Evolution of Circumstellar Disks and Planet Formation

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California State University Northridge (CSUN)

Jet Propulsion Laboratory

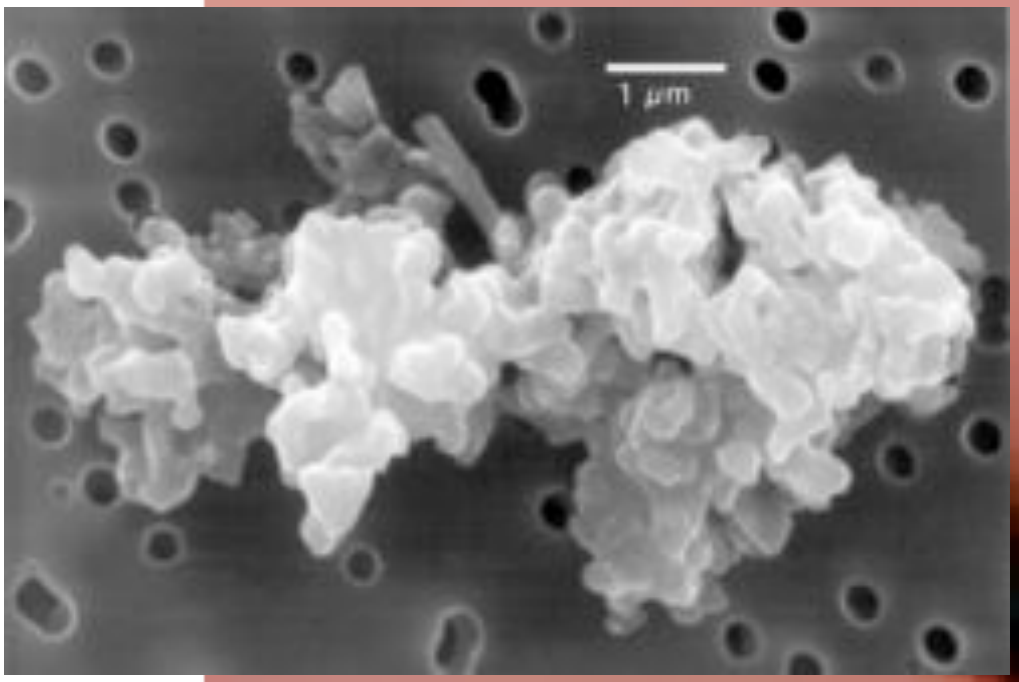
Collaborators

Aaron Boley (Vancouver), Axel Brandenburg (Stockholm), Kees Dullemond (Heidelberg), Mario Flock (JPL), Anders Johansen (Lund), Tobias Heinemann (KITP), Hubert Klahr (Heidelberg), Min-Kai Lin (ASU), Mordecai-Mark Mac Low (AMNH), Colin McNally (Copenhagen), Krzysztof Mizerski (Warsaw), Satoshi Okuzumi (JPL), Sijme-Jan Paardekooper (London), Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), Alex Richert (PSU), Neal Turner (JPL), Miguel de Val-Borro (Princeton), Andras Zsom (MIT).

San Francisco State University, Oct 31st, 2016

Outline

- Observational constraints
- Planet Formation
  - The need for turbulence
    - Active and dead zones
    - Magneto-rotational instability
    - Convective Overstability
- Active/dead boundary
  - Rossby wave instability
- Vortex-trapping mode of planet formation


1 µm

Protoplanetary Disks



PP disk fact sheet

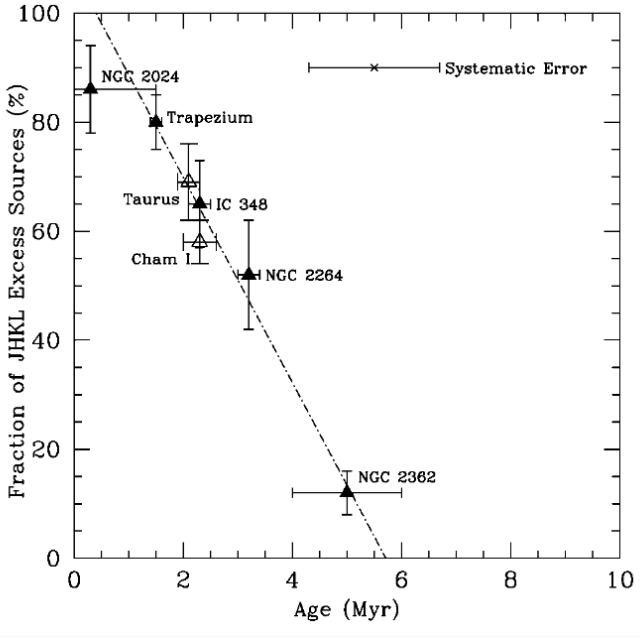
Density: 10^{13} – 10^{15} cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

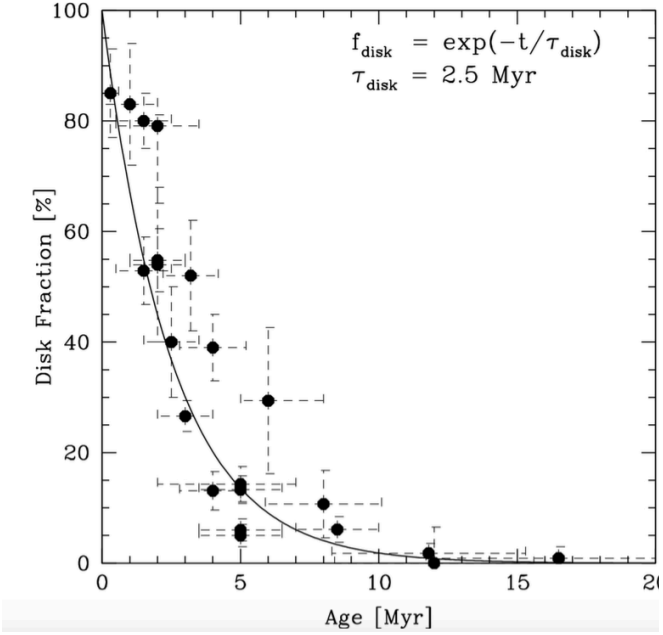
Scale: 0.1-100AU
(1 AU = 1.49 x 10^{13} cm)

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

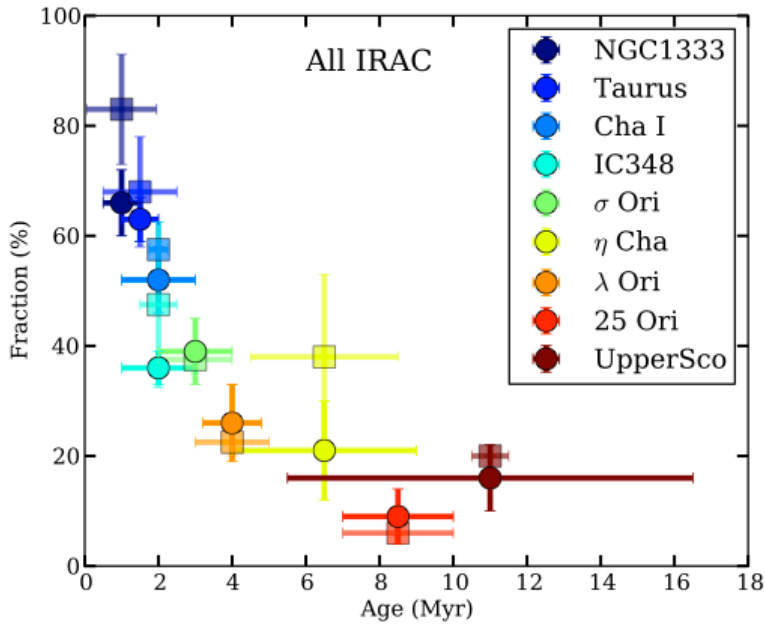
Disk lifetime



(Haisch et al. 2001)

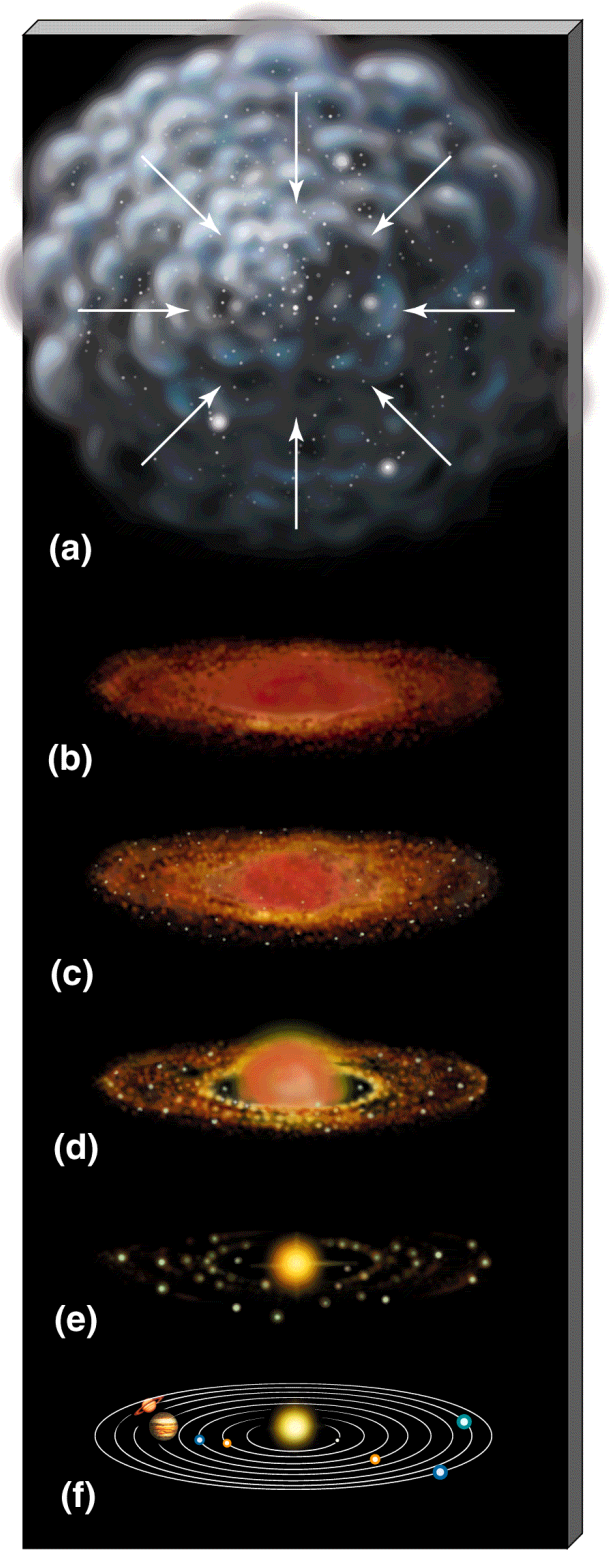


(Mamajek et al. 2009)



(Ribas et al. 2014)

Disks dissipate with an e-folding time of 2.5 Myr



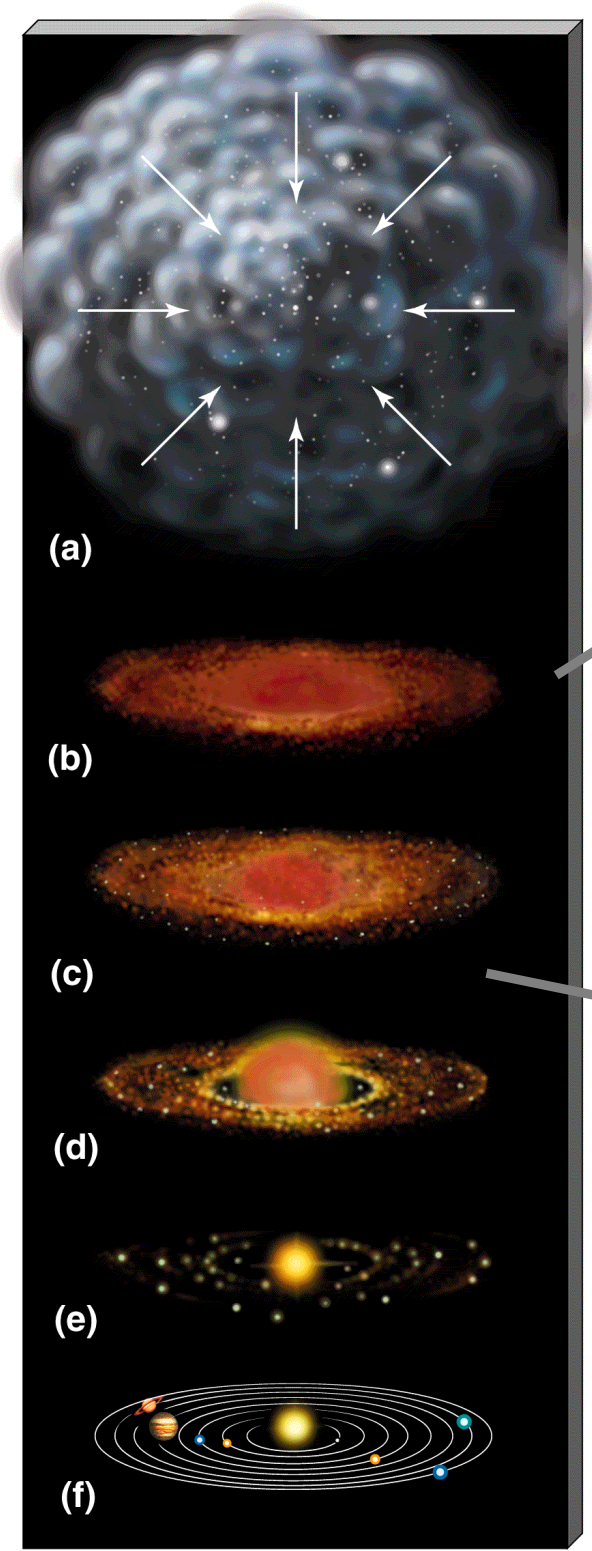
Planet Formation

Gas-rich phase (< 10 Myr)

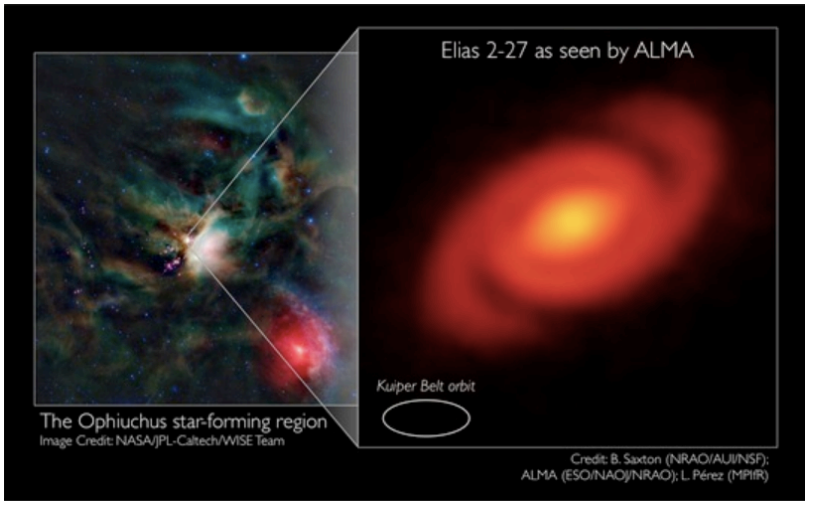
Primordial Disks

Gas-poor phase (>10 Myr)

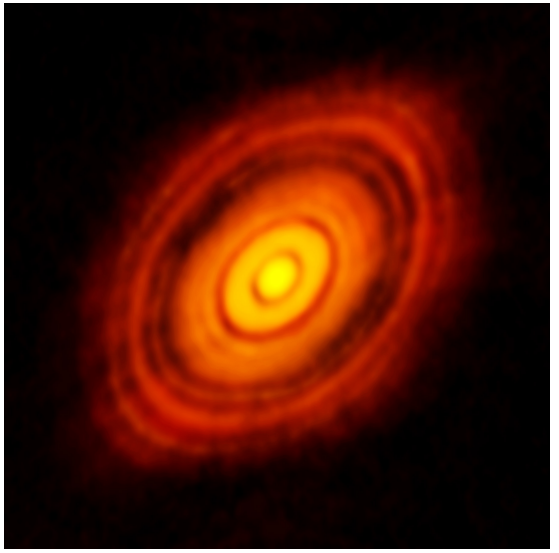
Debris Disks



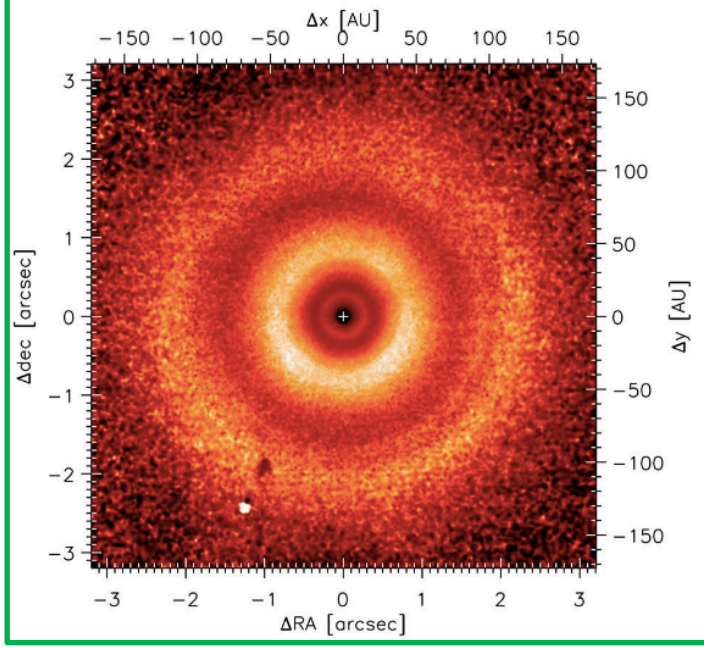
Elias 2-27



HL Tau



TW Hya





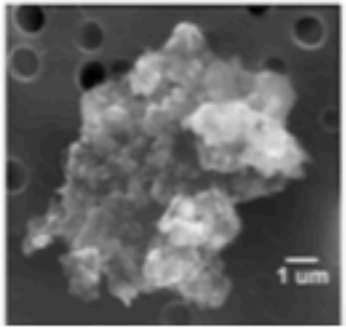
Planet Formation

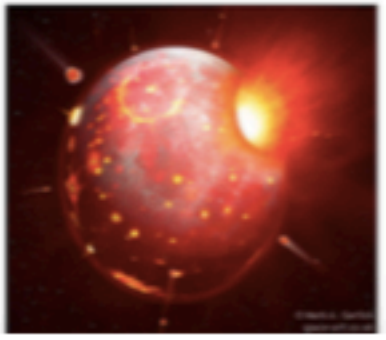
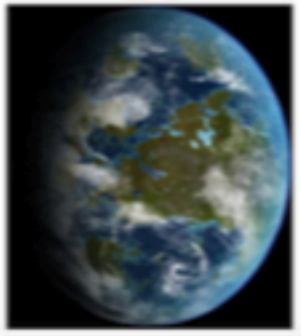
Planetesimal Hypothesis (Safronov 1969)

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

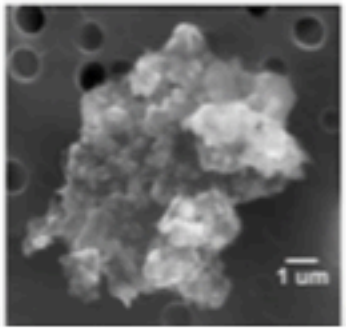
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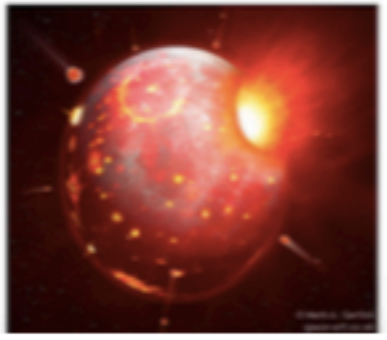
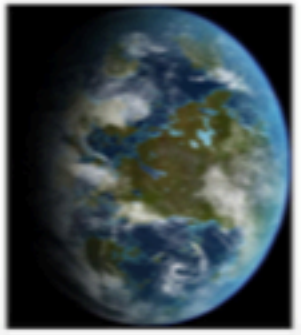
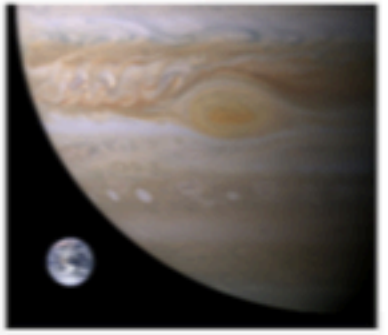
From dust to peebles
μm -> cm : hit-and-stick by van der Walls

From pebbles to planetesimals
Here be dragons....

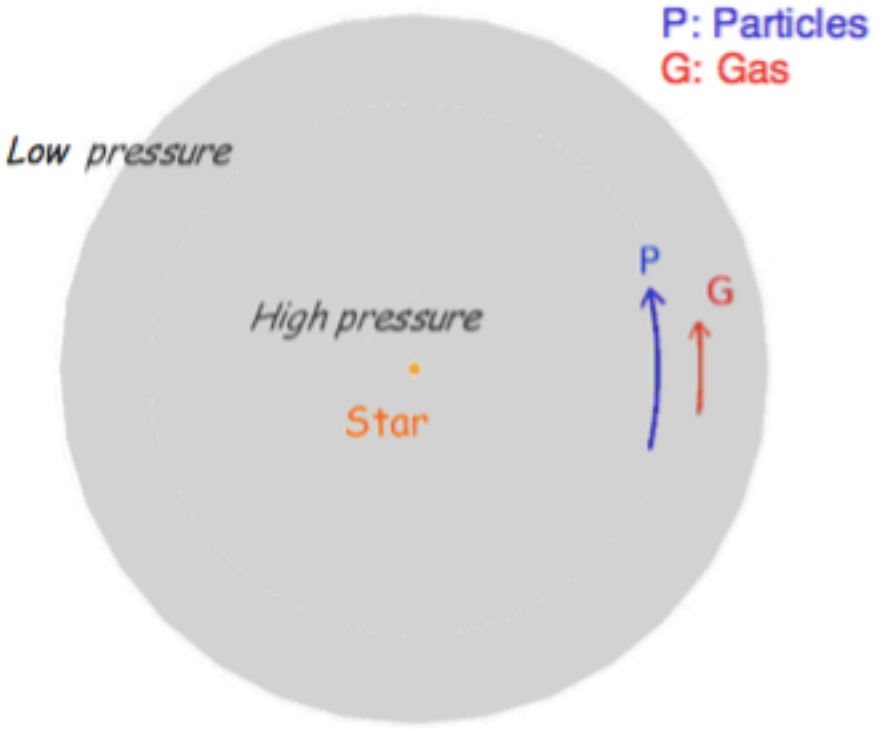
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From planetary embryos to planets
Rocky planets: binary collisions
Gas giants: Attract gaseous envelope

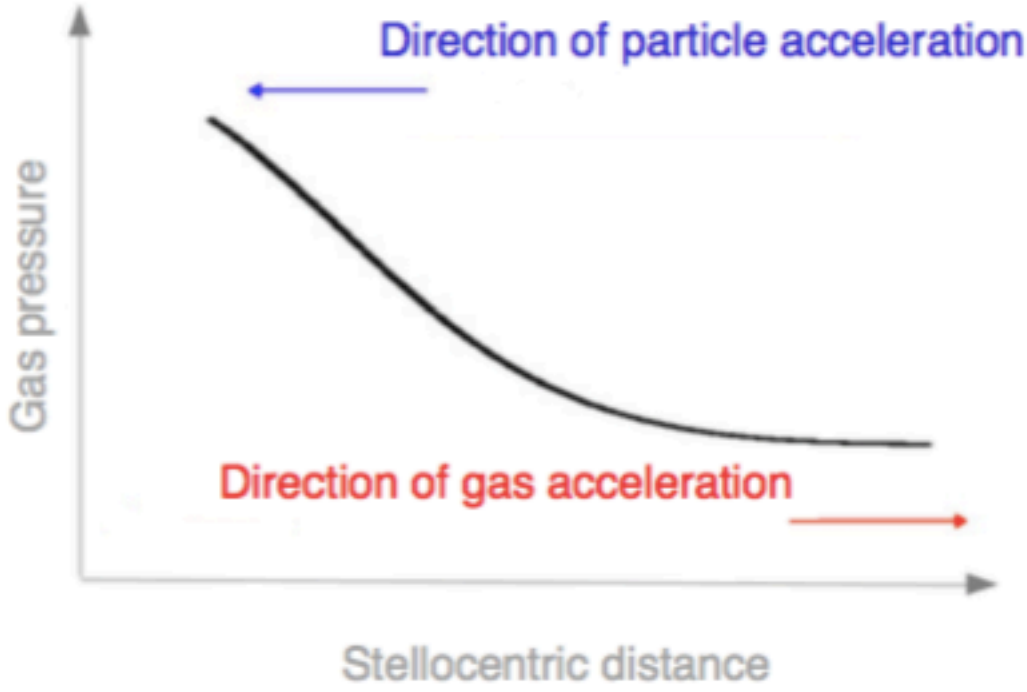


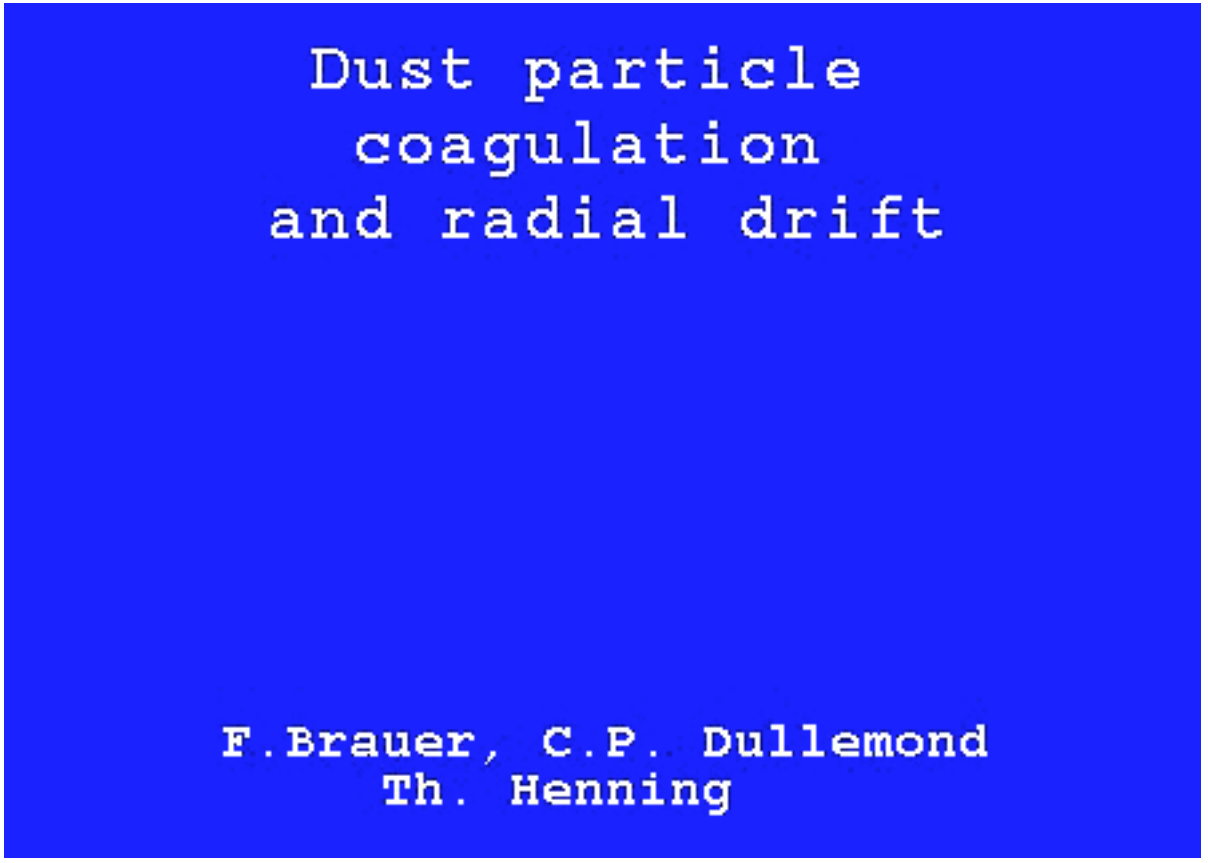
Particle drift



Adapted from Whipple (1972)



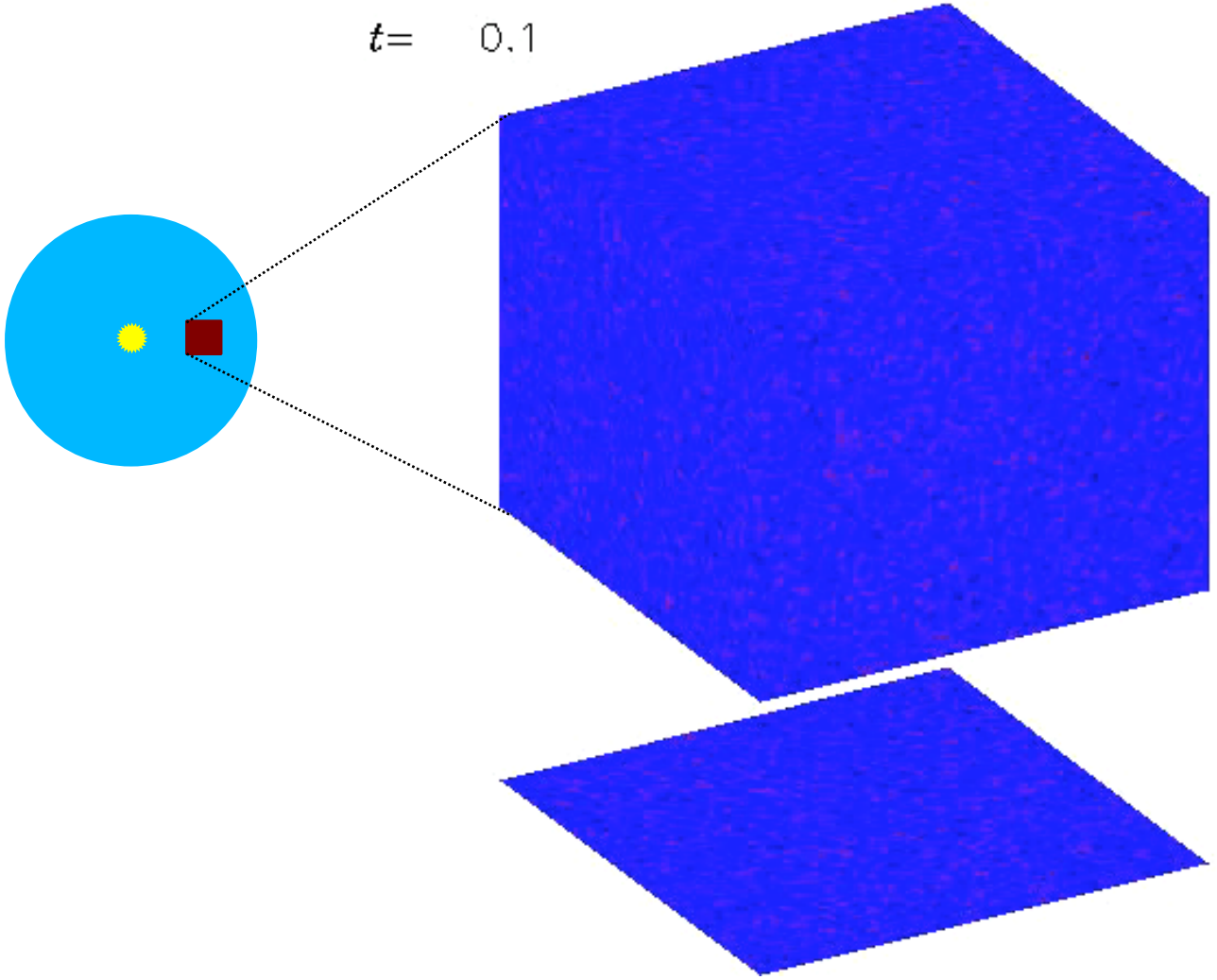
Particle Coagulation and drift



Brauer et al. (2008)

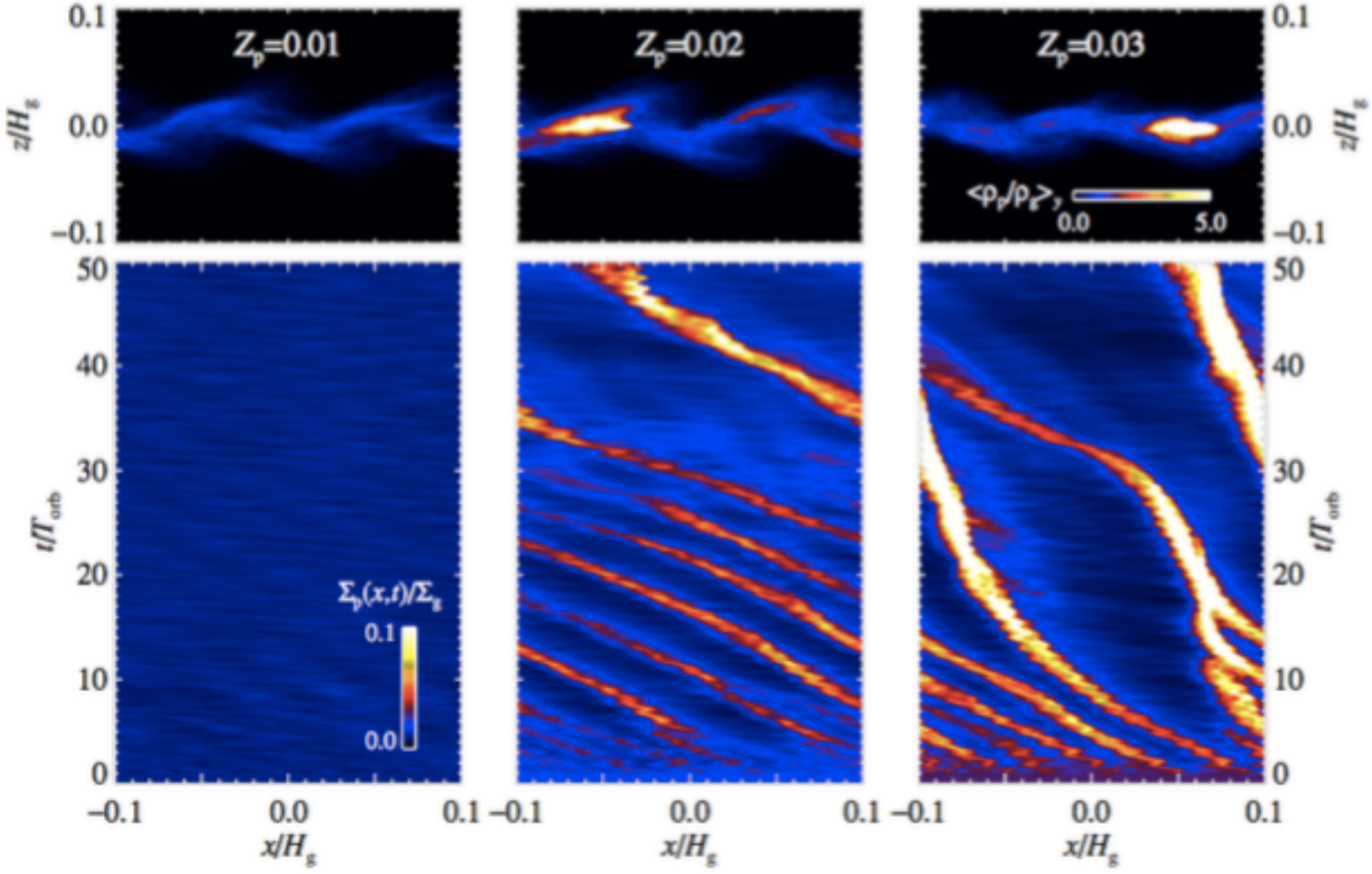
Streaming Instability

The particle drift is linearly unstable



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

Streaming Instability does not "work" for solar metallicity

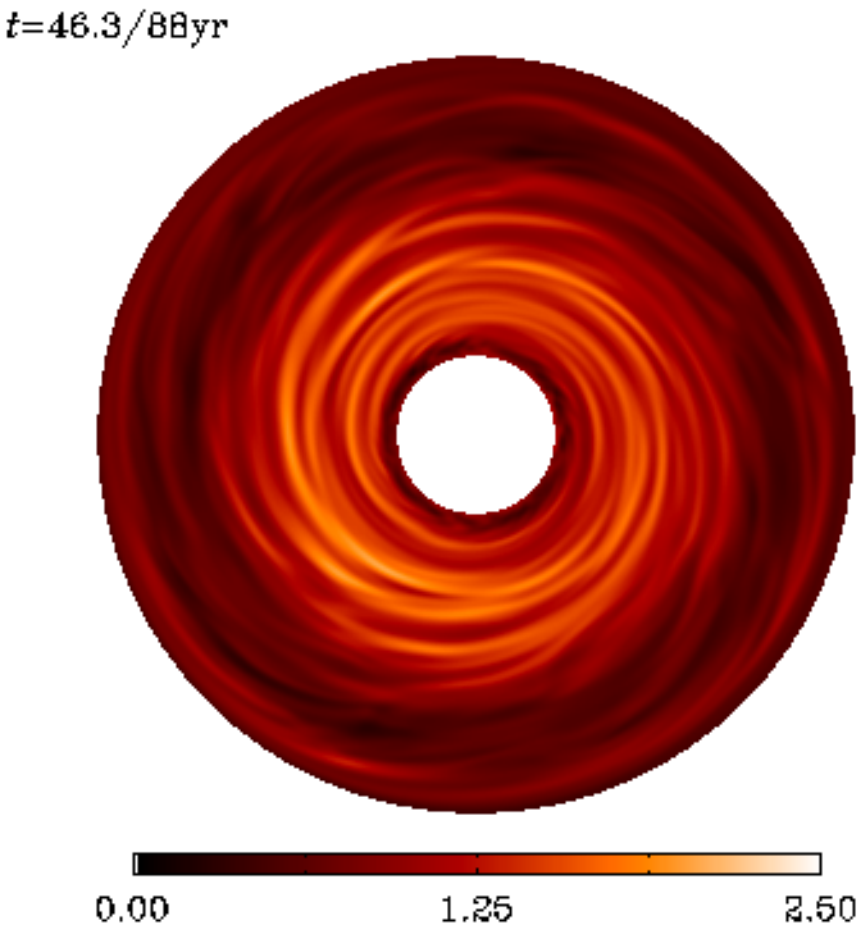


Johansen et al. (2011)

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

Magneto-Rotational Instability

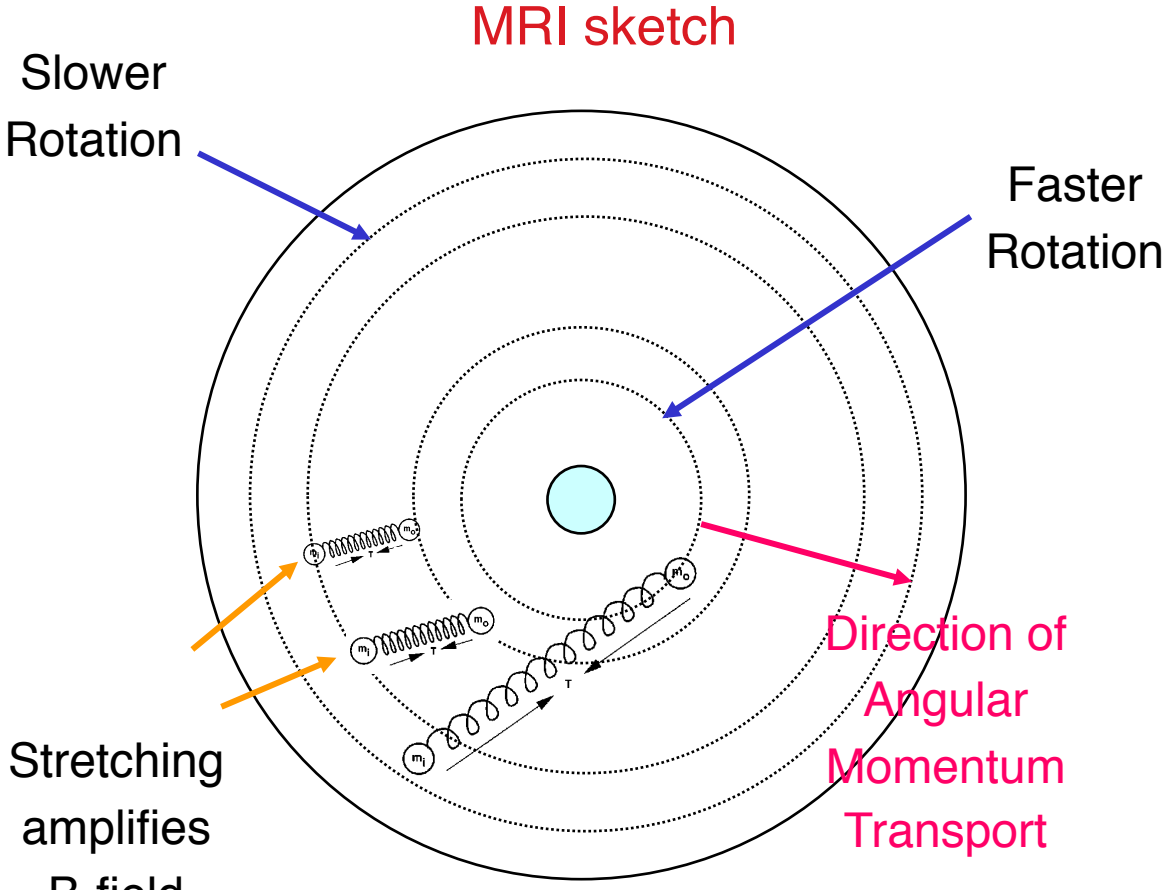
Turbulence in disks is enabled by the
Magneto-Rotational Instability (Balbus & Hawley, 1991)



Magnetized disk

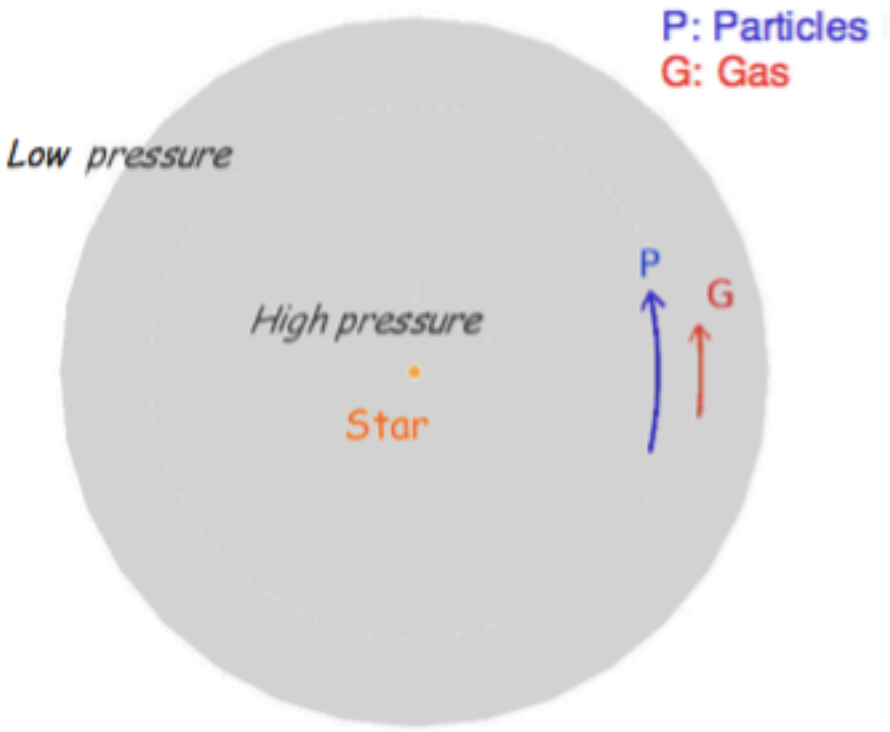
Lyra et al. (2008a)

MRI sketch

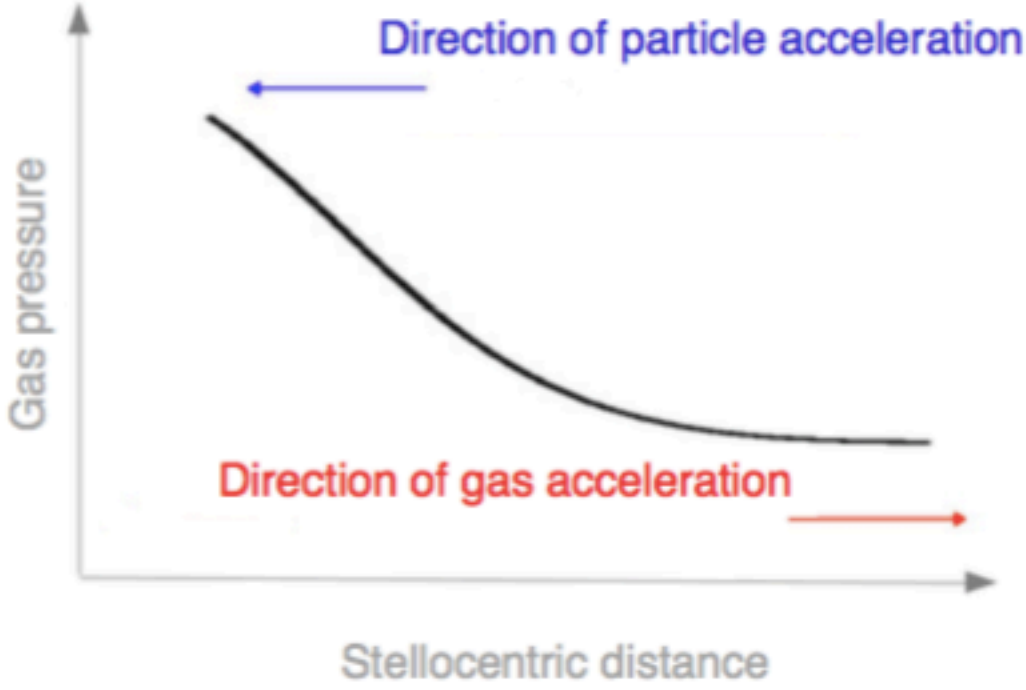


Unstable if angular velocity decreases outward

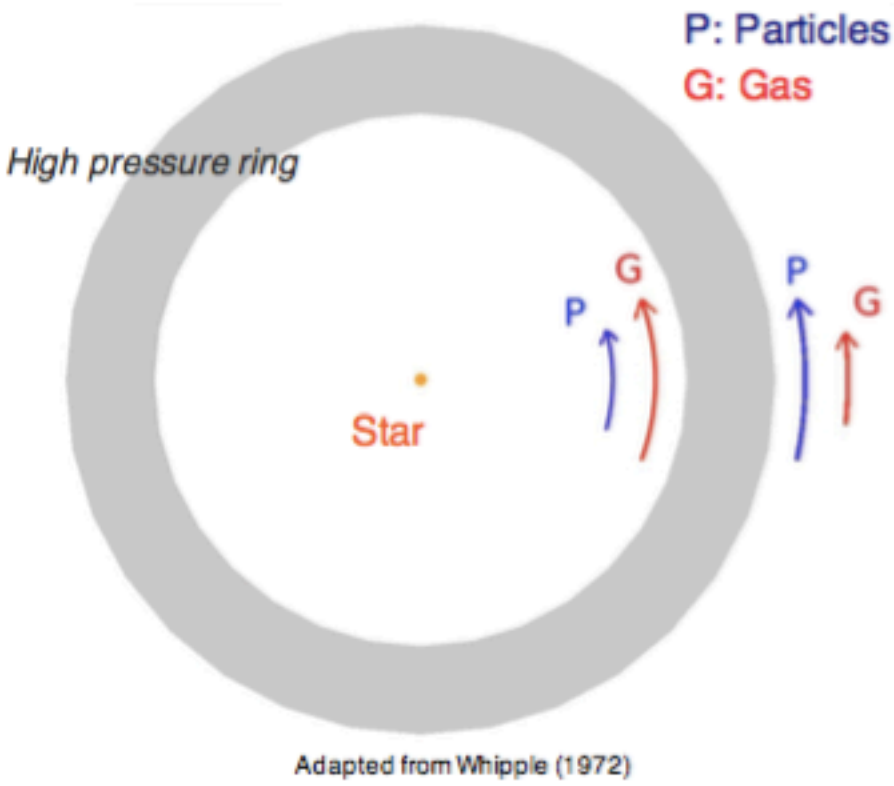
Particle drift

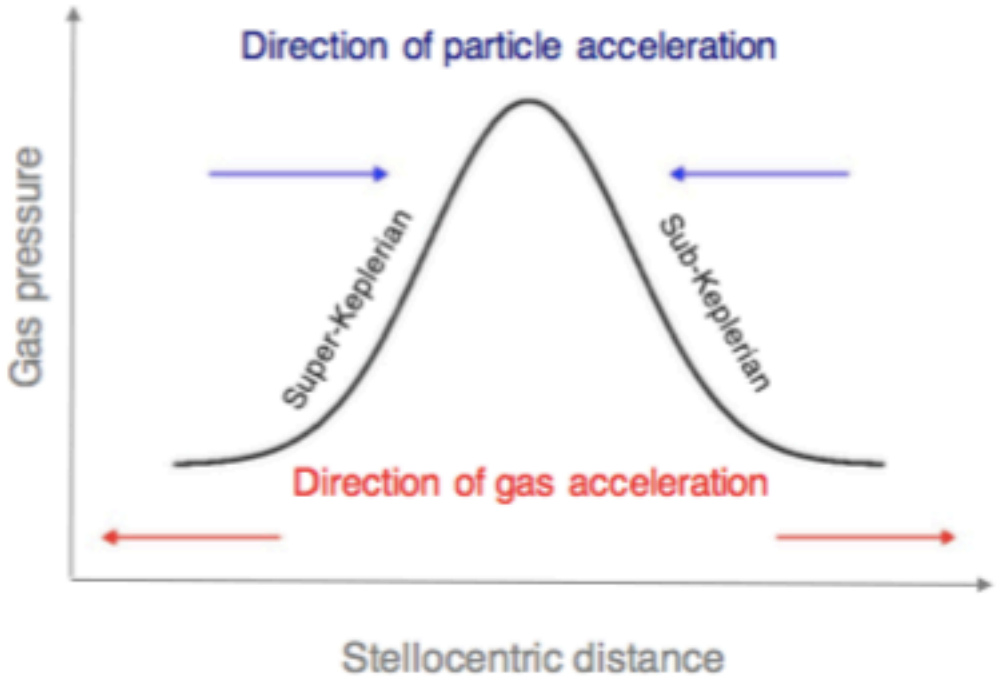


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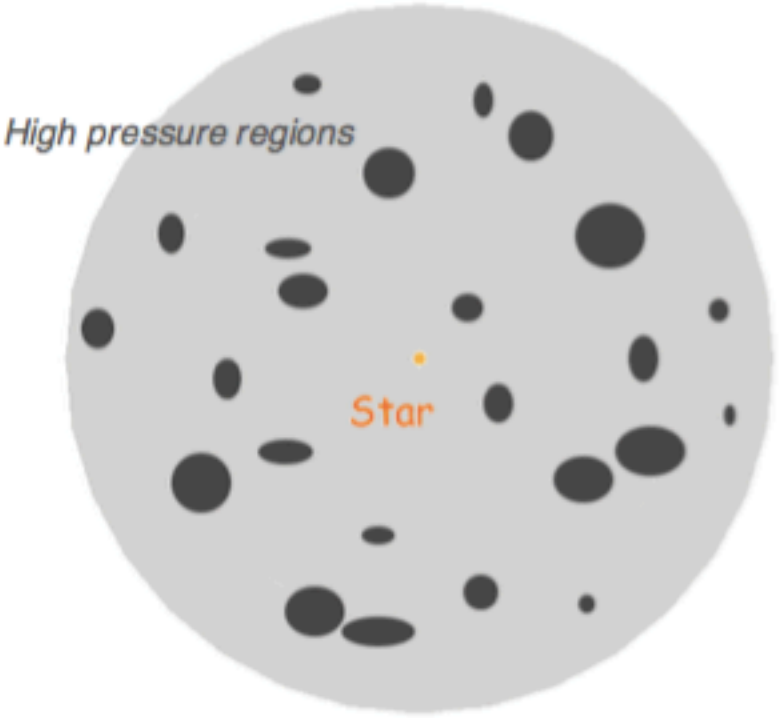


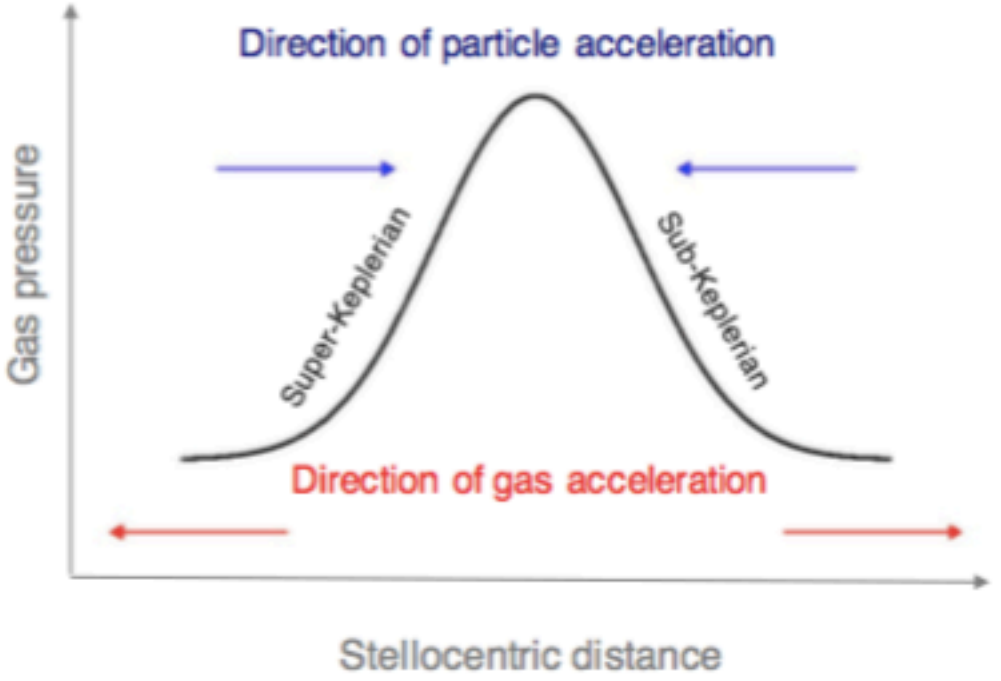
Pressure Trap



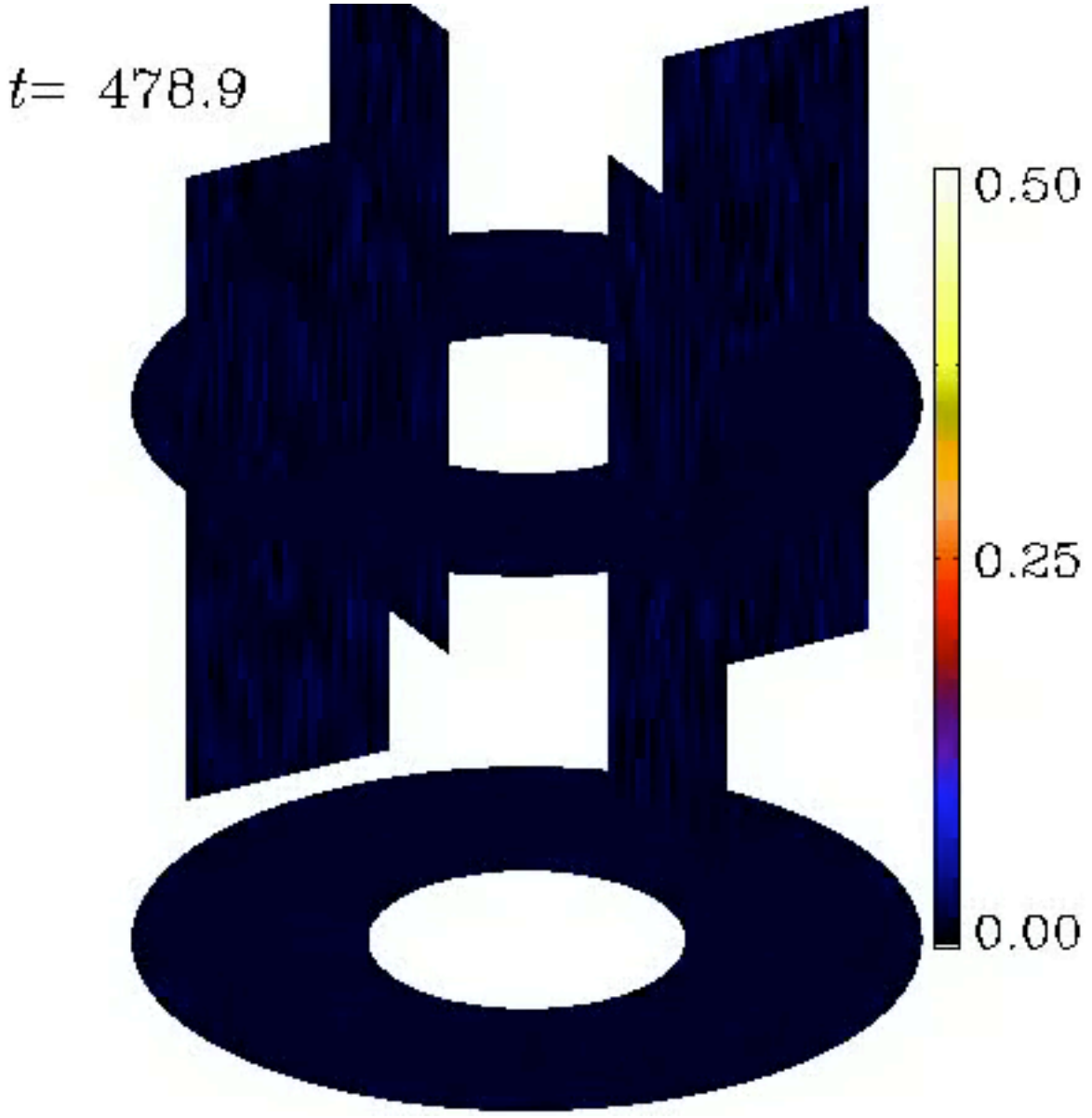


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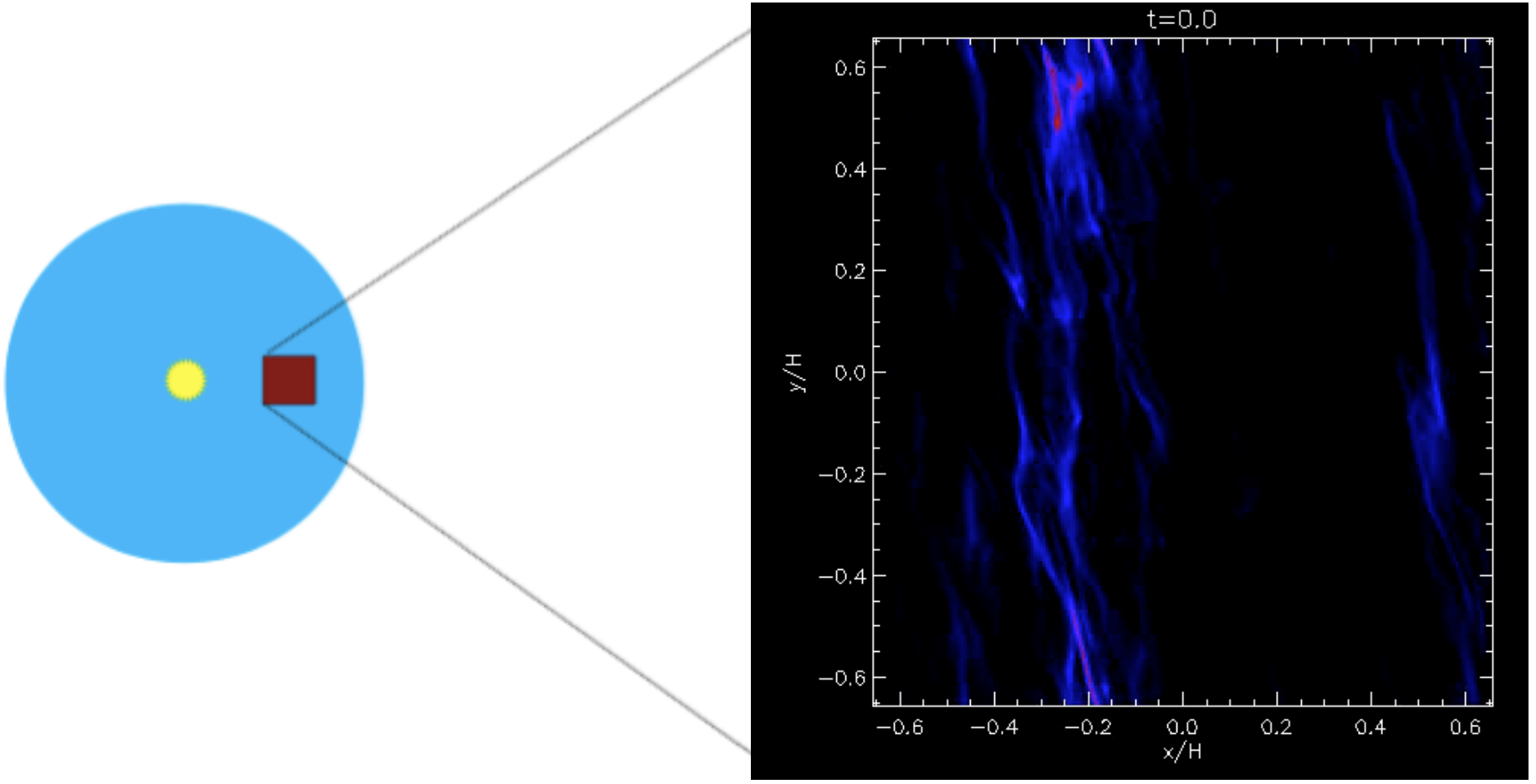


Turbulence concentrates solids mechanically in pressure maxima



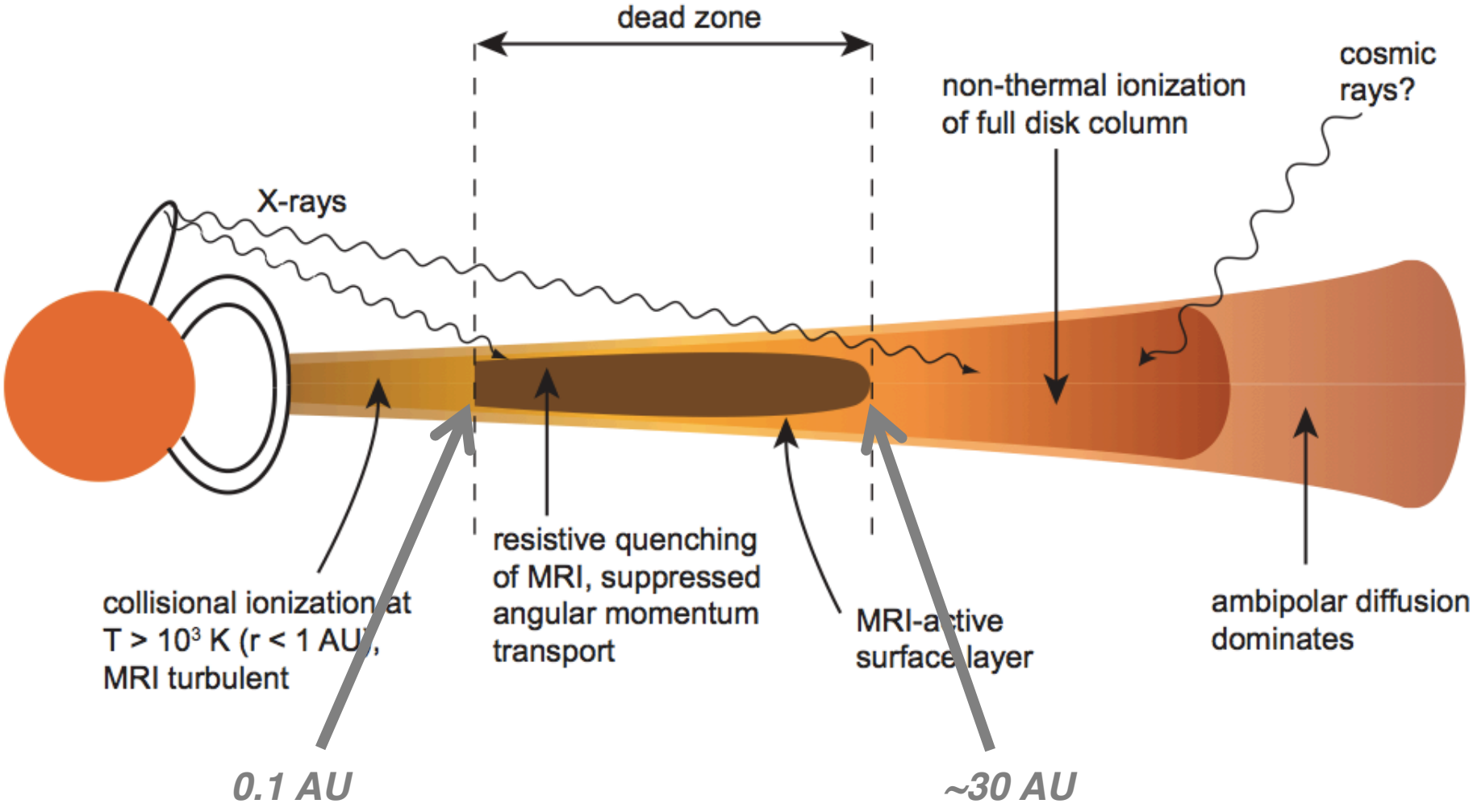
Lyra et al. (2008a)

Gravitational collapse into planetesimals

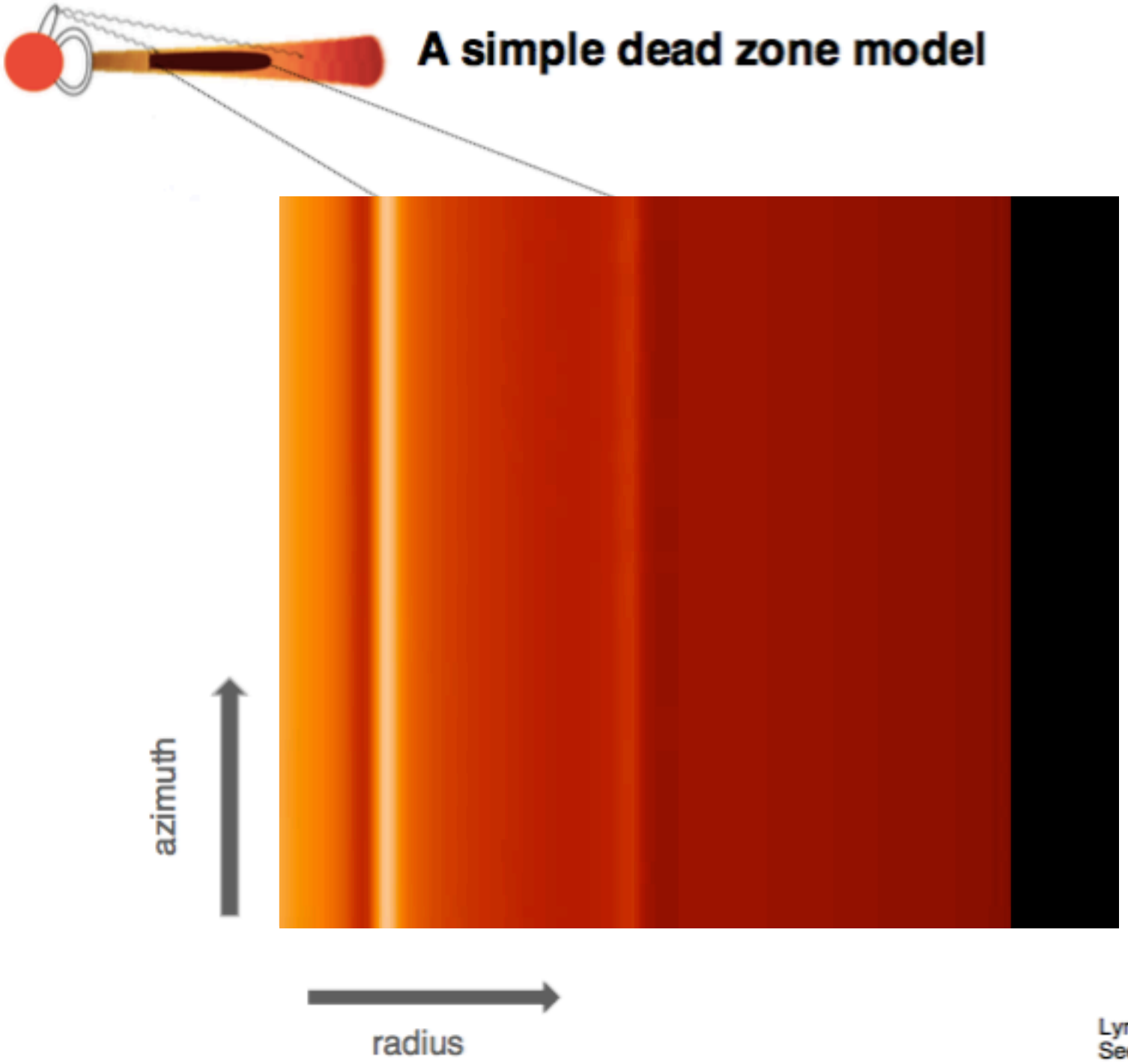


Johansen et al. (2007)

Dead zones


dead zone
cosmic rays?
non-thermal ionization of full disk column
X-rays
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent
resistive quenching of MRI, suppressed angular momentum transport
MRI-active surface layer
ambipolar diffusion dominates
0.1 AU
~30 AU

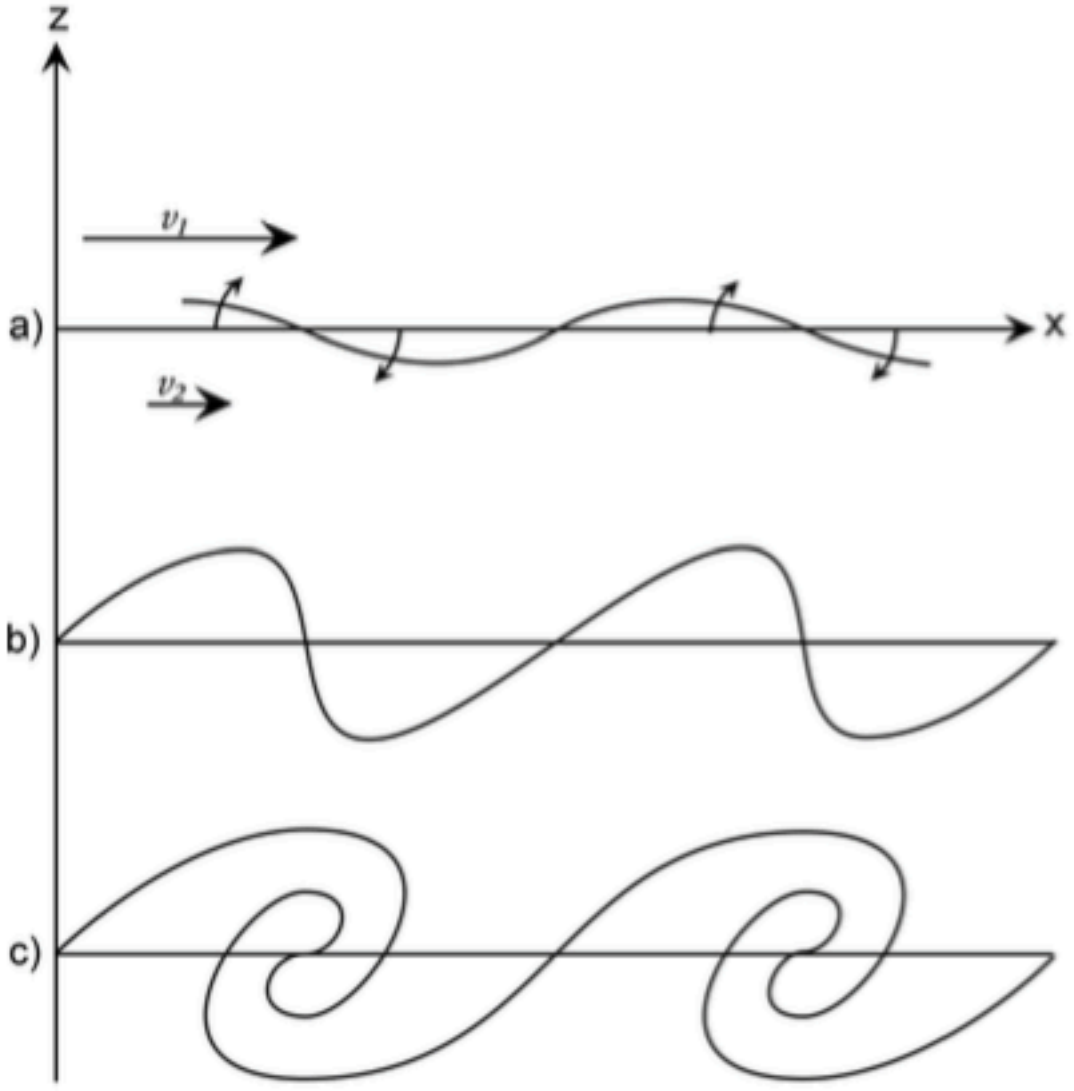
A simple dead zone model



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

Rossby wave instability

(or… Kelvin-Helmholtz in differentially rotating disks)











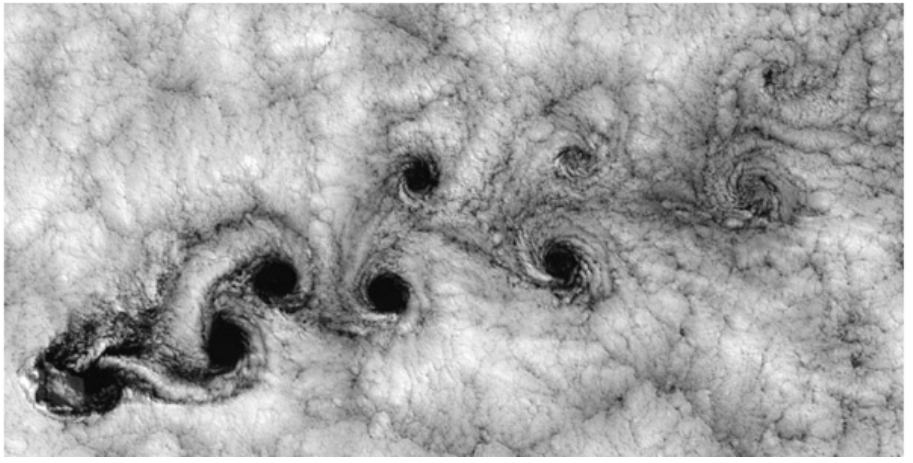
Vortices – an ubiquitous fluid mechanics phenomenon











Vortices – an ubiquitous fluid mechanics phenomenon

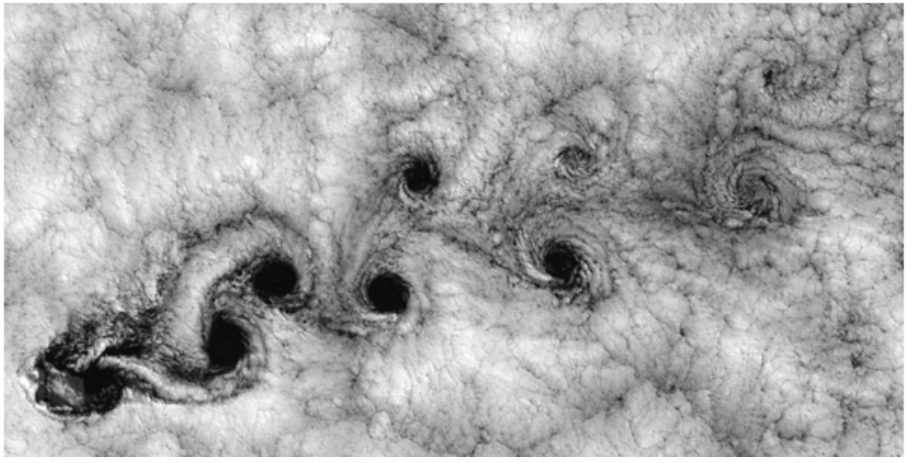






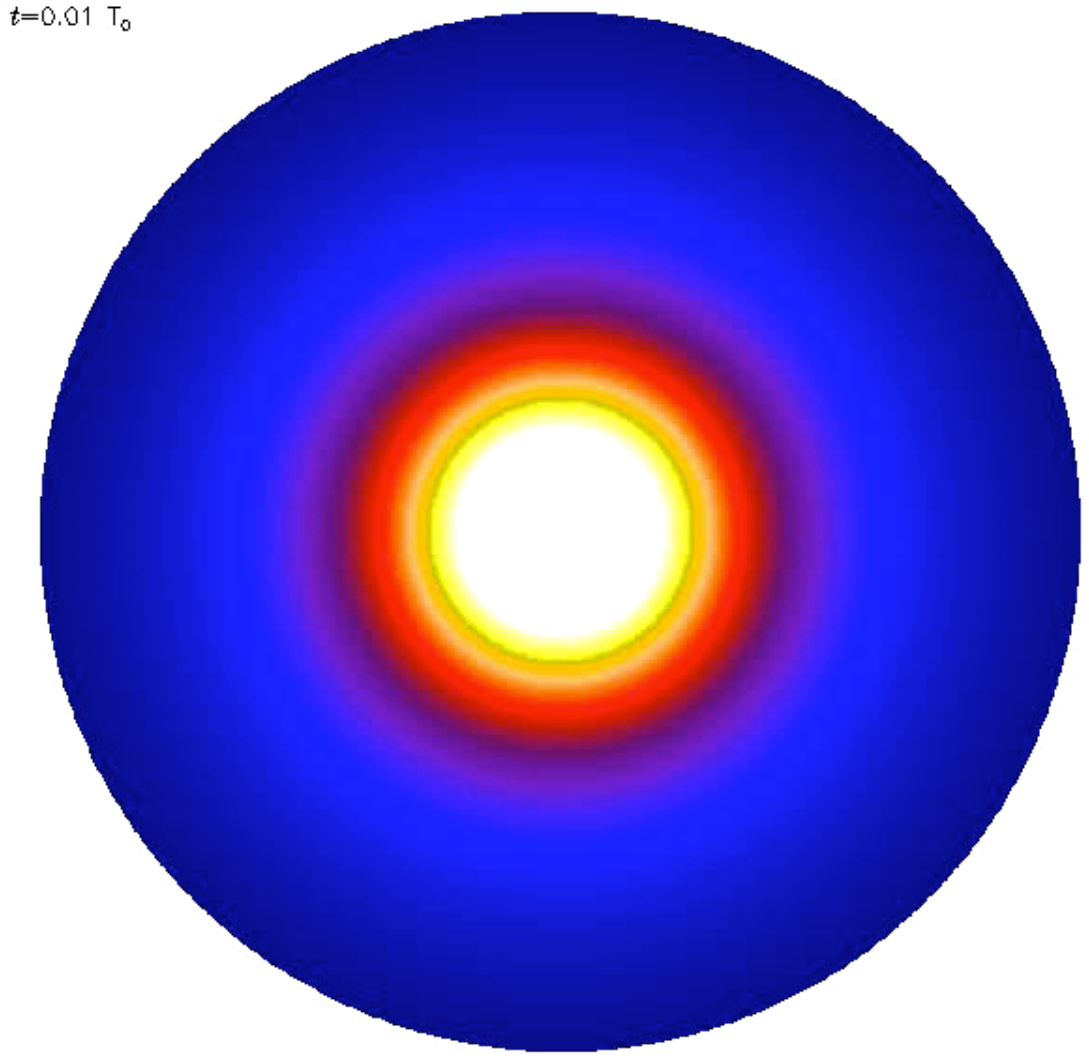
Von Kármán *vortex street*







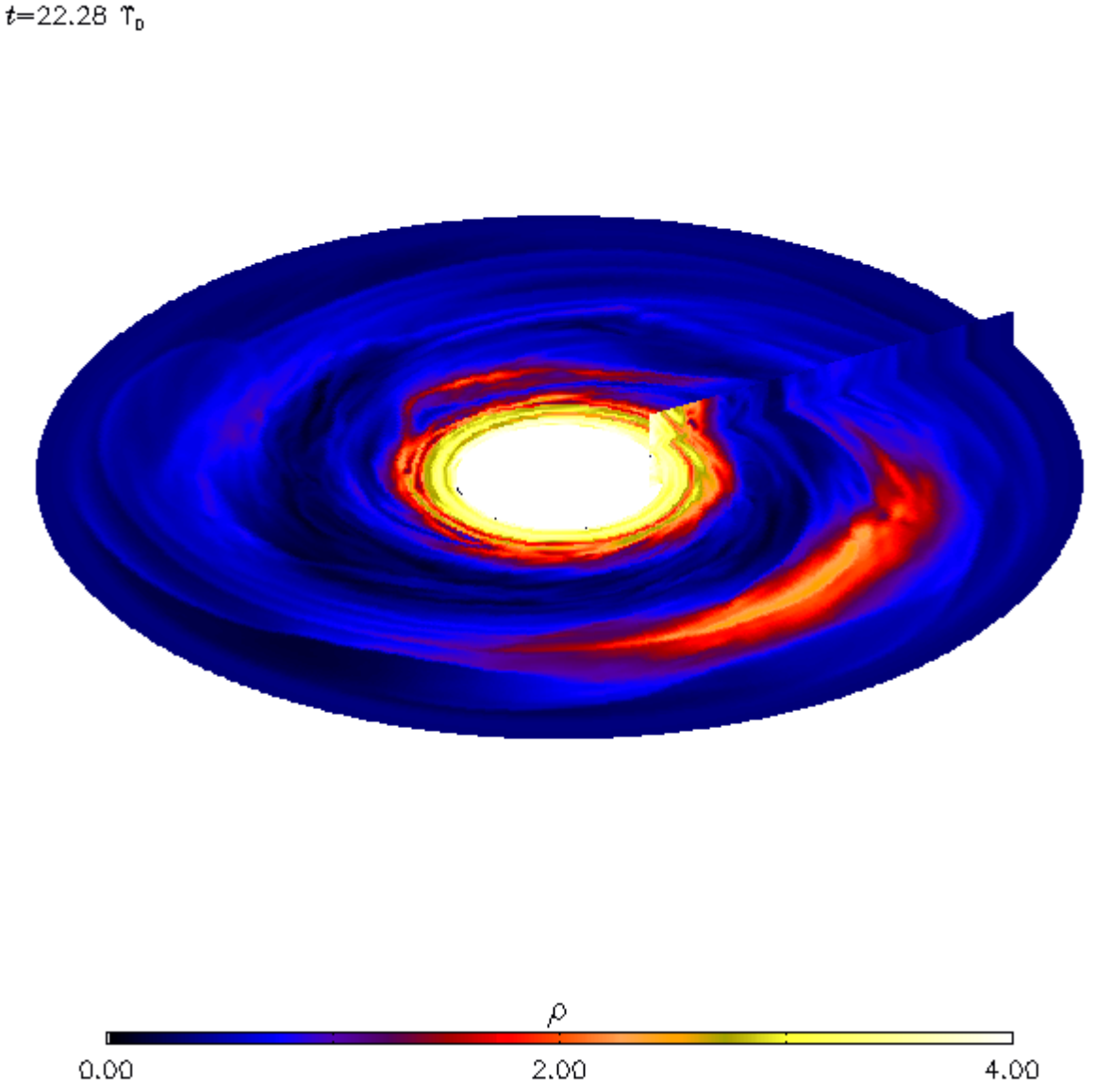
Inner (0.1 AU) active/dead zone boundary

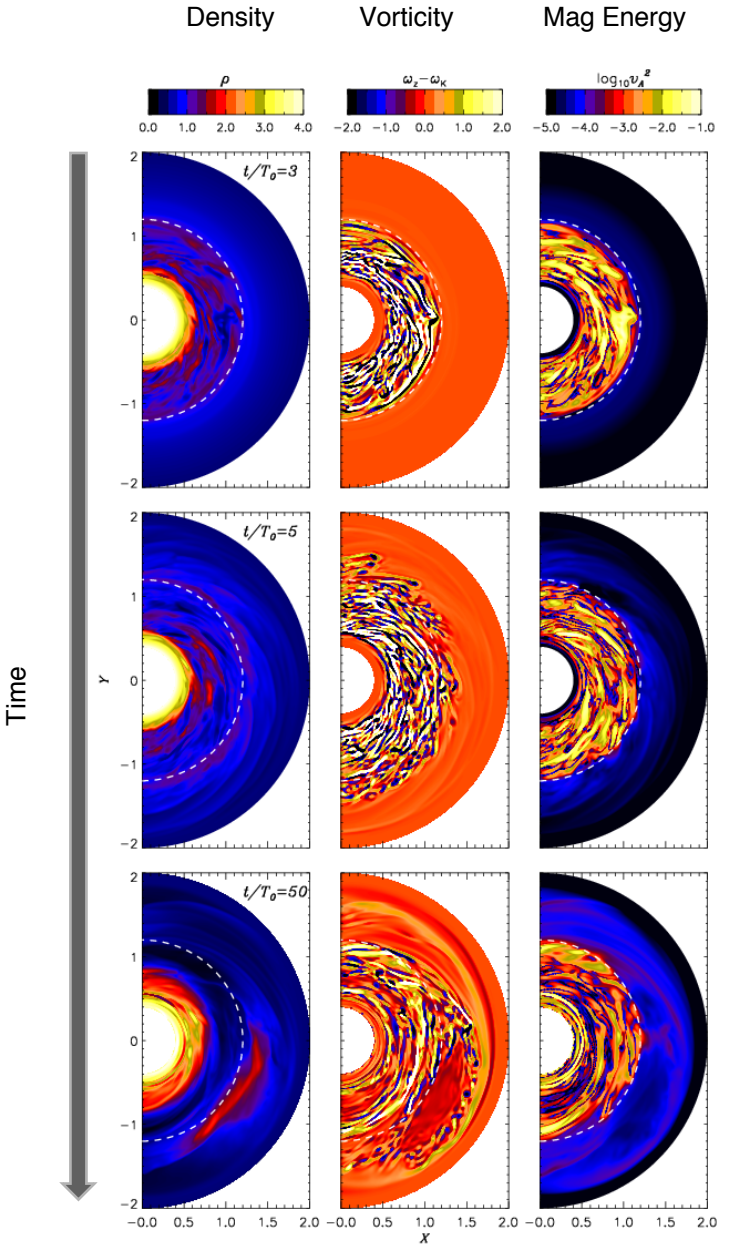


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Inner (0.1AU) active/dead zone boundary





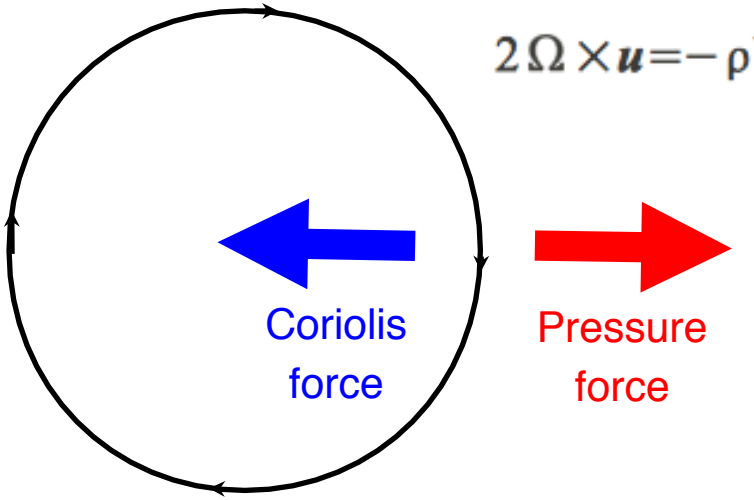
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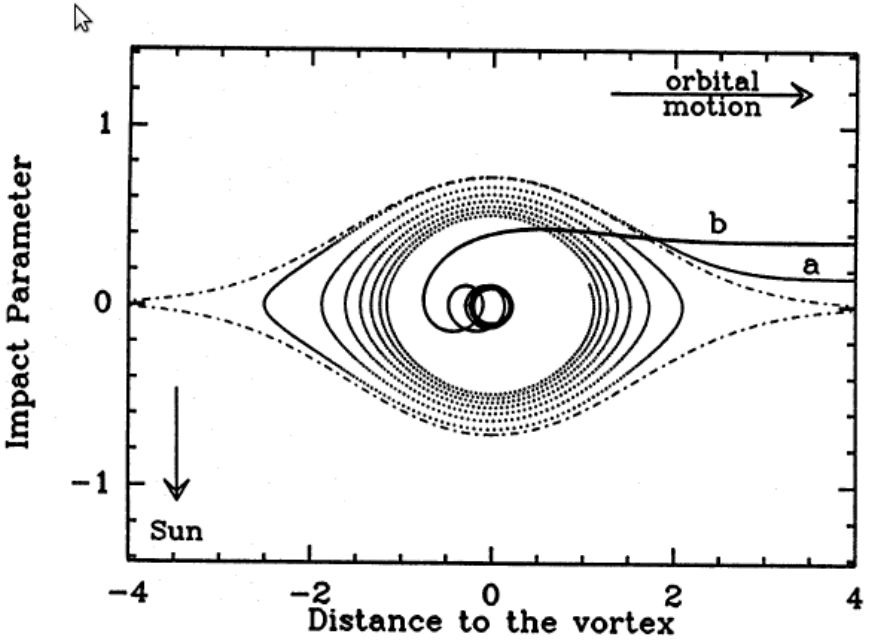
The Tea-Leaf effect

Geostrophic balance:

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



Vortex
streamline



Barge & Sommeria (1995)

Particles 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)

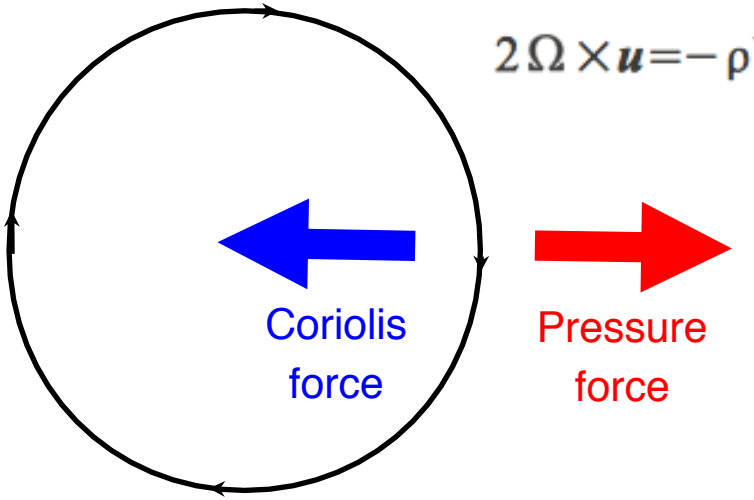
Speed up planet formation enormously

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

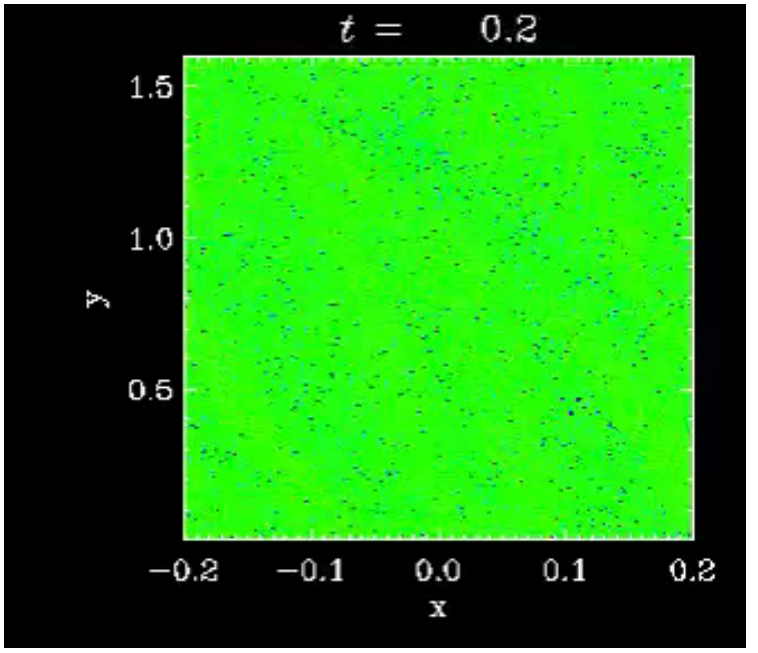
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Vortex
streamline



Raettig, Lyra, & Klahr (2013)

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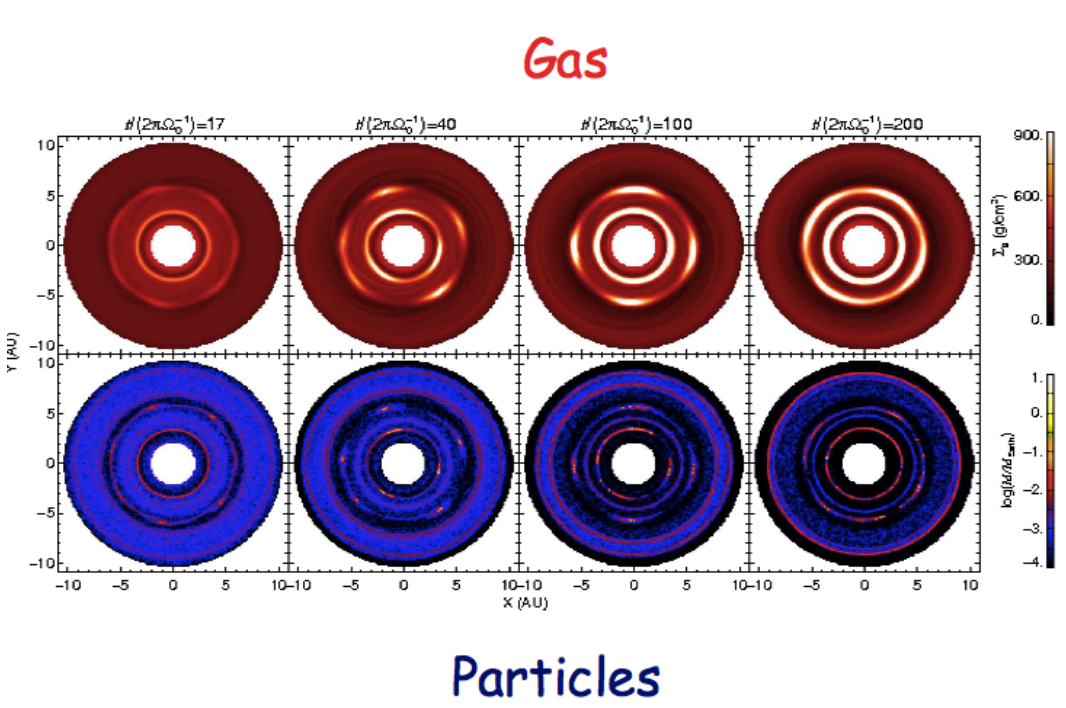
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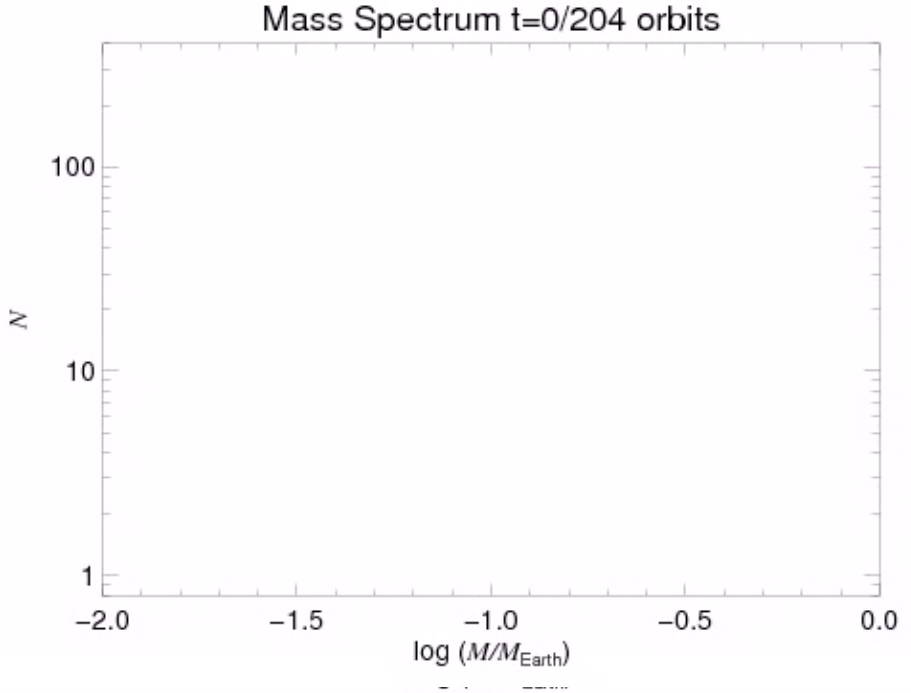
(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

Speed up planet formation enormously

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Vortices and Planet Formation

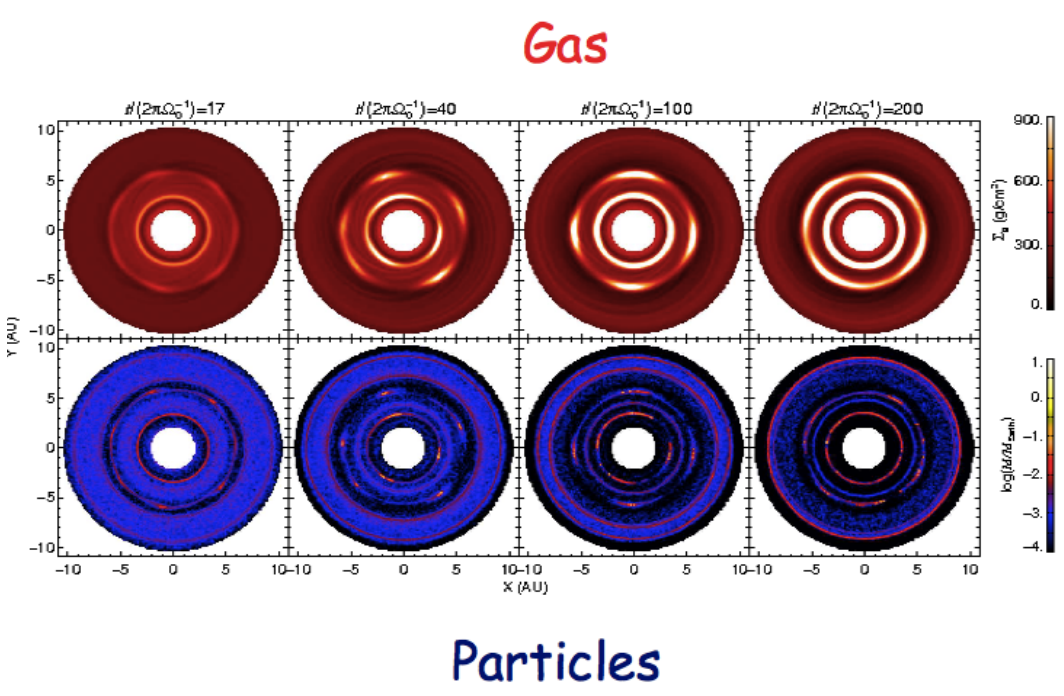


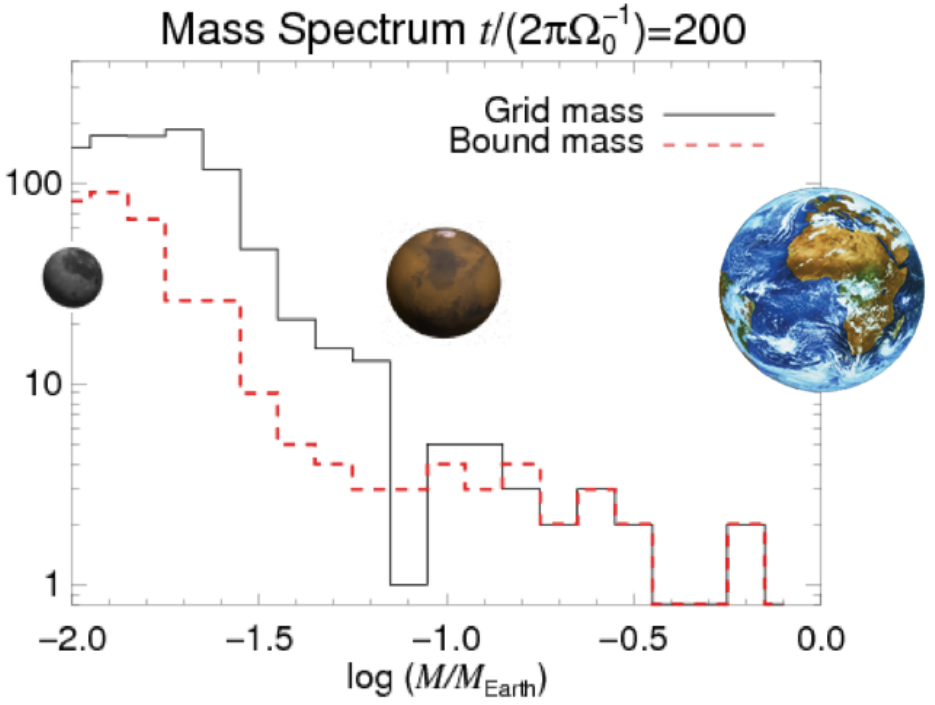


Collapse into Mars mass objects

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

Vortices and Planet Formation

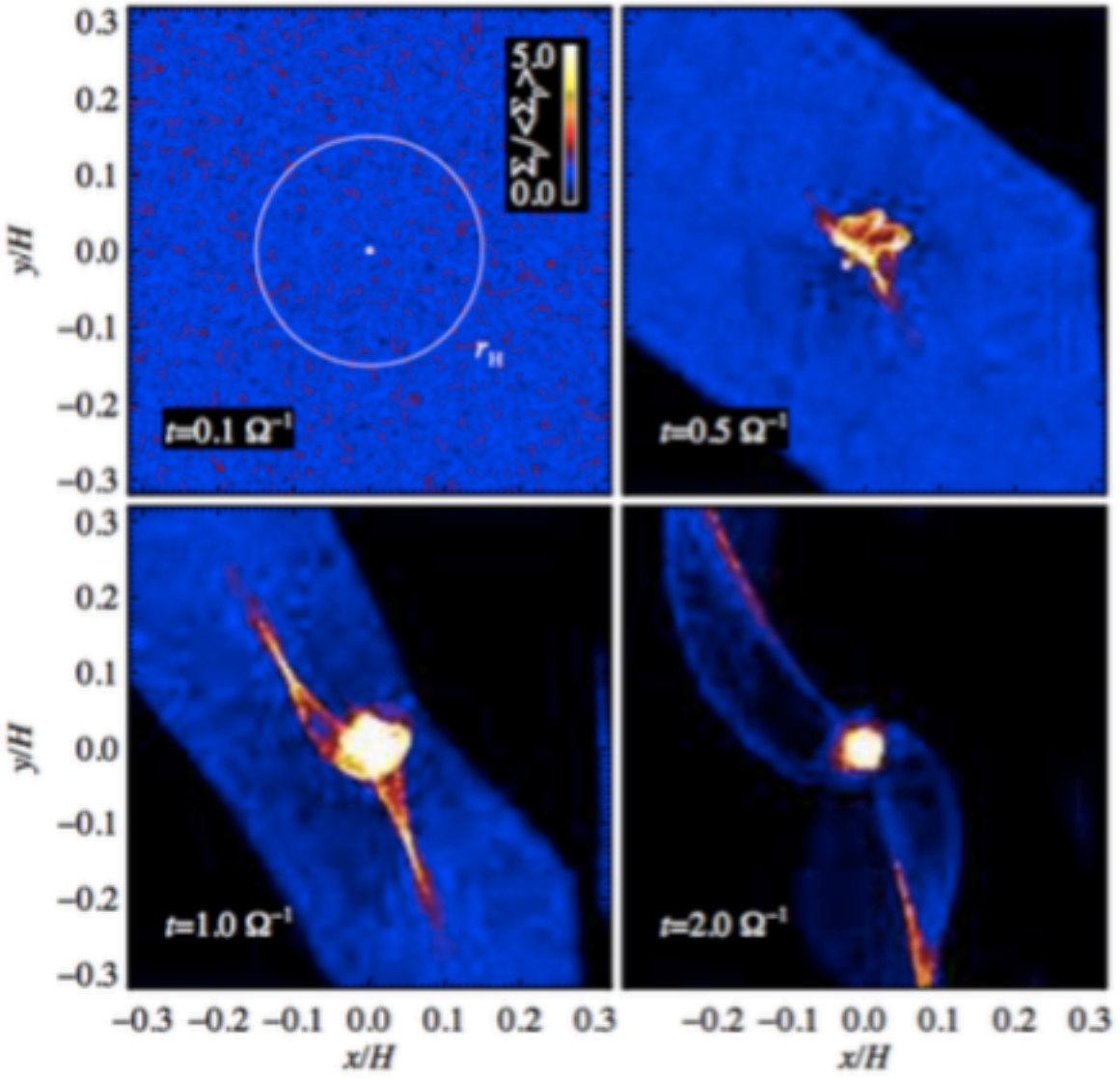




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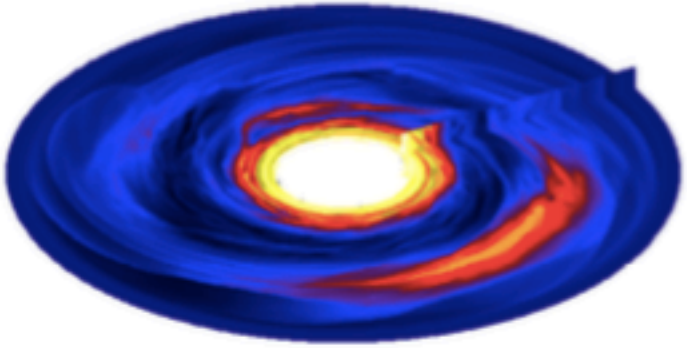
Gas drag makes the motion dissipative.
Enhances accretional radius.



Lambrechts & Johansen (2012)

Sustaining vortices in disks

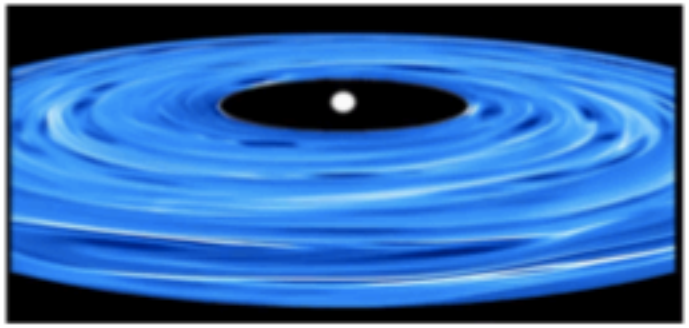
Rossby wave instability



Lovelace & Hohlfeld (1978), Toomre (1981), Papaloizou & Pringle (1984, 1985), Hawley et al. (1987), Lovelace et al. (1999), Li et al. (2000,2011), Tagger (2001), Varniere & Tagger (2006), de Val-Borro et al. (2007), Lyra et al. (2008b,2009ab), Mehuet et al. (2010, 2012abc), Lin & Papaloizou (2011ab, 2012), Lyra & Mac Low (2012), Regaly et al. (2012, 2013), Lin (2012ab, 2013), Ataiee et al. (2013, 2014), Lyra et al. (2014)

Powered by:
Modification of shear profile
(external vorticity reservoir)

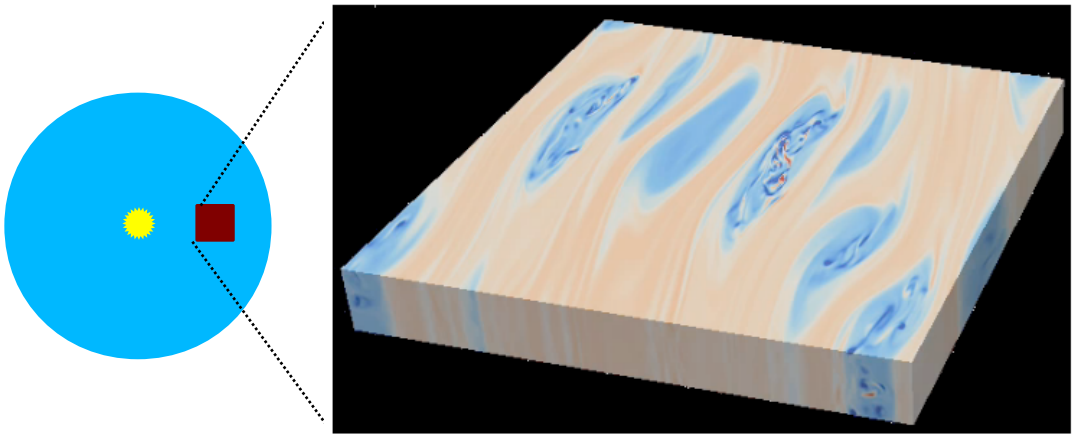
Convective Overstability



Klahr & Bodenheimer (2003), Klahr (2004), Johnson & Gammie (2005), Petersen et al. (2007ab), Lesur & Papaloizou (2010), Lyra & Klahr (2011), Raettig et al. (2013) Klahr & Hubbard (2014), Lyra (2014), Latter (2015)

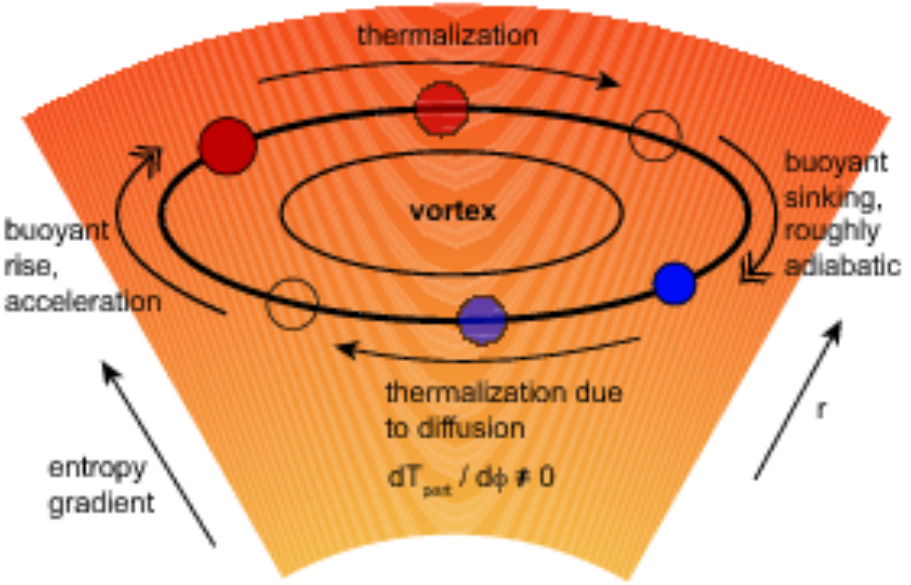
Powered by:
Buyoancy, thermal diffusion
(baroclinic source term)

Convective Overstability (née Baroclinic Instability)



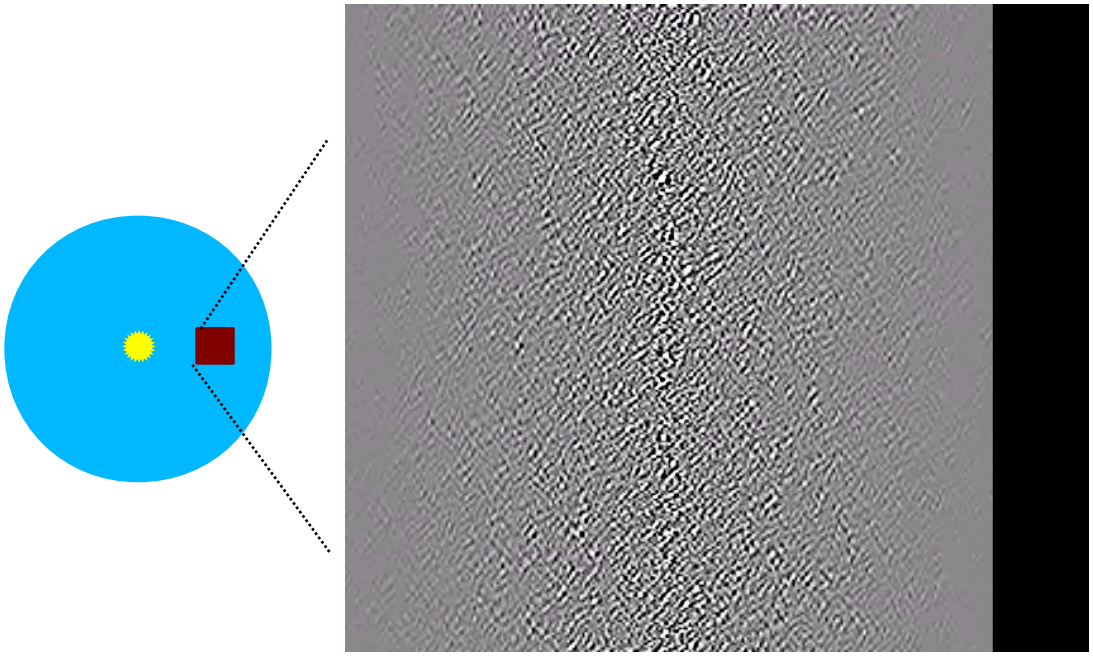
Lesur & Papaloizou (2010)

Sketch of the
Convective Overstability



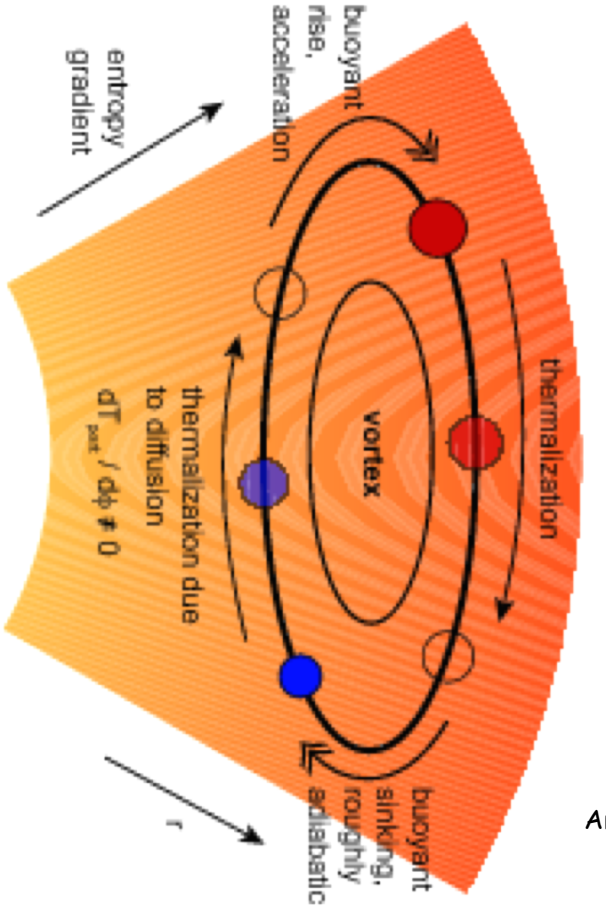
Armitage (2010)

Convective Overstability



Lyra & Klahr (2011)

Sketch of the
Convective Overstability

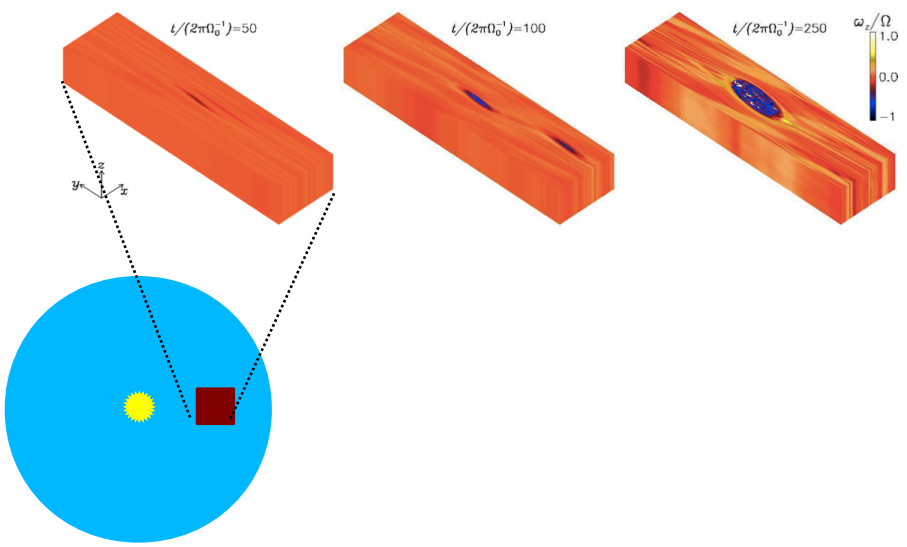


Armitage (2010

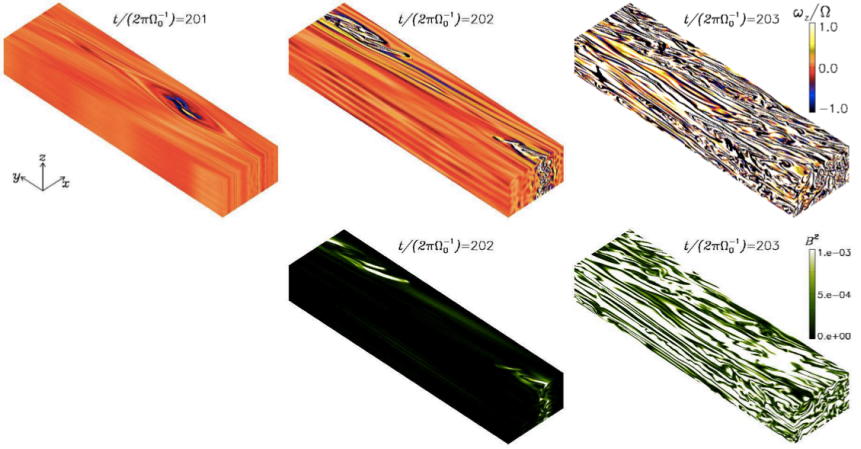
Vortices and MHD

What happens when the disk is magnetized?

Hydro



MHD

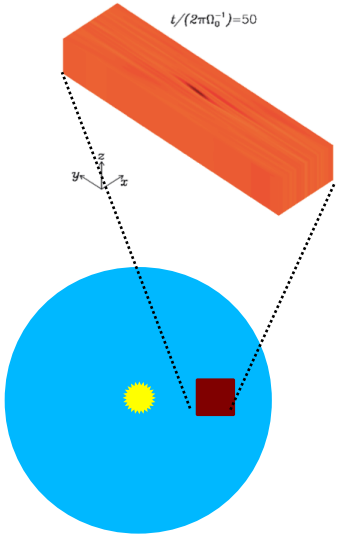


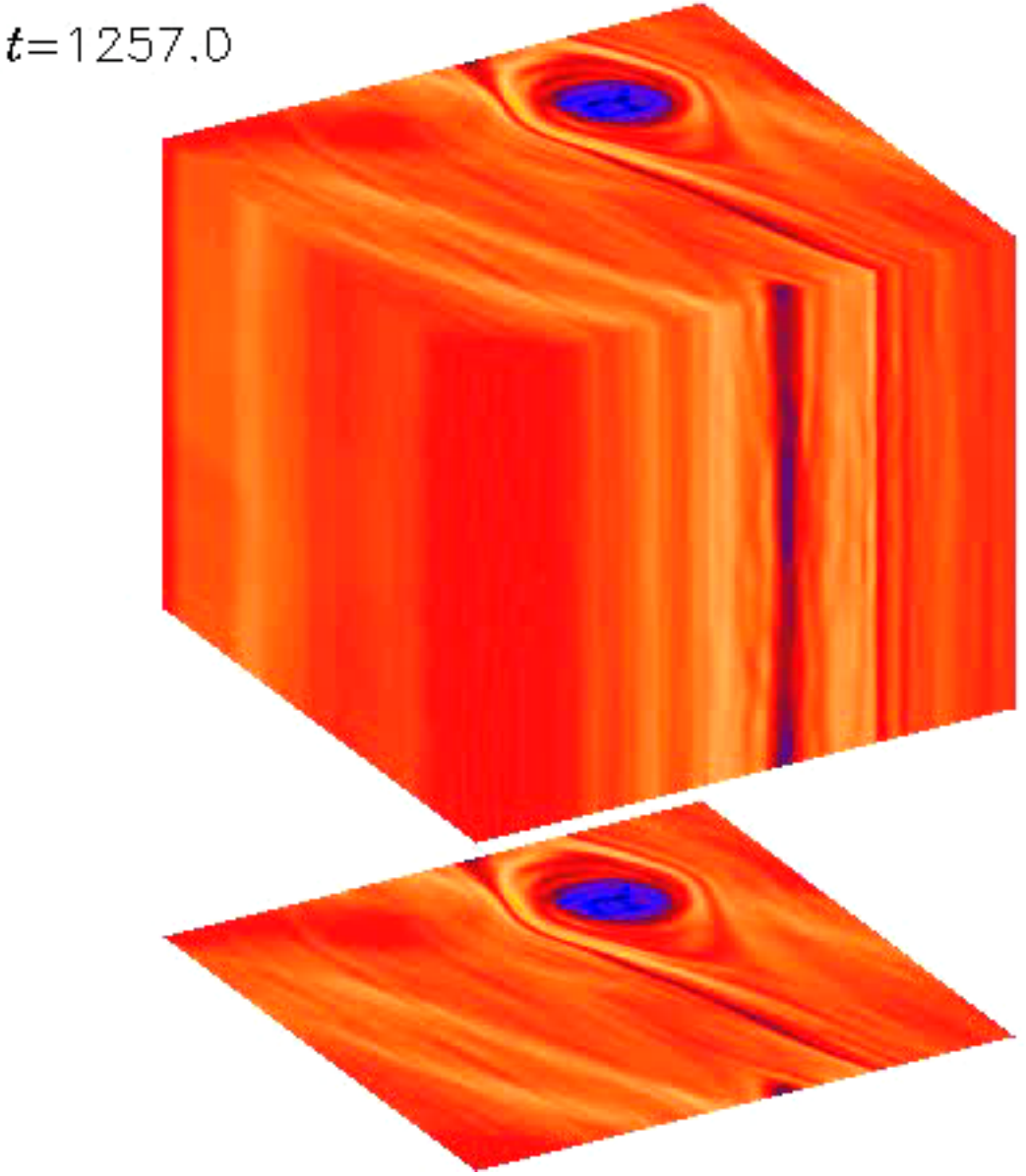
Vorticity

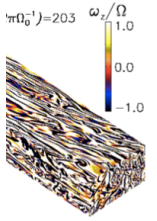
Mag. Energy

Lyra & Klahr (2011)

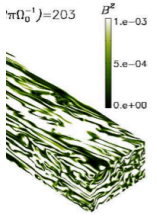
Vortices and MHD







Vorticity

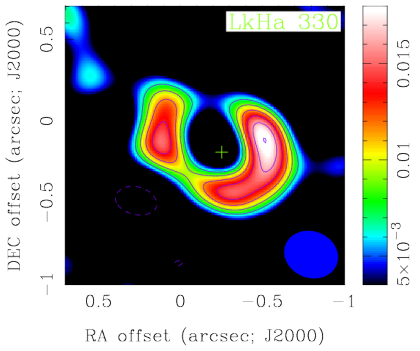


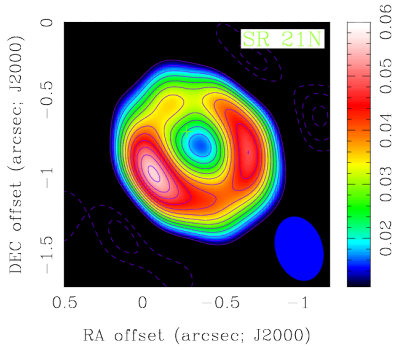
Mag. Energy

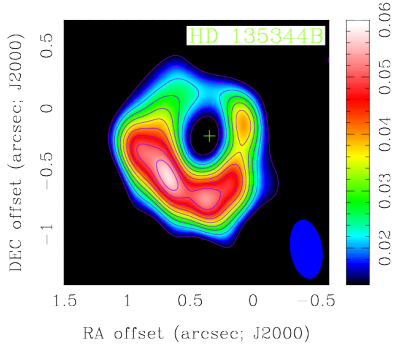
Observational evidence in protoplanetary disks (Exonebulae)

Observations

Brown et al. (2009)



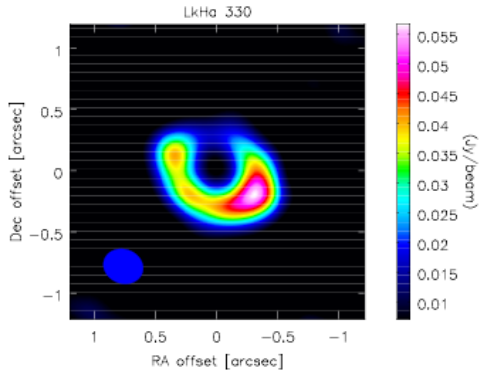


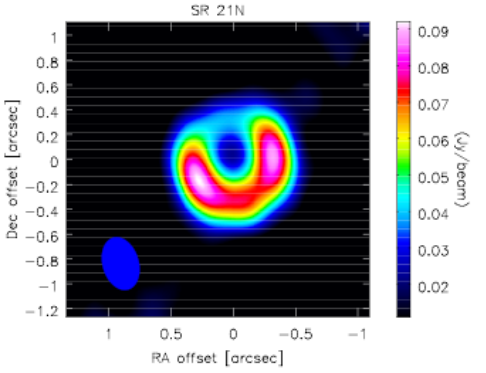


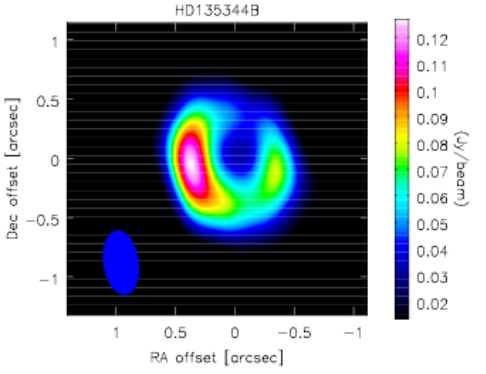
Models

Simulated observations

Regaly et al. (2012)







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.

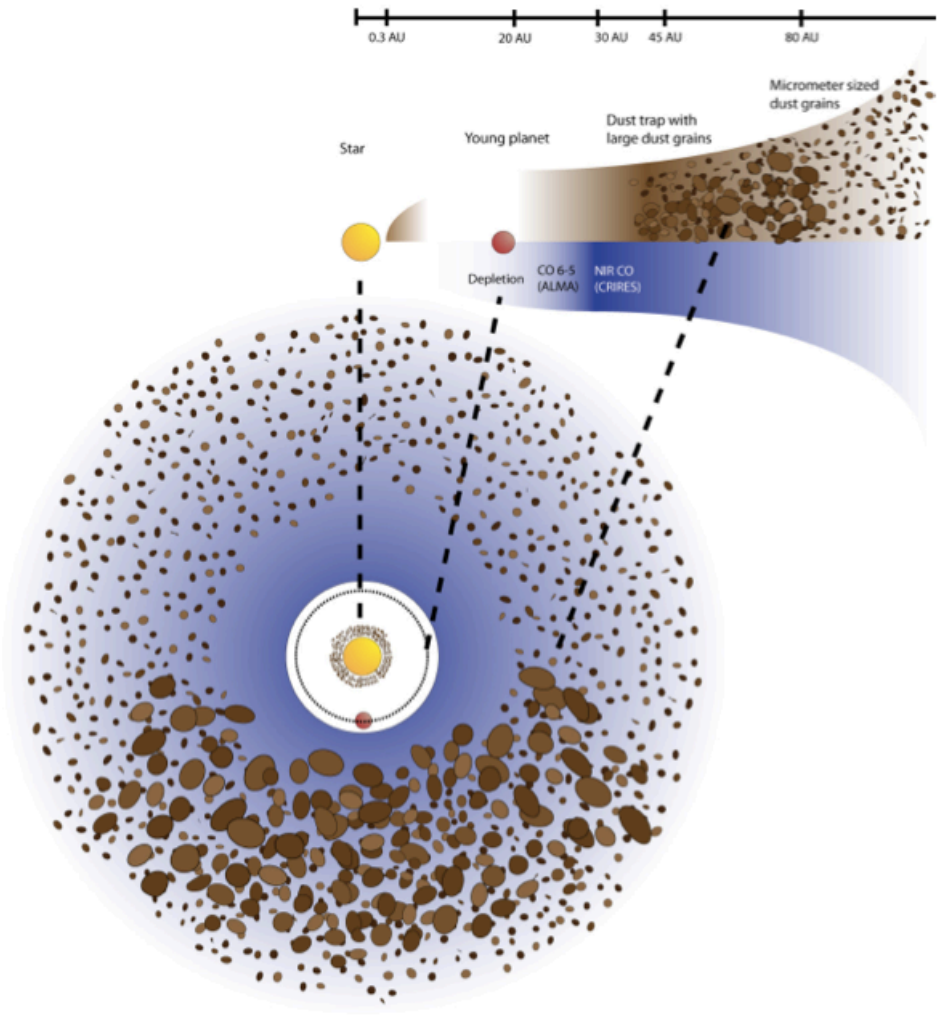
Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

Down

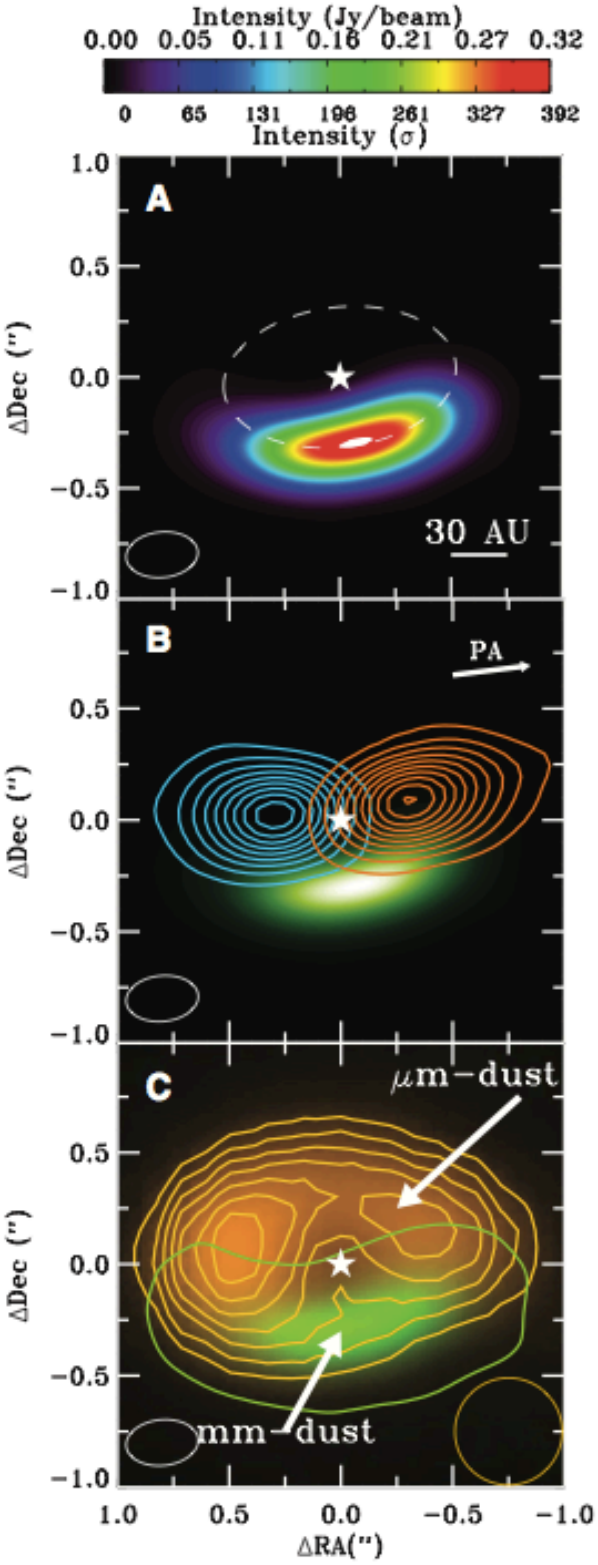
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

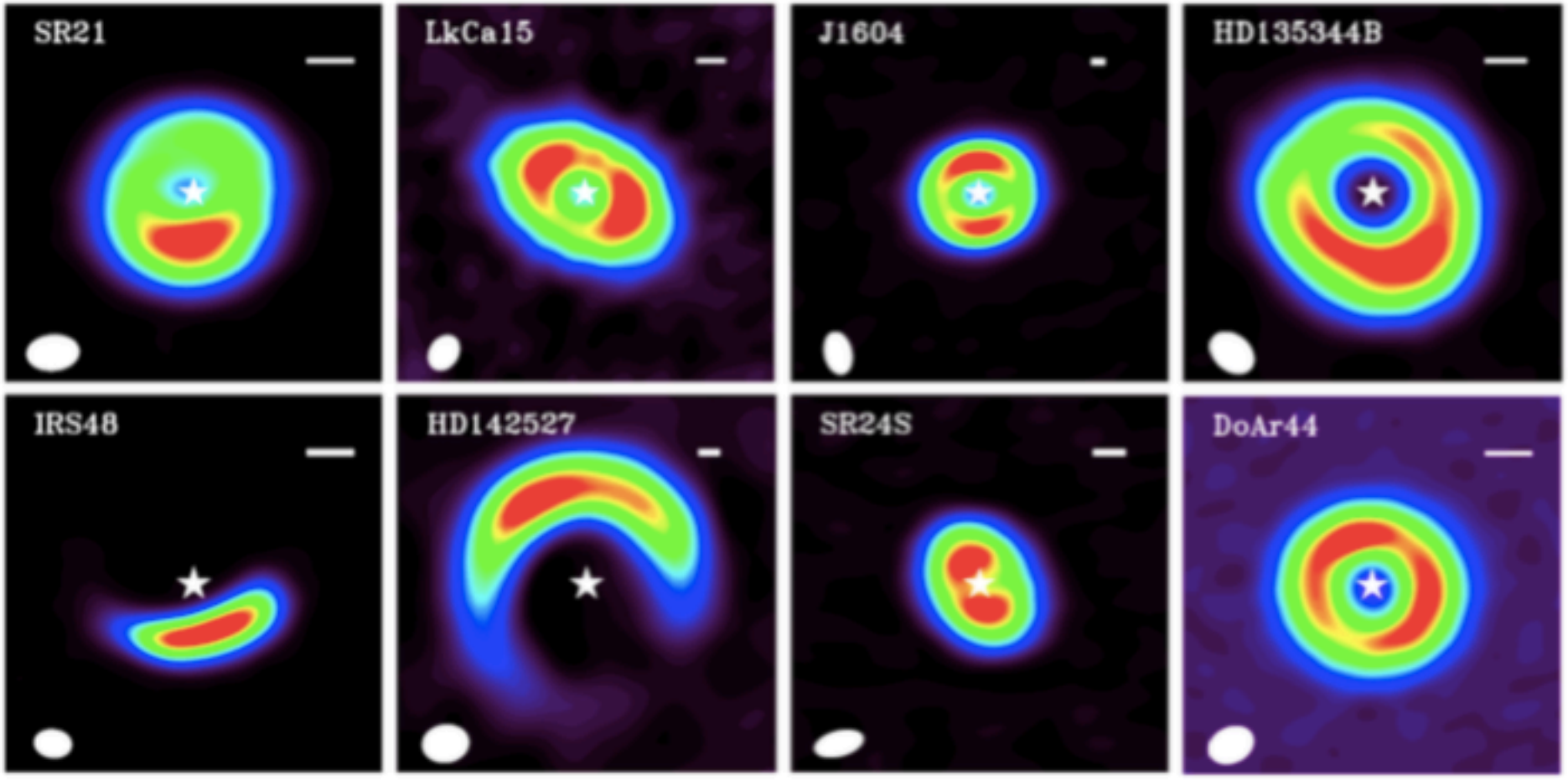


asymmetric mm dust at 63 AU

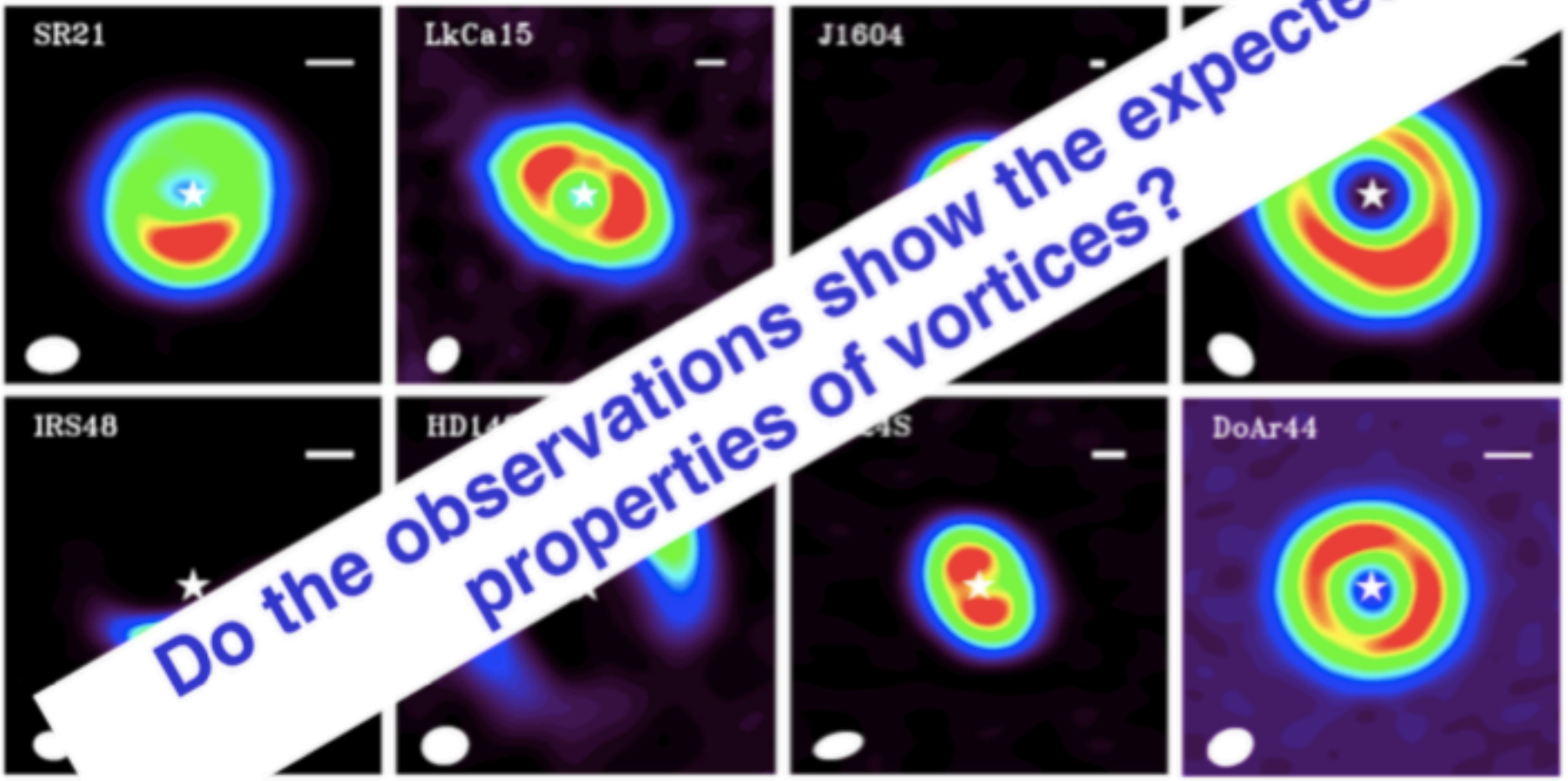
Gas detection: Keplerian rotation

Micron-sized dust follows gas

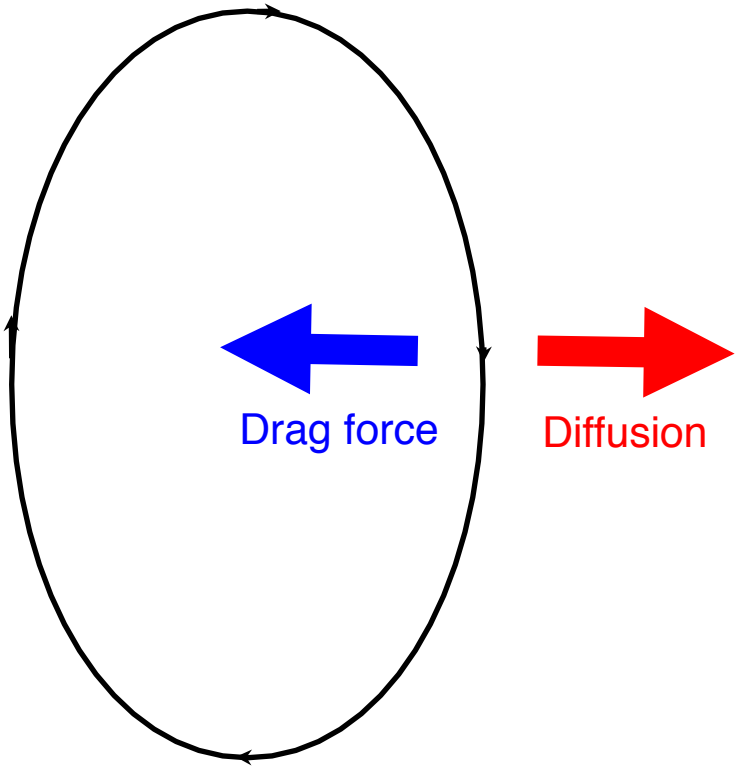
“Asymmetries” everywhere



“Asymmetries” everywhere



Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

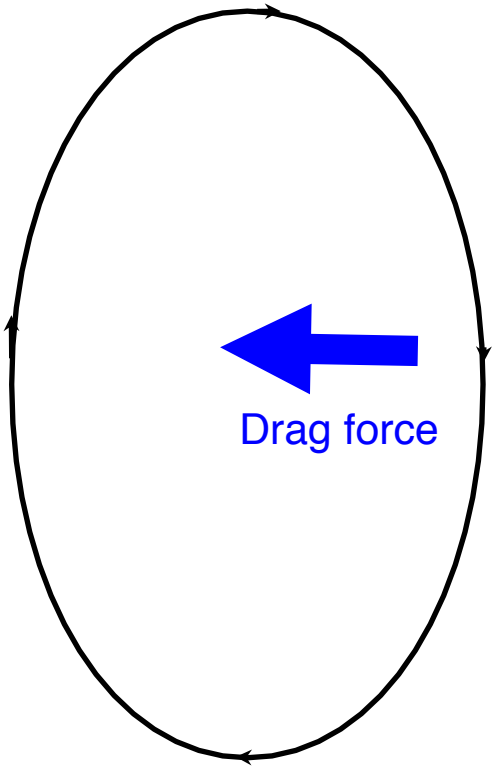
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v}\cdot\boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla}\cdot\boldsymbol{v} + D\nabla^2\rho_d,$$

advection

compression

diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

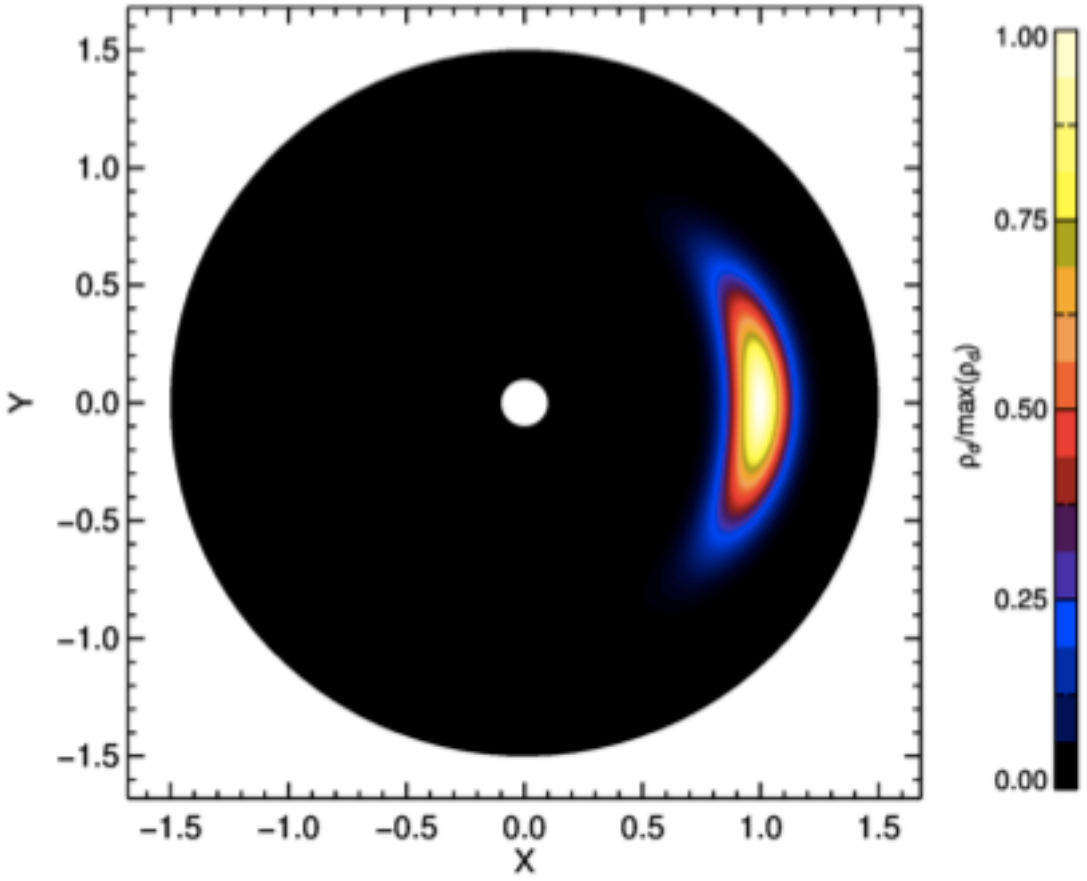
Lyra & Lin (2013)

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

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

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 trapping



Solution for

H/r=0.1 χ*=4* *S*=1

Solution

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

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

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

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

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

Lyra & Lin (2013)

Derived quantities

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

Lyra & Lin (2013)

Gas distribution

$$\rho_g(a) = \rho_{g\max} \exp\left(-\frac{a^2}{2H_g^2}\right),$$

Maximum dust density

$$\rho_{d\max} = \varepsilon\,\rho_0\,(S+1)^{3/2}$$

Gas contrast

$$\frac{\rho_{g\max}}{\rho_{g\min}} = \exp\left[\frac{f^2(\chi)}{2\chi^2\omega_V^2}\right],$$

Dust contrast

$$\frac{\rho_{d\max}}{\rho_{d\min}} = \frac{\rho_{g\max}}{\rho_{g\min}} \exp(S),$$

Total trapped mass

$$\int \rho_d(a,z)dV = (2\pi)^{3/2}\,\varepsilon\rho_0\,\chi H H_g^2$$

Vortex size

$$a_s = H(\chi\omega_V)^{-1}$$

H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function
ε = dust-to-gas ratio

Applying the model to Oph IRS 48

Observed parameters

Aspect ratio: 3.1

Dust contrast: 130

Temperature: 60K

Trapped mass: 9 M_{Earth}

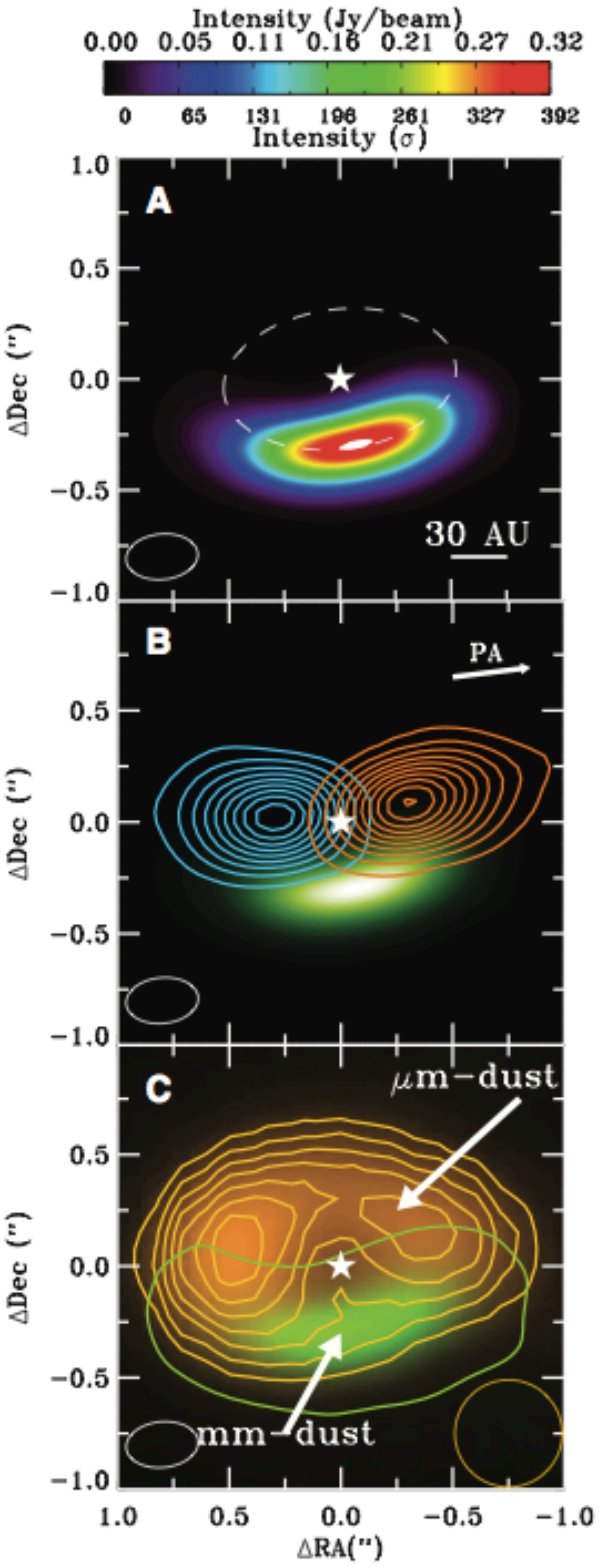
Derived parameters

S=4.8

Stokes number, St=0.008

$\delta = 0.005$, $v_{rms} = 4\%\ c_s$

Trapped mass: 11 M_{Earth}



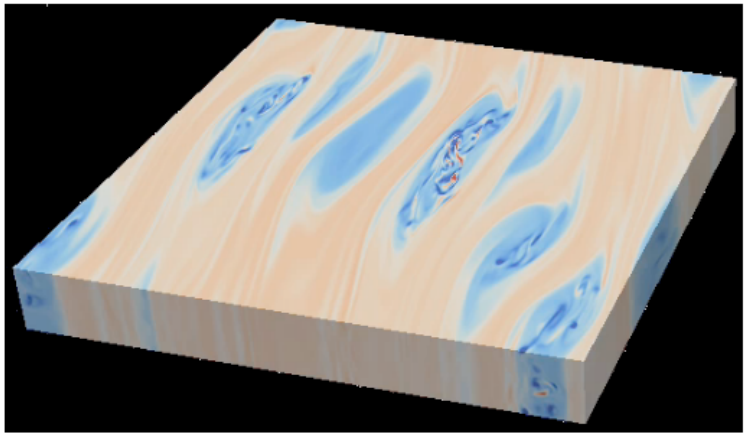
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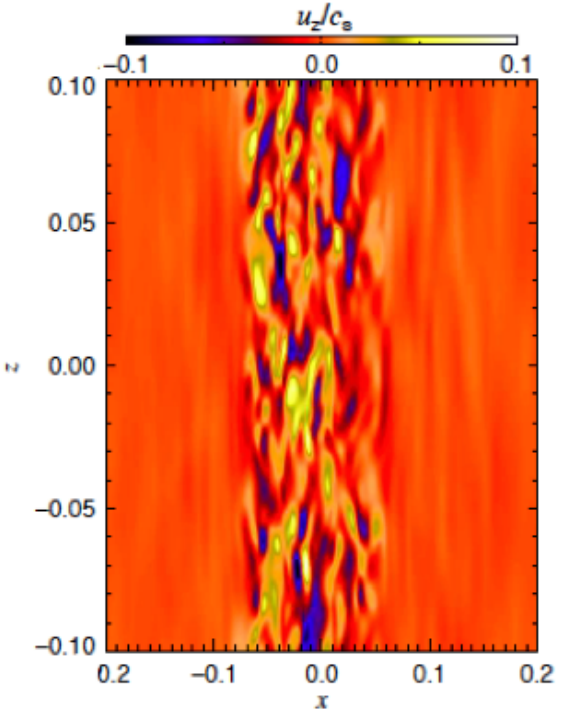
Micron-sized dust follows gas

Lyra & Lin (2013)

Turbulence in vortex cores



Lesur & Papaloizou (2010)

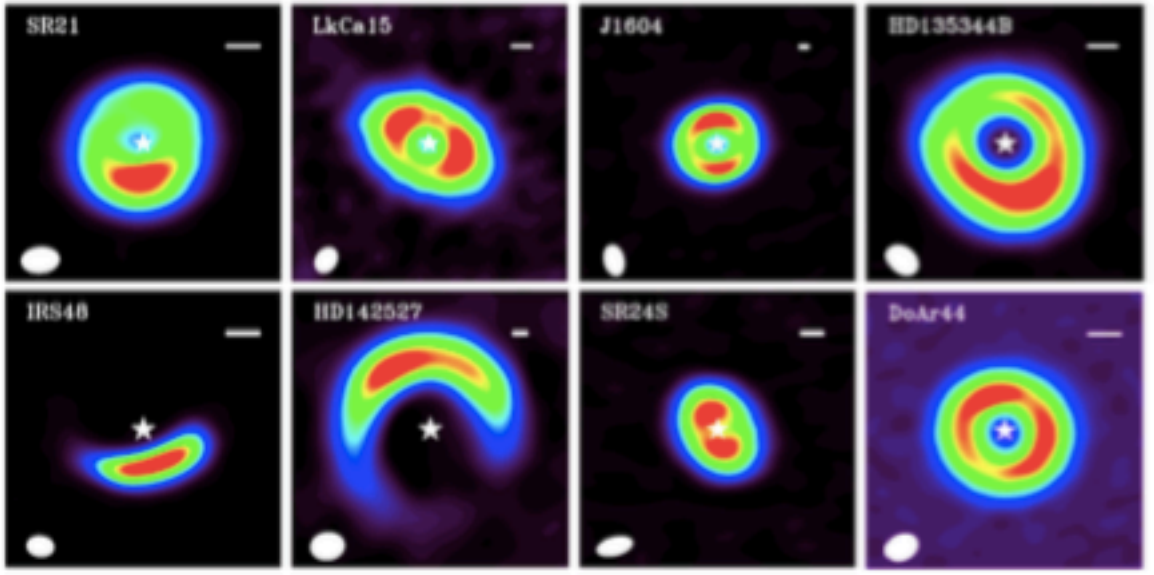


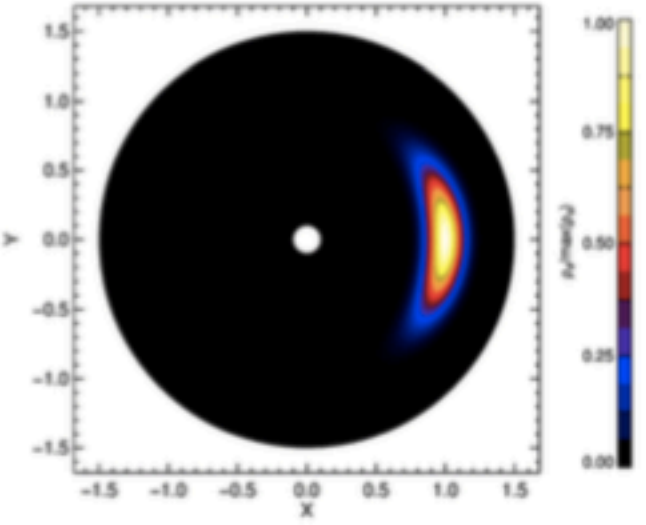
Lyra & Klahr (2011)

Turbulence in vortex cores:

max at ~10% of sound speed
rms at ~3% of sound speed

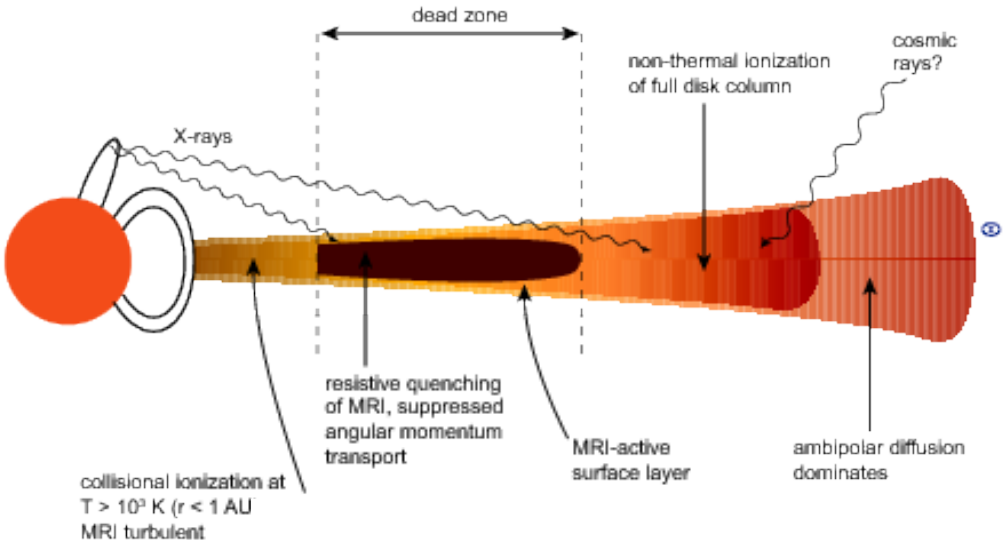
Observed asymmetries consistent with vortices…



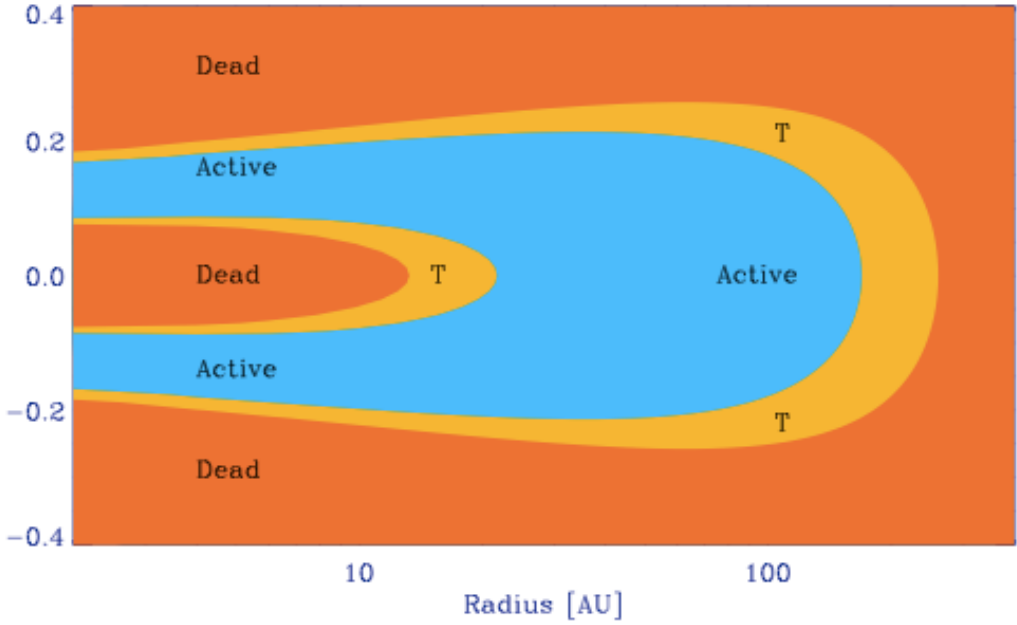


But origin still elusive…

Outer Dead/Active zone transition KHI



Armitage (2010)



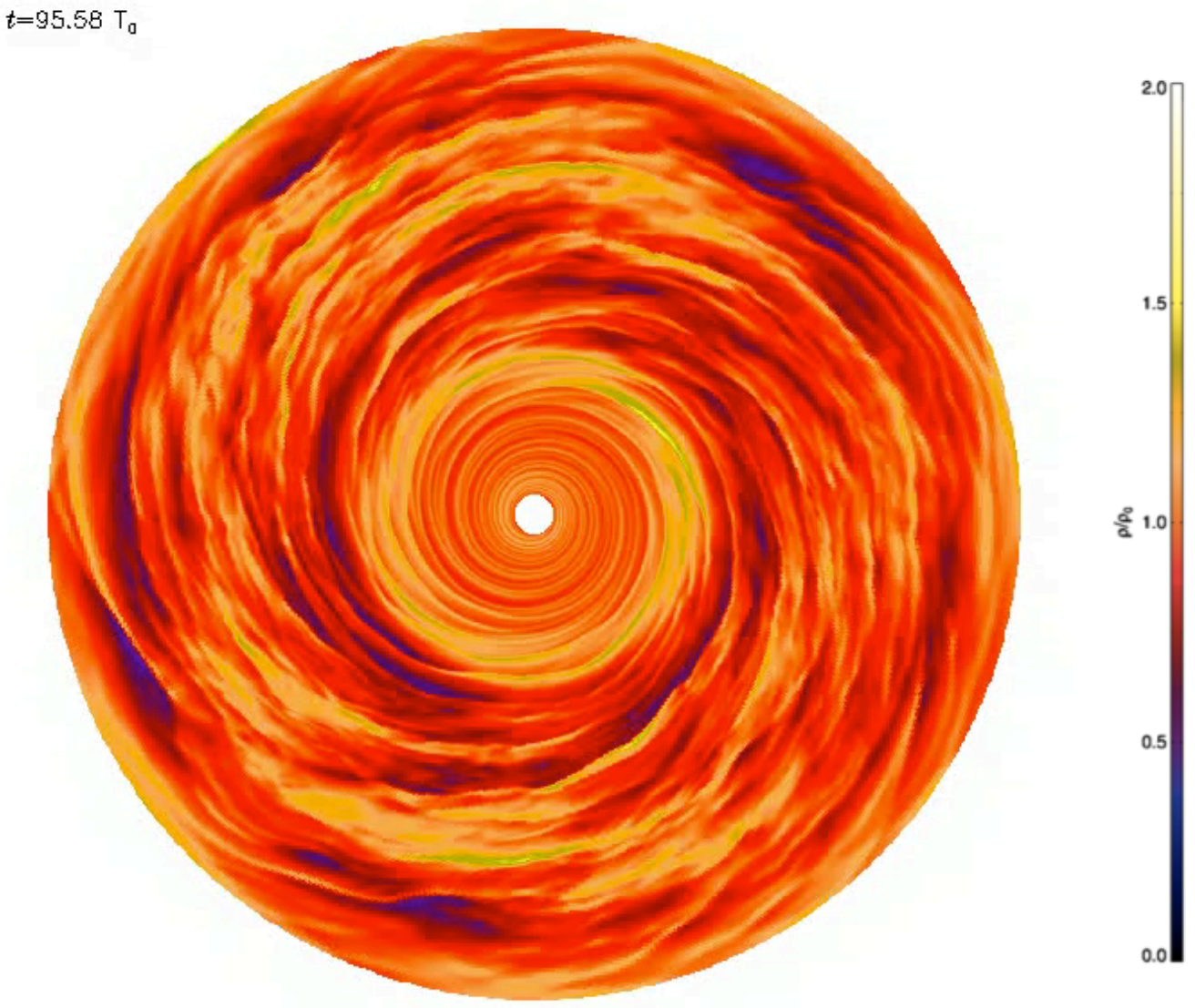
Dzyurkevitch et al (2013)

The **outer** dead zone transition in ionization supposed

TOO SMOOTH

to generate an KH-unstable bump.

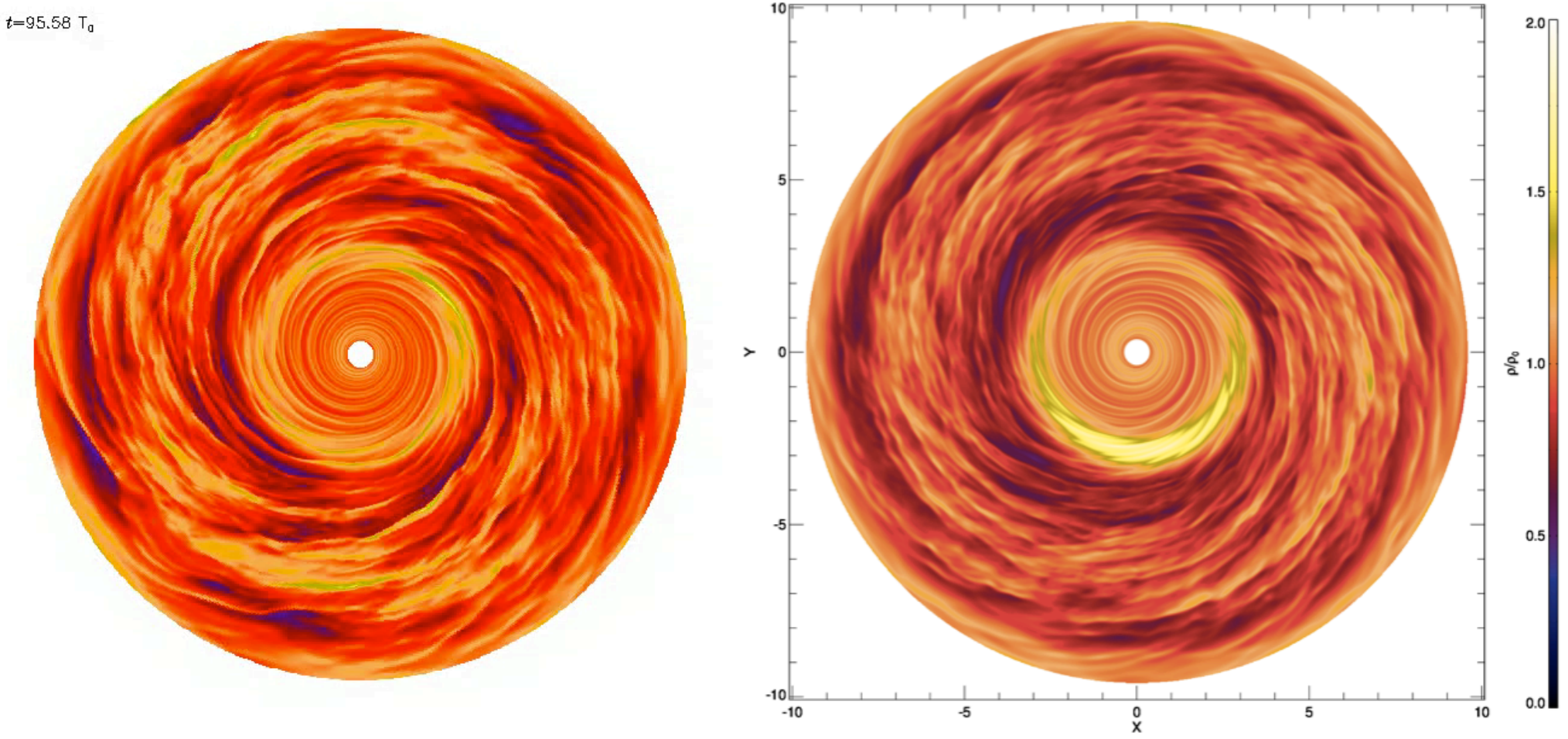
Outer Dead/Active zone transition: 3D MHD



Resistive inner disk + magnetized outer disk

Lyra et al (2015)

Outer Dead/Active zone transition KHI

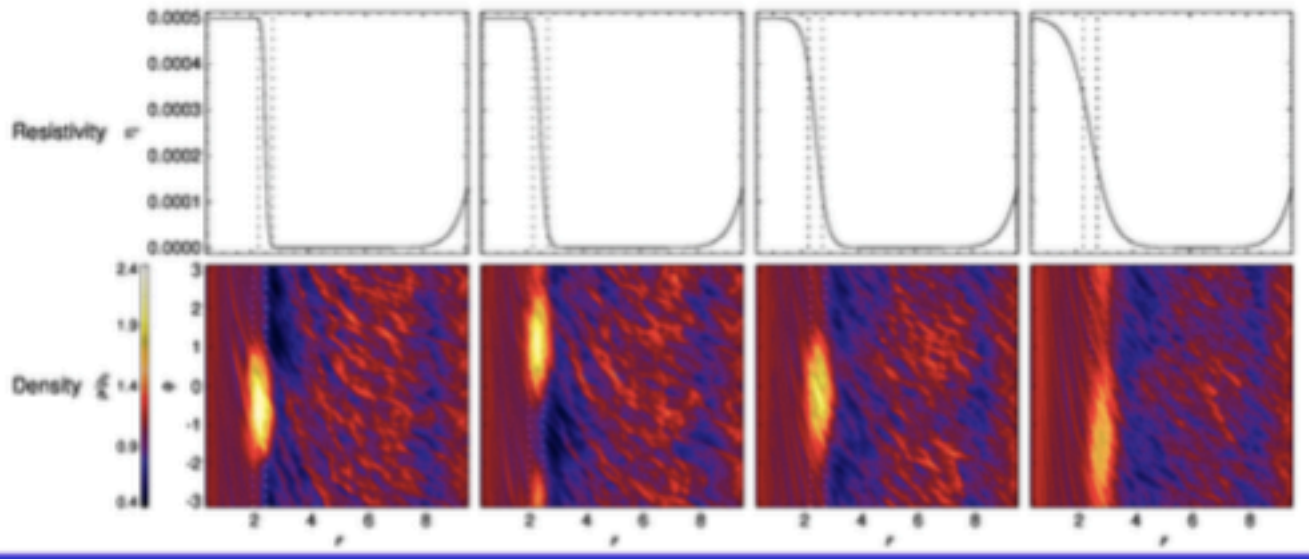


Resistive inner disk + magnetized outer disk

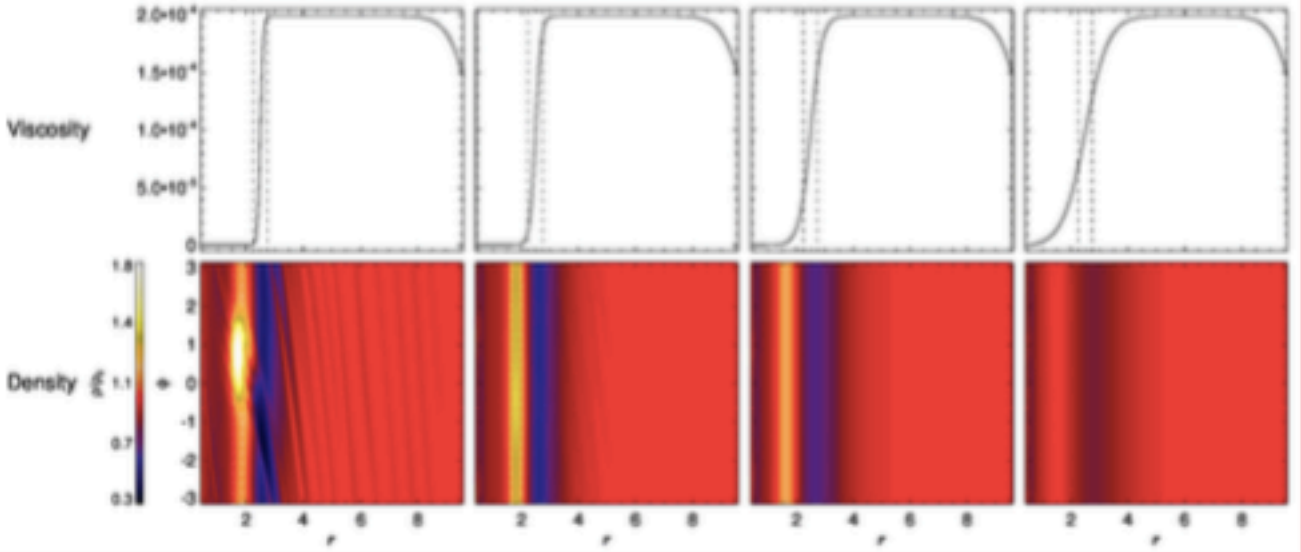
Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI

MHD

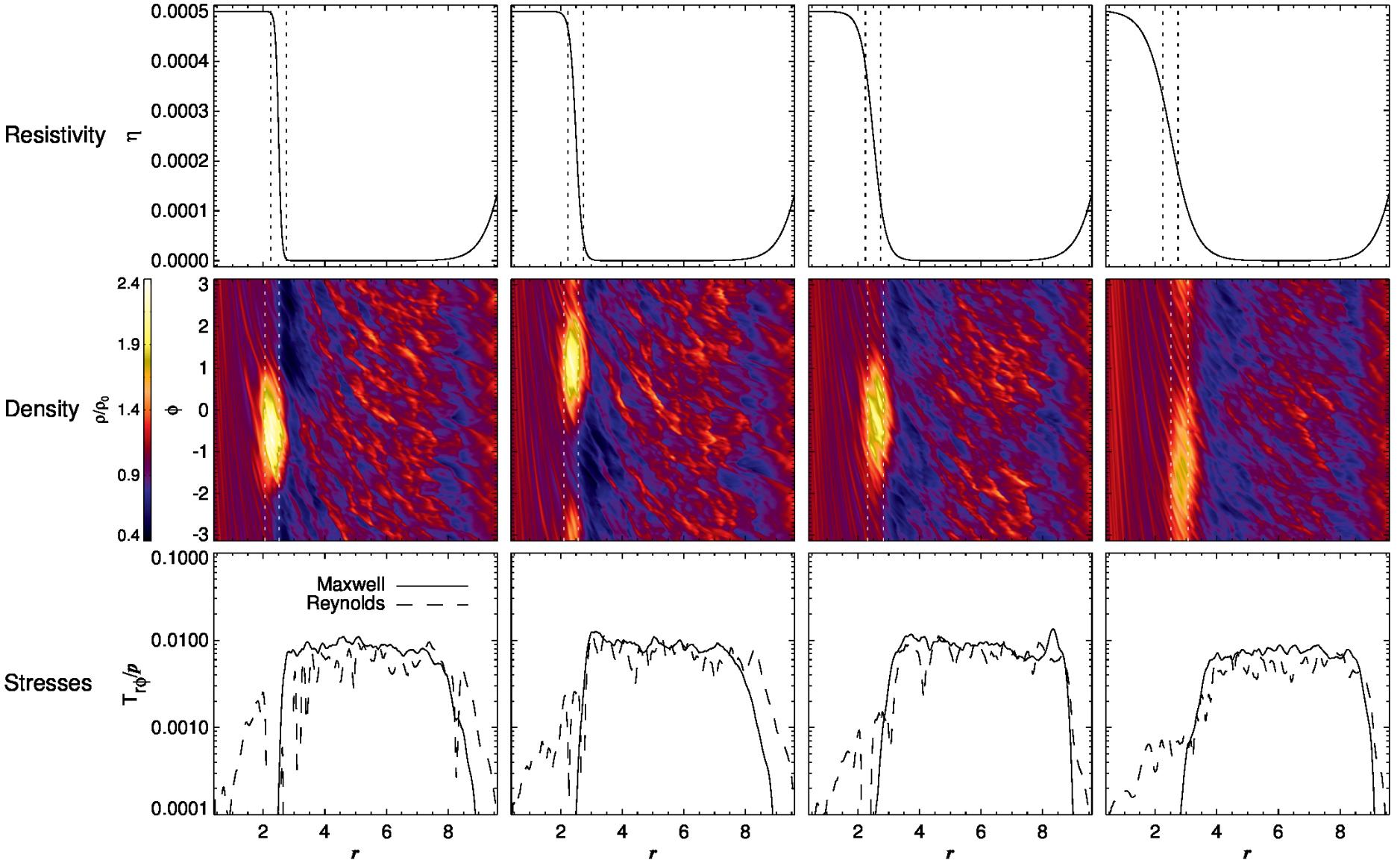


Hydro



Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

Open question: stratification

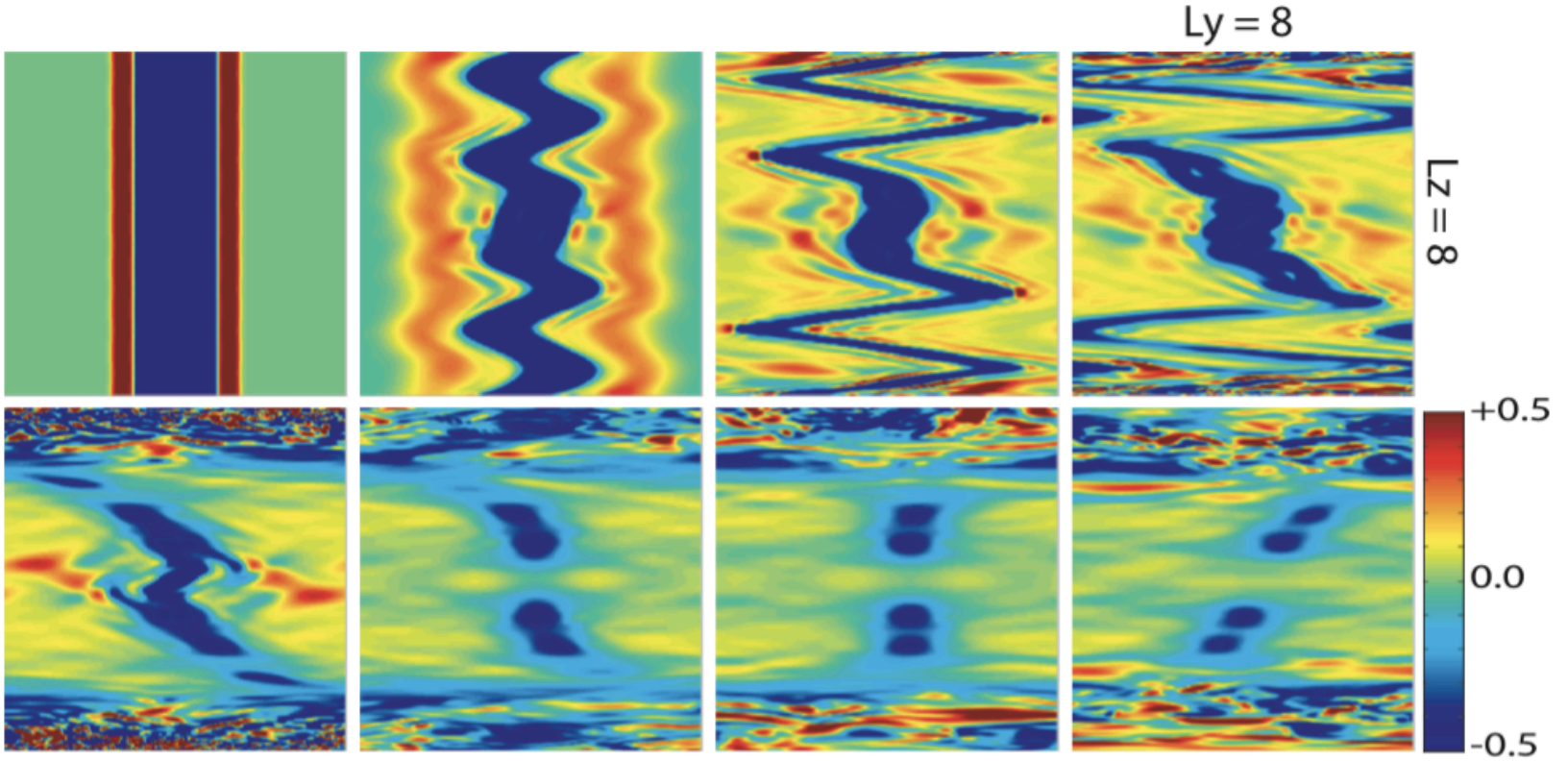
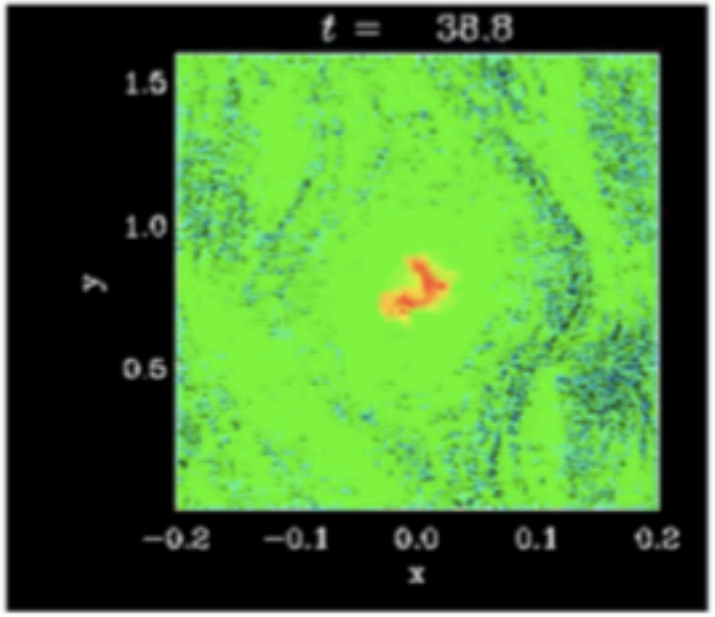


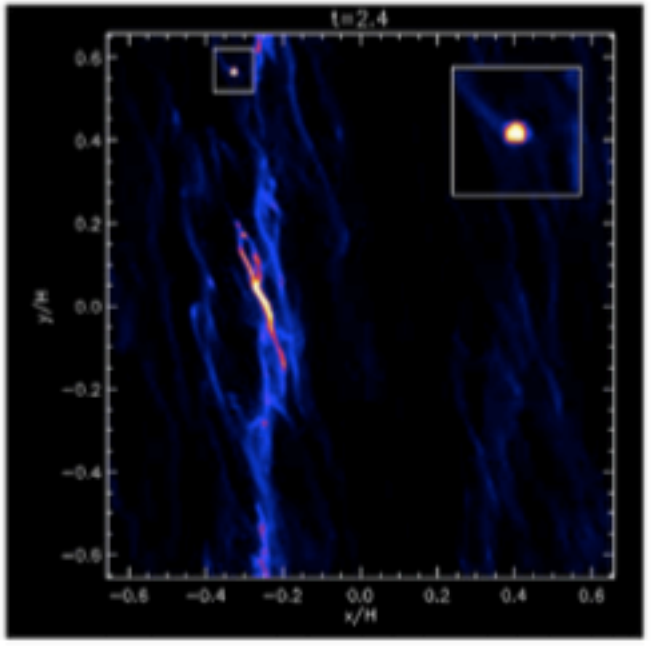
FIG. 3.—Tall, columnar vortex: y-z slices at $x = 0$ of the z-component of vorticity $\tilde{\omega}_z$. *Blue*: Anticyclonic vorticity. *Red*: Cyclonic vorticity. The initial elliptical column had aspect ratio $\chi = 4$ and vorticity $\tilde{\omega}_z = 0.625$, corresponding to a Rossby number Ro = 0.3125. The times corresponding to each frame are $t/\tau_{\rm orb} = 0.0$, 2.1, 4.2, 6.4, 51, 102, 153, and 204. [*This figure is available as an mpeg animation in the electronic edition of the Journal.*]

Barranco & Marcus (2005)

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
- [illegible] of our model predictions!!
- [illegible] t?)

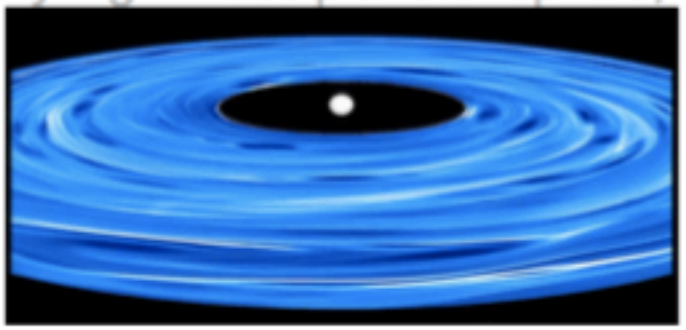




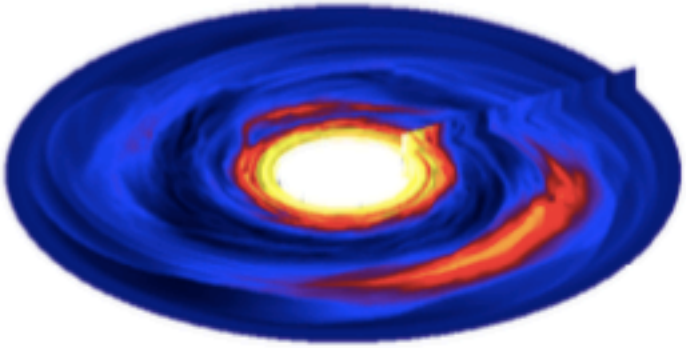
Conclusions

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- 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
- Several candidates: PWL/GQ Planets
- very high-mass planets: spirals, turbulent sun ser?)

Baroclinic instability

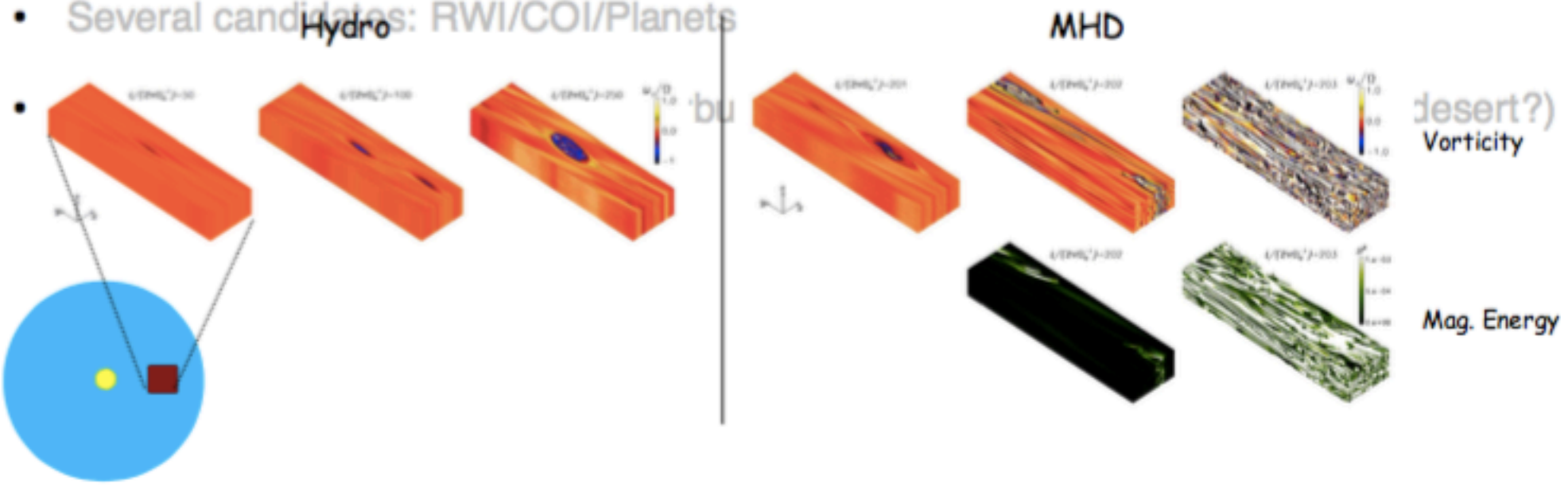


Rossby wave instability



Conclusions

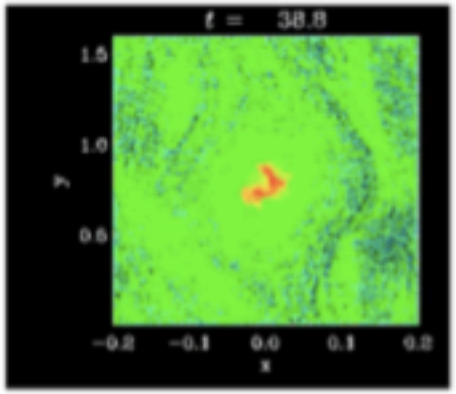
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- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortices do not survive magnetization
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Several candidates: RWI/COI/Planets
- 'bu desert?)

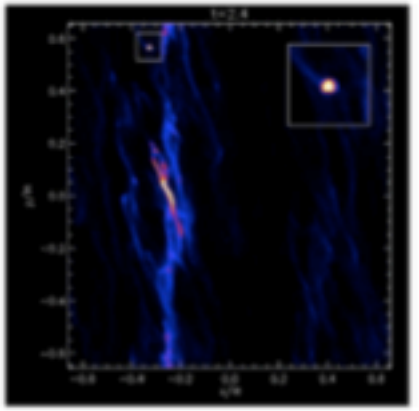


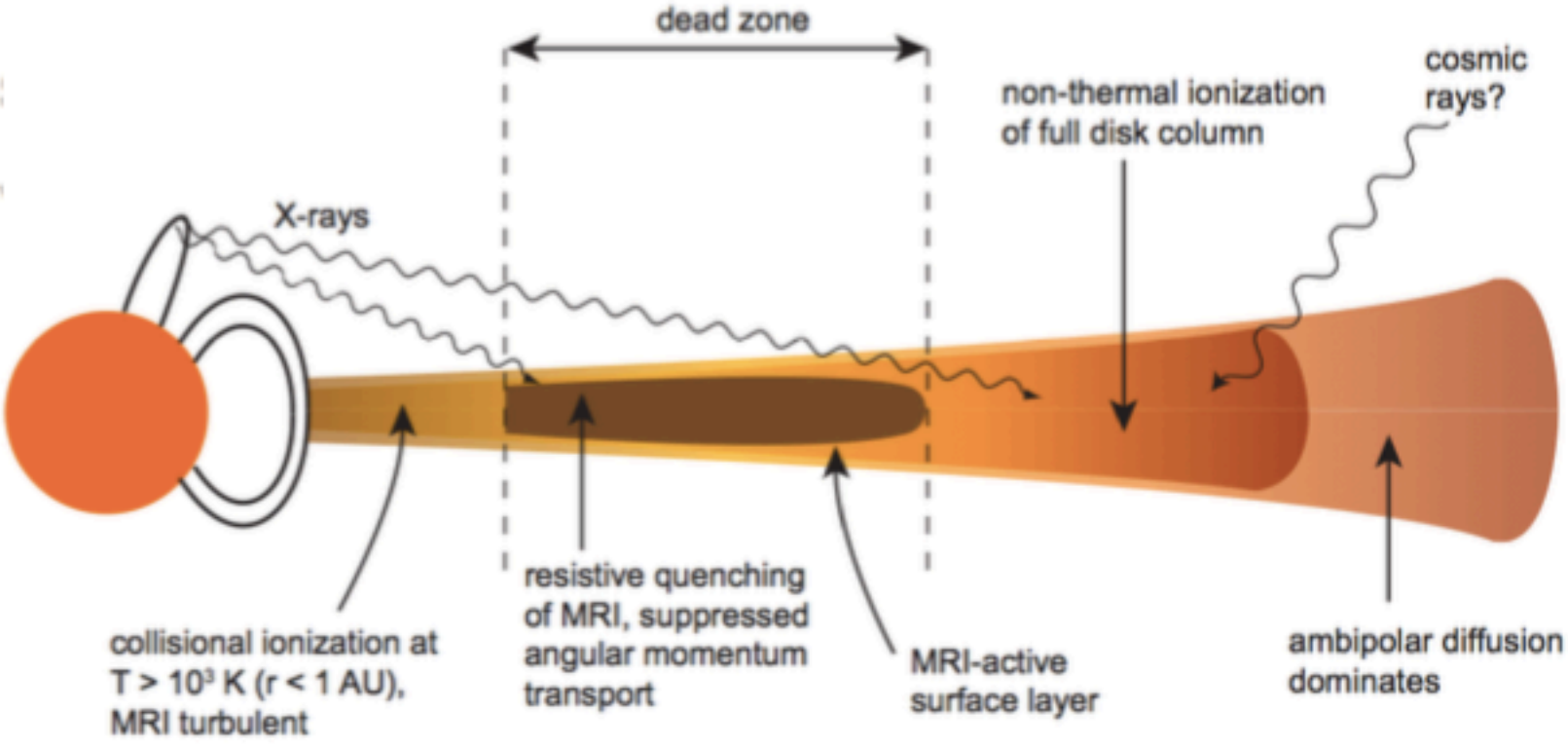
Lyra & Klahr (2011)

Conclusions

- Two mod ces
- Two sust ive Overstability
- Vortices
- **Vortex-assisted and streaming instability are complementary**
-
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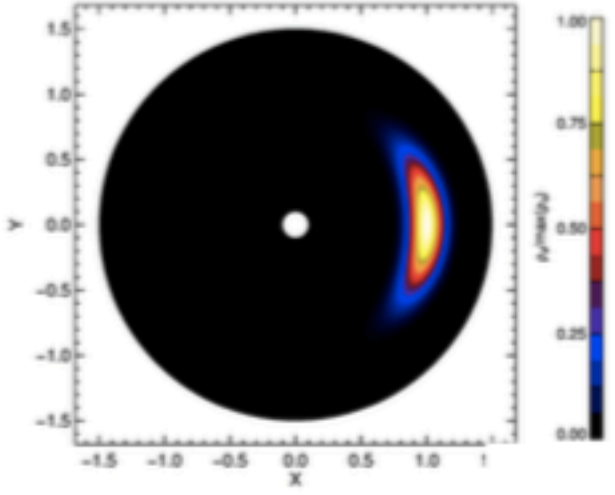


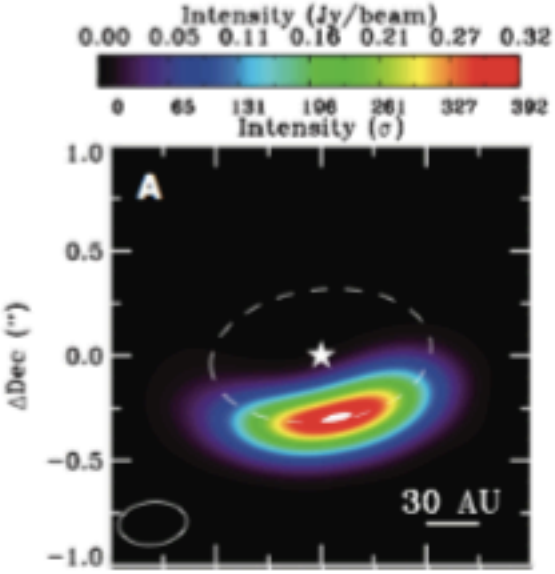
Conclusions

- 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

- Two modes
- Two susten
- Vortices do
- Vortex-assis
- Vortex-trapp
- Several possible culprits for asymmetries: RWI/COI/Planets
- Very high-mass planets: spirals, turbulent surf and high accretion rates (BD desert?)

