Evolution of circumstellar disks and planet formation

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Collaborators

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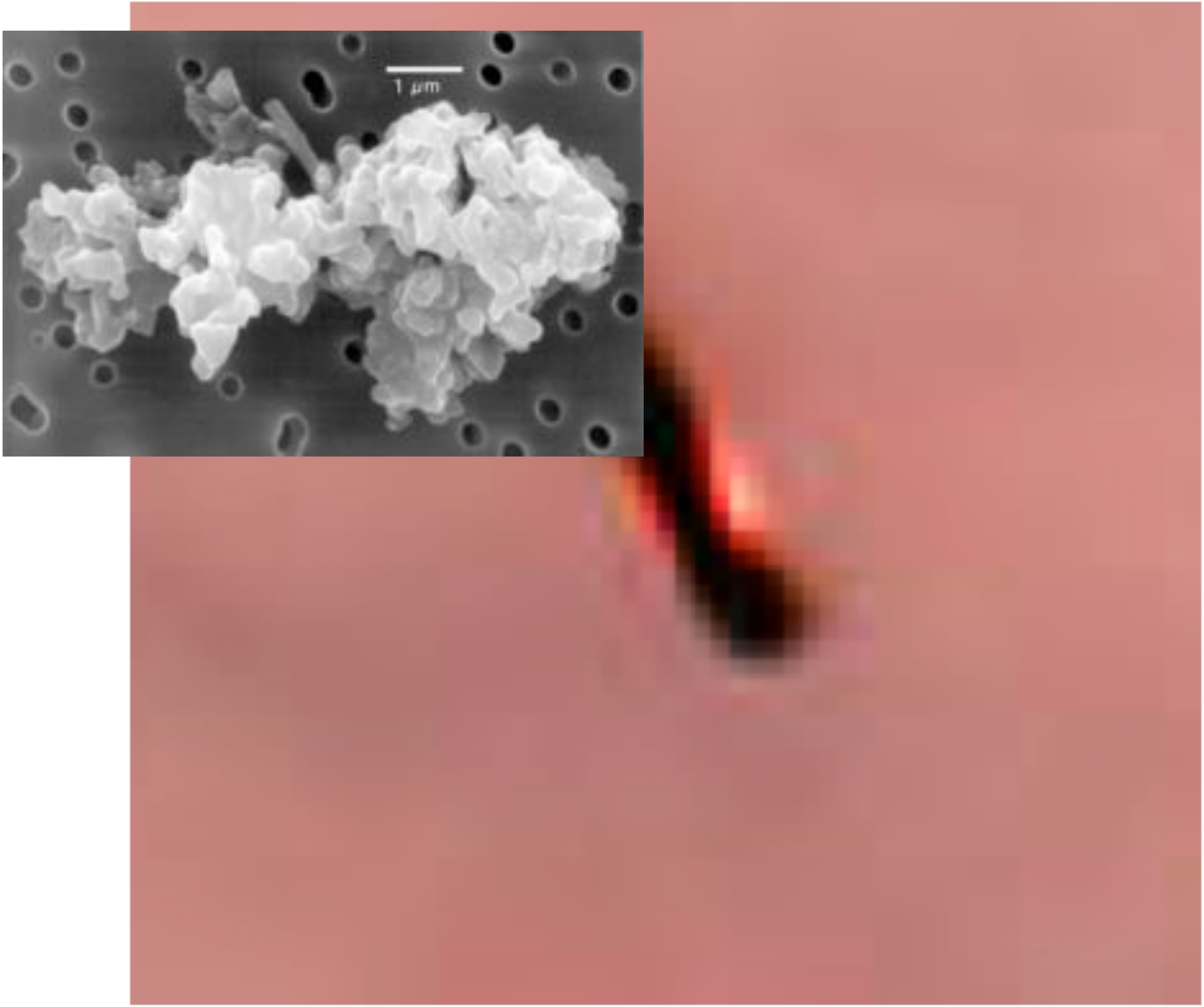
CSU Fullerton, Oct 16th 2015

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

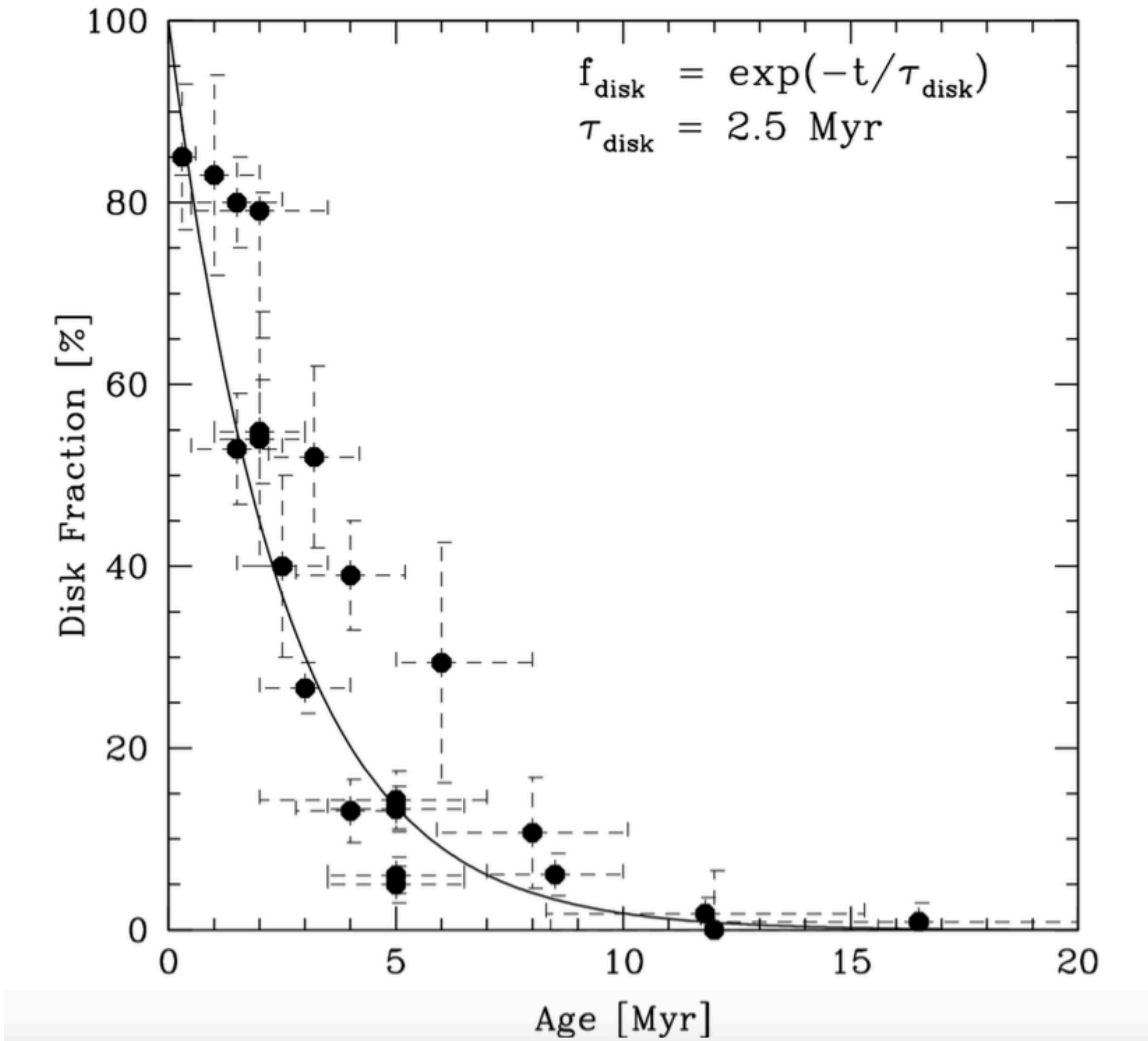
Density: $10^{13} – 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

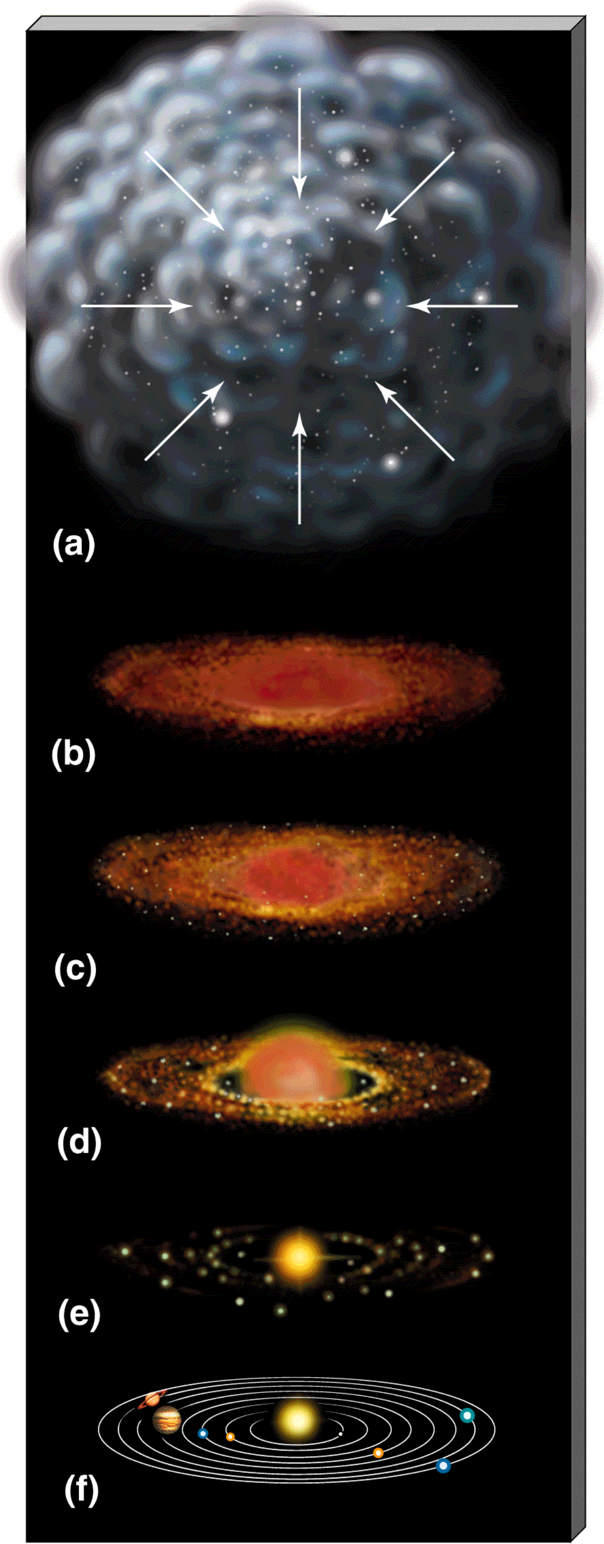
Scale: 0.1-100AU
(1 AU = 1.49×10^{13} cm)

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

Disk lifetime



Disks dissipate with an e-folding time of 2.5 Myr



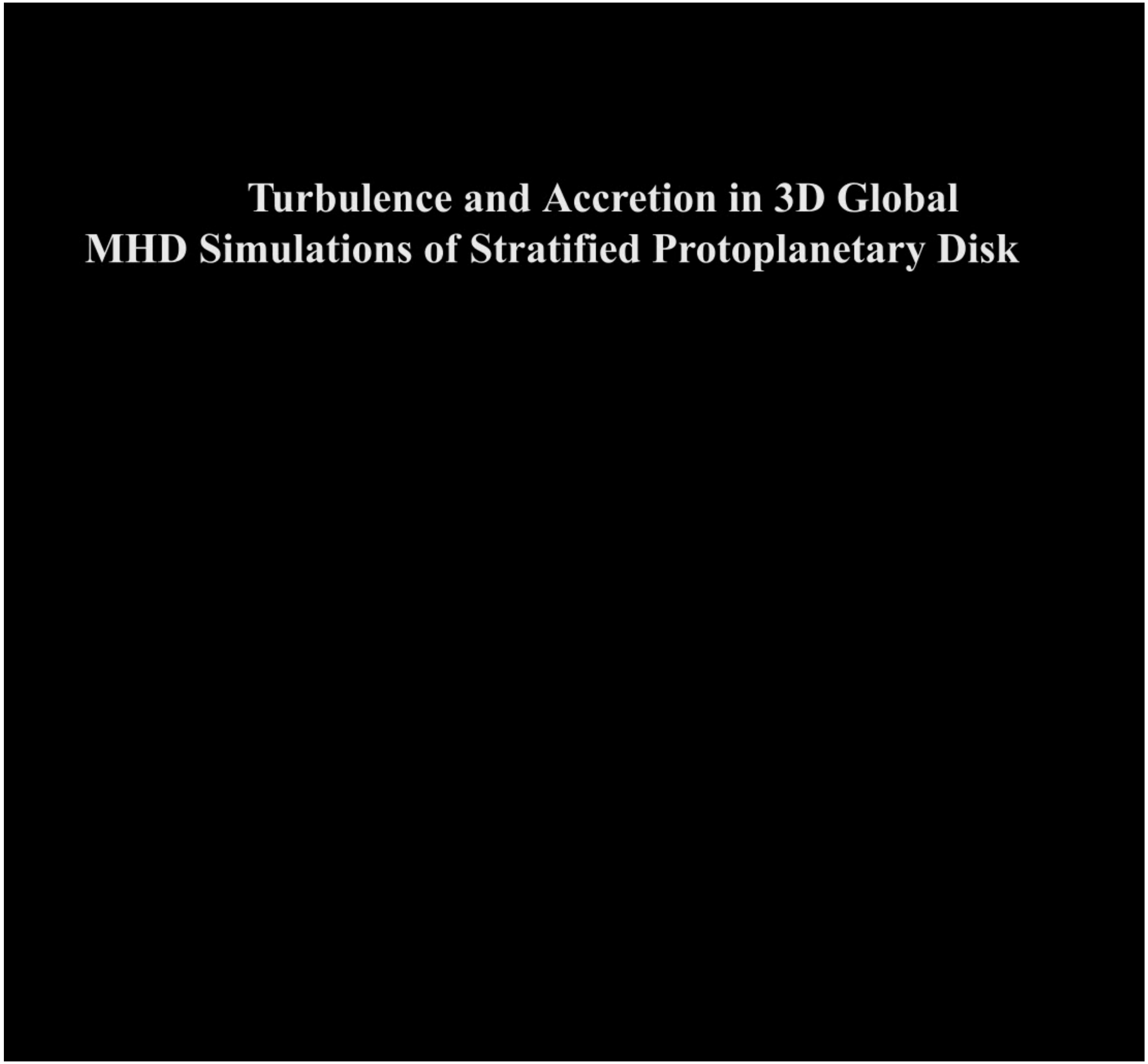
Disk evolution

Gas-rich phase (< 10 Myr)
Primordial Disks

Transition phase (~10 Myr)
Transitional Disks

Gas-poor phase (>10 Myr)
Debris Disks

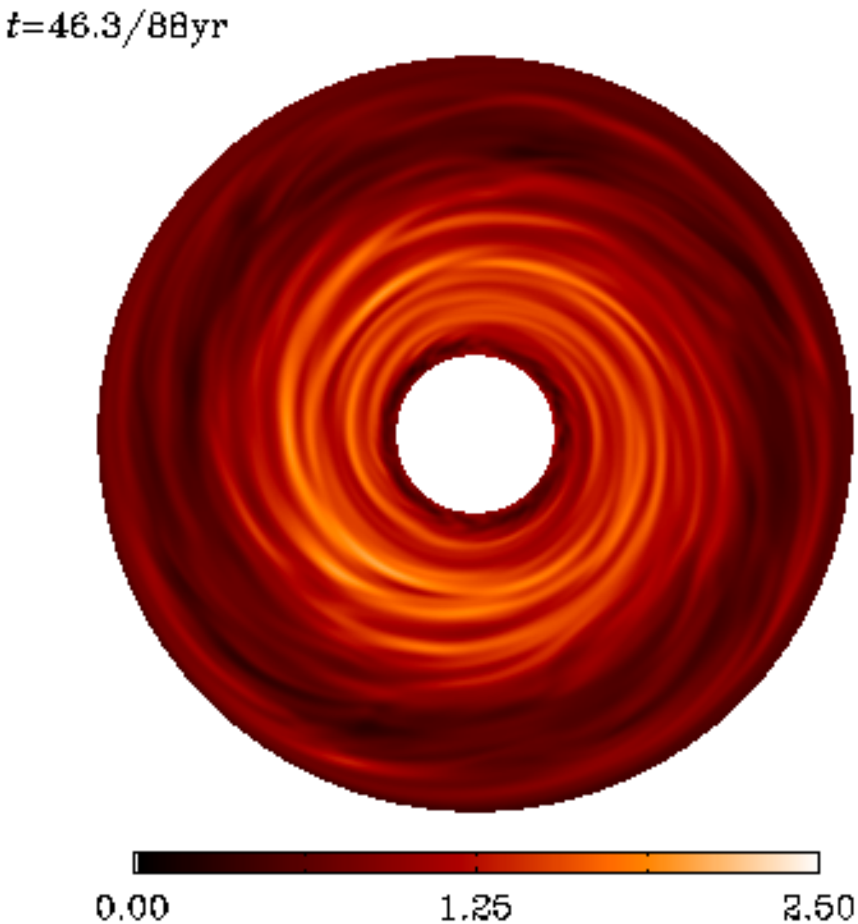
Magneto-Rotational Instability



Video credit: Mario Flock (MPIA/CEA)

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability

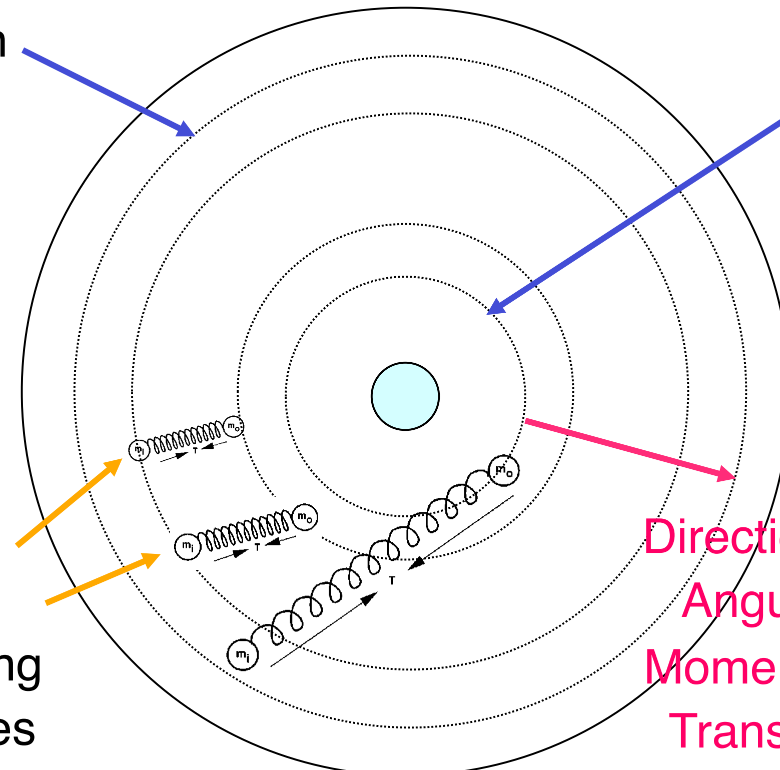


Magnetized disk
Lyra et al. (2008a)

MRI sketch

Slower Rotation

Faster Rotation



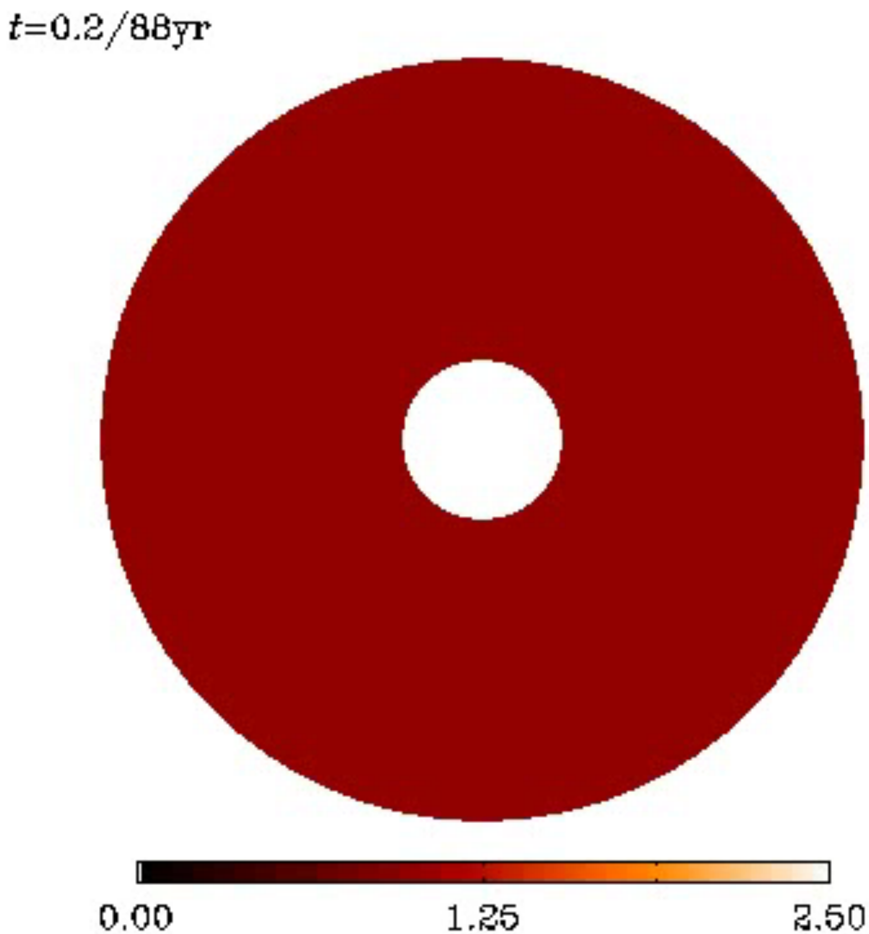
Stretching amplifies B-field

Direction of Angular Momentum Transport

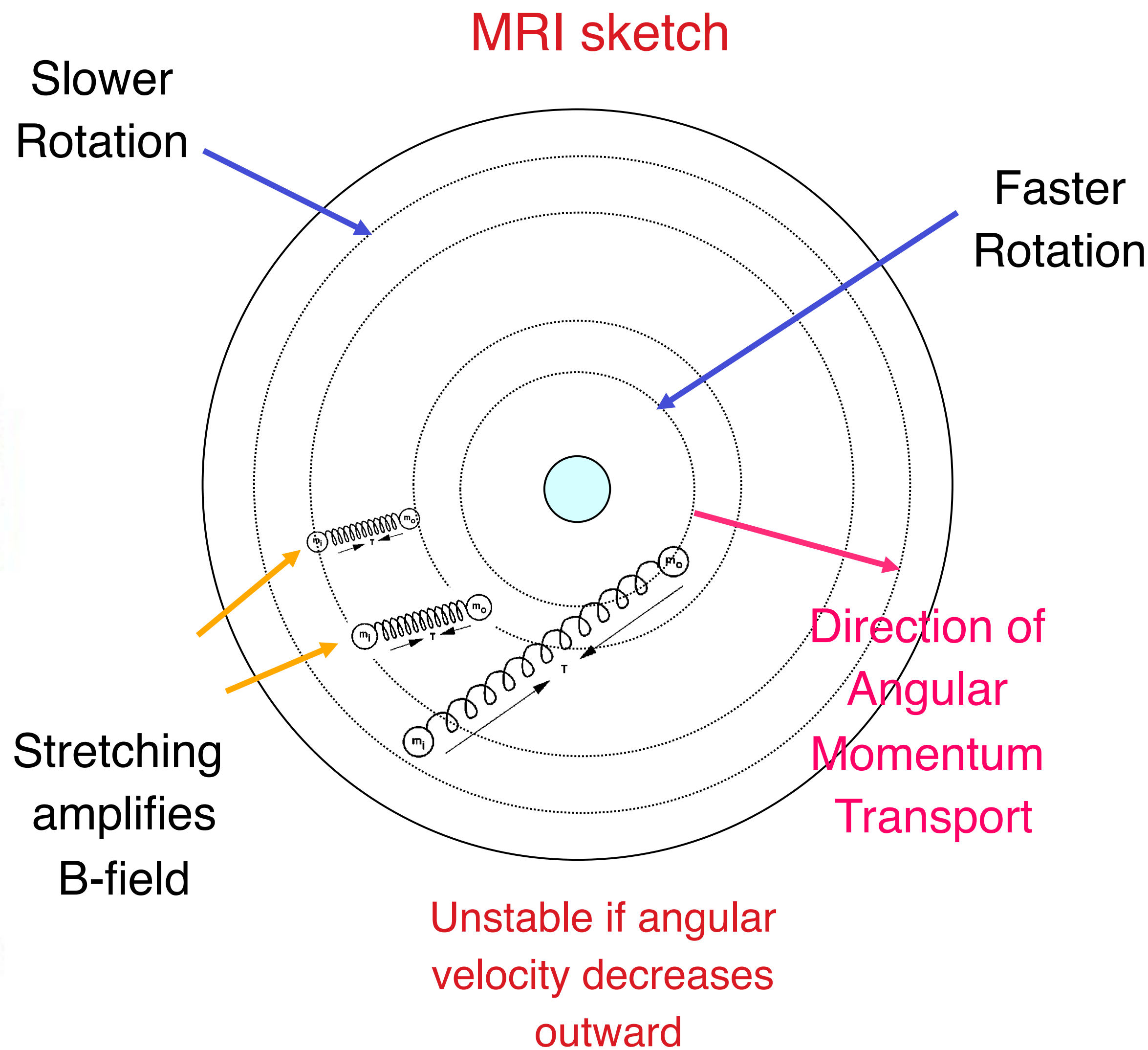
Unstable if angular velocity decreases outward

Accretion in disks occurs via turbulent viscosity

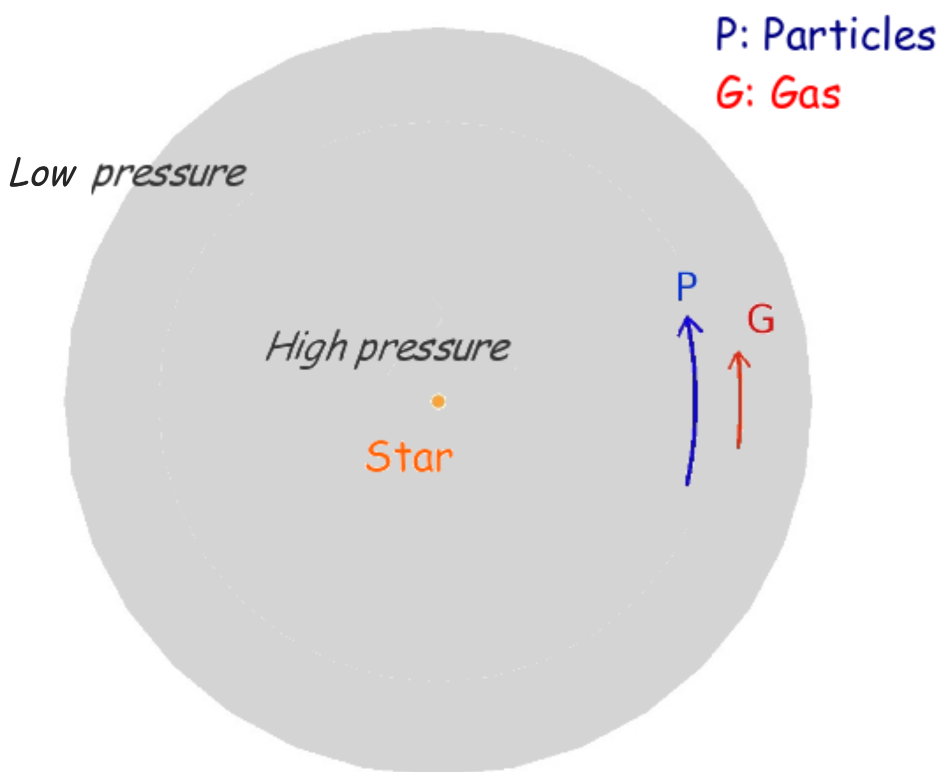
Turbulence in disks is enabled by
the Magneto-Rotational Instability



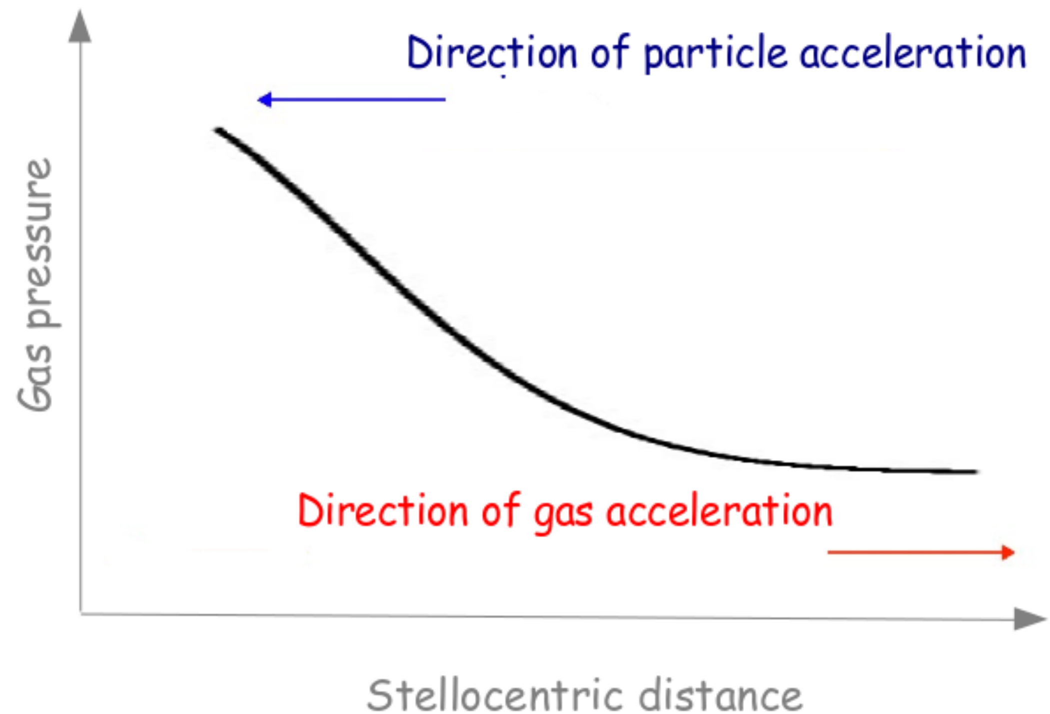
Magnetized disk
Lyra et al. (2008a)



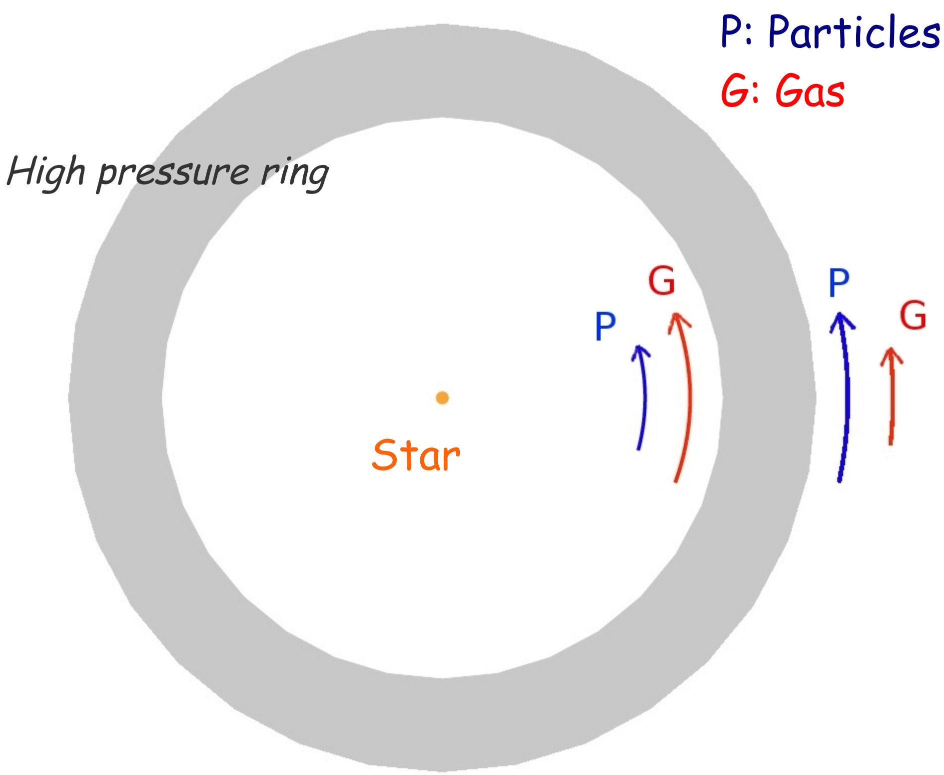
Particle drift



Adapted from Whipple (1972)



Pressure Trap



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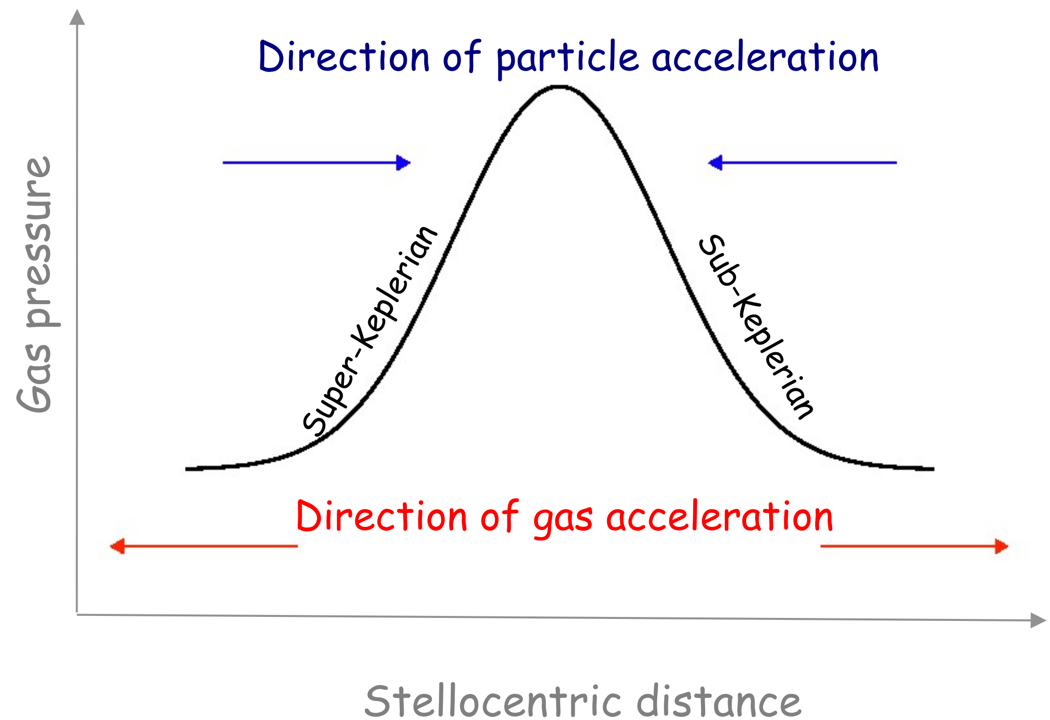
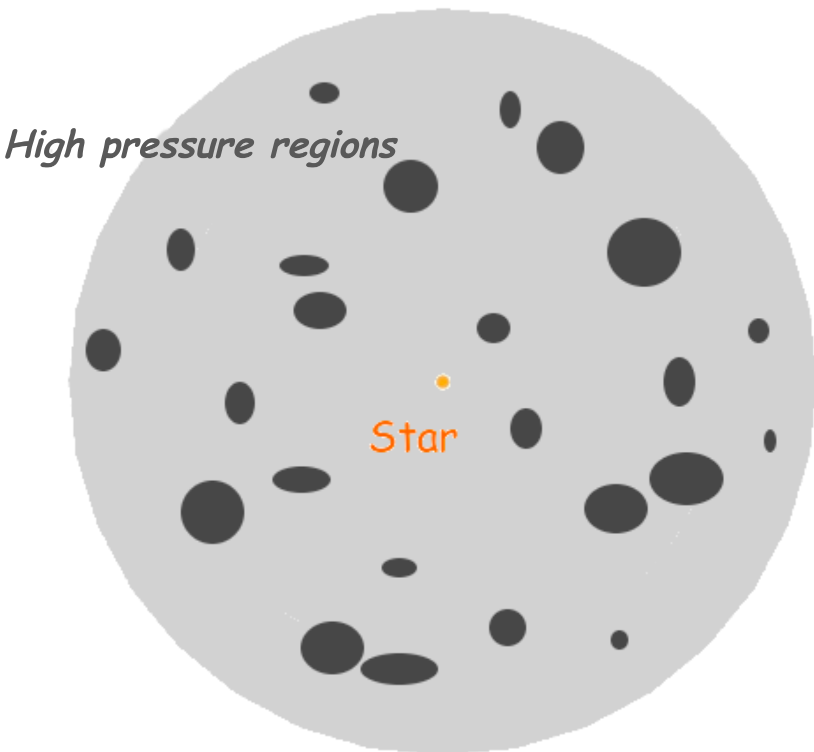
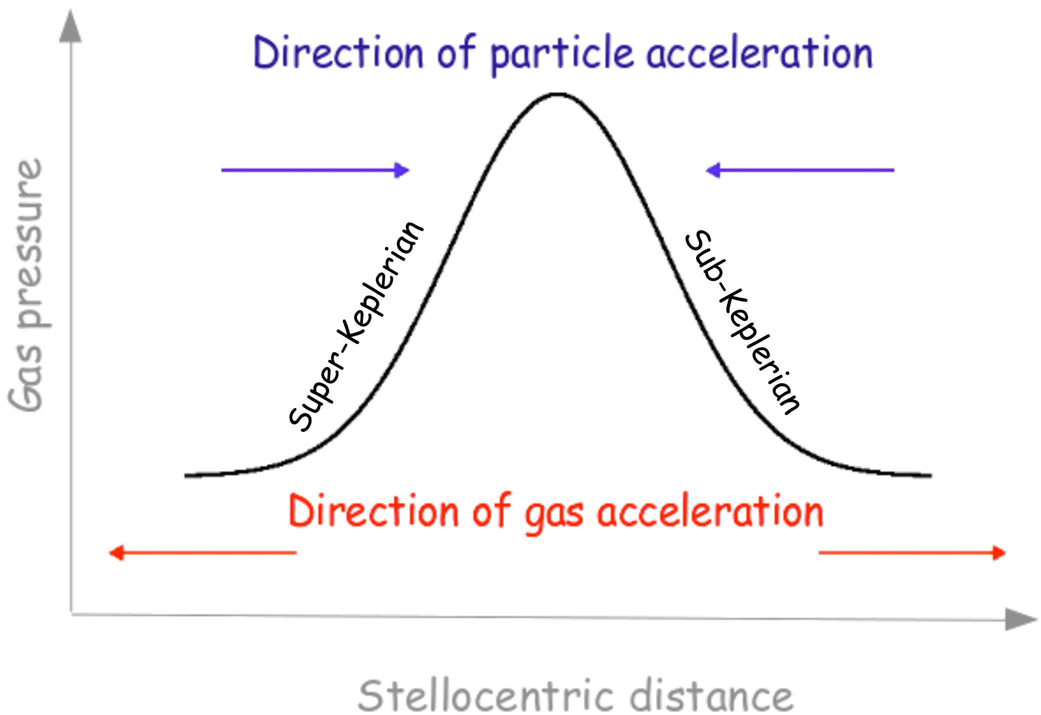
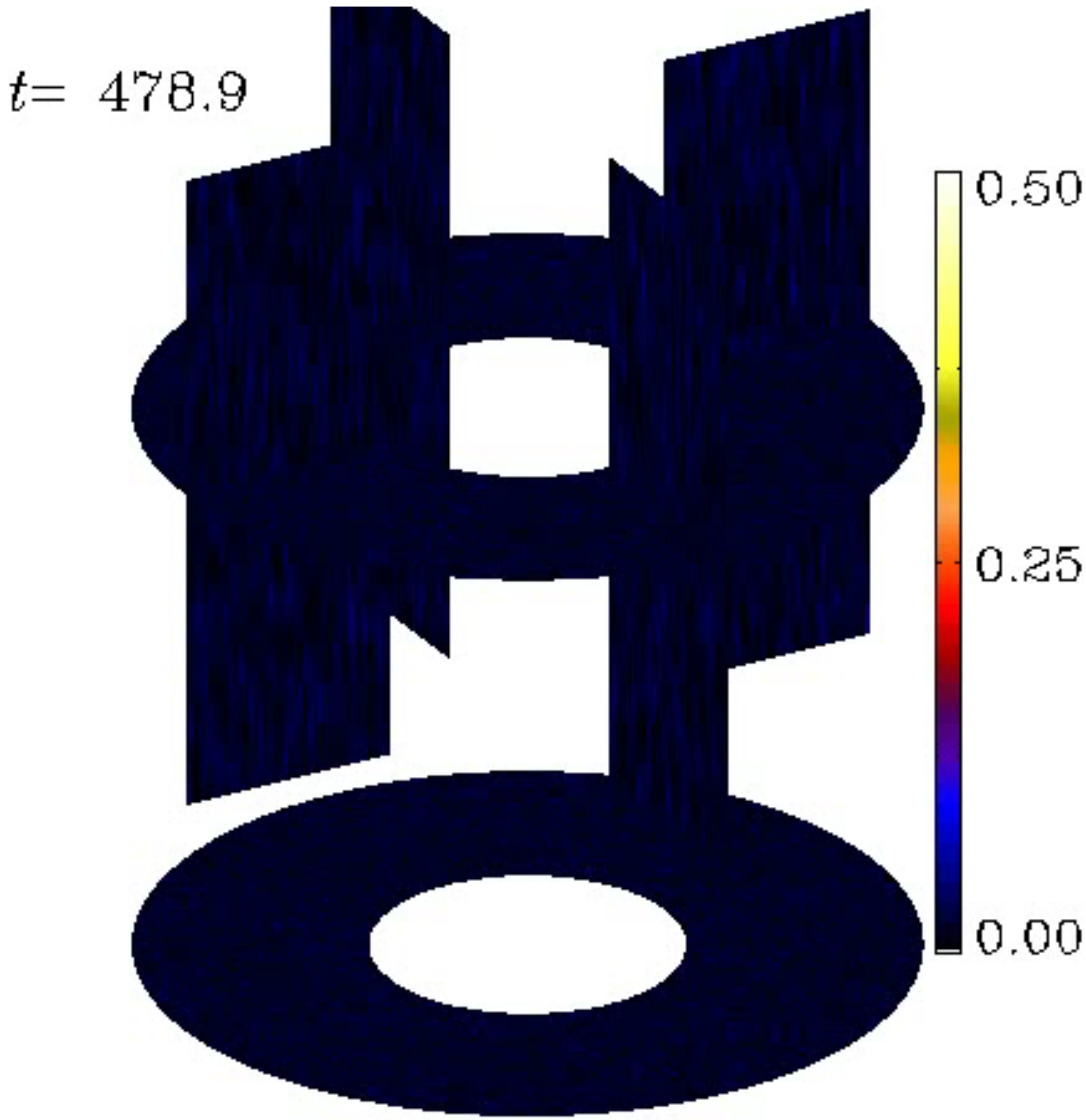


Pressure Trap



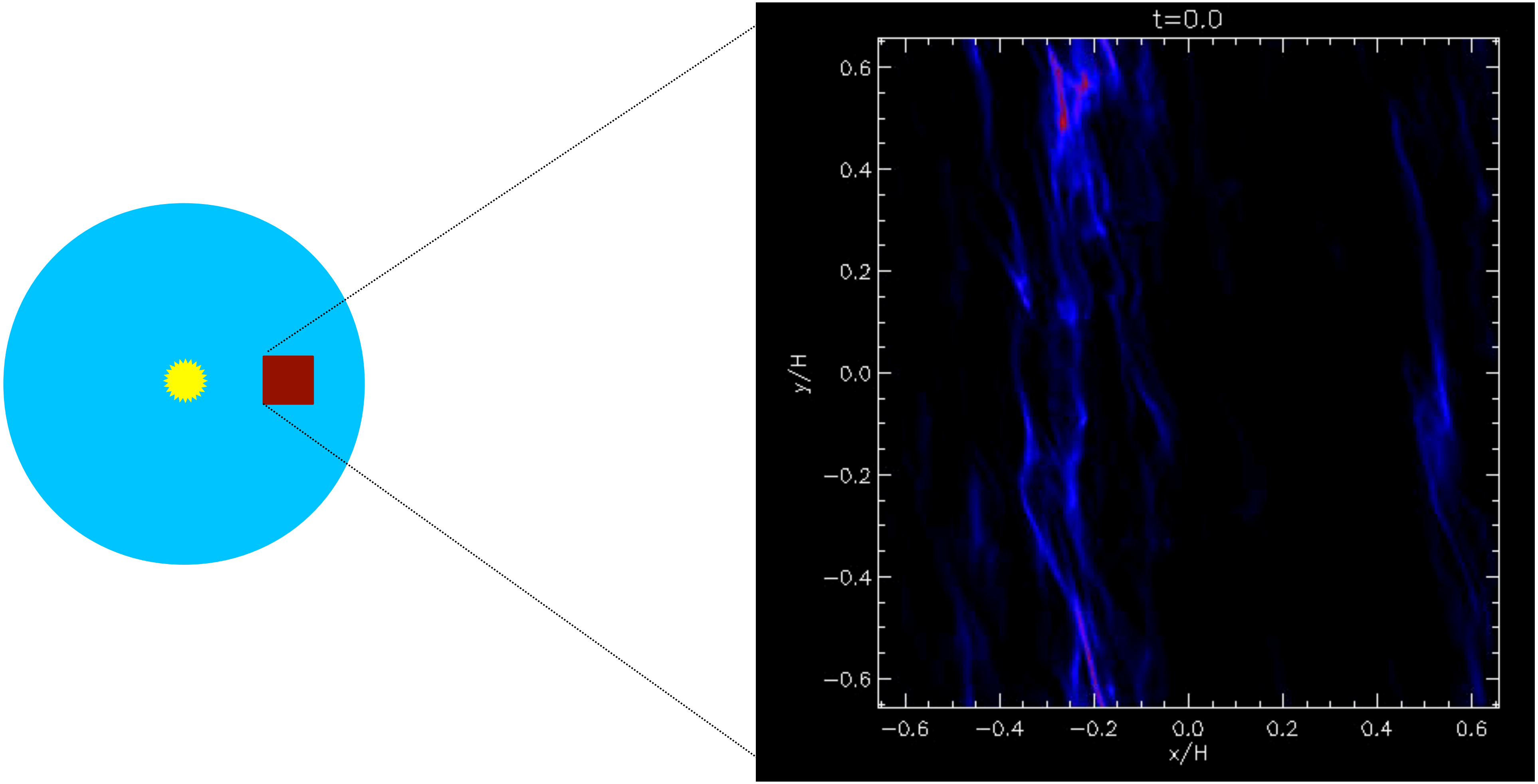


Turbulence concentrates solids mechanically in pressure maxima



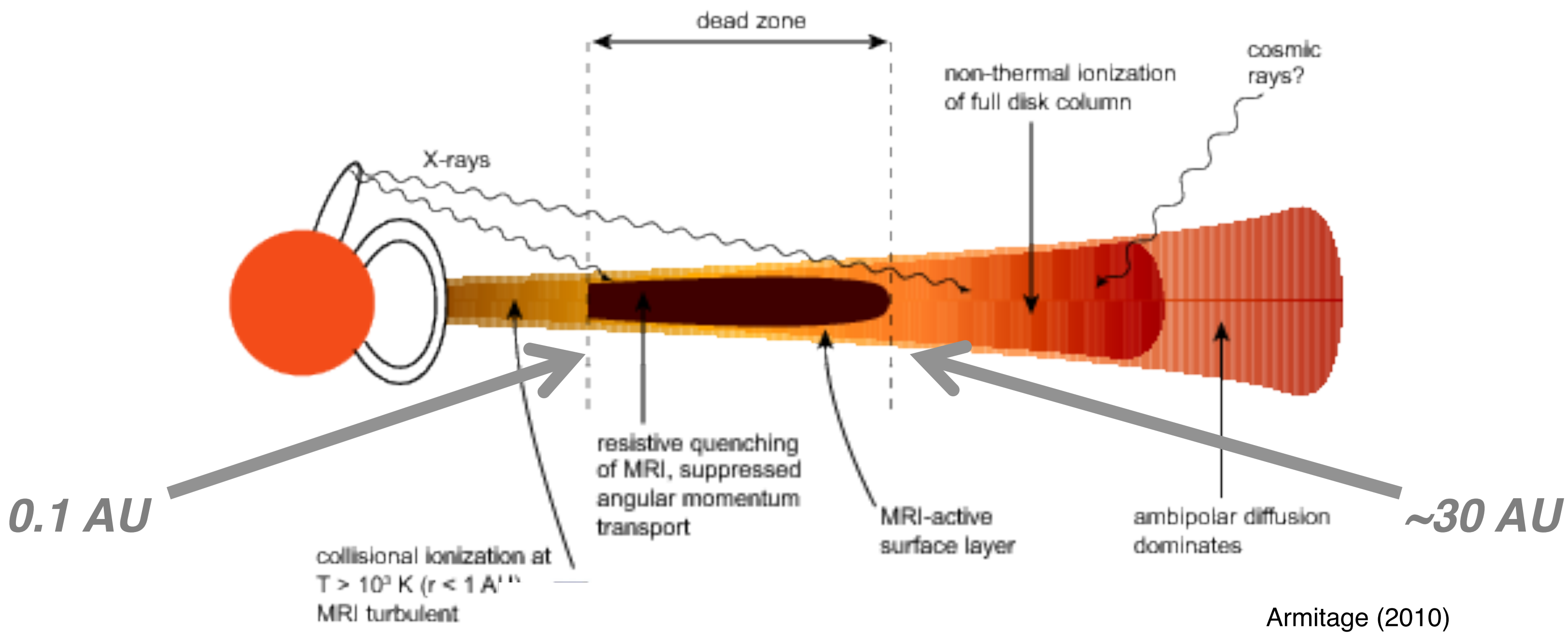
Lyra et al. (2008a)

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)

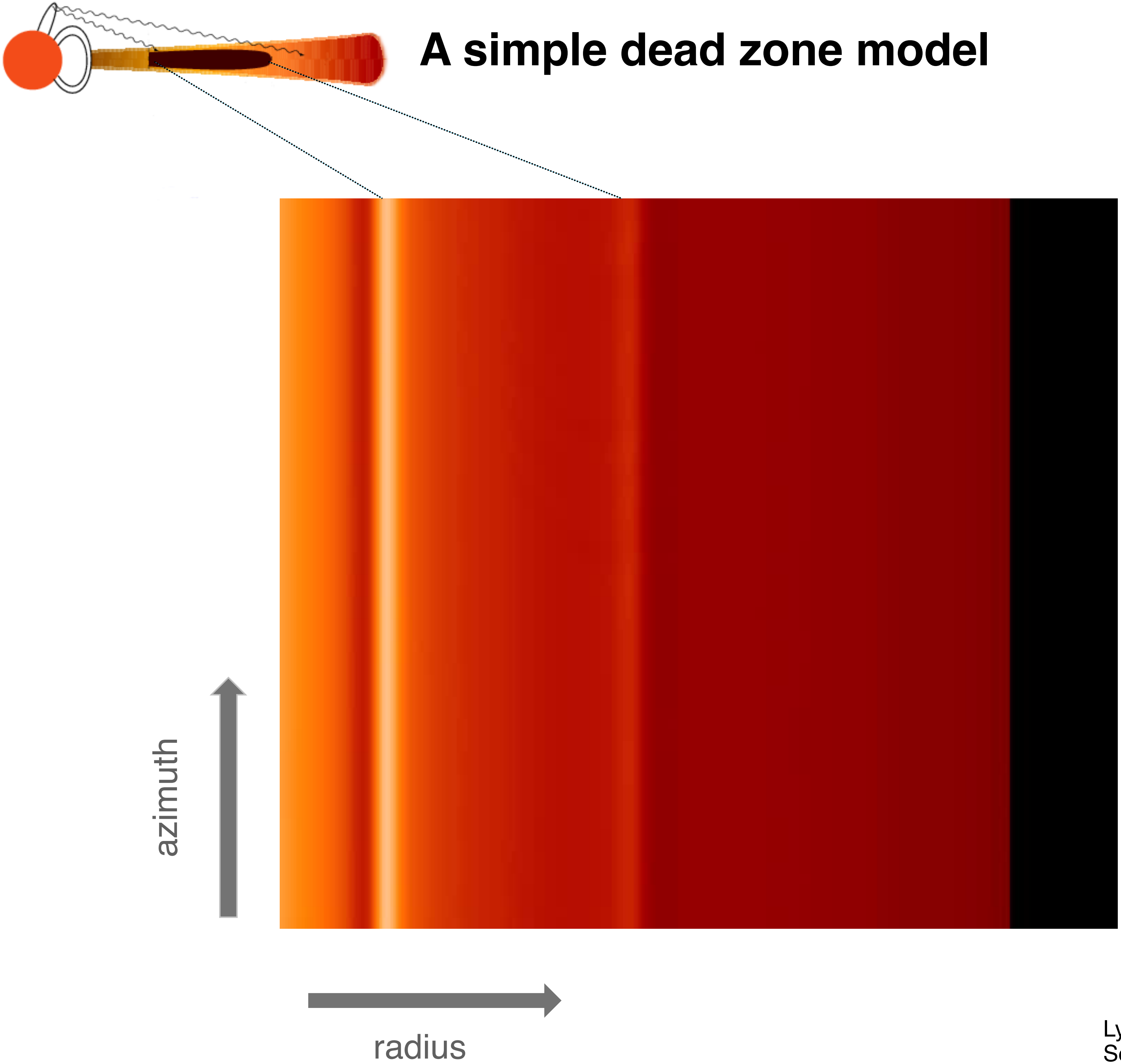
Therefore, accretion is **layered**

(Gammie 1996)

There should be a **magnetized, active zone**,

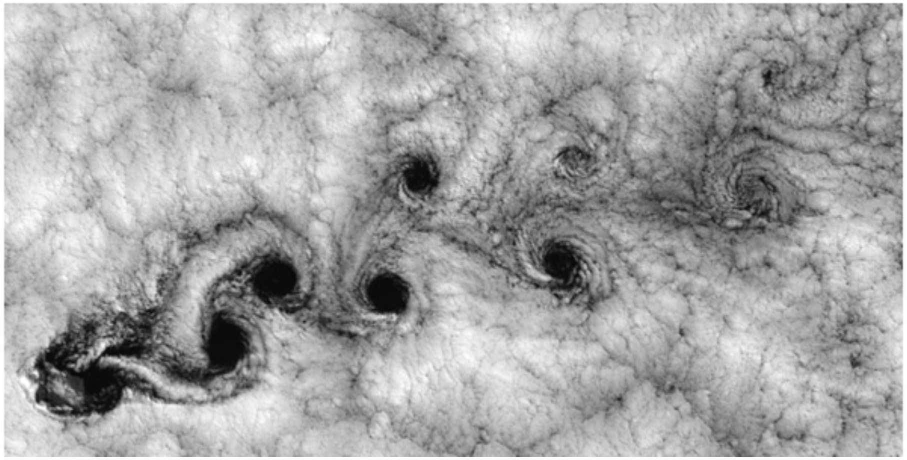
and a **non-magnetic, dead zone.**

A simple dead zone model



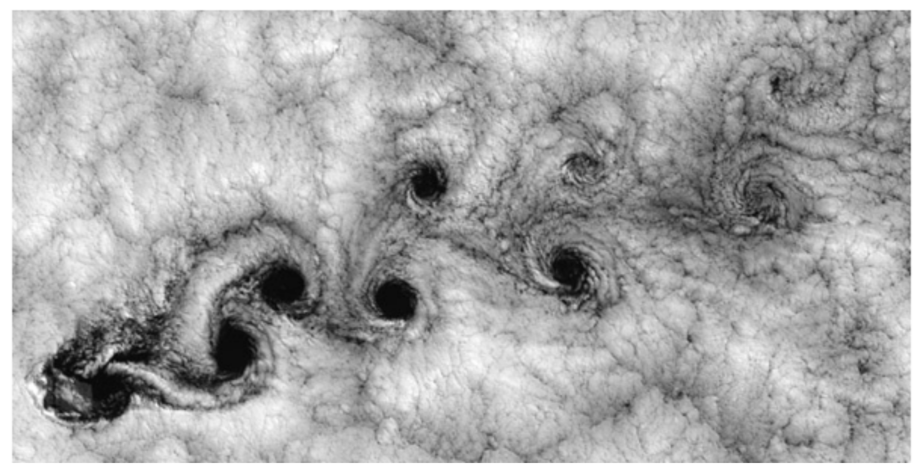
Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

Vortices – an ubiquitous fluid mechanics phenomenon



Vortices – an ubiquitous fluid mechanics phenomenon

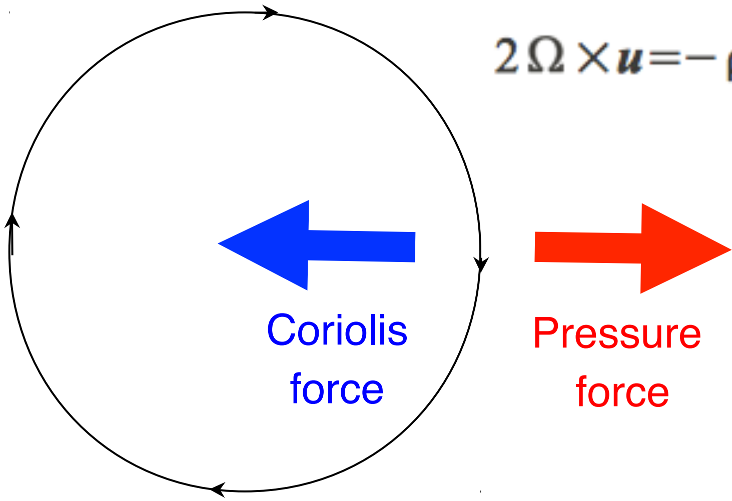
Von Kármán *vortex street*



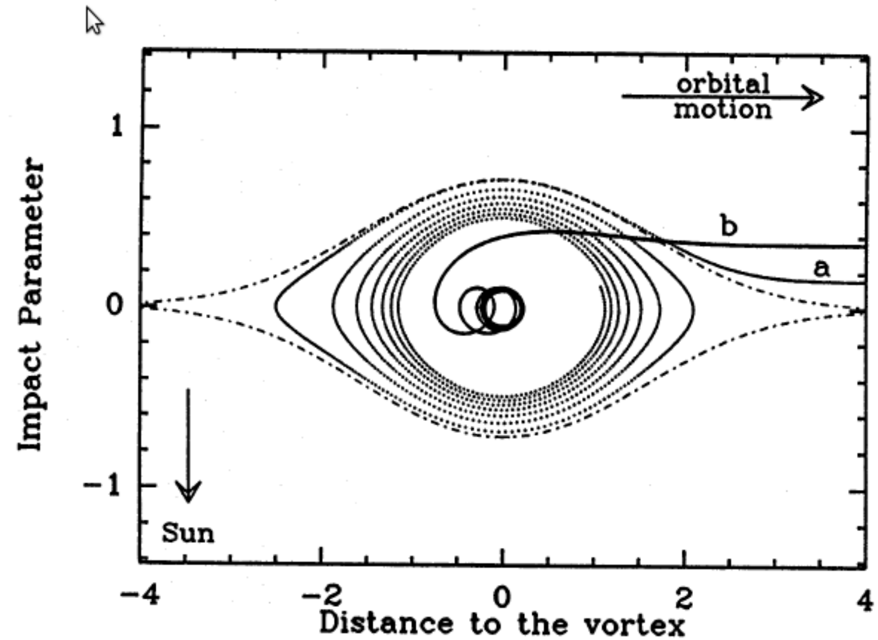
The Tea-Leaf effect

Geostrophic balance:

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



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, Adams & Watkins 1996, Tanga et al. 1996)

Speed up planet formation enormously

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

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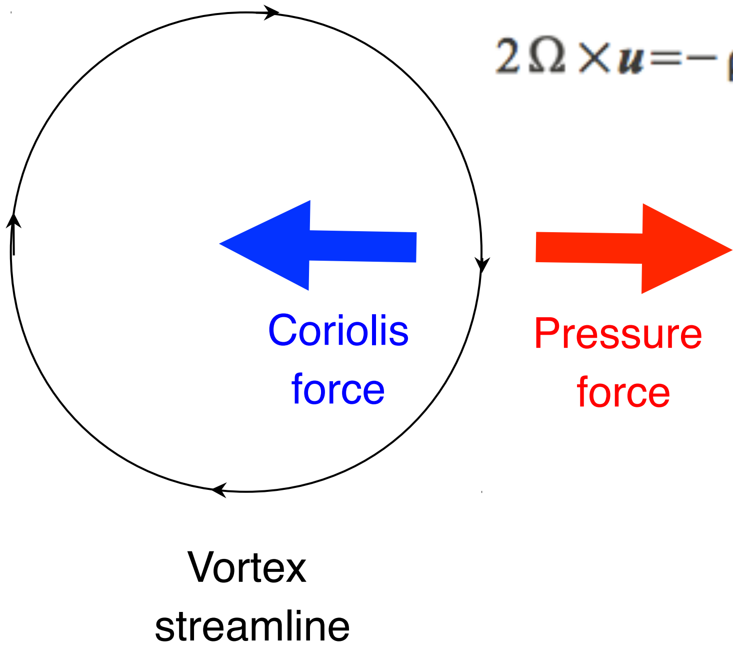

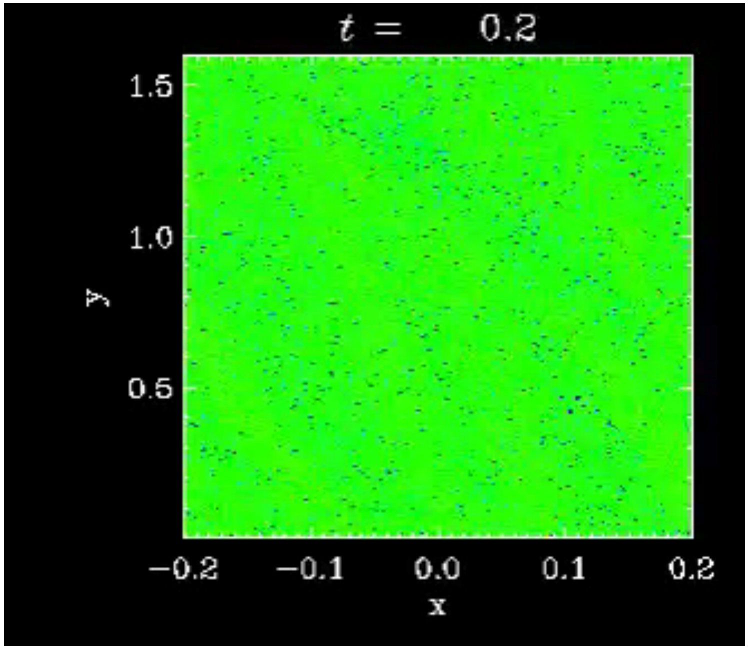

Raettig et al. (2012)

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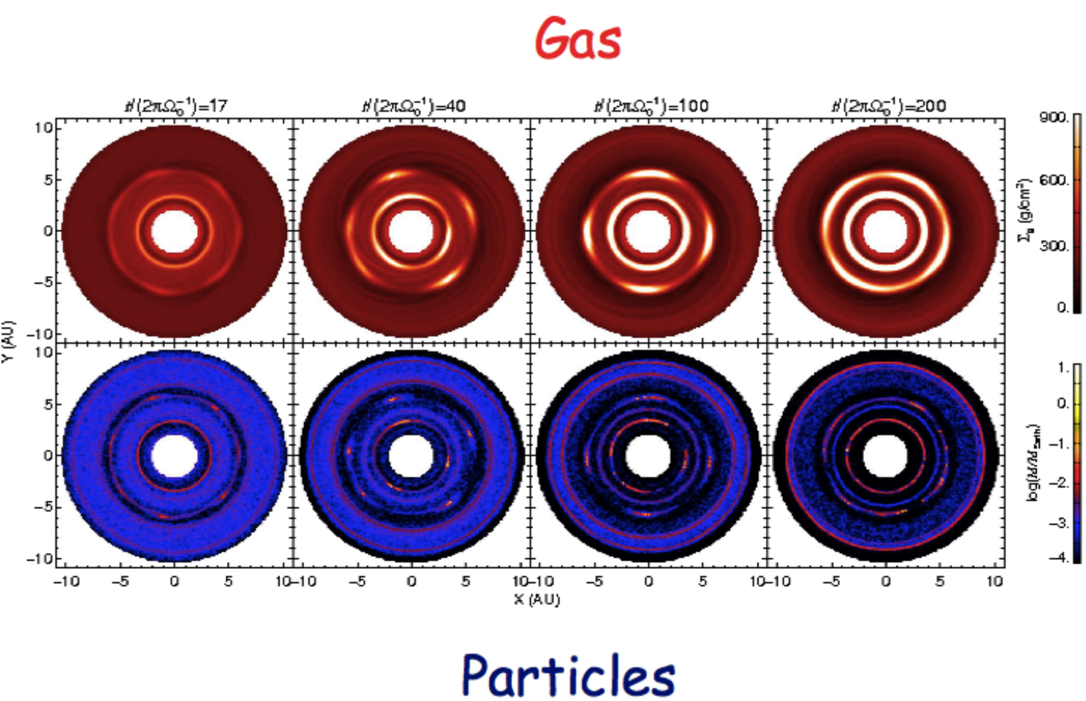
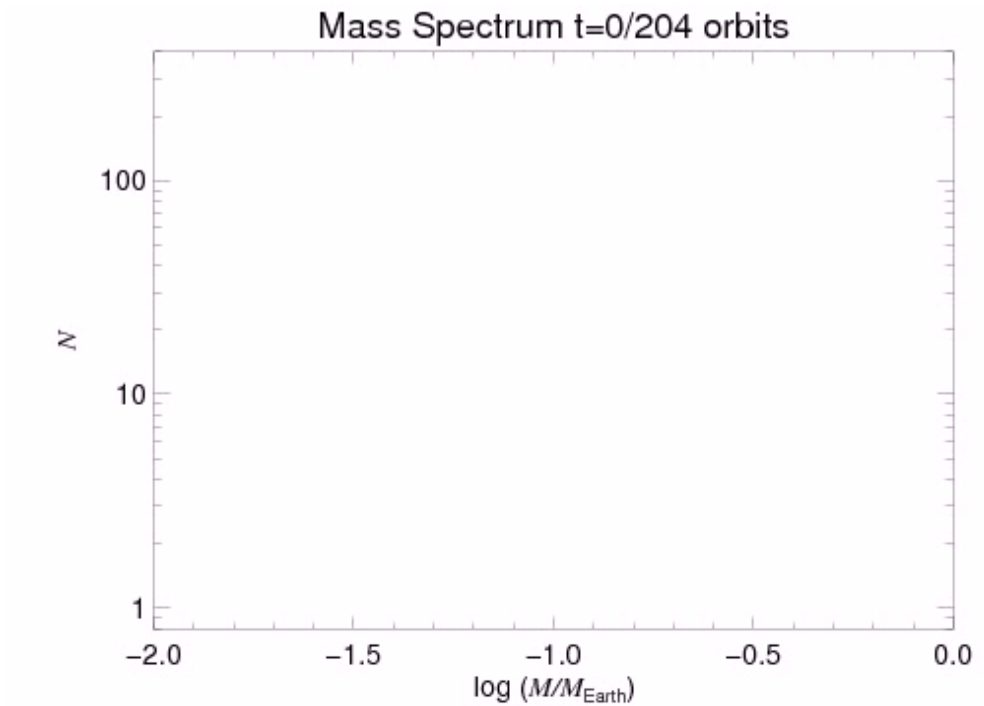
Vortices and Planet Formation

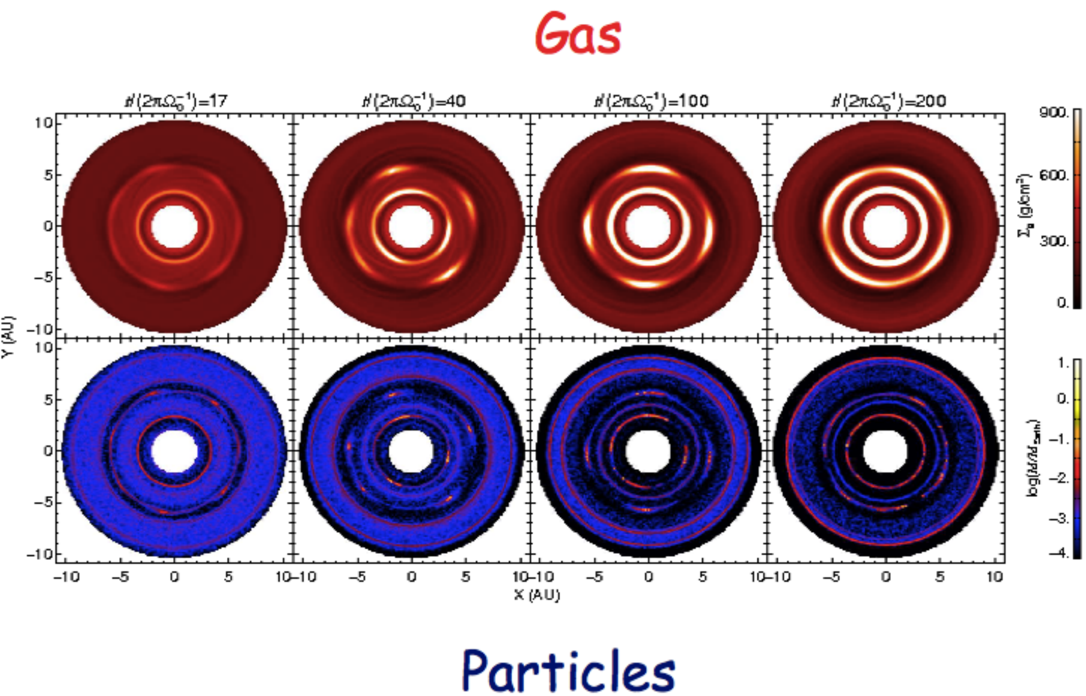


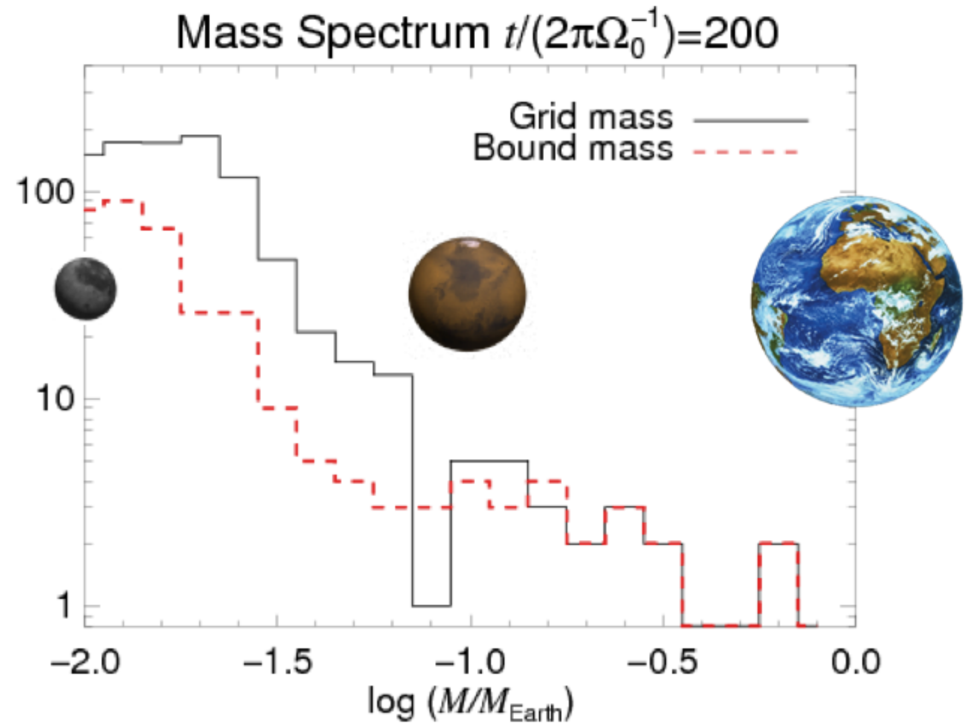


Collapse into Mars mass objects

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

Vortices and Planet Formation





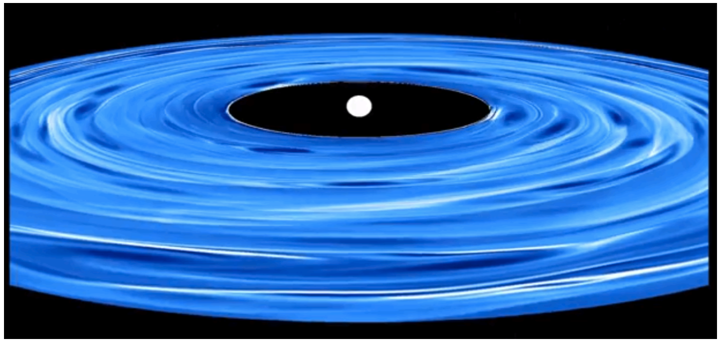
Collapse into Mars mass objects

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

Sustaining vortices in disks

Baroclinic instability

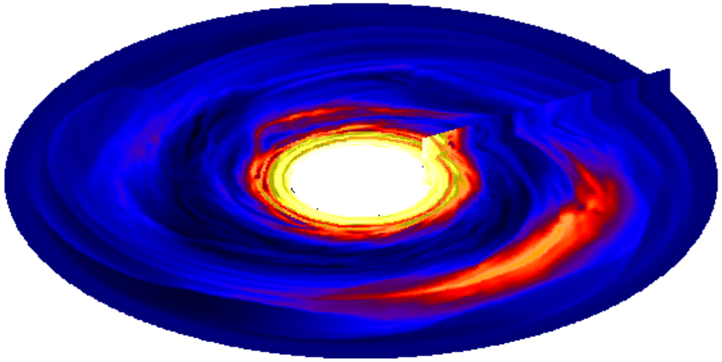
(Convective overstability)



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)

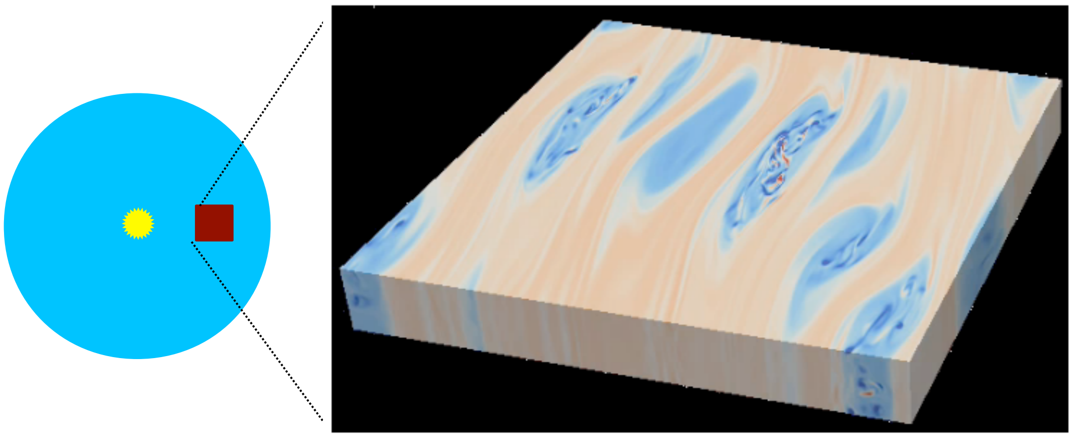
Rossby wave instability



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)

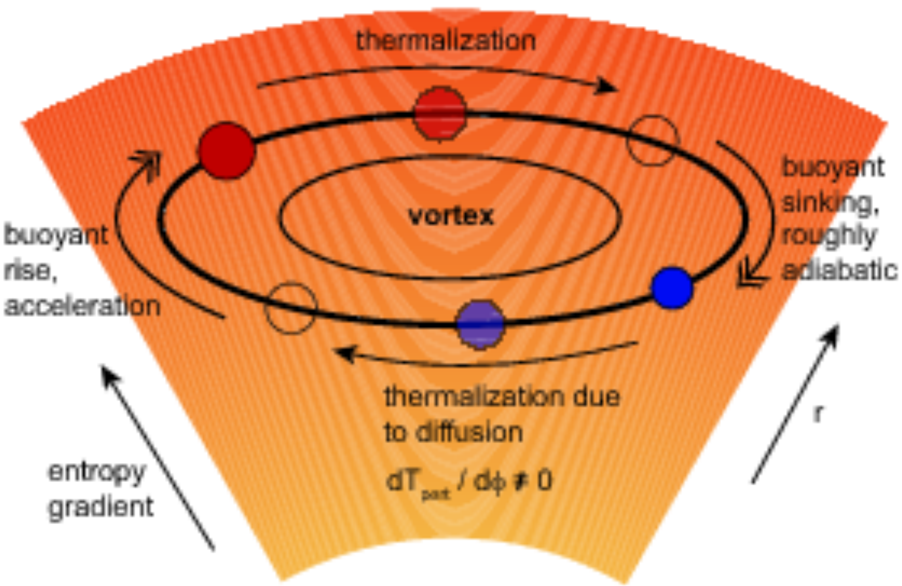
Powered by:
Modification of shear profile
(external vorticity reservoir)

Baroclinic Instability – Excitation and self-sustenance of vortices



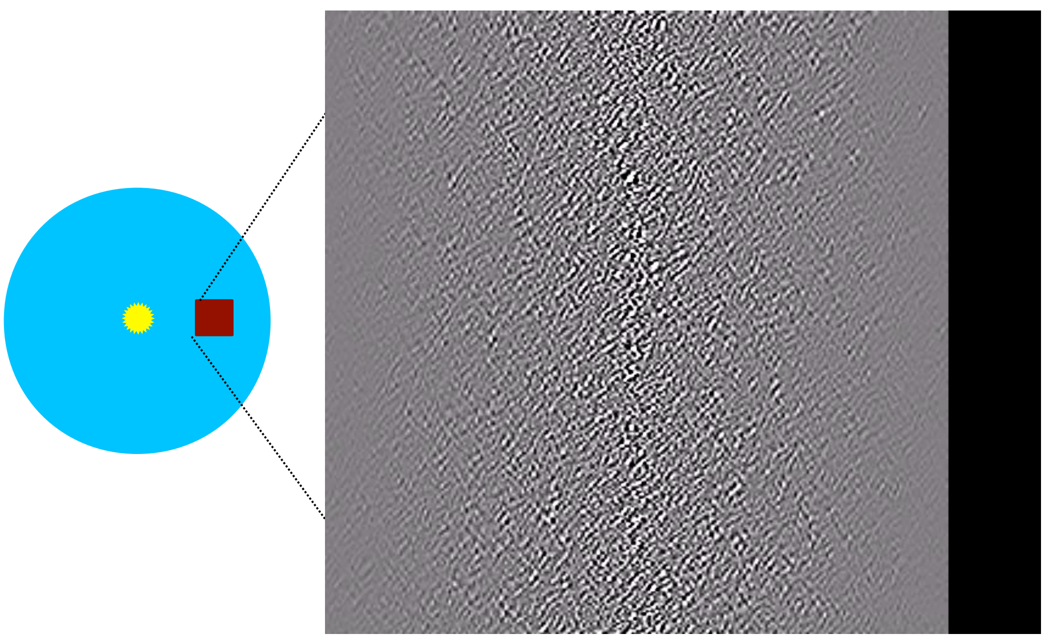
Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability



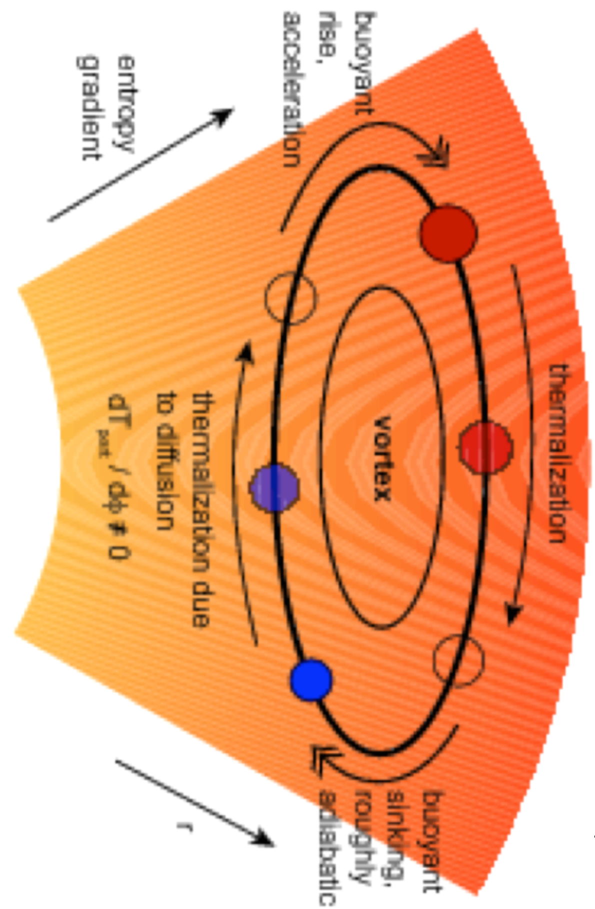
Armitage (2010)

Baroclinic Instability – Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

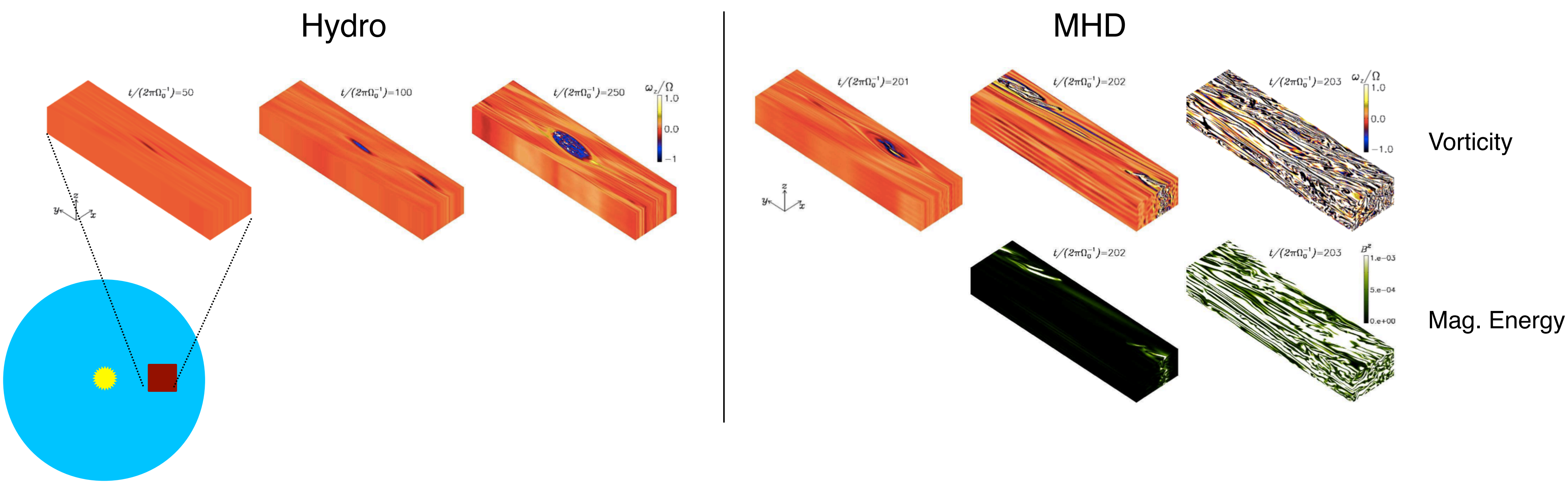
Sketch of the
Baroclinic Instability



Armitage (2010

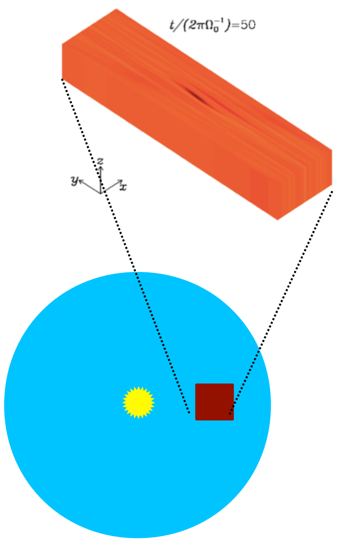
Baroclinic instability and layered accretion

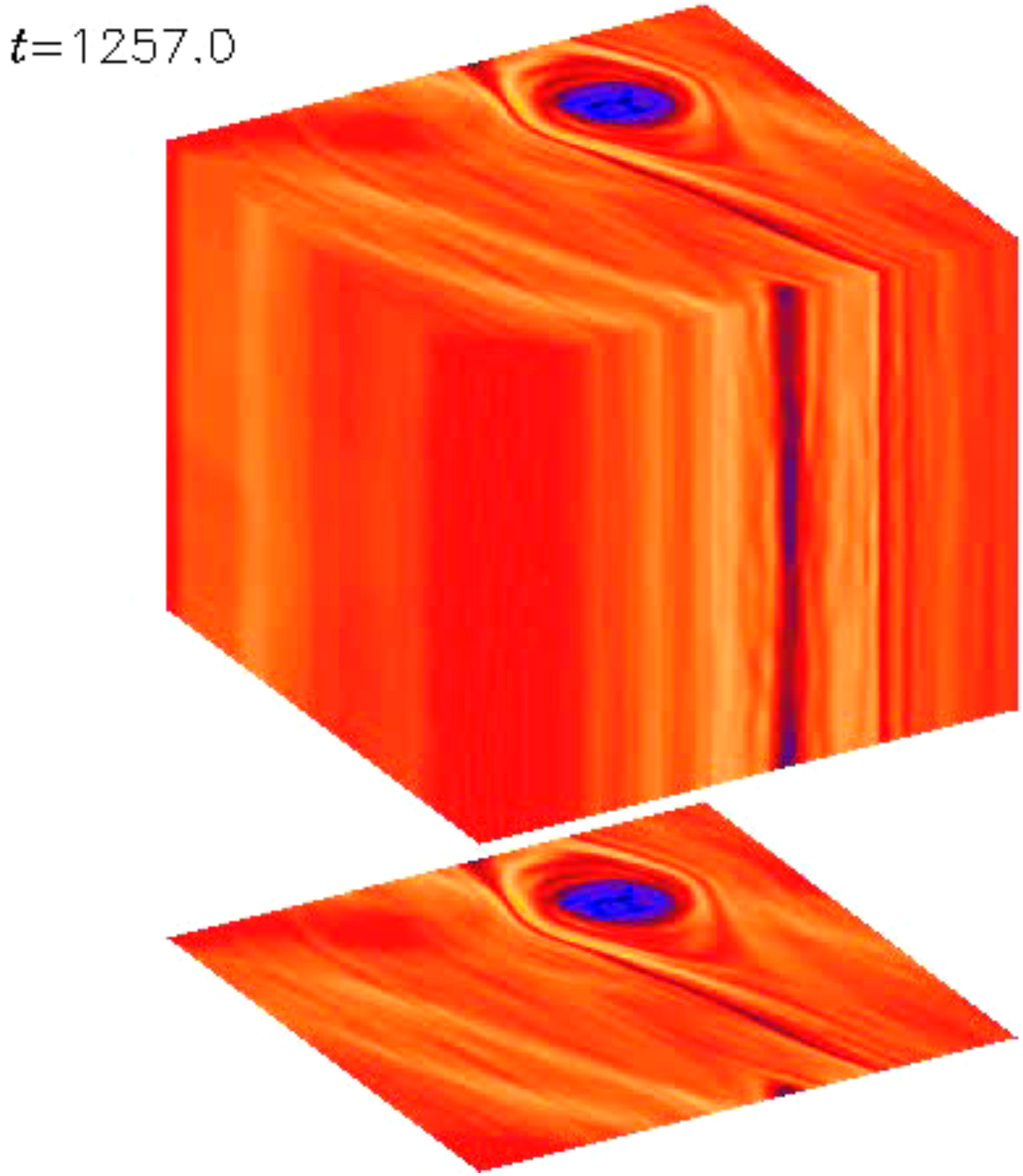
What happens when the vortex is magnetized?

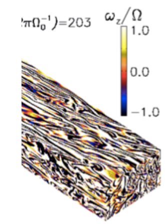


Lyra & Klahr (2011)

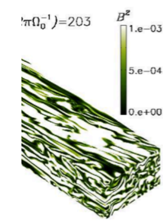
Baroclinic instability and layered accretion







Vorticity



Mag. Energy

Baroclinic instability and layered accretion

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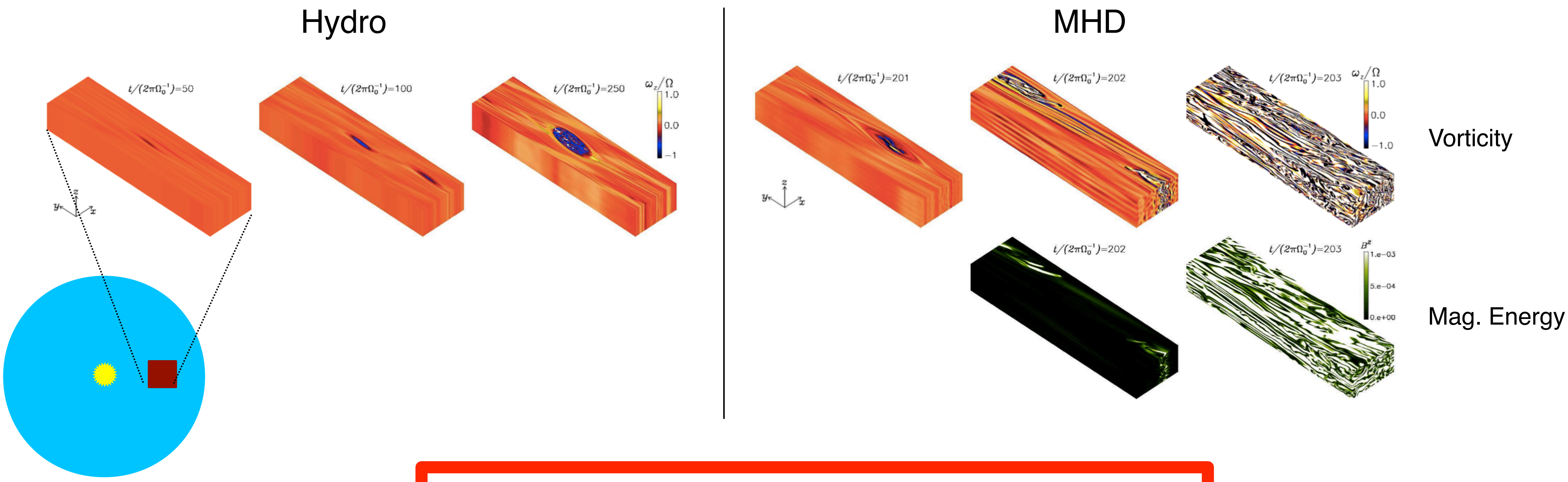


Lyra & Klahr (2011)

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

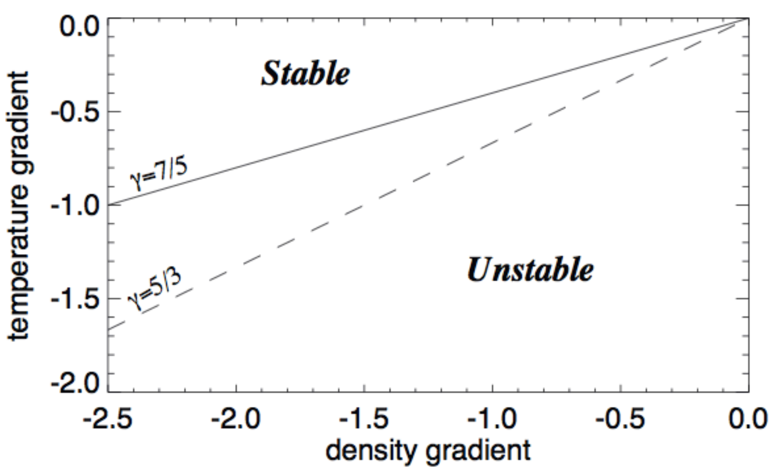
The “Baroclinic Instability” is LINEAR (Convective Overstability)

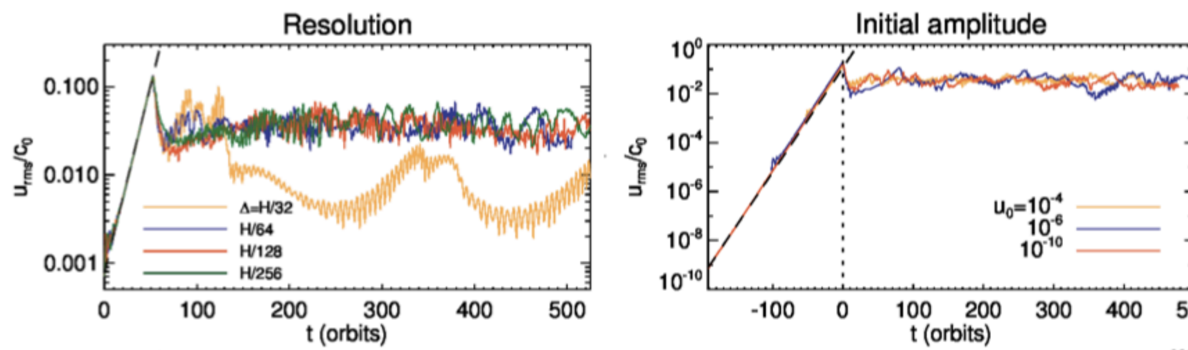
Klahr & Hubbard (2014), Lyra (2014)

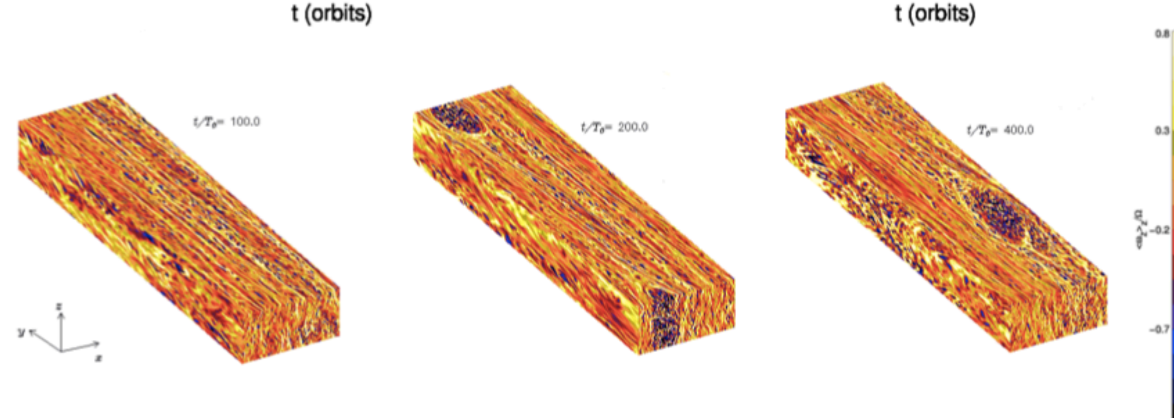
$$\frac{\partial\rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u},$$
$$\frac{\partial\boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\boldsymbol{u} = -\frac{1}{\rho}\boldsymbol{\nabla}p + \boldsymbol{g},$$
$$\frac{\partial p}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,p = -\gamma p\boldsymbol{\nabla}\cdot\boldsymbol{u} - \frac{p}{T}\frac{(T-T_0)}{\tau},$$

$$\bar{\omega}^3 + i\varsigma\bar{\omega}^2 - \bar{\omega}\mu^2(\kappa^2+N^2) - i\varsigma\kappa^2\mu^2 = 0,$$
$$\varsigma = 1/\gamma\tau \qquad \mu^2 = k_z^2/k^2.$$

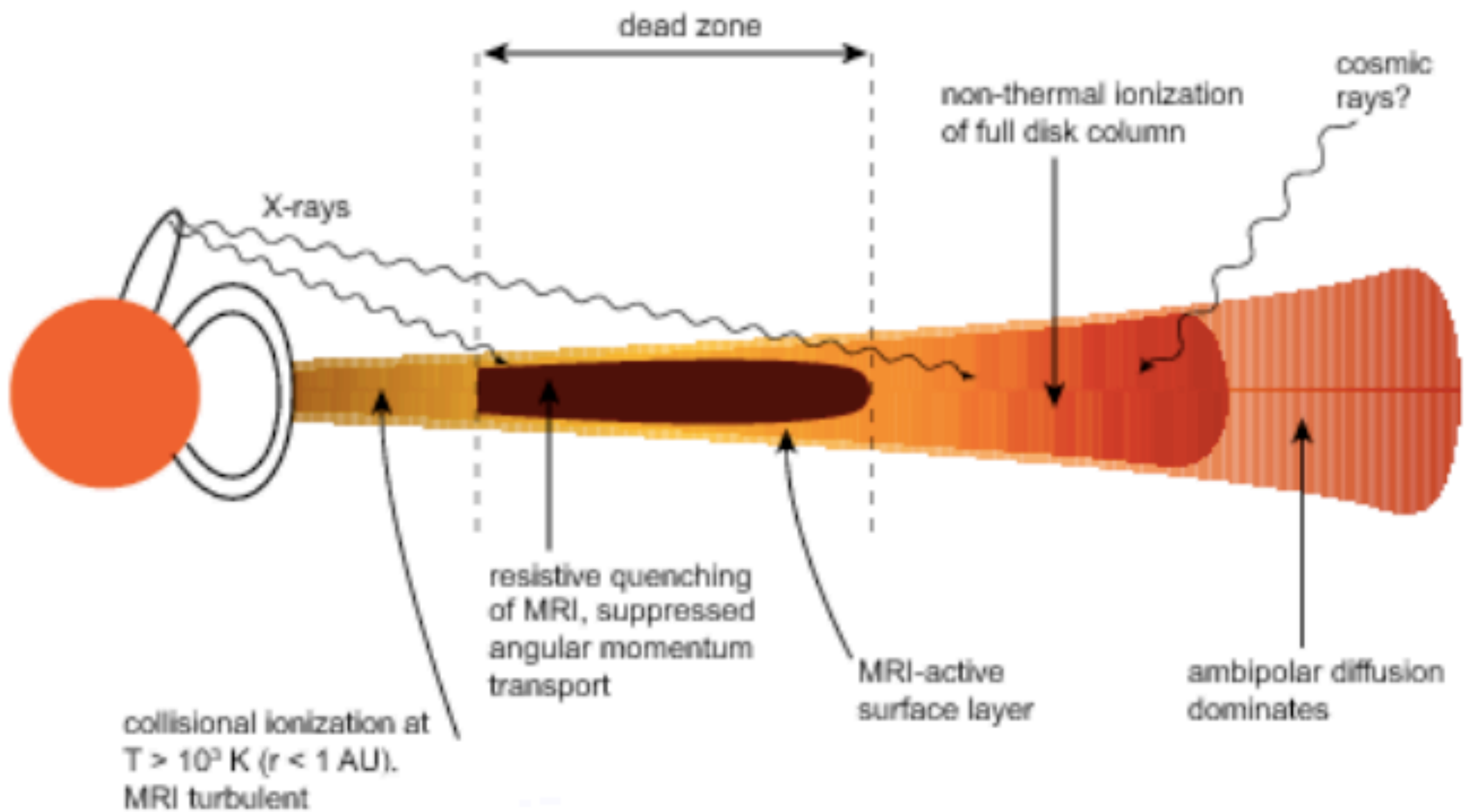
$$\tau_{\max} = \frac{1}{\gamma}\left|\frac{k}{k_z}\right|\frac{1}{\sqrt{\kappa^2+N^2}} \qquad \sigma_{\max} = -\frac{1}{4}\left|\frac{k_z}{k}\right|\frac{N^2}{\sqrt{\kappa^2+N^2}}$$

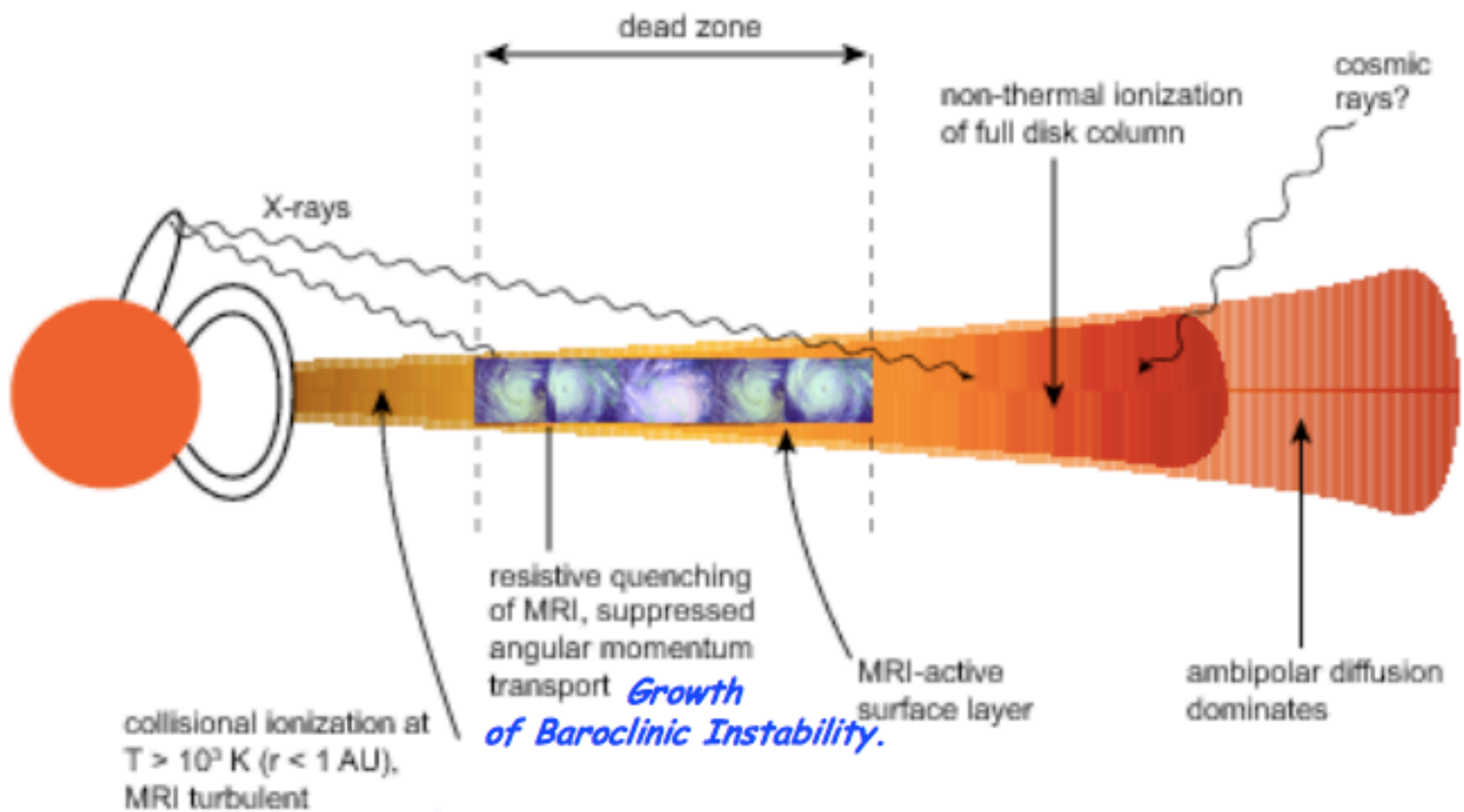






Lyra (2014)


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
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of Baroclinic Instability.
MRI-active
surface layer
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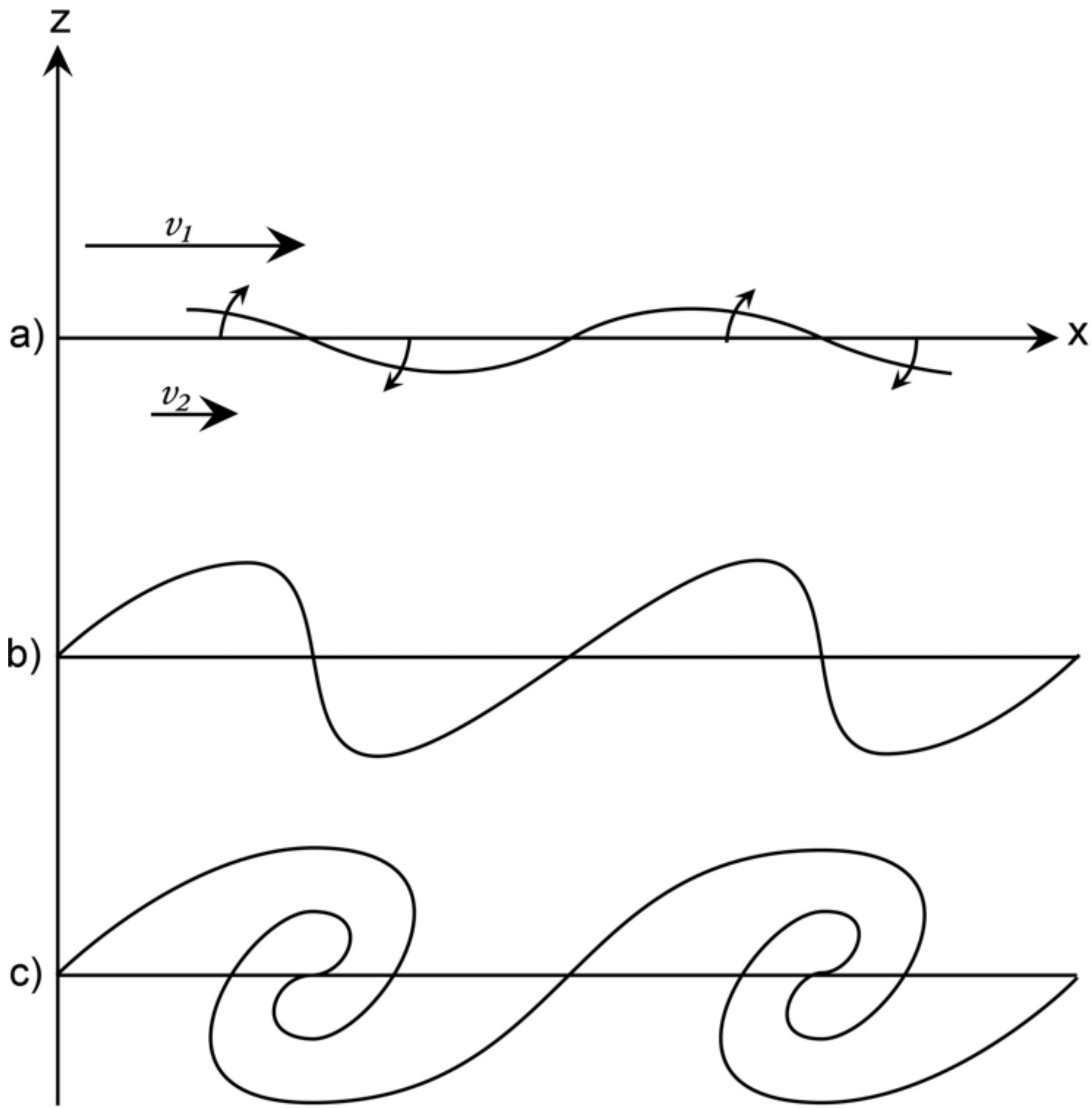
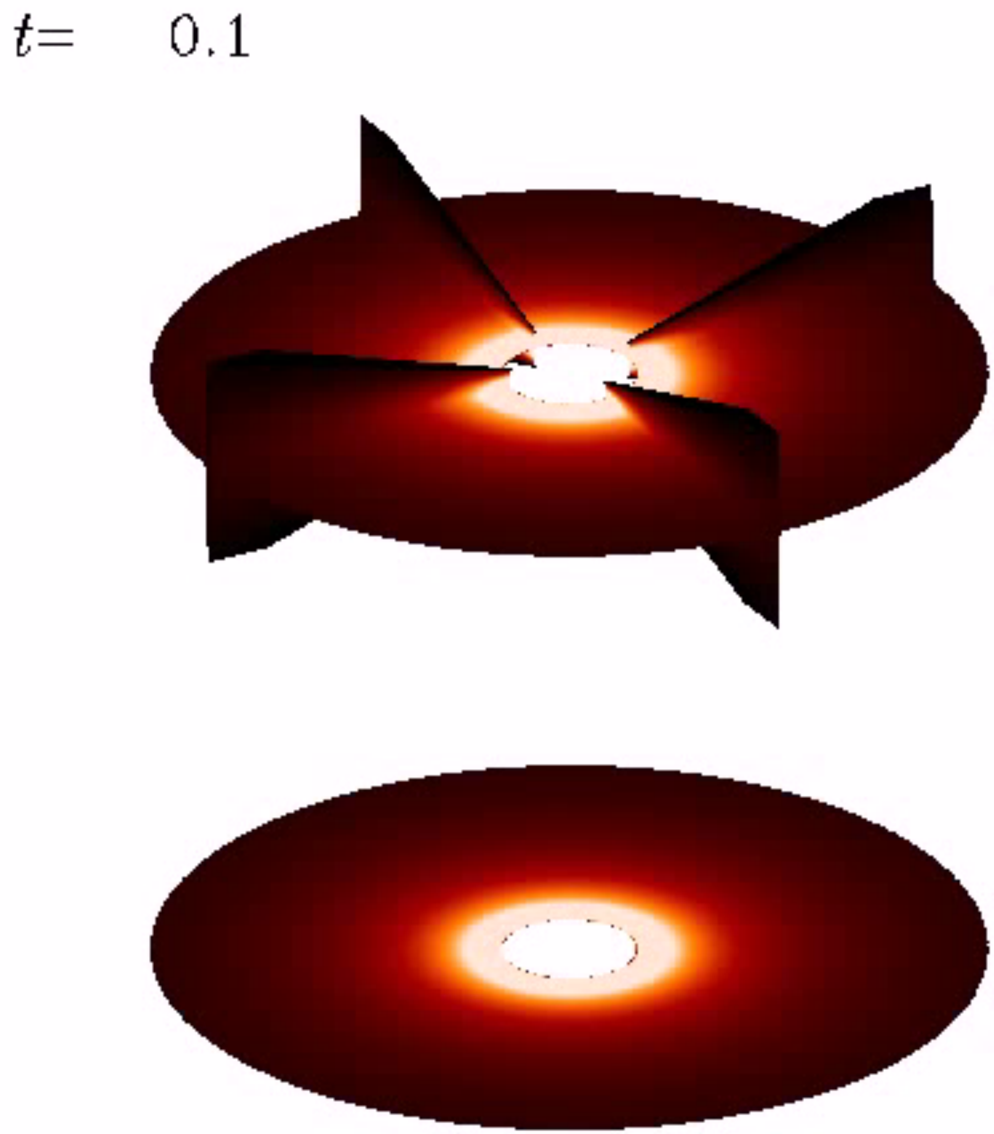
T > 10³ K (r < 1 AU),
MRI turbulent

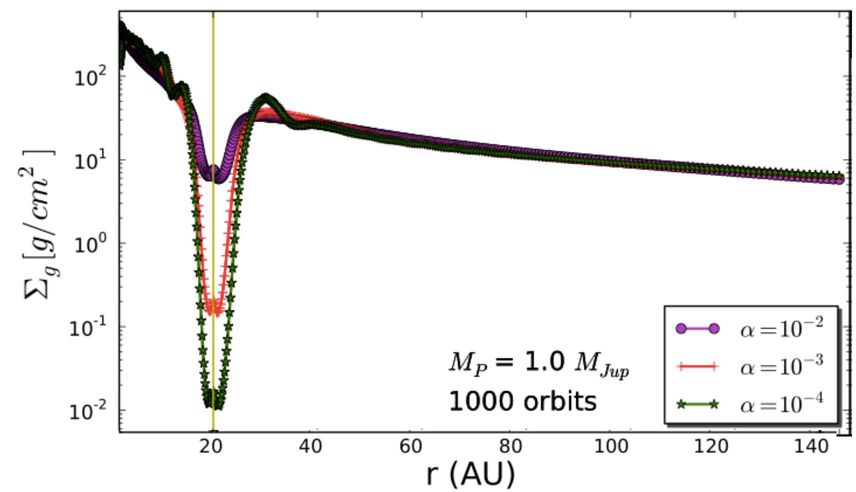
Rossby Wave Instability
(or… **Kelvin-Helmholtz** in rotating disks)



Planetary gap RWI

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





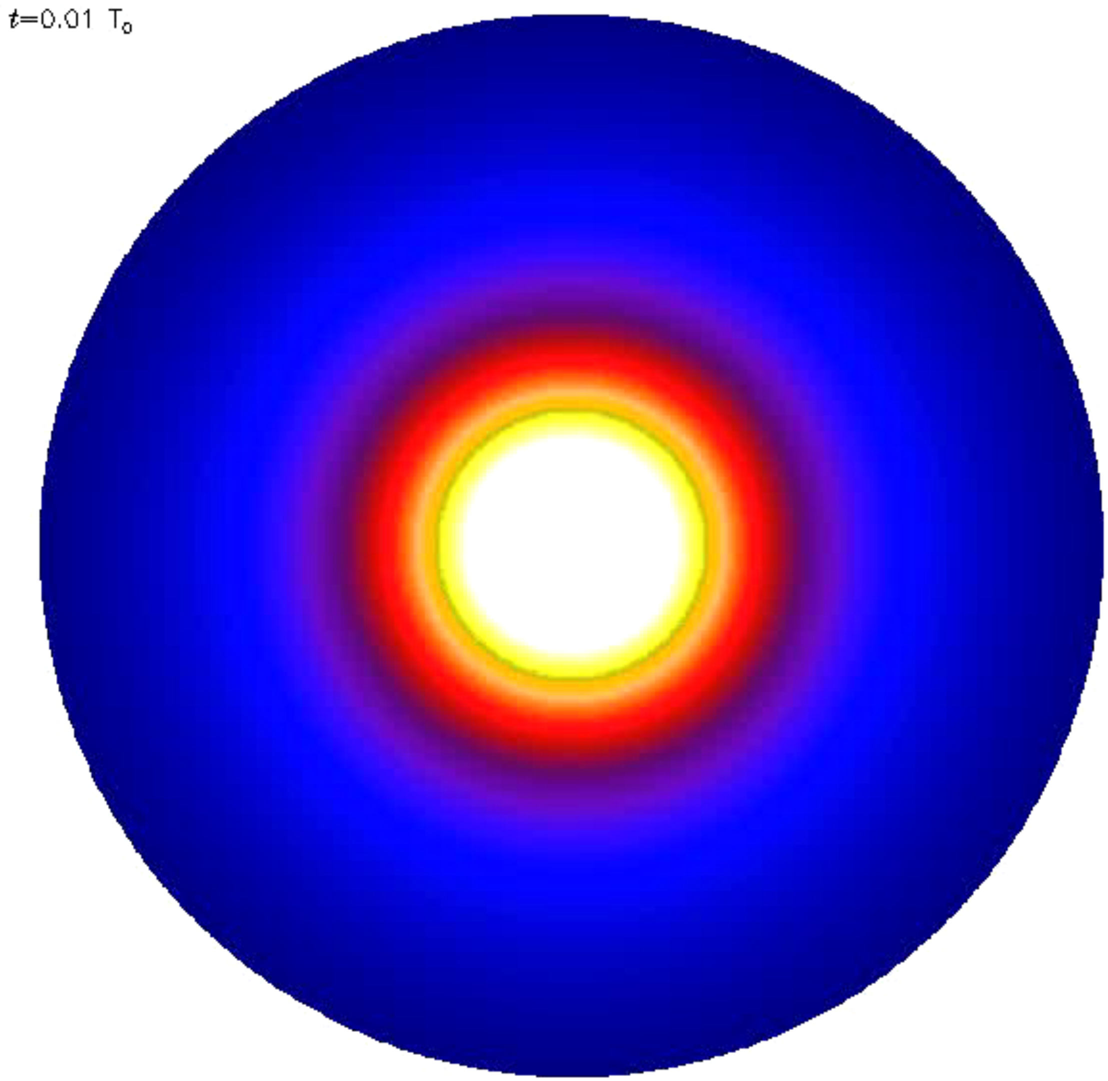
Pinilla et al. (2012)

Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

Lyra (2009)

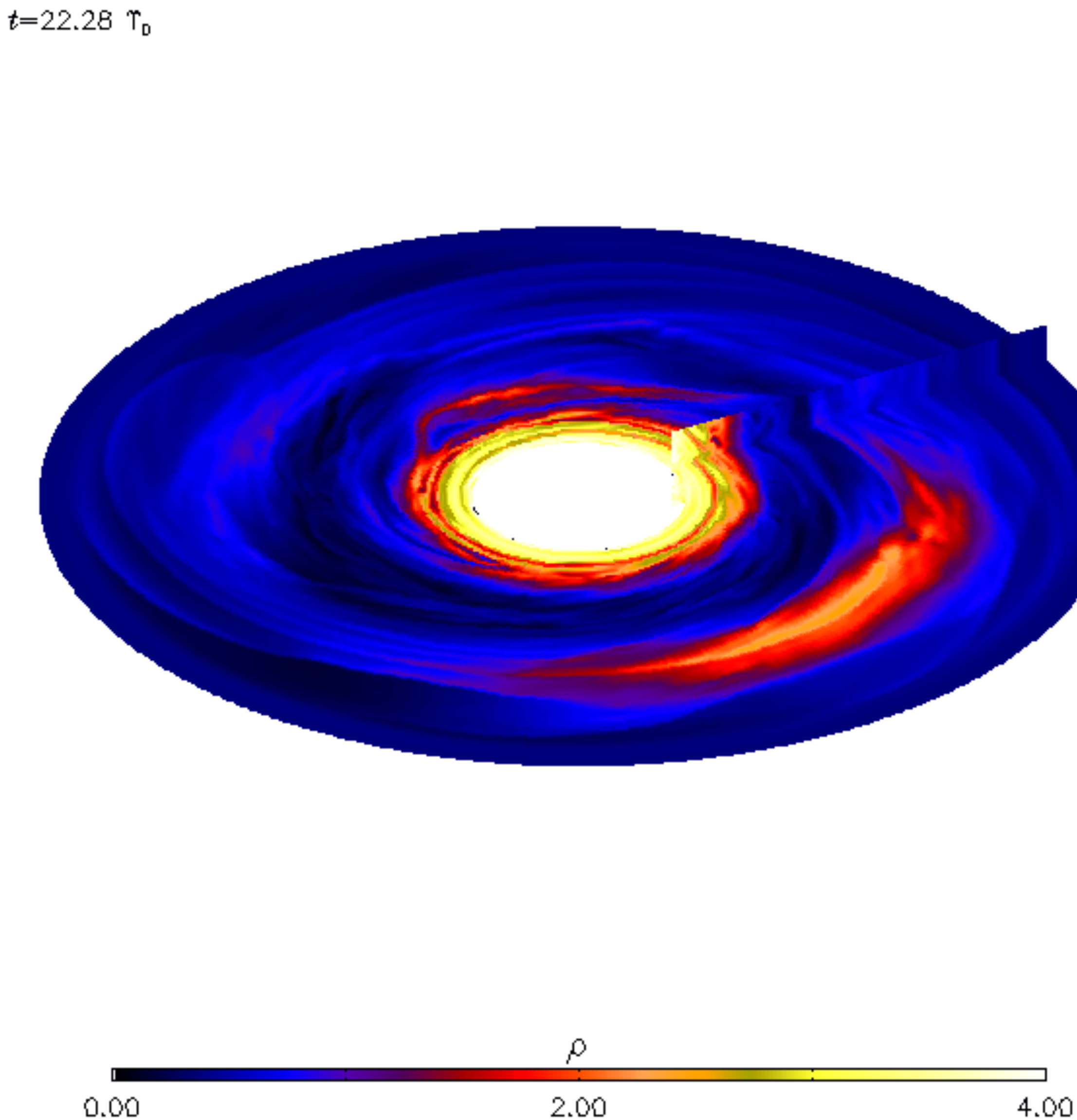
Active/dead zone boundary

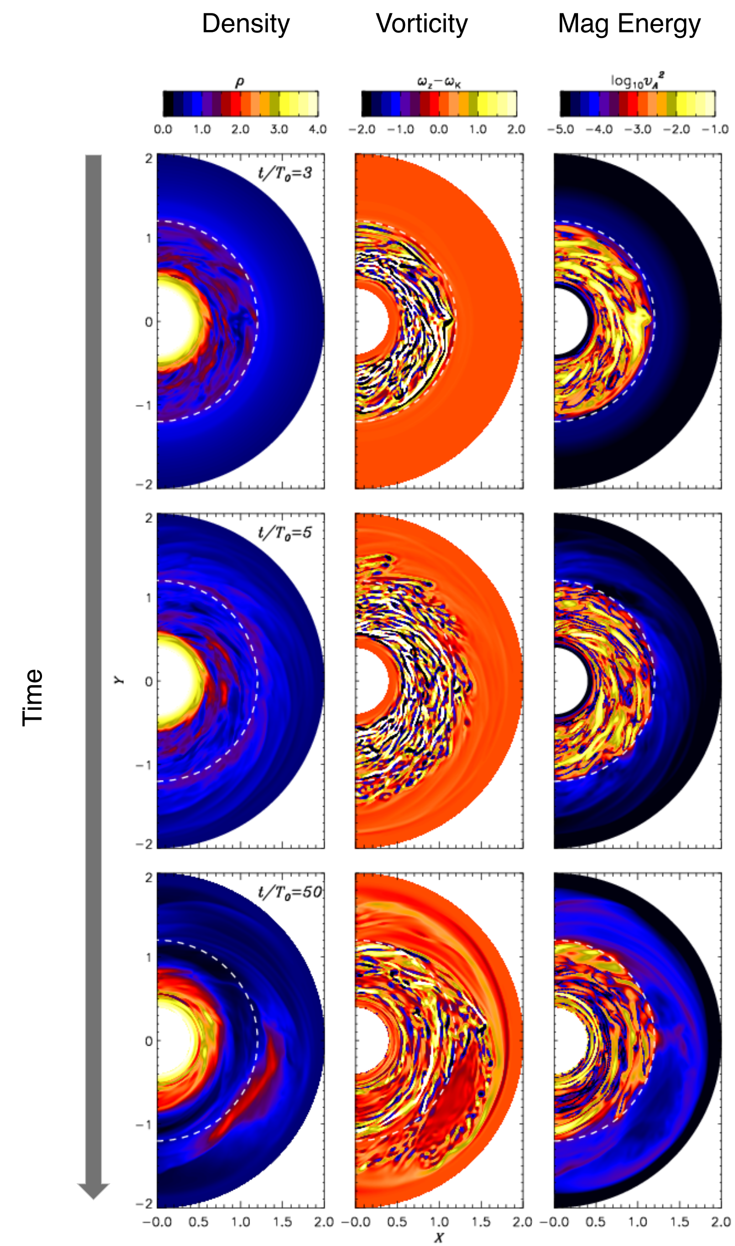


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Active/dead zone boundary

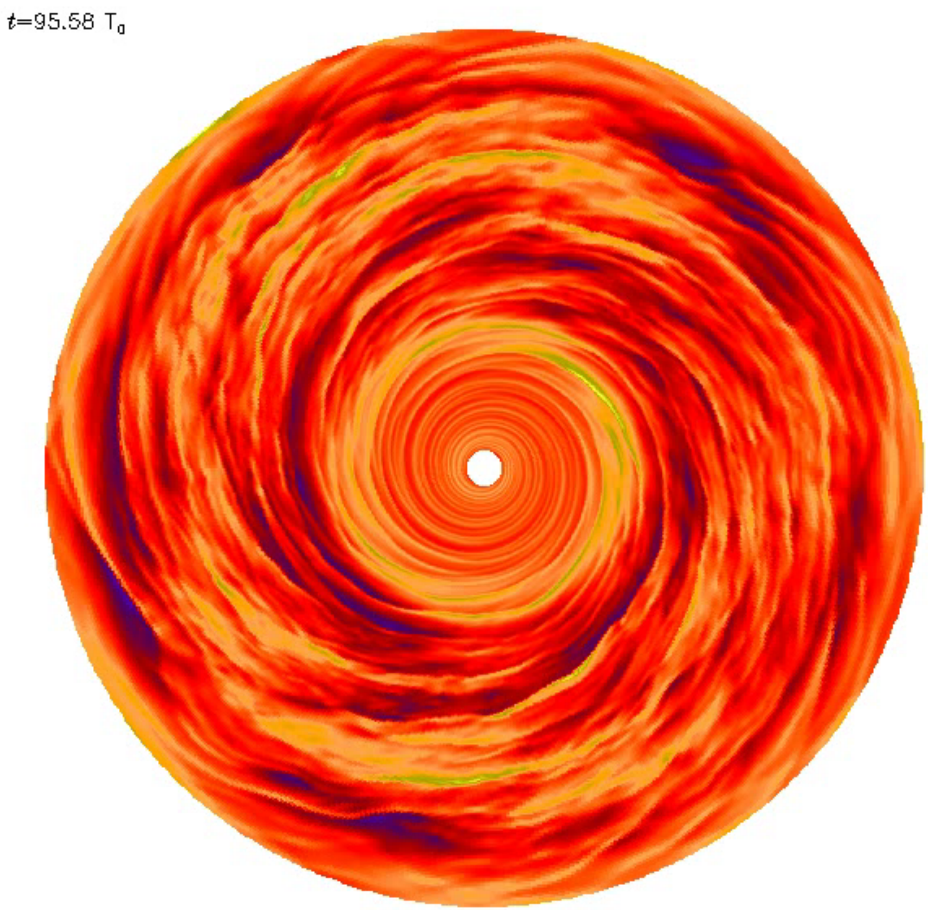


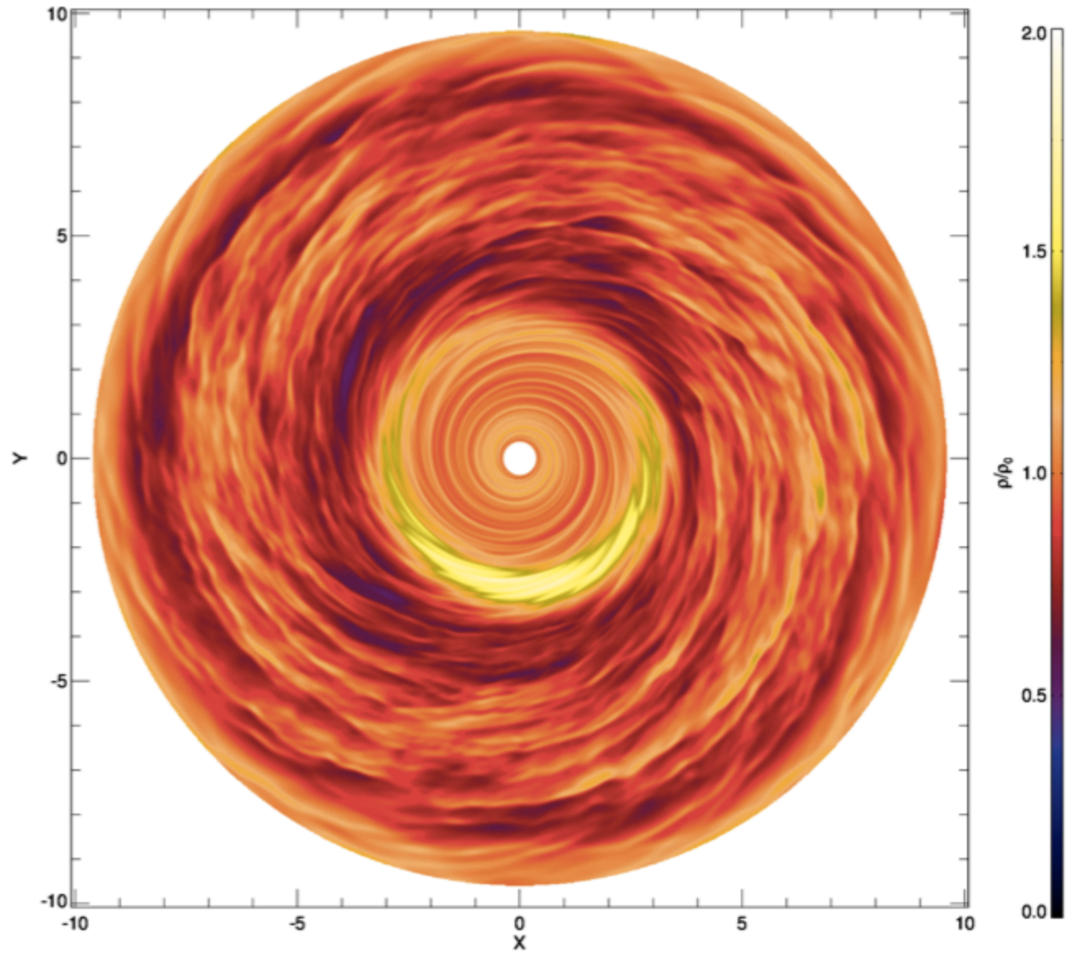


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Outer Dead/Active zone transition RWI





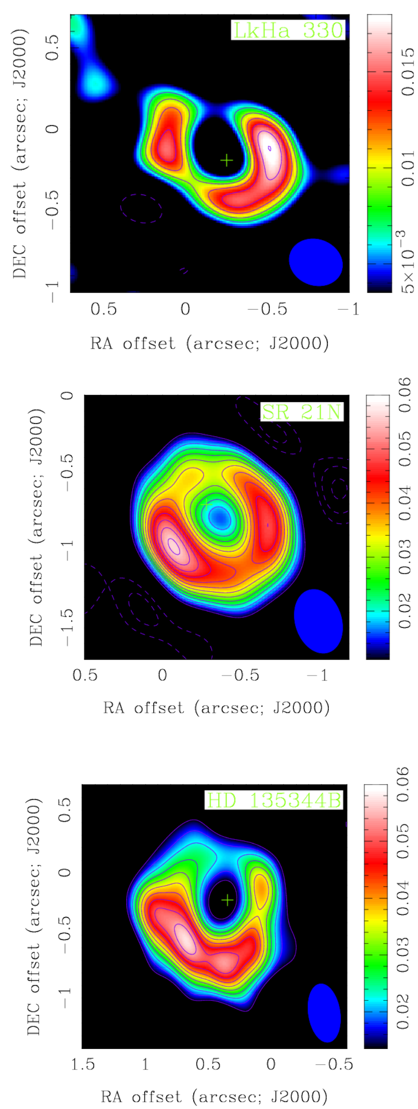
Resistive inner disk + magnetized outer disk

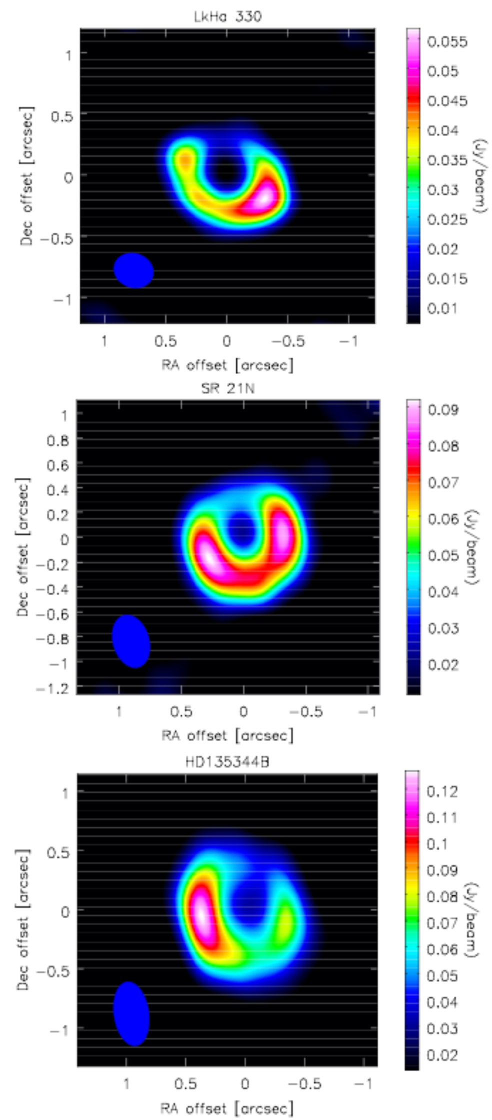
Lyra, Turner, & McNally (2015)

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

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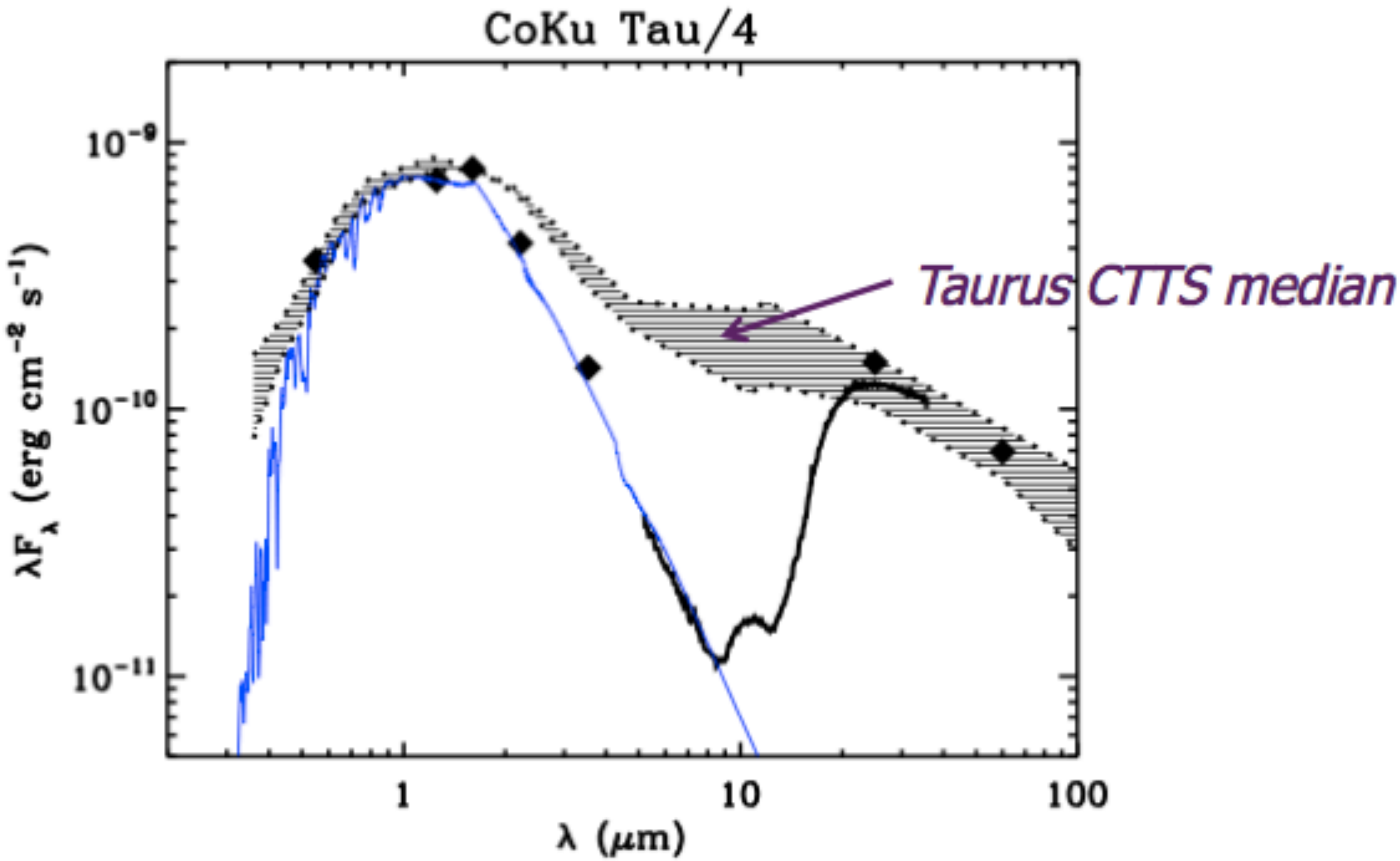
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection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

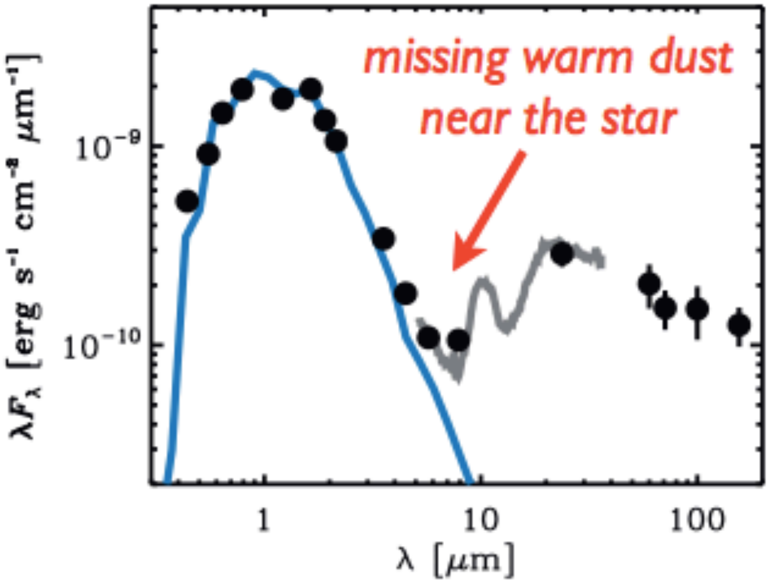
van der Marel et al. 2013

A possible huge vortex observed with ALMA

Transition Disks: Disks with missing hot dust.



the “transition” disks (and what that means)



[e.g., Furlan et al. 2009]

“These objects represent...disks whose inner regions are relatively devoid of distributed matter, although the outer regions still contain substantial amounts of dust.”

[Strom et al. 1989]

what I mean:

a disk with a large reduction in optical depth near the star (i.e., a “cavity” or “hole”)

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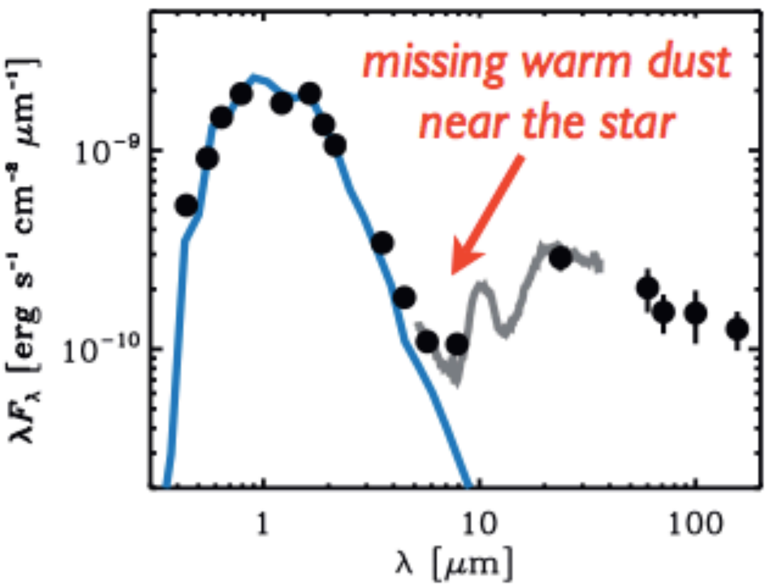

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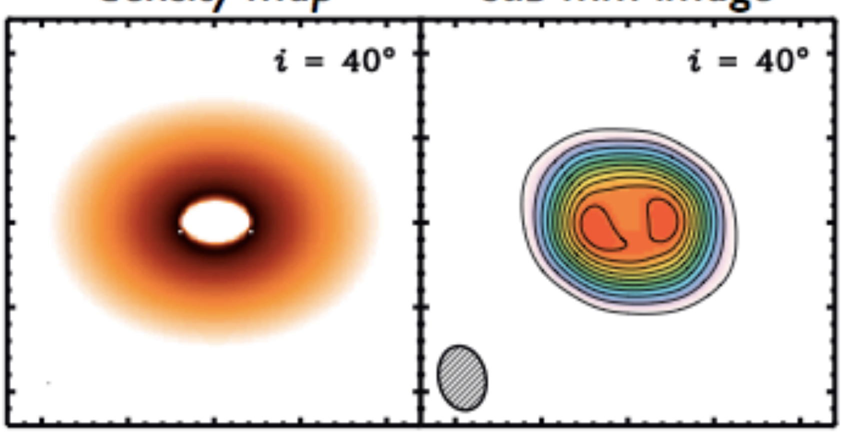
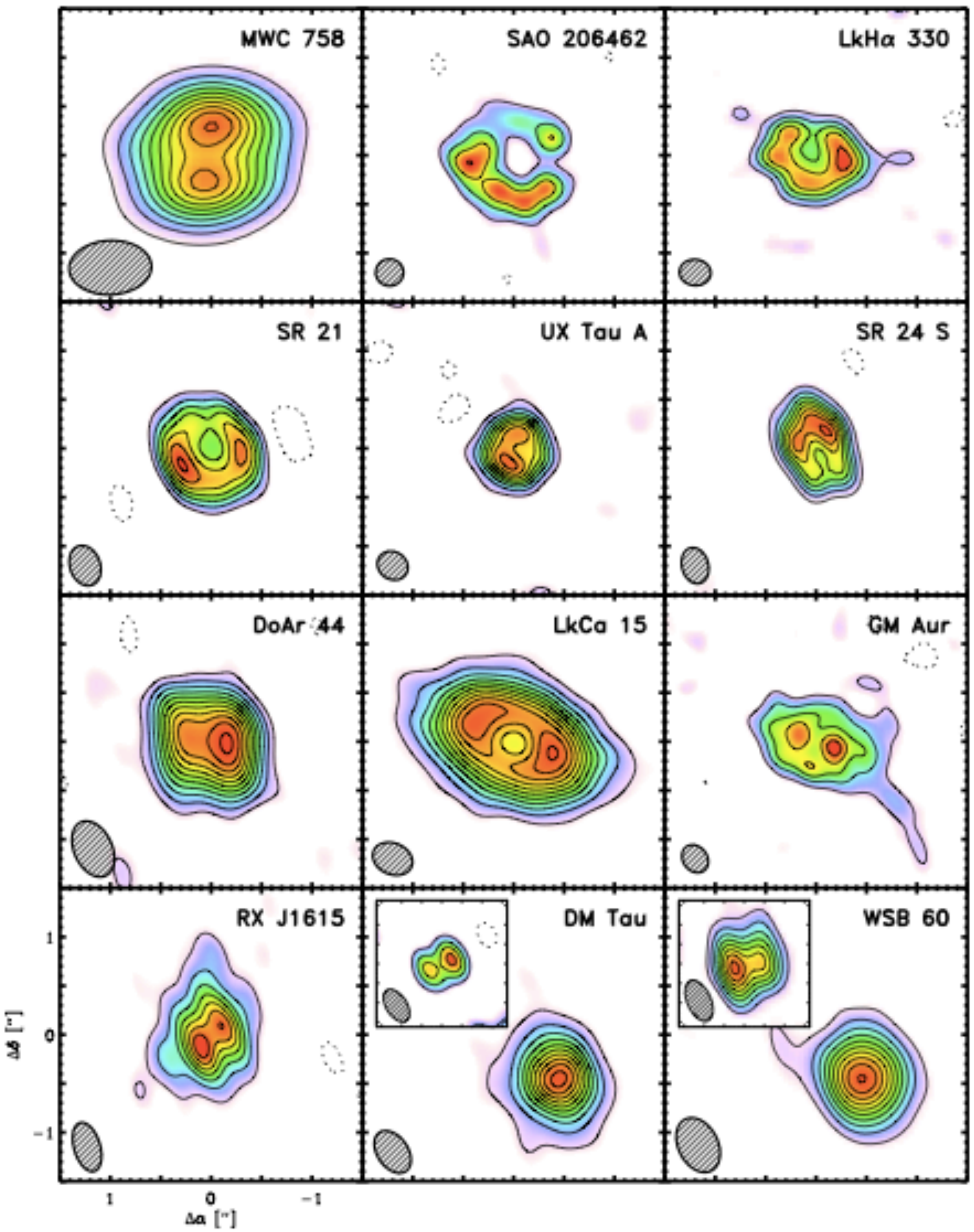
model density map | *synthetic sub-mm image*

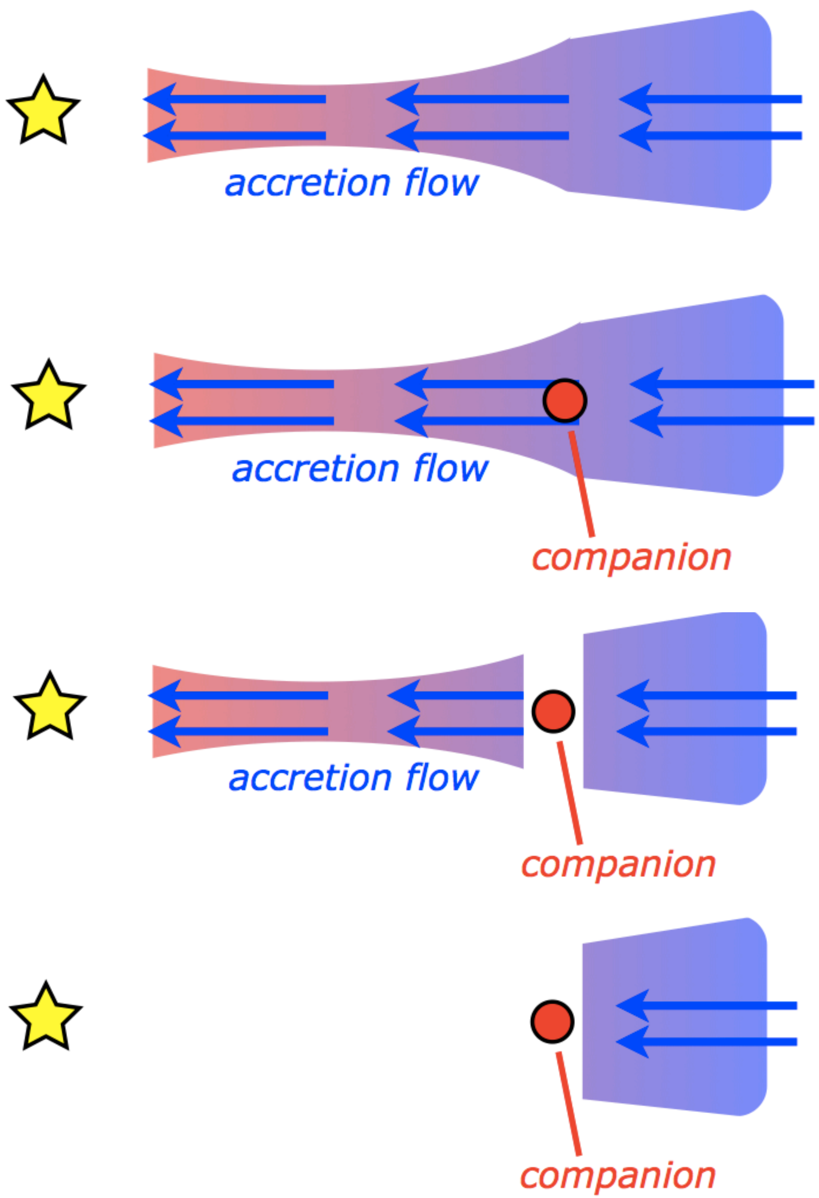


Resolved transition disks with SMA



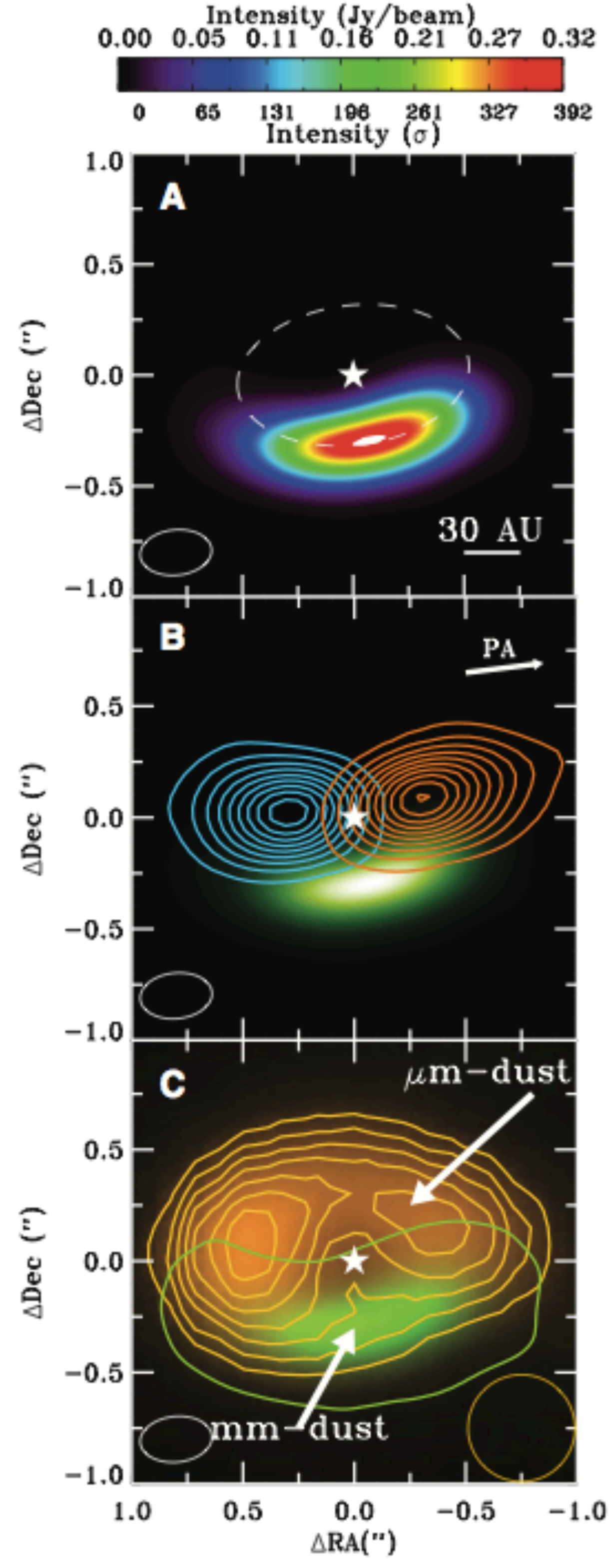
0.85mm
0.3" ~ 20 AU resolution

Planetary companion



See James Owen's talk

The Oph IRS 48 "dust trap"



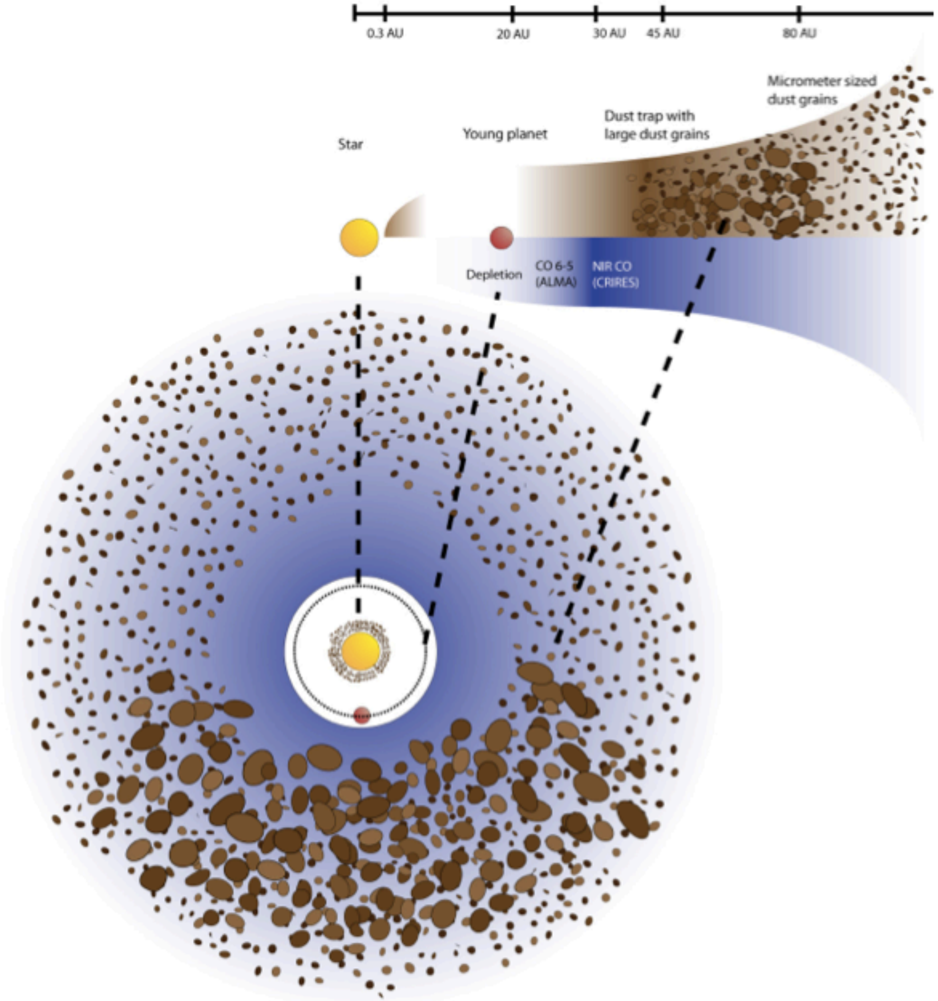
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

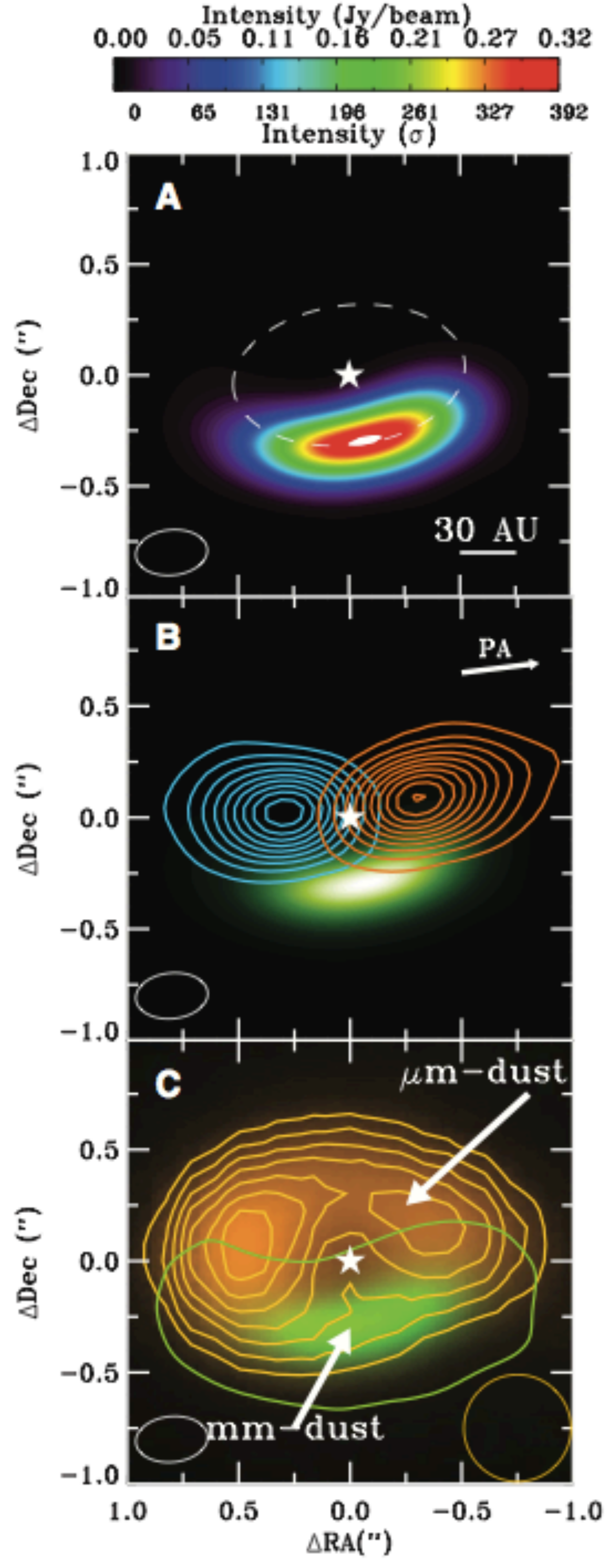
Micron-sized dust follows gas

van der Marel et al. (2013)

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)



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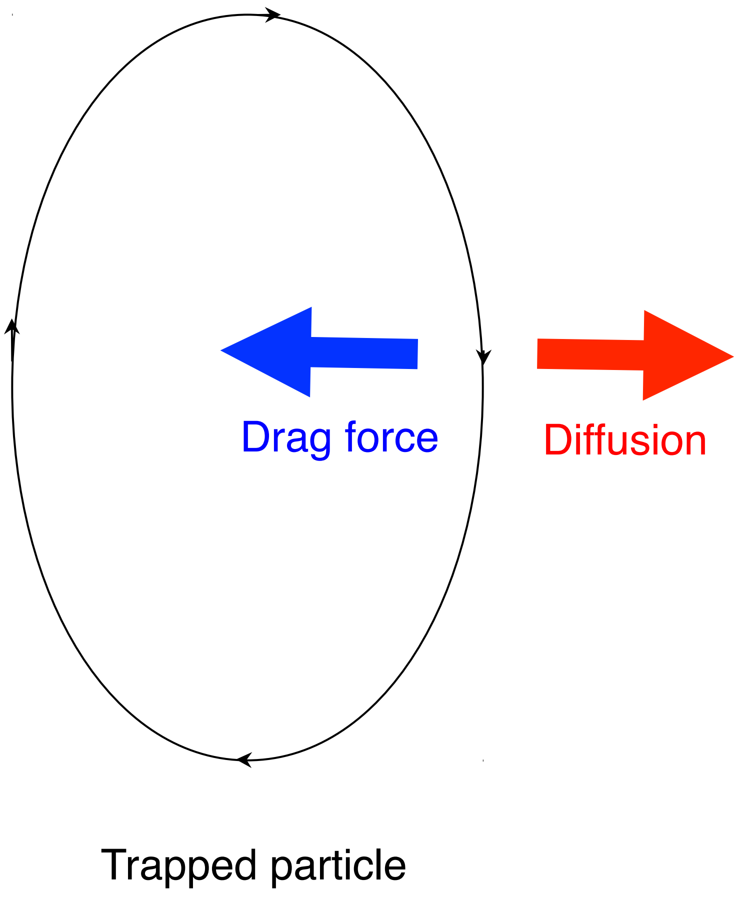
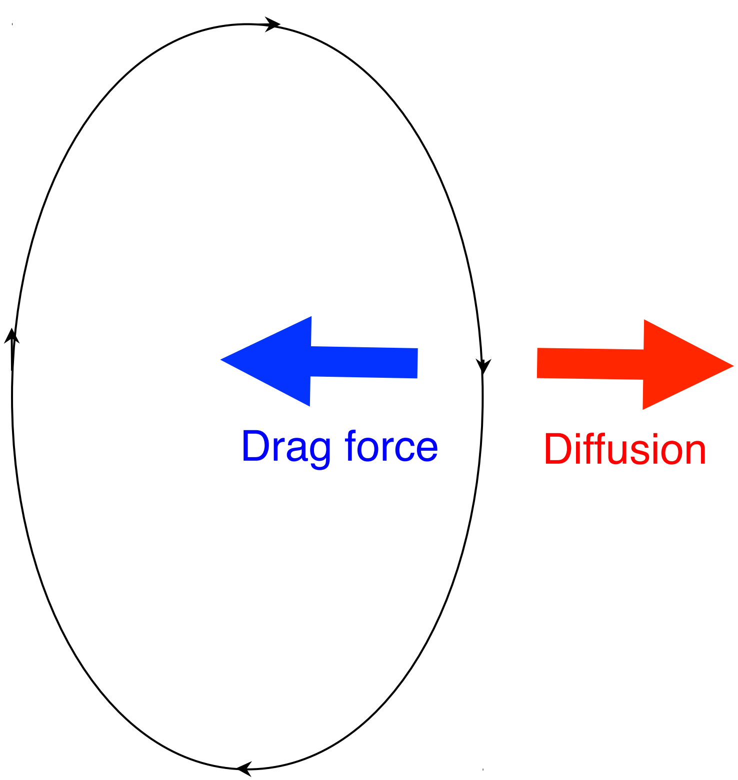
Drag-Diffusion Equilibrium



Drag-Diffusion Equilibrium



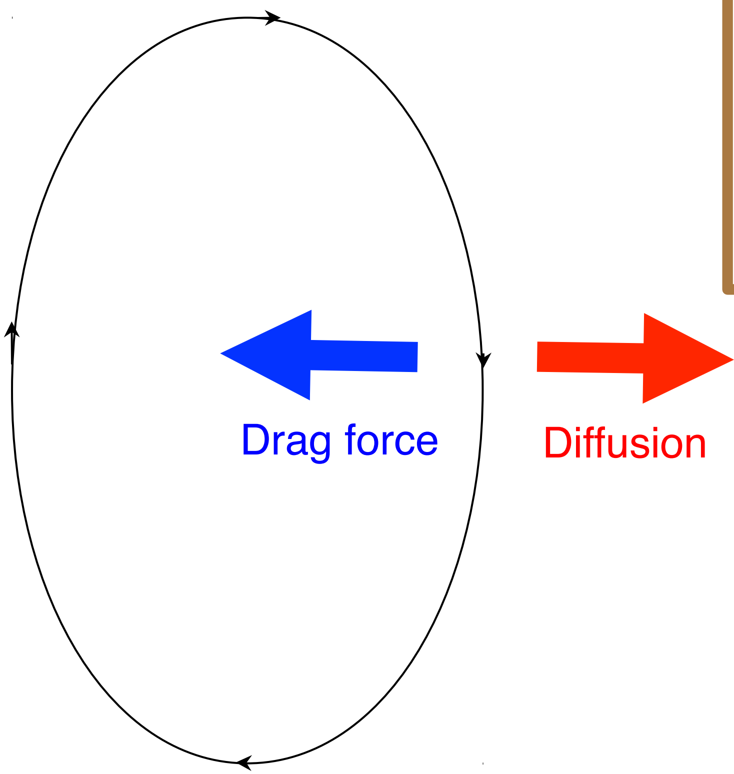
Trapped particle

Dust continuity equation

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

- $-(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d$: **advection**
- $\rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v}$: **compression**
- $D\nabla^2 \rho_d$: **diffusion**

Drag-Diffusion Equilibrium



Steady-state solution

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

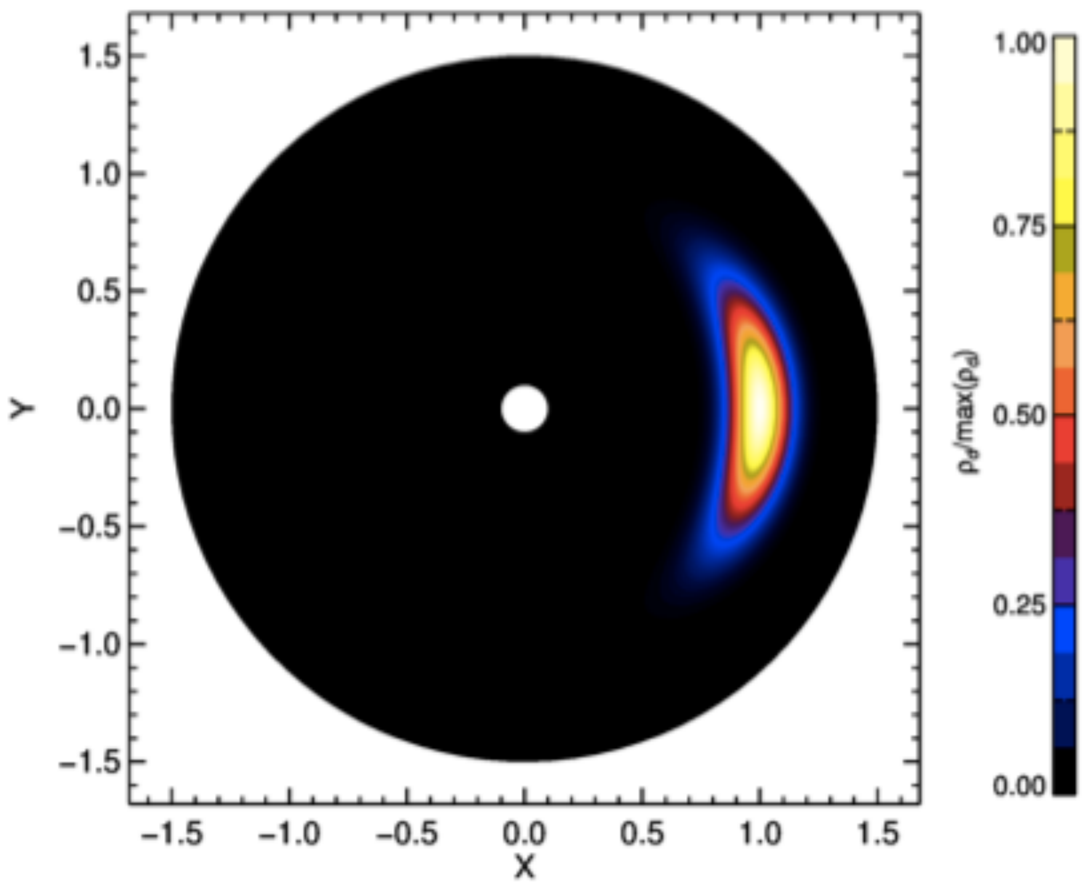
Lyra & Lin (2013)

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

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

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

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

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

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

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

a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
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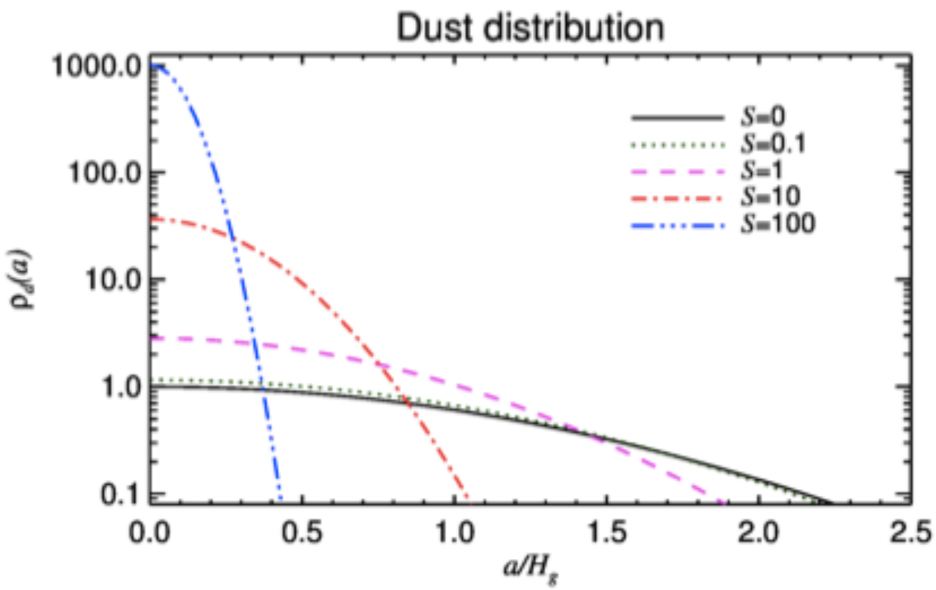
$f(\chi)$ = model-dependent scale function

Solution for

$H/r=0.1$ $\chi=4$ $S=1$

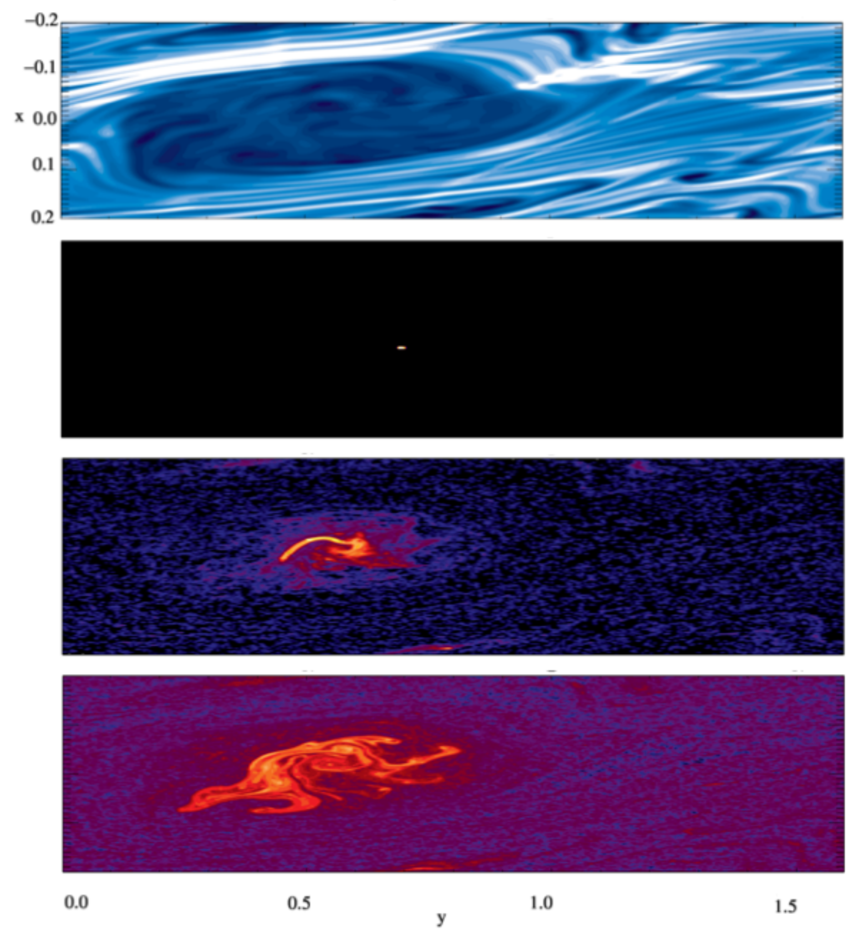
Lyra & Lin (2013)

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}

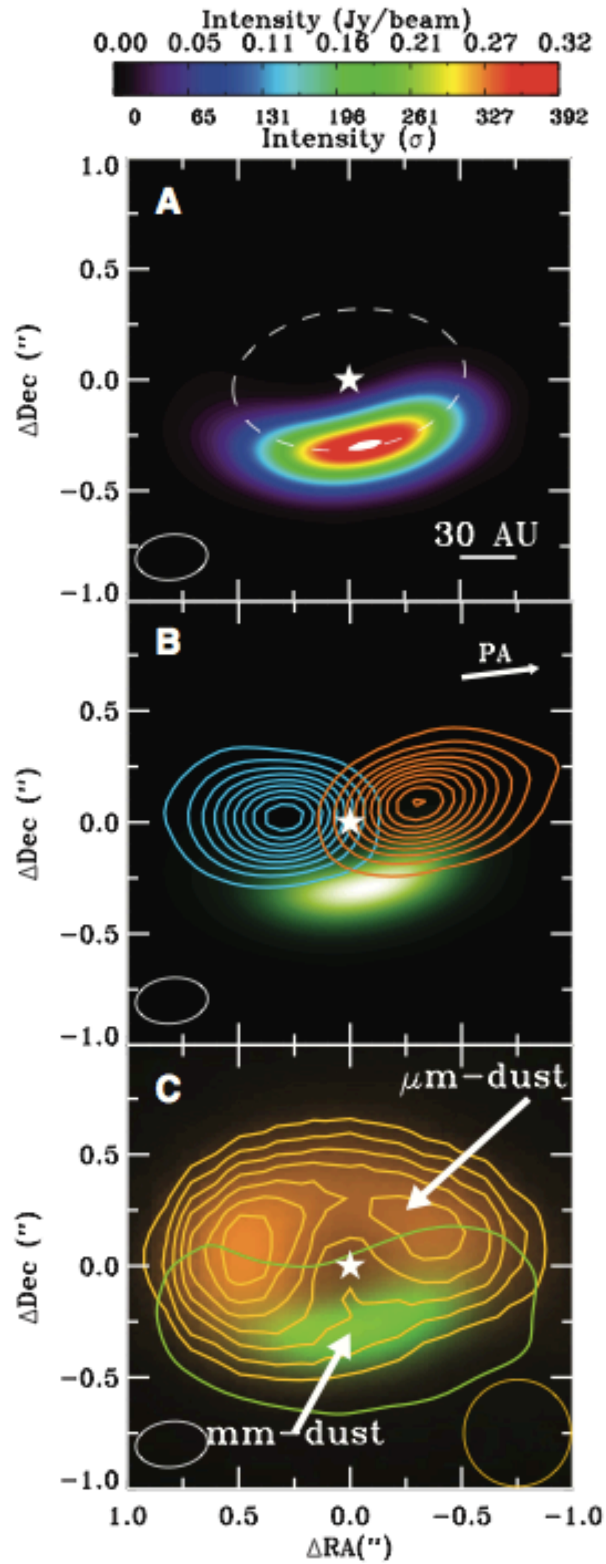
Derived parameters

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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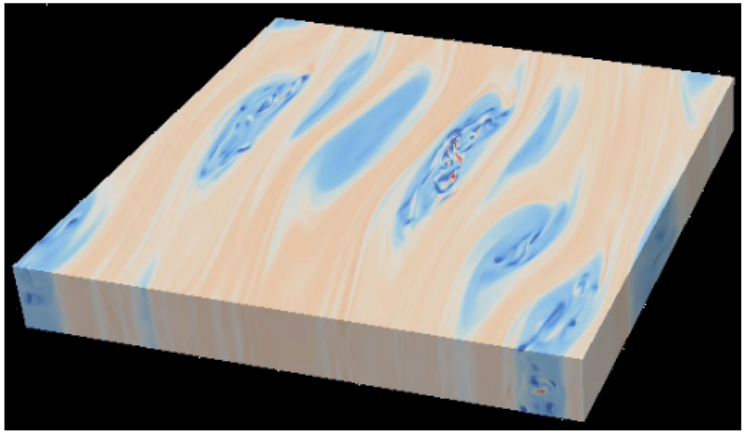
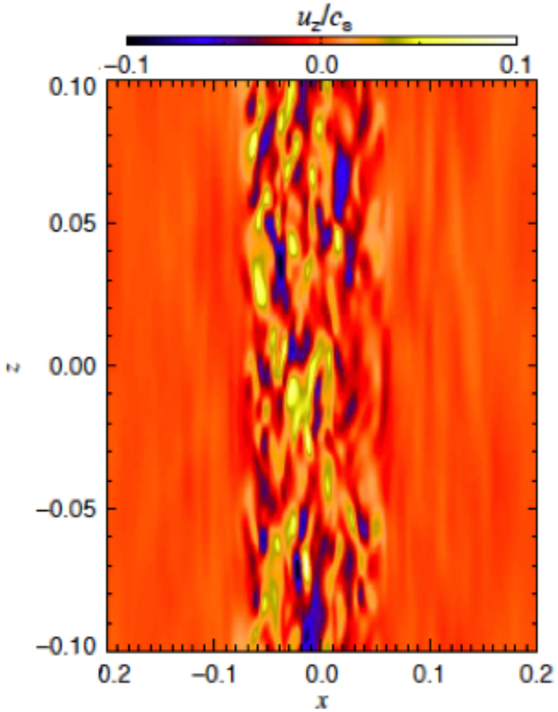
Lyra & Lin (2013)

Turbulence in vortex cores



Lesur & Papaloizou (2010)



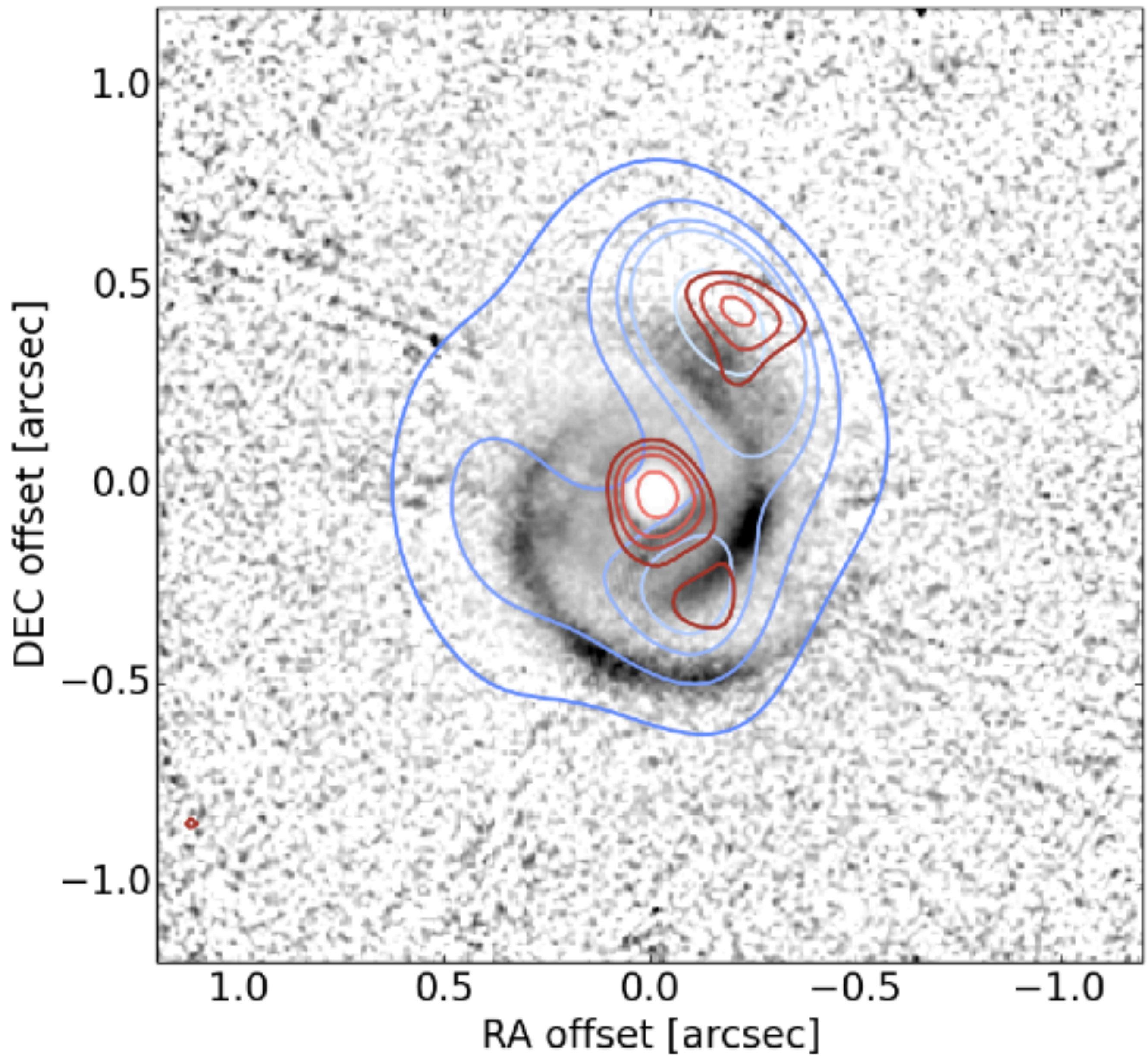
Lyra & Klahr (2011)

Turbulence in vortex cores:

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

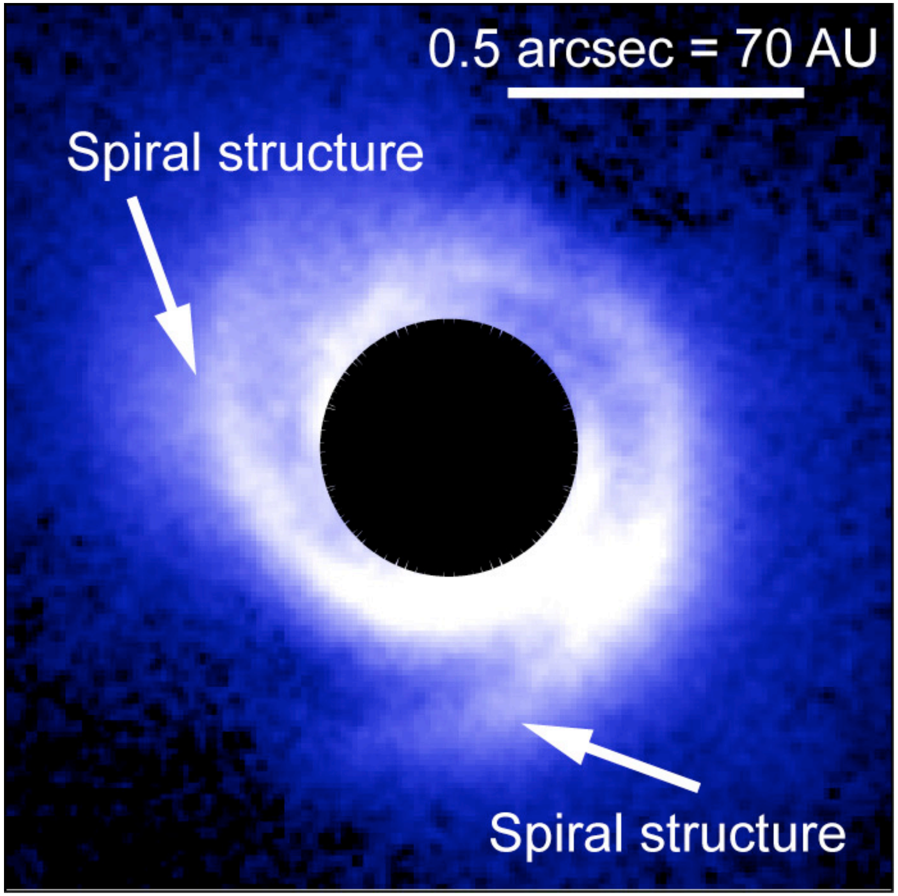
SPHERE-ALMA-VLA overlay of MWC 758

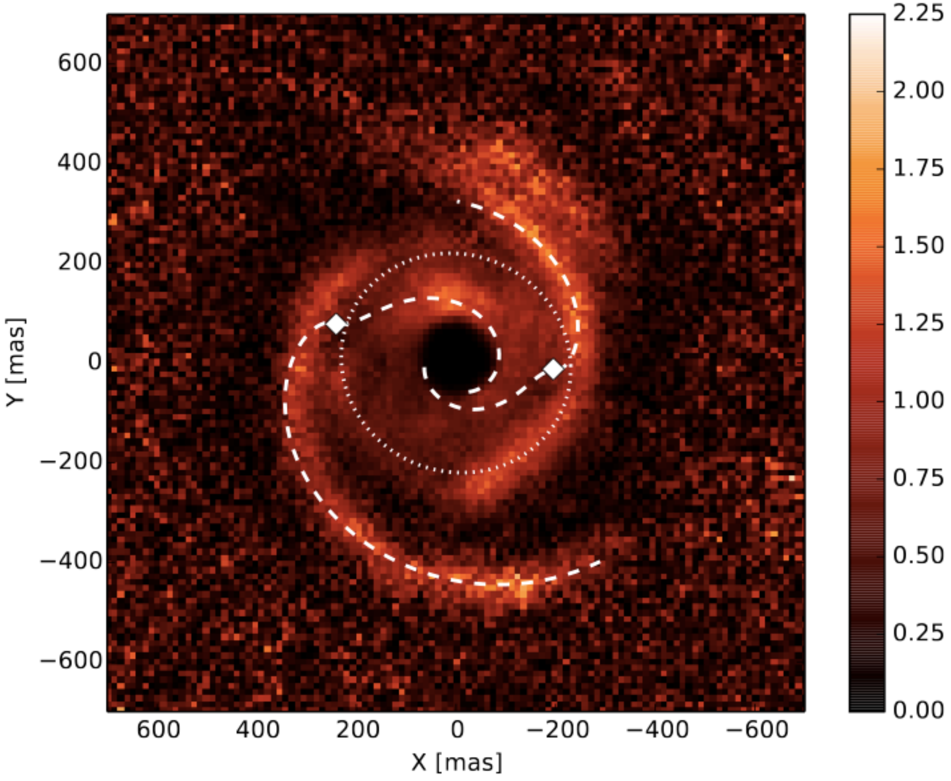
SPHERE (*μm*)
ALMA (*mm*)
VLA (*m*)



Marino et al., (2015, accepted)

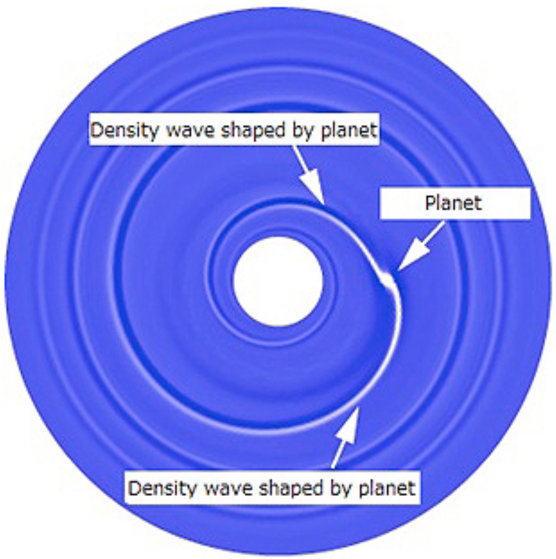
Observational evidence: Spirals





Spiral arm fitting leads to problems

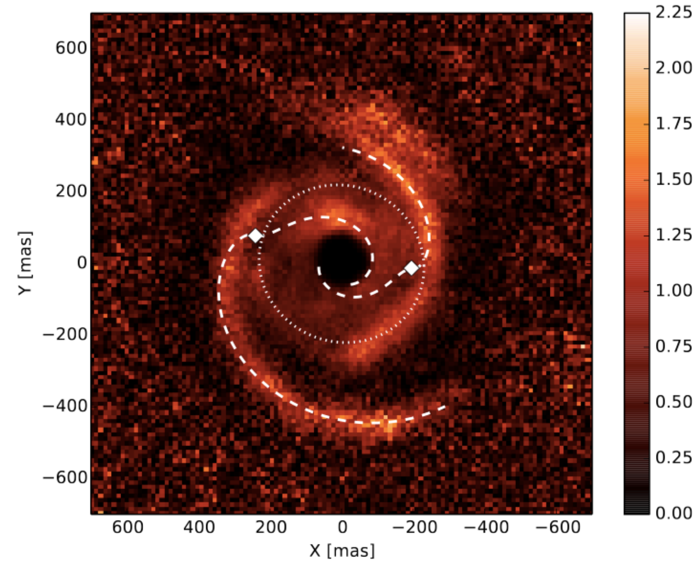
Analytical spiral fit



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

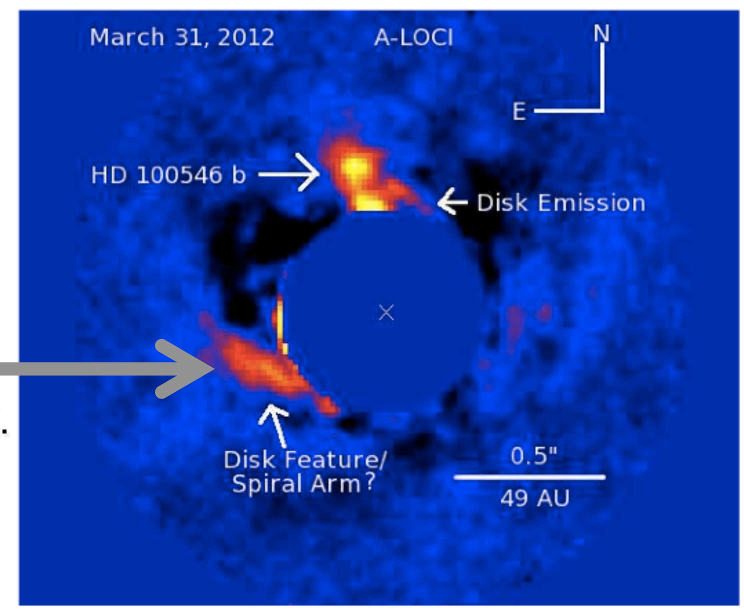
Rafikov (2002)
Muto et al. (2012)

Spirals are too wide hotter (300K) than ambient gas (50K).



Benisty et al. (2015)

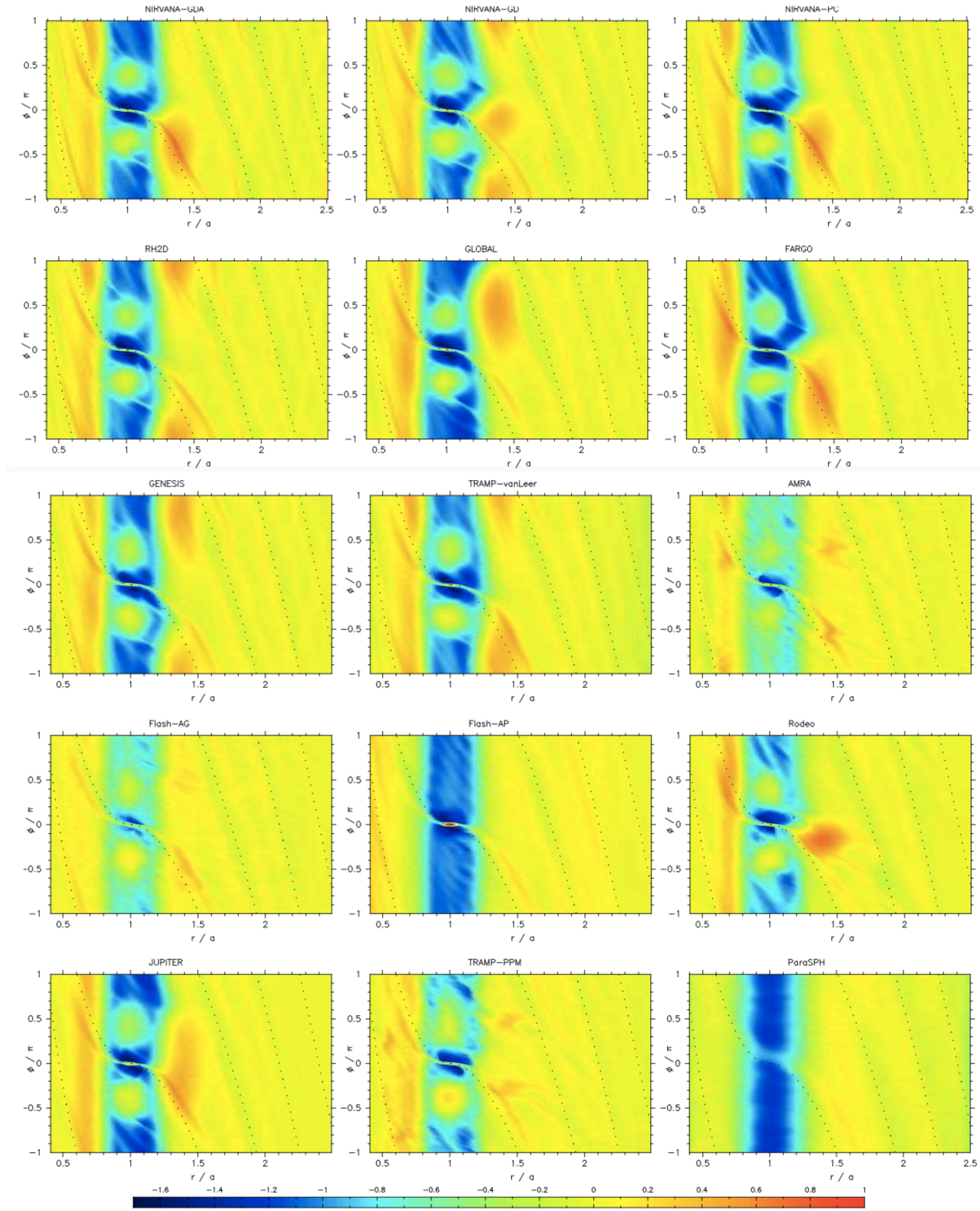
Spiral has little polarization. Must be thermal emission at 1000K.



Currie et al. (2014)

The code comparison project of 2006 (de Val-Borro et al. 2006)

Problem of choice:
2D ‘vanilla’ planet-disk interaction.

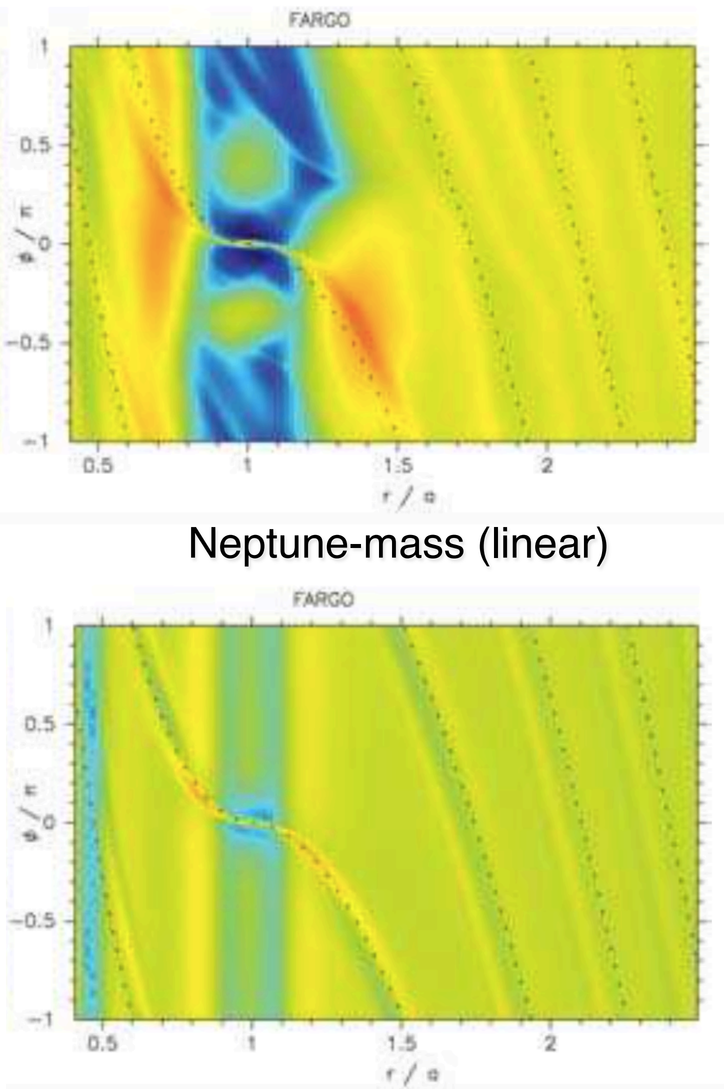


The “hot spiral problem” has never been a problem

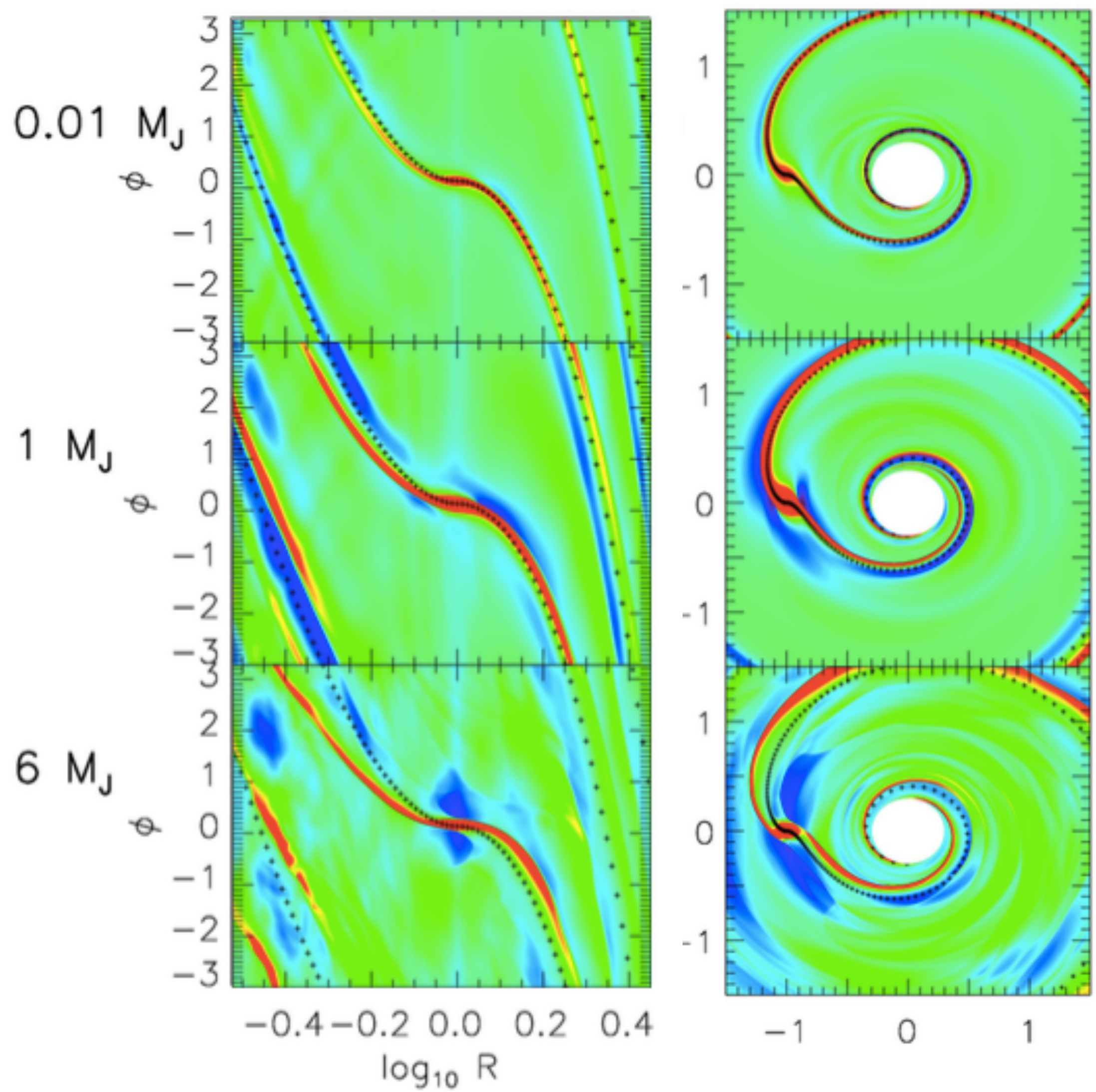
Wakes of high-mass planets are not sonic, but *supersonic*.

Jupiter-mass (non-linear)

Neptune-mass (linear)

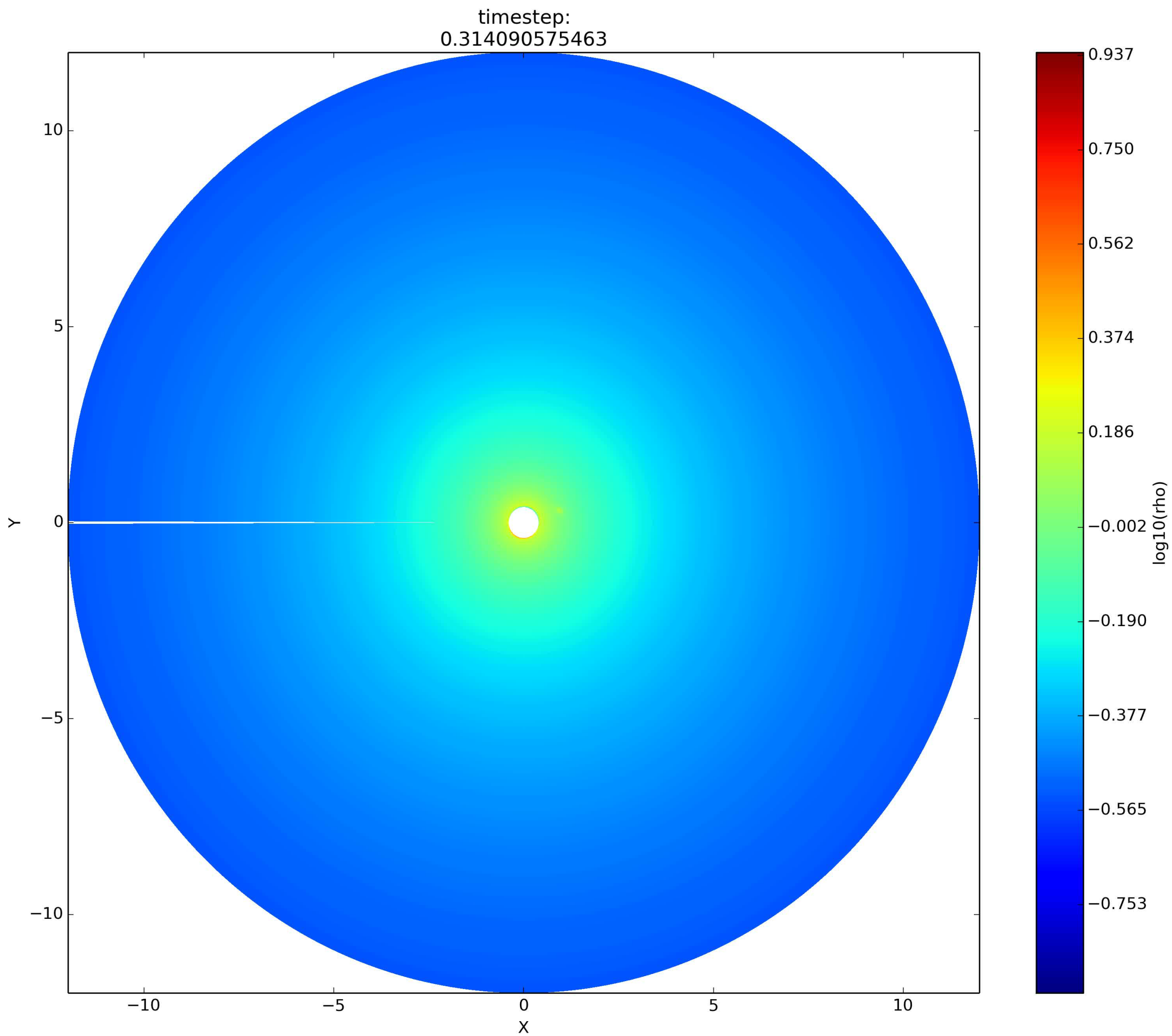


de Val-Borro al. (2006)



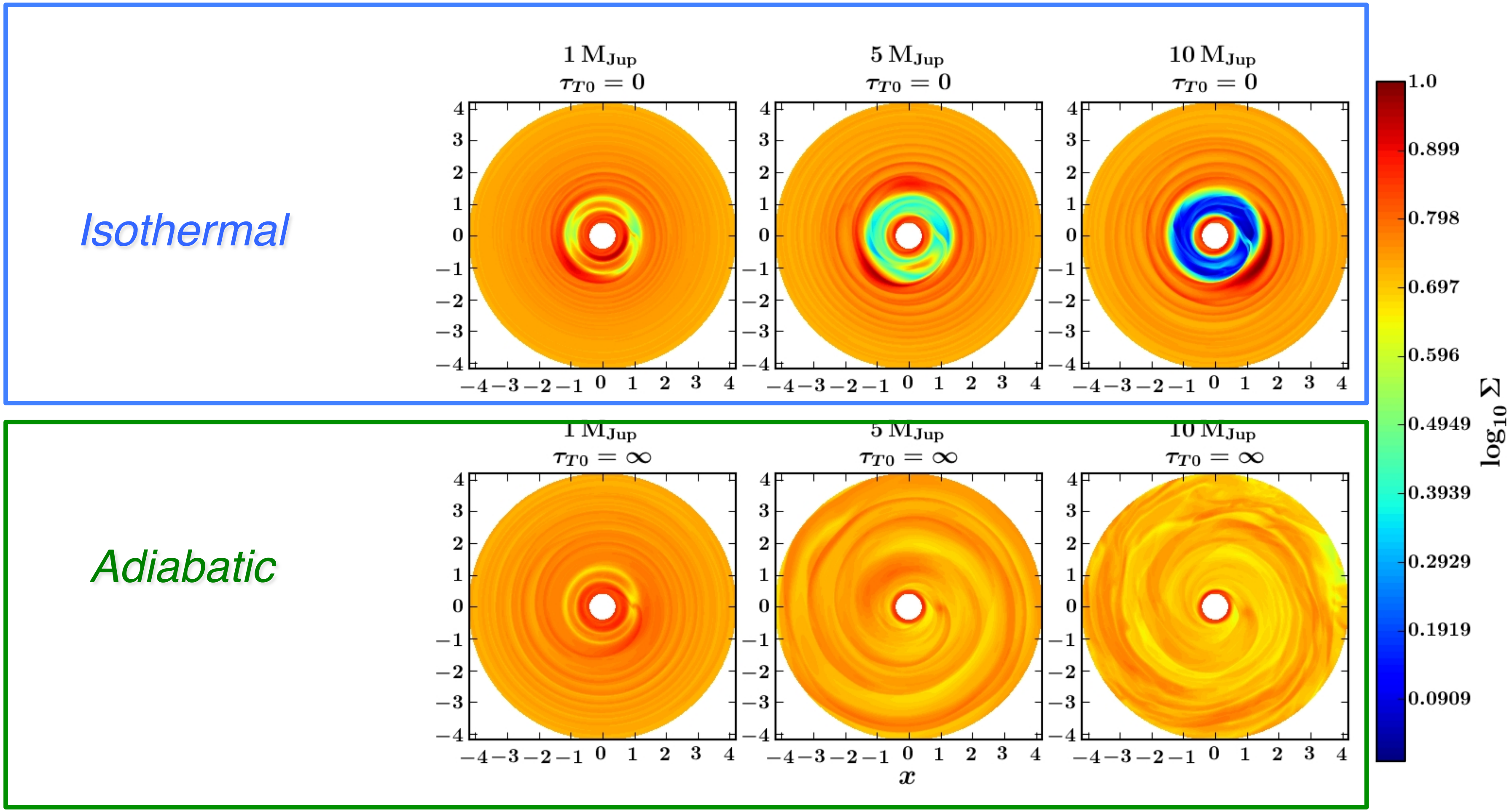
Zhu et al. (2015)

Spiral wake of high-mass planets in non-isothermal disks



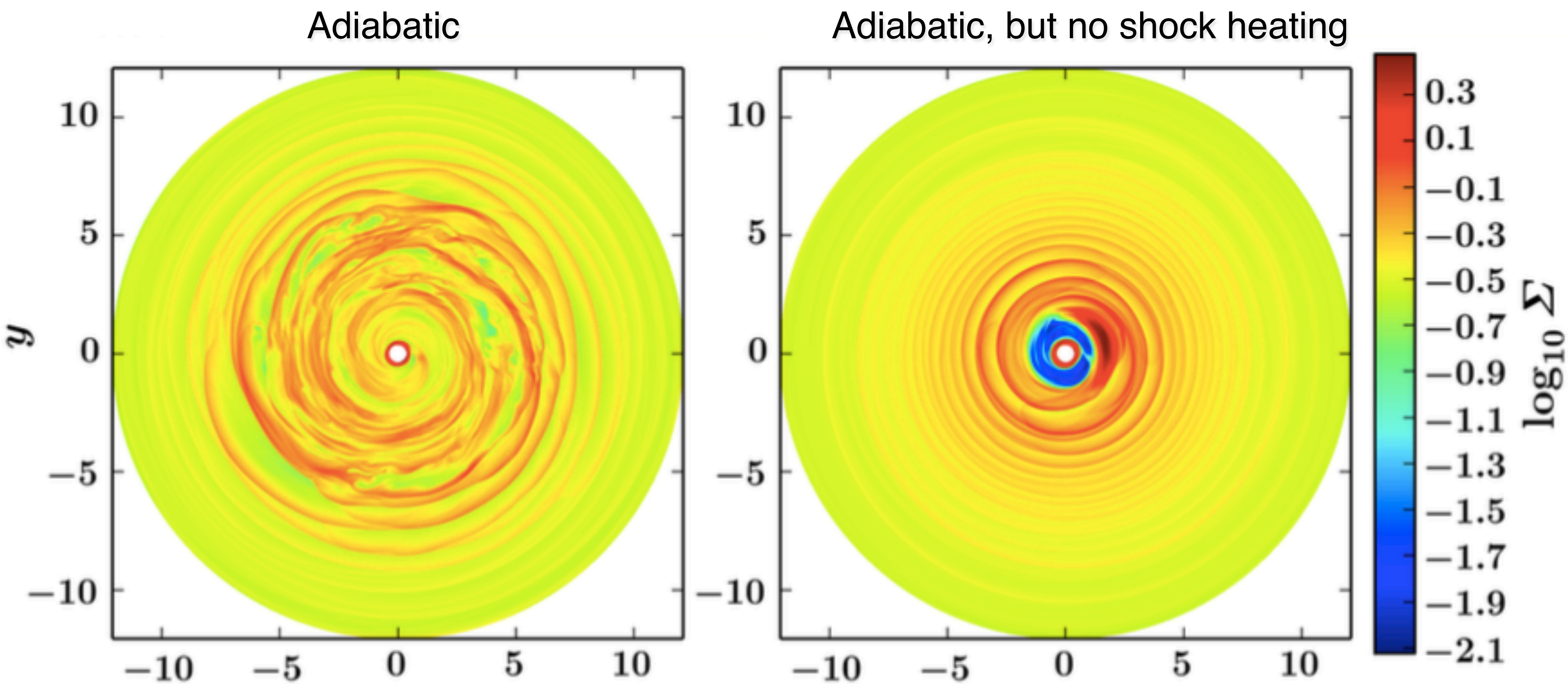
Richert et al. (2015)

Shows up for high-mass planets in adiabatic disks



Richert et al. (2015)

The energy source: shock heating!



Richert et al. (2015)

Disk structure

$$T\frac{Ds}{Dt} = -c_V \frac{(T - T_{ref})}{t_{cool}} + \Gamma_{sh},$$

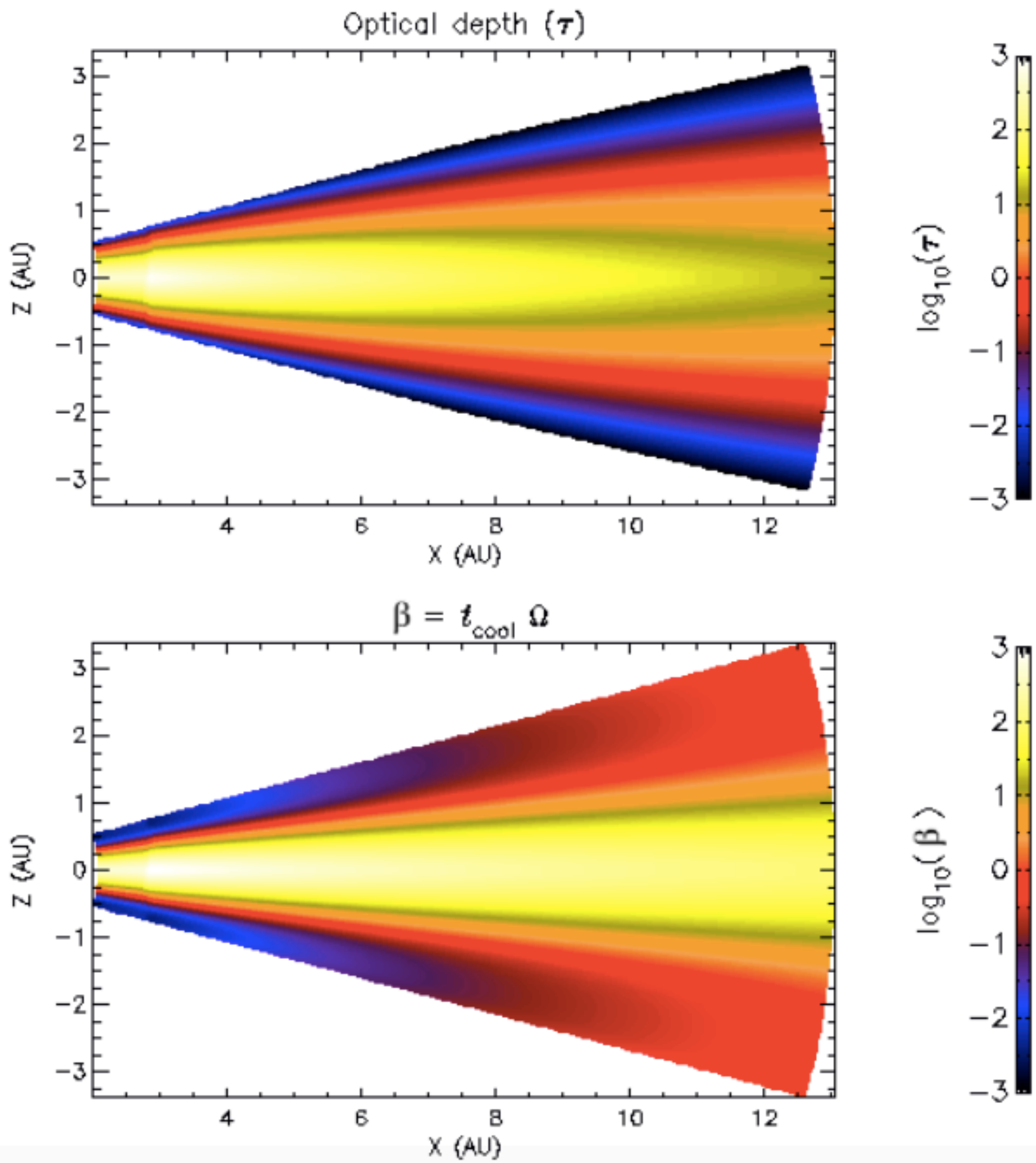
$$t_{rad} = E/\dot{E}$$

$$\dot{E} = \nabla \cdot \boldsymbol{F}$$

$$t_{cool} \equiv \frac{\int E dV}{\int F \hat{\boldsymbol{n}} \cdot d\boldsymbol{A}}.$$

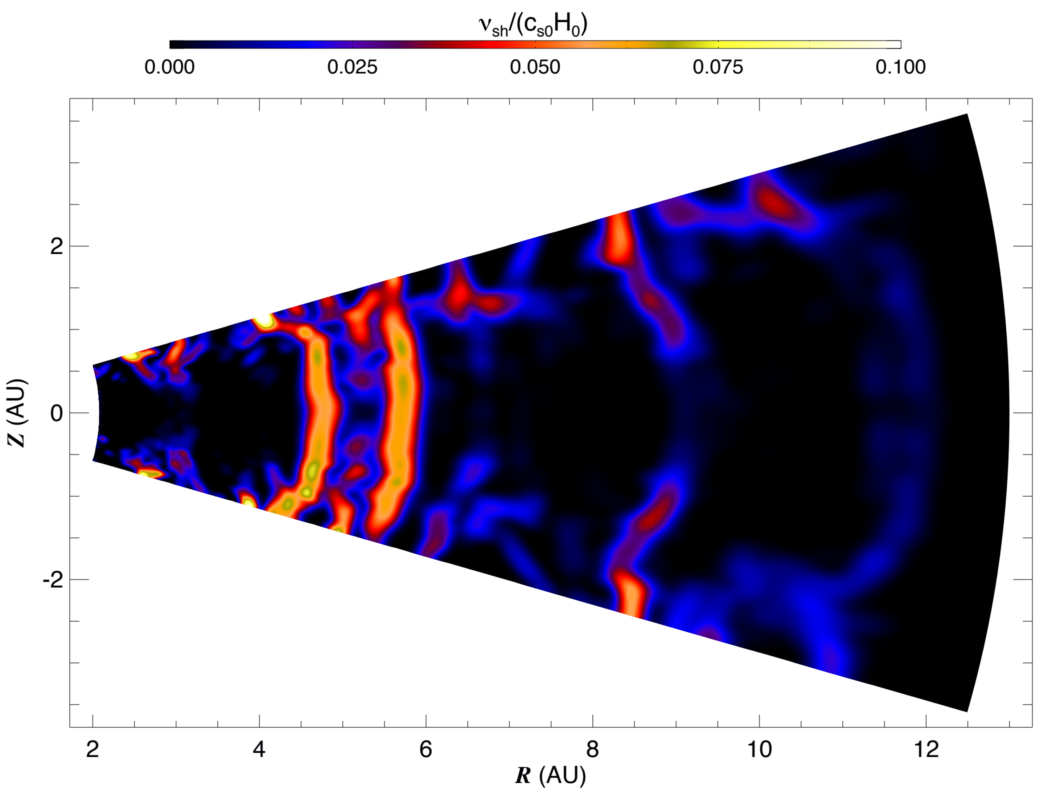
$$t_{cool} = \frac{c_V \rho H \tau_{eff}}{3\sigma T^3}.$$

$$\tau_{eff} = \frac{3\tau}{8} + \frac{\sqrt{3}}{4} + \frac{1}{4\tau}.$$

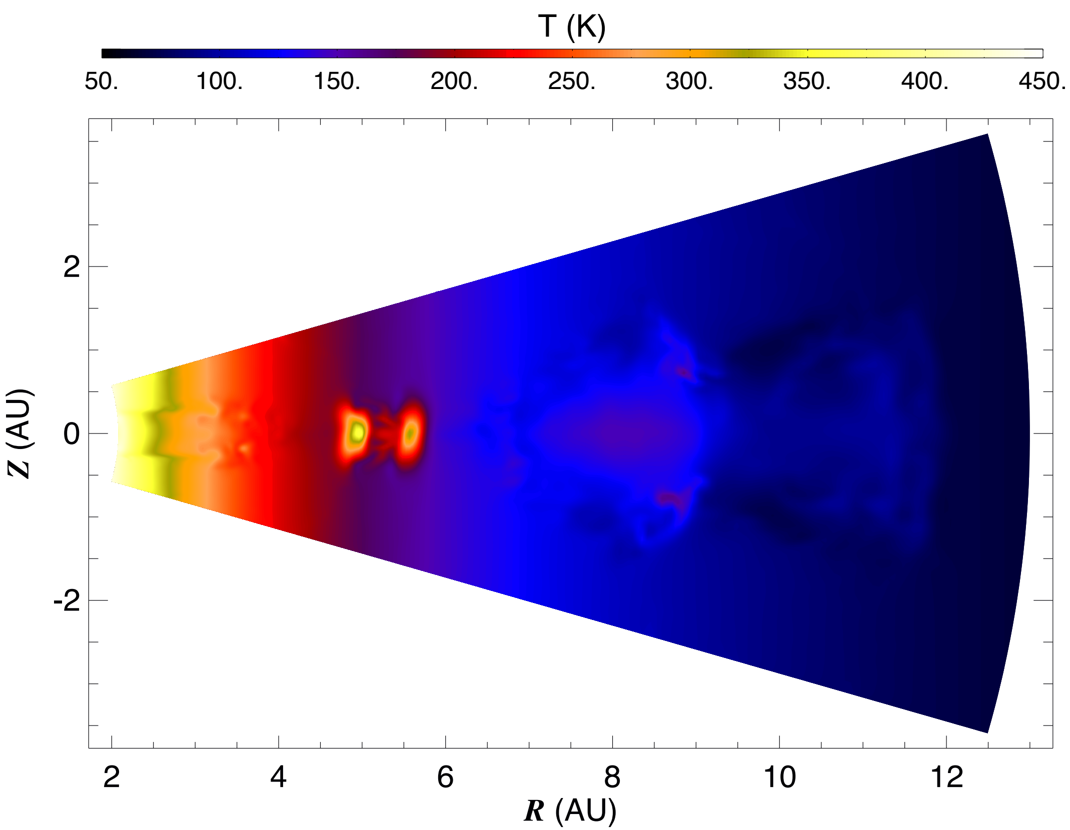


Shock bores

Velocity convergence

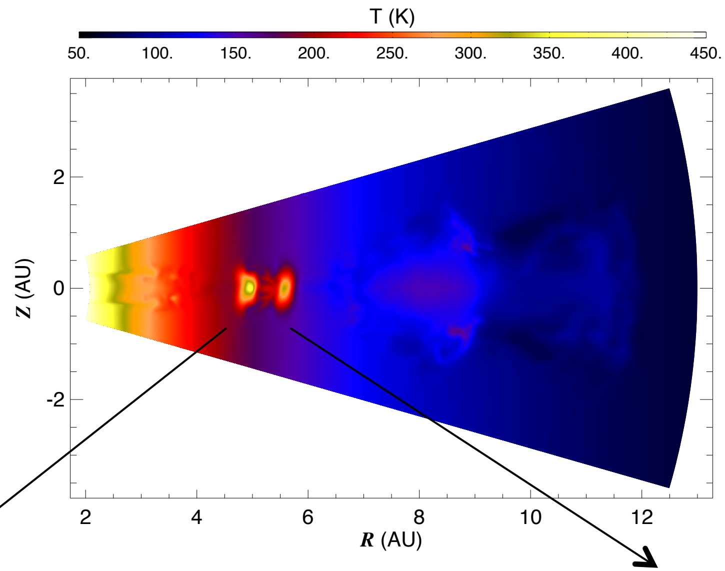


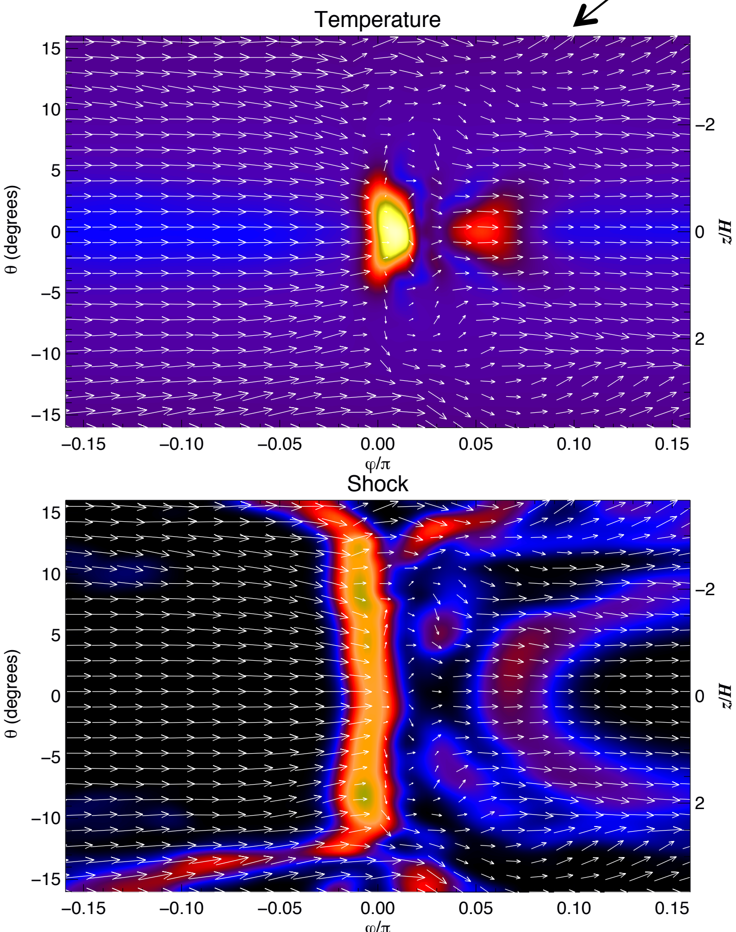
Temperature



Lyra et al. (2015b, submitted)

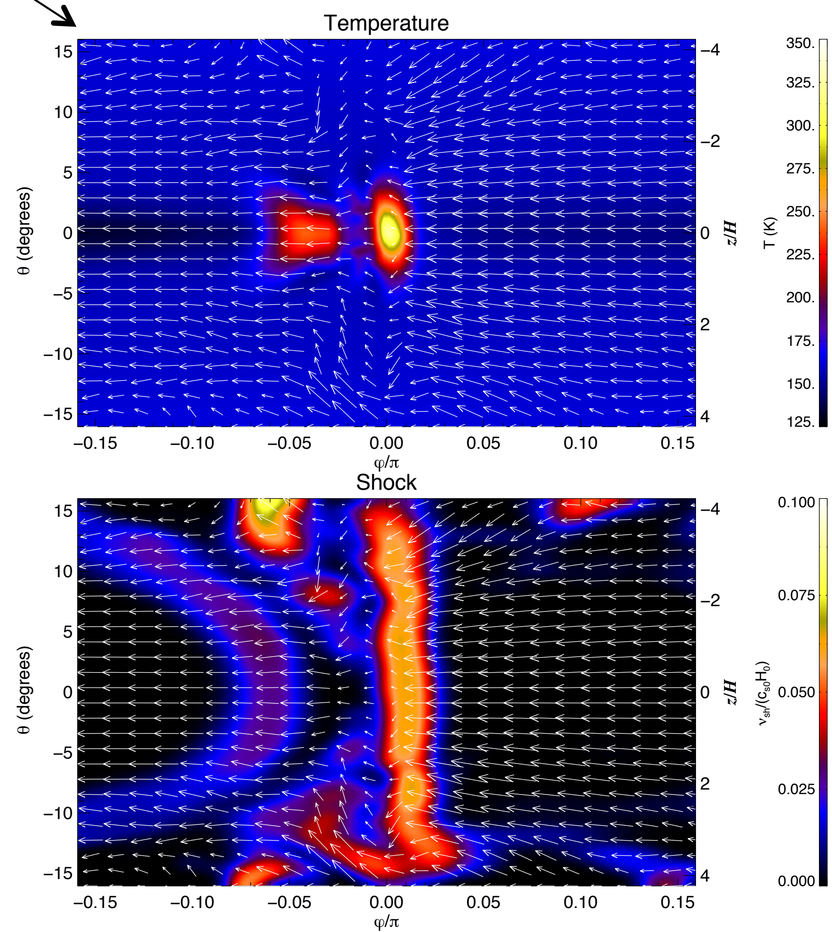
3D shocks: bores and breaking waves





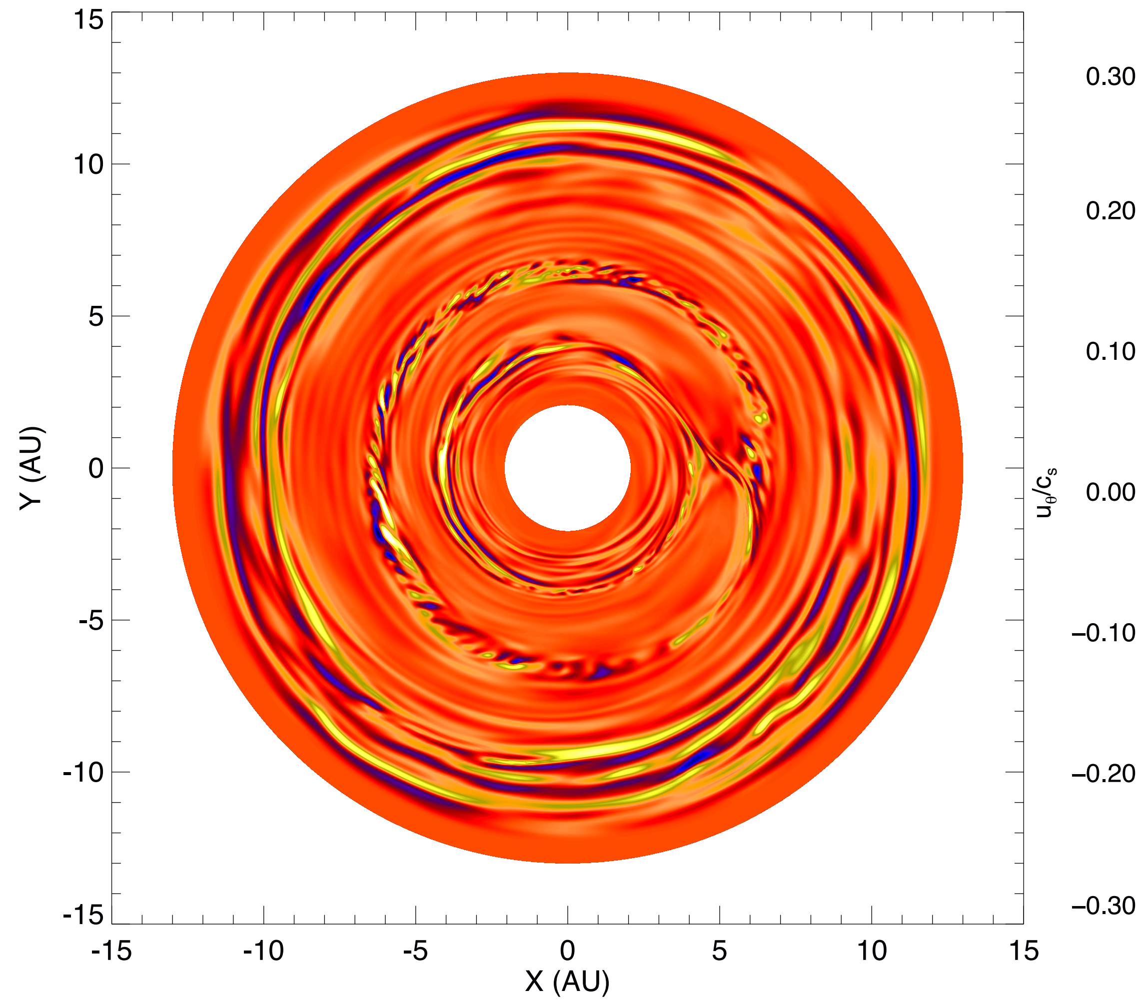
Temperature

Div u
(shock)



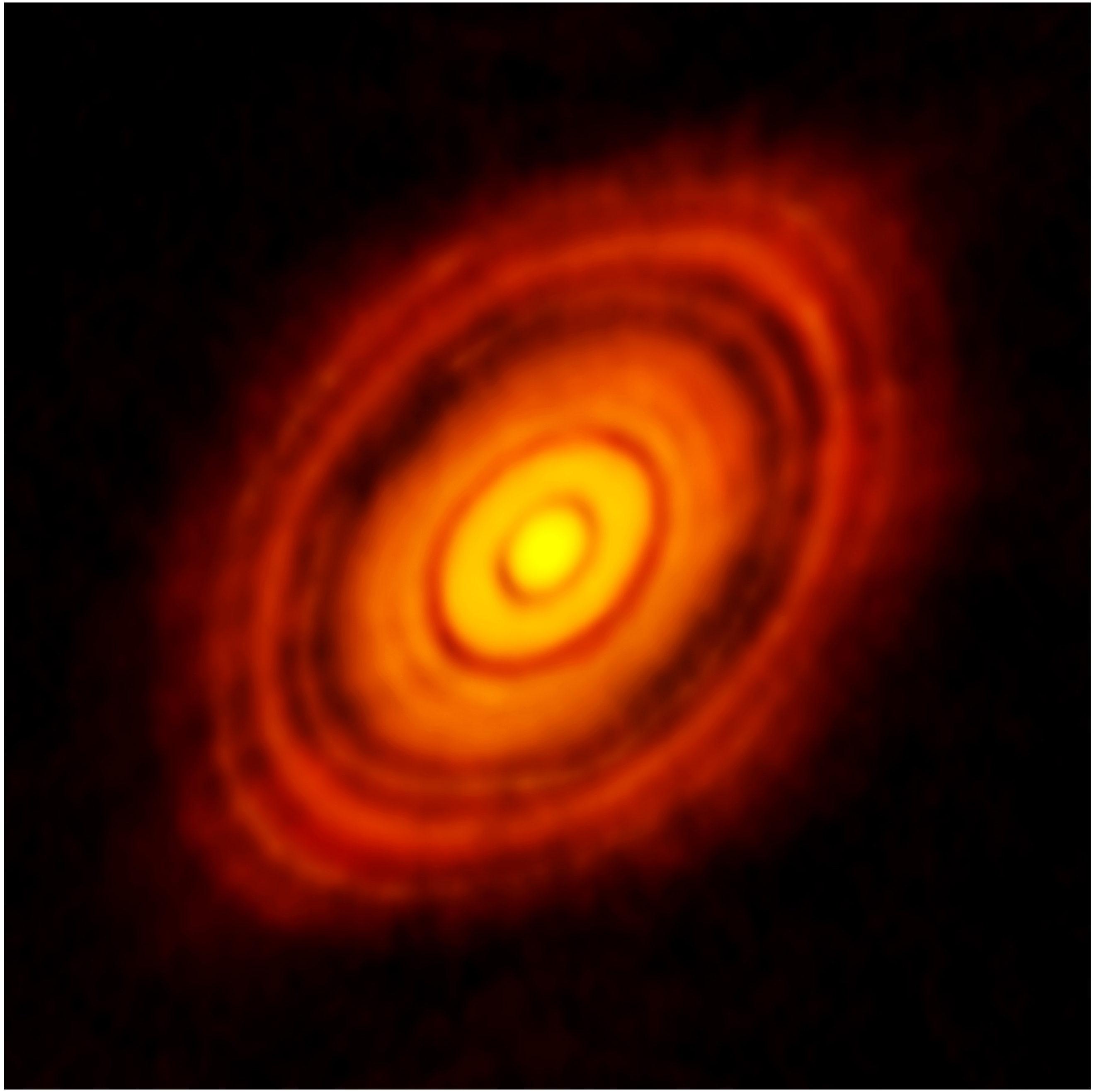
Lyra et al. (2015b, submitted)

Turbulent surf



Lyra et al. (2015b, submitted)

HL Tau



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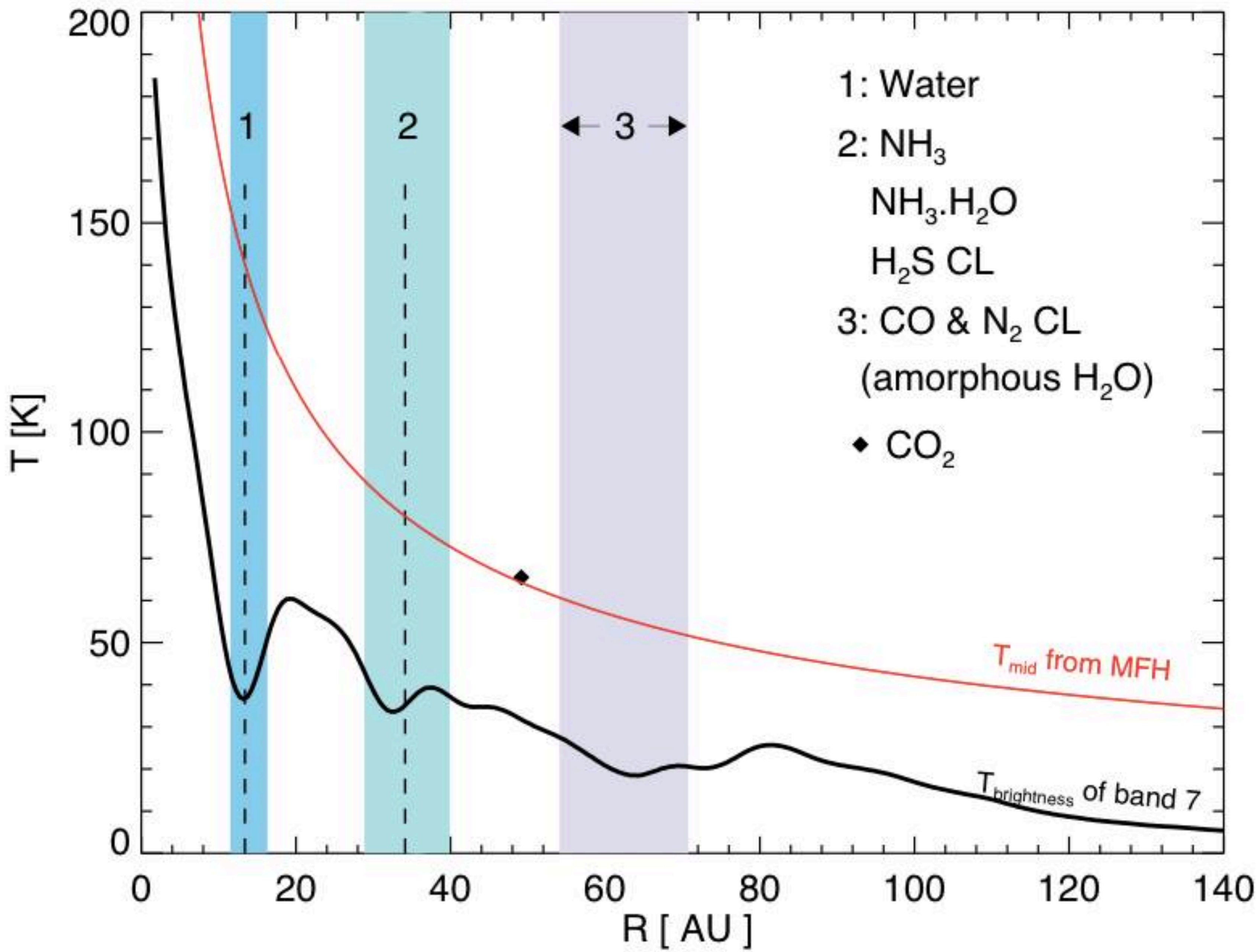
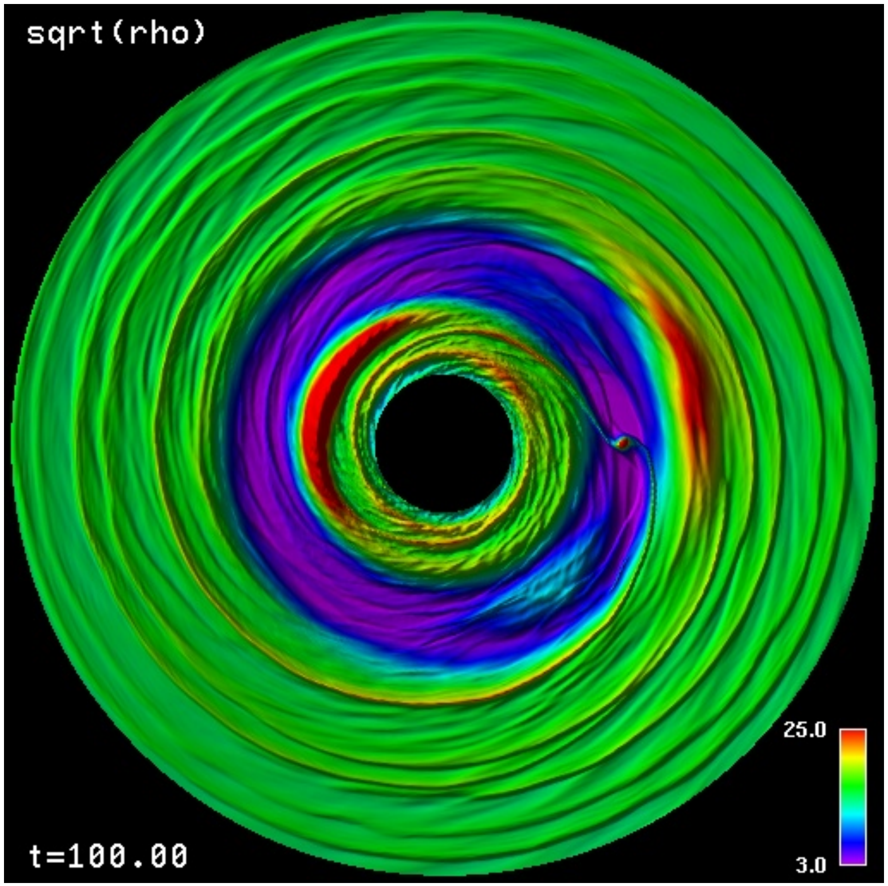
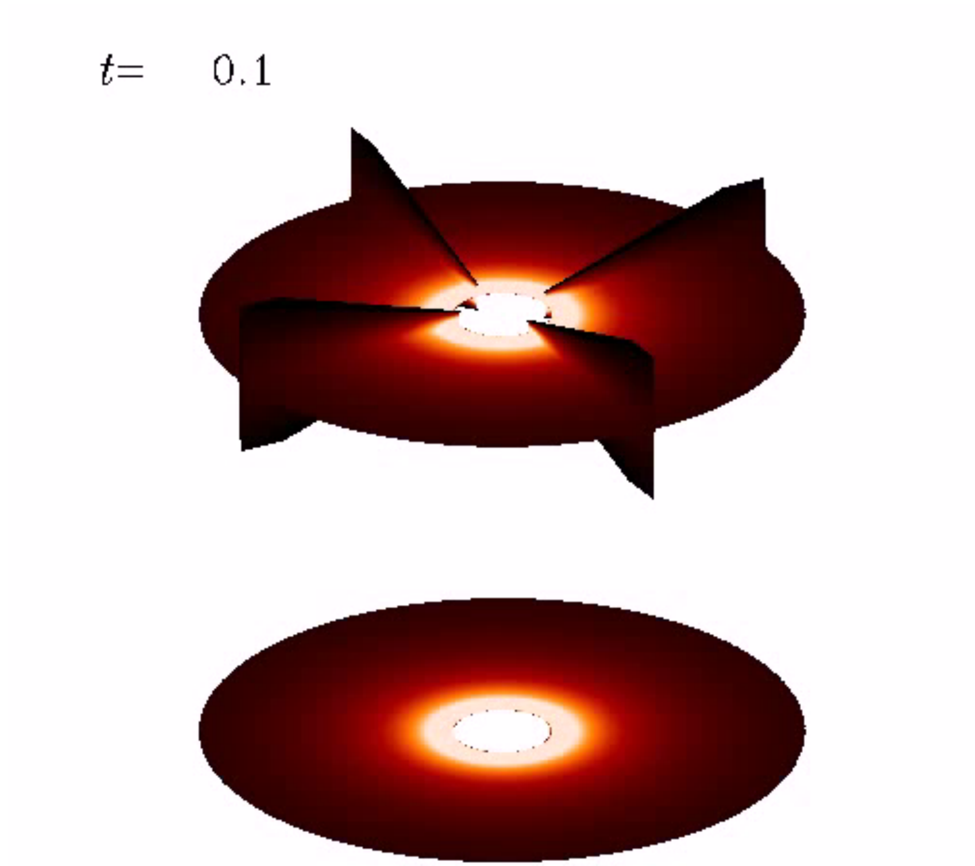


200
150
100
50
0
T [K]
0
20
40
60
80
100
120
140
R [AU]
1
2
3
1: Water
2: NH3
NH3.H2O
H2S CL
3: CO & N2 CL
(amorphous H2O)
CO2
Tmid from MFH
Tbrightness of band 7

Planet-disk interaction: gaps, spirals, and vortices.

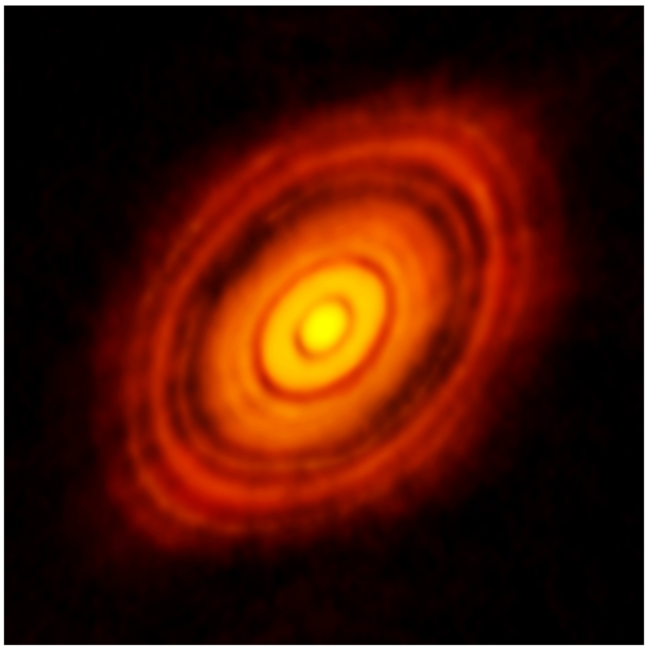


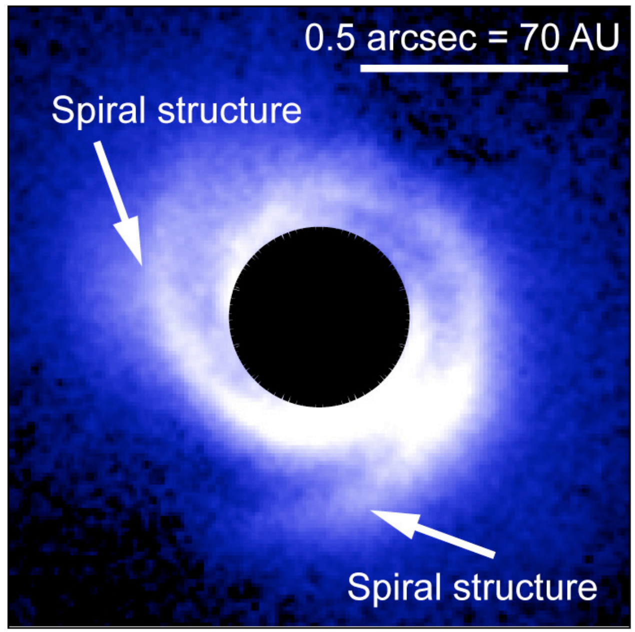


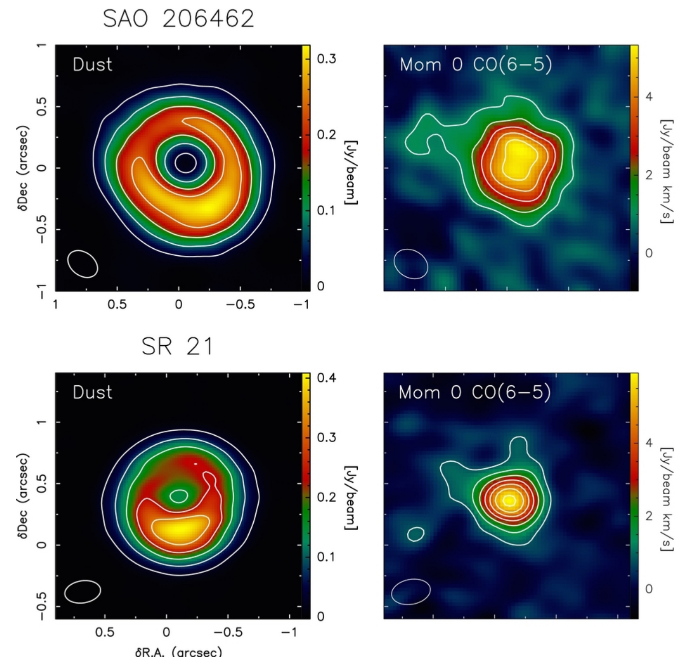
Lyra (2009)

See Clement Baruteau's talk

Observational evidence: gaps, spirals, and vortices

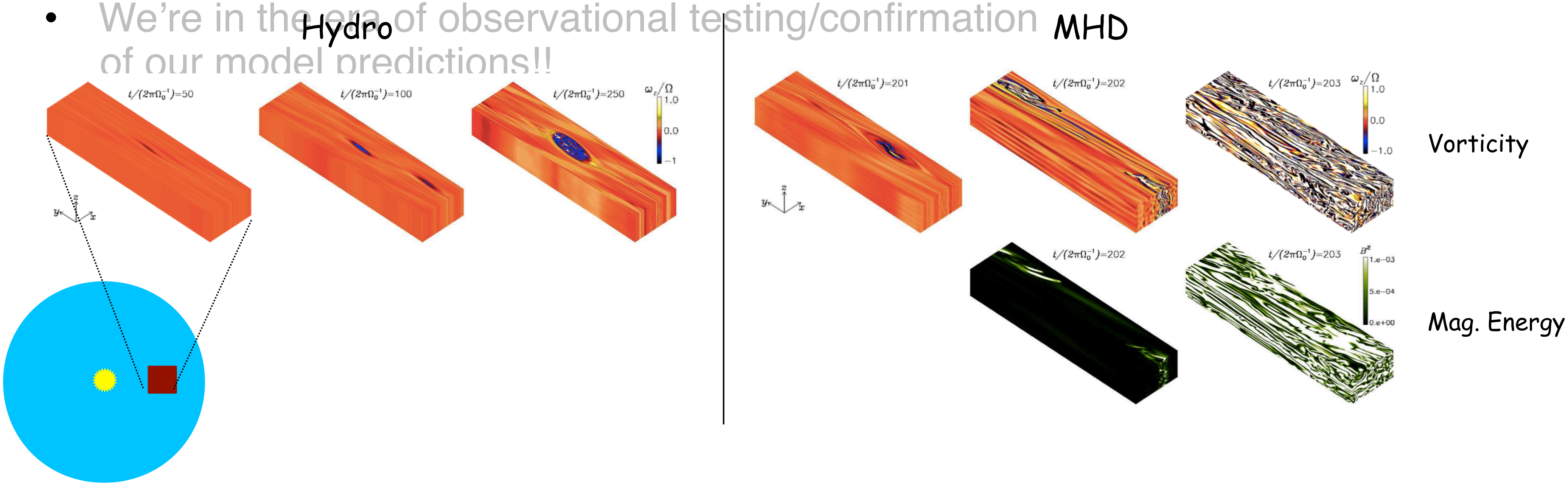






Conclusions

- Vortices exist in the dead zone only
- Two sustenance modes: Kelvin-Helmholtz 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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- Vortex-assisted is a complementary formation mode to streaming instability
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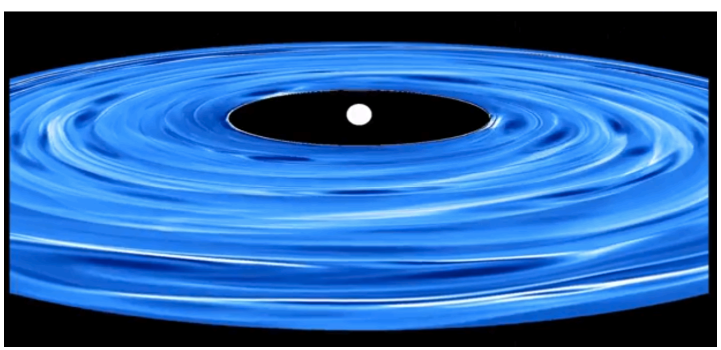
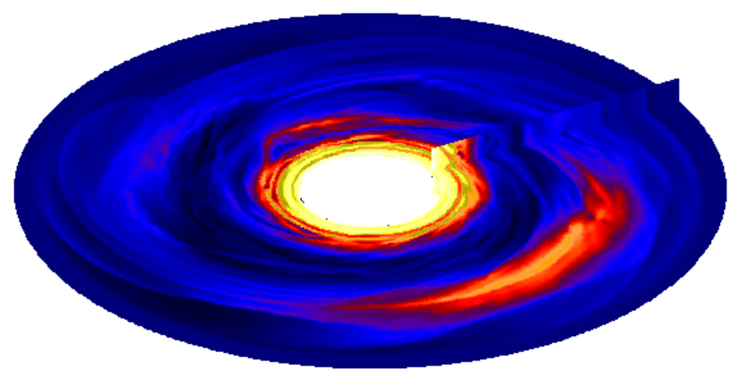
Baroclinic instability



Rossby wave instability



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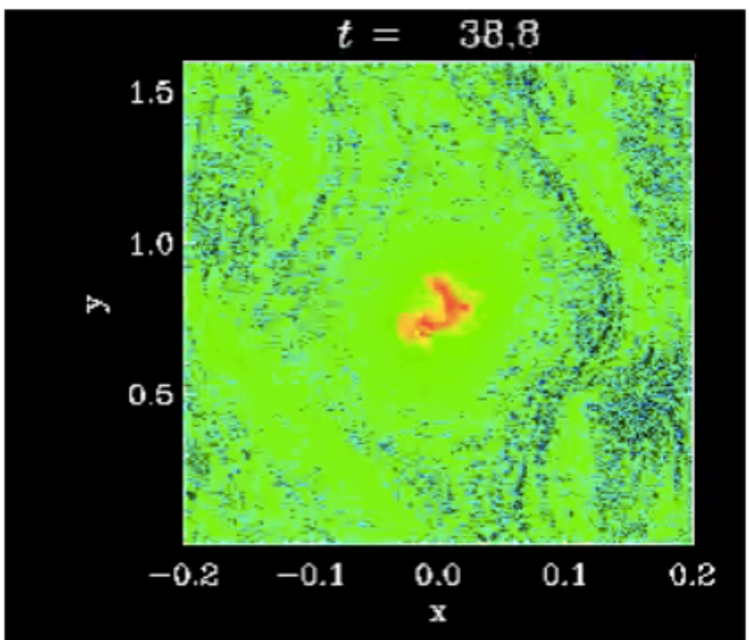

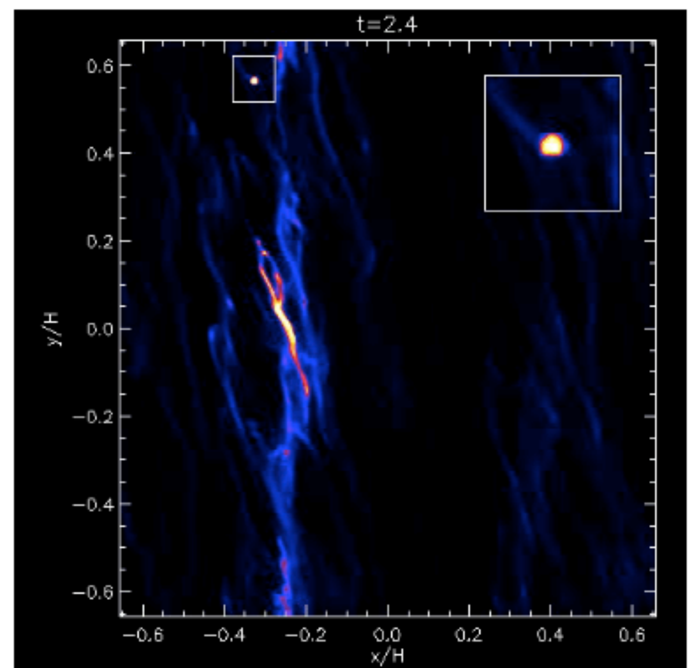

Conclusions

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- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
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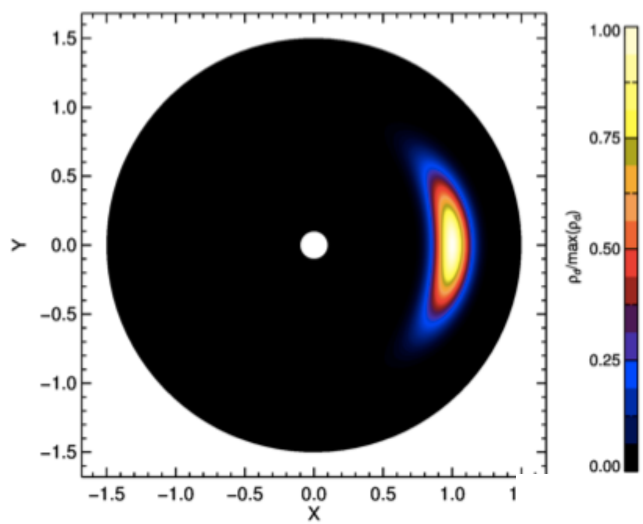
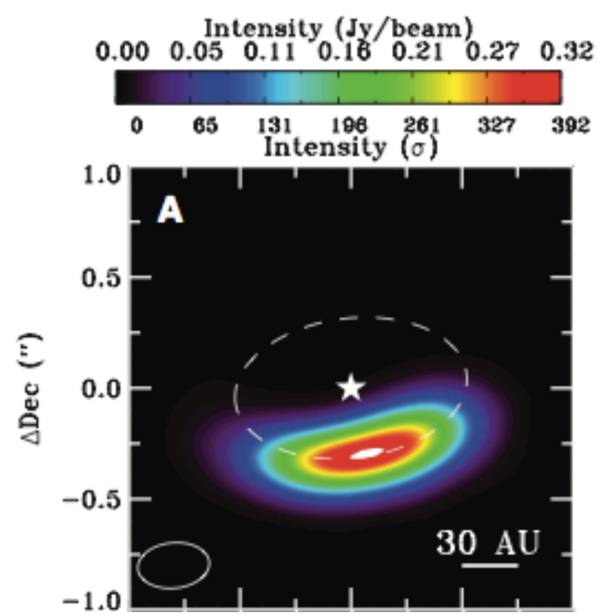
$$\rho_d(a,z) = \varepsilon\rho_0\,(S+1)^{3/2}\,\exp\left\{-\frac{\left[a^2 f^2(\chi)+z^2\right]}{2H^2}(S+1)\right\}$$

Lyra & Lin (2013)





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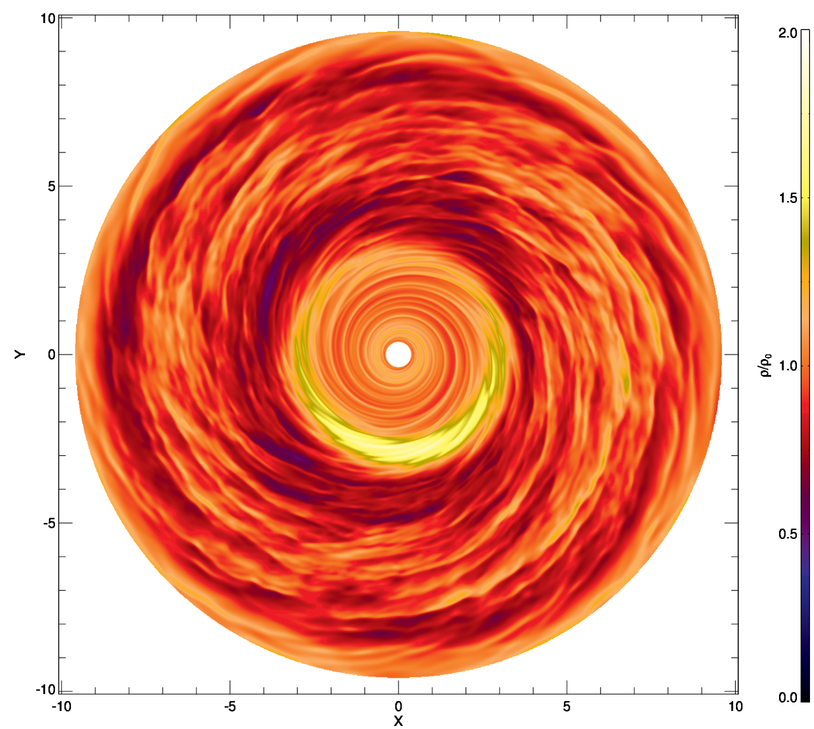

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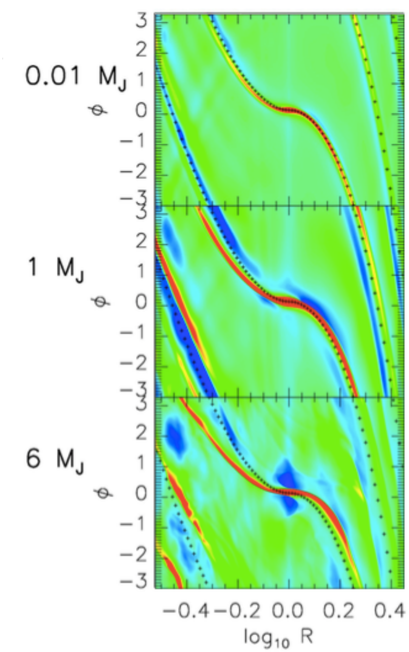

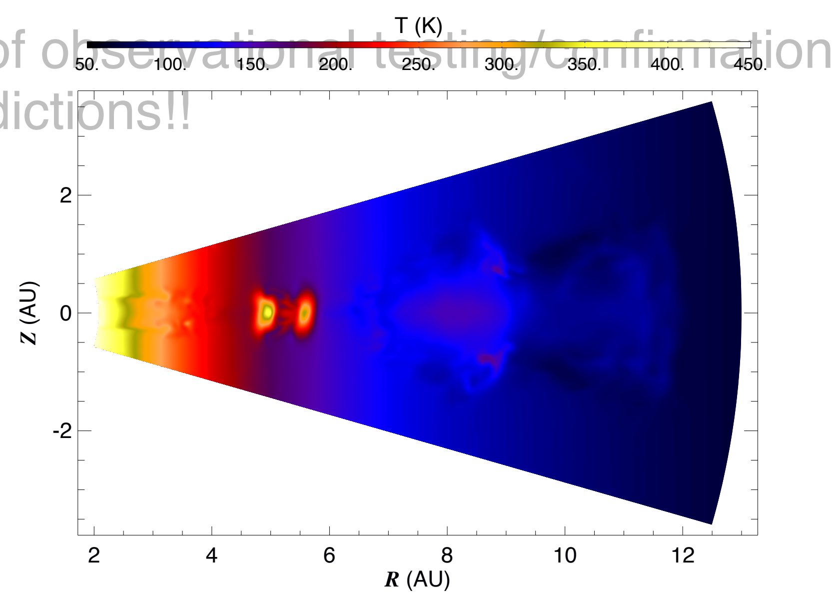

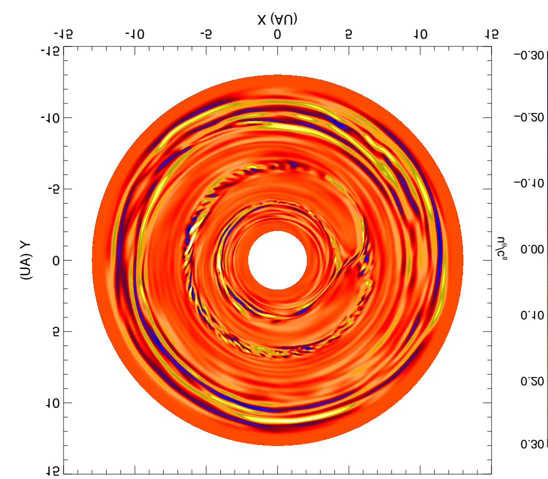

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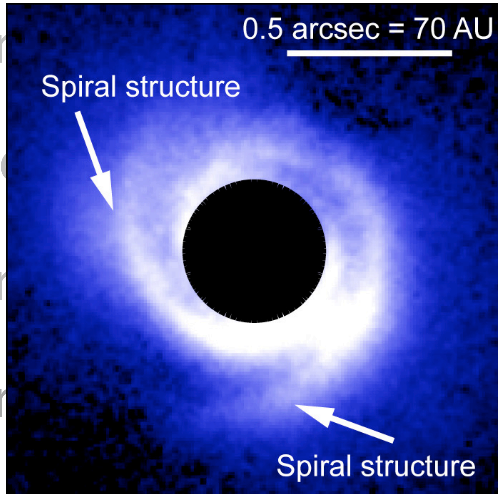

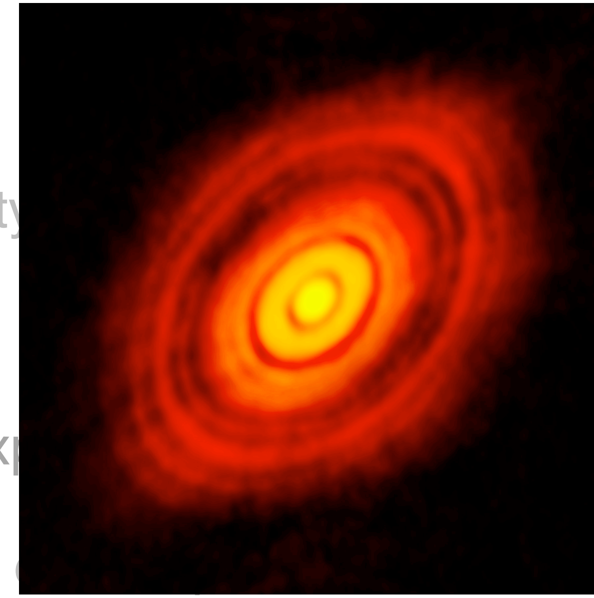

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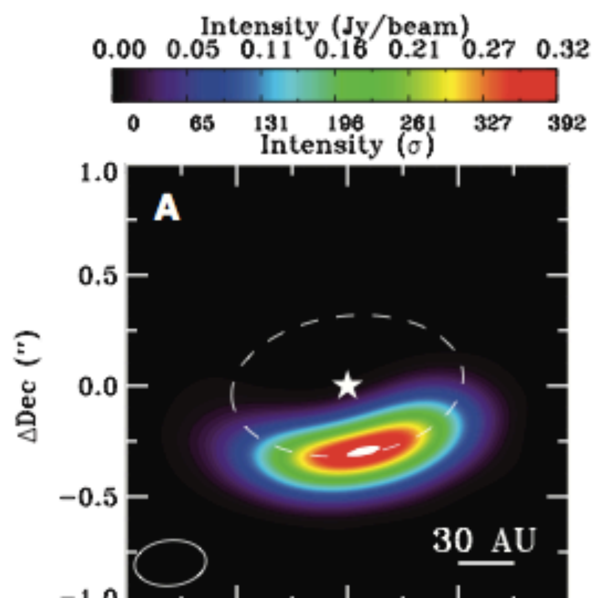

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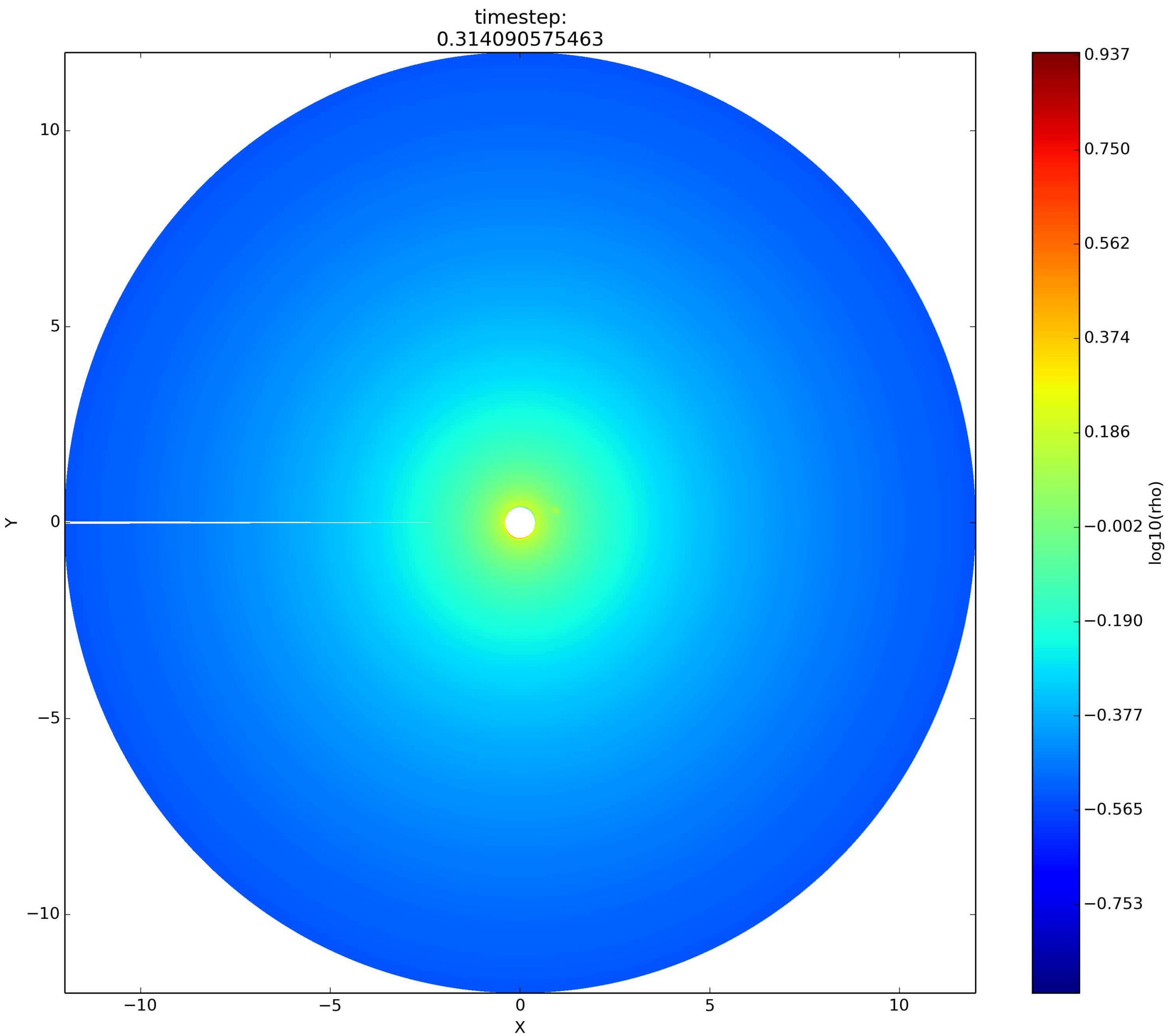

Richert et al. (2015, submitted)