The birth of planets:
Signatures in Circumstellar Disks

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Warsaw, July 24th, 2018

Outline

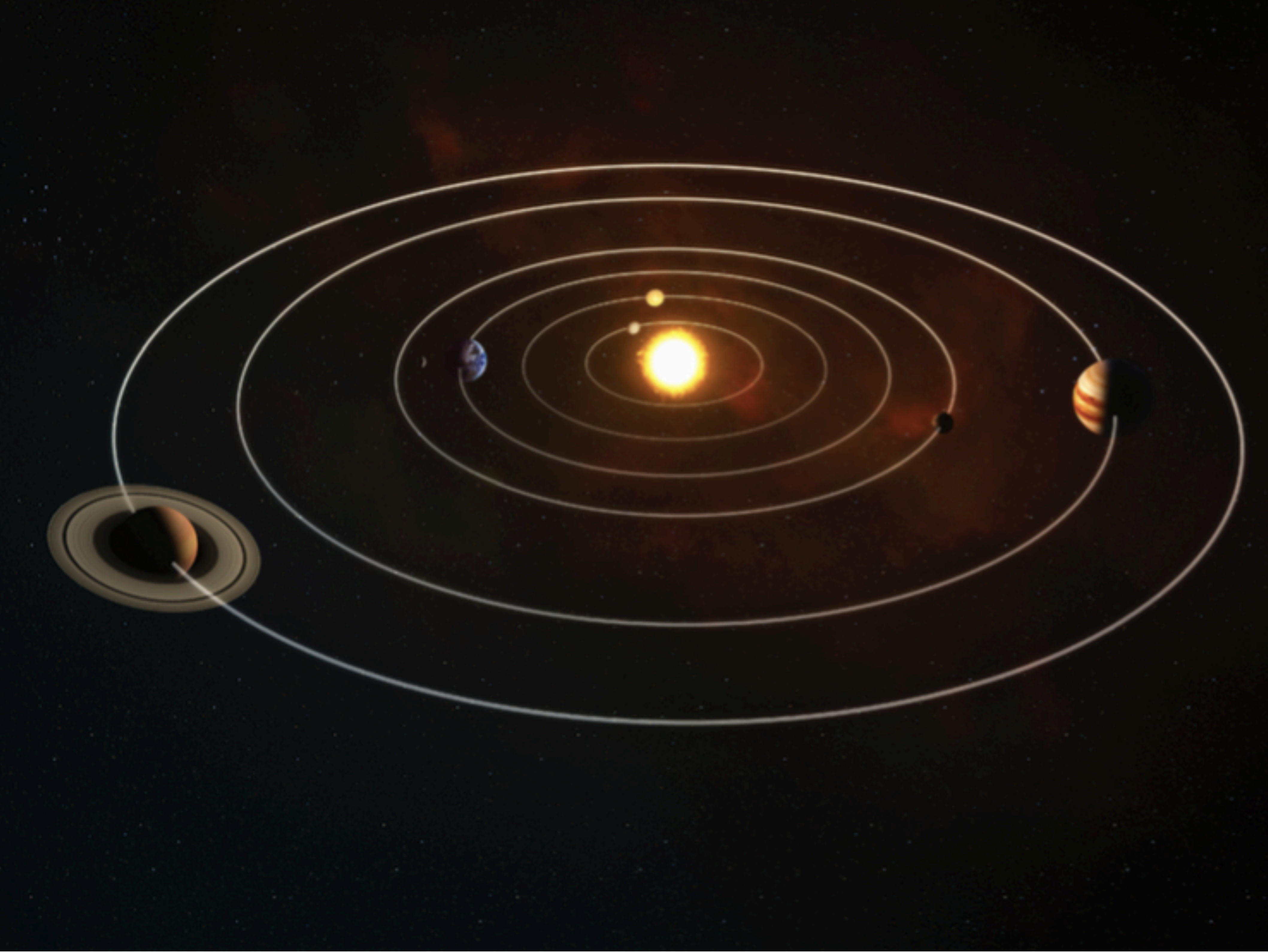
- Observational constraints

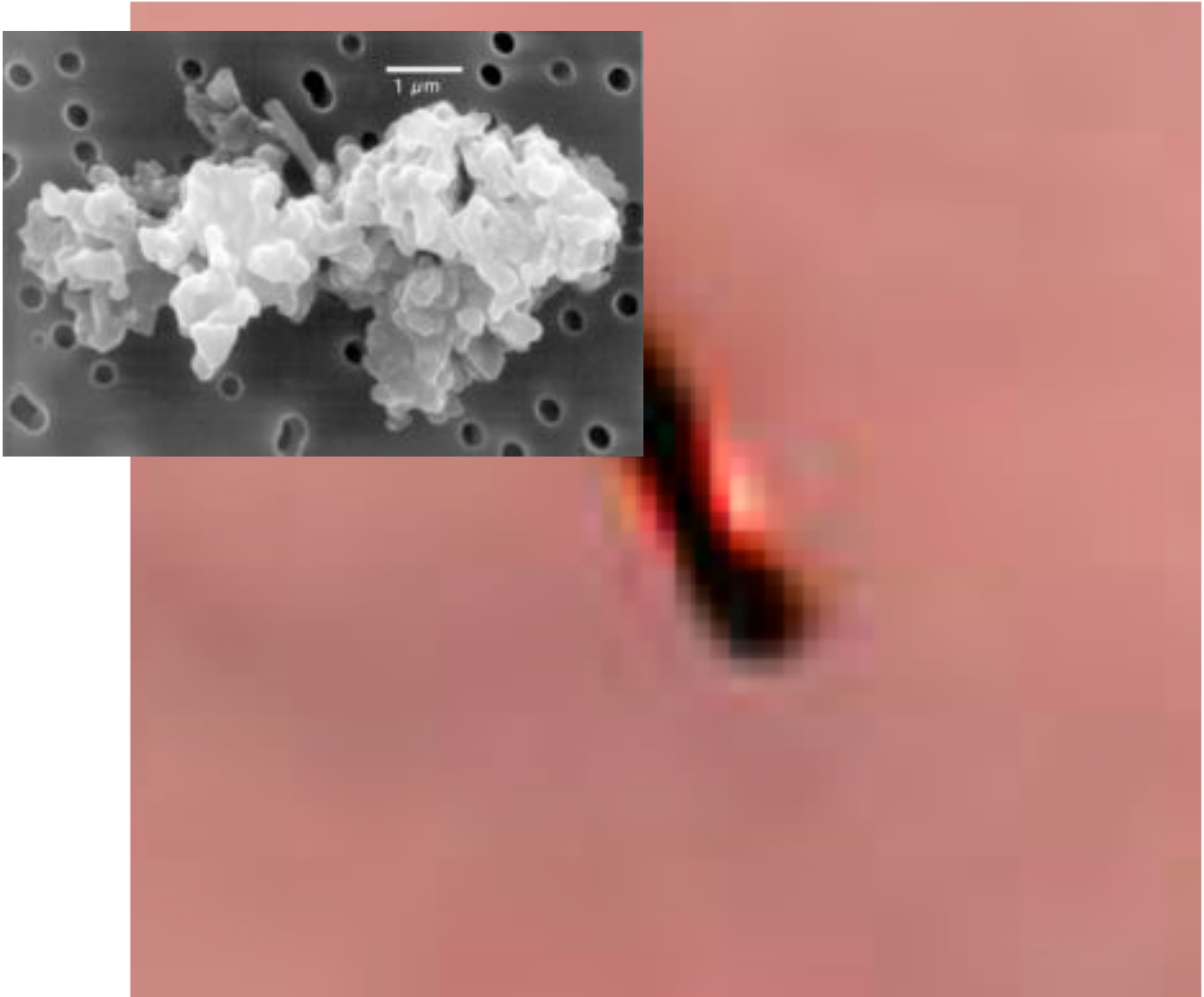
- The need for turbulence
  - "Streaming" Instability
  - Vortex trapping

- The importance of ionization: "active" and "dead" zones
  - Vortices in the "dead" zone

- The view of ALMA

- Observability




1 μm

Protoplanetary Disks

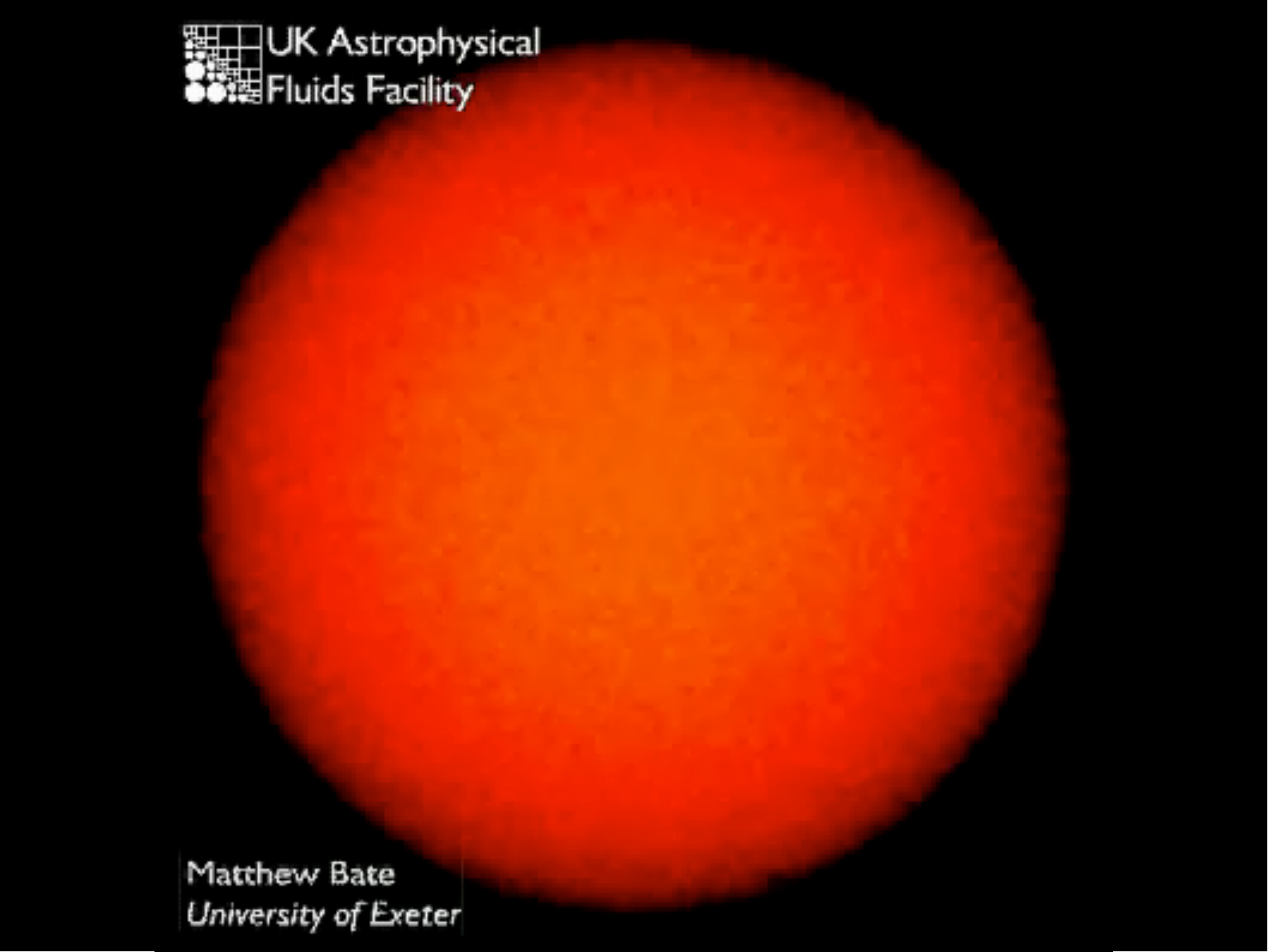
PP disk fact sheet

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

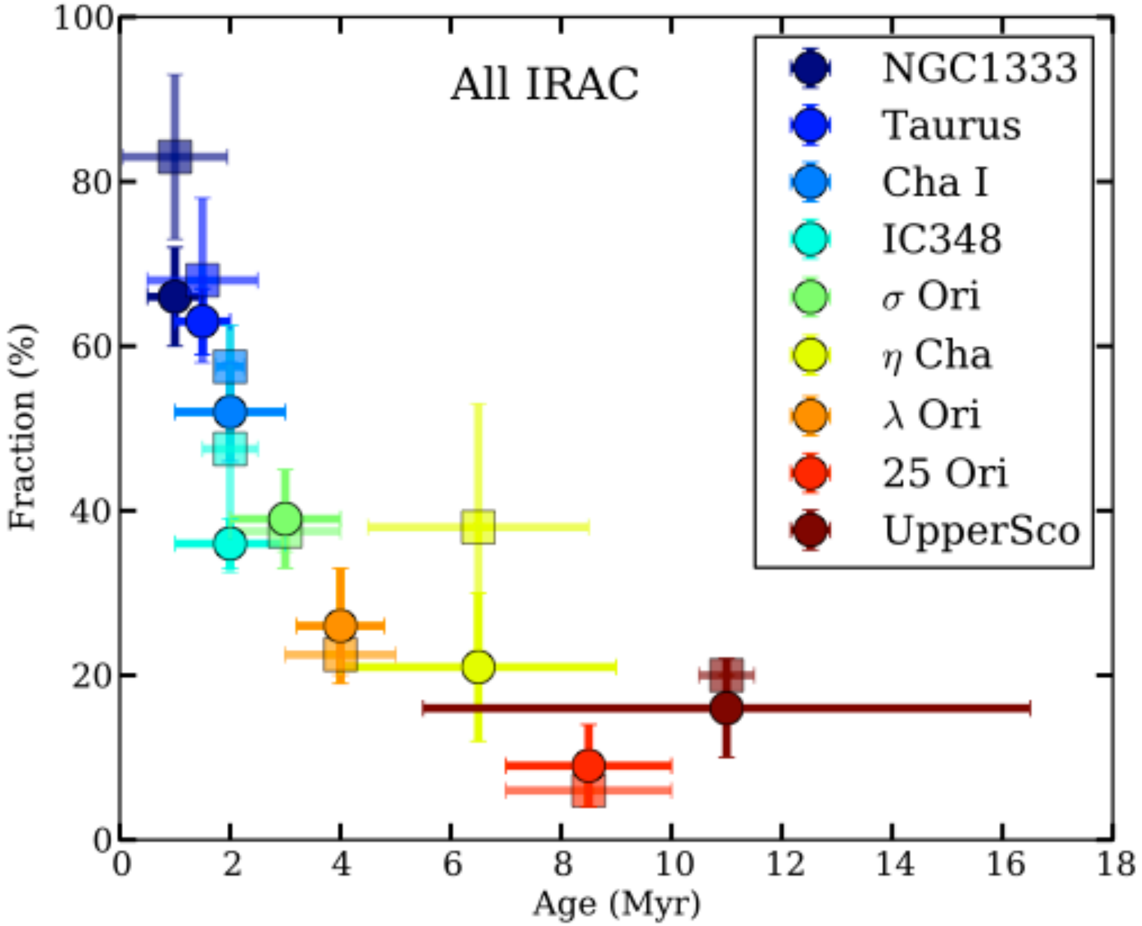
Temperature: 10-1000 K

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

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

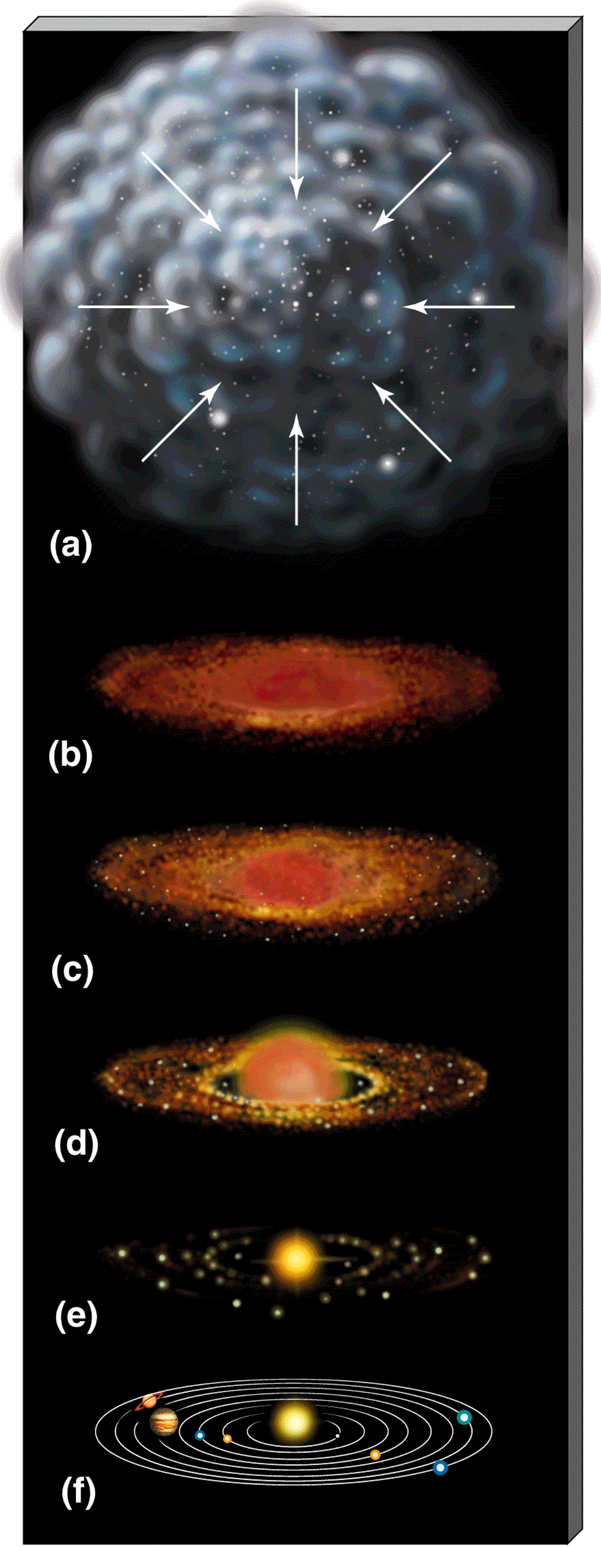

UK Astrophysical
Fluids Facility
Matthew Bate
University of Exeter

Disk lifetime



(Ribas et al. 2014)

Disks dissipate within ~10Myr



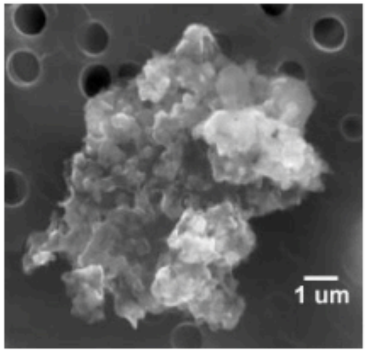
Disk Evolution

Gas-rich phase (< 10 Myr)
Primordial Disks

Gas-poor phase (>10 Myr)
Debris Disks

Planet Formation

"Planets form in disks of gas and dust"



A miracle happens

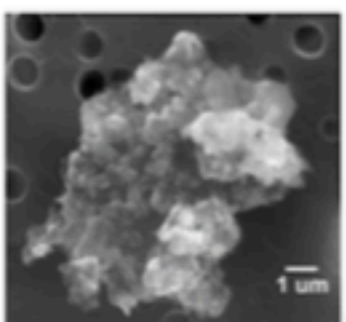
Planet Formation

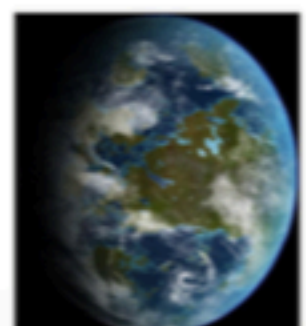
Planetesimal Hypothesis (Safronov 1969)

From dust to peebles
μm -> cm : hit-and-stick by van der Walls

From planetesimals to planetary embryos
km -> 1000 km : Gravity

From planetary embryos to planets
Rocky planets: binary collisions
Gas giants: Attract gaseous envelope





Planet Formation

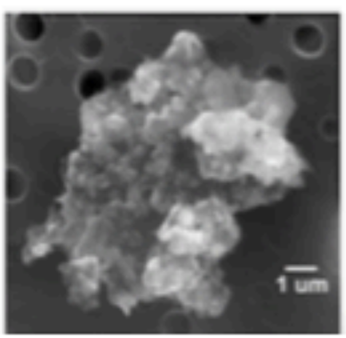
Planetesimal Hypothesis (Safronov 1969)

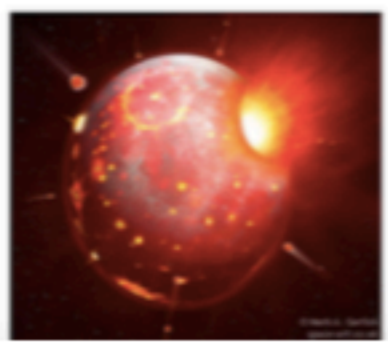
From dust to peebles
μm -> cm : hit-and-stick by van der Walls

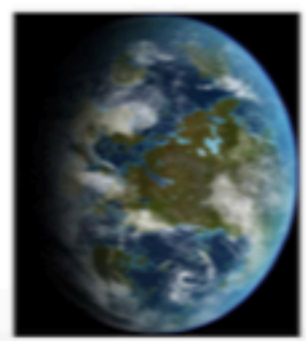
From pebbles to planetesimals
Here be dragons….

From planetesimals to planetary embryos
km -> 1000 km : Gravity

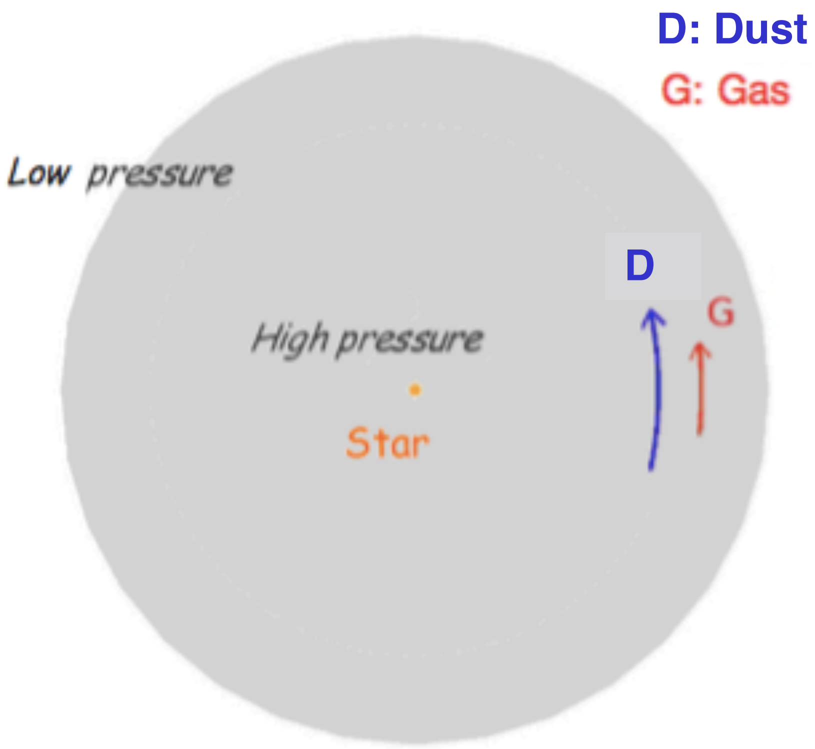
From planetary embryos to planets
Rocky planets: binary collisions
Gas giants: Attract gaseous envelope



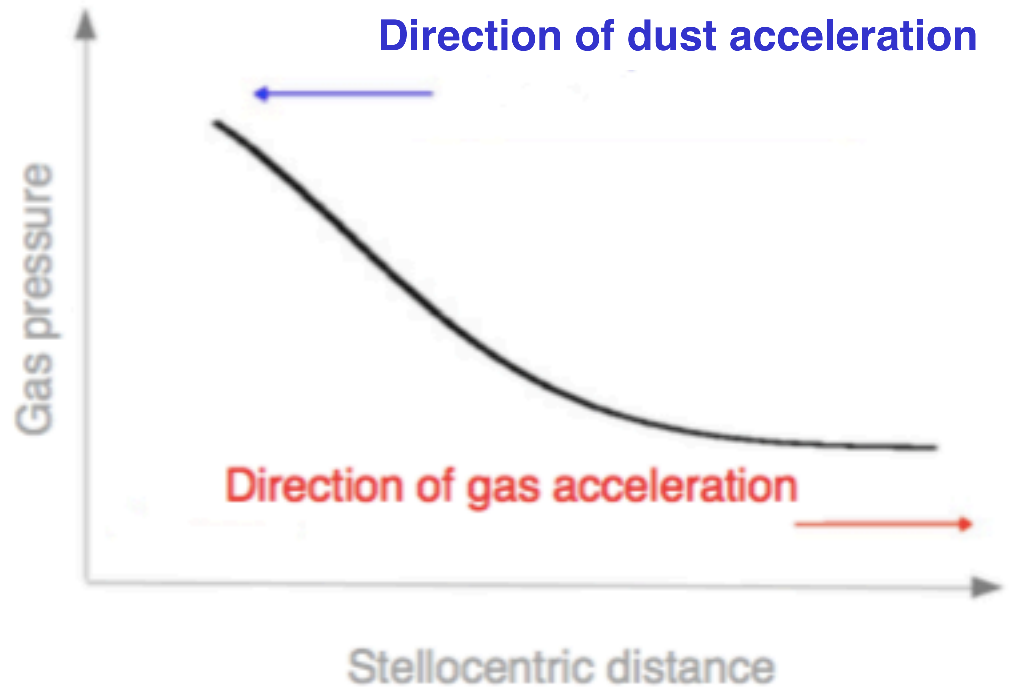




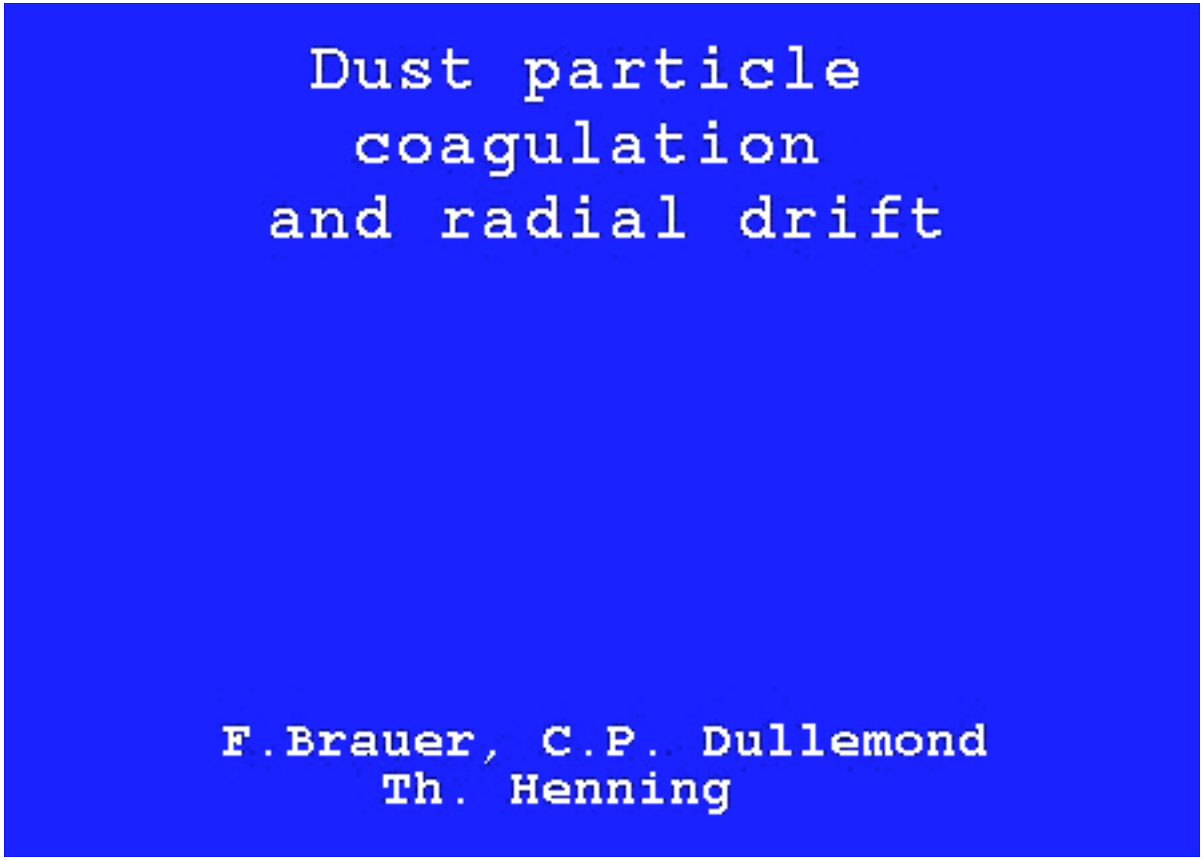
Dust Drift



Adapted from Whipple (1972)



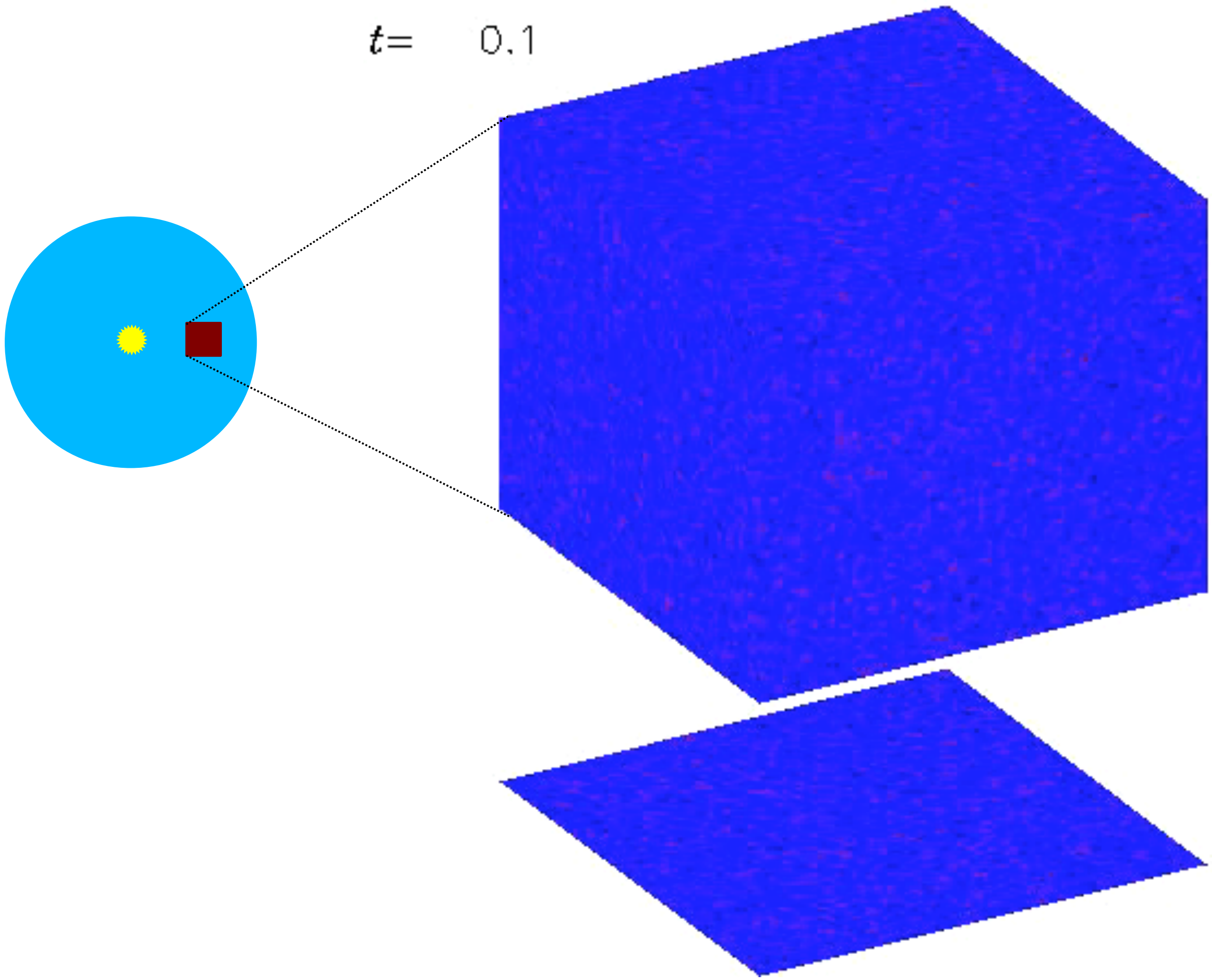
Dust Coagulation and drift



Brauer et al. (2008)

Streaming Instability

The dust drift is hydrodynamically unstable



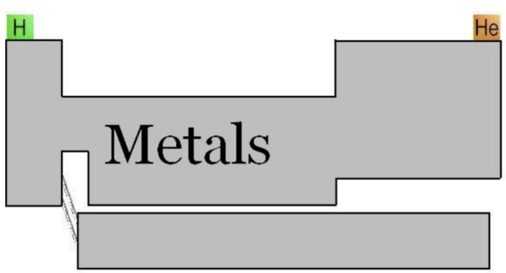
Youdin & Goodman (2005), Johansen & Youdin (2007), Youdin & Johansen (2007)

Streaming Instability does not "work" for solar composition

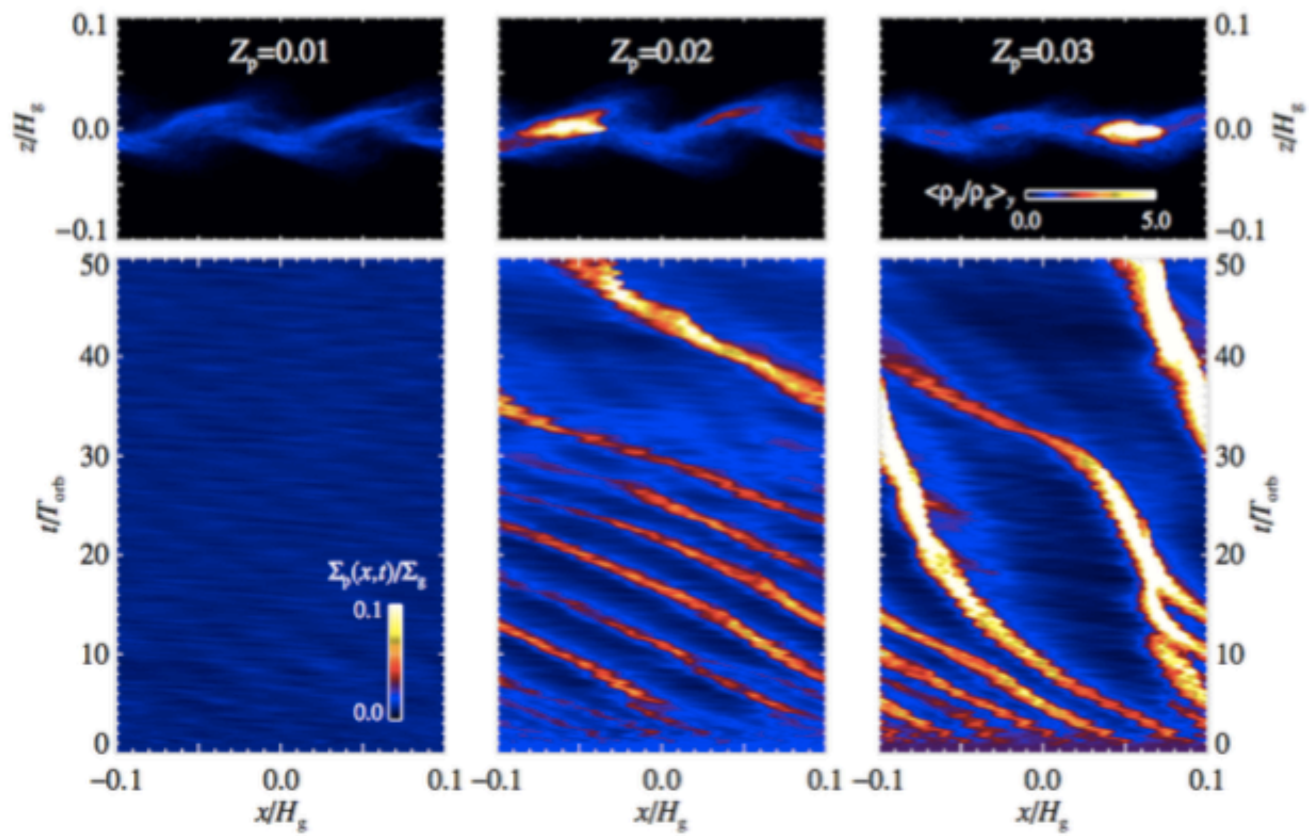
Solar composition:

H (X) ~ 0.74
He (Y) ~ 0.25
Metals (Z) ~ 0.01

The Astronomer's Periodic Table:

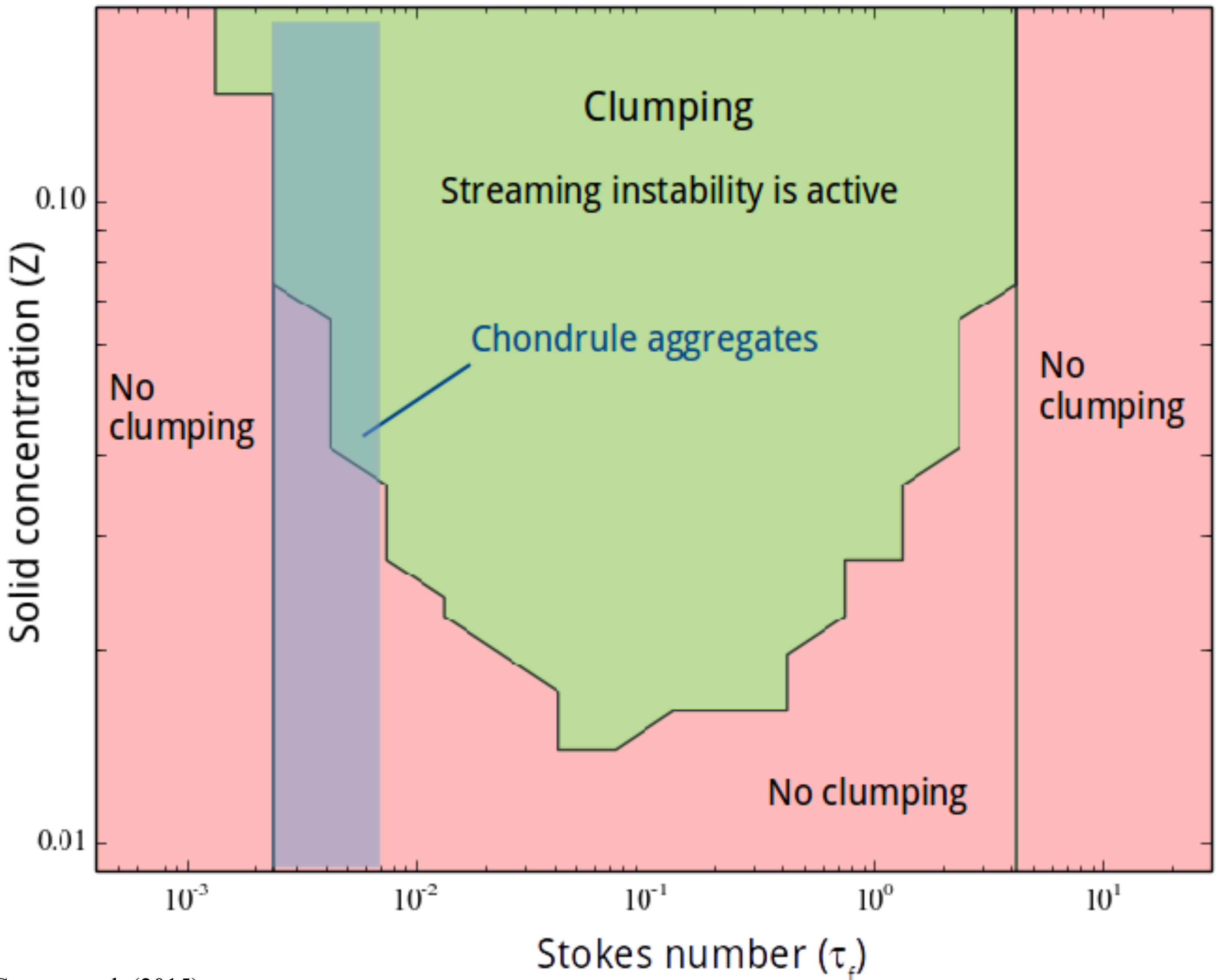


Metallicity



Johansen et al. (2011)

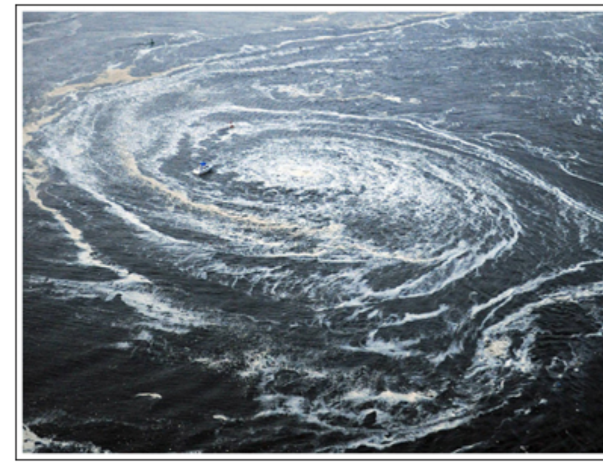
Streaming Instability does not "work" for solar metallicity



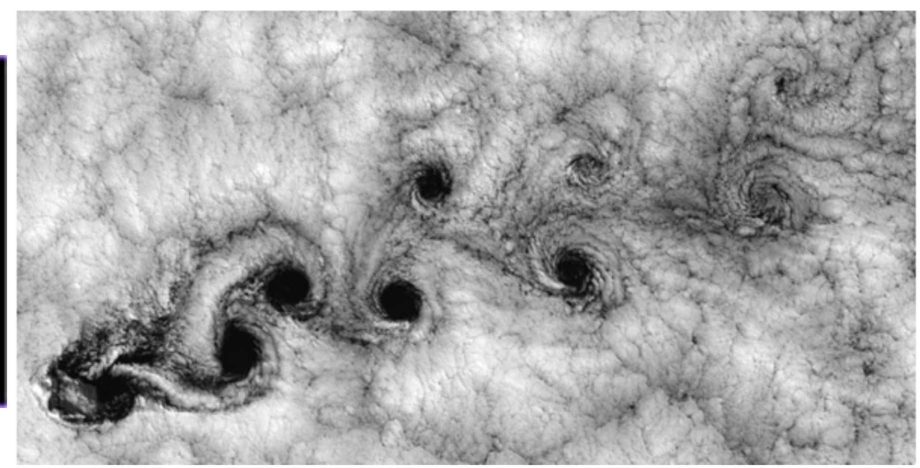
Carrera et al. (2015)

Vortices – an ubiquitous fluid mechanics phenomenon

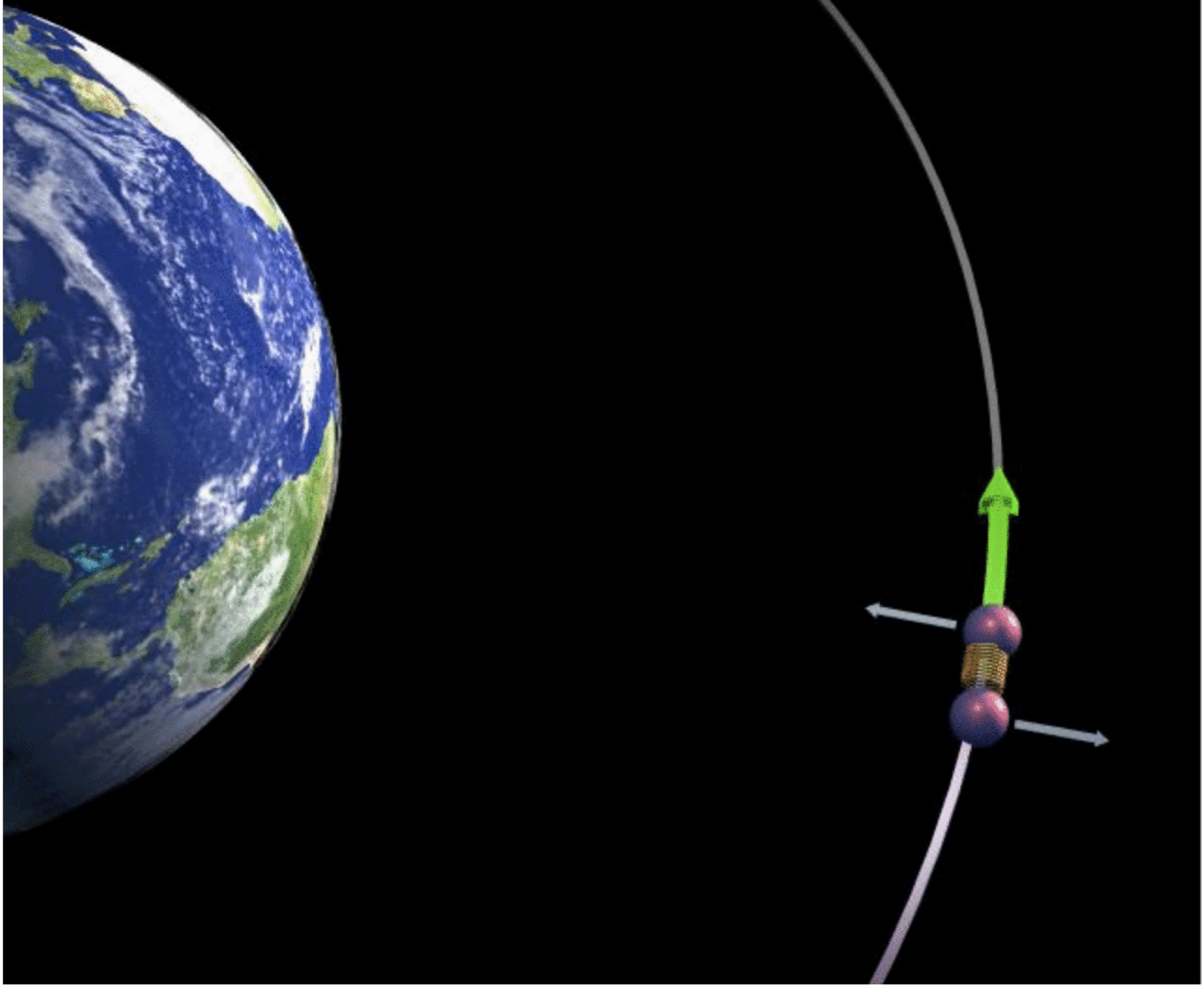




Von Kármán *vortex street*

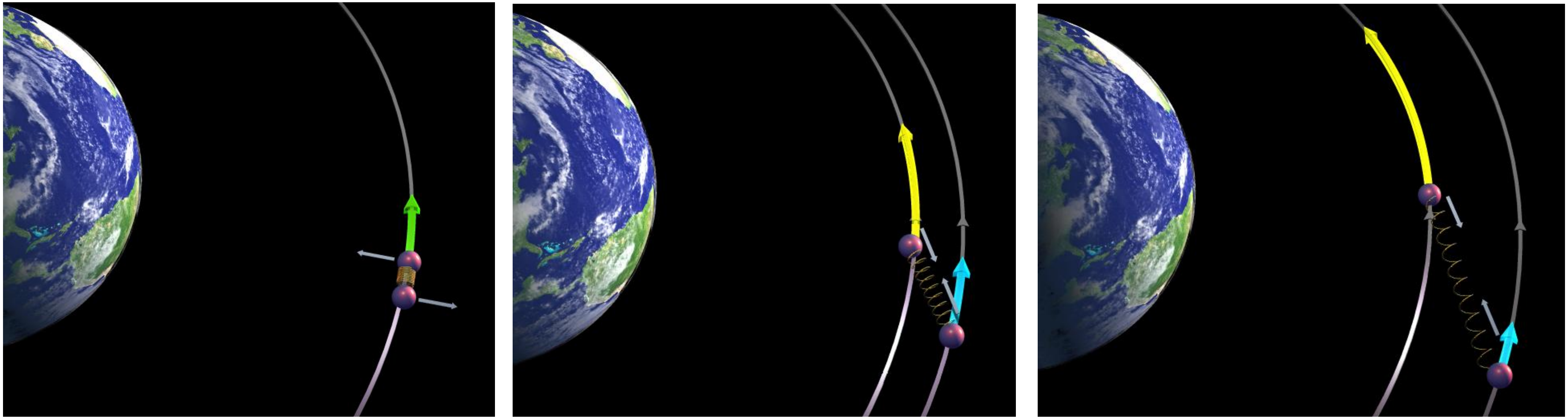



Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk



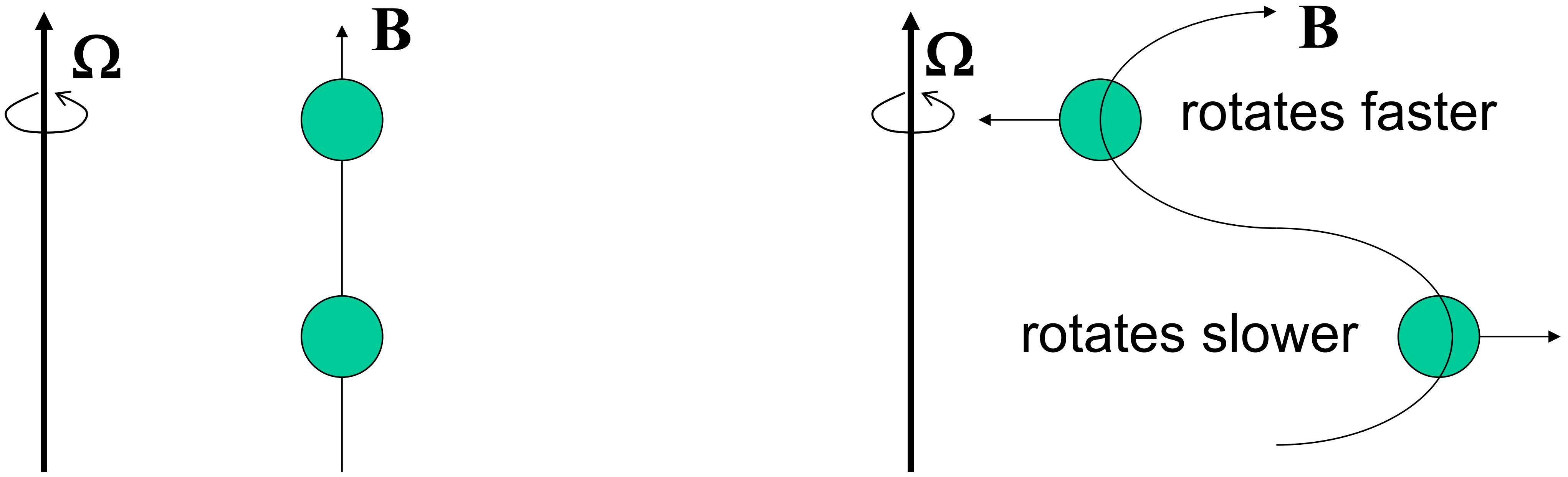
Stretching builds up tension

Tension resists shear



Beads exchange angular momentum

Magnetorotational Instability (MRI)

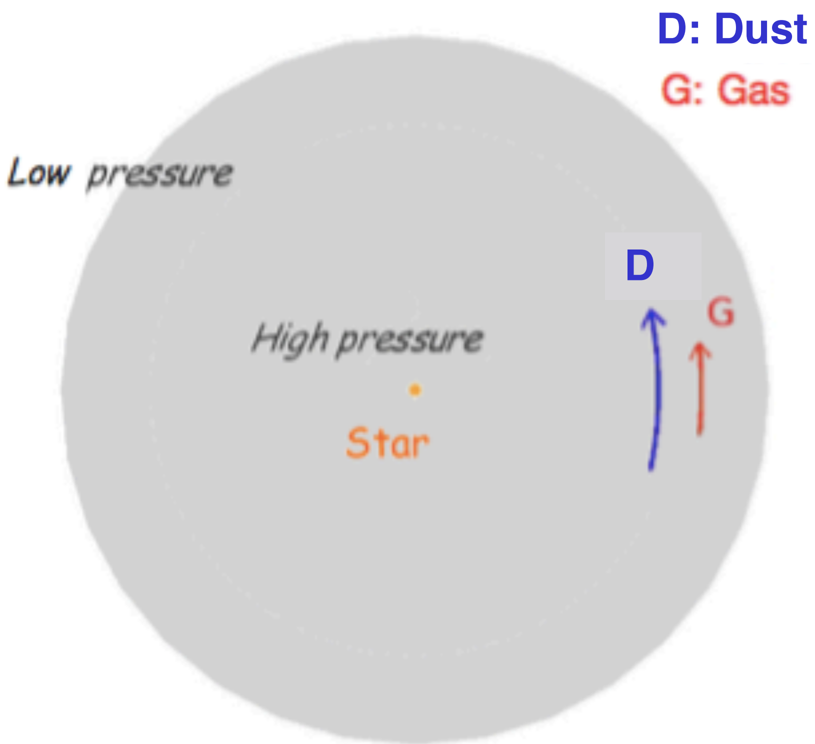


Magnetic fields

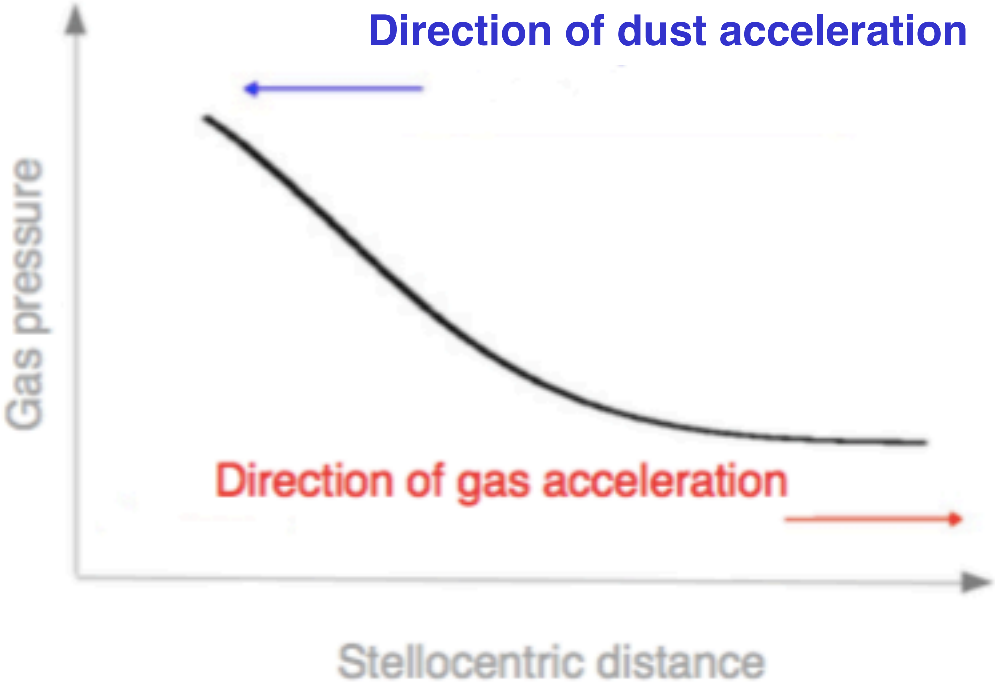
in a conducting rotating plasma behave

EXACTLY like ***springs***!

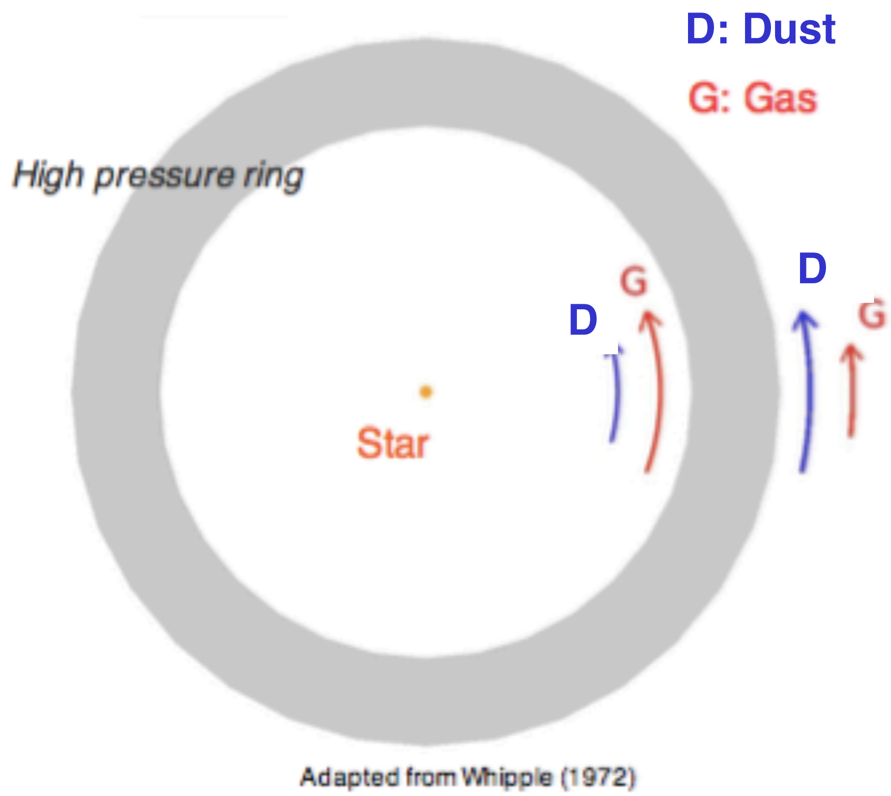
Dust Drift

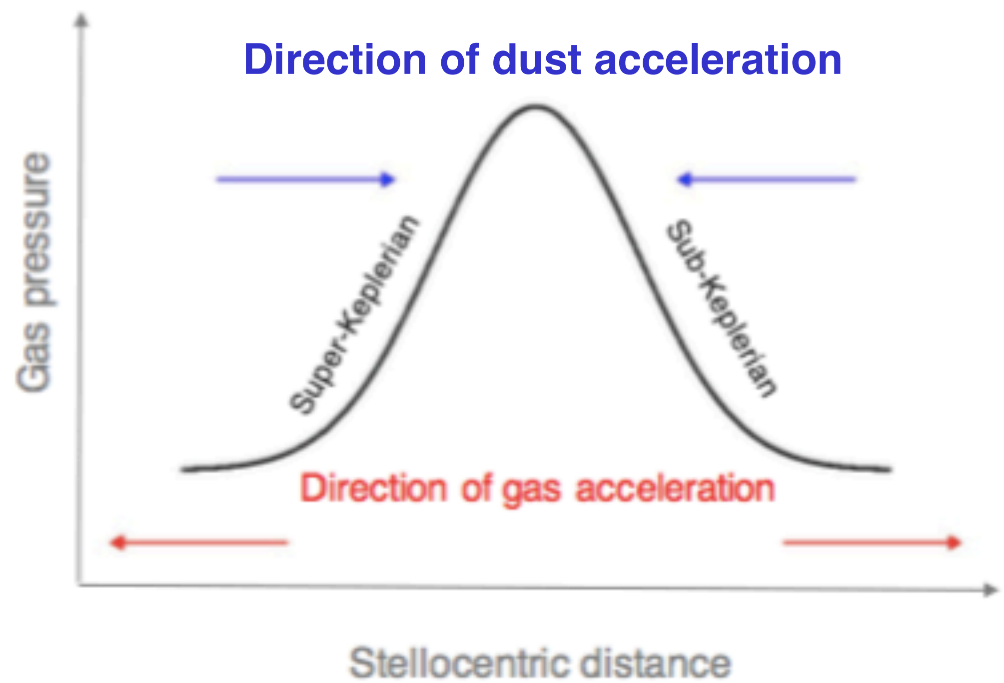


Adapted from Whipple (1972)

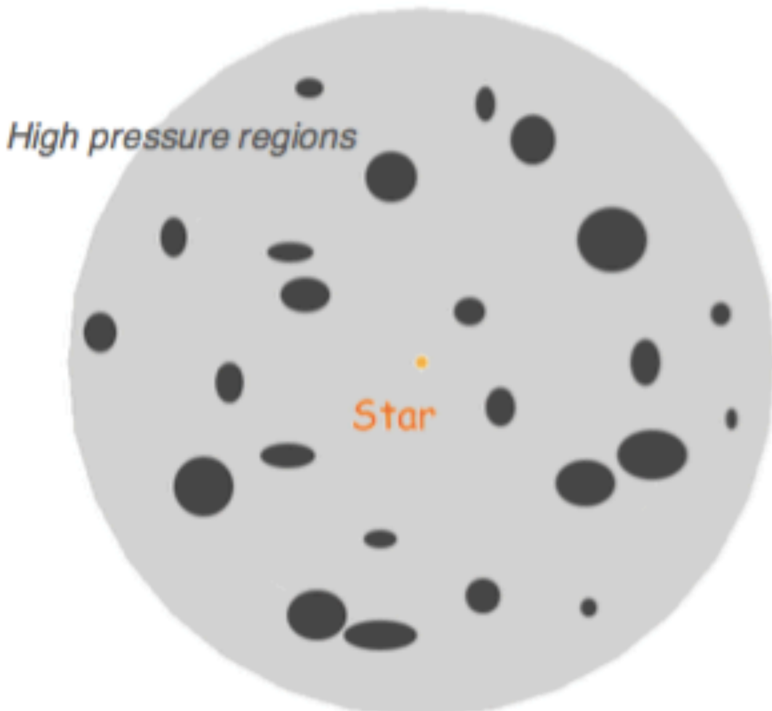


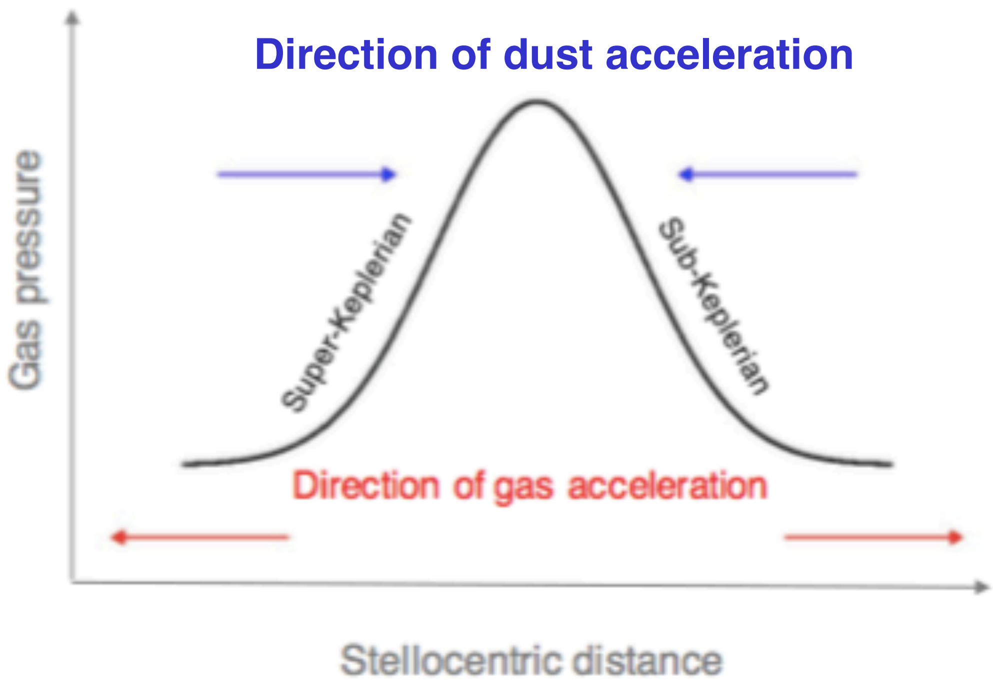
Pressure Trap



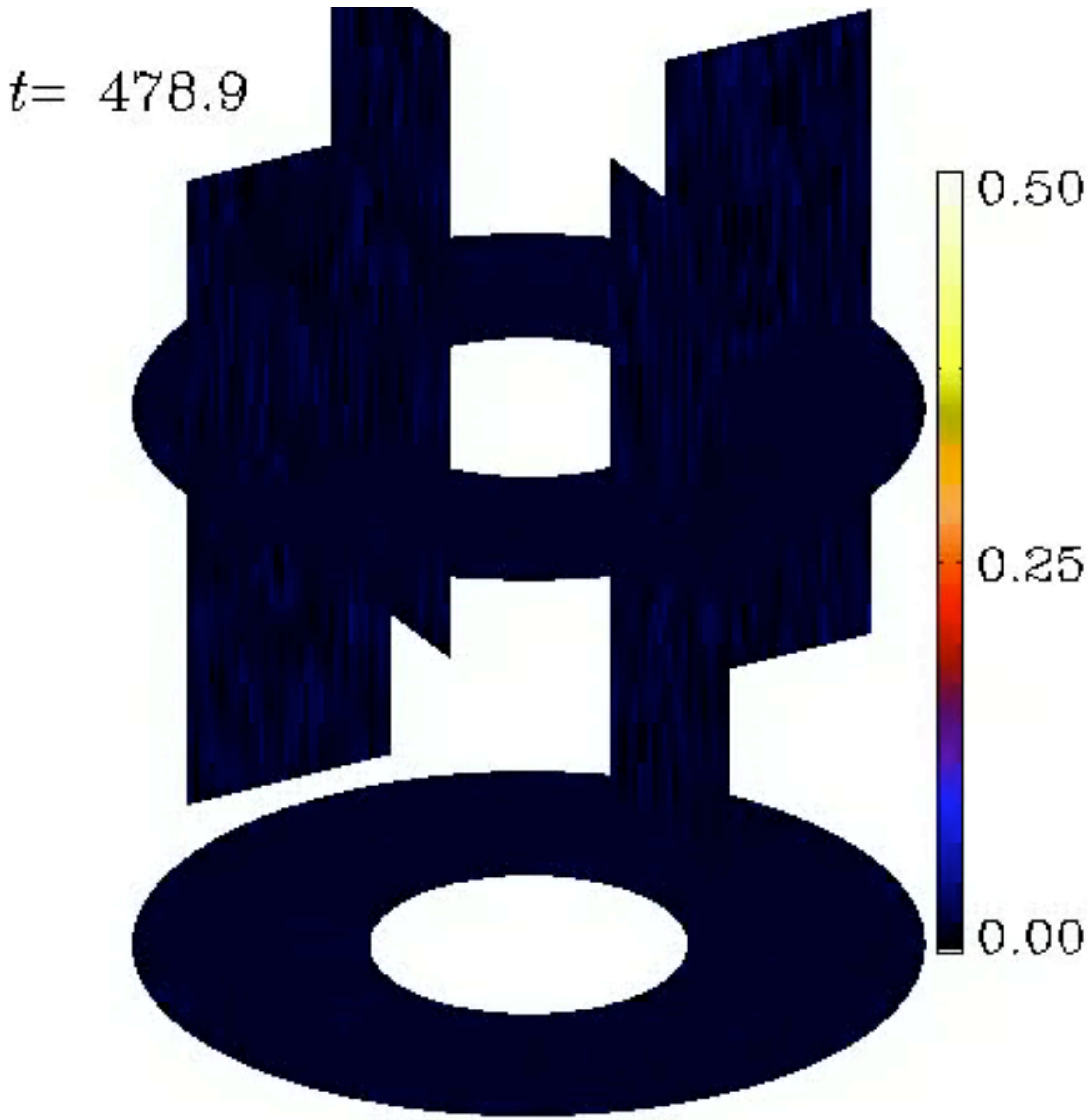


Pressure Trap



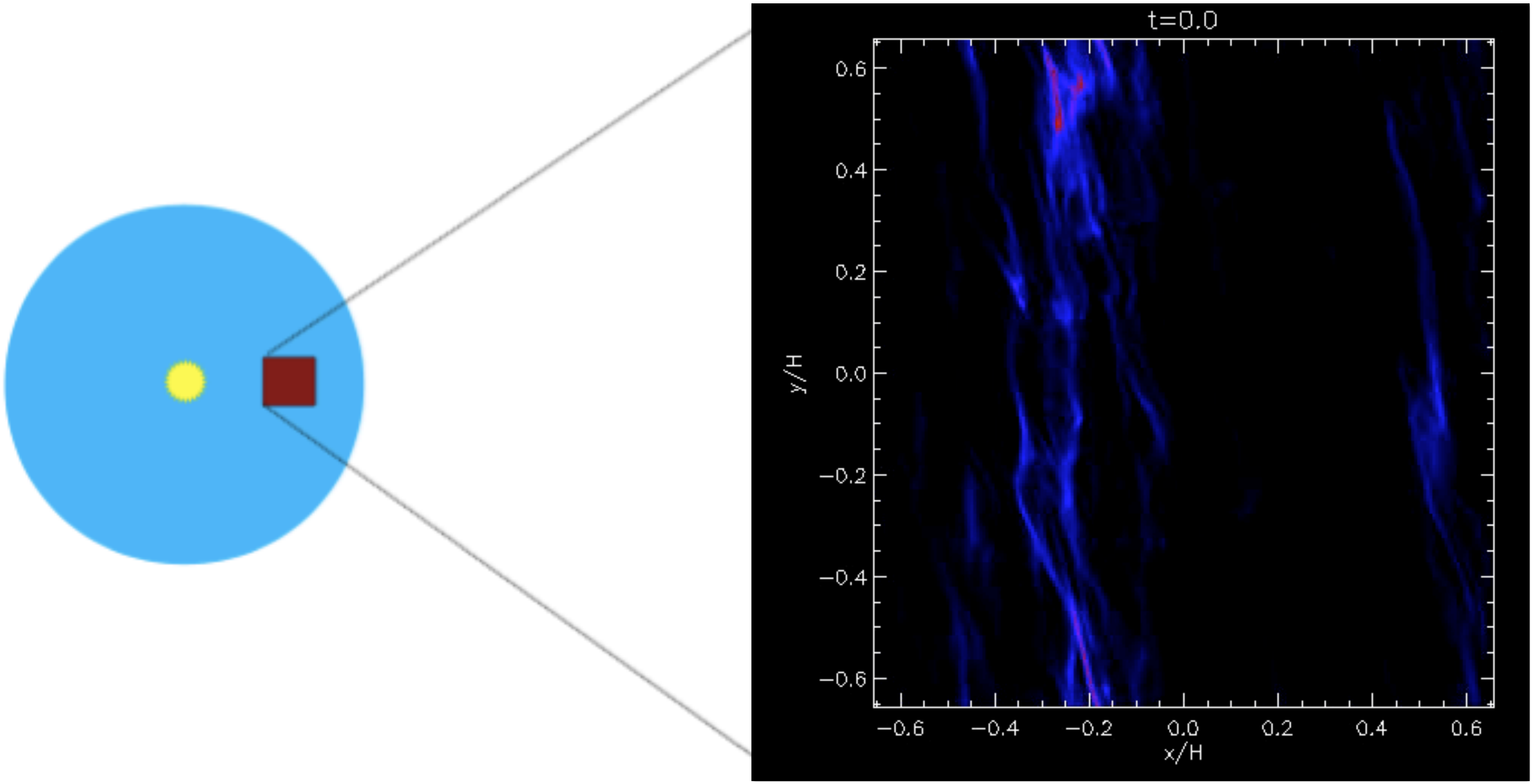


Turbulence concentrates solids mechanically in pressure maxima



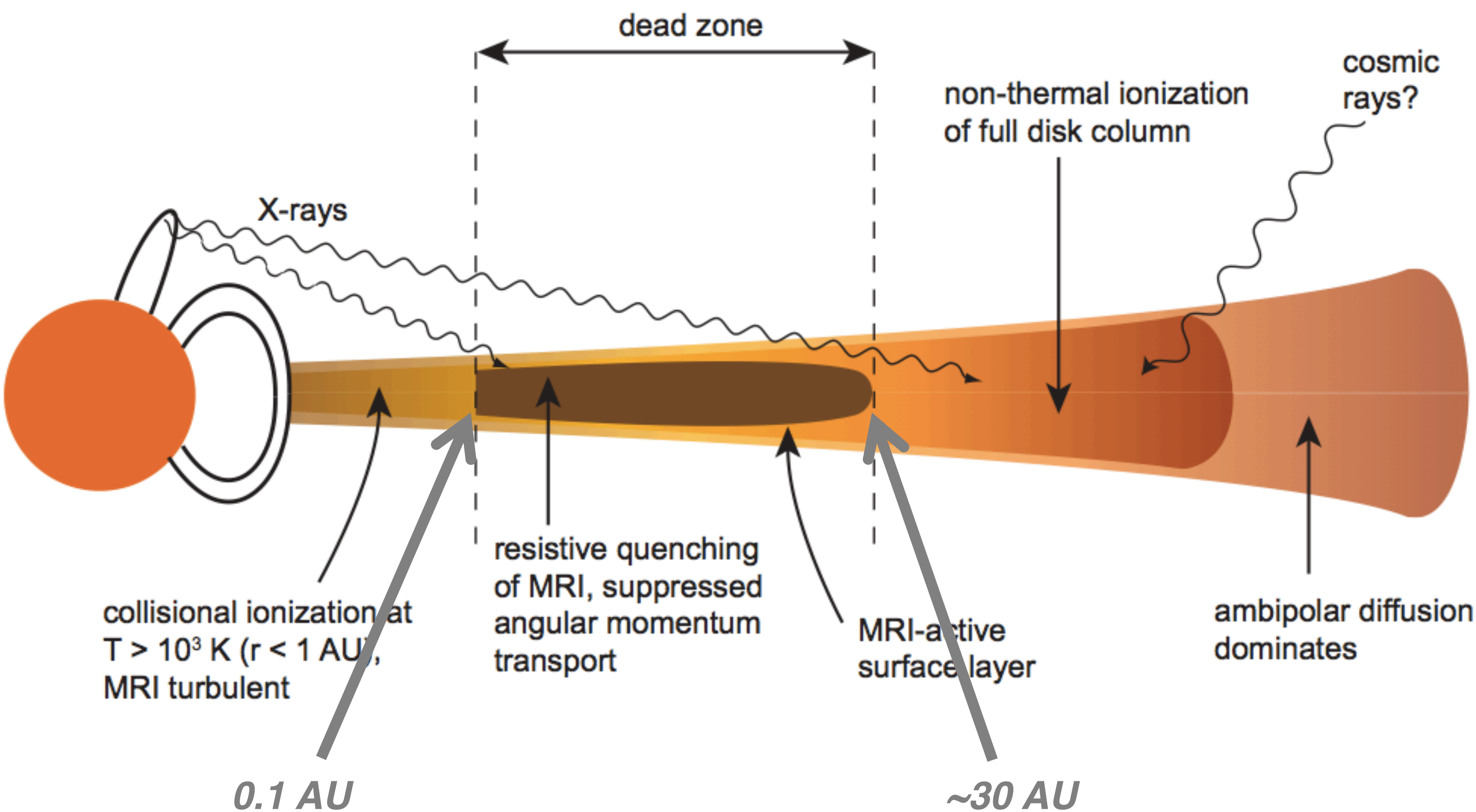
Lyra et al. (2008a)

Gravitational collapse into planetesimals



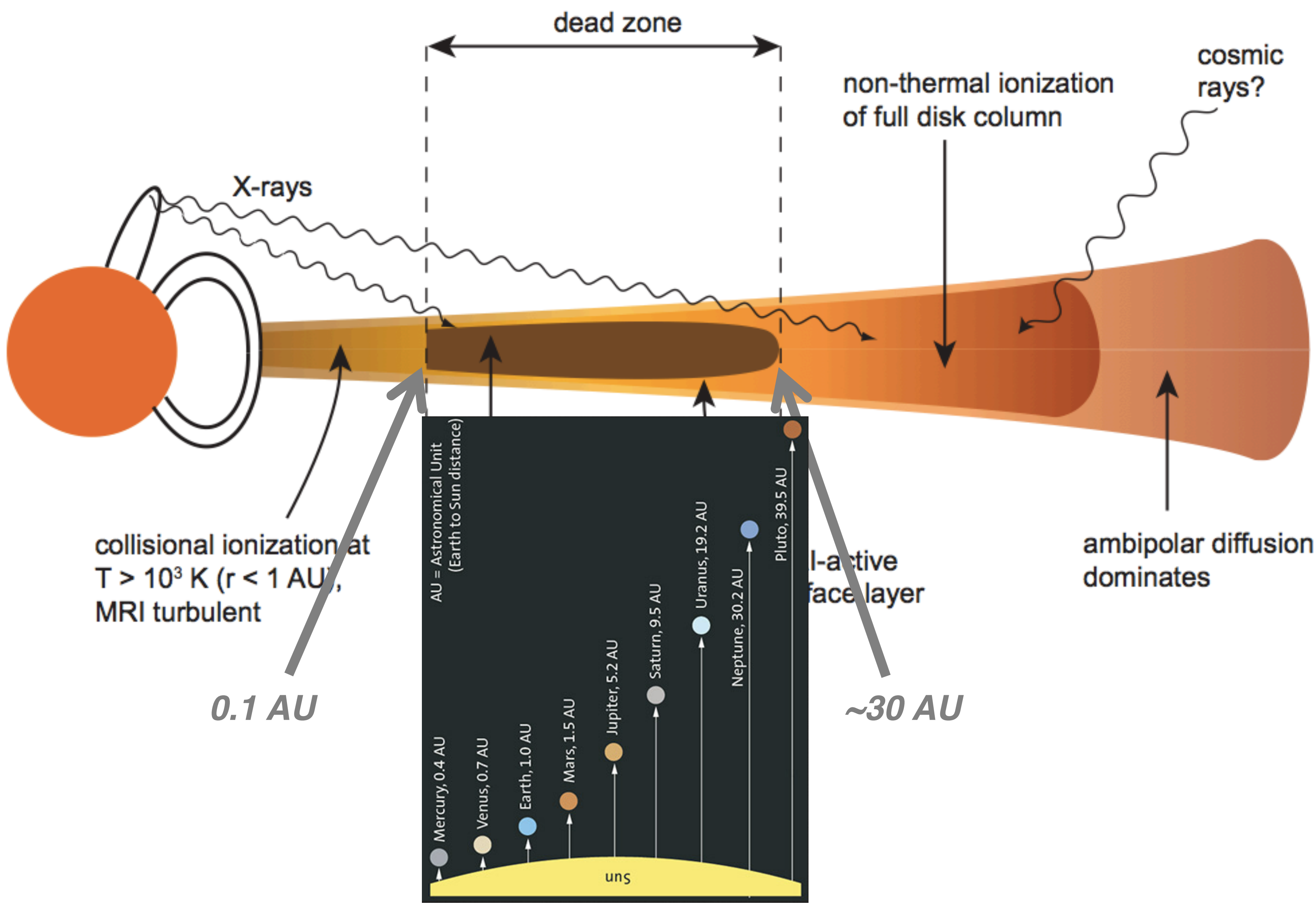
Johansen et al. (2007)

Dead zones

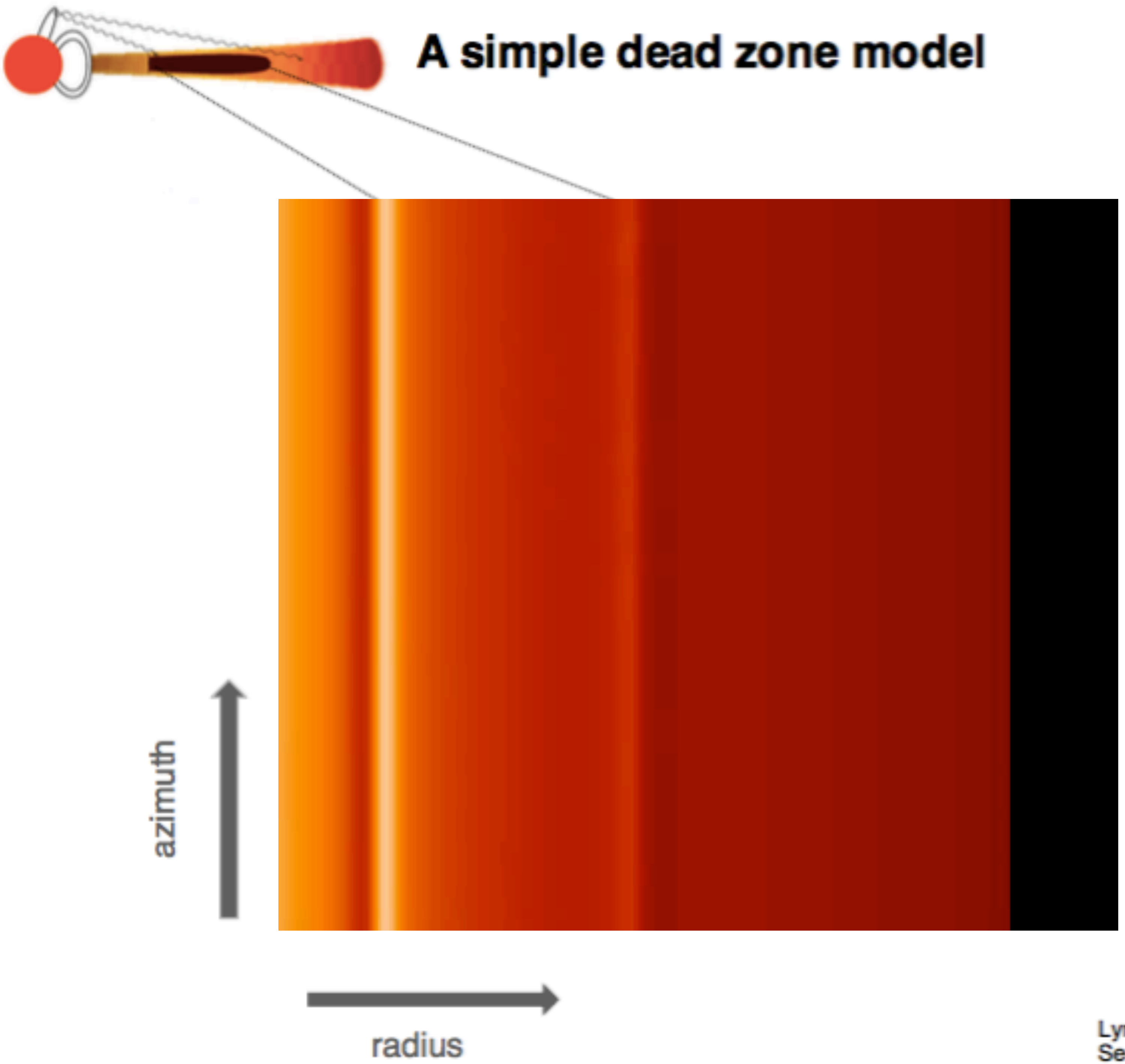


There should be a **magnetized, active zone**
and a **non-magnetic, dead zone**

Dead zones

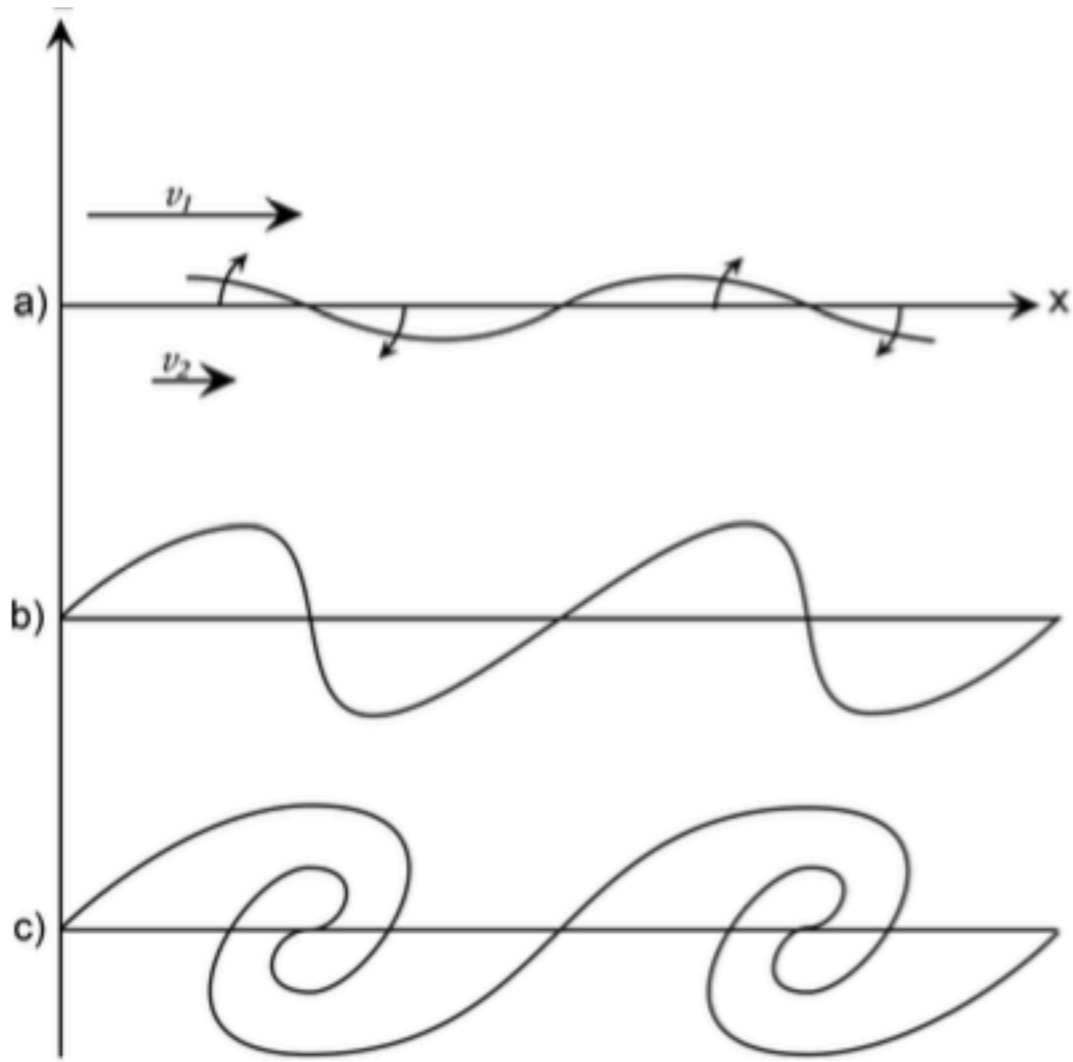

dead zone
non-thermal ionization
of full disk column
cosmic
rays?
X-rays
collisional ionization at
T > 10³ K (r < 1 AU),
MRI turbulent
active
surface layer
ambipolar diffusion
dominates
0.1 AU
~30 AU
AU = Astronomical Unit
(Earth to Sun distance)
Mercury, 0.4 AU
Venus, 0.7 AU
Earth, 1.0 AU
Mars, 1.5 AU
Jupiter, 5.2 AU
Saturn, 9.5 AU
Uranus, 19.2 AU
Neptune, 30.2 AU
Pluto, 39.5 AU
Sun

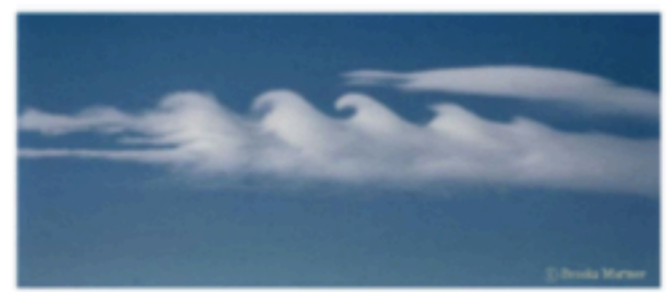
A simple dead zone model



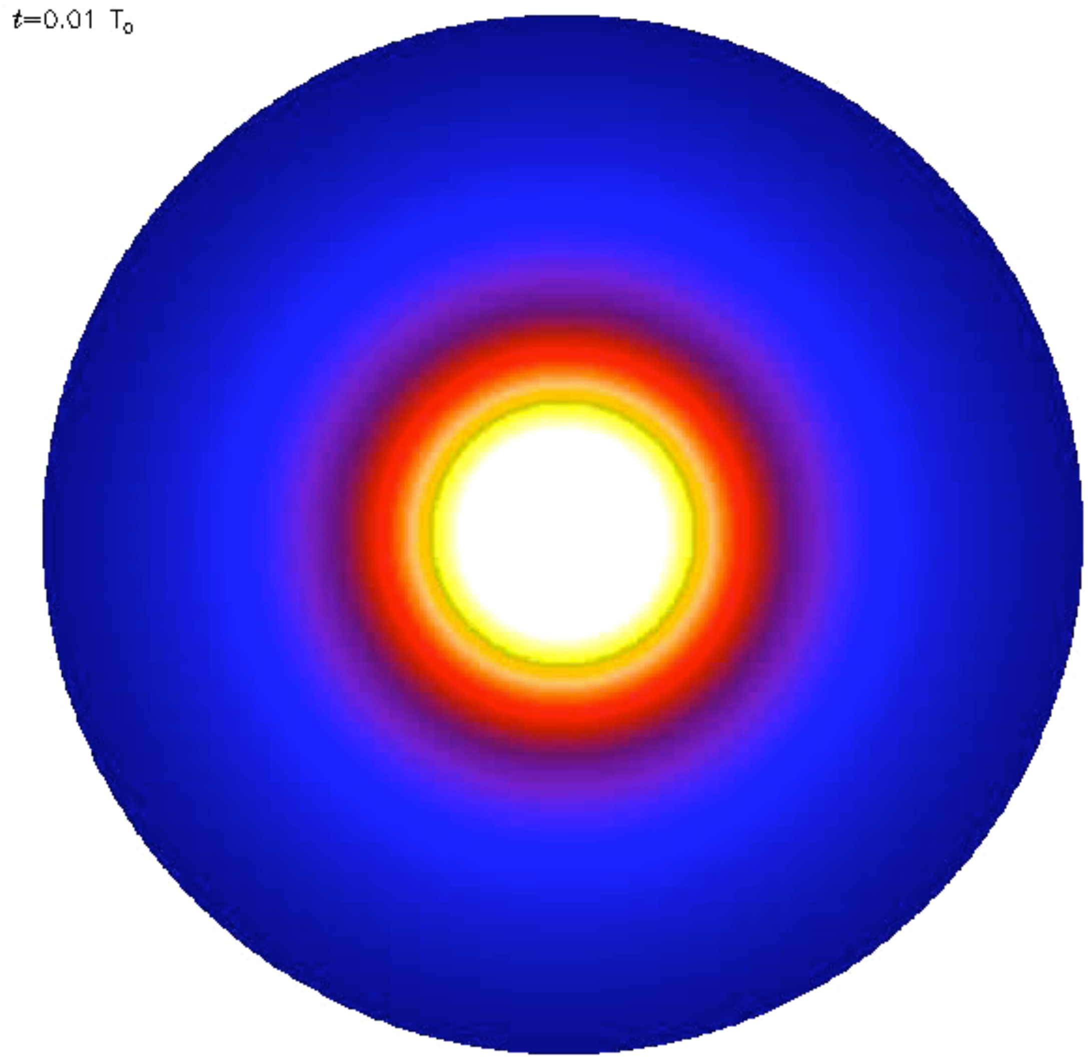
Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

Rossby wave instability
(Kelvin-Helmholtz Instability in rotating disks)





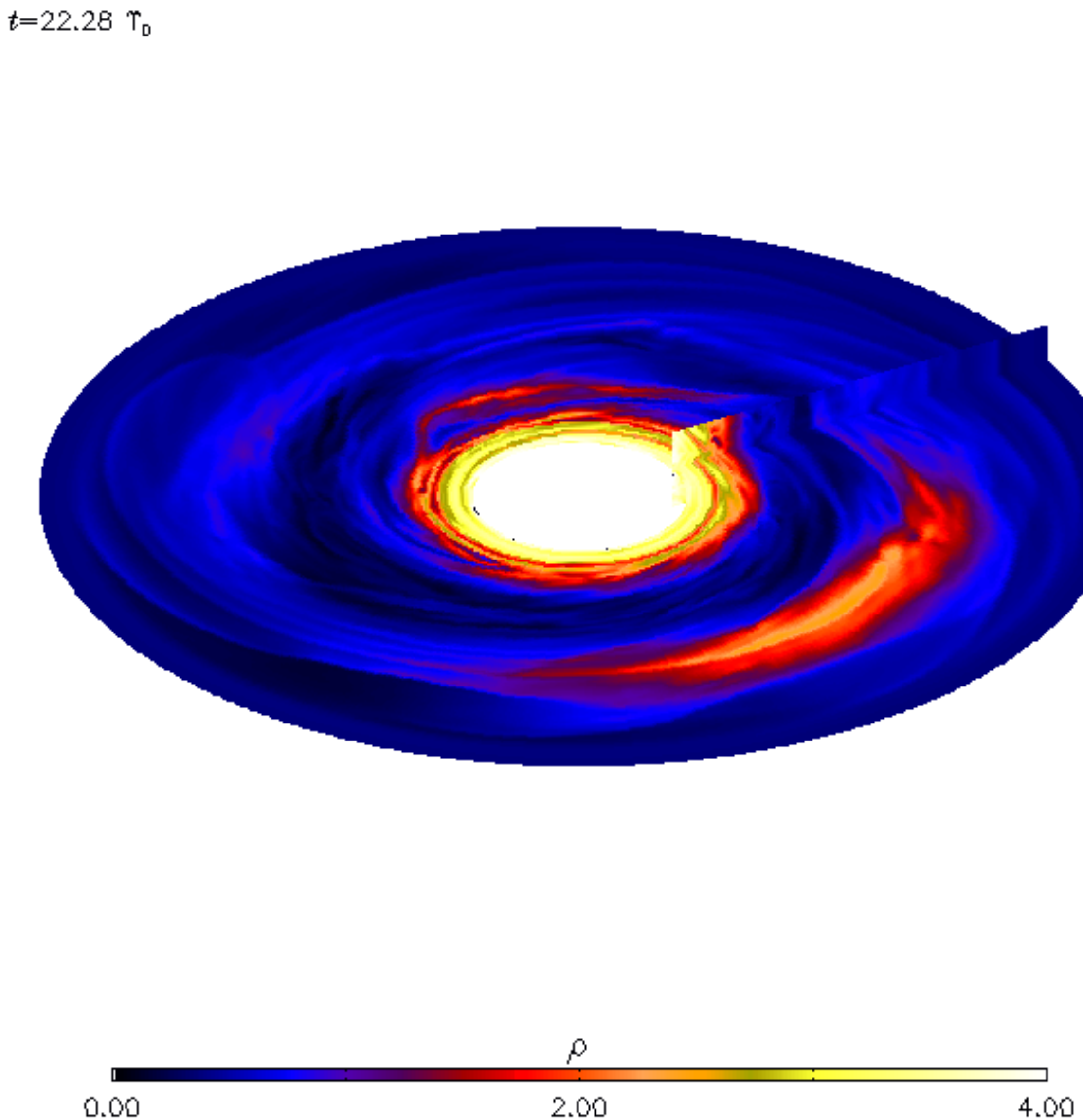
Inner (0.1 AU) active/dead zone boundary

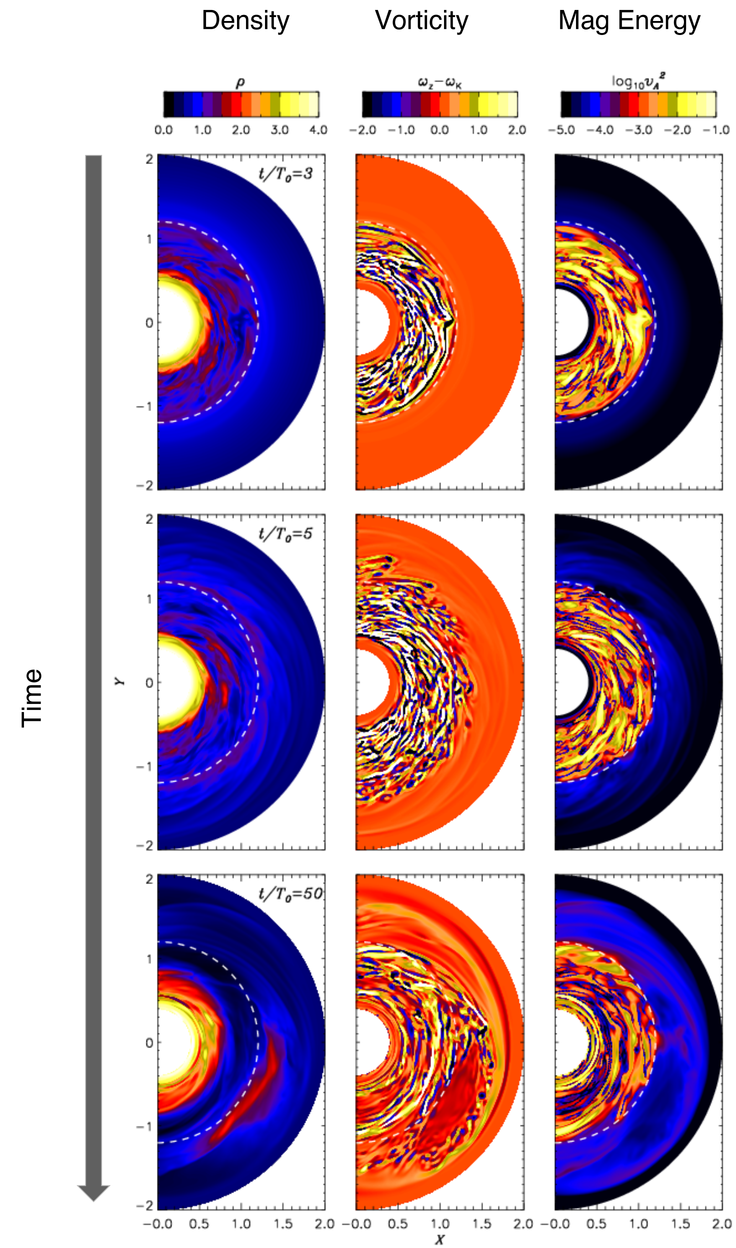


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Inner (0.1AU) active/dead zone boundary





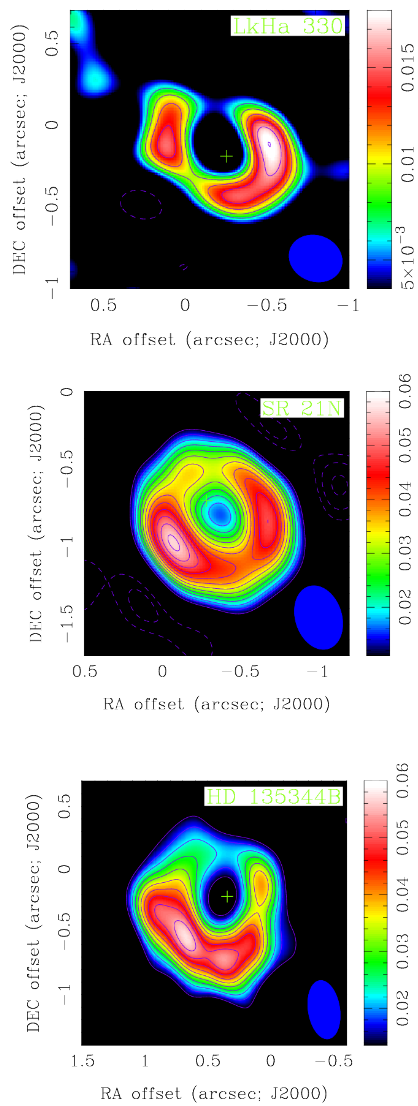
Magnetized inner disk + resistive outer disk

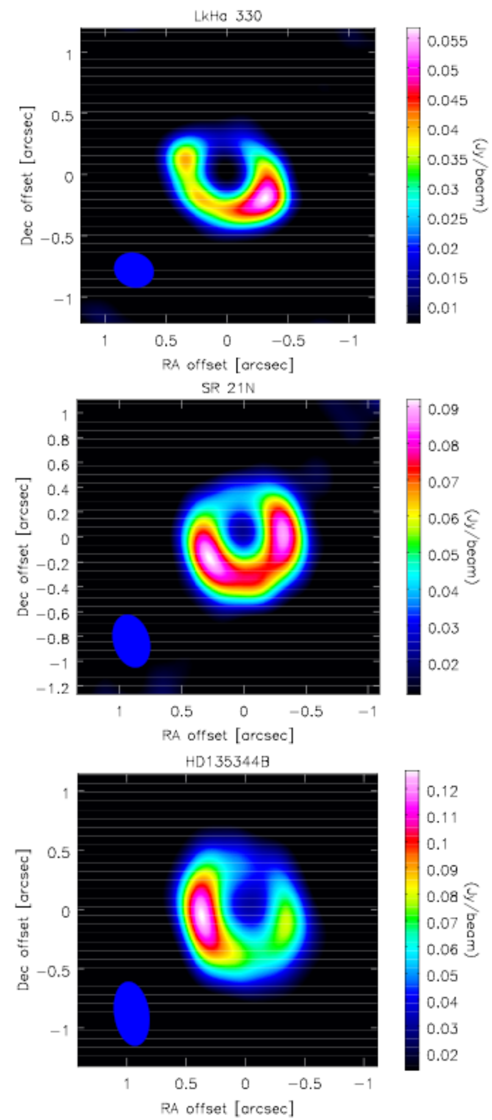
Lyra & Mac Low (2012)

A possible detection of vortices in disks?

Observations

Brown et al. (2009)





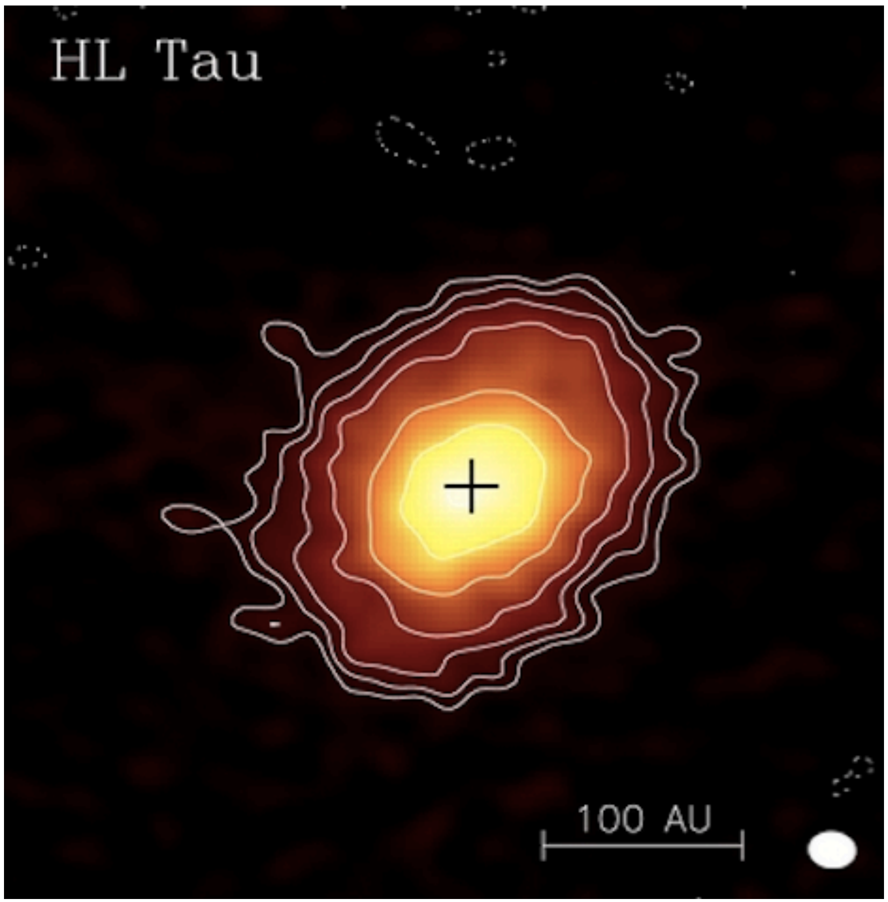
Models

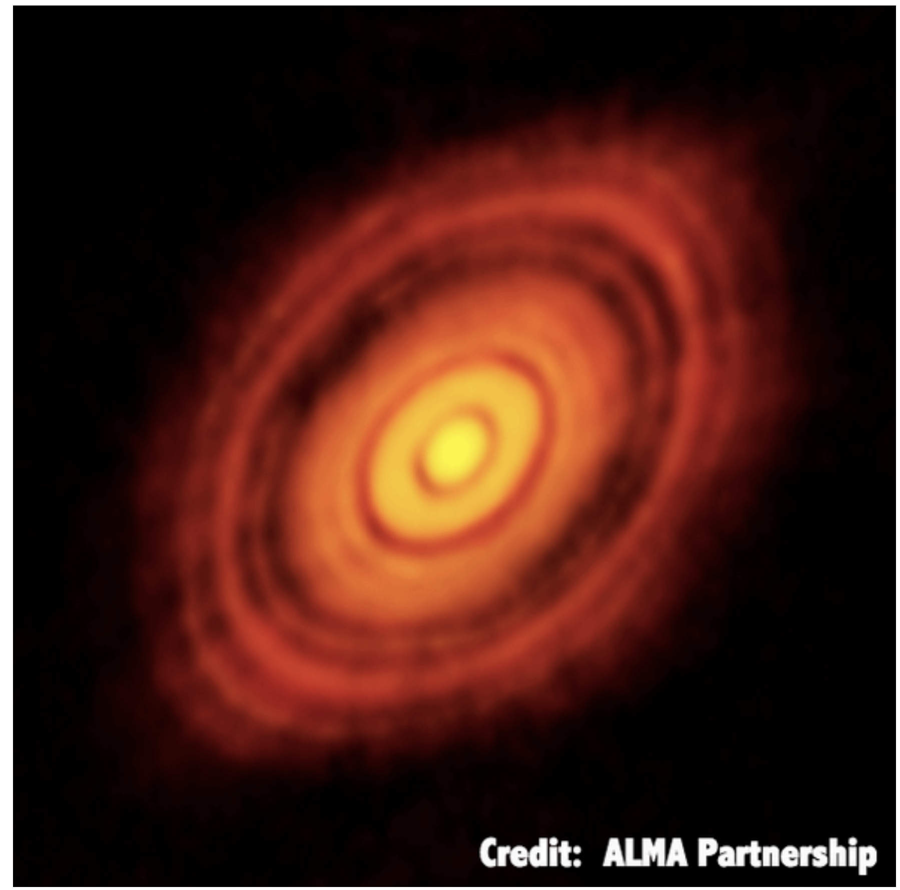
Simulated observations of Rossby vortices

Regaly et al. (2012)

The Atacama Large Millimeter Array (ALMA)

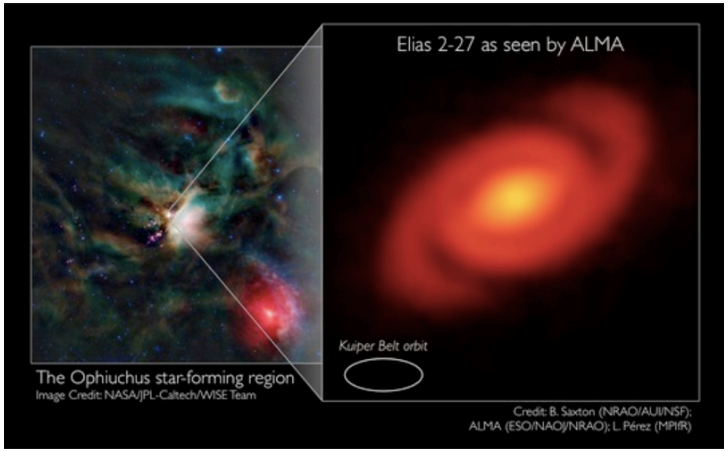
Before ALMA **ALMA**



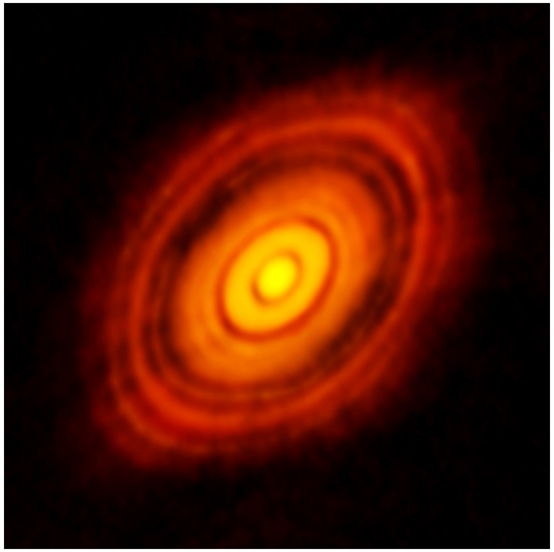


The ALMA view of Protoplanetary Disks

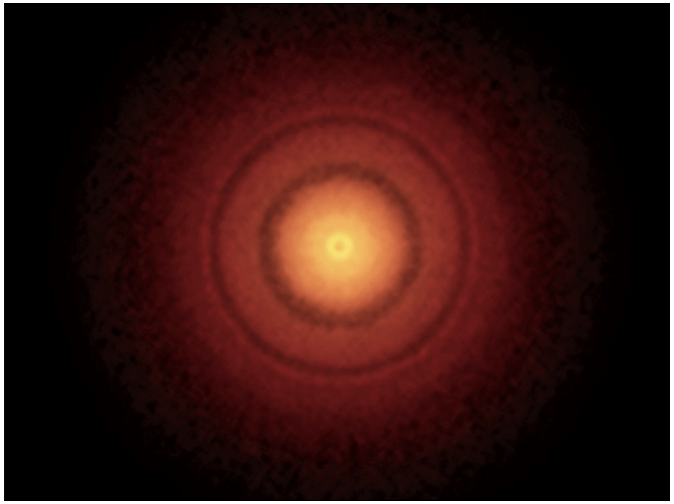
Elias 2-27



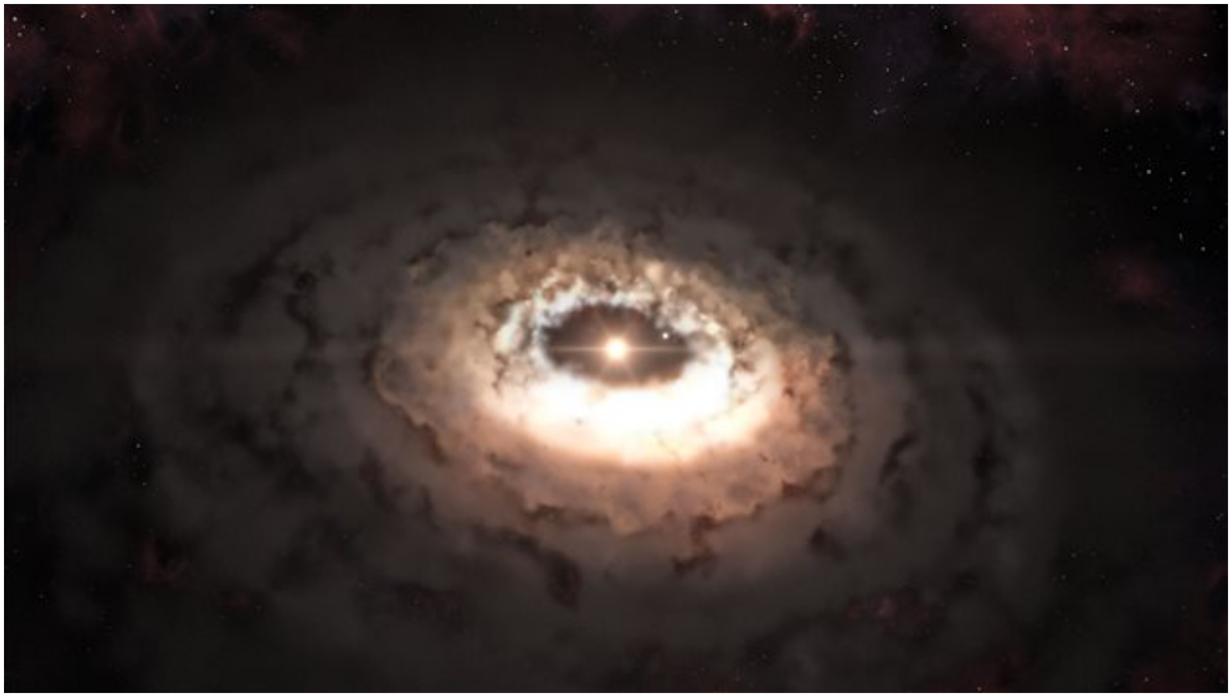
HL Tau



TW Hya



Oph IRS 48



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]

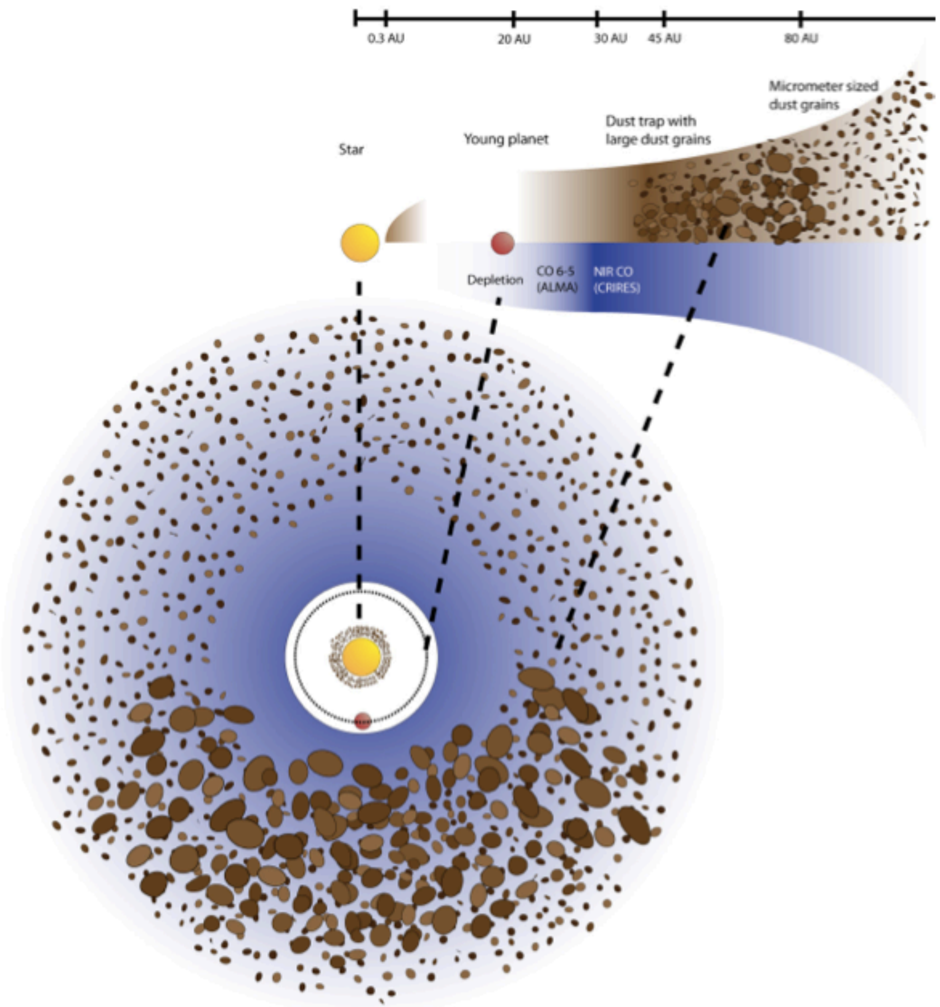
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection 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

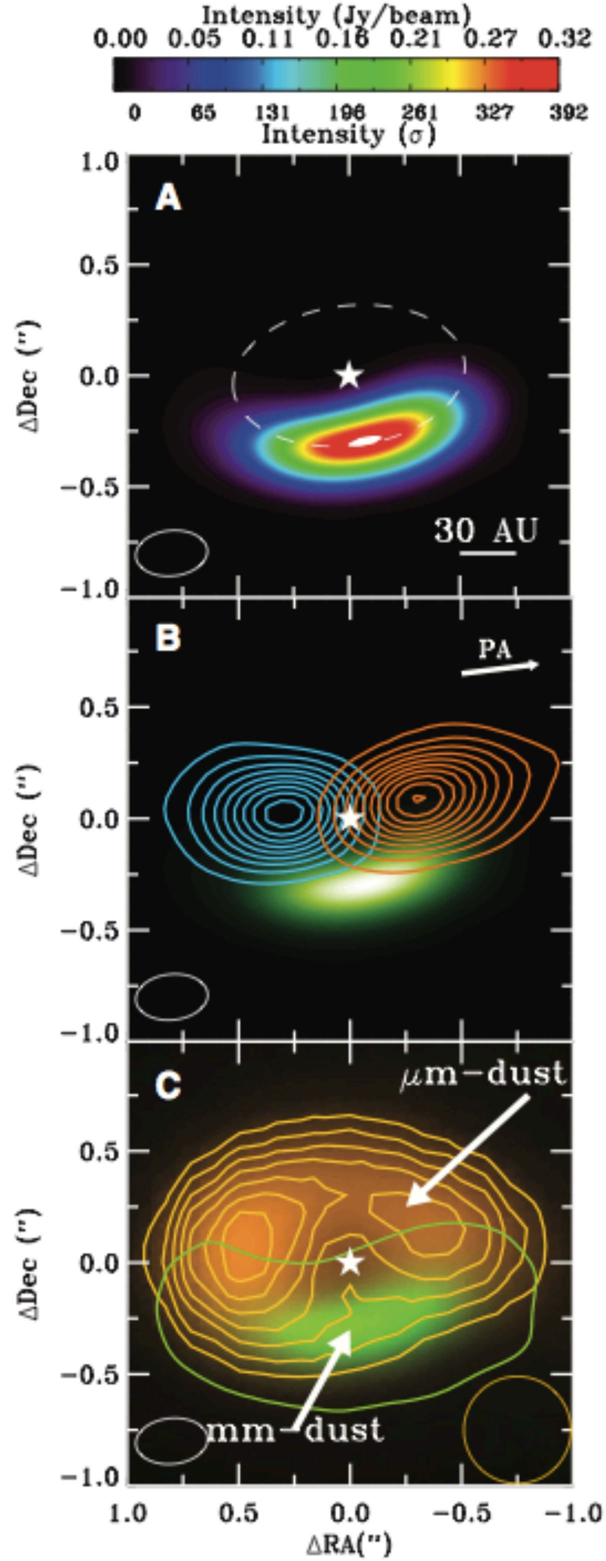
van der Marel et al. 2013

A huge vortex observed with ALMA

The Oph IRS 48 "comet formation factory"



van der Marel et al. (2013)

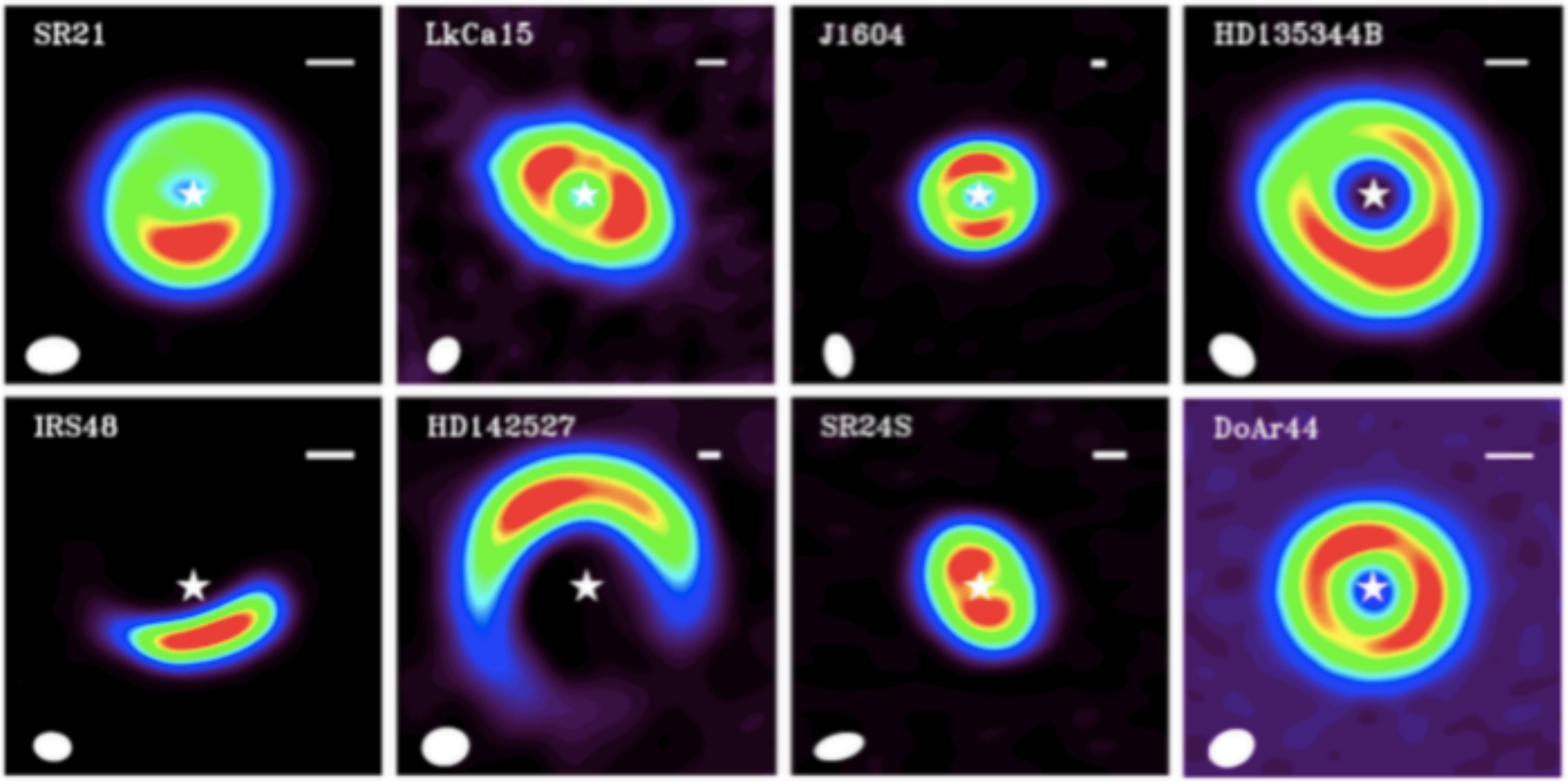


asymmetric mm dust at 63 AU

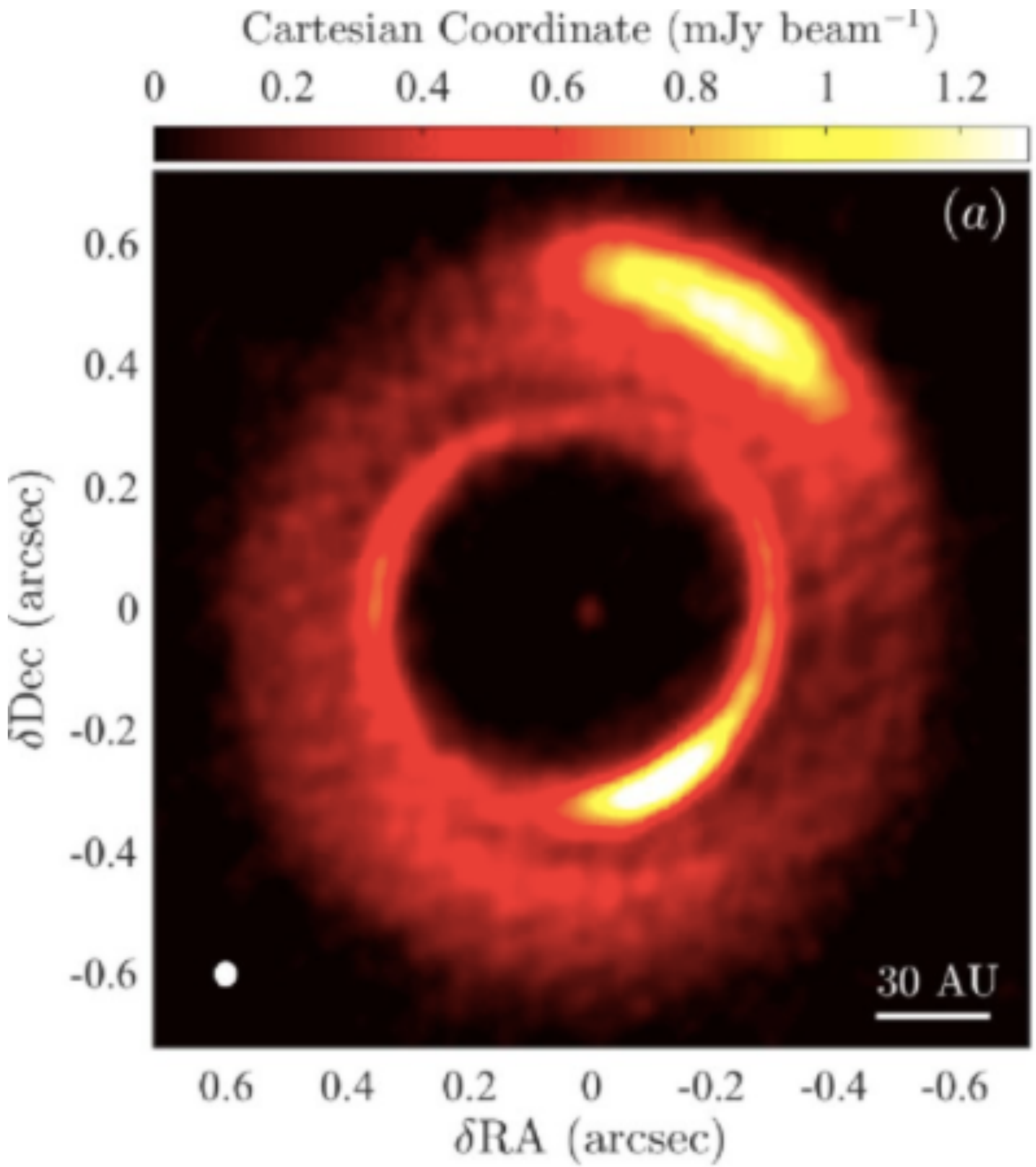
Gas detection: Keplerian rotation

Micron-sized dust follows gas

Vortices everywhere!
Extrasolar nebulae

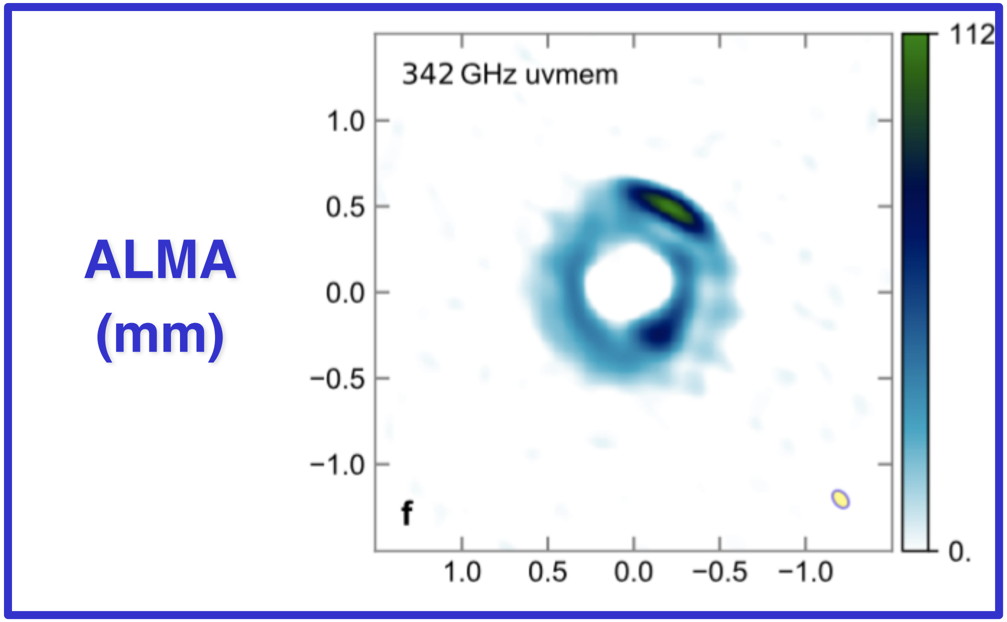


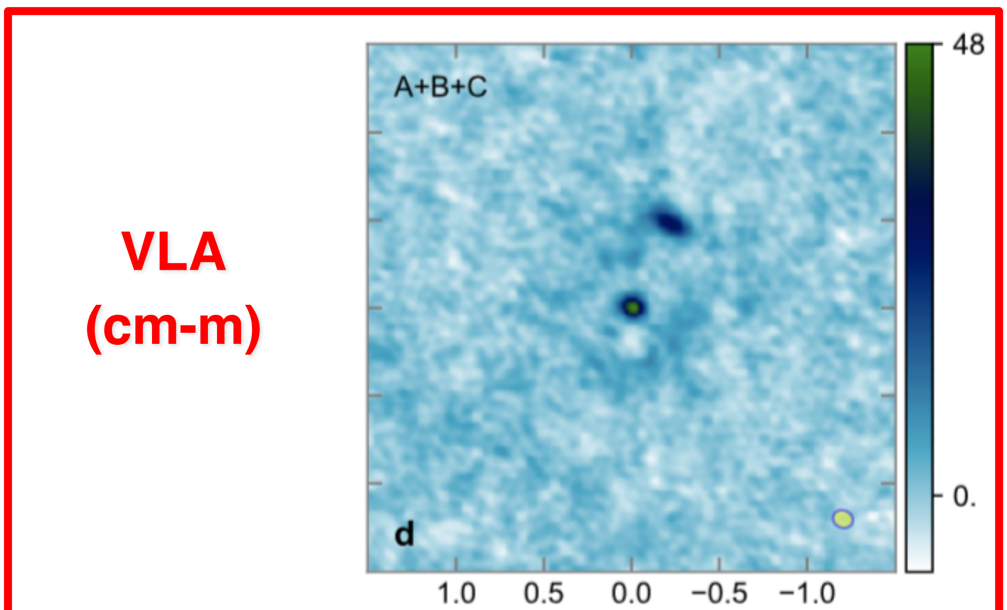
MWC 758



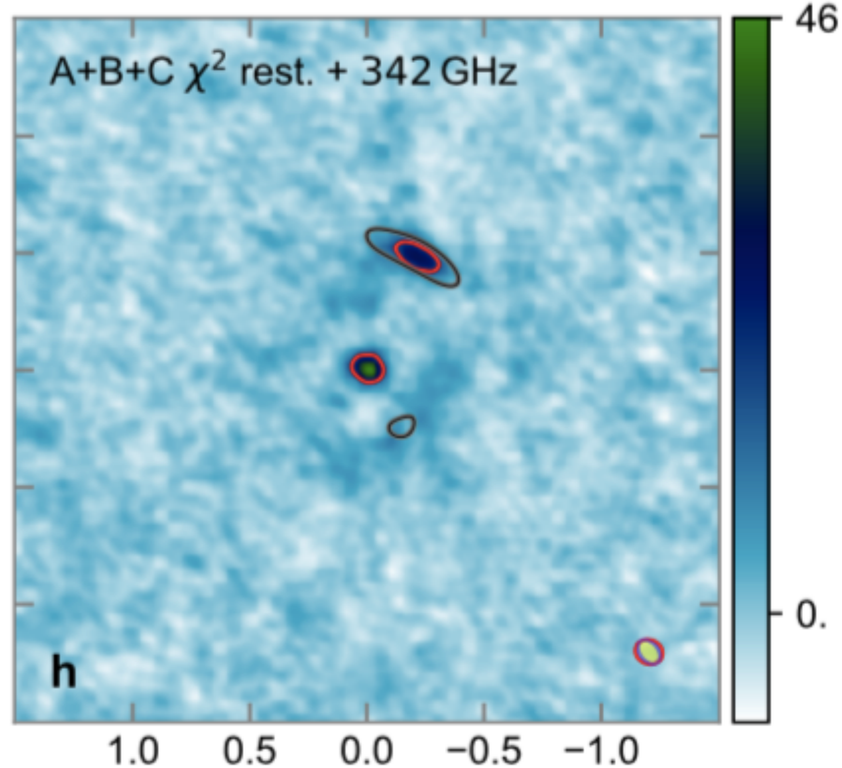
Cartesian Coordinate (mJy beam^{-1})
0
0.2
0.4
0.6
0.8
1
1.2
(a)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δDec (arcsec)
30 AU
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δRA (arcsec)

Pebble trapping

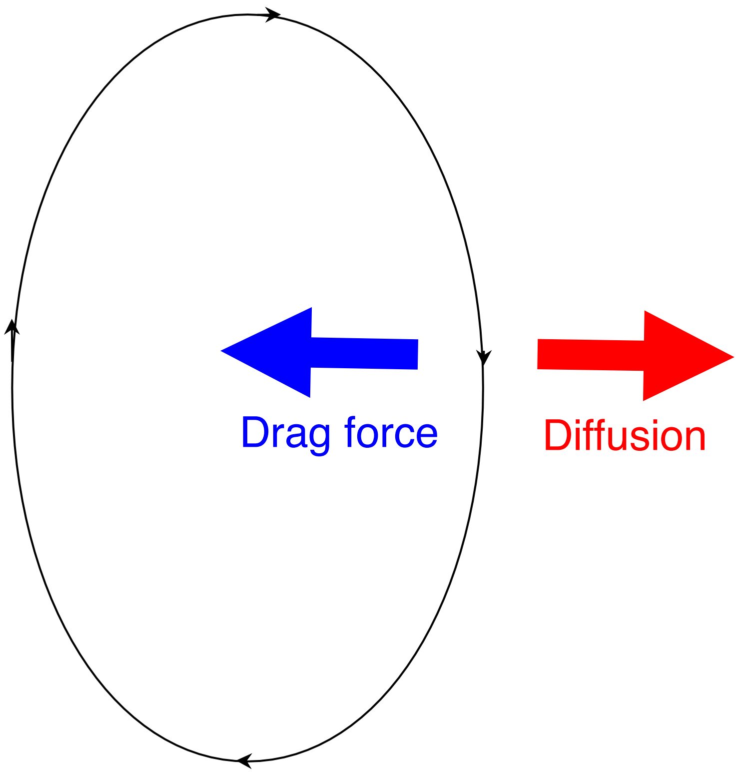




Overlay



Drag-Diffusion Equilibrium



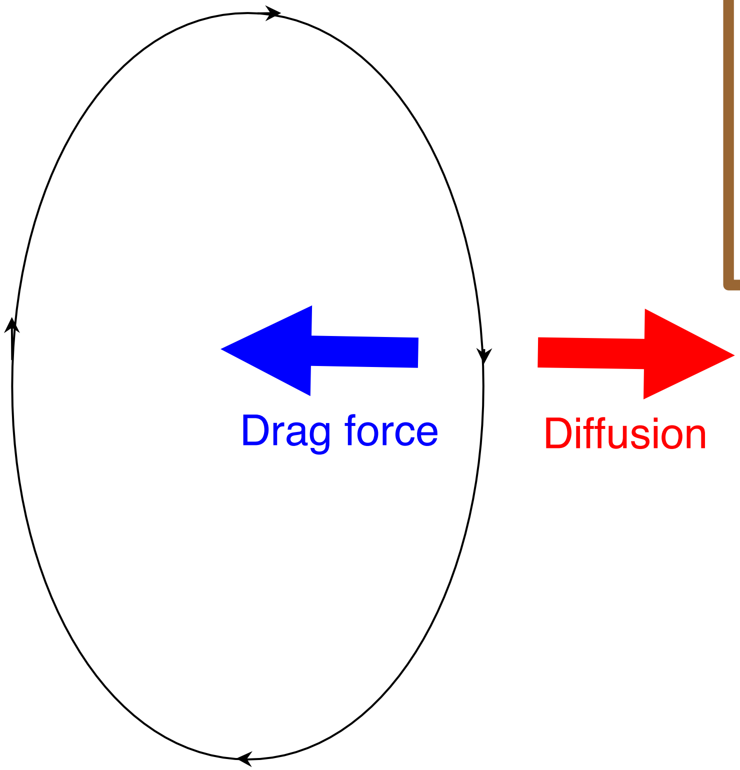
Trapped particle

Dust continuity equation

$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

advection — **compression** — **diffusion**

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

$$\rho_d(a,z) = \varepsilon\rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1)\right\}$$

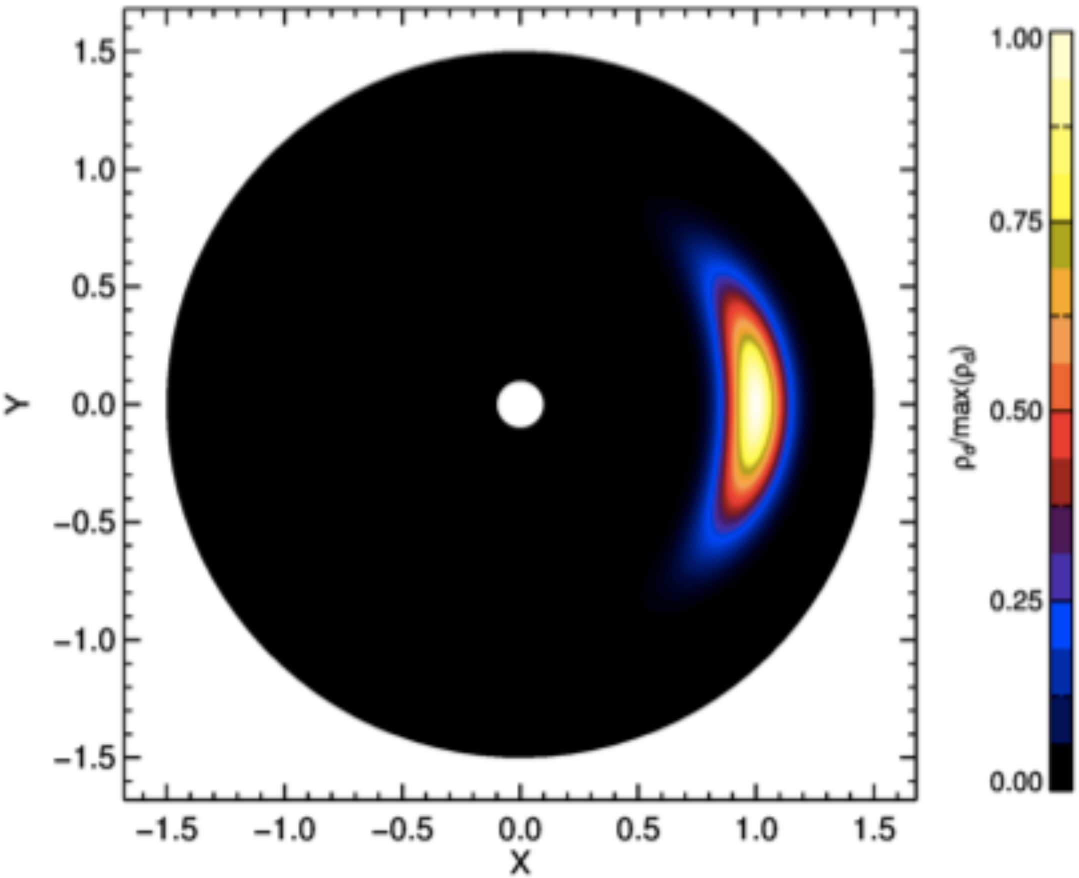
Lyra & Lin (2013)

$$S = \frac{St}{\delta}$$

$$\delta = v_{\rm rms}^2 / c_s^2,$$

a	= vortex semi-minor axis
H	= disk scale height (temperature)
χ	= vortex aspect ratio
δ	= diffusion parameter
St	= Stokes number (particle size)
$f(\chi)$	= model-dependent scale function

Analytical solution for dust in drag-diffusion equilibrium



Solution for

H/r=0.1 χ*=4* *S*=1

Solution

$$\rho_d(a) = \rho_{d\,\mathrm{max}} \exp\left(-\frac{a^2}{2H_V^2}\right),$$

$$H_V = \frac{H}{f(\chi)}\sqrt{\frac{1}{S+1}}$$

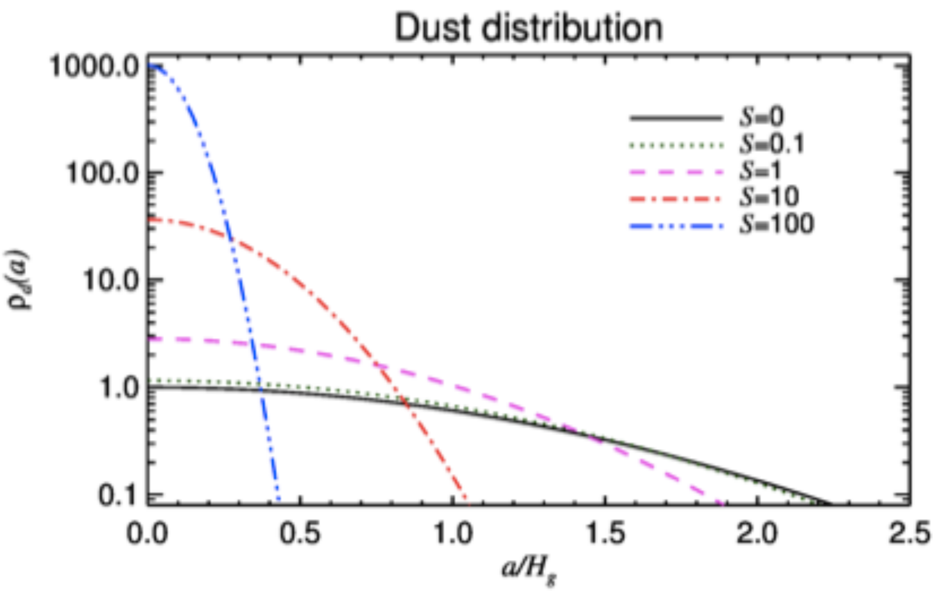
$$S = \frac{St}{\delta}$$

$$\delta = v_{\mathrm{rms}}^2 / c_s^2,$$

a = distance to vortex center
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (grain size)
$f(\chi)$ = model-dependent scale function

Lyra & Lin (2013)

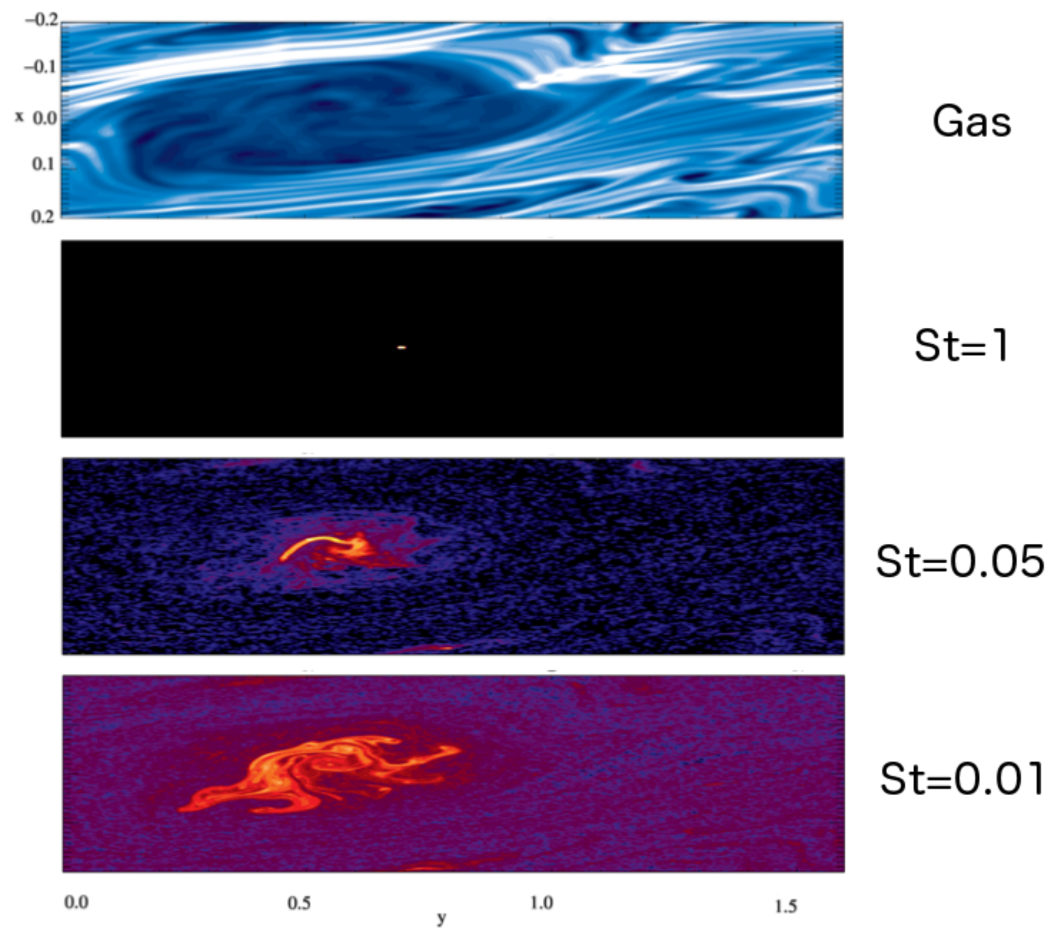
Analytical vs Numerical



$$S = \mathrm{St}/\delta$$

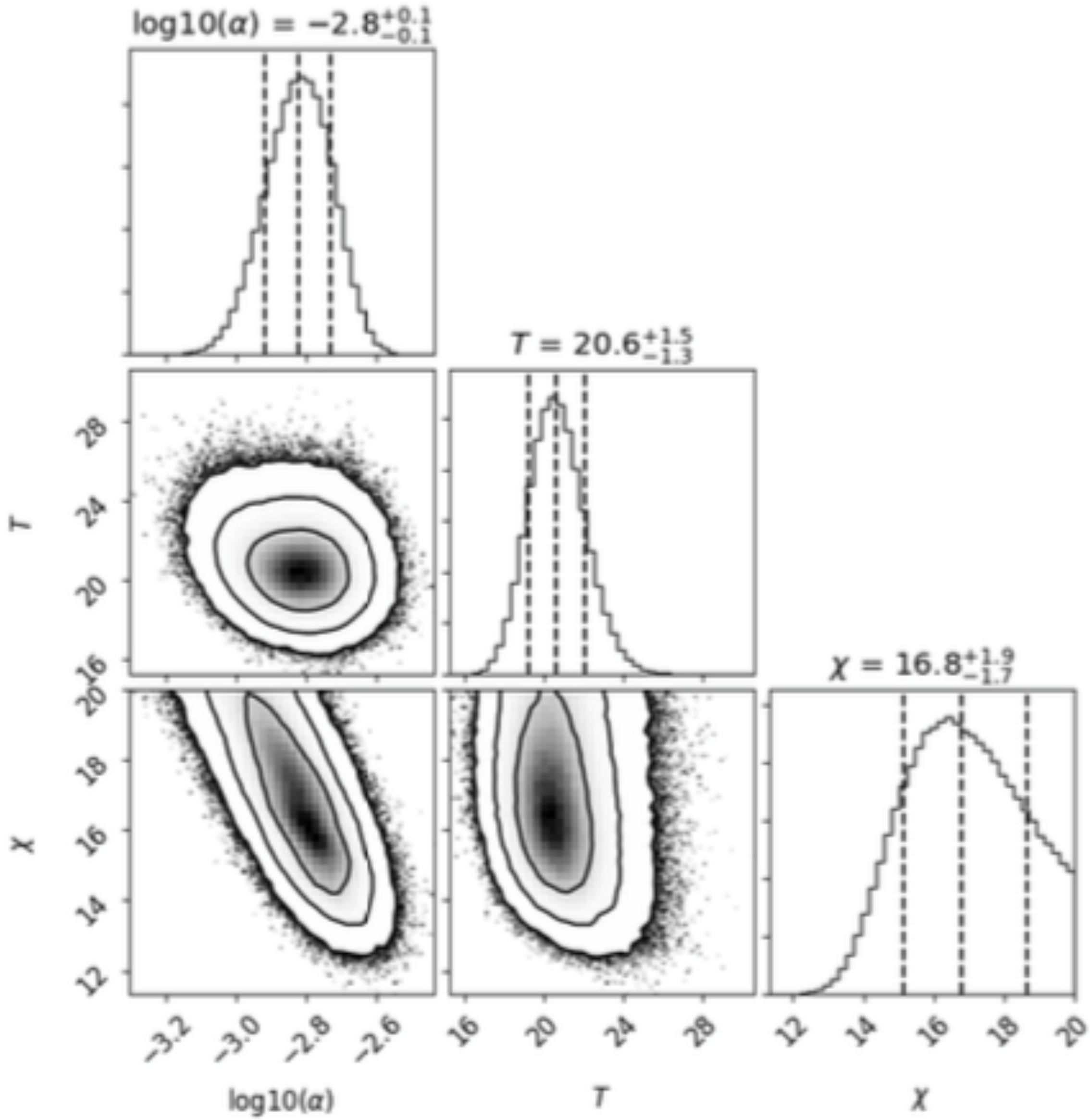
$$\delta = v_{\rm rms}^2 / c_s^2,$$

Lyra & Lin (2013)



Raettig et al (2015)

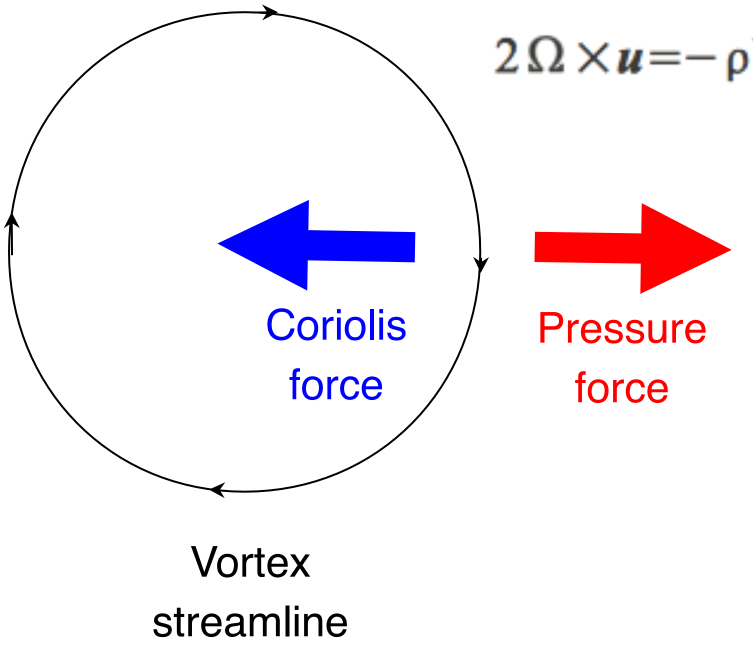
Observational vs Analytical

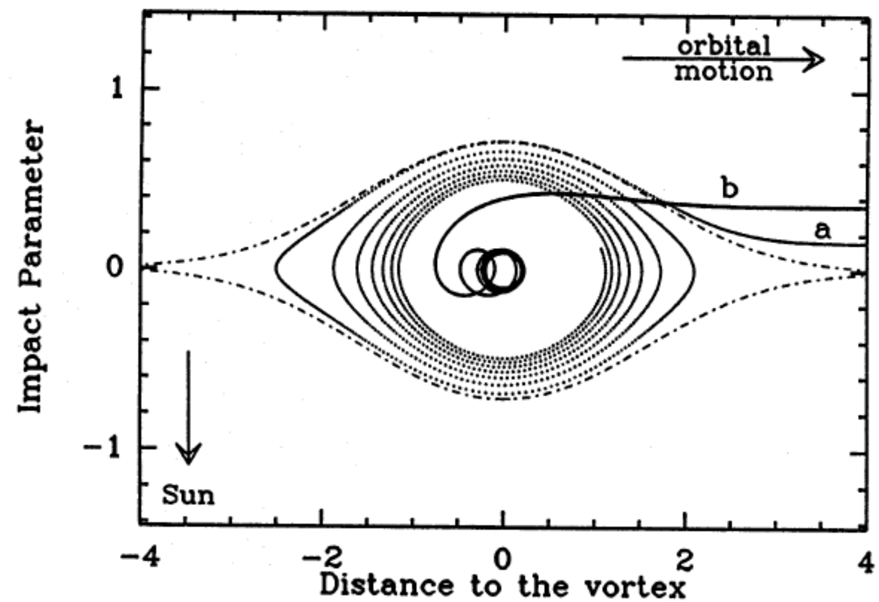


The Tea-Leaf effect

Geostrophic balance:

$$2\Omega \times \boldsymbol{u} = -\rho^{-1} \nabla p$$





Barge & Sommeria (1995)

Grains do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation

(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

Speed up planet formation enormously

(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

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Geostrophic balance:

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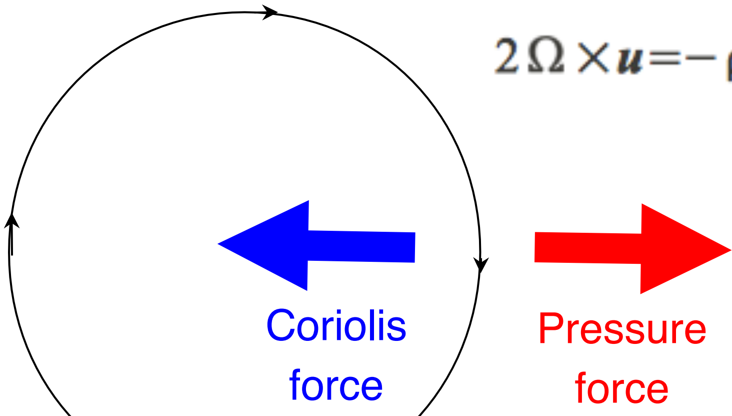
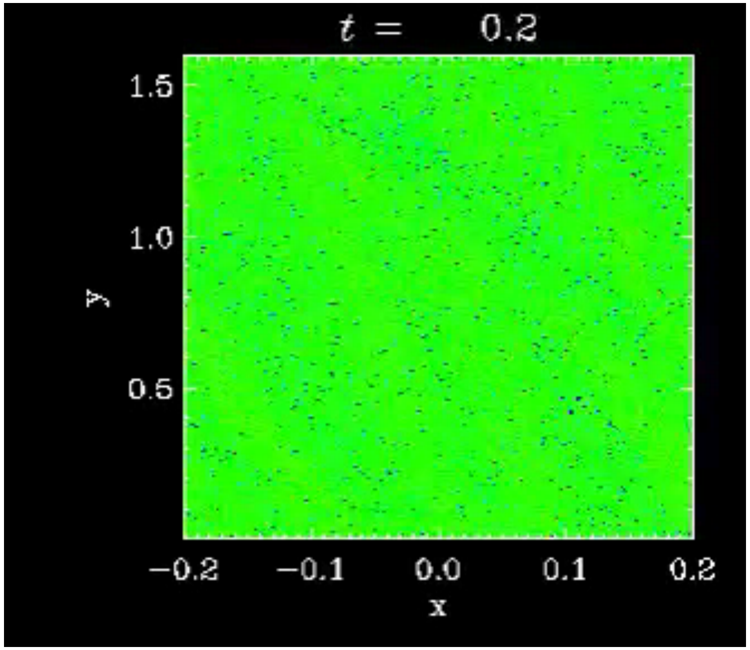


Vortex streamline



Raettig, Lyra, & Klahr (2013)

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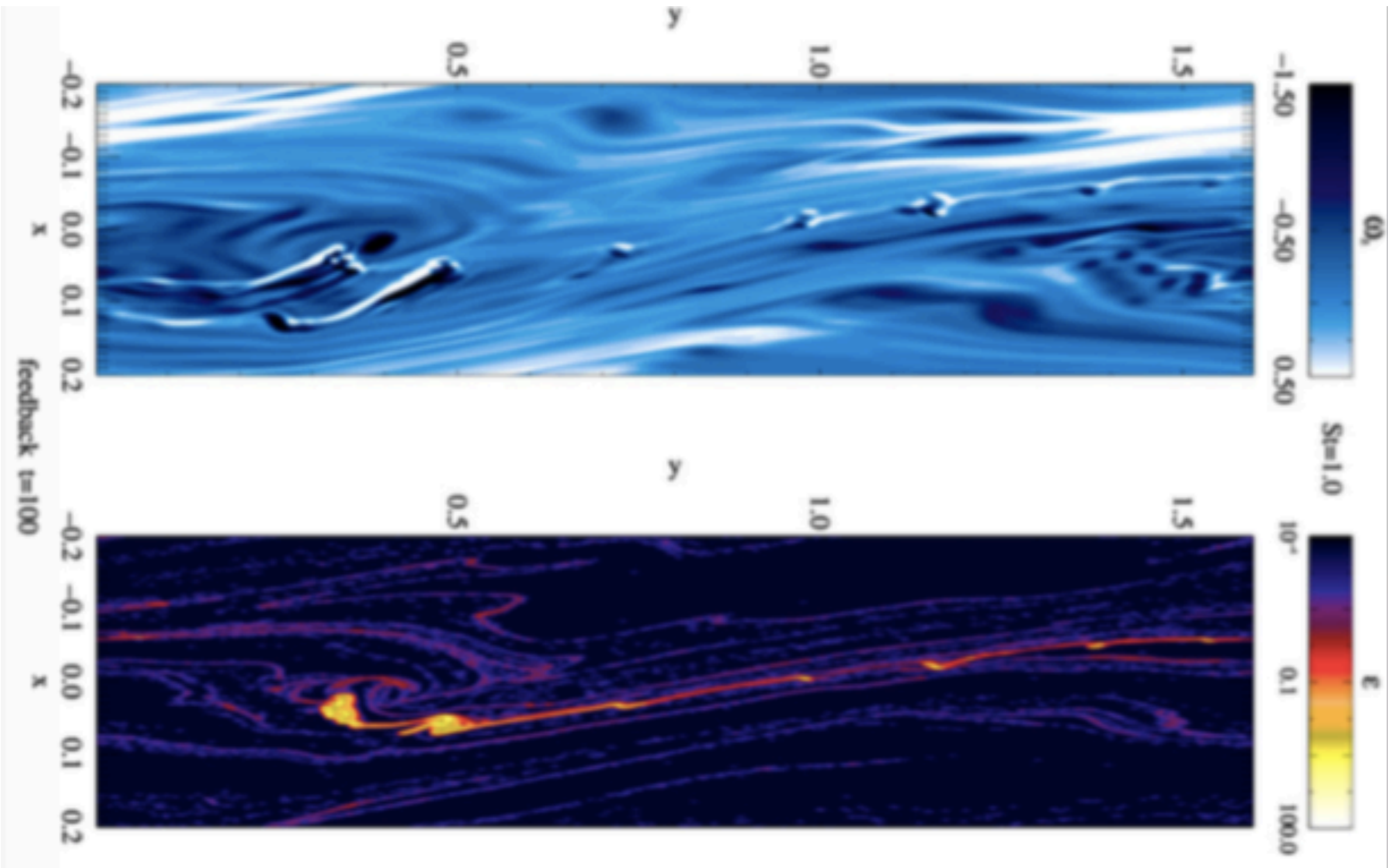
Clumping

Easily reaches dust-to-gas ratio > 1
even for solar (and sub-solar) metallicities.

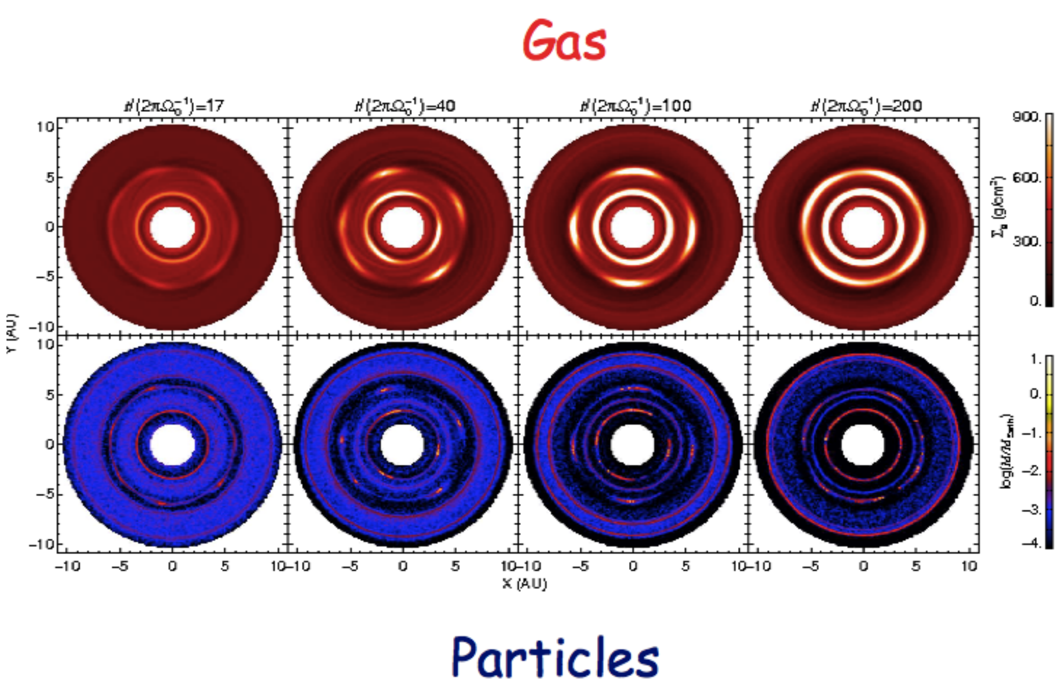


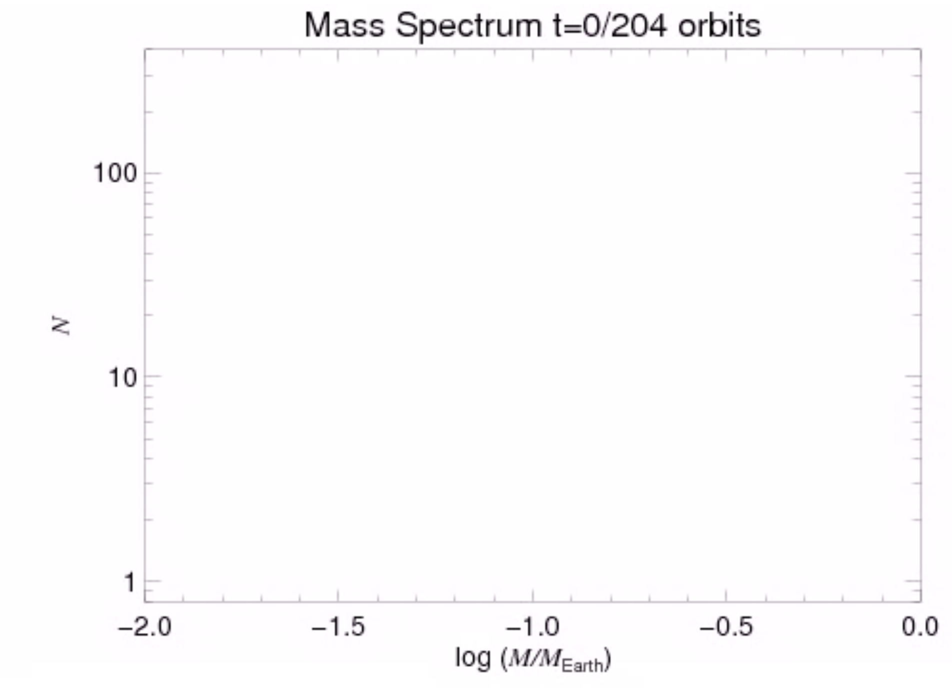
Gas vorticity

grains-to-gas ratio

Raettig et al. (2015)

Vortices and Planet Formation

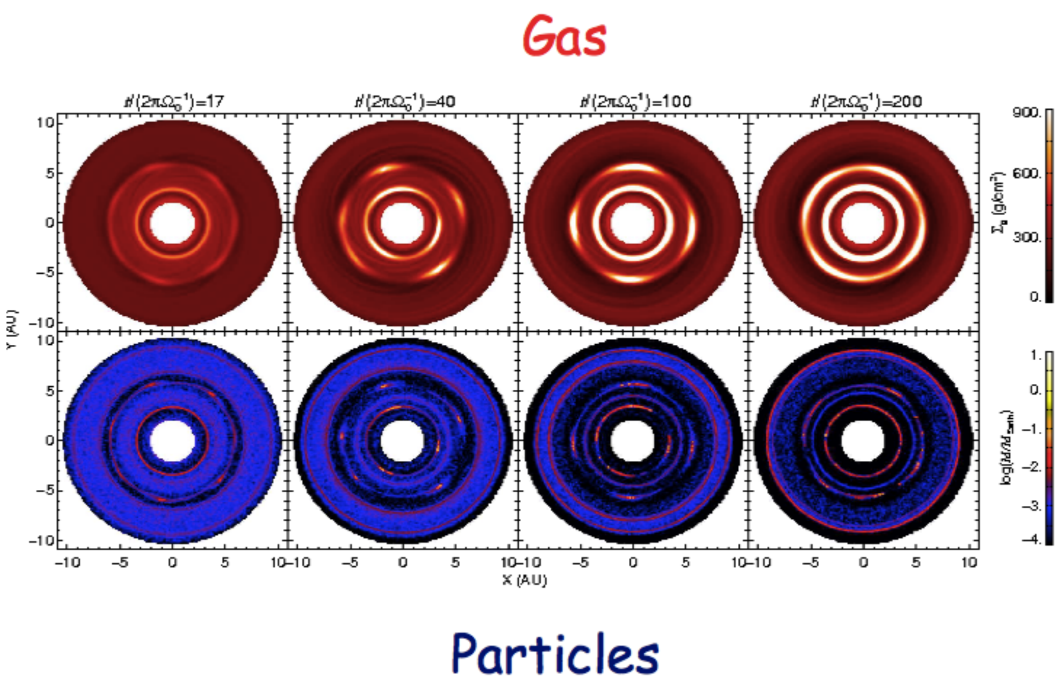


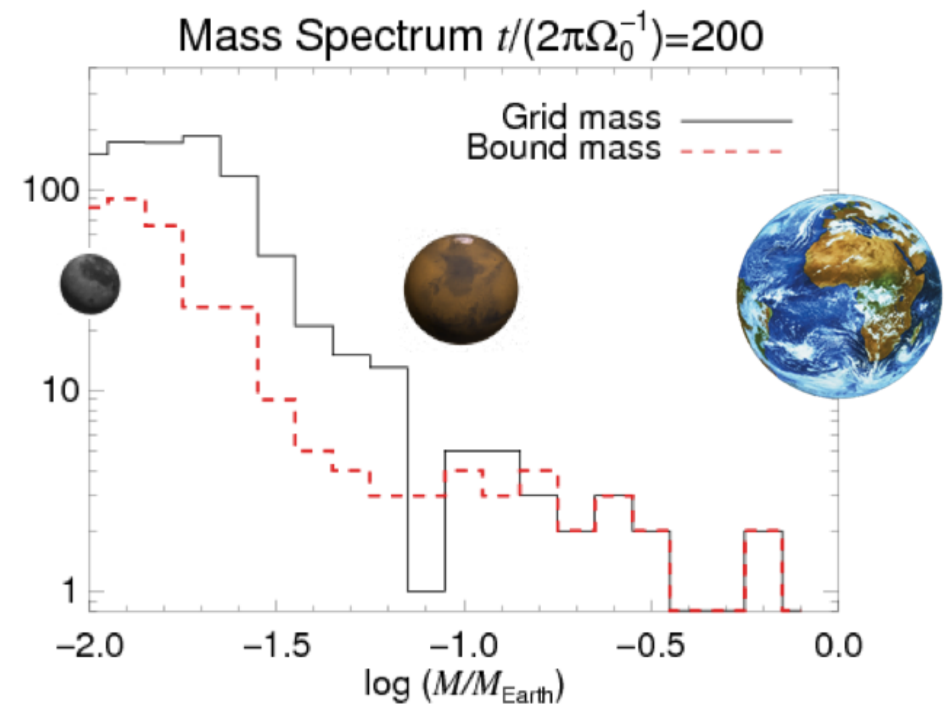


Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a,
Lambrechts & Johansen 2012)

Vortices and Planet Formation



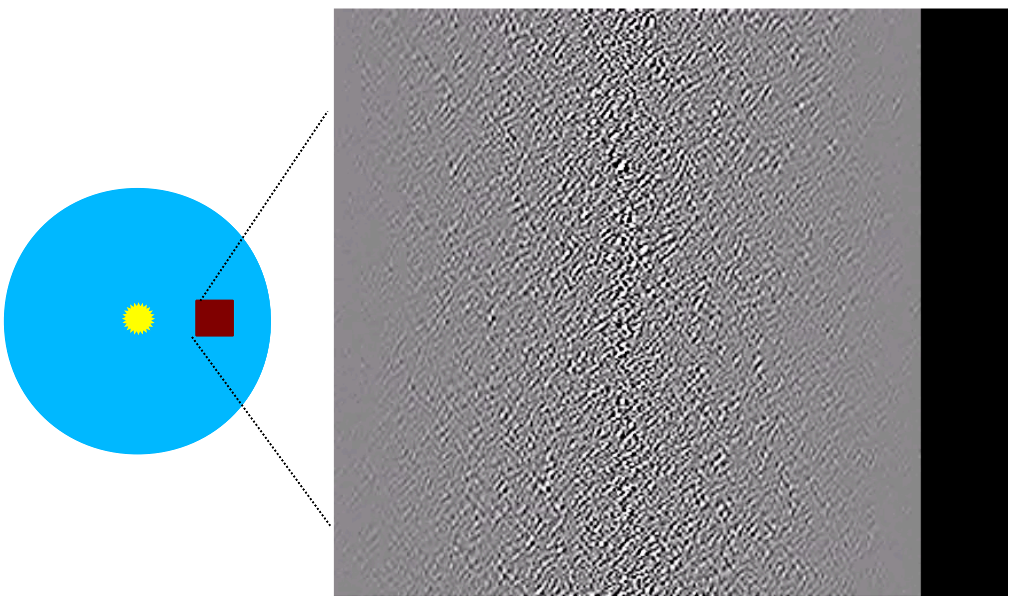


Collapse into Mars mass objects

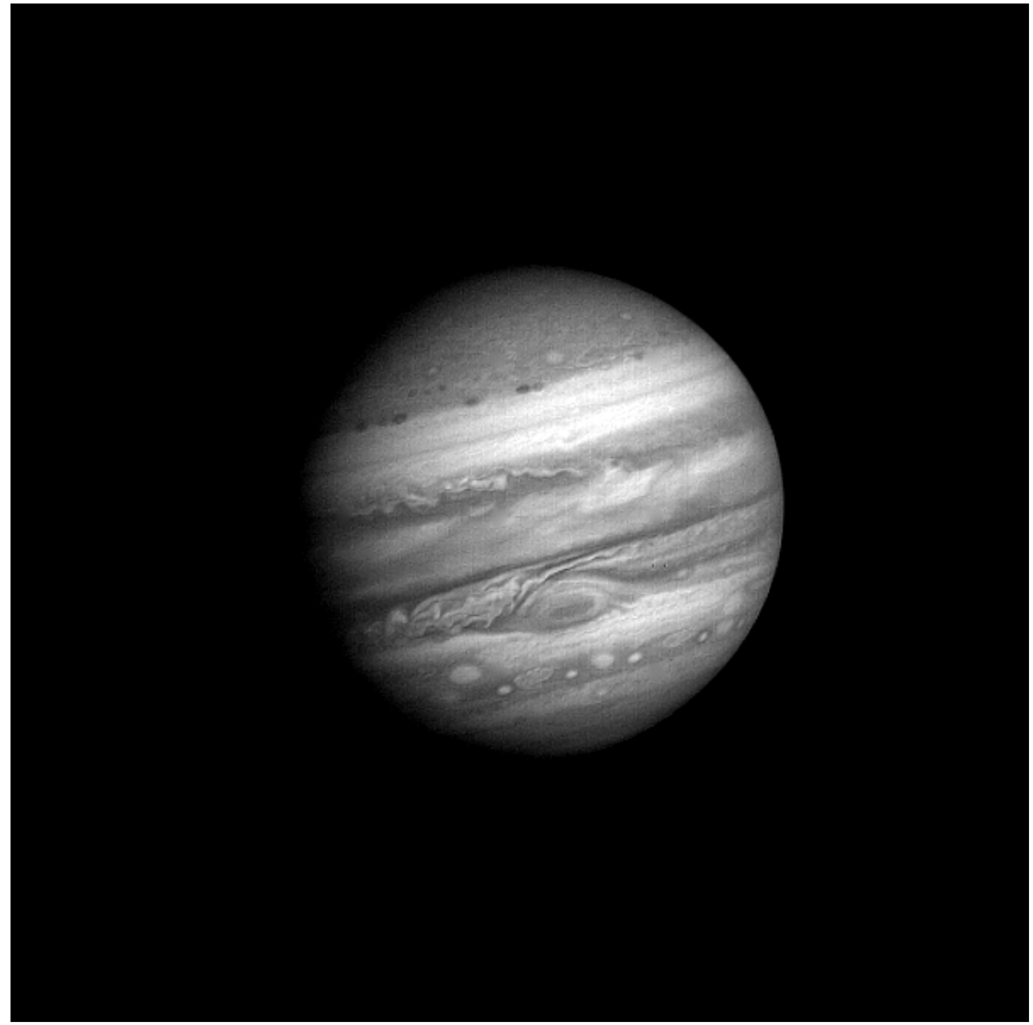
(Lyra et al. 2008b, 2009a,
Lambrechts & Johansen 2012)

Convection ?

Vortices in the dead zone

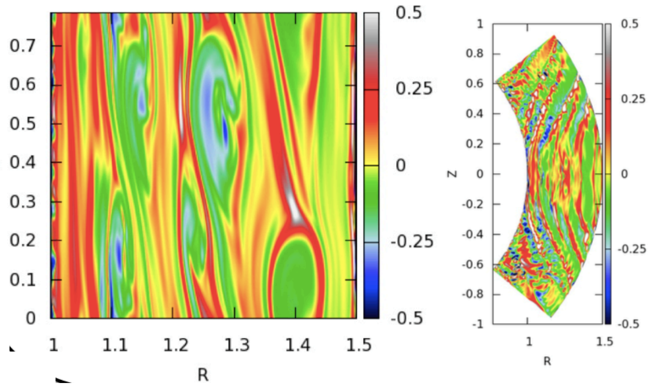


Lyra & Klahr (2011)



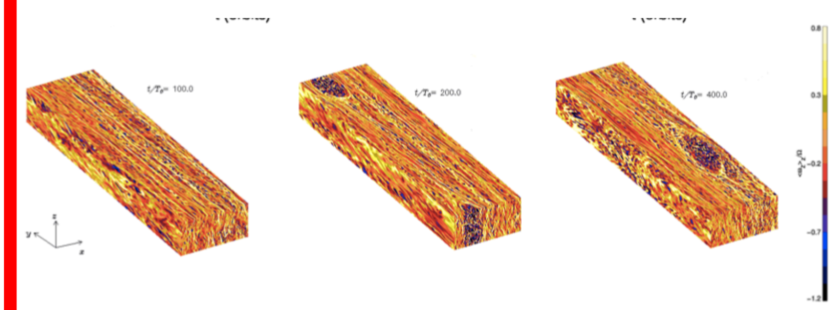
Thermal Instabilities

Vertical Shear Instability



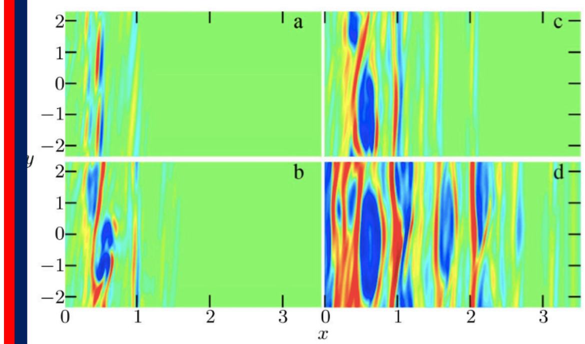
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability

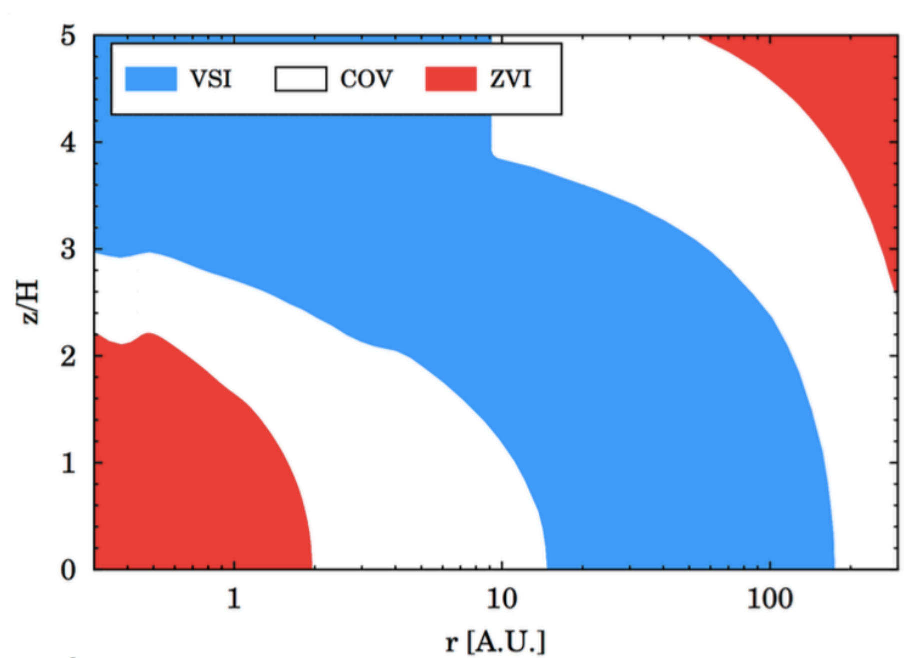


Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

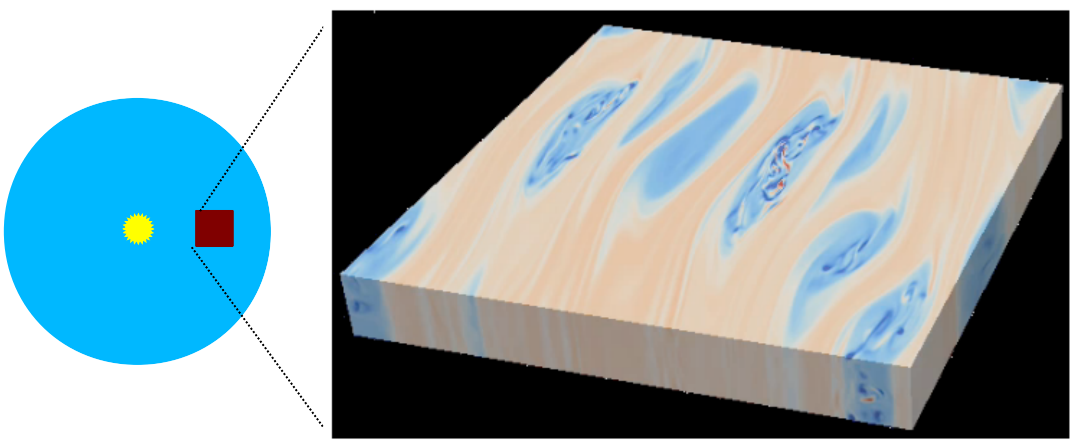
Zombie Vortex Instability



Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

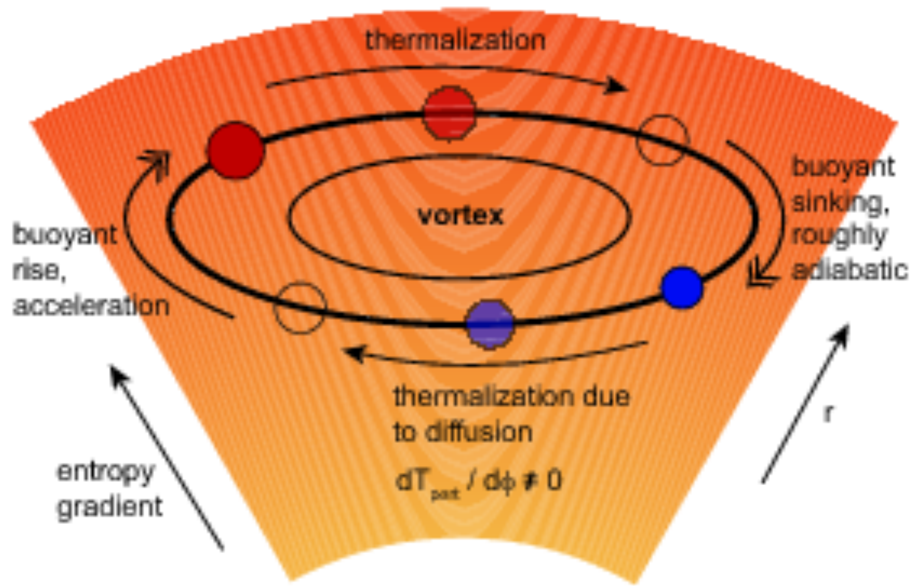


Convective Overstability



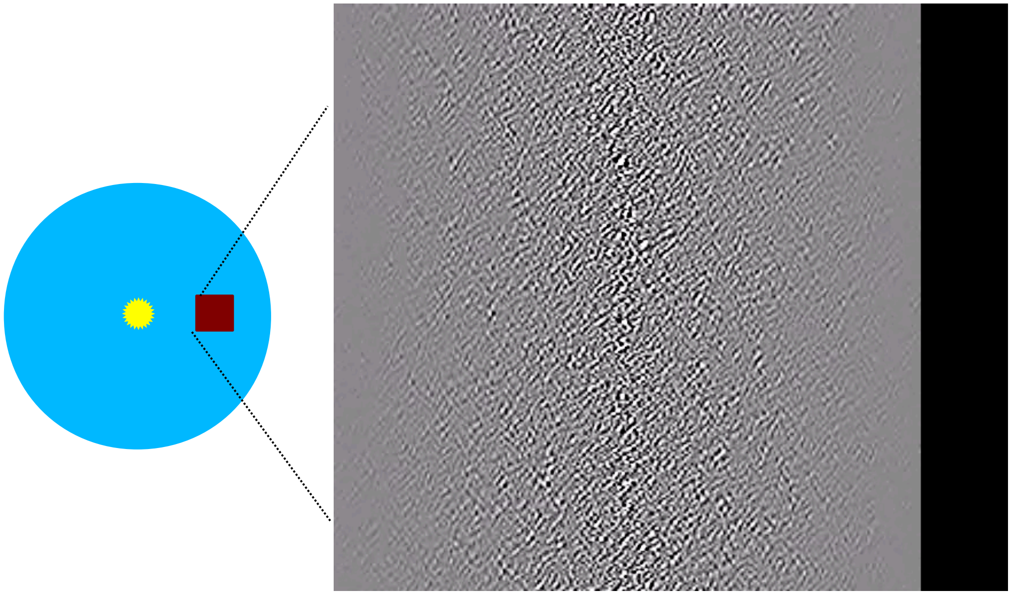
Lesur & Papaloizou (2010)

Sketch of the Convective Overstability



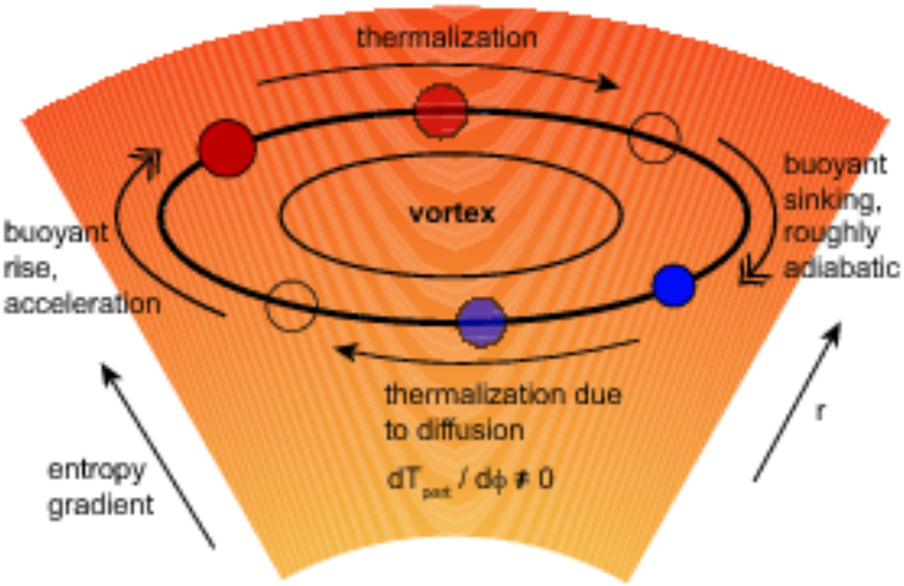
Armitage (2010)

Convective Overstability



Lyra & Klahr (2011)

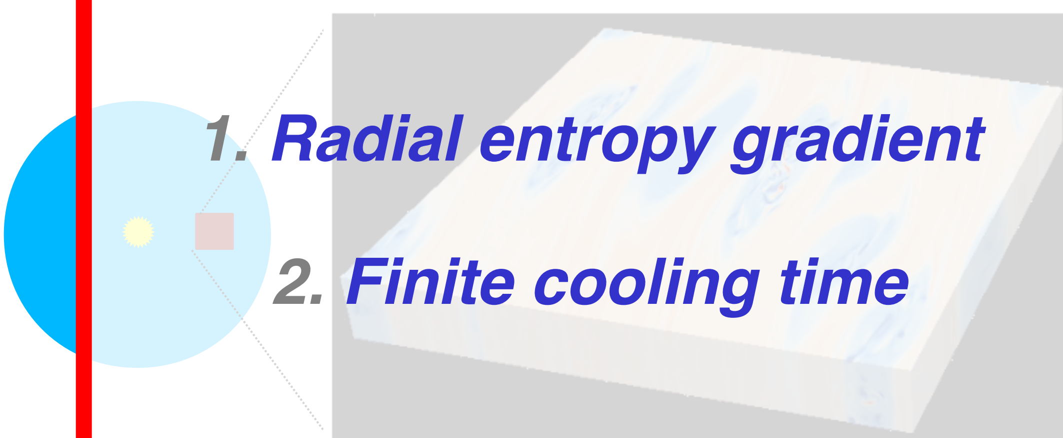
Sketch of the
Convective Overstability



Armitage (2010)

Convective Overstability

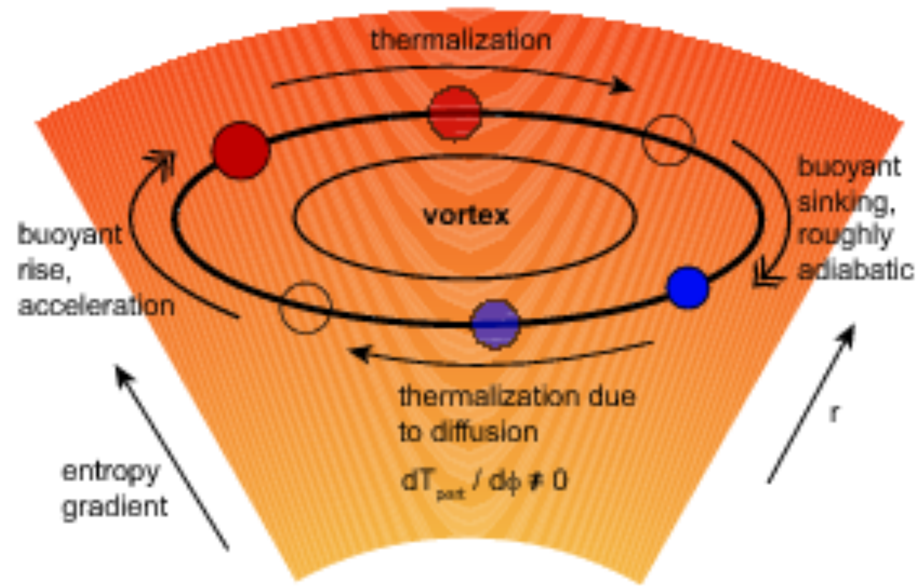
Sketch of the
Convective Overstability



1. *Radial entropy gradient*

2. *Finite cooling time*

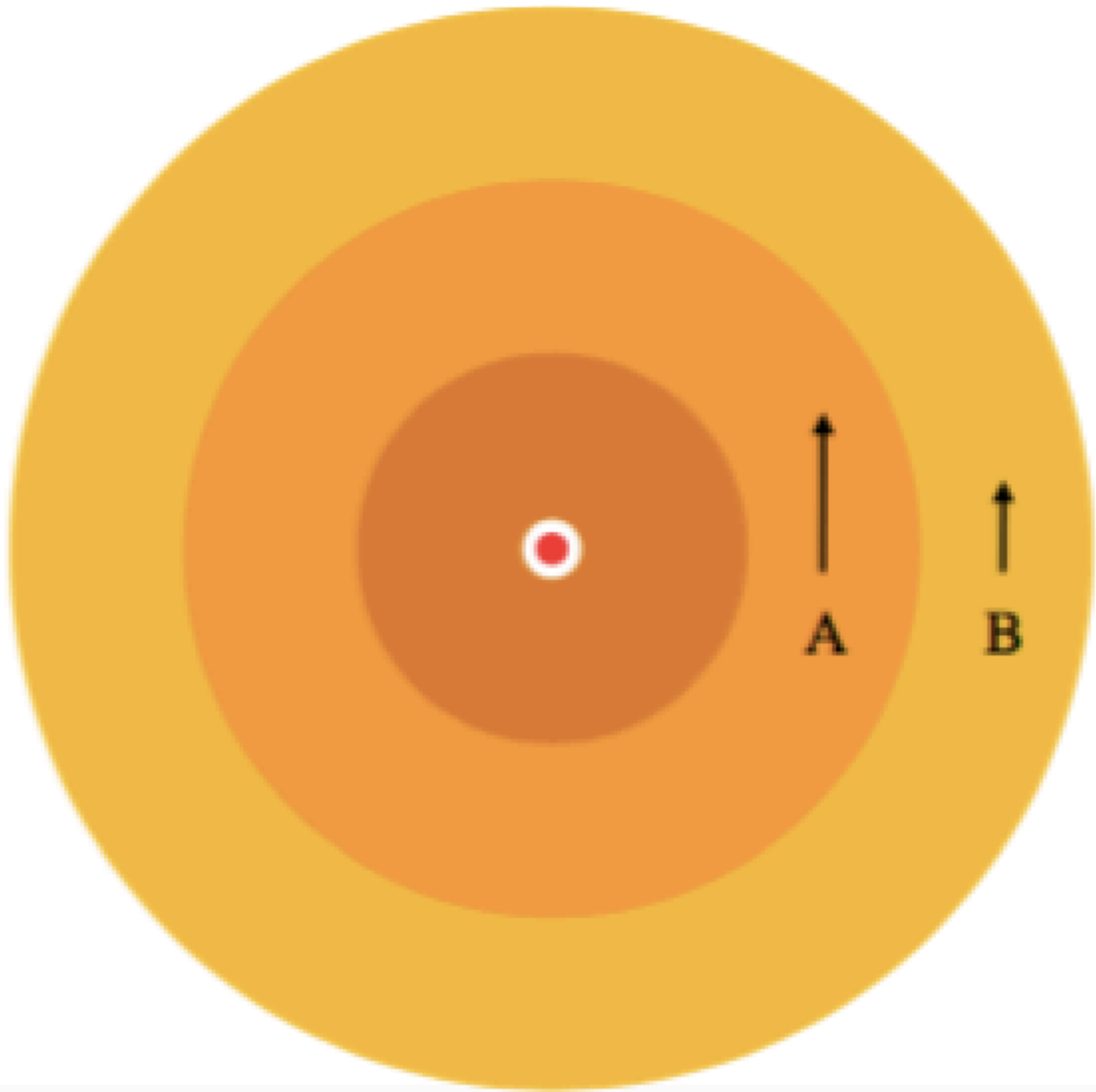
Lesur & Papaloizou (2010)



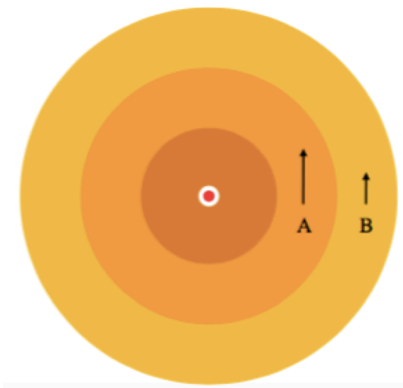
Armitage (2010)

Vertical Shear Instability

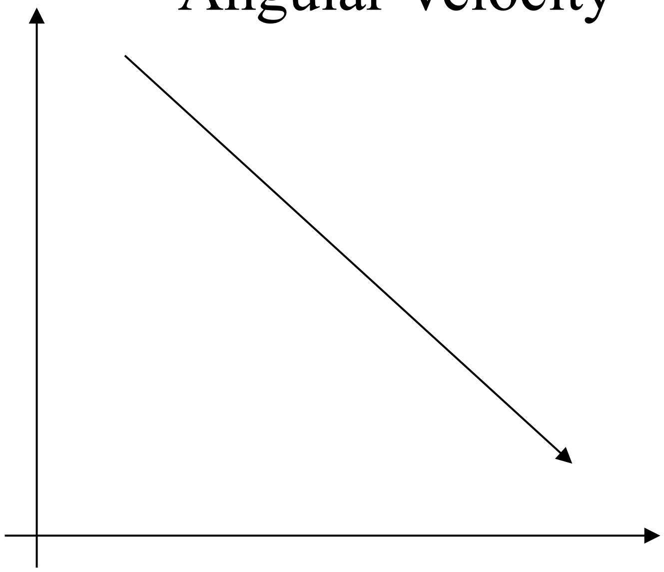
Rayleigh criterion



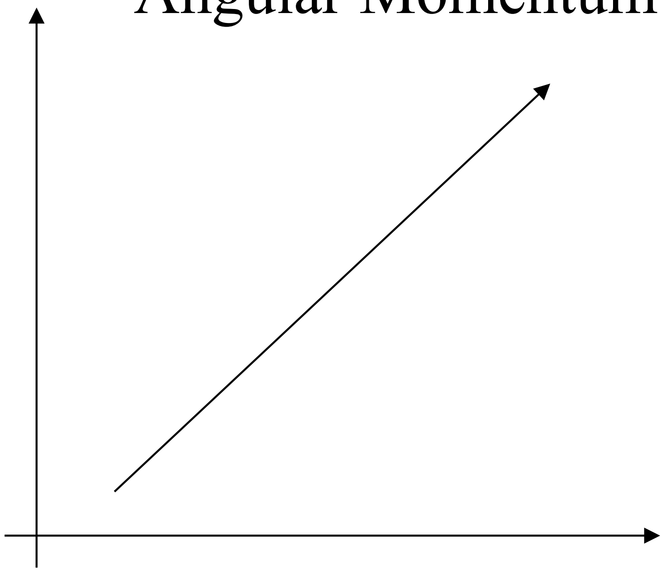
Stability (Rayleigh criterion)



Angular Velocity

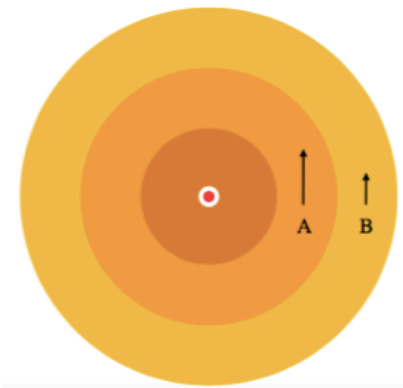


Angular Momentum ($r^2 \Omega$)

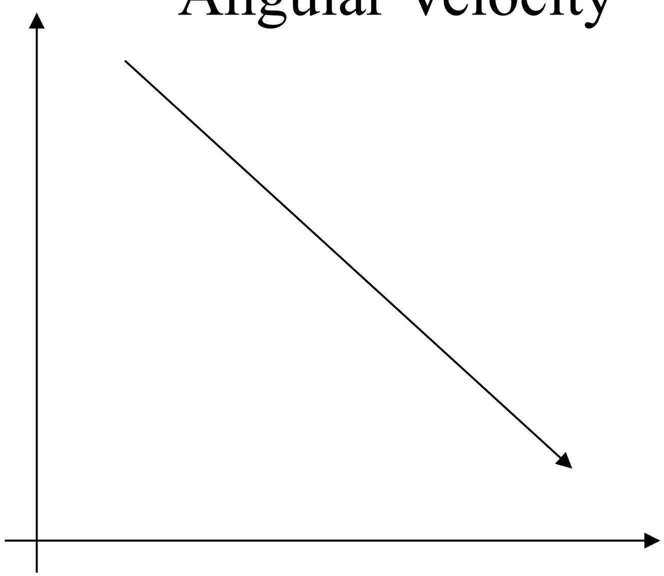


$$|d \ln\Omega / d\ln r| < 2$$

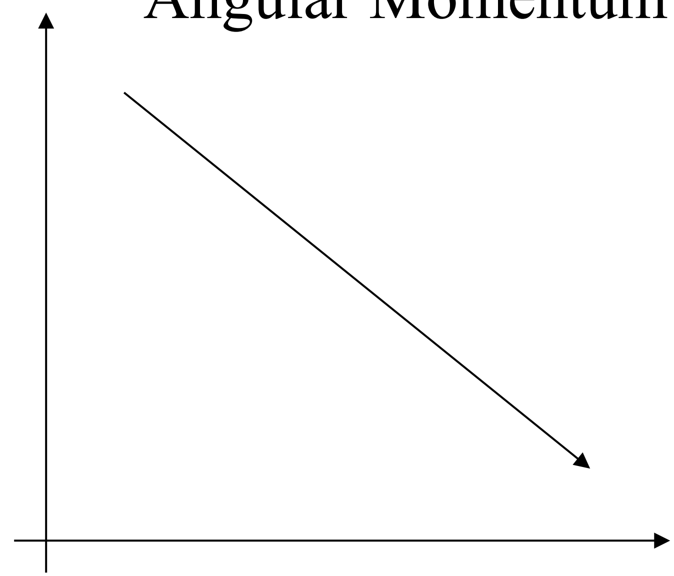
Rayleigh instability



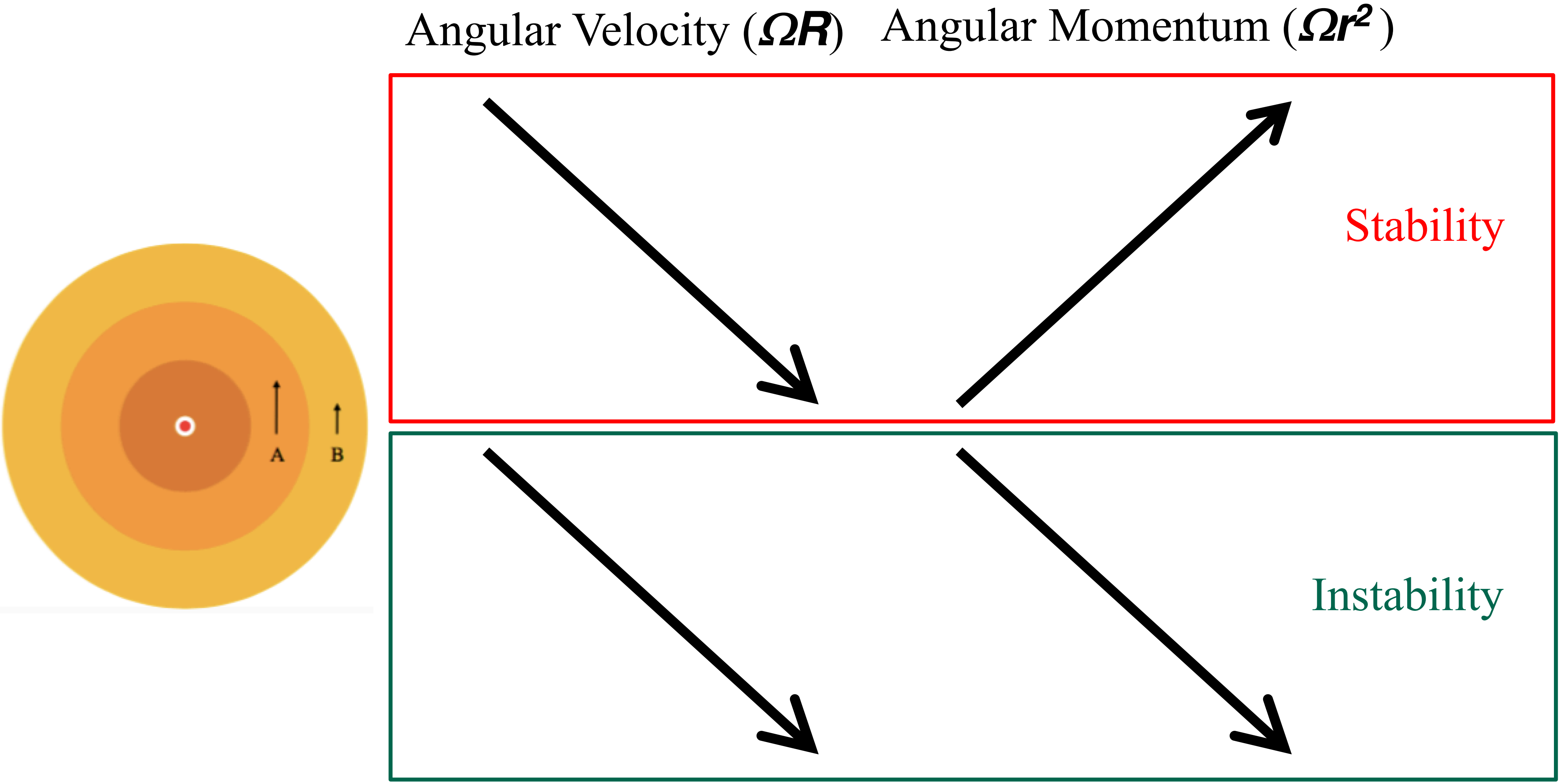
Angular Velocity



Angular Momentum (***$r^2\,\Omega$***)



$$|d \ln\Omega / d\ln r| > 2$$

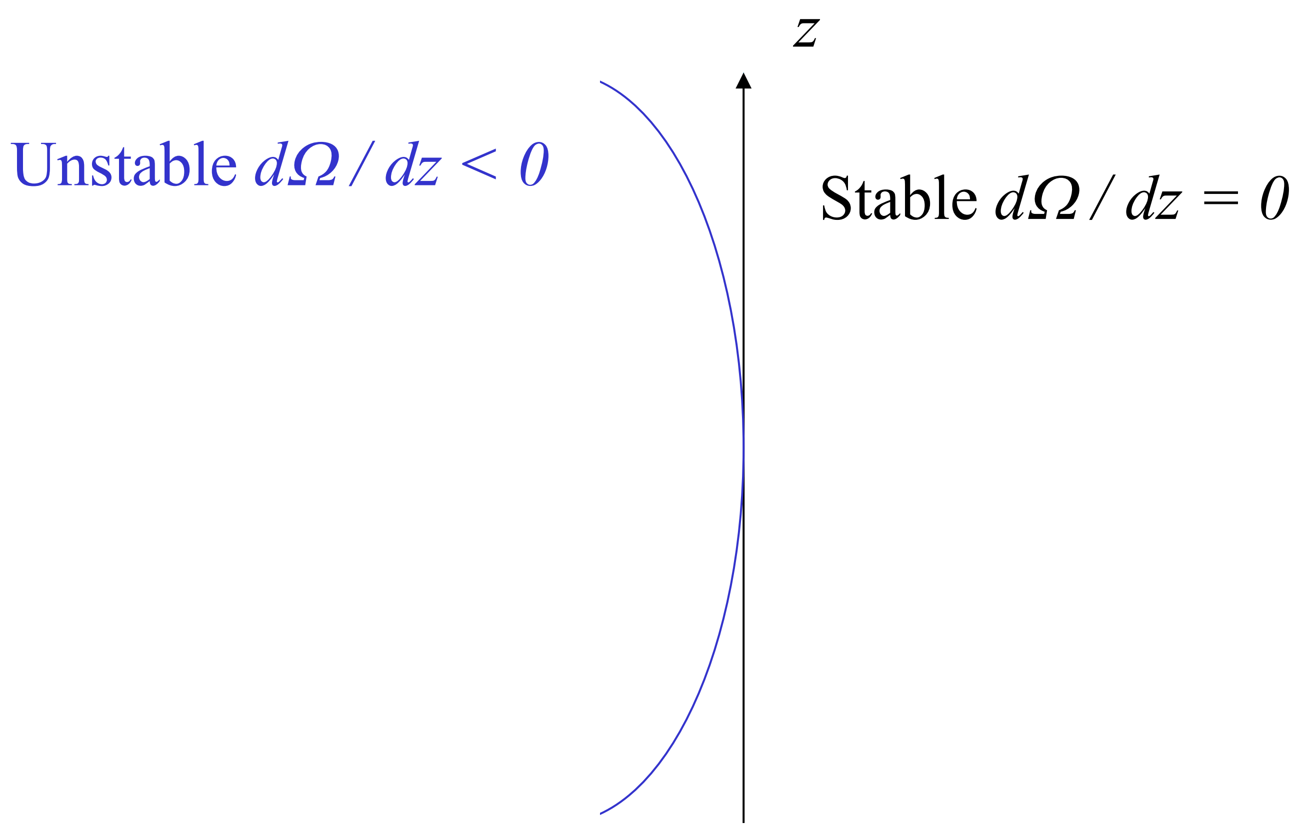

Angular Velocity (ΩR)
Angular Momentum (Ωr²)
Stability
Instability
A
B

Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p,$$

$$c_{\rm s}^2 = c_0^2 \left(\frac{R}{R_0}\right)^q,$$

$$\Omega = \Omega_{\rm K}\left[1 + \frac{1}{2}\left(\frac{H}{R}\right)^2 \left(p + q + \frac{q}{2}\frac{Z^2}{H^2}\right)\right]$$



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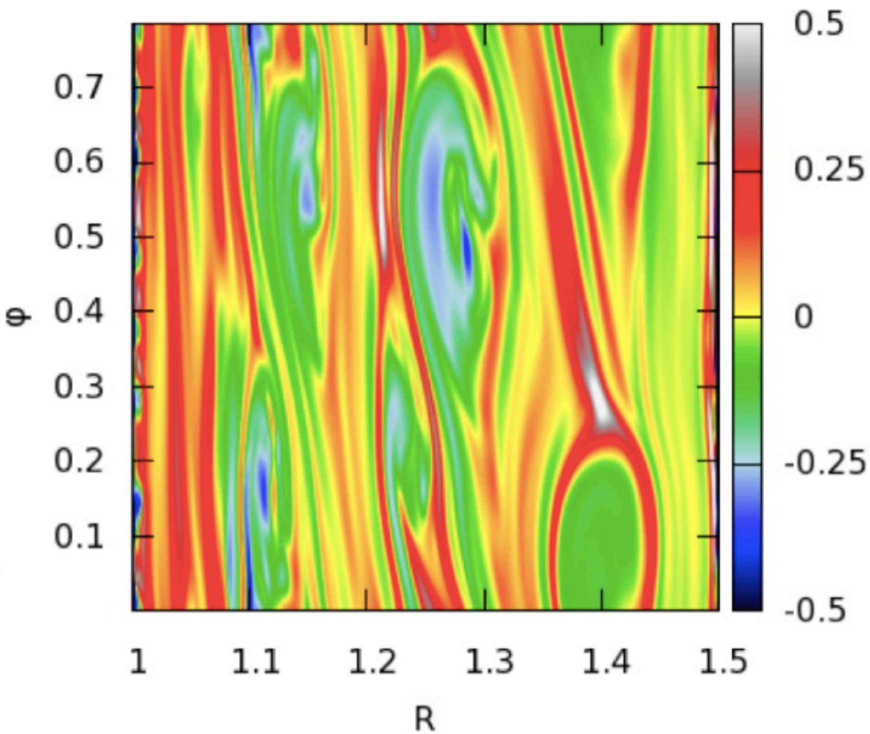

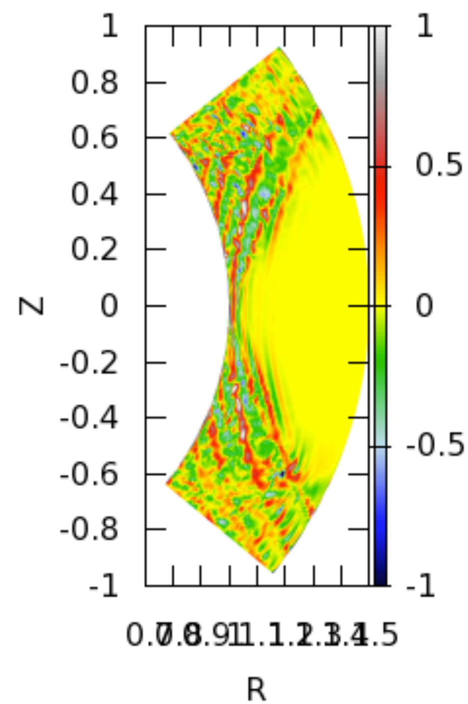

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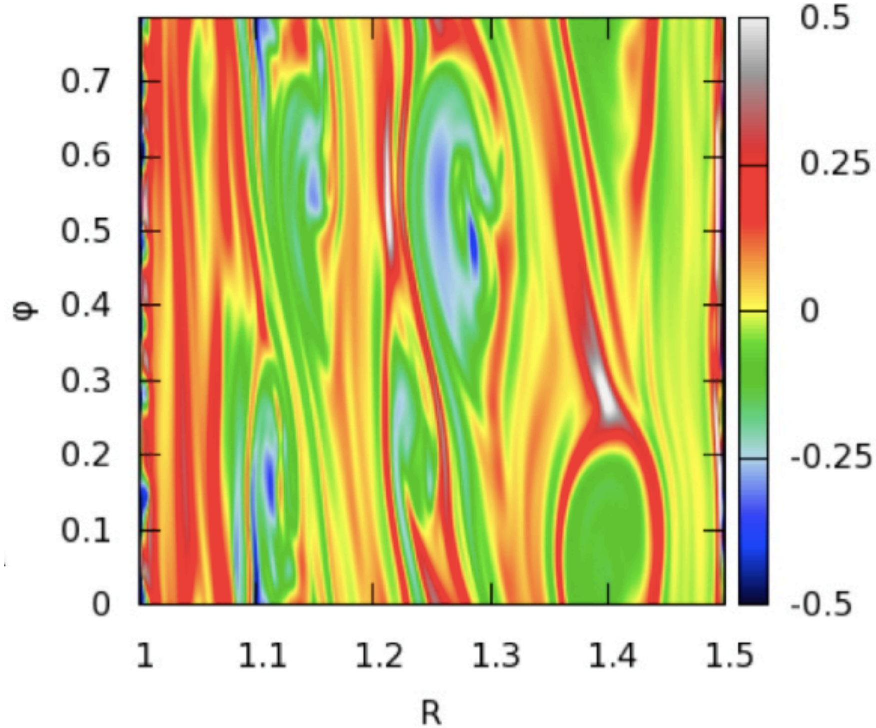
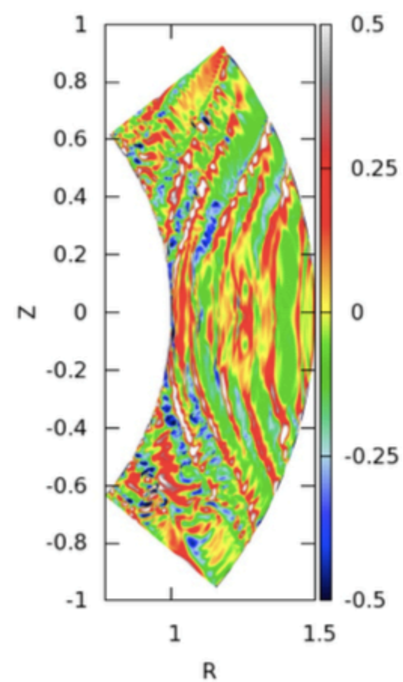
$d\Omega / dz \;!= 0\;;\; \kappa_z^2 < 0$ => Rayleigh unstable

Solberg-Hoiland stability criterion

$$\kappa^2 + N^2 > 0$$





Nelson et al. (2013)

Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p ,$$

$$c_s^2 = c_0^2 \left(\frac{R}{R_0}\right)^q ,$$

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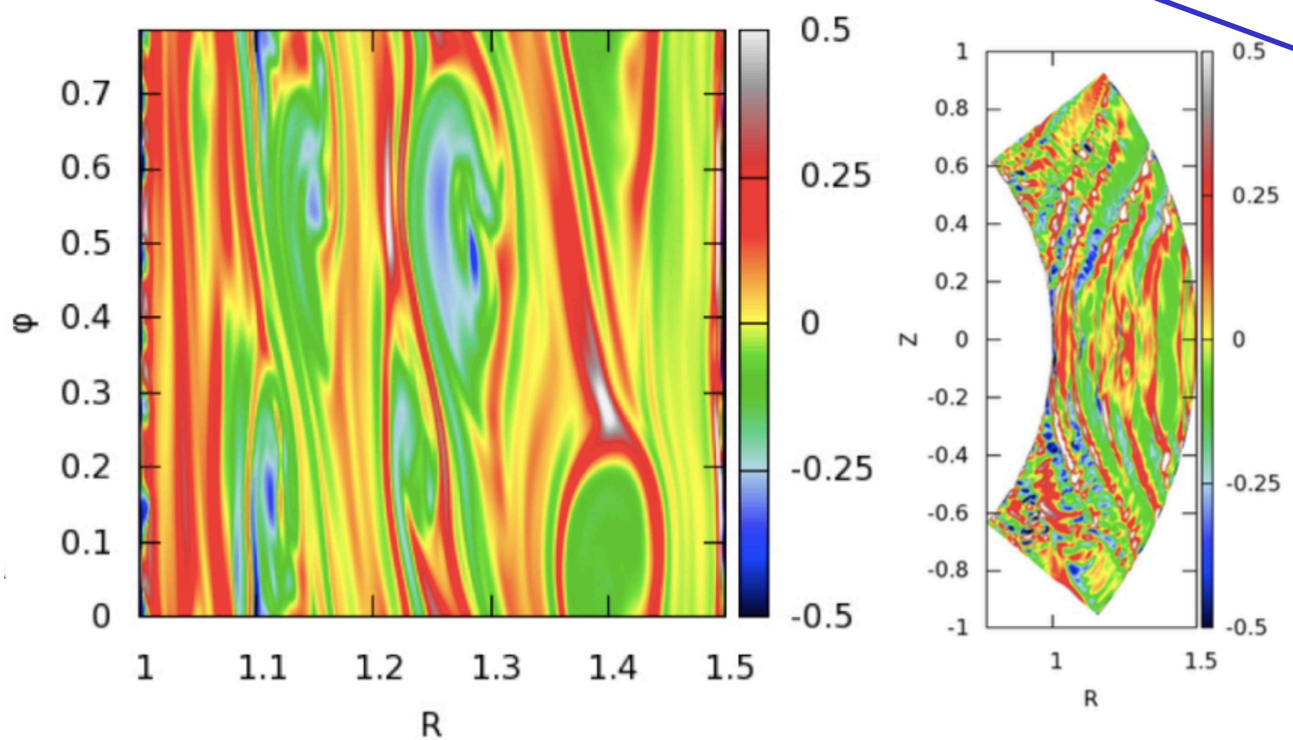
$d\Omega / dz$!= 0 ; $\kappa_z^2 < 0$ => Rayleigh unstable

Solberg-Hoiland stability criterion

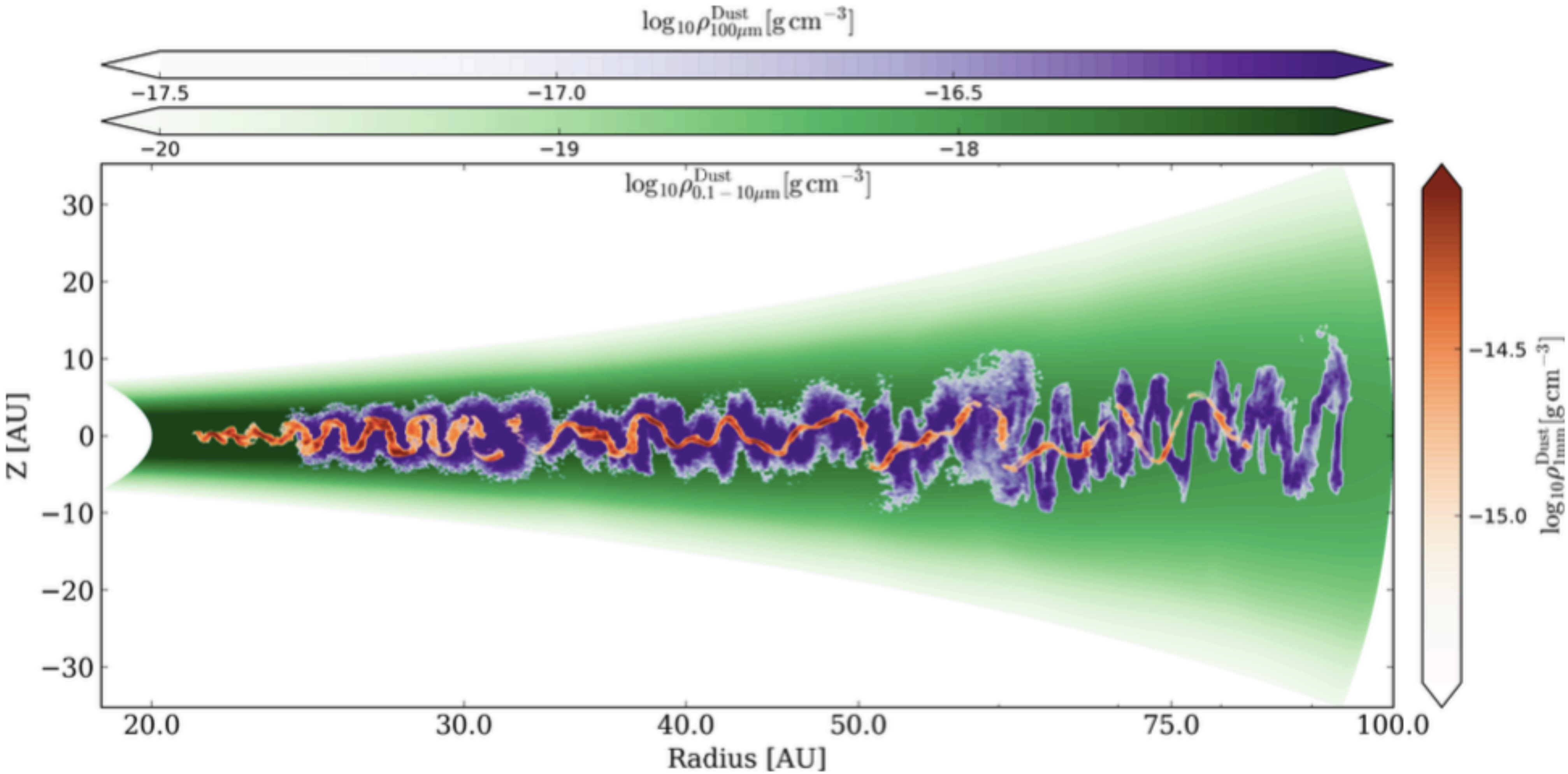
$\kappa^2 + N^2 > 0$

Buoyancy stabilizes!



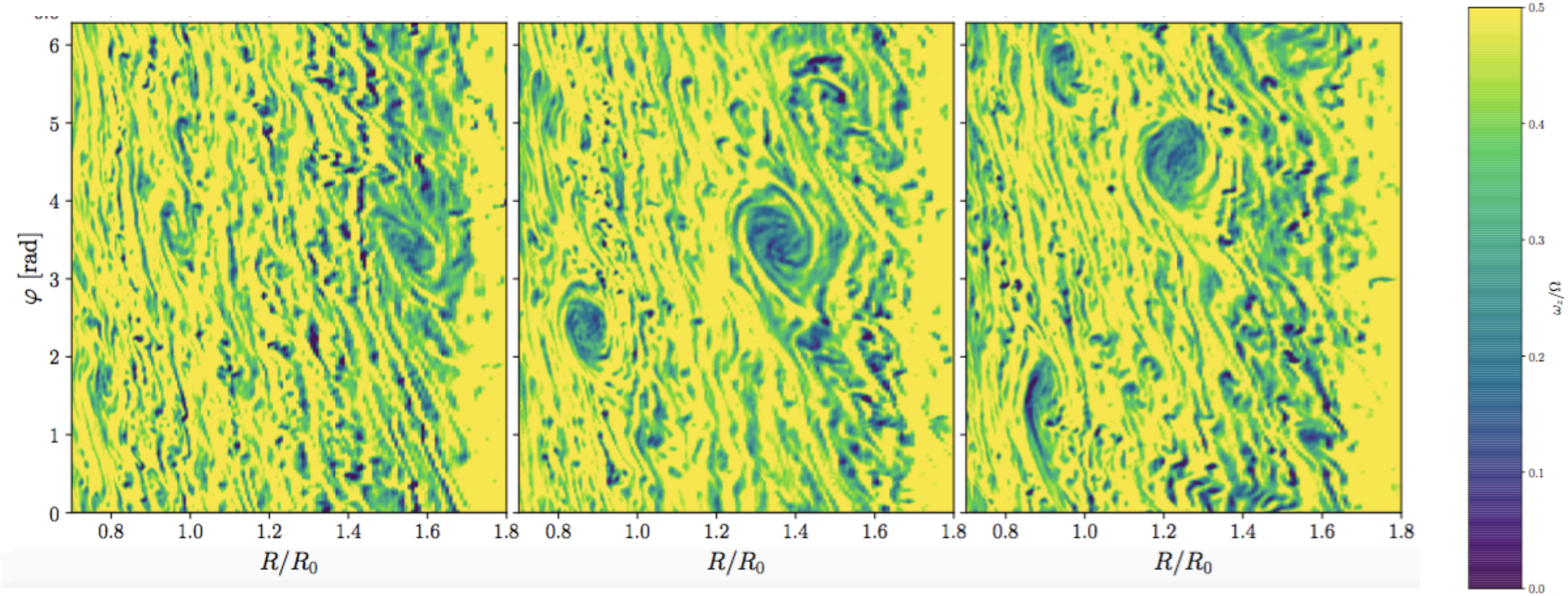
Nelson et al. (2013)

Dust in Vertical-Shear turbulence



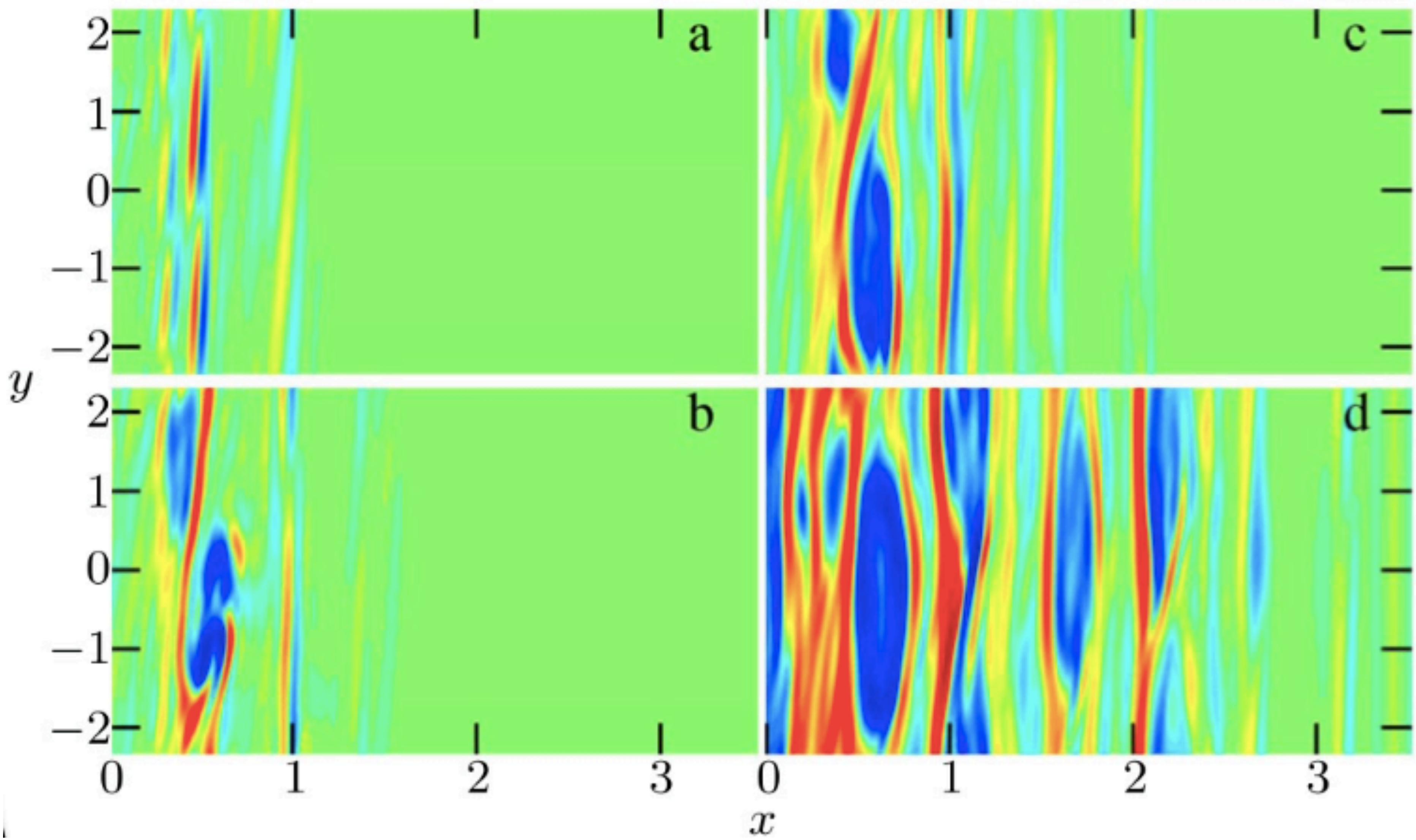
Flock et al. (2017)

3D VSI saturates into vortices



Manger & Klahr (2018)

Zombie Vortex Instability

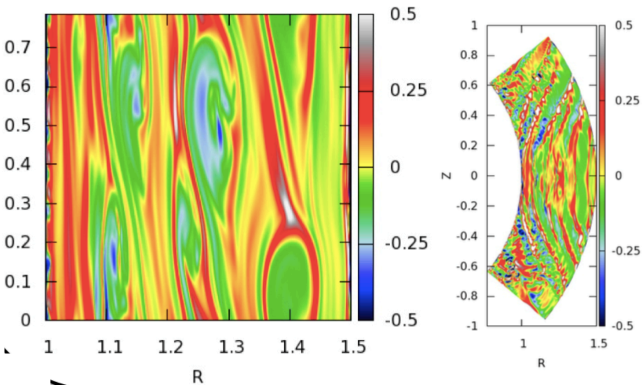


Cascade of baroclinic critical layers

Marcus et al. (2015, 2016)

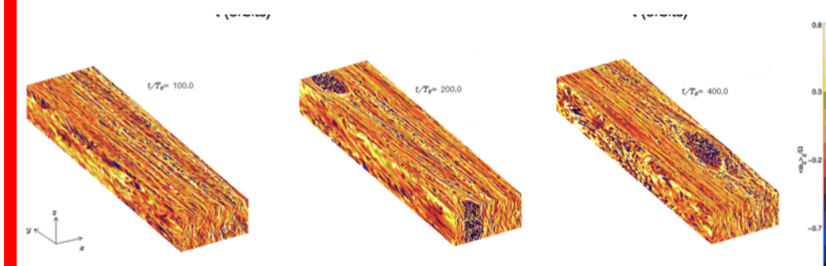
Thermal Instabilities

Vertical Shear Instability



Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

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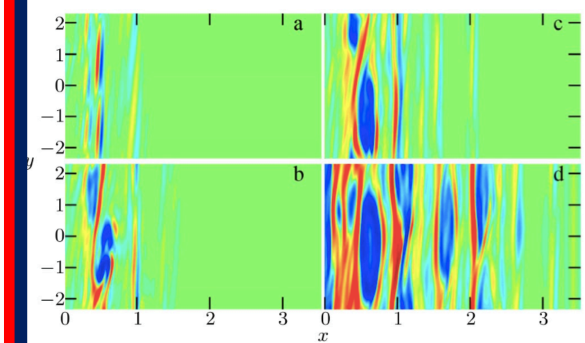


Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

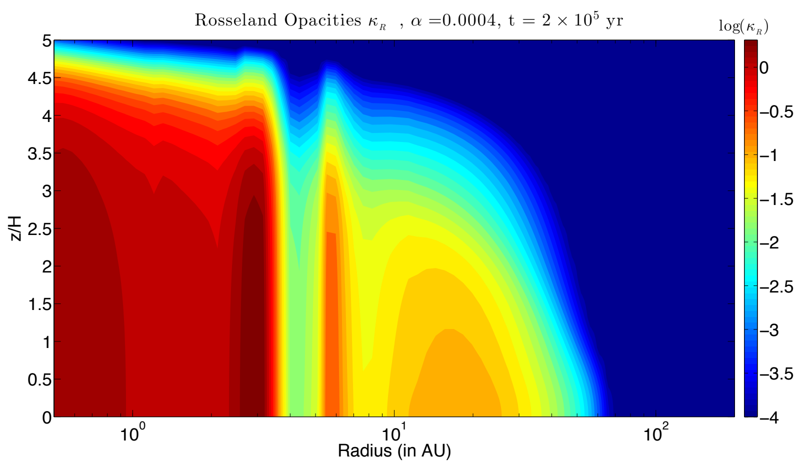
$\Omega\tau << 1$
($\kappa < 1$ cm^2/g)

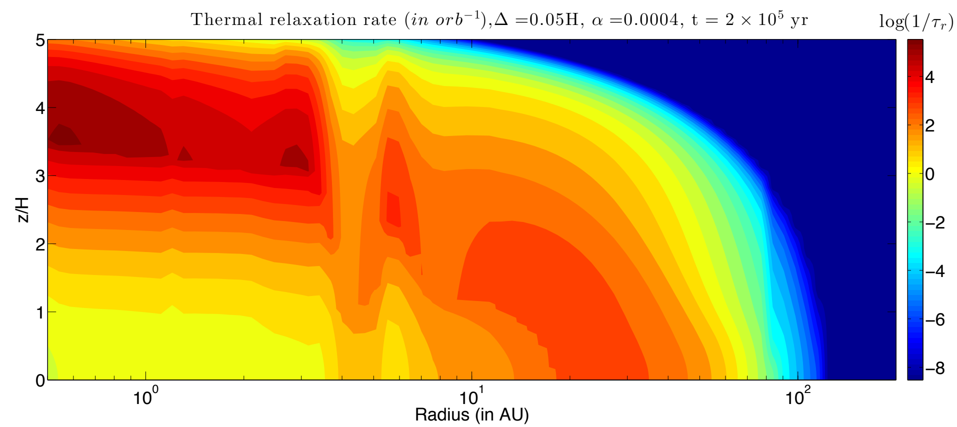
$\Omega\tau \sim 1$
($\kappa \sim 1$–50 cm^2/g)

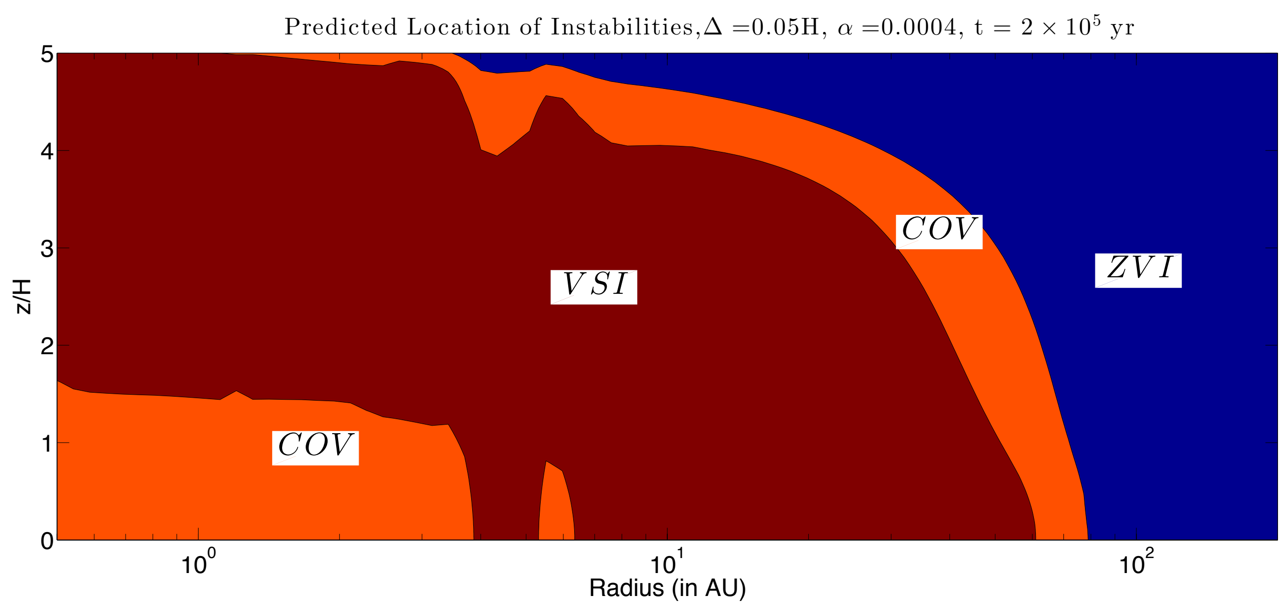
$\Omega\tau >> 1$
($\kappa > 50$ cm^2/g)

Opacity

Synthesis



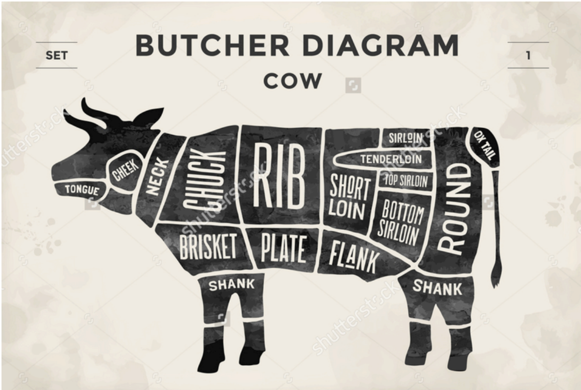


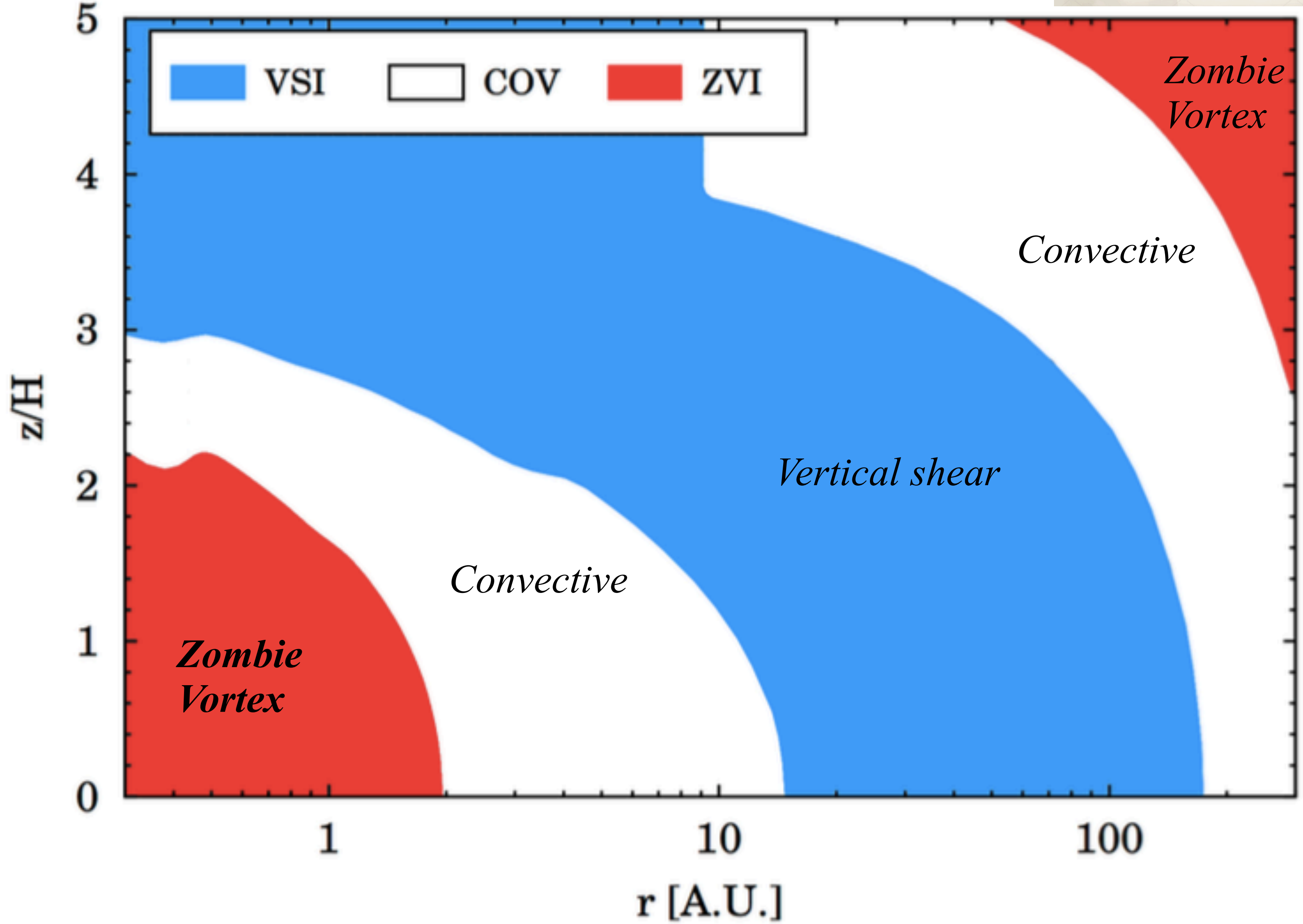


Cuzzi, Estrada, & Umurhan, in prep

Synthesis

A “butcher diagram” for hydro instabilities.

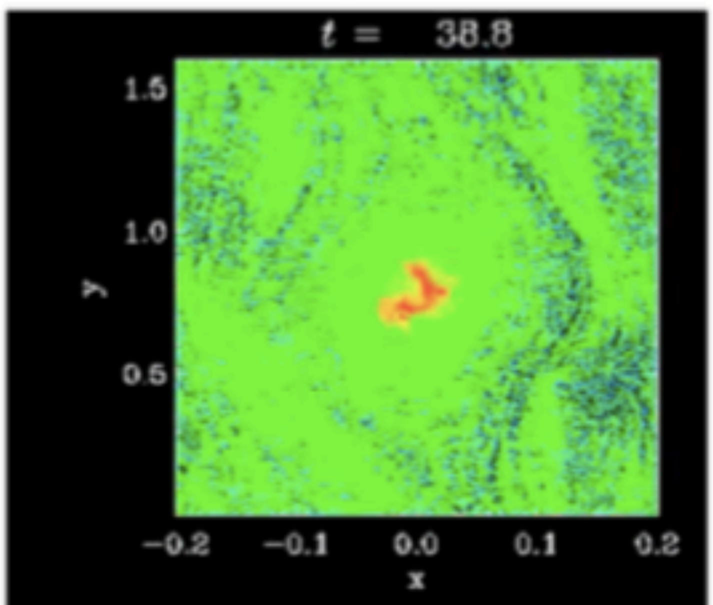


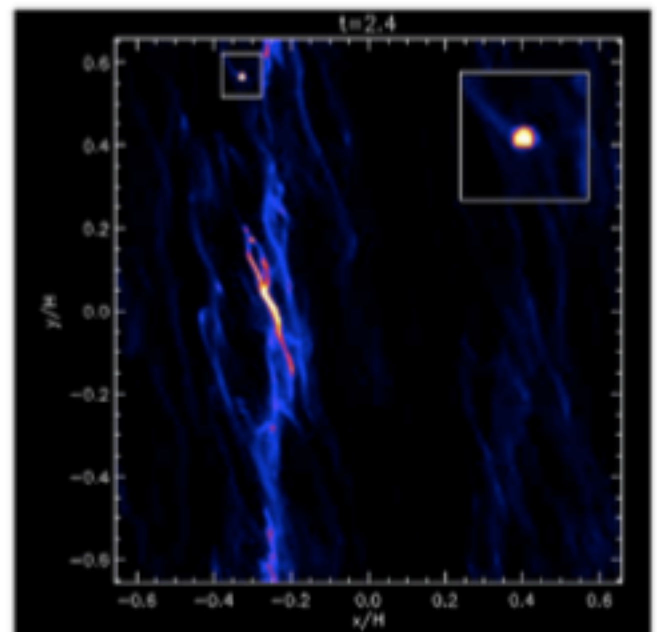


Malygin et al. (2017)

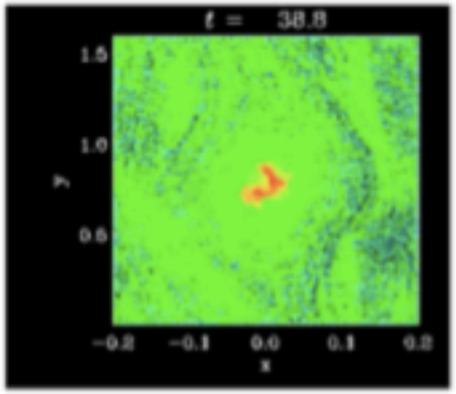
Conclusions

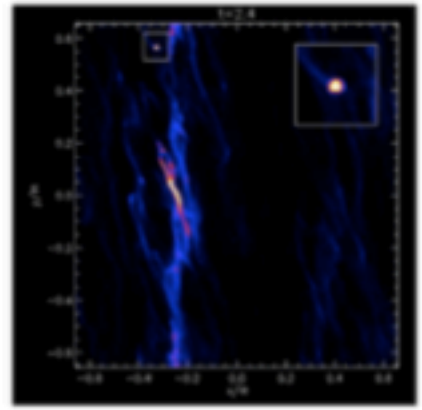
- Two modes of planet formation: Streaming Instability and Vortices
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortices do not survive magnetization
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- of our model predictions!!
- t?)



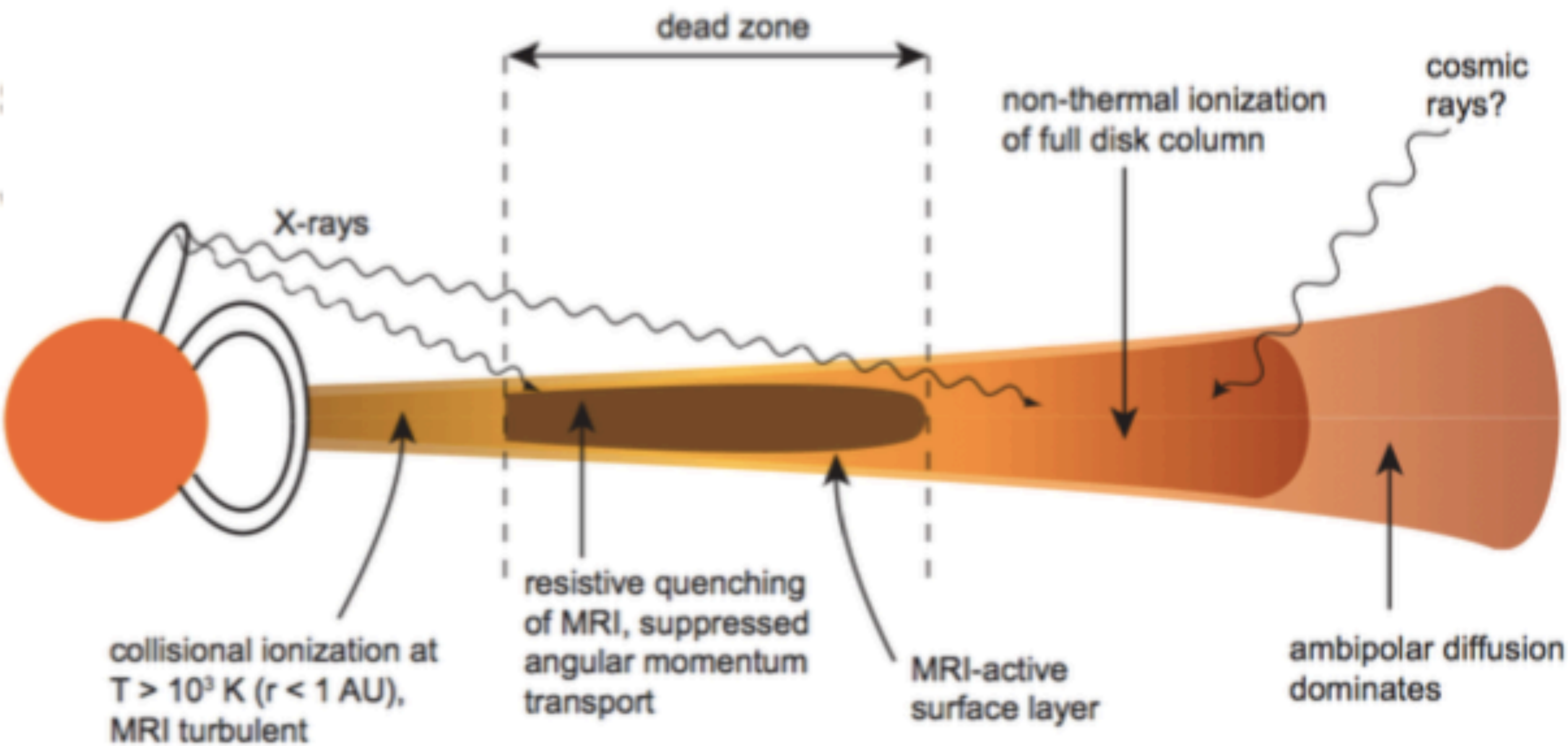


Conclusions





- Two mod … ces
- Two sust … ive Overstability
- Vortices …
- Vortex-assisted and streaming instability are complementary
- … s
- …
- … D desert?)

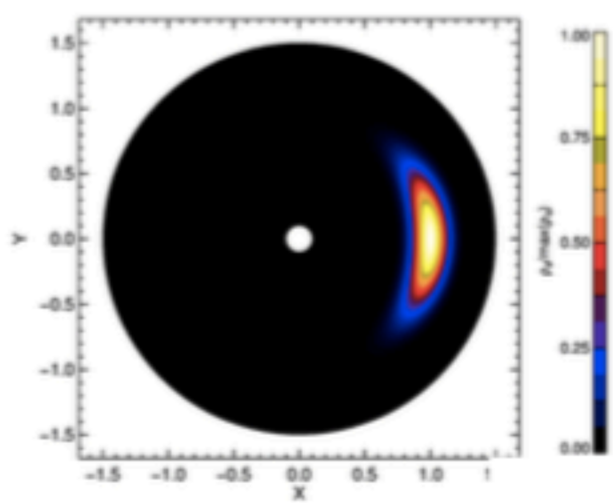


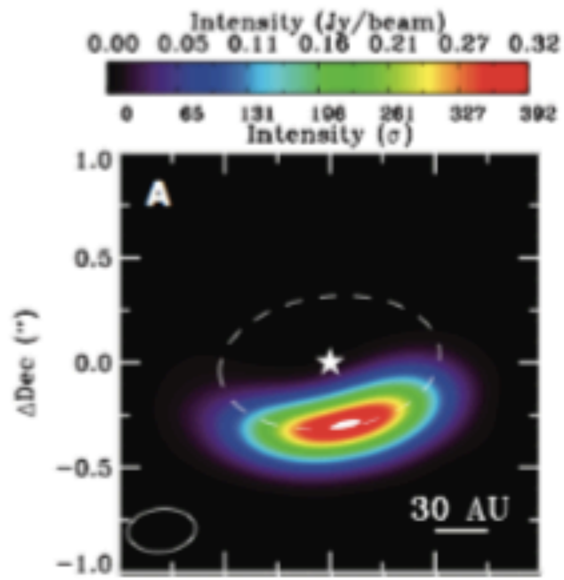
Conclusions

- Two modes of planet formation
- Two sustenance modes: Rossb
- Vortices do not survive magne
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Several candidates: RWI/COI/Planets
- Very hig ... es (BD desert?)

$$\rho_d(a,z) = \varepsilon \rho_0 (S+1)^{3/2} \exp\left\{ -\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1) \right\}$$

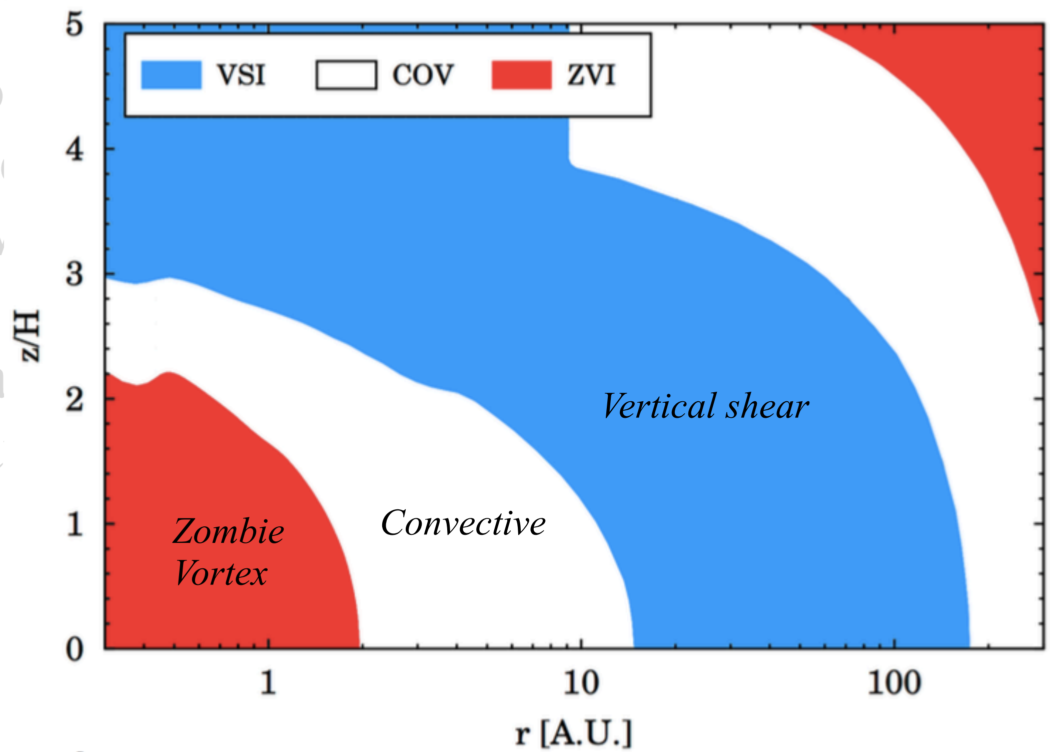
Lyra & Lin (2013)





Conclusions

- Disk vo ... ation
  - T
  - W



- Dust tra ... ns the observa

- Possible origin: Thermal instabilities in MRI-dead zone
  - Vertical Shear Instability
    - *Vertical violation of Solberg-Hoiland criterion*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyancy*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy frequency*