# Evolution of circumstellar disks and planet formation

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**Caltech - JPL**

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Western Washington University, Bellingham WA

Jan 29th, 2015

# Outline

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

# Protoplanetary Disks

**PP disk fact sheet**

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

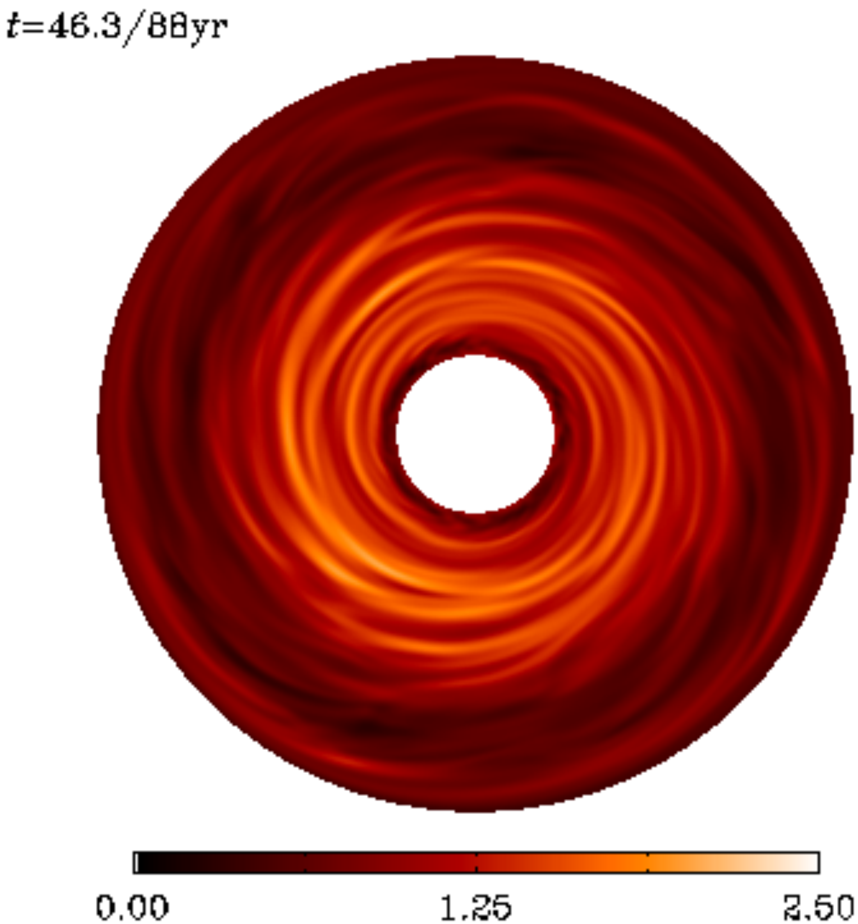
Temperature: 10-1000 K

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

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

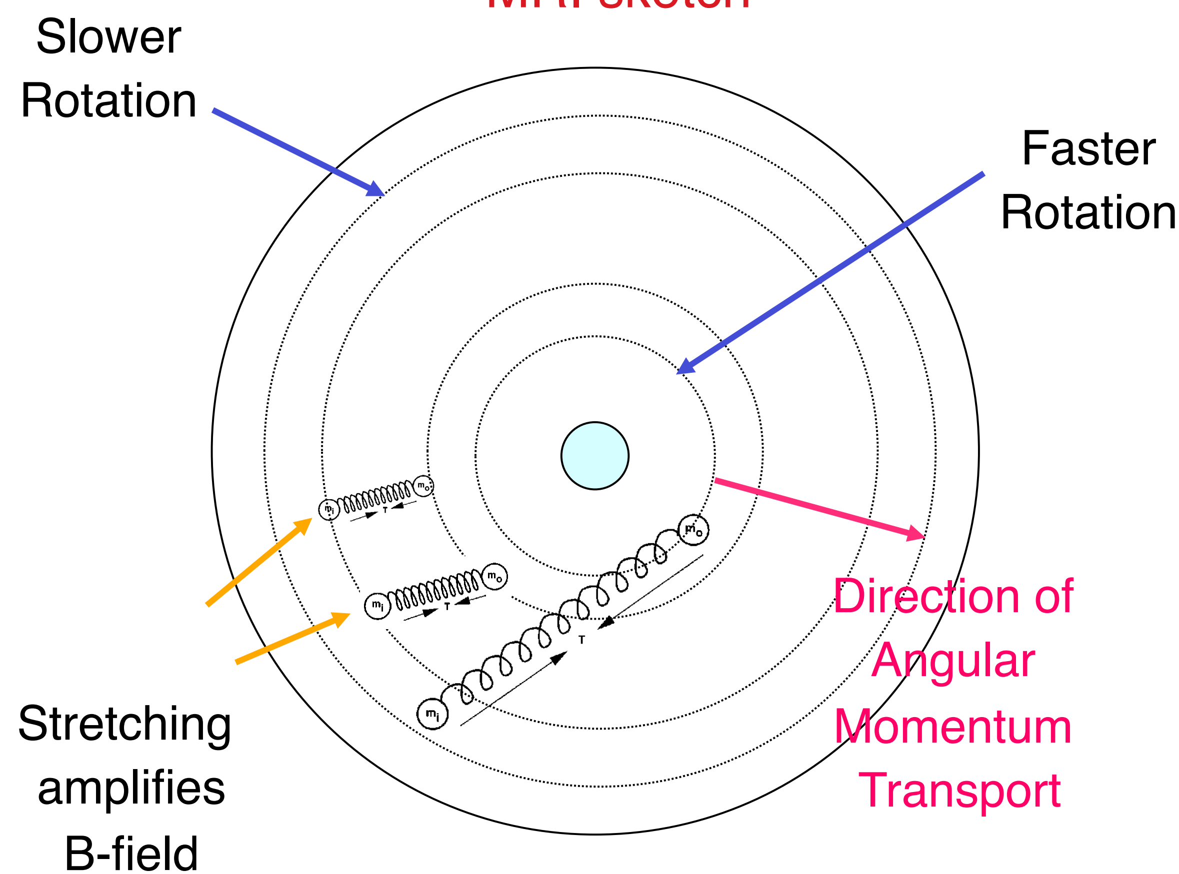
# Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability




Magnetized disk
Lyra et al. (2008a)

MRI sketch




Unstable if angular velocity decreases outward

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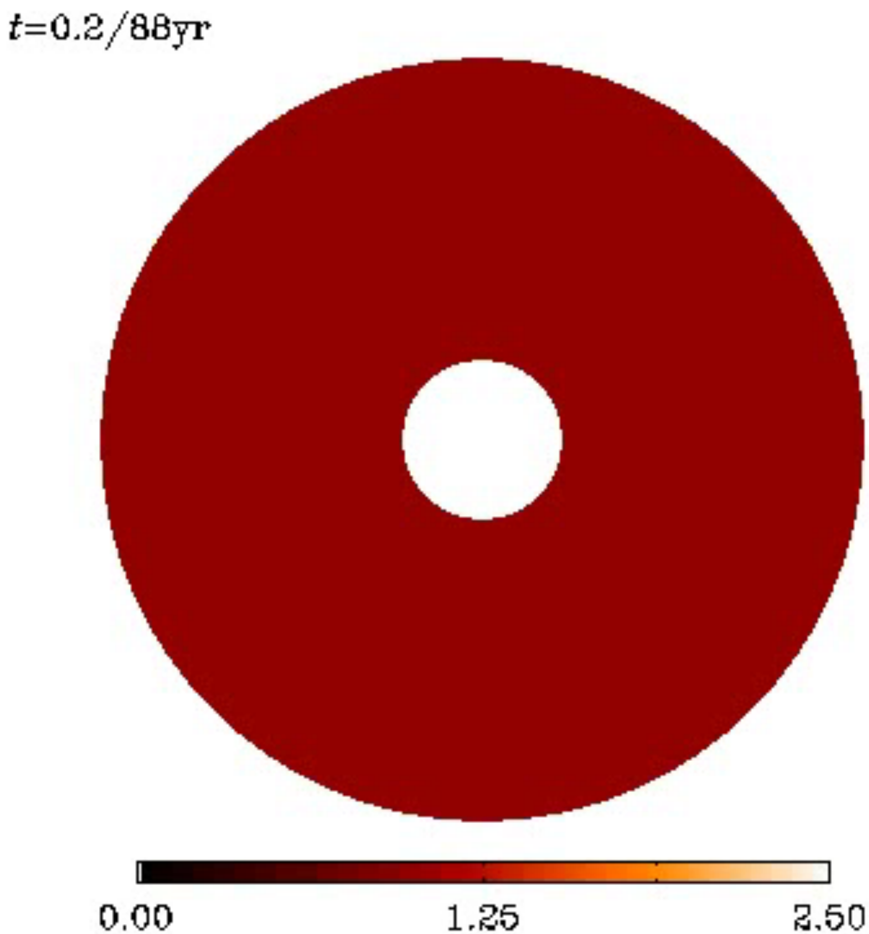


Magnetized disk

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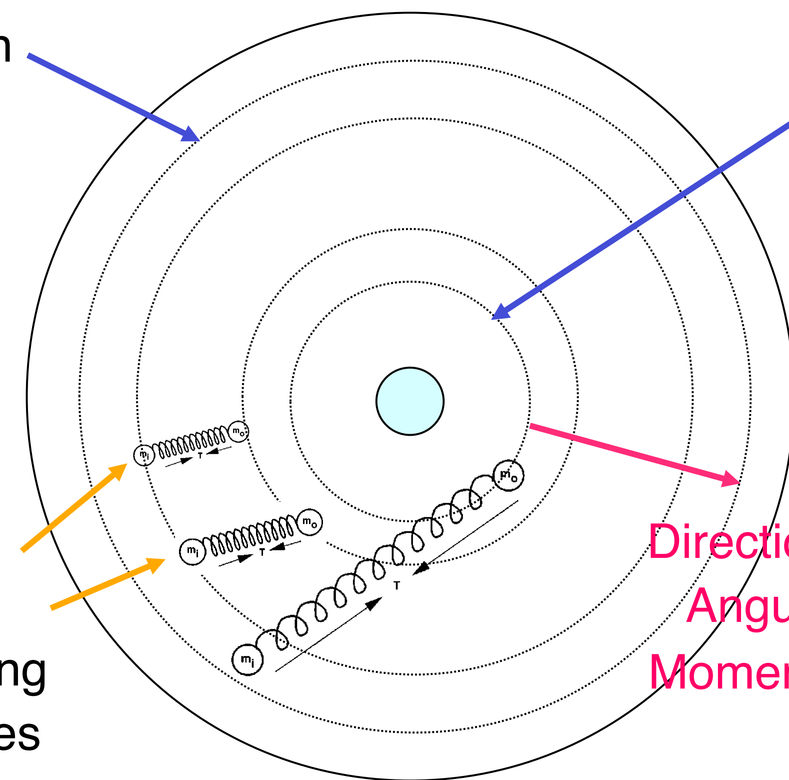


Unstable if angular
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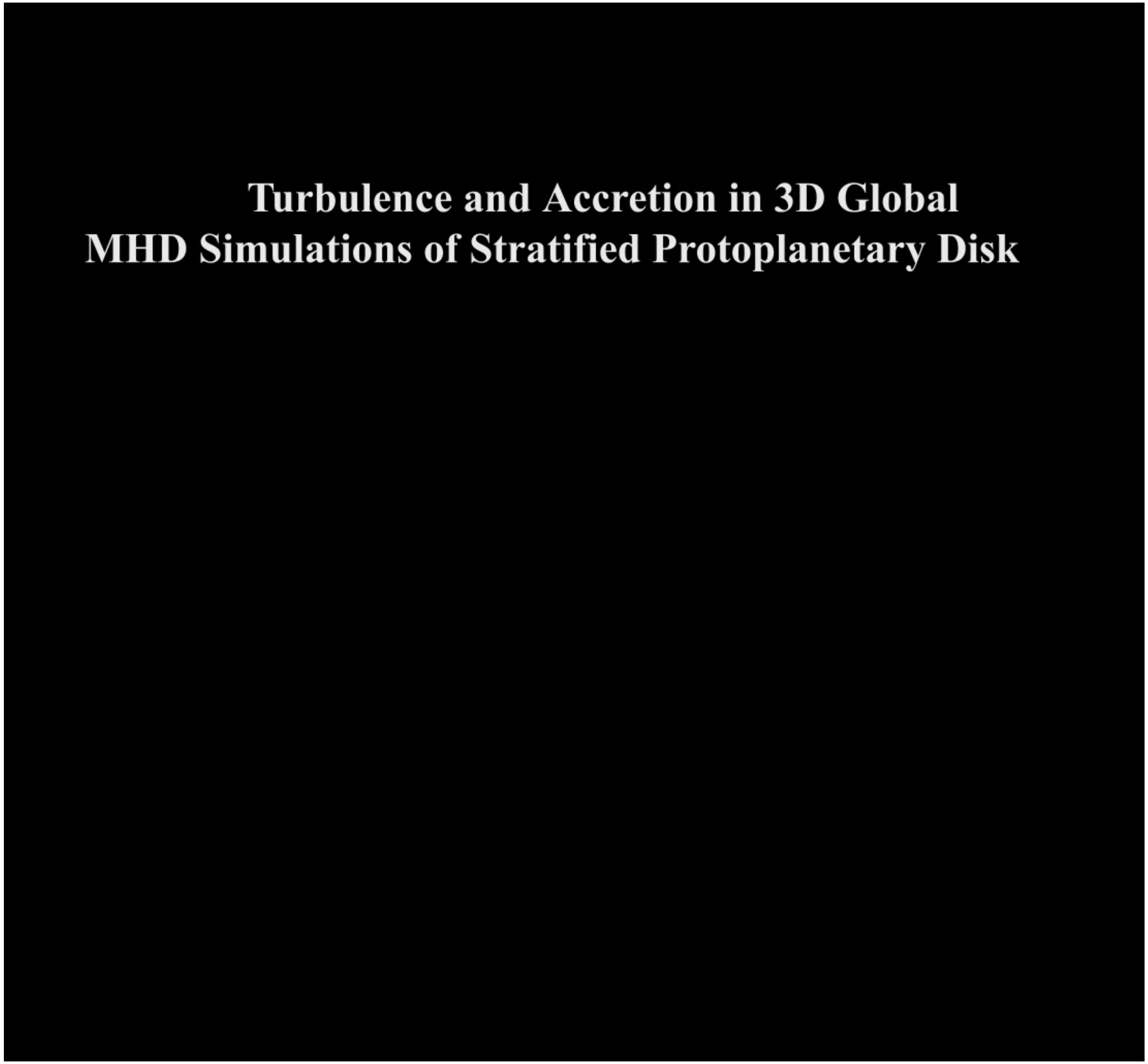
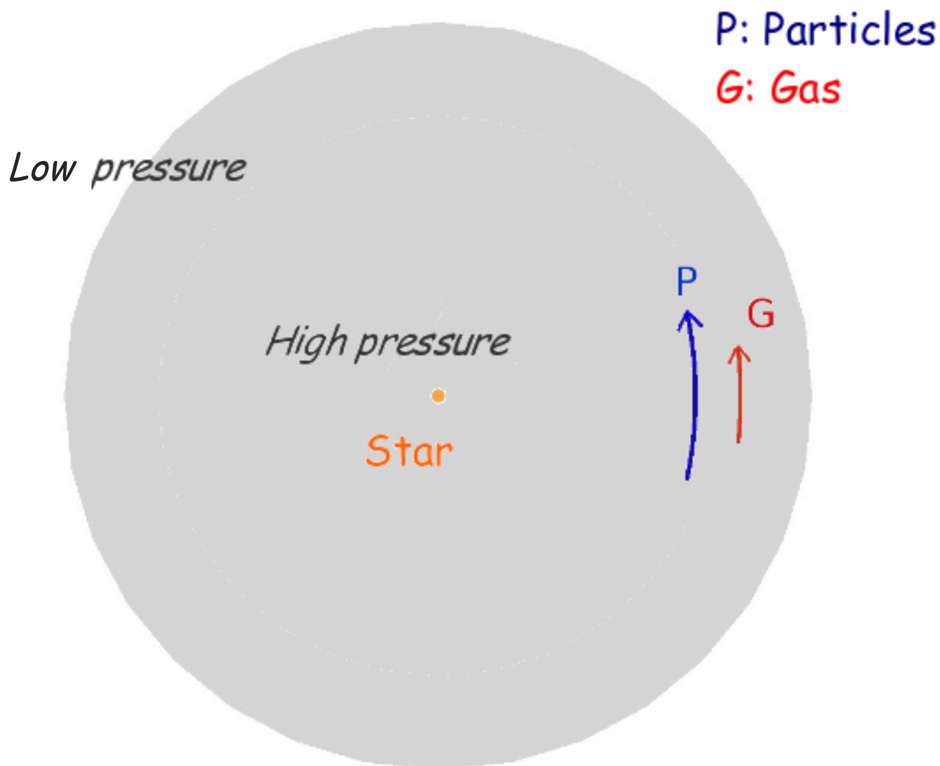
outward

# Magneto-Rotational Instability

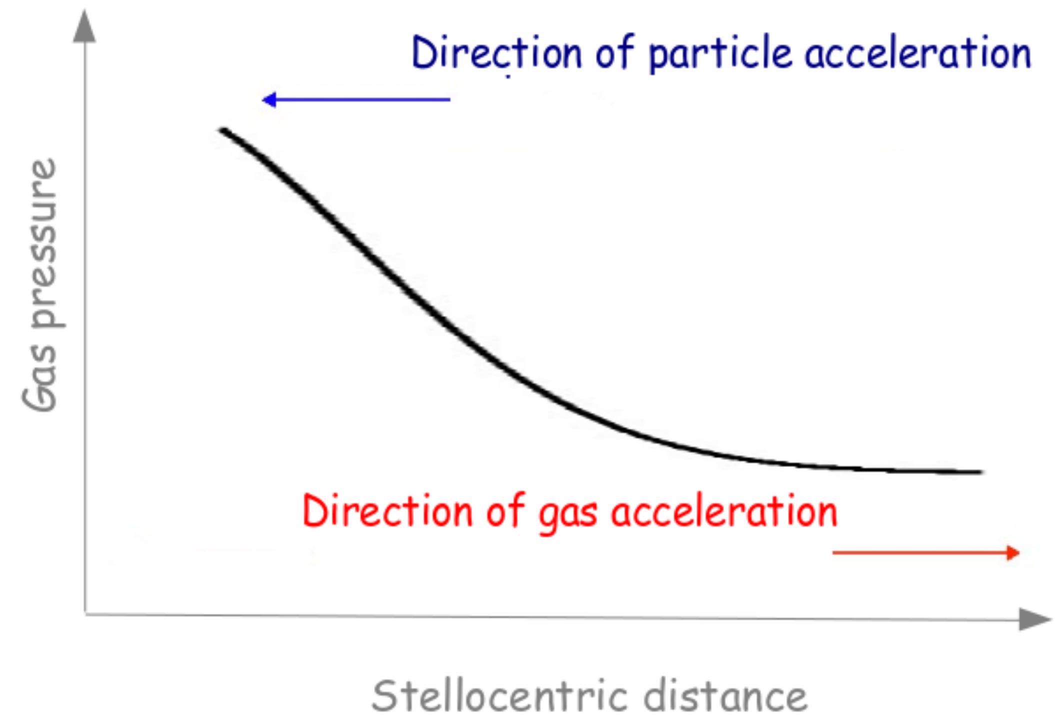



Video credit: Mario Flock (MPIA/CEA)

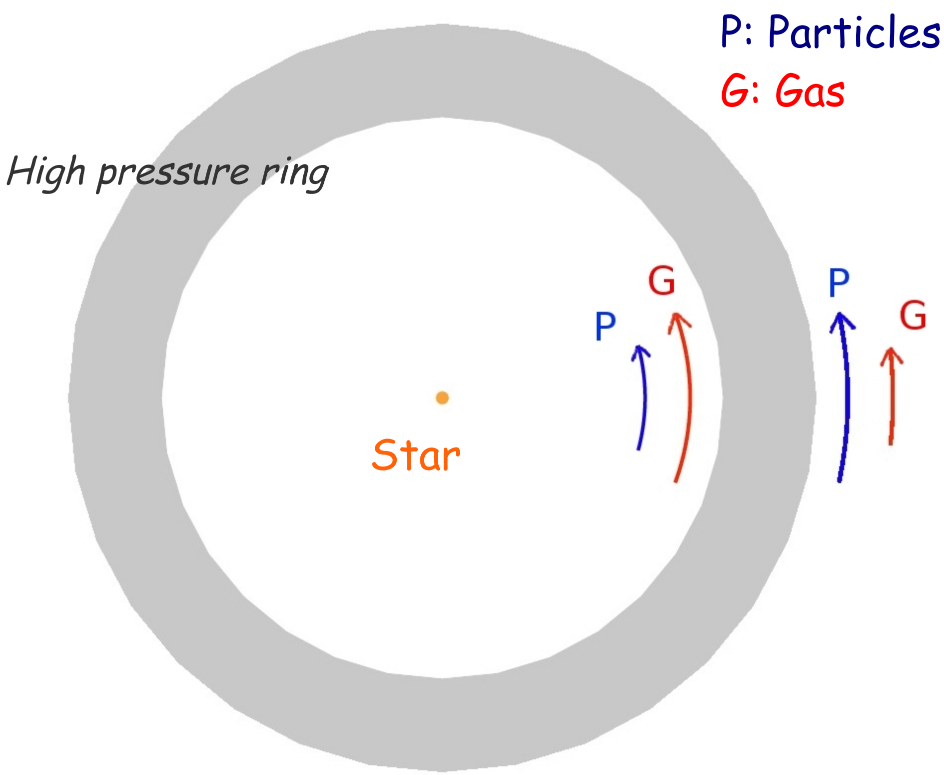
# Particle drift




Adapted from Whipple (1972)



# Pressure Trap

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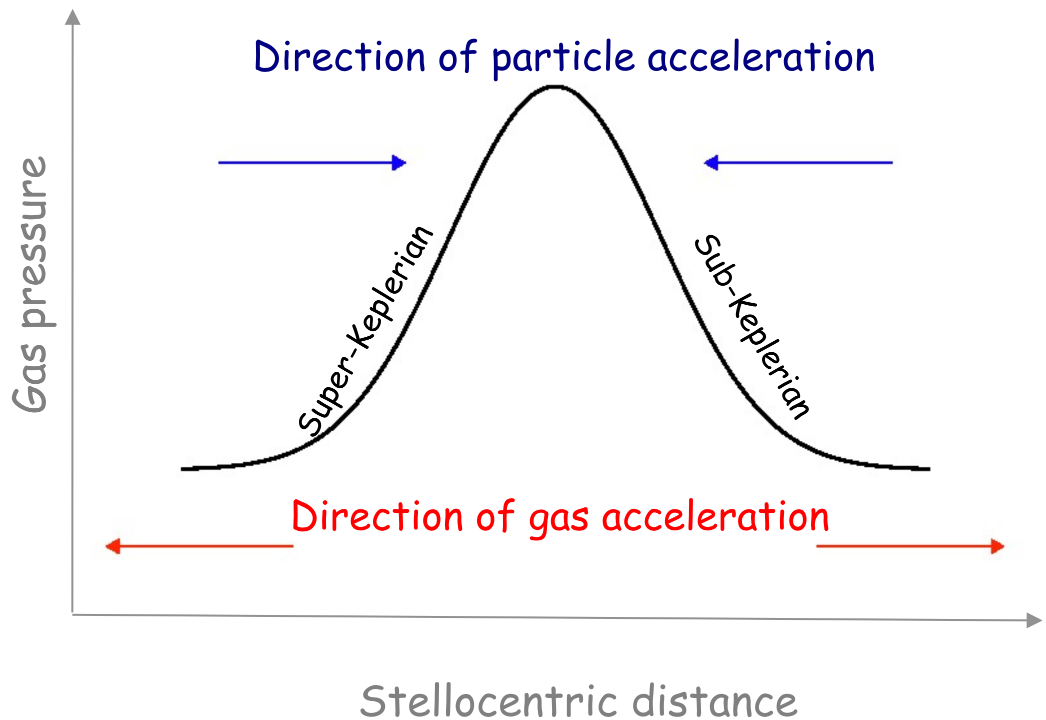

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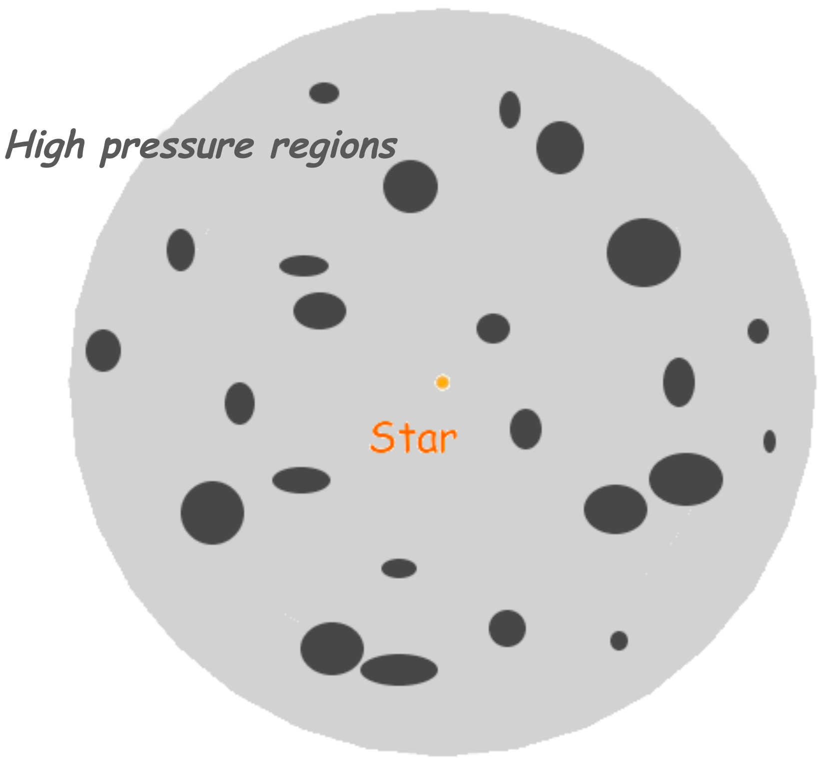
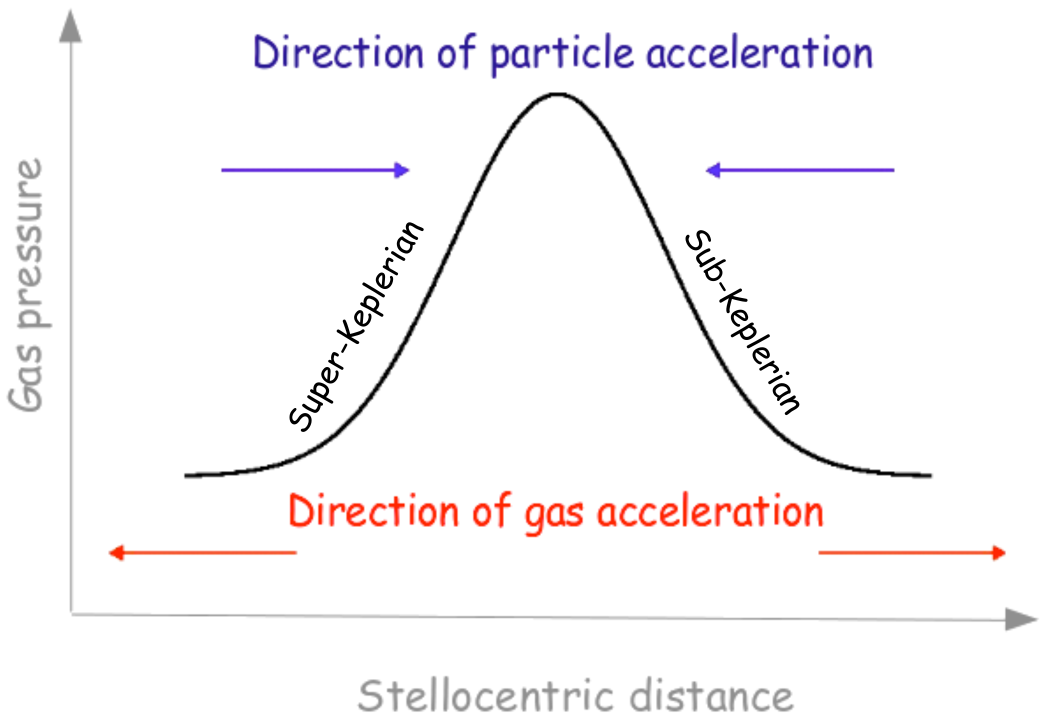
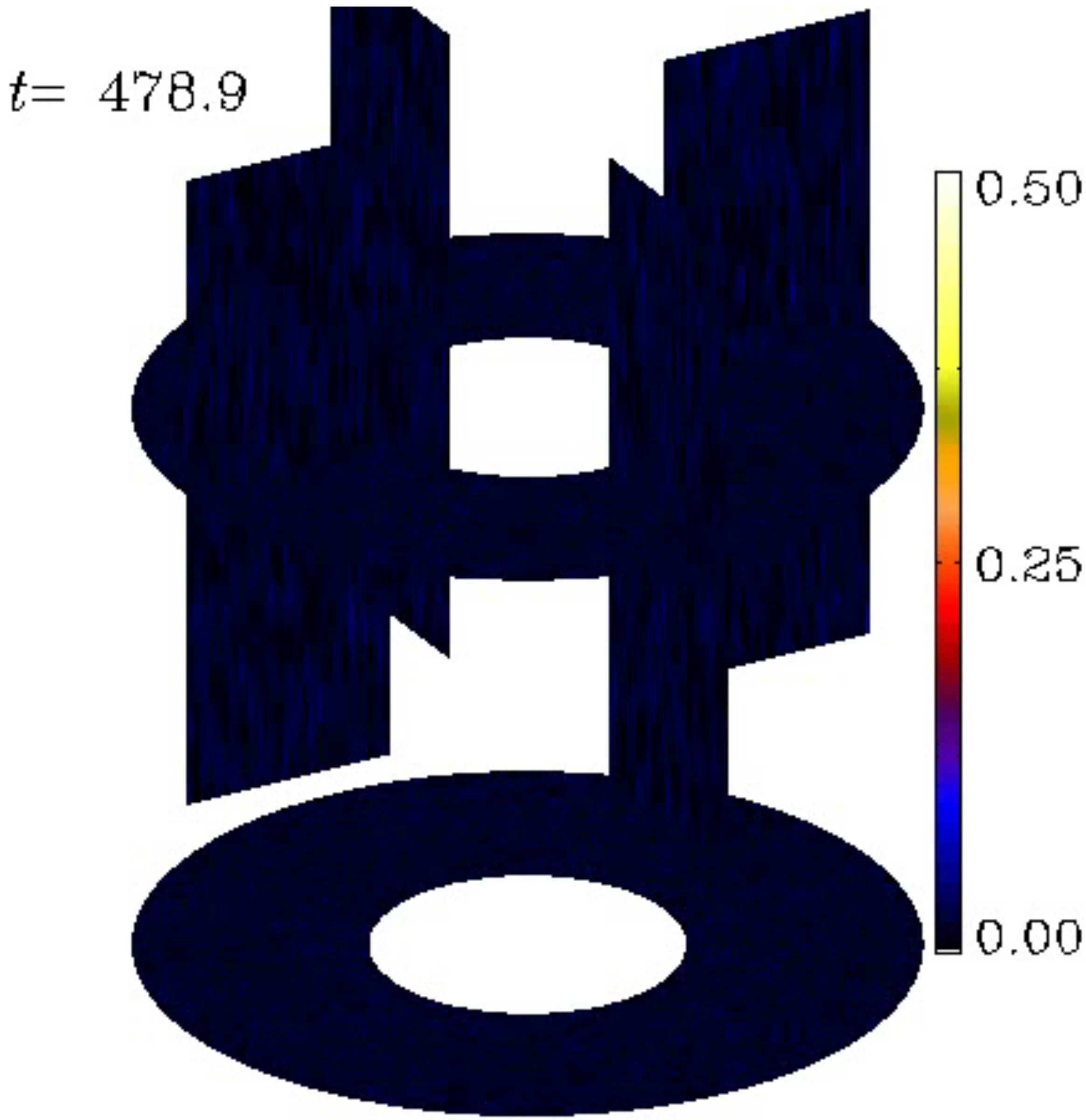


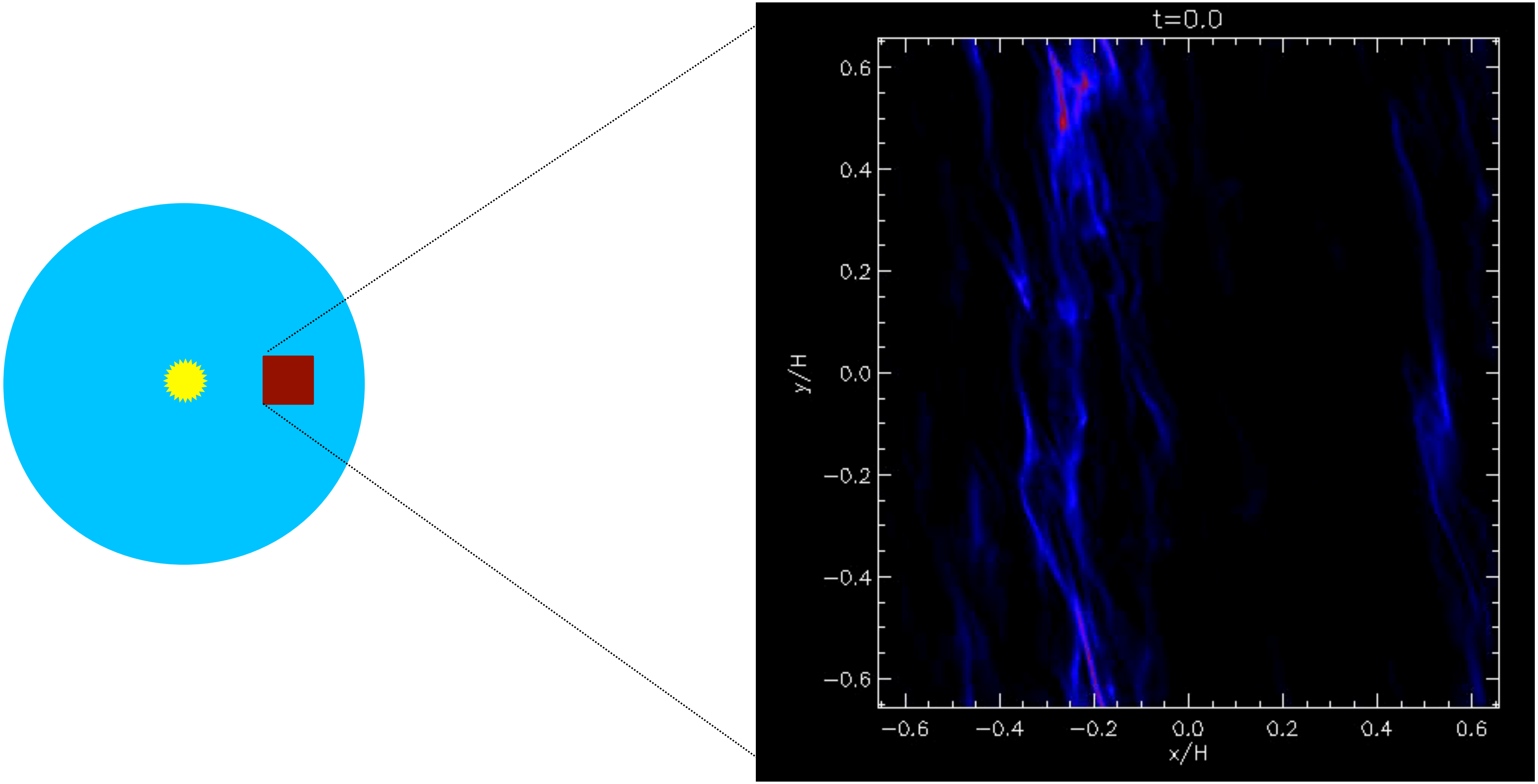



# Turbulence concentrates solids mechanically in pressure maxima



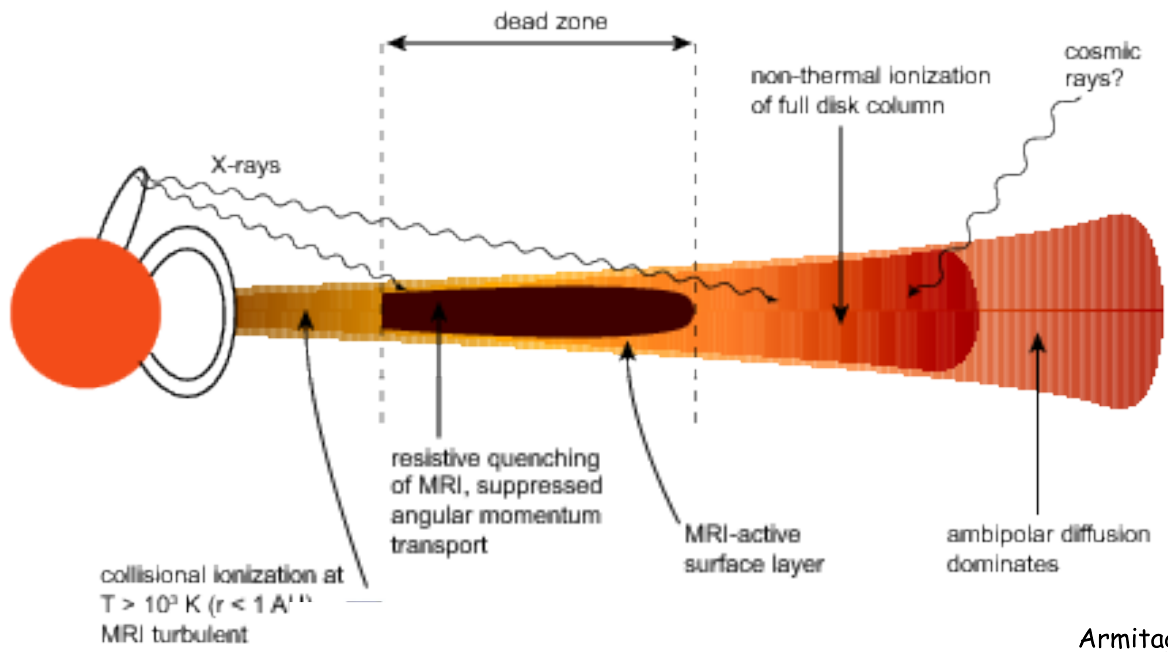

Lyra et al. (2008a)

# Gravitational collapse into planetesimals




Johansen et al. (2007)

# Dead zones are robust features of protoplanetary disks




Armitage (2010)

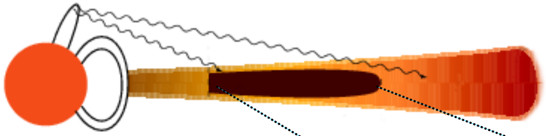
Disks are cold and thus poorly ionized

(Blaes & Balbus 1994)

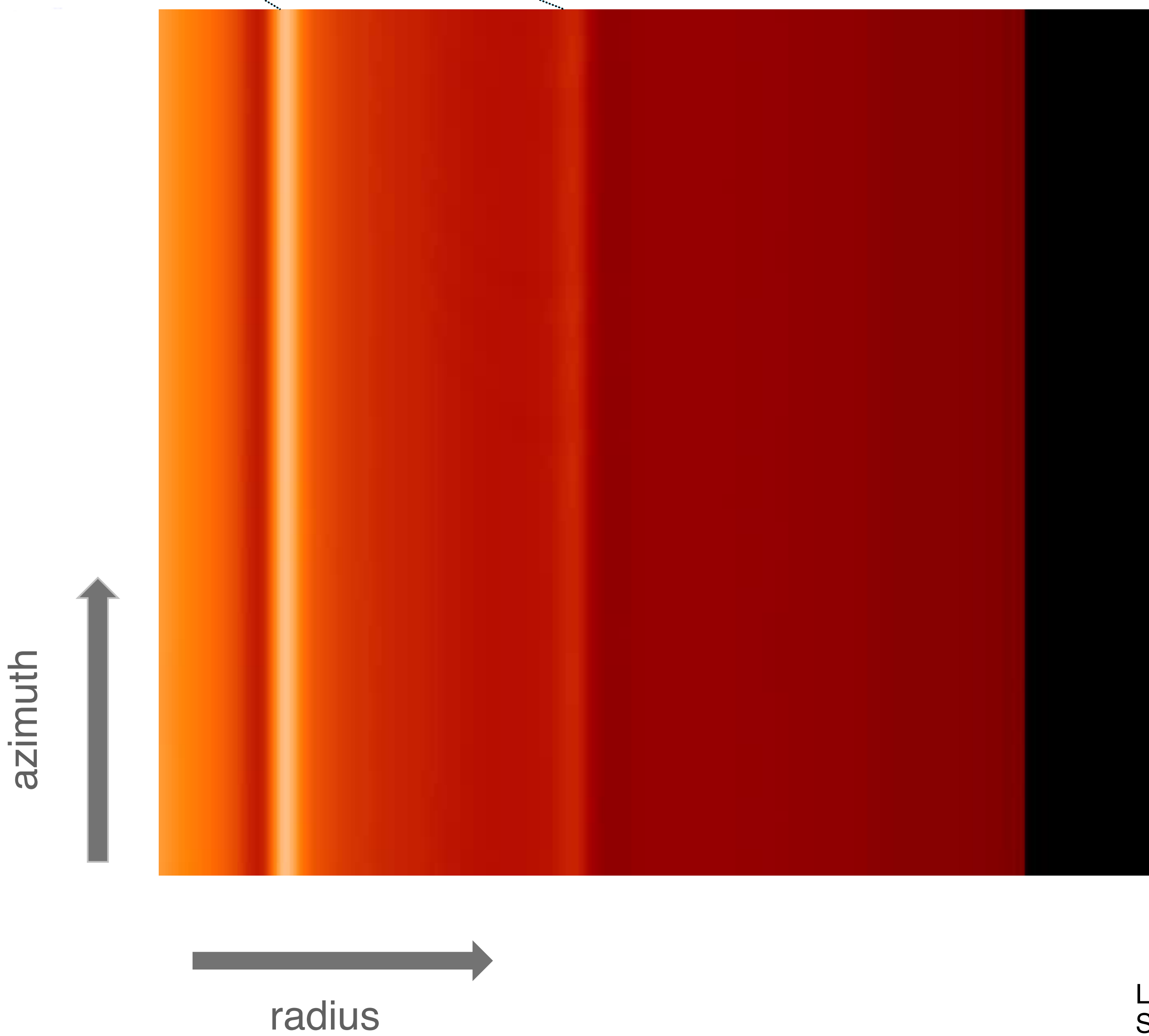
Therefore, accretion is **layered**

(Gammie 1996)

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



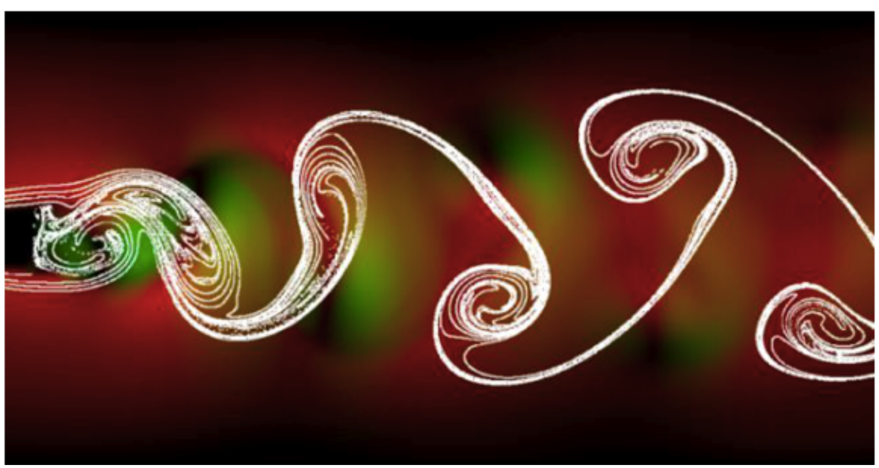
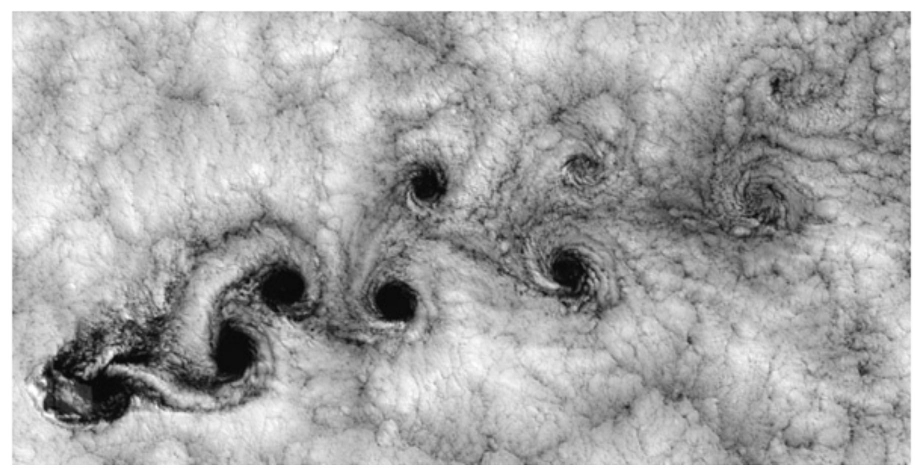
# A simple dead zone model




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

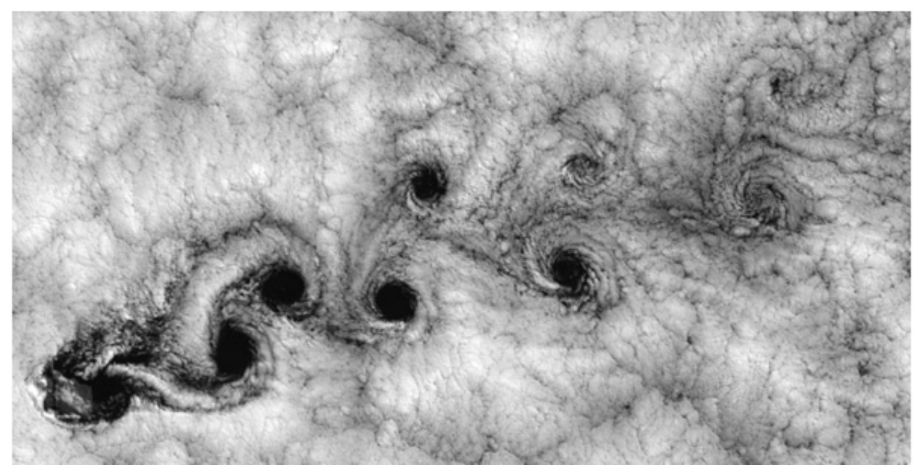
# Vortices – an ubiquitous fluid mechanics phenomenon



# Vortices – an ubiquitous fluid mechanics phenomenon

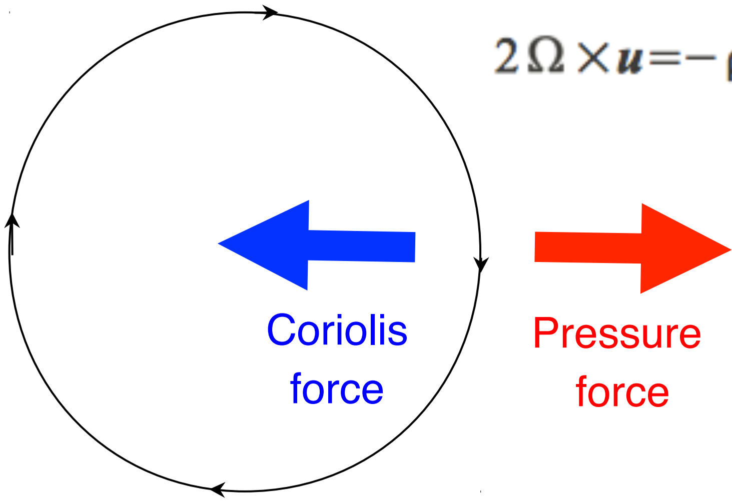
## Von Kármán *vortex street*



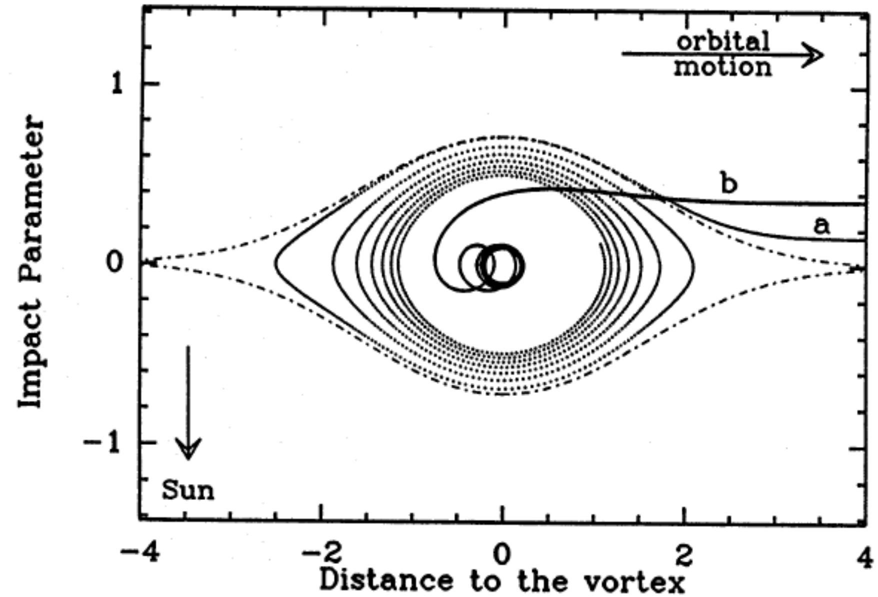
# The Tea-Leaf effect

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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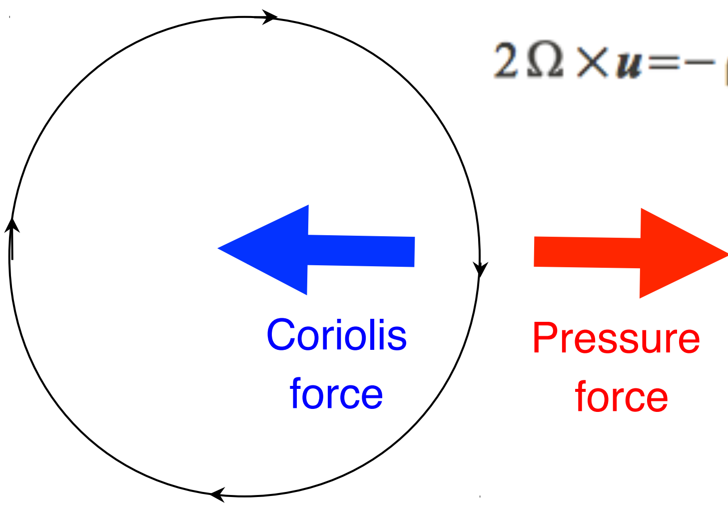
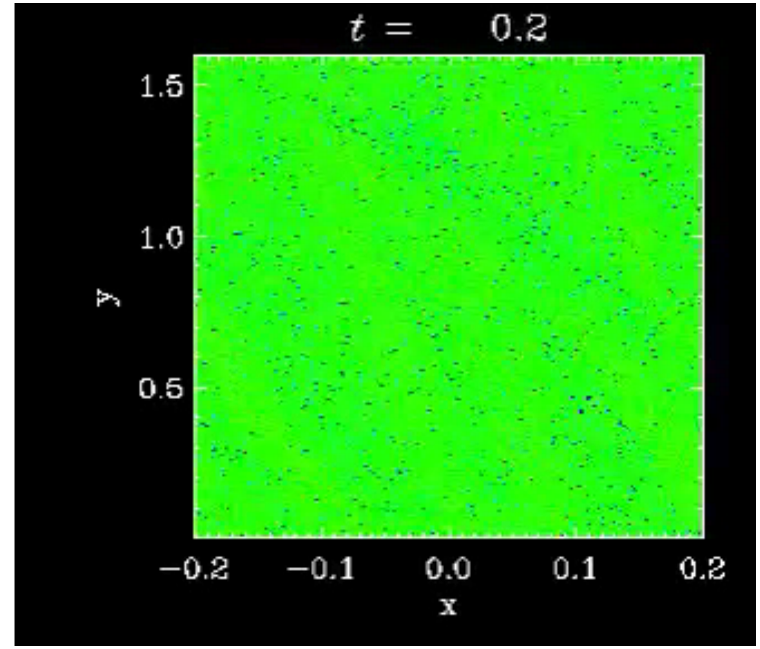



Vortex
streamline




Raettig et al. (2012, 2015)

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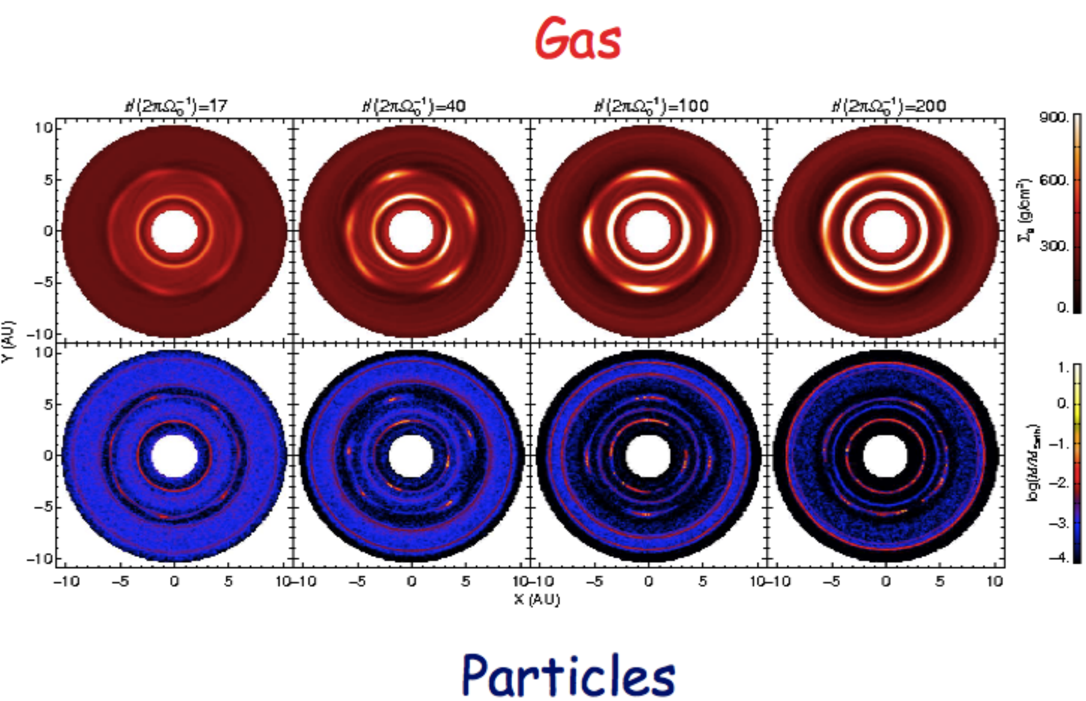
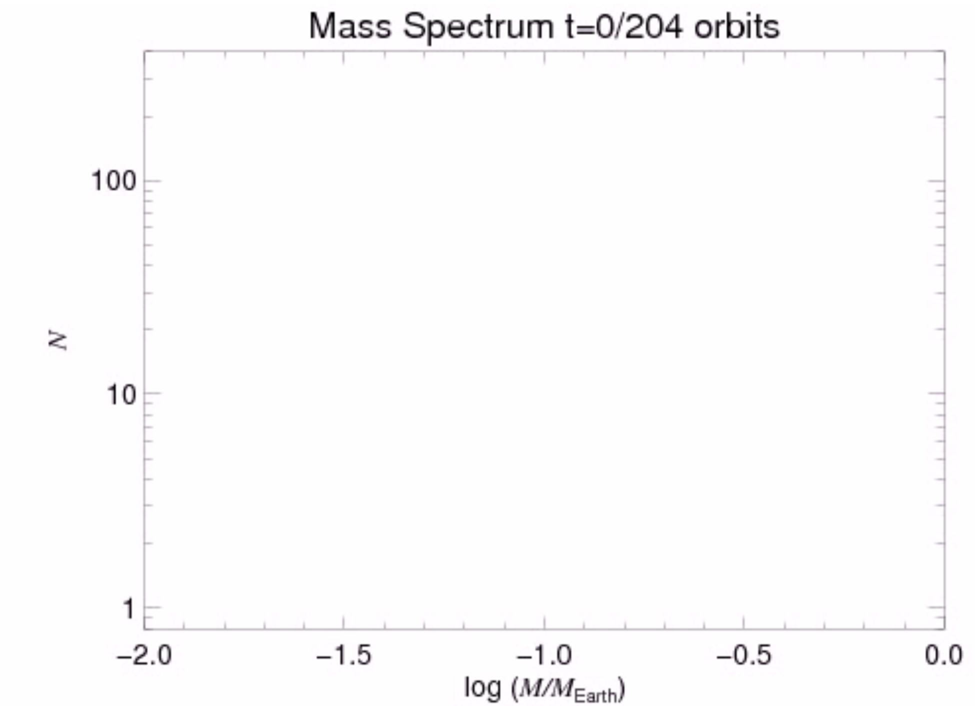
# Vortices and Planet Formation

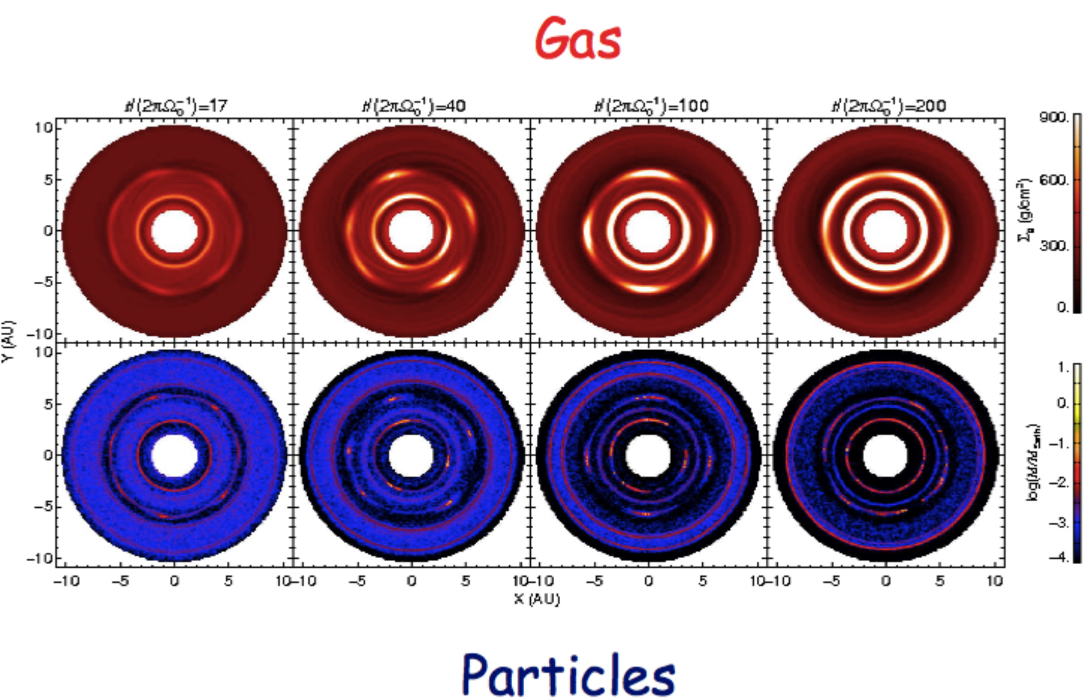


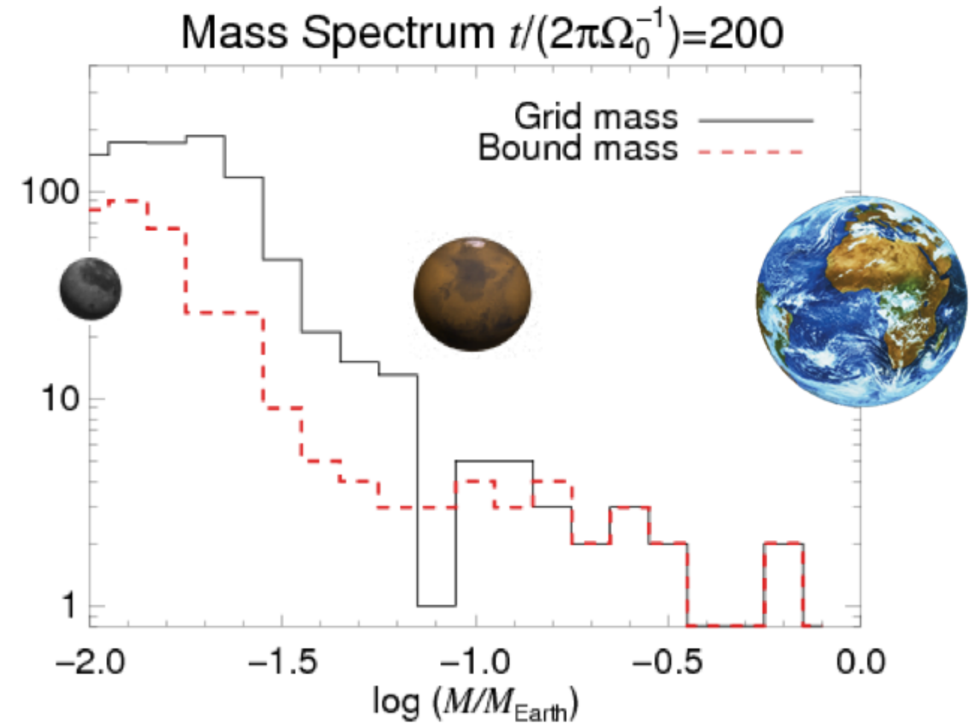




Collapse into Mars mass objects

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

# Vortices and Planet Formation




Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a,
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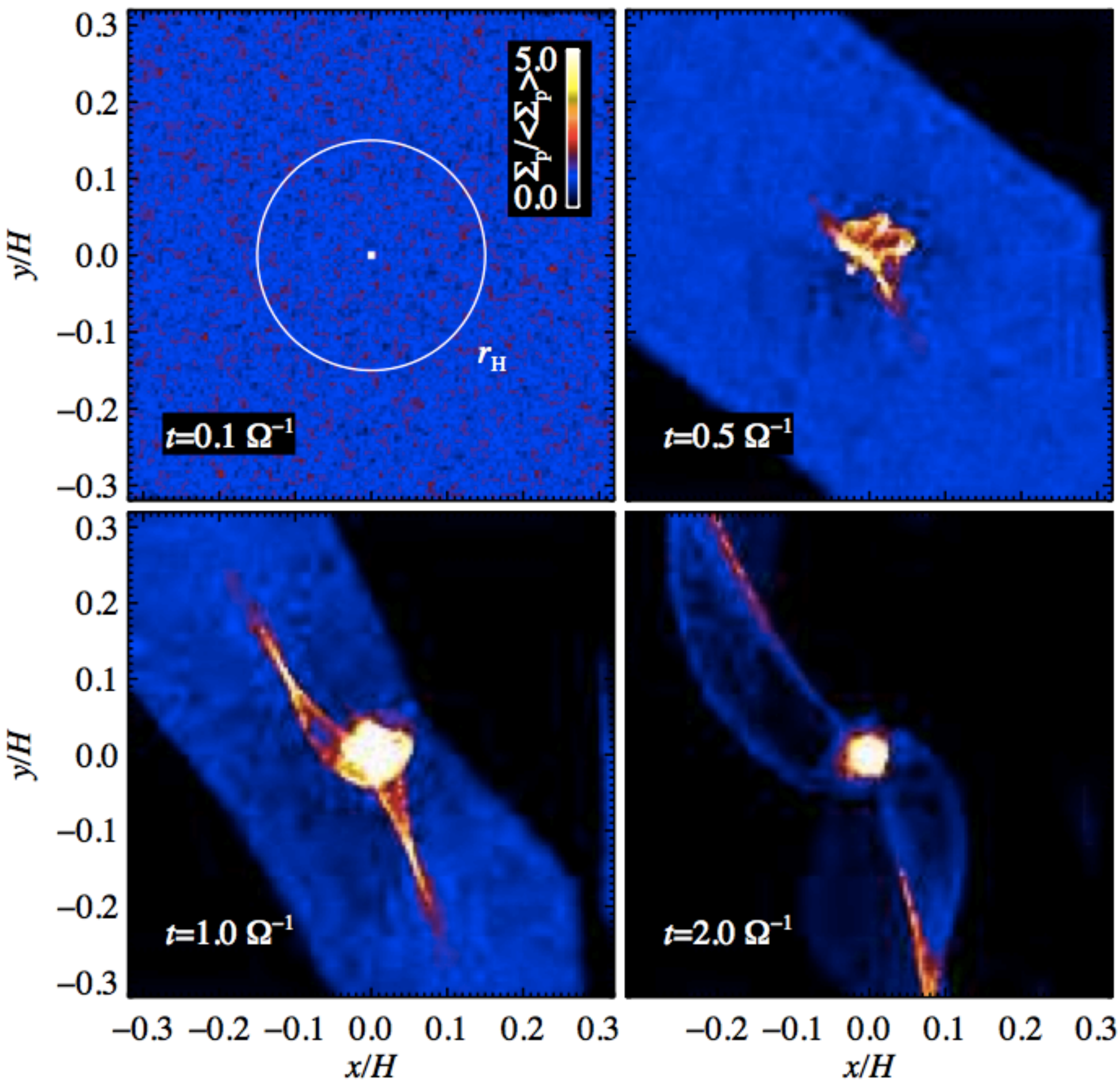
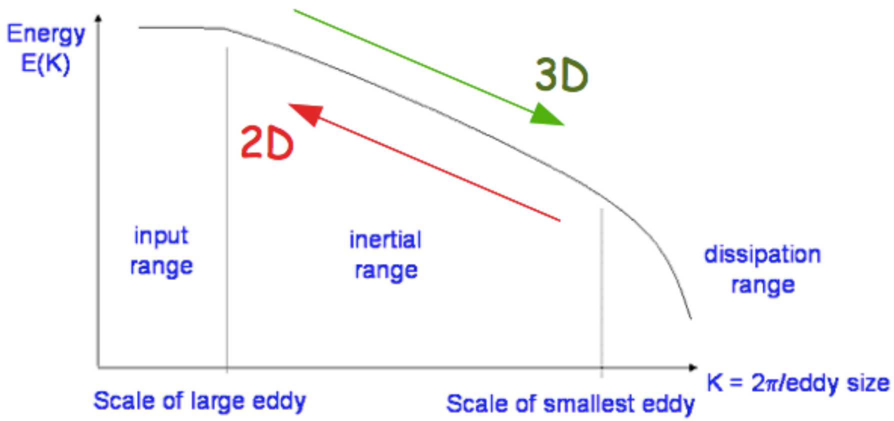
# Rapid formation of planetary cores

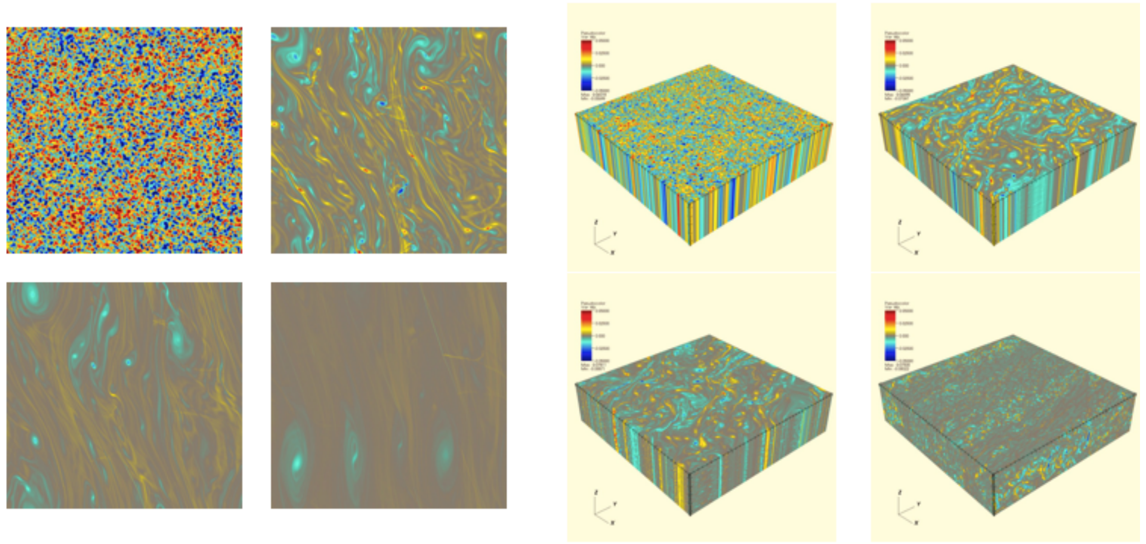



Lambrechts & Johansen (2012)

# The energy cascade




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



2D

3D

**Inverse Cascade**

No 3D instability
Eddies merge

**Direct Cascade**

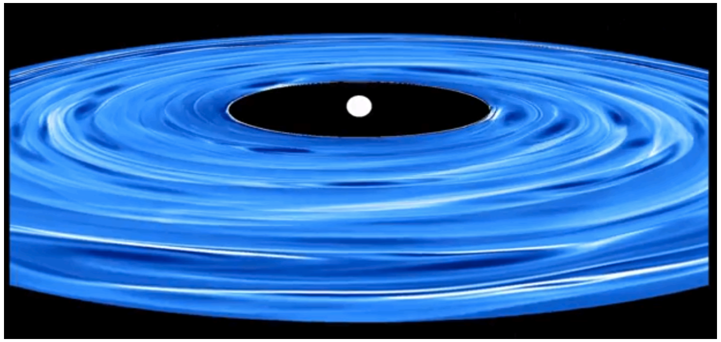
Destruction occurs
faster than merging

# Sustaining vortices in disks

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

## Baroclinic instability

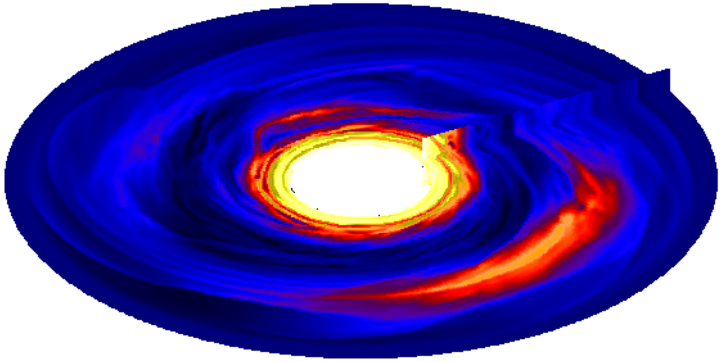
*(Convective overstability)*



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:
Buyoancy, thermal diffusion
(baroclinic source term)

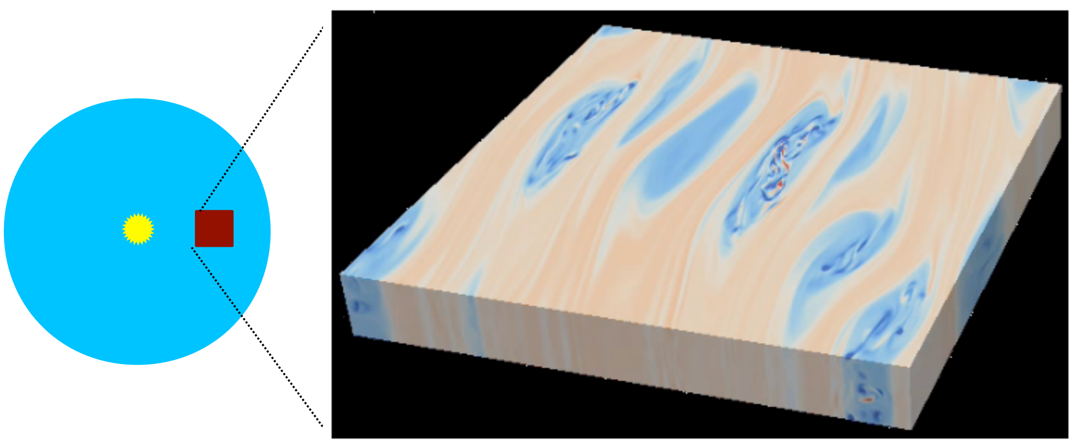
## Rossby wave instability



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)

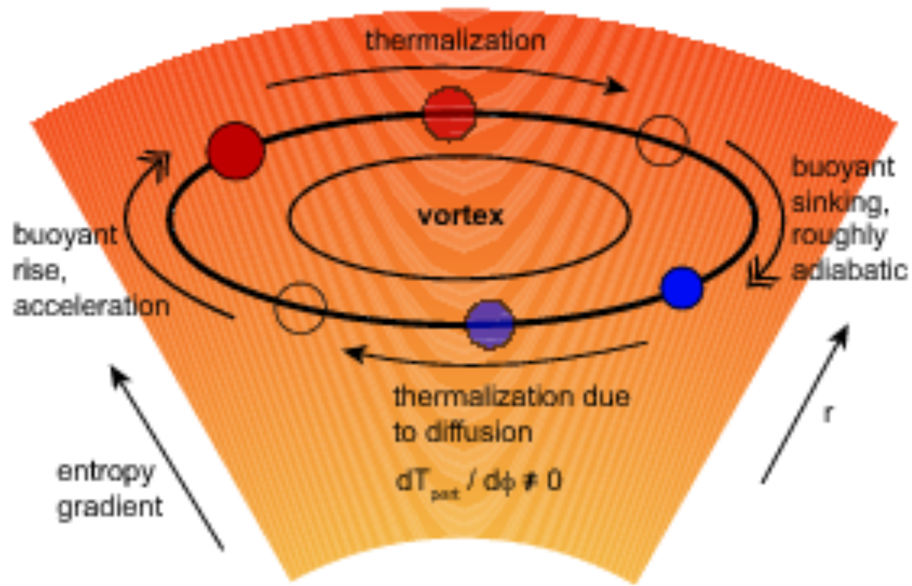
Powered by:
Modification of shear profile
(external vorticity reservoir)

# Baroclinic Instability – Excitation and self-sustenance of vortices



Lesur & Papaloizou (2010)

## Sketch of the Baroclinic Instability




Armitage (2010)

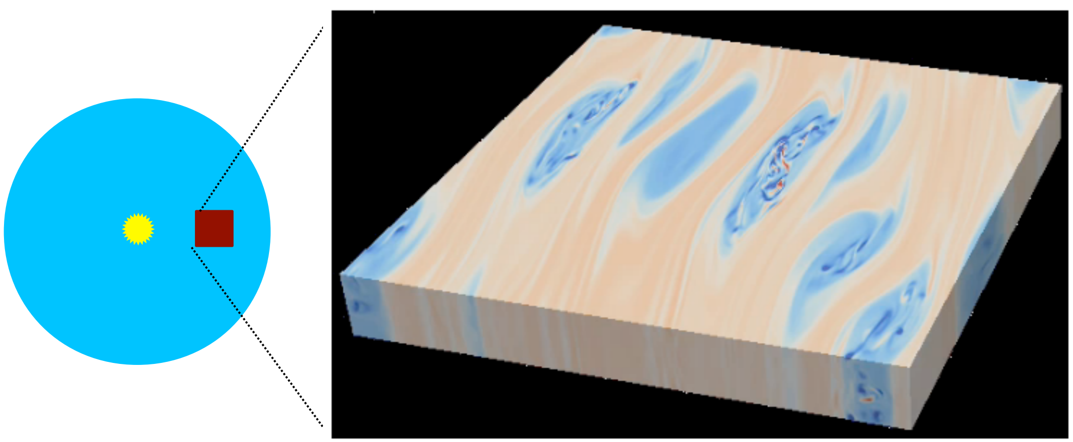
$$\frac{\partial \omega}{\partial t} = -(\boldsymbol{u}\cdot\nabla)\omega - \omega(\nabla\cdot\boldsymbol{u}) + (\omega\cdot\nabla)\boldsymbol{u} + \frac{1}{\rho^2}\nabla\rho\times\nabla p + \nu\nabla^2\omega$$

advection — compression — stretching — baroclinicity — dissipation

# Baroclinic Instability – Excitation and self-sustenance of vortices

*1. Radial entropy gradient*

*2. Thermal diffusion*



Lesur & Papaloizou (2010)

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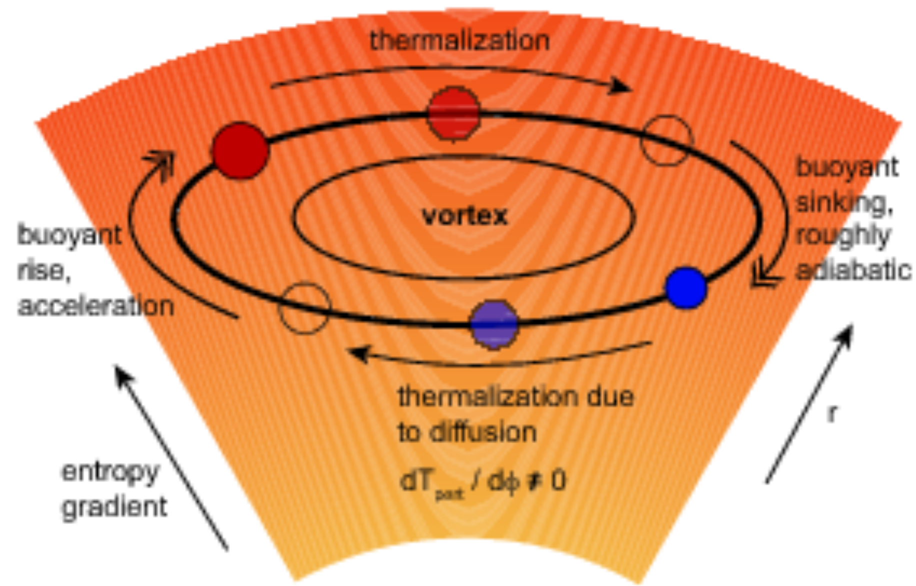


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advection, compression, stretching, baroclinicity, dissipation

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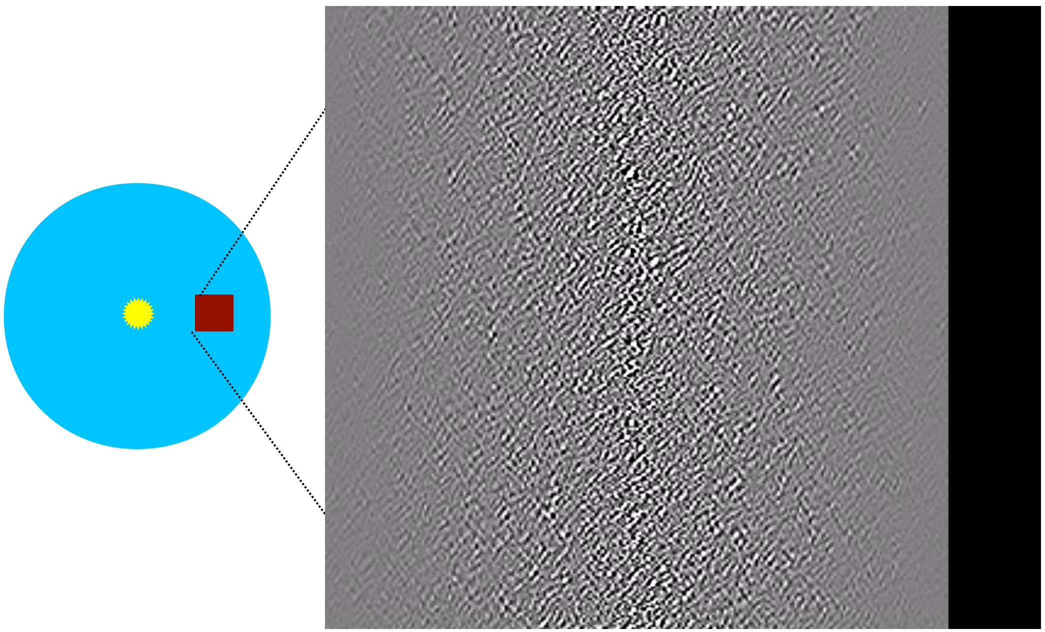
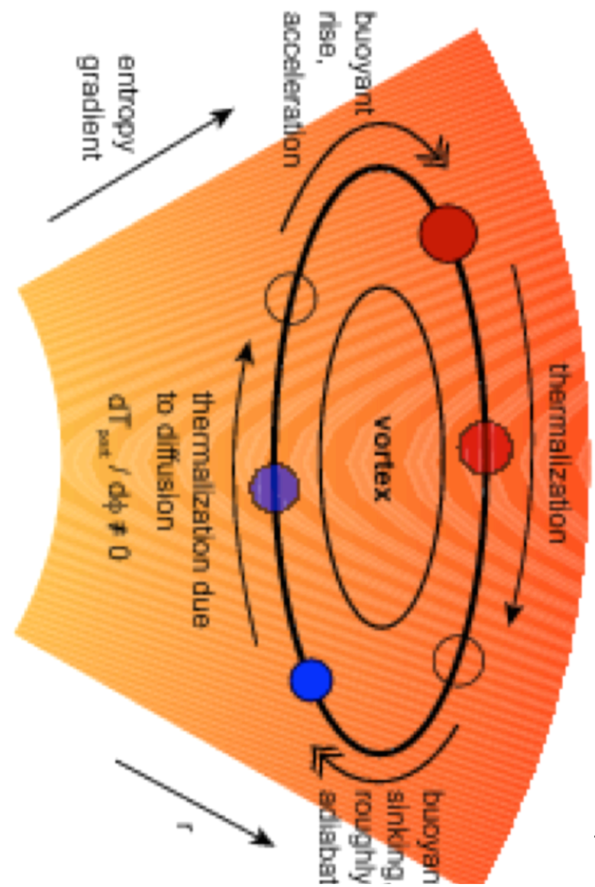


Lyra & Klahr (2011)

Sketch of the Baroclinic Instability

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advection

compression

stretching

baroclinicity

dissipation

# The “Baroclinic Instability” is LINEAR (Convective Overstability)

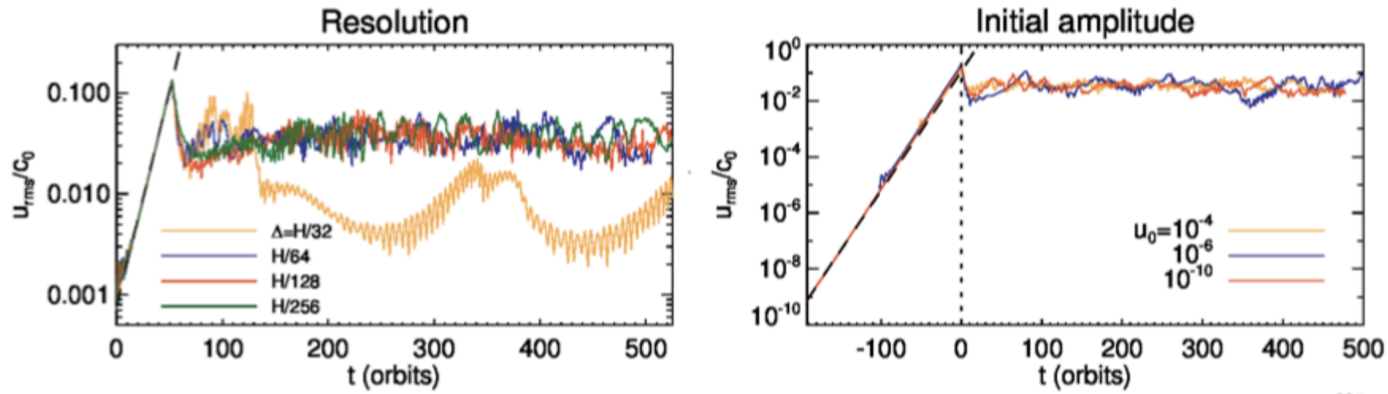
Klahr & Hubbard (2014), Lyra (2014)

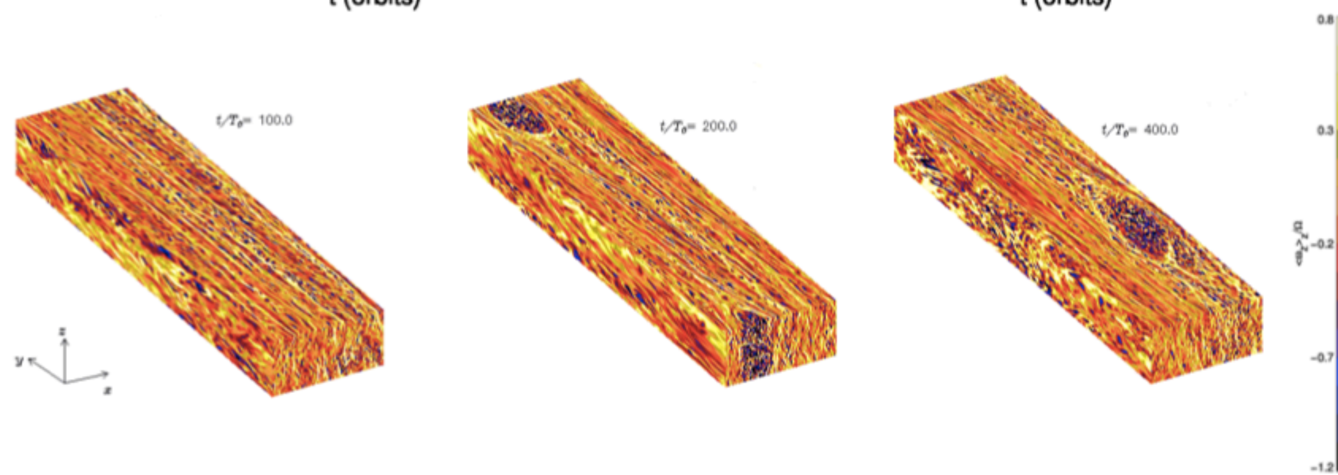
$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u},$$
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\boldsymbol{u} = -\frac{1}{\rho}\boldsymbol{\nabla}p + \boldsymbol{g},$$
$$\frac{\partial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

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

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

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



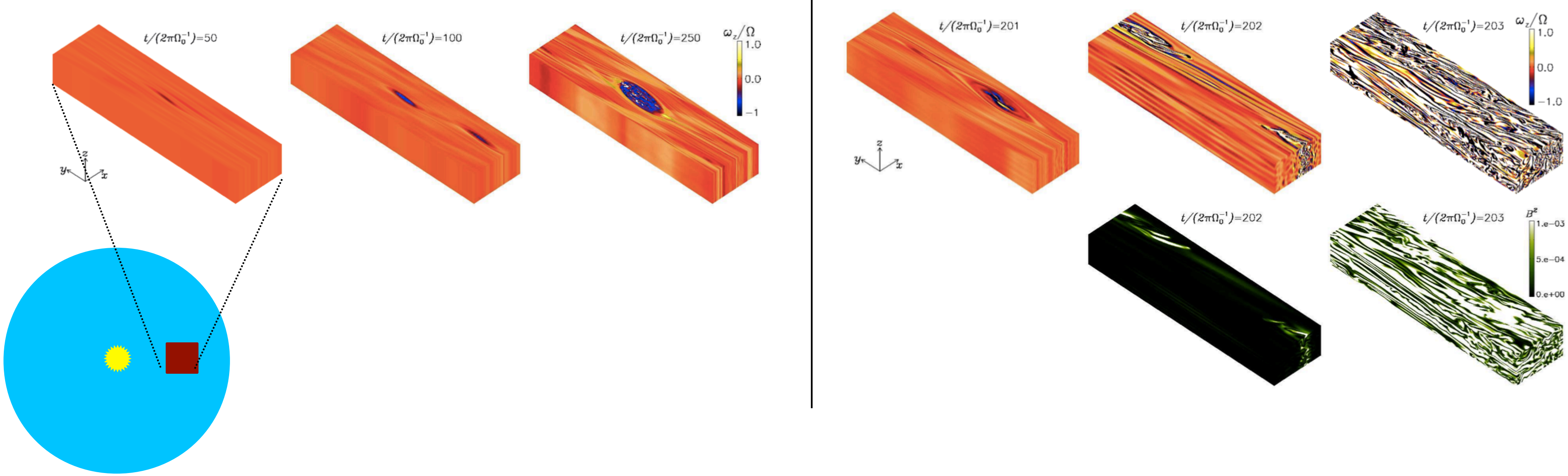




Lyra (2014)

# Baroclinic instability and layered accretion

What happens when the vortex is magnetized?

Hydro | MHD

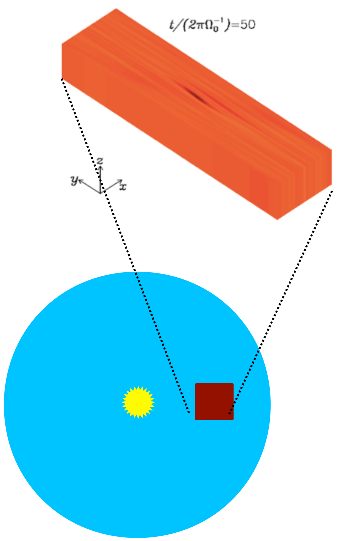


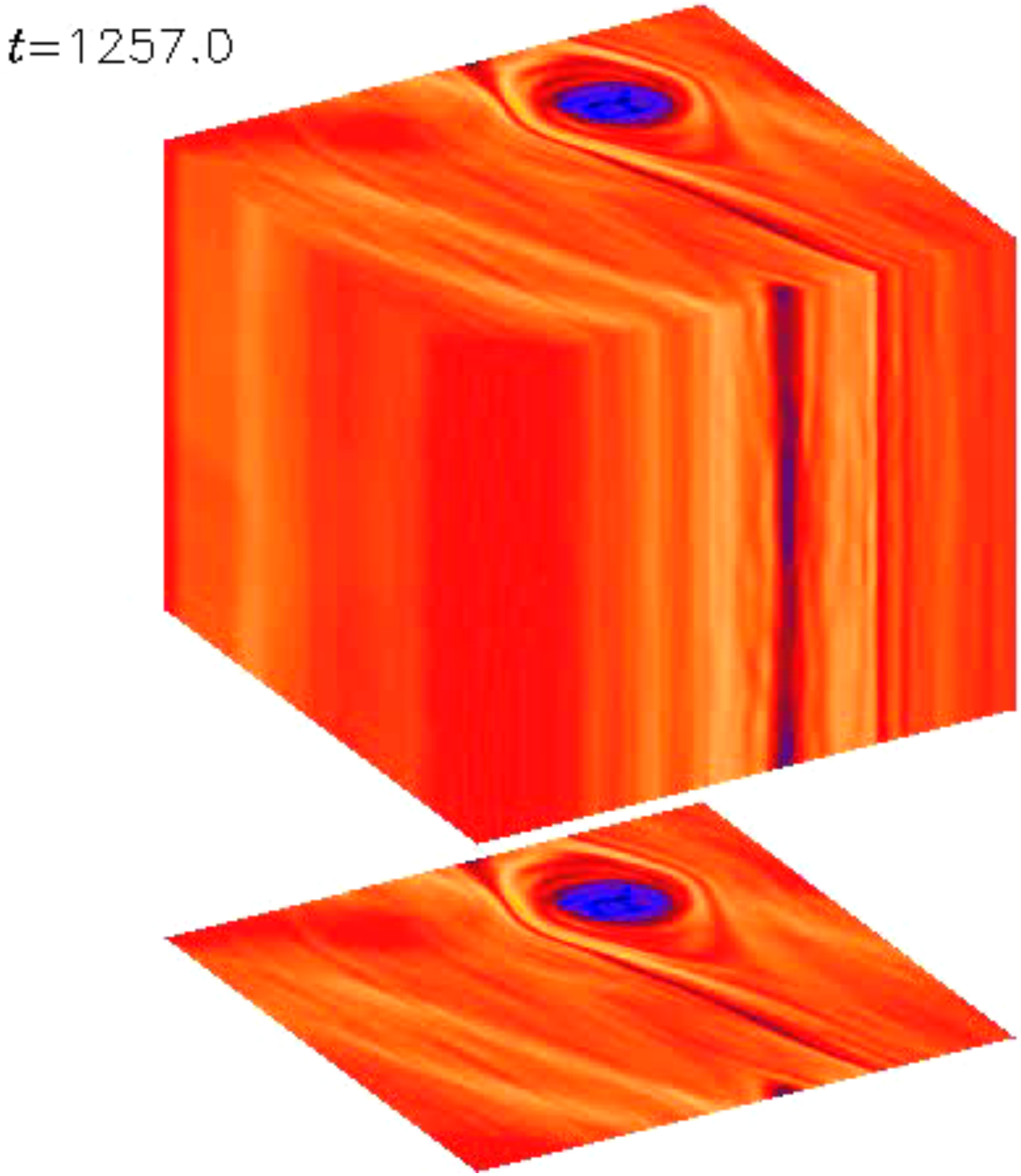
Vorticity

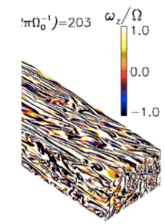
Mag. Energy

Lyra & Klahr (2011)

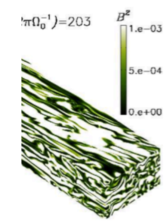
# Baroclinic instability and layered accretion




Vorticity




Mag. Energy

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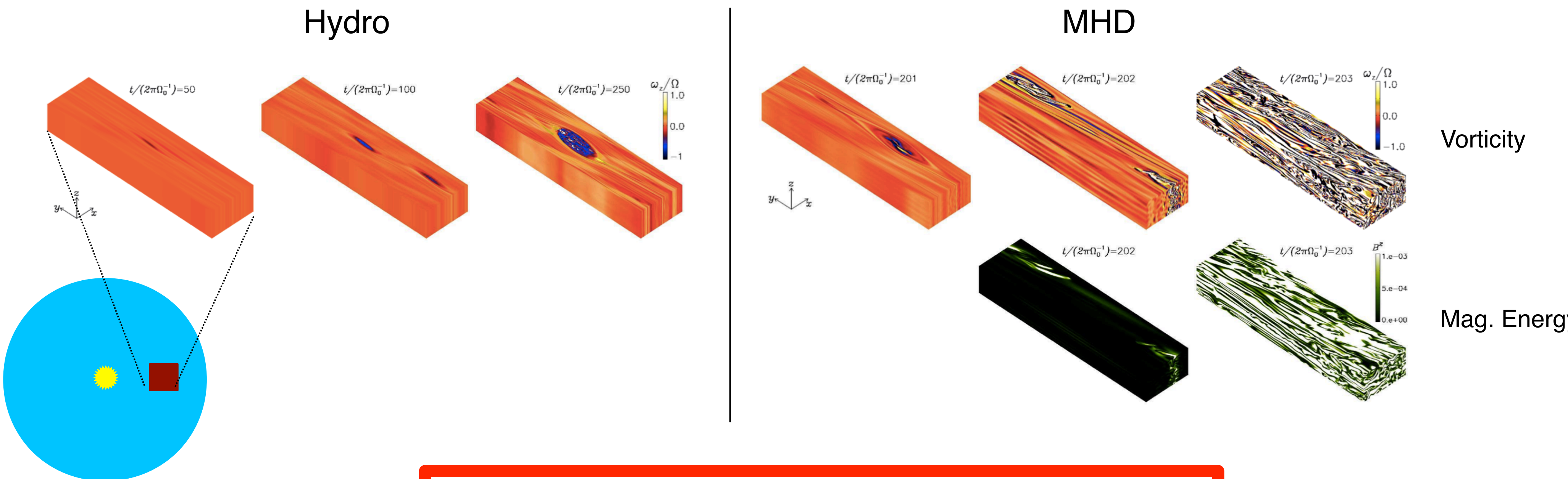
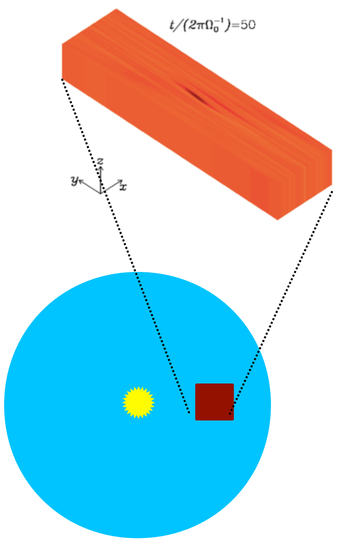
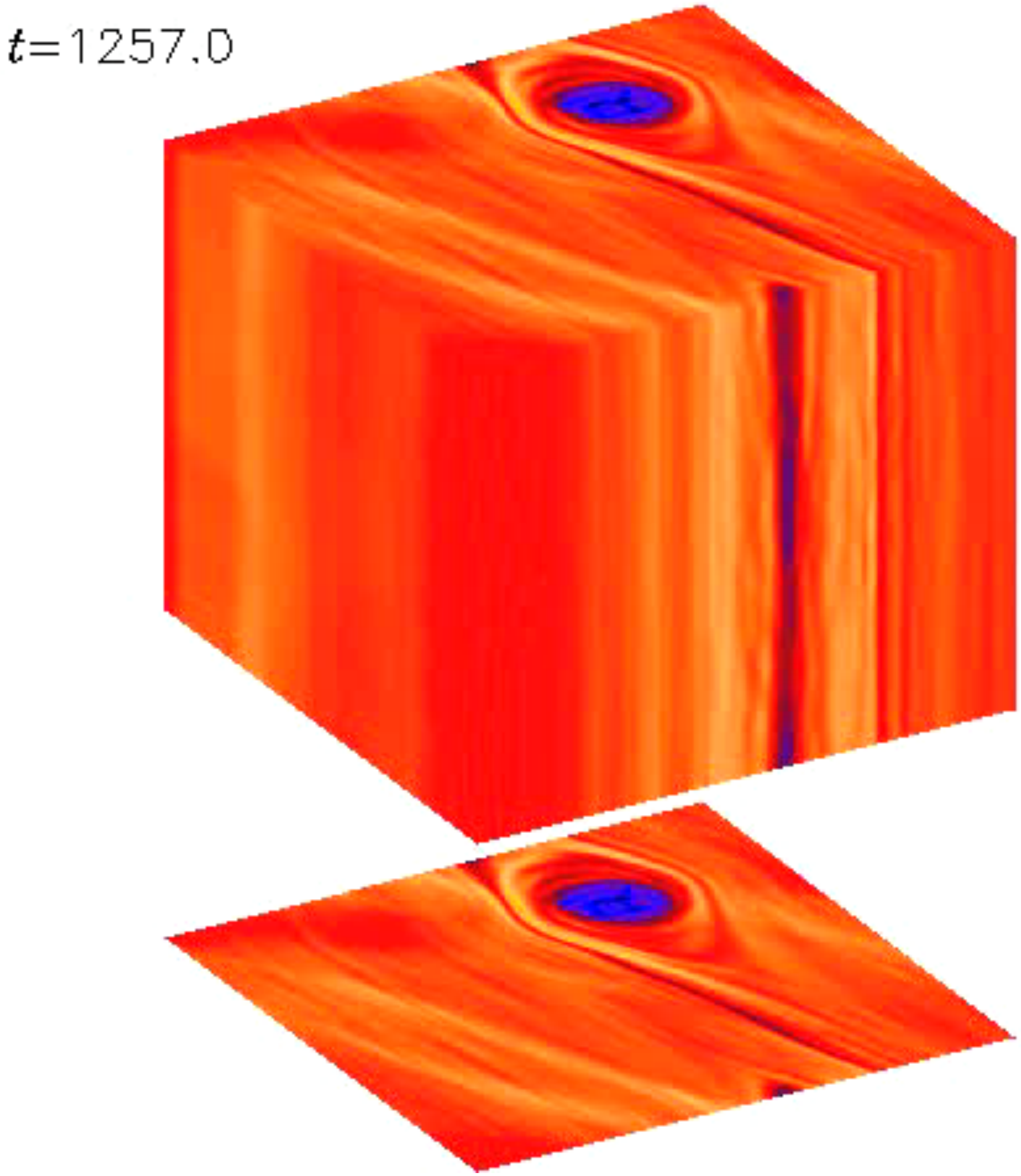


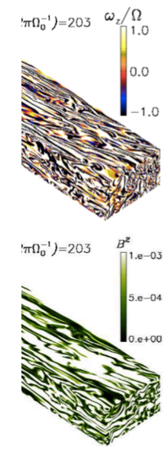

Lyra & Klahr (2011)

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

# Baroclinic instability and layered accretion



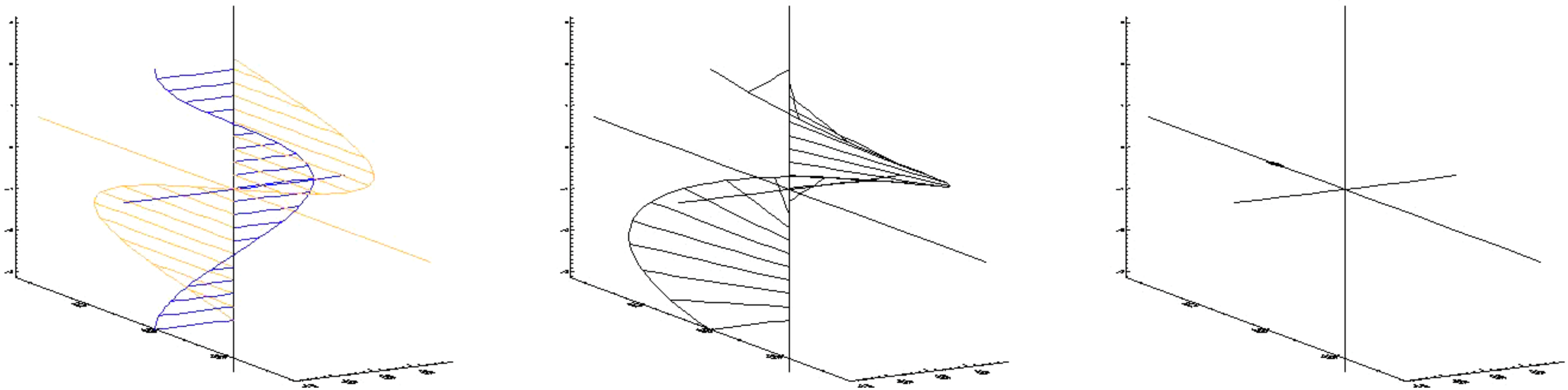



Vorticity

Mag. Energy

Lyra & Klahr (2011)

# Fluid in rigid rotation supports a spectrum of oscillations



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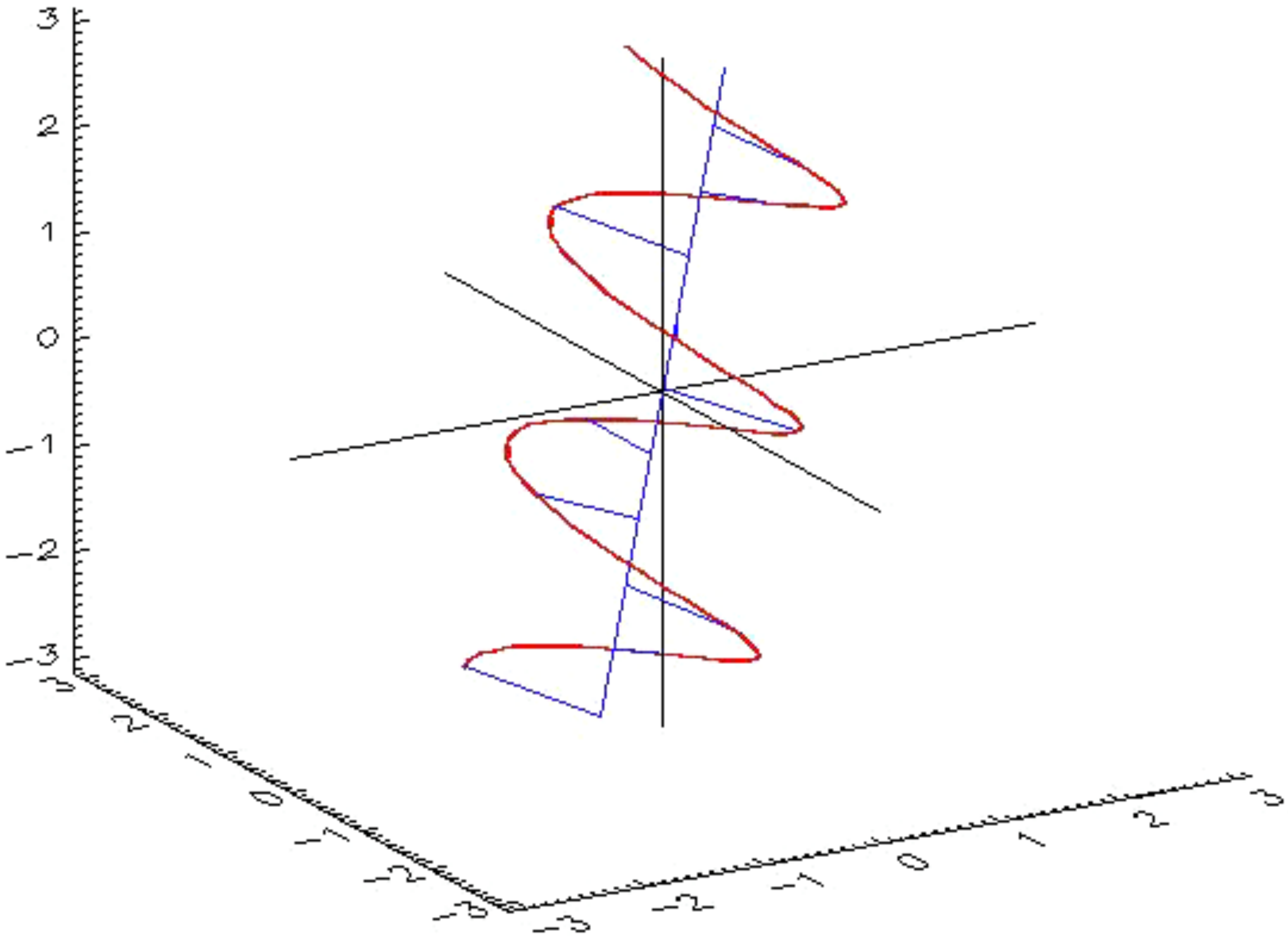
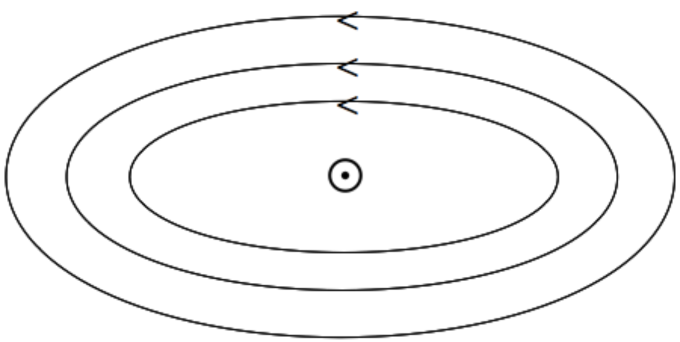
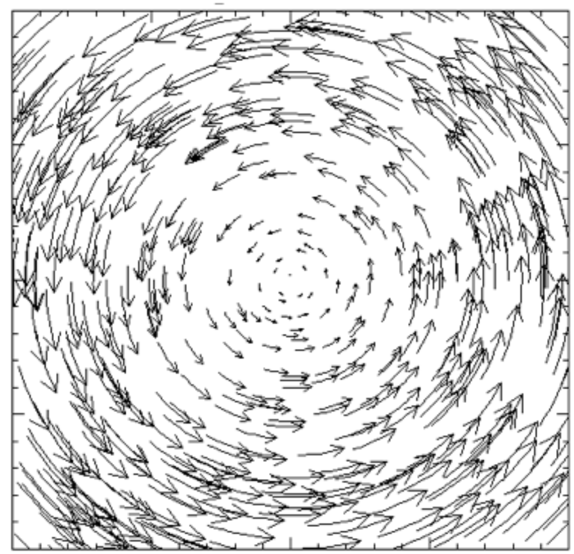


# Introducing ellipticity: Strain



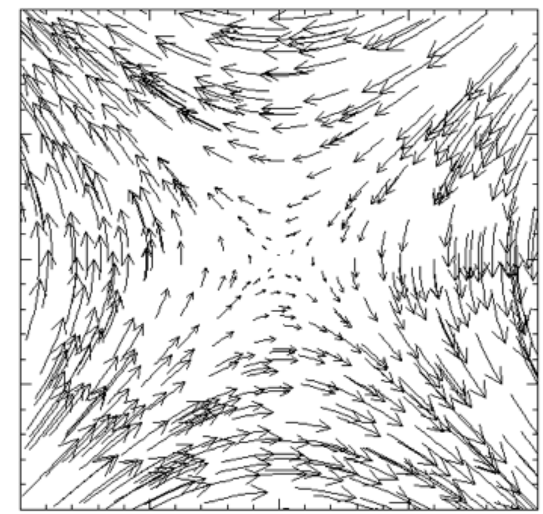
$=$

Rigid rotation



$+$

Strain field

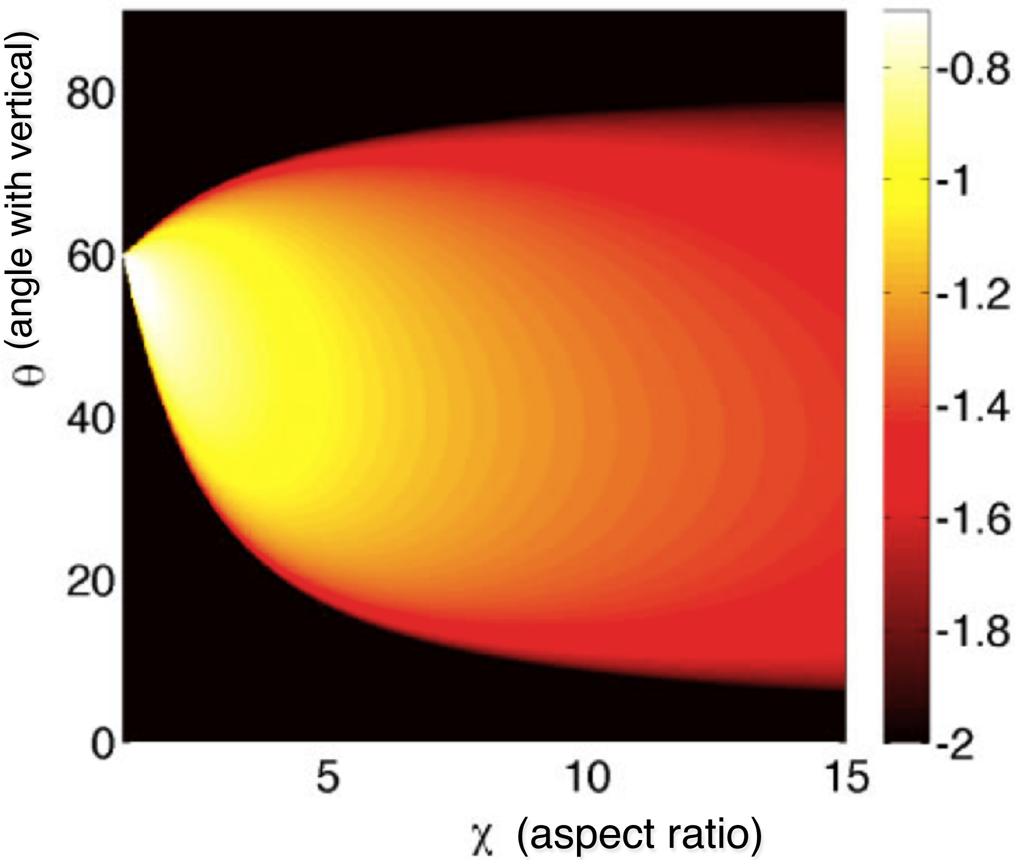


$U=[-(1-\epsilon)y,(1-\epsilon)x]$ $\quad$ $[-y,x]$ $\quad$ $-\epsilon[y,x]$

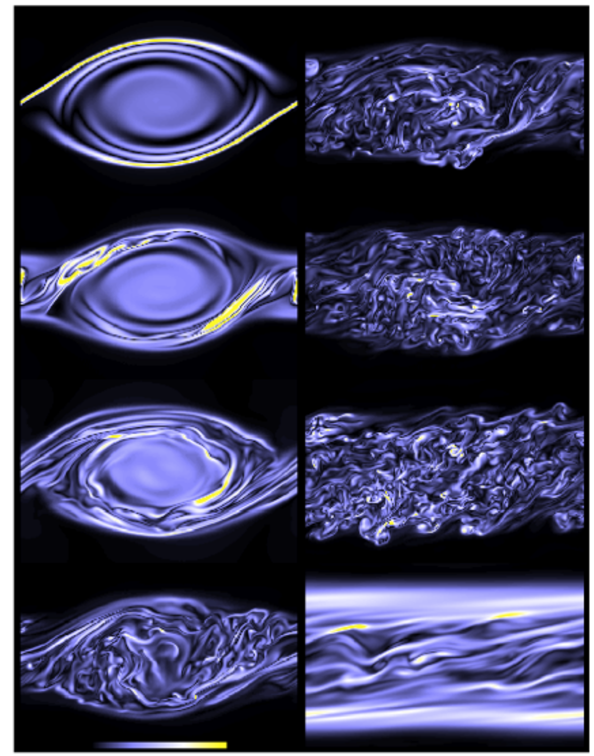
Rigid rotation is stable.

Strain is ***not*** necessarily so.

# Elliptic Instability



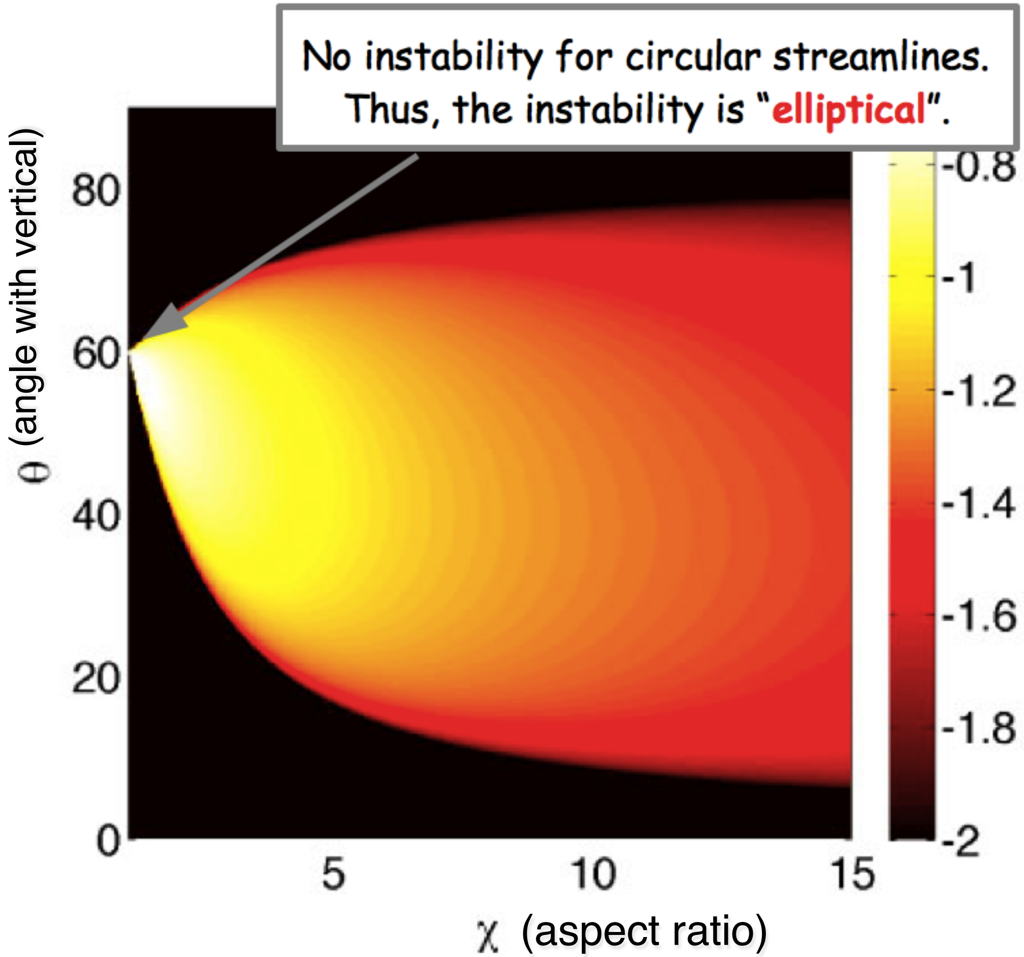

Lesur & Papaloizou (2009)
After Bayly (1986)



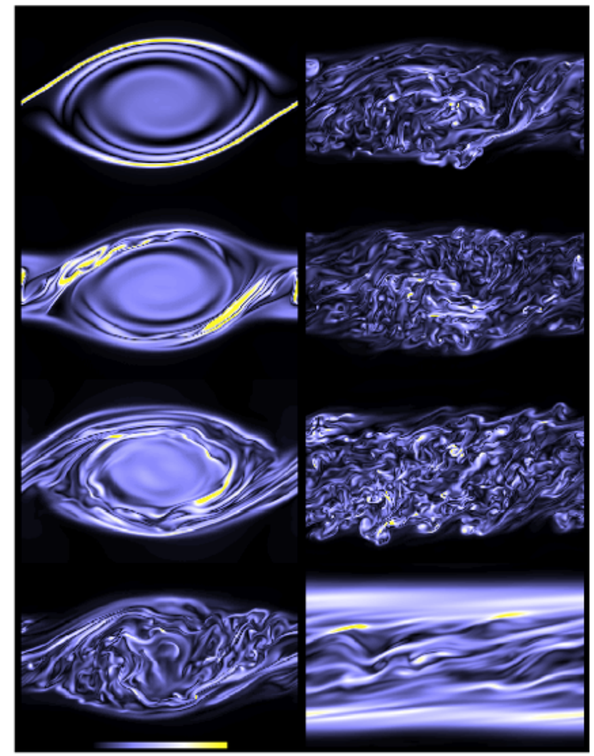
Vortex coherence is destroyed.
Energy cascades forward and dissipates.
The flow relaminarizes.

McWilliams (2010)

# Elliptic Instability



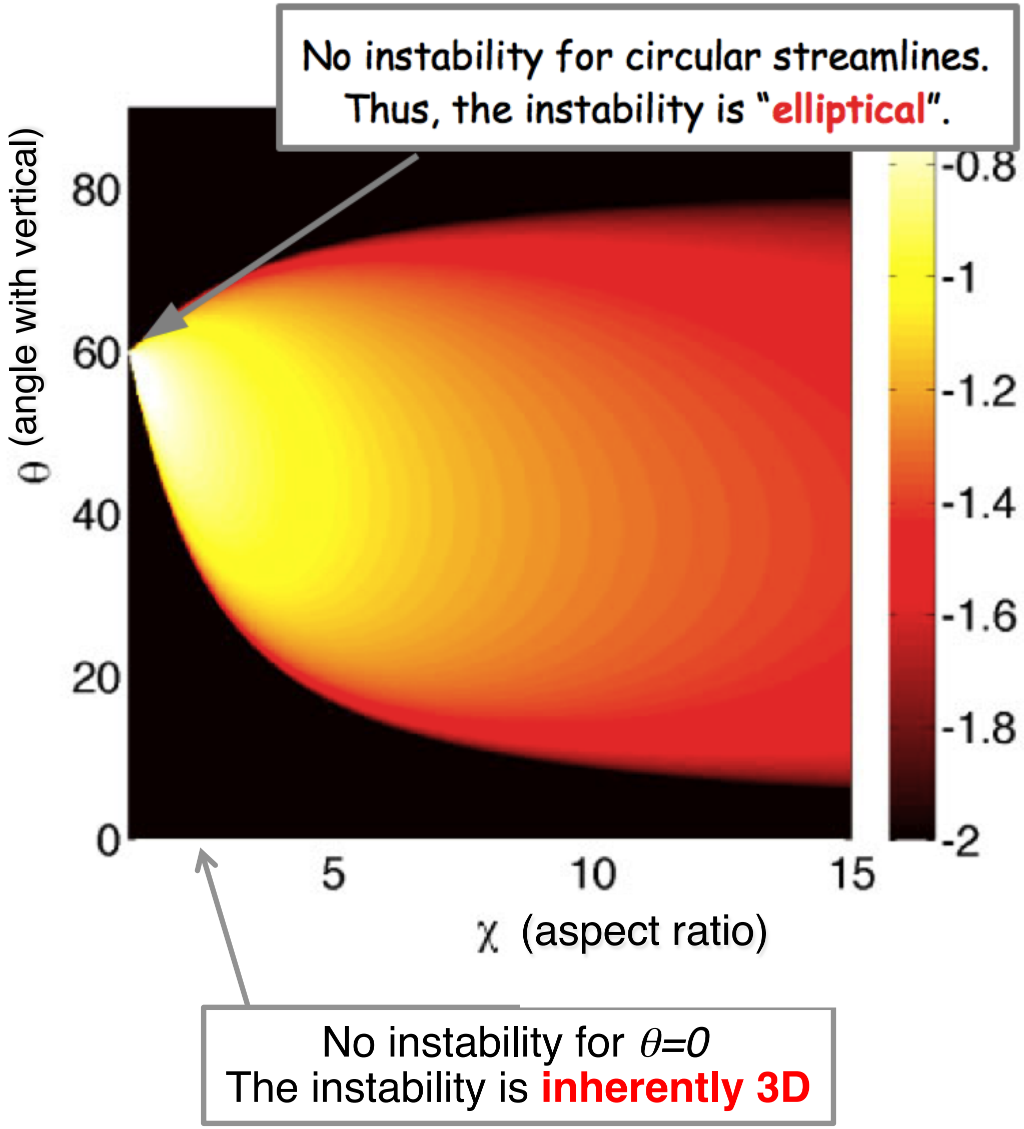

Lesur & Papaloizou (2009)
After Bayly (1986)

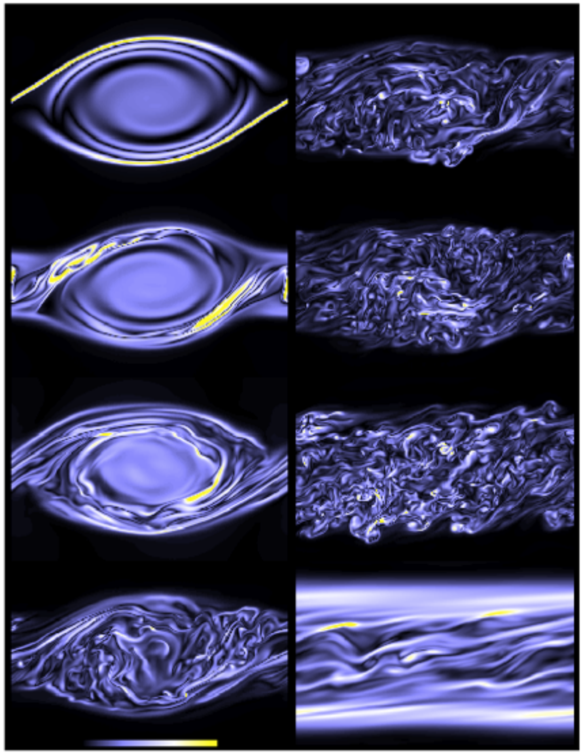


Vortex coherence is destroyed
Energy cascades forward and dissipates
The flow relaminarizes

McWilliams (2010)

# Elliptic Instability

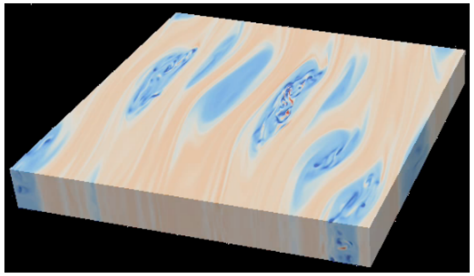


Vortex coherence is destroyed
Energy cascades forward and dissipates
The flow relaminarizes

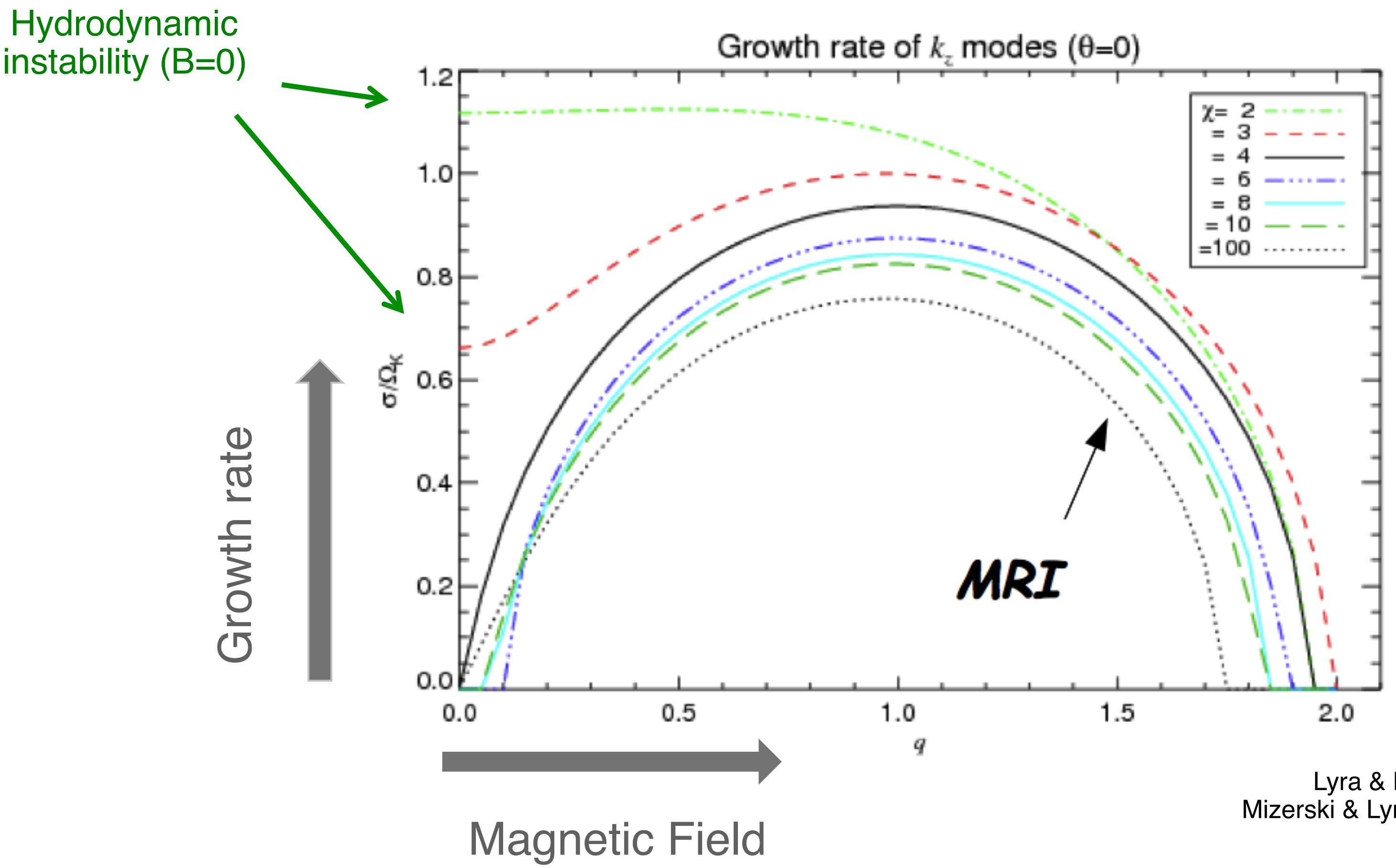
McWilliams (2010)

# Magneto-Elliptic Instability



Lesur & Papaloizou (2010)

See also
Pierrehumbert 1986
Bayly 1986
Kerswell 2002
Lesur & Papaloizou 2009
Lesur & Papaloizou 2010
Lyra & Klahr 2011
Lyra 2013

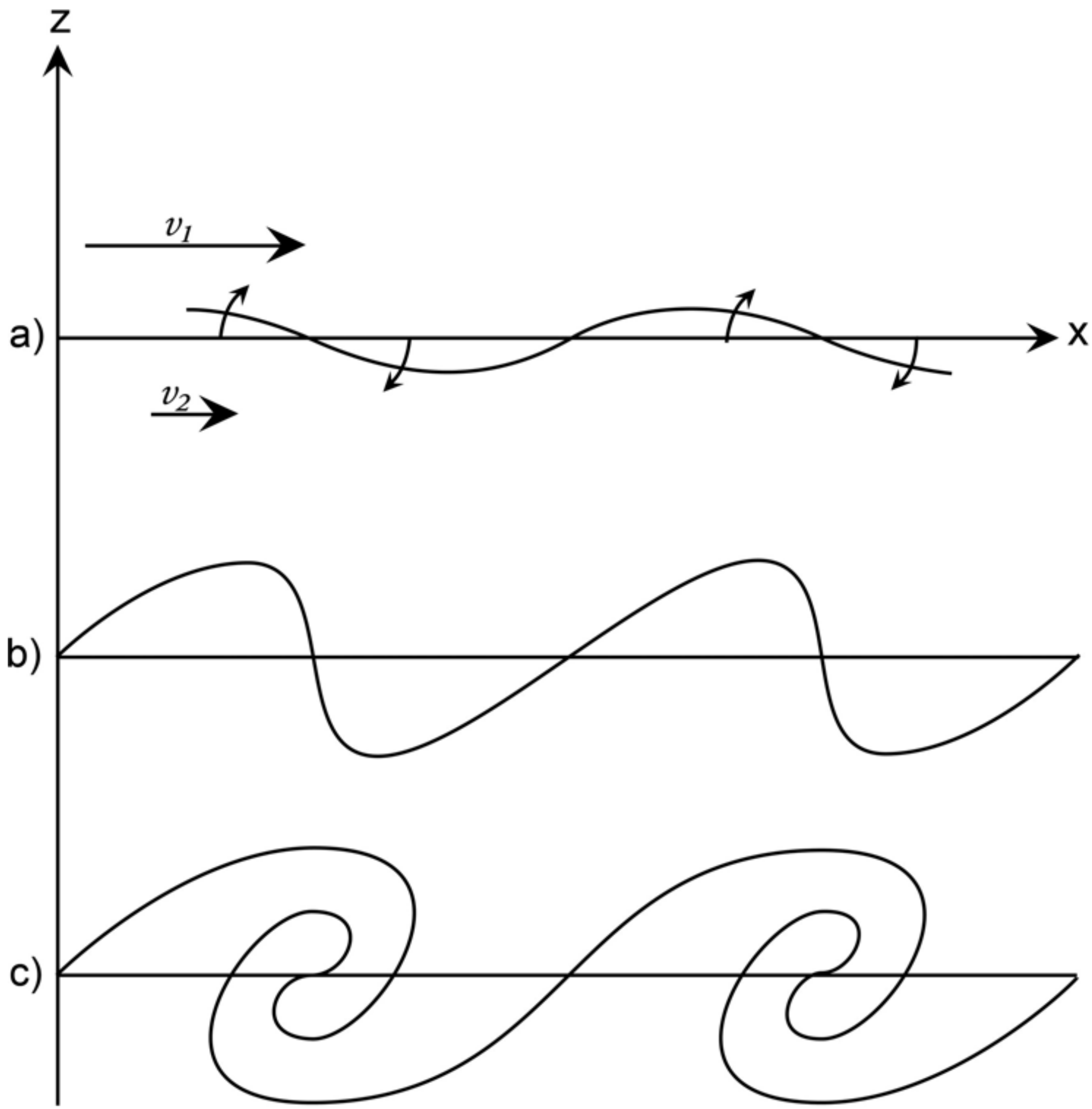



Lyra & Klahr 2011, *A&A*
Mizerski & Lyra 2012, *J. Fluid Mech.*

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

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

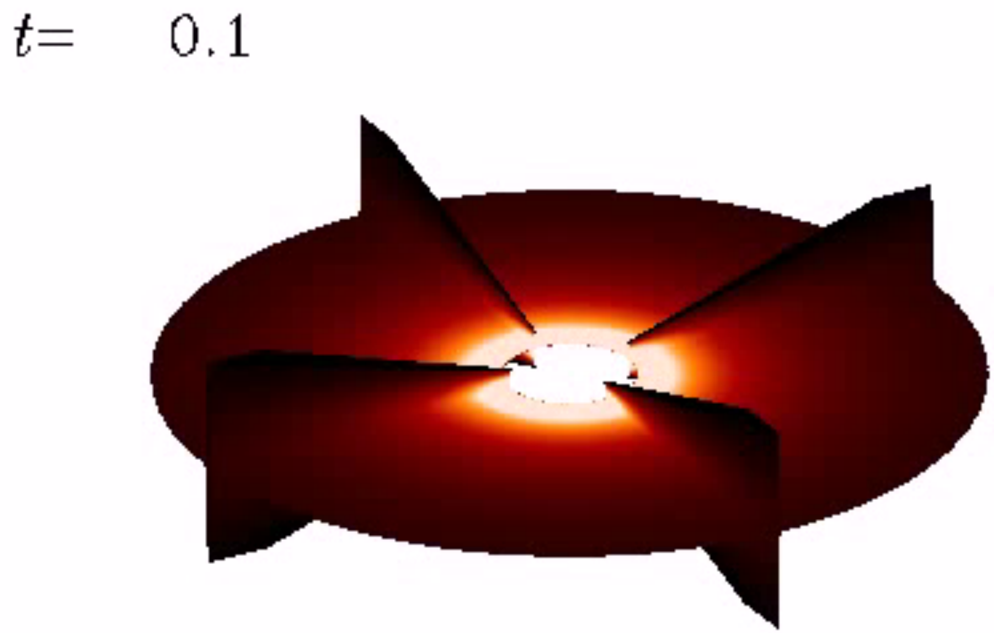
# Rossby Wave Instability
(or.... Kelvin-Helmholtz in rotating disks)

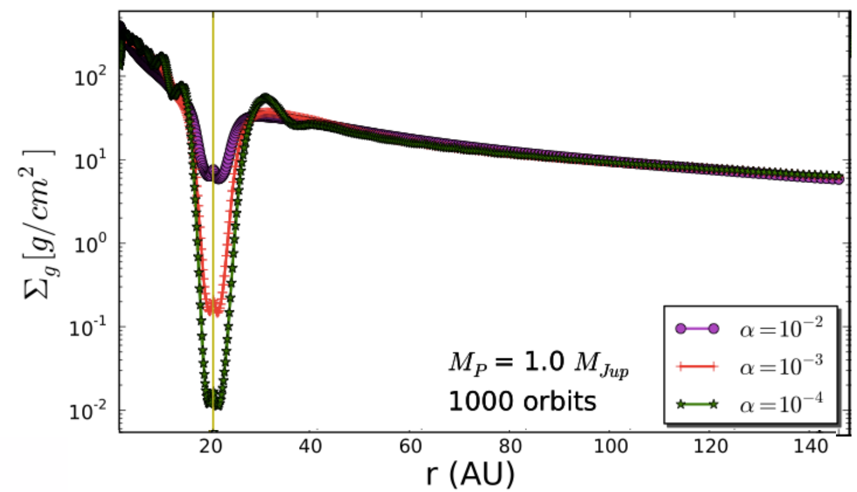




# Planetary gap RWI

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

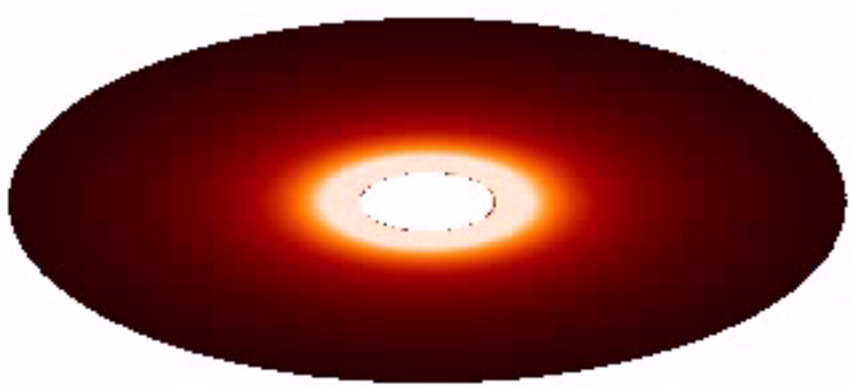



Pinilla et al. (2012)

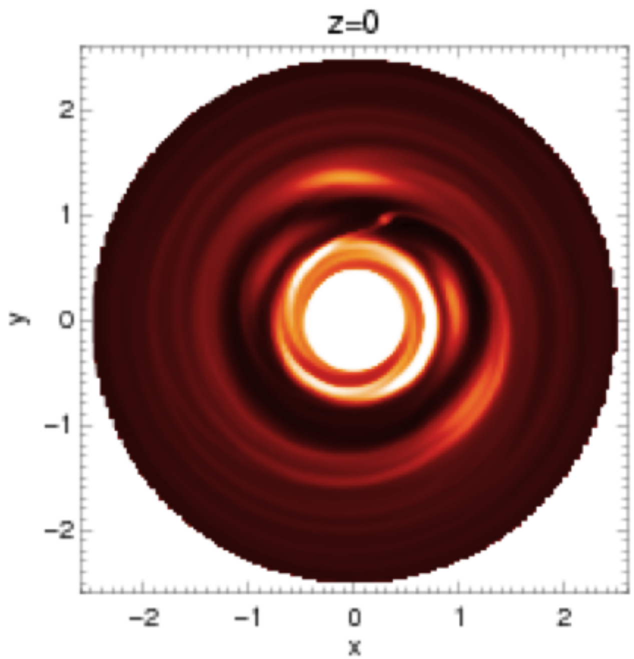
Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

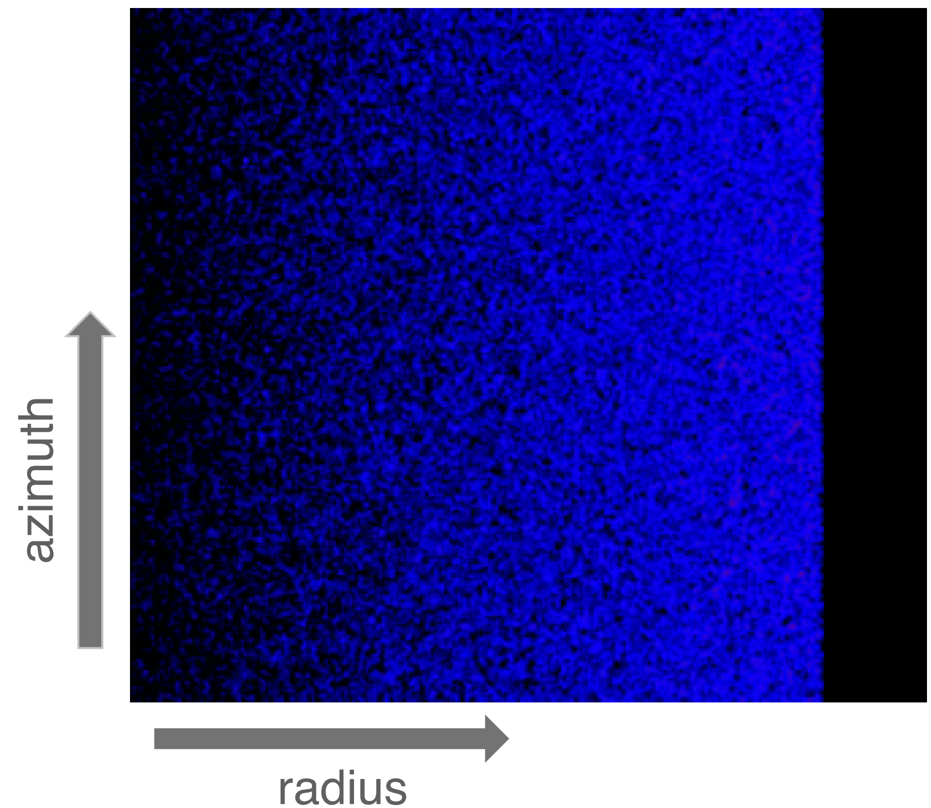


Lyra (2009)

# Planetary gap RWI

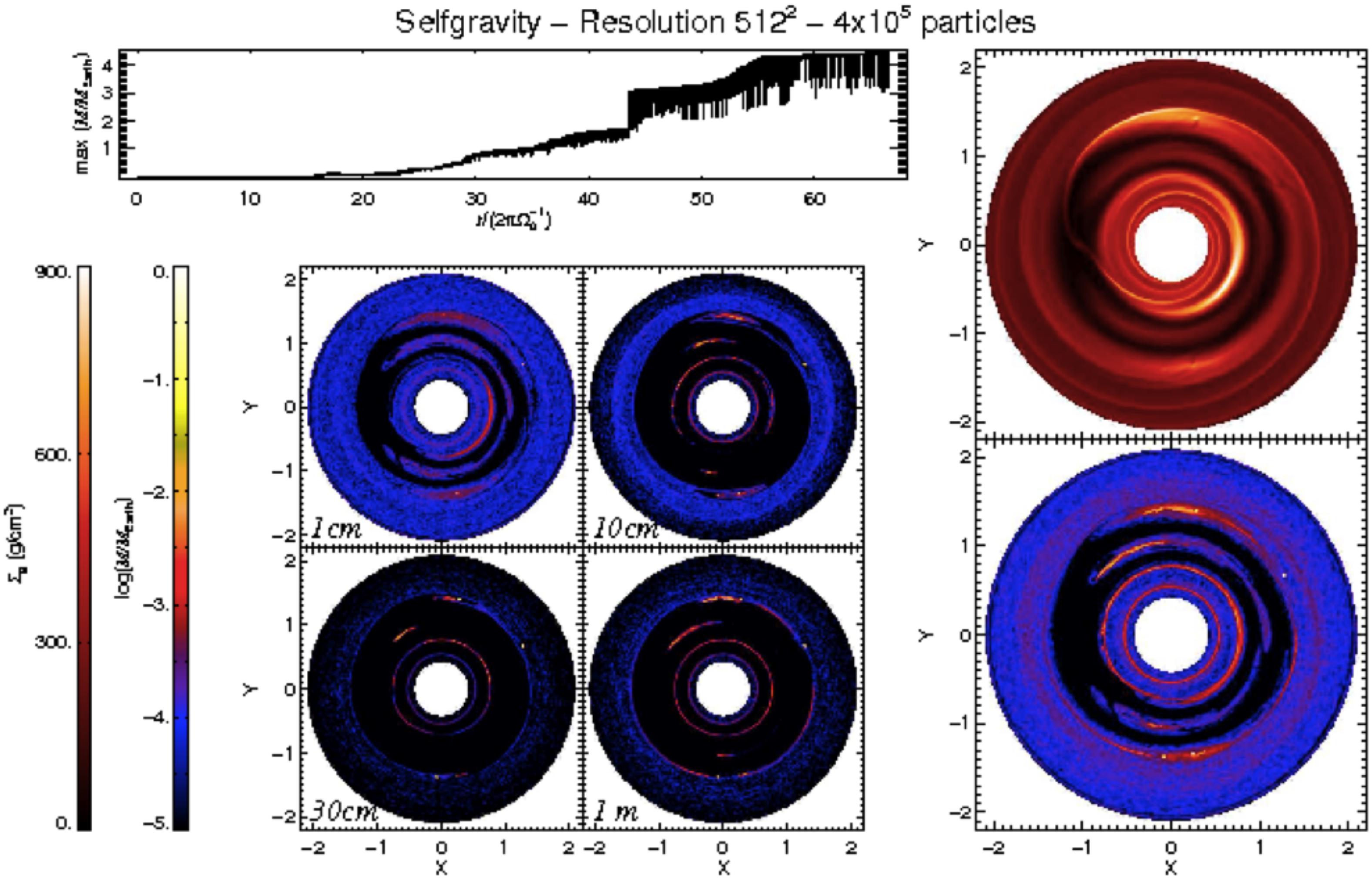



Lyra et al. (2009b),
see also de Val-Borro et al. (2007)




"Secondary" planet formation burst
following the formation of a giant planet.

## Vortex trapping




**3 Super-Earths formed + Mars mass Trojans**

Lyra et al. (2009b)

# Peggy Varnière & Michel Tagger
# RWI at dead zone boundary

## Reviving Dead Zones in Accretion Disks by Rossby Vortices at their Boundaries

P. Varnière[1,2] & M. Tagger[3]

[1] Department of Physics & Astronomy, Rochester University, Rochester NY 14627-0171
[2] LAOG, Université J. Fourier UMR 5571 France, e-mail: pvarni@pas.rochester.edu
[3] Service d'Astrophysique (UMR Astroparticules et cosmologie) CEA/Saclay F-91191 Gif sur Yvette e-mail: tagger@cea.fr

the date of receipt and acceptance should be inserted later

**Abstract.** Models of the accretion disks of Young Stellar Objects show that they should not be ionized at a few AU from the star, and thus not subject to the MHD turbulence believed to cause accretion. This has been suggested to create a 'Dead Zone' where accretion remains unexplained. Here we show that the existence of the Dead Zone self-consistently creates a density profile favorable to the Rossby Wave Instability of Lovelace et al. (1999). This instability will create and sustain Rossby vortices in the disk which could lead to enhanced planet formation.

**Key words.** accretion disks; Instabilities; planetary systems: formation

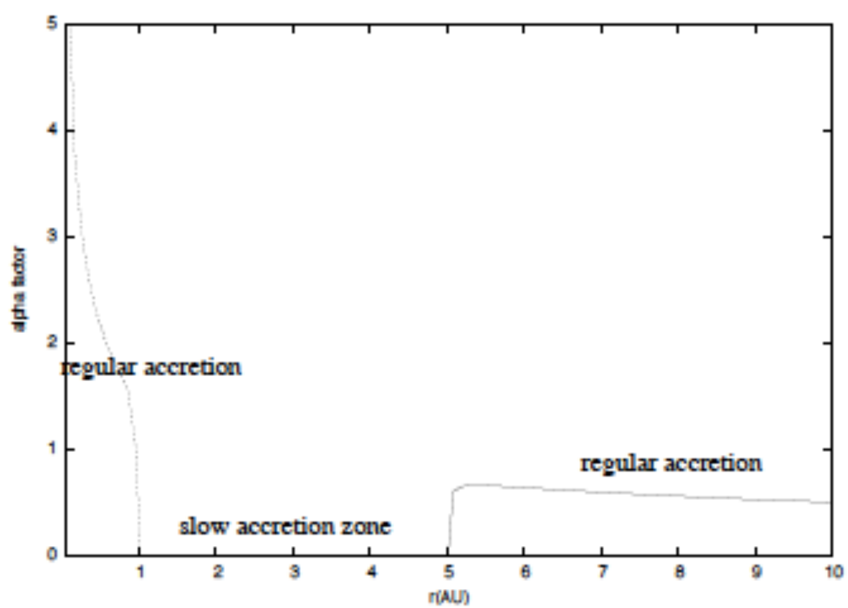



**Fig. 1.** Profile of the $\alpha$-viscosity implemented to represent a Dead Zone between 1 and 5 AU with $(\epsilon, \delta_r) = (10^{-5}, 50)$.

Varnière & Tagger (2006)

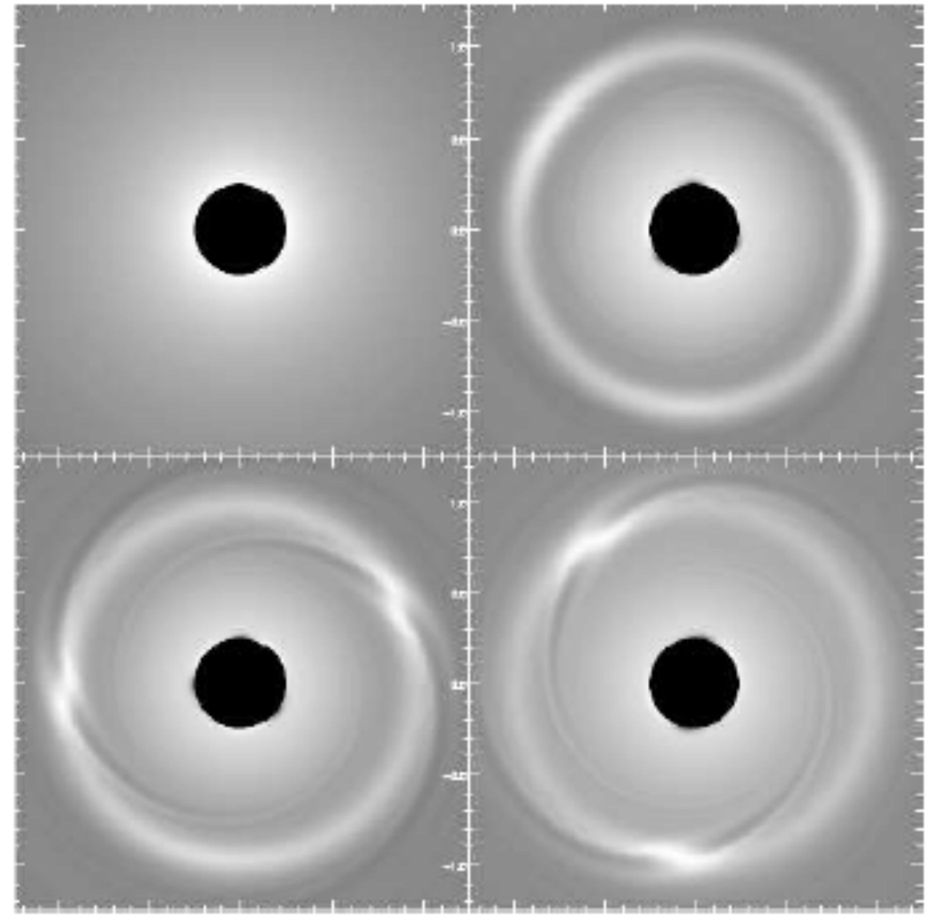
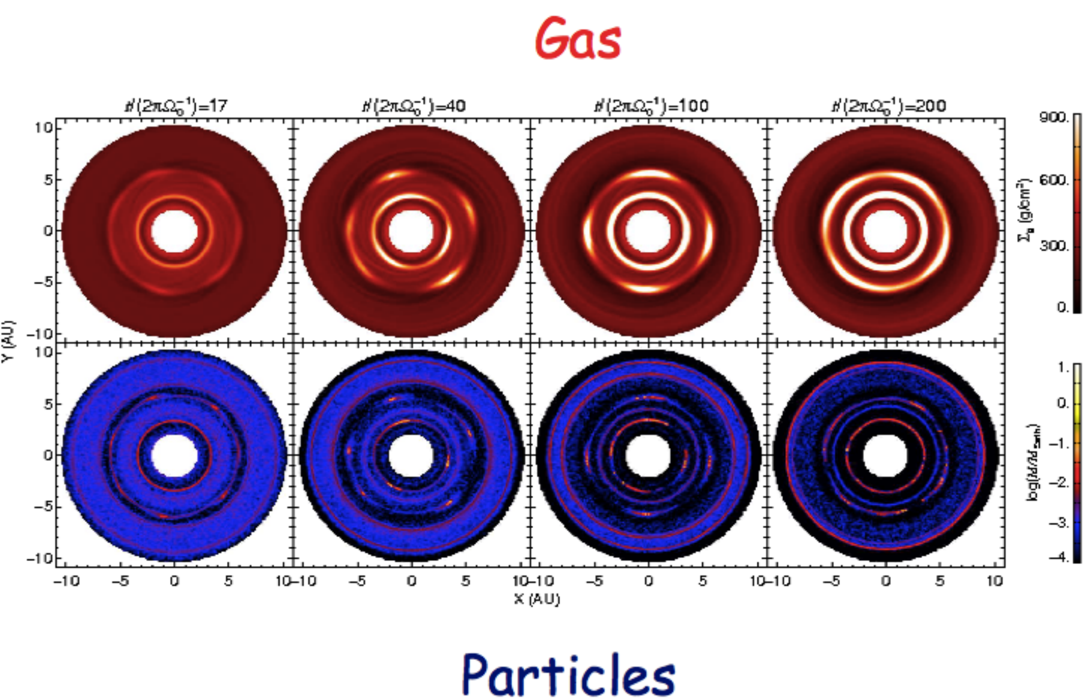
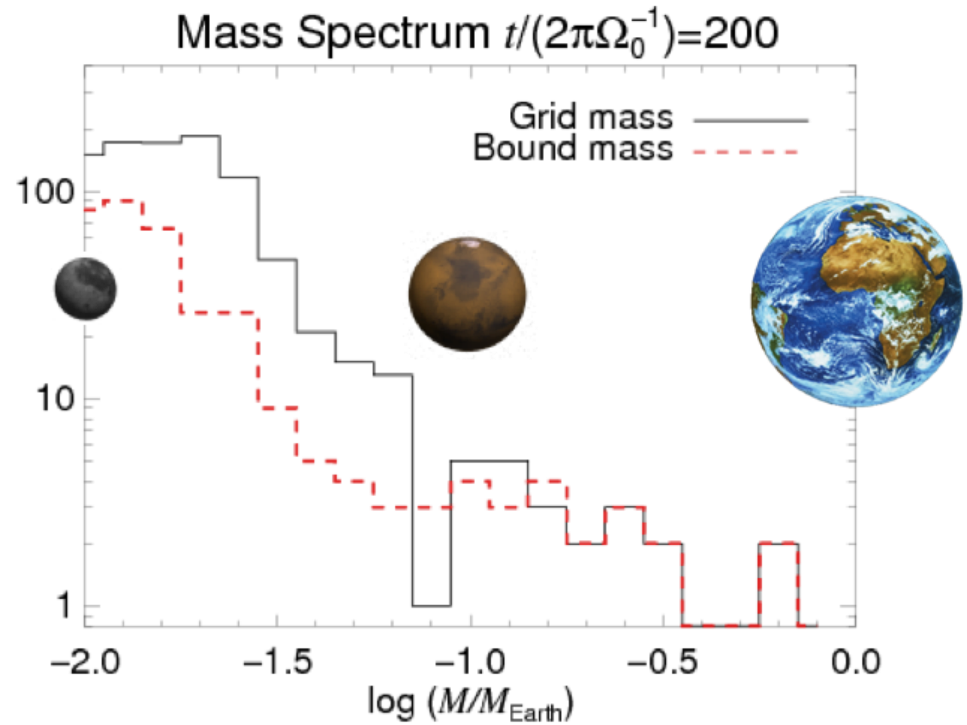


**Fig. 3.** Zoom of the first 2 inner AU of the simulation at $t = 0, 100, 200, 300$ years, showing the density. One sees three vortices forming, later evolving to two vortices, near the outer edge of the Dead Zone.

# Vortices and Planet Formation

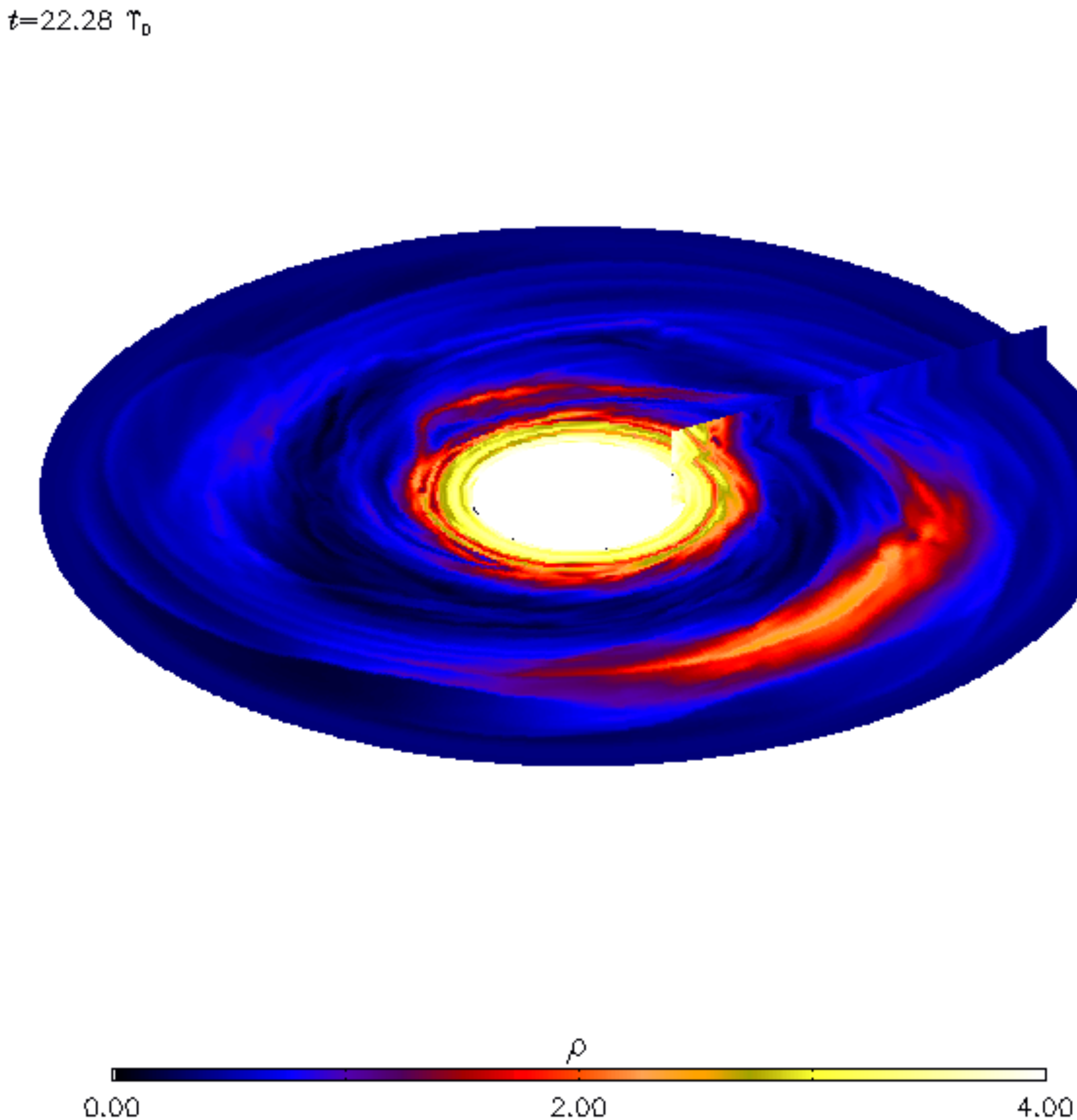


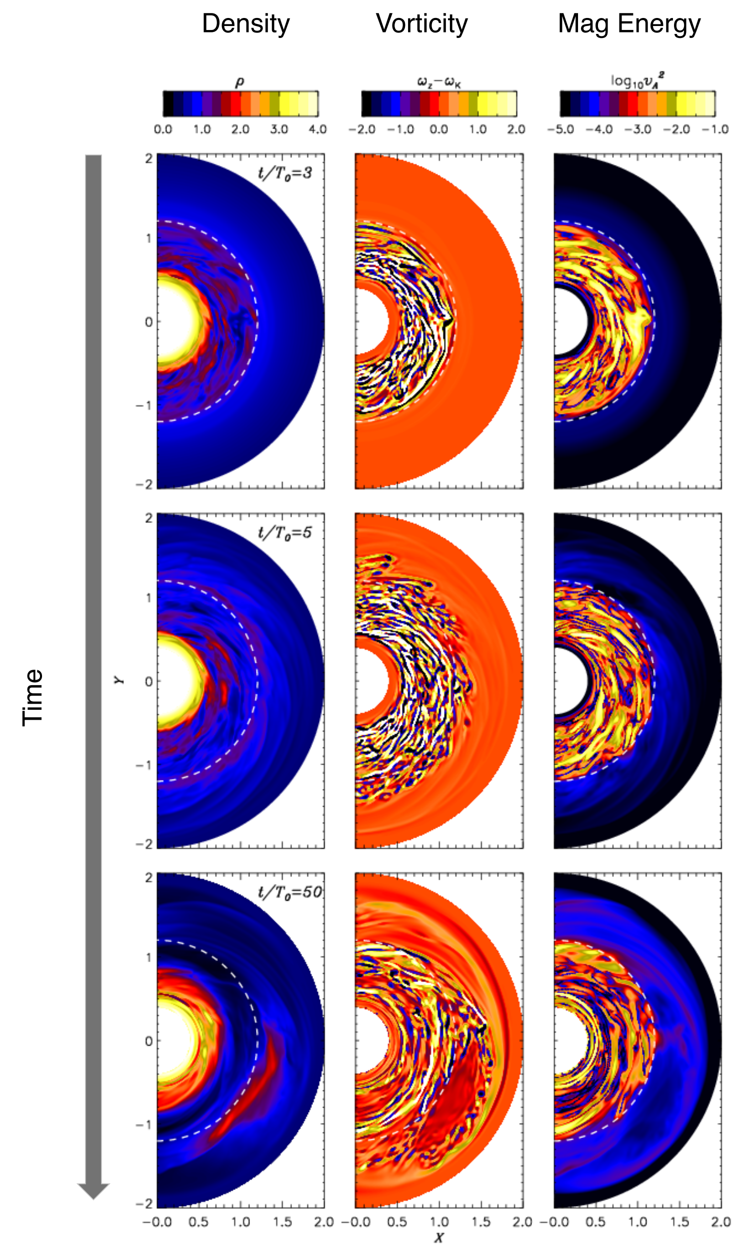




Collapse into Mars mass objects

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

# Active/dead zone boundary

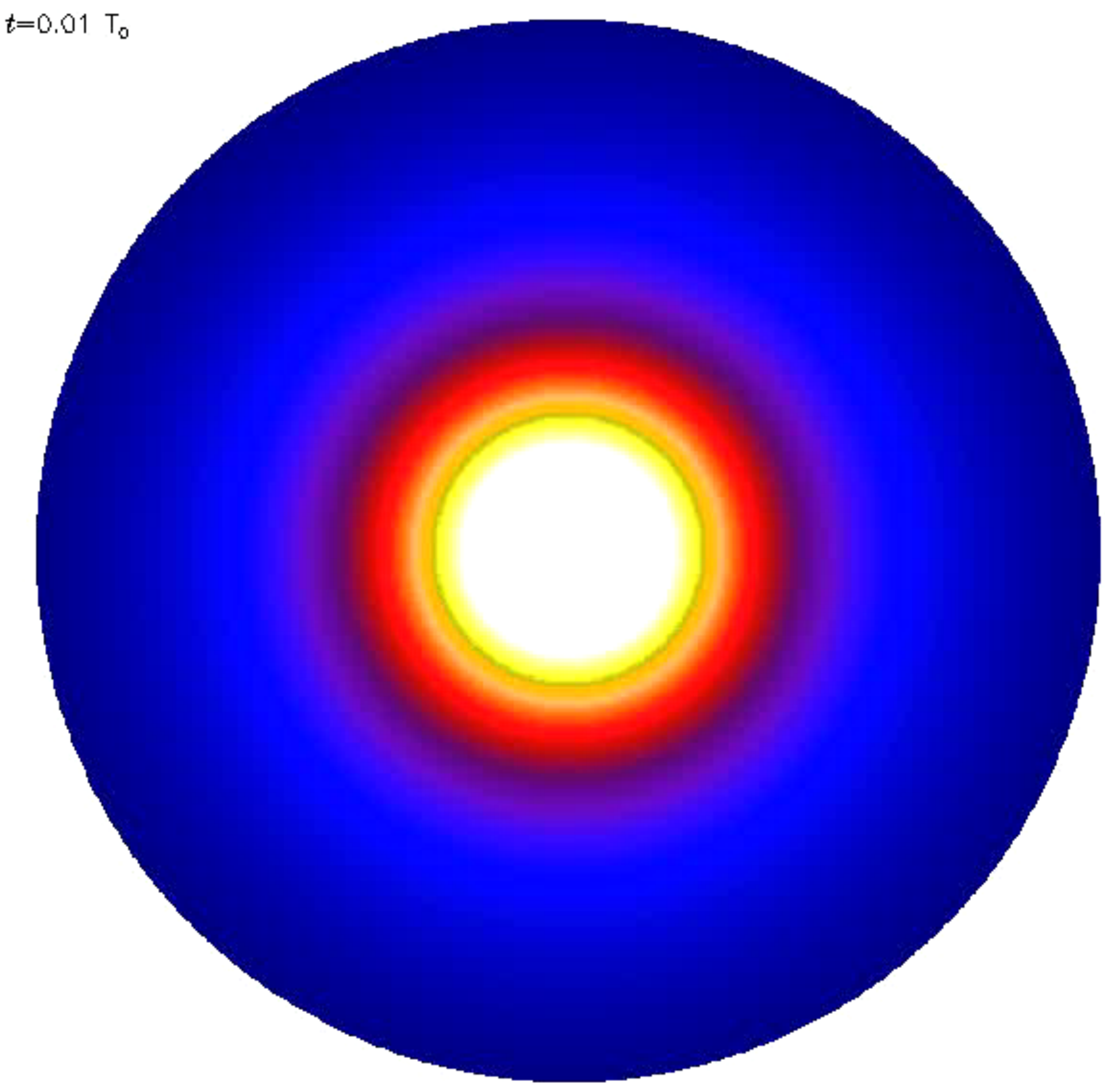


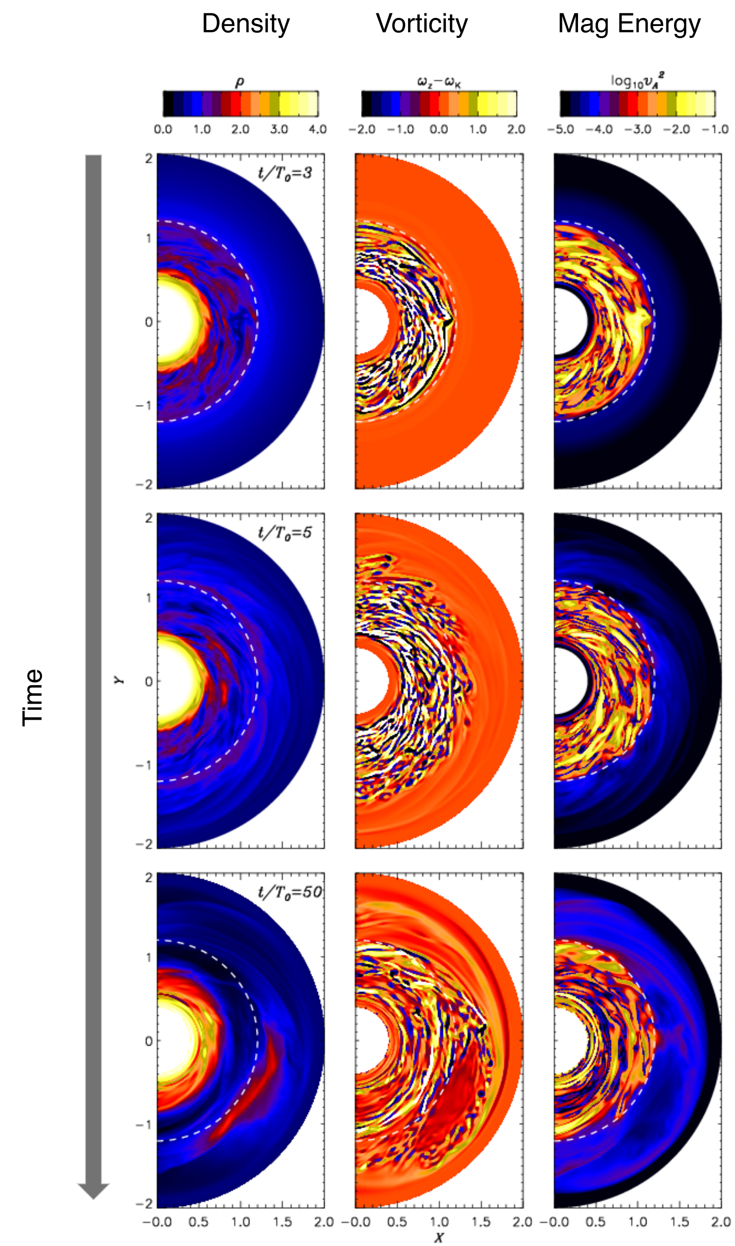




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

# Active/dead zone boundary



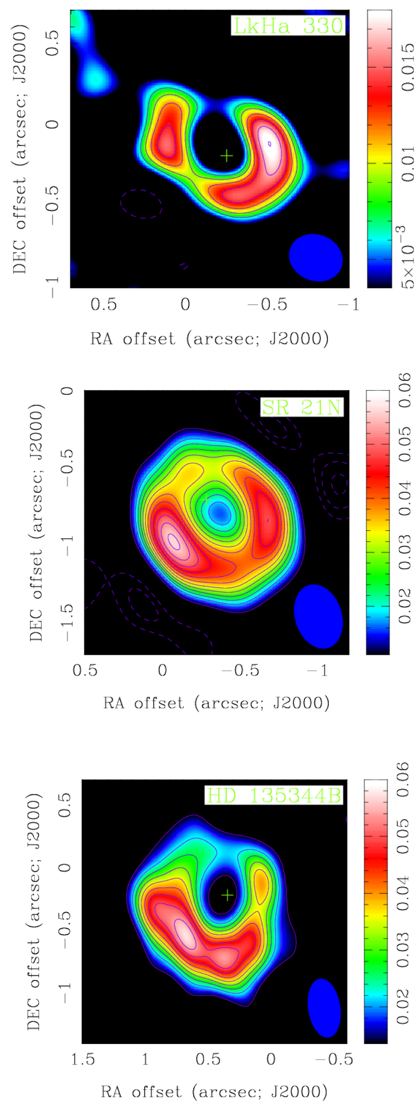

Magnetized inner disk + resistive outer disk

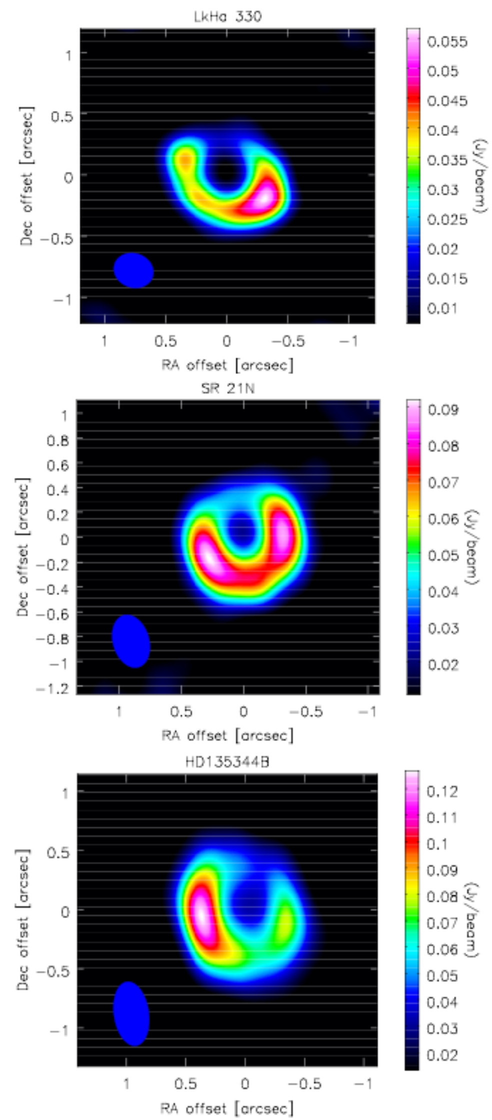
Lyra & Mac Low (2012)

# 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

## A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1]* Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

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

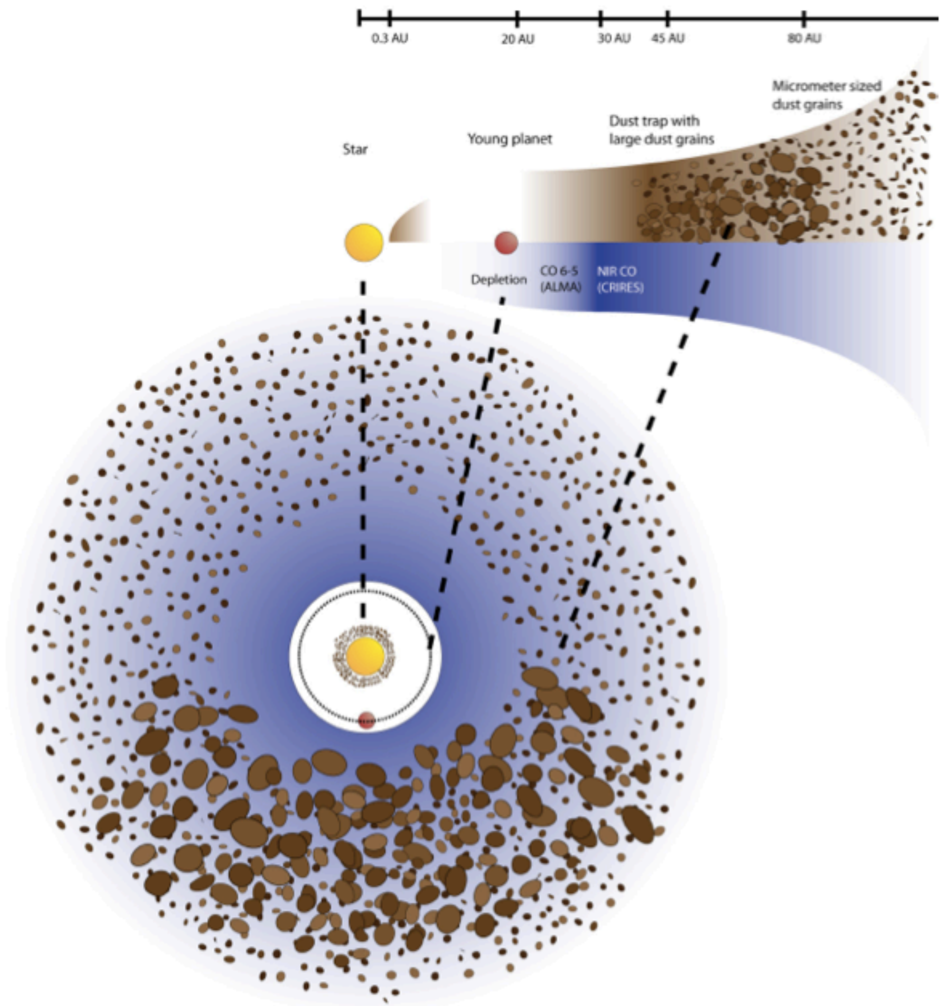


iencemag.org SCIENCE VOL 340 7 JUNE 2013 1199

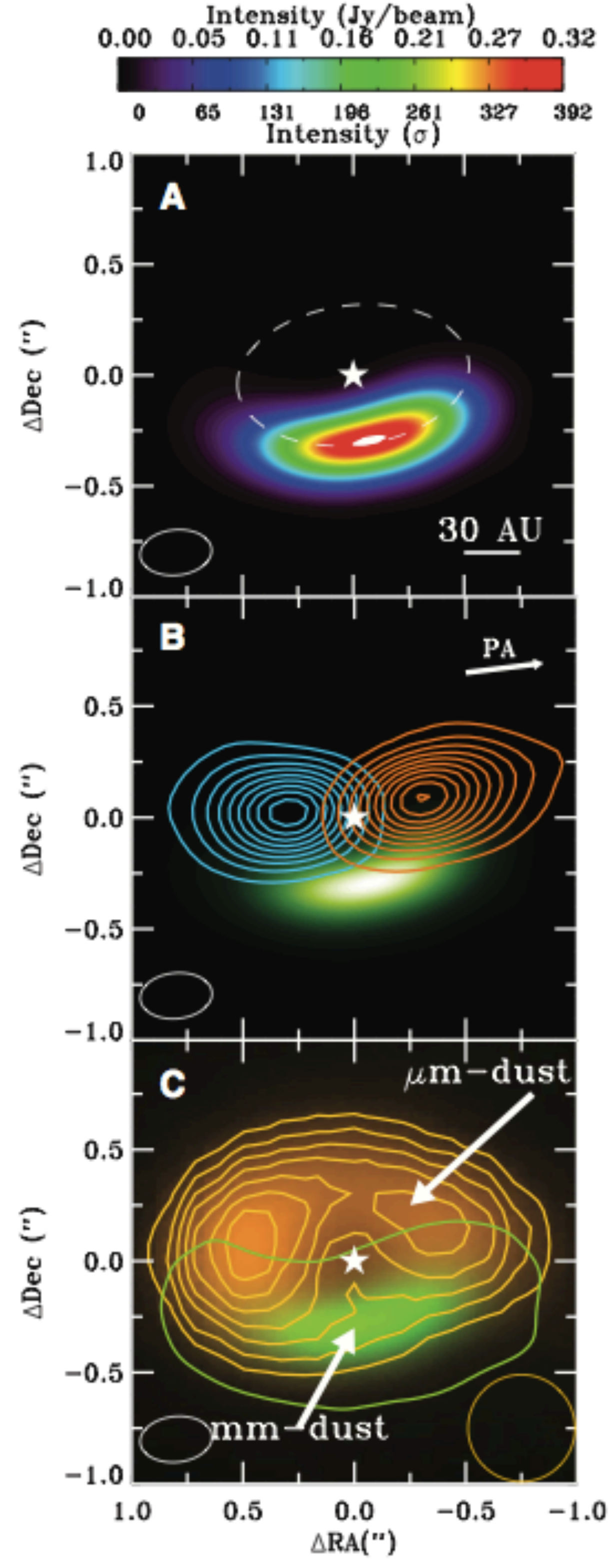
van der Marel et al. 2013

A possible huge vortex observed with ALMA

# The Oph IRS 48 “dust trap”




van der Marel et al. (2013)

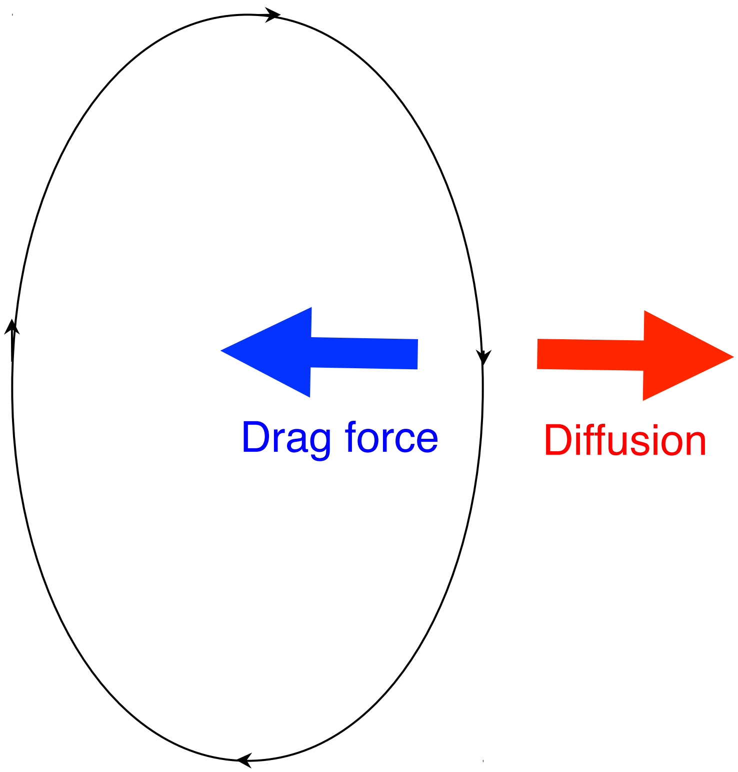



asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

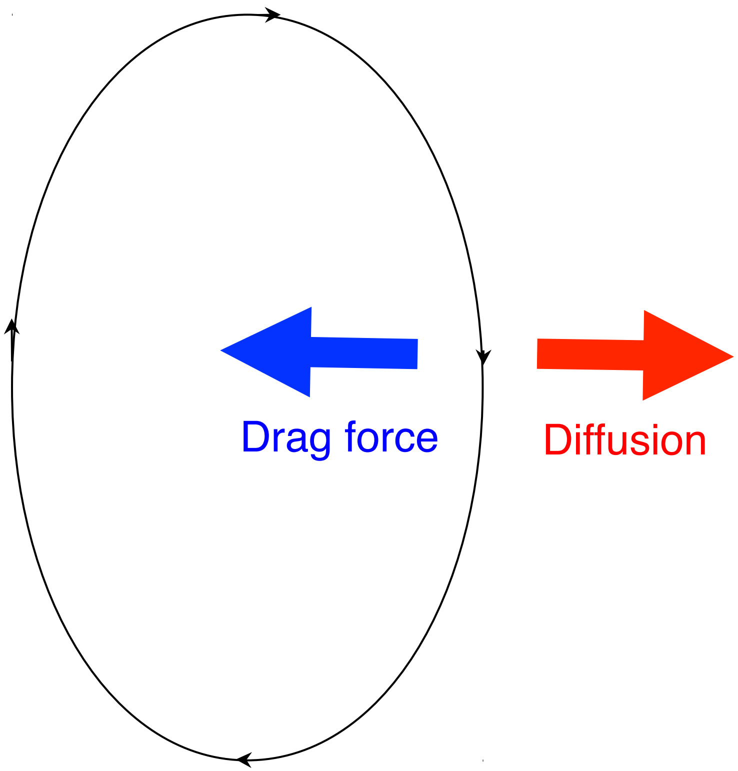
Micron-sized dust follows gas

# Drag-Diffusion Equilibrium




Trapped particle

# Drag-Diffusion Equilibrium

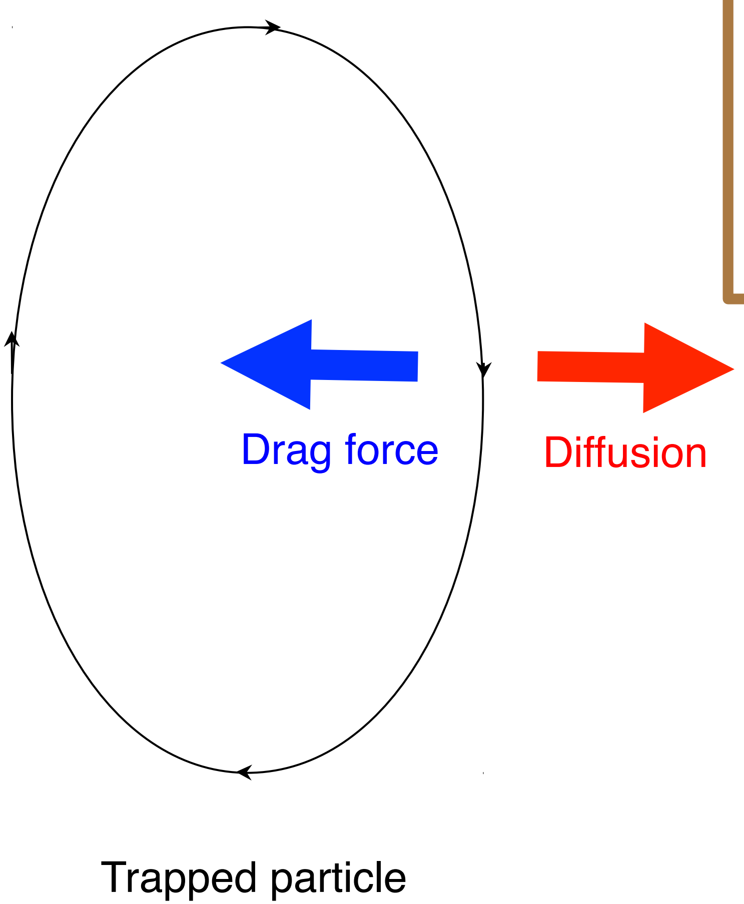



Trapped particle

Dust continuity equation

$$\frac{\partial \rho_d}{\partial t} = \underbrace{-(\boldsymbol{v}\cdot\boldsymbol{\nabla})\rho_d}_{\text{advection}} \underbrace{-\rho_d \boldsymbol{\nabla}\cdot\boldsymbol{v}}_{\text{compression}} + \underbrace{D\nabla^2\rho_d}_{\text{diffusion}},$$

# Drag-Diffusion Equilibrium




Steady-state solution

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

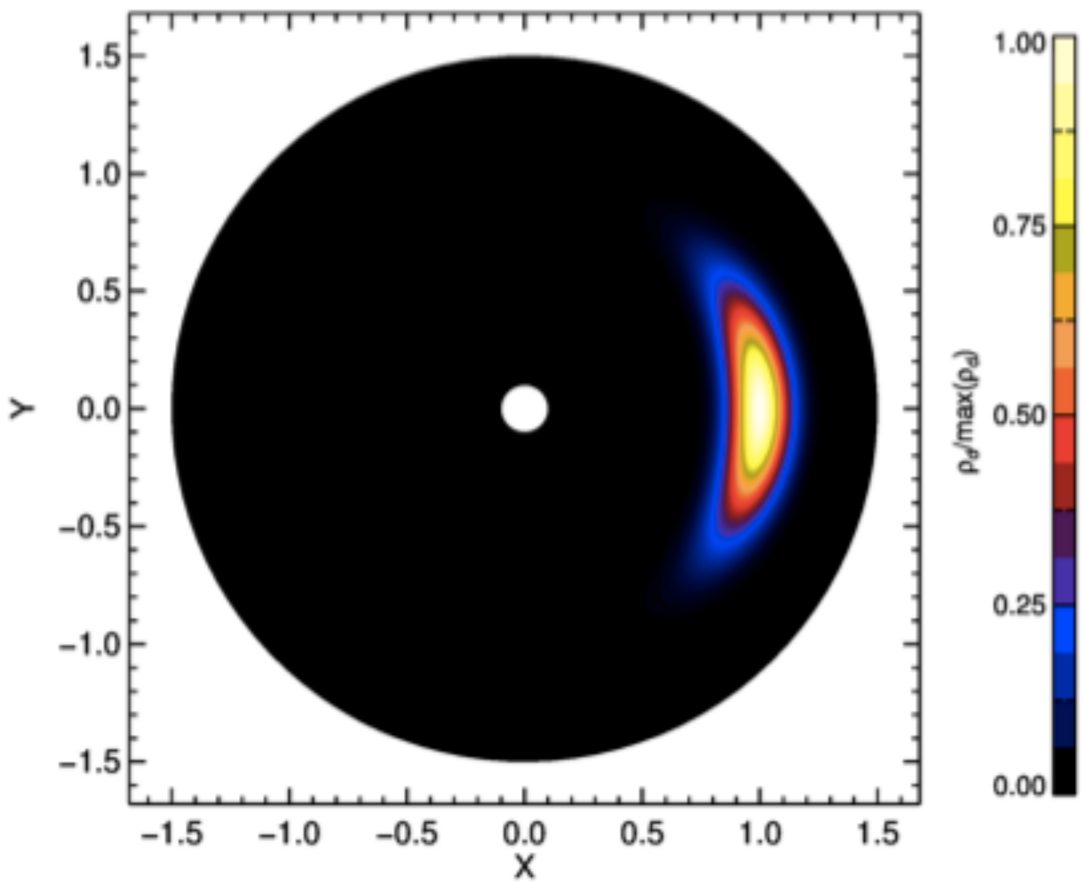
Lyra & Lin (2013)

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

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

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

# Analytical solution for dust trapping




**Solution**

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

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

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

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

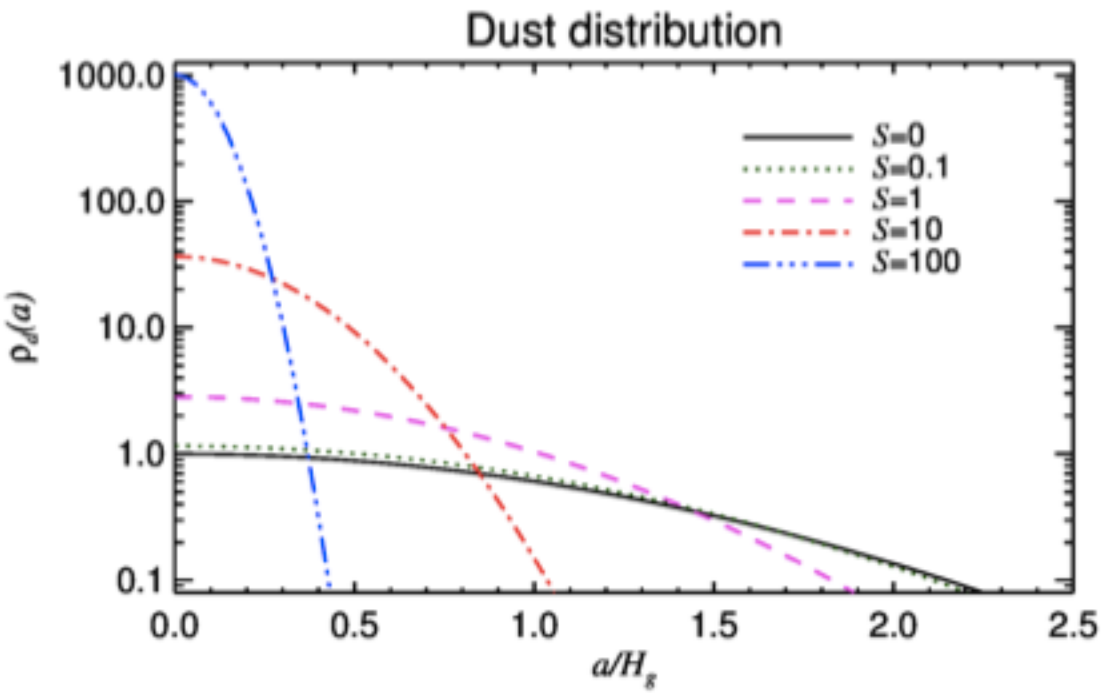
Solution for

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

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

Lyra & Lin (2013)

# Analytical solution for dust trapping

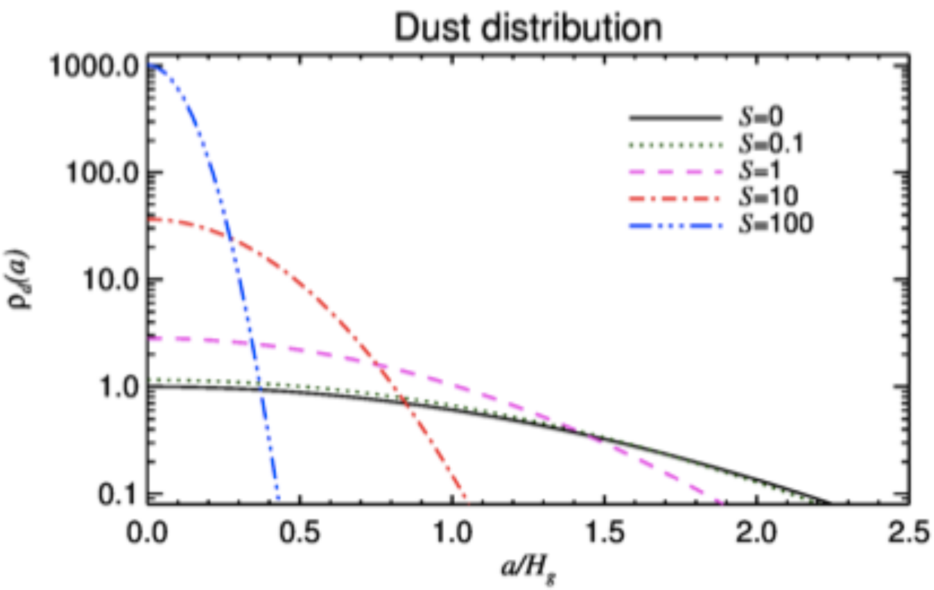



$$S = \frac{St}{\delta}$$

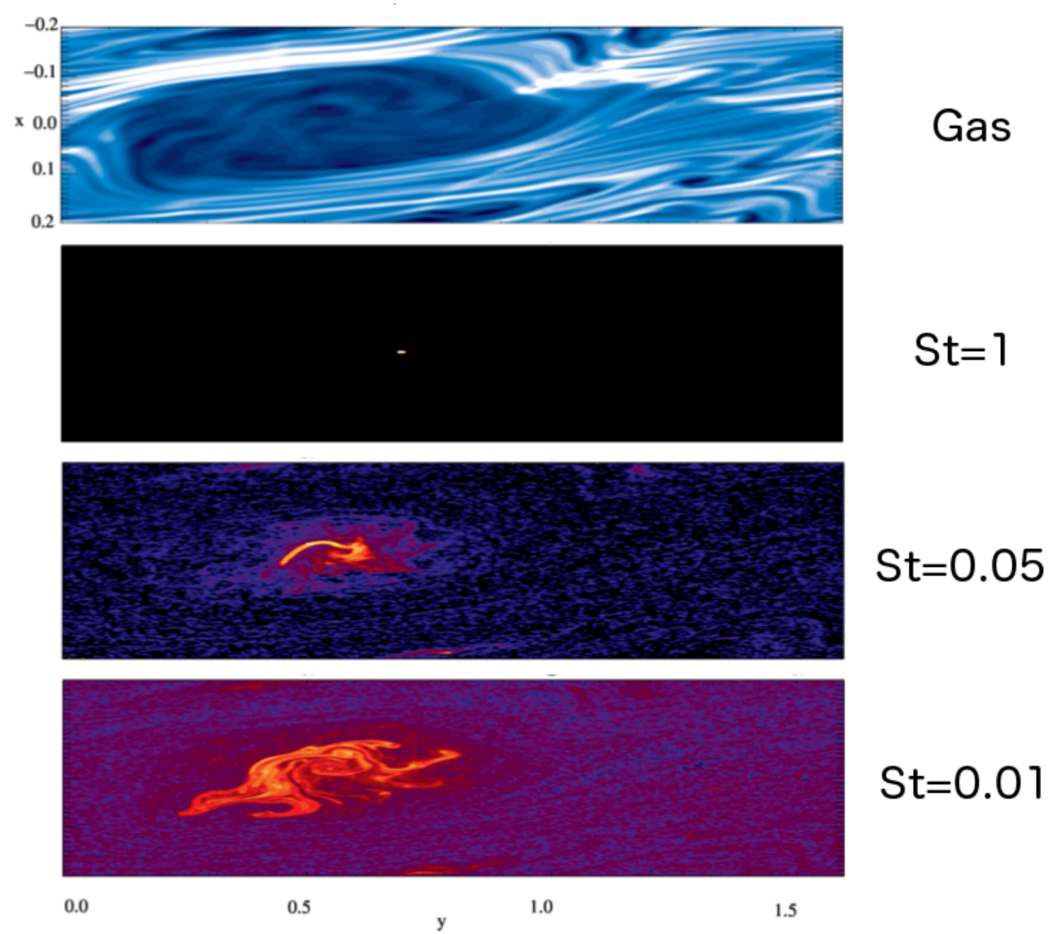
$$\delta = v_{\rm rms}^2 / c_s^2,$$

Lyra & Lin (2013)

# Analytical vs Numerical




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)
$\chi$ = vortex aspect ratio
$\delta$ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function
$\varepsilon$ = 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 $M_{Earth}$***

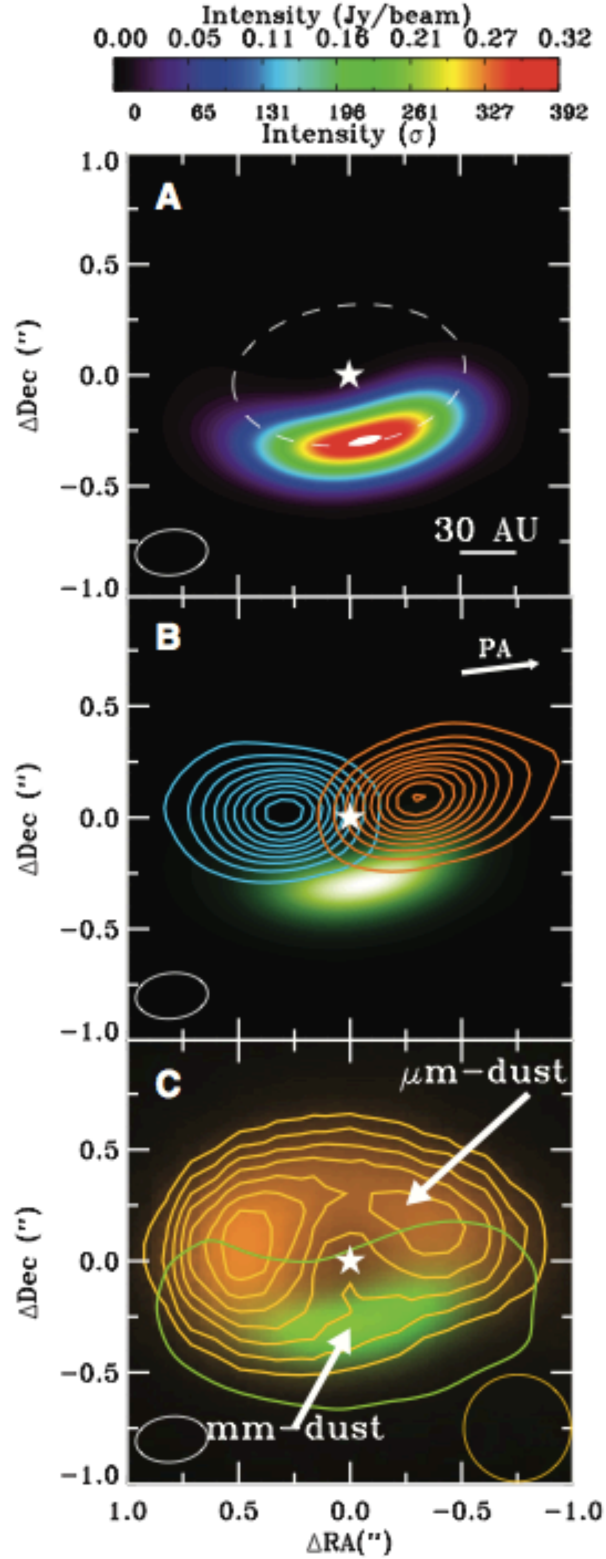
Derived parameters

S=4.8

Stokes number, St=0.008

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

***Trapped mass: 11 $M_{Earth}$***



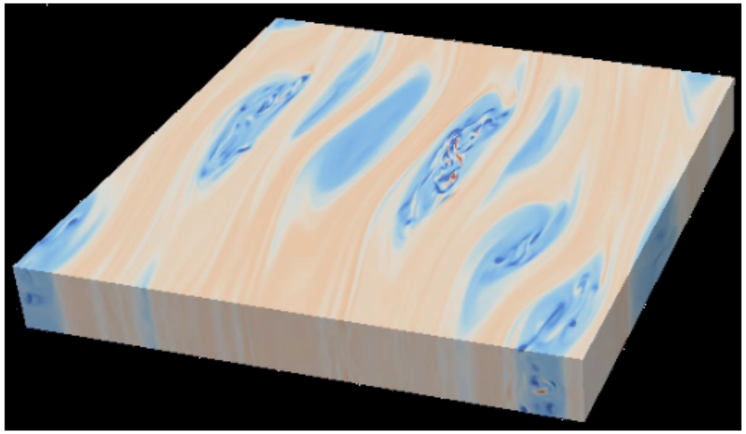

asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

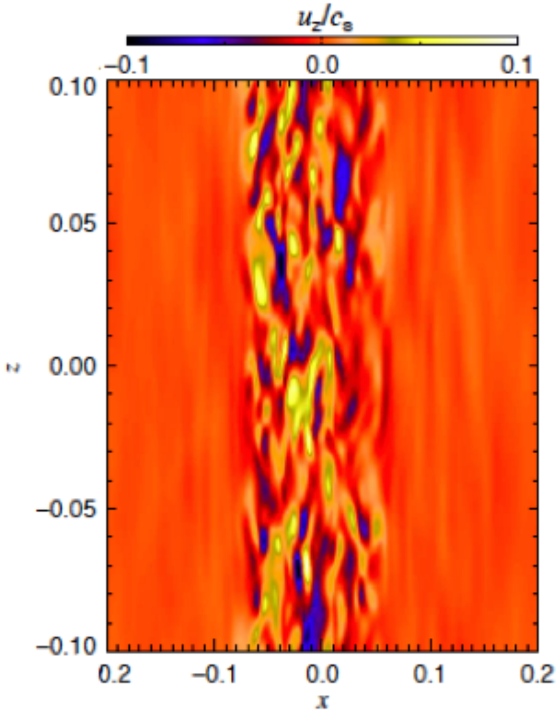
Micron-sized dust follows gas

Lyra & Lin (2013)

# Turbulence in vortex cores



Lesur & Papaloizou (2010)




Lyra & Klahr (2011)

Turbulence in vortex cores:

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

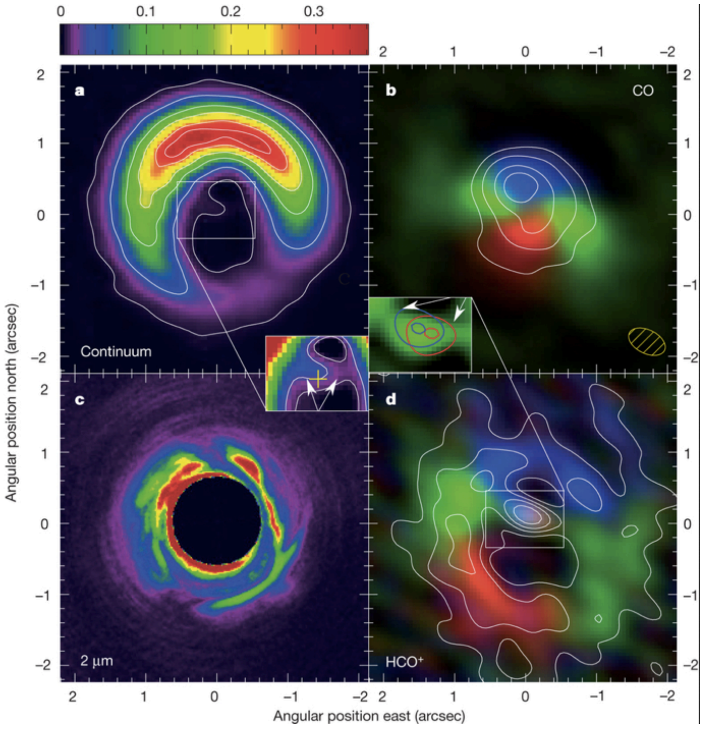
# HD 142527

**Observed parameters**

Aspect ratio: 10

Dust contrast: 30

Temperature: 25K

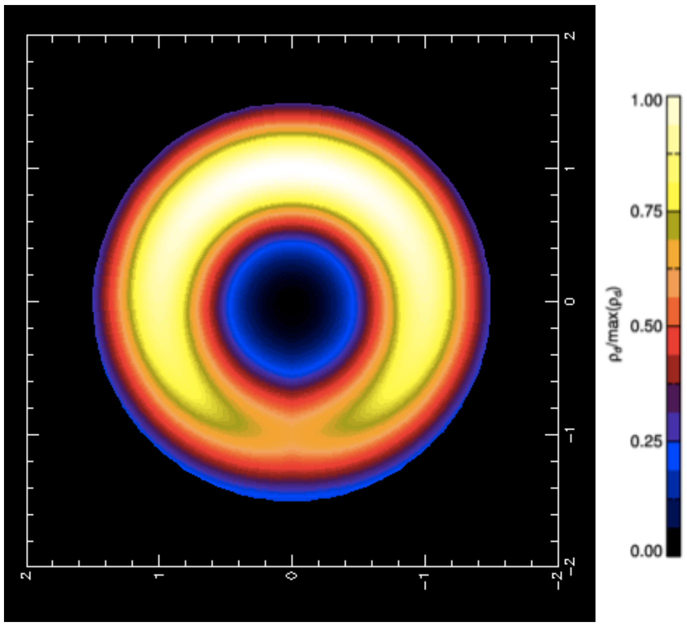



**Derived parameters**

S=3.5

Stokes number, St=0.004

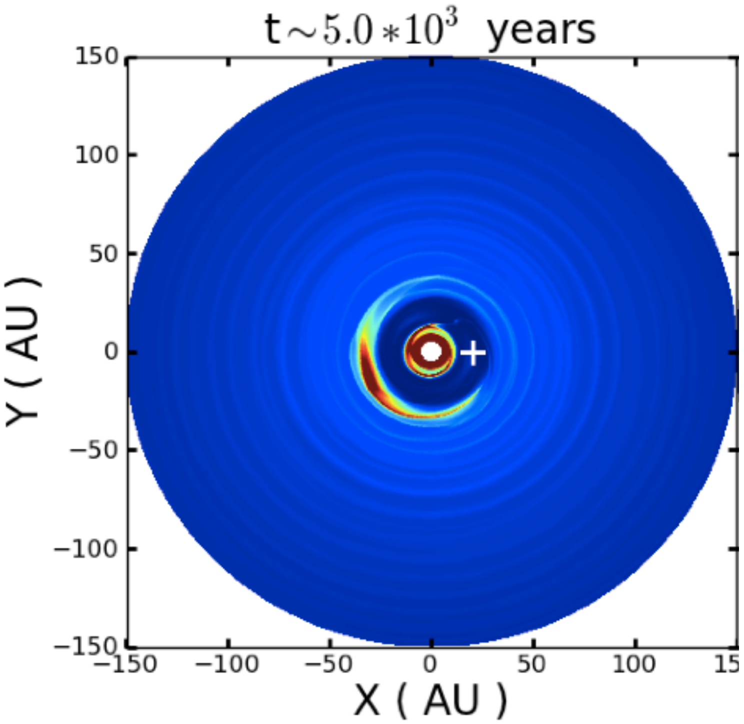
$\delta$ = 0.001, $v_{rms}$ = 4% $c_s$



It seems to have the properties of vortices.

But… is it really a vortex?

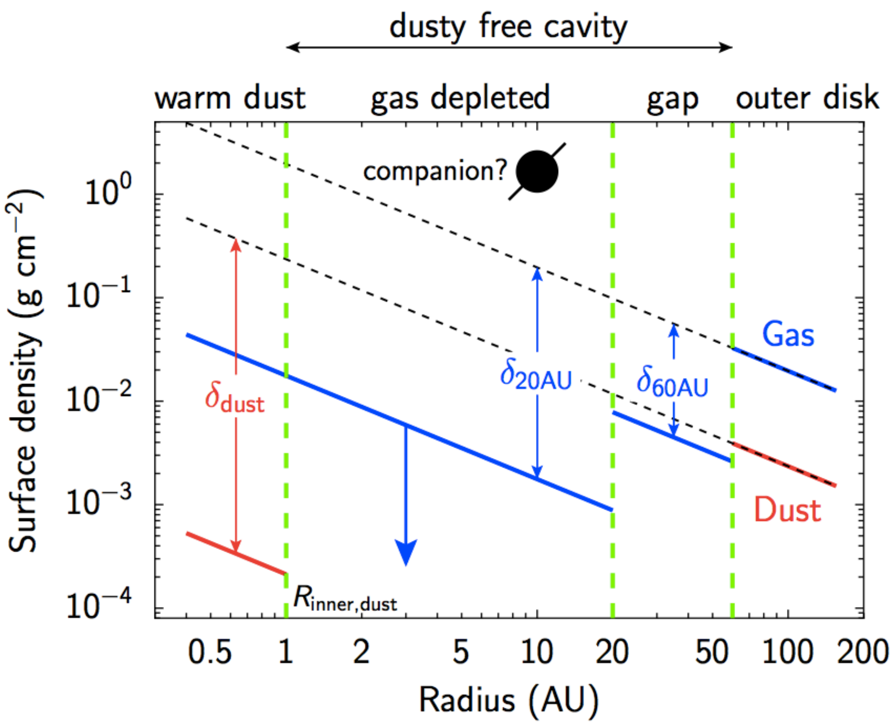
# The dust trap is too far from the planet!



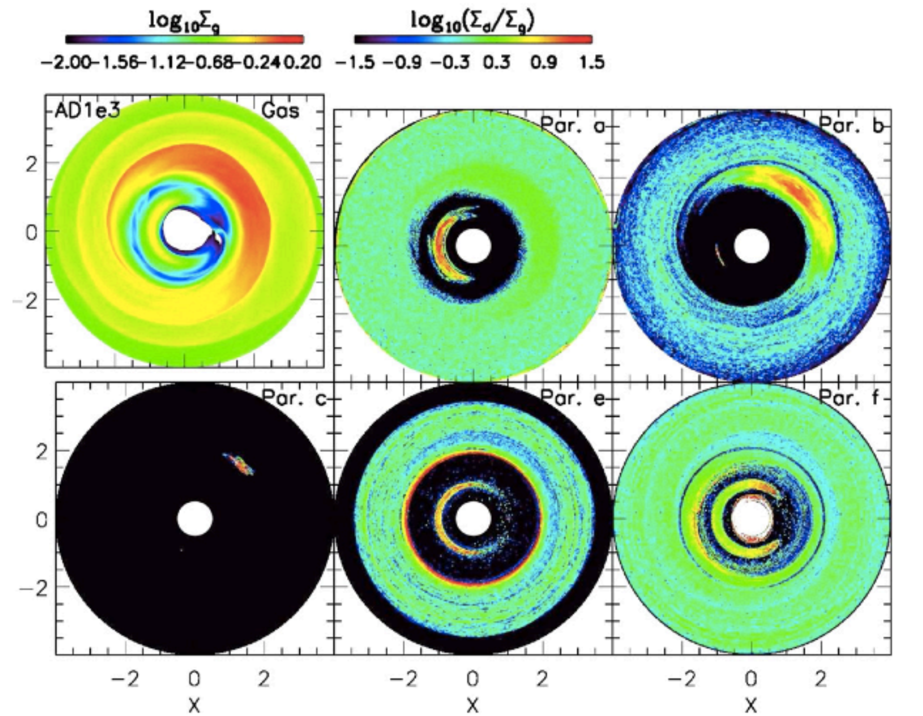

A gap in gas emission suggests a 10 MJ planet at **15-20 AU**.

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

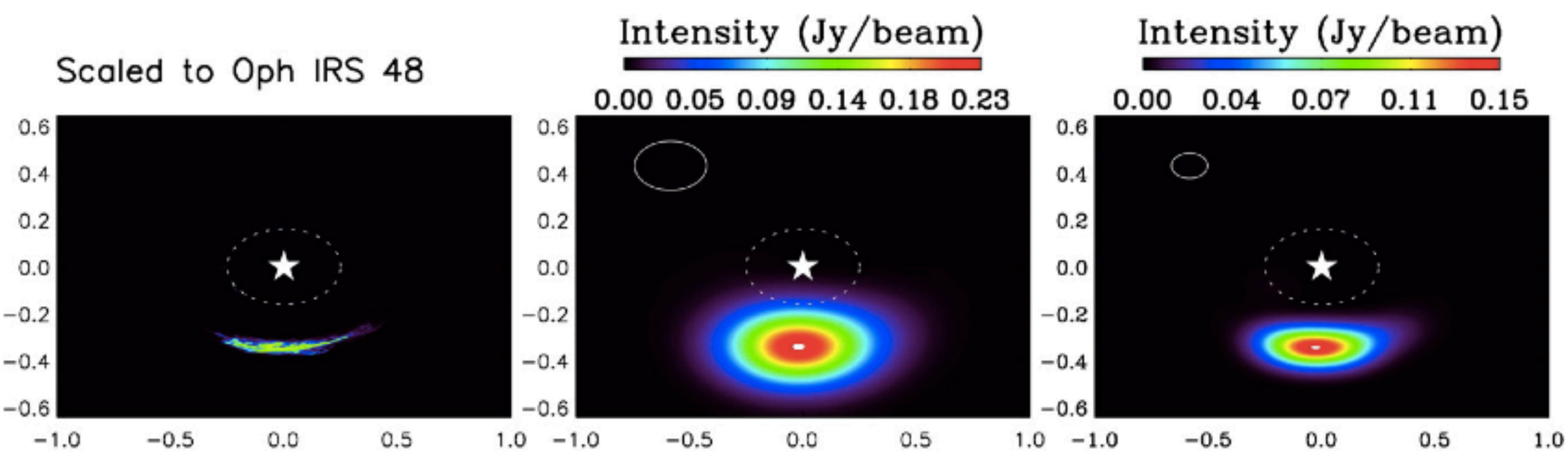
# Still “sorta” possible




Bruderer et al. (2014)




Zhu & Stone (2014)

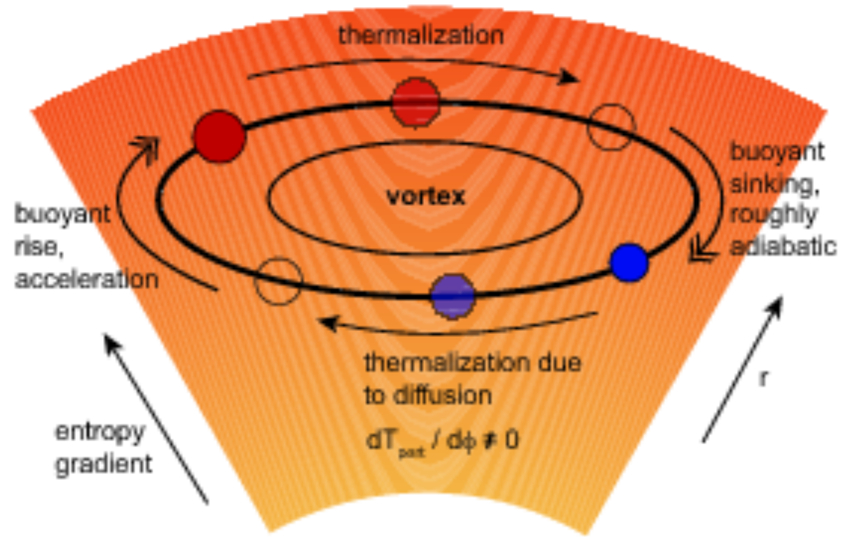


# Convective overstability

*1. Radial entropy gradient*

*2. Thermal diffusion*

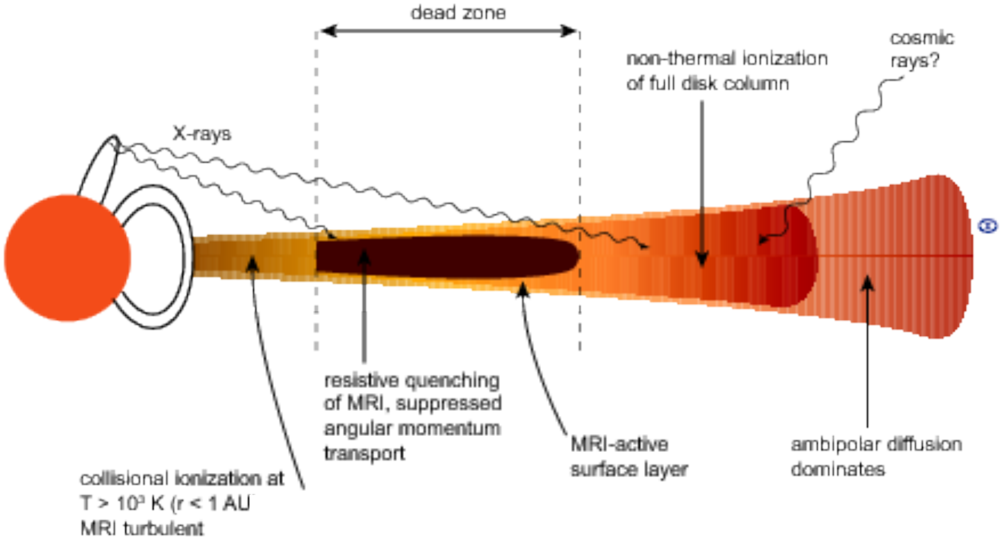
$$t_{\mathrm{rad}} = \frac{c_V \Sigma \tau_{\mathrm{eff}}}{6\sigma T^3}$$



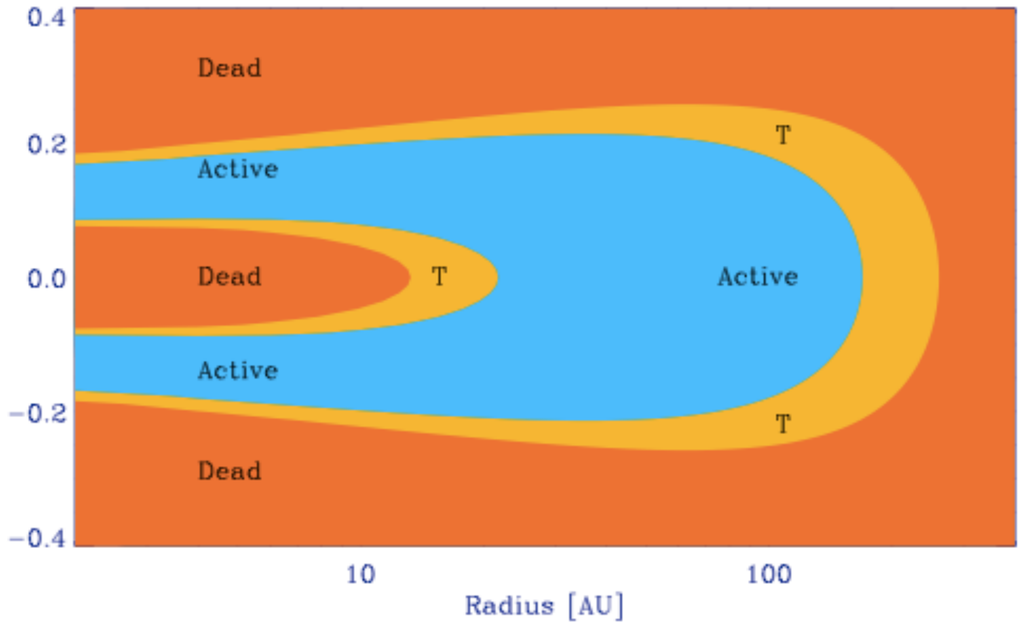

The thermal diffusion time
for the gas in IRS Oph 48 is
**0.1 orbits.**

**Too close to isothermal for convective overstability**

# Outer Dead/Active zone transition RWI fails!



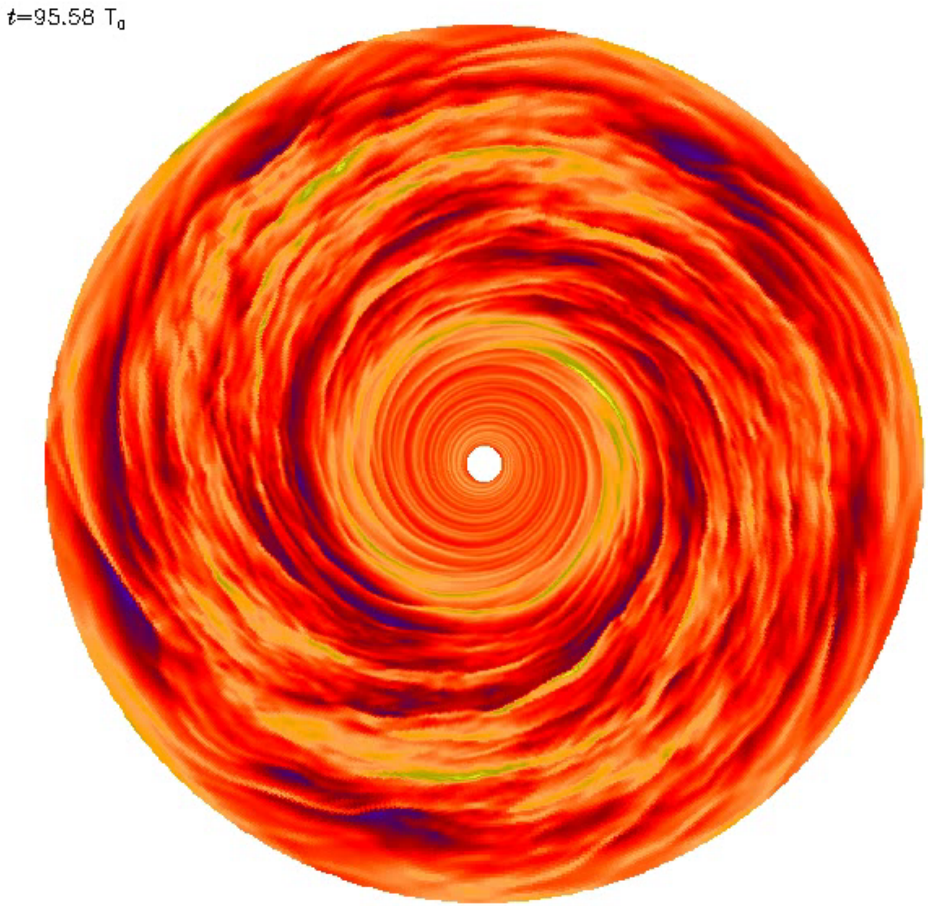

Armitage (2010)

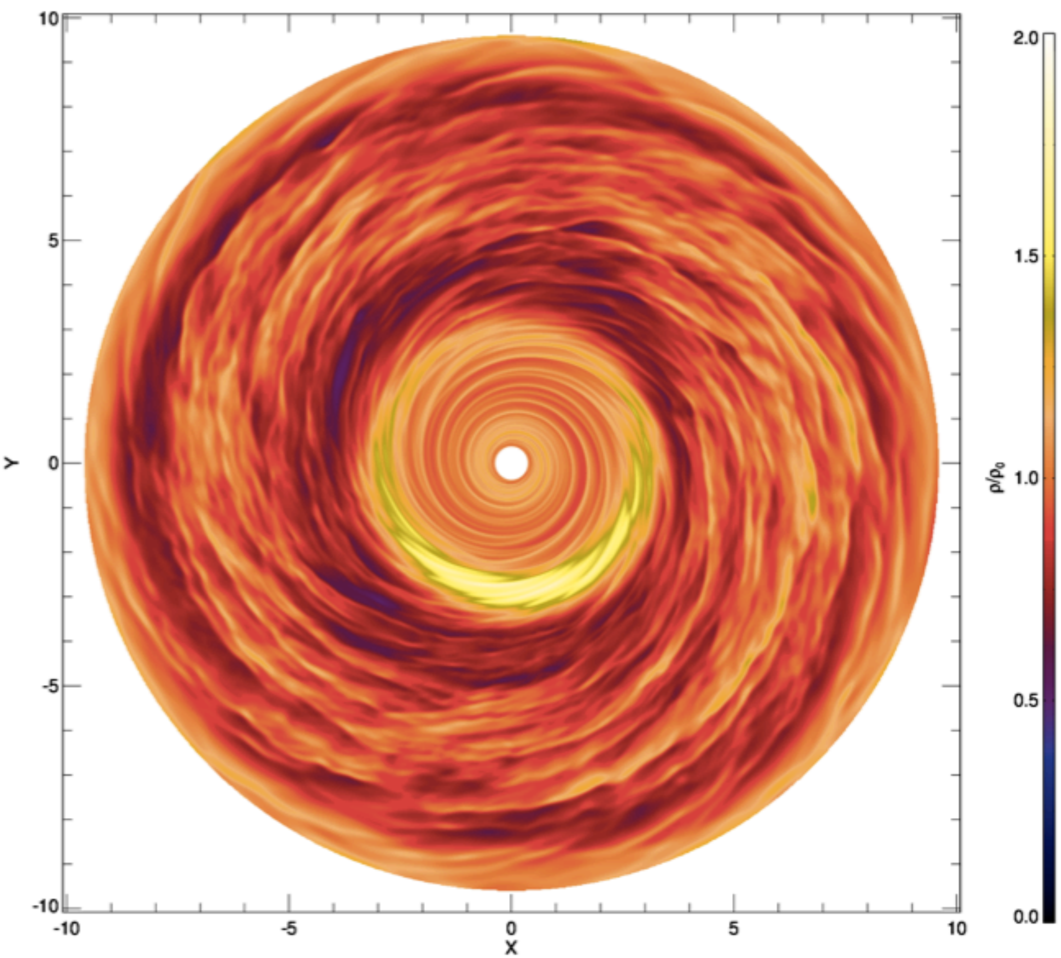



Dzyurkevitch et al (2013)

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!




Resistive inner disk + magnetized outer disk

Lyra et al (2015)

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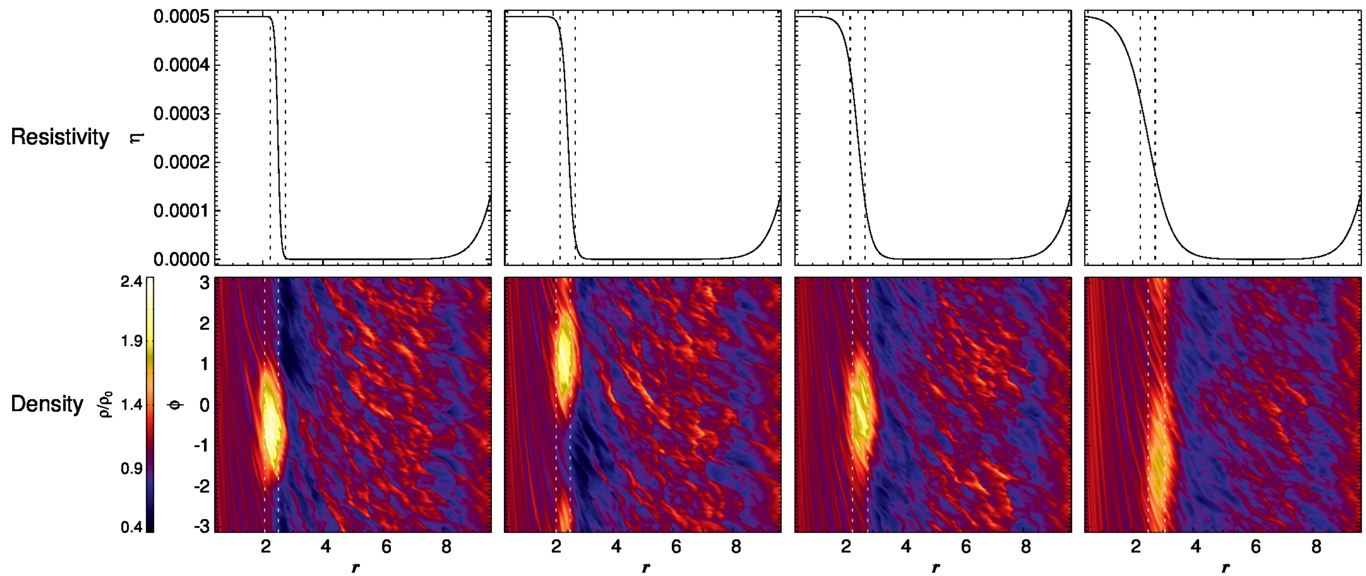
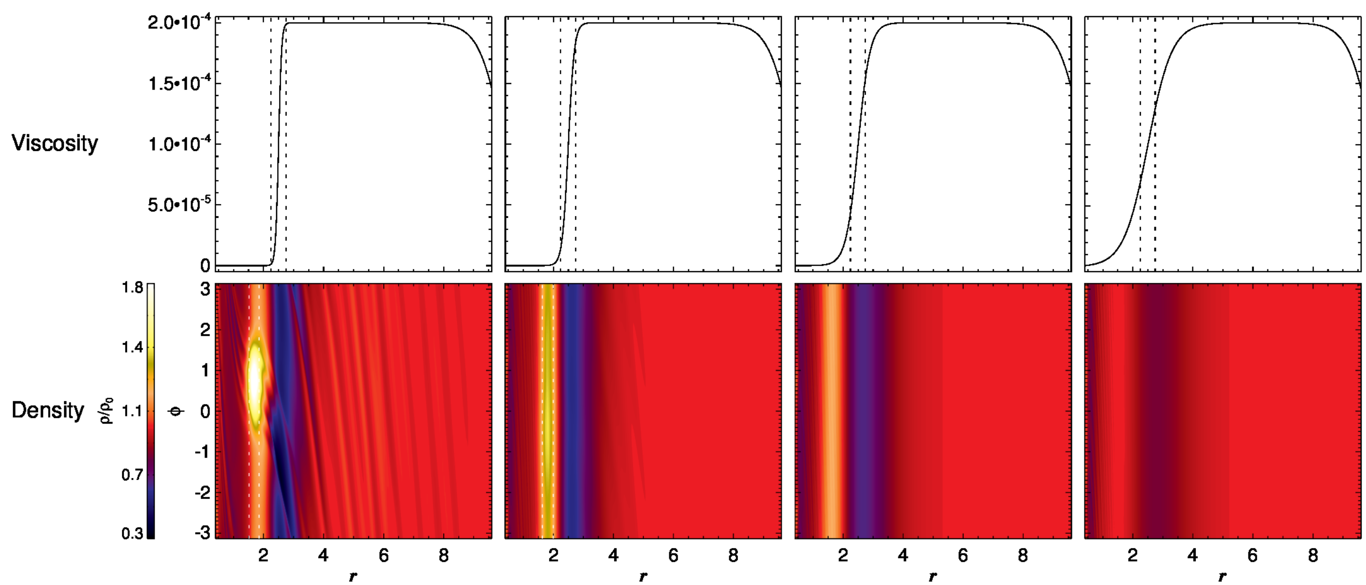
**MHD**




**Hydro**




Lyra et al (2015)

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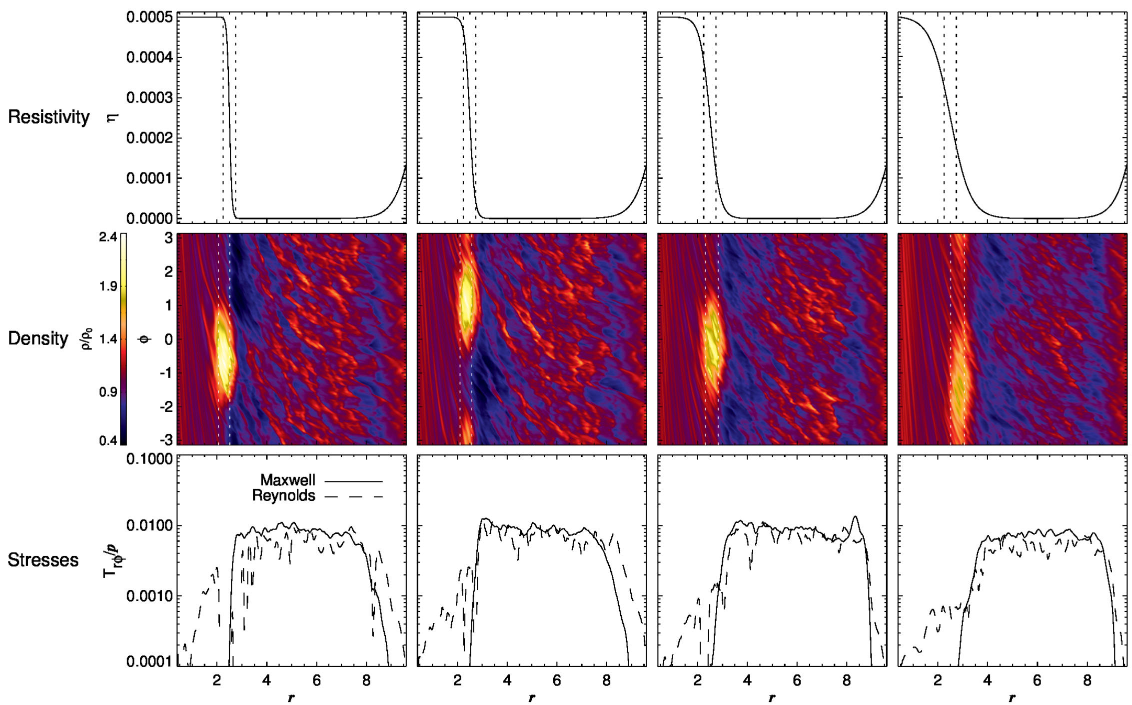



Lyra et al. (2015)

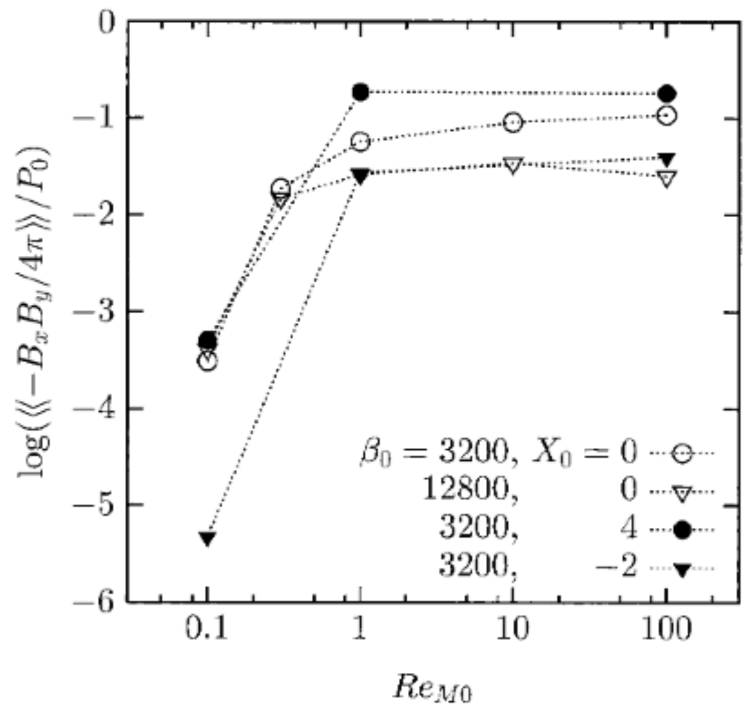
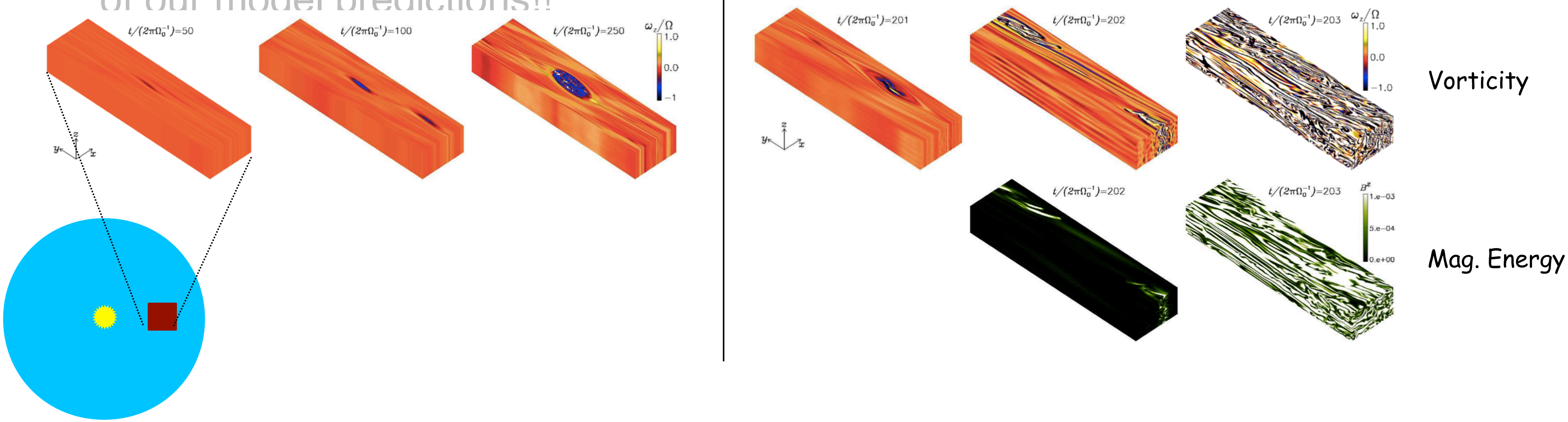



FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number $\mathrm{Re}_{M0}$. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) 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 era of observational testing/confirmation of our model predictions!!




Lyra & Klahr (2011)

## 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
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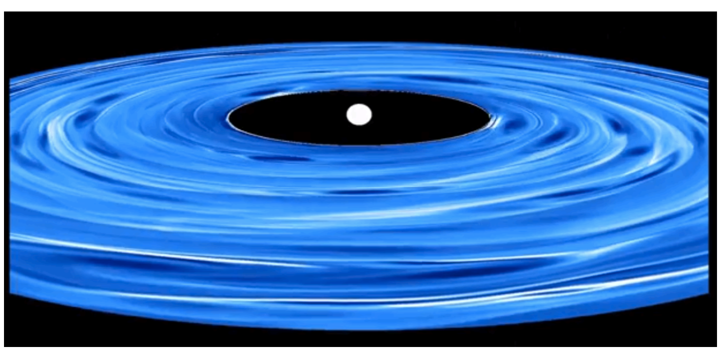
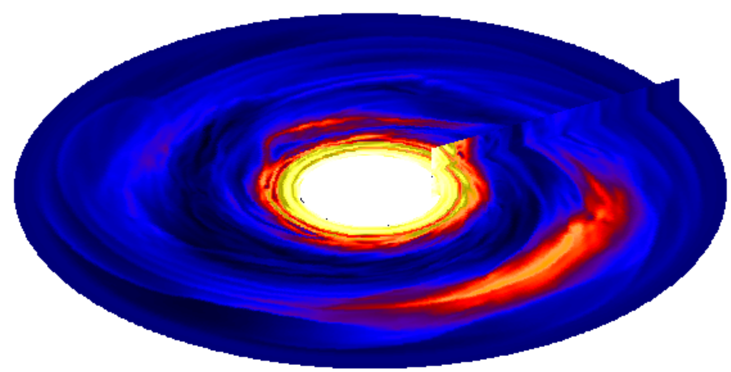
Baroclinic instability



Rossby wave instability



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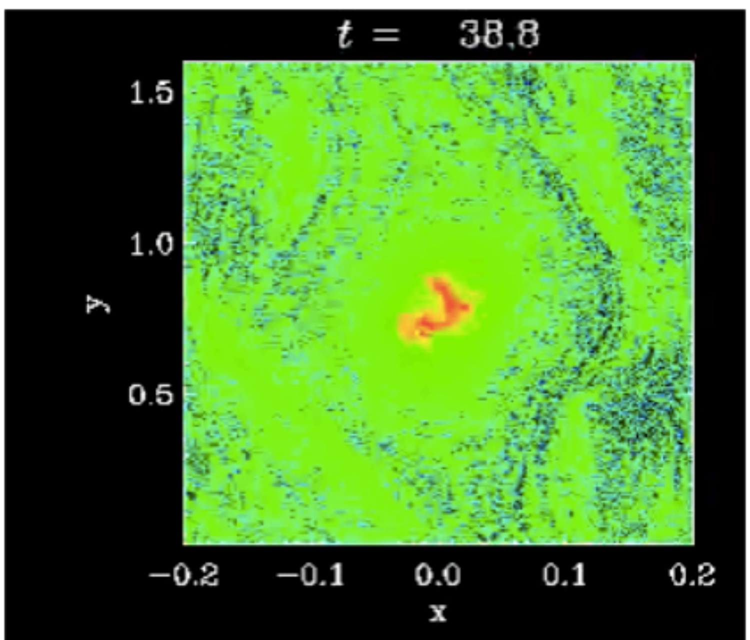


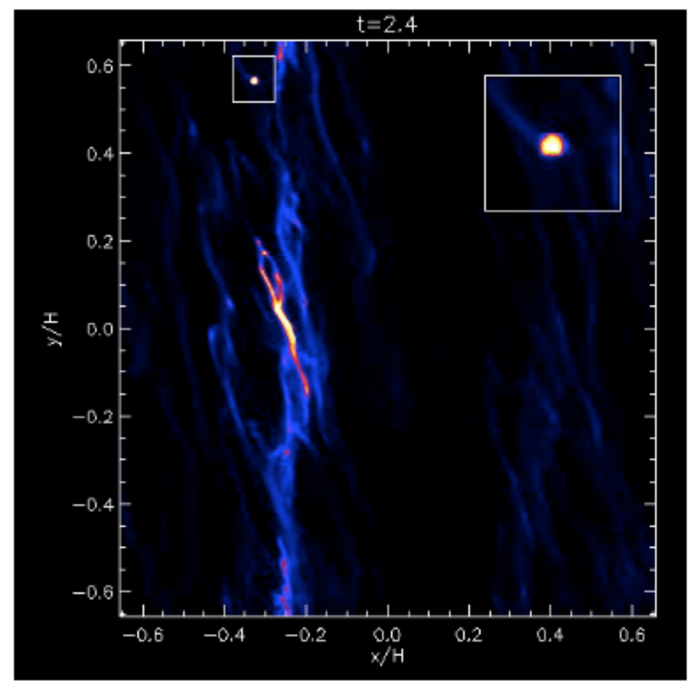

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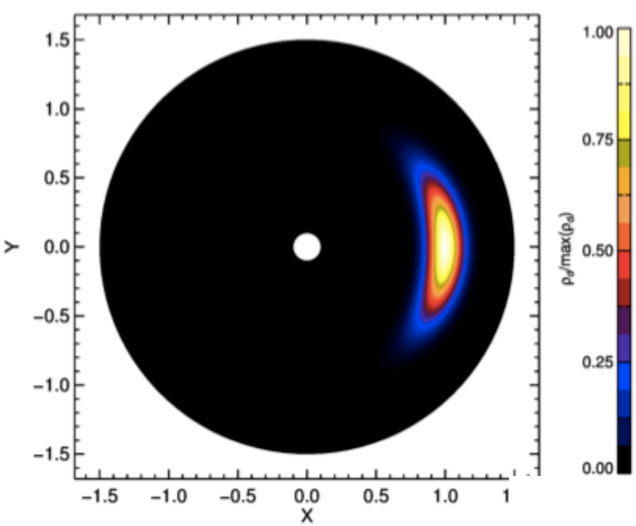
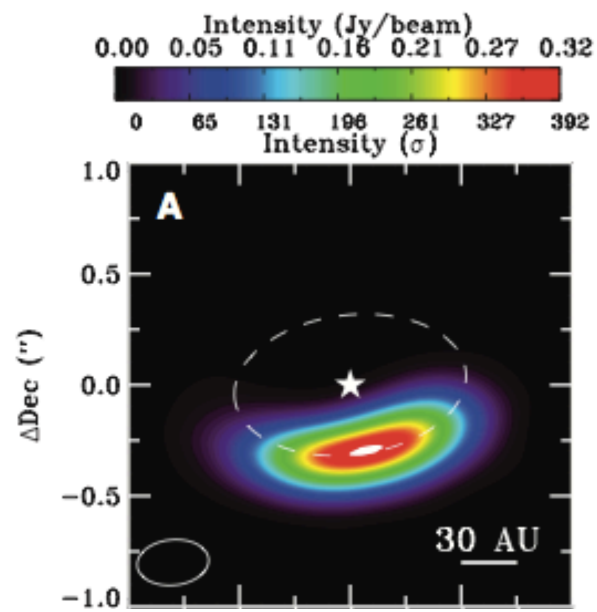
$$\rho_d(a,z) = \varepsilon\rho_0(S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin (2013)



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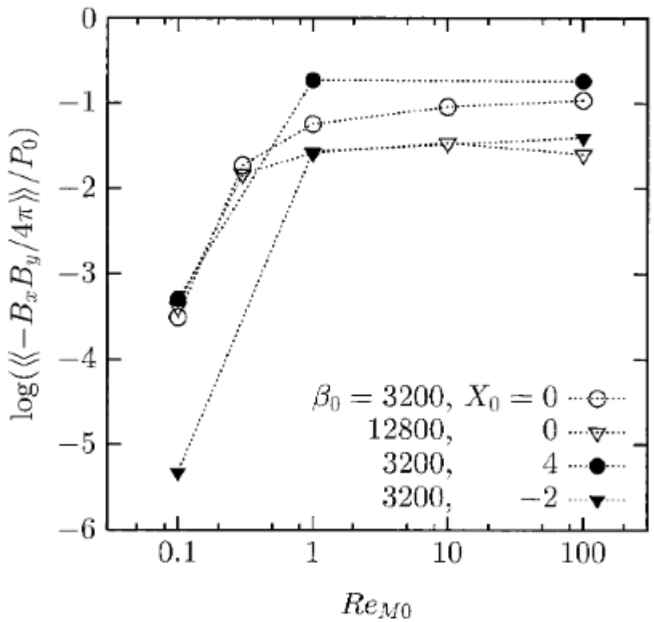


zone only

Rossby Wave Instability and Convective Overstability

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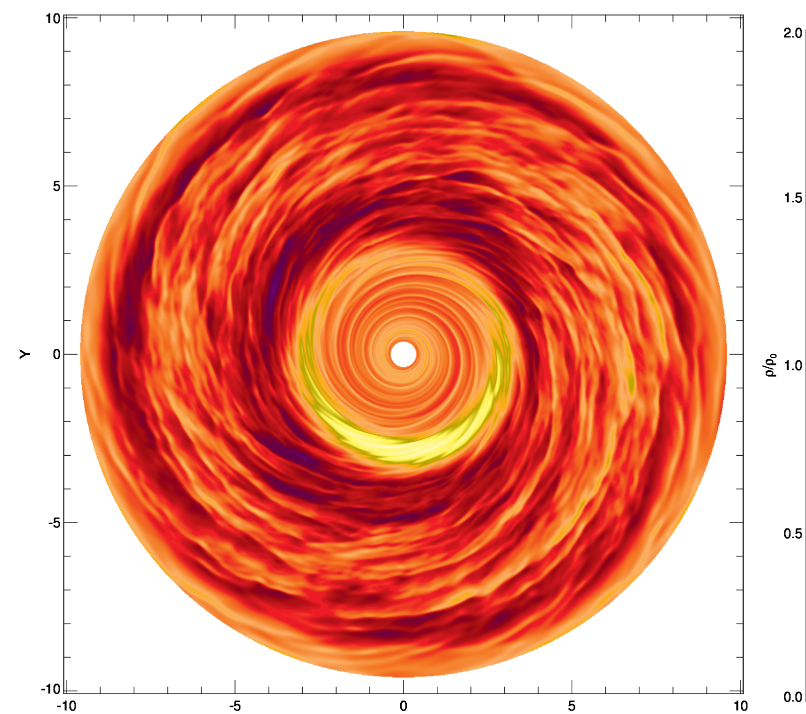

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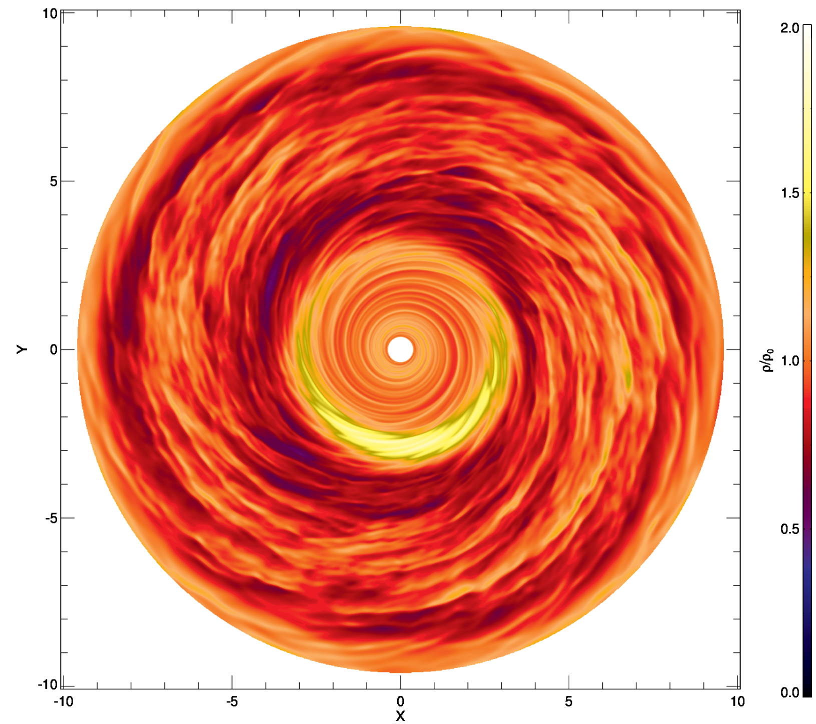


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