STARS - S05

Wladimir (Wlad) Lyra
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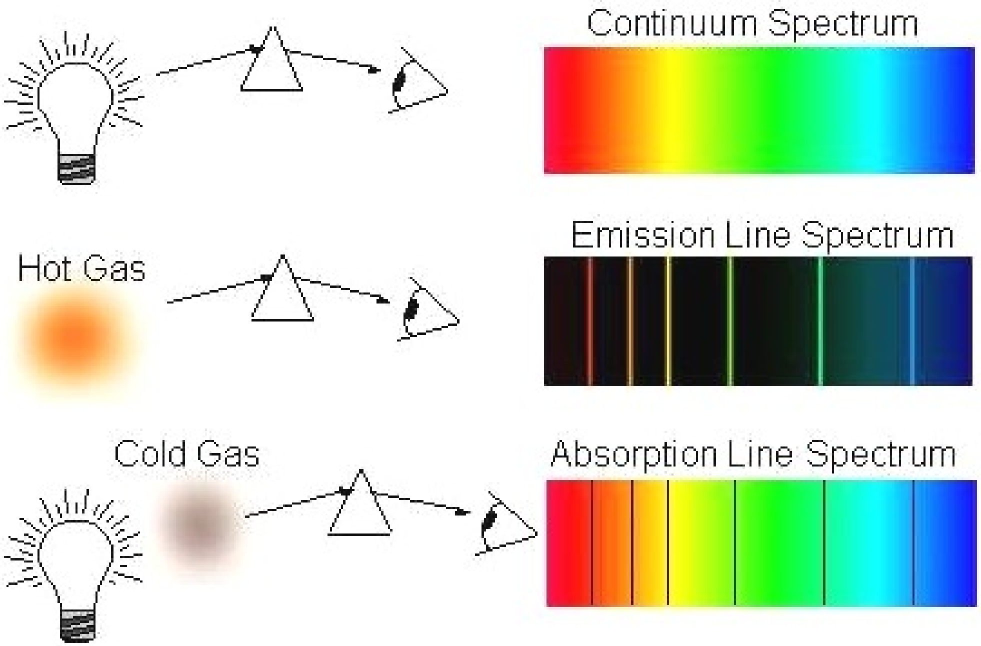
AMNH After-School Program

American Museum of Natural History

From last class

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

From last class

Kirchhoff's three laws of spectroscopy

Stellar spectra are absorption spectra, thus hot source covered by colder gas

Spectral lines are chemical fingerprints, a

otometric passbands UBVRI

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ndividual accuracy. Photomet

of stars can be automatedly

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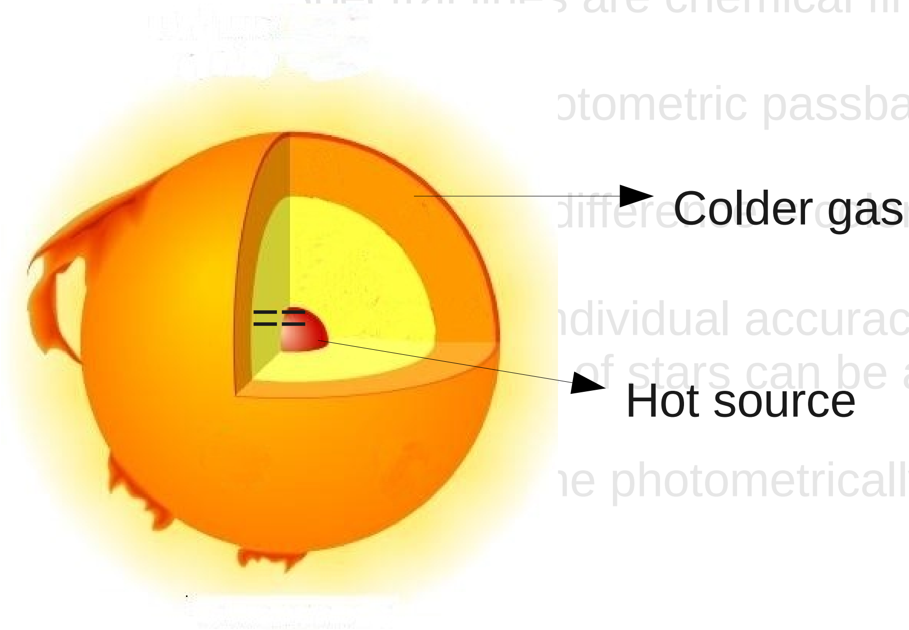
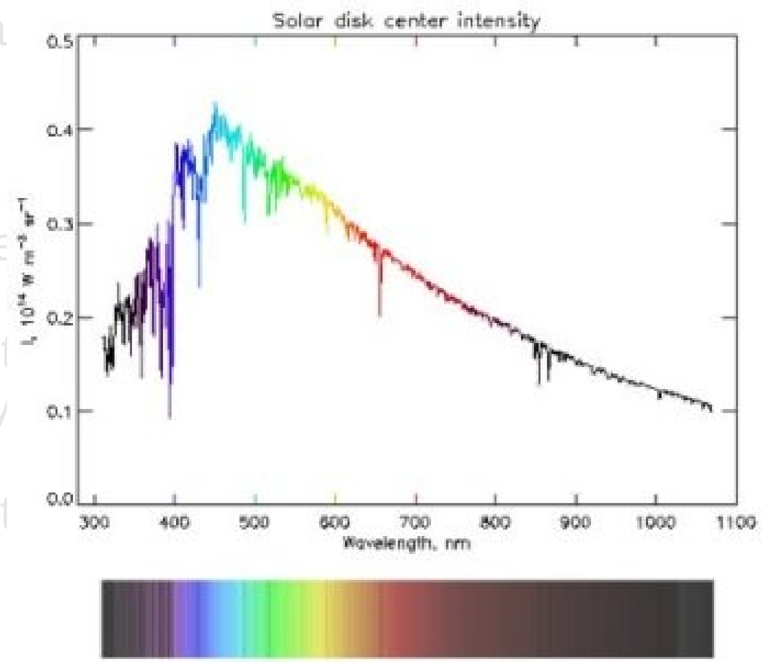
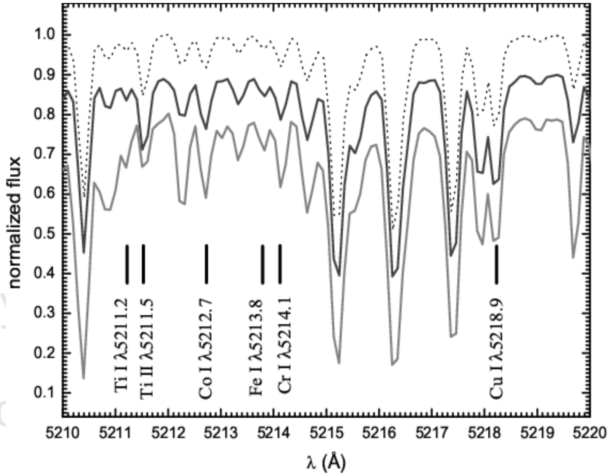




From last class

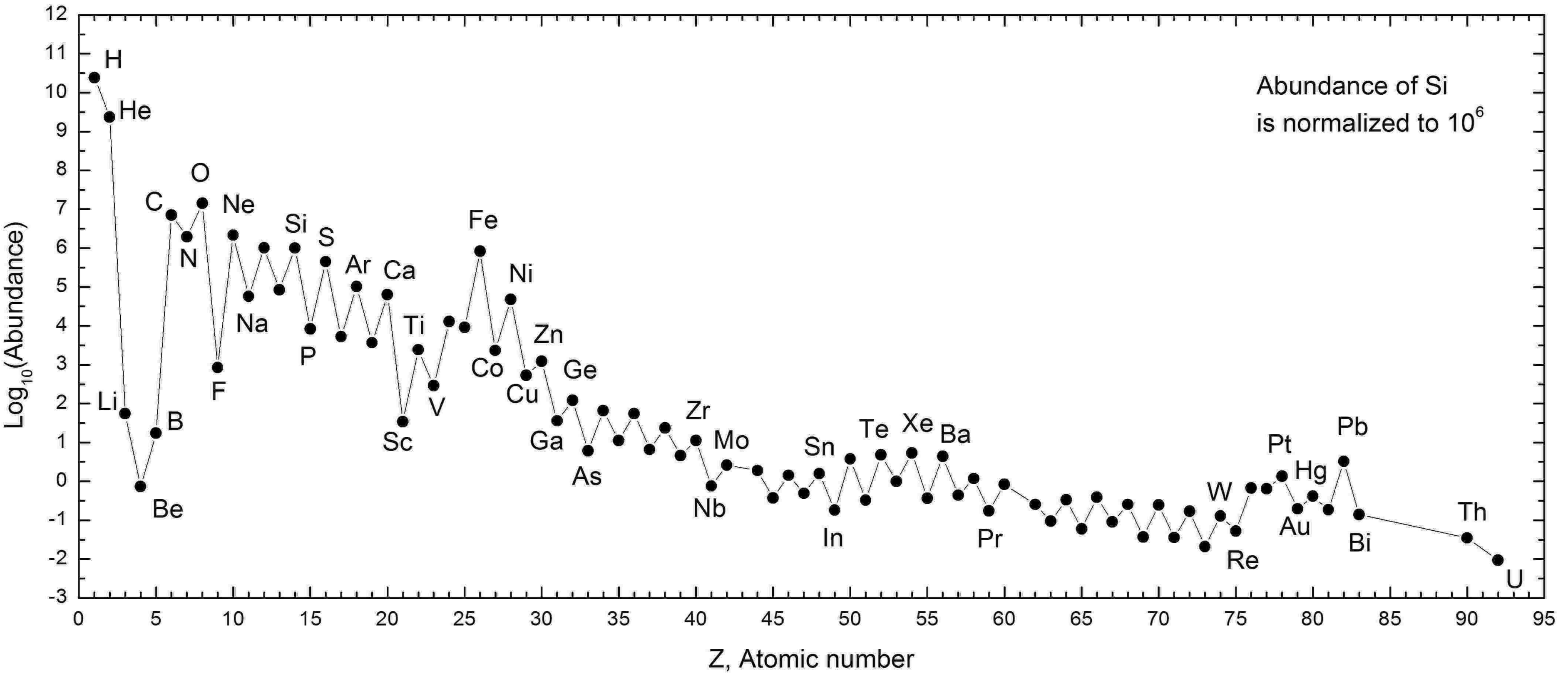


Kirchhoff's three laws of spectroscopy

Stellar spectra are absorption spectra, thus hot source co

Spectral lines are chemical signatures, and a mine of information

Five photometric passbands UBVRI. Five magnitudes.



From last class

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Spectro ... ics.
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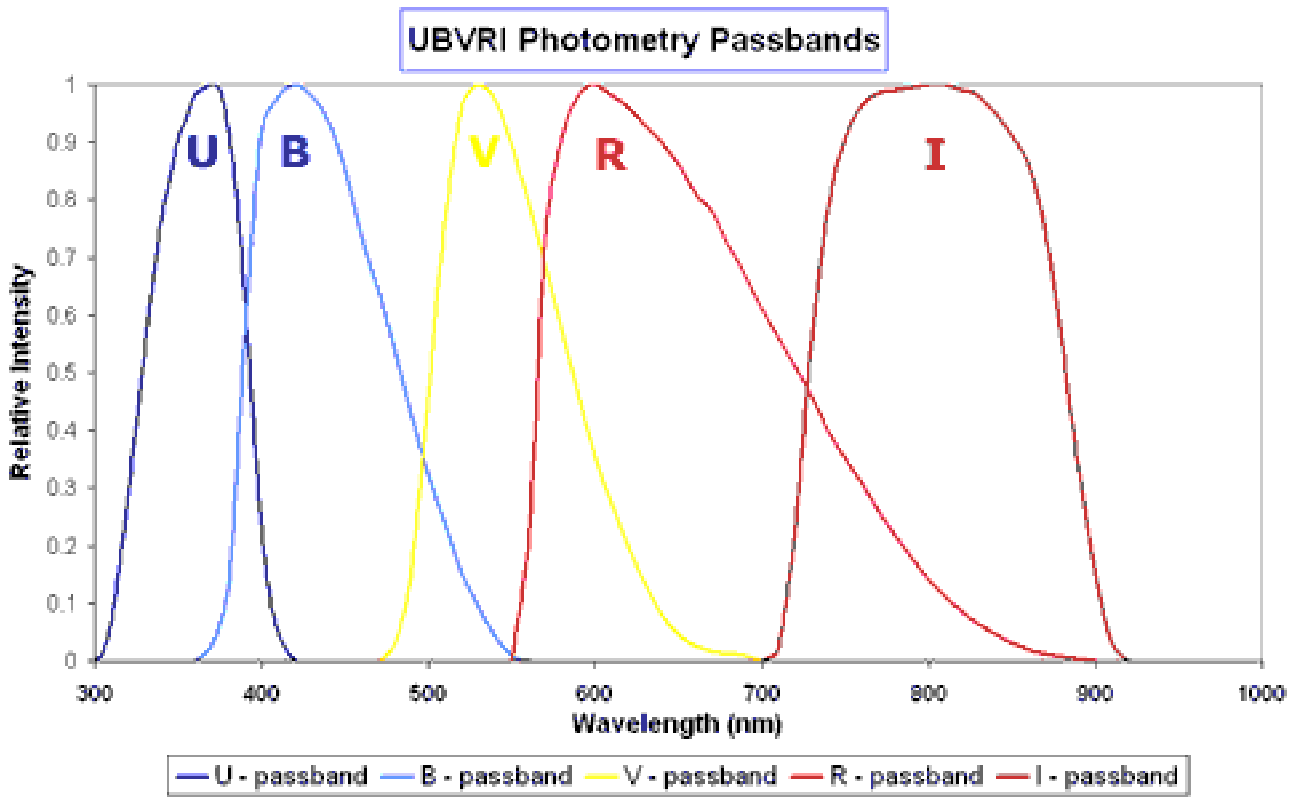


From last class

Kirchhoff's three laws of spectroscopy

Stellar spectra are absorption spectra, thus hot source covered by colder gas

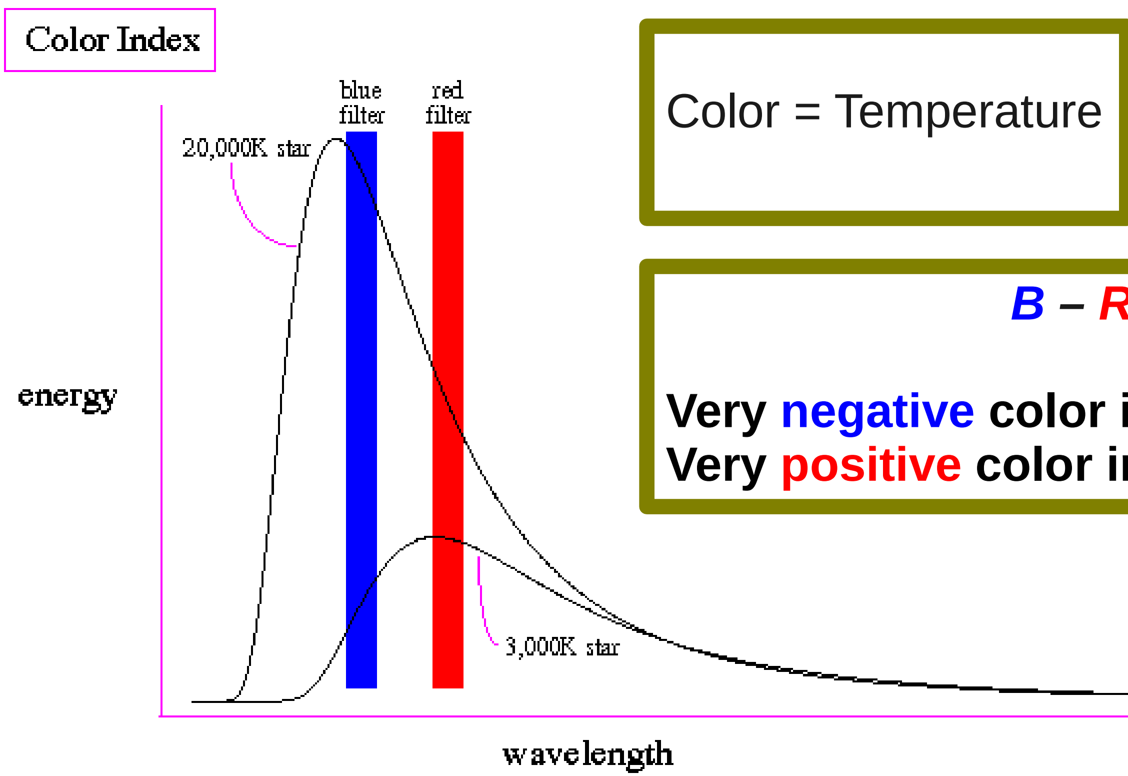
Spectral lines are chemical fingerprints, and a mine of information

Five photometric passbands UBVRI. Five magnitudes.

Magnitude difference = color. A measurement of temperature.

large number statistics.
asured in a single frame.

diagram.



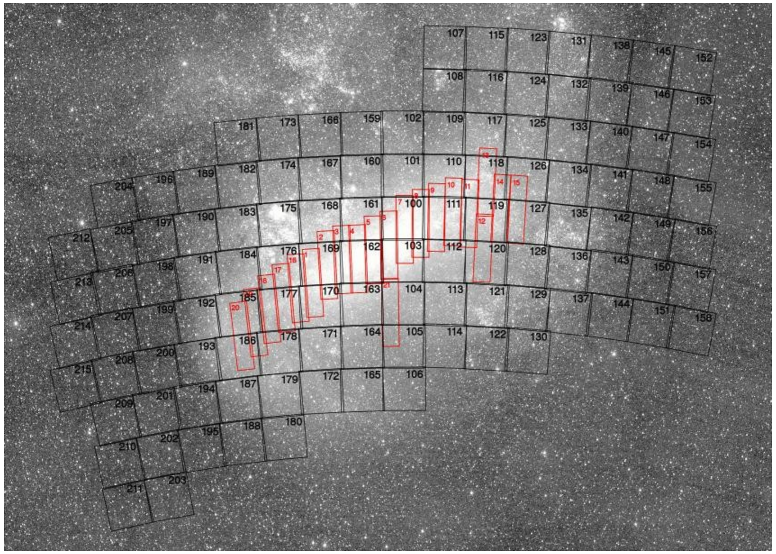
Color = Temperature

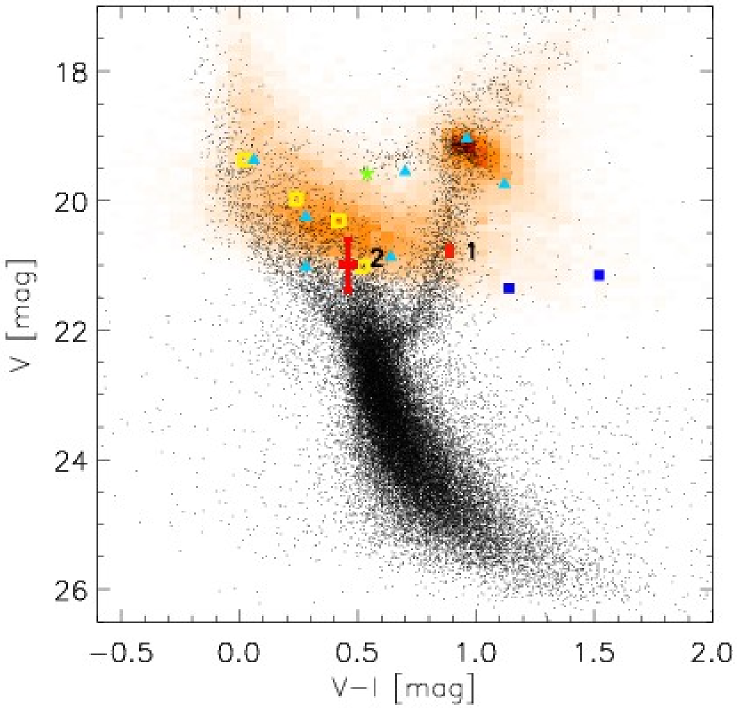
B* – *R

Very negative color index: blue
Very positive color index: red

From last class

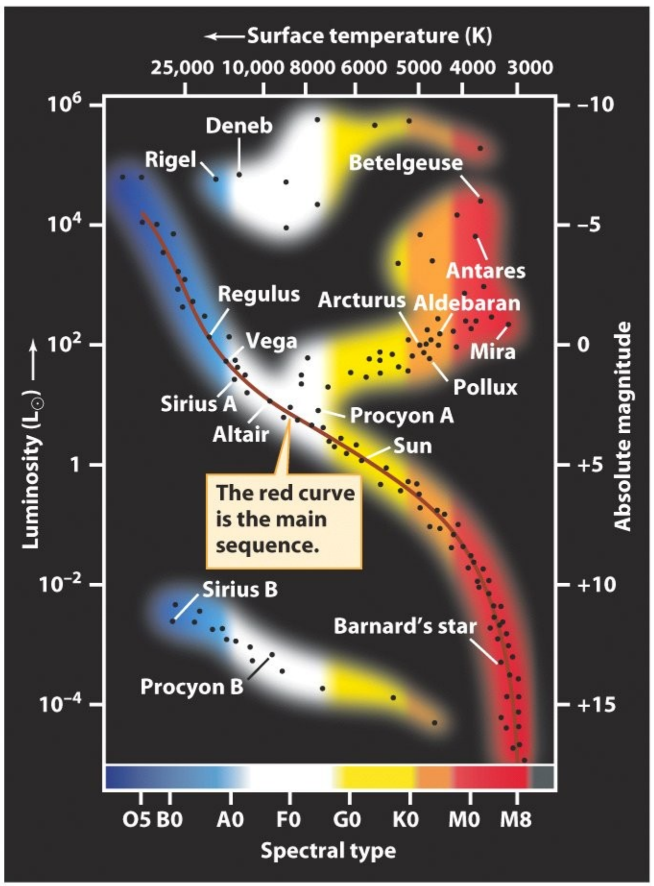
Spectroscopy = individual accuracy. Photometry = large number statistics.
Tens of thousands of stars can be automatedly measured in a single frame.



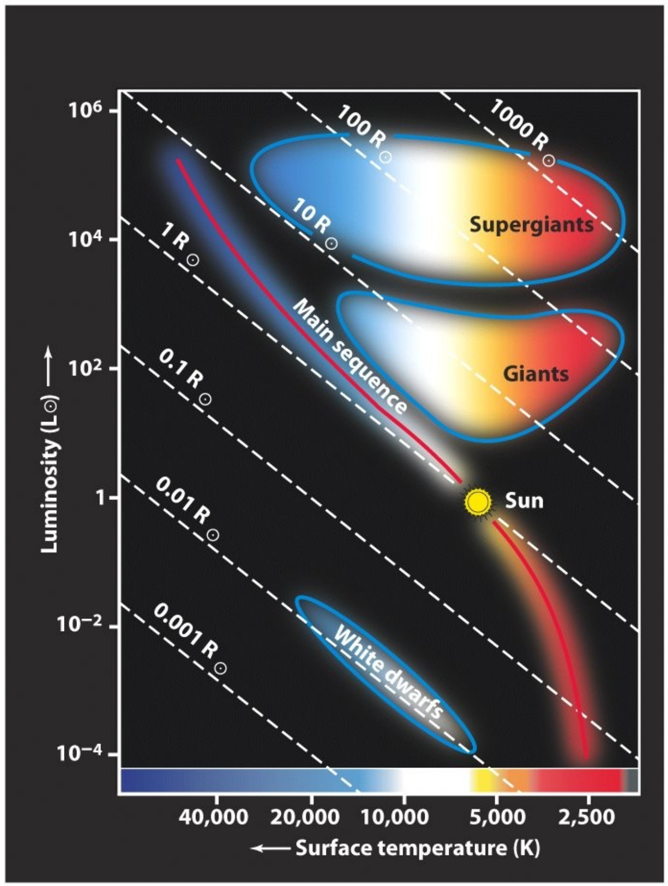


From last class

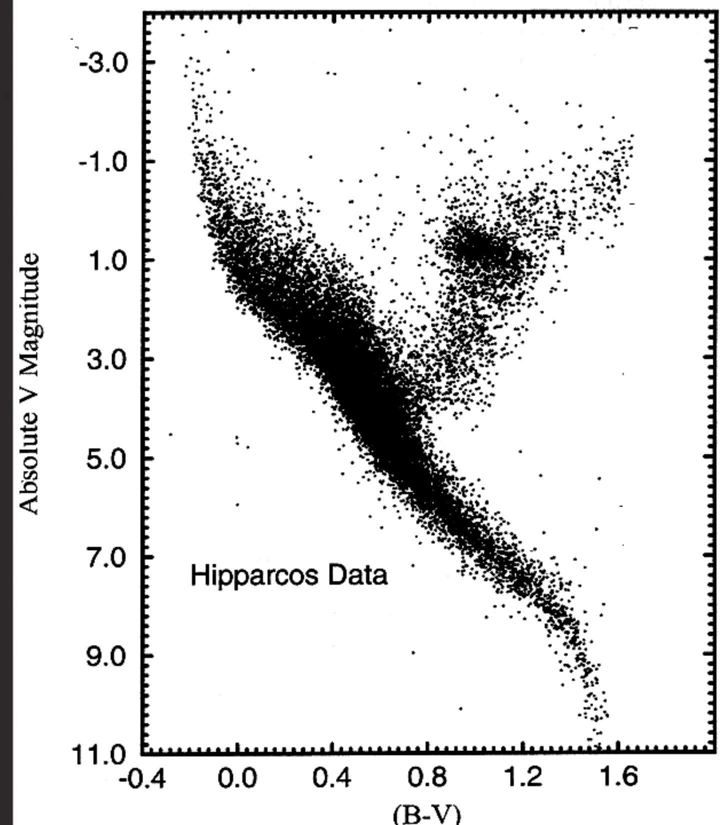
Color-Magnitude Diagram (CMD) is the photometric equivalent of the HR diagram.



(a) A Hertzsprung-Russell (H-R) diagram



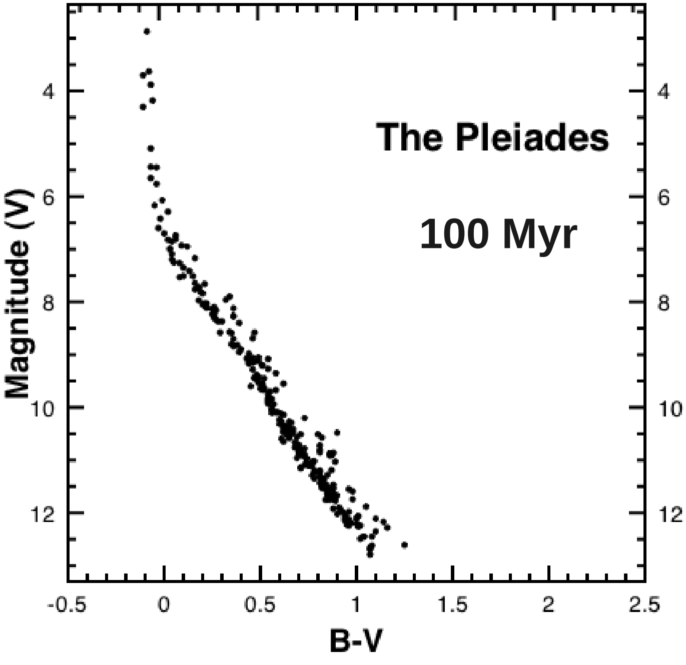
(b) The sizes of stars on an H-R diagram



Spectral type = Temperature = Color

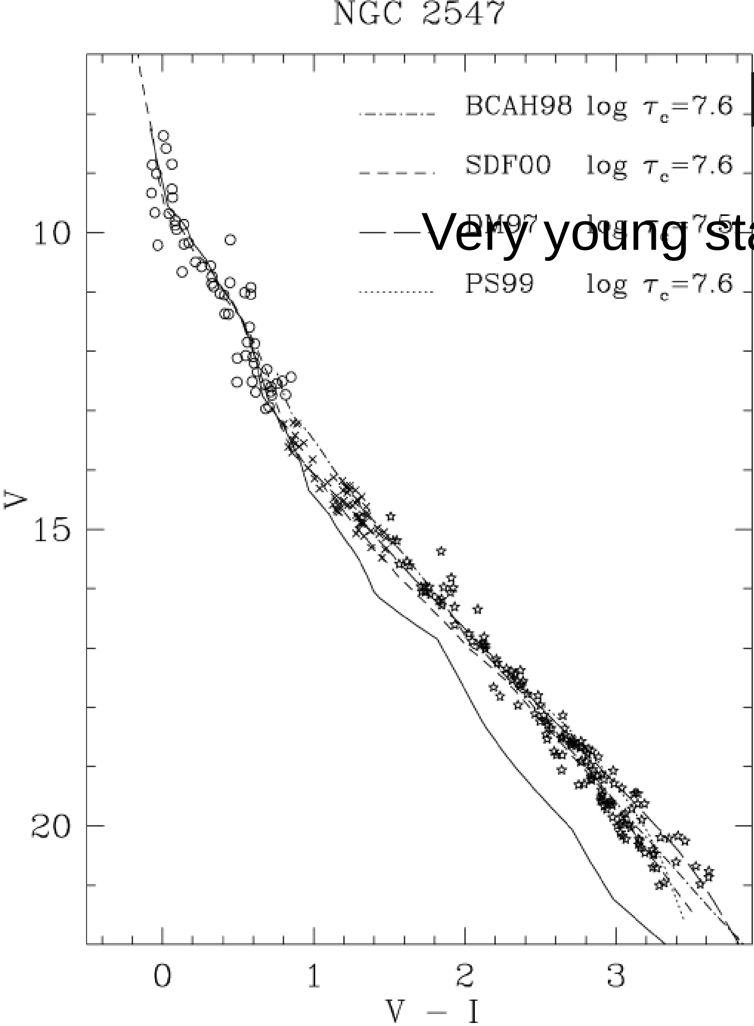
From last class

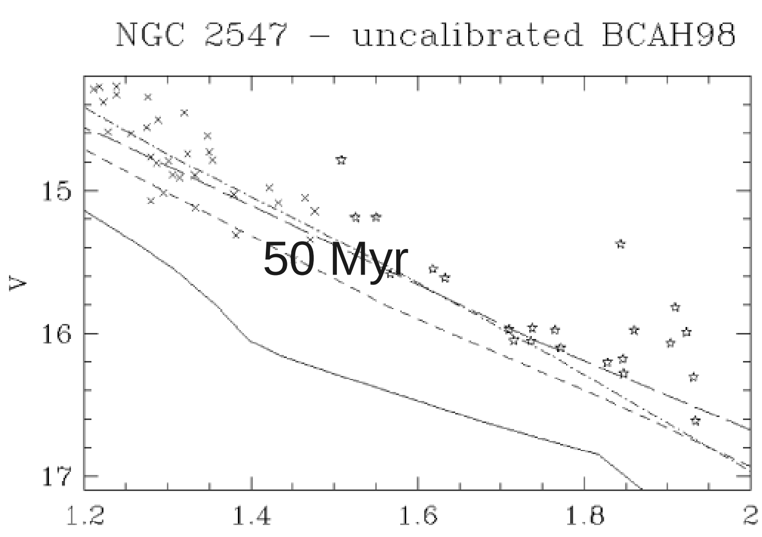
Young stars are found in the main sequence



From last class

Very young stars are found in the pre main sequence



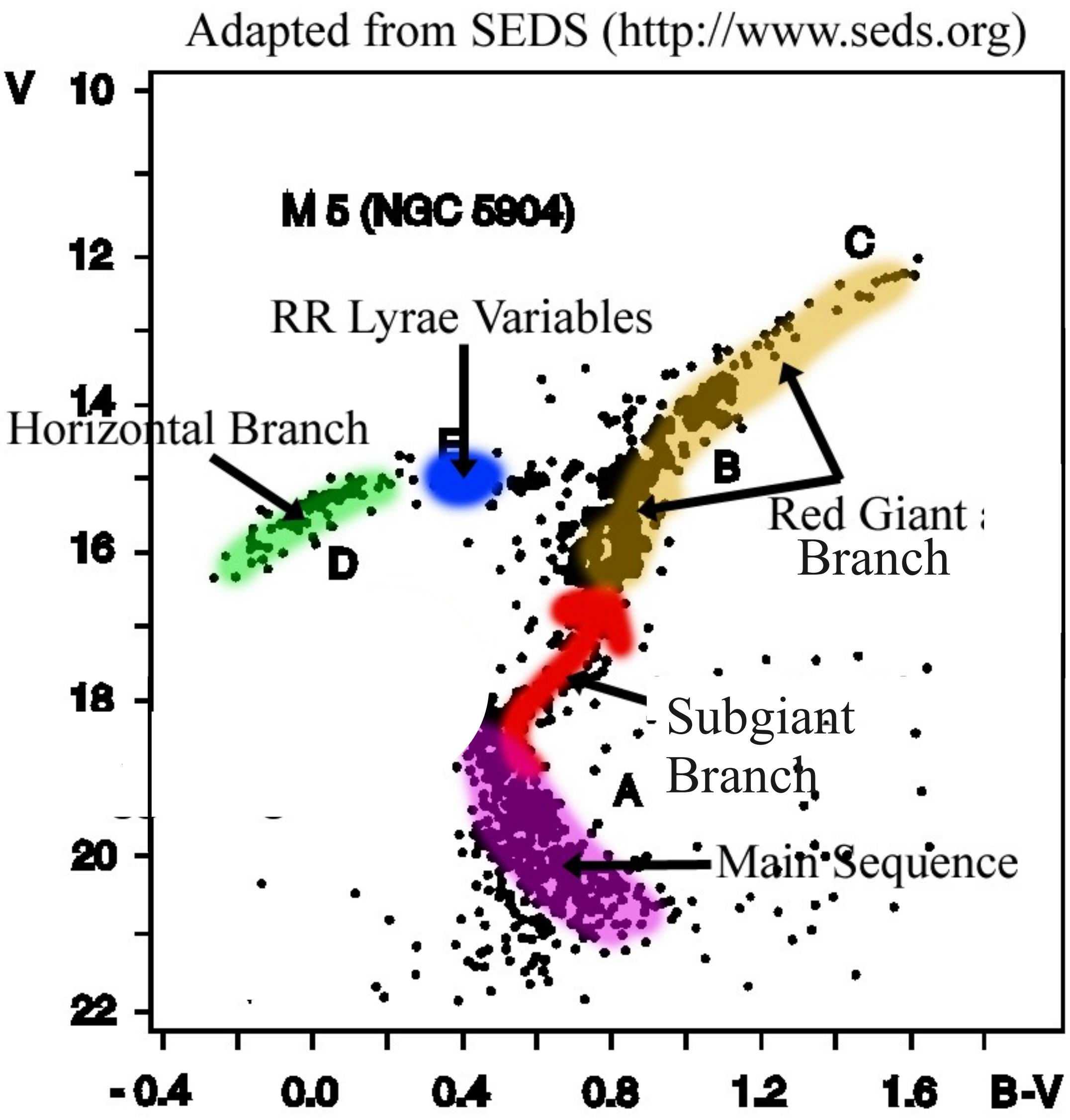


NGC 2547

The Pre Main Sequence is the locus of nascent, baby stars

From last class

Evolved stars are found in special branches in the HR diagram

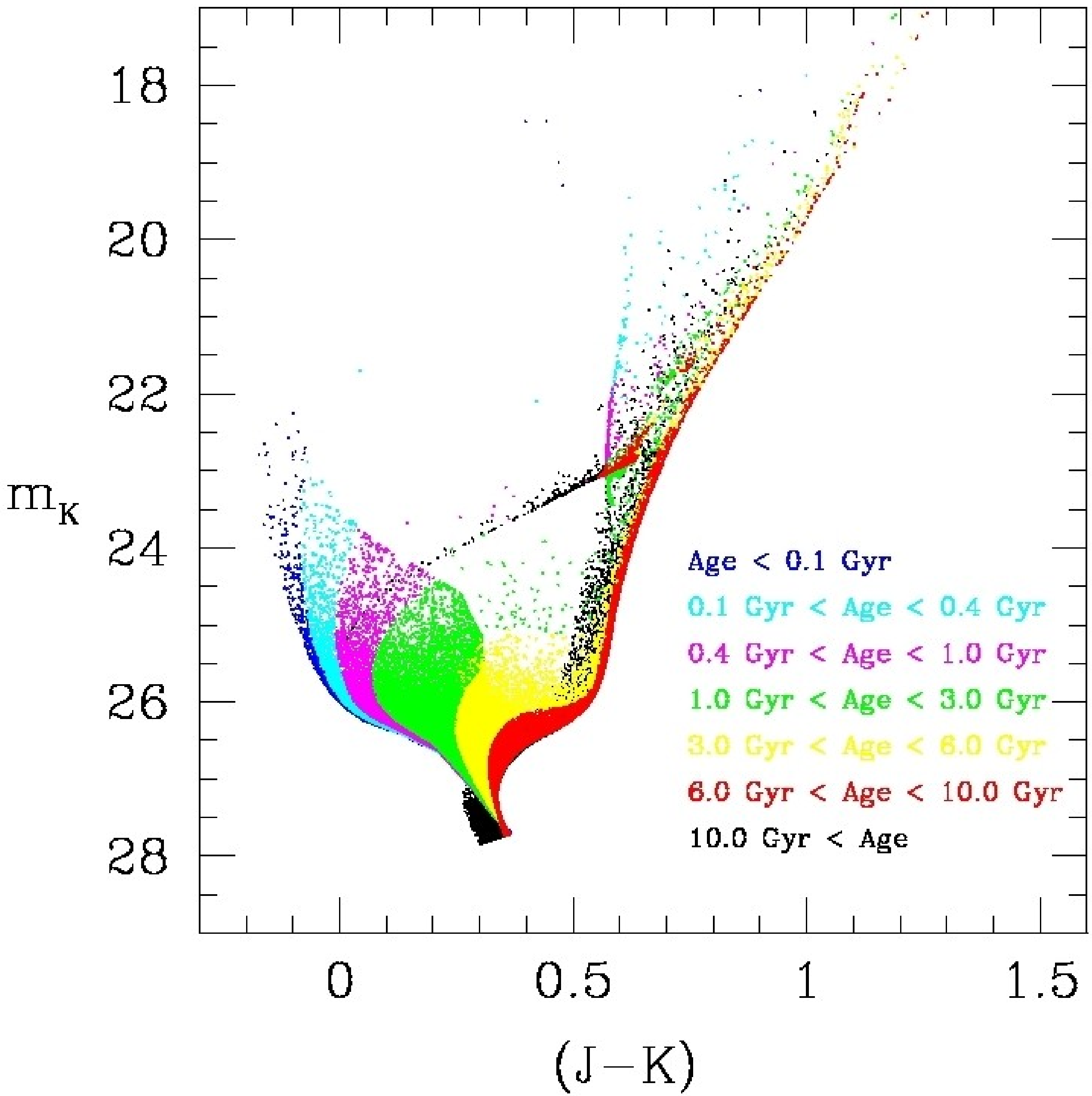


Subgiant Branch
Red Giant Branch (RGB)
Horizontal Branch (HB)
Asymptotic Giant Branch (AGB)

Loci of evolved, dying stars, undergoing
Post-Main Sequence evolution

From last class

Which is understood as an evolutionary sequence



Main Sequence (dwarf)

Subgiant

Red Giant

Horizontal Branch

Asymptotic Giant Branch

T I M E

Outline

- **Theory of Stellar Evolution**

  - **Star Formation**
    - Stellar nurseries/Molecular Clouds
    - Turbulent Fragmentation

  - **Pre Main Sequence Evolution**
    - Birthline, Hayashi tracks

  - **Main Sequence Evolution**
    - Lifetime
    - Nuclear processes
      - PP chain
      - CNO cycle

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)***

The ISM is very inhomogeneous. Many components, of different densities and temperatures.

For **star formation**, we are interested in the **dense**, **cold** regions.

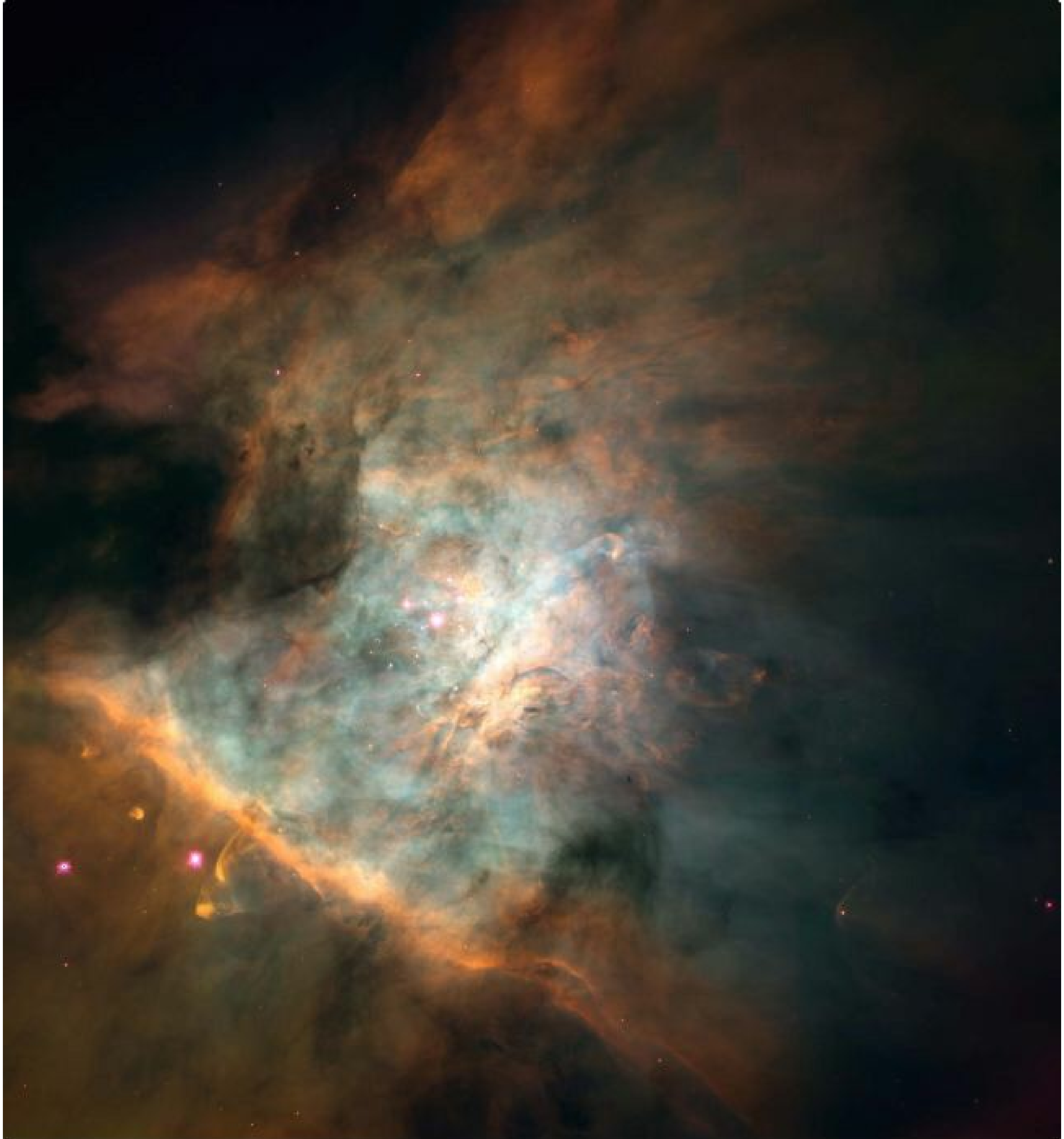
Star Formation

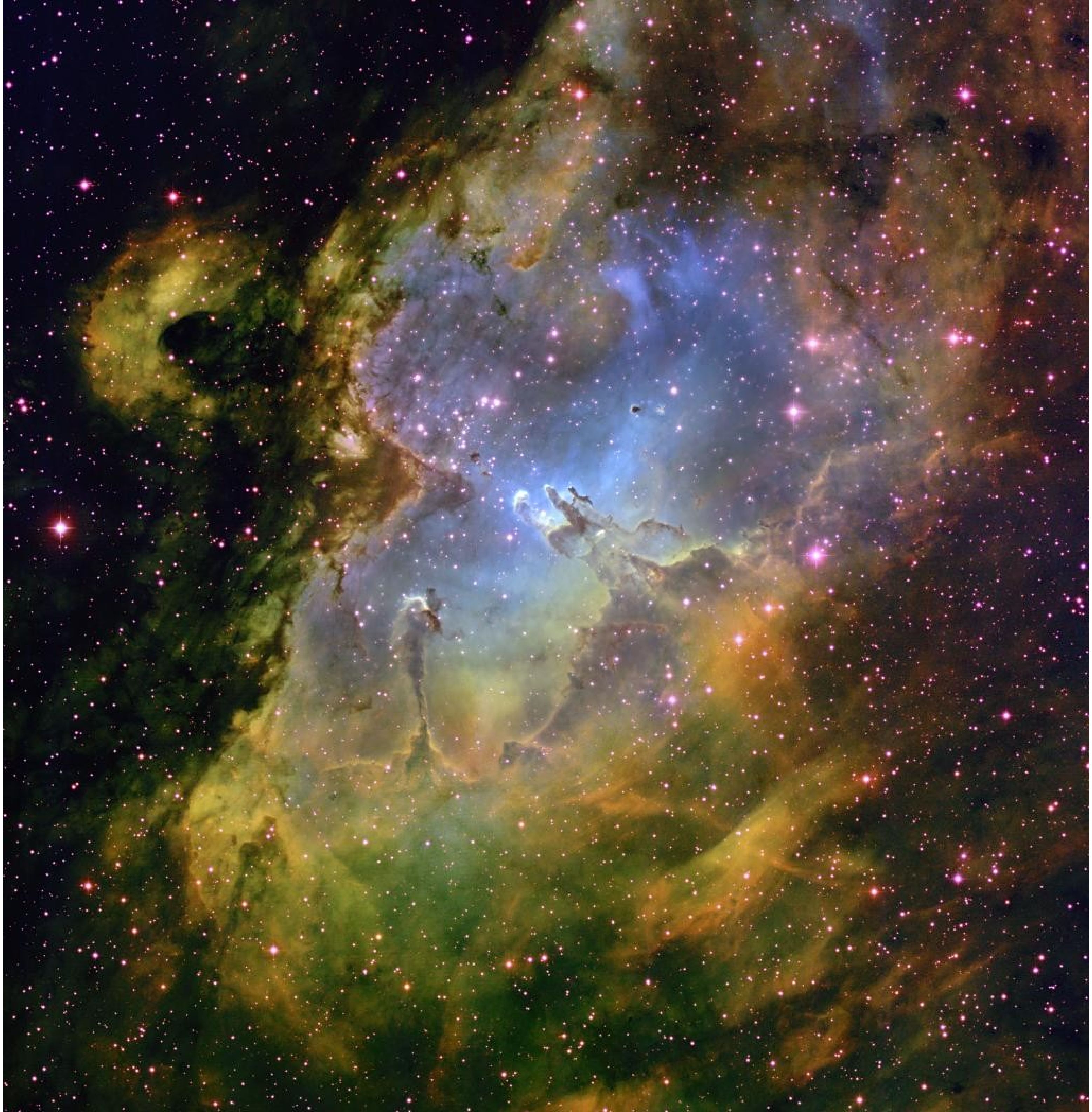
A process by which gas collapses gravitationally, to form stars.

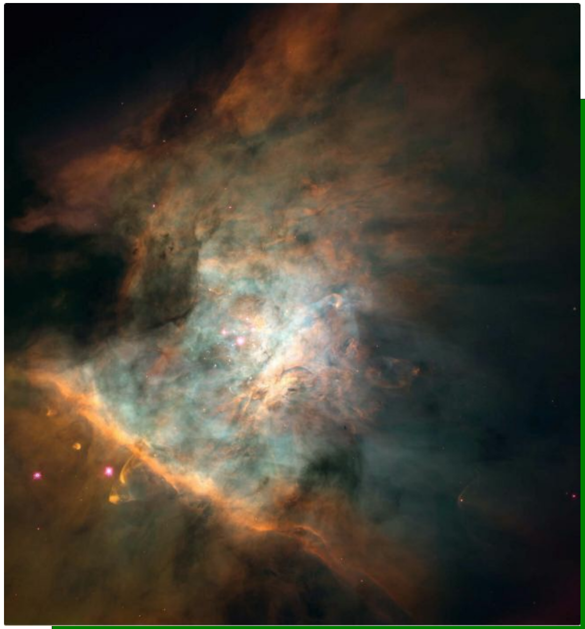
Has to beat hydrostatic equilibrium. Regulated by Gravity (density) vs Pressure (temperature).

The densities necessary for star formation are ***far greater*** than the average density of the ISM

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





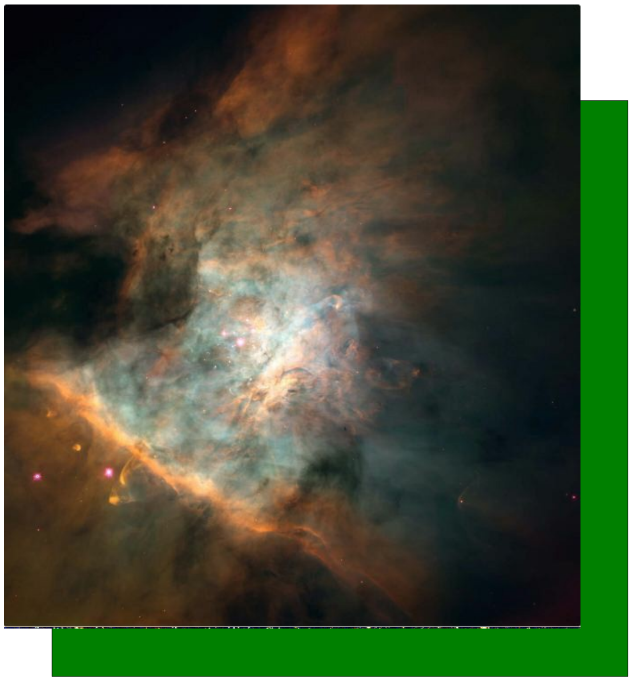


Molecular Cloud Fact Sheet

Temperature	10-50 K
Density	$10^2 – 10^6$ atoms/cm^3
(ISM Density	1 atom/cm^3)

Irregular and turbulent

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



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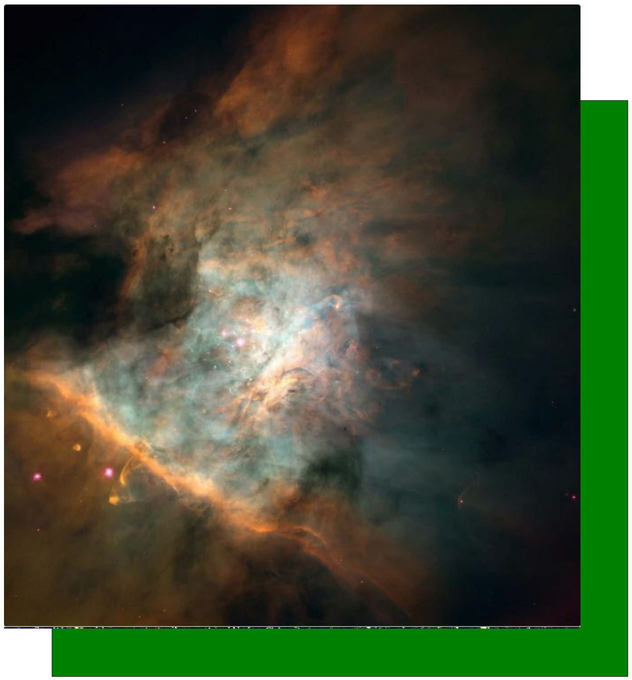


Molecular Cloud Fact Sheet

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

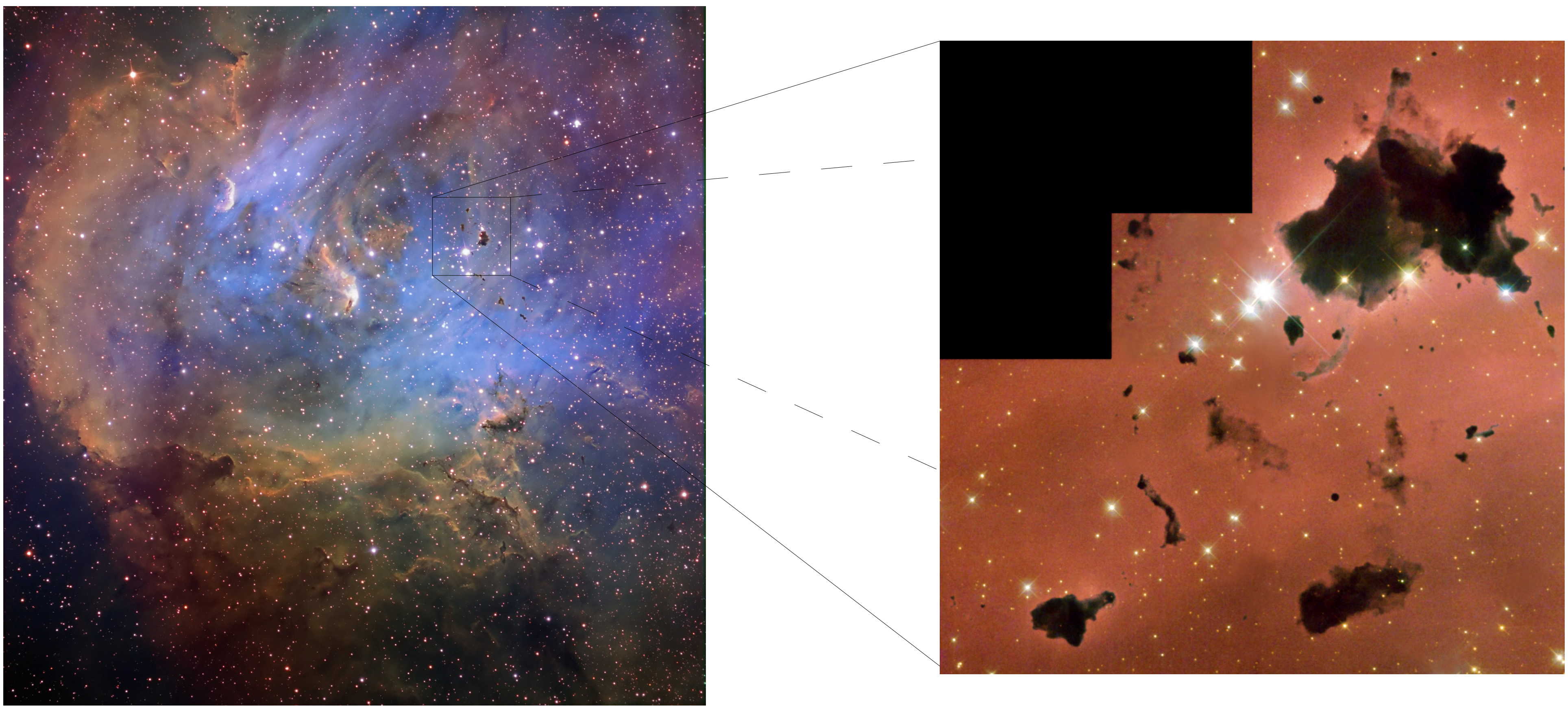
Star Formation

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

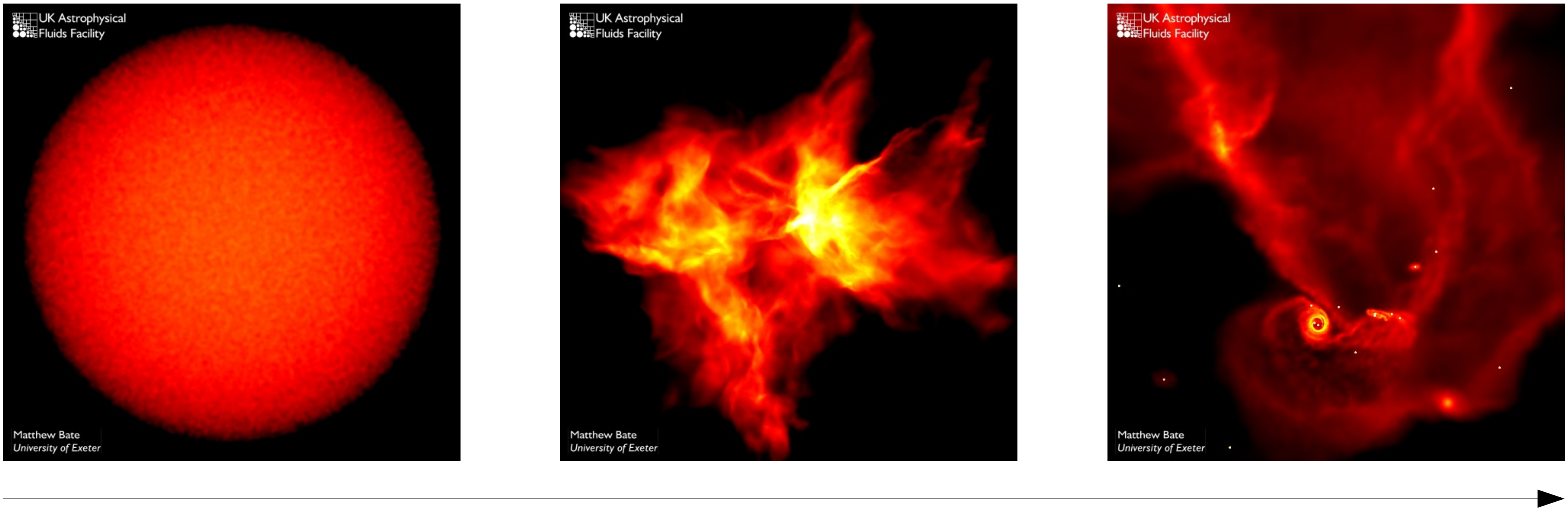
Even the average density of Molecular Clouds is too low.

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

These Dense Cloud Cores are set by ***turbulence***



The Turbulent Model of Star Formation

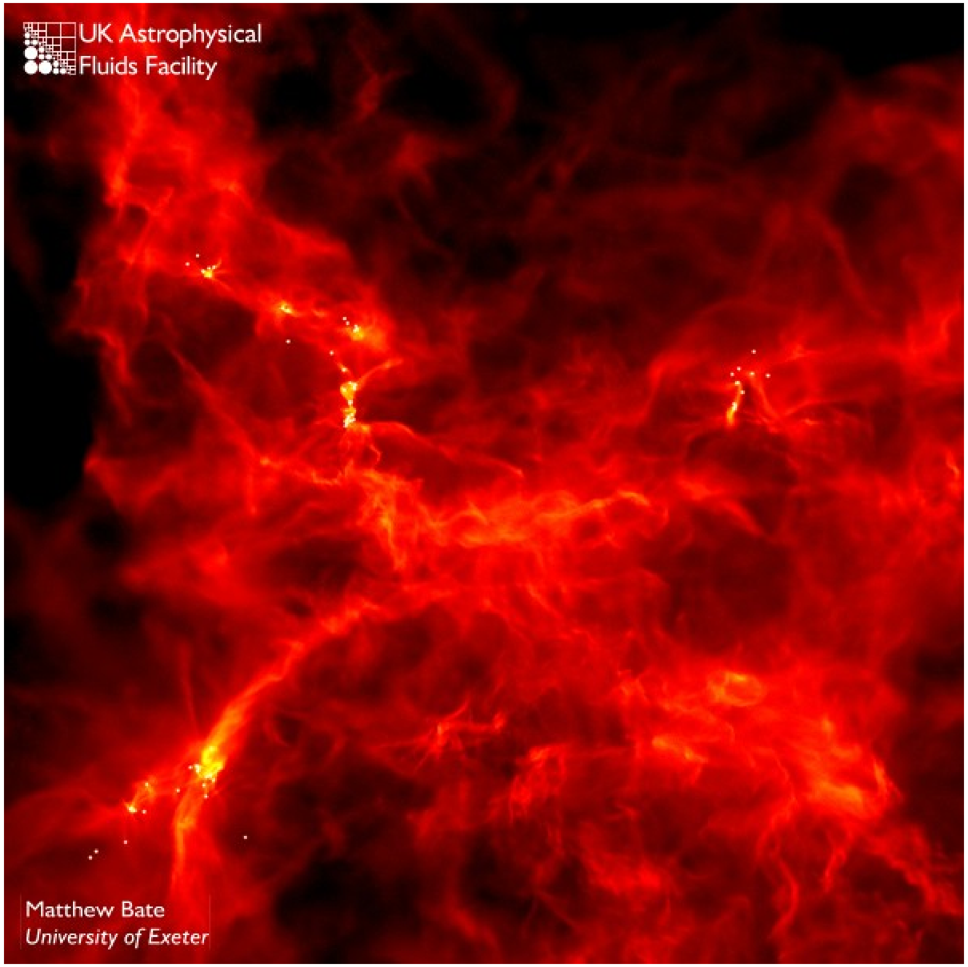


time

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

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

The Turbulent Model of Star Formation



Computer simulation

Observation

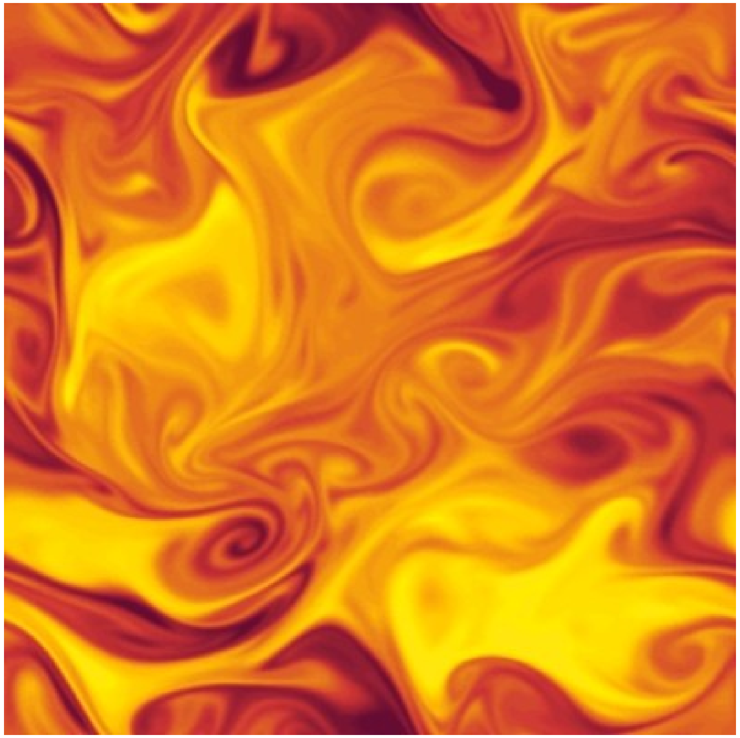
Turbulence fragments a Molecular cloud into a clumpy structure of high and low density regions

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

How many stars of given mass?

Star formation is set by turbulent fragmentation

<u>But what is turbulence?</u>



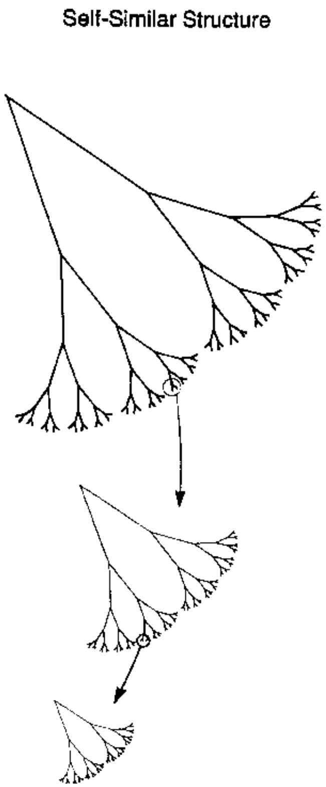
How many stars of given mass?

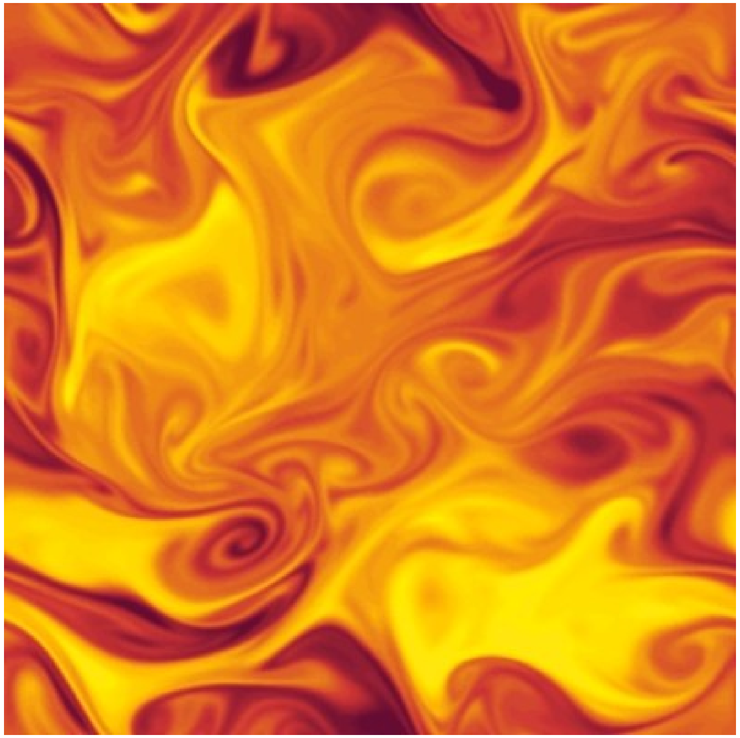
Star formation is set by turbulent fragmentation

But what is turbulence?

Random, but with some properties

Self-similar flow





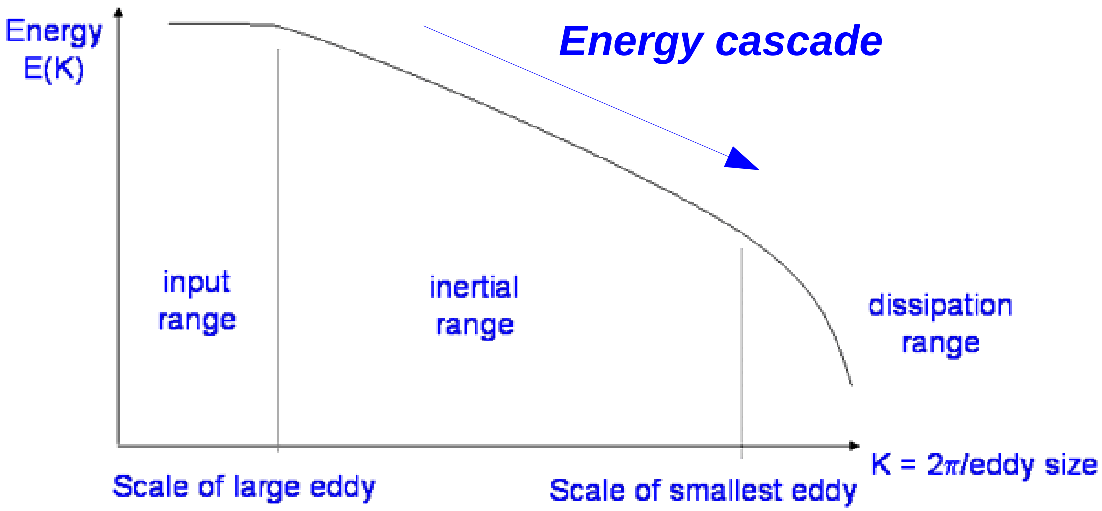
Self-similar structure

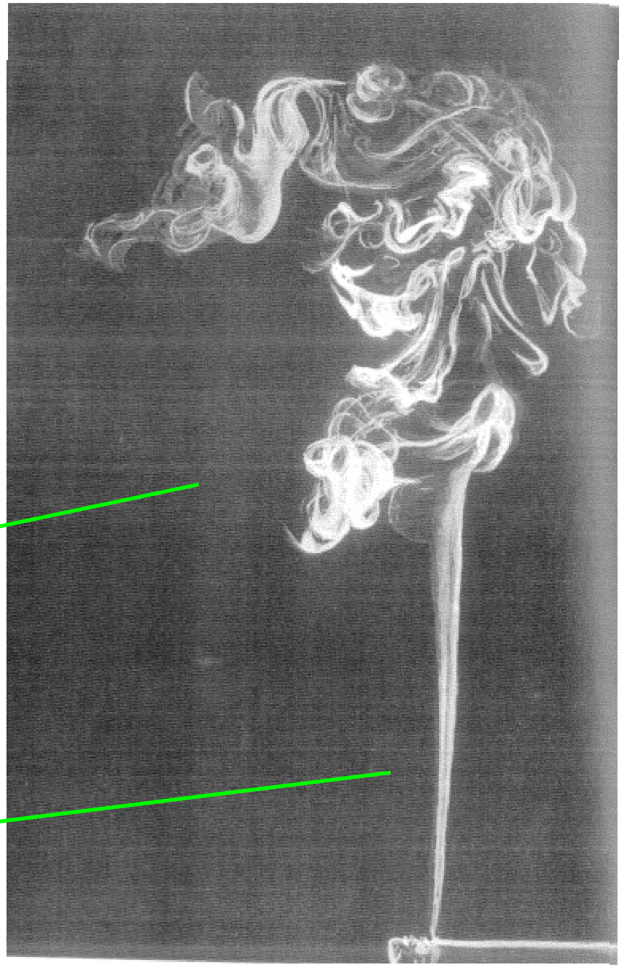
Any part looks equal to the whole

How many stars of given mass?

Star formation is set by turbulent fragmentation

Turbulence is self-similar!





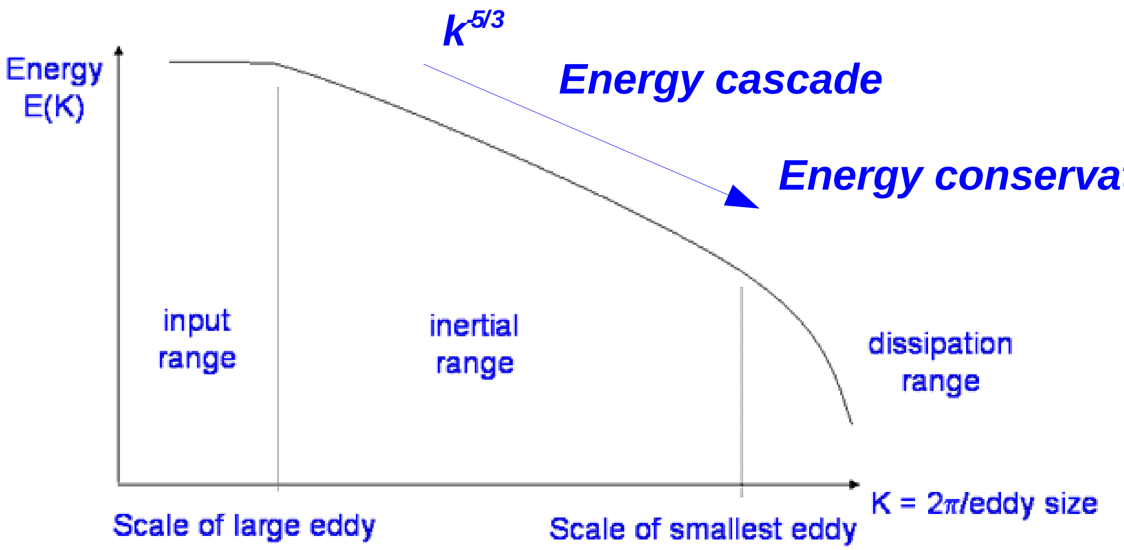
Turbulent flow

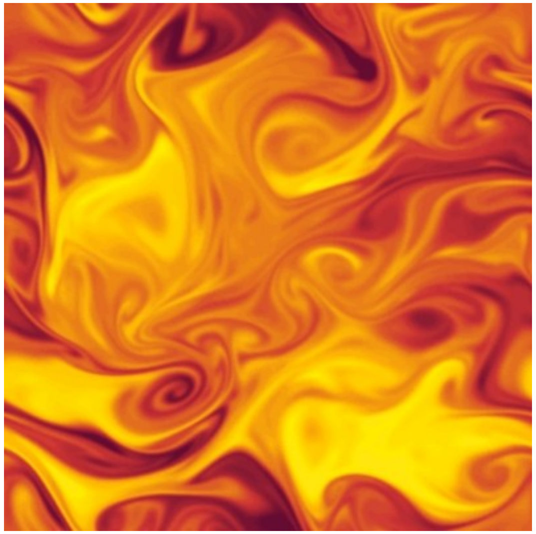
Laminar flow

How many stars of given mass?

Star formation is set by turbulent fragmentation

Turbulence is self-similar!





Turbulence has statistical properties that are moderately well understood

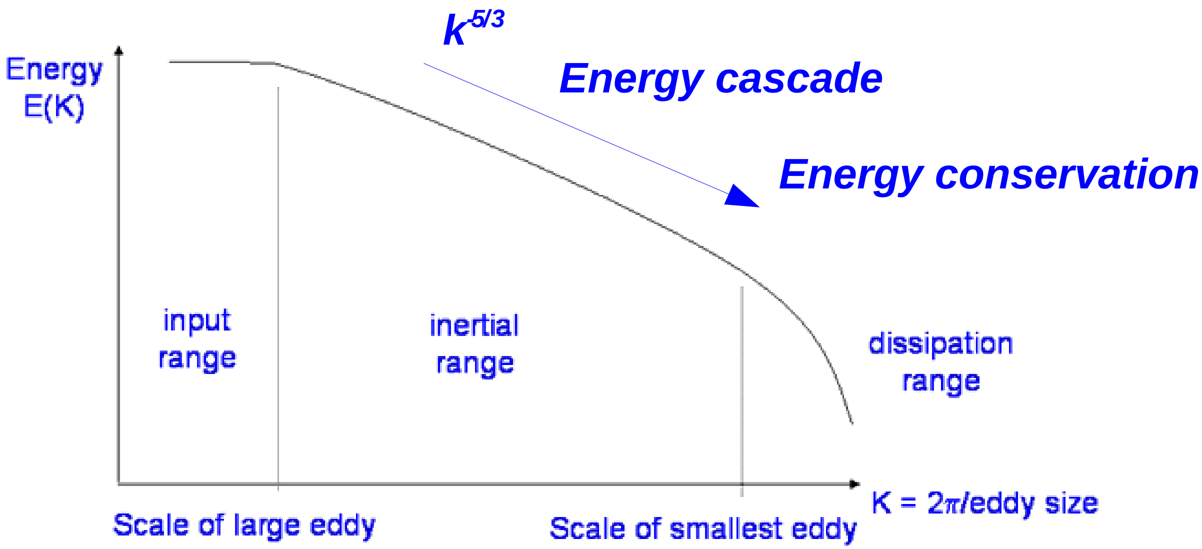
Energy ***cascades*** from large scales to smaller scales ***obeying energy conservation***

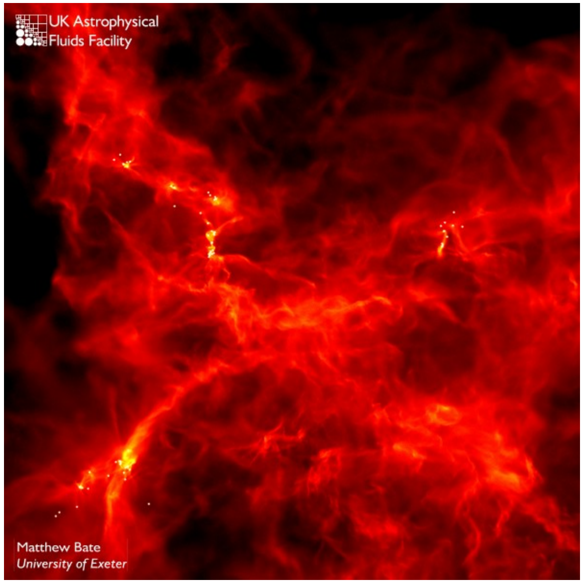
Due to ***energy conservation***, the slope is ***universal***.

Kolmogorov slope $E(k) \propto k^{-5/3}$, $k=2\pi/\lambda$, λ=eddy size

How many stars of given mass?

Star formation is set by turbulent fragmentation





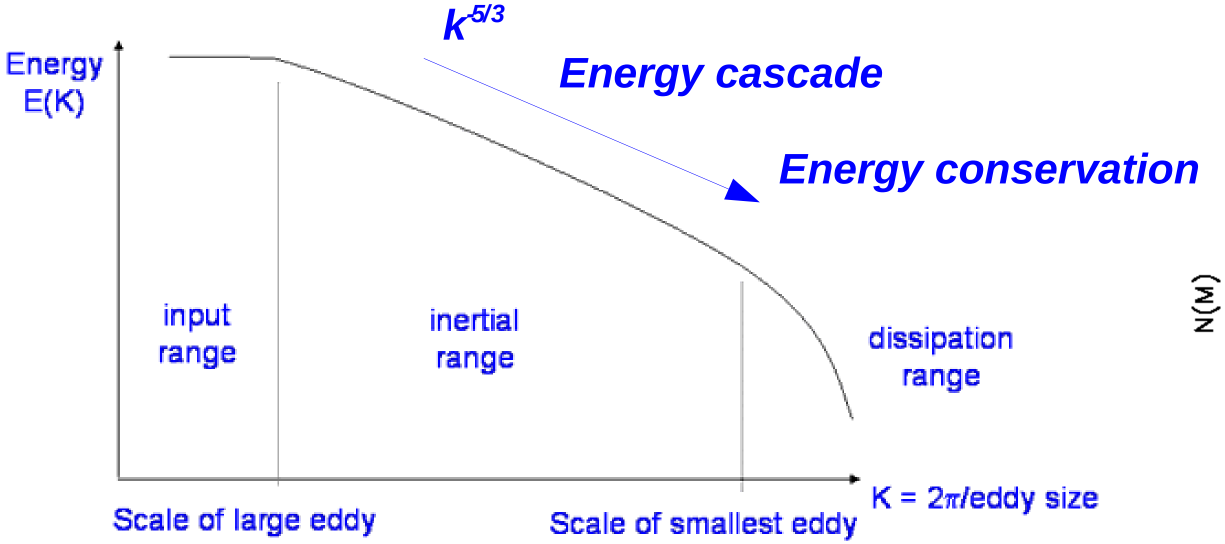
The ***spectrum of sizes*** is well determined

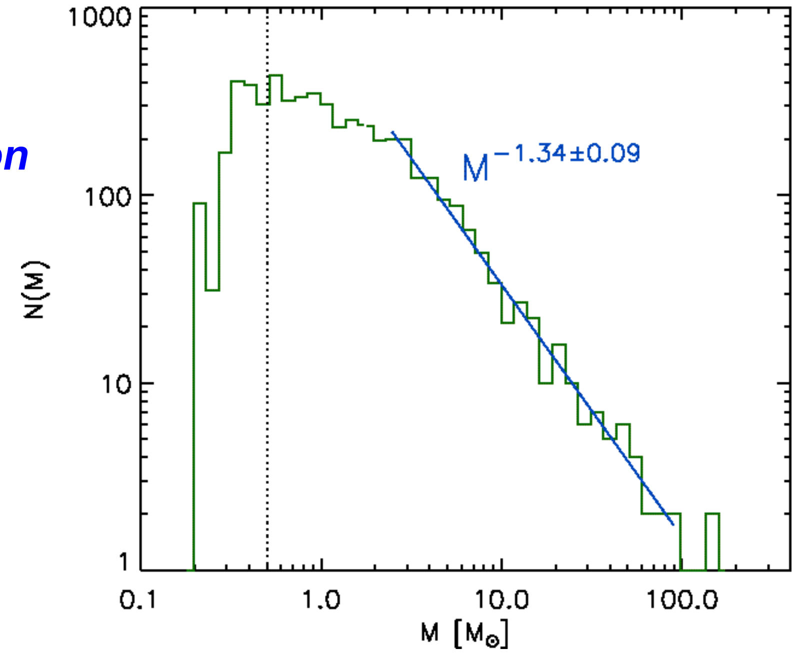
Size determines the ***mass***

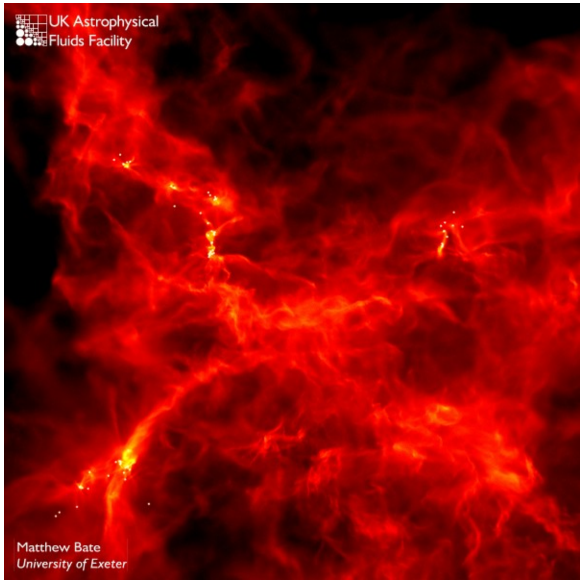
So the ***spectrum of mass*** should also be well determined

How many stars of given mass?

Star formation is set by turbulent fragmentation







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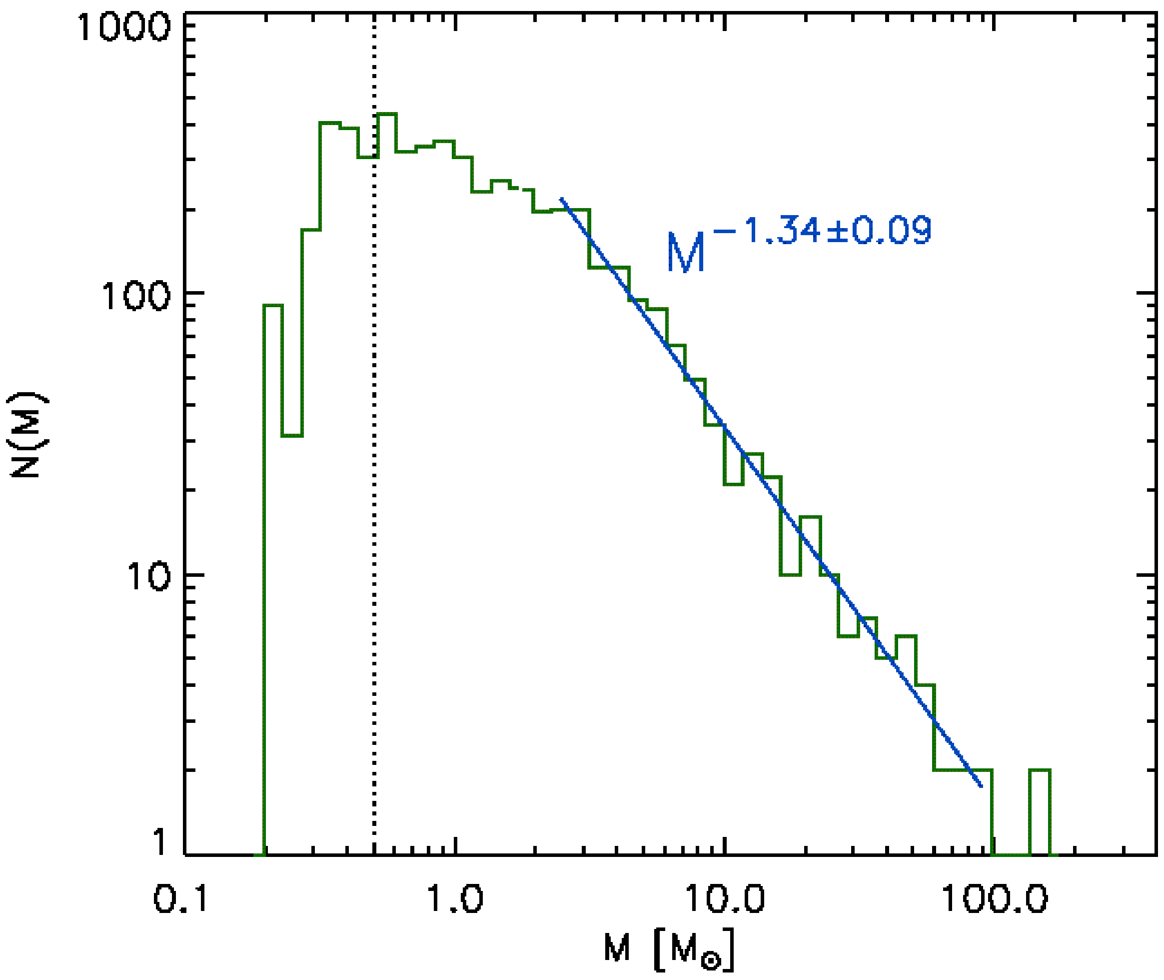
The Initial Mass Function



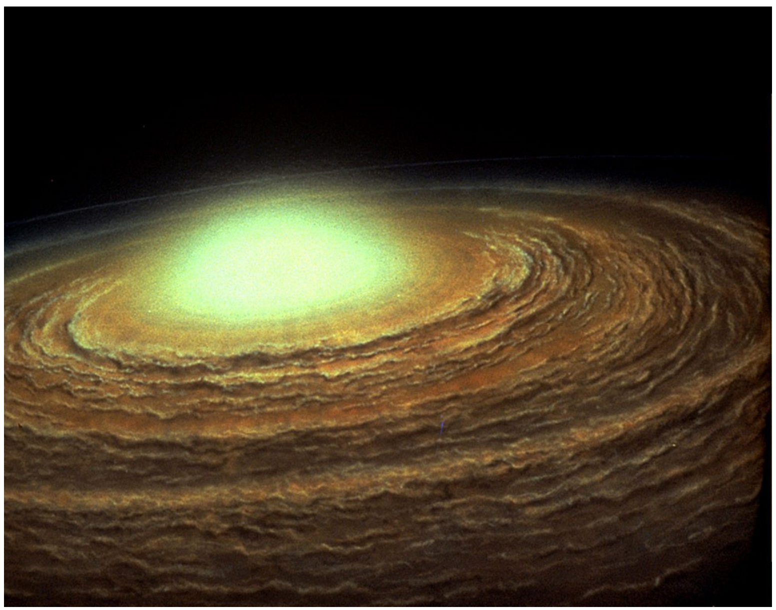
Lots of low mass stars
Very few high mass stars

Most common mass: 0.5 Msun

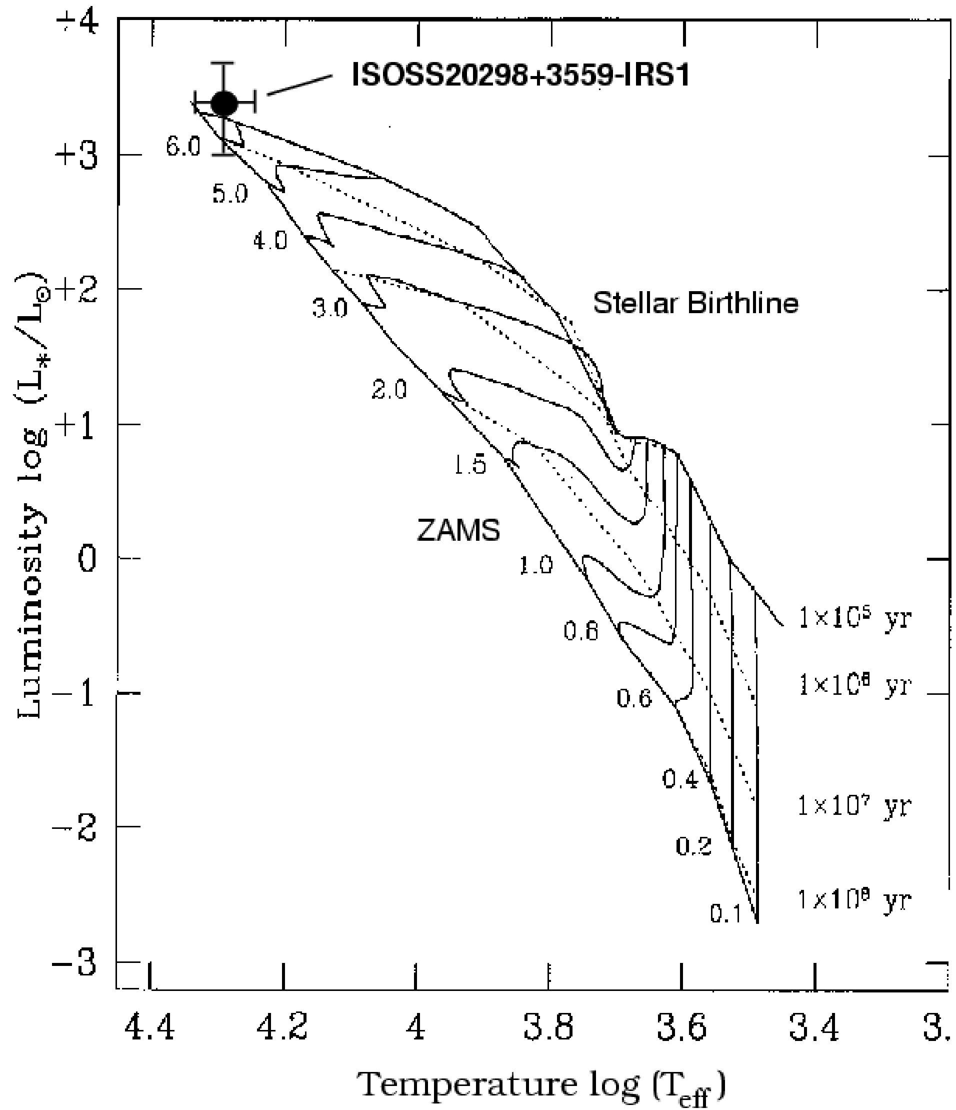
Back to Star Formation – The Birthline

When accretion stops and the dust is cleared, a protostar is revealed

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).

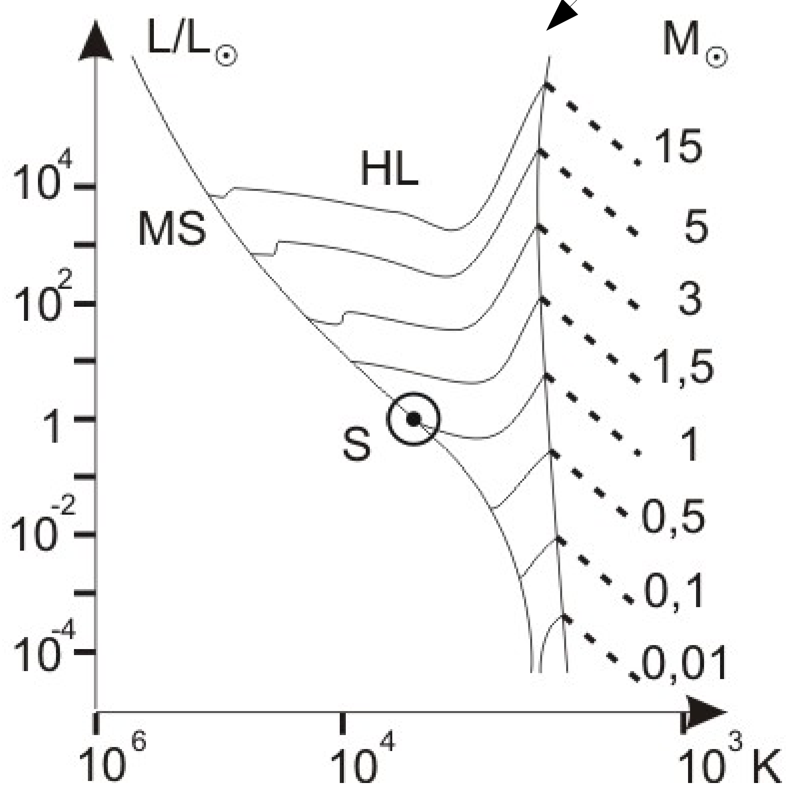


Pre Main Sequence Evolution

Birthline - The Hayashi limit

Lowest temperature that can maintain hydrostatic equilibrium

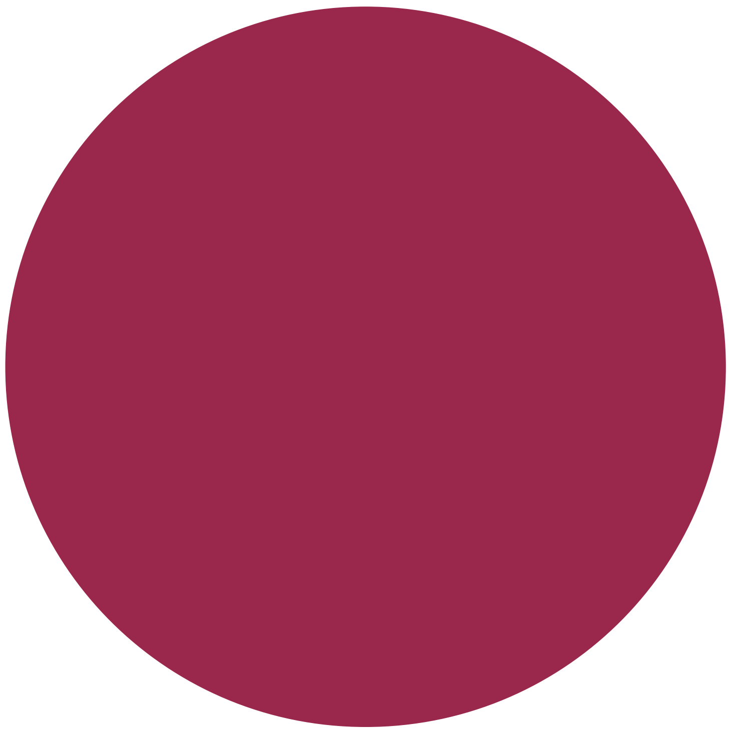
Hayashi calculated the maximum radius that a star in hydrostatic equilibrium can have.



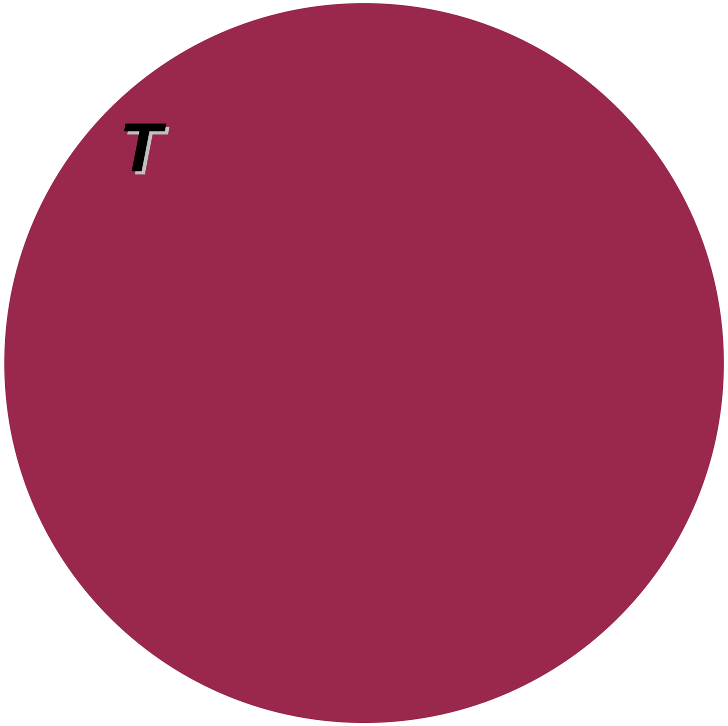
Hayashi forbidden zone

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

Pre Main Sequence Evolution

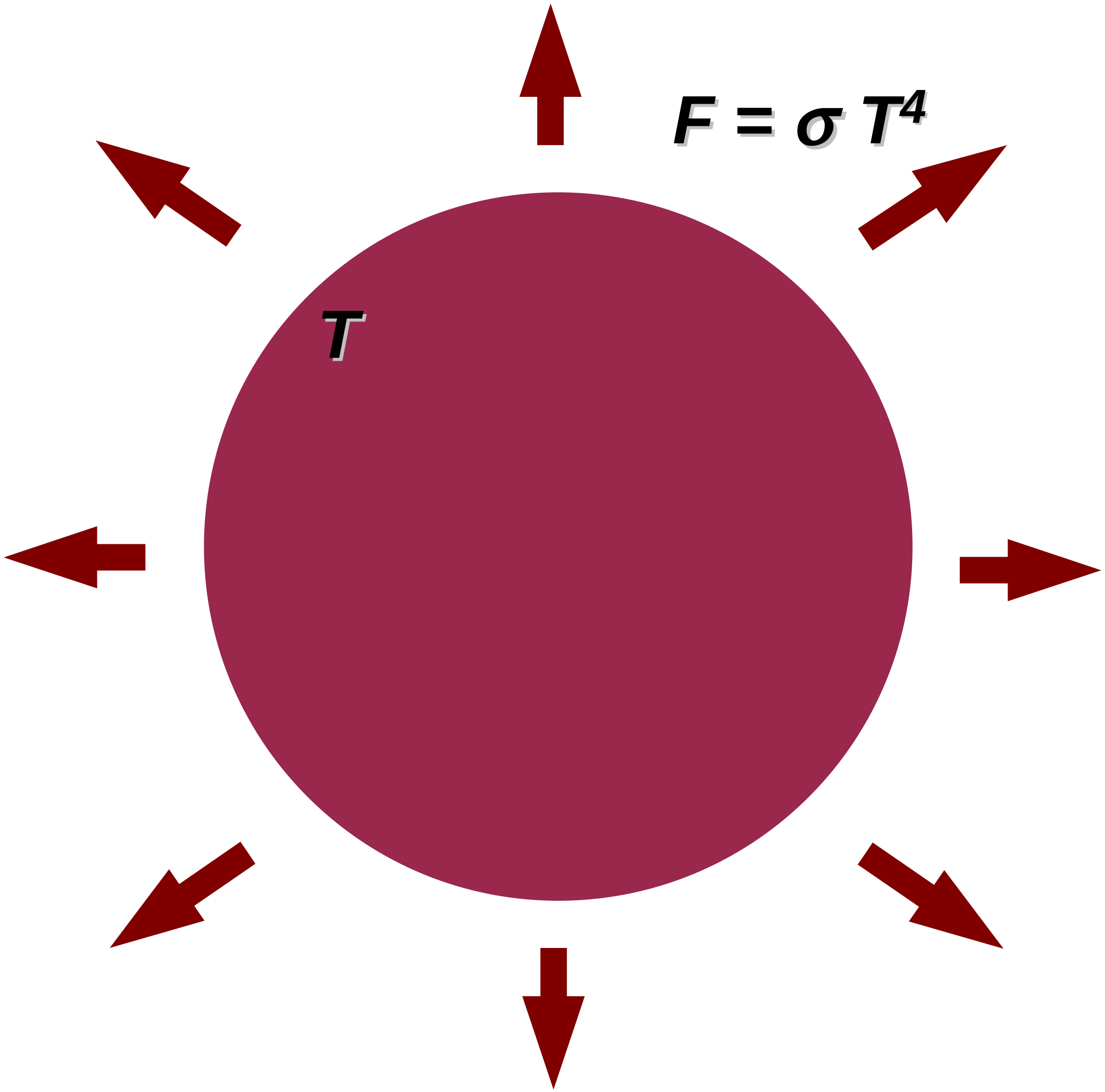


Pre Main Sequence Evolution



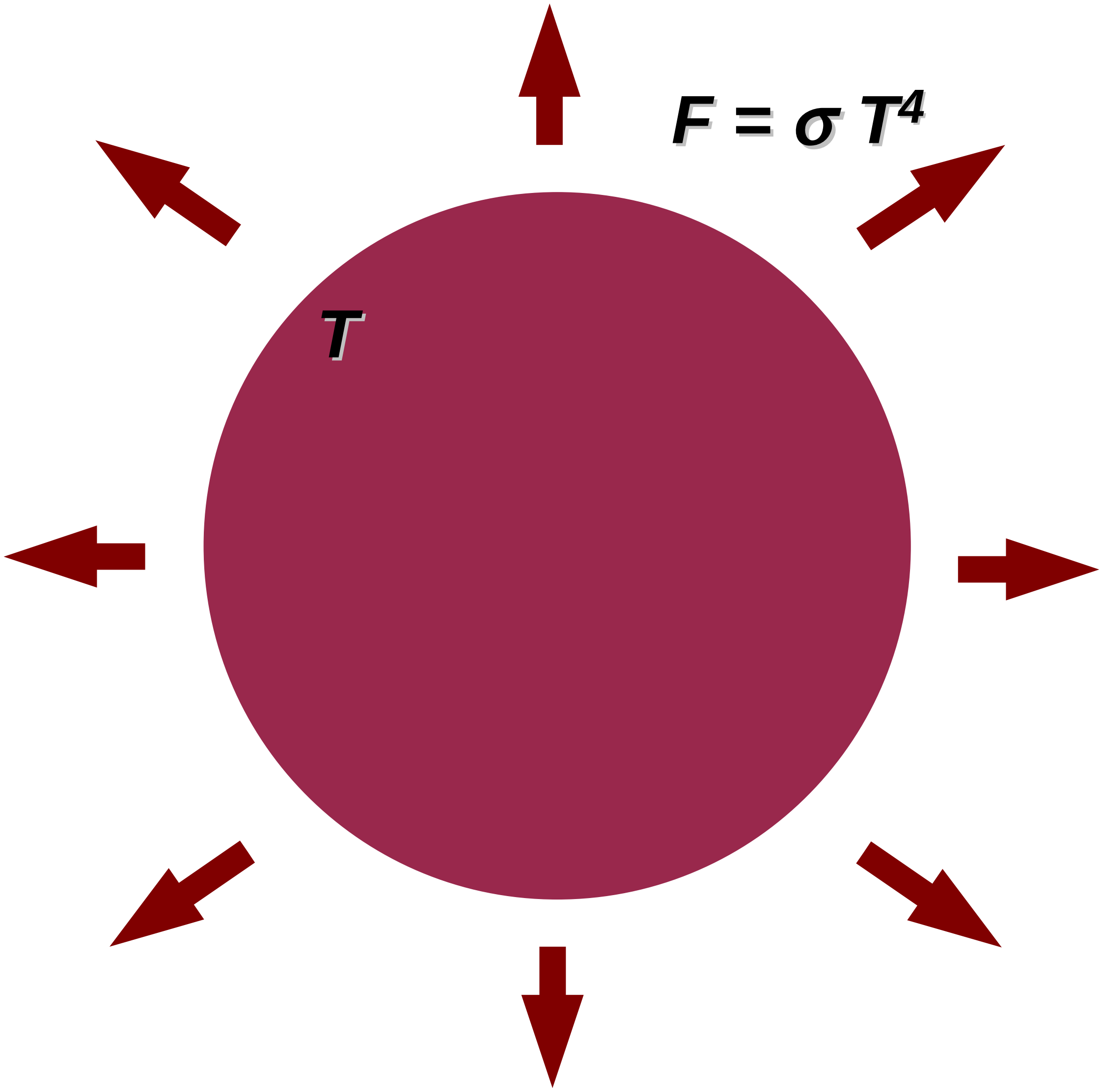
It has a temperature

Pre Main Sequence Evolution



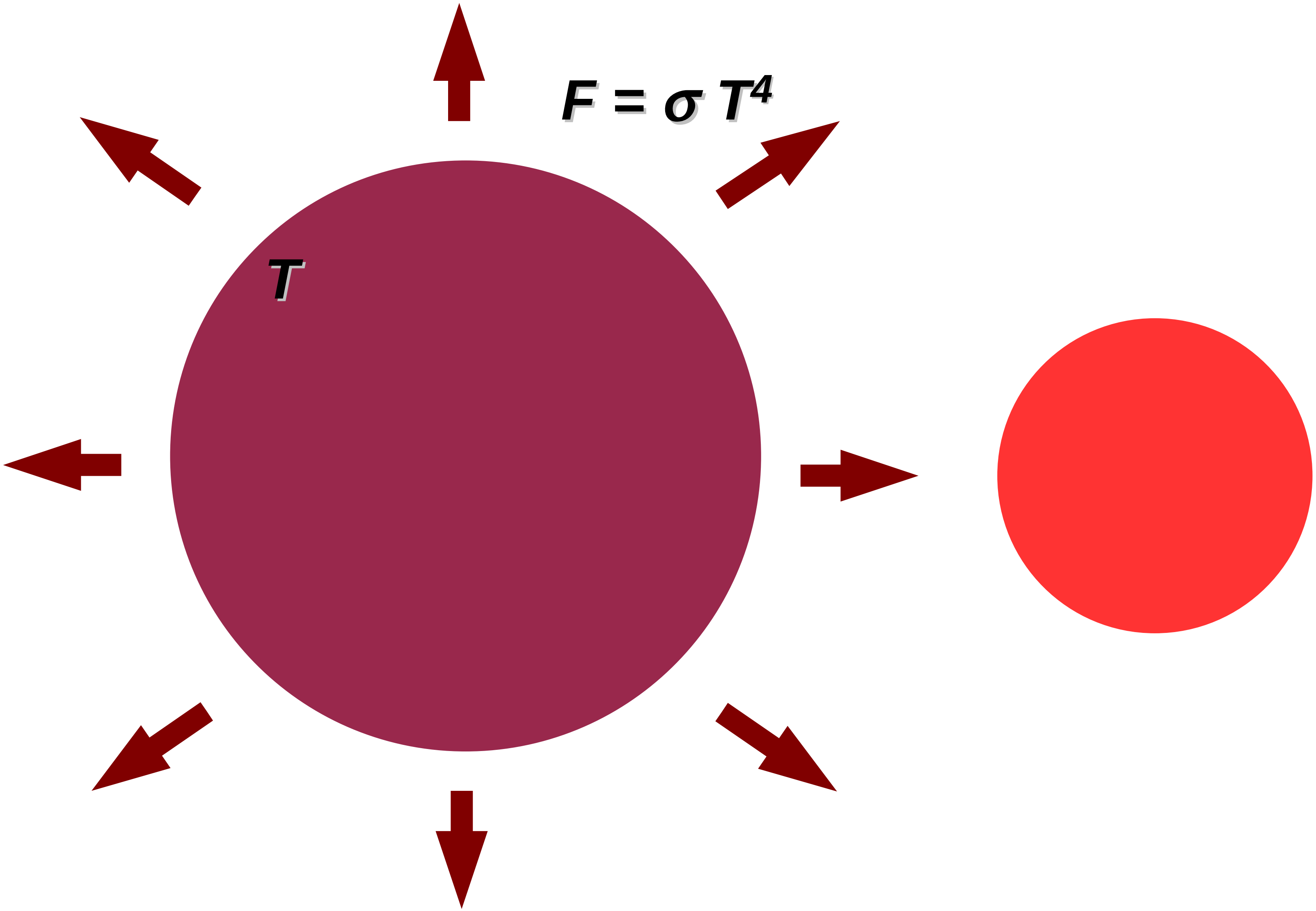
It has a temperature, thus a flux

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



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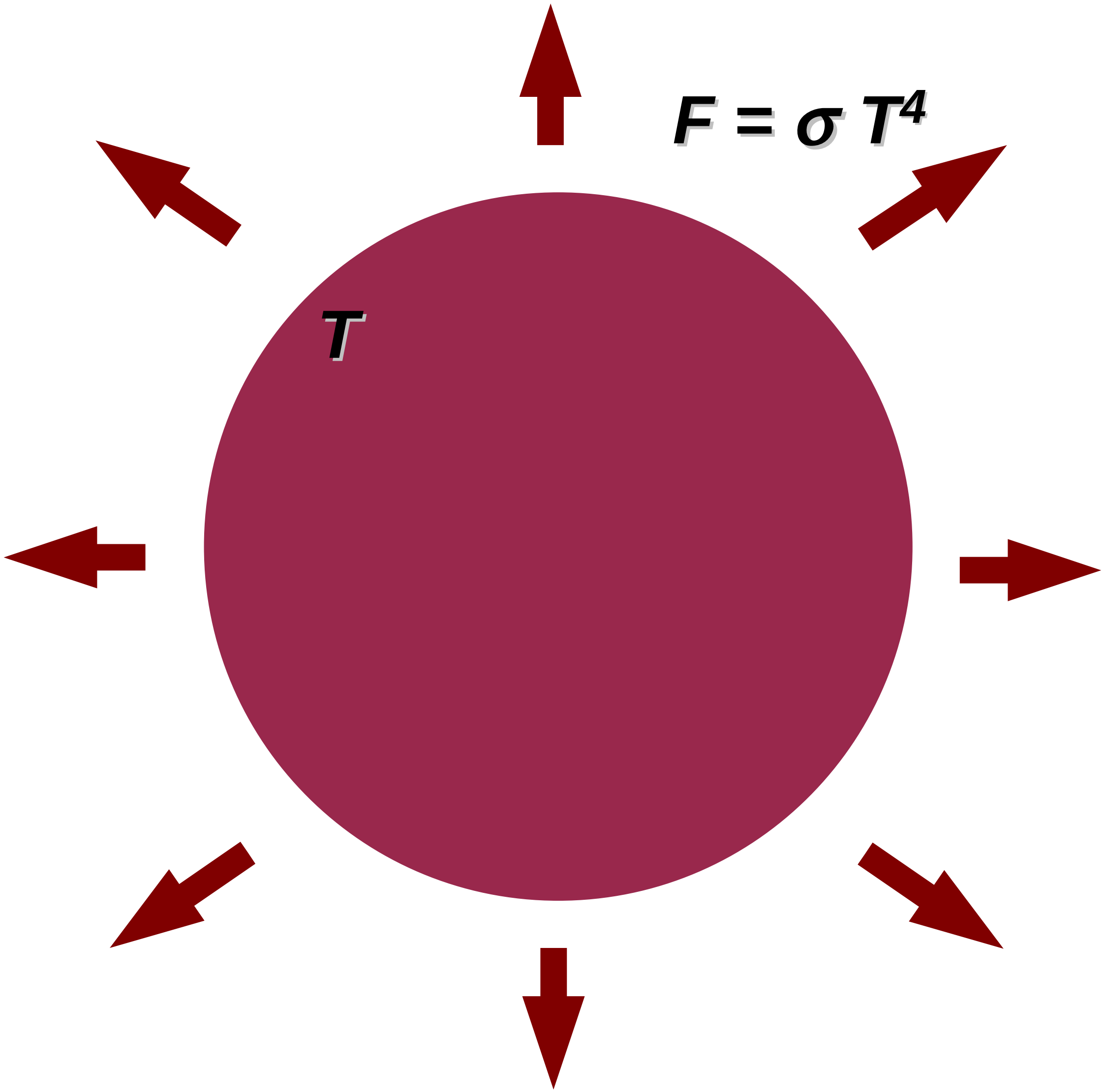

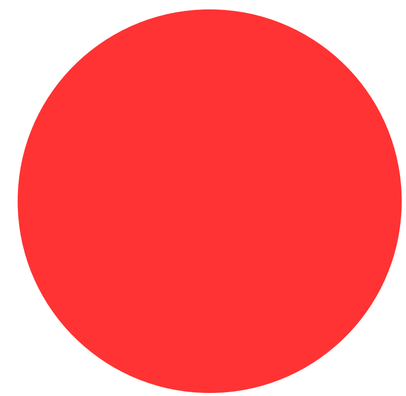

Contraction raises the pressure
The star heats up
Energy is radiated away
The star loses support and contracts

It has a temperature, thus a flux
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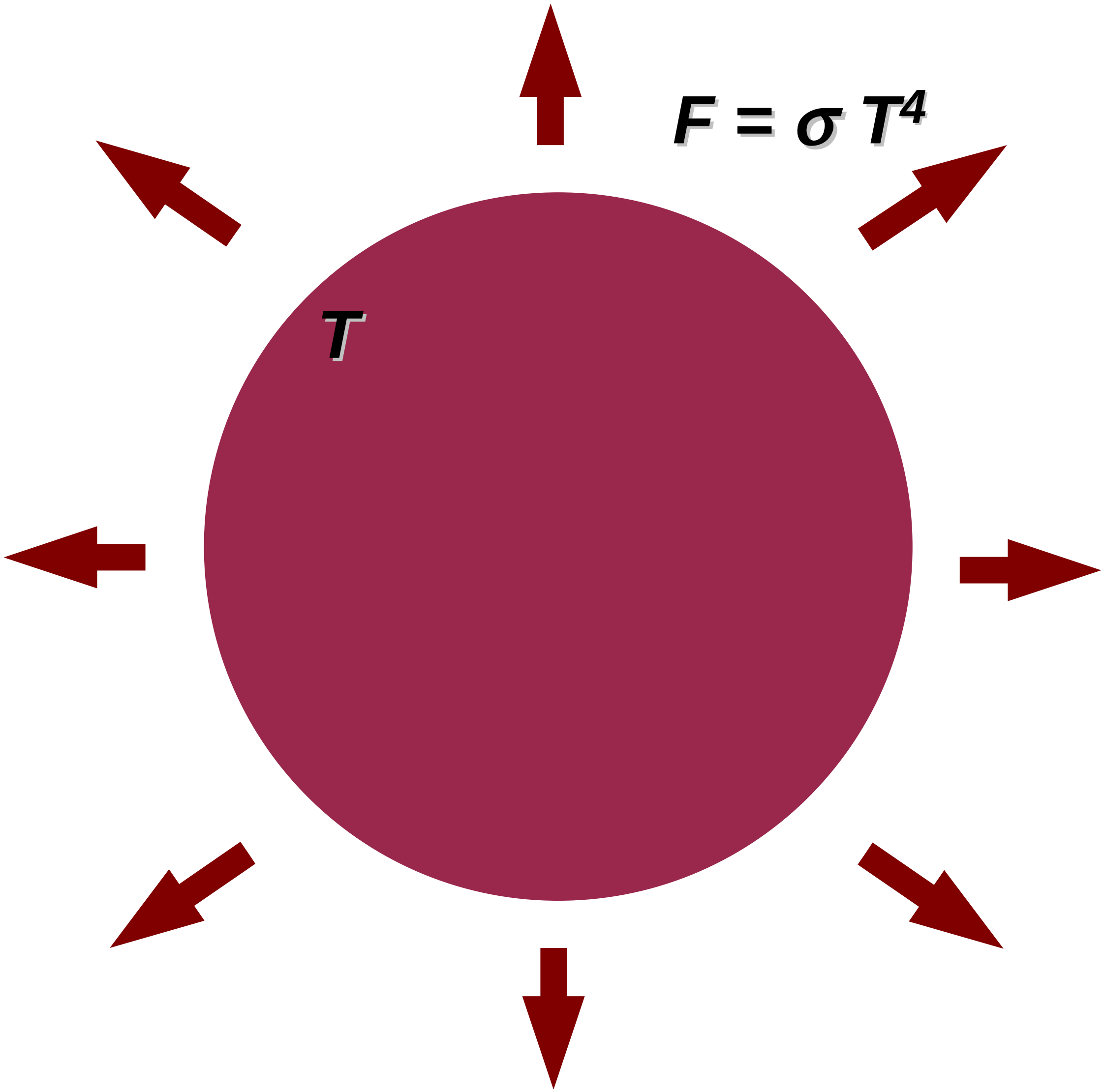
Pre Main Sequence Evolution



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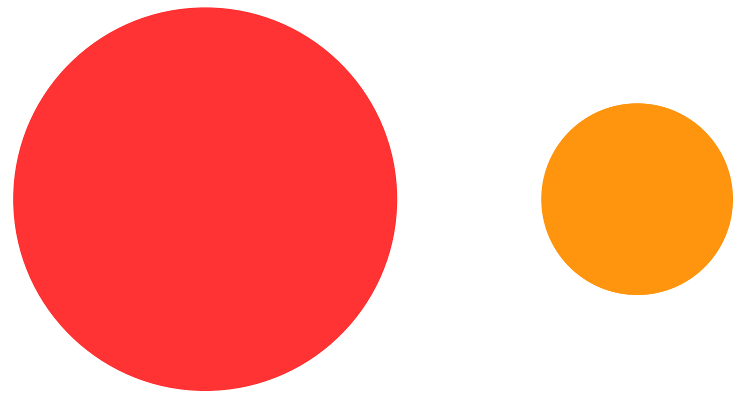

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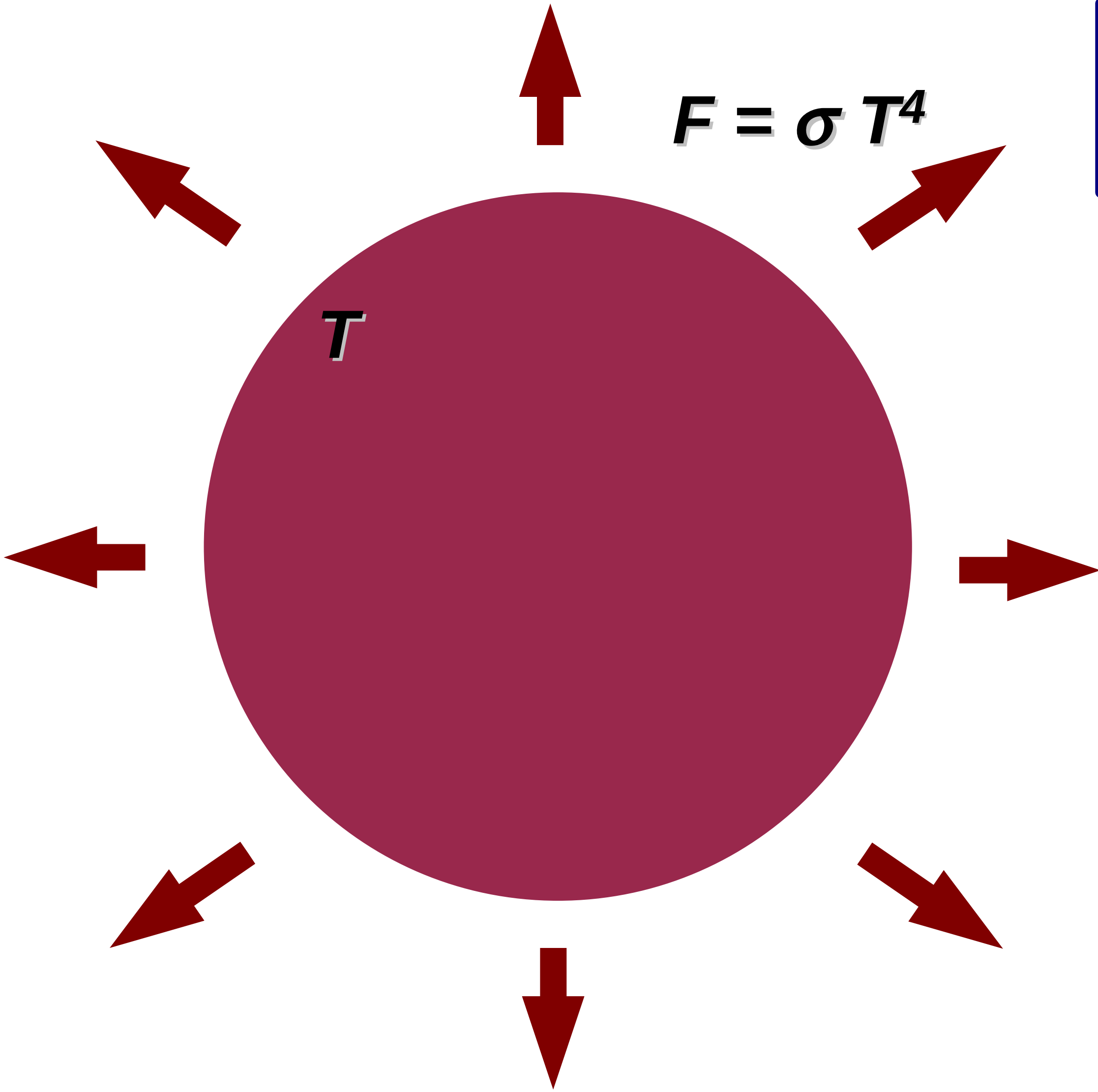
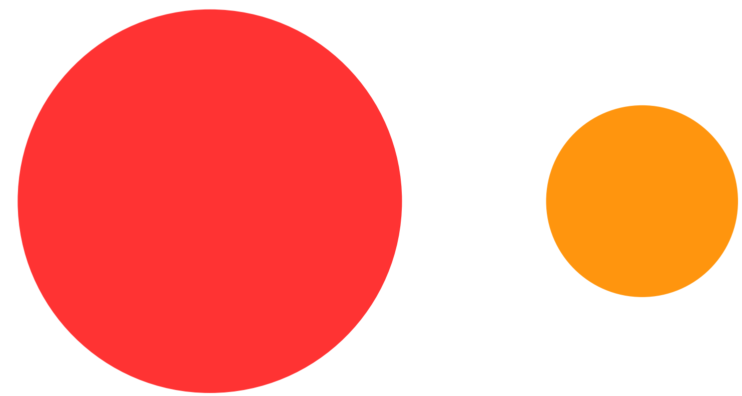
Pre Main Sequence Evolution



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
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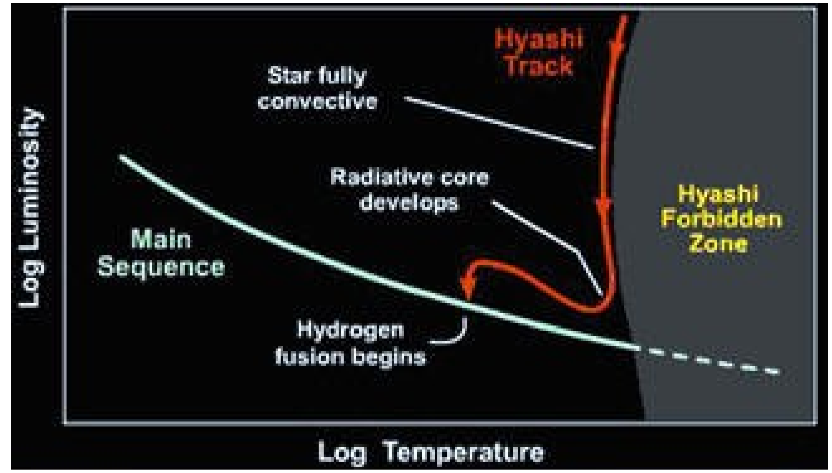
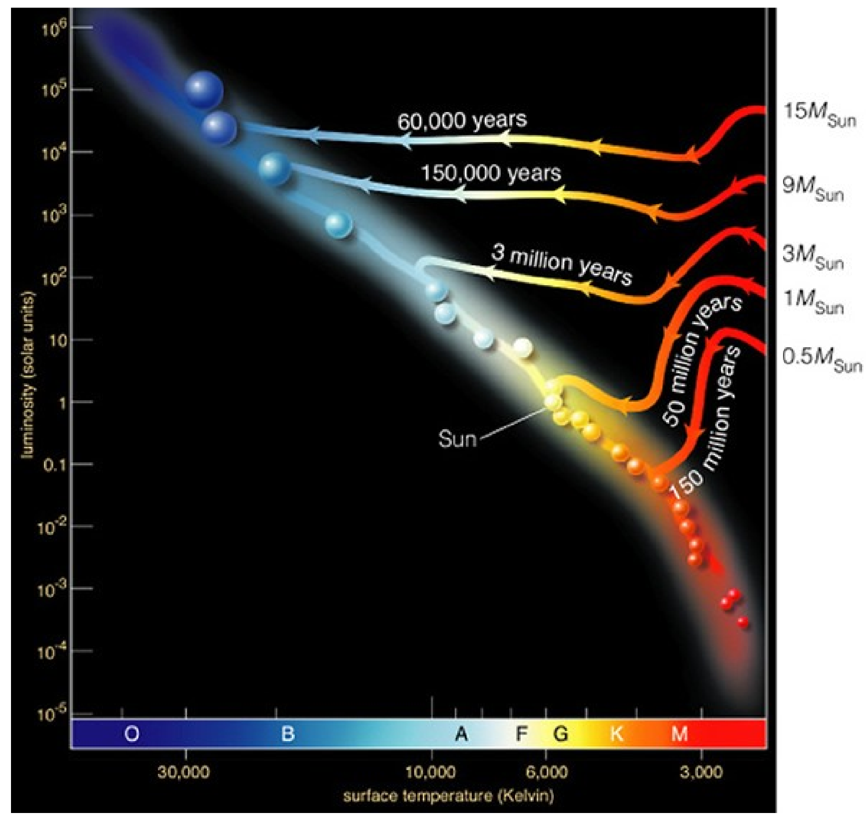
Pre Main Sequence Evolution

Hayashi Tracks

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

Slow contraction under quasi-hydrostatic equilibrium





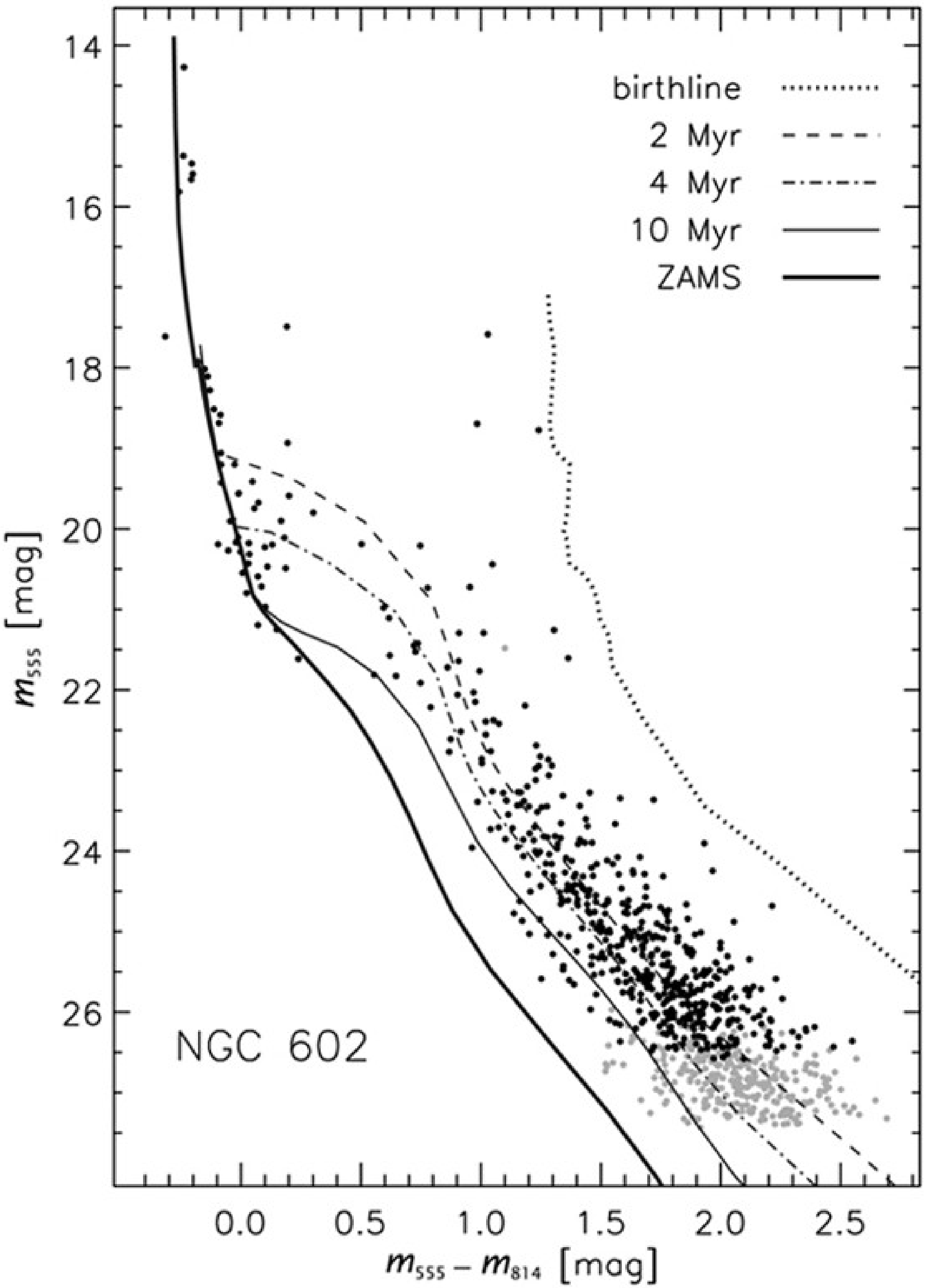
End or pre main sequence evolution?

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

Nuclear Processes

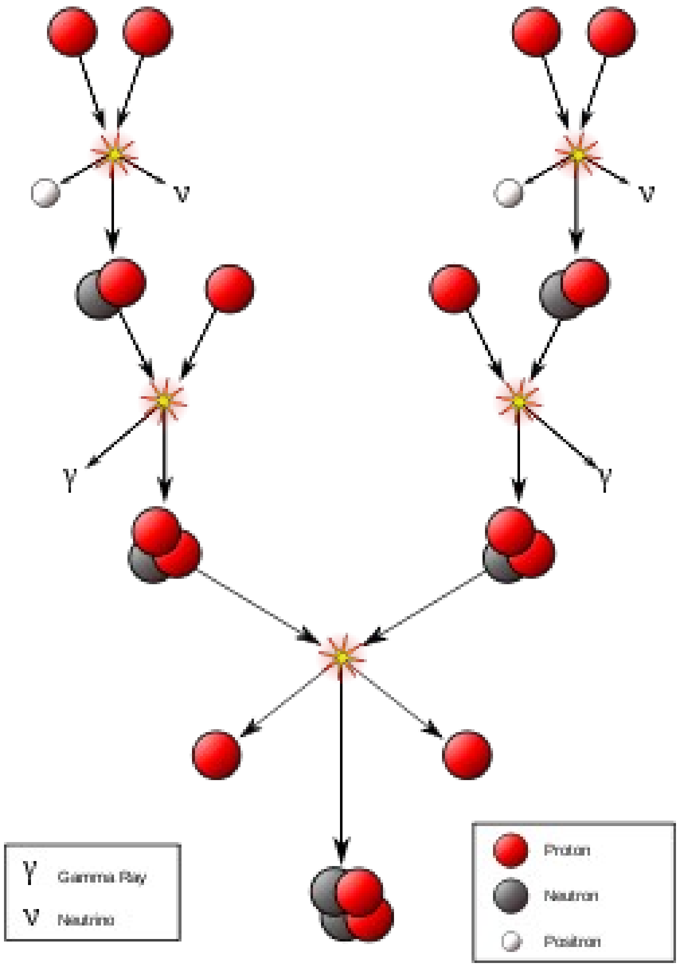
Proton proton chain

2 protons fuse into a deuterium. (one of the protons decayed into a neutron, a positron, and a neutrino)

Positrons instantly annihilate with electrons

Deuterium fuses with proton, makes helium-3

Two helium-3 fuse into helium-4.



Main fusion reaction for low mass stars

Nuclear Processes

CNO cycle

Main fusion reaction for stars more massive than 1.5 Solar mass

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

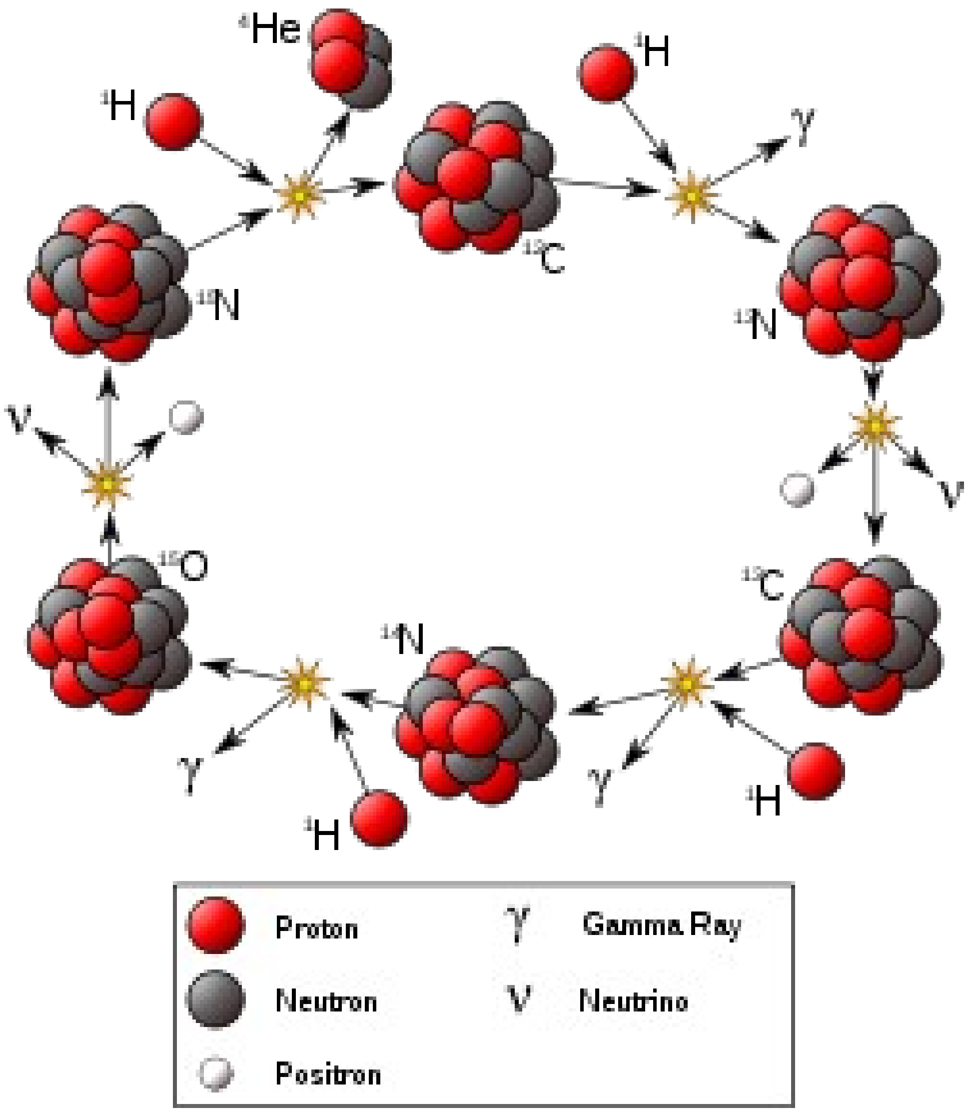
$$N_7^{13} \rightarrow C_6^{13} + \overline{e}_1^0 + \nu_0^0$$

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

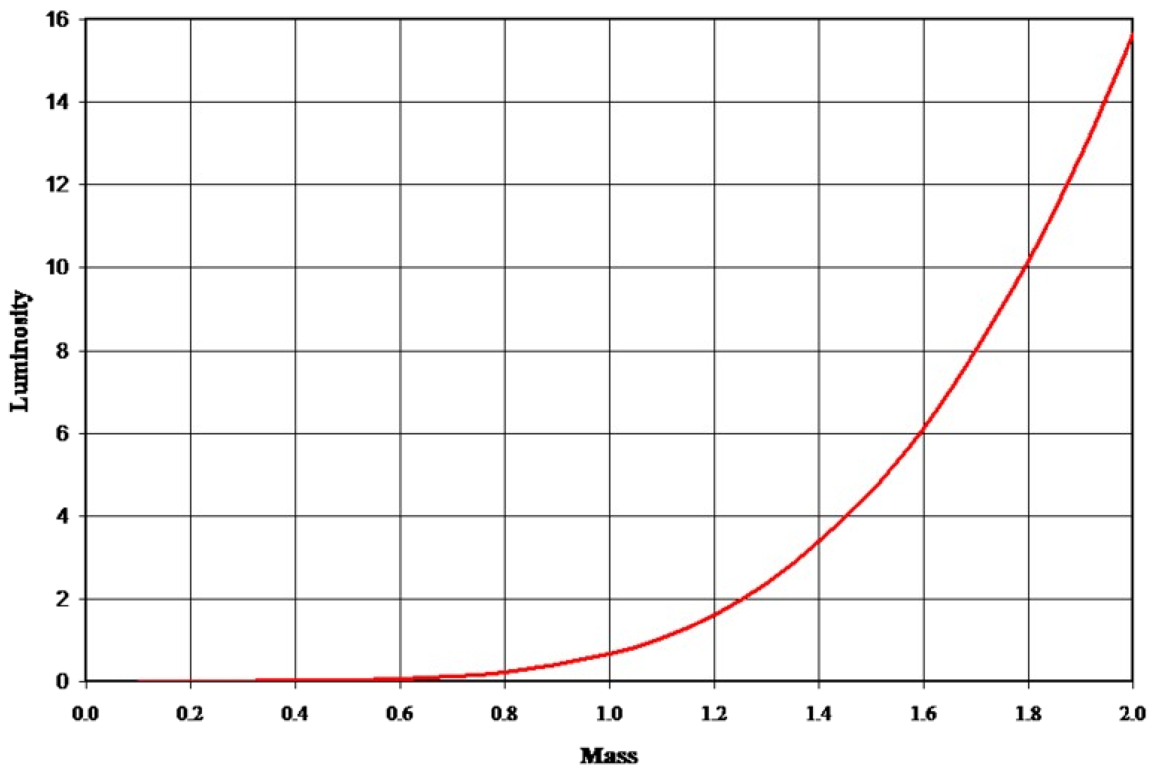
$$N_7^{14} + H_1^1 \rightarrow O_8^{15} + \gamma_0^0$$

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

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



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



$$L \propto M^{3.5}$$

$$E \propto M$$

$$t \propto M^{-2.5}$$

Lifetime in the Main Sequence

$$t_{star} / t_{Sun} = \left(M_{star} / M_{Sun} \right)^{-2.5}$$

10 Msun – 1 million years

1 Msun - 10 billion years

0.1 Msun – 100 trillion years

High mass stars life fast and die young.

Low mass stars will still be around long after we are gone

Let's summarize

The ISM is not empty. In dense molecular clouds, stars begin to form.

Star formation is governed by gravitational collapse. Thermal pressure opposes it.

Clouds are turbulent. Only the densest clumps form stars.

Angular momentum leads to a circumstellar disk.

Planets … formation.

…s

Let's summarize

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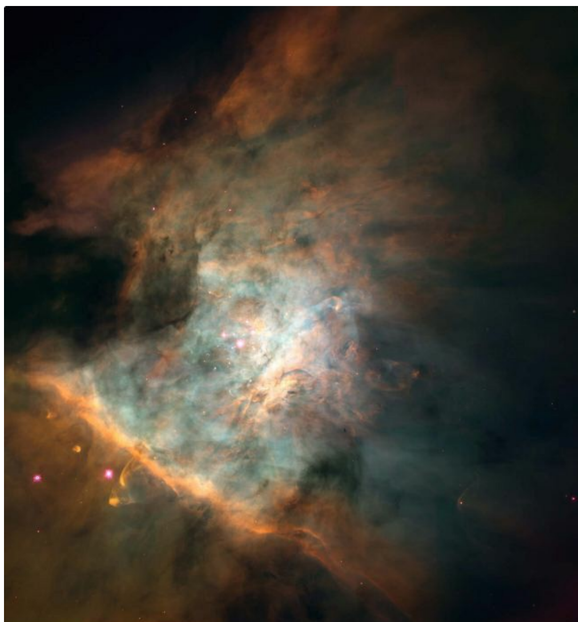


Molecular Cloud Fact Sheet

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

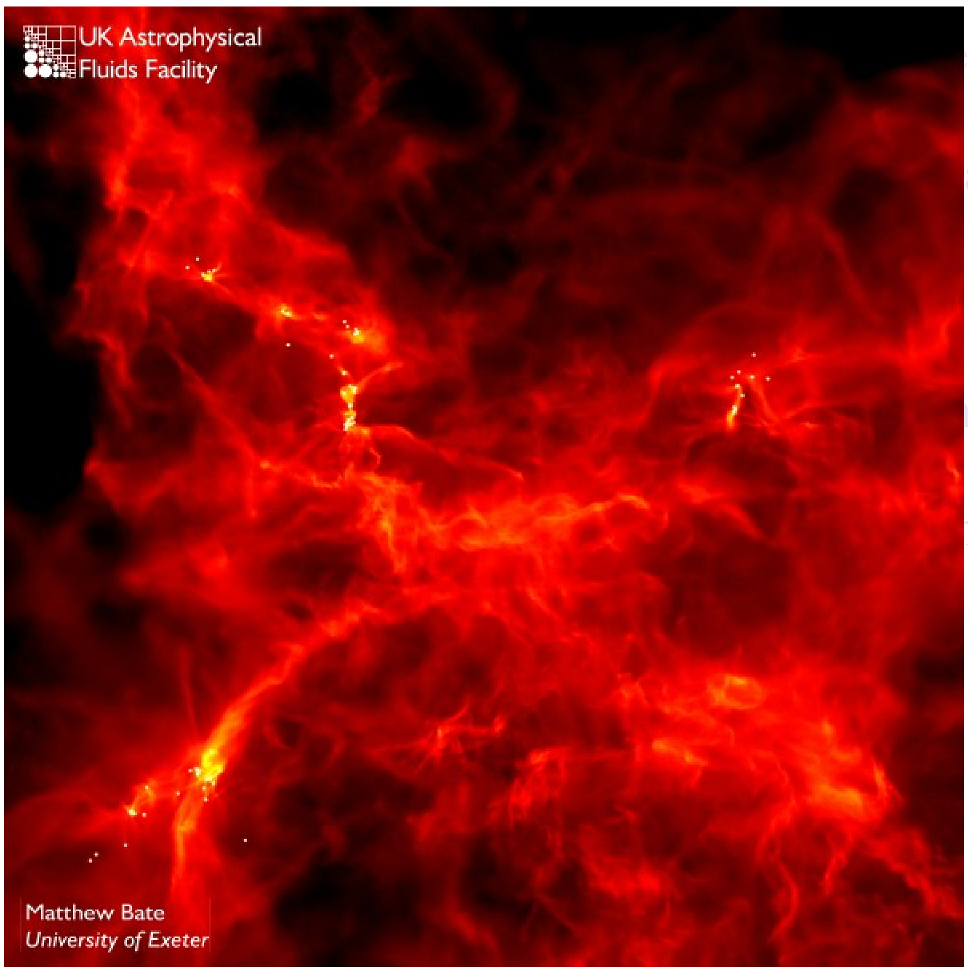
Sizes	10-100 parsecs
Mass	$10^2 - 10^6$ solar masses

Let's summarize

The ISM is not empty. In dense molecular clouds, stars begin to form.

Star formation is governed by gravitational collapse. Thermal pressure opposes it.

Clouds are turbulent. Only the densest clumps form stars.



Computer simulation

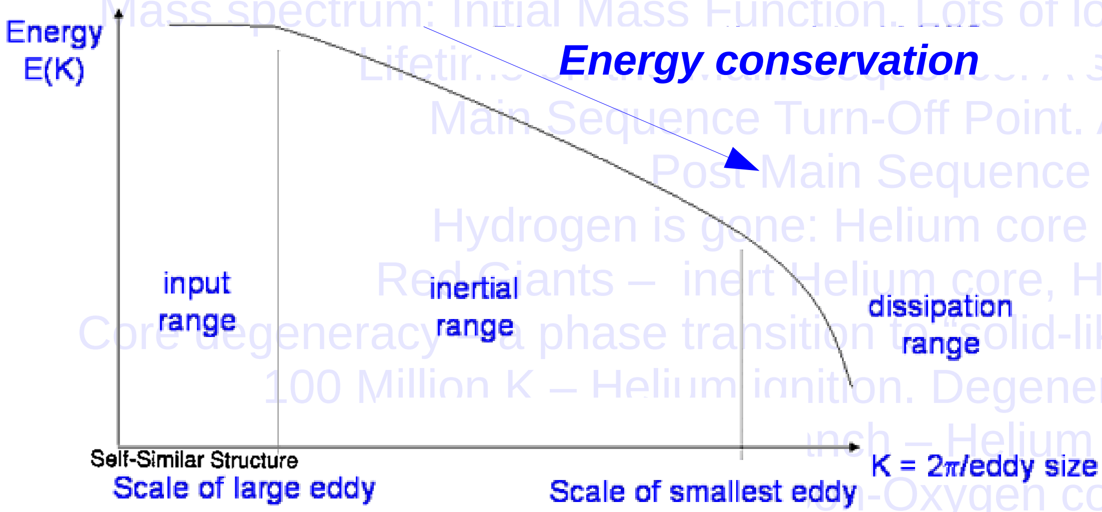
Observation

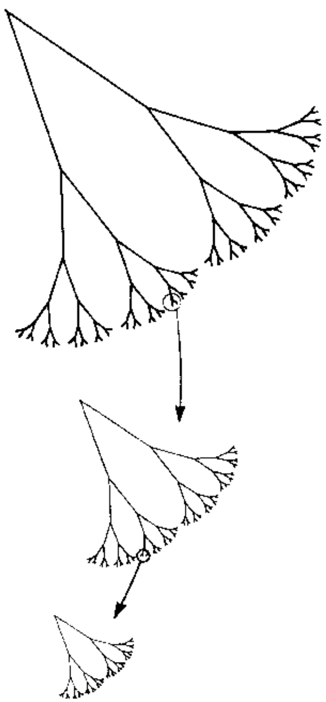
Let's summarize

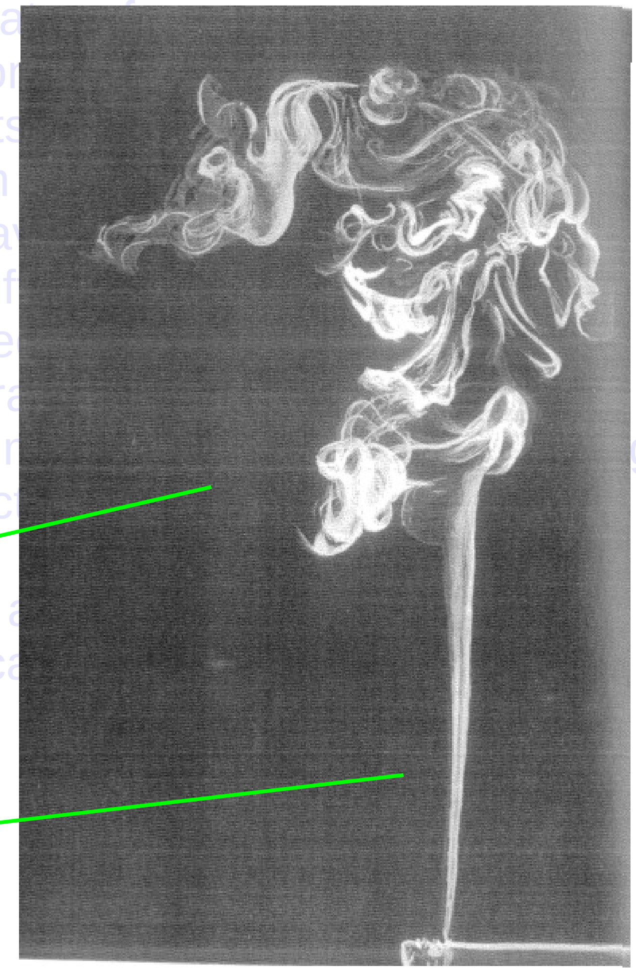
Turbulence is a self-similar flow. Size spectrum is well defined.

Turbulent fragmentation of a molecular cloud leads to a well defined mass spectrum.

Mass spectrum: Initial Mass Function. Lots of low mass stars, few high mass stars.







Turbulent flow

Laminar flow

Let's summarize

Turbulence is a self-similar flow. Size spectrum is well defined.

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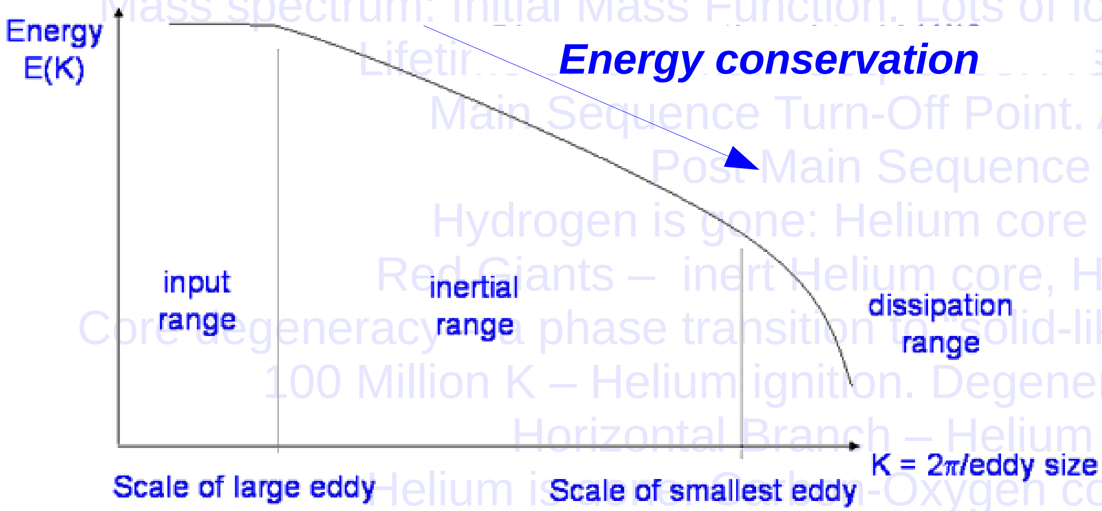
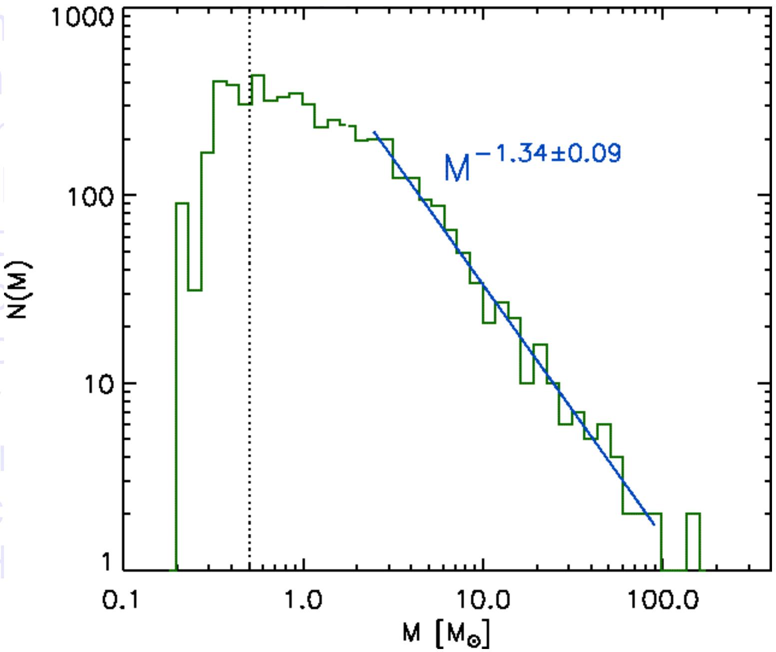
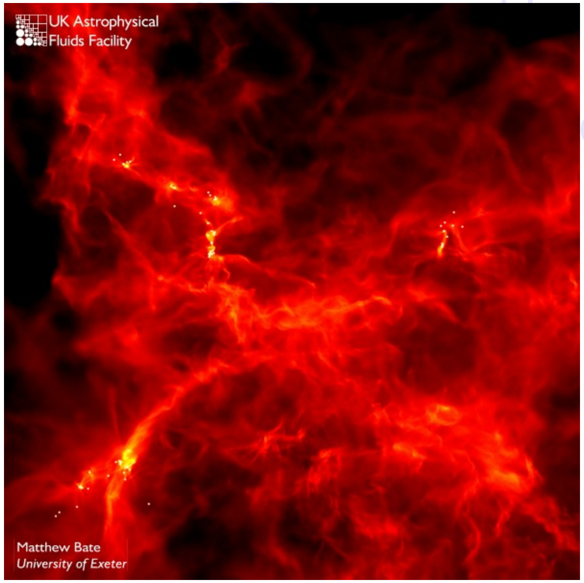
Mass spectrum: Initial Mass Function. Lots of low m Lifetim stron Main Sequence Turn-Off Point. An i Post Main Sequence Evol Hydrogen is gone: Helium core cont Red Giants – inert Helium core, Hydro Core degeneracy – a phase transition to "solid-like" b 100 Million K – Helium ignition. Degeneracy Horizontal Branch – Helium Mai Helium is gone: Carbon-Oxygen core c Asymptotic Giant Branch (AGB) star – inert CO core, H Violent pulsations eventually Planetary Nebula osed degenerate core is seen as a white dwarf White dwarfs cool in long timescales







Let's summarize

Turbulence is a self-similar flow. Size spectrum is well defined.

Turbulent fragmentation of a molecular cloud leads to a well defined mass spectrum.

Mass spectrum: ***Initial Mass Function***. Lots of low mass stars, few high mass stars.

Lifetime on the Main Sequence: A strong function of mass.

Main Sequence Turn-Off Point. An indicator of age.

Re … g

Core degenerac … ntraction stops.

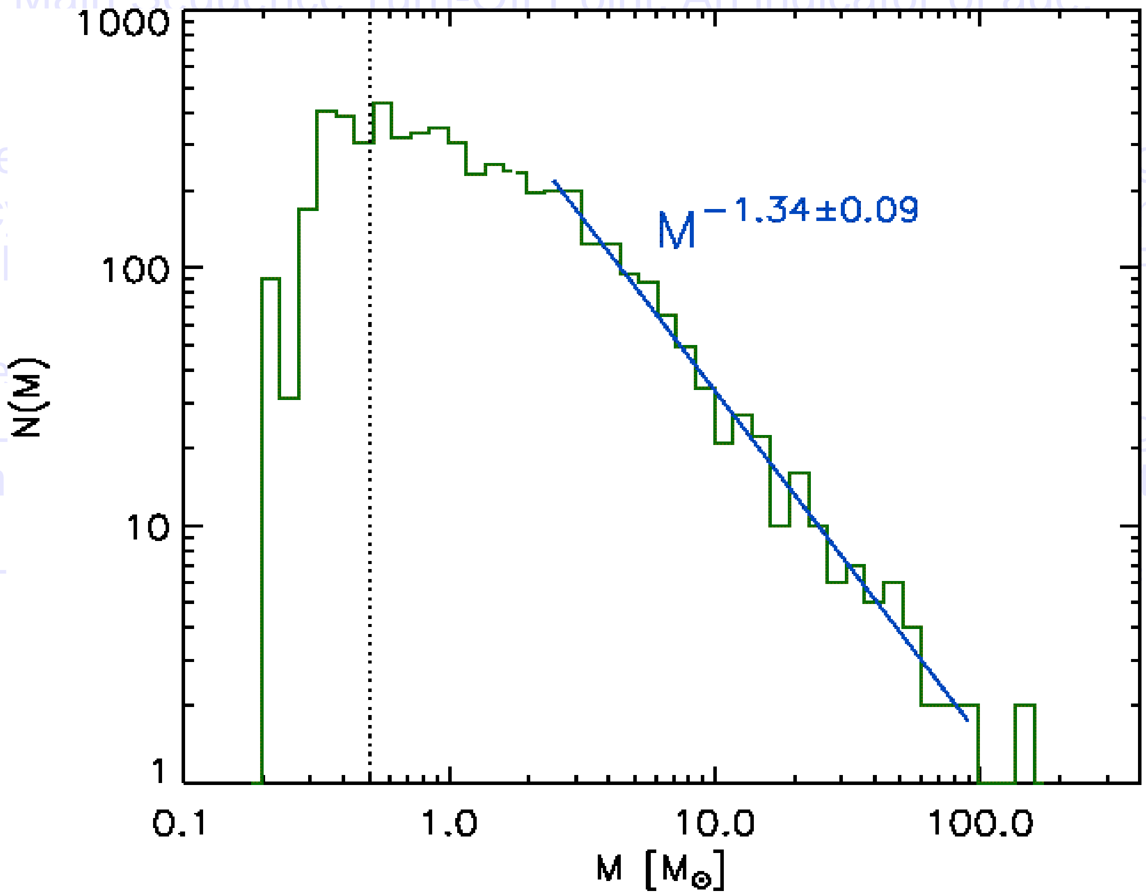
100 Mill … Flash)

He

Asymptotic Giant B … gen Shell Burning

AGB are un … tmosphere

T



Lots of low mass stars

Very few high mass stars

Most common mass: 0.5 Msun

Let's summarize

The ISM is not empty. In dense molecular clouds, stars begin to form.

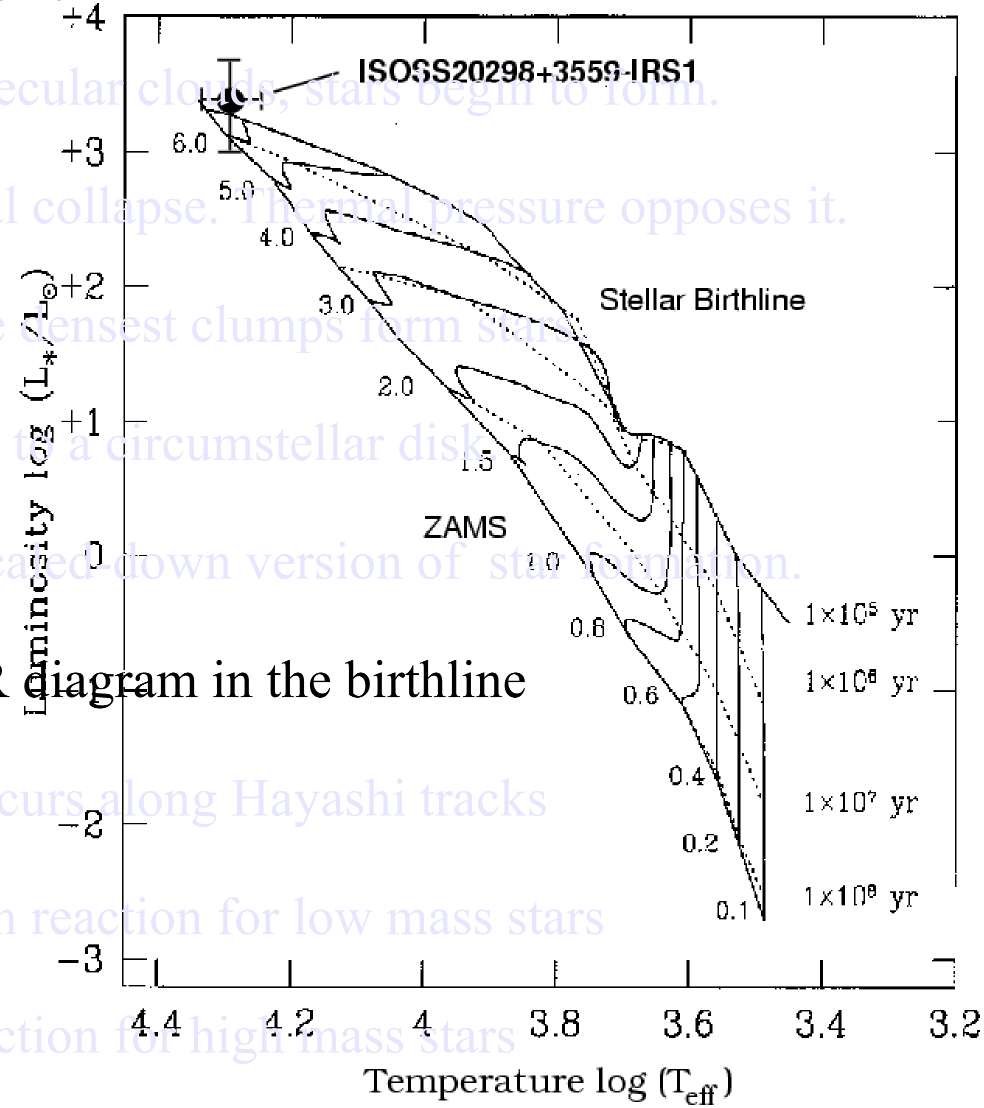
Star formation is governed by gravitational collapse. Thermal pressure opposes it.

Clouds are turbulent. Only the densest clumps form stars.

Angular momentum leads to a circumstellar disk.

Planets form in the turbulent disk in a scaled-down version of star formation.

Protostars appear in the HR diagram in the birthline



Gravitational contraction occurs along Hayashi tracks

Proton-proton chain is the main reaction for low mass stars

CNO cycle is the main reaction for high mass stars

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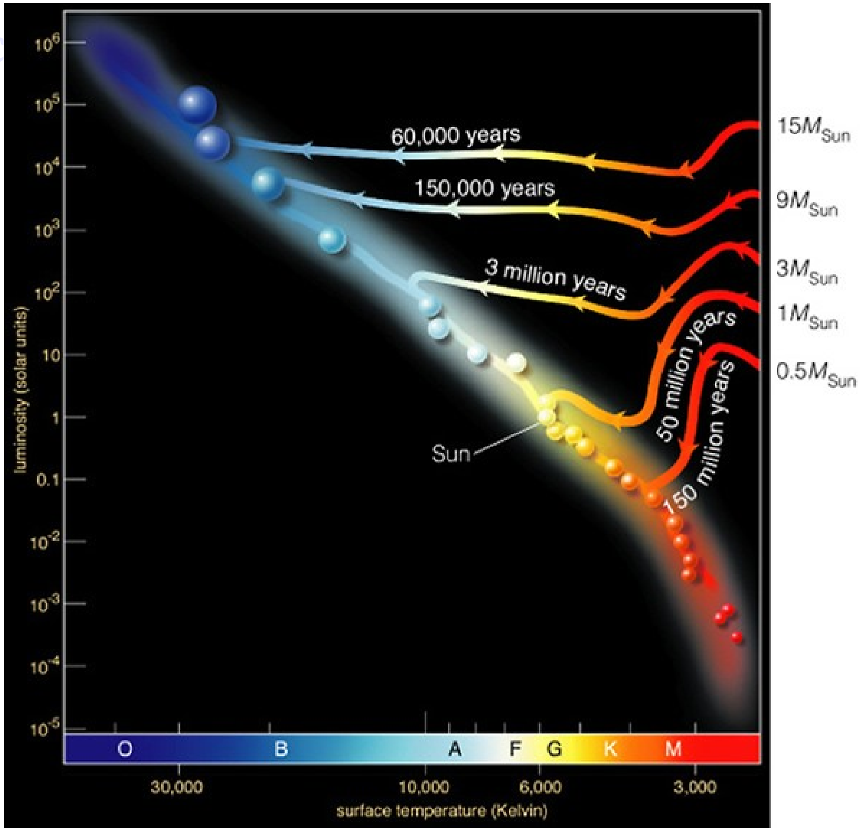

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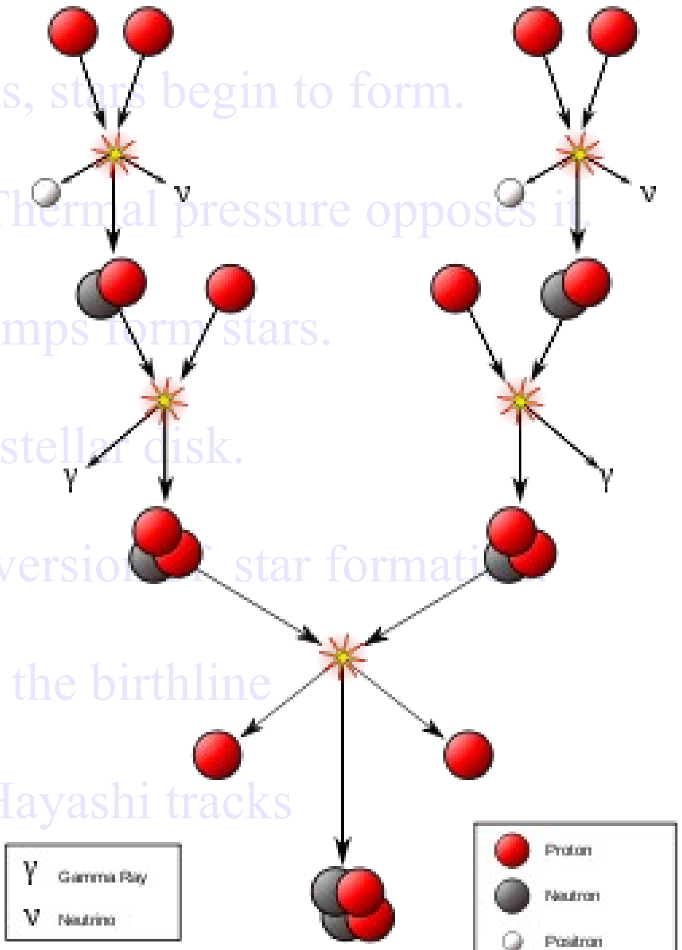

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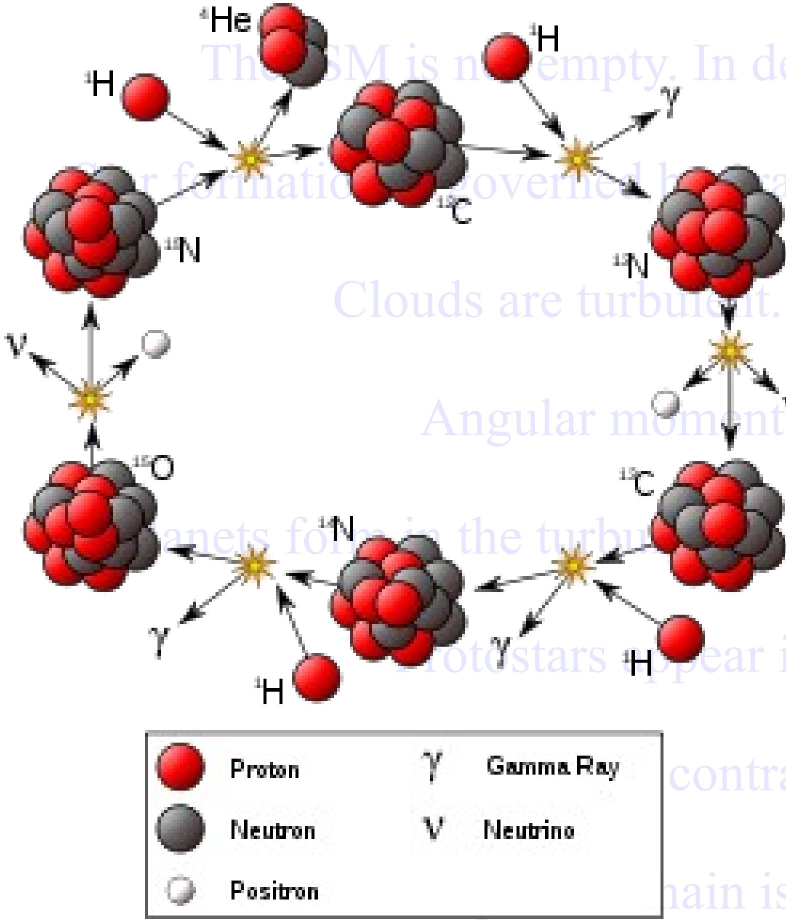

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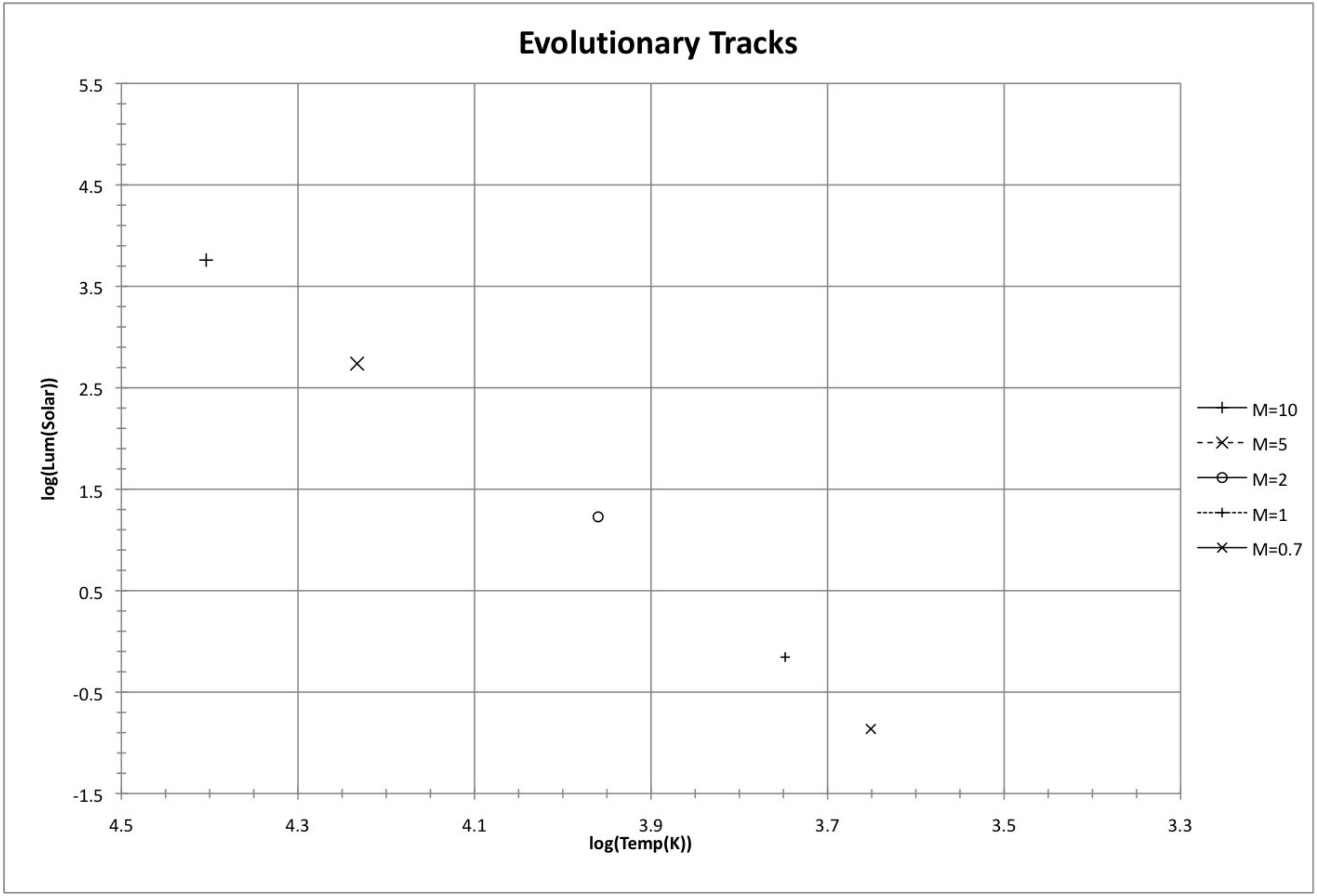
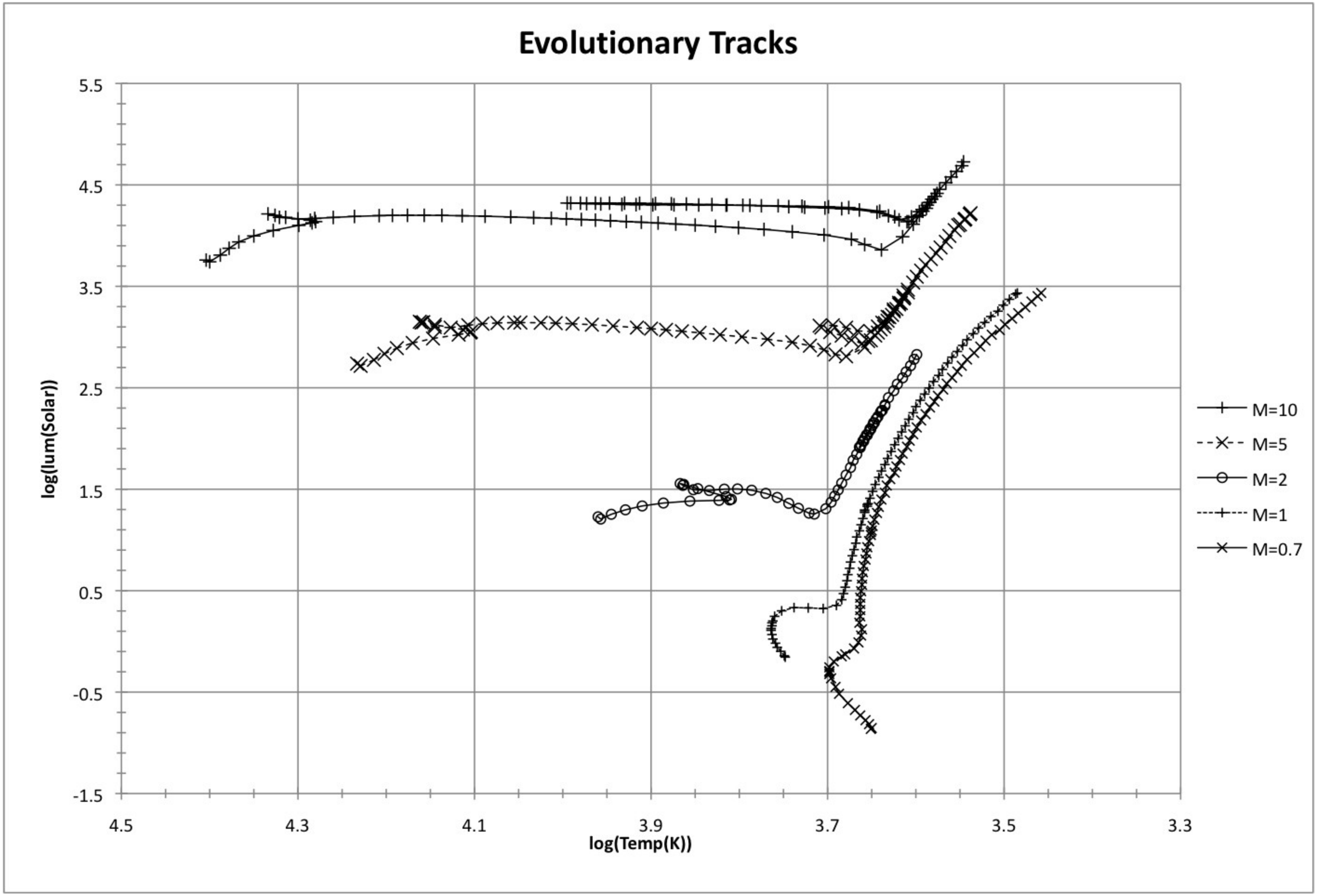


Evolutionary Tracks
log(Lum(Solar))
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
4.5
4.3
4.1
3.9
3.7
3.5
3.3
log(Temp(K))
M=10
M=5
M=2
M=1
M=0.7



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