

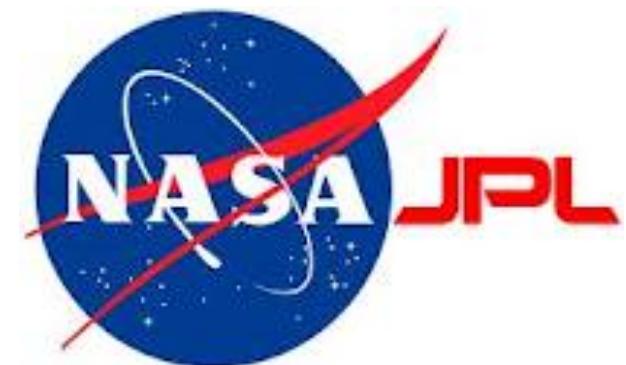
Evolution of circumstellar disks and planet formation

Wladimir (Wlad) Lyra

Sagan Fellow



Caltech - JPL



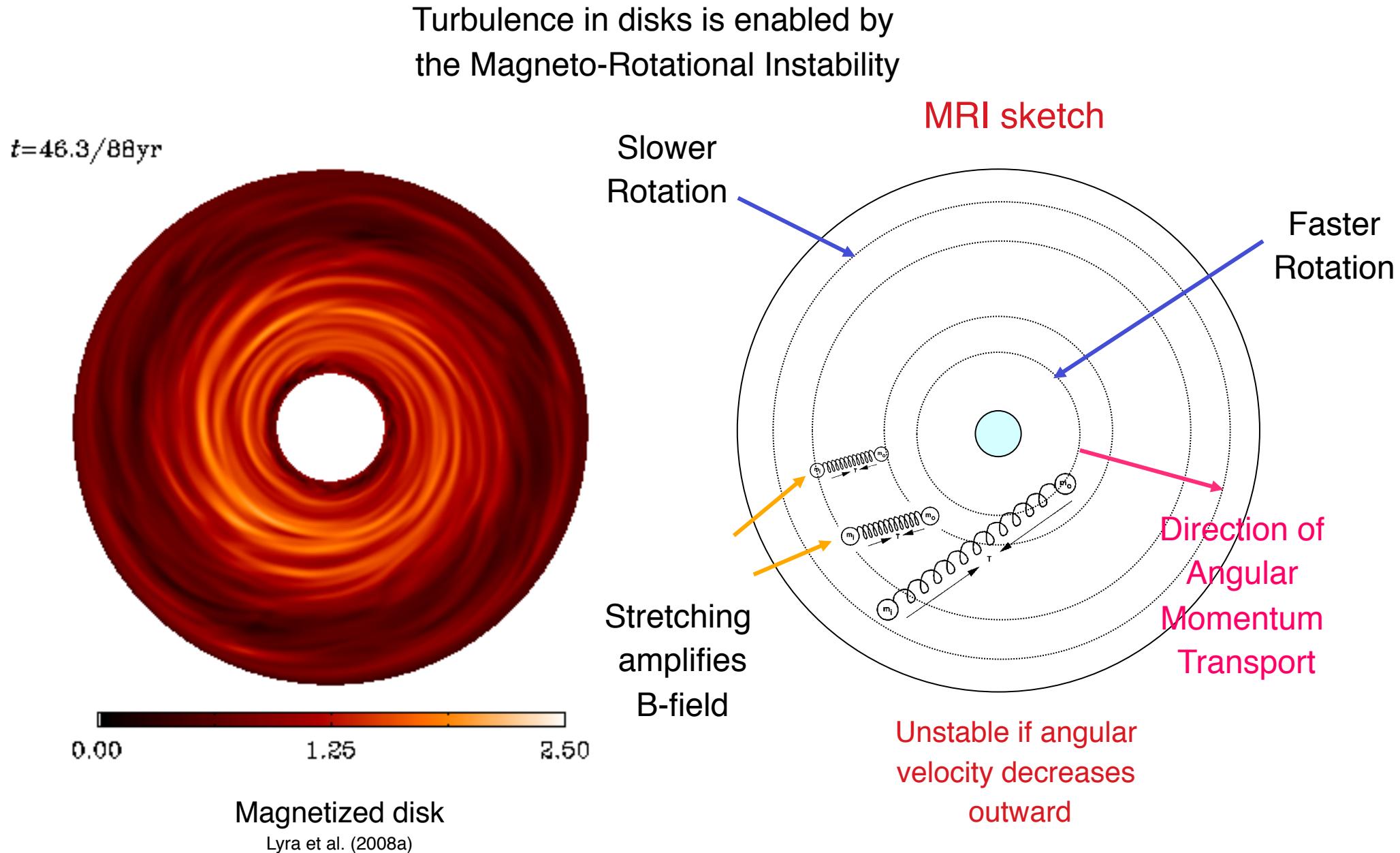
Collaborators:

Axel Brandenburg (Stockholm), Anders Johansen (Lund), Brandon Horn (Columbia),
Hubert Klahr (Heidelberg), Marc Kuchner (Goddard), Min-Kai Lin (CITA)
Mordecai-Mark Mac Low (AMNH), Sijme-Jan Paardekooper (Cambridge),
Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), Zsolt Sandor (Innsbruck),
Neal Turner (JPL), Andras Zsom (MIT).

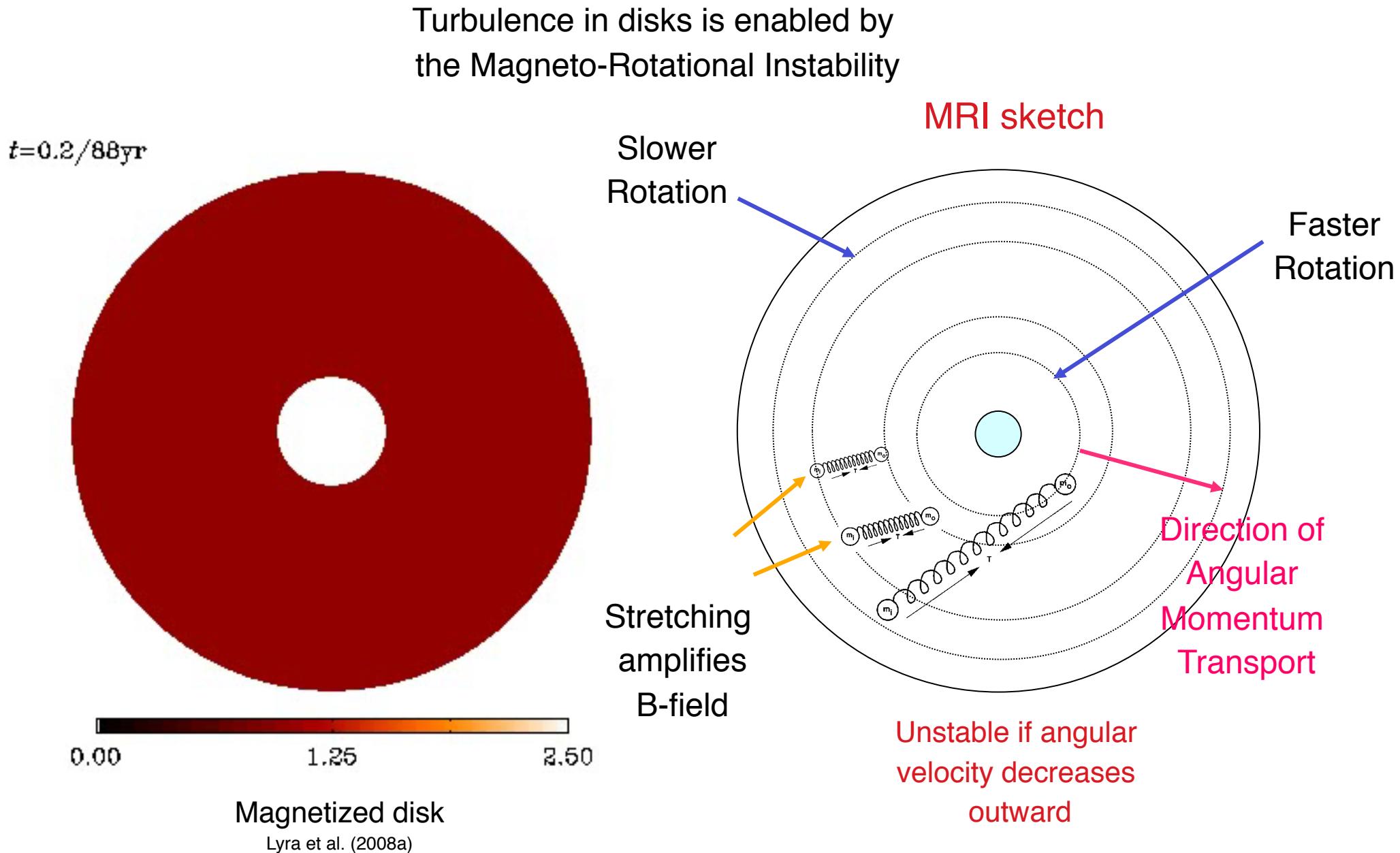
Outline

- 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

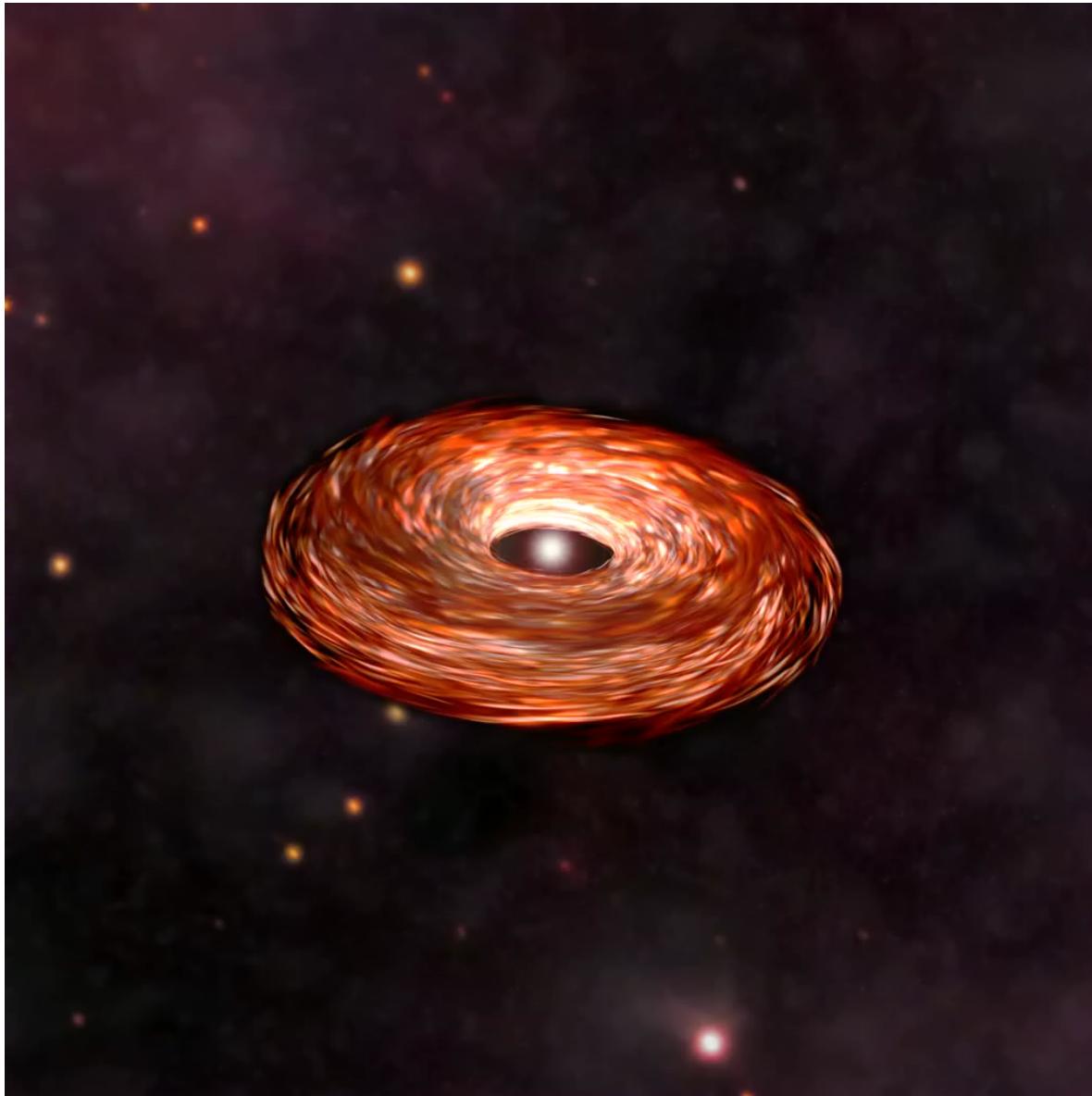
Accretion in disks occurs via turbulent viscosity



Accretion in disks occurs via turbulent viscosity

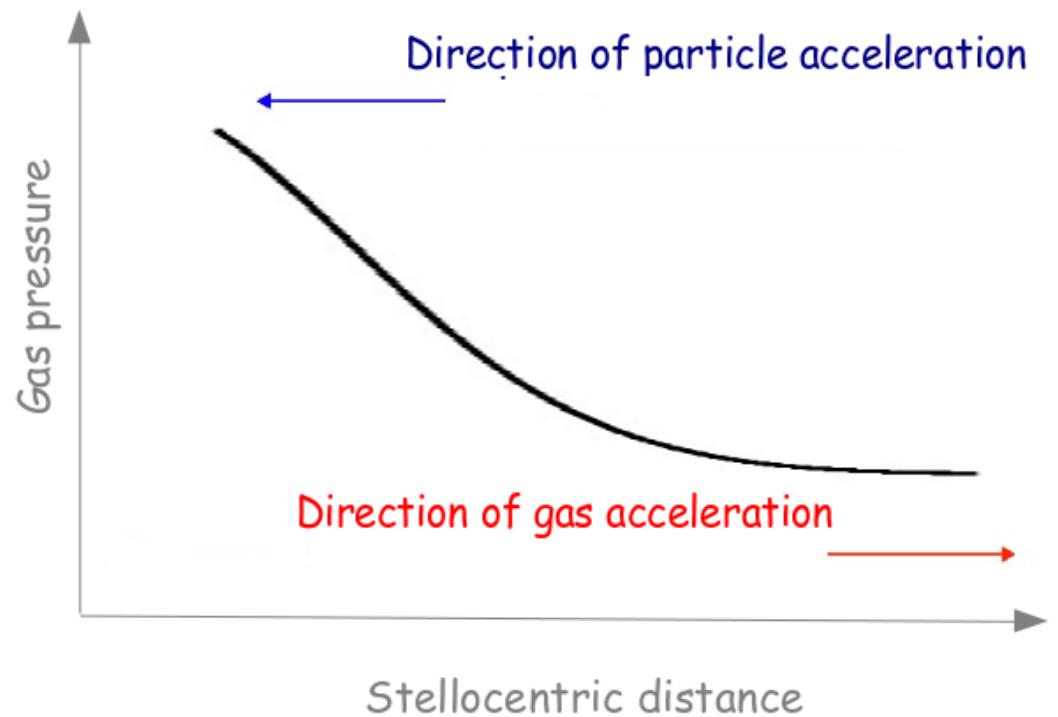
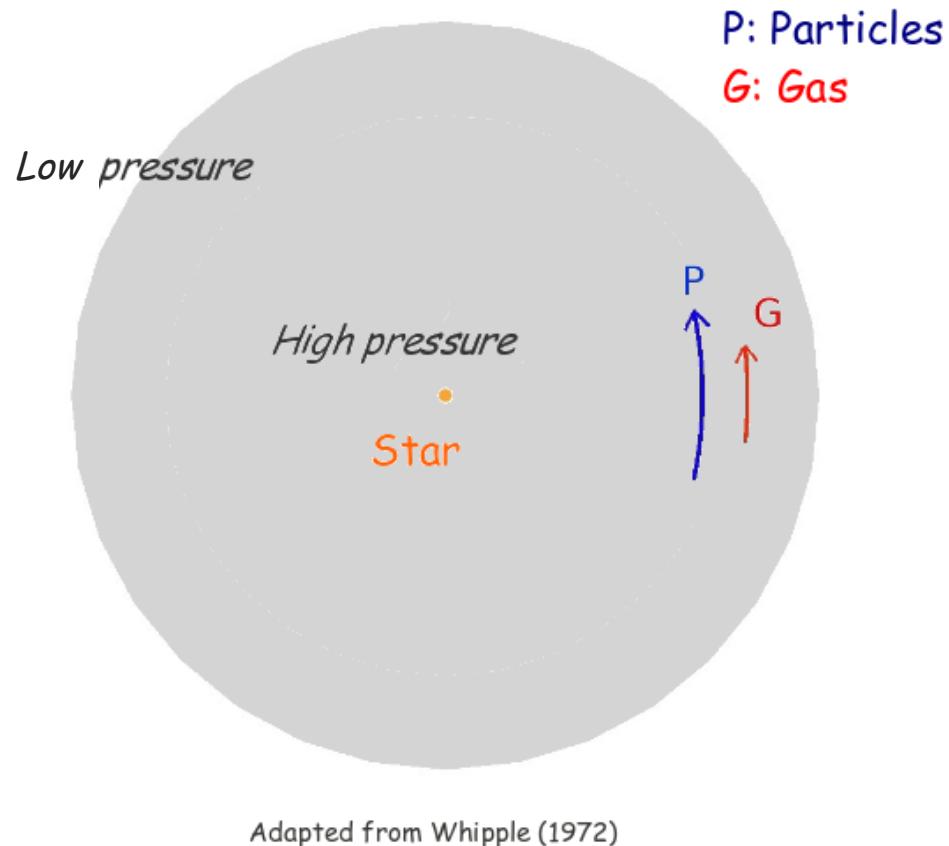


Magneto-Rotational Instability

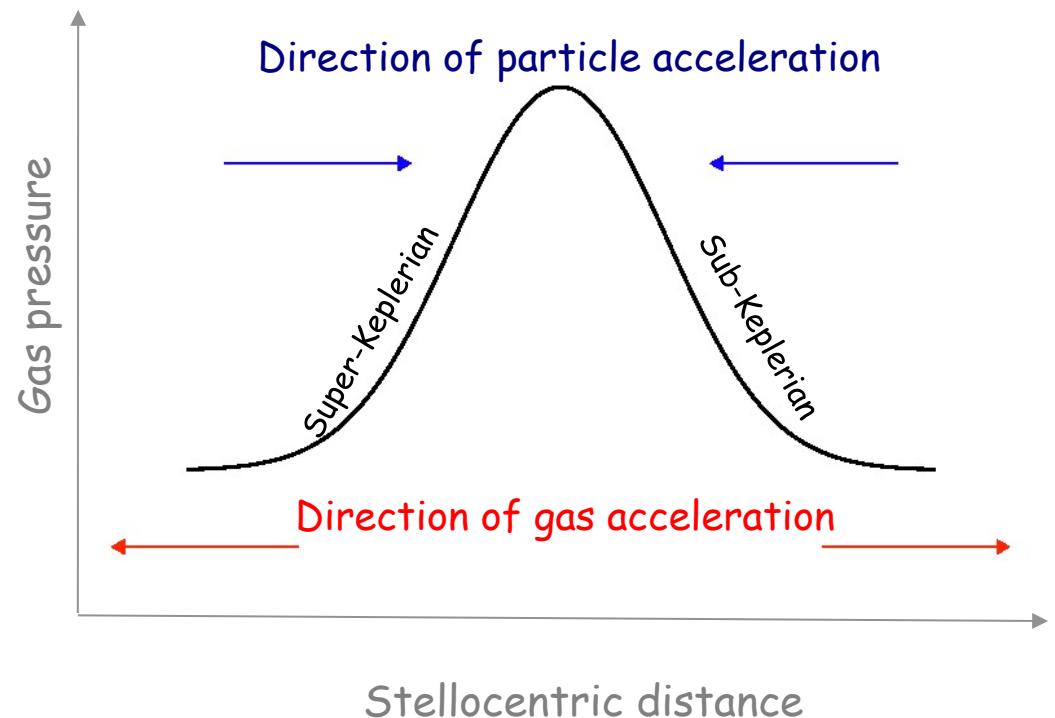
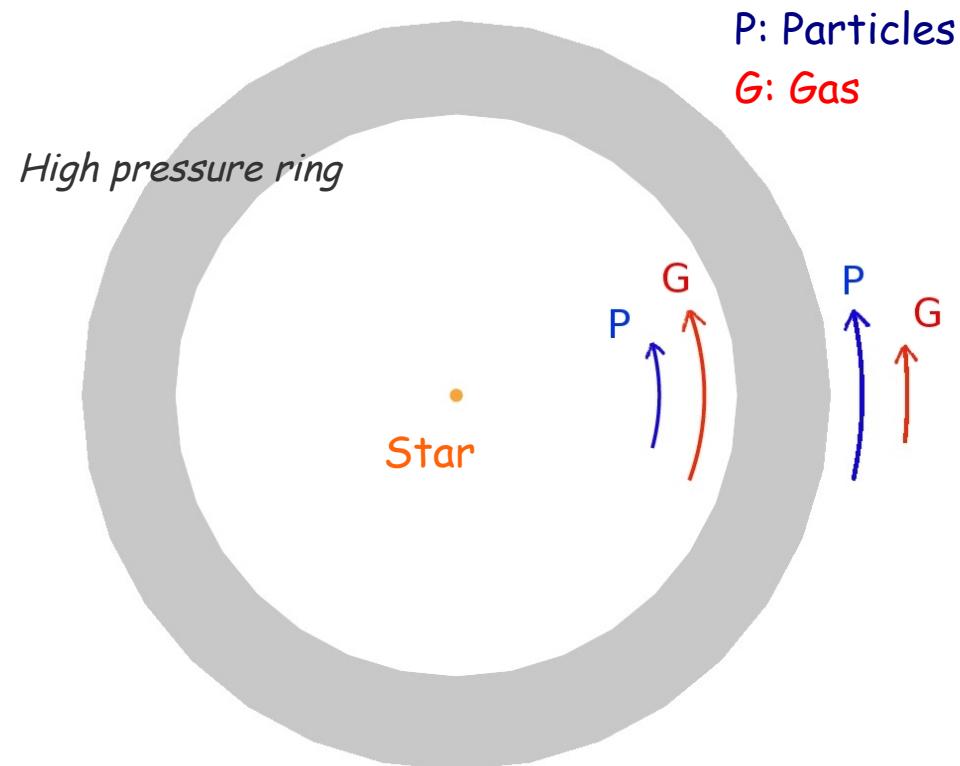


Video credit: Mario Flock (MPIA/CEA)

Particle drift

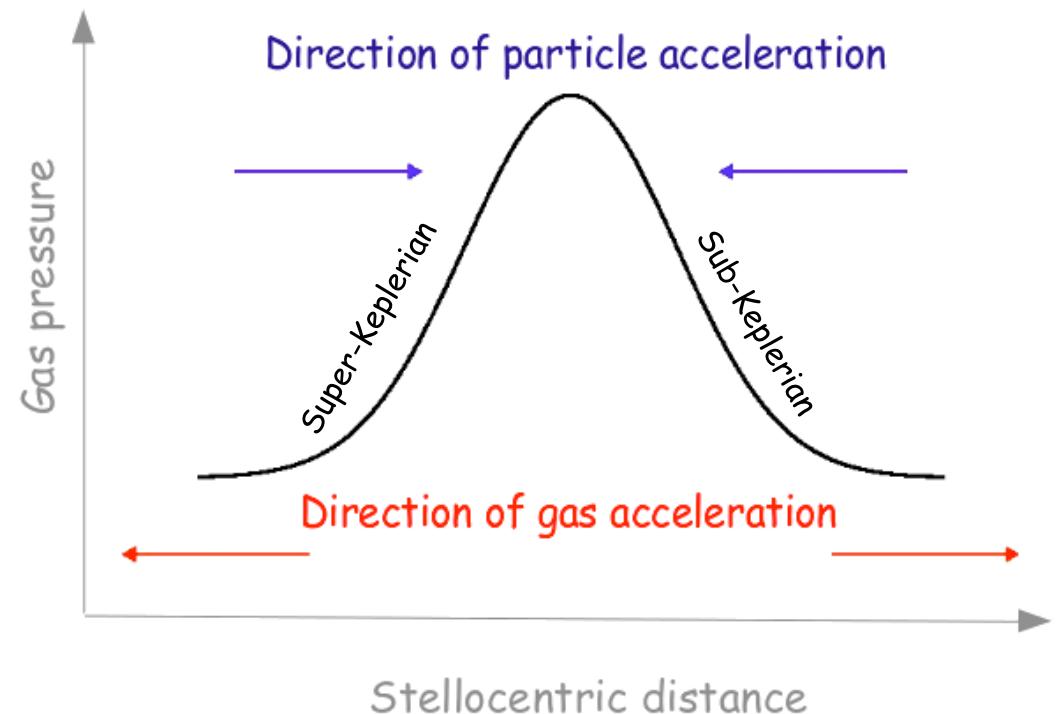
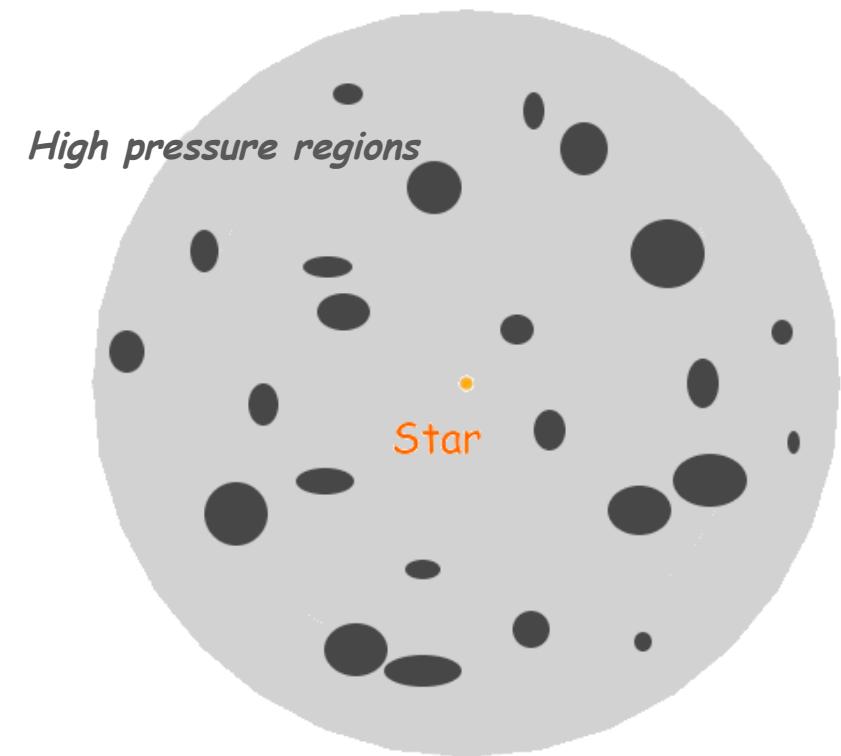


Pressure Trap

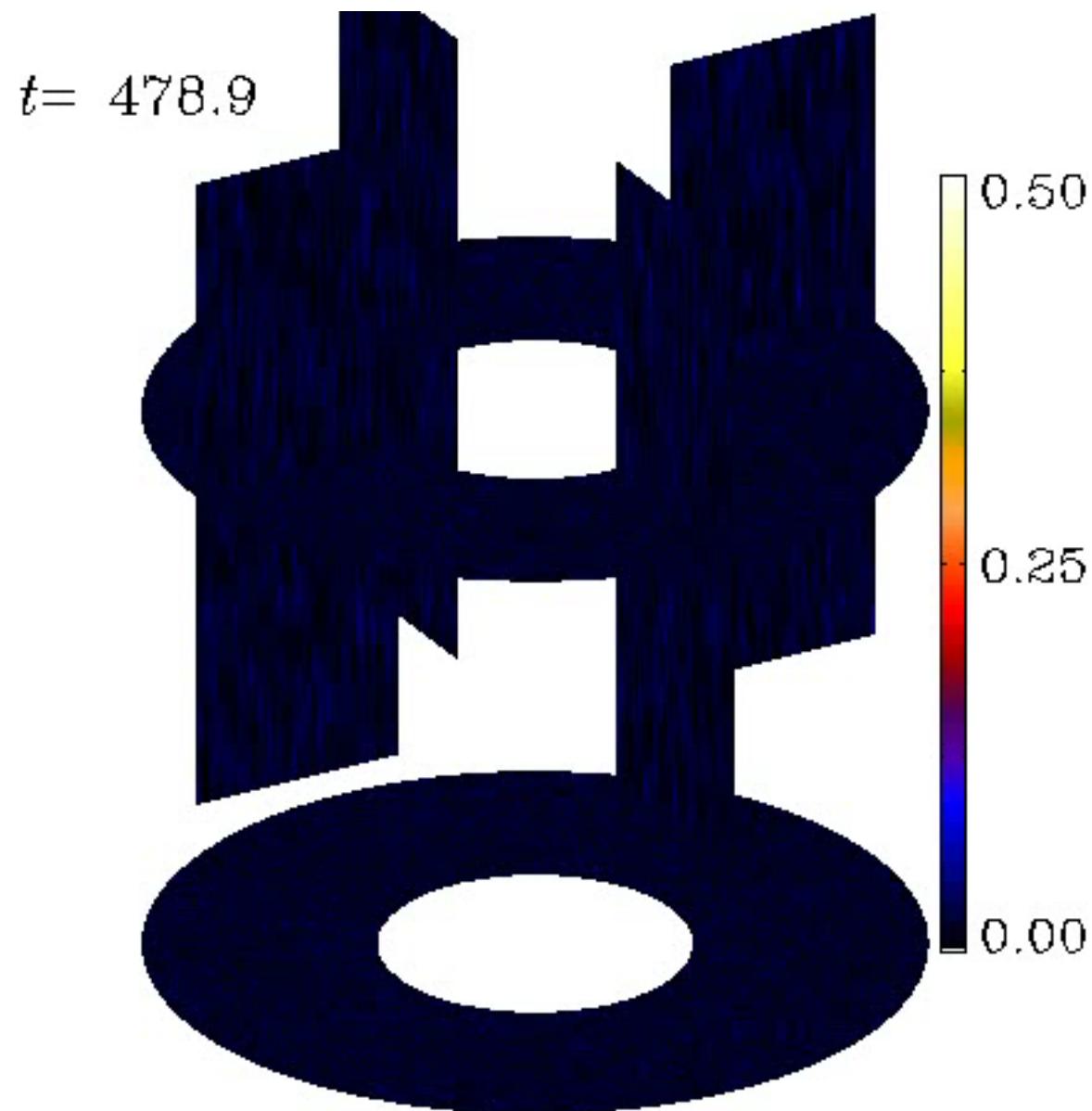


Adapted from Whipple (1972)

Pressure Trap

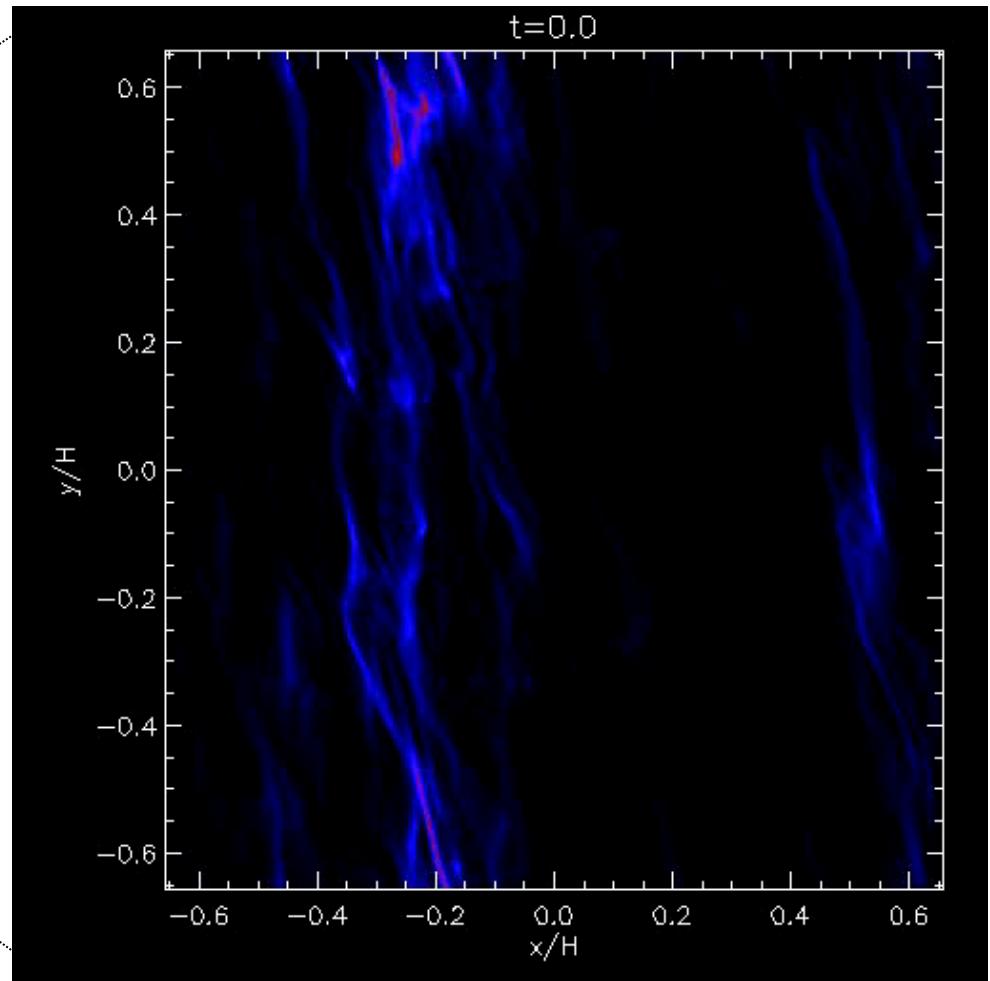
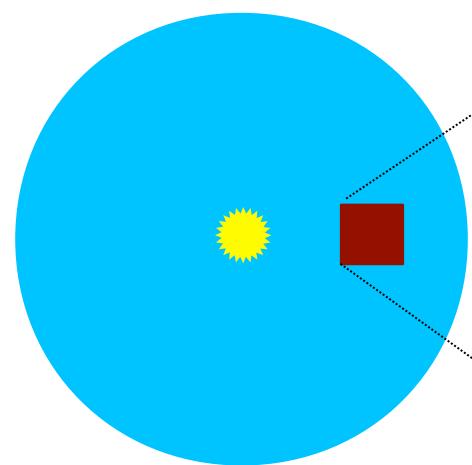


Turbulence concentrates solids mechanically in pressure maxima



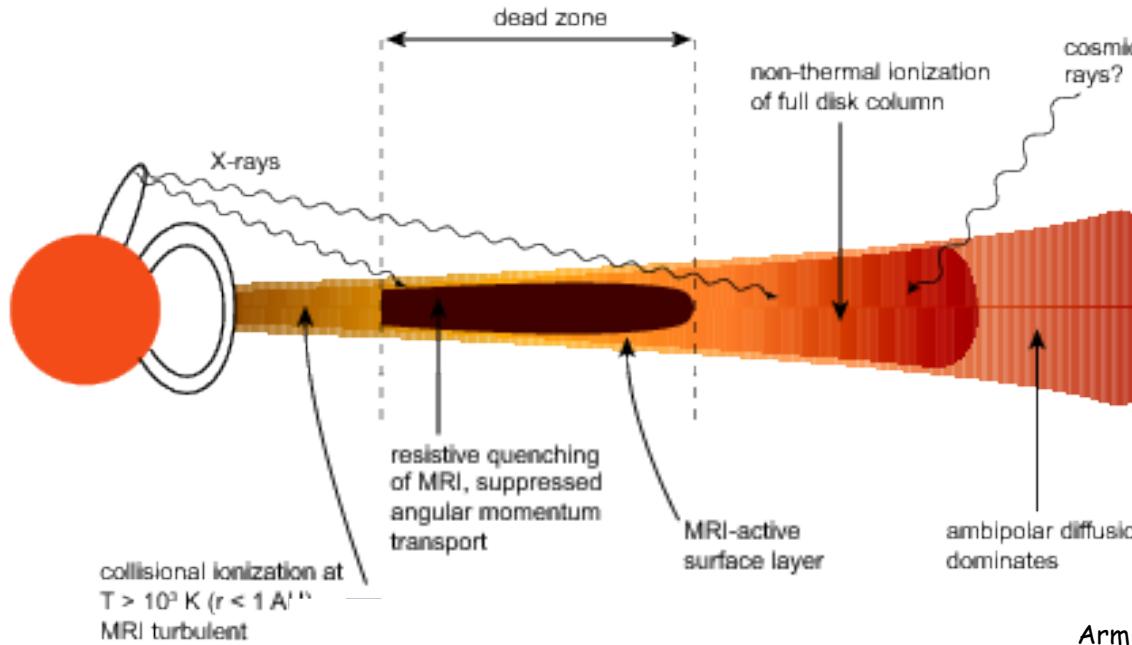
Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

Dead zones are robust features of accretion disks



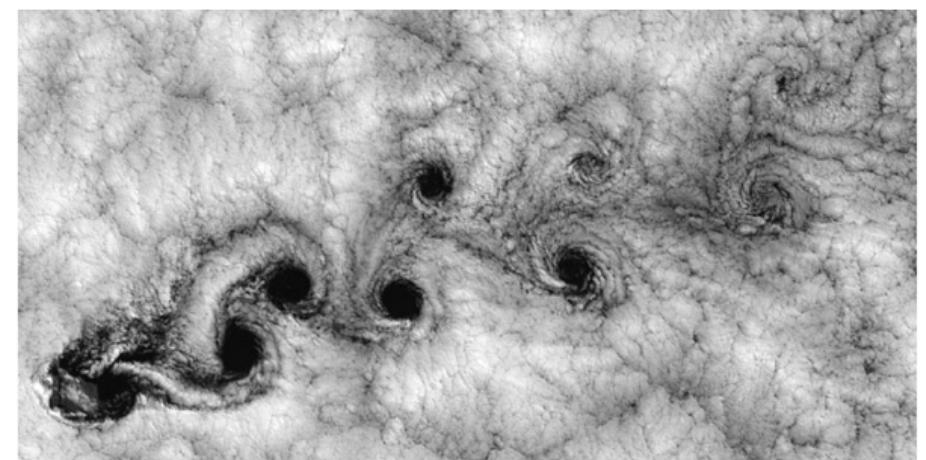
Armitage (2010)

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

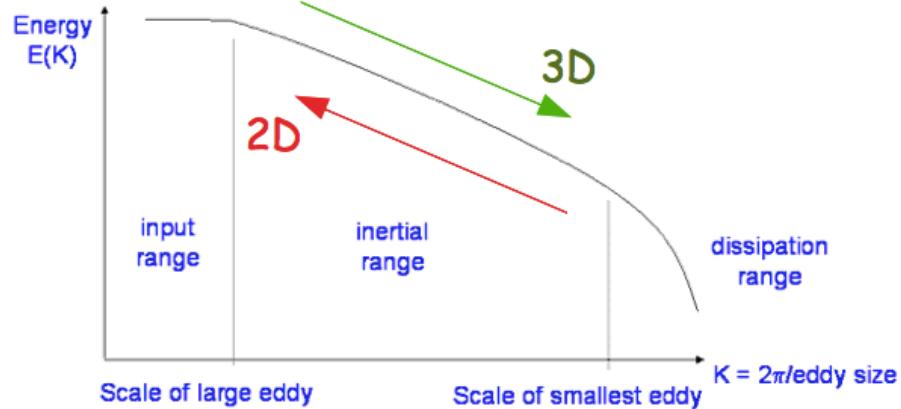
Therefore, accretion is **layered** (Gammie 1996)

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

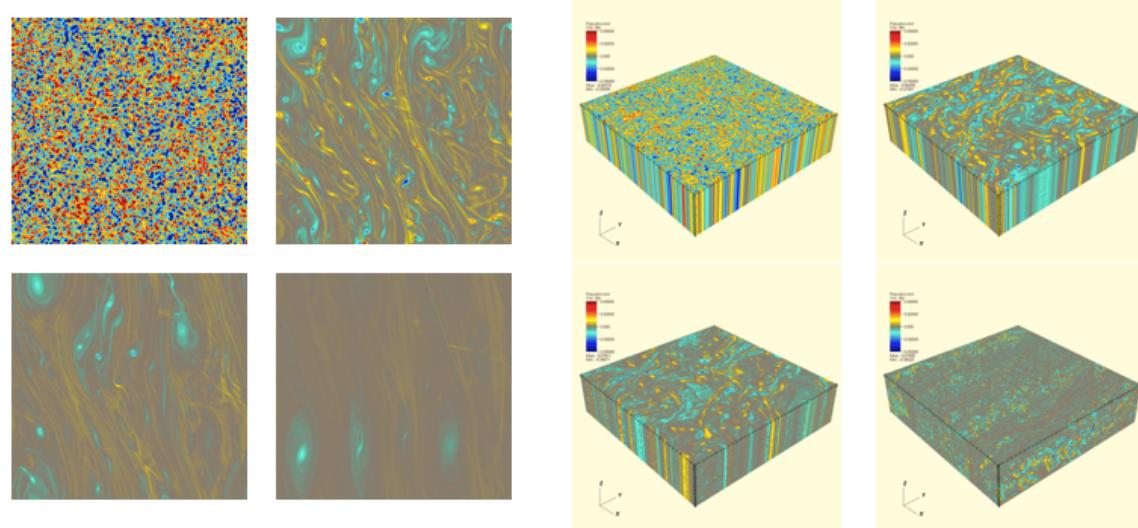
Vortices - An ubiquitous fluid mechanics phenomenon



The energy cascade



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



2D

3D

Inverse Cascade

No 3D instability
Eddies merge

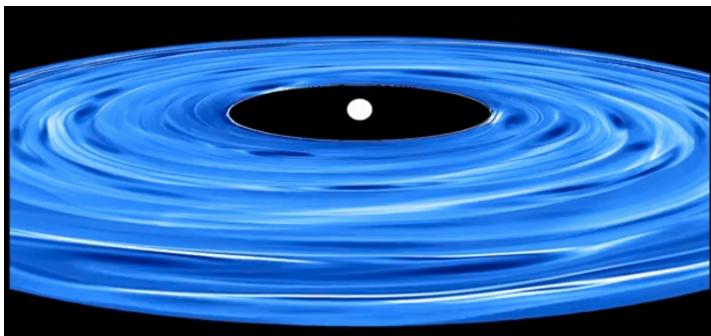
Direct Cascade

Destruction occurs
faster than merging

Sustaining vortices in disks

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

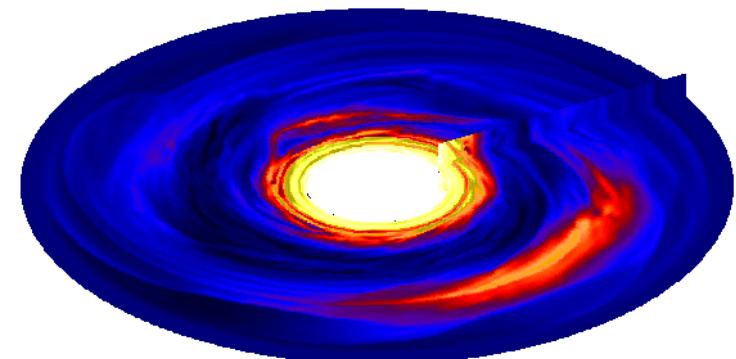
Baroclinic instability



Klahr & Bodenheimer (2003)
Lyra & Klahr (2011)
Raettig et al. (2013)
Lyra (2014)

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

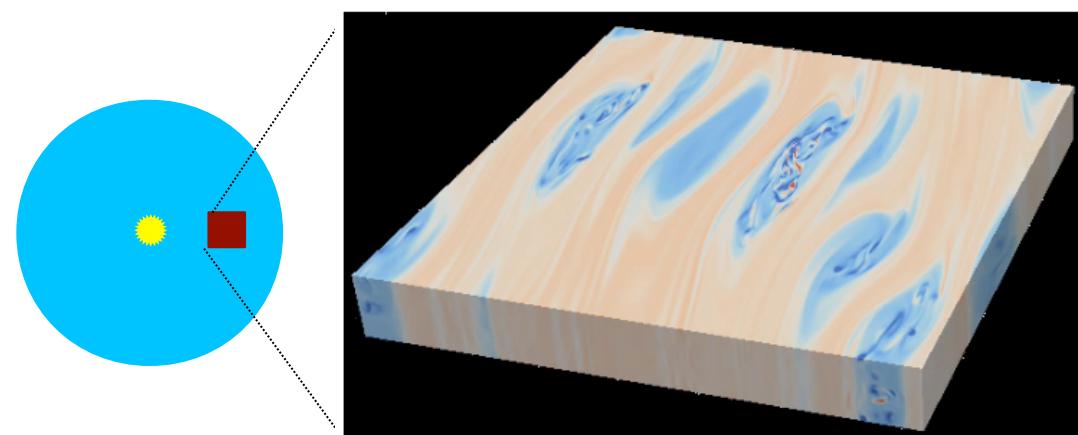
Rossby wave instability



Lovelace et al. (1999)
Lyra et al. (2008b, 2009ab)
Lyra & Mac Low (2012)
Lyra & Turner (2014)

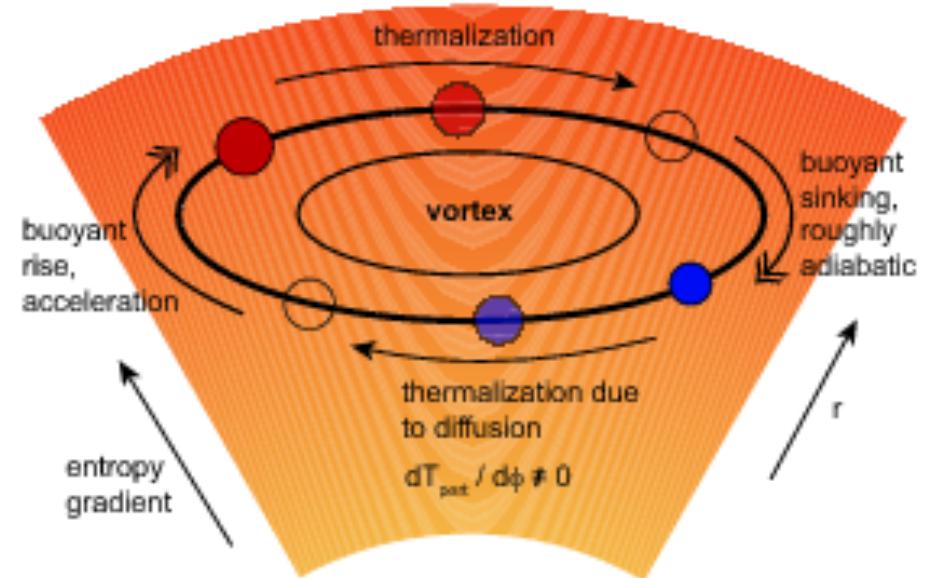
Powered by:
Modification of shear profile
(**external vorticity reservoir**)

Baroclinic Instability - Excitation and self-sustenance of vortices



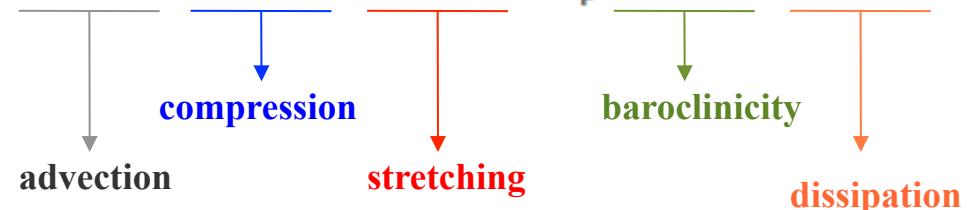
Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability



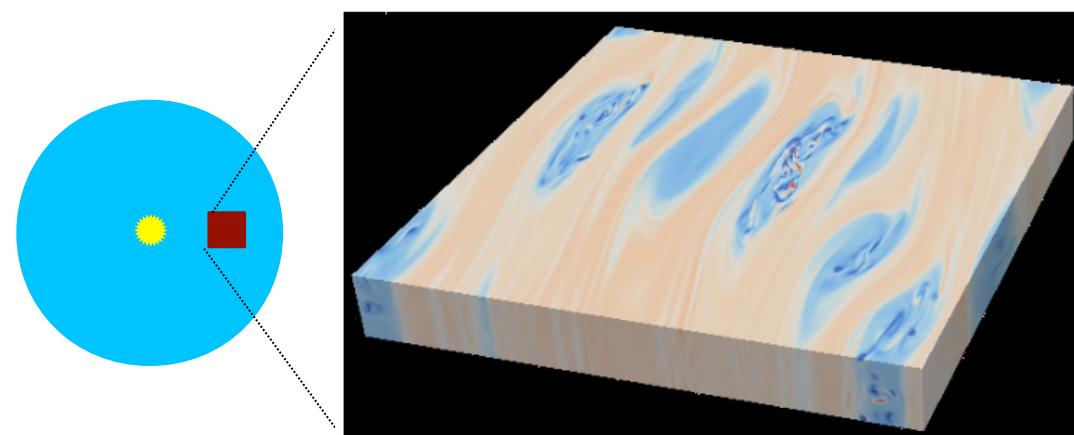
Armitage (2010)

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



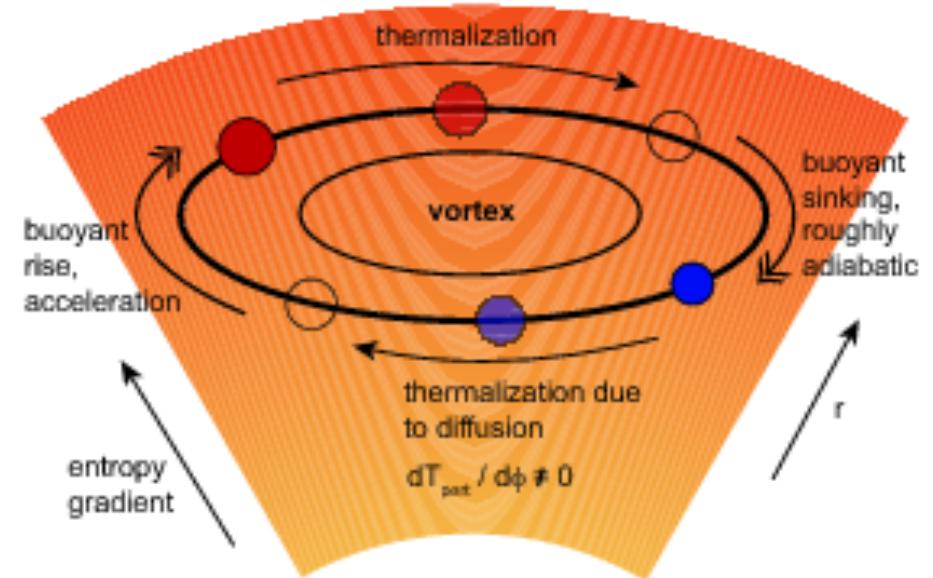
Baroclinic Instability - Excitation and self-sustenance of vortices

1. Radial entropy gradient
2. Thermal diffusion



Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability



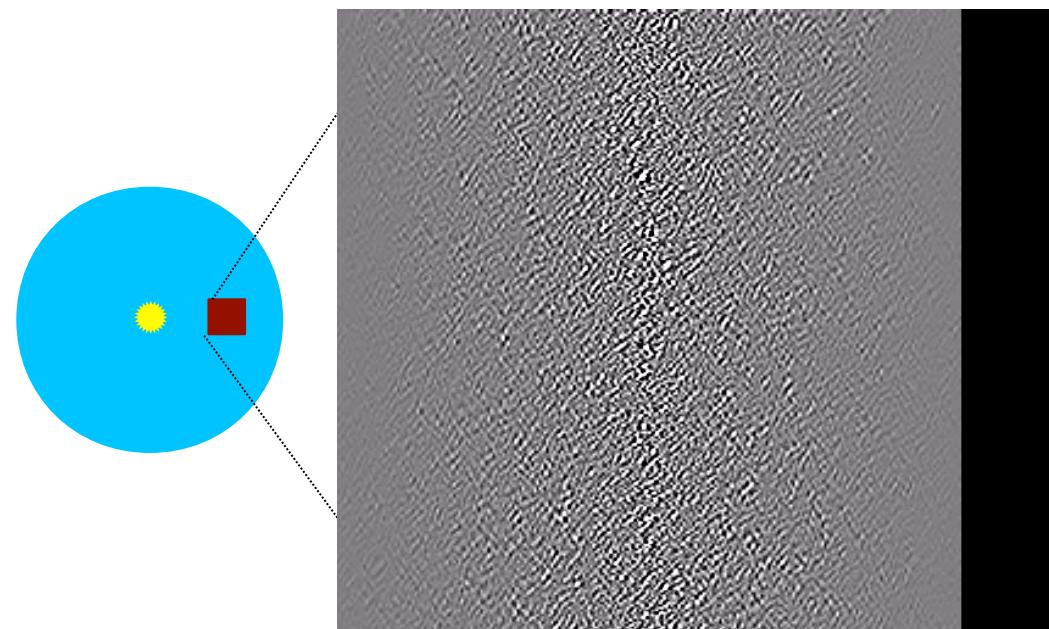
Armitage (2010)

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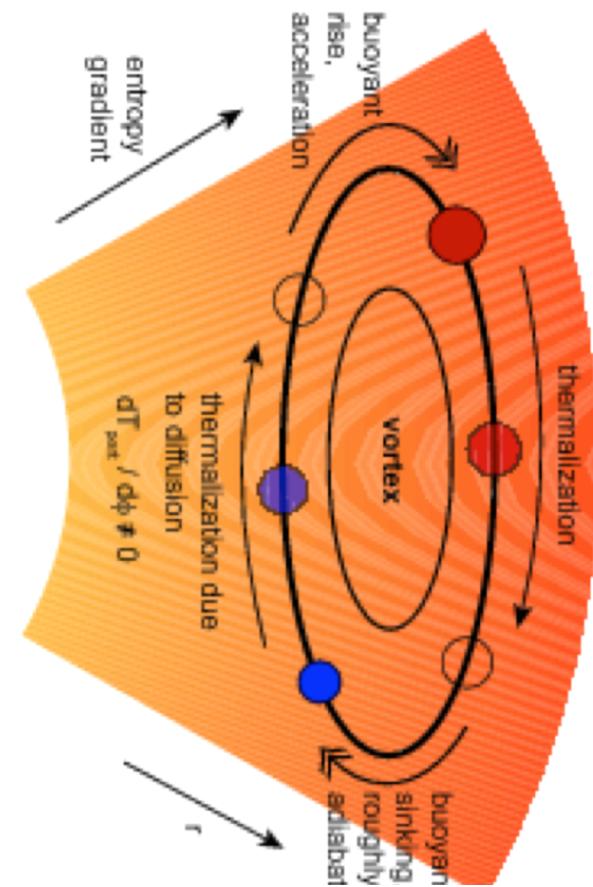
advection compression stretching baroclinicity dissipation

Baroclinic Instability - Excitation and self-sustenance of vortices

1. Radial entropy gradient
2. Thermal diffusion

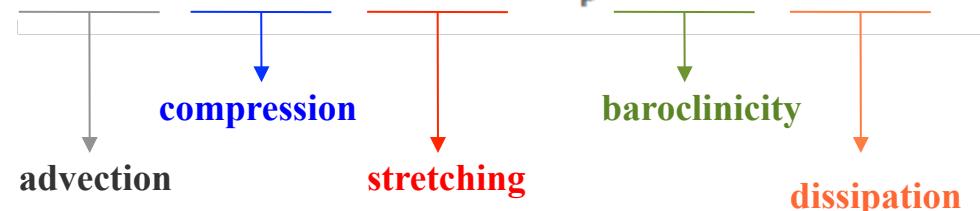


Sketch of the
Baroclinic Instability



Armitage (2010)

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



The “Baroclinic Instability” is LINEAR (Convective Overstability)

Klahr & Hubbard (2014), Lyra (2014)

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

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

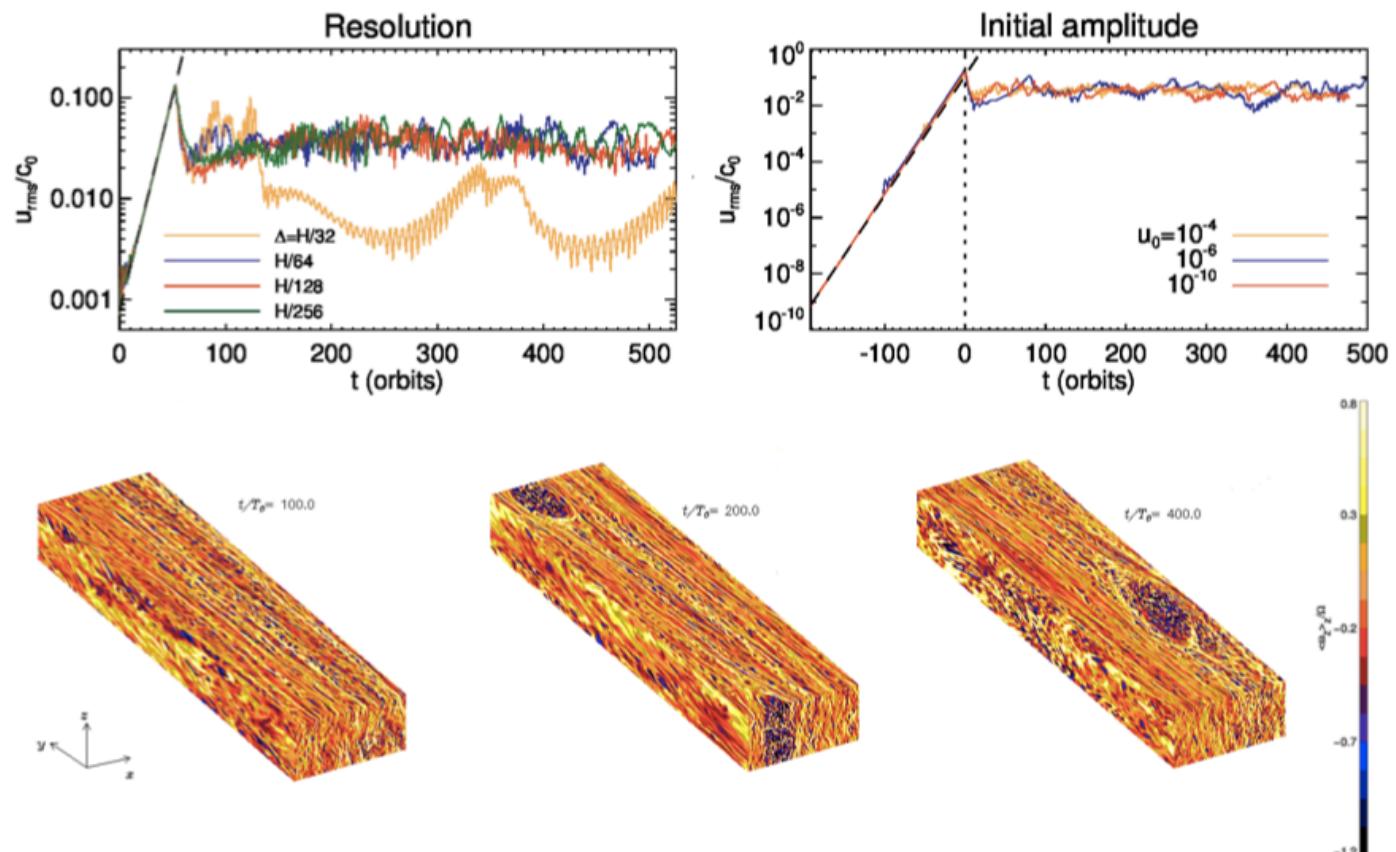
$$\frac{\partial p}{\partial t} + (\mathbf{u} \cdot \nabla) p = -\gamma p \nabla \cdot \mathbf{u} - \frac{p}{T} \frac{(T - T_0)}{\tau},$$

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

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

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

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

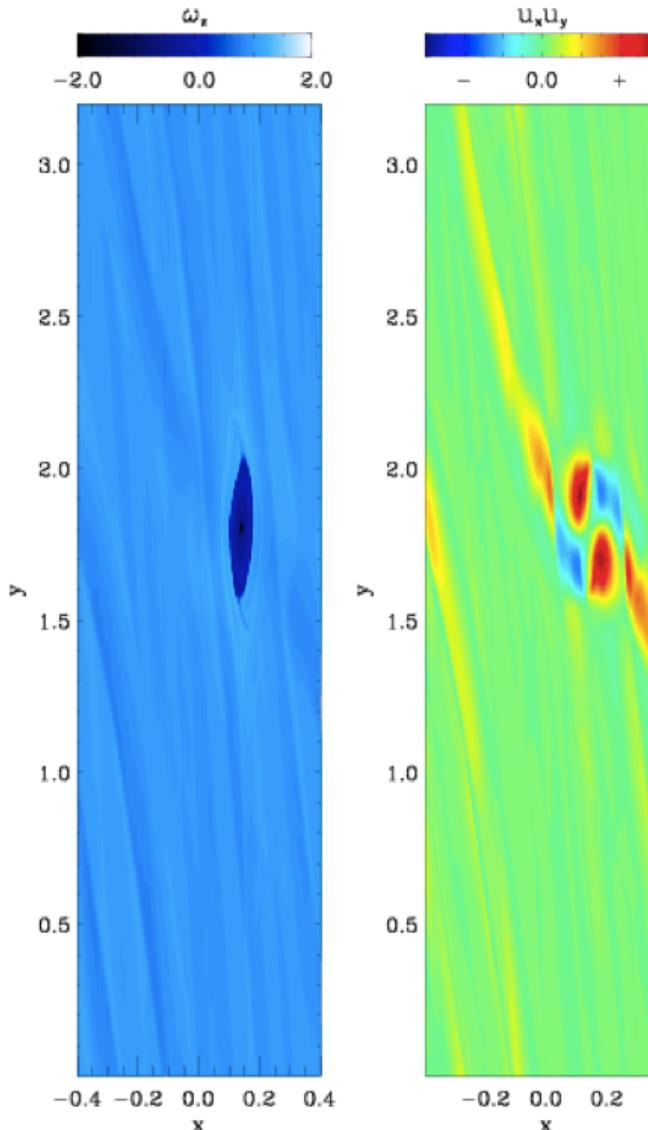
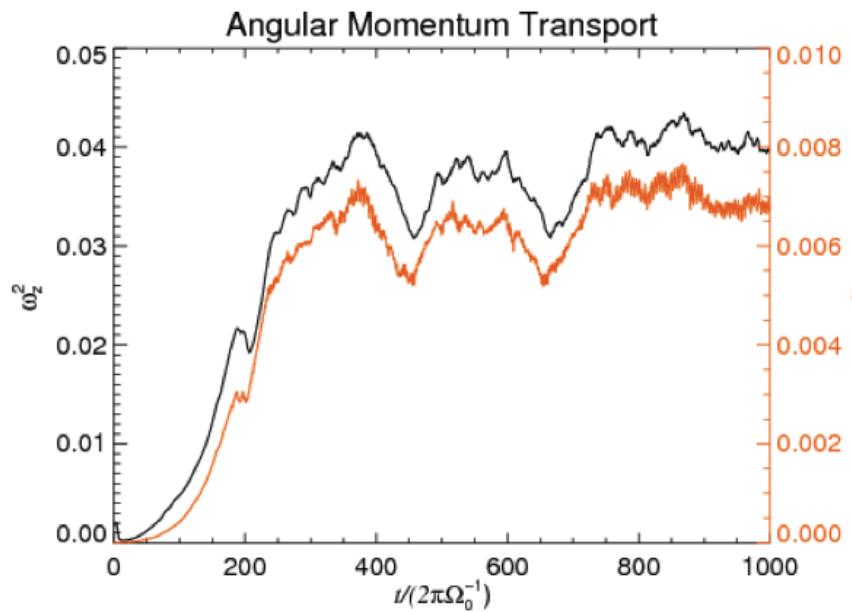


Lyra (2014)

Baroclinic Instability and Accretion

Raettig, Lyra, & Klahr (2012)

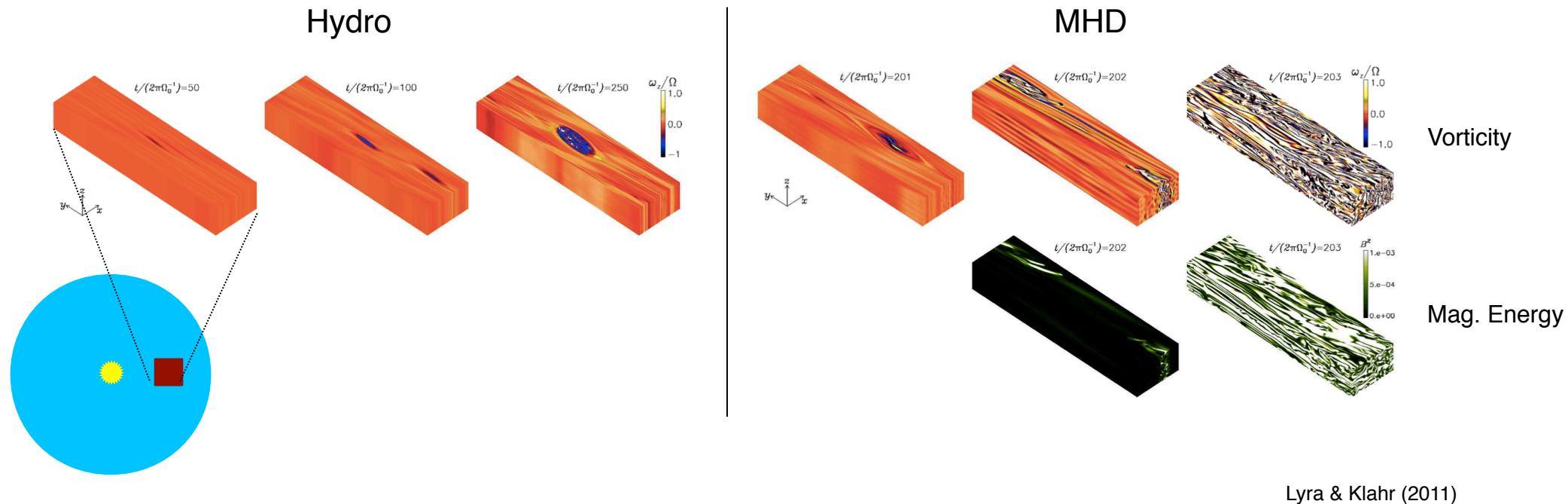
Large mass accretion rates,
comparable to the MRI!



The angular momentum is carried by
waves excited by the vortex
(see also Heinemann & Papaloizou 2008, 2009)

Baroclinic instability and layered accretion

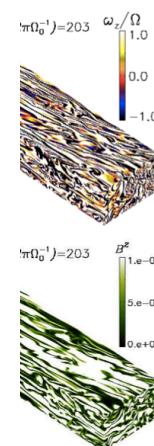
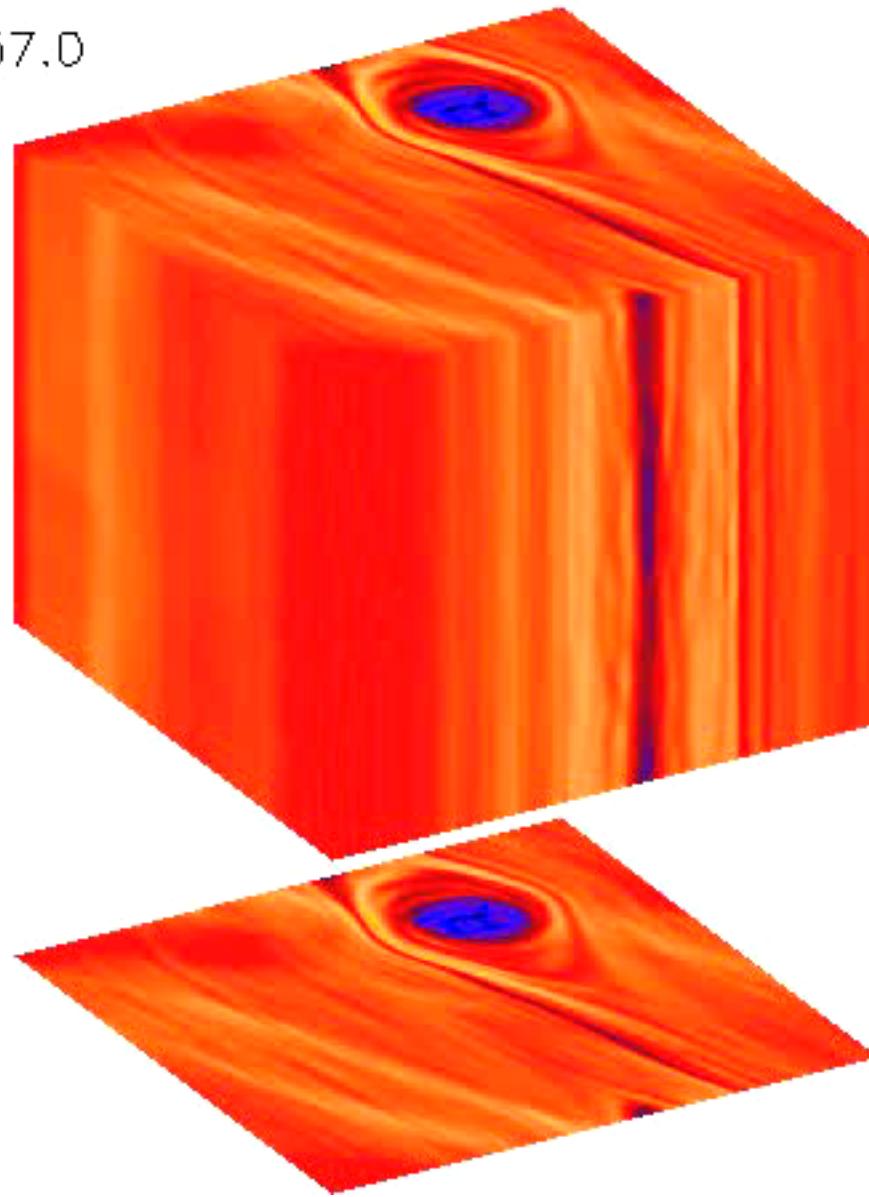
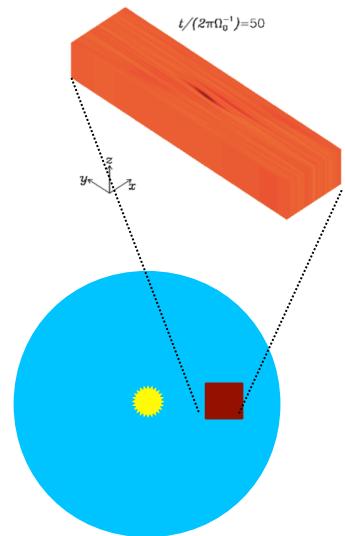
What happens when the vortex is magnetized?



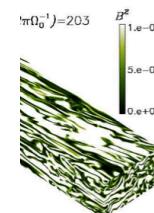
Lyra & Klahr (2011)

Baroclinic instability and layered accretion

$t=1257.0$



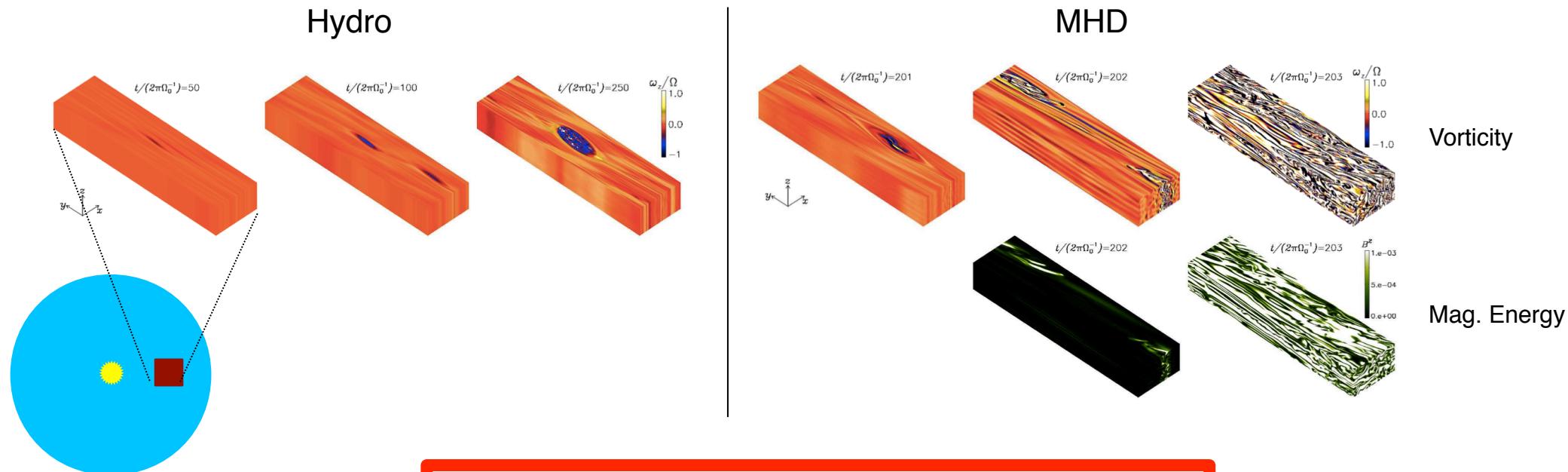
Vorticity



Mag. Energy

Baroclinic instability and layered accretion

What happens when the vortex is magnetized?

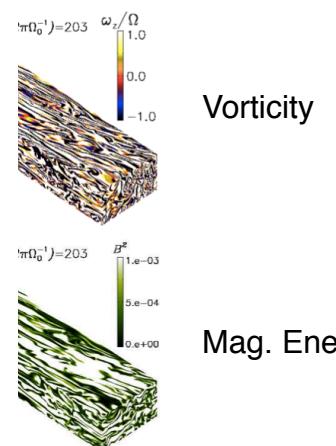
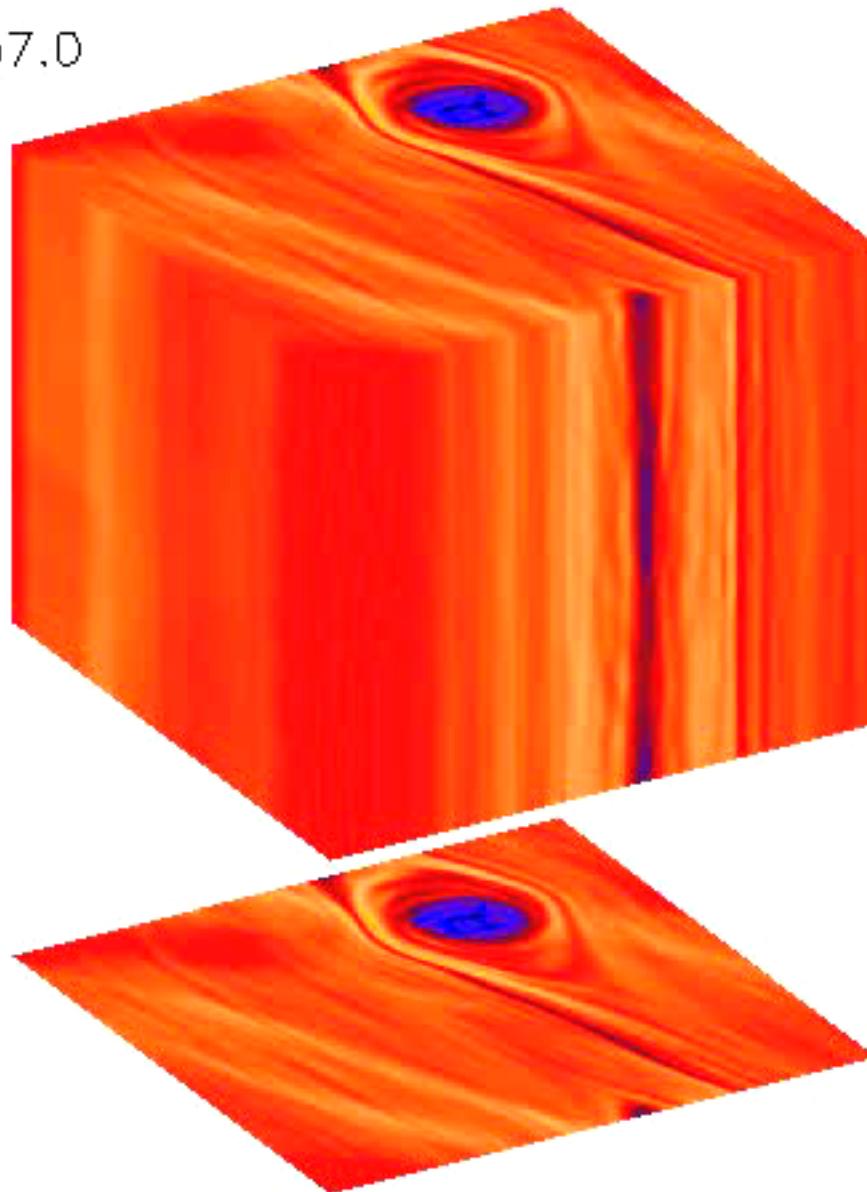
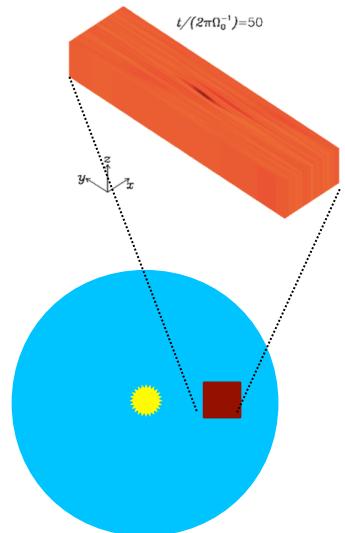


Baroclinic vortices
do **not** survive magnetization

Lyra & Klahr (2011)

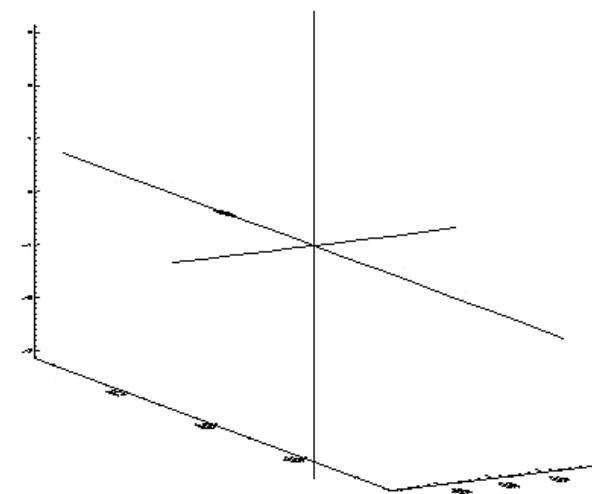
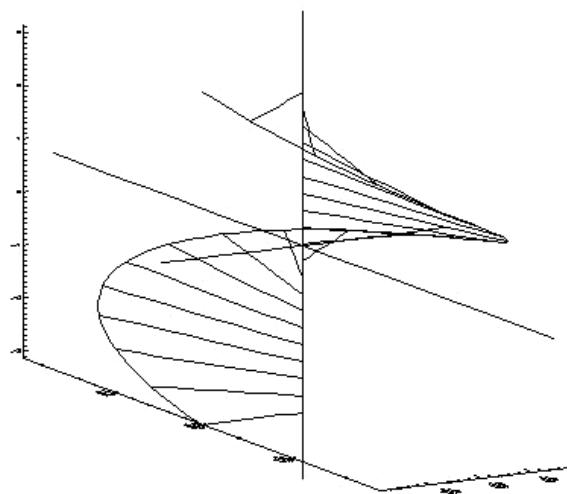
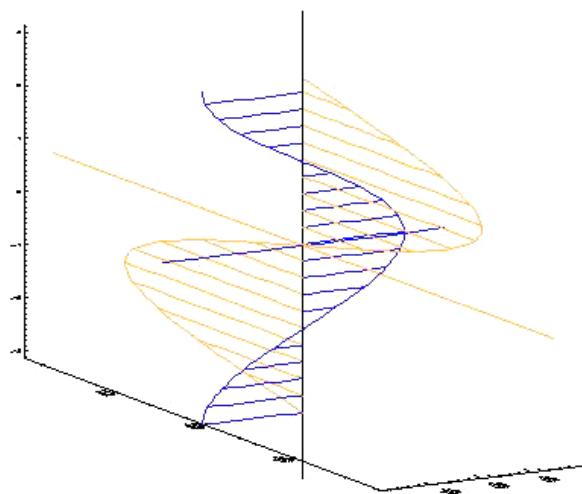
Baroclinic instability and layered accretion

$t=1257.0$

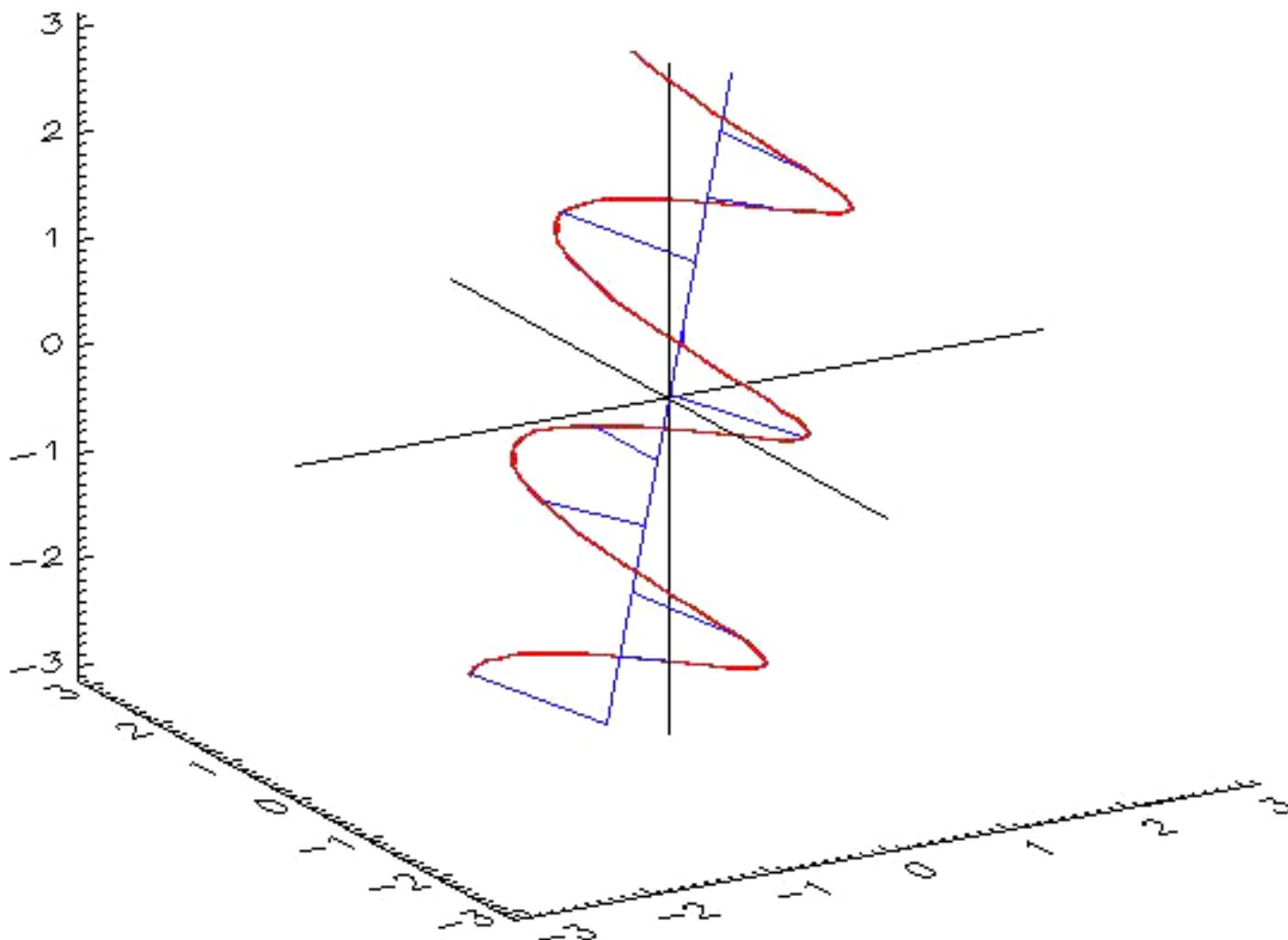


Lyra & Klahr (2011)

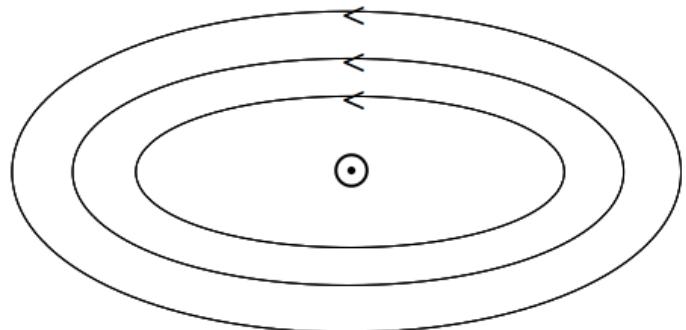
Fluid in rigid rotation supports a spectrum of oscillations



Fluid in rigid rotation supports a spectrum of oscillations

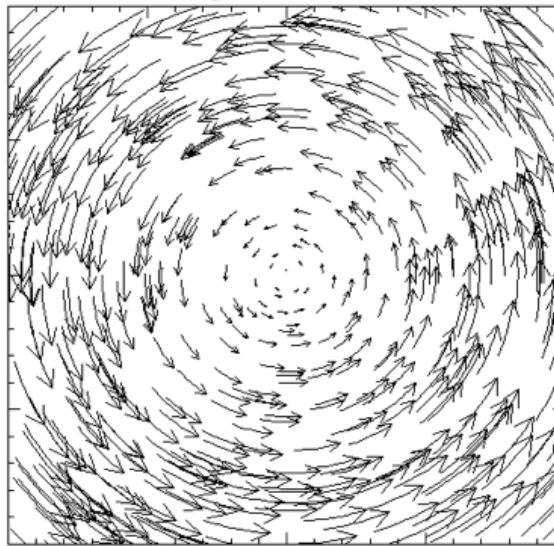


Introducing ellipticity: Strain



$$U = [-(1-\epsilon)y, (1-\epsilon)x]$$

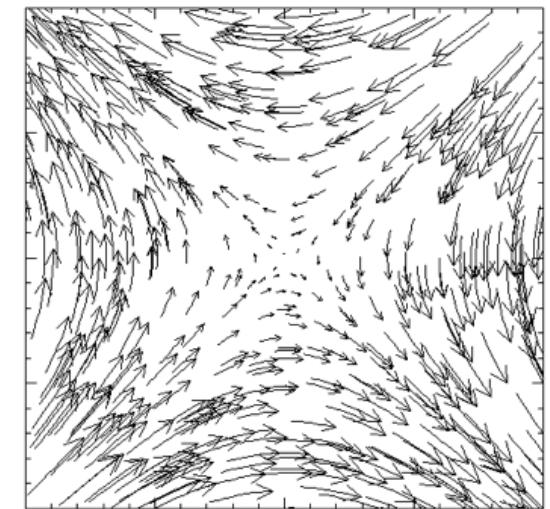
=



$$[-y, x]$$

Rigid rotation

+

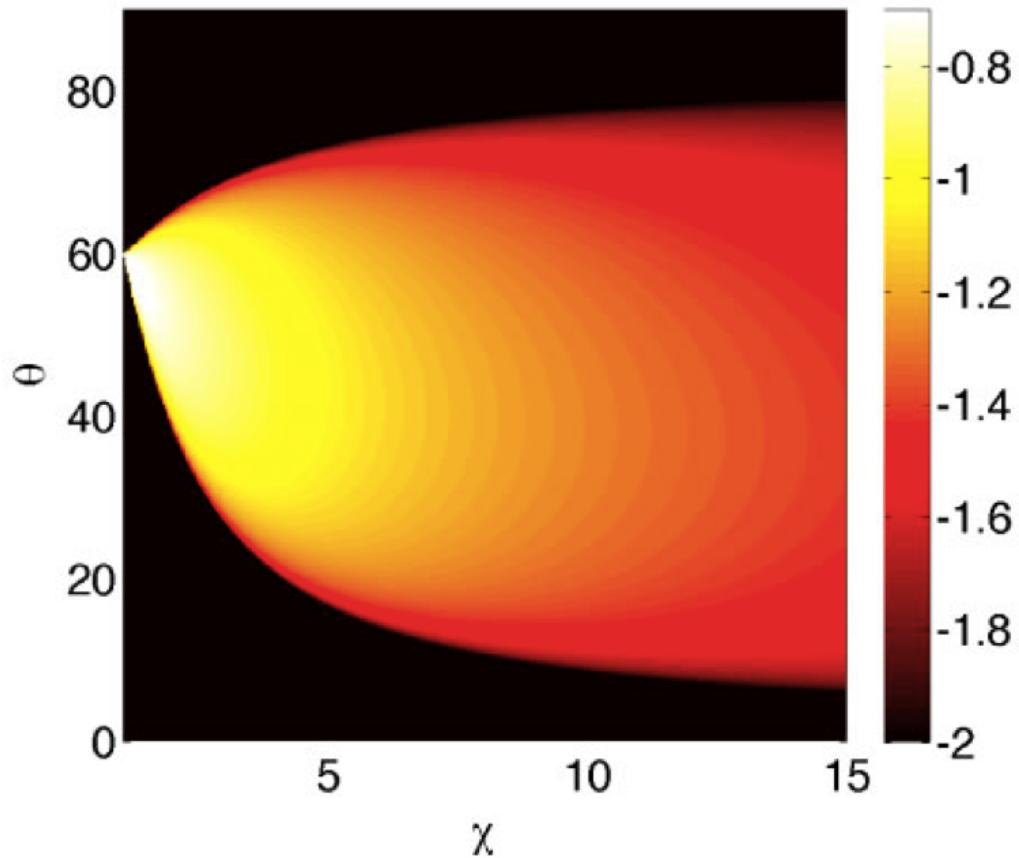


$$-\epsilon [y, x]$$

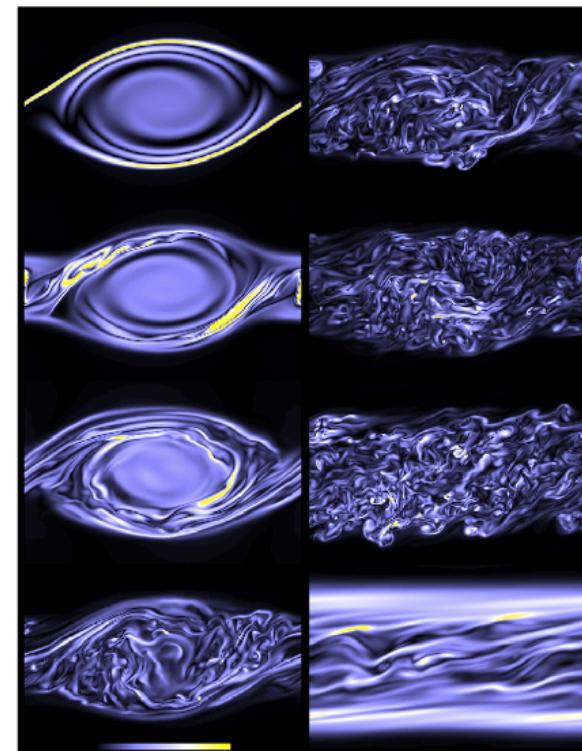
Strain field

Rigid rotation is stable.
Strain is **not** necessarily so.

Elliptic Instability



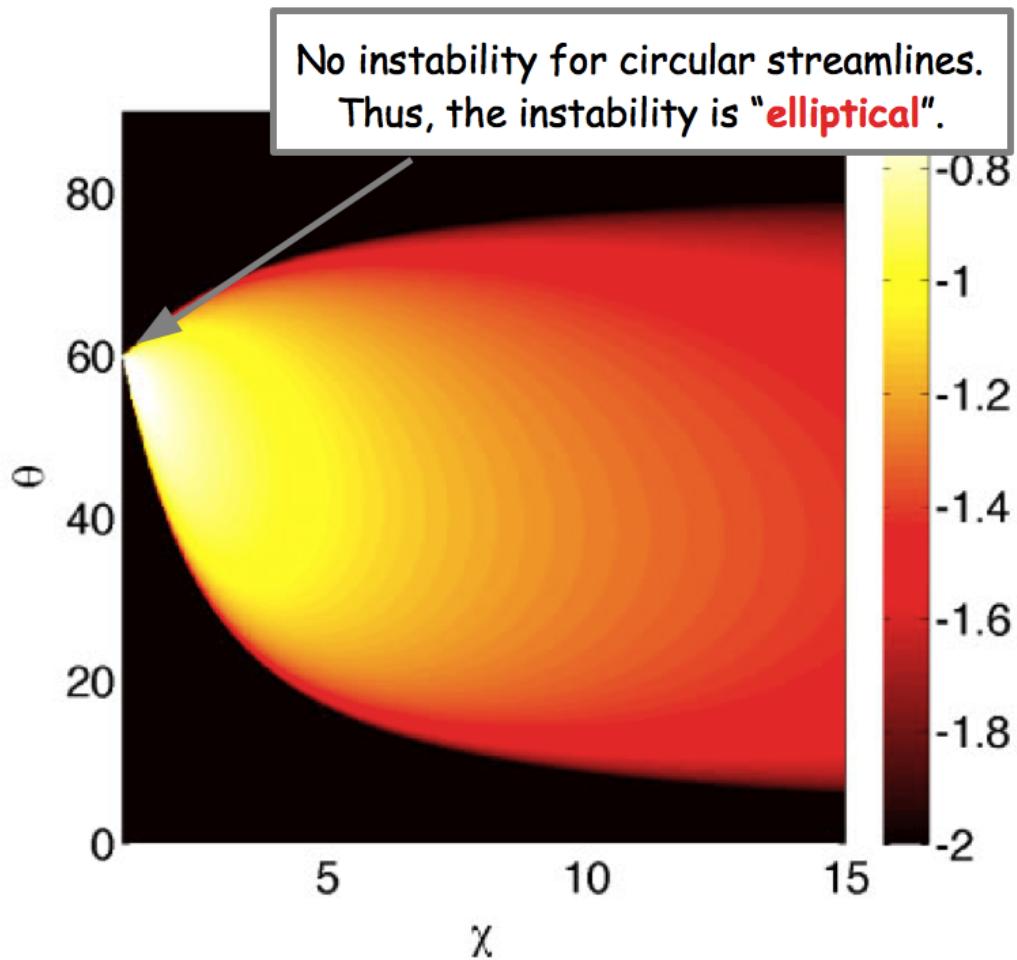
Lesur & Papaloizou (2009)
After Bayly (1986)



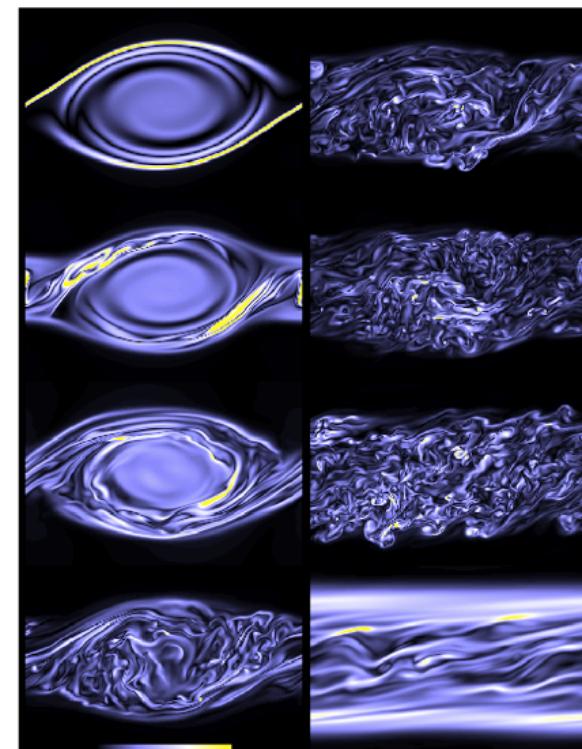
Vortex coherence is destroyed.
Energy cascades forward and dissipates.
The flow relaminarizes.

McWilliams (2010)

Elliptic Instability



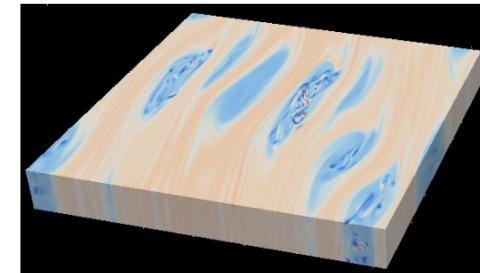
Lesur & Papaloizou (2009)
After Bayly (1986)



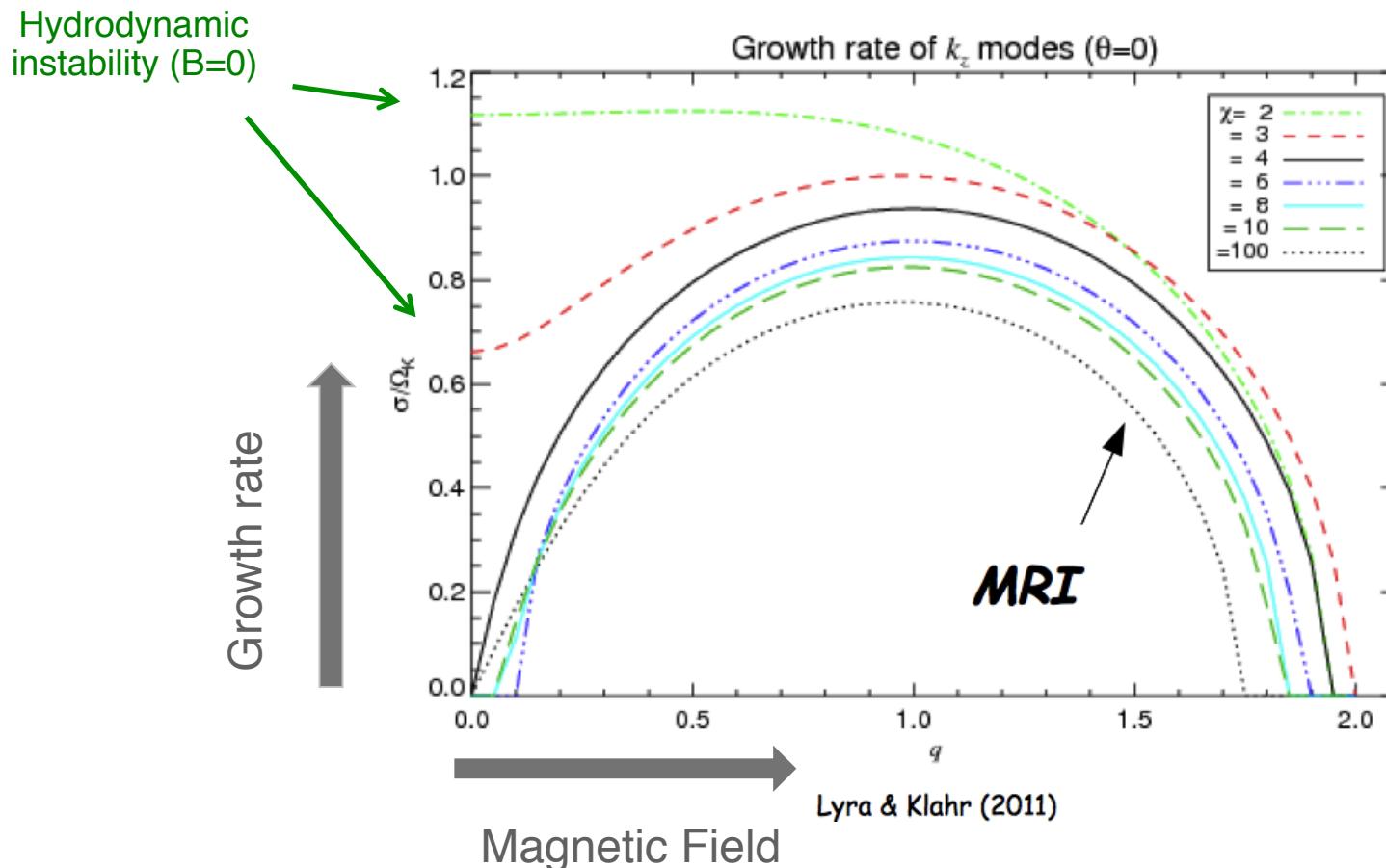
Vortex coherence is destroyed
Energy cascades forward and dissipates
The flow relaminarizes

McWilliams (2010)

“Elliptic” Instability



Lesur & Papaloizou (2010)



See also

Pierrehumbert 1986

Bayly 1986

Kerswell 2002

Lesur & Papaloizou 2009

Lesur & Papaloizou 2010

Lyra & Klahr 2011

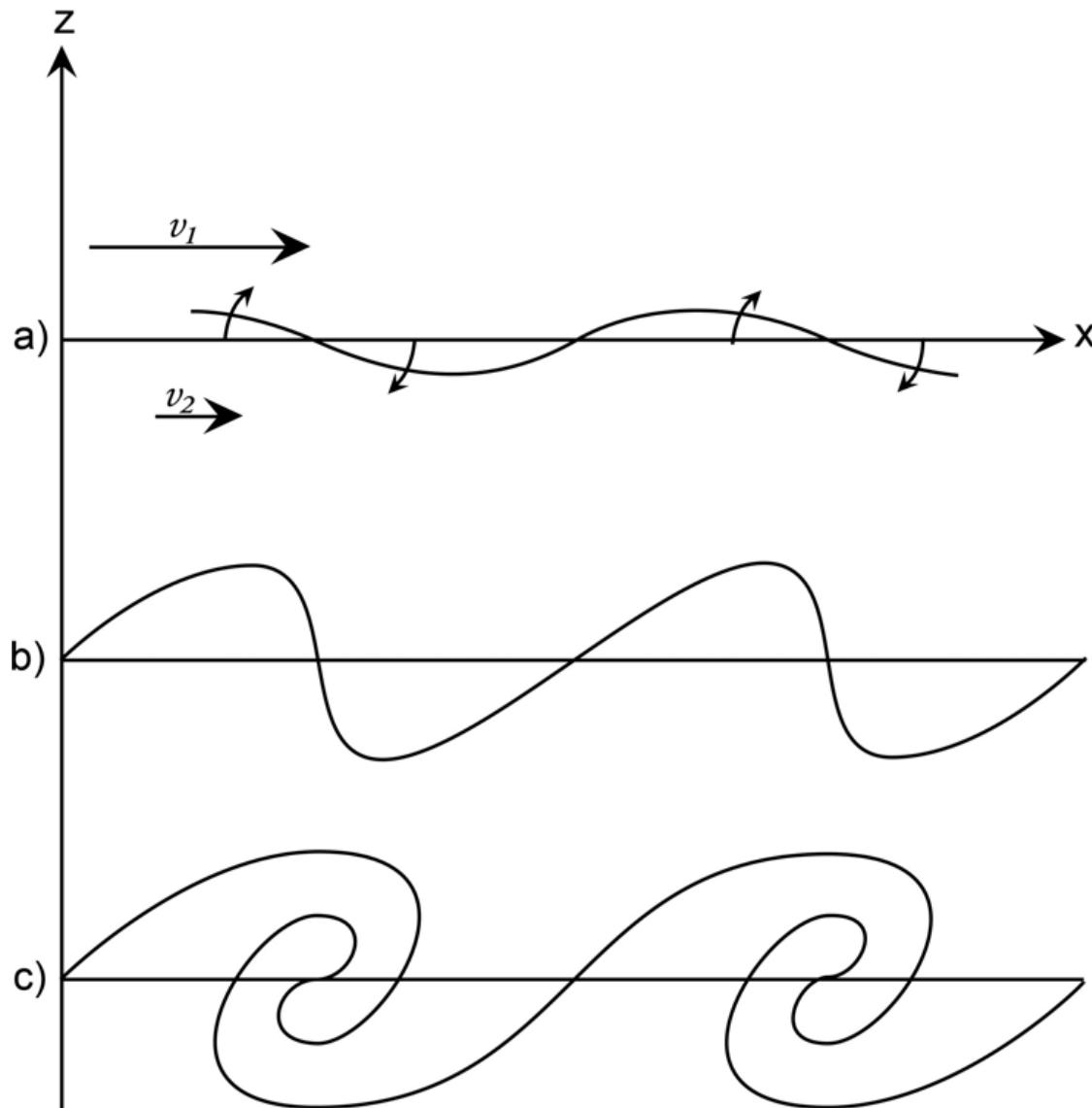
Lyra 2013

Infinitely elongated vortices are equivalent to **shear flows**.

They are subject to an MRI-like instability when magnetized.

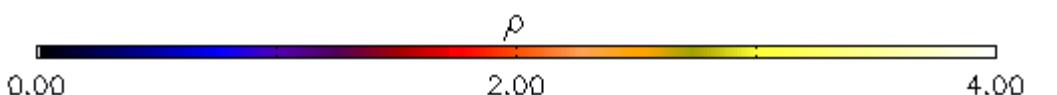
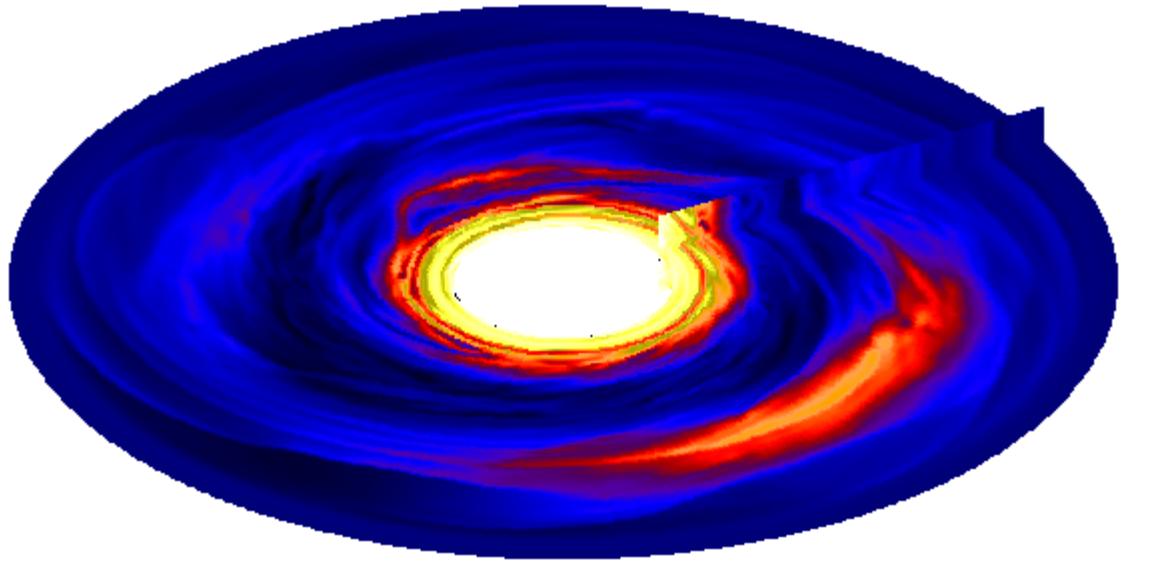
Rossby Wave Instability

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



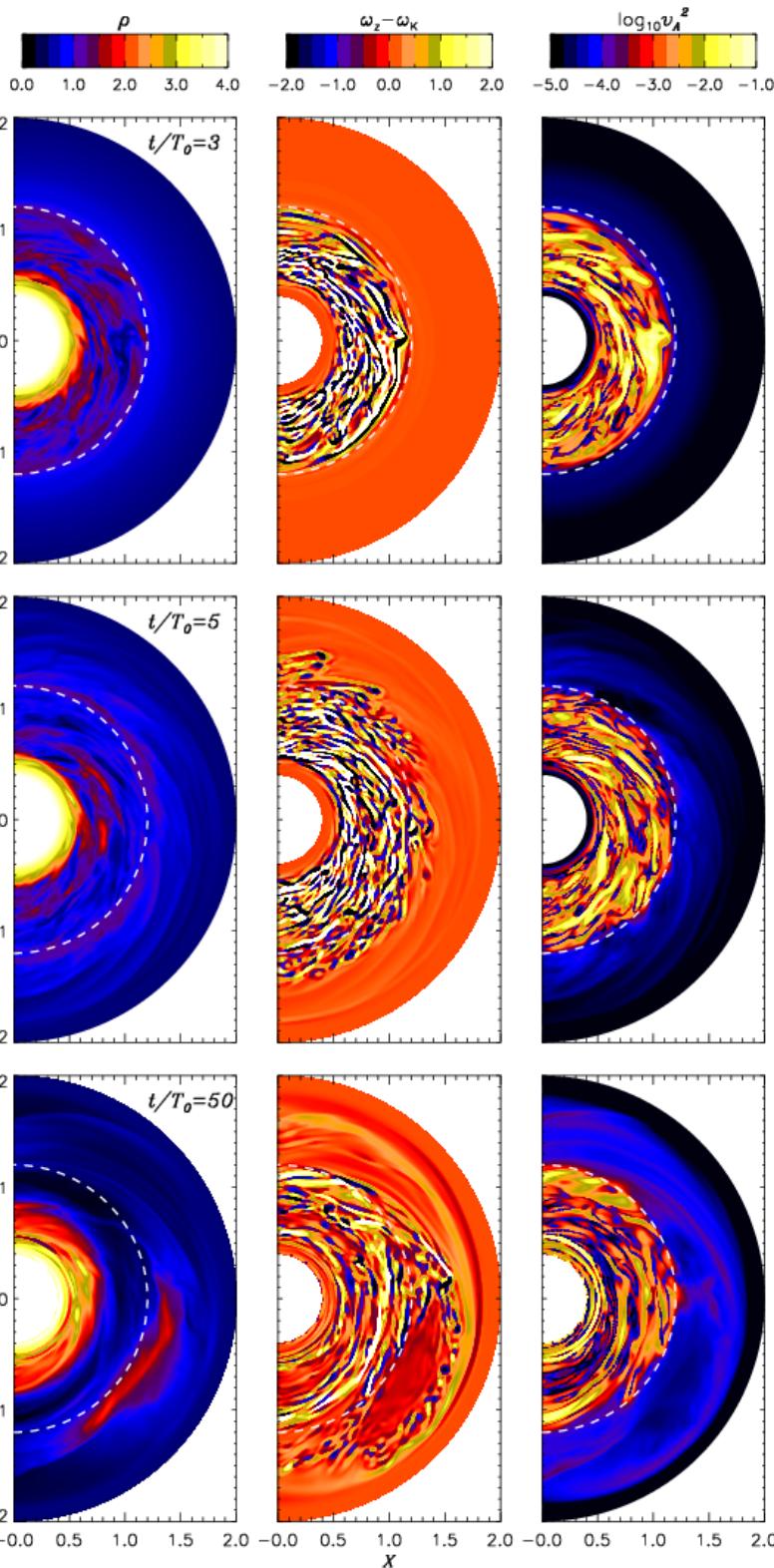
Active/dead zone boundary

$t=22.28 T_0$



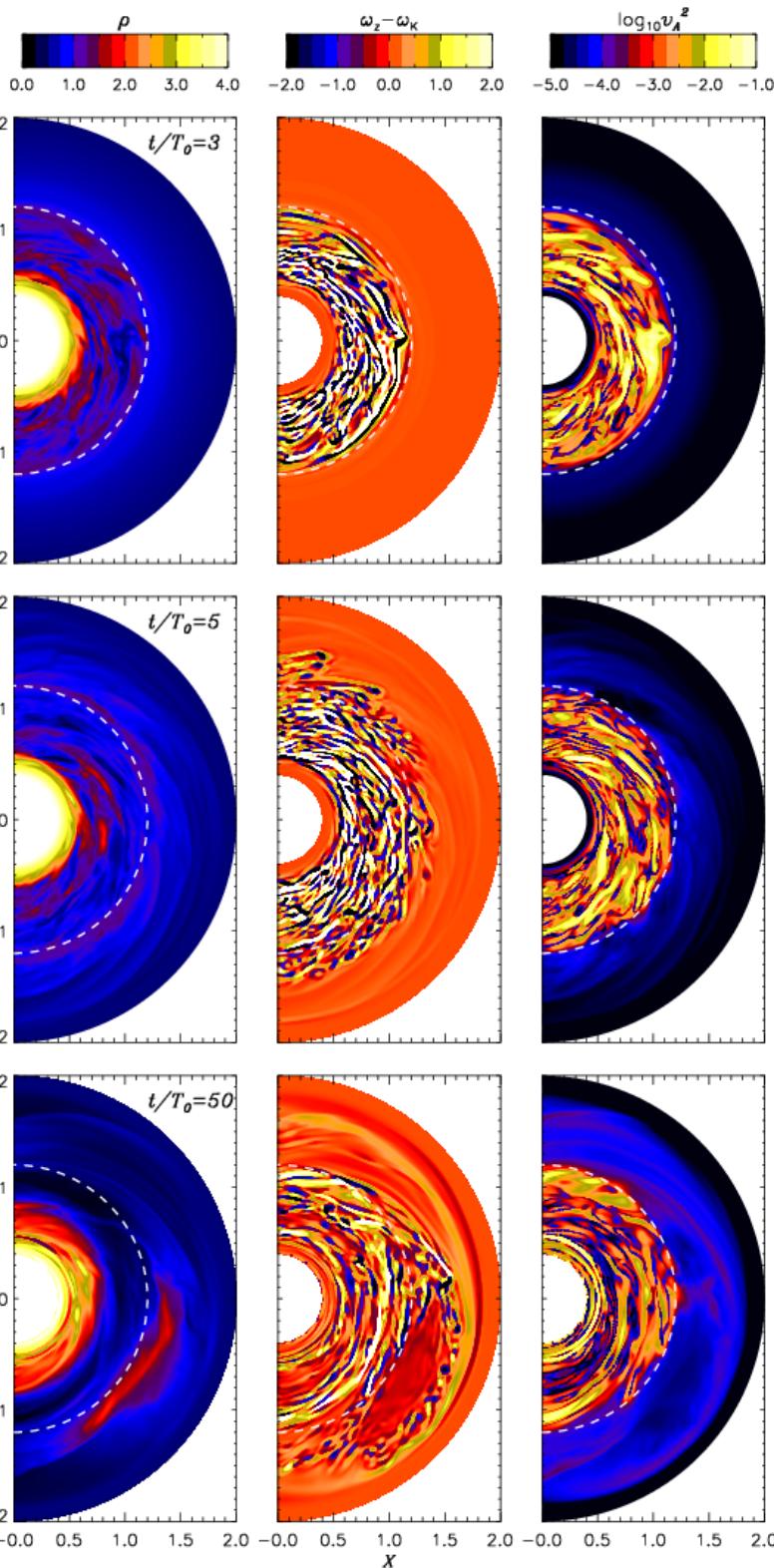
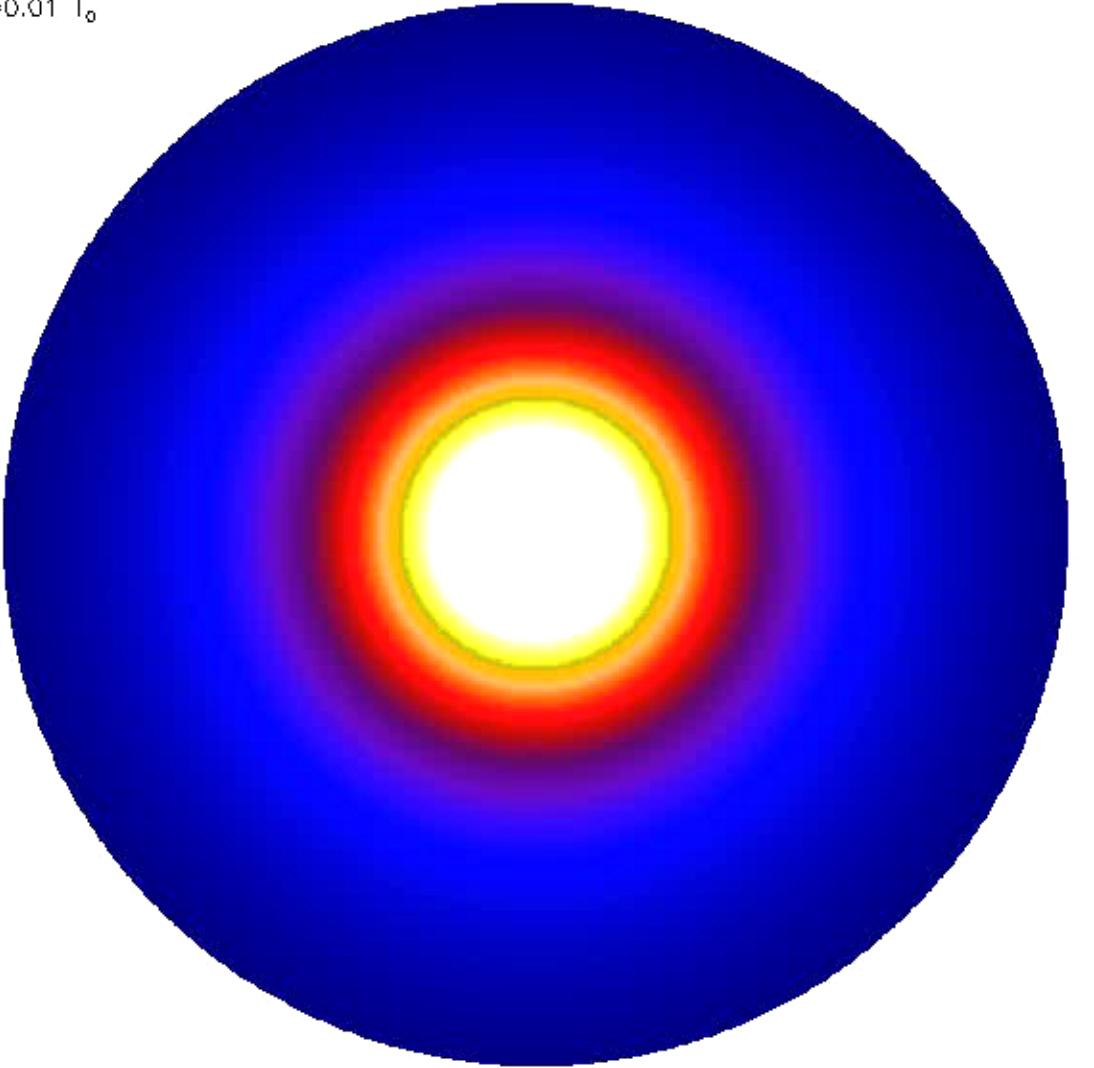
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)



Active/dead zone boundary

$t=0.01 T_0$



Magnetized inner disk + resistive outer disk

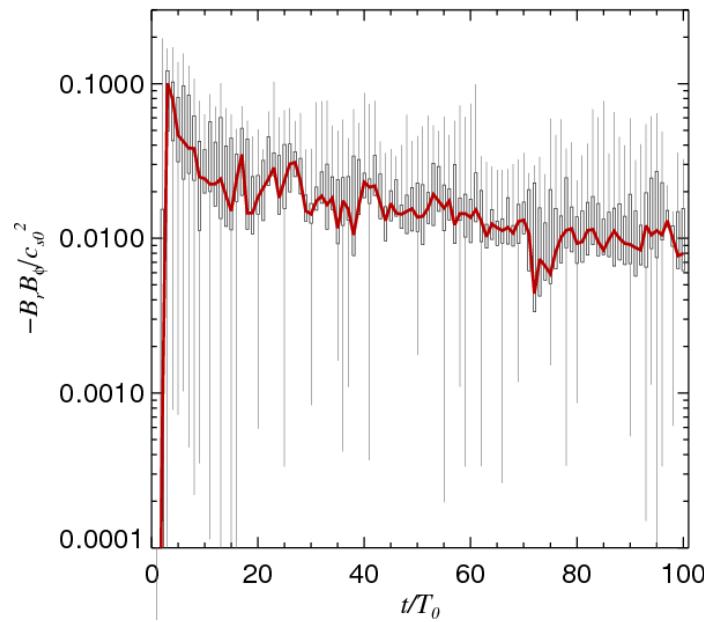
Lyra & Mac Low (2012)

Significant angular momentum transport

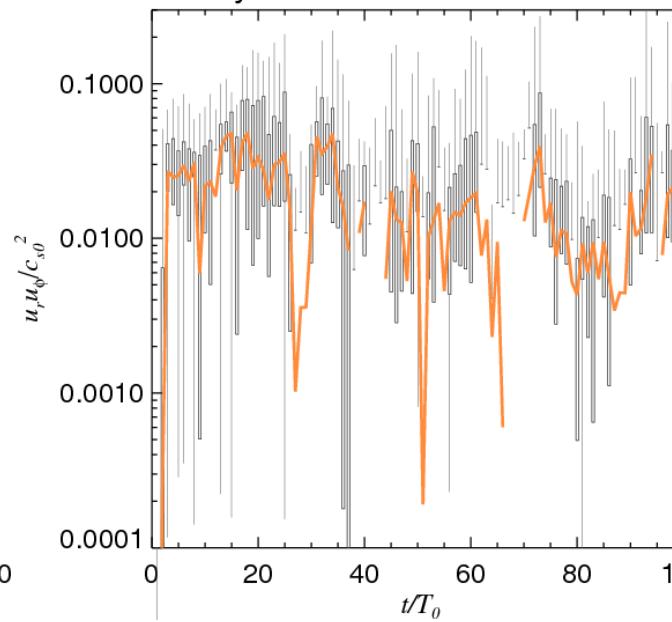
Active zone

Dead zone

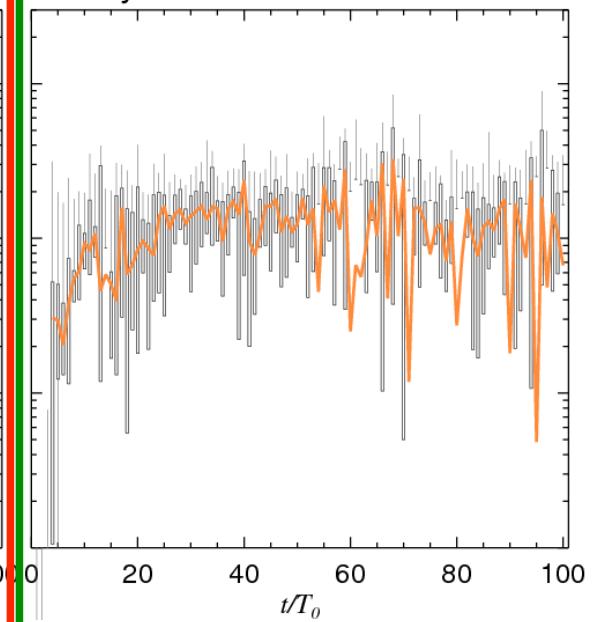
Maxwell stress – active zone



Reynolds stress – active zone

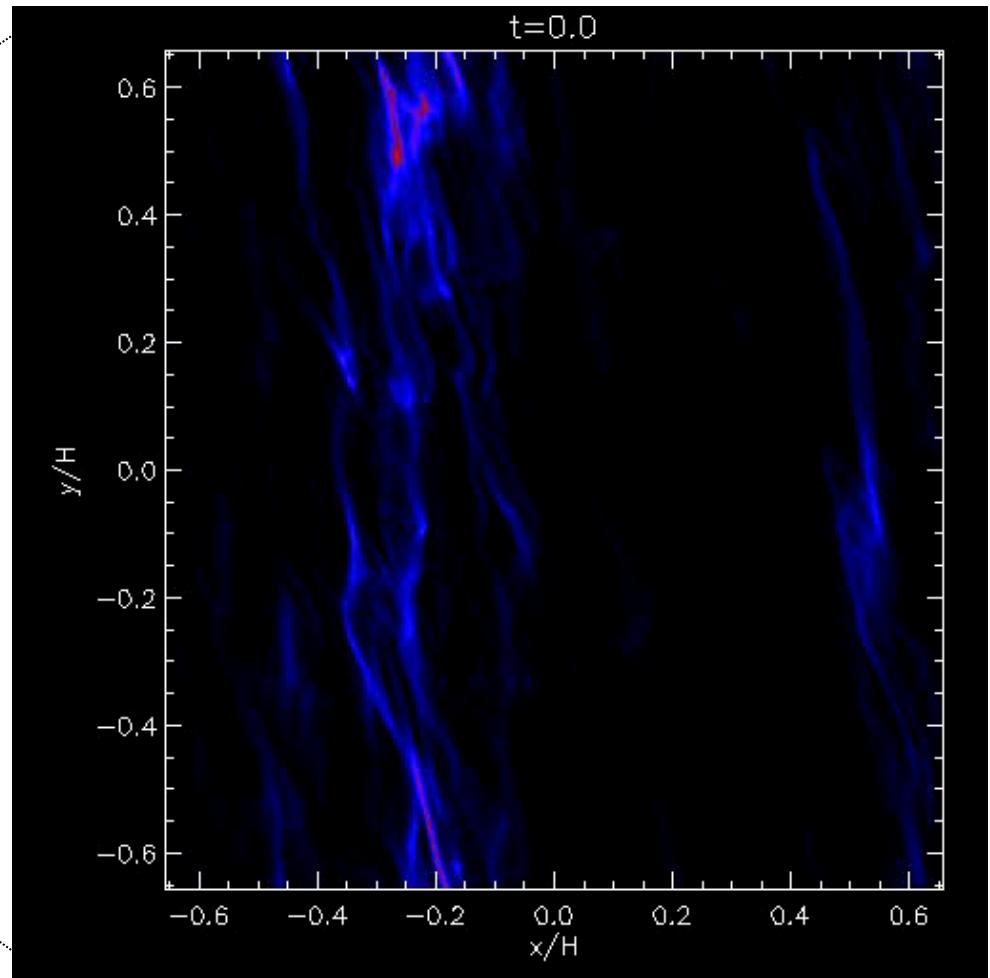
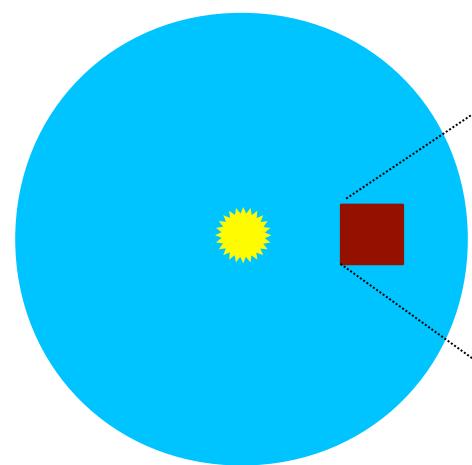


Reynolds stress – dead zone



Large mass accretion rates in the **dead zone,
comparable to the MRI in the **active zone**!**

Gravitational collapse into planetesimals



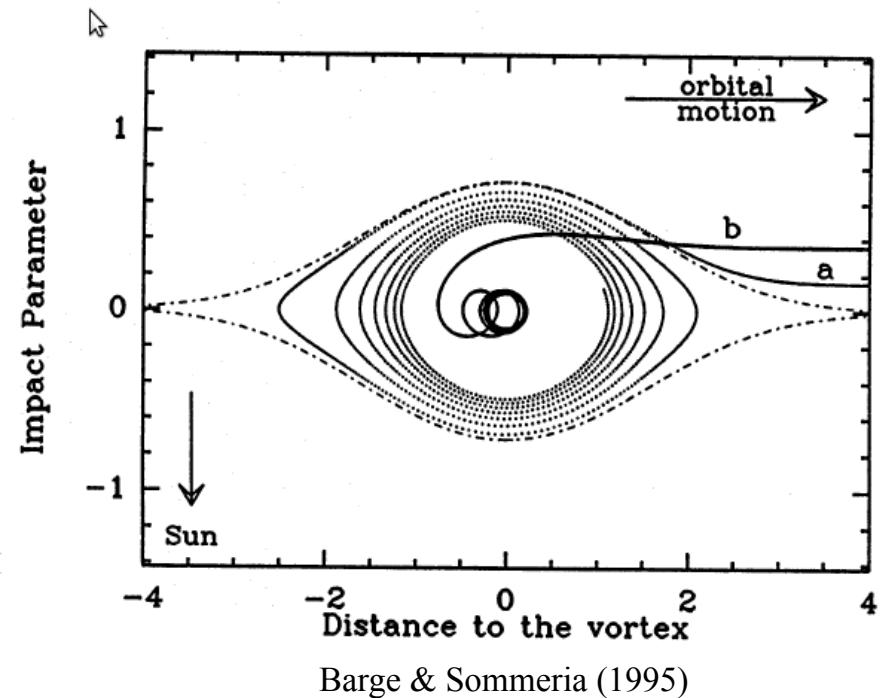
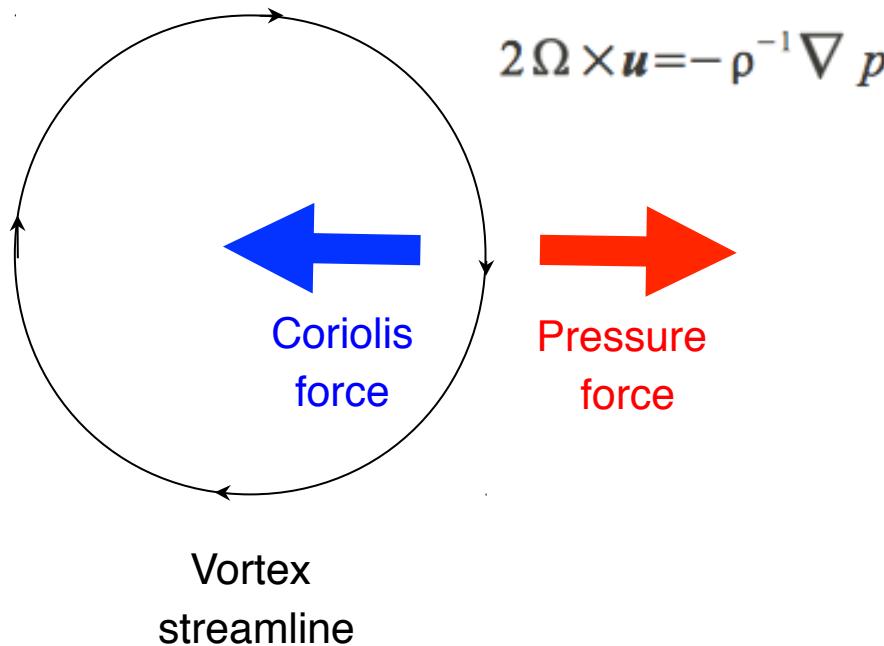
Johansen et al. (2007)

Turbulent eddies concentrate solids,
turning them into planetesimals...

...and vortices are **huge** eddies!

The Tea-Leaf effect

Geostrophic balance:



Barge & Sommeria (1995)

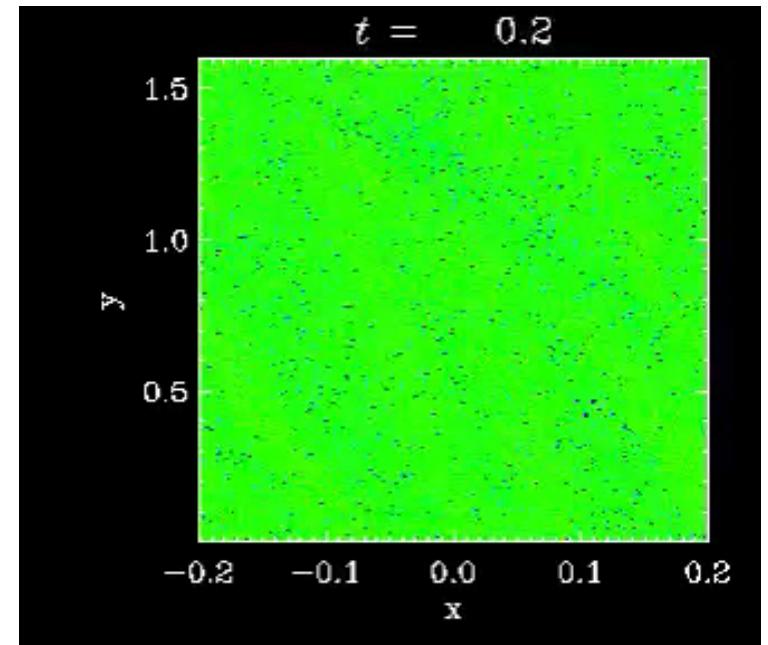
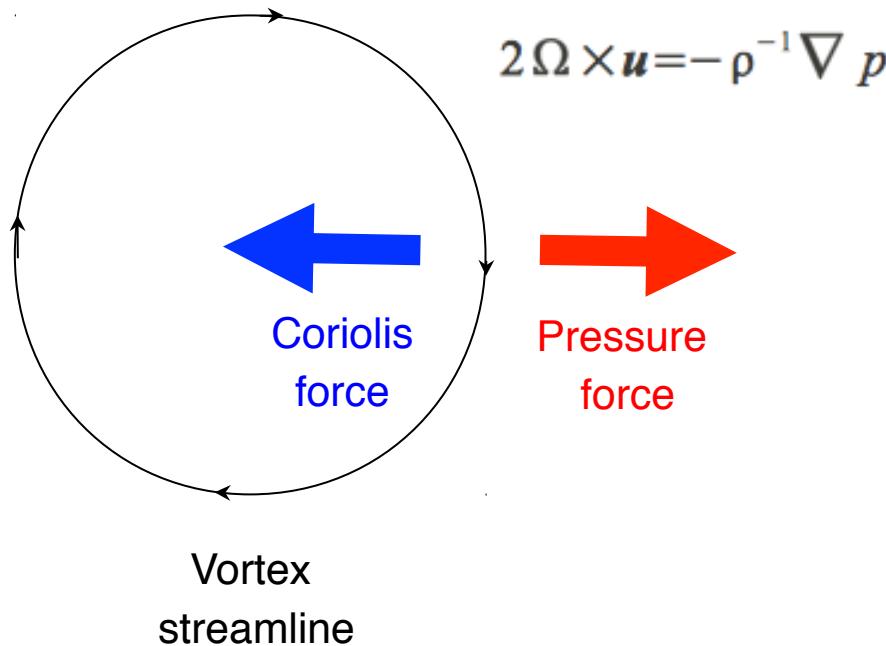
Particles do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation (Barge & Sommeria 1995)

Speed up planet formation enormously
(Lyra et al. 2008b, 2009a, 2009b, Raettig, Lyra & Klahr 2012)

The Tea-Leaf effect

Geostrophic balance:



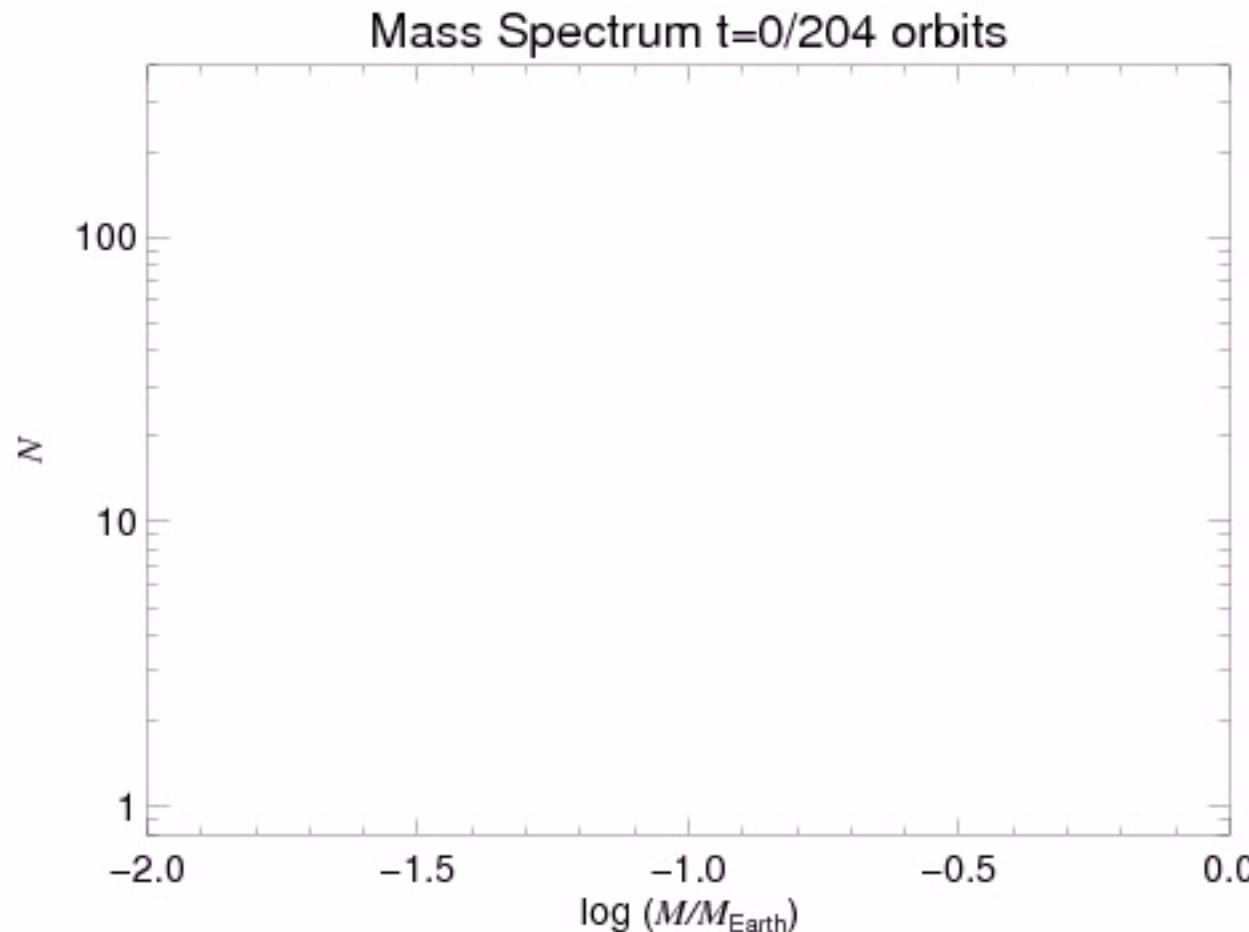
Raettig et al. (2012)

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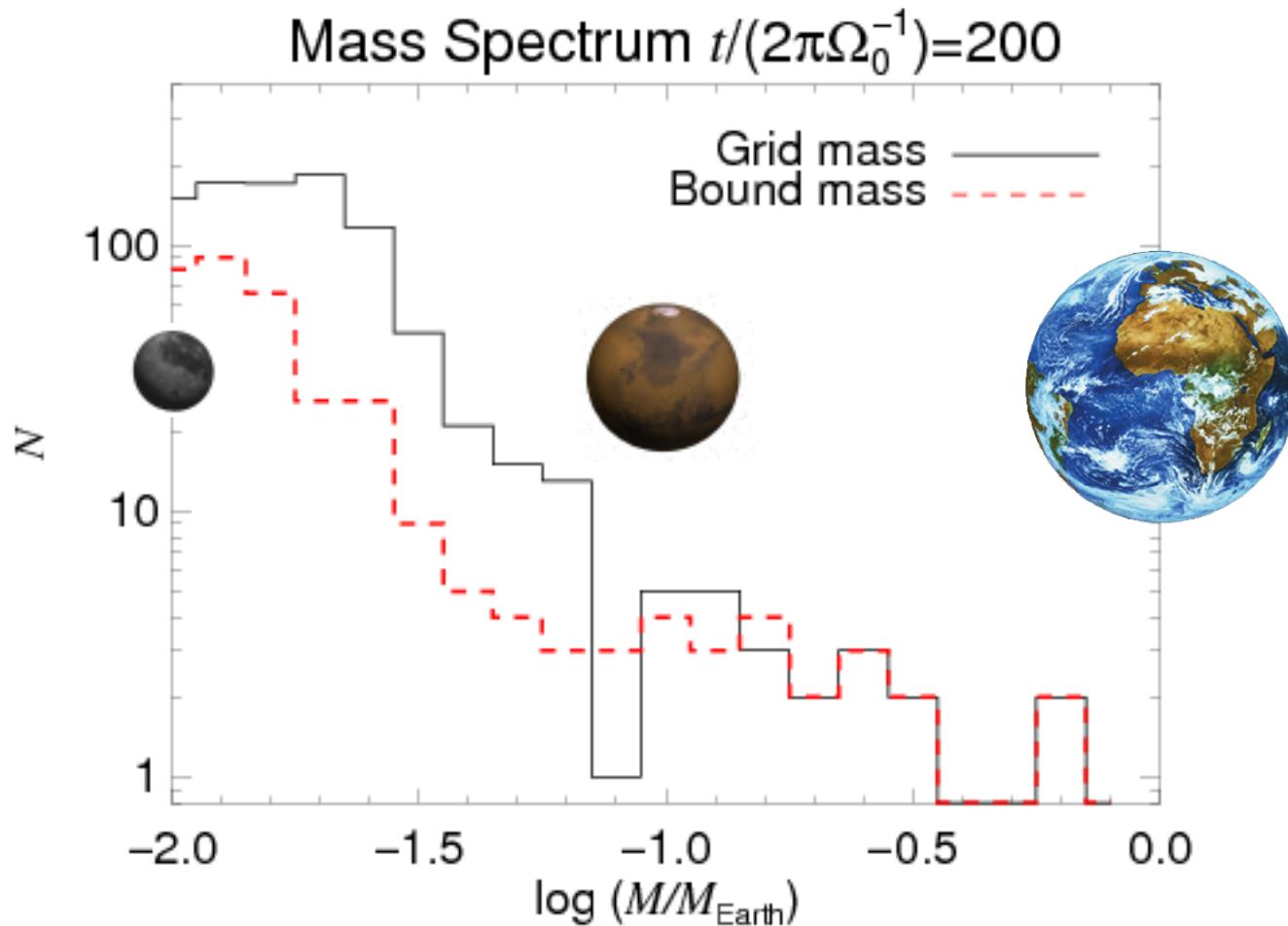
Speed up planet formation enormously
(Lyra et al. 2008b, 2009a, 2009b, Raettig, Lyra & Klahr 2012)

The Initial Mass Function of planets



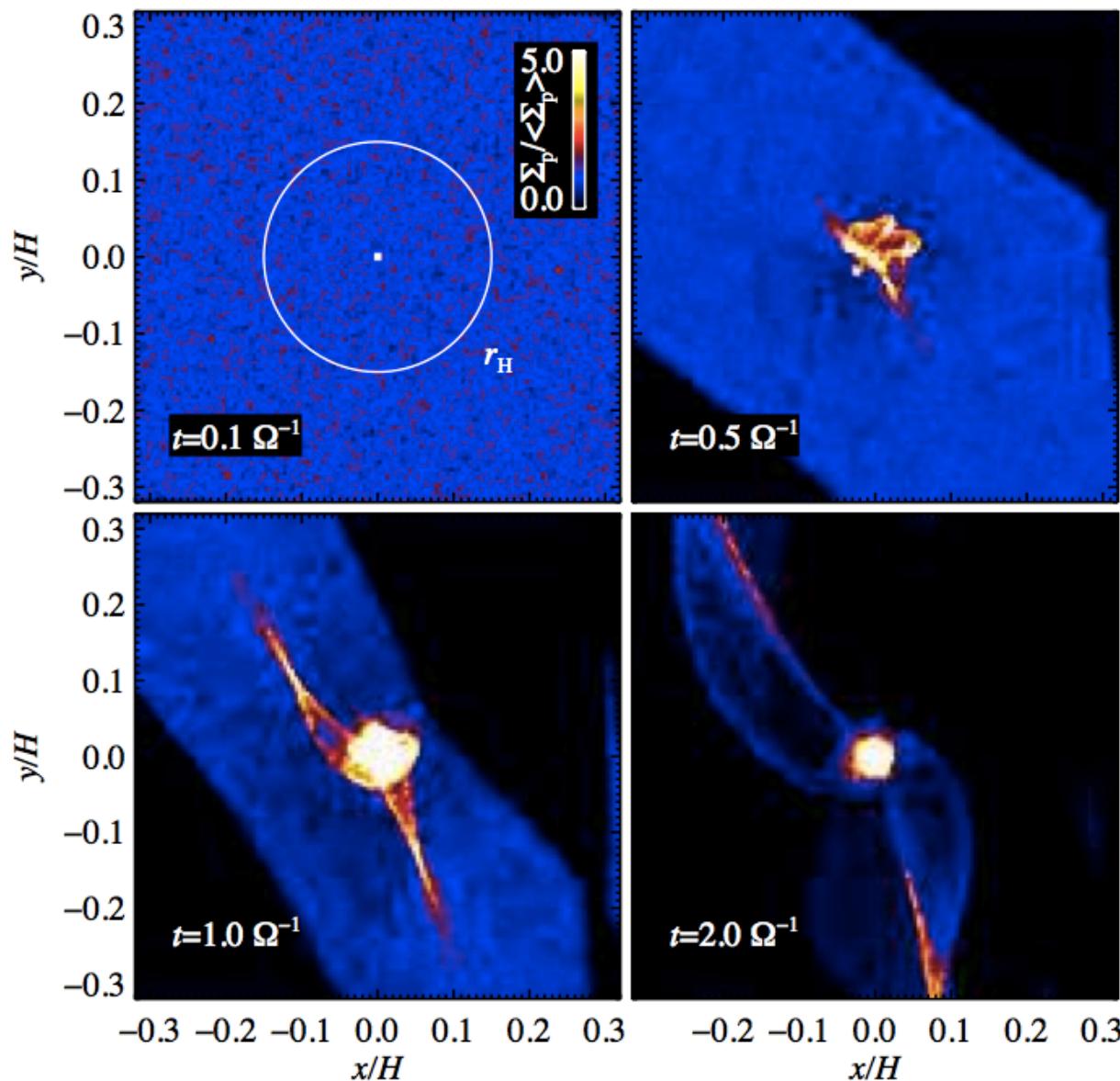
- Mass spectrum by the end of the simulation
 - 300 bound clumps were formed
- Power law $d(\log N)/d(\log M) = -2.3 \pm 0.2$
- 20 of these are more massive than Mars

The Initial Mass Function of planets



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Rapid formation of planetary cores

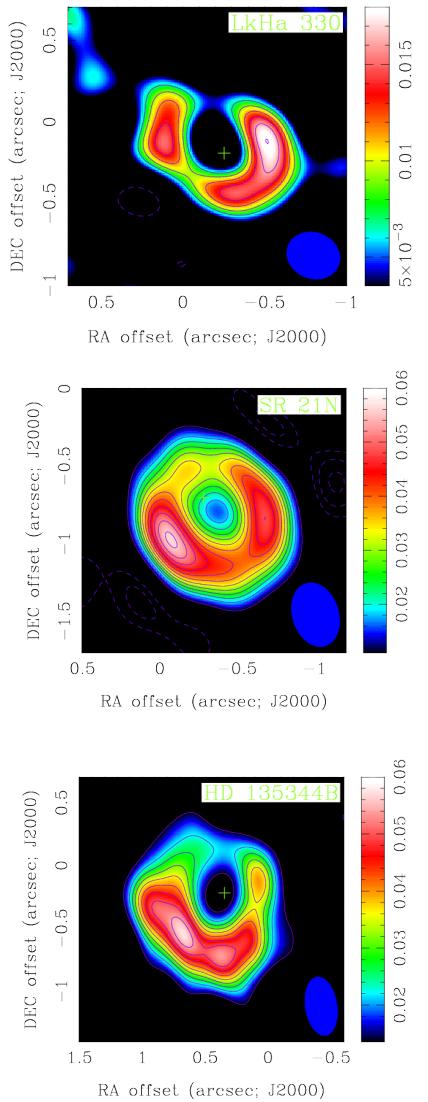


Lambrechts & Johansen (2012)

A possible detection of vortices in disks?

Observations

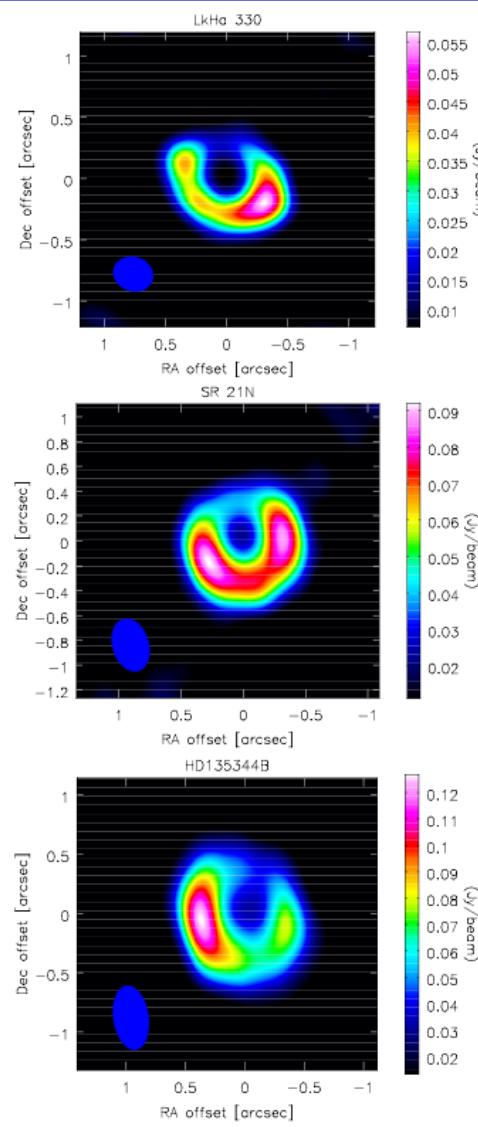
Brown et al. (2009)



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

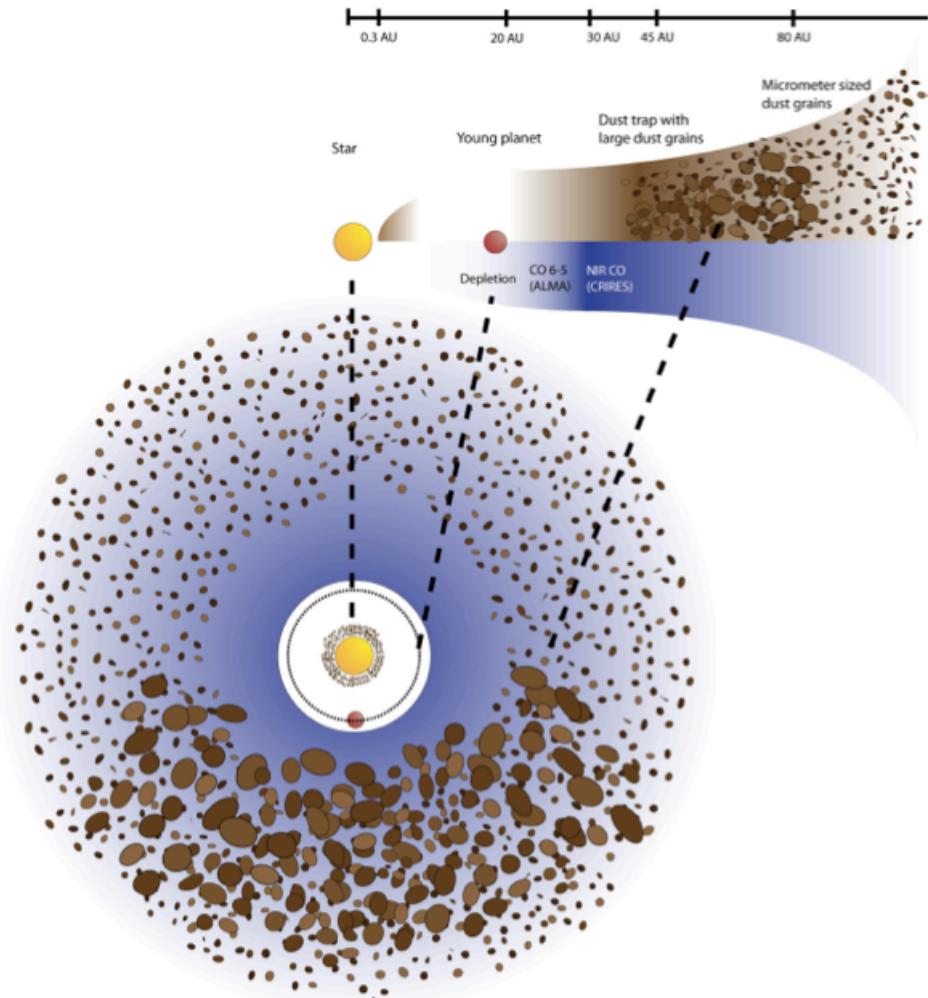
iencemag.org SCIENCE VOL 340 7 JUNE 2013

1199

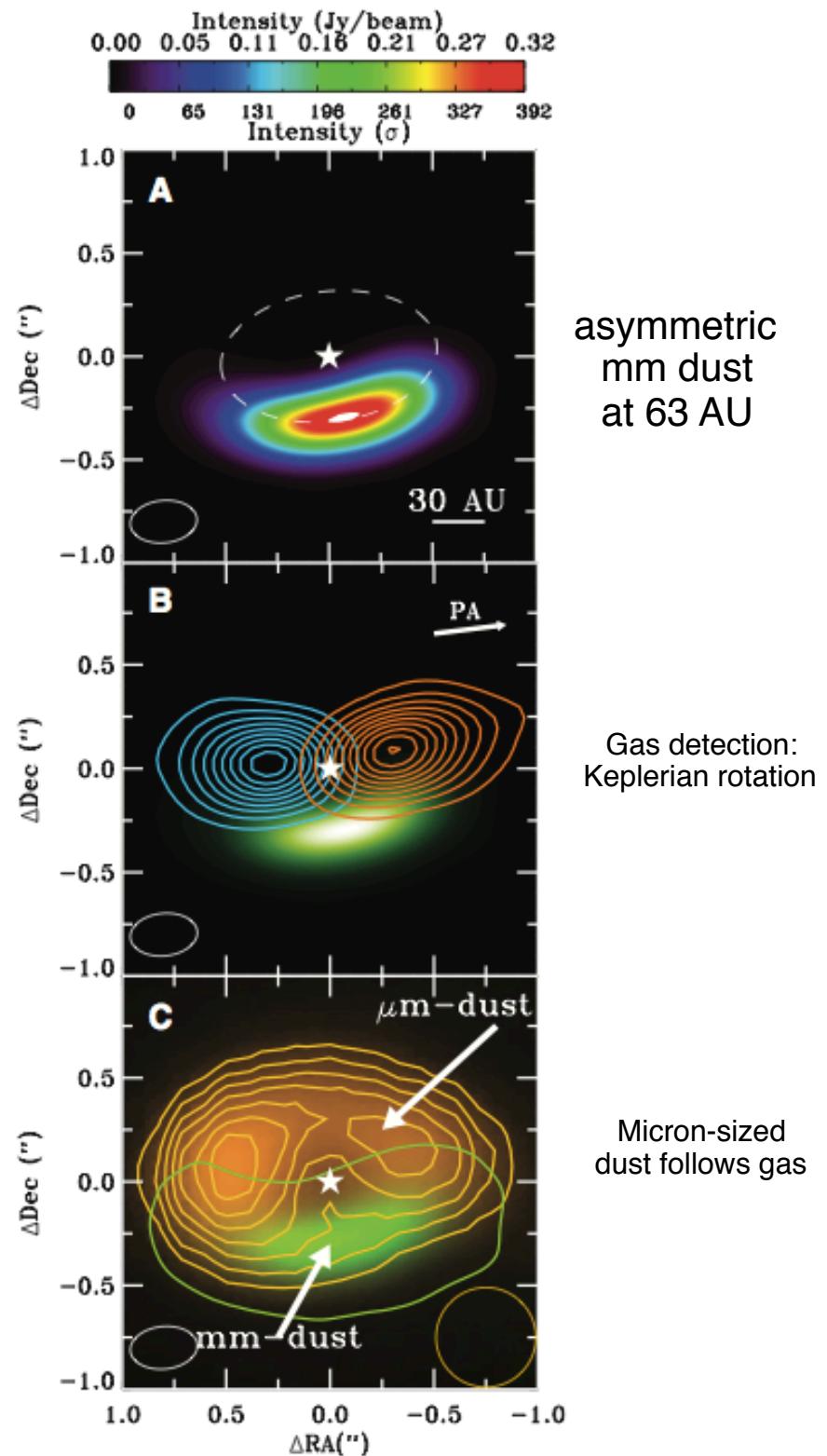
van der Marel et al. 2013

A possible huge vortex observed with ALMA

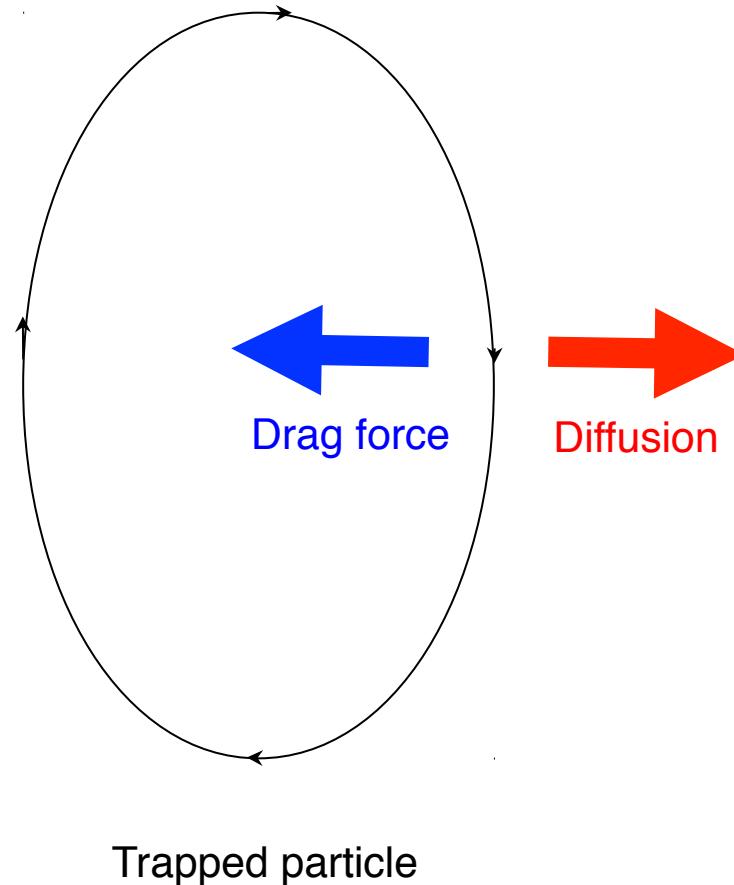
The Oph IRS 48 “dust trap”



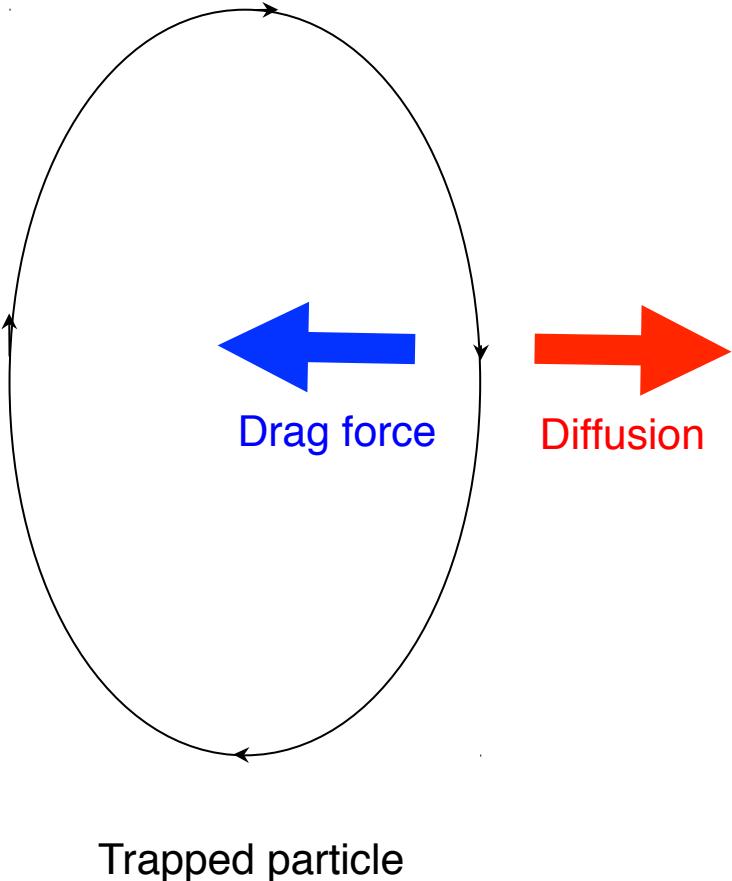
van der Marel et al. (2013)



Drag-Diffusion Equilibrium



Drag-Diffusion Equilibrium



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

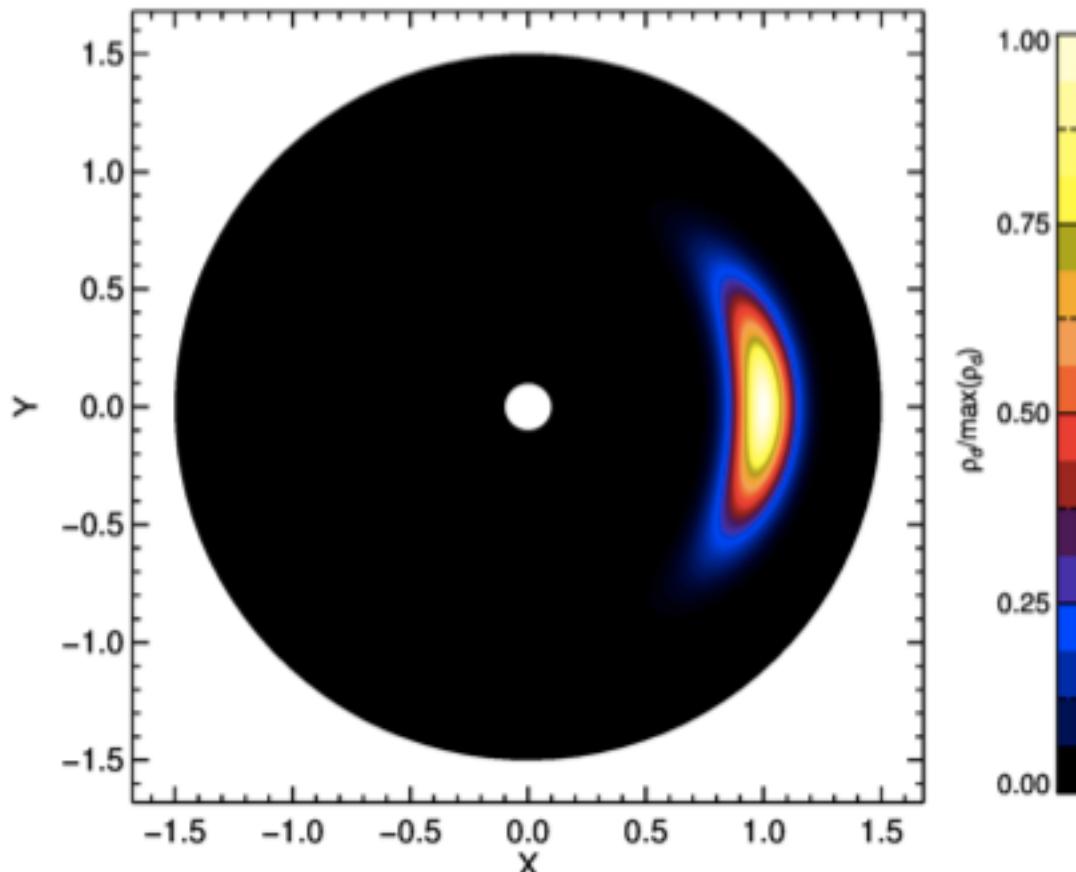
Lyra & Lin (2013)

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

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

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

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

Solution

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

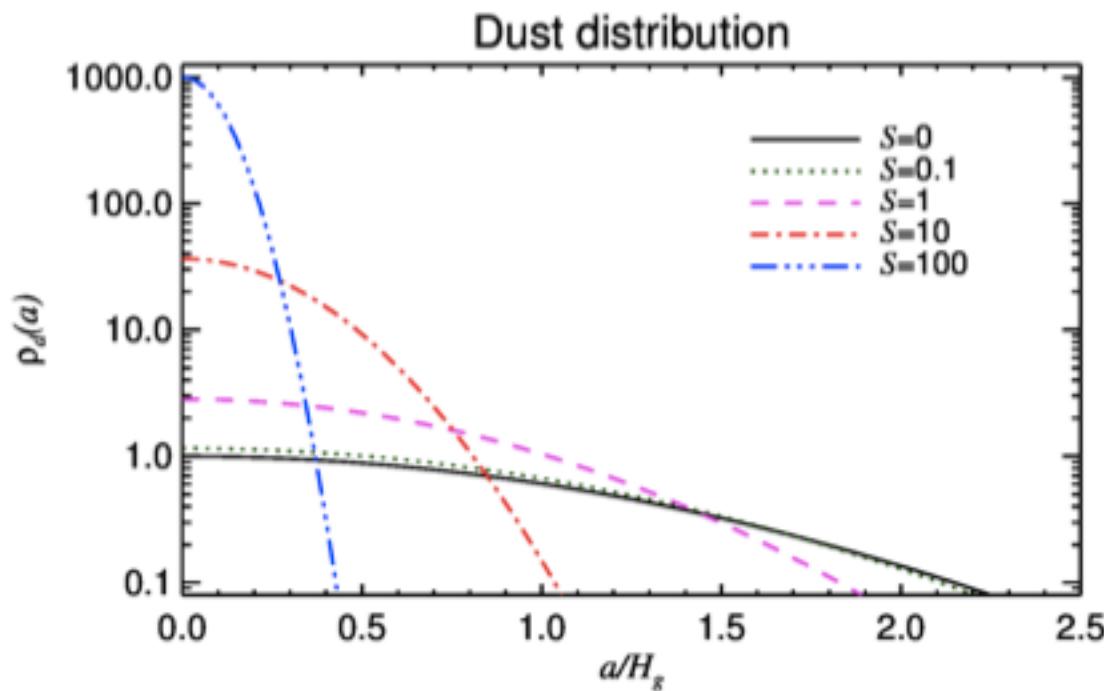
$$H_V = \frac{H}{f(\chi)} \sqrt{\frac{1}{S+1}}$$

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

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

- a = vortex semi-minor axis
 H = disk scale height (temperature)
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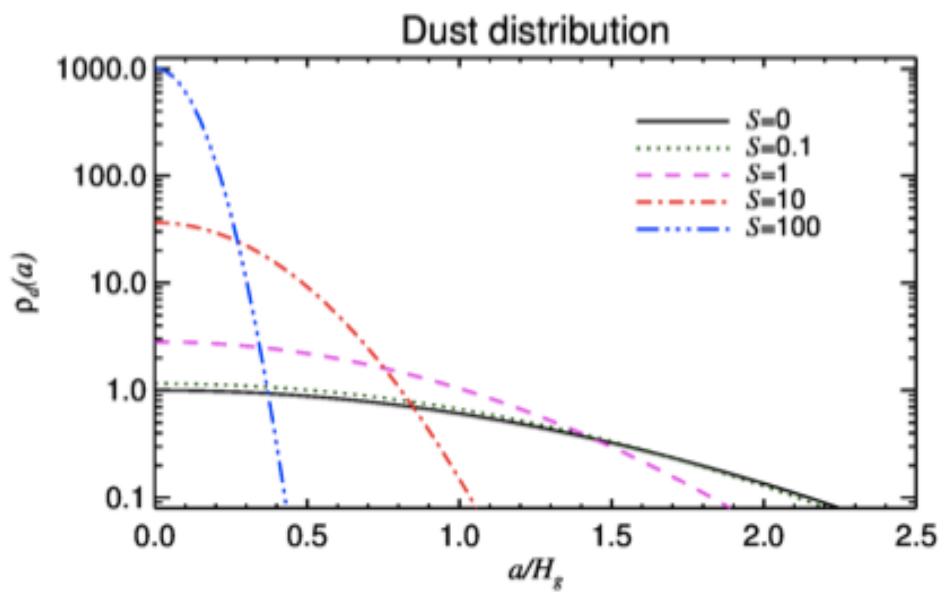
Analytical solution for dust trapping



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

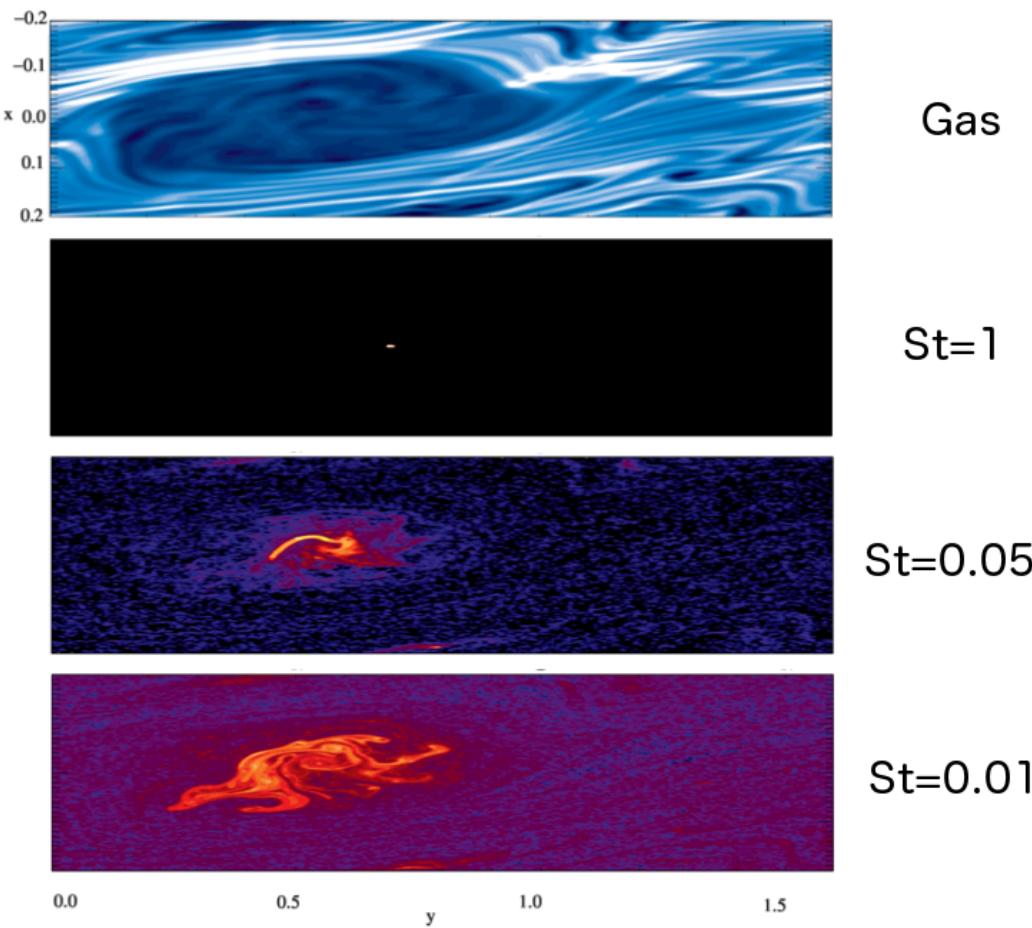
$$\delta = v_{\text{rms}}^2 / c_s^2,$$

Analytical vs Numerical



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

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



Derived quantities

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

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: $9 M_{Earth}$

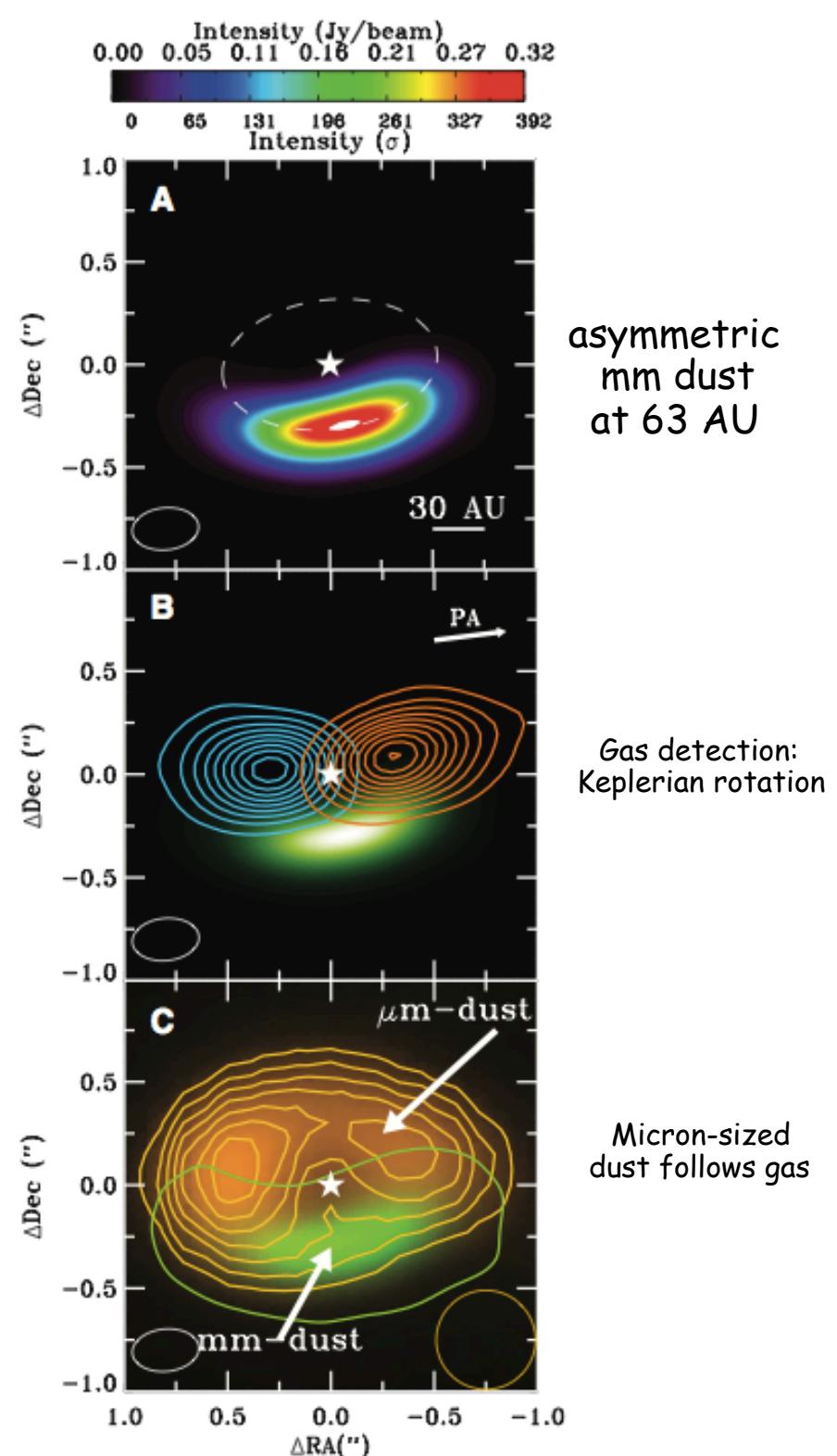
Derived parameters

$S=4.8$

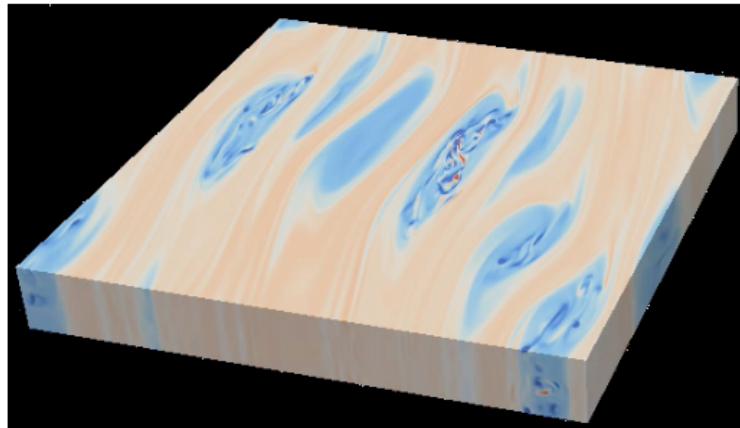
Stokes number, $St=0.008$

$d = 0.005$, $V_{rms} = 4\% C_s$

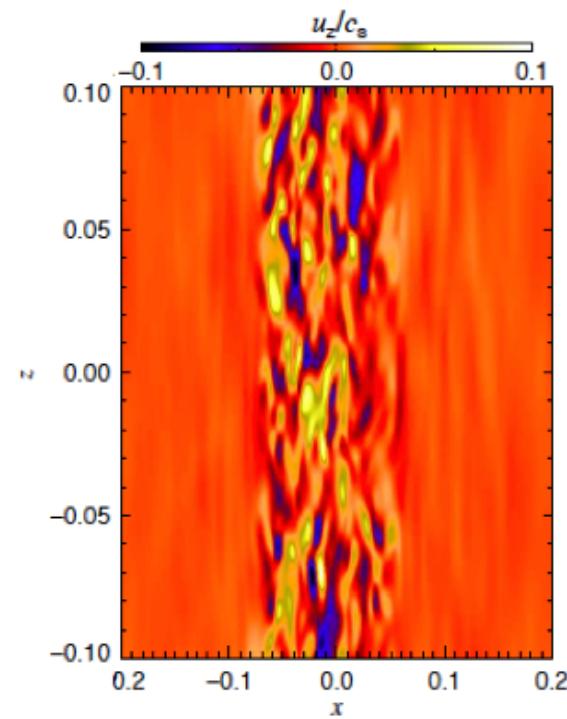
Trapped mass: $11 M_{Earth}$



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

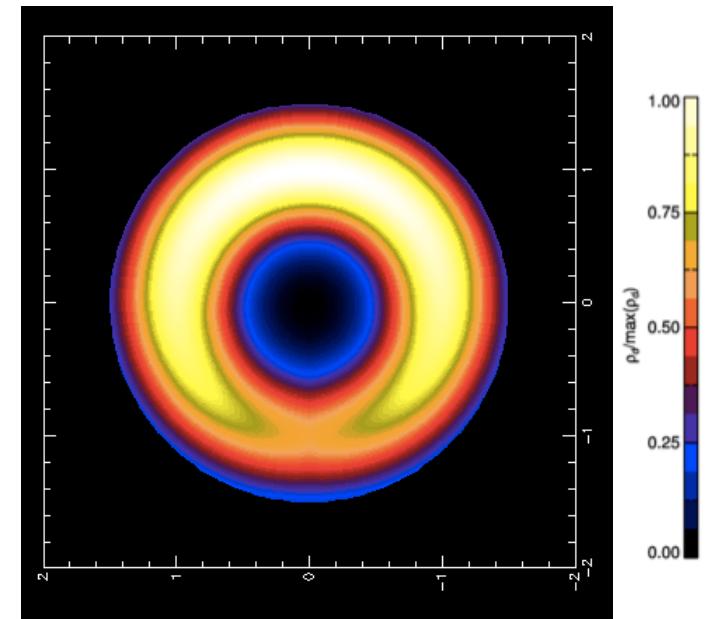
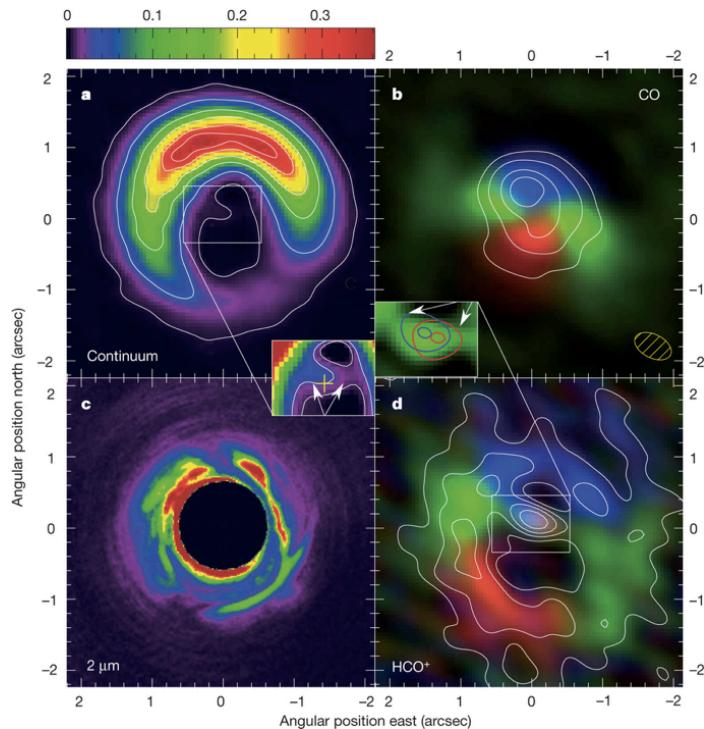
Temperature: 25K

Derived parameters

$S=3.5$

Stokes number, $St=0.004$

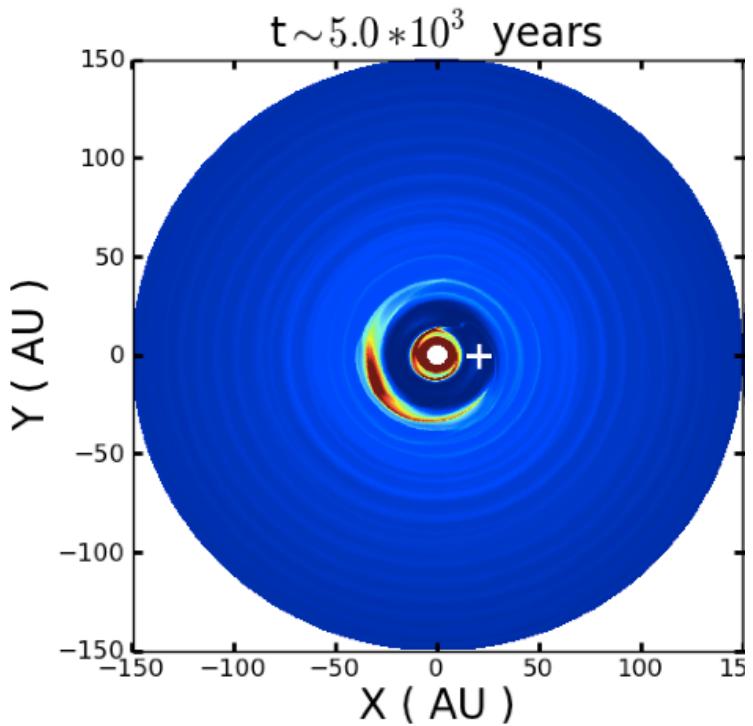
$\delta = 0.001$, $v_{rms} = 4\% cs$



It seems to have the properties
of vortices.

But... is it really a vortex?

The dust trap is too far from the planet!



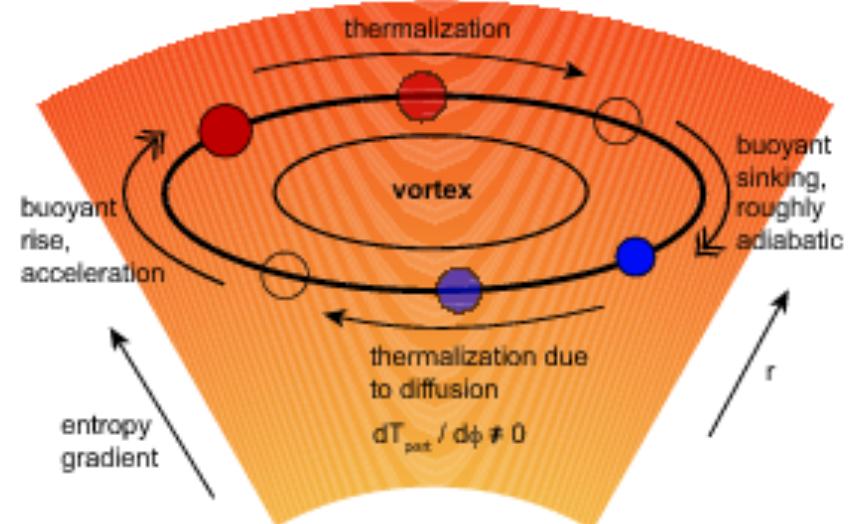
A gap in gas emission suggests
a 10 MJ planet at **15-20 AU**.

The trap is centered at **63 AU**.

Baroclinic instability

1. Radial entropy gradient
2. Thermal diffusion

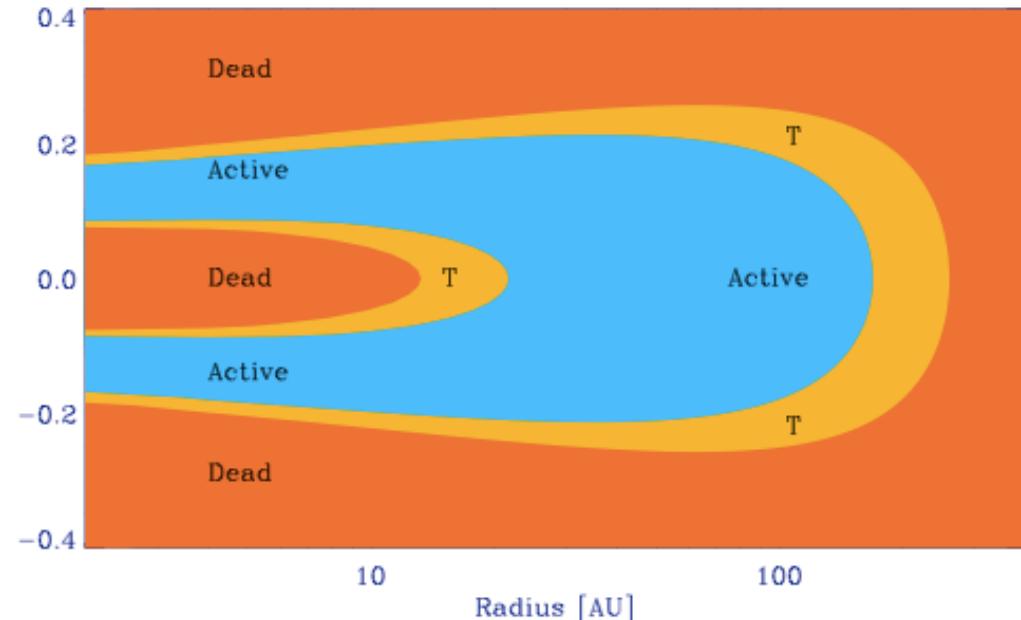
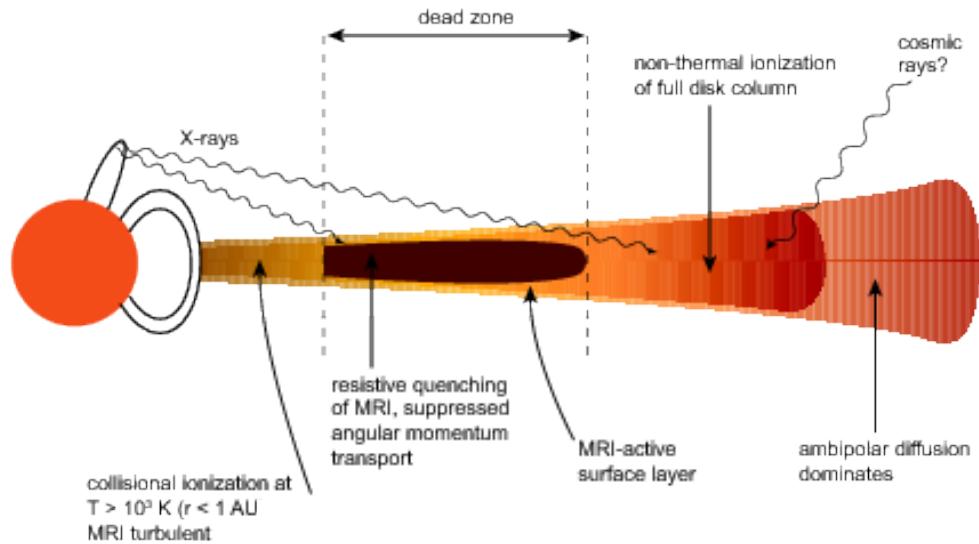
$$t_{\text{rad}} = \frac{c_v \sum \tau_{\text{eff}}}{6\sigma T^3}$$



The thermal diffusion time
for the gas in IRS Oph 48 is
0.1 orbits.

Too close to isothermal for the baroclinic instability.

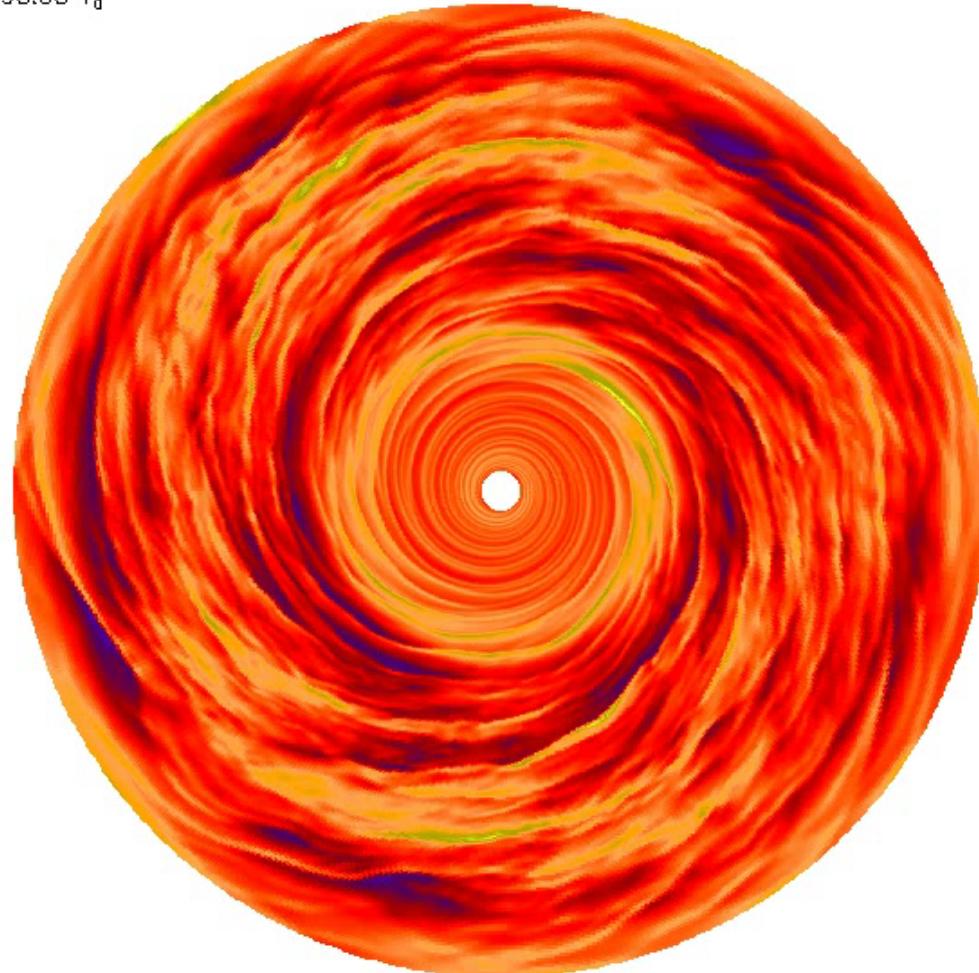
Outer Dead/Active zone transition RWI fails!



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

Outer Dead/Active zone transition RWI does *NOT* fail!

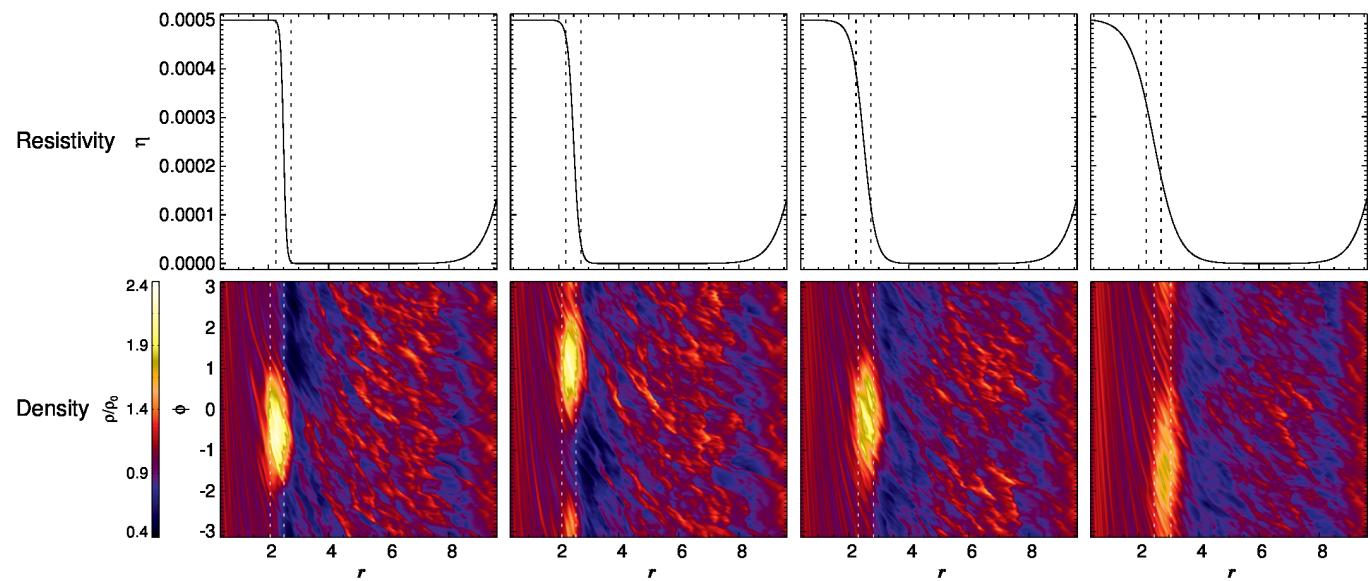
$t=95.58 T_0$



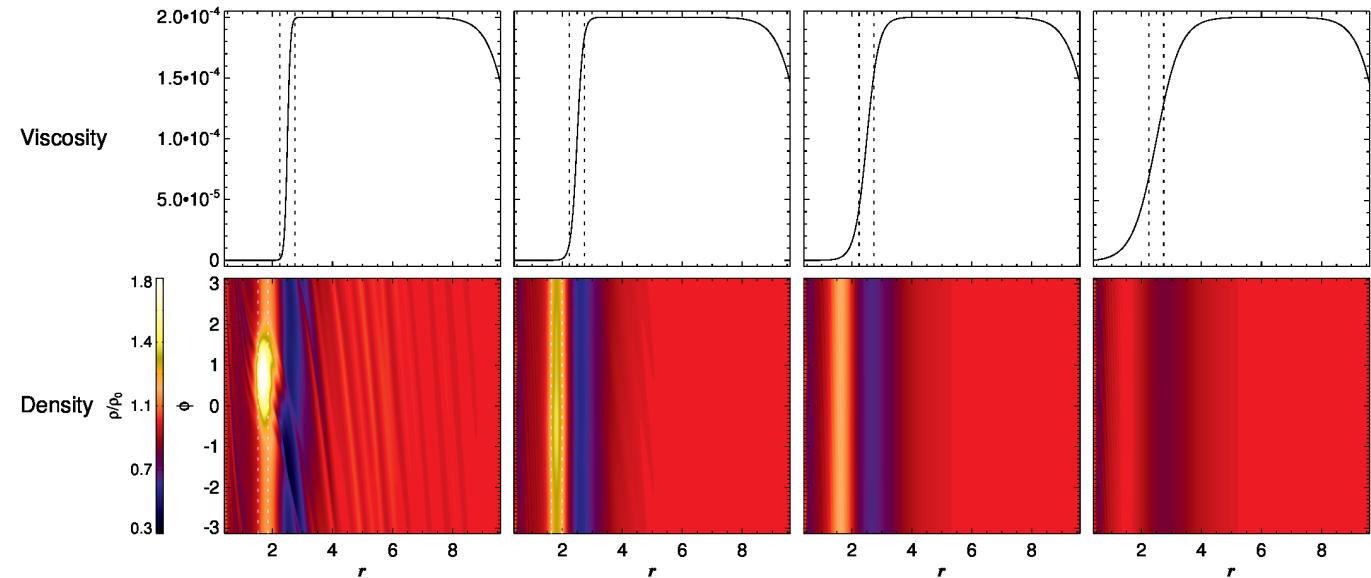
Resistive inner disk + magnetized outer disk
Lyra & Turner (2014, submitted)

Outer Dead/Active zone transition RWI

MHD



Hydro



Outer Dead/Active zone transition RWI

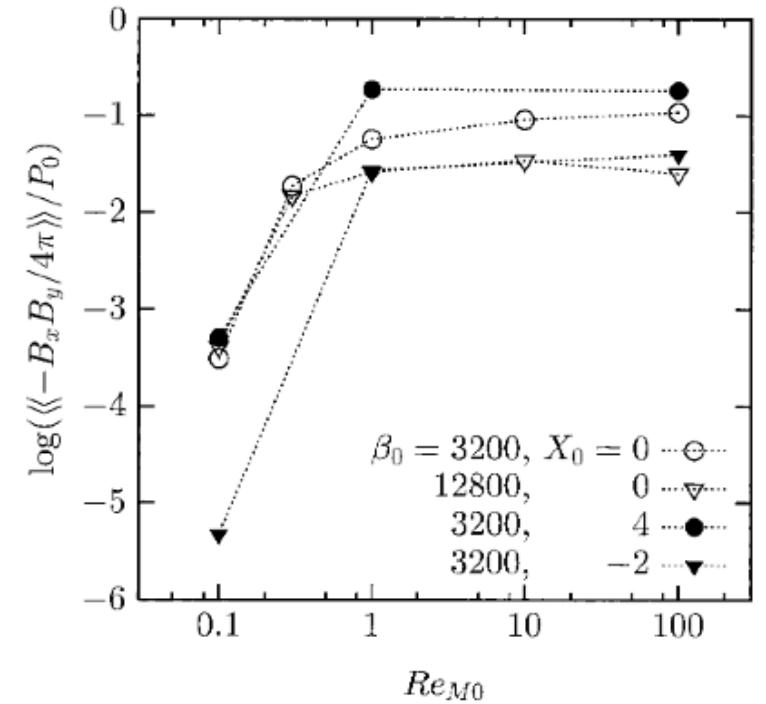
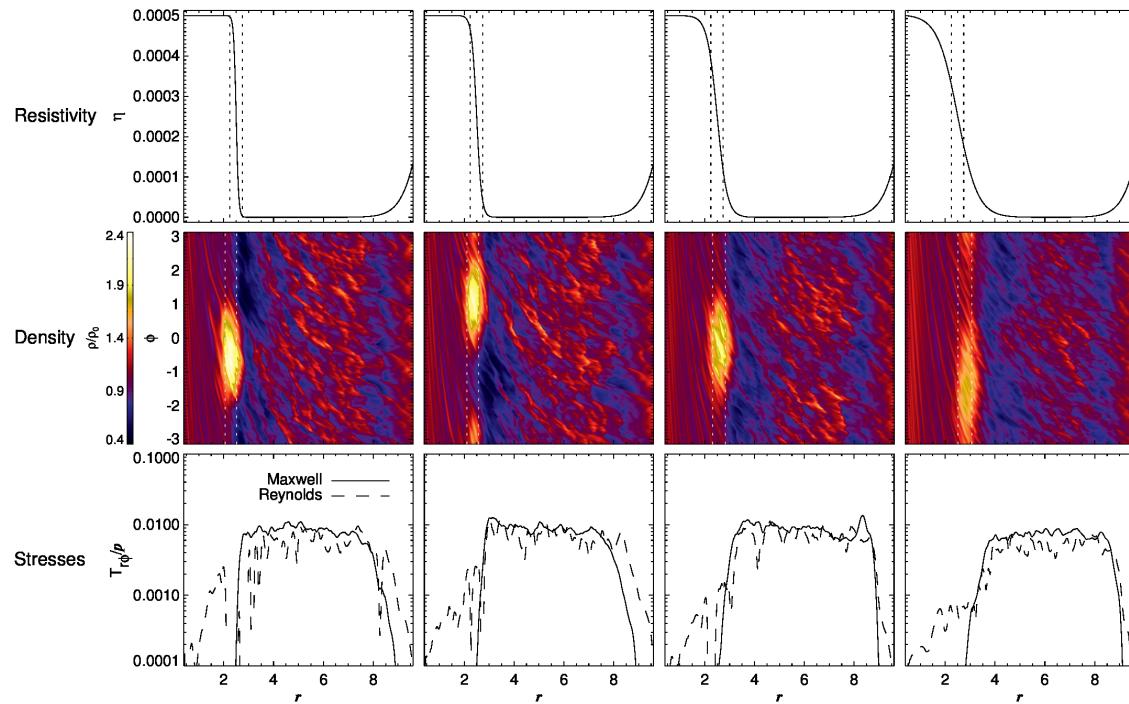
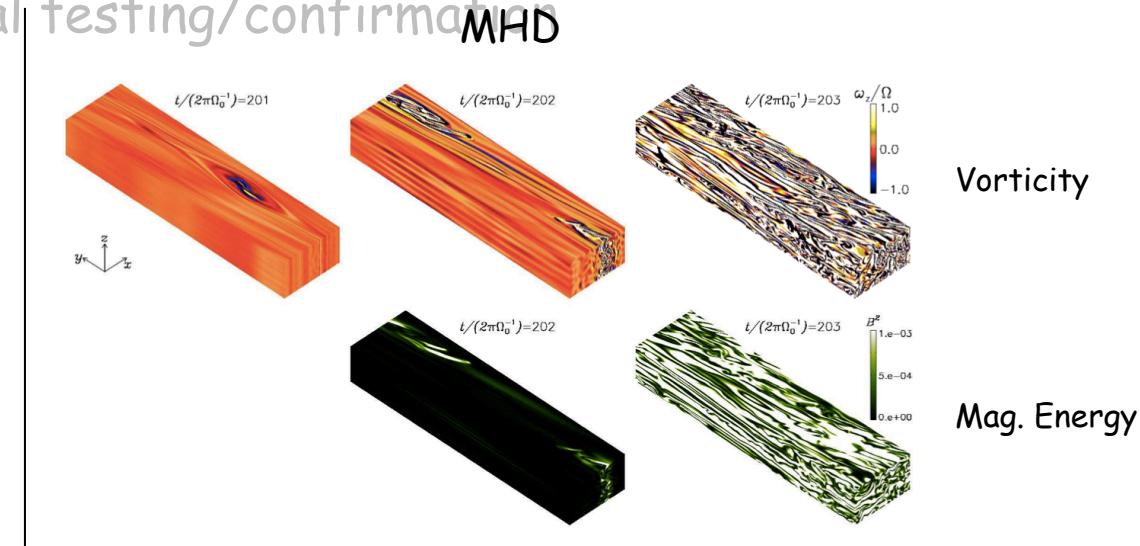
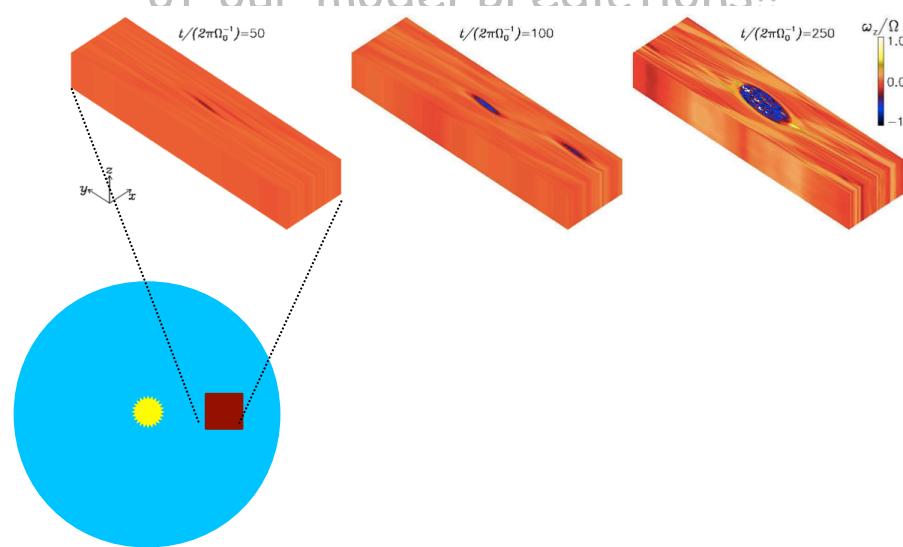


FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number Re_{M0} . Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and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

Sano and Stone (2002)

Conclusions

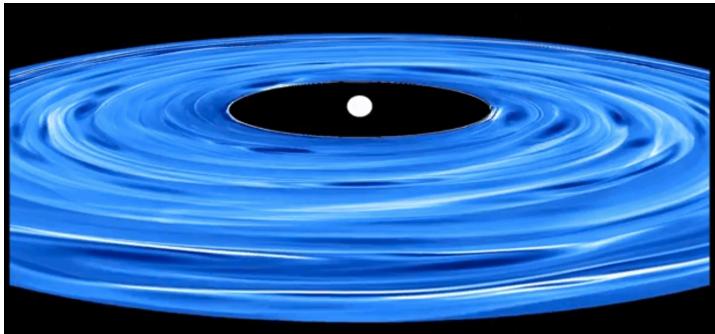
- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may be the culprit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



Conclusions

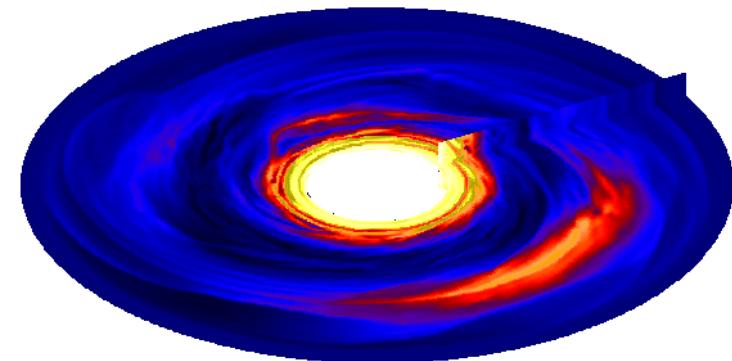
- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted is a complementary formation mode to streaming instability
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may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

Baroclinic instability



Klahr & Bodenheimer (2003)
Lyra & Klahr (2011)
Raettig et al. (2013)
Lyra (2014)

Rossby wave instability

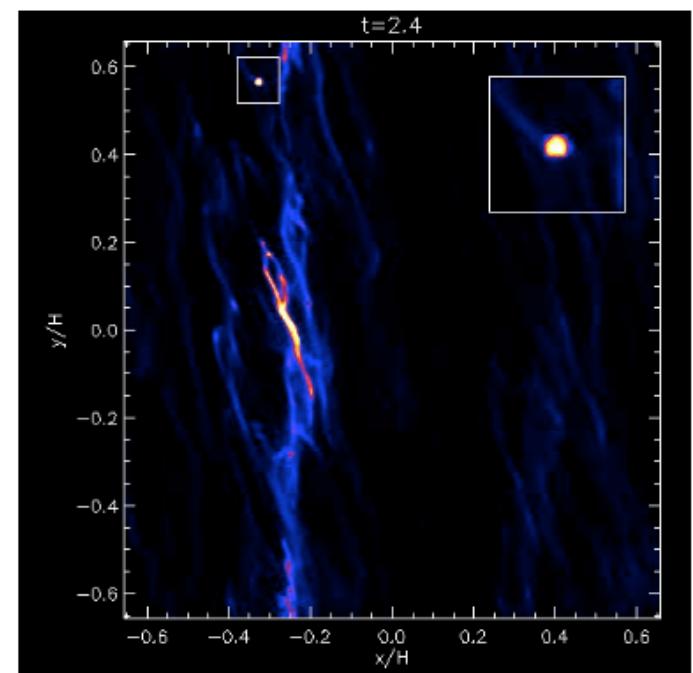
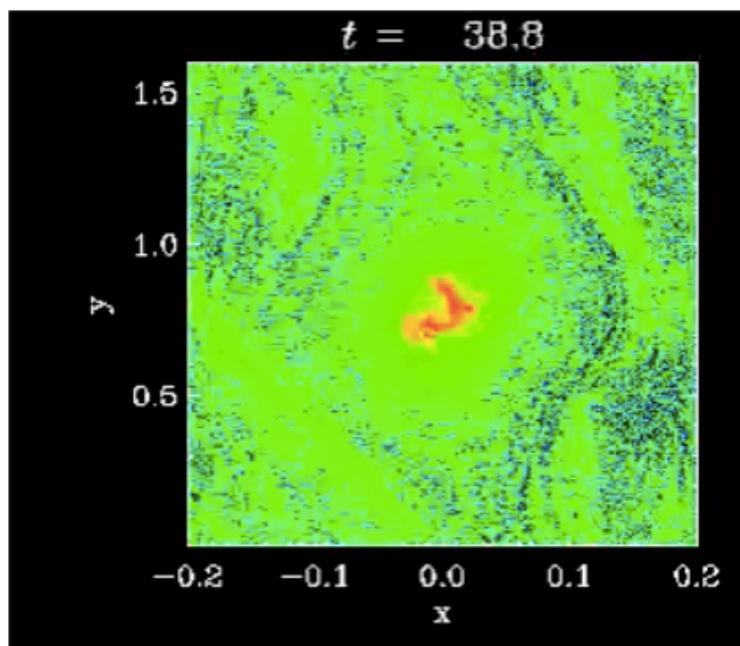


Lovelace et al. (1999)
Lyra et al. (2008b, 2009ab)
Lyra & Mac Low (2012)

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

VI. VORTEX TRAPPED DUST TRAPS:

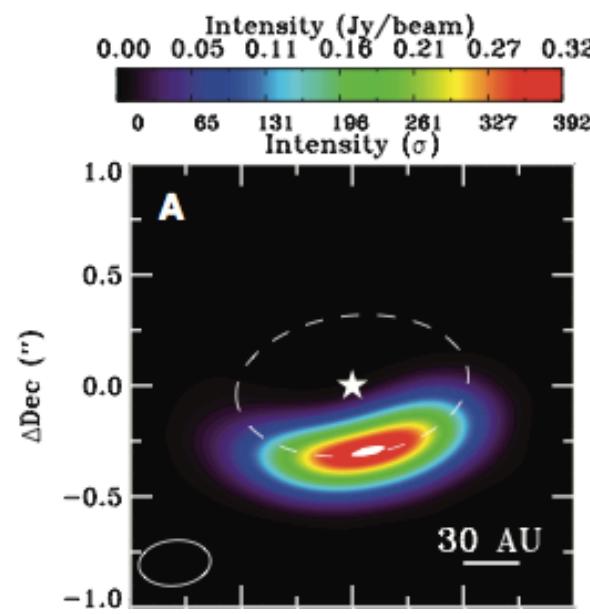
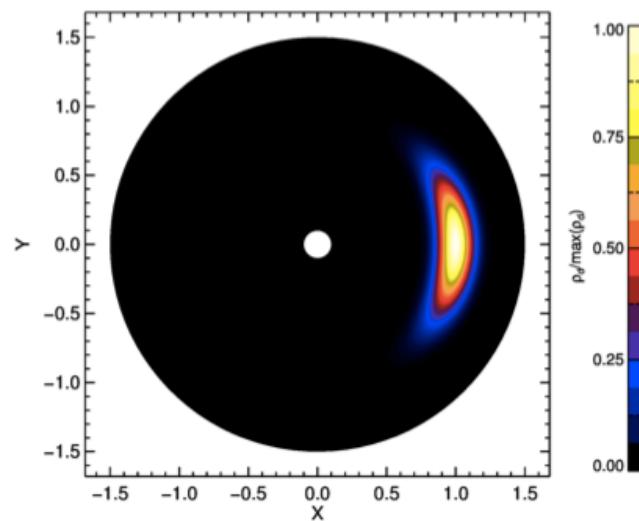


Conclusions

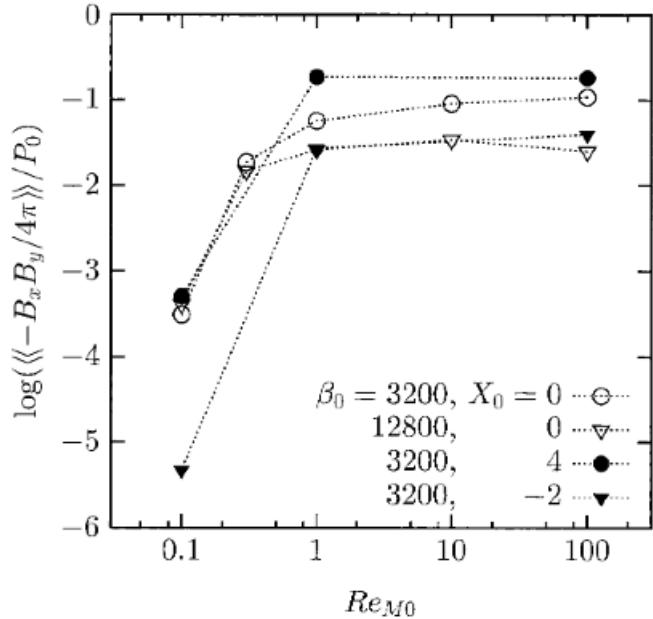
- Vortices exist in the dead zones
- Two sustenance modes: Rossby wave and shear
- Vortex-assisted and streaky
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may be the culprit of these dust traps
- We're in the era of observational tests of our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



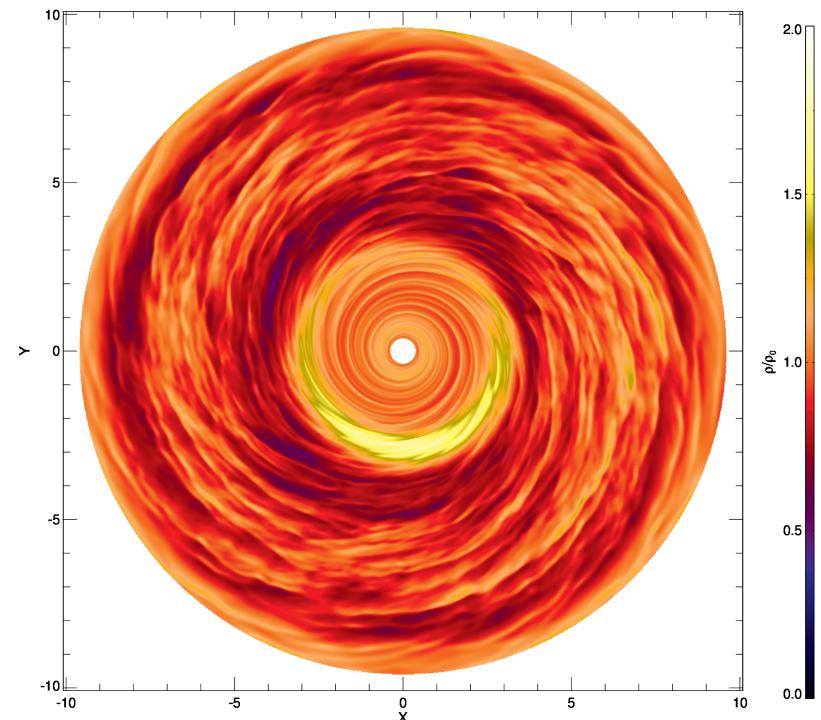
1d zone only

Rossby Wave Instability and Convective Overstability

ear

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 of our model predictions!!



Conclusions

- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Inst
- Vortex-assisted and strea
- Vortex-trapped dust in drag-diffusion eqi
- Rossby wave instability may be the culprit
- We're in the era of observational testing/confirmation of our model predictions!!

