Evolution of circumstellar disks and planet formation

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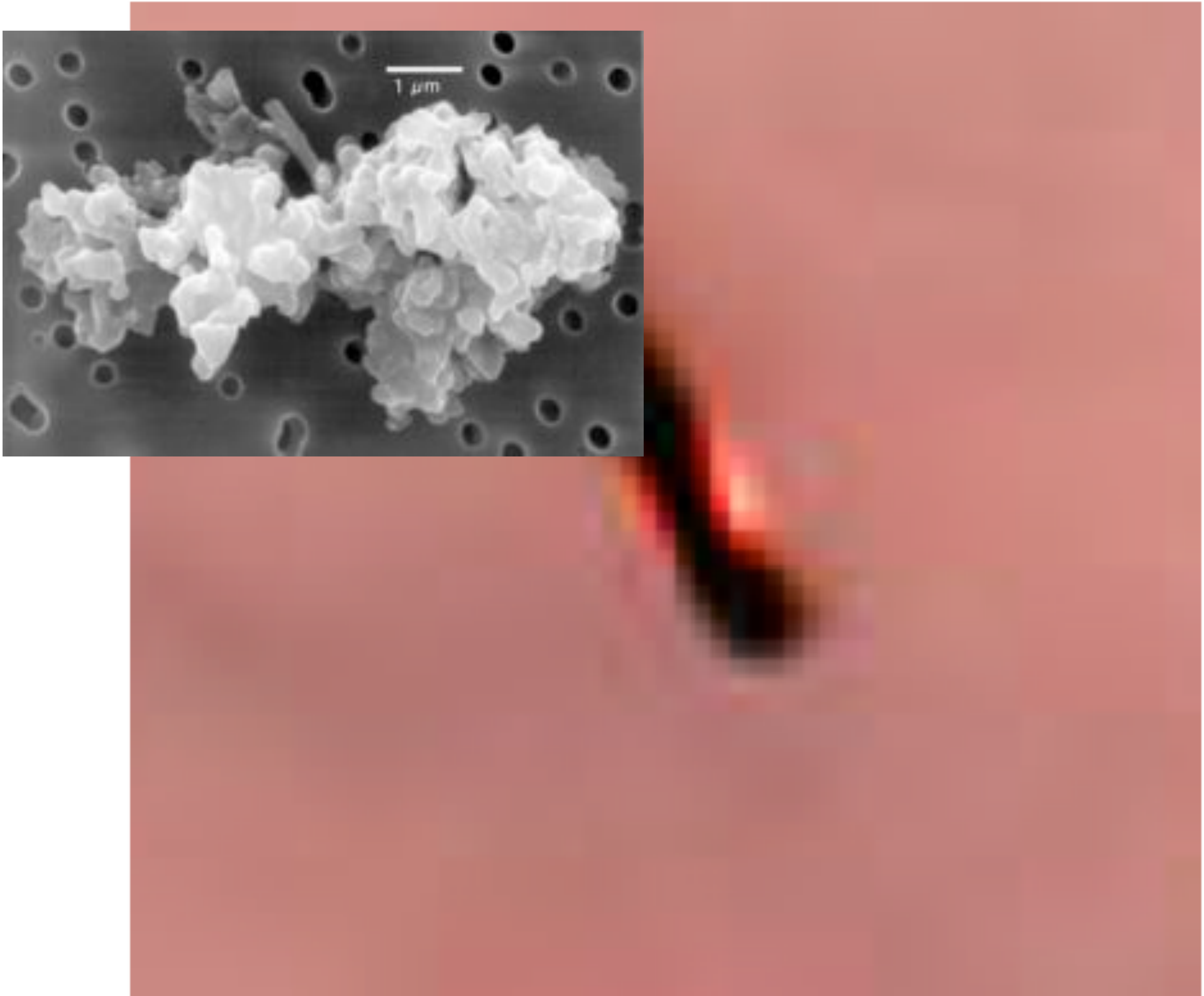
Amsterdam, The Netherlands

March 11th, 2015

Outline

- Turbulence
    - Active and dead zones
    - Magneto-rotational and baroclinic instability
    - Vortices and elliptic instability
- Active/dead boundary
    - Rossby wave instability
- Vortex-mode of planet formation
- Observational constraints


1 μm

Protoplanetary Disks

PP disk fact sheet

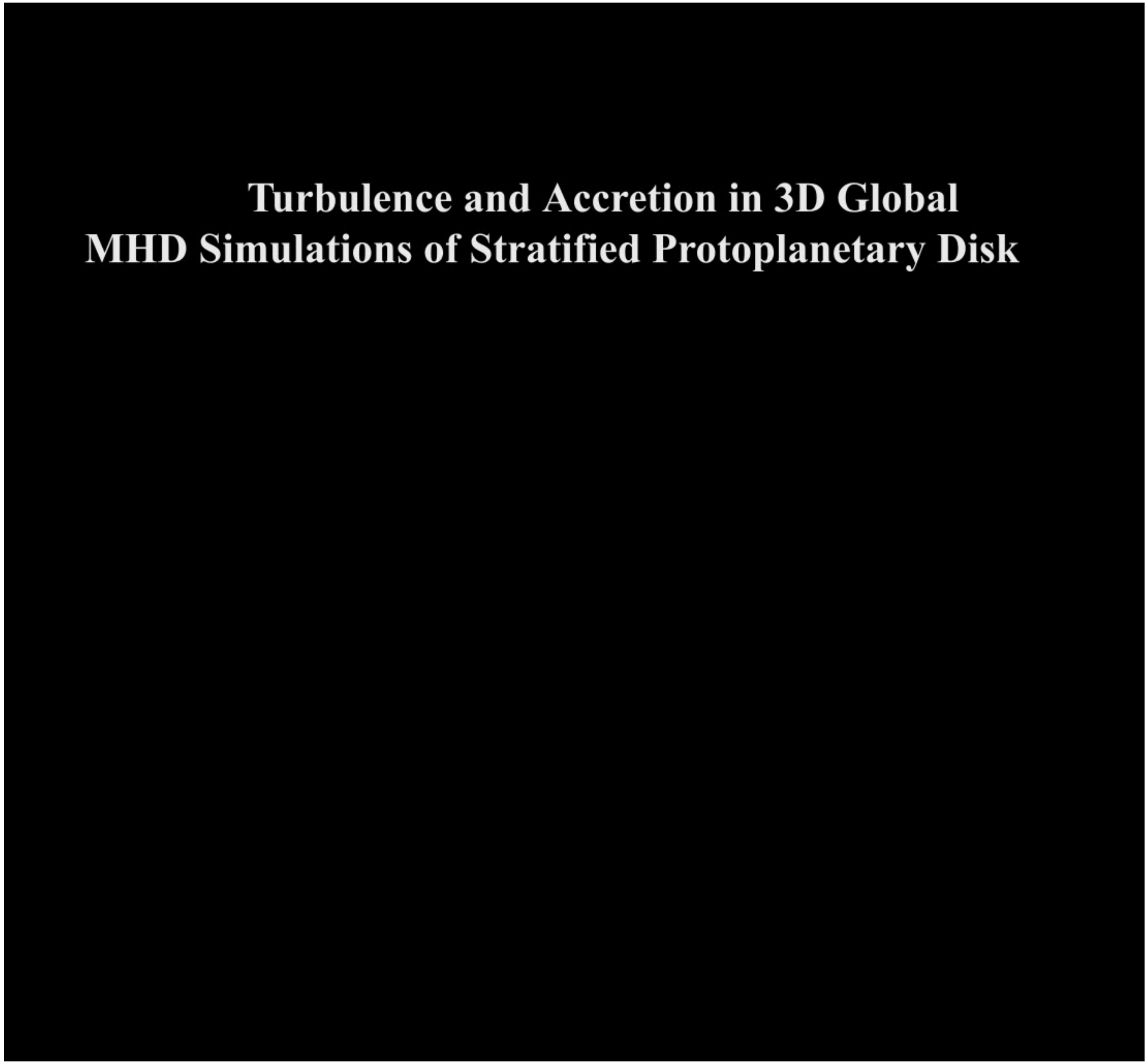
Density: $10^{13} – 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

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} = 2×10^{33} g)

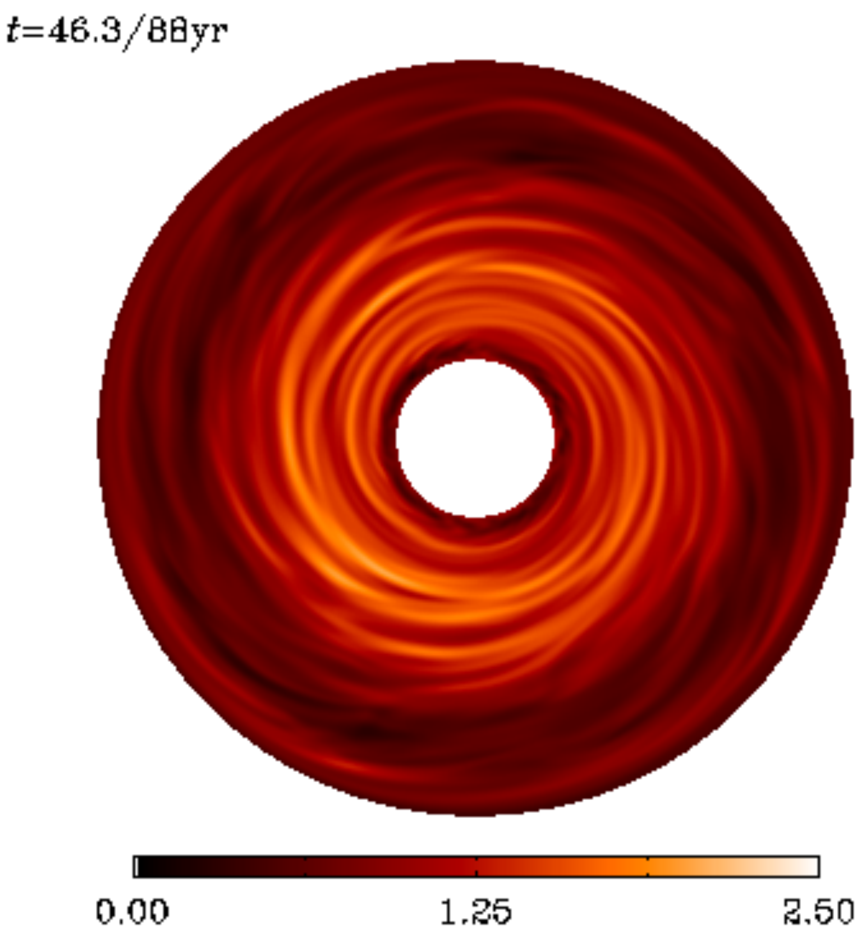
Magneto-Rotational Instability



Video credit: Mario Flock (MPIA/CEA)

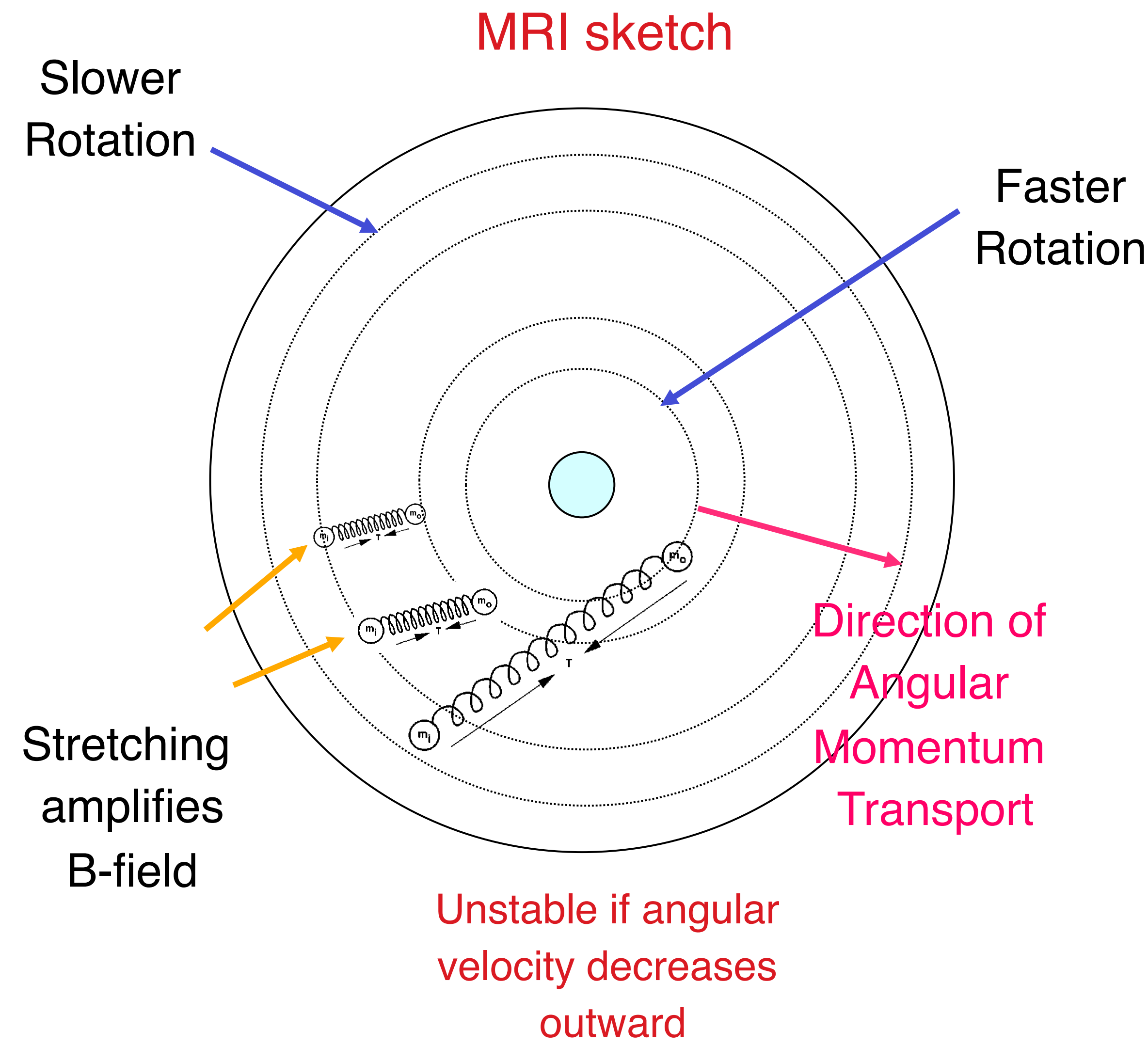
Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability



Magnetized disk

Lyra et al. (2008a)



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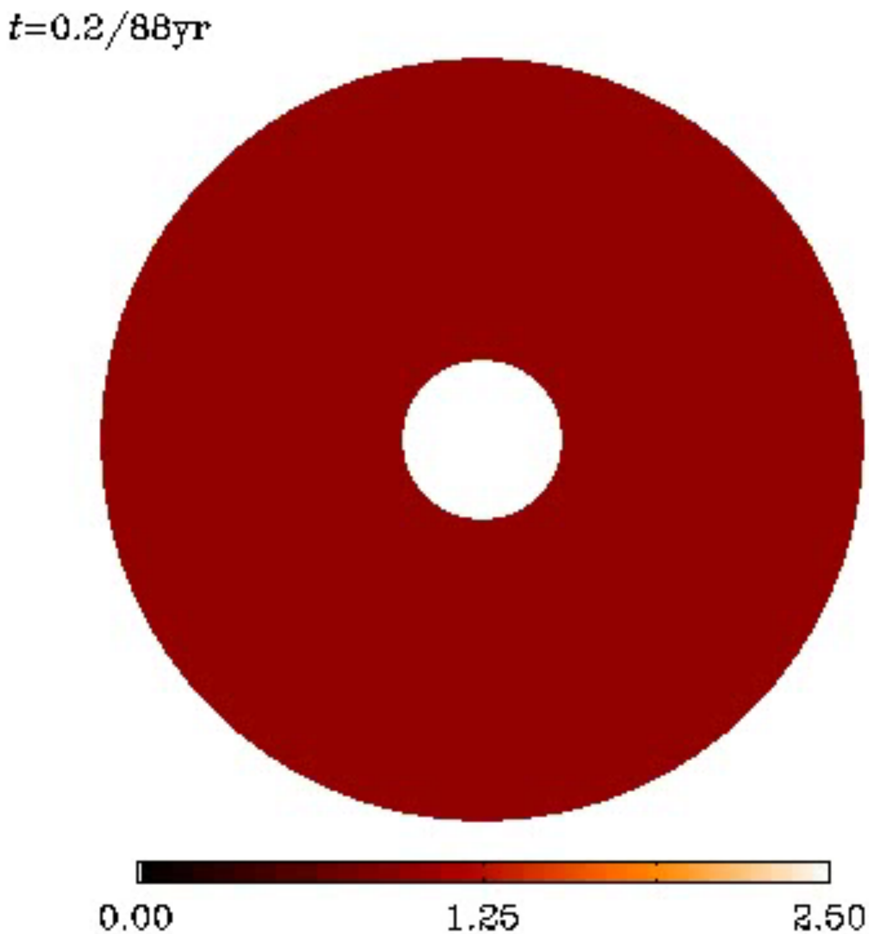
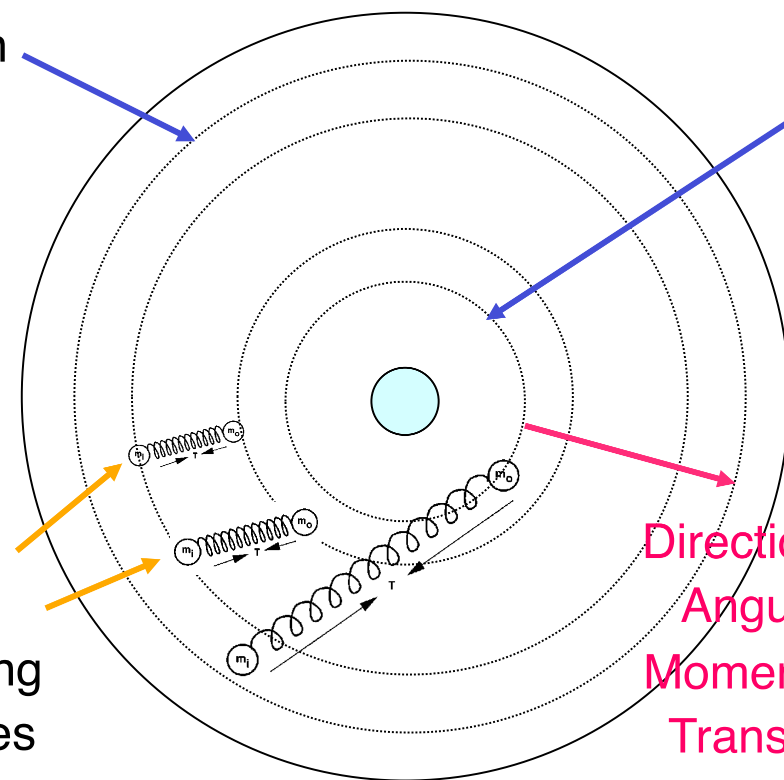


Magnetized disk

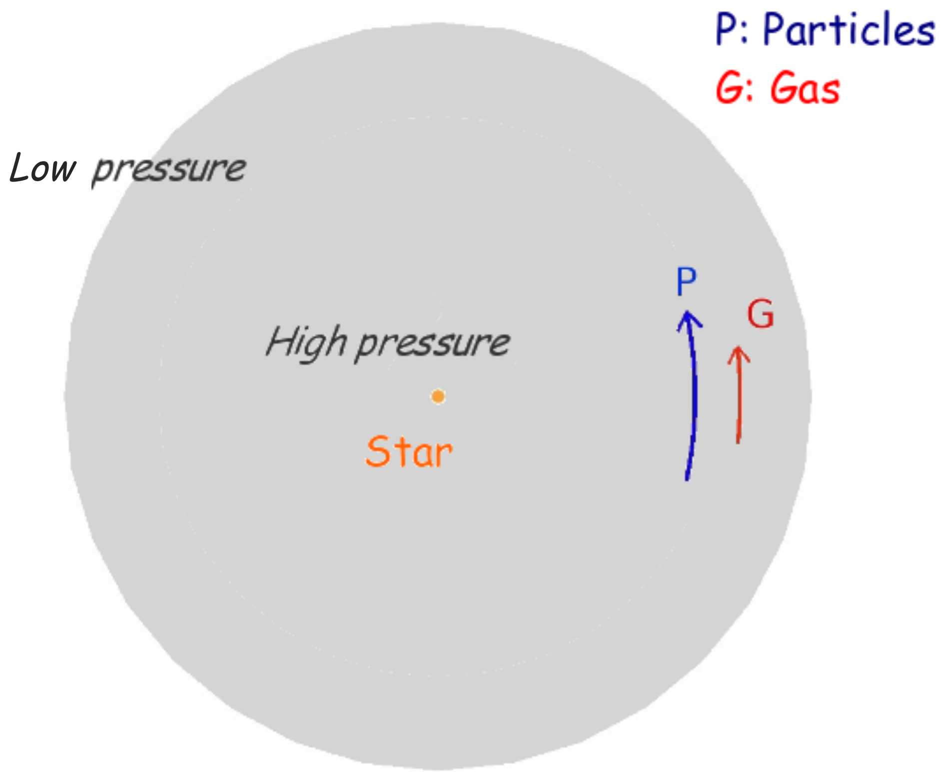
Lyra et al. (2008a)

MRI sketch

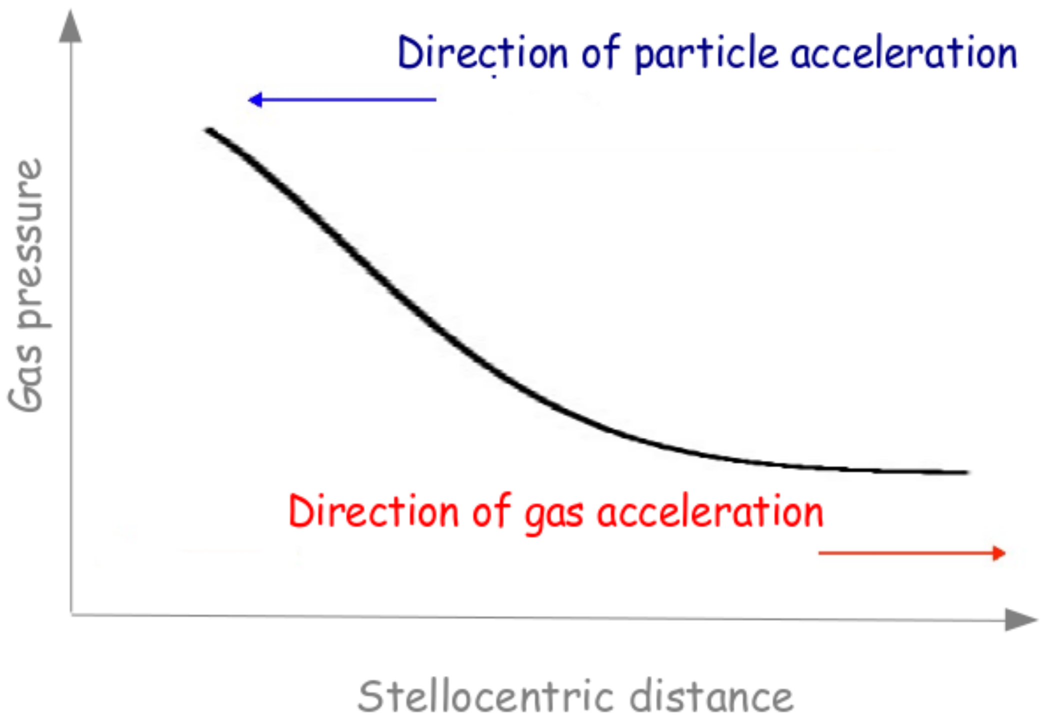


Unstable if angular
velocity decreases
outward

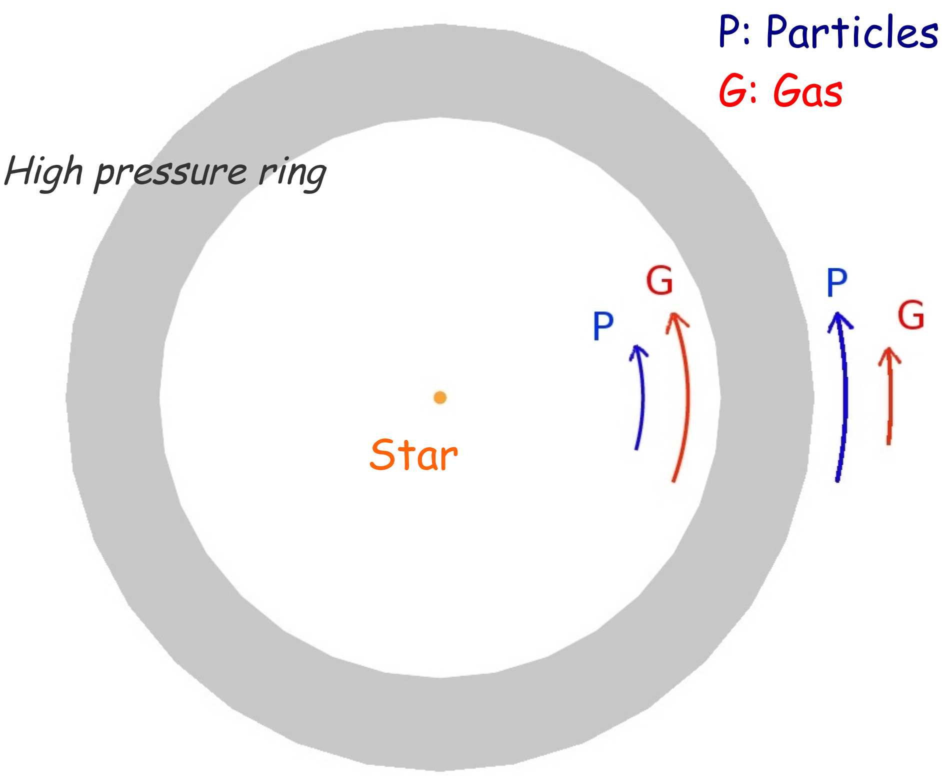
Particle drift



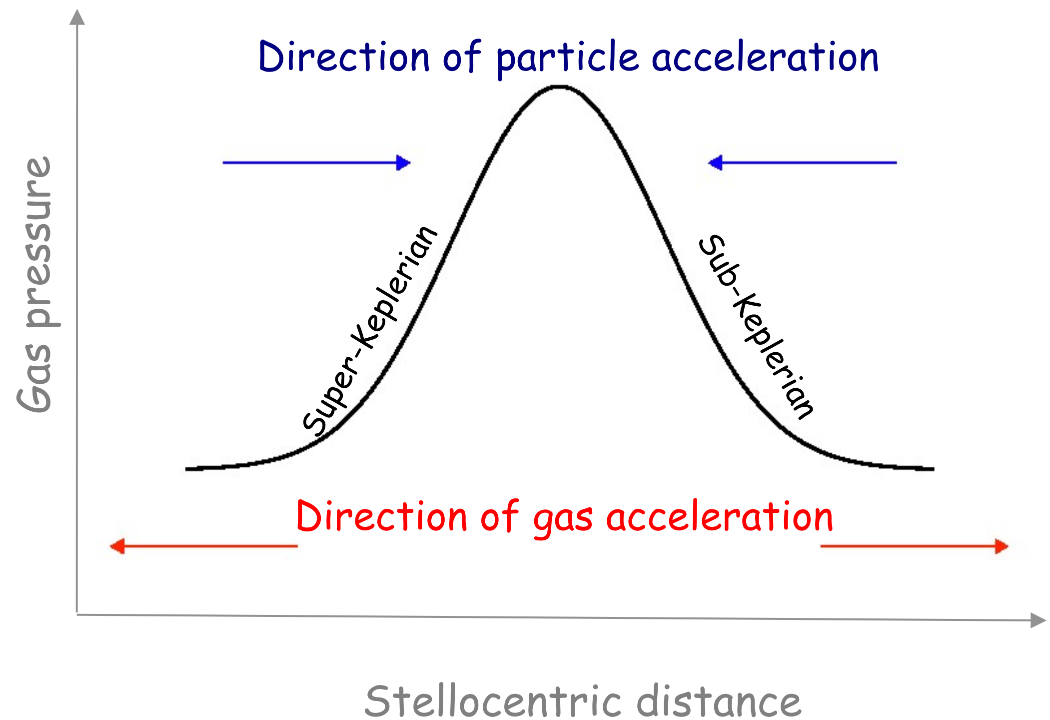
Adapted from Whipple (1972)



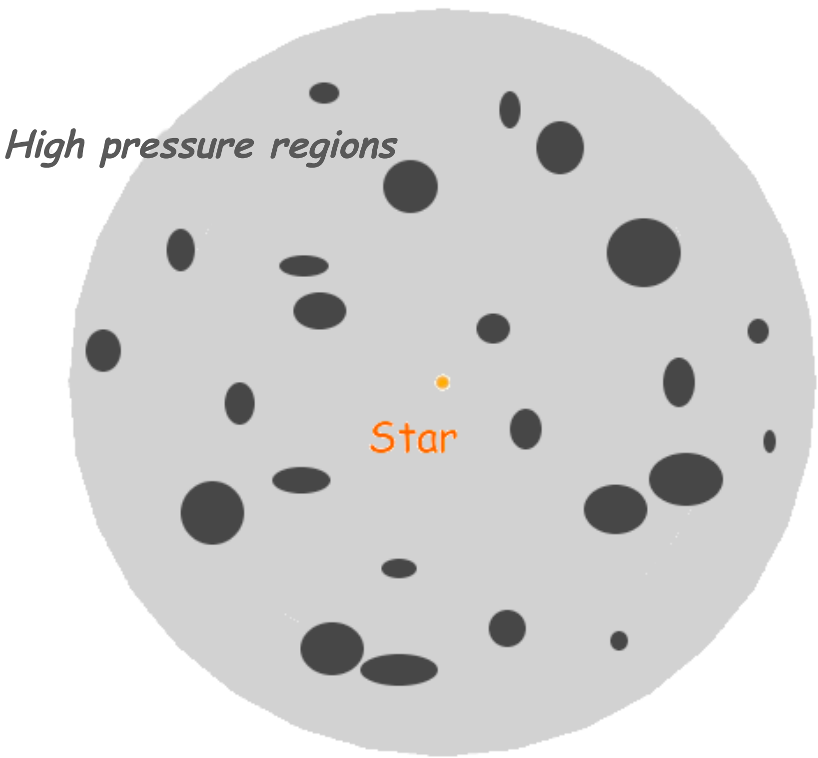
Pressure Trap

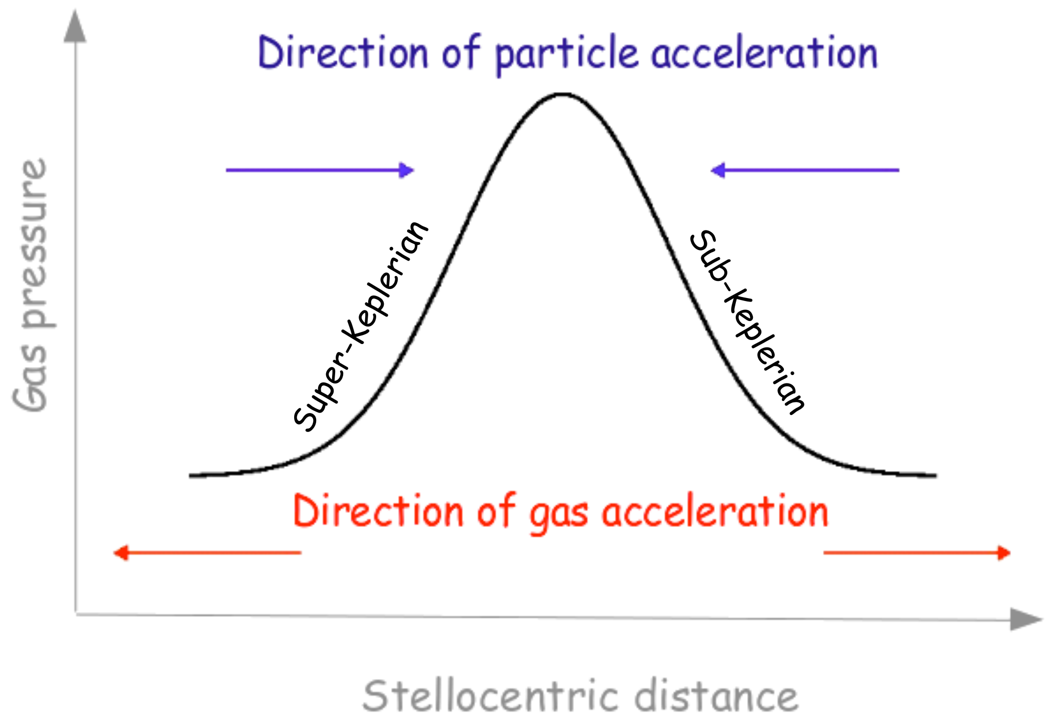


Adapted from Whipple (1972)

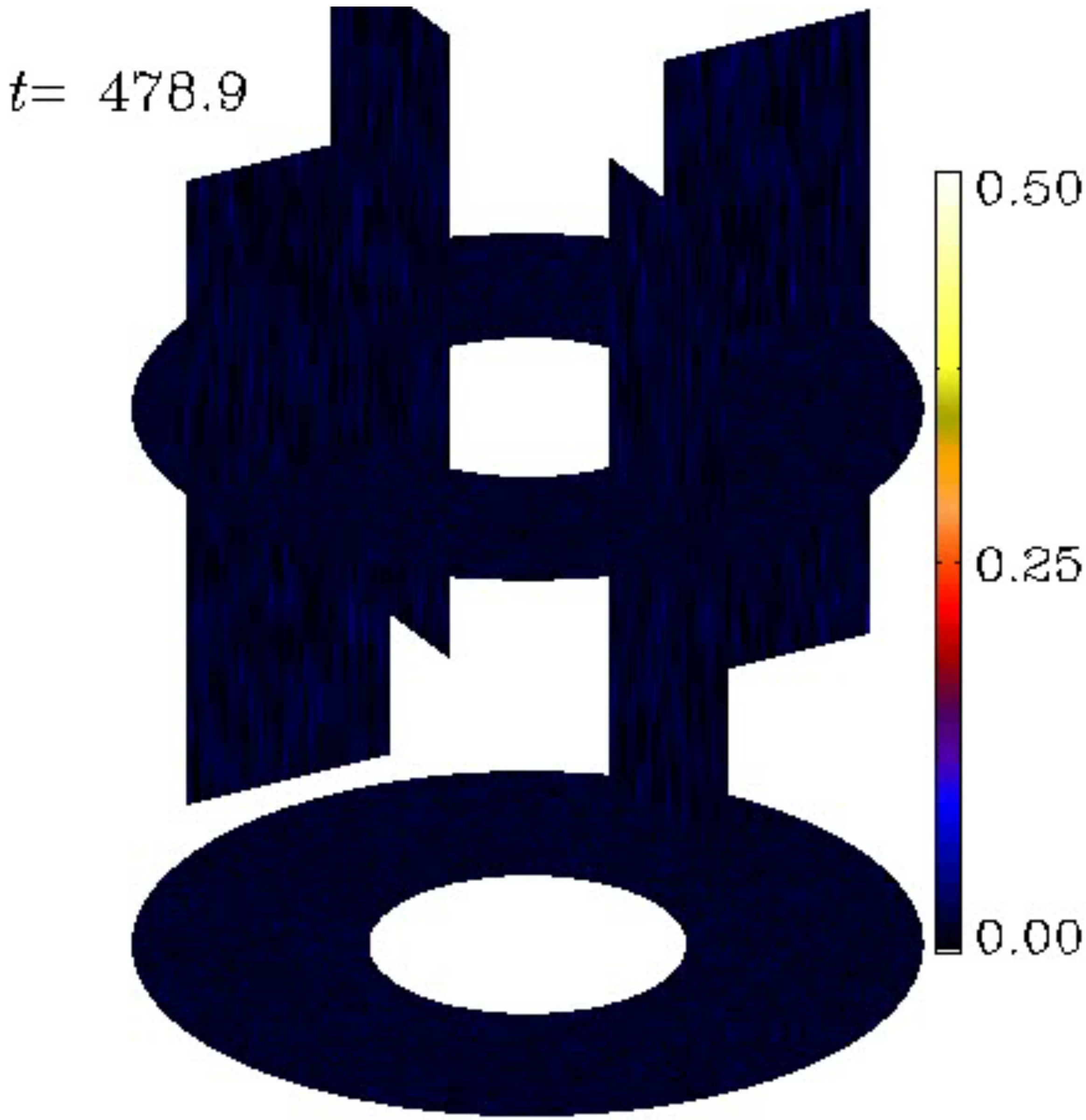


Pressure Trap



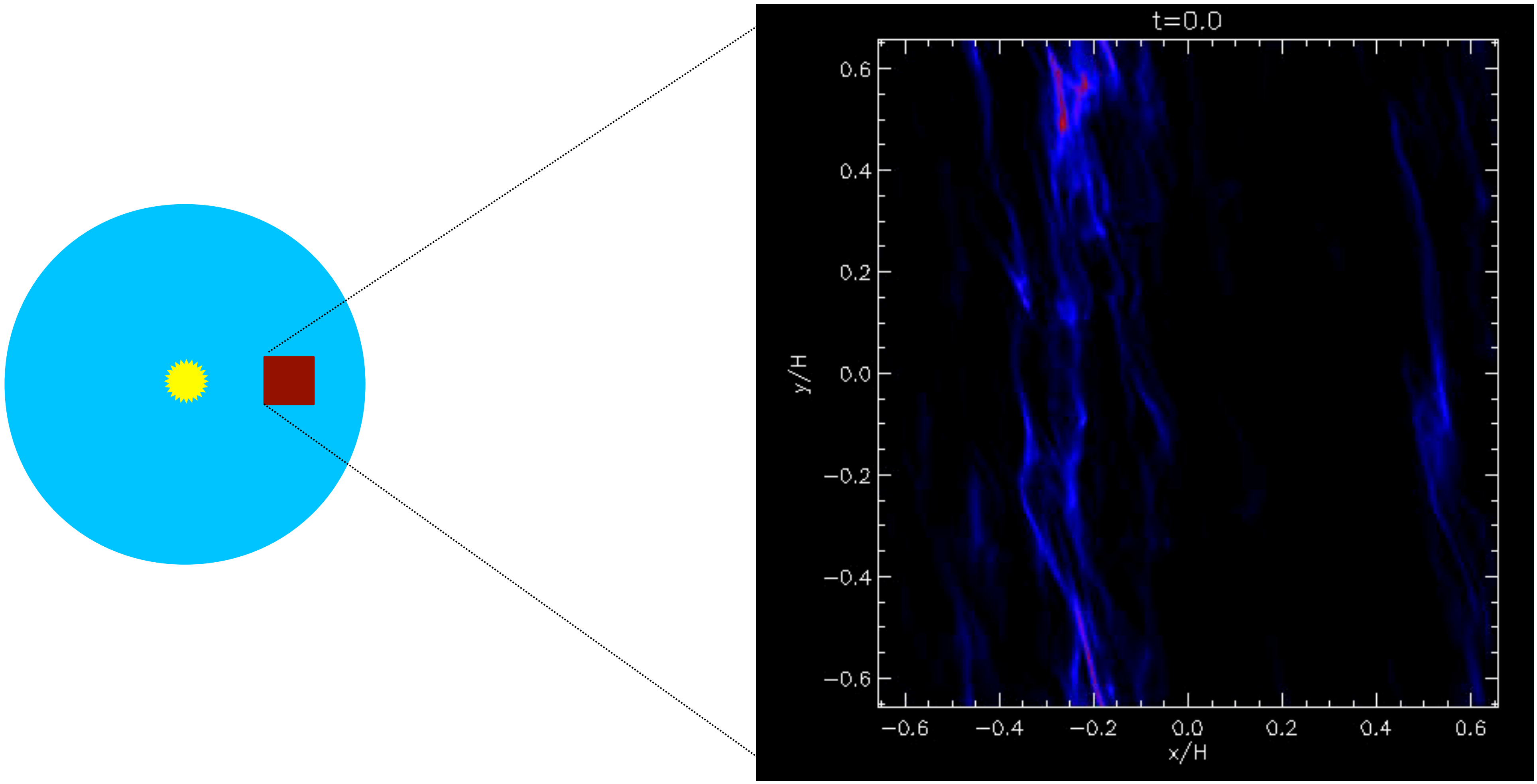


Turbulence concentrates solids mechanically in pressure maxima



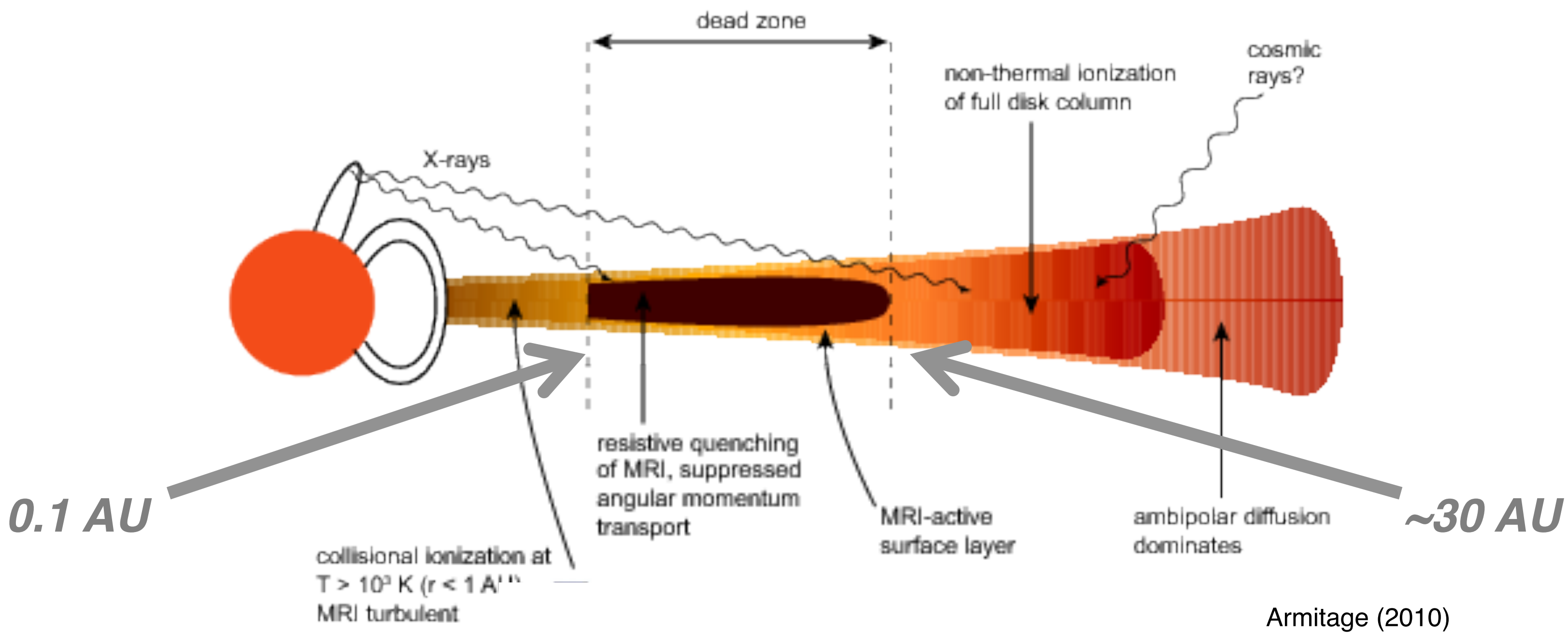
Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

Dead zones are robust features of protoplanetary disks



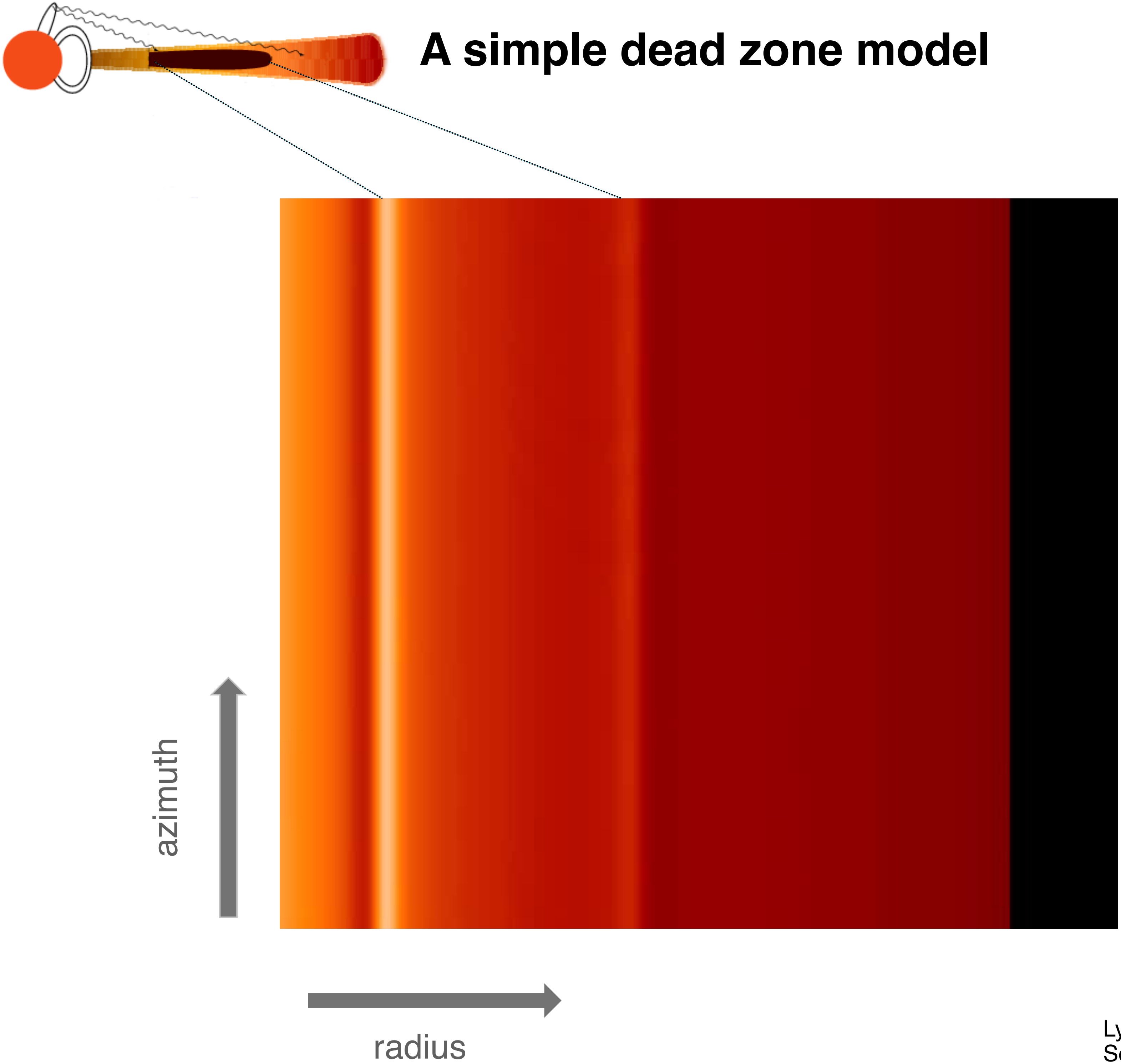
Armitage (2010)

Disks are cold and thus poorly ionized
(Blaes & Balbus 1994)

Therefore, accretion is **layered**
(Gammie 1996)

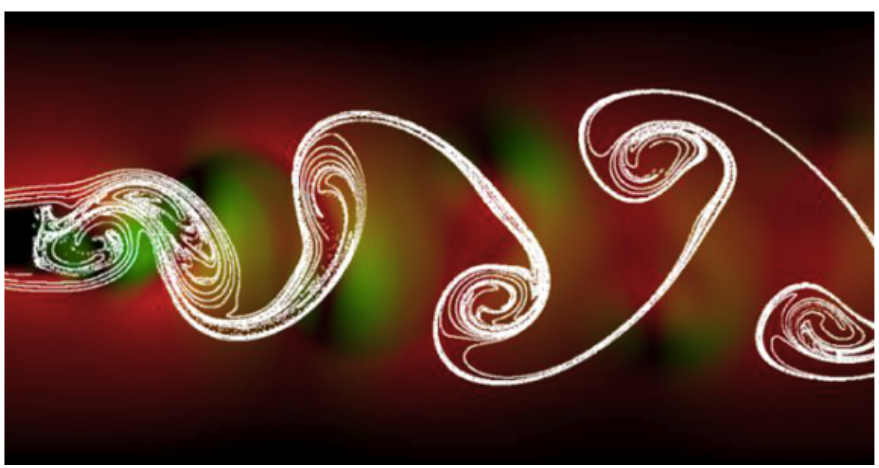
There should be a **magnetized, active zone**,
and a **non-magnetic, dead zone.**

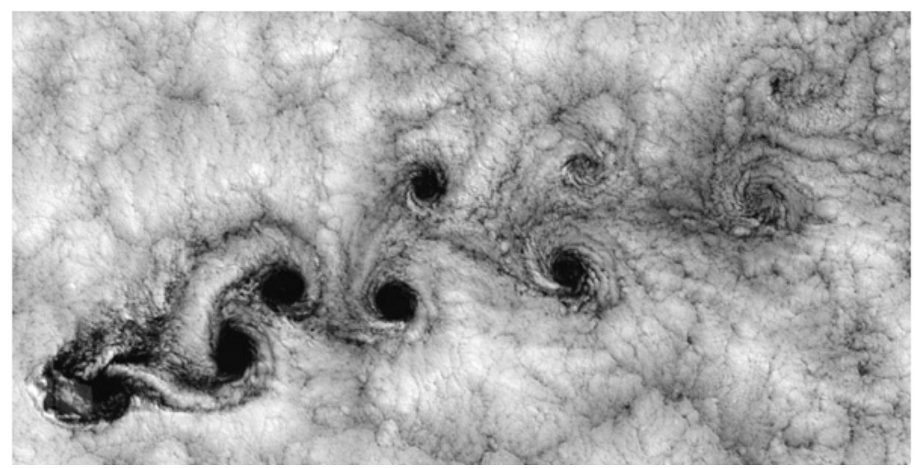
A simple dead zone model



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

Vortices – an ubiquitous fluid mechanics phenomenon

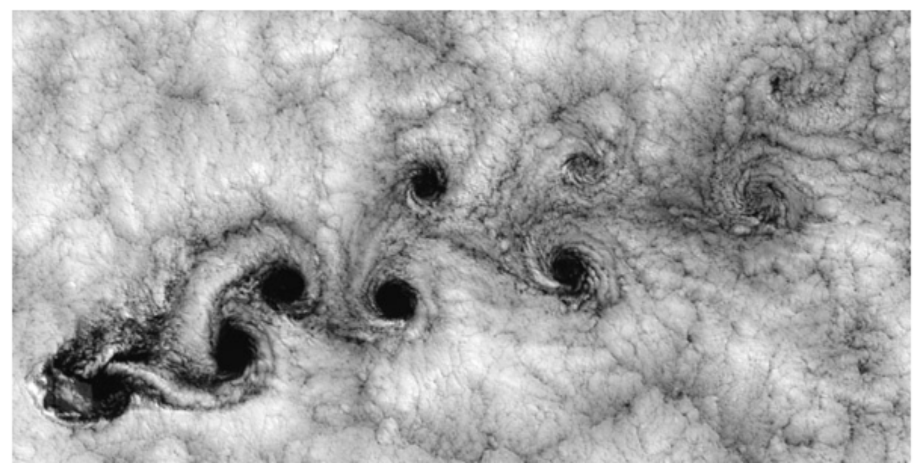




Vortices – an ubiquitous fluid mechanics phenomenon



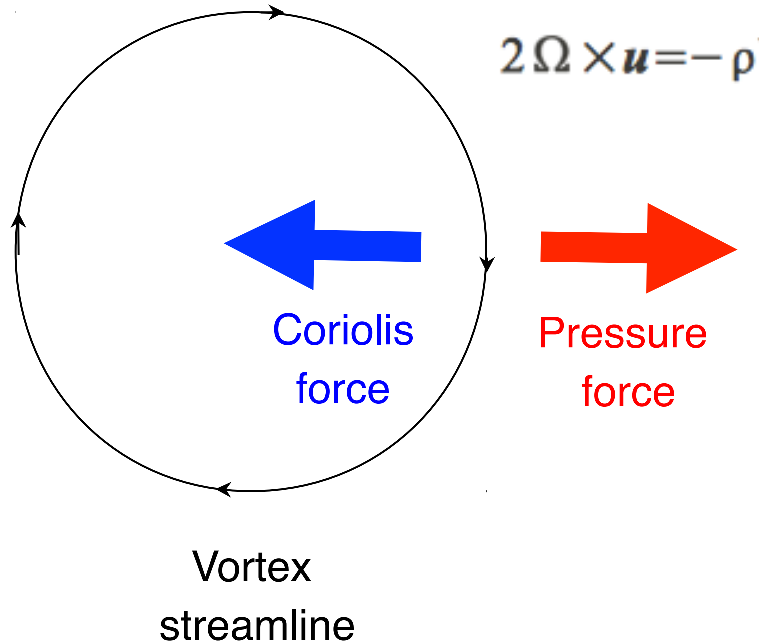
Von Kármán *vortex street*

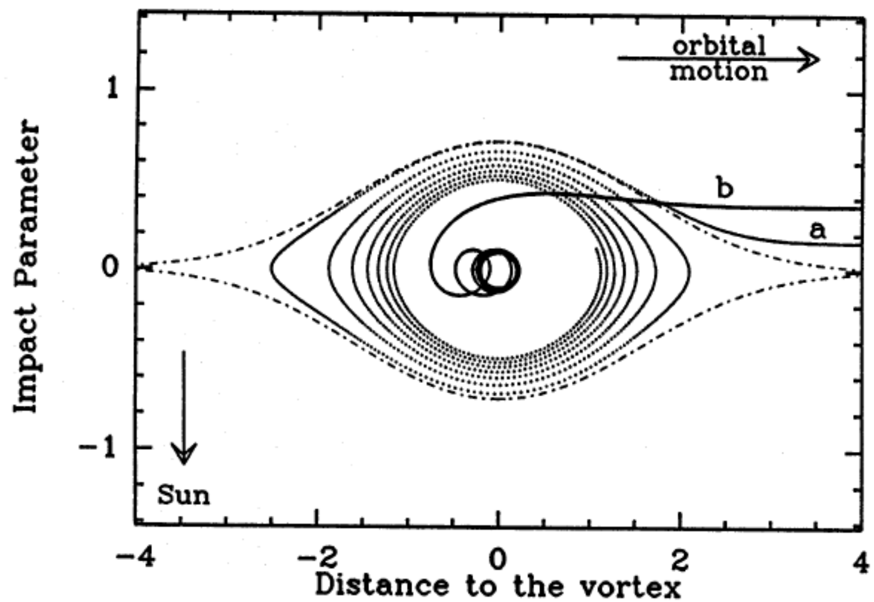



The Tea-Leaf effect

Geostrophic balance:

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





Barge & Sommeria (1995)

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

Aid to planet formation

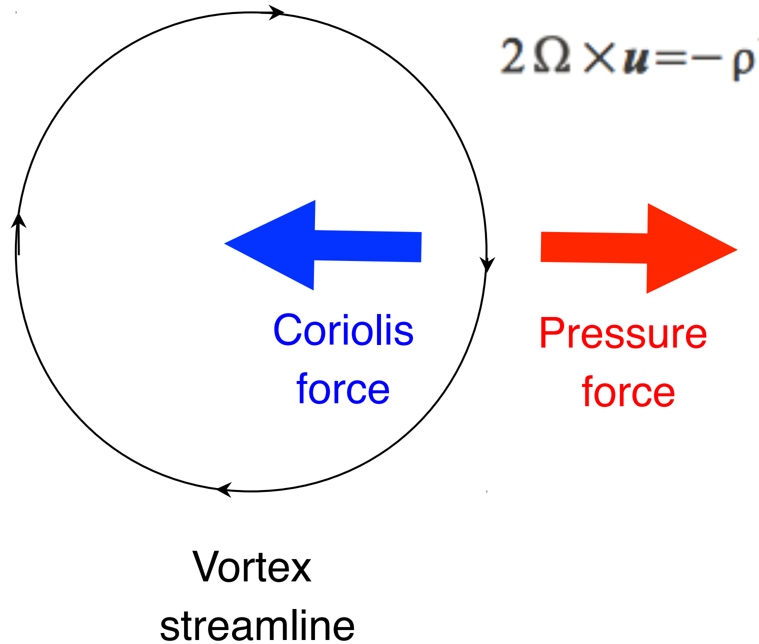
(Barge & Sommeria 1995, Adams & Watkins 1996, Tanga et al. 1996)

Speed up planet formation enormously

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

The Tea-Leaf effect

Geostrophic balance:



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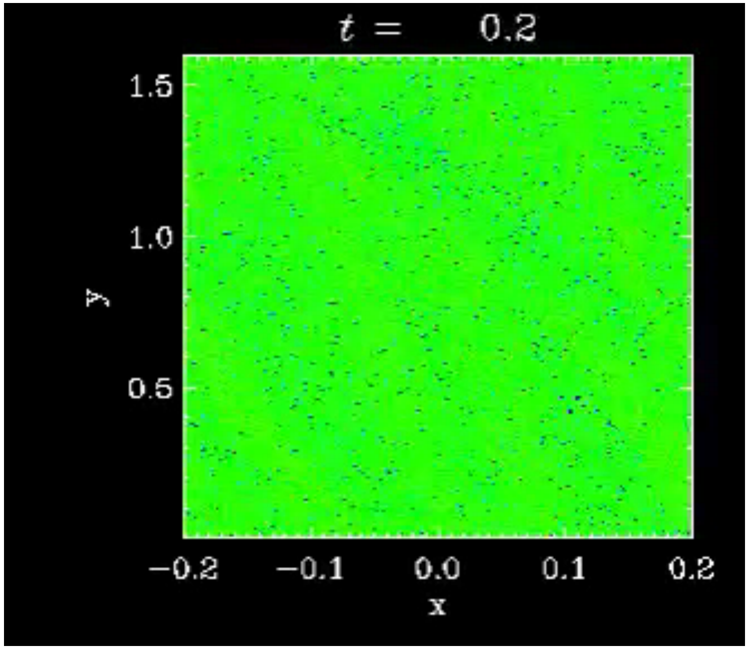

Raettig et al. (2012)

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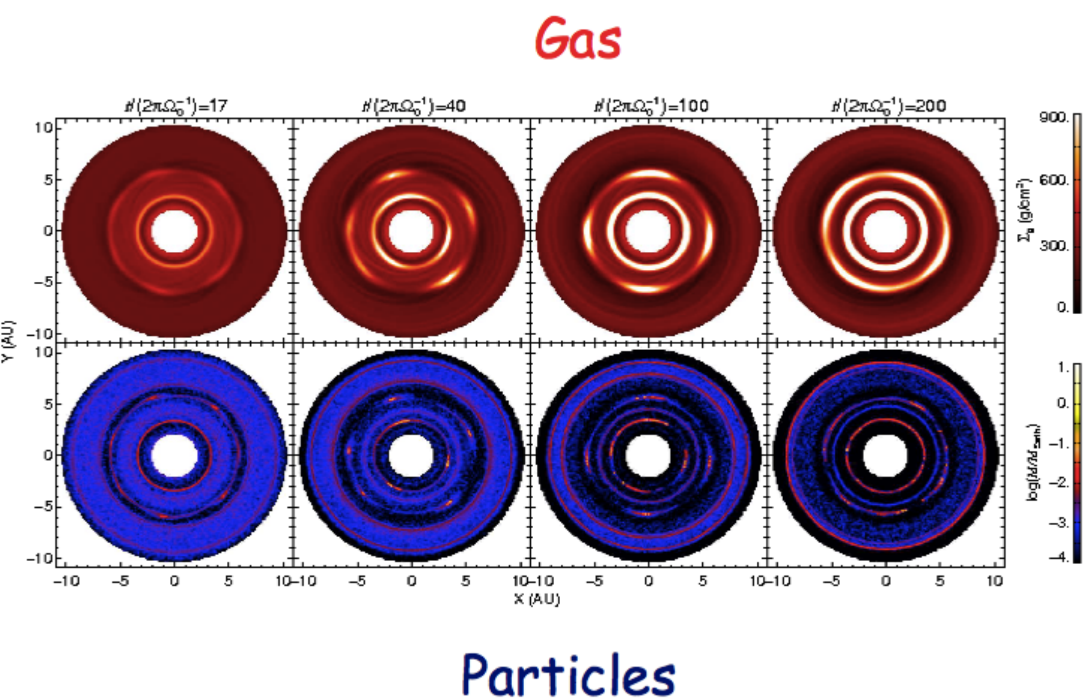
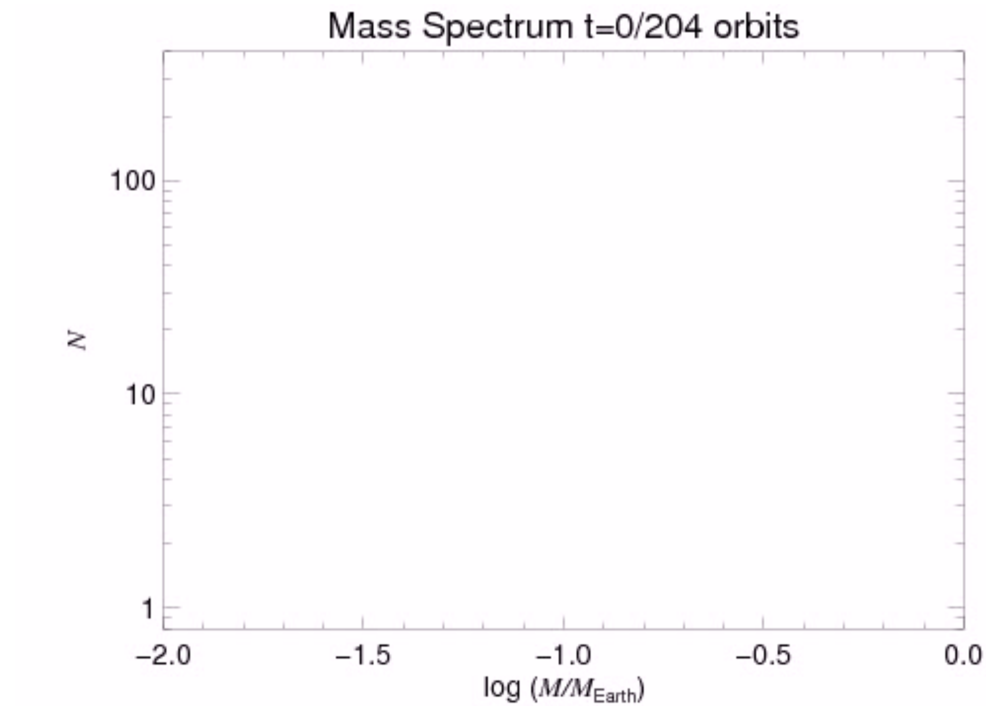
Vortices and Planet Formation

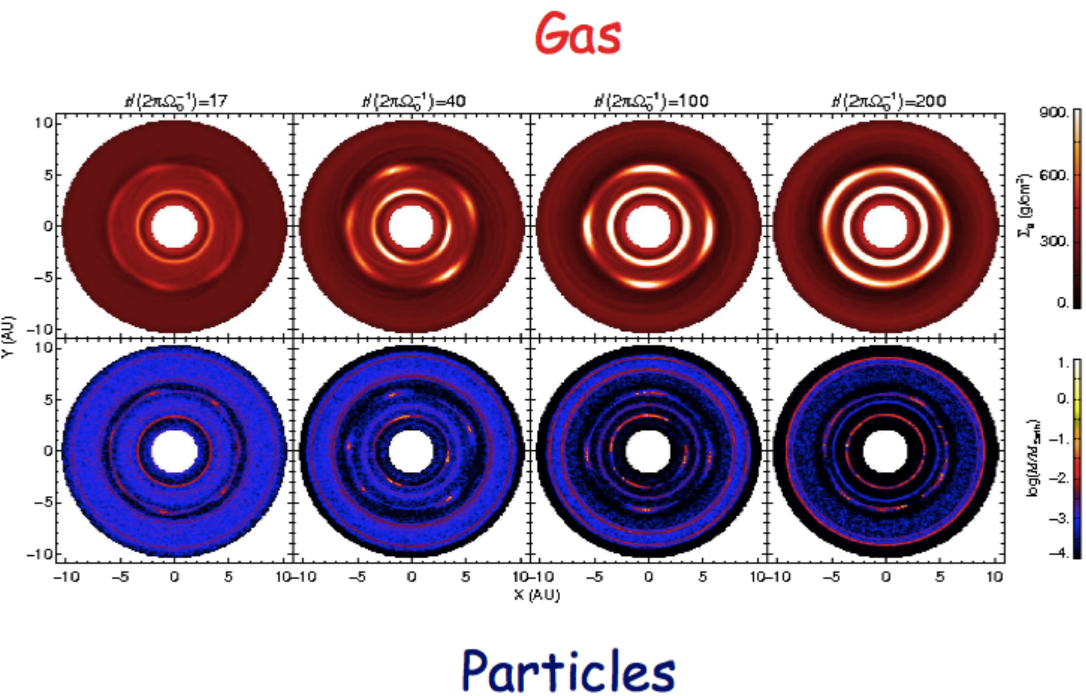


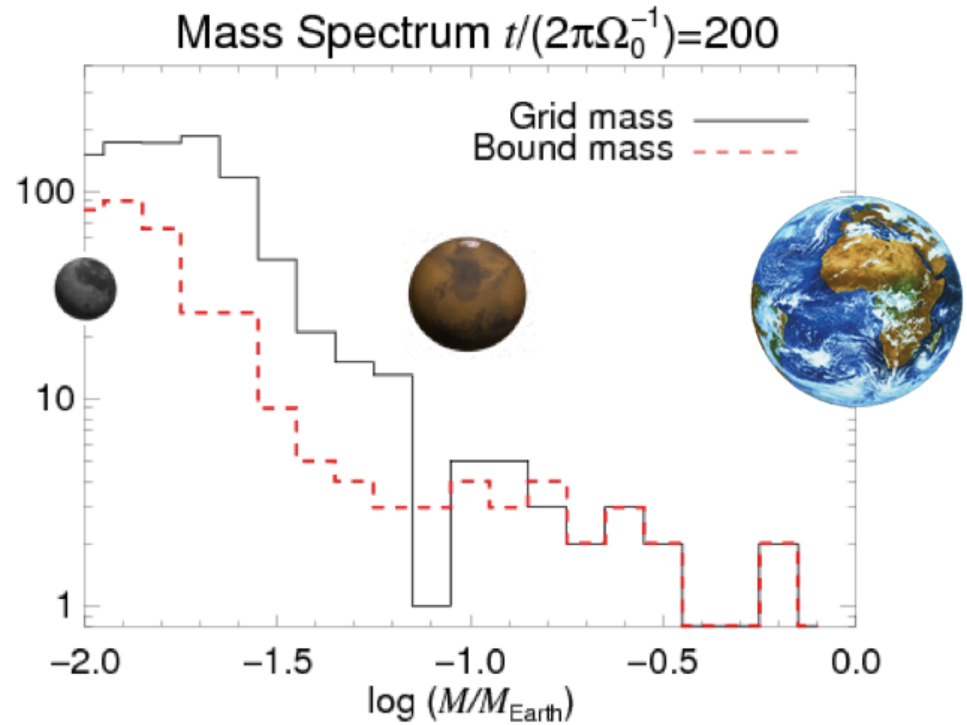


Collapse into Mars mass objects

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

Vortices and Planet Formation





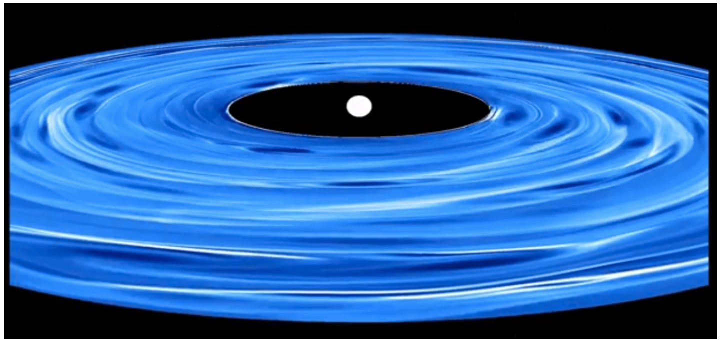
Collapse into Mars mass objects

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

Sustaining vortices in disks

Baroclinic instability

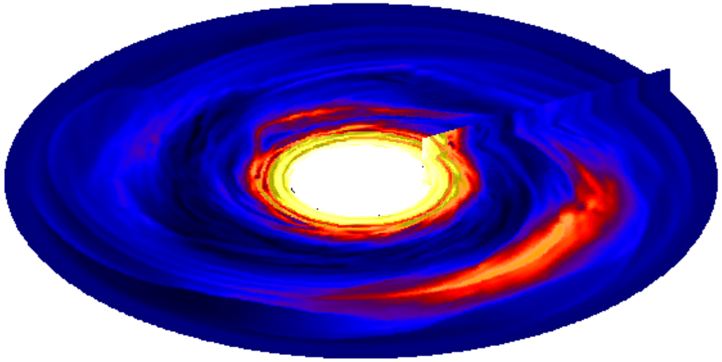
(Convective overstability)



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)

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

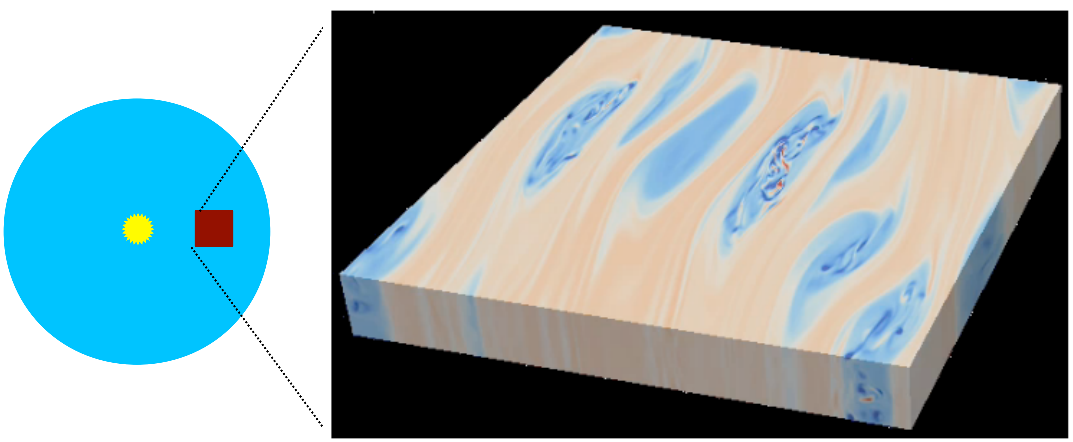
Rossby wave instability



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)

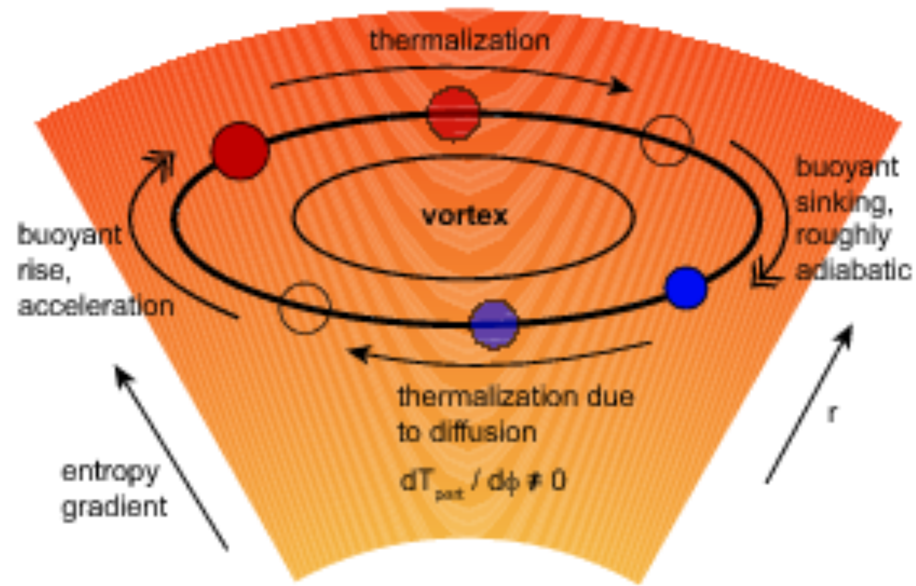
Powered by:
Modification of shear profile
(external vorticity reservoir)

Baroclinic Instability – Excitation and self-sustenance of vortices



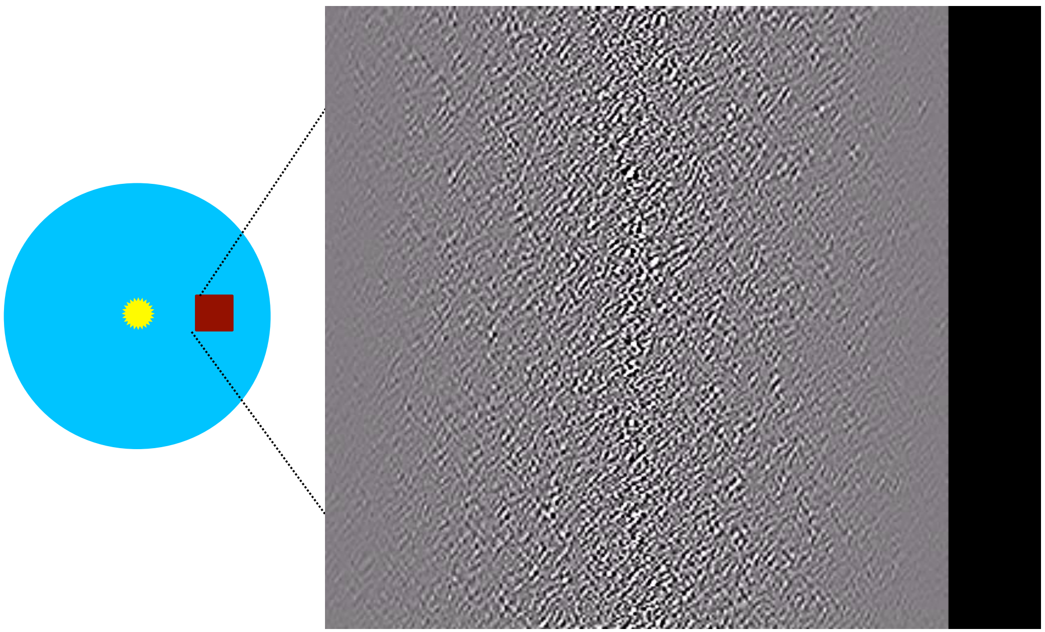
Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability



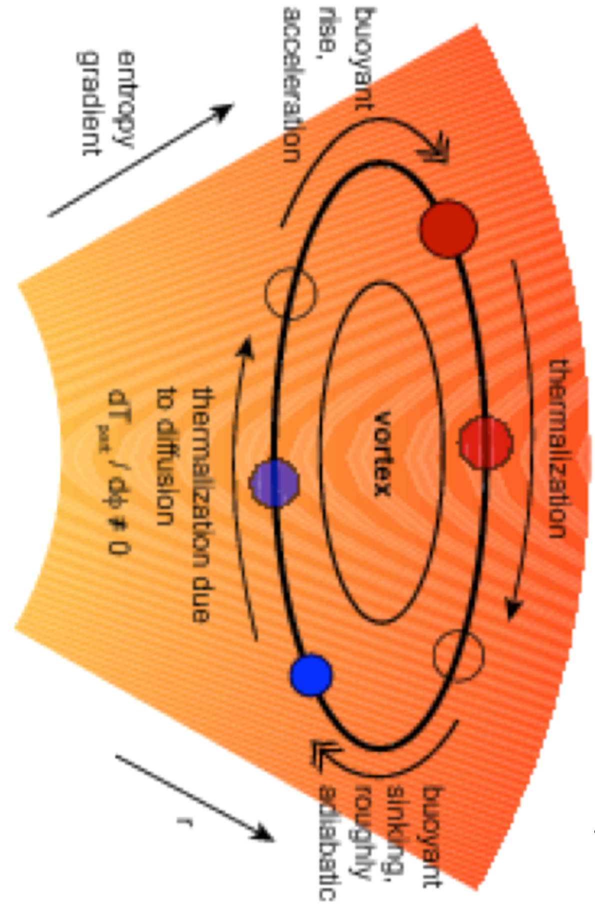
Armitage (2010)

Baroclinic Instability – Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

Sketch of the Baroclinic Instability

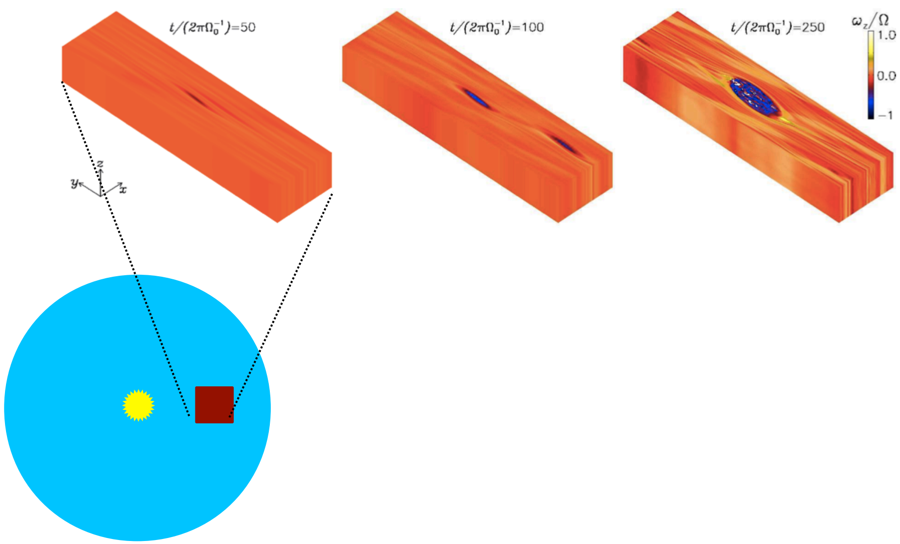


Armitage (2010

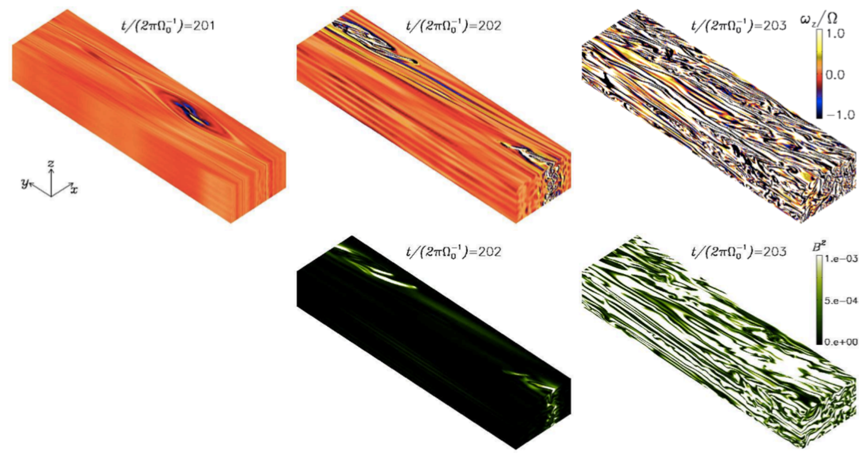
Baroclinic instability and layered accretion

What happens when the vortex is magnetized?

Hydro



MHD

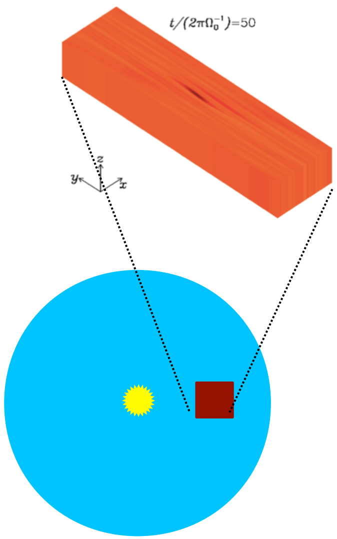


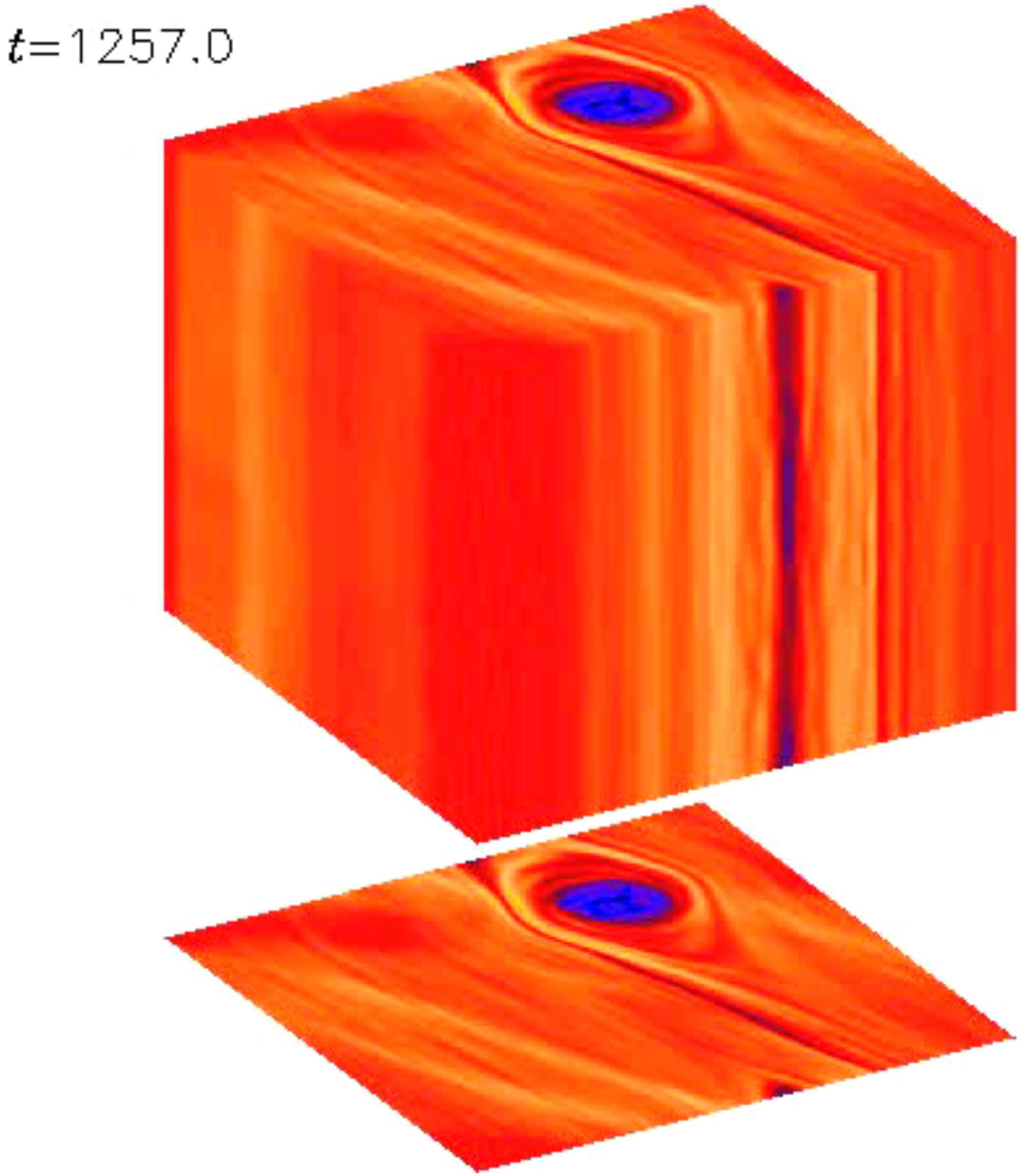
Vorticity

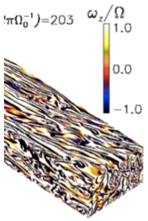
Mag. Energy

Lyra & Klahr (2011)

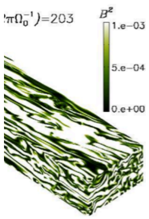
Baroclinic instability and layered accretion







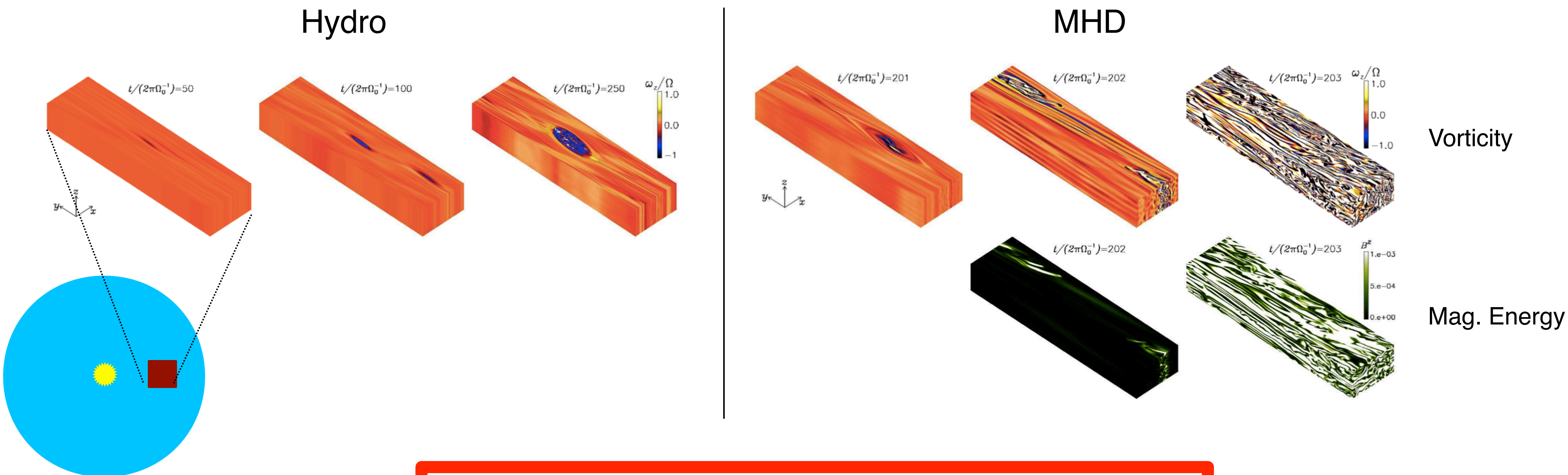
Vorticity



Mag. Energy

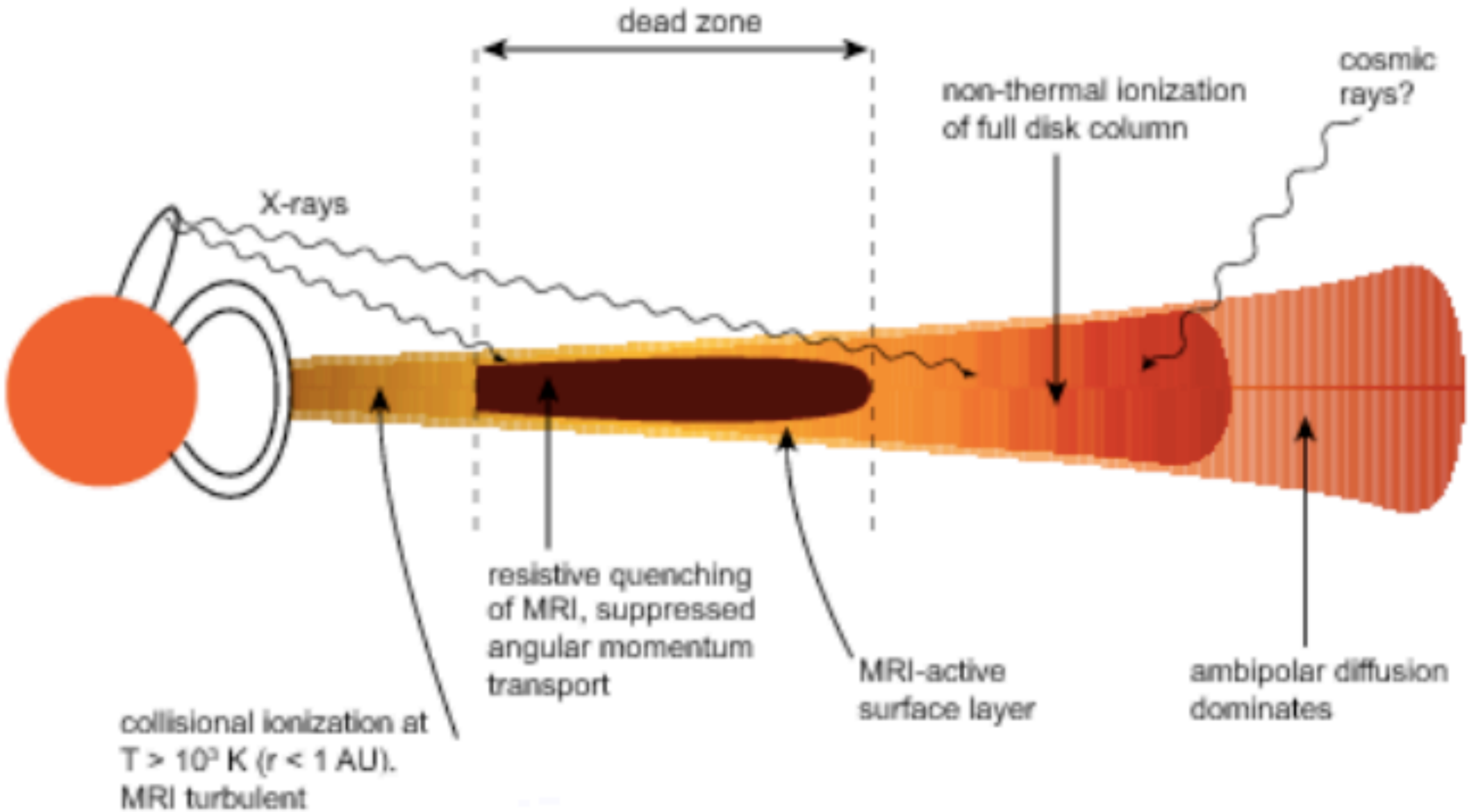
Baroclinic instability and layered accretion

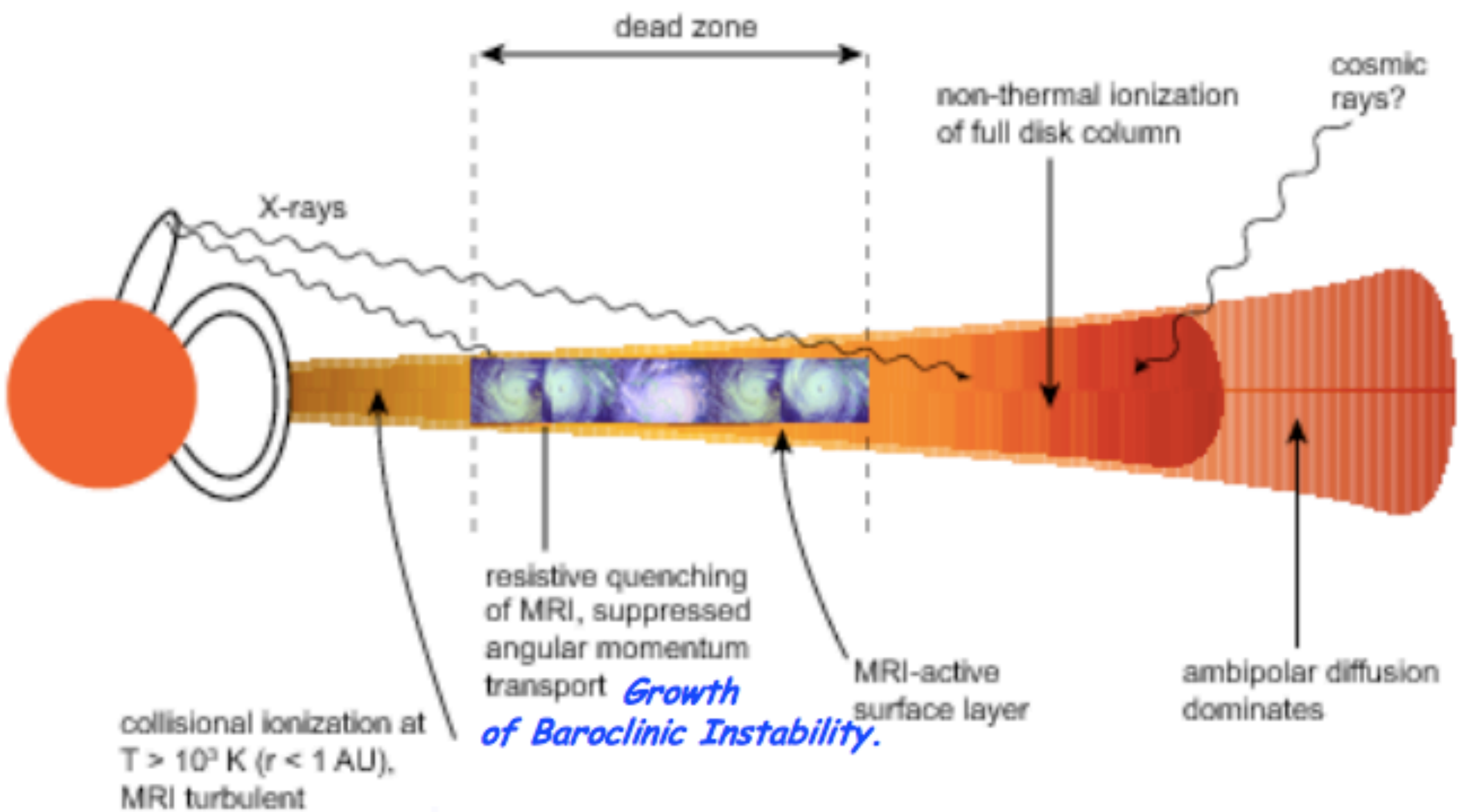
What happens when the vortex is magnetized?



Lyra & Klahr (2011)

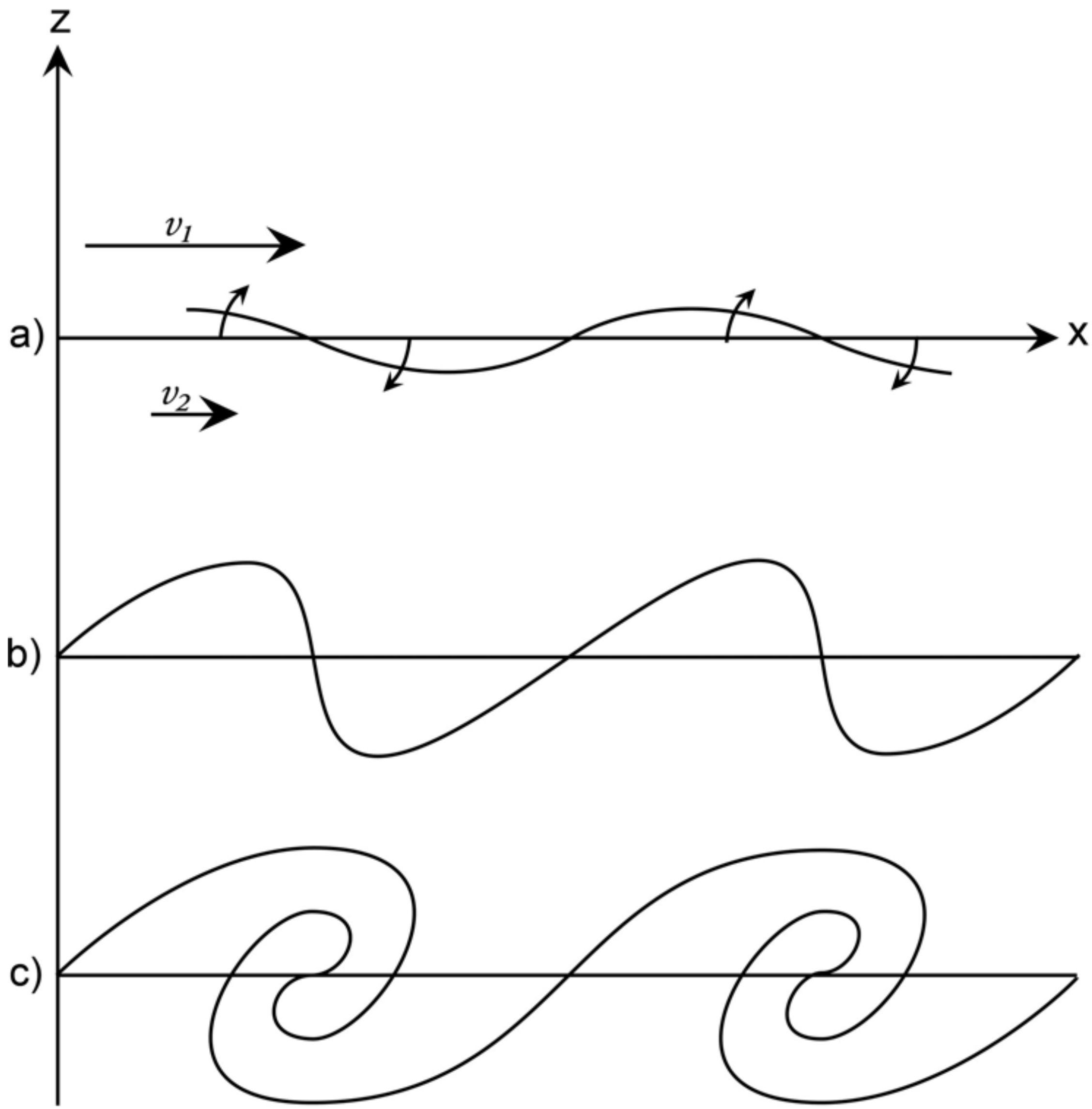
Baroclinic vortices
do ***not*** survive magnetization


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



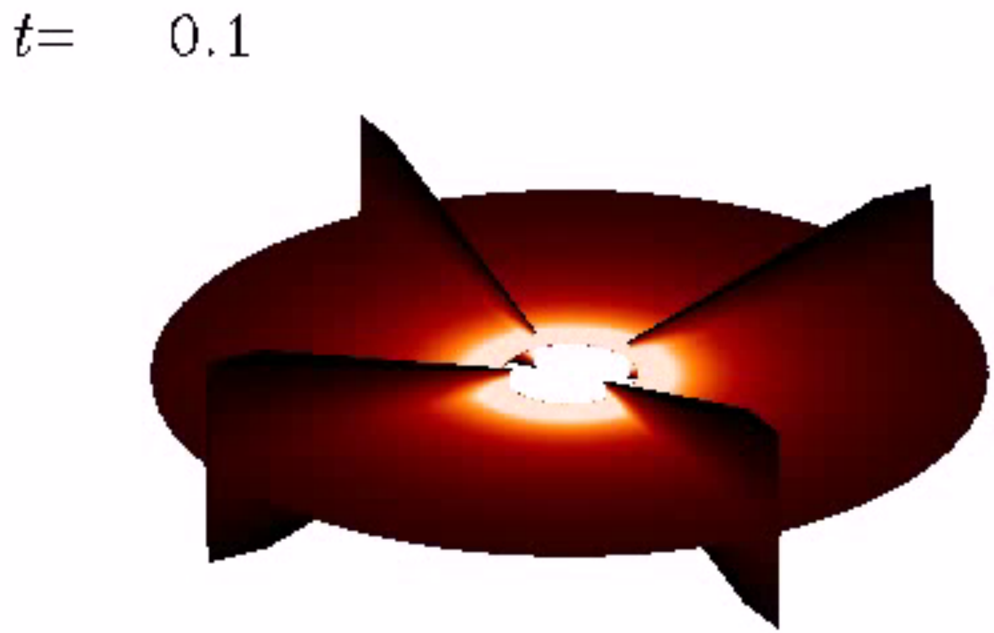
dead zone
cosmic rays?
non-thermal ionization of full disk column
X-rays
resistive quenching of MRI, suppressed angular momentum transport
Growth of Baroclinic Instability.
MRI-active surface layer
ambipolar diffusion dominates
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent

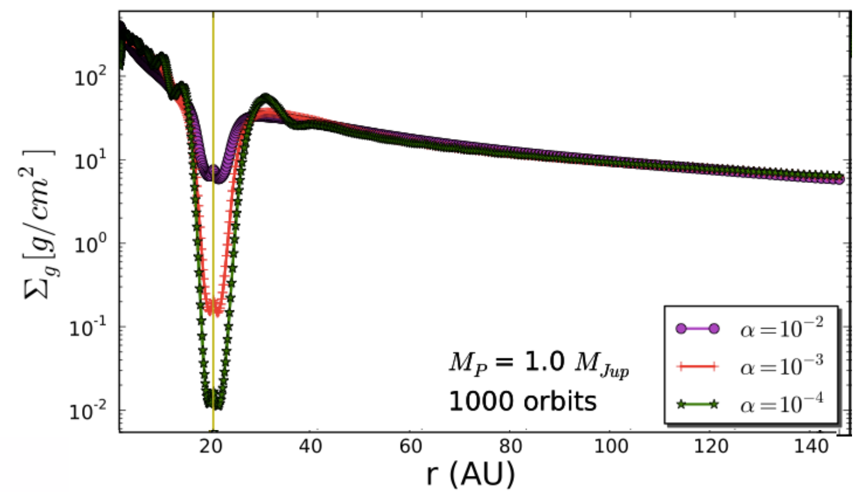
Rossby Wave Instability
(or… **Kelvin-Helmholtz** in rotating disks)



Planetary gap RWI

(de Val-Borro et al. 2006, 2007)

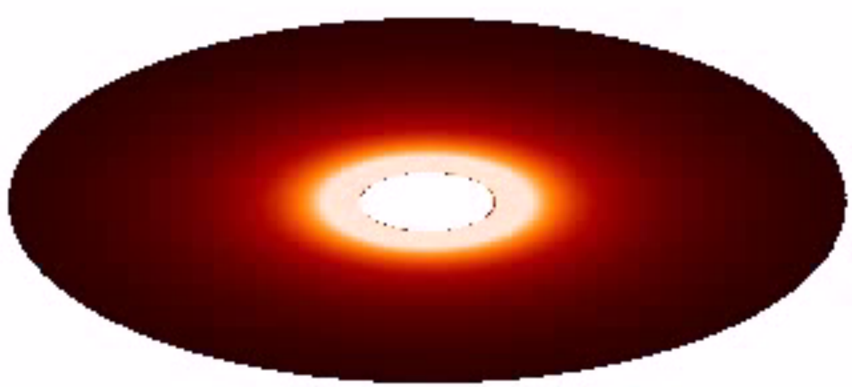




Pinilla et al. (2012)

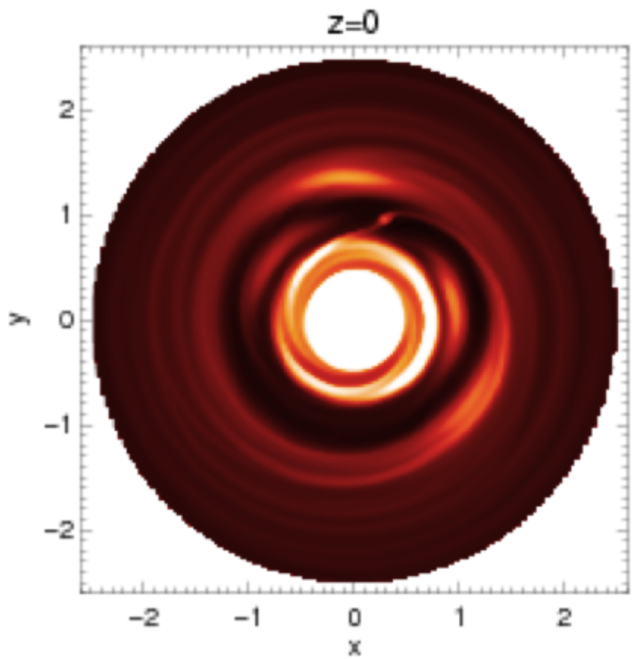
Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

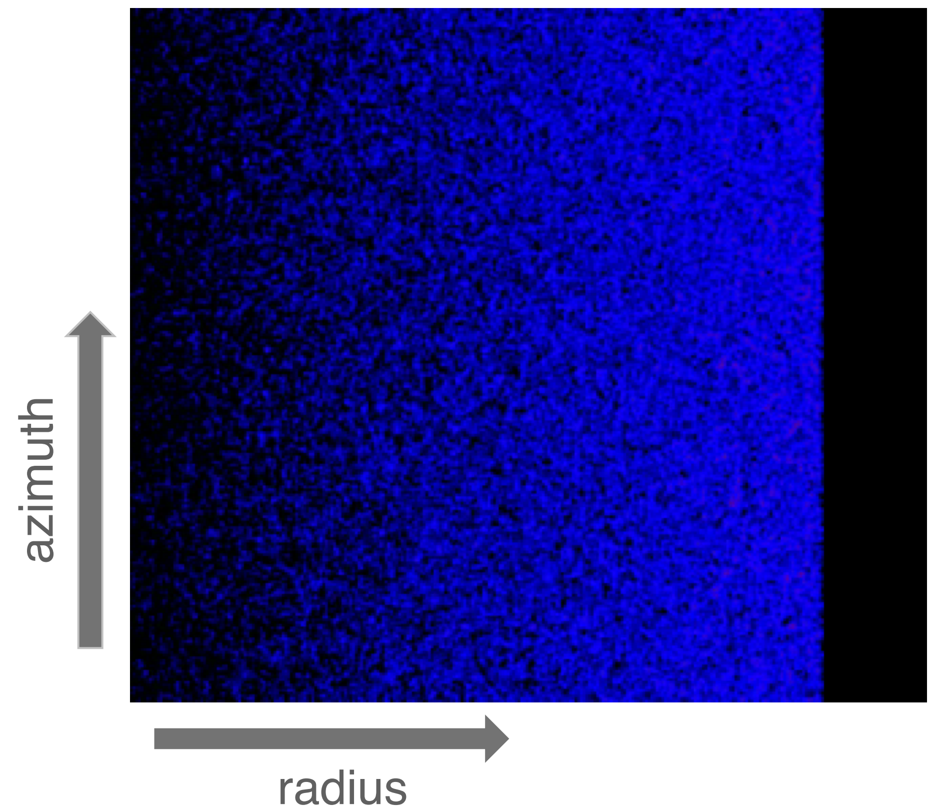


Lyra (2009)

Planetary gap RWI



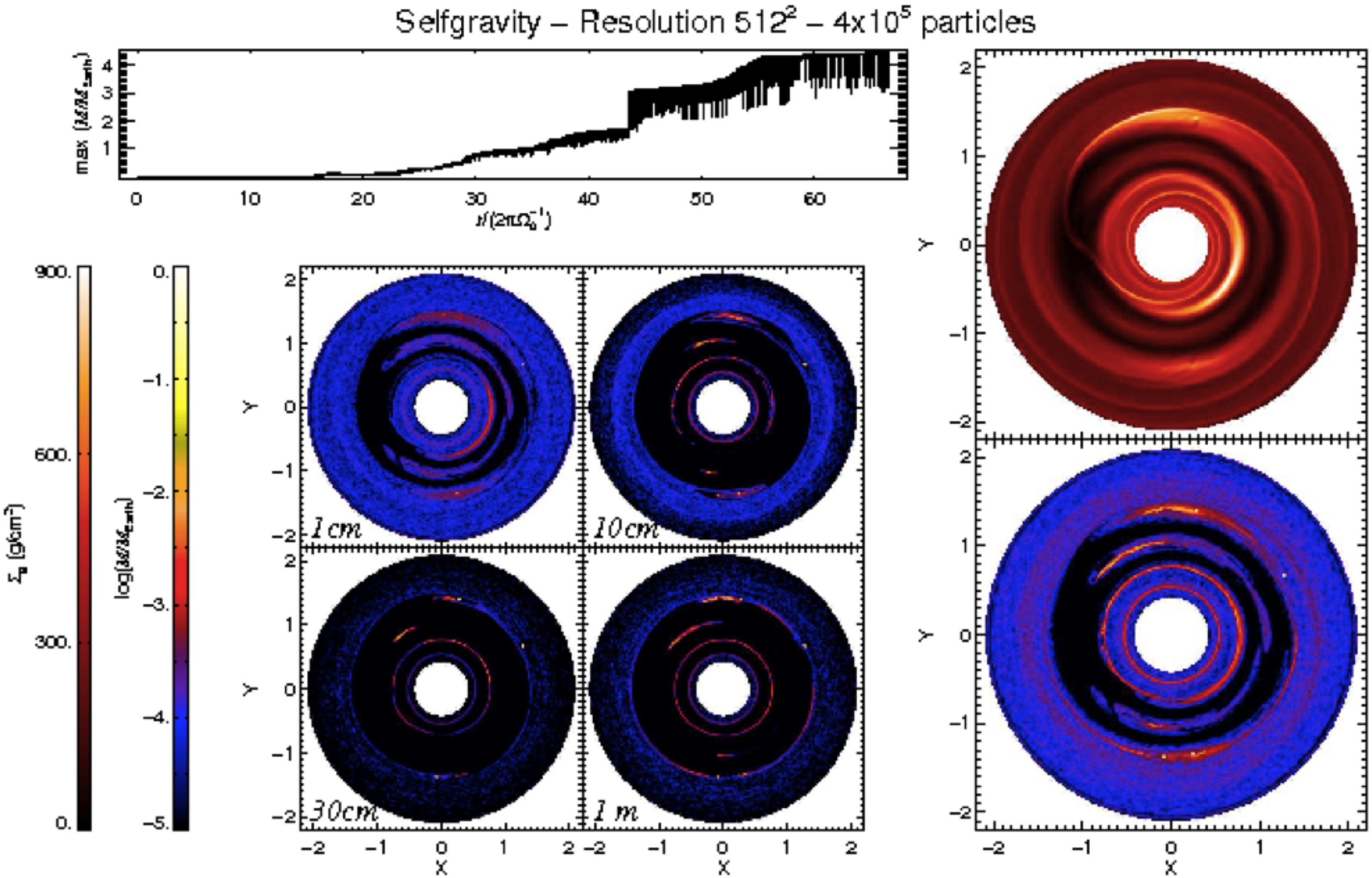
Lyra et al. (2009b),
see also de Val-Borro et al. (2007)



Burst of formation in gap vortices

Plus Trojan planets in Lagrangian clouds

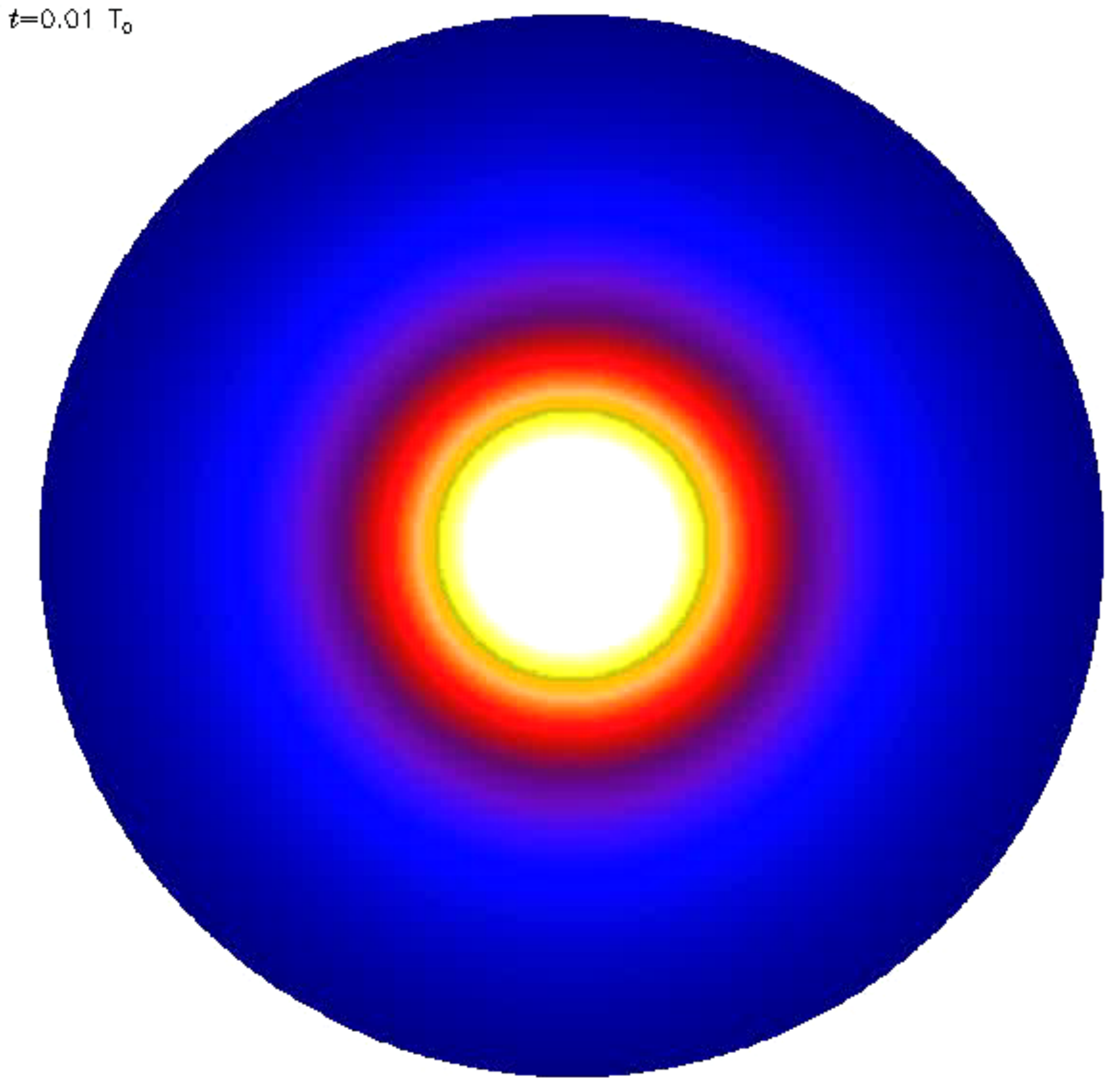
Vortex trapping



3 Super-Earths formed + Mars mass Trojans

Lyra et al. (2009b)

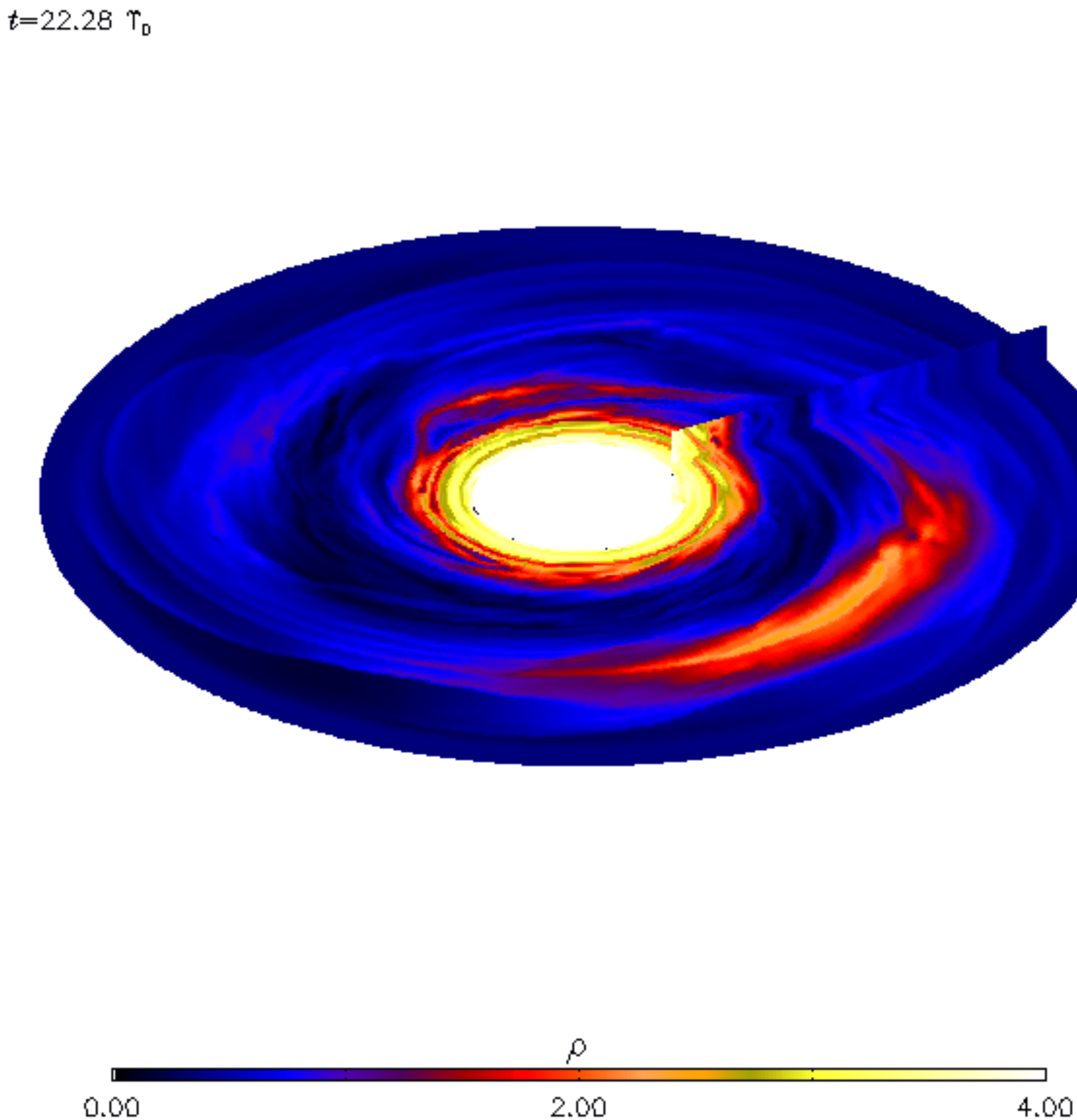
Active/dead zone boundary

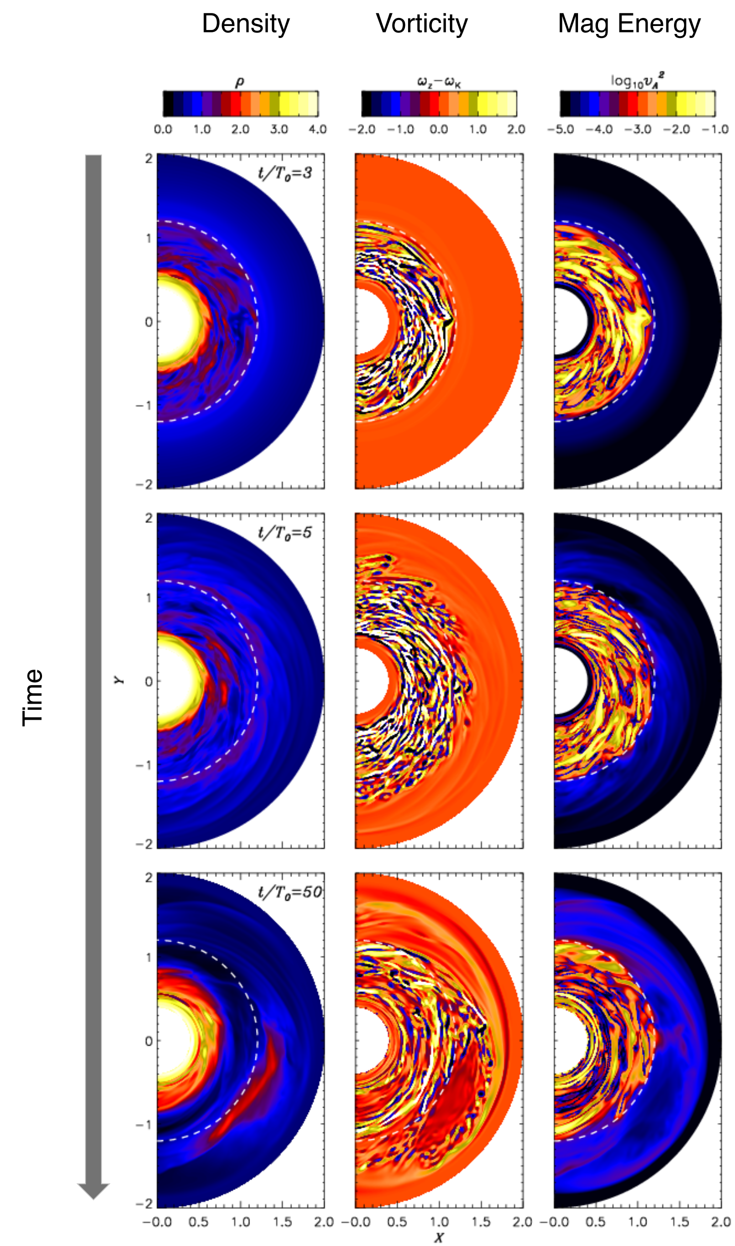


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Active/dead zone boundary

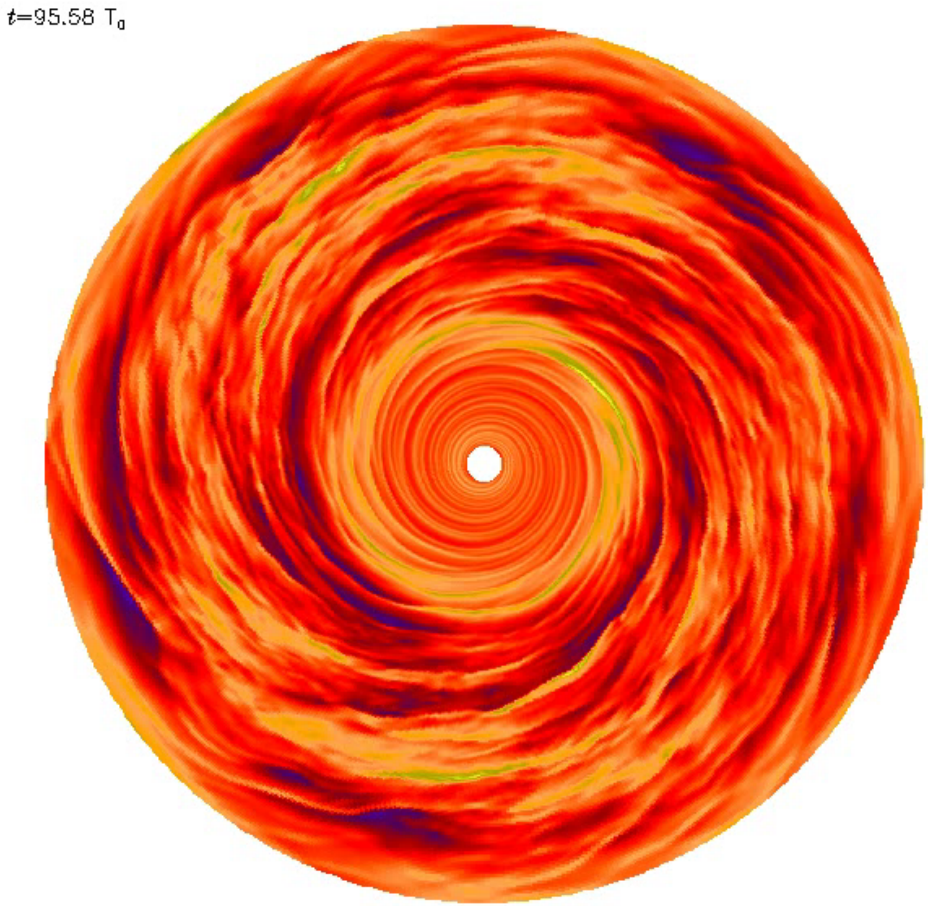


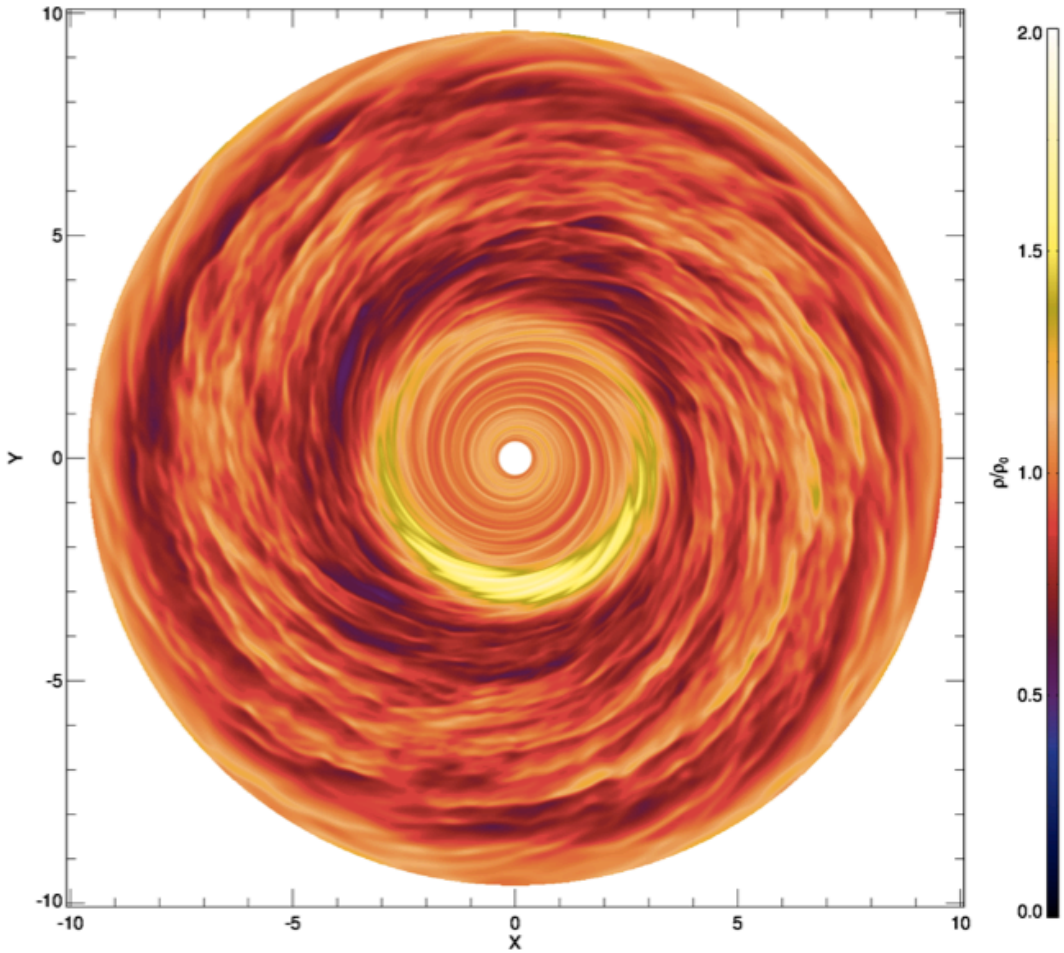


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Outer Dead/Active zone transition RWI





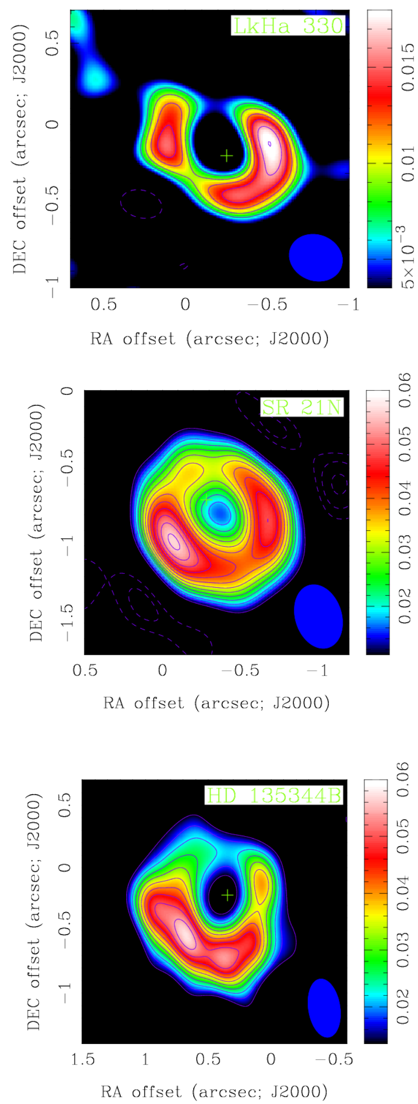
Resistive inner disk + magnetized outer disk

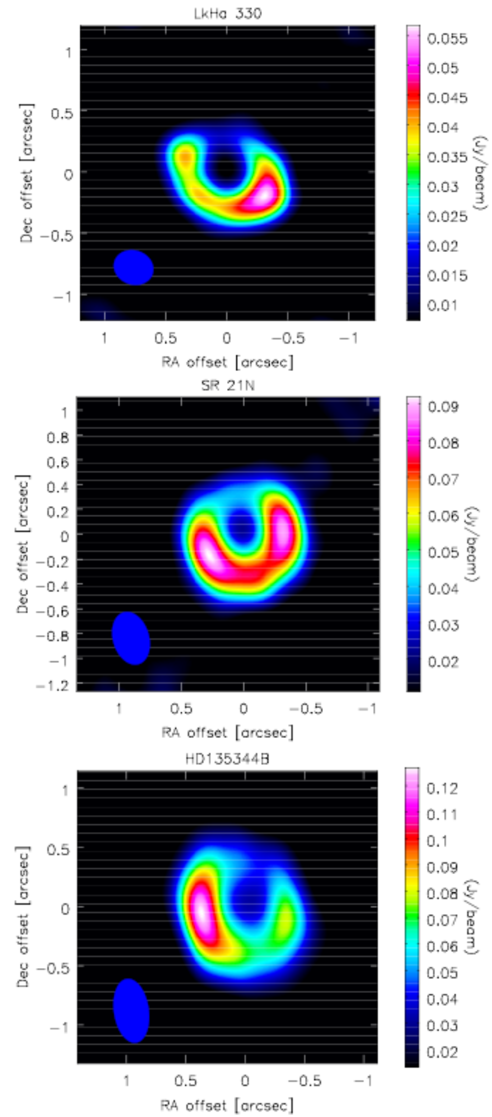
Lyra, Turner, & McNally (2015)

A possible detection of vortices in disks?

Observations

Brown et al. (2009)





Models

Simulated observations of Rossby vortices

Regaly, Sándor 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]

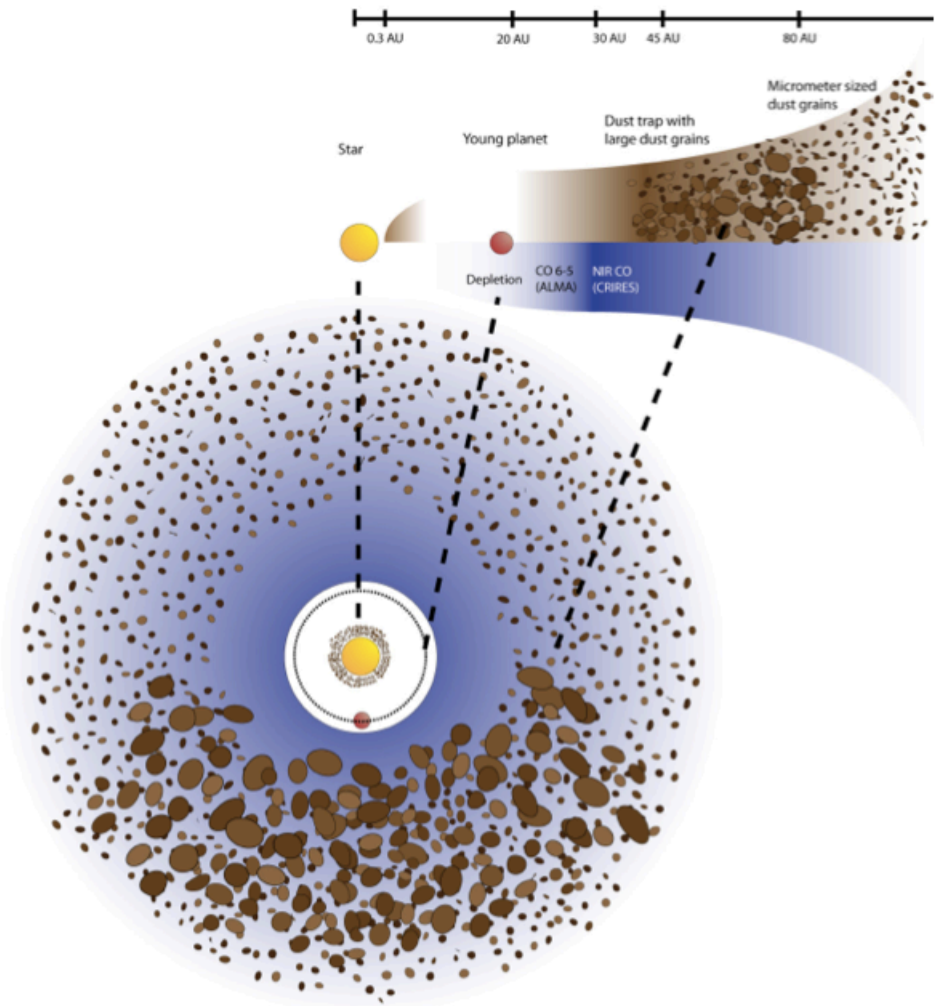
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection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

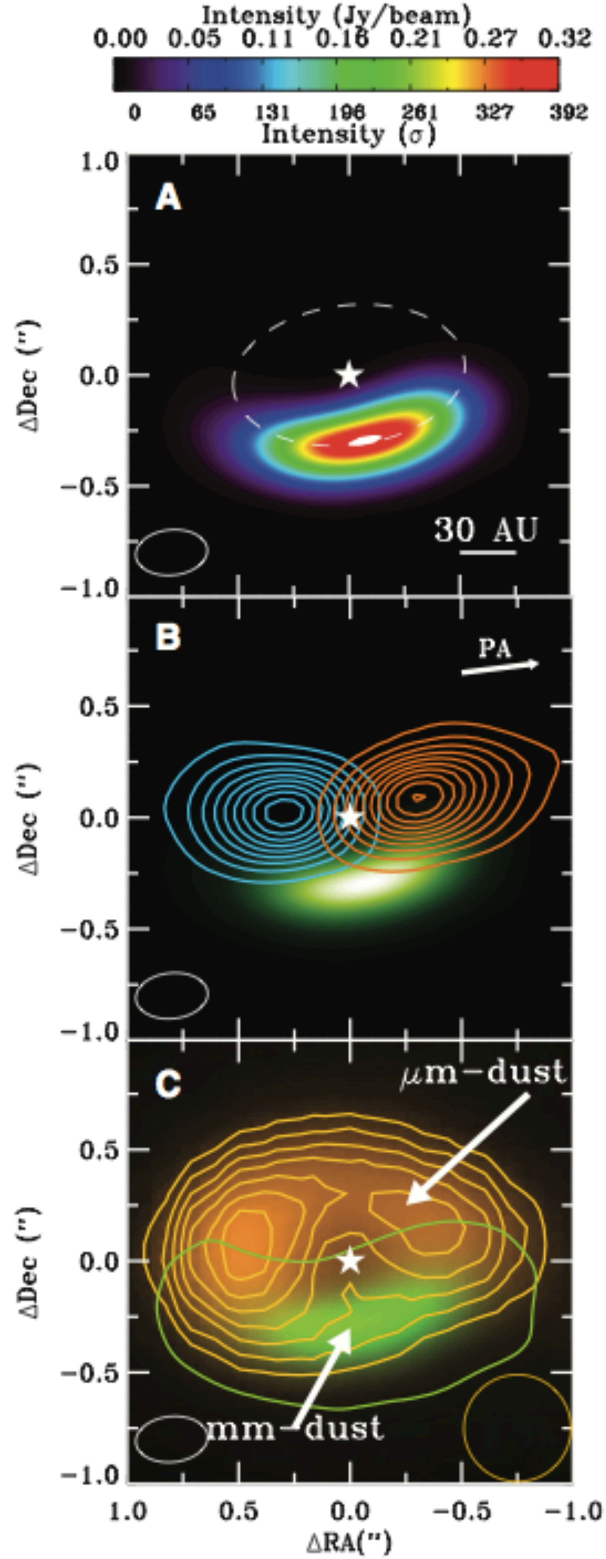
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

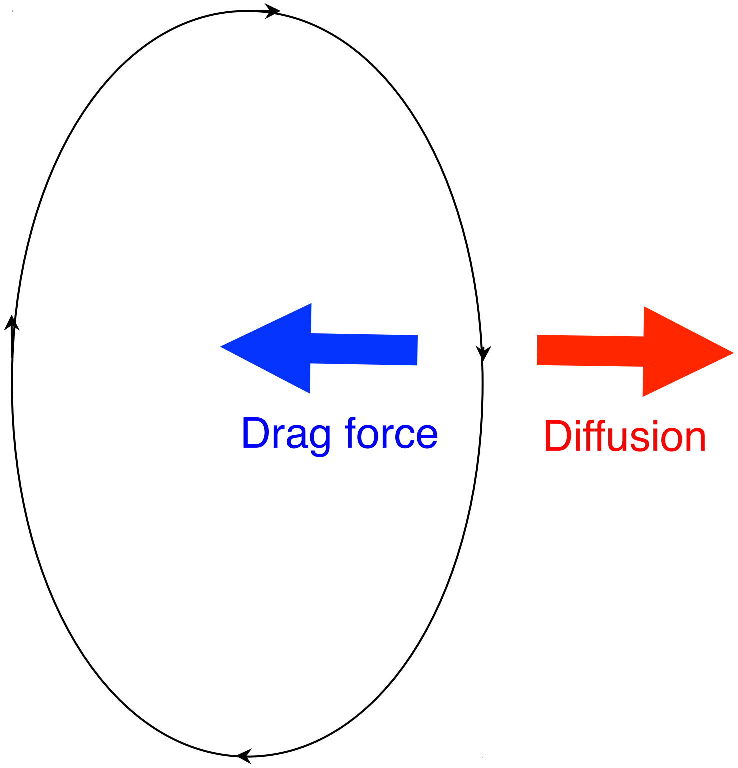


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

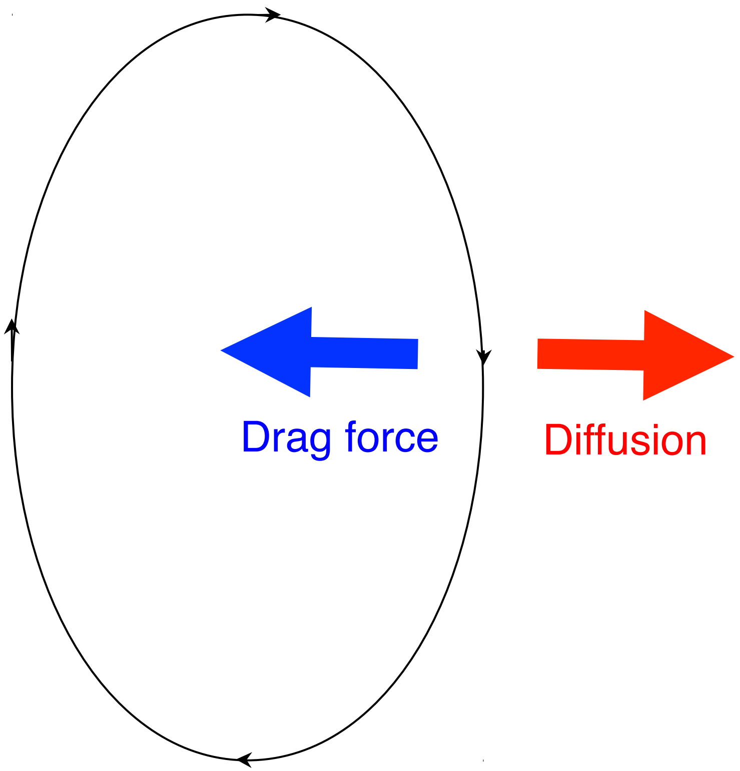
Micron-sized dust follows gas

Drag-Diffusion Equilibrium



Trapped particle

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

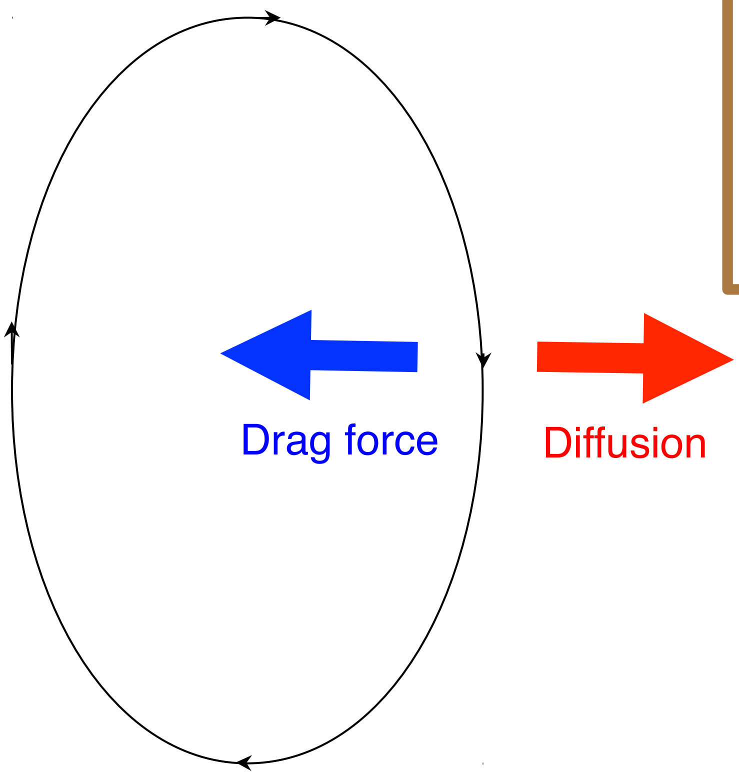
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

advection

compression

diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

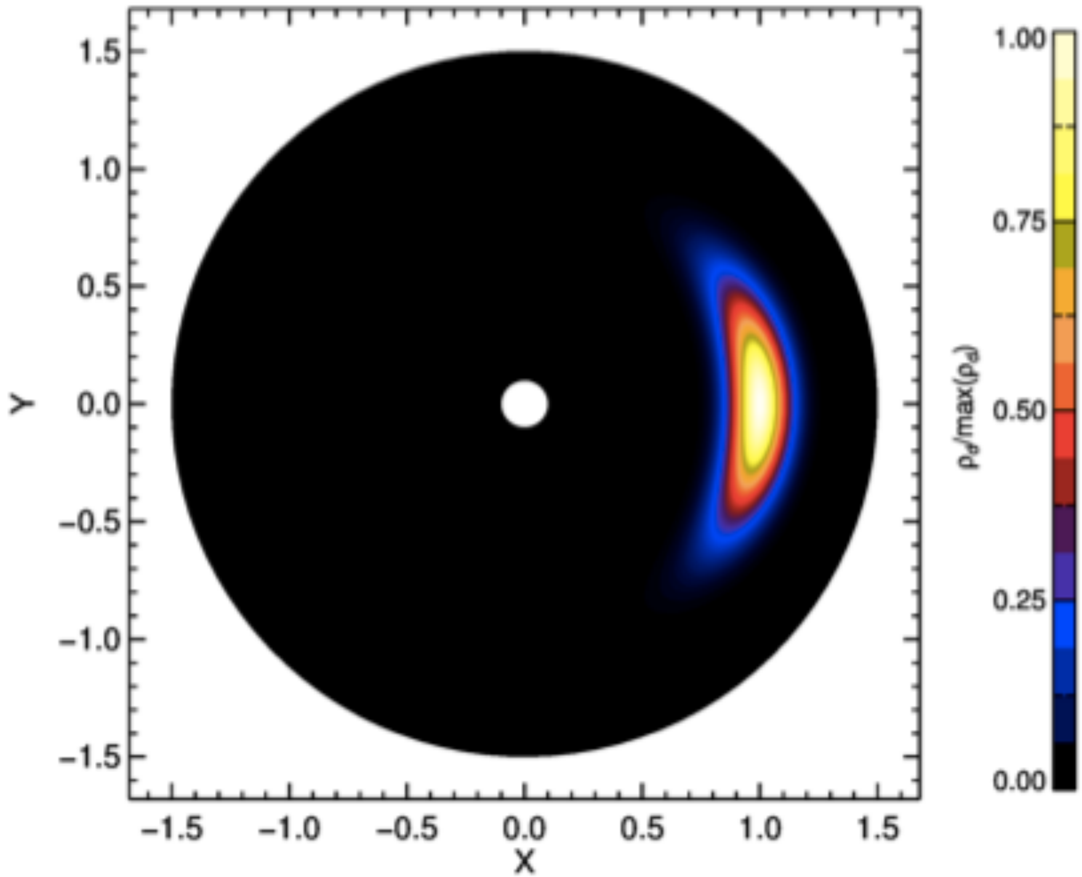
Lyra & Lin (2013)

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

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

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

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

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

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

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

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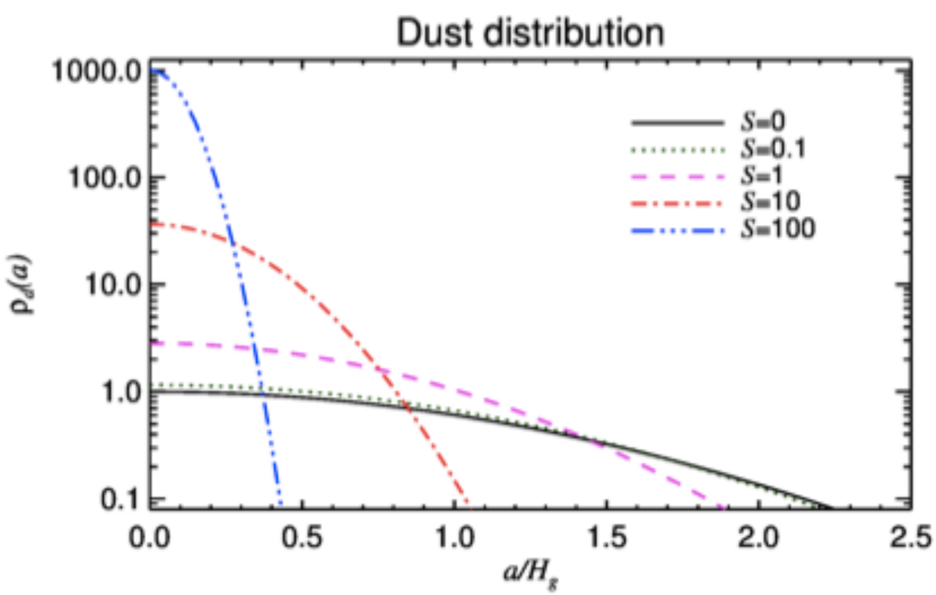
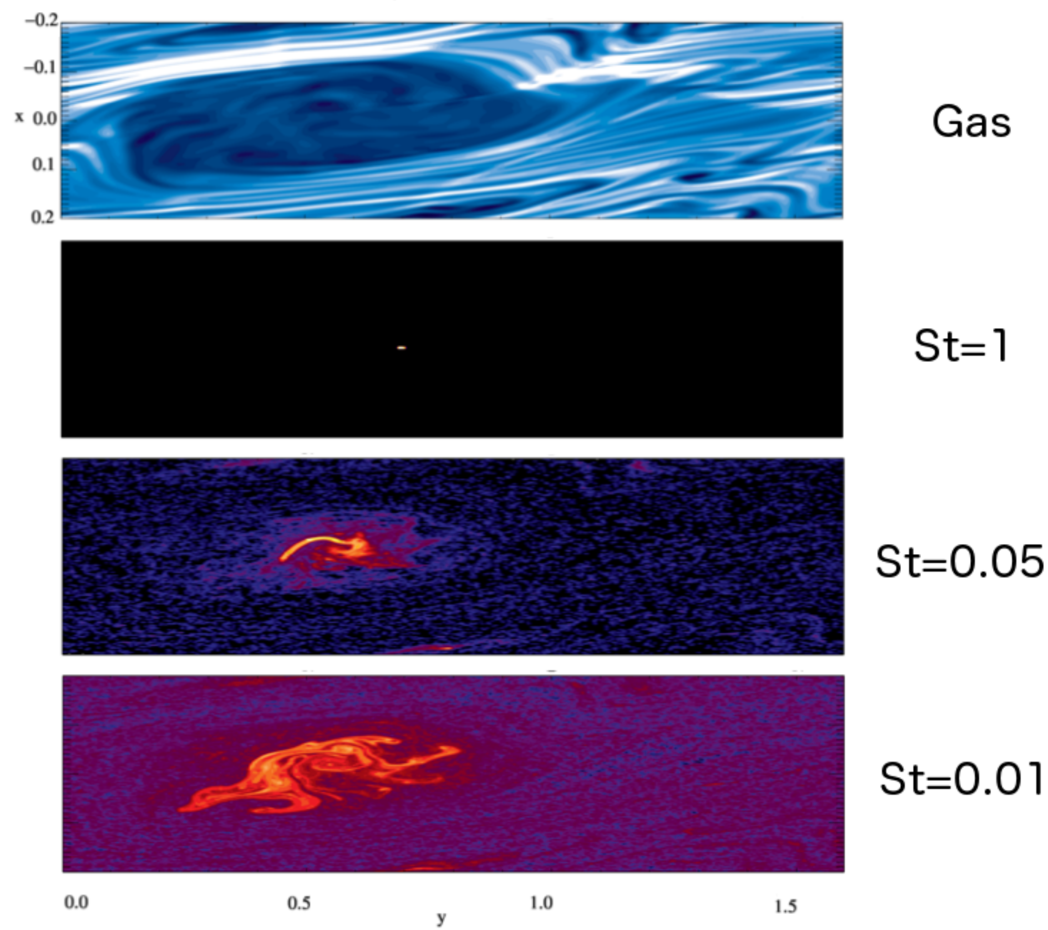
Lyra & Lin (2013)

Analytical vs Numerical



$$S = \frac{St}{\delta} \qquad \delta = v_{\rm rms}^2 / c_s^2,$$

Lyra & Lin (2013)



Raettig et al (2015)

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}

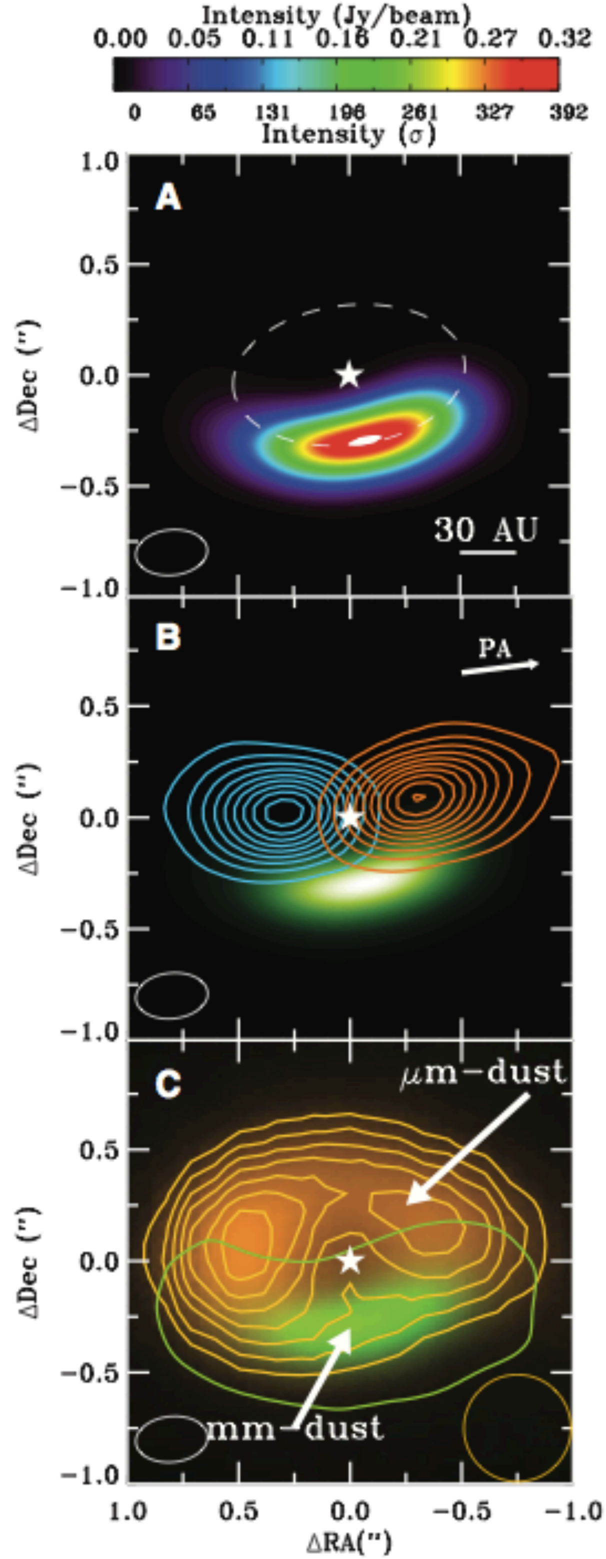
Derived parameters

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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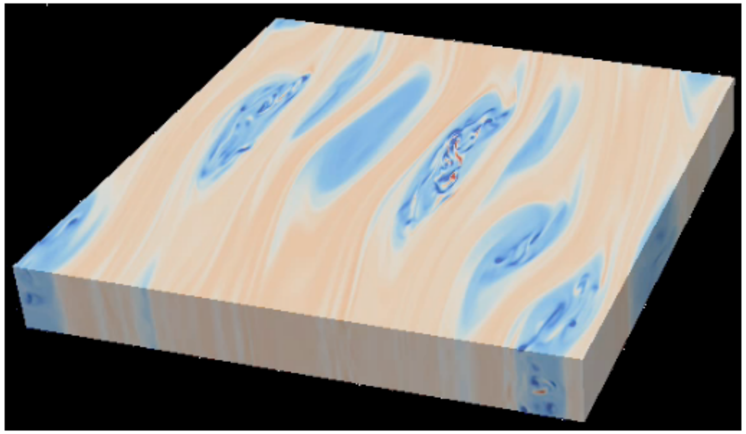
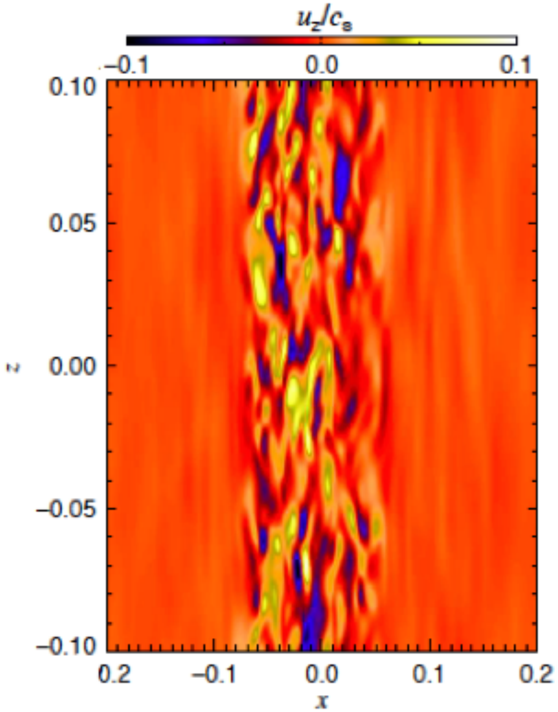
Lyra & Lin (2013)

Turbulence in vortex cores



Lesur & Papaloizou (2010)

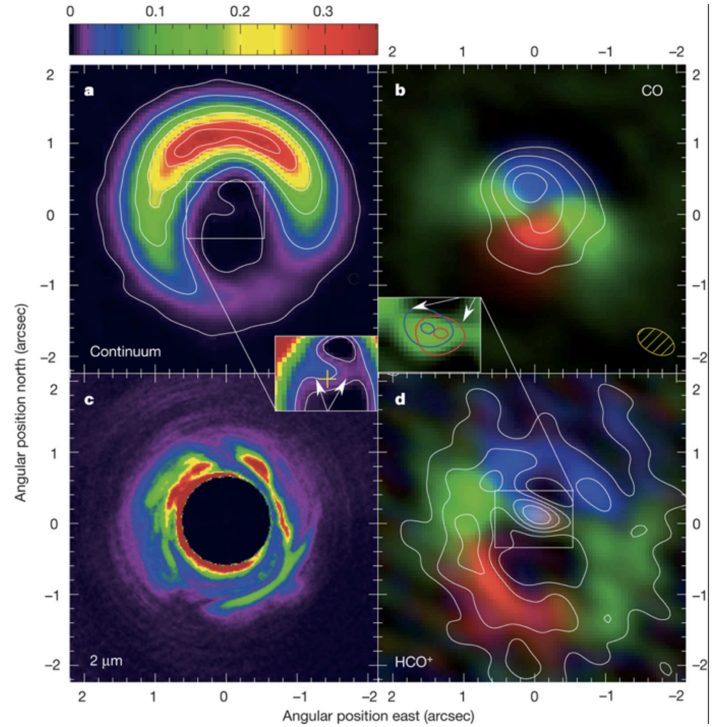


Lyra & Klahr (2011)

Turbulence in vortex cores:

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

HD 142527

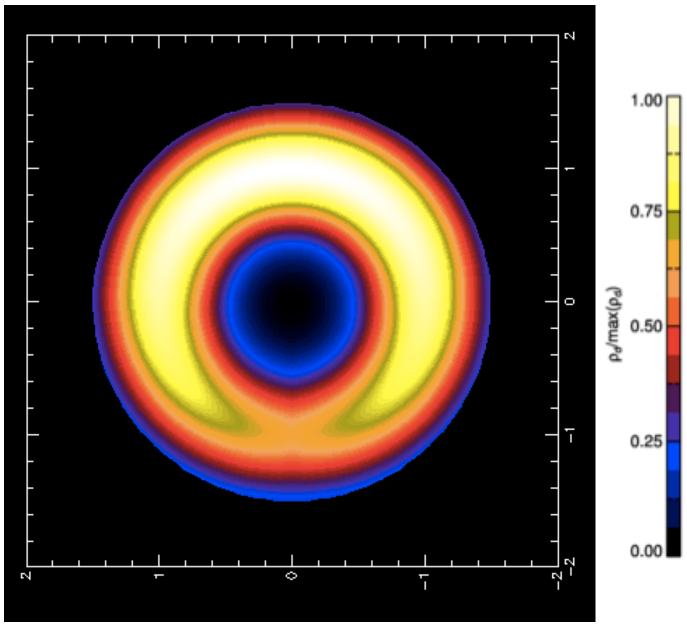


Observed parameters

Aspect ratio: 10

Dust contrast: 30

Temperature: 25K



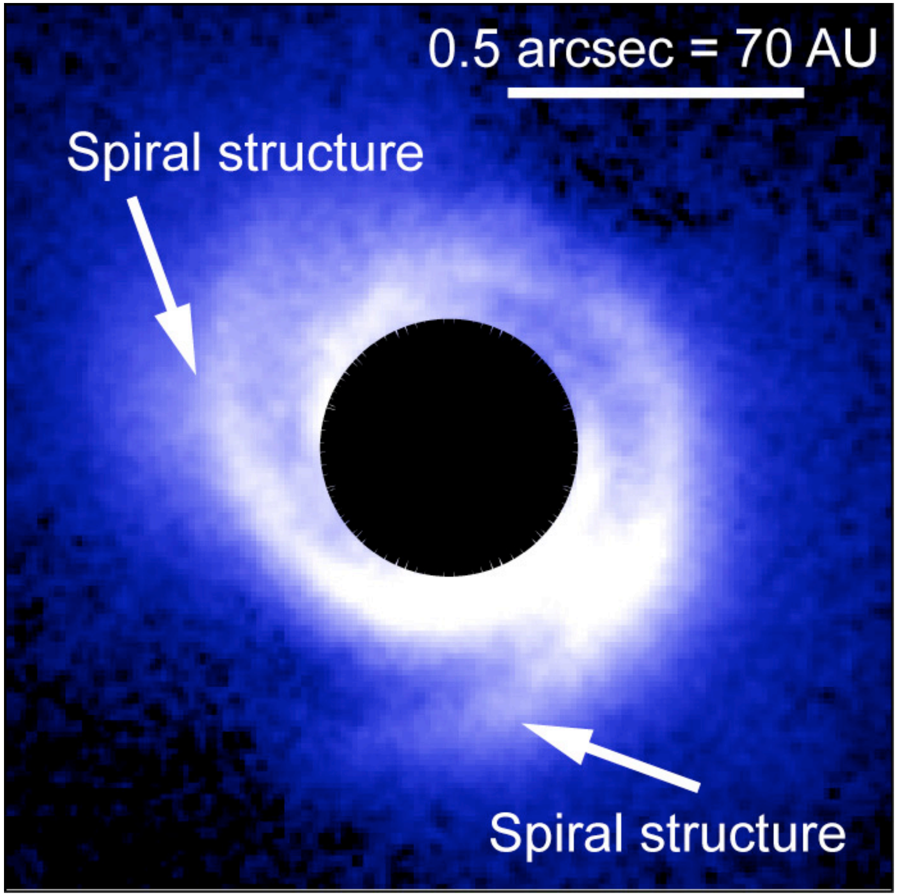
Derived parameters

S=3.5

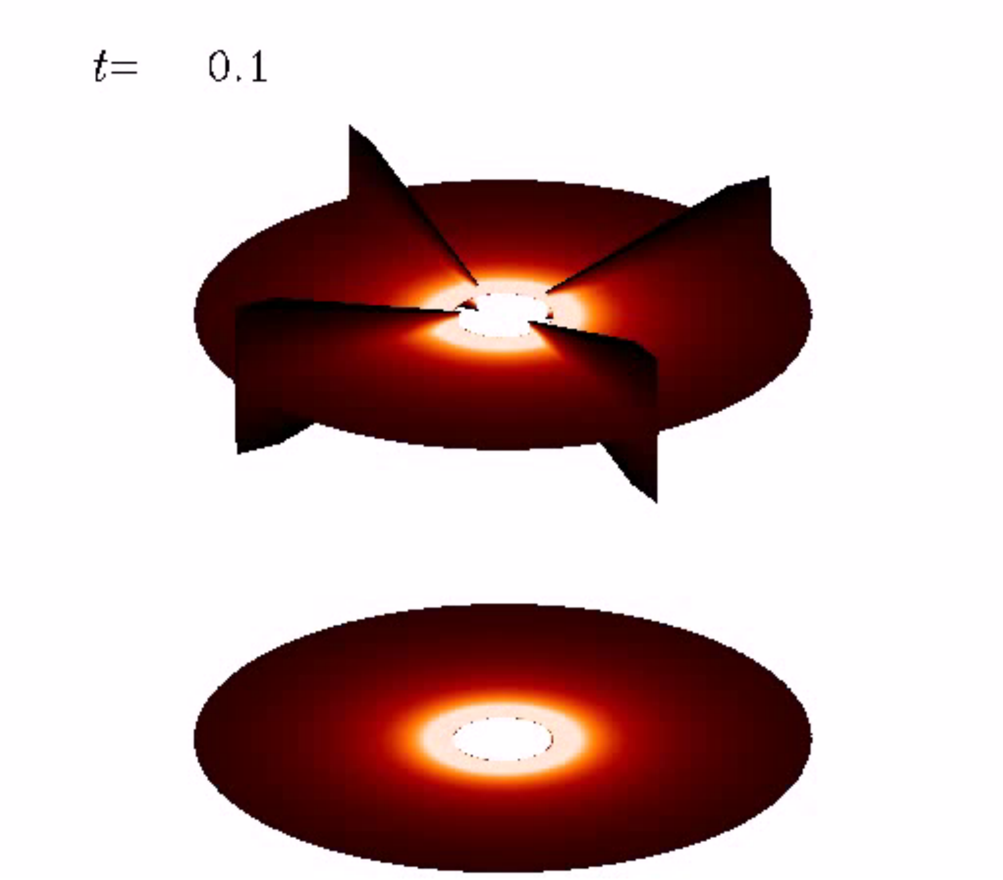
Stokes number, St=0.004

δ = 0.001, v_{rms} = 4% c_s

Spirals in transition disks

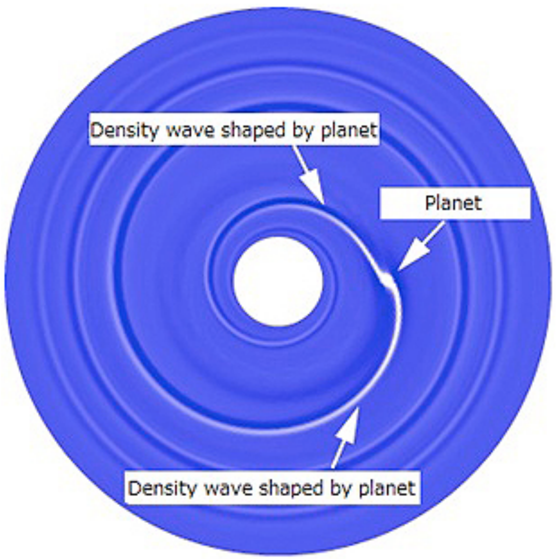


Muto et al. (2012)



Spiral arm fitting leads to problems

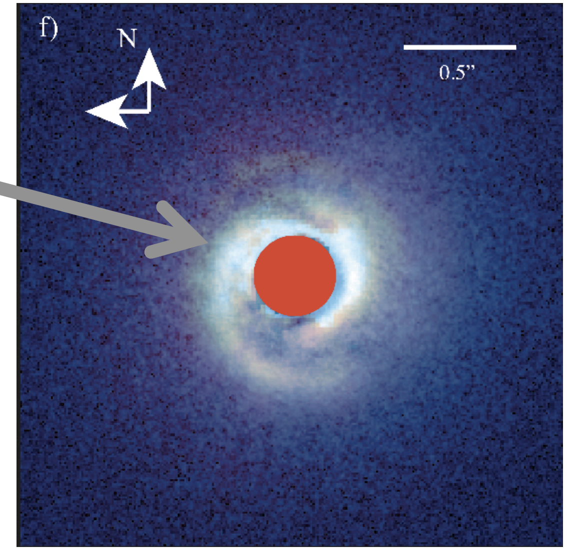
Analytical spiral fit



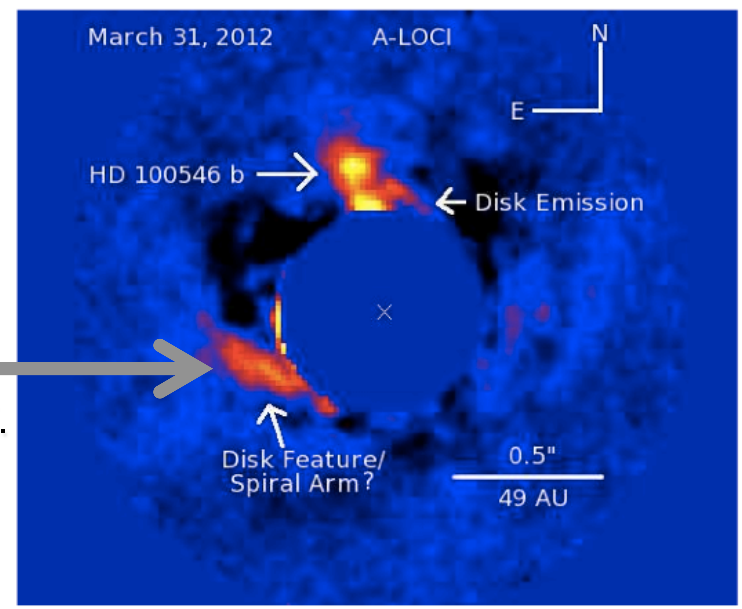
$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \left(\frac{r}{r_c}\right)^{-\alpha} \right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \right) \right\},$$

Rafikov (2002)
Muto et al. (2012)

Spiral is too wide, hotter (300K) than ambient gas (50K).

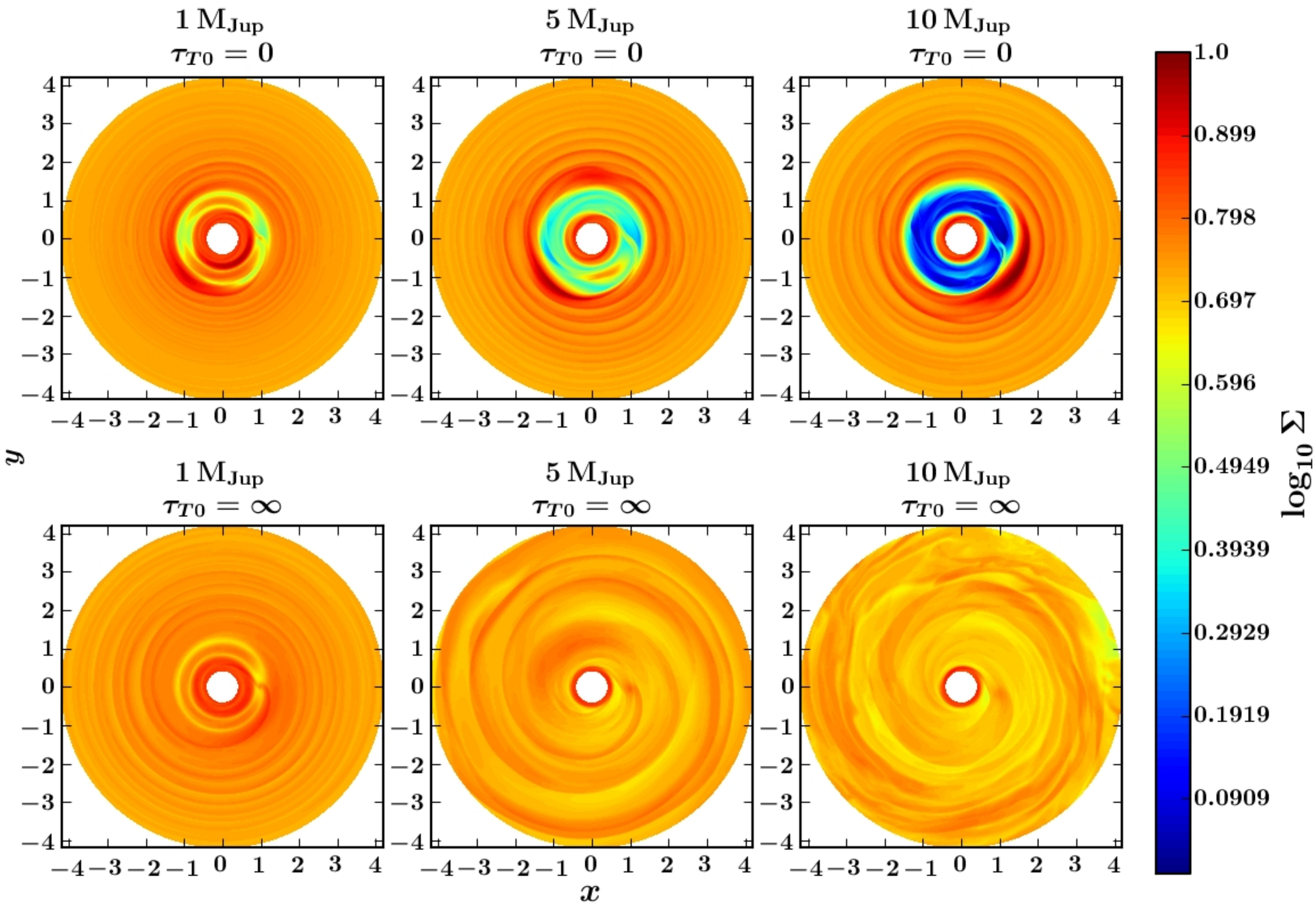


Spiral has little polarization. Must be thermal emission at 1000K.



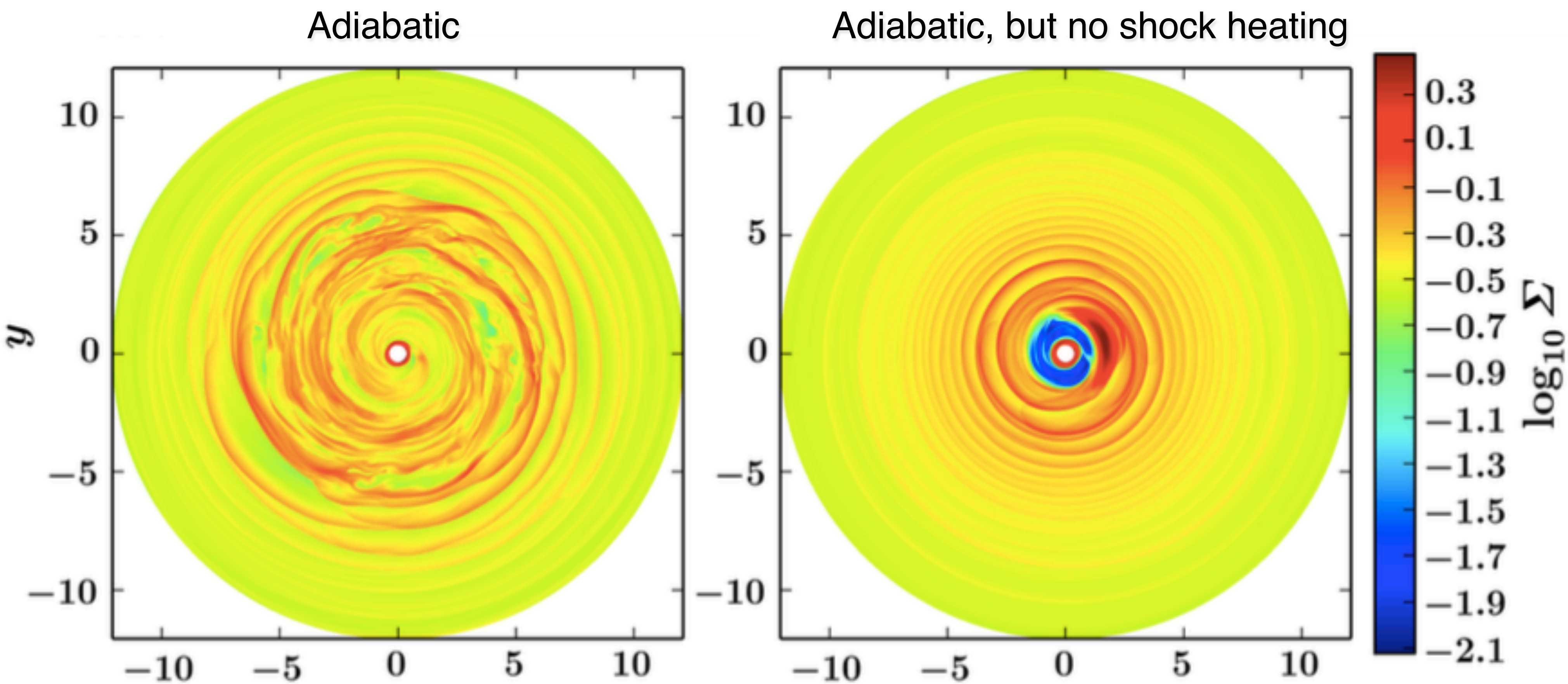
Currie et al. (2014)

Isothermal vs Adiabatic



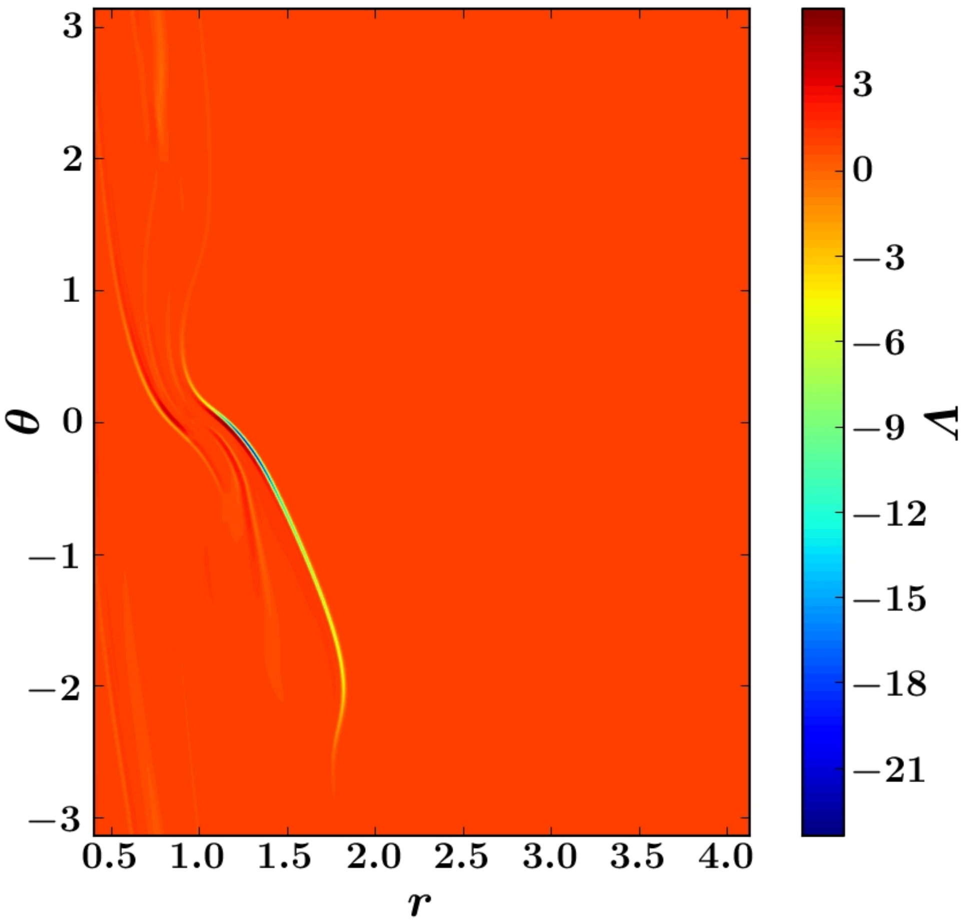
Richert et al. (2015, submitted)

The energy source: shock heating!

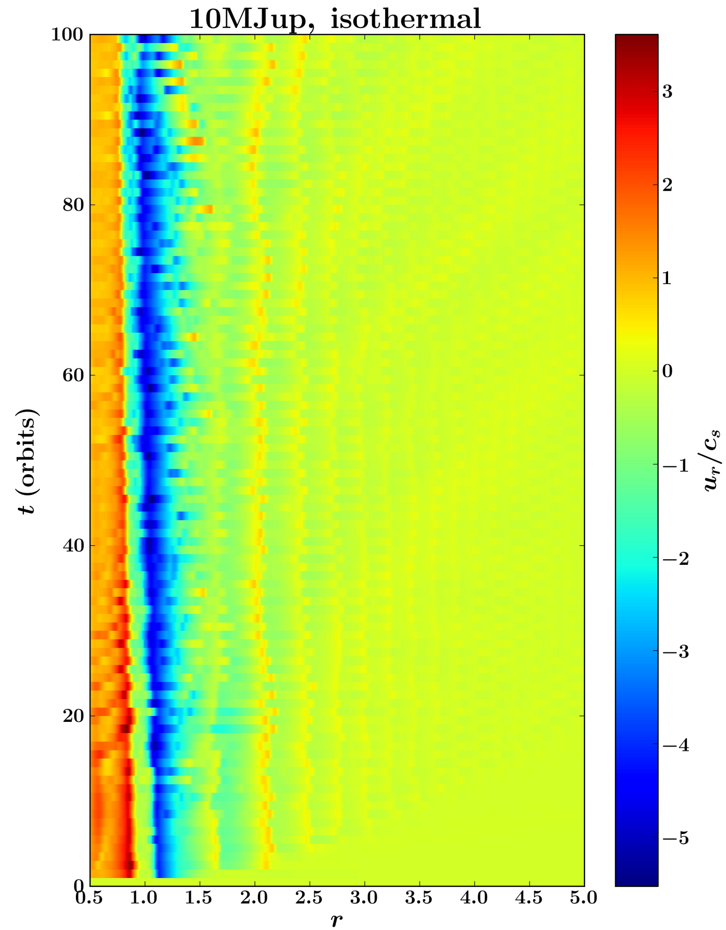


Richert et al. (2015, submitted)

The spiral is buoyantly unstable



The spiral has Ma >~ 1



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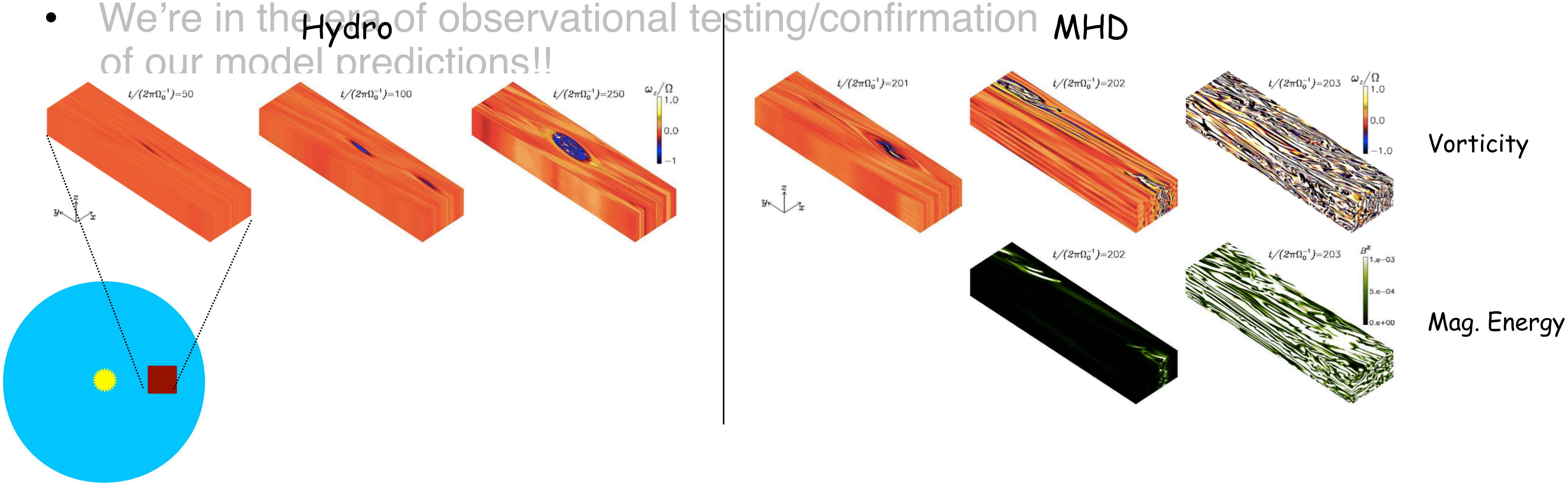
Conclusions

- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may be the culprit of these dust traps
- We're in the era of observational testing/confirmation of our model predictions!!



Lyra & Klahr (2011)

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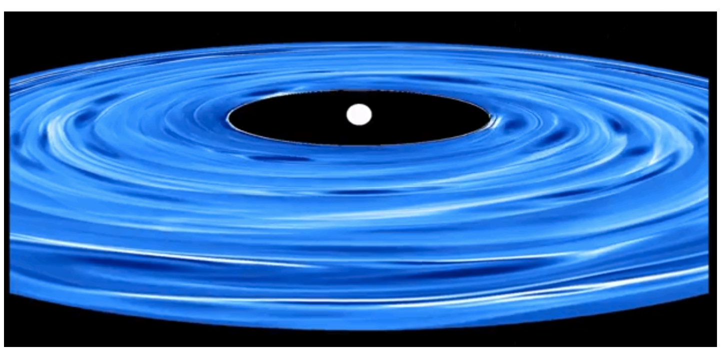
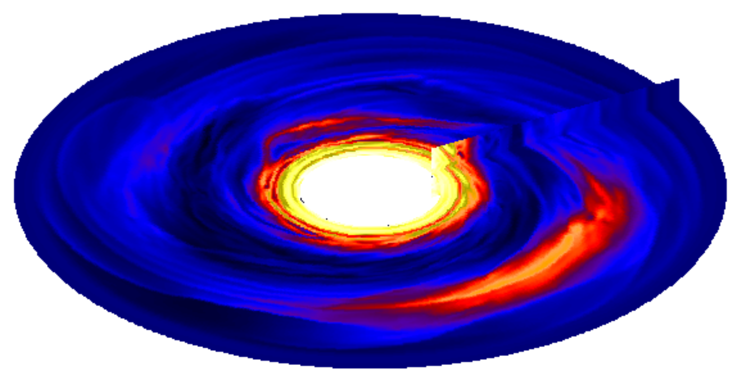
Baroclinic instability



Rossby wave instability



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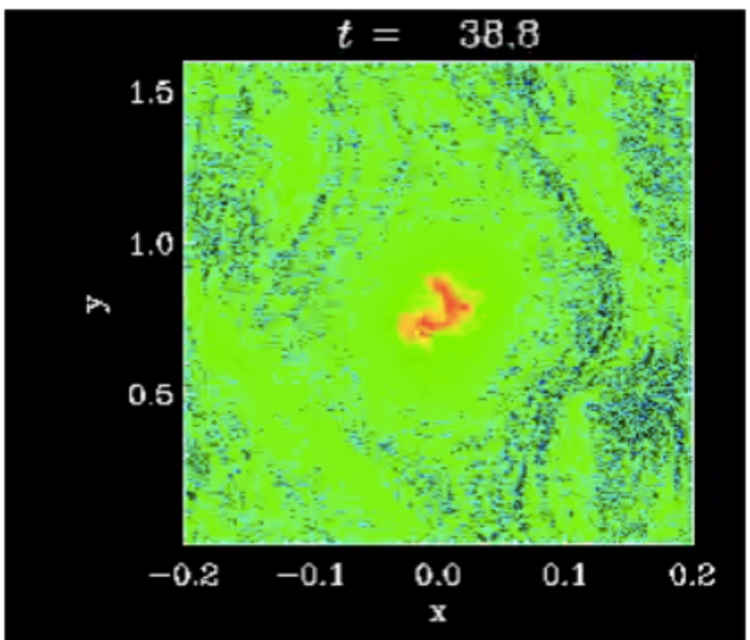

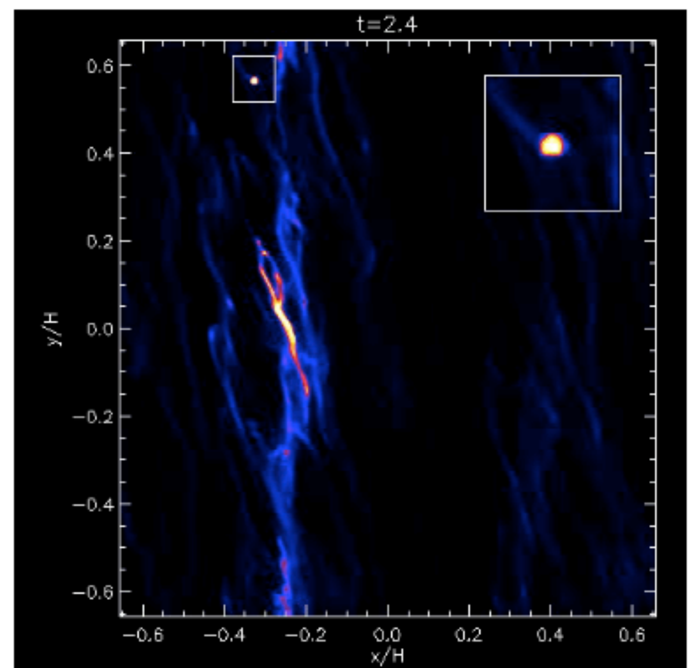

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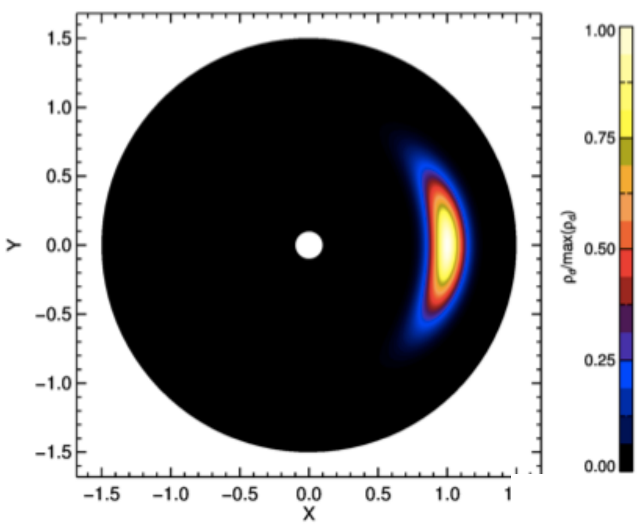

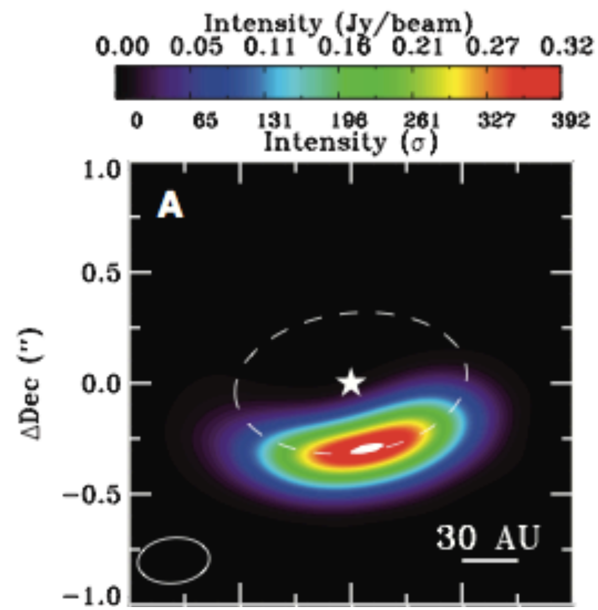

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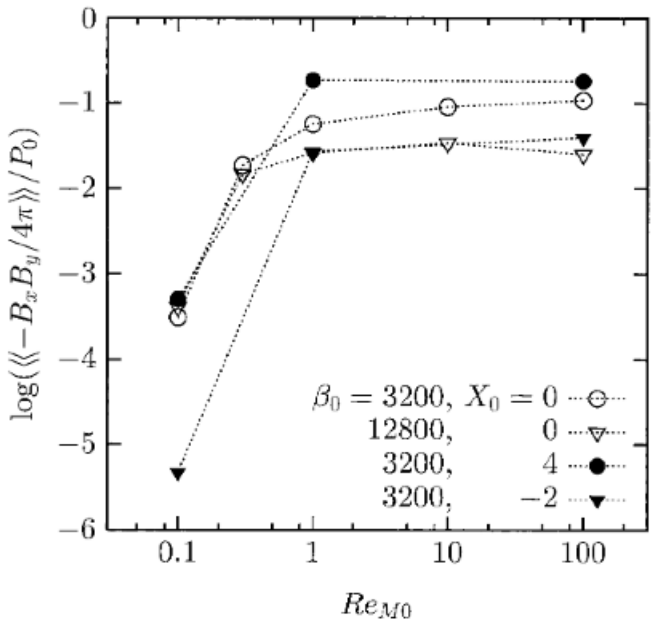

zone only

Rossby Wave Instability and Convective Overstability

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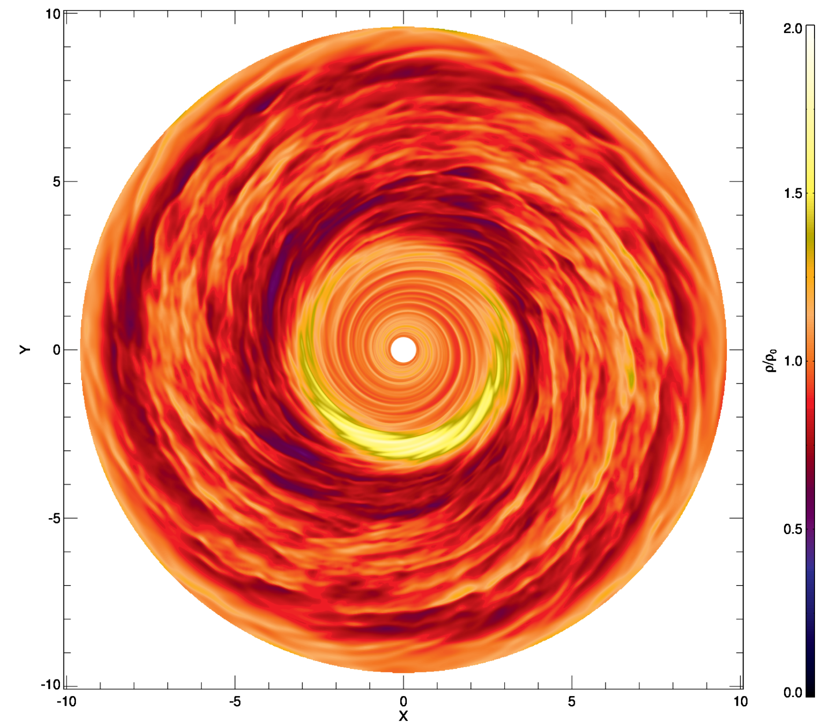

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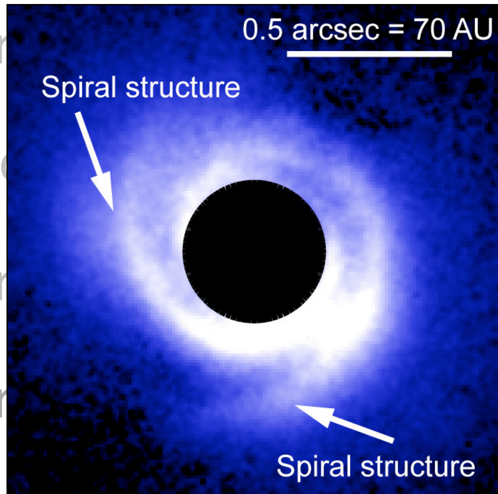

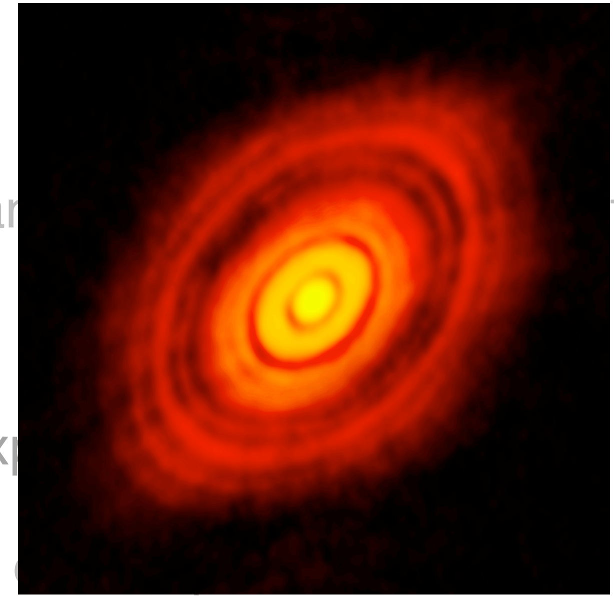

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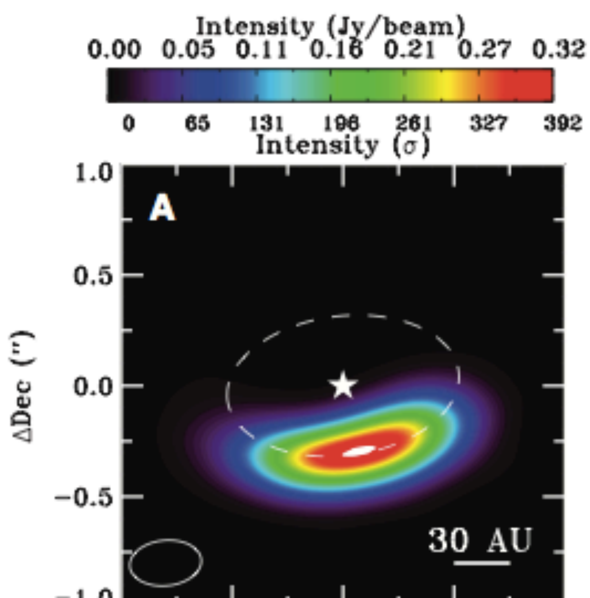

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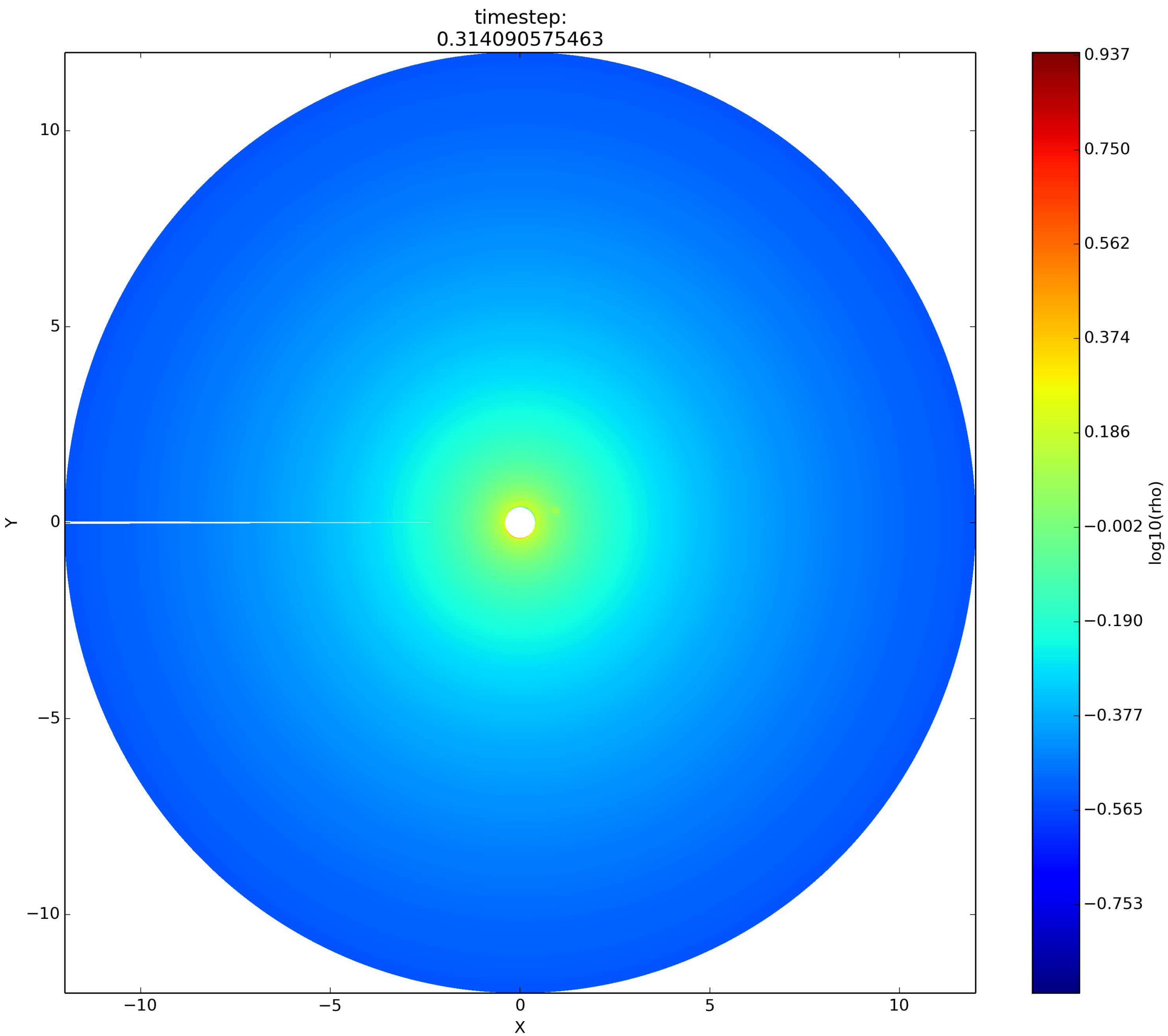

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