The vortex mode of planet formation

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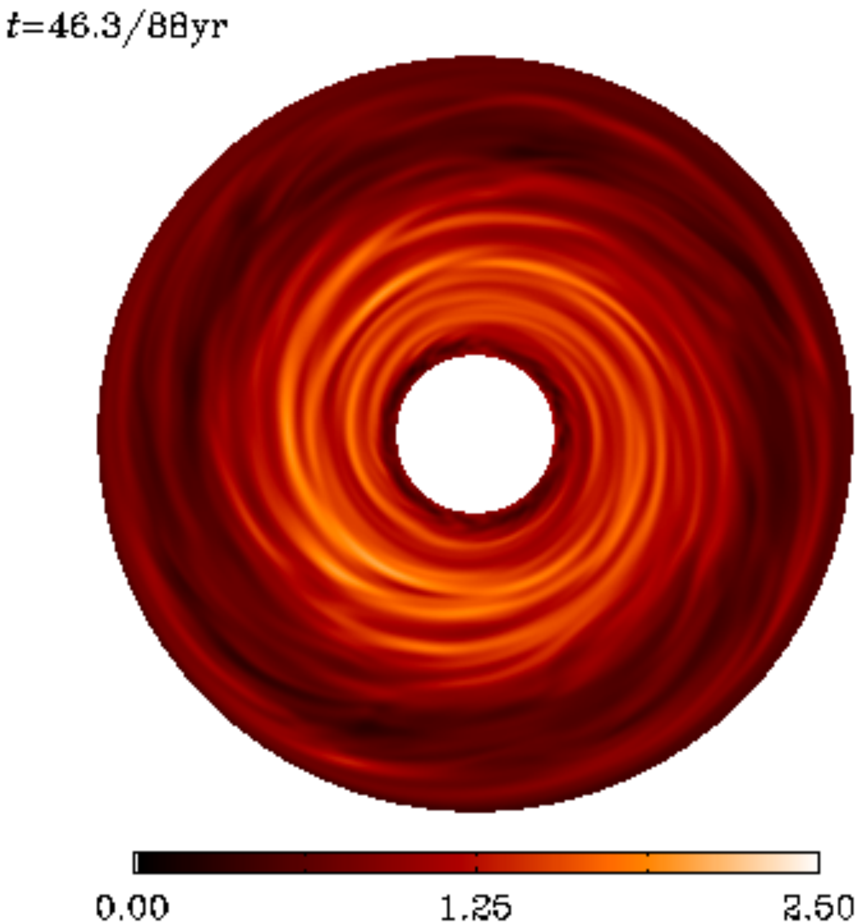
Outline

- 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

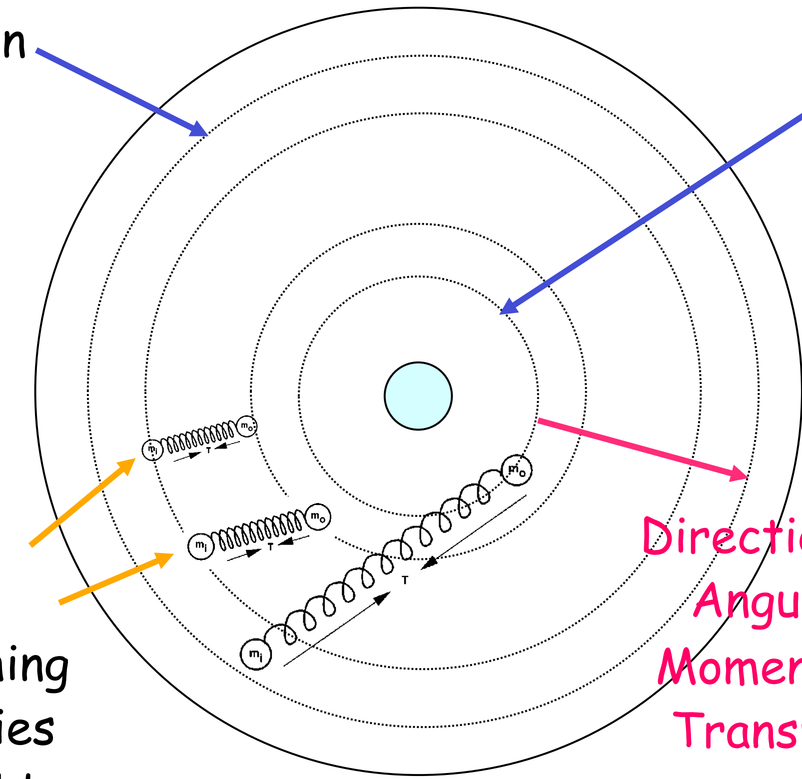
Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability



Magnetized disk
Lyra et al. (2008a)

MRI sketch



Unstable if angular velocity decreases outward

Accretion in disks occurs via turbulent viscosity

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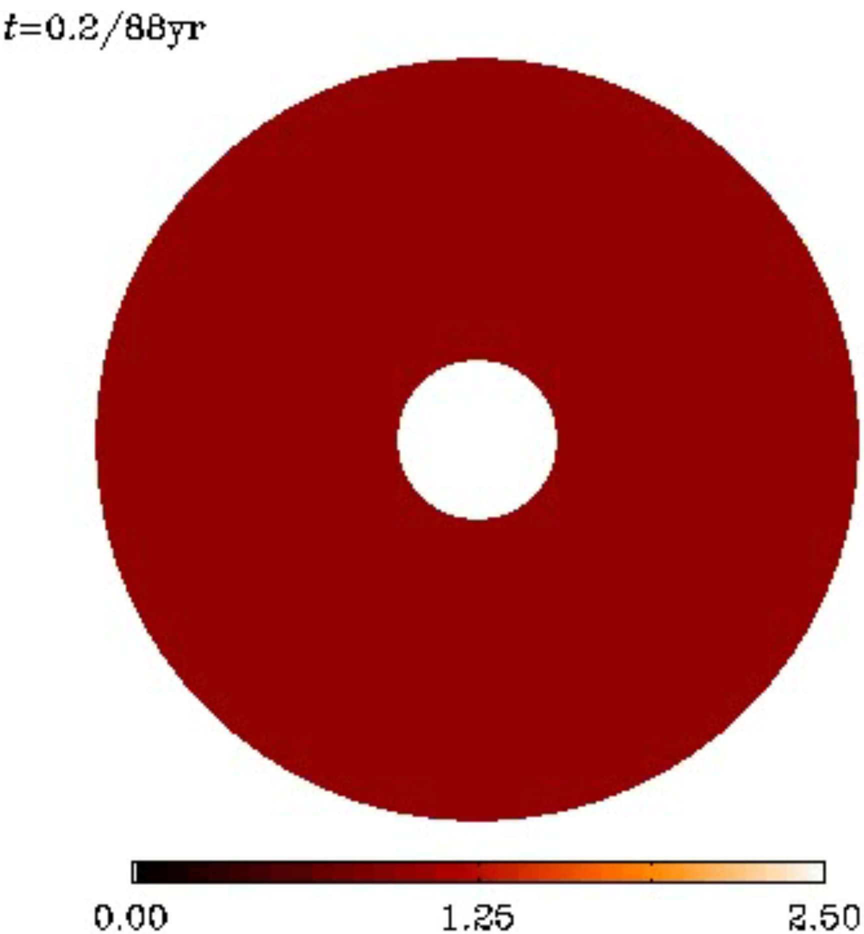
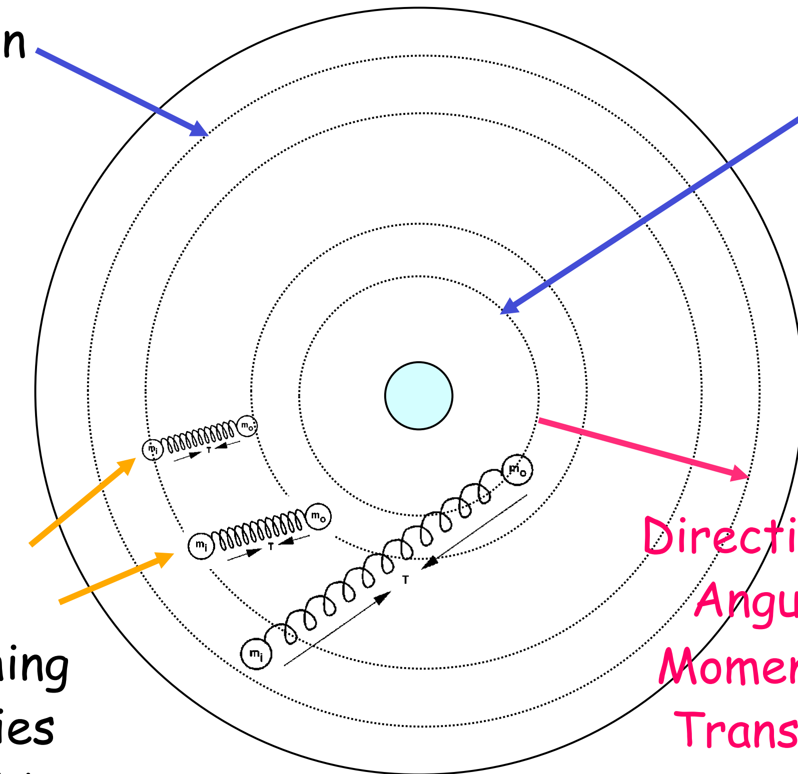


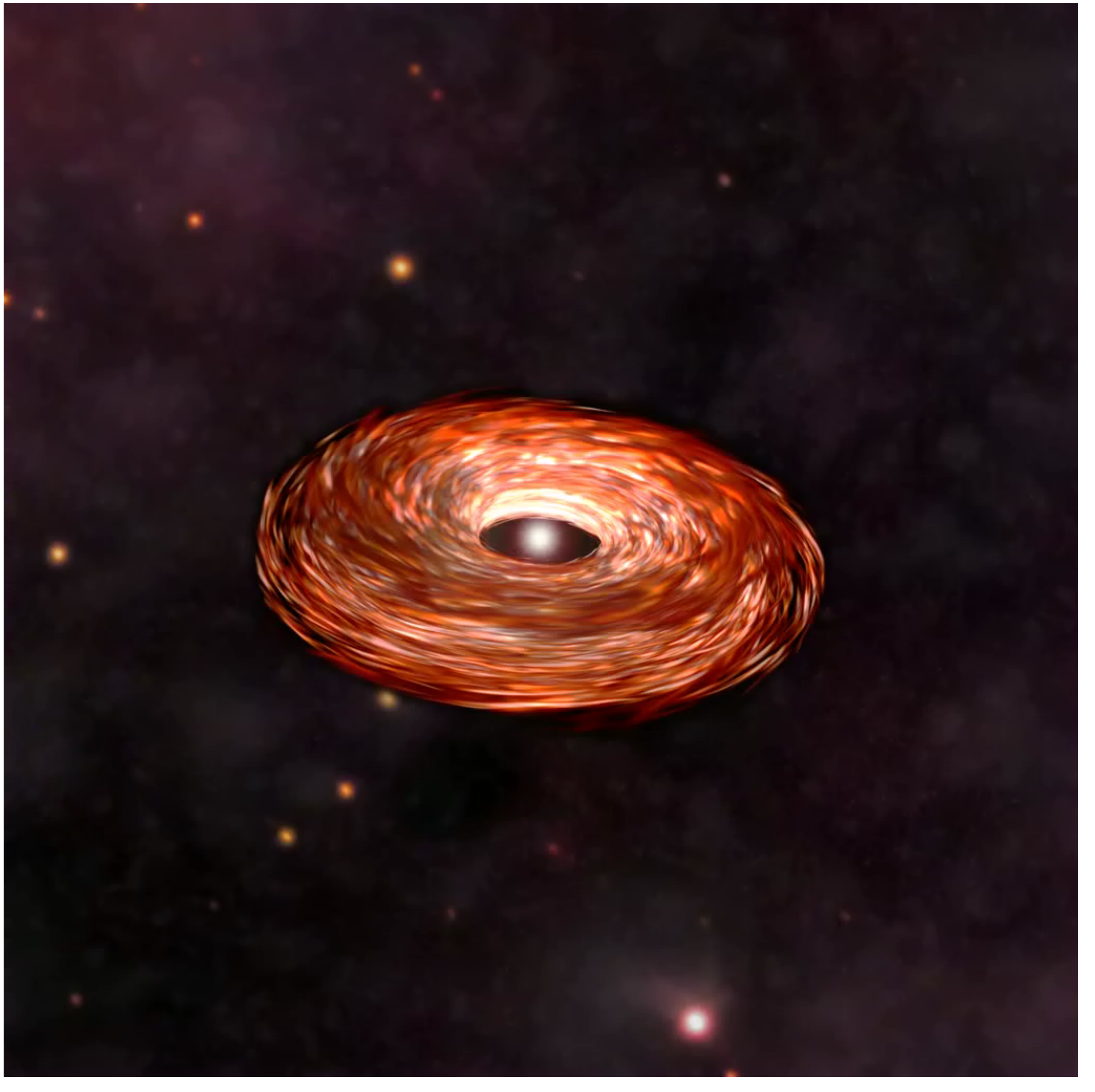
Magnetized disk
Lyra et al. (2008a)

MRI sketch



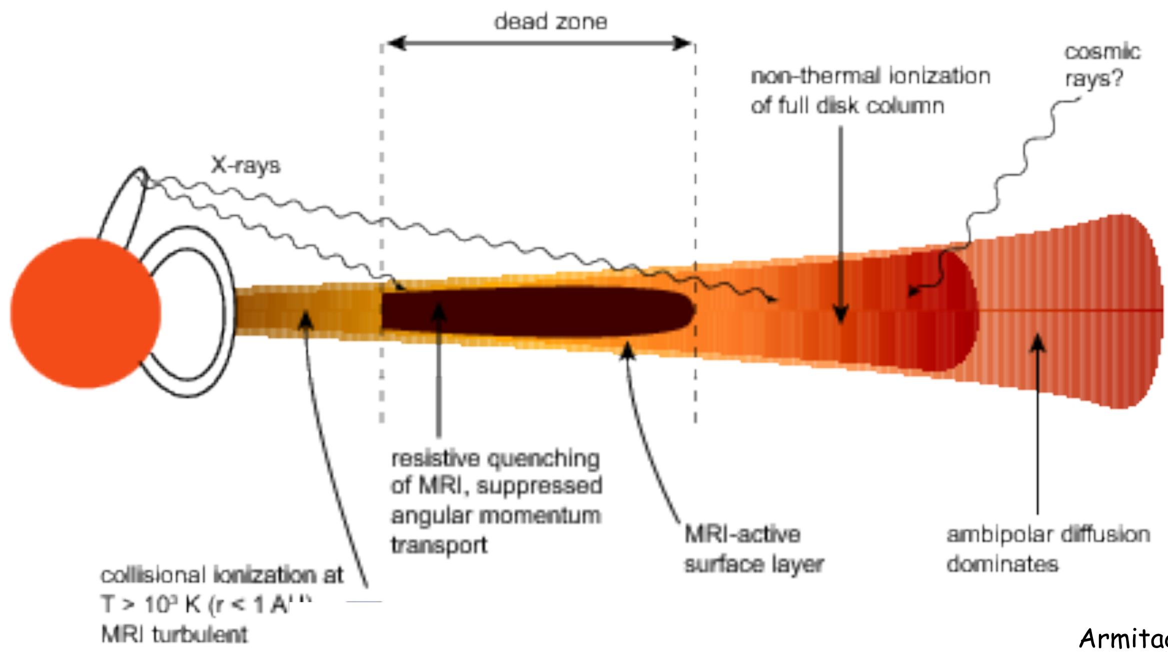
Unstable if angular velocity decreases outward

Magneto-Rotational Instability



Video credit: Mario Flock (MPIA/CEA)

Dead zones are robust features of accretion disks



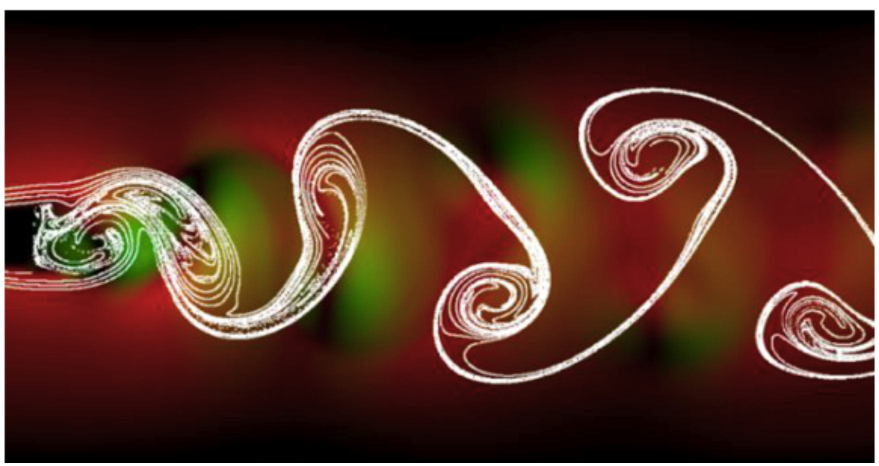
Armitage (2010)

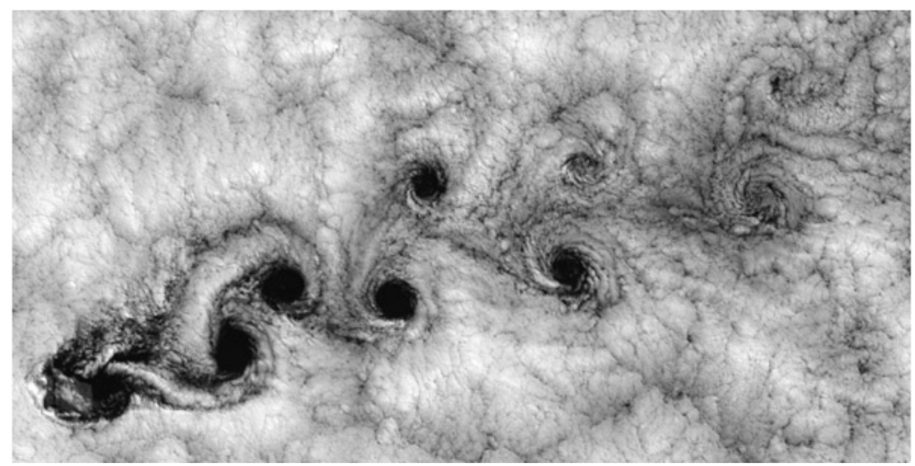
Disks are cold and thus poorly ionized
(Blaes & Balbus 1994)

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

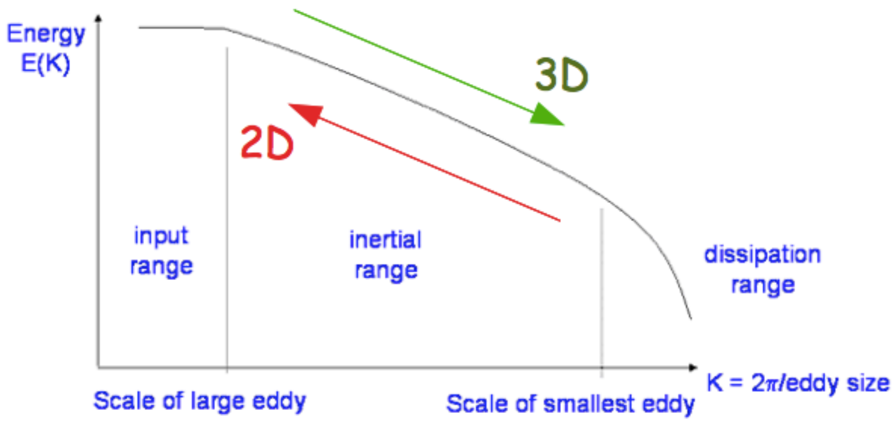
There should be a **magnetized, active zone**,
and a **non-magnetic, dead zone.**

Vortices – An ubiquitous fluid mechanics phenomenon

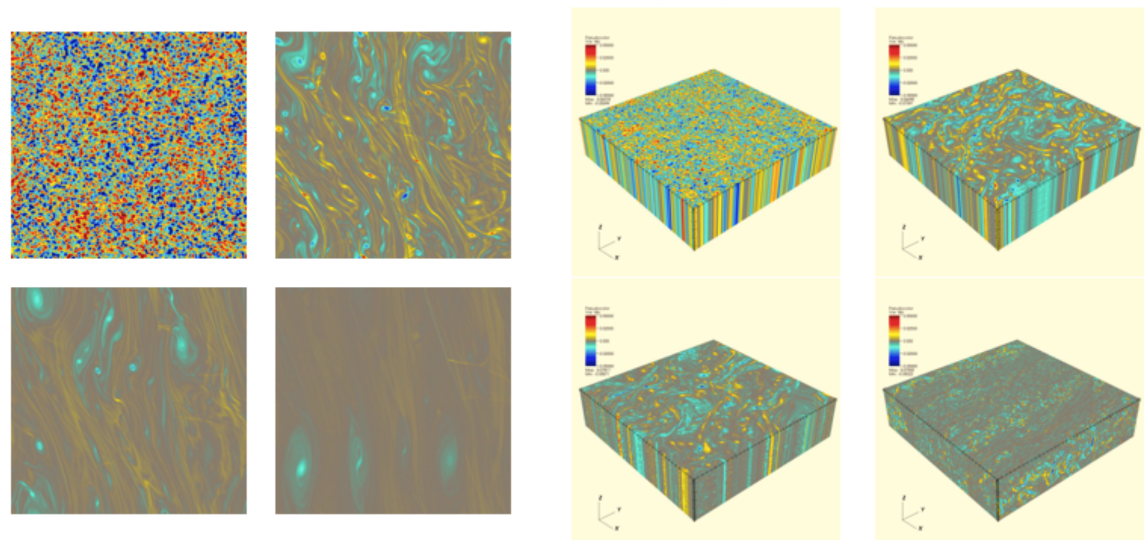




The energy cascade



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



2D

3D

Inverse Cascade

No 3D instability
Eddies merge

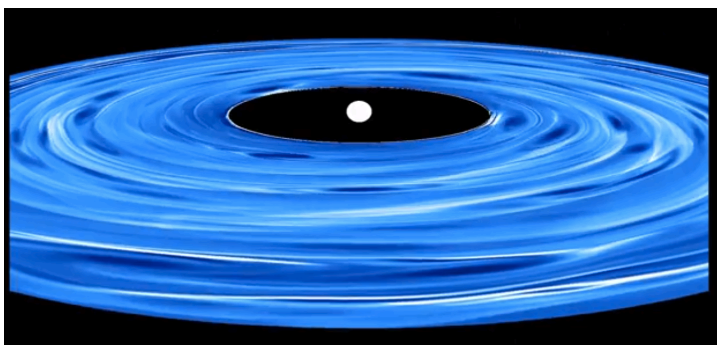
Direct Cascade

Destruction occurs
faster than merging

Sustaining vortices in disks

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

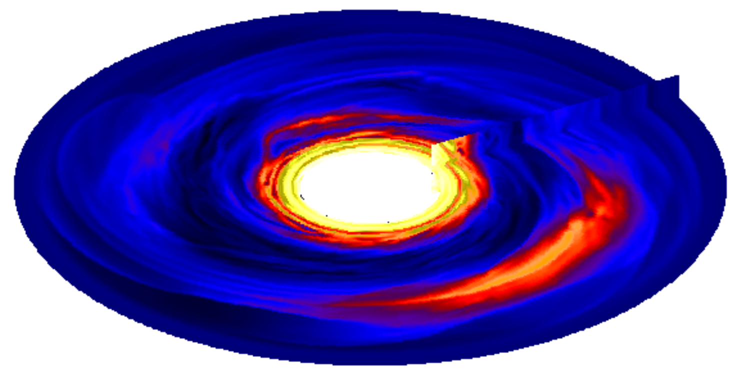
Baroclinic instability



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

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

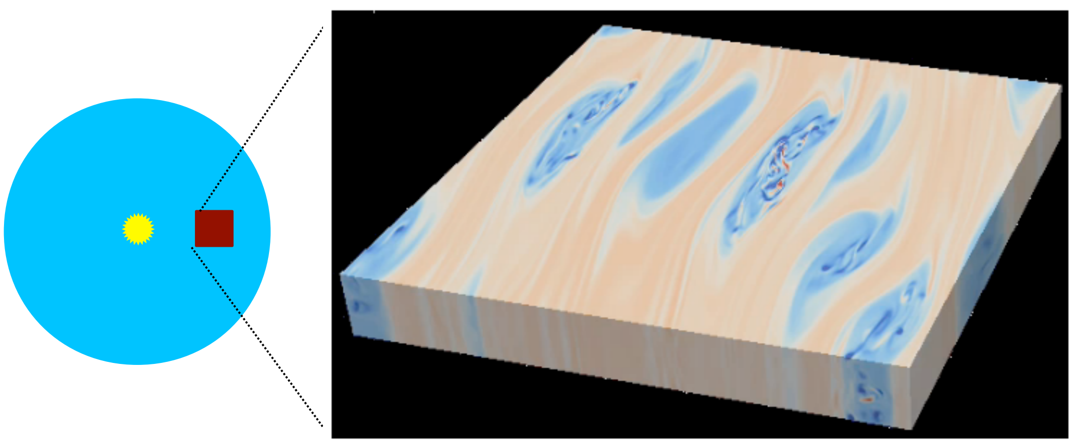
Rossby wave instability



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

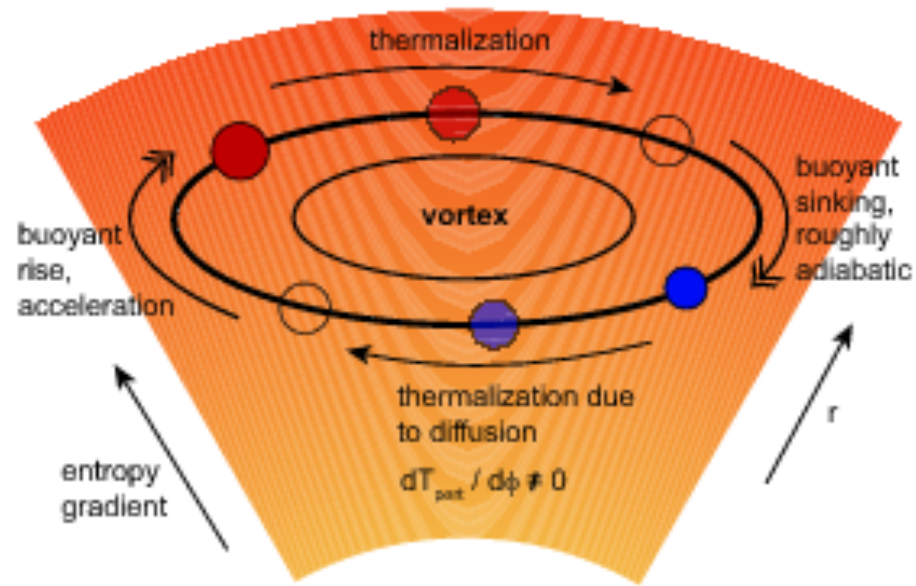
Powered by:
Modification of shear profile
(external vorticity reservoir)

Baroclinic Instability - Excitation and self-sustenance of vortices



Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability



Armitage (2010)

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

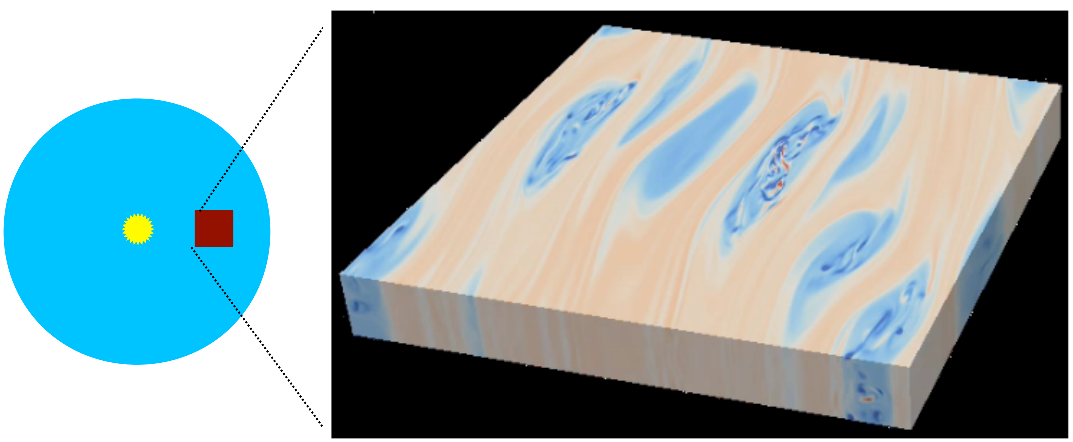
advection | compression | stretching | baroclinicity | dissipation

Baroclinic Instability - Excitation and self-sustenance of vortices

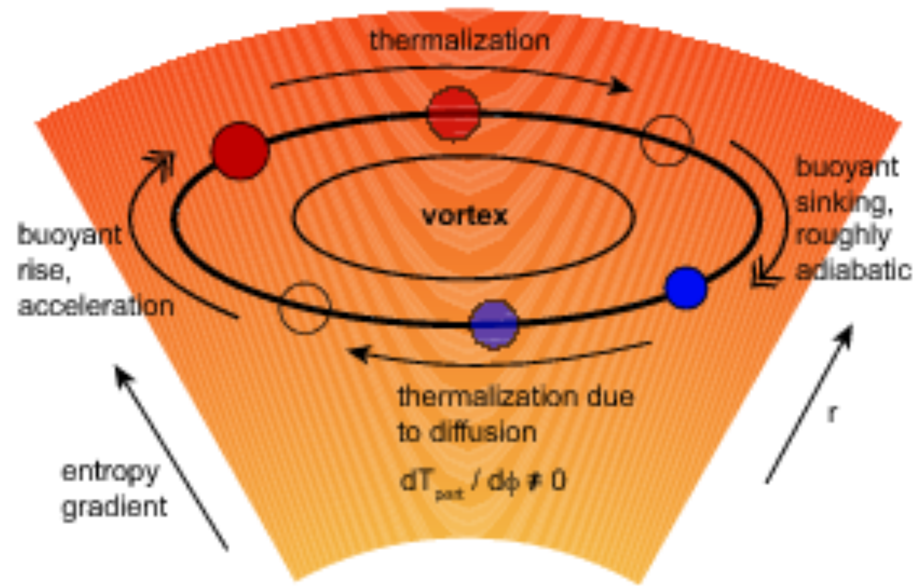
1. Radial entropy gradient

2. Thermal diffusion

Sketch of the Baroclinic Instability



Lesur & Papaloizou (2010)



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advection — compression — stretching — baroclinicity — dissipation

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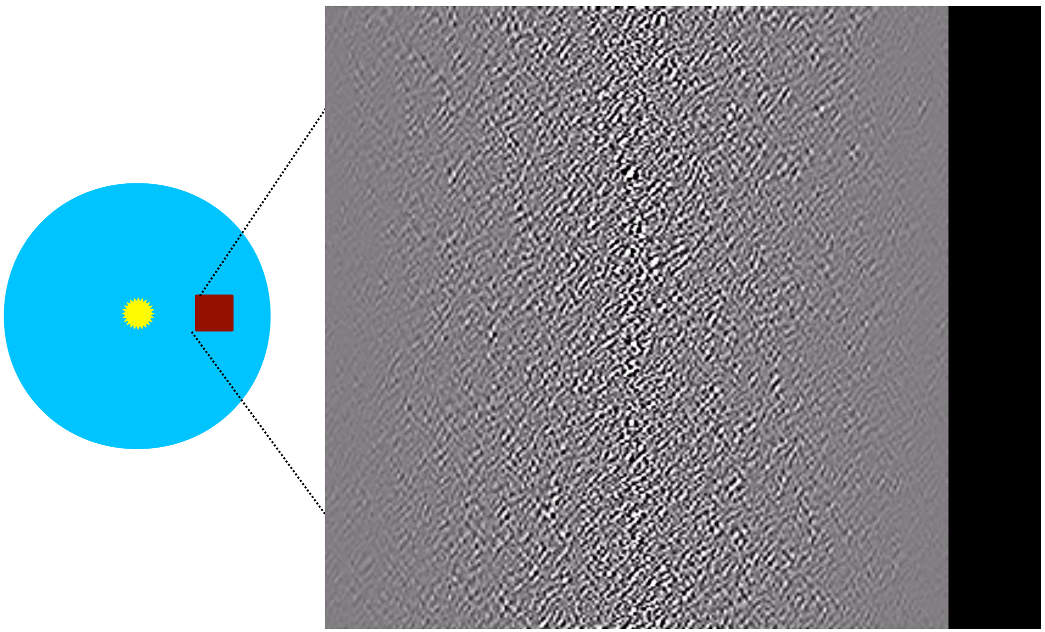
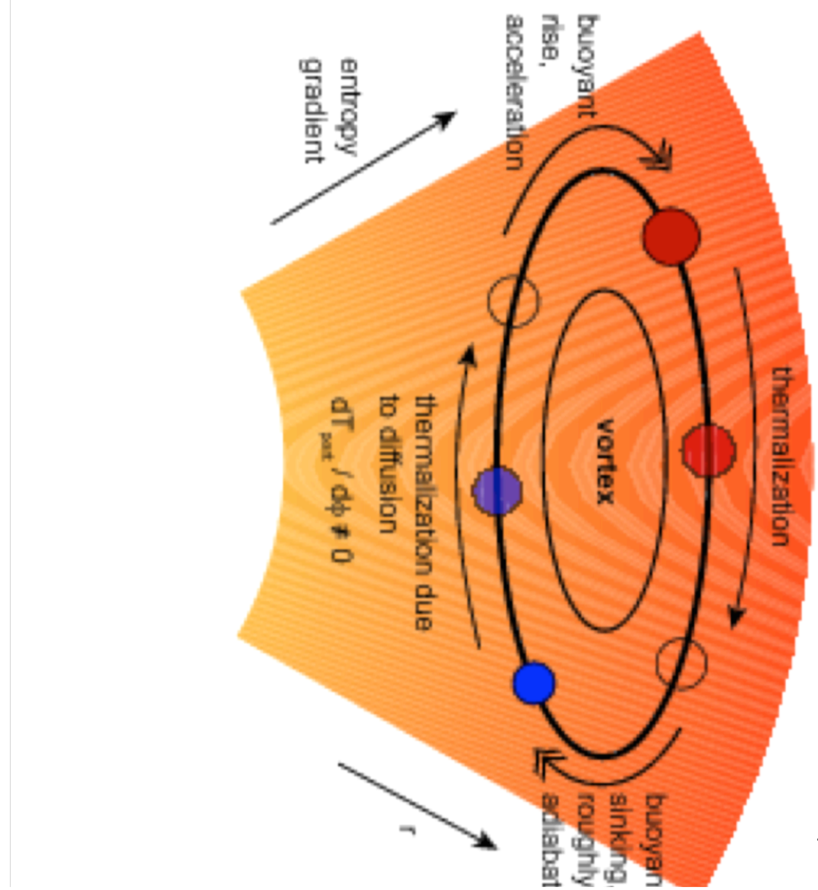


Lyra & Klahr (2011)

Sketch of the Baroclinic Instability



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advection

compression

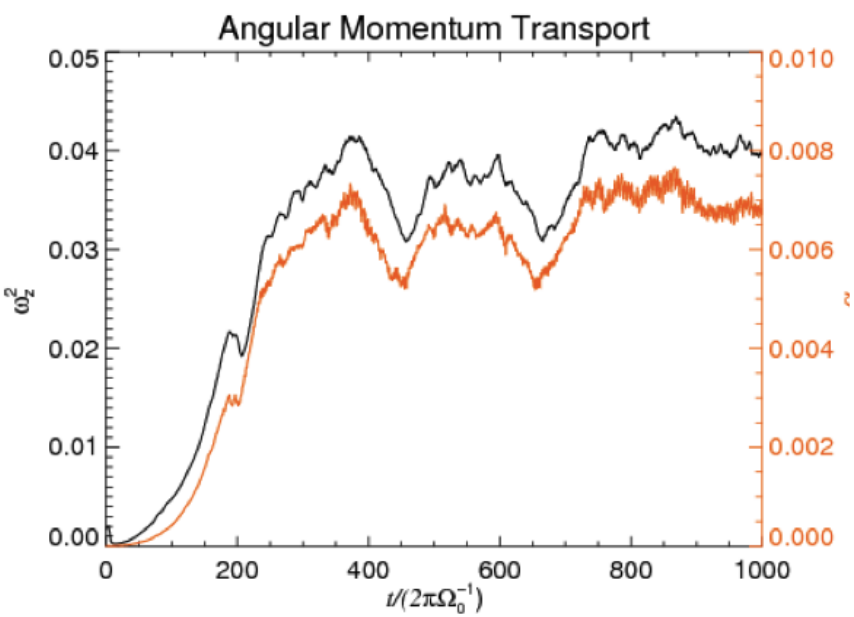
stretching

baroclinicity

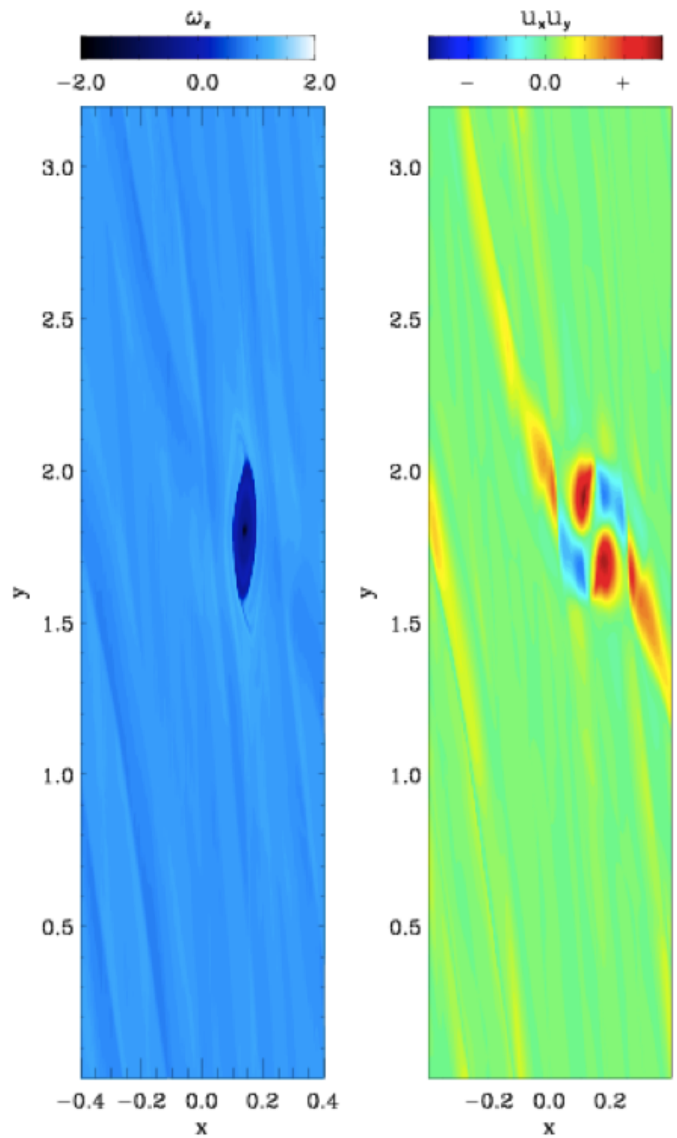
dissipation

Baroclinic Instability and Accretion

Large mass accretion rates, comparable to the MRI!



Raettig, Lyra, & Klahr (2012)

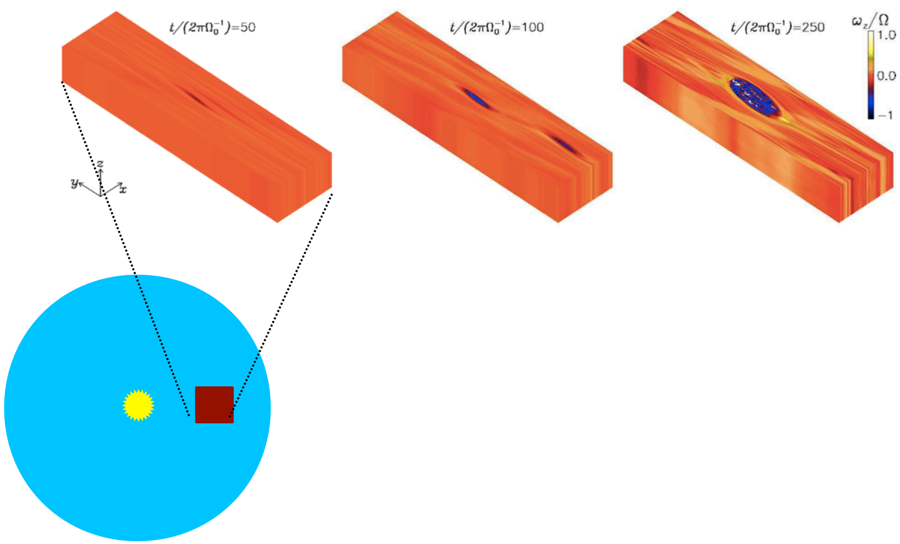


The angular momentum is carried by *waves* excited by the vortex
(see also Heinemann & Papaloizou 2008,2009)

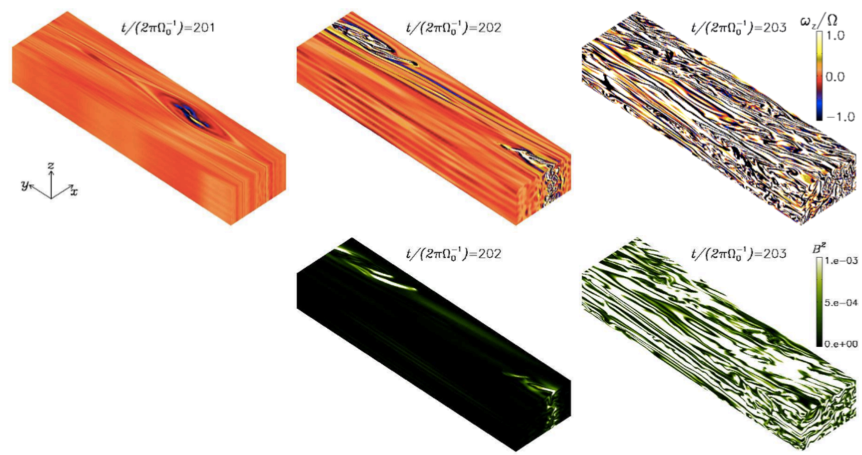
Baroclinic instability and layered accretion

What happens when the vortex is magnetized?

Hydro



MHD

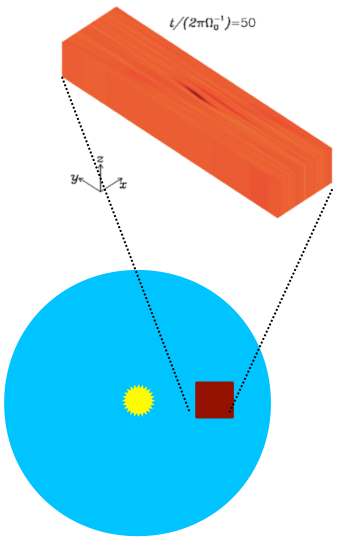


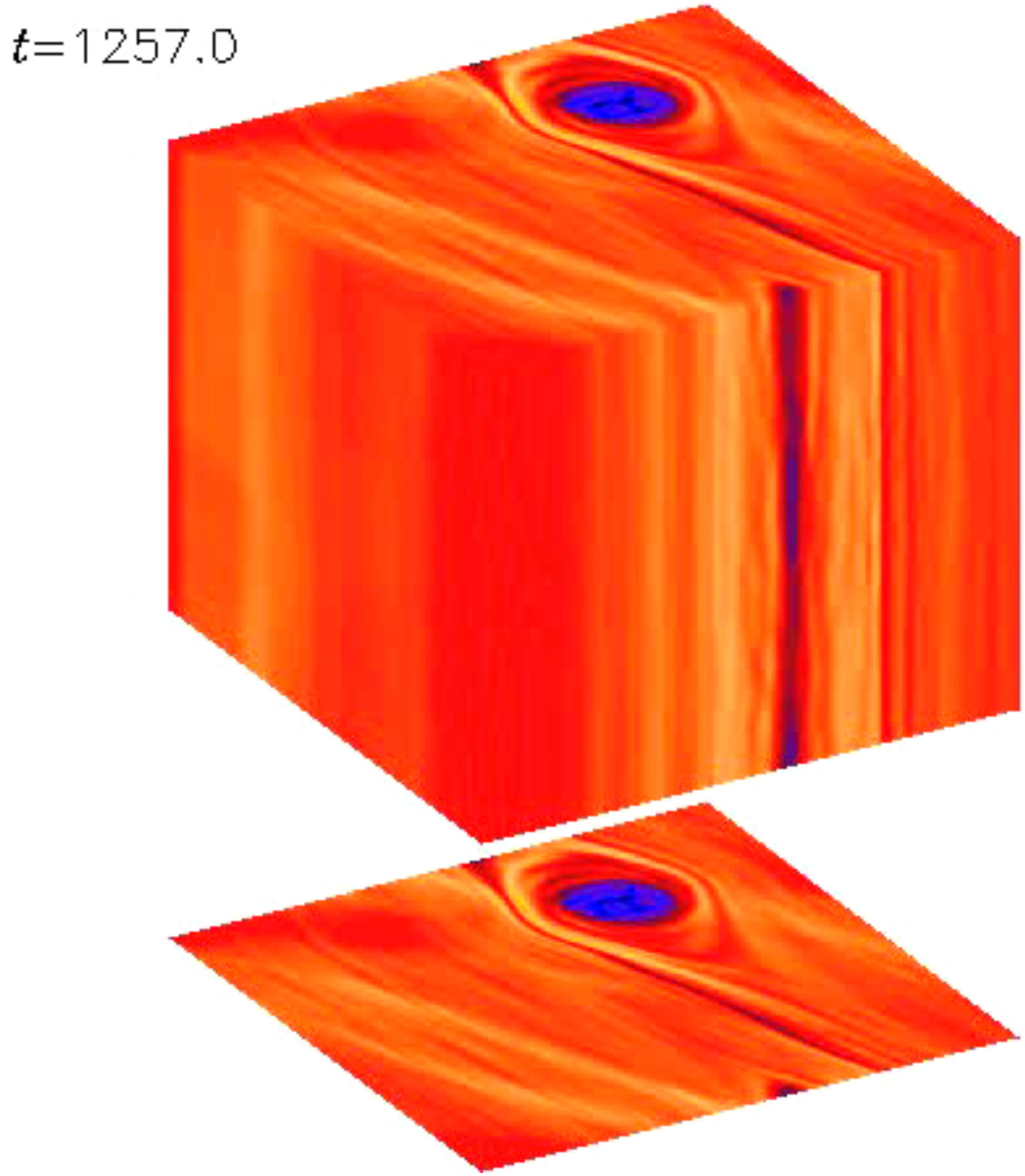
Vorticity

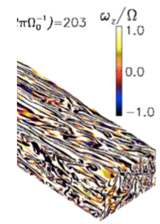
Mag. Energy

Lyra & Klahr (2011)

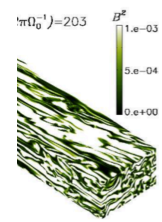
Baroclinic instability and layered accretion







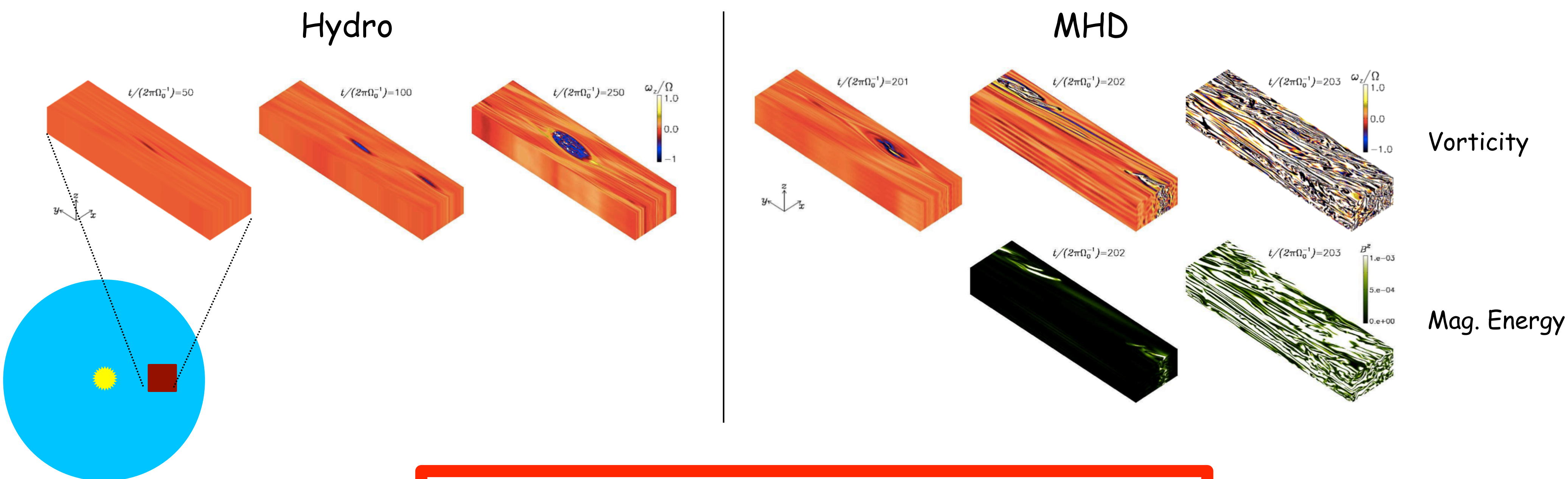
Vorticity



Mag. Energy

Baroclinic instability and layered accretion

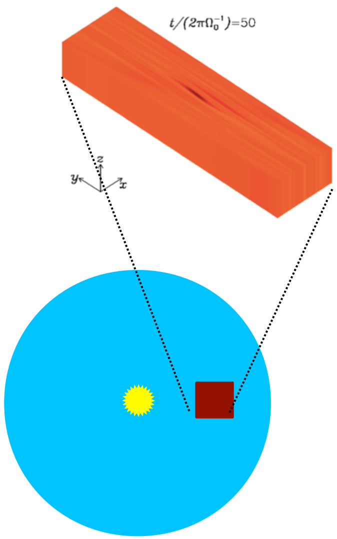
What happens when the vortex is magnetized?

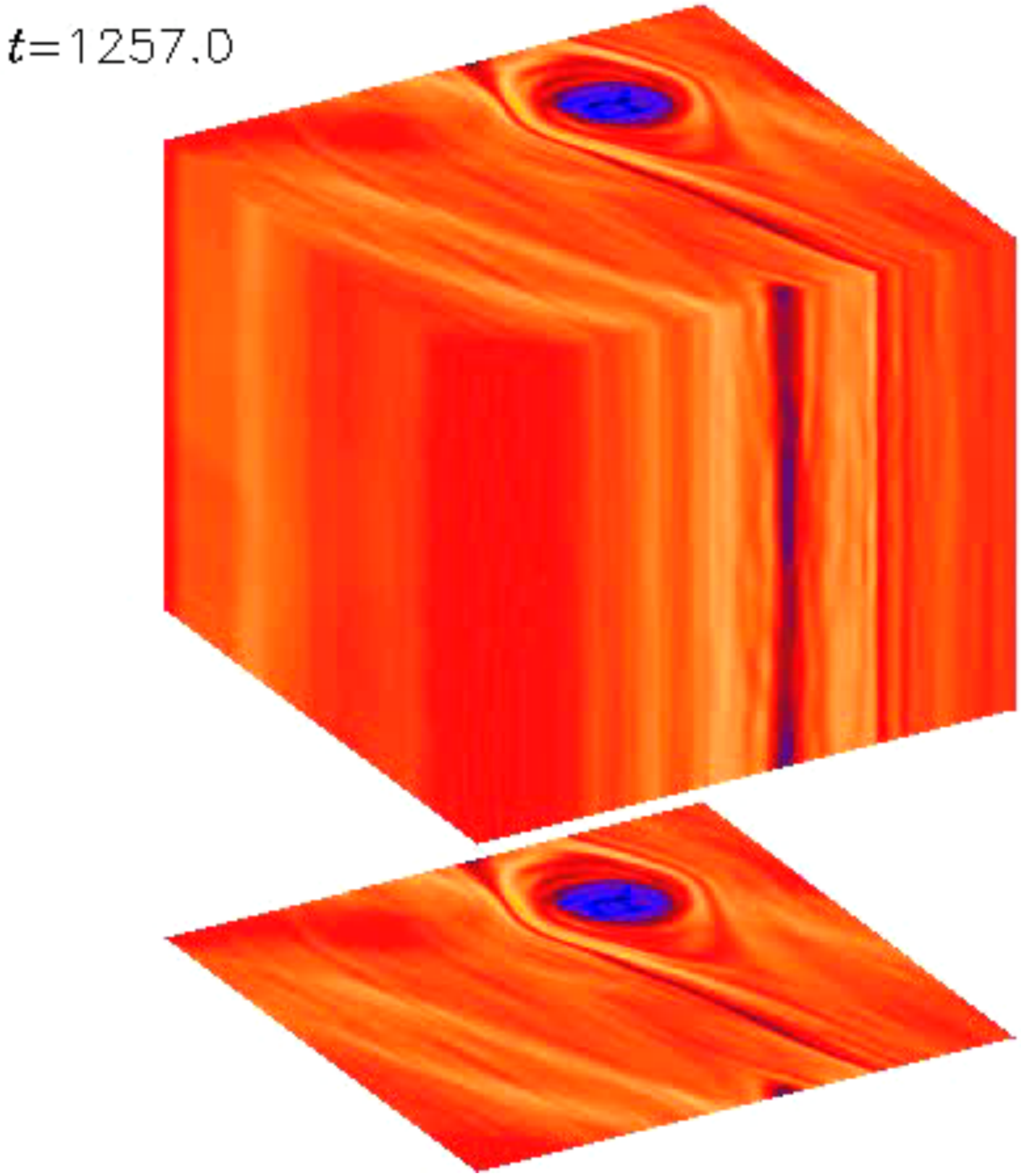


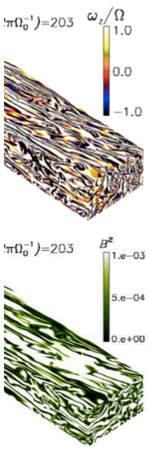
Lyra & Klahr (2011)

Baroclinic vortices do *not* survive magnetization

Baroclinic instability and layered accretion





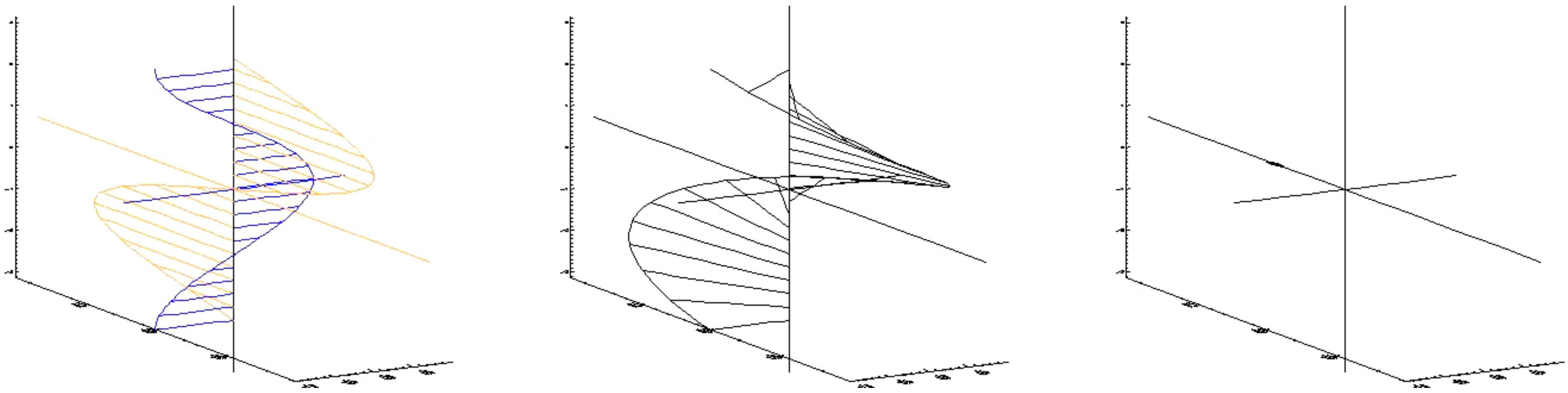


Vorticity

Mag. Energy

.yra & Klahr (2011)

Fluid in rigid rotation supports a spectrum of oscillations



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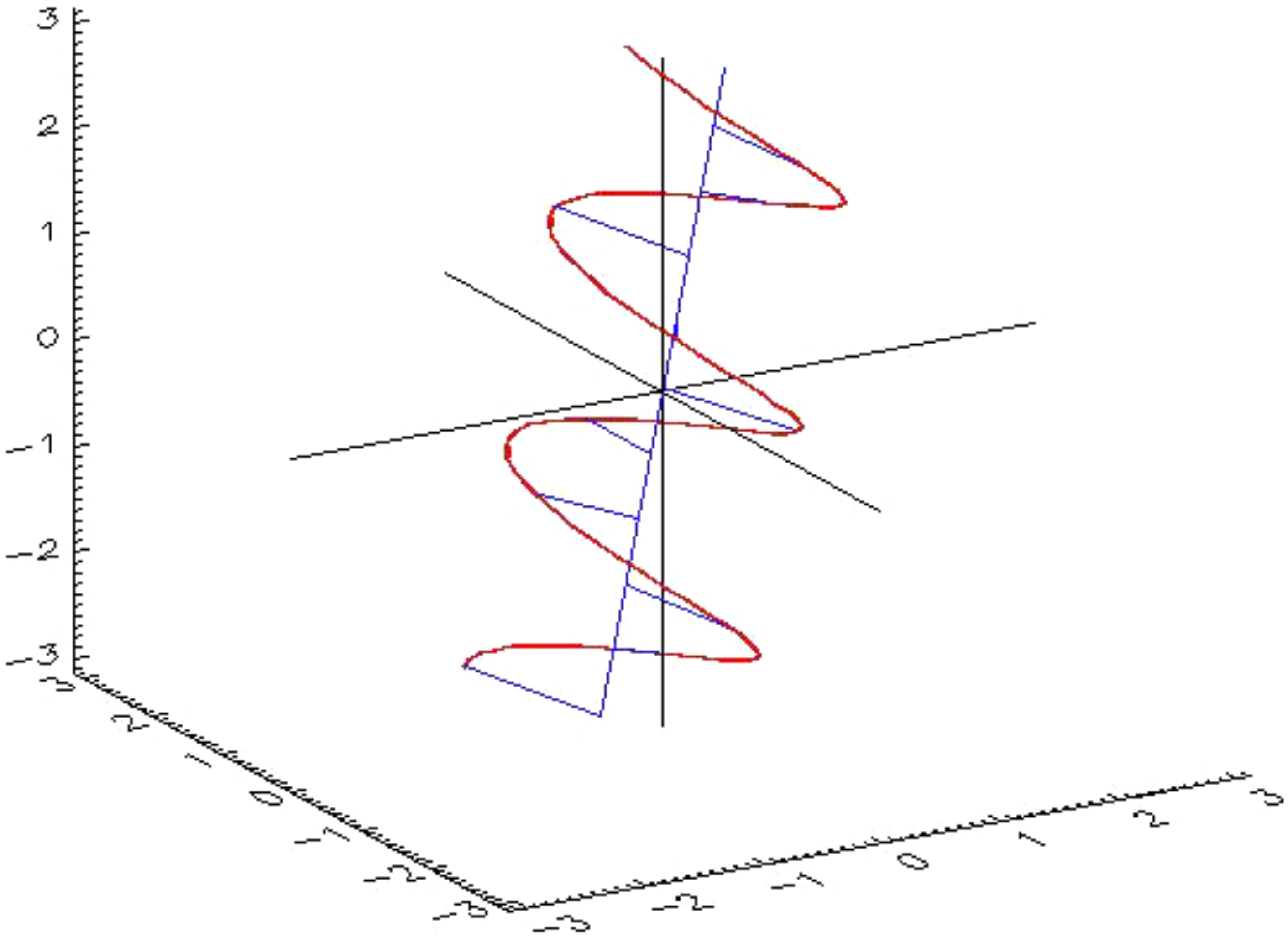
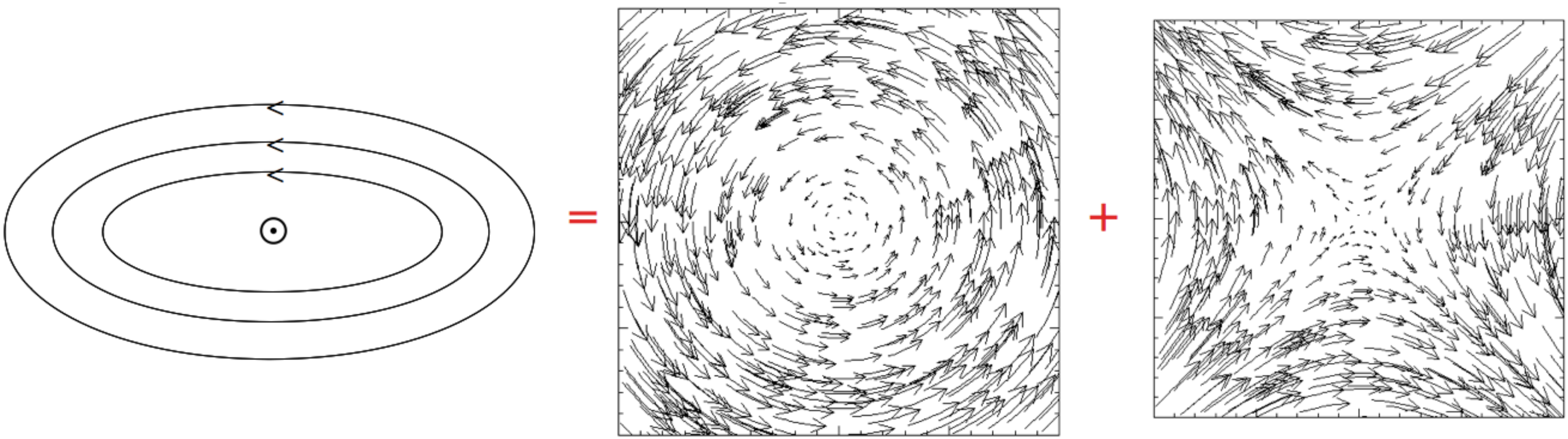


Introducing ellipticity: Strain

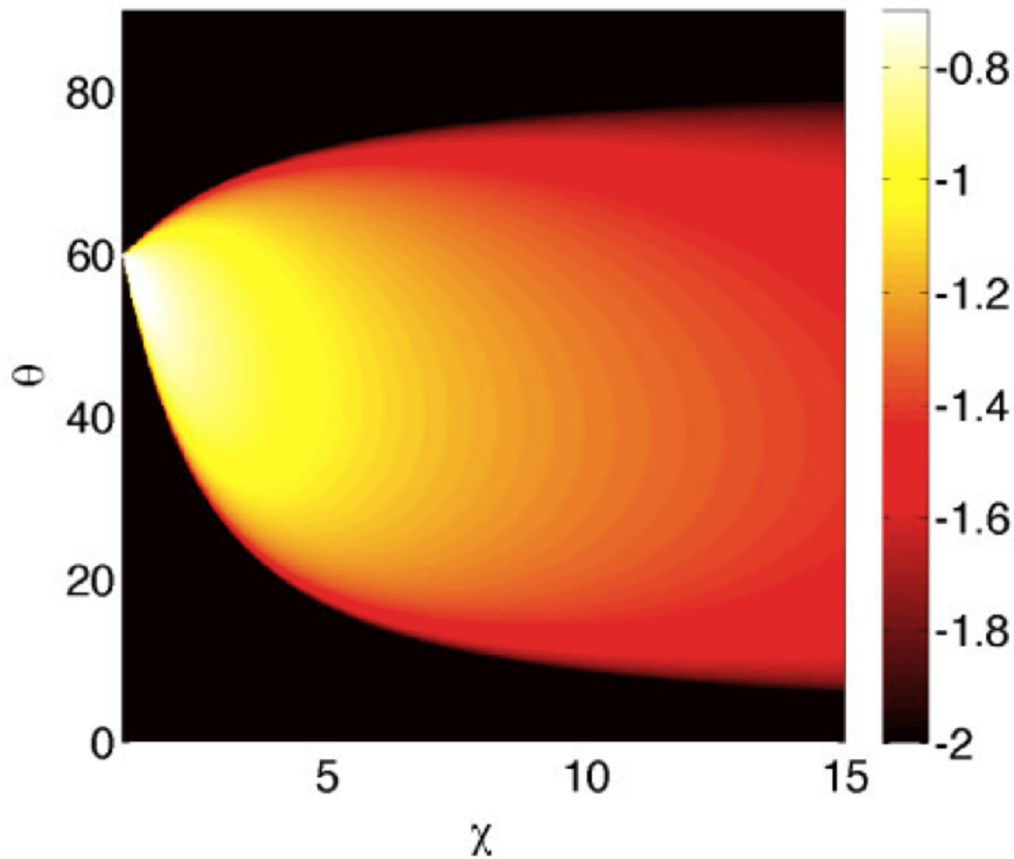
Rigid rotation | Strain field



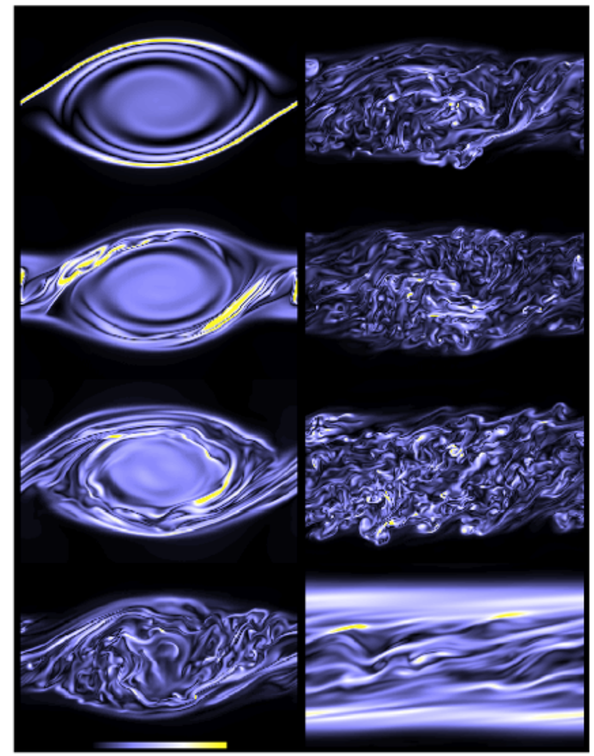
$U=[-(1-\epsilon)y,(1-\epsilon)x]$ = $[-y,x]$ + $-\epsilon[y,x]$

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

Elliptic Instability



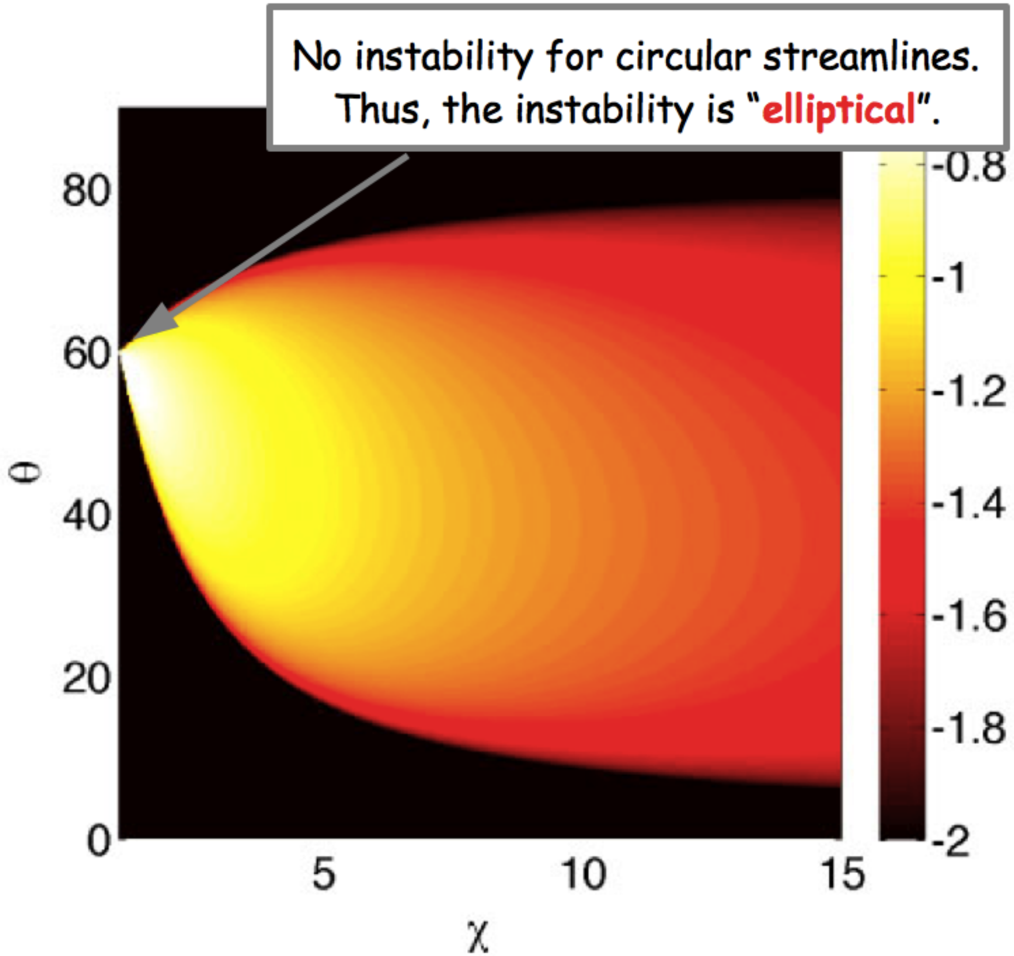
Lesur & Papaloizou (2009)
After Bayly (1986)



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

McWilliams (2010)

Elliptic Instability



Lesur & Papaloizou (2009)
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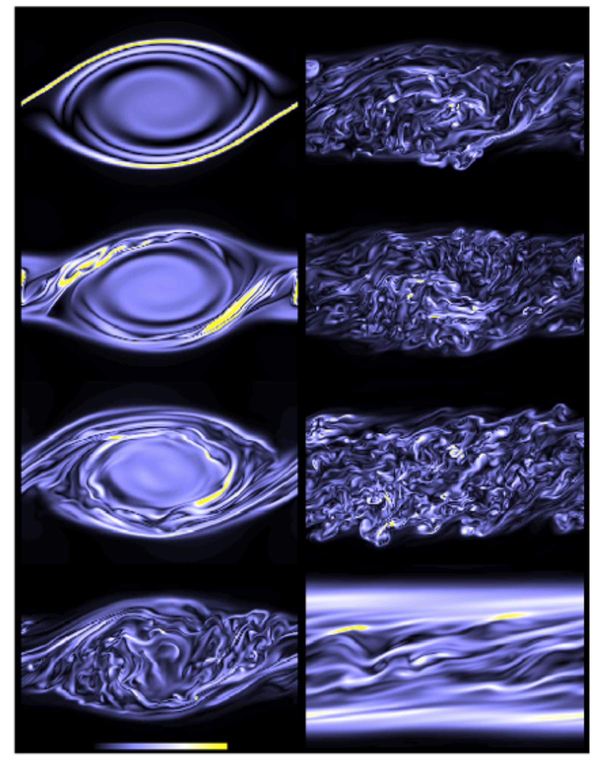

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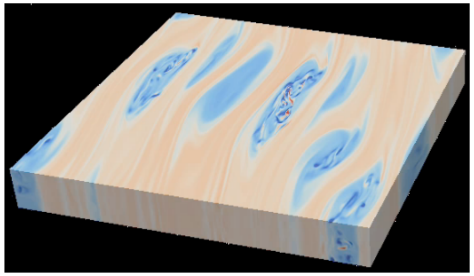
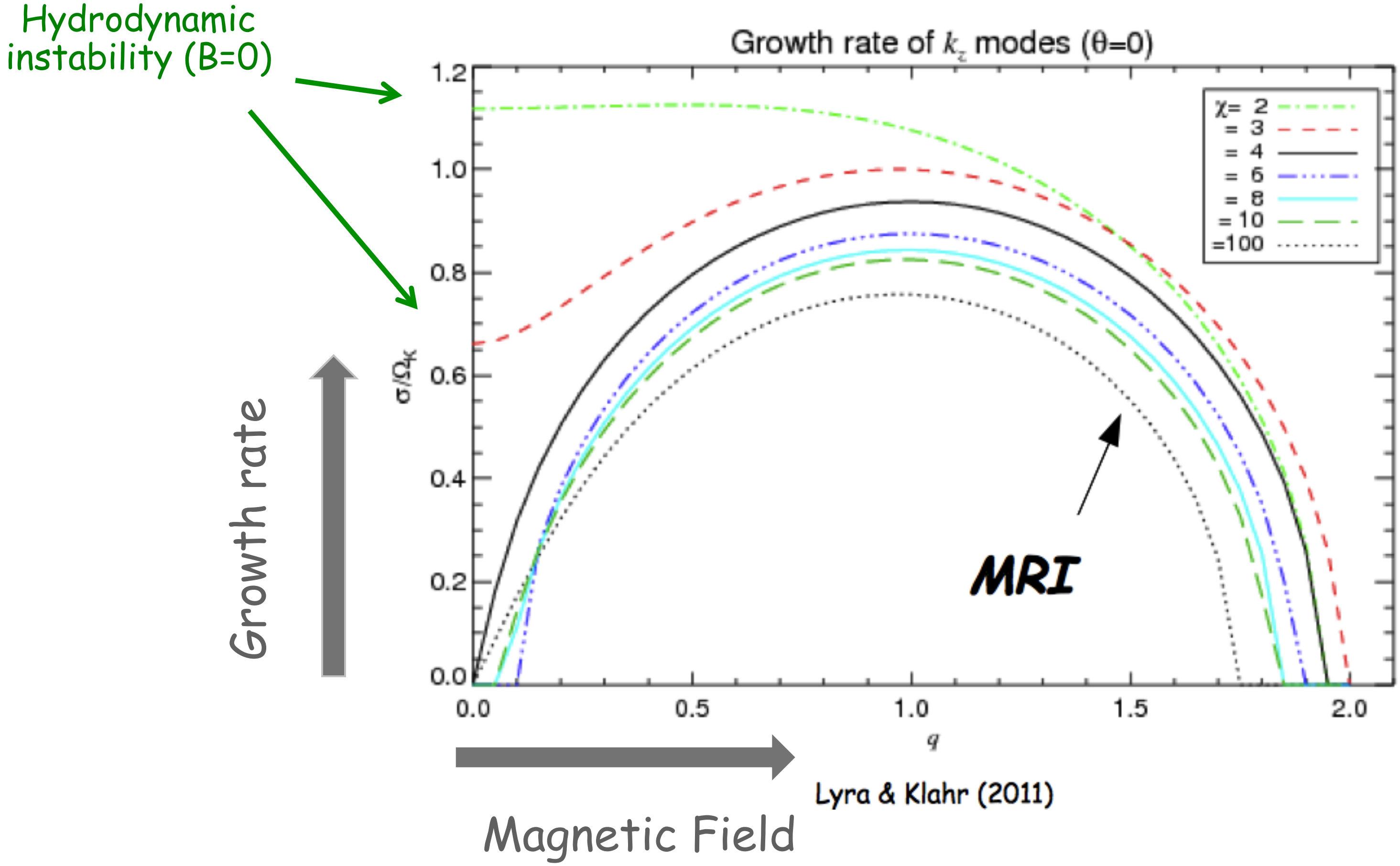
McWilliams (2010)

"Elliptic" Instability



Lesur & Papaloizou (2010)

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



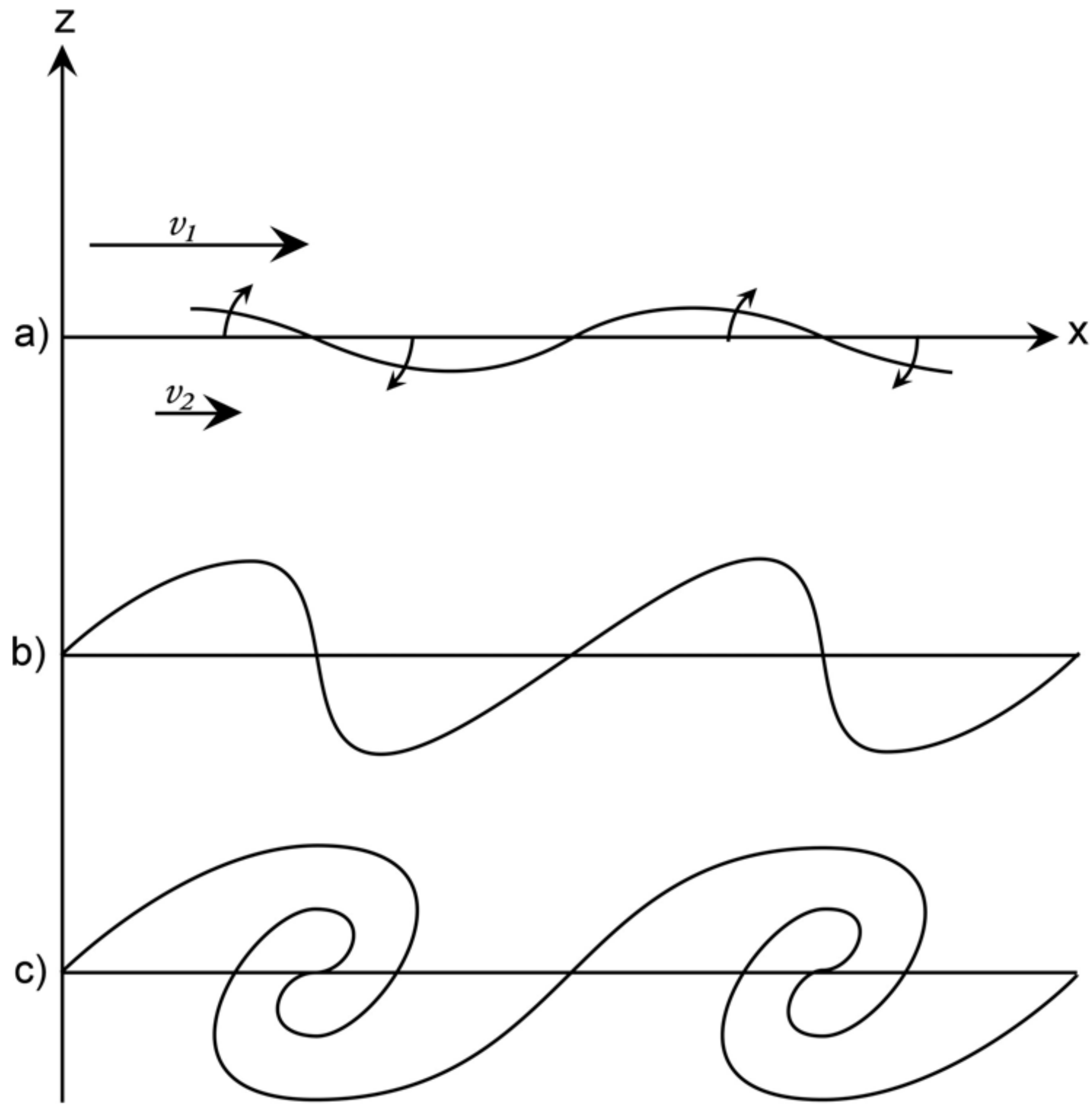
Lyra & Klahr (2011)

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

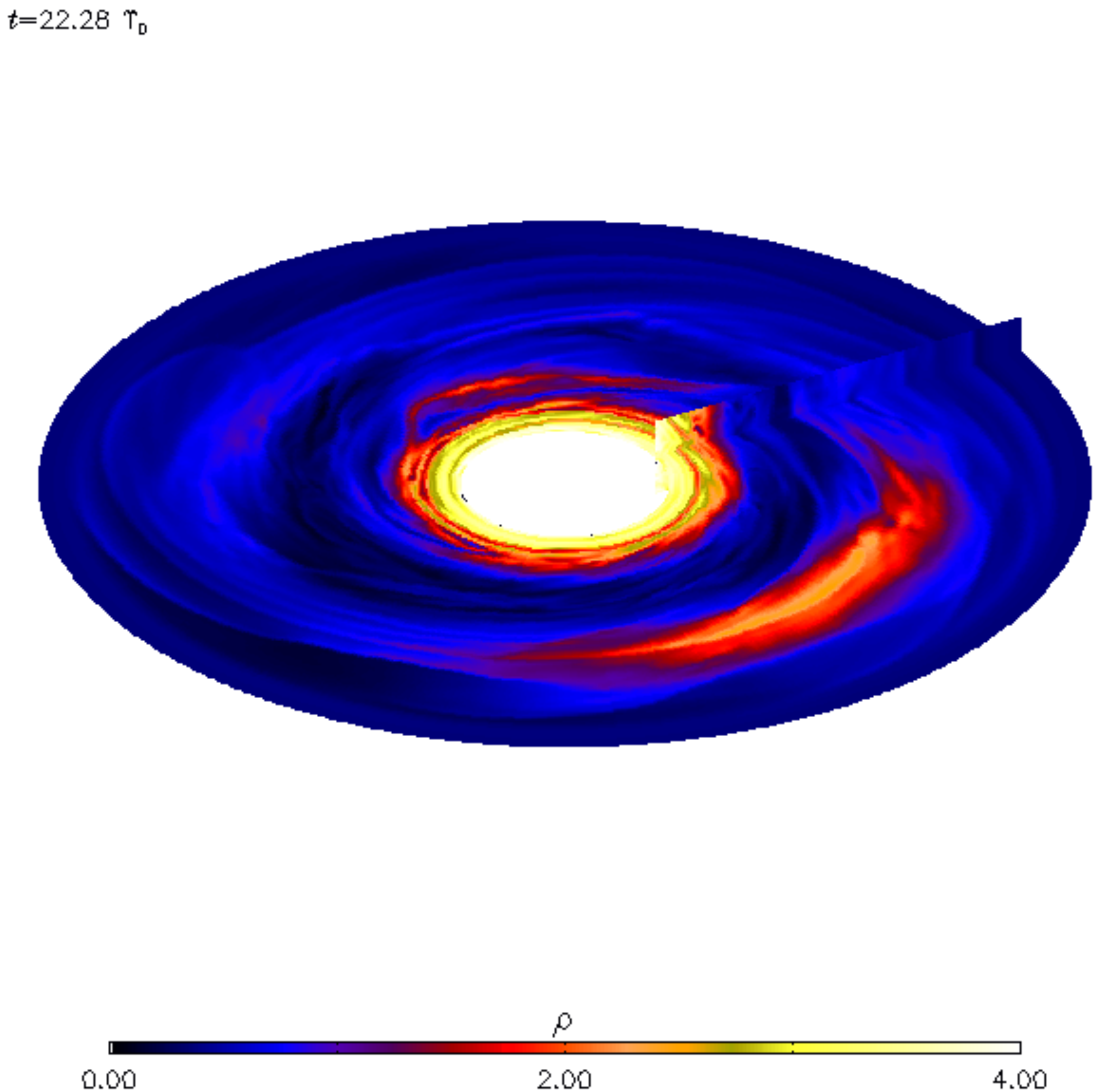
They are subject to an MRI-like instability when magnetized.

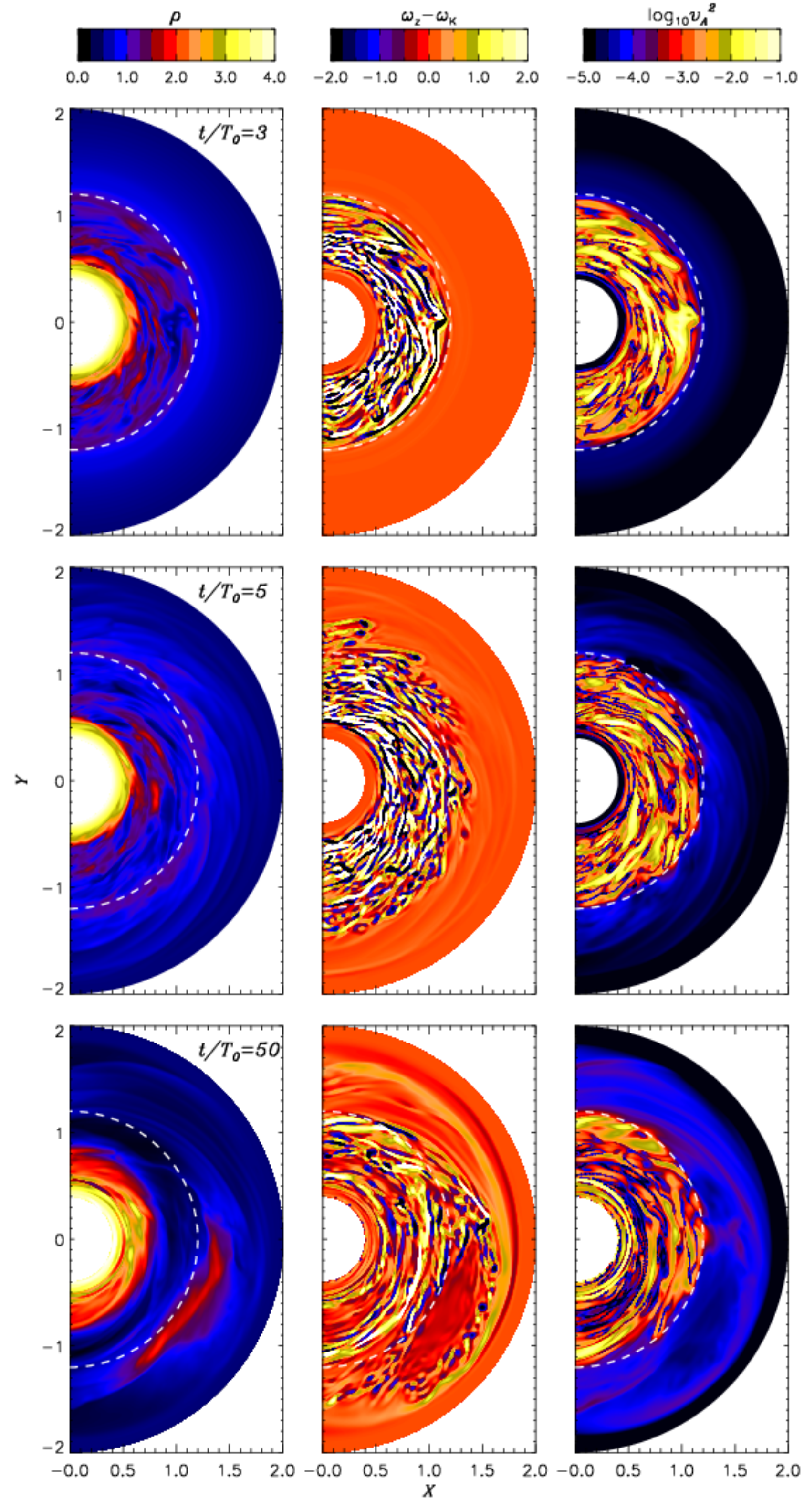
Rossby Wave Instability

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



Active/dead zone boundary

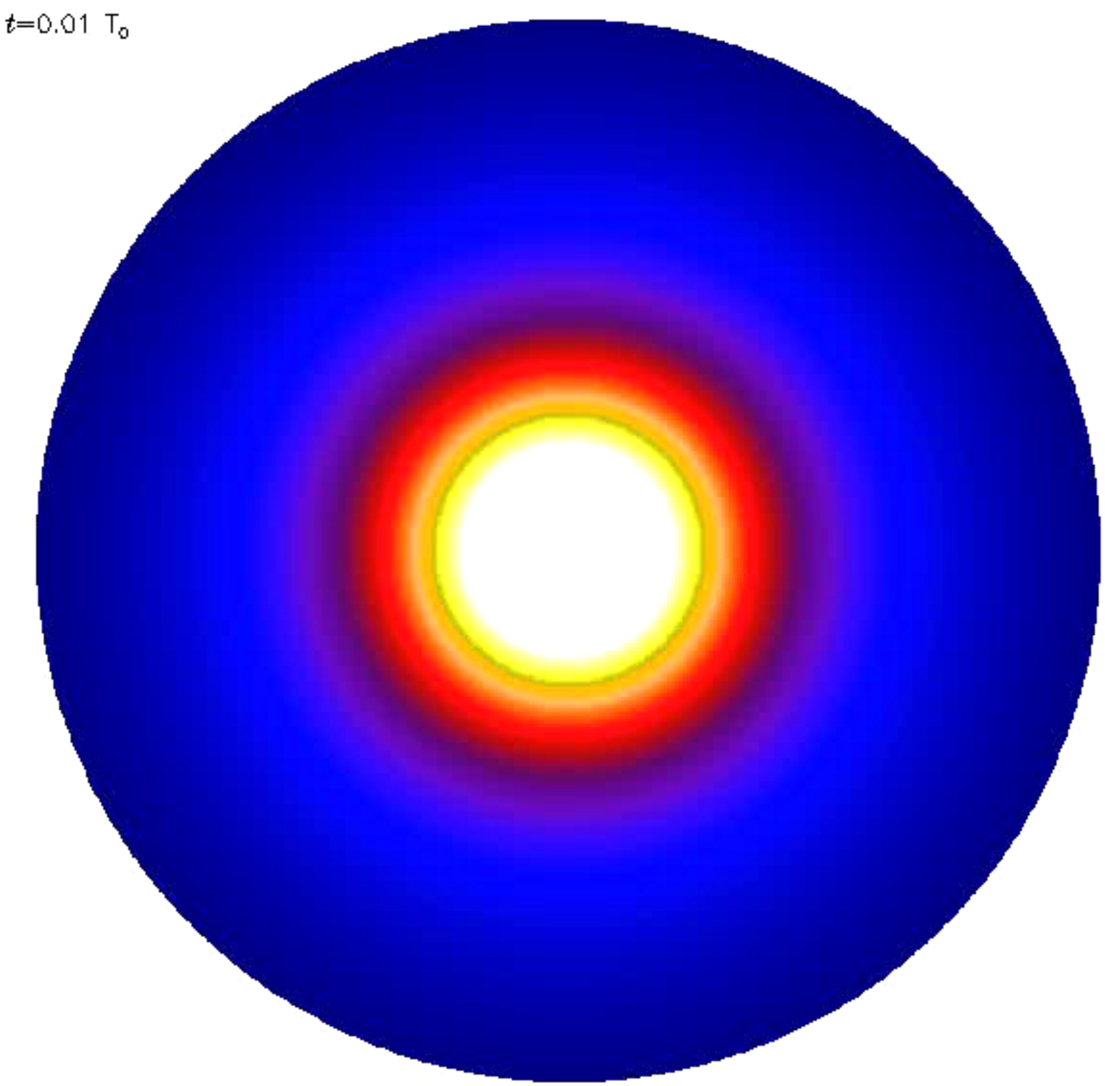


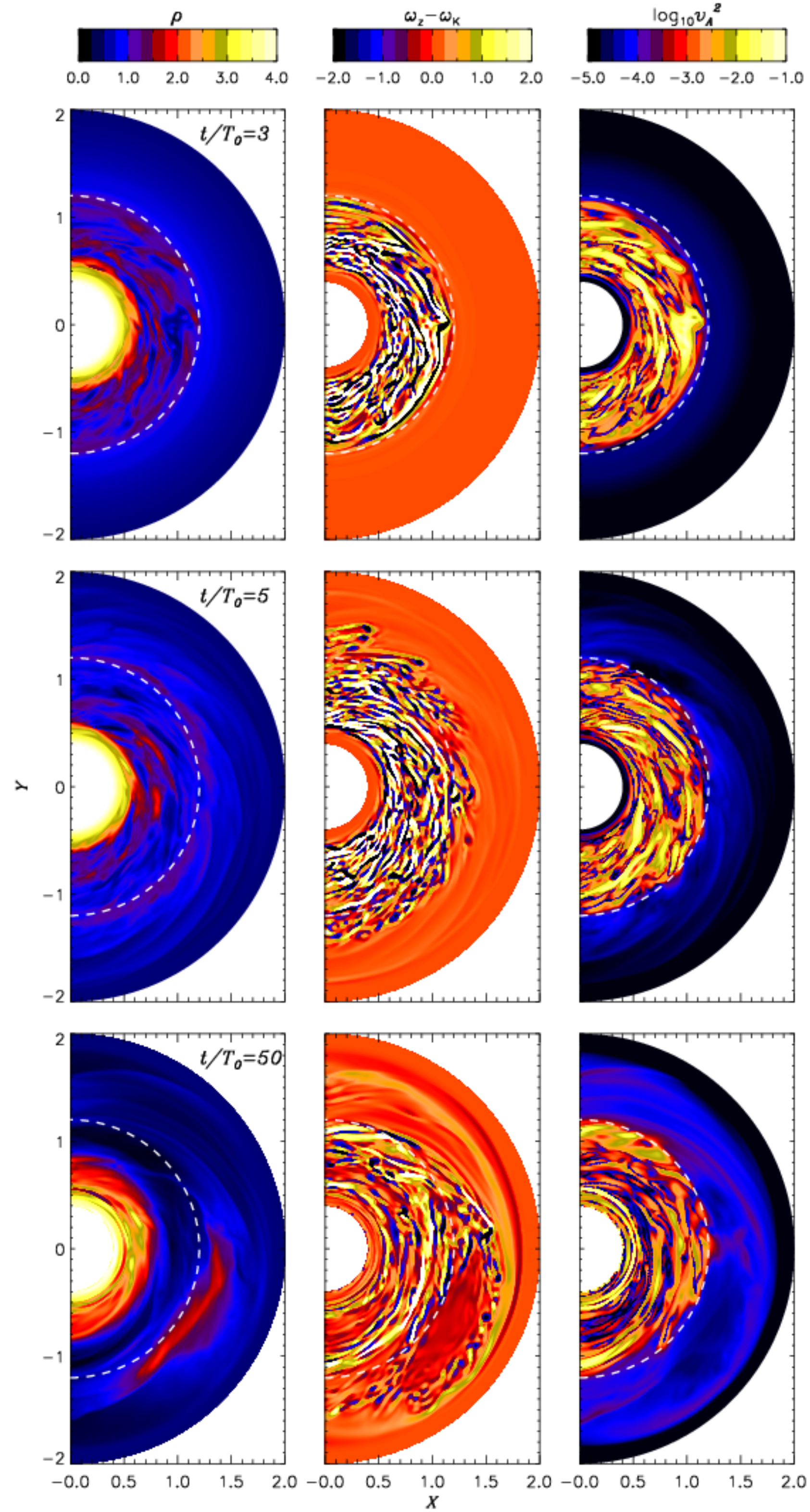


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Active/dead zone boundary





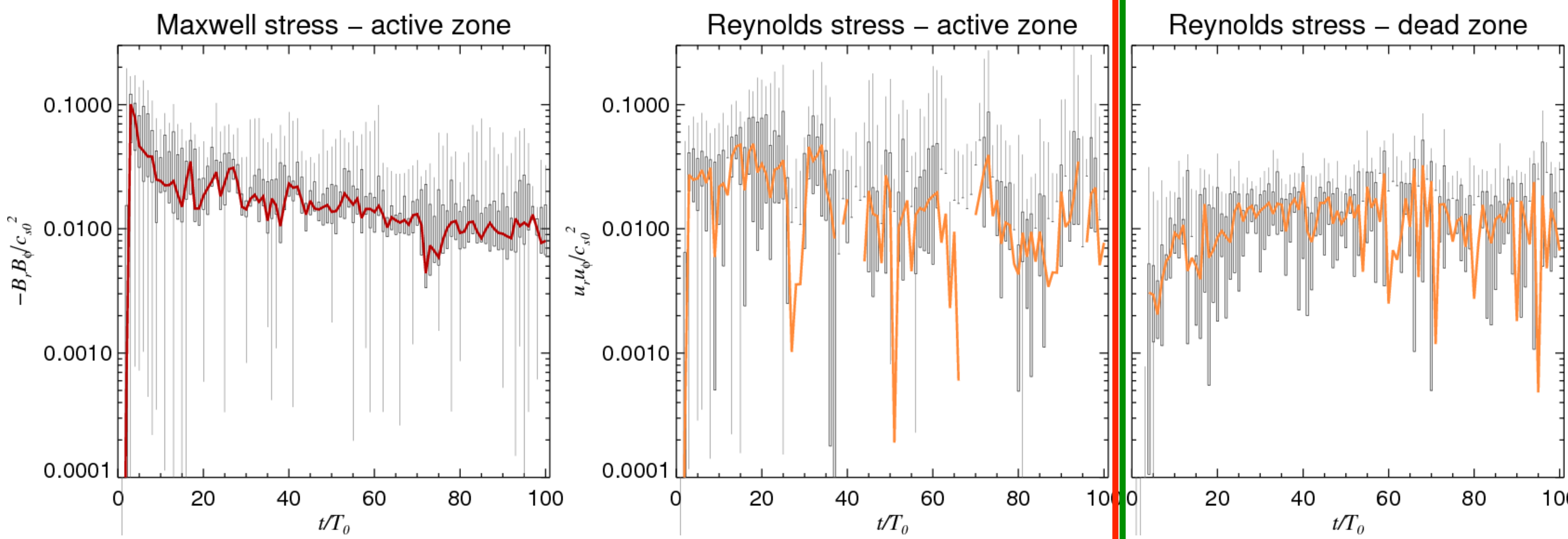
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Significant angular momentum transport

Active zone

Dead zone

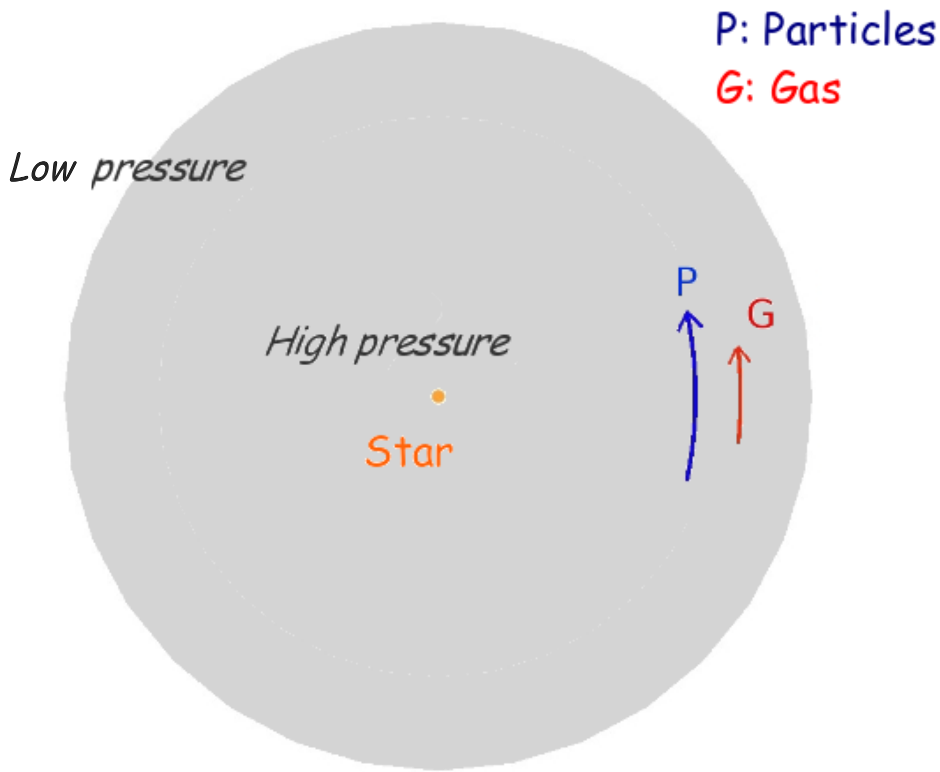


Large mass accretion rates in the dead zone,

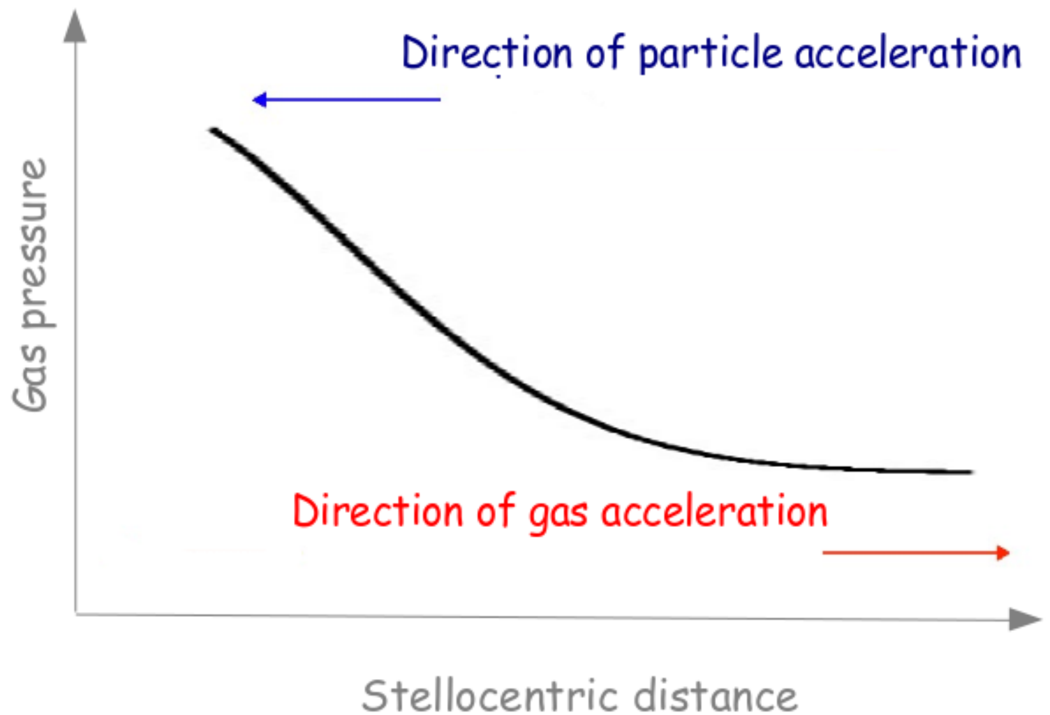
comparable to the MRI in the active zone!

Lyra & Mac Low (2012)

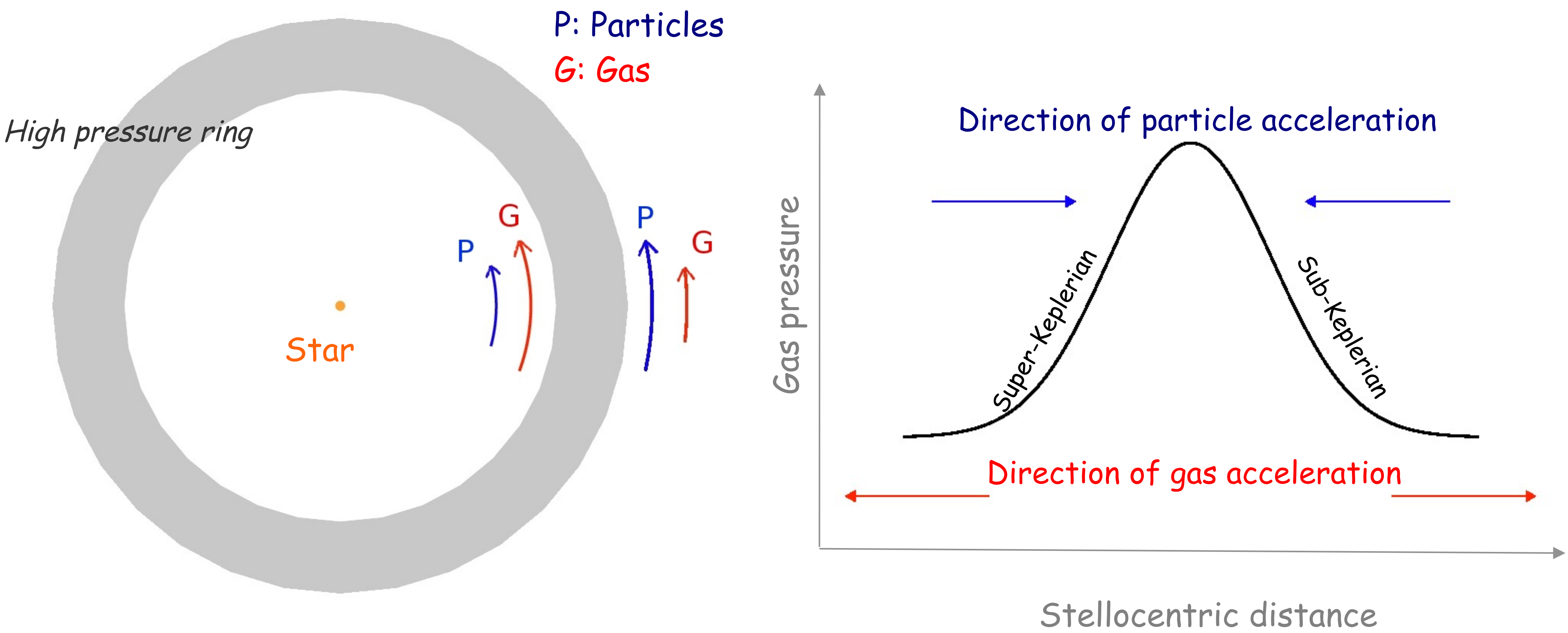
Particle drift



Adapted from Whipple (1972)



Pressure Trap



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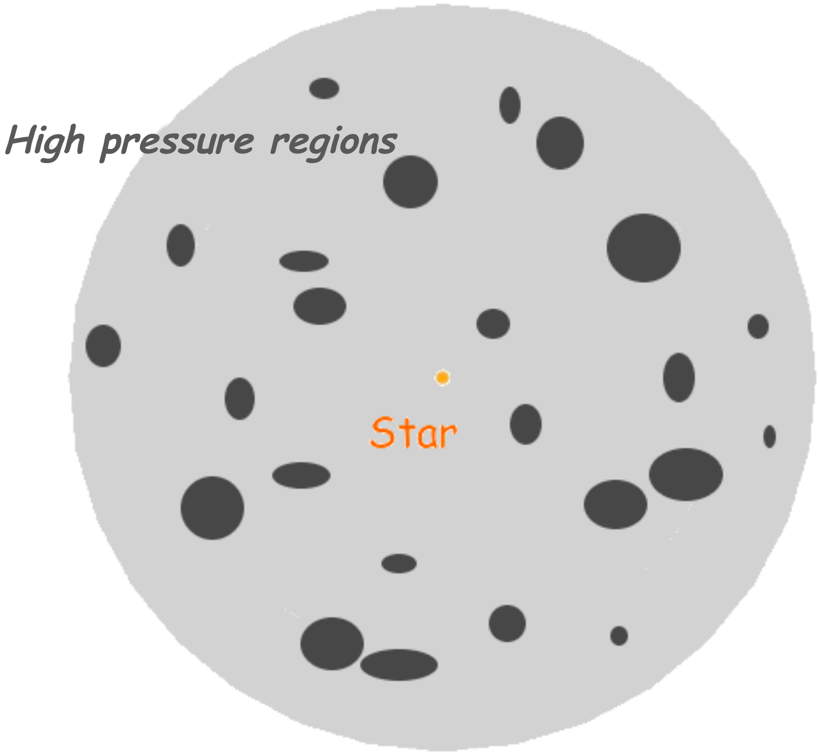
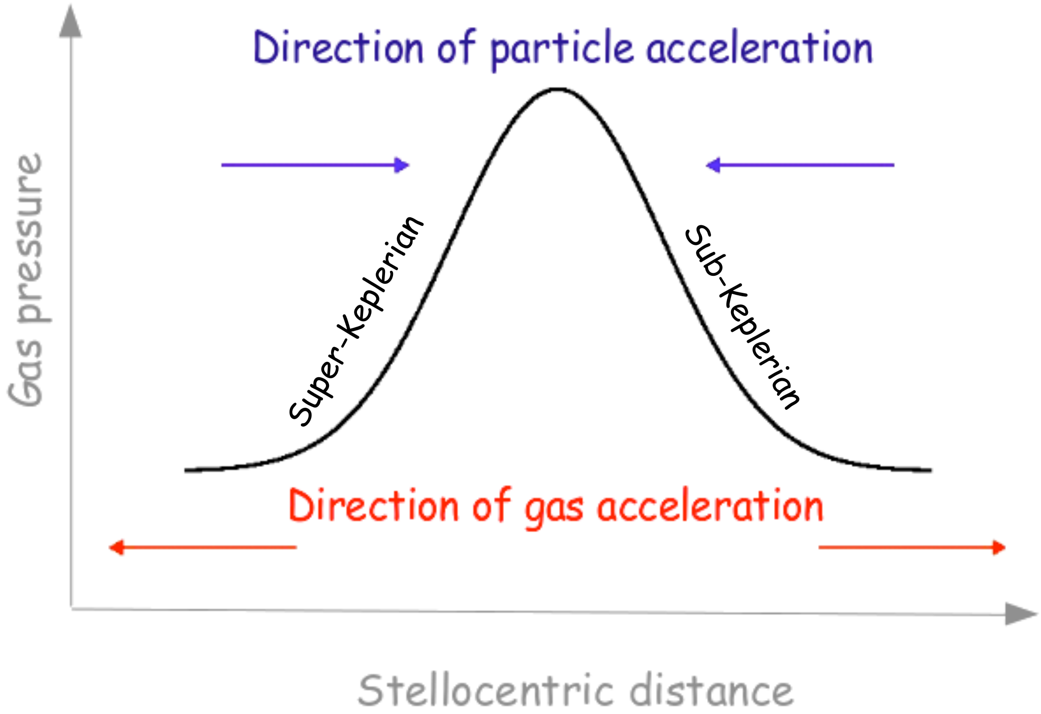
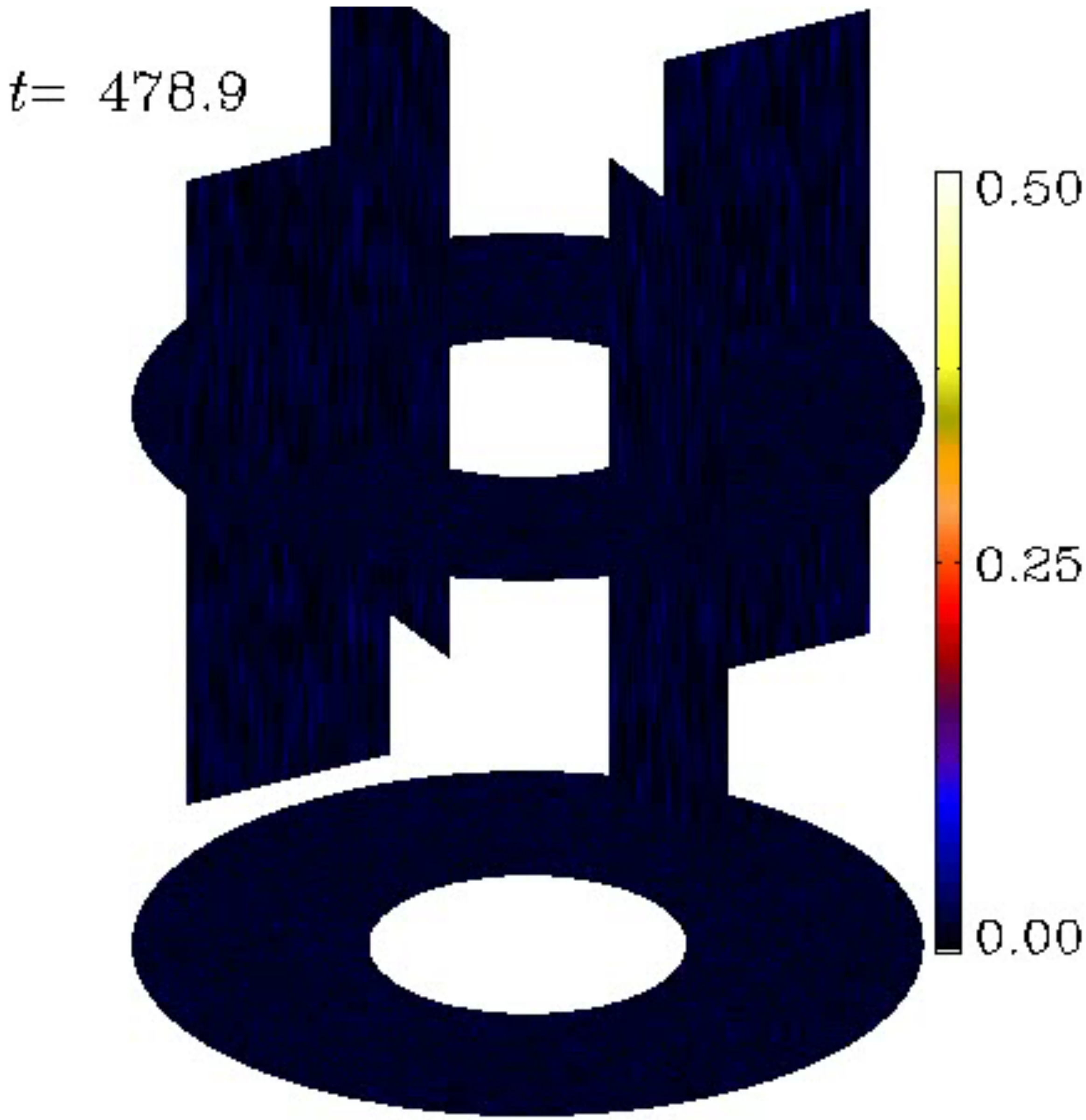


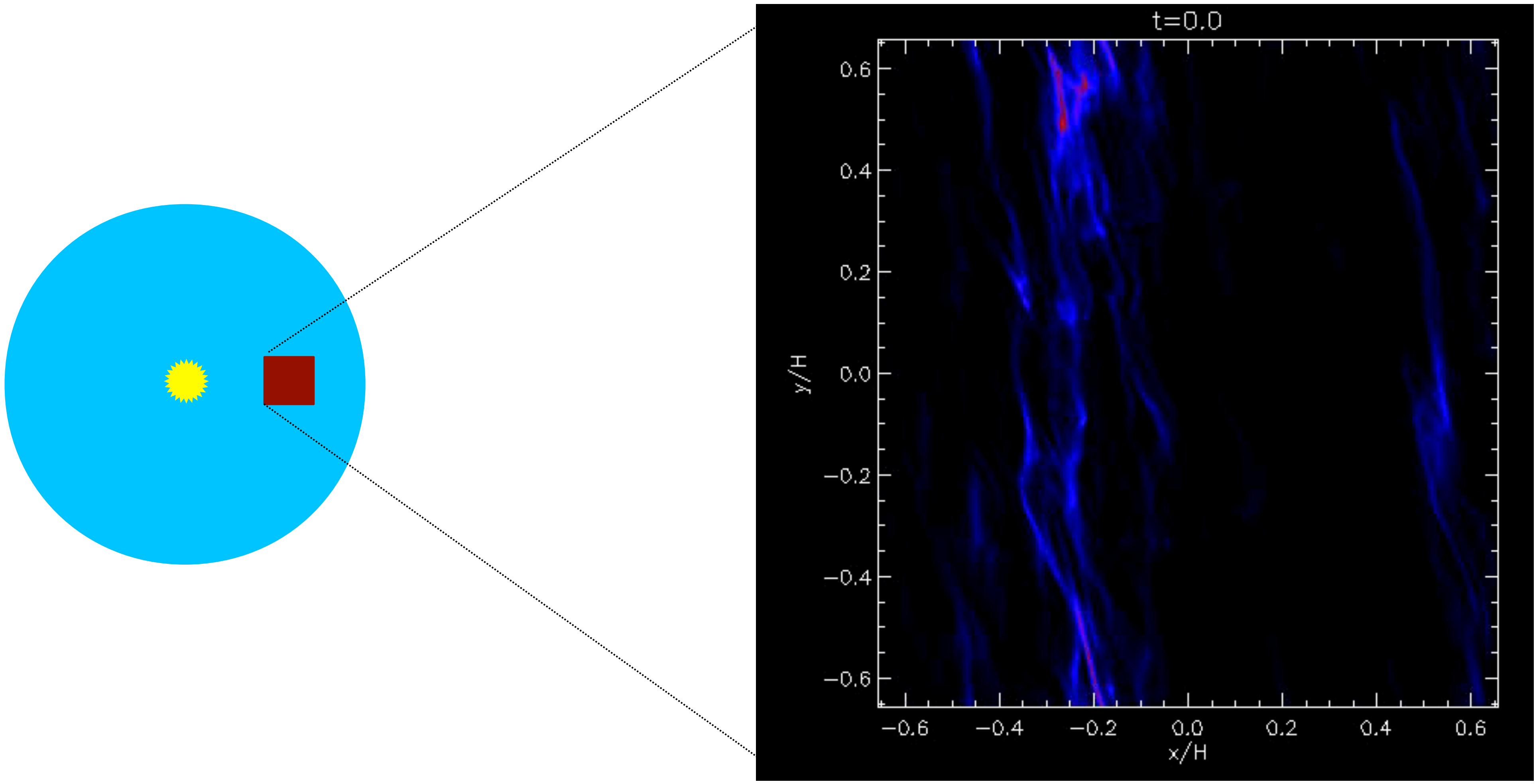


Turbulence concentrates solids mechanically in pressure maxima



Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

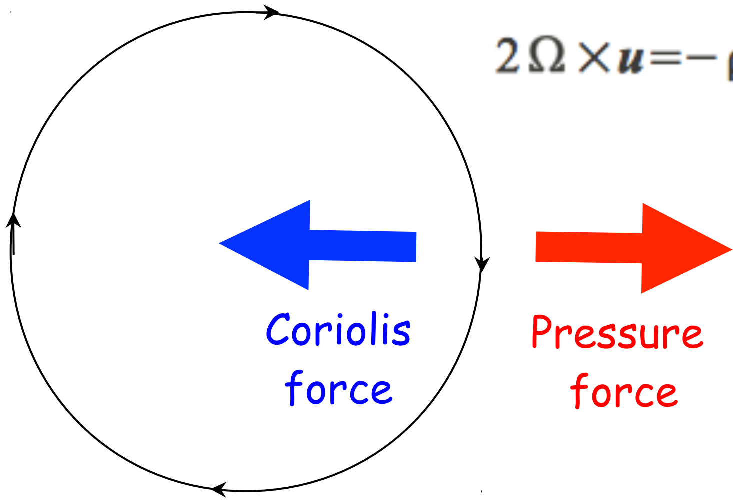
Turbulent eddies concentrate solids, turning them into planetesimals...

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

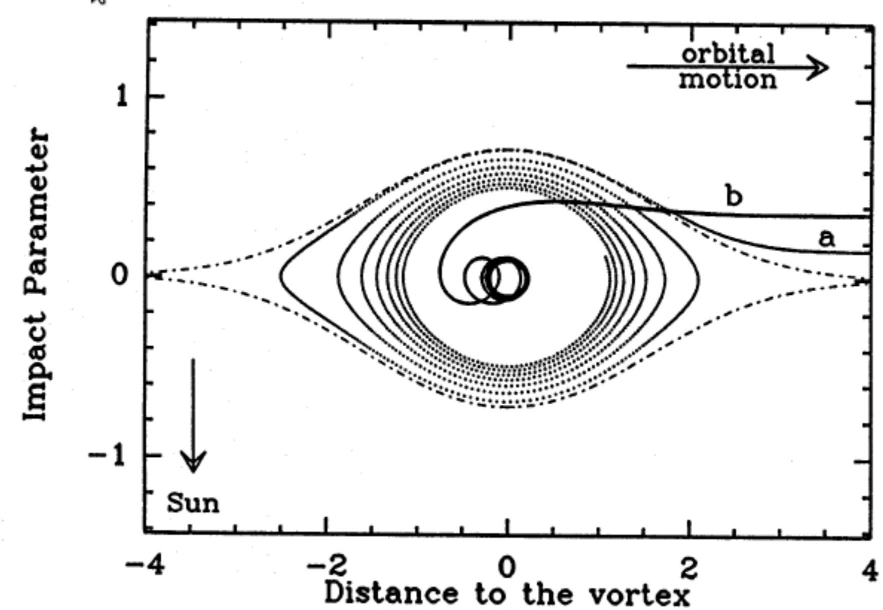
The Tea-Leaf effect

Geostrophic balance:

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



Vortex streamline



Barge & Sommeria (1995)

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

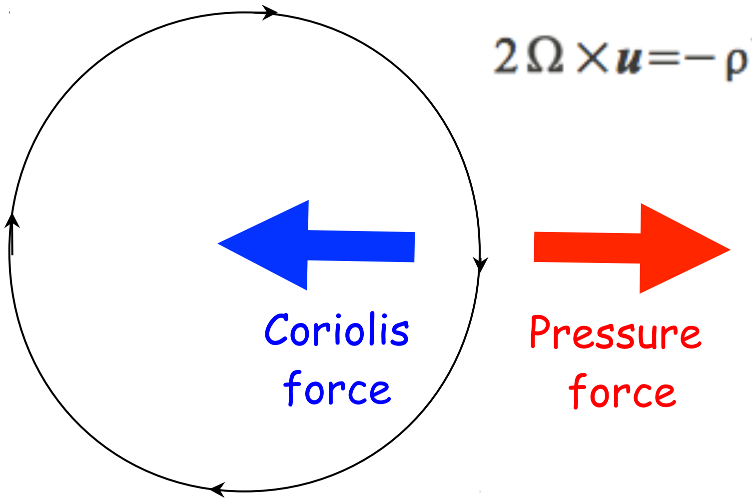
Aid to planet formation (Barge & Sommeria 1995)

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

The Tea-Leaf effect

Geostrophic balance:

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



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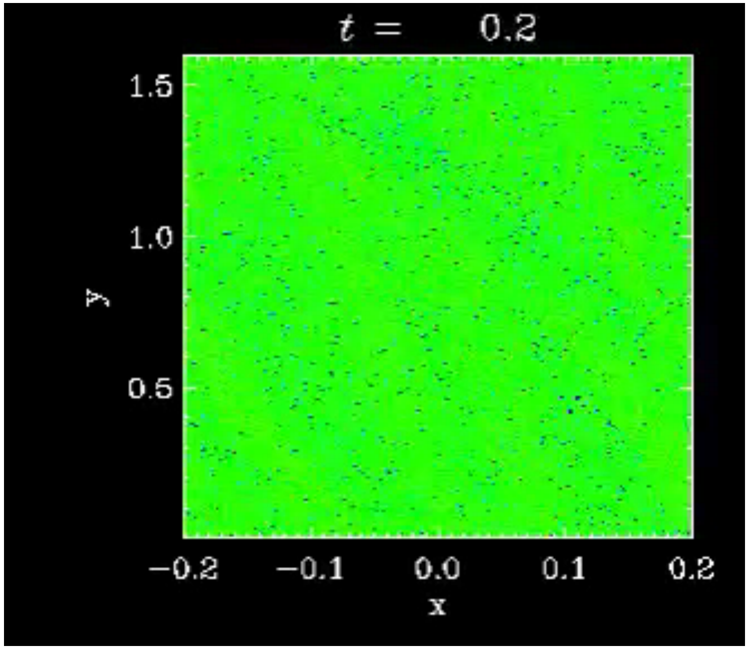

Raettig et al. (2012)

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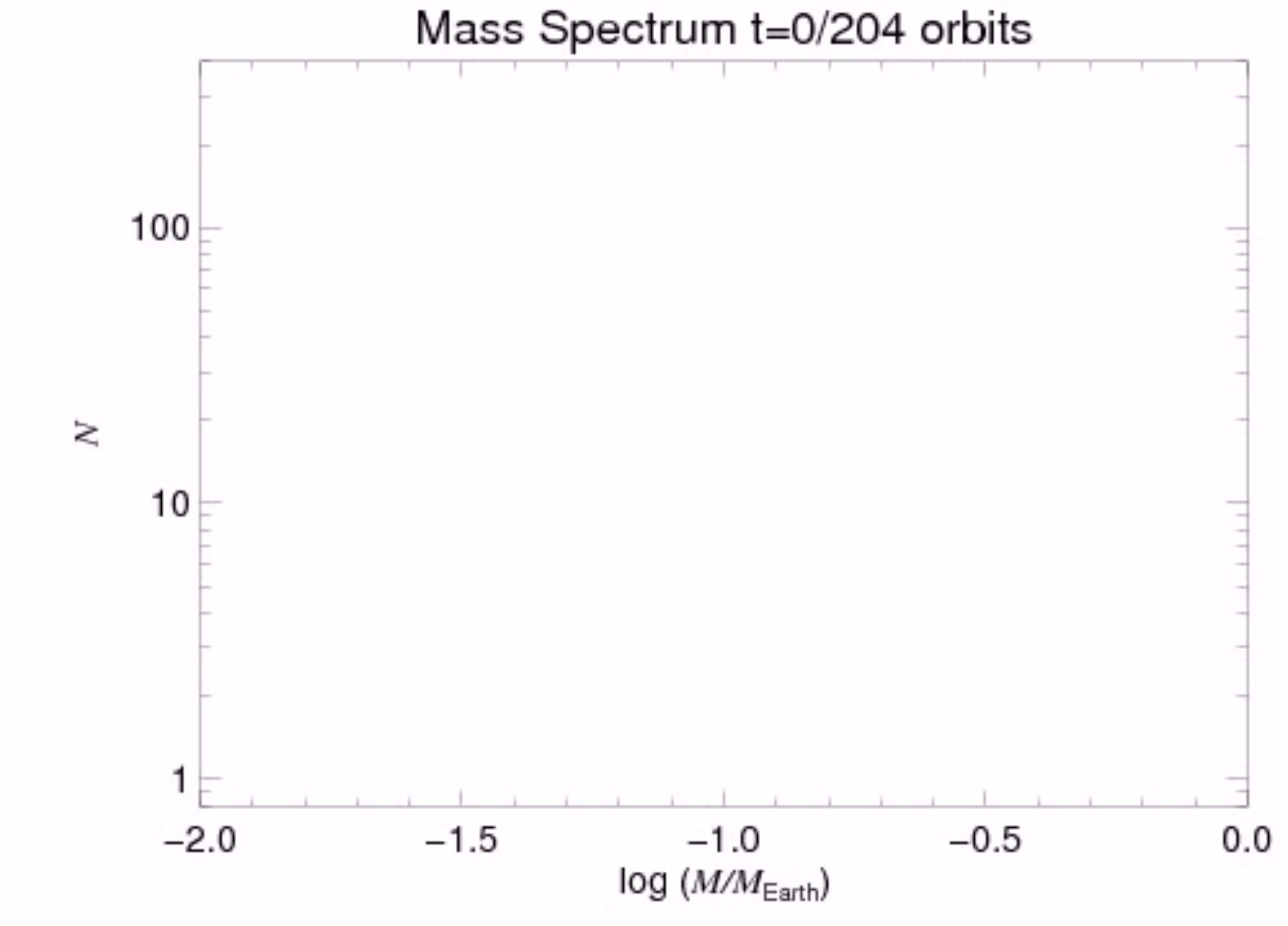
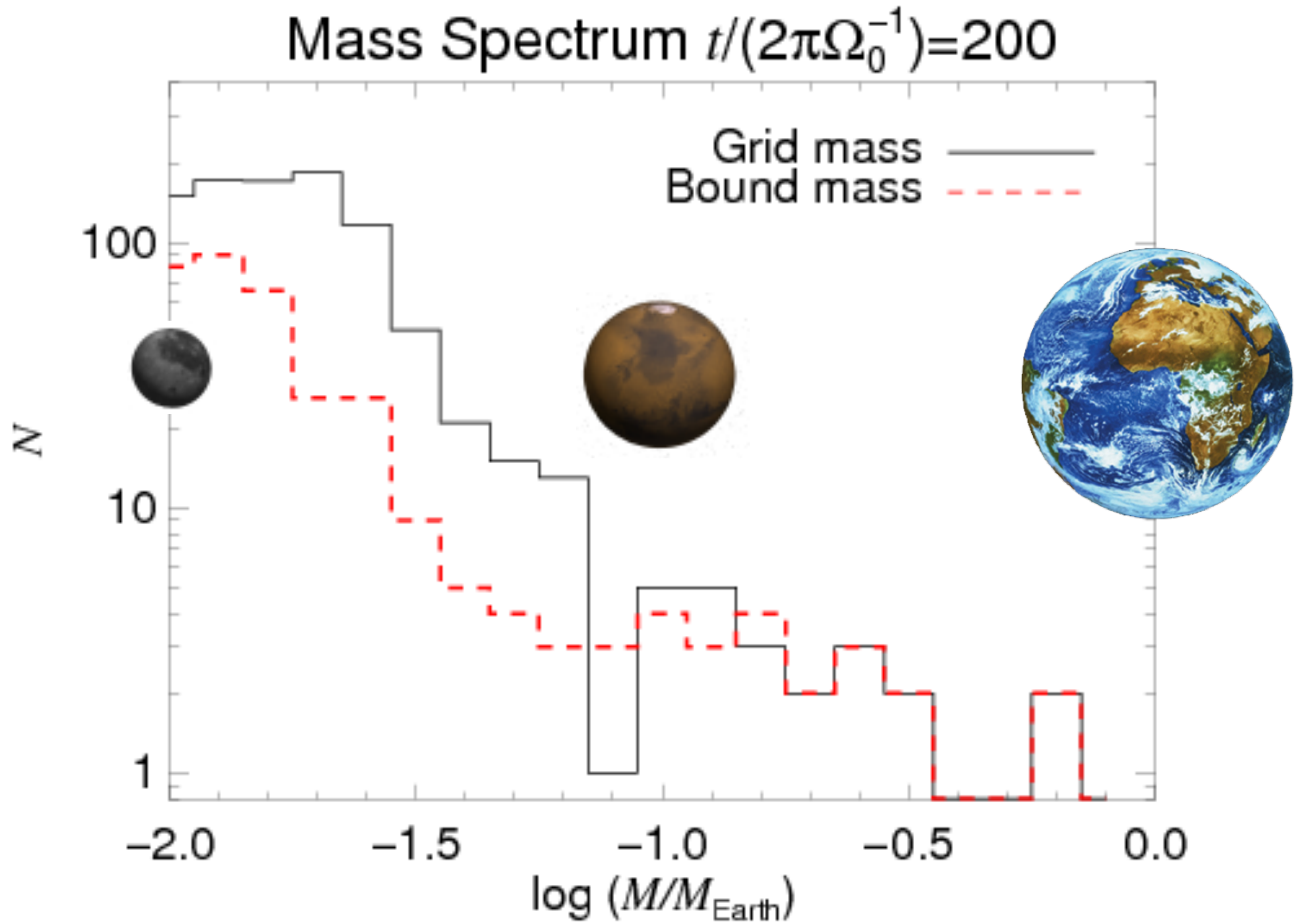
The Initial Mass Function of planets



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

Lyra et al. (2009)

The Initial Mass Function of planets



- Mass spectrum by the end of the simulation
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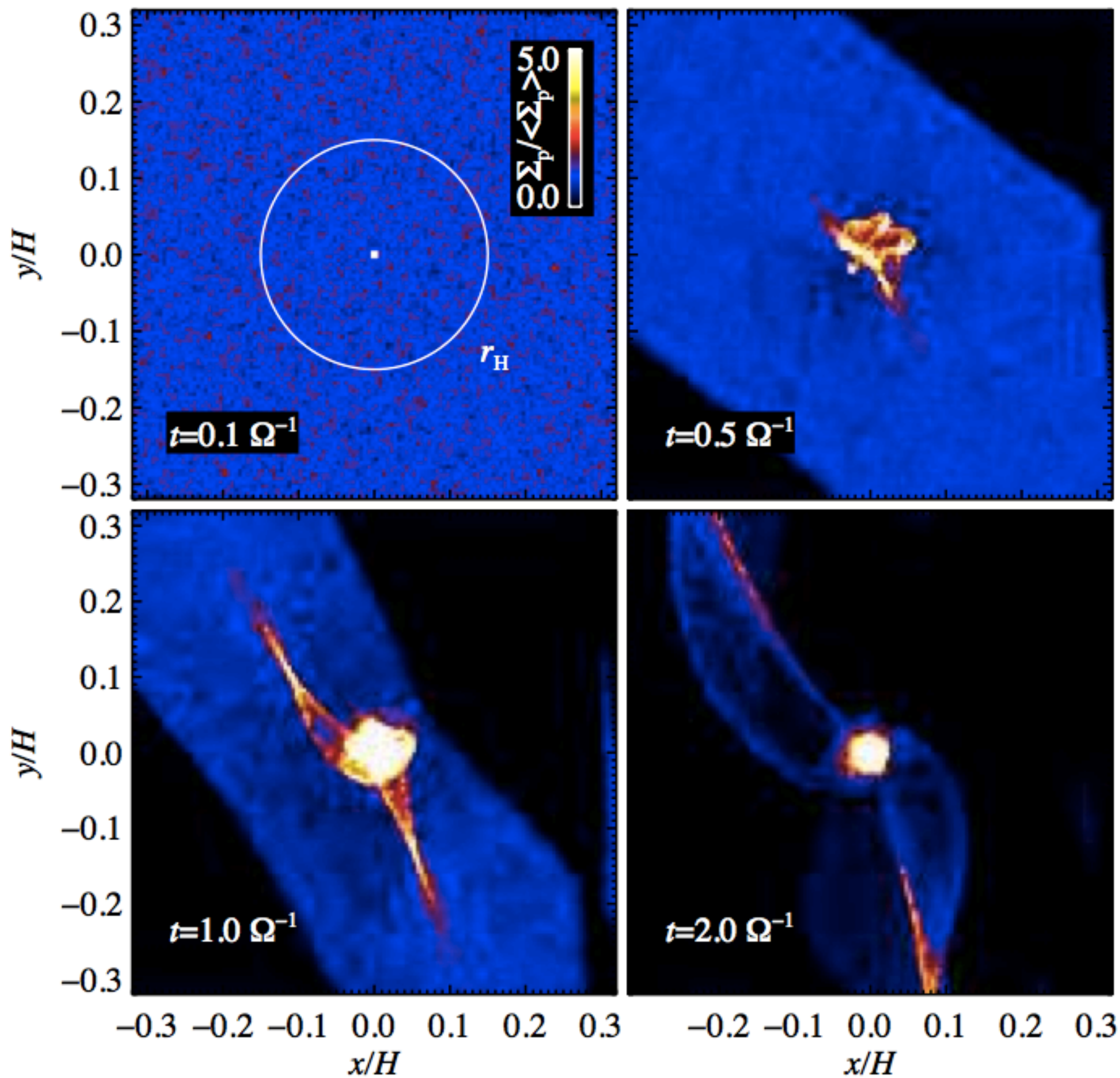
Lyra et al. (2009)

Rapid formation of planetary cores

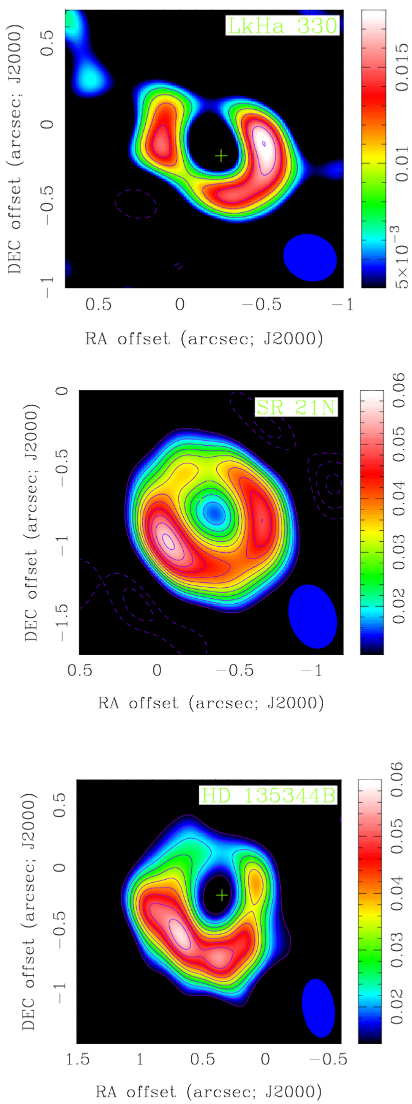


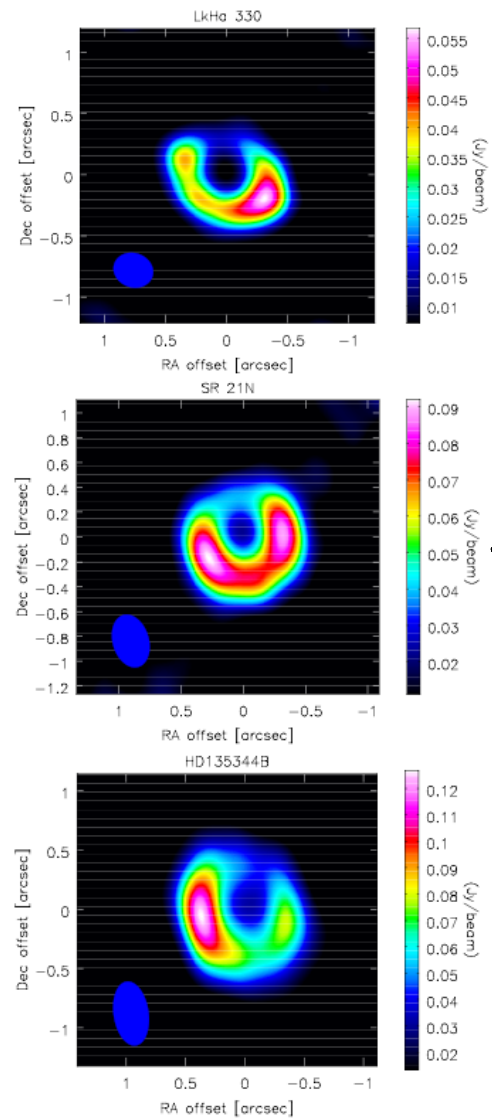
Lambrechts & Johansen (2012)

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

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

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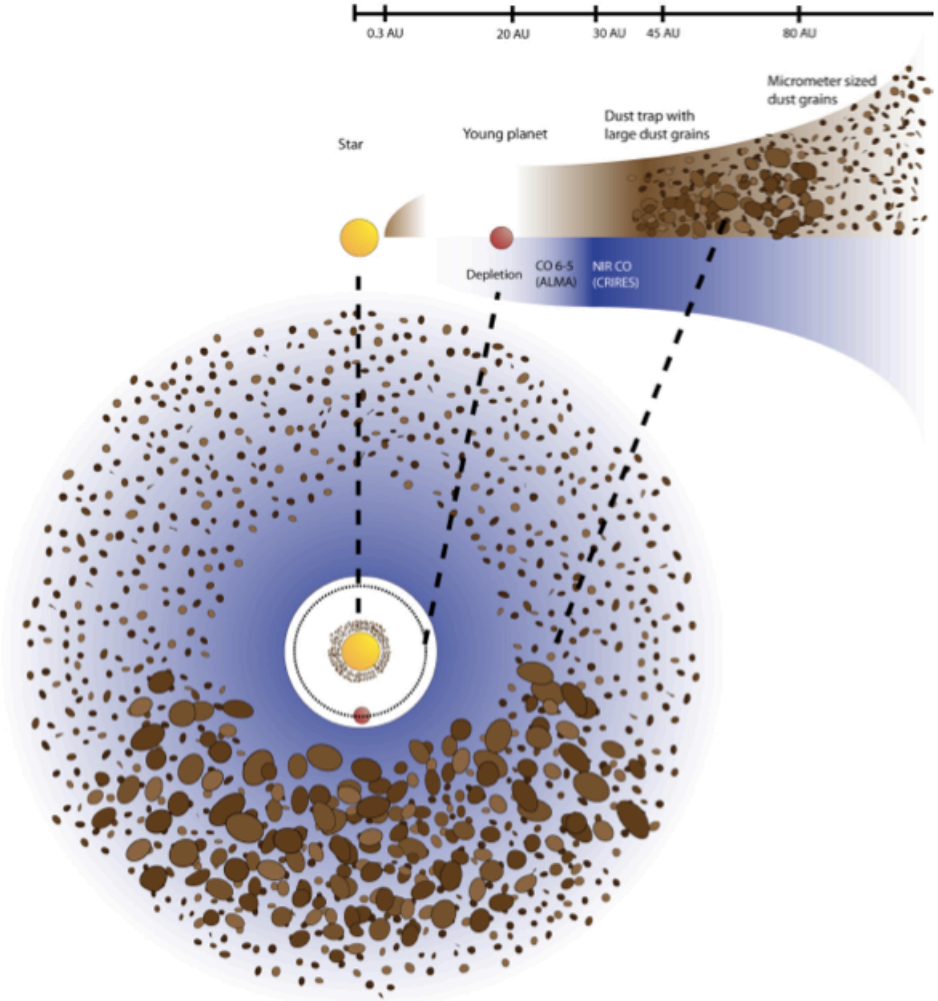
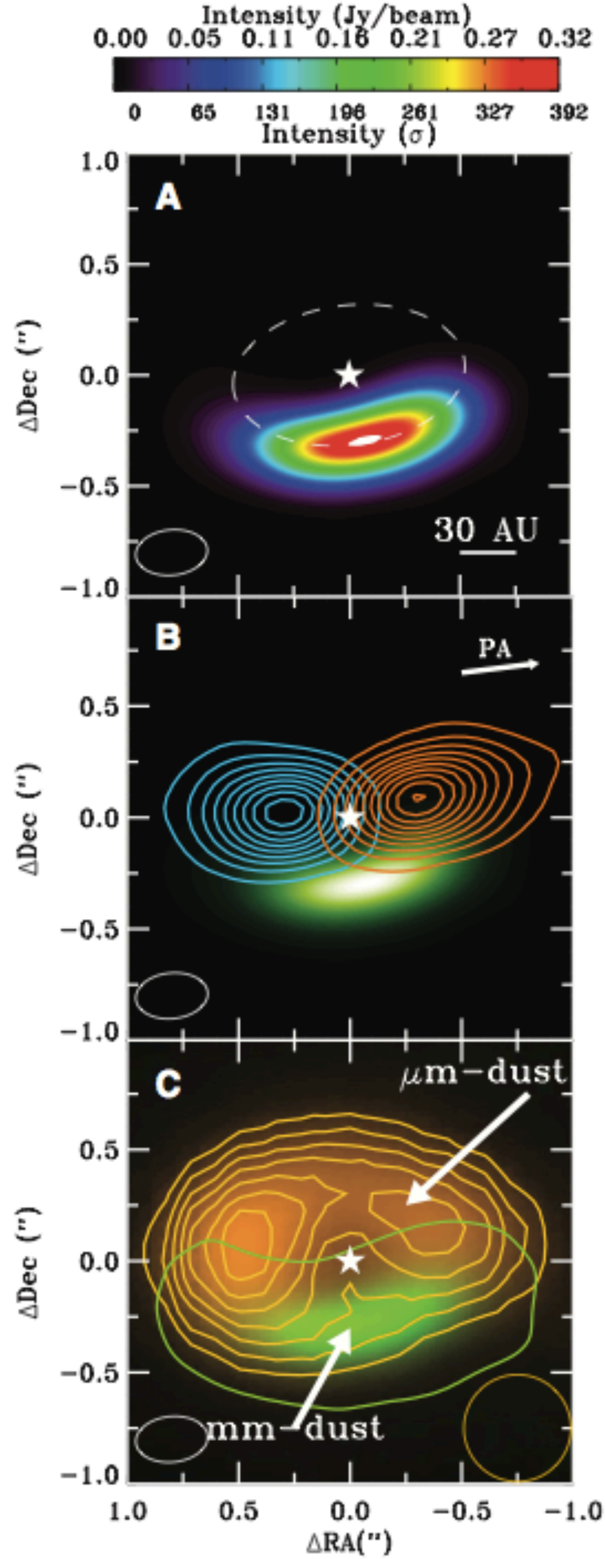
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

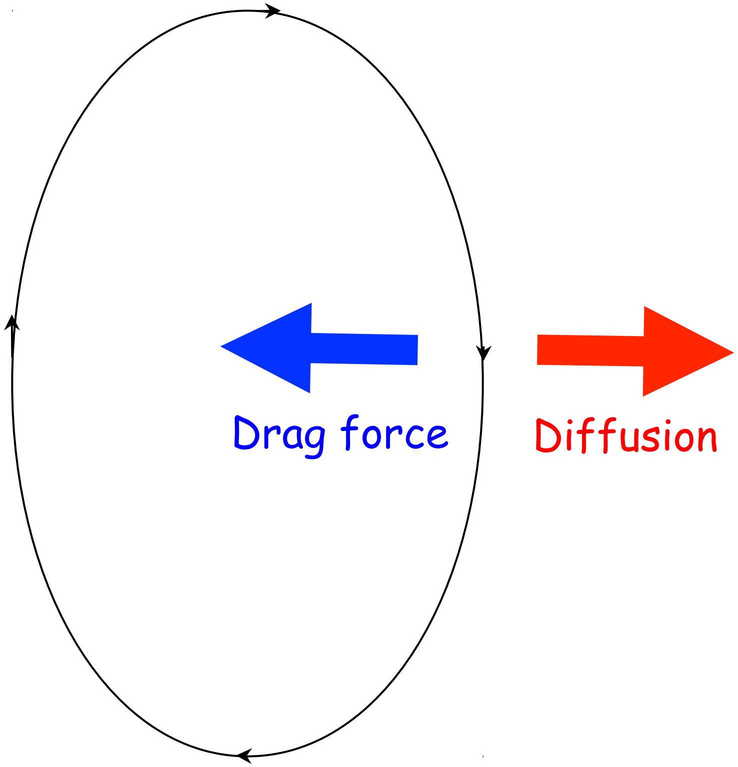


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

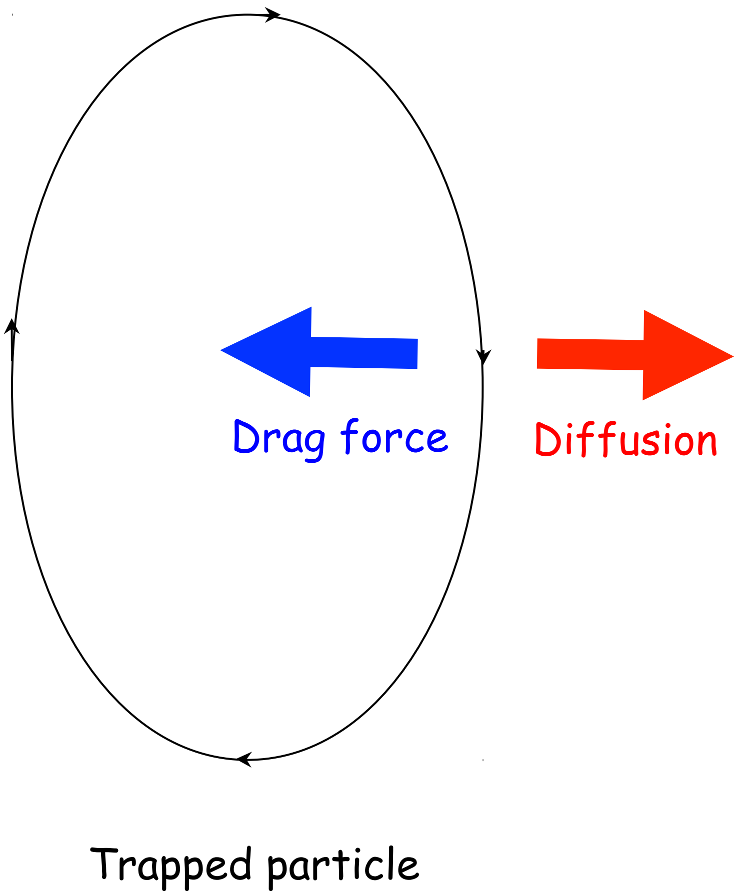
Micron-sized dust follows gas

Drag-Diffusion Equilibrium



Trapped particle

Drag-Diffusion Equilibrium



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

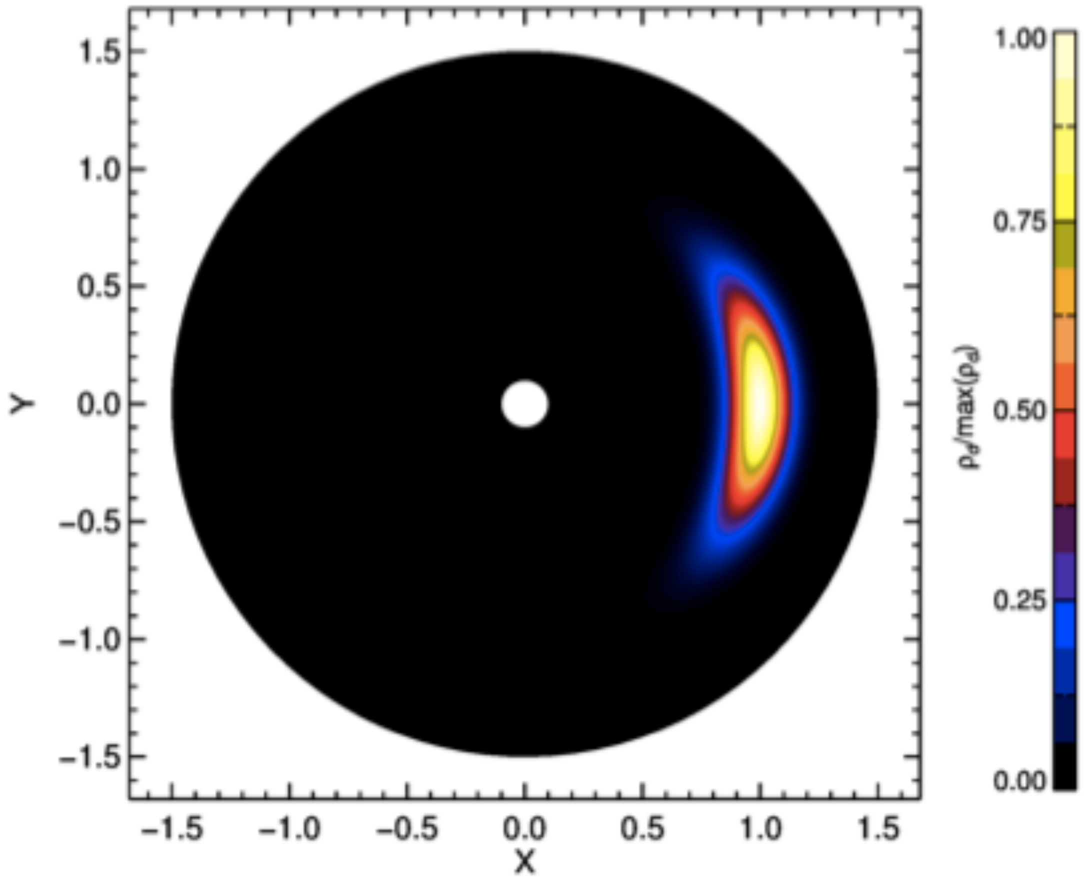
Lyra & Lin (2013)

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

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

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

Analytical solution for dust trapping



Solution

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

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

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

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

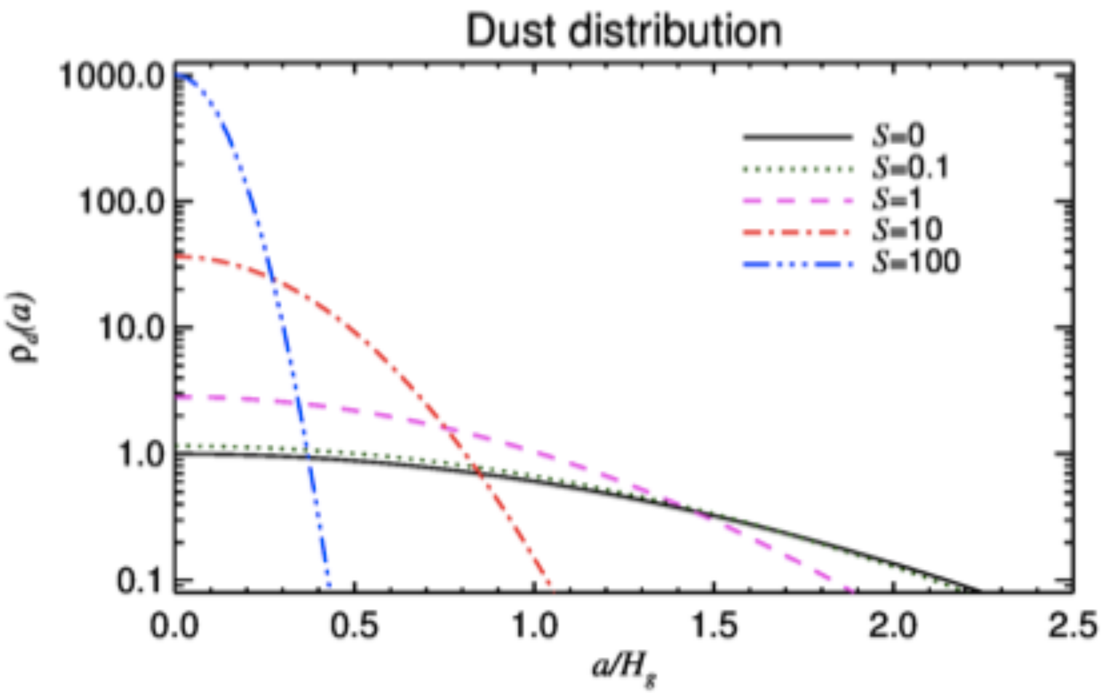
a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

Solution for

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

Lyra & Lin (2013)

Analytical solution for dust trapping

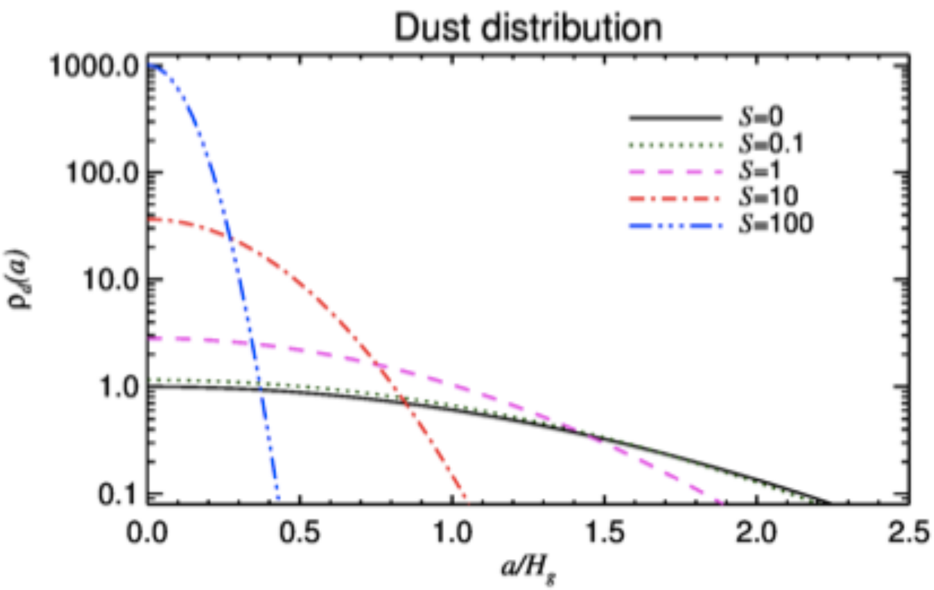


$$S = \frac{St}{\delta}$$

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

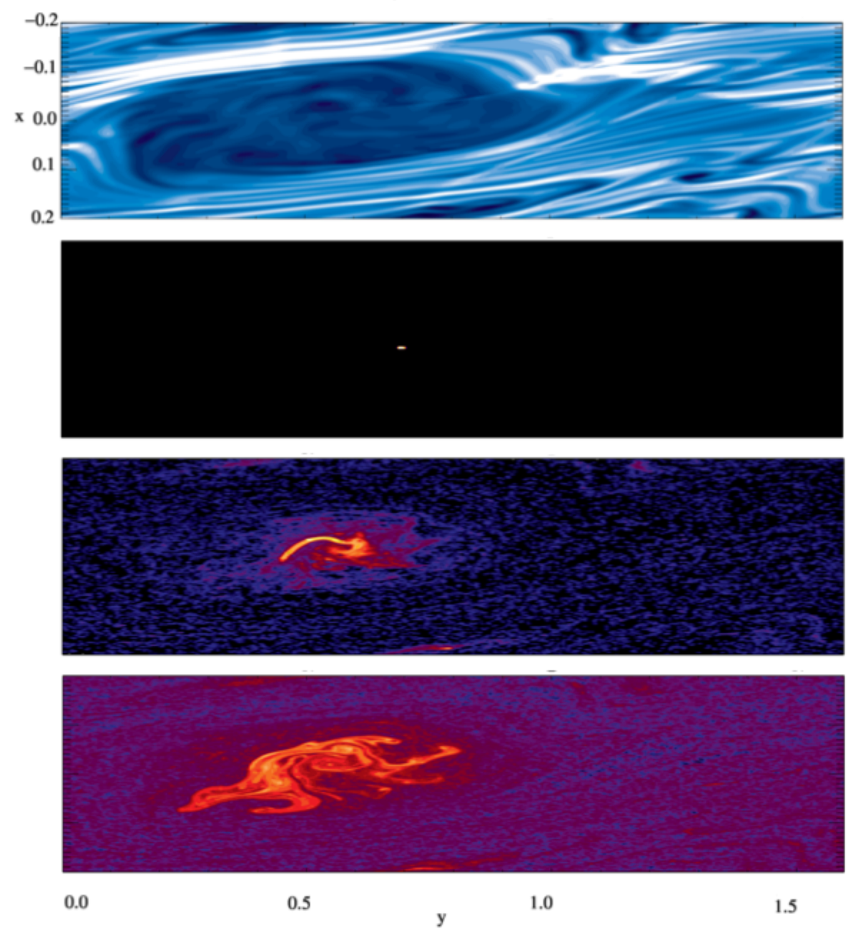
Lyra & Lin (2013)

Analytical vs Numerical



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

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



Gas

St=1

St=0.05

St=0.01

Derived quantities

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

Lyra & Lin (2013)

Gas distribution

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

Maximum dust density

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

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)	St = Stokes number (particle size)
χ = vortex aspect ratio	$f(\chi)$ = model-dependent scale function
δ = diffusion parameter	ε = dust-to-gas ratio

Applying the model to Oph IRS 48

Observed parameters

Aspect ratio: 3.1

Dust contrast: 130

Temperature: 60K

Trapped mass: 9 M_{Earth}

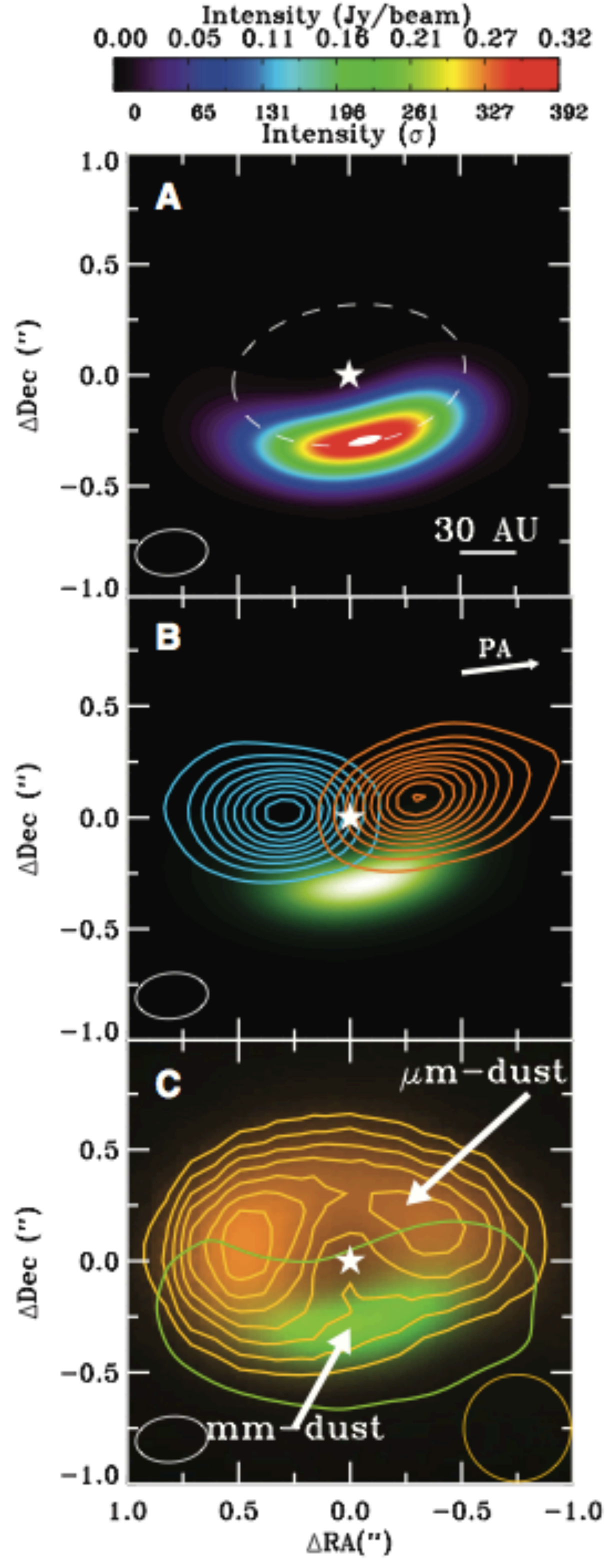
Derived parameters

S=4.8

Stokes number, St=0.008

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

Trapped mass: 11 M_{Earth}



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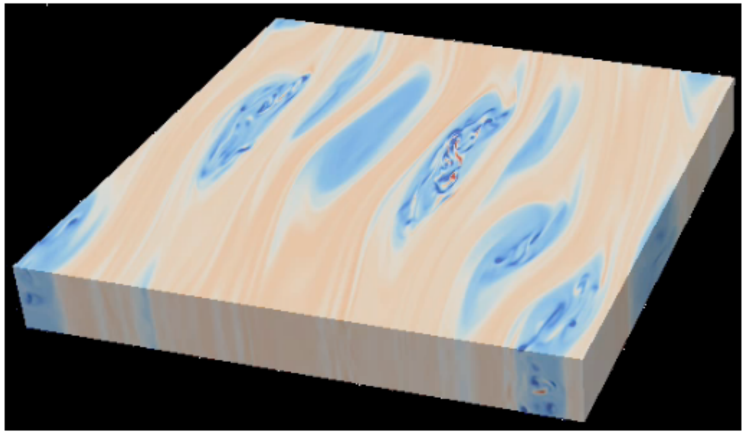
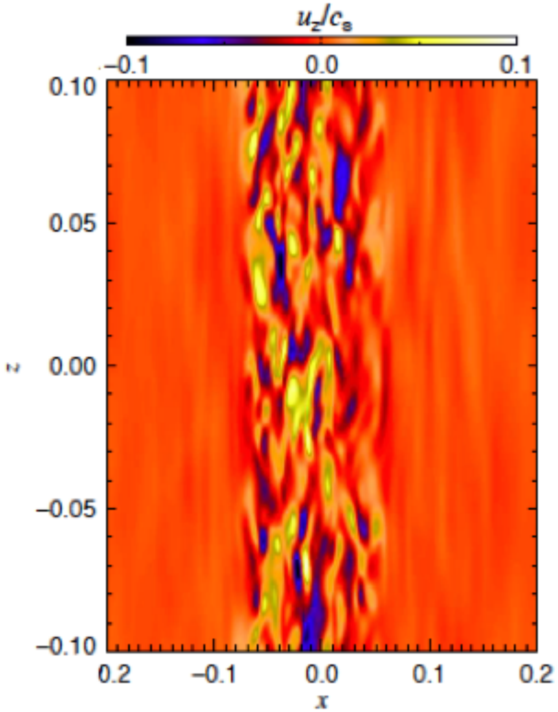
Lyra & Lin (2013)

Turbulence in vortex cores



Lesur & Papaloizou (2010)



Lyra & Klahr (2011)

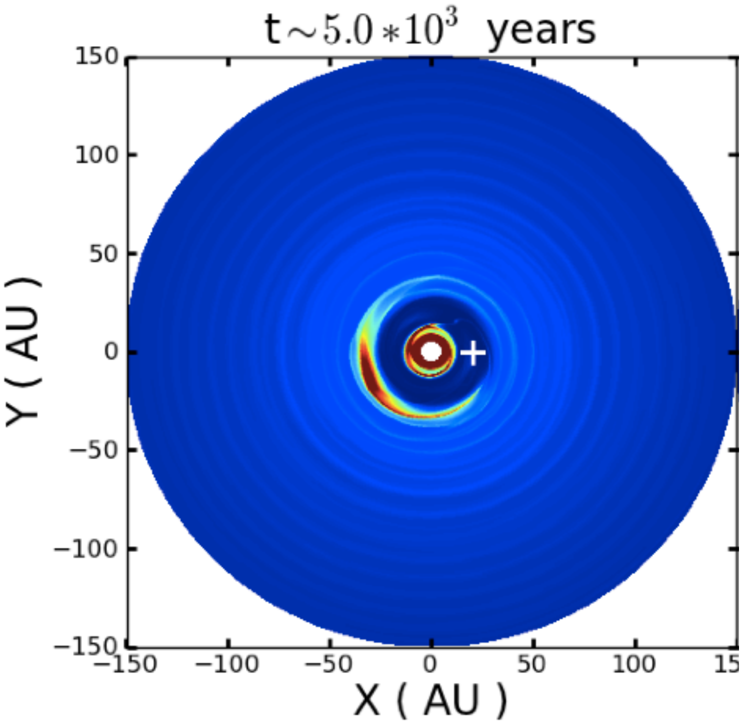
Turbulence in vortex cores:

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

It seems to have the properties
of vortices.

But… is it really a vortex?

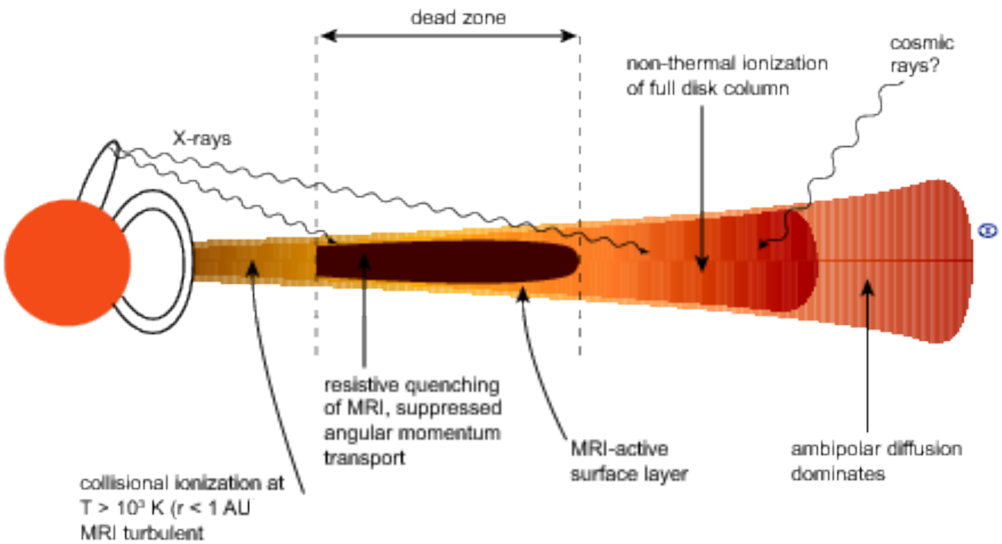
The dust trap is too far from the planet!



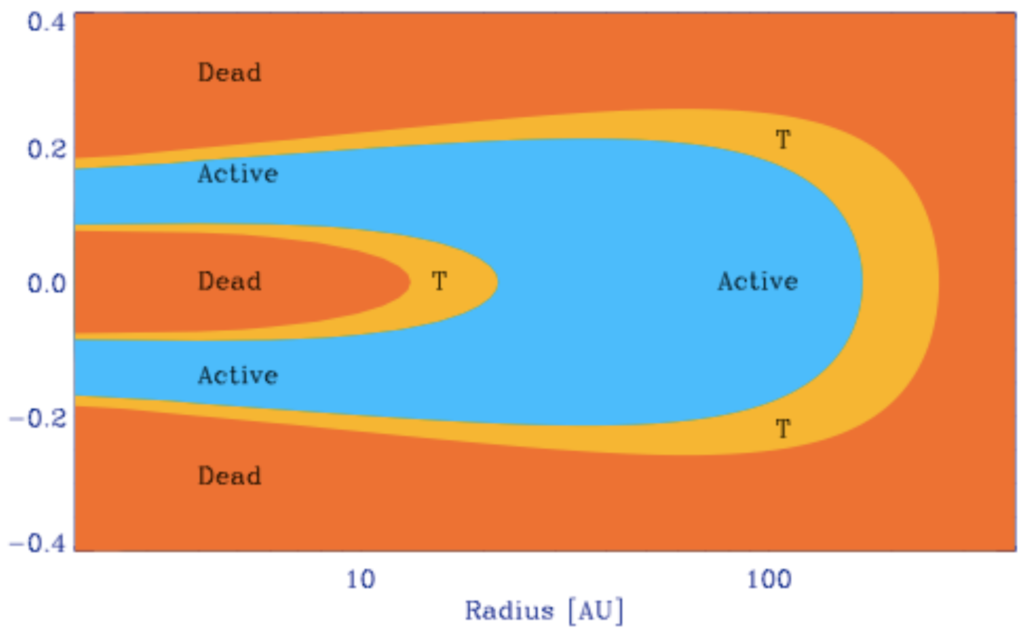
A gap in gas emission suggests a 10 MJ planet at **15-20 AU**.

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

Dead zone RWI fails!



Armitage (2010)



Dzyurkevitch et al (2013)

The **outer** dead zone transition in ionization is

TOO SMOOTH

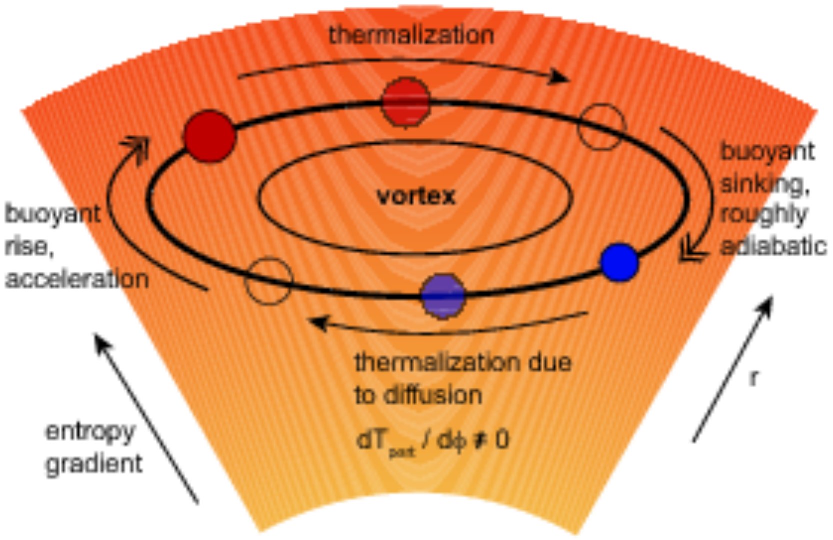
to generate an RWI-unstable bump.

Baroclinic instability

1. Radial entropy gradient

2. Thermal diffusion

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

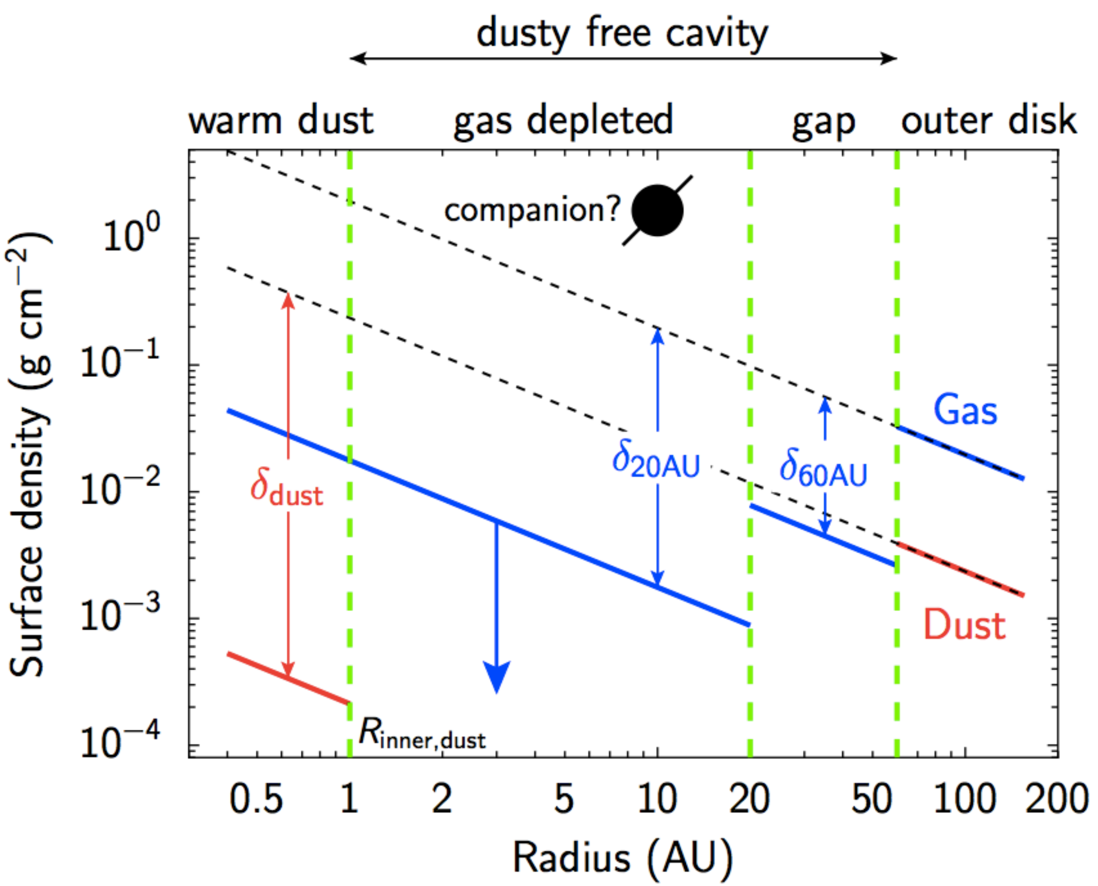


The thermal diffusion time
for the gas in IRS Oph 48 is
0.1 orbits.

Too close to isothermal for the baroclinic instability.

Addendum

The dust trap WAS too far from the planet!



New analysis (Bruderer et al. 2014)
better explains the system,
with a shallow gap at 60 AU,
consistent with a (~x) Neptune-mass planet.

HD 142527

Observed parameters

Aspect ratio: 10

Dust contrast: 30

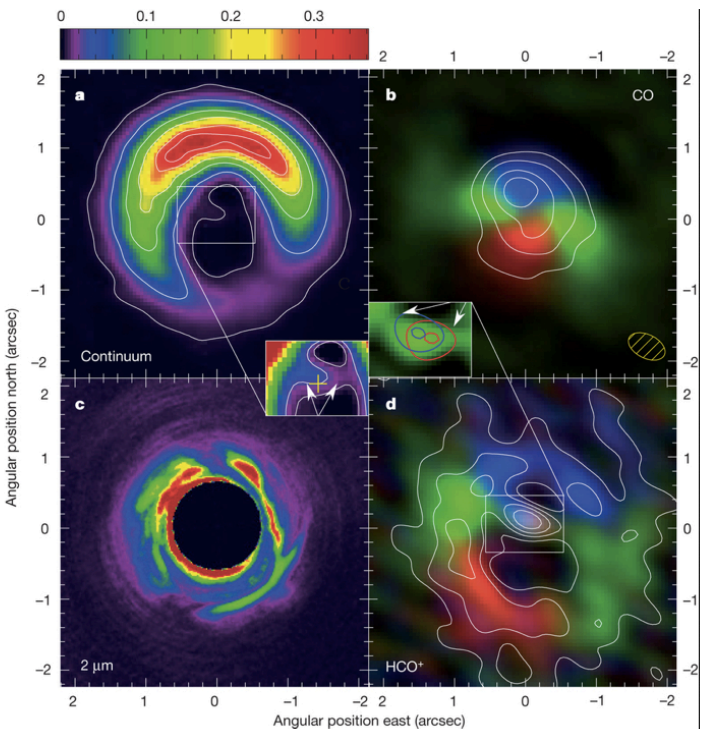
Temperature: 25K

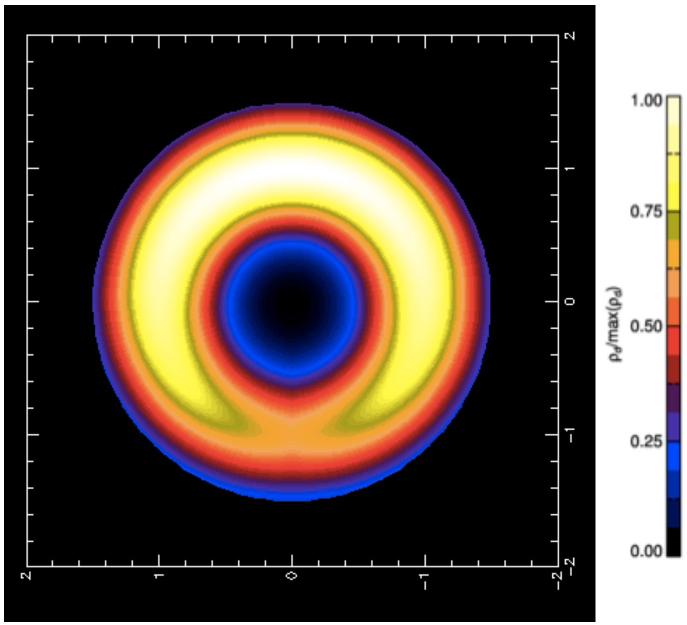
Derived parameters

S=3.5

Stokes number, St=0.004

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





Conclusions

We're in the era of observational testing/confirmation of our model predictions!!