Radiative Processes in Astrophysics

Prof Wladimir Lyra

Live Oak, 1119-G
Office Hours: Mon 4:00pm-5:00pm
Class hours: Mon/Wed 5:00pm-6:15pm

California State University, Northridge
1958

Quick Bio

Wladimir Lyra

B.Sc. in Astronomy, Federal University of Rio de Janeiro (UFRJ, **Brazil**), 1999-2003.

Research Assistant 2003-2004
Space Telescope Science Institute (*STScI*, Baltimore **MD**)
Cerro Tololo Interamerican Observatory (*CTIO*, La Serena – **Chile**)
European Southern Observatory (*ESO*, Munich – **Germany**)
Lisbon Observatory, **Portugal**.

Ph.D. in Astronomy, Uppsala University (Uppsala, **Sweden**), 2004-2009.
Nordic Institute for Theoretical Physics (*NORDITA*, Stockholm, **Sweden**)
Max-Planck Institute for Astronomy (*MPIA*, Heidelberg, **Germany**)

Postdoctoral Researcher
American Museum of Natural History (*AMNH*, New York **NY**), 2009-2011.
Jet Propulsion Laboratory (NASA-JPL/Caltech, Pasadena **CA**), 2011-2015.

Stellar Astrophysics, Planetary Sciences
Solar-type stars, extrasolar planets, star formation, *circumstellar disks and planet formation*.
Hydrodynamics, plasma physics, turbulence, life in the universe, *icy moons and Europa*.

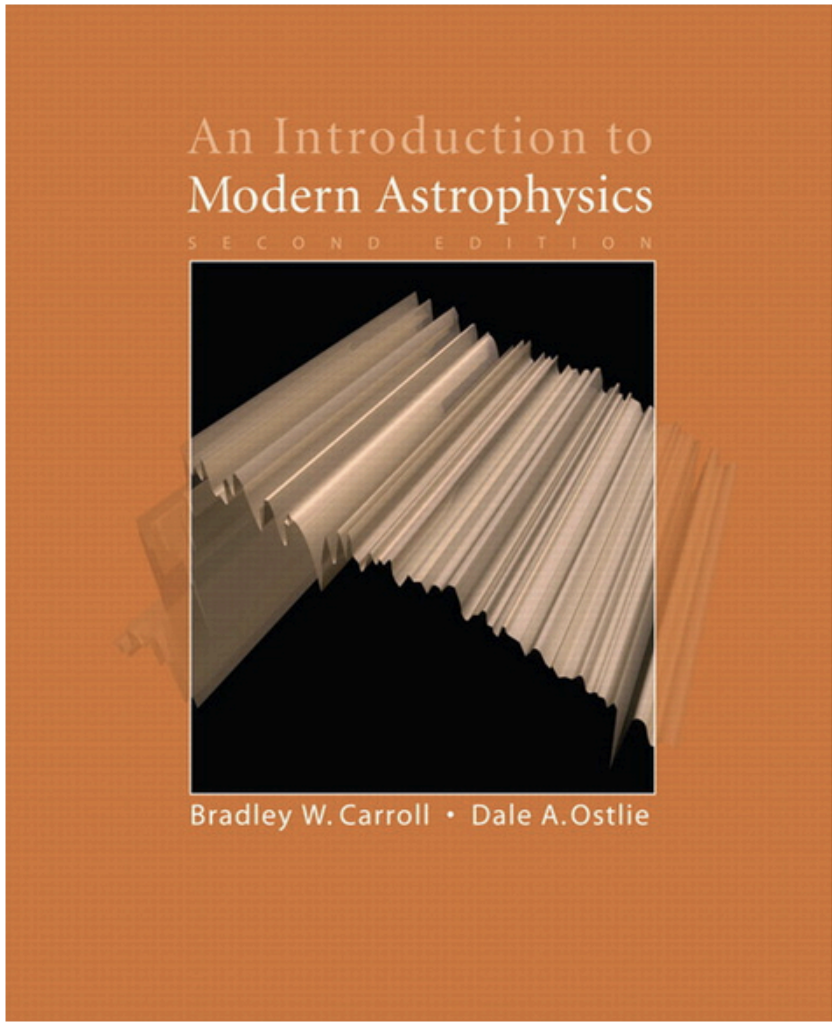
Grading

Homework	*(1/2)*
Exams	*(1/2)*
Midterm	
Exam	

Topics

- Radiative Transfer
- Stellar Structure
- Stellar Evolution
- Magnetohydrodynamics
- Cosmology

Books (or lack thereof)



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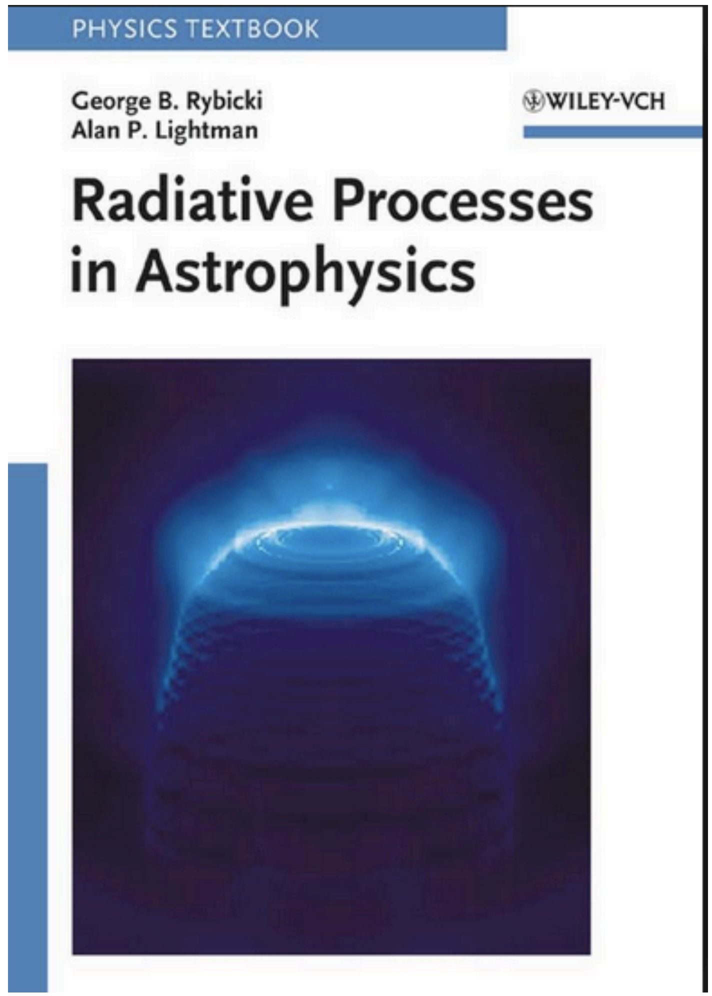

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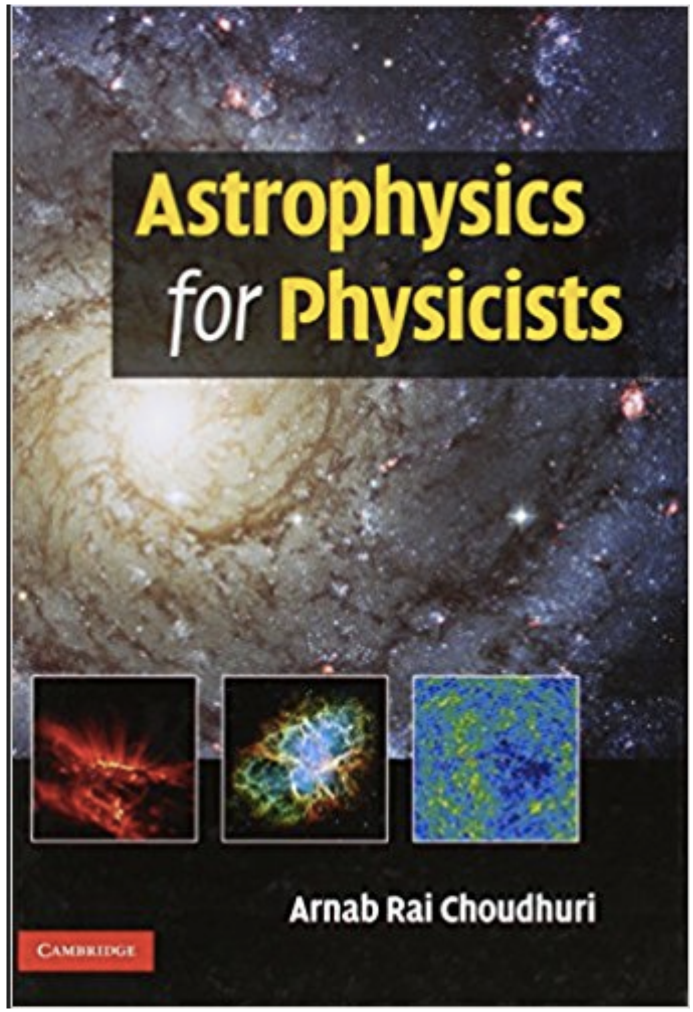

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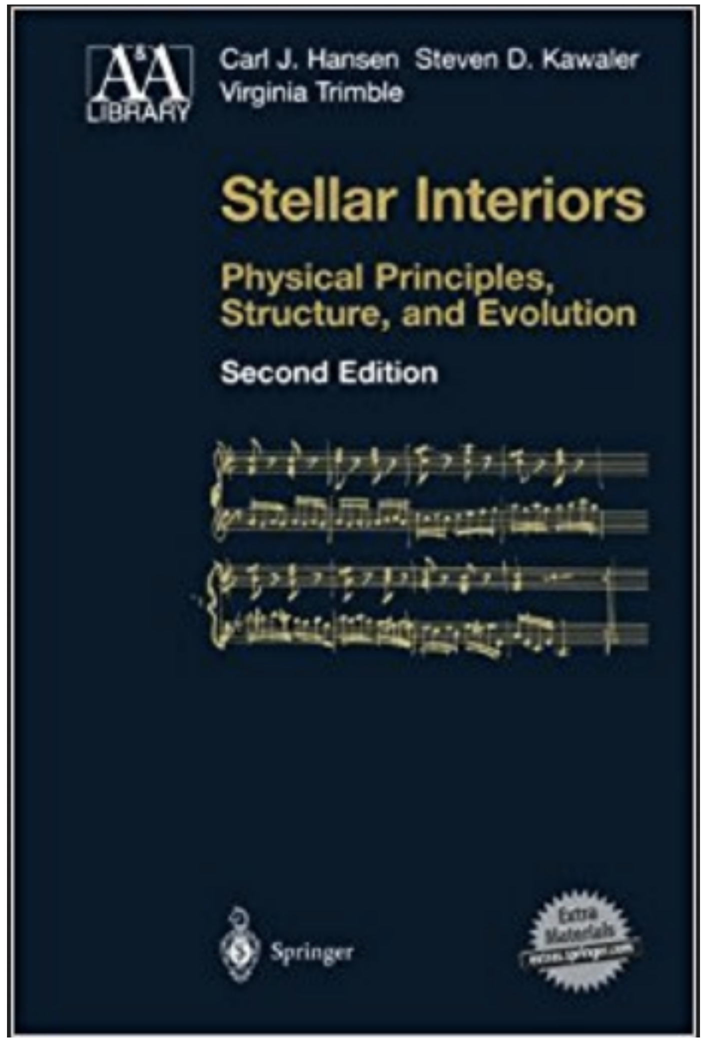

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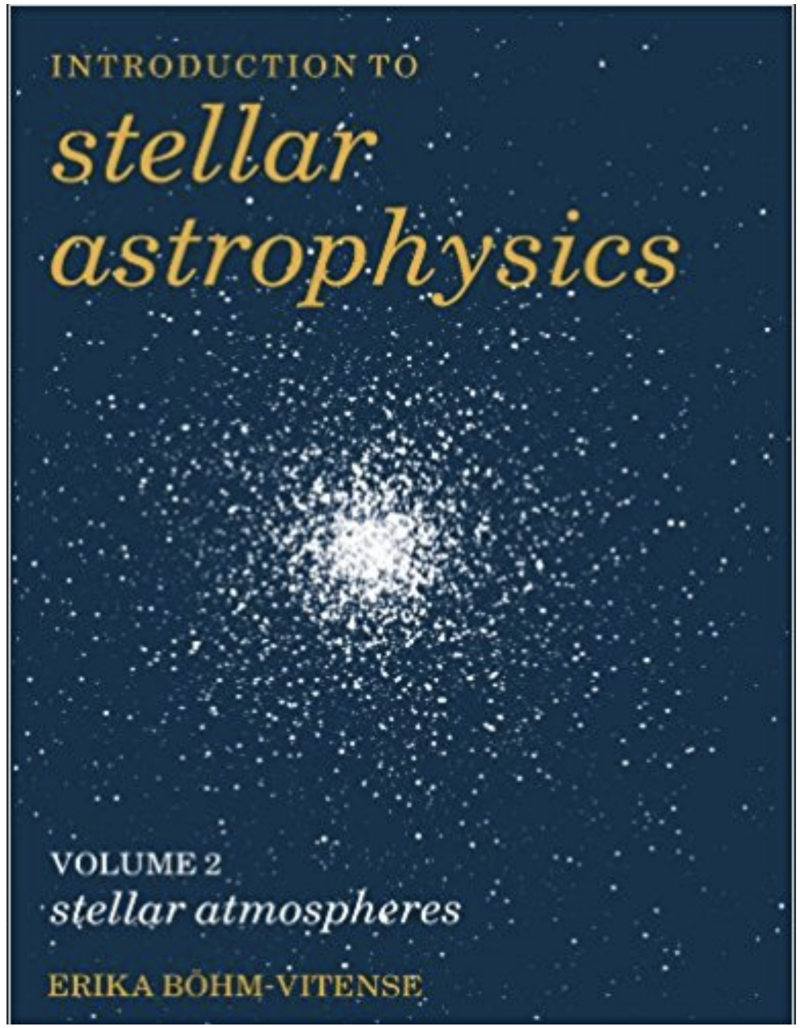

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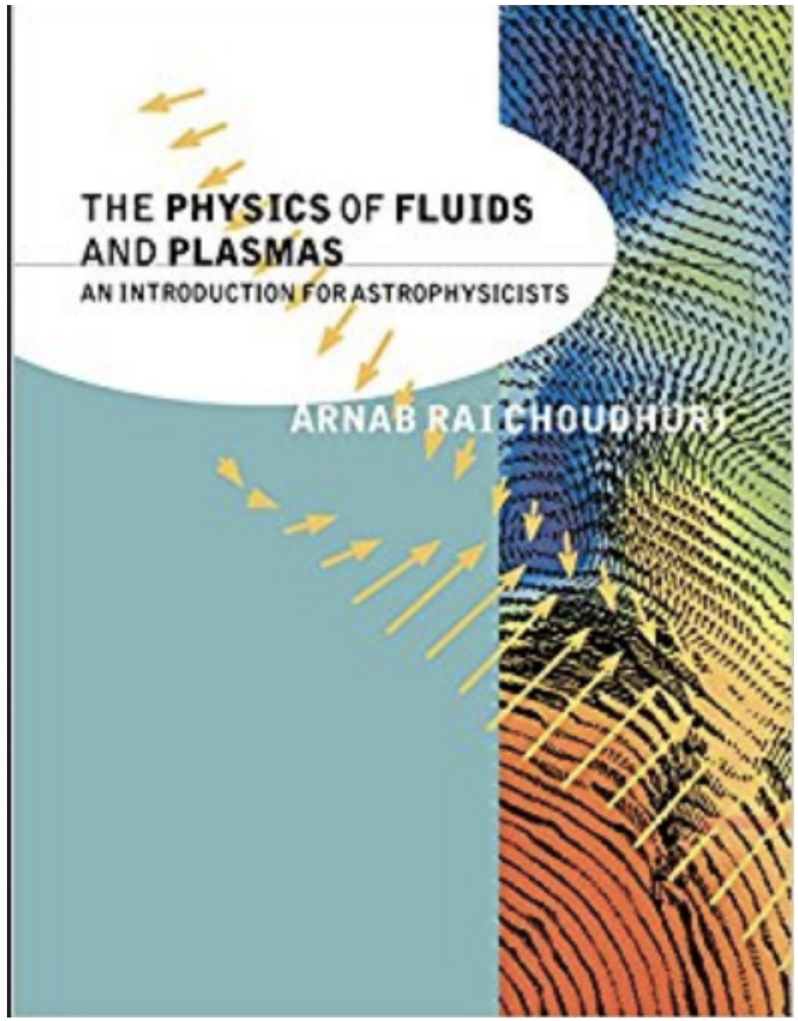

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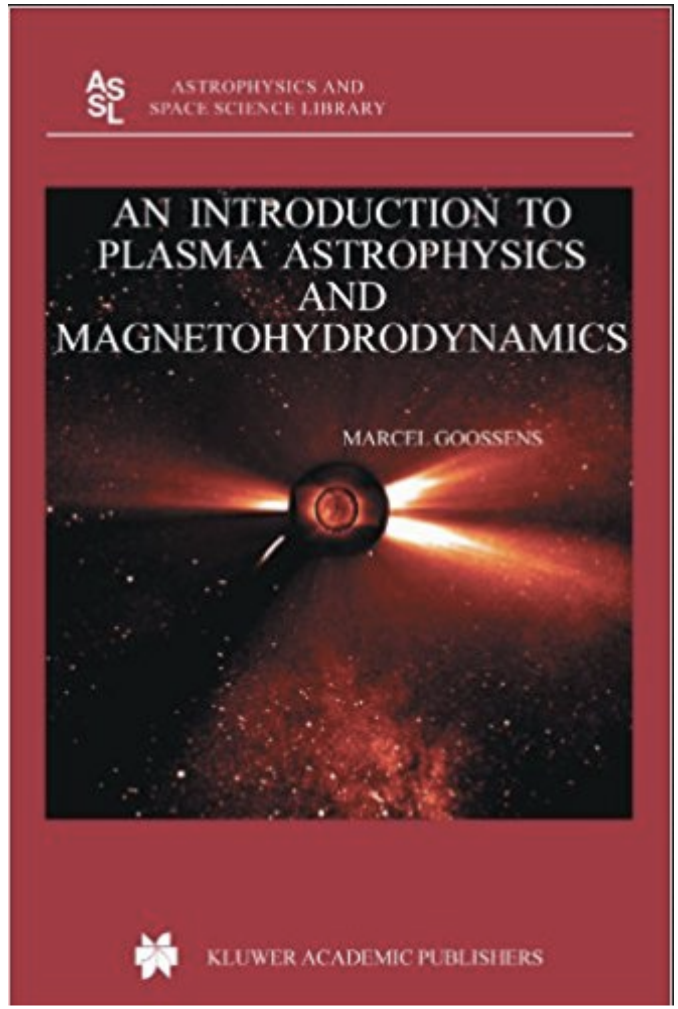

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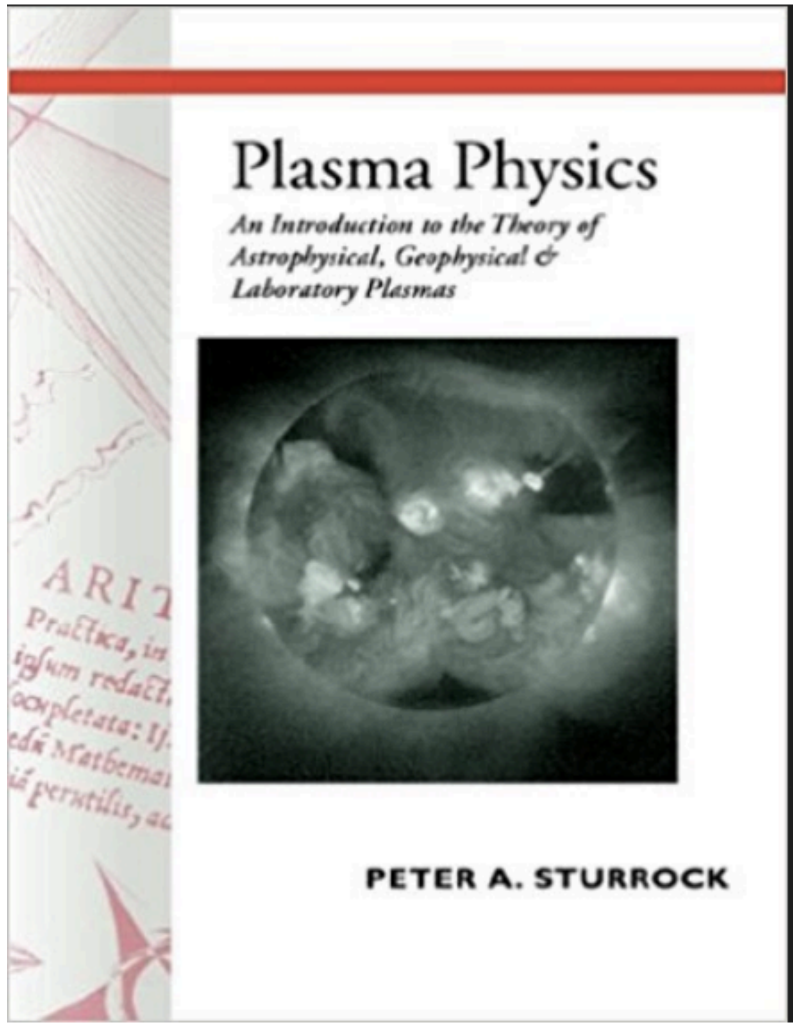

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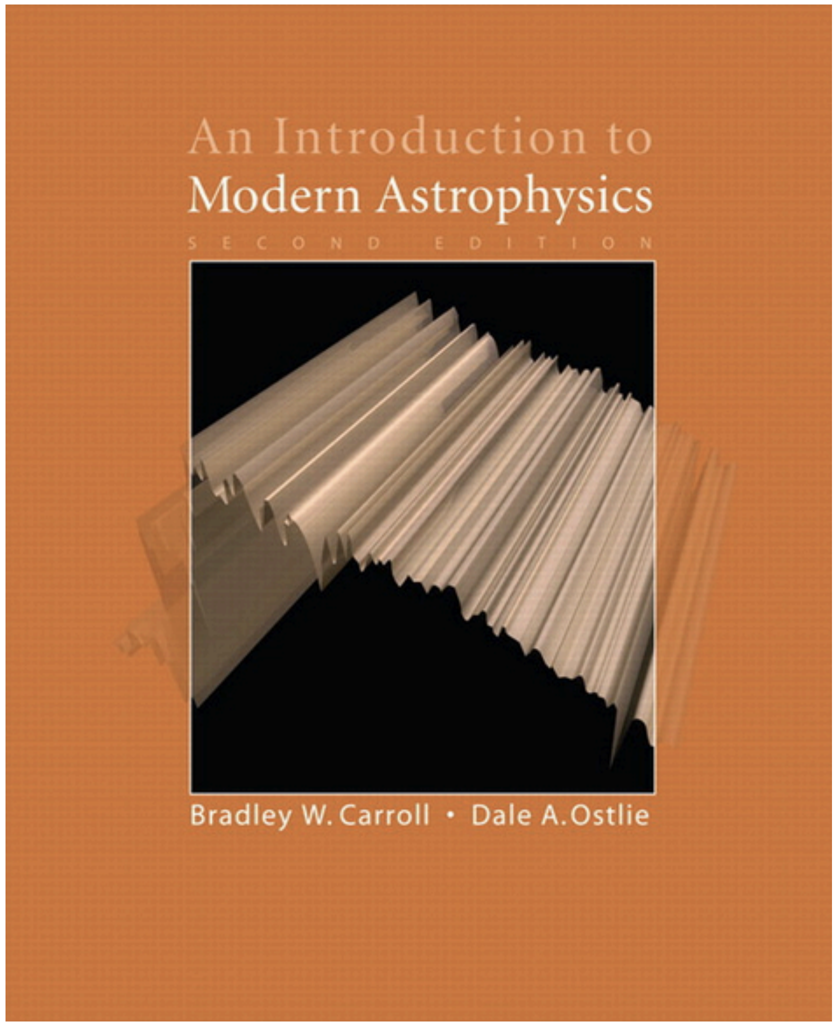
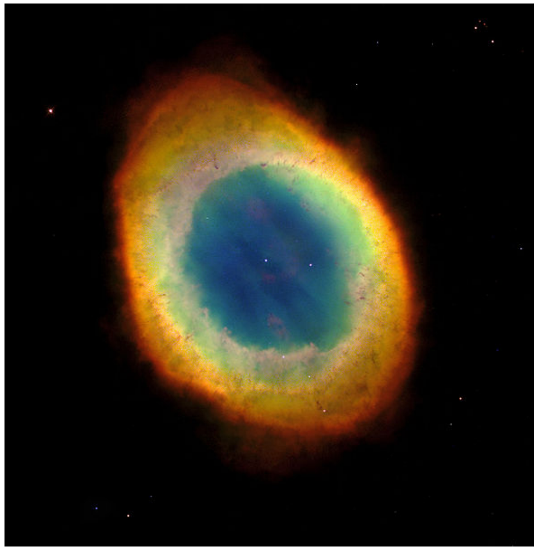
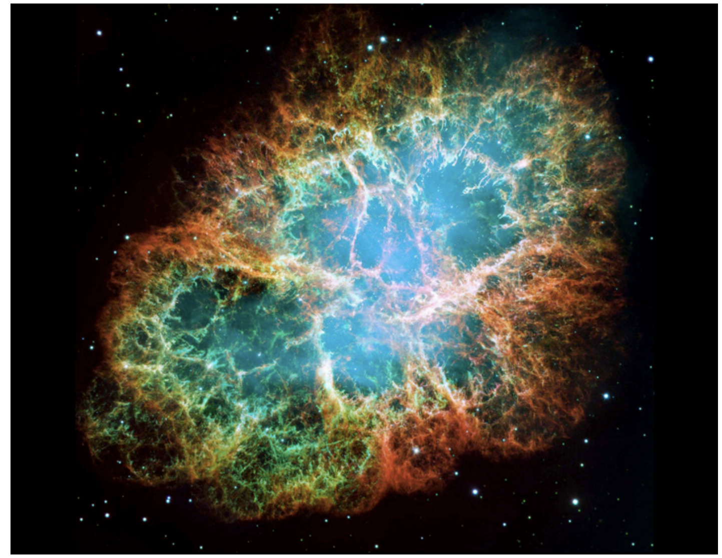
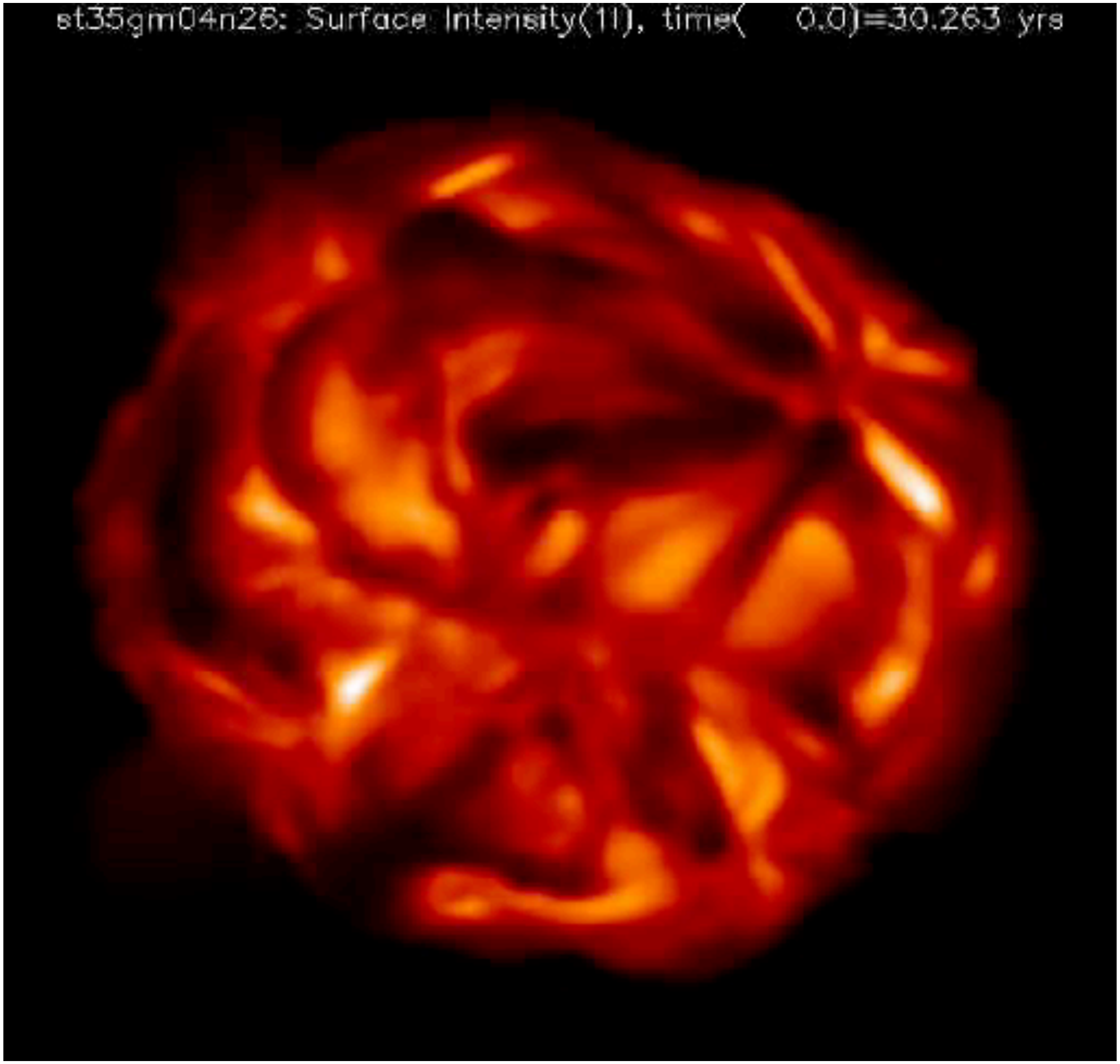







SPL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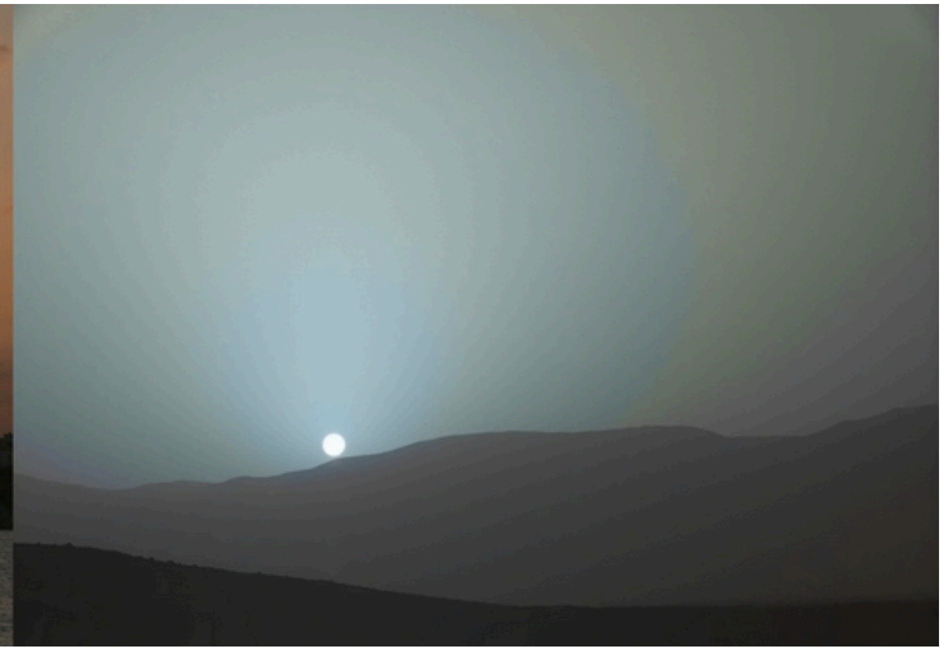
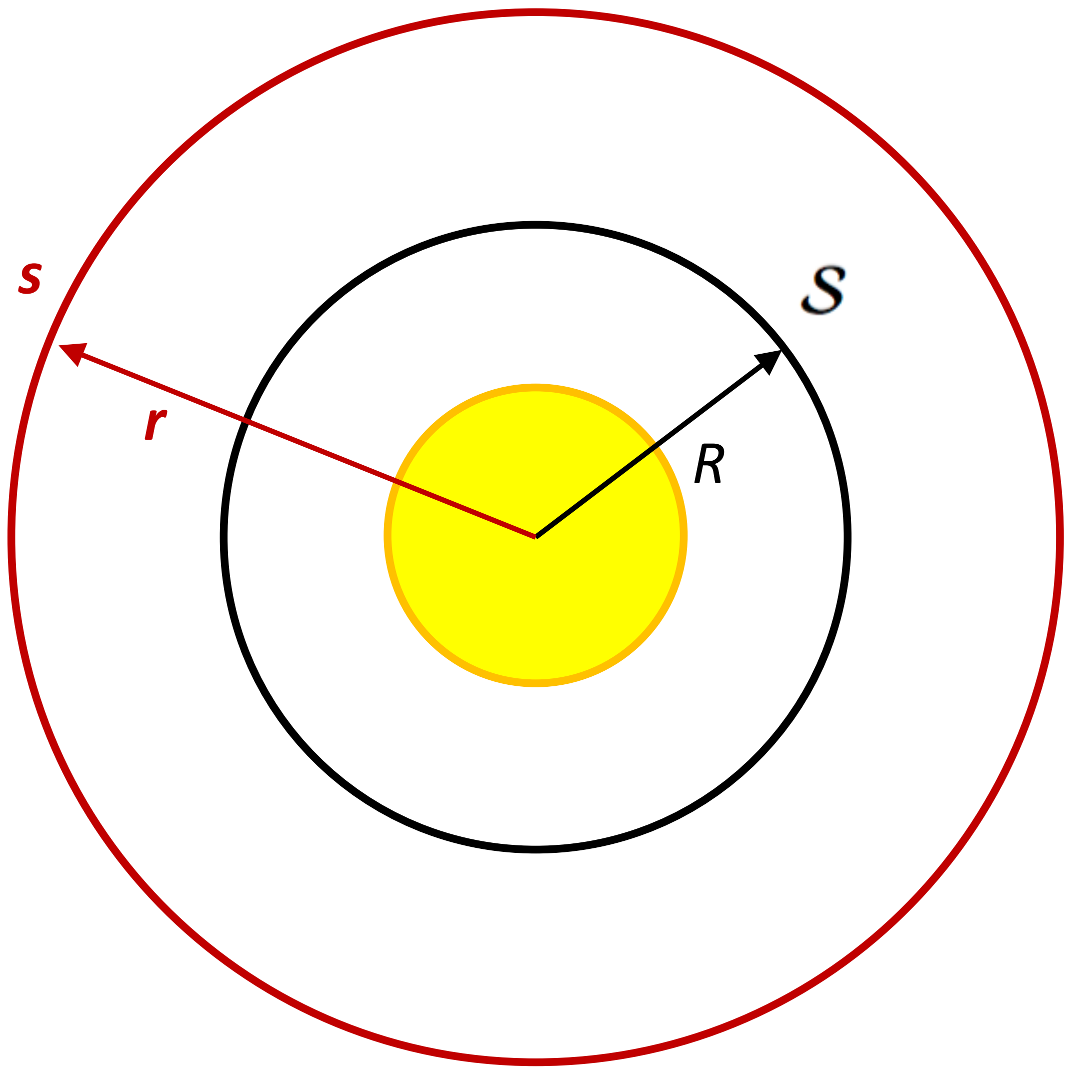


Outline

✓ Principles of Radiative Transfer


s
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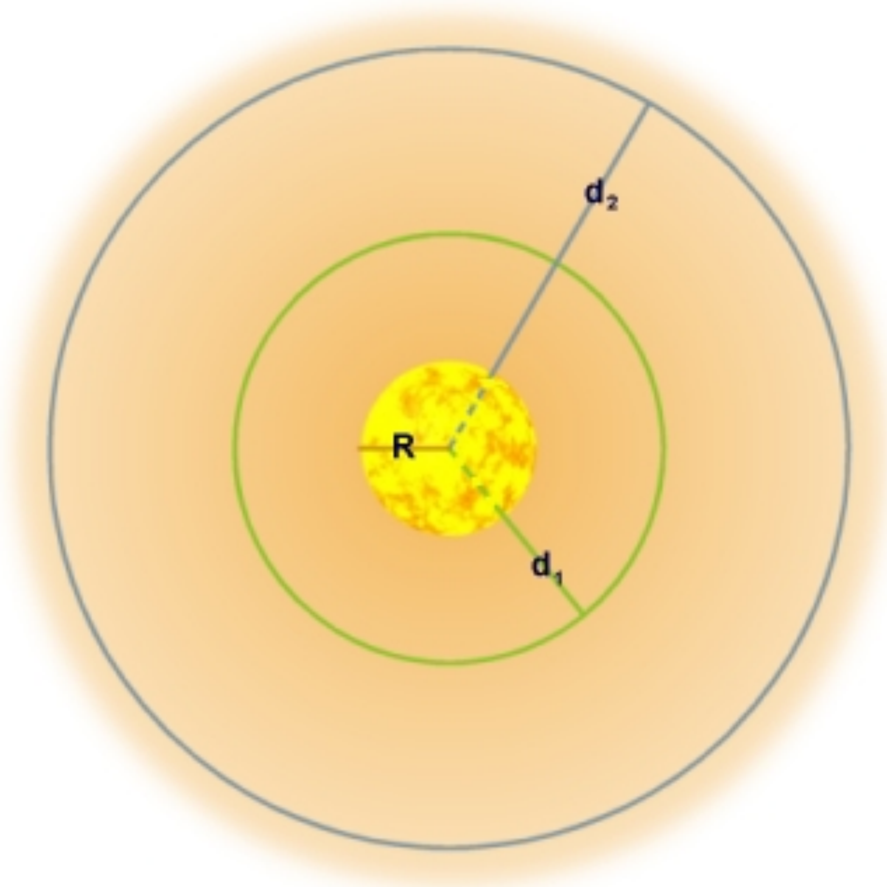


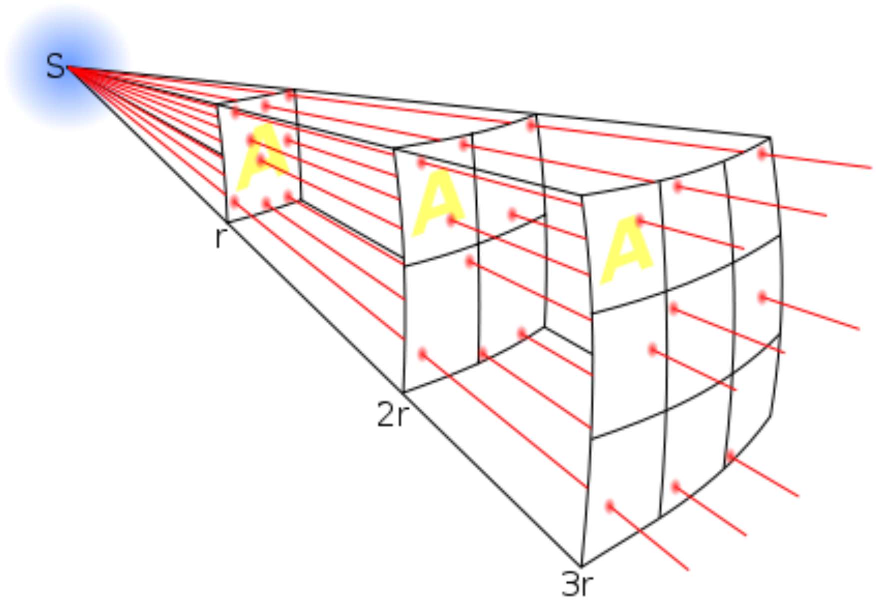
Inverse Square Law

$$f_1 = \frac{L}{4\pi d_1^2}$$

$$f_2 = \frac{L}{4\pi d_2^2}$$

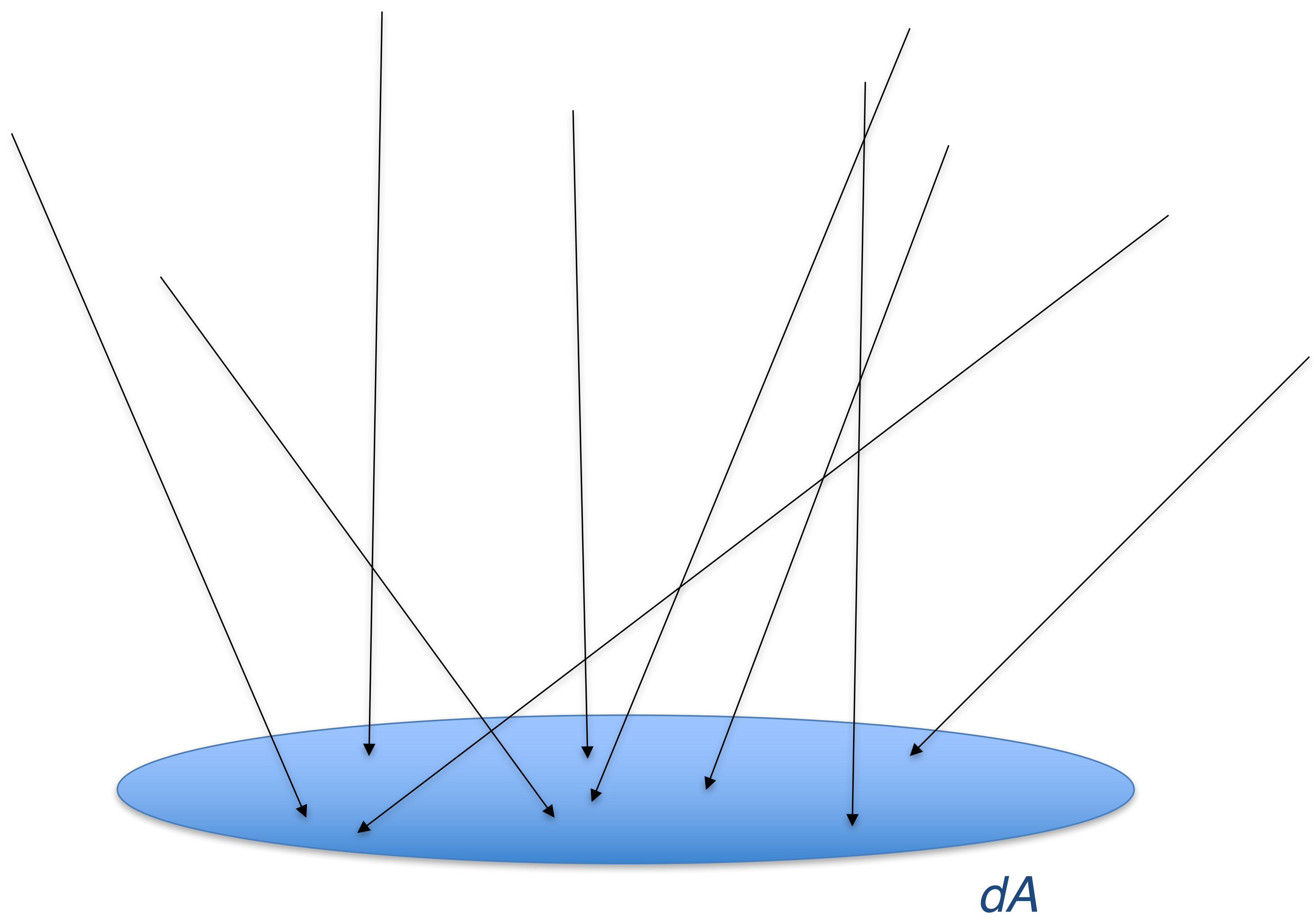
L = constant

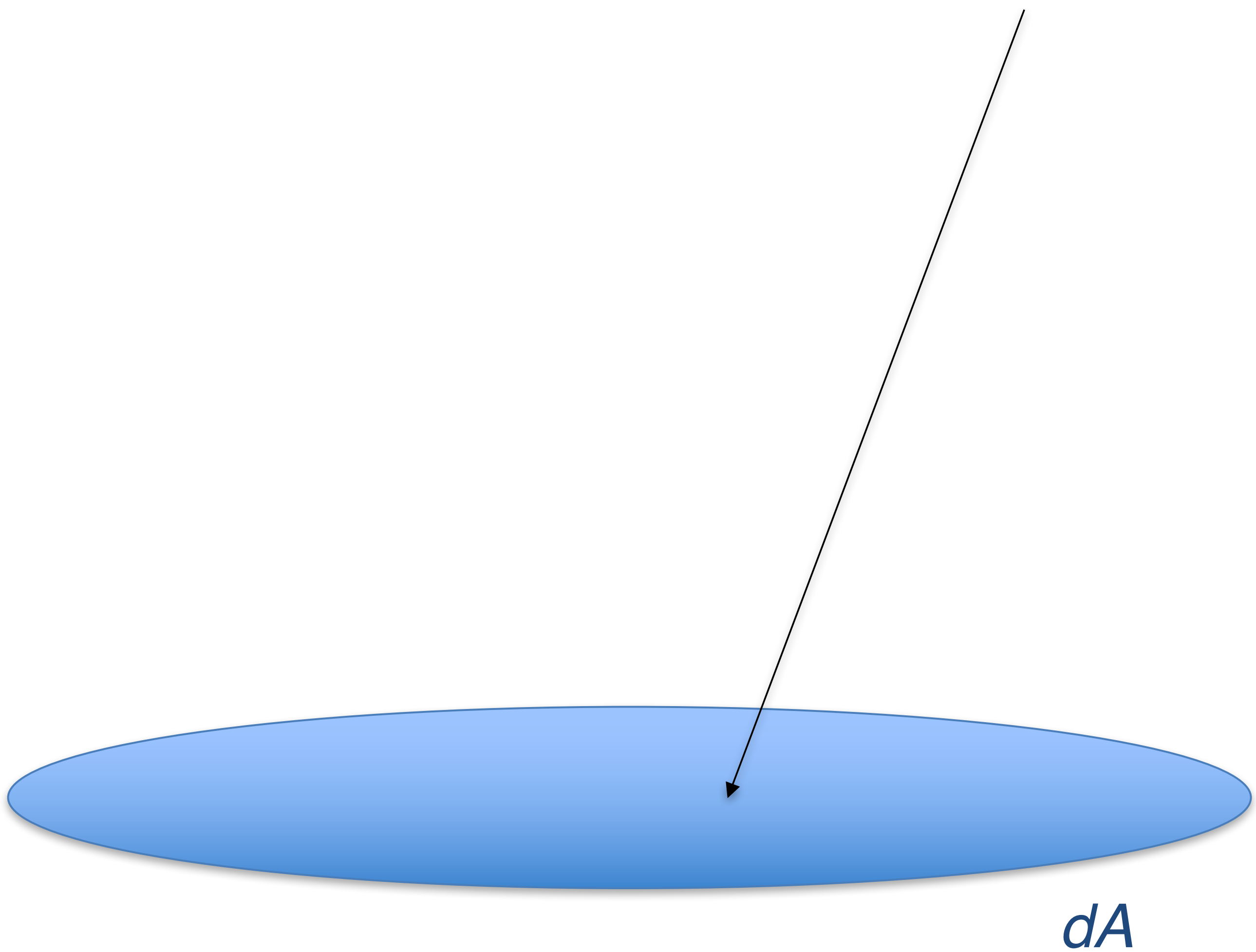
$f_2 < f_1$



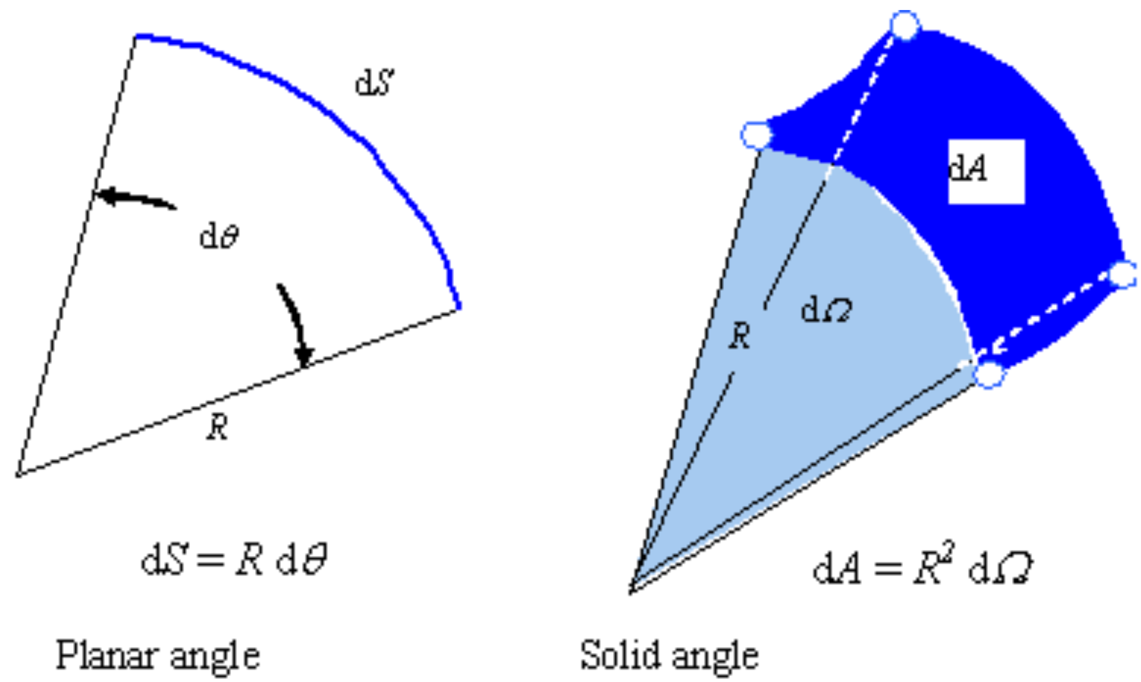
$$F \propto 1/r^2$$

As distance increases, the same energy spreads through a larger area

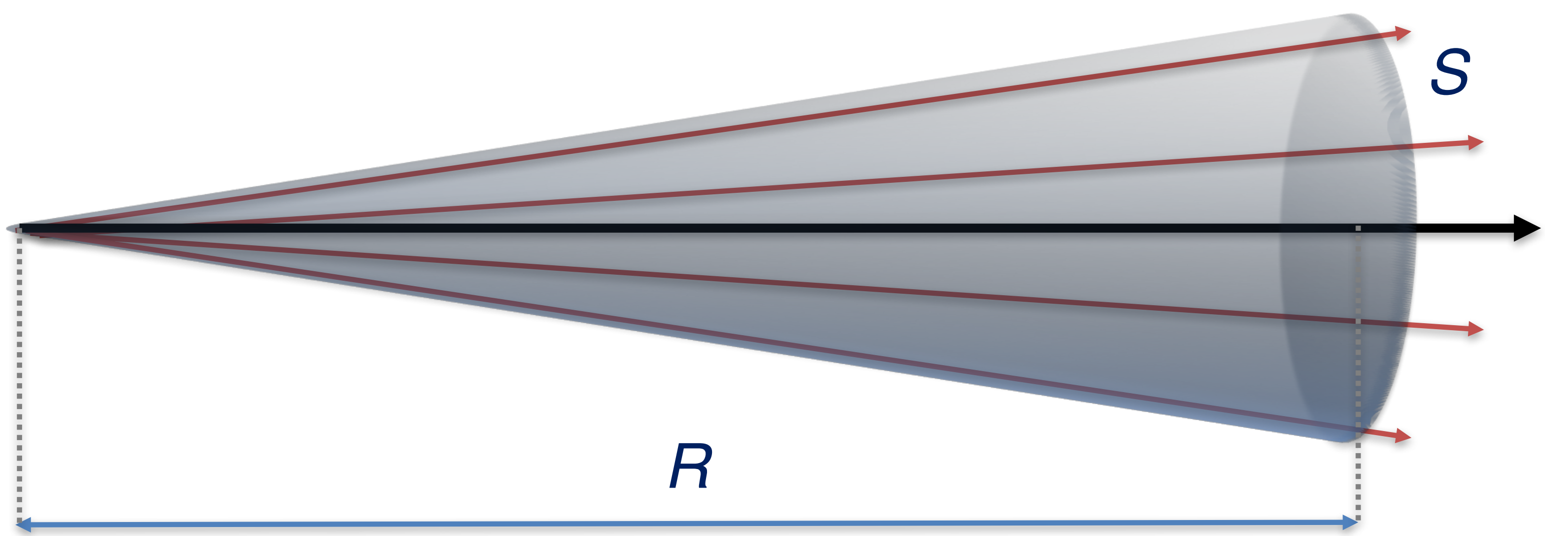

dA


dA

Planar vs solid angle

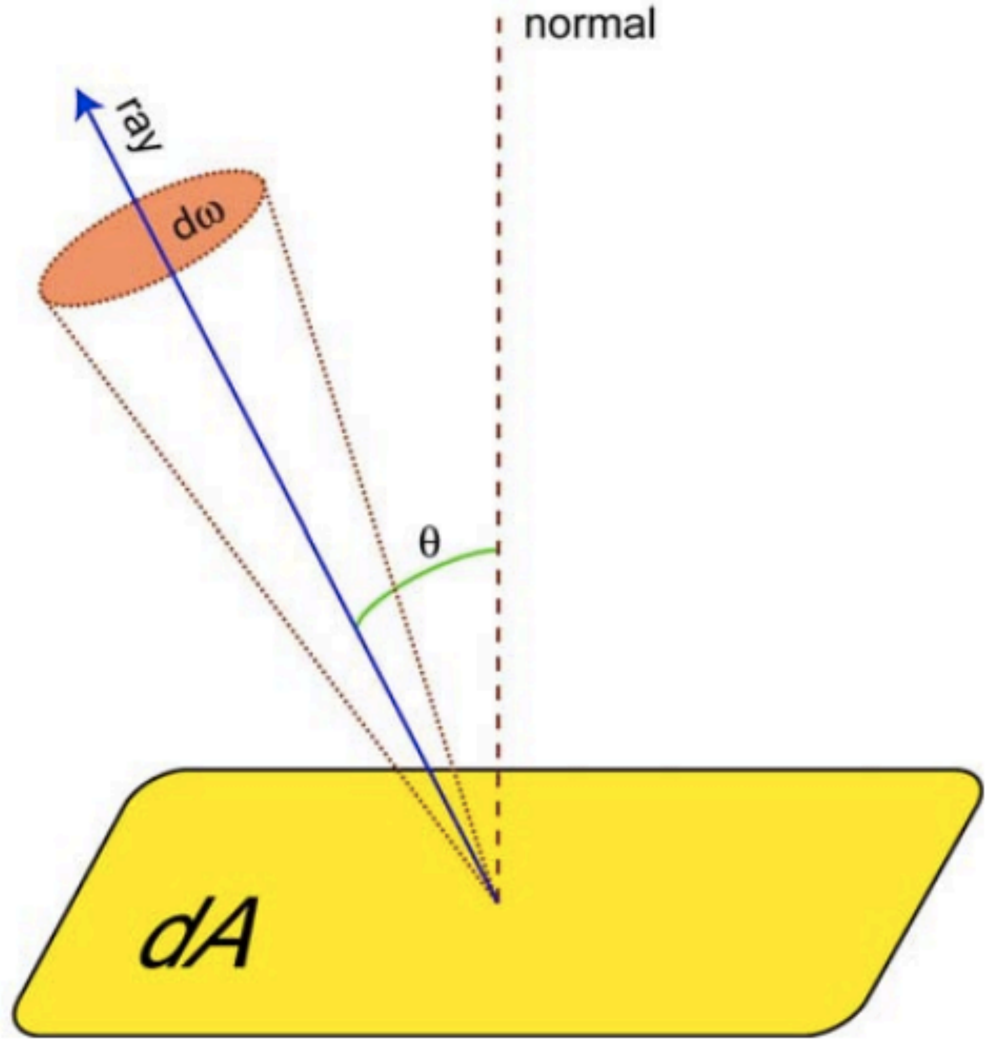


A planar angle encloses a length in the circumference of a circle;
Likewise, a solid angle encloses an area on the surface of a sphere.

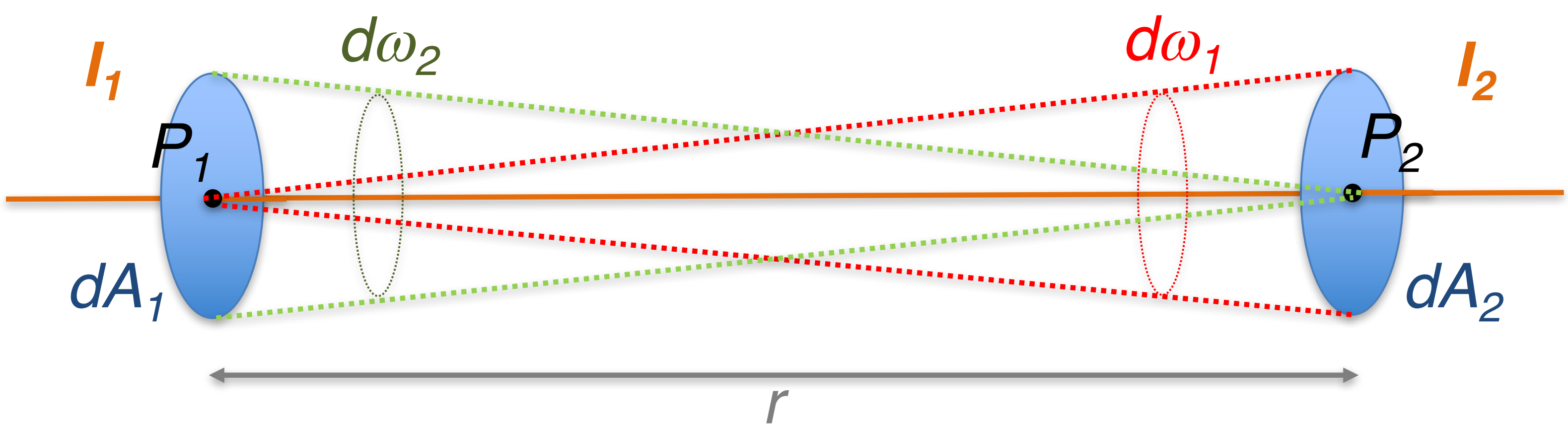


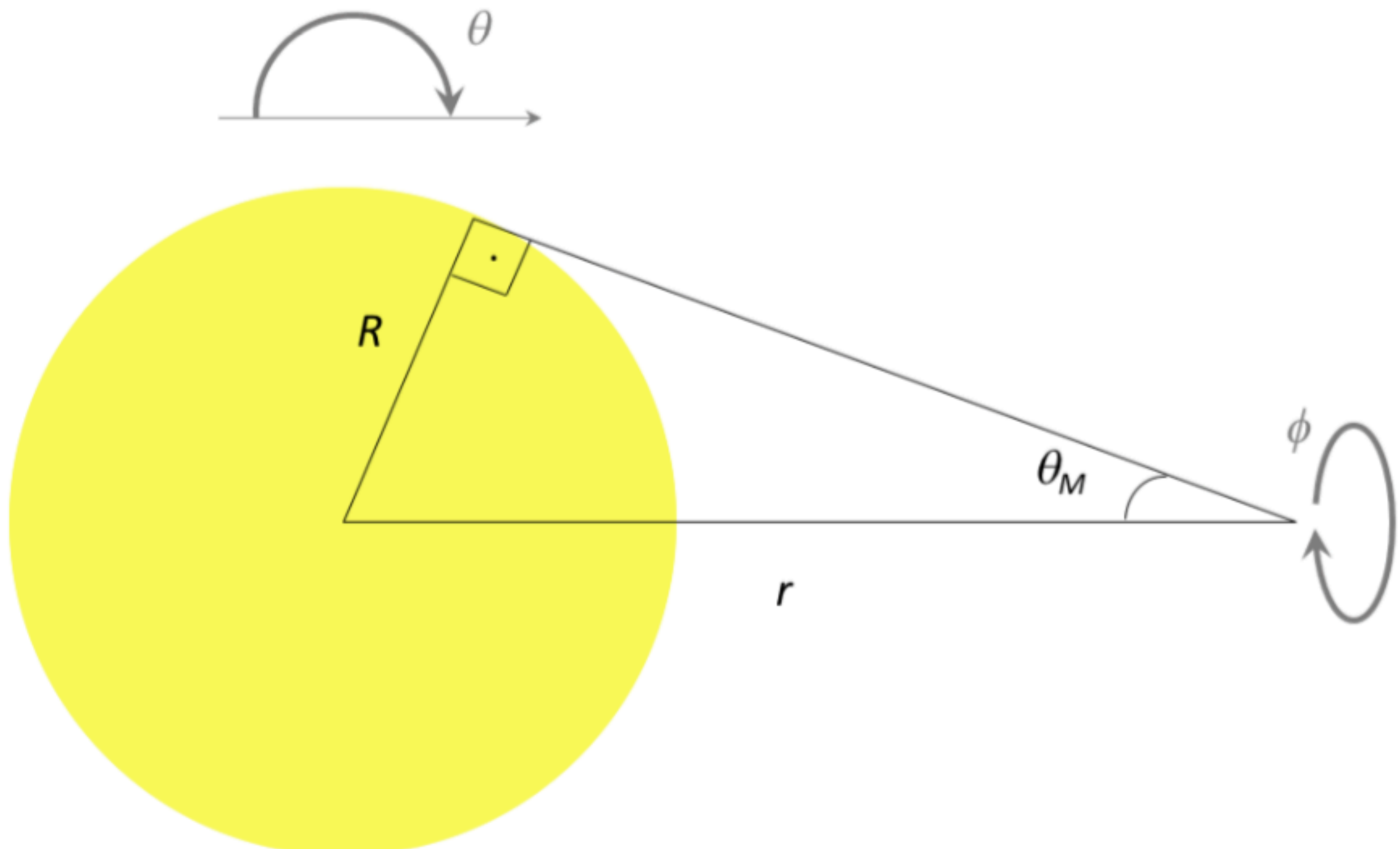
$$\omega = S/R^2$$

Intensity: geometry



Intensity does not depend on distance





θ
R
θM
r
ϕ

Understanding stars

With a quick look at the night sky, we realize two main differences between stars: brightness and color.

Magnitudes

Now here goes something really ancient....

A guy called Hipparchus (190BC – 120BC) thought it a good idea to come up with the following scheme :

- The brightest stars we see are of **first magnitude**
- Stars not so bright are of **second magnitude**
- The faintest stars we can see are of **fifth magnitude**

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Bright – Magnitude 1
Dim – Magnitude 5

*The scale is **reverse**!*

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- The brightest stars we see are of **first magnitude**
- Stars not so bright are of **second magnitude**
- The faintest stars we can see are of **sixth magnitude**

Bright – Magnitude 1
Dim – Magnitude 5

*The scale is **reverse**!*

Stellar Binocular
Magnitude 9

Amateur 6 inch
Magnitude 13

Hubble Space Telescope
Magnitude 30

Stellar Binocular

Magnitude 9

15 times dimmer than faintest for the naked eye

Amateur 6 inch

Magnitude 13

630 times dimmer than faintest for the naked eye

Hubble Space Telescope

Magnitude 30

4×10^9 times dimmer than faintest for the naked eye

Magnitudes

Big magnitude – Dim

Small (or negative) magnitude - Bright

The magnitude scale is ***logarithmic!***

Why?

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Why?

Because the ***eye's response*** is (nearly) logarithmic

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Why?

Because the ***eye's response*** is (nearly) logarithmic

Really?

The Moon is 500,000 times dimmer than the Sun as seen from Earth

Yet one can read with nothing but moonlight....

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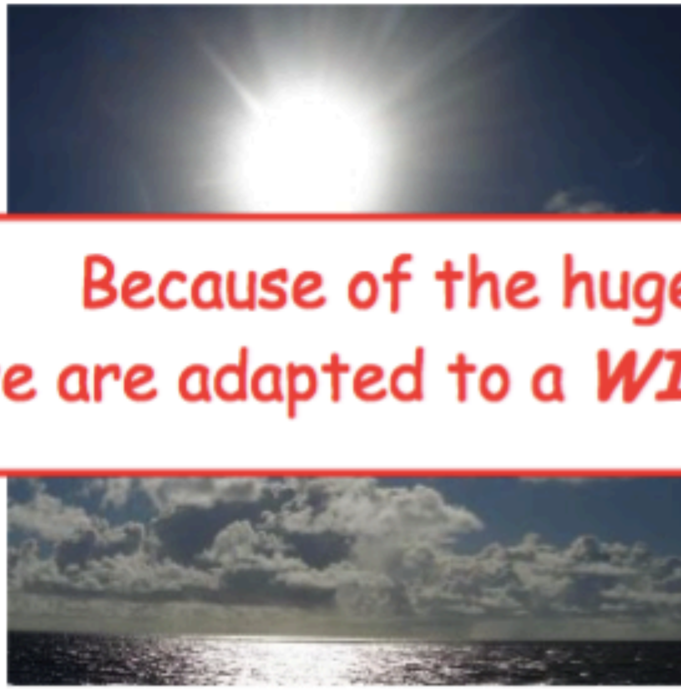
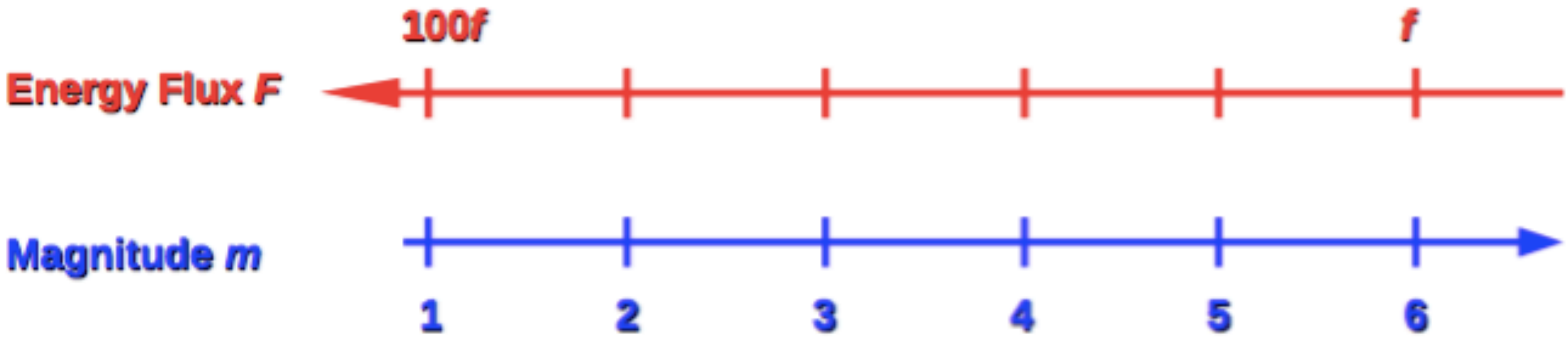


Because of the huge day-night contrast,
we are adapted to a ***WIDE RANGE*** in brightness

Yet one can read with nothing but moonlight....

How about magnitudes?

A difference of five magnitudes amounts to a factor 100 in brightness



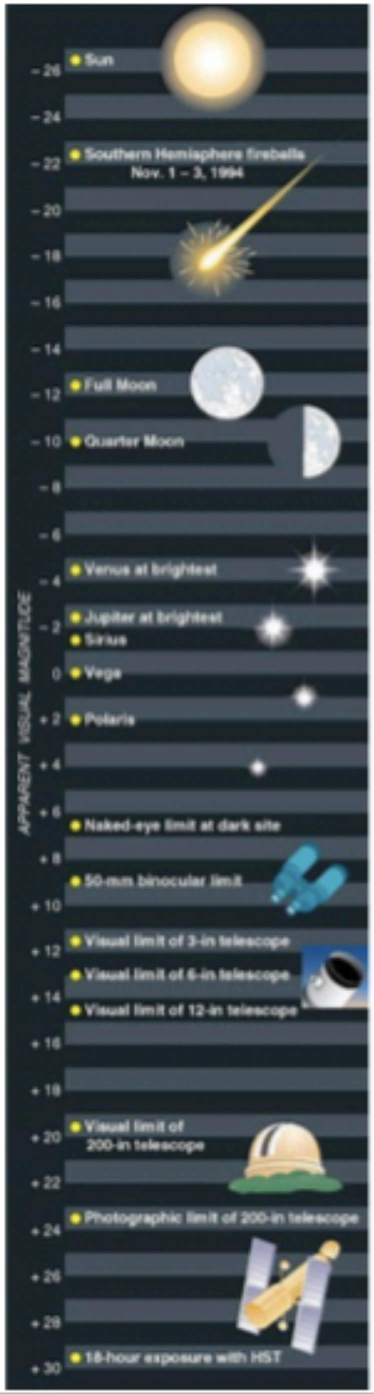
$$m = -2.5 \log F + C$$

m - stuff that Hipparchus came up with

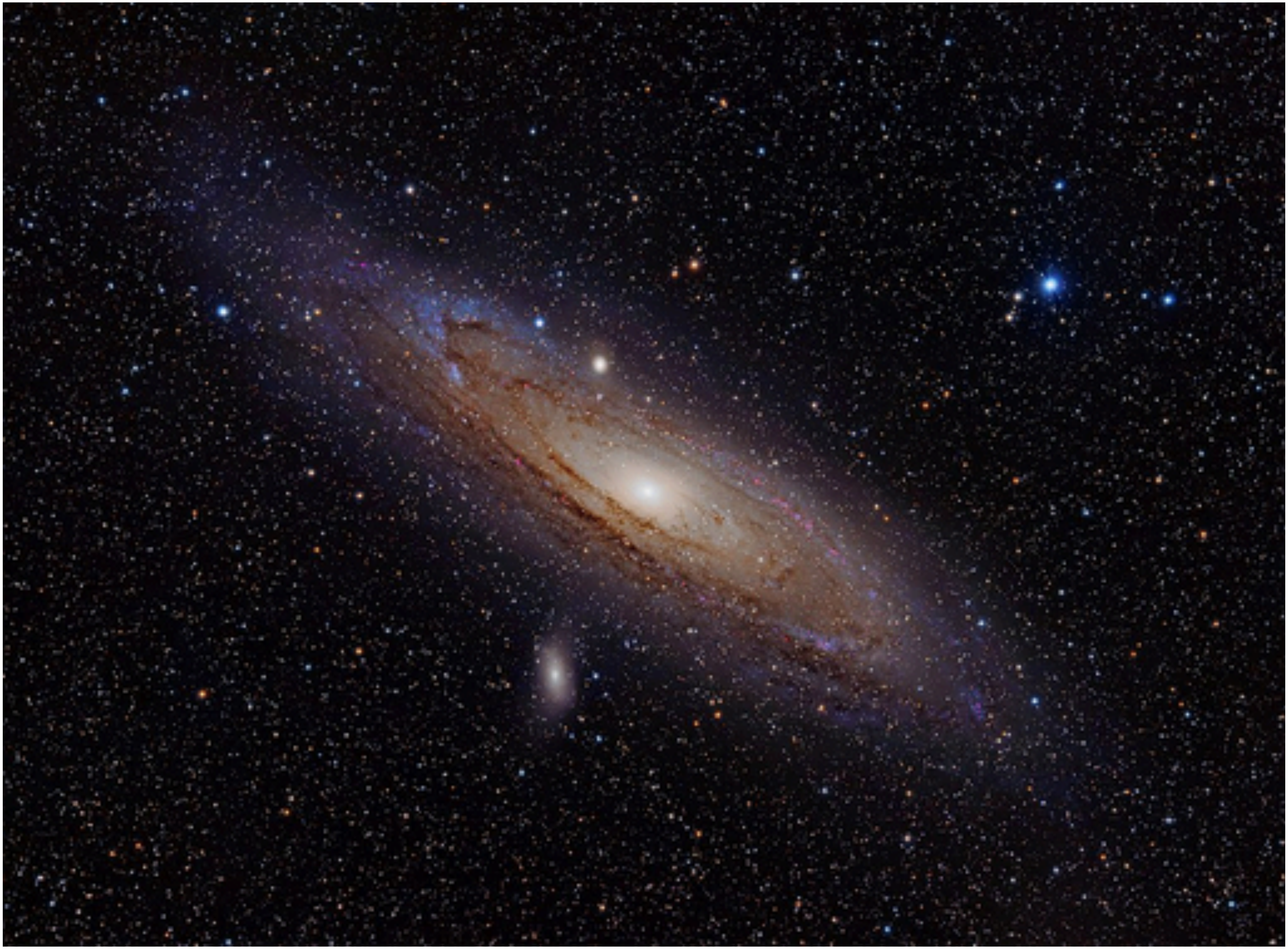
F - stuff that has physical meaning

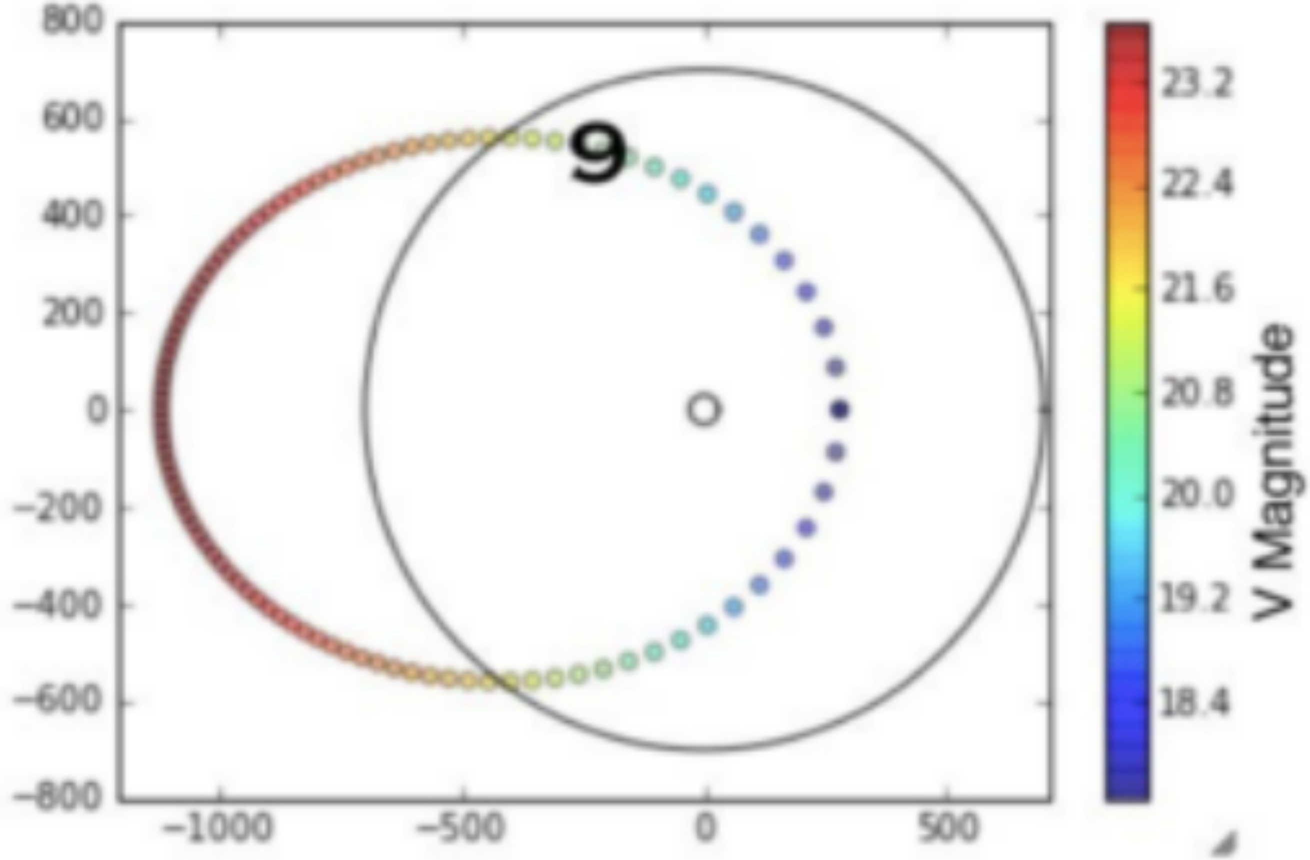
C - constant that make the two systems match

The system is tied so that Vega's magnitude is ZERO

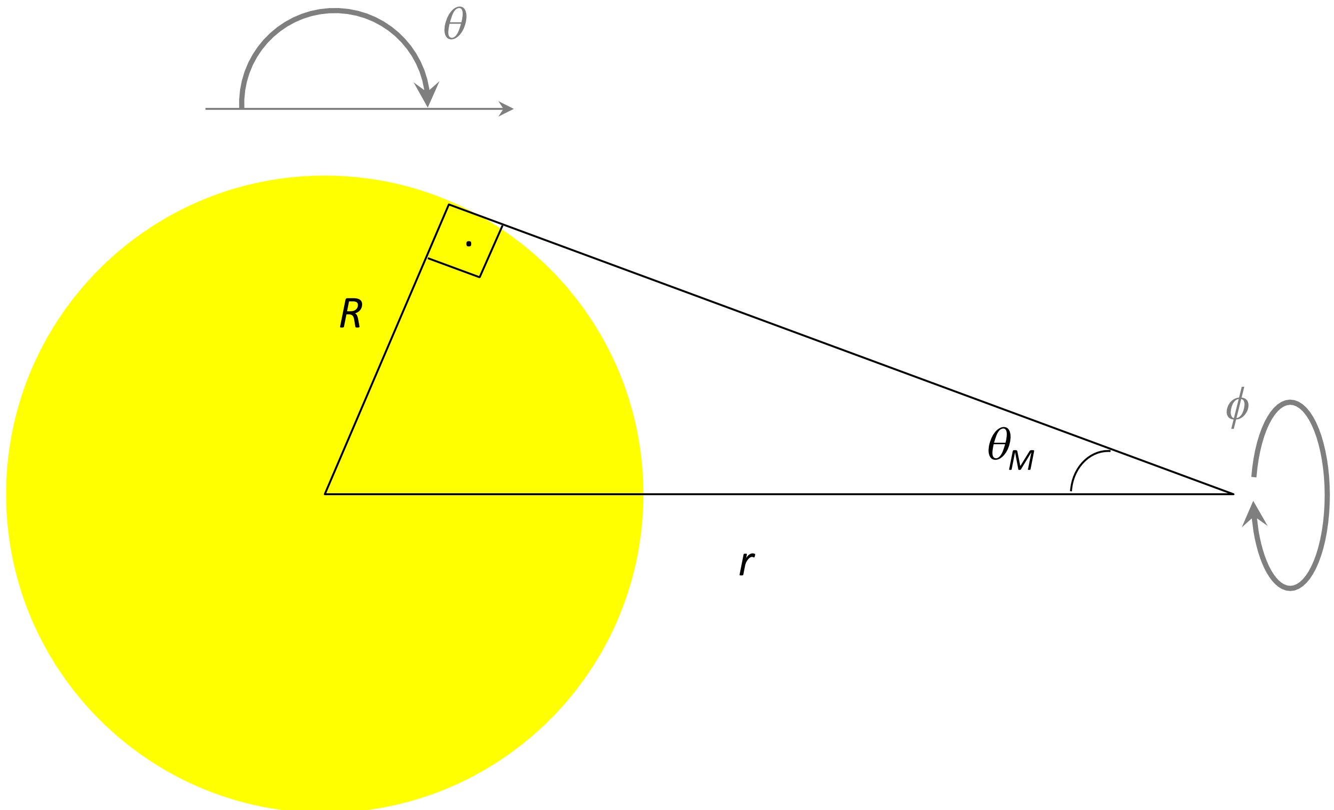


-26	Sun
-22	
-18	Comet
-12	Full Moon
-10	Quarter Moon
-4	Venus at brightest
-2	Jupiter at brightest
0	Vega
2	Polaris
6	Naked-eye limit at dark site
9	50mm binocular limit
11	Visual limit of 3-in telescope
13	Visual limit of 6-in telescope
15	Visual limit of 12-in telescope
20	Visual limit of 200-in telescope
24	Photographic limit of 200-in telescope
30	18-hour exposure with HST

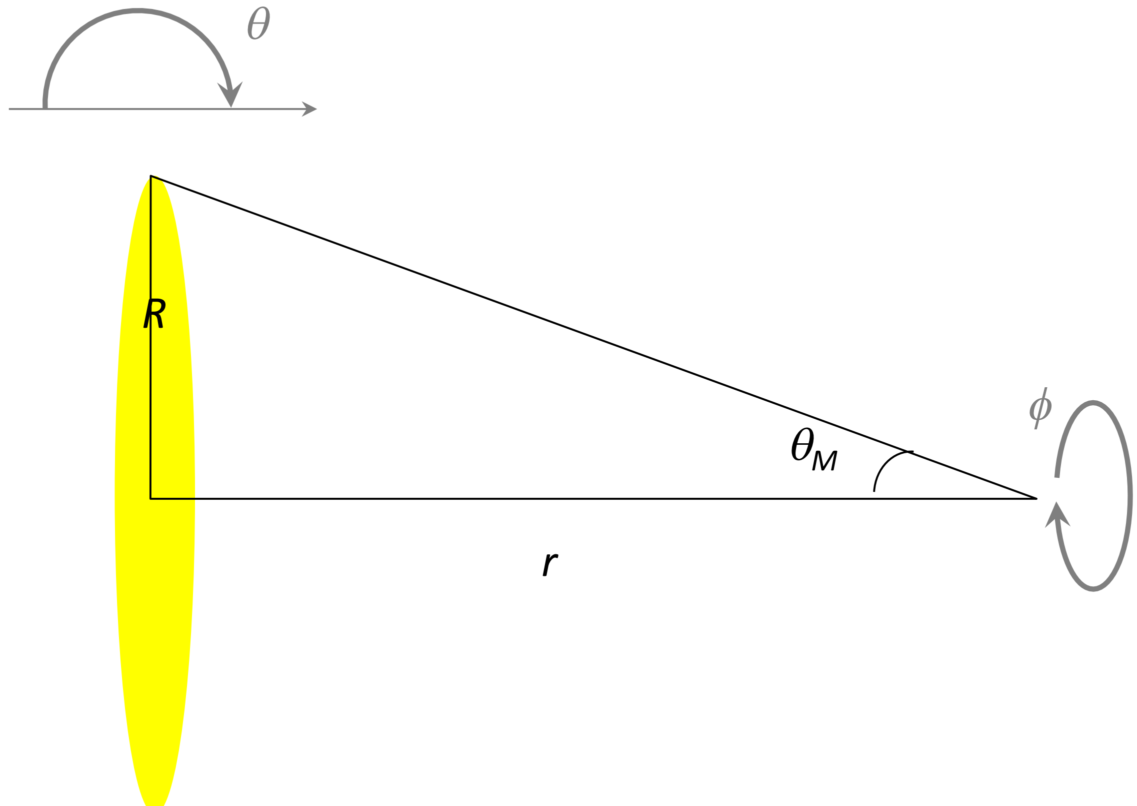




800
600
400
200
0
−200
−400
−600
−800
−1000
−500
0
500
9
23.2
22.4
21.6
20.8
20.0
19.2
18.4
V Magnitude

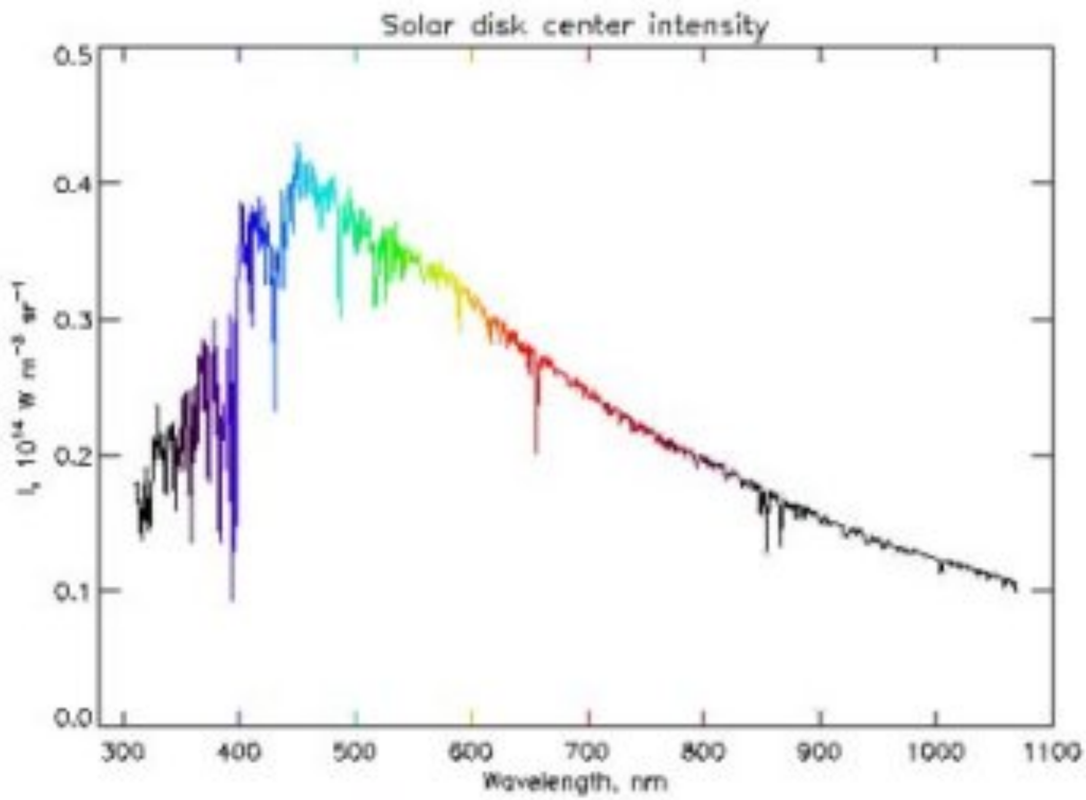


θ
R
θ_M
ϕ
r



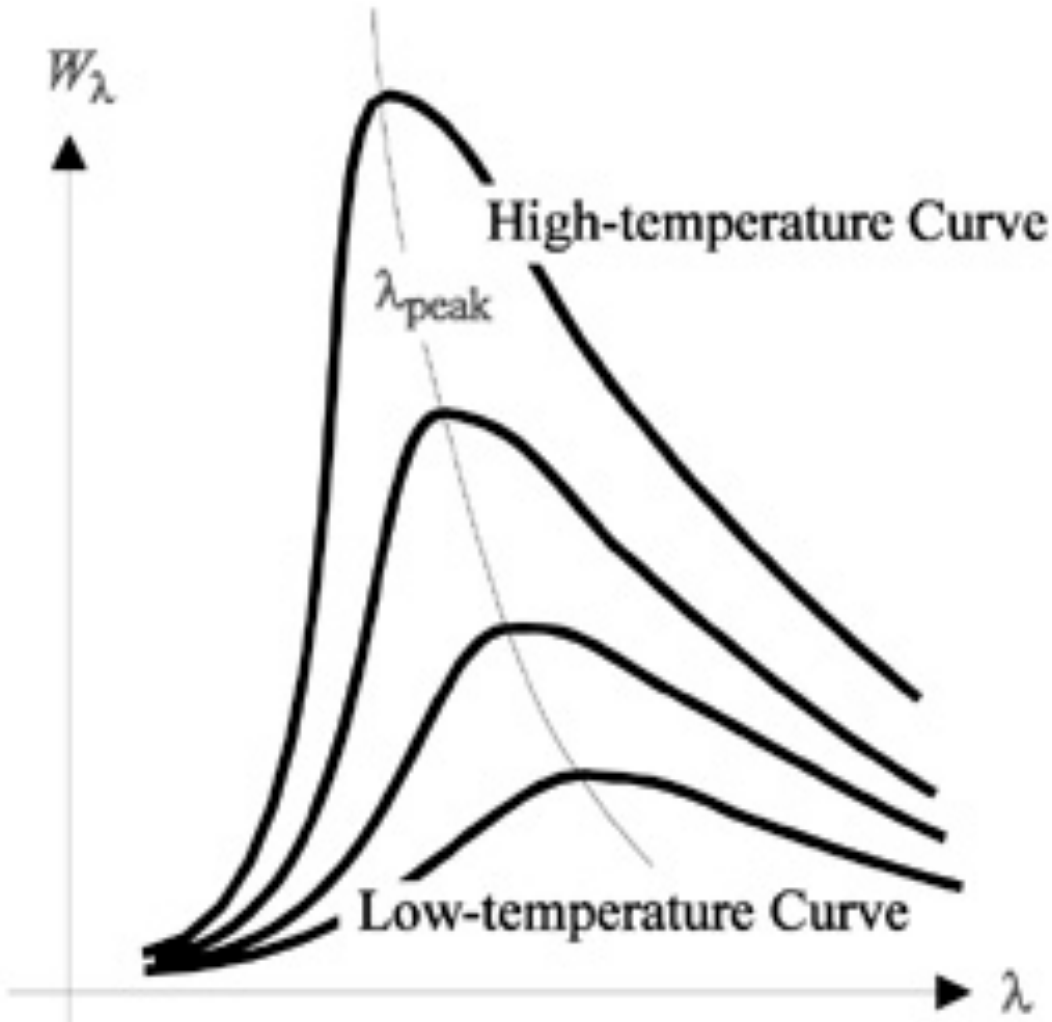
θ
R
θ_M
φ
r

The Solar Spectrum



Wien's displacement law

$$\lambda_{\max} T = const = 2.898 \times 10^{-3}\, mK$$



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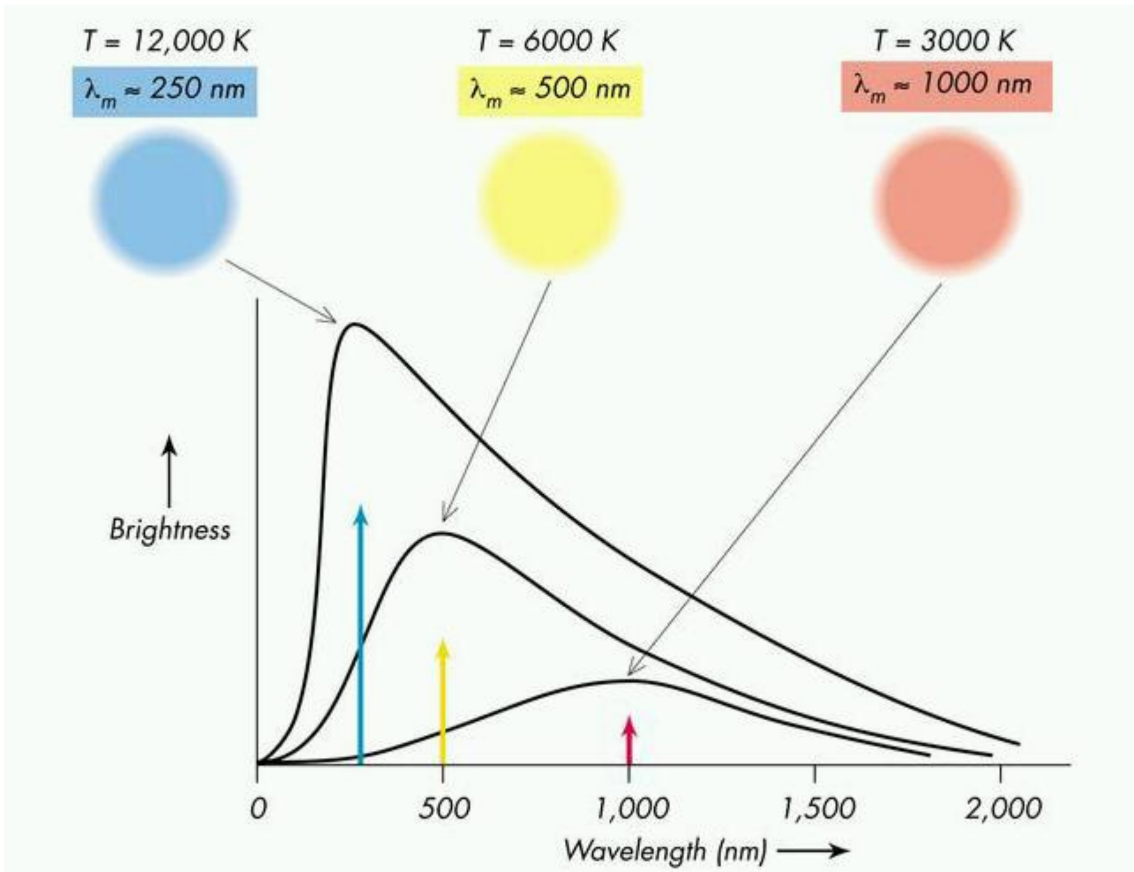
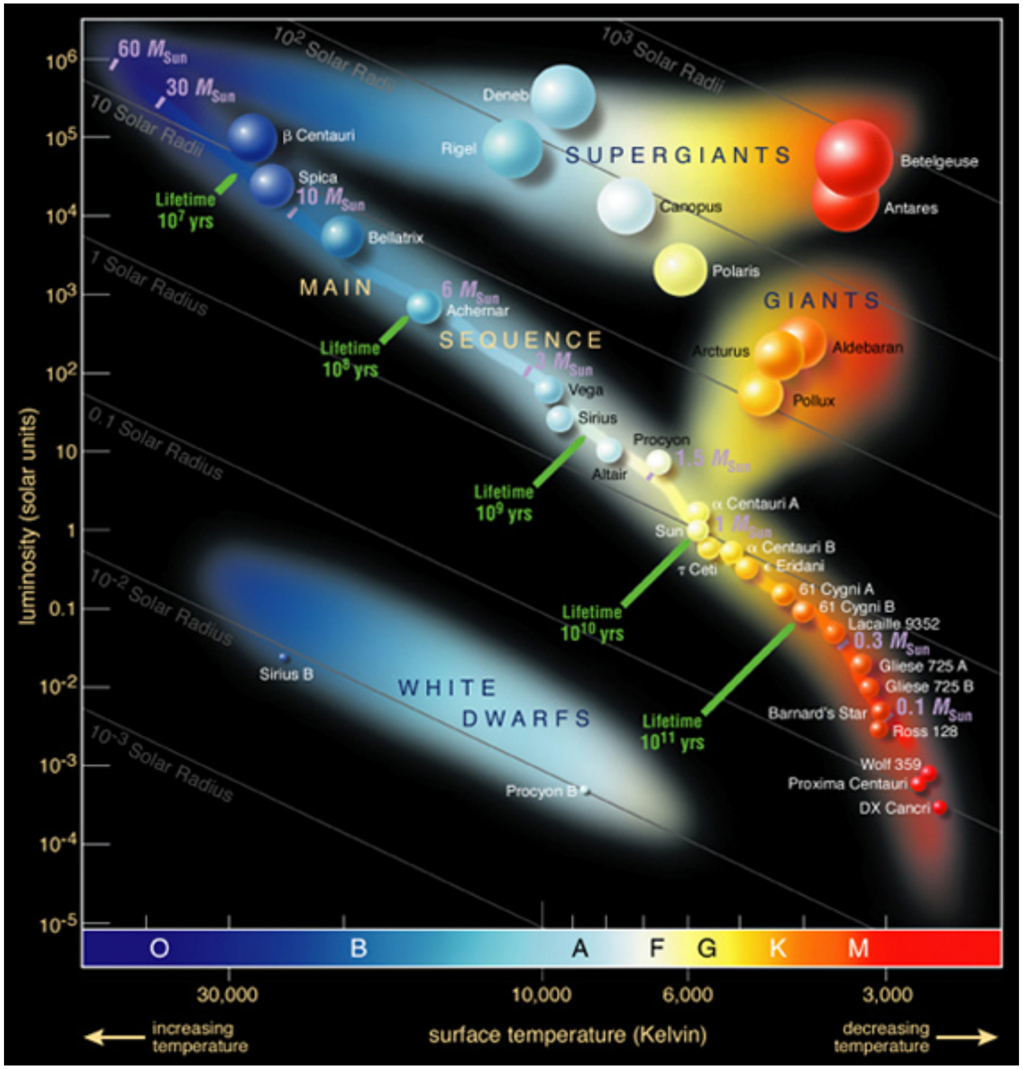
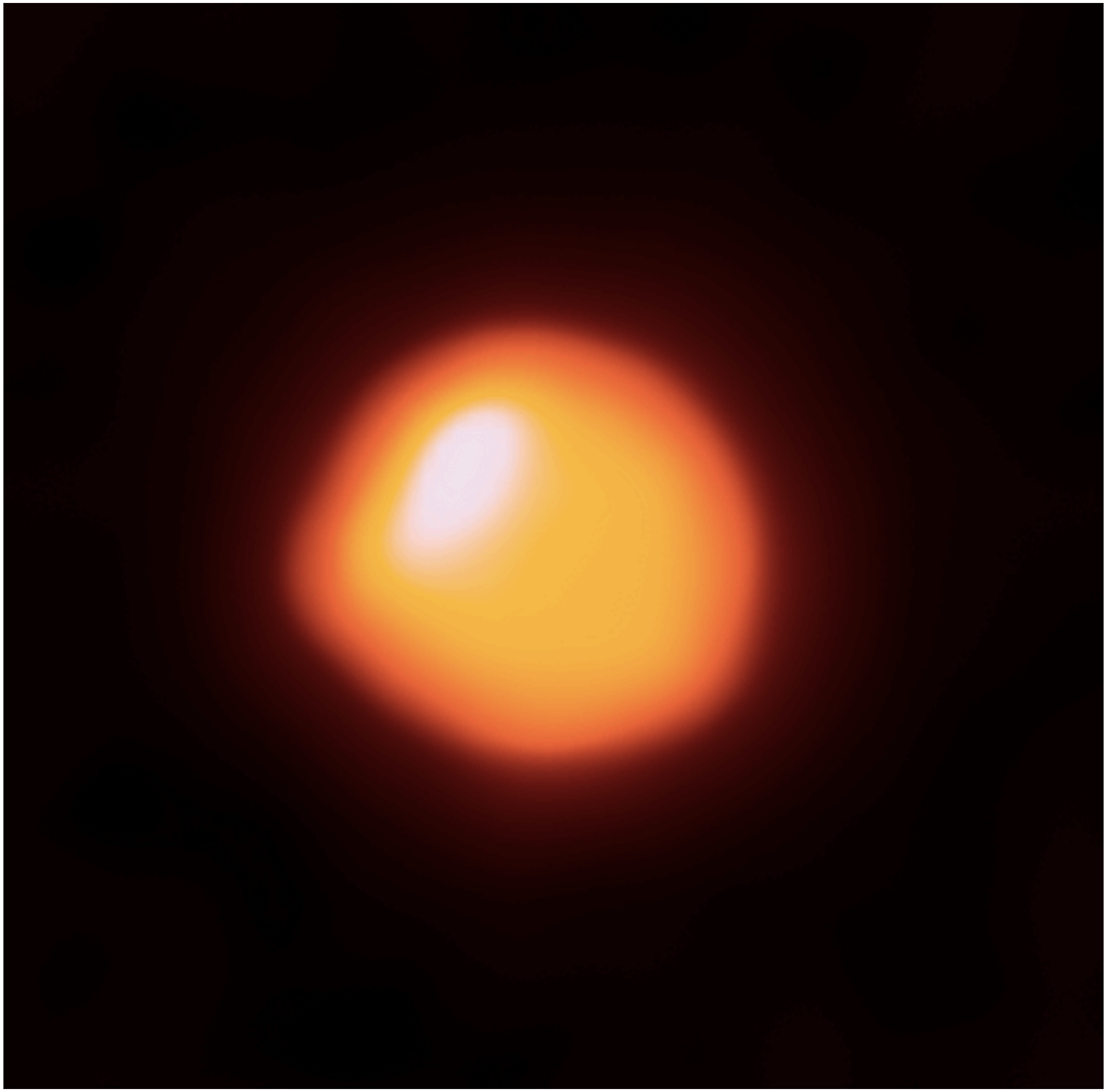
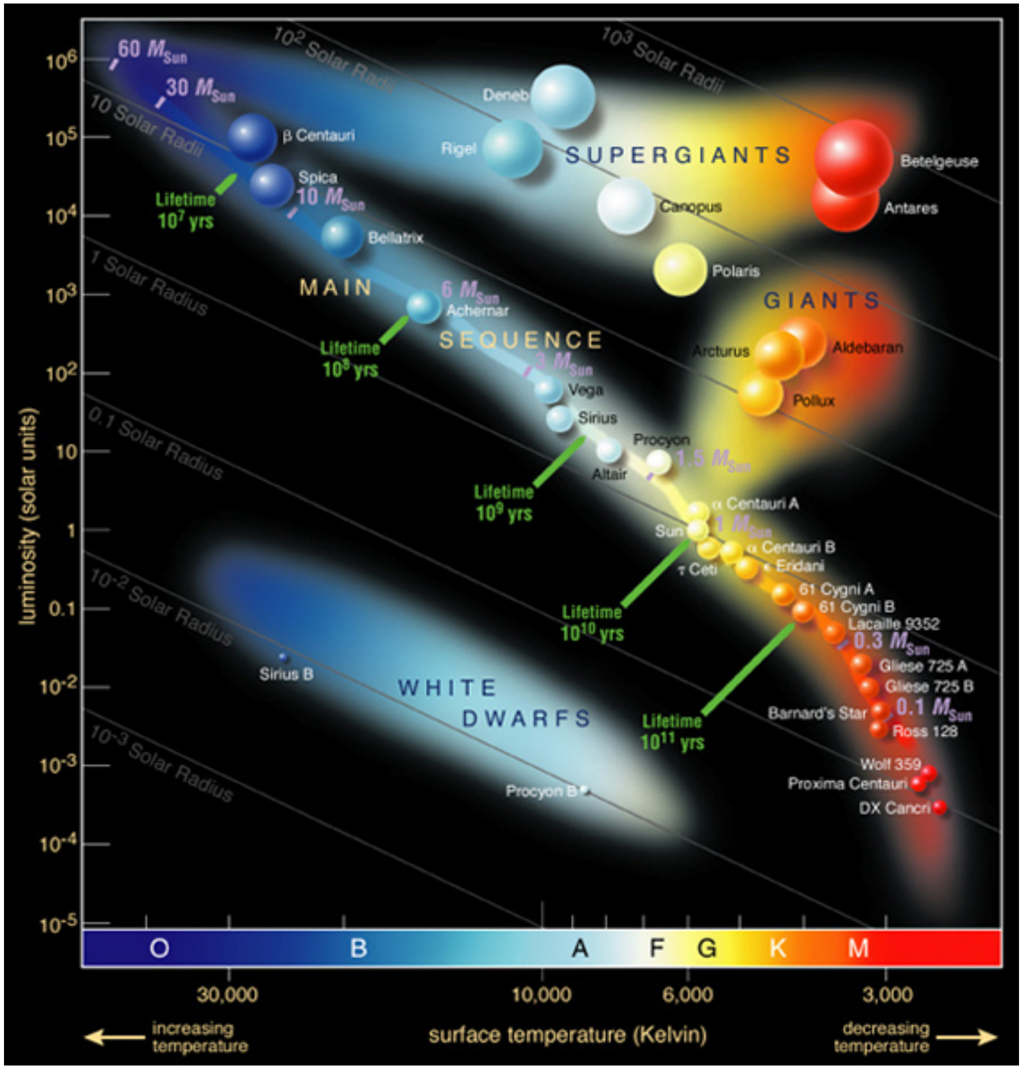




$$L = 4\pi R^2 \sigma T^4$$

- **Luminosity is a function of radius and a strong function of temperature**





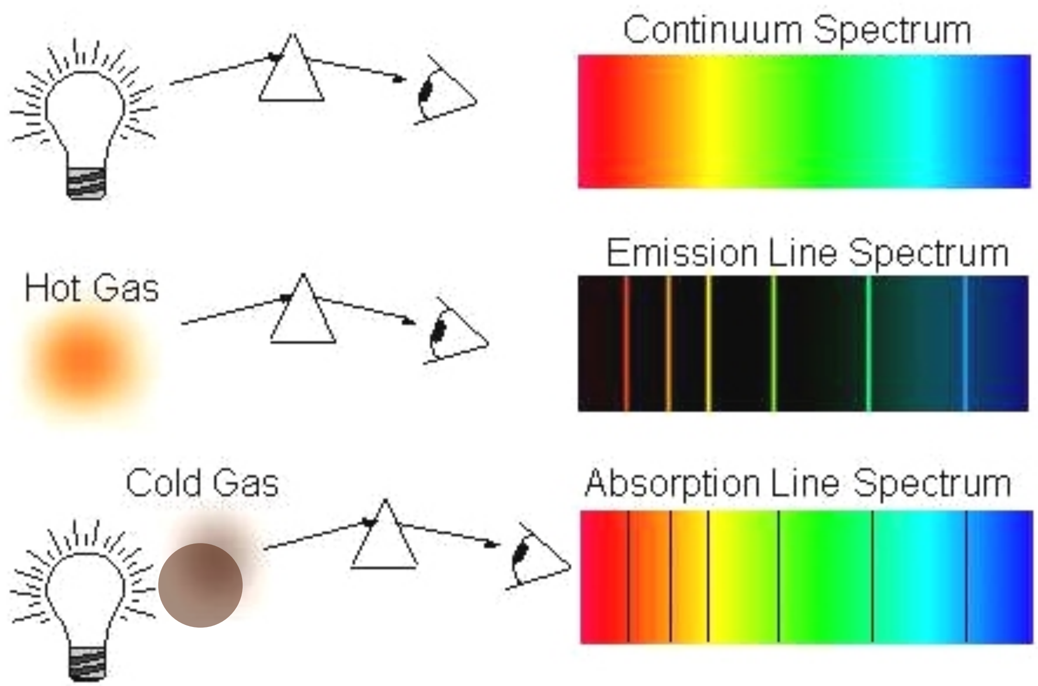
$$L = 4\pi R^2 \sigma T^4$$

$$\nu_{\max} \propto T$$

- **Luminosity is a function of radius and a strong function of temperature**
- **The wavelength of peak brightness goes bluer as the temperature rises**

Spectroscopy

Spectral lines – Kirchhoff's three empirical laws of spectroscopy



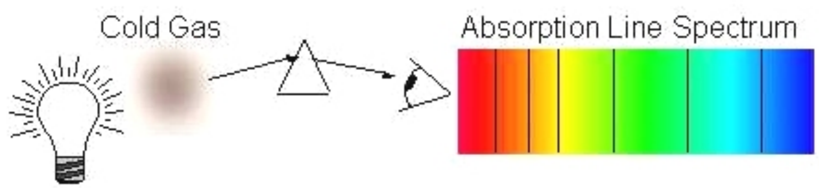
A hot solid or a hot dense gas produces a continuum spectrum.

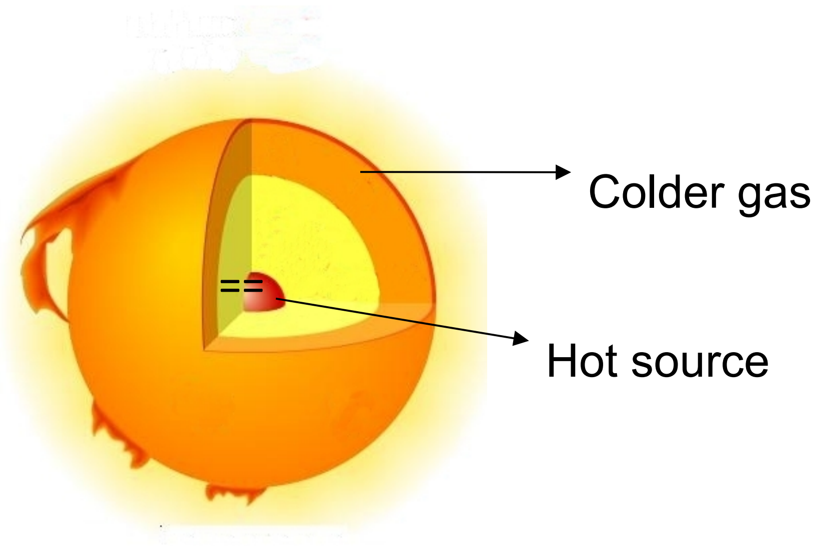
A hot low-density gas produces an emission-line spectrum.

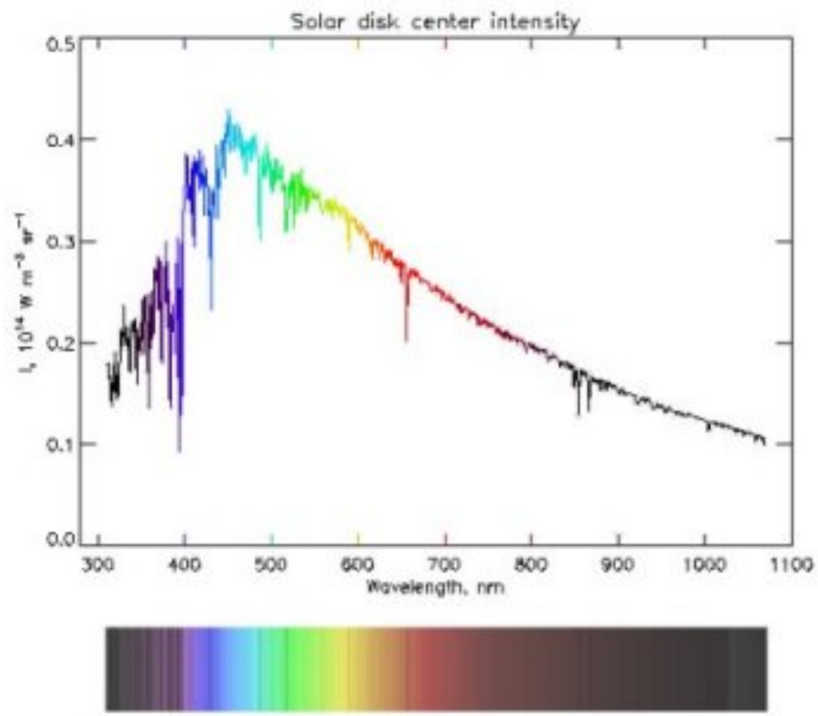
A continuous source viewed through a cold gas produces an absorption-line spectrum.

Spectroscopy

The third law is what applies to stars. We light we see comes from the hot interior, passing through a colder atmosphere. Thus, we see spectral lines.







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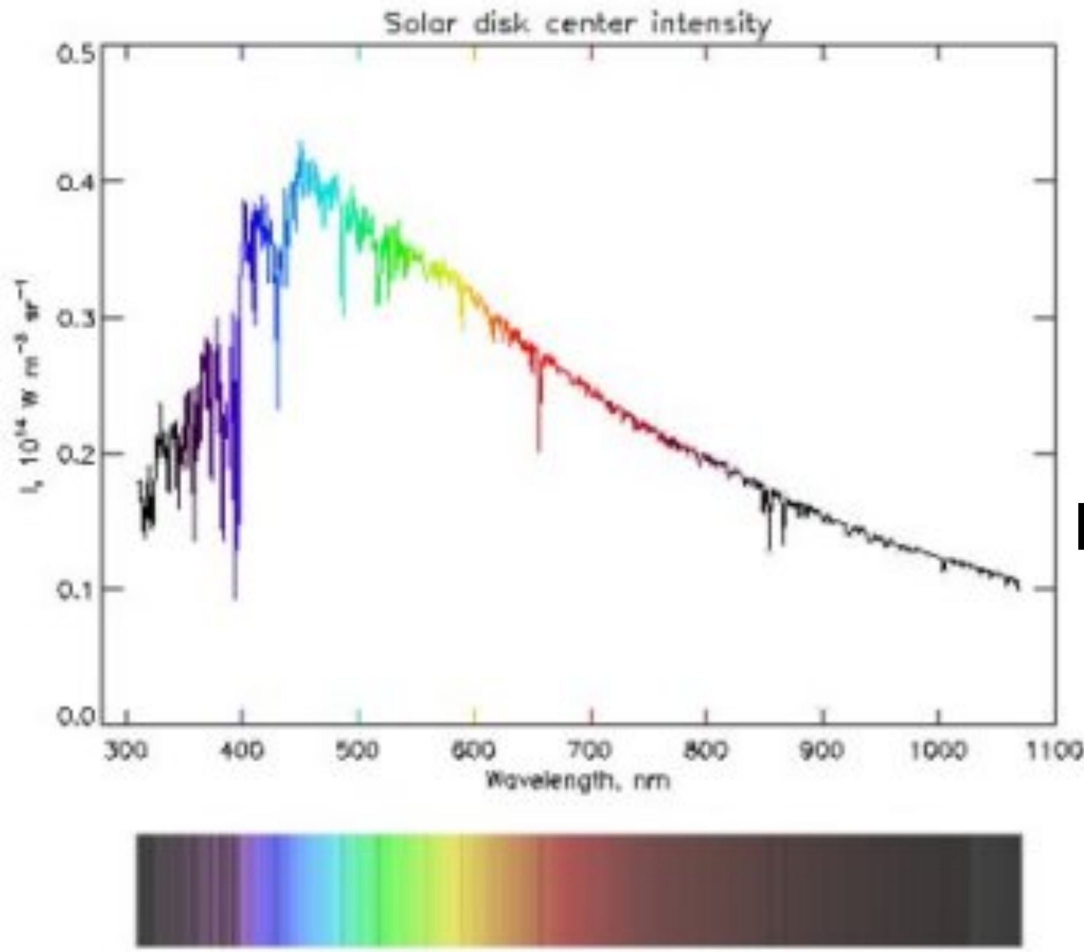
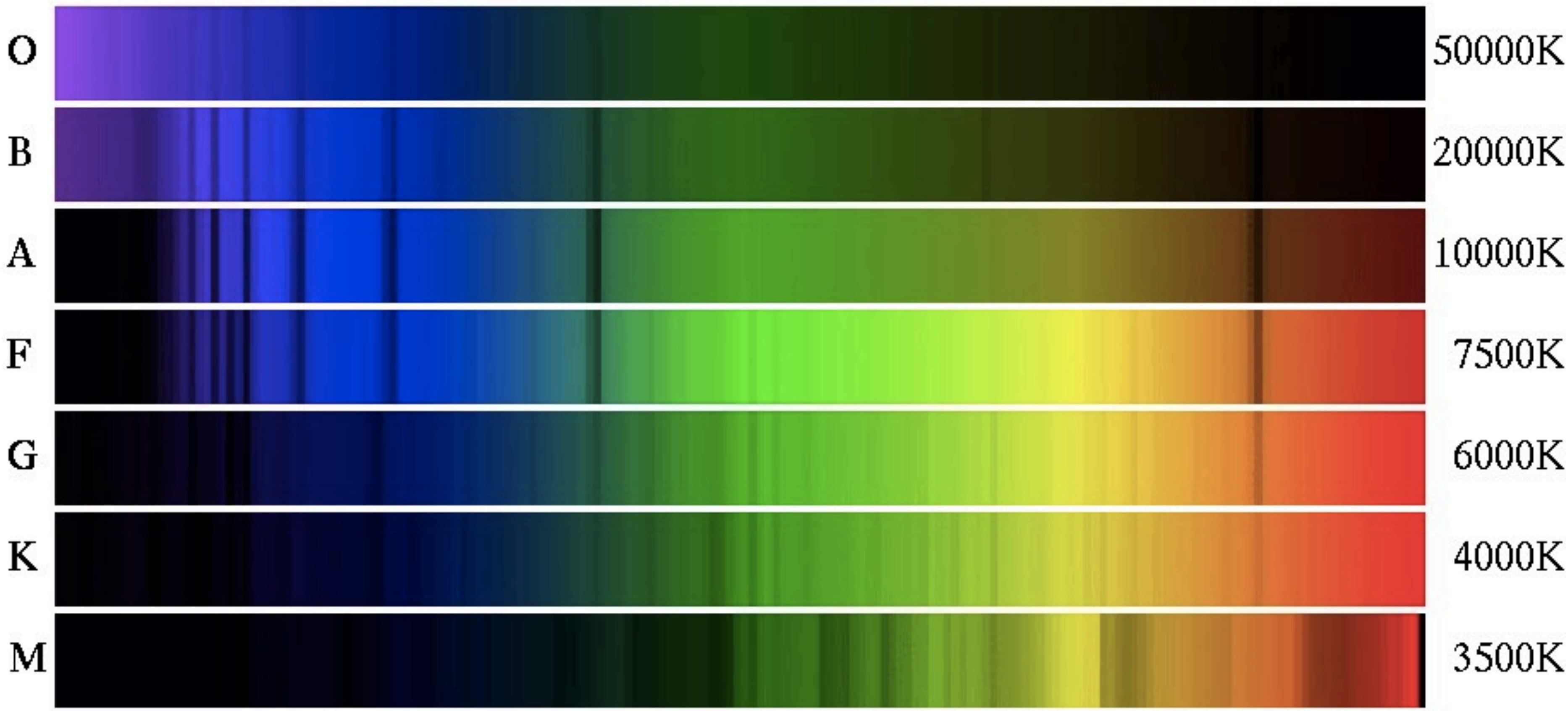


Main features:

Continuum
Absorption lines

Most prominent lines:
Ca II lines in the blue

Spectra of other stars have different features



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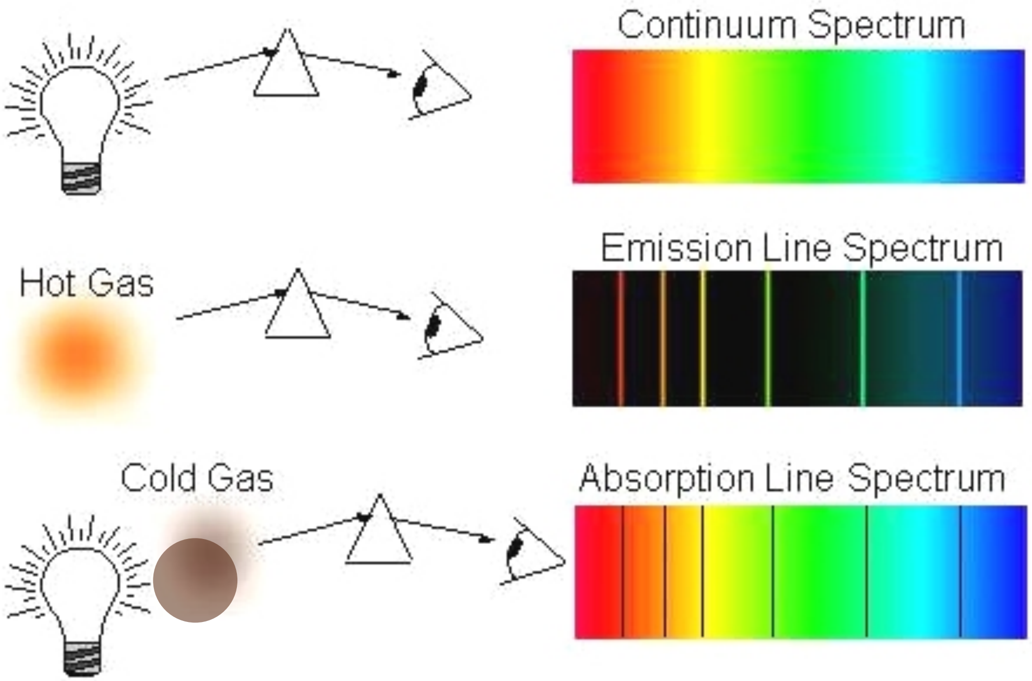

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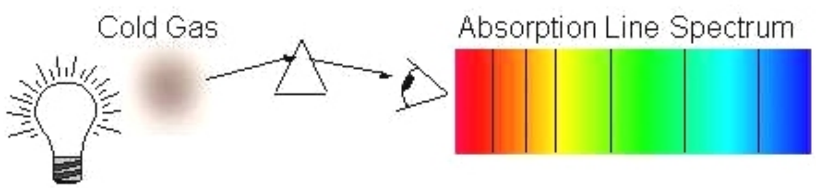
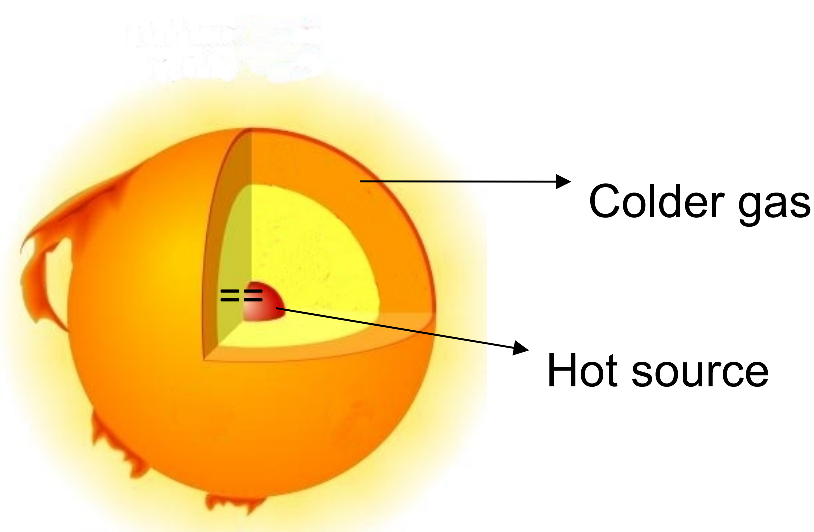
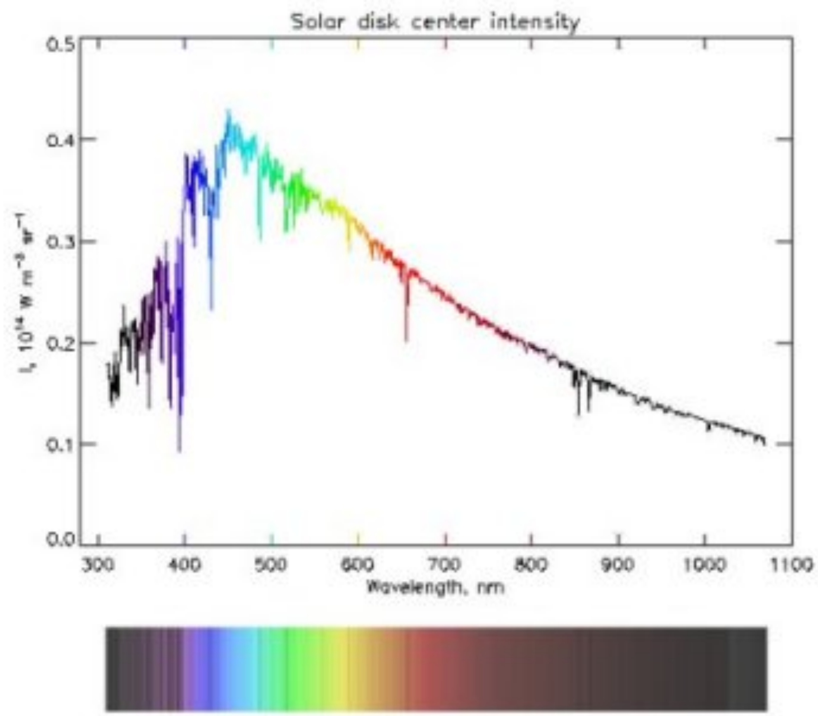
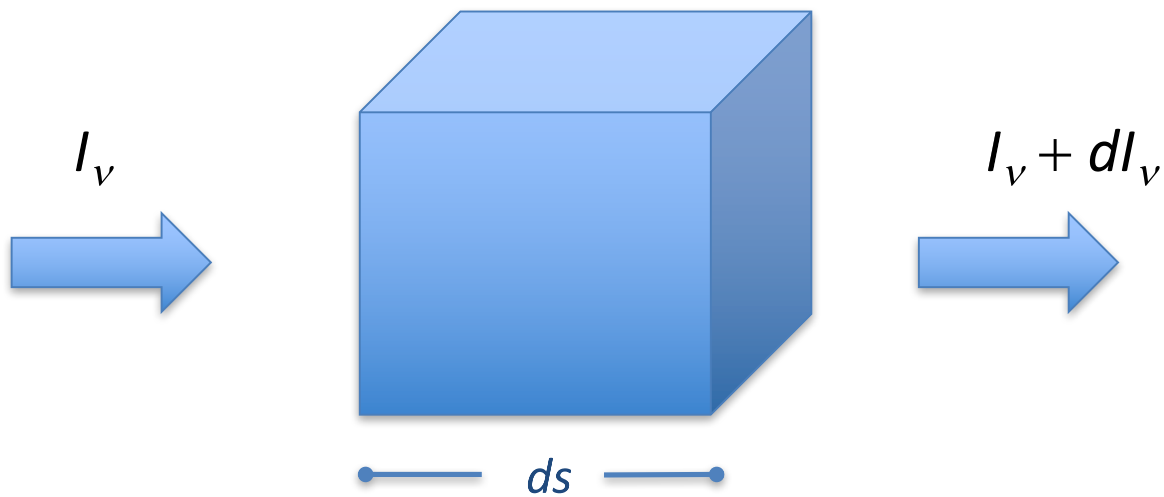






Emission and Absorption

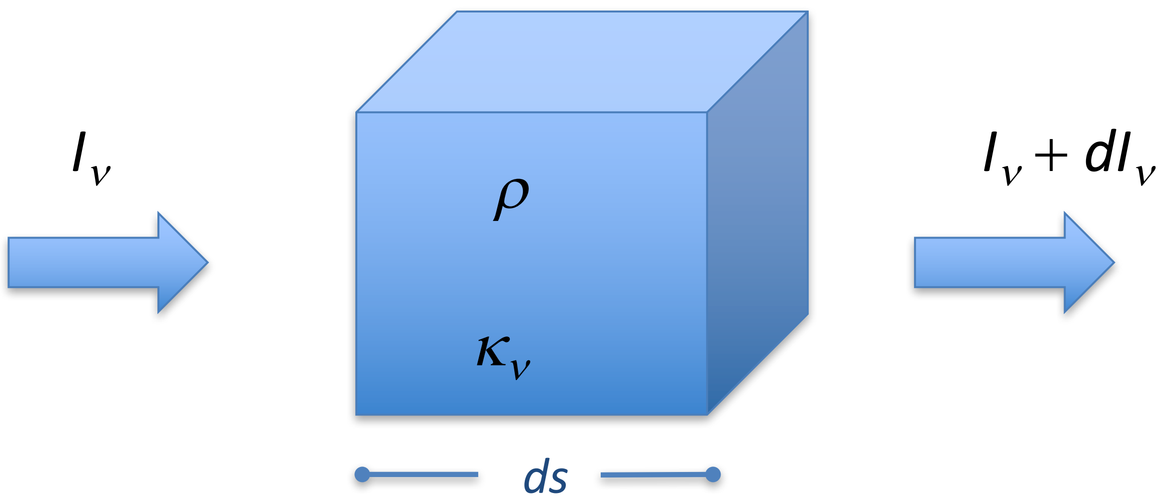
Emission and Absorption



Radiation of intensity I_ν shines through a cube of side ds.
What is the intensity that emerges from it?

What is the amount of intensity dI_ν that is added or subtracted from the beam?

Emission and Absorption



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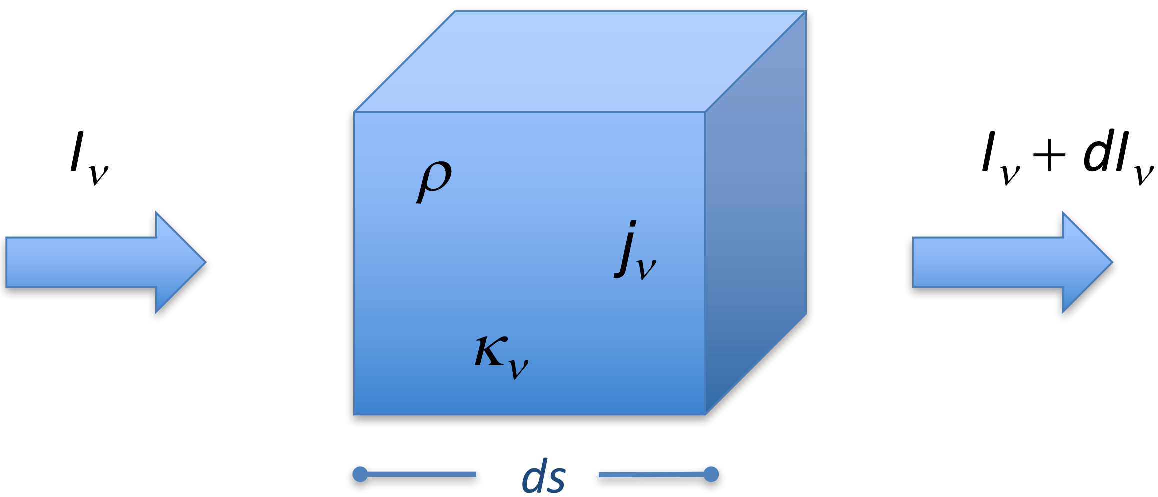

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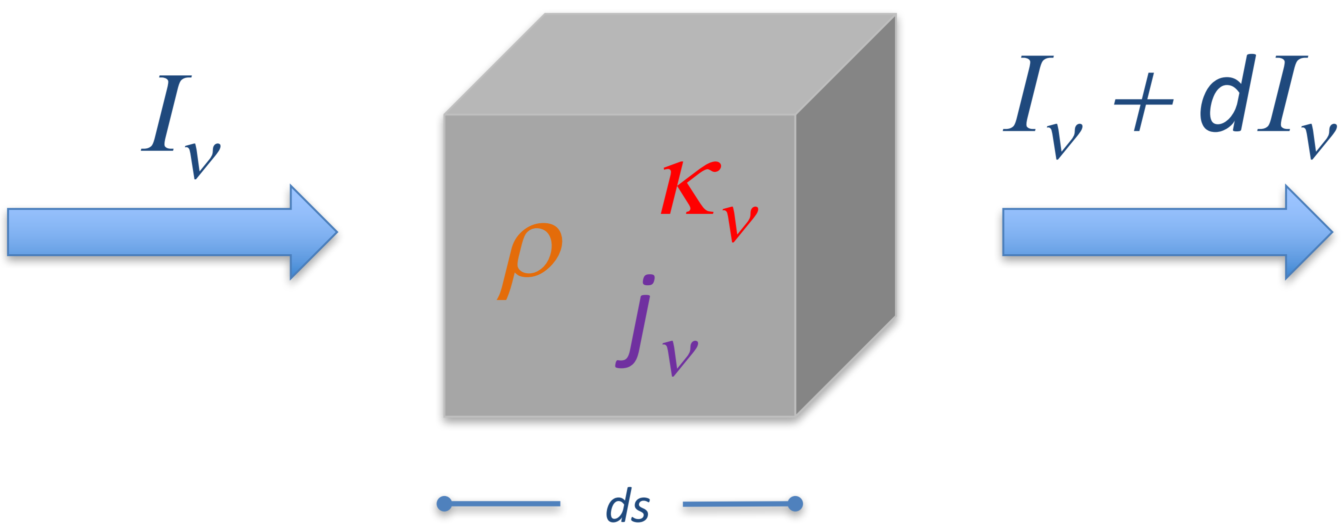
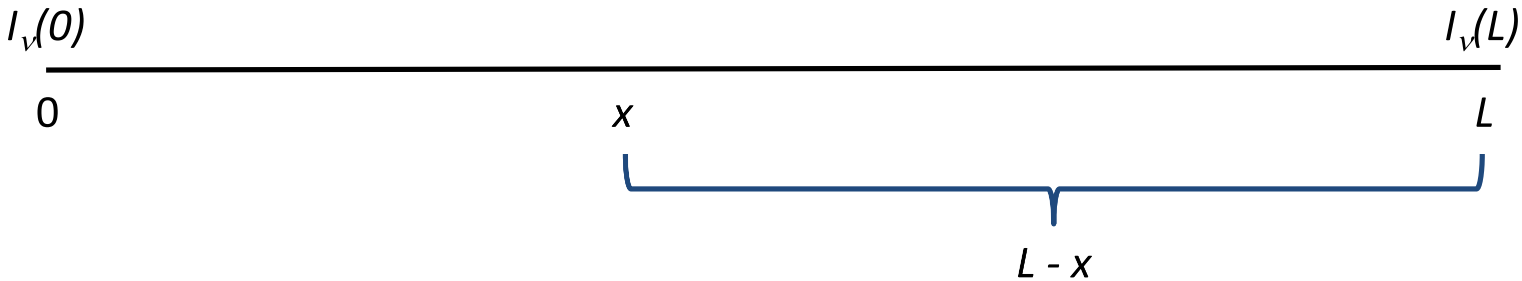
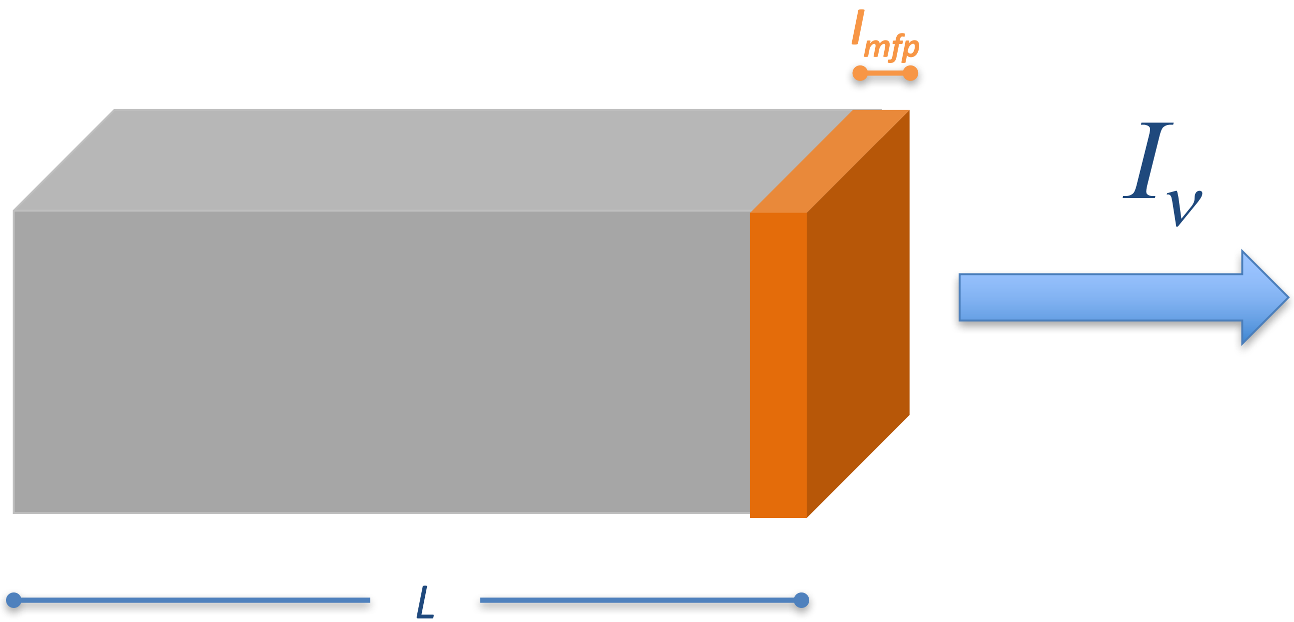


$$dI_\nu = -\kappa_\nu \rho \, I_\nu \, ds \; + j_\nu \rho \, ds$$

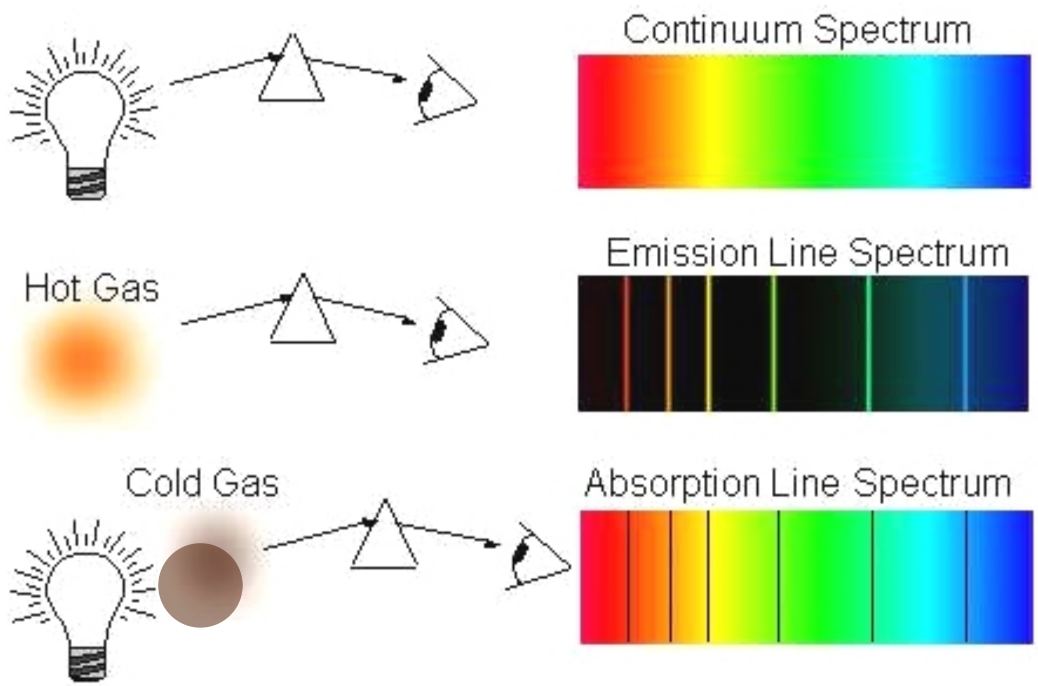

$I_\nu(0)$
$I_\nu(L)$
0
x
L
$L - x$



$$I_\nu = S_\nu = j_\nu \rho \, l_{\mathrm{mfp}}$$

Spectroscopy

Spectral lines – Kirchhoff's three empirical laws of spectroscopy



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Spectroscopy

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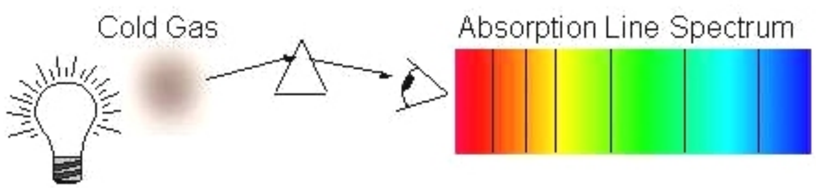
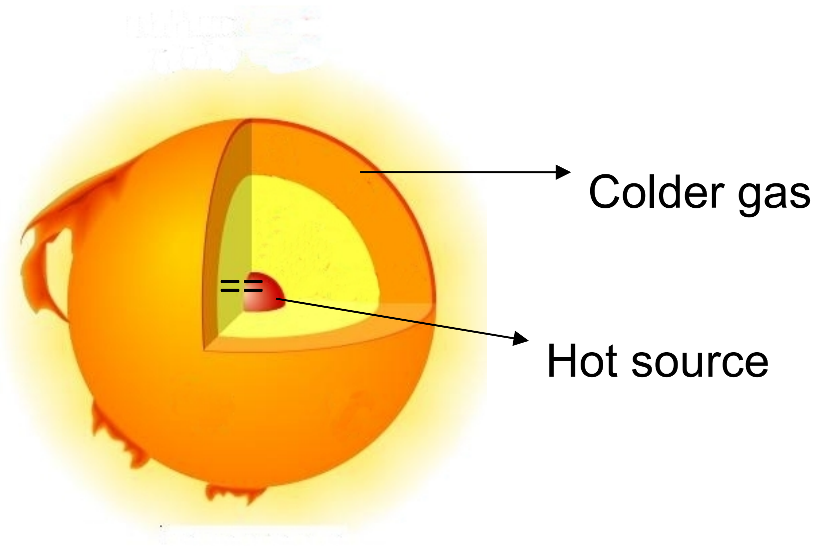
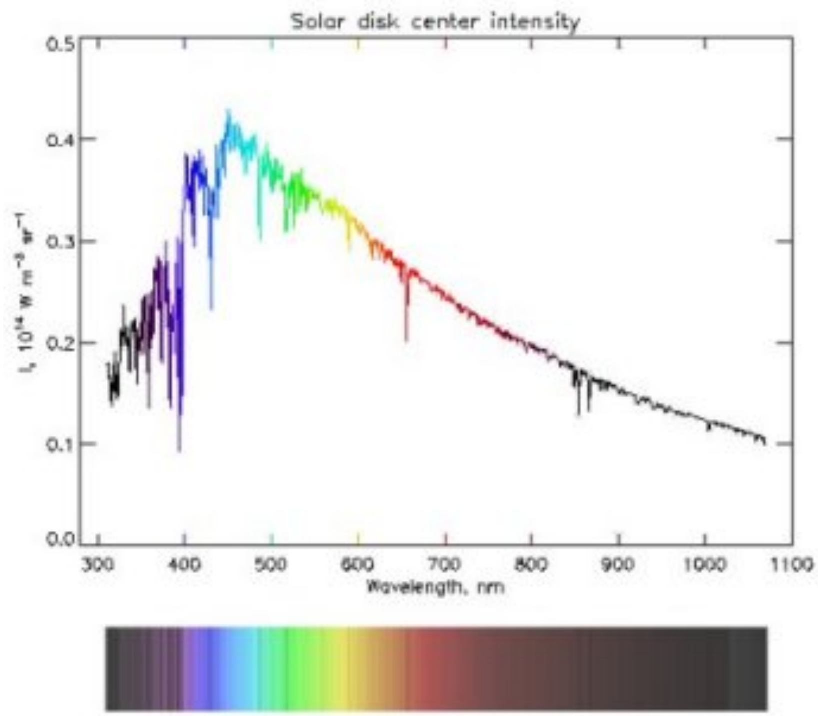
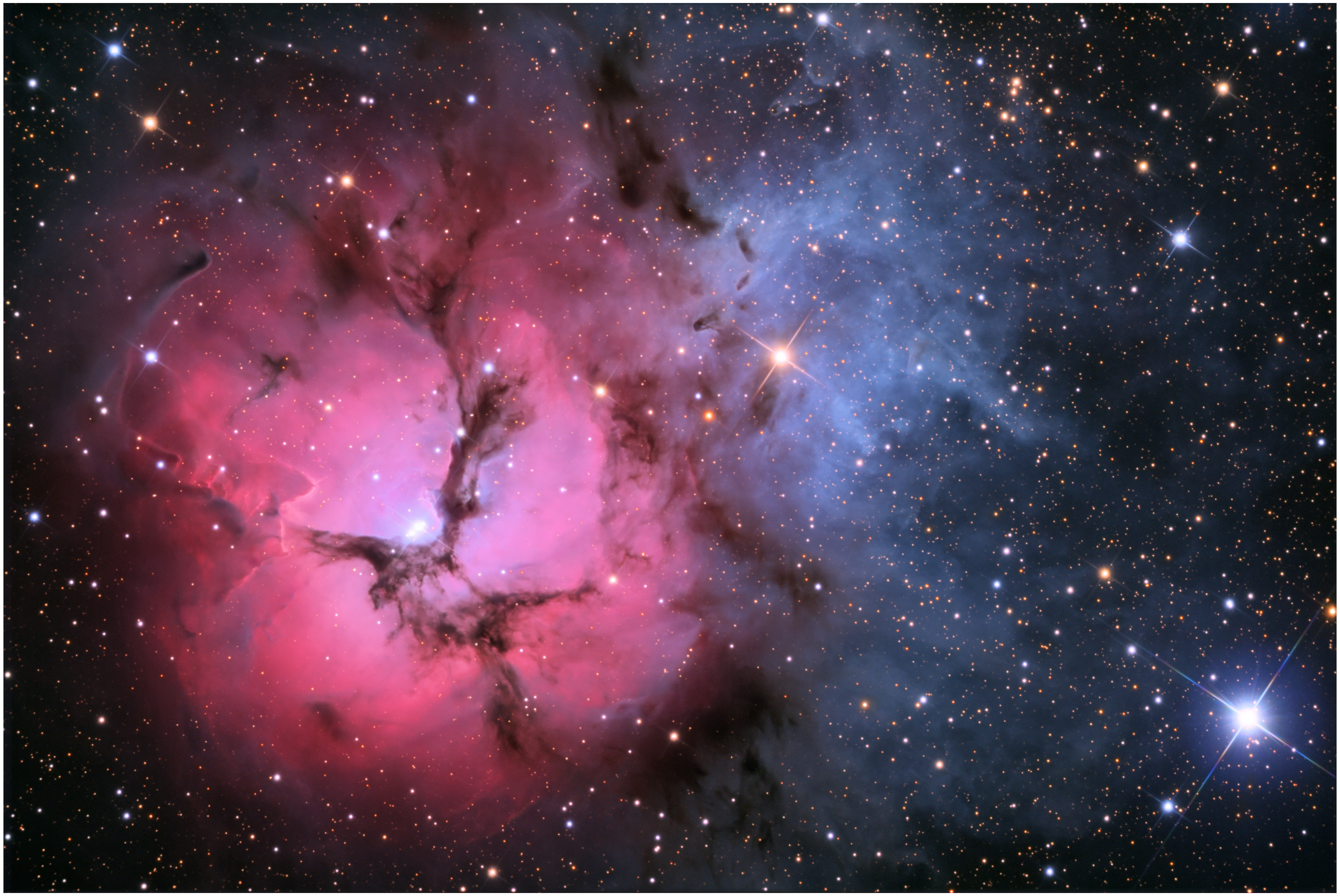
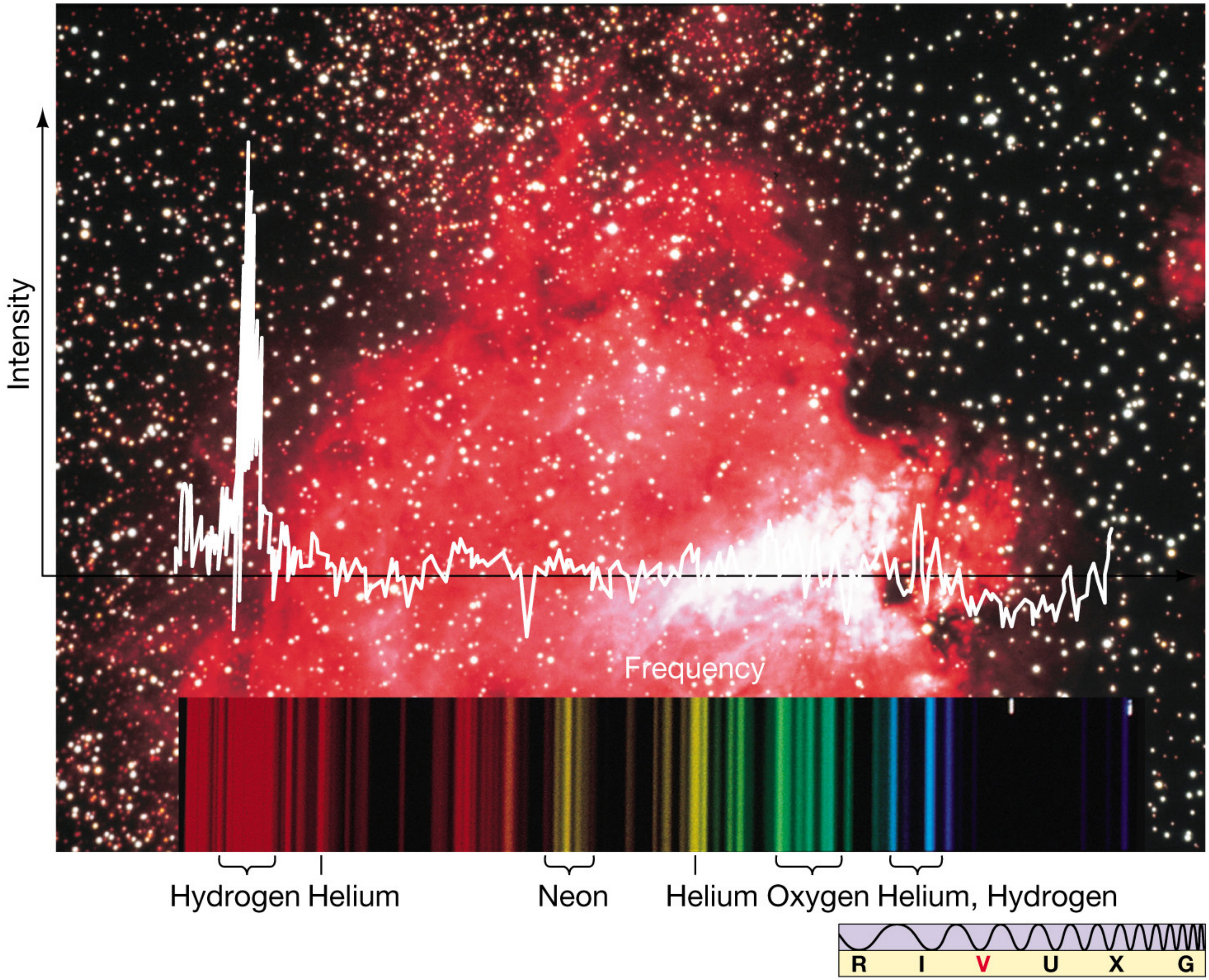






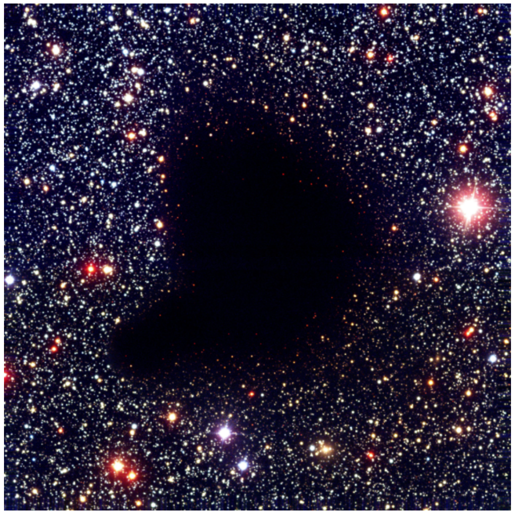
Emission and Absorption




Intensity
Frequency
Hydrogen
Helium
Neon
Helium
Oxygen
Helium, Hydrogen
R
I
V
U
X
G

Interstellar Nebulae

Interstellar clouds can be referred to as
absorption (dark), reflection or emission nebulae



Absorption Nebula

Reflection Nebula

Emission Nebula

Interstellar Nebulae

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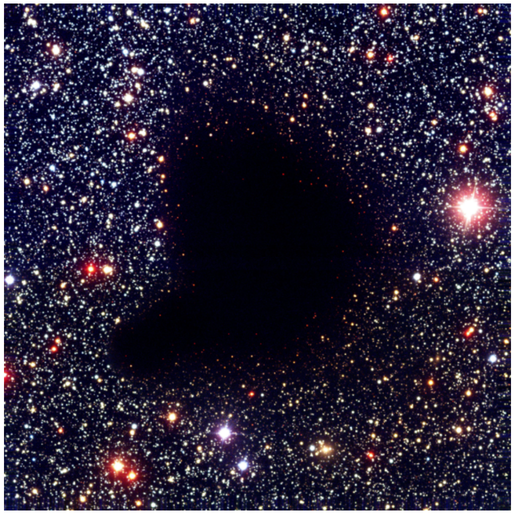
absorption (dark), reflection or emission nebulae



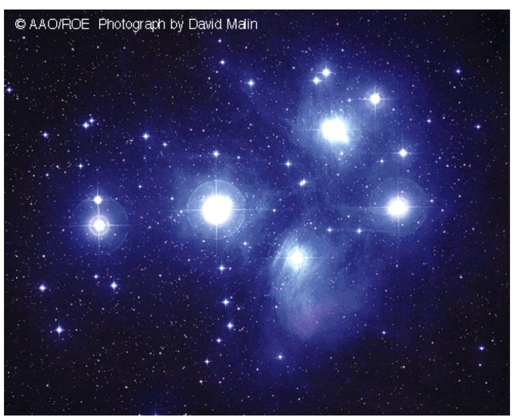
Absorption Nebula

Absorption Nebulae

A lot of gas and dust
simply blocking light

Interstellar Nebulae

Reflection Nebulae



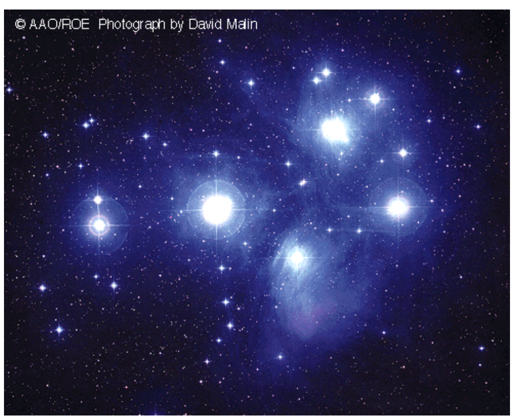
Physically the same as dark nebulae, but ***illuminated*** by nearby stars.

The dust shines by reflected light

Usually blue (why?)

Interstellar Nebulae

Reflection Nebulae



Physically the same as dark nebulae,
but ***illuminated*** by nearby stars.
The dust shines by reflected light

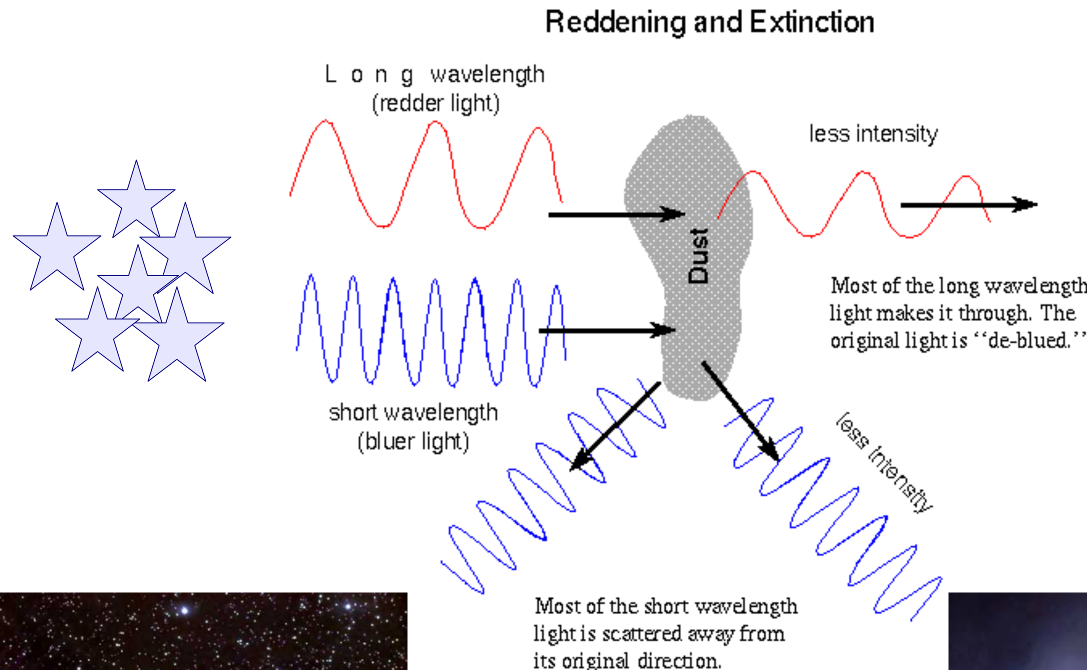
Usually blue (why?)

1. **Illuminated by blue/white stars**

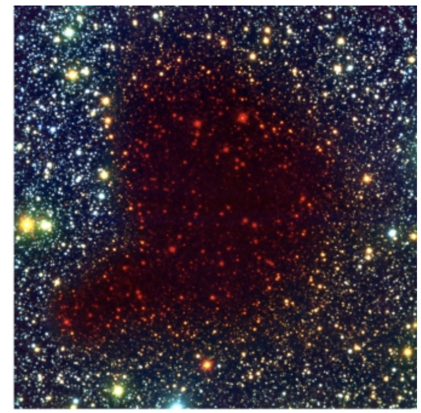
2. Same reason why the sky is blue
Blue is better scattered than red

Interstellar Nebulae

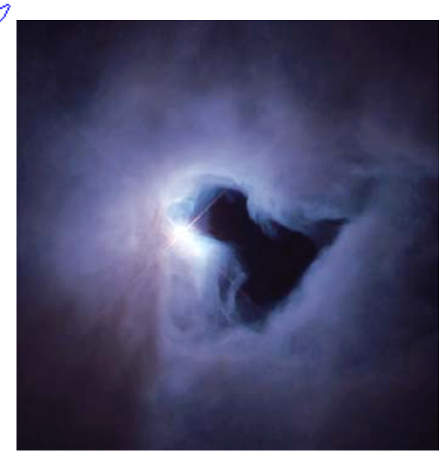
Absorption and reflection nebulae are the same object



Absorption



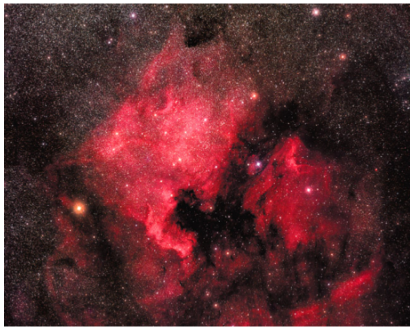
Reflection



Reflection + Absorption

Interstellar Nebulae

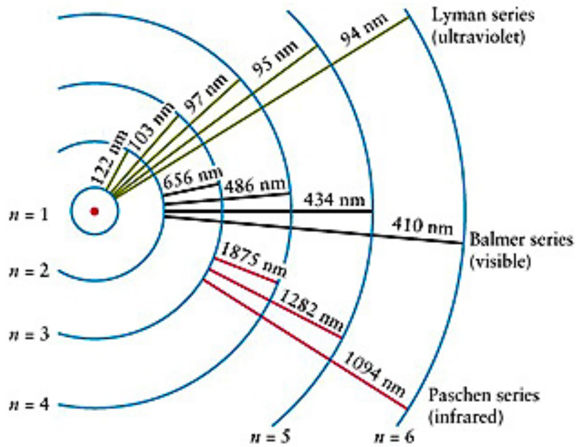
Emission Nebulae



Glow by their own light

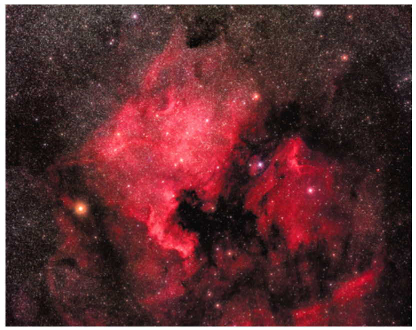
Illuminated by nearby OB stars,
very hot stars that emit ionizing radiation

When the electrons recombine, they cascade emitting light in all the atom's discrete set of wavelengths



Interstellar Nebulae

Emission Nebulae



Glow by their own light

Usually red (why?)

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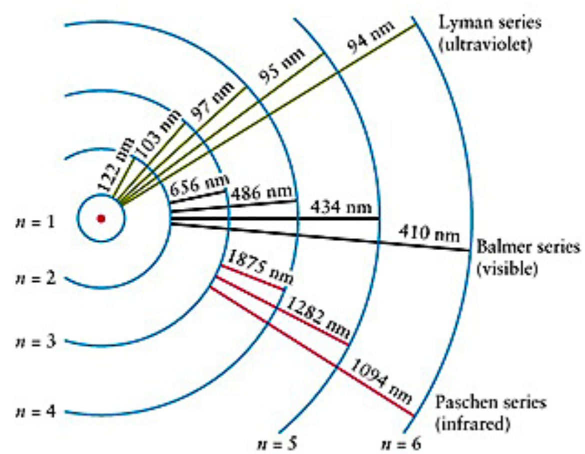
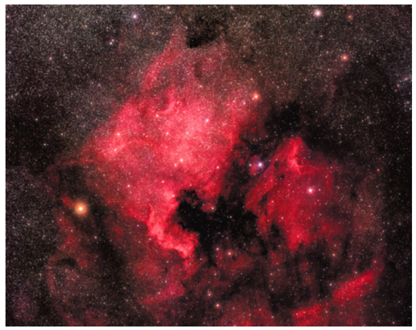
very hot stars that emit ionizing radiation

When the electrons recombine, they cascade emitting light in all the atom's discrete set of wavelengths



Interstellar Nebulae

Emission Nebulae

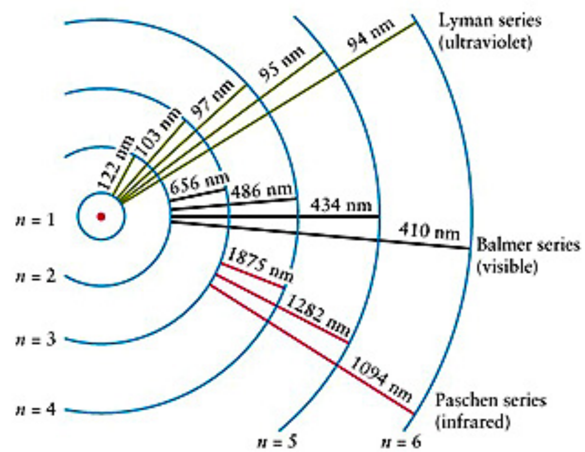


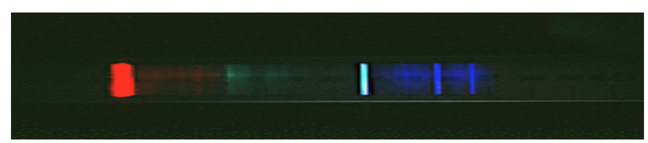
Hydrogen emission in the **6563 Å** line (Ha)

Glow by their own light
Usually red (why?)

Illuminated by nearby OB stars,
very hot stars that emit ionizing radiation

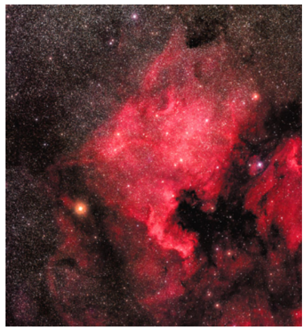
When the electrons recombine, they cascade emitting light in all the atom's discrete set of wavelengths



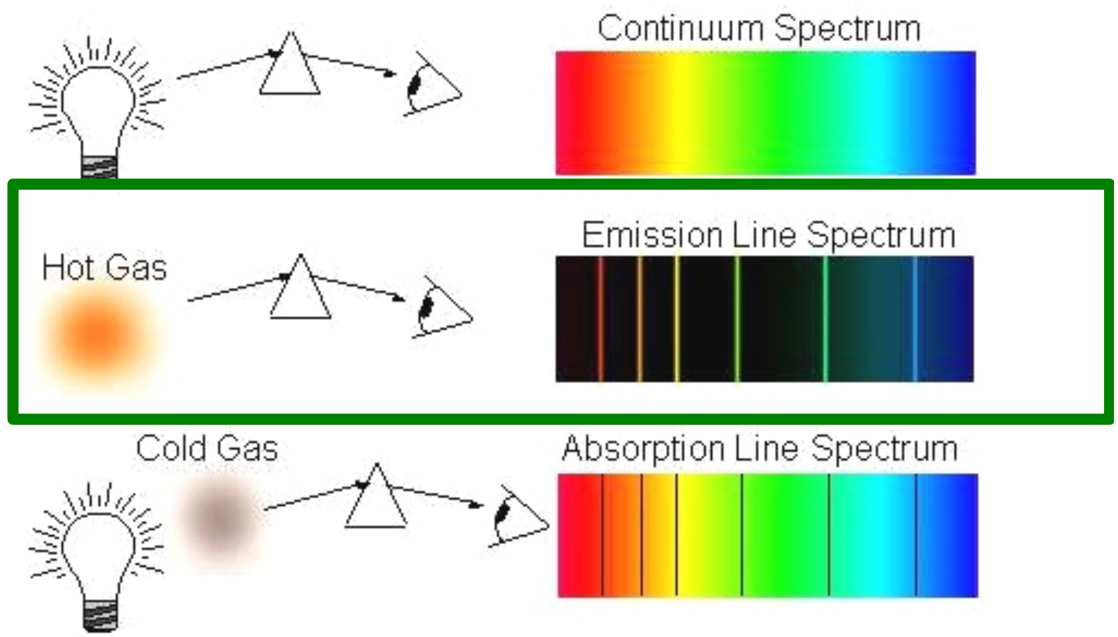


Interstellar Nebulae

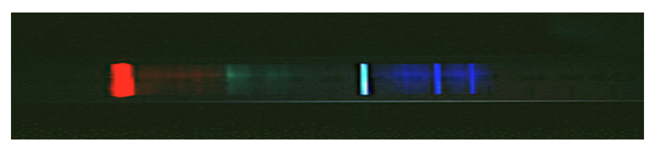
Emission Nebulae



Kirchhoff's laws



Hydrogen emission in the **6563 Å** line (Ha)

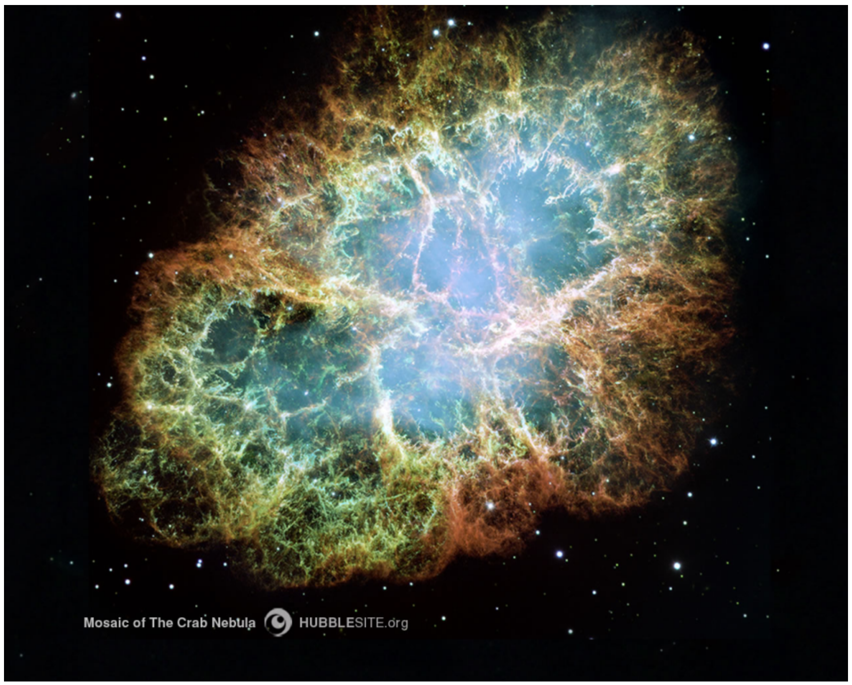


HII Regions

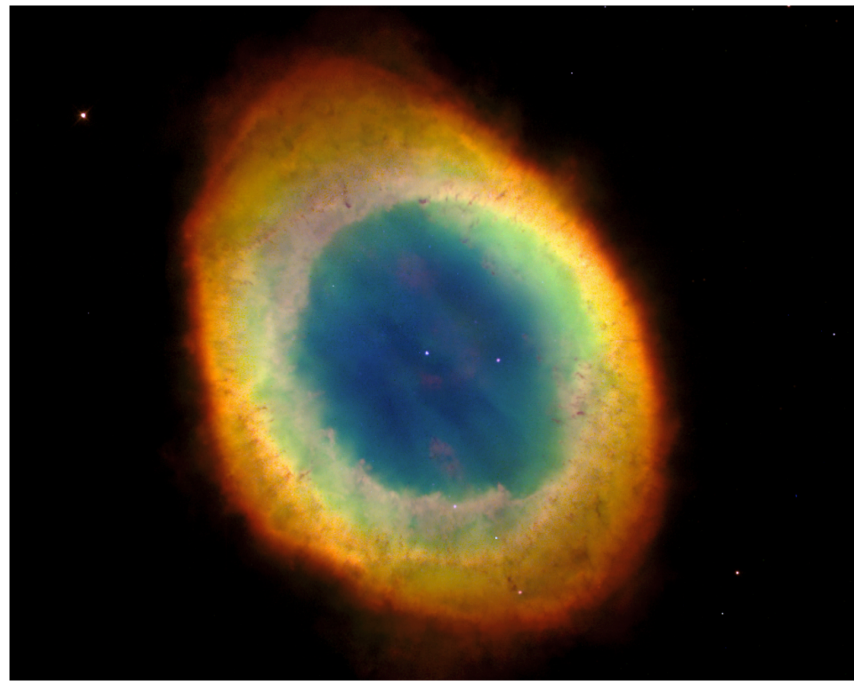
Emission Nebulae are also called HII Regions
HII for Ionized Hydrogen
(Neutral Hydrogen is HI)

Emission nebulae

Emission Nebulae are red because of hydrogen emission in H-alpha
Can you tell then why are Supernovae Remnants and Planetary Nebulae so colorful?



Crab Nebula
Supernova Remnant



Ring Nebula
Planetary Nebula

Emission nebulae

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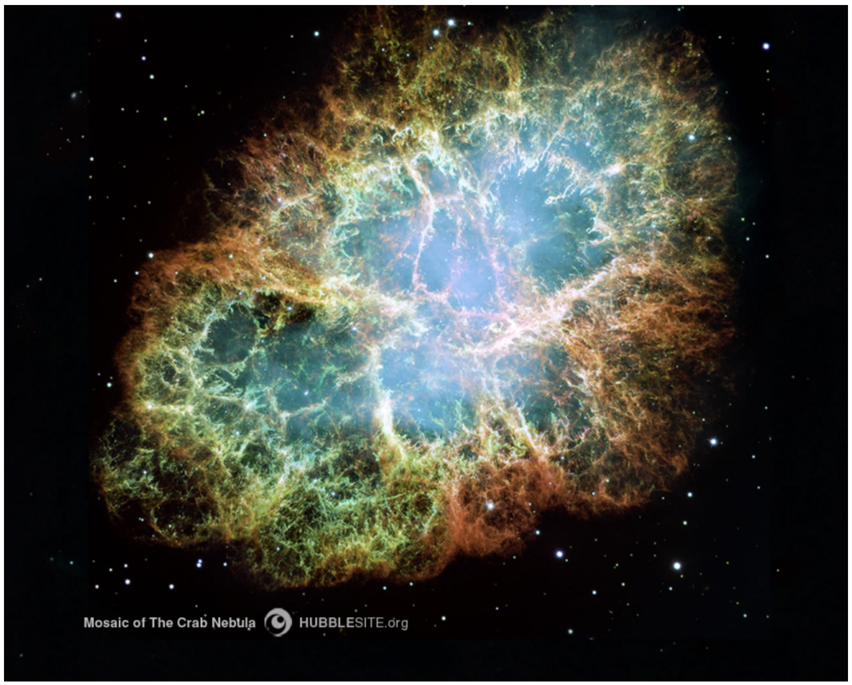

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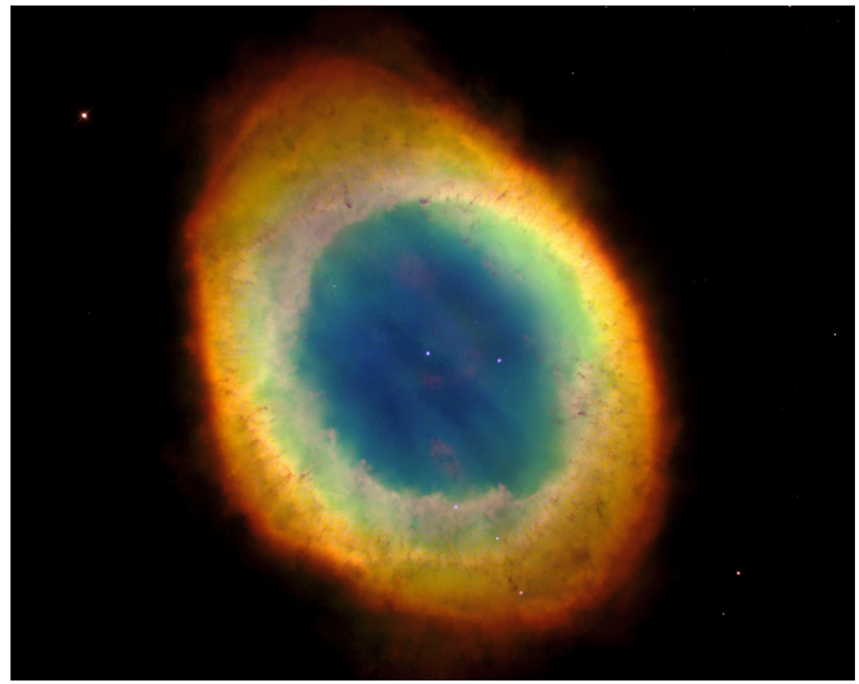
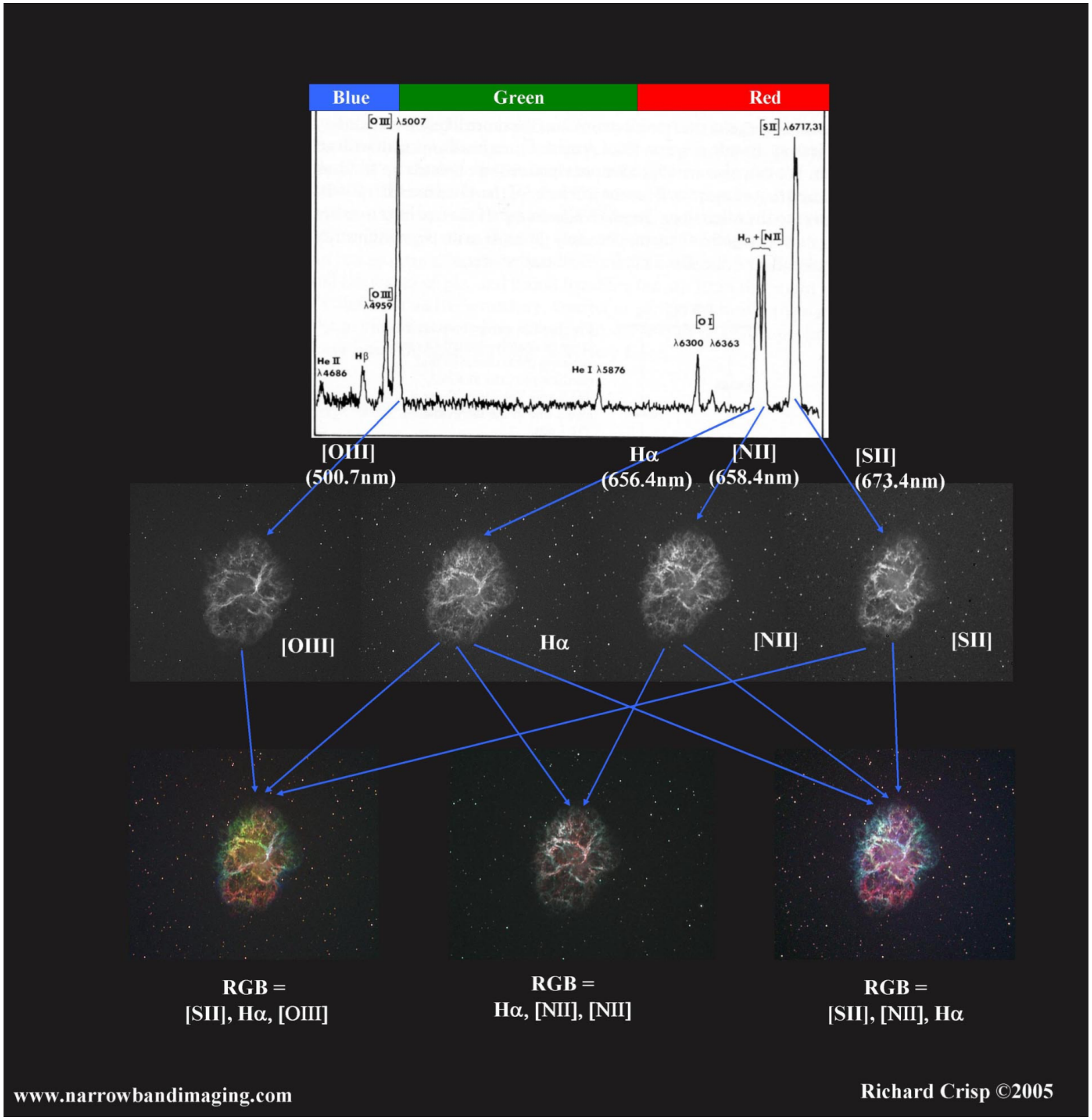
Supernova Remnant



Ring Nebula
Planetary Nebula

Chemically enriched !!
Not just hydrogen...



Spectrum of the Crab Nebula

Prominent **Silicon line** (redder than **H-alpha**) and **Oxygen line** (green)

Emission, Reflection, and Absorption in the same nebula

Trifid Nebula

An entanglement of nebulae...

The Antares-Rho Ophiuchi Region

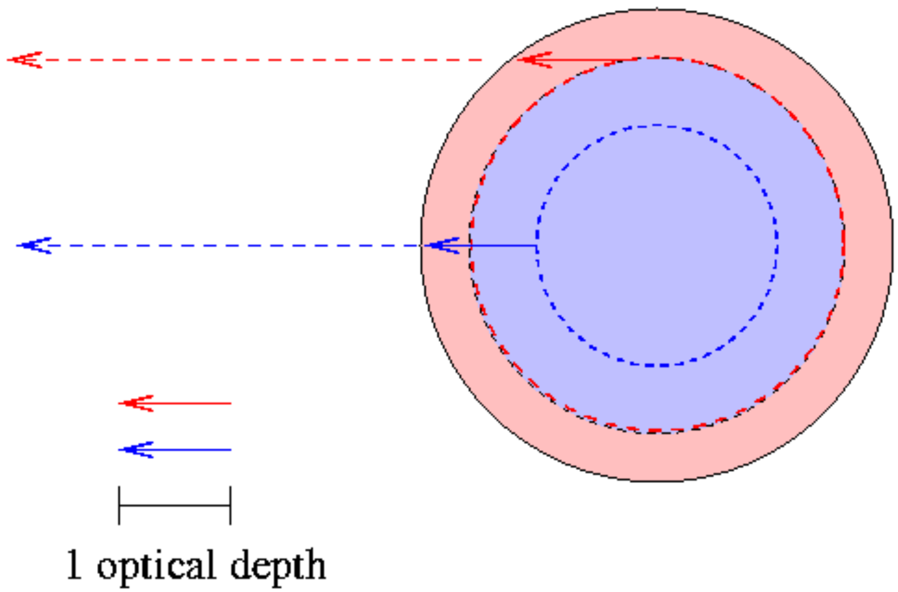
Can you sort what you see?

An entanglement of nebulae...

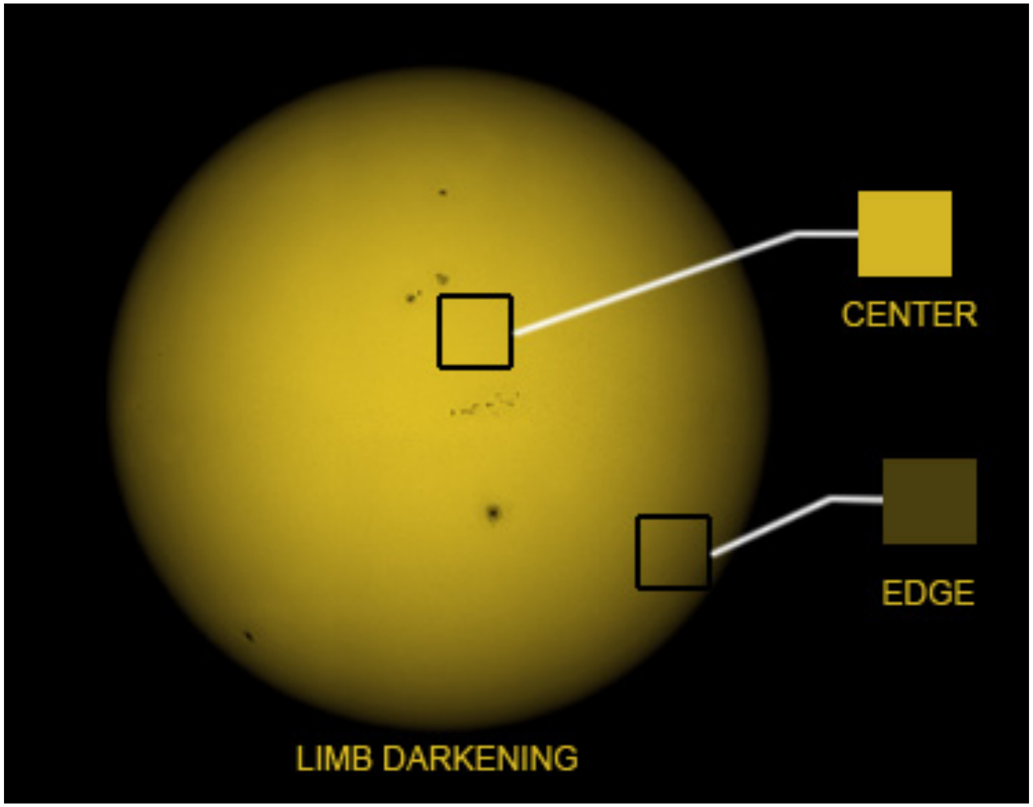
The Antares-Rho Ophiuchi Region

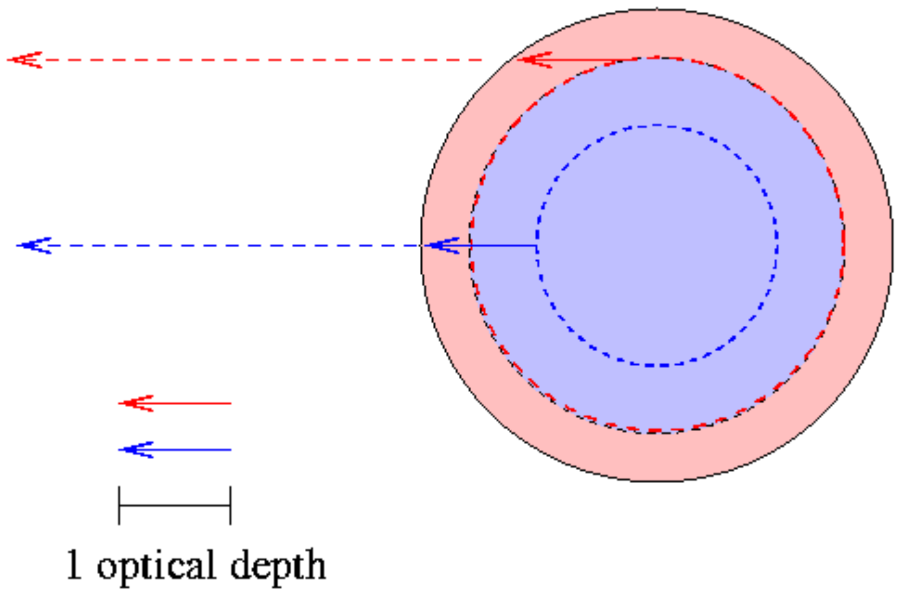
Can you sort what you see?

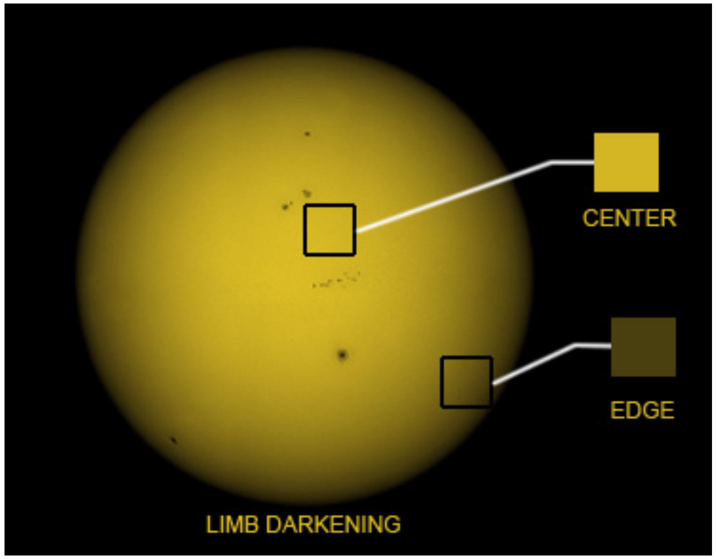
Limb brigthening


1 optical depth

Limb darkening

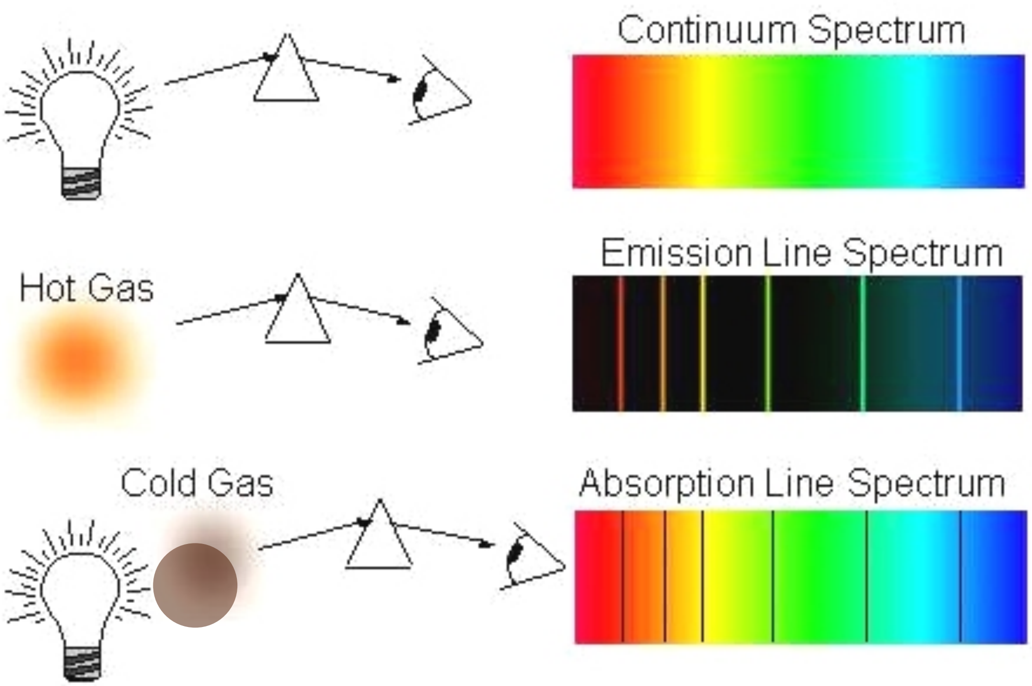



1 optical depth


CENTER
EDGE
LIMB DARKENING

Spectroscopy

Spectral lines – Kirchhoff's three empirical laws of spectroscopy

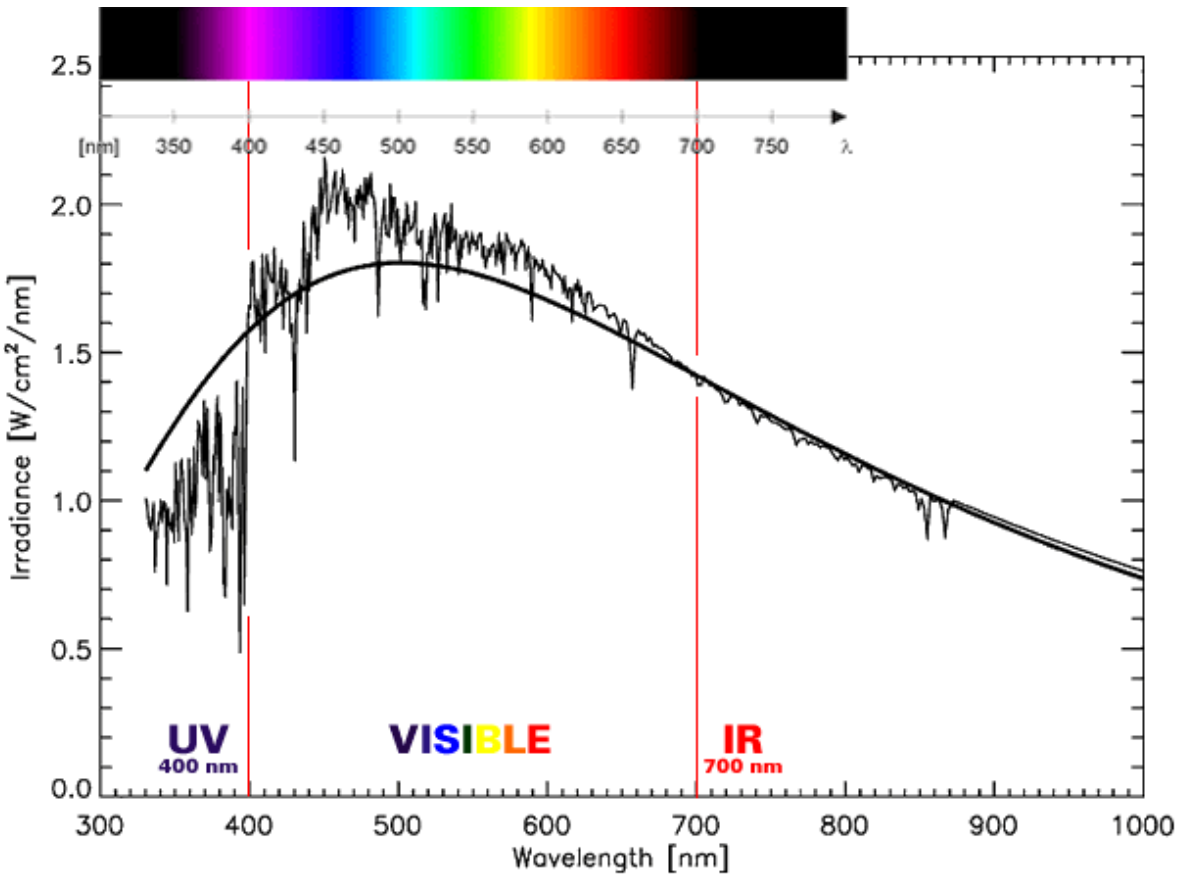


A hot solid or a hot dense gas produces a continuum spectrum.

A hot low-density gas produces an emission-line spectrum.

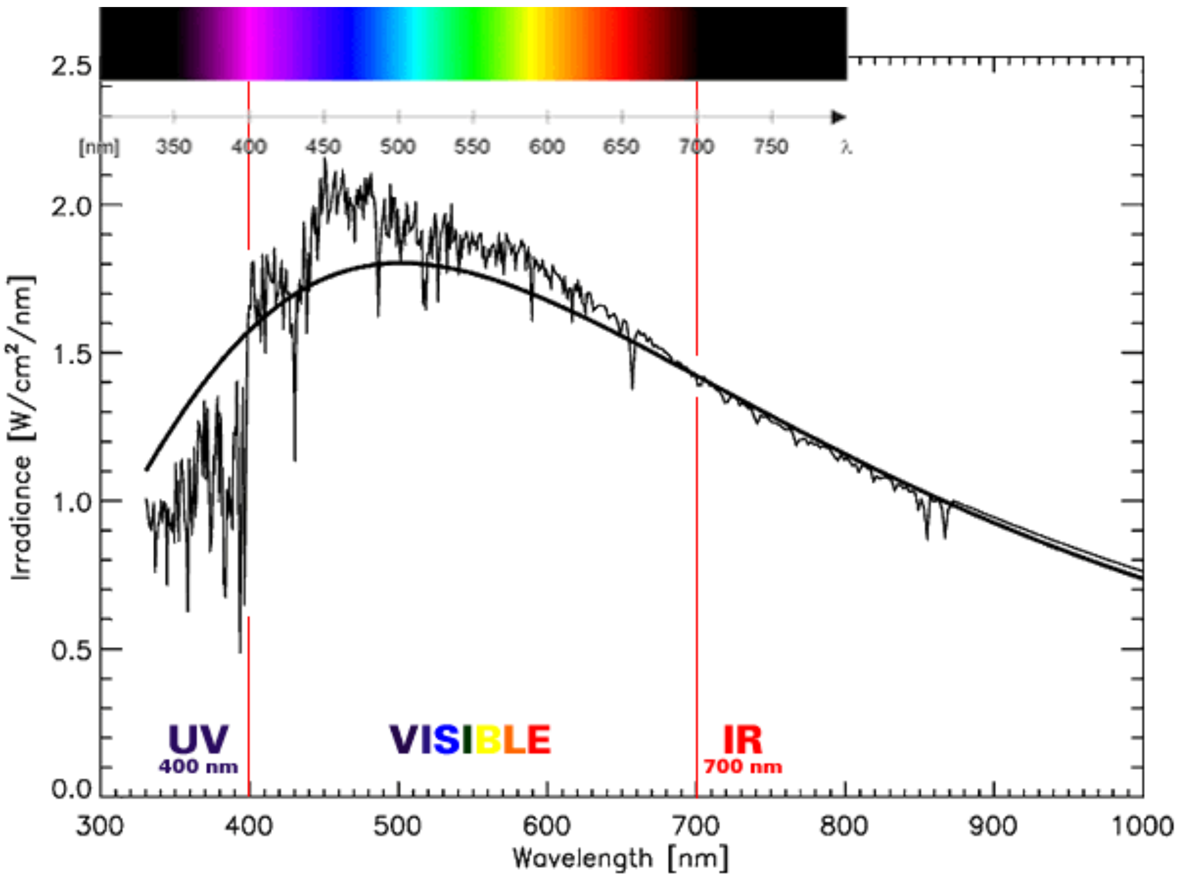
A continuous source viewed through a cold gas produces an absorption-line spectrum.

Solar Spectrum



The solar irradiance spectrum from 300 to 1000nm as measured by Labs and Neckel (1962) and corrected by Neckel and Labs (1984).
It roughly follows a black body radiation curve of 5777 K (thick line), particularly in the IR.

Solar Spectrum



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Main features:

Spectral lines: bound-bound transition (excitation/de-excitation)

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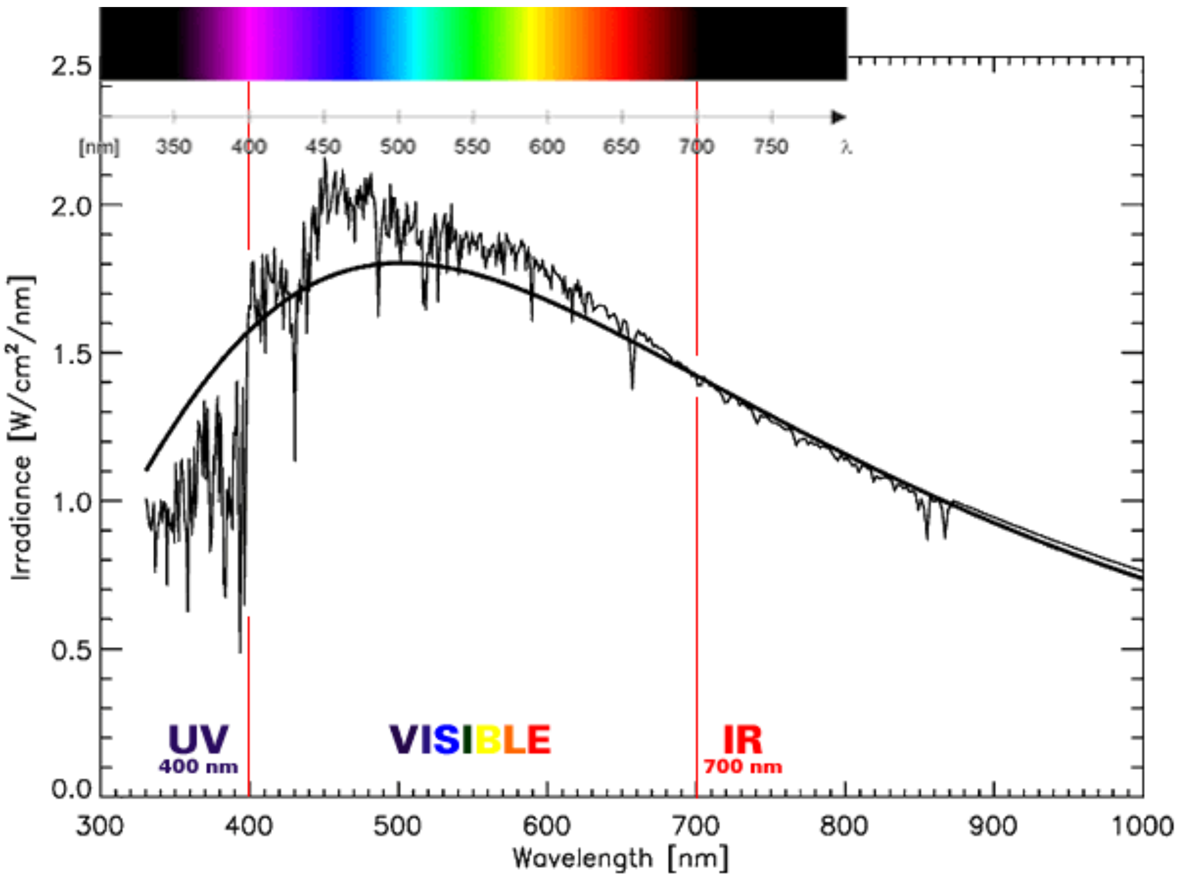

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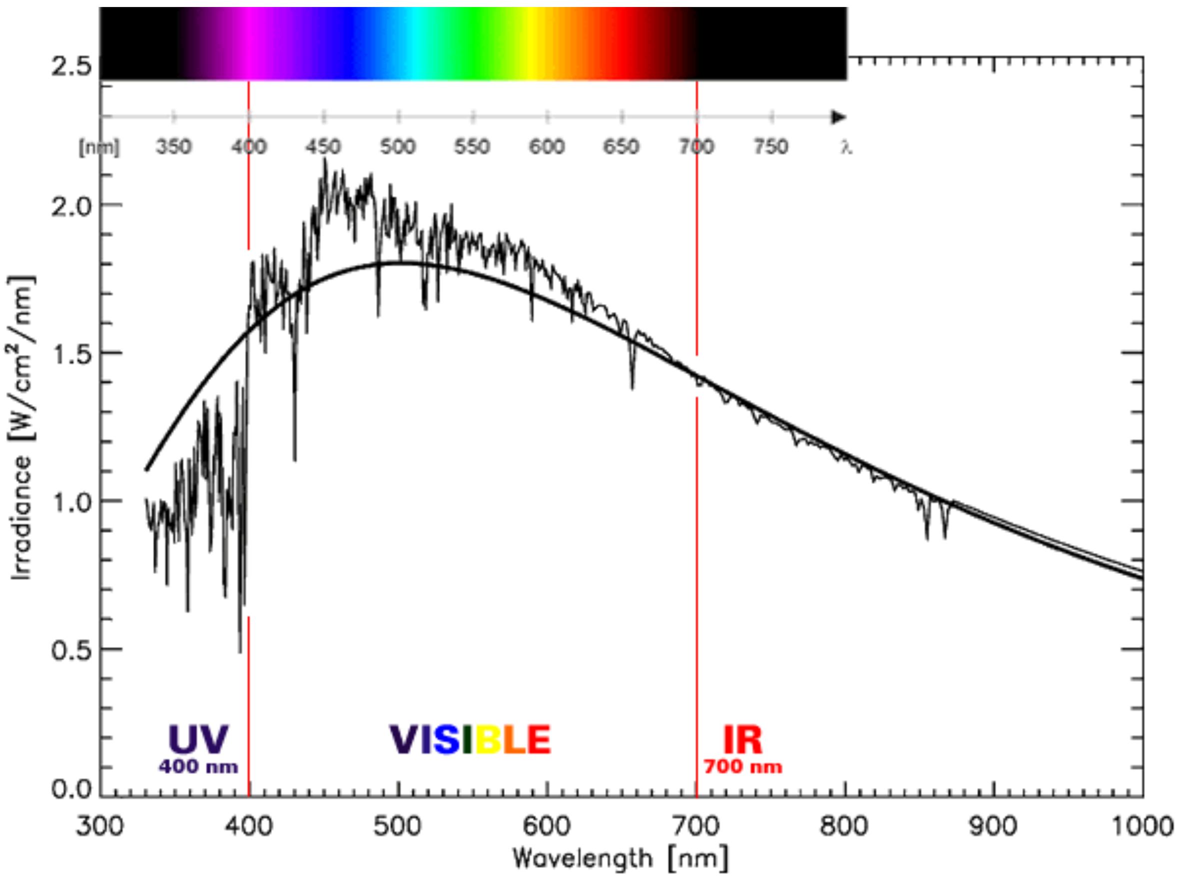

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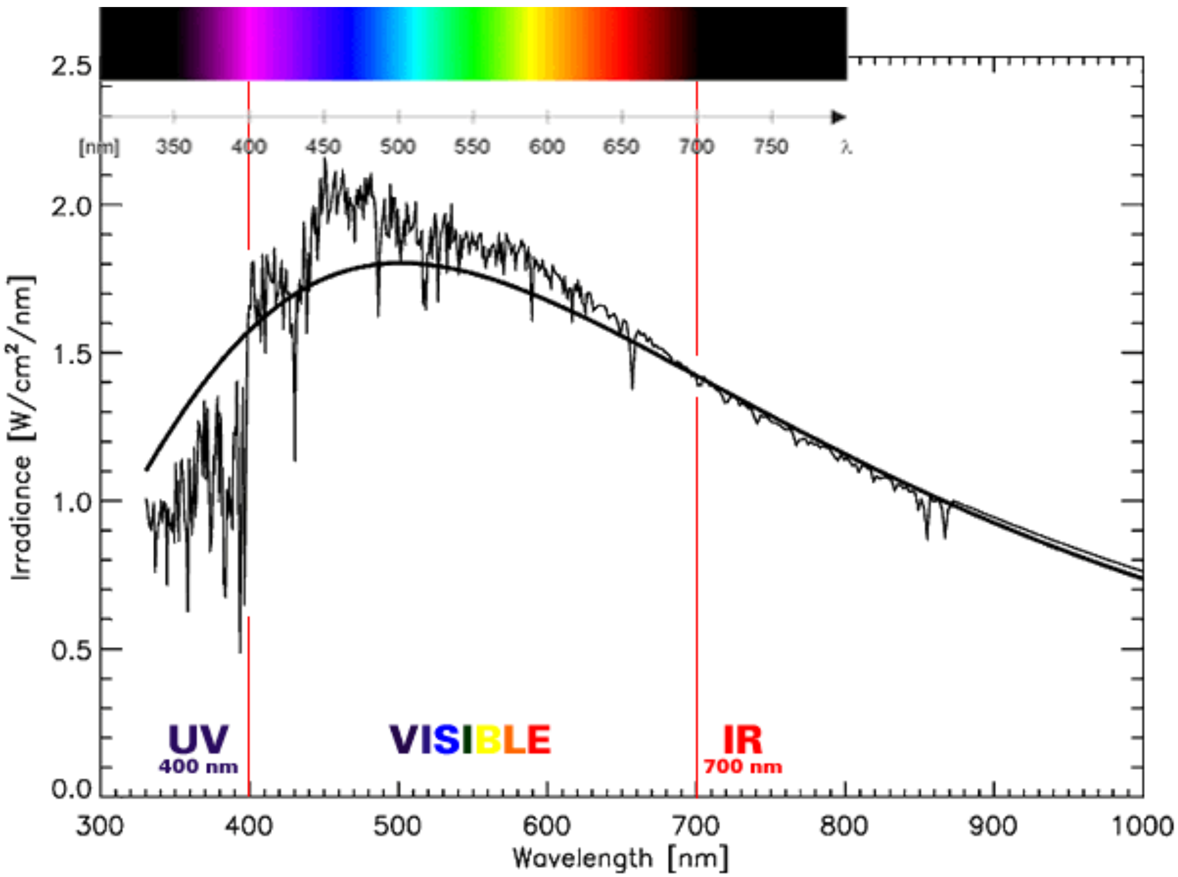
Continuum.
How it is formed?

Solar Spectrum



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Main features:

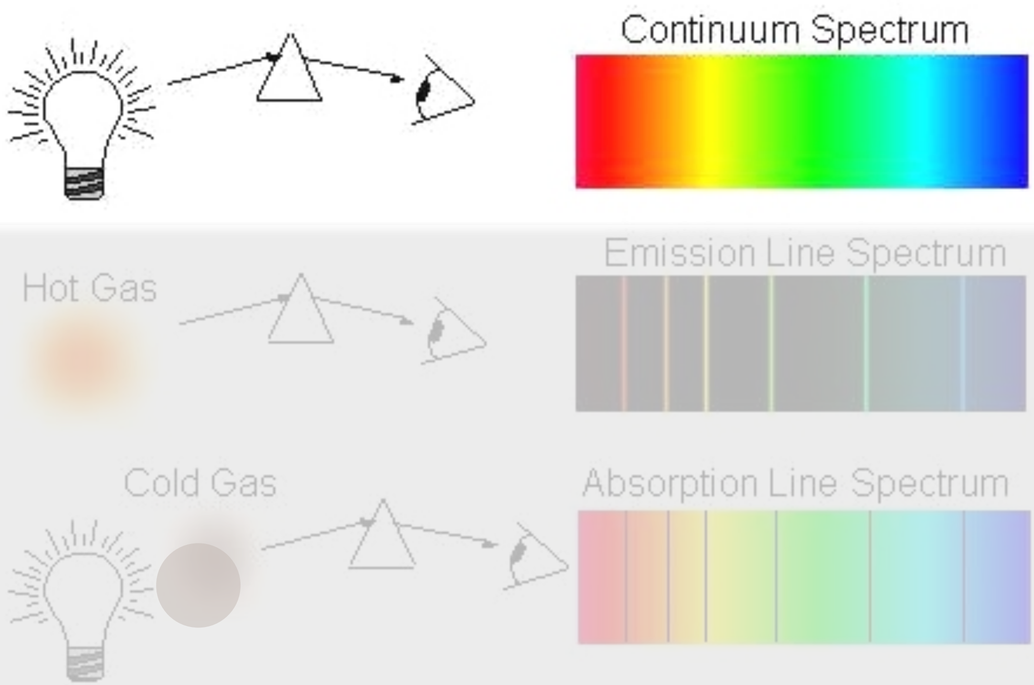
Spectral lines: bound-bound transition (excitation/de-excitation)

Balmer jump: bound-free transition (ionization/recombination)

Continuum.
How it is formed?
Must be ***free-free*** emission.

Spectroscopy

Continuum - Kirchhoff's first law

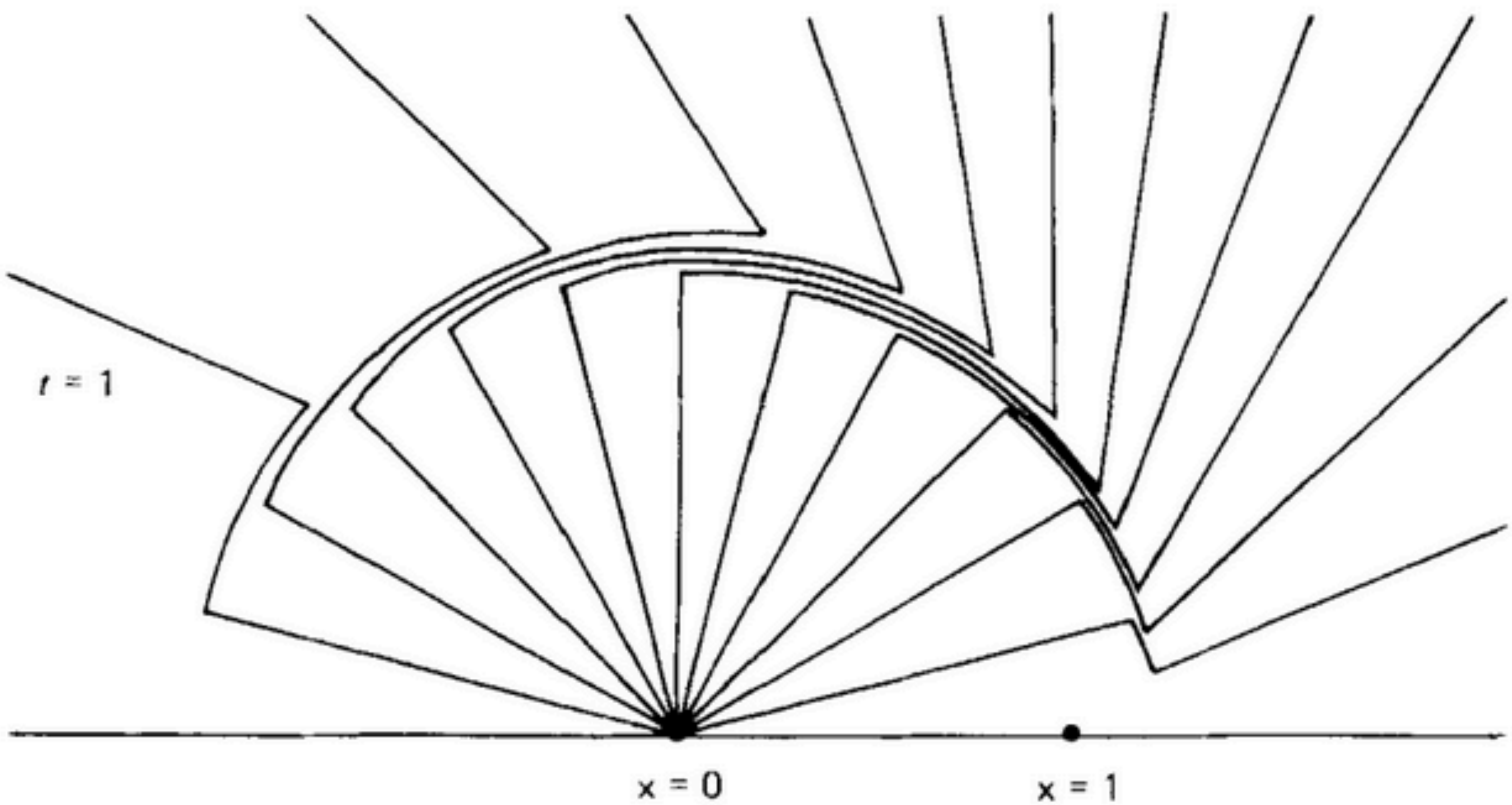


A hot solid or a hot dense gas produces a continuum spectrum.

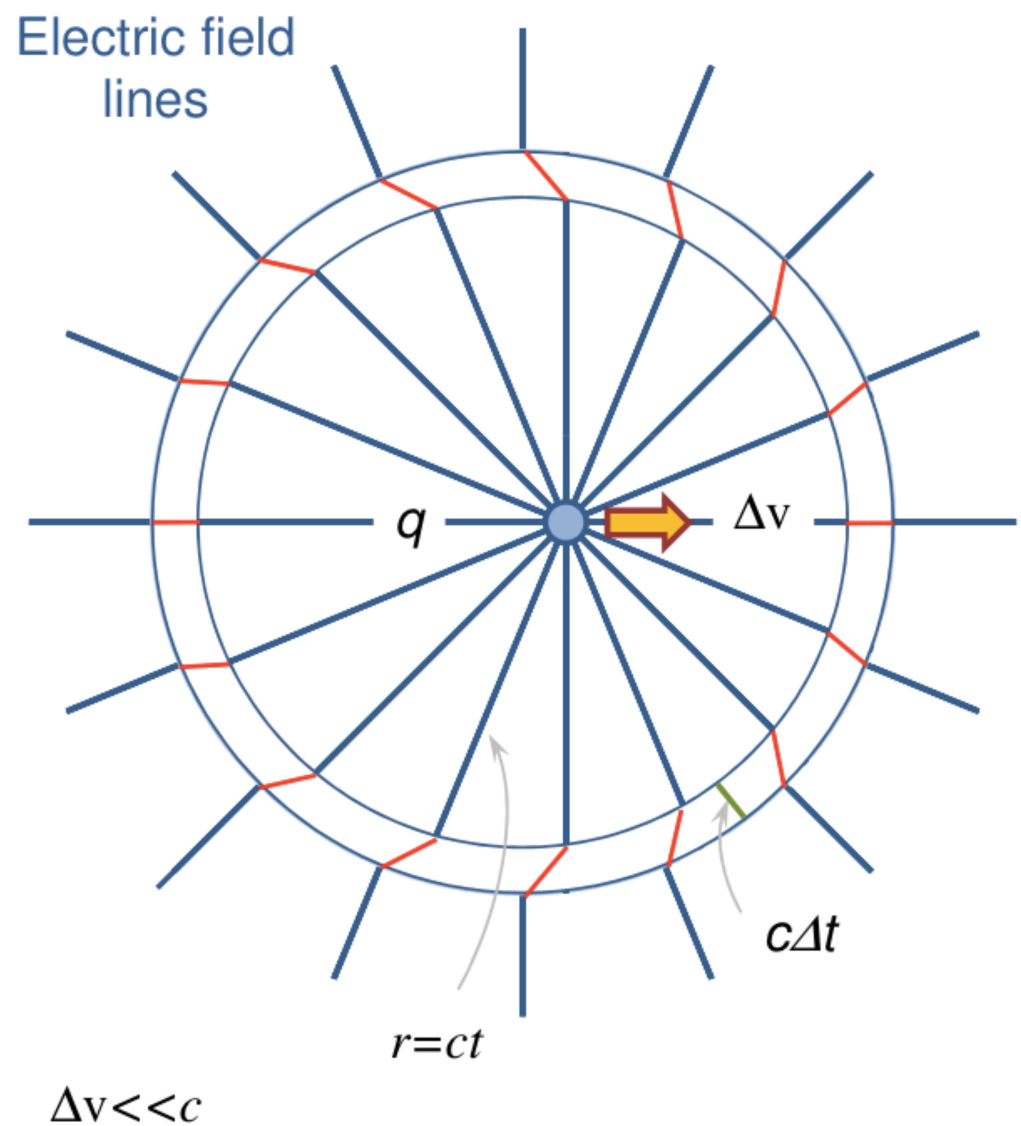
A hot low-density gas produces an emission-line spectrum.

A continuous source viewed through a cold gas produces an absorption-line spectrum.

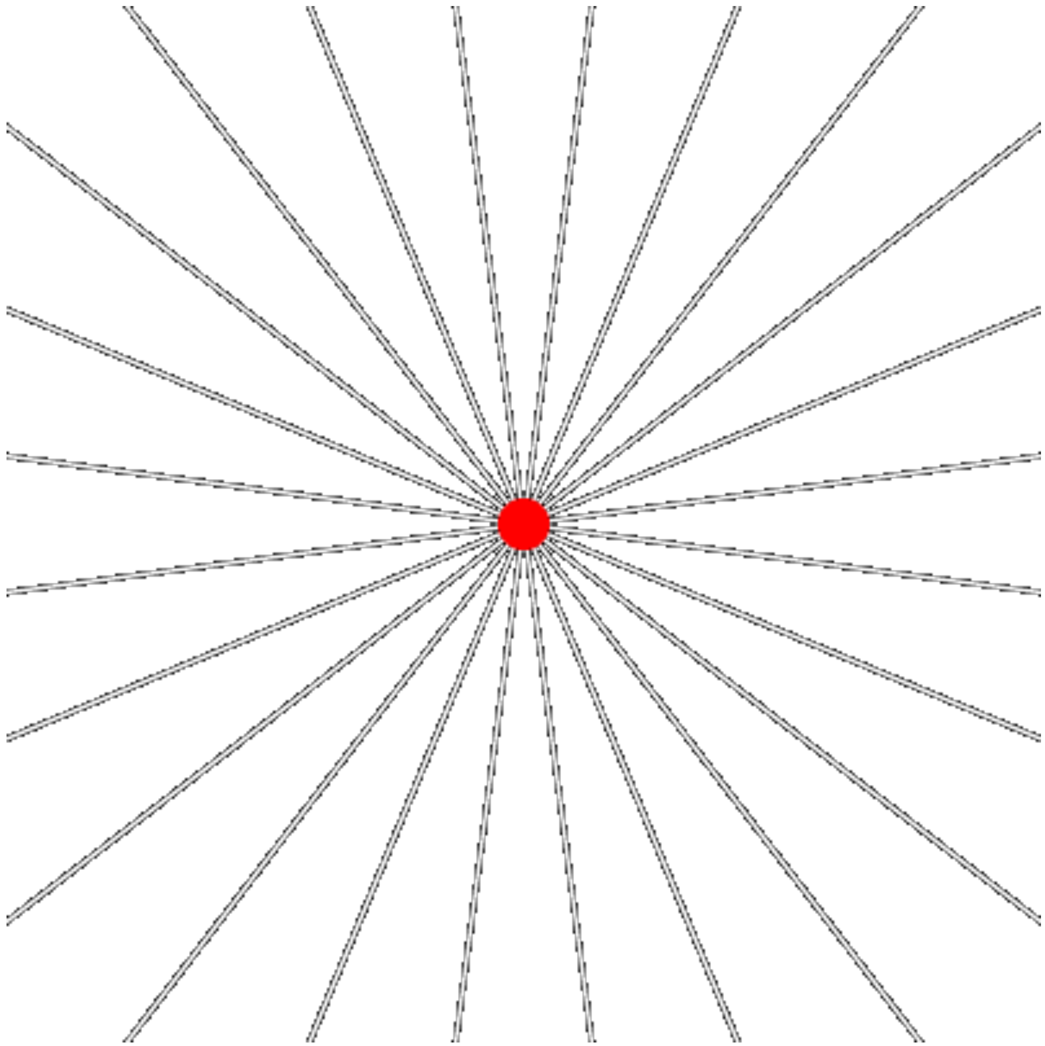
The figure shows how the radiation field arises. This is the situation after a charge that was moving suddenly stops. The charge stopped at x=0 and t=0, and the situation is shown at time t=1. The speed of light is c=1. Inside the radius x=ct=1 the field “knows” the charge has stopped, and the field lines point toward the charge in the electrostatic Coulomb configuration. Outside x=1 the news that the charge has stopped have not yet arrived, and the field points to where the charge would be, as if it is still moving. The discontinuity is the acceleration field. This field is a pulse propagating at the speed of light, and constitutes the radiation field.



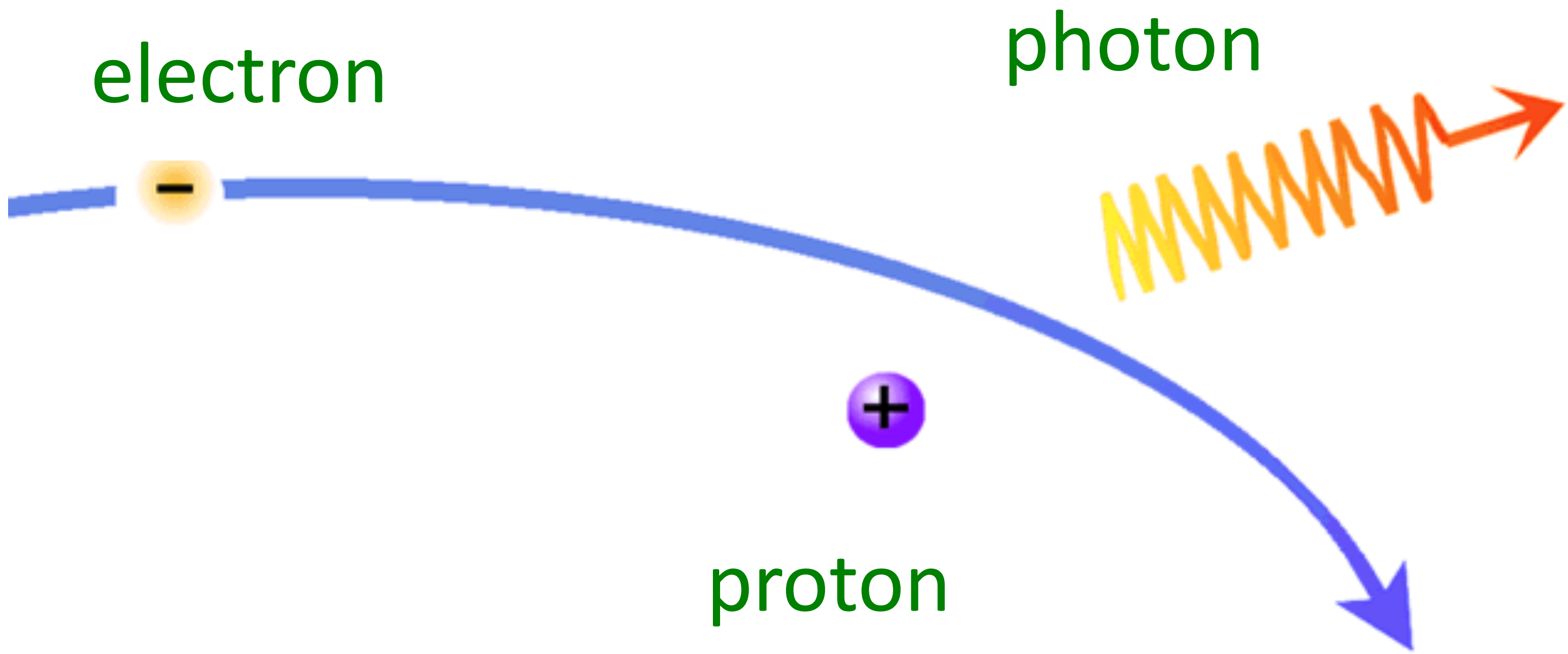
This is similar to the previous situation, but for the opposite case, of a charge that was at rest and suddenly starts to move. The field within a light crossing time knows that the charge is moving, but outside the light crossing time the field still points toward the origin, unaware that the charge is no longer at rest. The acceleration field, in red, is the only way to bridge the discontinuity while obeying Maxwell's equations.



Switch to slideshow to see this animated gif of the propagation of the acceleration field as a pulse. This pulse is radiation. Our eyes perceive it as light.



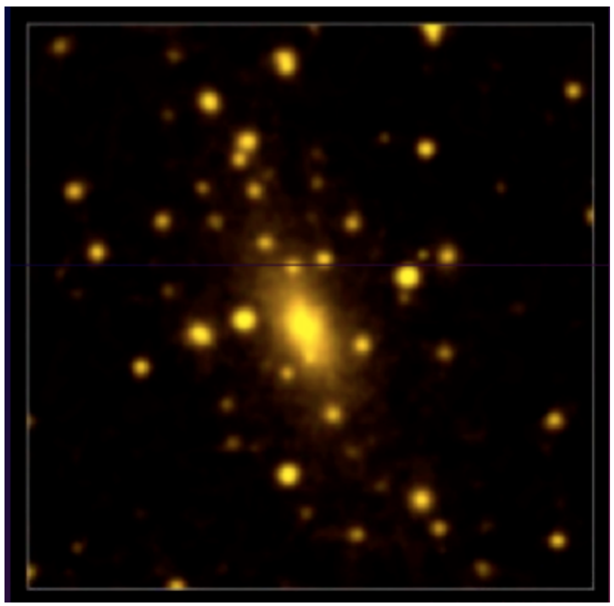
Bremsstrahlung
(braking radiation)



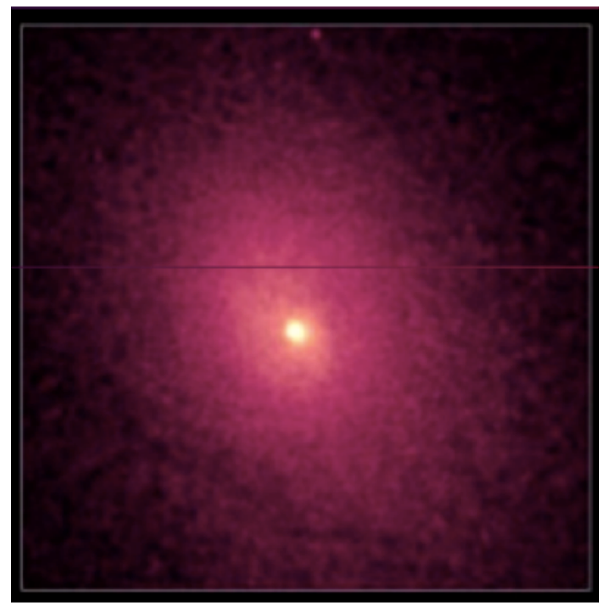
Bremsstrahlung in Astrophysics

Occurs whenever there is diffuse hot (ionized) gas

X-ray emission from clusters of galaxies



Optical
(Galaxy cluster Abell 2029)



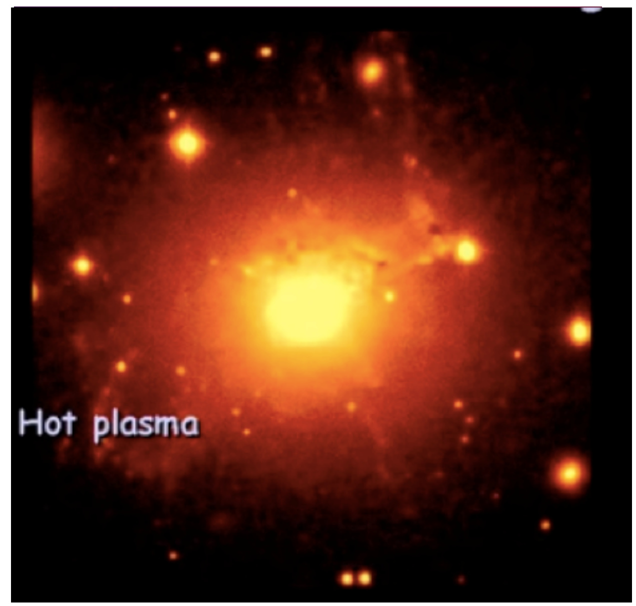
X-ray
(Diffuse emission)

Bremsstrahlung in Astrophysics

Occurs whenever there is diffuse hot (ionized) gas

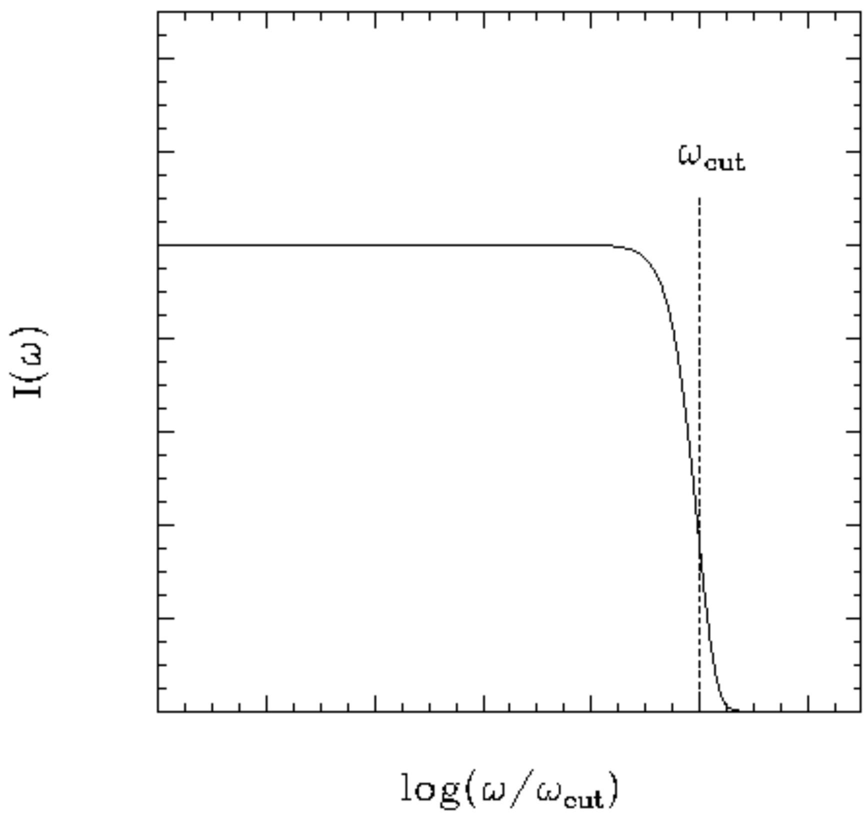
X-ray emission from clusters of galaxies

Optical
(Perseus cluster)



X-ray
(Diffuse emission)

Spectrum of Bremsstrahlung

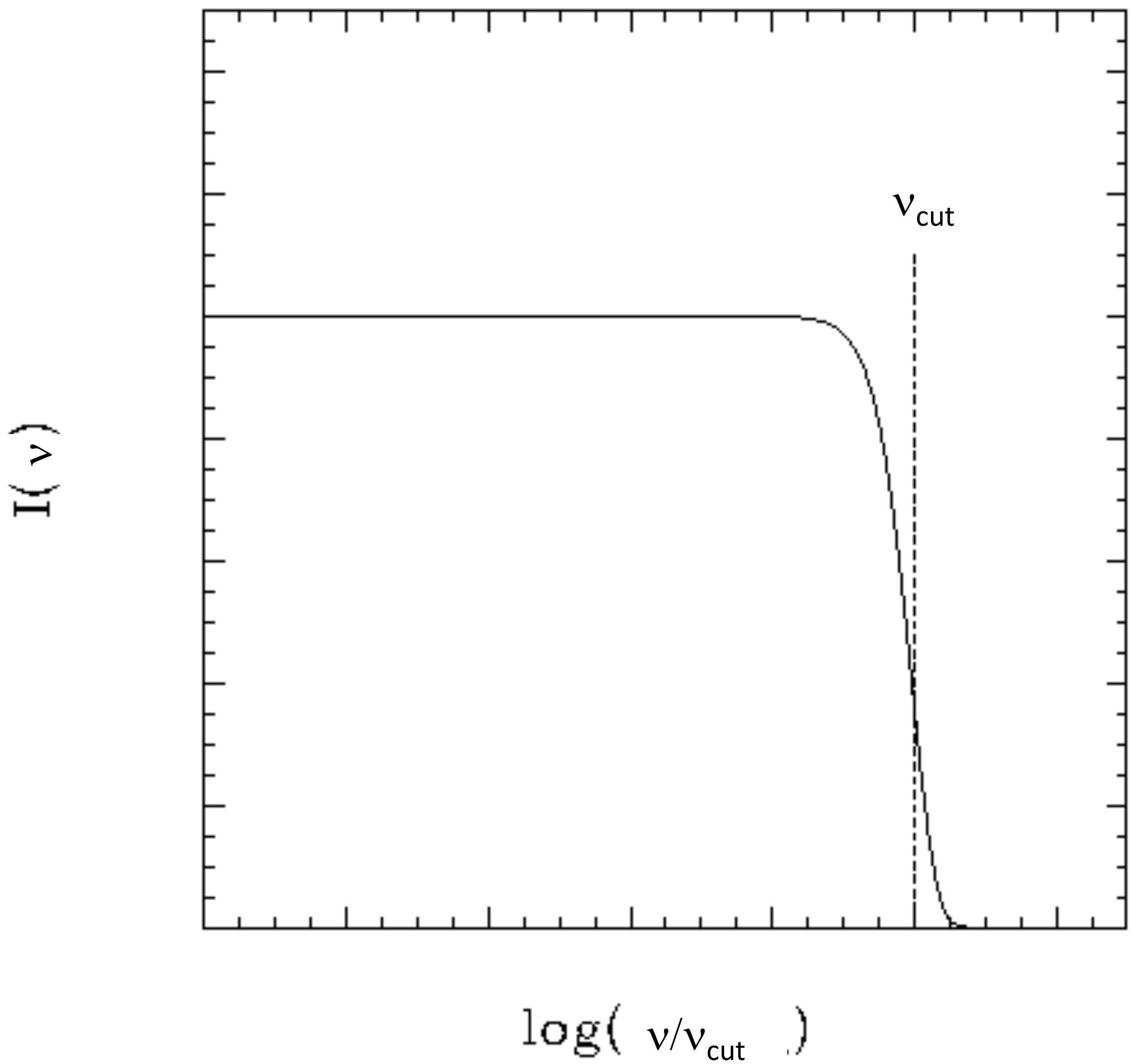


Main features:

The spectrum of Bremmstrahlung has **flat emissivity**.

At some point it must have a thermal cutoff, because high frequencies imply high energy and the electron cannot emit a photon with energy higher than its kinetic energy.

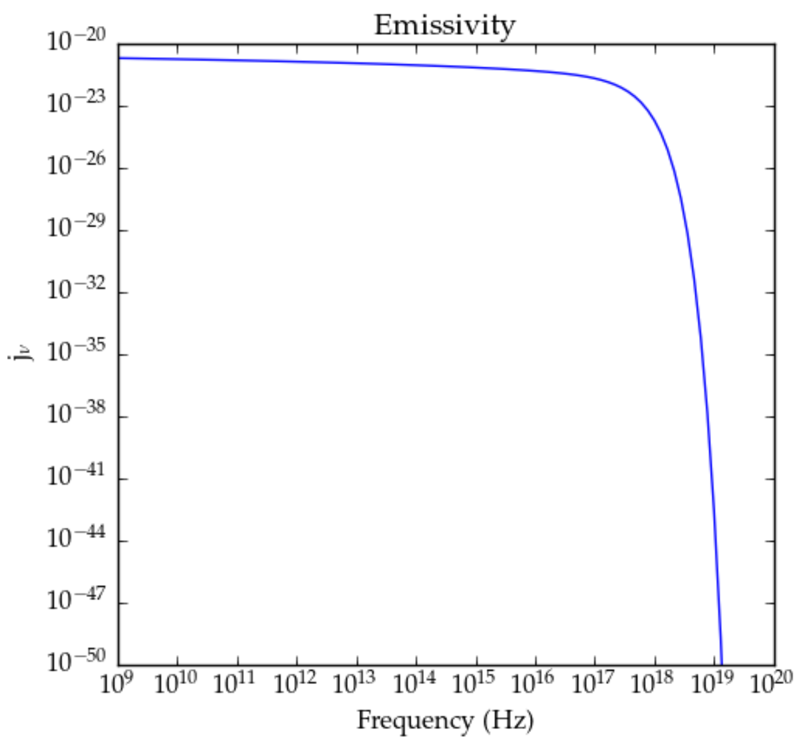
Spectrum of Bremsstrahlung

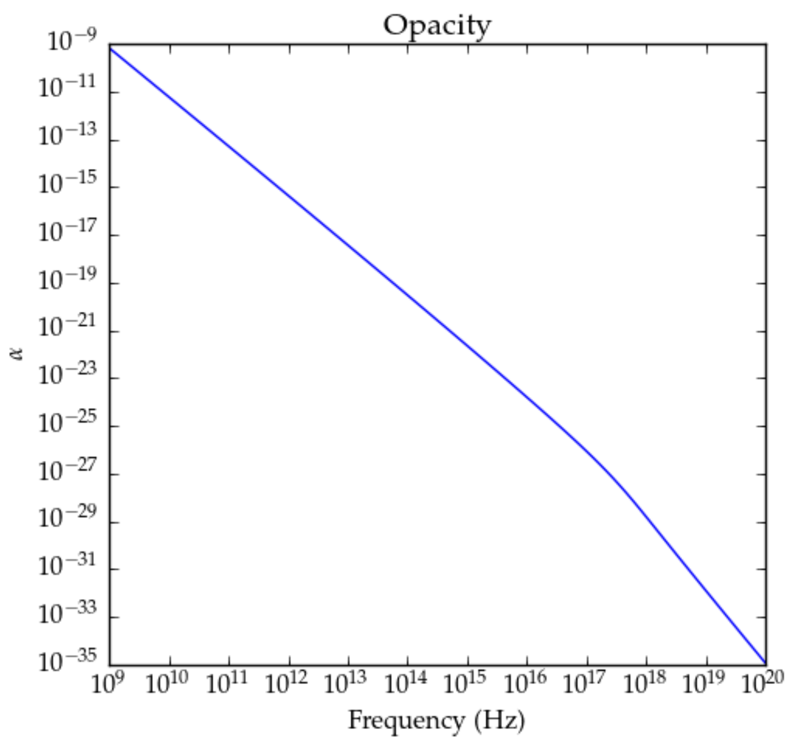


Opacity

Given the emissivity, Kirchhoff first law gives the opacity

$$\kappa_\nu = j_\nu B_\nu$$



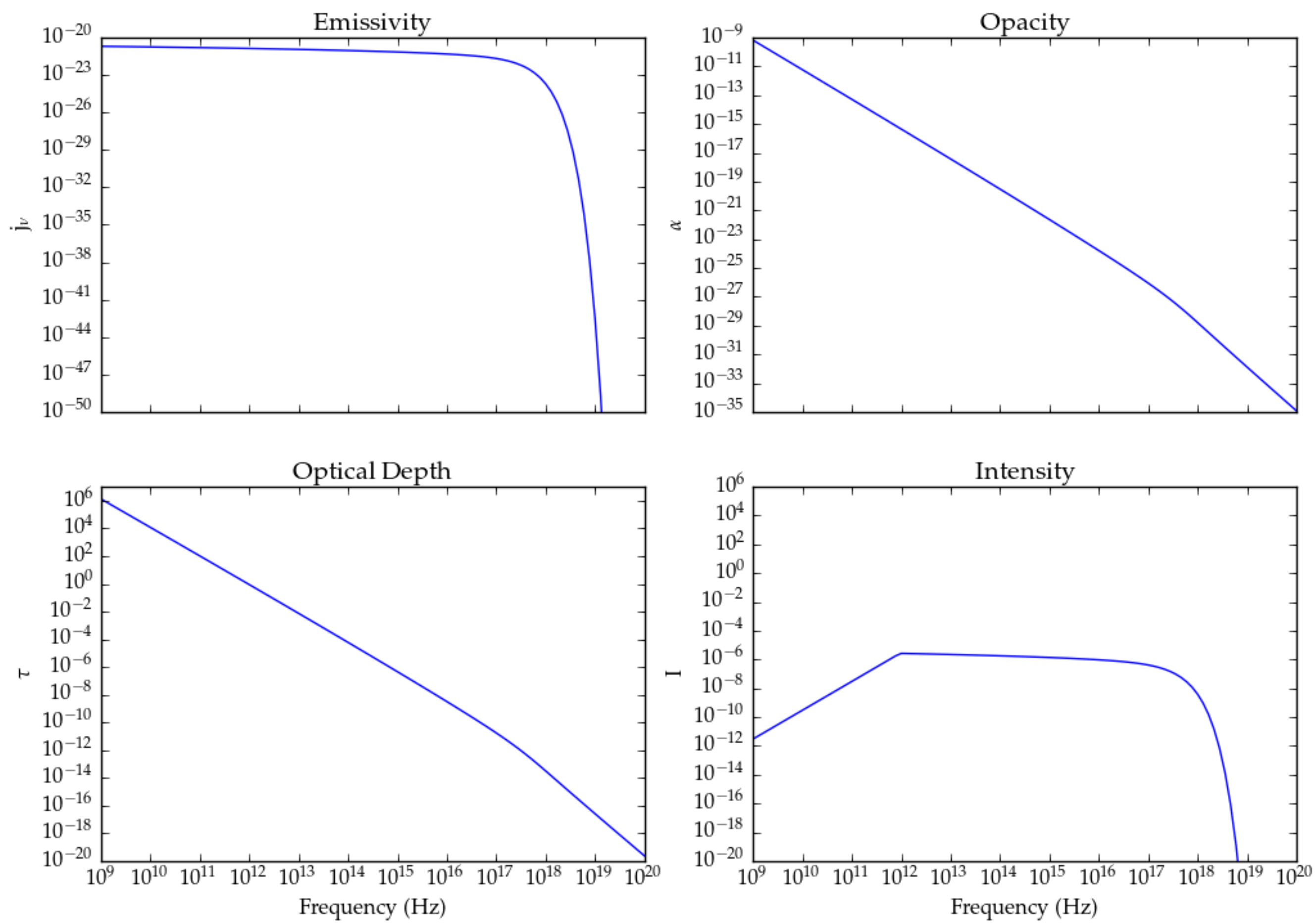


Opacity

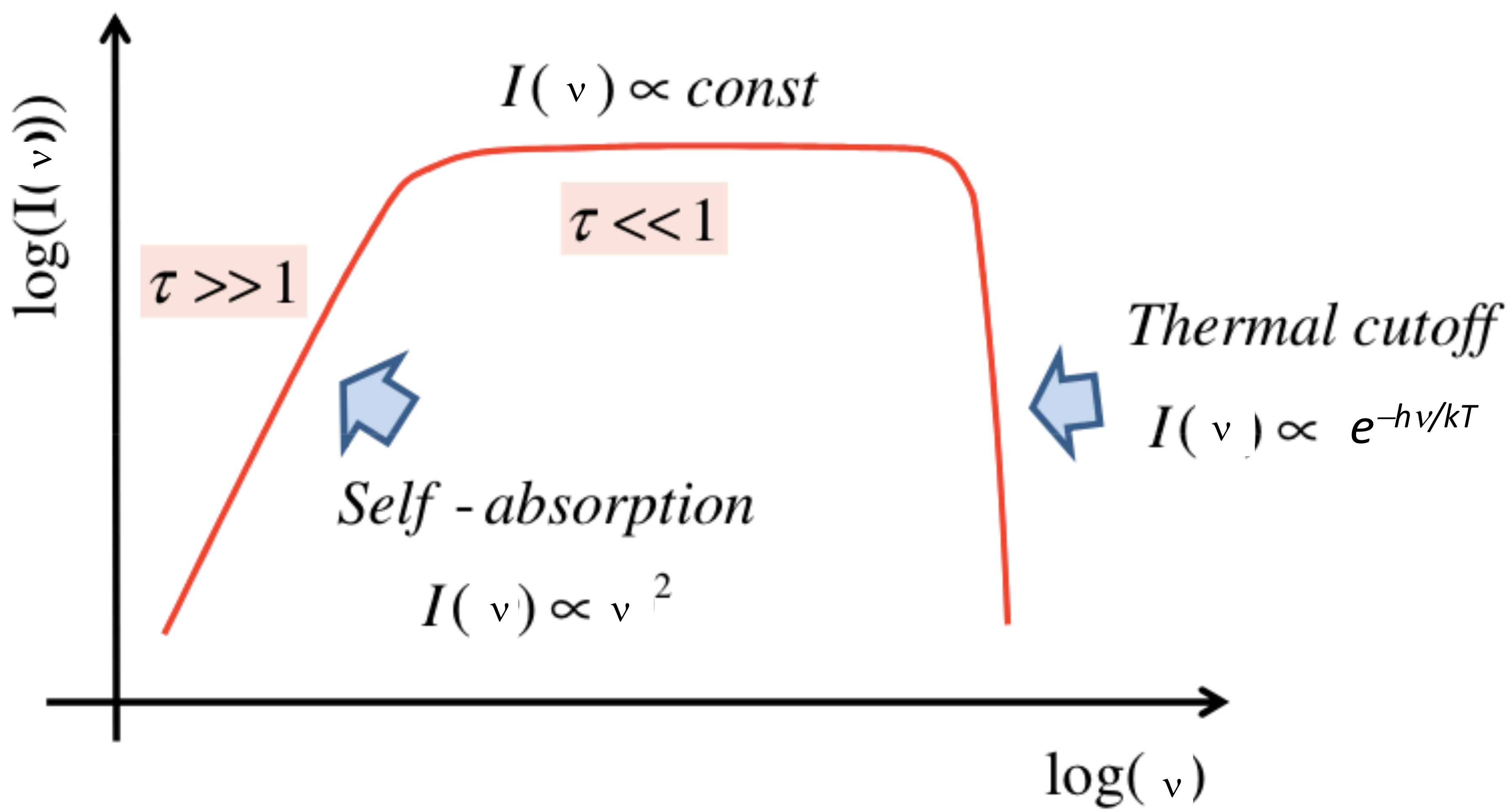
Electrons emit, electrons absorb.

At low frequency, the spectrum becomes optically-thick.

The ensemble of electrons is absorbing the radiation it emits.

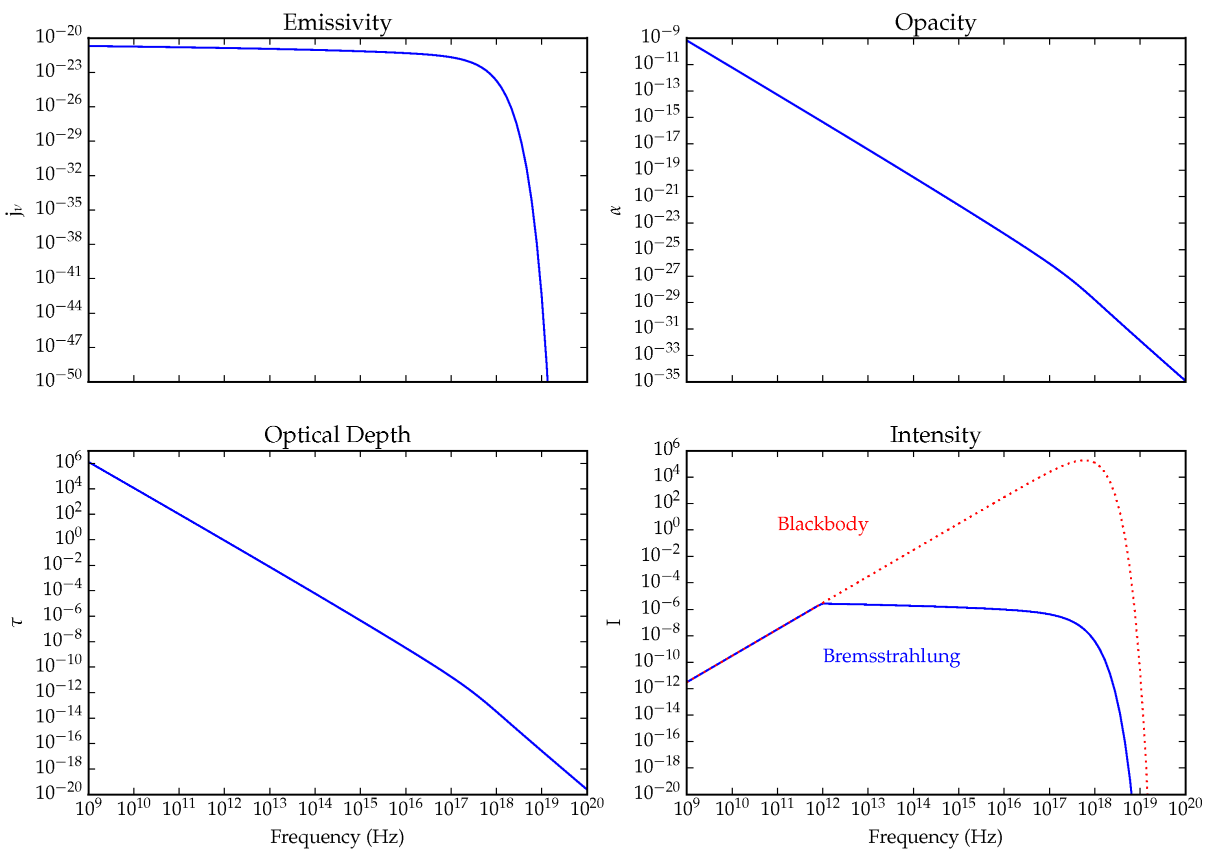


- Spectrum of Thermal Bremsstrahlung



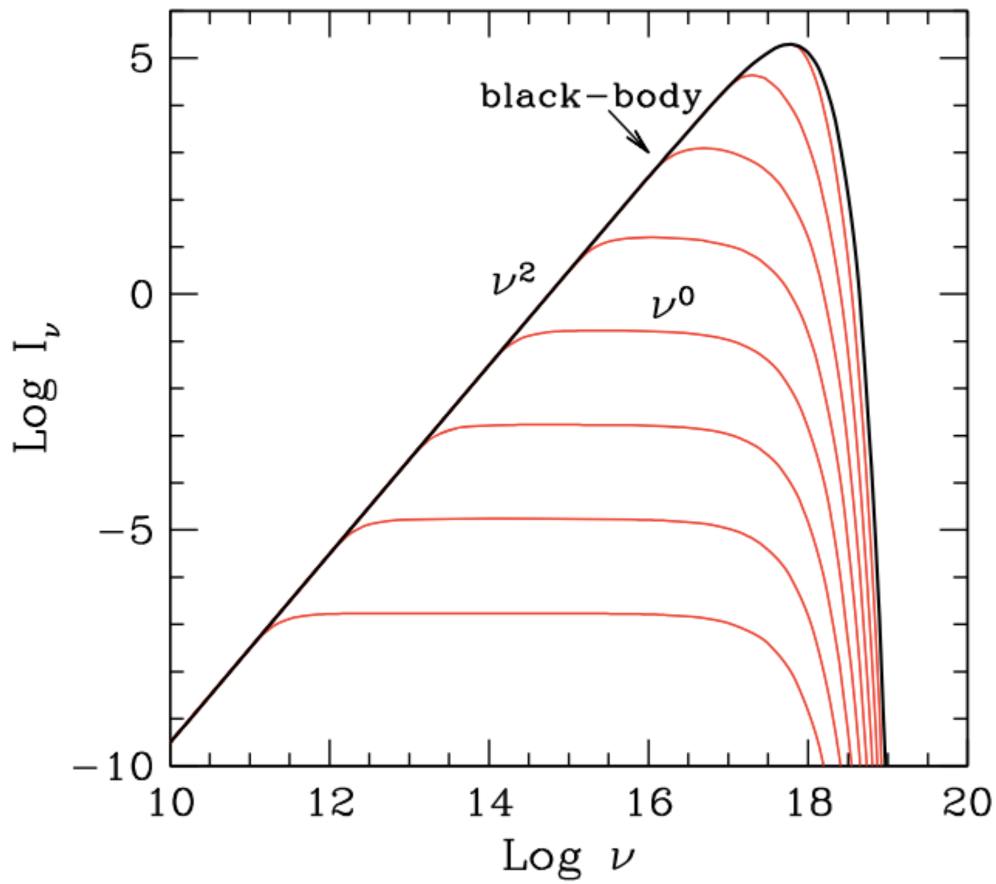
From Bremsstrahlung to Blackbody

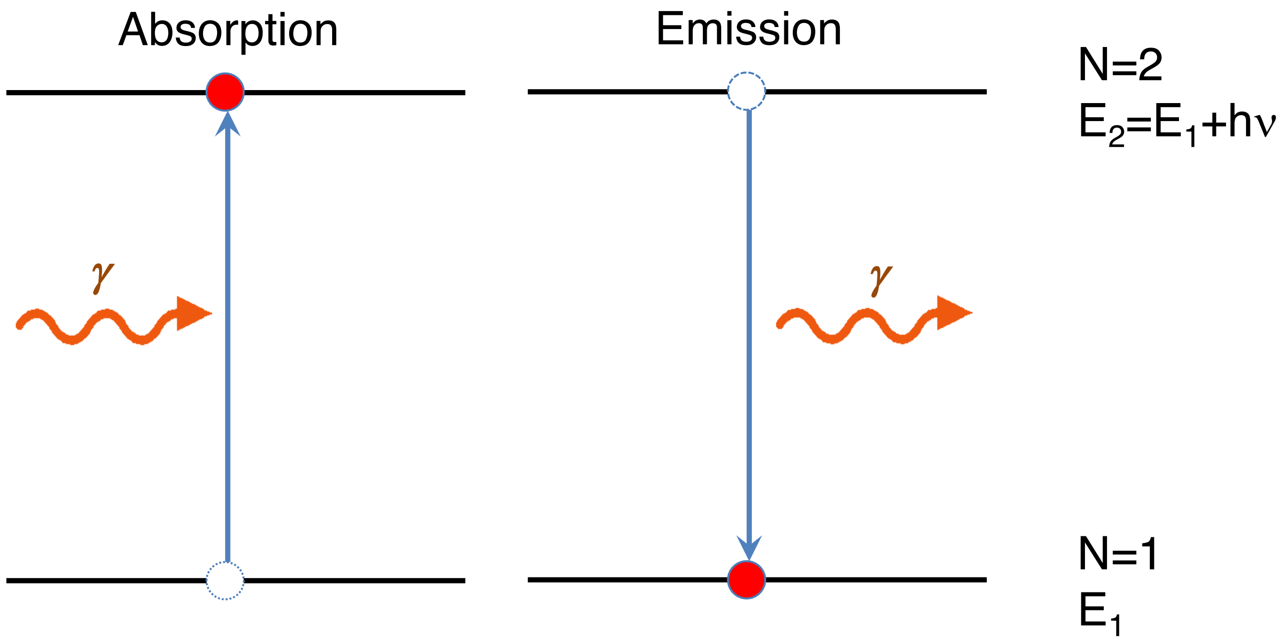
Compare the spectra of Bremsstrahlung to that of blackbody.
In the optically thick regime, they match.



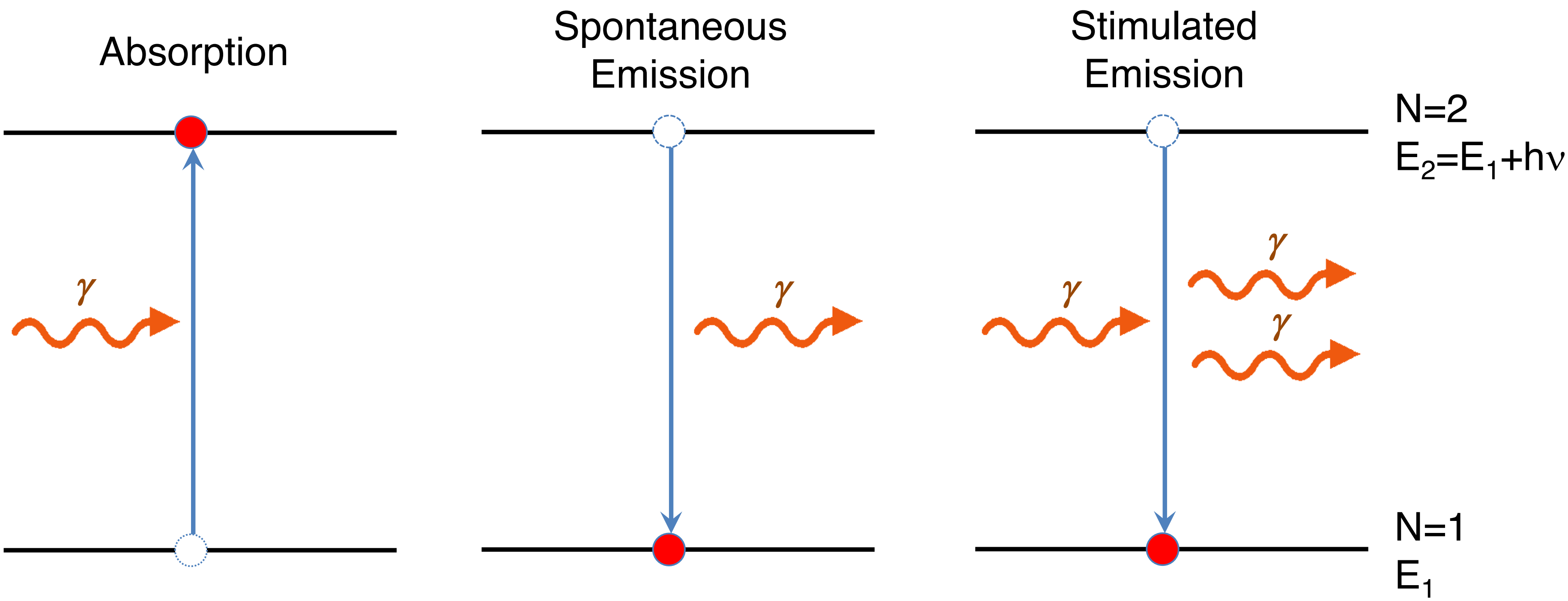
From Bremsstrahlung to Blackbody

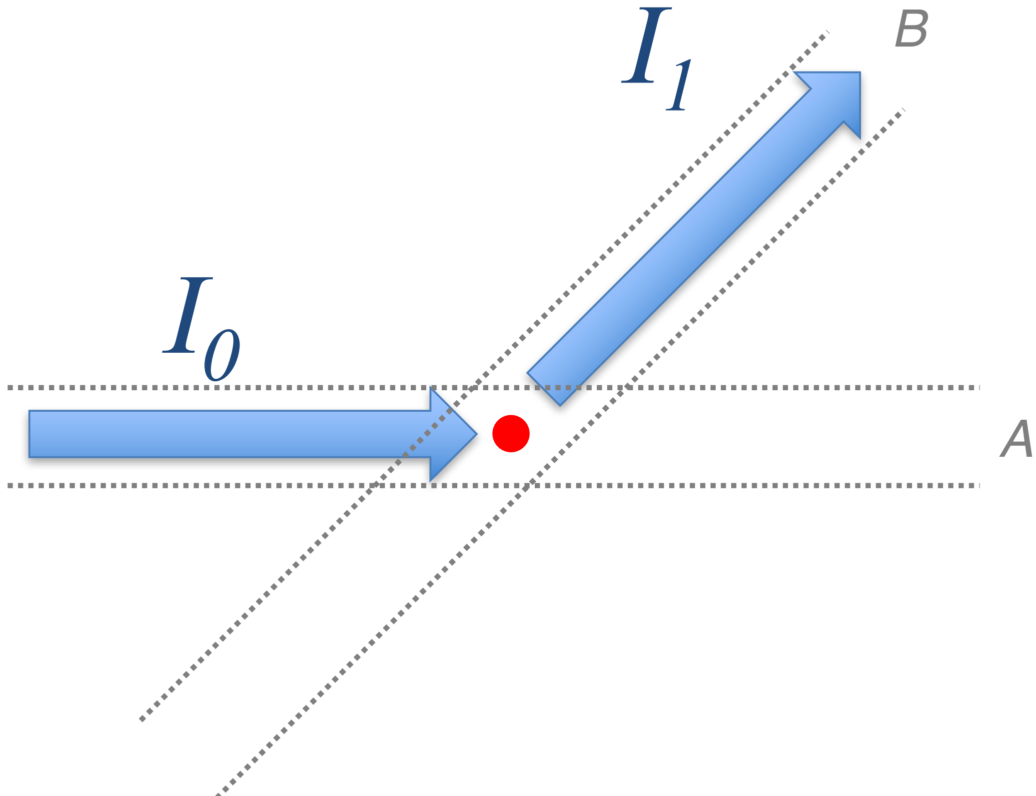
As one increases the density, one increases the optical depth. When the whole spectrum is optically thick, the whole spectrum becomes self-absorbed, and Bremmstrahlung becomes blackbody.



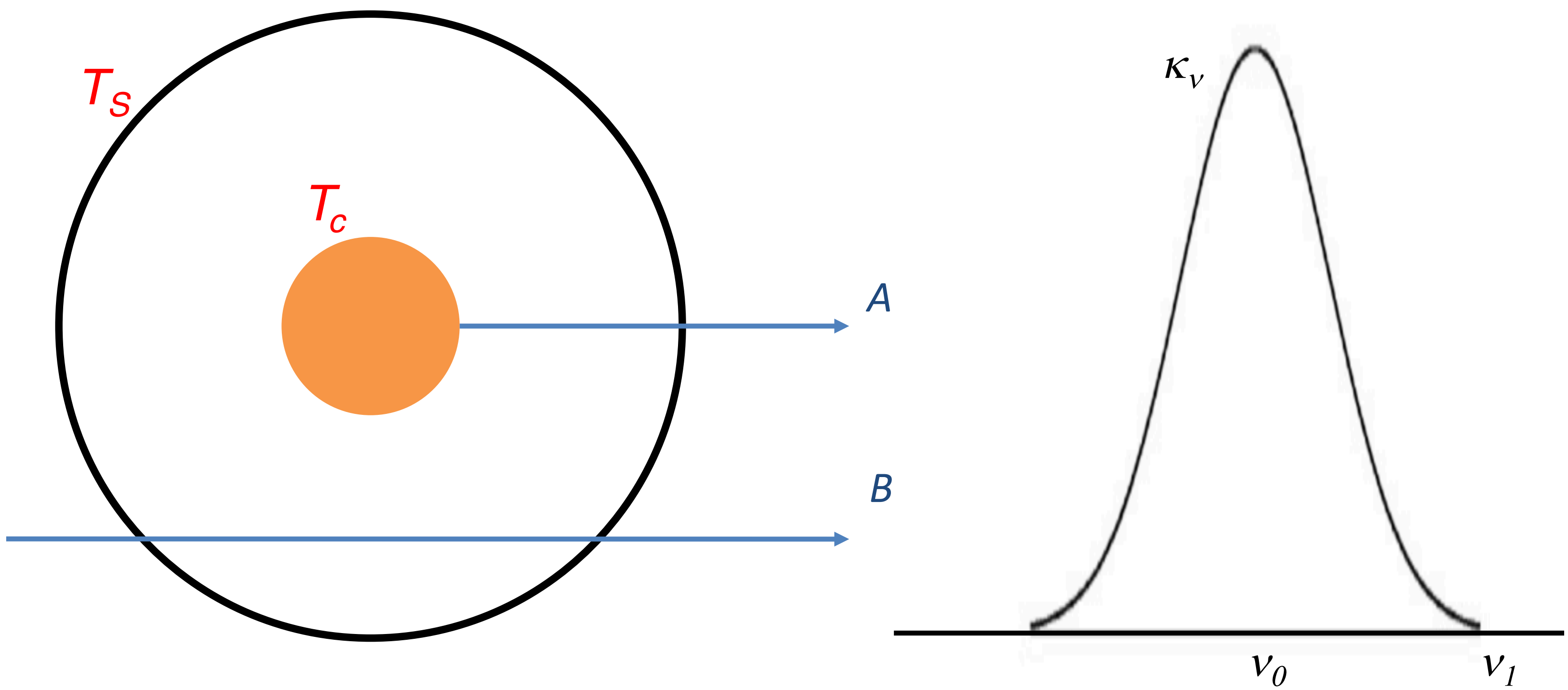


Absorption
Emission
γ
γ
N=2
E2=E1+hν
N=1
E1

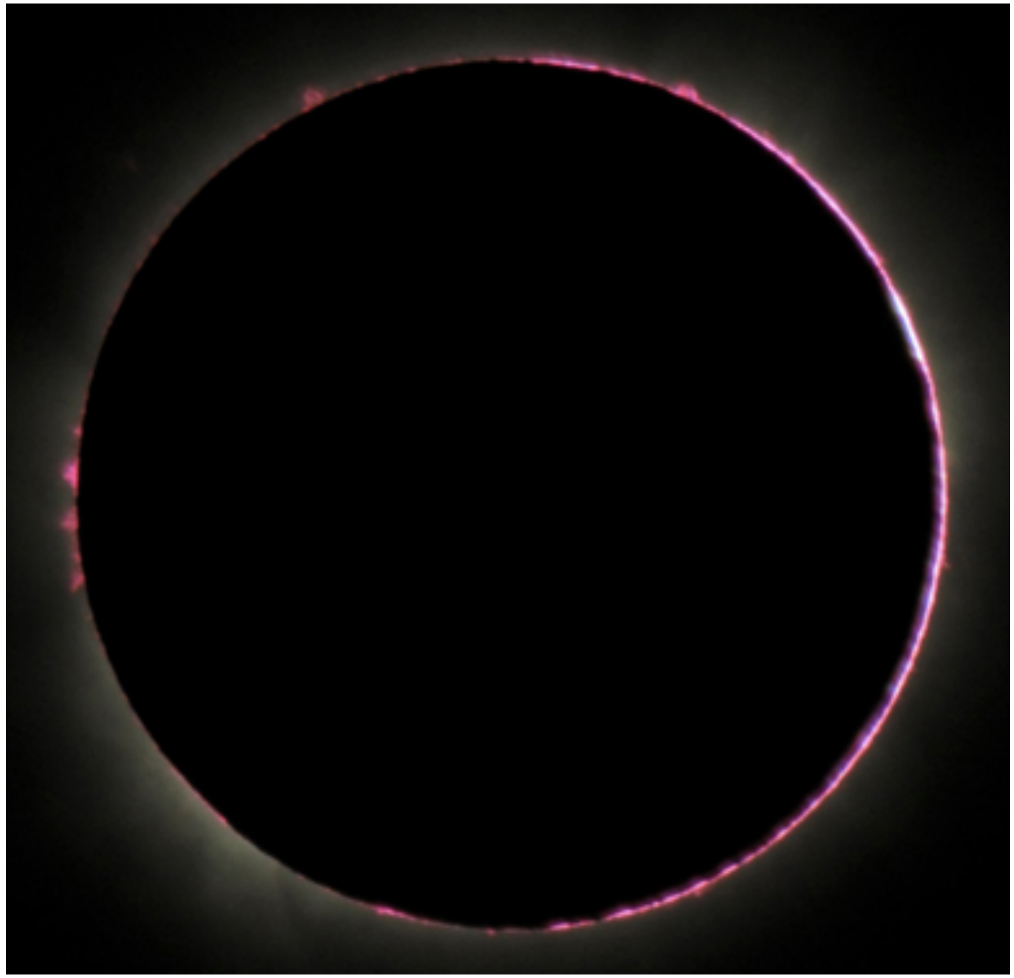

Absorption
Spontaneous Emission
Stimulated Emission
N=2
$E_2=E_1+h\nu$
N=1
E_1
γ
γ
γ
γ
γ

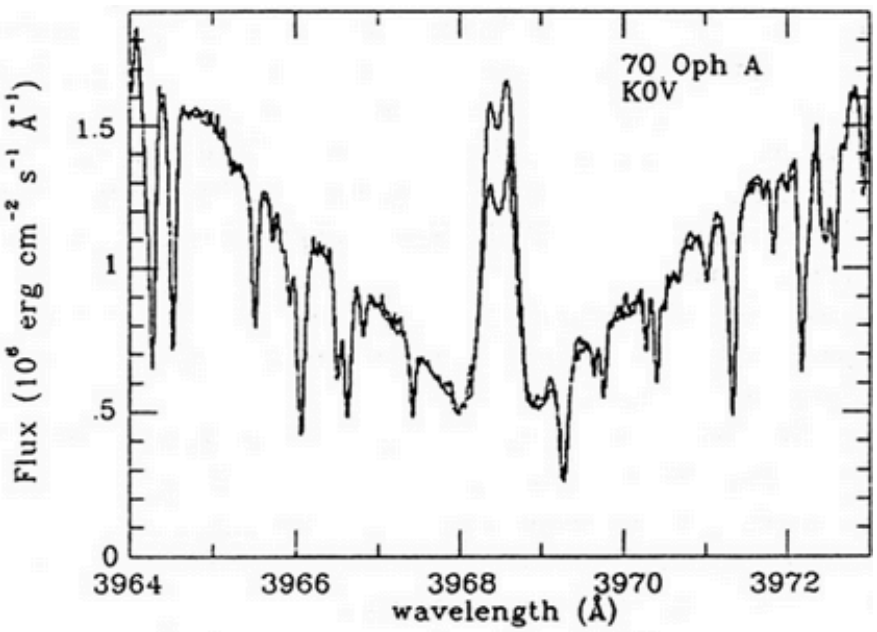


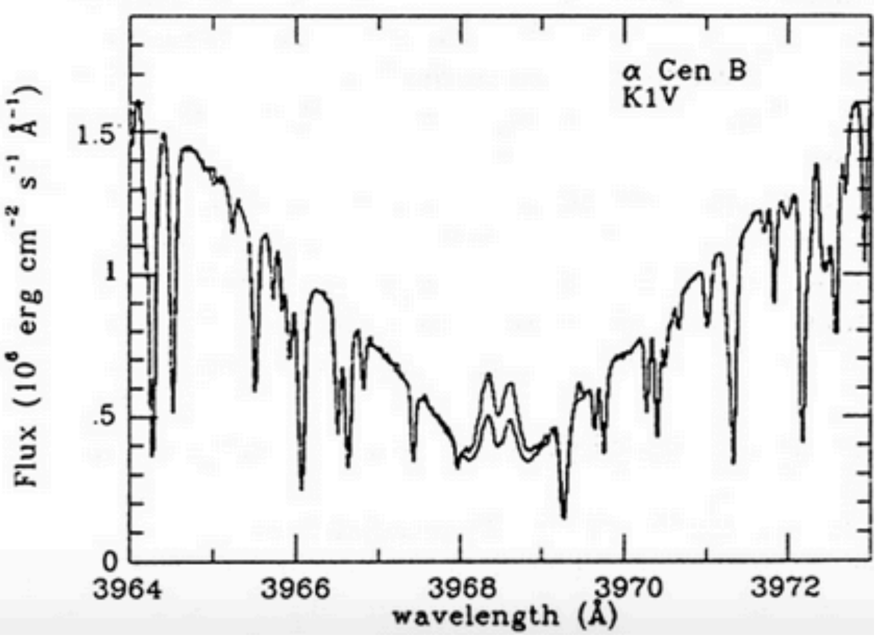
I_1
B
I_0
A

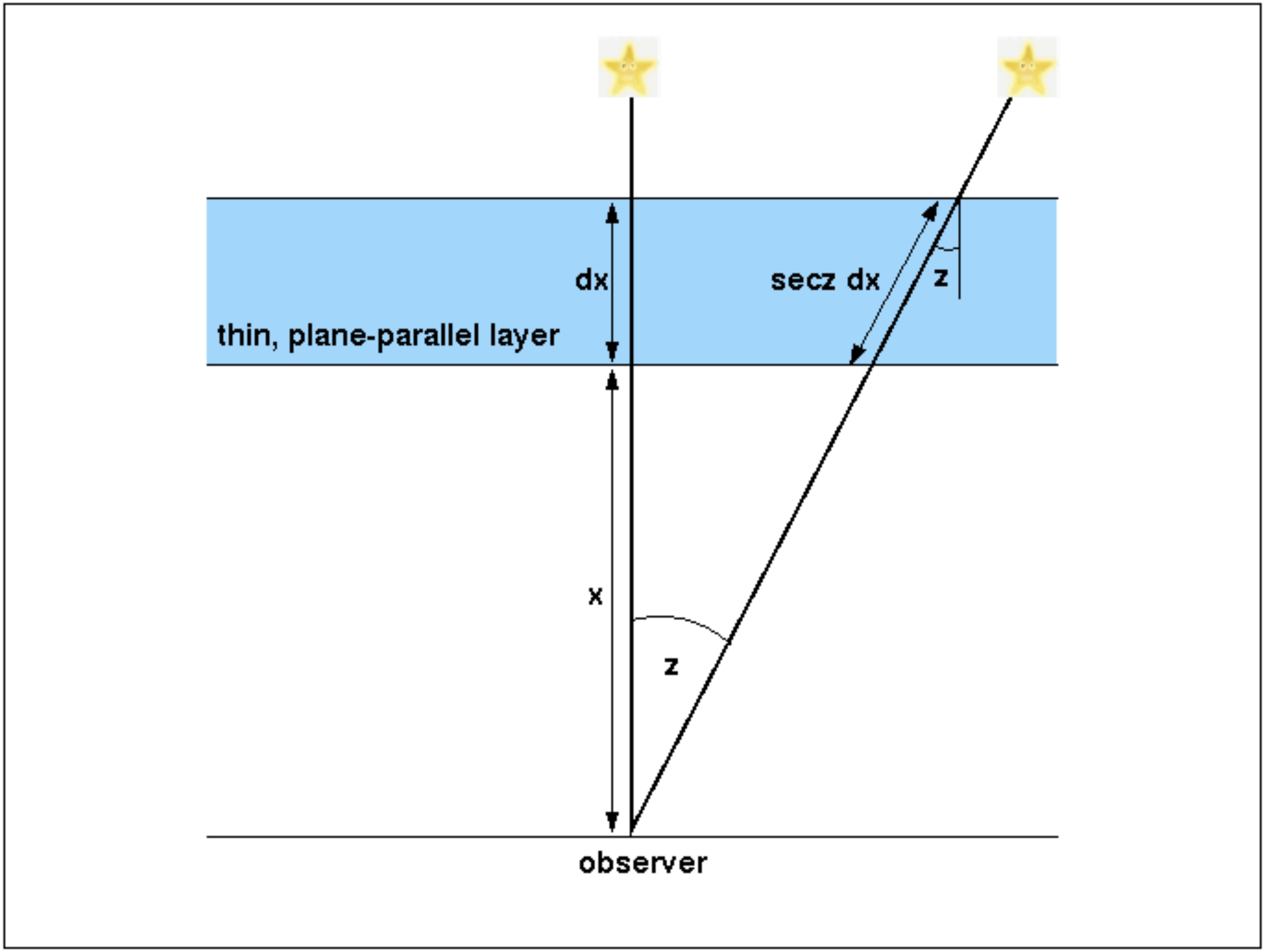


T_S
T_c
A
B
κ_ν
ν_0
ν_1

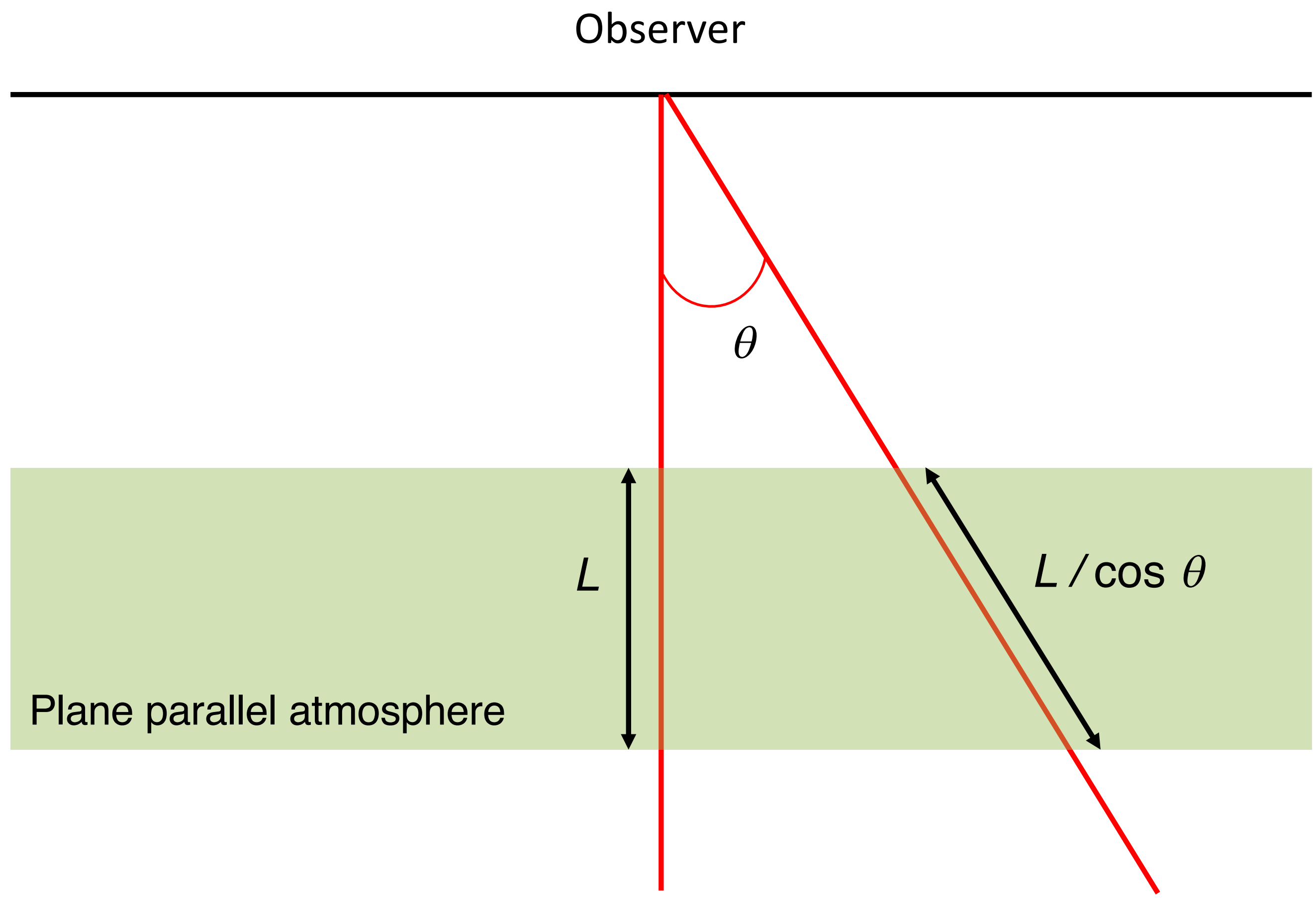



70 Oph A
K0V
Flux (10[6] erg cm[-2] s[-1] Å[-1])
wavelength (Å)
1.5
1
.5
0
3964
3966
3968
3970
3972


α Cen B
K1V
Flux (10[6] erg cm[-2] s[-1] Å[-1])
wavelength (Å)
1.5
1
.5
0
3964
3966
3968
3970
3972



dx
secz dx
z
thin, plane-parallel layer
x
z
observer

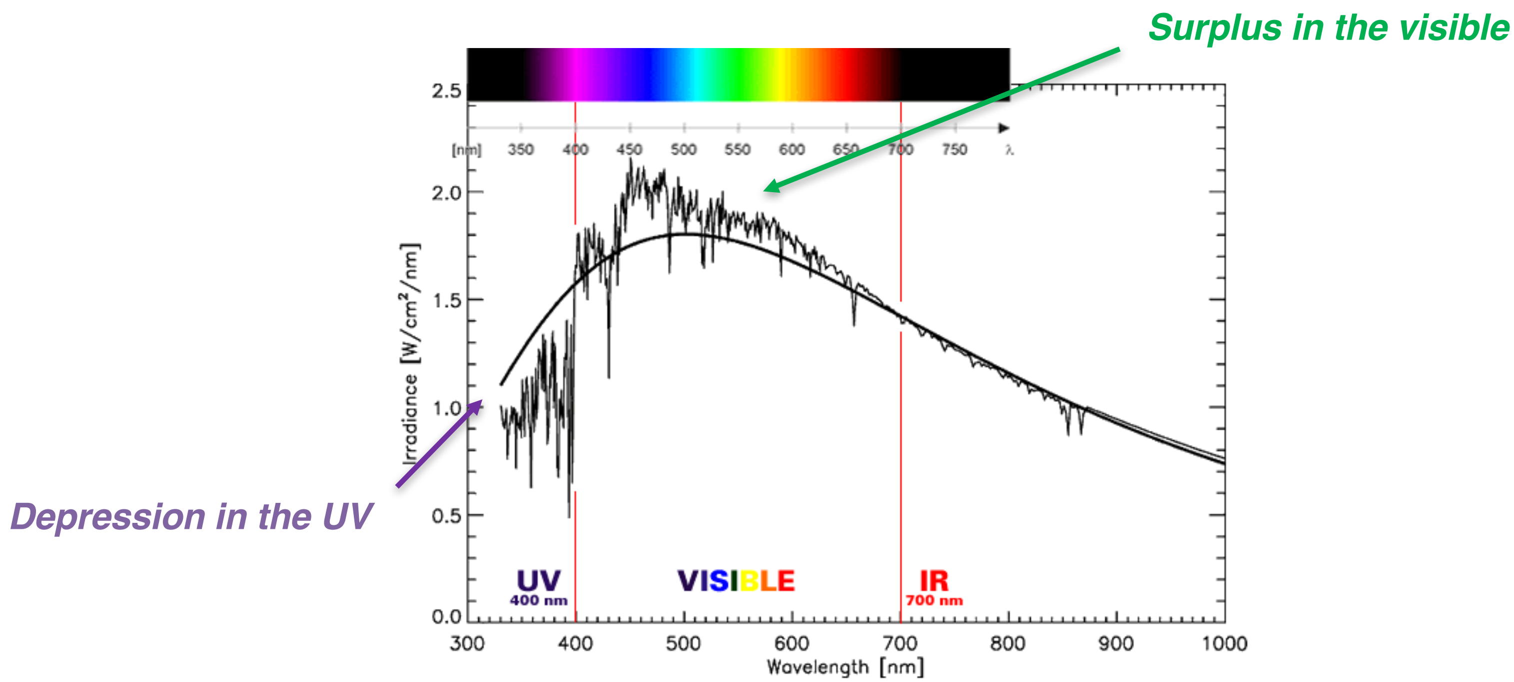


Observer
θ
L
$L / \cos\,\theta$
Plane parallel atmosphere

Radiative Equilibrium

$$\int \kappa_\nu \, S_\nu \, d\nu = \int \kappa_\nu \, J_\nu \, d\nu$$

Bolometric emission = Bolometric absorption



The solar irradiance spectrum from 300 to 1000nm as measured by Labs and Neckel (1962) and corrected by Neckel and Labs (1984).
It roughly follows a black body radiation curve of 5777 K (thick line), particularly in the IR.

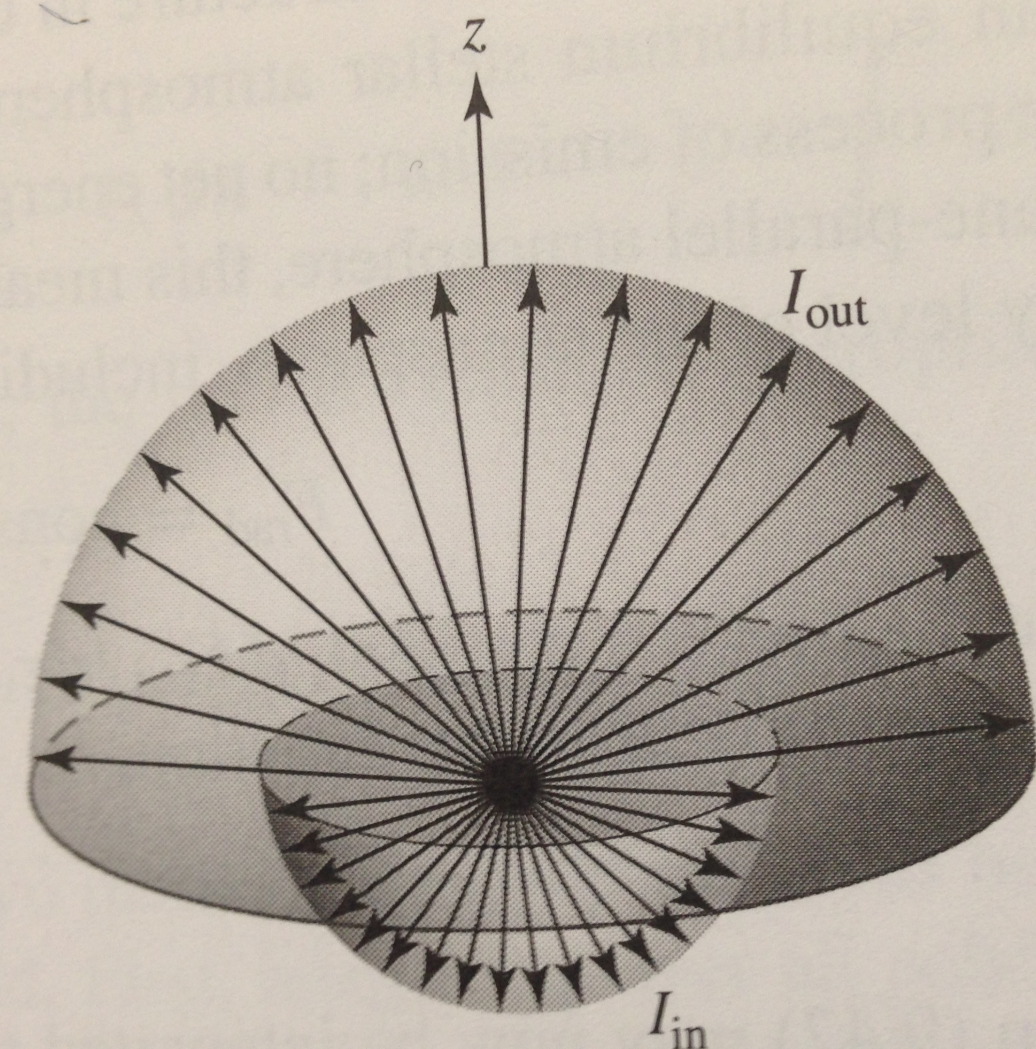
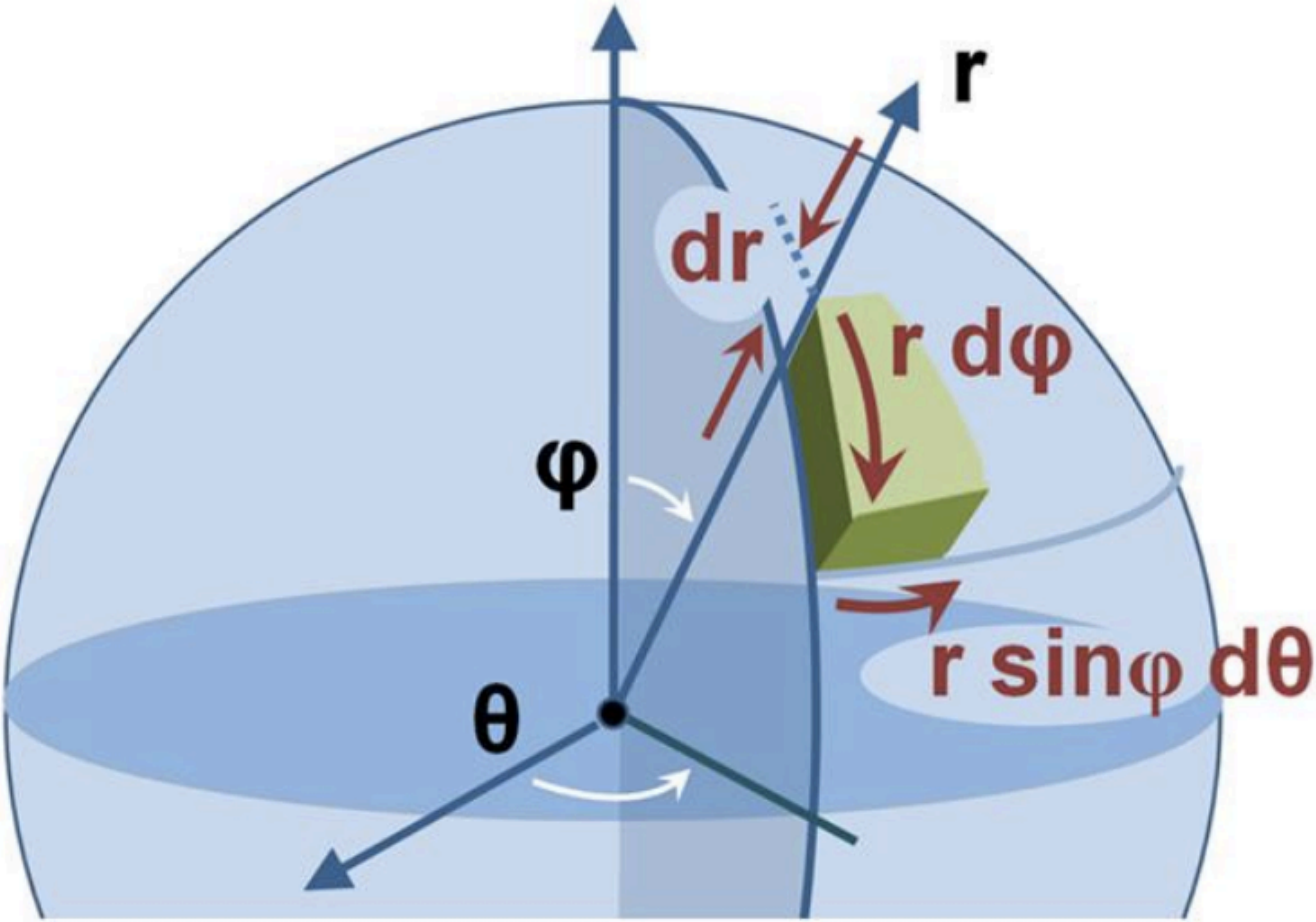
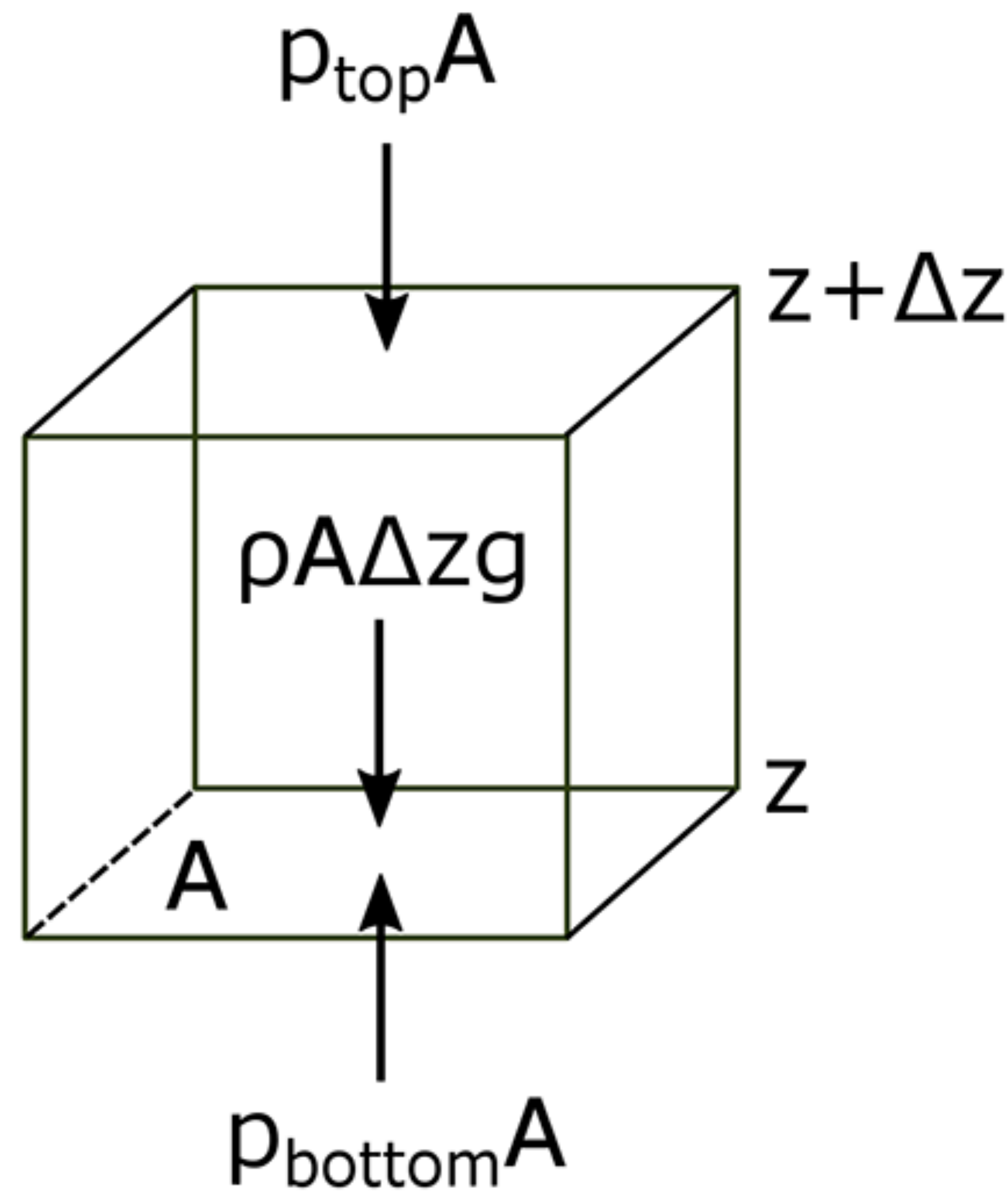


FIGURE 9.15 The Eddington approximation.

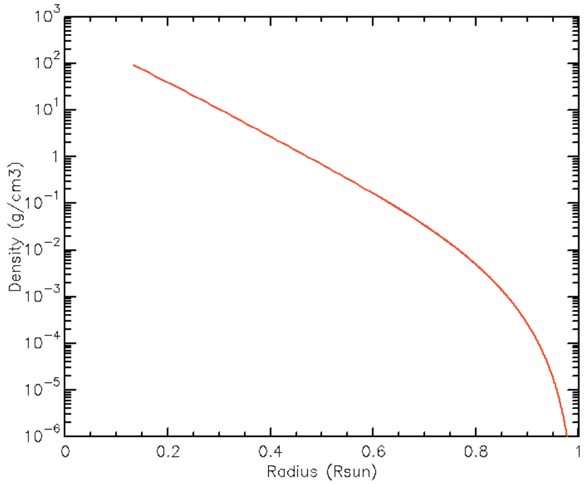

r
dr
r dφ
φ
r sinφ dθ
θ



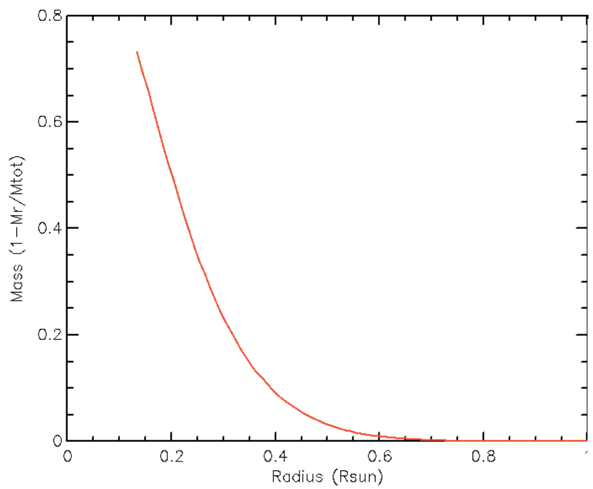
$p_{top}A$
$z+\Delta z$
$\rho A\Delta zg$
z
A
$p_{bottom}A$

Solar Model

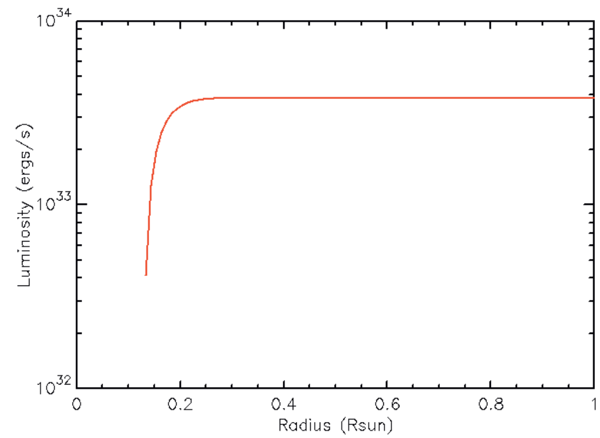
Density



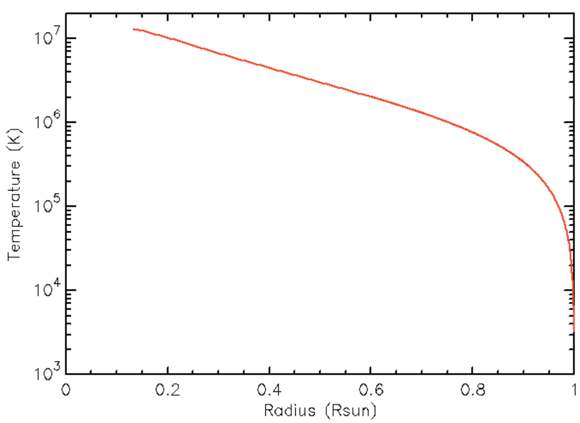
Mass



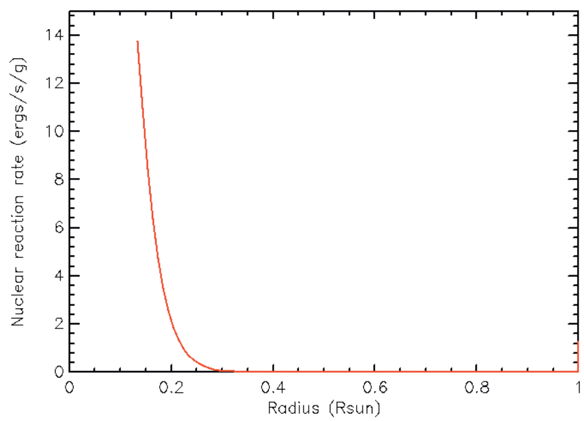
Luminosity



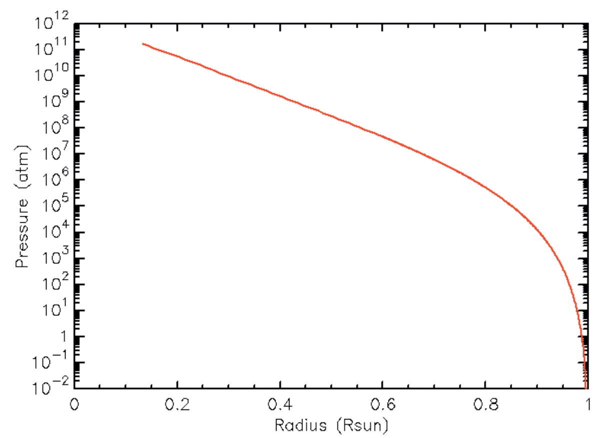
Temperature



Nuclear Reaction Rate



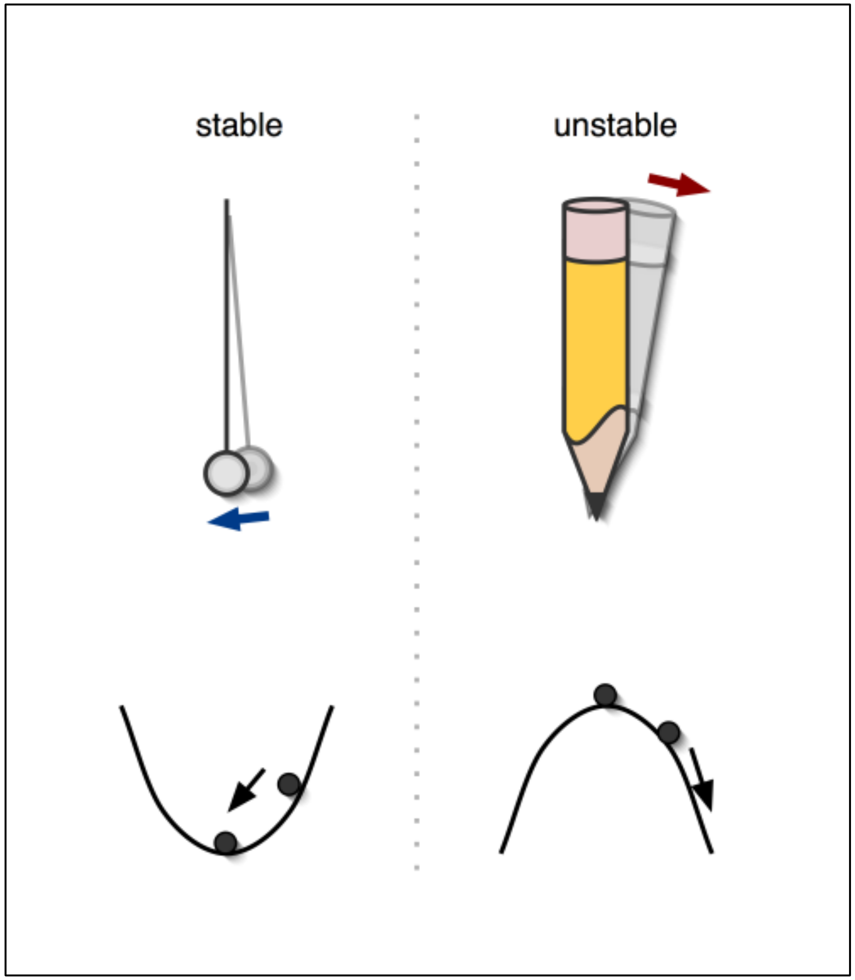
Pressure



Stable and Unstable Equilibria

Stable Equilibrium

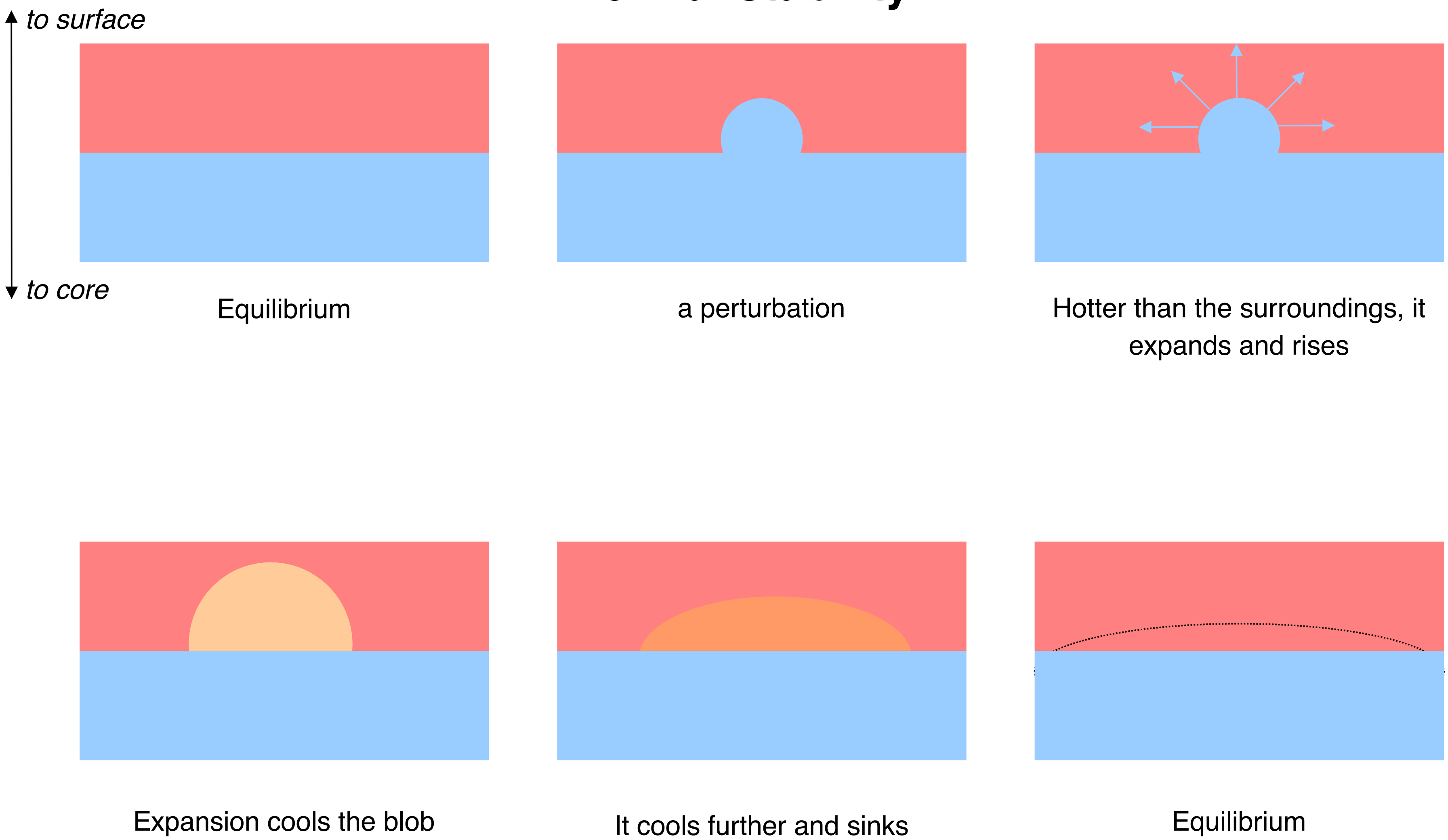
Returns to equilibrium position when disturbed



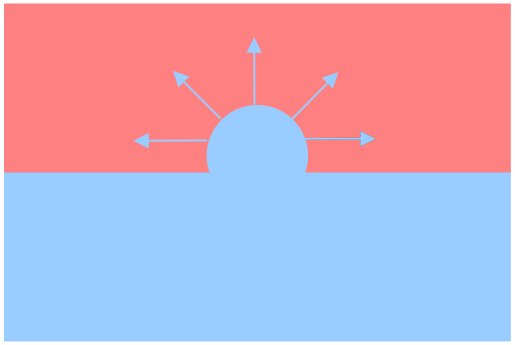
Unstable Equilibrium

Does not return to equilibrium position when disturbed

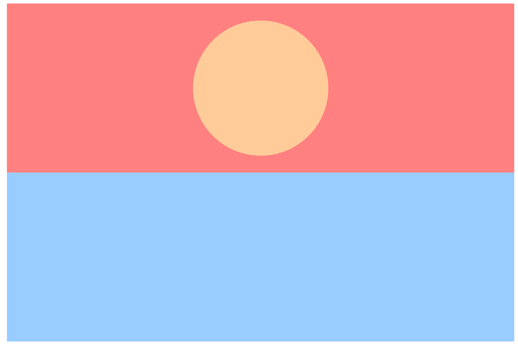
Thermal stability



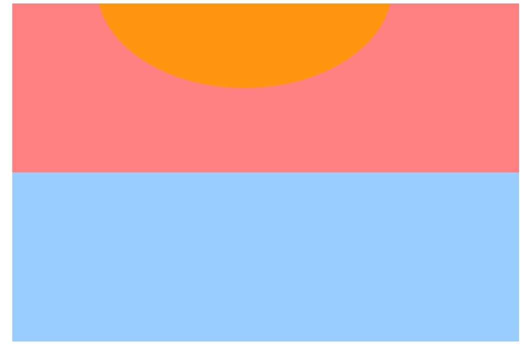
Thermal instability



Hotter than the surroundings
The blob expands and rises

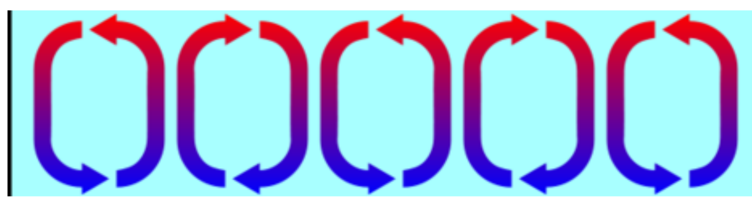


It rises faster than it cools

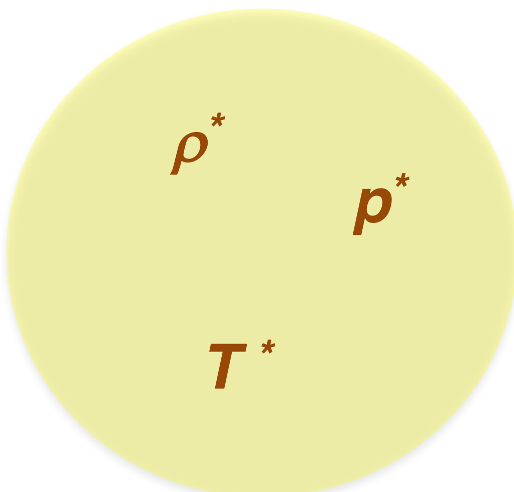


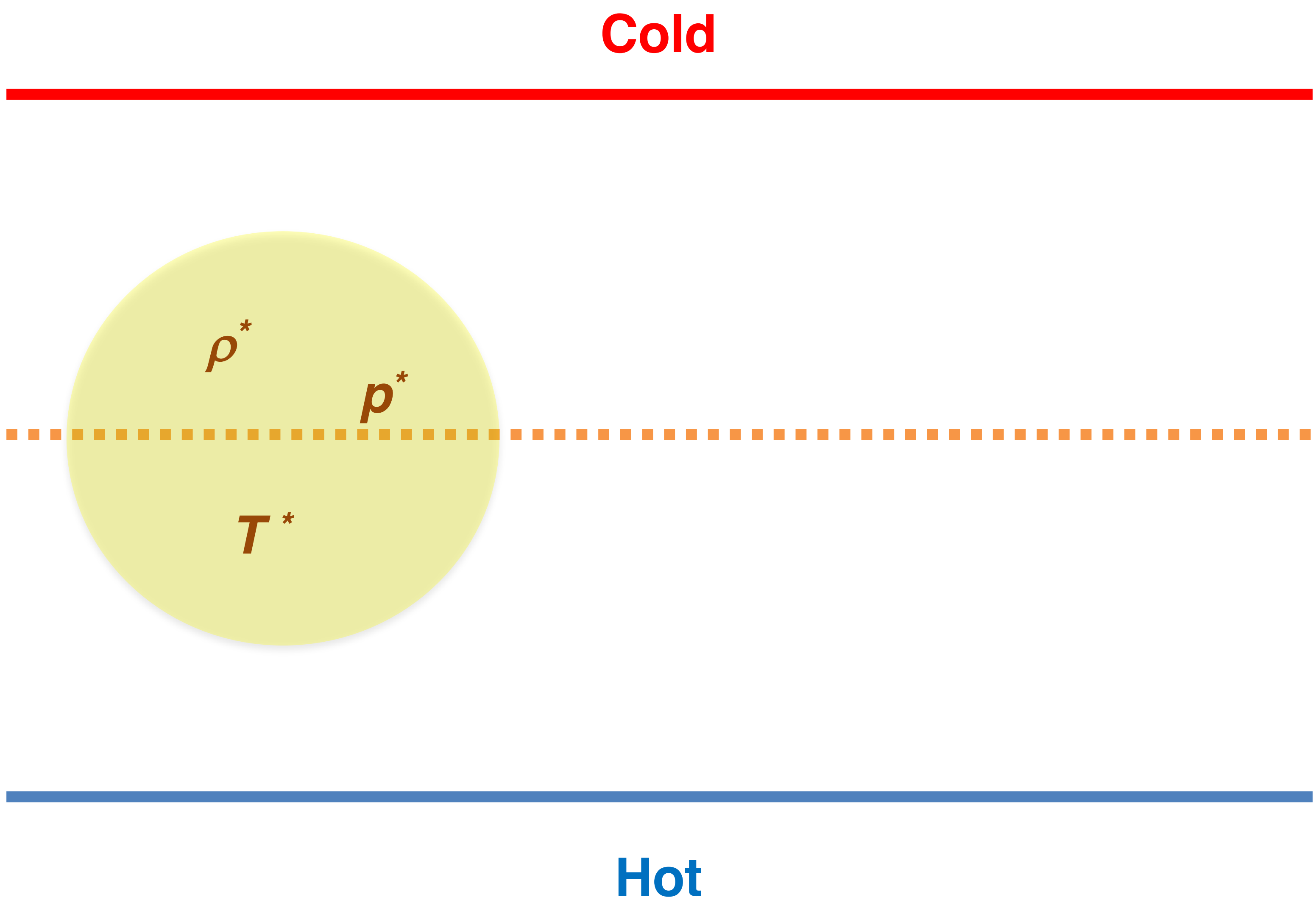
It keeps rising

It travels a great distance
before cooling and sinking

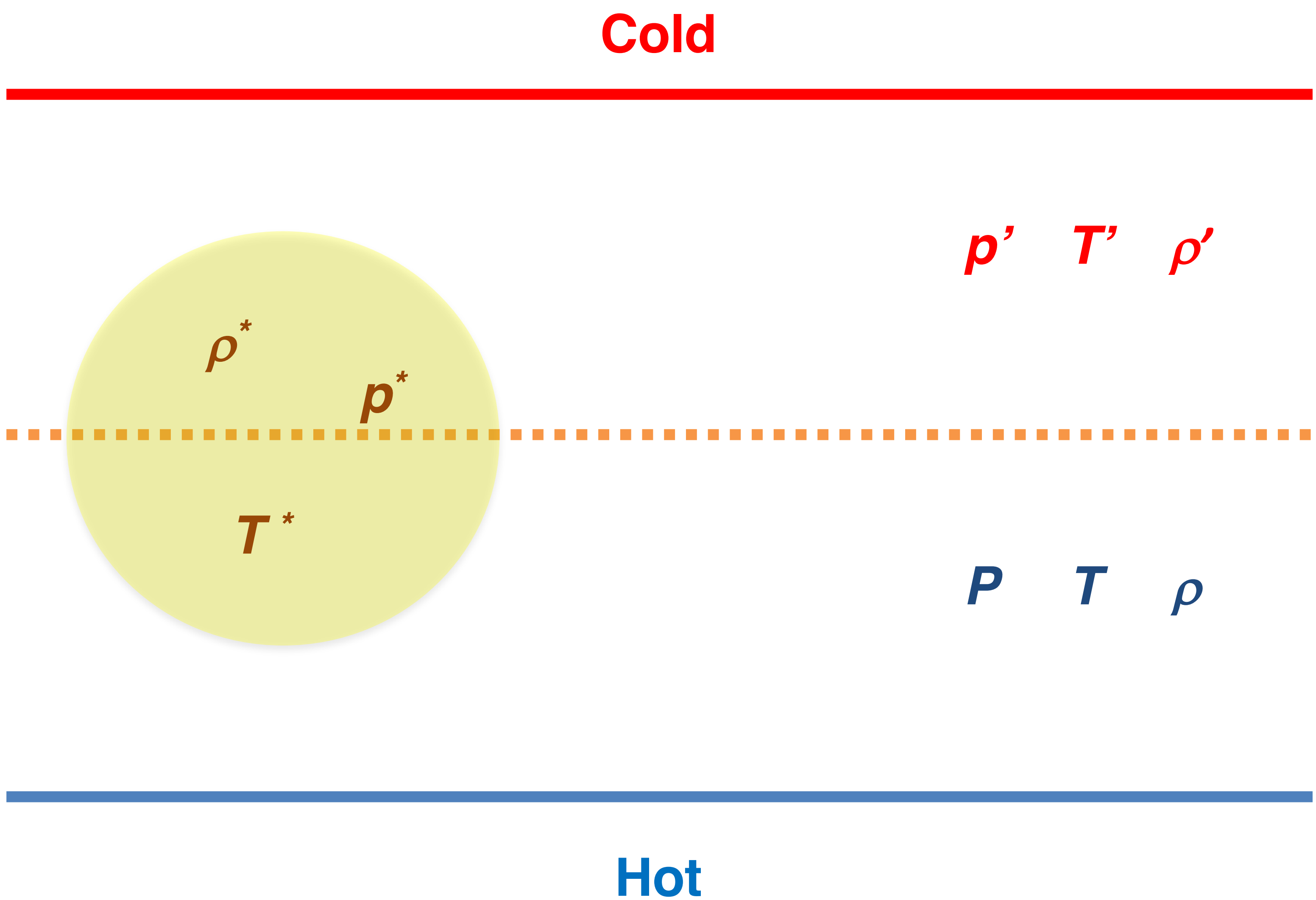


CONVECTION

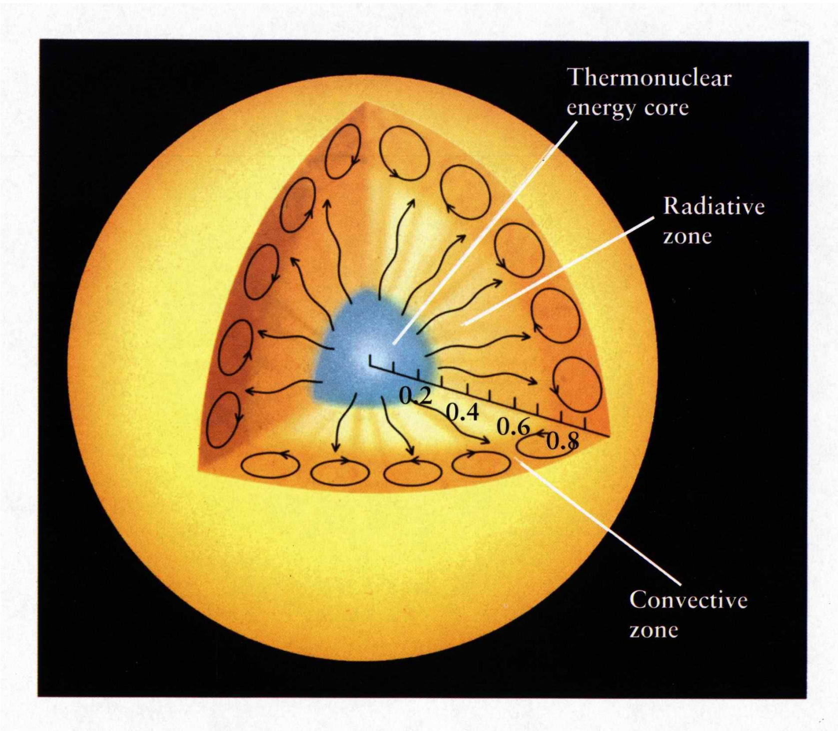

ρ*
p*
T*



Cold
ρ^*
p^*
T^*
Hot


Cold
p' T' ρ'
ρ*
p*
T *
P T ρ
Hot

Solar Structure



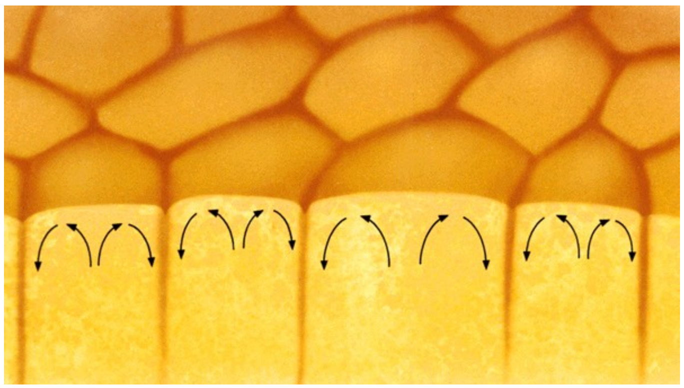
In **stable equilibrium**,
heat is transported by **radiation**
(without transport of mass).

In **unstable equilibrium**,
heat is transported by **convection**
(with transport of mass).

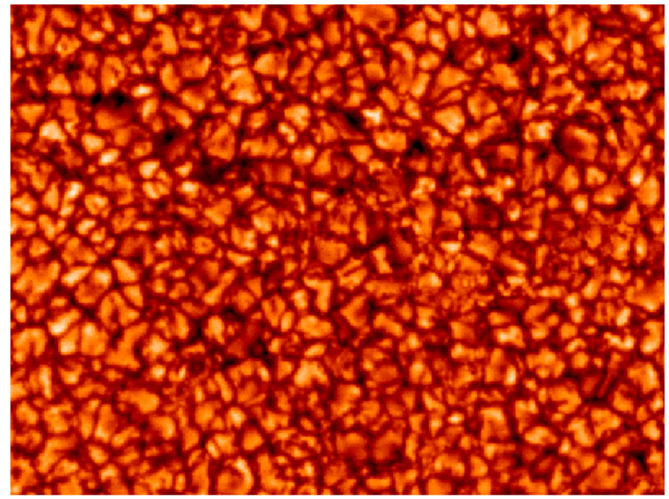
The Sun has a
radiative zone
in the interior

And a
convective zone
near the surface

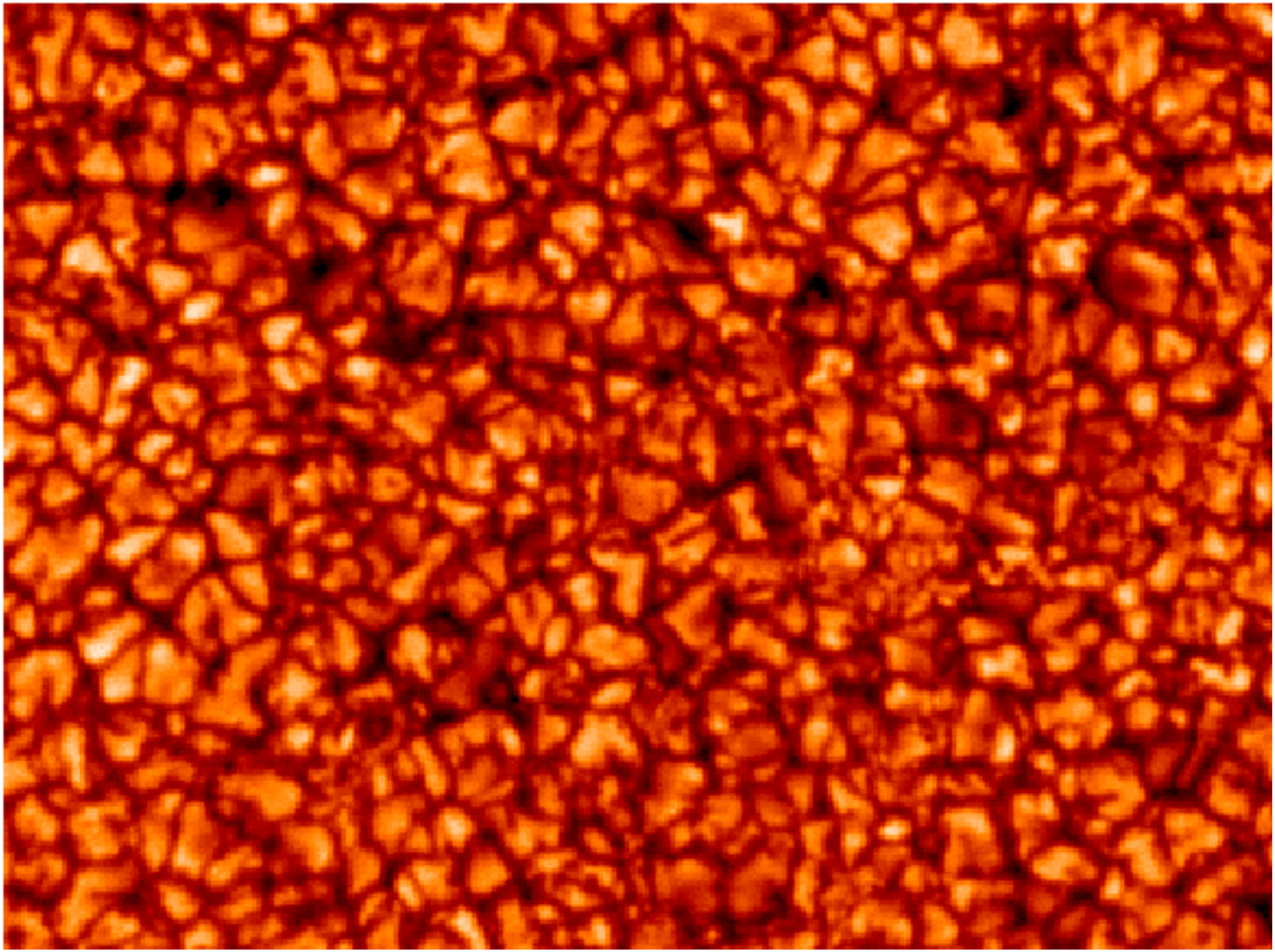
Granulation

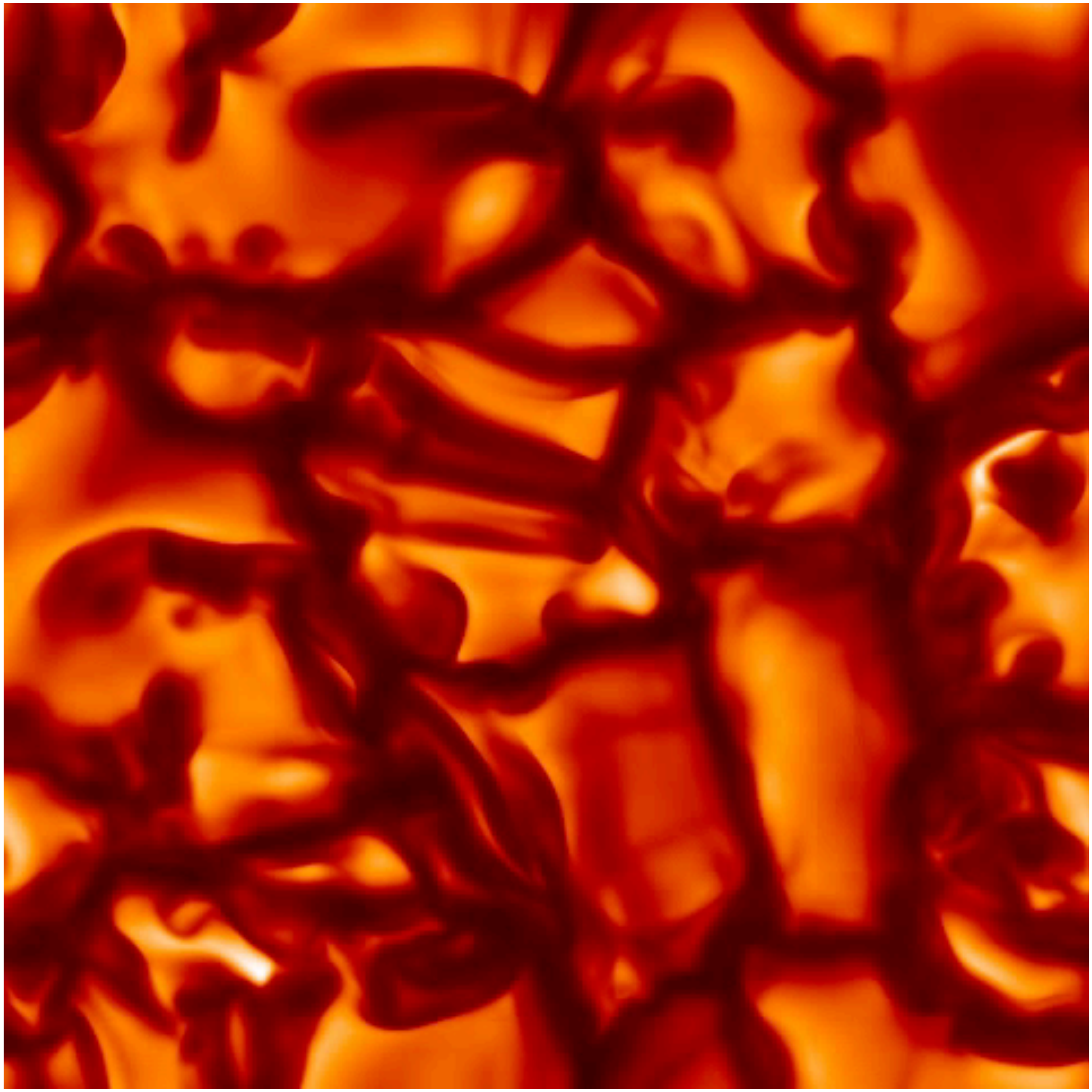


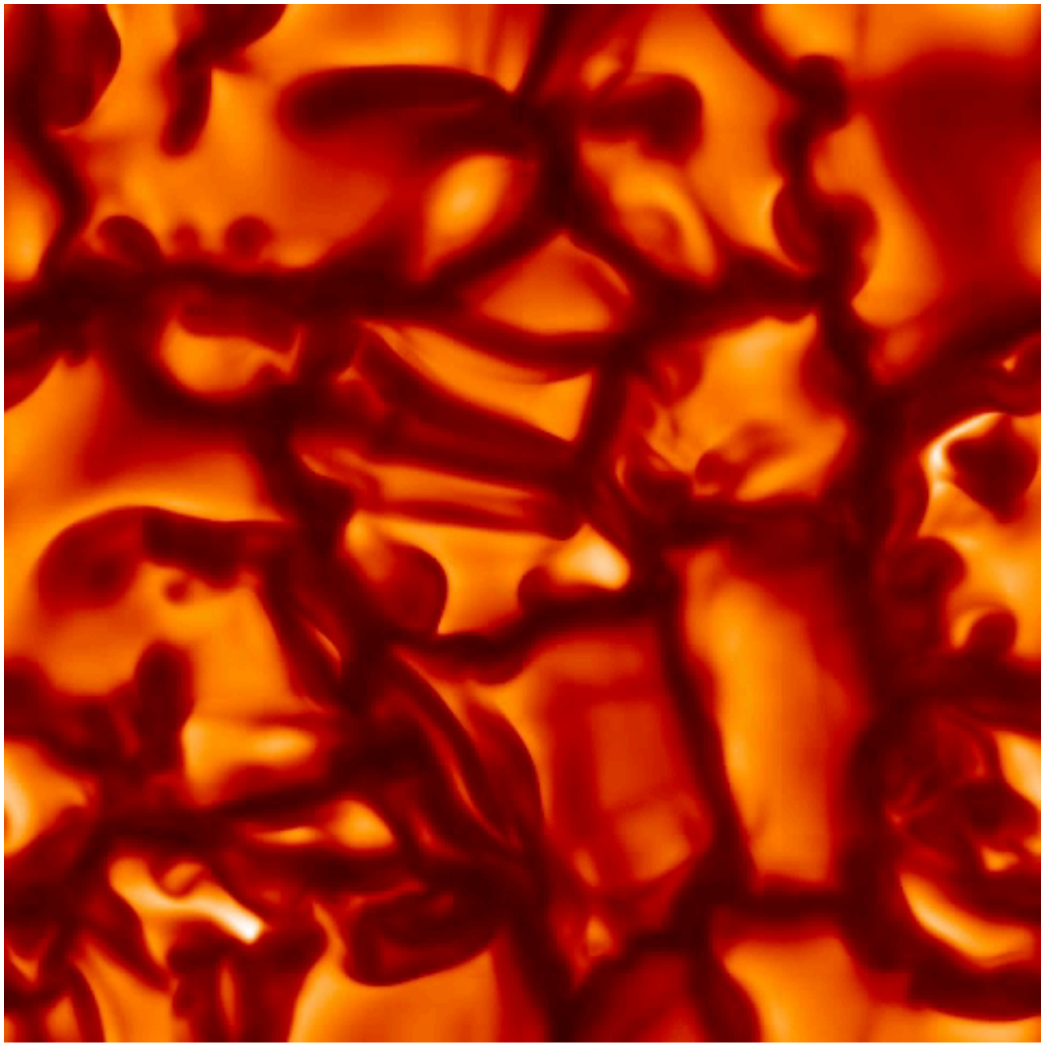
Convective cells



Close-up of the surface of the Sun





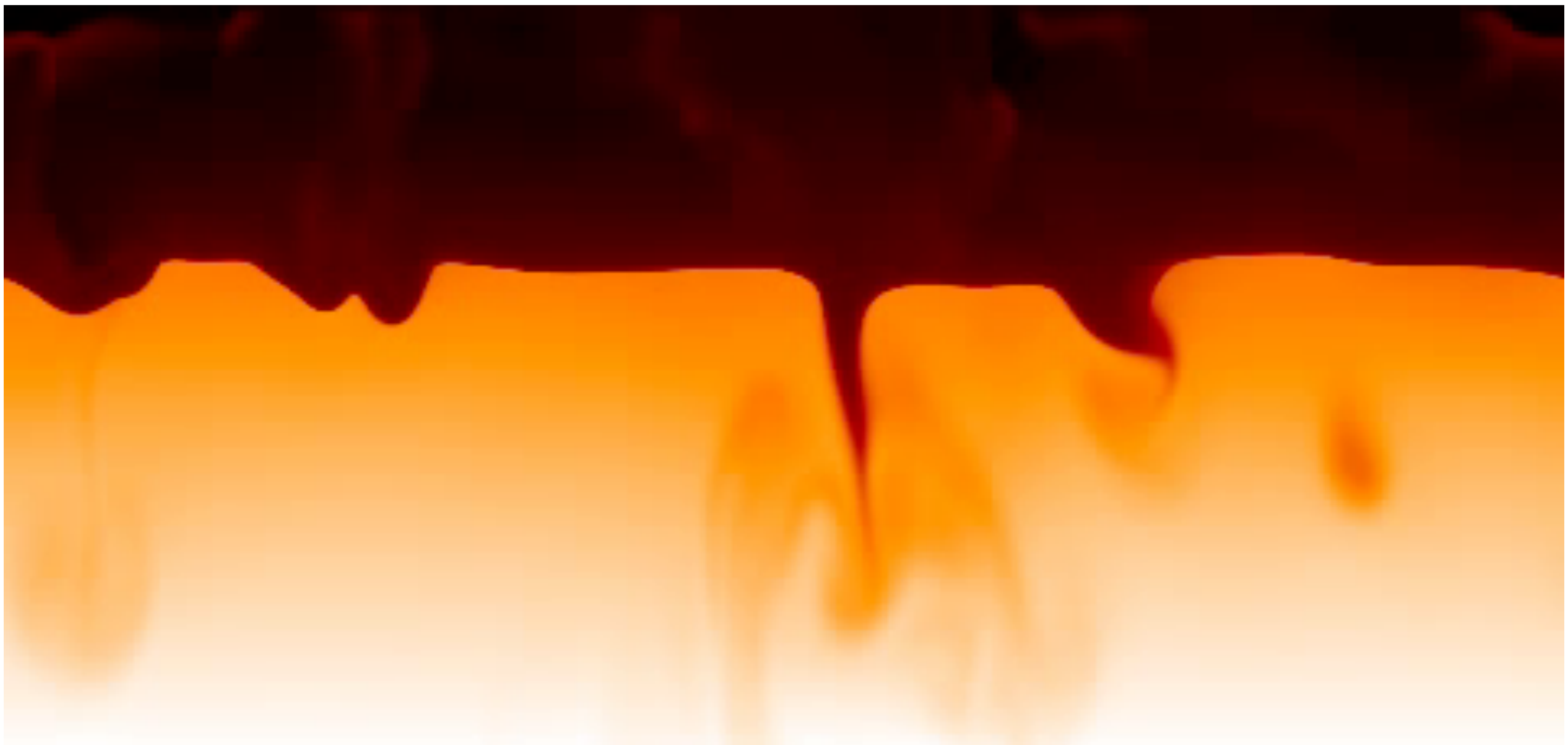


Simulation by Remo Collet.

Surface intensity

T_{eff} = 4400 K

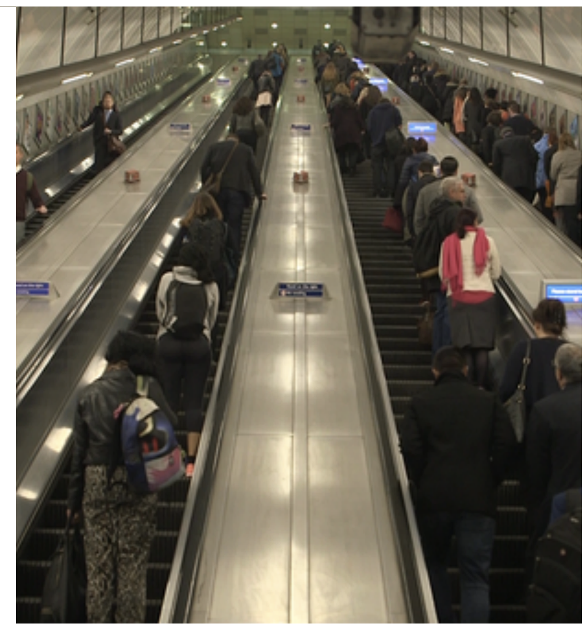
L = 4.4x10^6 km



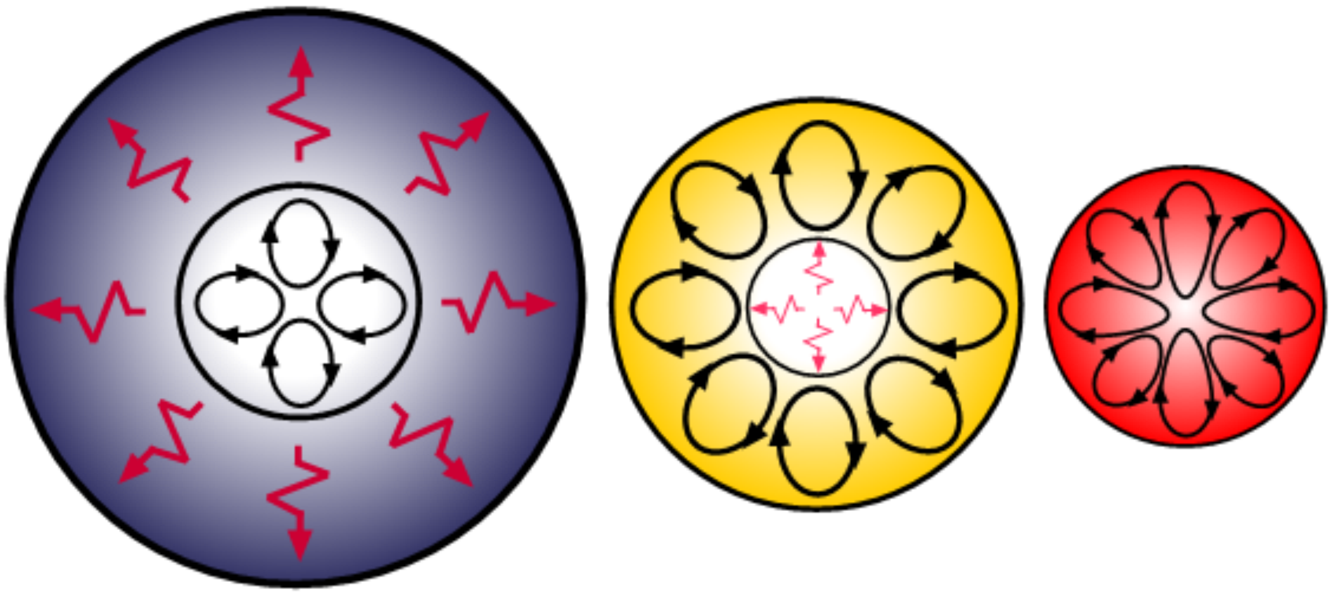
$L_z = 2x10^6$ km

Radiative Zone

Convective Zone



Stellar Structure



M > 1.5

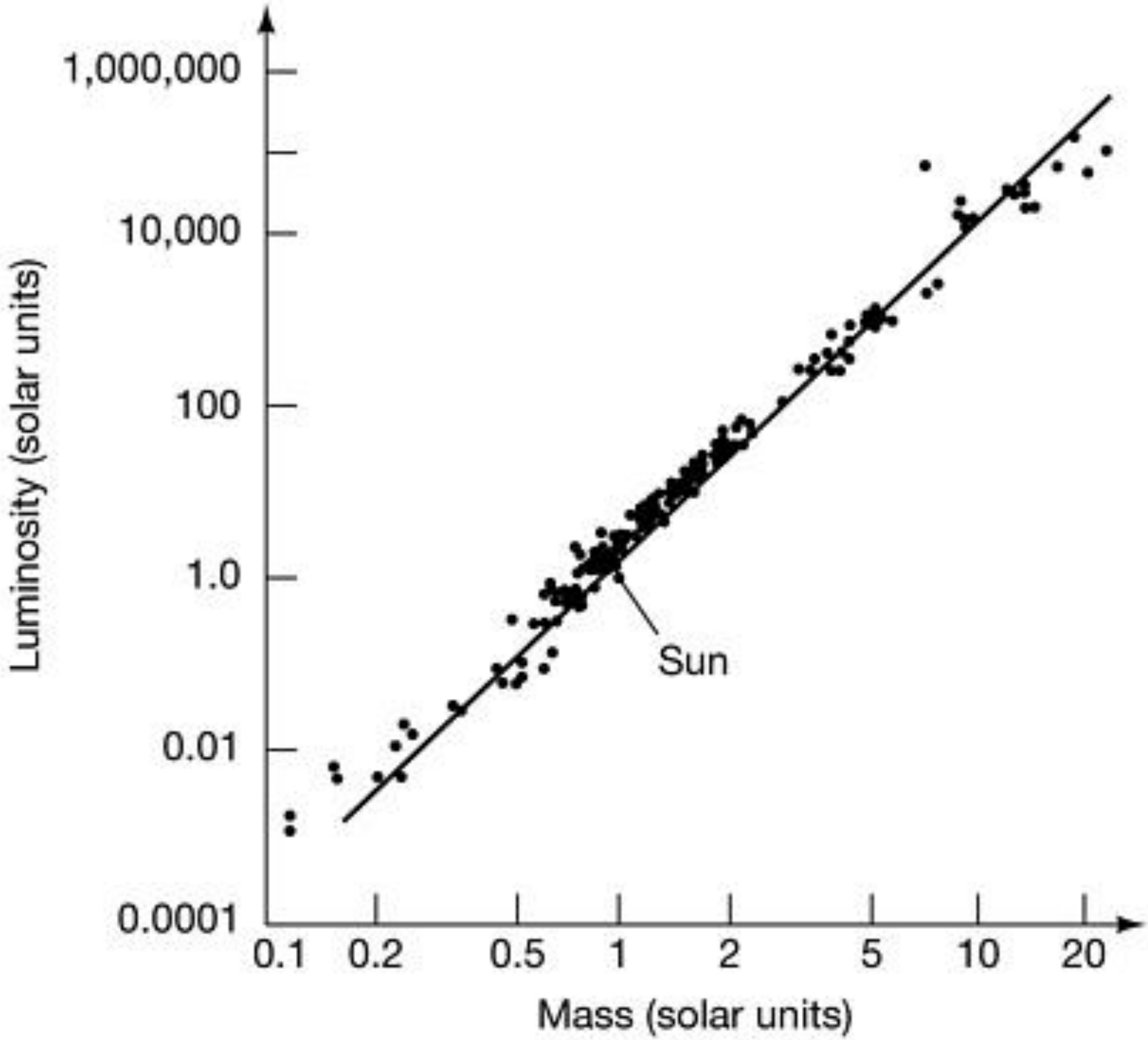
Convective Core
Radiative Envelope

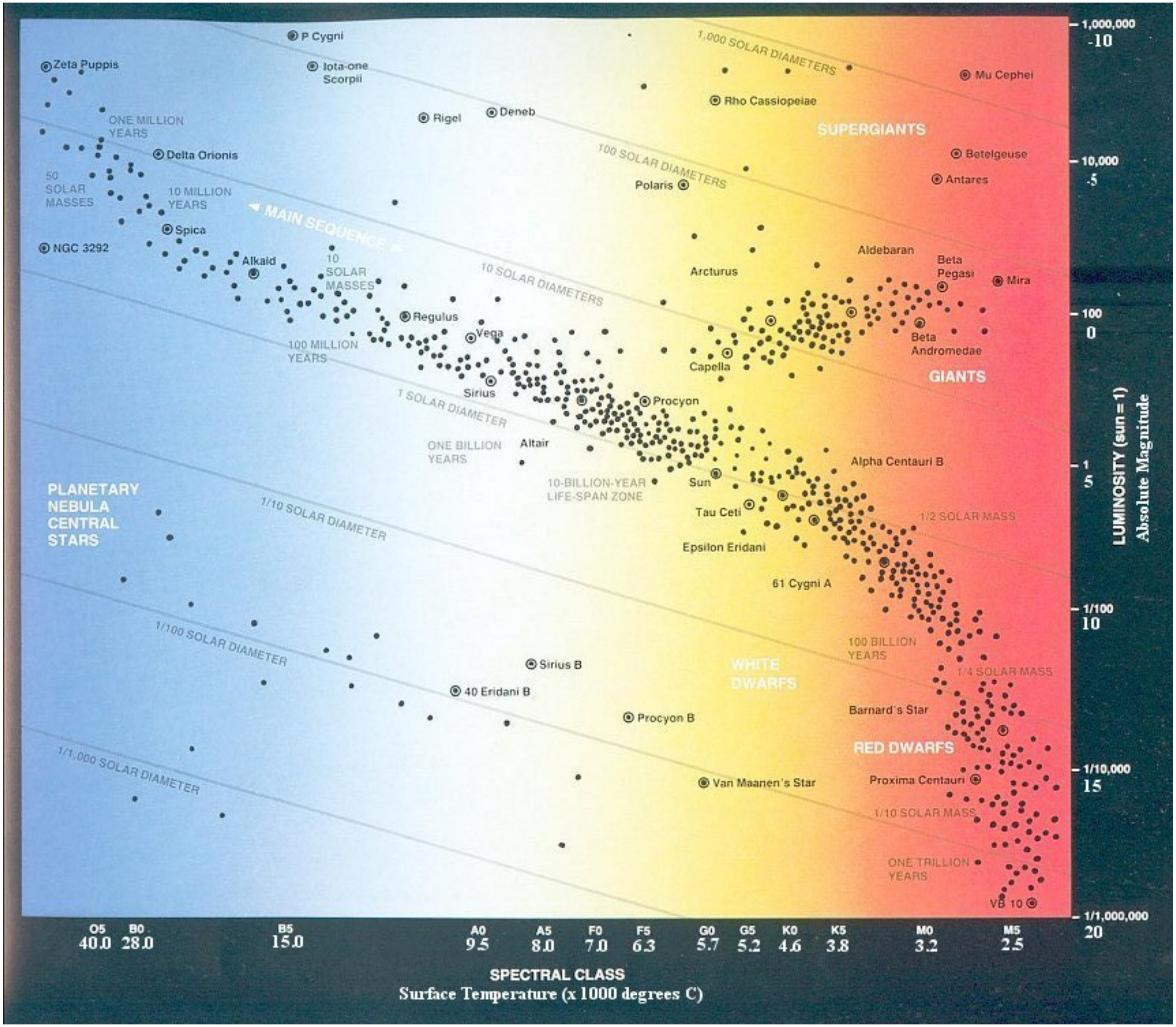
0.5 < *M* < 1.5

Radiative Core
Convective Envelope

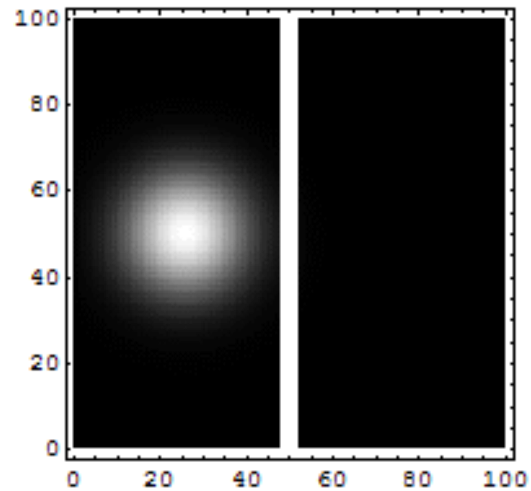
M < 0.5

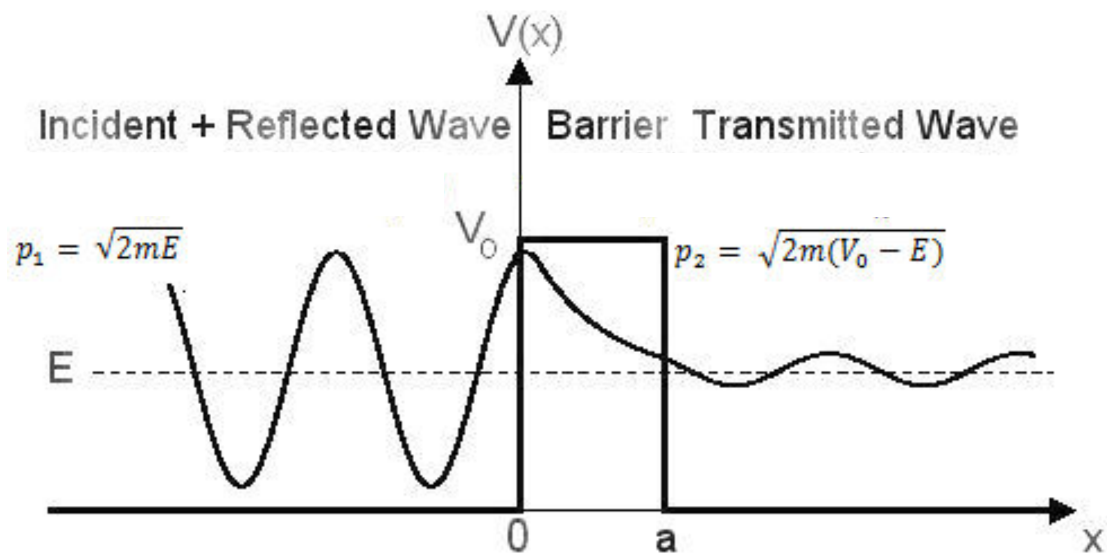
Fully Convective

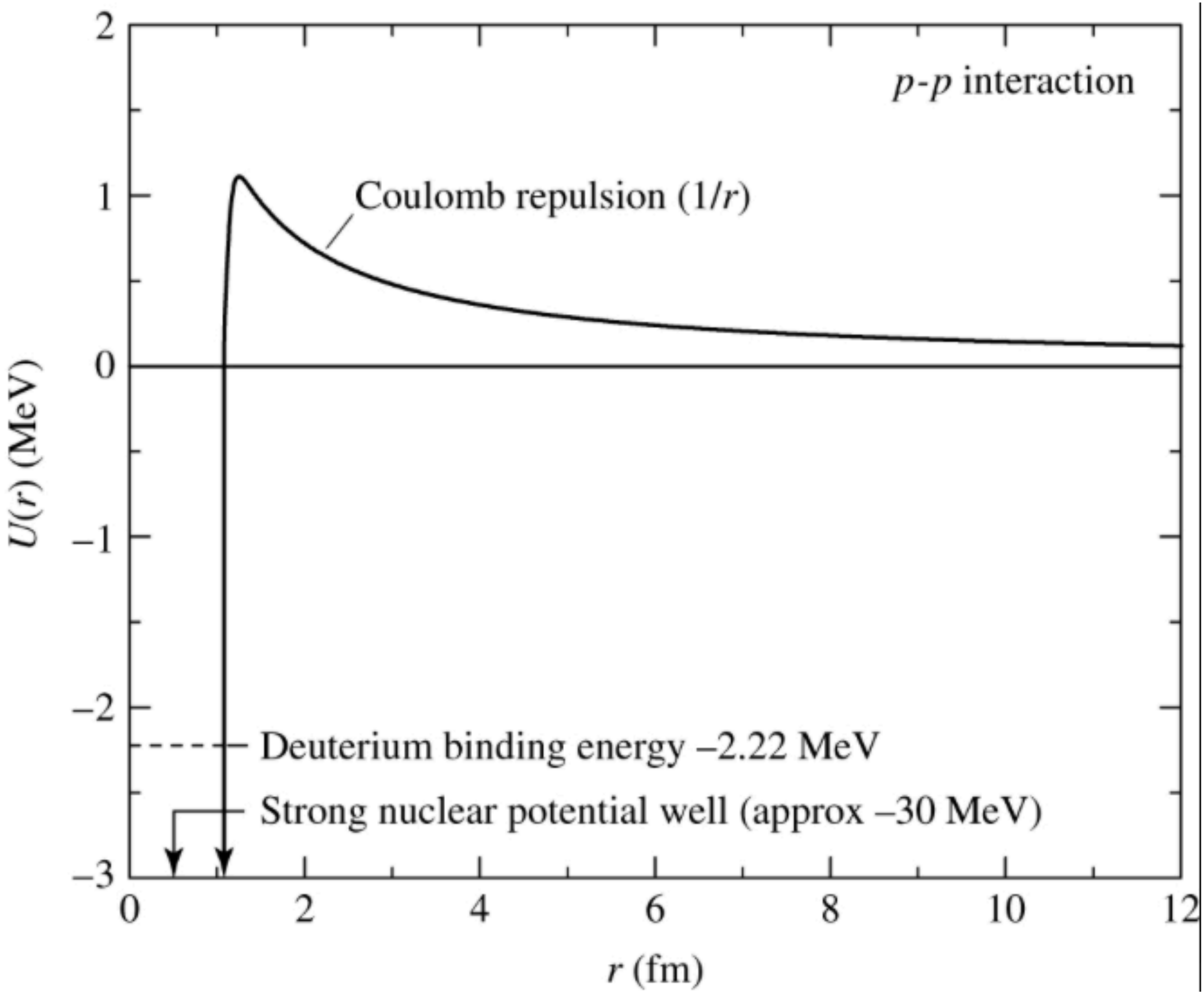

1,000,000
10,000
100
1.0
0.01
0.0001
Luminosity (solar units)
0.1
0.2
0.5
1
2
5
10
20
Mass (solar units)
Sun


P Cygni
Zeta Puppis
Iota-one Scorpii
1,000 SOLAR DIAMETERS
Mu Cephei
Rho Cassiopeiae
Rigel
Deneb
ONE MILLION YEARS
SUPERGIANTS
Delta Orionis
100 SOLAR DIAMETERS
Betelgeuse
50 SOLAR MASSES
10 MILLION YEARS
Polaris
Antares
MAIN SEQUENCE
Spica
NGC 3292
Aldebaran
Alkaid
10 SOLAR MASSES
Arcturus
Beta Pegasi
Mira
10 SOLAR DIAMETERS
Regulus
Vega
Beta Andromedae
100 MILLION YEARS
Capella
GIANTS
Sirius
Procyon
1 SOLAR DIAMETER
ONE BILLION YEARS
Altair
Alpha Centauri B
PLANETARY NEBULA CENTRAL STARS
10-BILLION-YEAR LIFE-SPAN ZONE
Sun
1/10 SOLAR DIAMETER
Tau Ceti
1/2 SOLAR MASS
Epsilon Eridani
61 Cygni A
100 BILLION YEARS
1/100 SOLAR DIAMETER
Sirius B
WHITE DWARFS
1/4 SOLAR MASS
40 Eridani B
Barnard's Star
Procyon B
RED DWARFS
1/1,000 SOLAR DIAMETER
Van Maanen's Star
Proxima Centauri
1/10 SOLAR MASS
ONE TRILLION YEARS
VB 10
1,000,000
-10
10,000
-5
100
0
1
5
1/100
10
1/10,000
15
1/1,000,000
20
LUMINOSITY (sun = 1)
Absolute Magnitude
O5 40.0
B0 28.0
B5 15.0
A0 9.5
A5 8.0
F0 7.0
F5 6.3
G0 5.7
G5 5.2
K0 4.6
K5 3.8
M0 3.2
M5 2.5
SPECTRAL CLASS
Surface Temperature (x 1000 degrees C)

Quantum Tunneling

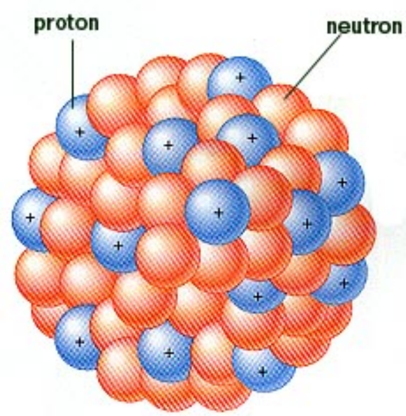




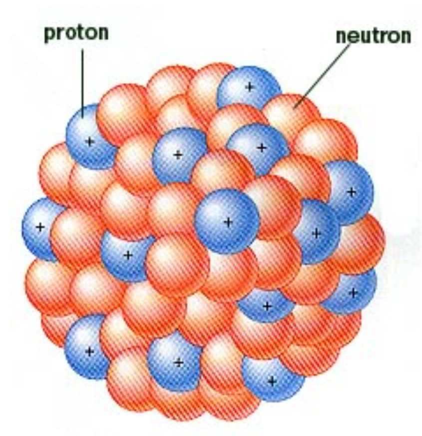


p-p interaction
Coulomb repulsion (1/r)
Deuterium binding energy –2.22 MeV
Strong nuclear potential well (approx –30 MeV)
U(r) (MeV)
r (fm)
2
1
0
–1
–2
–3
0
2
4
6
8
10
12

How is an atomic nucleus bound together if the protons are like-charged?



How is an atomic nucleus bound together
if the protons are like-charged?



Another force of nature exists at nuclear distances
Not Gravity. Not Electromagnetism.

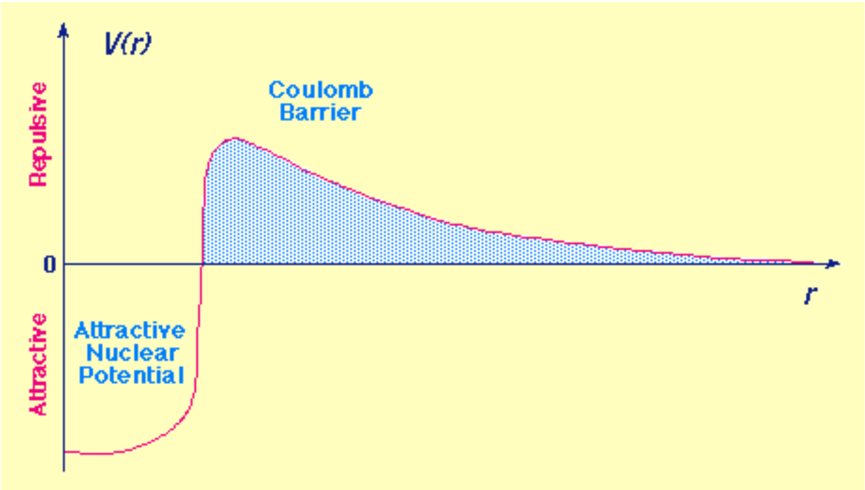
Strong Force

The Coulomb force (EM) between protons is repulsive,
but the strong force between protons is attractive!

The Coulomb Barrier

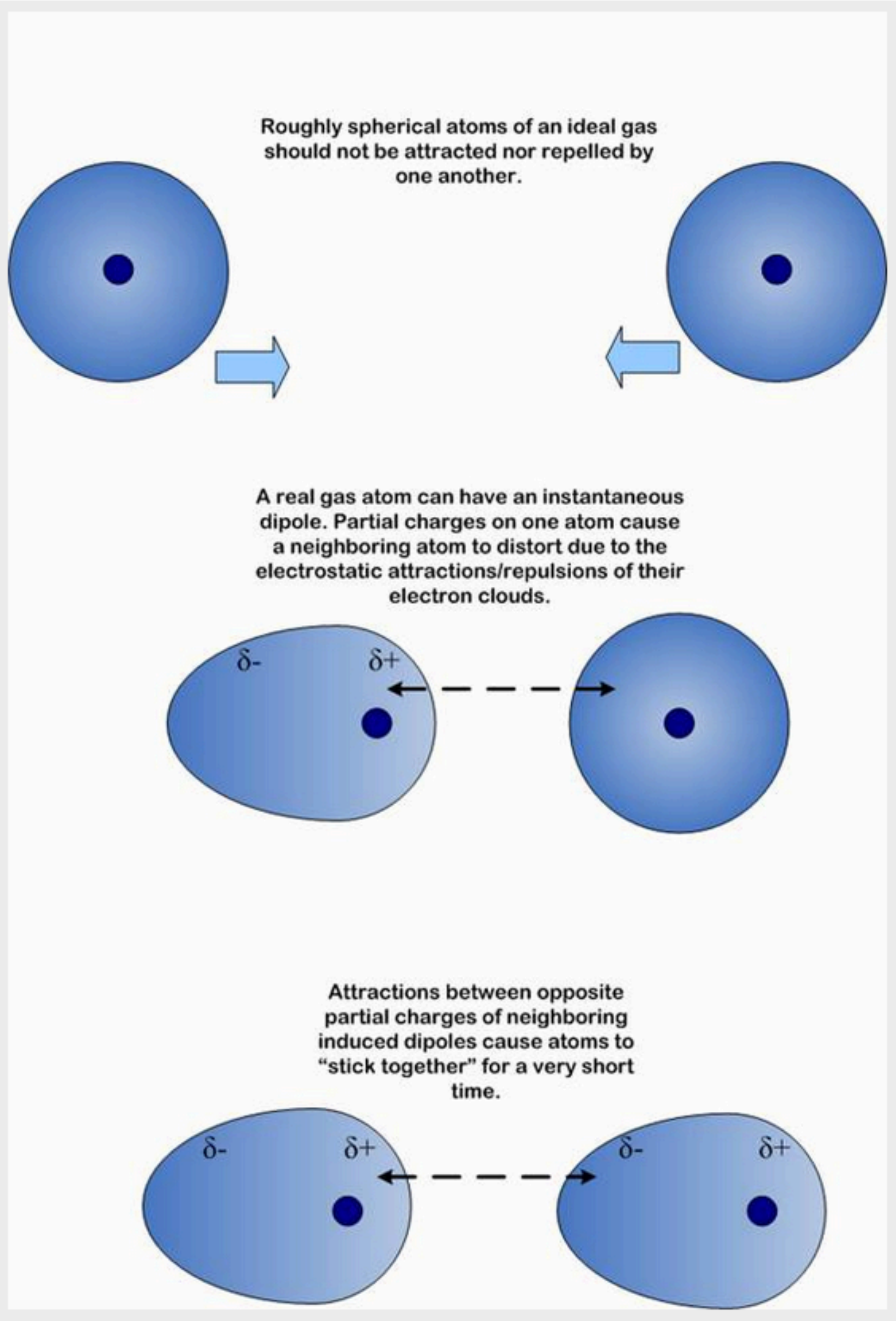
Protons are like-charged and thus repel each other

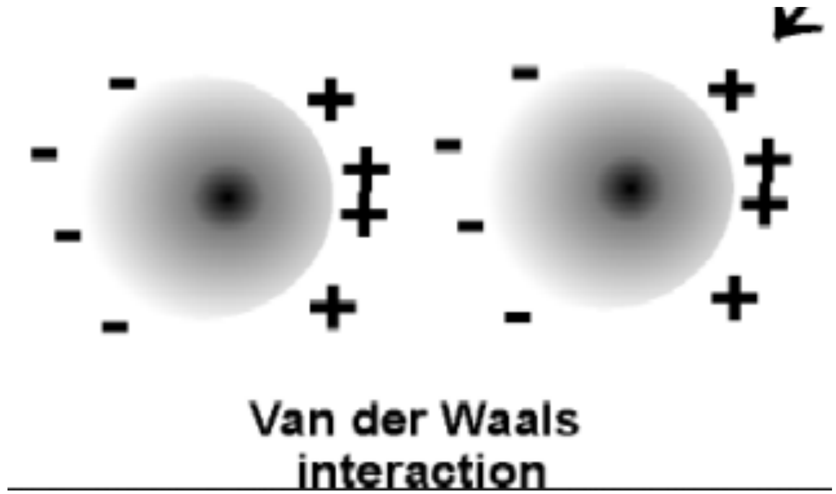
You need to get them really close so that nuclear forces start to operate

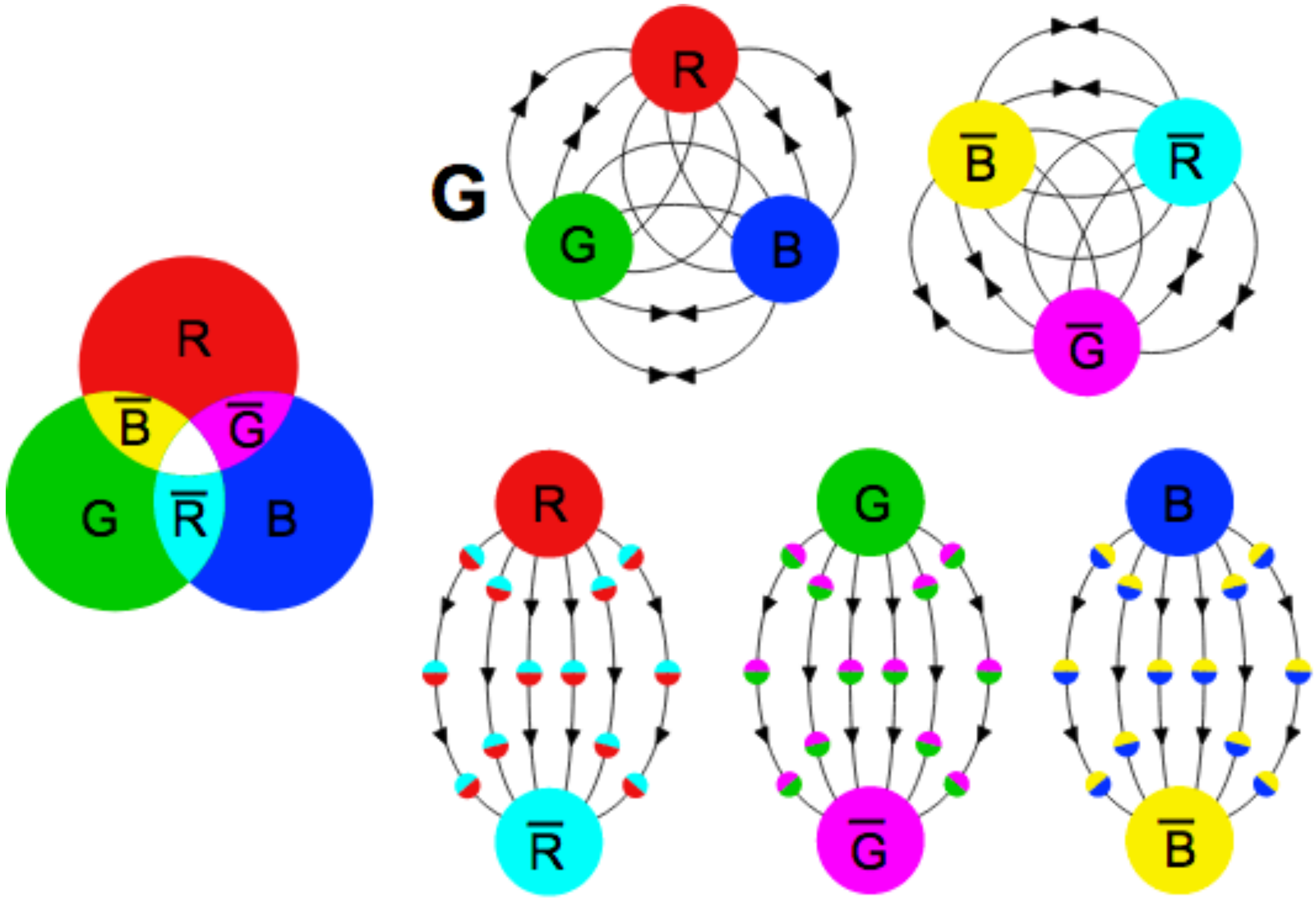


Really close means: packed together - HIGH DENSITY

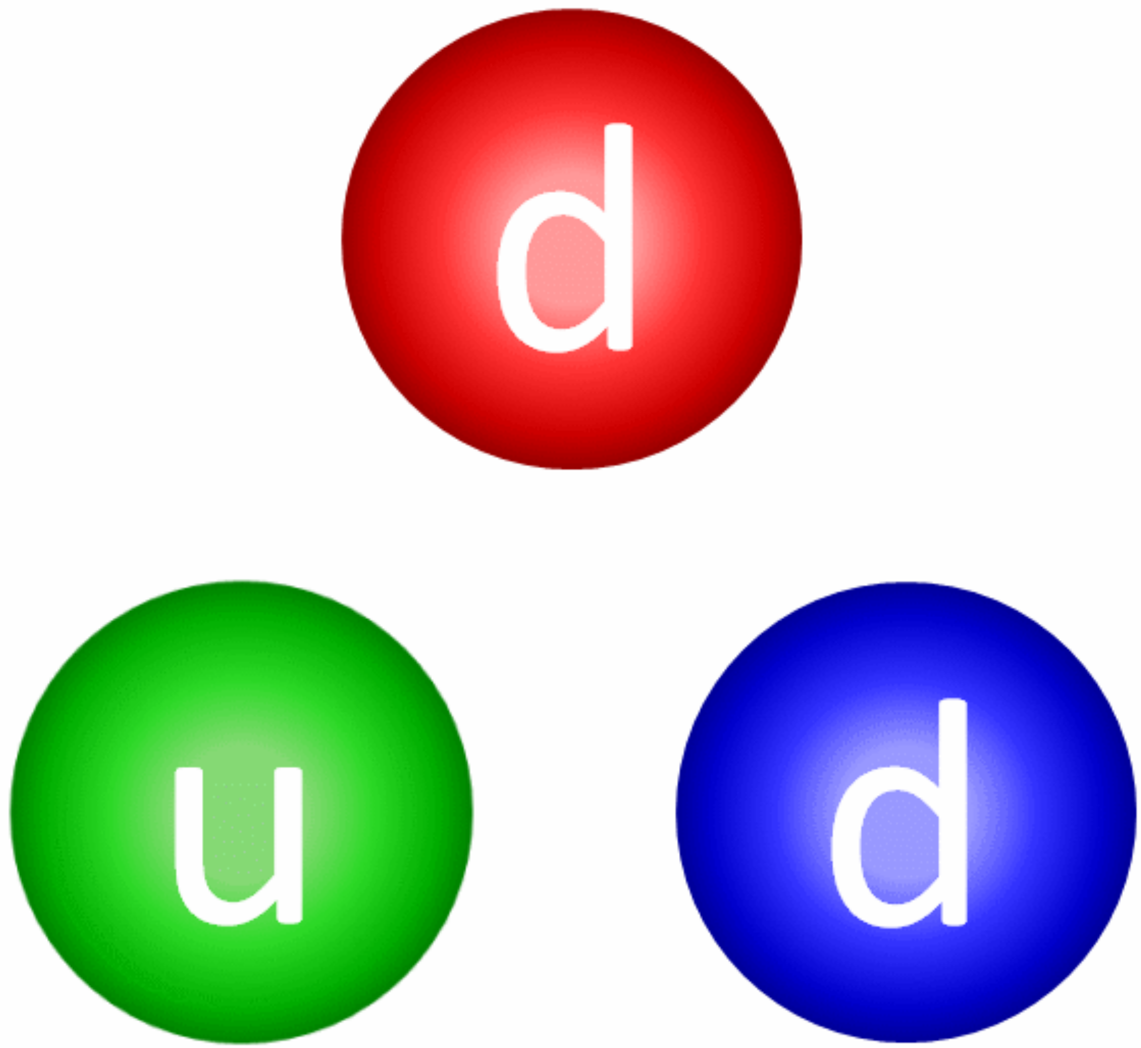
fast speeds - HIGH TEMPERATURE

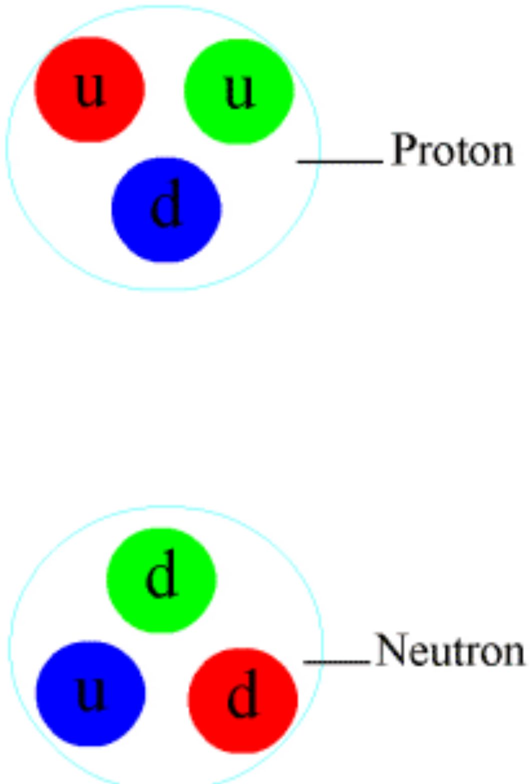

Roughly spherical atoms of an ideal gas should not be attracted nor repelled by one another.
A real gas atom can have an instantaneous dipole. Partial charges on one atom cause a neighboring atom to distort due to the electrostatic attractions/repulsions of their electron clouds.
δ-
δ+
Attractions between opposite partial charges of neighboring induced dipoles cause atoms to "stick together" for a very short time.
δ-
δ+
δ-
δ+


Van der Waals interaction

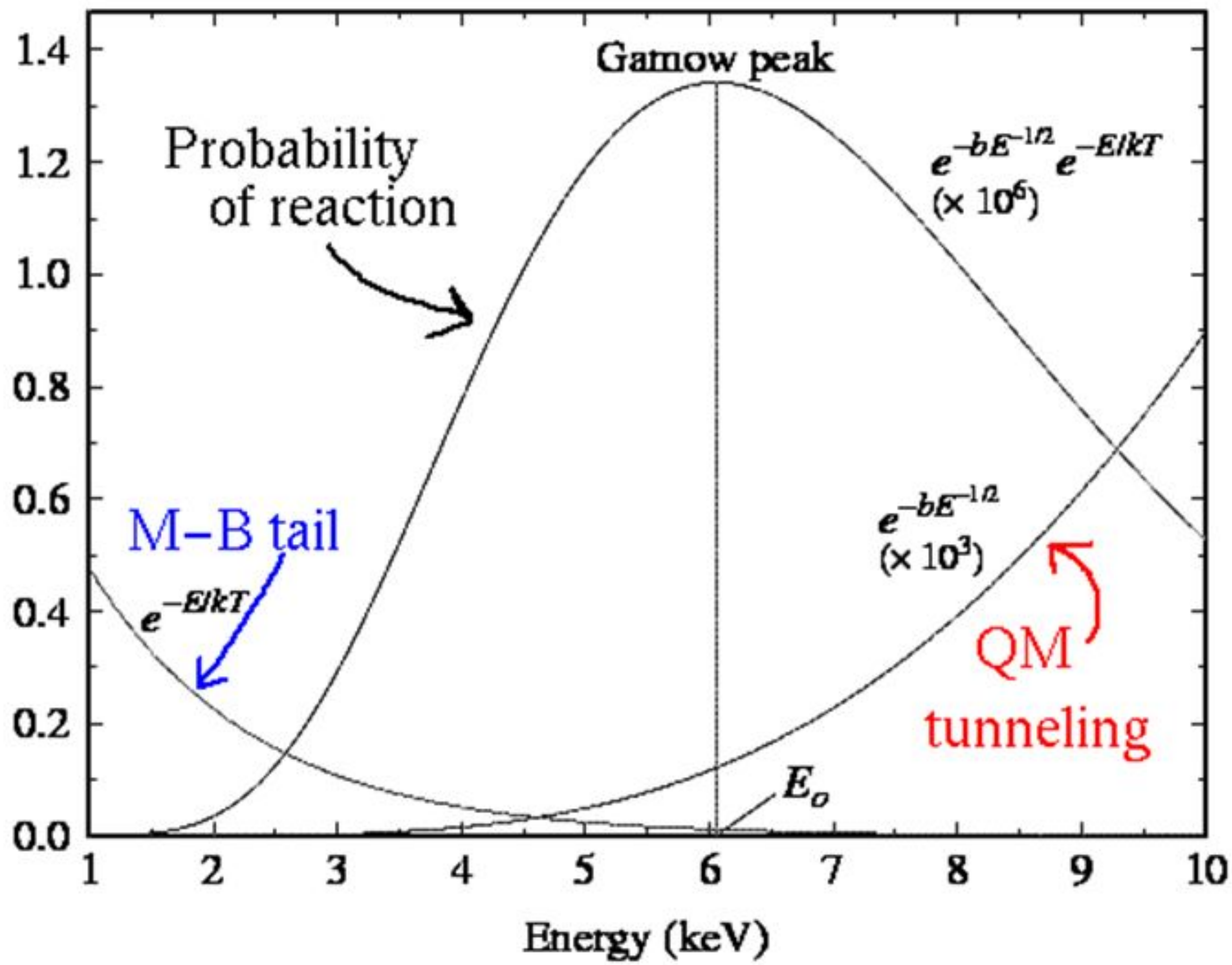


G
R
G
B
$\bar{B}$
$\bar{R}$
$\bar{G}$


d
u
d

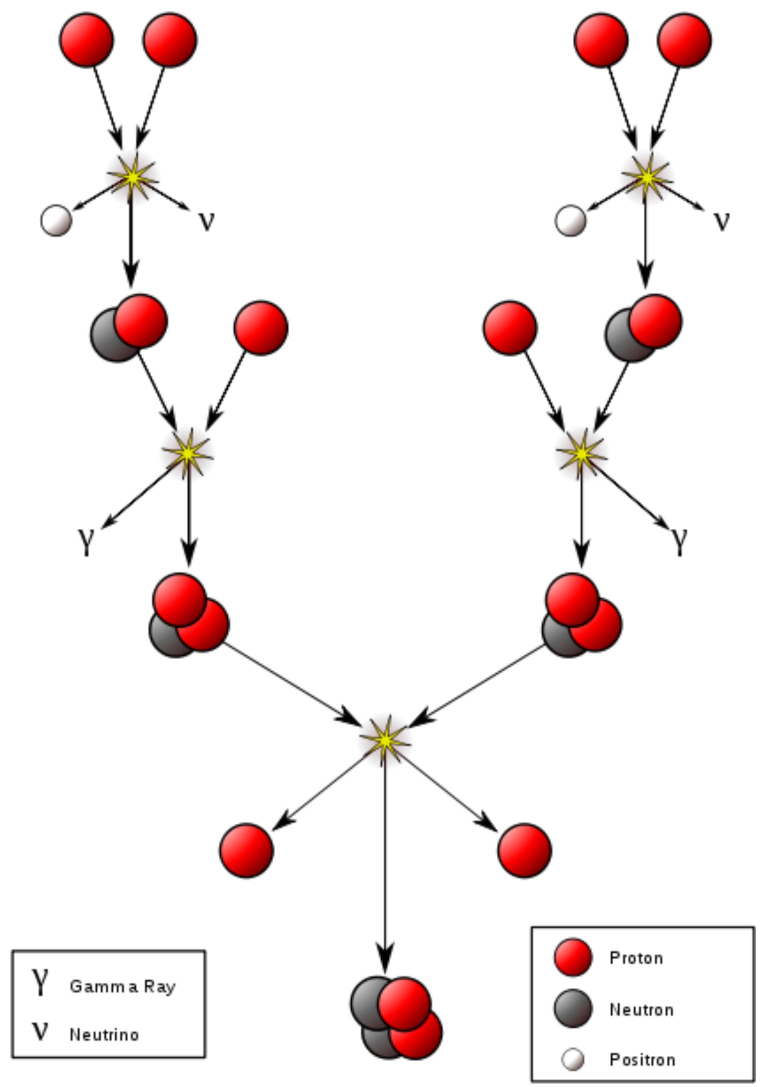


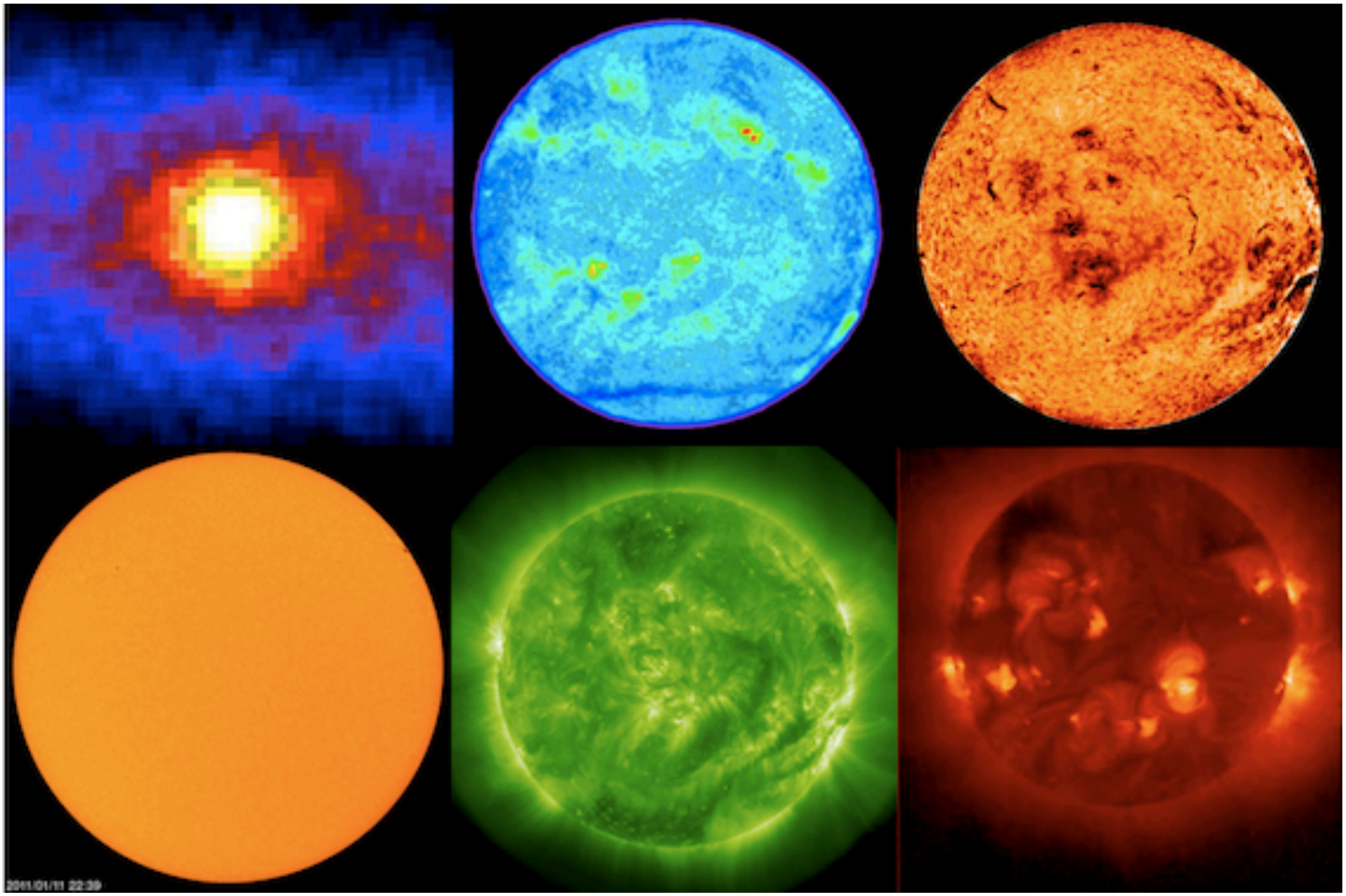
$$V_{\text{Yukawa}}(r) = -g^2 \frac{e^{-\mu r}}{r},$$



Gamow peak
Probability of reaction
$e^{-bE^{-1/2}}e^{-E/kT}$ (× 10^6)
M−B tail
$e^{-E/kT}$
$e^{-bE^{-1/2}}$ (× 10^3)
QM tunneling
E_o
Energy (keV)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
8
9
10

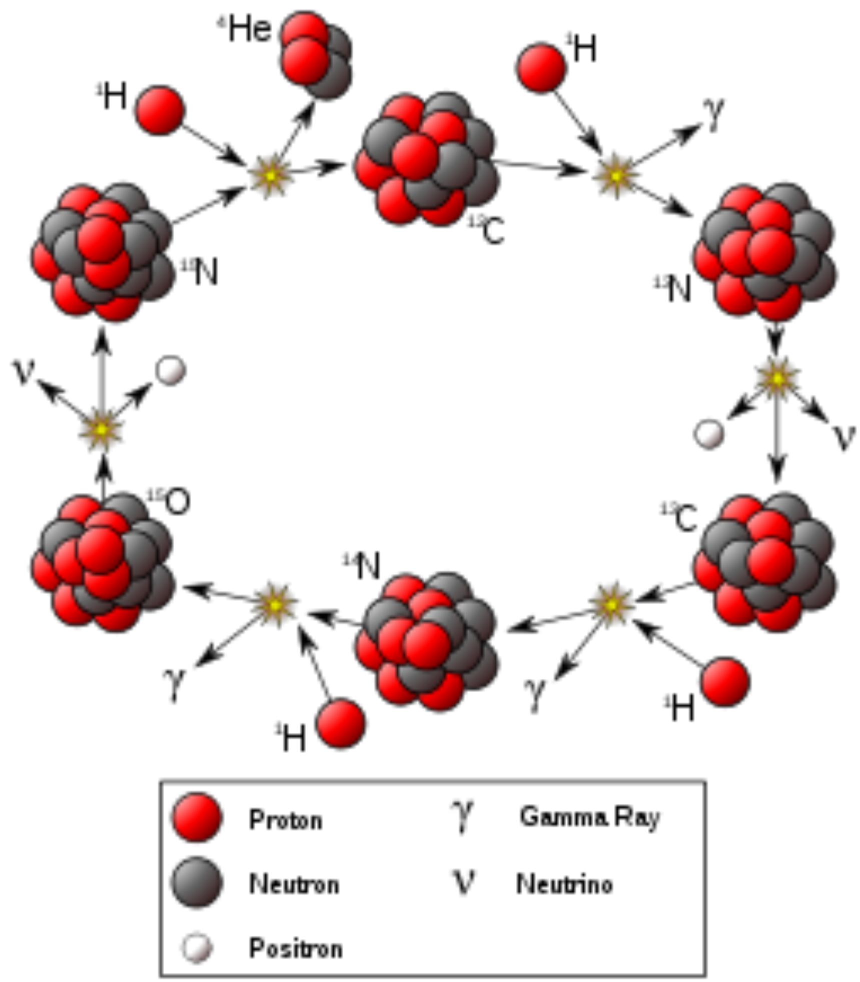
Proton-proton chain



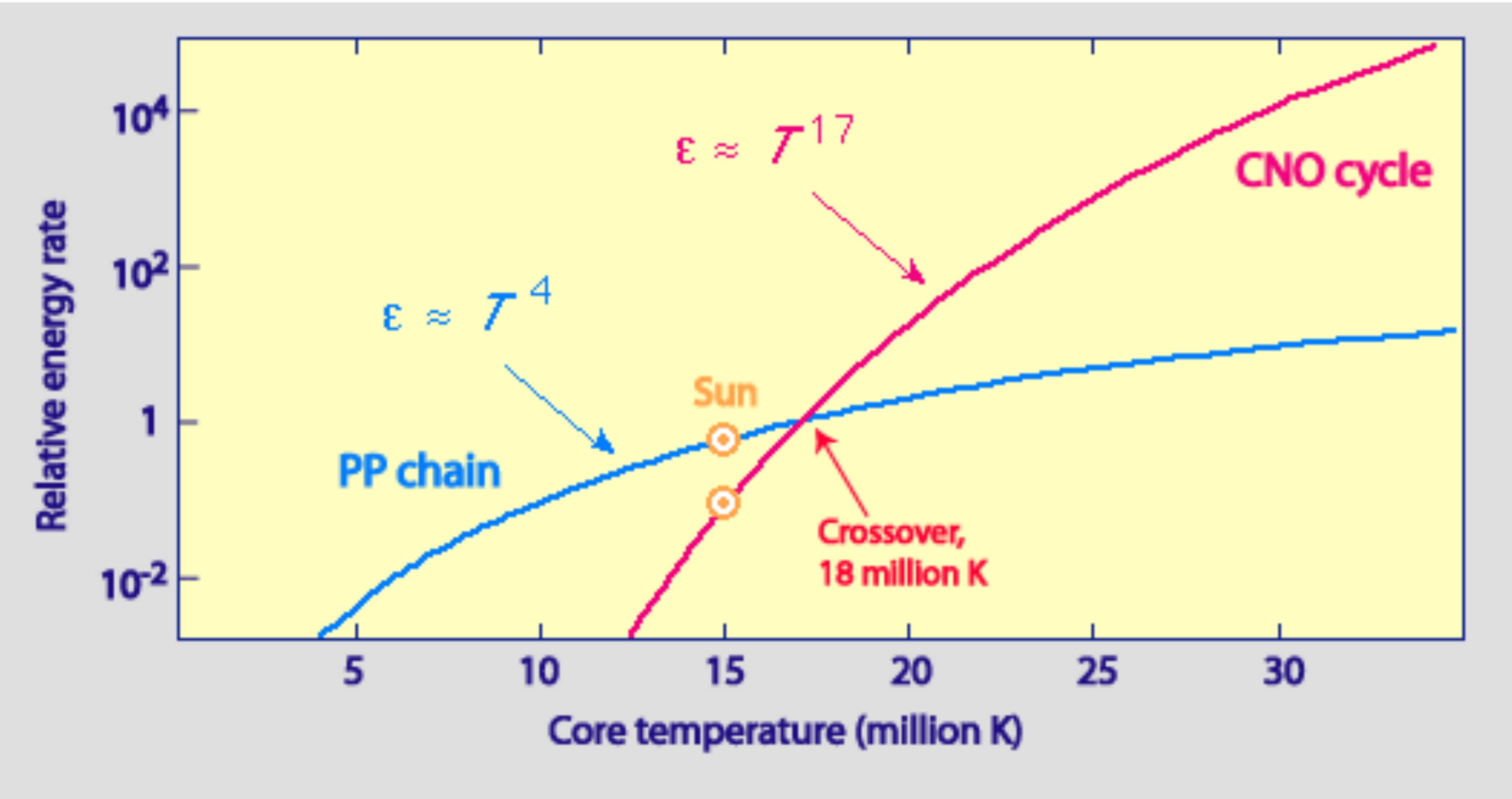

2011/01/11 22:39

CNO cycle

$$C_6^{12} + H_1^1 \rightarrow N_7^{13} + \gamma_0^0$$
$$N_7^{13} \rightarrow C_6^{13} + \overline{e}_1^0 + \nu_0^0$$
$$C_6^{13} + H_1^1 \rightarrow N_7^{14} + \gamma_0^0$$
$$N_7^{14} + H_1^1 \rightarrow O_8^{15} + \gamma_0^0$$
$$O_8^{15} \rightarrow N_7^{15} + \overline{e}_1^0 + \nu_0^0$$
$$N_7^{15} + H_1^1 \rightarrow C_6^{12} + He_2^4$$

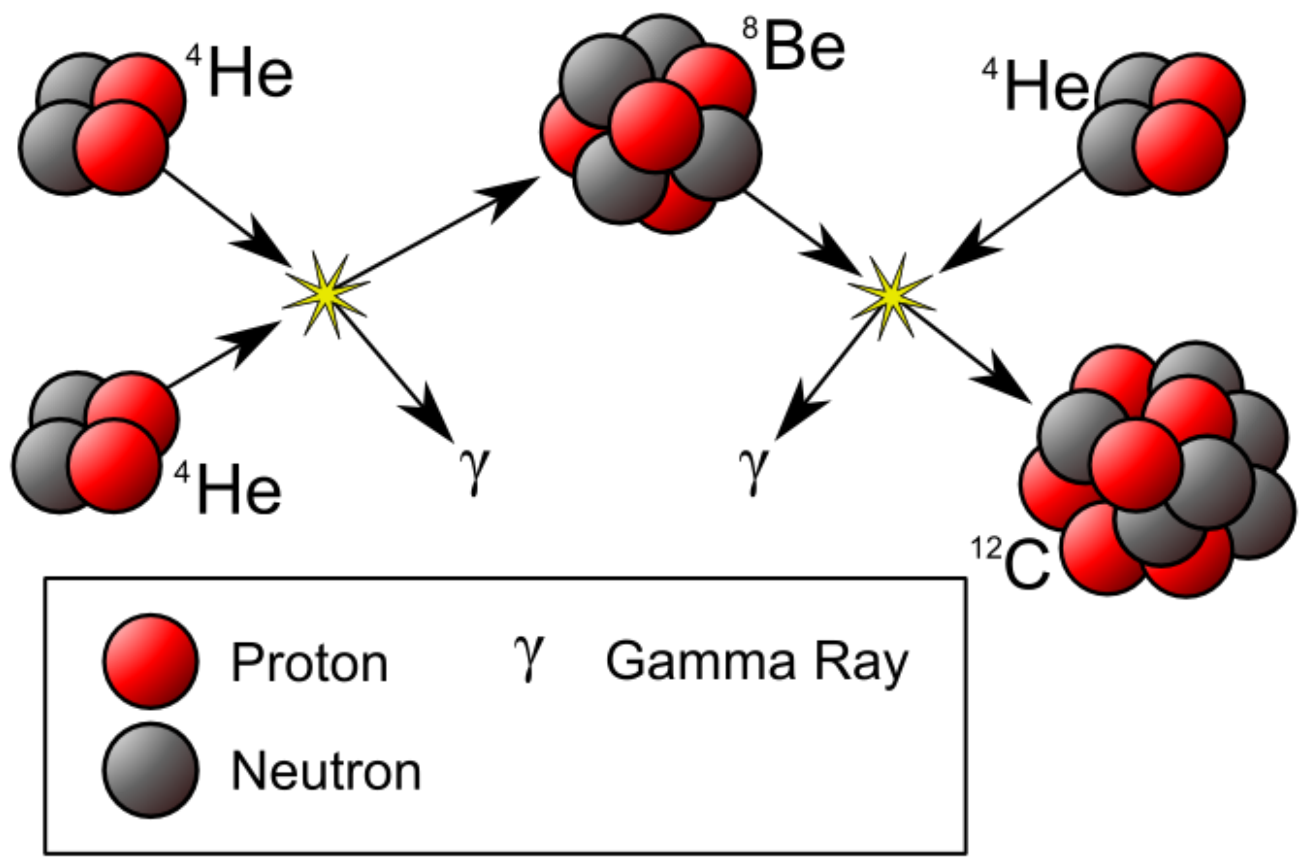


End of cycle:
4 H burned into He
C used as catalyst



Relative energy rate
10^4
10^2
1
10^{-2}
5
10
15
20
25
30
Core temperature (million K)
$\varepsilon \approx T^{17}$
CNO cycle
$\varepsilon \approx T^4$
Sun
PP chain
Crossover,
18 million K

Triple alpha



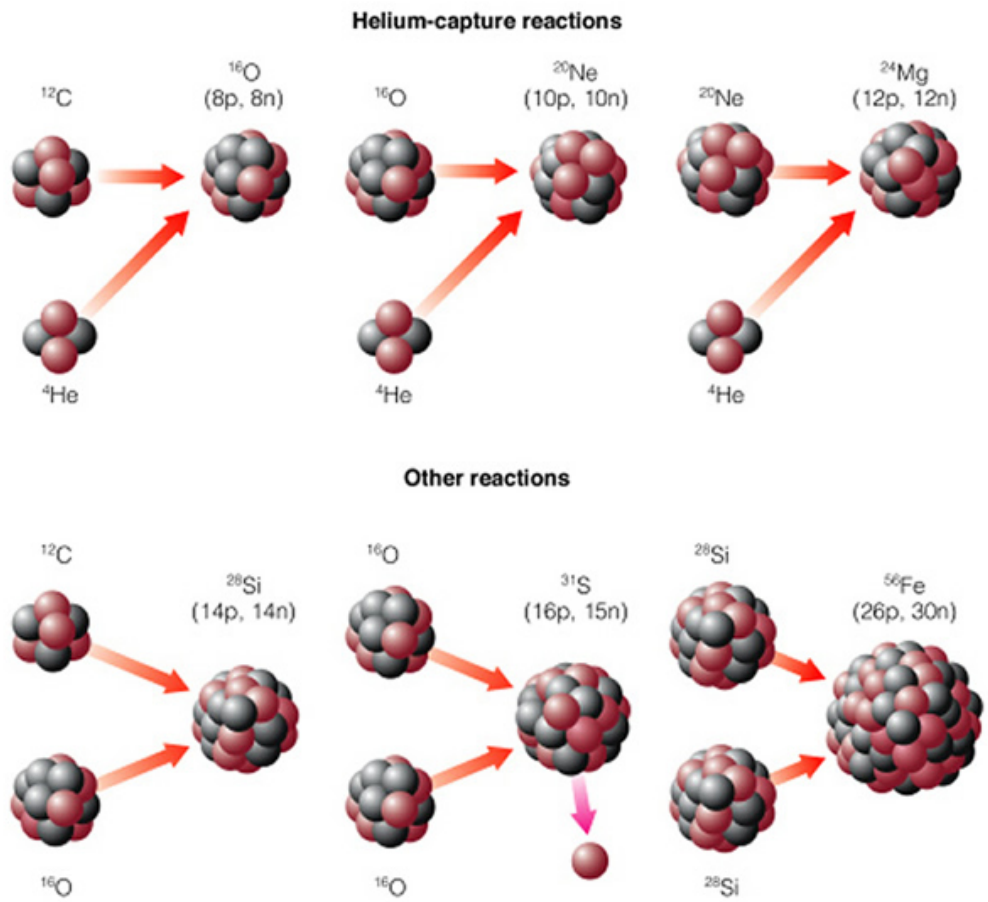
Alpha Ladder

Carbon → O,Ne,Mg (600 million K)

Neon → O, Mg (1.5 Billion K)

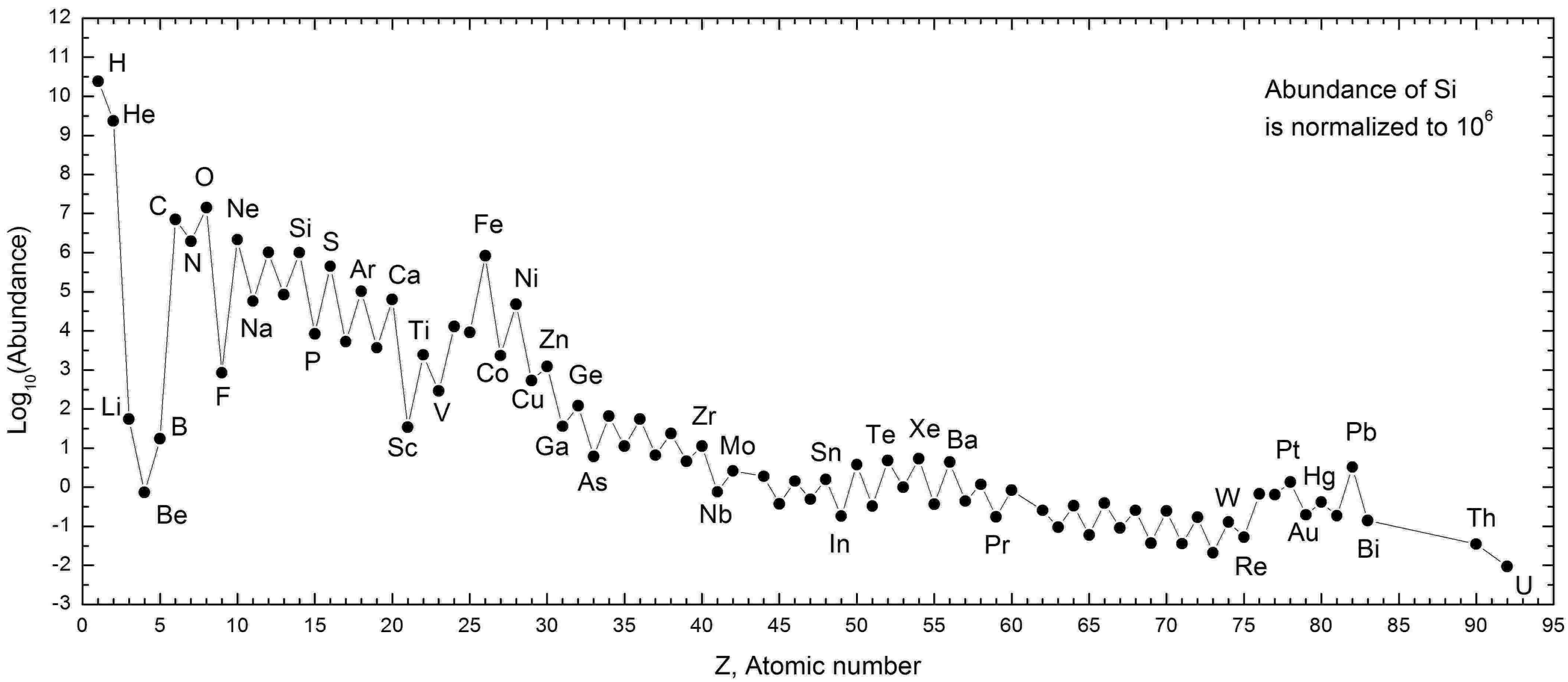
Oxygen → Si, S, P (2.1 Billion K)

Silicon → Fe, Ni (3.5 Billion K)

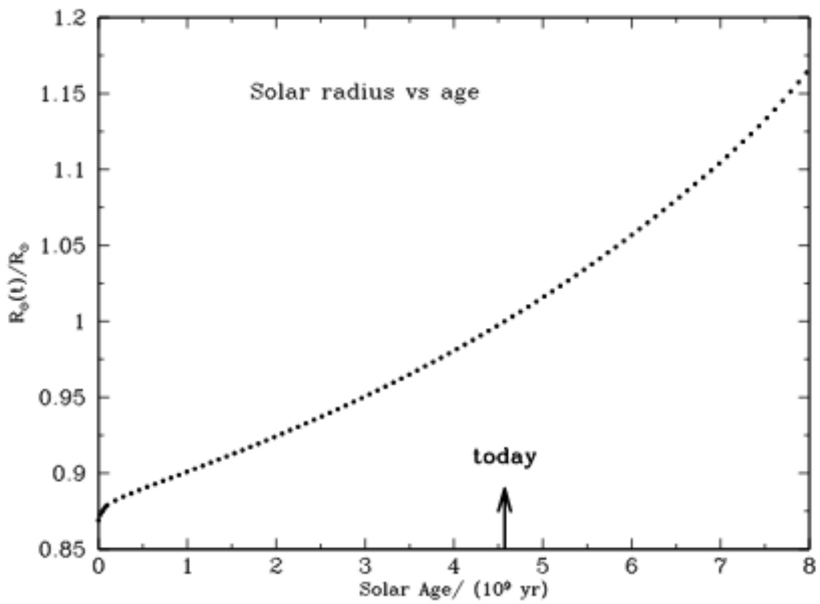


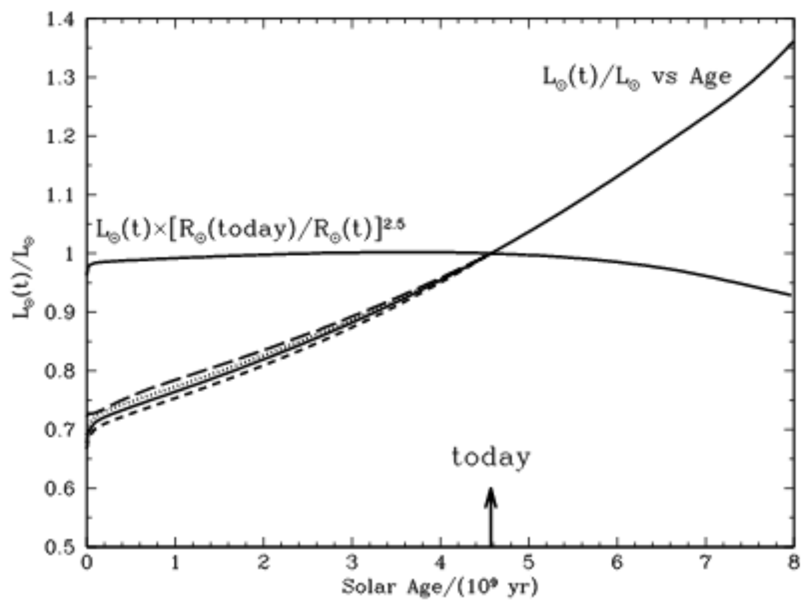
The Sun's abundance pattern

Elements with even atomic number are more abundant than those with odd

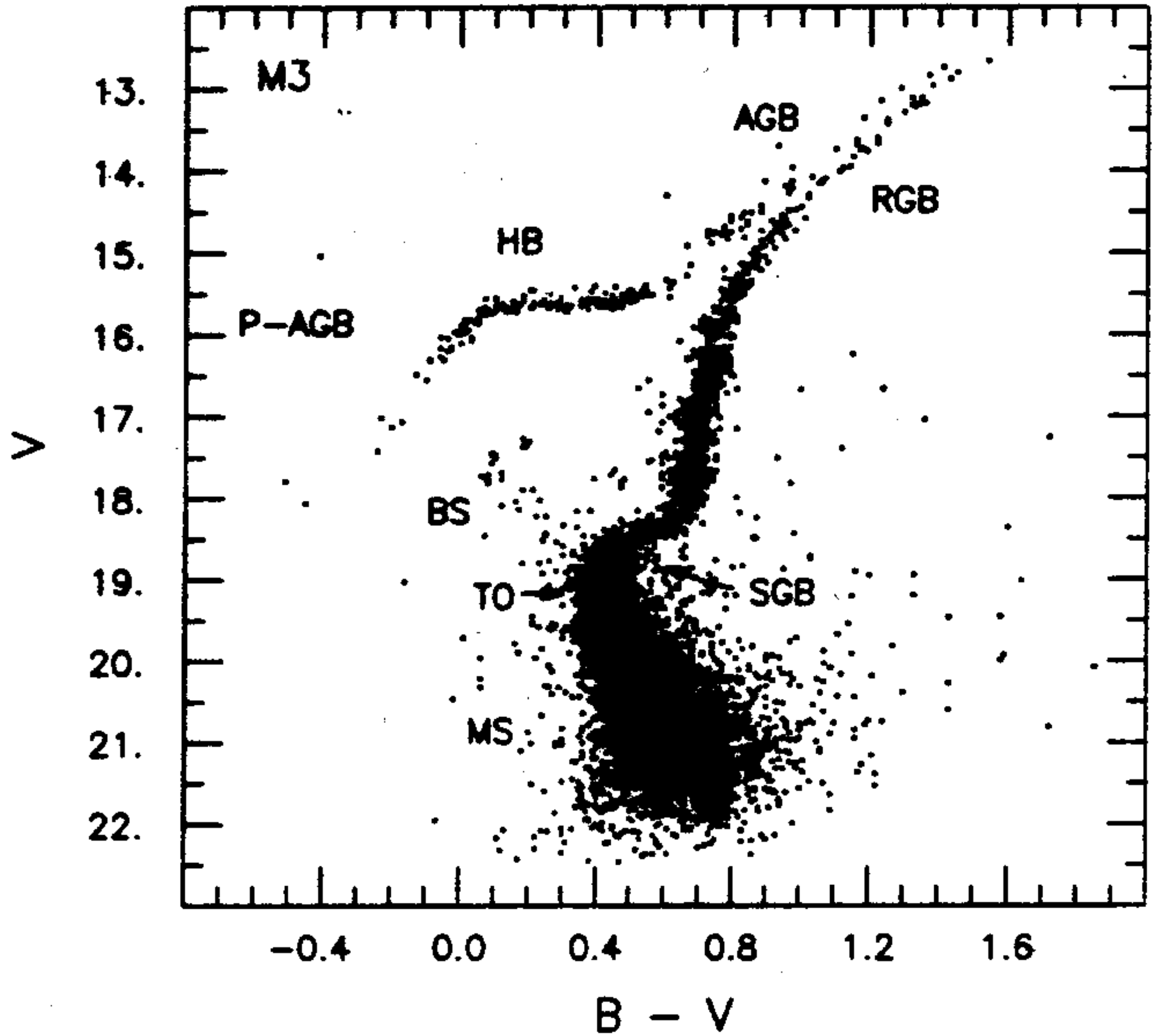


Solar evolution in the main sequence





Bahcall et al. 2001


M3
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HB
P-AGB
BS
TO
SGB
MS
V
13.
14.
15.
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18.
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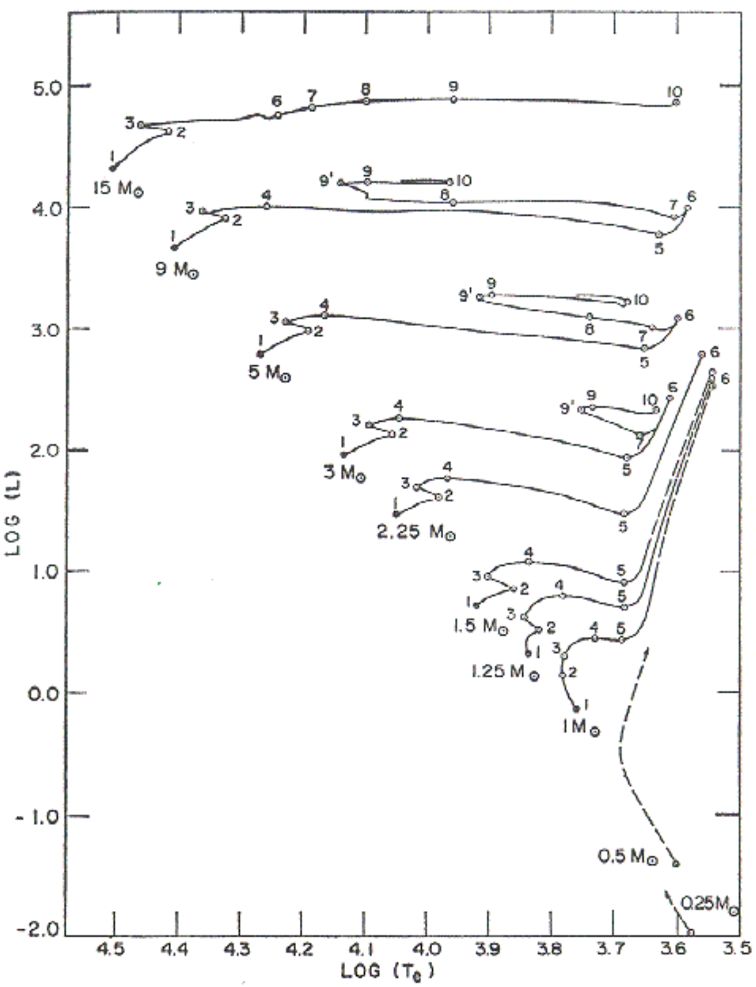
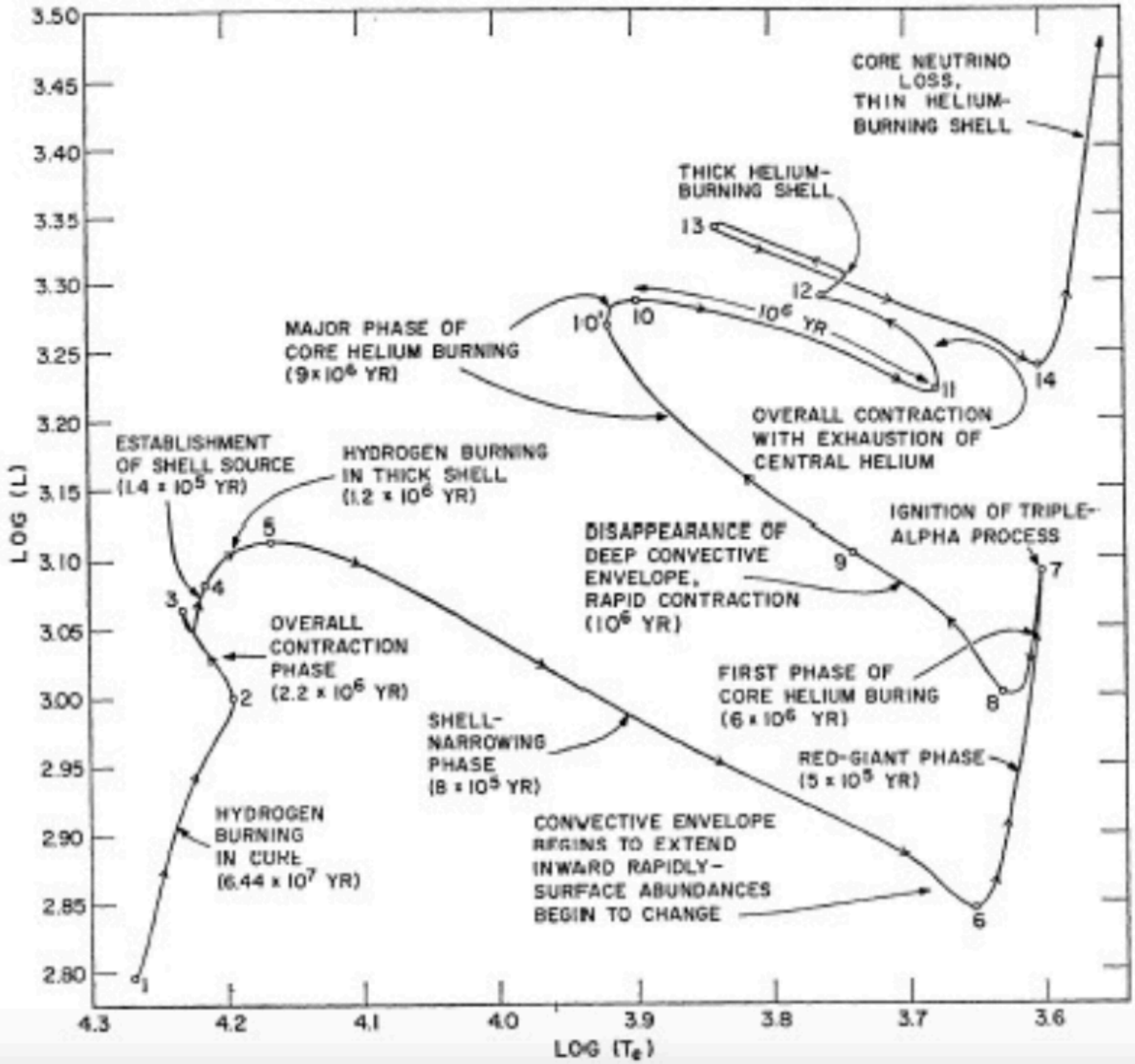
−0.4
0.0
0.4
0.8
1.2
1.6
B − V

Evolutionary tracks



Schaller et al. (1992)



3.50
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3.25
3.20
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3.05
3.00
2.95
2.90
2.85
2.80
LOG (L)
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
LOG (Tₑ)
CORE NEUTRINO LOSS, THIN HELIUM-BURNING SHELL
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RED-GIANT PHASE (5 × 10⁵ YR)
HYDROGEN BURNING IN CORE (6.44 × 10⁷ YR)
CONVECTIVE ENVELOPE BEGINS TO EXTEND INWARD RAPIDLY-SURFACE ABUNDANCES BEGIN TO CHANGE
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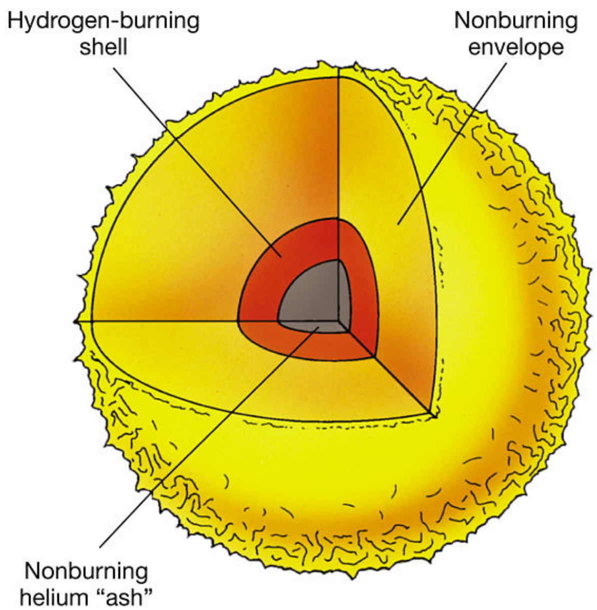
Hydrogen gone in the core

Star stops producing energy.

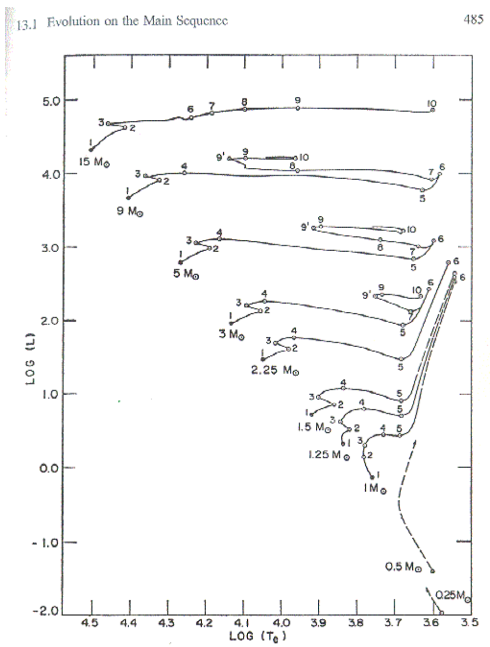
The star **contracts** and **heats** up.

Eventually, the temperature becomes high enough to
burn hydrogen *around* the Helium core

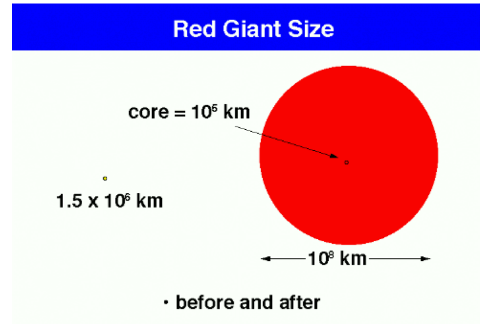
Hydrogen shell burning



The star reaches
the subgiant branch



Red giant branch

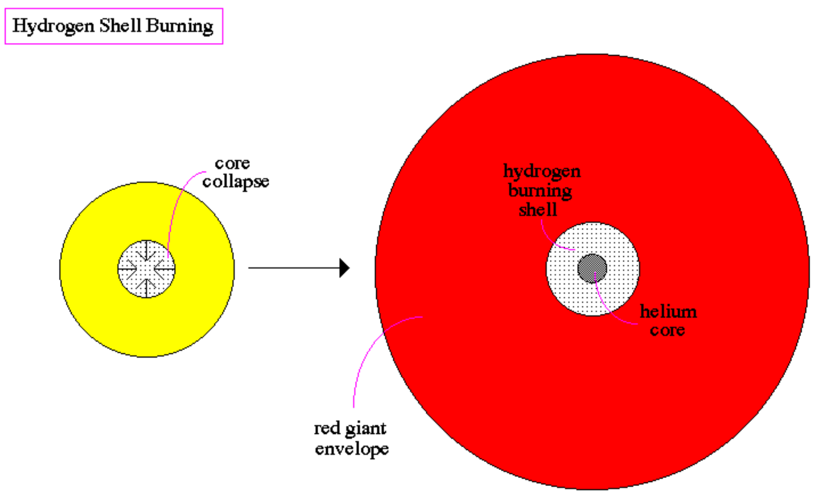


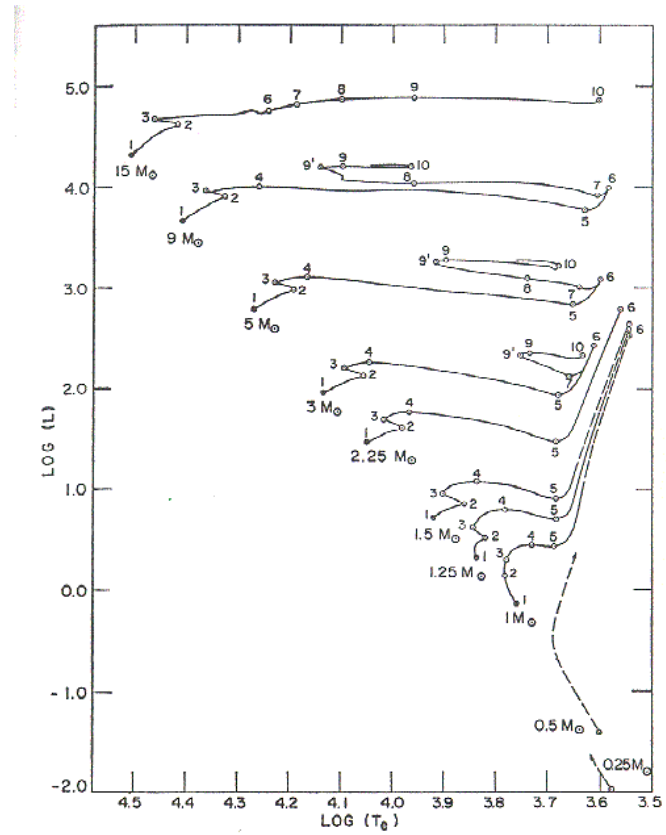
Hydrogen shell burning involves:

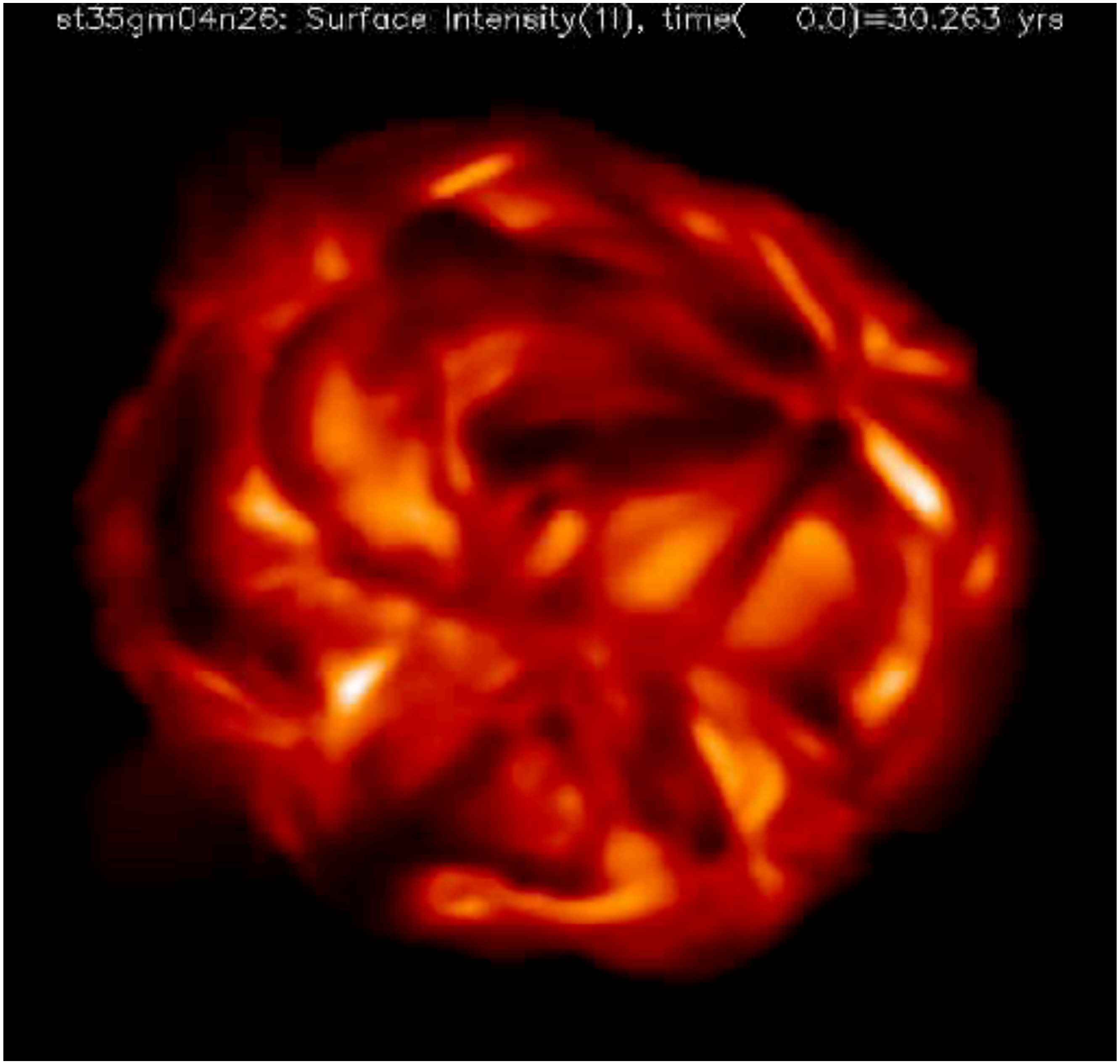
More fuel than in MS-hydrogen burning
Higher temperatures
(thus more efficient)

A lot more of energy is being produced than in the MS-phase.

The star gets very luminous and ***swells***.

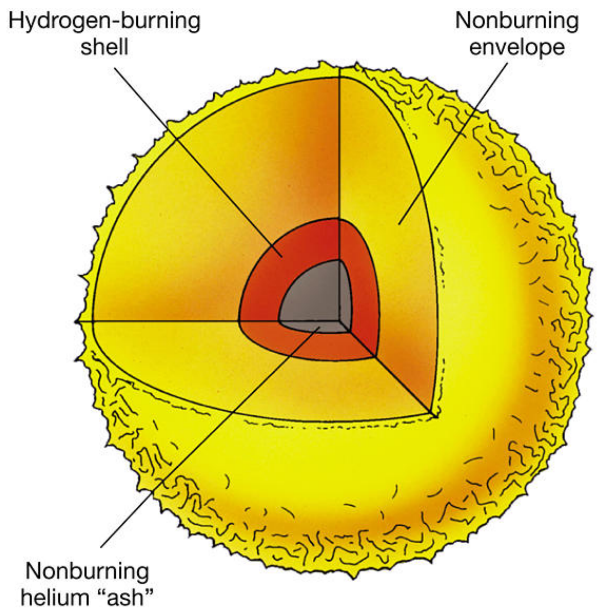





st35gm04n26: Surface Intensity(11), time(0,0)=30.263 yrs

What happens to the inert Helium core?

Hydrogen shell burning



What happens to the inert Helium core?

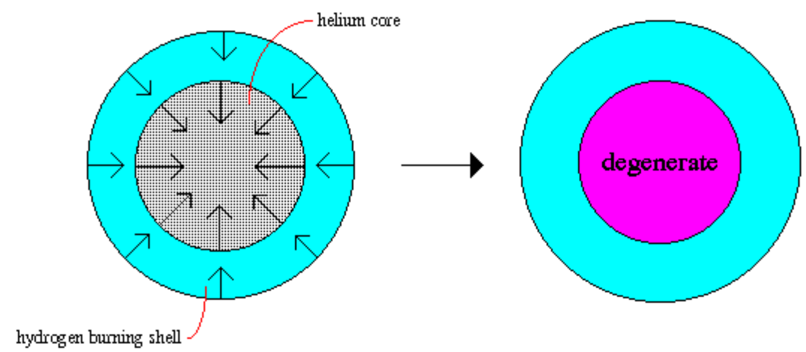
It keeps contracting and heating

At some point the density is so high it goes ***degenerate***

A ***phase transition*** has occured

The core stops behaving like a gas and starts behaving more ***like a solid***

Core Dengeneracy



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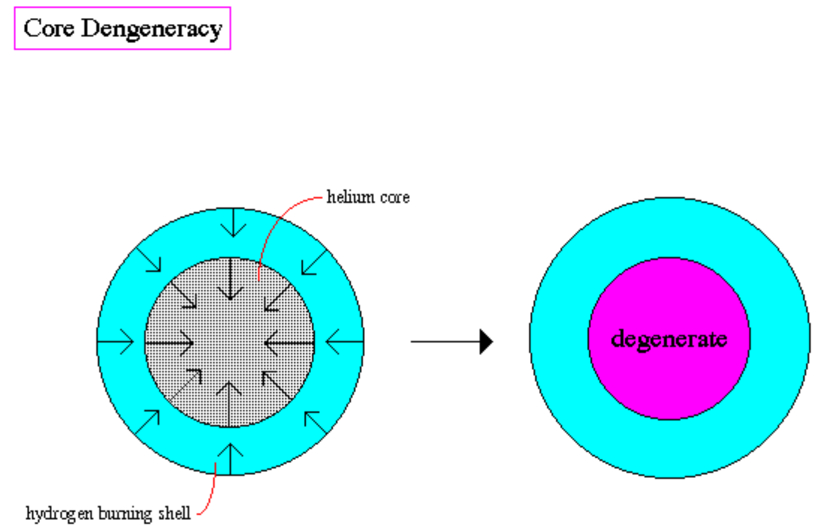


Ideal Gas

$$P \propto \rho T$$

Temperature rises, pressure rises
Temperature falls, pressure falls

Radiative loss → cooling →
less support against gravity → **contraction**

Degenerate Matter

$$P \propto \rho^{4/3}$$

If temperature rises or falls, pressure couldn't care less

Radiative losses can continue indefinitely
The degenerate core is stable

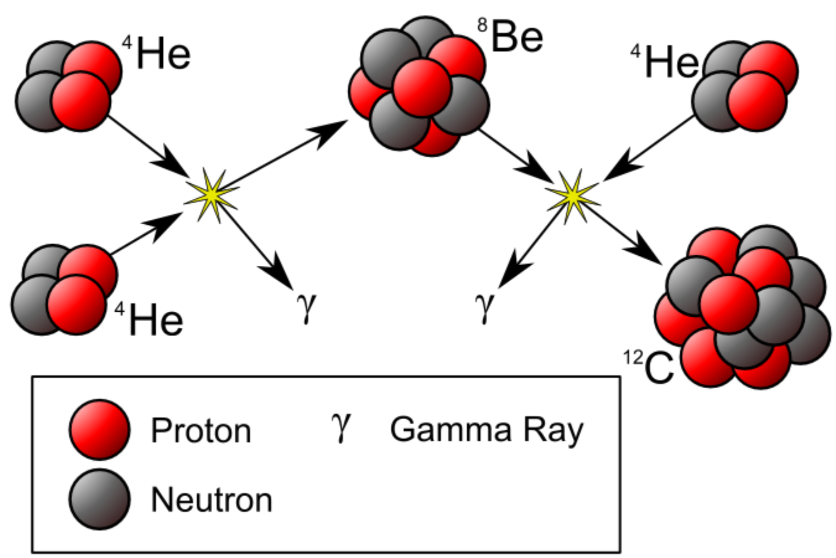
Helium Fusion

The inner degenerate Helium core is stable
But the outer Helium core keeps contracting and heating

At the tip of the Red Giant Branch,
when the temperature reaches 100 million K,
HELIUM FUSION begins

Triple Alpha

3 He → C + energy
(C + He → O + energy)



The Helium Flash

Under normal (non-degenerate) conditions …

Ideal Gas

$$P \propto \rho T$$

Nuclear reactions start

Heating → Expansion → Cooling

Cooling = Less nuclear reactions

Cooling → Contraction → Heating

Thermostat keeps nuclear reactions "tuned"

Controlled fusion

The Helium Flash

Non-degenerate vs degenerate

Ideal Gas

$$P \propto \rho T$$

Nuclear reactions start

Heating → Expansion → Cooling

Cooling = Less nuclear reactions

Cooling → Contraction → Heating

Thermostat keeps nuclear reactions “tuned”

Controlled fusion

Degenerate Matter

$$P \propto \rho^{4/3}$$

Nuclear reactions start

Heating

Star does not expand

Nuclear burning increases

More heating

The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

Ideal Gas

$$P \propto \rho T$$

Nuclear reactions start

Heating → Expansion → Cooling

Cooling = Less nuclear reactions

Cooling → Contraction → Heating

Thermostat keeps nuclear reactions “tuned”

Controlled fusion

Degenerate Matter

$$P \propto \rho^{4/3}$$

Nuclear reactions start

Heating

Star does not expand

Nuclear burning increases

More heating

No thermostat

Runaway temperature rise

Runaway fusion

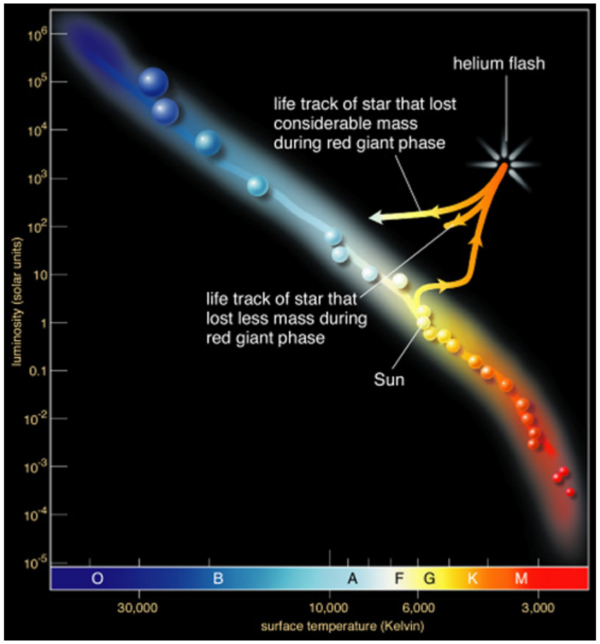
The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

No thermostat! Core just gets hotter and hotter

Runaway Helium burning: **100 billion times the Solar output** in just a few seconds

Helium Flash



The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

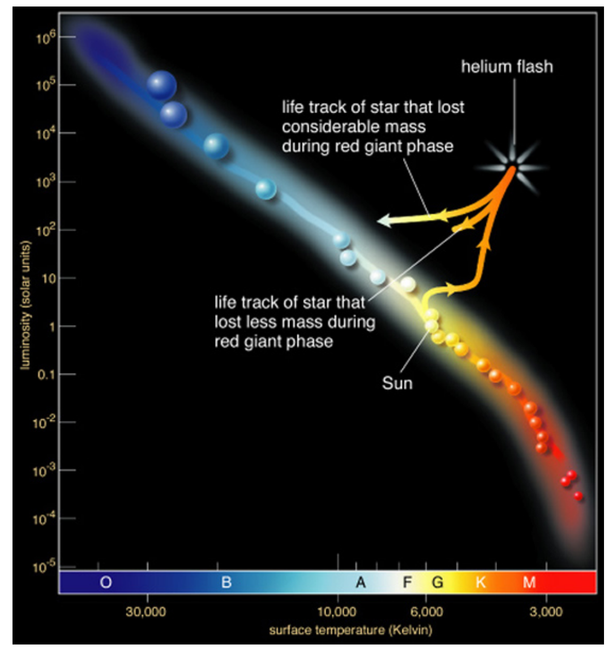
No thermostat! Core just gets hotter and hotter

Runaway Helium burning: **100 billion times the Solar output** in just a few seconds

Helium Flash

Yet, nothing is seen

Why?



The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

No thermostat! Core just gets hotter and hotter

Runaway Helium burning: **100 billion times the Solar output** in just a few seconds

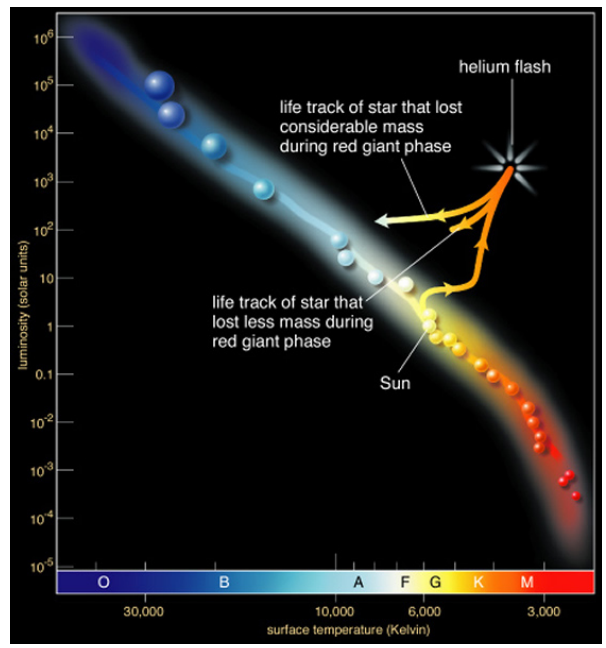
Helium Flash

Yet, nothing is seen

Why?

The energy is *ALL* used to lift the degeneracy

(i.e., to "melt" the degenerate
core back into a normal gas)



Helium then burns ***steadily*** in a core of normal gas

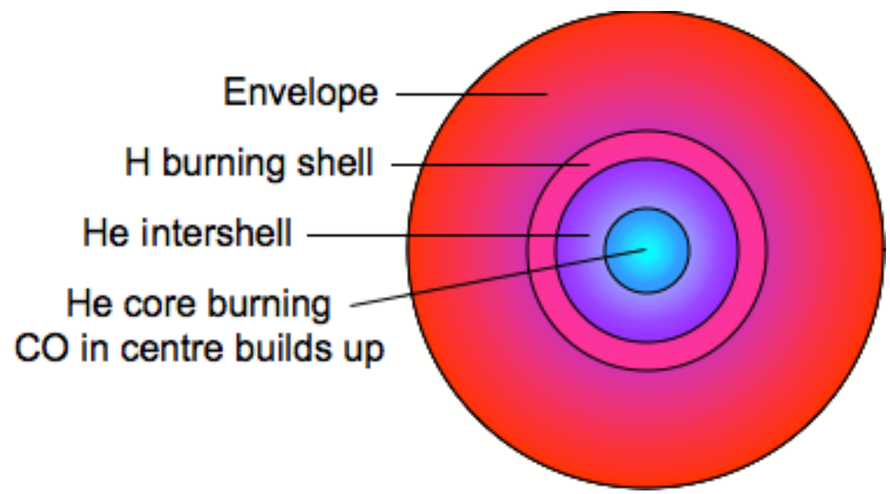
The Horizontal Branch

Helium burning in the core

Hydrogen shell burning

In the HR diagram, the star sets in the **Horizontal Branch**

The Horizontal Branch is the Helium Main Sequence



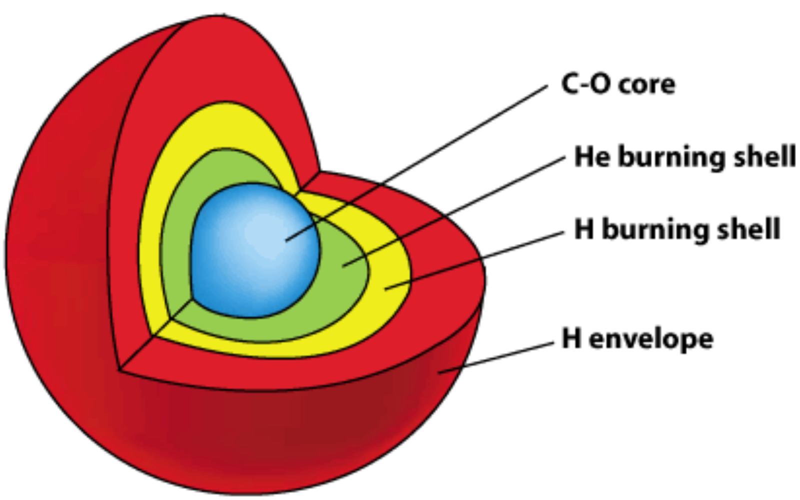
Helium exhausted in the core

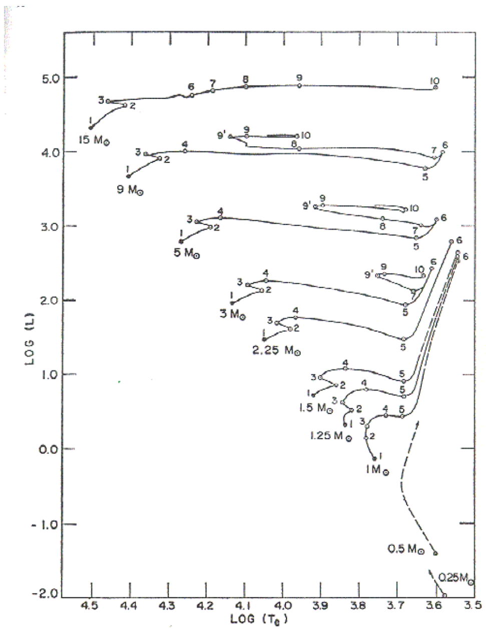
The Carbon-Oxygen core **contracts** and **heats** up.

Helium shell burning

More energy is available, the star swells and becomes a red giant *again*

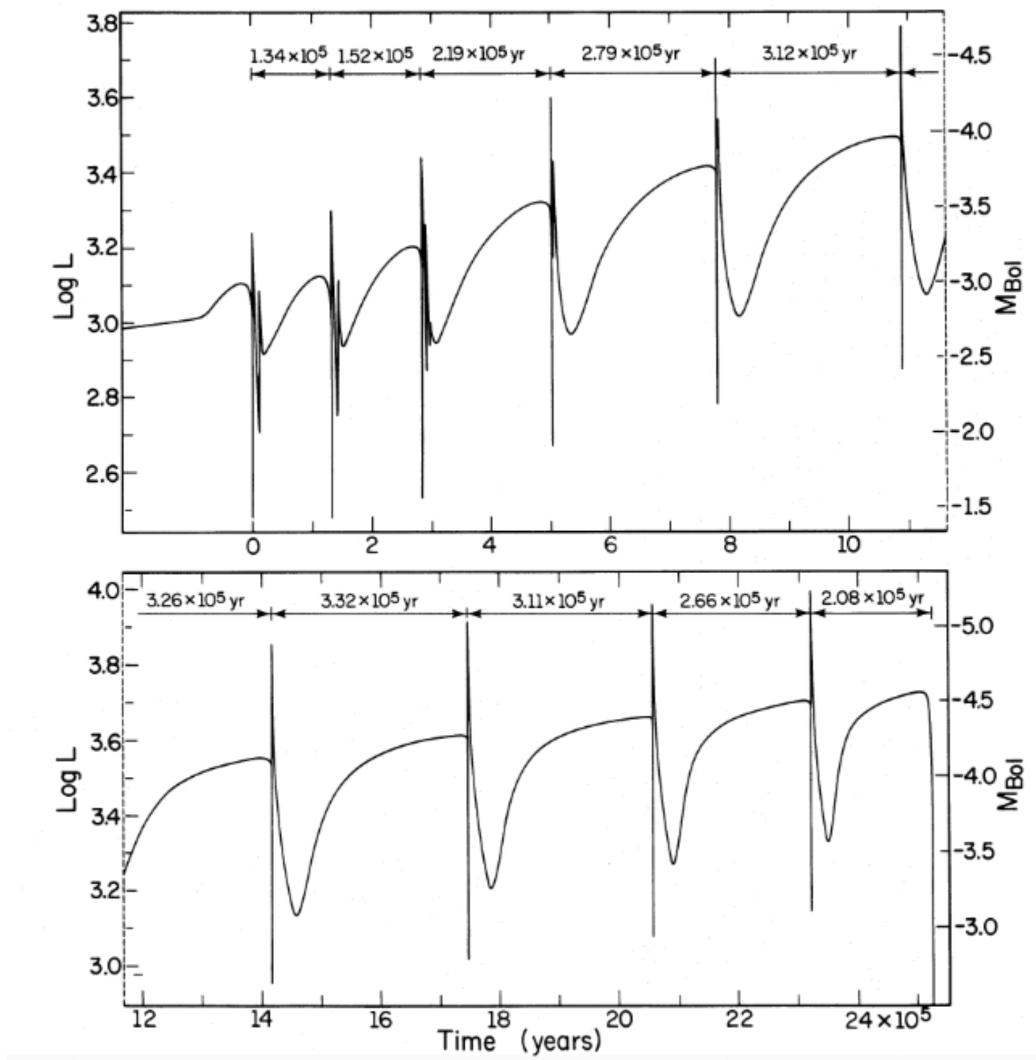
The star reaches the *Asymptotic Giant Branch*

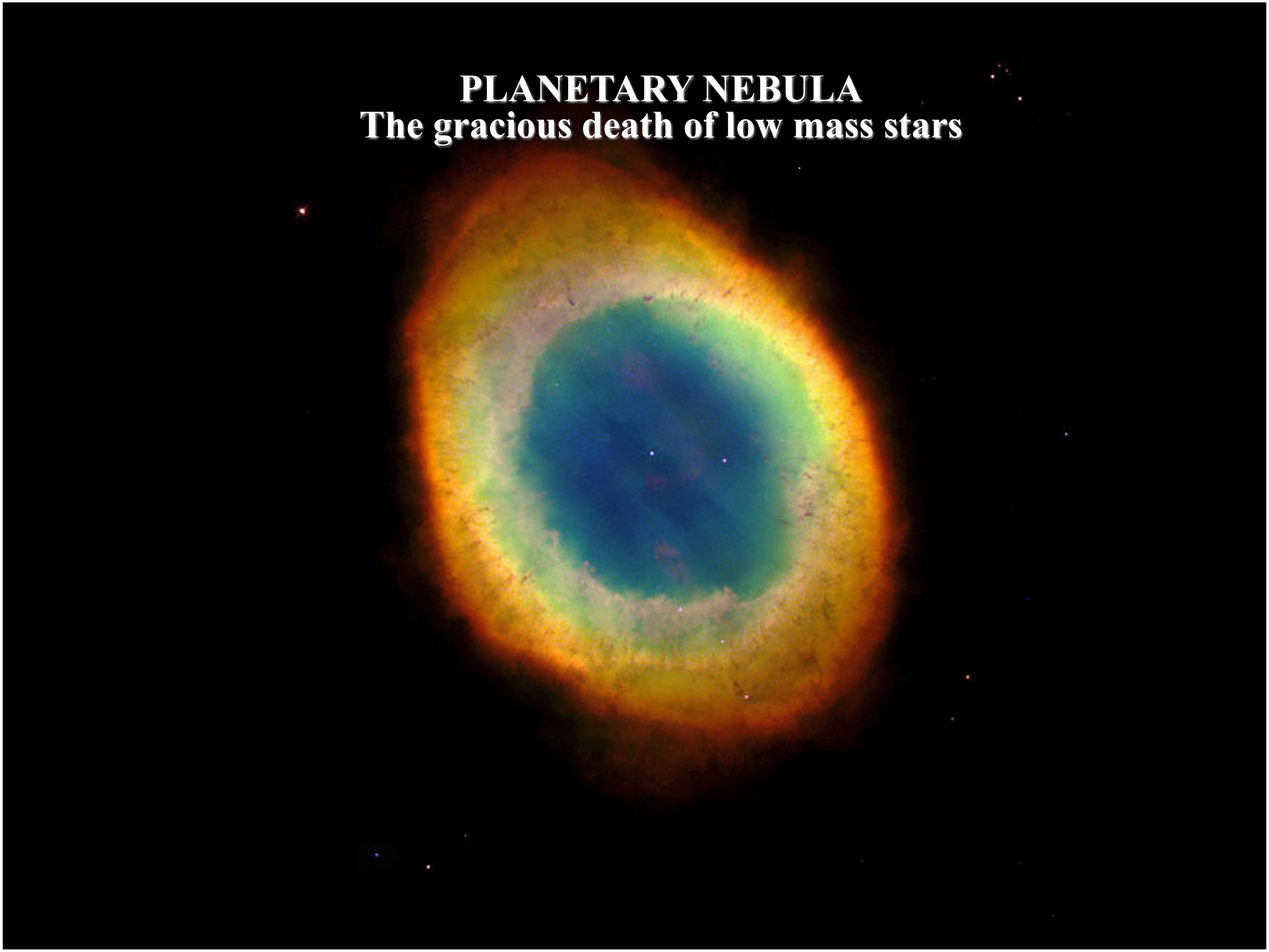


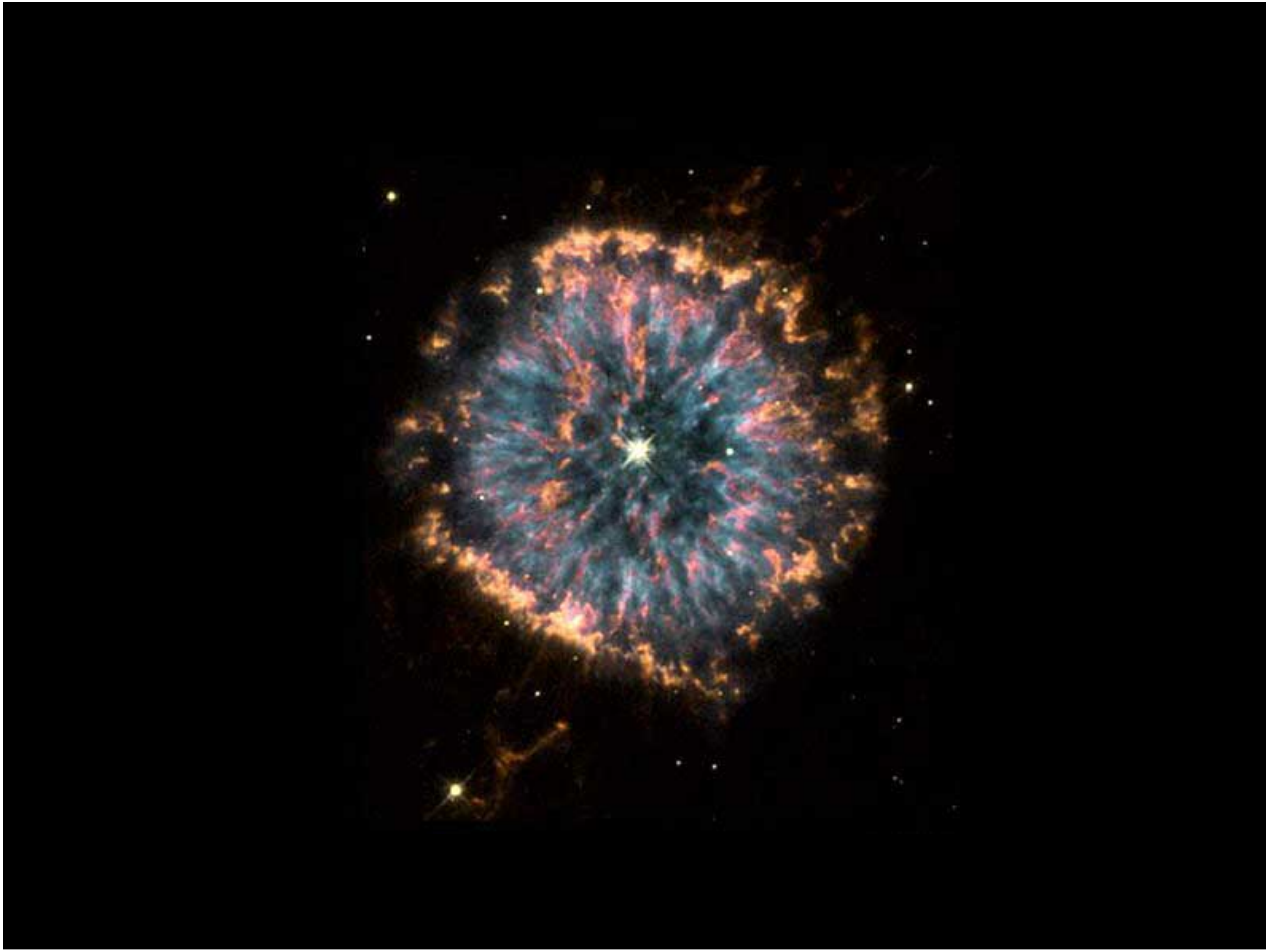


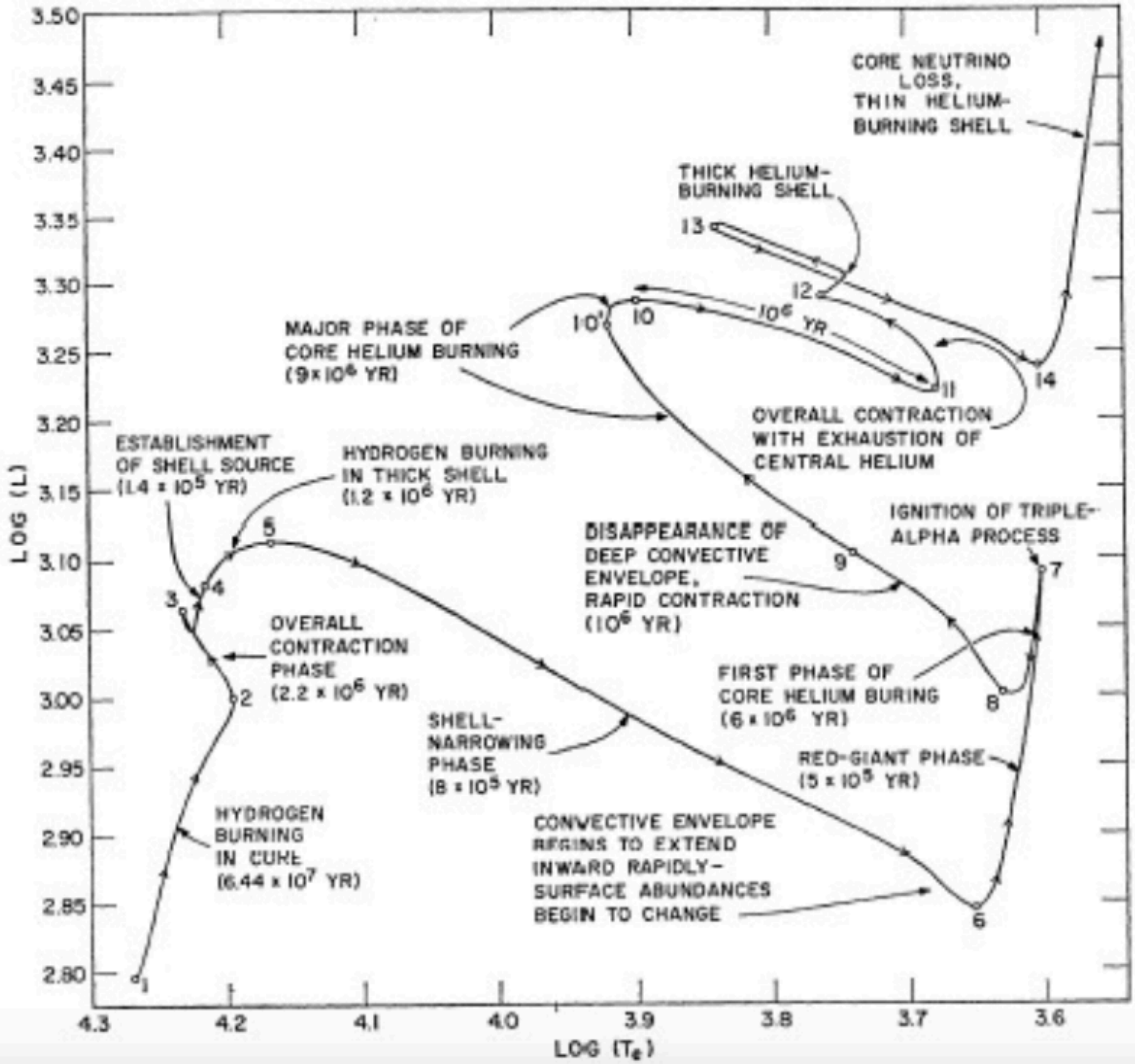
Thermal pulses in AGB stars

A series of Helium flashes




PLANETARY NEBULA
The gracious death of low mass stars





LOG (L)
LOG (T_e)
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3.40
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3.30
3.25
3.20
3.15
3.10
3.05
3.00
2.95
2.90
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4.2
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3.9
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3.7
3.6
CORE NEUTRINO LOSS, THIN HELIUM-BURNING SHELL
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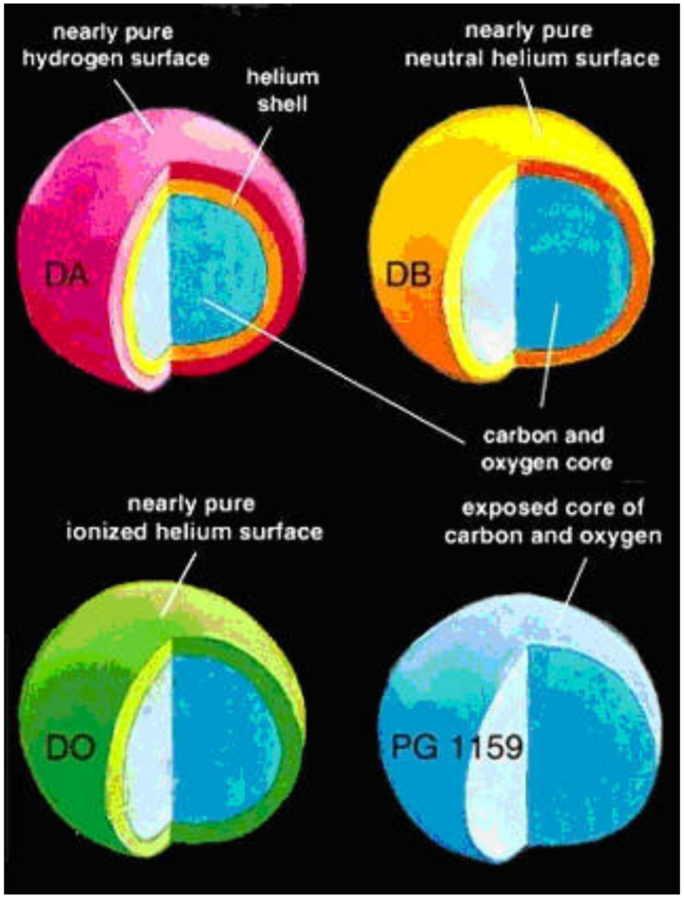
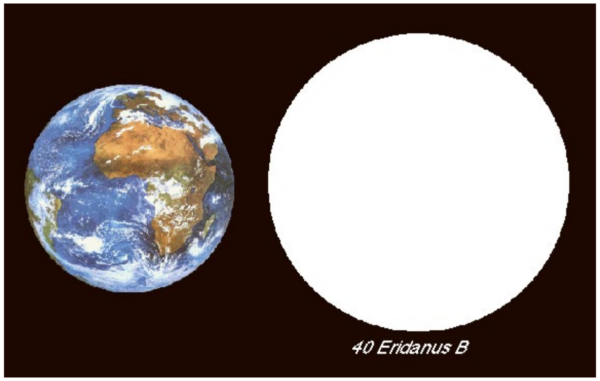
White dwarfs

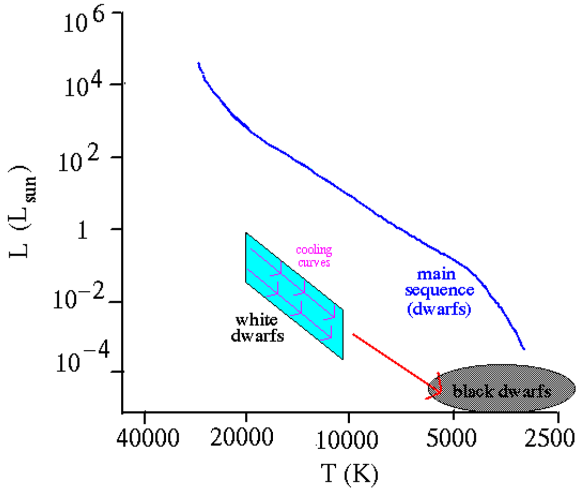
White dwarfs are the exposed degenerate core of the star



Types of white dwarfs



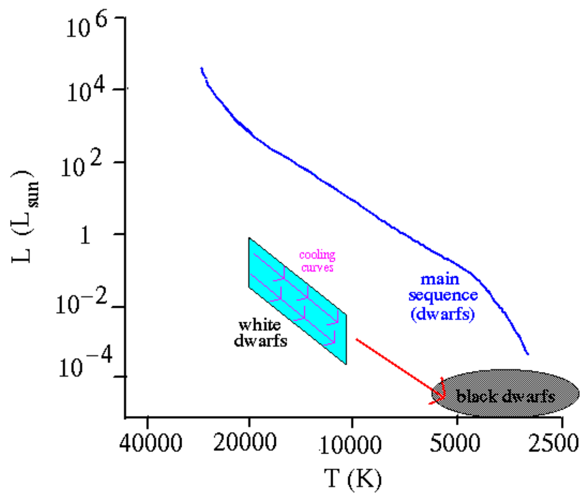
White dwarfs have planetary dimensions...



… and they do little but cooling.

White dwarfs

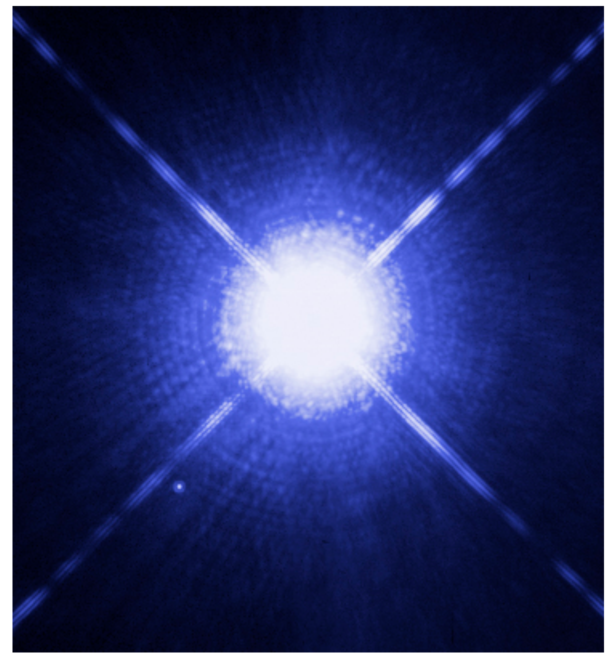
White dwarfs are the exposed degenerate core of the star



No energy production
Supported by degenerate pressure

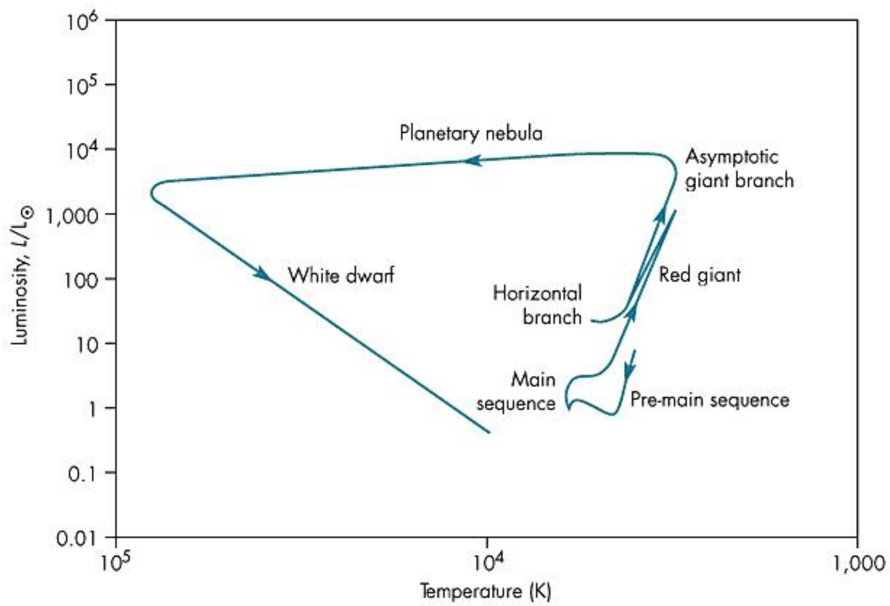
Cooling takes a long time
10^{15} yr to cool down to background temperature

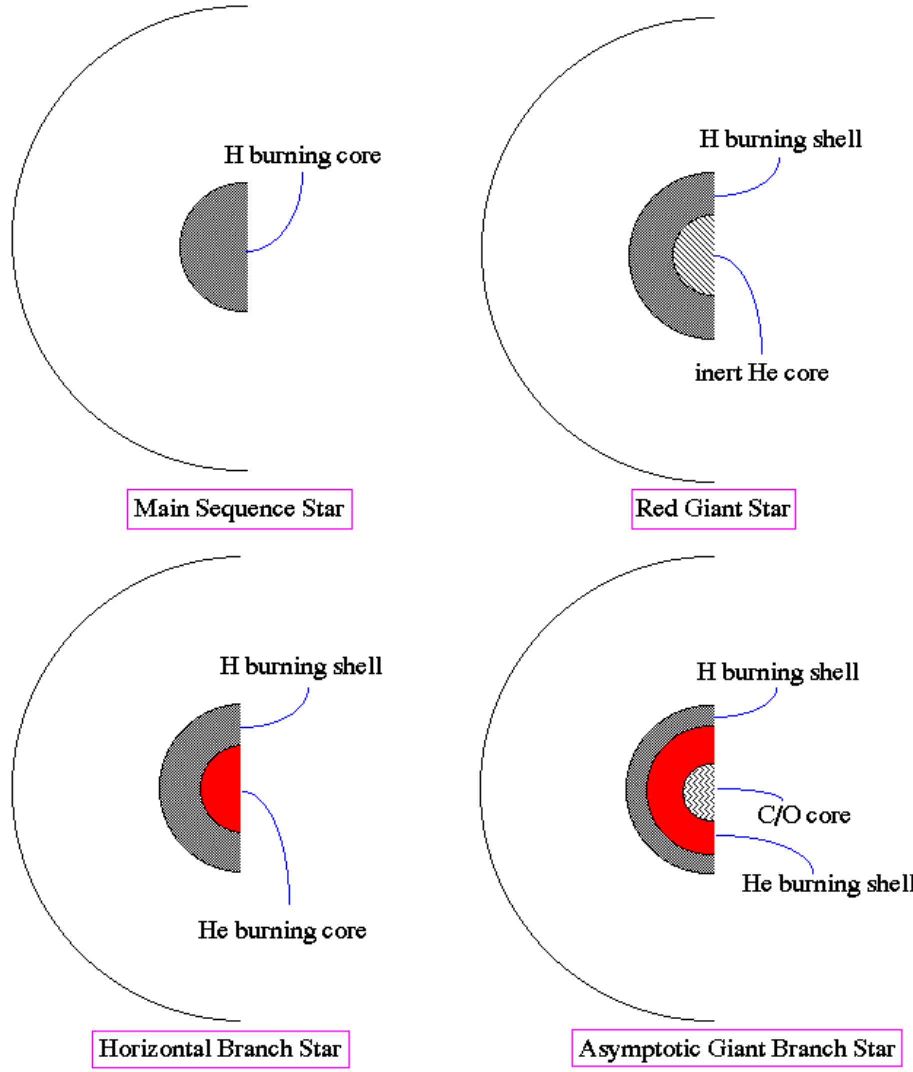
The universe is not old enough to have black dwarfs
Coldest white dwarfs ~5000 K.



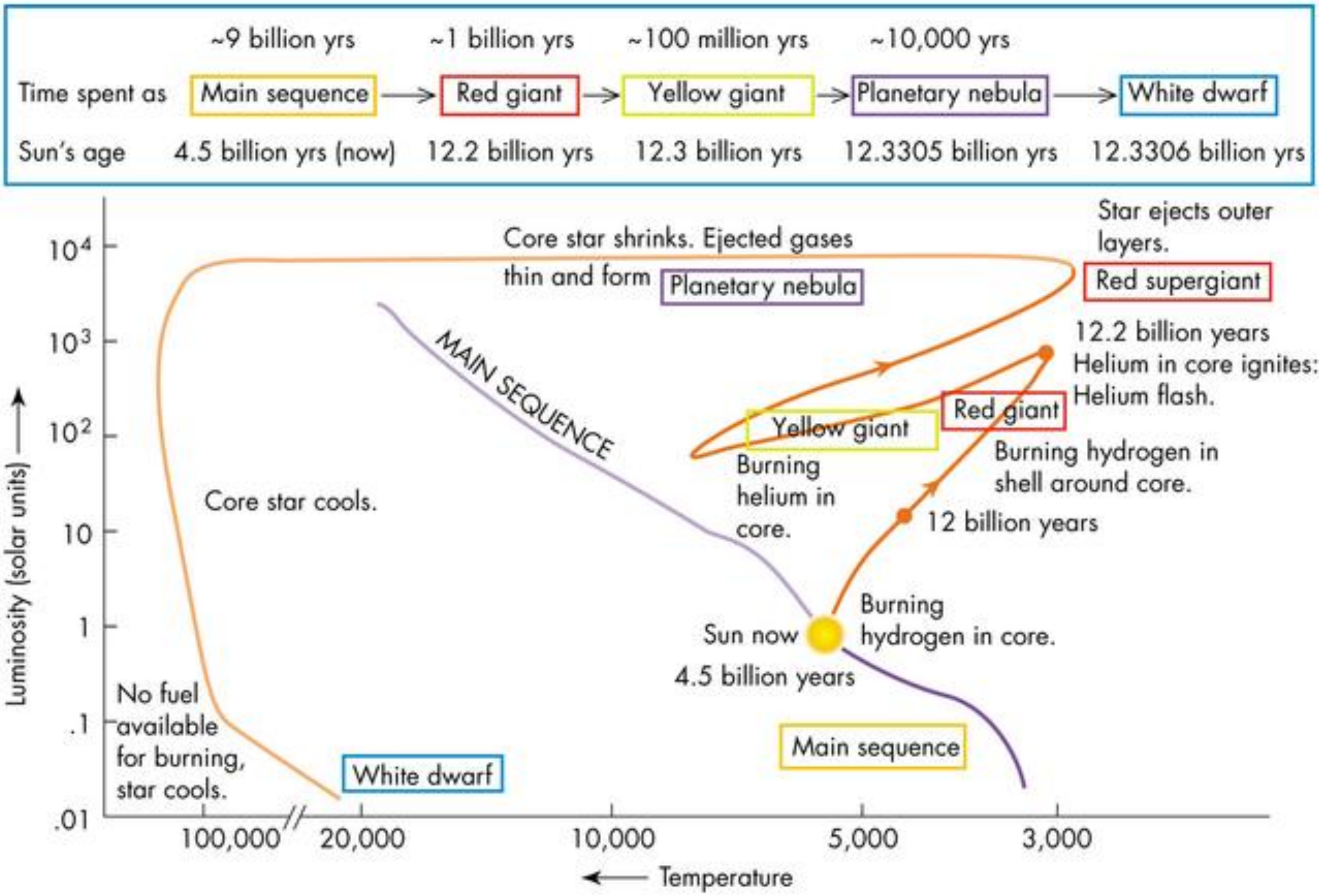
Sirius A (Main Sequence star) and **Sirius B** (White Dwarf)

Evolution of a low mass star



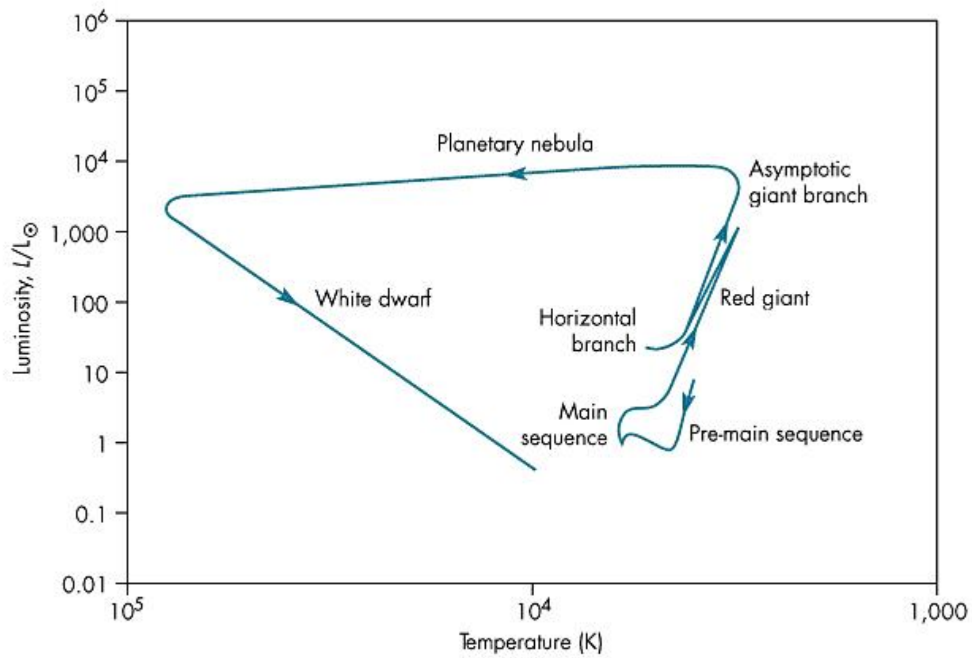


Post-Main Sequence Evolution - Timescales



Evolution of high mass stars

The evolution we covered in last class is for low mass stars ($M < 4\ M_\odot$)



High mass stars differ basically due to the ***temperature of the core***.

Evolution of high mass stars (*$4 < M/M_\odot < 8$*)

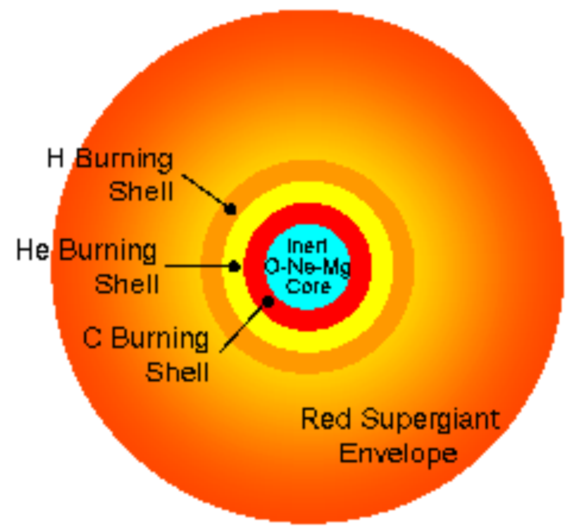
The Helium Flash never happens

The star reaches Helium burning temperatures
before the core becomes degenerate

They also reach temperatures
hot enough to burn **Carbon**

600 million K

Leaves a O-Ne-(Mg)
white dwarf.



Evolution of high mass stars

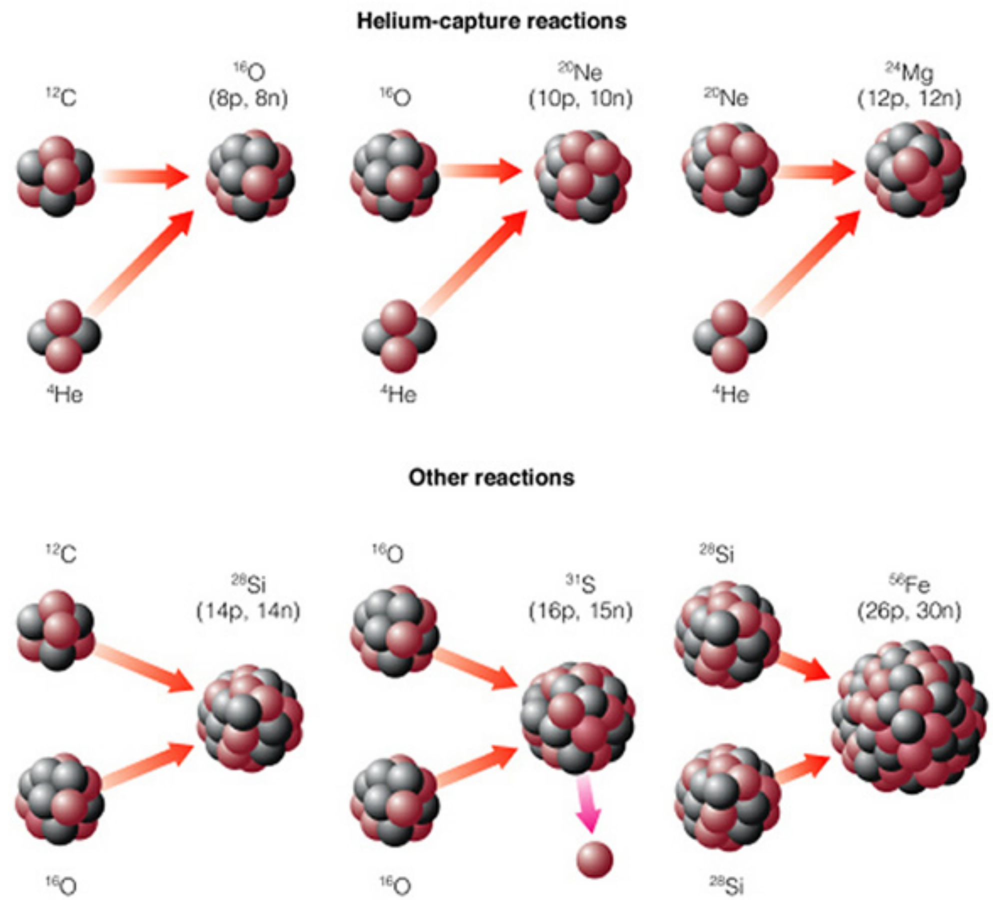
$M > 8\ M_\odot$

Carbon → O,Ne,Mg (600 million K)

Neon → O, Mg (1.5 Billion K)

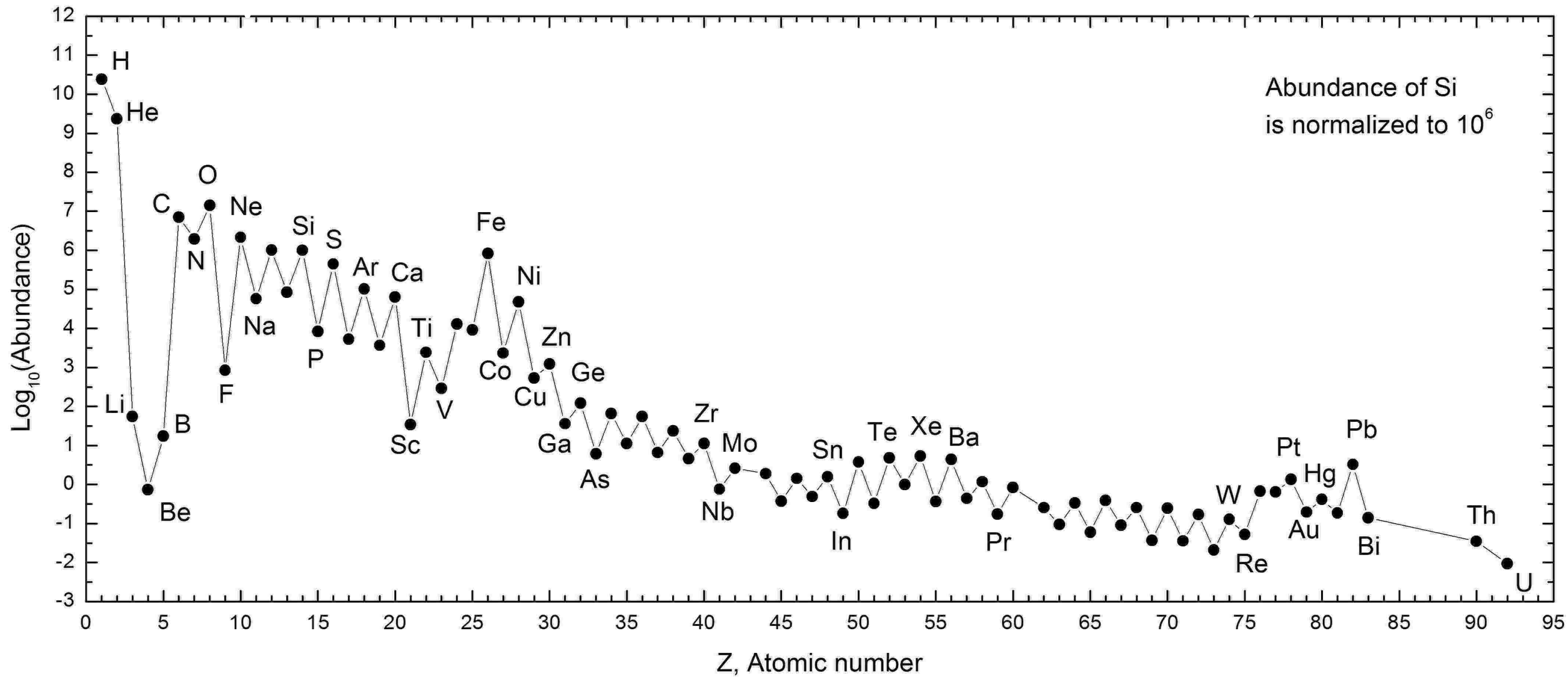
Oxygen → Si, S, P (2.1 Billion K)

Silicon → Fe, Ni (3.5 Billion K)



The Sun's abundance pattern

Because of the alpha ladder, elements with even atomic number are more abundant than those with odd



Evolution of high mass stars

$M > 8\ M_{\odot}$

TIMESCALES FOR NUCLEAR BURNING

Hydrogen – 10 Myr
Helium – 1 Myr
Carbon – 1000 yr
Neon ~ 10 yr
Oxygen ~ 1 yr
Silicon ~ 1 day

Evolution of high mass stars $M > 8\ M_{\odot}$

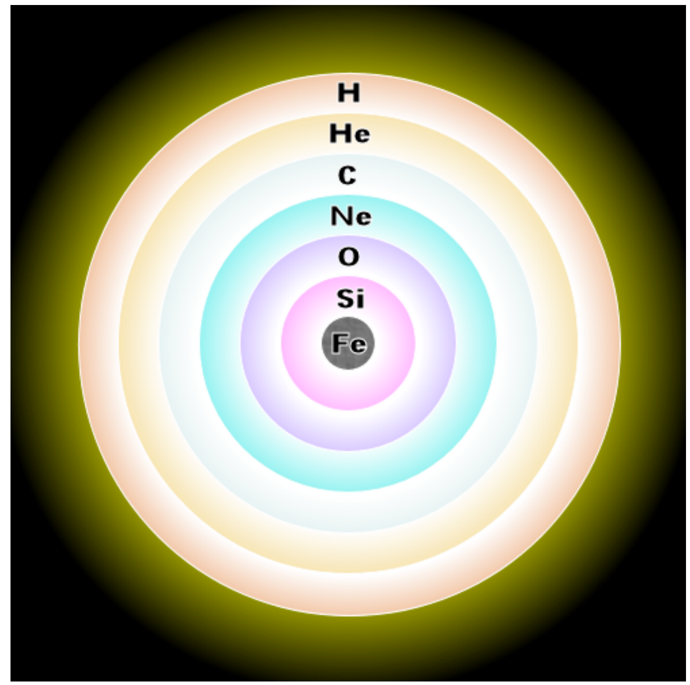
The star develops an **"onion layers structure"** of burning shells

Carbon → O,Ne,Mg (600 million K)

Neon → O, Mg (1.5 Billion K)

Oxygen → Si, S, P (2.1 Billion K)

Silicon → Fe, Ni (3.5 Billion K)

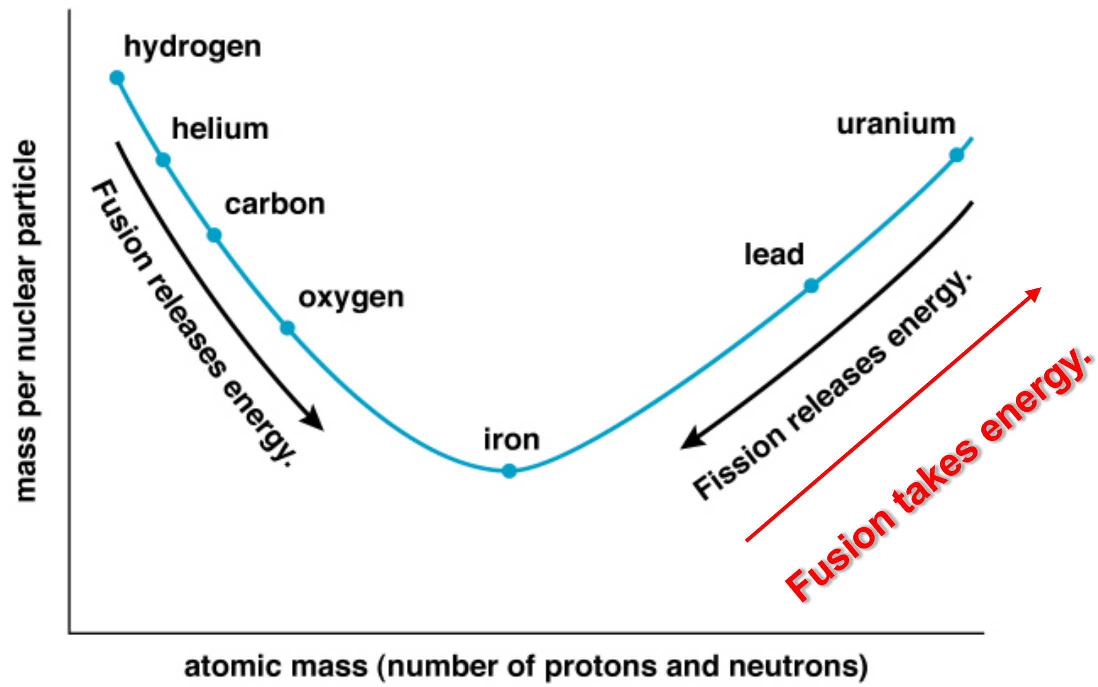


*But **Iron** is a **DEAD END** !!*

Iron is a dead end

Iron is the most tightly bound element

Fusion beyond Iron TAKES energy

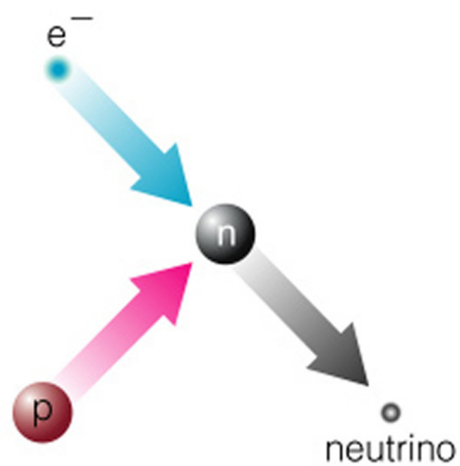


No fusion reactions left to yield energy!!

Core collapse

At densities of 10^{10} g/cm^3
(remember: nuclear densities are ~10^{14} g/cm^3)

Neutronization

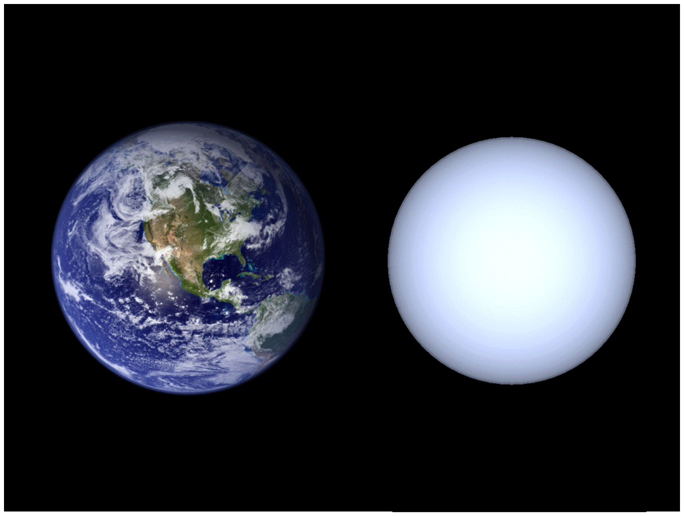


Proton + electron $\longrightarrow$ neutron + neutrino

($p + e^- \longrightarrow n + \nu$)

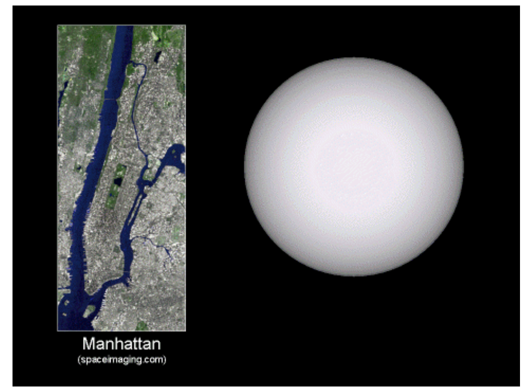
Electrons lost: electron degeneracy pressure is gone

Catastrophic collapse



A second later

Collapse speed: 0.25c



6000 km
10^{10} g/cm^3

10 km
10^{14} g/cm^3

Nuclear densities!
Neutron degeneracy
provides support against gravity

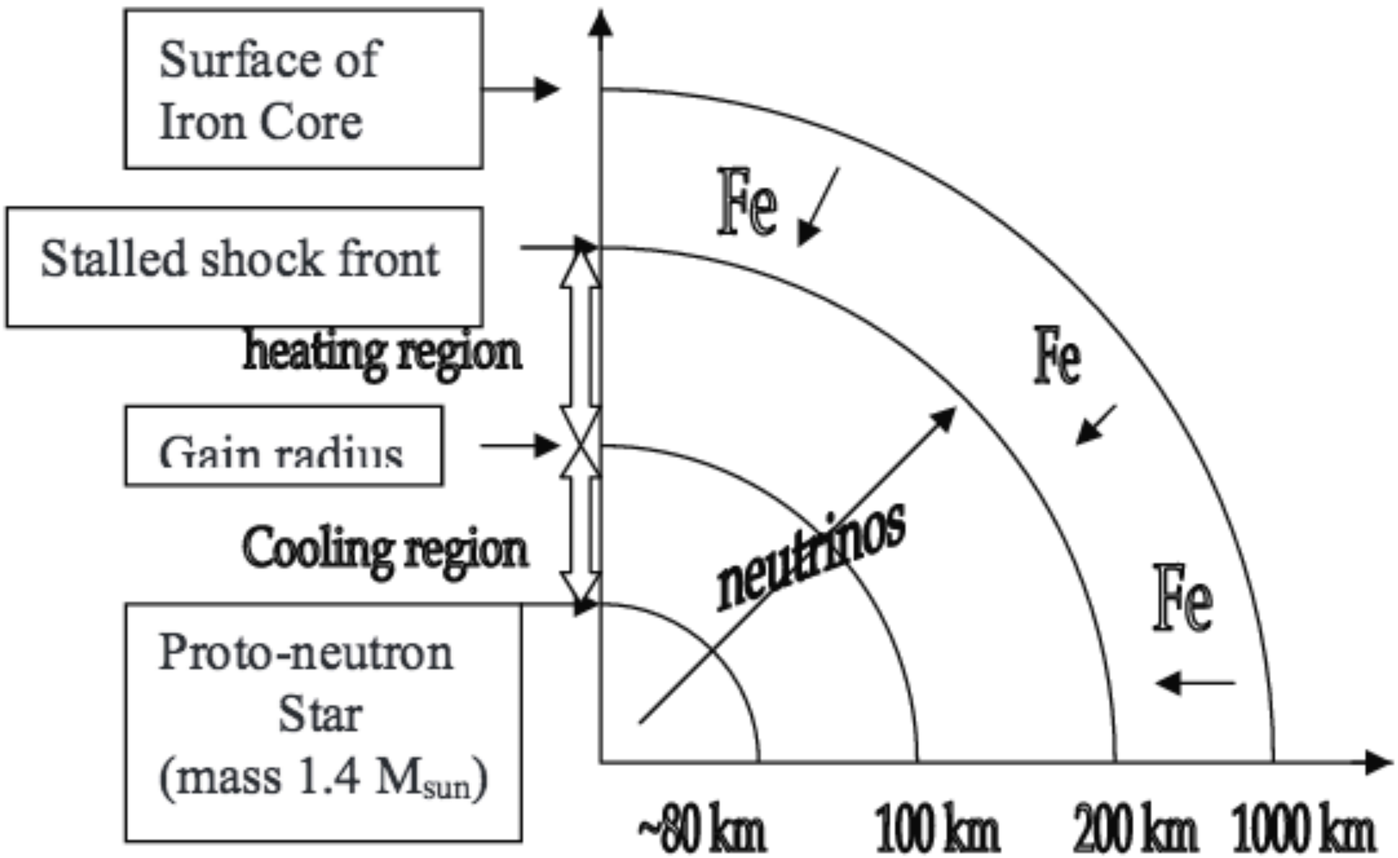


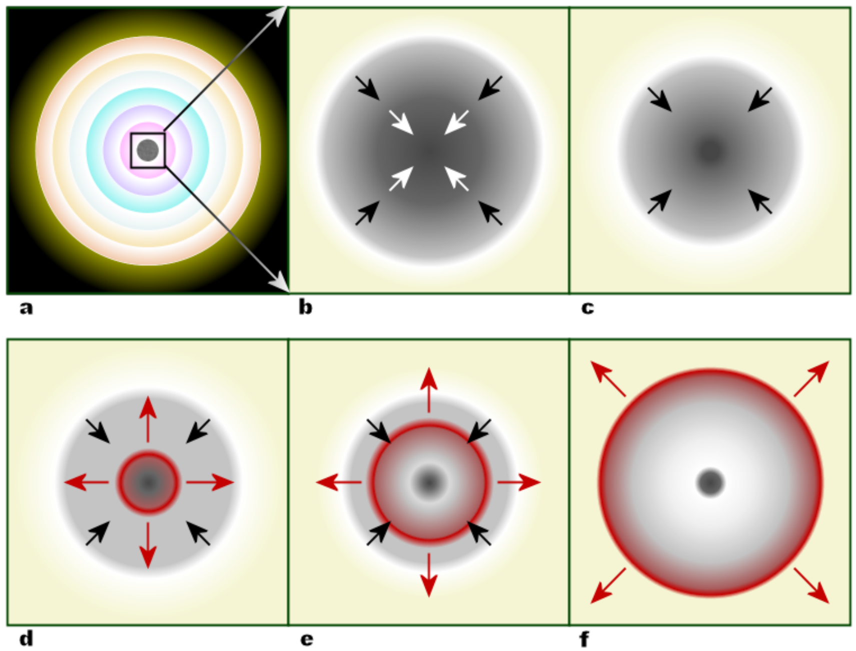
Figure 1. Core collapse Supernova

Core Bounce

Neutronization

Iron core collapses

The inner core stabilizes and stops collapsing.



The core overshoots the equilibrium radius and bounces.

The kinetic energy that was directed inwards is redirected outwards

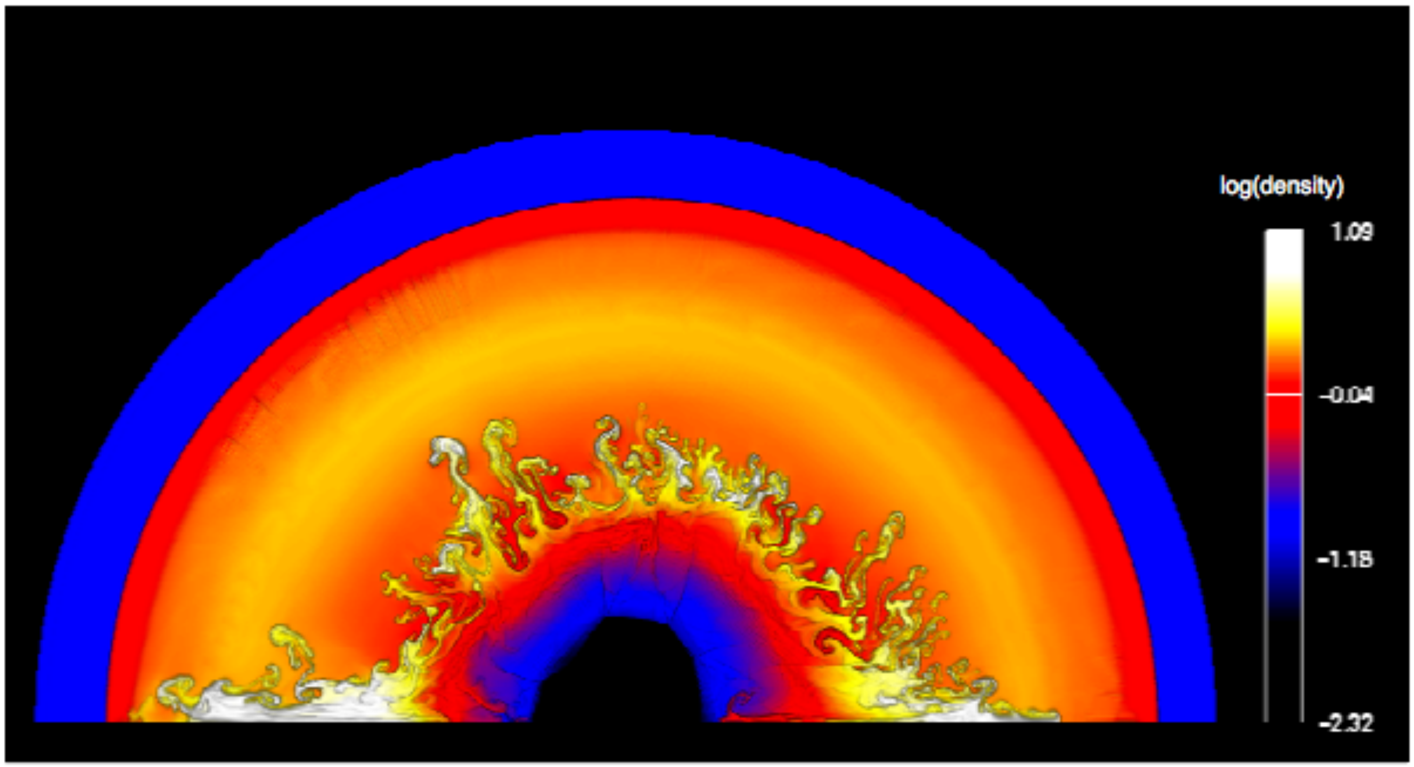
Pressure wave hits infalling gas

The Thermonuclear Shock Wave

Infalling gas meeting the rebouncing core generates a ***shock wave***

The blastwave generates ***explosive nuclear reactions*** along its path

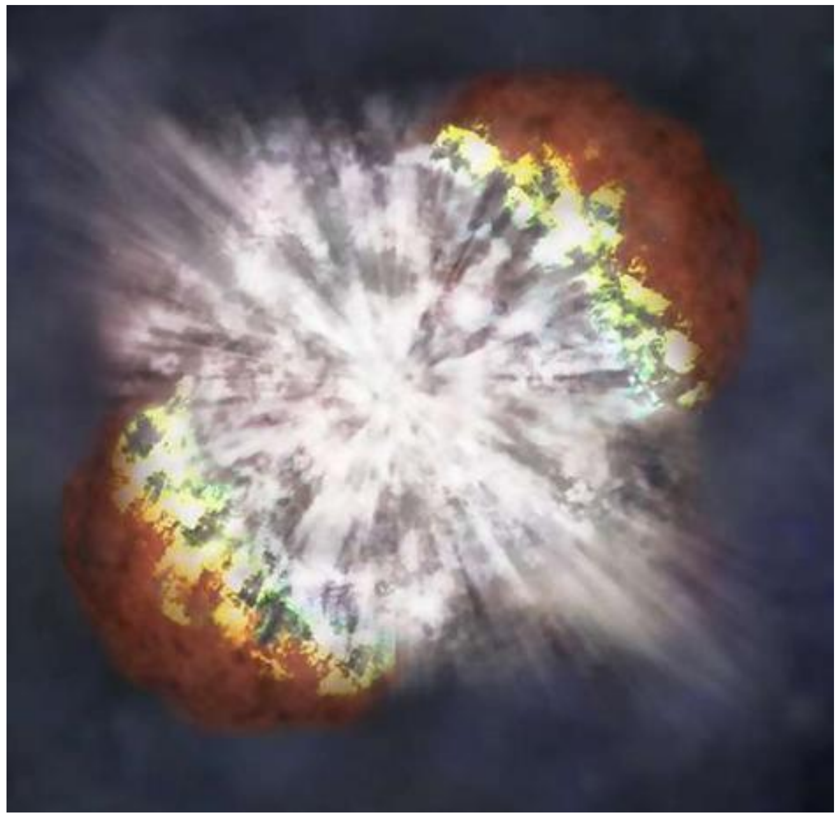
Violently heats and accelerates the stellar envelope



Supernova!

In a few hours, the shockwave reaches the surface

From the outside, the star is seen to explode.



Supernova 1987A

Confirmation of the theory

A **burst of neutrinos** 4 hours before the event

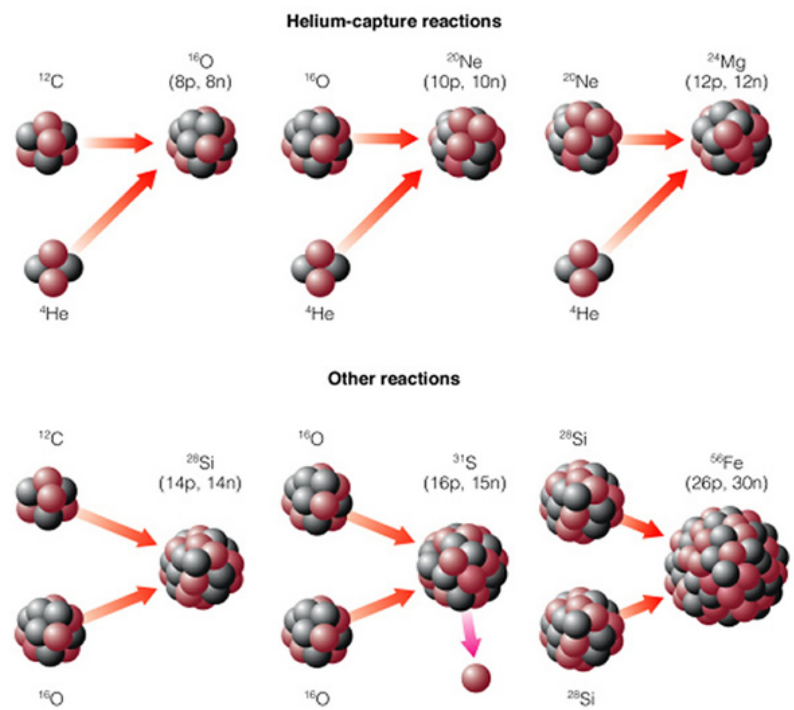
The progenitor had a mass of **20 $M_{\odot}$**.

Alpha ladder

Low mass stars produce elements up to Carbon and Oxygen

High mass stars produce all the rest of the periodic table

Up to Iron we have basically alpha reactions



Neutron capture

Beyond the Iron peak, nucleosynthesis occur by neutron capture and beta decay

$$(n \longrightarrow p + e^{-} + \nu)$$

The process is classified according to the neutron flux

S-process

(slow neutron capture)

Neutron capture occurs
slower
than beta decay

Works up to bismuth (Z=83)

Where?
AGB stars + Supernovae

R-process

(rapid neutron capture)

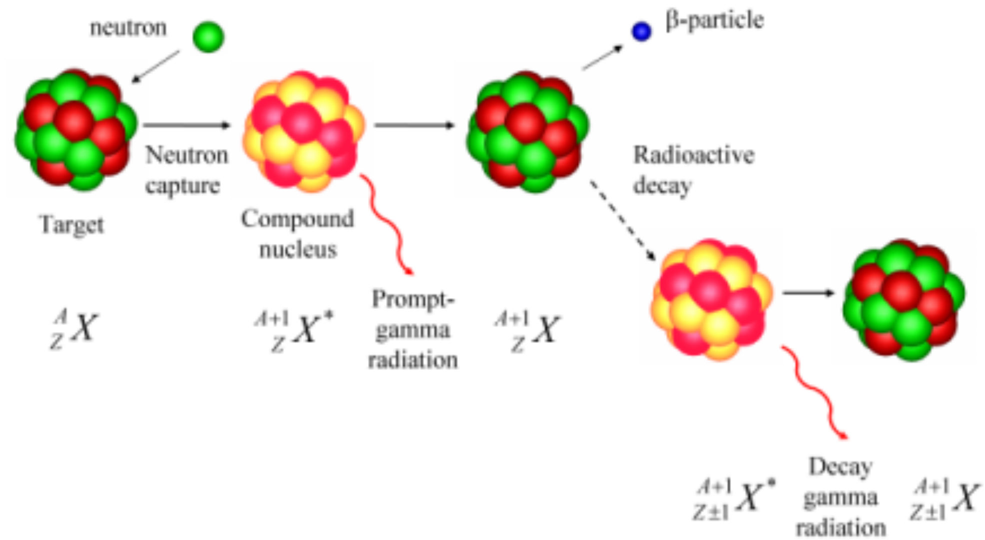
Neutron capture occurs
faster
than beta decay

Really heavy stuff
All the way to Uranium

Where?
Supernovae

Neutron capture

Beyond the Iron peak, nucleosynthesis occurs by ***neutron capture*** and ***beta decay***

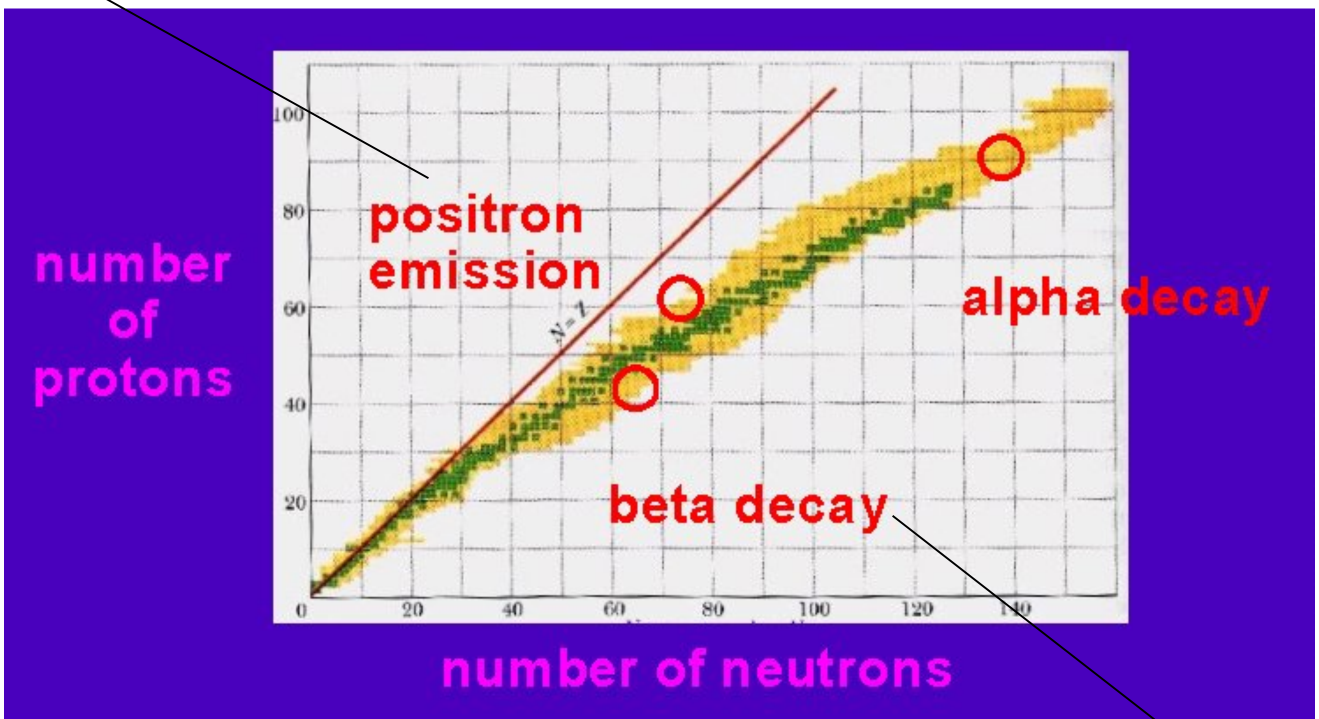


Neutron capture produces isotopes
Neutron capture proceeds until the nuclide goes unstable (radioactive)

If a proton decays, the atomic number decreases
But if a neutron decays, the atomic number increases!

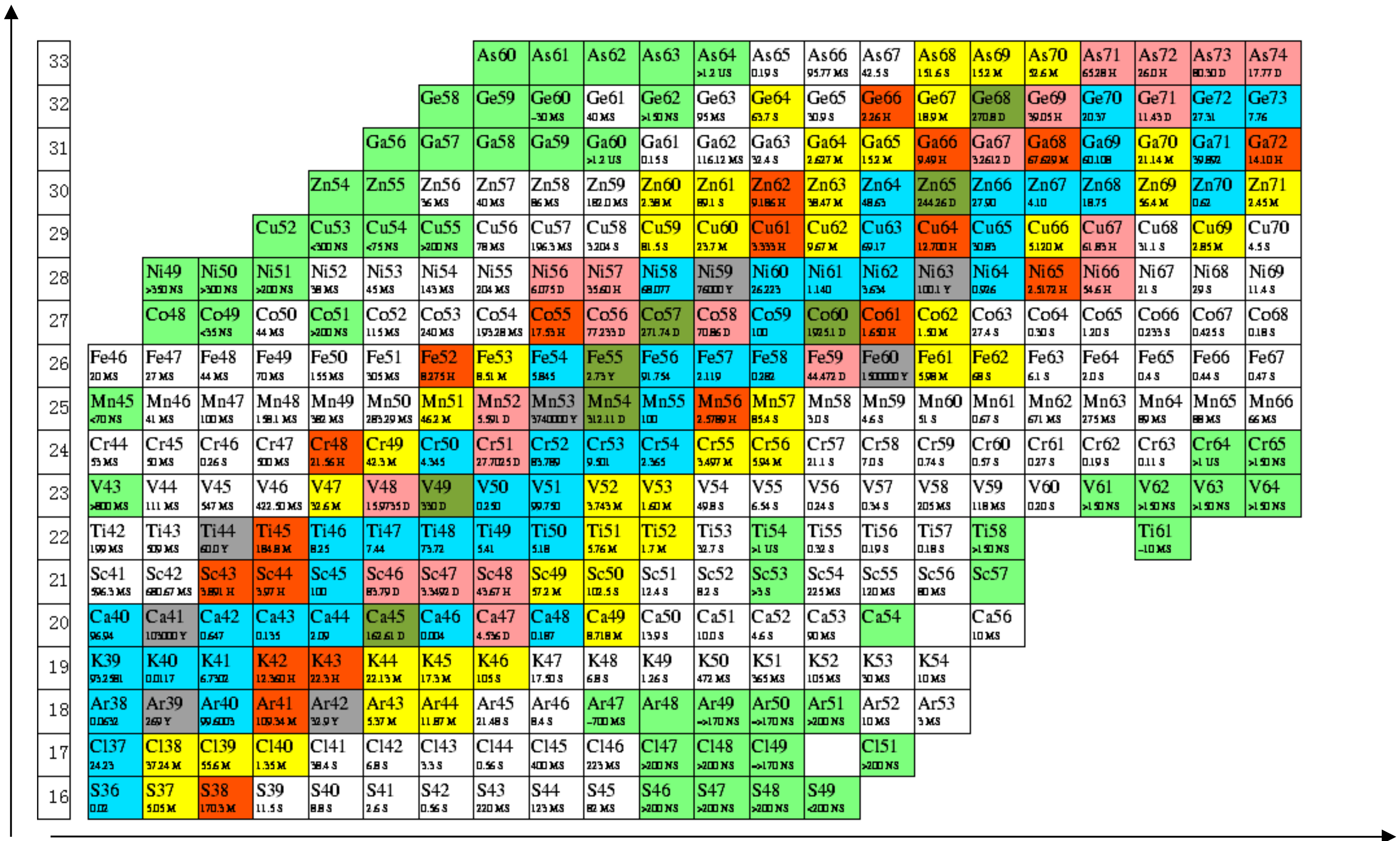
Climbing the periodic table

Proton decays



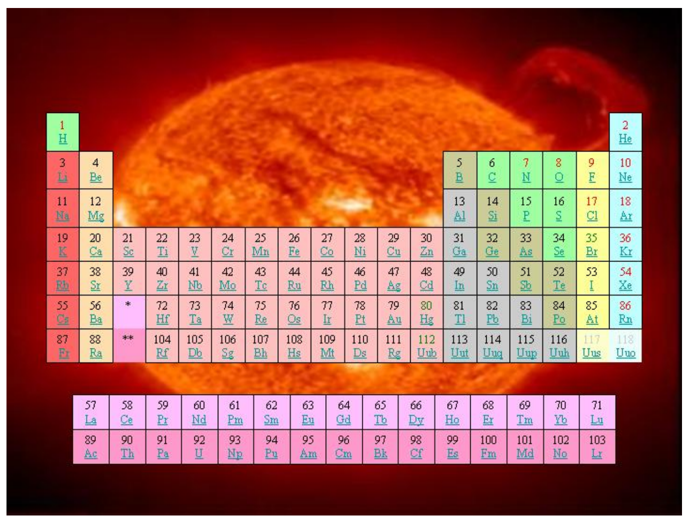
Neutron decays

Ta-dah!


33 As60 As61 As62 As63 As64 As65 As66 As67 As68 As69 As70 As71 As72 As73 As74
32 Ge58 Ge59 Ge60 Ge61 Ge62 Ge63 Ge64 Ge65 Ge66 Ge67 Ge68 Ge69 Ge70 Ge71 Ge72 Ge73
31 Ga56 Ga57 Ga58 Ga59 Ga60 Ga61 Ga62 Ga63 Ga64 Ga65 Ga66 Ga67 Ga68 Ga69 Ga70 Ga71 Ga72
30 Zn54 Zn55 Zn56 Zn57 Zn58 Zn59 Zn60 Zn61 Zn62 Zn63 Zn64 Zn65 Zn66 Zn67 Zn68 Zn69 Zn70 Zn71
29 Cu52 Cu53 Cu54 Cu55 Cu56 Cu57 Cu58 Cu59 Cu60 Cu61 Cu62 Cu63 Cu64 Cu65 Cu66 Cu67 Cu68 Cu69 Cu70
28 Ni49 Ni50 Ni51 Ni52 Ni53 Ni54 Ni55 Ni56 Ni57 Ni58 Ni59 Ni60 Ni61 Ni62 Ni63 Ni64 Ni65 Ni66 Ni67 Ni68 Ni69
27 Co48 Co49 Co50 Co51 Co52 Co53 Co54 Co55 Co56 Co57 Co58 Co59 Co60 Co61 Co62 Co63 Co64 Co65 Co66 Co67 Co68
26 Fe46 Fe47 Fe48 Fe49 Fe50 Fe51 Fe52 Fe53 Fe54 Fe55 Fe56 Fe57 Fe58 Fe59 Fe60 Fe61 Fe62 Fe63 Fe64 Fe65 Fe66 Fe67
25 Mn45 Mn46 Mn47 Mn48 Mn49 Mn50 Mn51 Mn52 Mn53 Mn54 Mn55 Mn56 Mn57 Mn58 Mn59 Mn60 Mn61 Mn62 Mn63 Mn64 Mn65 Mn66
24 Cr44 Cr45 Cr46 Cr47 Cr48 Cr49 Cr50 Cr51 Cr52 Cr53 Cr54 Cr55 Cr56 Cr57 Cr58 Cr59 Cr60 Cr61 Cr62 Cr63 Cr64 Cr65
23 V43 V44 V45 V46 V47 V48 V49 V50 V51 V52 V53 V54 V55 V56 V57 V58 V59 V60 V61 V62 V63 V64
22 Ti42 Ti43 Ti44 Ti45 Ti46 Ti47 Ti48 Ti49 Ti50 Ti51 Ti52 Ti53 Ti54 Ti55 Ti56 Ti57 Ti58 Ti61
21 Sc41 Sc42 Sc43 Sc44 Sc45 Sc46 Sc47 Sc48 Sc49 Sc50 Sc51 Sc52 Sc53 Sc54 Sc55 Sc56 Sc57
20 Ca40 Ca41 Ca42 Ca43 Ca44 Ca45 Ca46 Ca47 Ca48 Ca49 Ca50 Ca51 Ca52 Ca53 Ca54 Ca56
19 K39 K40 K41 K42 K43 K44 K45 K46 K47 K48 K49 K50 K51 K52 K53 K54
18 Ar38 Ar39 Ar40 Ar41 Ar42 Ar43 Ar44 Ar45 Ar46 Ar47 Ar48 Ar49 Ar50 Ar51 Ar52 Ar53
17 Cl37 Cl38 Cl39 Cl40 Cl41 Cl42 Cl43 Cl44 Cl45 Cl46 Cl47 Cl48 Cl49 Cl51
16 S36 S37 S38 S39 S40 S41 S42 S43 S44 S45 S46 S47 S48 S49

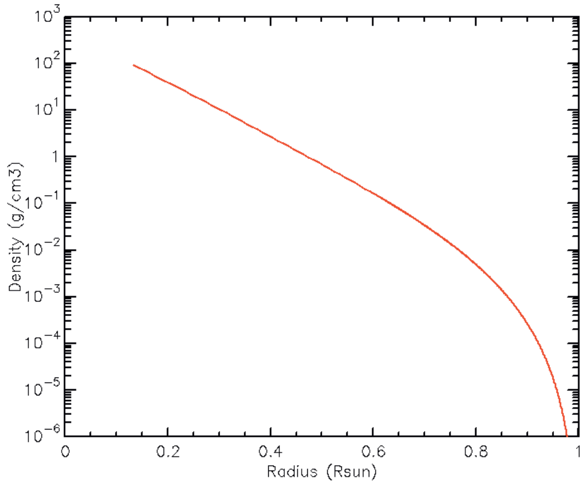
Nucleosynthesis summary

Element	# of Protons	Site
H	1	Big Bang
He, C, O	2,6,8	Big Bang + Low and High Mass stars
Ne - Fe	10-26	High mass stars
Co - Bi	27-83	S and R process, AGB and SN
Po - U	84-92	R process in SN

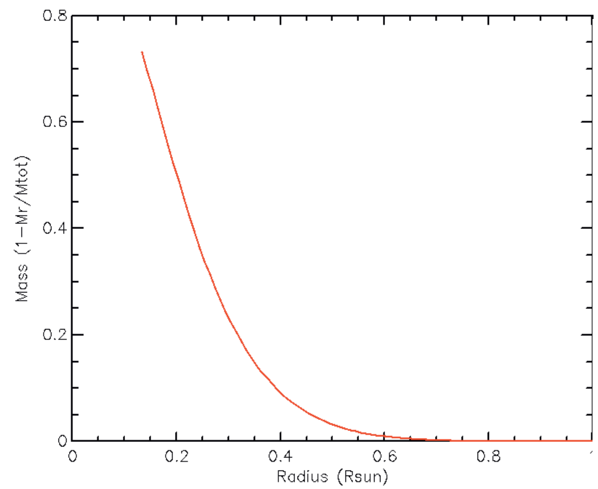


Solar Model (statstar)

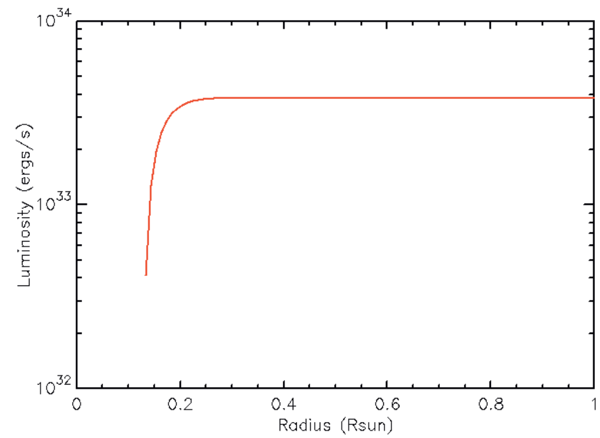
Density



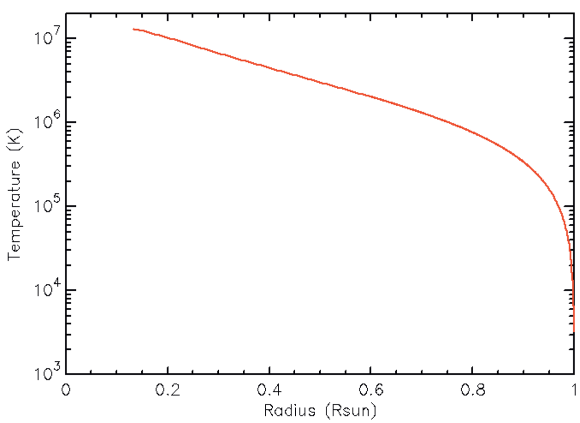
Mass



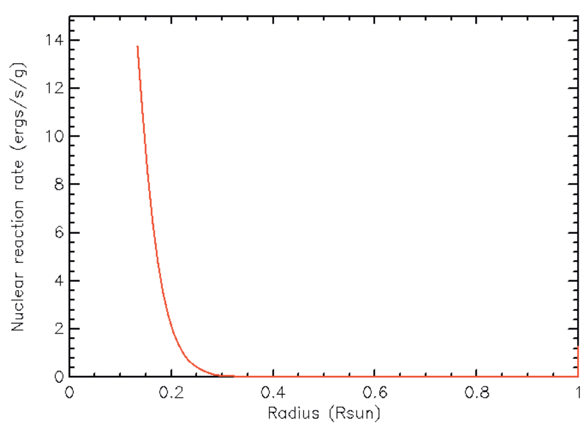
Luminosity



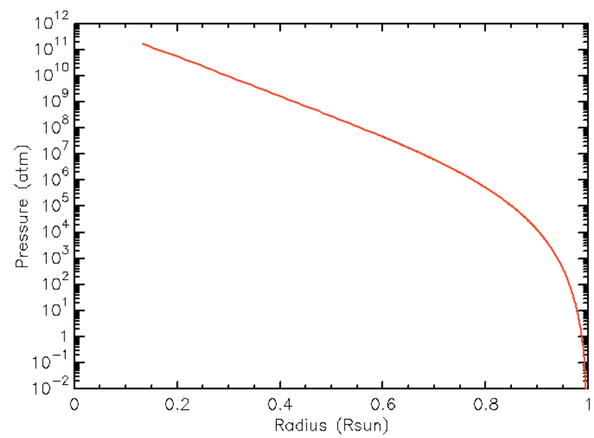
Temperature



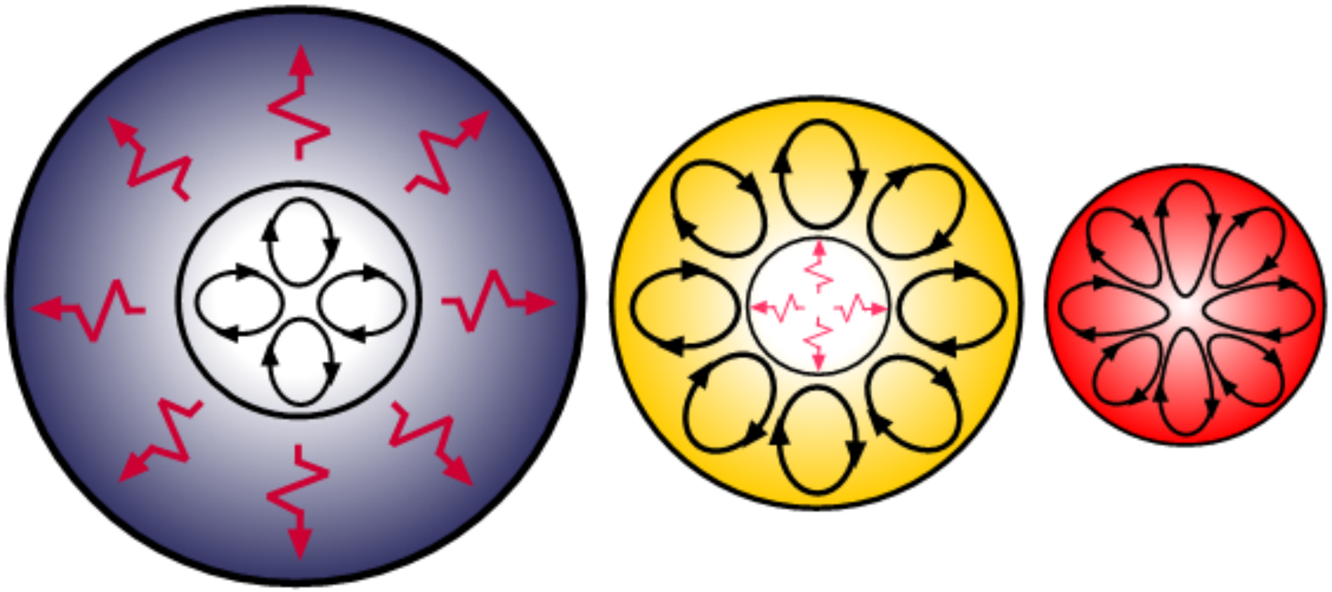
Nuclear Reaction Rate



Pressure



Stellar Structure



M > 1.5

Convective Core
Radiative Envelope

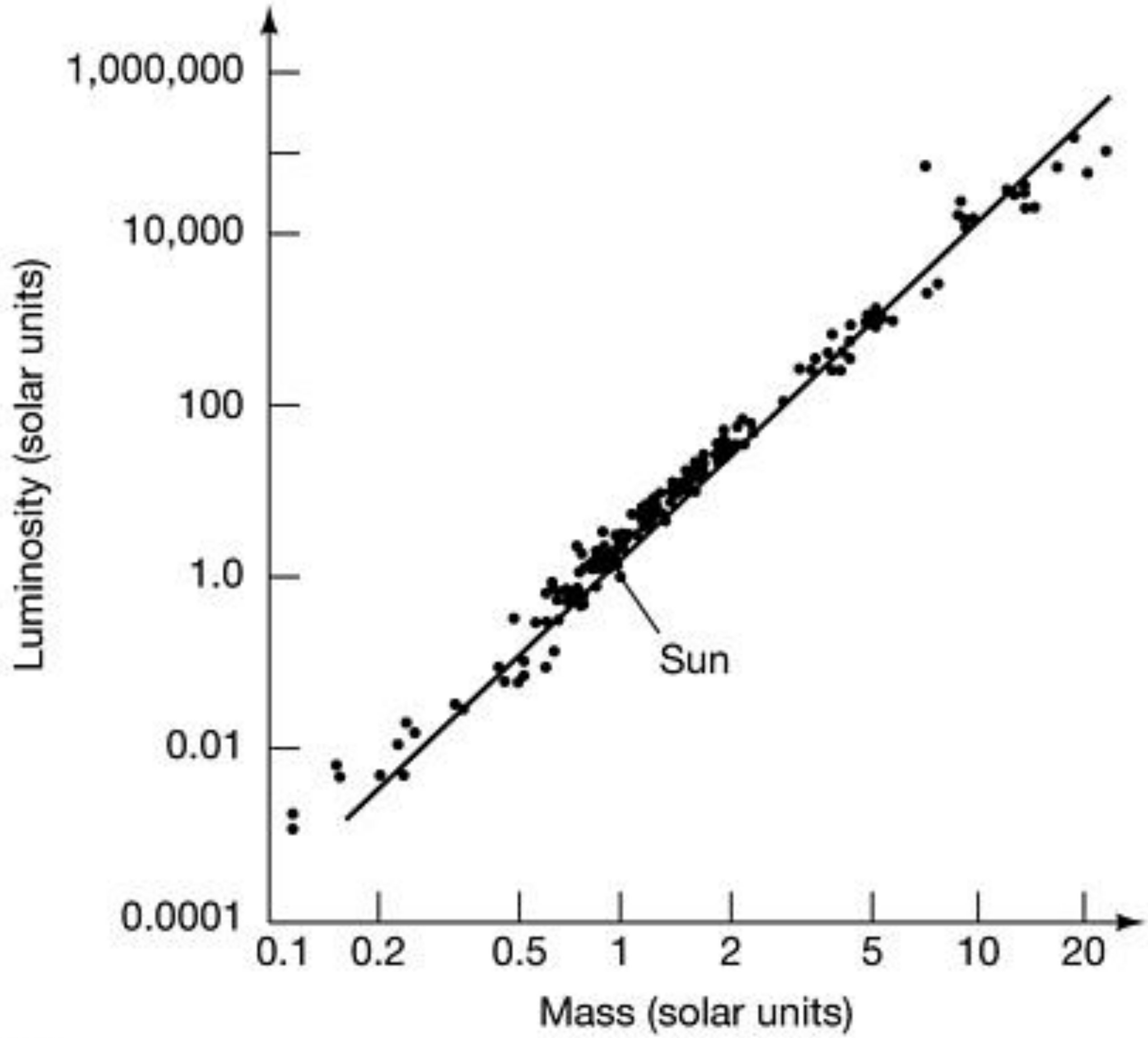
0.5 < *M* < 1.5

Radiative Core
Convective Envelope

M < 0.5

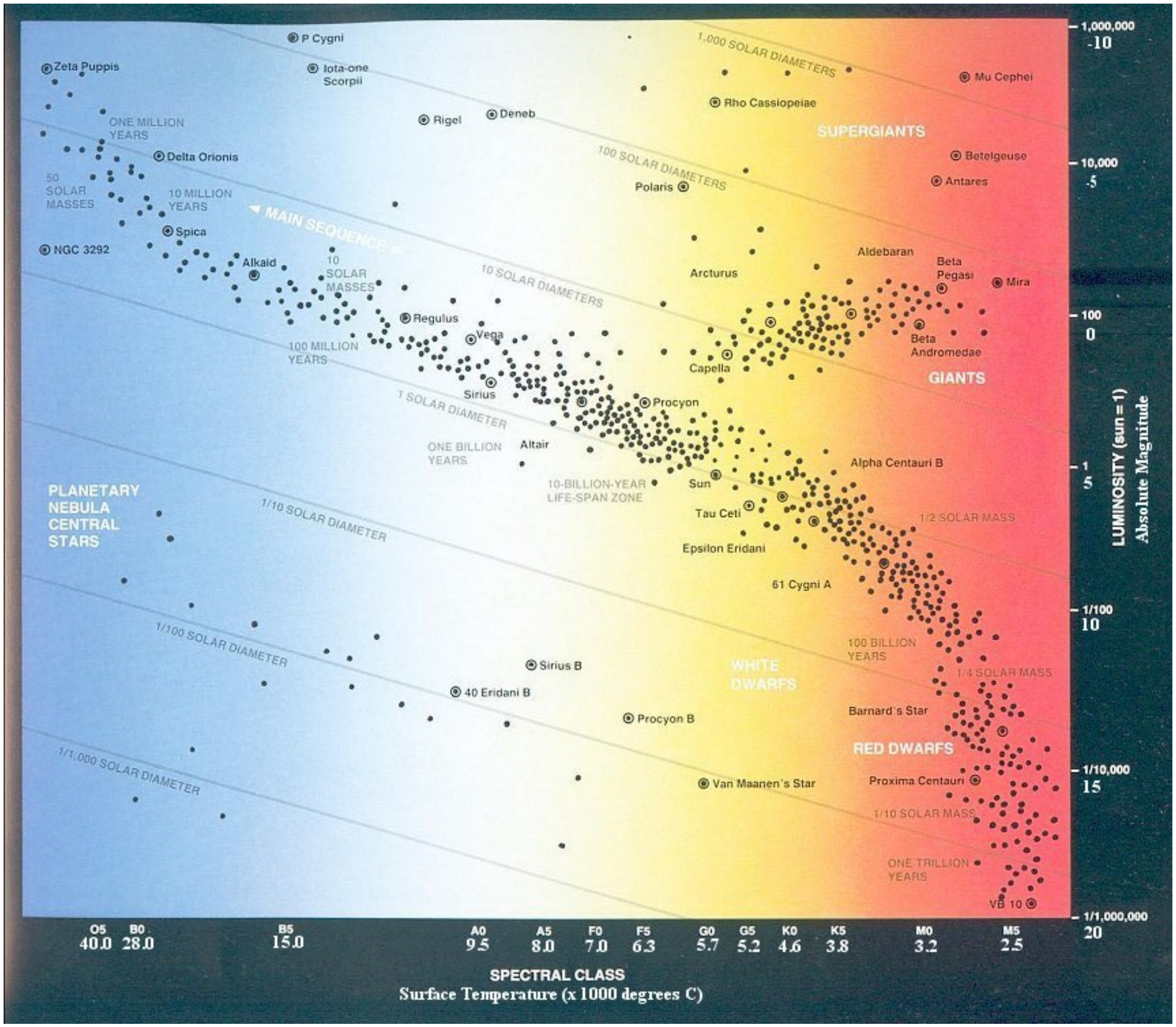
Fully Convective

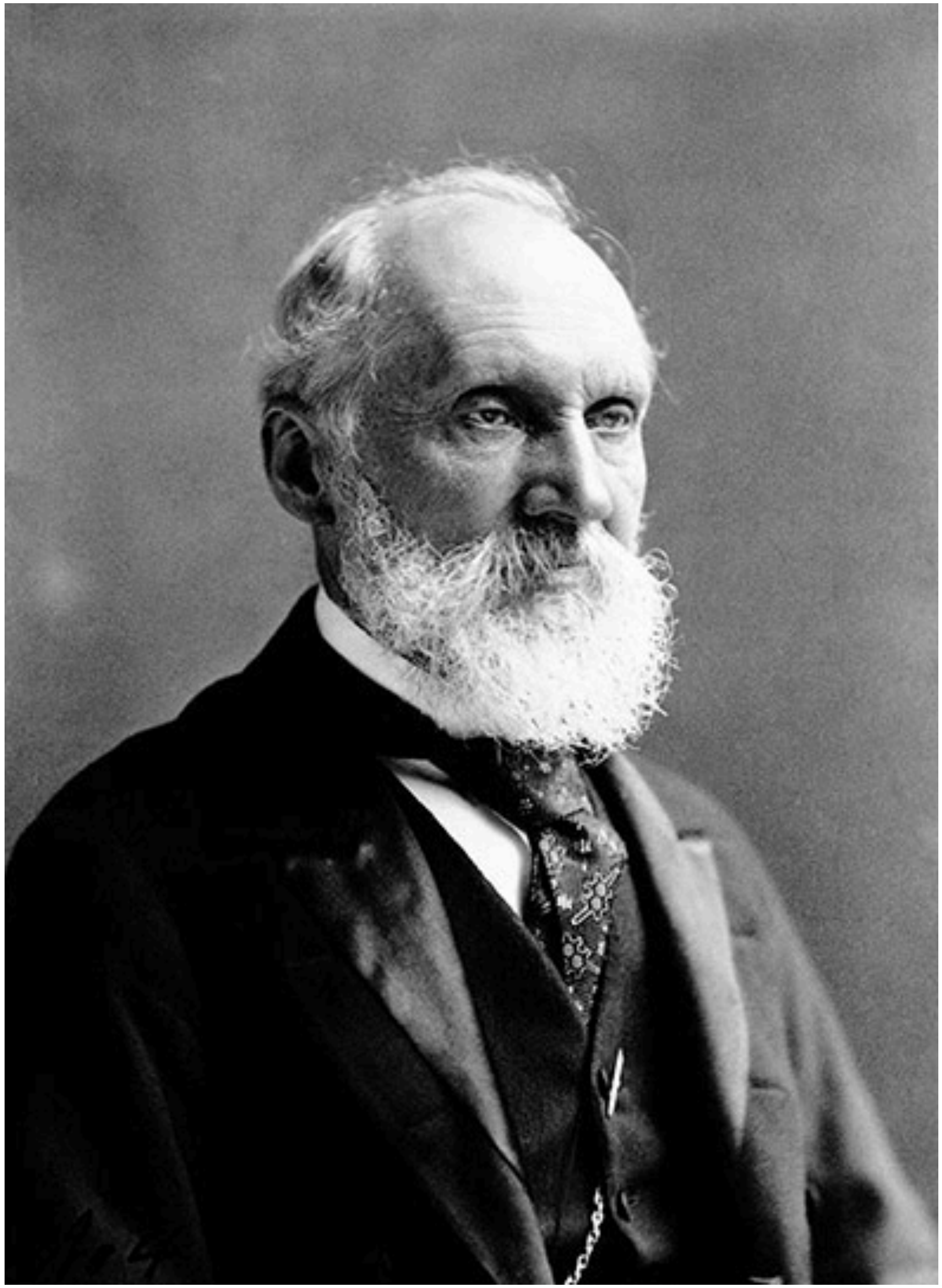
Mass-Luminosity relation



Main Sequence: Temperature-Luminosity relation

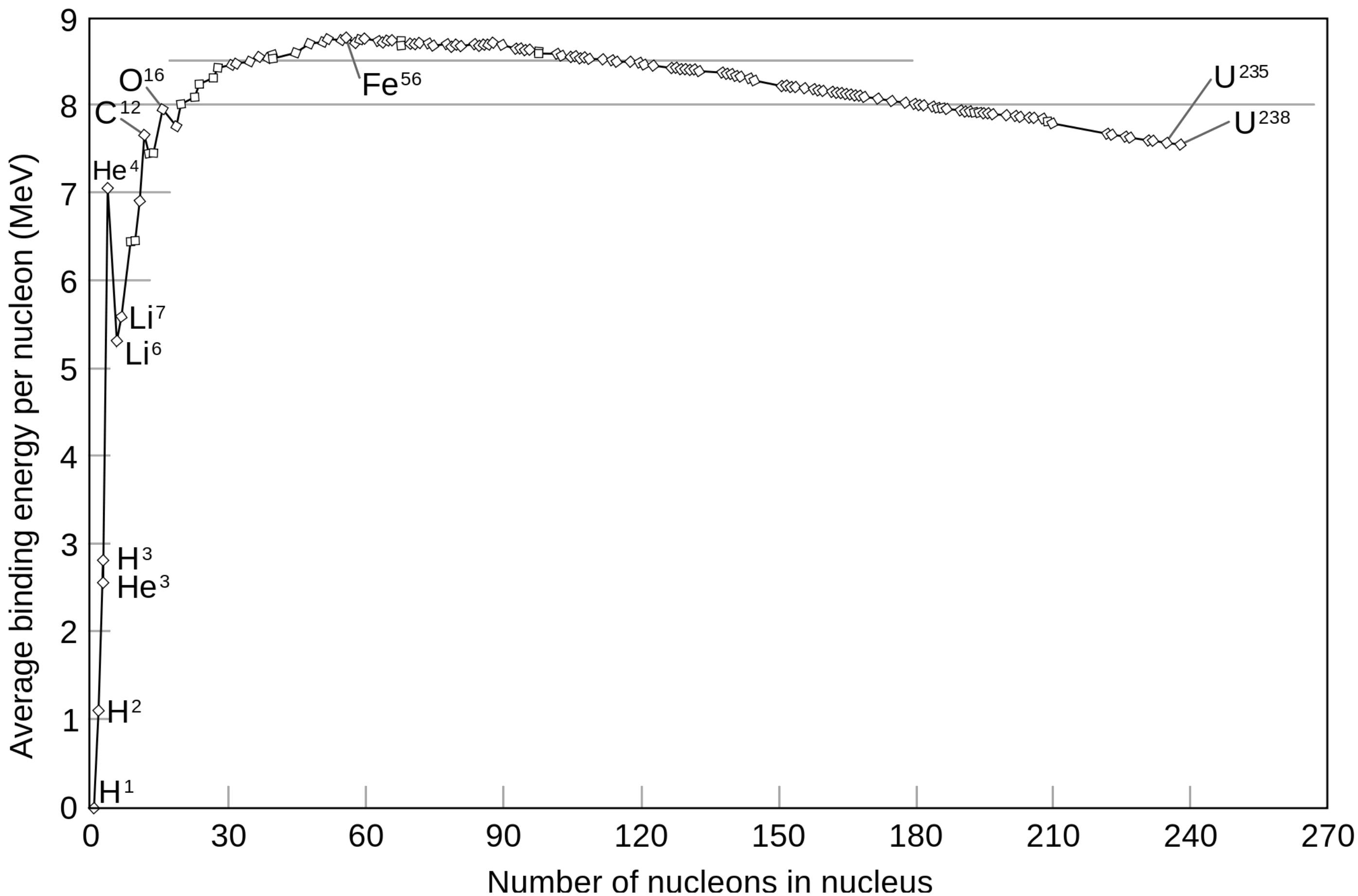
L propto T^6



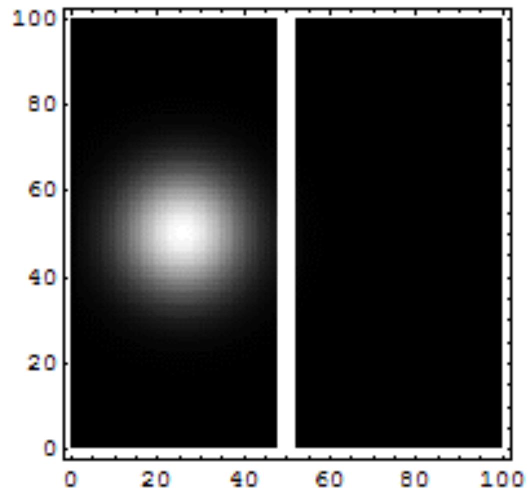


Nucleosynthesis

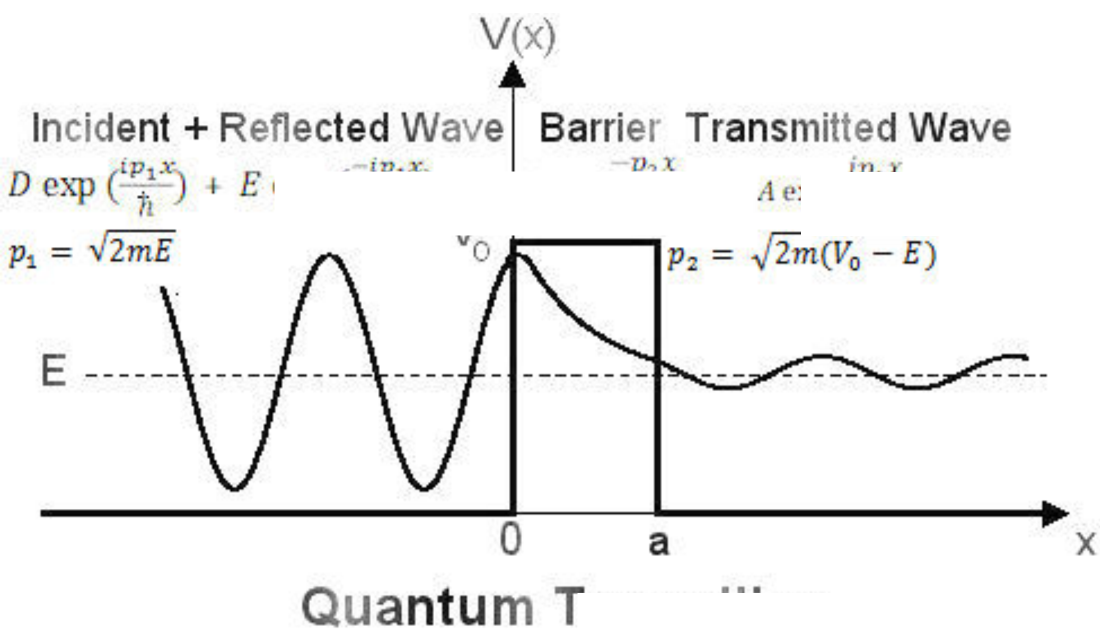
A nucleus is always found to be less massive than the combined mass of nucleons. The difference is the binding energy. The elements of the iron peak (Fe, Ni, Co) are the most tightly bound nuclei.



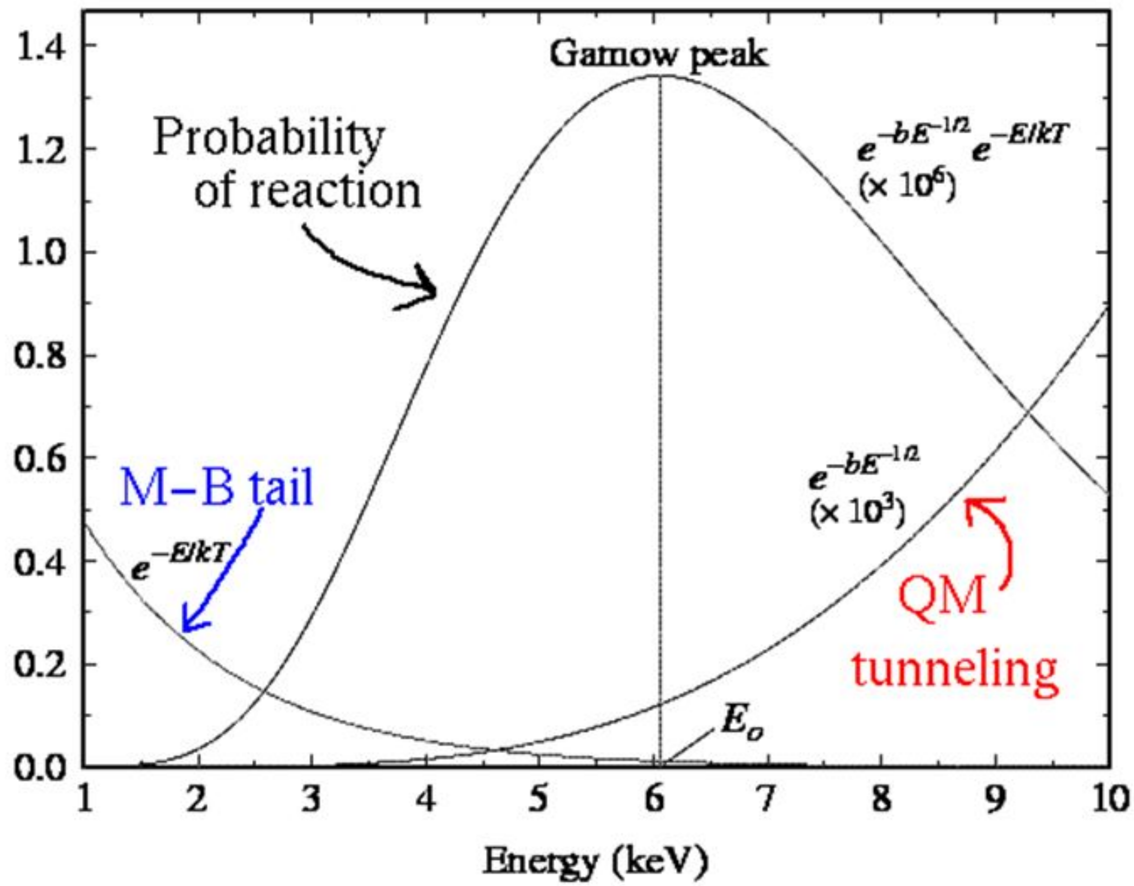
Quantum Tunneling



The temperature in the solar core is still too low to allow fusion considering only the thermal motion of the particles. Tunneling has to be taken into account.

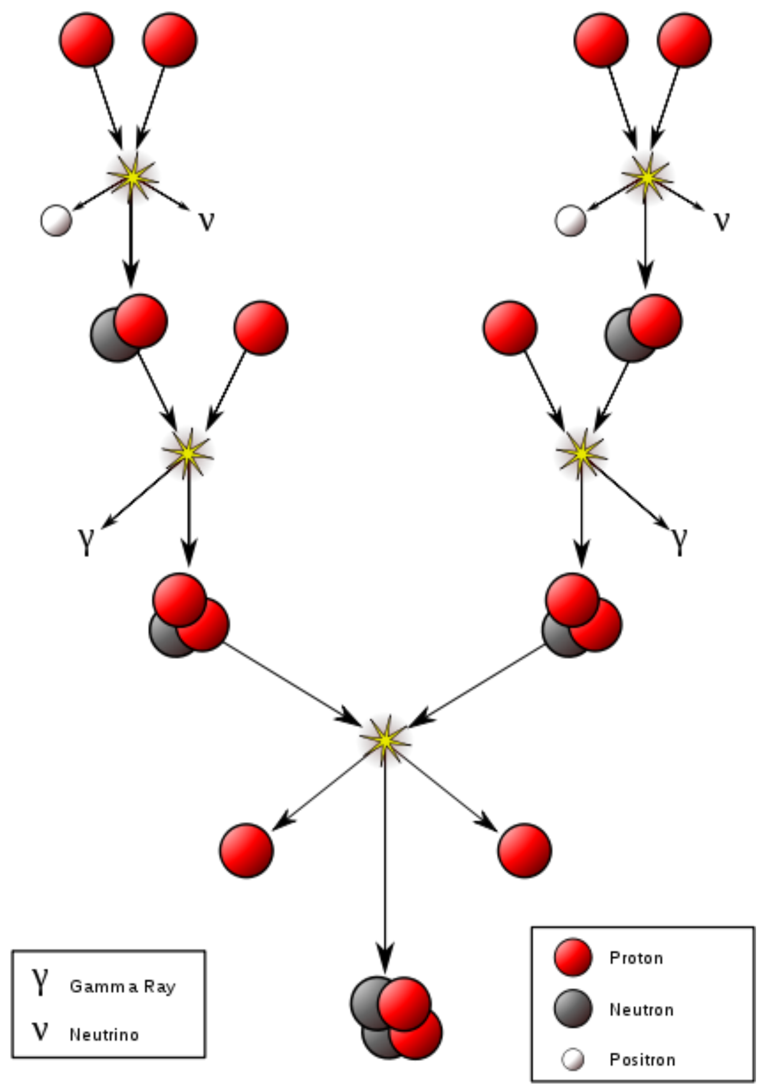


Gamow-Peak



Combining thermal (Maxwell-Boltzmann) with quantum tunnelling.

Proton-proton chain



CNO cycle

$$C_6^{12} + H_1^1 \rightarrow N_7^{13} + \gamma_0^0$$

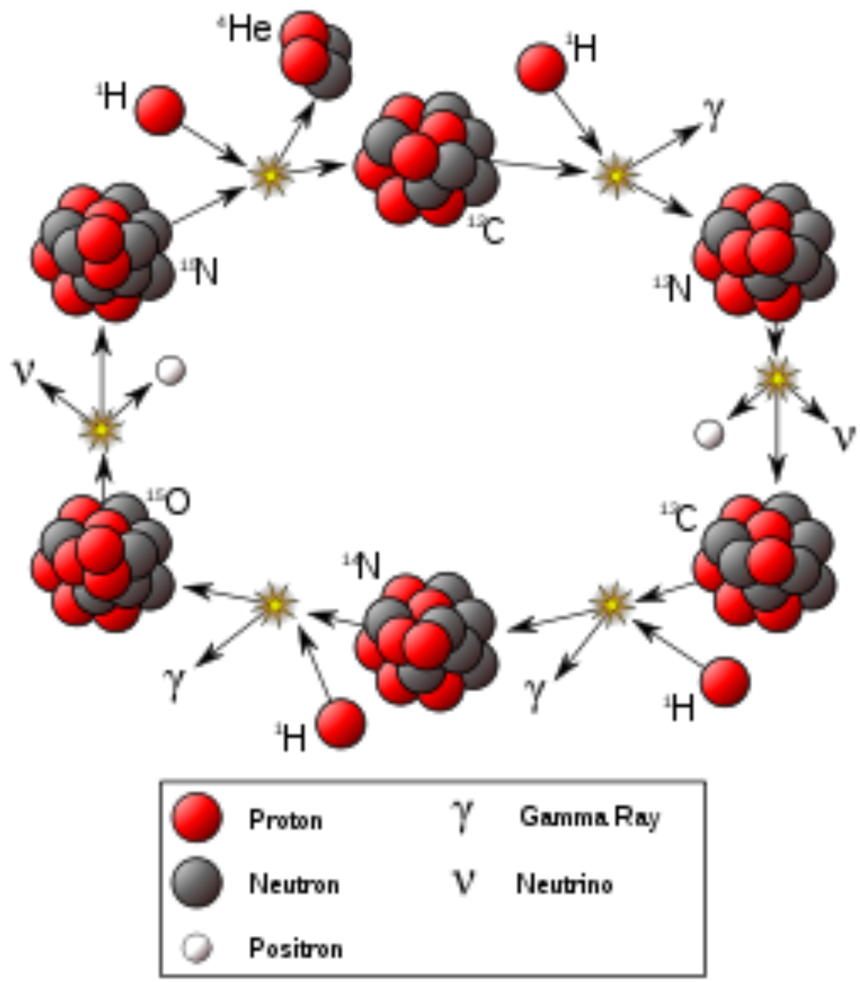
$$N_7^{13} \rightarrow C_6^{13} + \overline{e}_1^0 + \nu_0^0$$

$$C_6^{13} + H_1^1 \rightarrow N_7^{14} + \gamma_0^0$$

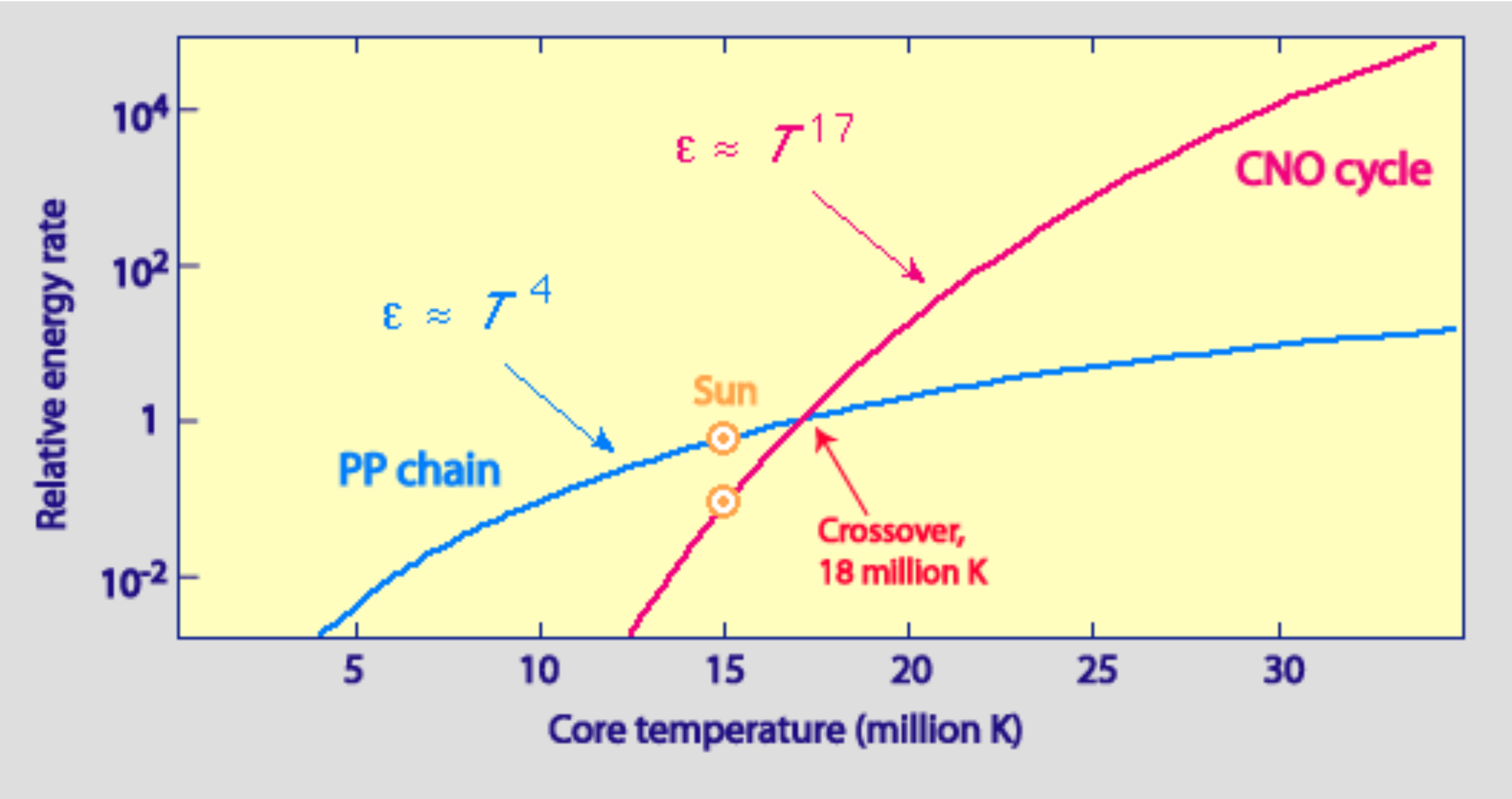
$$N_7^{14} + H_1^1 \rightarrow O_8^{15} + \gamma_0^0$$

$$O_8^{15} \rightarrow N_7^{15} + \overline{e}_1^0 + \nu_0^0$$

$$N_7^{15} + H_1^1 \rightarrow C_6^{12} + He_2^4$$



End of cycle:
4 H burned into He
C used as catalyst



Proton-proton dominates up to 15 x 10^7 K
CNO takes over after that.

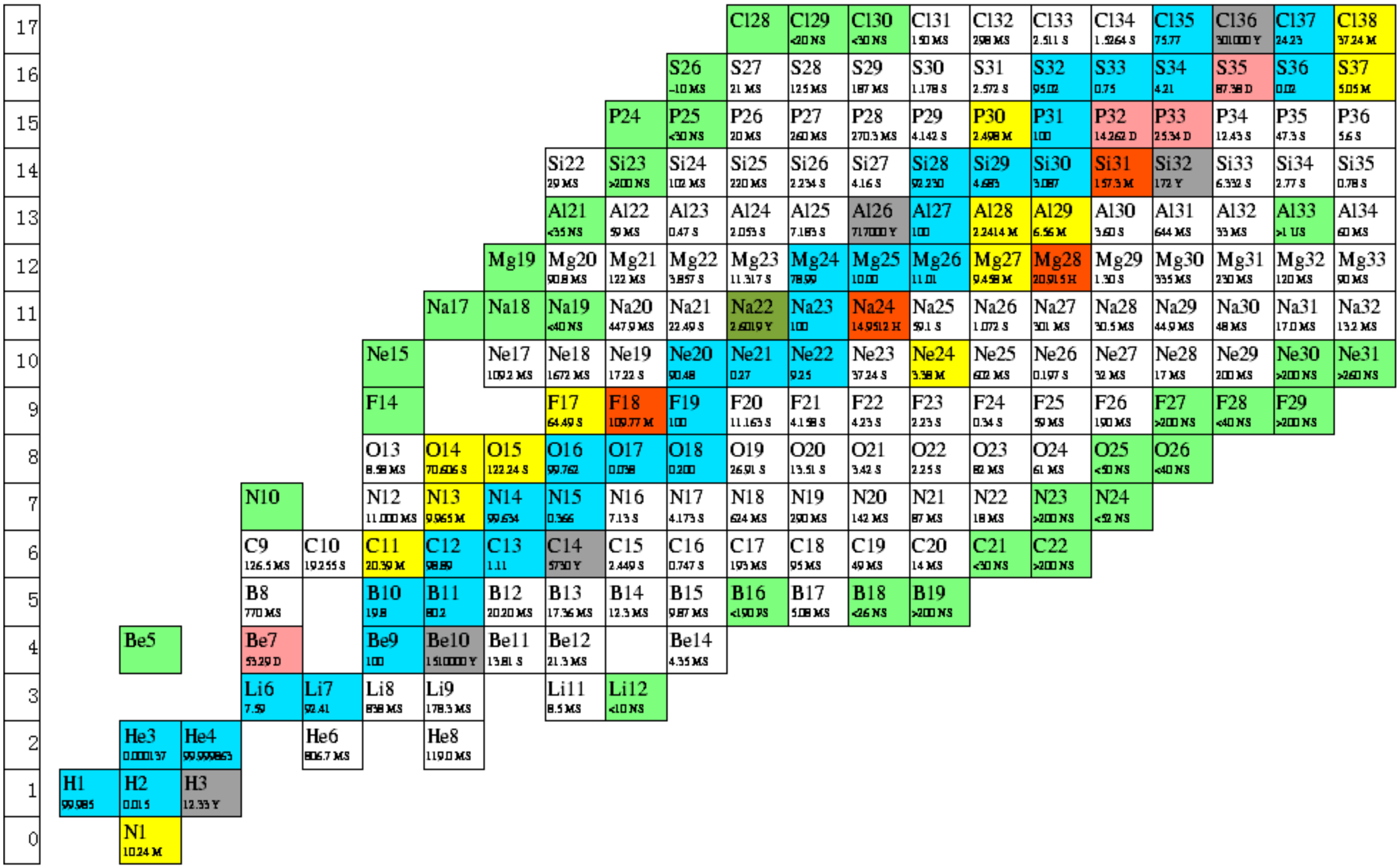
17												Cl28	Cl29 <20 NS	Cl30 <30 NS	Cl31 150 MS	Cl32 298 MS	Cl33 2.511 S	Cl34 1.5264 S	Cl35 75.77	Cl36 301000 Y	Cl37 24.23	Cl38 37.24 M
16											S26 ~10 MS	S27 21 MS	S28 125 MS	S29 187 MS	S30 1.178 S	S31 2.572 S	S32 95.02	S33 0.75	S34 4.21	S35 87.38 D	S36 0.02	S37 5.05 M
15										P24	P25 <30 NS	P26 20 MS	P27 260 MS	P28 270.3 MS	P29 4.142 S	P30 2.498 M	P31 100	P32 14.262 D	P33 25.34 D	P34 12.43 S	P35 47.3 S	P36 5.6 S
14									Si22 29 MS	Si23 >200 NS	Si24 102 MS	Si25 220 MS	Si26 2.234 S	Si27 4.16 S	Si28 92.230	Si29 4.683	Si30 3.087	Si31 157.3 M	Si32 172 Y	Si33 6.332 S	Si34 2.77 S	Si35 0.78 S
13									Al21 <35 NS	Al22 59 MS	Al23 0.47 S	Al24 2.053 S	Al25 7.183 S	Al26 717000 Y	Al27 100	Al28 2.2414 M	Al29 6.56 M	Al30 3.60 S	Al31 644 MS	Al32 33 MS	Al33 >1 US	Al34 60 MS
12								Mg19	Mg20 90.8 MS	Mg21 122 MS	Mg22 3.857 S	Mg23 11.317 S	Mg24 78.99	Mg25 10.00	Mg26 11.01	Mg27 9.458 M	Mg28 20.915 H	Mg29 1.30 S	Mg30 335 MS	Mg31 230 MS	Mg32 120 MS	Mg33 90 MS
11							Na17	Na18	Na19 <40 NS	Na20 447.9 MS	Na21 22.49 S	Na22 2.6019 Y	Na23 100	Na24 14.9512 H	Na25 59.1 S	Na26 1.072 S	Na27 301 MS	Na28 30.5 MS	Na29 44.9 MS	Na30 48 MS	Na31 17.0 MS	Na32 13.2 MS
10						Ne15		Ne17 109.2 MS	Ne18 1672 MS	Ne19 17.22 S	Ne20 90.48	Ne21 0.27	Ne22 9.25	Ne23 37.24 S	Ne24 3.38 M	Ne25 602 MS	Ne26 0.197 S	Ne27 32 MS	Ne28 17 MS	Ne29 200 MS	Ne30 >200 NS	Ne31 >260 NS
9						F14			F17 64.49 S	F18 109.77 M	F19 100	F20 11.163 S	F21 4.158 S	F22 4.23 S	F23 2.23 S	F24 0.34 S	F25 59 MS	F26 190 MS	F27 >200 NS	F28 <40 NS	F29 >200 NS	
8						O13 8.58 MS	O14 70.606 S	O15 122.24 S	O16 99.762	O17 0.038	O18 0.200	O19 26.91 S	O20 13.51 S	O21 3.42 S	O22 2.25 S	O23 82 MS	O24 61 MS	O25 <50 NS	O26 <40 NS			
7				N10		N12 11.000 MS	N13 9.965 M	N14 99.634	N15 0.366	N16 7.13 S	N17 4.173 S	N18 624 MS	N19 290 MS	N20 142 MS	N21 87 MS	N22 18 MS	N23 >200 NS	N24 <52 NS				
6				C9 126.5 MS	C10 19.255 S	C11 20.39 M	C12 98.89	C13 1.11	C14 5730 Y	C15 2.449 S	C16 0.747 S	C17 193 MS	C18 95 MS	C19 49 MS	C20 14 MS	C21 <30 NS	C22 >200 NS					
5				B8 770 MS		B10 19.8	B11 80.2	B12 20.20 MS	B13 17.36 MS	B14 12.3 MS	B15 9.87 MS	B16 <190 PS	B17 5.08 MS	B18 <26 NS	B19 >200 NS							
4		Be5		Be7 53.29 D		Be9 100	Be10 1510000 Y	Be11 13.81 S	Be12 21.3 MS		Be14 4.35 MS											
3				Li6 7.59	Li7 92.41	Li8 838 MS	Li9 178.3 MS		Li11 8.5 MS	Li12 <10 NS												
2		He3 0.000137	He4 99.999863		He6 806.7 MS		He8 119.0 MS															
1	H1 99.985	H2 0.015	H3 12.33 Y																			
0		N1 10.24 M																				

Beyond Helium

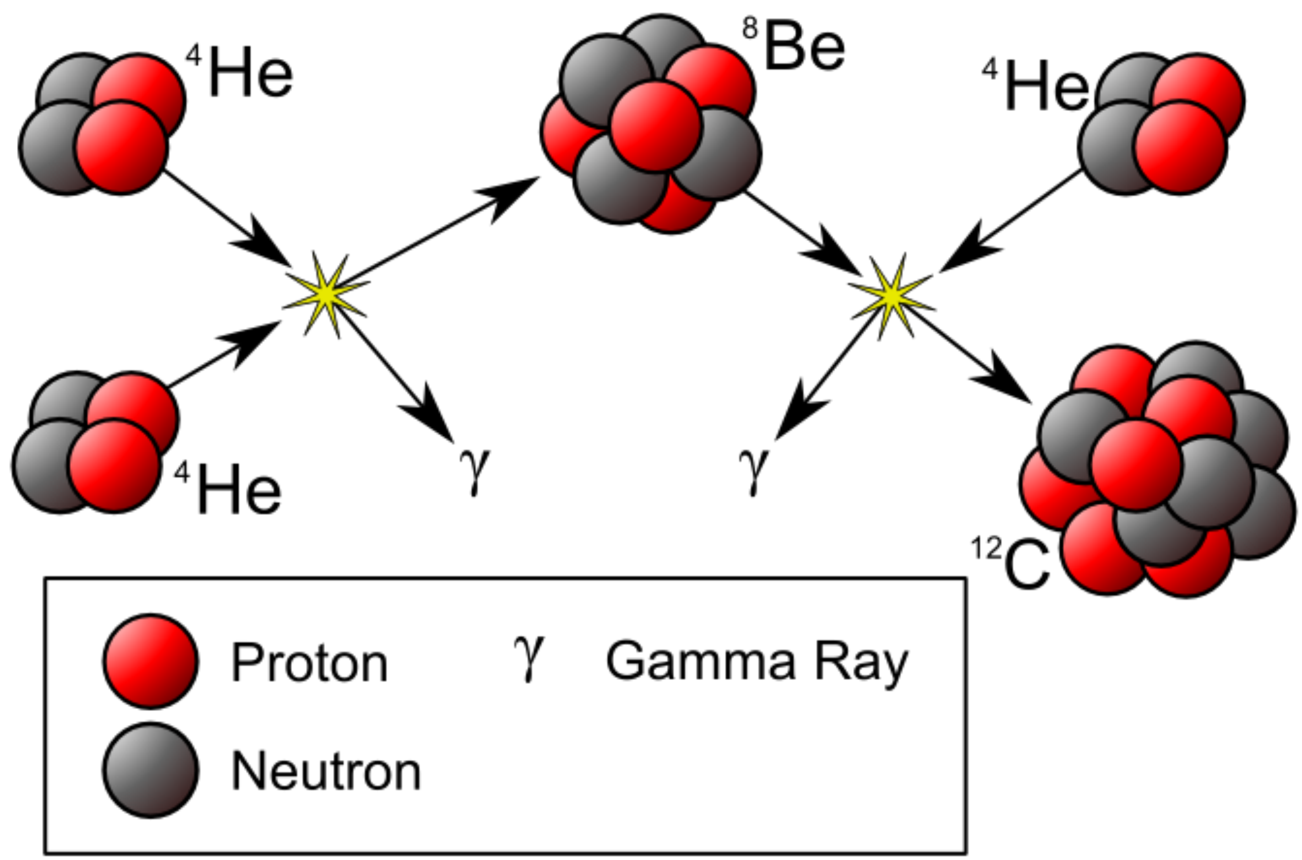
$^{1}H + ^{4}He = ^{5}X$

$^{4}He + ^{4}He = ^{8}X$

But there is no stable nuclide of mass 5 or 8….



Triple alpha



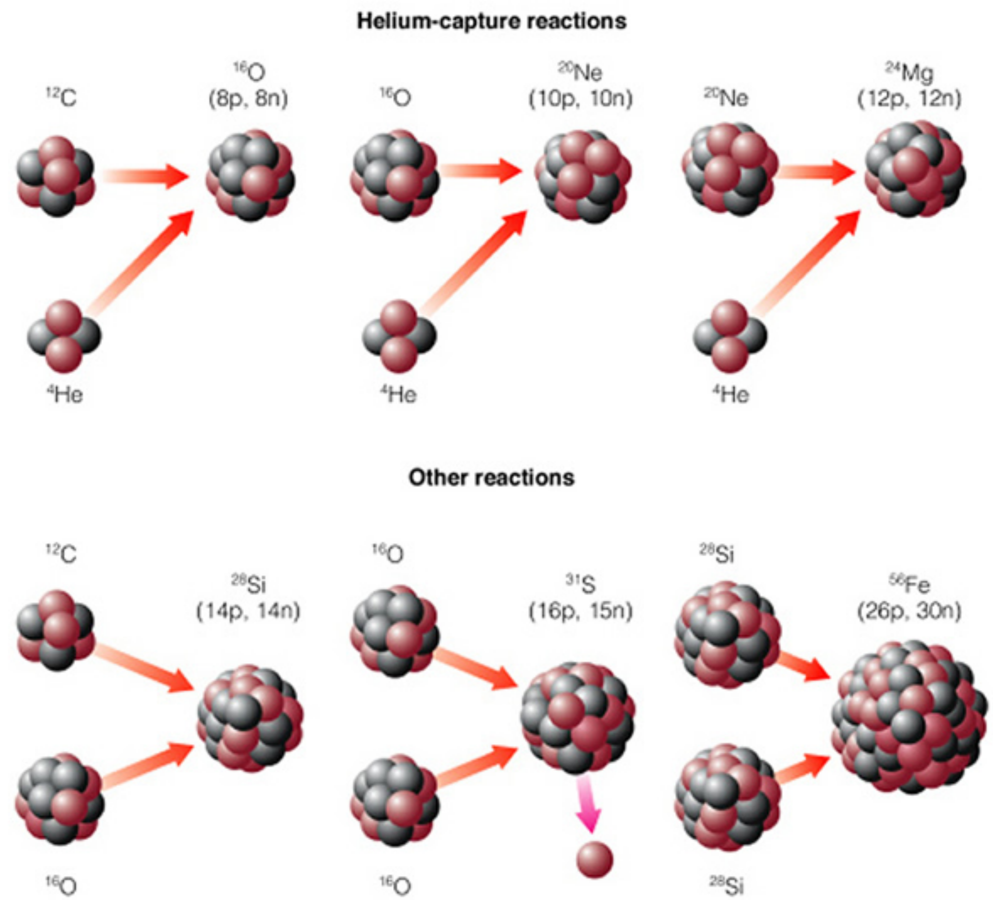
Alpha Ladder

Carbon → O,Ne,Mg (600 million K)

Neon → O, Mg (1.5 Billion K)

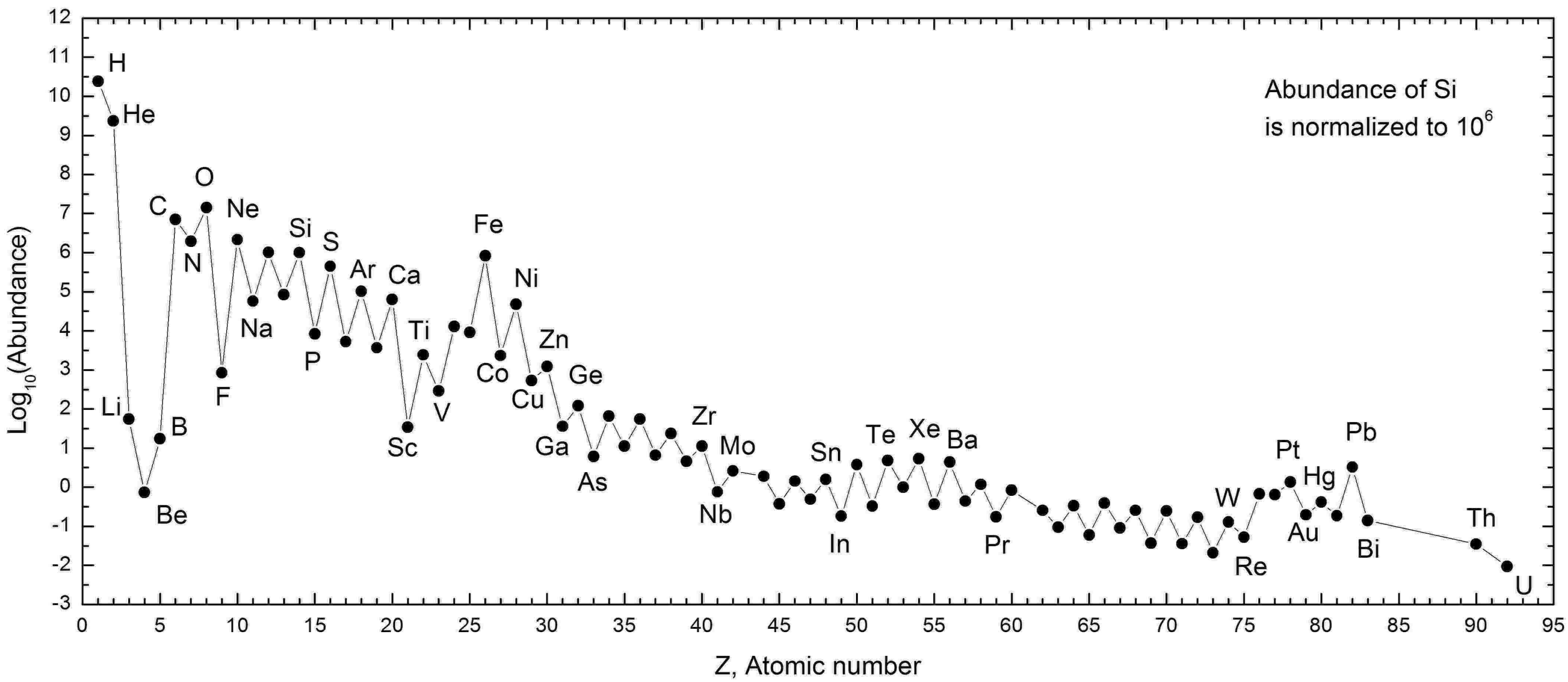
Oxygen → Si, S, P (2.1 Billion K)

Silicon → Fe, Ni (3.5 Billion K)

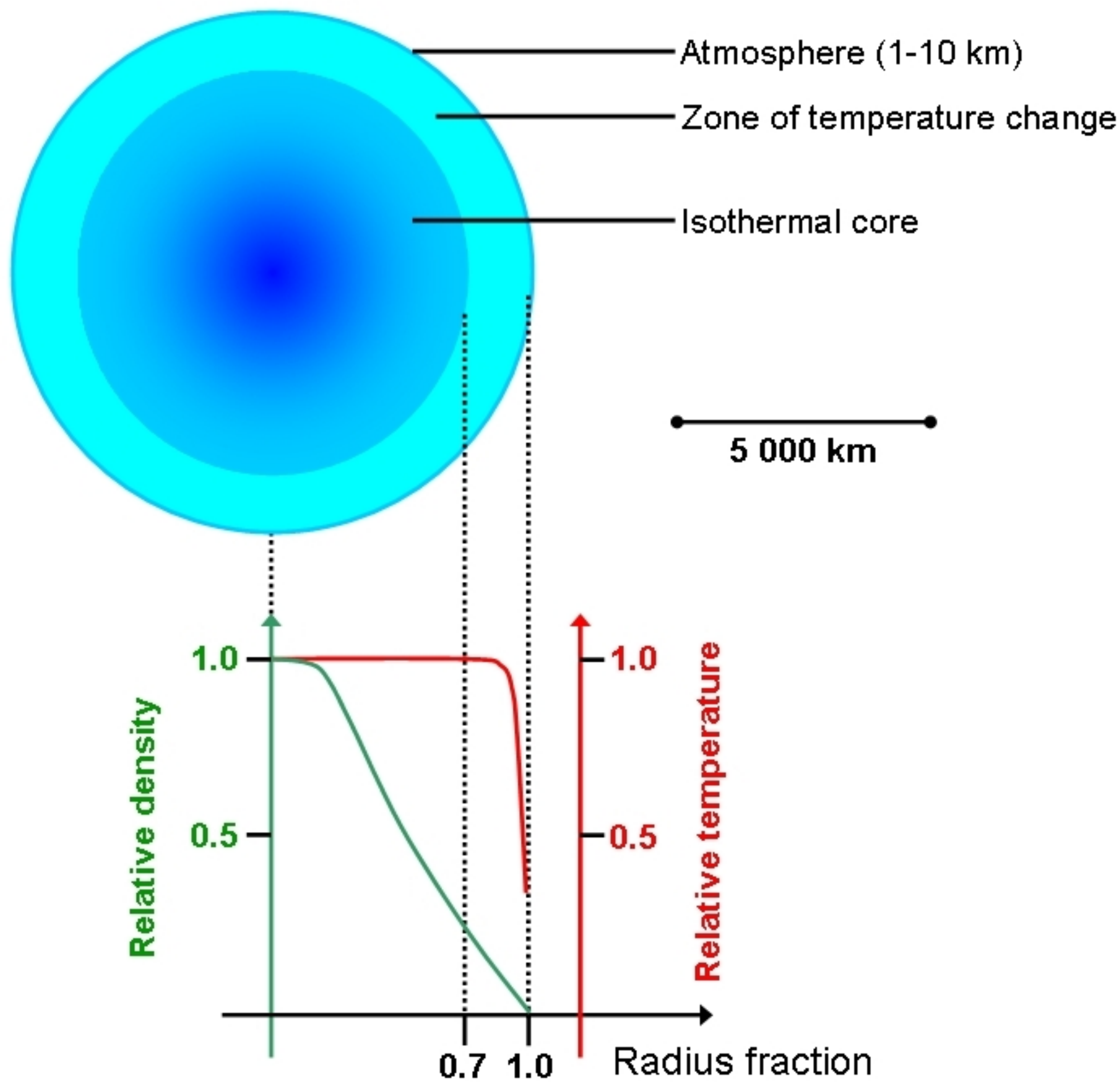


The Sun's abundance pattern

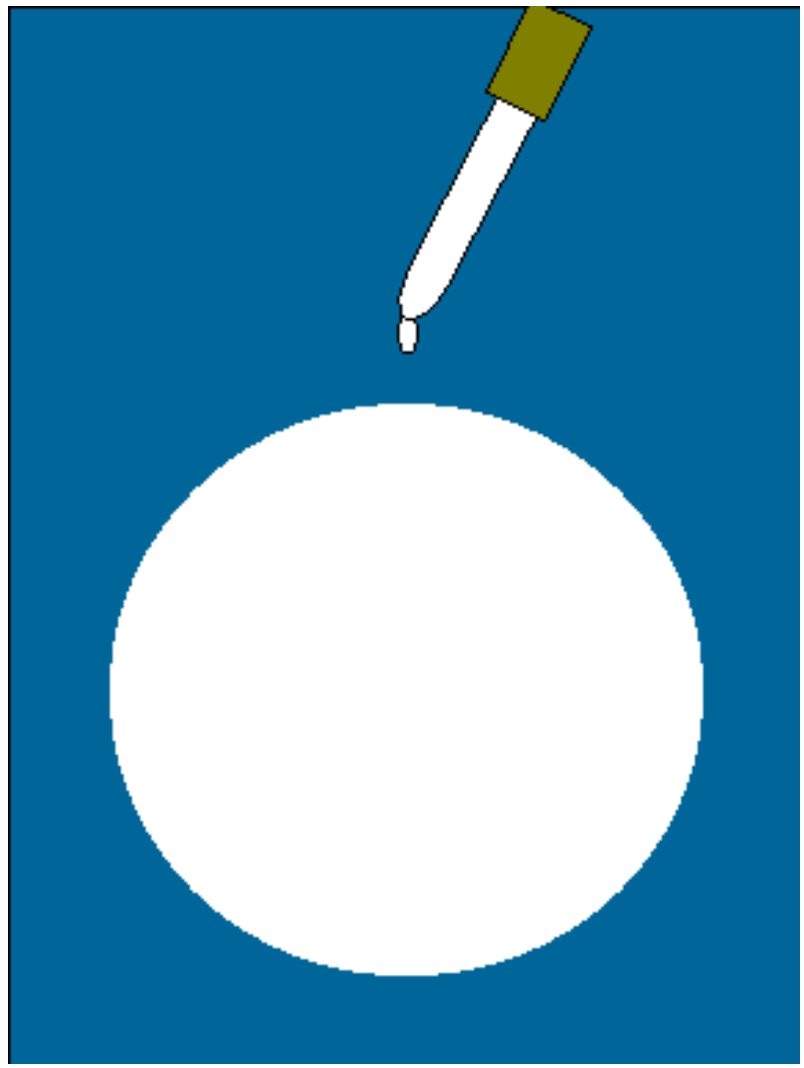
Elements with even atomic number are more abundant than those with odd



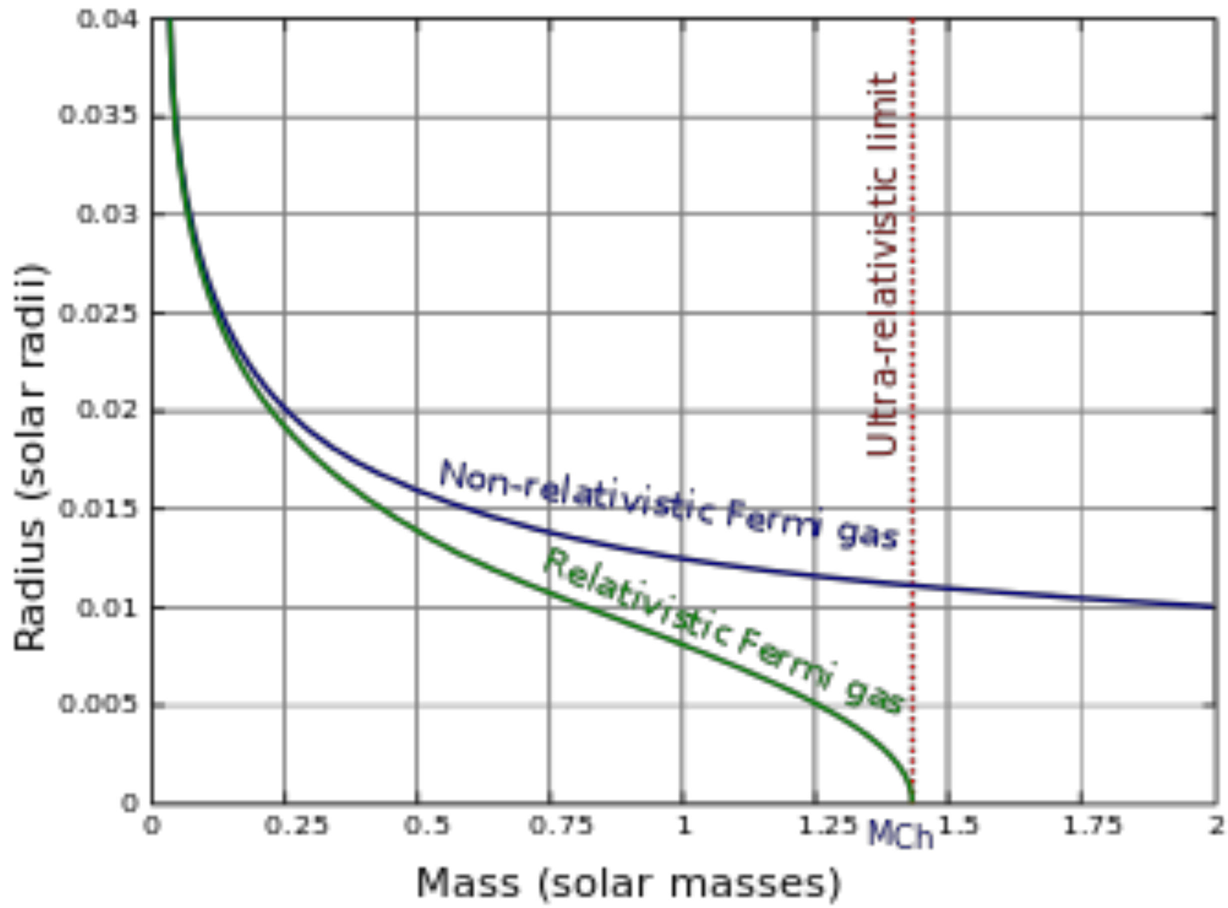
White Dwarf Structure



White dwarf Mass-Radius relationship



White dwarf Mass-Radius relationship

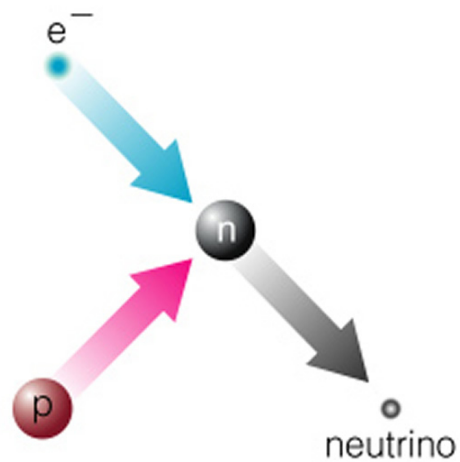


Collapse

Iron core contracts

At densities of 10^{10} g/cm^3
(remember: nuclear densities are ~10^{14} g/cm^3)

Neutronization



Proton + electron $\longrightarrow$ neutron + neutrino

$$(p + e^- \longrightarrow n + n)$$

Urca process

Free neutrons are unstable!

Neutron $\longrightarrow$ Proton + electron + neutrino

$$(n \longrightarrow p + e^{-} + n)$$

Proton + electron $\longrightarrow$ neutron + neutrino

$$(p + e^{-} \longrightarrow n + n)$$

Urca process

Free neutrons are unstable!

Beta decay

Neutron ⟶ Proton + electron + neutrino

$$(n \longrightarrow p + e^{-} + \nu)$$

Inverse Beta Decay

Proton + electron ⟶ neutron + neutrino

$$(p + e^{-} \longrightarrow n + \nu)$$

Urca process

Free neutrons are unstable!

Beta decay

Neutron $\longrightarrow$ Proton + electron + neutrino

$$(n \longrightarrow p + e^{-} + n)$$

Inverse Beta Decay

Proton + electron $\longrightarrow$ neutron + neutrino

$$(p + e^{-} \longrightarrow n + n)$$

Urca process

Free neutrons are unstable!

Beta decay

Neutron ⟶ Proton + electron + ***neutrino***

$(n \longrightarrow p + e^{-} + n)$

Inverse Beta Decay

Proton + electron ⟶ neutron + ***neutrino***

$(p + e^{-} \longrightarrow n + n)$

A flood of neutrinos!!

Urca process

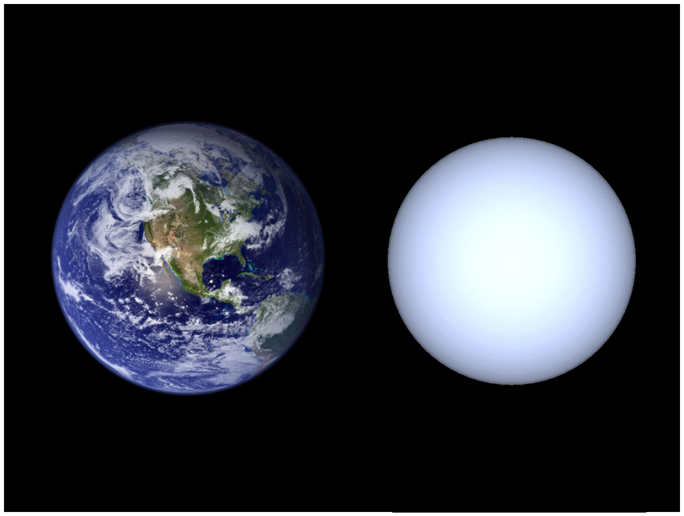
Mario Schenberg

George Gamow

Urca Casino

"The energy disappears from the core of the star as quickly as the money disappeared at that roulette table"

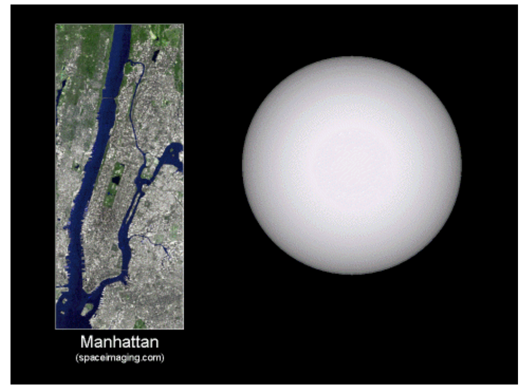
Catastrophic collapse



A second later

→

Collapse speed: 0.25c



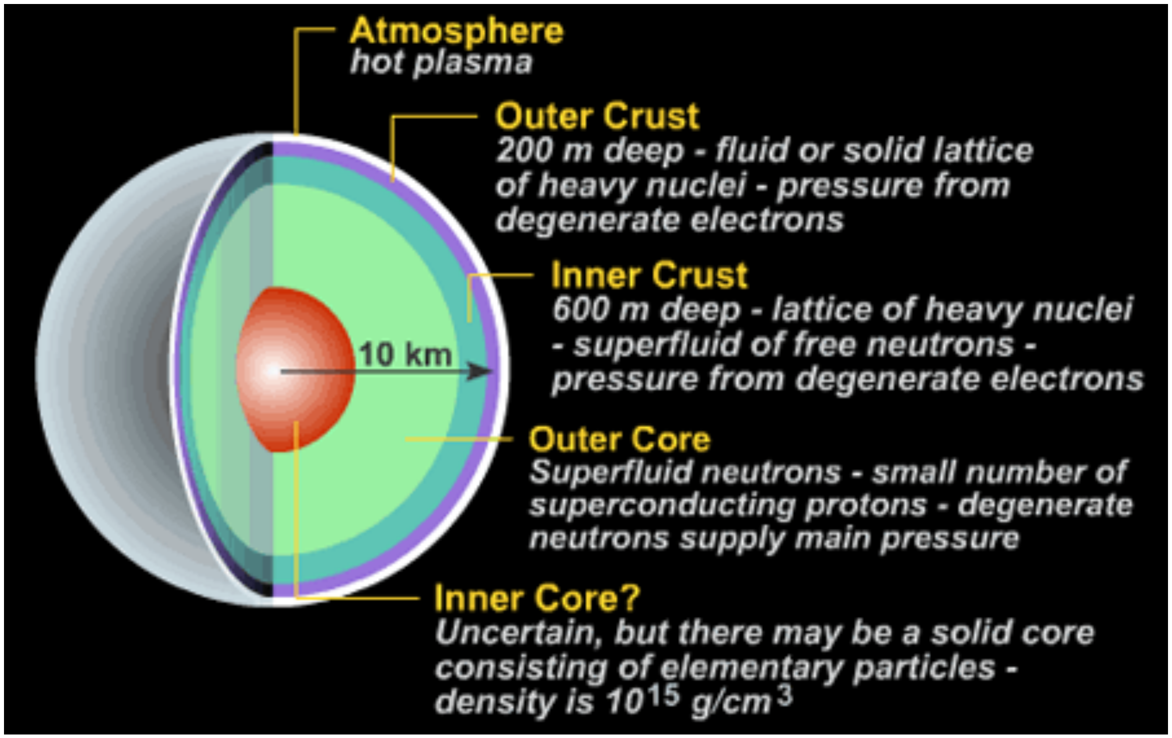
6000 km
10^{10} g/cm^3

10 km
10^{14} g/cm^3

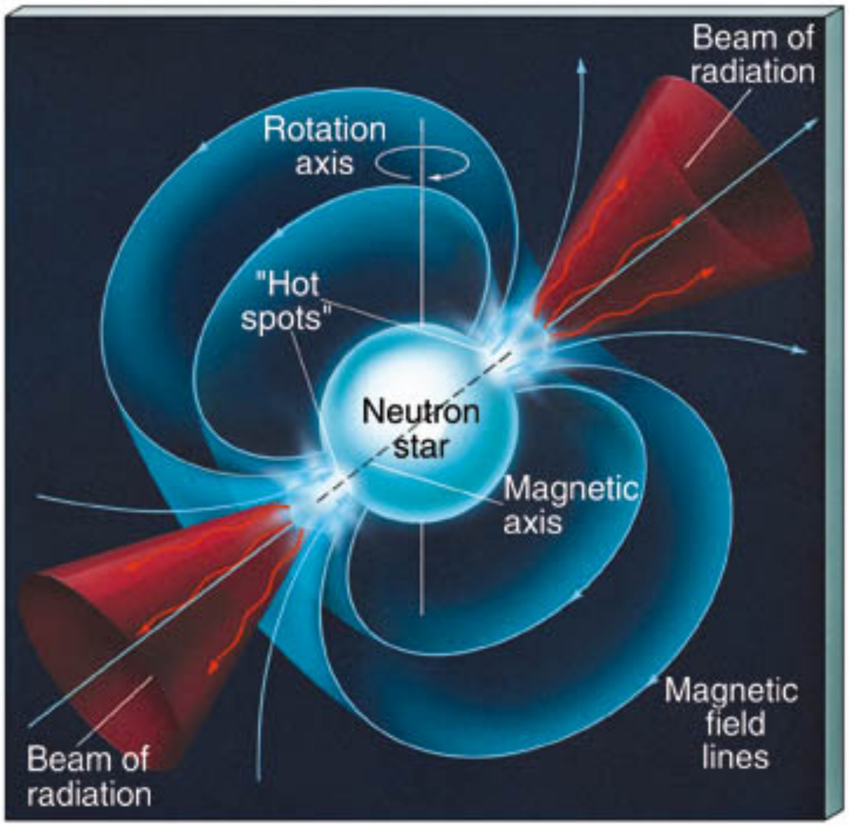
Nuclear densities!

Neutron degeneracy
provides support against gravity

Structure of Neutron Stars



Pulsars

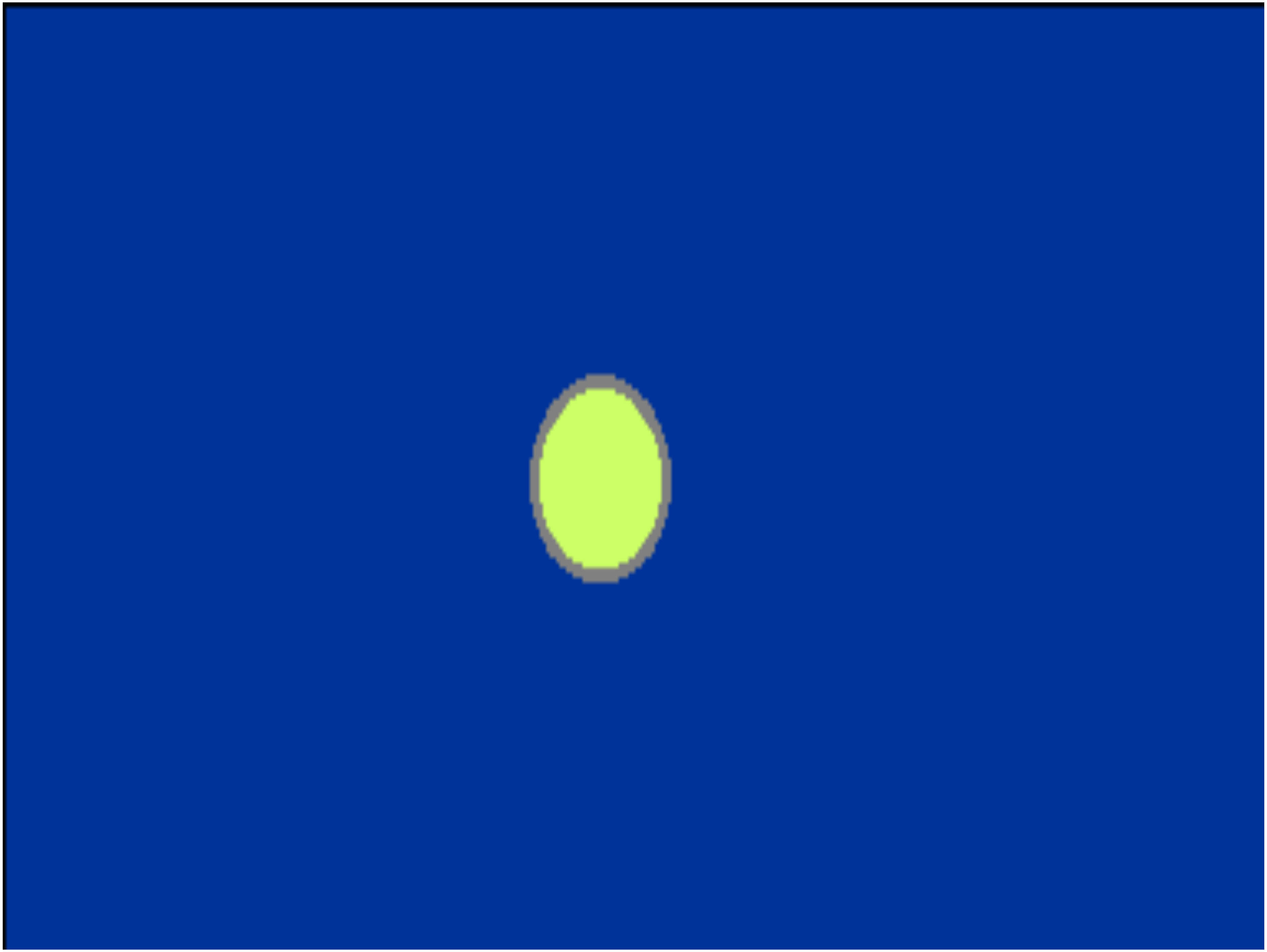


Spinning neutron star

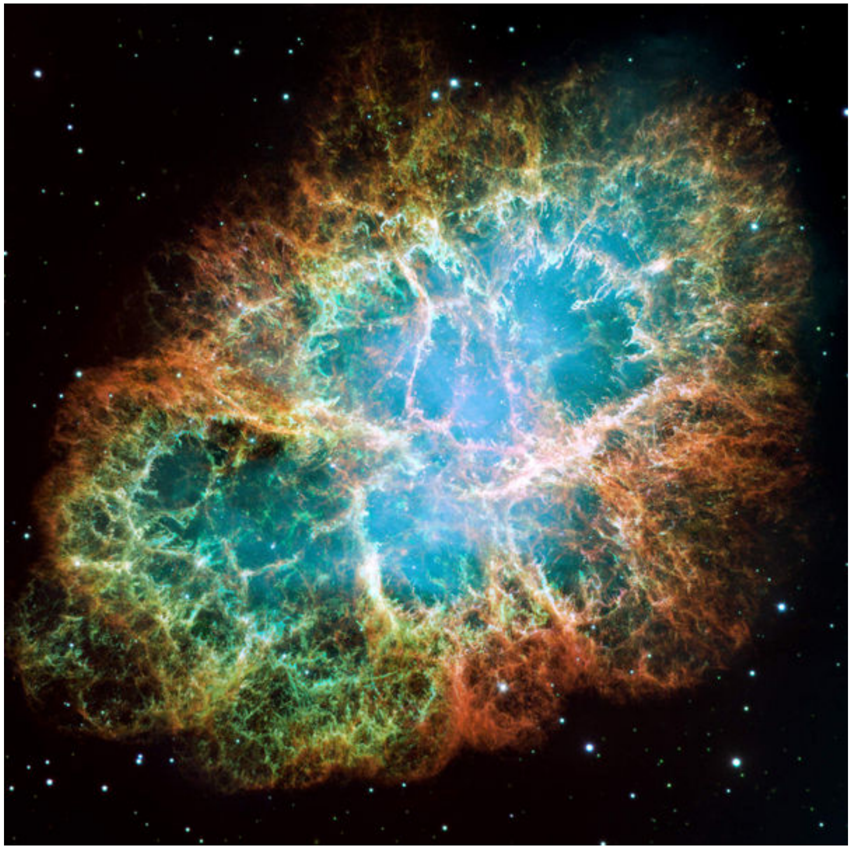
The collapse increases the rotation rate

Intense magnetic fields give out non-thermal radiation

(like Earth's aurorae, but A LOT more luminous)



Supernova Remnants



Crab Nebula
Expanding shell of the
supernova seen in 1054AD

Crab Pulsar
Pulsar detected at the
center of the shell

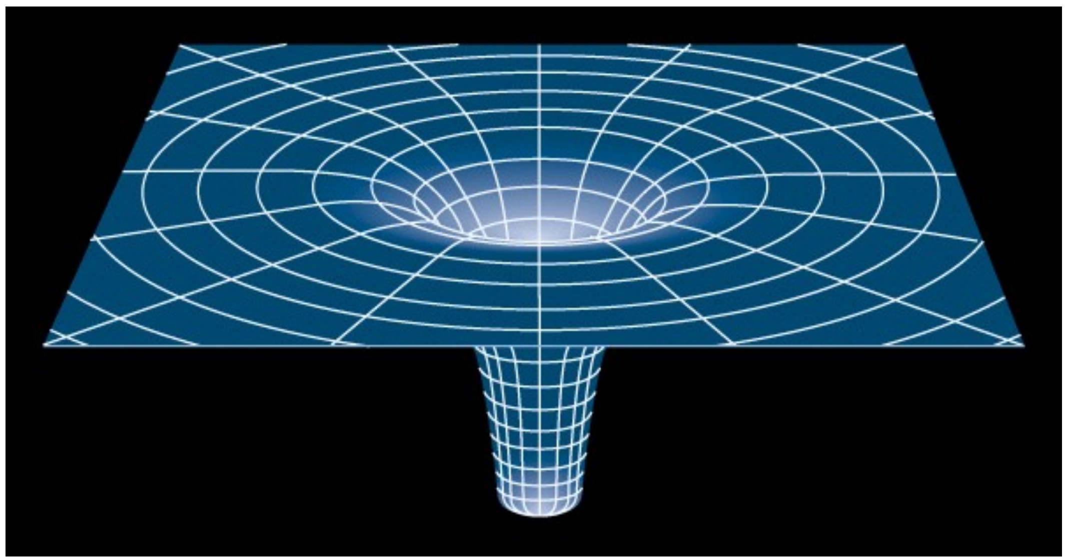
Black Hole – Gravity's ultimate victory

If the remnant has more than 3 solar masses,
neutron degeneracy cannot hold gravity

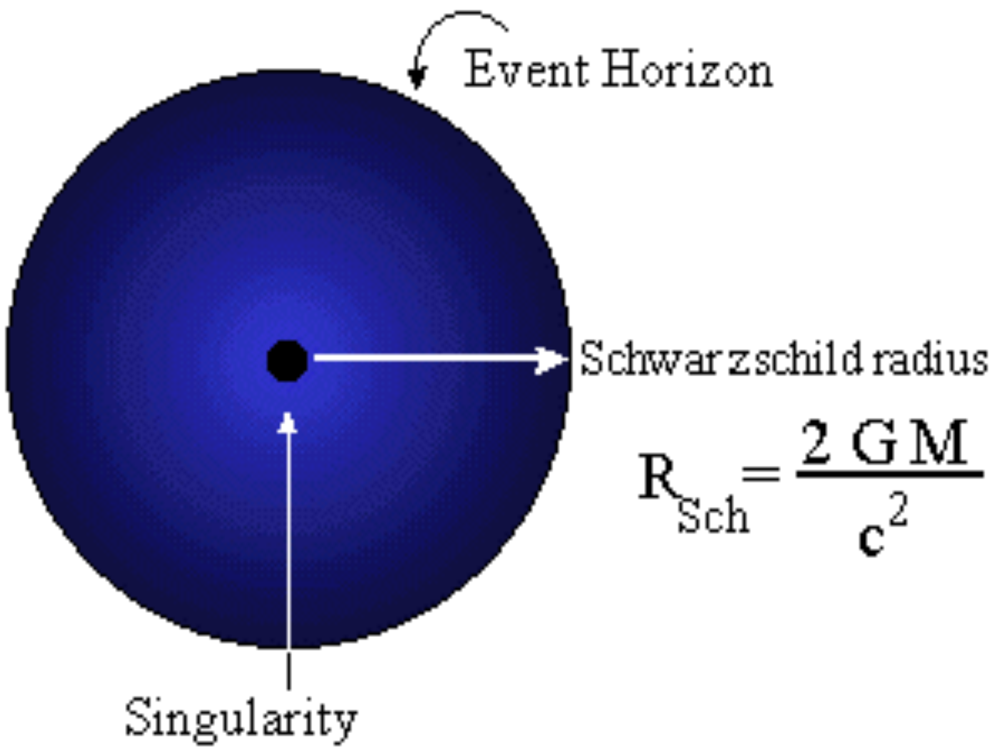
Actually, no known force can hold gravity at that point

The star implodes to a point of infinite density and finally rests in peace.

A hole in spacetime



Black Hole Anatomy



Schwarzschild radius

Radius beyond which not even light can escape

Event Horizon

The sphere of radius R_s

The event horizon is ***not*** a physical boundary

Where does the mass go?
Good question...
We cannot see the **singularity**

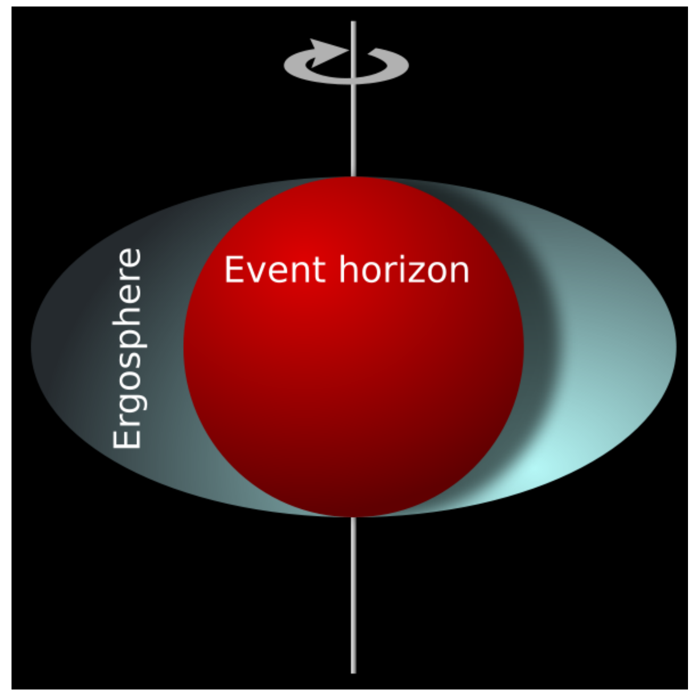
The "No-Hair" Theorem

"Black holes have no hair"

Black holes are very simple stuff. All information is lost apart from

MASS, ***CHARGE***, and ***SPIN***

These 3 quantities completely specify a black hole



A spinning black hole

Hidden Companions

Hidden = Low Luminosity

Cygnus X1

Blue star orbiting an unseen object

From the orbit, the compact object must have a mass of **8 Msun**

Too massive to be a white dwarf or neutron star.

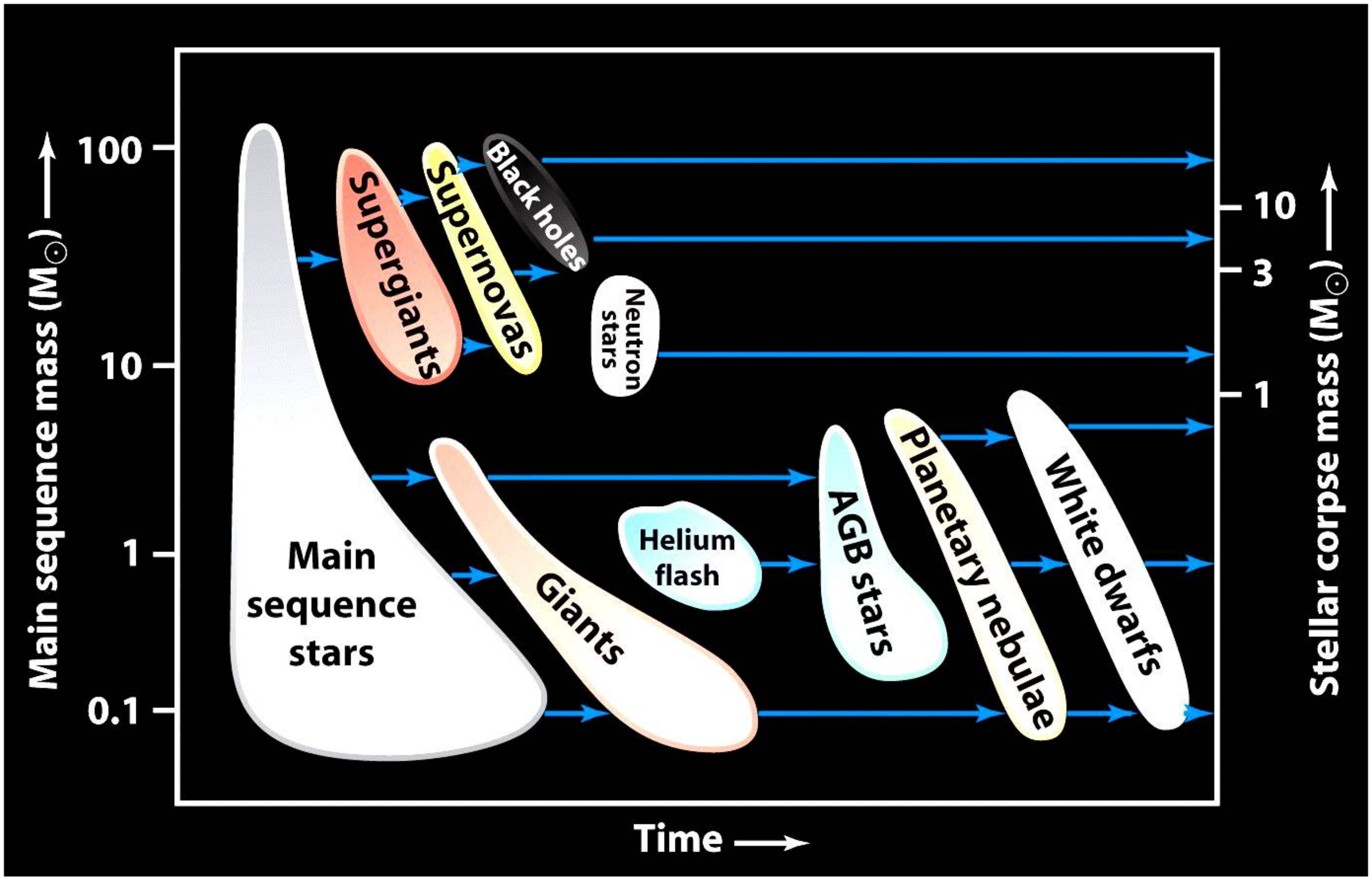
It's a Black Hole!!

The compact object emits ***X-rays*** from a region smaller than 0.1AU

Accretion disk around the black hole!!

Friction heats up the gas to ***1 million K***
Very hot stuff emits X-rays

Summary of Stellar Evolution

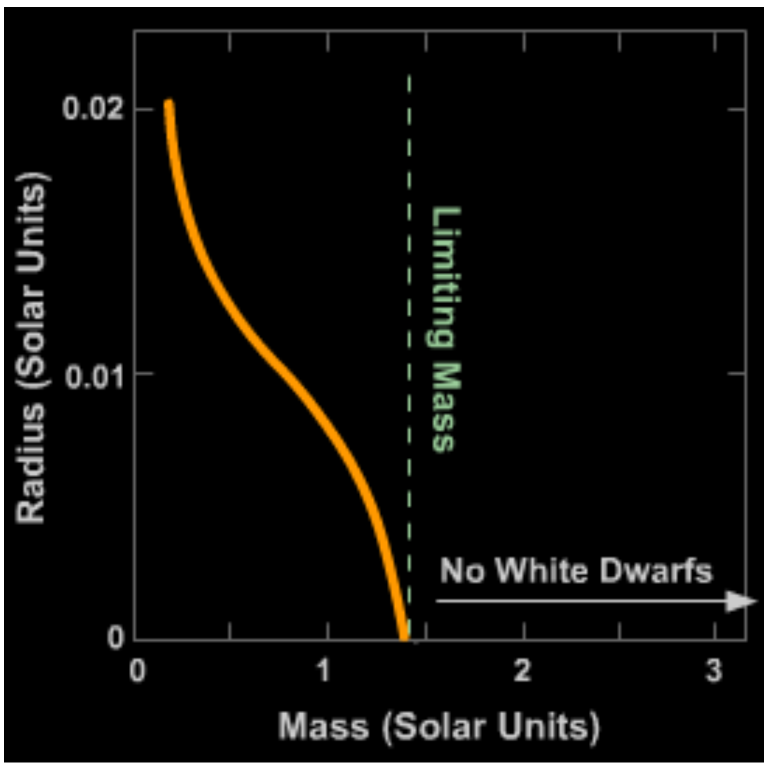


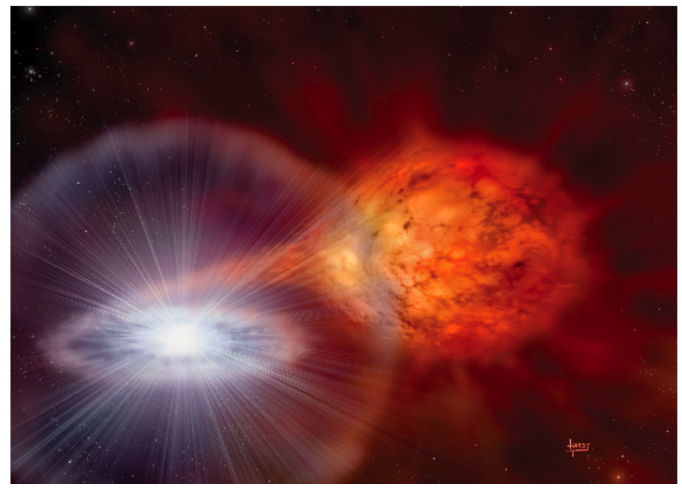
The other Supernovae

Supernovae Type Ia (White dwarf binary Supernovae)

White dwarf + Ordinary star

Steady and slow accretion onto a denegerate C-O white dwarf below the **Chandrasekhar limit**





Mass-Radius relationship for degenerate matter.

Beyond 1.4 $M_\odot$, electron degeneracy cannot hold against gravity

The other Supernovae

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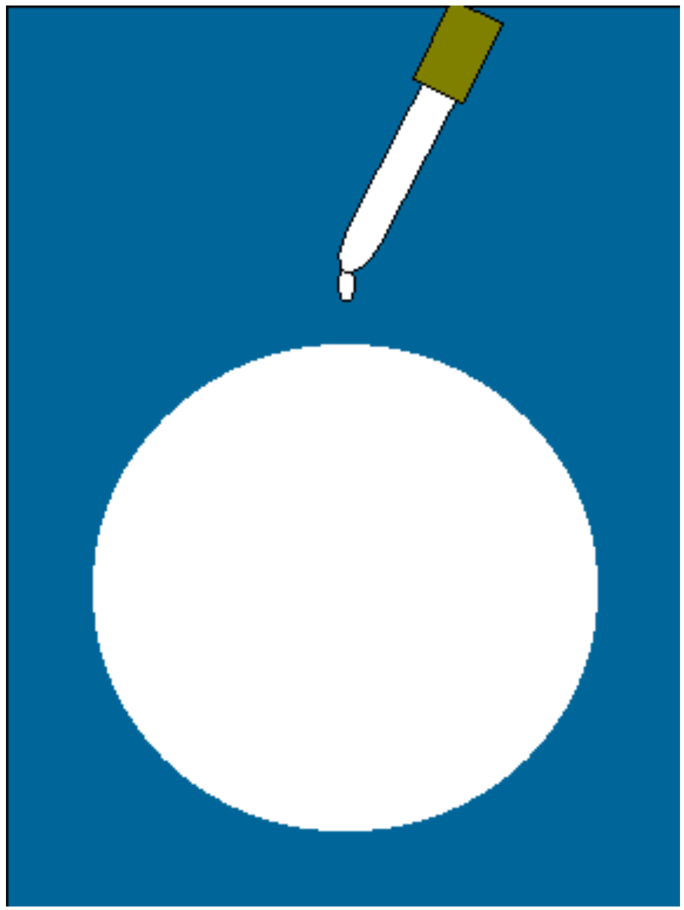
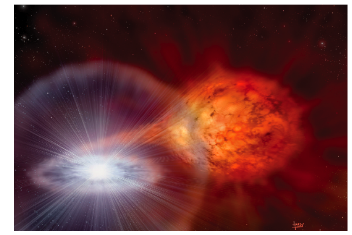
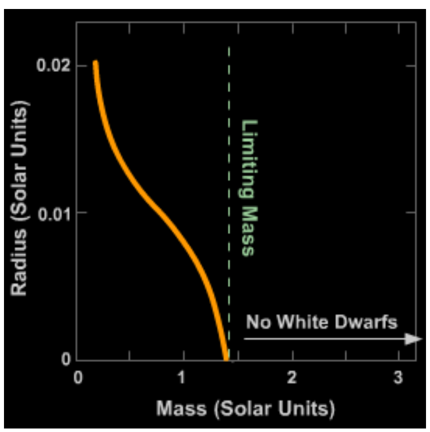




Chandrasekhar limit



The other Supernovae

Supernovae type Ia (White dwarf binary Supernovae)

White dwarf + Ordinary star

When the limit is achieved, the degenerate core implodes and achieves **carbon fusion** temperatures

This deflagrates a thermonuclear flame.

Carbon Detonation

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Supernovae type Ia (White dwarf binary Supernovae)

White dwarf + Ordinary star

When the limit is achieved, the degenerate core implodes and achieves **carbon fusion** temperatures

This deflagrates a thermonuclear flame.

Carbon Detonation

So powerful that **no remnant** is left.

If the **Black Hole** is **gravity's ultimate victory**,

the **Carbon detonation** is **pressure's ultimate victory**!

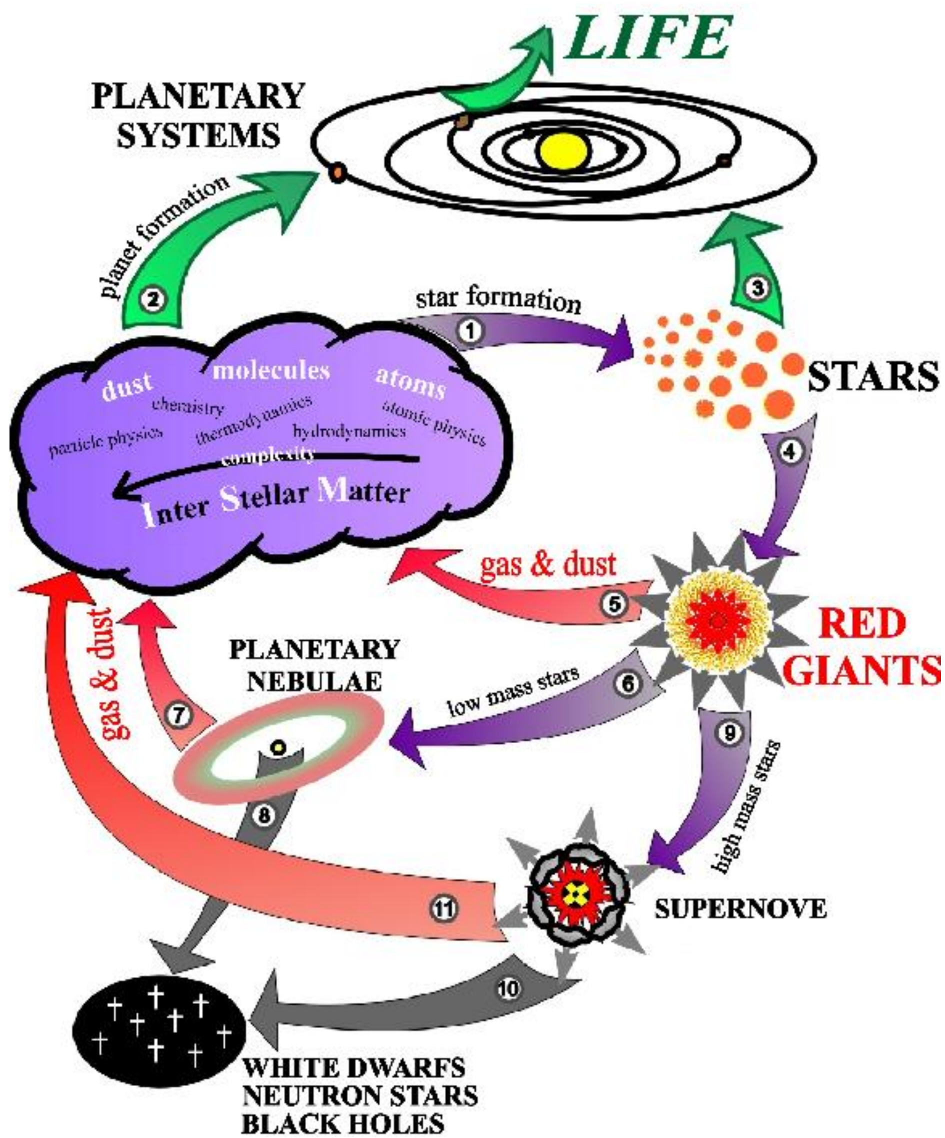
Chemical Enrichment of the Galaxy

Planetary Nebulae and **Supernovae** eject gas **enriched in metals** into the ISM

Recycling of matter

Remember, supernovae are massive stars, they live shortly (10 Myr or less). The SN recycling is practically instantaneous!

New generations of stars are enriched in metals.



Chemical Enrichment of the Galaxy

In the beginning there was Hydrogen and Helium

Stars form

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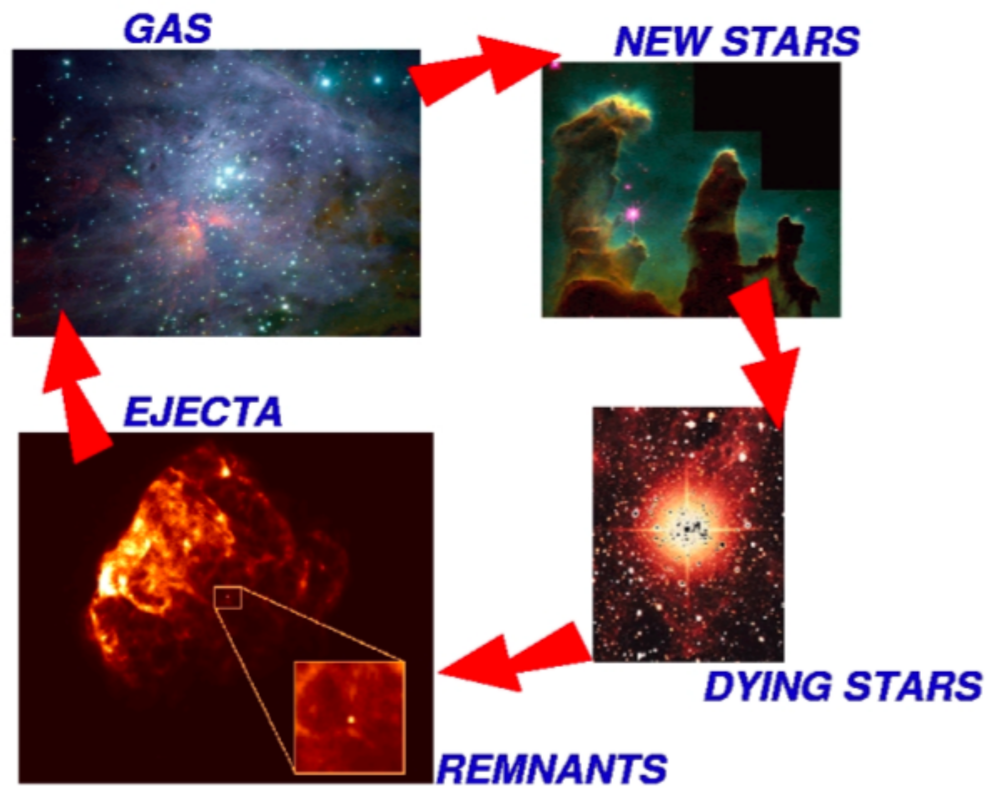


Chemical Enrichment of the Galaxy

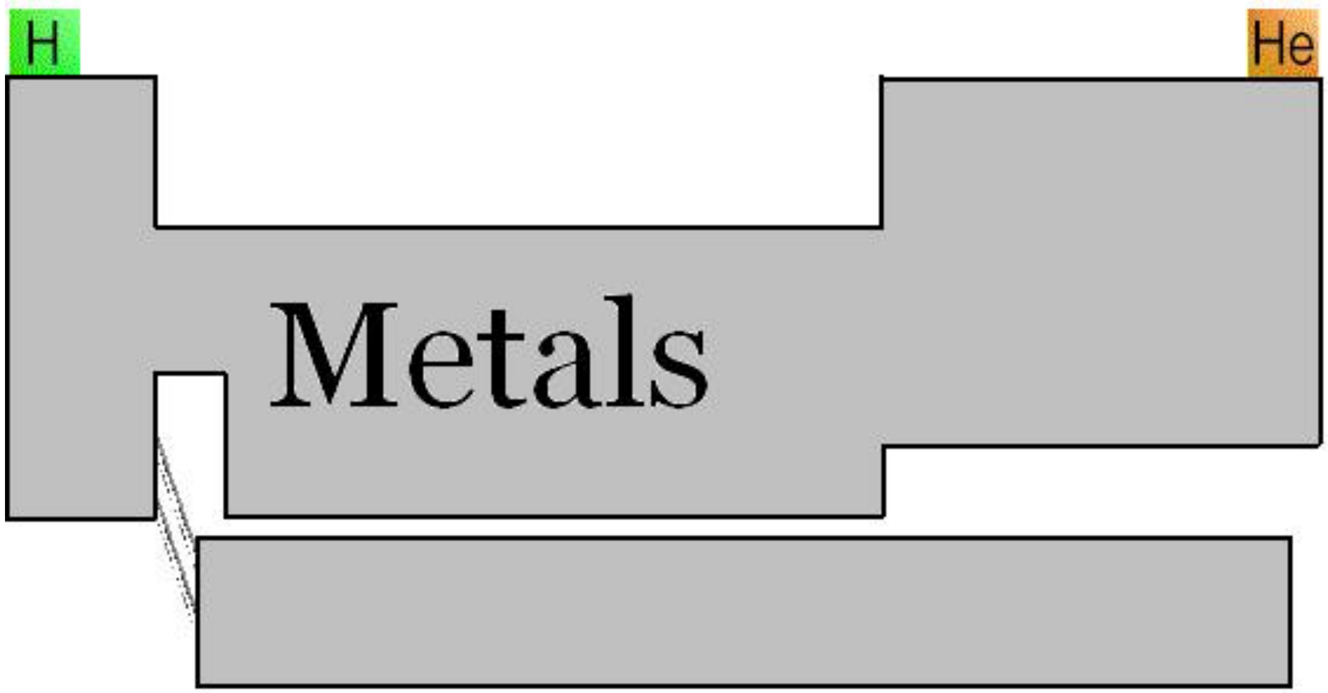
Some astrochemistry jargon

Metal: anything that is not Hydrogen or Helium

Some astrochemistry jargon

Metal: anything that is not Hydrogen or Helium

The Astronomer's Periodic Table



Some astrochemistry jargon

Metal: anything that is not Hydrogen or Helium

X: Hydrogen abundance
Y: Helium abundance
Z: All the rest (i.e., abundance of metals)

$$X+Y+Z=1$$

Sun: X=0.749, Y=0.238, Z=0.013

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The Astronomer's *Simplified* Periodic Table

H	He	Z

Some astrochemistry jargon

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Metallicity

Iron abundance (normalized to solar)

$$[Fe/H] = \log \left(\frac{N_{Fe}}{N_H}\right)_{\star} - \log \left(\frac{N_{Fe}}{N_H}\right)_{\odot}$$

Sun: [Fe/H] = 0.0

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Sun: [Fe/H] = 0.0

Negative → Less metals than the Sun

Positive → More metals than the Sun

Chemical Enrichment of the Galaxy

In the beginning there was
Hydrogen and Helium

Stars form

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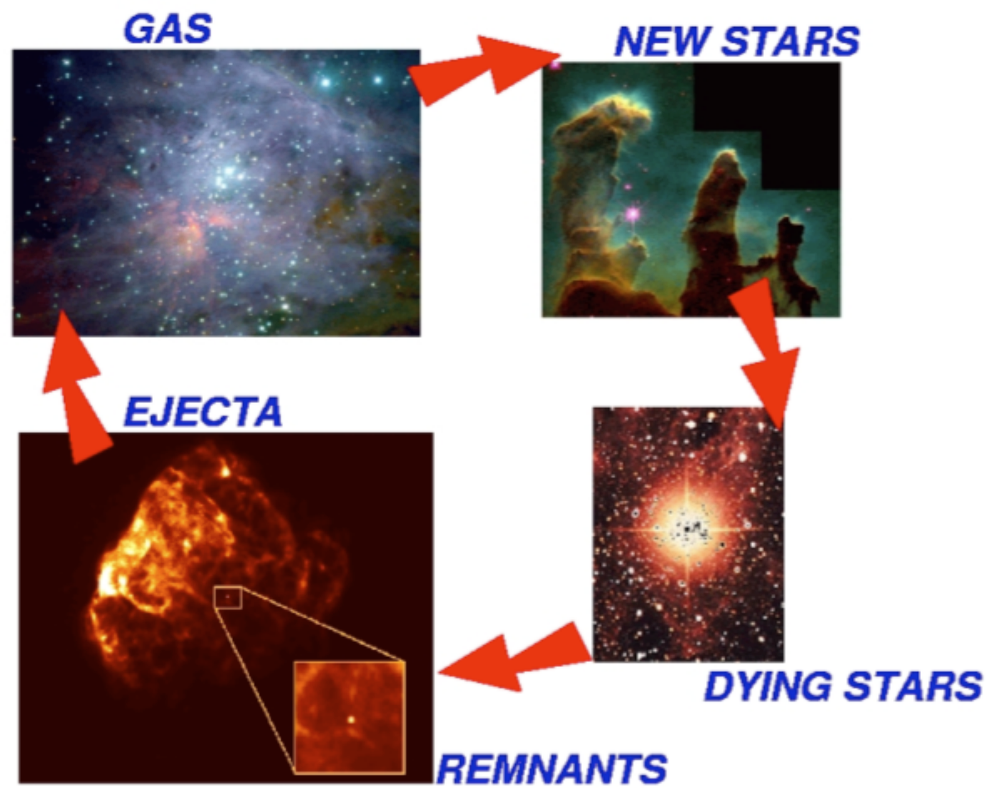
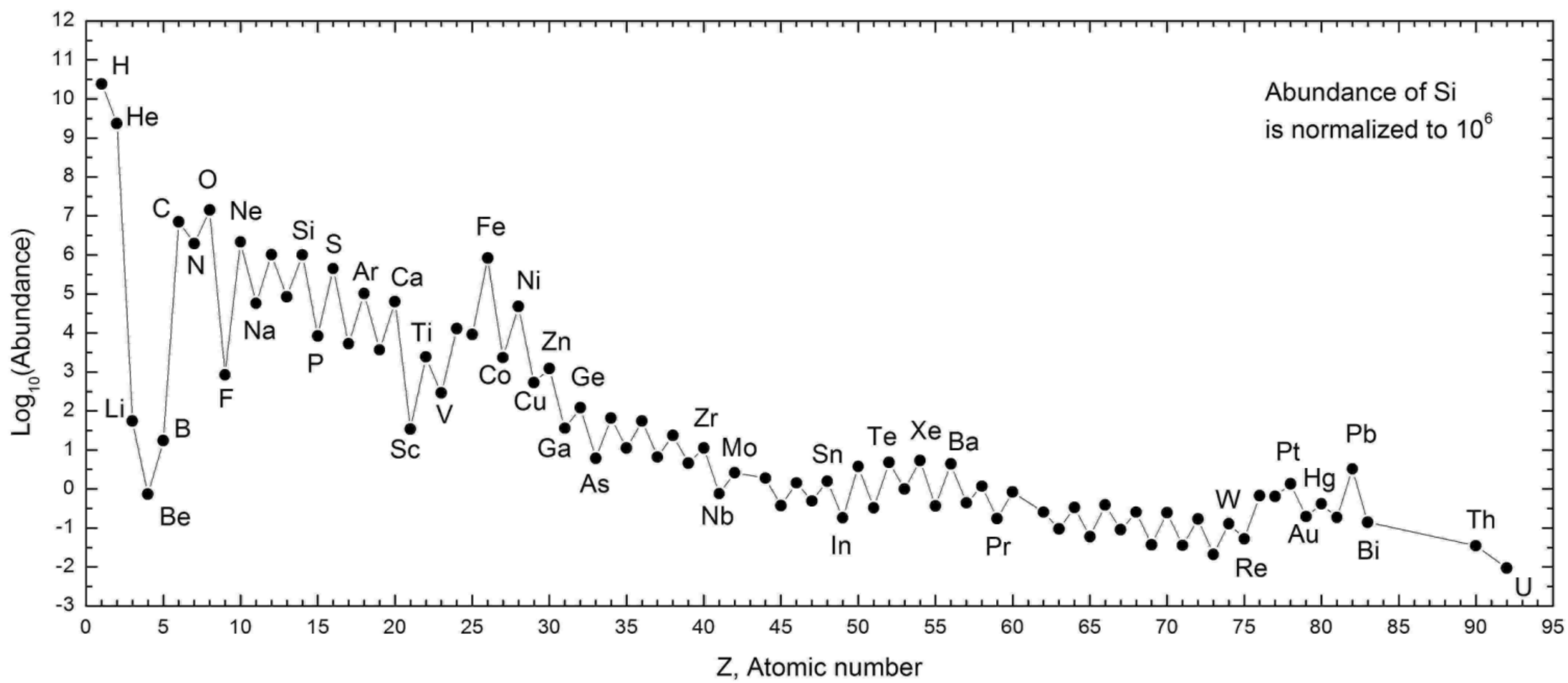


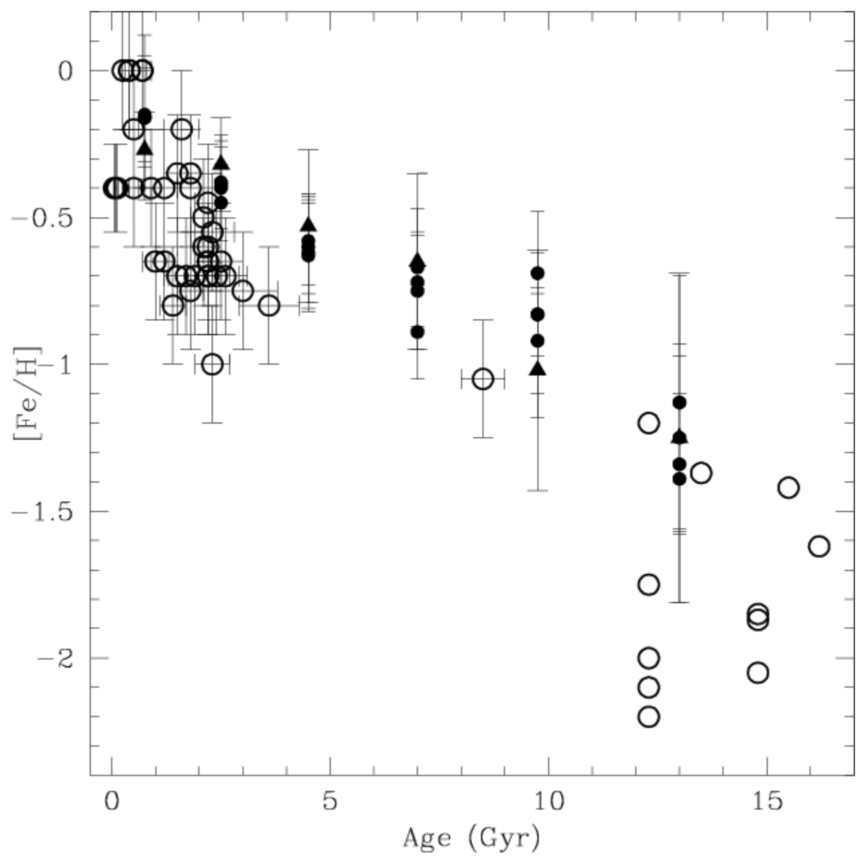
Insight

The Sun (or stars in general) do NOT self-enrich its atmosphere. They were formed out of gas that already contained those elements.



Age-Metallicity Relationship

The **overall metallicity** of the Galaxy **increases in time** as successive generations of stars enrich the ISM

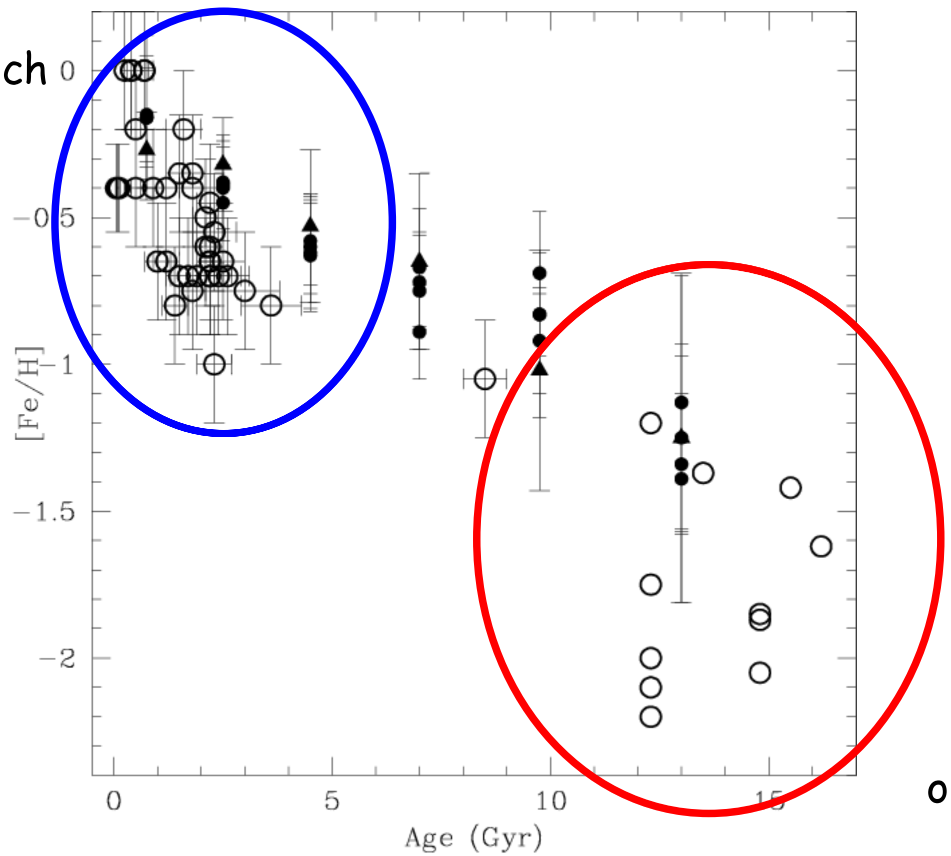


Age of the stars

Stellar Populations

More old terminology we are stuck with

Population I
young and metal-rich

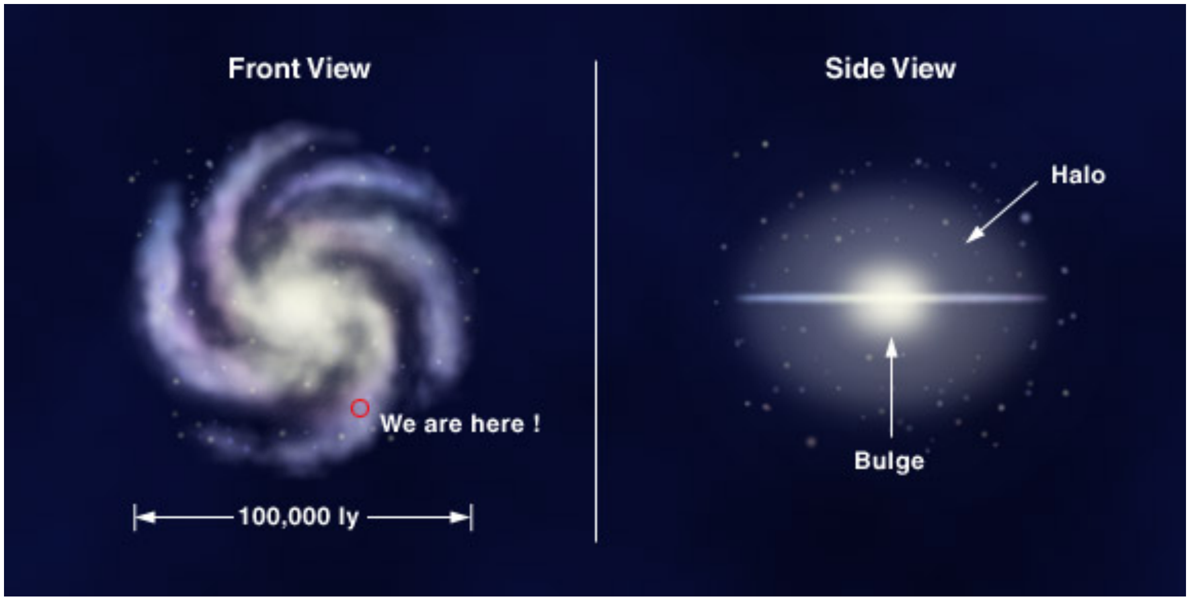


Population II
old and metal-poor

Age of the stars

Stellar Populations

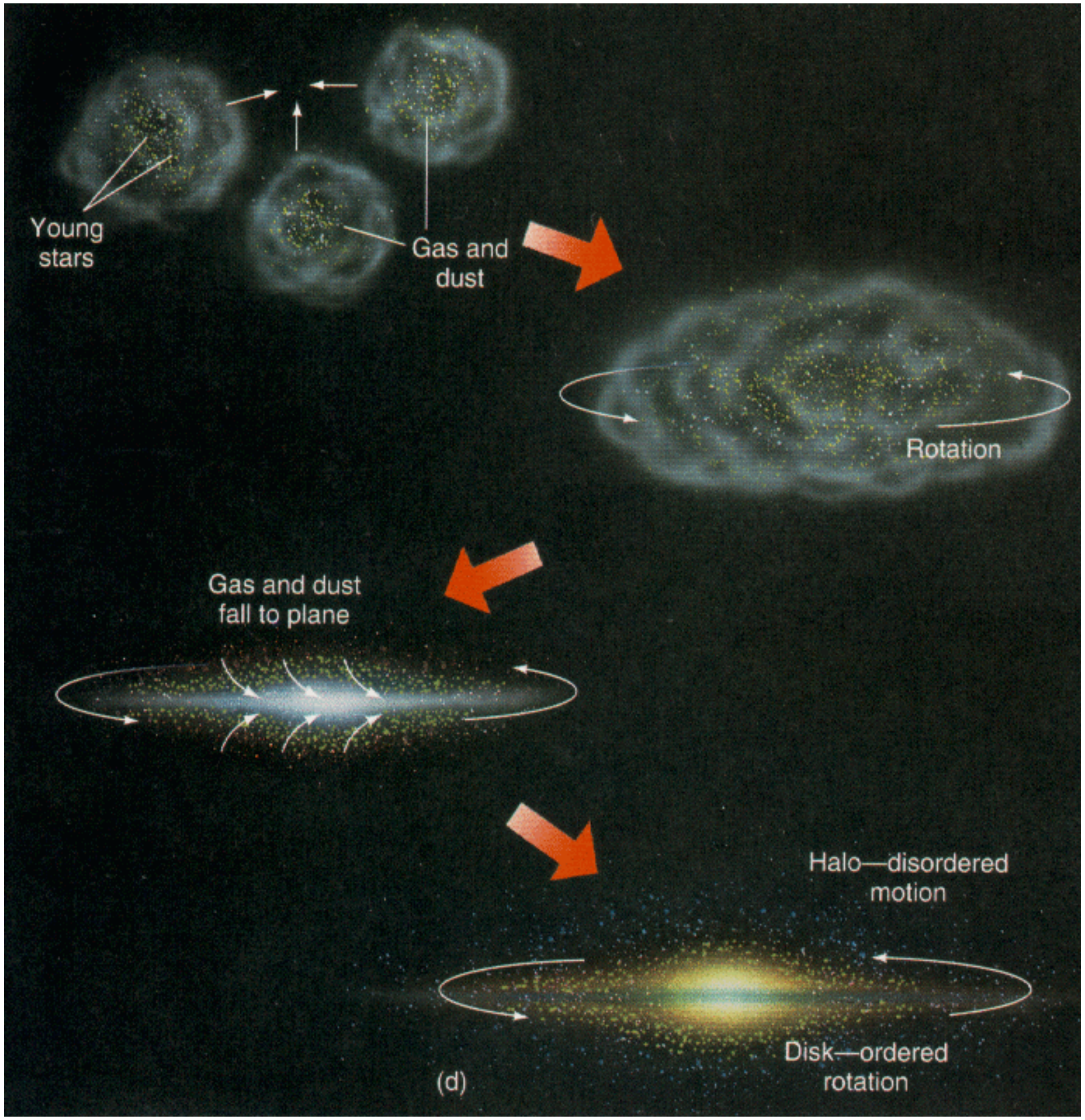
Where do we find the different populations?



Galactic Structure

Bulge
Halo
Disk

Galaxy formation



The **Halo** is the first structure that forms, during the collapse of the original cloud

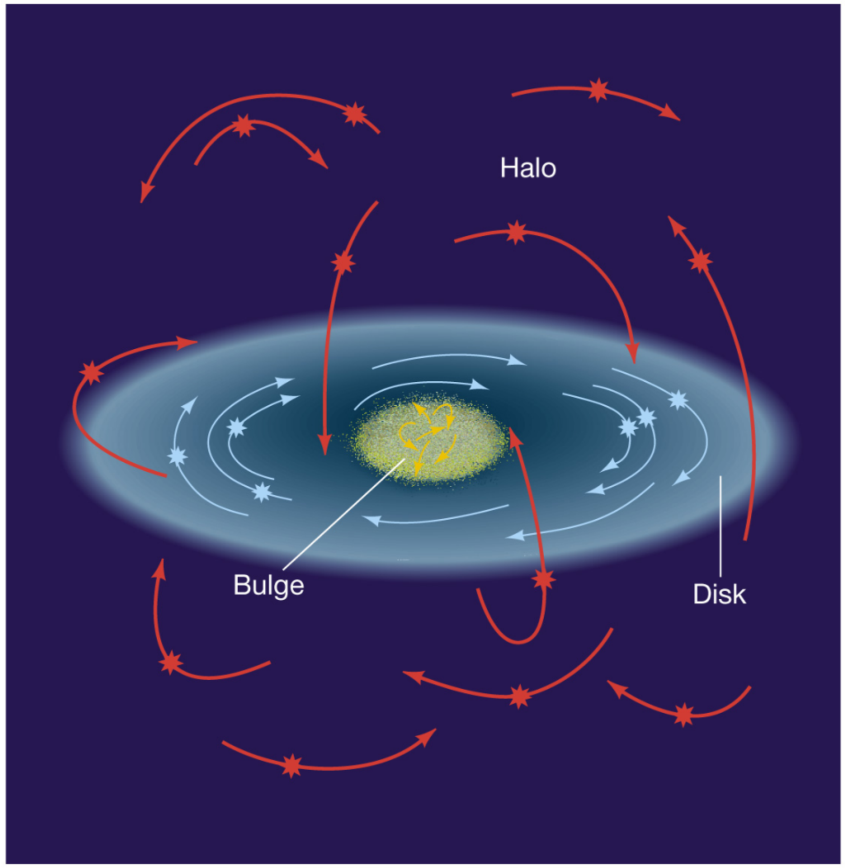
The **Disk** forms later, as the gas settles

Halo: disordered motion
Disk: ordered motion

Stellar Populations

Population II
old and metal-poor
Halo Stars

Star formation ceased long ago

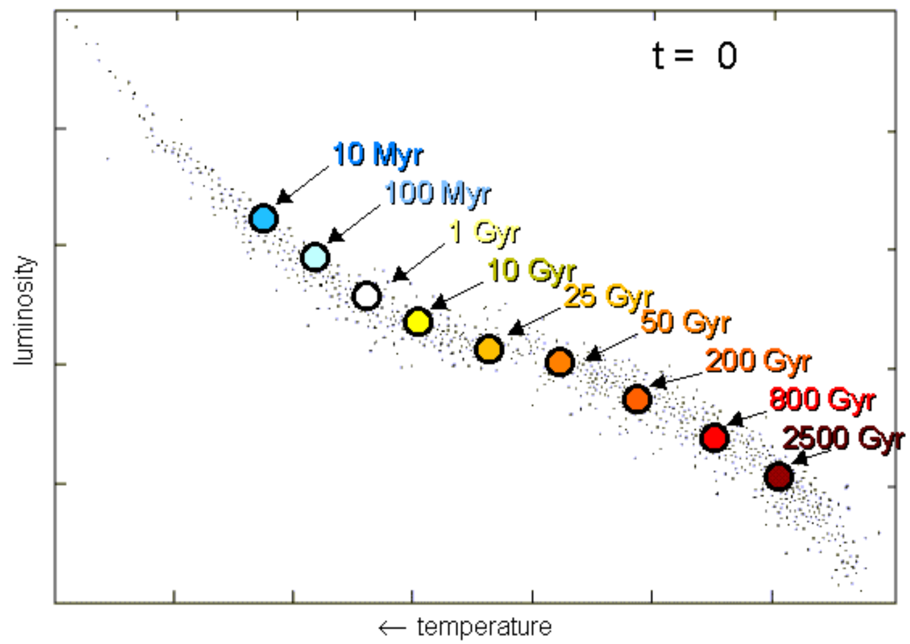


Population I
young and metal-rich

Disk Stars

Star formation is ongoing

Insight



Blue stars are <u>invariably</u> young

Red stars are <u>usually</u> (but not always) old

Example of Population I – Young Open Clusters

Open Clusters are usually young

Why? Because they are formed in the ***disk***, and are subject to Galactic tides!
(there is a lot of gas around)

They are disrupted in a few orbits
They retain their physical integrity only for a few millions of years, before the stars disperse
Still hanging around their birthplaces – the **Spiral Arms**

All disk stars (the Sun included) were born in Open Clusters

The Pleiades

Are there old open clusters?

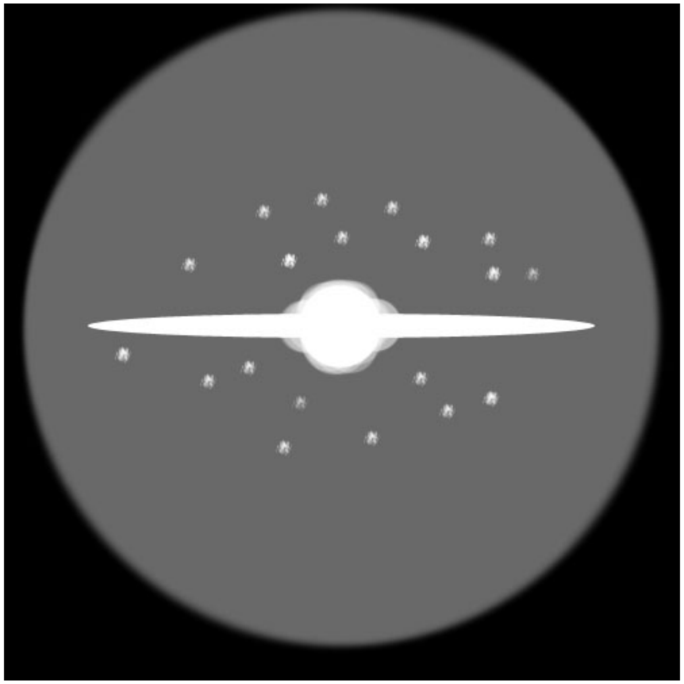
Yes, **M67**, for instance, which is **4 Gyr old**

It is an open cluster that is **massive** enough to remain gravitationally bound

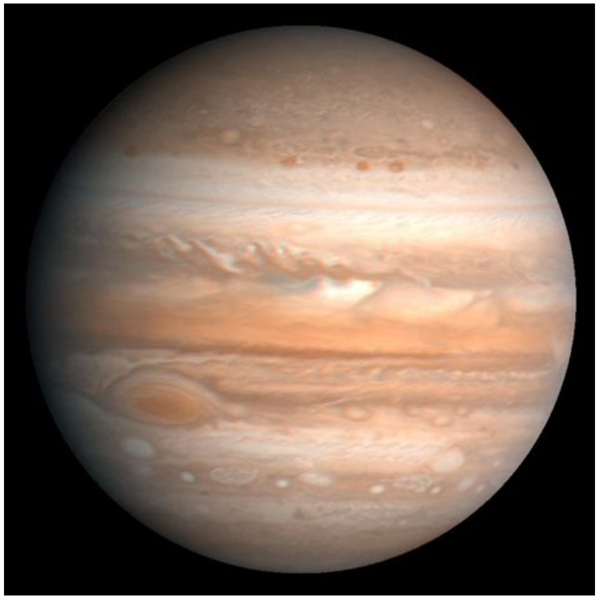
Example of Population II – Globular Clusters

Globular clusters are old systems of stars in the Halo

They are spherical (globular) because they are massive
Gravity could shape the system into a spherical configuration



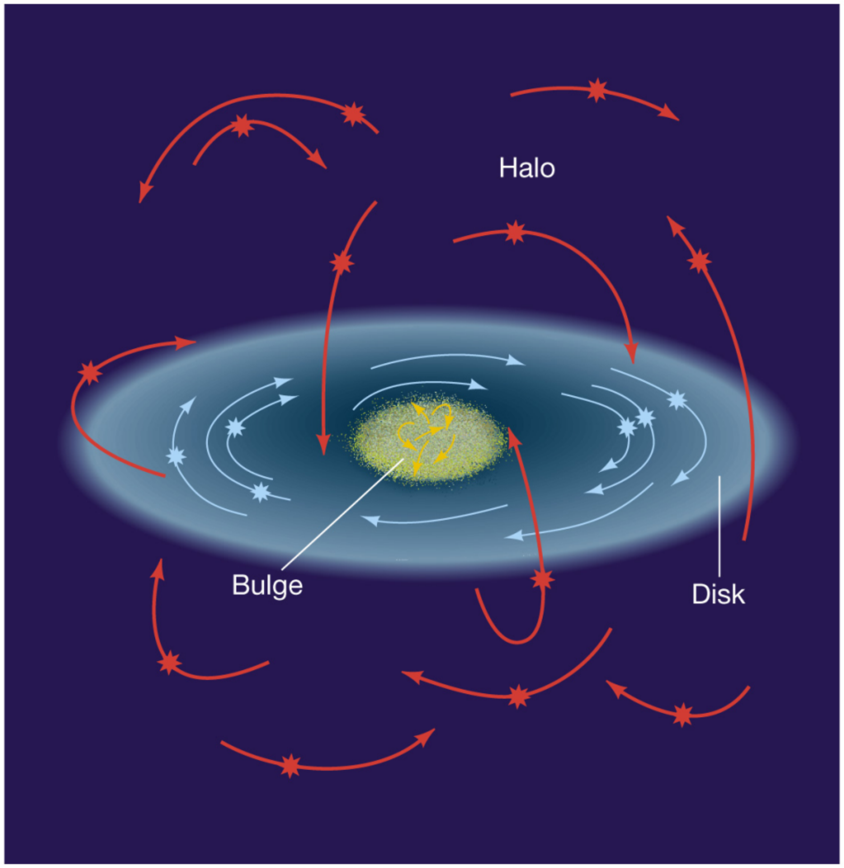
A "mass-sphericity" analogy...



Stellar Populations

Population II
old and metal-poor
Halo Stars

Star formation ceased long ago



Population I
young and metal-rich

Disk Stars

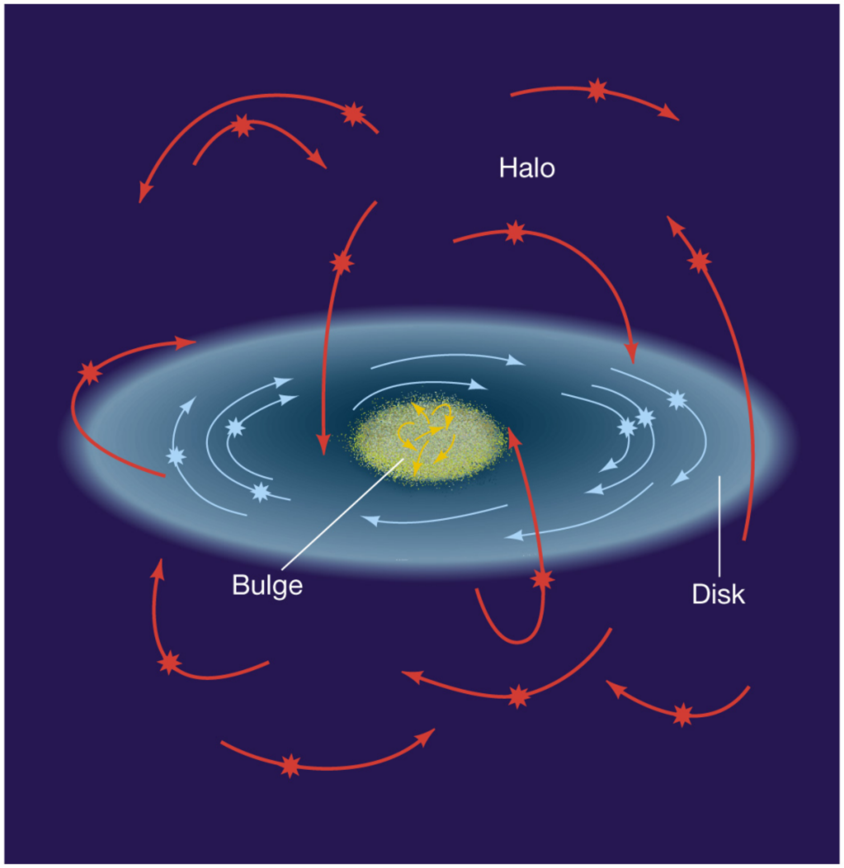
Star formation is ongoing

Stellar Populations

How about the Bulge??

Population II
old and metal-poor
Halo Stars

Star formation ceased long ago



Population I
young and metal-rich

Disk Stars

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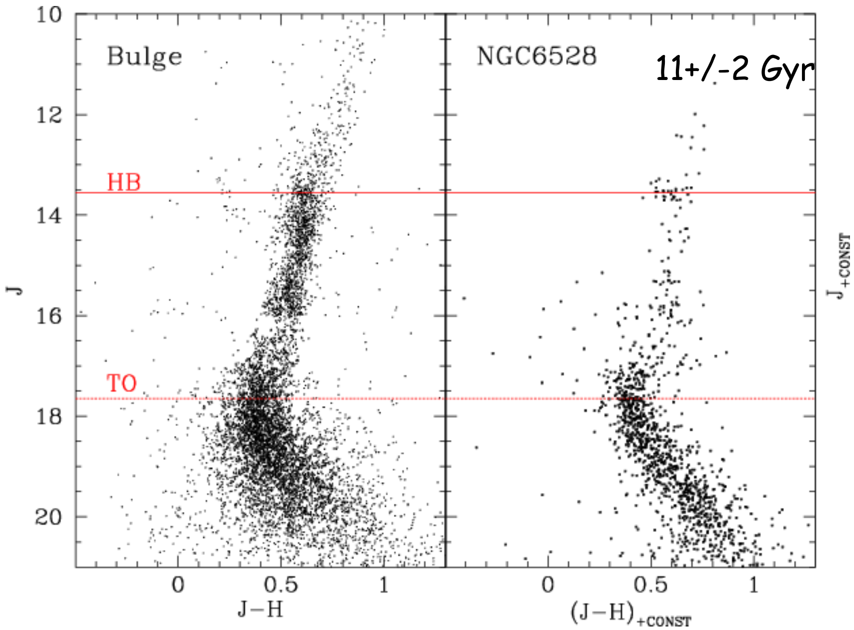
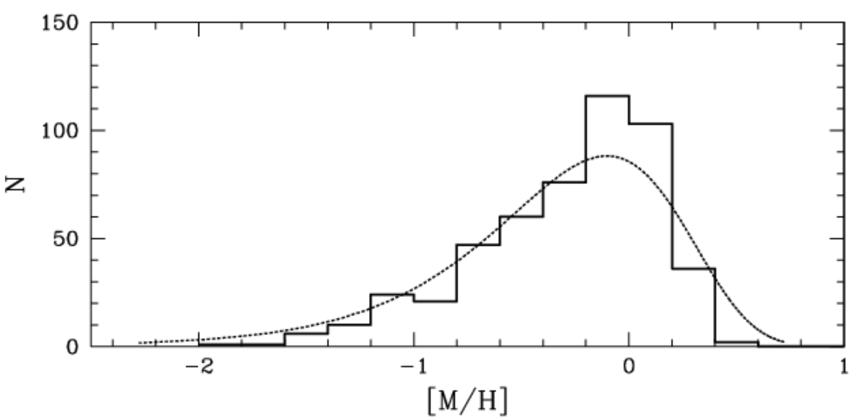
Stellar Populations



Metallicity Distribution of the Bulge



Bulge stars are old and metal rich

The Bulge is an old structure,
but quite dense

Star formation rate (SFR) is proportional to the density

More gas, more stars....

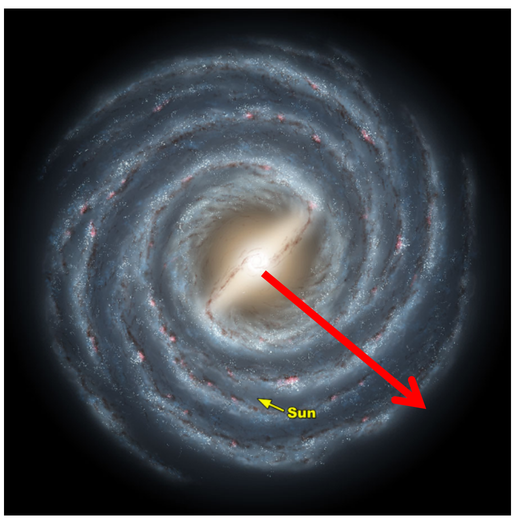
So, the chemical enrichment was fast!!

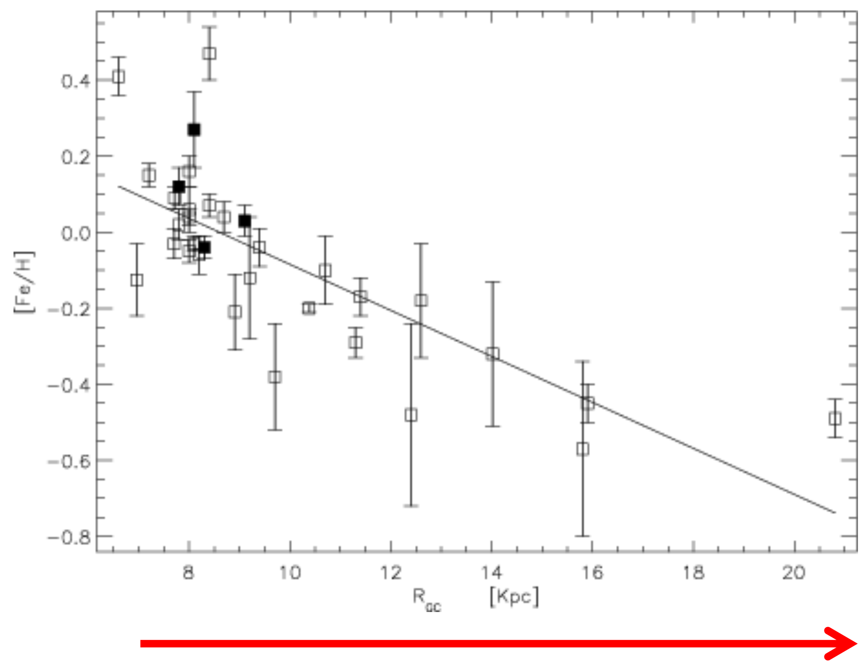
The Galactic Radial Metallicity Gradient

Star formation rate (SFR) is proportional to the density

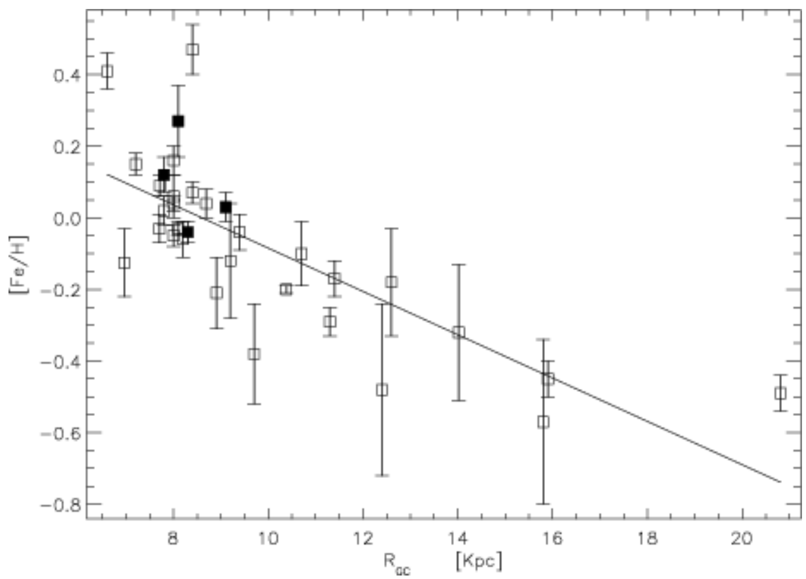
A galaxy's density decreases with radius
So, the SFR decreases with radius

Central part (Bulge) → High gas density → Fast chemical enrichment
Outer disk → Low gas density → Slow chemical enrichment





Stellar Populations
Why we shouldn't use the terminology



Population I - young and metal-rich
Population II – old and metal-poor

There exists **old metal rich stars** (bulge)

As well as **young metal poor stars** (outer disk)

Use of "stellar populations" is **discouraged**.

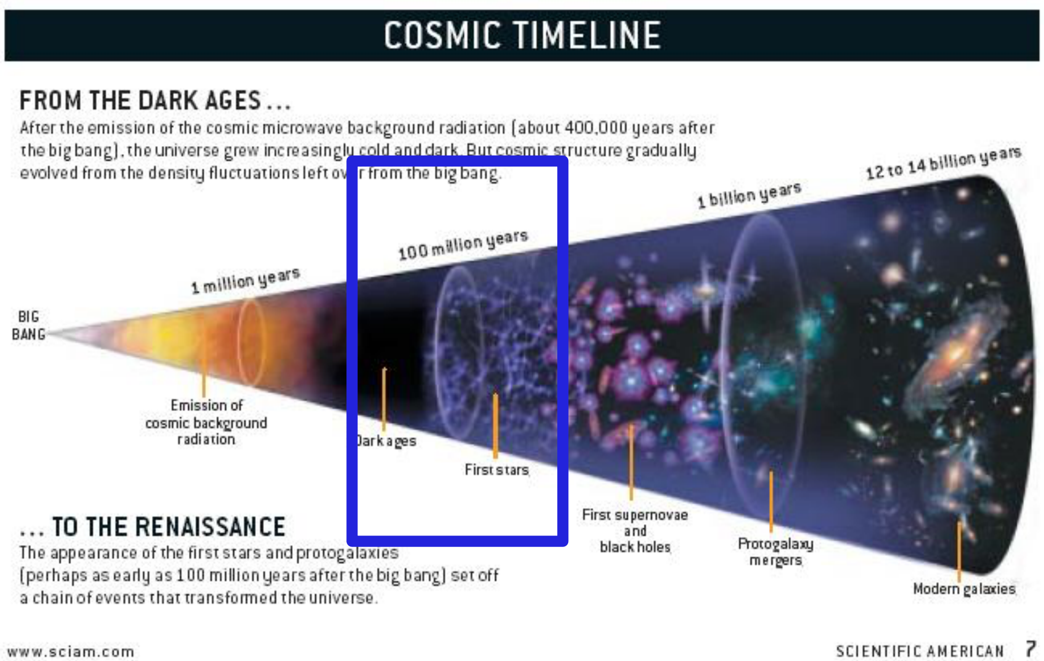
Use *age* and *metallicity* when you can.

Exception to the rule - Pop III stars

Pop I – metal rich, young

Pop II – metal poor, old

Pop III – metal free, extinct



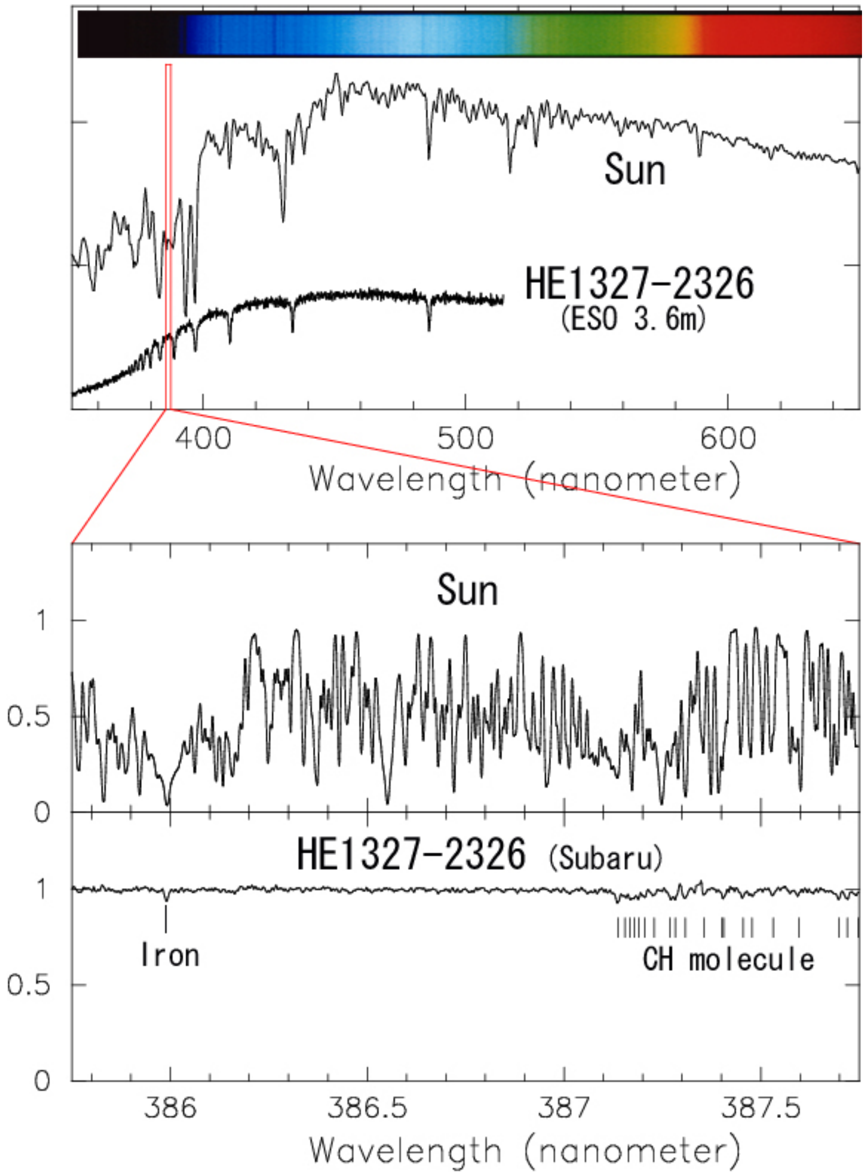
The First Stars

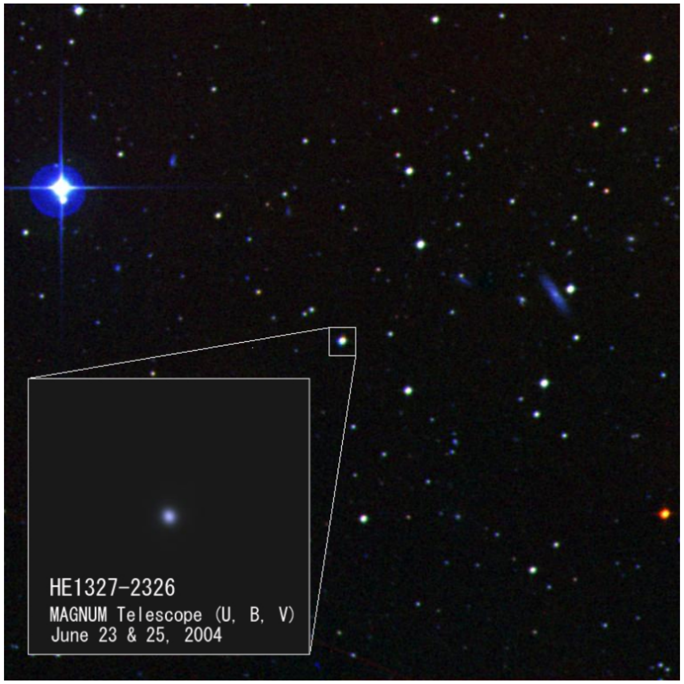
Purely Hydrogen and Helium, nothing else.

We cannot see them since they are gone.

But... the second generation of stars may still be around

Very metal poor stars – HE 1327-2326





[Fe/H] = -5.2

How much less iron than the Sun?
300,000 times less

Let's summarize

Beyond the Iron peak, nucleosynthesis occurs by ***neutron capture*** and ***beta decay***

$(n \longrightarrow p + e^- + n)$

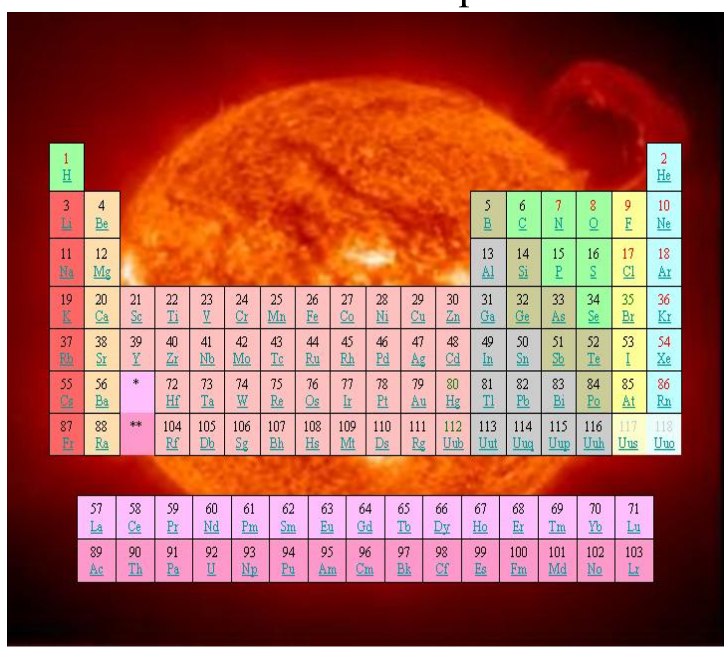
The process is classified according to the neutron flux

S-process	**R-process**
(slow neutron capture)	(rapid neutron capture)
Neutron capture occurs **slower** than beta decay	Neutron capture occurs **faster** than beta decay
Works up to bismuth (Z=83)	Really heavy stuff All the way to Uranium
Where? **AGB stars + Supernovae**	Where? **Supernovae**

Let's Summarize

Element	# of Protons	Site
H	1	Big Bang
He, C, O	2,6,8	Big Bang + Low and High Mass stars
Ne - Fe	10-26	High mass stars
Co - Bi	27-83	S and R process, ABG and SN
Po - U	84-92	R process in SN

Nucleosynthesis: Stars are where the periodic table is cooked



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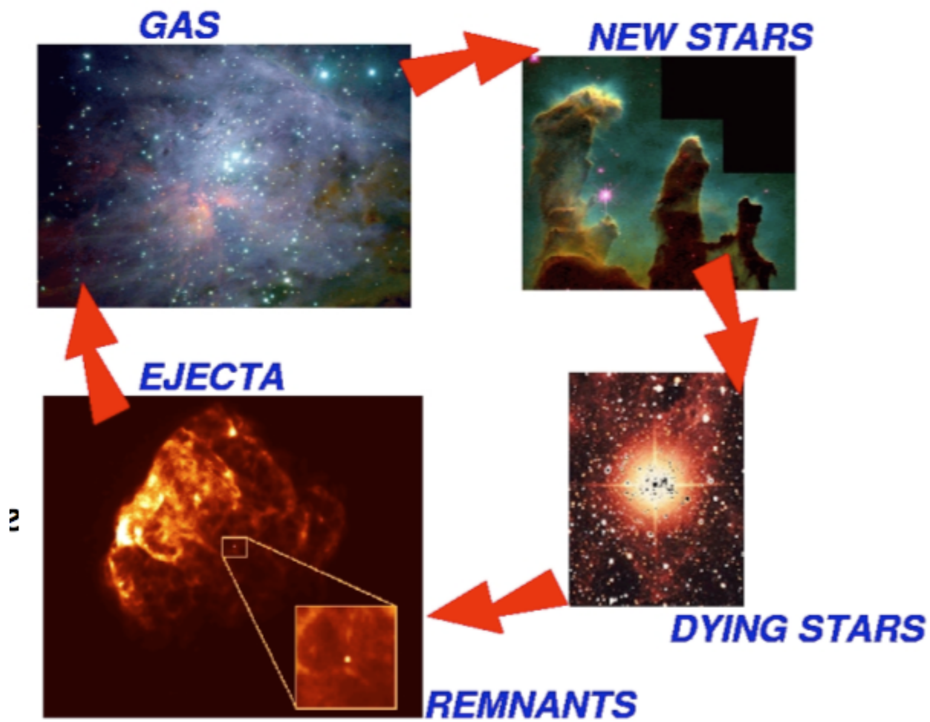
Some astrochemistry jargon

Successive generations of stars enrich the Galaxy in metals



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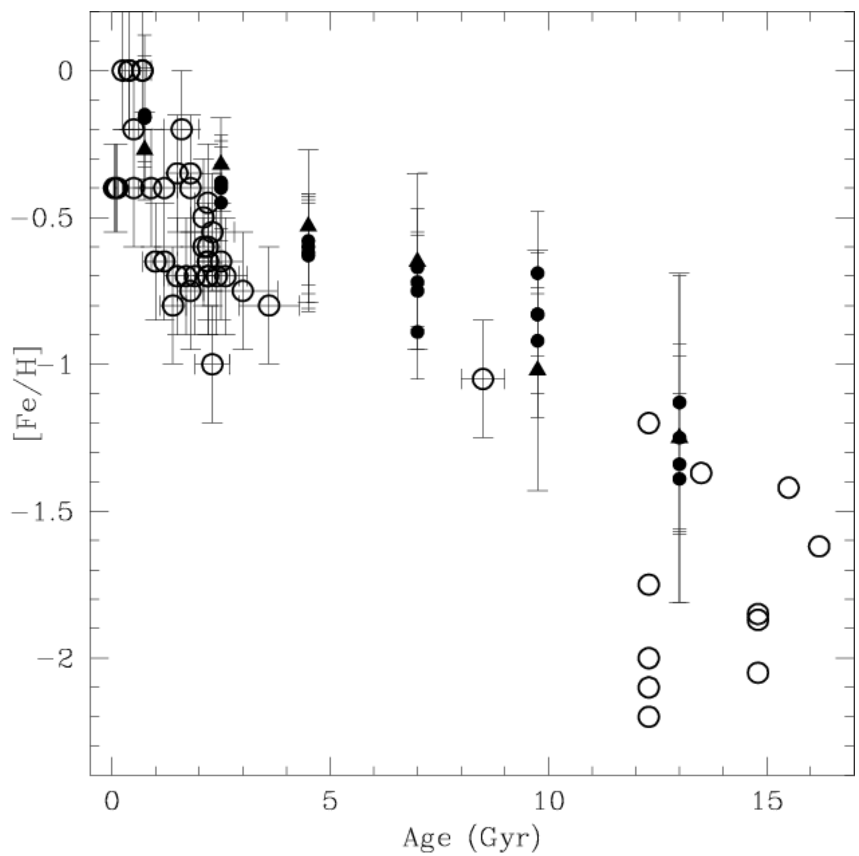
Some astrochemistry jargon

Successive generations of stars enrich the Galaxy in metals

An age-metallicity relation can be traced



Age of the stars

Let's summarize

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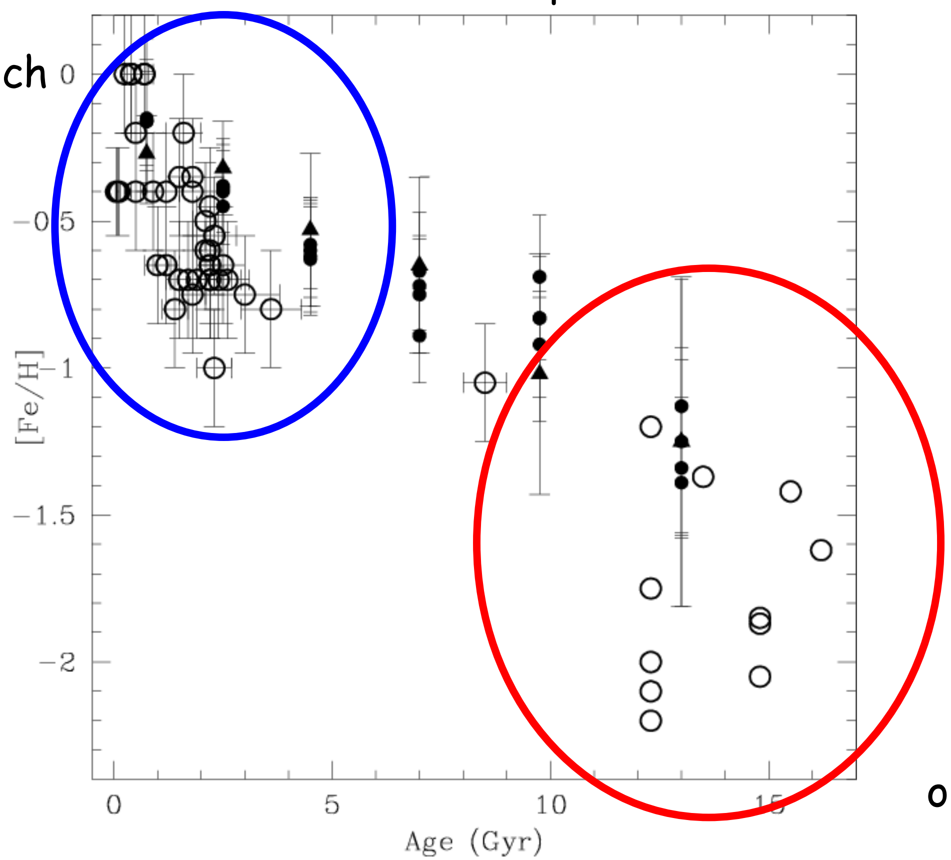
Population I

young and metal-rich



Population II

old and metal-poor

Age of the stars

Let's summarize

Some astrochemistry jargon
Successive generations of stars enrich the Galaxy in metals
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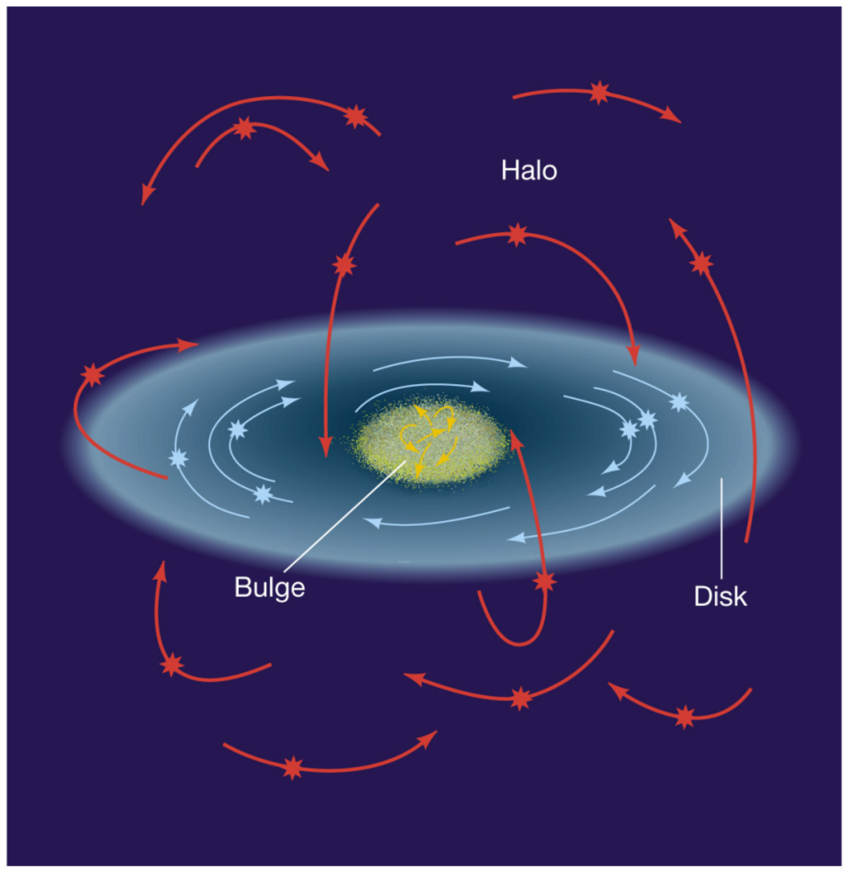
Pop I – Disk stars ; Pop II – Halo stars

Population II
old and metal-poor
Halo Stars

Star formation ceased long ago



Population I
young and metal-rich

Disk Stars

Star formation is ongoing

Let's summarize

Some astrochemistry jargon

Successive generations of stars enrich the Galaxy in metals

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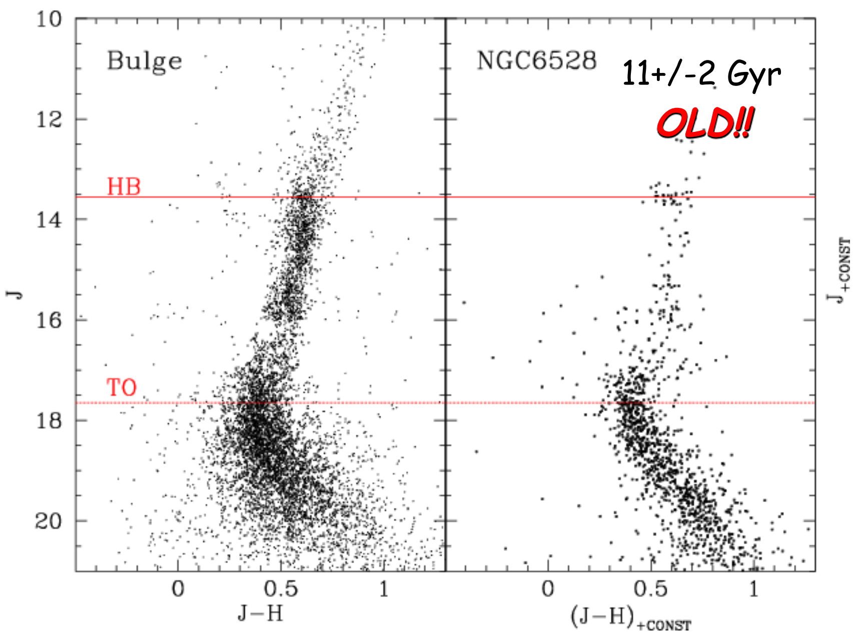
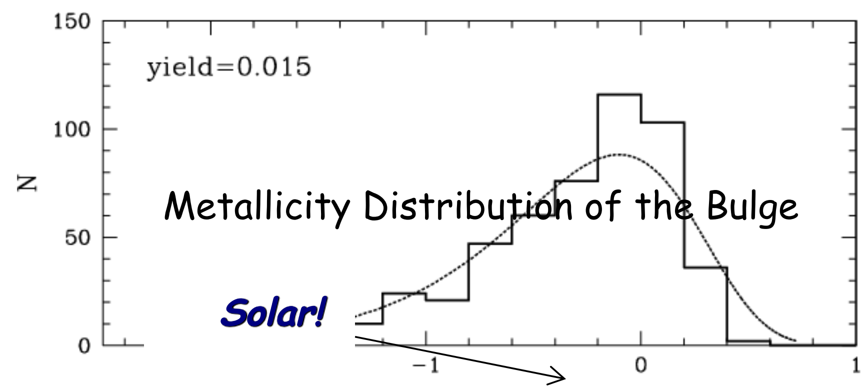
Bulge stars break the classification. They are old and metal rich.

Age of the Bulge





Let's summarize

Some astrochemistry jargon

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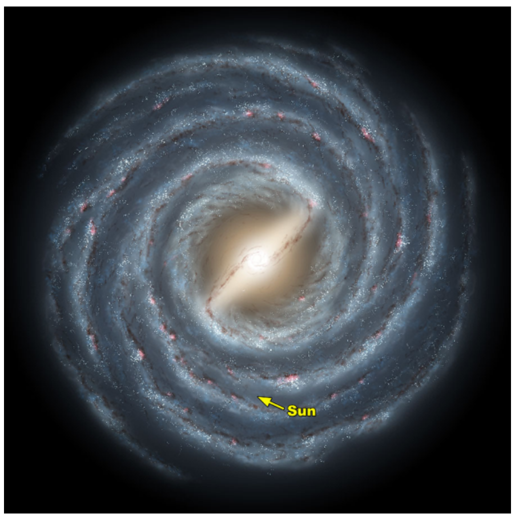
That's because the bulge is dense. More gas, more stars. Fast chemical enrichment.



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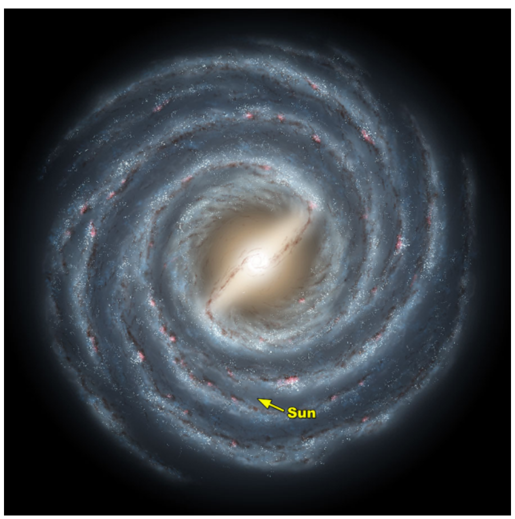
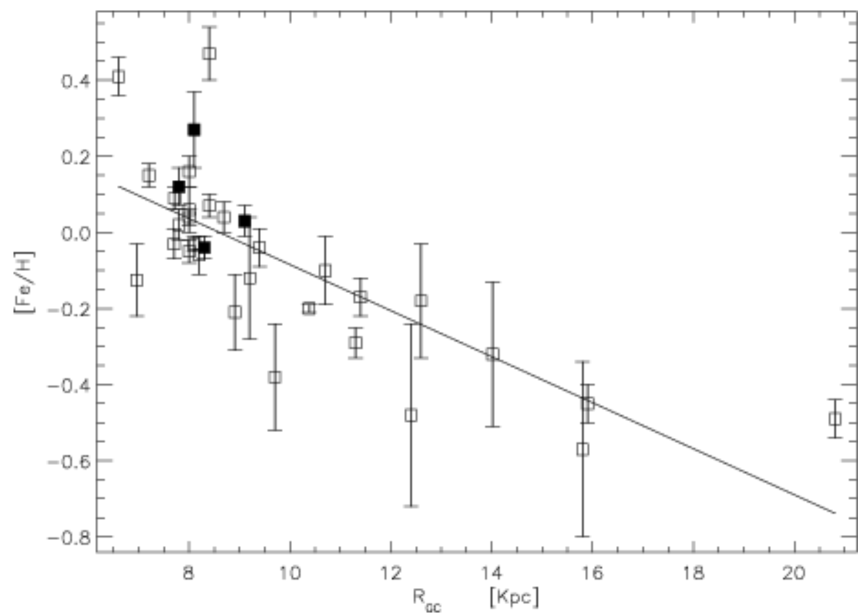
The Galaxy has a radial metallicity gradient



Metallicity



Galactocentric

Let's summarize

Successive ge... y in metals
An c... ed

Pop... s
Bulge stars bre... nd metal rich.
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The Galaxy has a radial metallicity gradient

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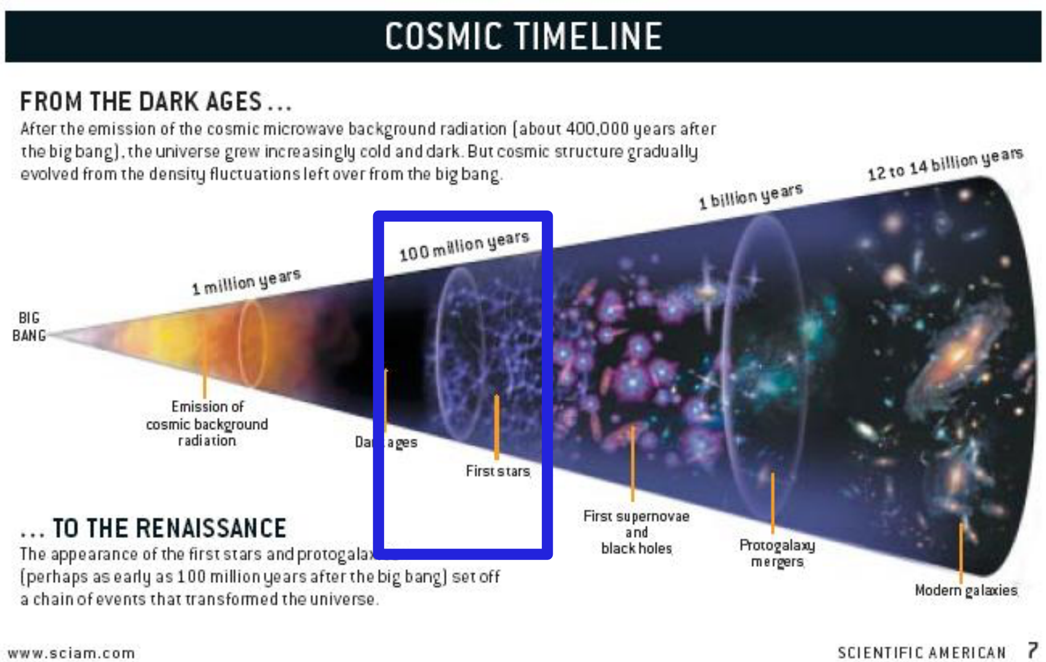
Pop II – metal poor, old

Pop III – metal free, extinct

Population III stars - Metal free, the first stars



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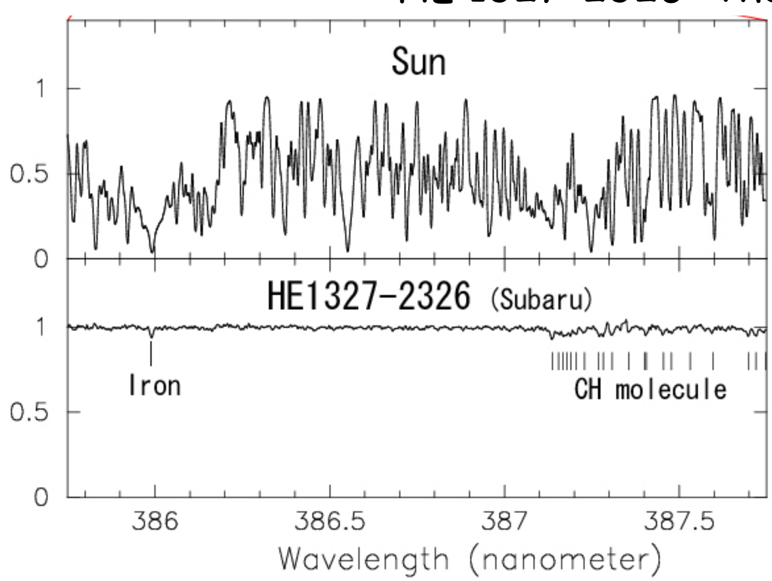
Population III stars – Metal free, the first stars

HE 1327-2326: The most metal poor star ever found



[Fe/H] = -5.2

300,000 times less Iron than the Sun

Star Formation

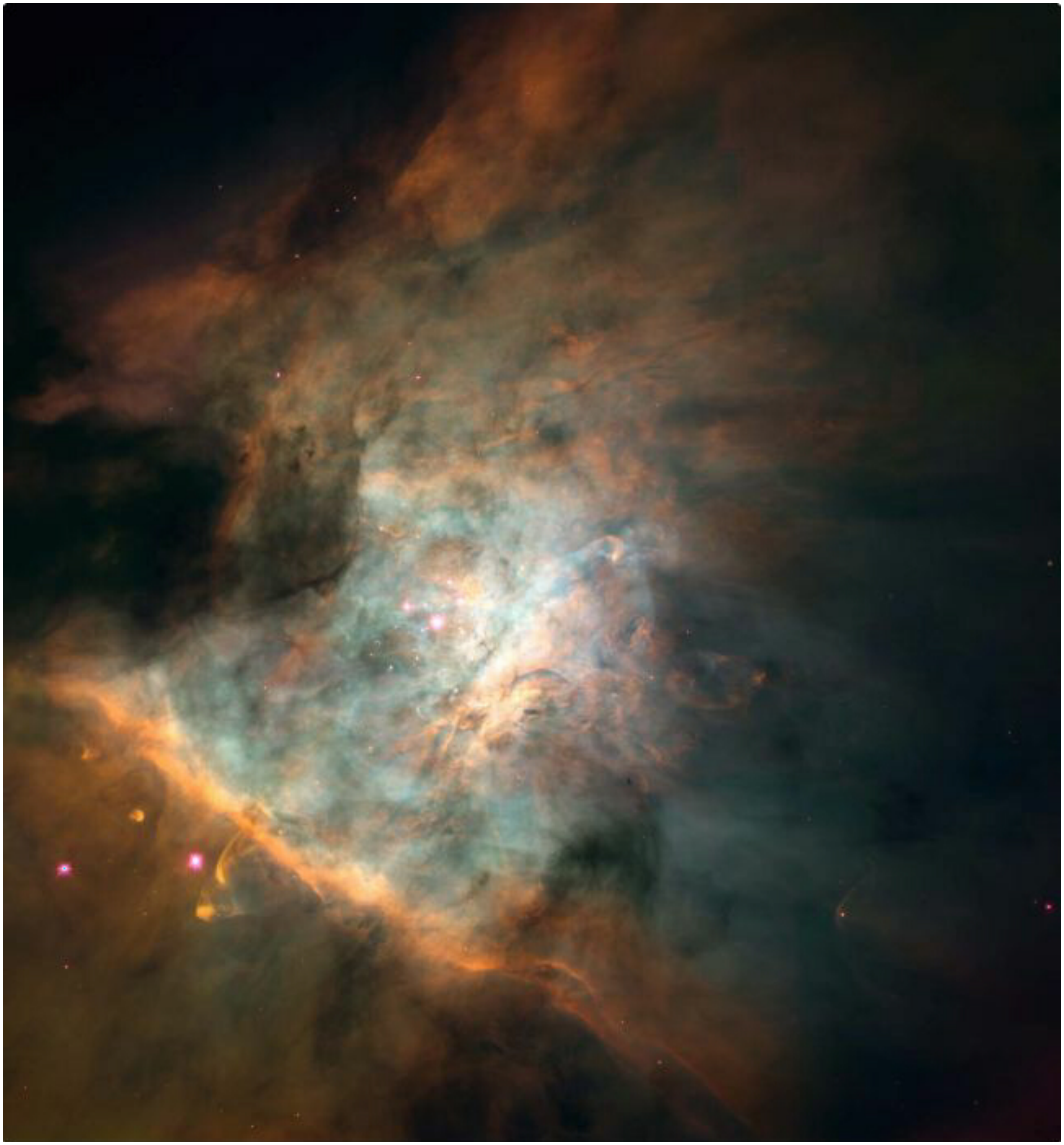
The space between stars is ***NOT EMPTY***, it is just very low density

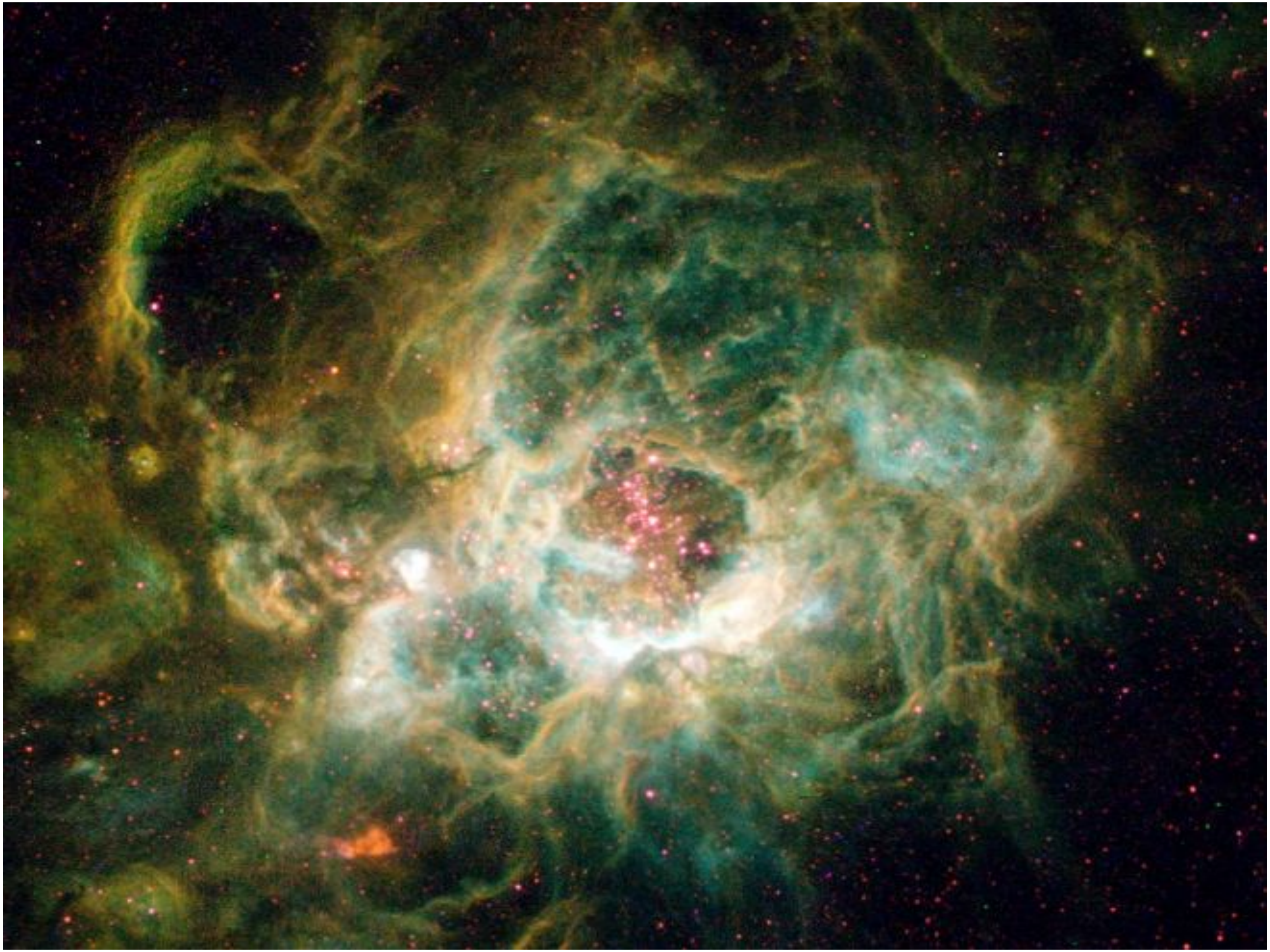
Some of it is gas (99%), some of it is dust (1%).
This matter is called ***INTERSTELLAR MEDIUM (ISM)***

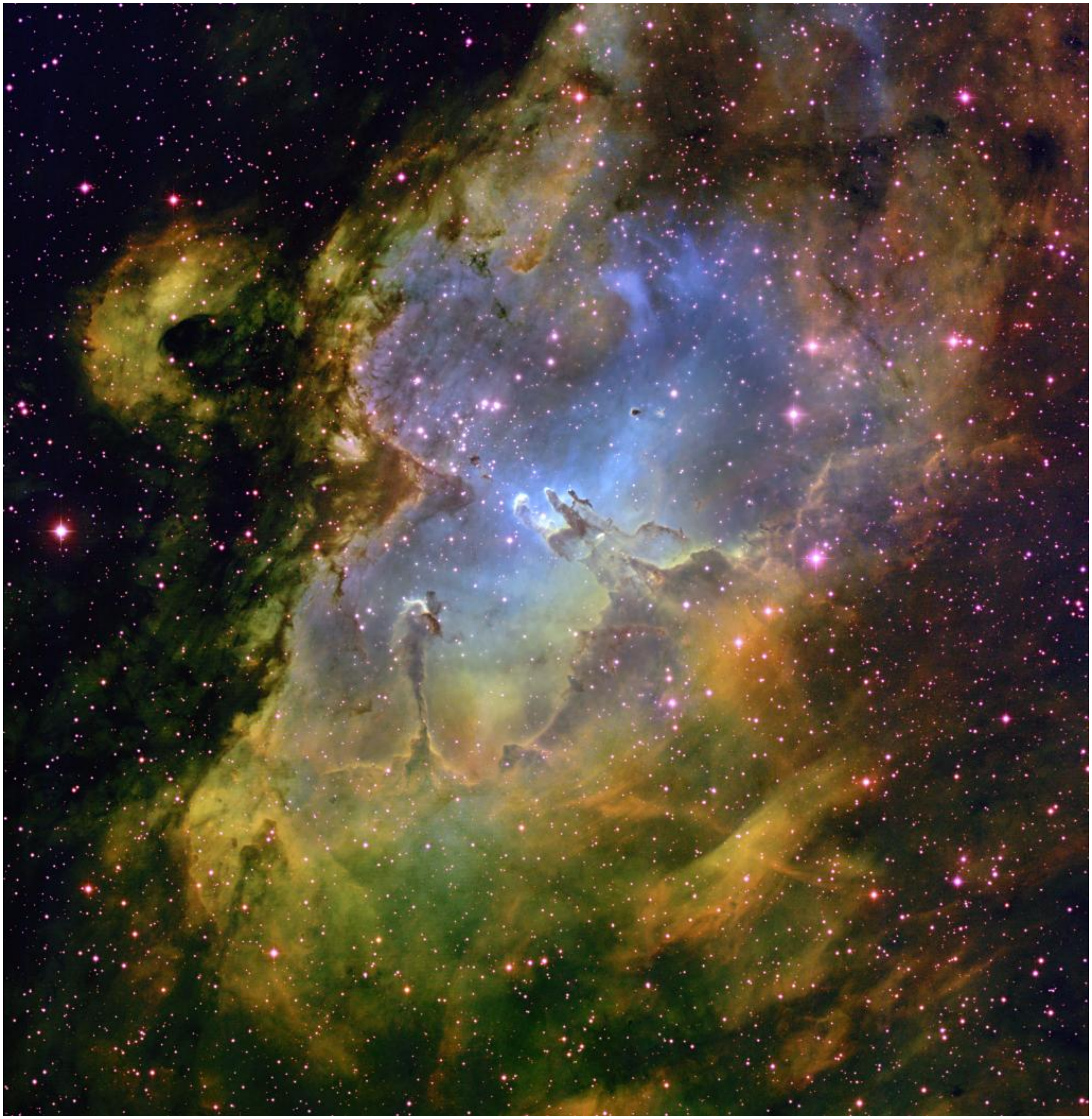
Star Formation

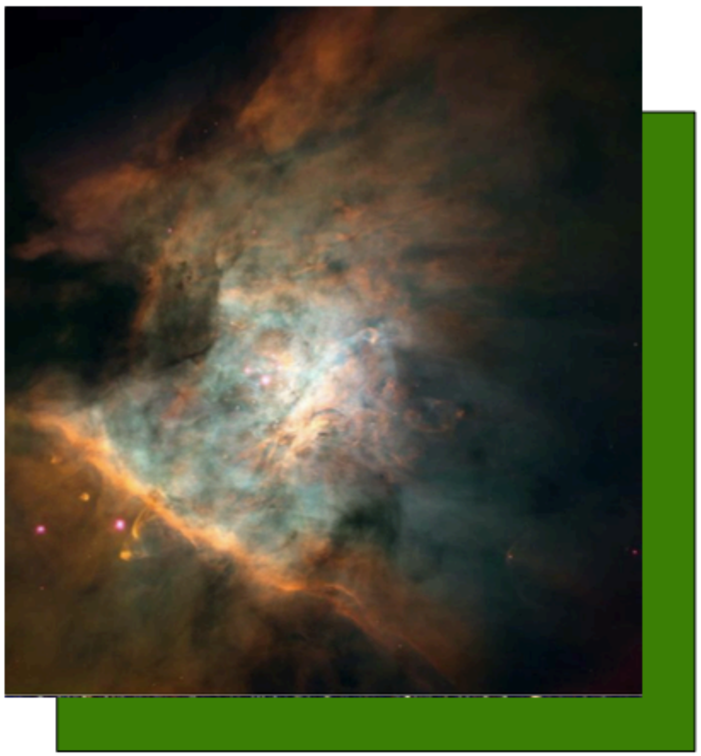
Gas collapses gravitationally, to form stars.

Star formation occurs in the ***densest regions of the ISM***, called ***Molecular Clouds***









Molecular Cloud Fact Sheet

Temperature	10-50 K
Density	$10^2 – 10^6$ atoms/cm^3
(ISM Density	1 atom/cm^3)
(Air density	**10^{19} atoms/cm^3**)

Irregular and turbulent

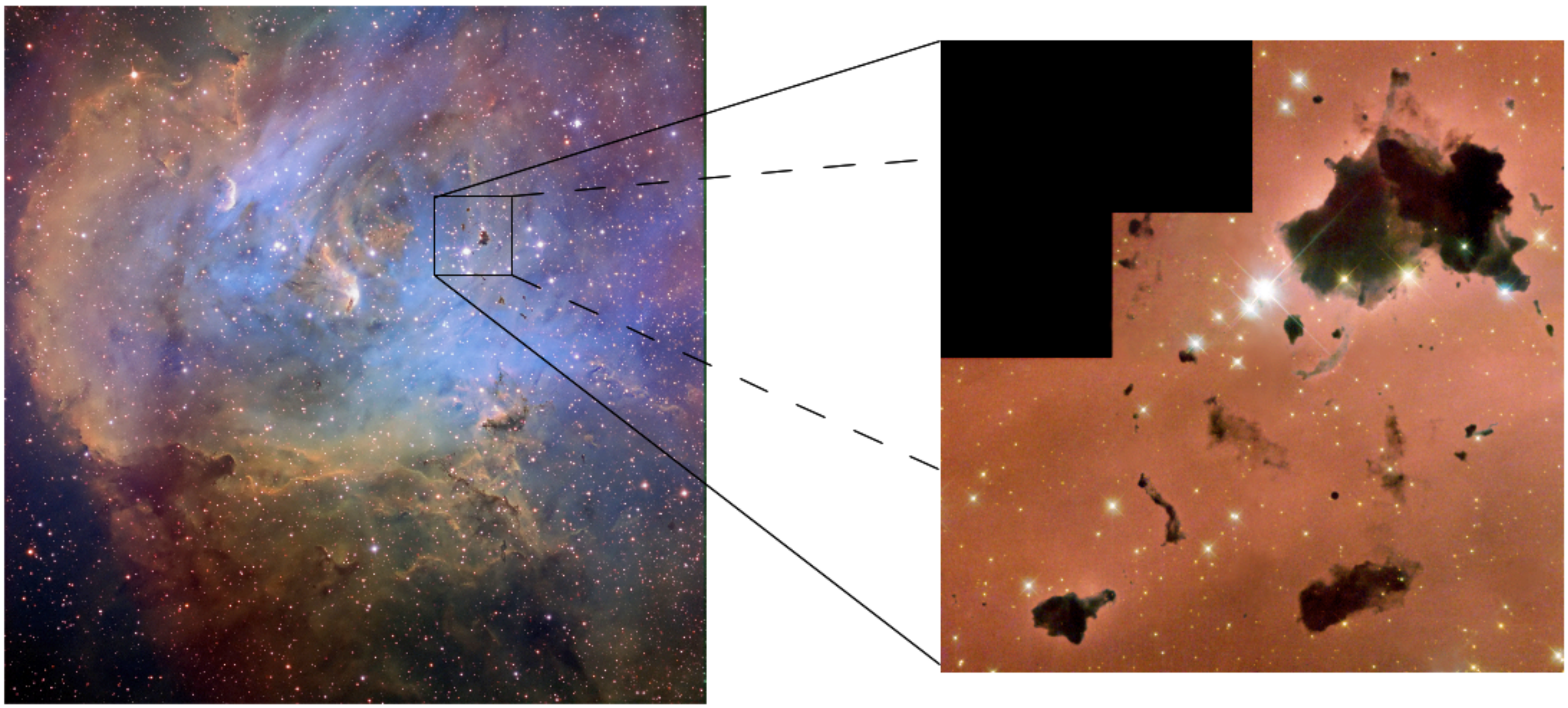
Sizes	10-100 parsecs
Mass	$10^2 – 10^6$ solar masses

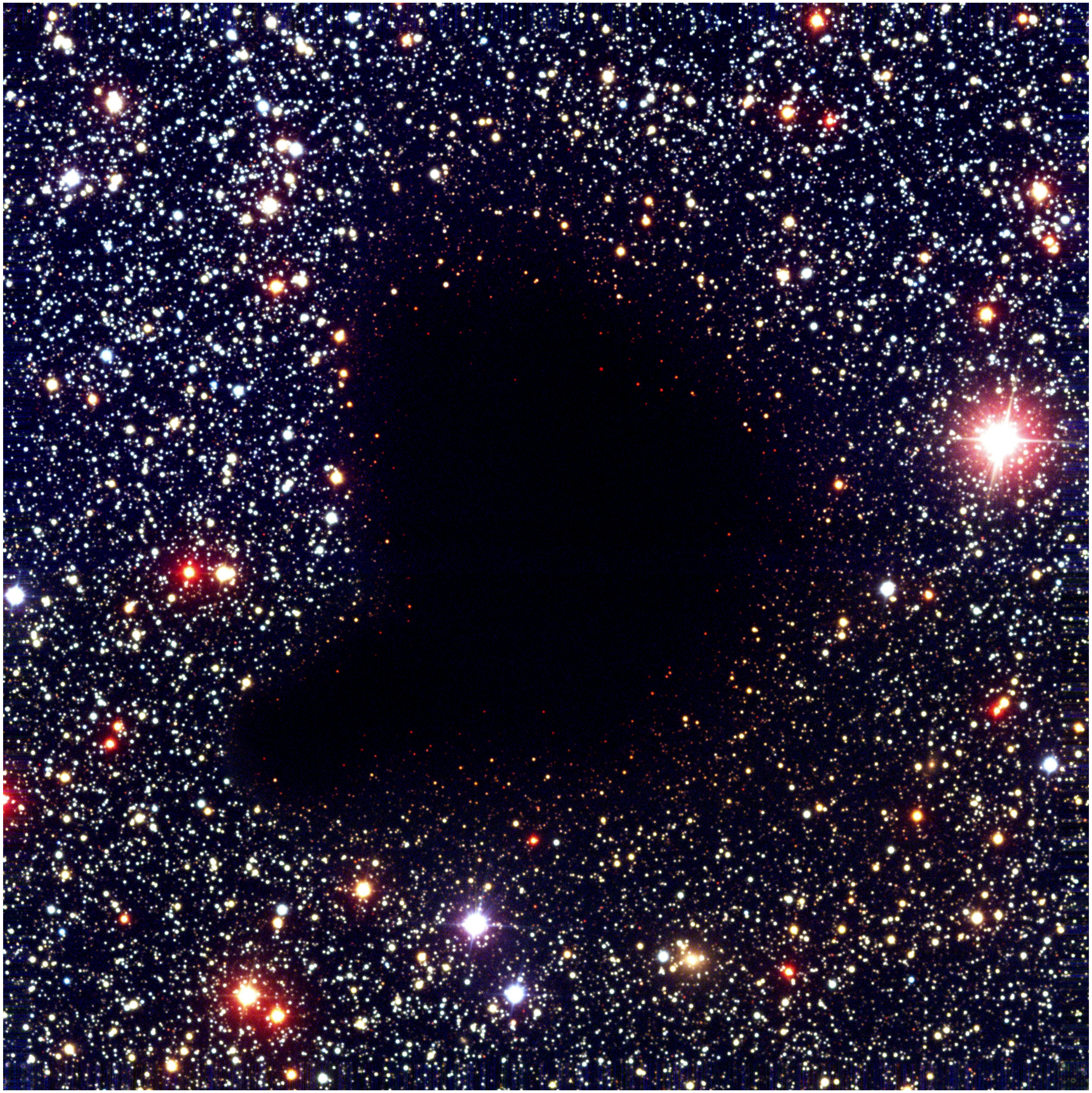
Star Formation

Star formation occurs in the densest regions of the ISM, called Molecular Clouds

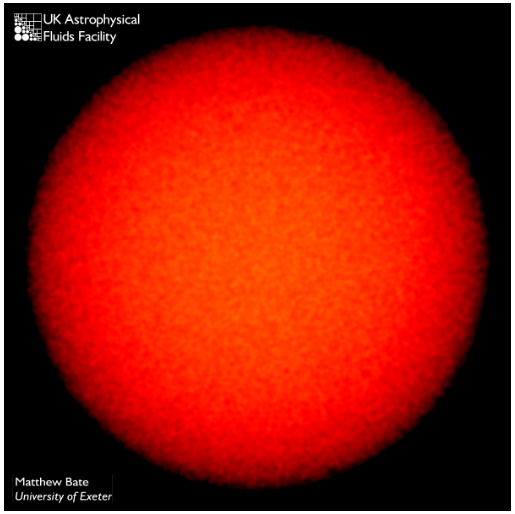
Even the average density of Molecular Clouds is too low.

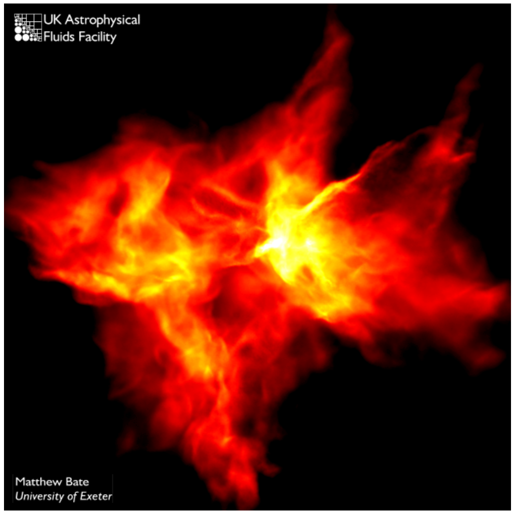
Star formation occurs in the ***densest parts of the cloud only***.

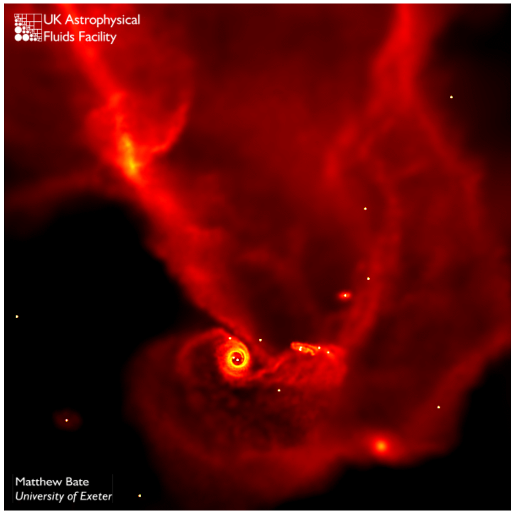




Star Formation



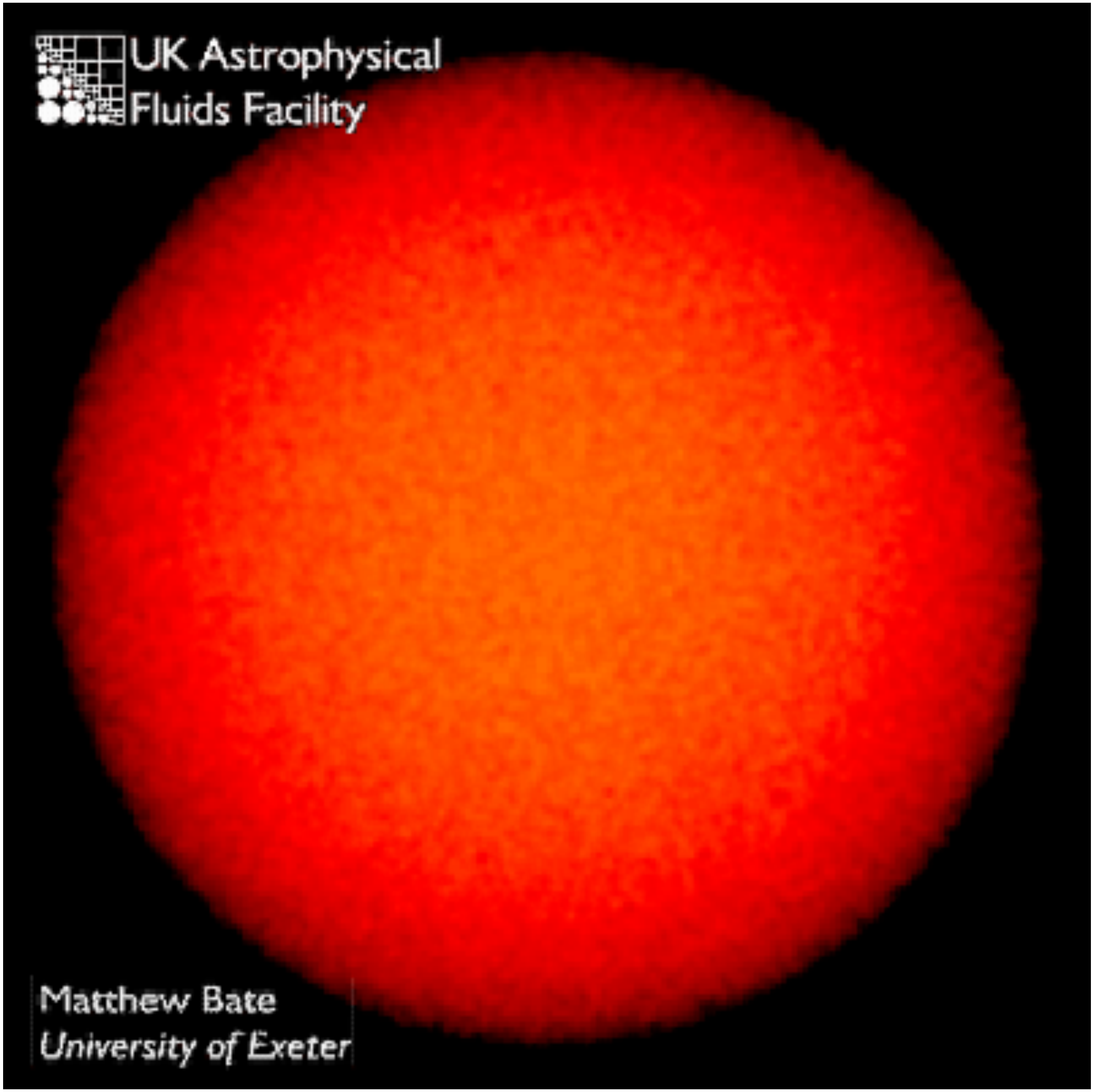




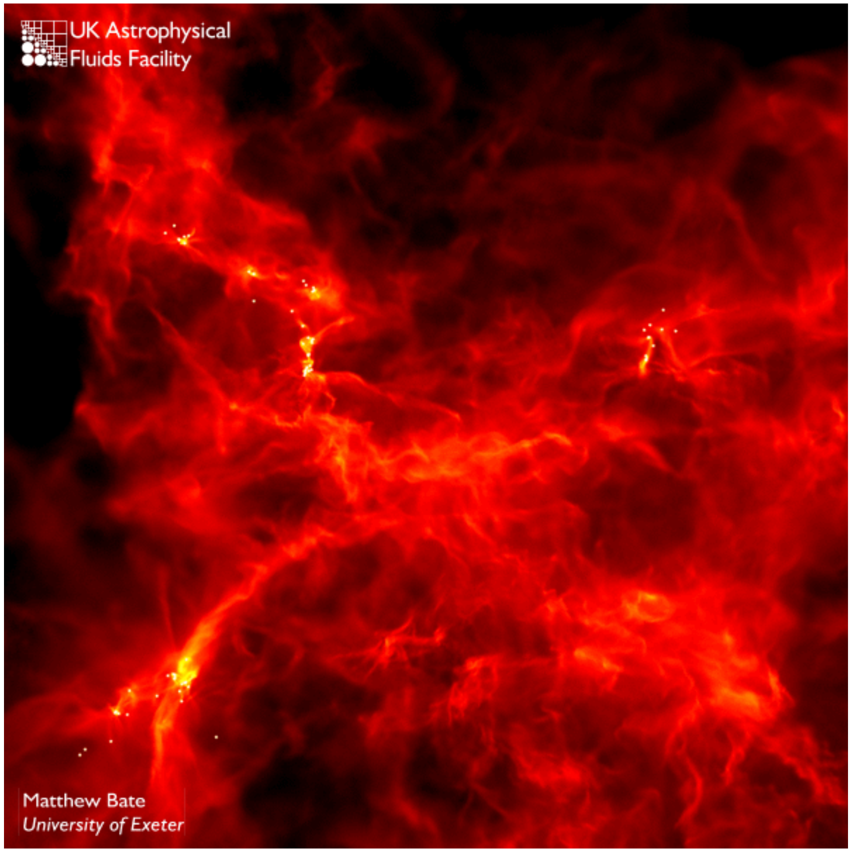
time

A Molecular cloud fragments into a clumpy structure of high and low density regions

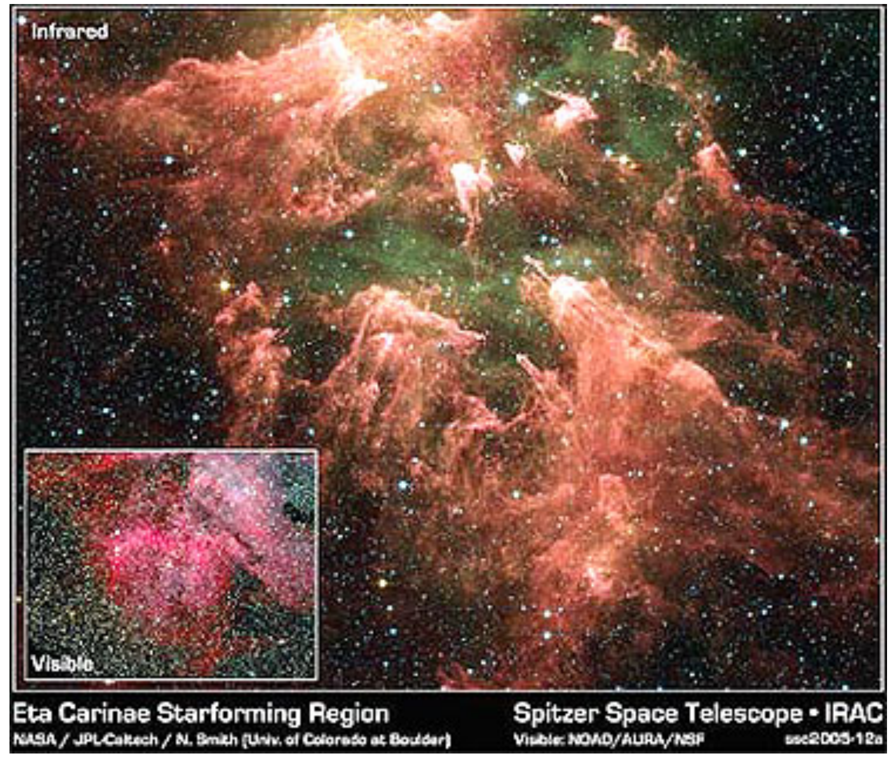
The densest clumps are massive enough to undergo gravitational collapse and form stars


UK Astrophysical
Fluids Facility
Matthew Bate
University of Exeter

Star Formation



Computer simulation

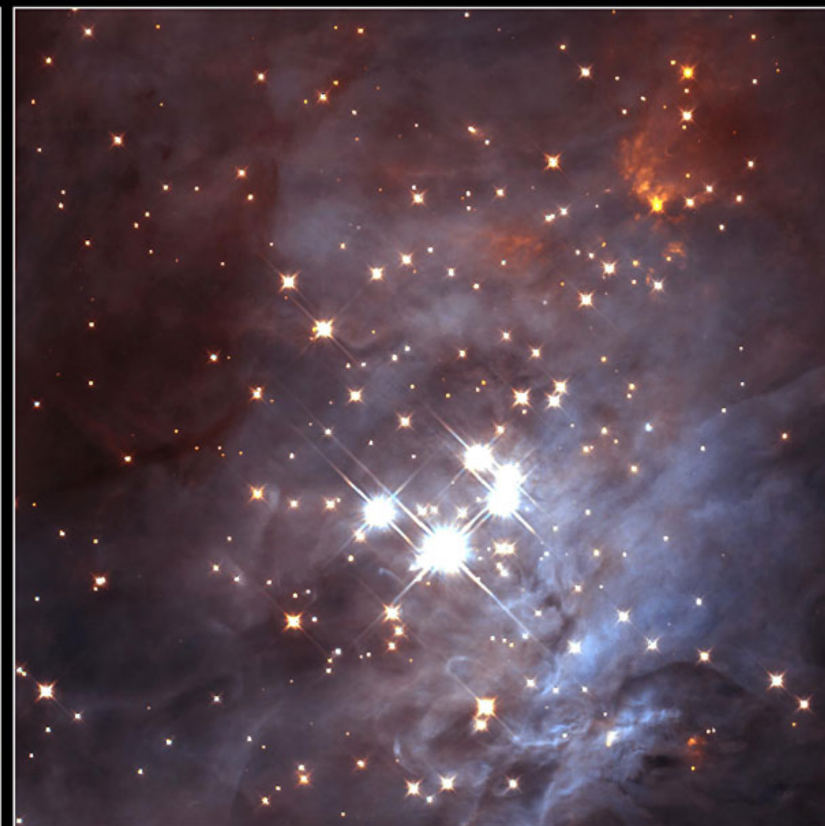


Observation


The Orion Nebula
HUBBLESITE.org

Visible • WFPC2

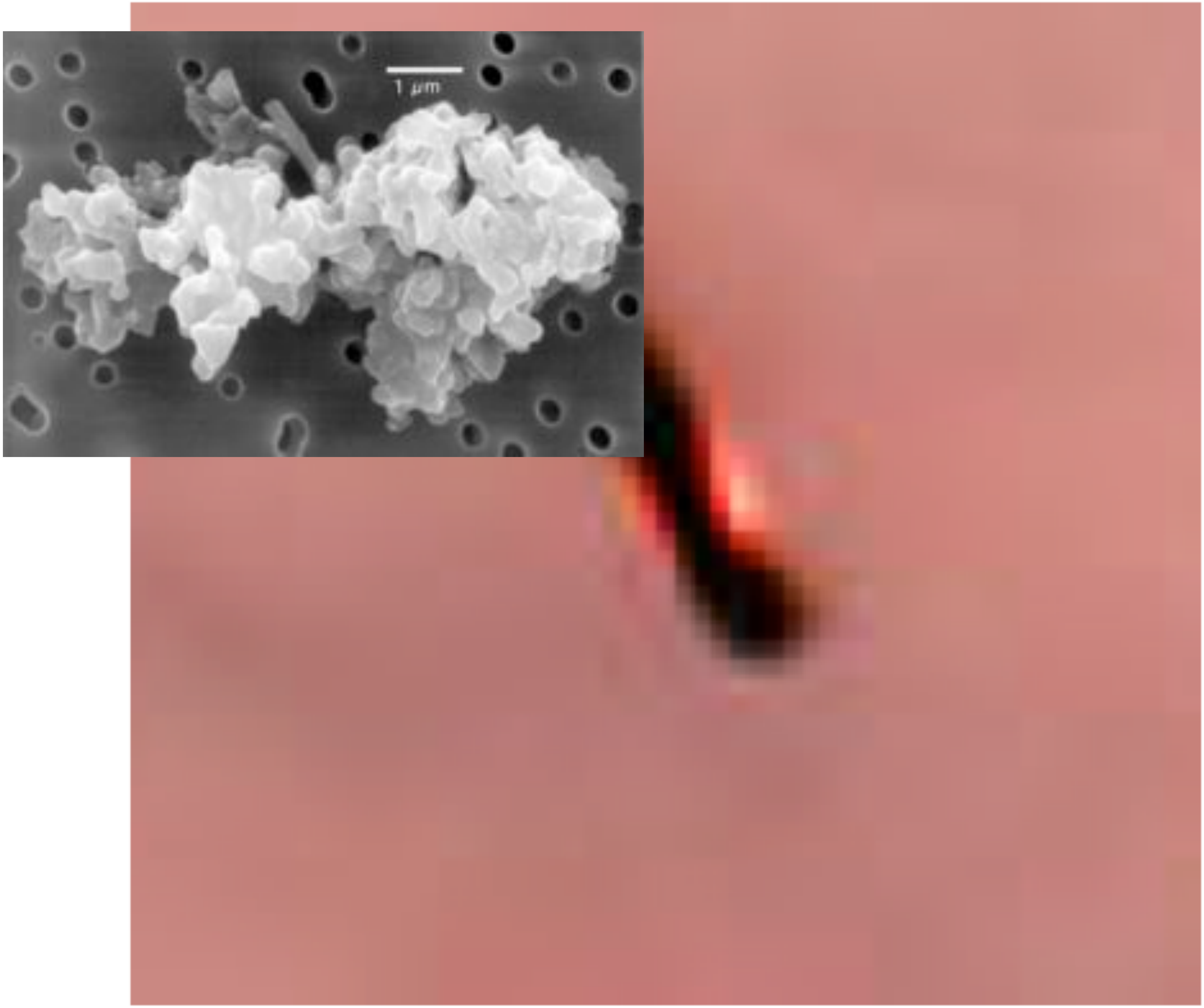
Infrared • NICMOS

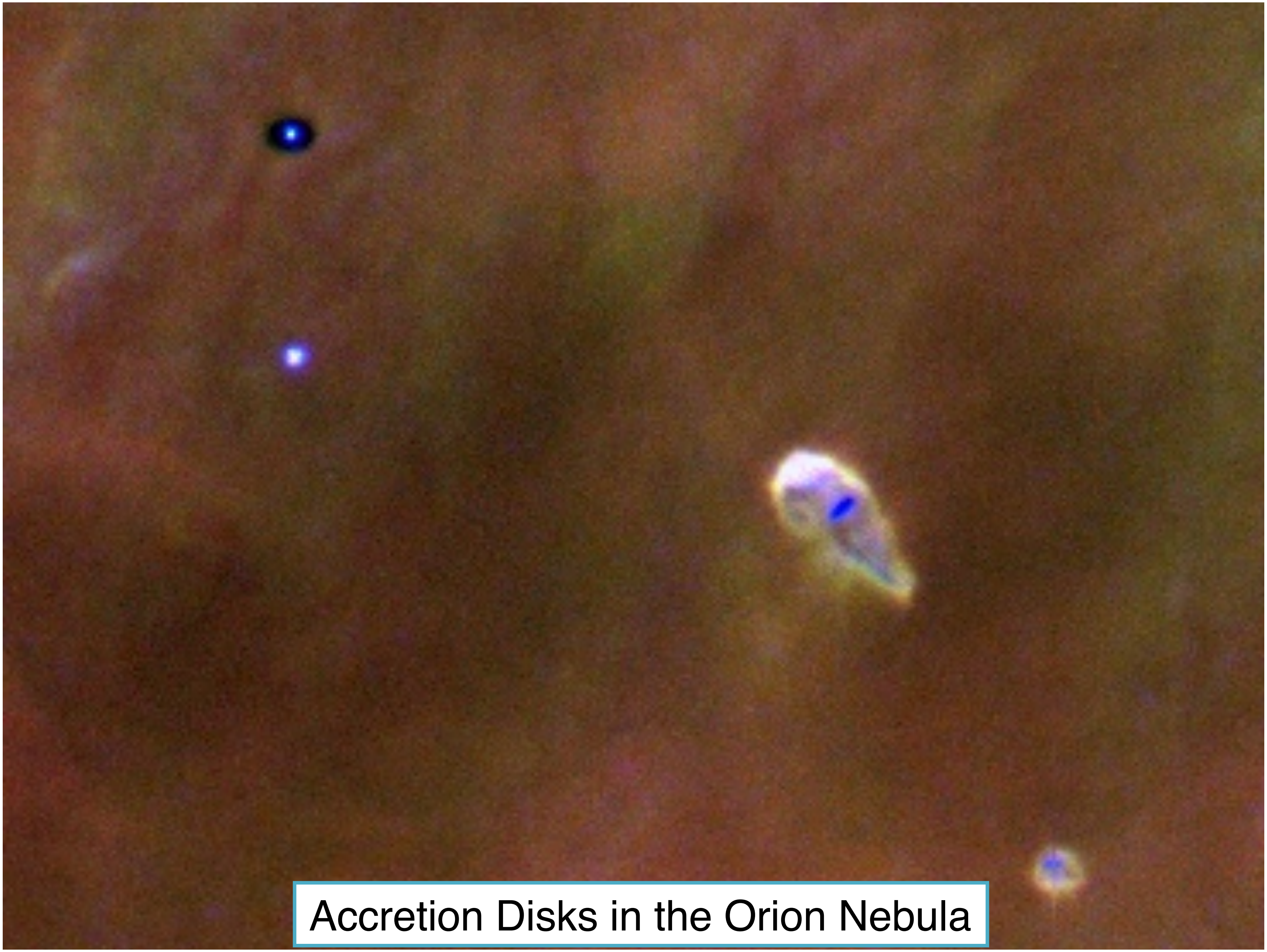


Trapezium Cluster • Orion Nebula

WFPC2 • **Hubble Space Telescope** • NICMOS

NASA and K. Luhman (Harvard-Smithsonian Center for Astrophysics) • STScI-PRC00-19


1 µm



Accretion Disks in the Orion Nebula

Protoplanetary Disks

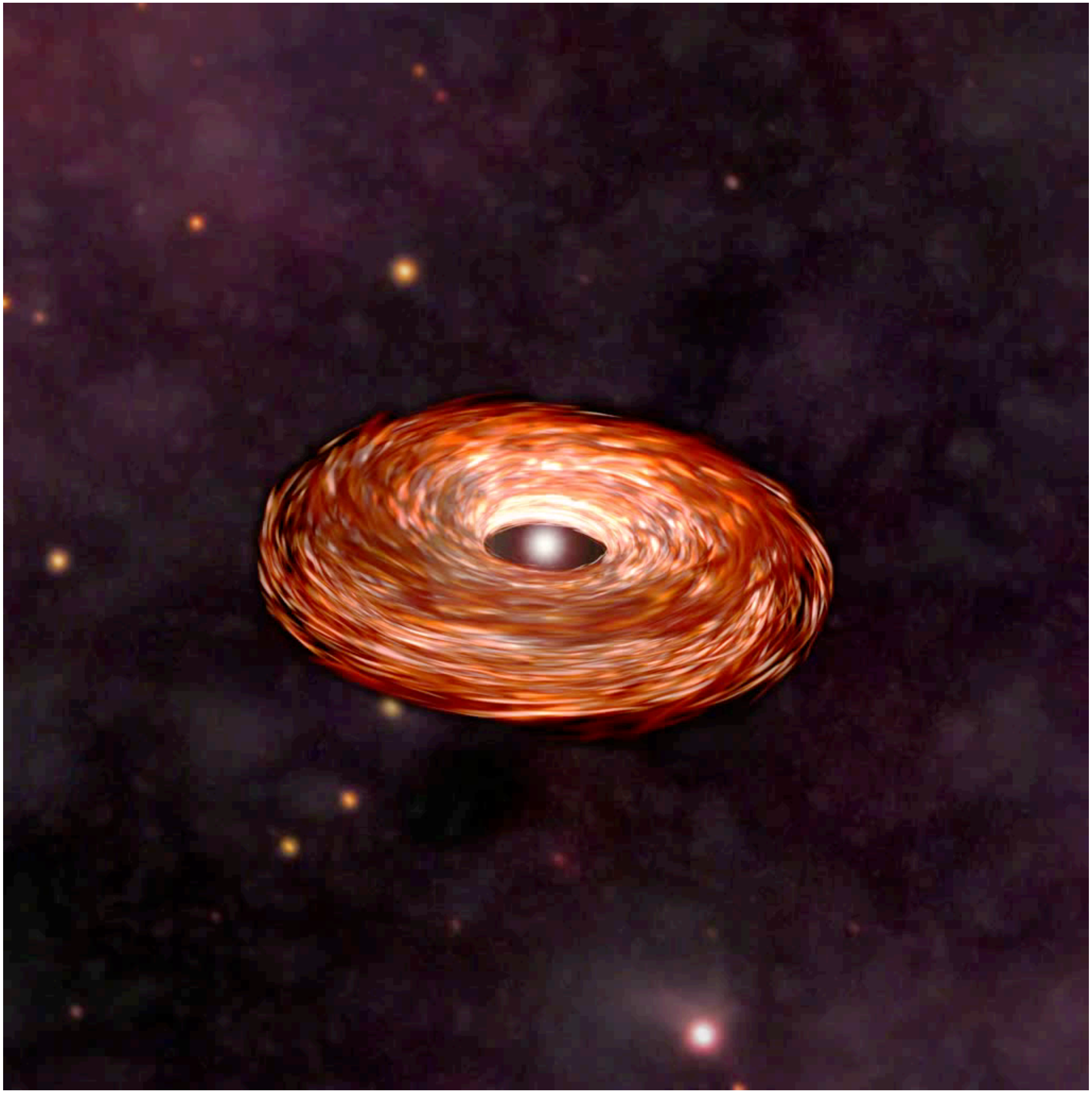
PP disk fact sheet

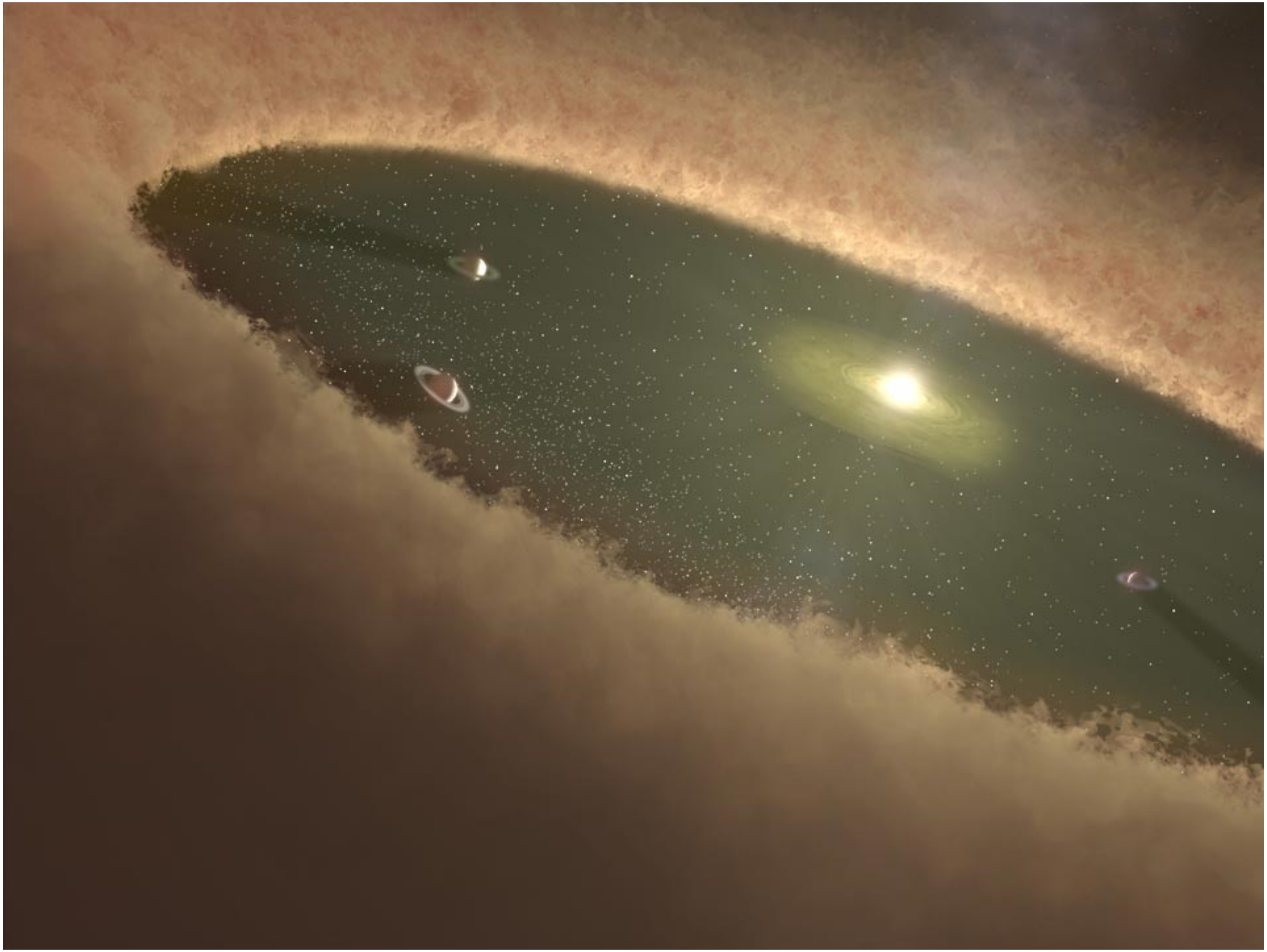
Density: $10^{13} – 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

Scale: 0.1-100AU
(1 AU = 1.49 x 10^{13} cm)

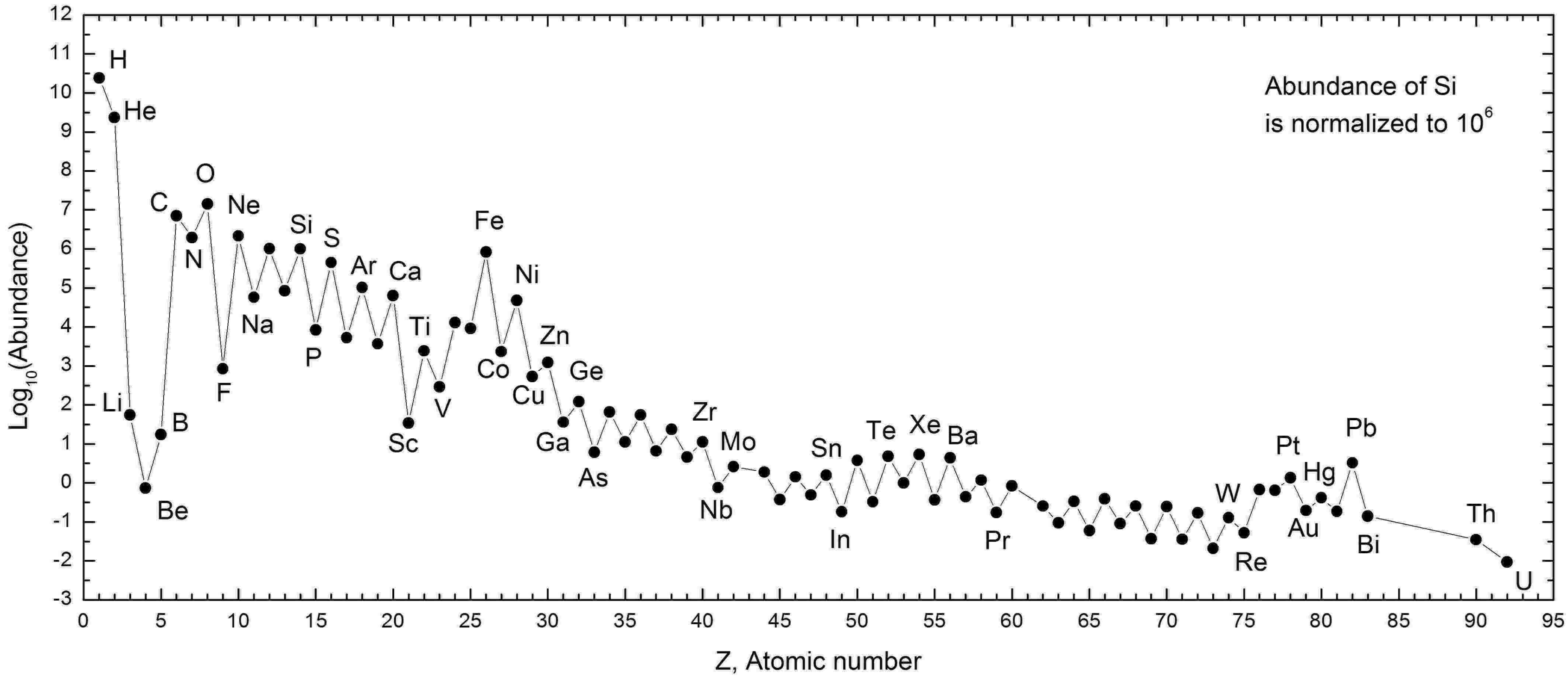
Mass: $10^{-3} – 10^{-1}$ M_{sun}
(1 M_{sun} = 2 x 10^{33} g)





Chemical Composition

The chemical composition of the Sun



<u>Most abundant elements, in order:</u>

H (71%) He (27%)

0 (1.04%) C (0.46%)

Ne (0.13%) Fe (0.11%) N (0.1%)

Si (0.06%), Mg (0.05%), S (0.04%)

What will the chemistry of the mixture be?

H (71%)

He (27%)

0 (1.04%)

C (0.46%)

Ne (0.13%)

Fe (0.11%)

N (0.1%)

Si (0.06%)

Volatiles

Refractory

What will the chemistry of the mixture be?

H H H H H He H H H H H H H H H H H H H H H H H H H H H H H He H
H H H H H H H H H H H H H H H H H He H H H H H H H H H H H O H
H H H H H H H H H H H H H H H H H H H H H H H H H H H H H H H H
C H H H H H H H H He H H H H H H H H H H H H H H H H H H H H H
H H H H H H H H H H H He H H H H H H H H H H H H H H H H H H H
H H H H H H He H H H H H H H H O H H H H H H H H H H H H H H H
H H He H H H H H O H H H H H H H H H H H H H H H H H H H H H Ne
H H H H H H H H H H H H H H H H He H H H H H H H H H H H H H H
H H H H H H H H H H H H H H H H He H H H O H H H H H H H H H H
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H H H H H H H H H H H H H H H H H H H H H H H H H H H H H H H H
H H He H H H H H H H H H H H H H H H H He H H H H H C H H H H H
H H H H H H H H H H H H H H H O H H H H H H H H He H H H H H H
H H H H H H H H H H H H H H H H He H H H H H H H H H H H H H H
H H H H H H H H He H H H H H H H H H H H H H H H H H H H H H C
H H H H H H H H H H H H H H H H H H H H H H H H H H H H H H He
H H H H H H H H H H H H H He H H H H He H H H H H H H H H H H
HH H H H H H H N H H H H H H H H H H H H H H H H H H H H H H H
H H H H H He H H H H H H O H H H H H H H H H H H H H O H H H H
H H H H H H H H H H He H H H H H H H H H H H H H H H H H H H H
H H H H H H H H H H H H H H H H O H H H H H H H H H H H C H H H
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H H H H H H H H H H H Fe H H H H H H H H H H H H H H H H H H H
H H H H H H H H H H

H_2

He

H_20

CH_4

Ne

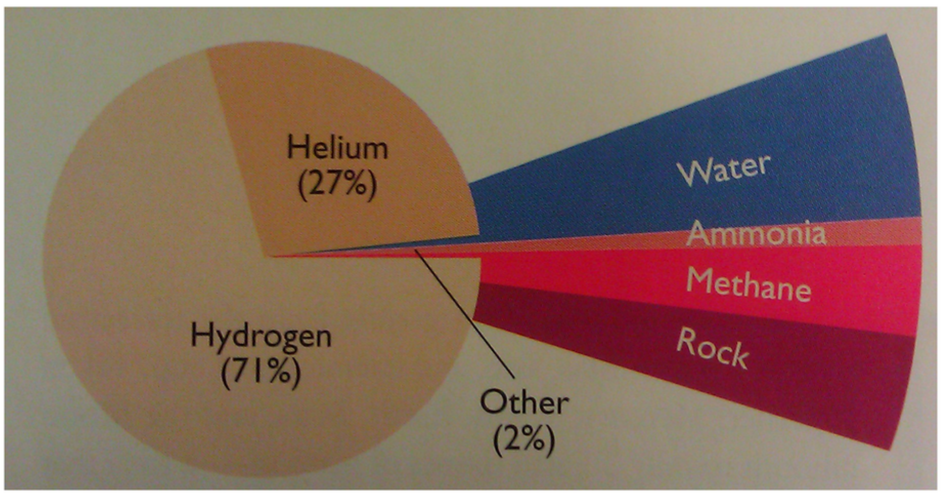
NH_3

Fe, Si

What will the chemistry of the mixture be?

H (71%)
He (27%)
0 (1.04%)
C (0.46%)
Ne (0.13%)
Fe (0.11%)
N (0.1%)
Si (0.06%)

H_2 He
H_20 - Water
CH_4 - Methane
Ne
NH_3 - Ammonia
Fe, Si – Rocks (metals and silicates)



Classes of planets

Rocky Planets

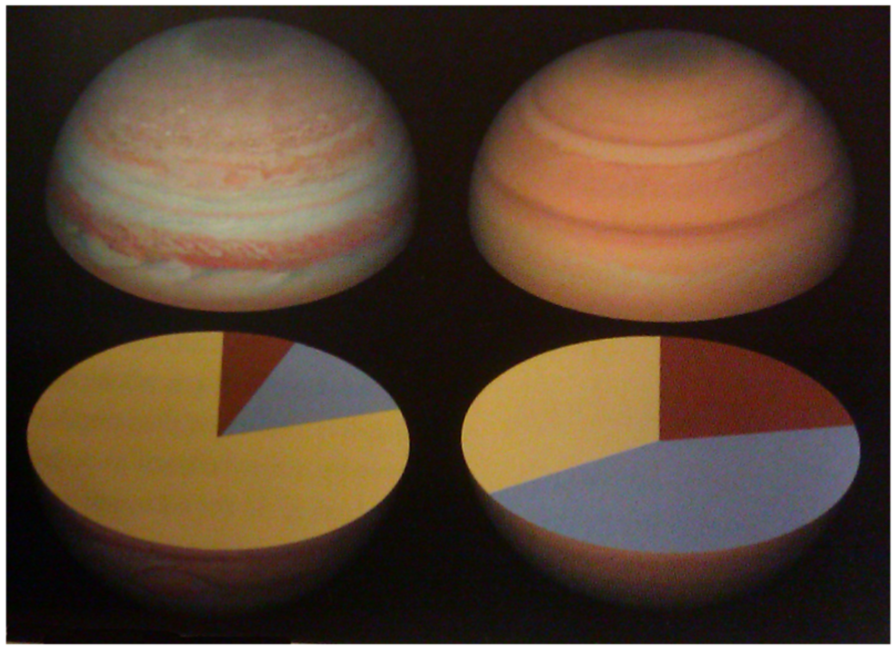
Gas Giants

Ice Giants

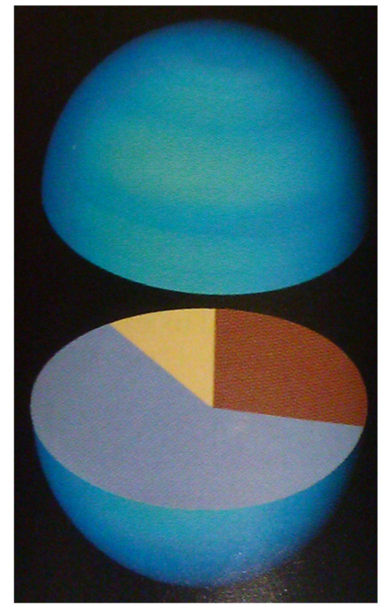
Earth

Jupiter

Saturn



Uranus/Neptune

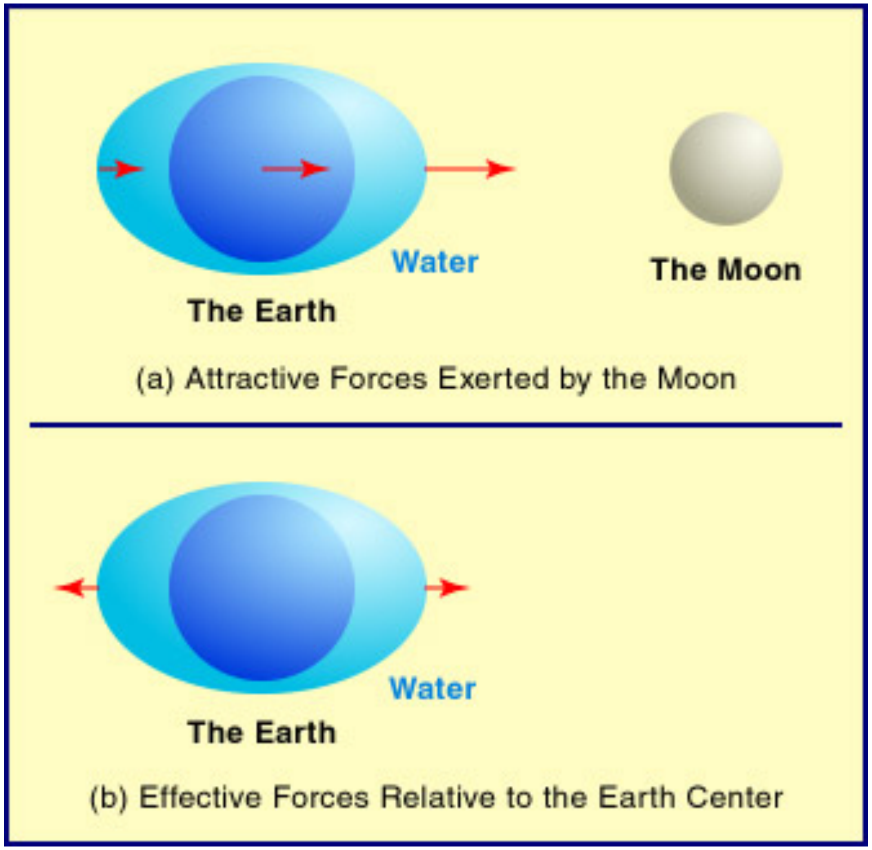


Rock

Gas

Ice

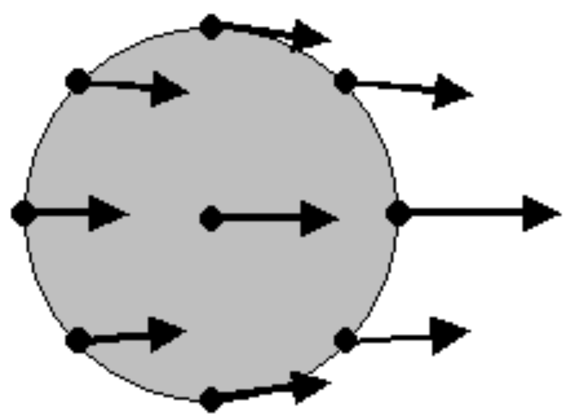
Tides



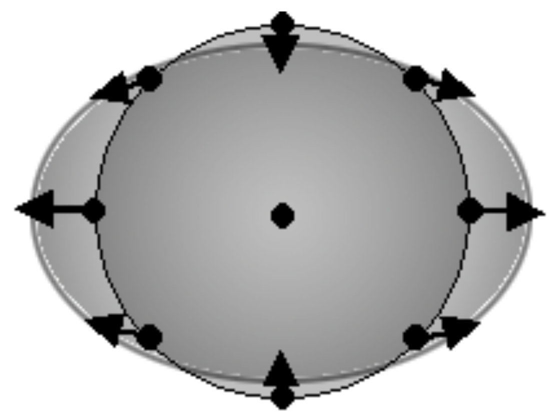
The side closer to the Moon experiences a greater pull than the side further out.

The effective result is a *differential* force we call **Tidal Force**.

Tides

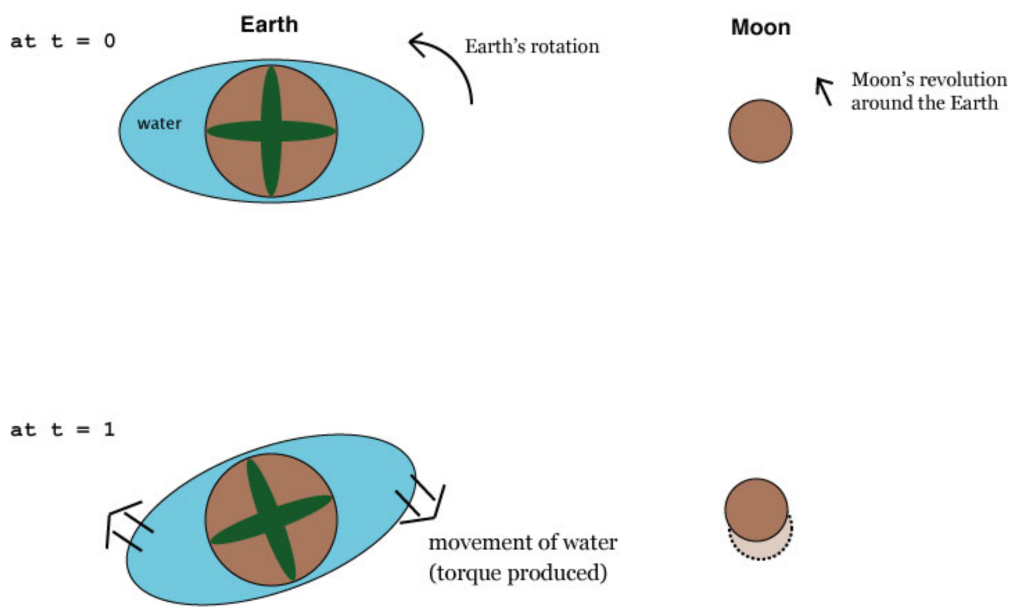


Forces relative to the Sun (or primary body)



Forces relative to the center of the Earth

Tidal locking



Earth's bulk rotates once a day.

Tidal bulge rotates with the Moon's orbital period: once a month.

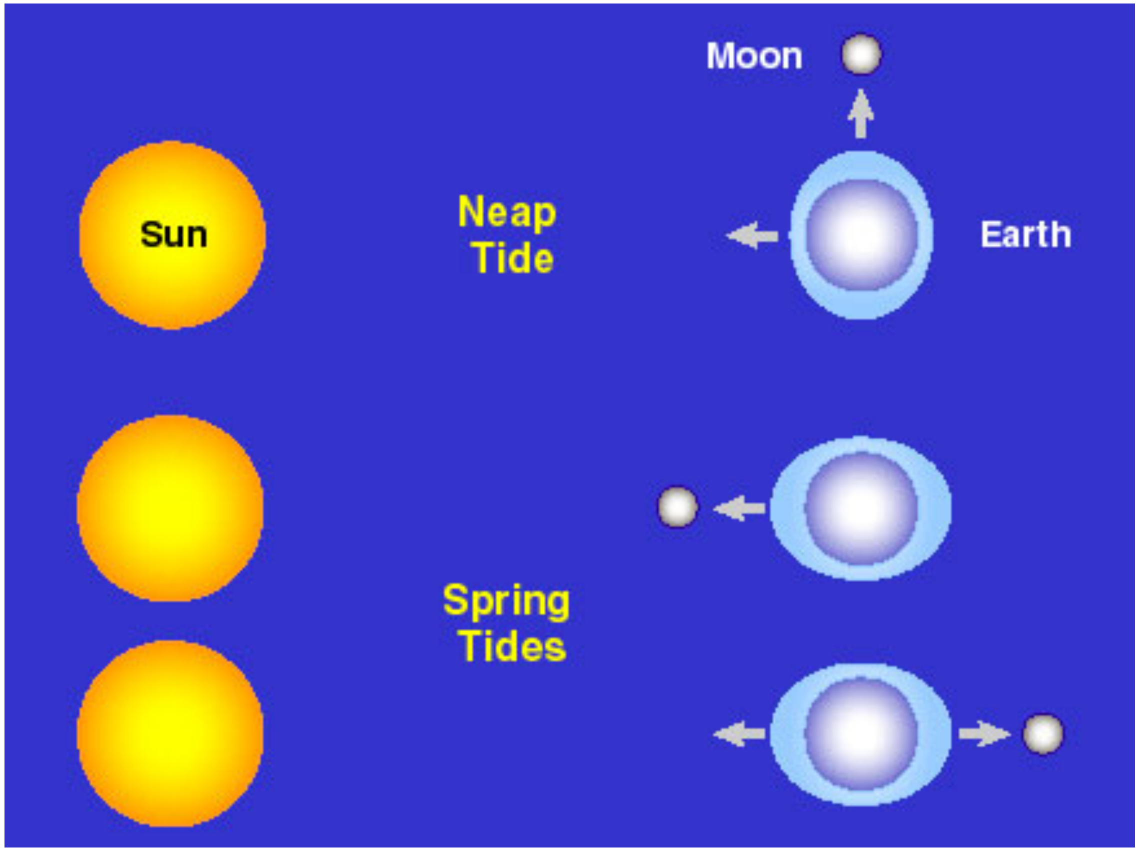
GENERATES FRICTION

Works as a brake that slows down Earth's rotation

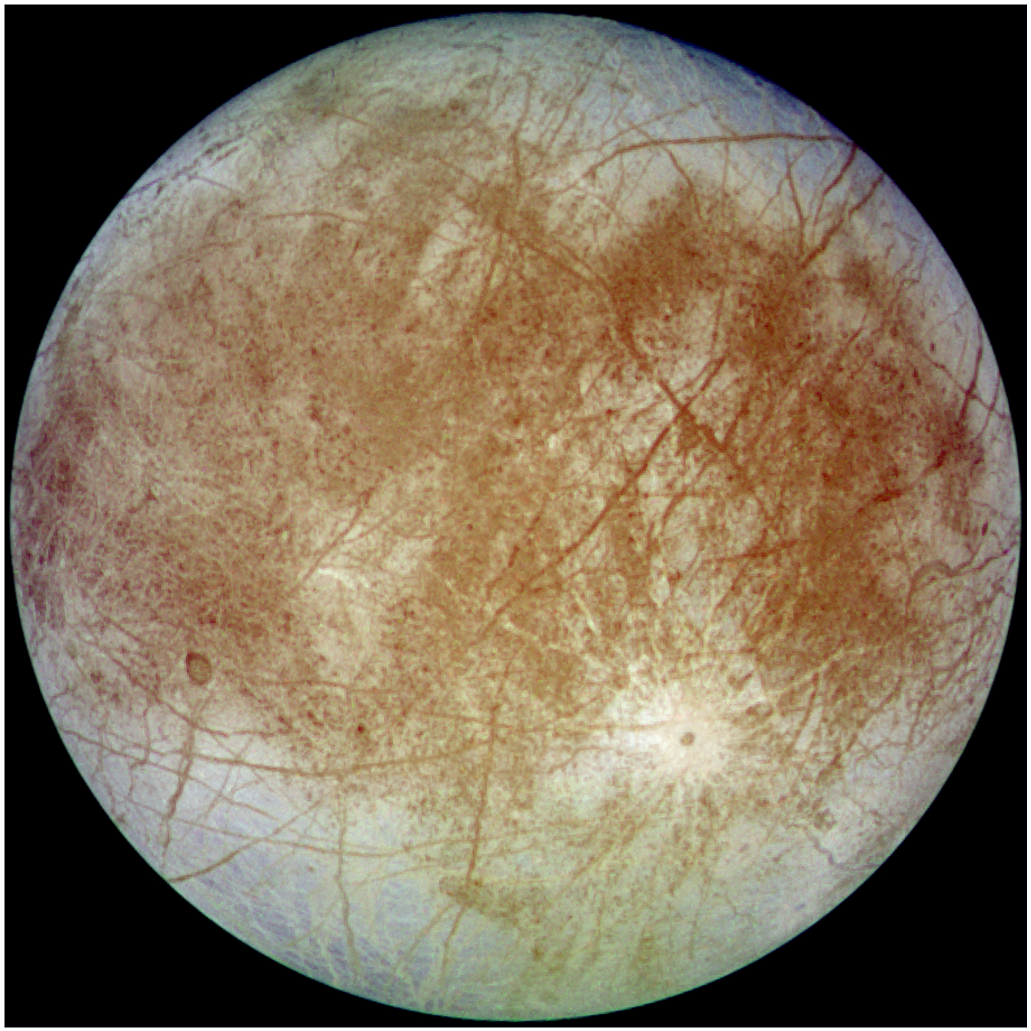
The process will continue until Earth's rotational period equals the orbital period of the Moon.

(The Earth has already tidally locked the Moon long ago.)

Tides

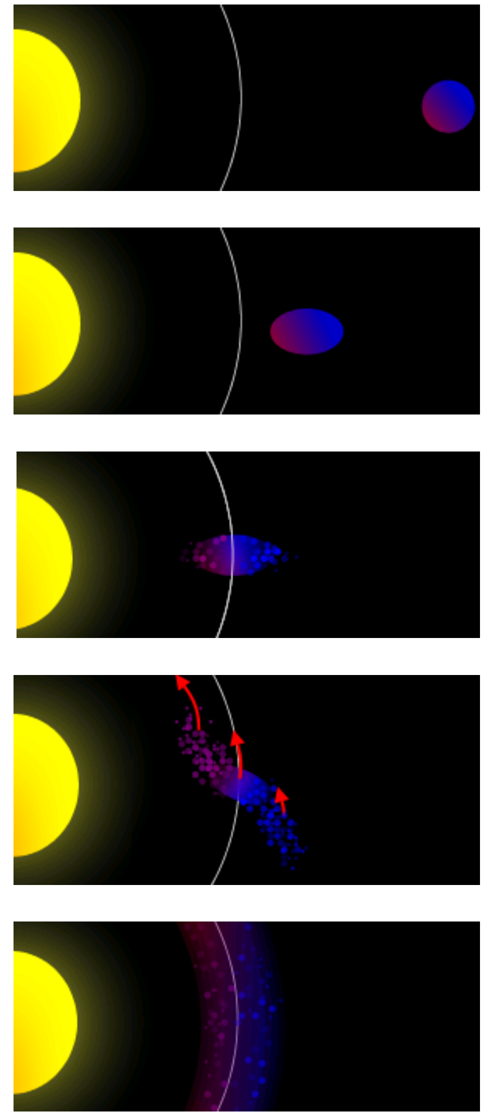


Europa

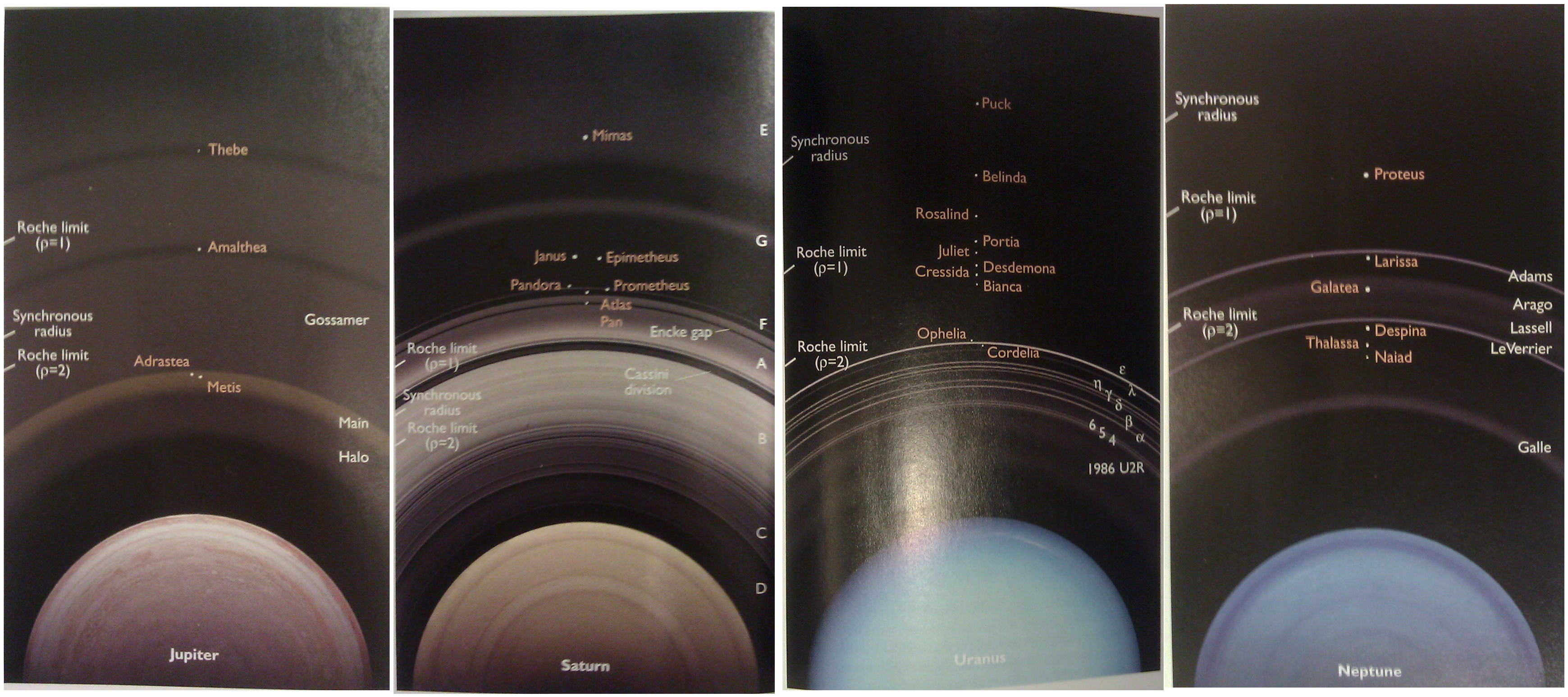


Roche Limit

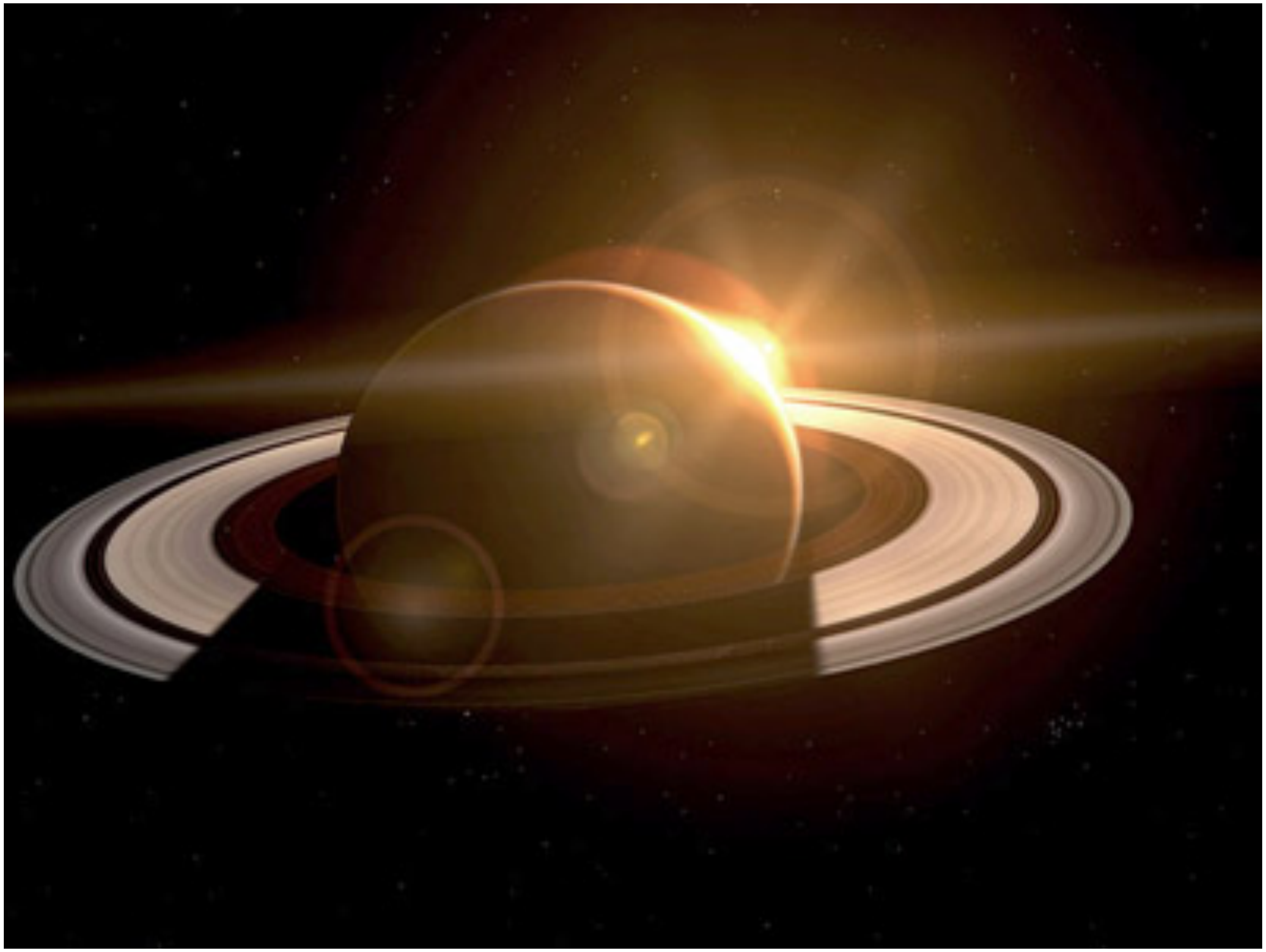
Limit where the
tidal force is **stronger** than the internal forces
holding the body together



All ring systems are inside their planet's Roche limit

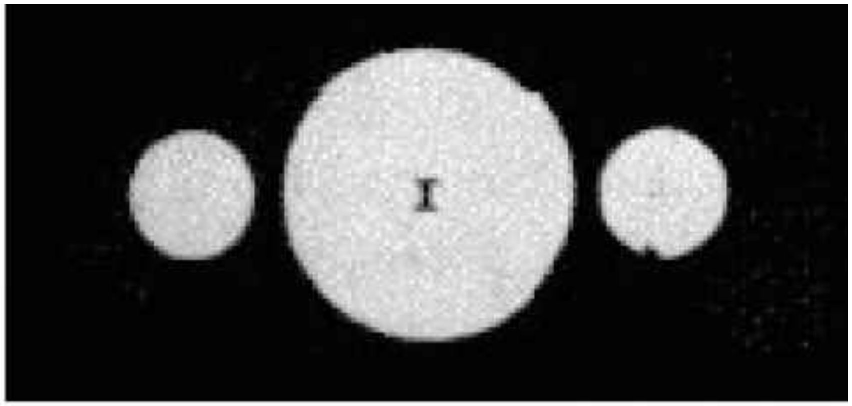


Planetary Rings



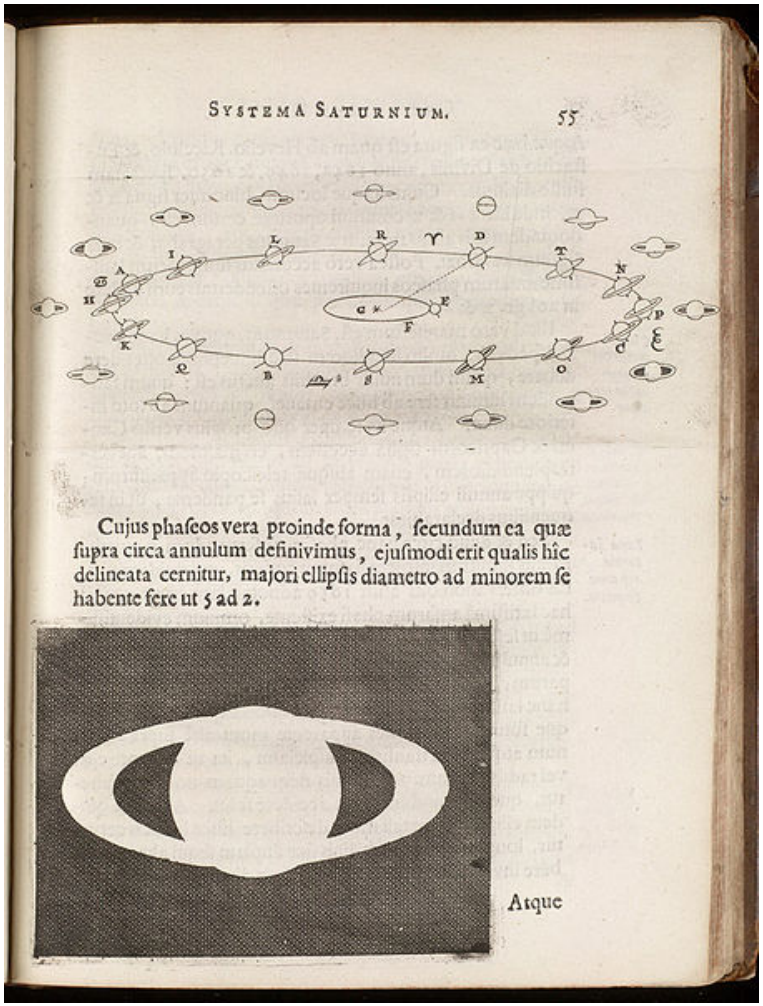
Planetary Rings

Galileo's drawing, 1610.



"I do not know what to say in a case
so surprising, so unlooked for, so novel."

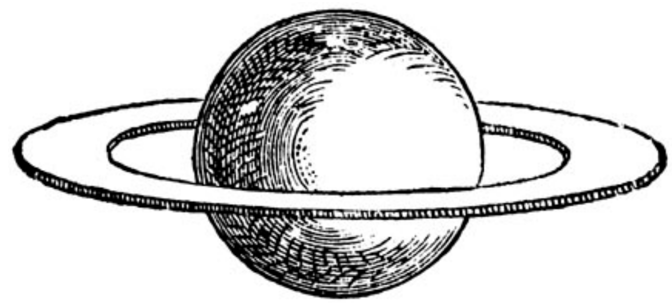
Planetary Rings


SYSTEMA SATURNIUM. 55

Cujus phaſeos vera proinde forma, ſecundum ea quæ ſupra circa annulum definivimus, ejuſmodi erit qualis hîc delineata cernitur, majori ellipſis diametro ad minorem ſe habente fere ut 5 ad 2.

Atque

Huygens's drawings, 1659.



“Saturn is surrounded by a thin flat disk, nowhere touching the planet”

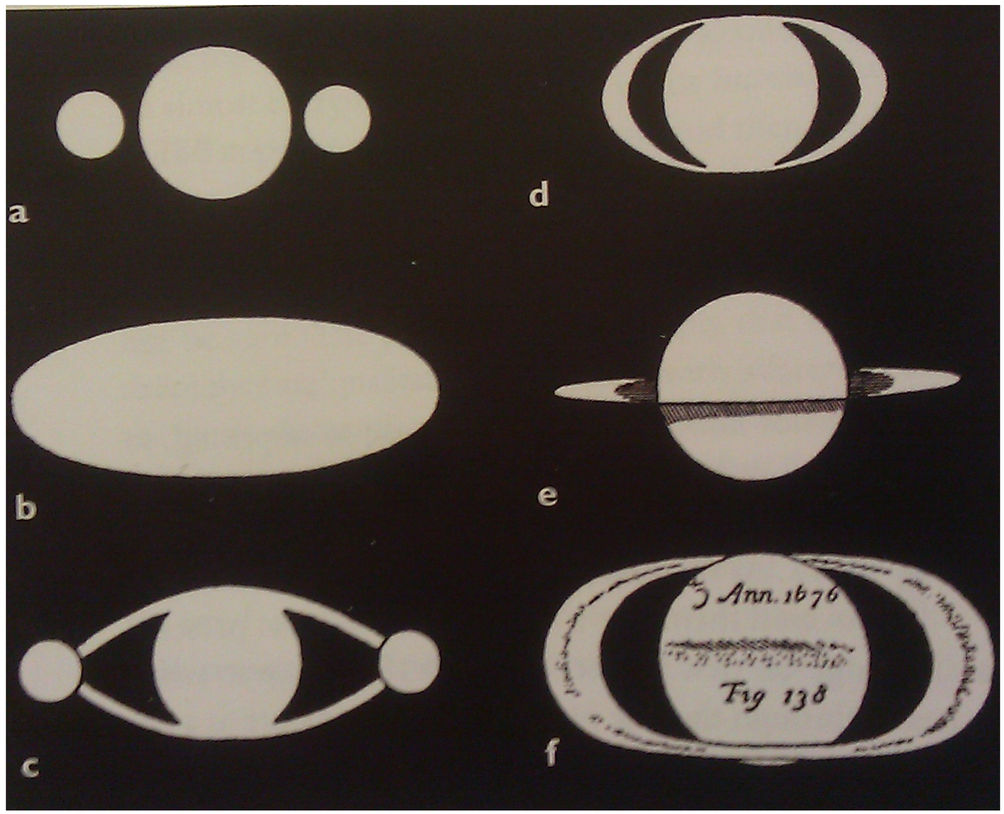
Planetary Rings

Other drawings from the 17th century

Galileo, 1610

Gassendi, 1634

Fontana, 1646



Riccioli, 1648

Huygens, 1655

Cassini, 1676

Planetary Rings

What are these rings???

Solid? Liquid? Particulate?

Planetary Rings

Maxwell's proof

James Clerk Maxwell
(1831-1879)

Planetary Rings

Maxwell's proof

There are some questions in Astronomy, to which we are attracted rather on account of their peculiarity, […] than from any direct advantage which their solution would afford to mankind.

[…] I am not aware that any practical use has been made of Saturn's Rings […]

But when we contemplate the Rings from a purely scientific point of view, they become the most remarkable bodies in the heavens. [..] When we have actually seen that great arch swung over the equator of the planet without any visible connection, we cannot bring out minds to rest. […] We must explain its motion on the principles of mechanics.

[...]
60 pages of calculations
[...]

[…] We conclude, therefore, that the rings must consist of disconnected particles; these may be either solid or liquid, but they must be independent. […] The final result, therefore, of the mechanical theory is, that the only system of rings which can exist is one composed of an indefinite number of unconnected particles, revolving around the planet with different velocities according to their respective distances.

By A. Hall.

T	1859, May 29^{d}·0077	Washington M.S.T.	
Log q	9·303310		
ϖ	281° 58′ 10″·7	or	π = 75° 9′ 46″·1
☊	357 7 56·8		
i	95 50 56·8		ι = 84 9 3·2

Motion Retrograde.

The comet will probably be visible after its perihelion passage.

On the Stability of the Motion of Saturn's Rings; an Essay which obtained the Adams' Prize for the Year 1856, *in the University of Cambridge.* By J. Clerk Maxwell, M.A. late Fellow of Trinity College, Cambridge: Professor of Natural Philosophy in the Marischal College and University of Aberdeen. Cambridge: Macmillan and Co., 1859.

The following abstract of an important paper has been kindly drawn up by the Astronomer Royal for the use of the readers of the *Monthly Notices:*—

The remarkable essay of which we have given the title was published in the beginning of the present year. The subject of it is so interesting, the difficulty of treating it in its utmost generality so considerable, and the results at which the author arrives so curious, that we think a brief abstract of it will be acceptable to the readers of the *Monthly Notices.* We shall commence with a very imperfect reference to preceding investigations on the same subject.

The first to which we shall allude is Laplace's, in the *Mécanique Céleste,* livre III. chapitre vi. Laplace considers a ring of *Saturn* as a solid, the form of which is investigated as if it were fluid (a mode of treatment whose result, in respect of the form of equilibrium, is evidently good for a solid), and finds, that if the breadth and thickness of the ring are very small in comparison with its distance from *Saturn,* its section may be an ellipse; and it appears that the formula for the proportion of the axes of the ellipse admits of its being considerably flattened. But Laplace rather inclines to the supposition that there are several rings, each existing by its own proper theory. Then remarking on the appearances noticed by some observers which seem to indicate irregularities in the rings, he adds, "J'ajoute que ces inégalités sont nécessaires pour maintenir l'anneau en équilibre autour de *Saturne,*" and gives an in-

C

Planetary Rings

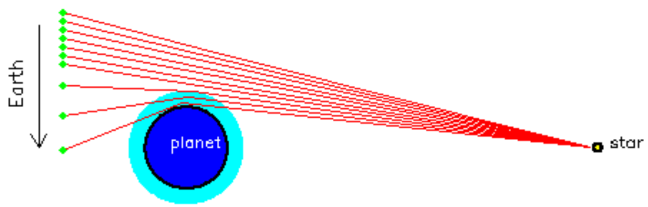
Why only Saturn has rings?

Carl Sagan

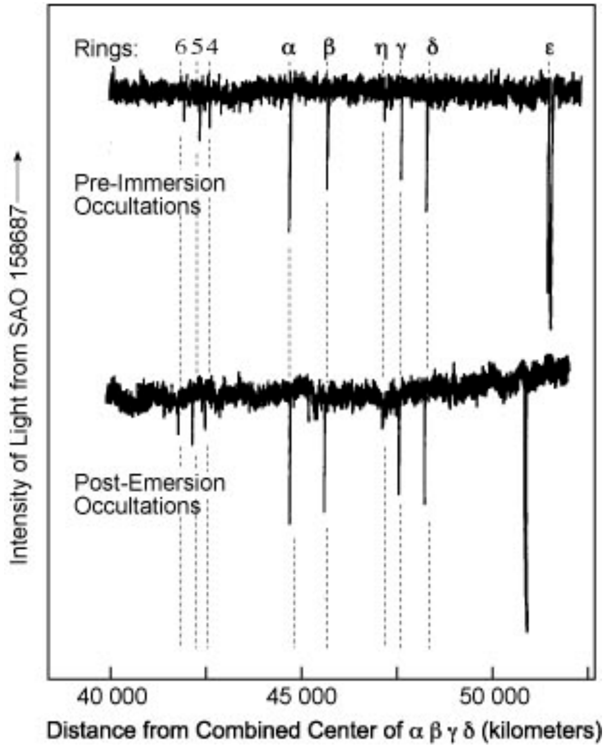
Rings of Uranus

Occultations

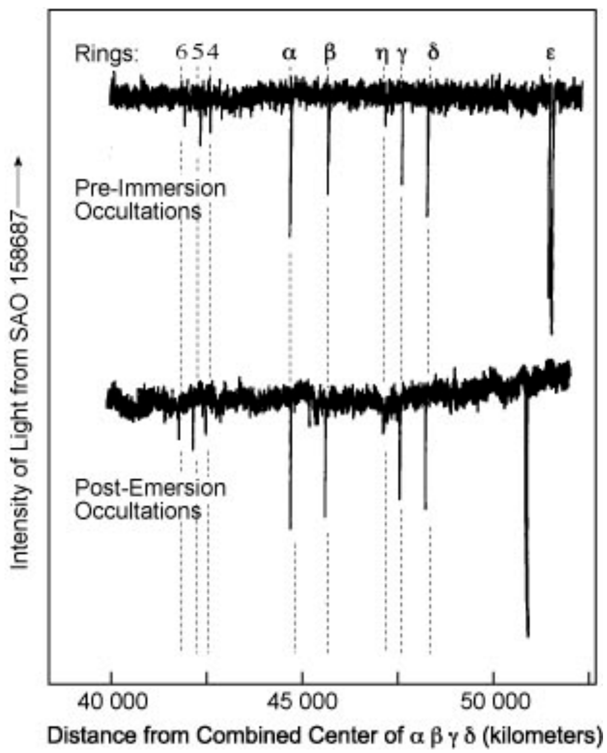
stellar occultation

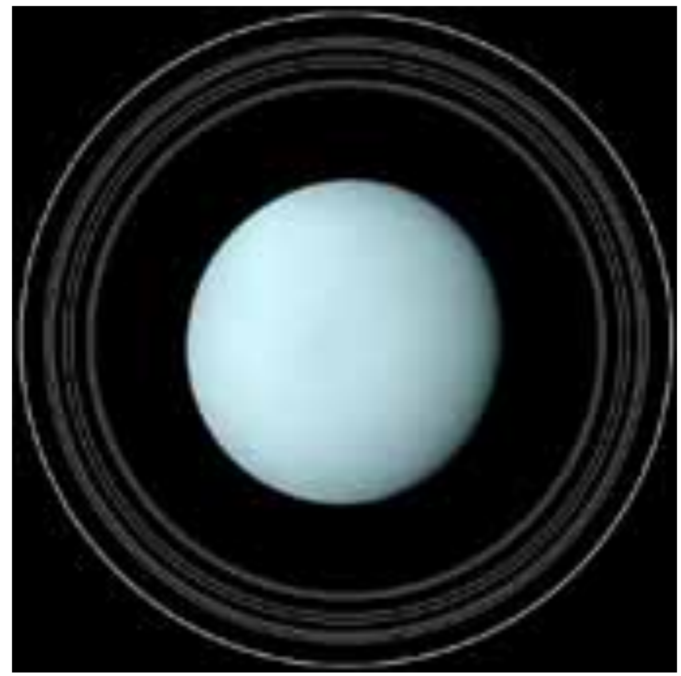


Uranus occults a star

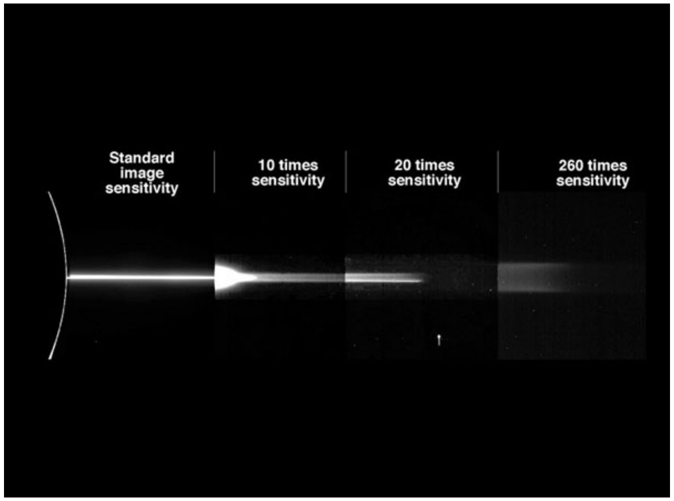


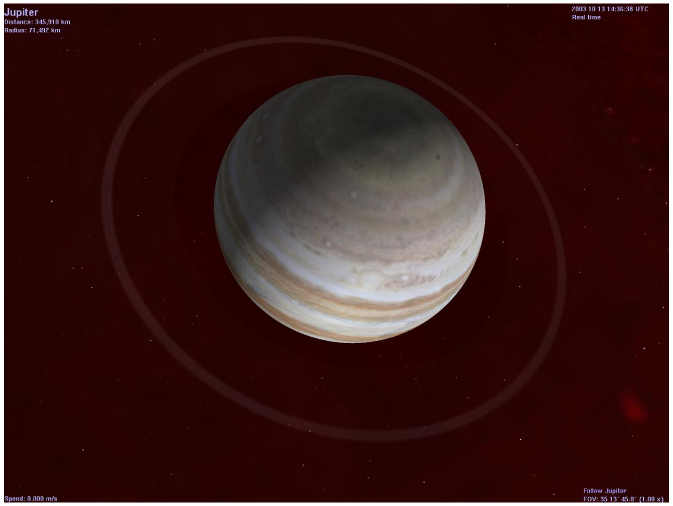
Rings of Uranus





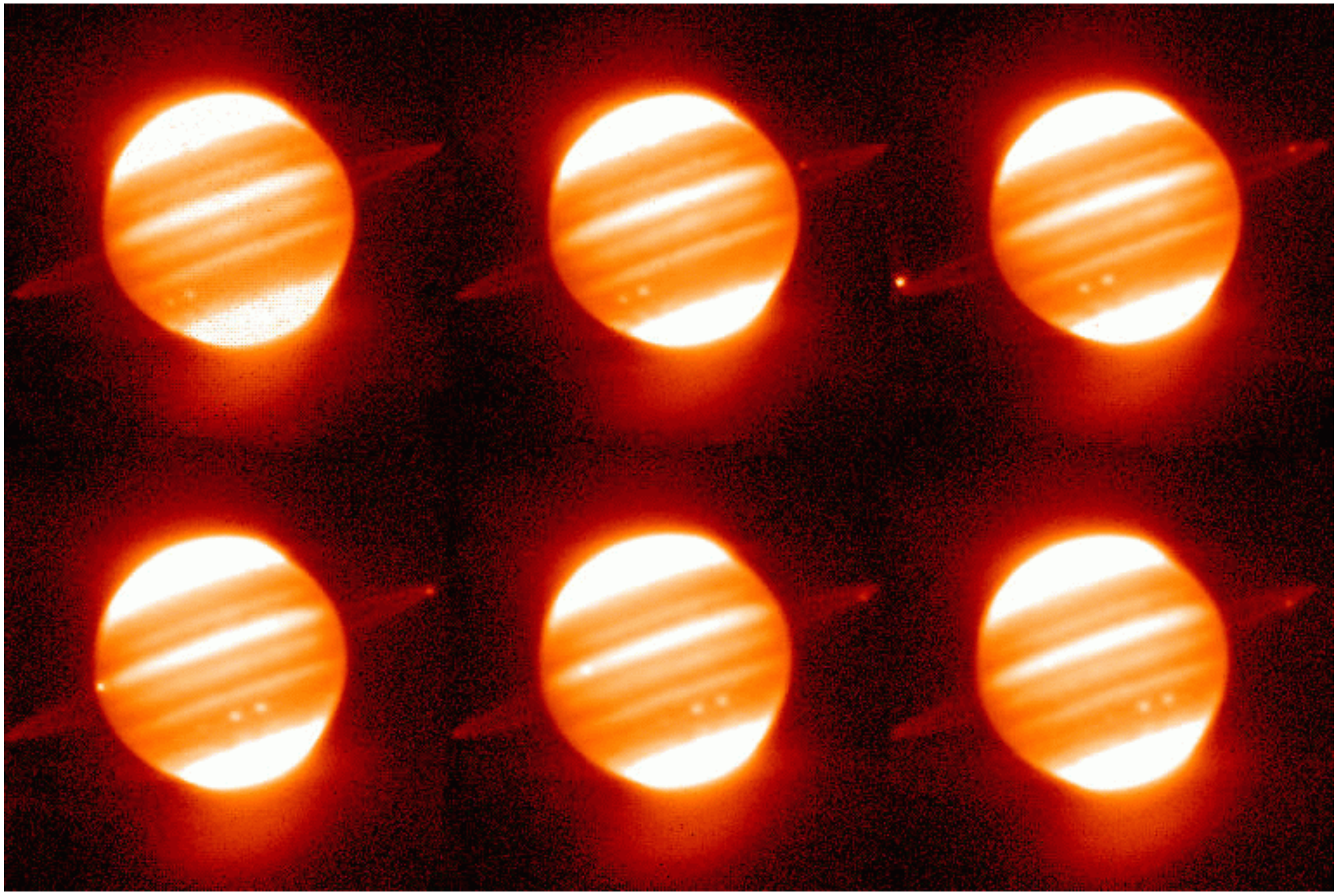
Rings of Jupiter





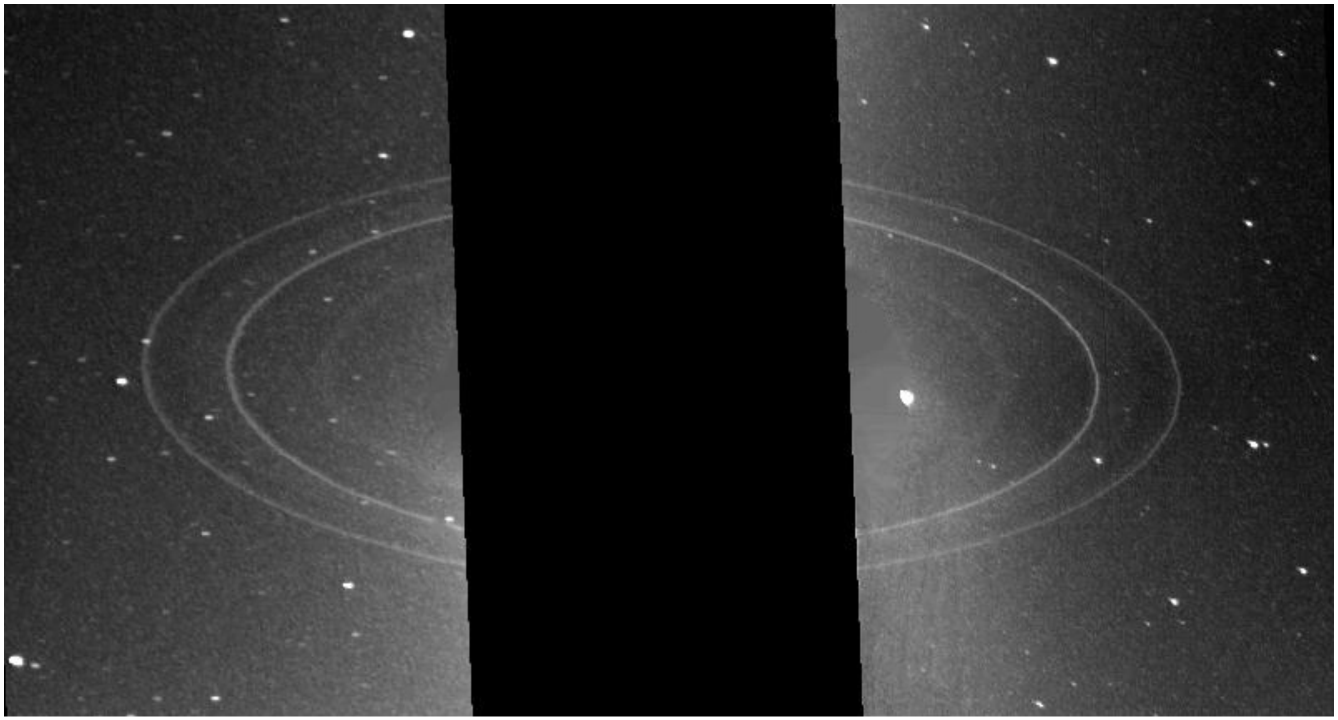
A very faint ring system
discovered by Voyager 1.

Rings of Jupiter



Viewed with Keck,
with a methane filter.

Rings of Neptune



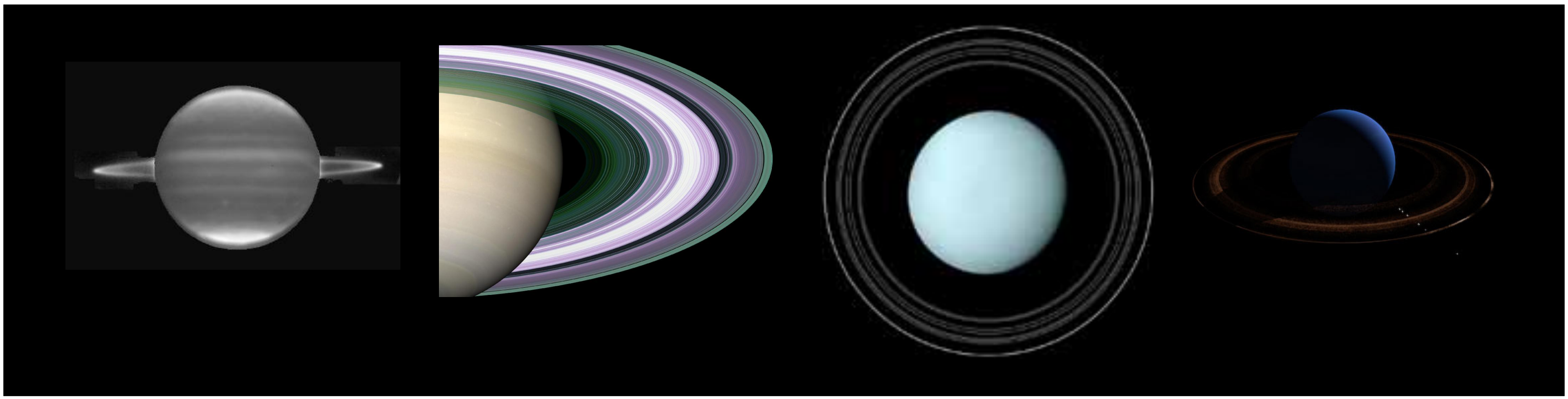
A very faint ring system,
similar to Jupiter's rings
discovered by Voyager 2.

Rings of Neptune

Arcs!!!

Ring Systems

Jupiter | Saturn | Uranus | Neptune



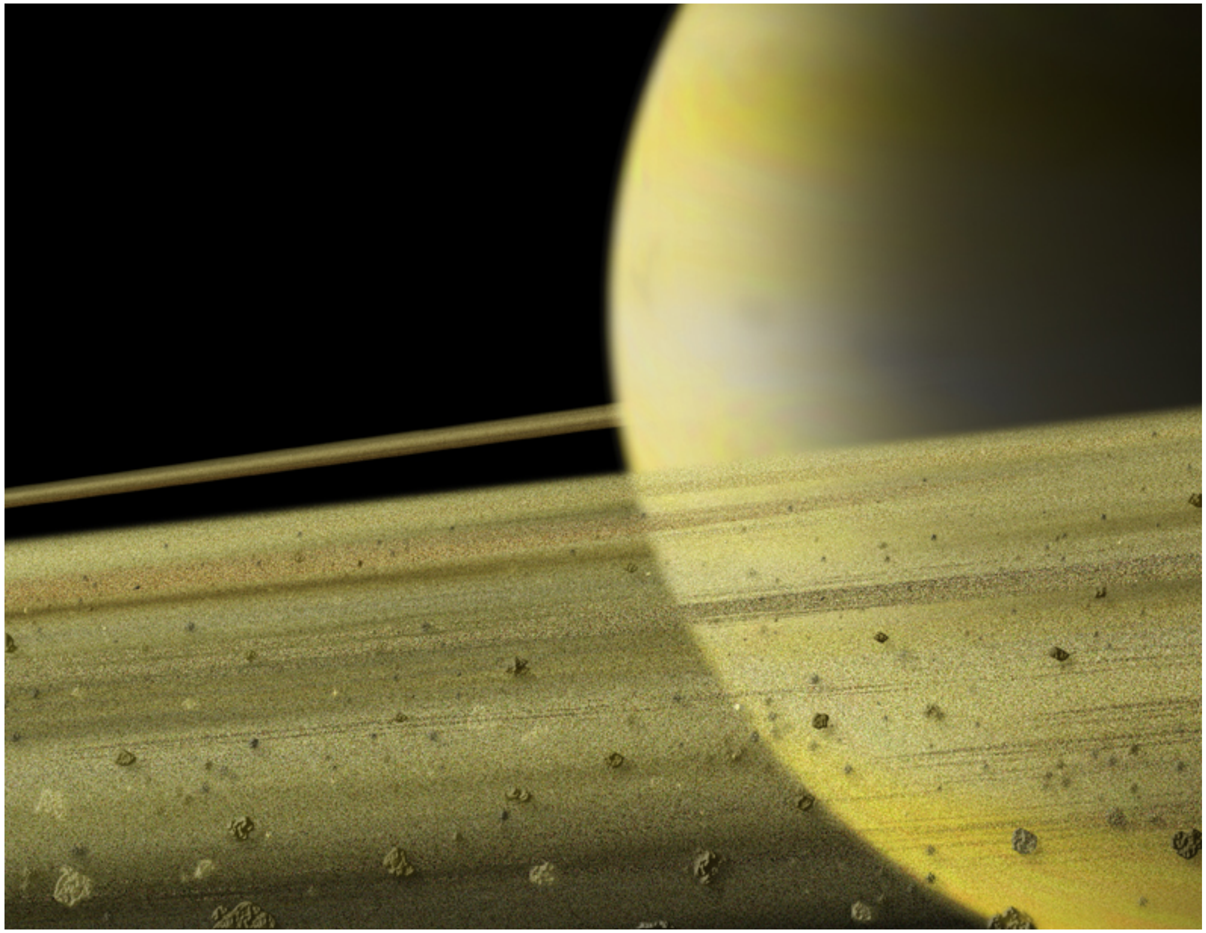
Fine, diffuse dust, very dark.

Icy boulders, very bright.

Rocky boulders, dark.

Pebbles (?) Dark and reddish (?)

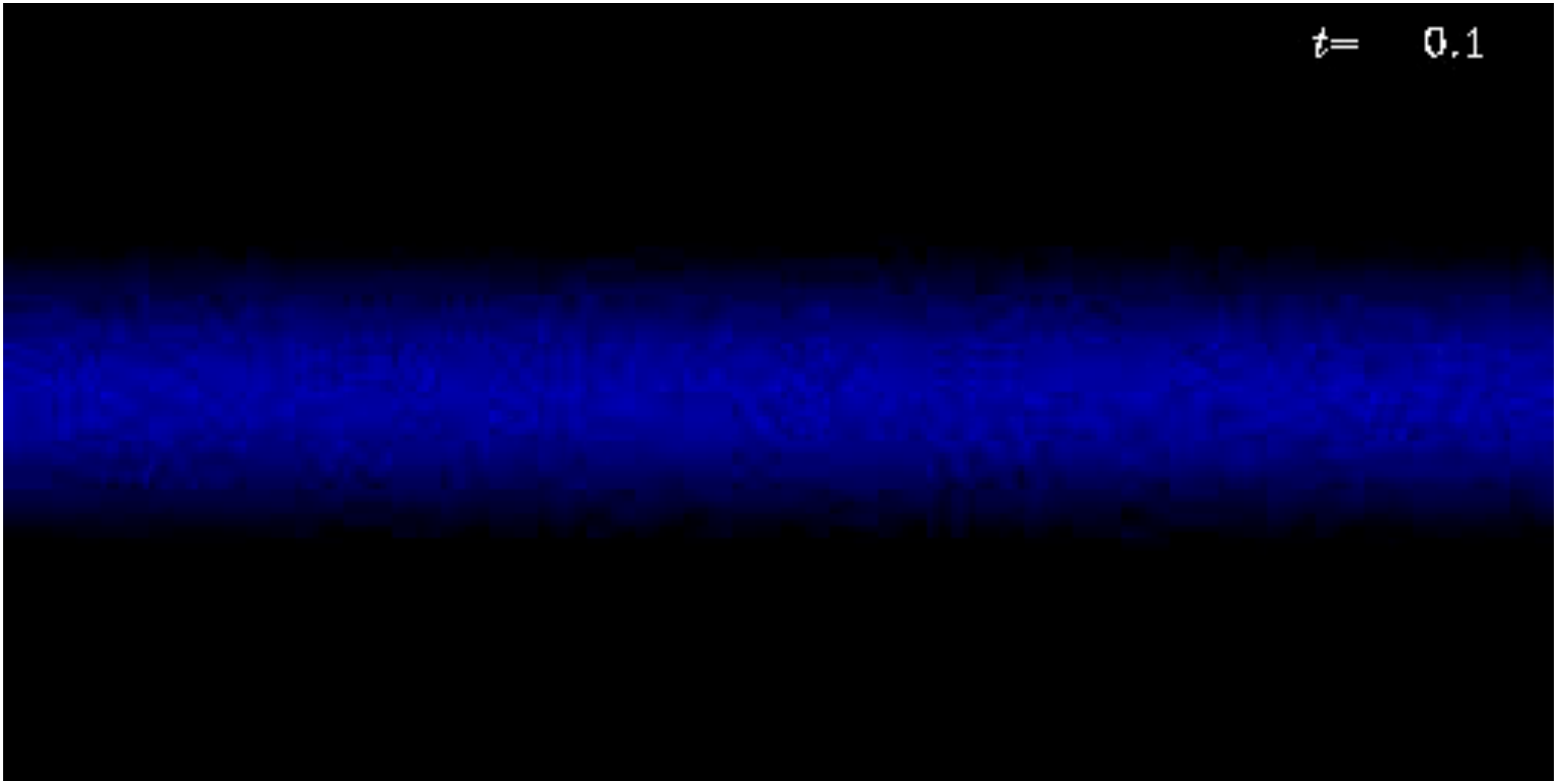
Ring formation: Competing theories



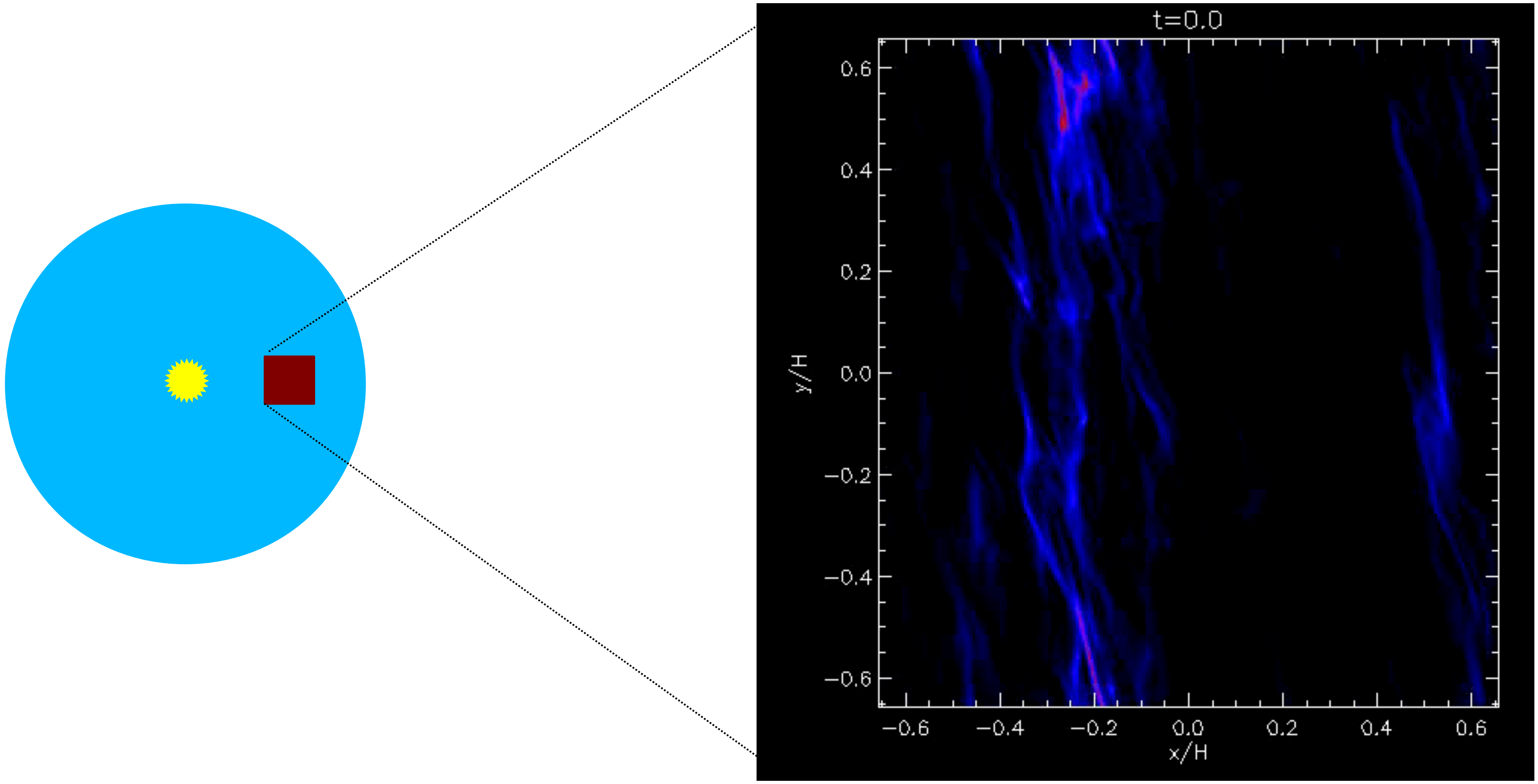
1). Moon that got too close

2). Leftover material that could not coalesce into moons

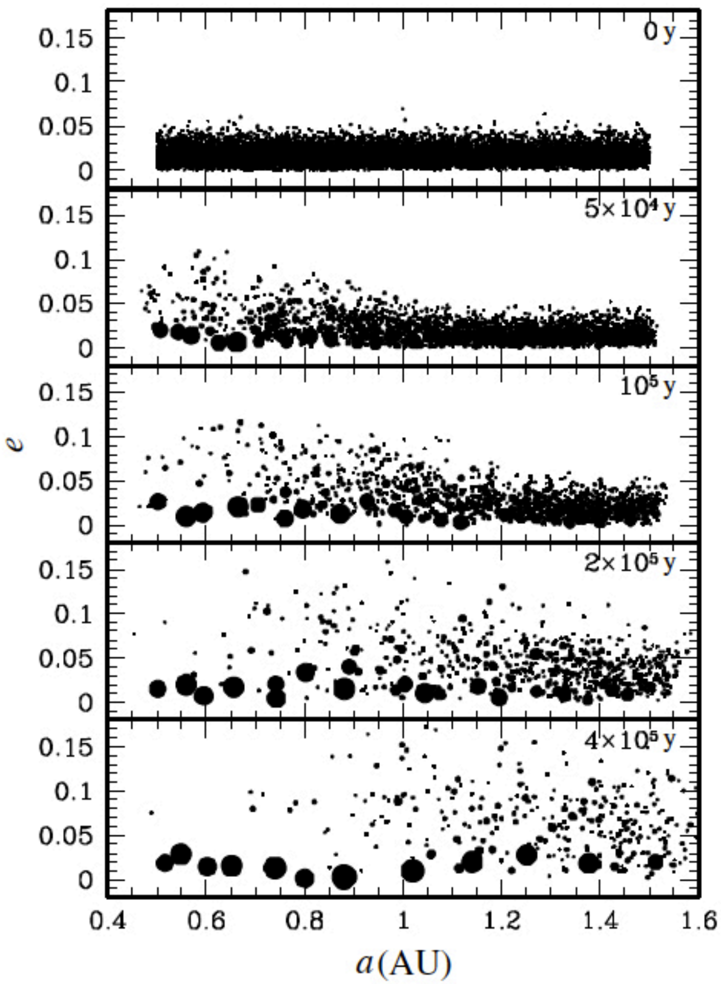
Sedimentation



Gravitational collapse into planetesimals

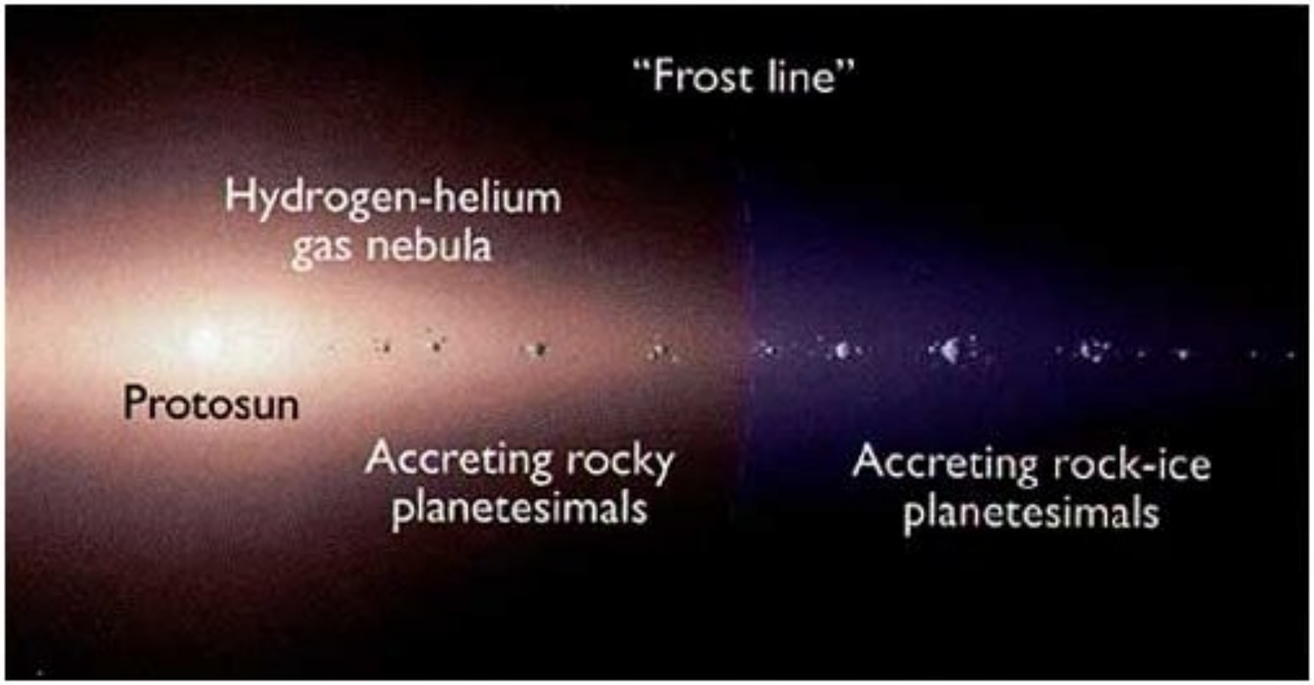


Oligarchs



(Kokubo + Ida 2002)

The Snowline

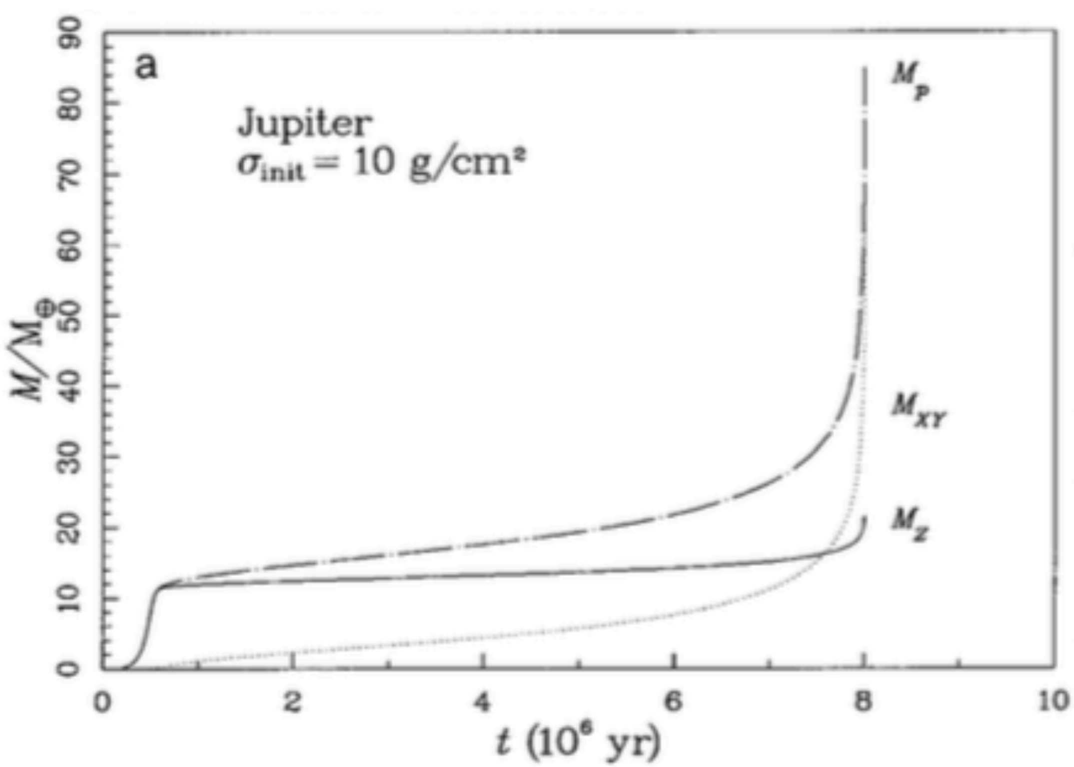


Volatiles in gas phase

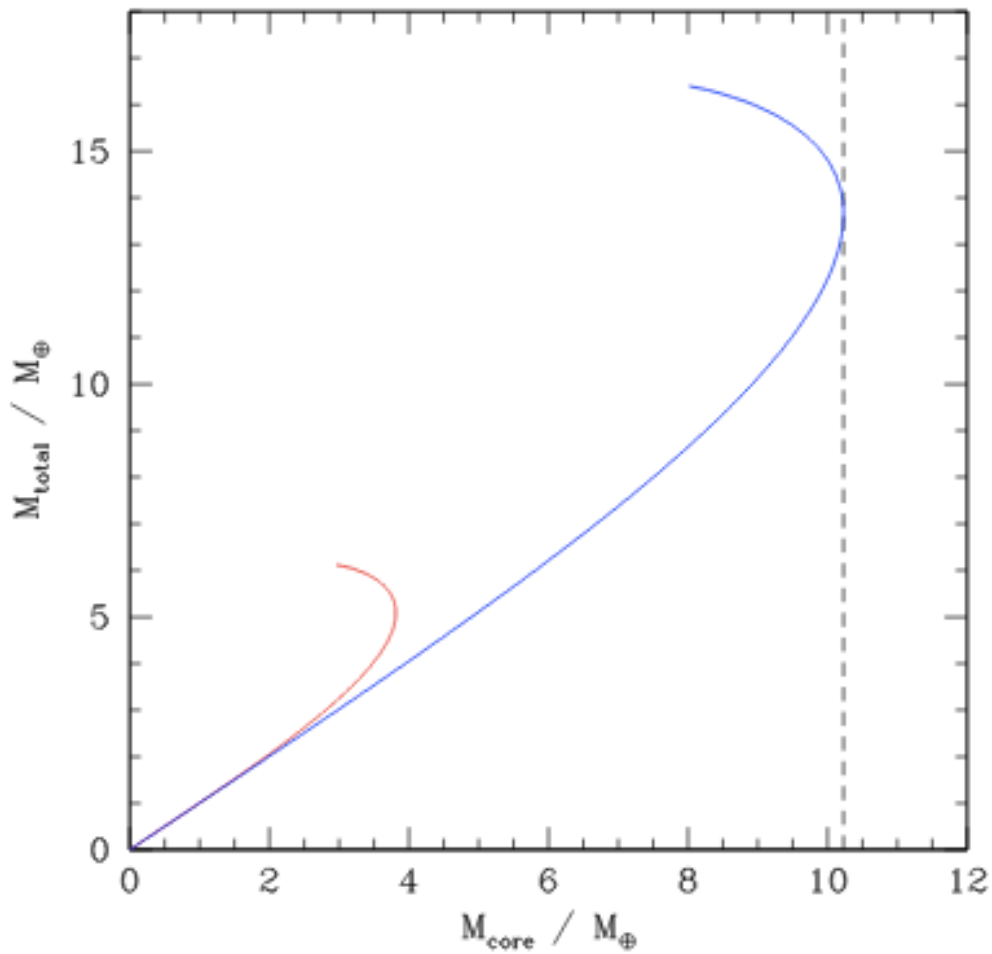
Volatiles in solid phase

Colder than ~150K, the volatiles (H_20, CH_4, NH_3) condense into ***ices***.

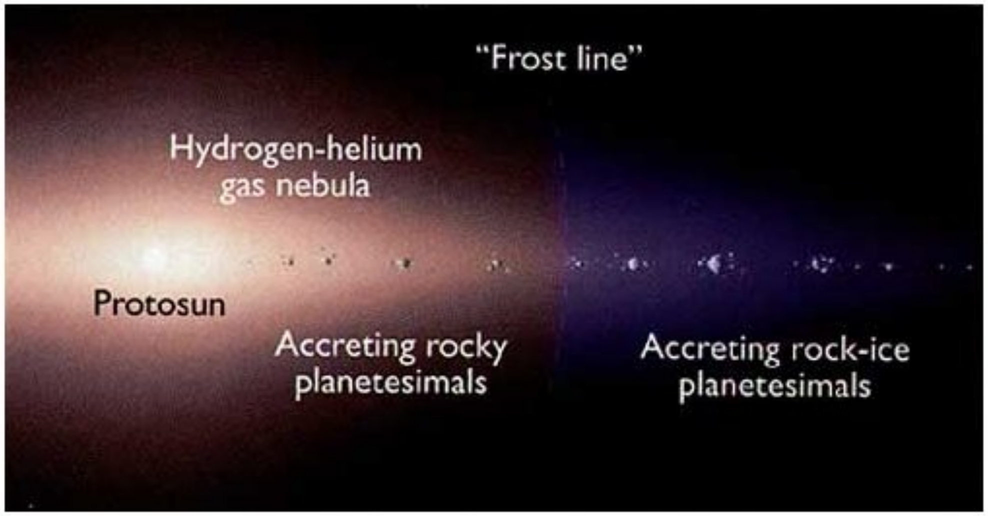
Core Accretion



Critical core mass



Formation



Volatiles in gas phase

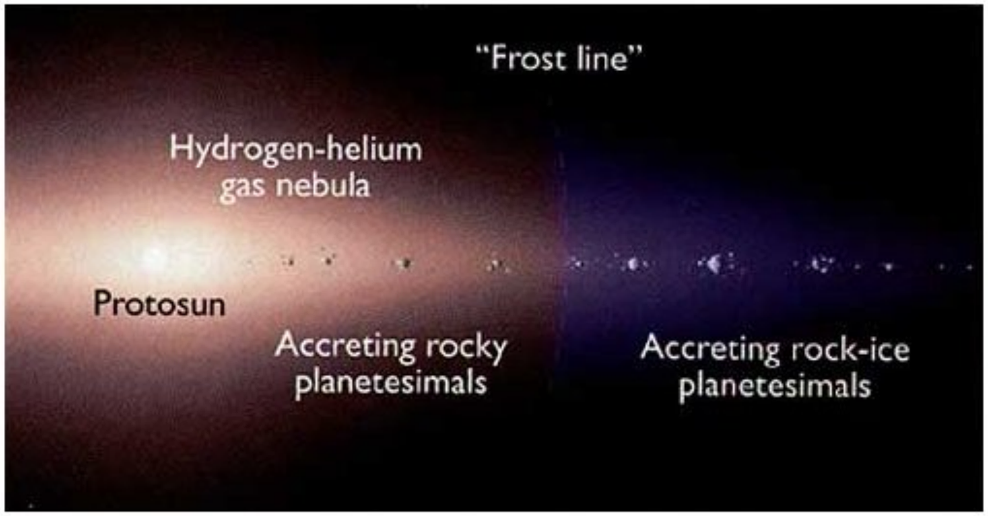
Volatiles in solid phase

Colder than ~150K, the volatiles (H_20, CH_4, NH_3) condense into ***ices***.

Formation

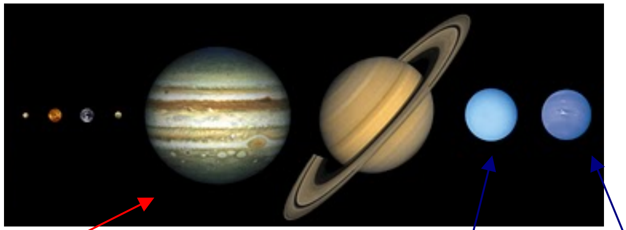
Inward of snowline

Accreting
rocky cores
(small)



Outward of snowline

Ice comes to aid!
Growing big
icy/rocky cores.



These guys got so big they started accreting gas from the nebula!

These ones never did.
They are just the icy/rocky cores.

Potential of oblate bodies

Newton's second theorem

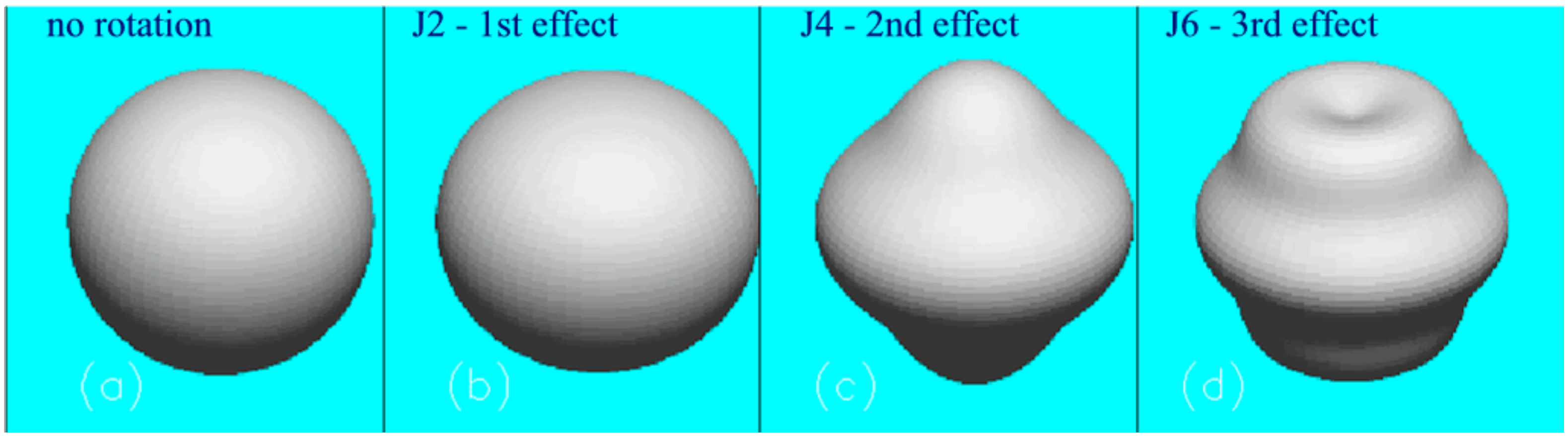
"A spherically symmetric body affects external objects as if all its mass was concentrated in its center"

But planets are not spherically symmetric

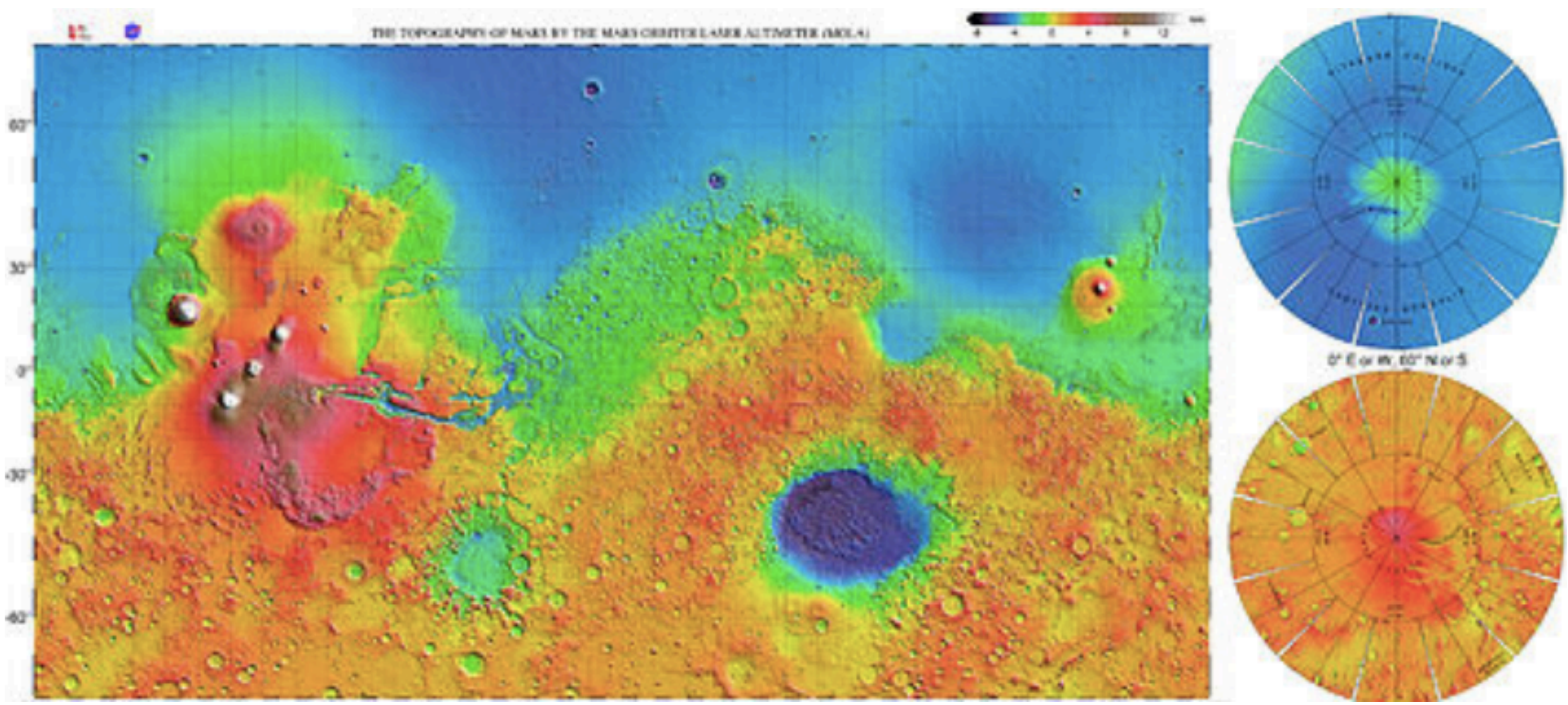
Oblateness caused by rotation

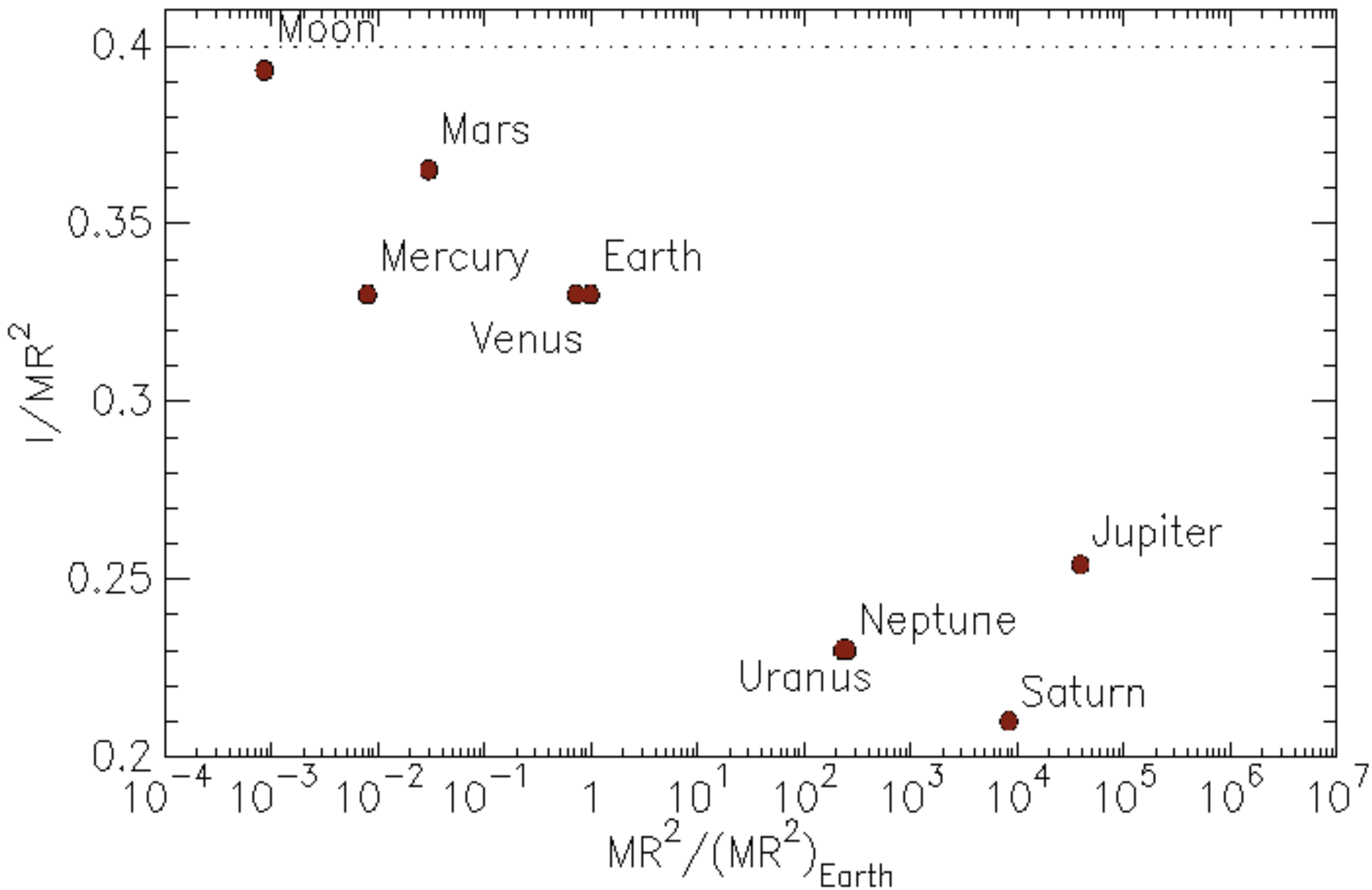
Gravitational Potential

$$\Phi_g(r,\phi,\theta) = -\frac{GM}{r}\left[1 - \sum J_n P_n(\cos\theta)\left(\frac{R}{r}\right)^n\right]$$



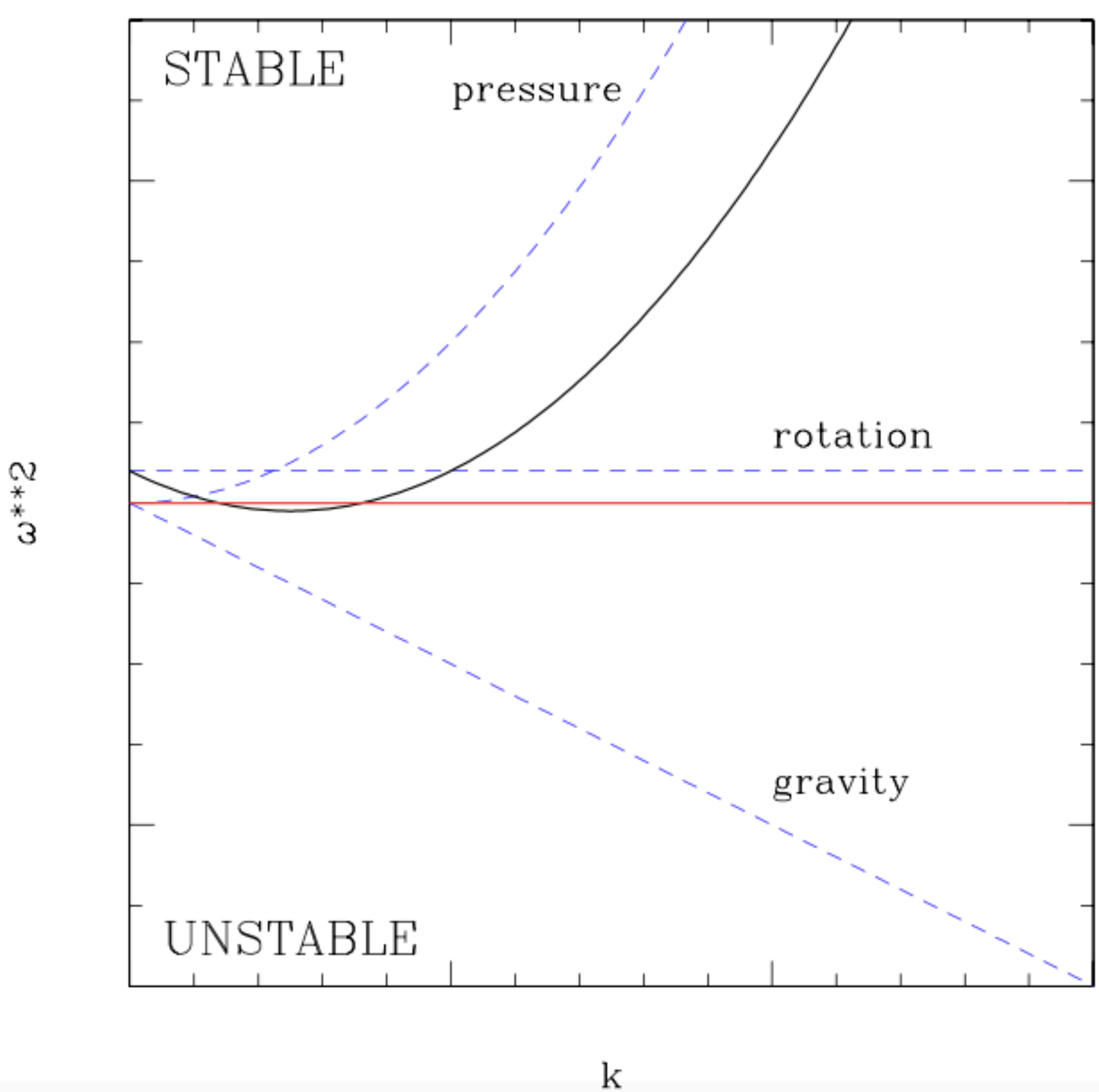
	J_2 (x10^{-6})	J_4 (x10^{-6})	J_6 (x10^{-6})
Jupiter	14696.4+/-0.2	587+/-2	34+/-5
Saturn	16290.7+/-0.3	936+/-3	86+/-9


THE TOPOGRAPHY OF MARS BY THE MARS ORBITER LASER ALTIMETER (MOLA)
60°
30°
0°
-30°
-60°
0° E or W, 60° N or S

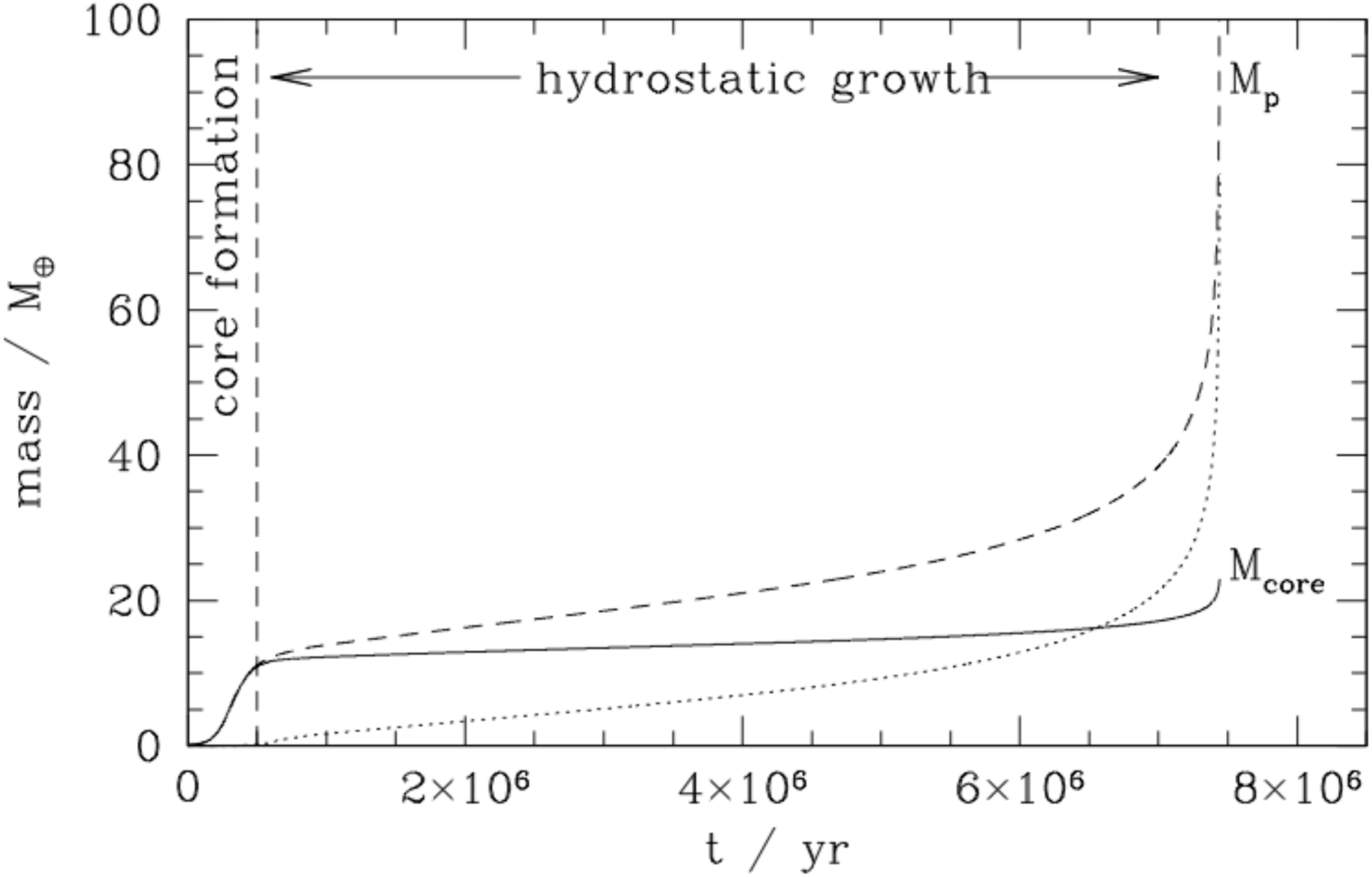


Moon
Mars
Mercury
Earth
Venus
Jupiter
Neptune
Uranus
Saturn
0.4
0.35
0.3
0.25
0.2
I/MR^2
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
$MR^2/(MR^2)_{Earth}$

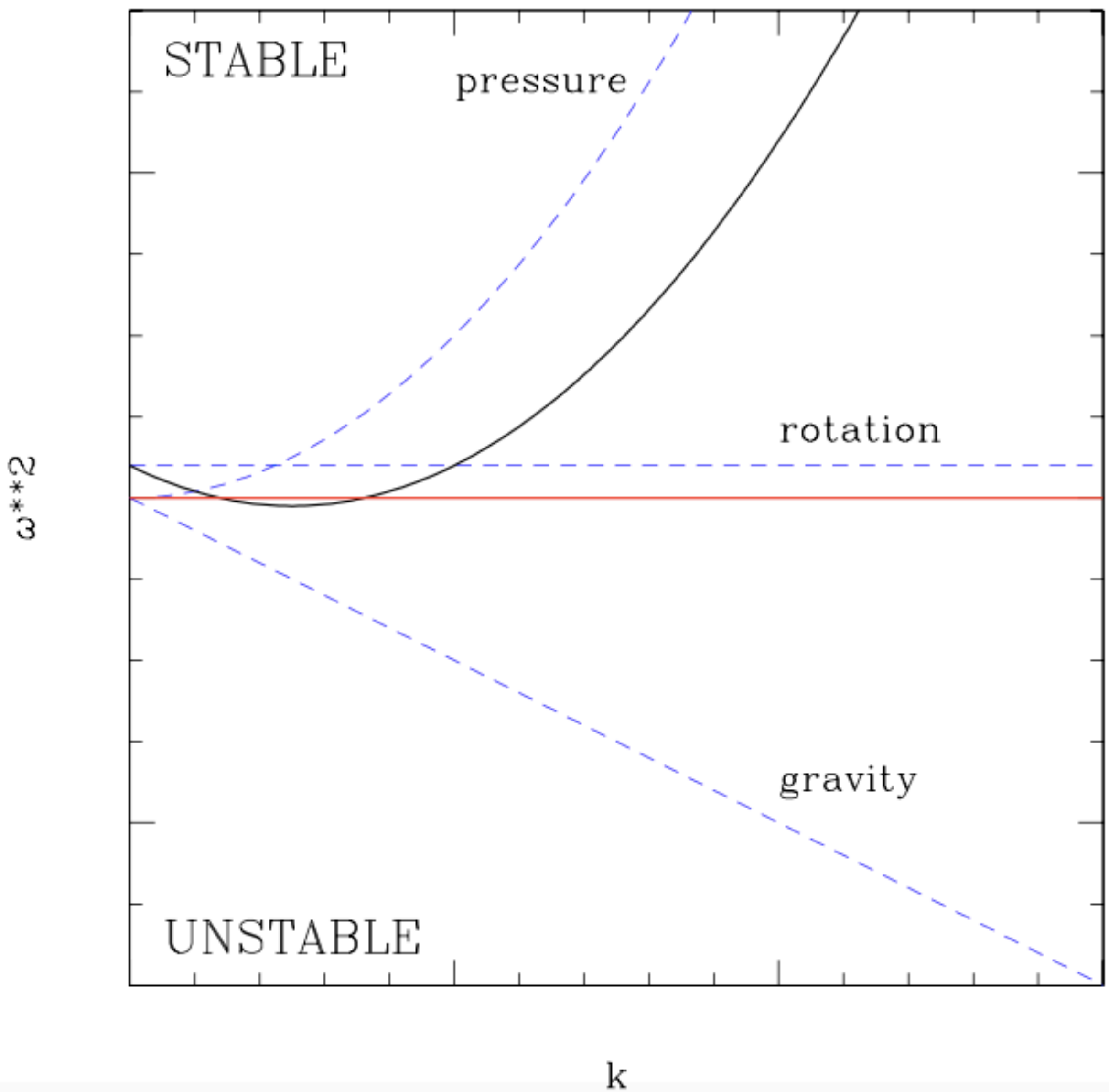
Gravitational Instability



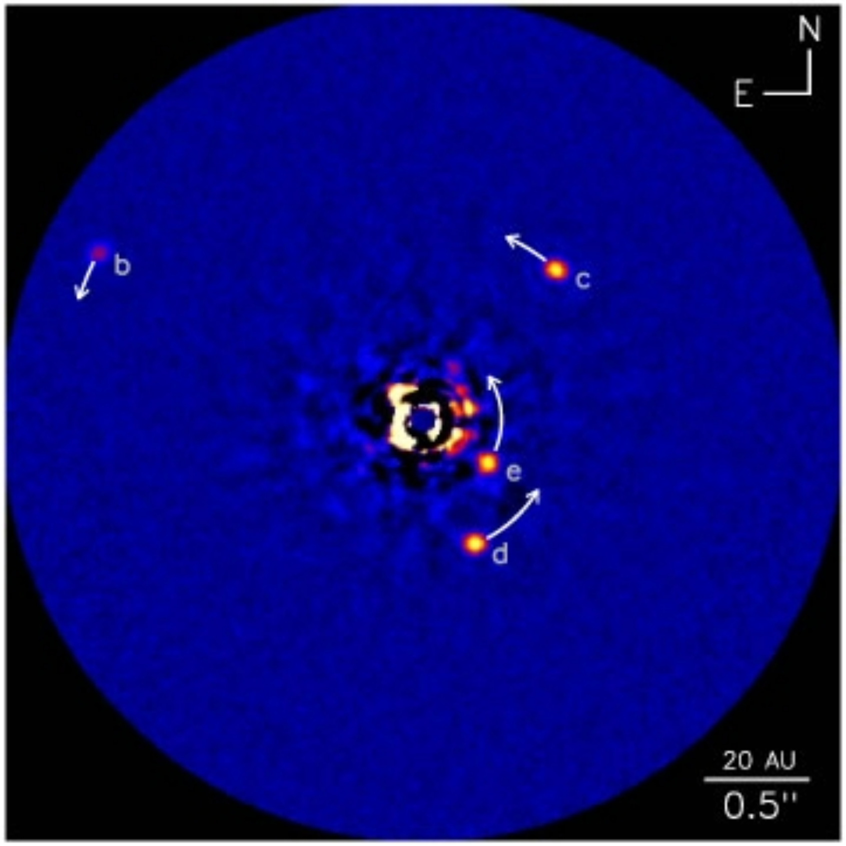
Core accretion



Gravitational Instability



HR 8799: Four high-mass planets at wide orbits

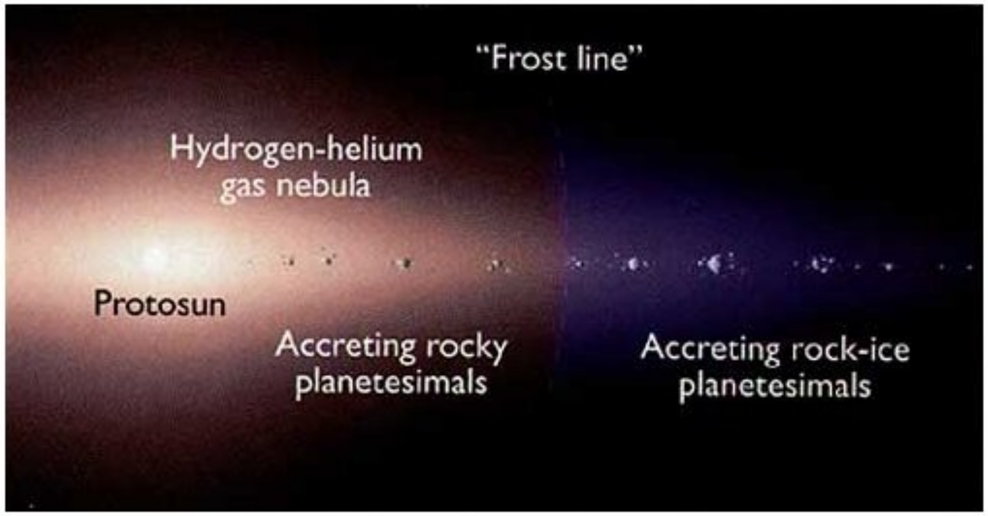


Companion (in order from star)	Mass	Semimajor axis (AU)
e	7^{+3}_{-2} M_J	14.5 ± 0.5
d	7^{+3}_{-2} M_J	24±0
c	7^{+3}_{-2} M_J	38±0
b	5^{+2}_{-1} M_J	68±0

Formation by Core Accretion

Inward of snowline

Accreting
rocky cores
(small)



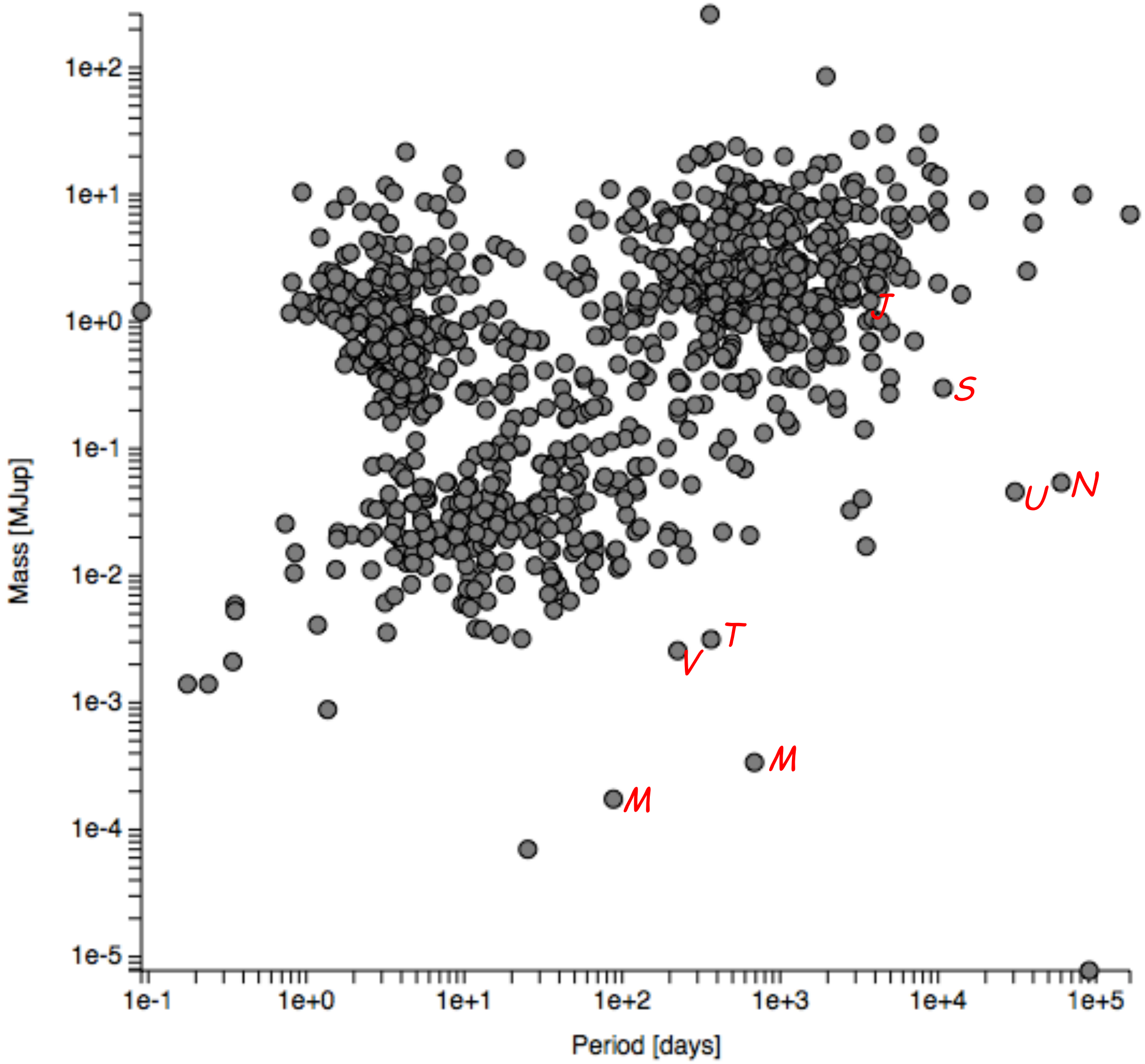
Outward of snowline

Ice comes to aid!
Growing big
icy/rocky cores.

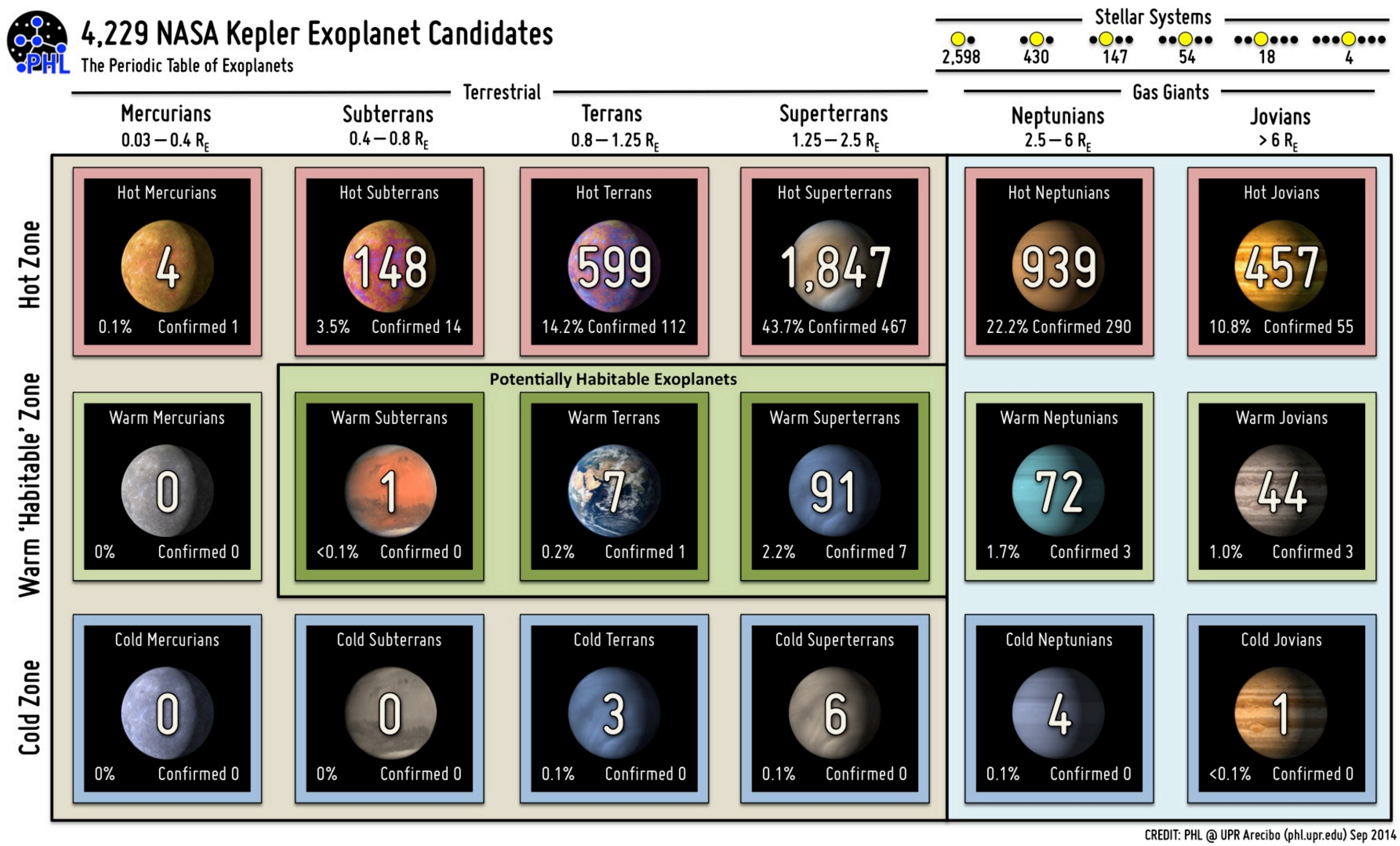
These guys got so big they started accreting gas from the nebula!

These ones never did. They are just the icy/rocky cores.

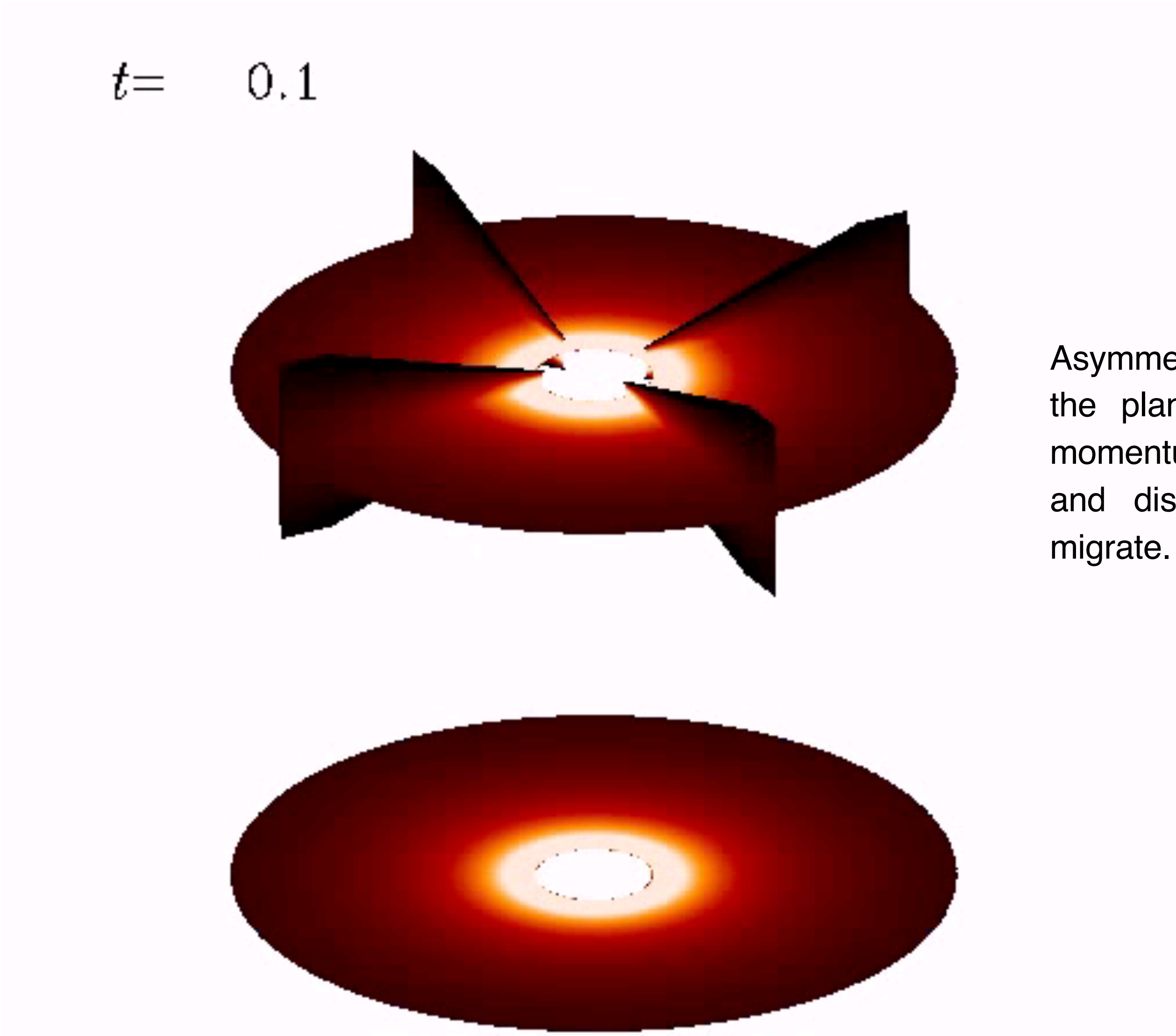
Mass-period distribution of planets



Kepler: “Period table” of exoplanets

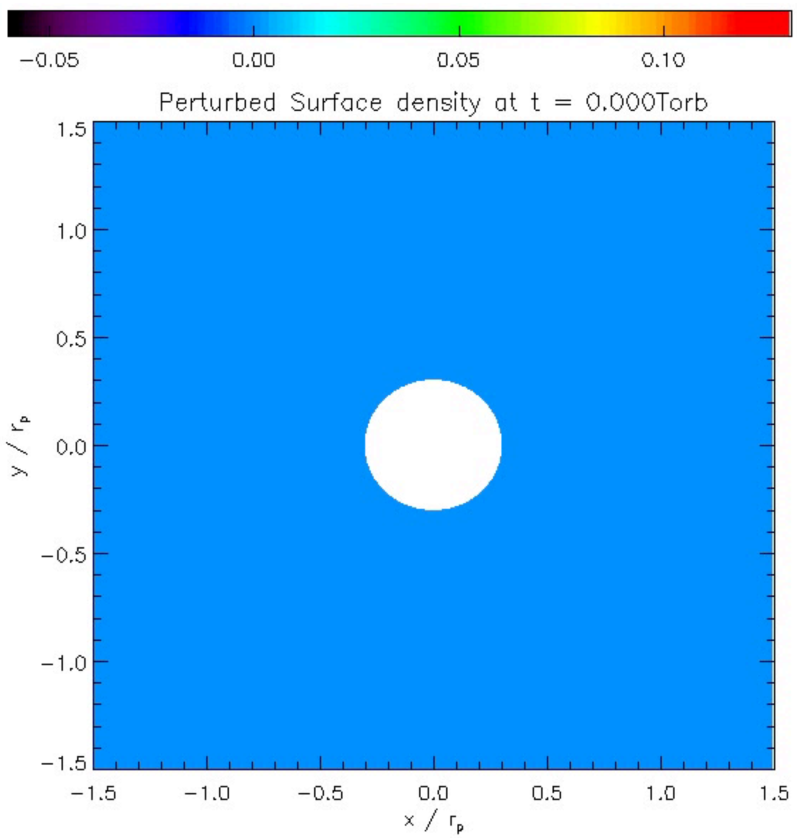


Migration



Asymmetries in the wake generated by the planet lead to non-zero angular momentum exchange between planet and disk, and the planet starts to migrate.

Migration



Asymmetries in the wake generated by the planet lead to non-zero angular momentum exchange between planet and disk, and the planet starts to migrate.

Two main ways to calculate torque:

1. Follow gas packets *in time*, and see how they exchange angular momentum with the planet.
   - Impulse approximation

2. Analyse how *azimuthal asymmetries* in the steady-state gas distribution in the disk $\Sigma(r,\phi)$ gravitationally pull on the planet.

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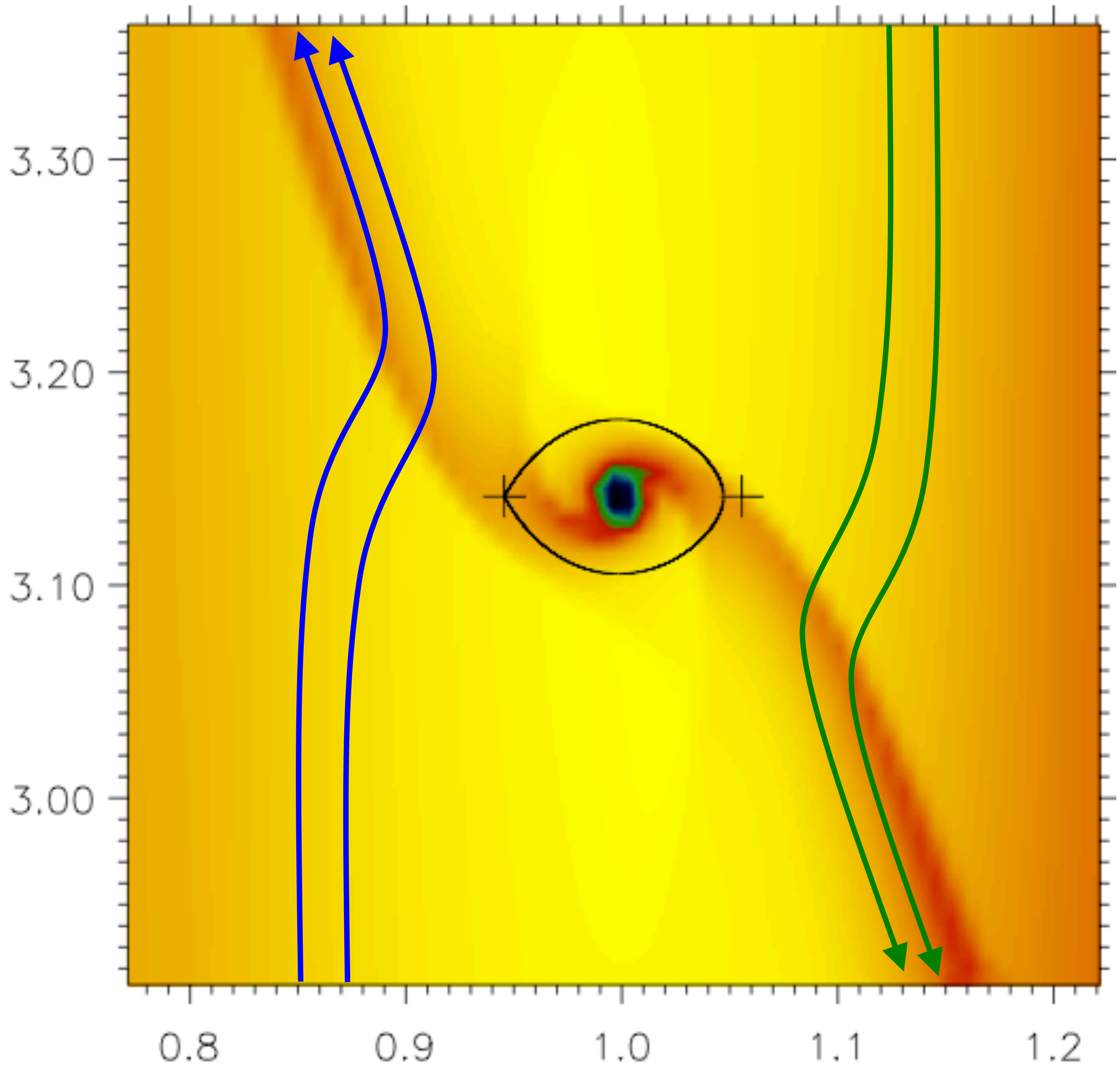
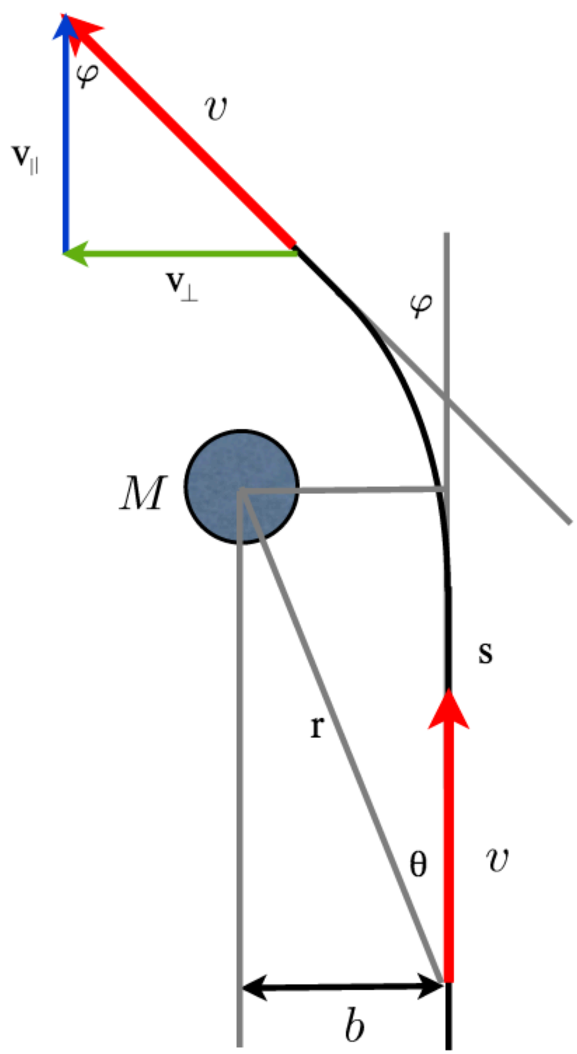
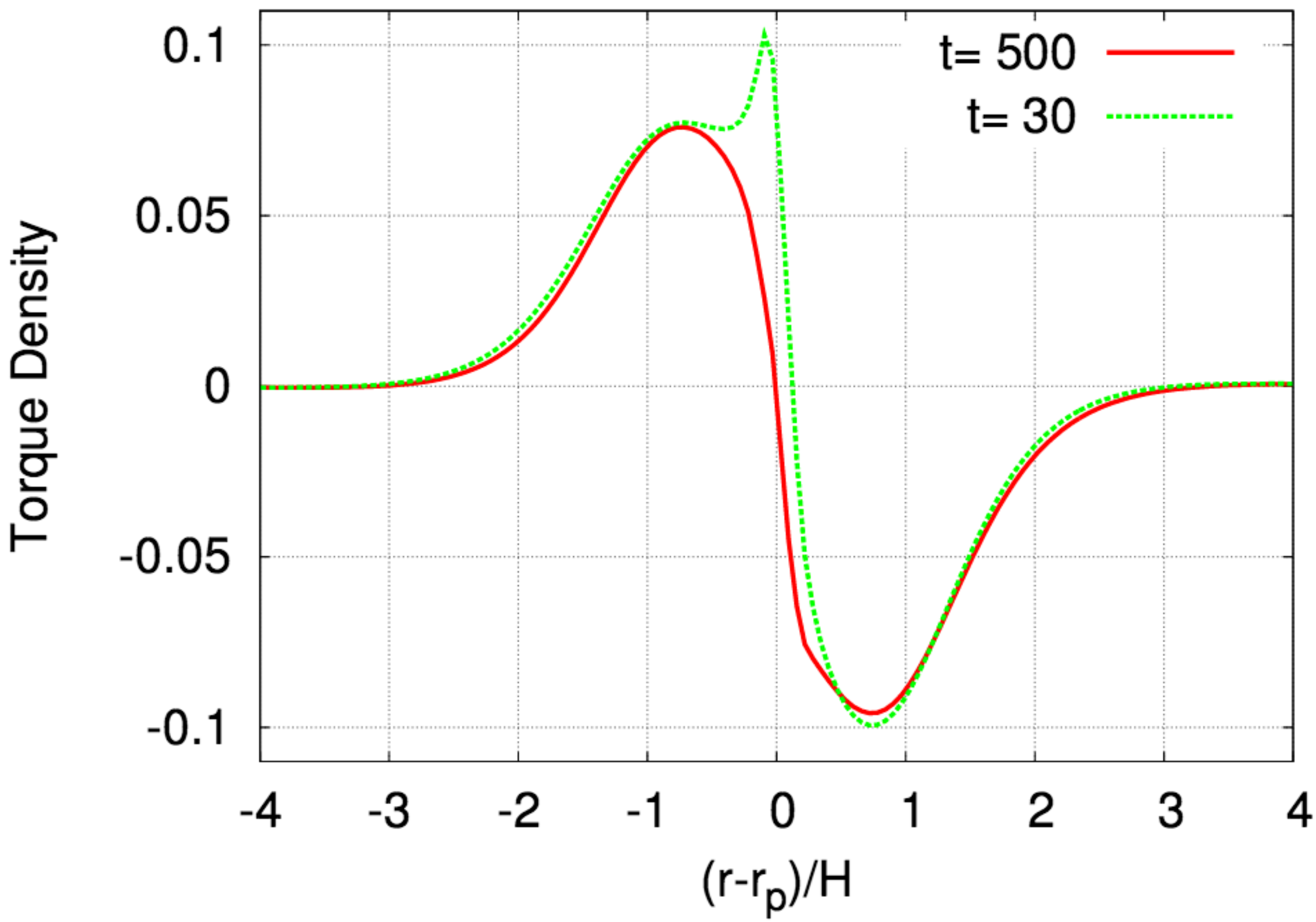

3.30
3.20
3.10
3.00
0.8
0.9
1.0
1.1
1.2

Migration: Impulse approximation





t= 500
t= 30
Torque Density
0.1
0.05
0
-0.05
-0.1
-4
-3
-2
-1
0
1
2
3
4
(r-r_p)/H

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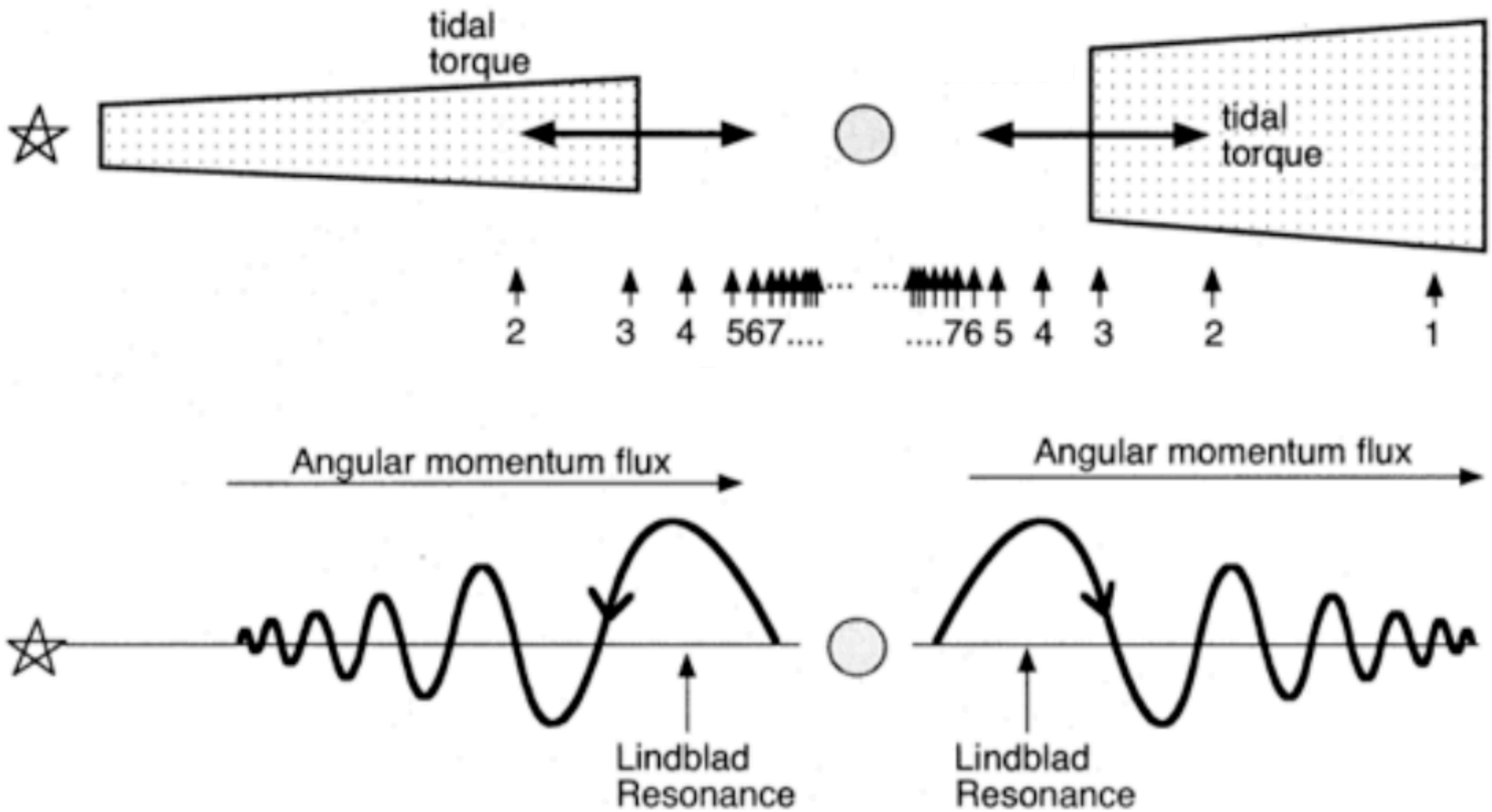
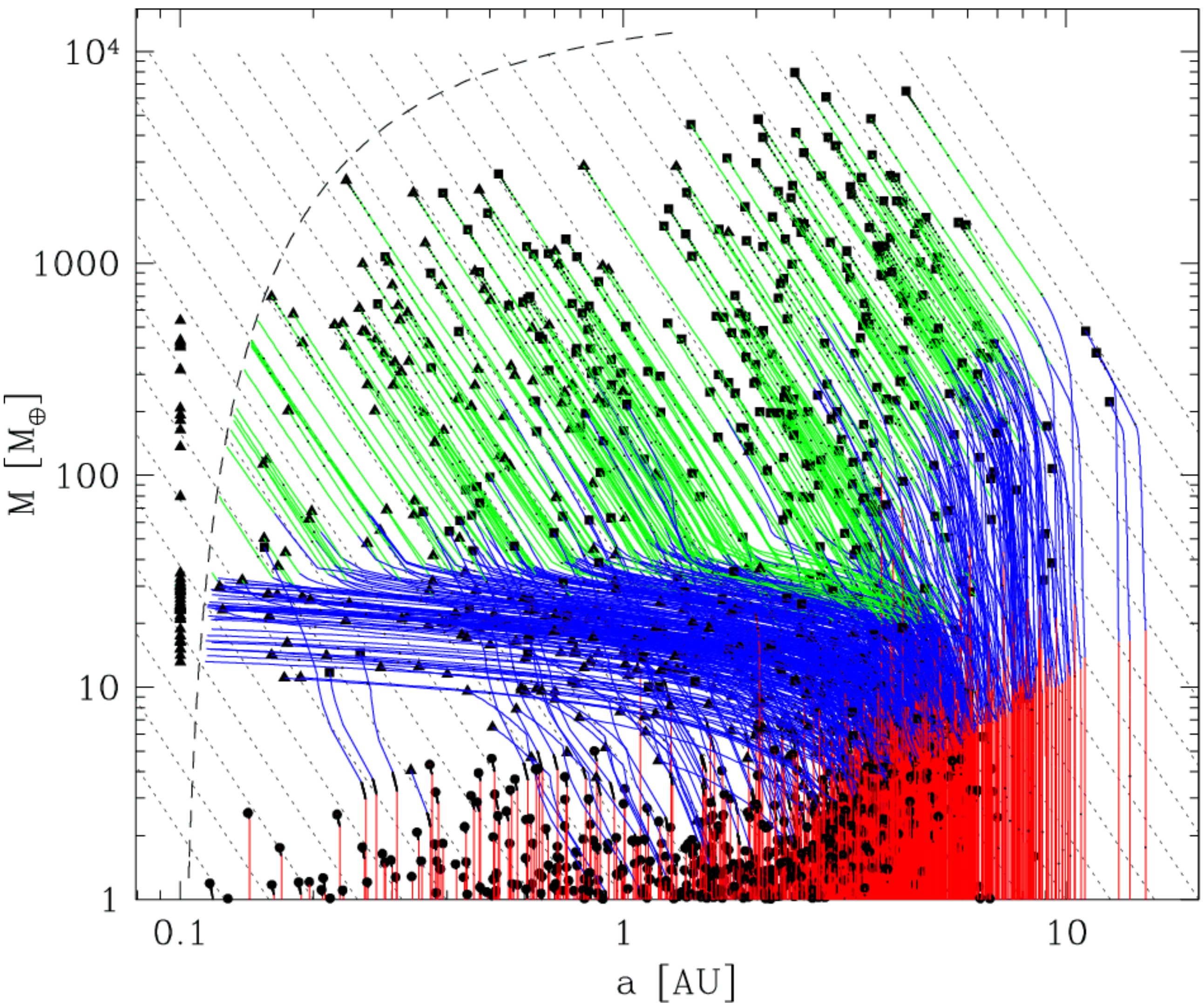
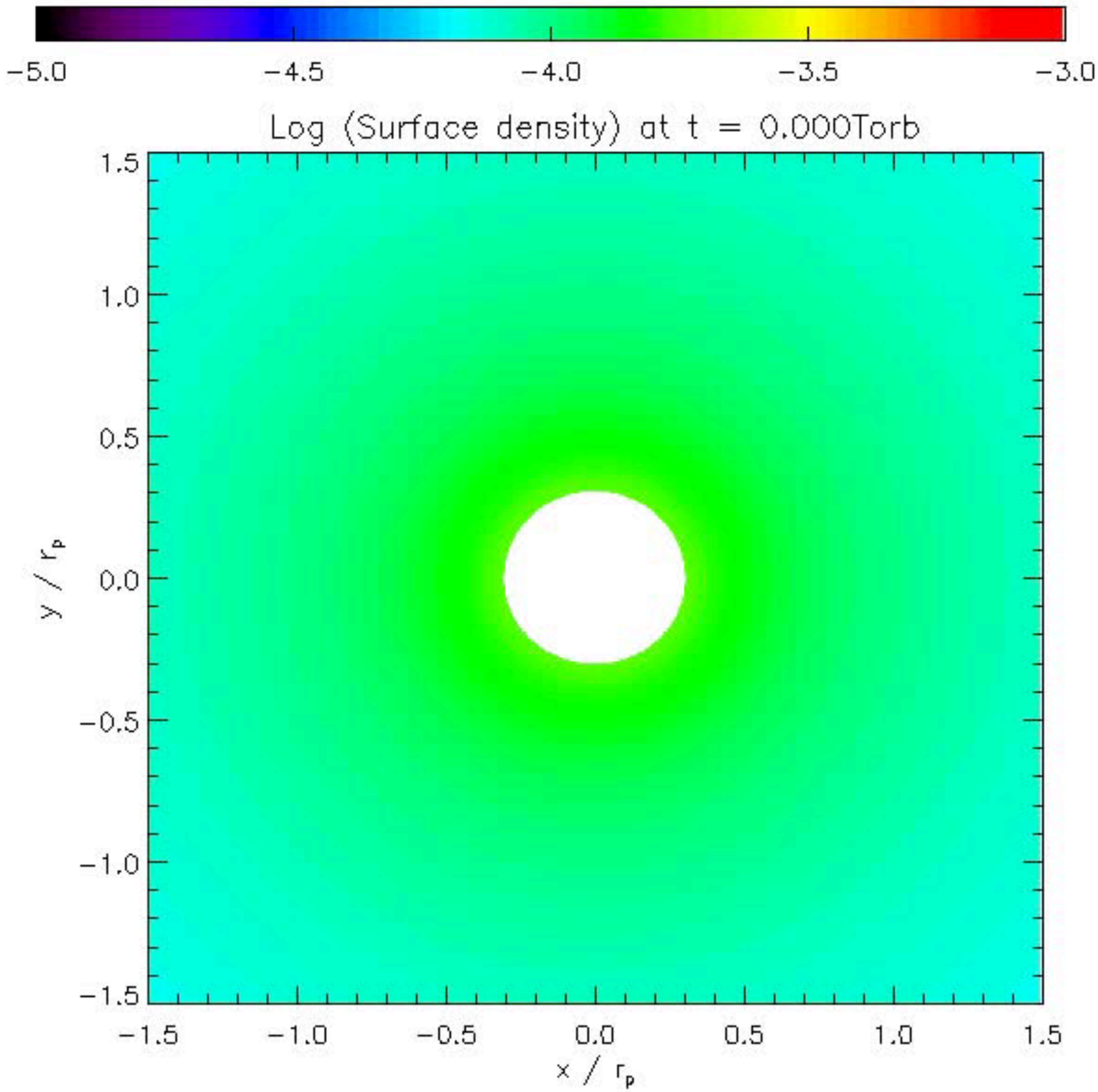


tidal
torque
tidal
torque
2
3
4
567....
....76
5
4
3
2
1
Angular momentum flux
Angular momentum flux
Lindblad
Resonance
Lindblad
Resonance

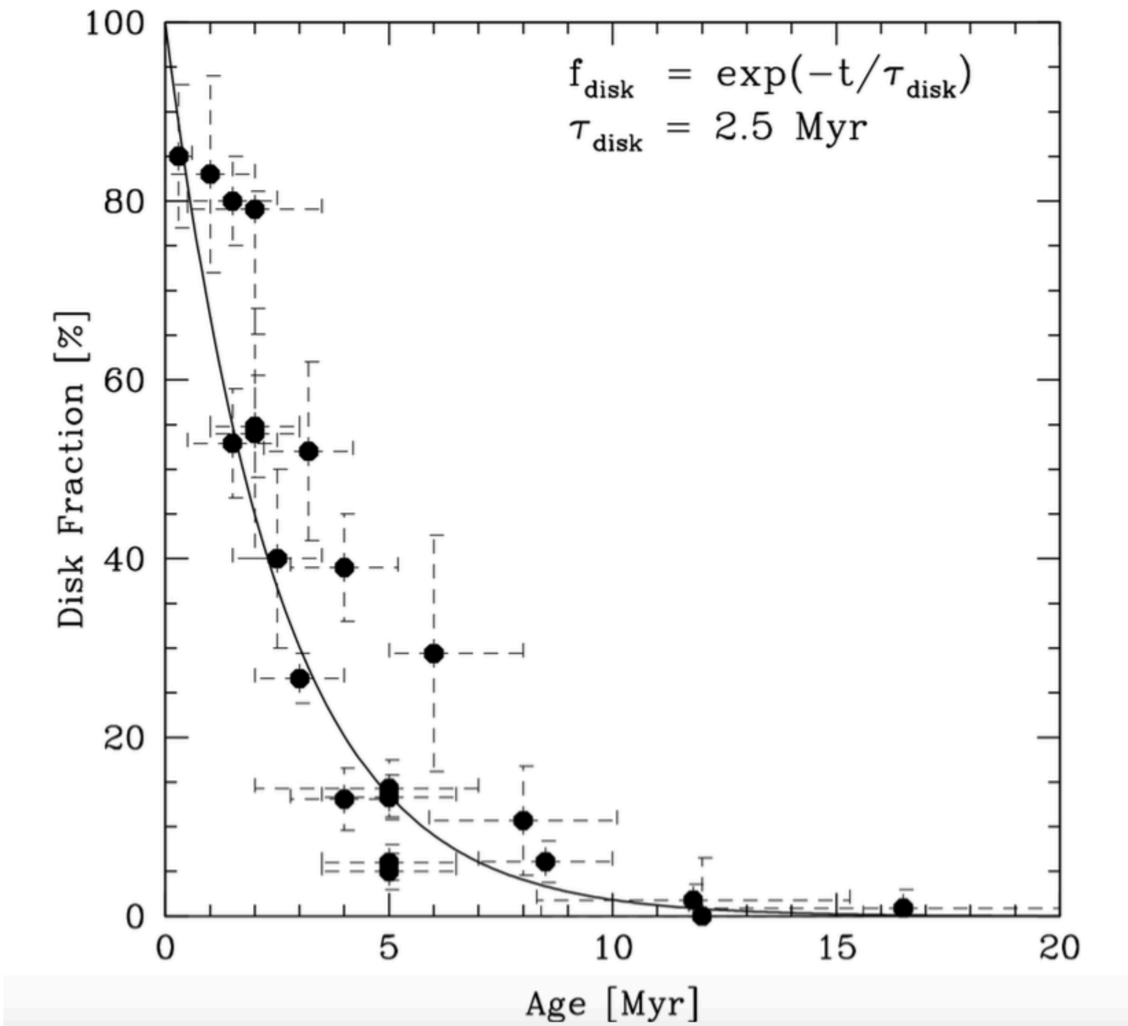
Planet Population Synthesis



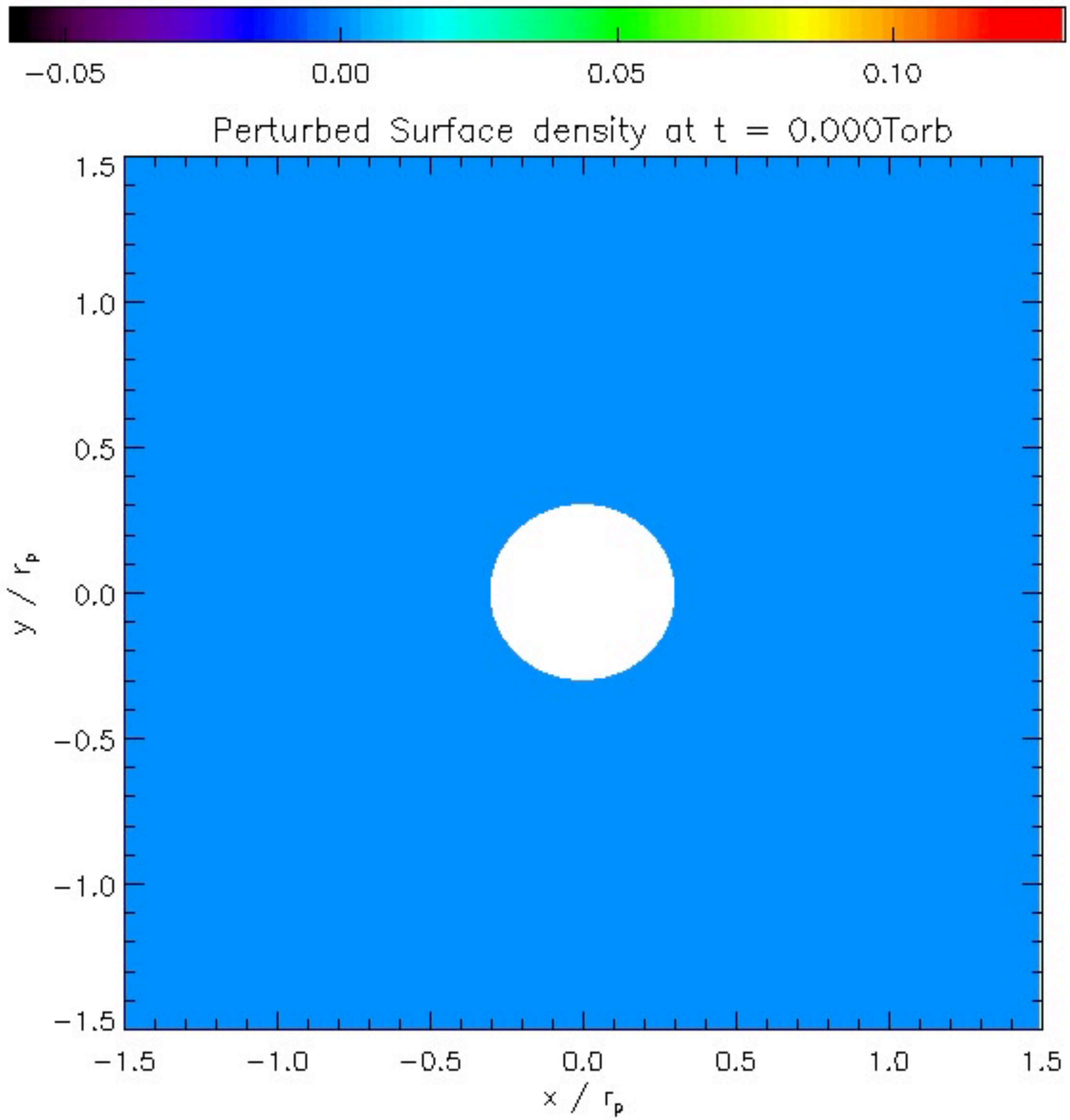


-5.0
-4.5
-4.0
-3.5
-3.0
Log (Surface density) at t = 0.000Torb
y / r_p
x / r_p
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5

Disk lifetime

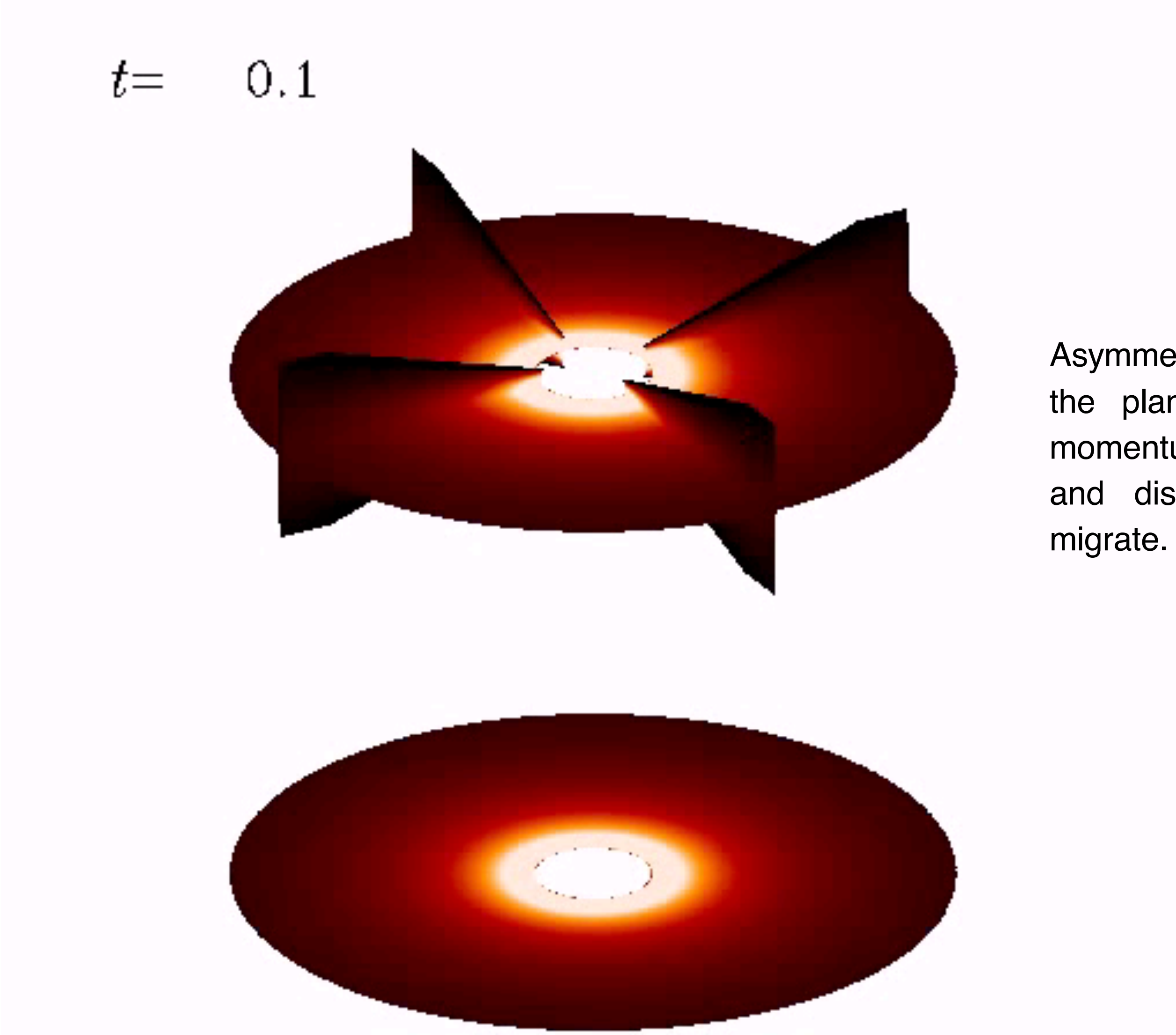


Disks dissipate with an e-folding time of 2.5 Myr



−0.05
0.00
0.05
0.10
Perturbed Surface density at t = 0.000Torb
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y / r_p
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
x / r_p

Migration



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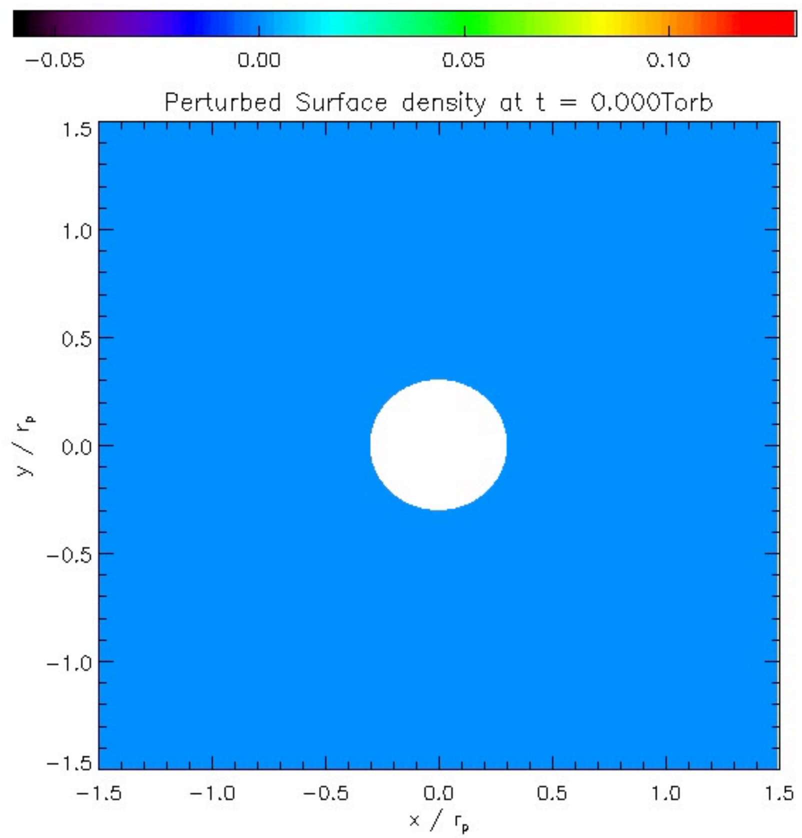
Migration



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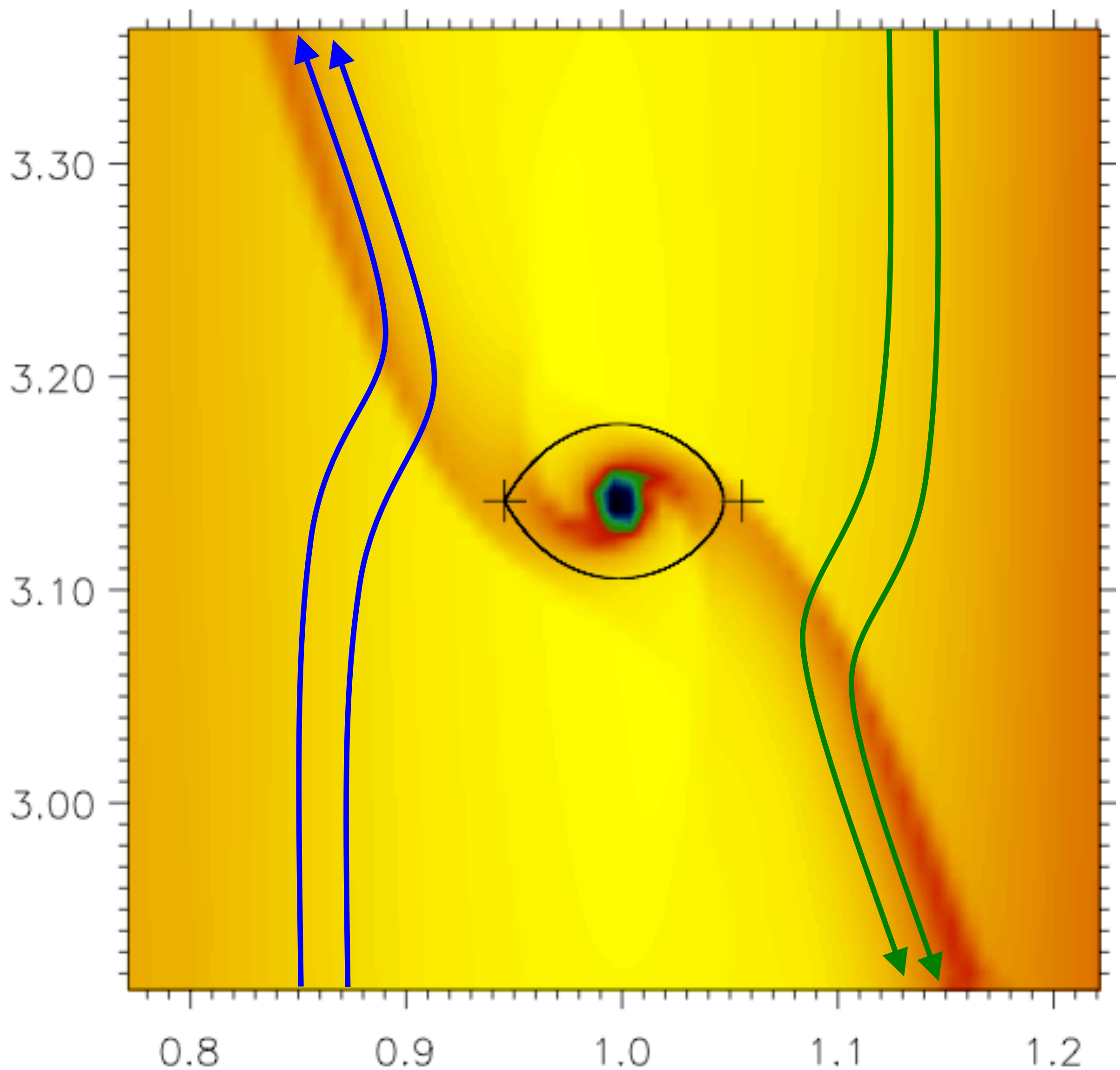
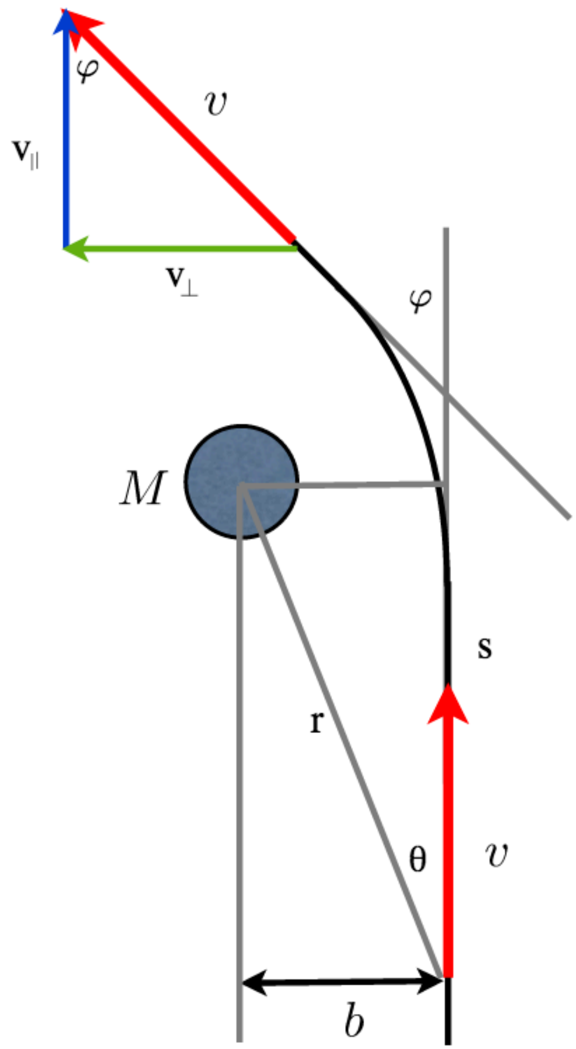
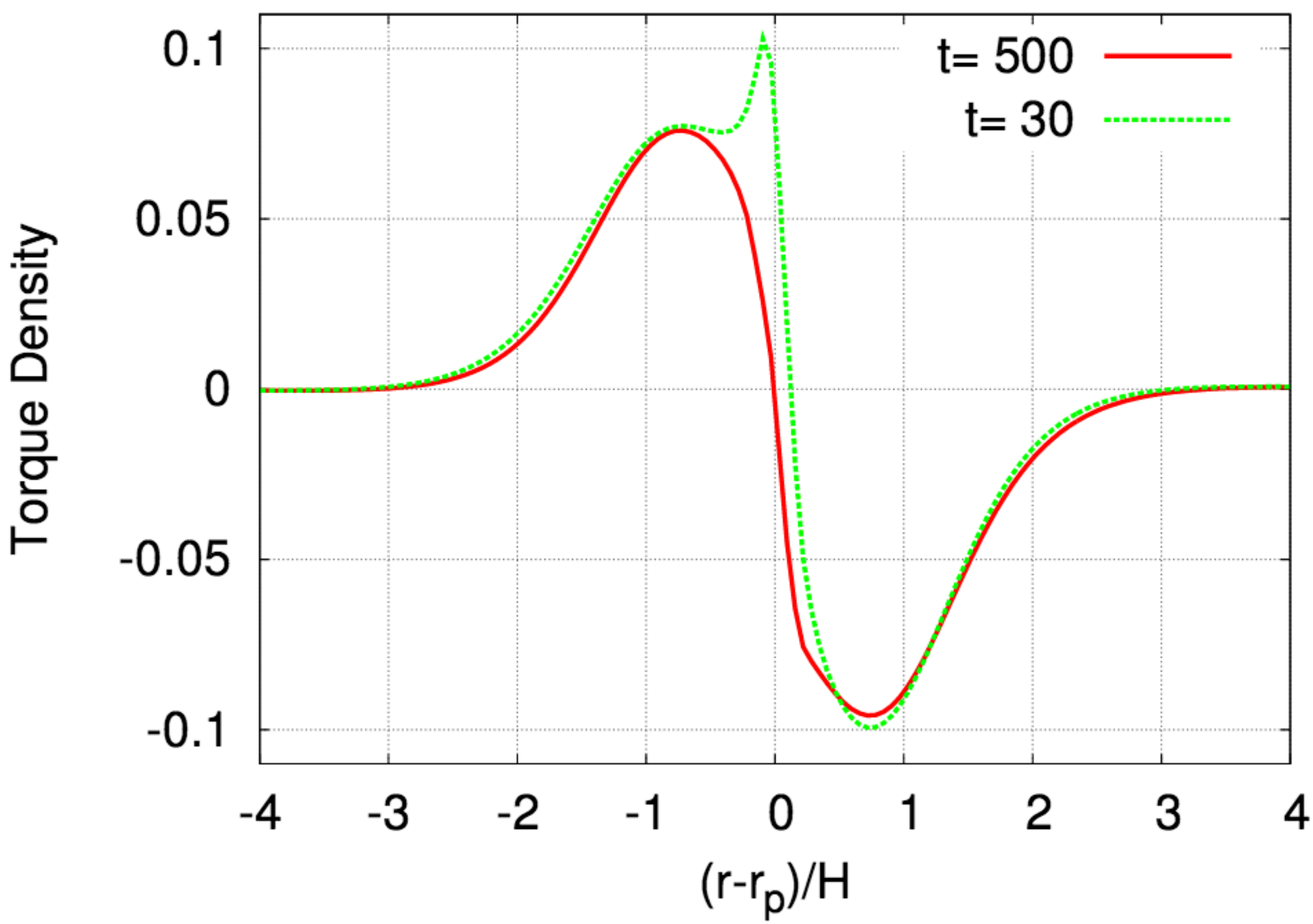

3.30
3.20
3.10
3.00
0.8
0.9
1.0
1.1
1.2

Migration: Impulse approximation





t= 500
t= 30
Torque Density
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0.05
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-0.05
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-4
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-1
0
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4
(r-r_p)/H

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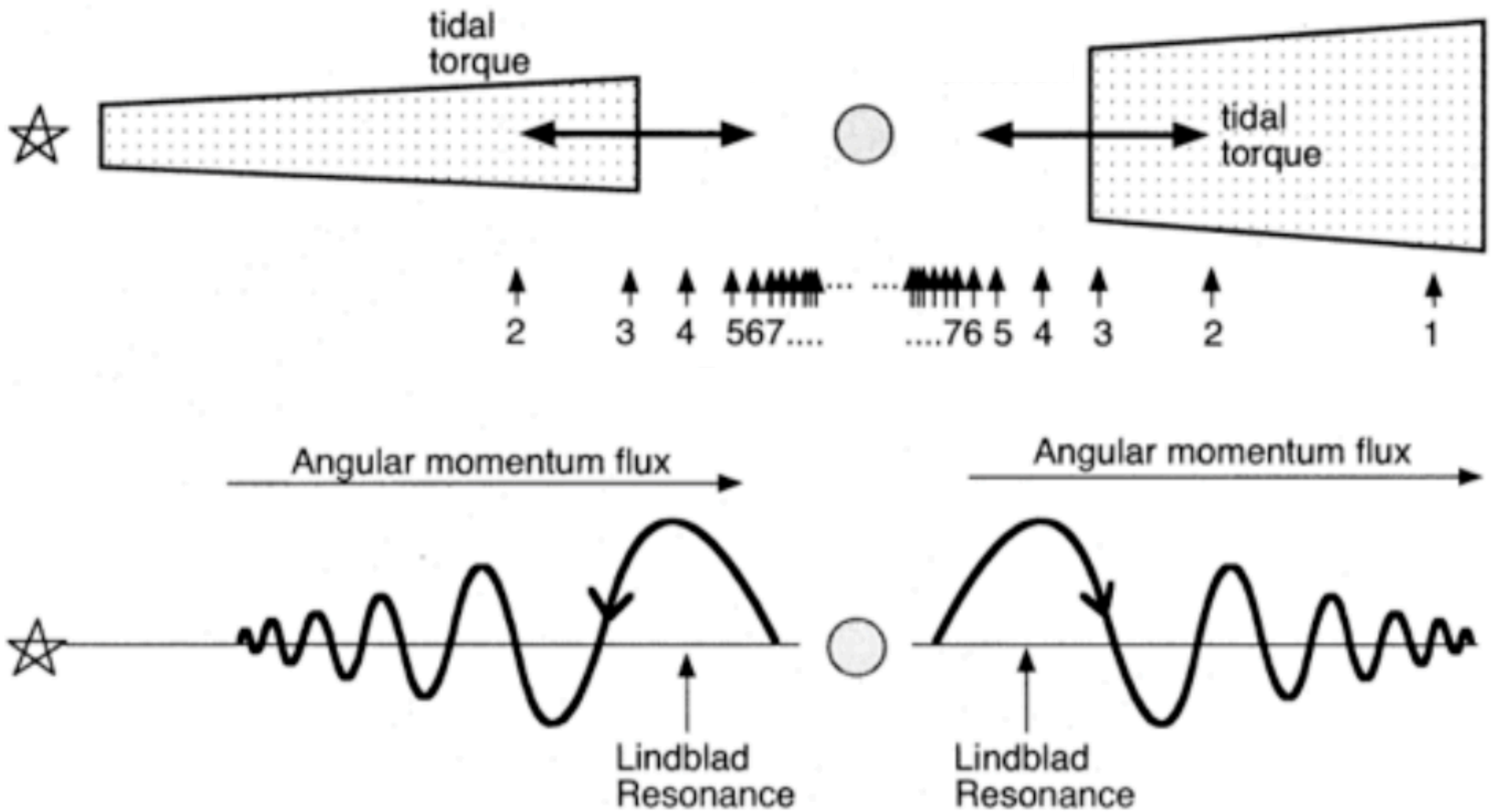
tidal
torque
tidal
torque
2
3
4
567....
....76
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Angular momentum flux
Angular momentum flux
Lindblad
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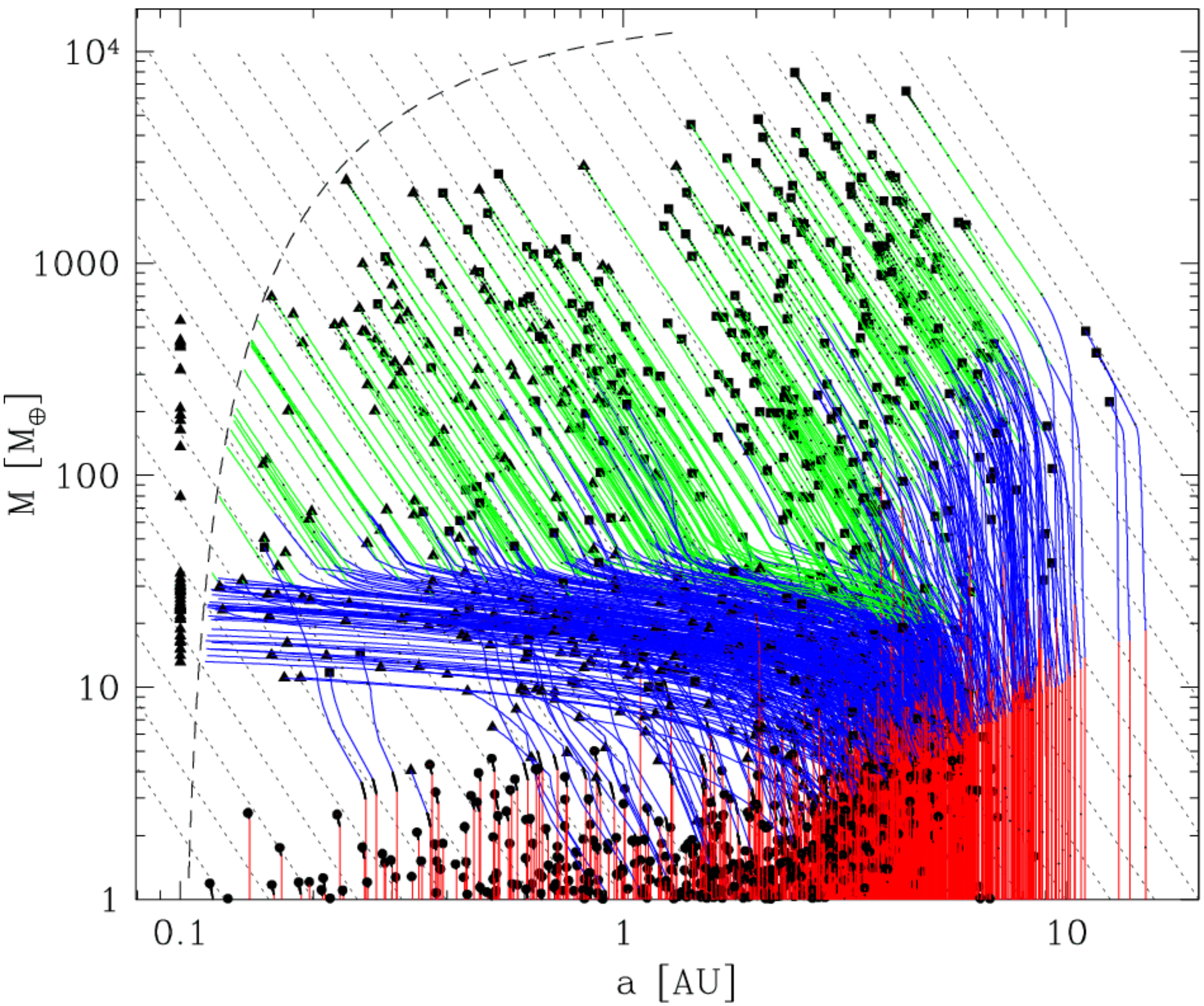
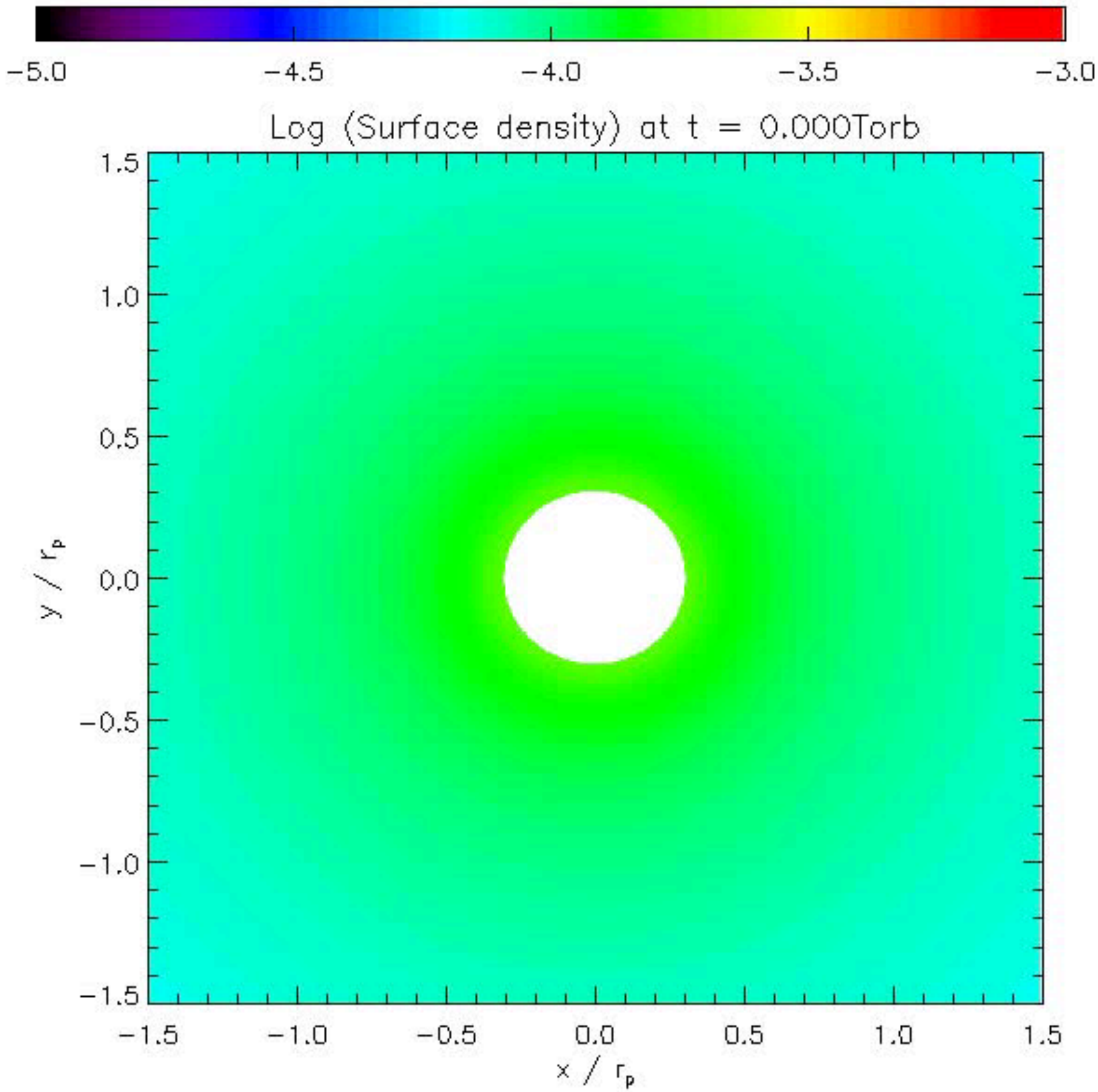
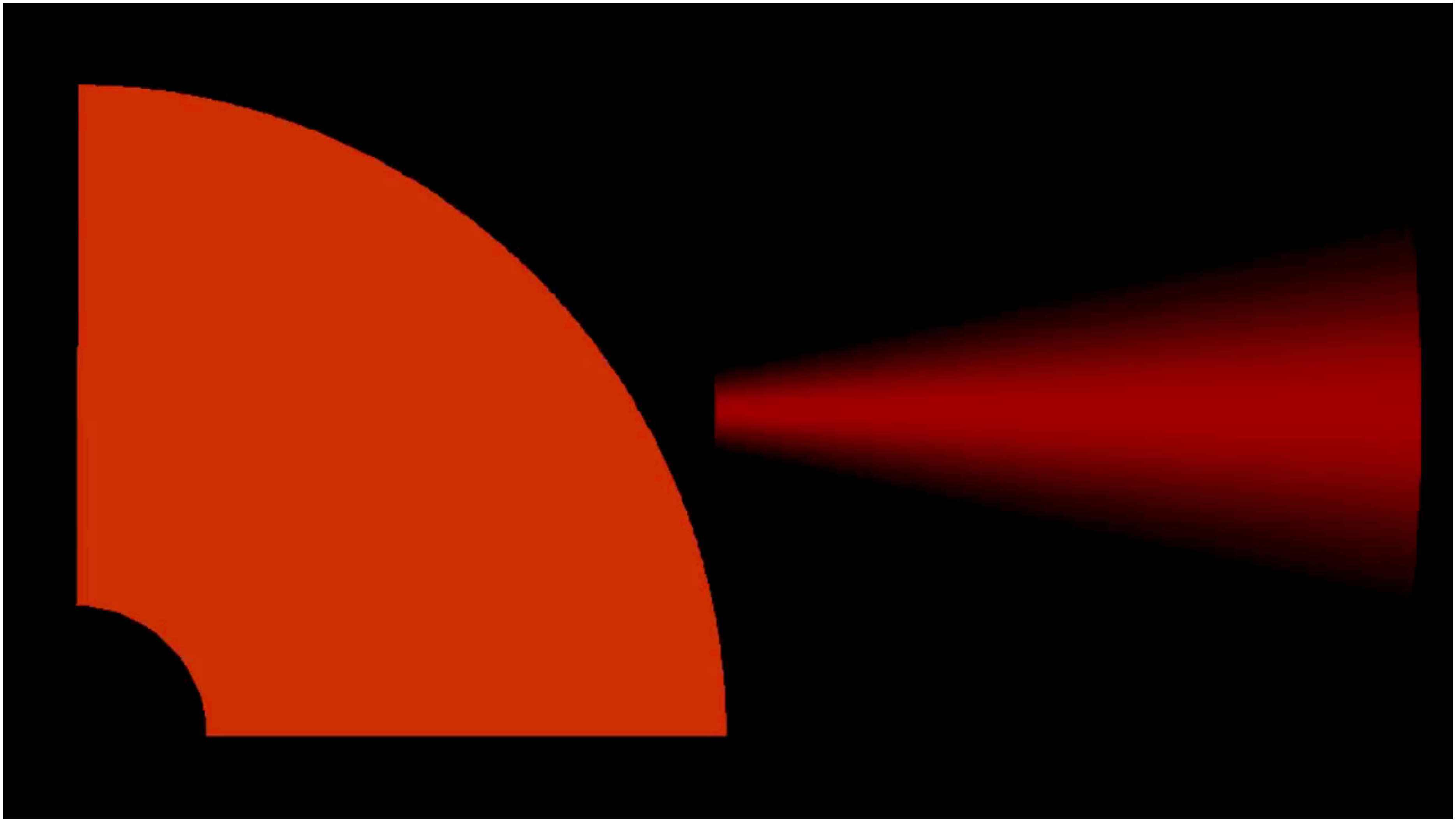
Resonance

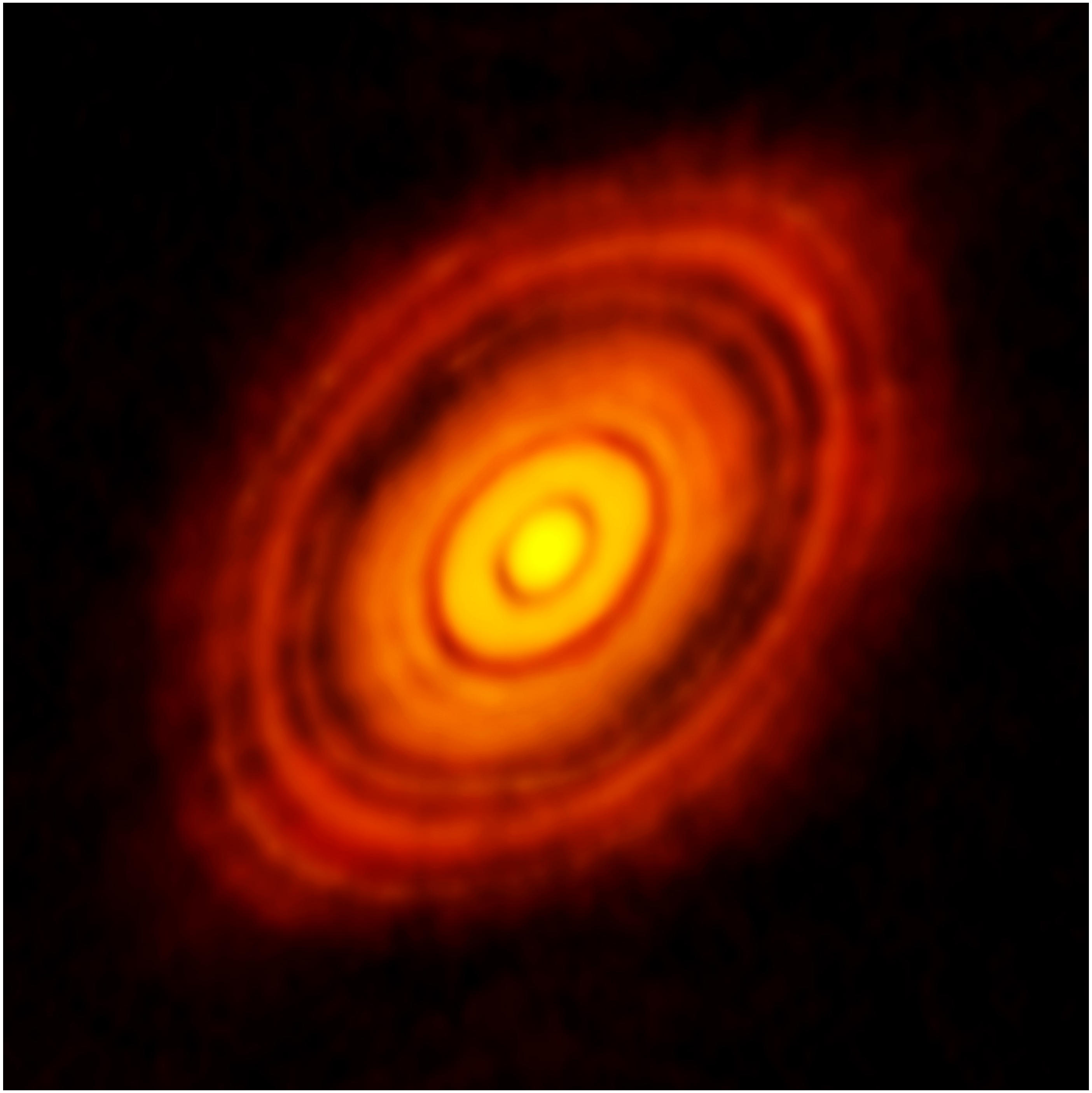
Planet Population Synthesis



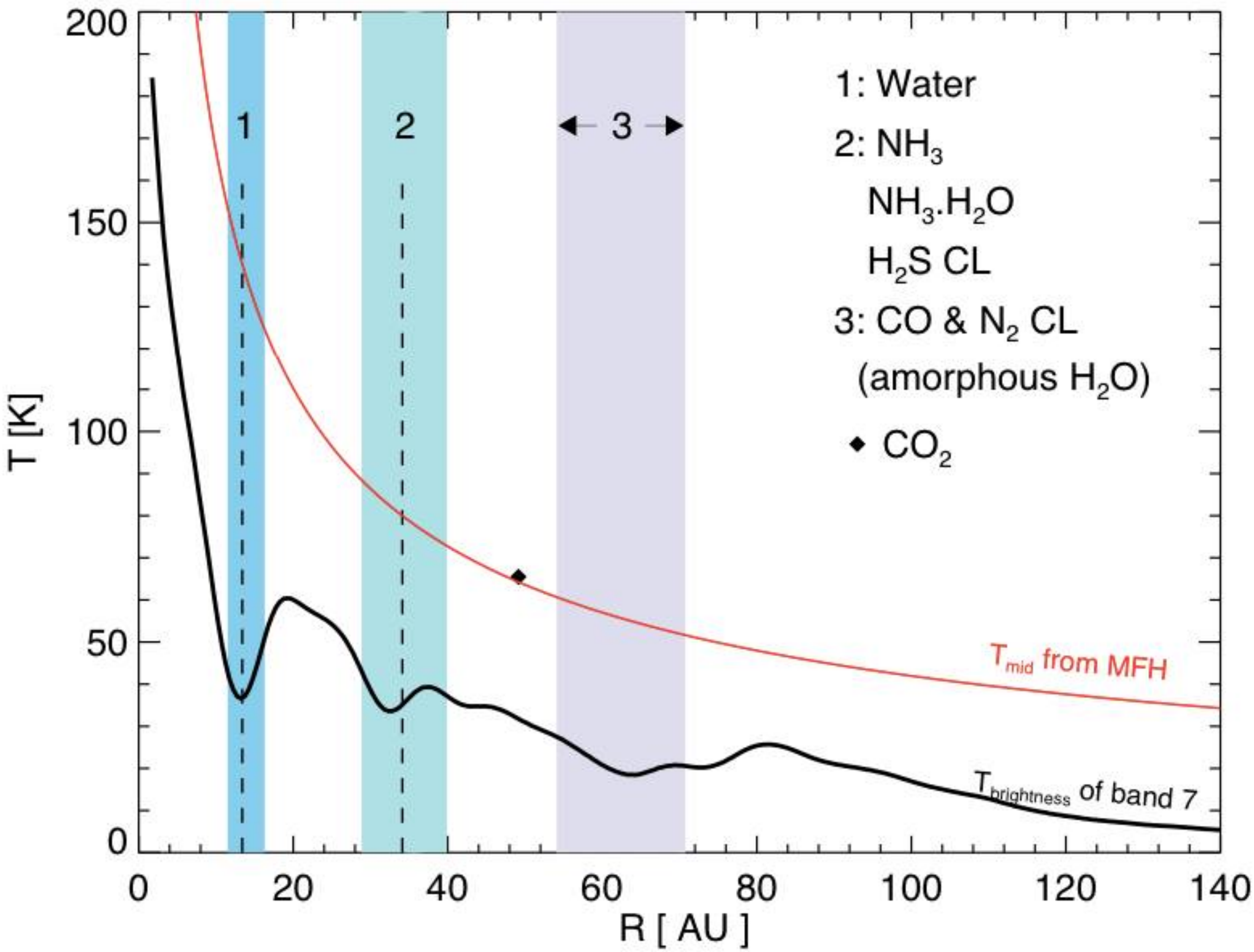


−5.0
−4.5
−4.0
−3.5
−3.0
Log (Surface density) at t = 0.000Torb
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y / r_p
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
x / r_p





HL Tau

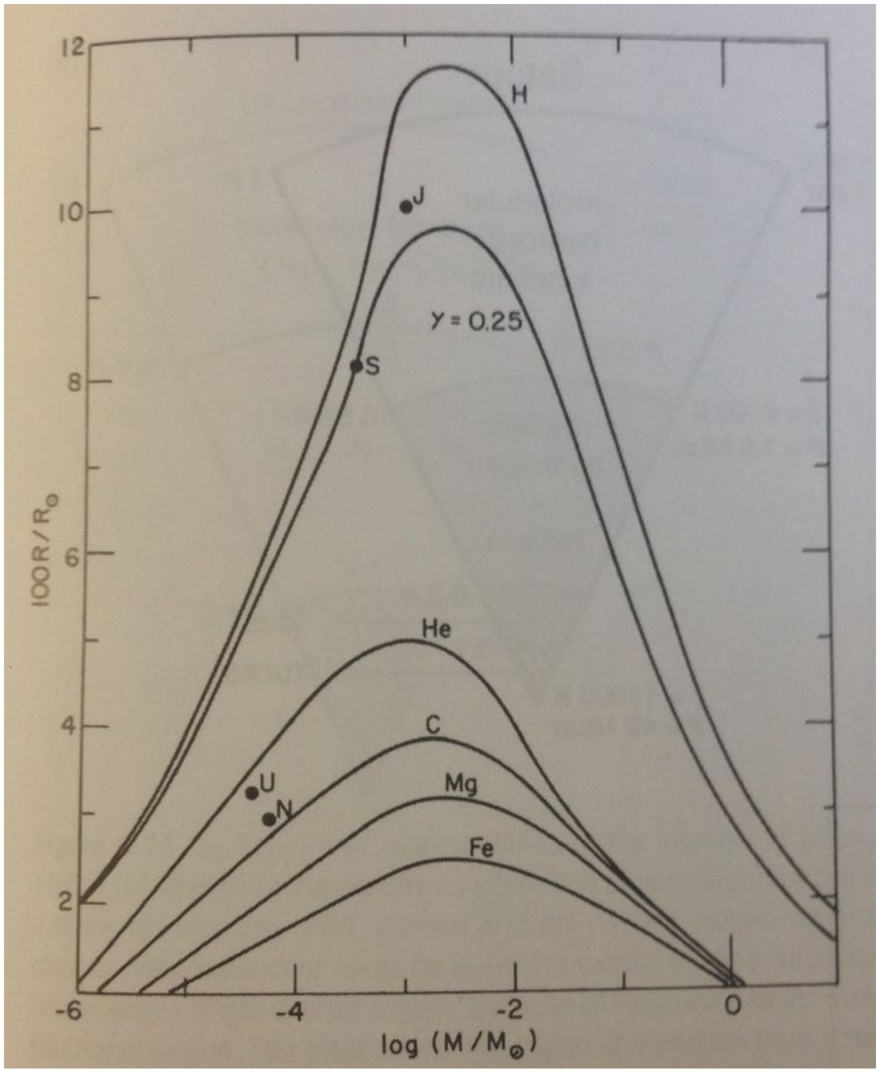


1: Water
2: NH3
NH3.H2O
H2S CL
3: CO & N2 CL
(amorphous H2O)
◆ CO2
1
2
3
Tmid from MFH
Tbrightness of band 7
T [K]
R [AU]
0
50
100
150
200
0
20
40
60
80
100
120
140

Jupiter and saturn differ by almost a factor 3 in mass, but have almost the same radius.

Why?

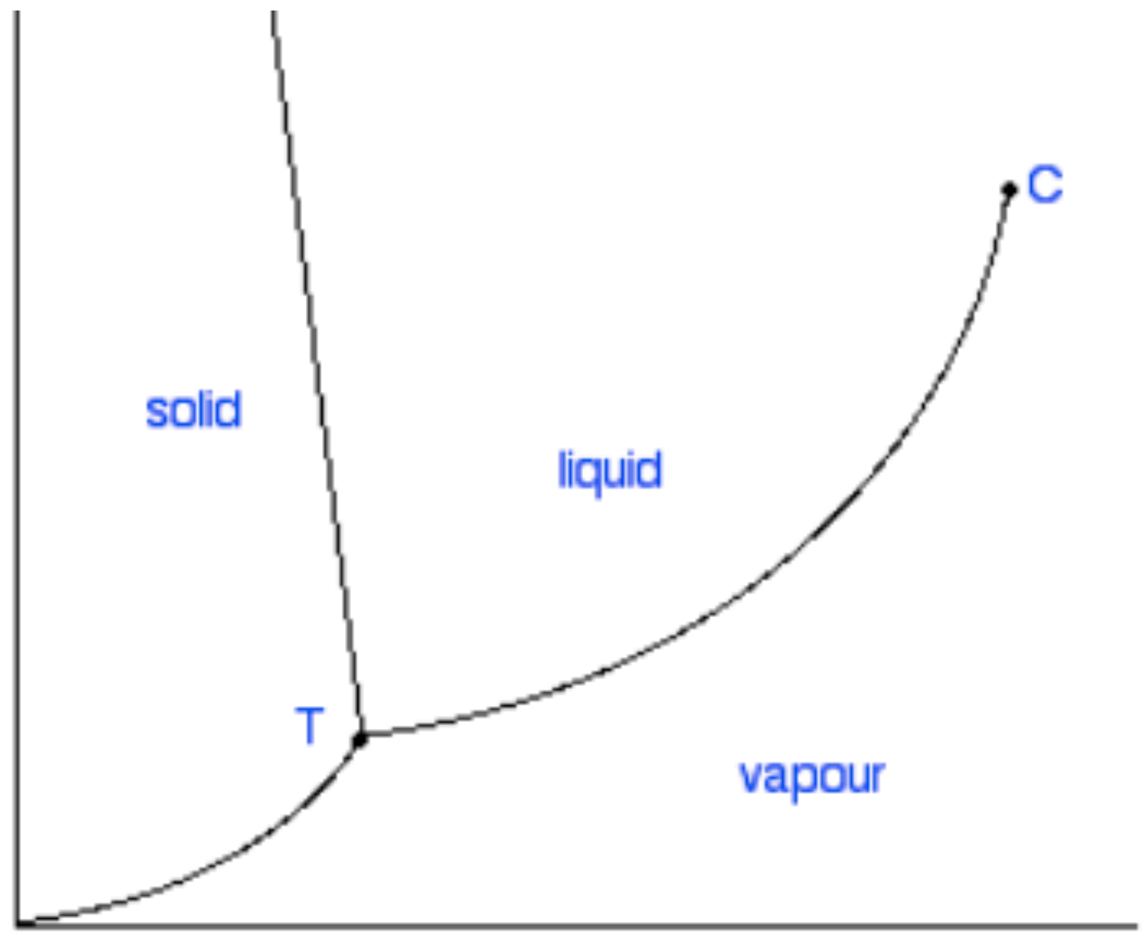
Radius vs mass curves for different compositions.



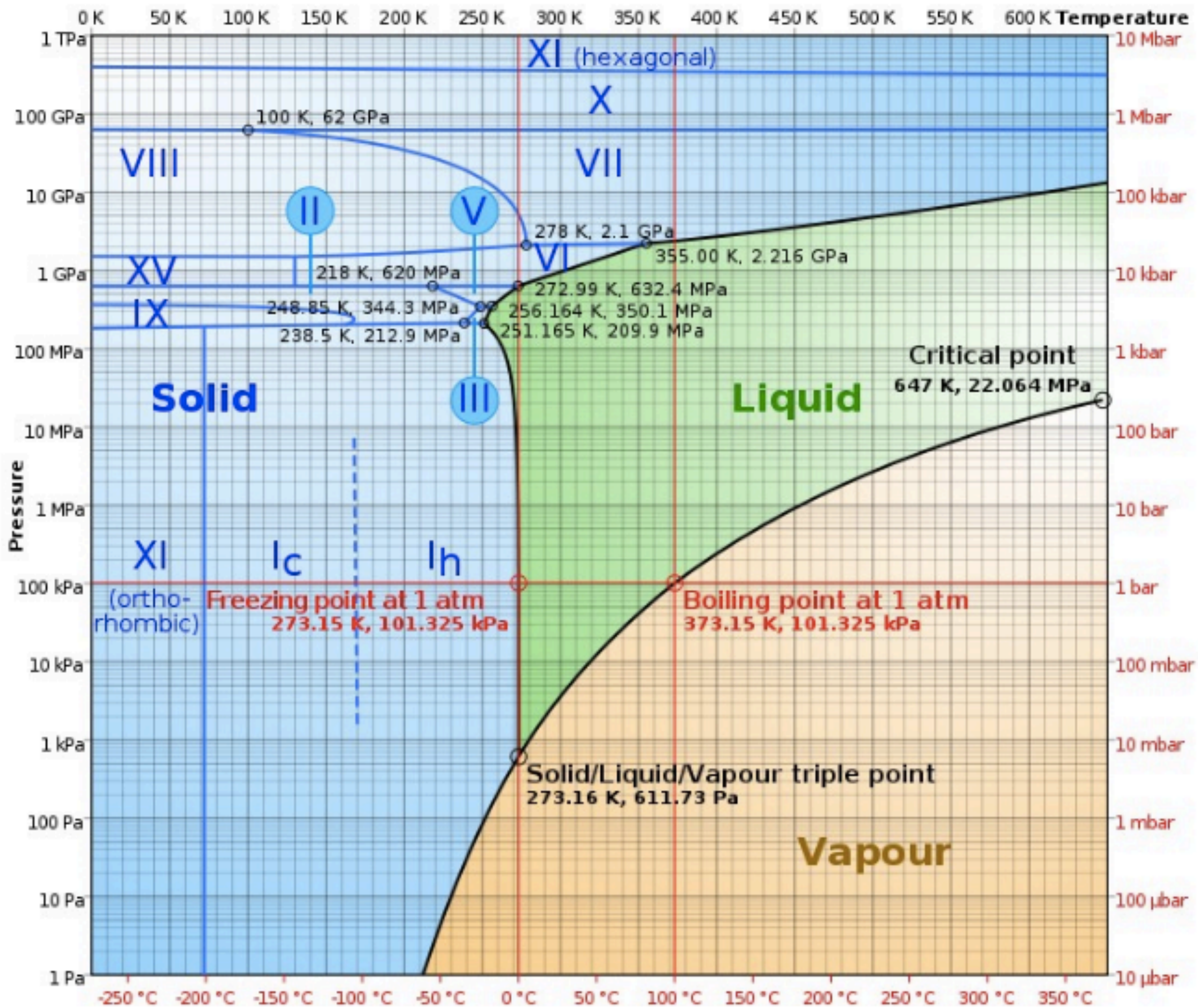
N=1 polytrope

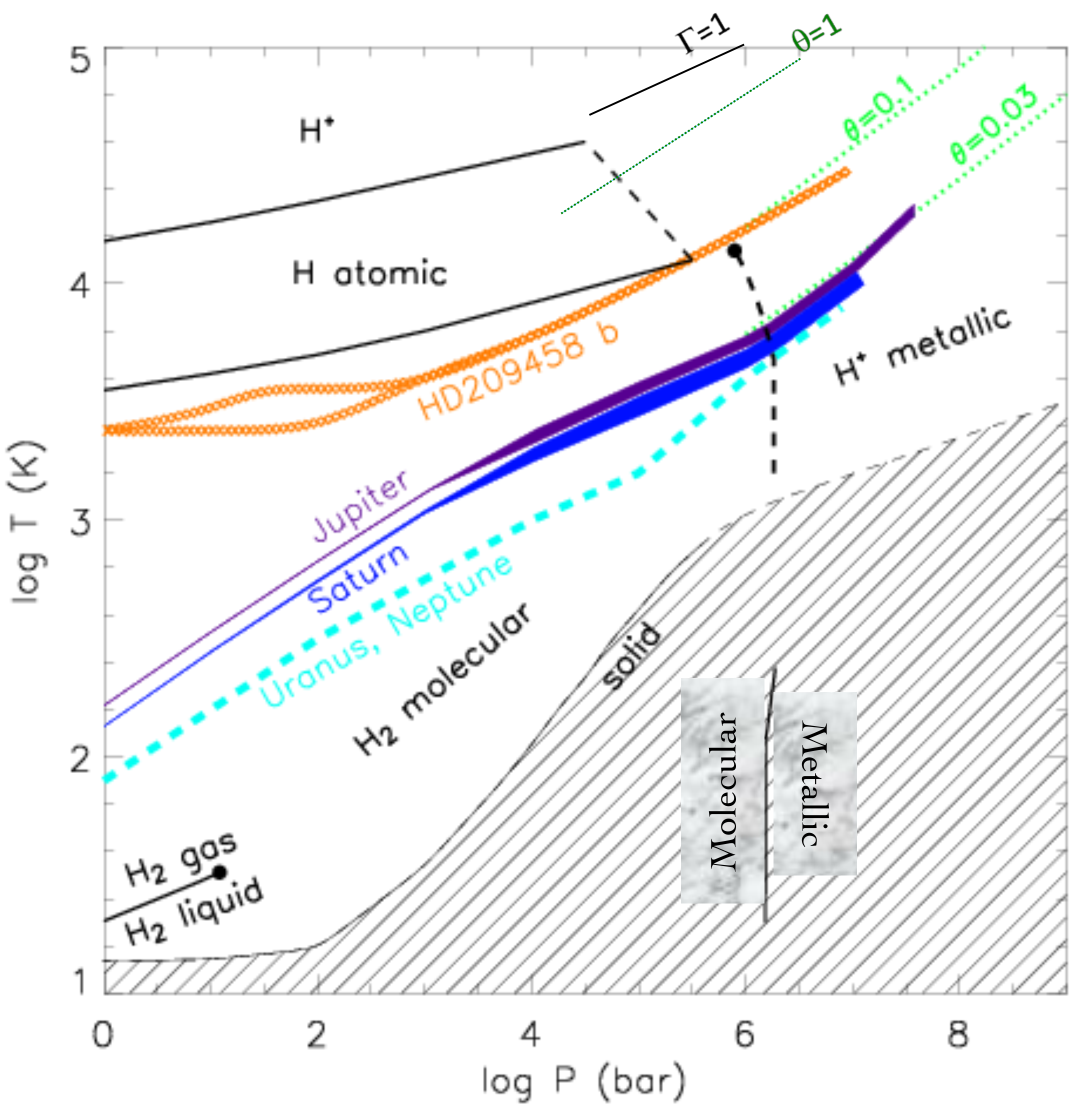
Flat on top, over almost two orders of magnitude in mass

Phase diagrams



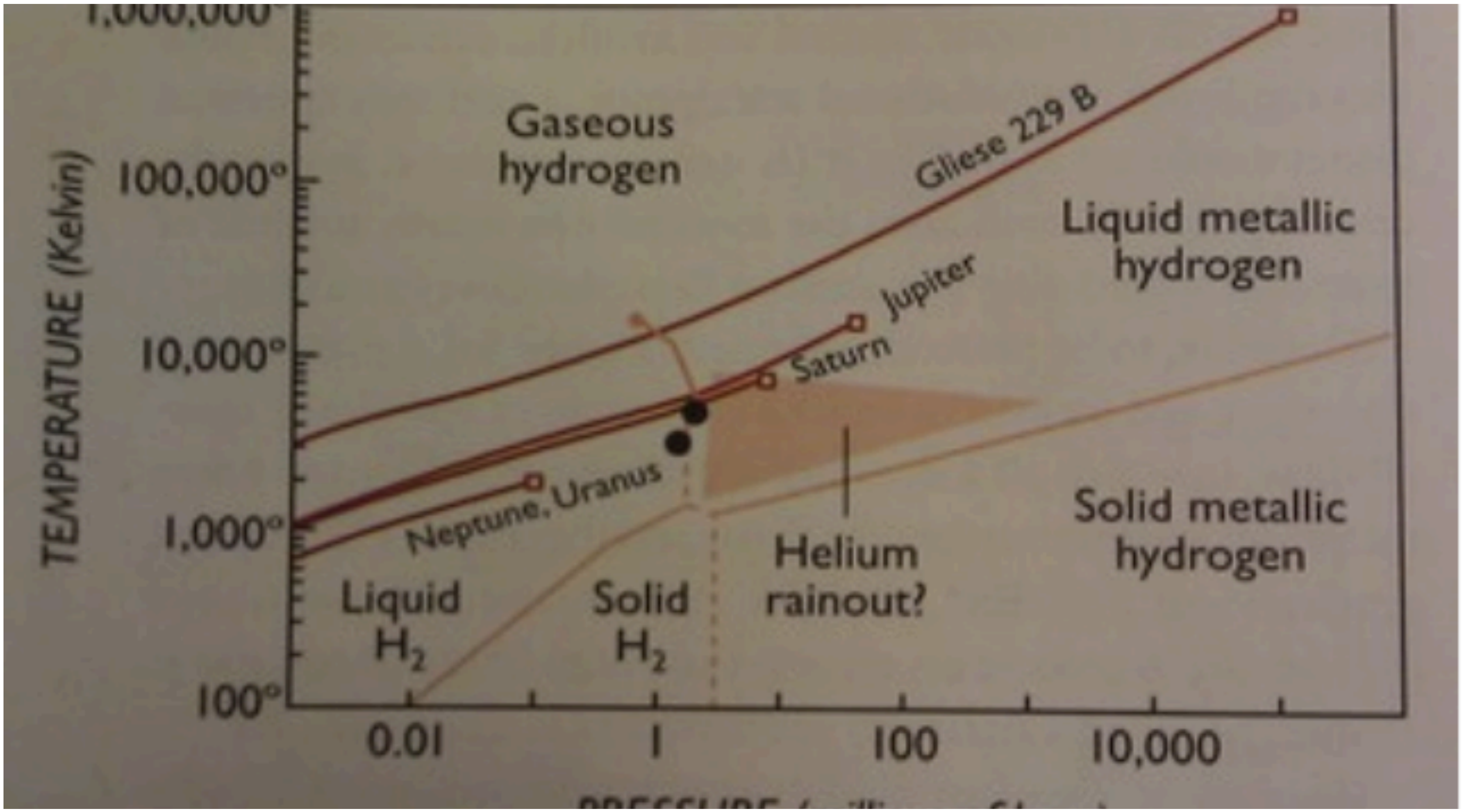
A lot more happens at high pressure



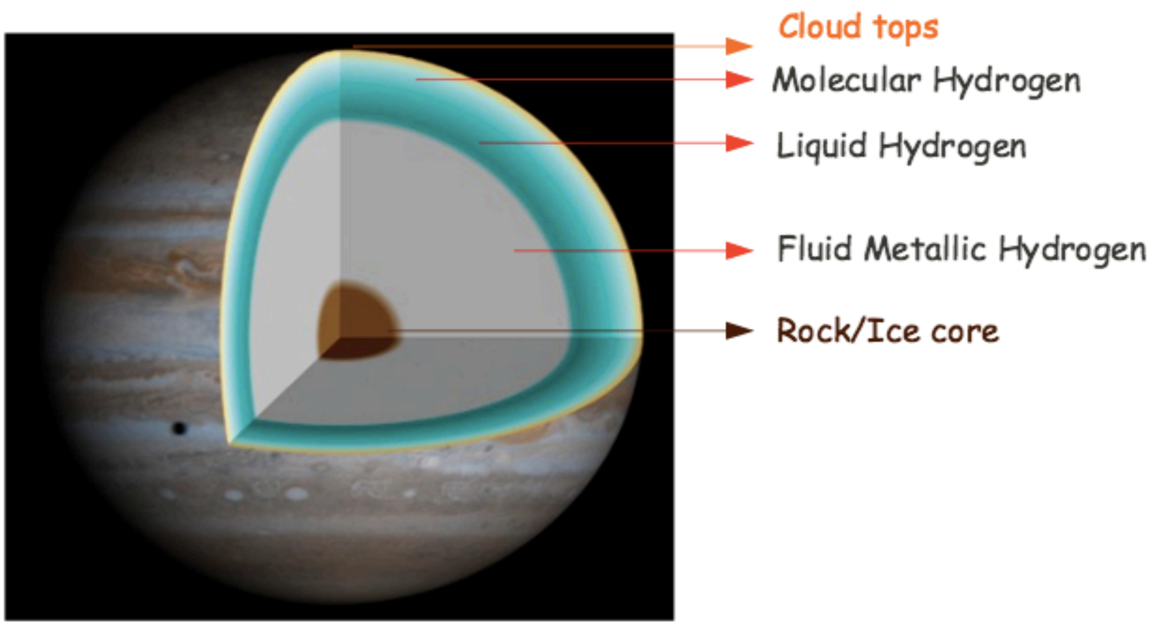


Γ=1
θ=1
θ=0.1
θ=0.03
H⁺
H atomic
HD209458 b
H⁺ metallic
Jupiter
Saturn
Uranus, Neptune
H₂ molecular
solid
Molecular
Metallic
H₂ gas
H₂ liquid
log T (K)
log P (bar)
5
4
3
2
1
0
2
4
6
8

Phases of hydrogen

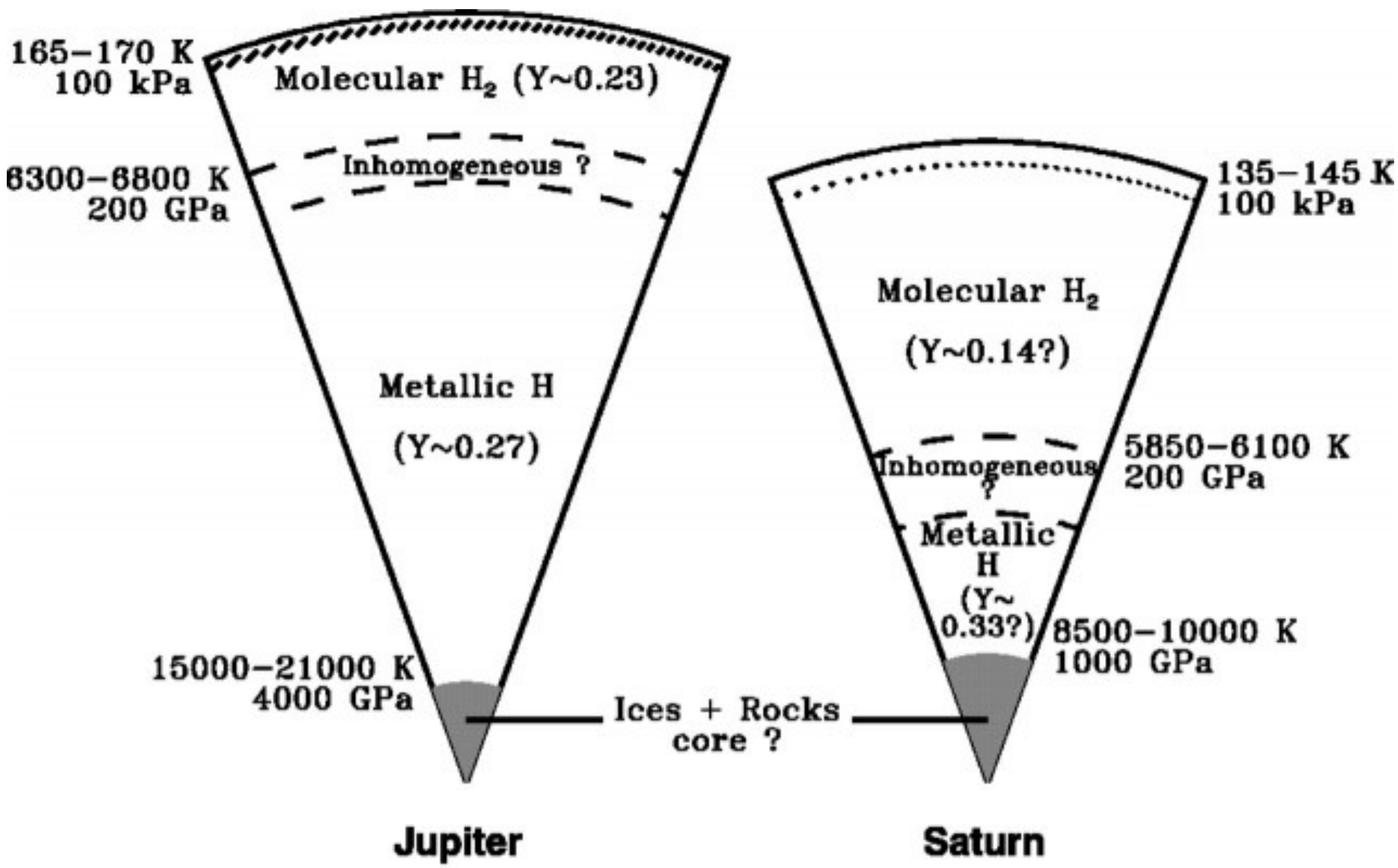


Interior of Jupiter

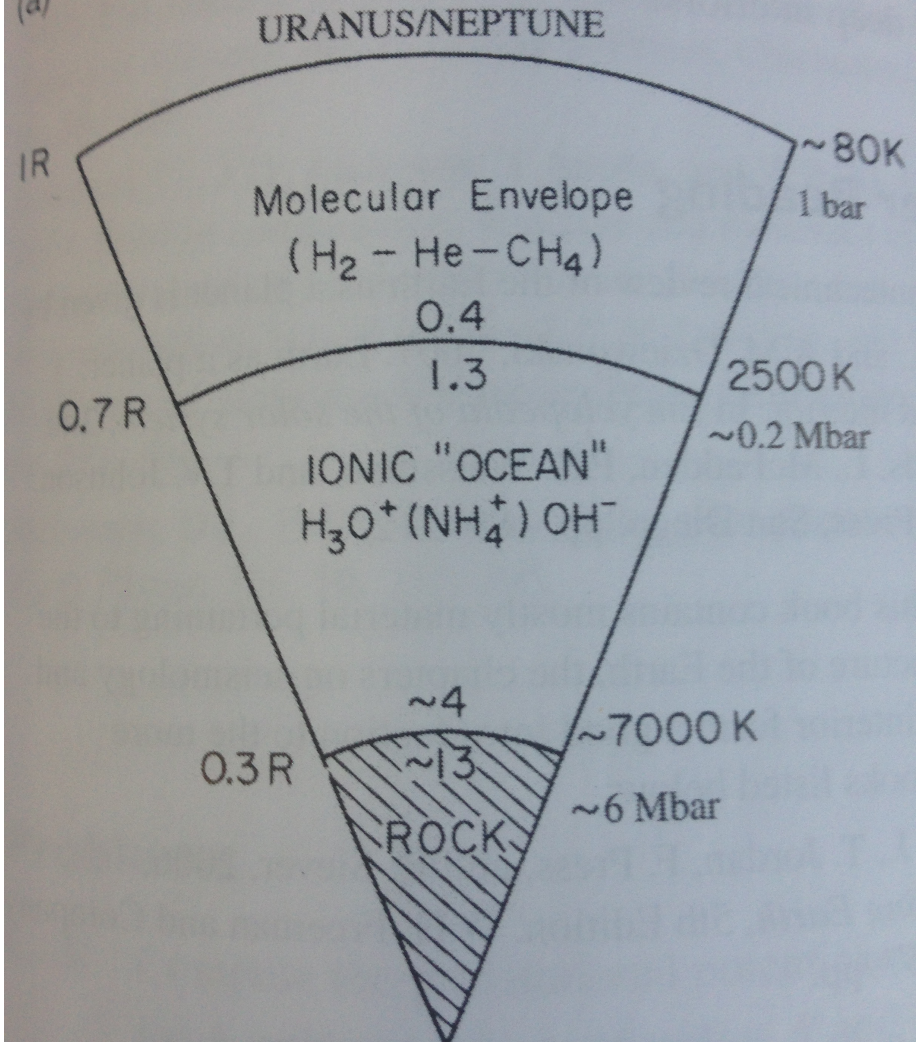


Pressure = weight/area

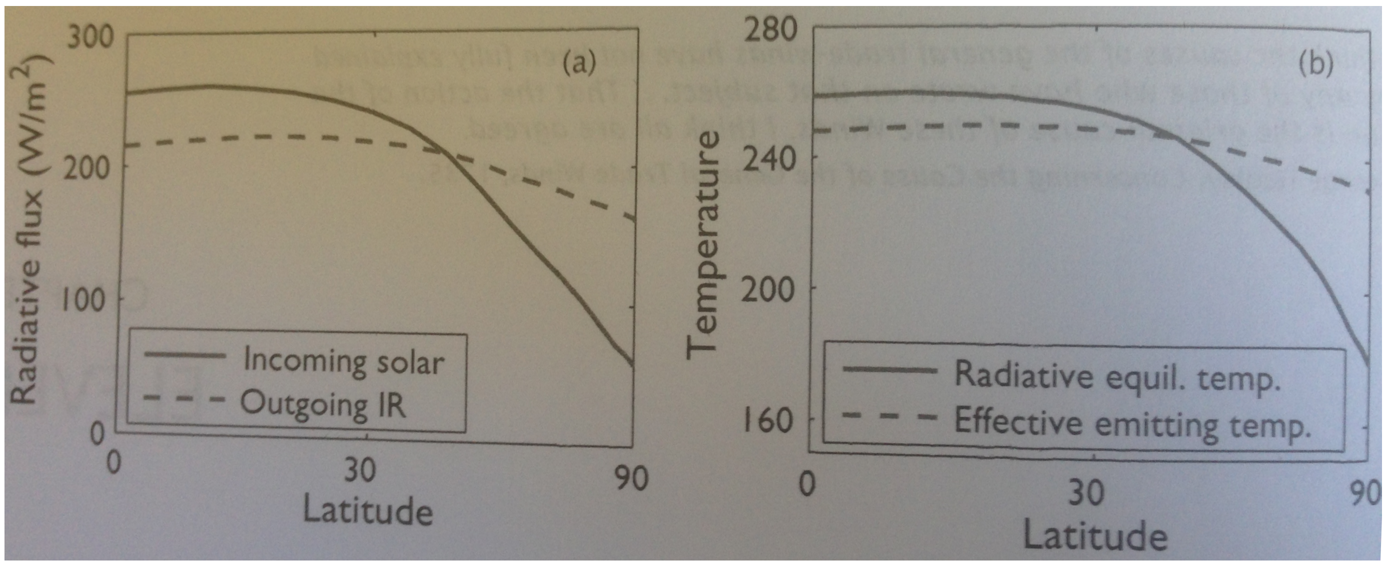
Pressure at center
70 million atmospheres


165–170 K
100 kPa
Molecular H_2 (Y~0.23)
6300–6800 K
200 GPa
Inhomogeneous ?
Metallic H
(Y~0.27)
15000–21000 K
4000 GPa
135–145 K
100 kPa
Molecular H_2
(Y~0.14?)
5850–6100 K
200 GPa
Inhomogeneous
?
Metallic
H
(Y~
0.33?)
8500–10000 K
1000 GPa
Ices + Rocks
core ?
Jupiter
Saturn

(a)

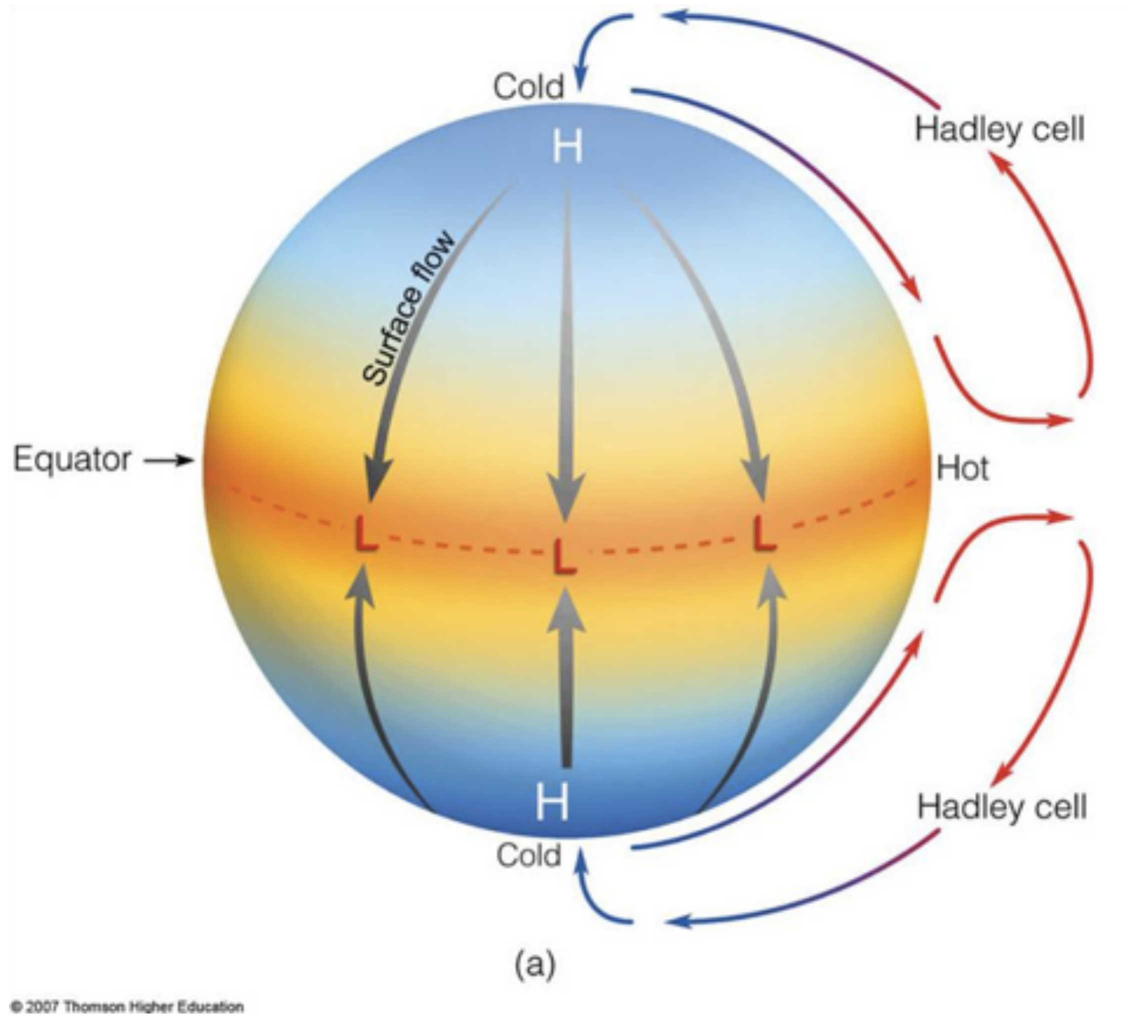

URANUS/NEPTUNE
1R
~80K
1 bar
Molecular Envelope
(H2 – He – CH4)
0.4
1.3
0.7 R
2500 K
~0.2 Mbar
IONIC "OCEAN"
H3O+ (NH4+) OH−
~4
~13
0.3 R
~7000 K
~6 Mbar
ROCK

Radiative equilibrium.

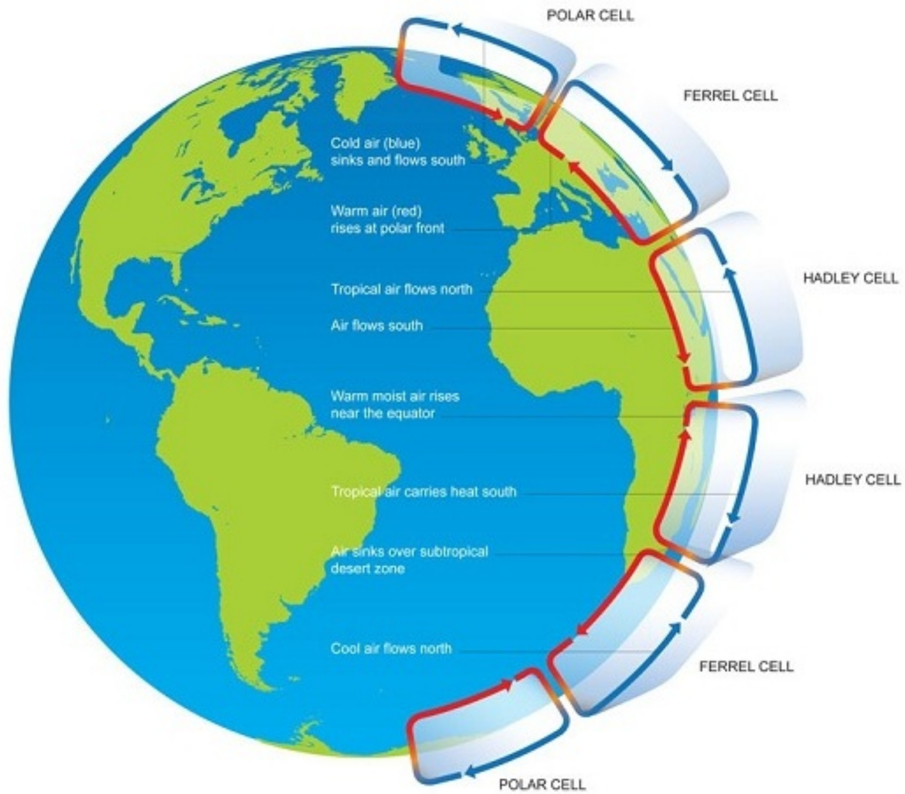


A function of latitude.
Evidence of transport!

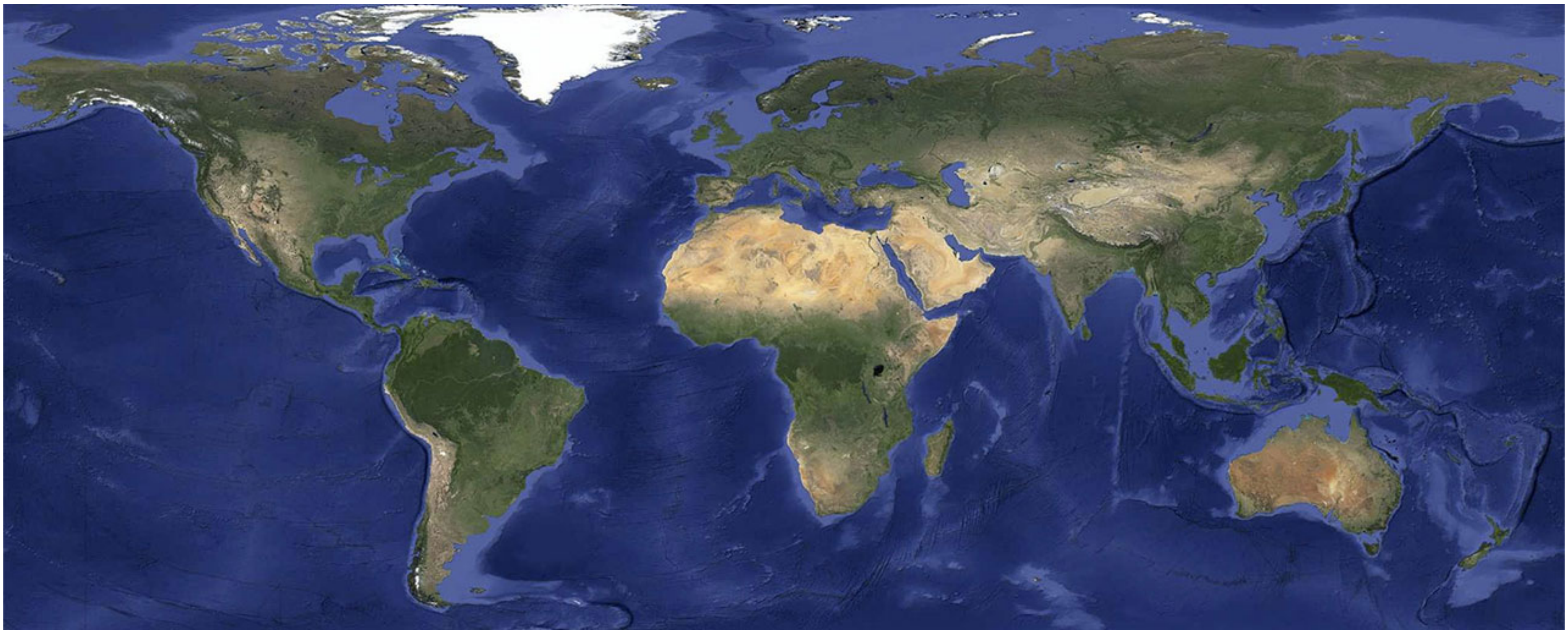
Hadley circulation



Hadley circulation with planetary rotation



The deserts are found in a line

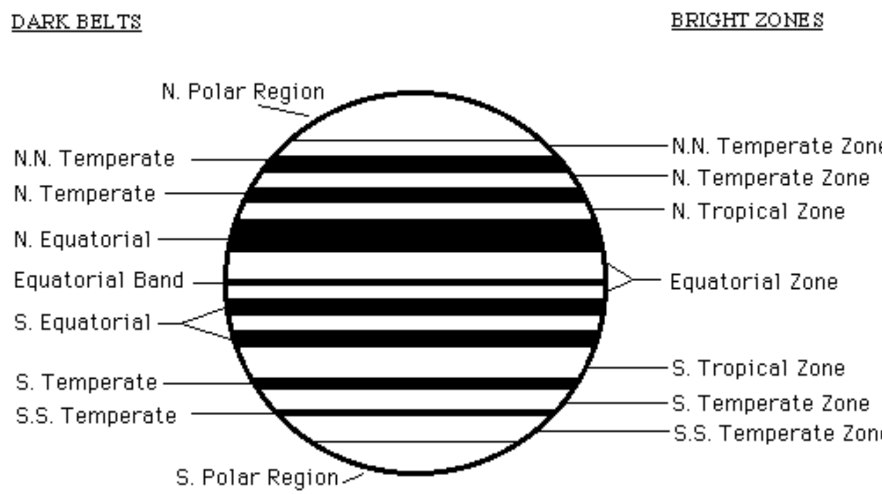


Boundary between descending Hadley cells.

Ascent: aircools and cannot hold moist, raining down. Makes the rain forests.

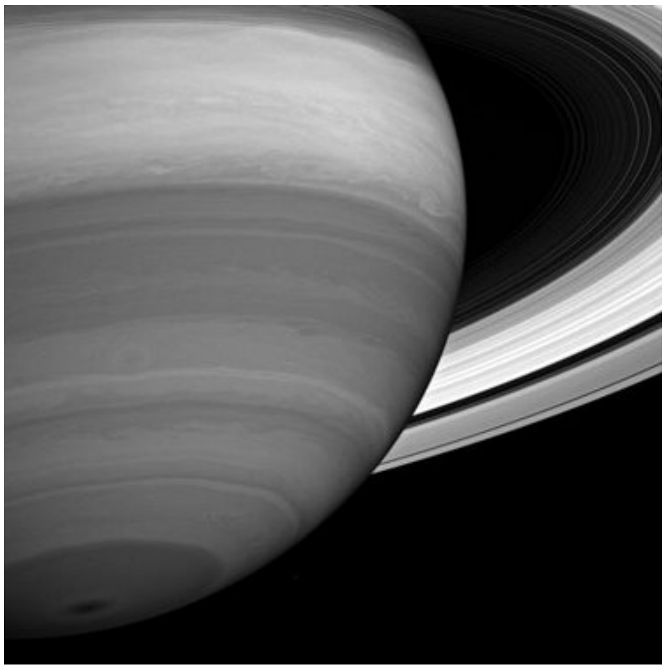
Descent: Dry air creates deserts.

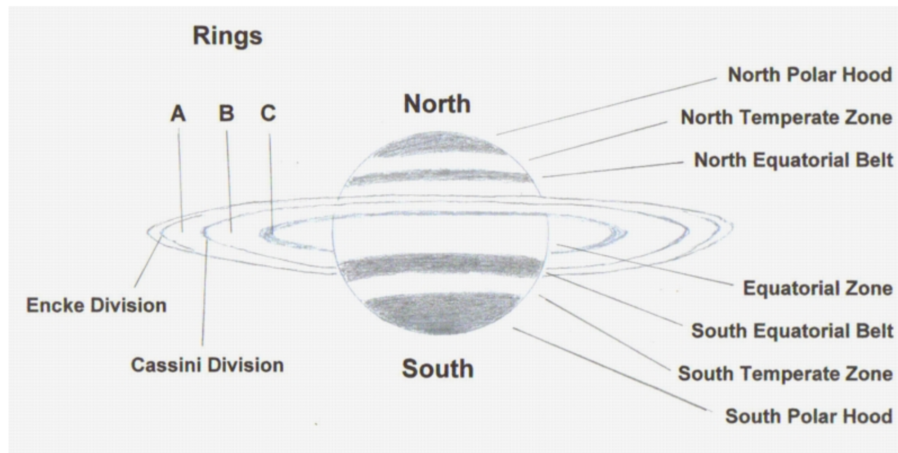
Atmospheres of the Giant Planets



Bands and Storms

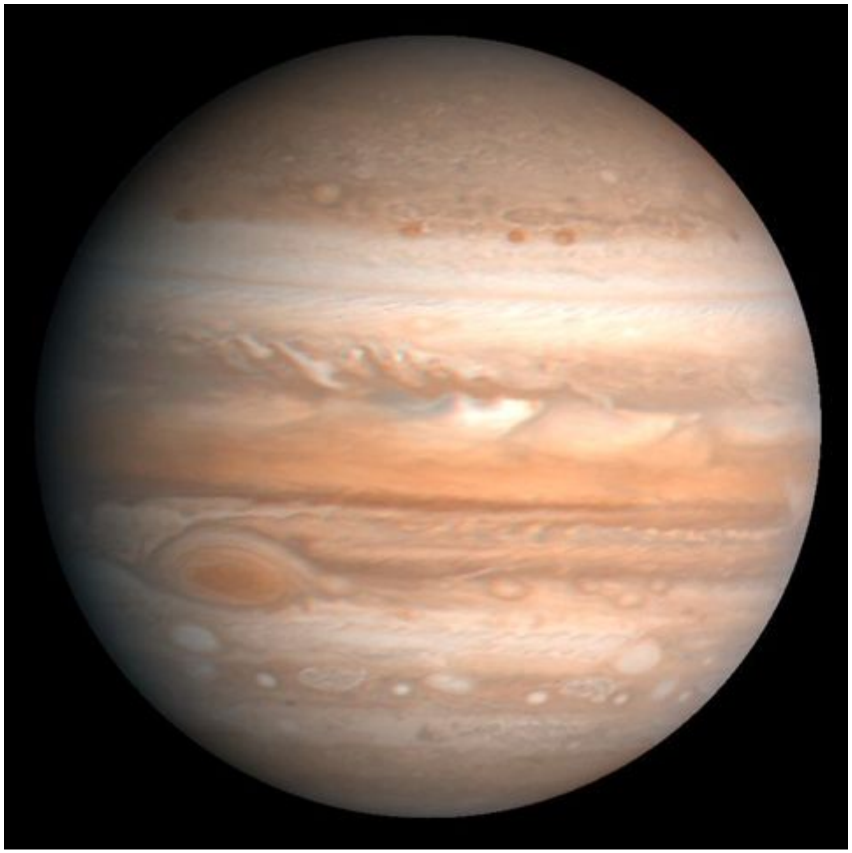
Atmospheres of the Giant Planets





Bands and Storms

Clouds of Jupiter

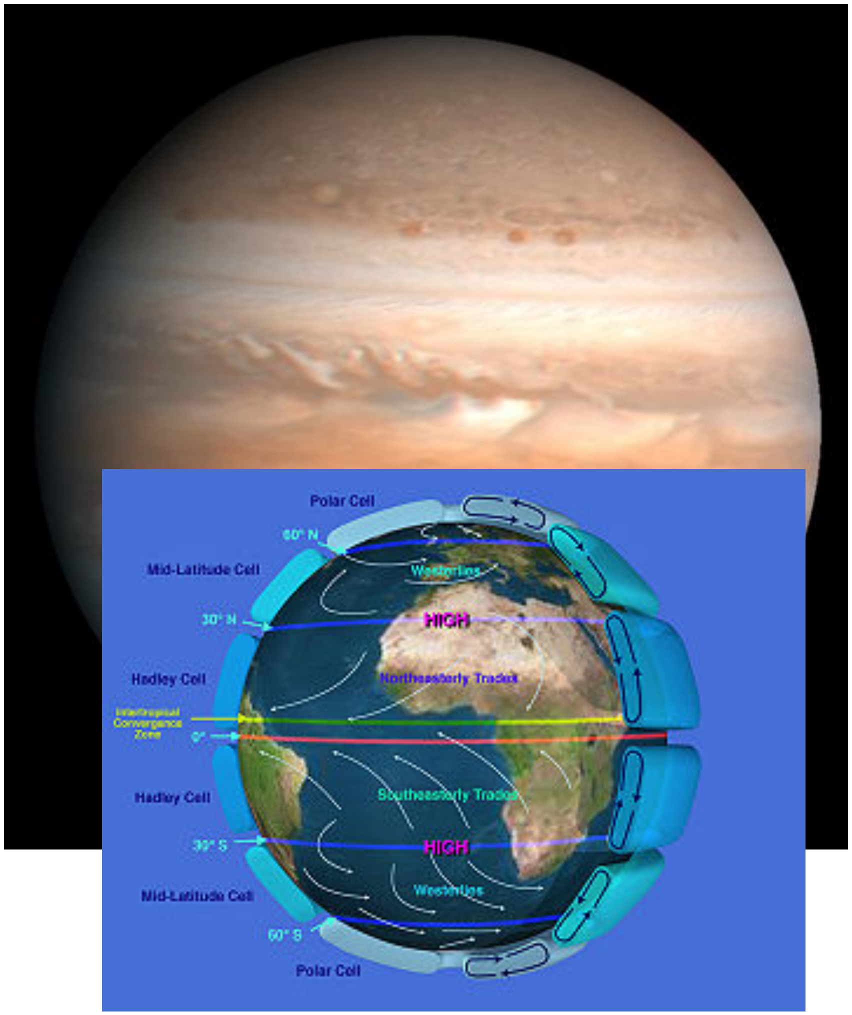


Bright ***Zones***
Dark ***Belts***

Dark brown color:
compounds of sulfur (S) and phosphorus (P)

Bright zones:
High ammonia clouds
shielding brown stuff below

Clouds of Jupiter



Bright ***Zones***
Dark ***Belts***

Dark brown color:
compounds of sulfur (S) and phosphorus (P)

Bright zones:
High ammonia clouds
shielding brown stuff below

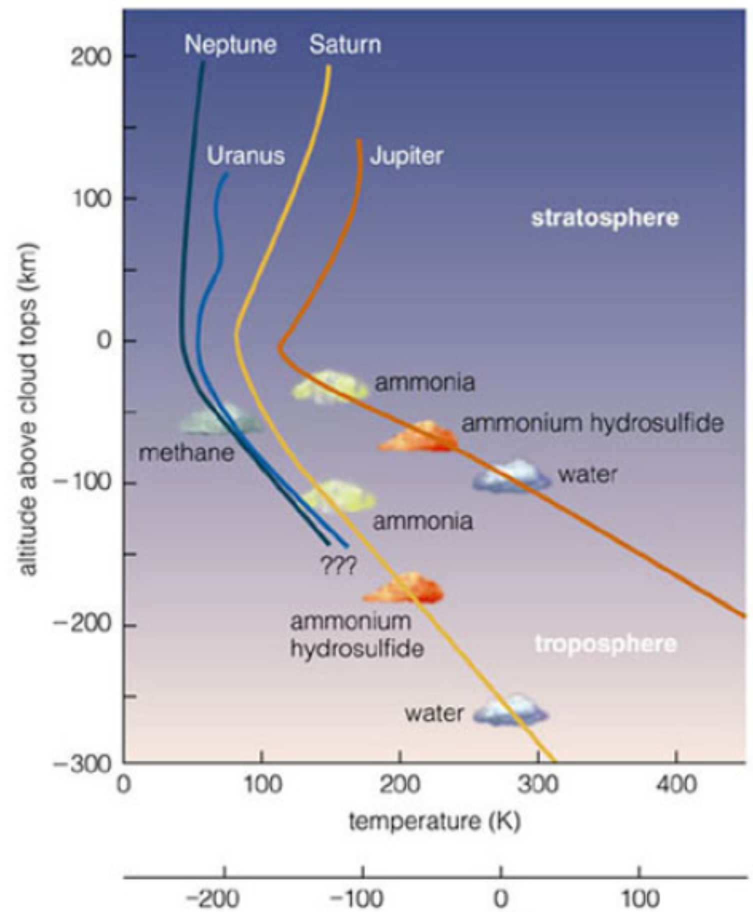
In Jupiter

Hot gas rises, **cools**,
ammonia condenses -> ***Zones***.

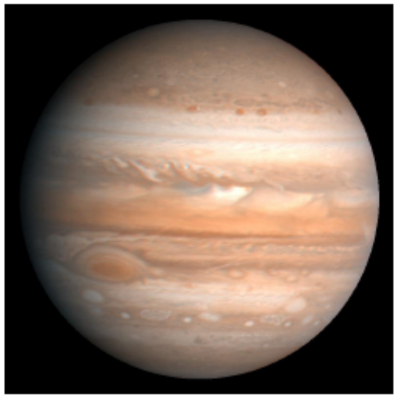
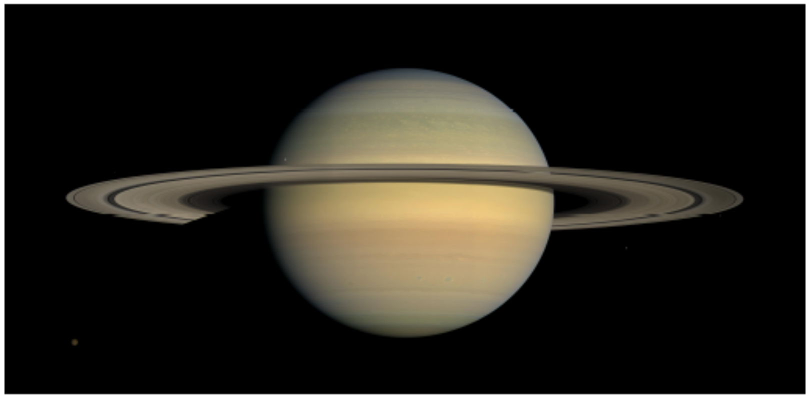
Cold air sinking,
dry in ammonia - > ***Belts***.

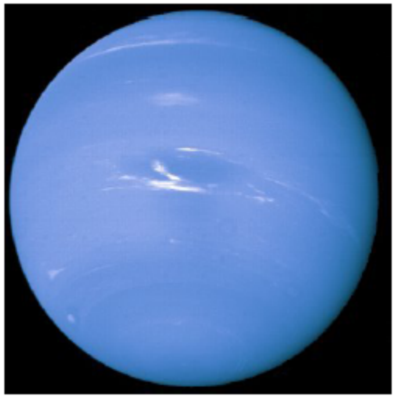
Clouds

$H_2 0$	~300K
NH_3	~140K
CH_4	~80K

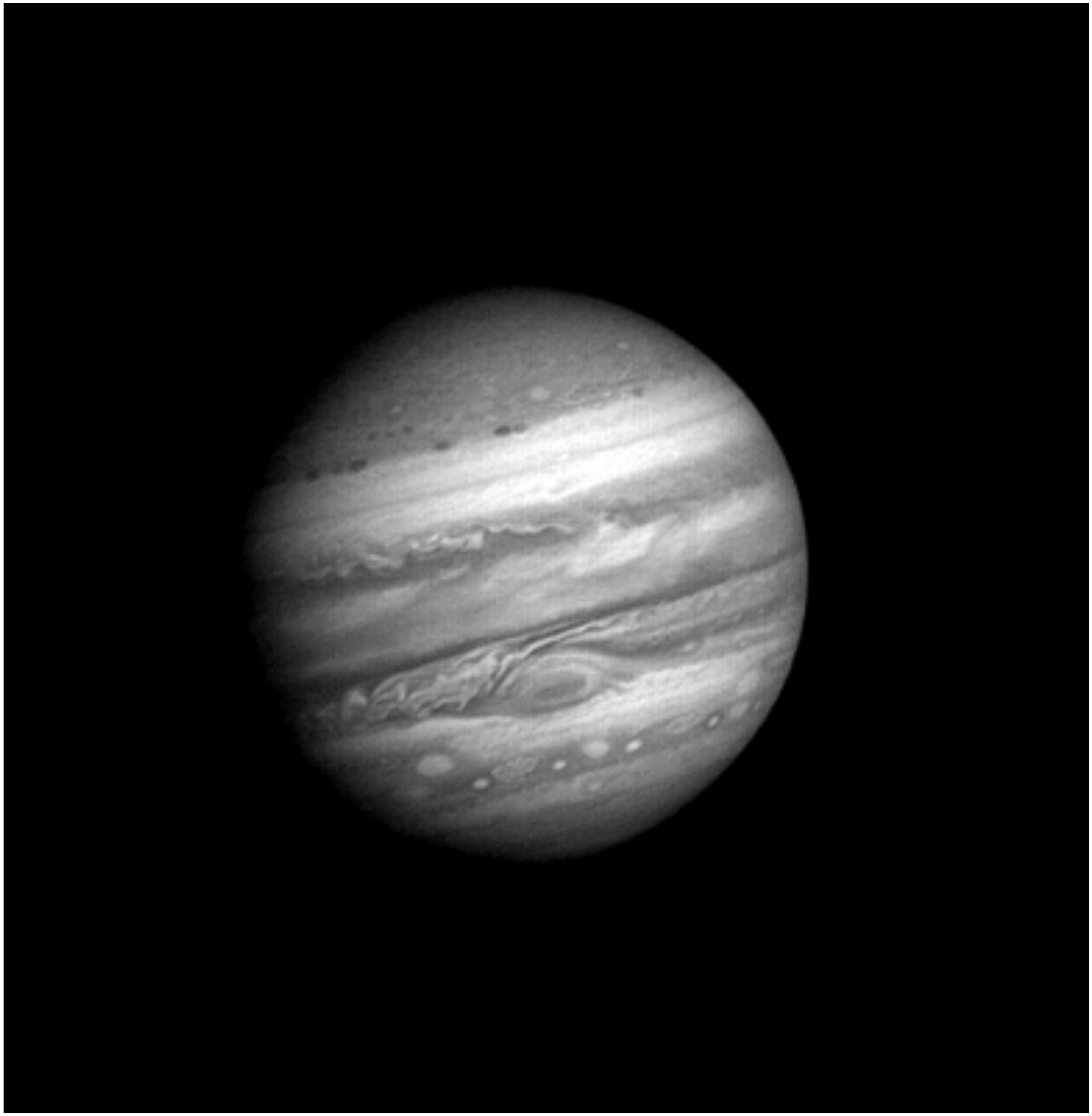


Ammonia and Methane Clouds

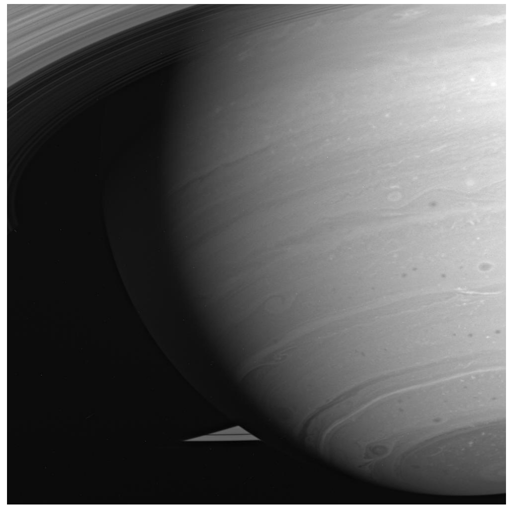



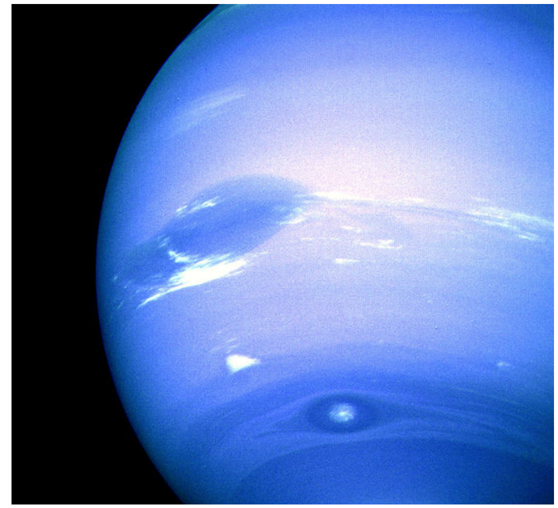


Jupiter and Saturn have ammonia clouds
Colder Uranus and Neptune have methane clouds



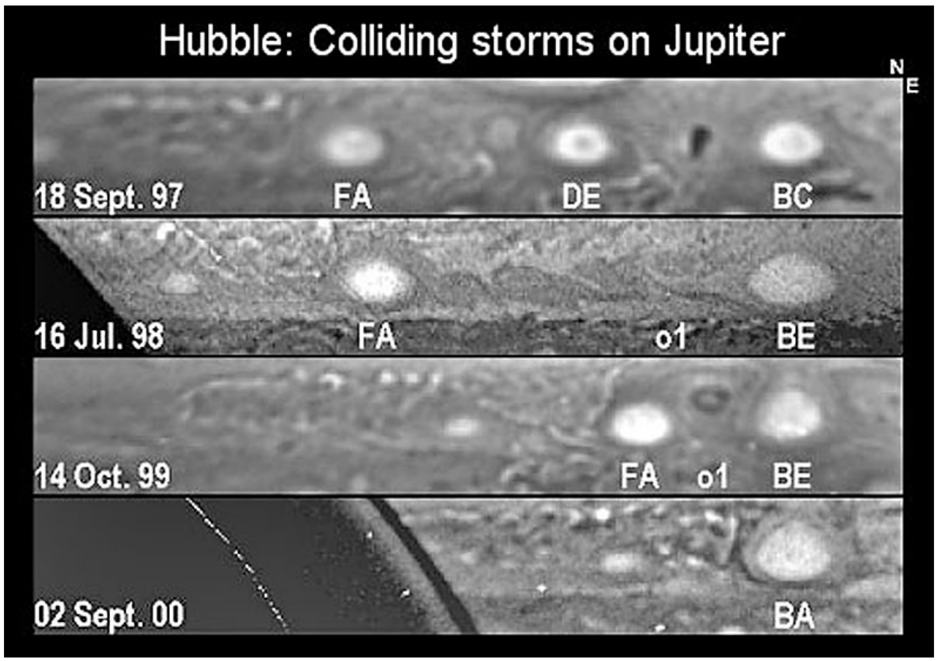
Storms



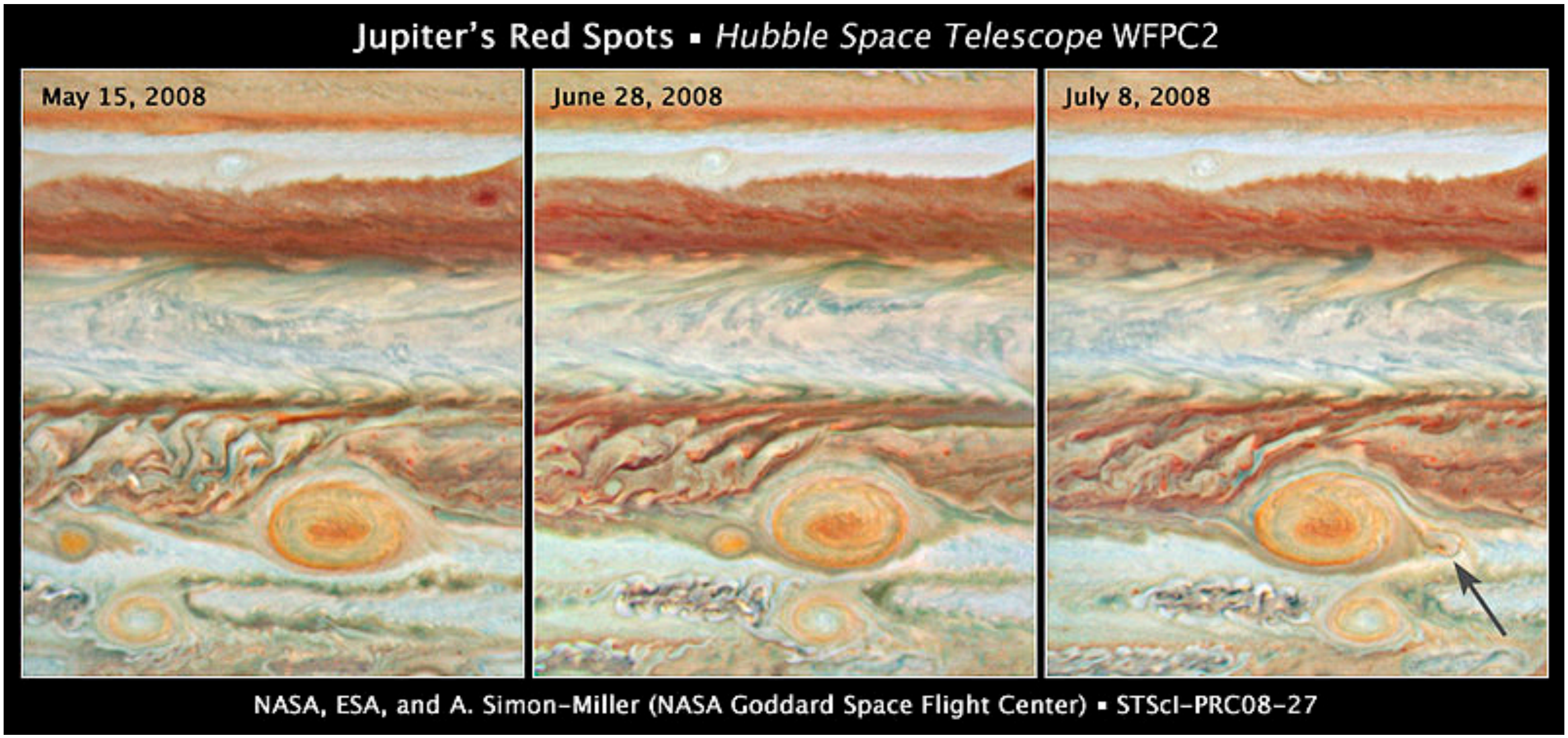


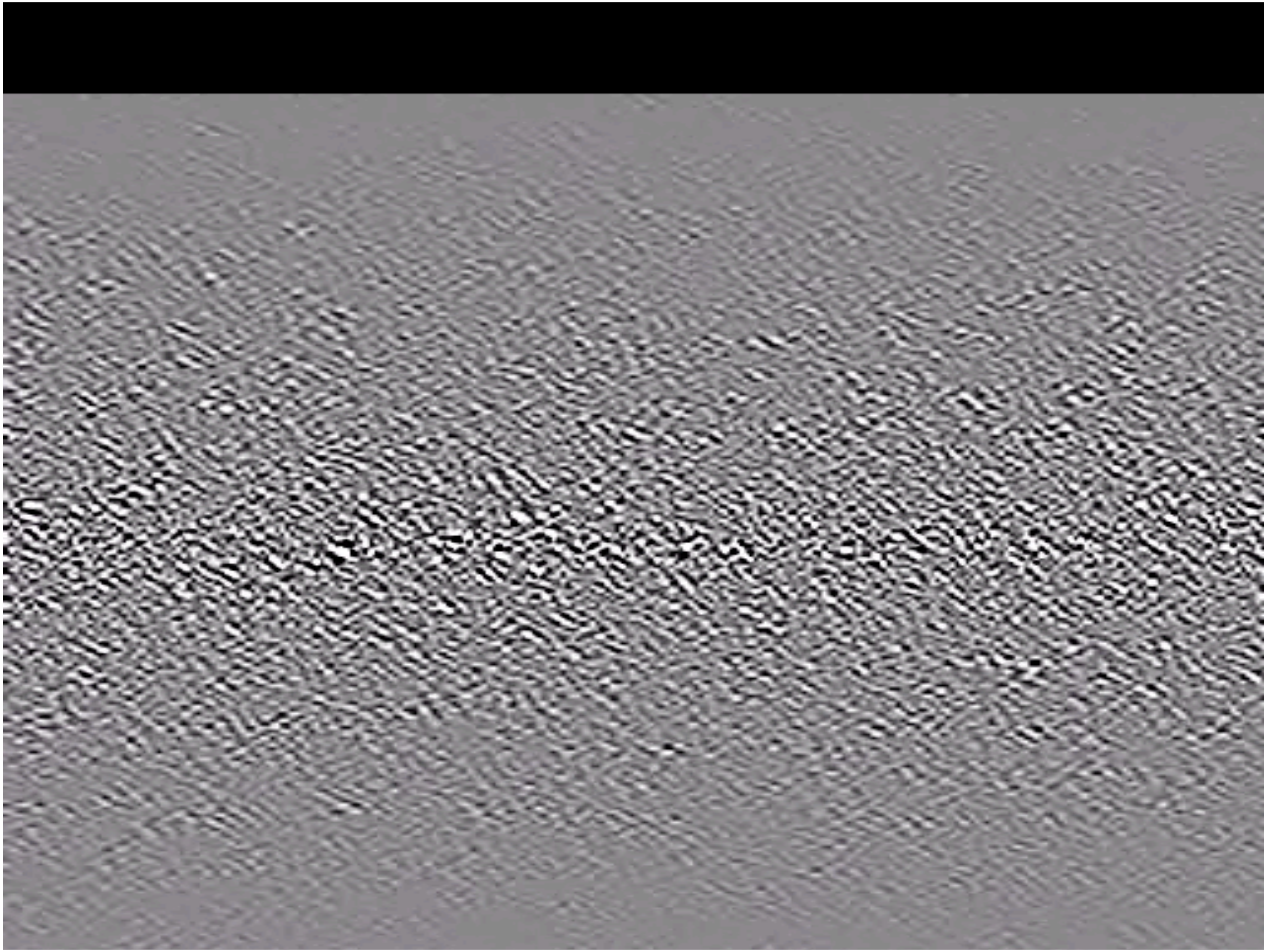
Conservation of vorticity

Merging Vortices

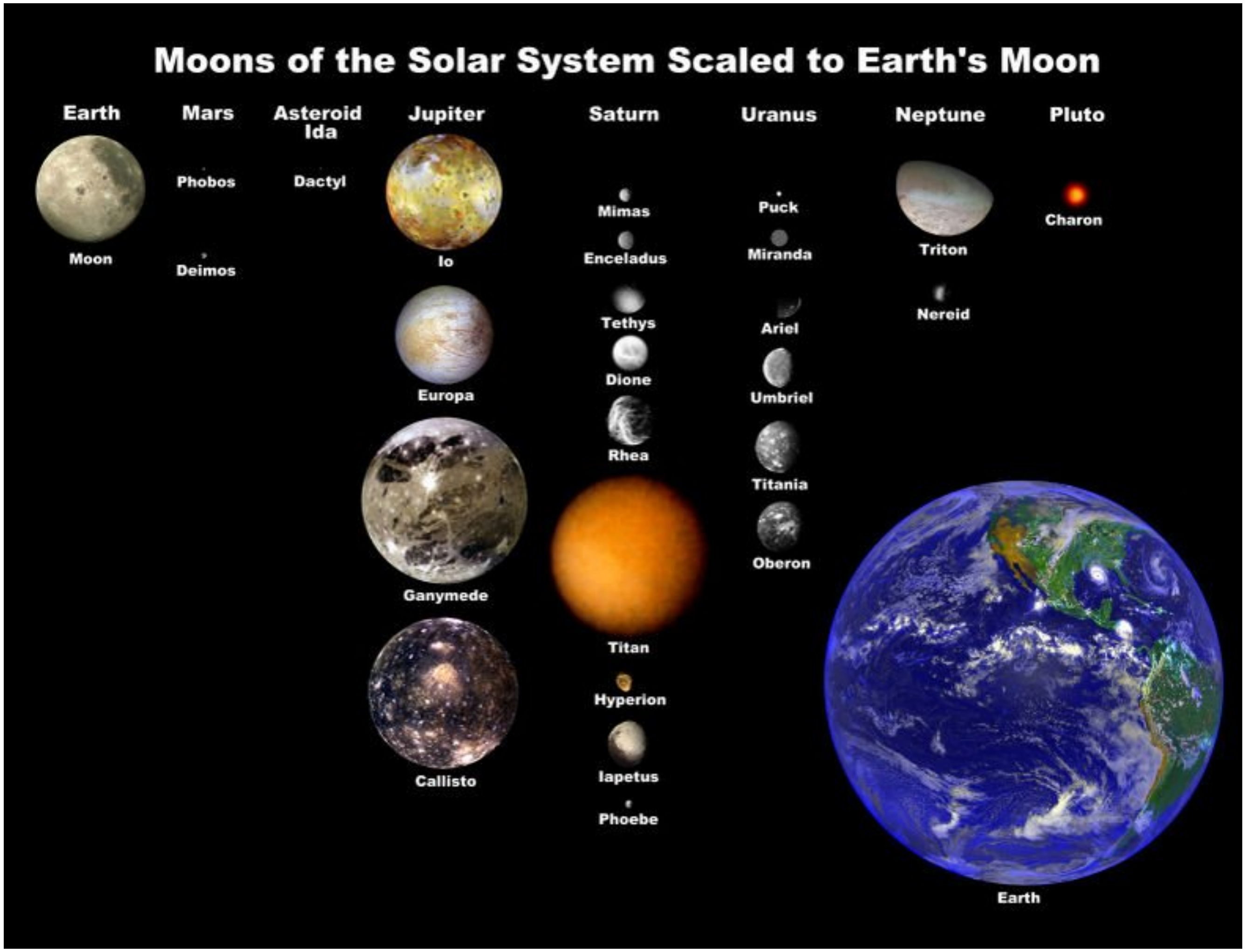


Jupiter's Red Spots





Satellites of the Outer Planets

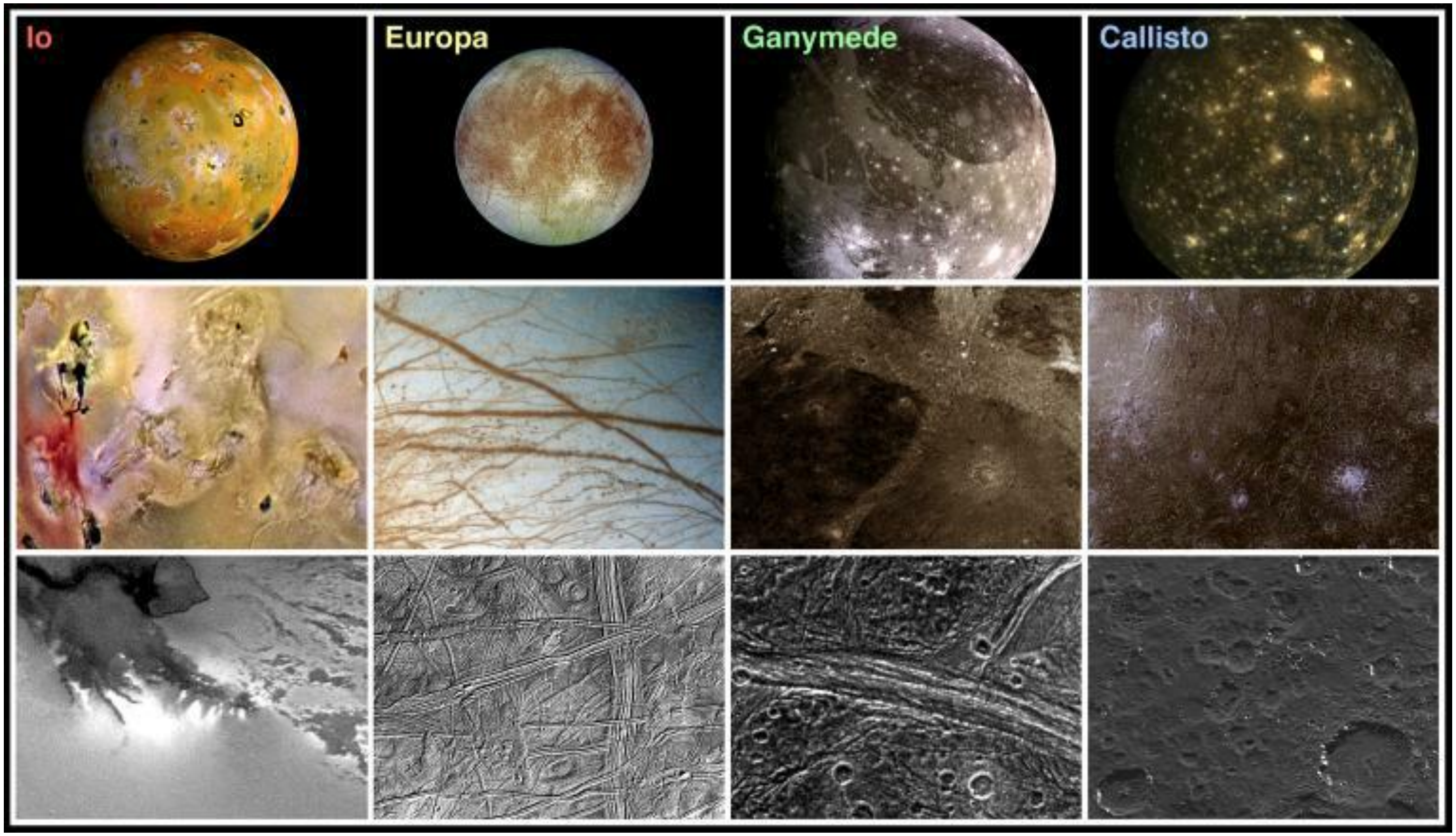


Size Comparison

Jupiter's family portrait

The Galilean Moons

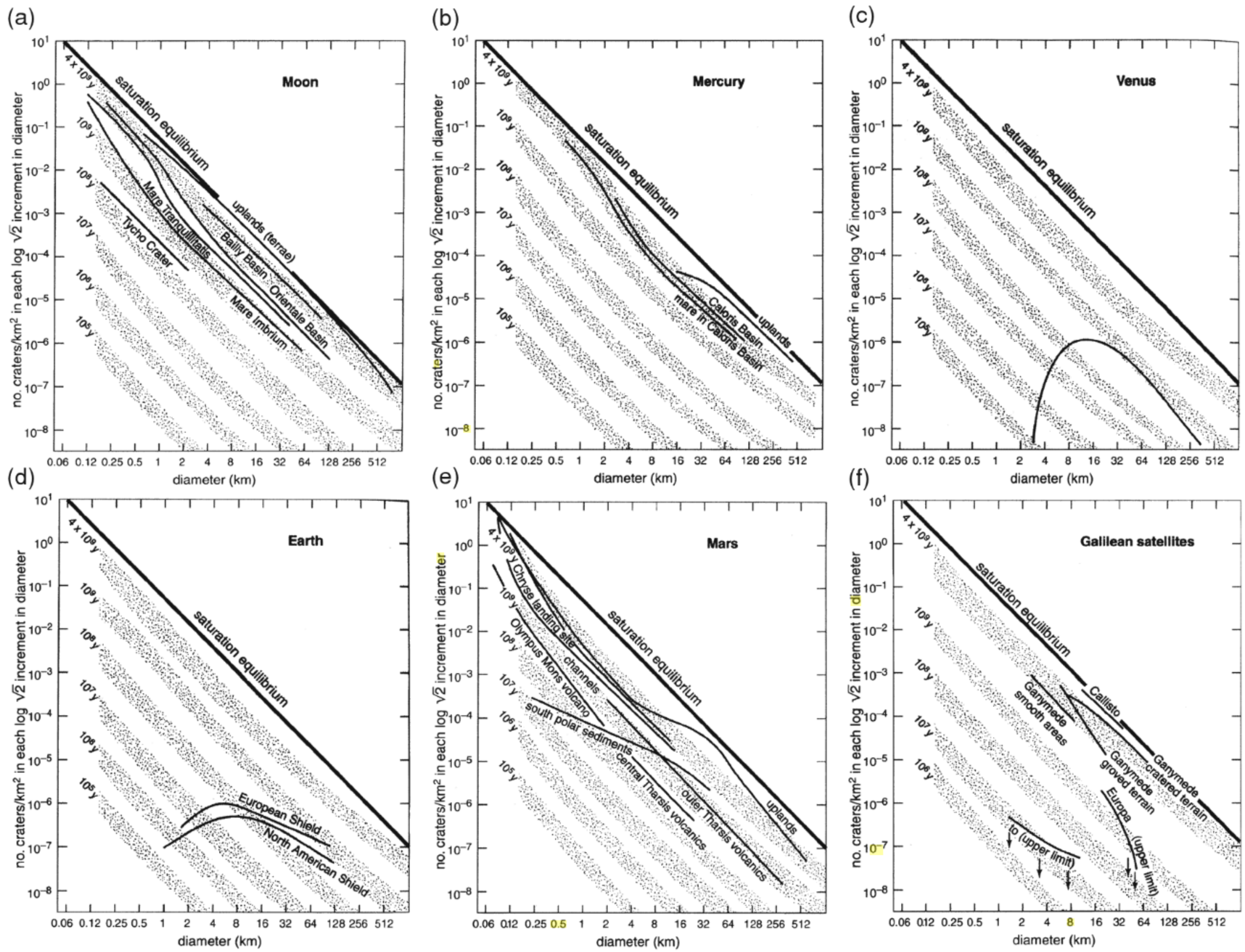
Surfaces of the Galilean Satellites



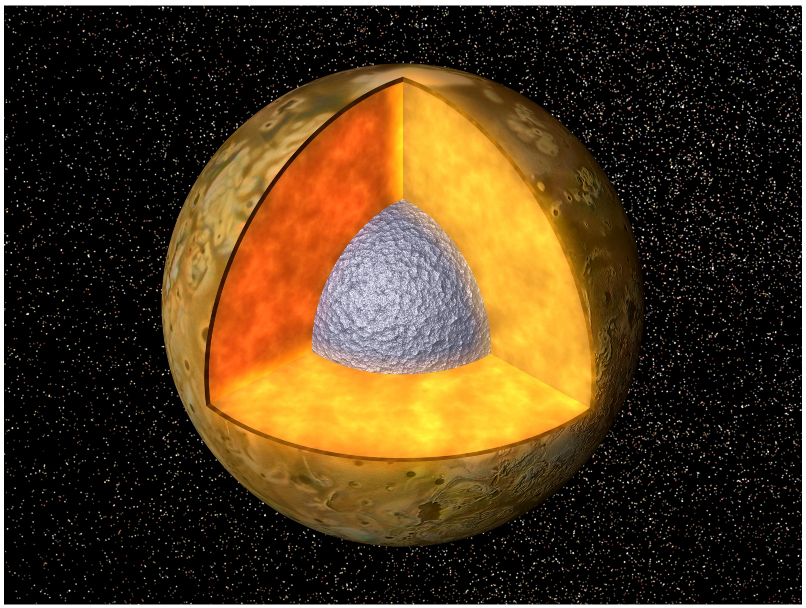
Young surfaces → Old surface

(Geologically Active)

Crater Counting



Io's interior



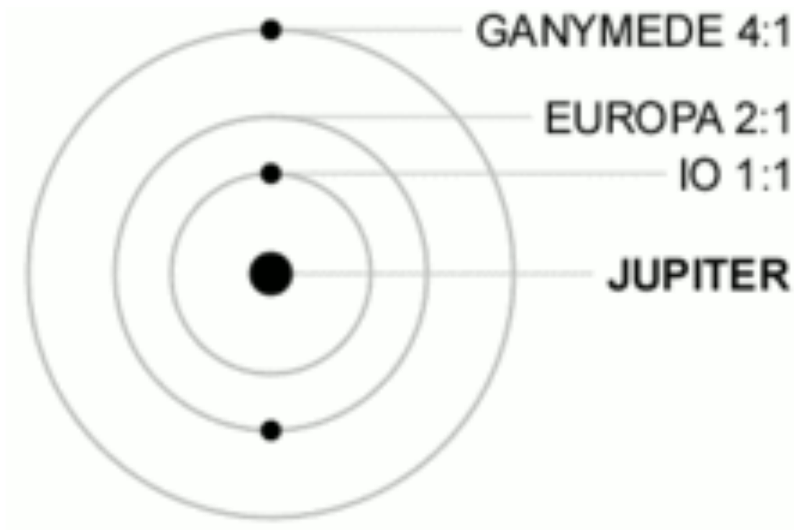
Thin silicate crust

Molten silicate interior

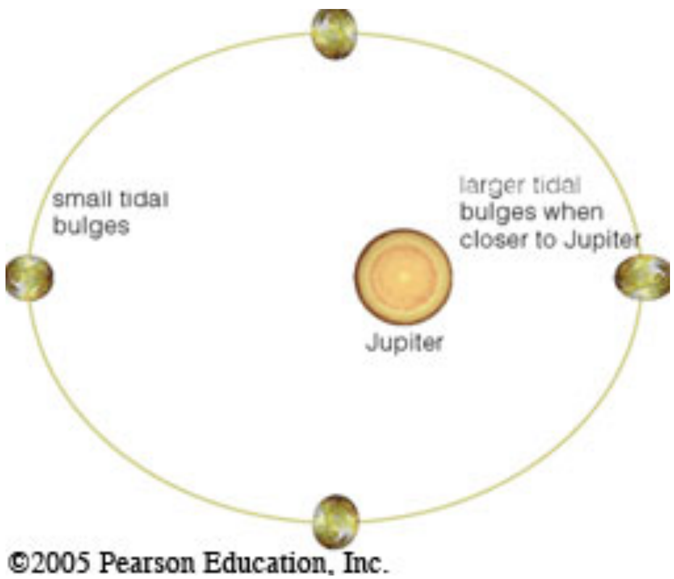
Iron rich core

Io is roughly the size of the Moon.
How does such a small body retain such a hot interior?

Laplace Resonance



Tidal Heating

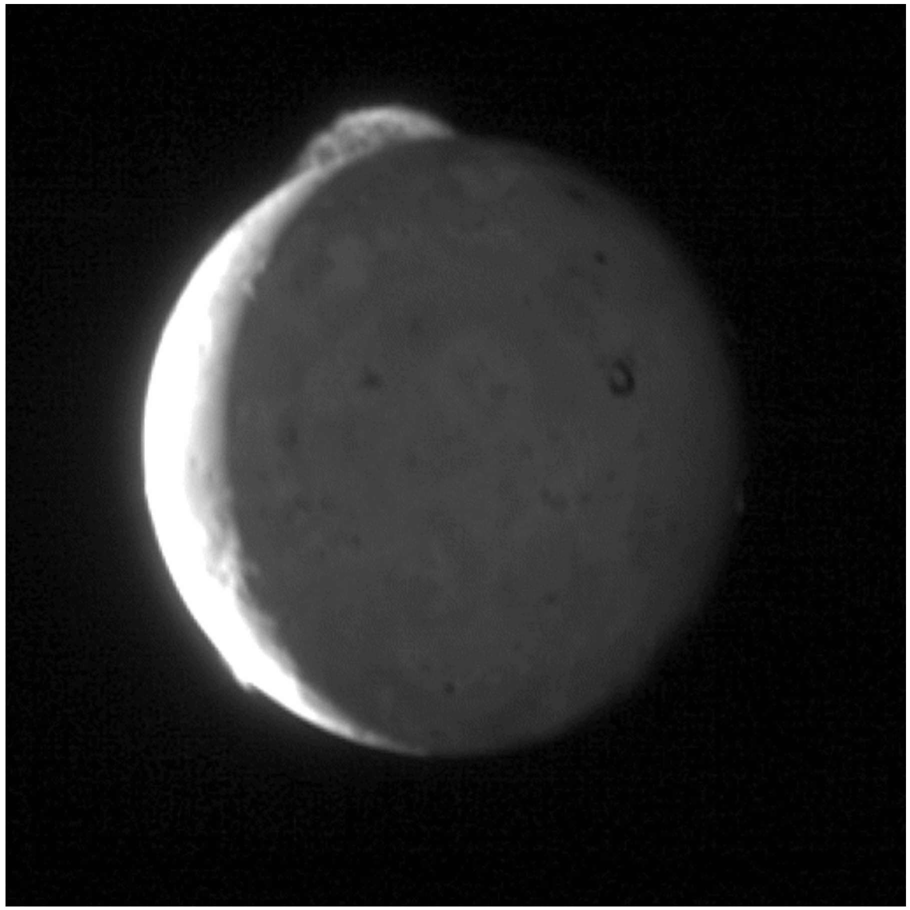


Periodic tug of Europa makes Io's orbit slightly elliptic (e ~ 0.004)

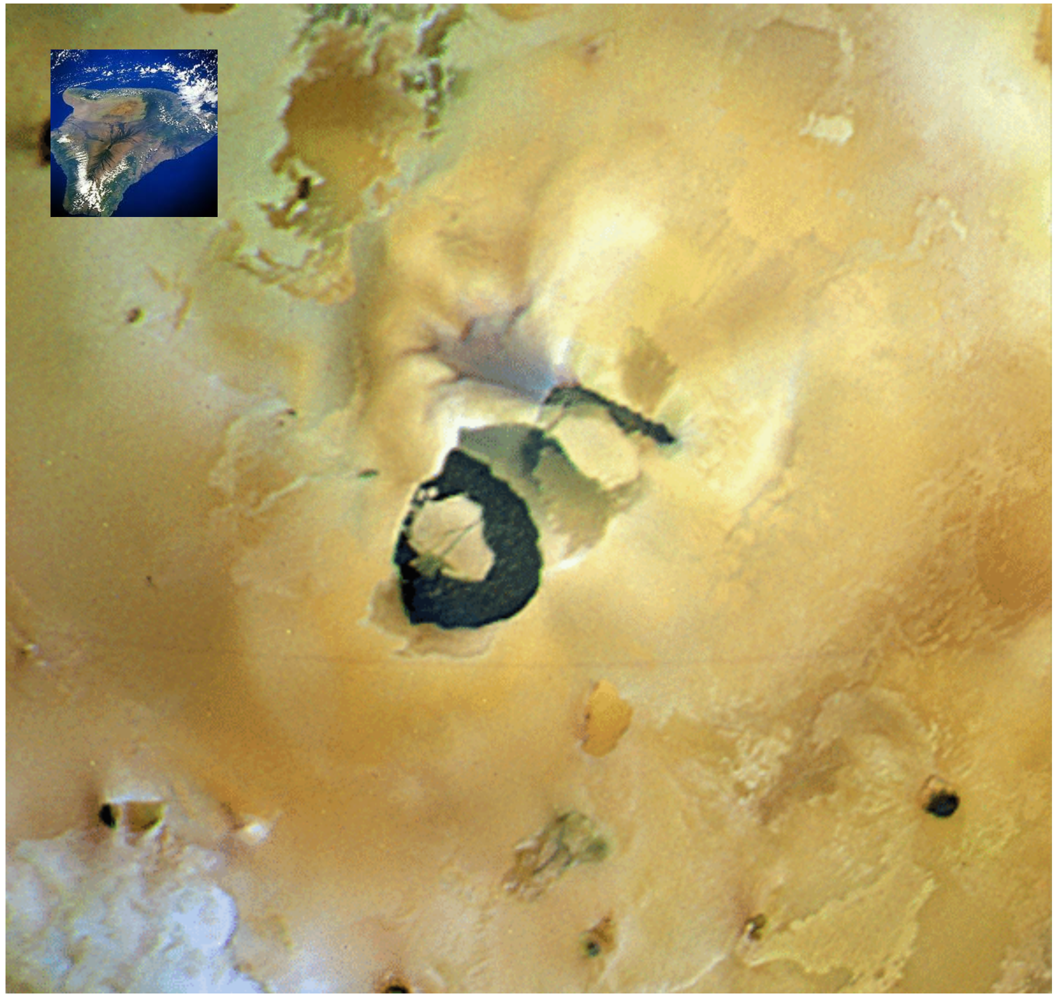
Difference in tidal bulge from closest to farthest from Jupiter:
100m

MASSIVE FRICTION!!!

Io's Volcanoes

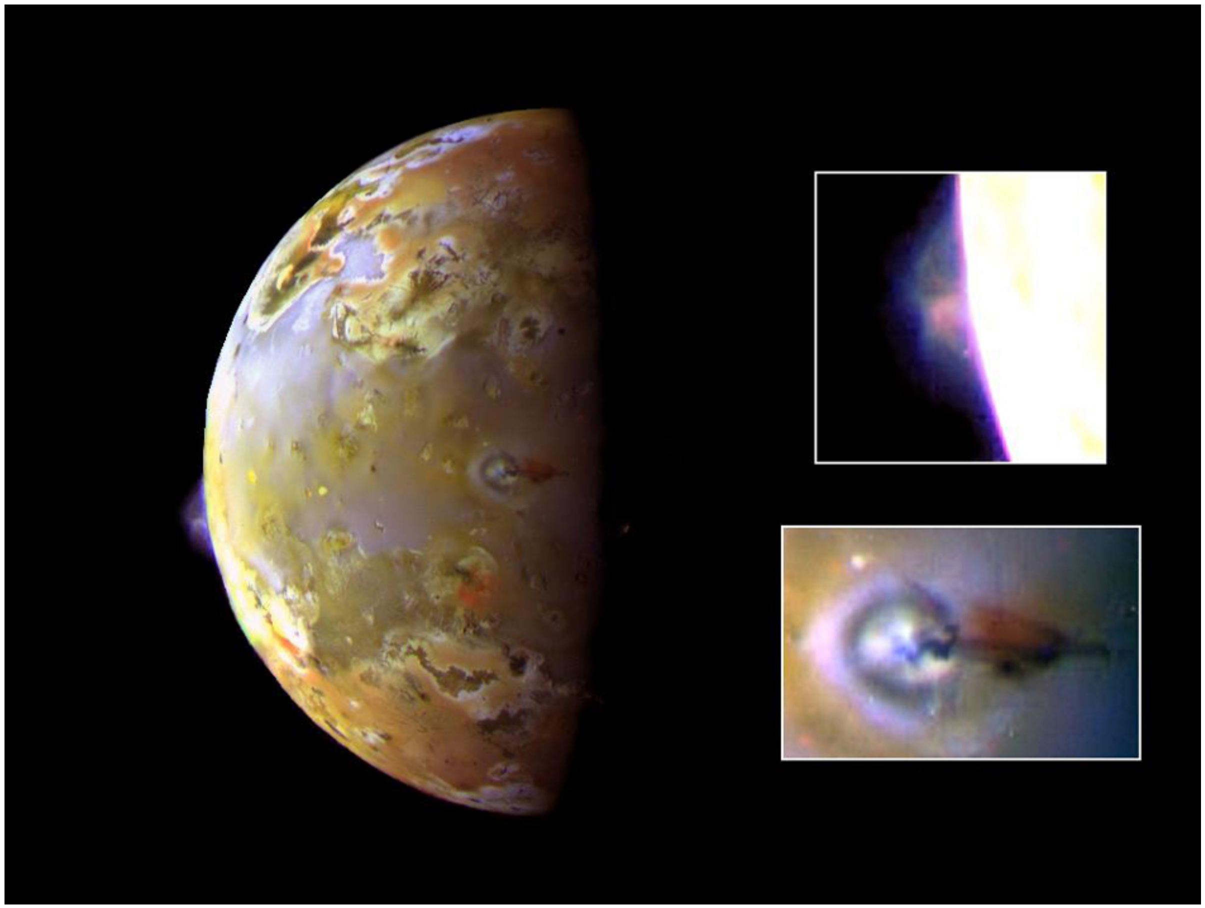


Io's Volcanoes

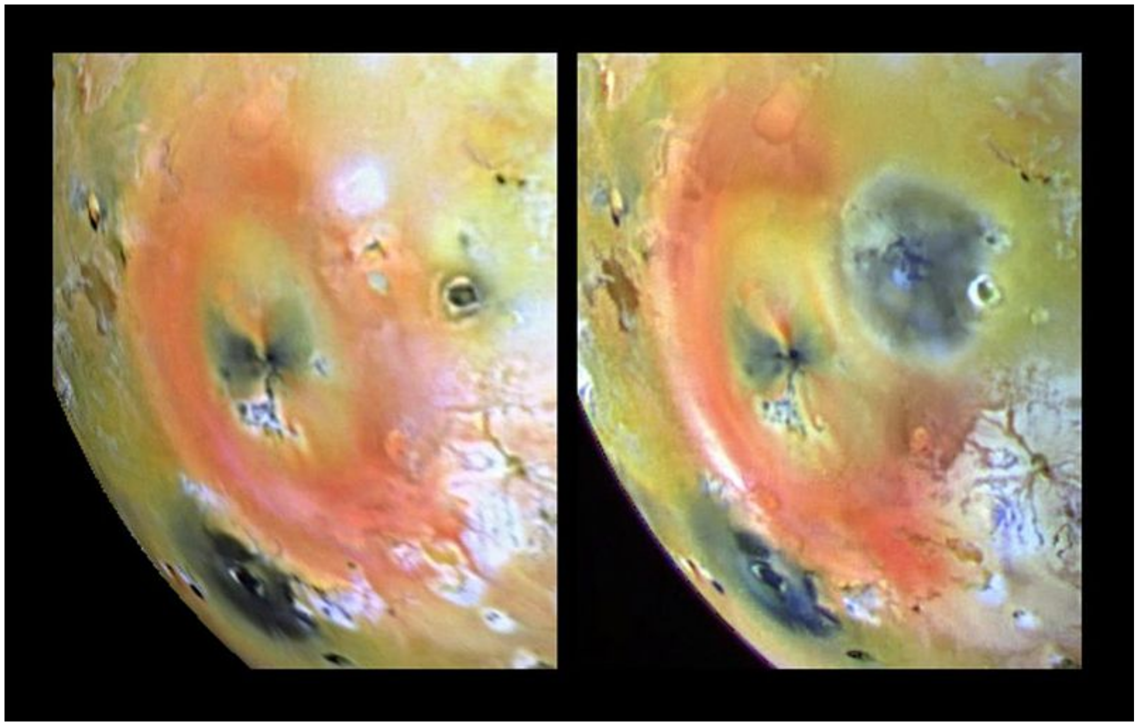


Loki

Active plumes

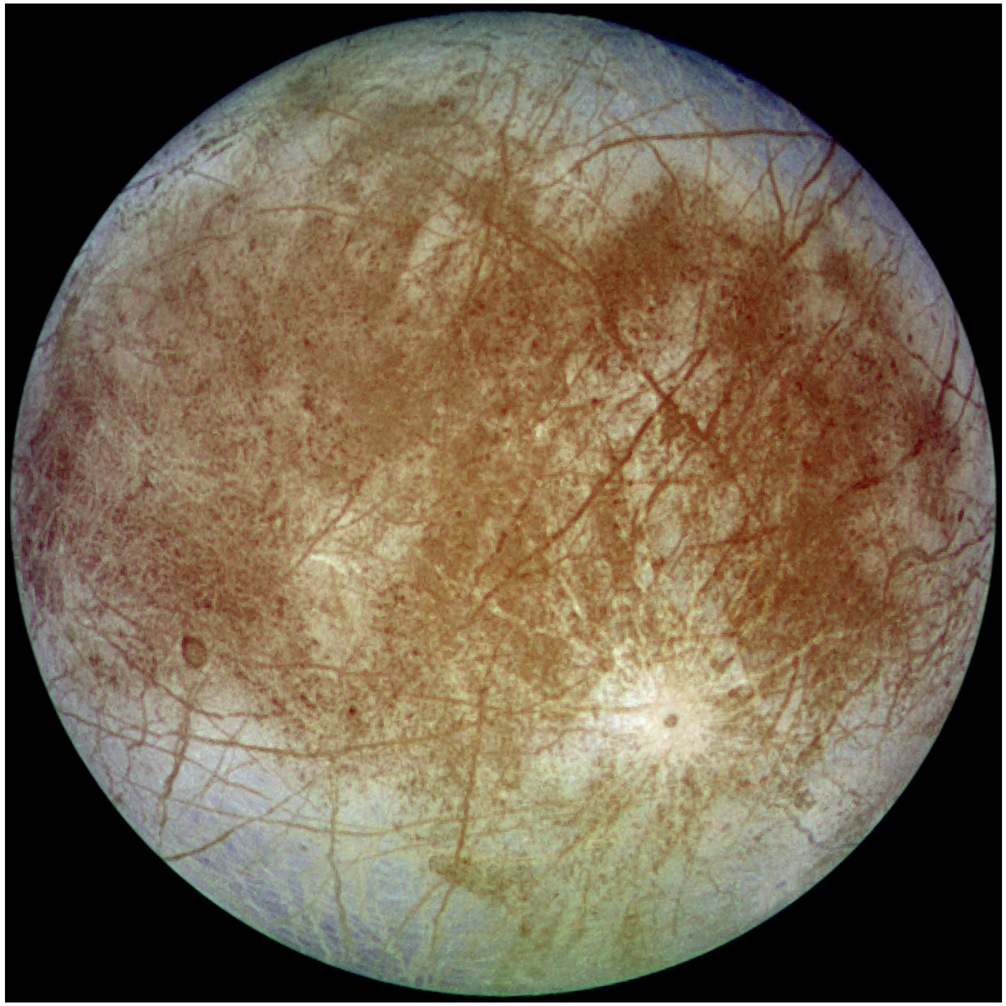


Io in action

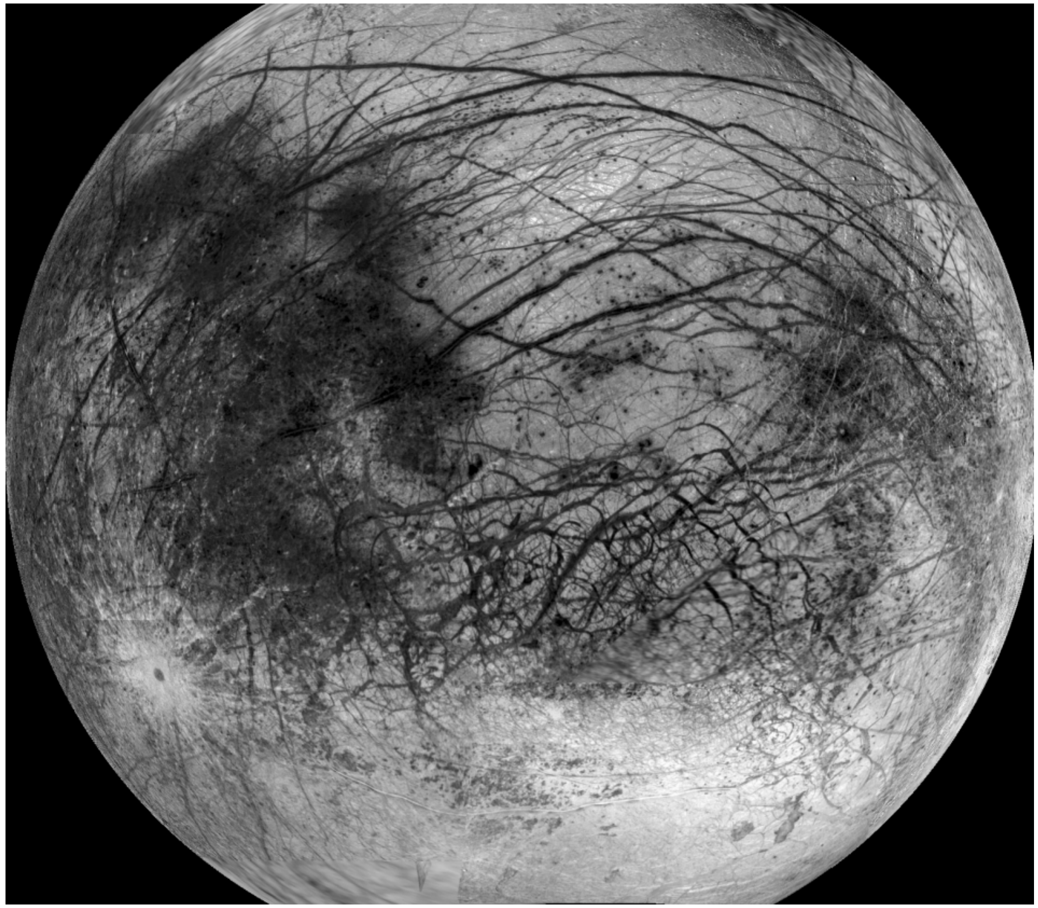


April 2007　　　　September 2007

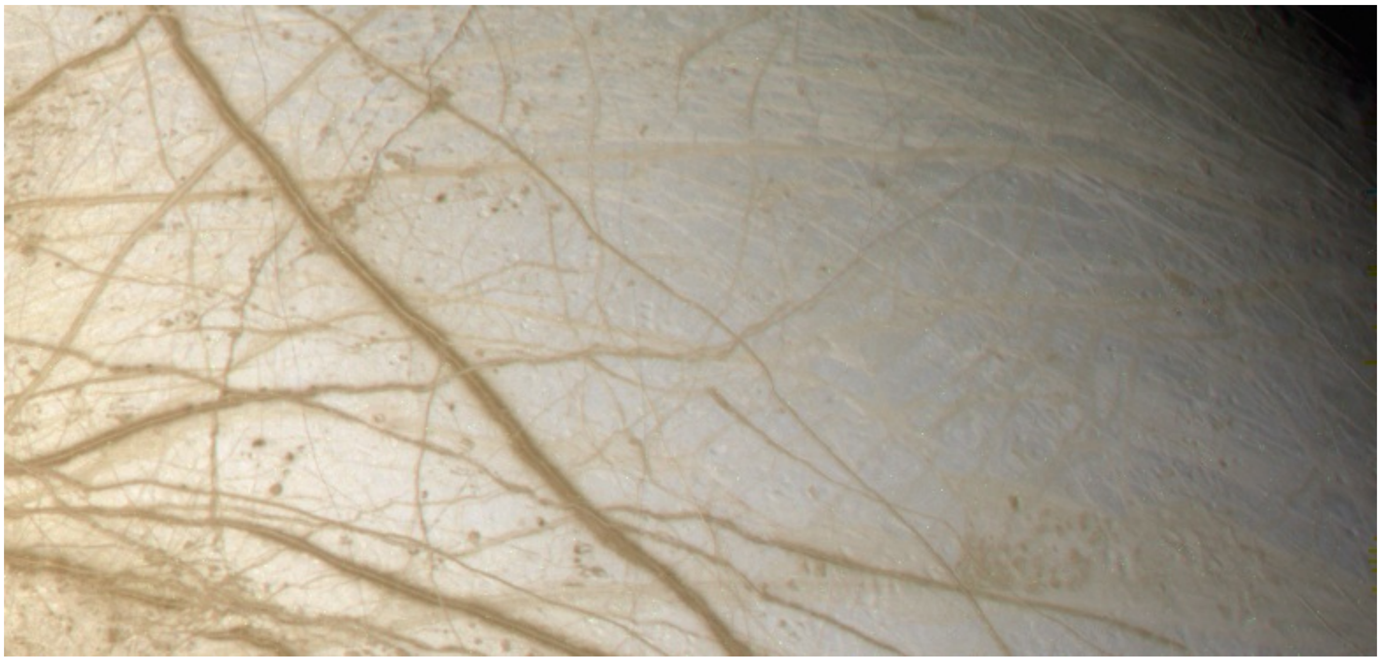
Europa



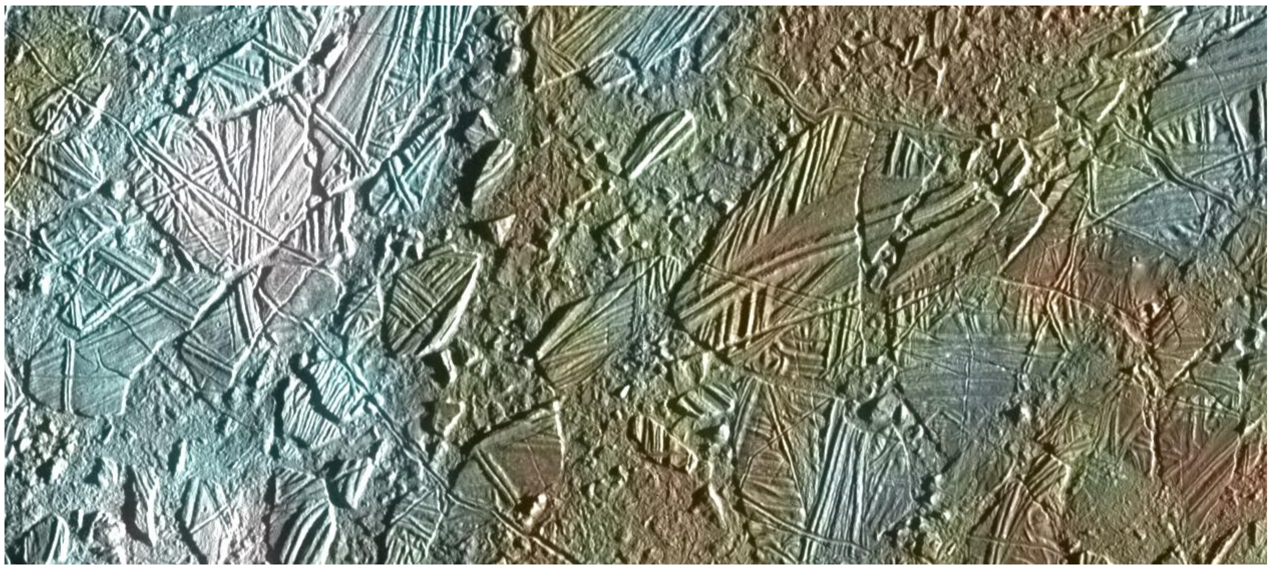
Europa



Ice Tectonics

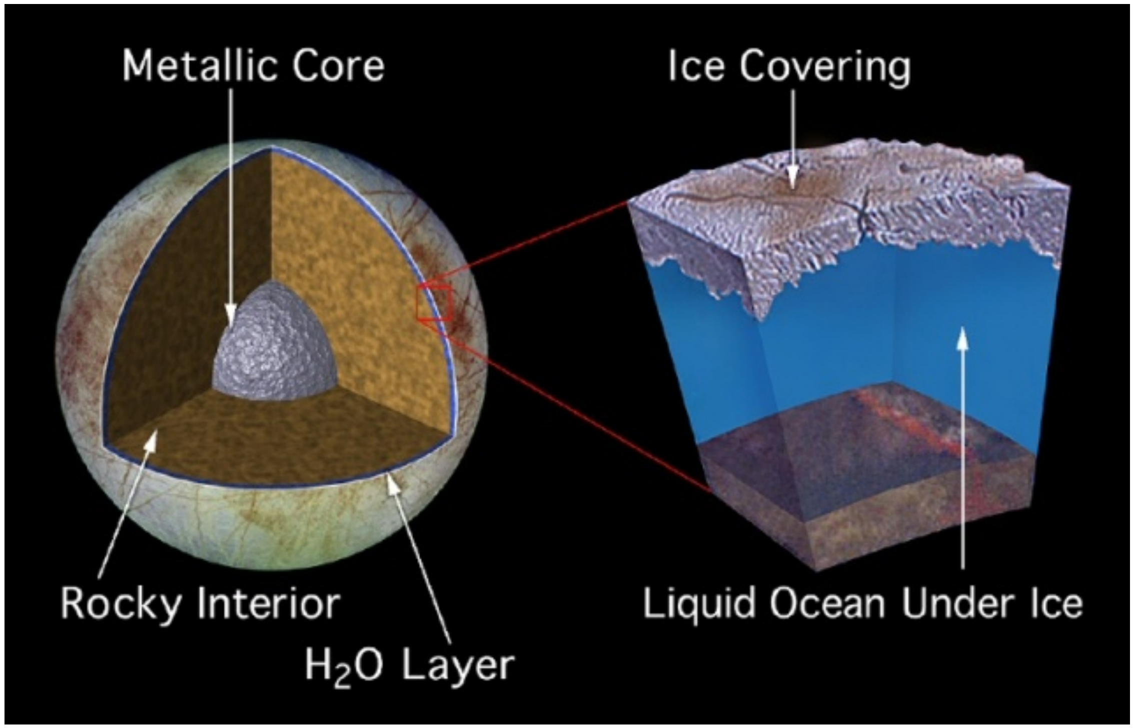


Surface features



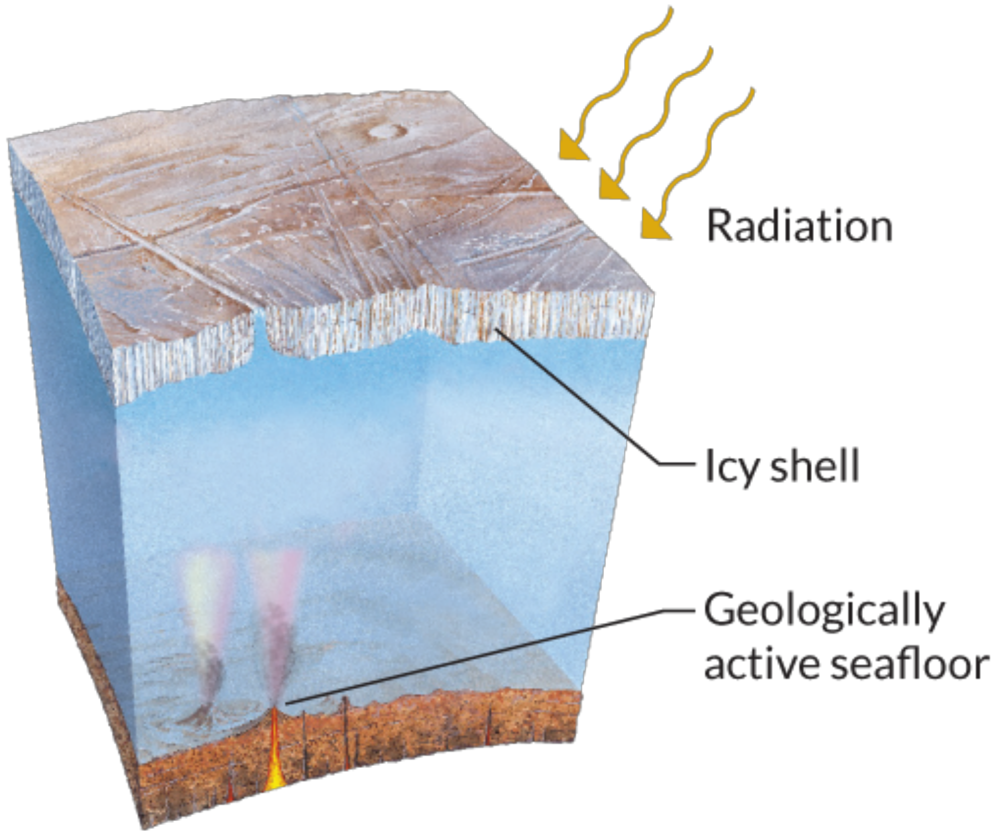
“Chaotic” terrain, as if subject to melting and refreezing

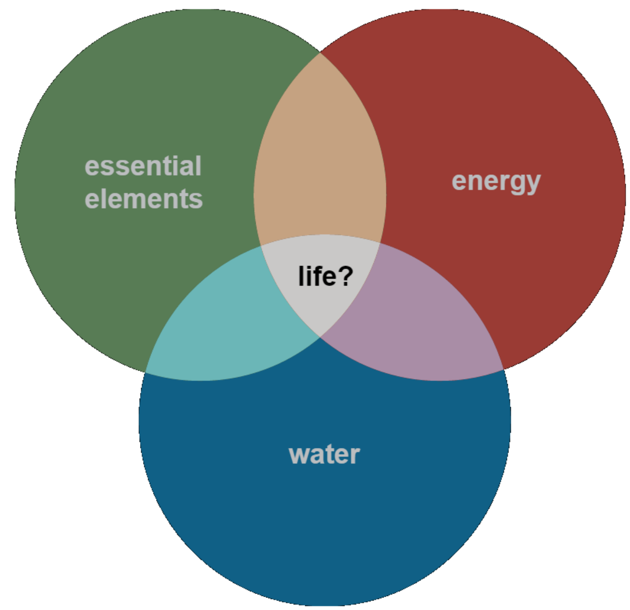
Europa Interior model

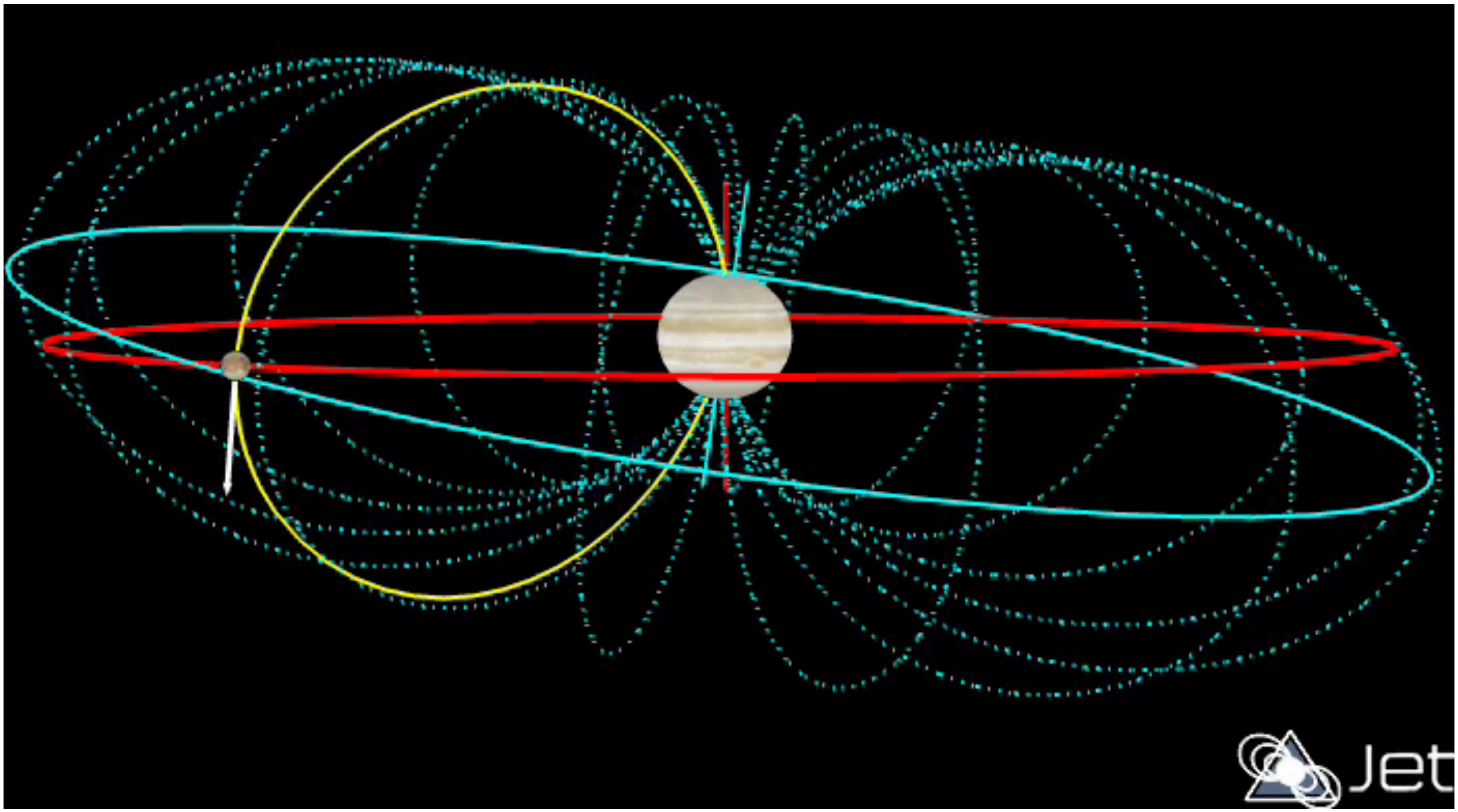


Icy crust floating on top of liquid ocean.
Very interesting for Life!

Life?


Radiation
Icy shell
Geologically
active seafloor


essential
elements
energy
life?
water



Induced magnetic field

Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto

K. K. Khurana*, M. G. Kivelson*†, D. J. Stevenson‡, G. Schubert*†, C. T. Russell*†, R. J. Walker* & C. Polanskey§

** Institute of Geophysics and Planetary Physics, † Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA*
‡ Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA
§ The Jet Propulsion Laboratory, 4800 Oak Grove Road, Pasadena, California 91109, USA

The Galileo spacecraft has been orbiting Jupiter since 7 December 1995, and encounters one of the four galilean satellites—Io, Europa, Ganymede and Callisto—on each orbit. Initial results from the spacecraft's magnetometer[1,2] have indicated that neither Europa nor Callisto have an appreciable internal magnetic field, in contrast to Ganymede[3] and possibly Io[4]. Here we report perturbations of the external magnetic fields (associated with Jupiter's inner magnetosphere) in the vicinity of both Europa and Callisto. We interpret these perturbations as arising from induced magnetic fields, generated by the moons in response to the periodically varying plasma environment. Electromagnetic induction requires eddy currents to flow within the moons, and our calculations show that the most probable explanation is that there are layers of significant electrical conductivity just beneath the surfaces of both moons. We argue that these conducting layers may best be explained by the presence of salty liquid-water oceans, for which there is already indirect geological evidence[5,6] in the case of Europa.

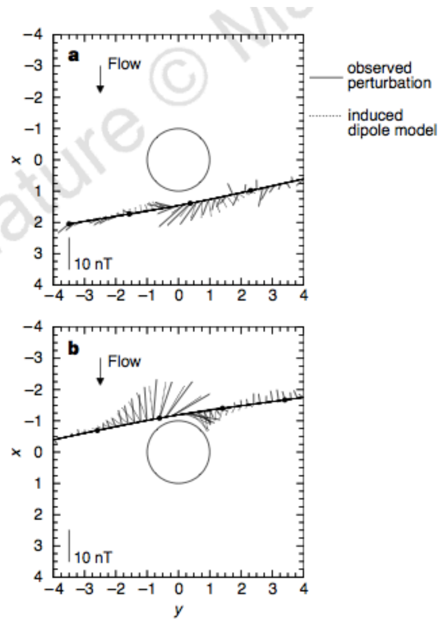
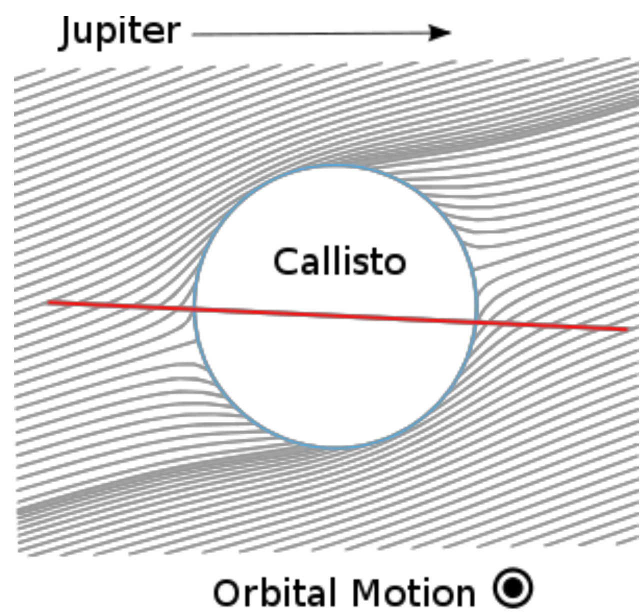
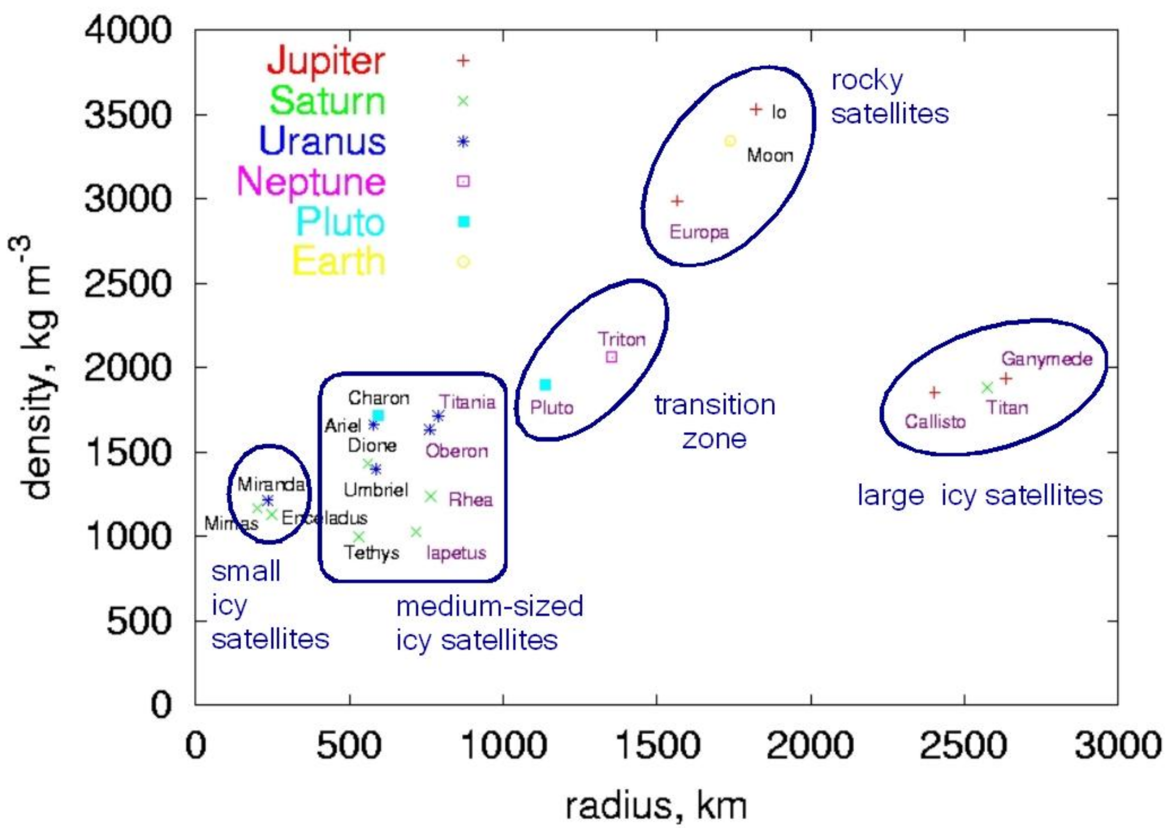
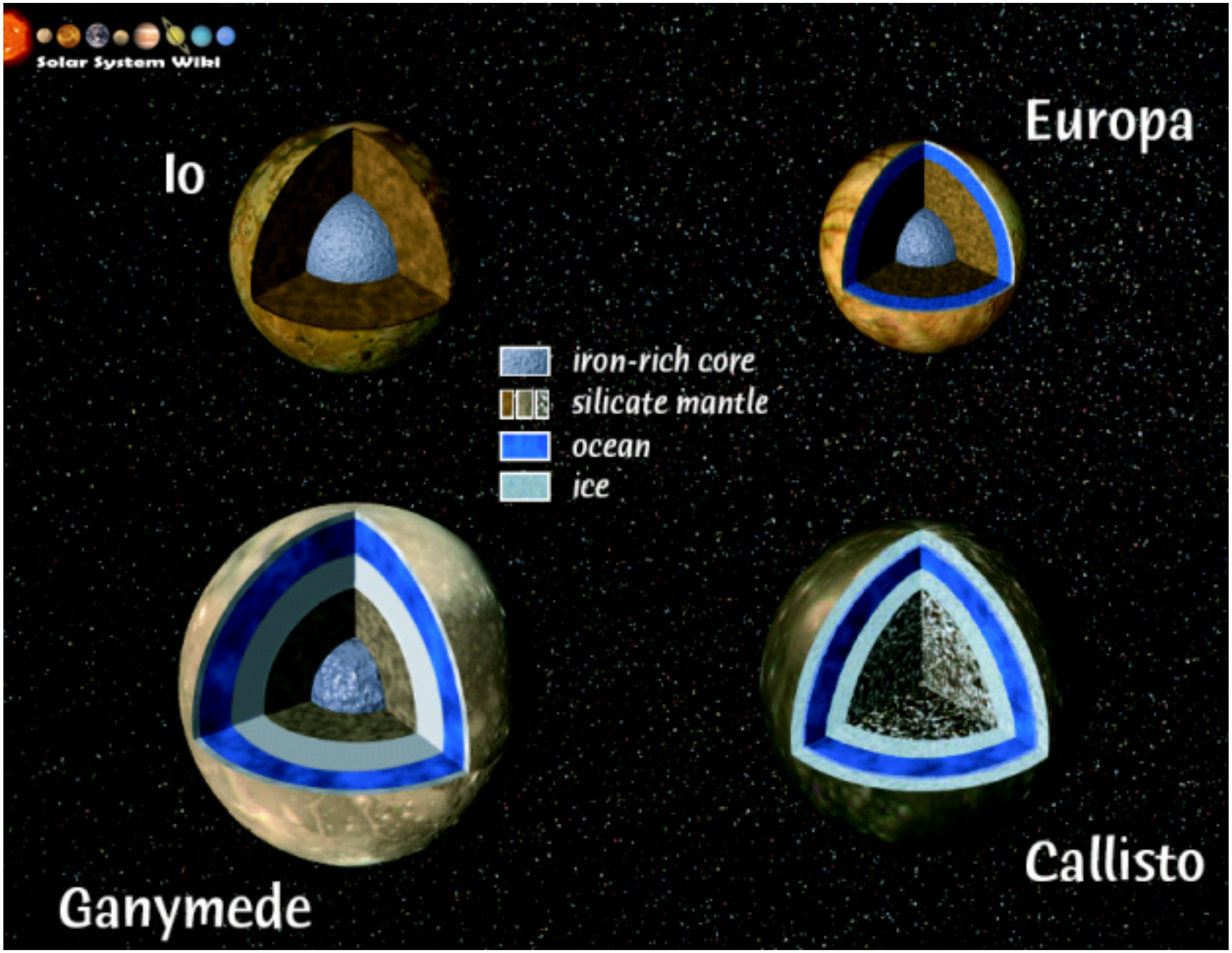


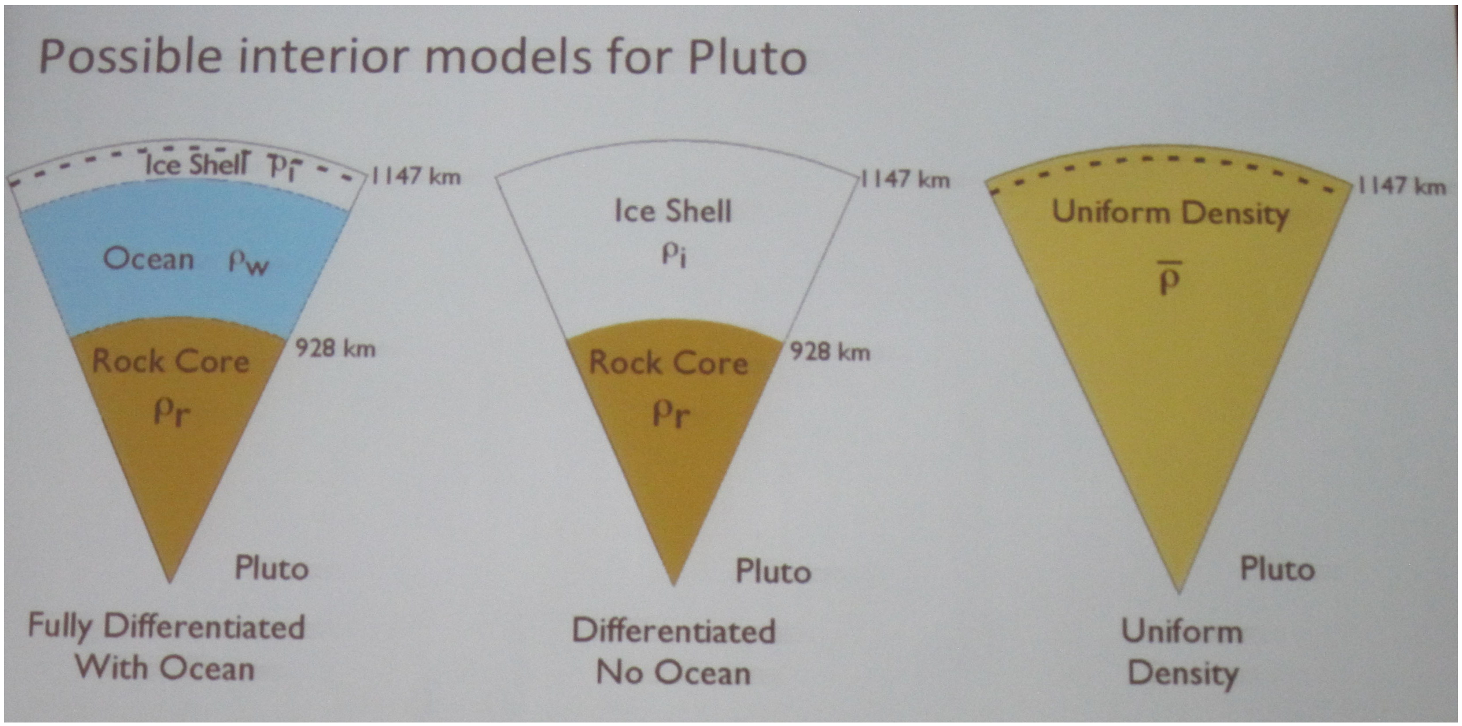
Figure 3 Magnetic field observations from the C3 and C9 passes. **a**, The magnetic field perturbations (vectors drawn with solid lines) and the modelled induction field (vectors shown dotted) along the trajectory of the C3 encounter in the *x*–*y* plane. **b**, The magnetic field perturbations and the modelled induction field for the C9 encounter. The distance scale is in units of R_C ($1R_C$ = radius of Callisto = 2,409 km).



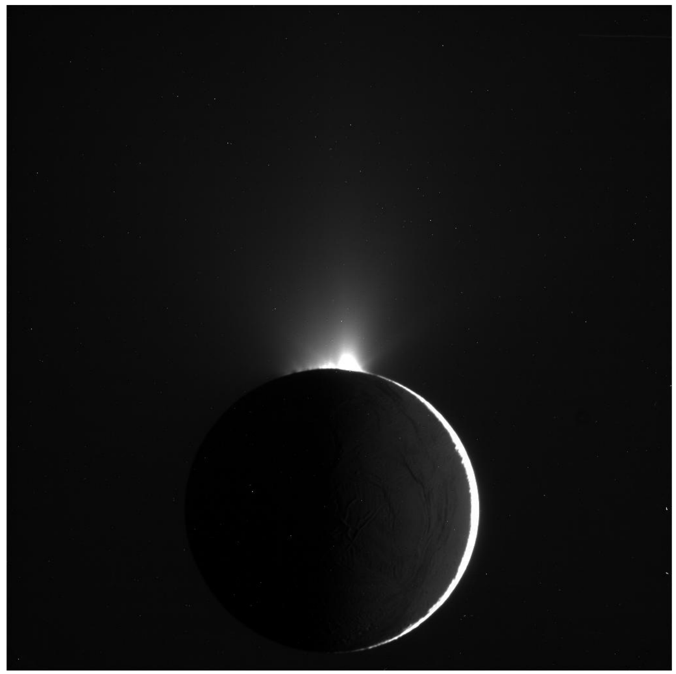


Jupiter
Saturn
Uranus
Neptune
Pluto
Earth
rocky satellites
Io
Moon
Europa
Triton
Pluto
transition zone
Ganymede
Callisto
Titan
large icy satellites
Charon
Titania
Ariel
Dione
Oberon
Umbriel
Rhea
Tethys
Iapetus
medium-sized icy satellites
Miranda
Mimas
Enceladus
small icy satellites
density, kg m-3
radius, km


Solar System Wiki
Io
Europa
iron-rich core
silicate mantle
ocean
ice
Ganymede
Callisto

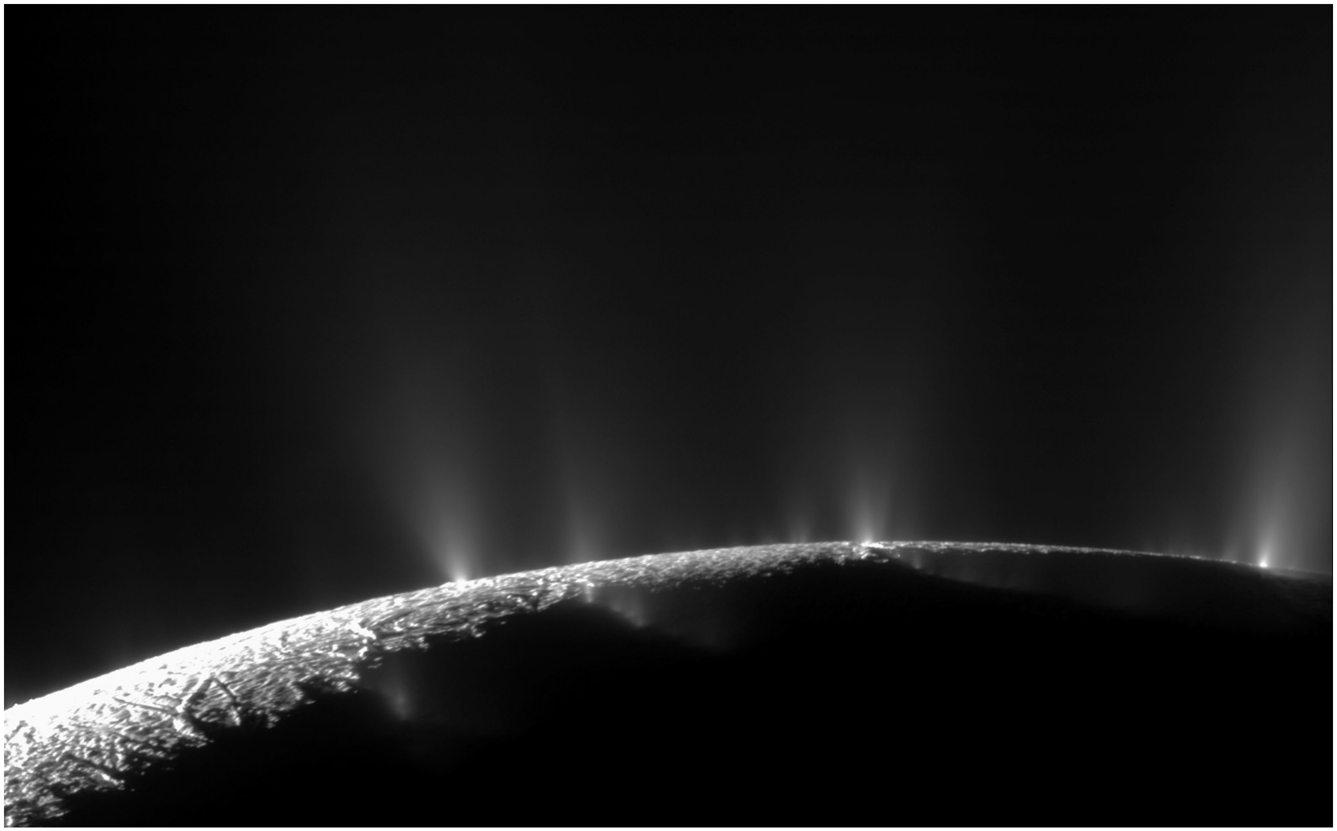

Possible interior models for Pluto
Ice Shell ρ_i
1147 km
Ocean ρ_w
928 km
Rock Core
ρ_r
Pluto
Fully Differentiated
With Ocean
Ice Shell
ρ_i
1147 km
Rock Core
ρ_r
928 km
Pluto
Differentiated
No Ocean
Uniform Density
$\bar{\rho}$
1147 km
Pluto
Uniform
Density

Enceladus



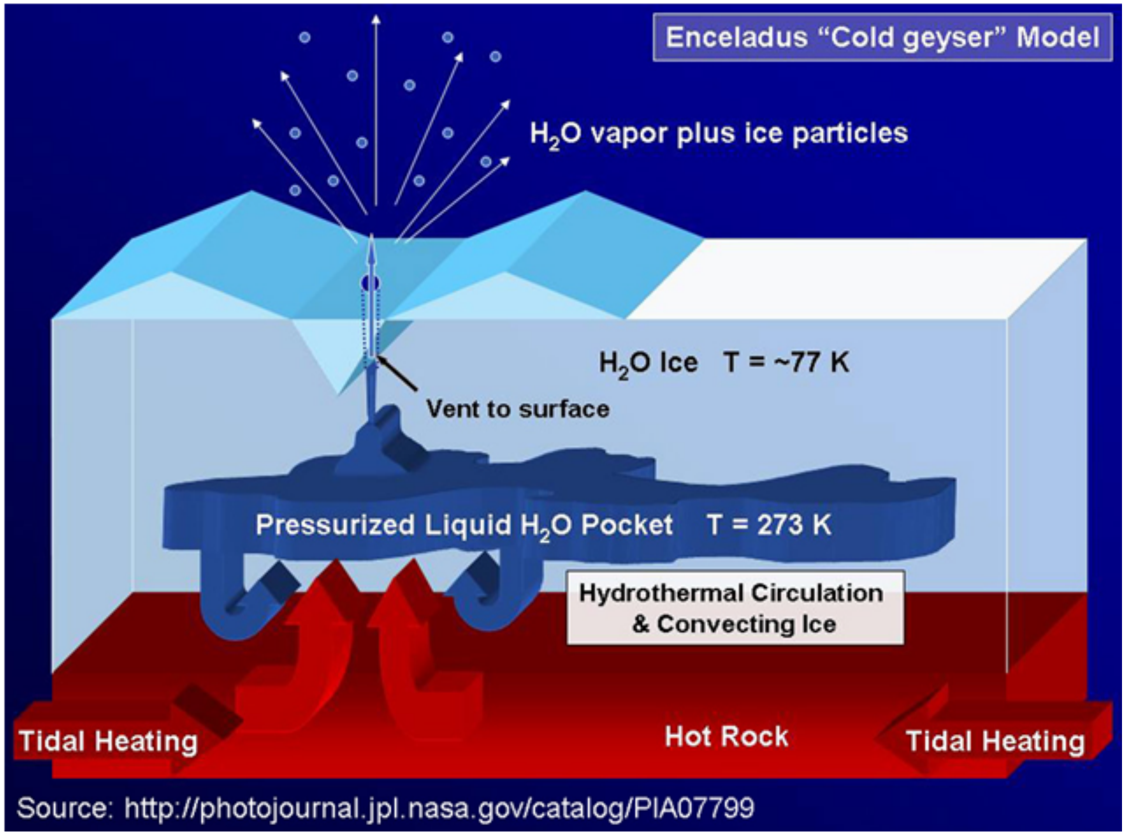
Plumes imaged by Cassini

Enceladus



Close up of the plumes

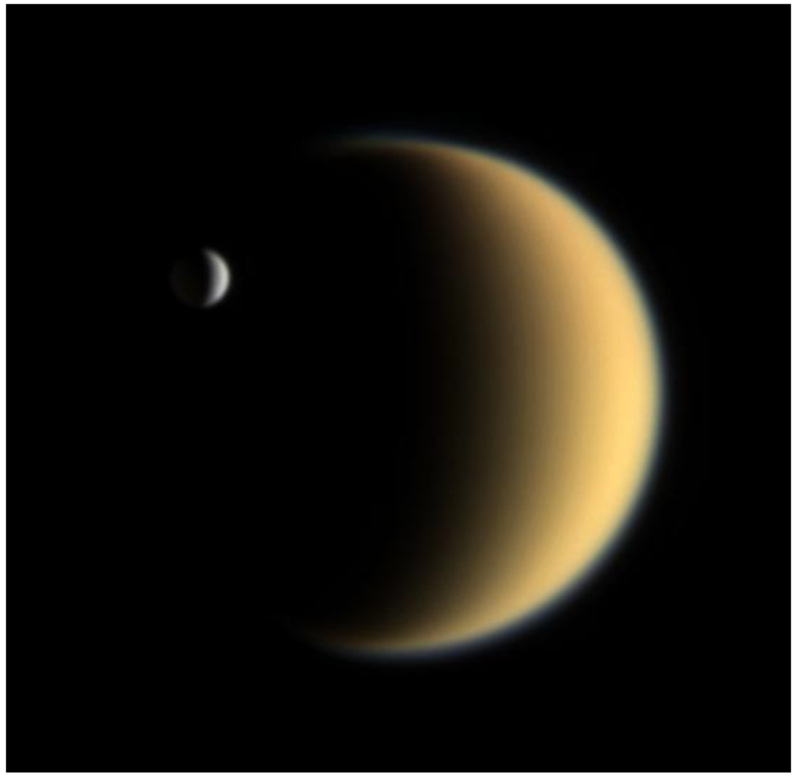
Enceladus



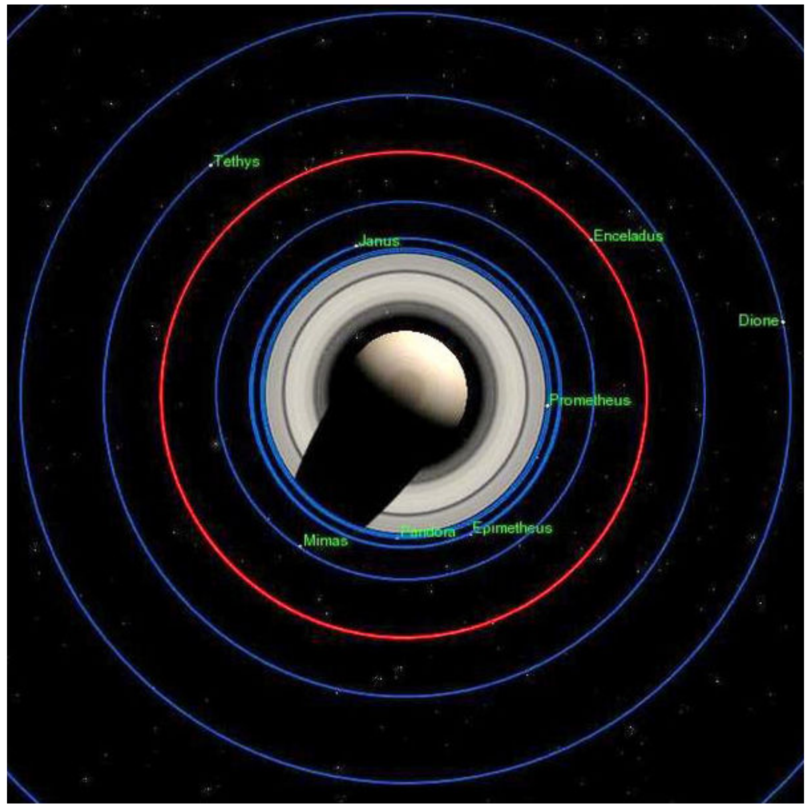
Enceladus “Cold geyser” Model
H_2O vapor plus ice particles
H_2O Ice T = ~77 K
Vent to surface
Pressurized Liquid H_2O Pocket T = 273 K
Hydrothermal Circulation & Convecting Ice
Tidal Heating
Hot Rock
Tidal Heating
Source: http://photojournal.jpl.nasa.gov/catalog/PIA07799

Enceladus

Enceladus and Titan

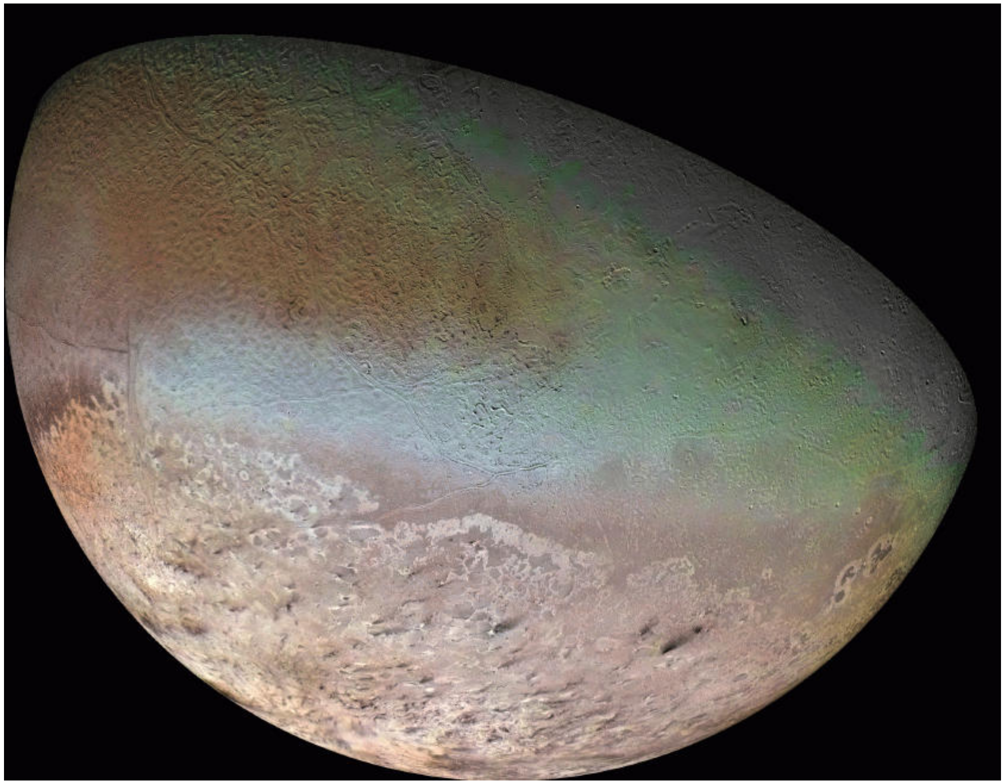


Tidal Heating!



2:1 resonance with Dione
keeps Enceladus' orbit eccentric
(e ~ 0.004)

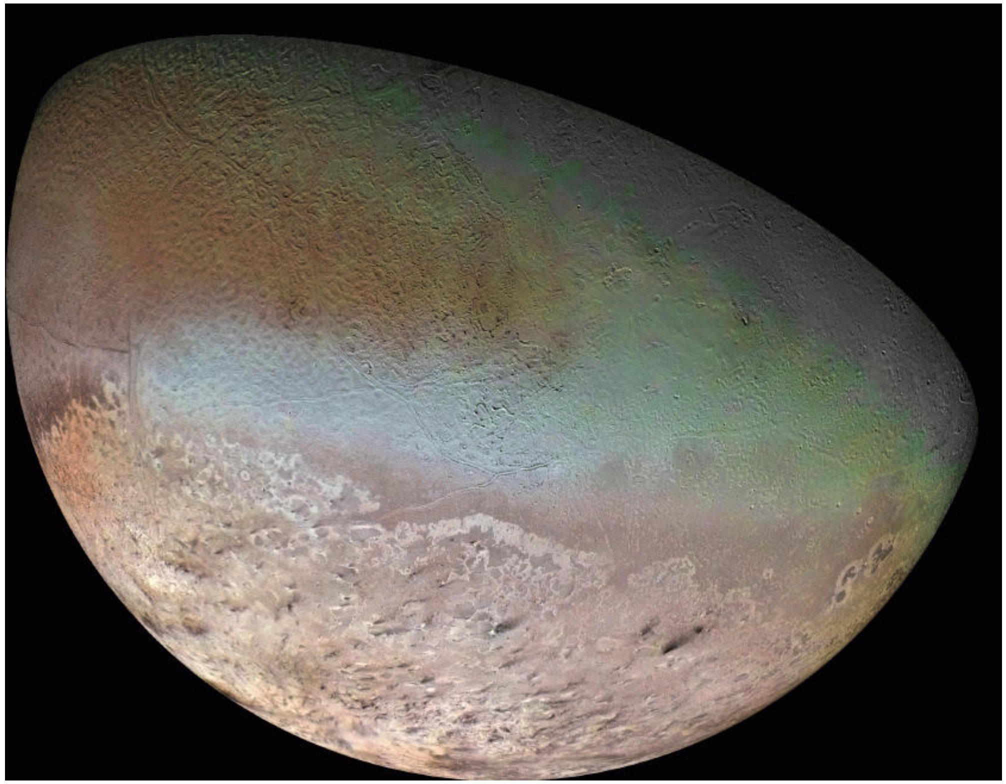
Triton – Neptune's large moon.



Frigid temperatures of 38K
All volatiles are either rock-solid or snow.

Yet, no craters. The surface is young.
Triton is geologically active !

Triton – Neptune's large moon.



Cantaloupe terrain

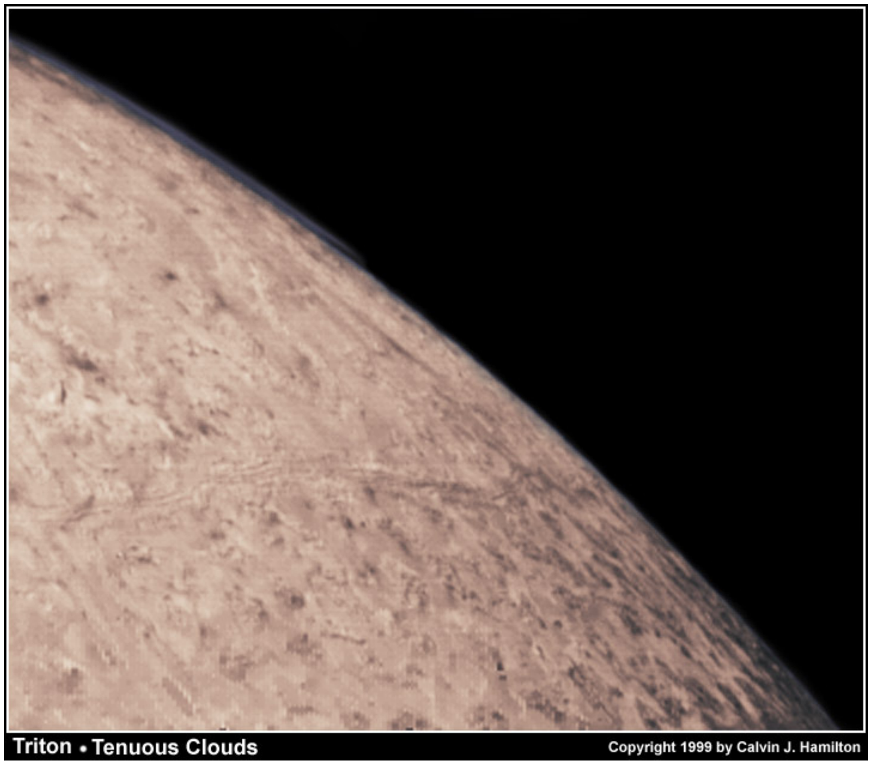
Dark streaks

Nitrogen snow

Frigid temperatures of 38K
All volatiles are either rock-solid or snow.

Yet, no craters. The surface is young.
Triton is geologically active !

Clouds on Triton



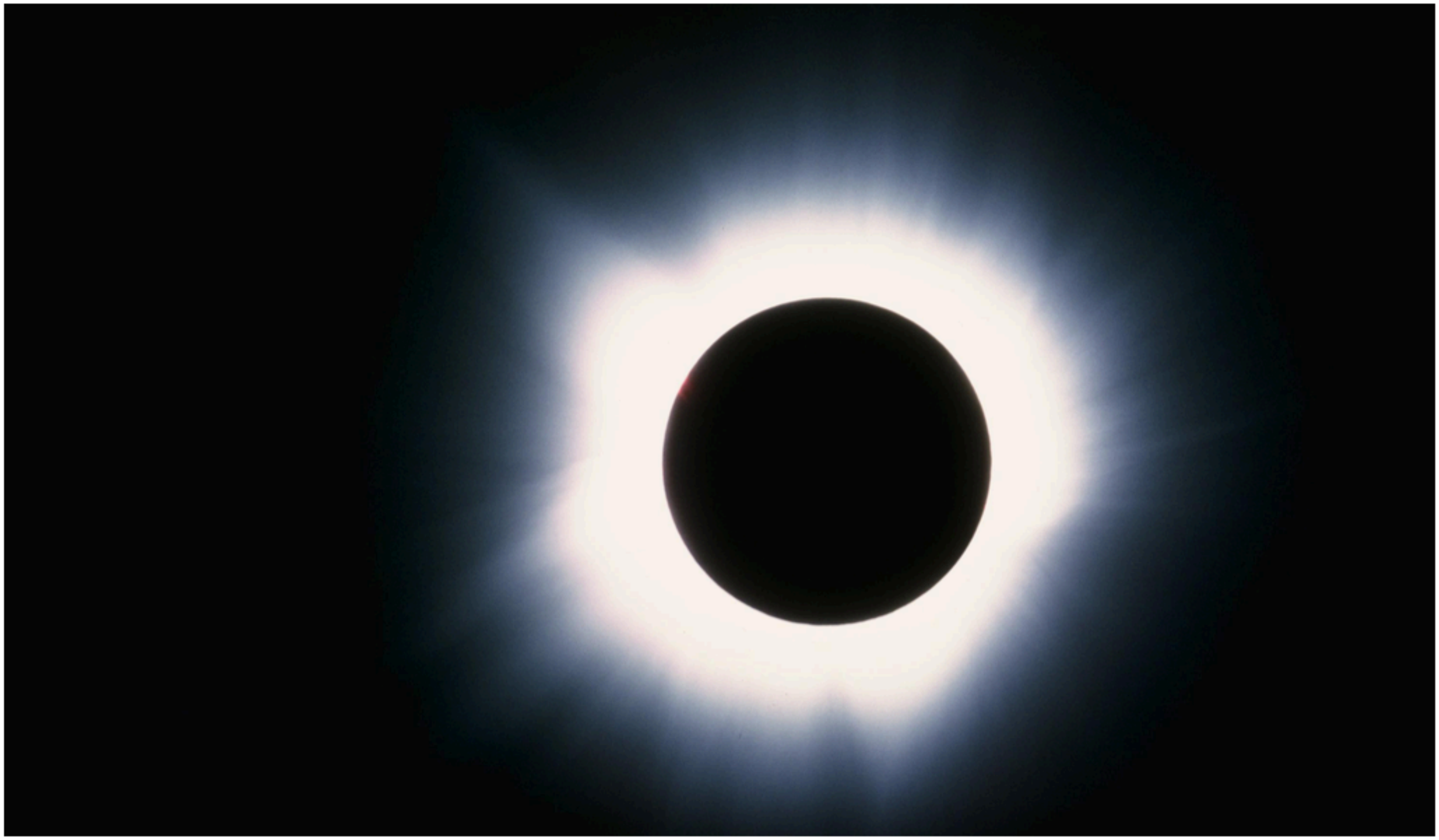
Nitrogen is near the sublimation point,
Forming a thin atmosphere

Dark streaks

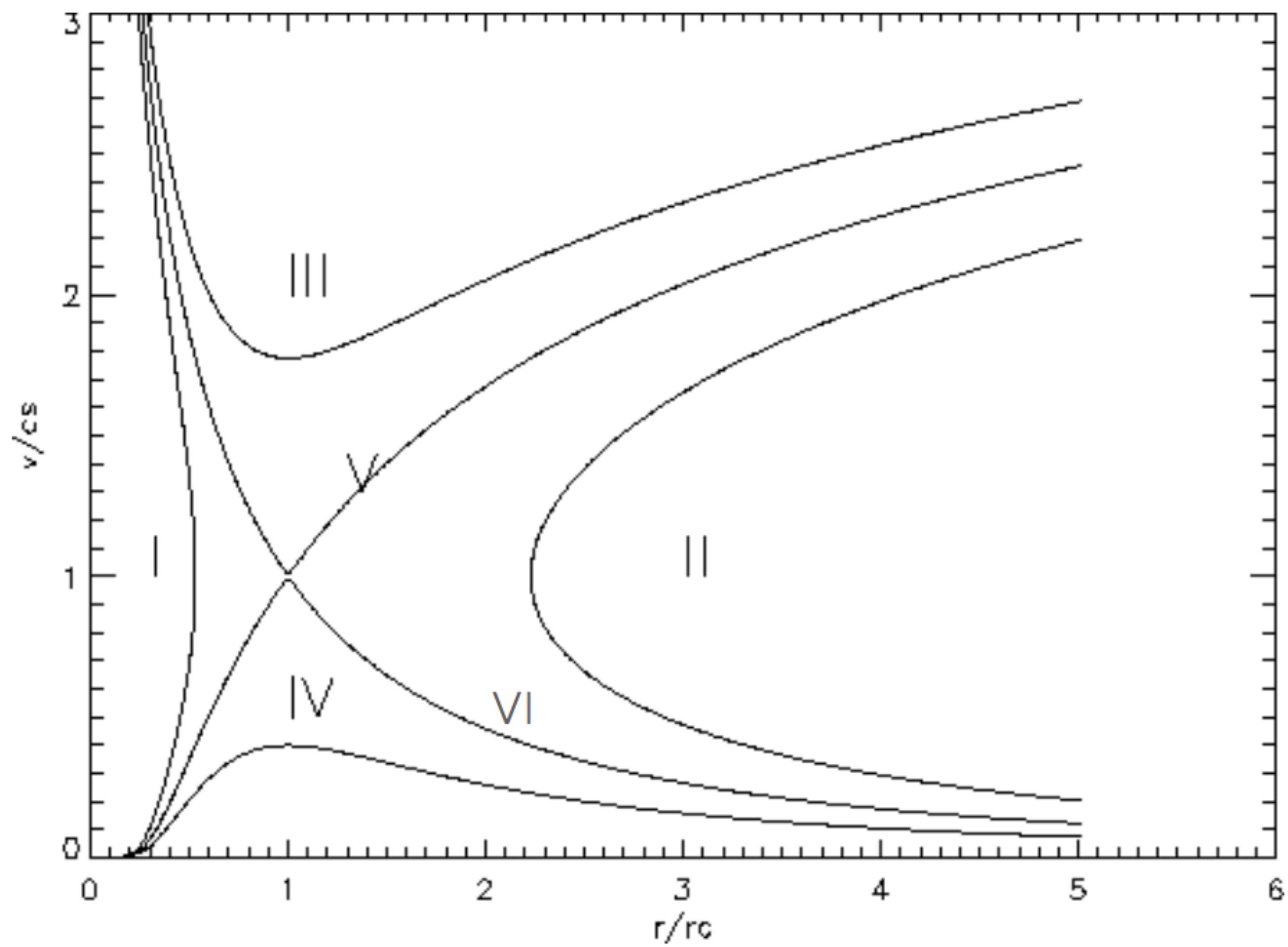
Geysers, caught by the wind

Powered not by tides,
But by *solid state greenhouse*
(solar heating
under the nitrogen snow).

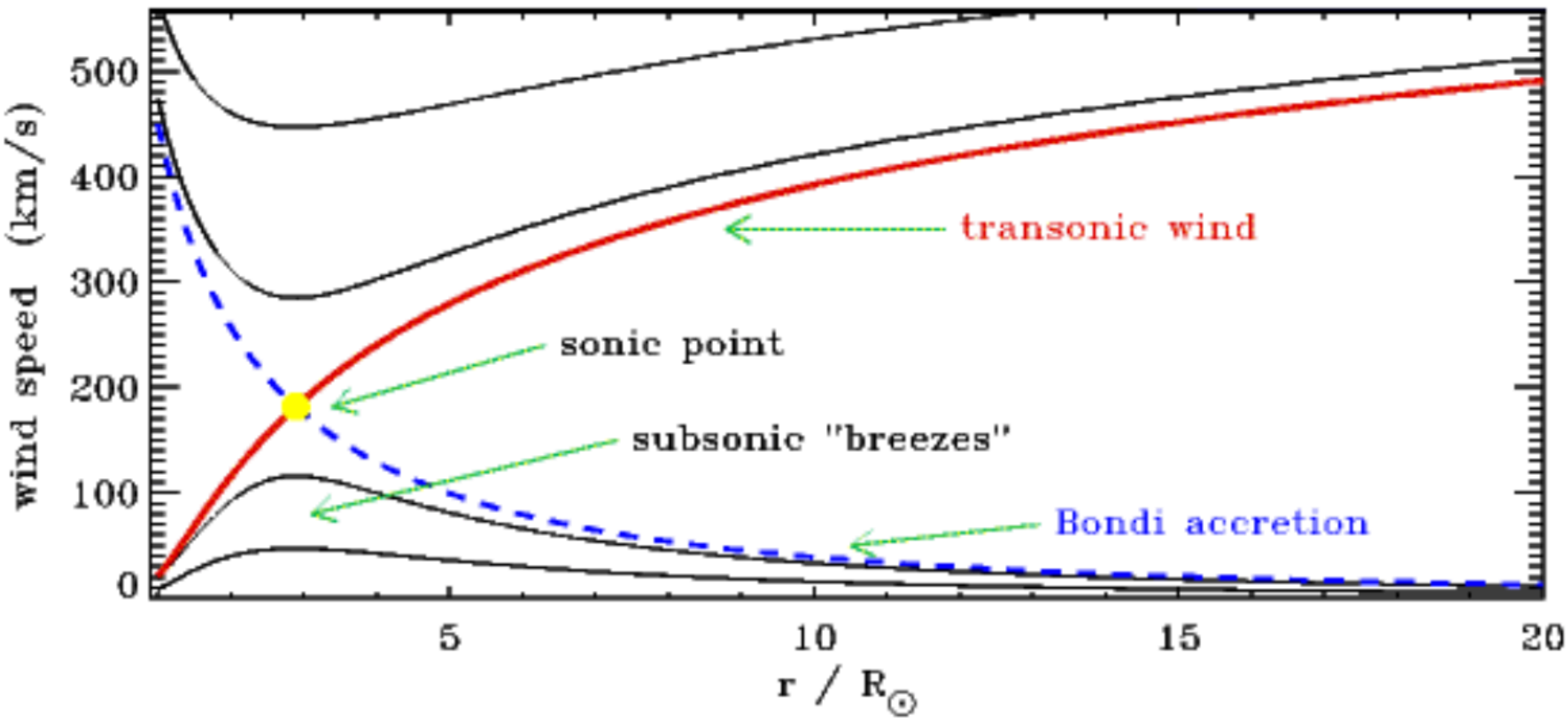
The Solar Corona



Parker wind

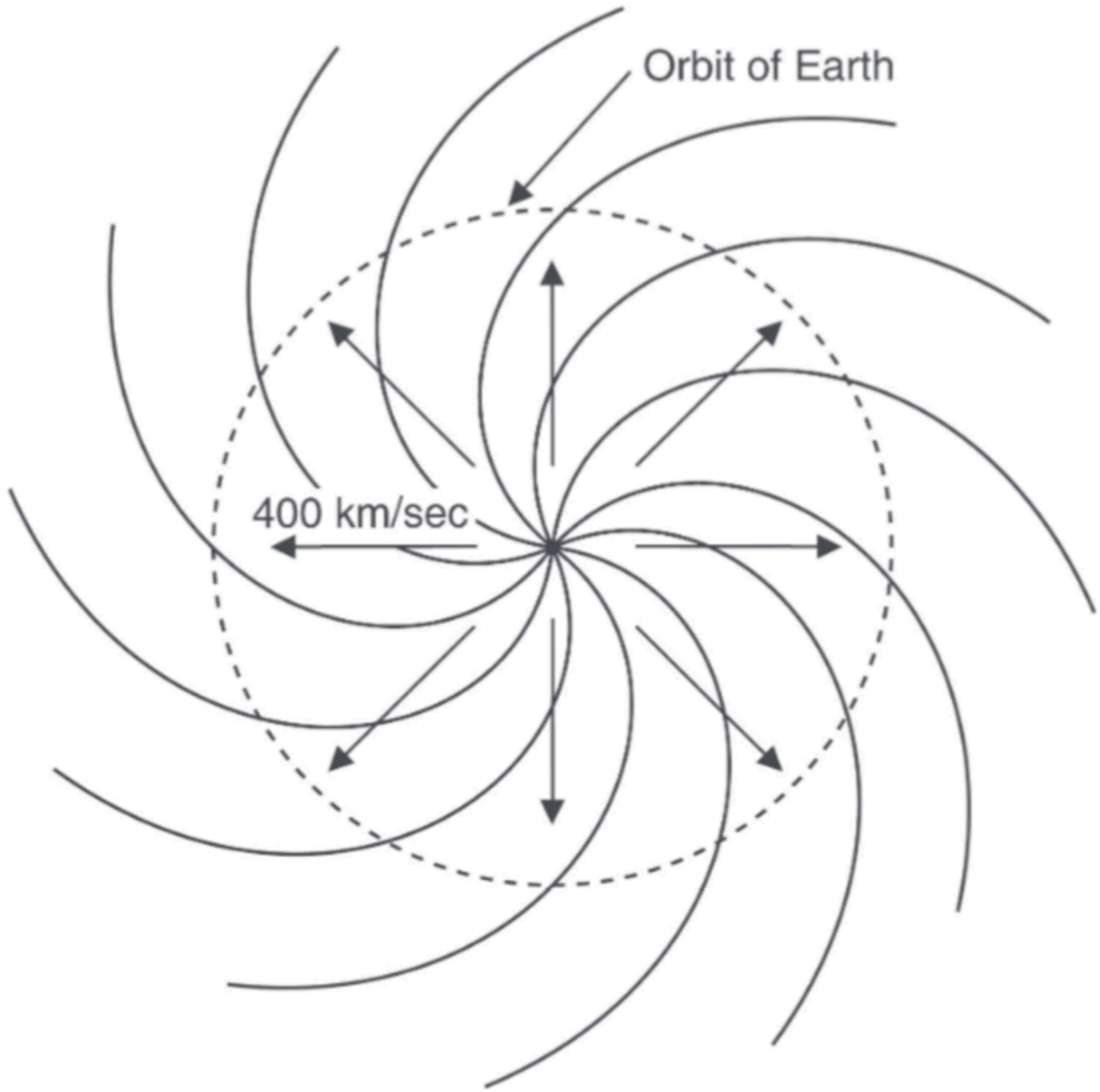


Parker wind

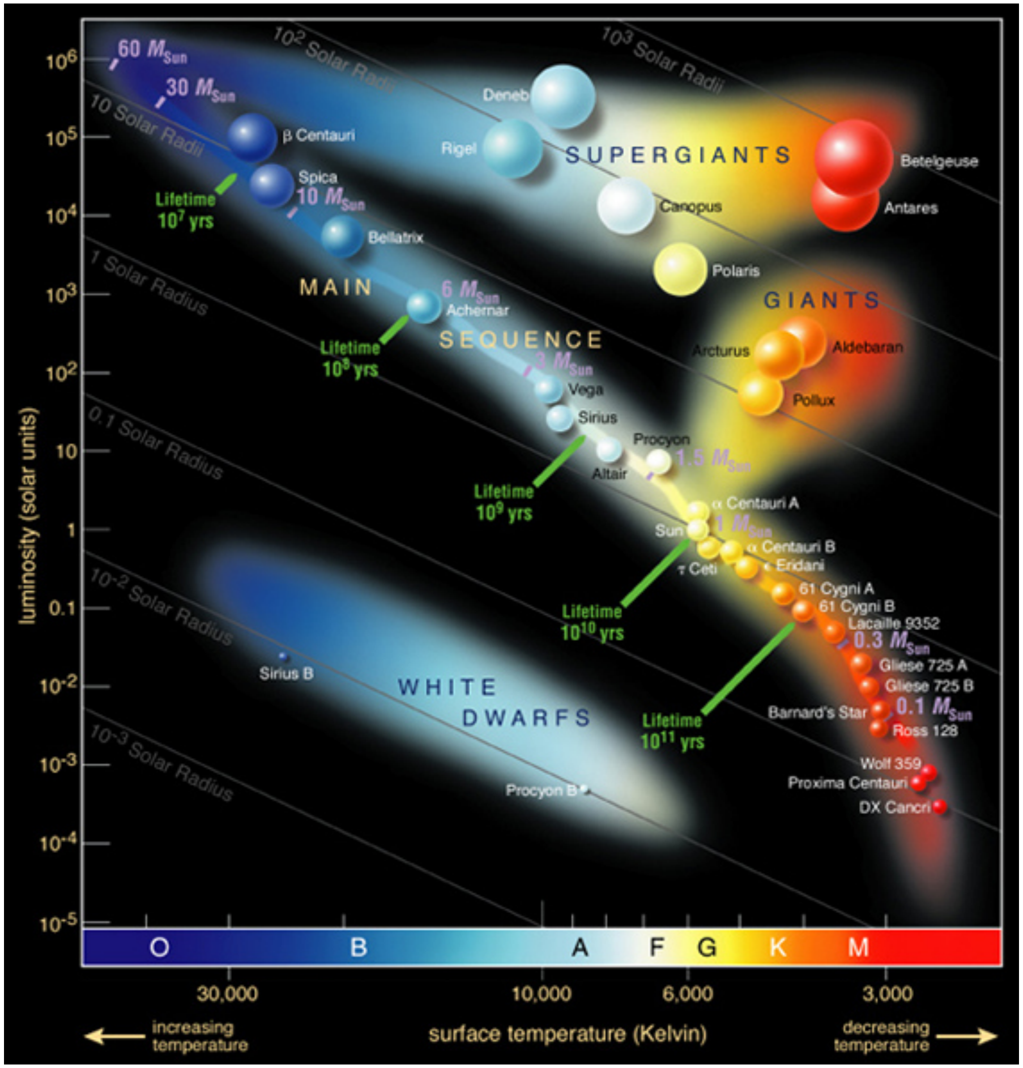


wind speed (km/s)
500
400
300
200
100
0
transonic wind
sonic point
subsonic "breezes"
Bondi accretion
5
10
15
20
r / $R_\odot$

Parker spiral



Types of stars – The HR diagram



HR stands for "Hertzsprung-Russel"

Temperature x Luminosity

Spectral Types

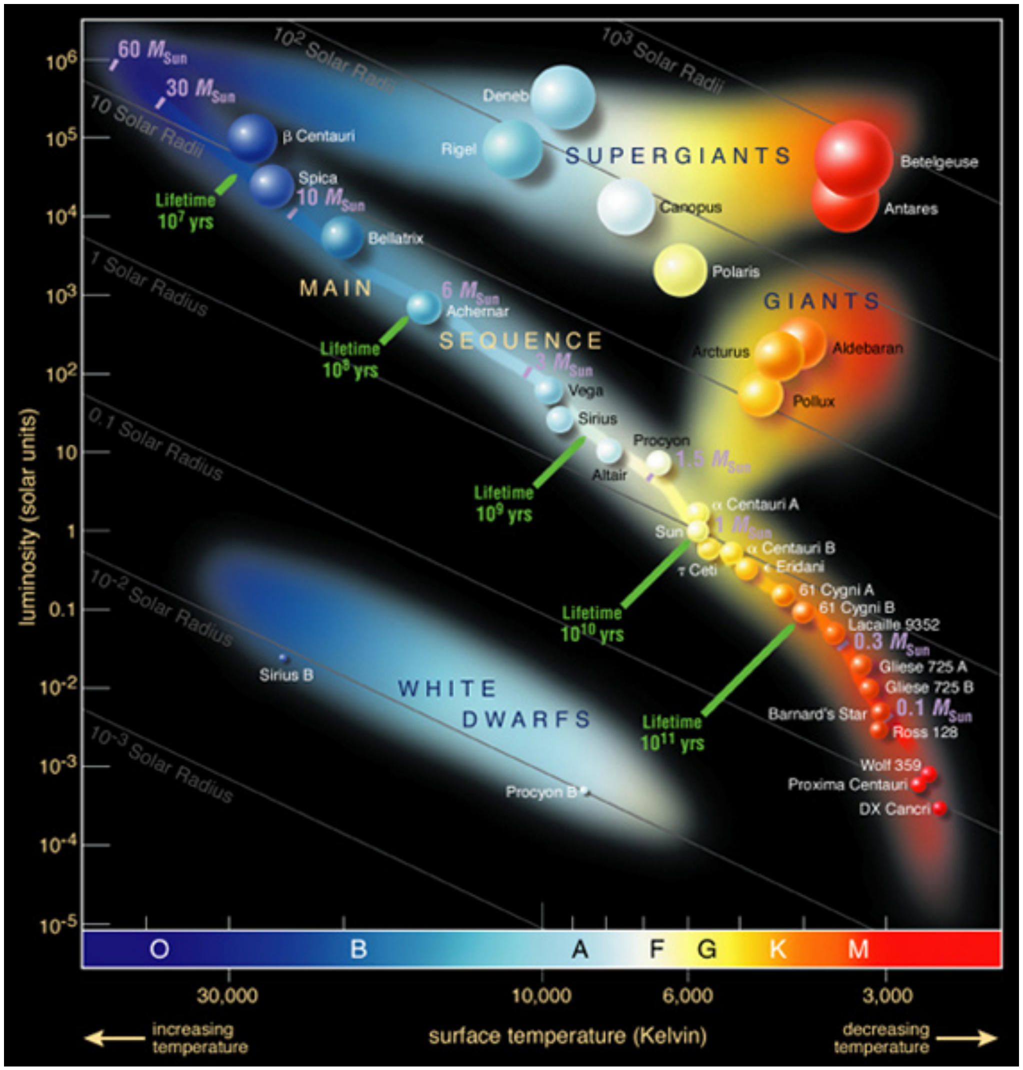
OBAFGKM

Each type is subdivided into ten numbered subtypes (eg, K8, B6)

Spectral Types

O B A F G K M

Types of stars – The HR diagram



Spectral Types

OBAFGKM

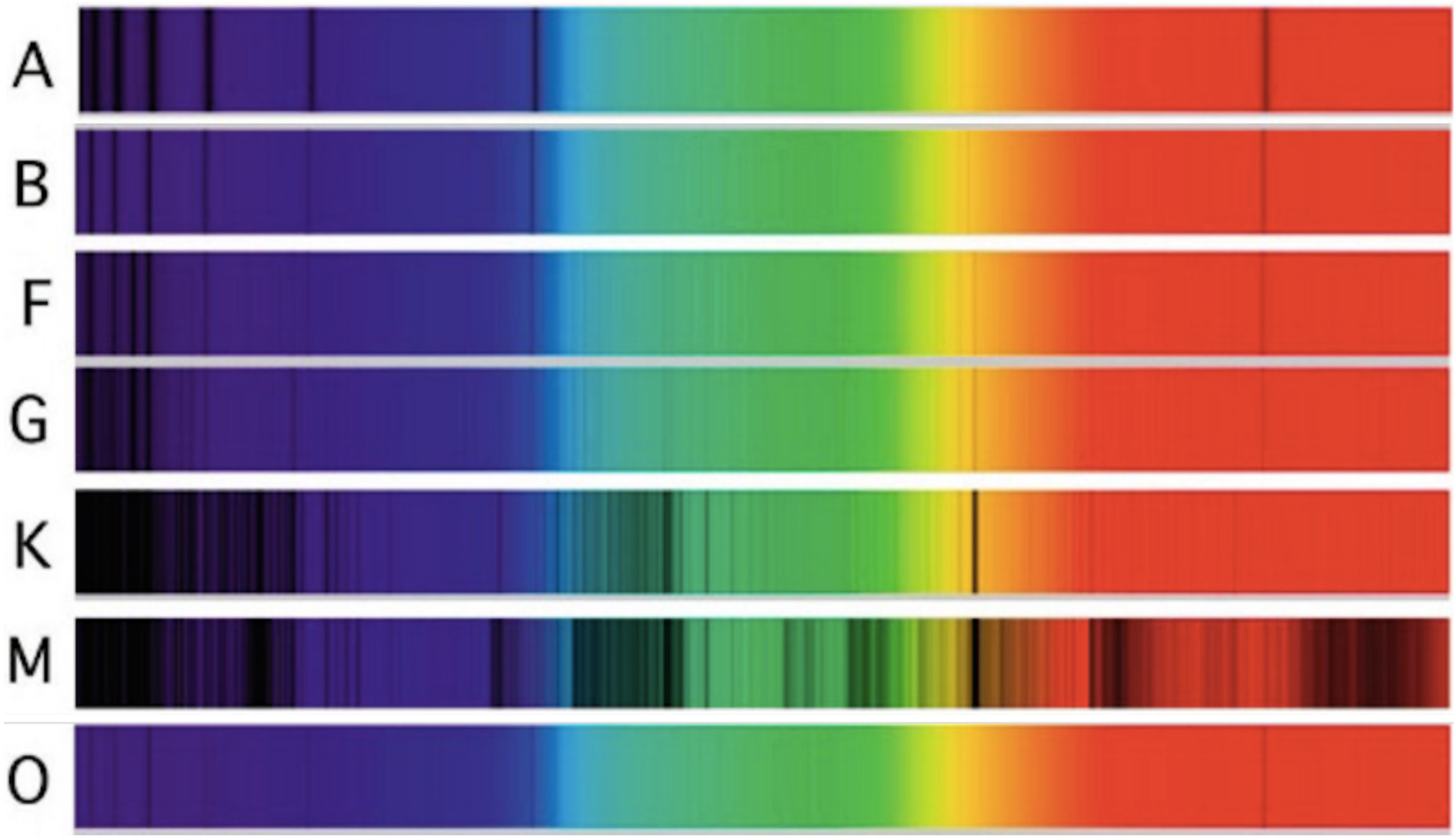
Each type is subdivided into ten numbered subtypes (eg, K8, B6)

Luminosity classes

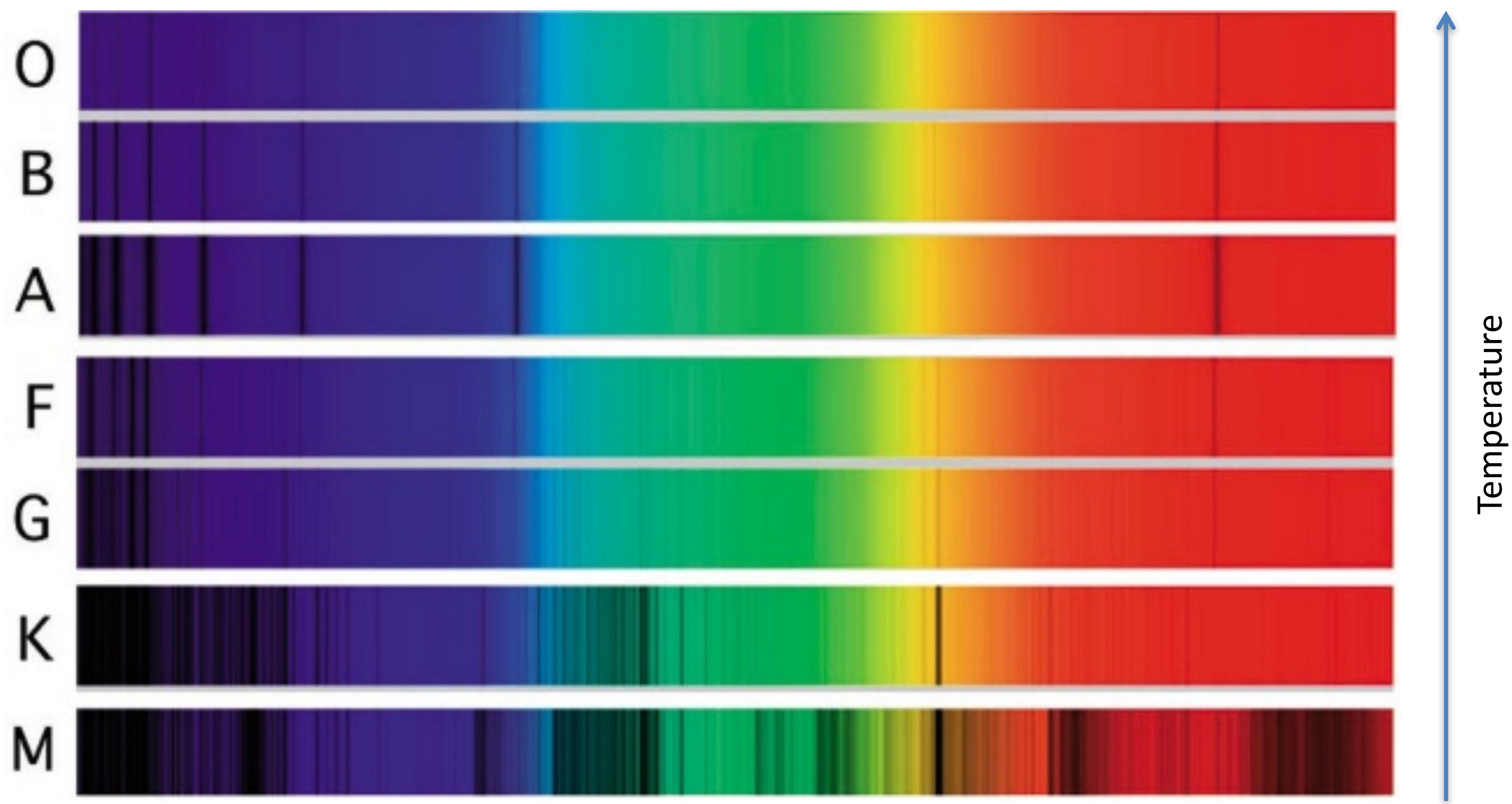
I - Supergiants
II - Bright giants
III - Giants
IV - Subgiants
V - Dwarfs
VI - Subdwarfs
VII - White Dwarfs

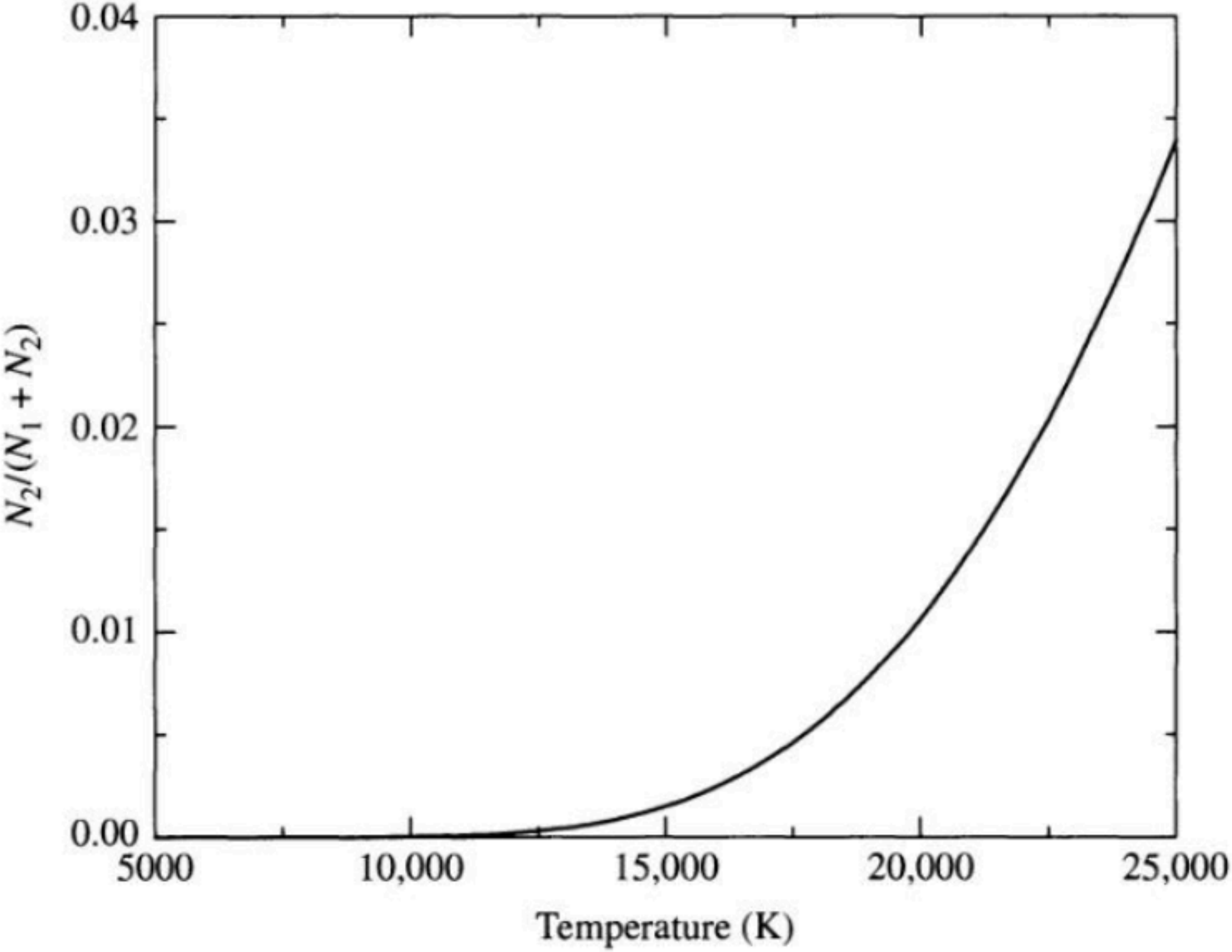
The **Sun** is a **G2V** star
Sirius is a **A1V** star
Betelgeuse is a **M2I** star
Pollux is a **K2III** star

Origin of spectral class nomenclature – Strength of Hydrogen lines

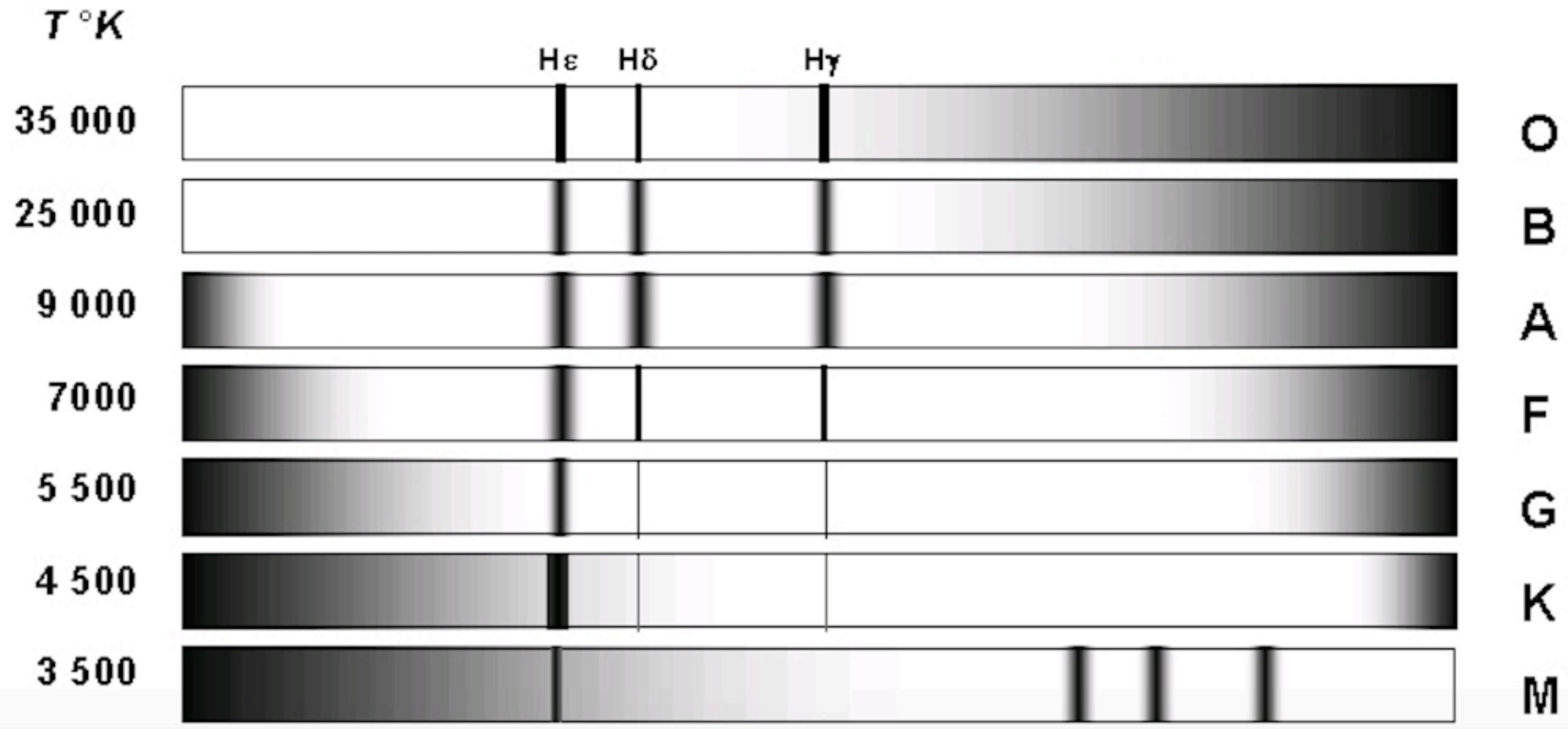


Ordering in Temperature

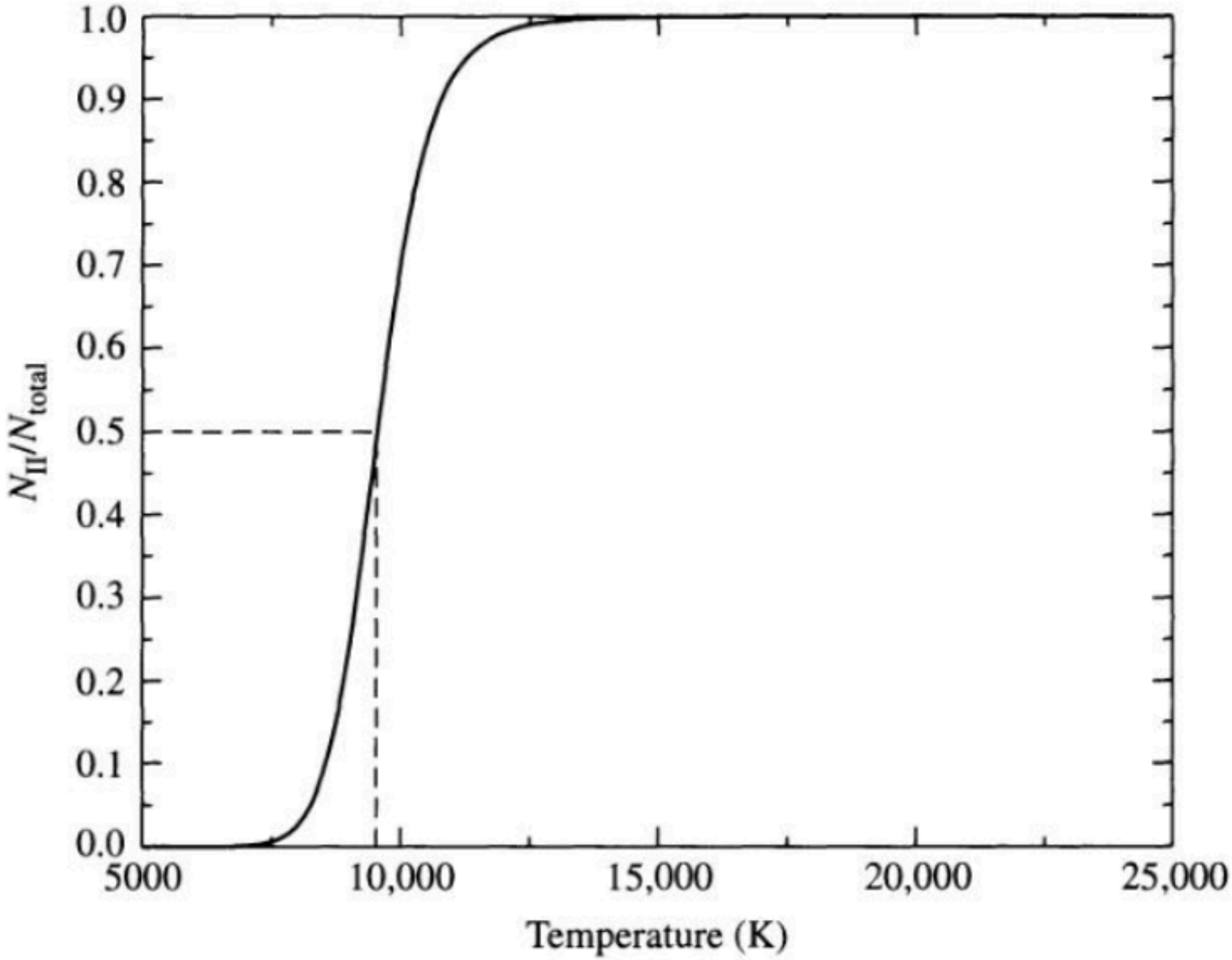




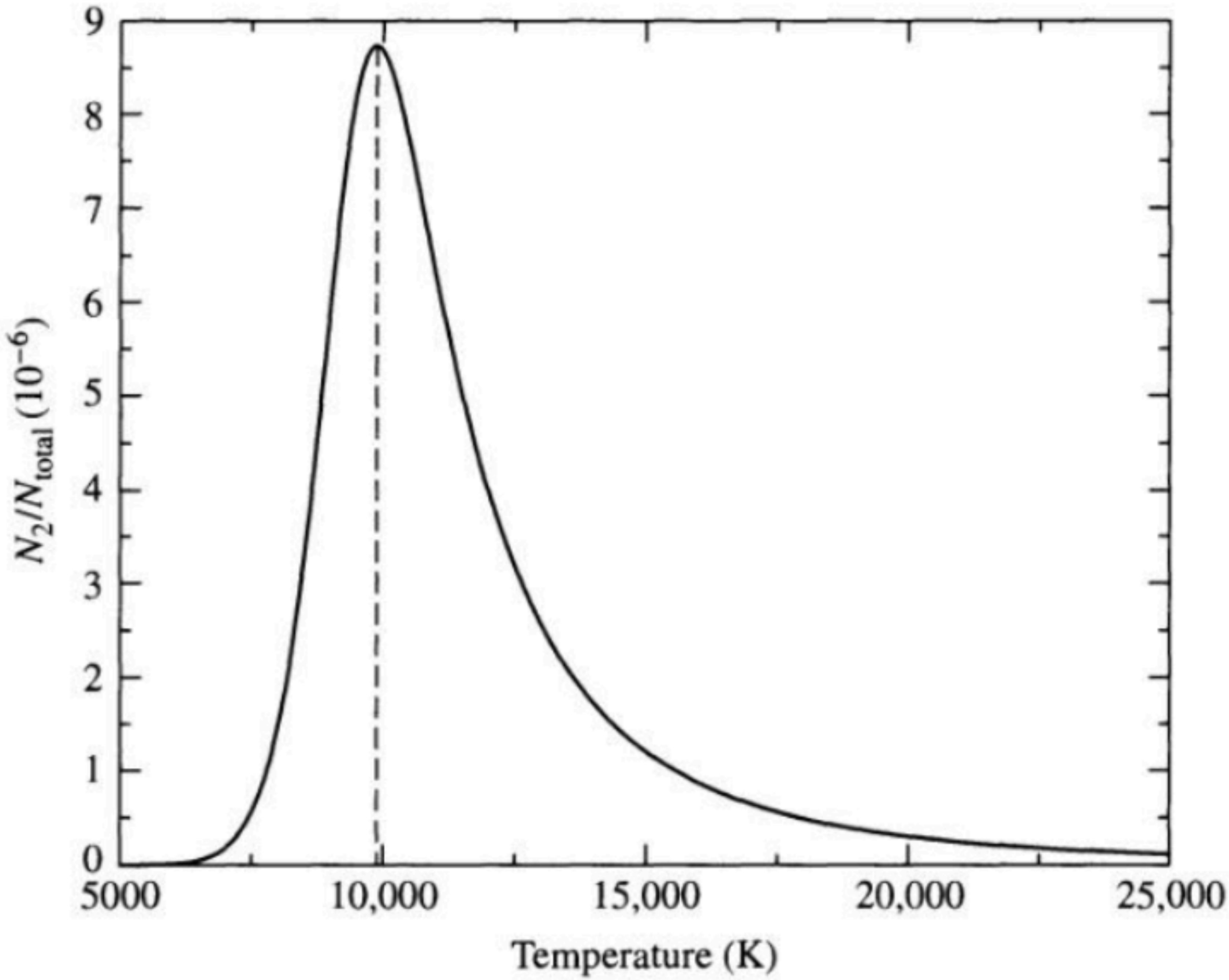
0.04
0.03
0.02
0.01
0.00
5000
10,000
15,000
20,000
25,000
Temperature (K)
$N_2/(N_1 + N_2)$



T °K
Hε
Hδ
Hγ
35 000
25 000
9 000
7000
5 500
4 500
3 500
O
B
A
F
G
K
M



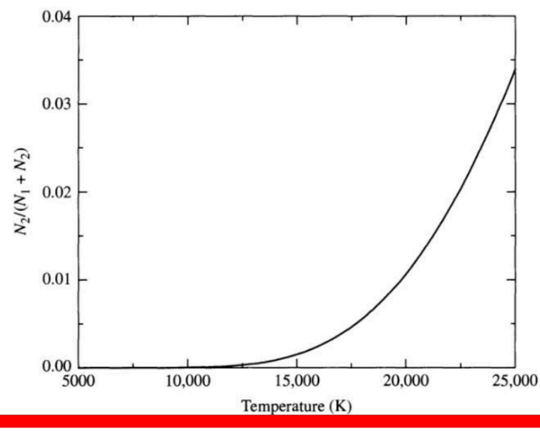
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
N_{II}/N_{total}
5000
10,000
15,000
20,000
25,000
Temperature (K)



9
8
7
6
5
4
3
2
1
0
5000
10,000
15,000
20,000
25,000
Temperature (K)
N_2/N_{total} (10^{-6})

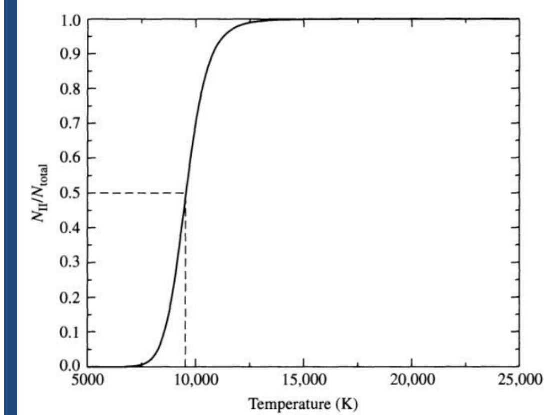
Saha Equation

Excitation

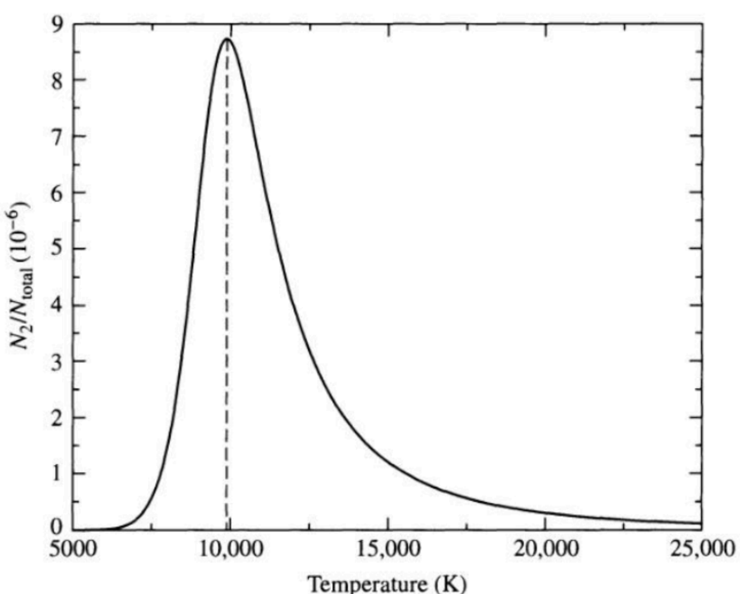


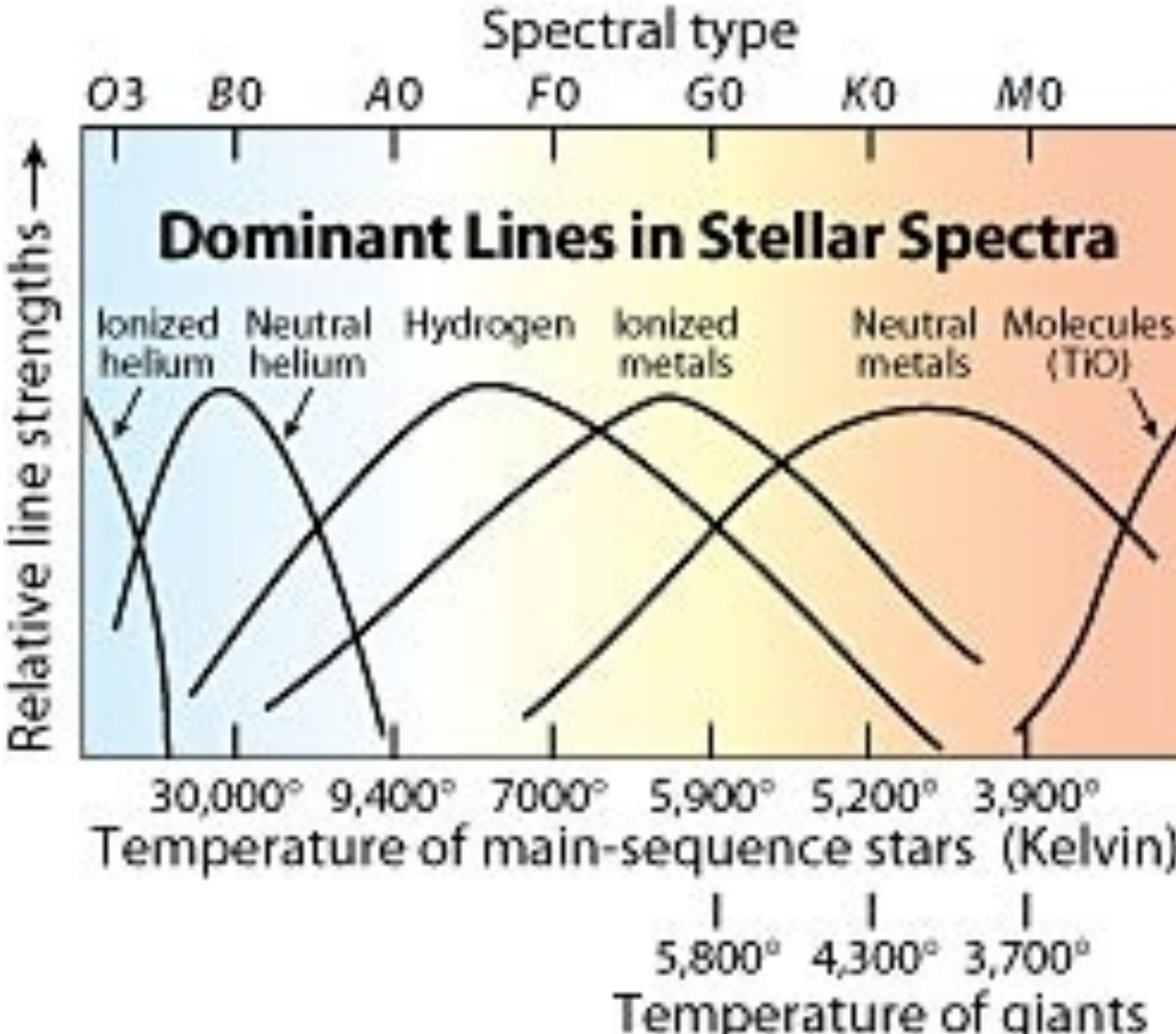
x

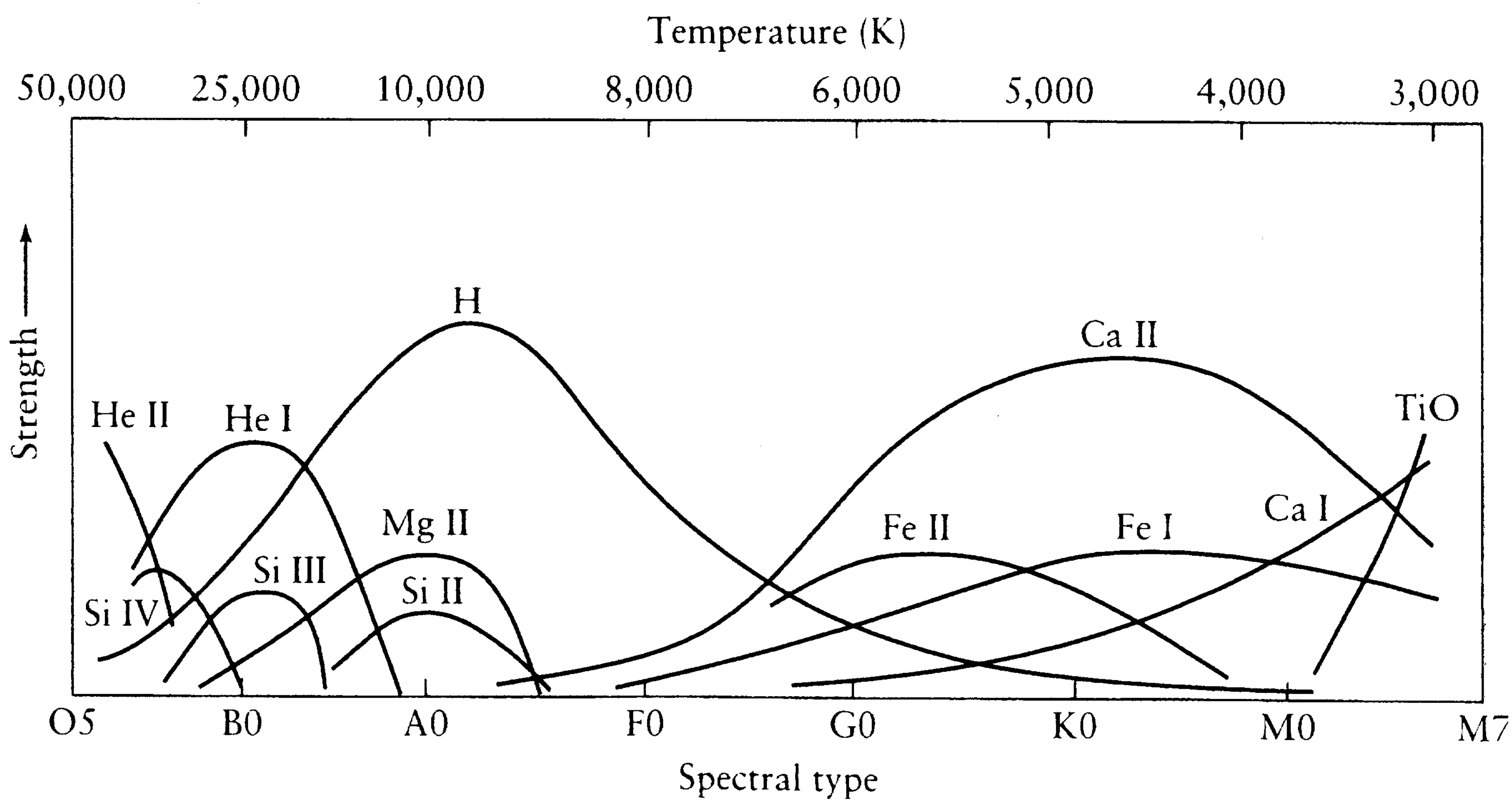
Ionization

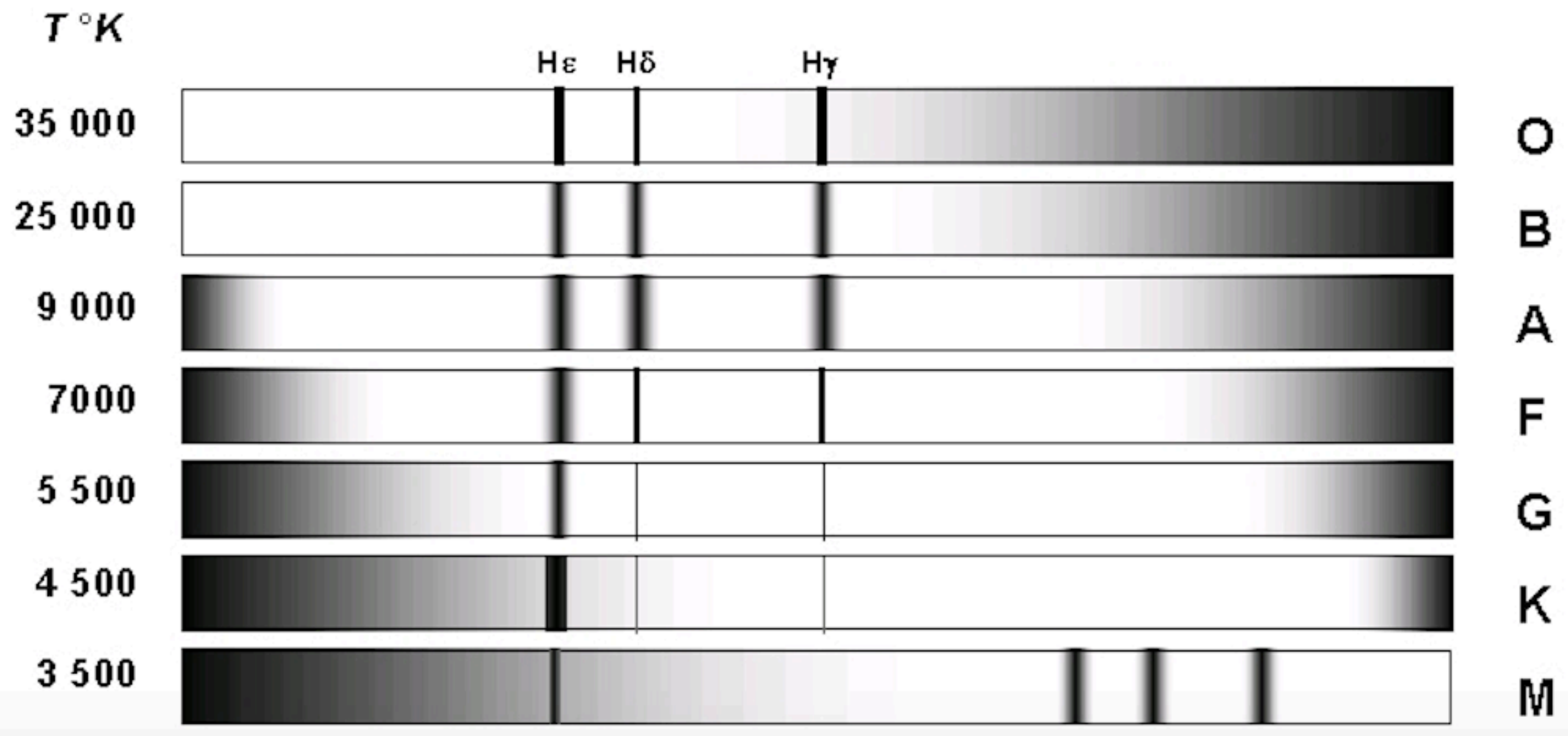


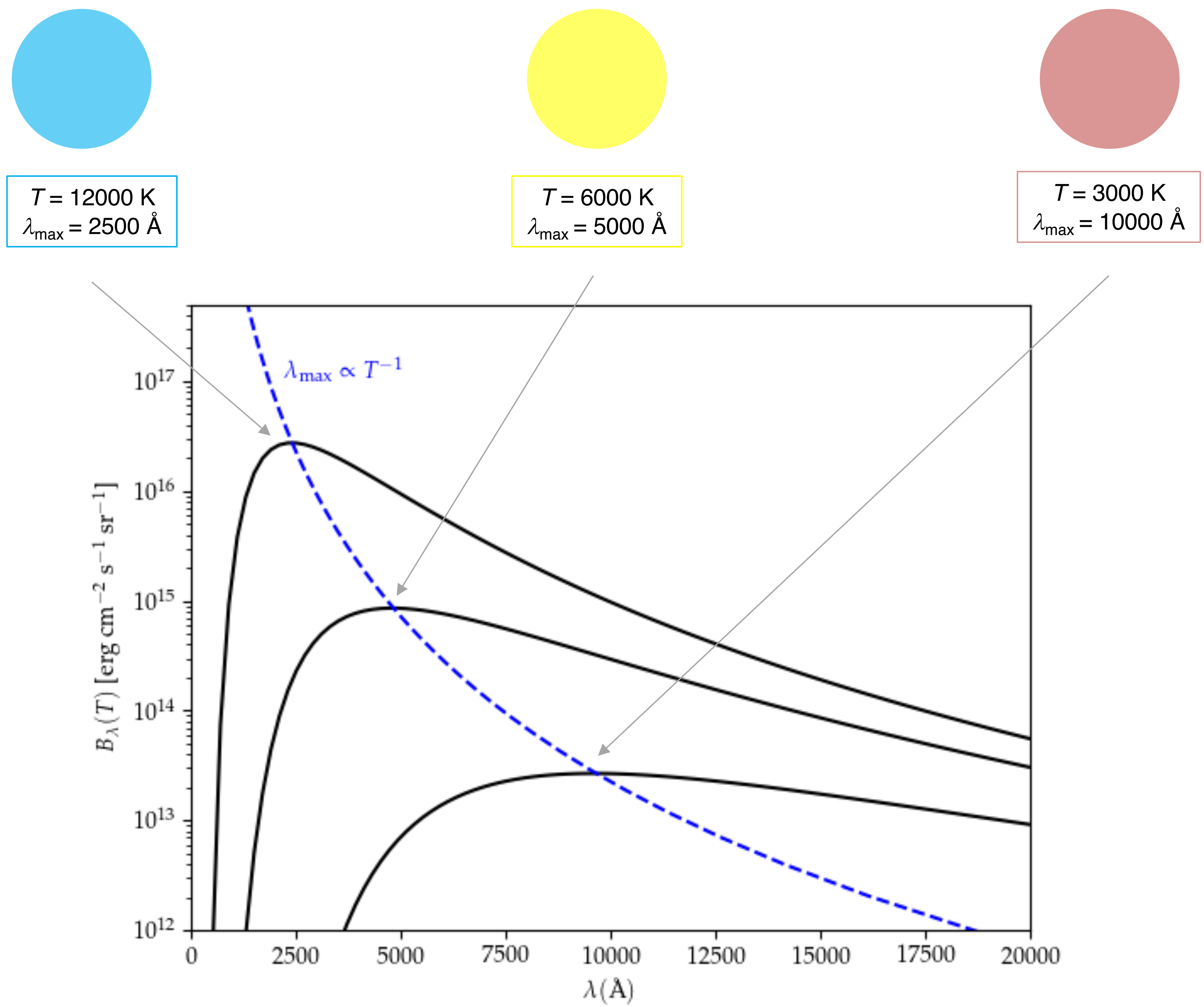
=




Spectral type
O3 B0 A0 F0 G0 K0 M0
Dominant Lines in Stellar Spectra
Relative line strengths →
Ionized helium
Neutral helium
Hydrogen
Ionized metals
Neutral metals
Molecules (TiO)
30,000° 9,400° 7000° 5,900° 5,200° 3,900°
Temperature of main-sequence stars (Kelvin)
5,800° 4,300° 3,700°
Temperature of giants


Temperature (K)
50,000
25,000
10,000
8,000
6,000
5,000
4,000
3,000
Strength
H
Ca II
He II
He I
TiO
Ca I
Fe II
Fe I
Mg II
Si III
Si II
Si IV
O5
B0
A0
F0
G0
K0
M0
M7
Spectral type

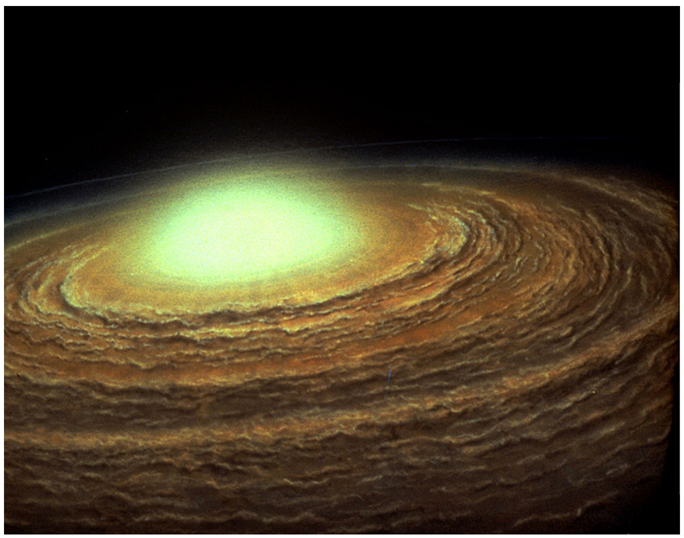

T °K
Hε
Hδ
Hγ
35 000
25 000
9 000
7000
5 500
4 500
3 500
O
B
A
F
G
K
M

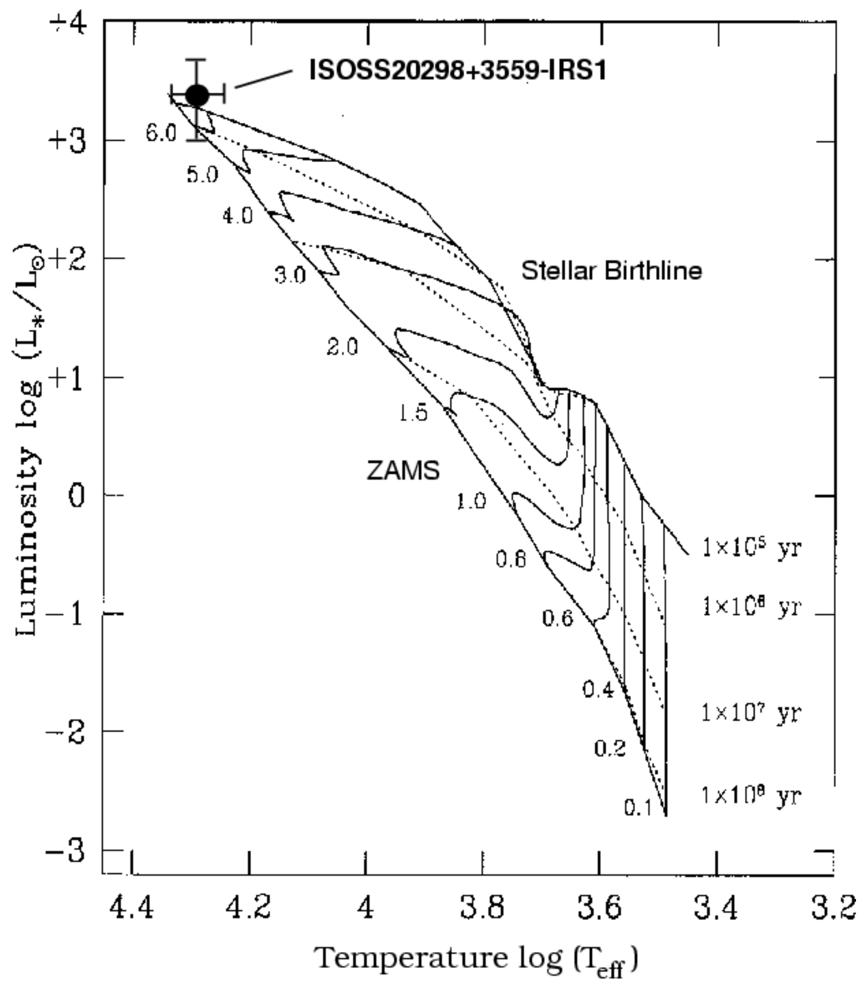


T = 12000 K
λmax = 2500 Å
T = 6000 K
λmax = 5000 Å
T = 3000 K
λmax = 10000 Å
λmax ∝ T^−1
10^17
10^16
10^15
10^14
10^13
10^12
B_λ(T) [erg cm^−2 s^−1 sr^−1]
0
2500
5000
7500
10000
12500
15000
17500
20000
λ(Å)

Star Formation – The Birthline

Protostars appear in the HR diagram at the **BIRTHLINE**





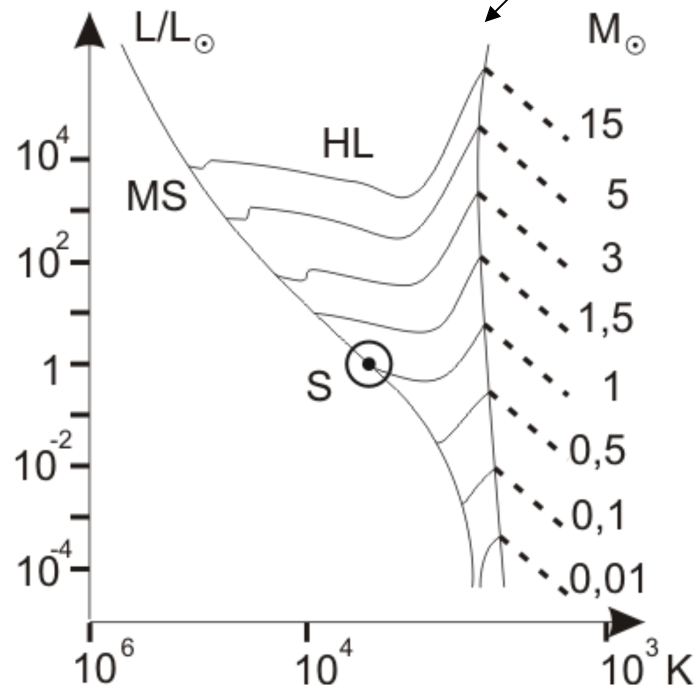
Pre main sequence evolution takes a protostar from the Birthline to the ZAMS (Zero Age Main Sequence).

Pre Main Sequence Evolution

Birthline - The Hayashi limit

Lowest temperature that can maintain hydrostatic equilibrium

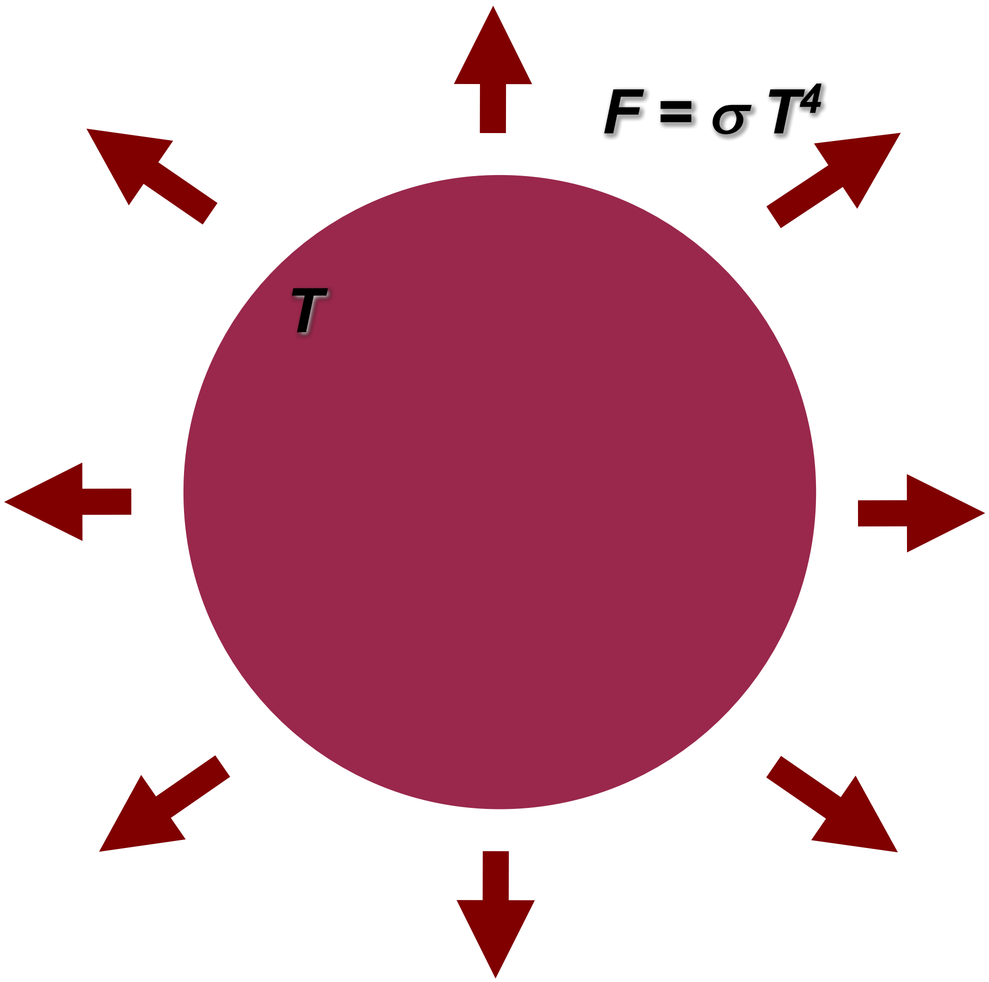
Hayashi calculated the maximum radius that a star in hydrostatic equilibrium can have.



Hayashi forbidden zone

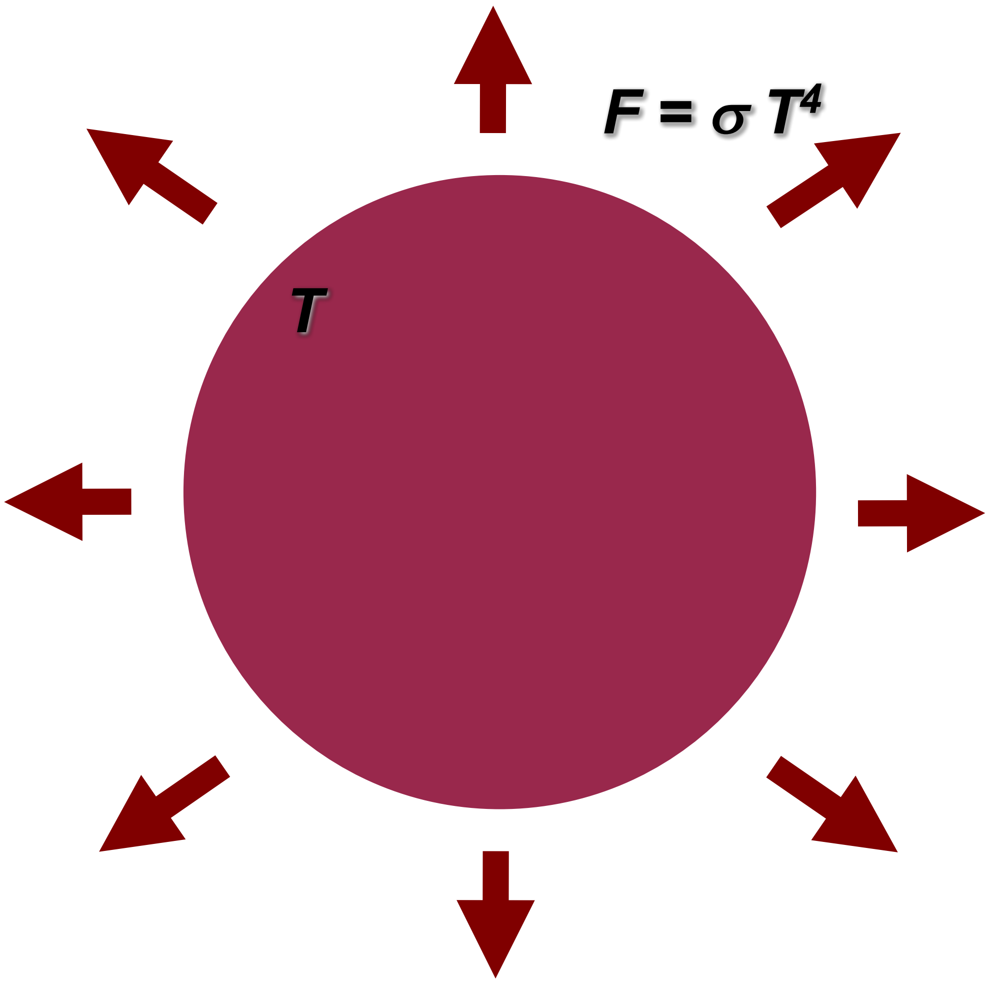
The result is almost a straight line in the HR diagram (meaning nearly constant temperature).

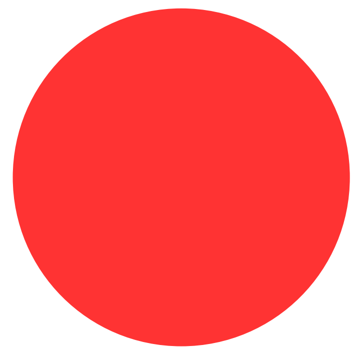
Pre Main Sequence Evolution



It has a temperature, thus a flux
Energy is radiated away
The star loses support and contracts

Pre Main Sequence Evolution



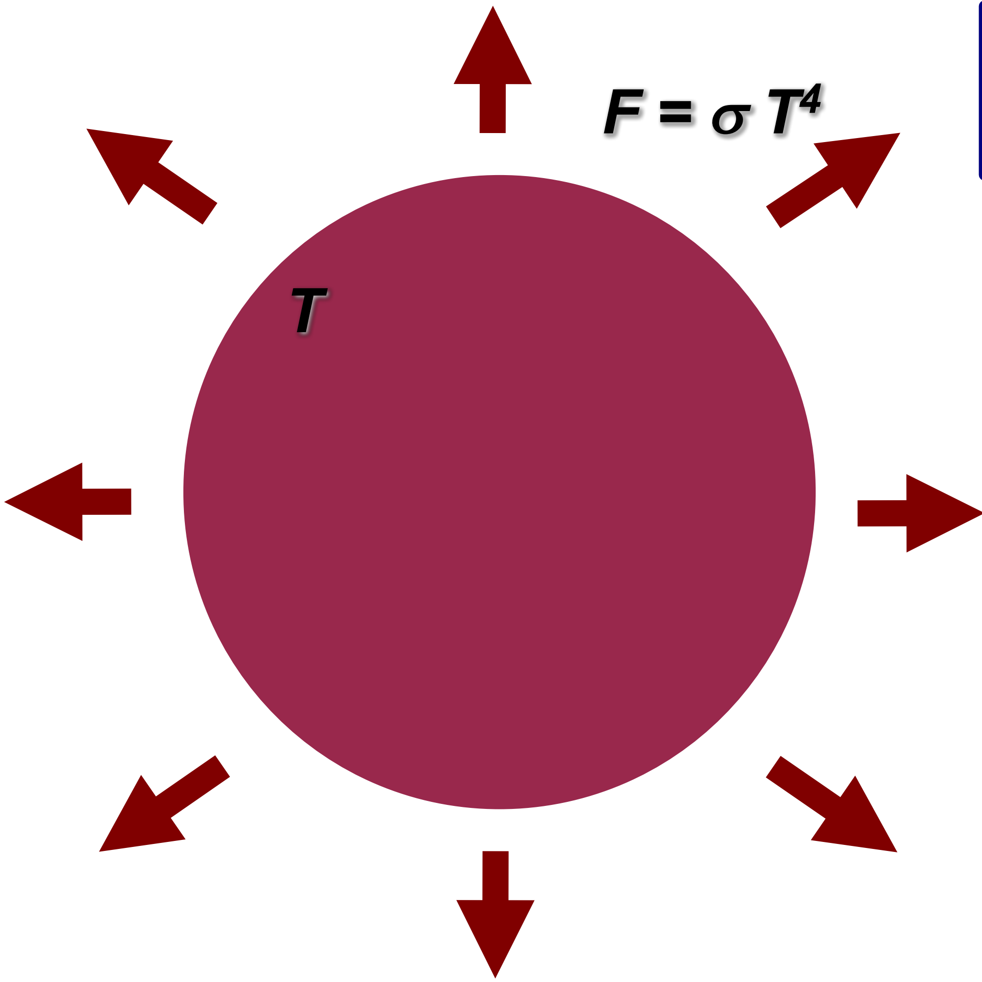


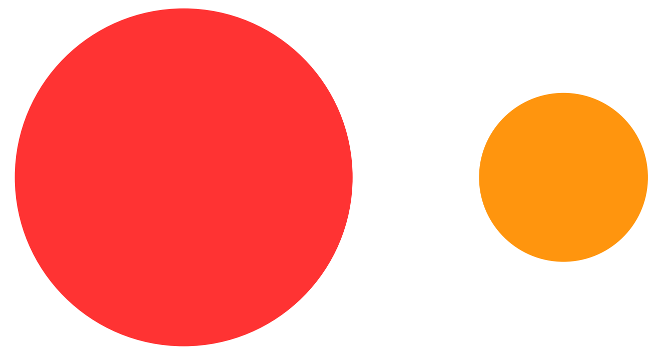
Contraction raises the pressure
The star heats up
Energy is radiated away
The star loses support and contracts

It has a temperature, thus a flux
Energy is radiated away
The star loses support and contracts

Pre Main Sequence Evolution

The protostar keeps contracting until the pressure and temperature in the center are high enough to ignite fusion





Contraction raises the pressure
The star heats up
Energy is radiated away
The star loses support and contracts

It has a temperature, thus a flux
Energy is radiated away
The star loses support and contracts

Pre Main Sequence Evolution

Hayashi Tracks

In the HR diagram, these contraction paths appear as **Hayashi tracks**

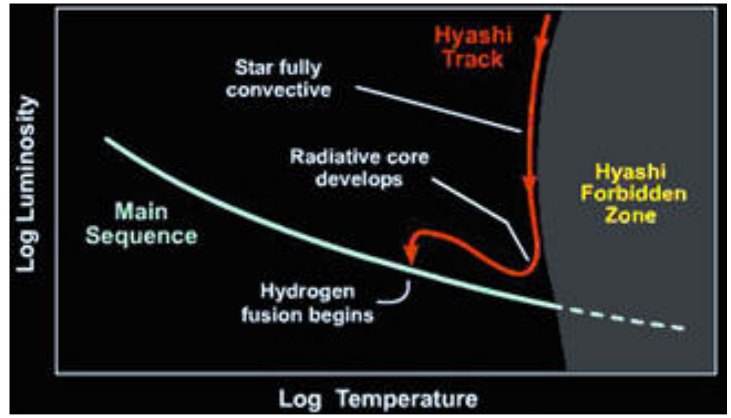
Slow contraction under quasi-hydrostatic equilibrium

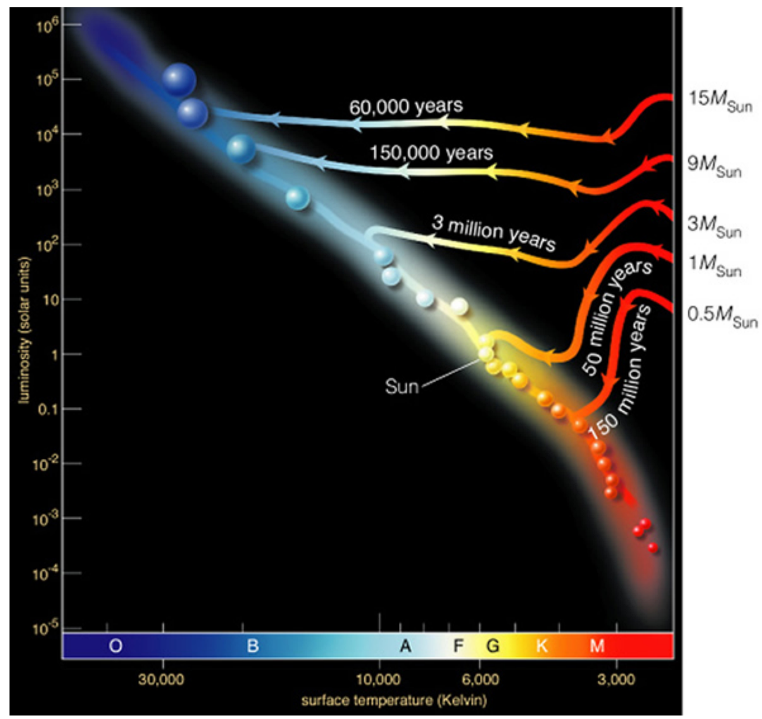
End or pre main sequence evolution?

Start of nuclear fusion!
(Star lands on the main sequence)

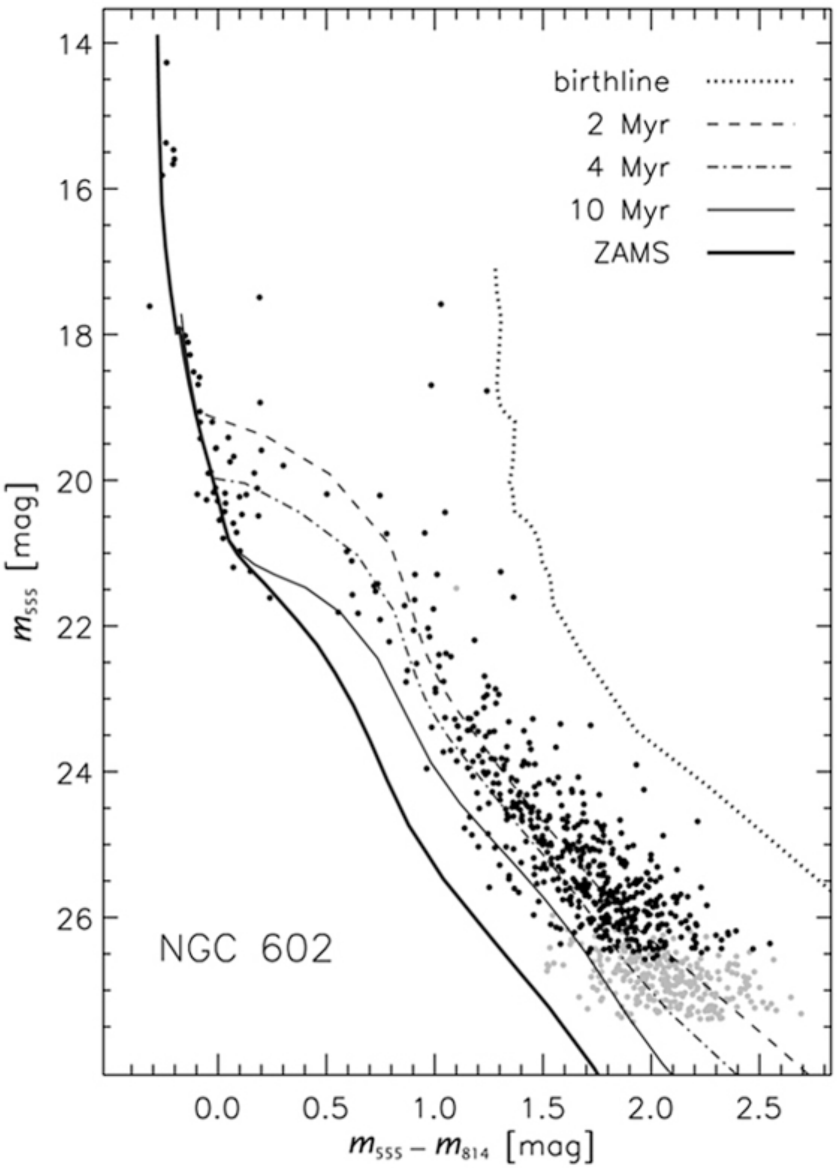
PMS evolution is faster for high mass stars

Gravity and pressure are ***finally*** balanced!



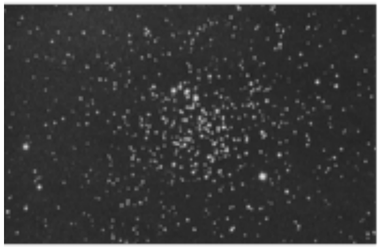


Pre Main Sequence Evolution



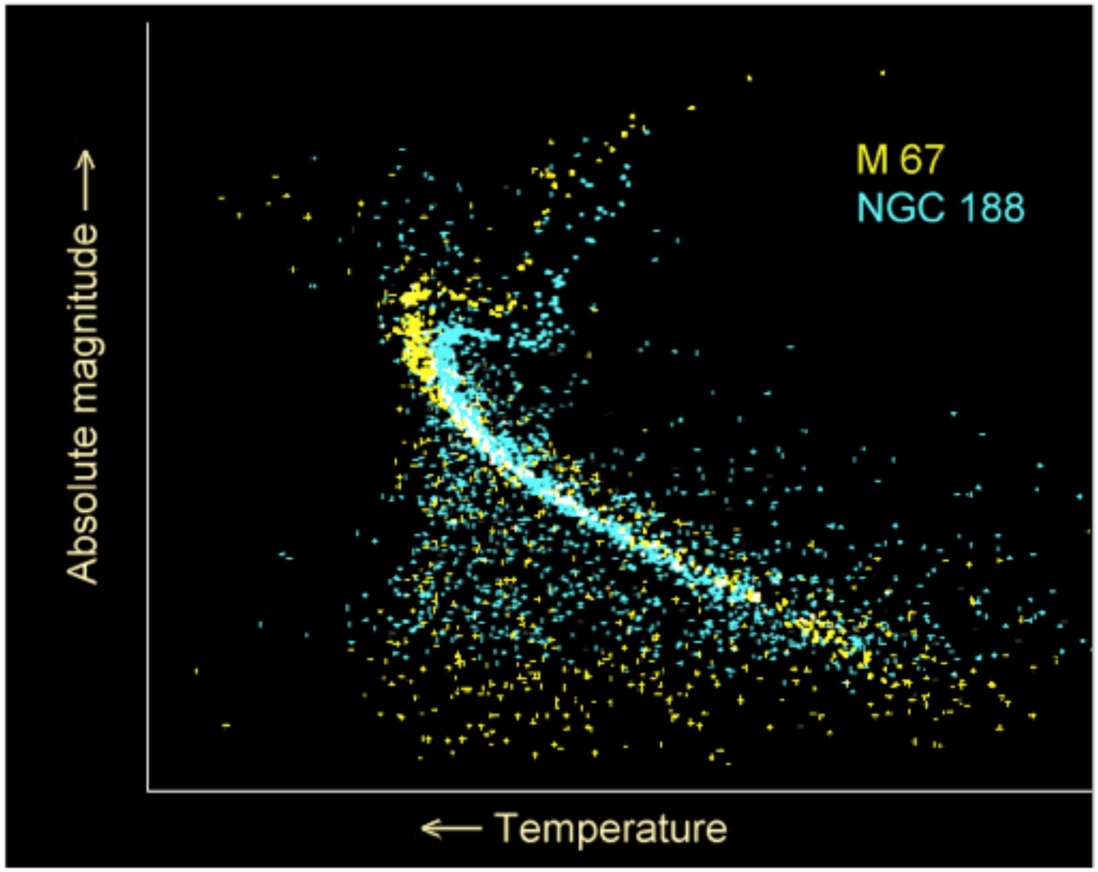
Line of constant age: ***ISOCHRONE***

ZAMS: Zero-Age Main Sequence



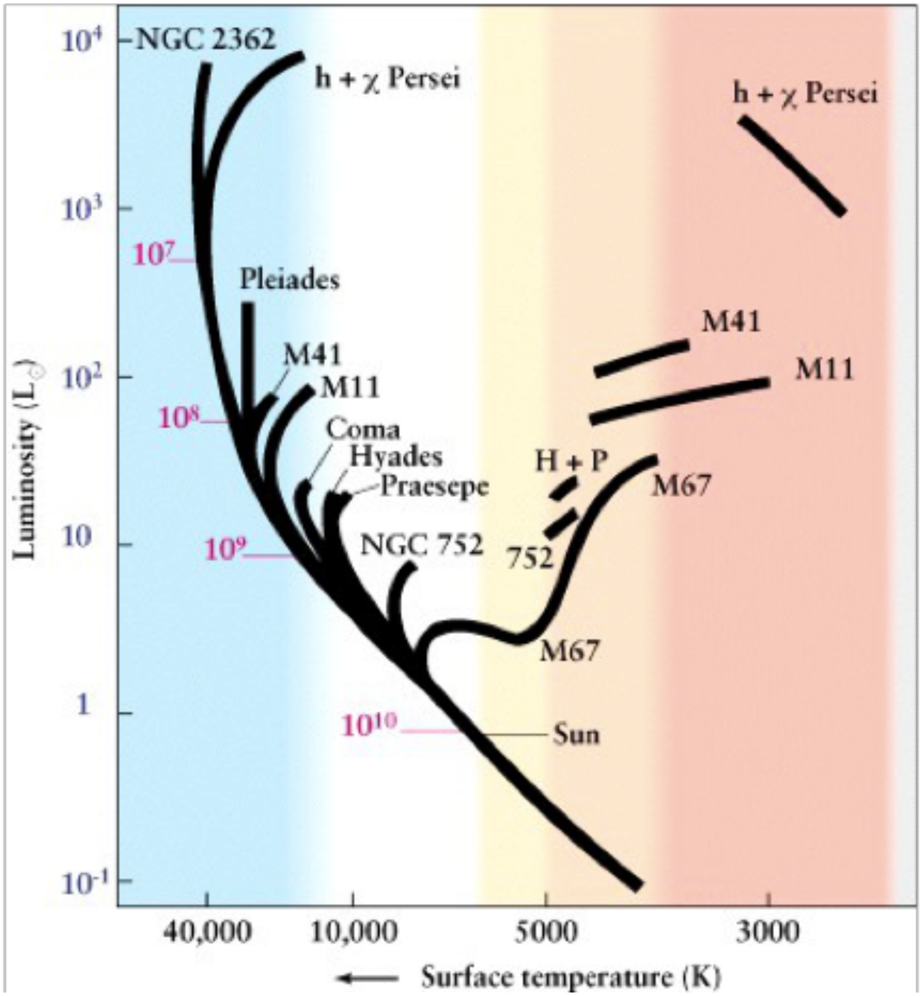
M67

NGC188



Which one is the older?

The Main Sequence Turn-Off Point



As stars age, they leave the main sequence

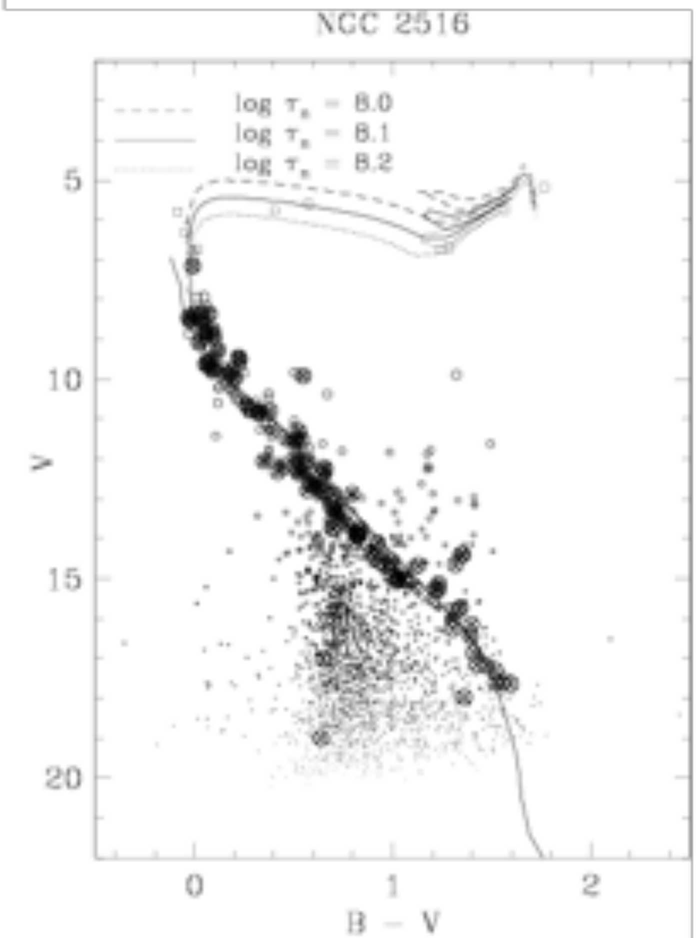
The point where stars are leaving the main sequence is called **turn-off point**

It is a function of age!

Application to clusters:

If you can tell the age of the star at the turn-off point, you can tell the age of the cluster.

The Main Sequence Turn-Off Point



Application to clusters:

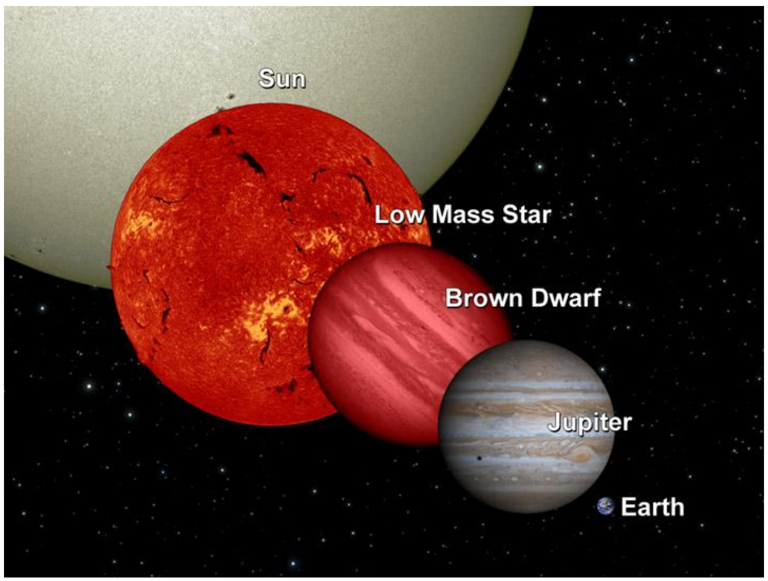
If you can tell the age of the star at the turn-off point, you can tell the age of the cluster.

Isochrone Fitting

NGC 2516 – Age ~150 Myr

Brown Dwarfs - Runt Stars

Brown dwarfs are objects with mass
below the **Hydrogen Burning Limit** of **0.08 $M_\odot$**



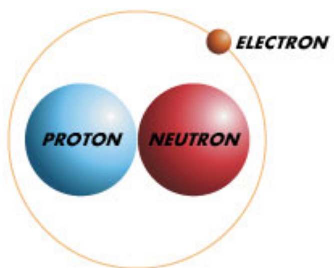
Star formation does not "know" about a hydrogen burning limit. Objects above and below it are formed.

Brown dwarfs are the runts of the litter.

Also called **Substellar Objects**

They do ***not*** burn Hydrogen,
but they burn **Deuterium**

Deuterium Burning

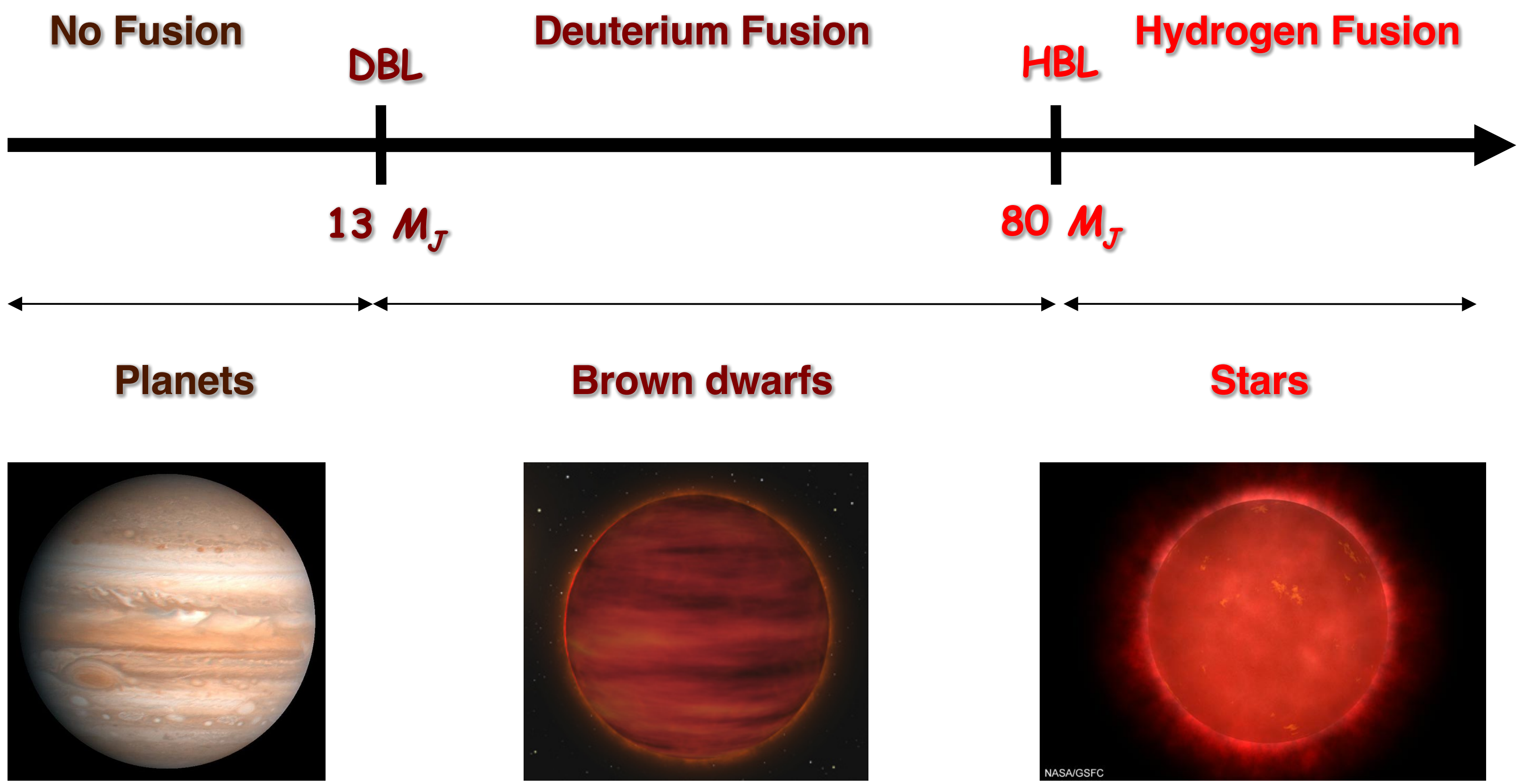


Deuterium has the **same charge** as hydrogen,
but is **heavier** – thus **easier to fuse**.

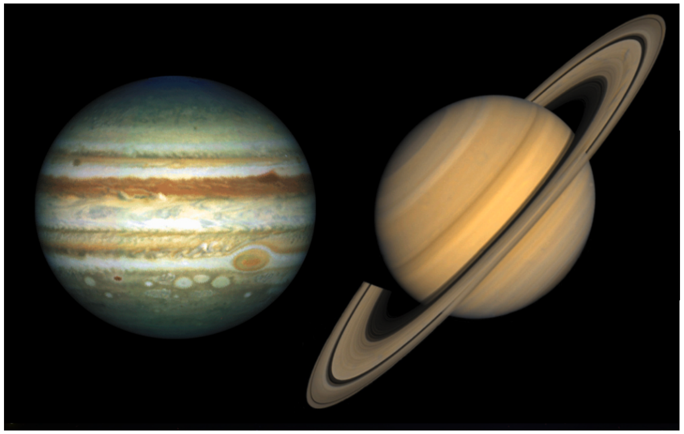
Hydrogen fusion requires temperatures of 10 million K,
but deuterium fuses at much lower temperatures.

Mass Range

Hydrogen Burning Limit (0.08 $M_{\odot}$ – 80 M_J)
Deuterium Burning Limit (0.013 $M_{\odot}$ – 13 M_J)



Radii of Brown Dwarfs



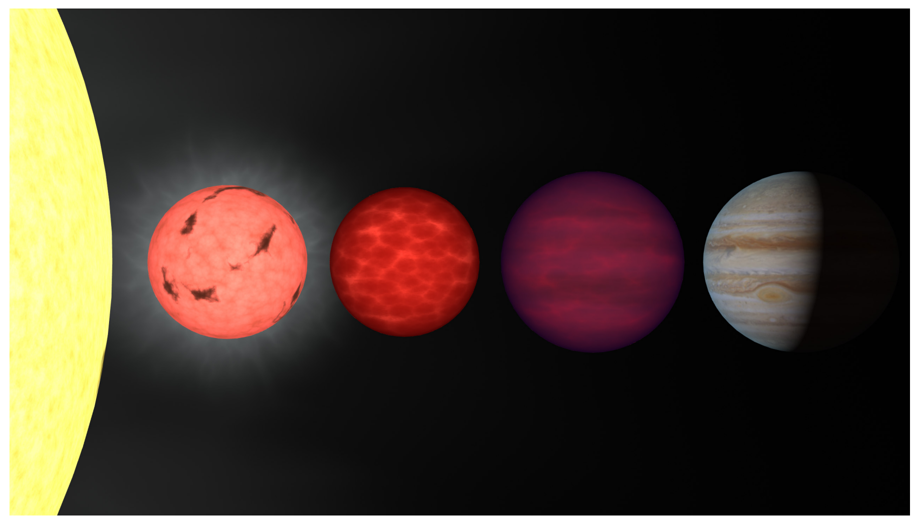
Jupiter is 3x more massive than Saturn

Yet their radii are similar.

Why?

They are partially degenerate!
In this regime, adding mass
just makes stuff denser.

The same applies to brown dwarfs



Brown dwarfs of all masses
(13 – 80 M_J)
are Jupiter-sized

Brown dwarf evolution

Deuterium fusion only lasts for 10^7 years !!

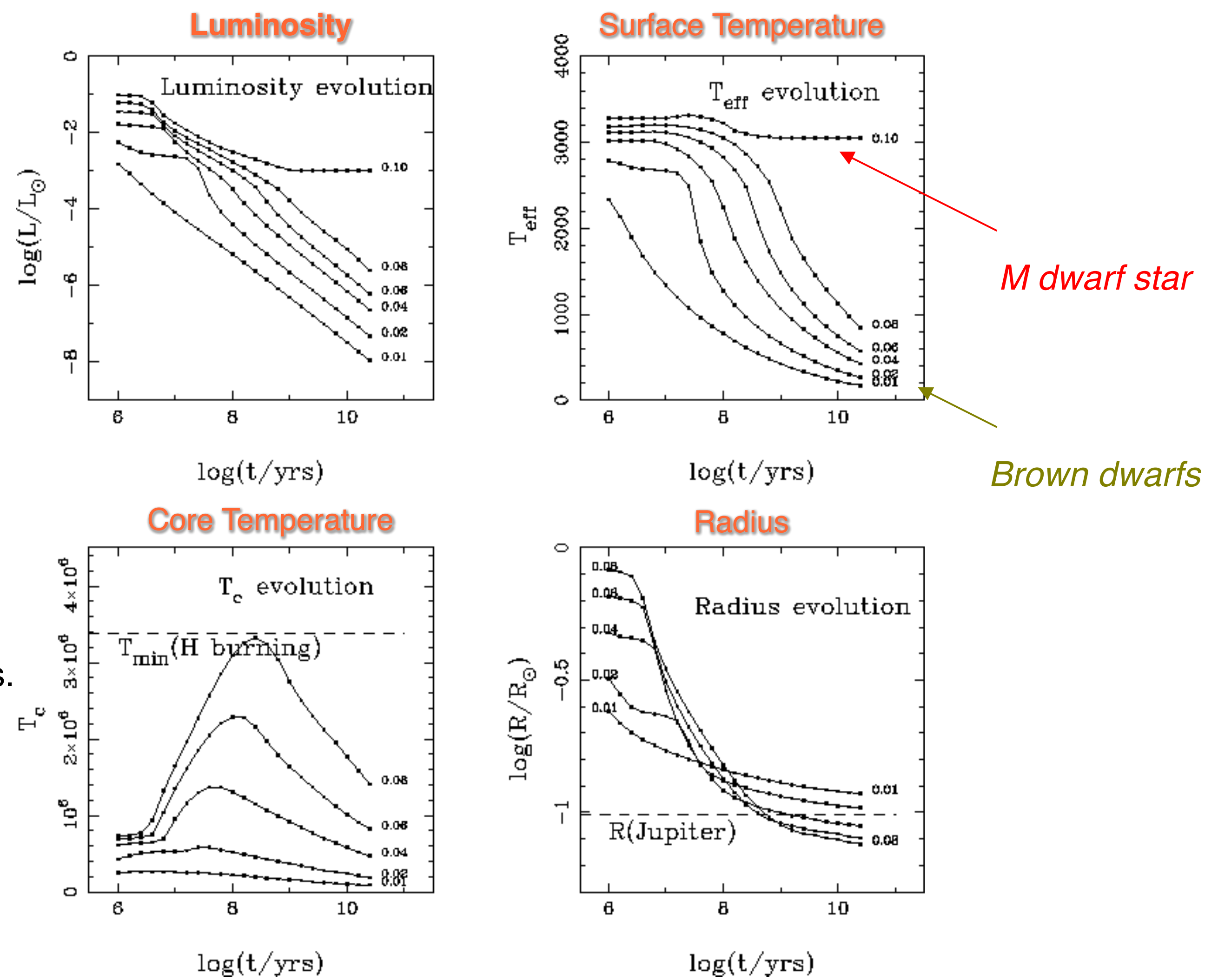
Brown dwarfs evolution after that is basically cooling

1) Deuterium burning (constant temperature, luminosity and radius)

2) Contraction. Radius falls. Core temperature rises.

3) Never achieves hydrogen burning temperatures. **Core goes degenerate.**

4) Cooling at constant radius.

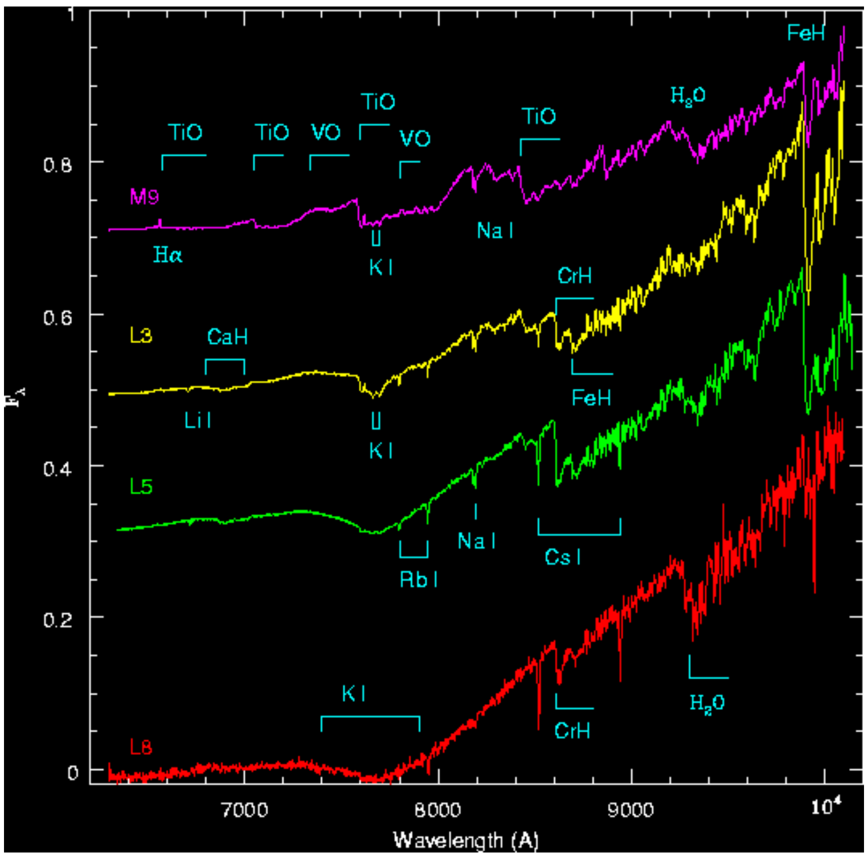


Brown dwarf atmospheres

Three new spectral types

OBAFGKM LTY

L dwarfs



Temperature range – 1300 – 2000 K

Spectral features – H_20, hydrites, no Ti0

T dwarfs

Temperature range – 700 – 1300 K

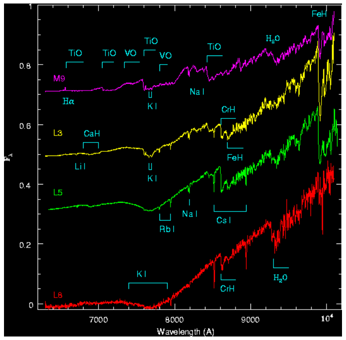
Spectral features – CH_4, no visible radiation

Y dwarfs

(not yet observed)

Temperature range - >700 K

(Predicted) Spectral features - NH_3



Brown dwarf atmospheres

Three new spectral types

OBAFGKM LTY

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Temperature range – 1300 – 2000 K
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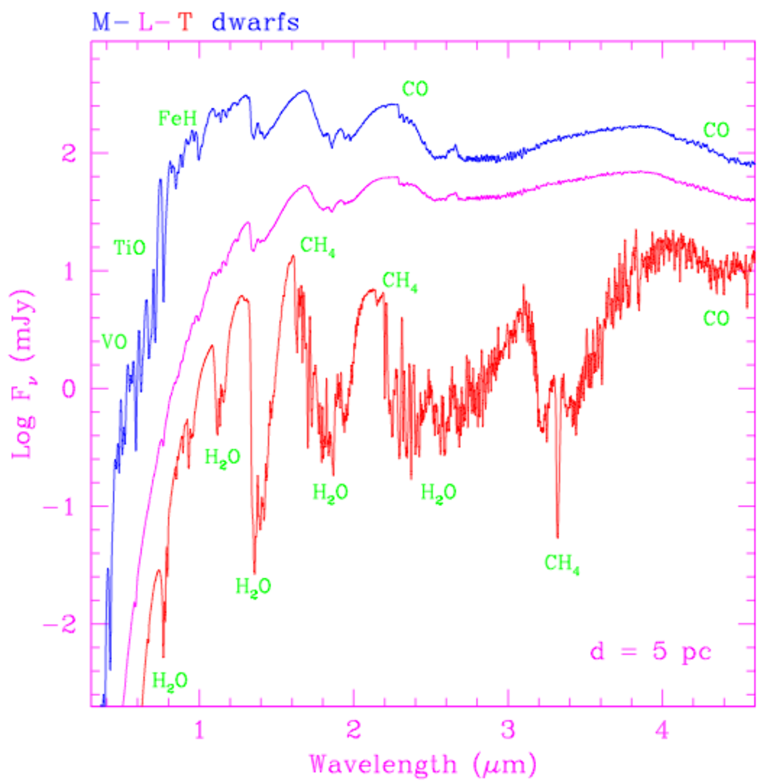

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Y dwarfs
(not yet observed)

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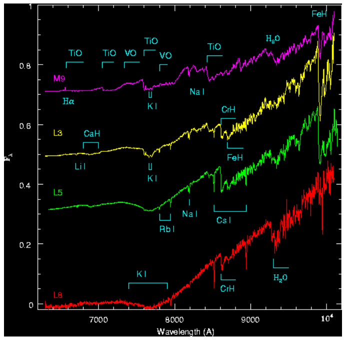

Brown dwarf atmospheres

Three new spectral types

OBAFGKM LTY

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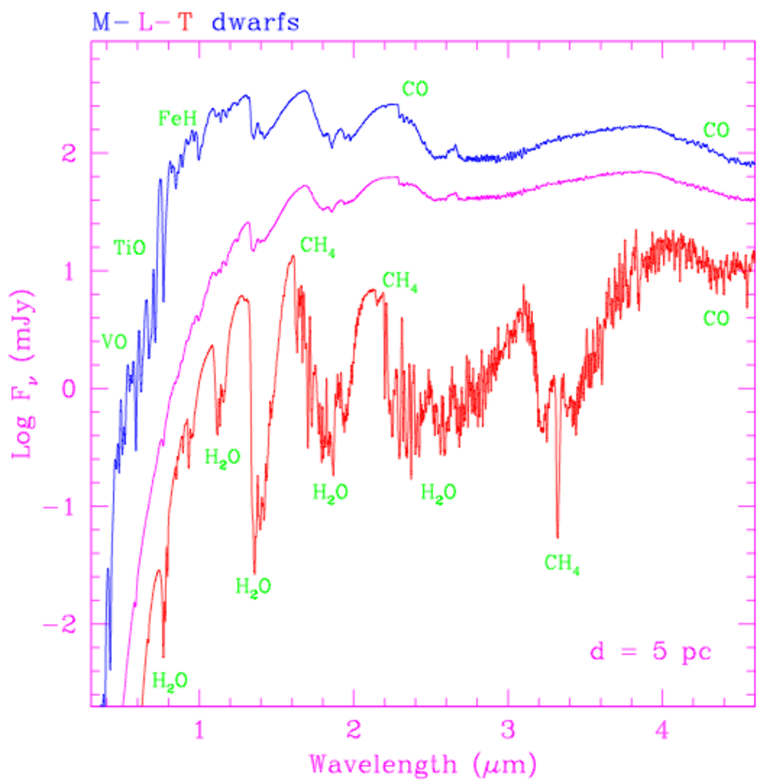


Y dwarfs
(not yet observed)

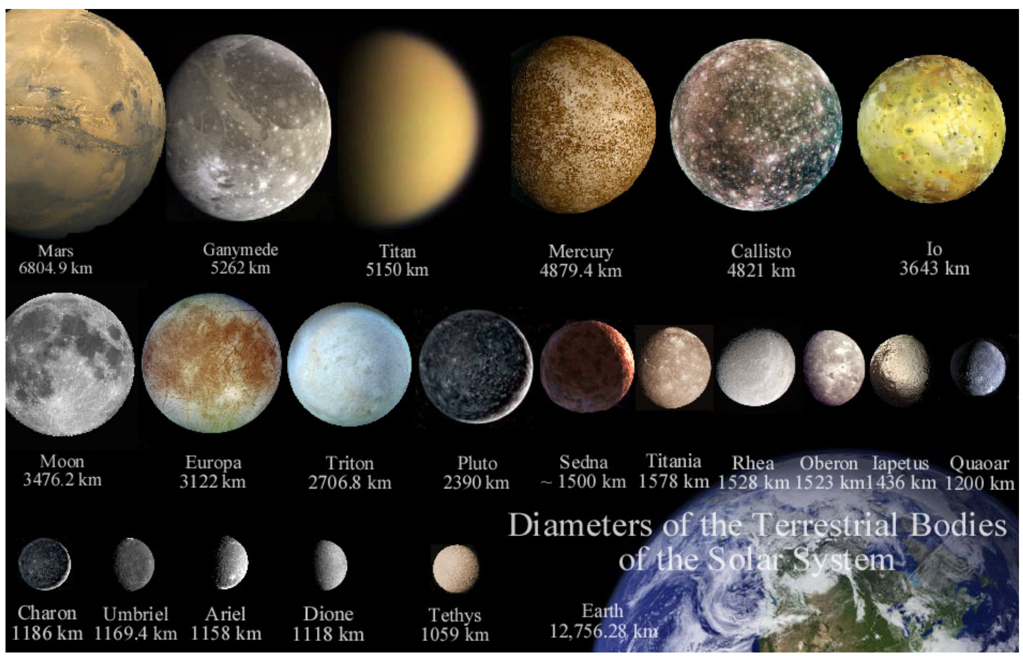
Temperature range - $T < 700$ K
(Predicted) Spectral features - NH_3

Free floating planets

As deuterium fusion is fast,
the transition between brown dwarfs and planets is blurred

Plus, the IMF does not stop at the Deuterium Burning Limit

There should be **planetary mass objects** orbiting in the Galaxy, **unbound to stars**, in much the same way that moon-sized stuff – Pluto for instance – freely orbit the Sun



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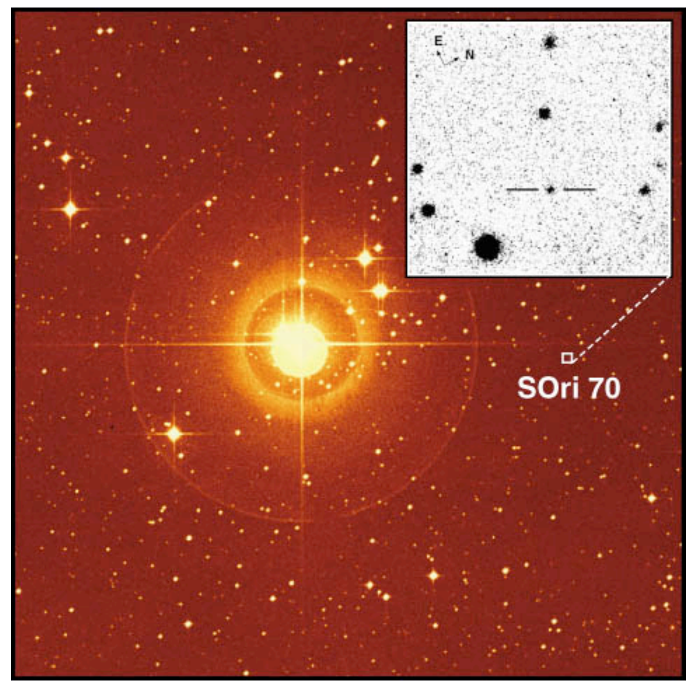
There should be **planetary mass objects** orbiting in the galaxy, **unbound to stars**, in much the same way as moon-sized stuff – Pluto for instance – freely orbit the Sun

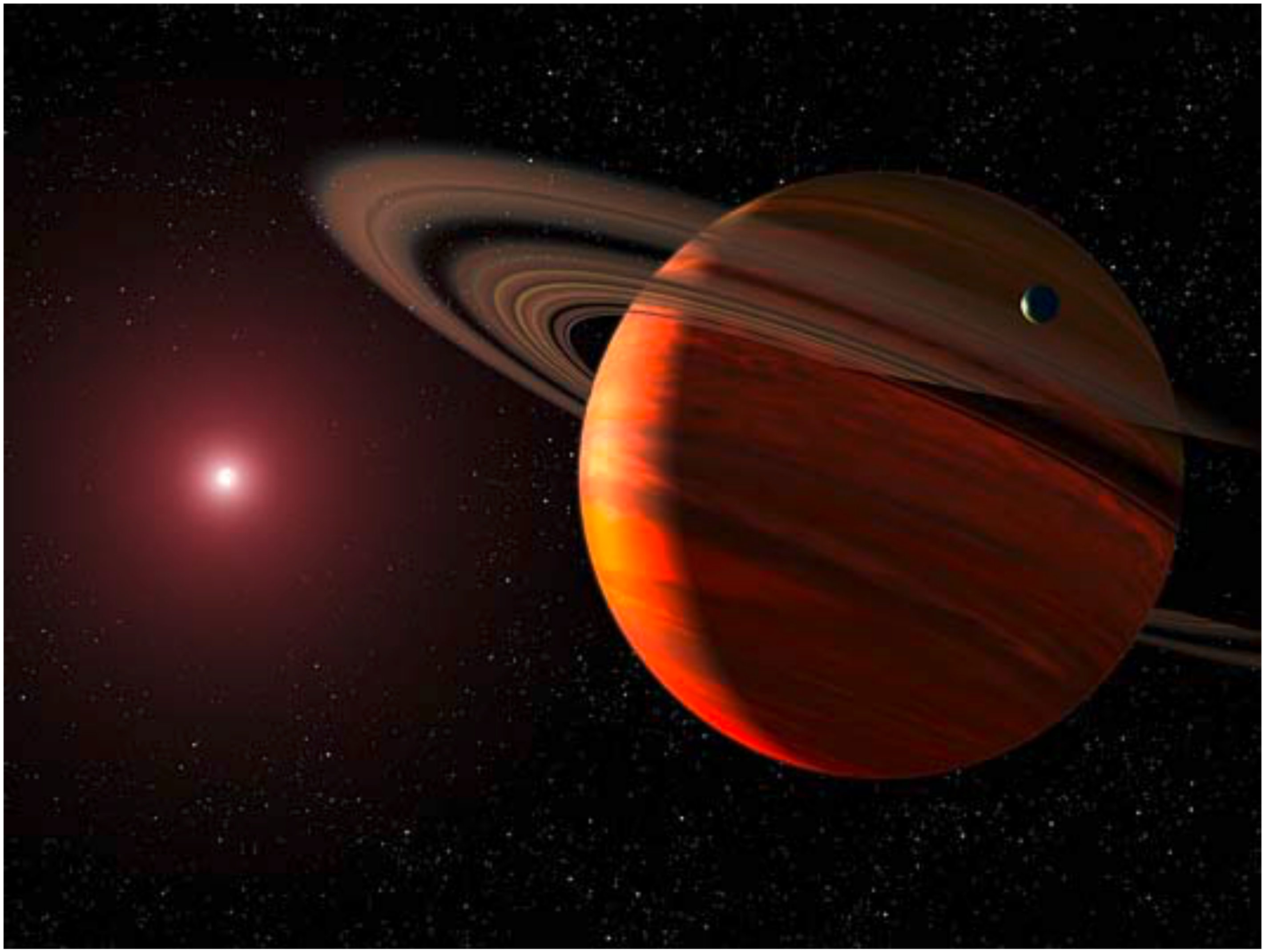
S Ori 70: best candidate.
Mass estimated in 3 M_J

Suggested names

Free floating planet
Rogue planet
Interstellar planet
Sub-brown dwarf
Planetar

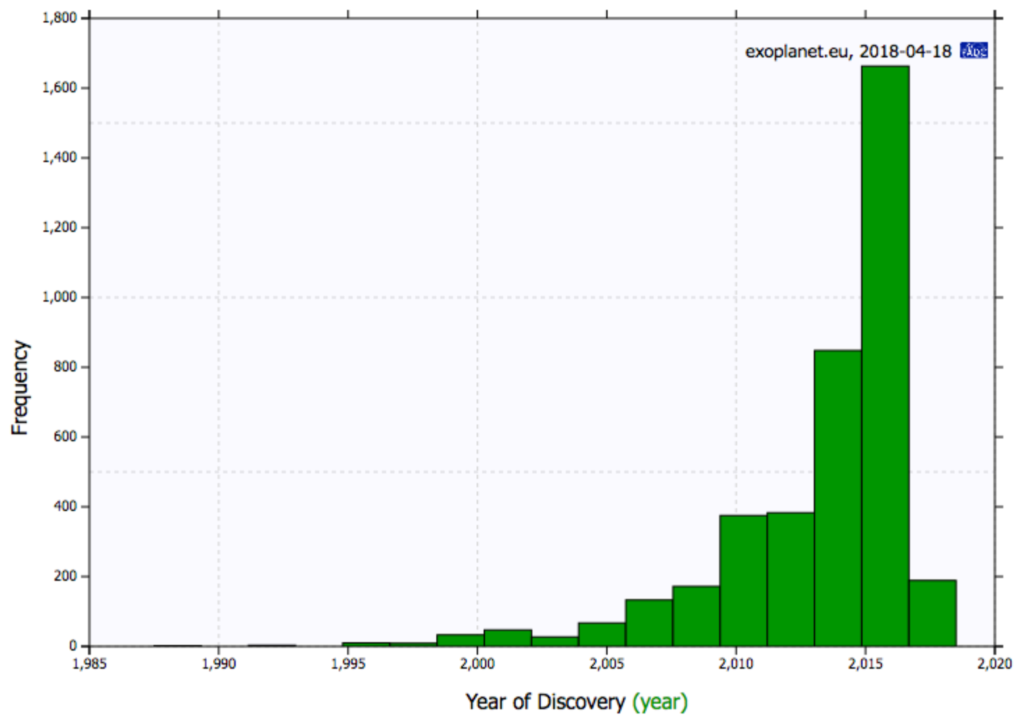


Extrasolar planets



Extrasolar planets

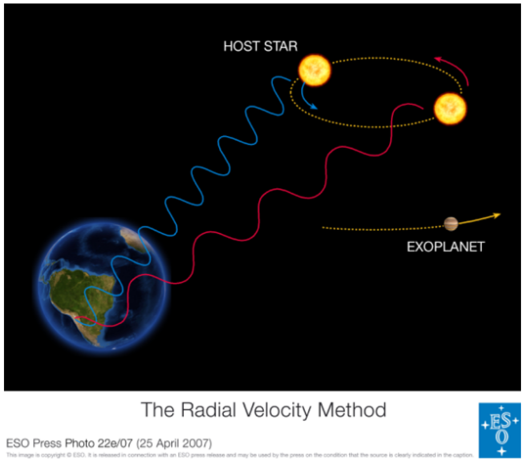
Rate of discoveries



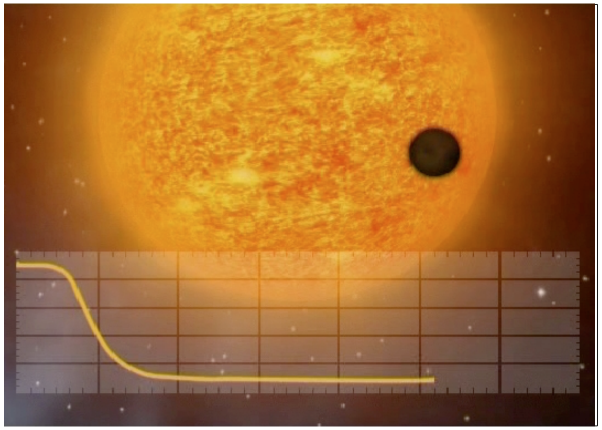
3504, and counting!

Extrasolar planets

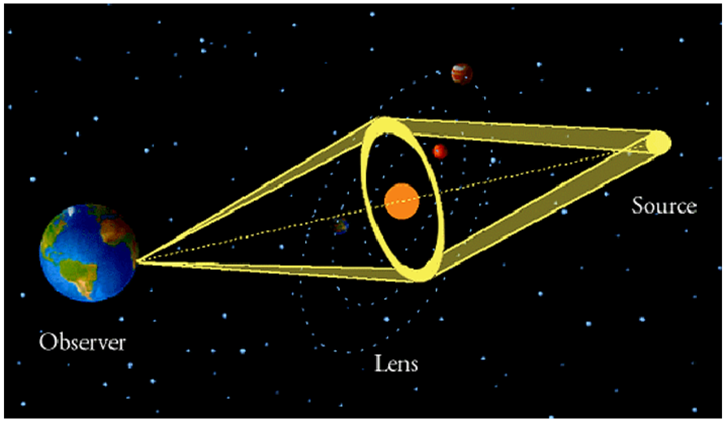
Detection methods



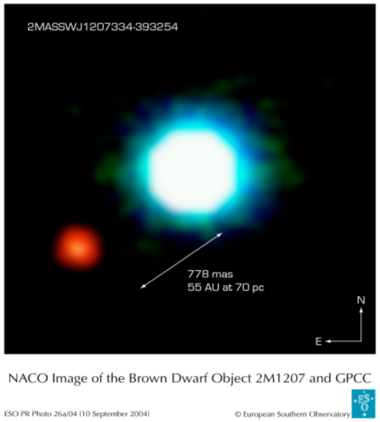
Radial Velocity



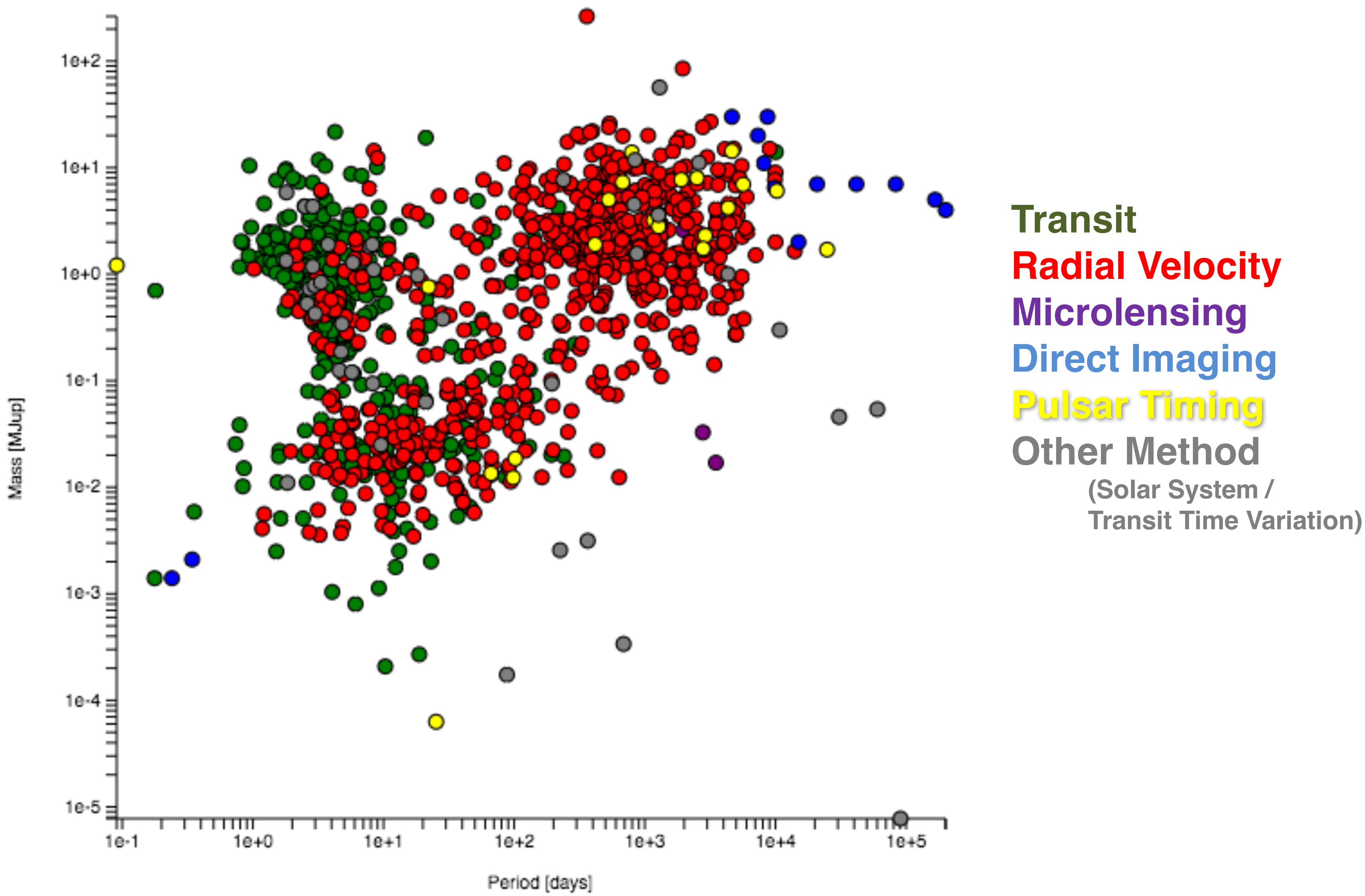
Transit



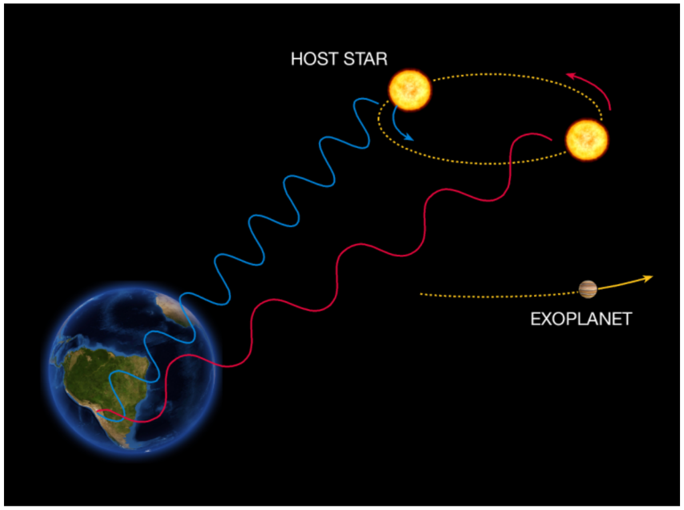
Microlensing



Direct Imaging


1e+2
1e+1
1e+0
1e-1
1e-2
1e-3
1e-4
1e-5
Mass [MJup]
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
1e+5
Period [days]
Transit
Radial Velocity
Microlensing
Direct Imaging
Pulsar Timing
Other Method
(Solar System /
Transit Time Variation)

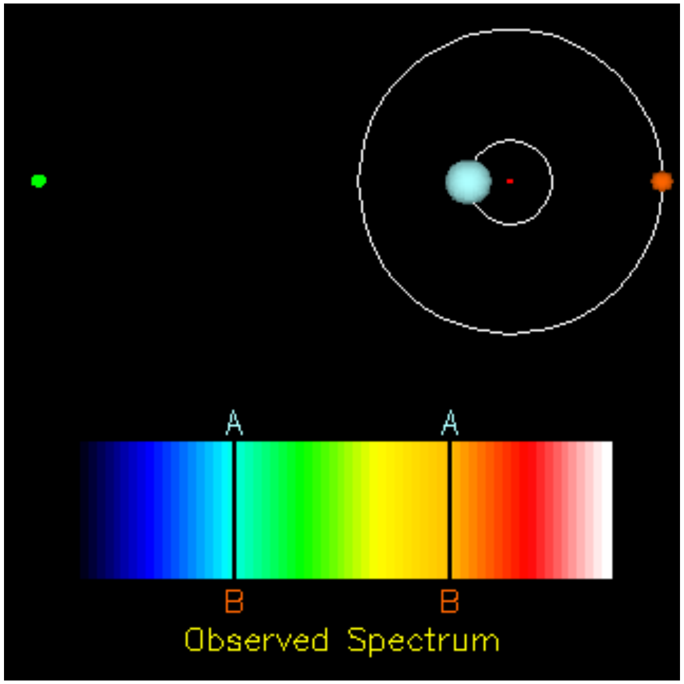
Extrasolar planets – Radial Velocity



The Radial Velocity Method

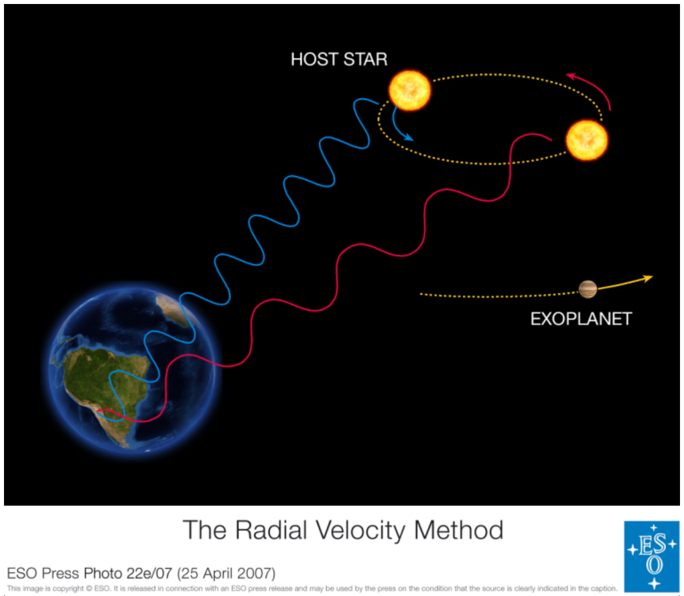
ESO Press Photo 22e/07 (25 April 2007)

Star and planet orbit a common center of mass



The star + planet system is essentially an astrometric binary

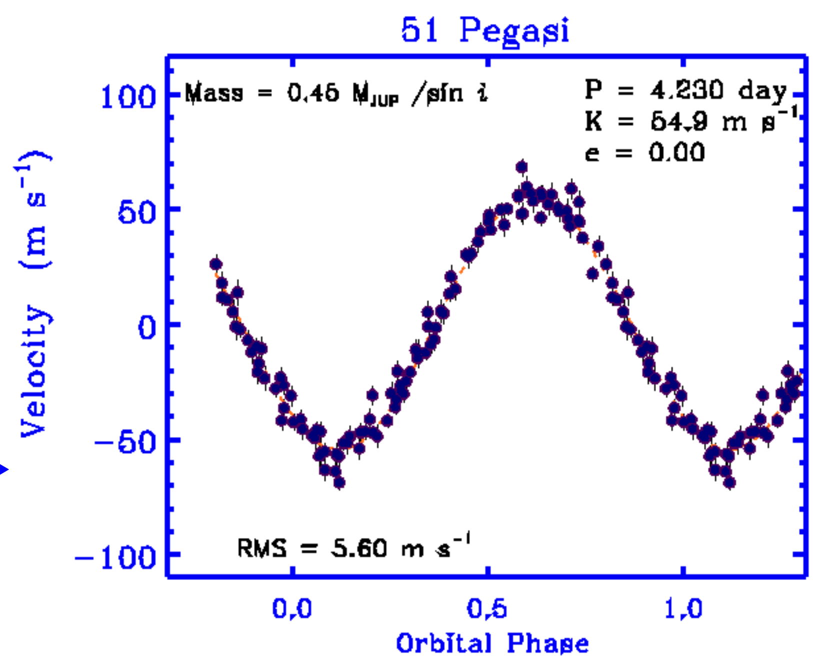
Extrasolar planets – Radial Velocity



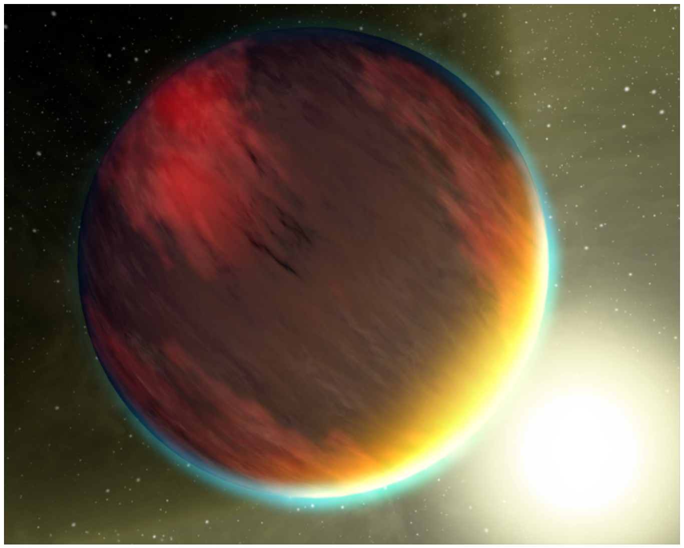
Star and planet orbit a
common center of mass

Measure radial velocity curves for thousands of stars and hope for the best

The first planet discovered
around a main sequence star
51 Peg b

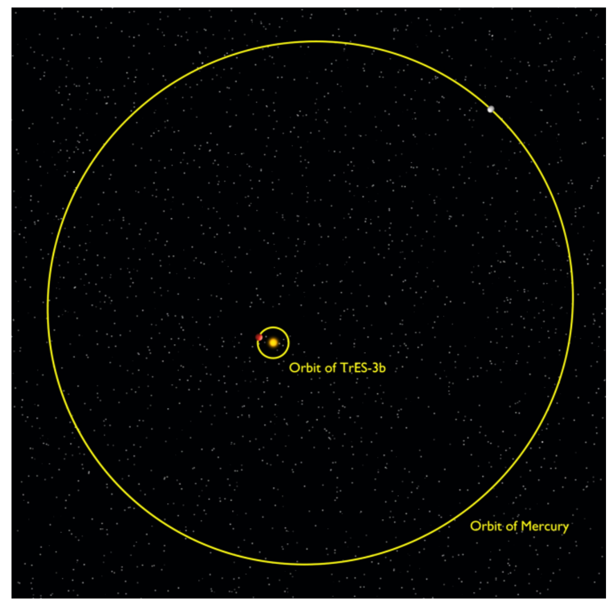


Extrasolar planets – Radial Velocity



Biased towards large wobbles

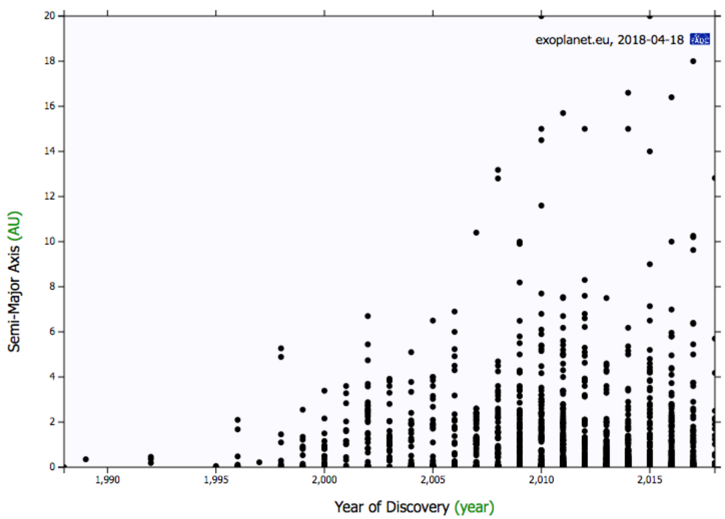
High velocities (big sinal)
Short periods (No need for long monitoring)

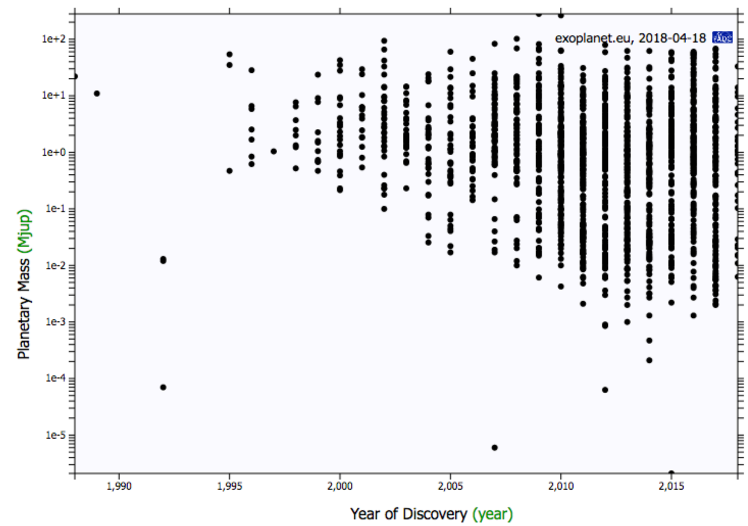


The technique preferentially finds
big planets close to their stars
(aka ***Hot Jupiters***)

Extrasolar planets – Radial Velocity

In time...

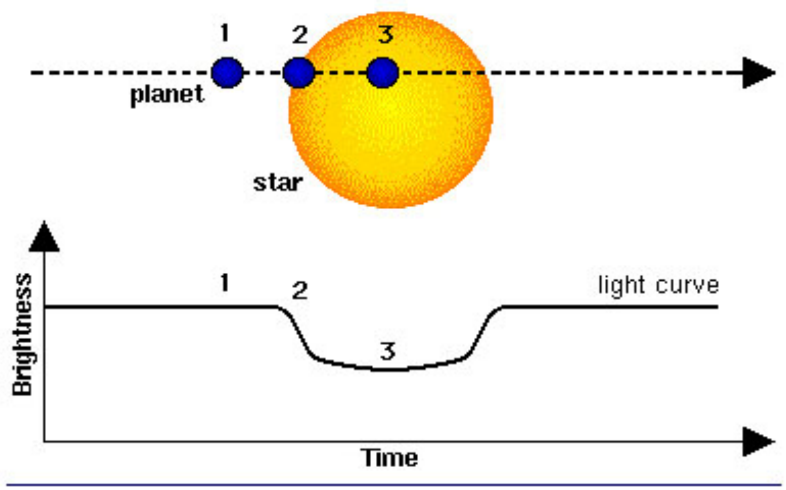




.... we have access to wider orbits...

.... and the sensitivity of the techniques increased, allowing for the detection of lower mass planets.

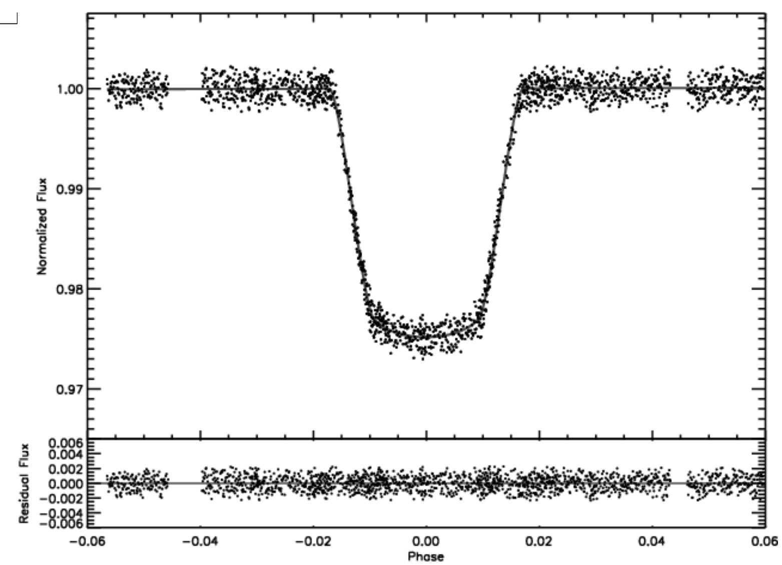
Extrasolar planets - Transit



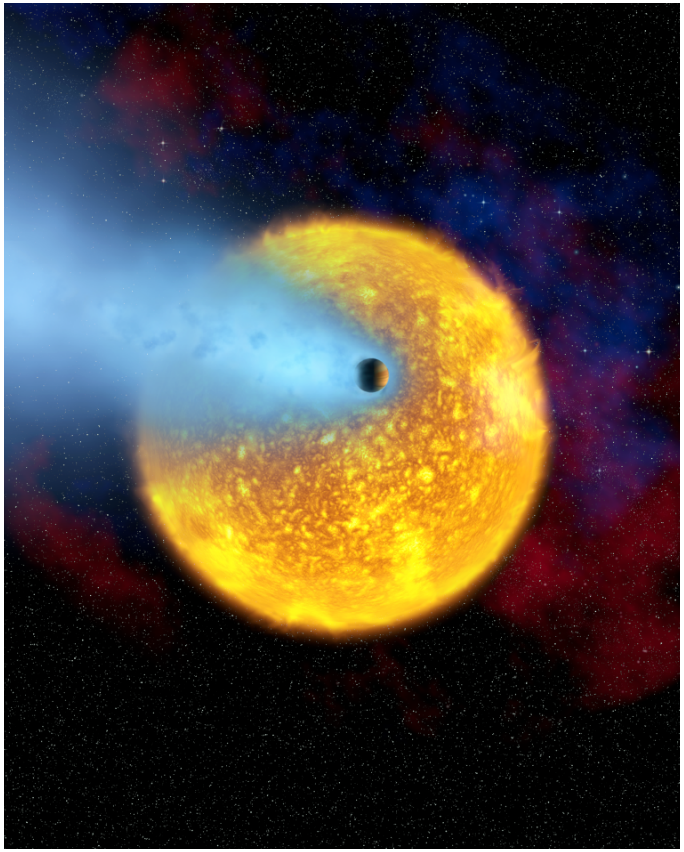
The planet transits the star if the orientation of the orbit is favorable

A Jupiter-size planet produces a 0.02 magnitude dip. Detectable!!

Measure light curves for thousands of stars and hope for the best

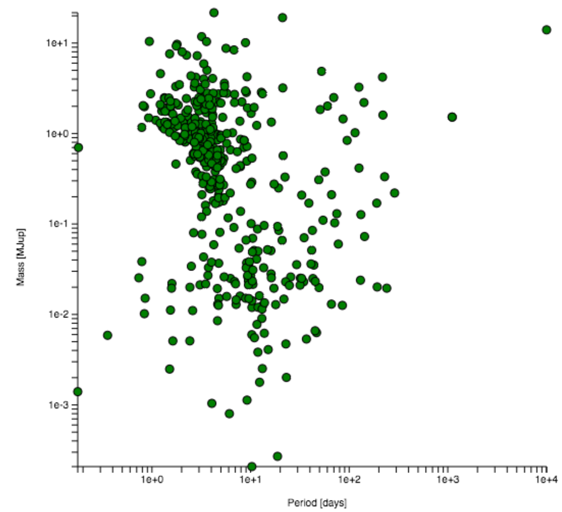


Extrasolar planets - Transit



Probability of favorable orientation
depends on the

$$\frac{\textbf{Size of the star}}{\textbf{Size of the orbit}}$$

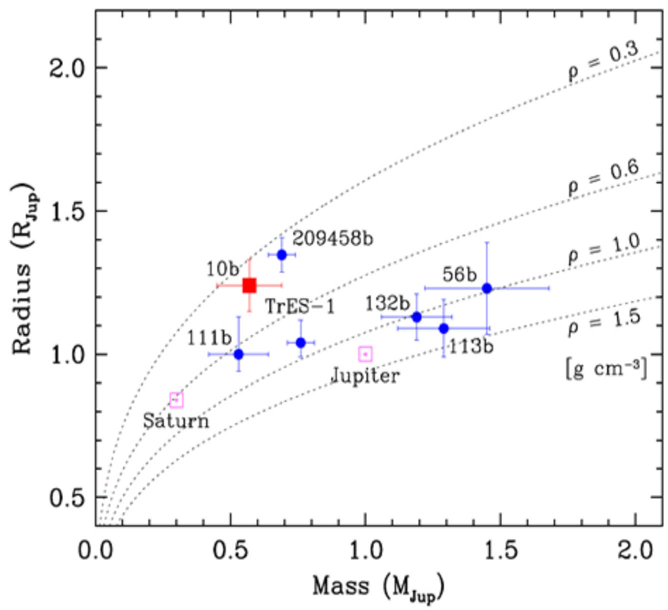


Also biased towards short period planets
(small orbits)

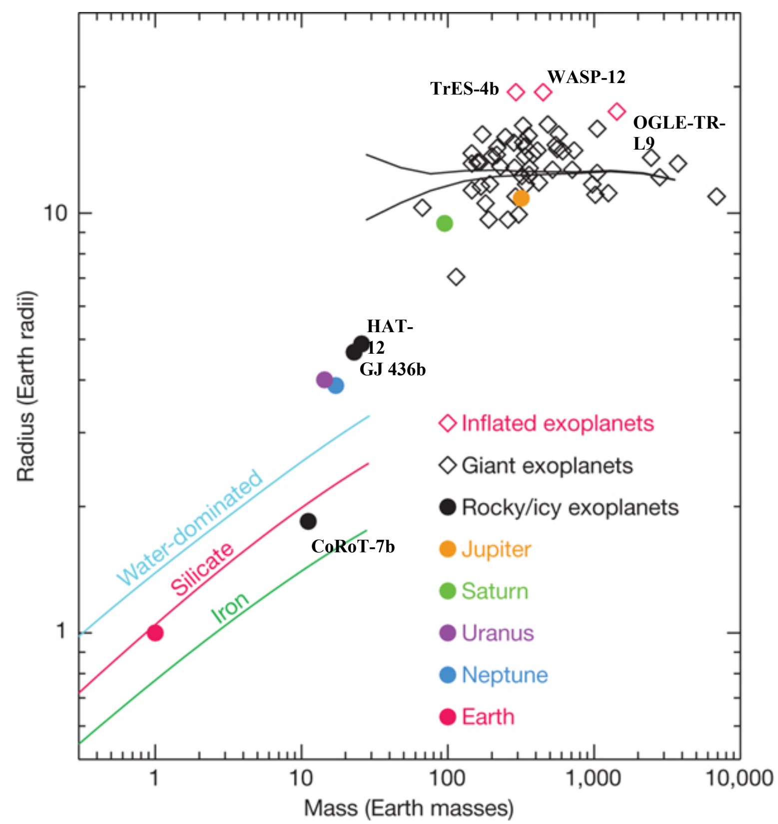
Extrasolar planets - Transit

Transits allow for determination of both mass and radius!

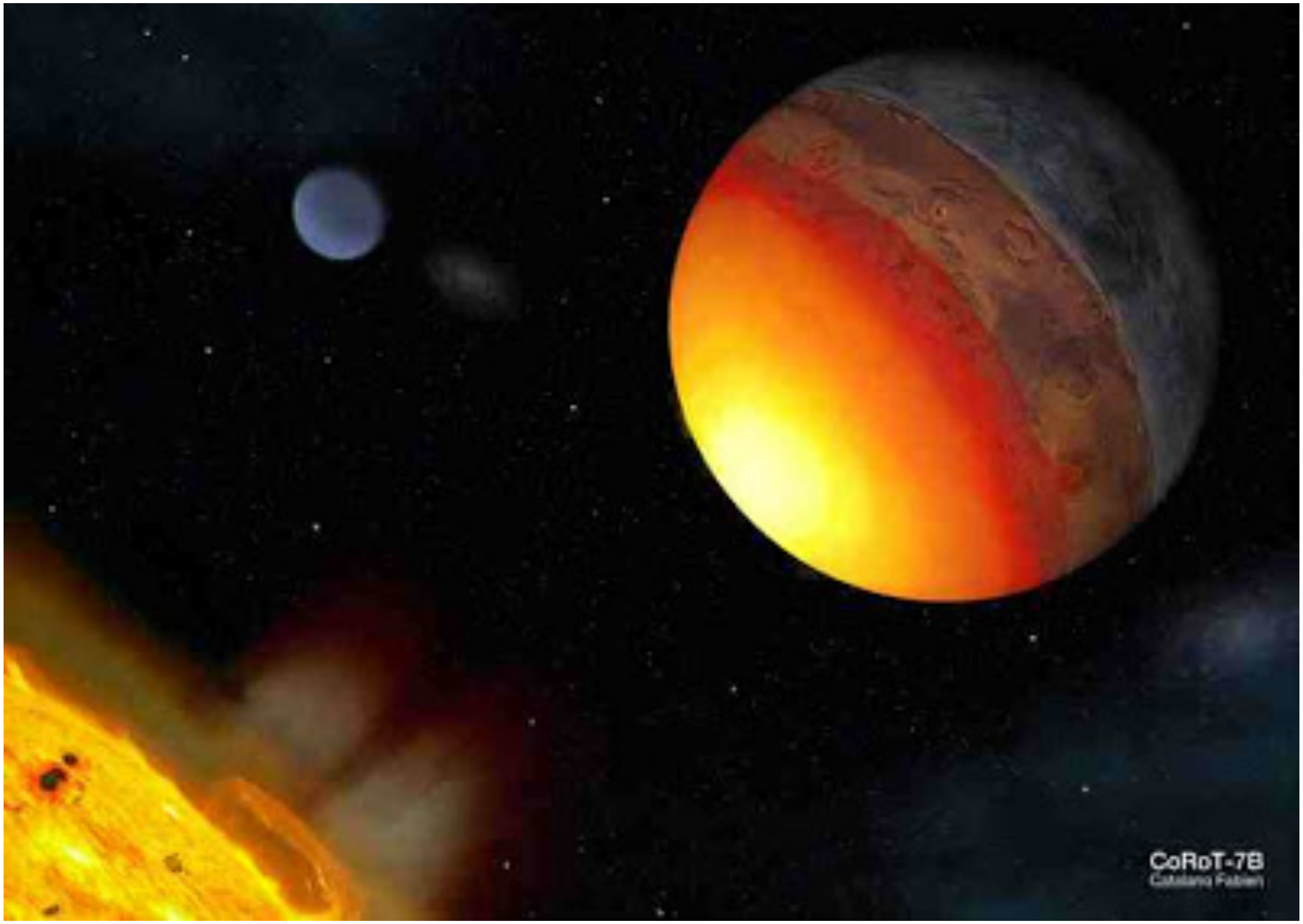
We can measure **densities**...



... and make educated guesses about **composition and structure** of the planets.

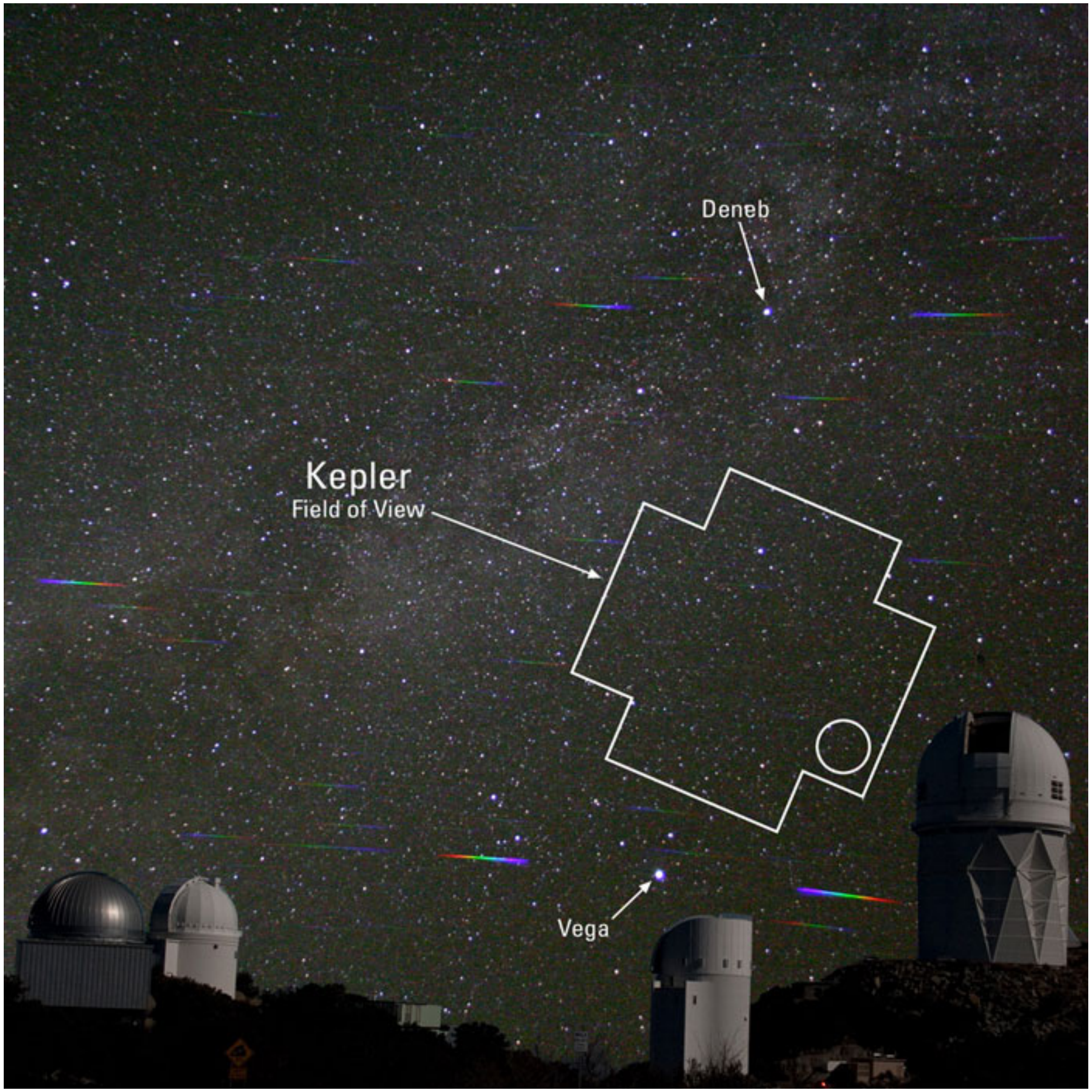


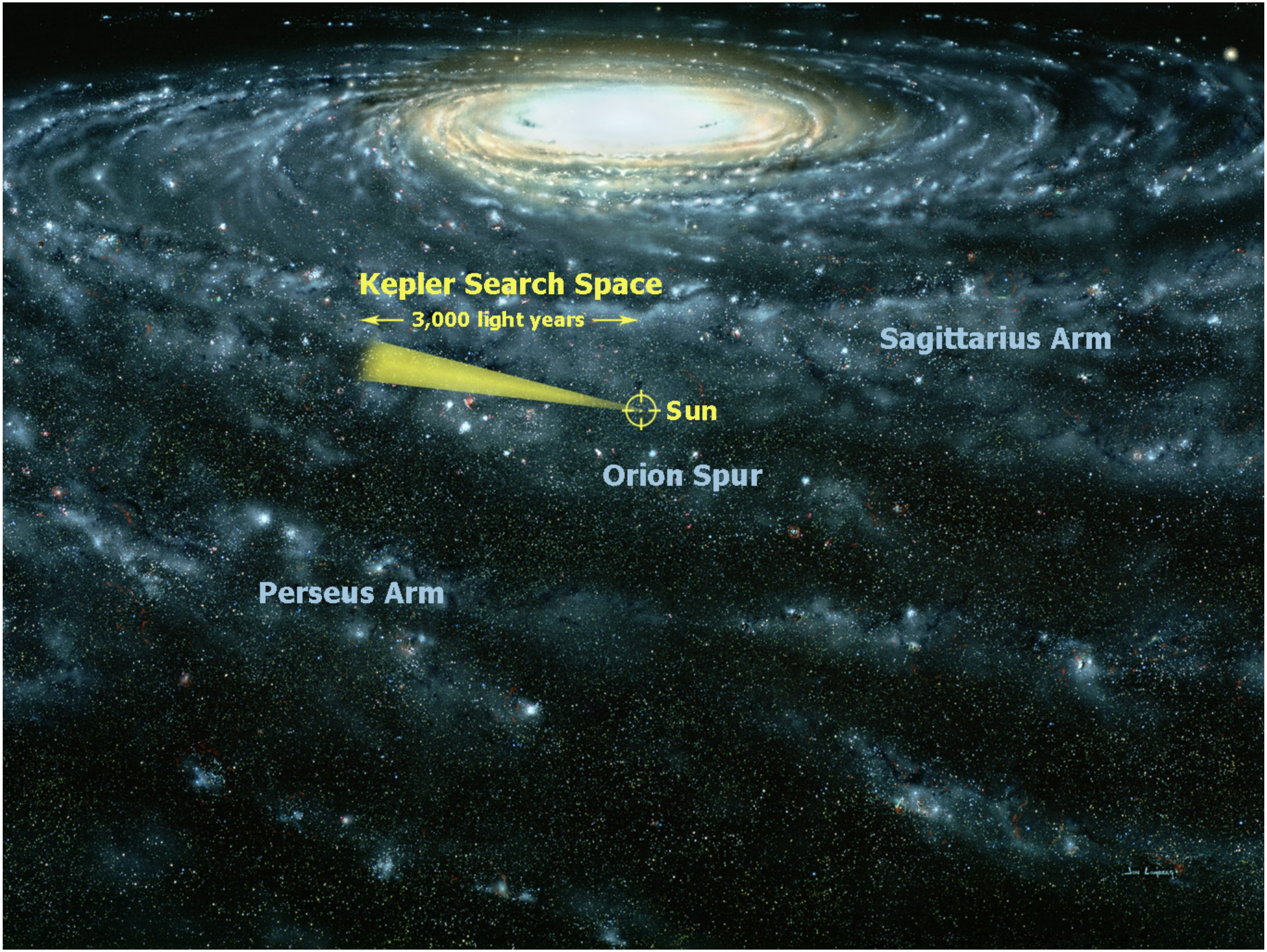
The first confirmed rocky exoplanet
CoRoT-7b



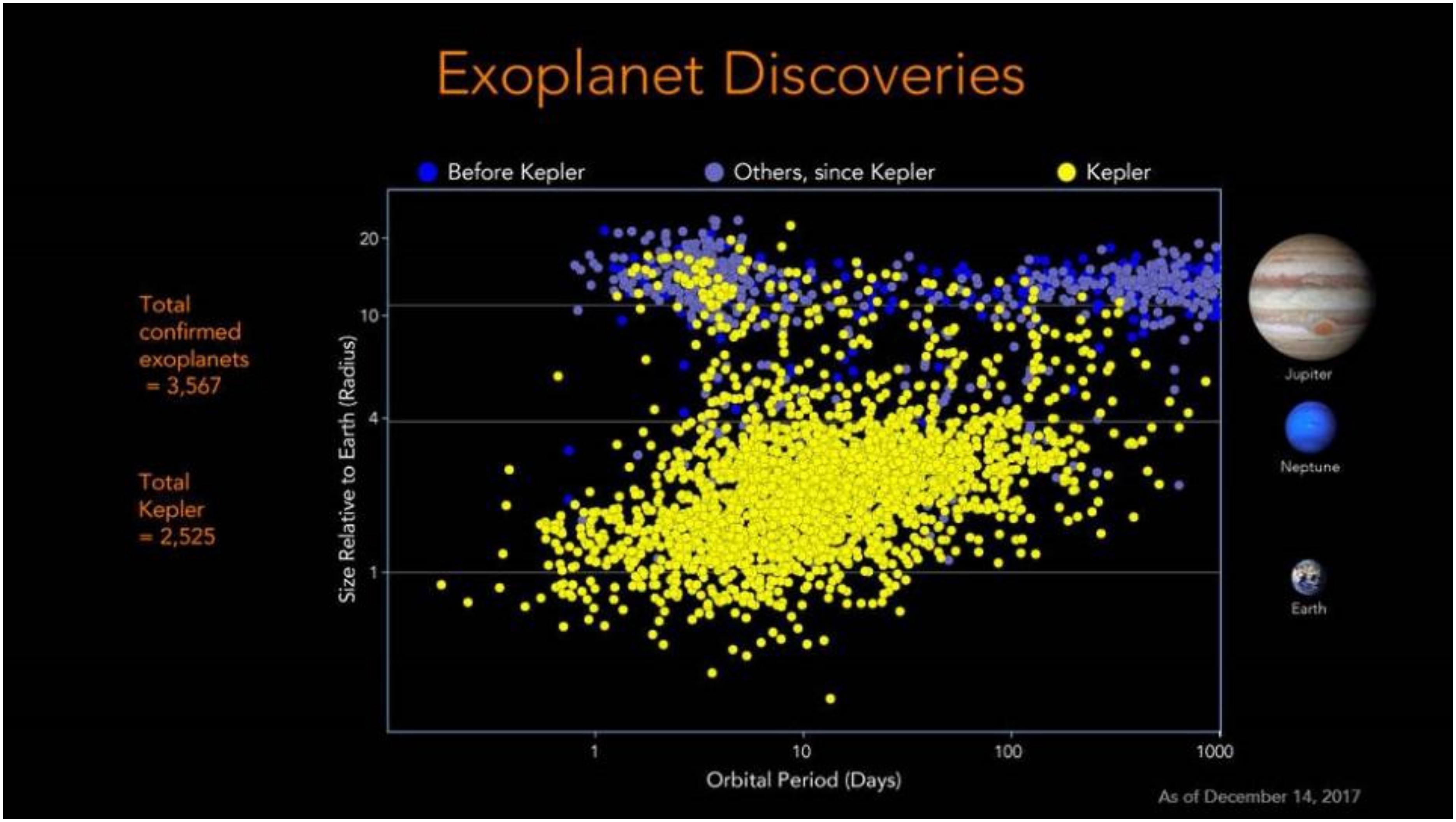
CoRoT-7b

Game Changer – The *Kepler* mission



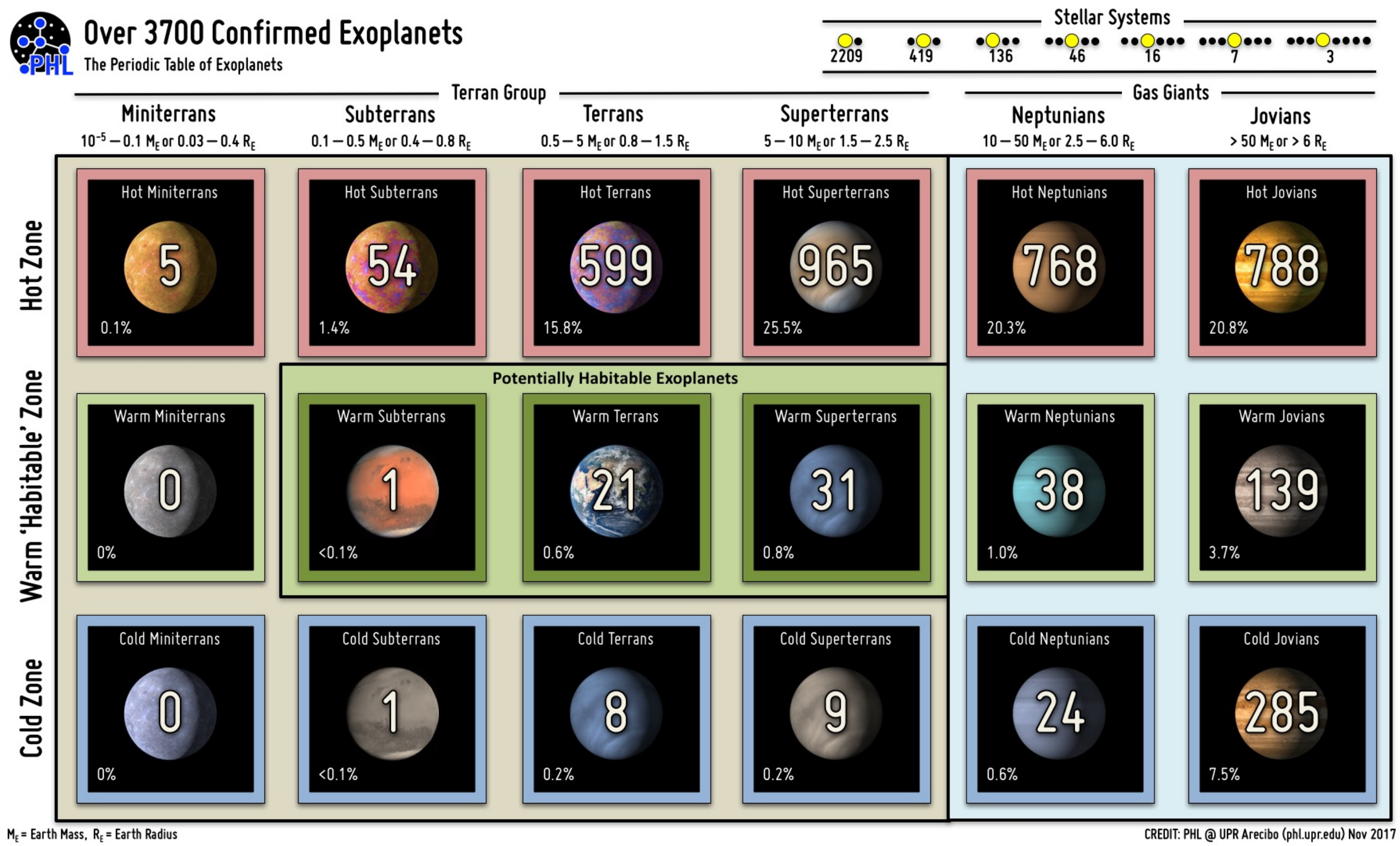


Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm



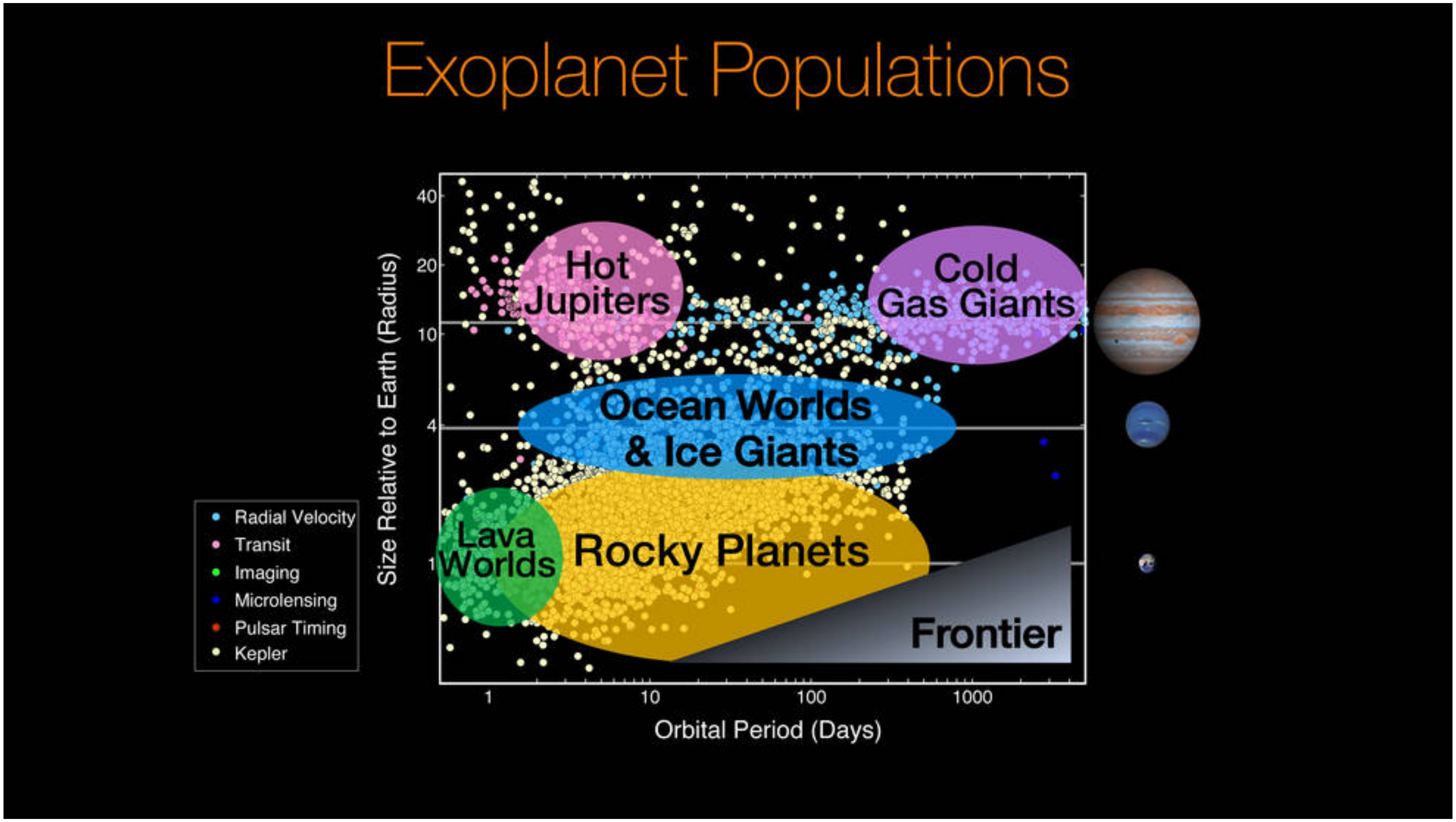
Exoplanet Discoveries
Before Kepler
Others, since Kepler
Kepler
Total confirmed exoplanets = 3,567
Total Kepler = 2,525
Size Relative to Earth (Radius)
20
10
4
1
1
10
100
1000
Orbital Period (Days)
Jupiter
Neptune
Earth
As of December 14, 2017

The “periodic table” of planets

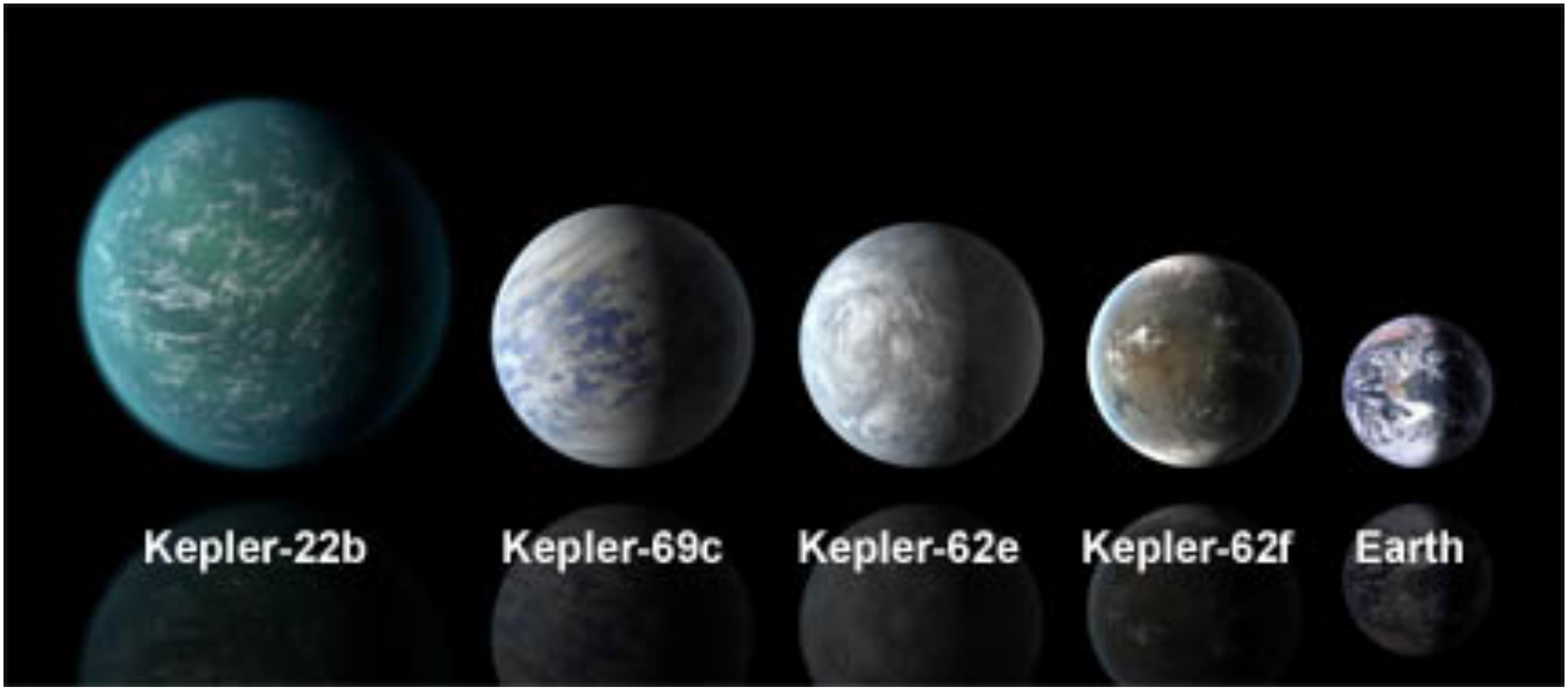


Hot Super-Earths are the most common type of planet

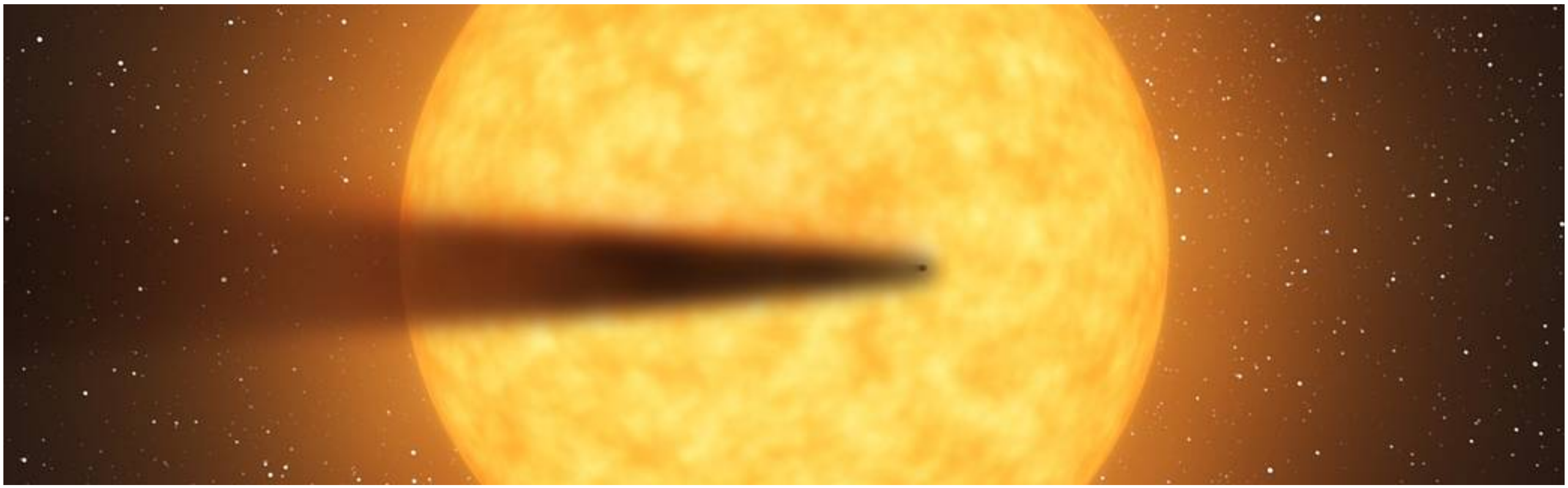
New types of planets



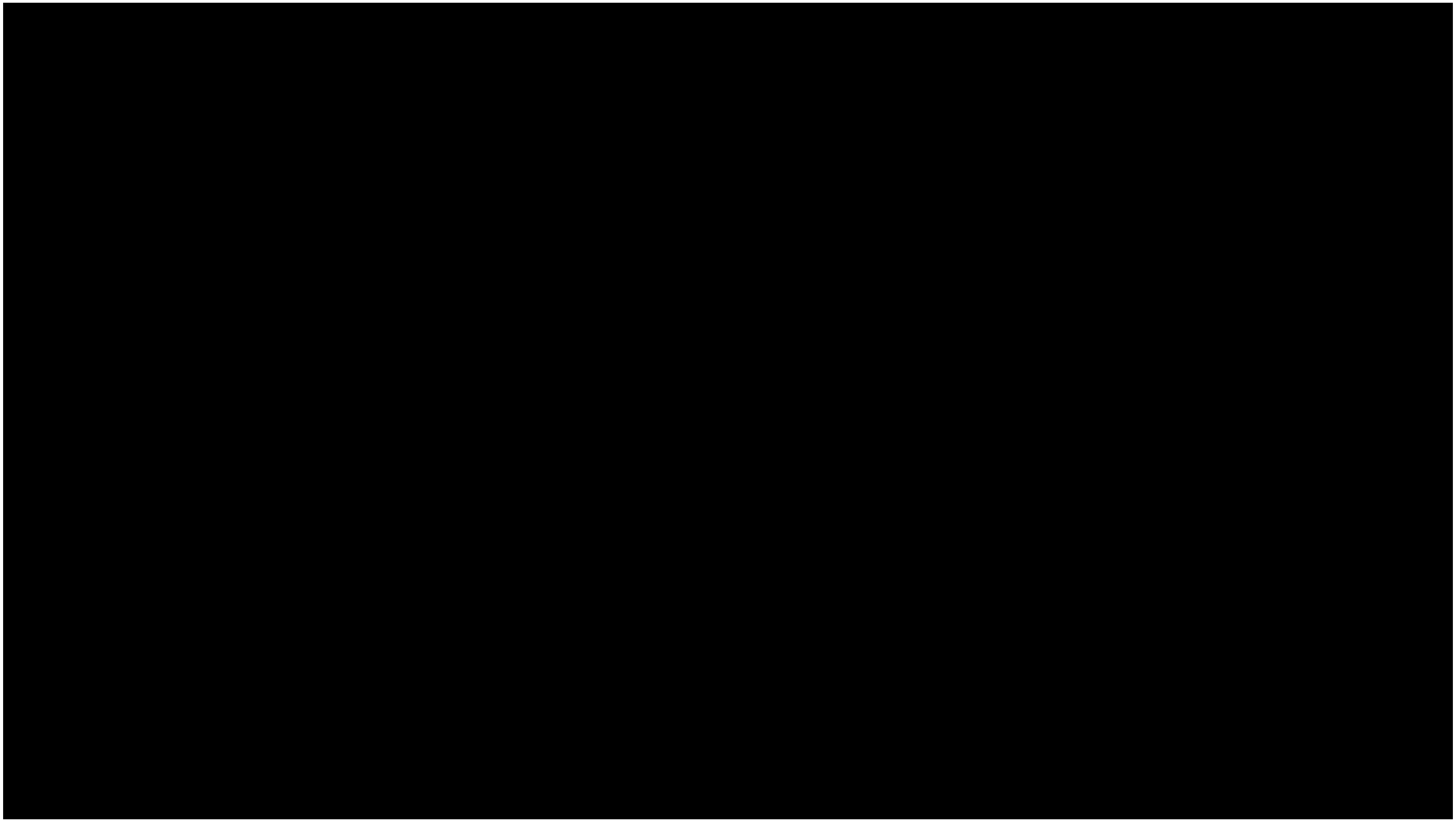
Super-Earths and Ocean Planets



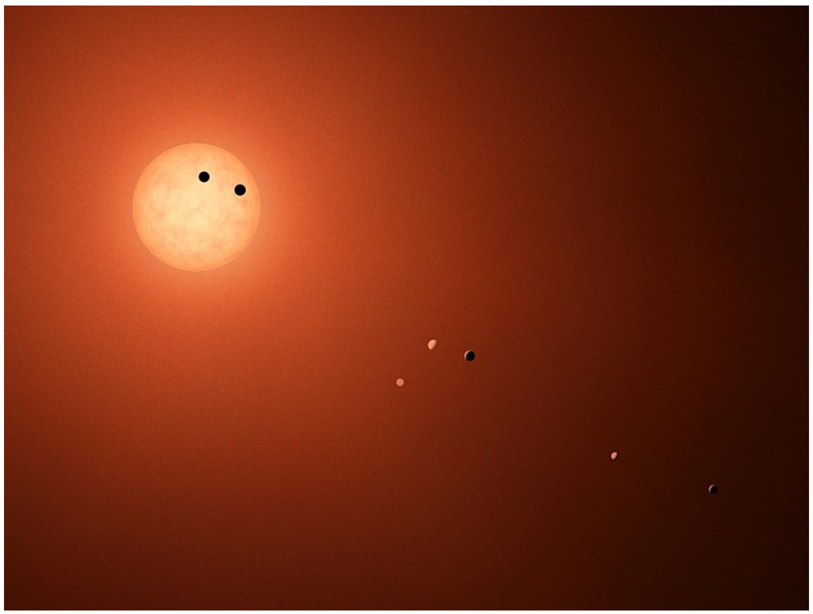
Evaporating Planet

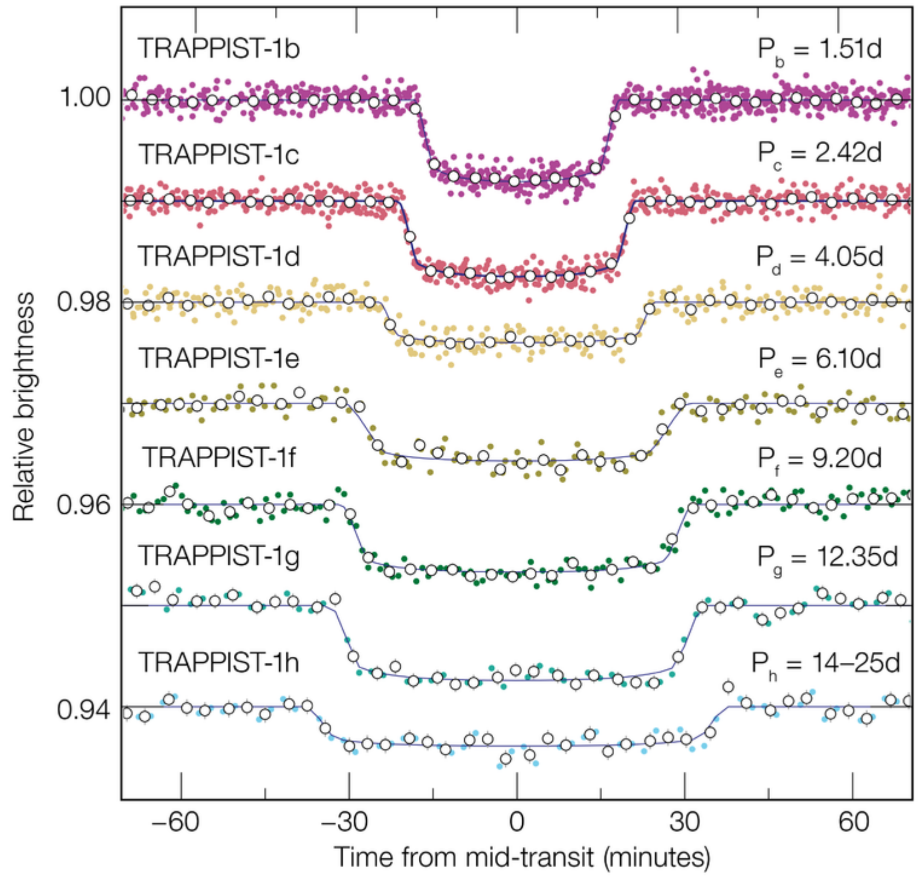


Transit Time Variation

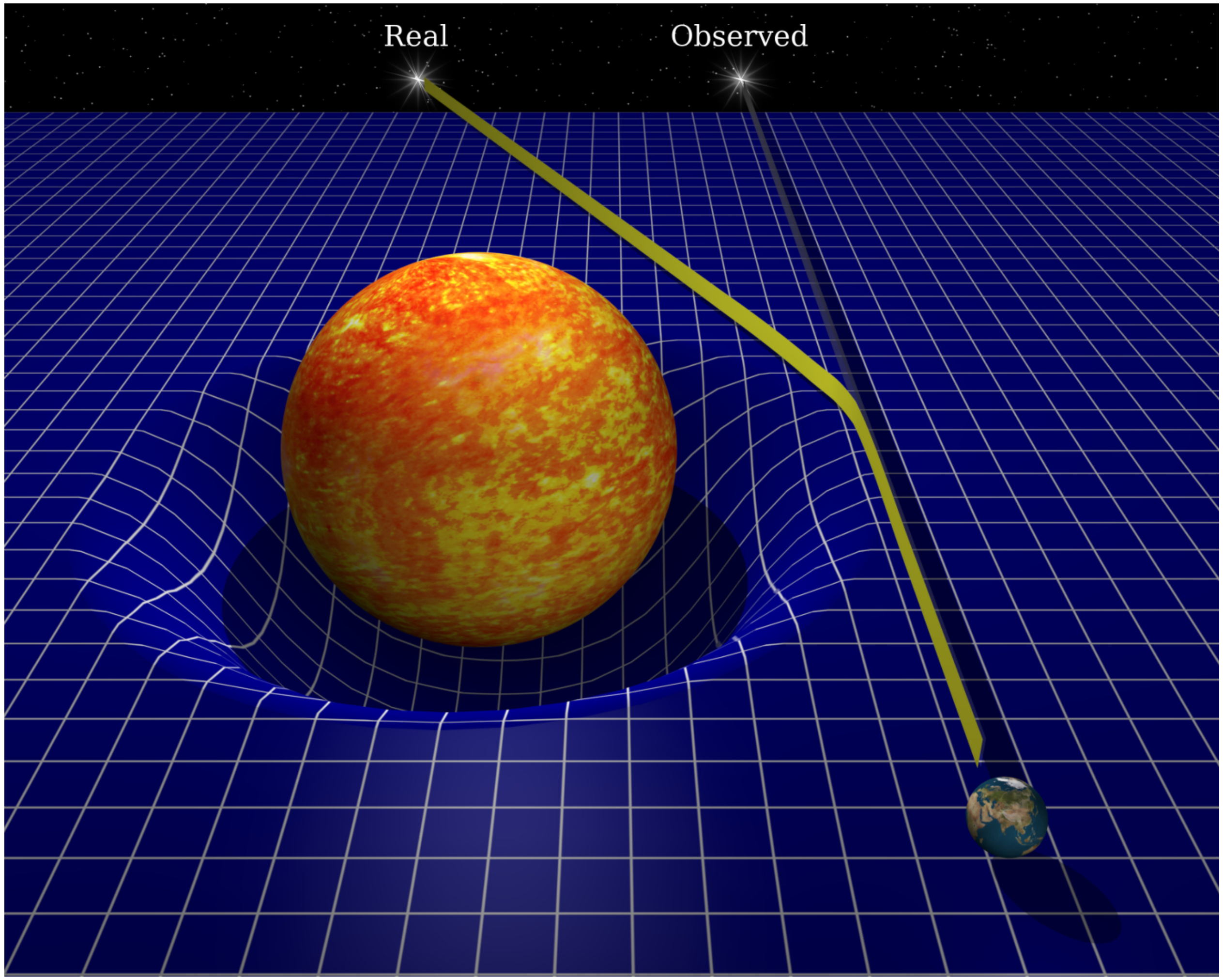


Recent results – Trappist system





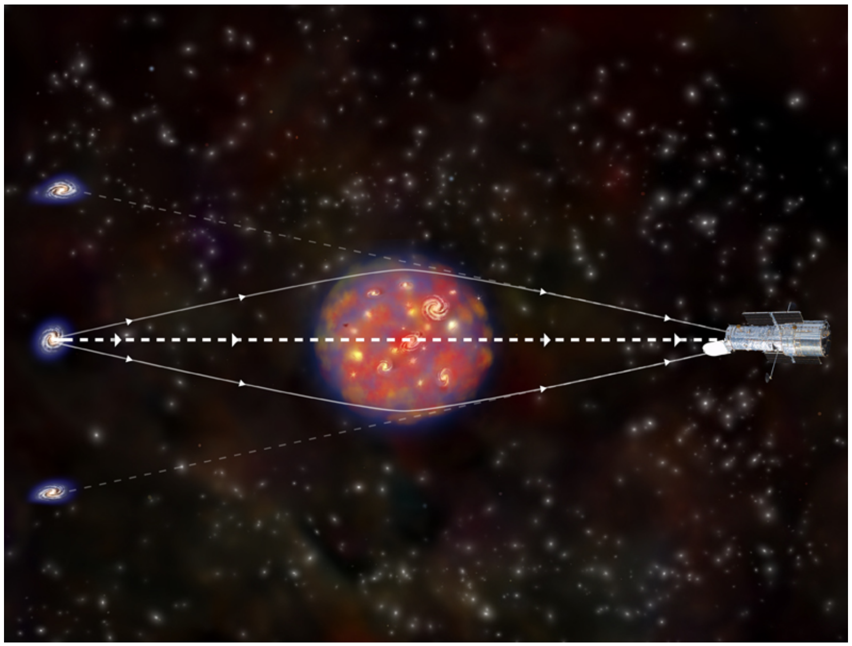
A little General Relativity

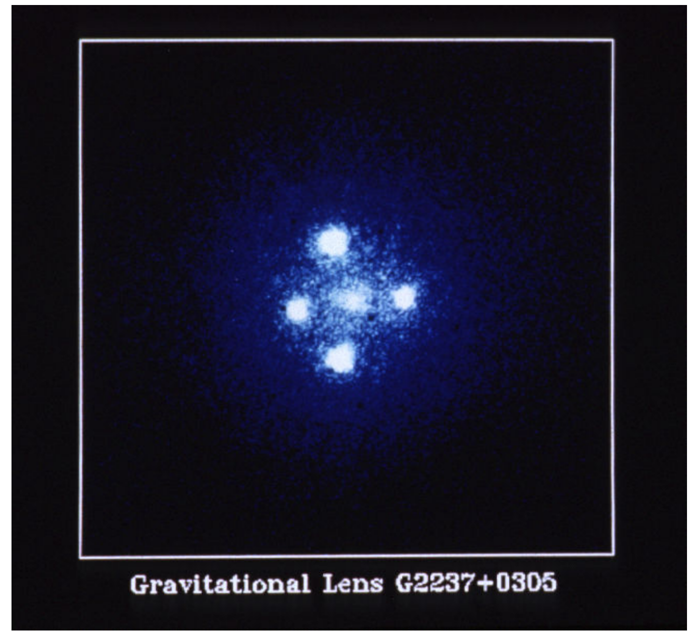


Gravity curves space, bending lightrays

"Mass tells Space how to bend, Space tells Mass how to move"

Gravitational Lensing

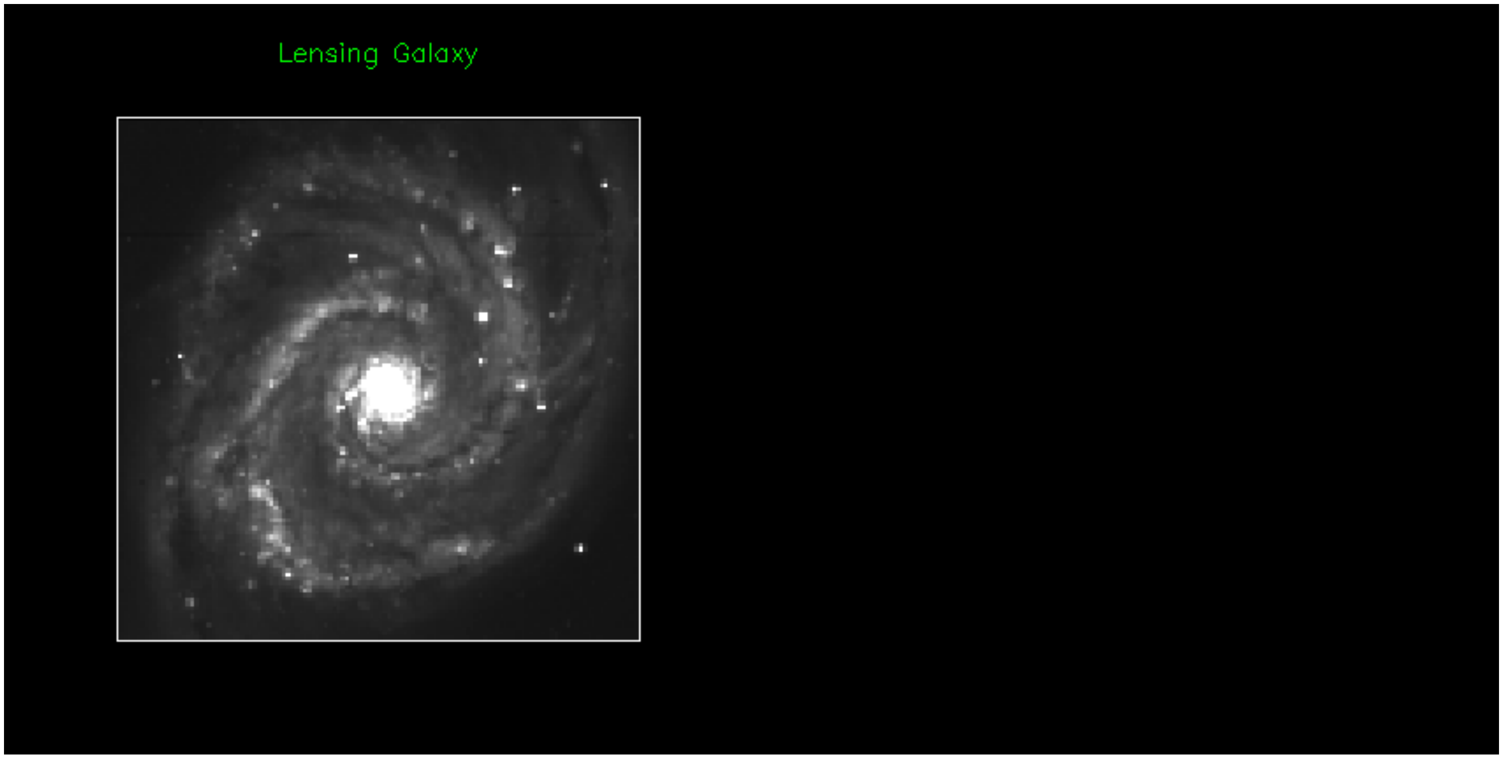




Gravity curves space, bending lightrays

We see multiple images of a lensed object.

Gravitational Lensing



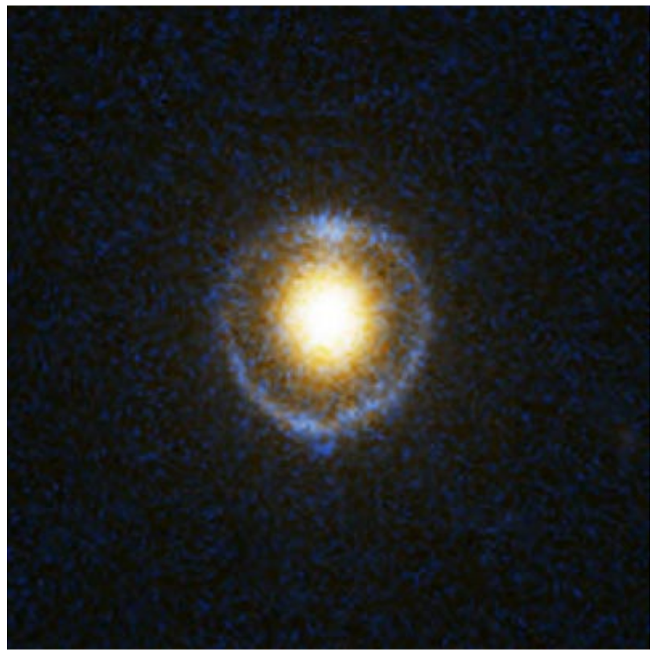
Gravitational Lensing

Lensing by a galaxy cluster

Multiple Arcs

Gravitational Lensing

Under perfect alignment, we see an
Einstein Ring



Gravitational Lensing

Under perfect alignment, we see an
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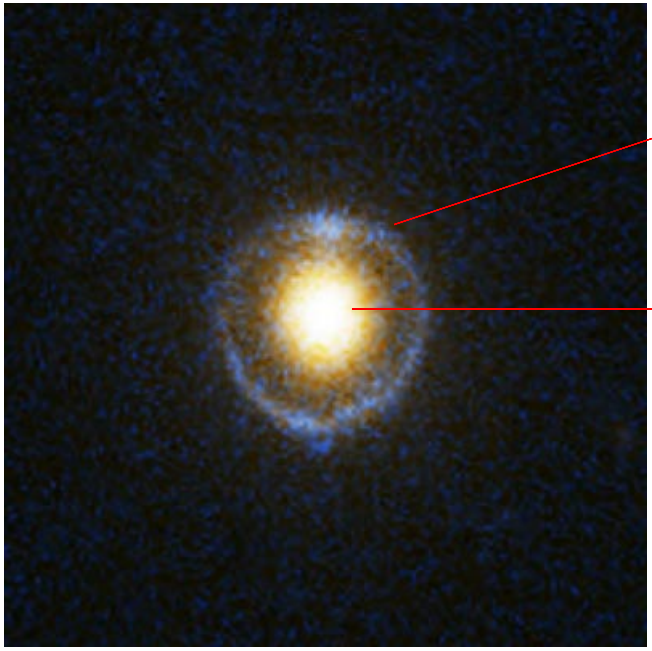
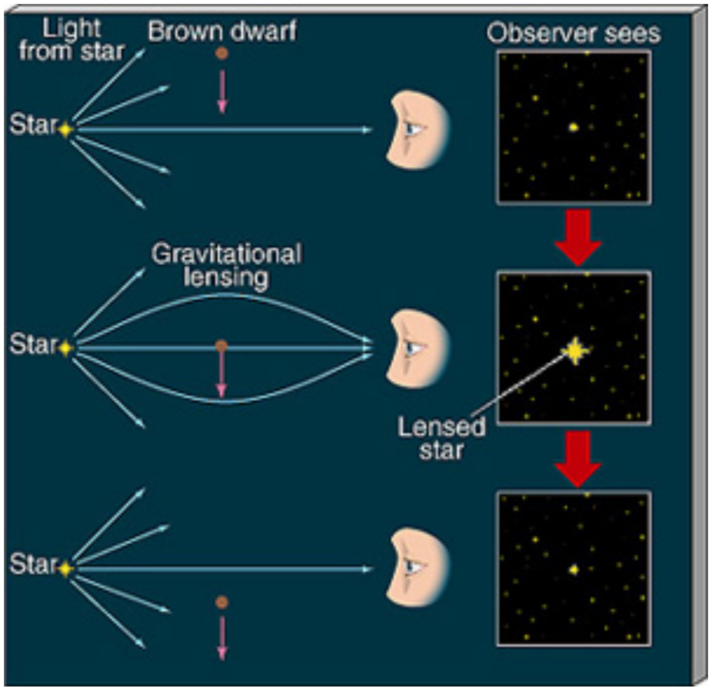


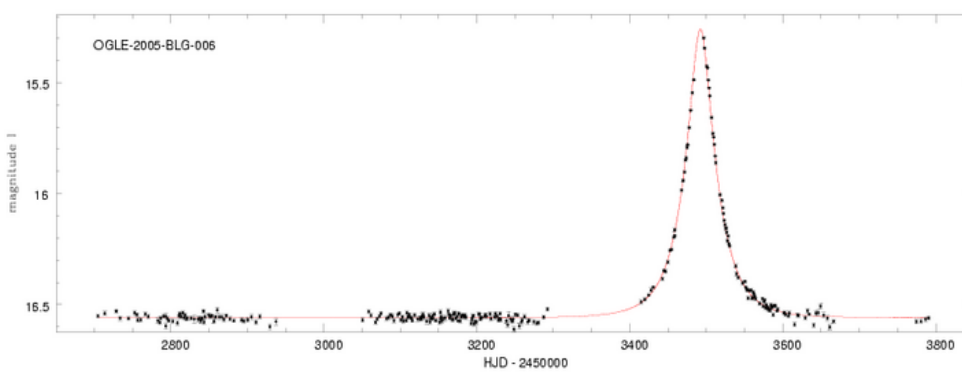
Microlensing



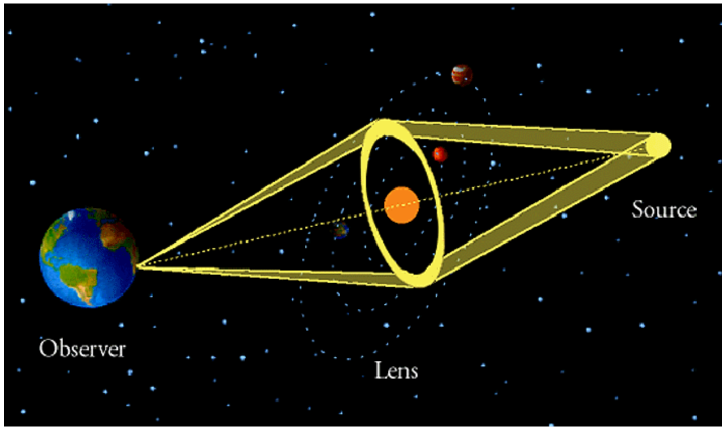
Microlensing
is a gravitational lensing event
produced not by a galaxy but by a
star or substellar object

We do not resolve the multiple images:
They all appear blurred

The lensing event is seen as a magnification of the lensed star.

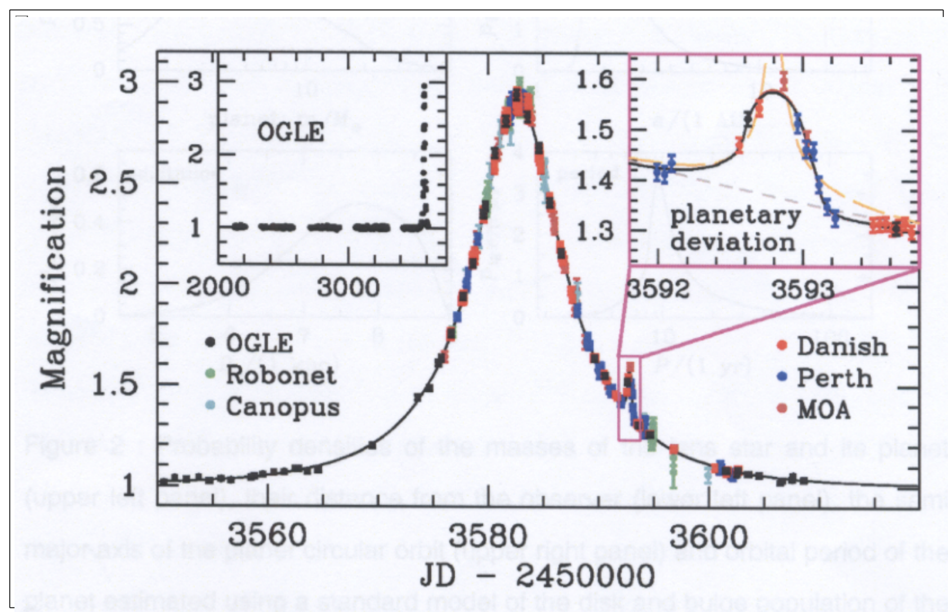


Extrasolar planets - Microlensing

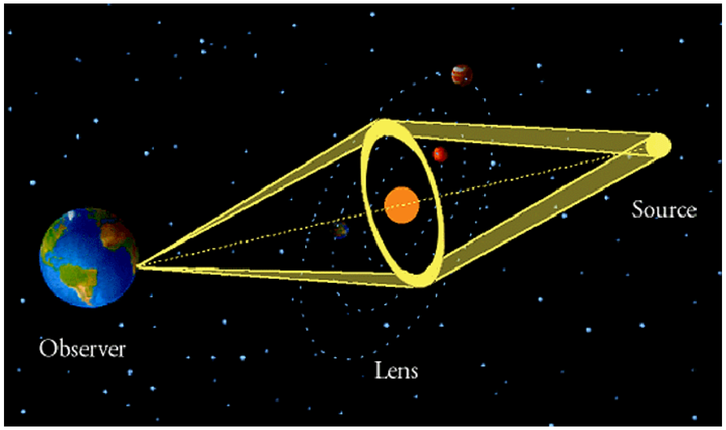


A planet around a lens star will produce a secondary lensing event

Monitor thousands of stars and hope for the best



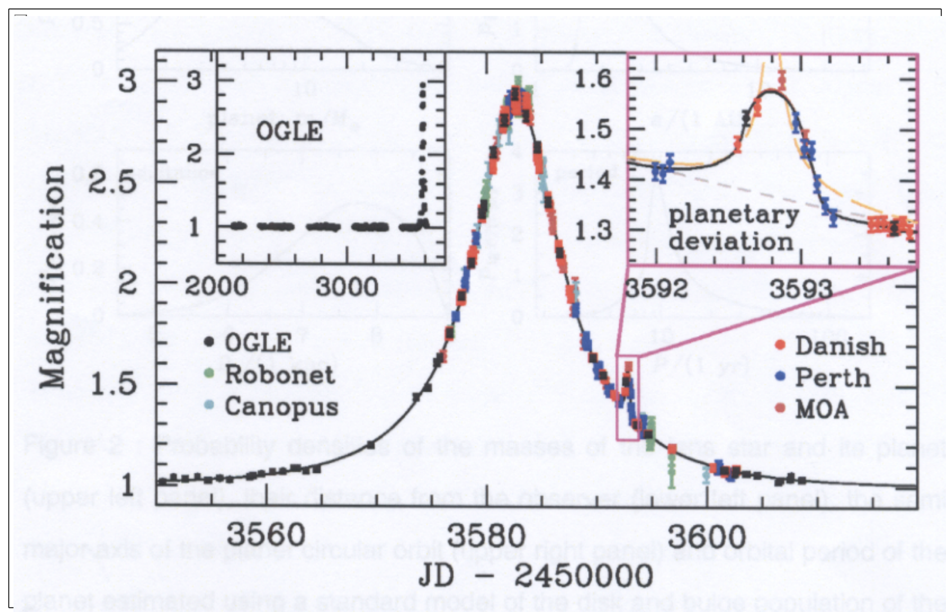
Extrasolar planets - Microlensing



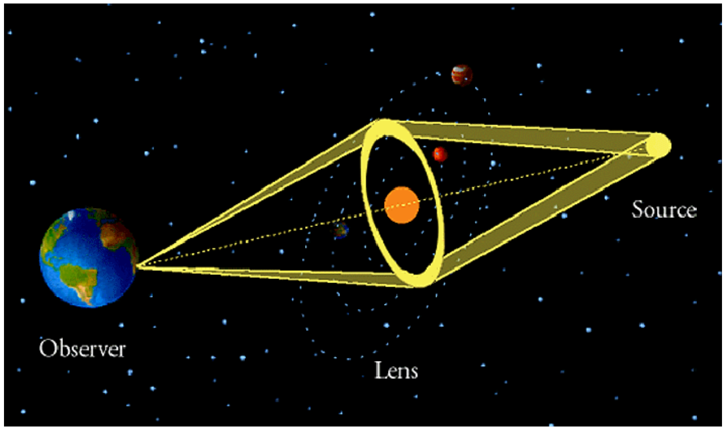
A planet around a lens star will produce a secondary lensing event

Monitor thousands of stars and hope for the best

Biased towards low mass stars (why?)



Extrasolar planets - Microlensing



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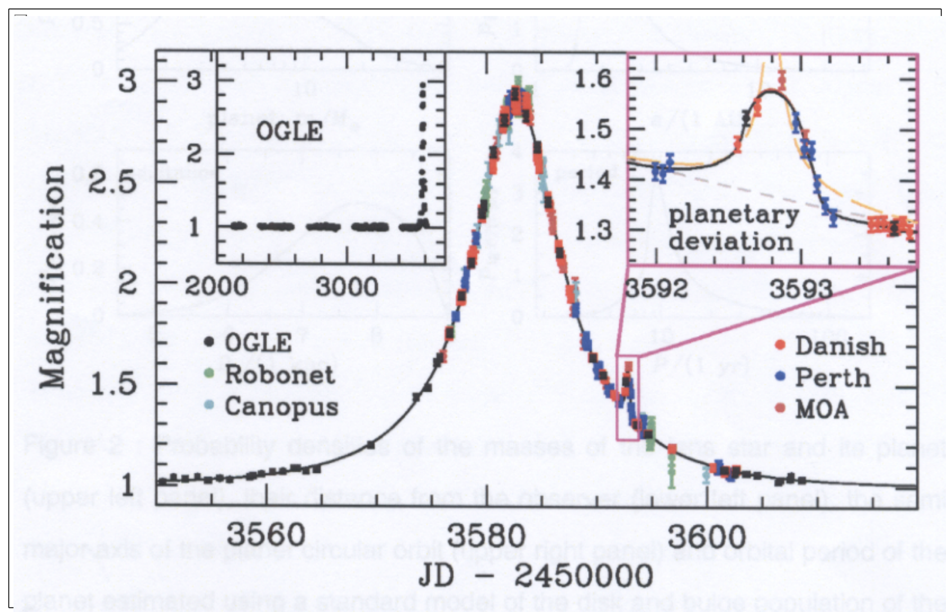
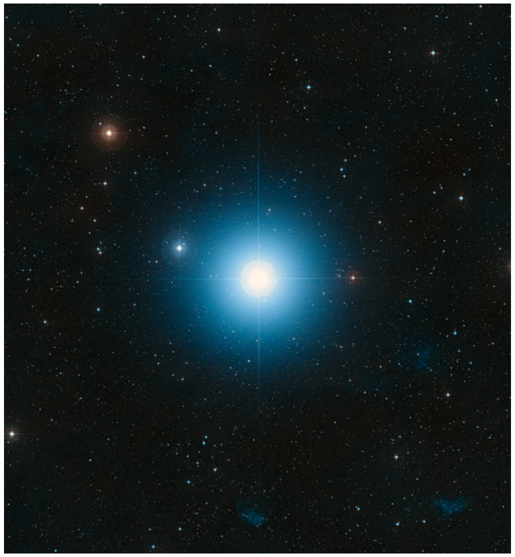


Monitor thousands of stars and hope for the best

Biased towards low mass stars (why?)

Because they are more numerous!
The lens star will more likely be a M star than a G star or whatever

Extrasolar planets – Direct Imaging

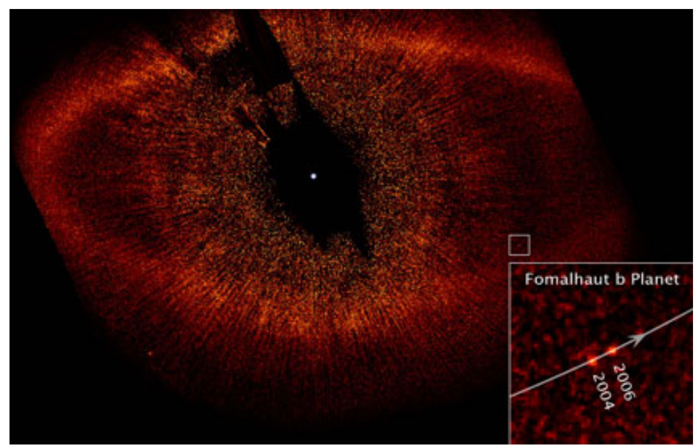


Fomalhaut
A3V star, V=1.2
8 parsecs away

A firefly next to a lighthouse

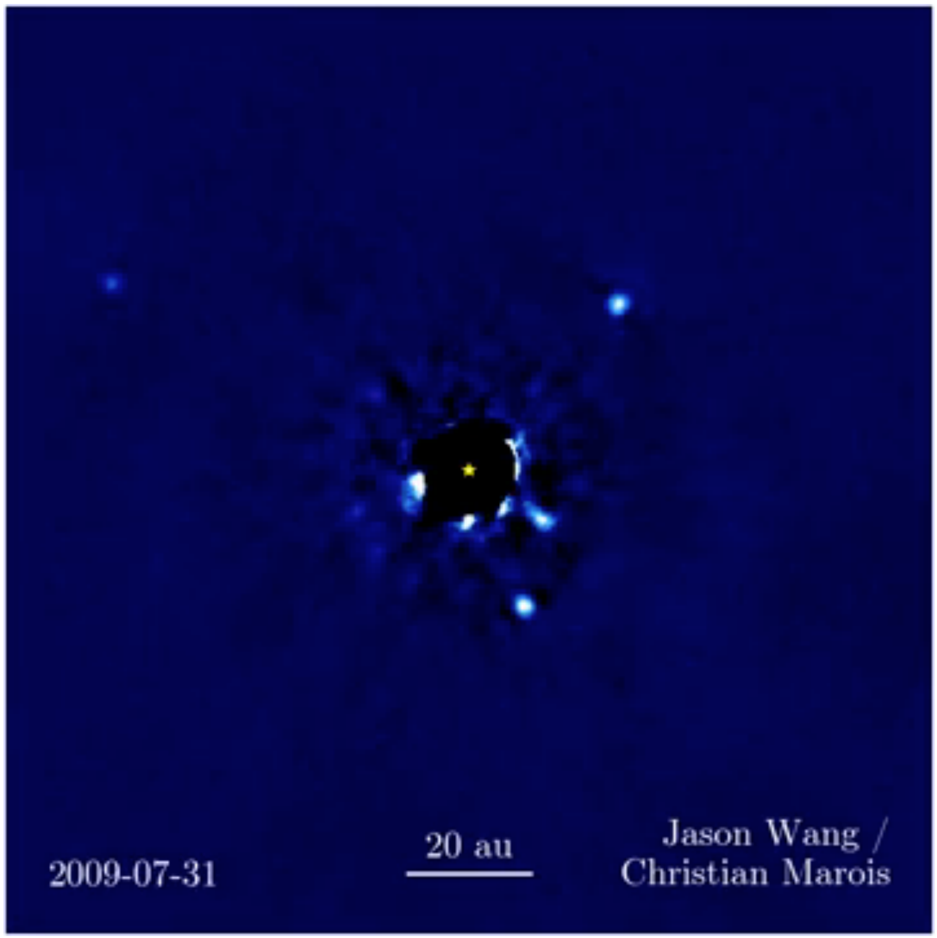
Block the starlight
and check the surroundings

“Block-image” thousands of stars and hope for the best



Extrasolar planets – Direct Imaging

Four planets around HR 8799



Extrasolar planets – Direct Imaging

Beta Pictoris b