The turbulent birth of planets

Wladimir (Wlad) Lyra
Sagan Fellow

NASA-JPL/Caltech

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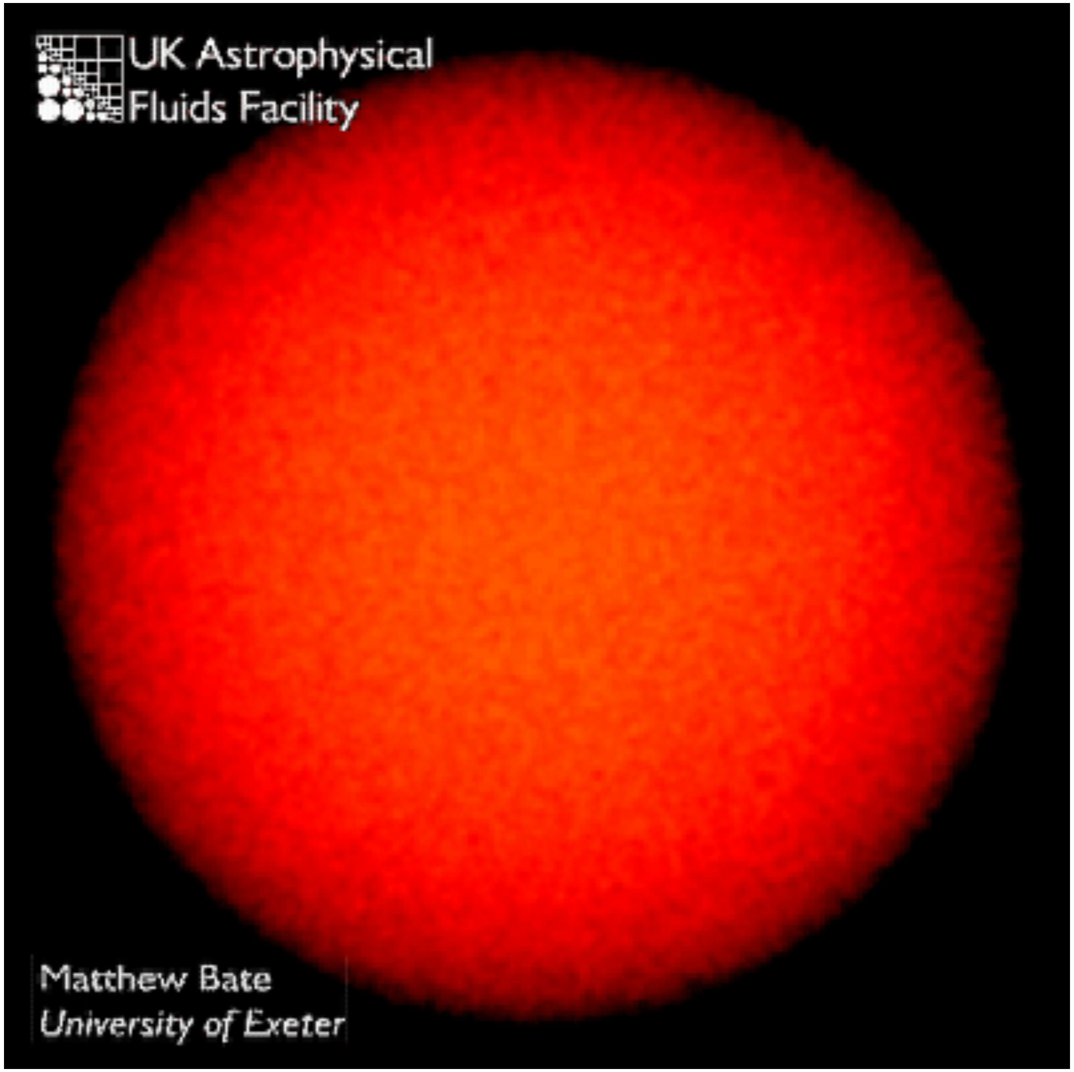
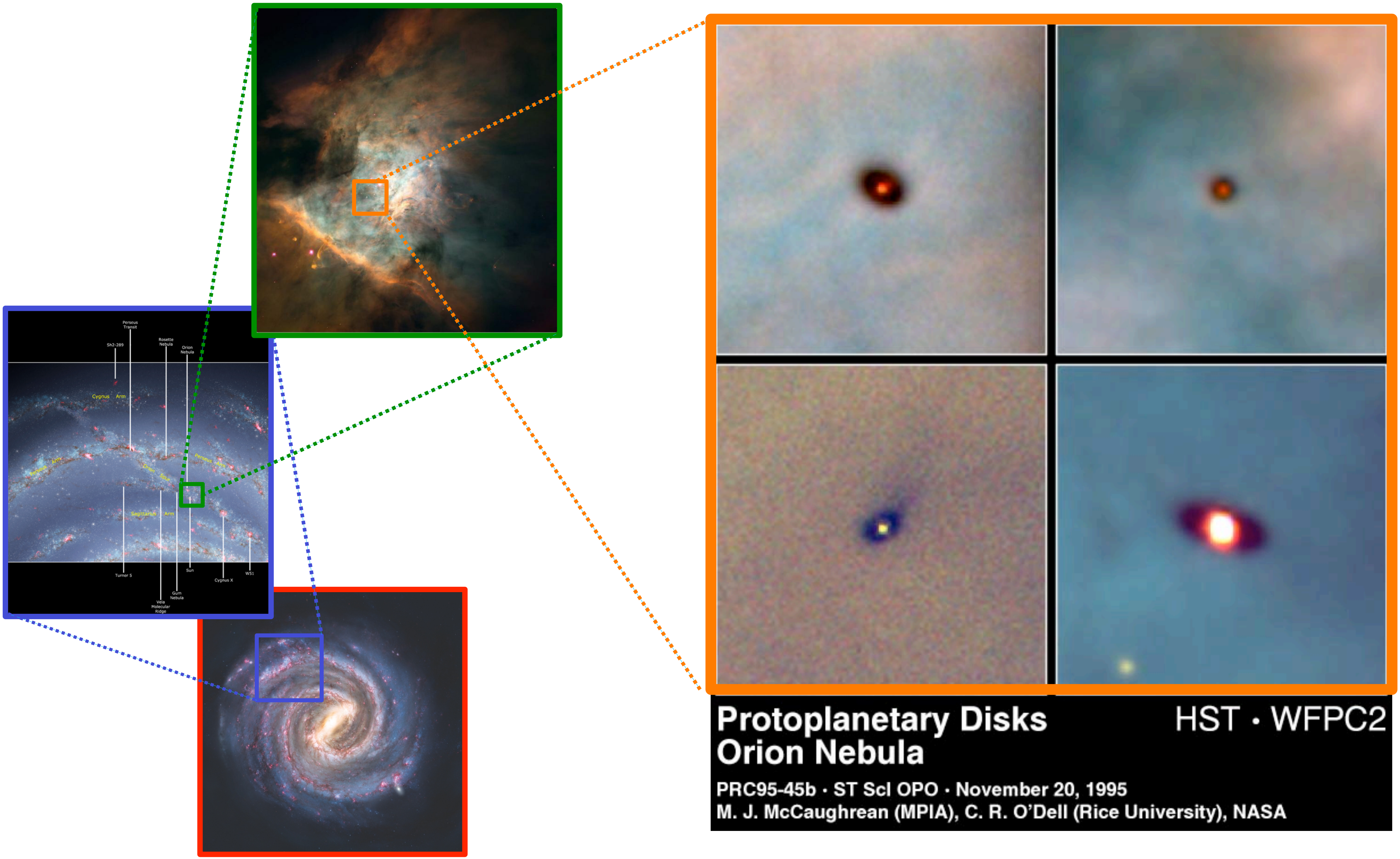
Star Formation



Protoplanetary Disks



Protoplanetary Disks

PP disk fact sheet

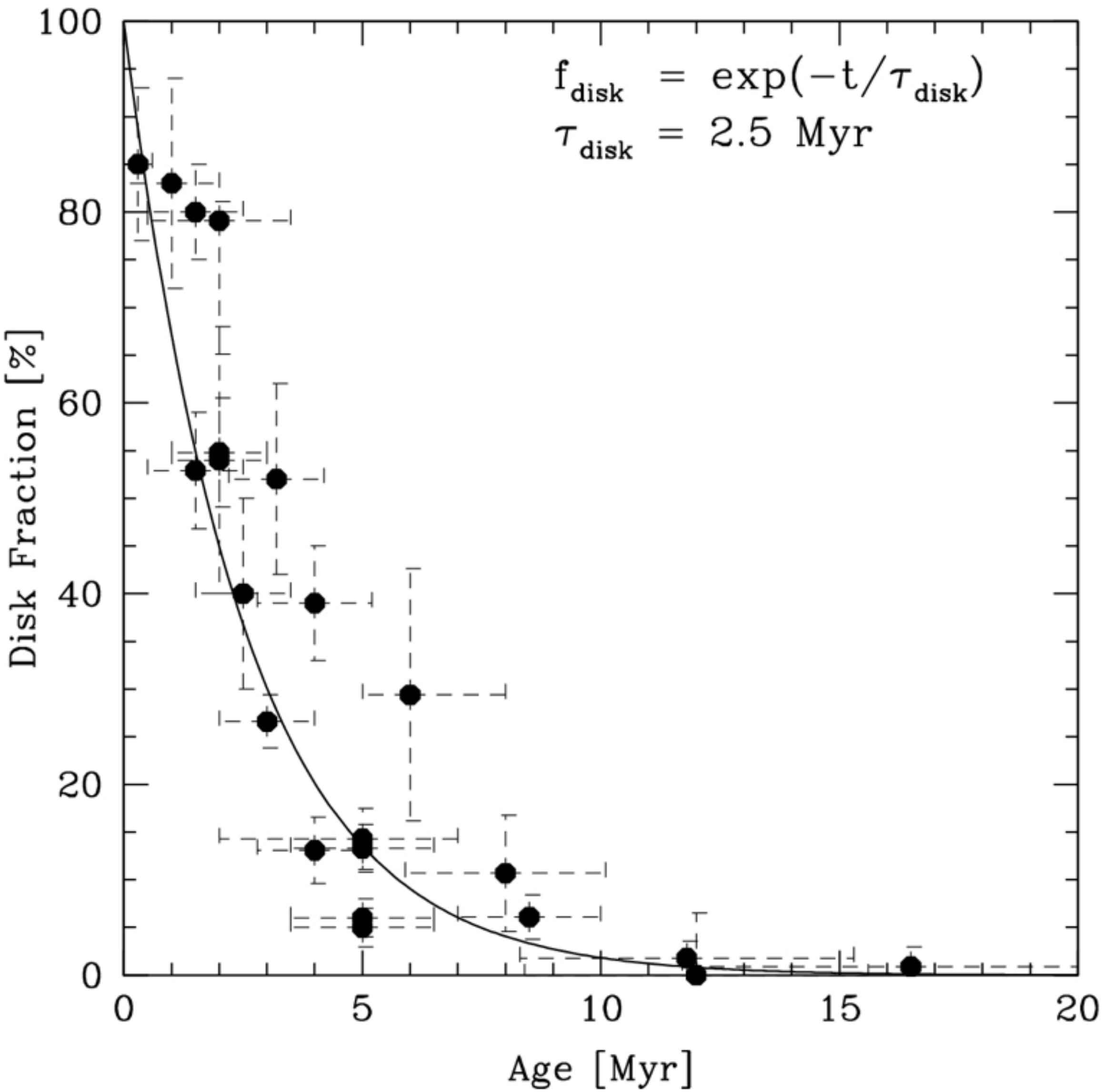
Density: 10^{13} - 10^{15} cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

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

Mass: 10^{-3} - 10^{-1} $M_{\odot}$
($1\ M_{\odot} = 2 \times 10^{33}$ g)

Disk Lifetime



Mamajek et al. (2009)

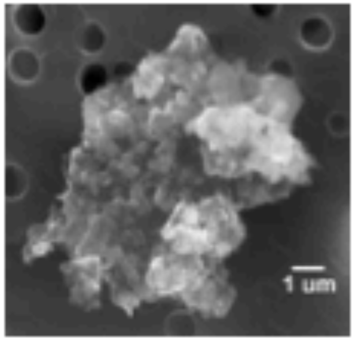
Disks evaporate with an *e*-folding time of *2.5 Myr*.

Take-home message #1:

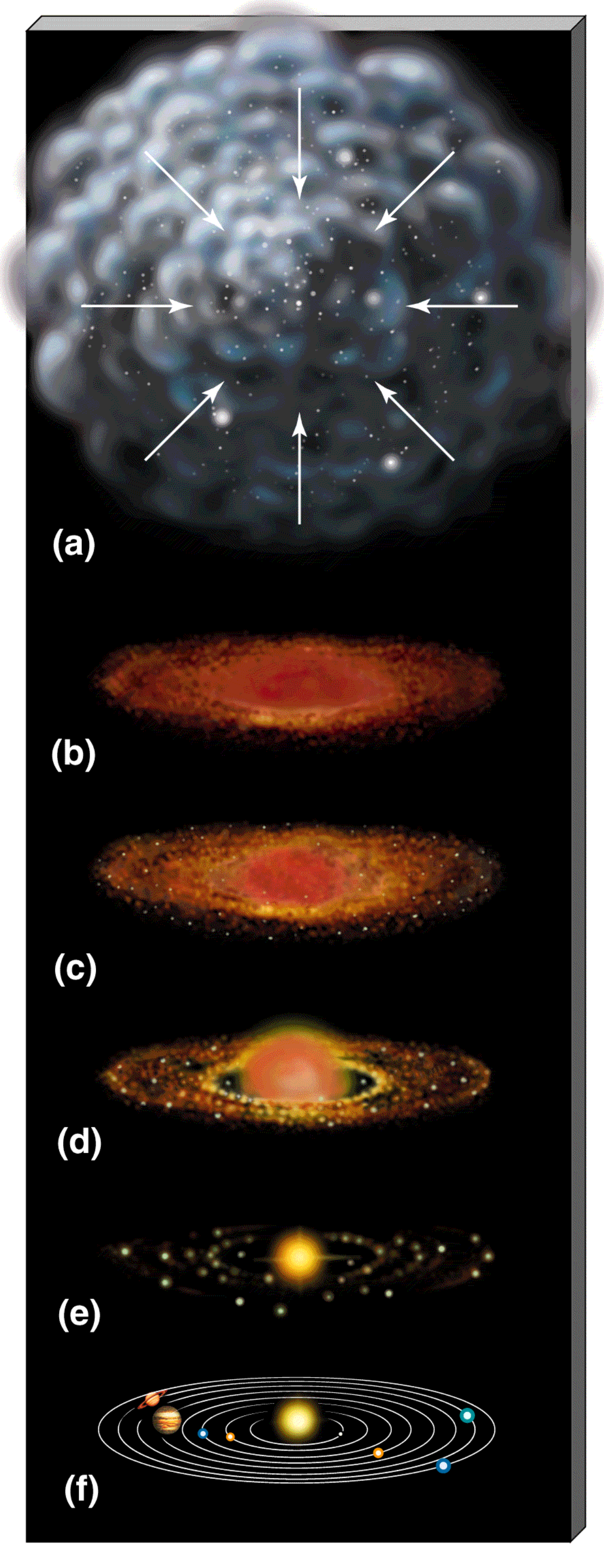
Planet formation
must happen within
10 million years

Planet Formation

"Planets form in disks of gas and dust"



A miracle happens →



Planet formation timeline

(a) Collapse of gas cloud (t = 0)
$n \sim 10^4 - 10^5$ cm^{-3} $T \sim 10$K

(b) **Protostar with disk** ($t \sim 0.1$ - 1 Myr)
$n \sim 10^5 - 10^8$ cm^{-3} $T \sim 10$-300 K

(c) **Planet Formation** ($t \sim 1$-10 Myr)
$n \sim 10^{14} - 10^{15}$ cm^{-3} $T \sim 10$-1000 K

(d) Disk evaporation ($t \sim 10$ Myr)

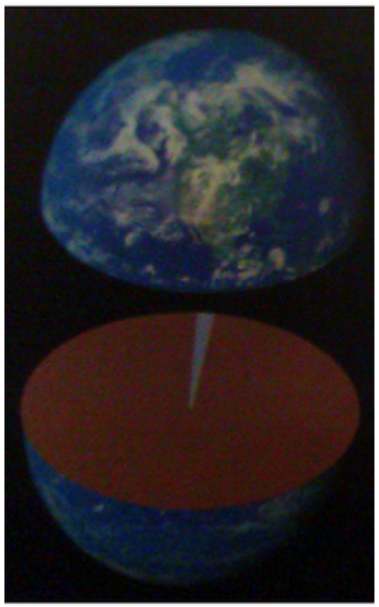
(e) Leftover disk of dust and debris ($t > 10$ Myr)
$n \sim 10$-100 cm^{-3}

(f) ***TA-DAH !!!***

Classes of planets

Rocky Planets

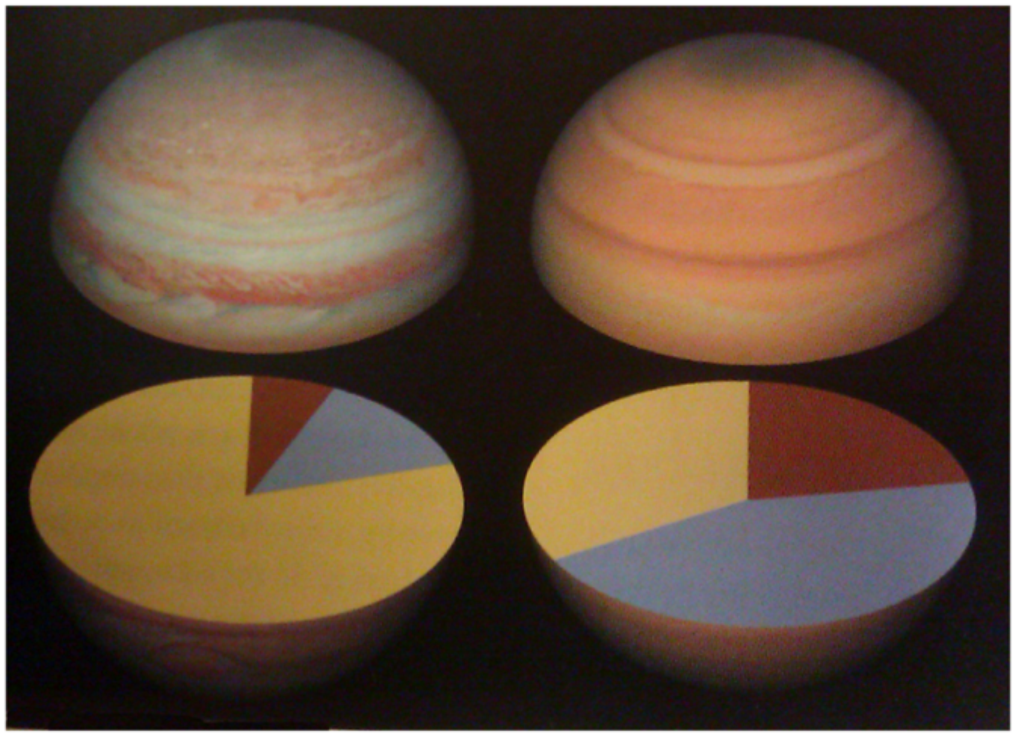
Earth



Gas Giants

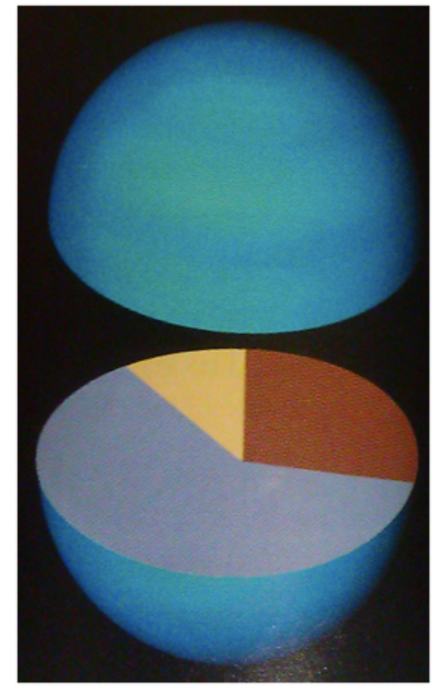
Jupiter

Saturn



Ice Giants

Uranus/Neptune



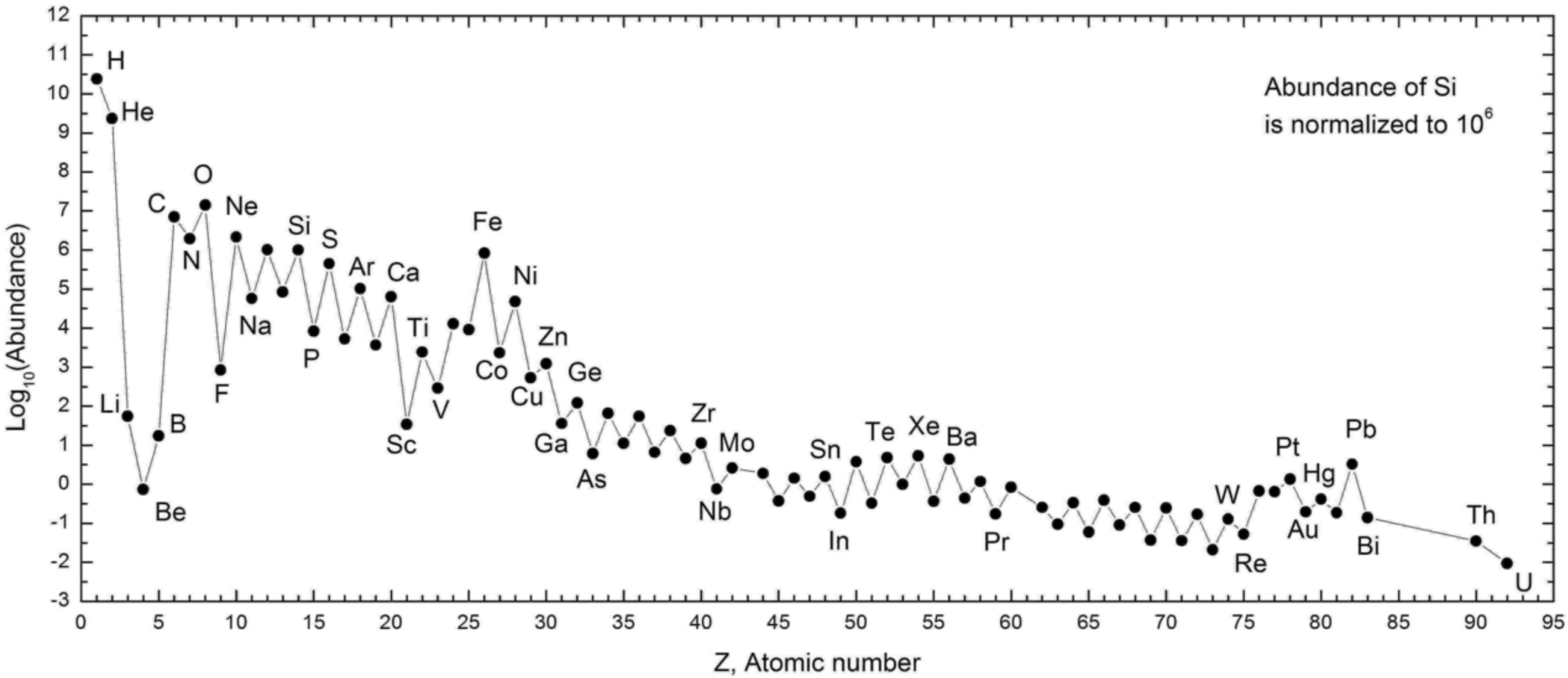
Rock

Gas

Ice

Chemical Composition

The chemical composition of the Sun



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

H (71%) He (27%)

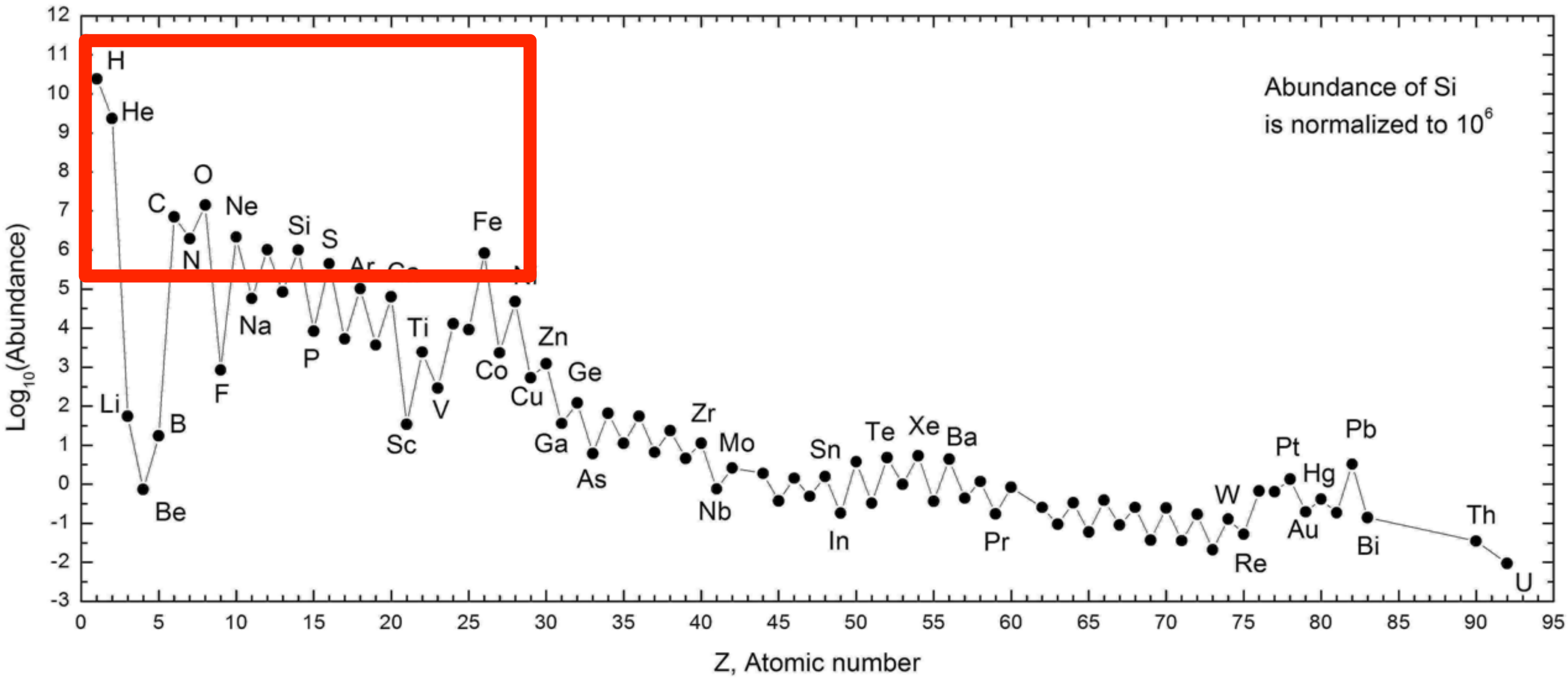
O (1.04%) C (0.46%)

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

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

Chemical Composition

The chemical composition of the Sun



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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
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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 H H H H H H H H
H H H H H H H H H He H H H H H Si 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
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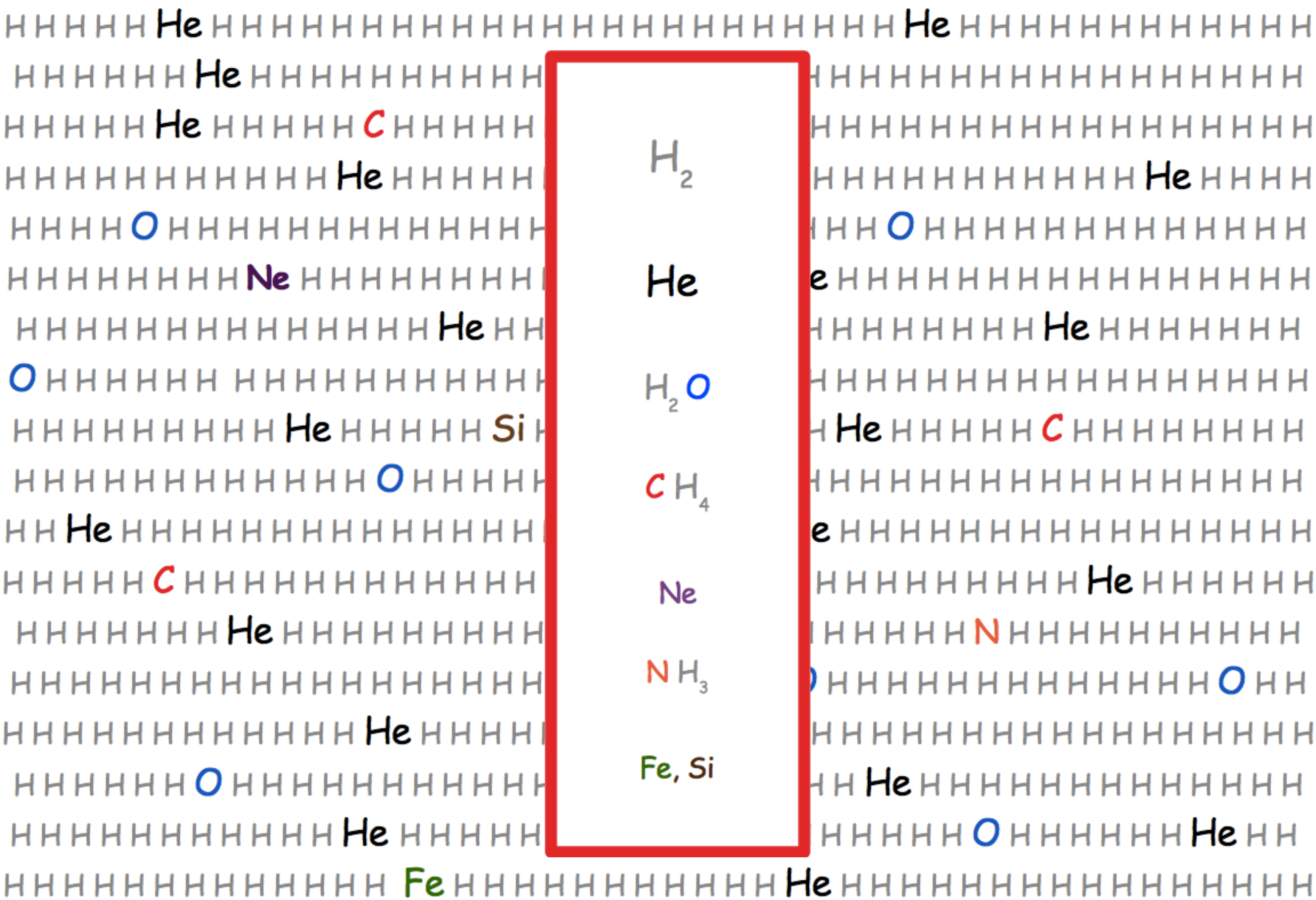
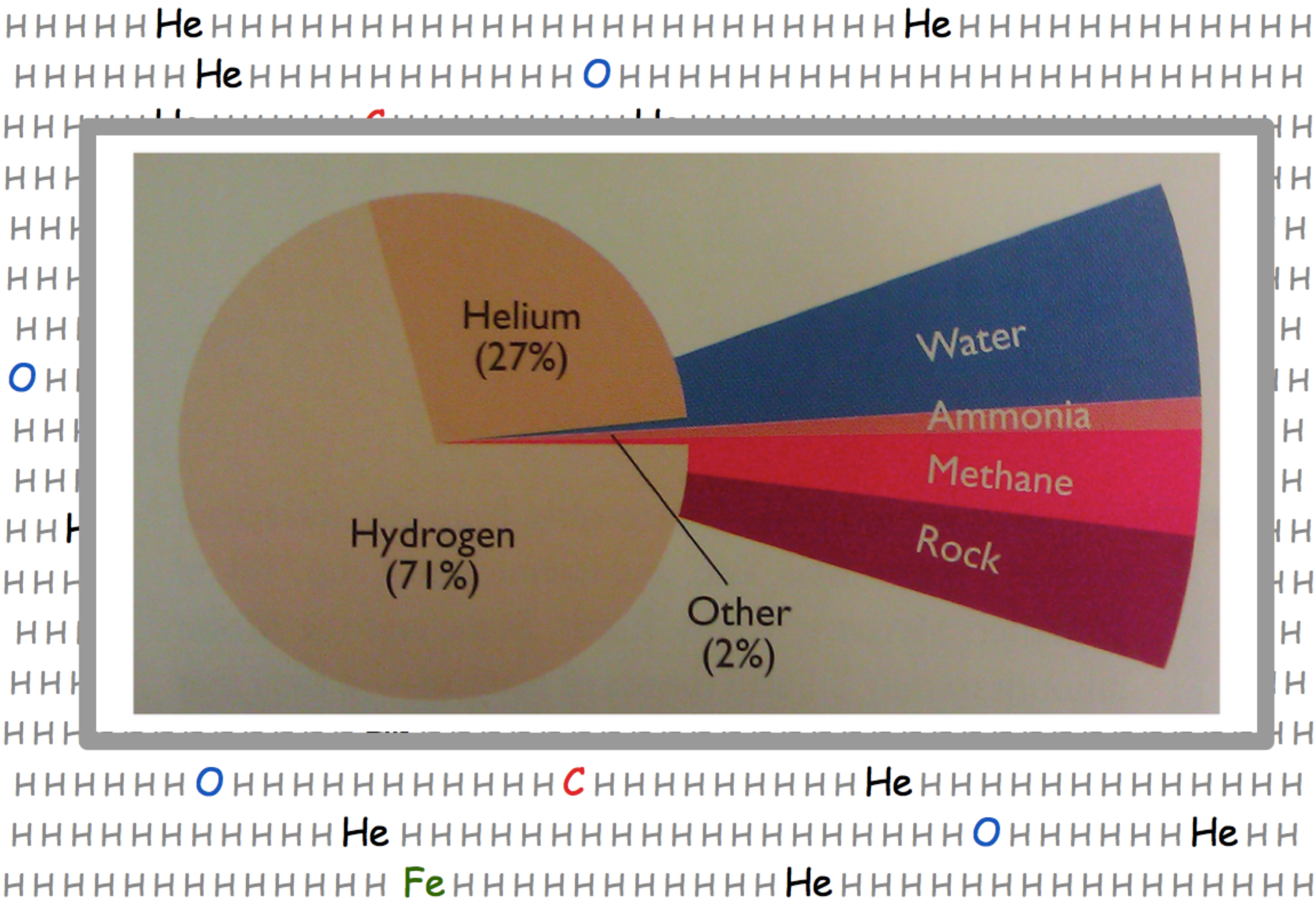
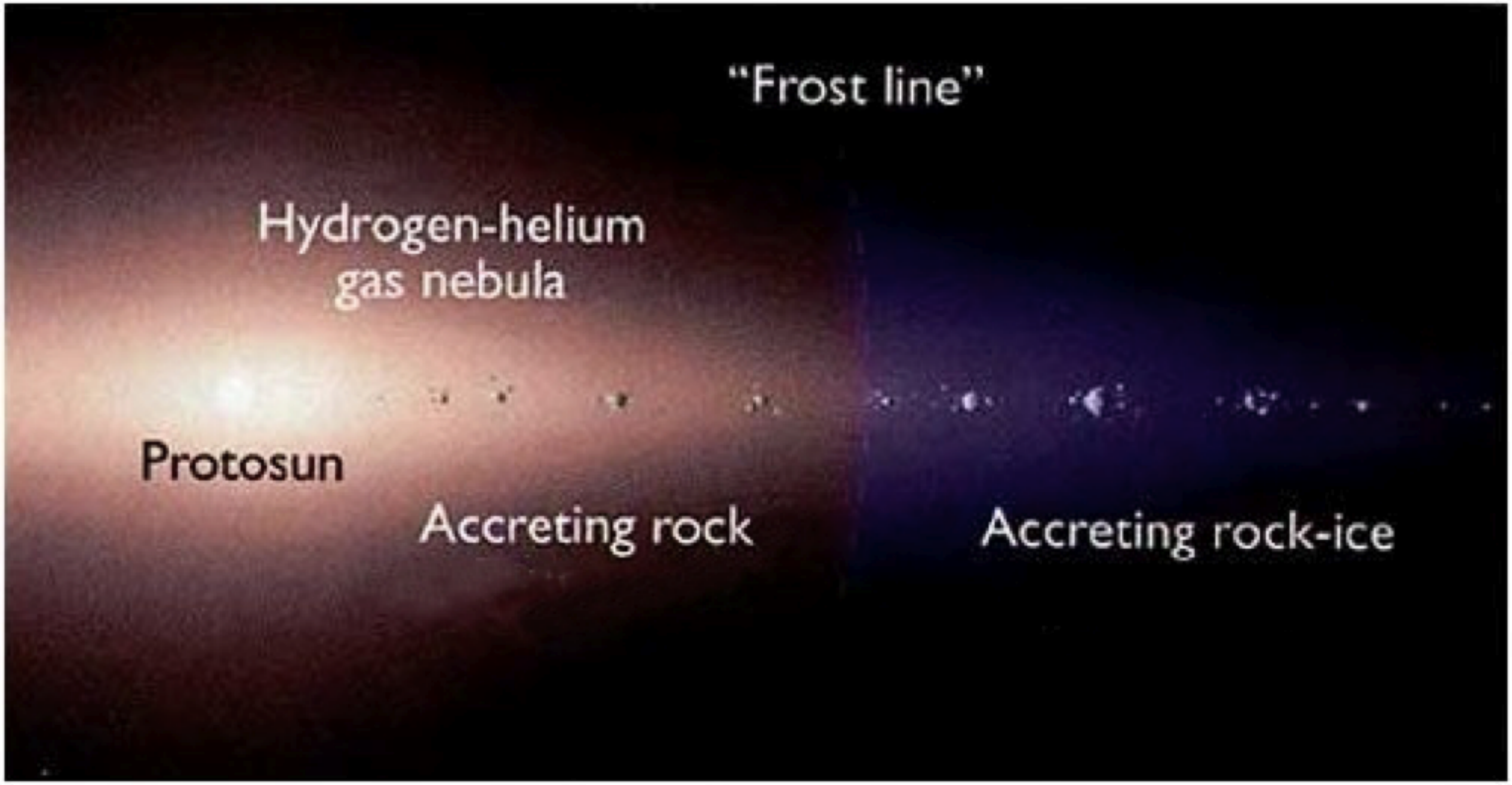
What will the chemistry of the mixture be?



What will the chemistry of the mixture be?



Temperature

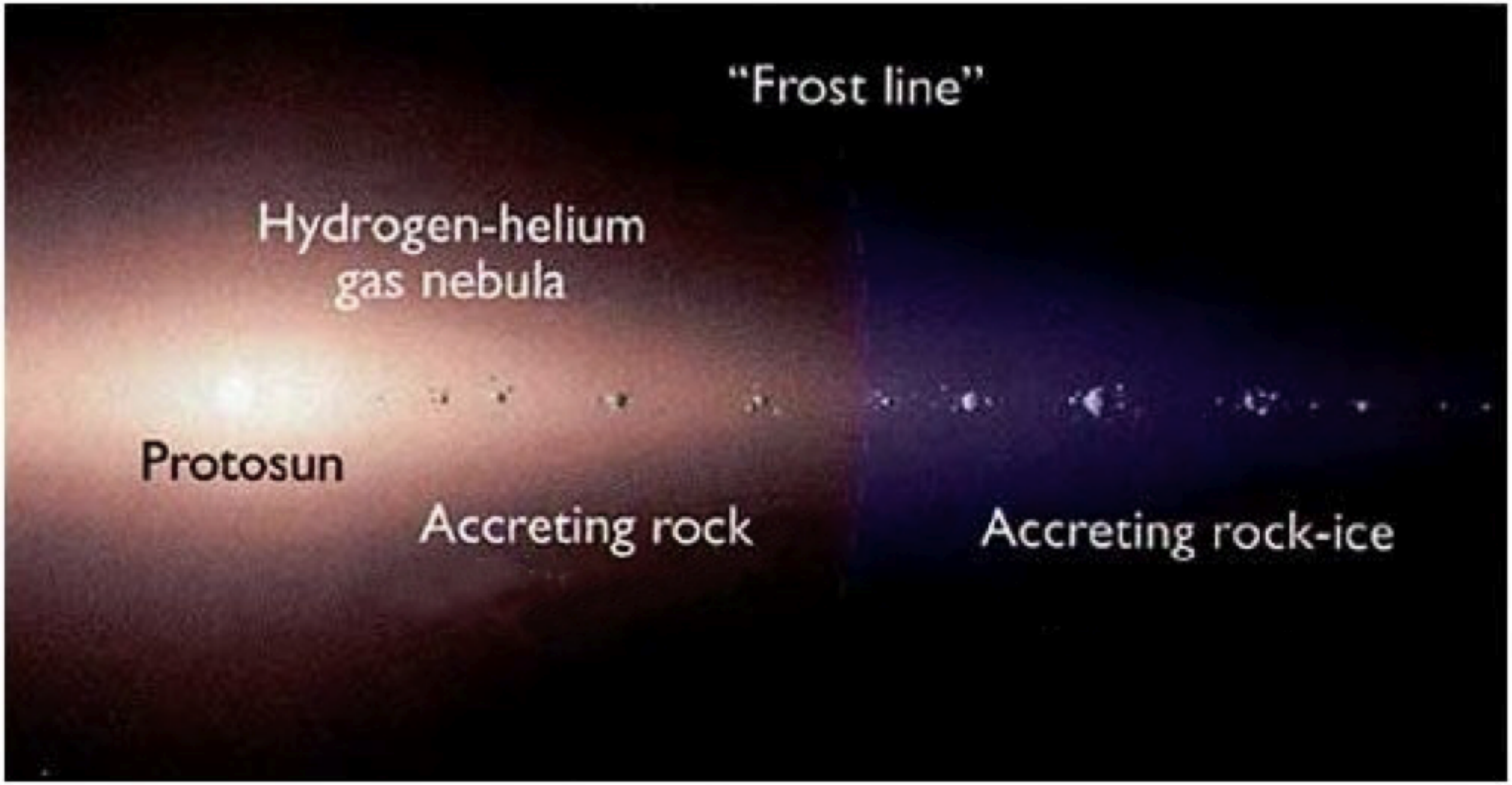


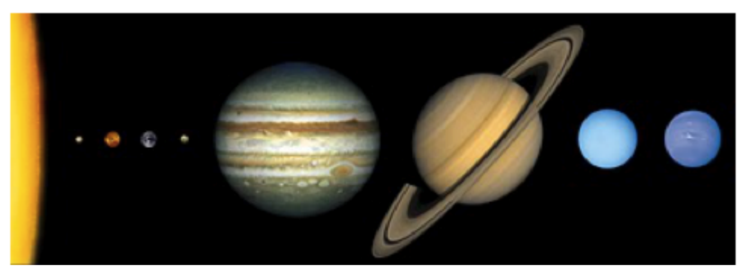
Volatiles in gas phase

Volatiles in solid phase

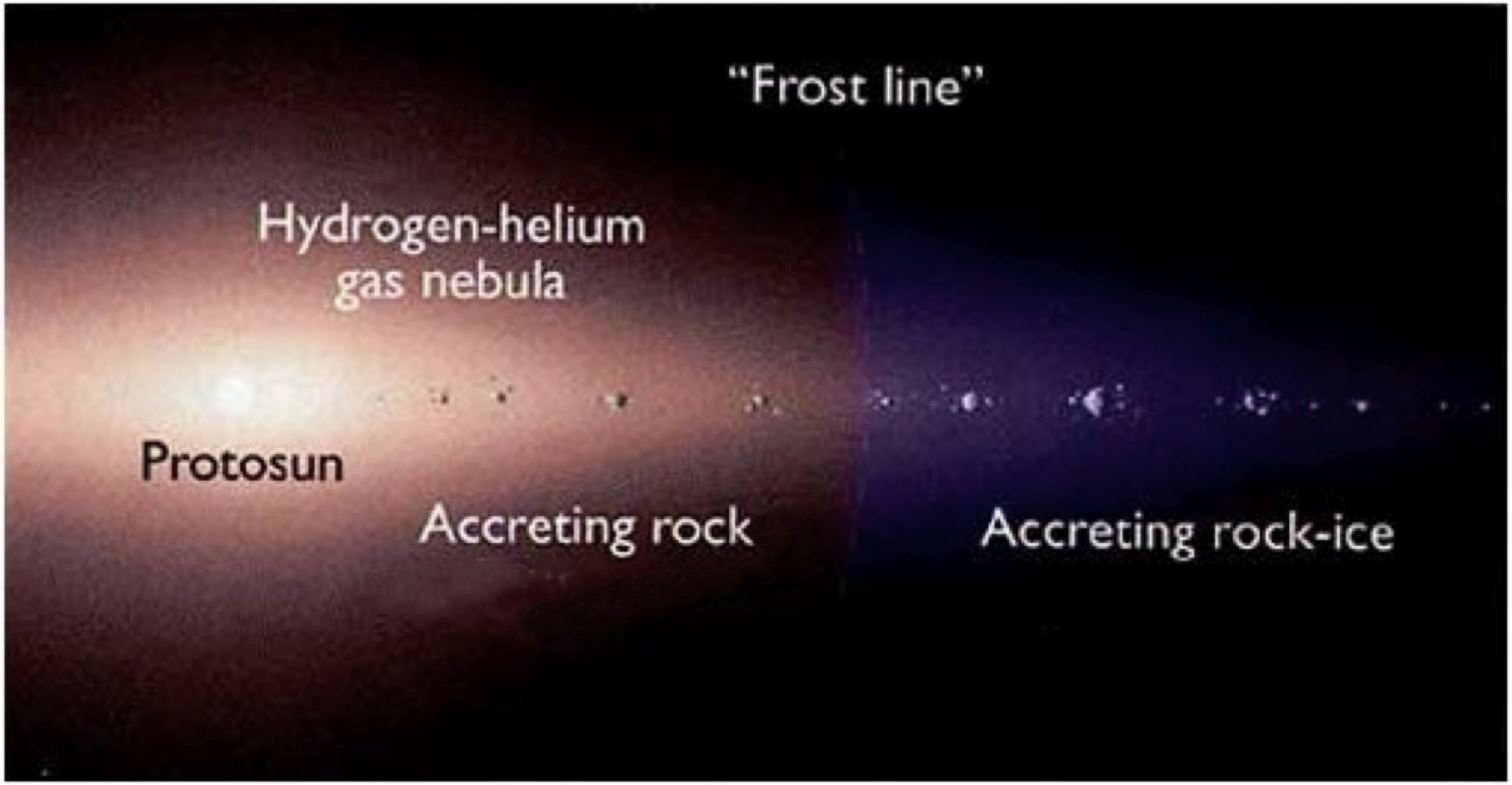
Colder than ~150K, the volatiles (H_2O, CH_4, NH_3) condense into ***ices***.

Formation


"Frost line"
Hydrogen-helium
gas nebula
Protosun
Accreting rock
Accreting rock-ice



Formation



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gas nebula
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Accreting rock
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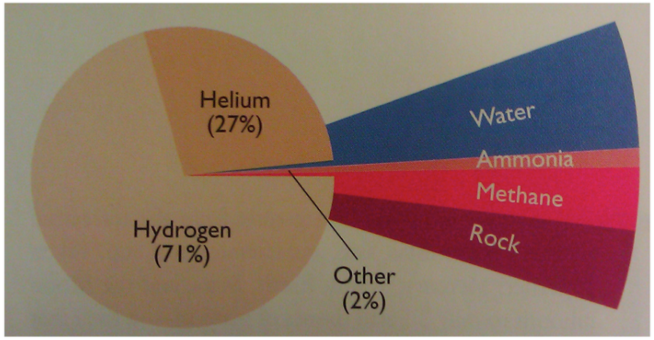
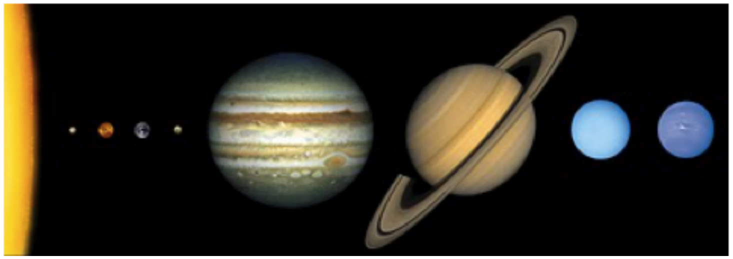


Helium
(27%)
Hydrogen
(71%)
Other
(2%)
Water
Ammonia
Methane
Rock



Formation

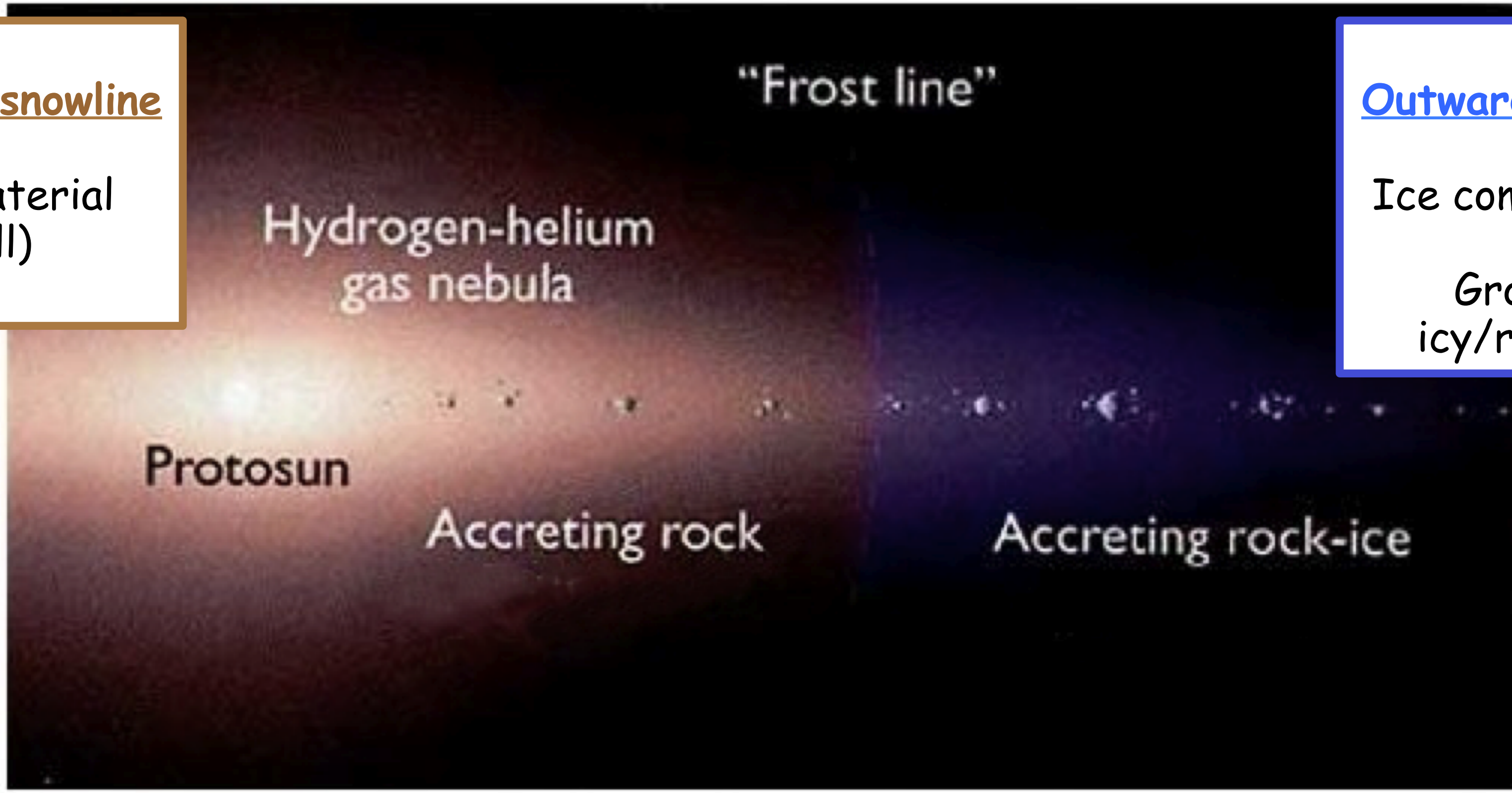
Inward of snowline

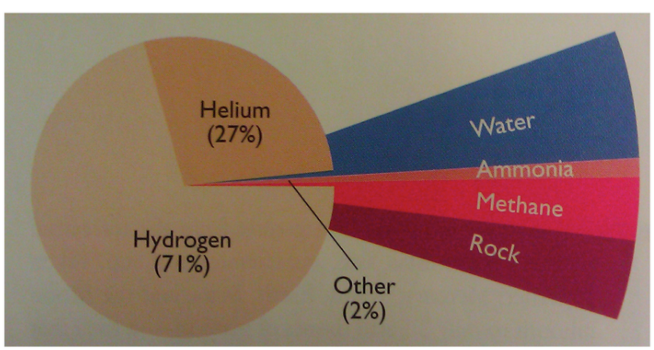
Rocky material (small)

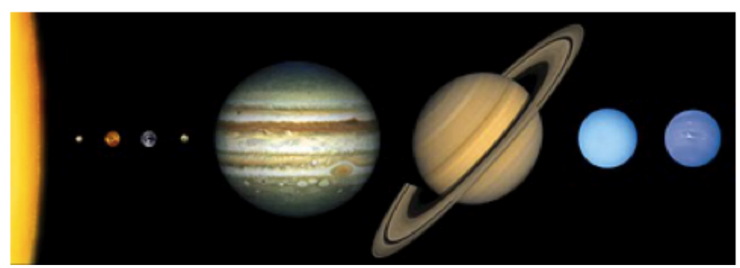
Outward of snowline

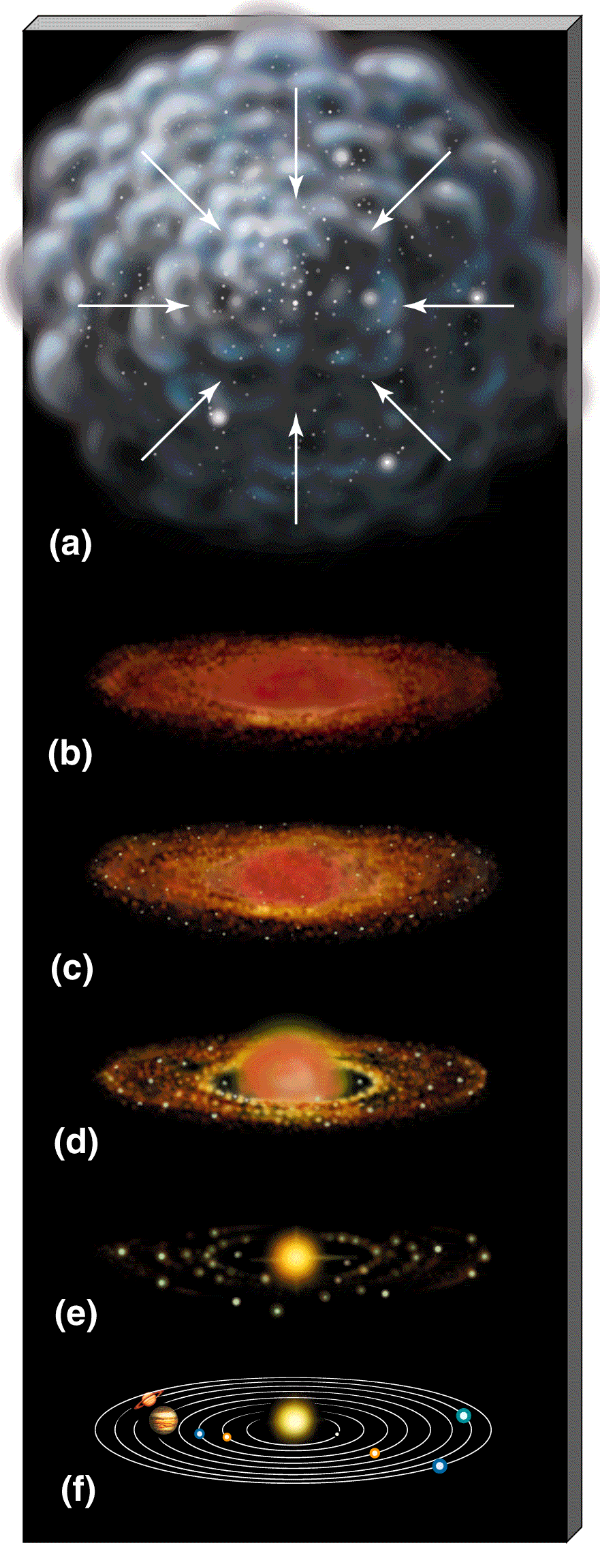
Ice comes to assist!

Growing big icy/rocky cores









Planet formation timeline

(a) Collapse of gas cloud (t = 0)
$n \sim 10^4 - 10^5$ cm^{-3} $T \sim 10K$

(b) Protostar with disk ($t \sim 0.1 - 1$ Myr)
$n \sim 10^5 - 10^8$ cm^{-3} $T \sim 10\text{-}300$ K

(c) Planet Formation ($t \sim 1\text{-}10$ Myr)
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$n \sim 10\text{-}100$ cm^{-3}

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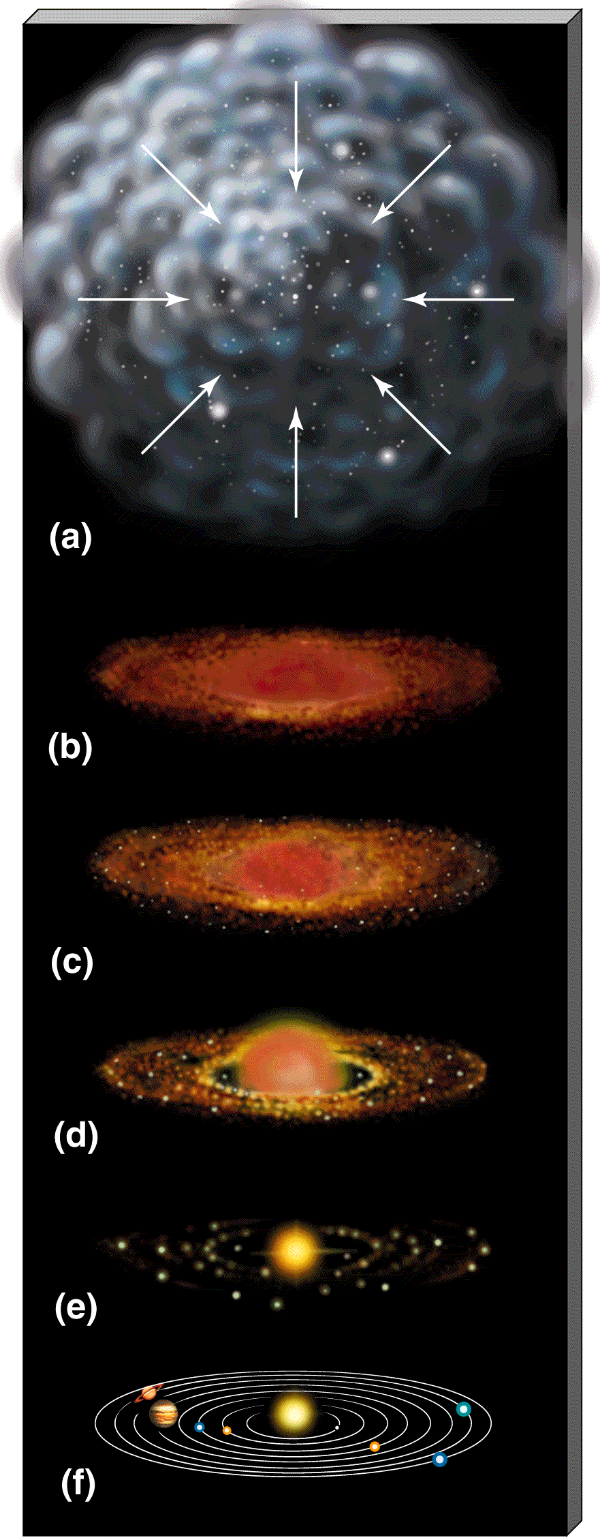

Planet formation timeline

(a) Collapse of gas cloud (t = 0)
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(b) Protostar wi **isk** (t ~ 0.1 - 1 Myr)
$n \sim 10^5 - 10^8$ c $T \sim 10\text{-}300\ K$

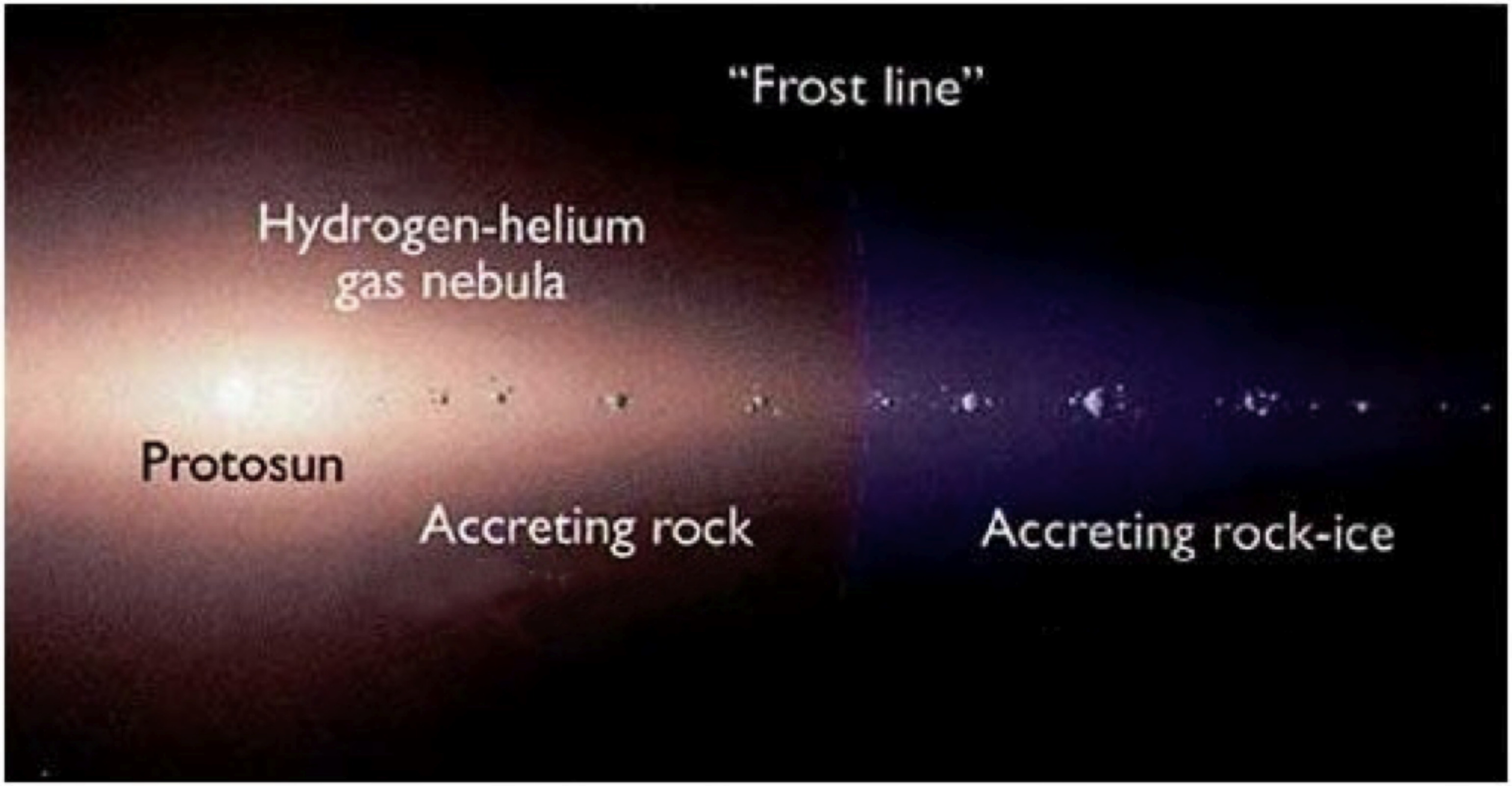
... a miracle happens ...

(d) Disk evap **ion** (t ~ 10 Myr)

(e) Leftover disk of **nd debris** (t > 10 Myr)
n ~ 10 00 cm^{-3}

(f) ***TA-DAH !!!***

The planetesimal hypothesis



How do planetesimals accrete??

The planetesimal hypothesis

From dust to rocks

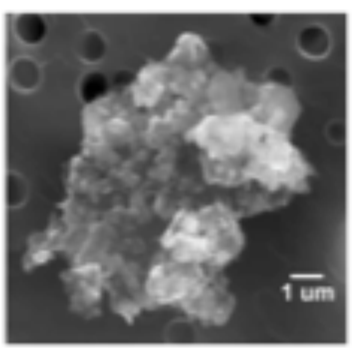
μm -> cm: Intermolecular forces cause sticking

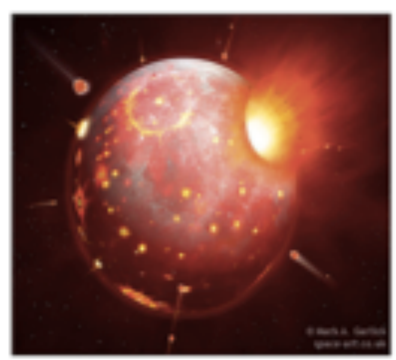
From rocks to planetesimals

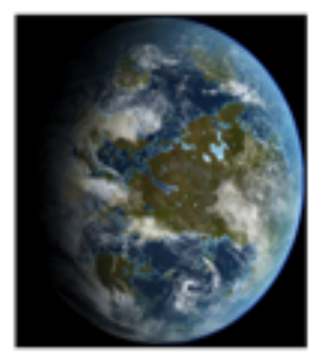
cm -> km: A miracle happens

From planetesimals to protoplanets

km -> 1000 km: gravitational focusing







The planetesimal hypothesis

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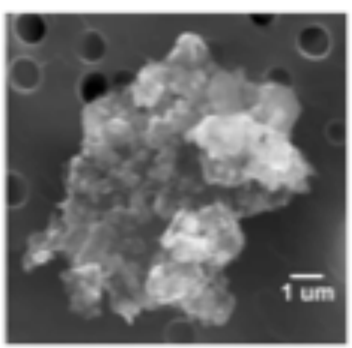
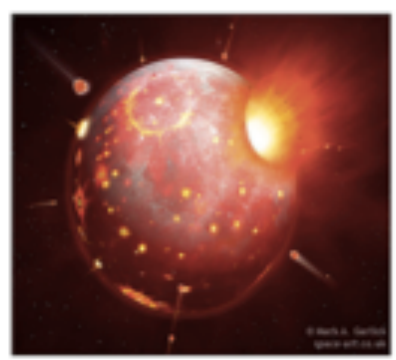
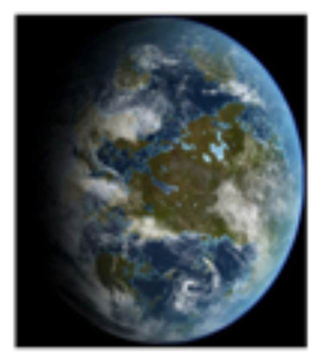






The meter size barrier

Growth barrier

- through Hit-and-Stick?

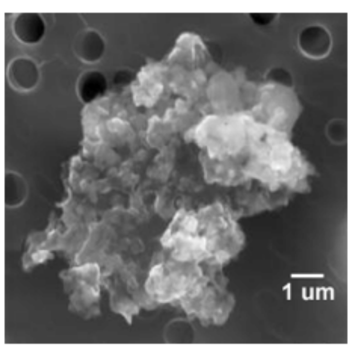
  They don't stick, they break

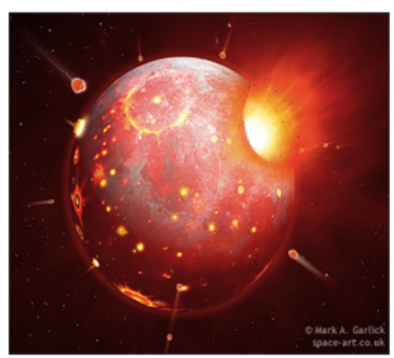
- through Gravity?

  They aren't massive enough

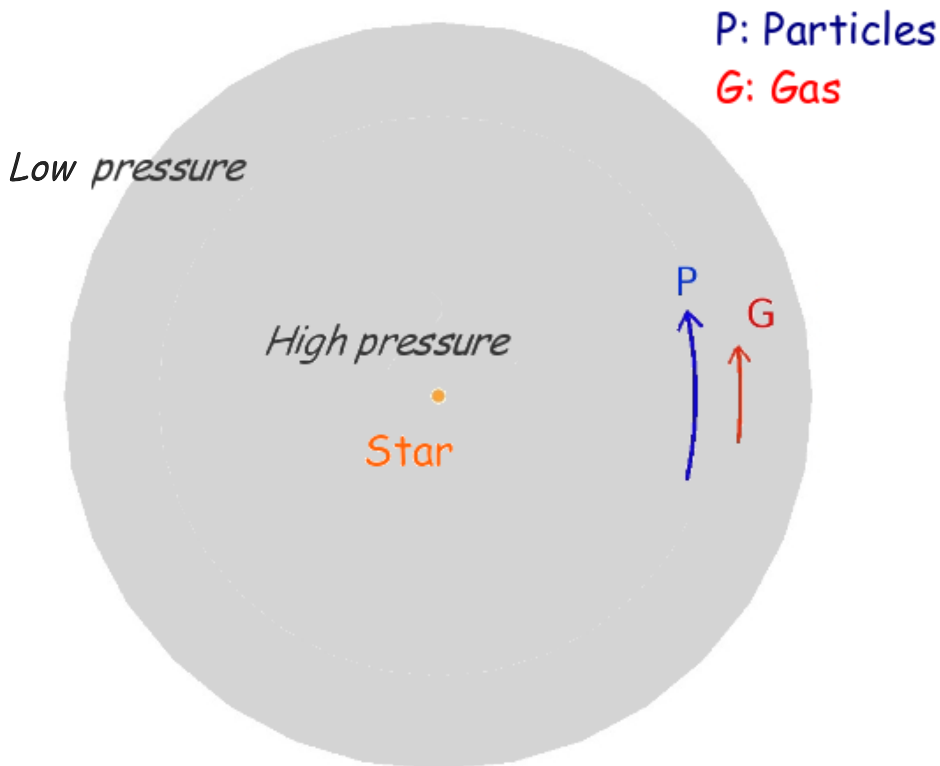
Timescale barrier

They migrate quite fast

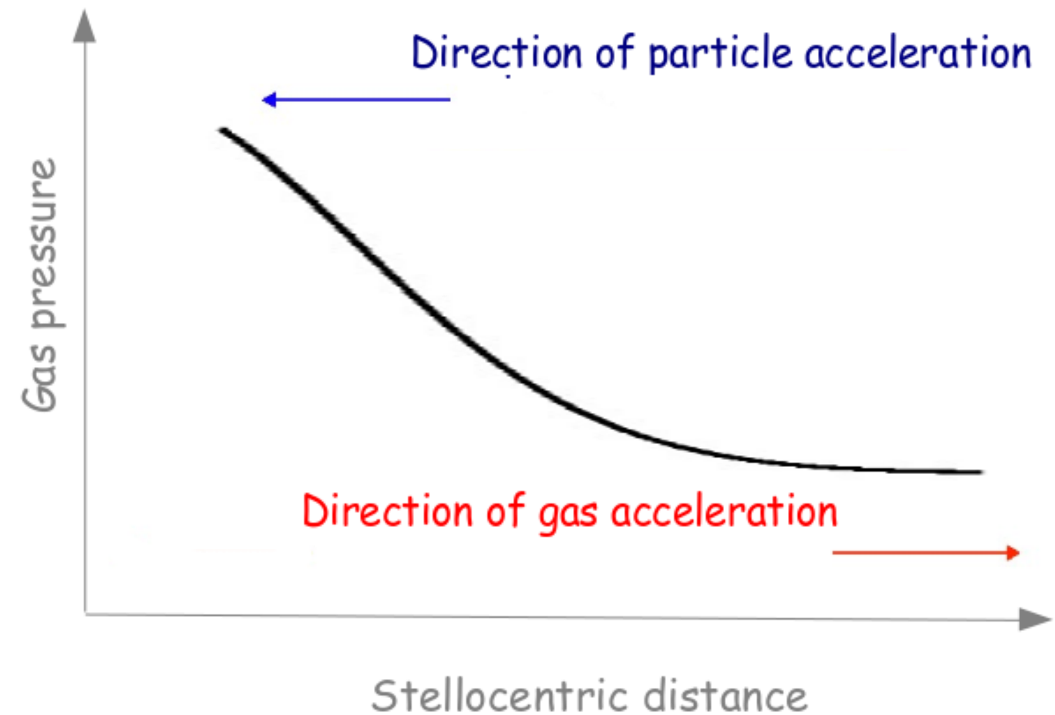



Particle drift



Adapted from Whipple (1972)



Take-home message #2:

Dust

moves toward

high pressure regions

The meter size barrier

Growth barrier

- through Hit-and-Stick?

They don't stick, they break

Gentle Collisions

- through Gravity?

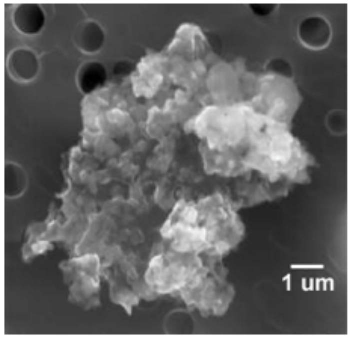
They aren't massive enough

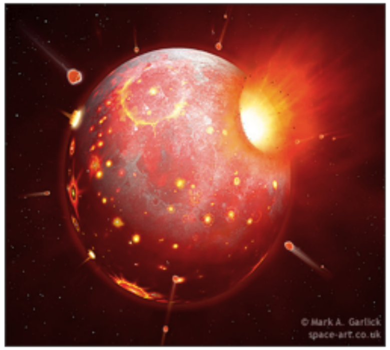
High number density

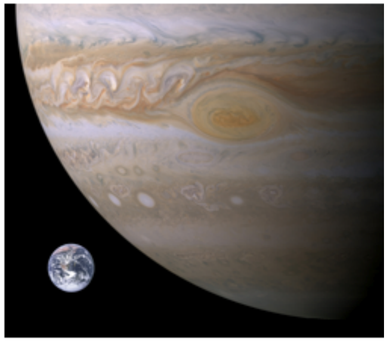
Timescale barrier

They migrate quite fast

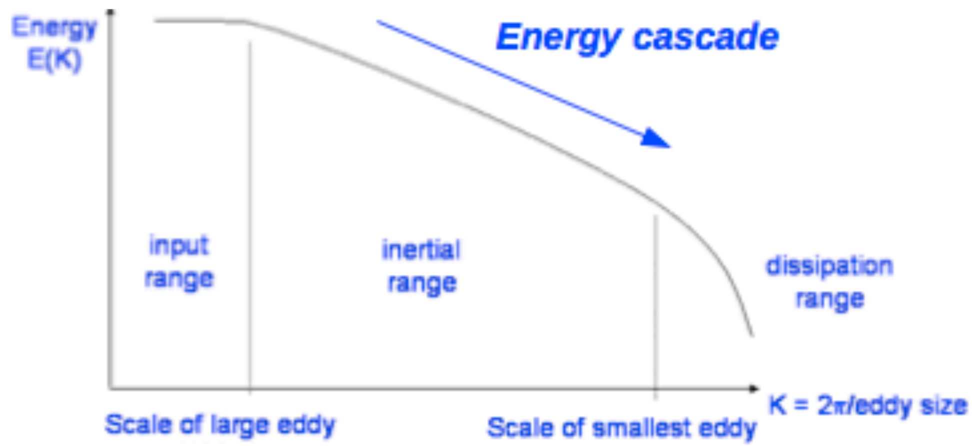
Stopping Mechanism

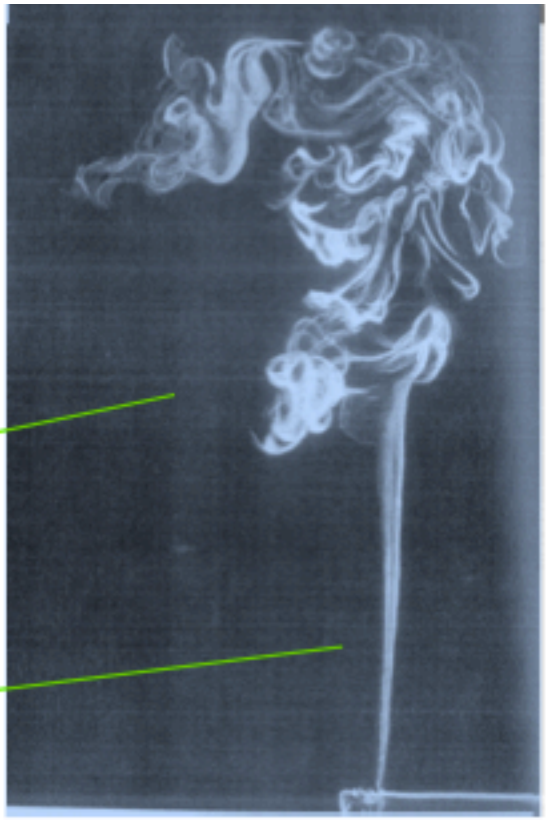




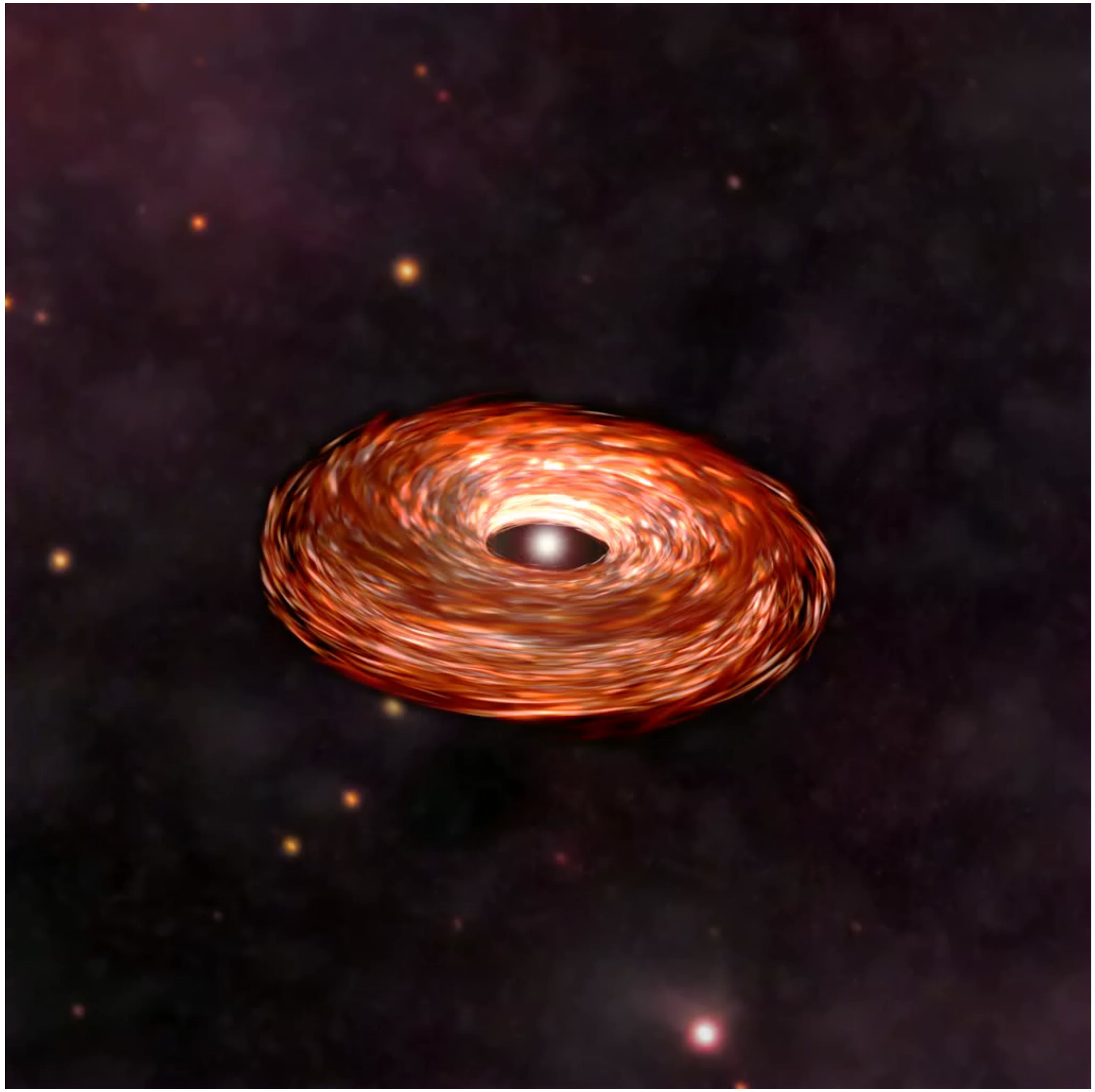


Turbulence


Energy
E(K)
Energy cascade
input
range
inertial
range
dissipation
range
K = 2π/eddy size
Scale of large eddy
Scale of smallest eddy

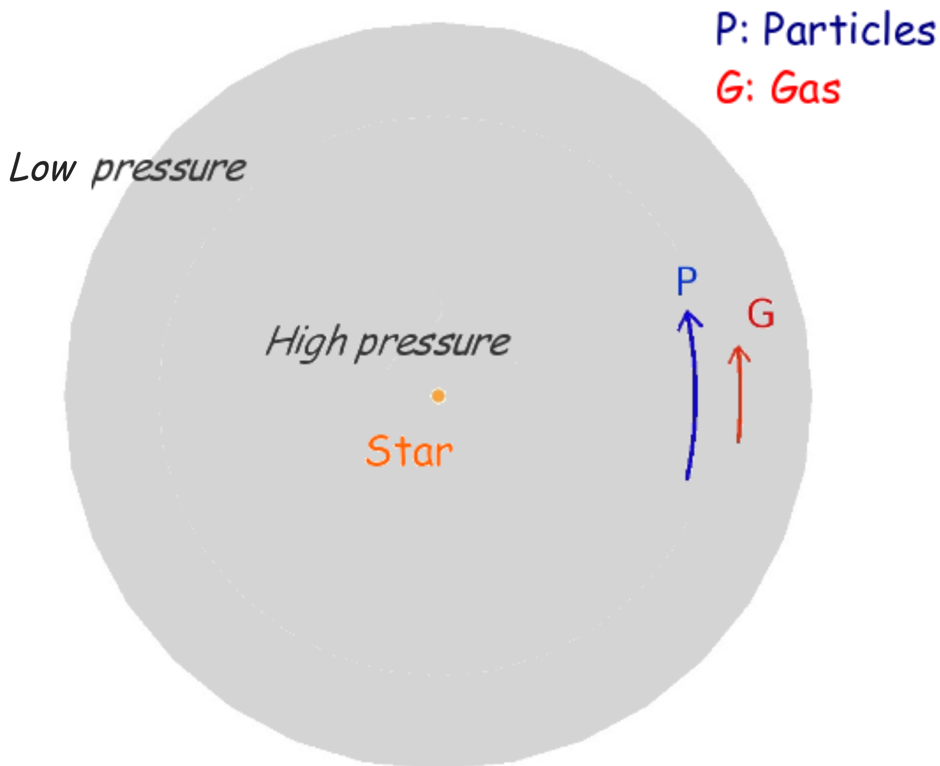

Turbulent flow
Laminar flow

Turbulence

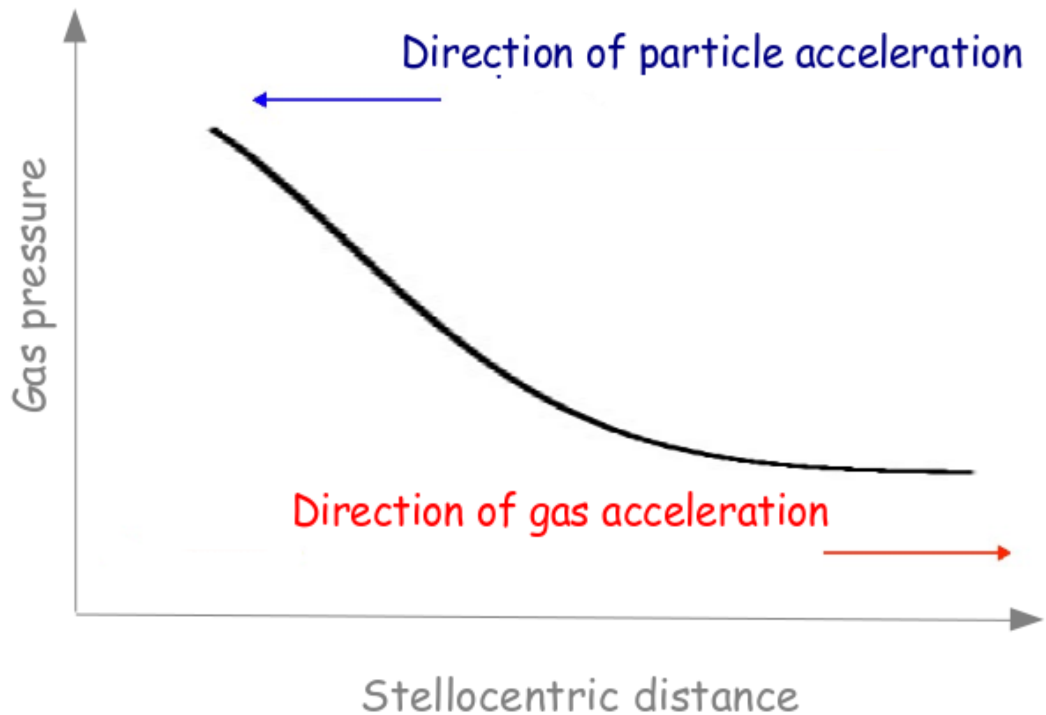


Credit: Mario Flock (MPIA)

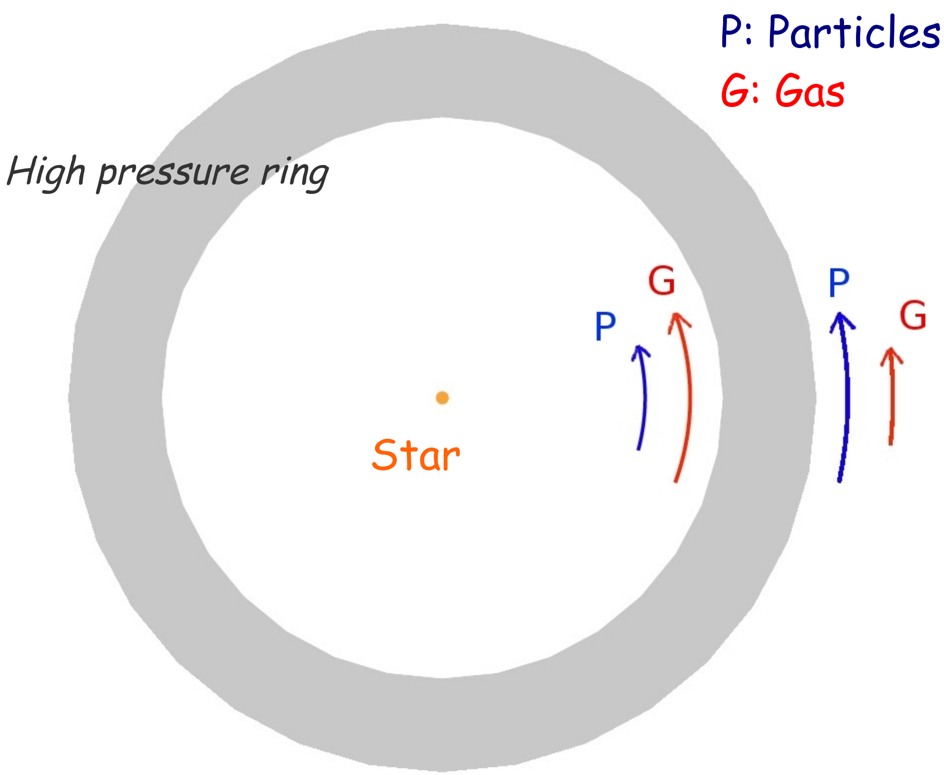
Particle drift



Adapted from Whipple (1972)



Pressure Trap



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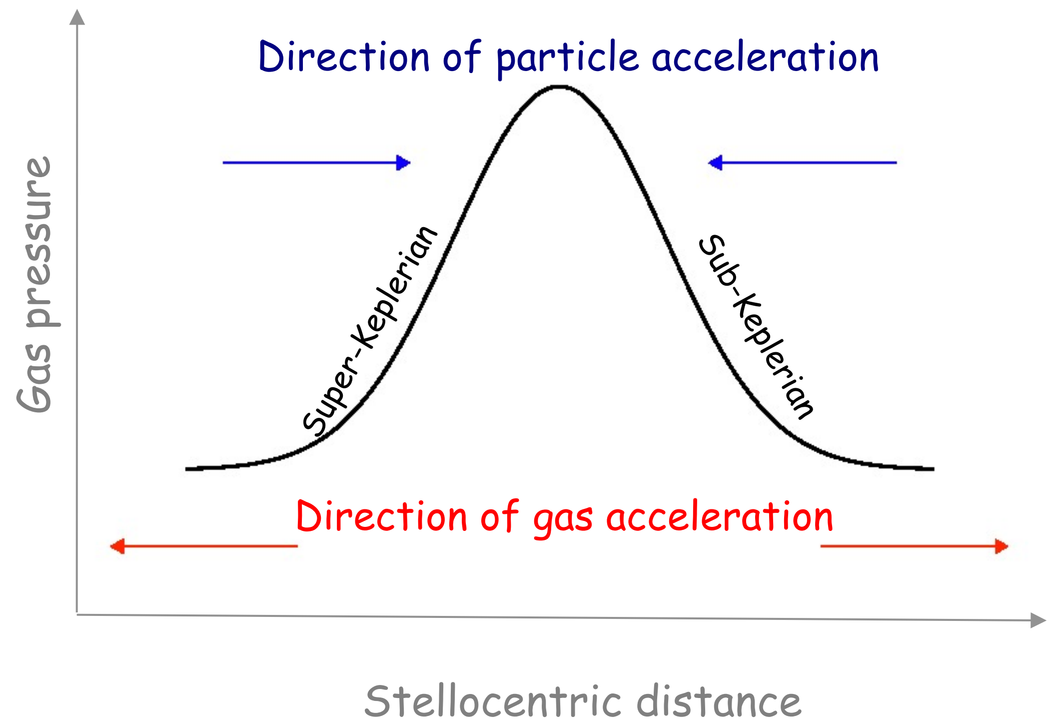

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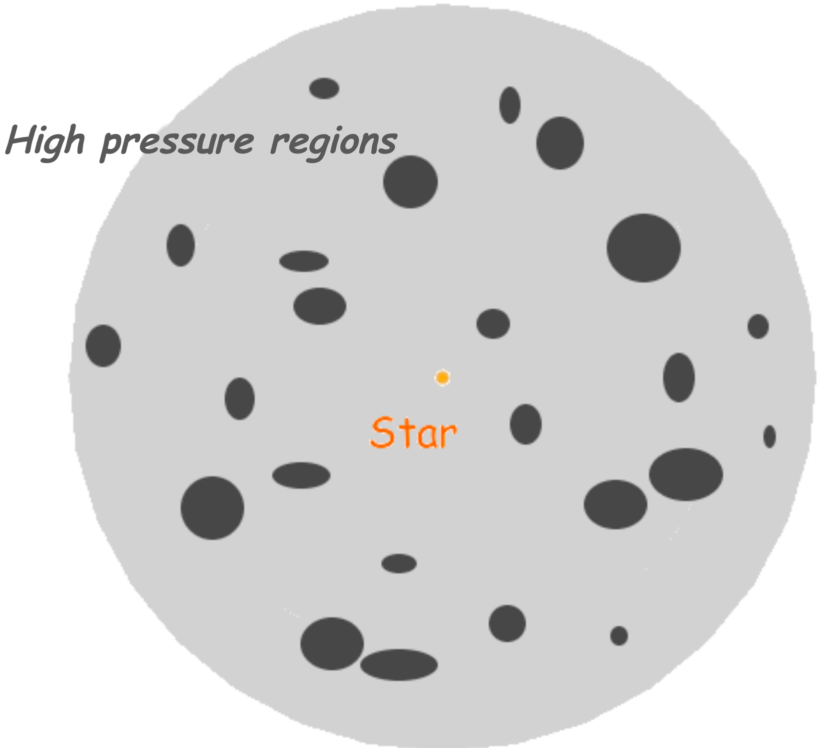
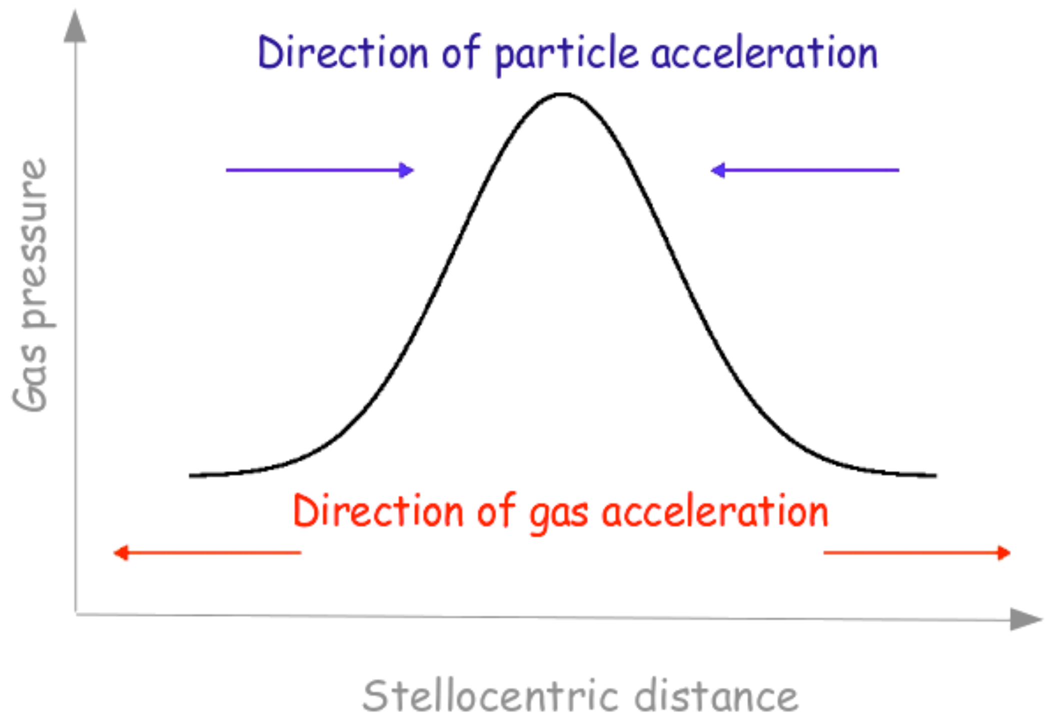
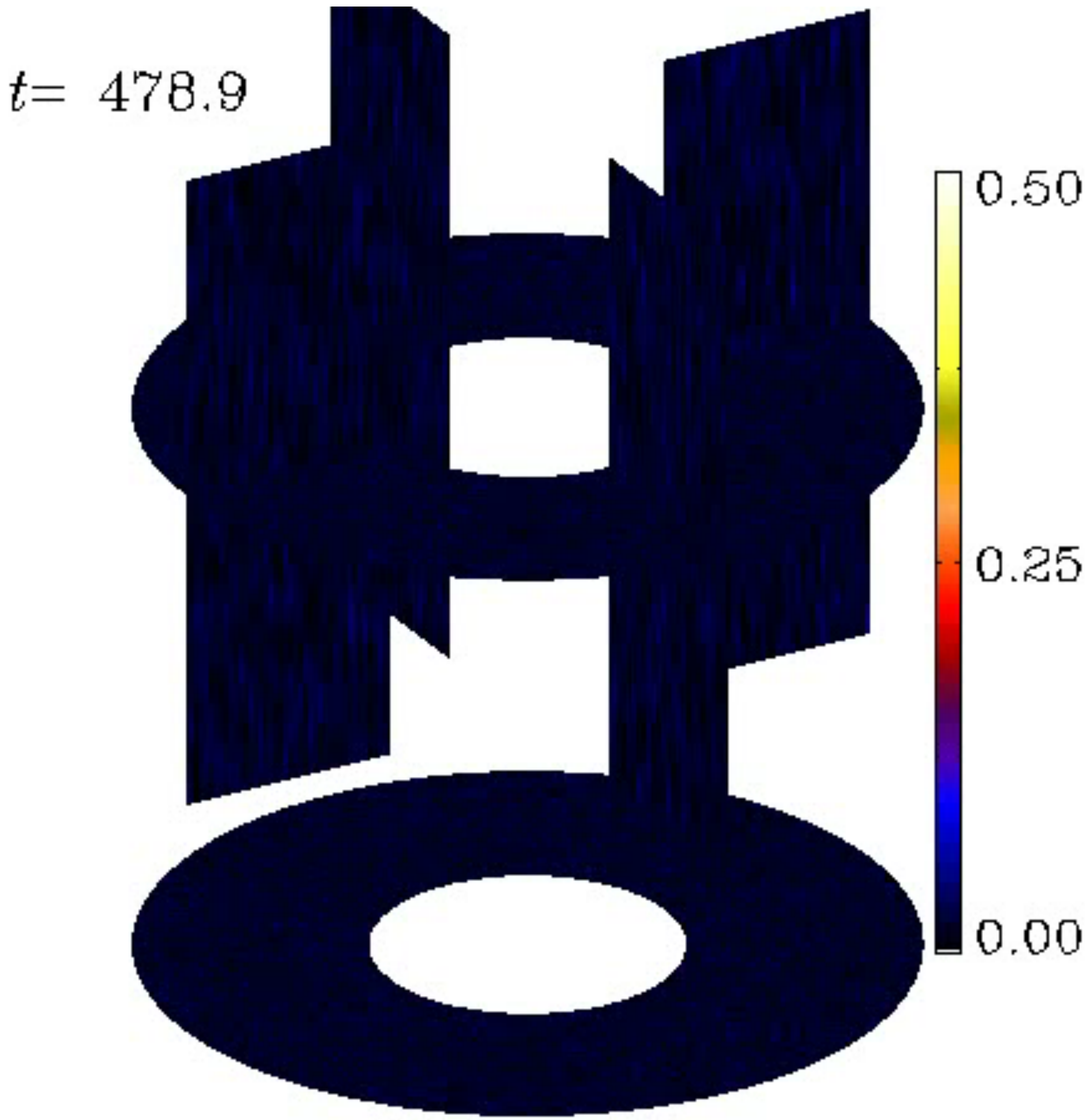


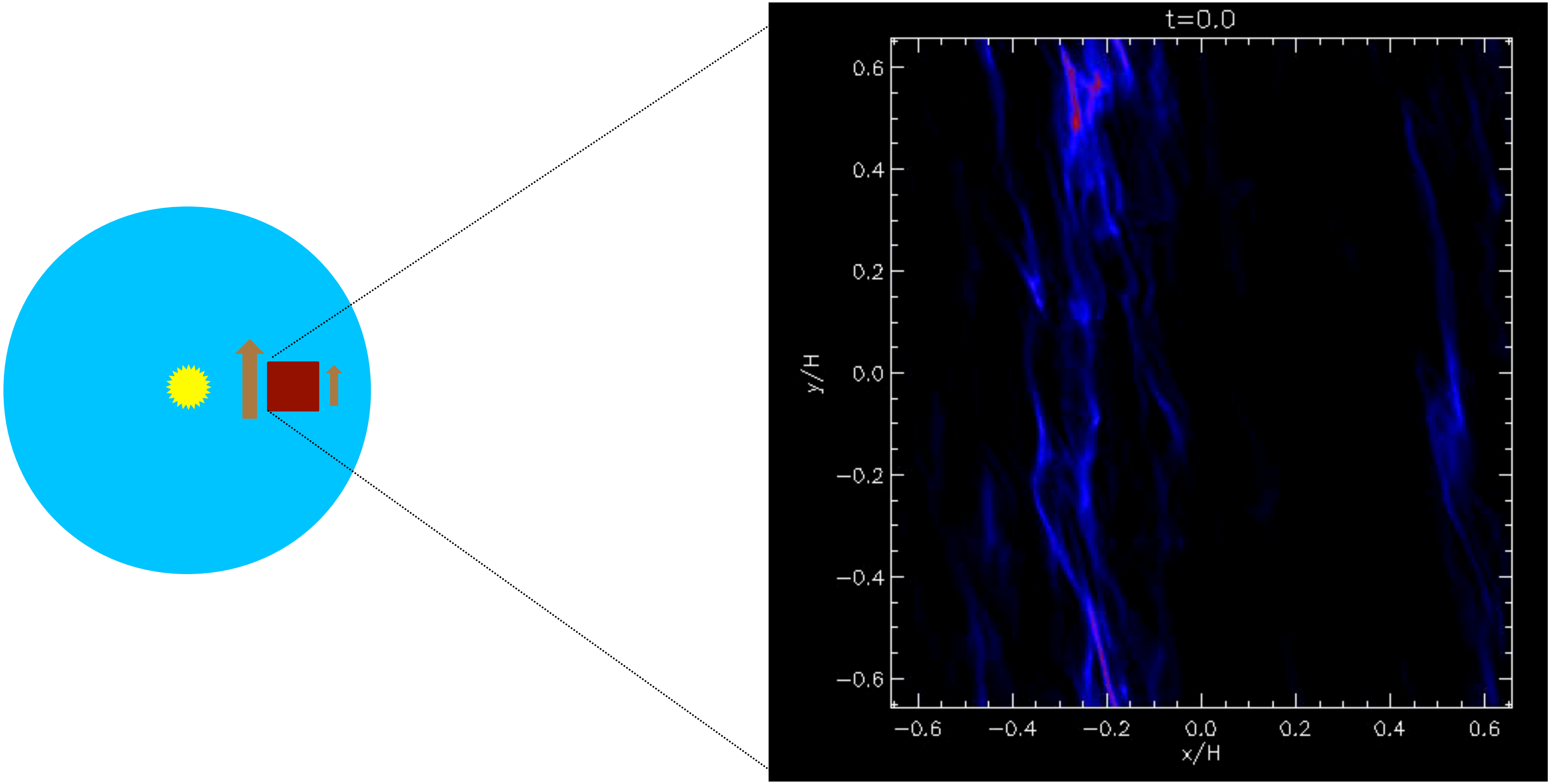


Turbulence concentrates solids mechanically in pressure maxima



Lyra et al. (2008a)

Gravitational collapse into planetesimals



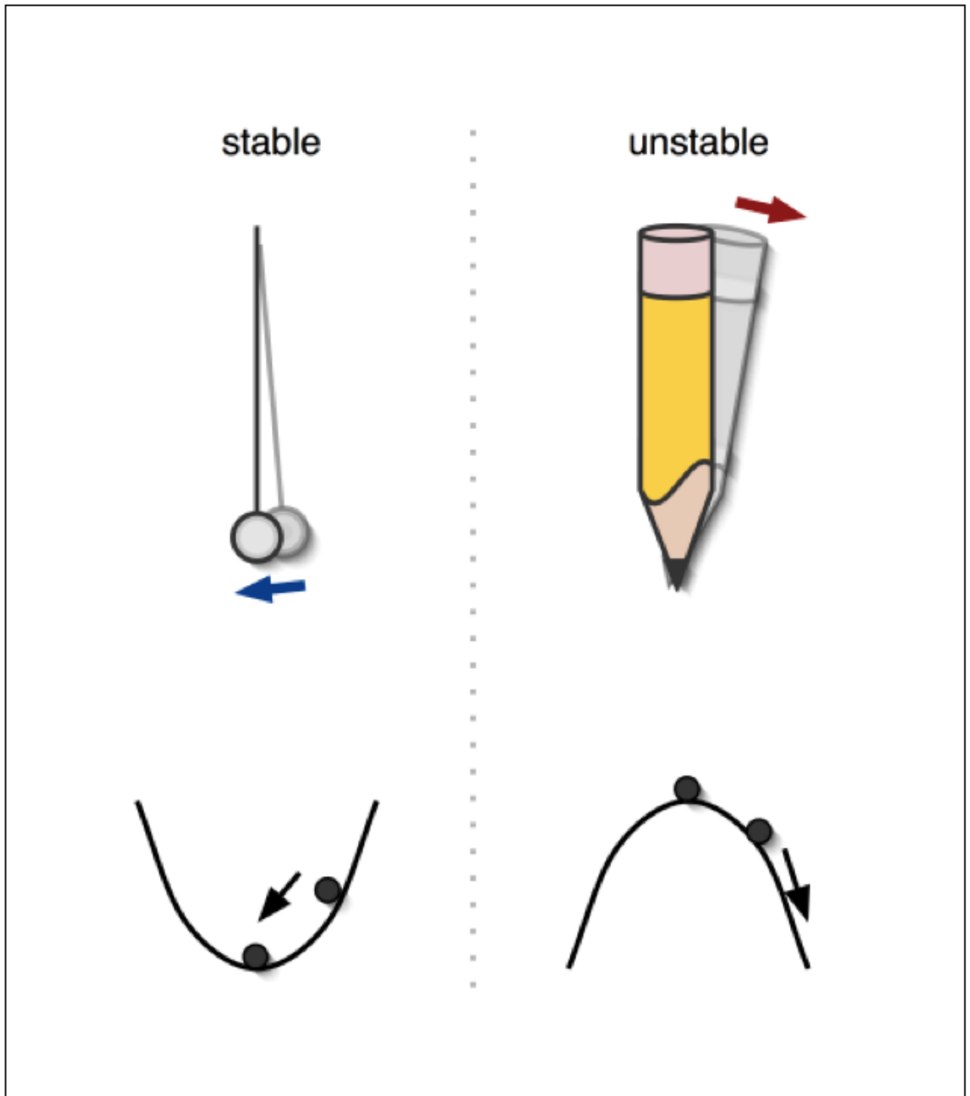
Credit; Anders Johansen
(Johansen et al. 2007)

The turbulence is a result of unstable equilibrium.

Stable and Unstable Equilibria

Stable Equilibrium

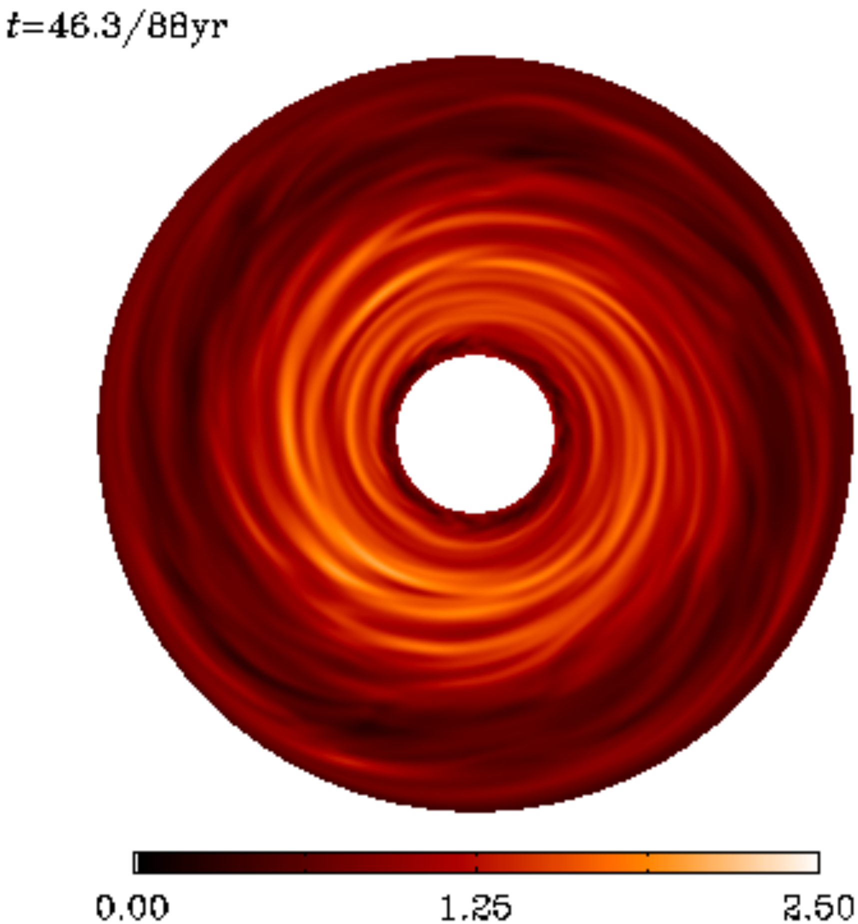
Returns to equilibrium position when disturbed



Unstable Equilibrium

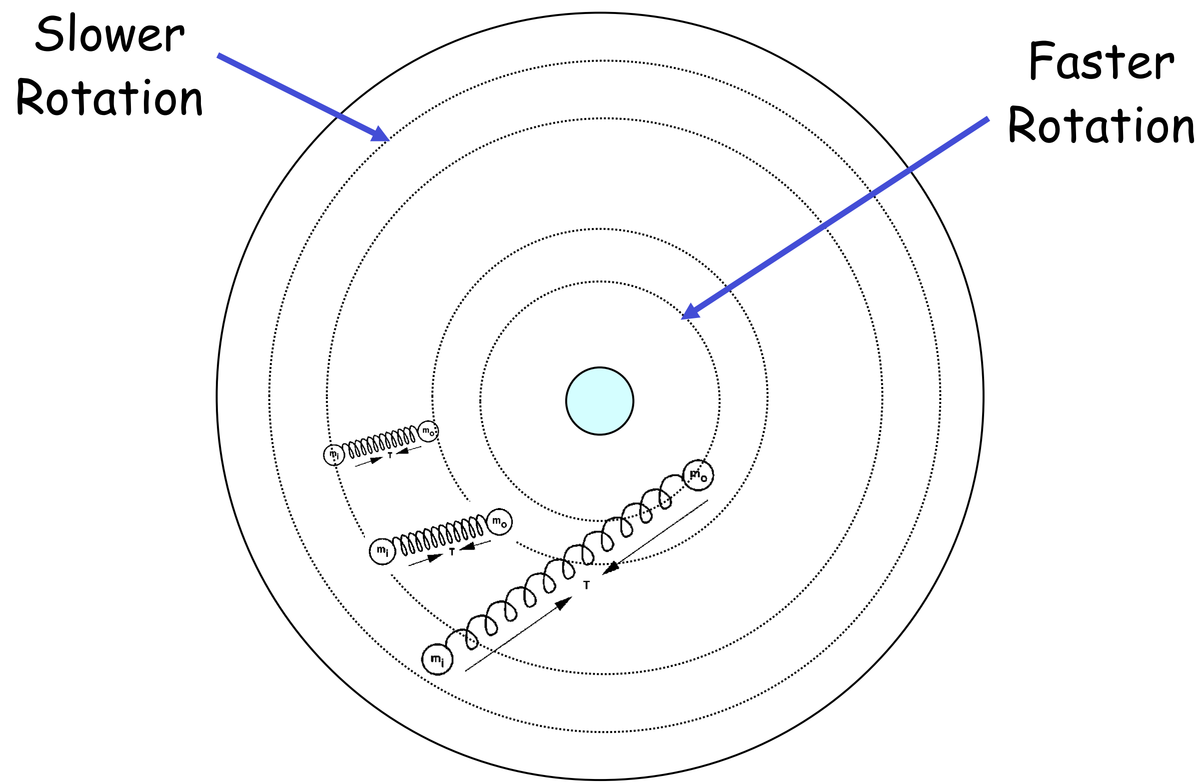
Does not return to equilibrium position when disturbed

The instability mechanism is magnetic



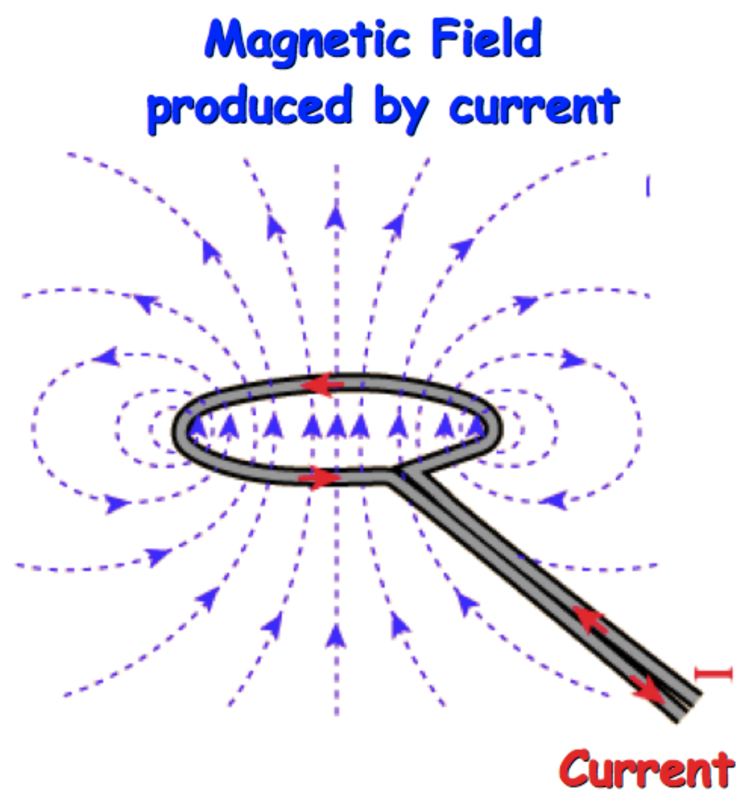
Magnetized disk

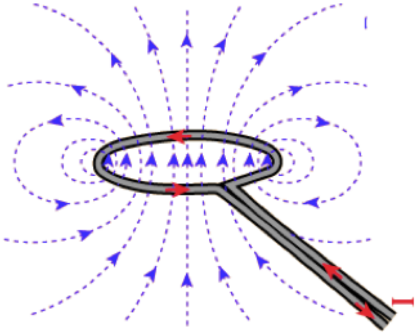
Lyra et al. (2008a)



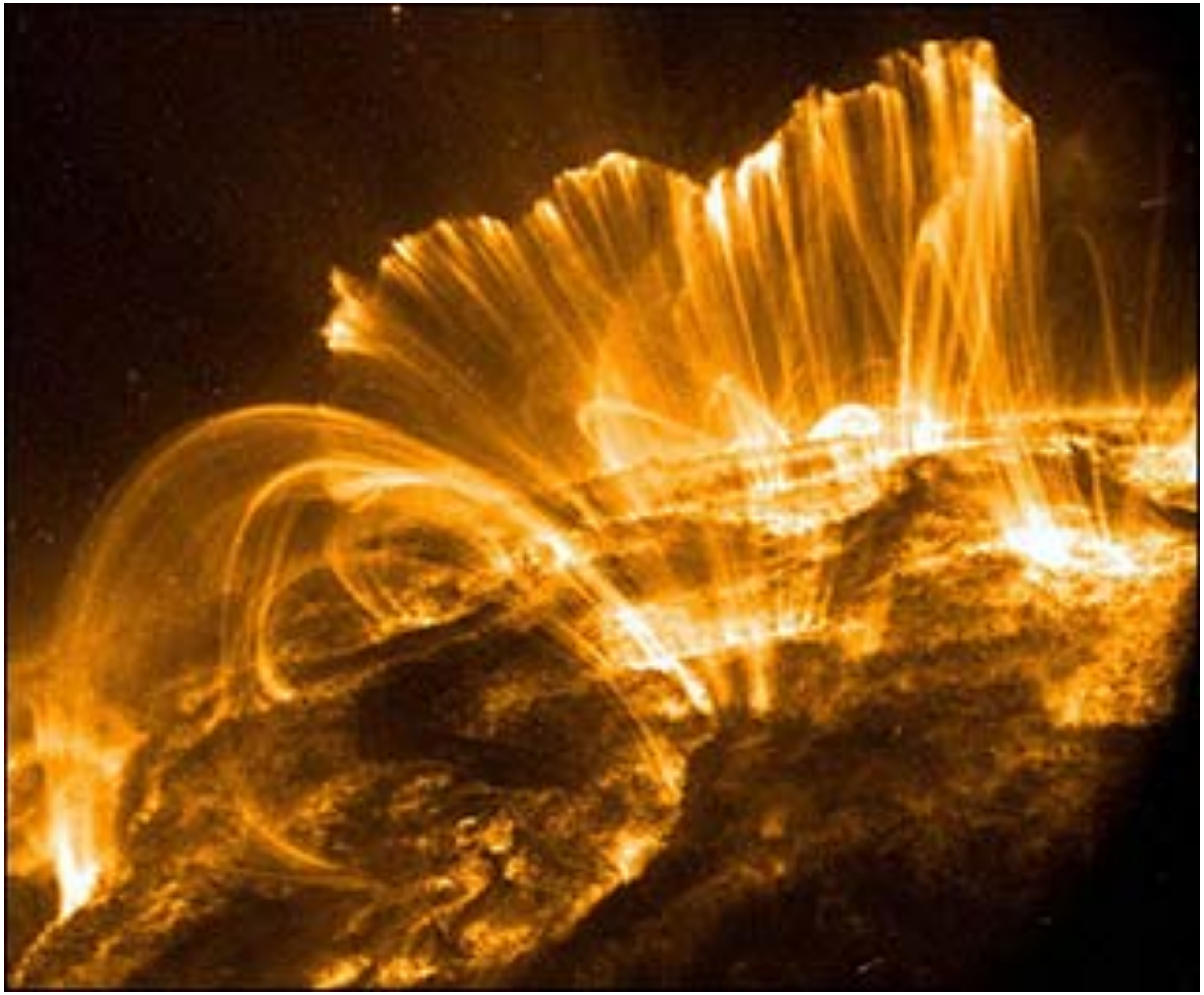
Magnetic Fields

Masses produce gravitational fields
Static charges produce electric fields
Moving charges produce **magnetic fields**

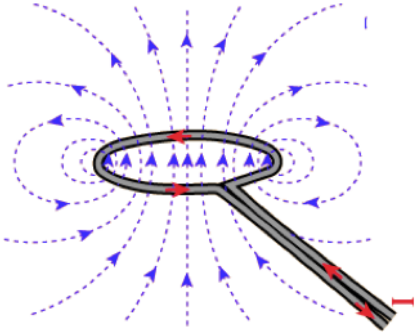


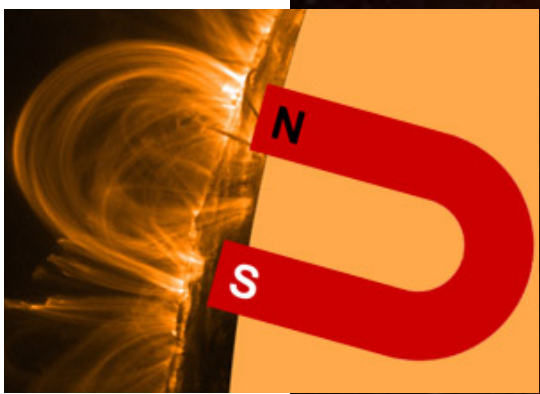


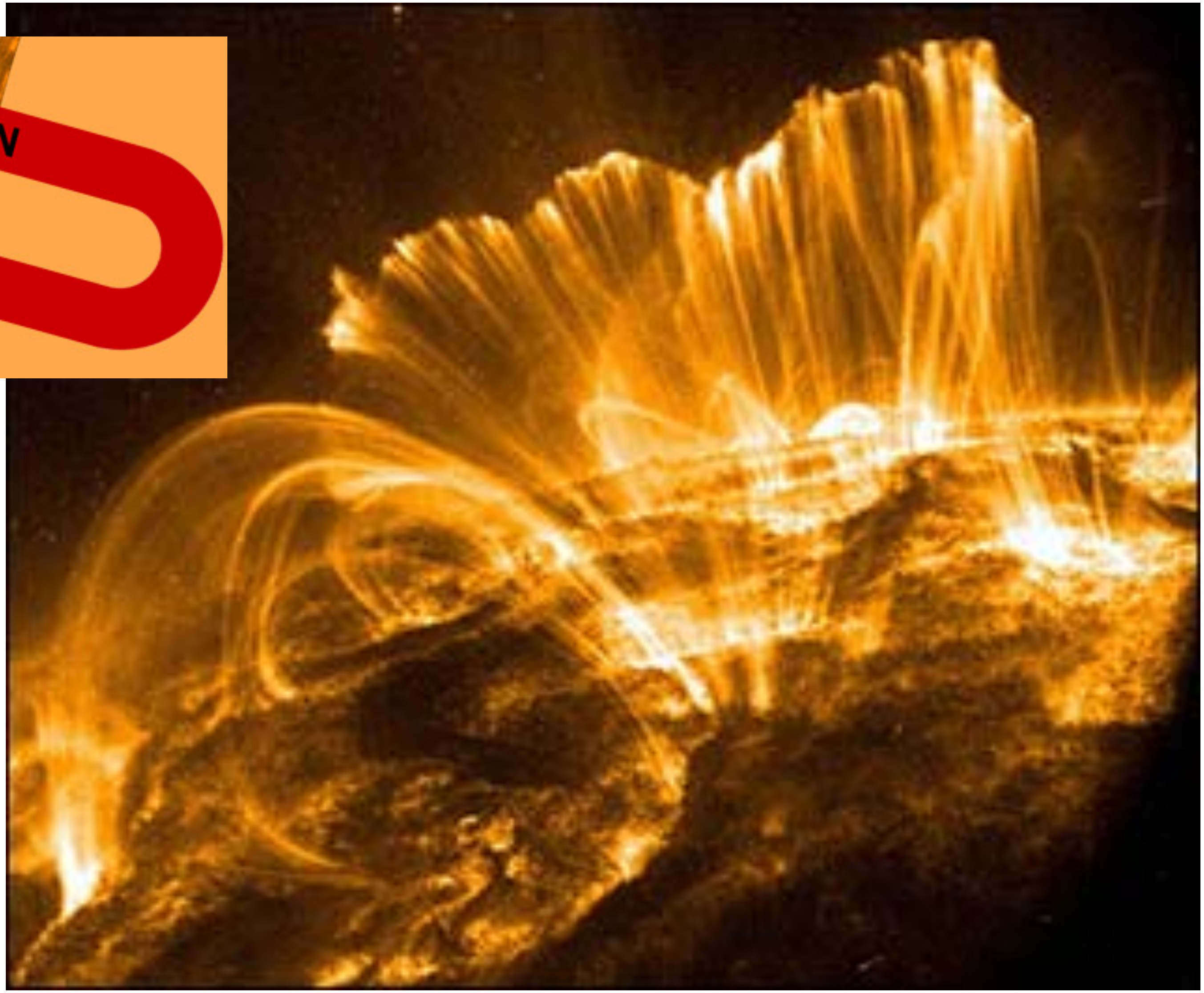
Magnetic Fields



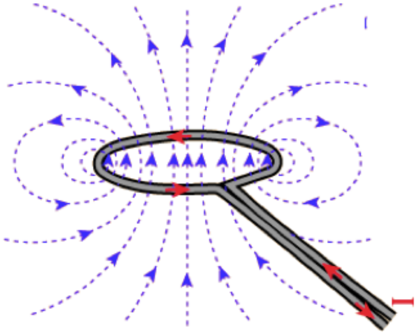
Magnetic Fields

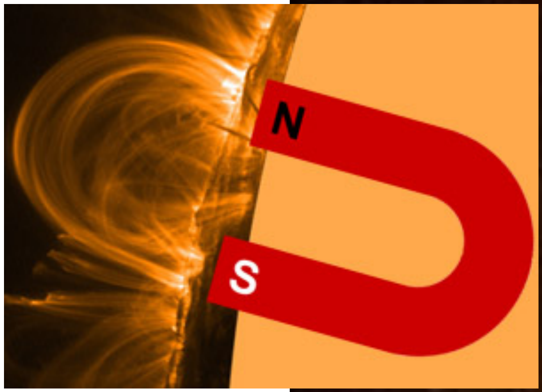






Magnetic Fields

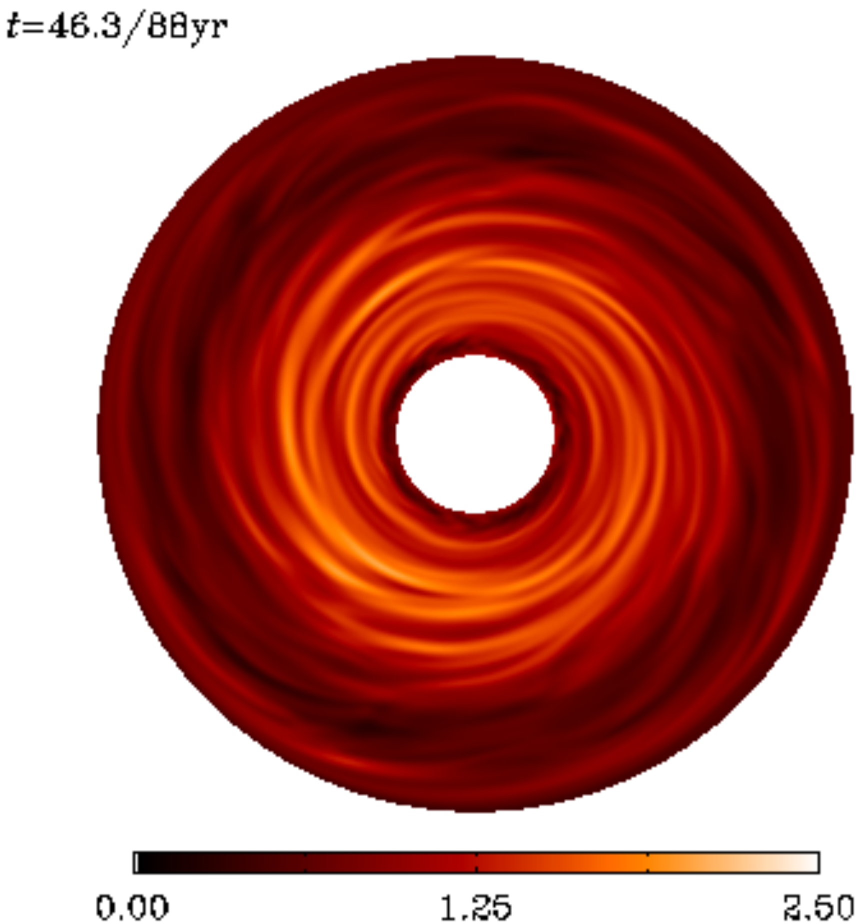




Ionized gas couples to magnetic fields

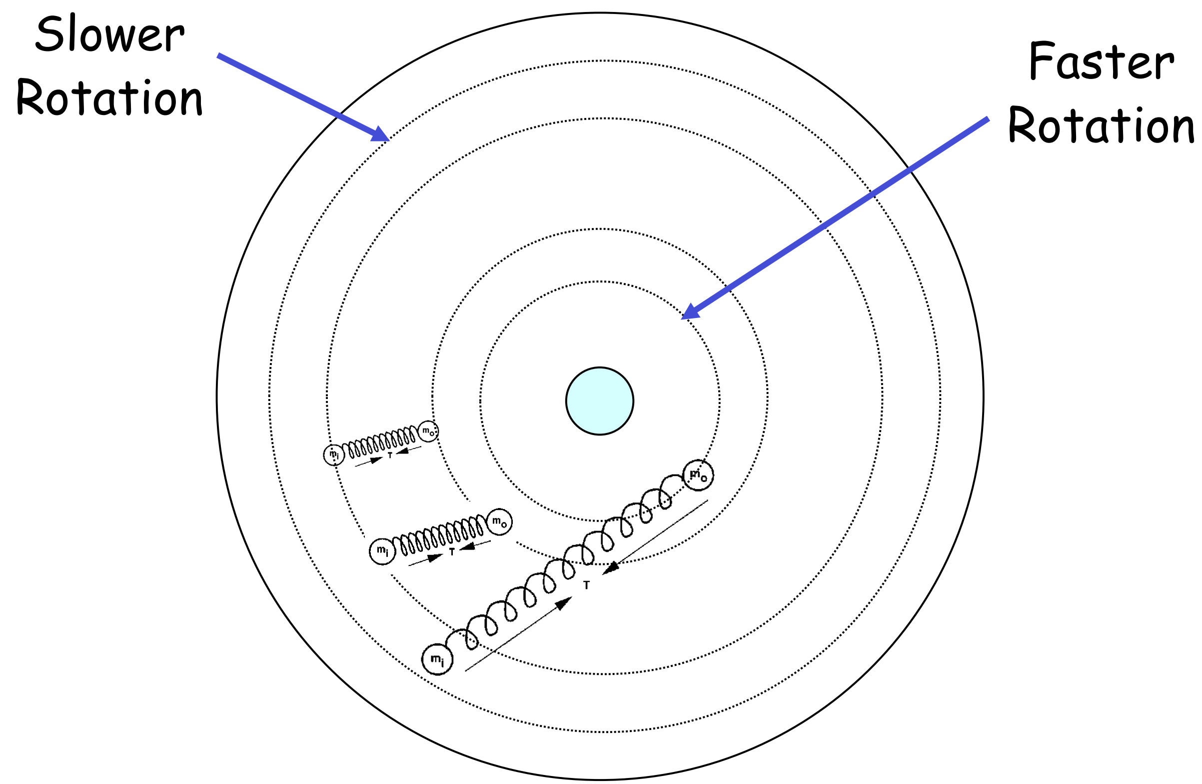
The instability mechanism is magnetic

Magnetic field lines have tension

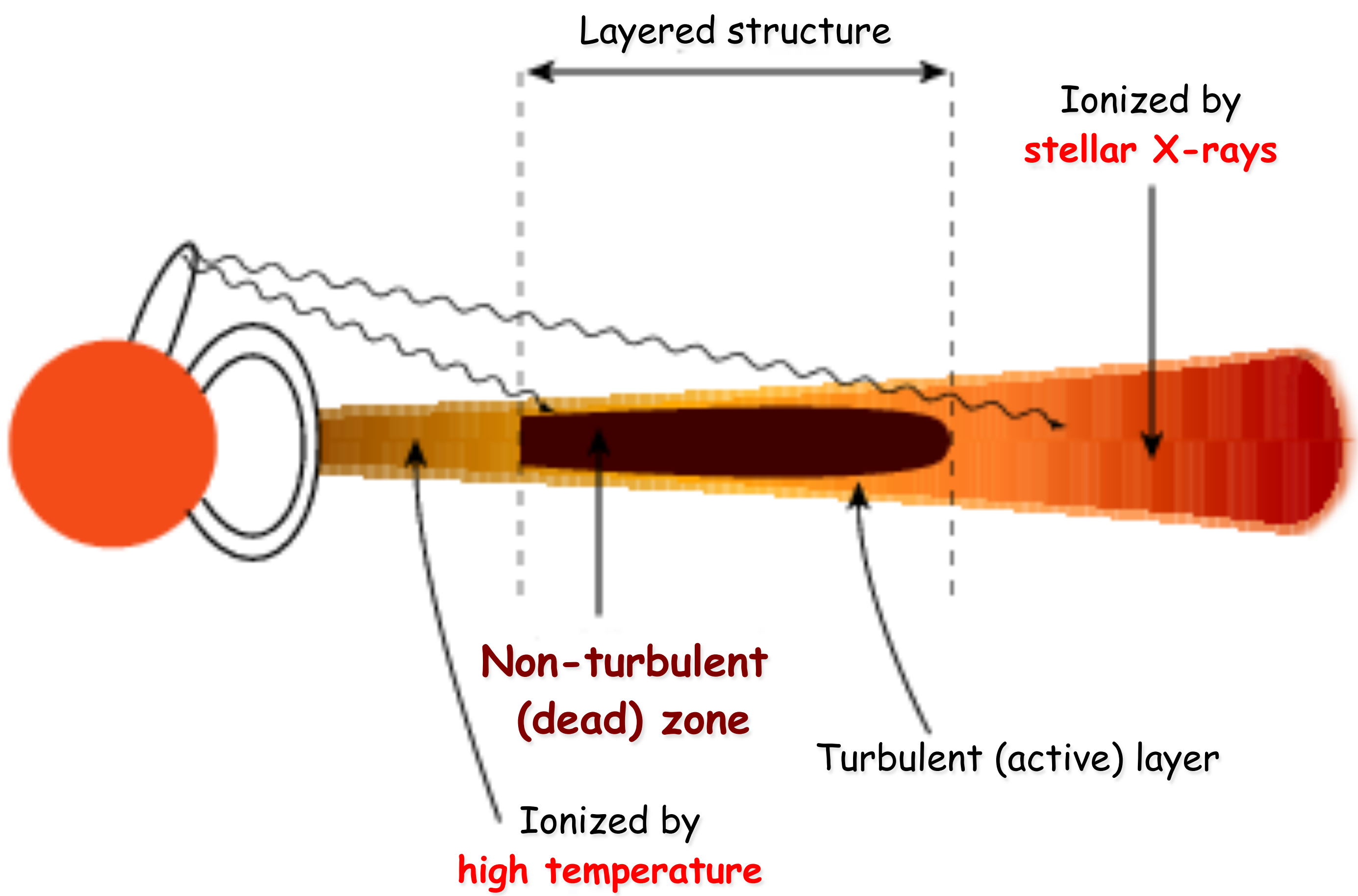


Magnetized disk

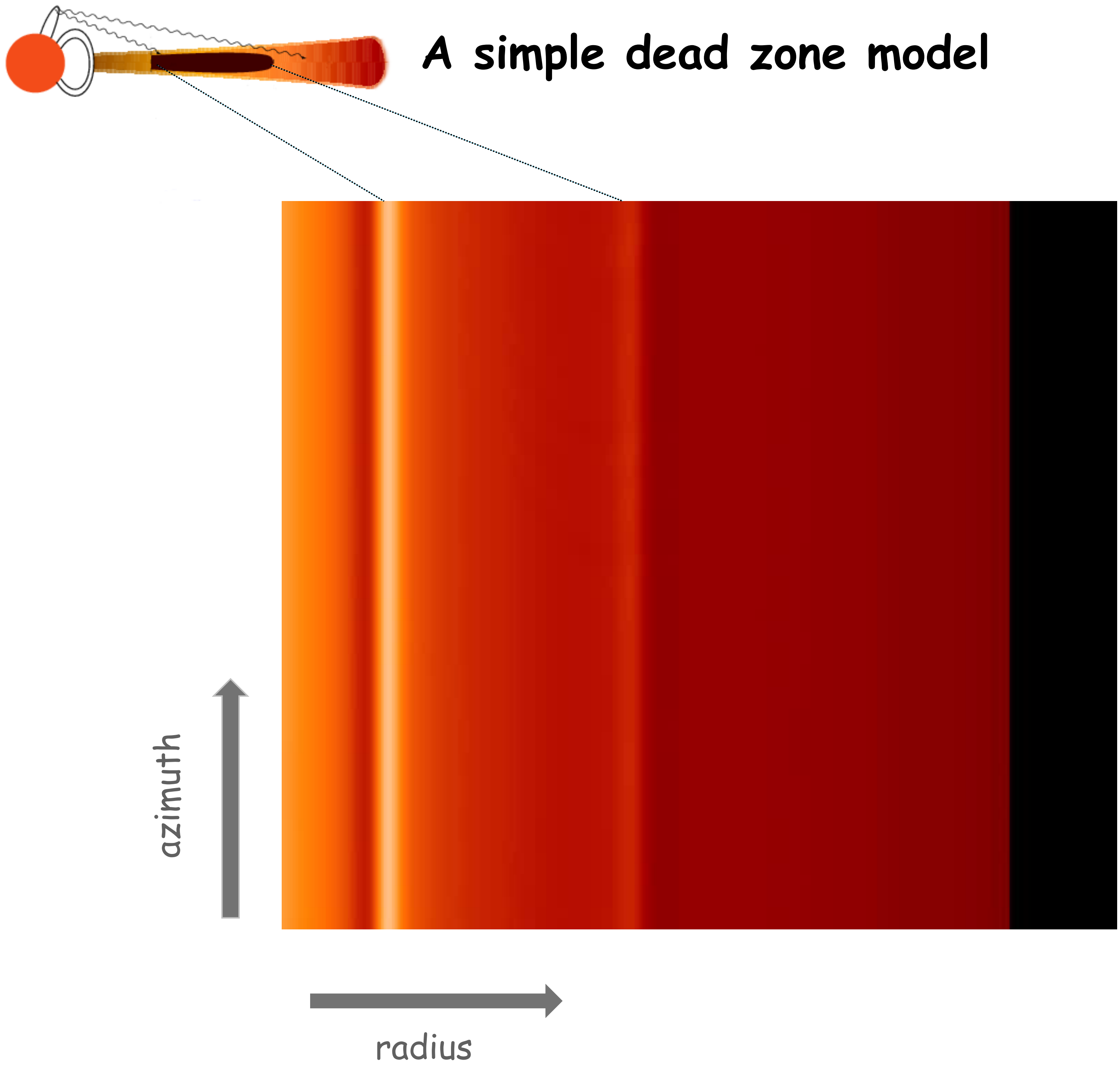
Lyra et al. (2008a)



Disks are not fully ionized

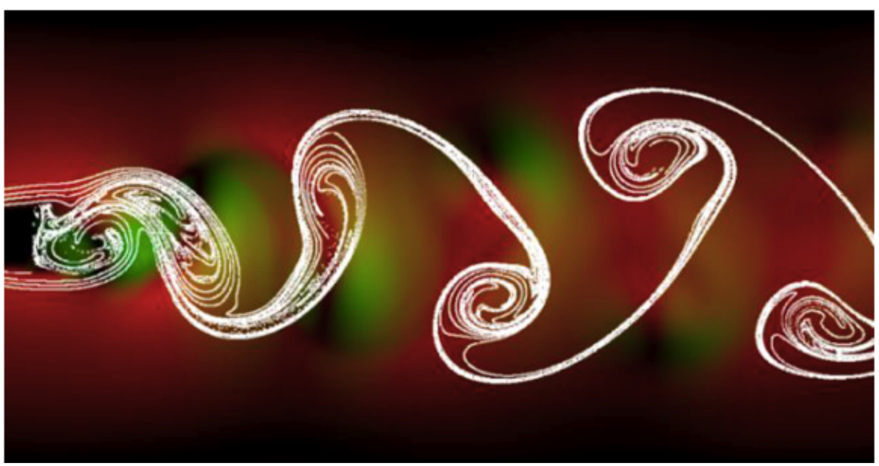


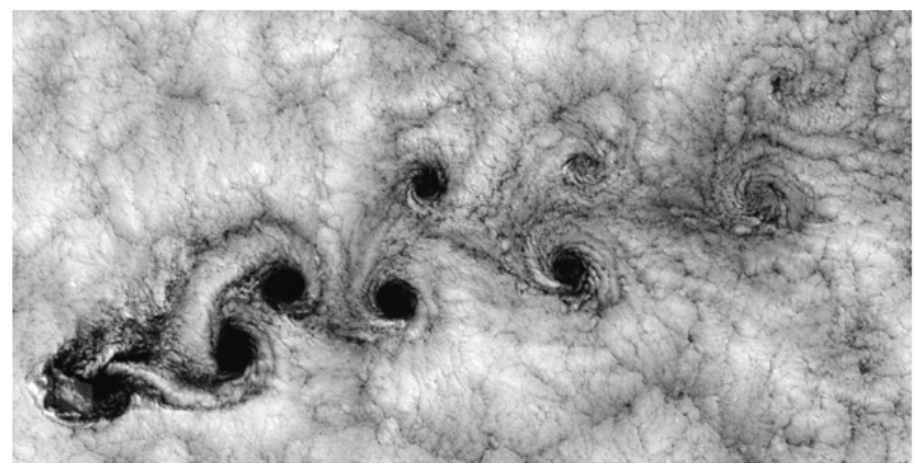
A simple dead zone model



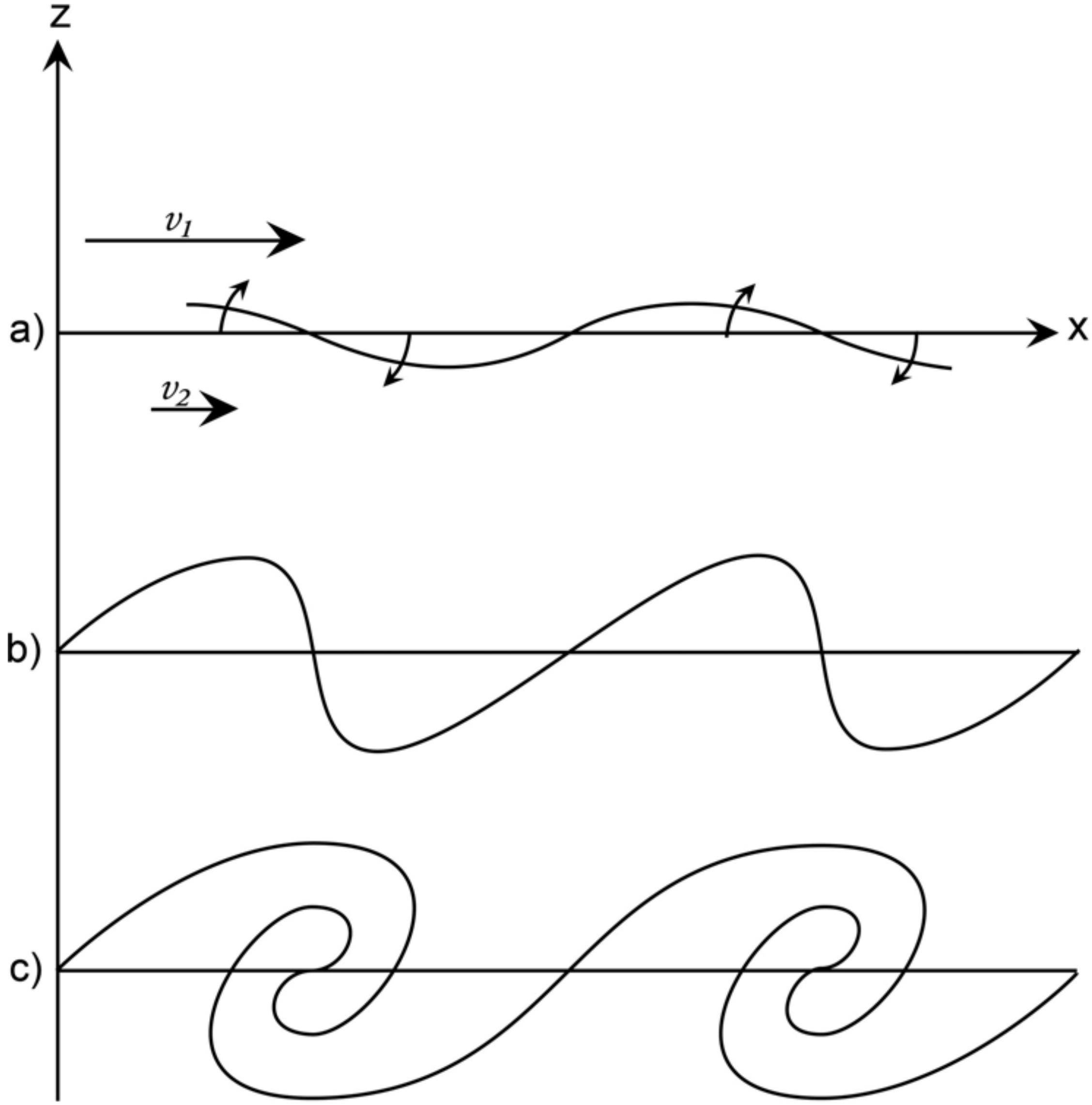
Lyra et al. (2008b)

Vortices – An ubiquitous fluid mechanics phenomenon

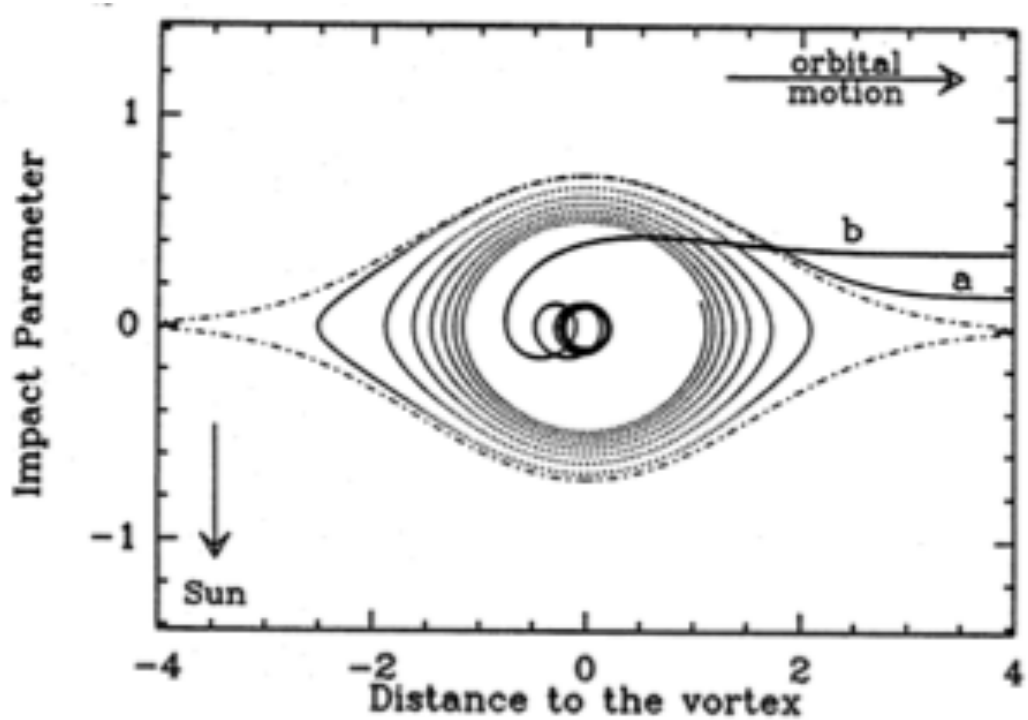




Kelvin-Helmholtz Instability



Tea-leaf effect



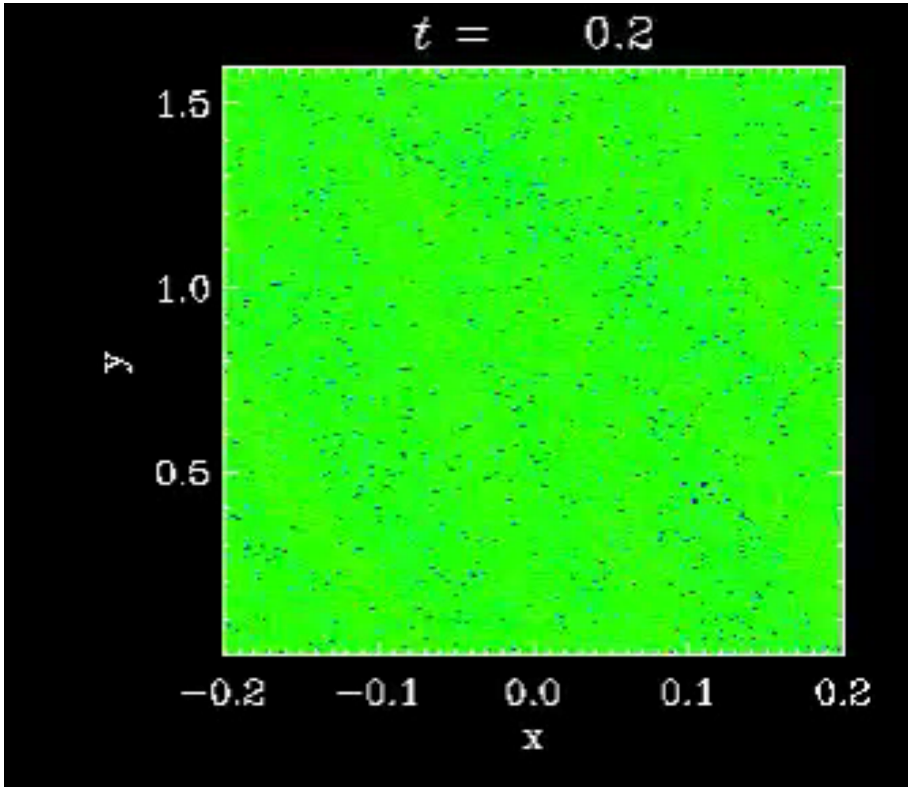
Barge & Sommeria (1995)

Particles sink to the center

Aid to planet formation (Barge & Sommeria 1995)

Speed up planet formation enormously
(Lyra et al. 2008b, 2009a, 2009b, Raettig, Lyra & Klahr 2012)

Tea-leaf effect



Credit: Natalie Raettig

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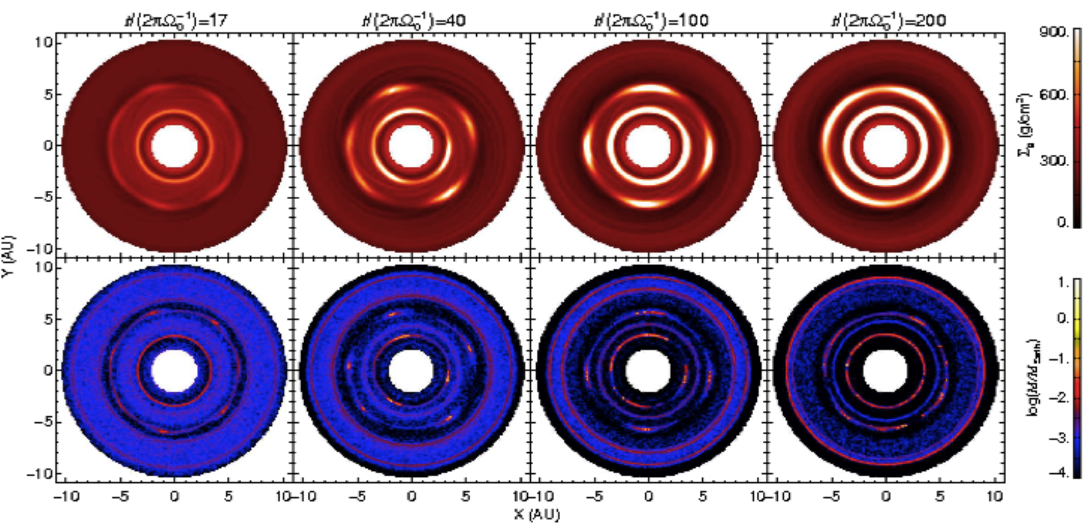
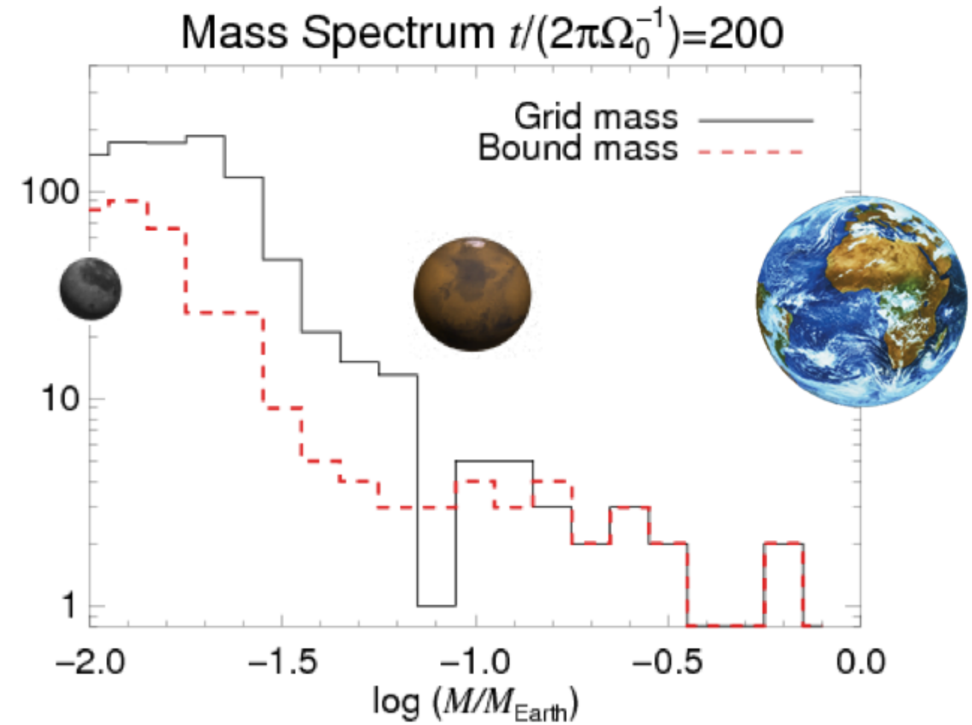
Vortices and Planet Formation

Gas



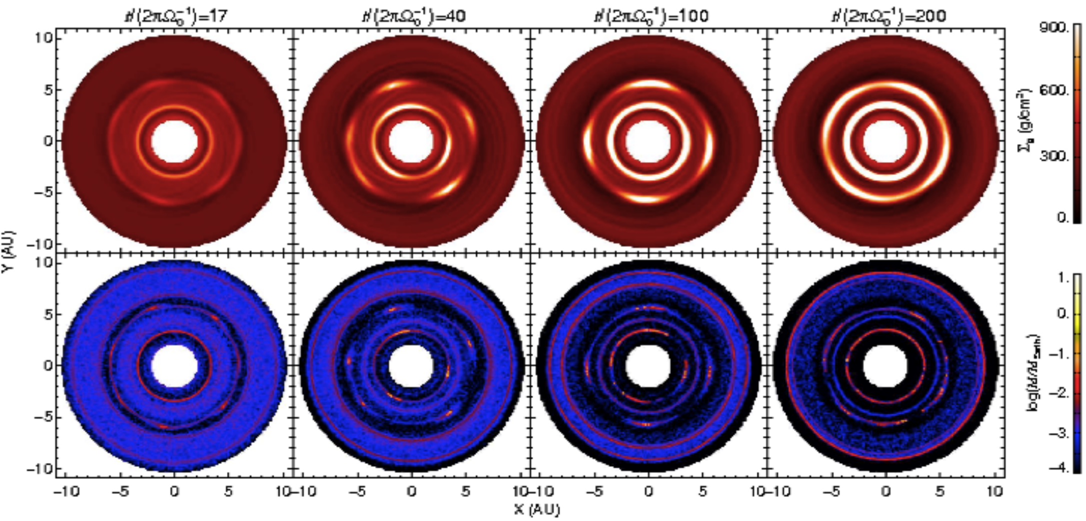
Particles



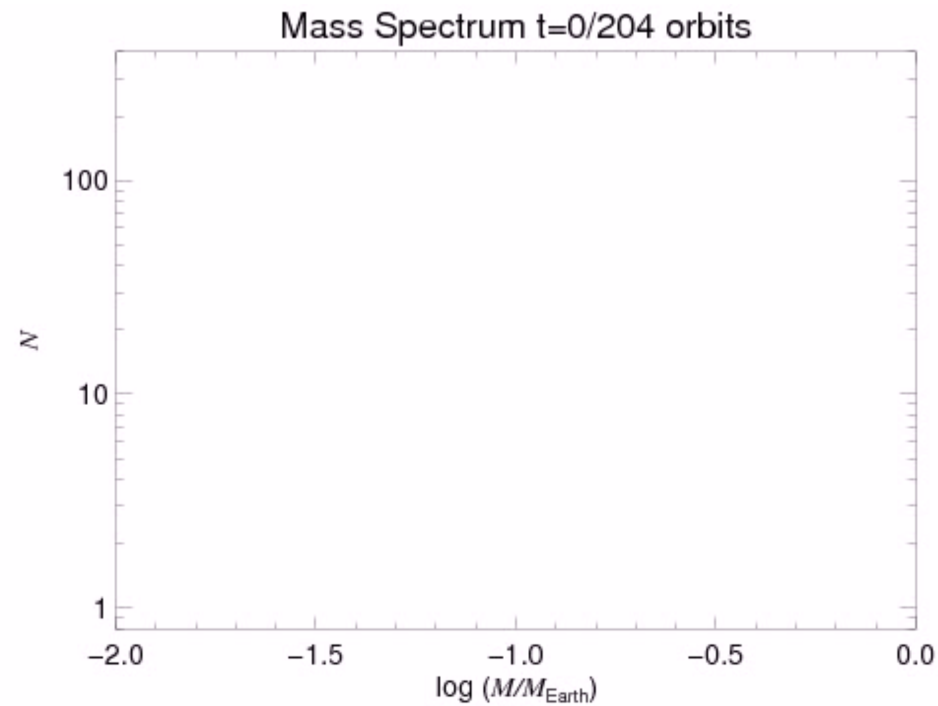
Collapse into Mars mass objects
(Lyra et al. 2008b, 2009a, 2009b,
see also Lambrets & Johansen 2012)

Vortices and Planet Formation

Gas



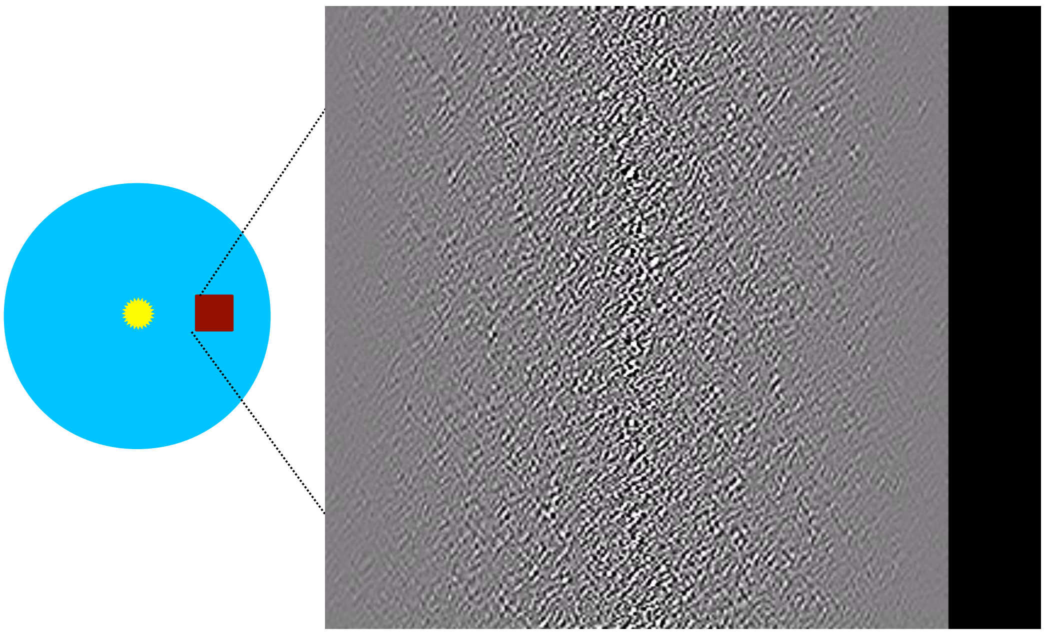
Particles



Collapse into Mars mass objects
(Lyra et al. 2008b, 2009a, 2009b,
see also Lambrets & Johansen 2012)

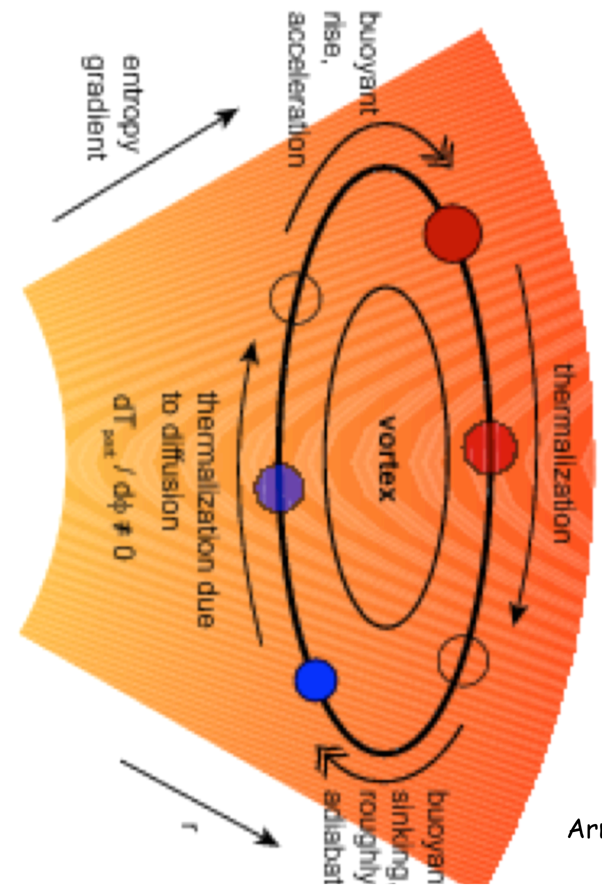
Baroclinic Instability - Excitation and self-sustenance of vortices

1. *Radial entropy gradient*
2. *Thermal diffusion*



Lyra & Klahr (2011)

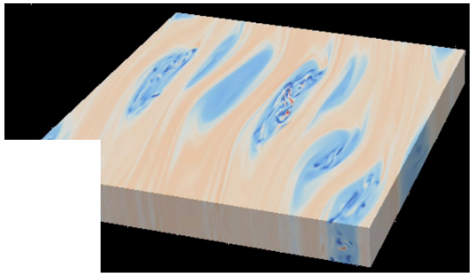
Sketch of the
Baroclinic Instability

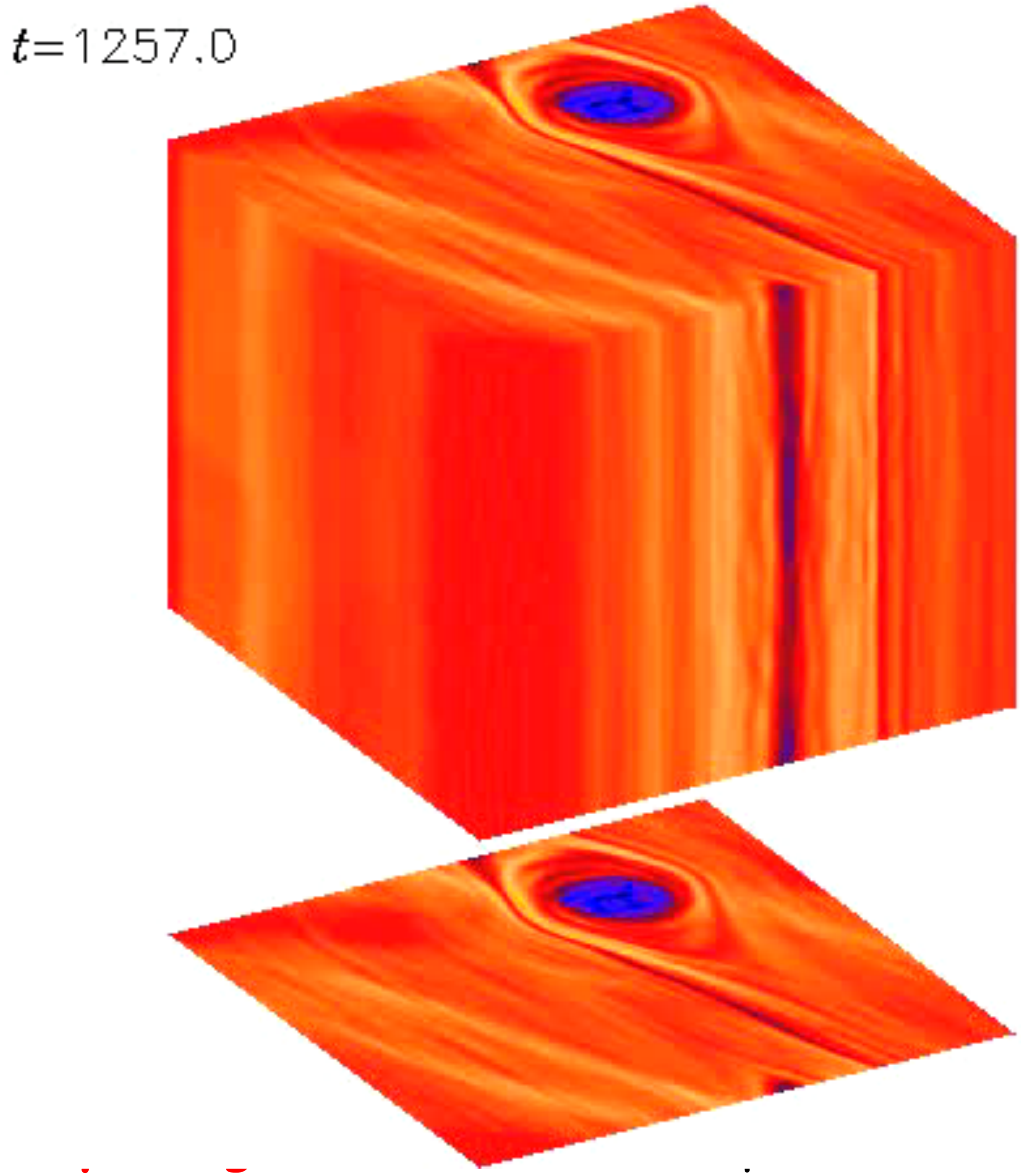


Armitage (2010)

$$\frac{\partial \omega}{\partial t} = \underbrace{-(\boldsymbol{u}\cdot\nabla)\omega}_{\text{advection}} \underbrace{-\,\omega(\nabla\cdot\boldsymbol{u})}_{\text{compression}} + \underbrace{(\omega\cdot\nabla)\boldsymbol{u}}_{\text{stretching}} + \underbrace{\frac{1}{\rho^2}\nabla\rho\times\nabla p}_{\text{baroclinicity}} + \underbrace{\nu\nabla^2\omega}_{\text{dissipation}}$$

"Elliptic" Instability





sur & Papaloizou (2010)

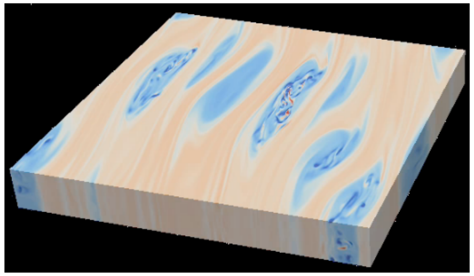
Hydrodynamic
instability (B=0

See also
Pierrehumbert 1986
Bayly 1986
Kerswell 2002
sur & Papaloizoy 2009
sur & Papaloizou 2010
Lyra & Klahr 2011
Lyra 2013

In ... ws.

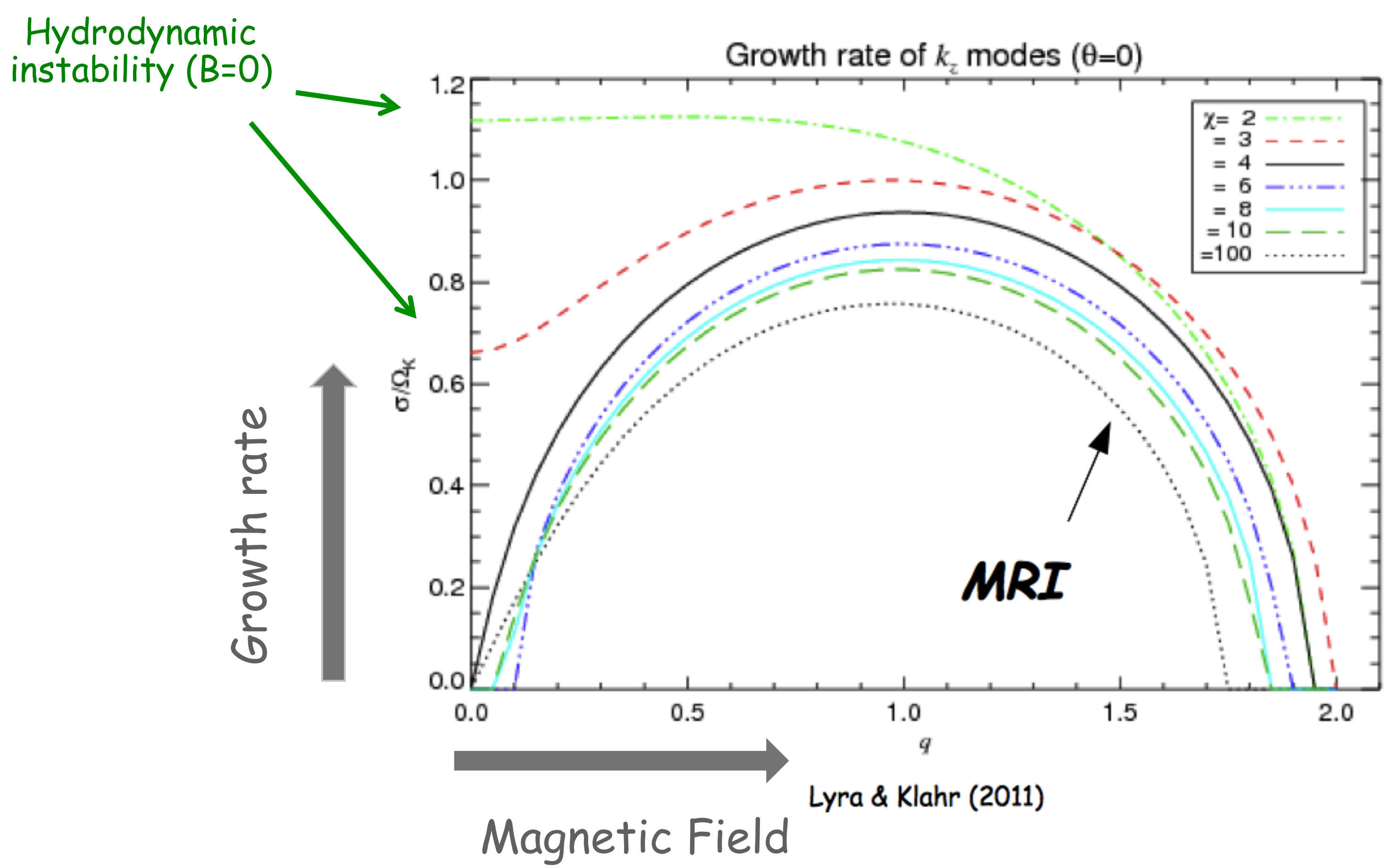
They are subject to an MRI-like instability when magnetized.

"Elliptic" Instability



Lesur & Papaloizou (2010)

See also
Pierrehumbert 1986
Bayly 1986
Kerswell 2002
Lesur & Papaloizoy 2009
Lesur & Papaloizou 2010
Lyra & Klahr 2011
Lyra 2013

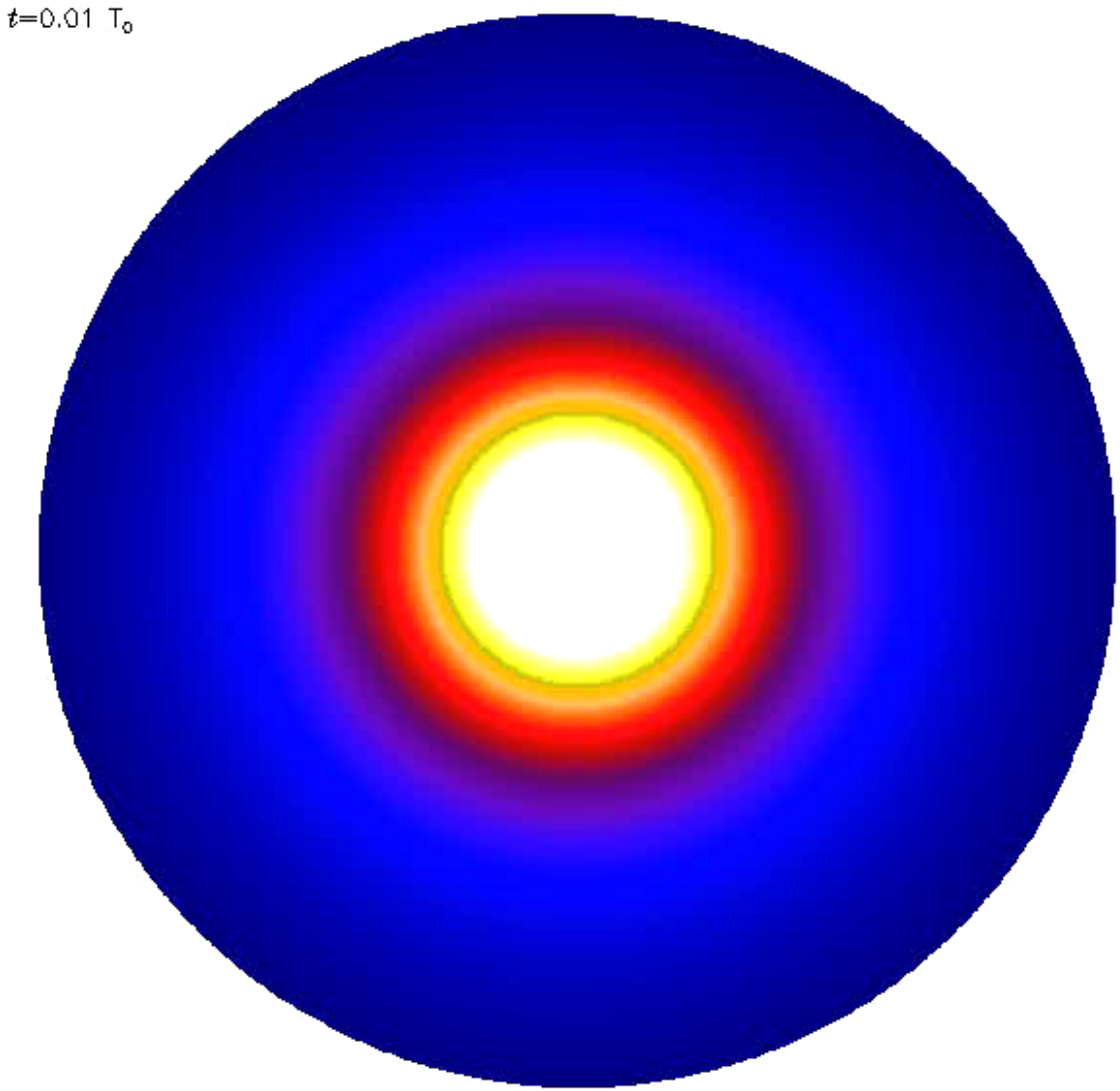


Lyra & Klahr (2011)

Infinitely elongated vortices are equivalent to **shear flows**.

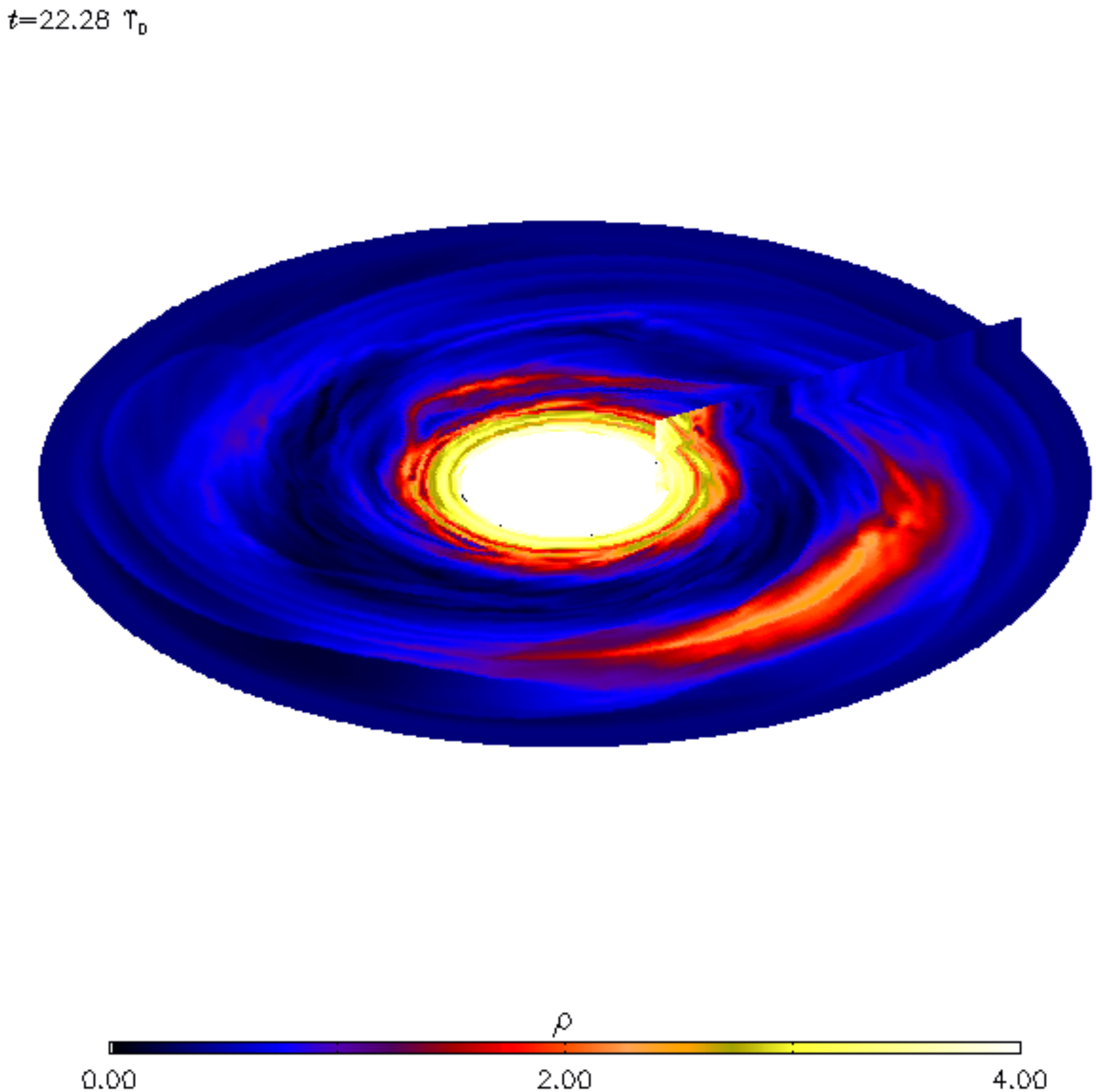
They are subject to an MRI-like instability when magnetized.

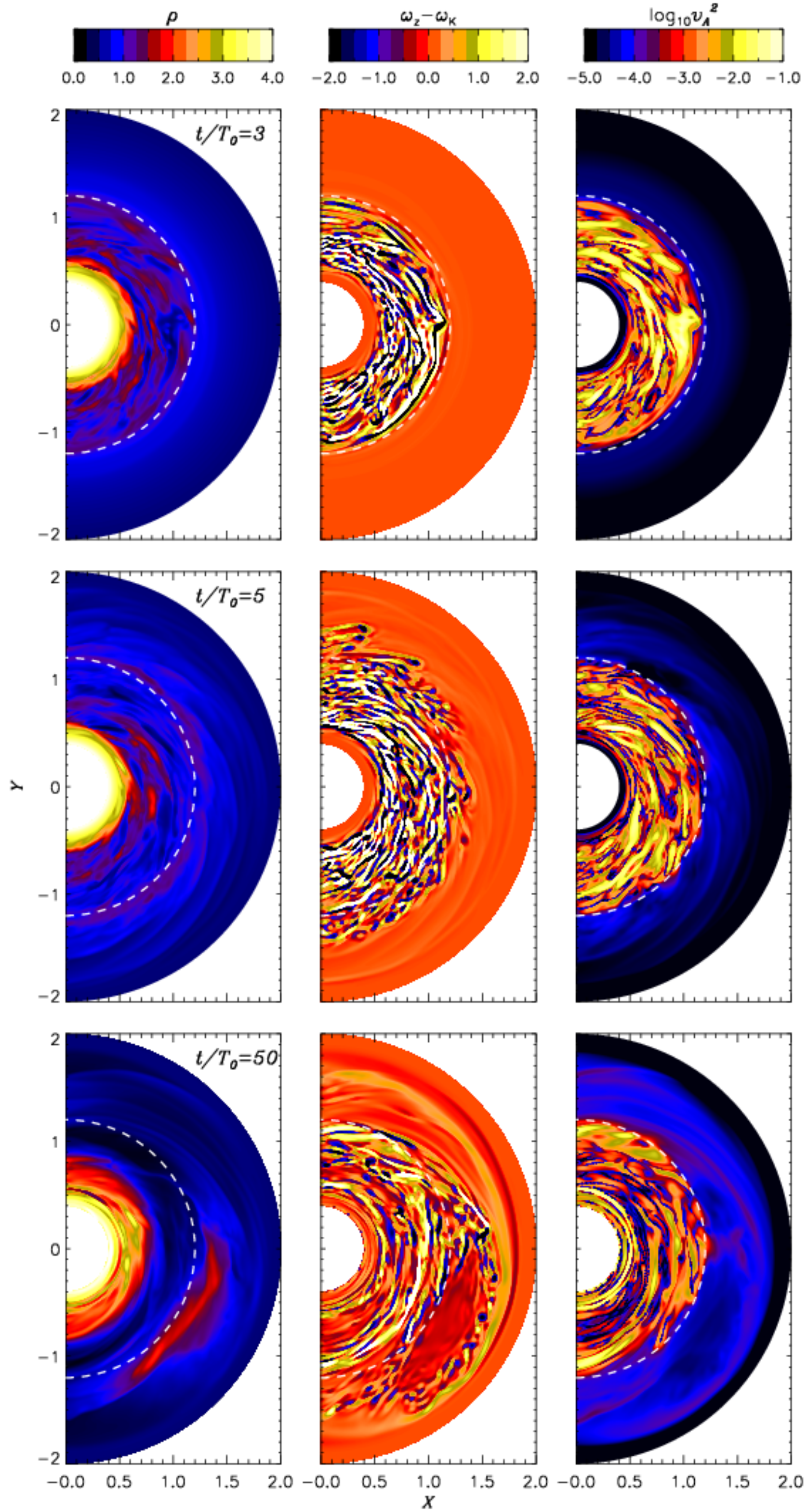
Realistic Active/Dead zone boundary



Lyra & Mac Low (2012)

Active/dead zone boundary





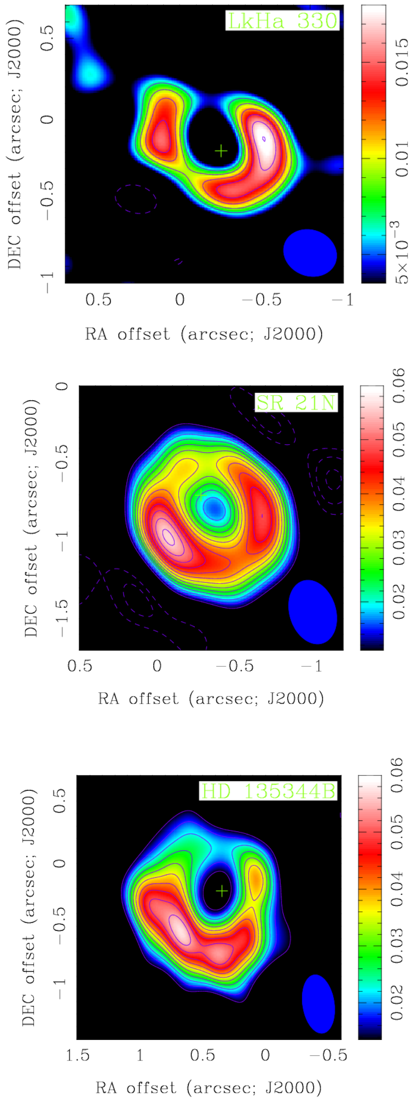
Magnetized inner disk + resistive outer disk

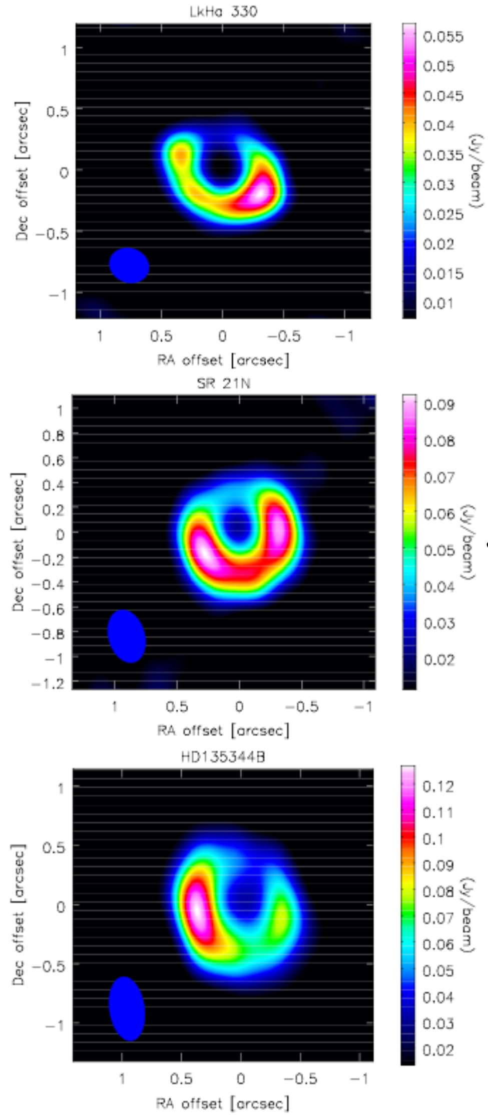
Lyra & Mac Low (2012)

A possible detection of vortices in disks?

Observations

Brown et al. (2009)





Models

Simulated observations of Rossby vortices

Regaly et al. (2012)

A possible huge vortex observed with ALMA

A Major Asymmetric Dust Trap in a Transition Disk

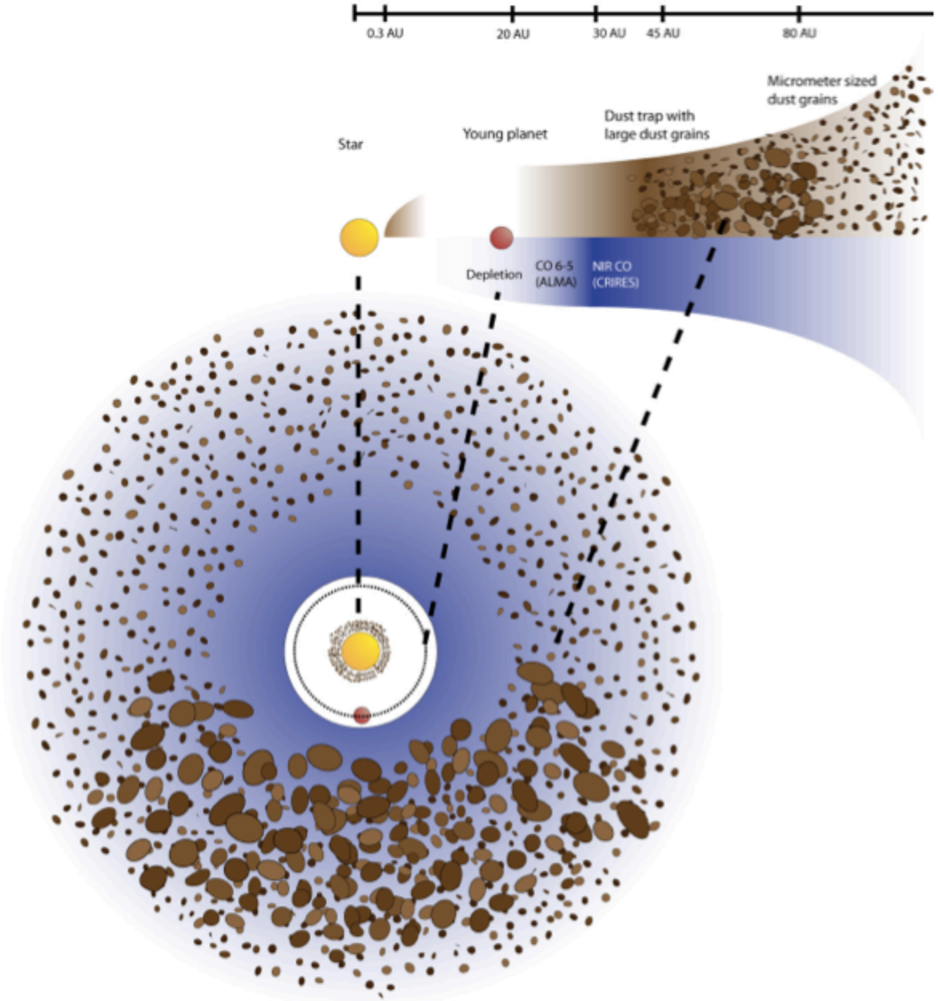
Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

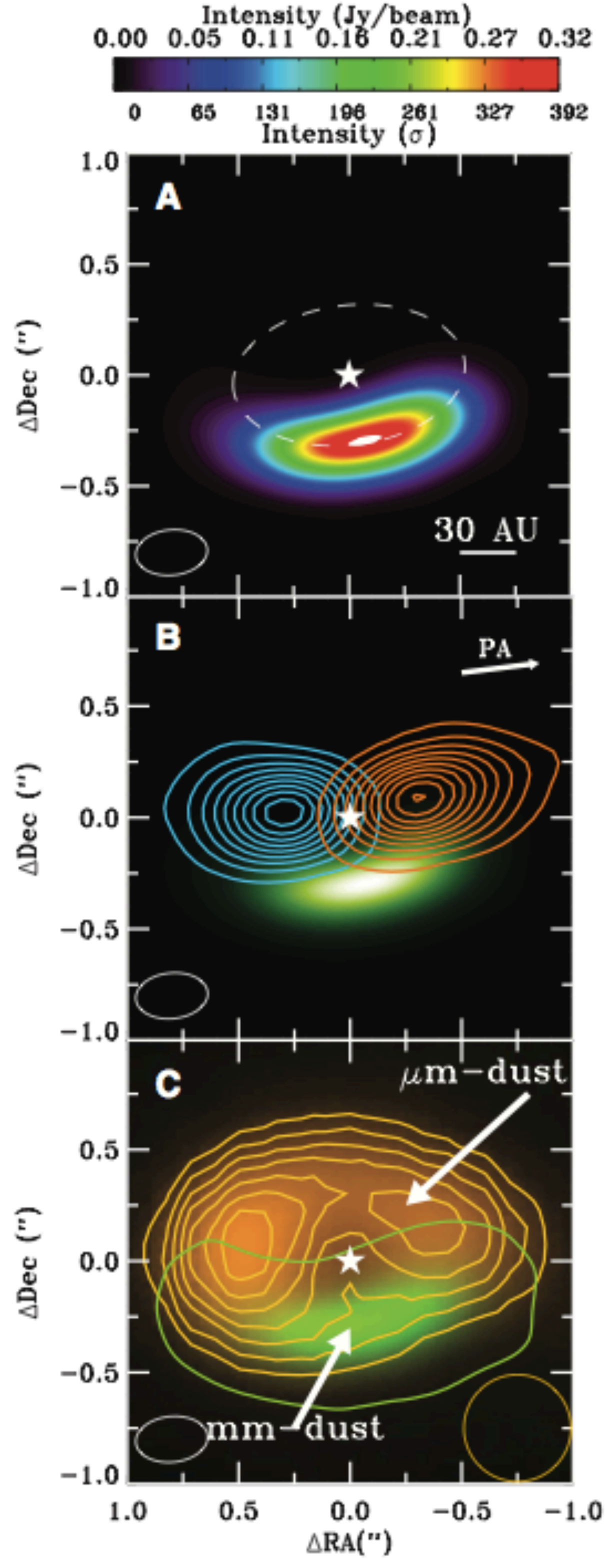
Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

van der Marel et al. 2013

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

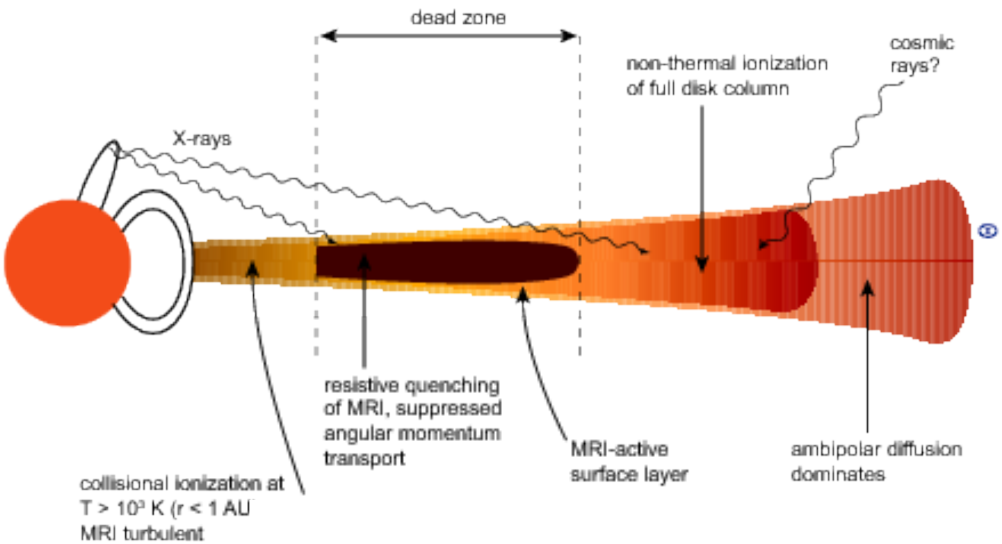


asymmetric mm dust at 63 AU

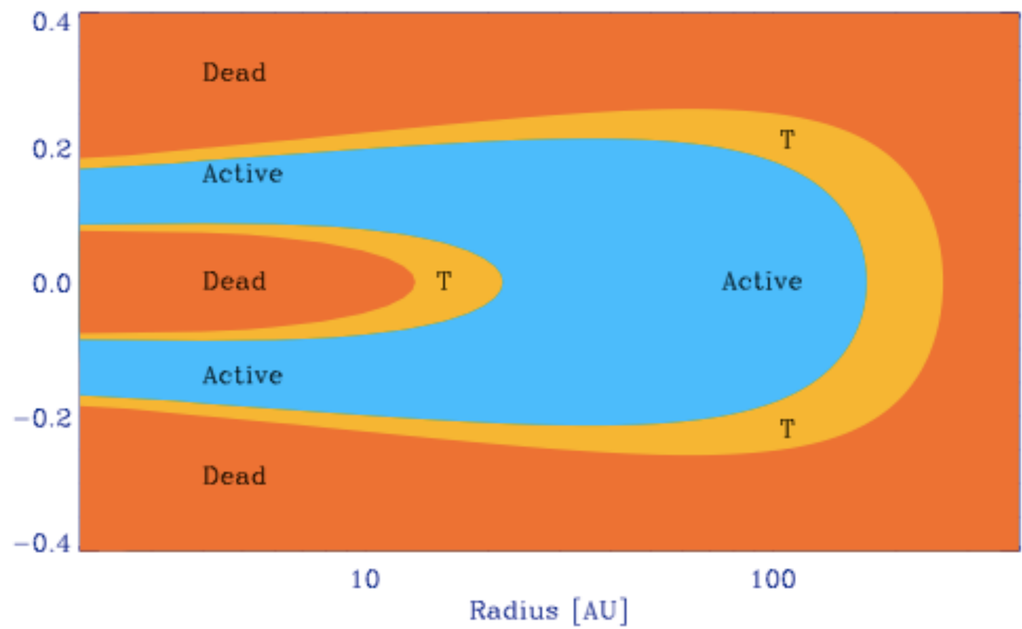
Gas detection: Keplerian rotation

Micron-sized dust follows gas

Outer dead zone transition fails to produce dust traps



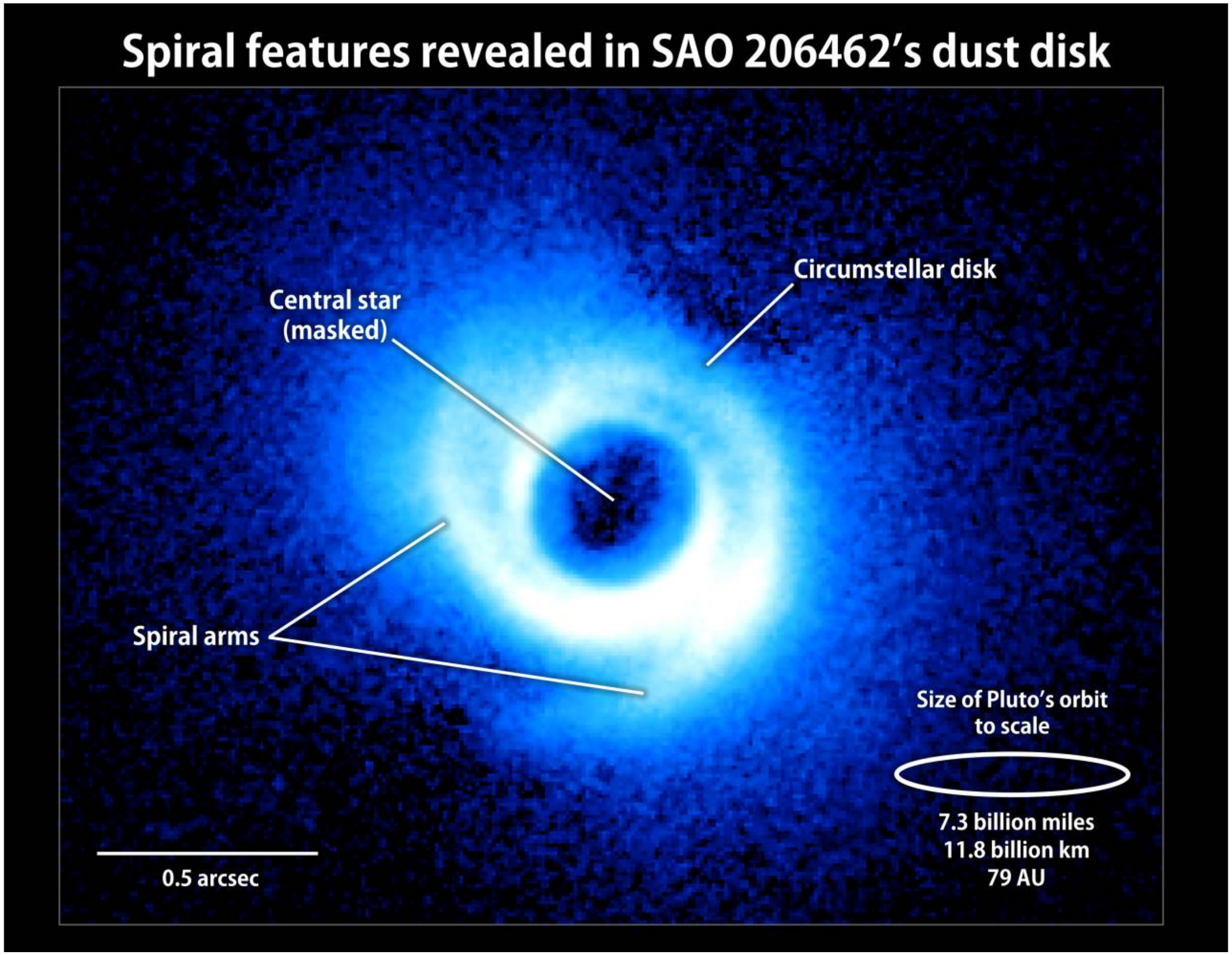
Armitage (2010)



Dzyurkevitch et al (2013)

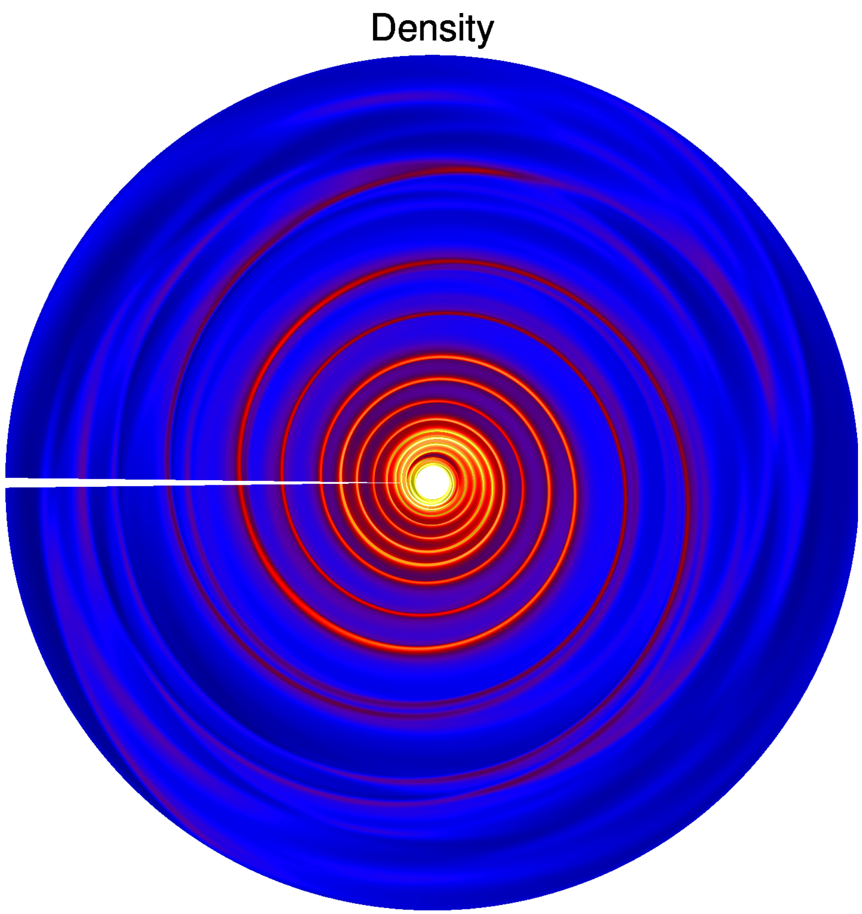
The **outer** dead zone transition in ionization is
TOO SMOOTH
to generate an KH-unstable bump.

Spirals in disks



Muto et al. (2012)
Favored explanation: planets.

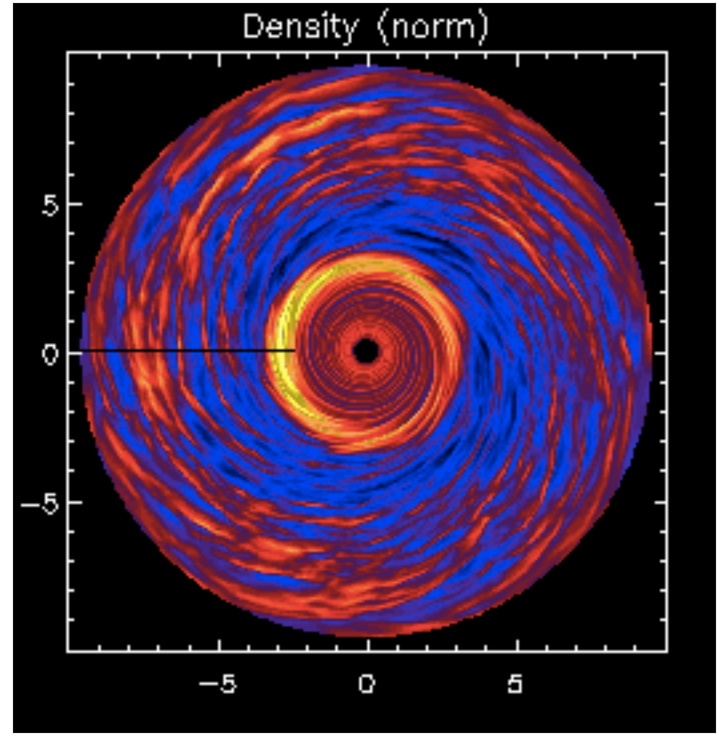
Outer active zone/inner dead zone transition



The **outer** active/dead zone transition is
TOO SMOOTH
to generate an RWI-unstable bump.

Waves from turbulent zone propagate into dead zone as **SPIRALS**.

Inner dead zone + Outer active zone model

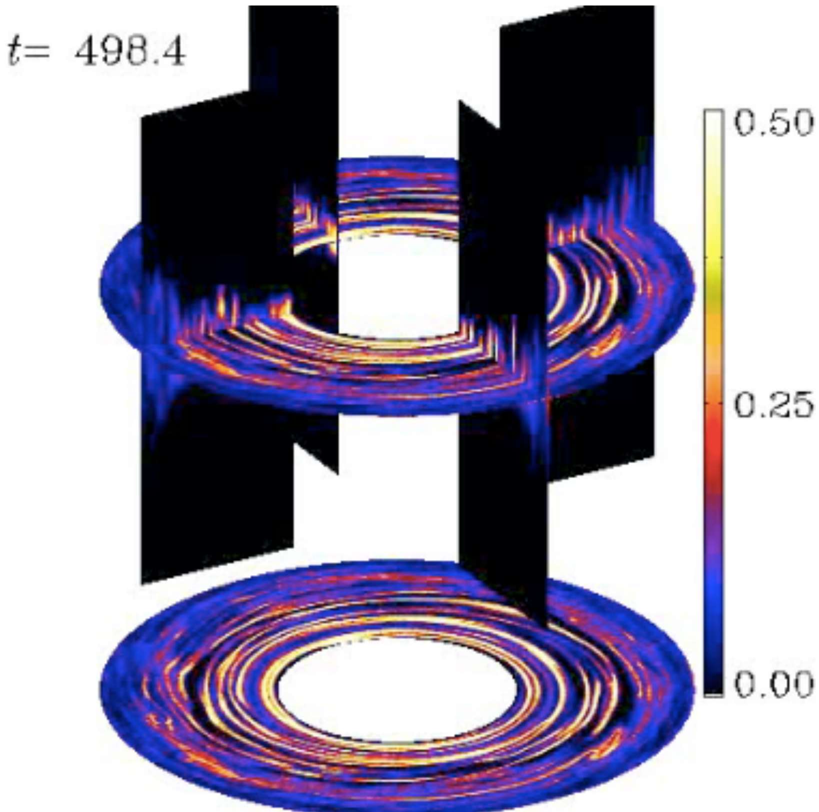


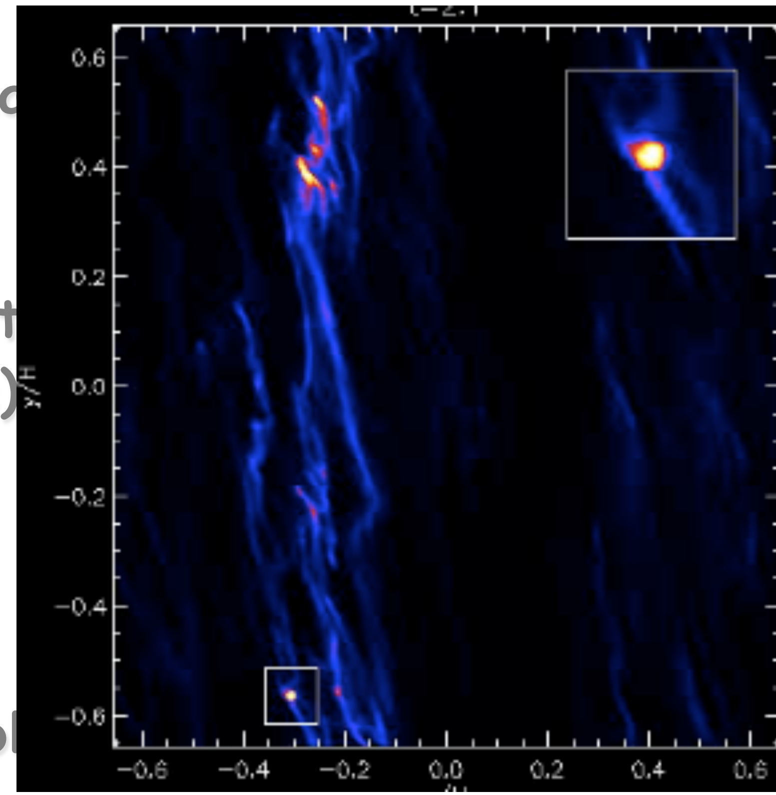
Moderately high resolution (32/H in the midplane), realistic resistivities.

Yes, a spiral propagates into the dead zone.
But a vortex forms anyway.

Conclusions

- **Planet formation in the active zone may occur through turbulence.**





- Pla … nc
- Th … rt … e) … s
- Ob … bl … e the…

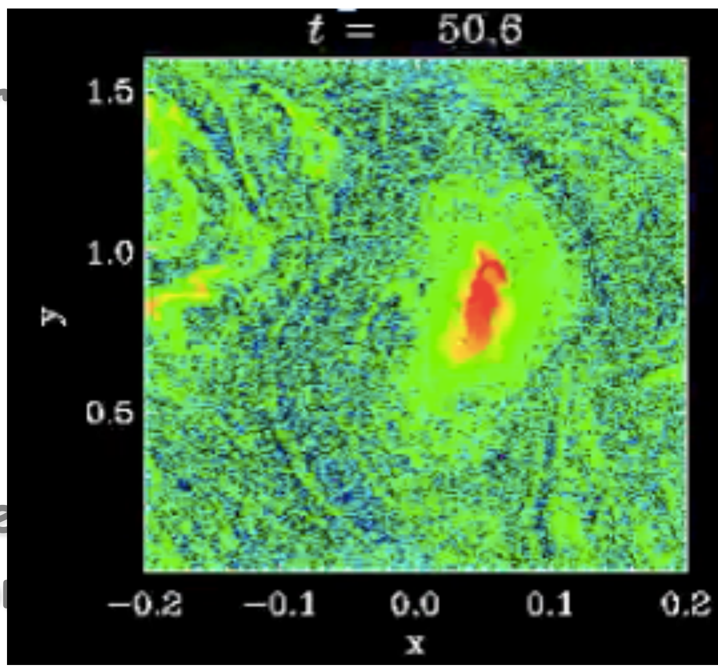
Conclusions

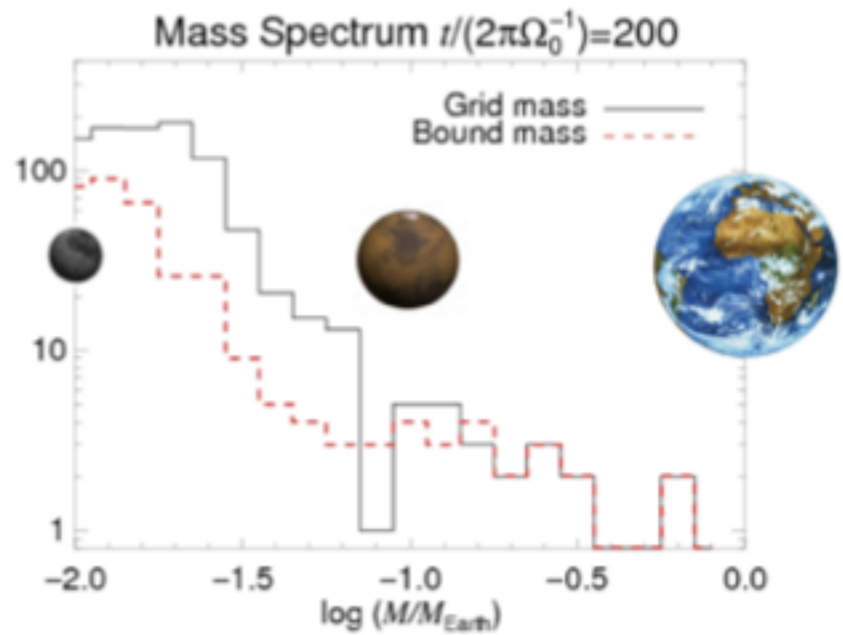
- Planet formation in the active zone may occur through turbulence.

- **Planet formation in the dead zone may occur through vortices.**

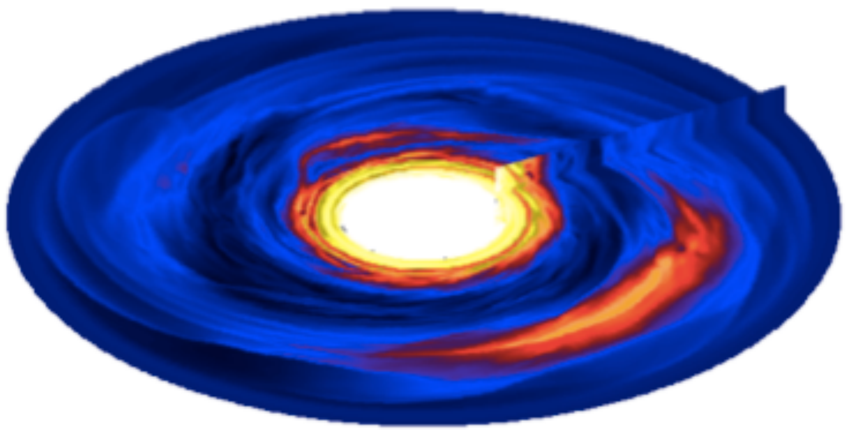
- Ther … vo
    - … wav
    - … pen

- Obse … ng c
theo





Conclusions



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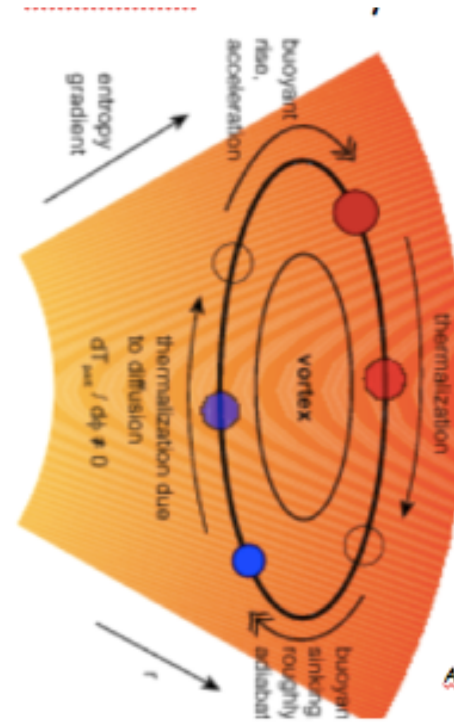
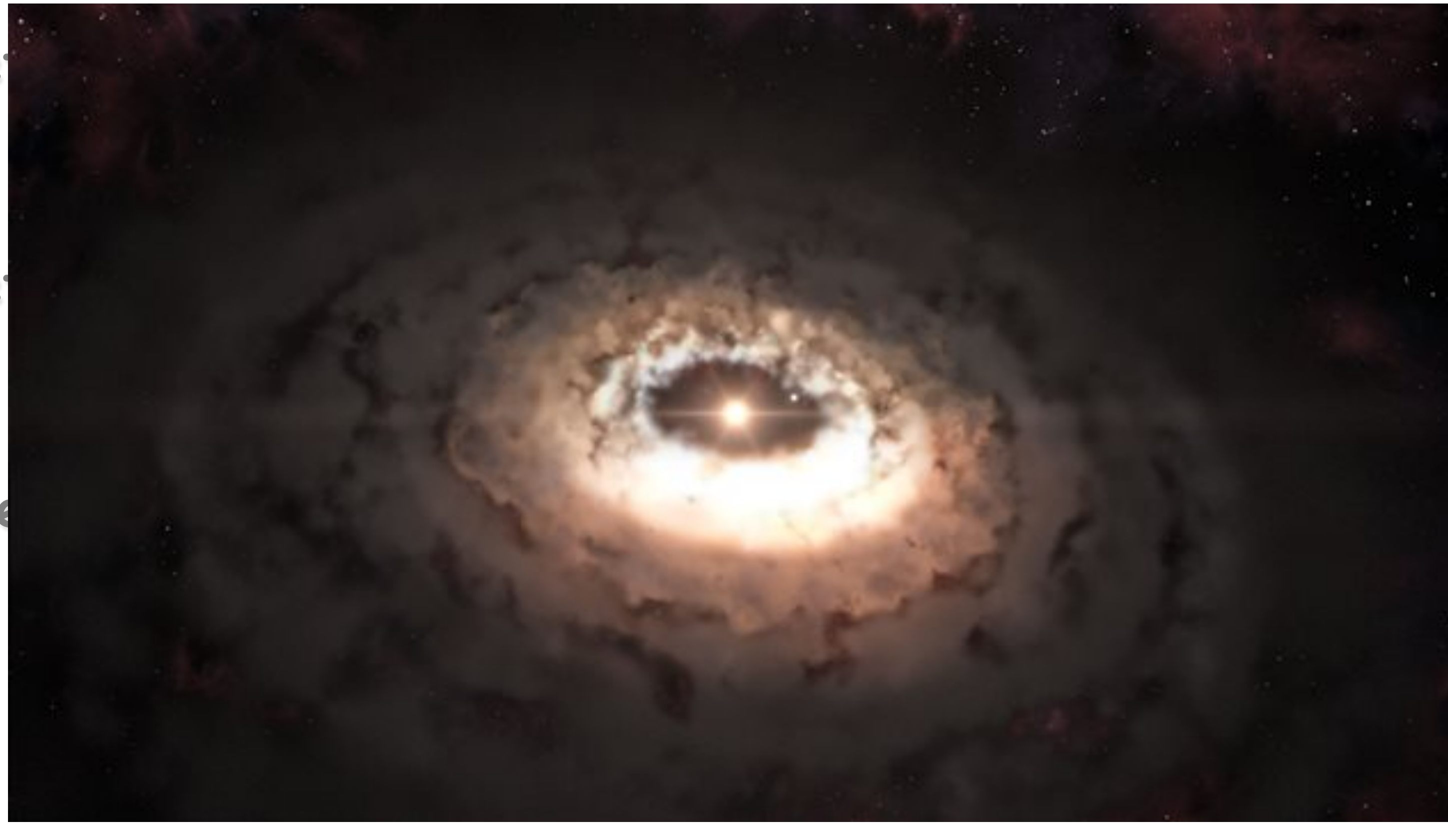


Armitage (2010)

- There are two ways to generate vortices
  - Kelvin-Helhmoltz (Rossby wave) – happens at active/dead transitions
  - Baroclinic instability – happens in the bulk of the dead zone

- Observations are finally becoming able to provide constrains to the theory

Conclusions



- **Observations are finally becoming able to provide constrains to the theory**