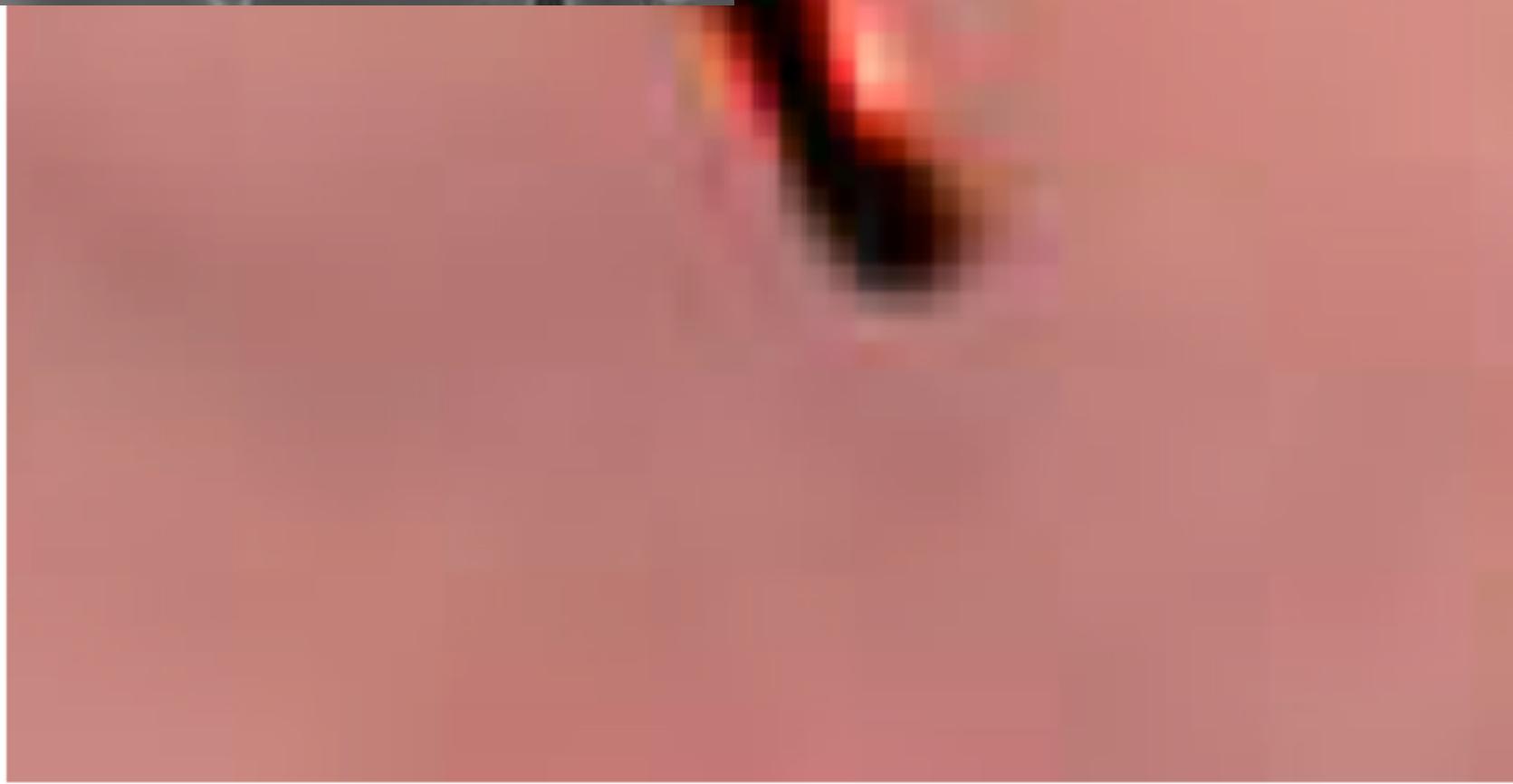
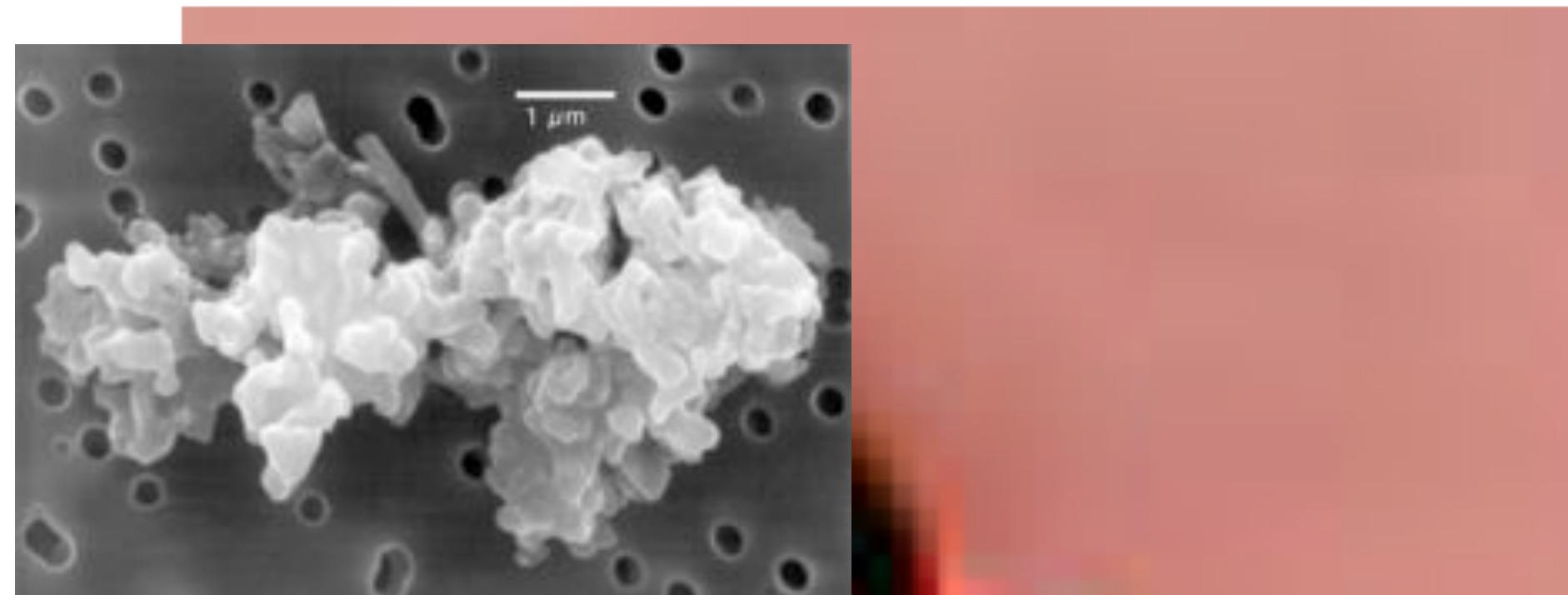


Evolution of circumstellar disks and planet formation

Wladimir Lyra

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

Observatório do Valongo
May 26th, 2015



Protoplanetary Disks



PP disk fact sheet

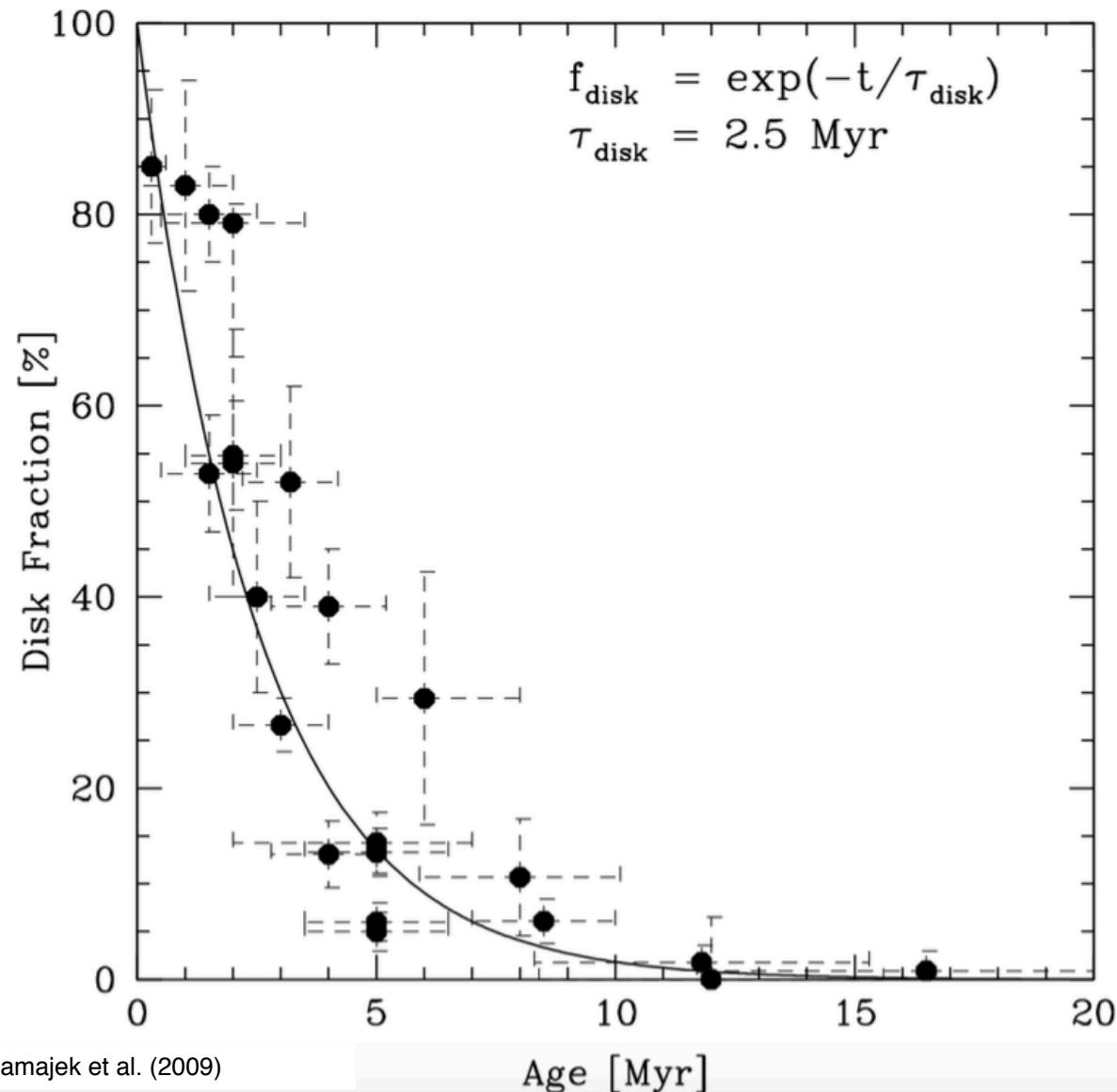
Density: $10^{13} - 10^{15} \text{ cm}^{-3}$
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

Scale: 0.1-100AU
(1 AU = $1.49 \times 10^{13} \text{ cm}$)

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

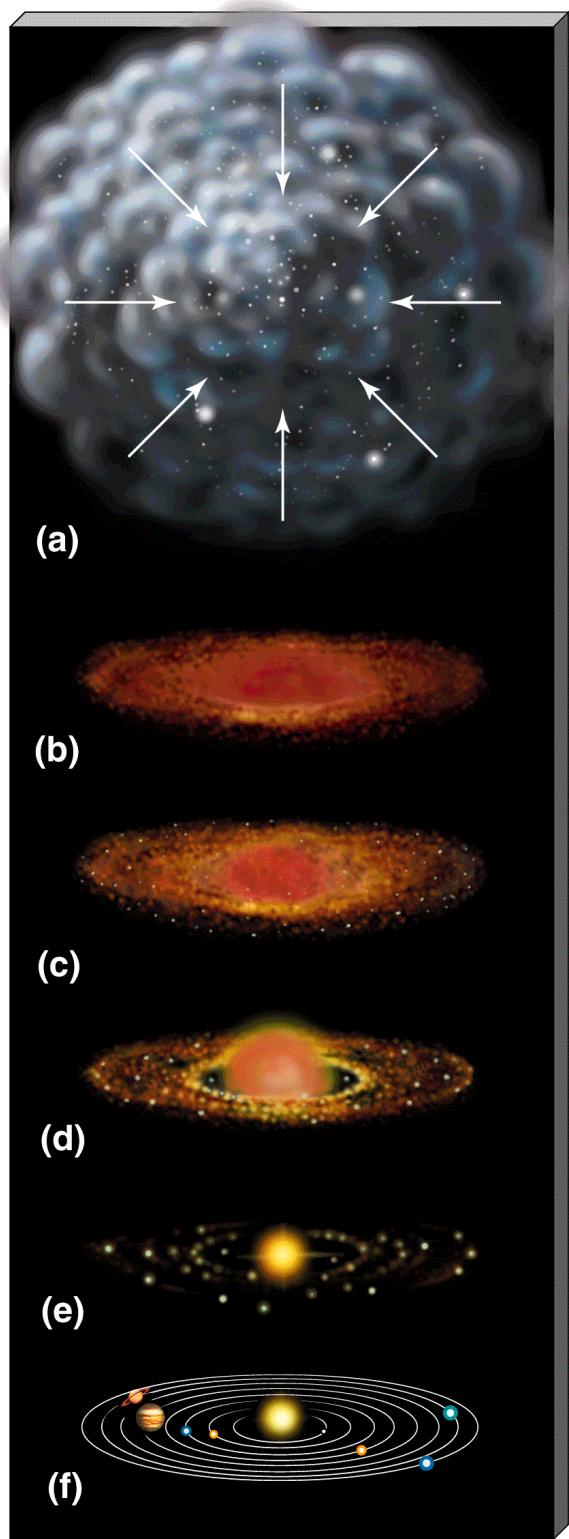
Disk lifetime



Mamajek et al. (2009)

Age [Myr]

Disks dissipate with an e-folding time of 2.5 Myr



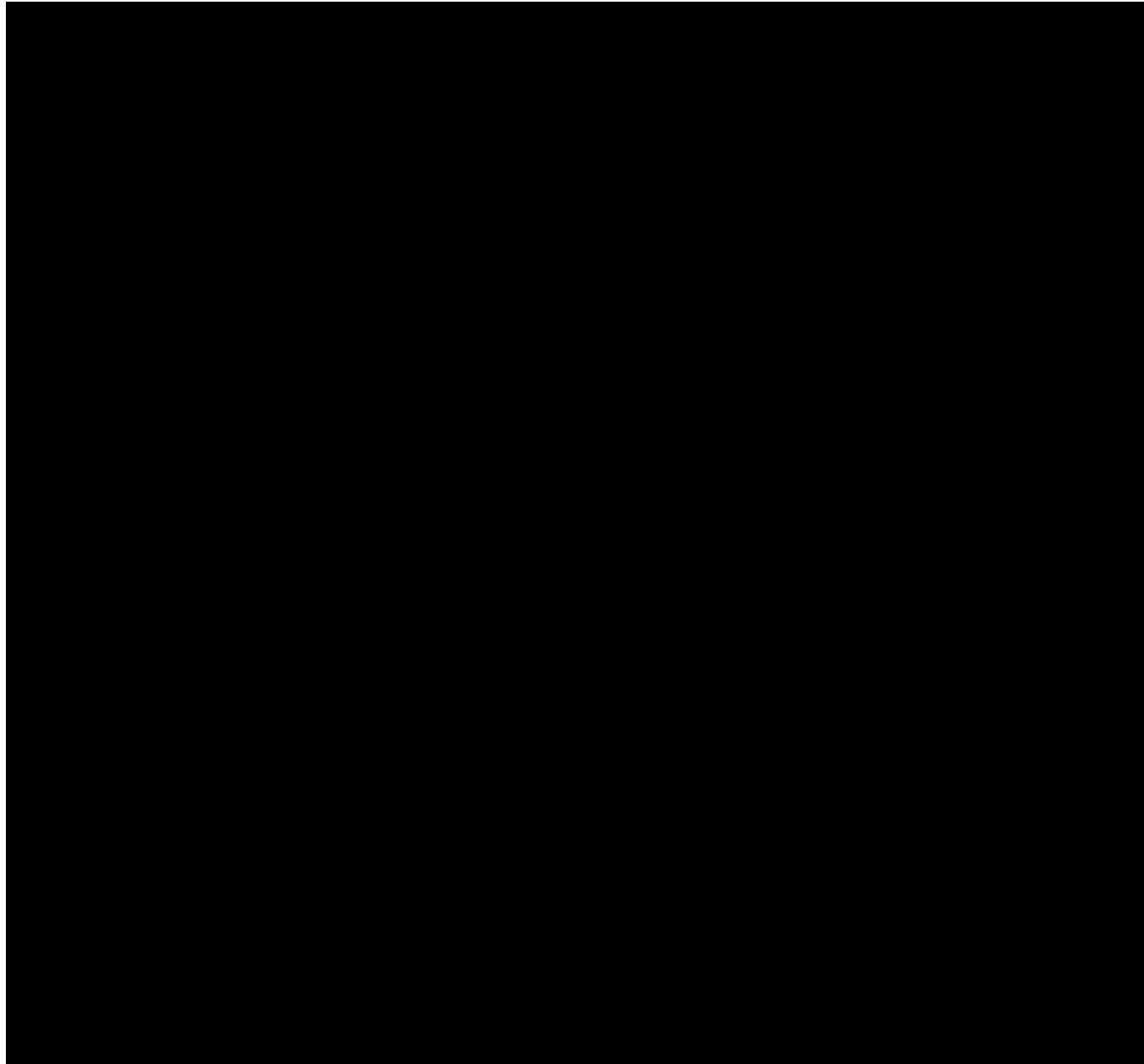
A disk life story

Gas-rich phase (< 10 Myr)
Primordial Disks

Thinning phase (~10 Myr)
Transitional Disks

Gas-poor phase (>10 Myr)
Debris Disks

Magneto-Rotational Instability

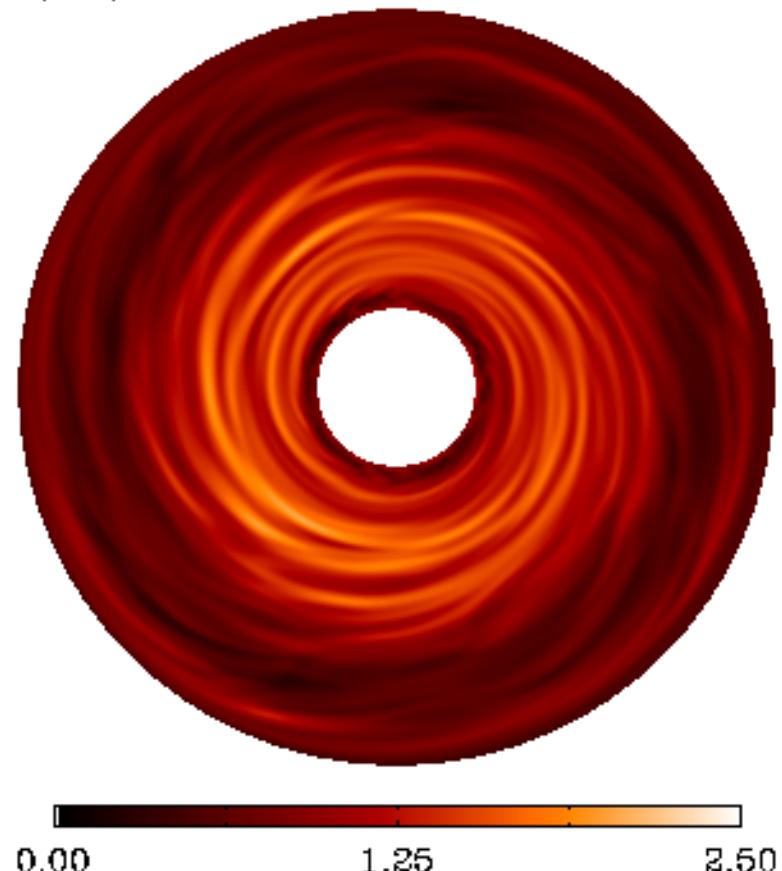


Video credit: Mario Pirok (MPI ASTRON)

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability

$t=46.3/88\text{yr}$



Slower
Rotation

Stretching
amplifies
B-field

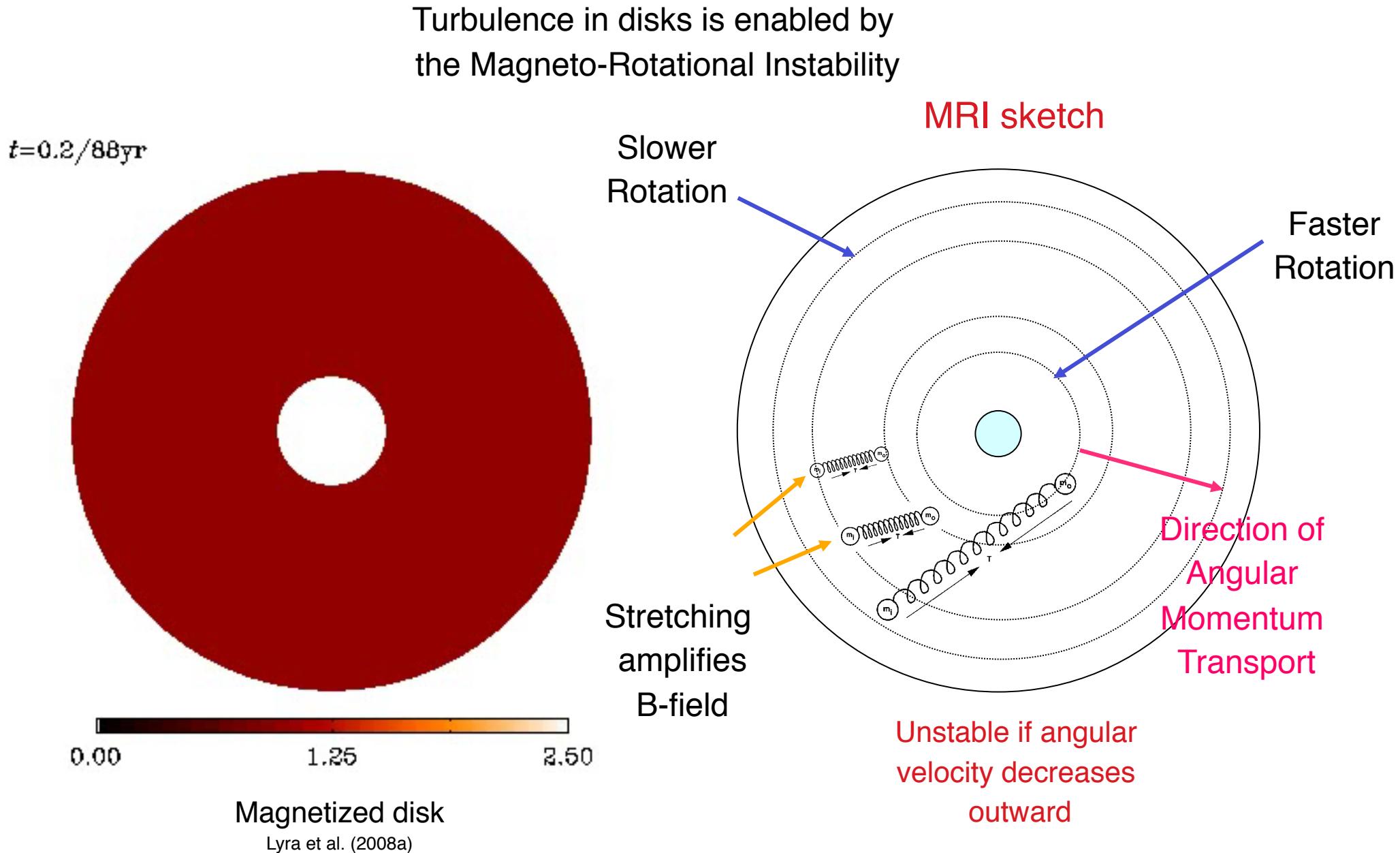
MRI sketch

Unstable if angular
velocity decreases
outward

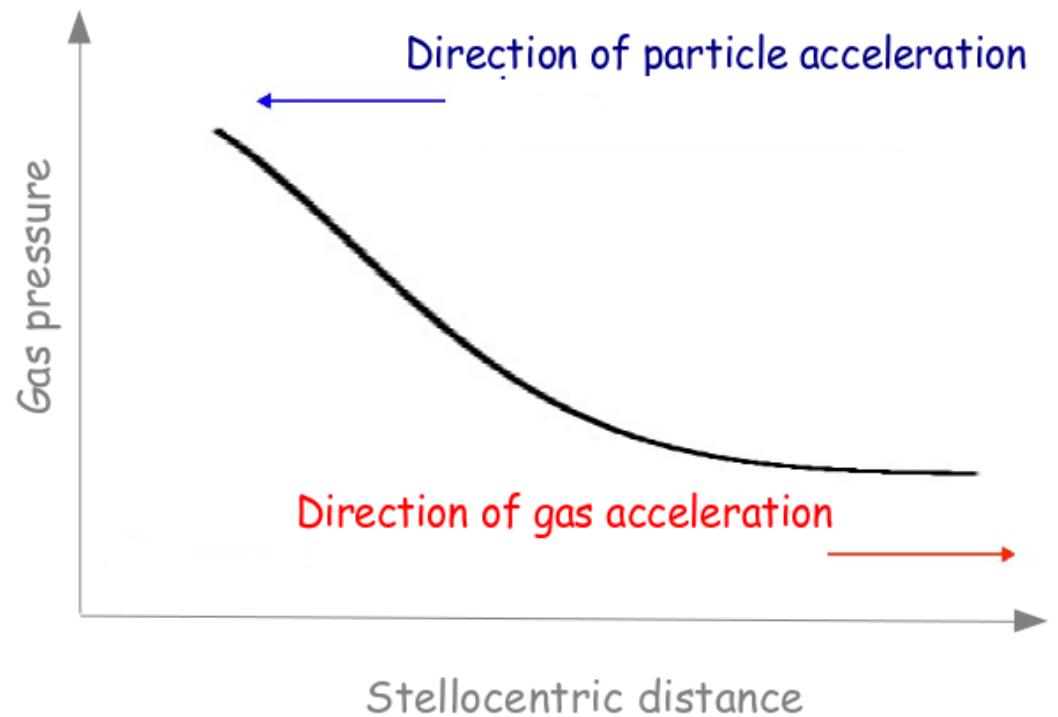
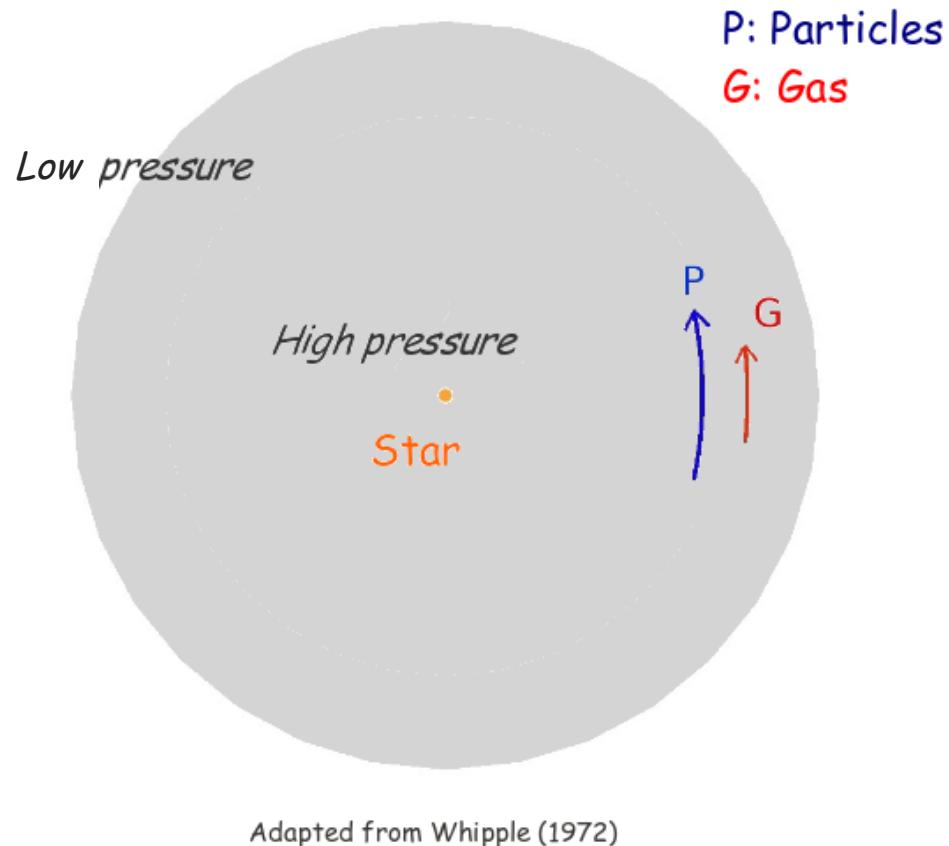
Faster
Rotation

Direction of
Angular
Momentum
Transport

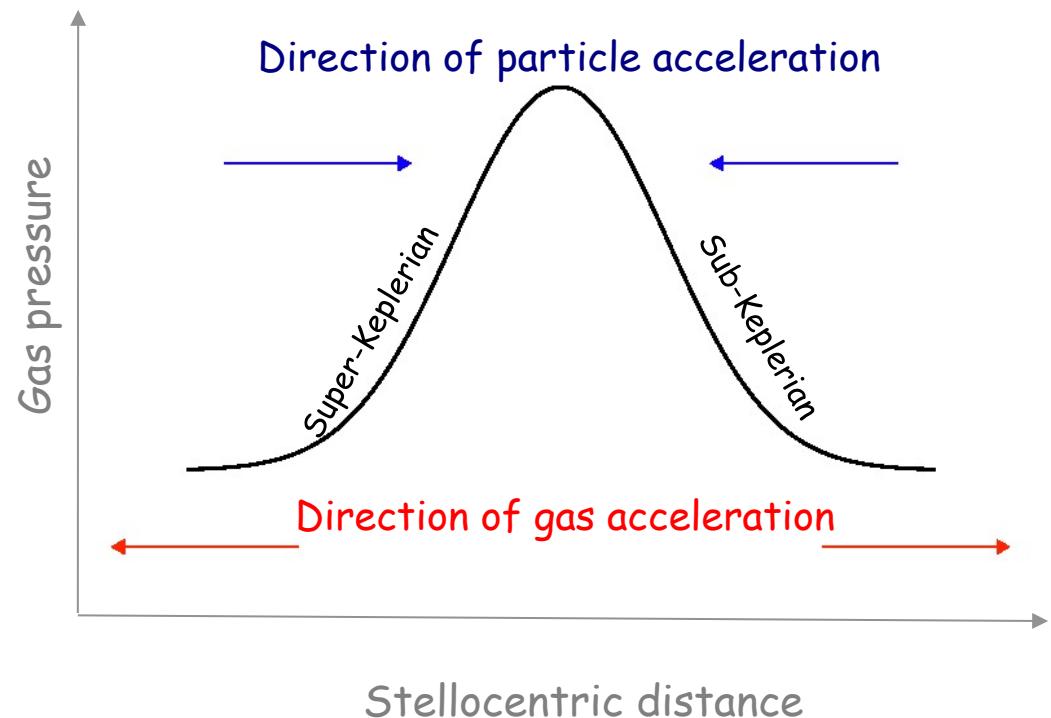
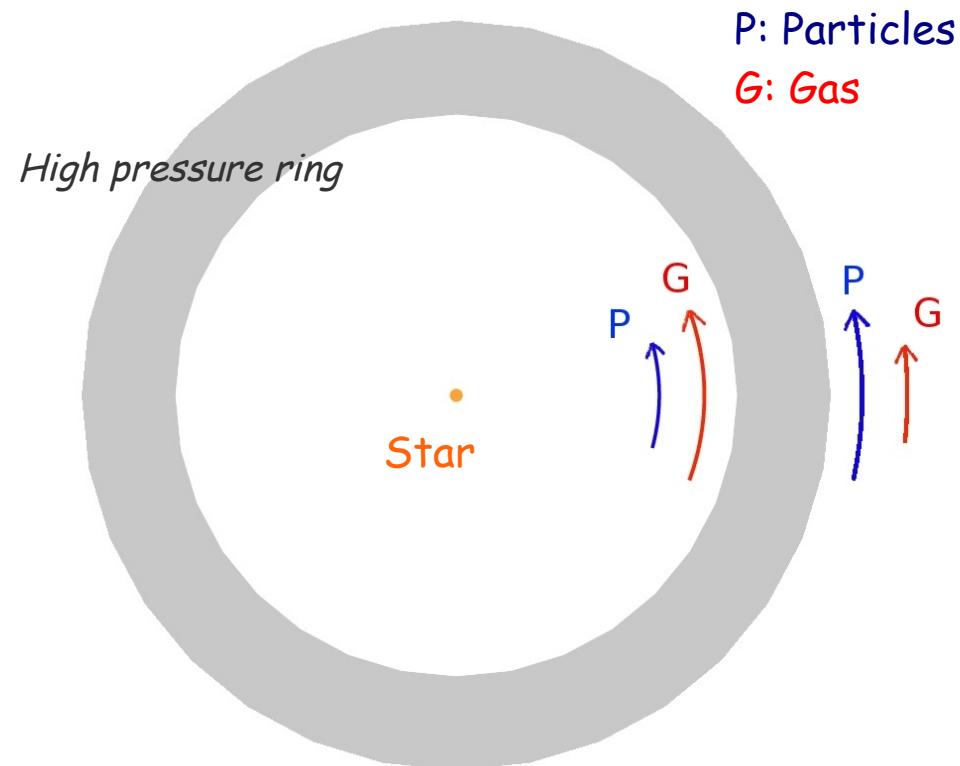
Accretion in disks occurs via turbulent viscosity



Particle drift

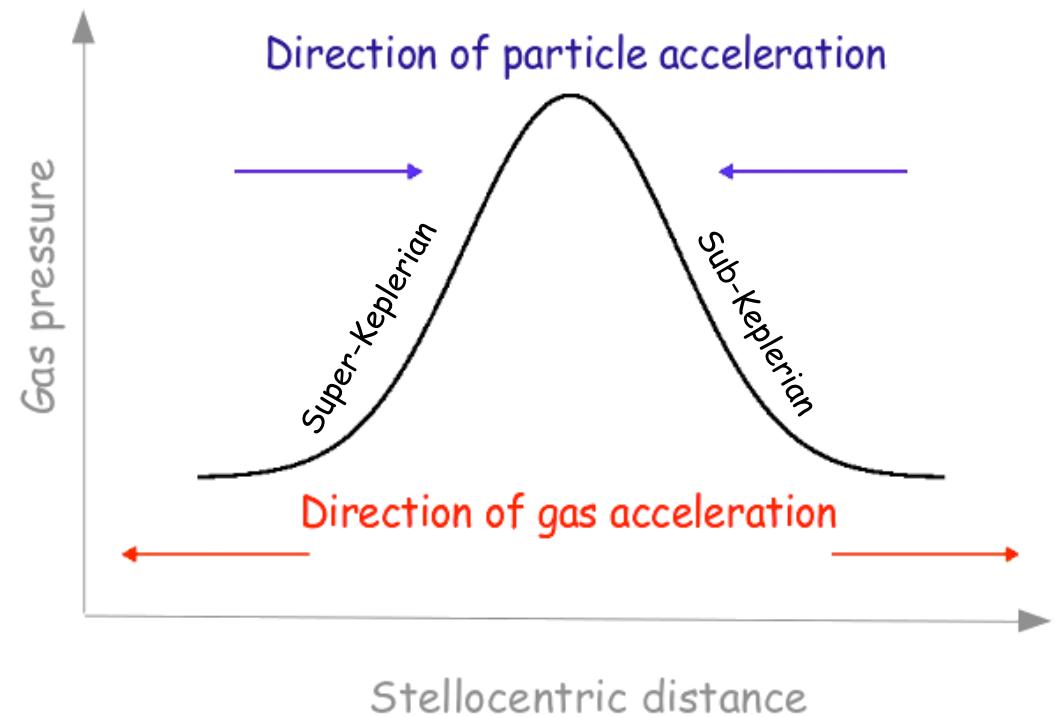
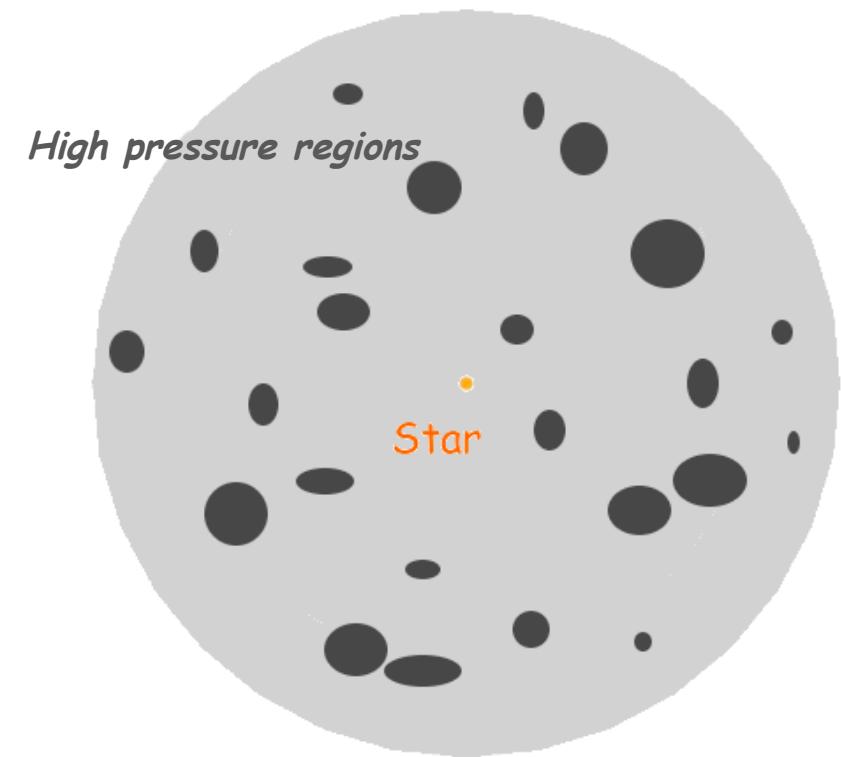


Pressure Trap

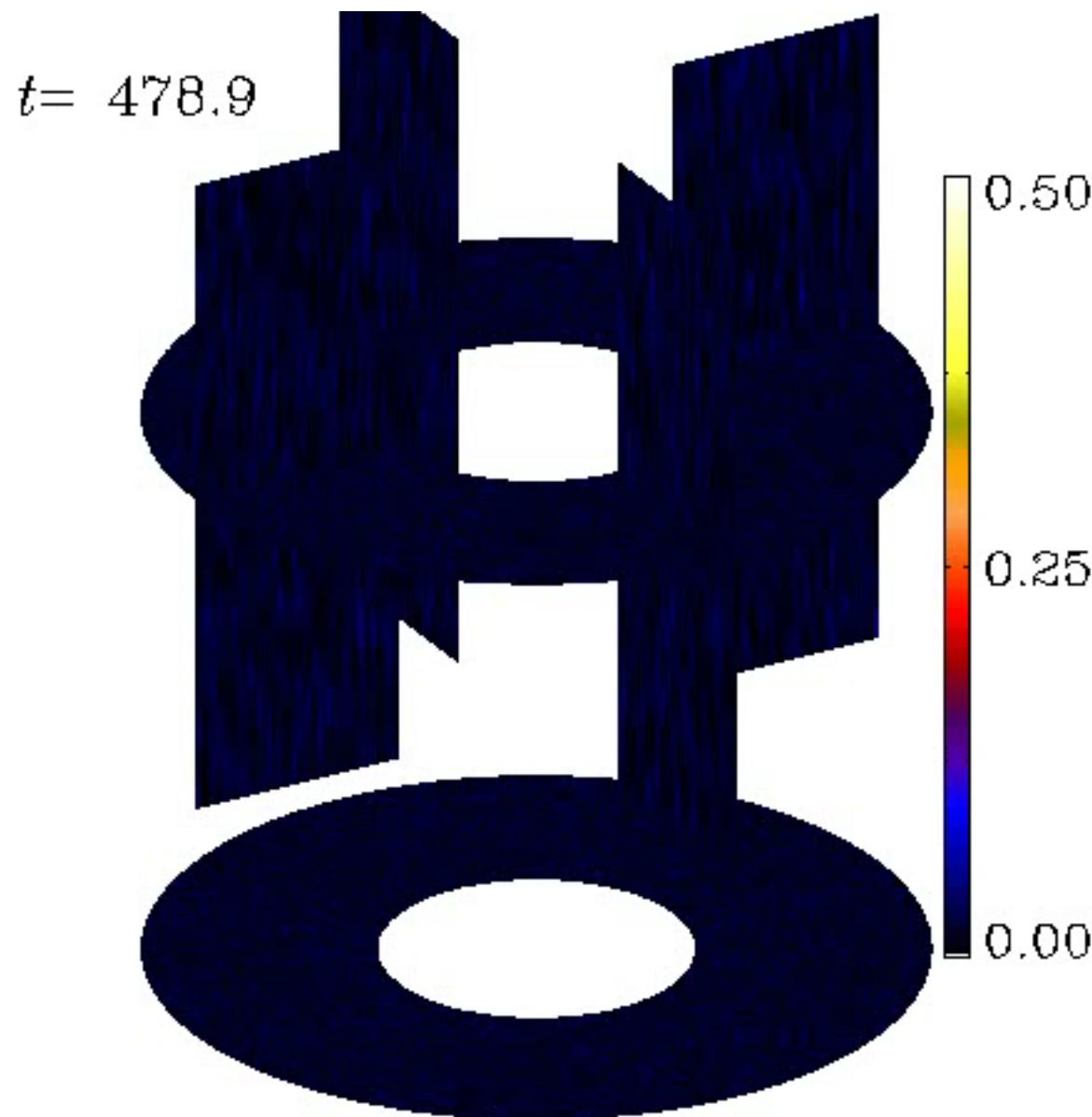


Adapted from Whipple (1972)

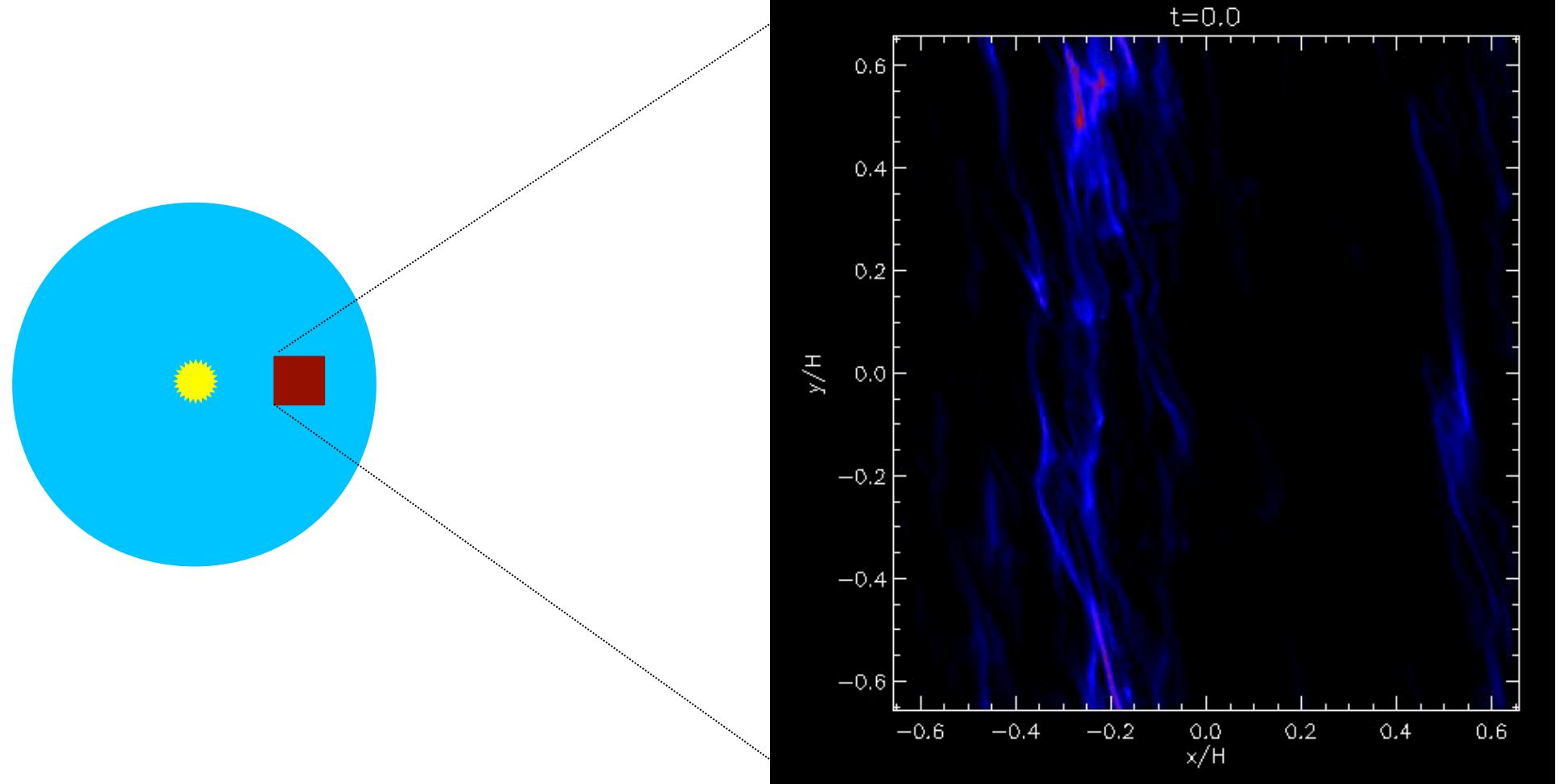
Pressure Trap



Turbulence concentrates solids mechanically in pressure maxima

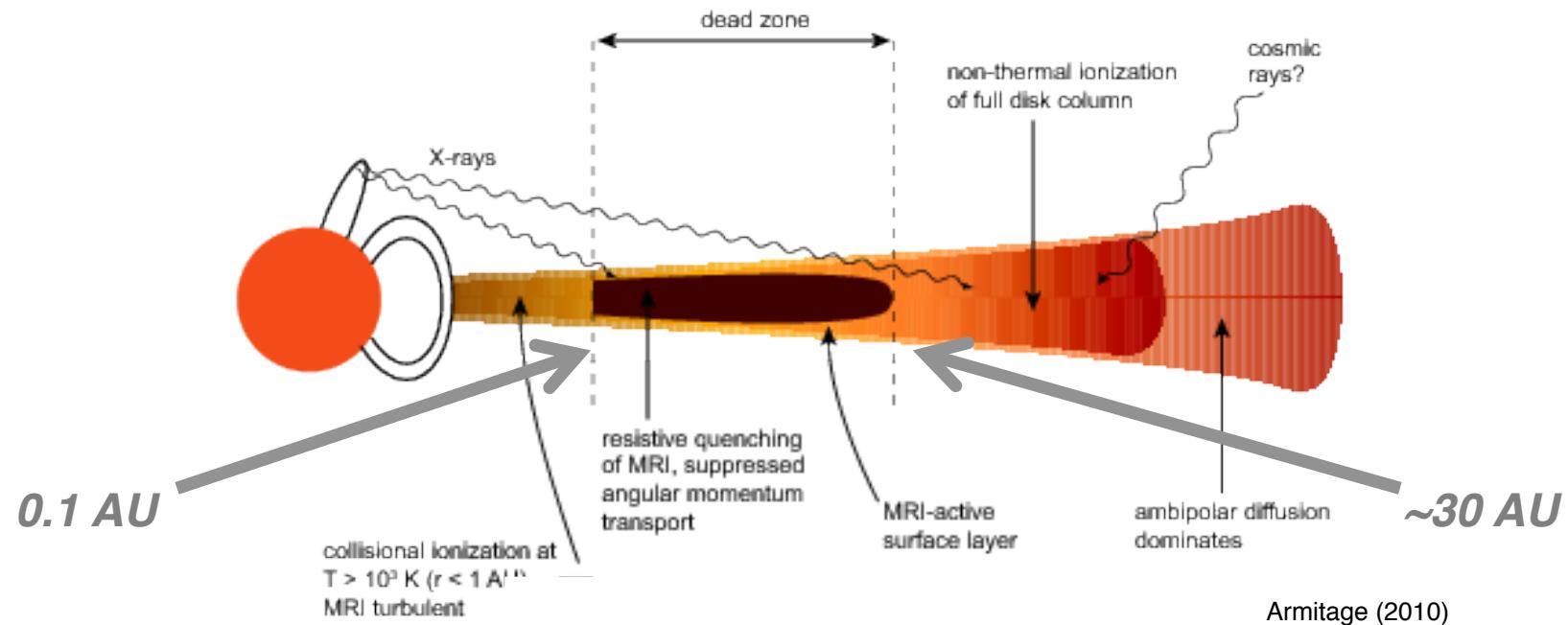


Gravitational collapse into planetesimals



Johansen et al. (2007)

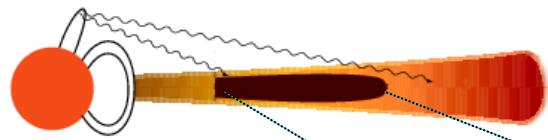
Dead zones are robust features of protoplanetary disks



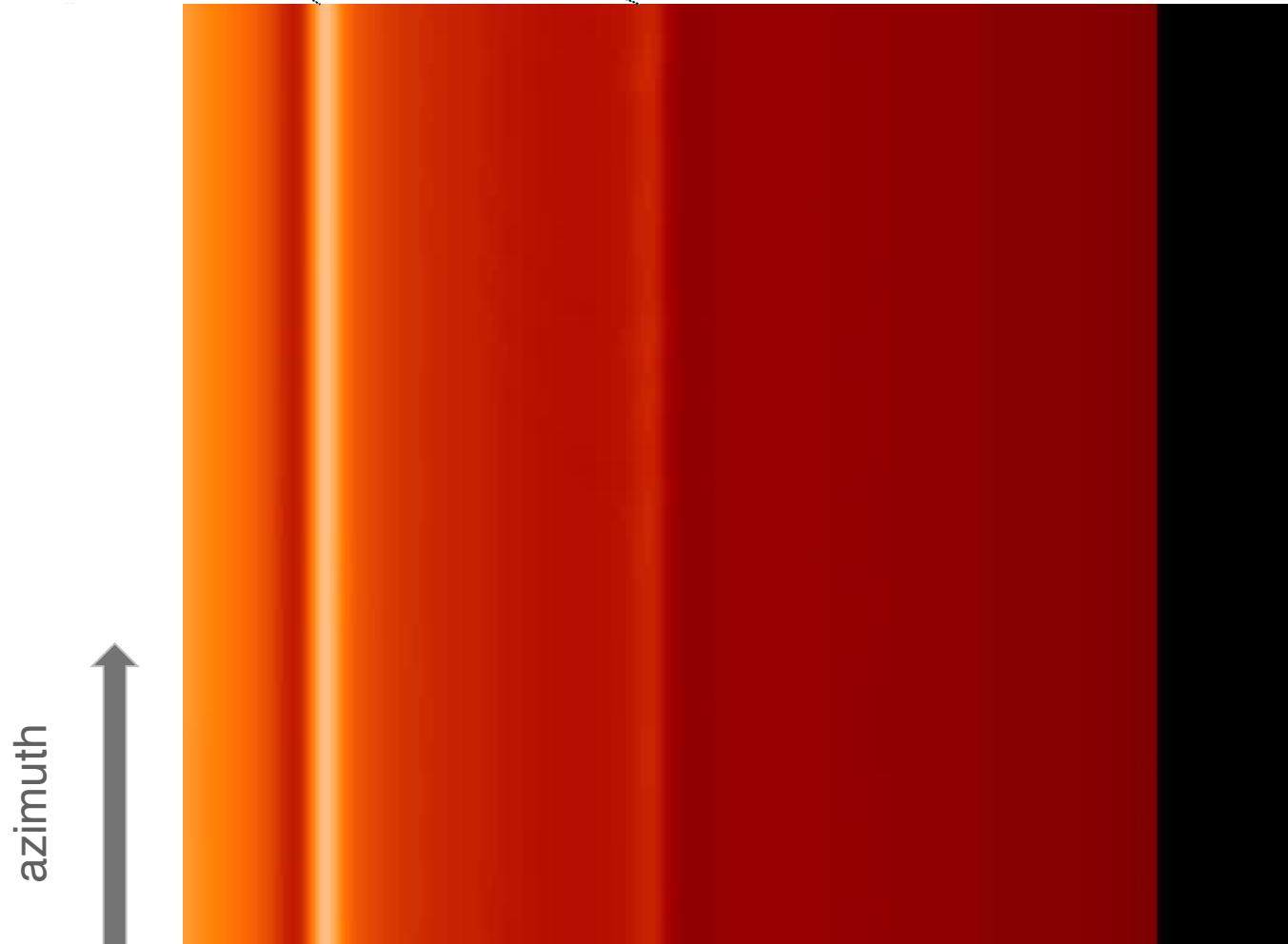
Disks are cold and thus poorly ionized
(Blaes & Balbus 1994)

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

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



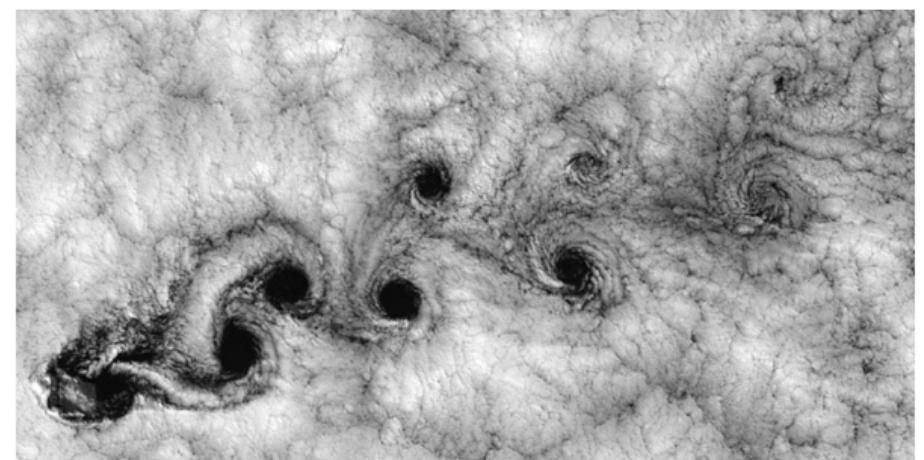
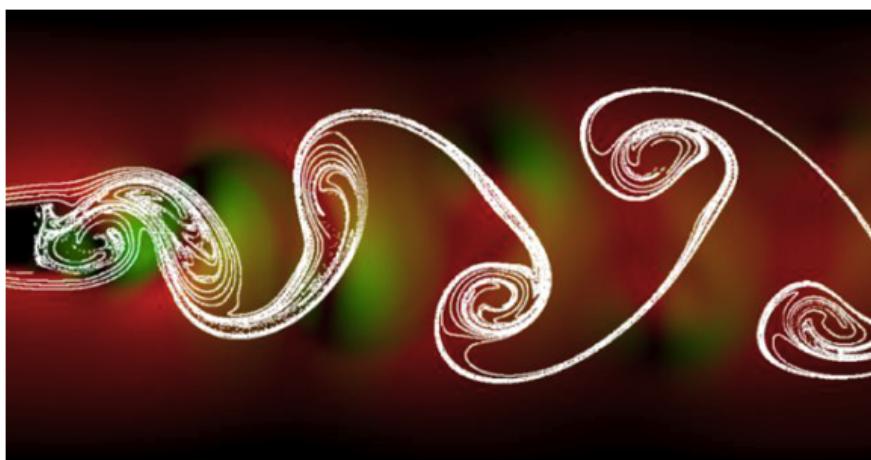
A simple dead zone model



radius

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

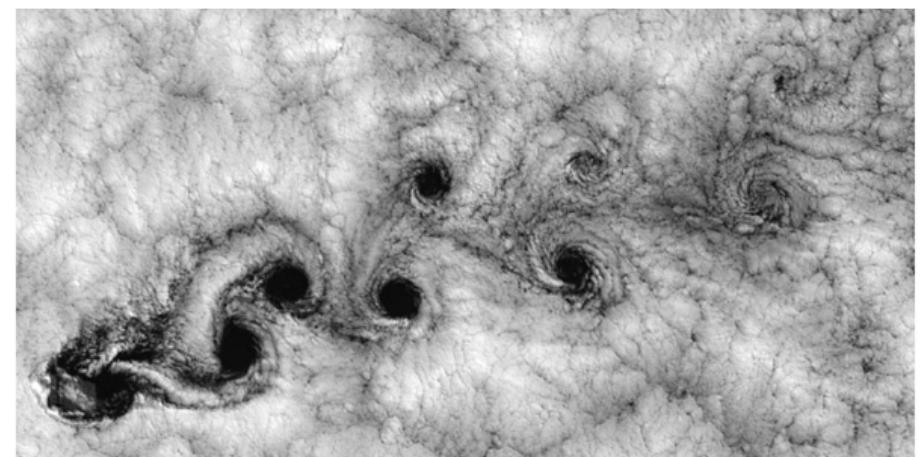
Vortices – an ubiquitous fluid mechanics phenomenon



Vortices – an ubiquitous fluid mechanics phenomenon

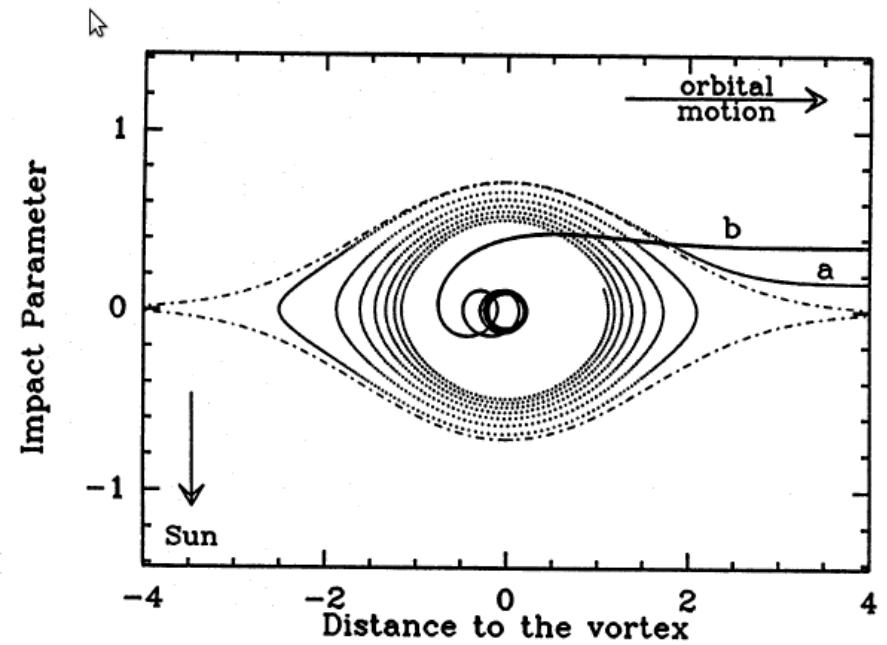
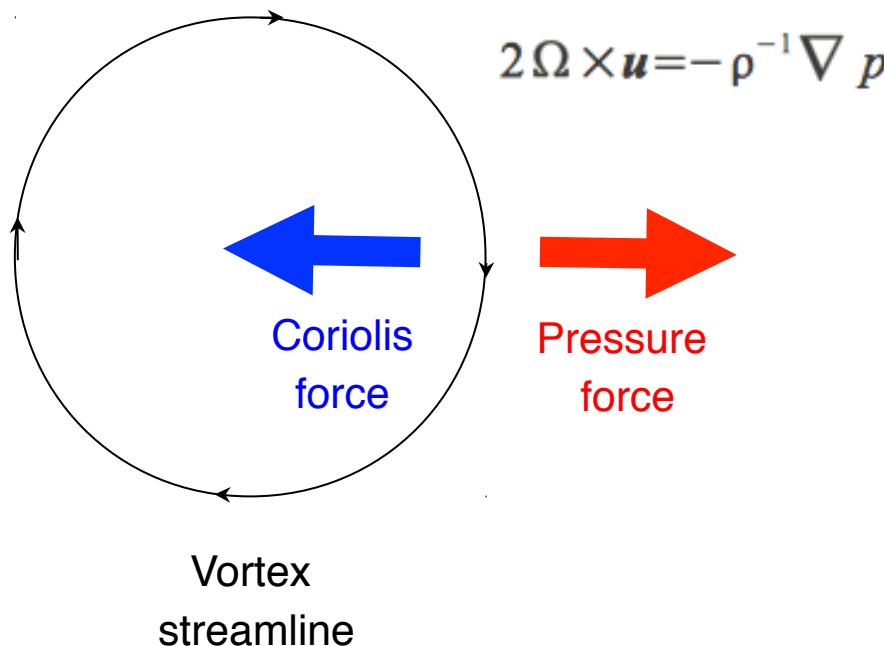


Von Kármán *vortex street*



The Tea-Leaf effect

Geostrophic balance:



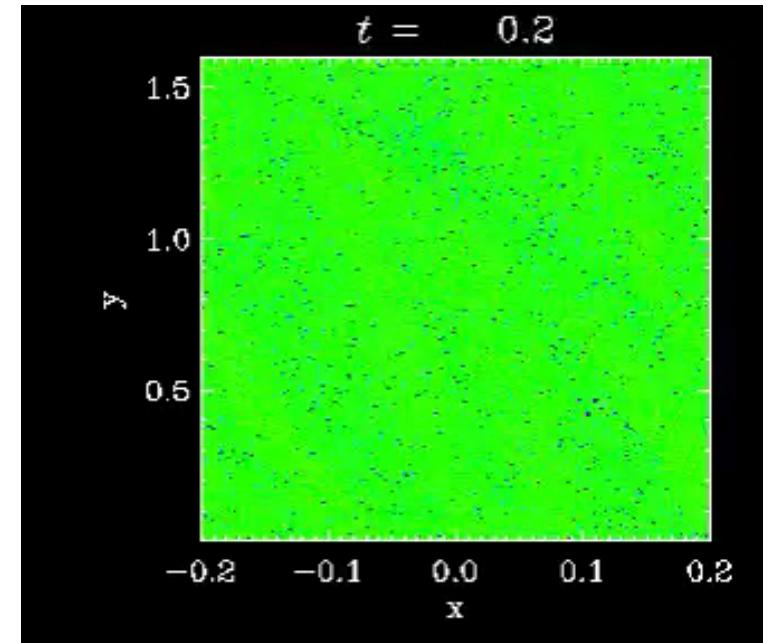
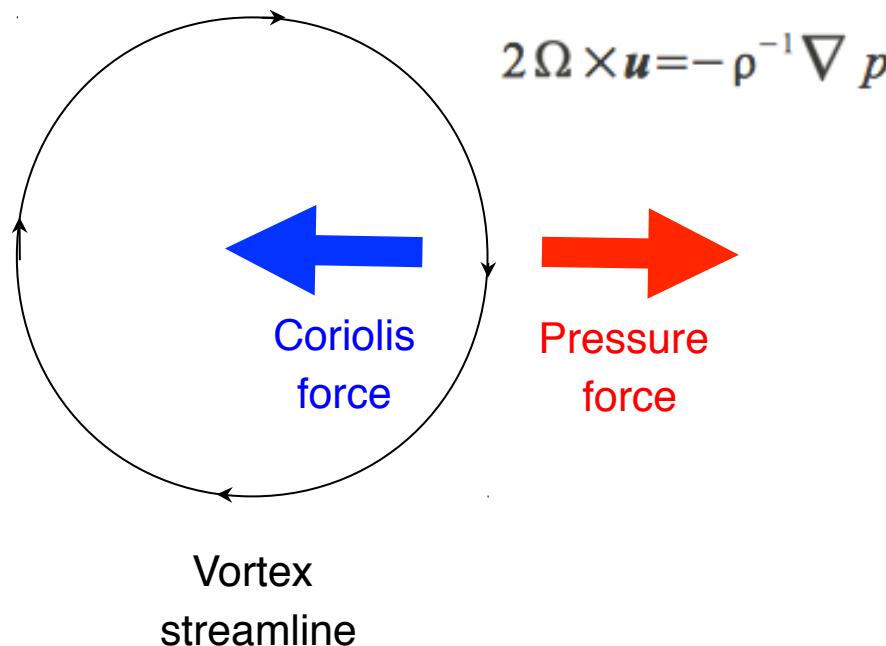
Particles do not feel the pressure gradient.
They sink towards the center, where they accumulate.

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:



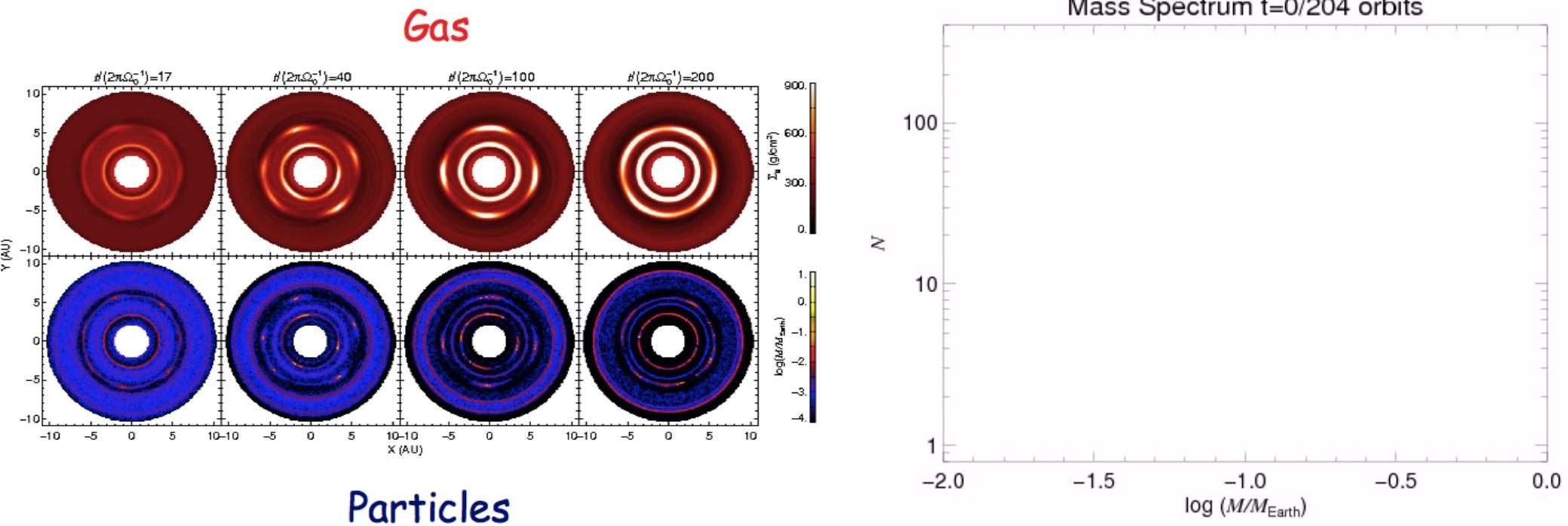
Raettig et al. (2012)

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)

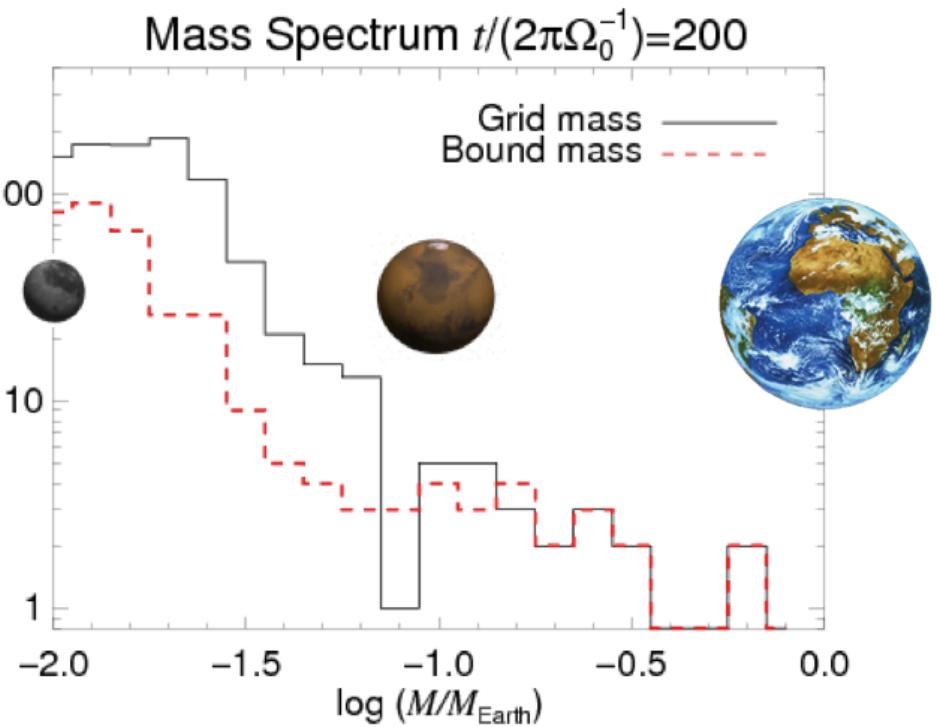
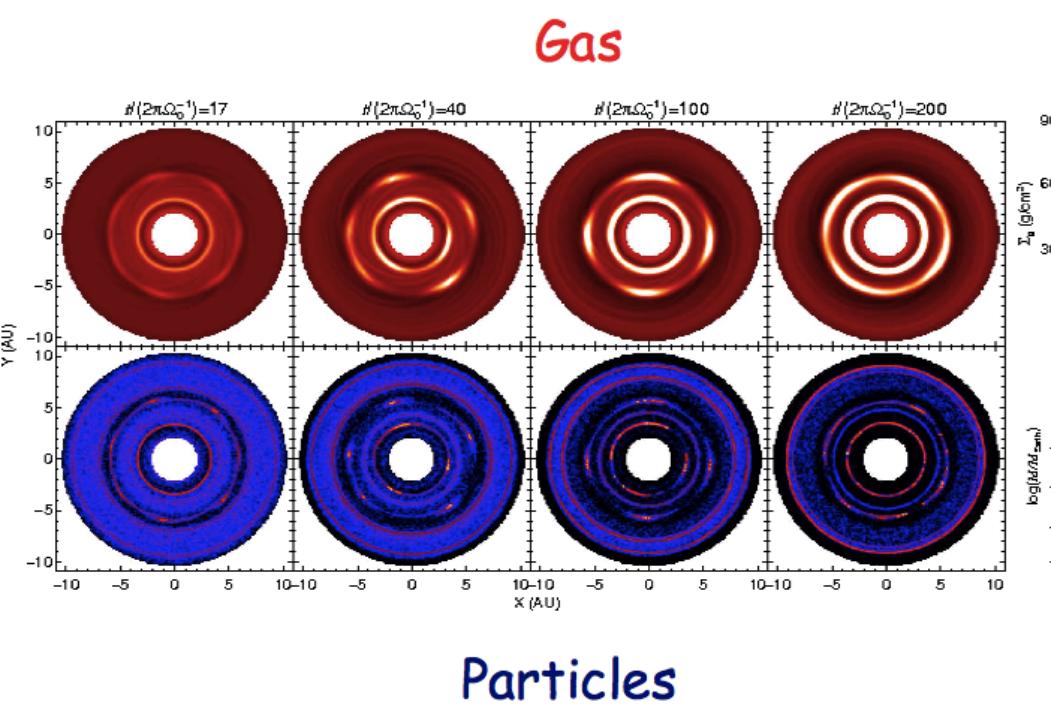
Vortices and Planet Formation



Collapse into Mars mass objects

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

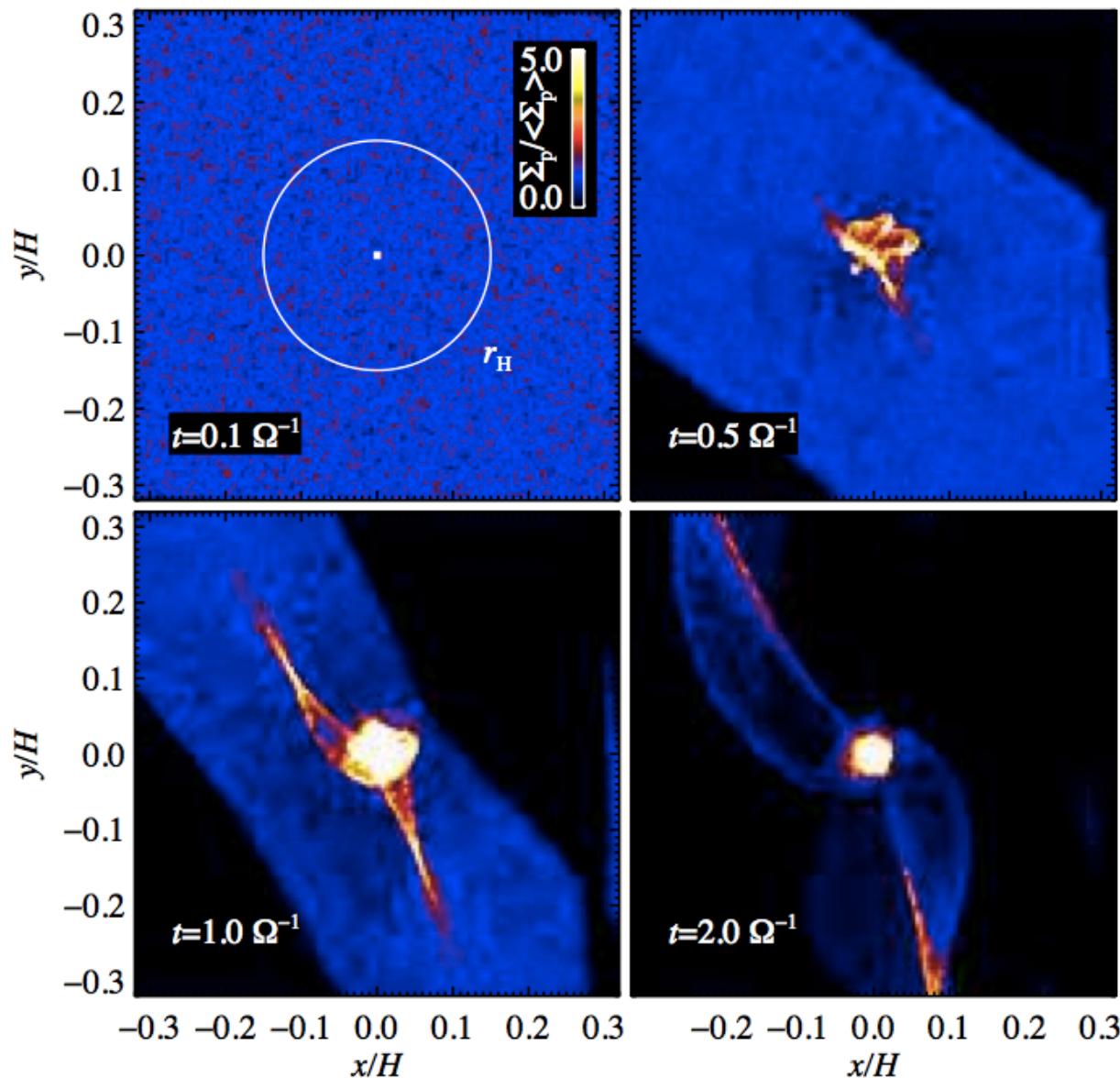
Vortices and Planet Formation



Collapse into Mars mass objects

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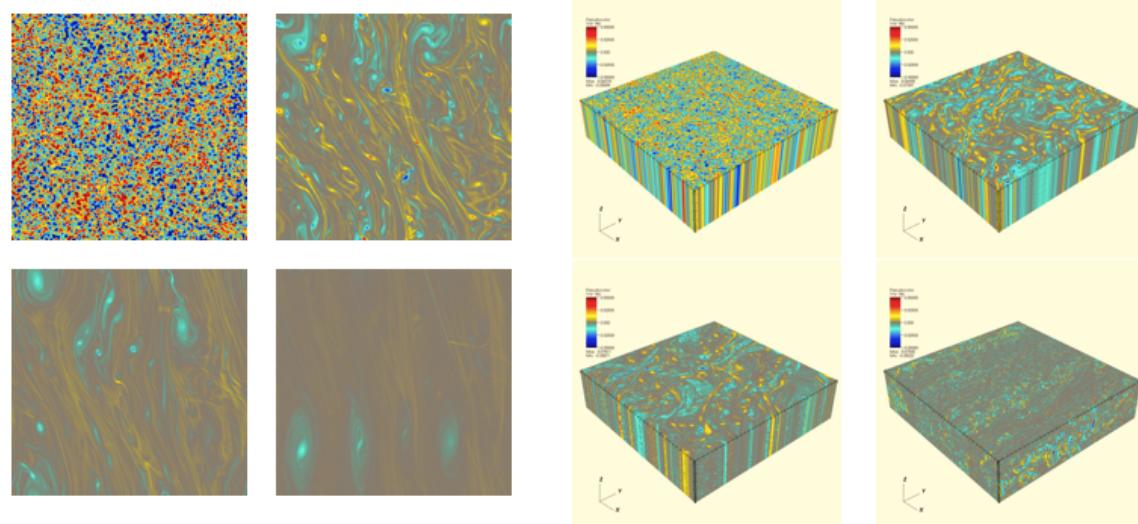
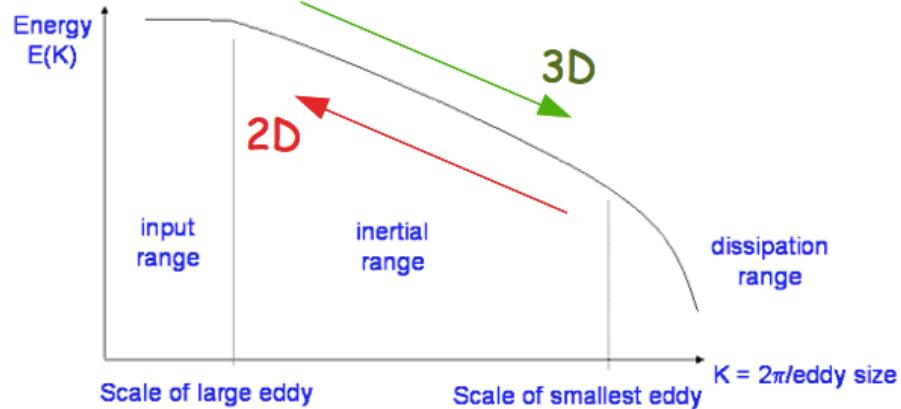
Rapid formation of planetary cores



Lambrechts & Johansen (2012)

The energy cascade

Shen et al. (2006)
See also Batchelor (1967)



2D

3D

Inverse cascade

No 3D instability
Eddies merge

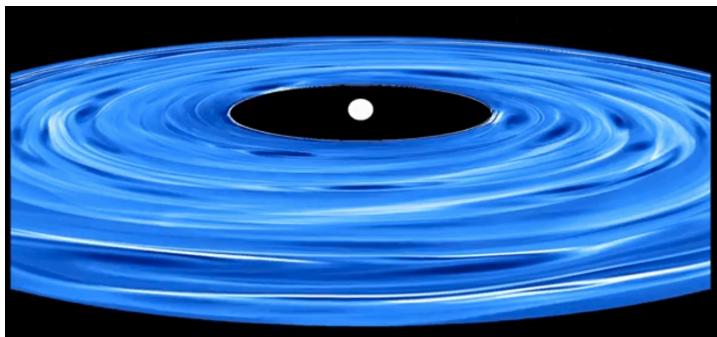
Direct cascade

Destruction occurs
faster than merging

Sustaining vortices in disks

Known mechanisms to
replenish the **vorticity**
lost in the direct cascade

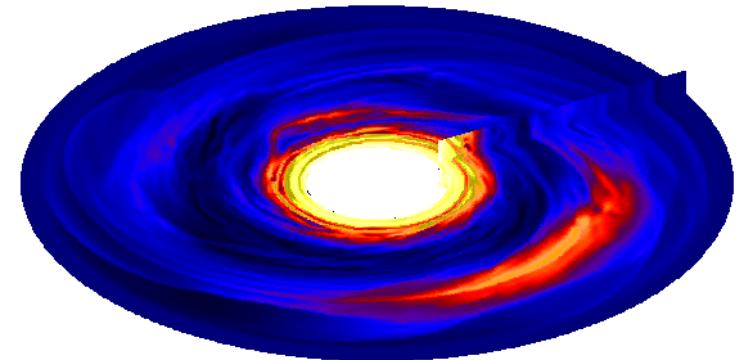
Baroclinic instability (*Convective overstability*)



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:
Buoyancy, thermal diffusion
(baroclinic source term)

Rossby wave instability

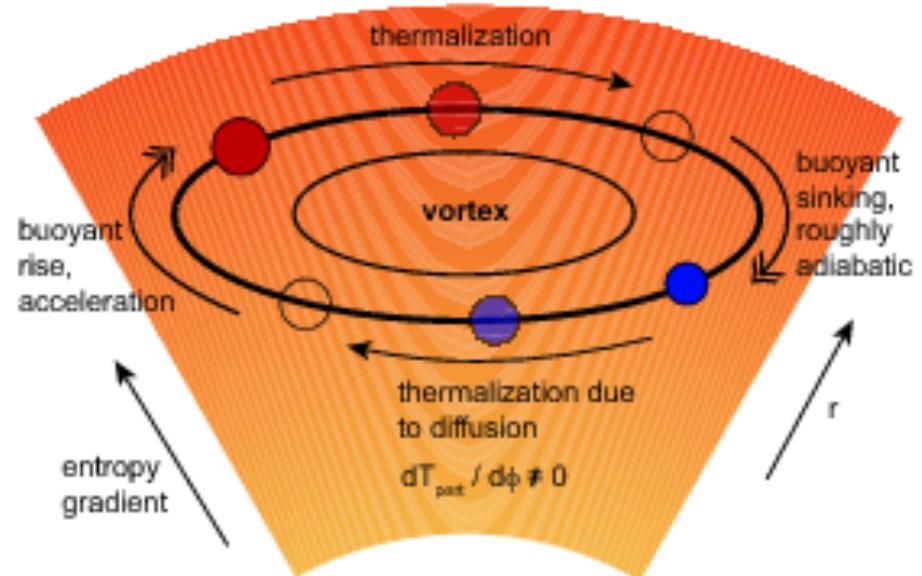


Lovelace & Hohlfeld (1978), Toomre (1981), Papaloizou & Pringle (1984, 1985), Hawley et al. (1987), Lovelace et al. (1999), Li et al. (2000, 2011), Tagger (2001), Varniere & Tagger (2006), de Val-Borro et al. (2007), Lyra et al. (2008b, 2009ab), Mehuet et al. (2010, 2012abc), Lin & Papaloizou (2011ab,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

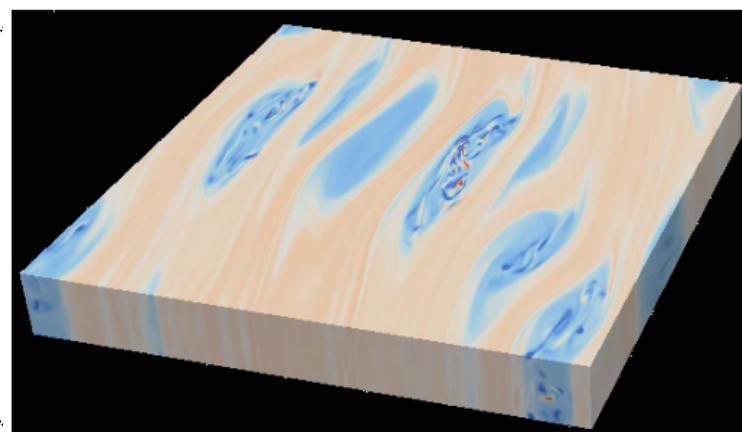
Powered by:
Modification of shear profile
(**external vorticity reservoir**)

Baroclinic Instability – Excitation and self-sustenance of vortices

Sketch of the
Baroclinic Instability



Armitage (2010)

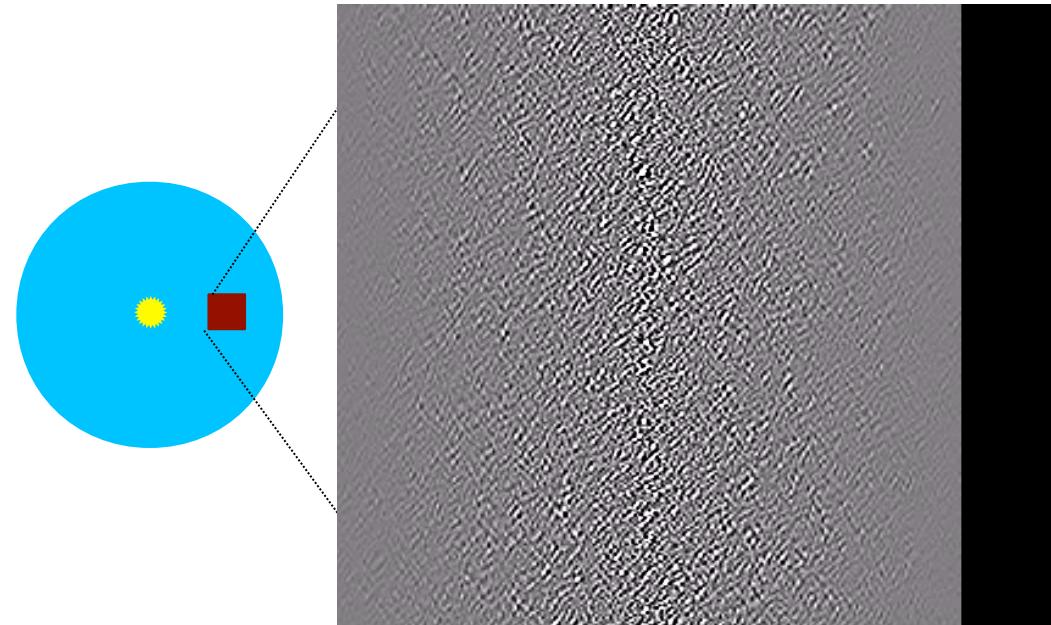


Lesur & Papaloizou (2010)

$$\frac{\partial \omega}{\partial t} = -(\mathbf{u} \cdot \nabla) \omega - \omega (\nabla \cdot \mathbf{u}) + (\omega \cdot \nabla) \mathbf{u} + \frac{1}{\rho^2} \nabla p \times \nabla p + \nu \nabla^2 \omega$$

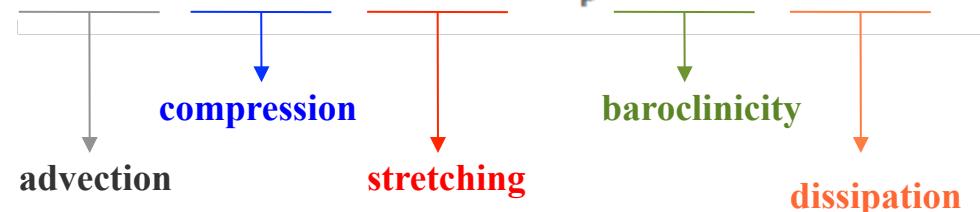
advection compression stretching baroclinicity dissipation

Baroclinic Instability – Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

$$\frac{\partial \omega}{\partial t} = -(\mathbf{u} \cdot \nabla) \omega - \omega (\nabla \cdot \mathbf{u}) + (\omega \cdot \nabla) \mathbf{u} + \frac{1}{\rho^2} \nabla p \times \nabla p + \nu \nabla^2 \omega$$



The “Baroclinic Instability” is LINEAR (Convective Overstability)

Klahr & Hubbard (2014), Lyra (2014)

$$\frac{\partial \rho}{\partial t} + (\mathbf{u} \cdot \nabla) \rho = -\rho \nabla \cdot \mathbf{u},$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla p + \mathbf{g},$$

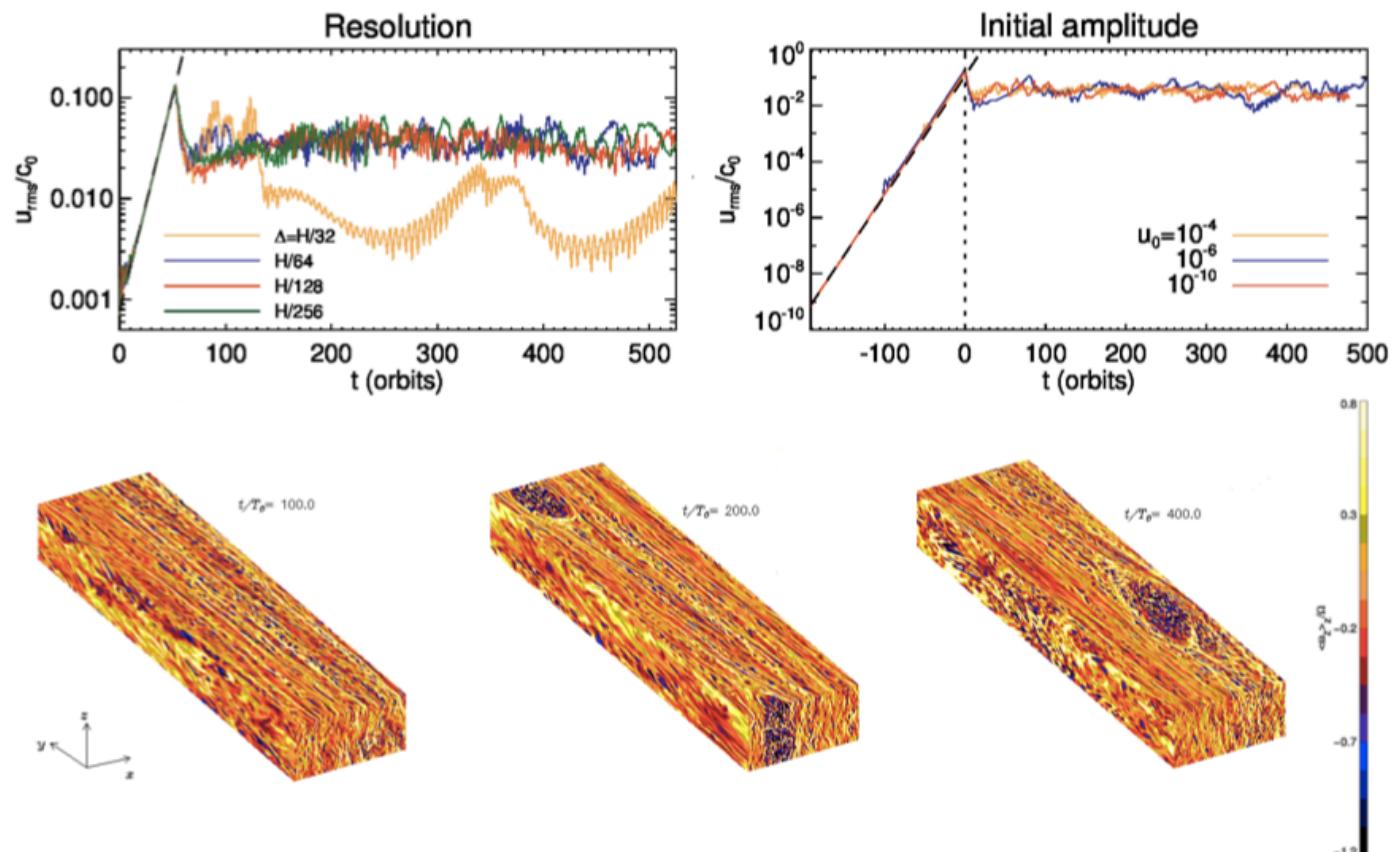
$$\frac{\partial p}{\partial t} + (\mathbf{u} \cdot \nabla) p = -\gamma p \nabla \cdot \mathbf{u} - \frac{p}{T} \frac{(T - T_0)}{\tau},$$

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

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

$$\bar{\omega}^3 + i\zeta\bar{\omega}^2 - \bar{\omega}\mu^2(\kappa^2 + N^2) - i\zeta\kappa^2\mu^2 = 0,$$

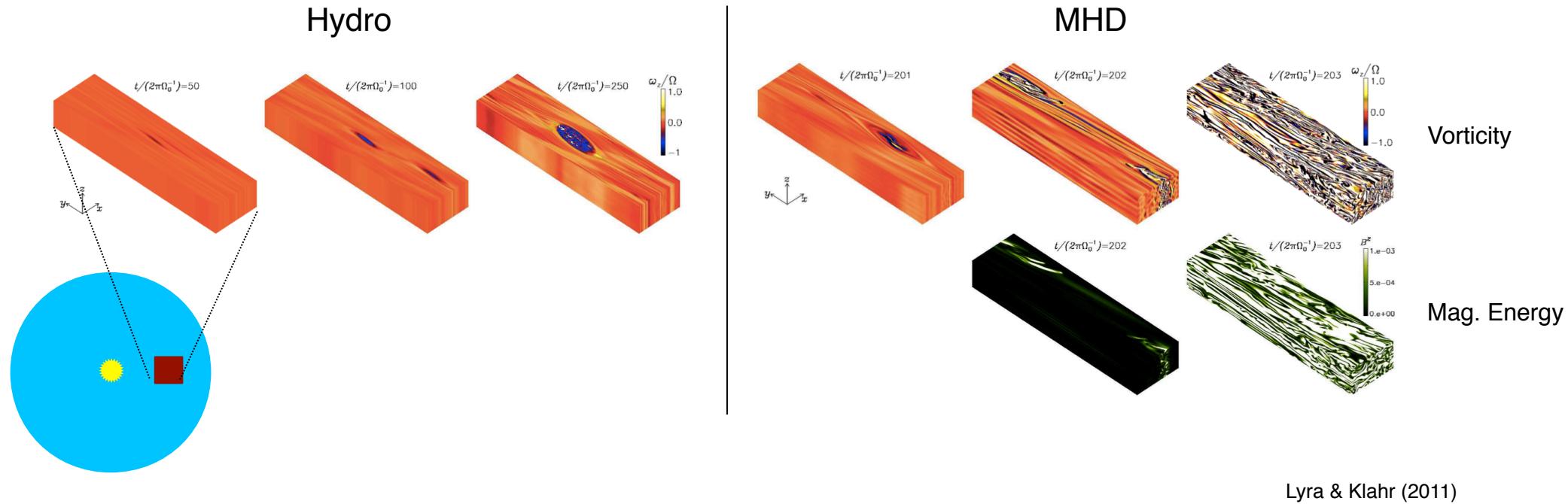
$$\zeta = 1/\gamma\tau \quad \mu^2 = -k_z^2/k^2.$$



Lyra (2014)

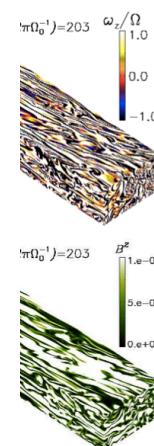
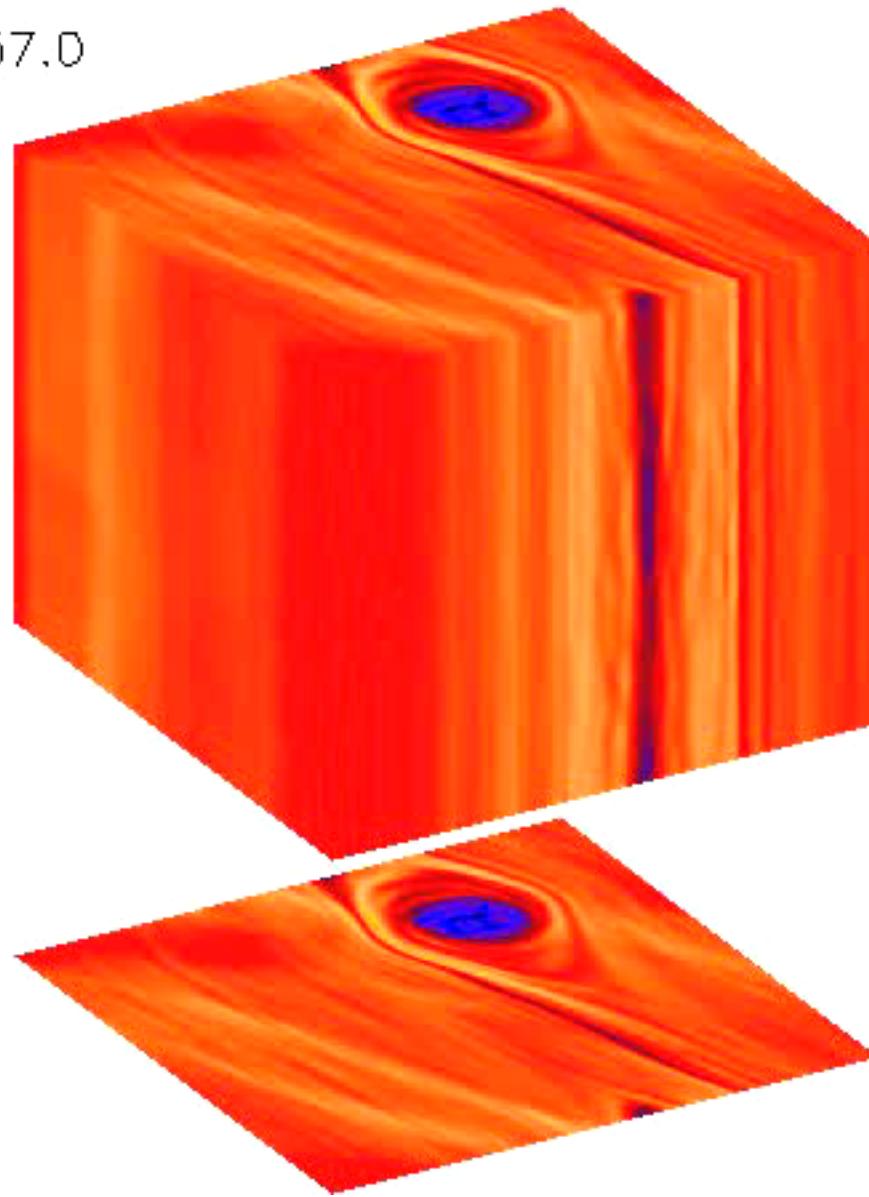
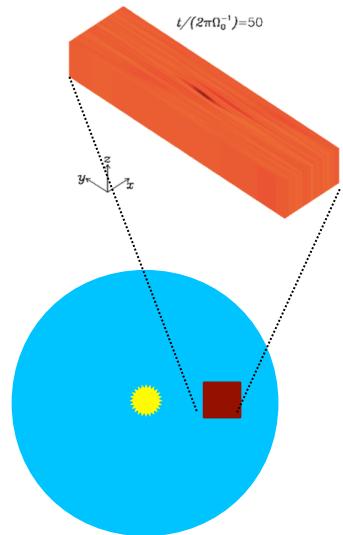
Baroclinic instability and layered accretion

What happens when the vortex is magnetized?

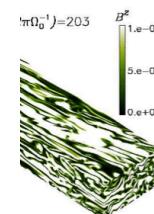


Baroclinic instability and layered accretion

$t=1257.0$



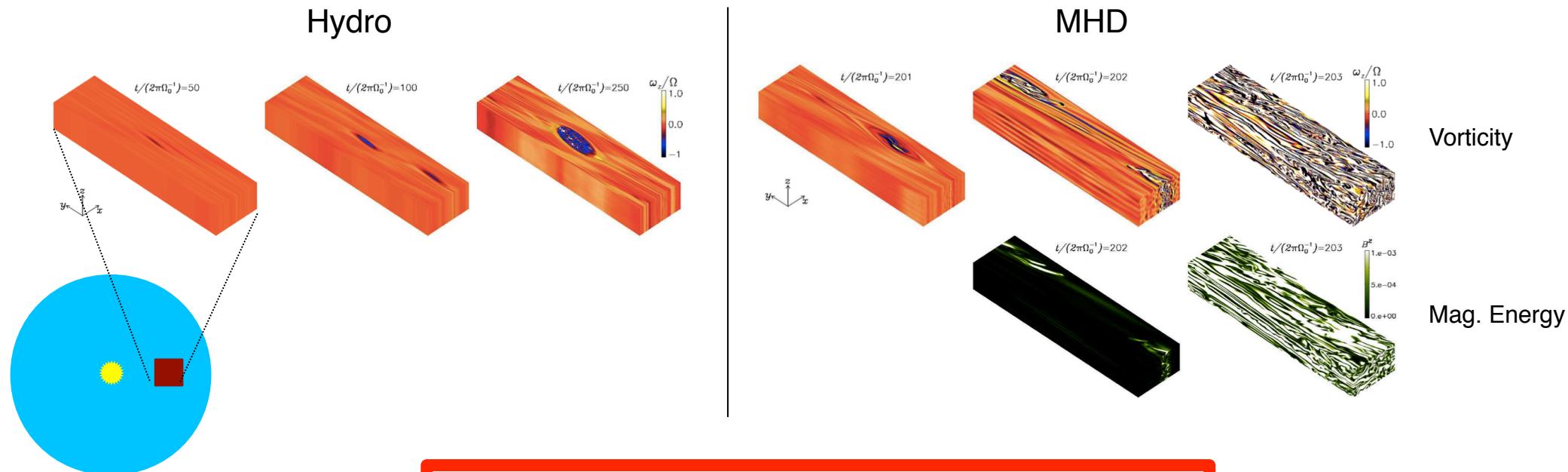
Vorticity



Mag. Energy

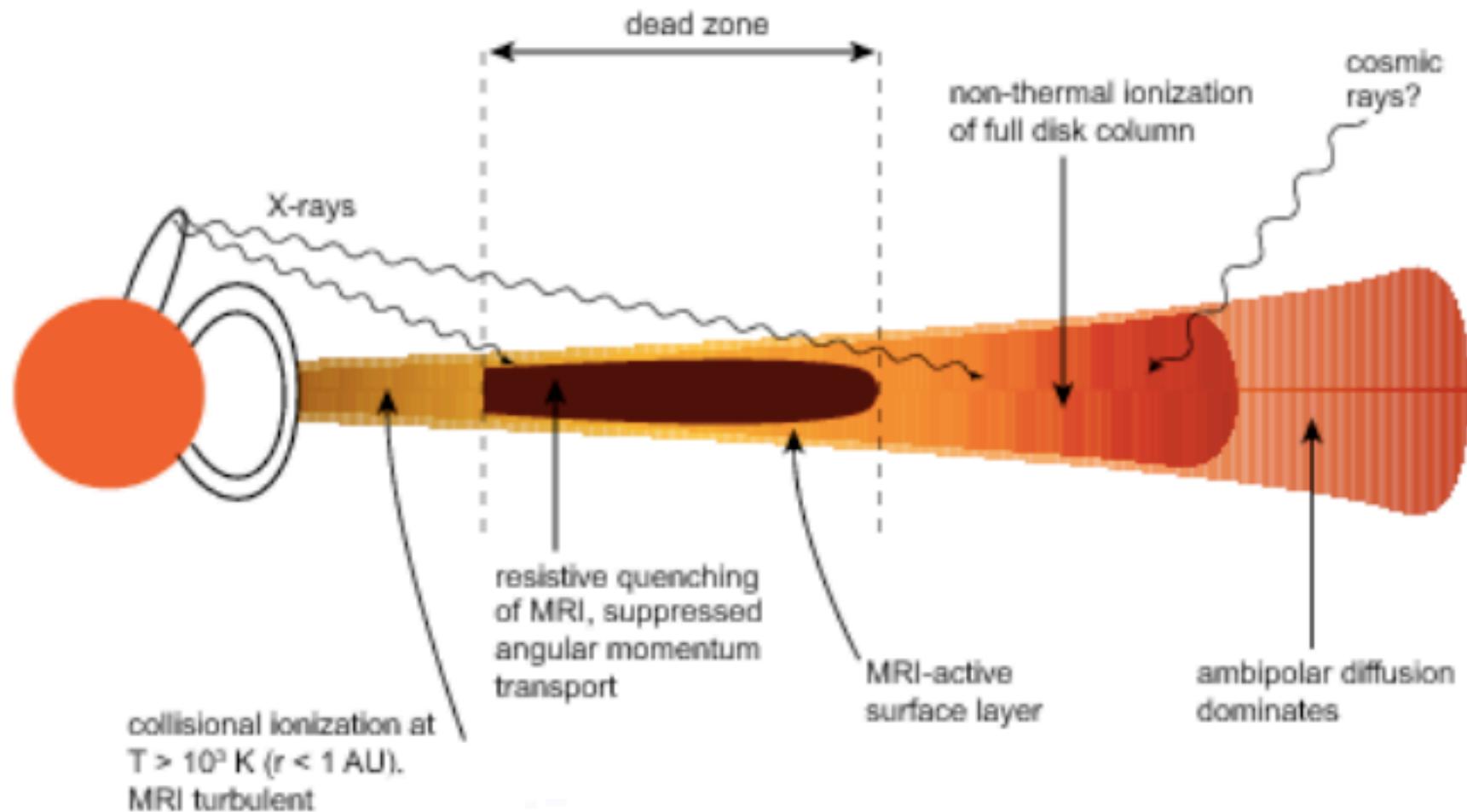
Baroclinic instability and layered accretion

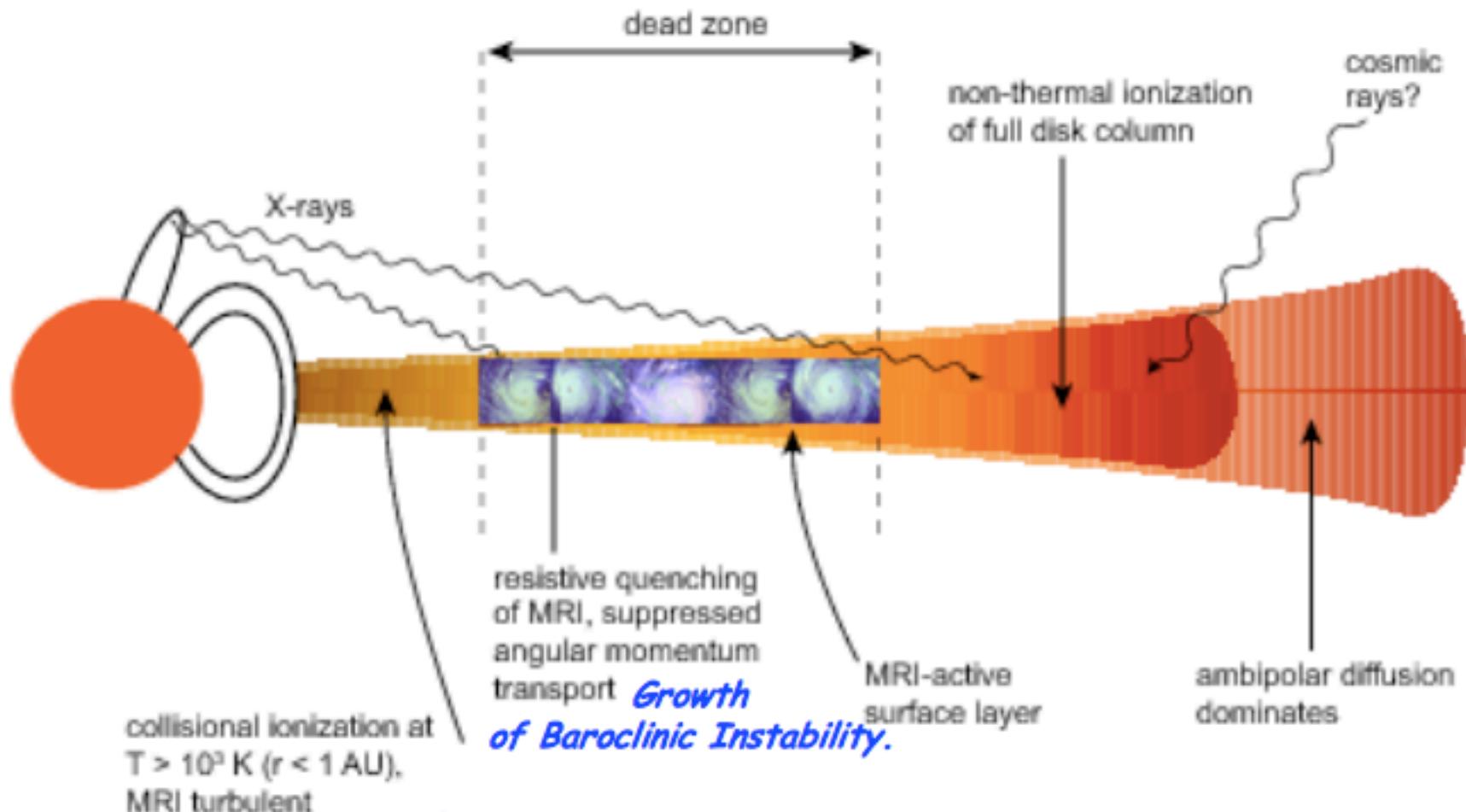
What happens when the vortex is magnetized?



Baroclinic vortices
do **not** survive magnetization

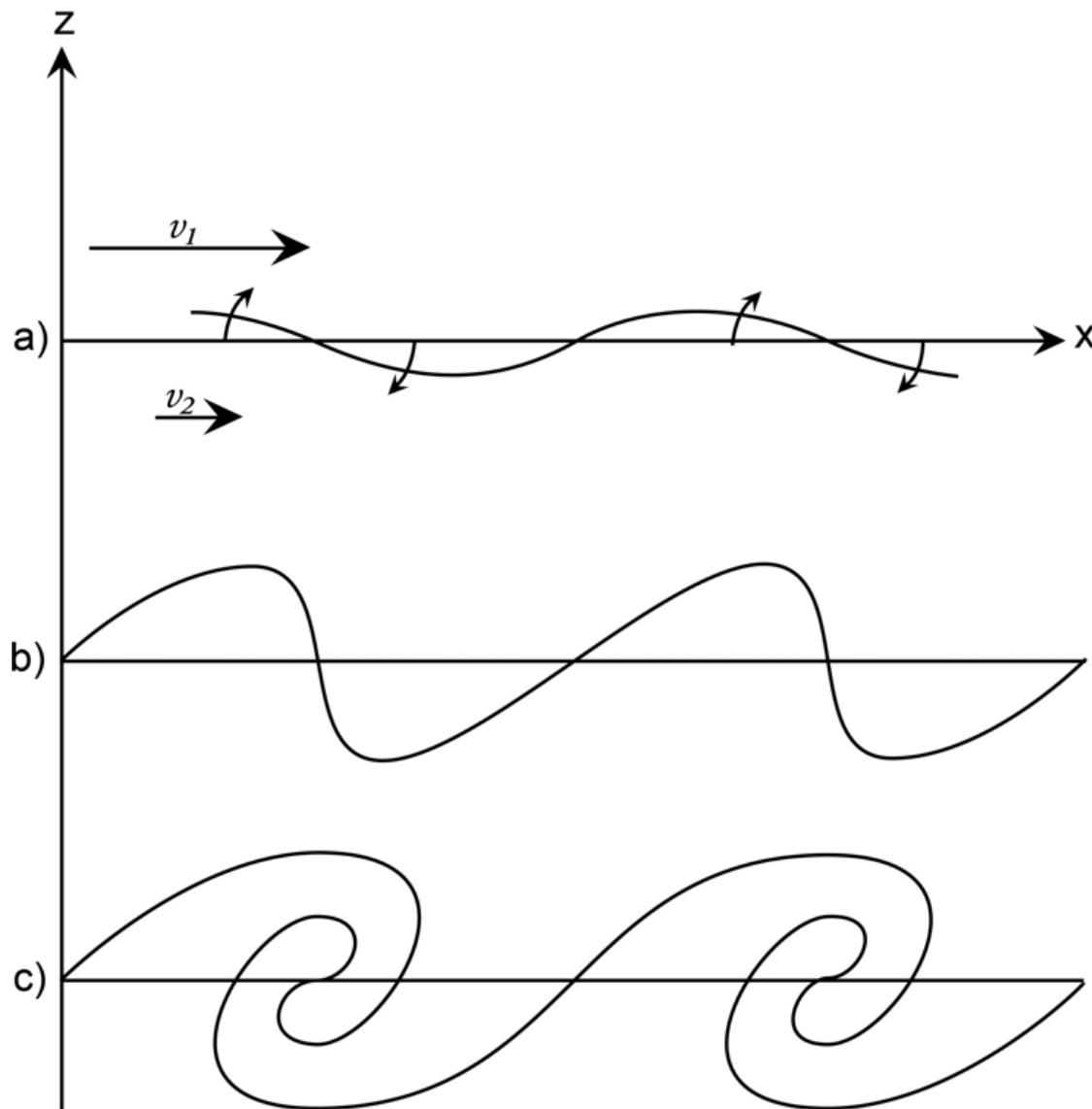
Lyra & Klahr (2011)





Rossby Wave Instability

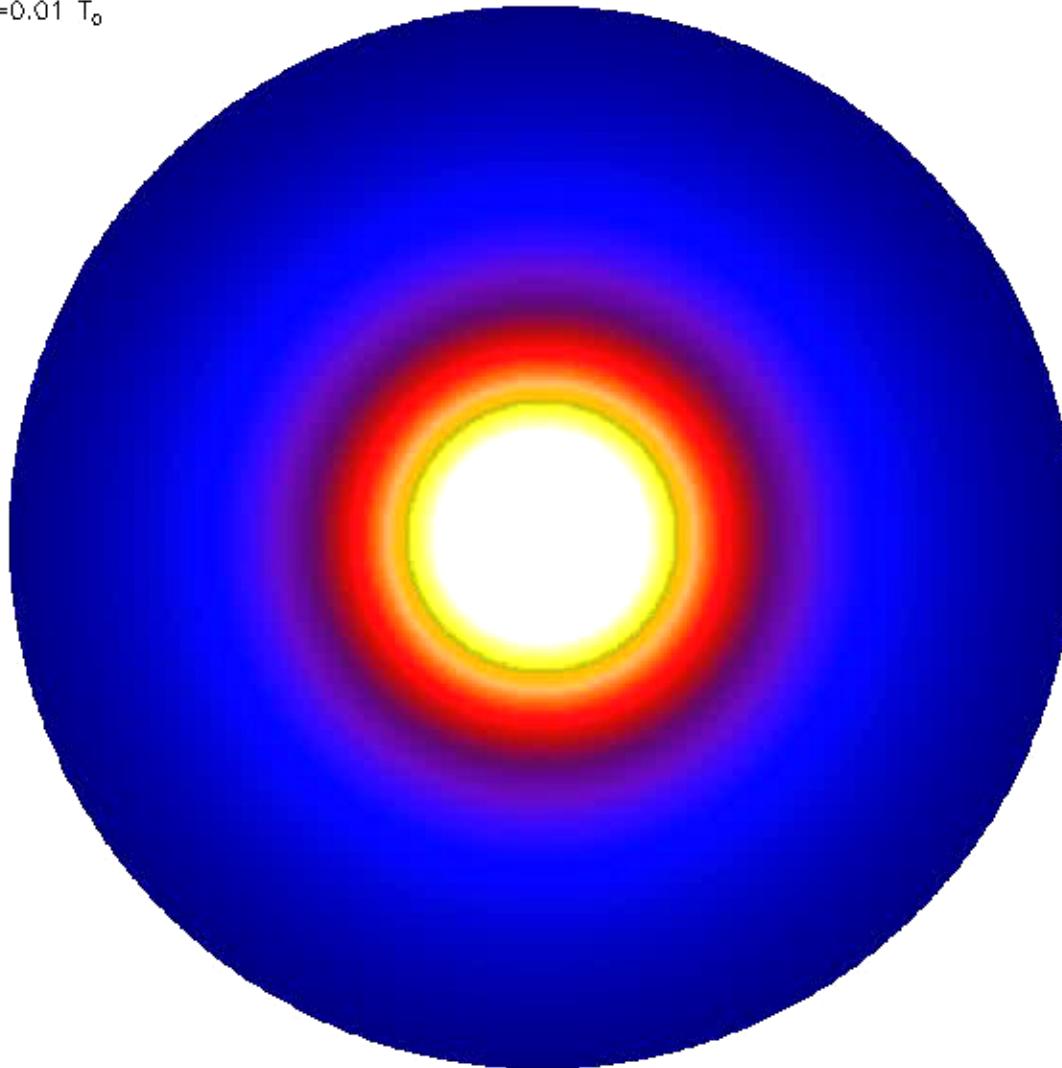
(or... Kelvin-Helmholtz in rotating disks)



© Brooks Martner

Active/dead zone boundary

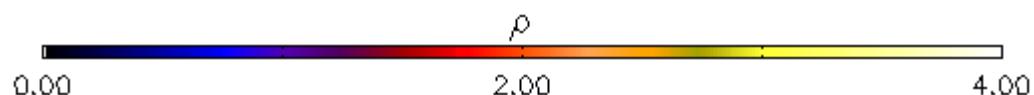
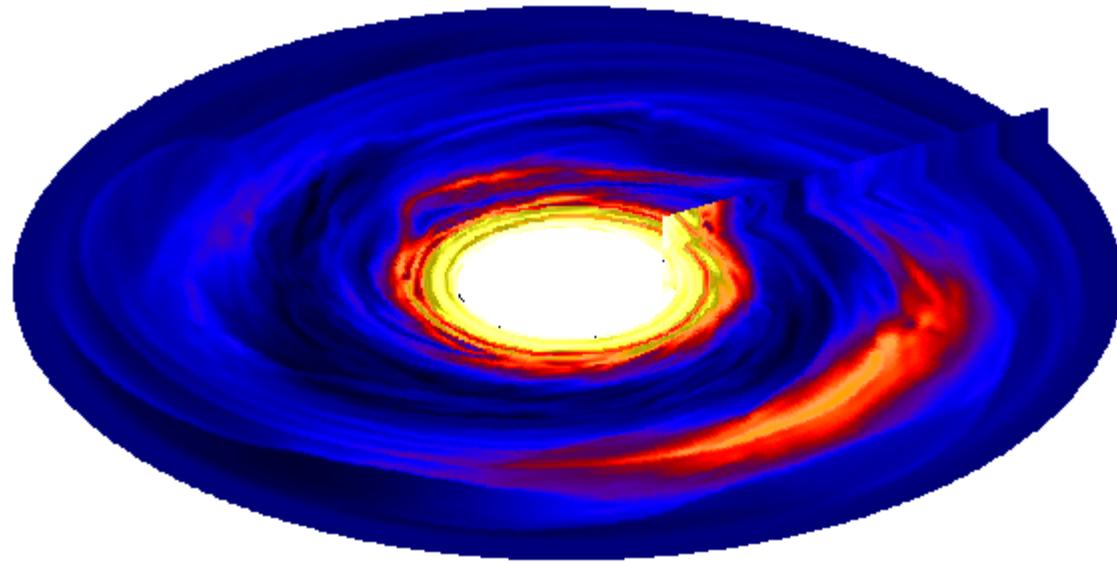
$t=0.01 T_0$



Magnetized inner disk + resistive outer disk
Lyra & Mac Low (2012)

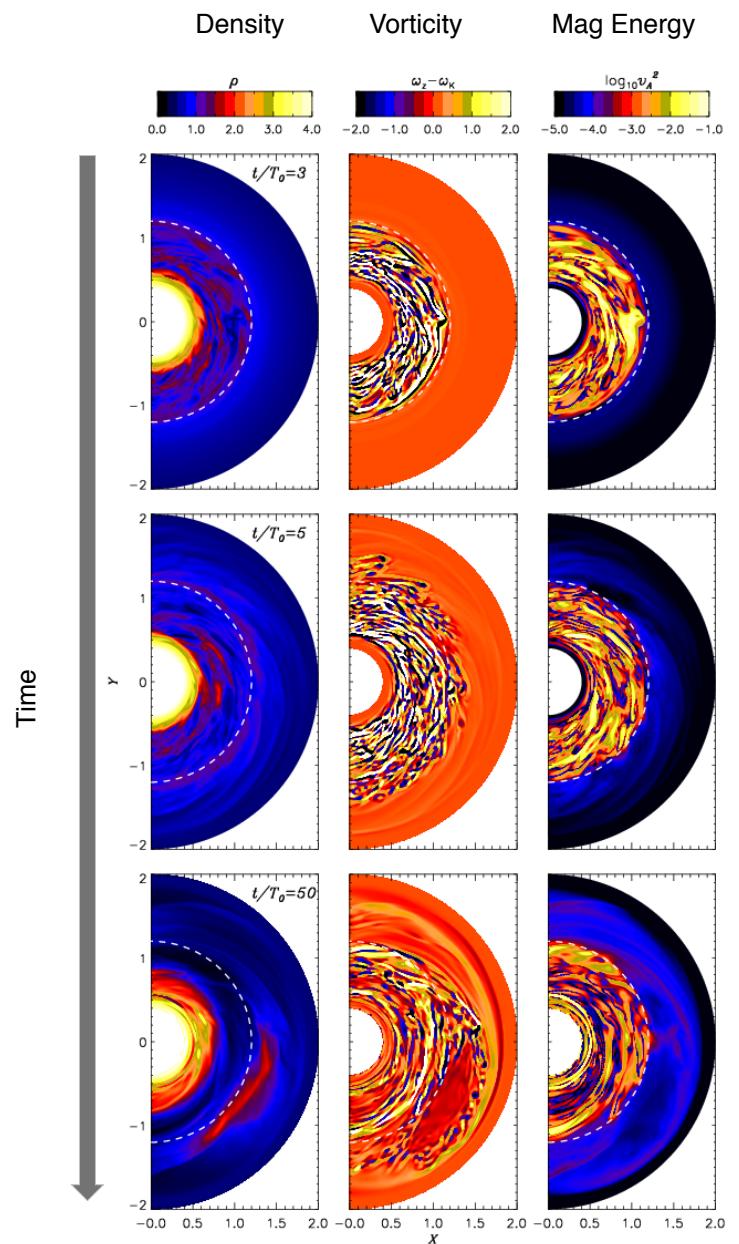
Active/dead zone boundary

$t=22.28 T_0$

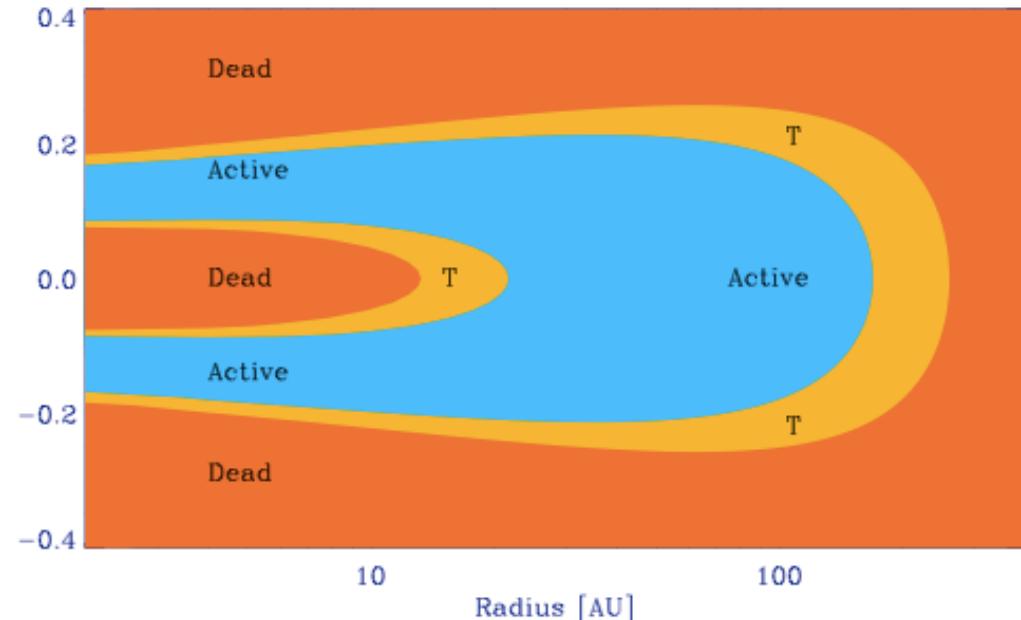
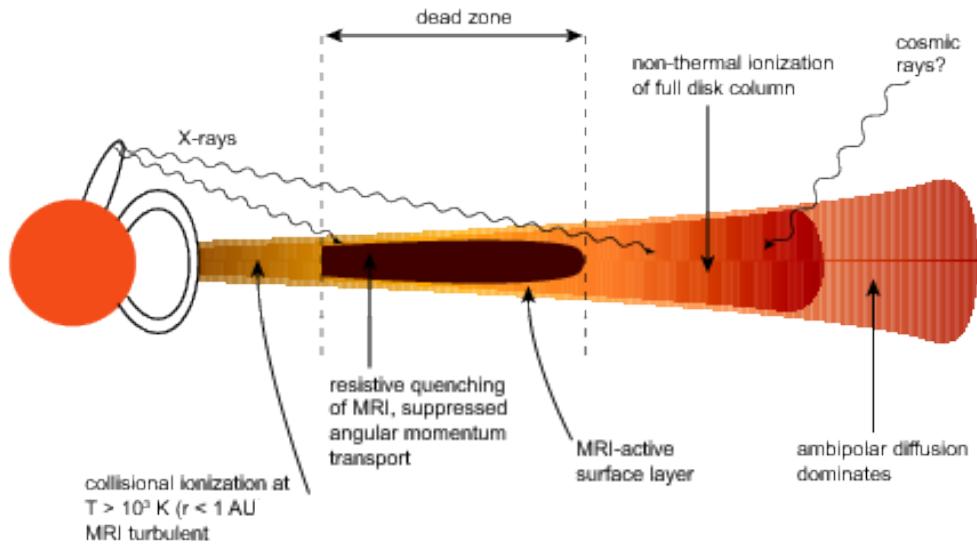


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)



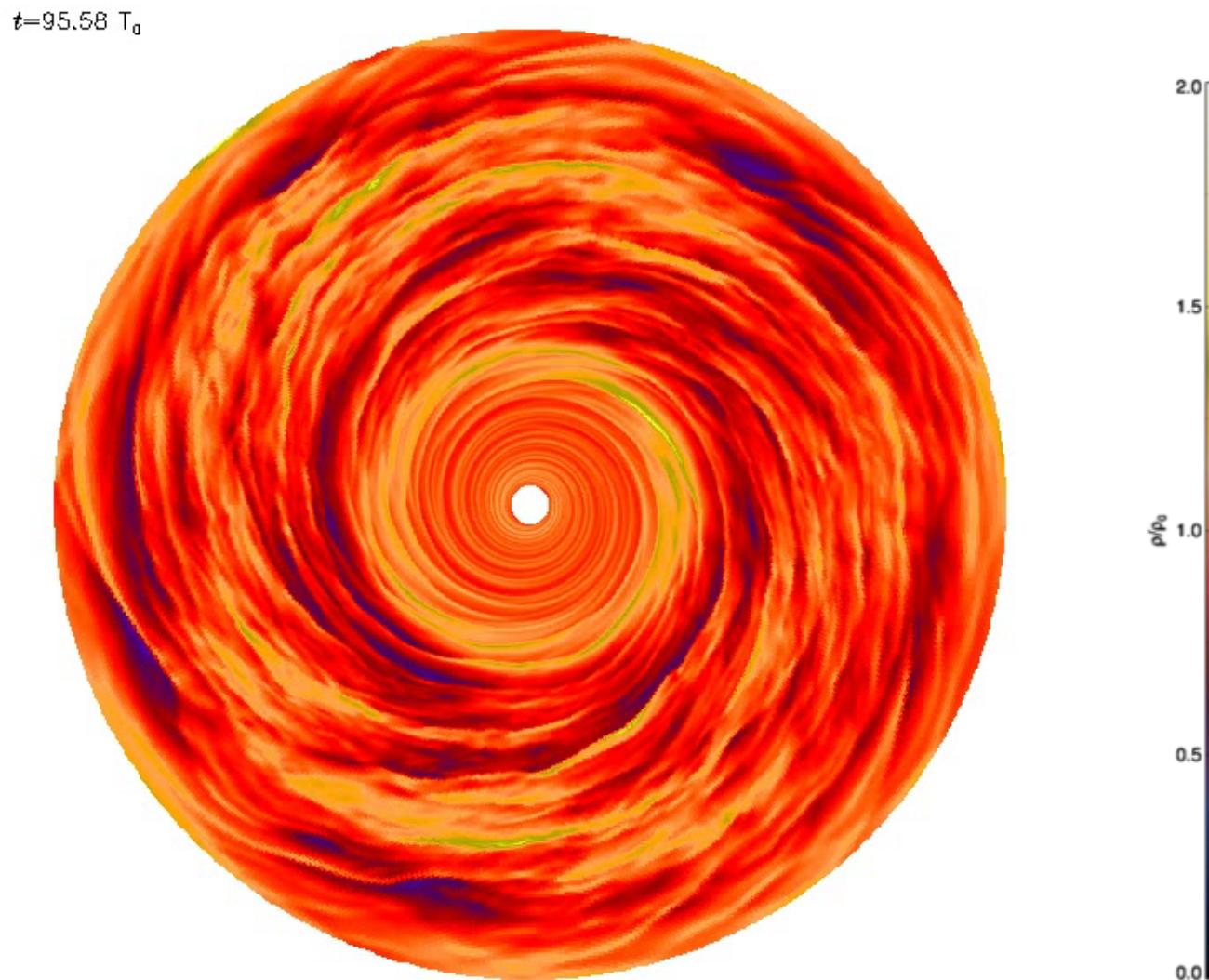
Outer Dead/Active zone transition RWI



Dzyurkevitch et al (2013)

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

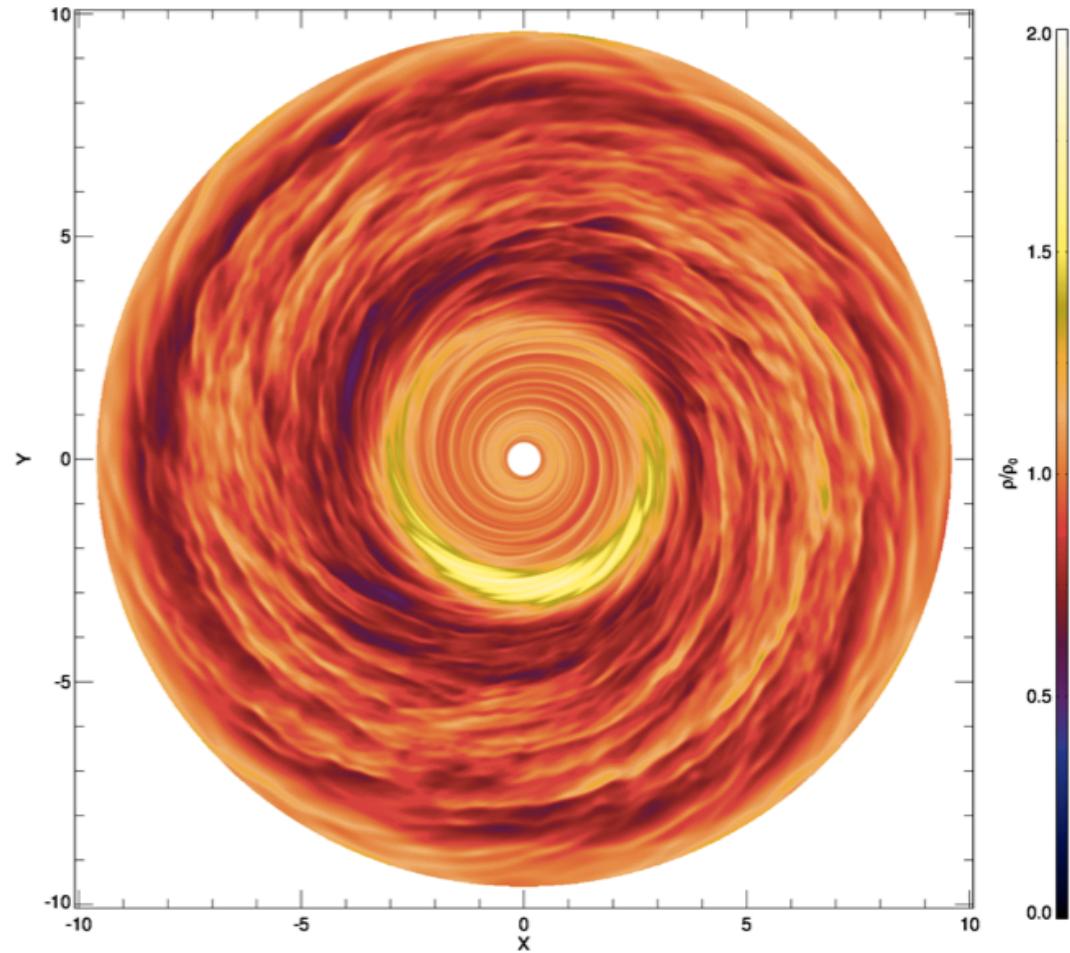
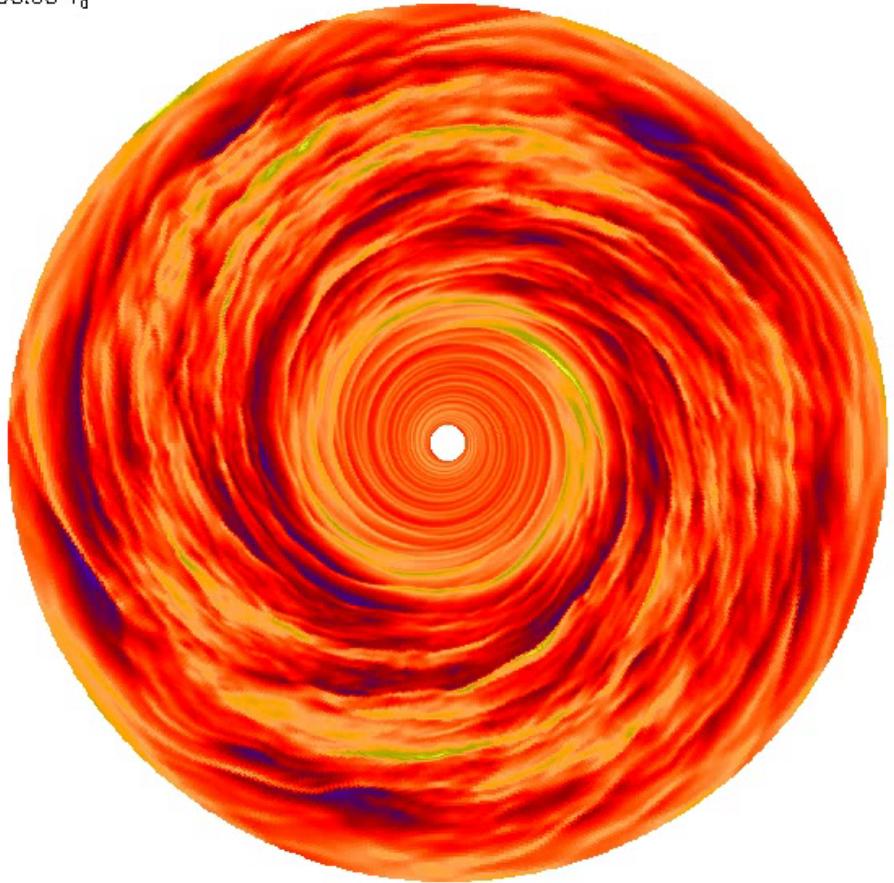
Outer Dead/Active zone transition: 3D MHD



Resistive inner disk + magnetized outer disk
Lyra et al (2015)

Outer Dead/Active zone transition RWI

$t=95.58 T_0$

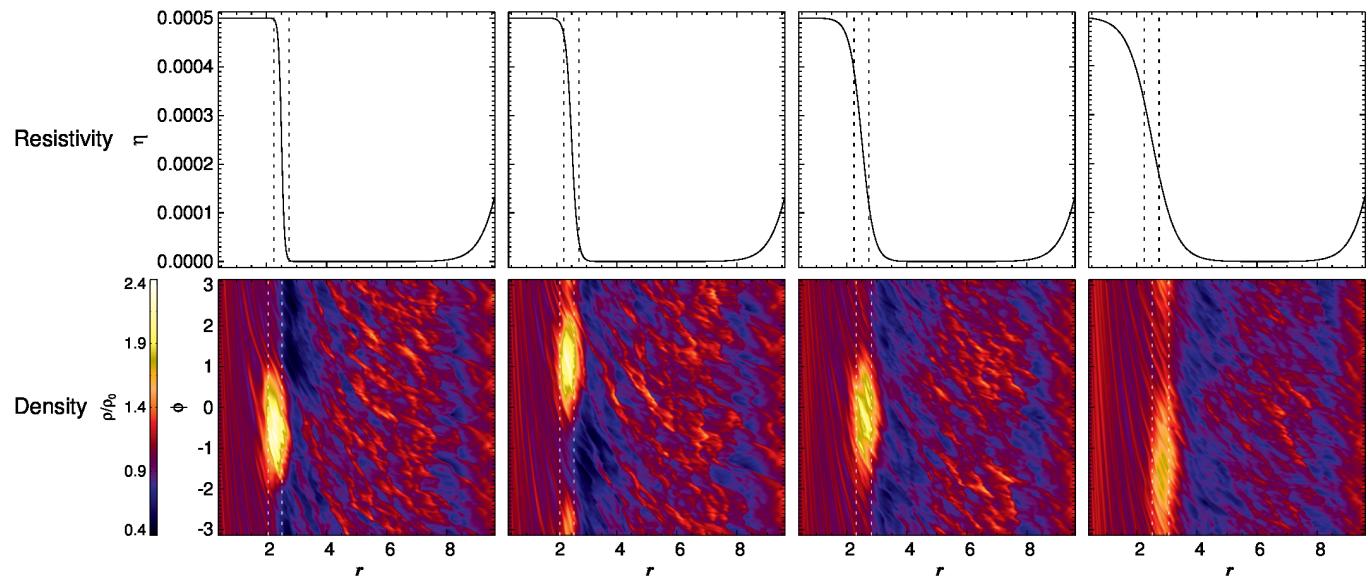


Resistive inner disk + magnetized outer disk

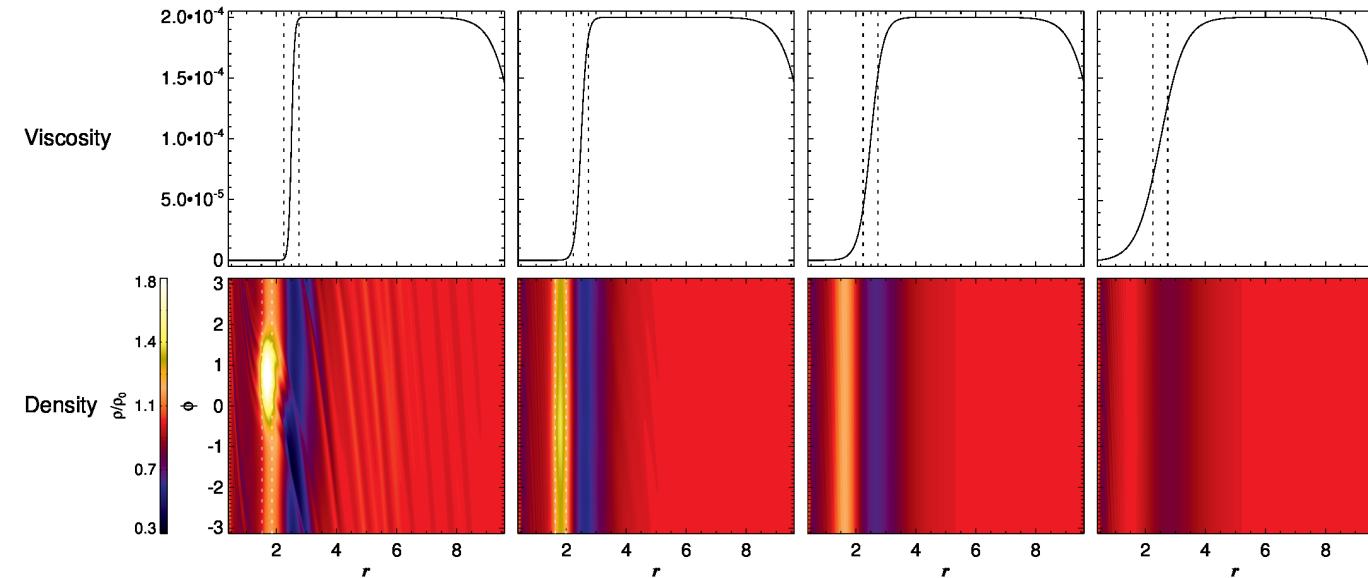
Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI

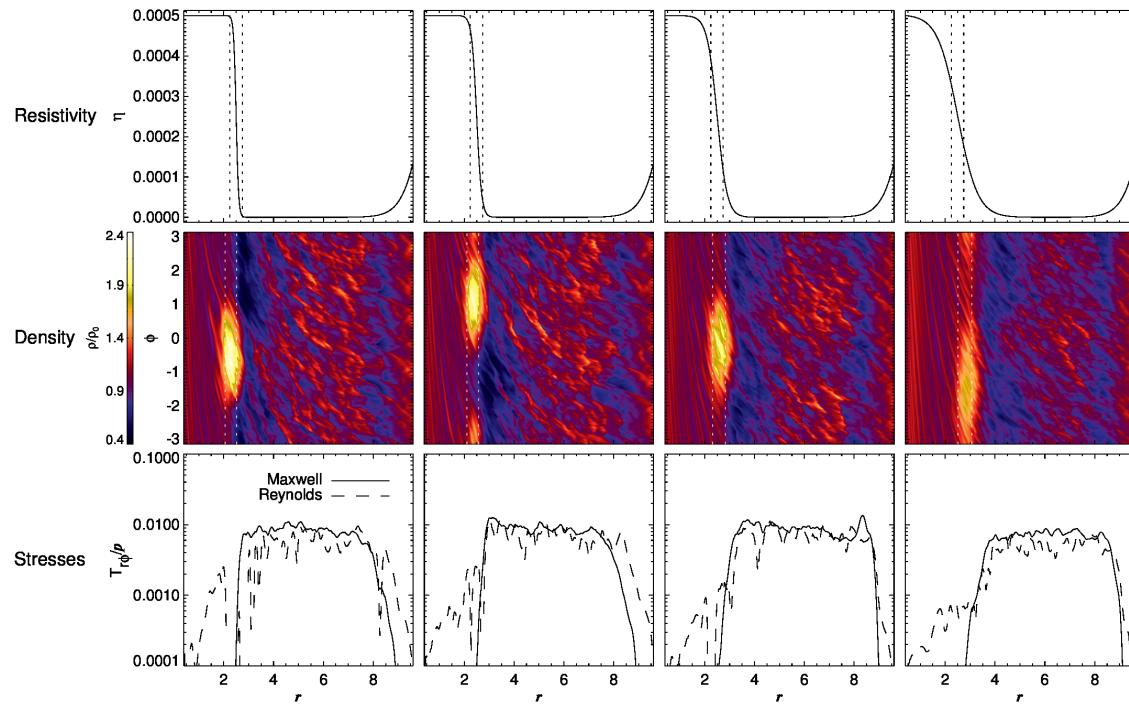
MHD



Hydro



Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

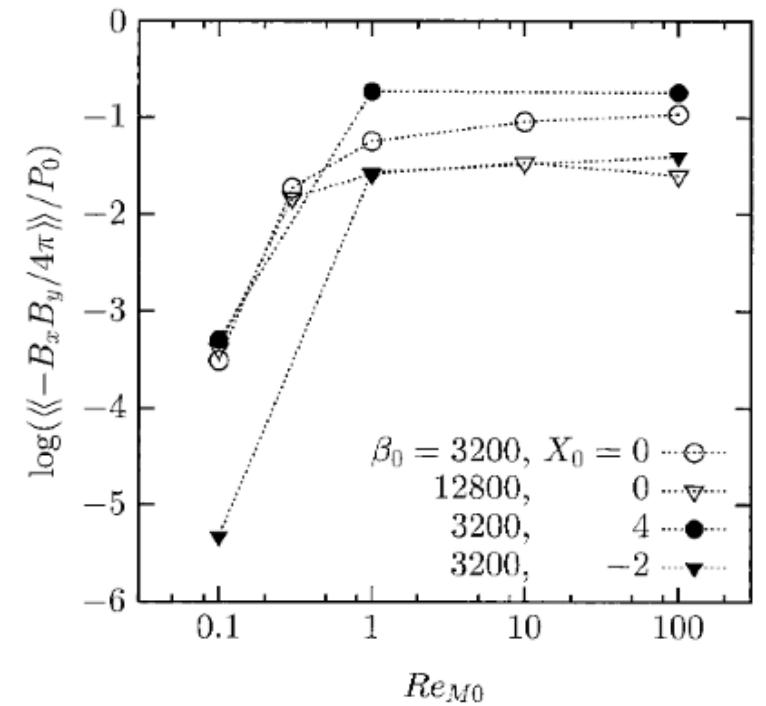


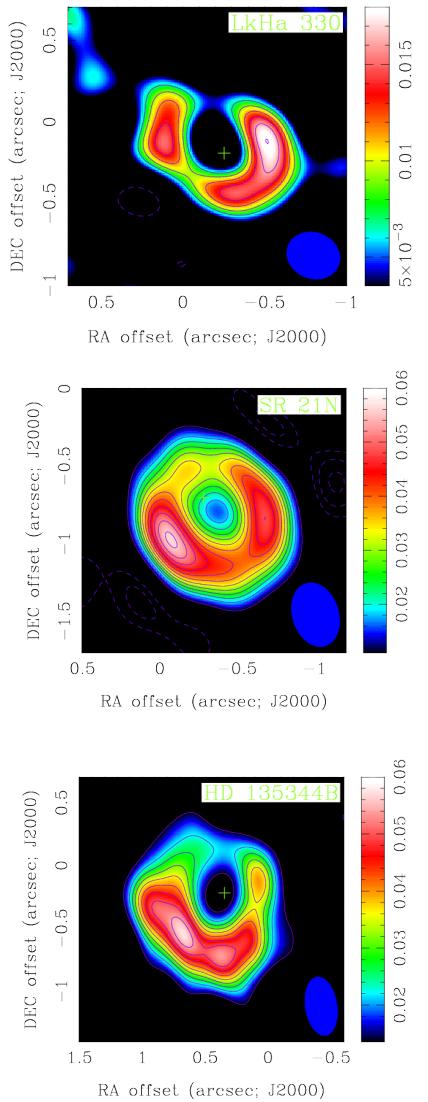
FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number Re_{M0} . Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and triangles ($X_0 = -2$).

Sano and Stone (2002)

A possible detection of vortices in disks?

Observations

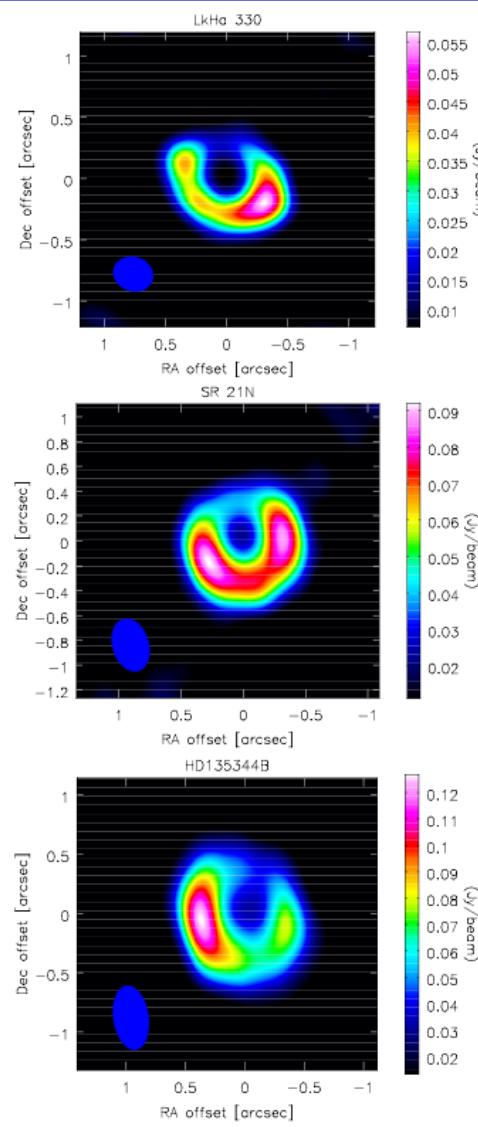
Brown et al. (2009)



Models

Simulated observations
of Rossby vortices

Regaly et al. (2012)



Oph IRS 48

Down



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 Geers⁷

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 forma-

tion mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

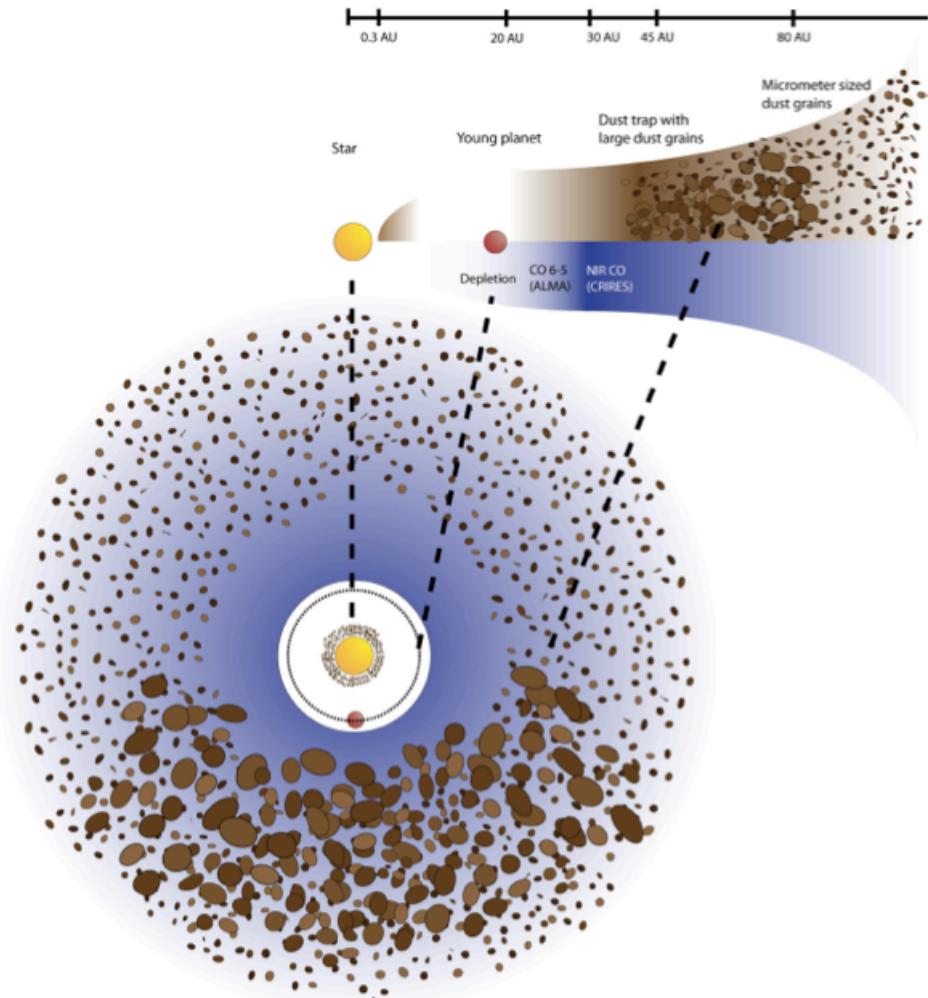
iencemag.org SCIENCE VOL 340 7 JUNE 2013

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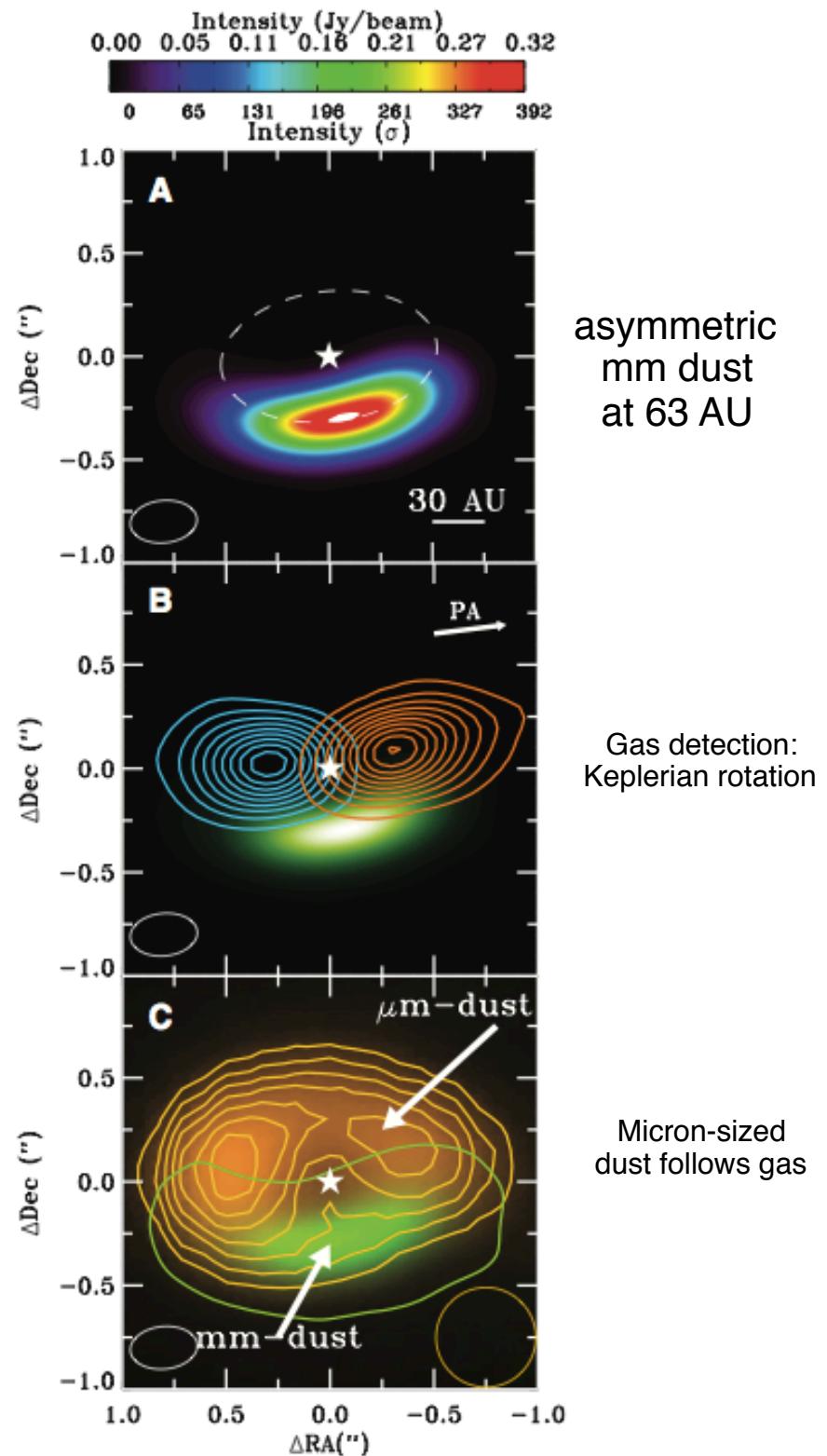
van der Marel et al. 2013

A possible huge vortex observed with ALMA

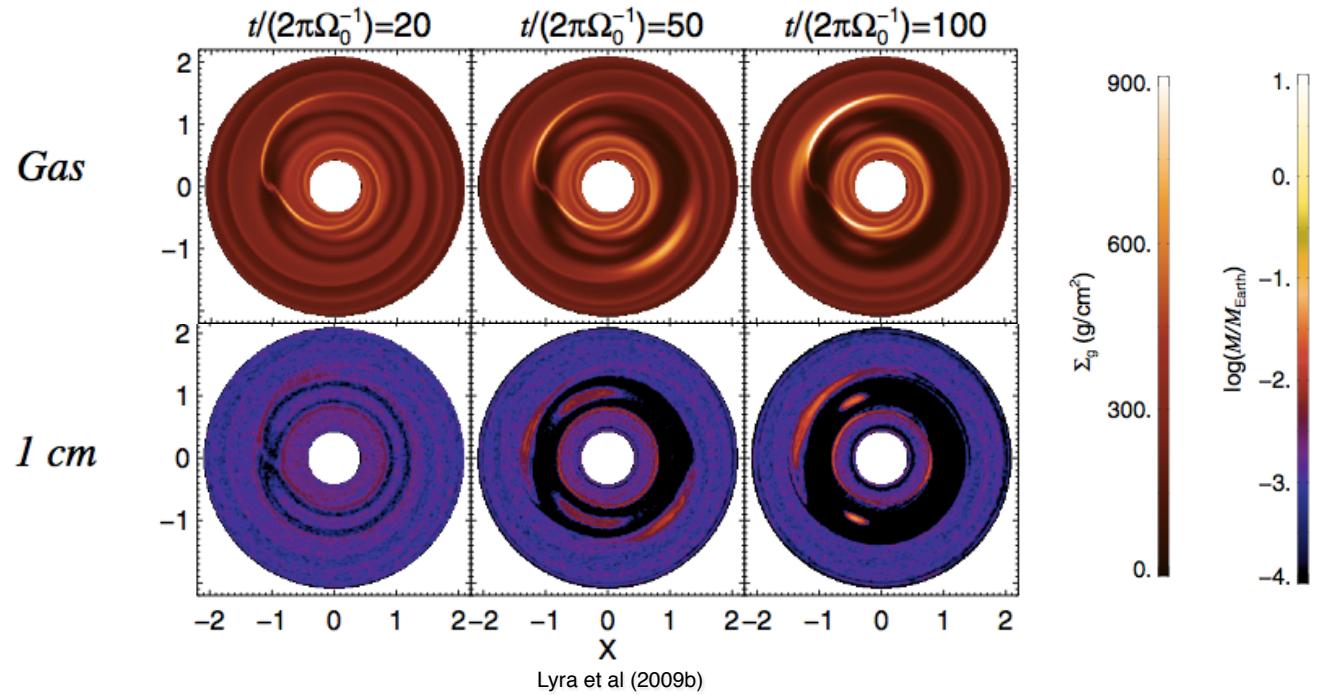
The Oph IRS 48 “dust trap”



van der Marel et al. (2013)

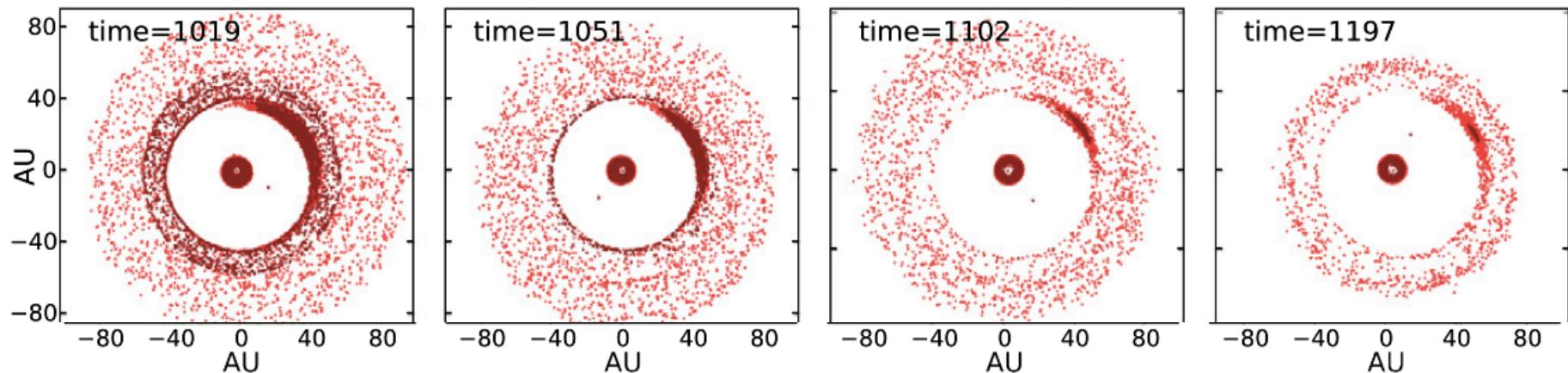


Dust Trapping



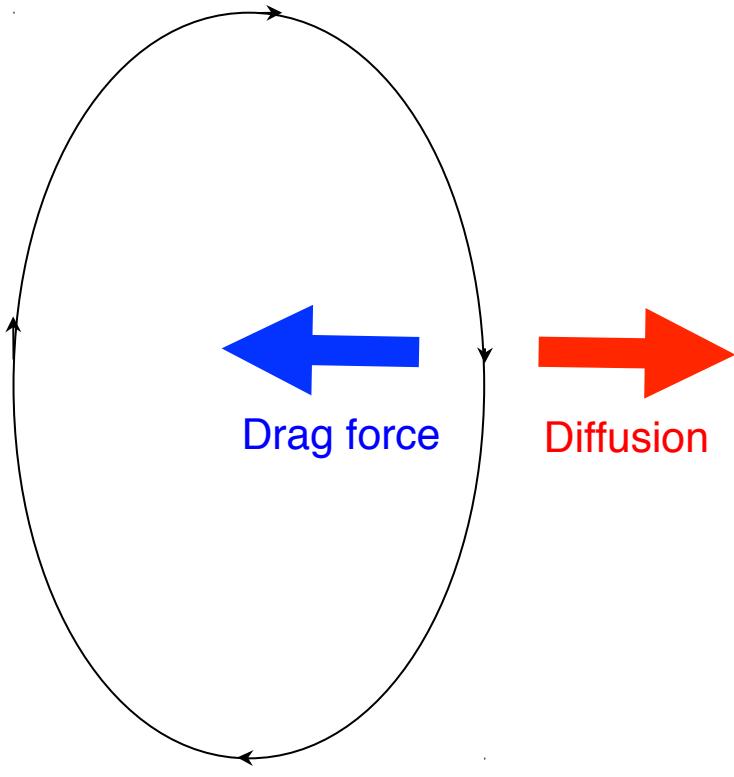
Lyra et al (2009b)

Turbulent “kicks” lead to steady state



Ataiee et al. (2013)

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

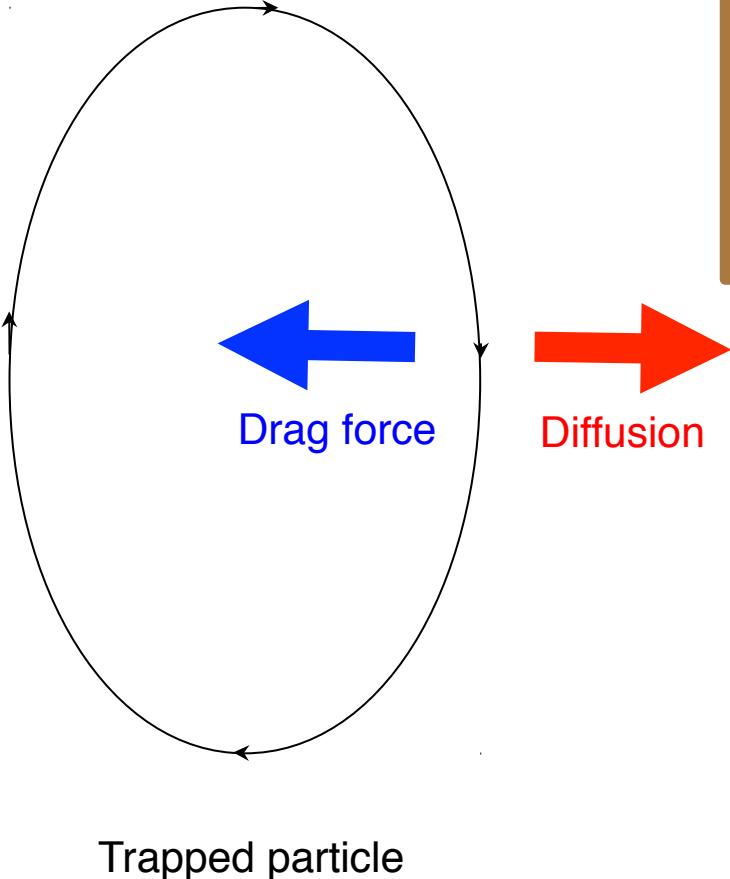
$$\frac{\partial \rho_d}{\partial t} = -(\mathbf{v} \cdot \nabla) \rho_d - \rho_d \nabla \cdot \mathbf{v} + D \nabla^2 \rho_d,$$

advection

compression

diffusion

Drag-Diffusion Equilibrium



Steady-state solution

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

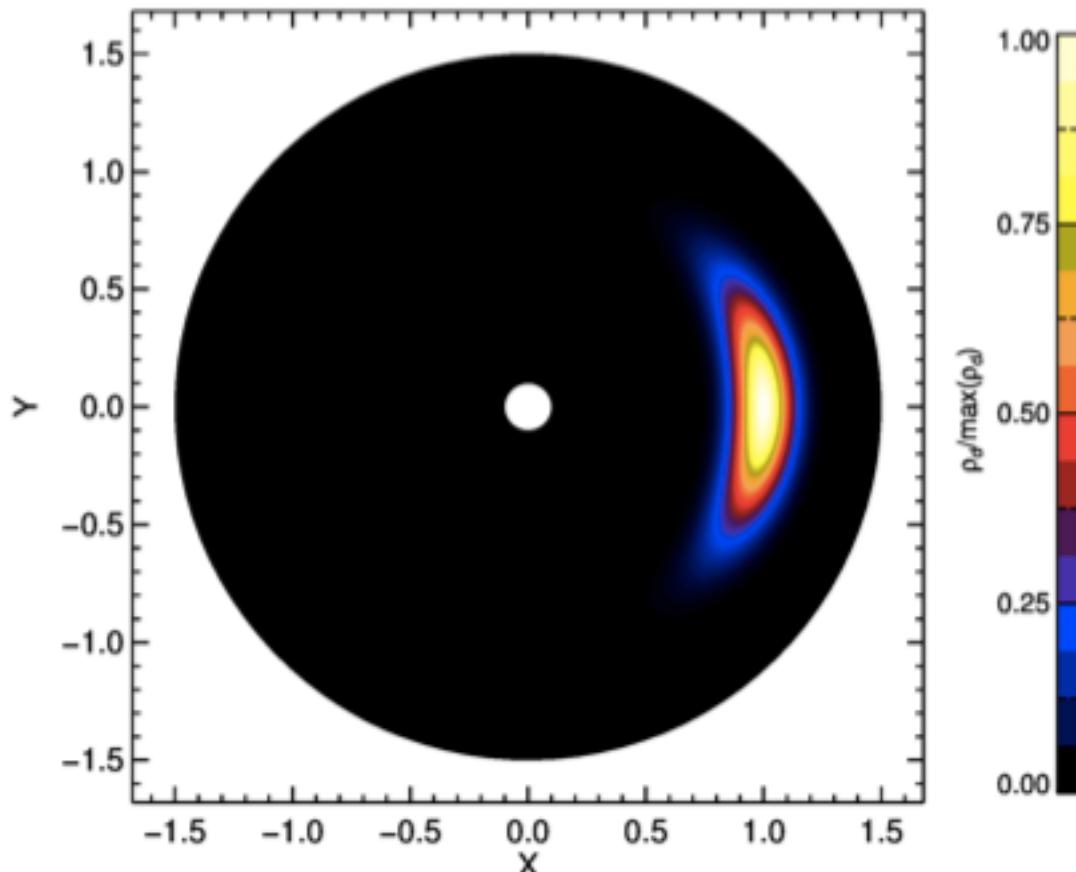
Lyra & Lin (2013)

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

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

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

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

Solution

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

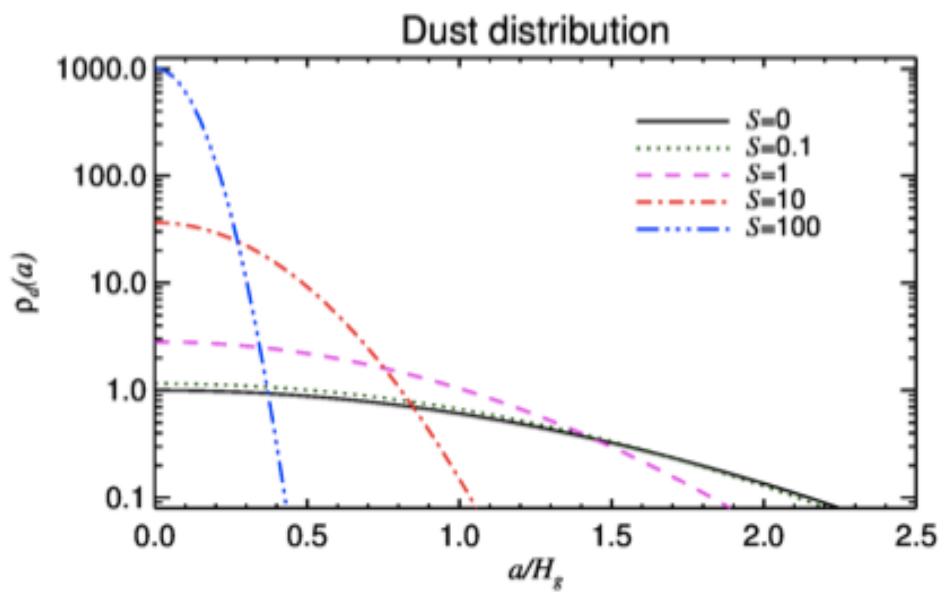
$$H_V = \frac{H}{f(\chi)} \sqrt{\frac{1}{S+1}}$$

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

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

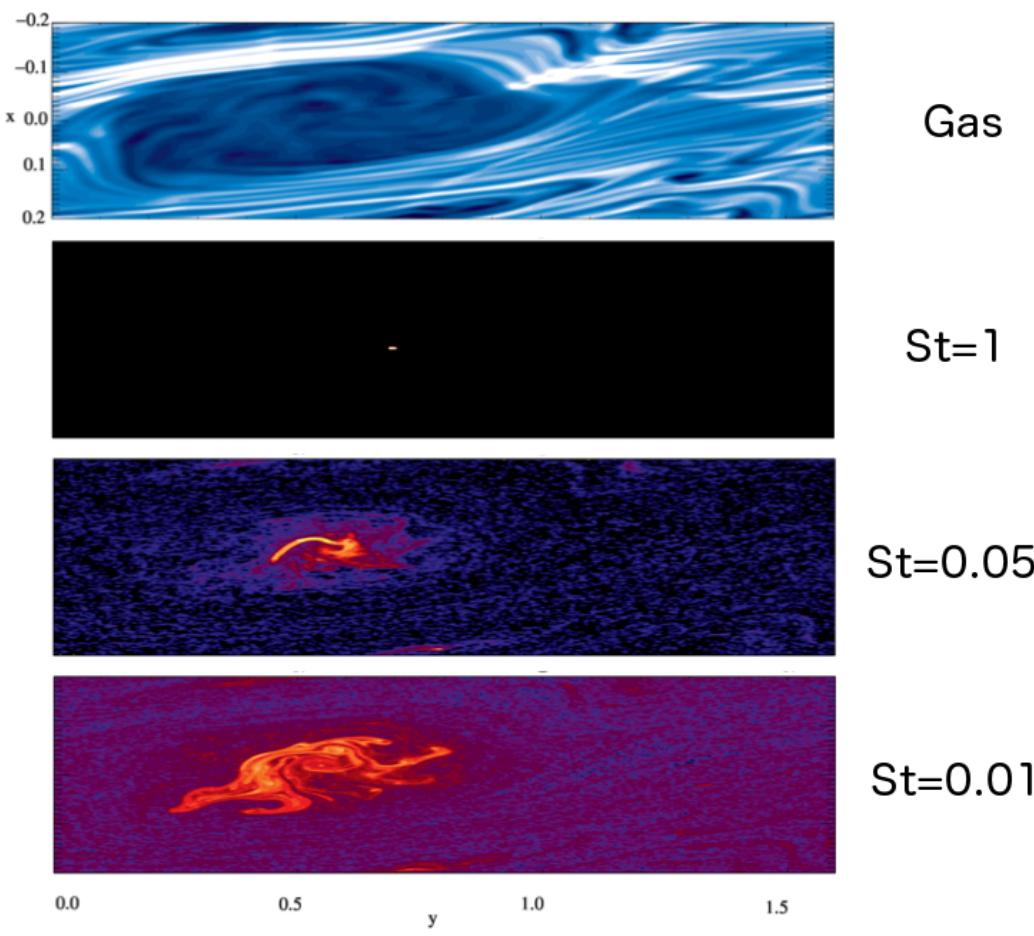
- a = vortex semi-minor axis
 H = disk scale height (temperature)
 χ = vortex aspect ratio
 δ = diffusion parameter
St = Stokes number (particle size)
 $f(\chi)$ = model-dependent scale function

Analytical vs Numerical



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

Lyra & Lin (2013)



Raettig et al (2015)

Derived quantities

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

Lyra & Lin (2013)

Gas distribution

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

Maximum dust density

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

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

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

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: $9 M_{Earth}$

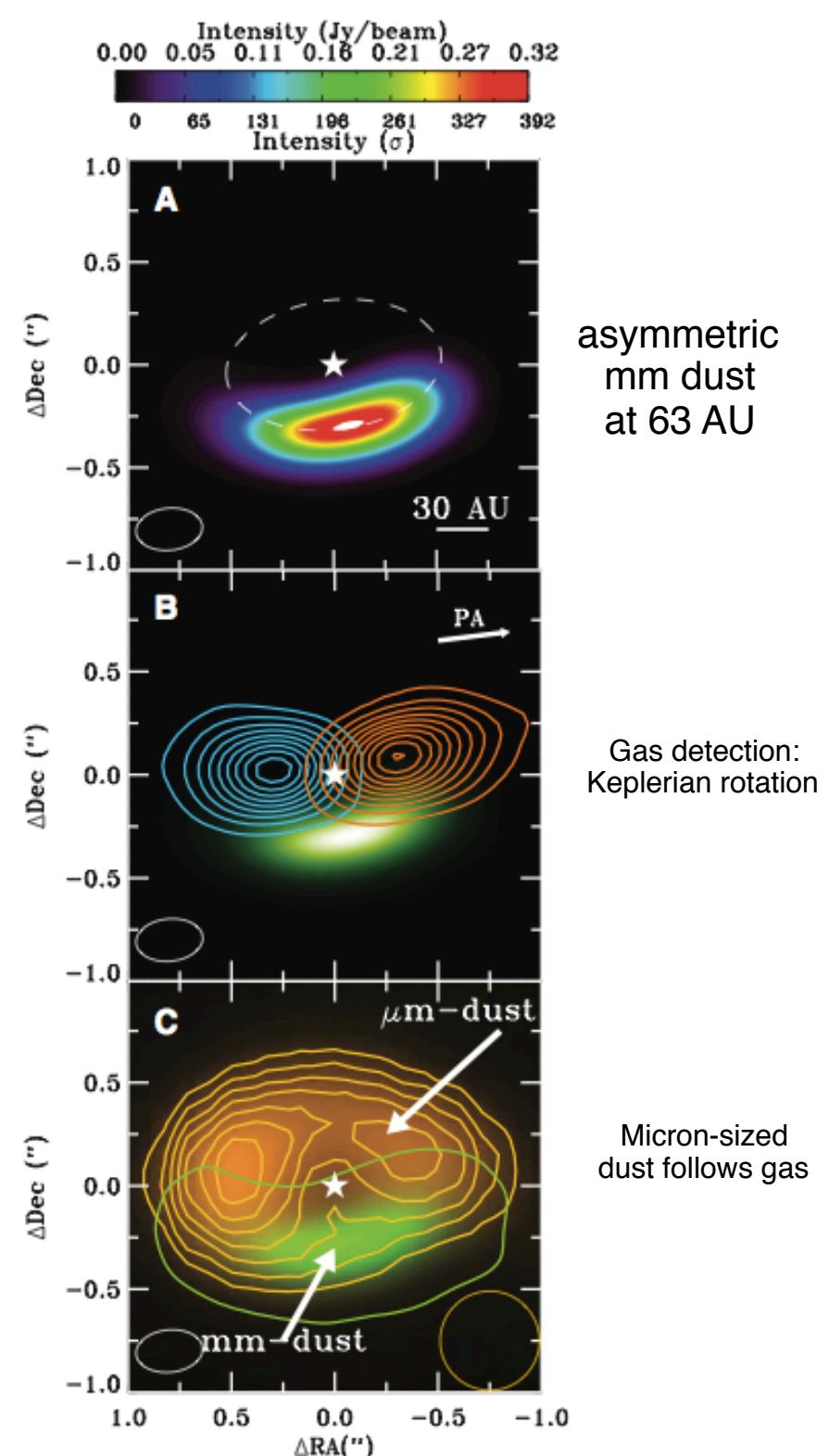
Derived parameters

$S=4.8$

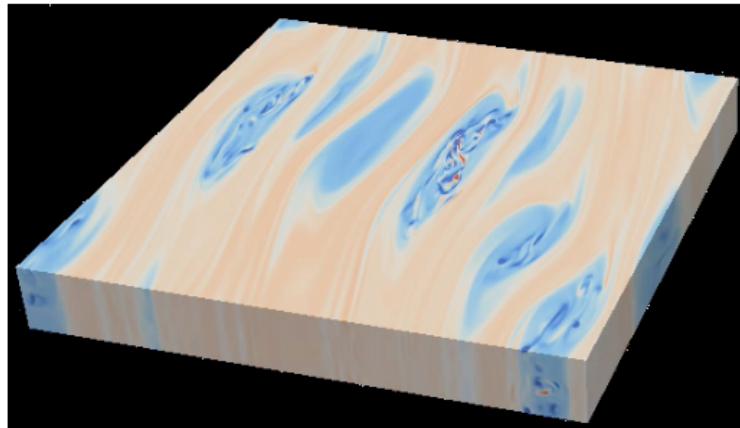
Stokes number, $St=0.008$

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

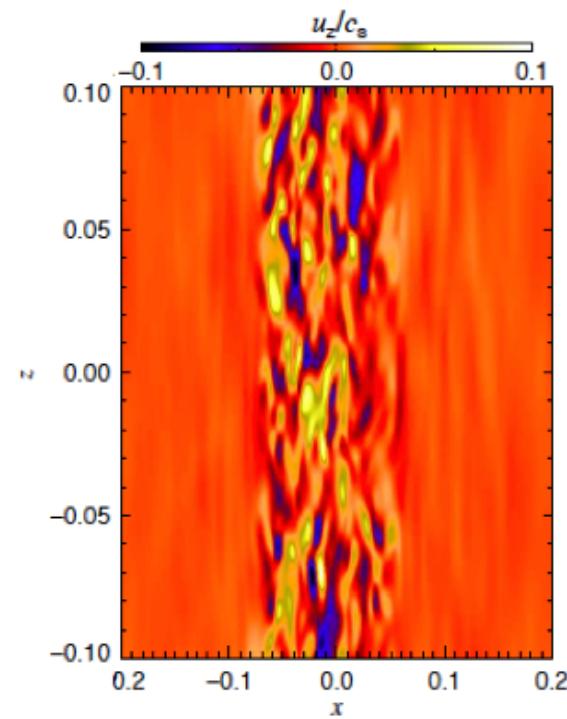
Trapped mass: $11 M_{Earth}$



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

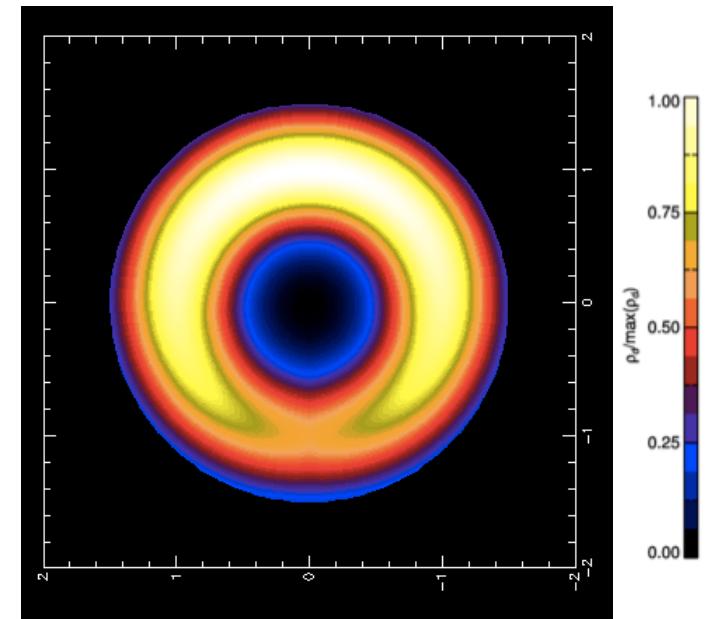
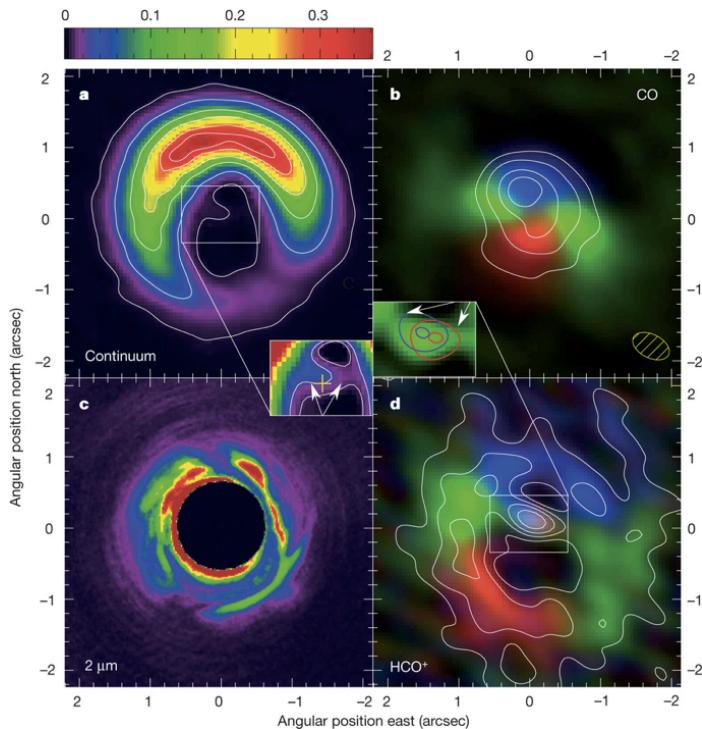
Temperature: 25K

Derived parameters

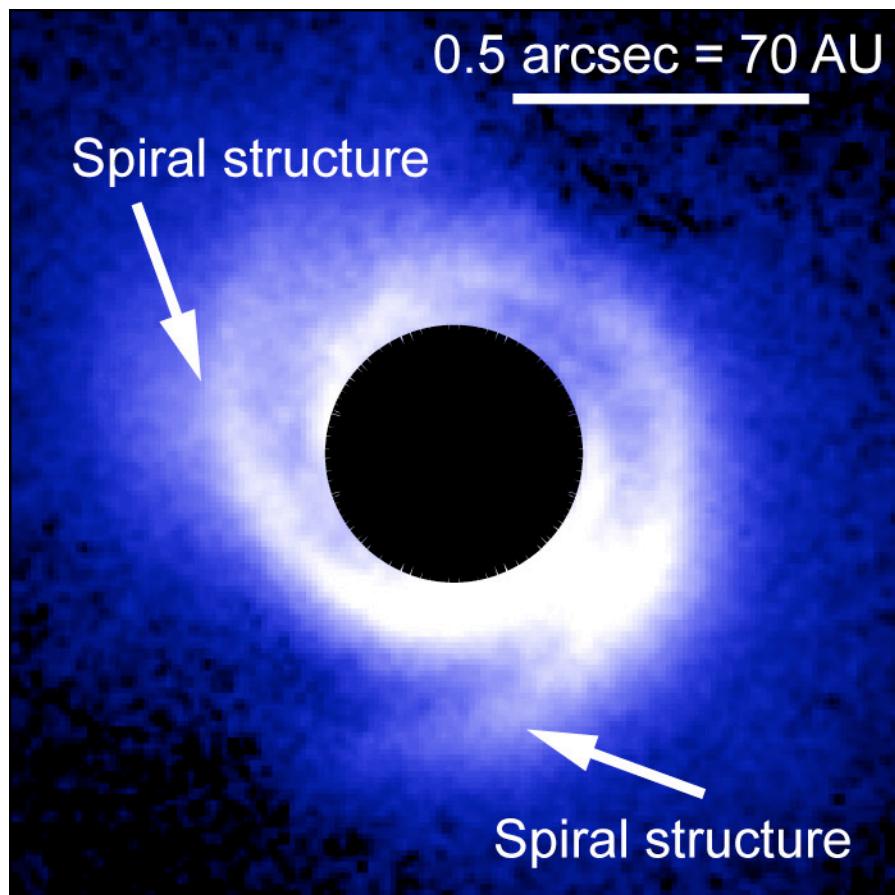
S=3.5

Stokes number, St=0.004

$\delta = 0.001$, $v_{rms} = 4\% Cs$

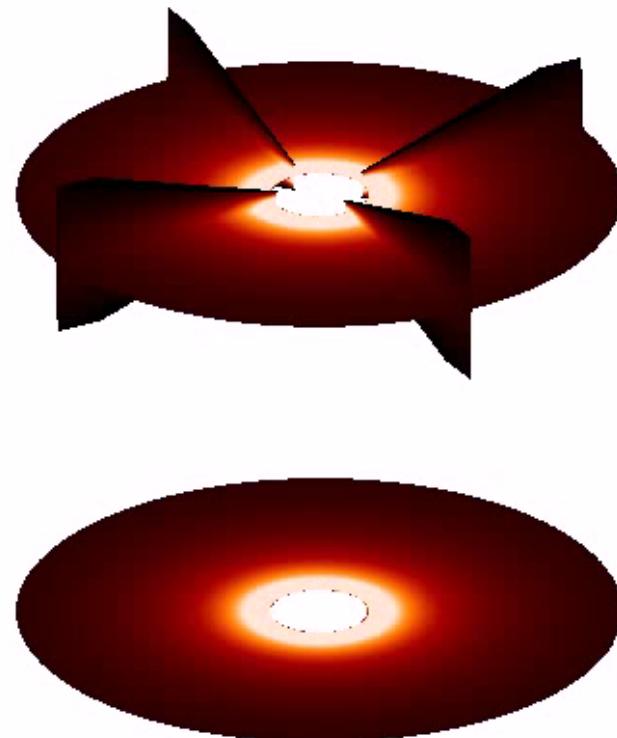


Spirals in transition disks



Muto et al. (2012)

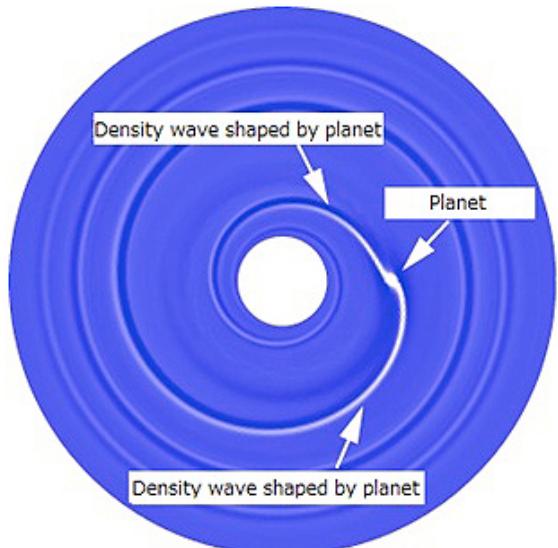
$t = 0.1$



Lyra (2009)

Spiral arm fitting leads to problems

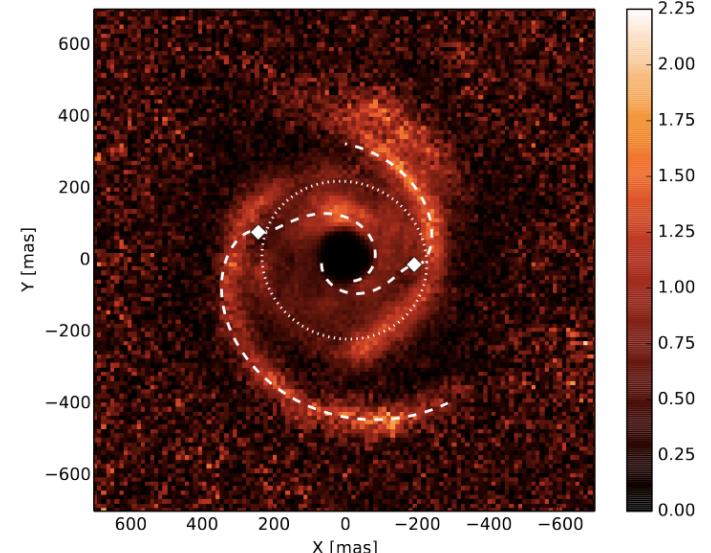
Analytical spiral fit



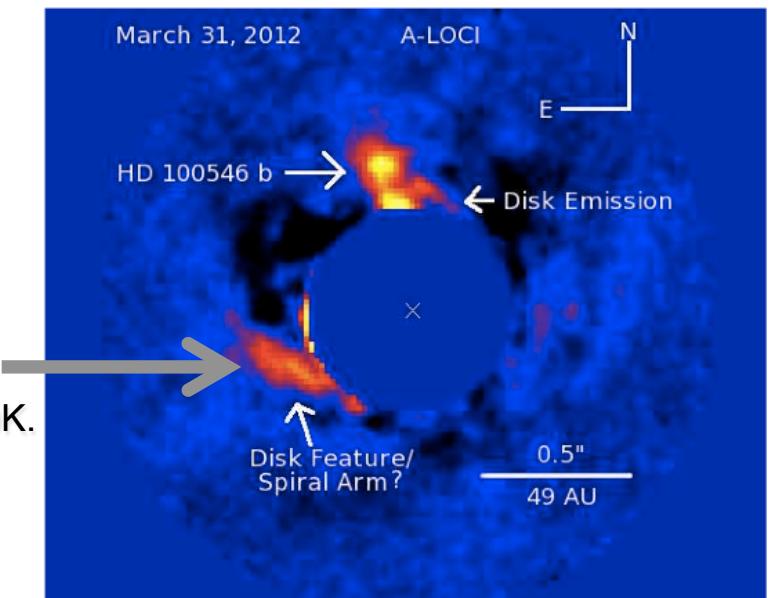
$$\theta(r) = \theta_c + \frac{\text{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c} \right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \left(\frac{r}{r_c} \right)^{-\alpha} \right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \right) \right\},$$

Rafikov (2002)
Muto et al. (2012)

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

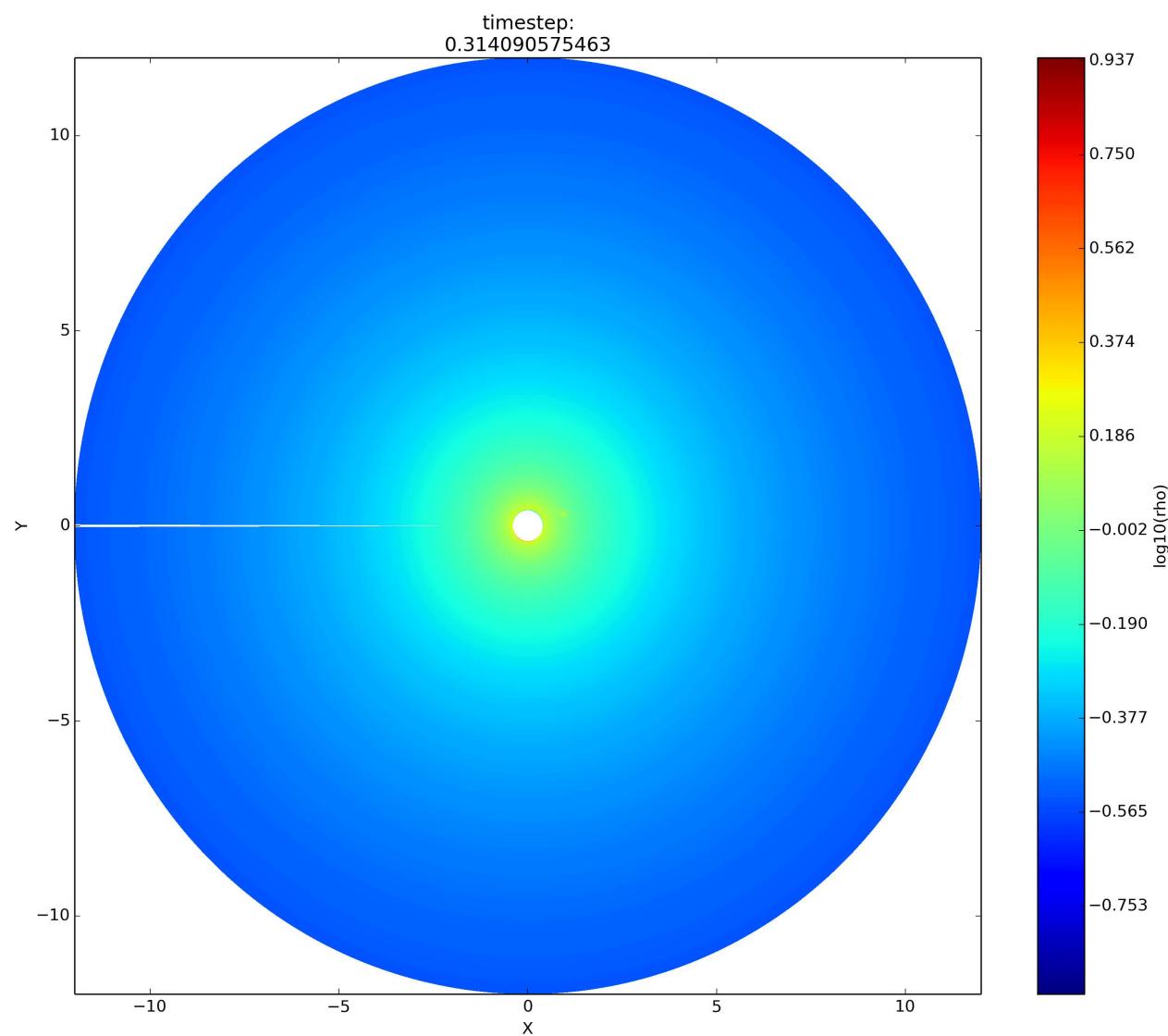


Spiral has little
polarization. Must be
thermal emission at 1000K.



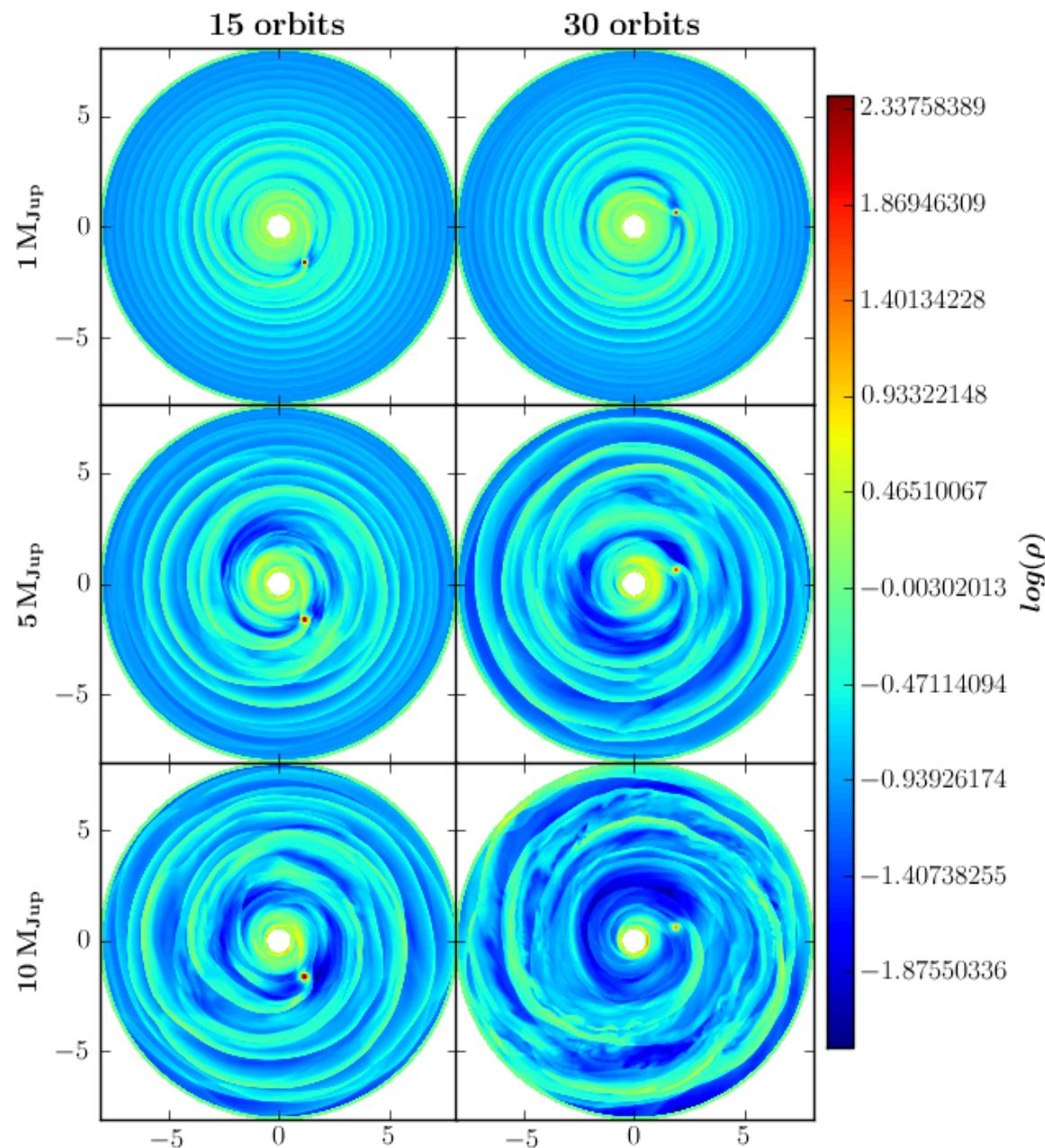
Currie et al. (2014)

Hot spirals

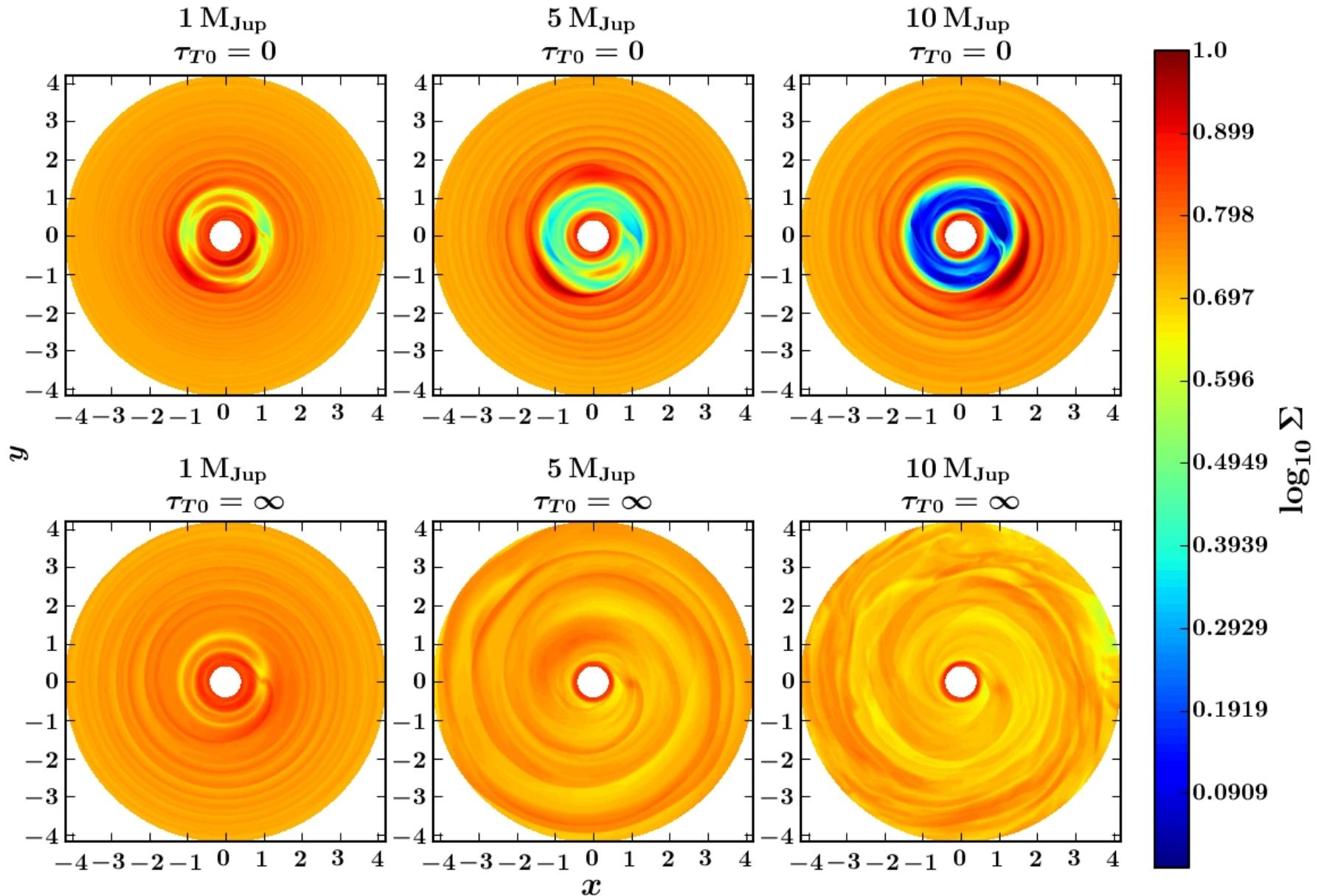


Richert et al. (2015)

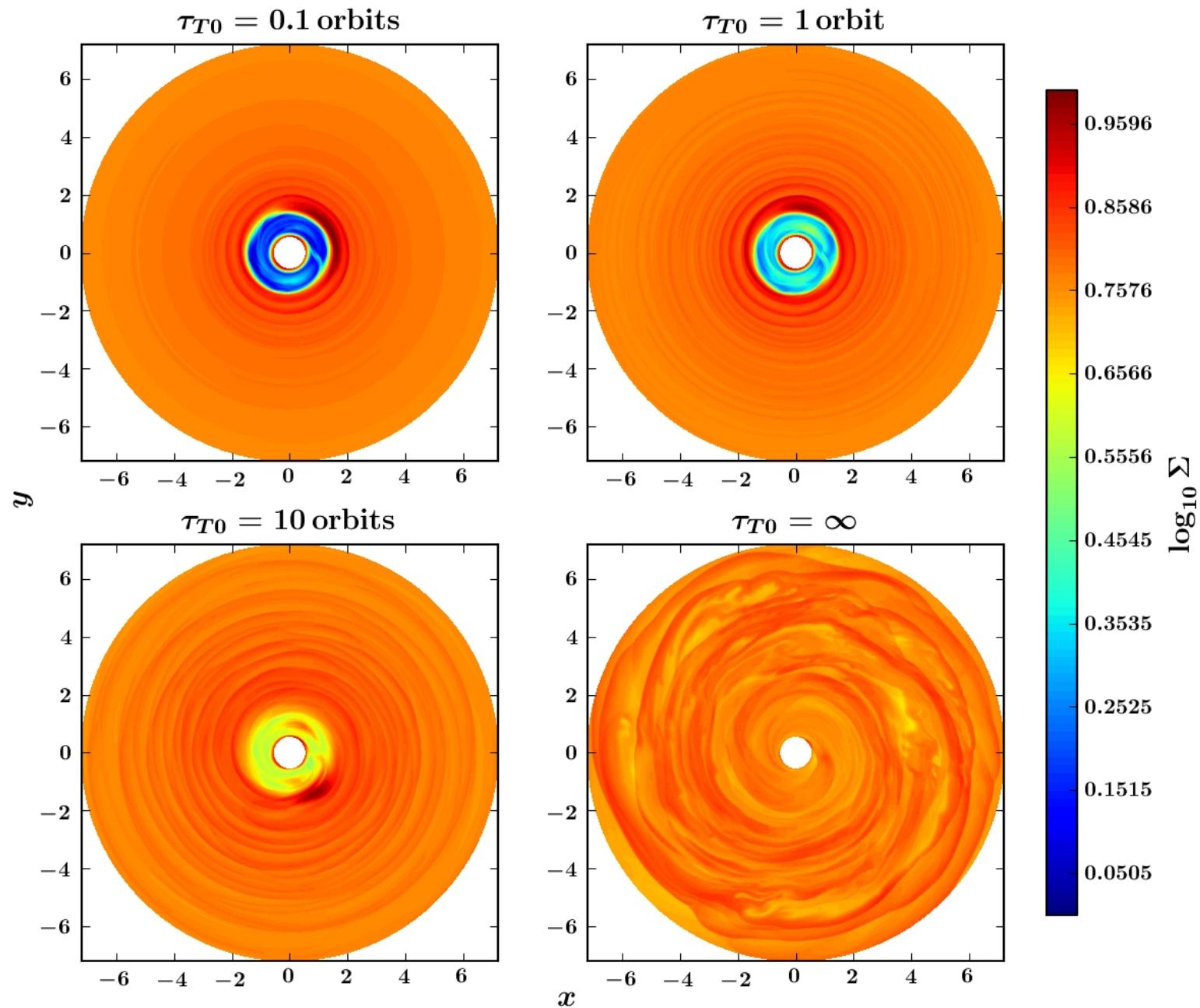
Some crazy turbulence showing up at high planet mass....



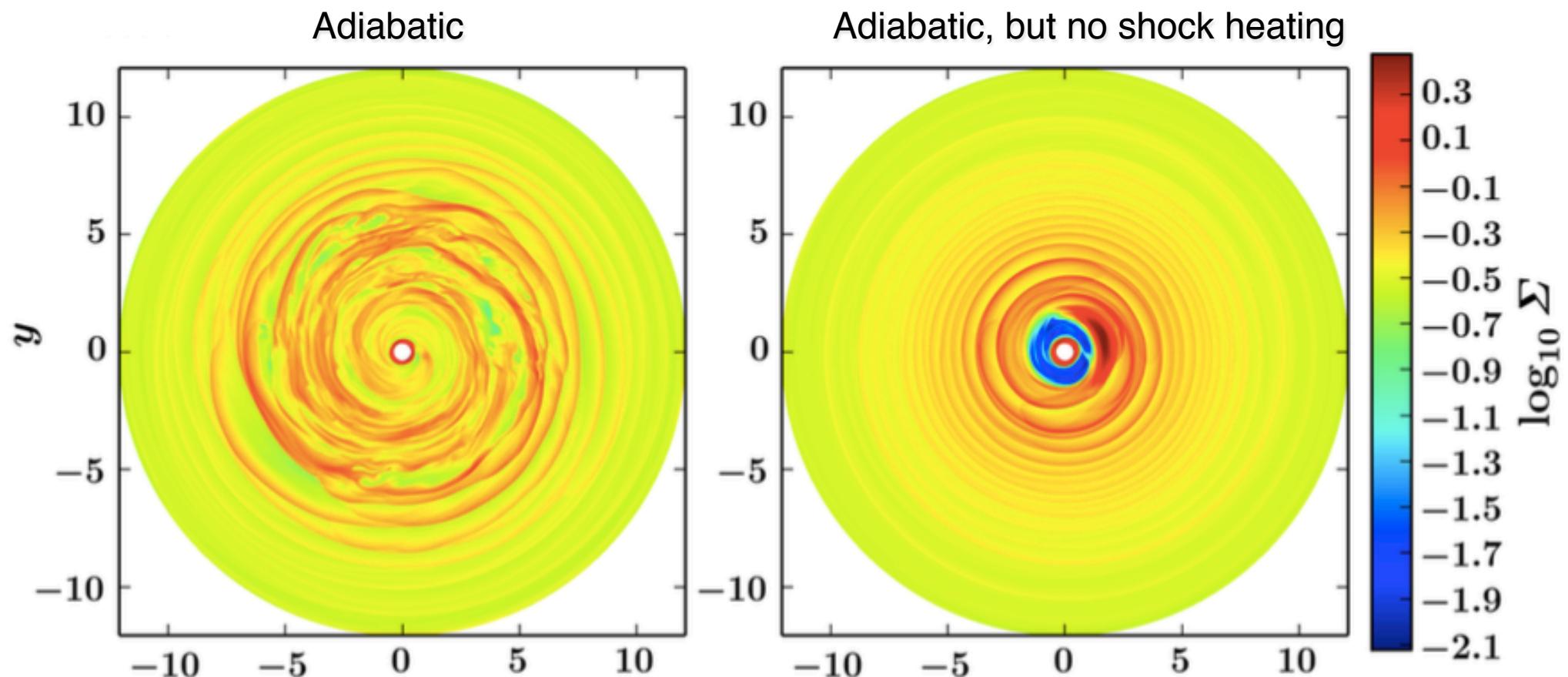
Isothermal vs Adiabatic



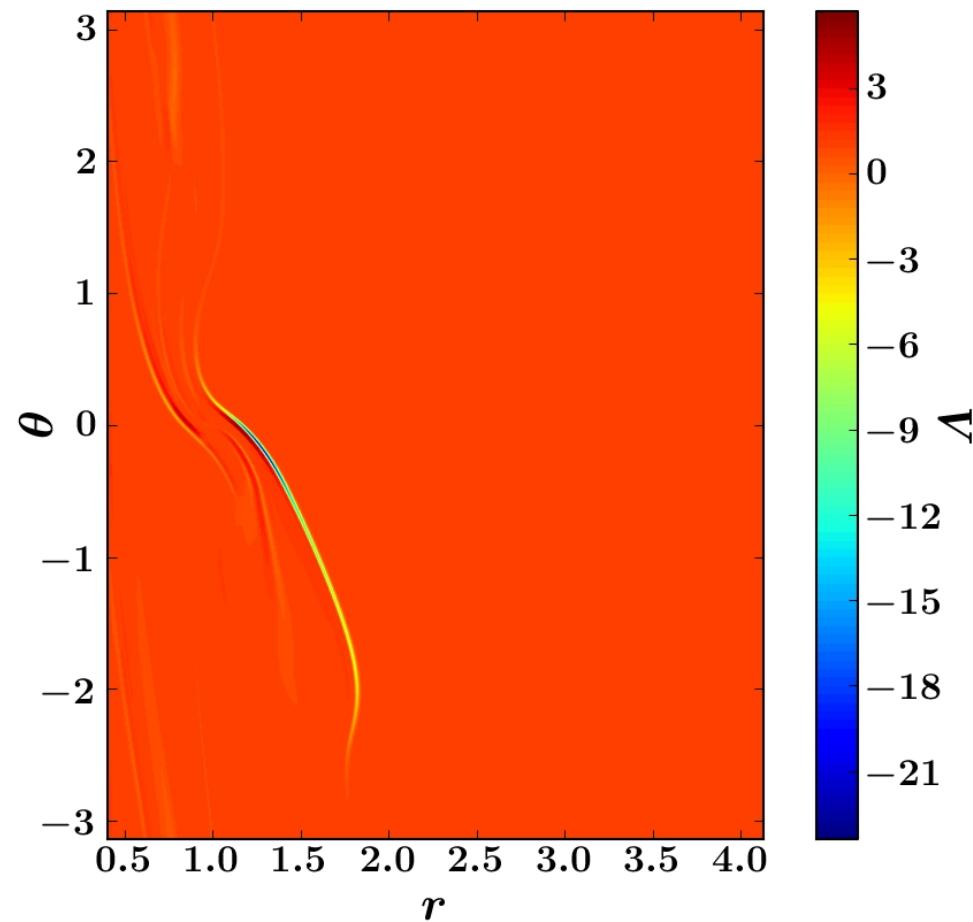
Shows up for long cooling times....



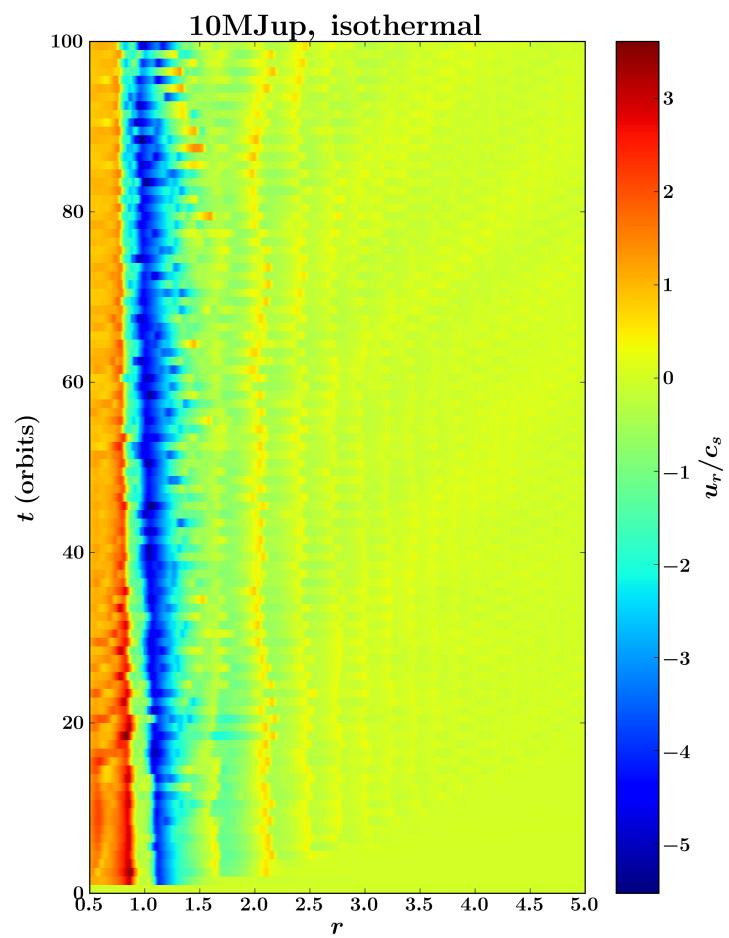
The energy source: shock heating!



The spiral is buoyantly unstable



The spiral has $\text{Ma} > \sim 1$



3D shocks: ascending bores and breaking waves

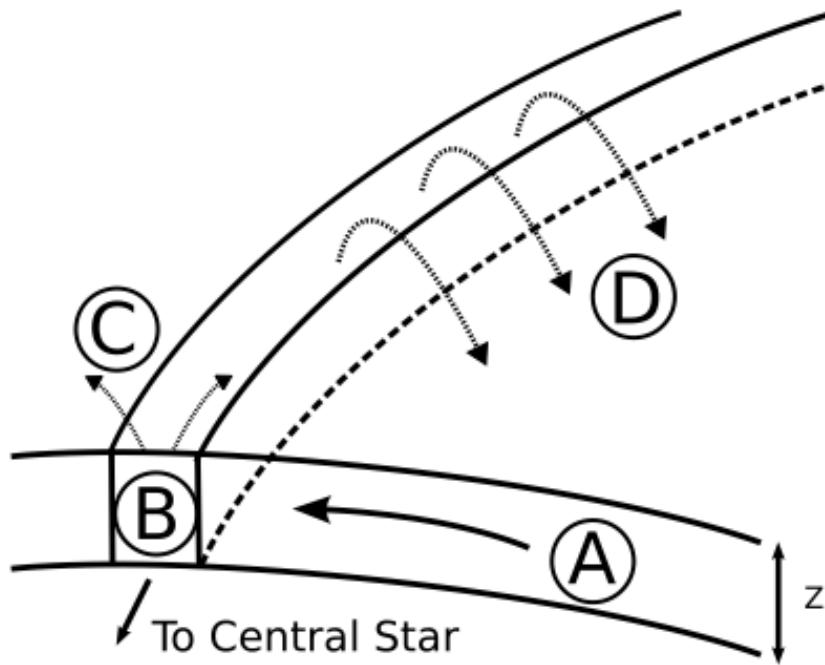
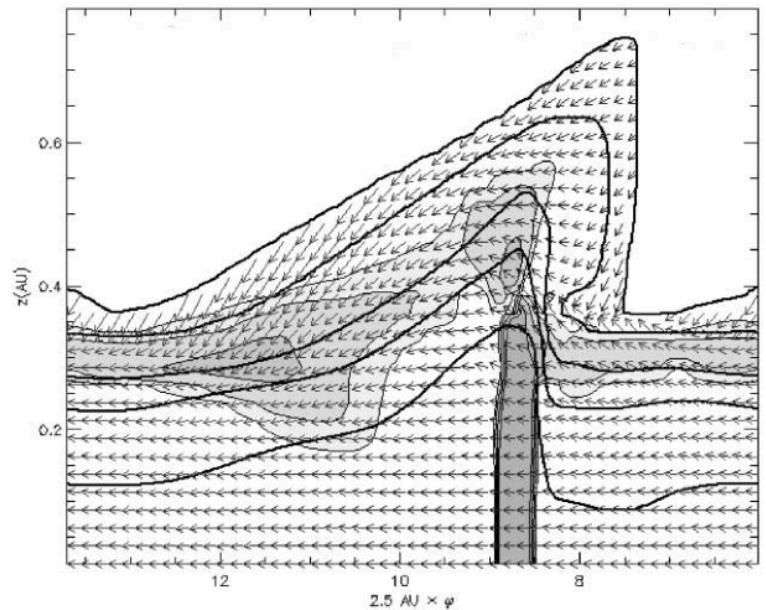
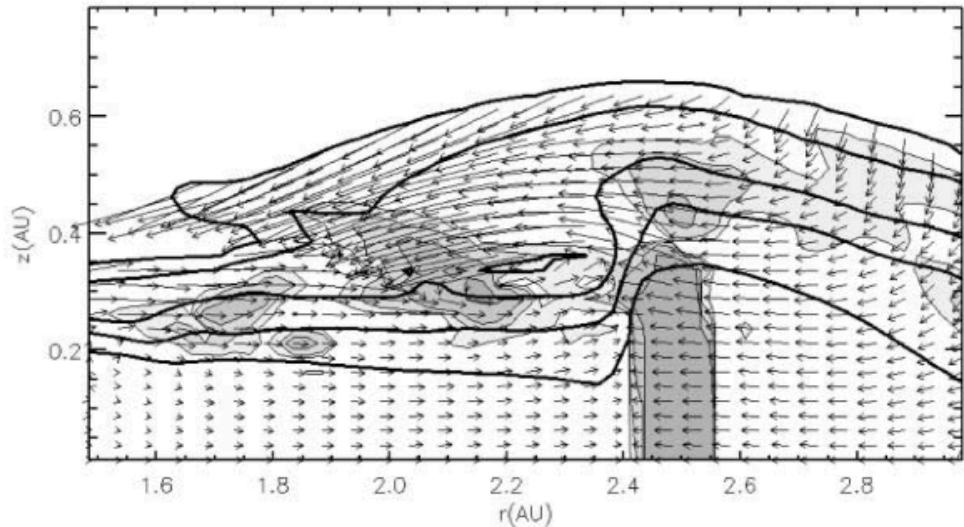
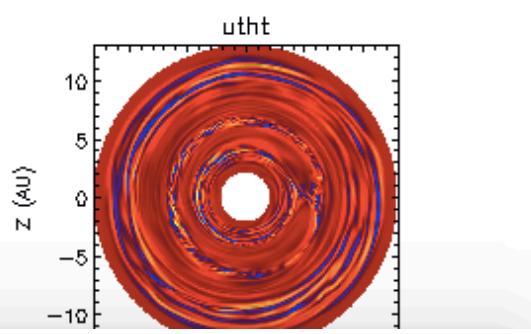
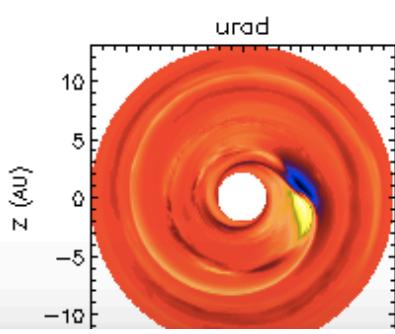
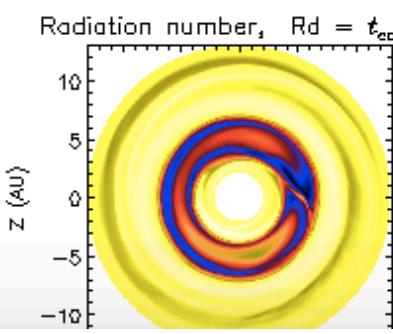
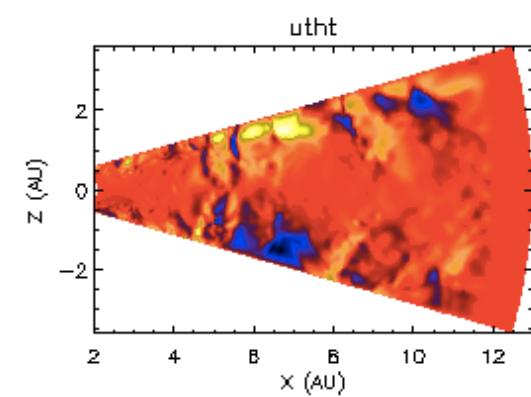
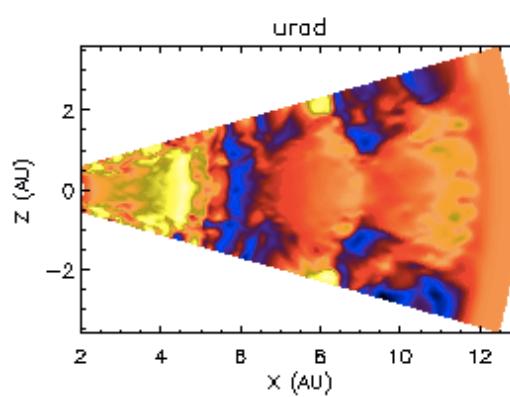
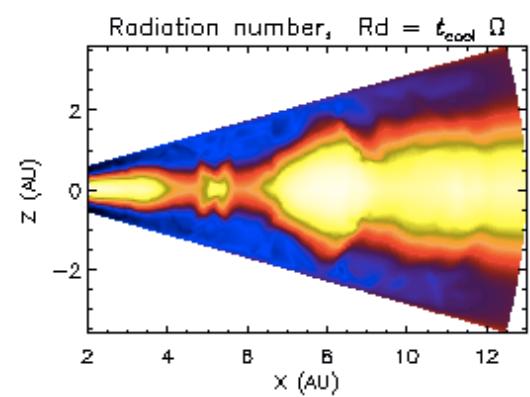
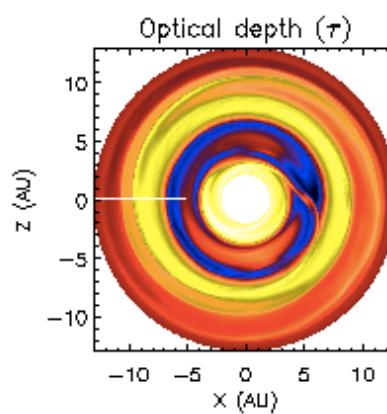
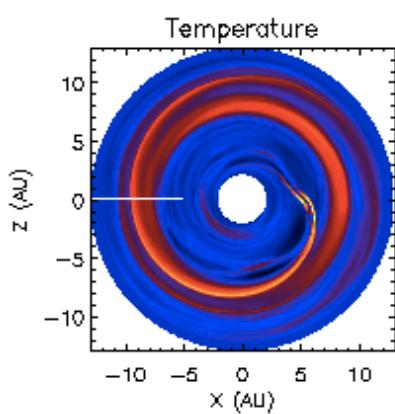
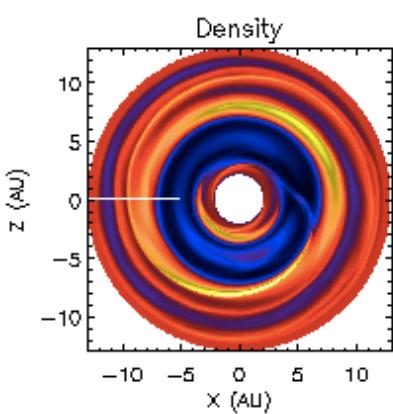
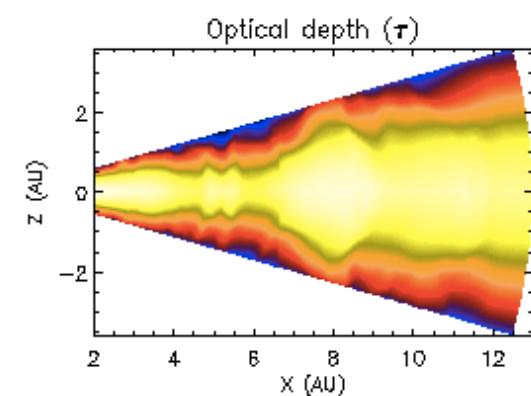
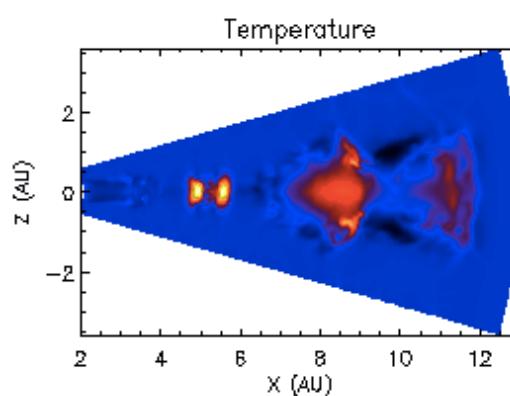
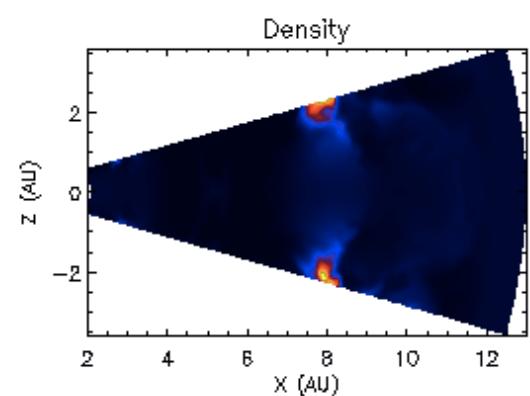


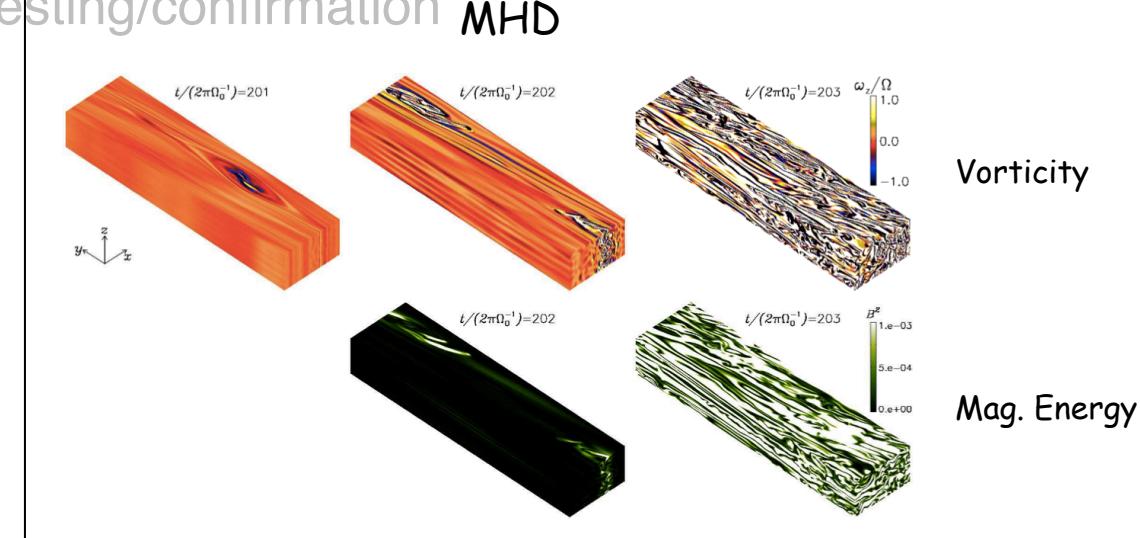
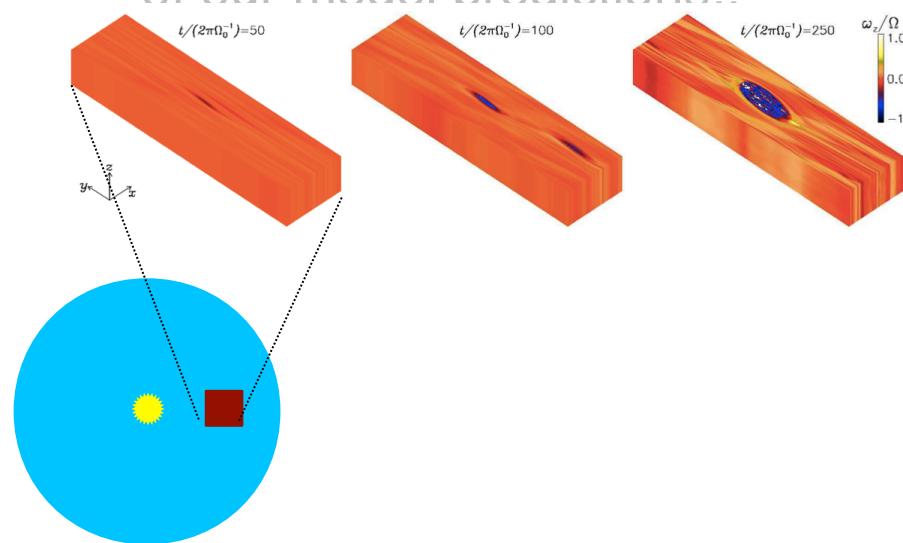
FIG. 2.—Cartoon depicting the gas flow in a shock bore in the frame of the spiral shock inside corotation. The gas in the preshock region flows into the spiral shock (A). The shock (B) causes the material to be out of vertical force balance and a rapid expansion results (C). Due to spiral streaming and the loss of pressure confinement, some of the gas will flow back over the spiral wave and break onto the disk in the preshock region at a radius inward from where it originated (D).





Conclusions

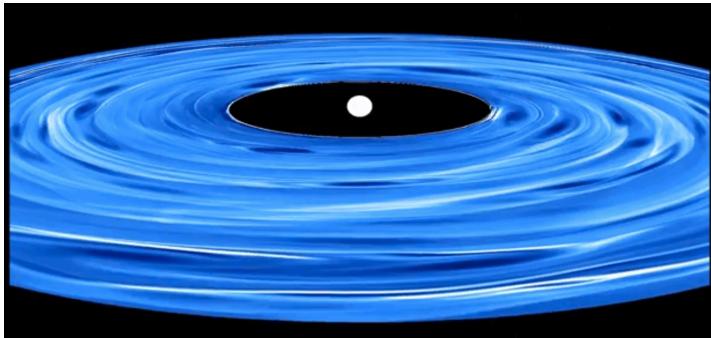
- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may be the culprit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



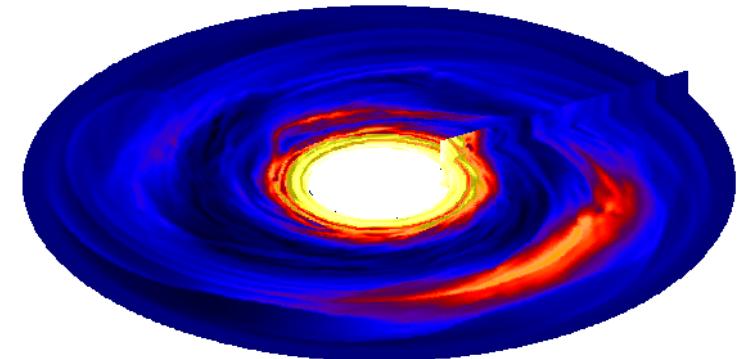
Conclusions

- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted is a complementary formation mode to streaming instability
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may be the culprit of these dust traps
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Baroclinic instability



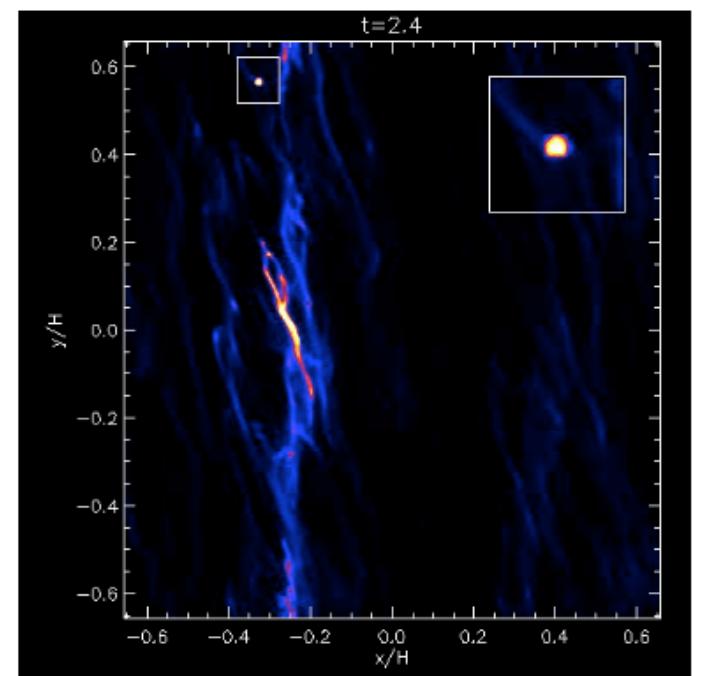
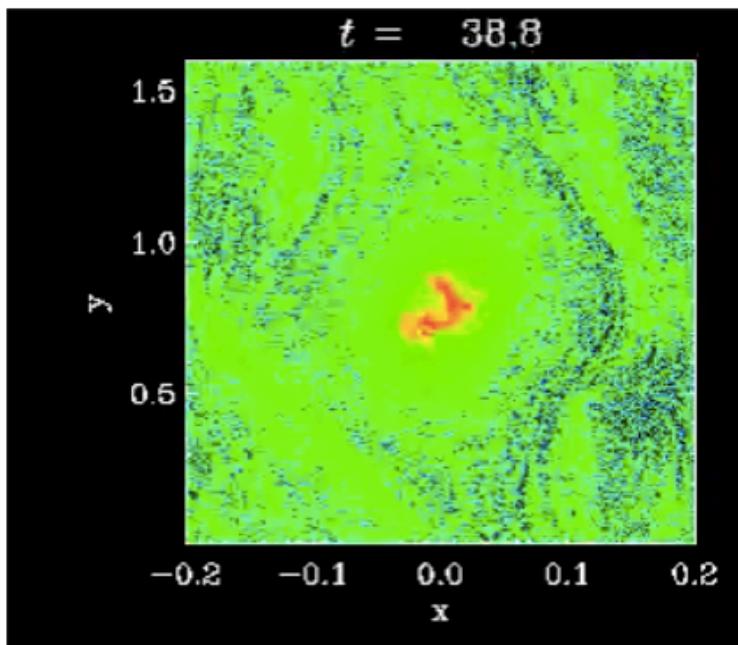
Rossby wave instability



Conclusions

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VI. VORTEX MODELLING PREDICTIONS:

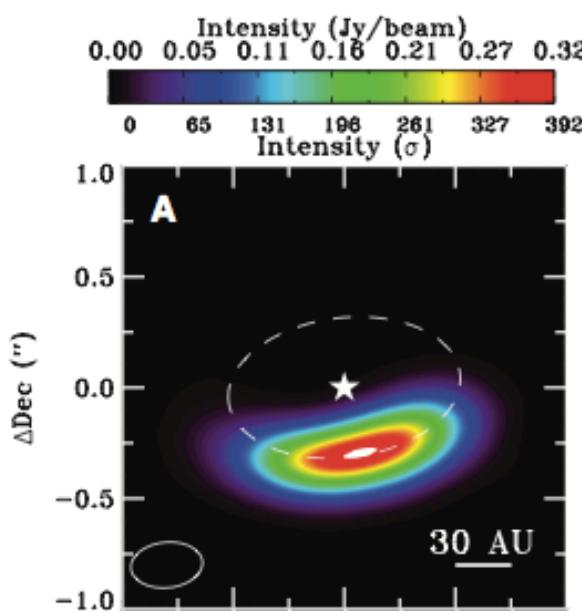
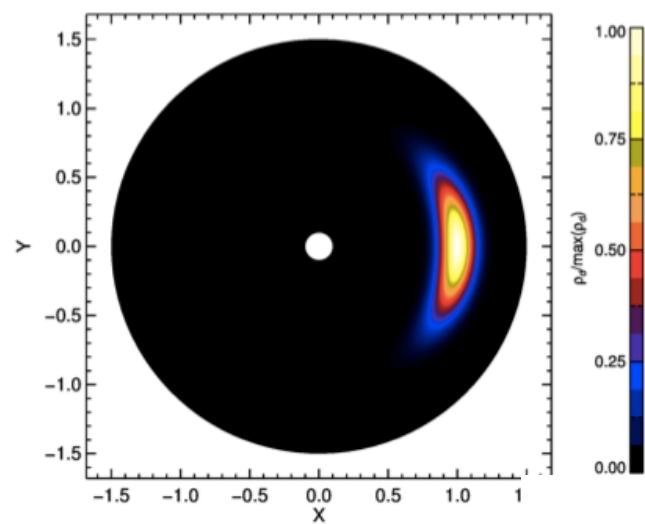


Conclusions

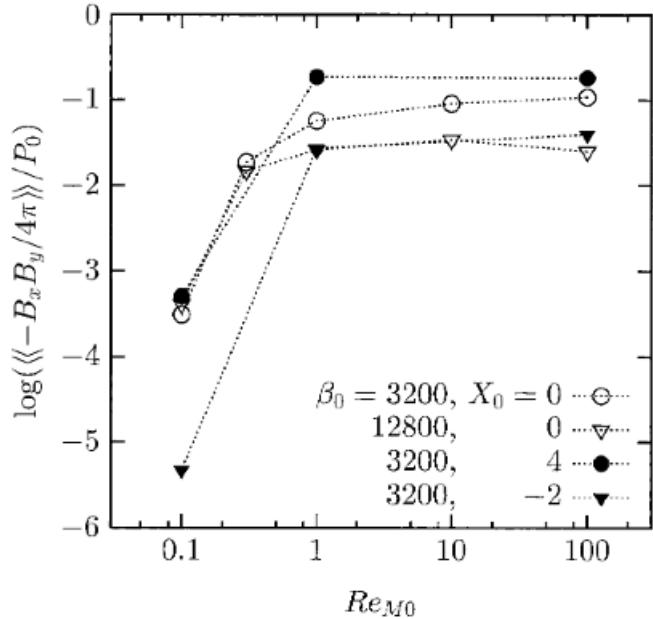
- Vortices exist in the dead zone
- Two sustenance modes: Rossby wave and vortex
- Vortex-assisted and streamwise diffusion
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may be the culprit of these dust traps
- We're in the era of observational tests of our model predictions!!

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

Lyra & Lin (2013)



Conclusions



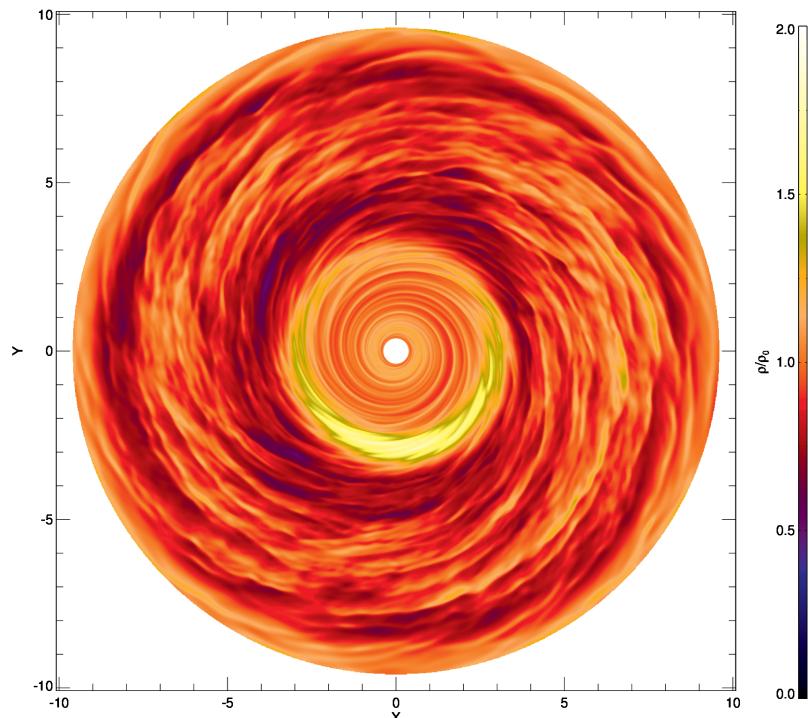
zone only

Rossby Wave Instability and Convective Overstability

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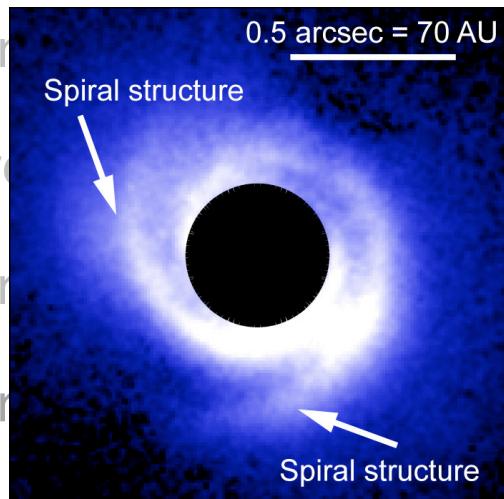
ig-diffusion equilibrium explains the observations

- Rossby wave instability may be the culprit of these dust traps
- We're in the era of observational testing/confirming of our model predictions!!



Conclusions

- Vorticity is concentrated in the innermost zone only
- Twists are concentrated in the outermost zone
- Vorticity is concentrated in the outermost zone
- Vorticity is concentrated in the outermost zone
- Rossby wave instability may be the culprit of these observations
- We're in the era of observational testing/confirmation of our model predictions!!

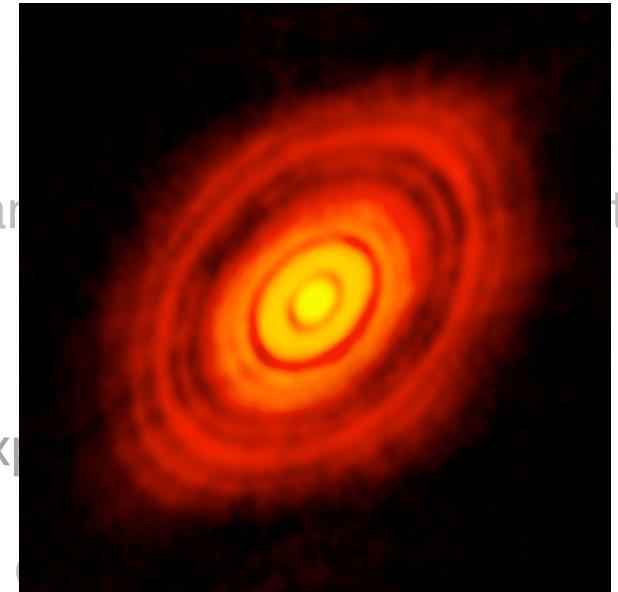


and zone only

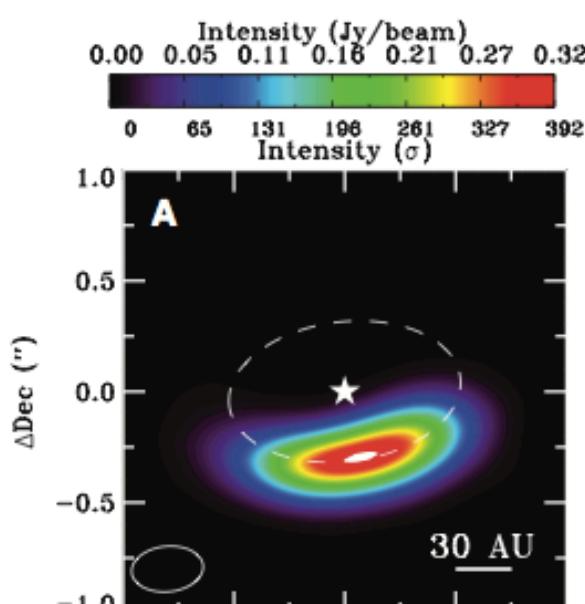
Rossby Wave Instability and

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Conclusions

- Vortices e
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- We're in th
- of our mode

