The vortex mode of planet formation

Wladimir (Wlad) Lyra
Sagan Fellow

Caltech - JPL

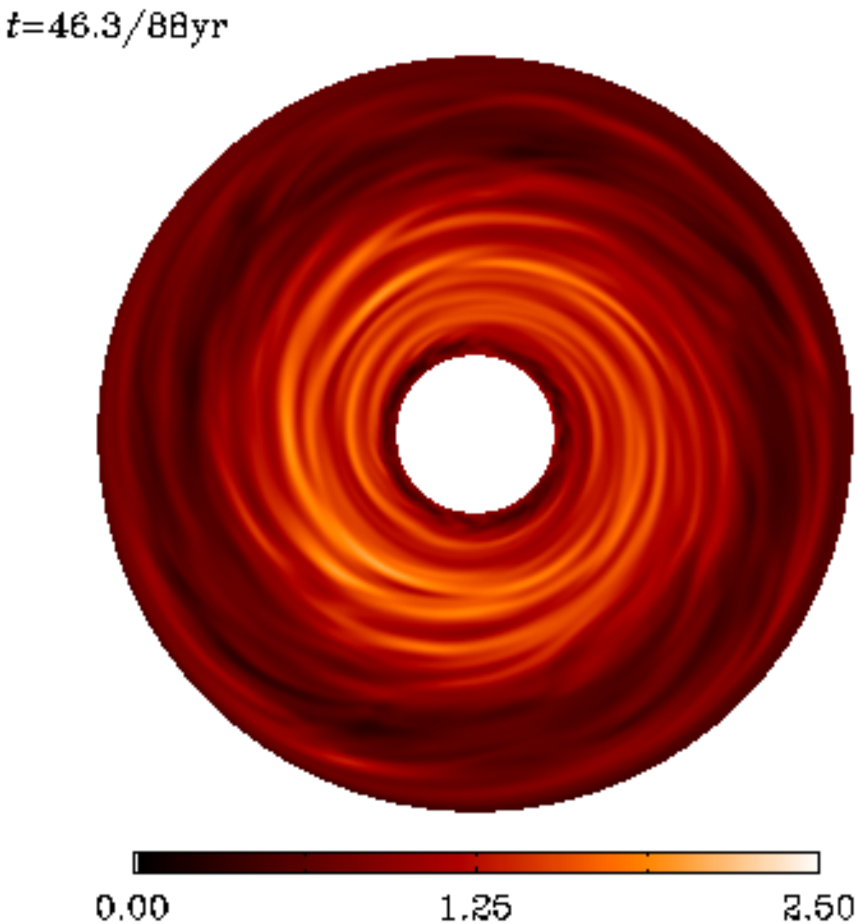
BAY AREA EXOPLANET MEETING #9 – SETI Institute, June 2014

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).

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability

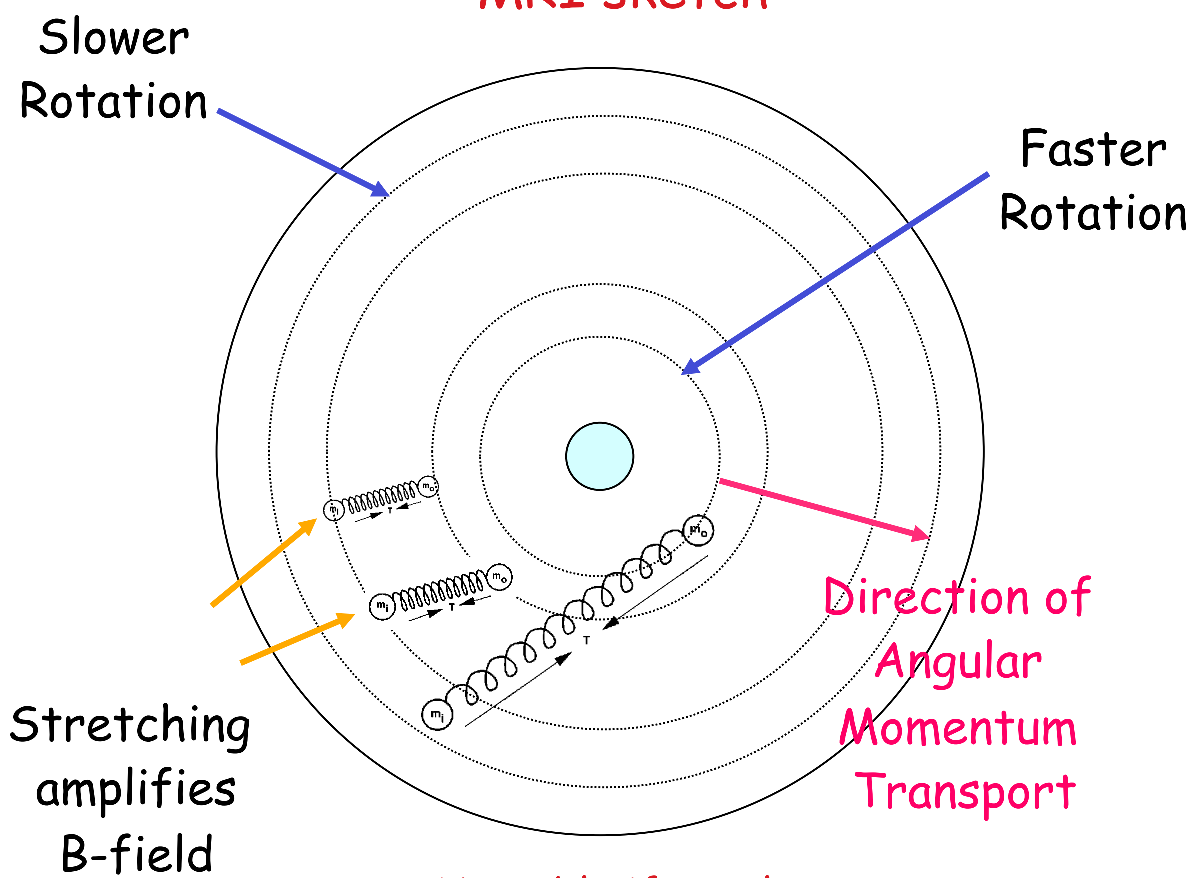
Balbus & Hawley (1991)



Magnetized disk

Lyra et al. (2008a)

MRI sketch

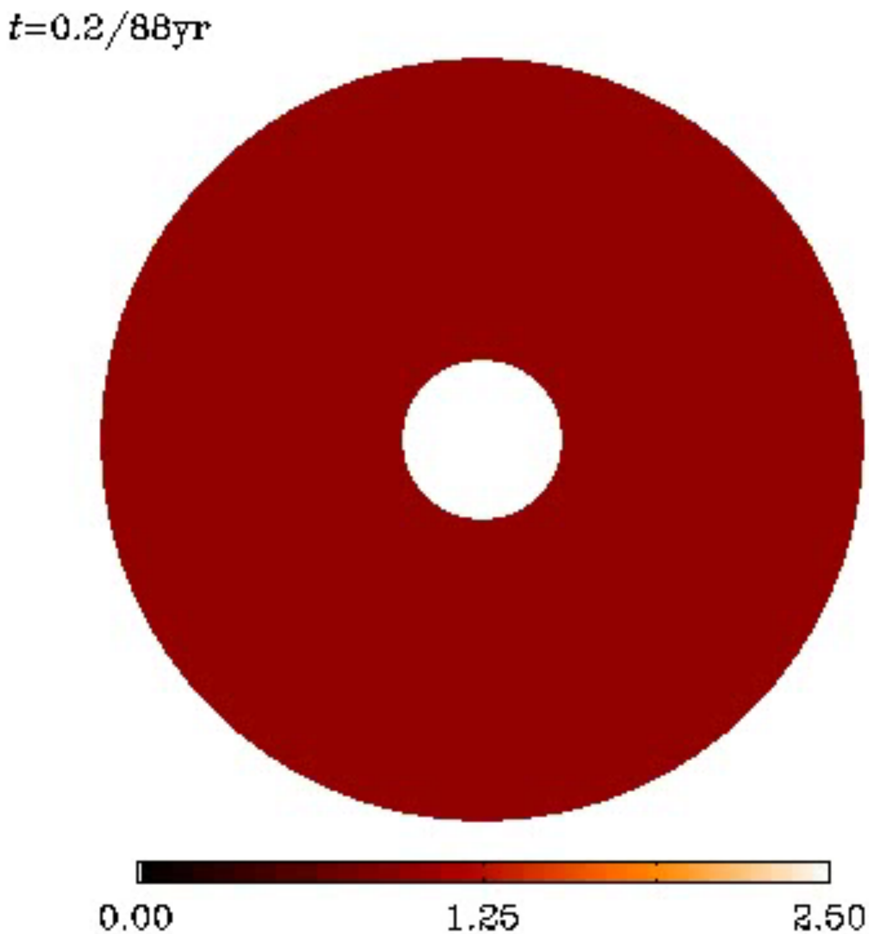


Unstable if angular velocity decreases outward

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability

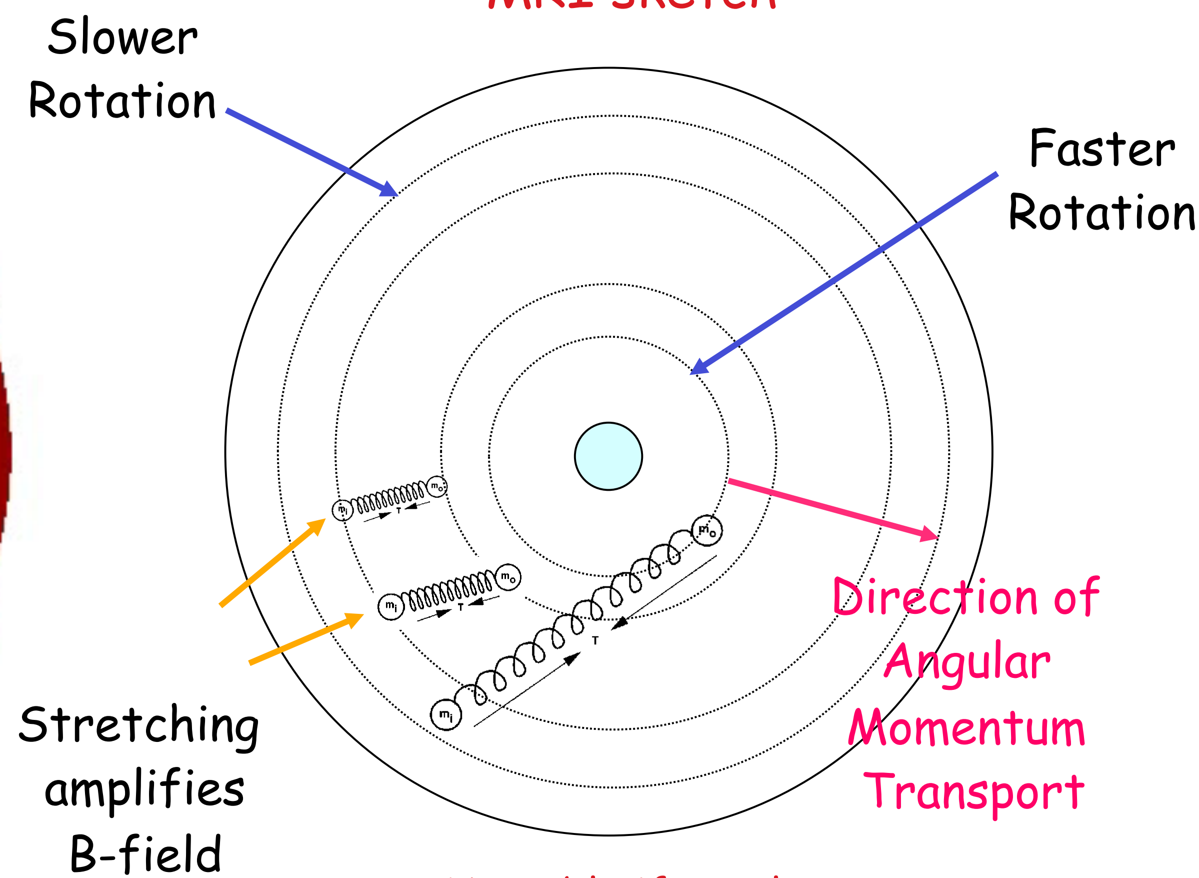
Balbus & Hawley (1991)



Magnetized disk

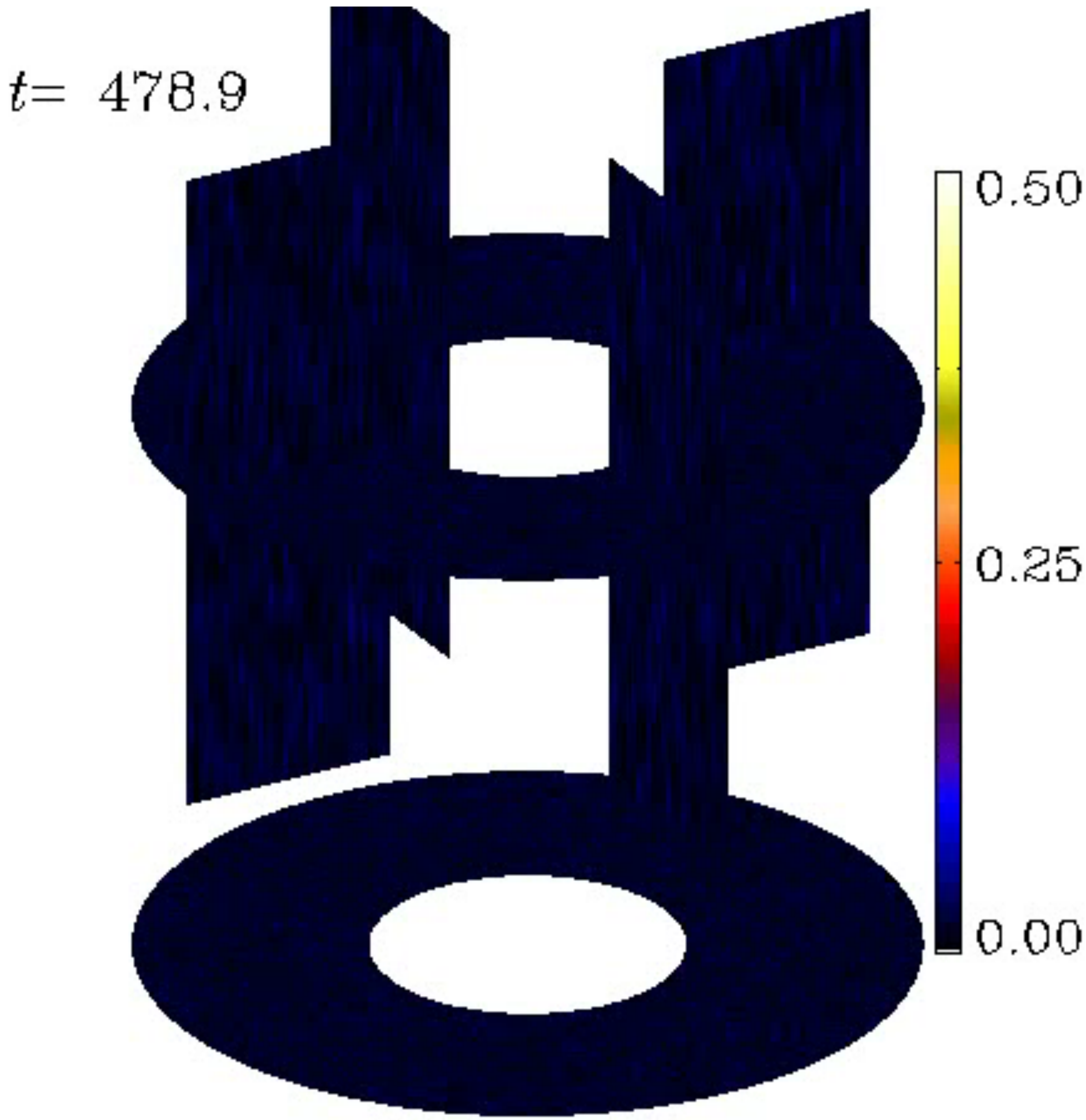
Lyra et al. (2008a)

MRI sketch



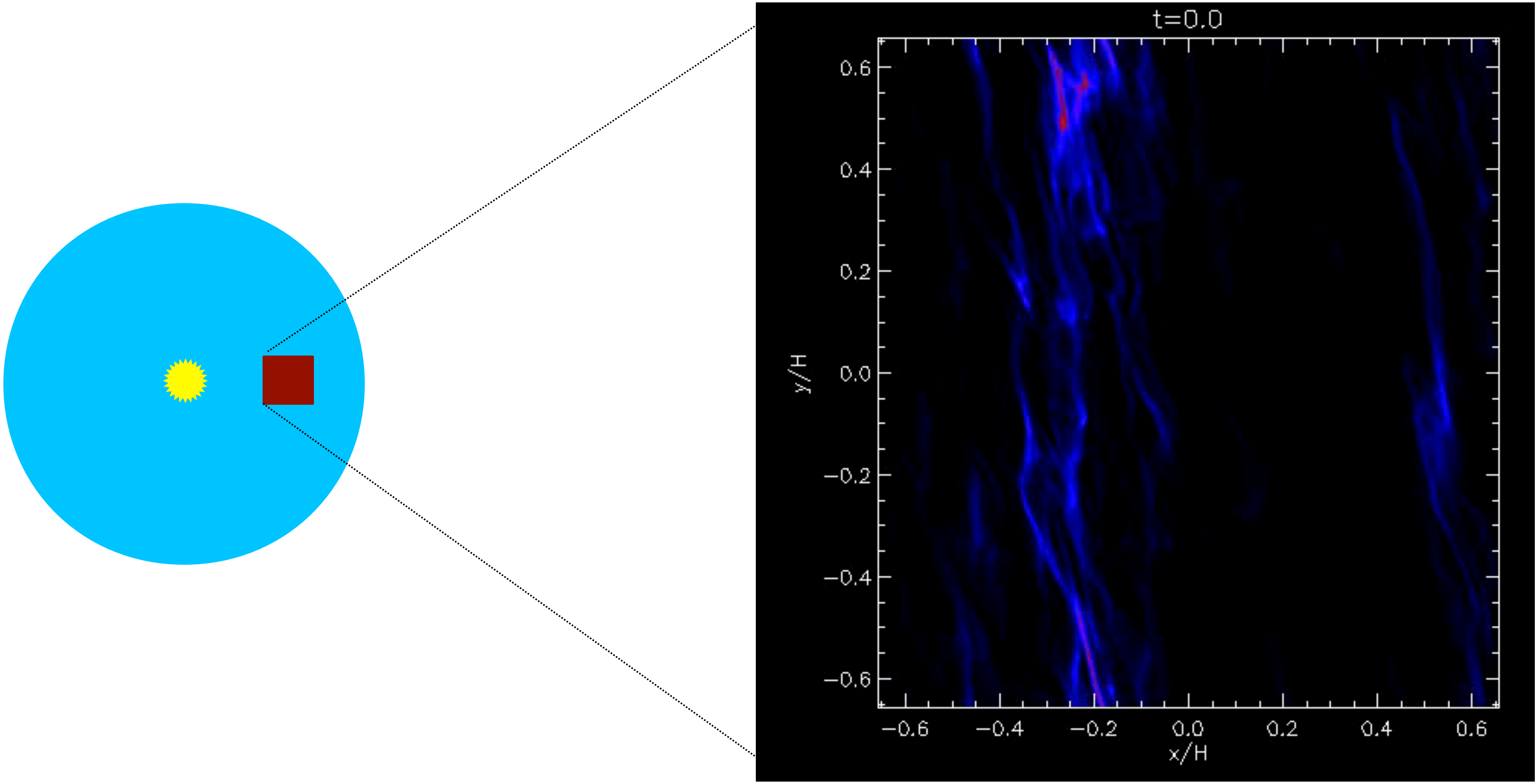
Unstable if angular velocity decreases outward

Turbulence concentrates solids mechanically in pressure maxima



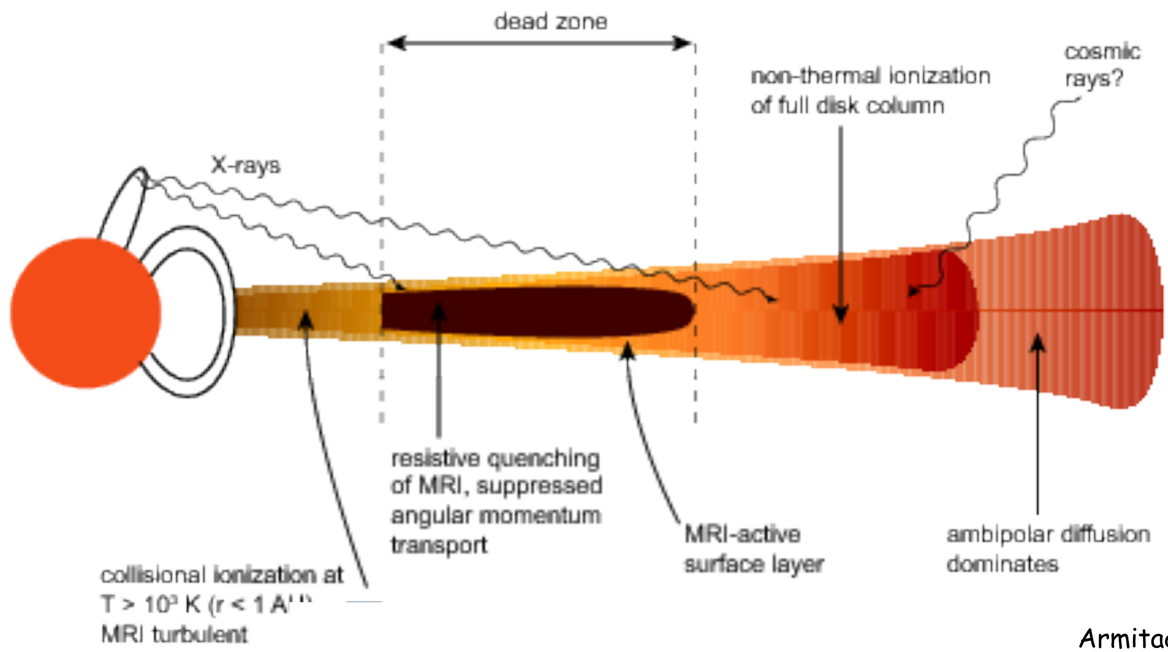
Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

Dead zones are robust features of accretion disks



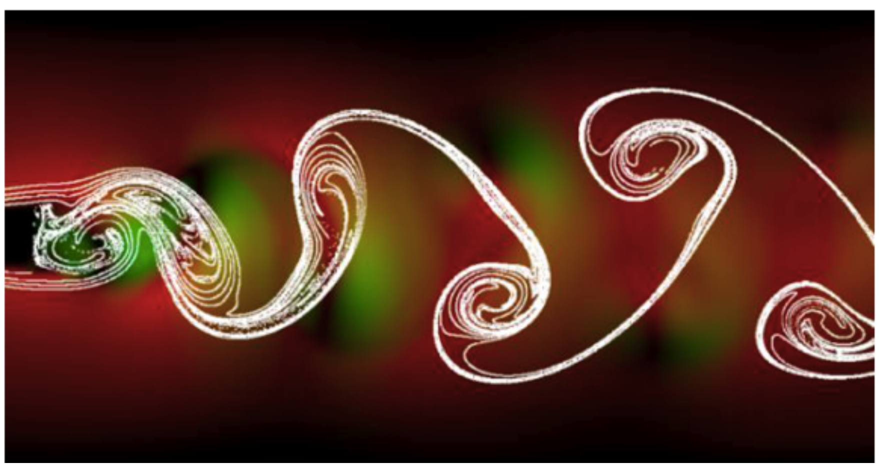
Armitage (2010)

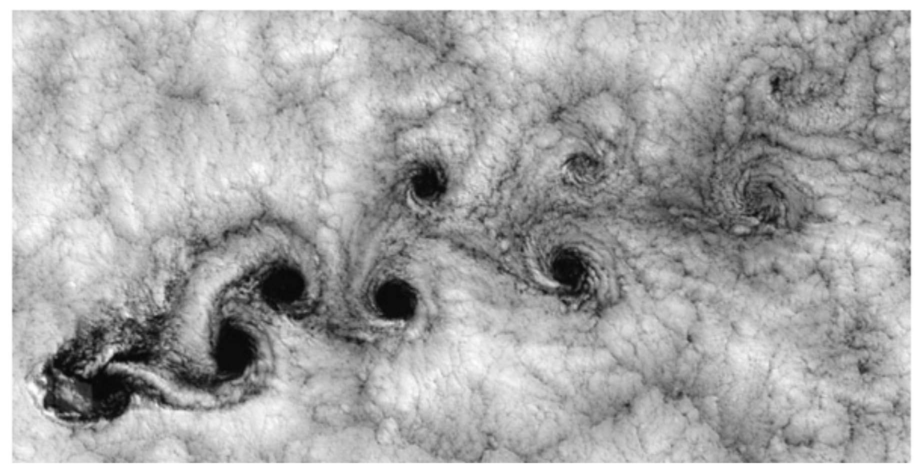
Disks are cold and thus poorly ionized
(Blaes & Balbus 1994)

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

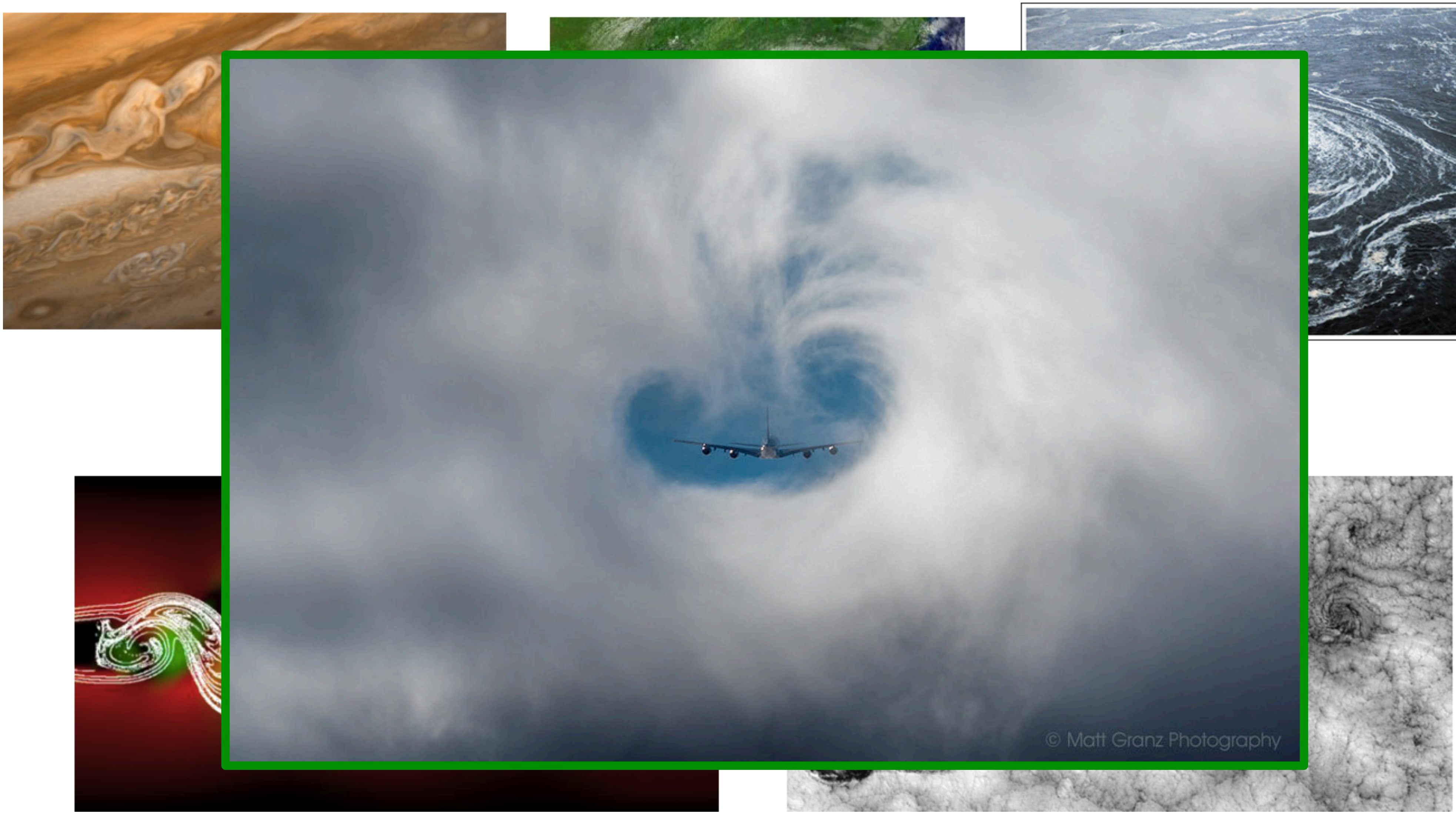
There should be a **magnetized, active zone**,
and a **non-magnetic, dead zone.**

Vortices – An ubiquitous fluid mechanics phenomenon





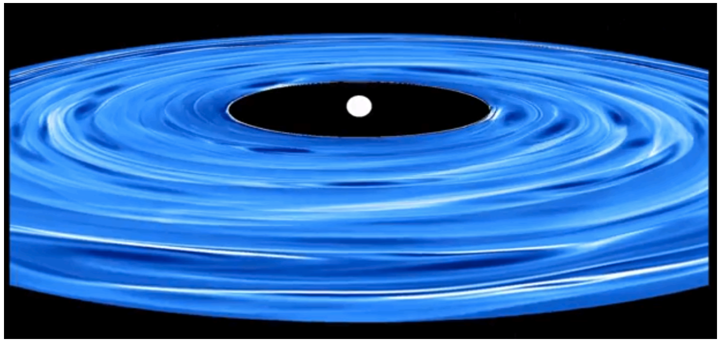
Vortices – An ubiquitous fluid mechanics phenomenon



Sustaining vortices in disks

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

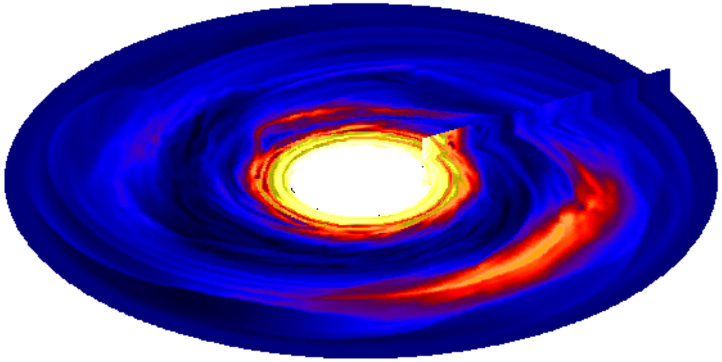
Baroclinic instability



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

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

Rossby wave instability

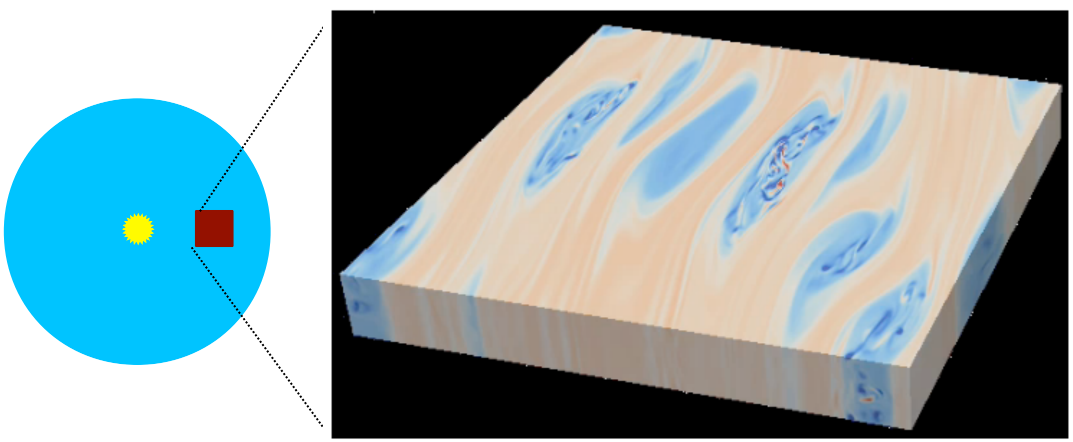


Lovelace et al. (1999)
Lyra et al. (2008b,2009ab)
Lyra & Mac Low (2012)

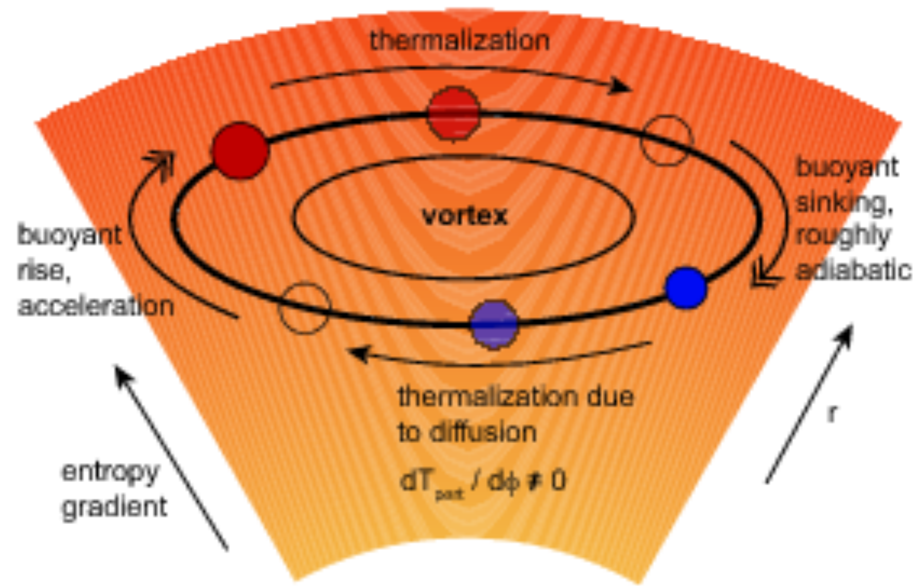
Powered by:
Modification of shear profile
(external vorticity reservoir)

Baroclinic Instability – Excitation and self-sustenance of vortices

Sketch of the
Baroclinic Instability



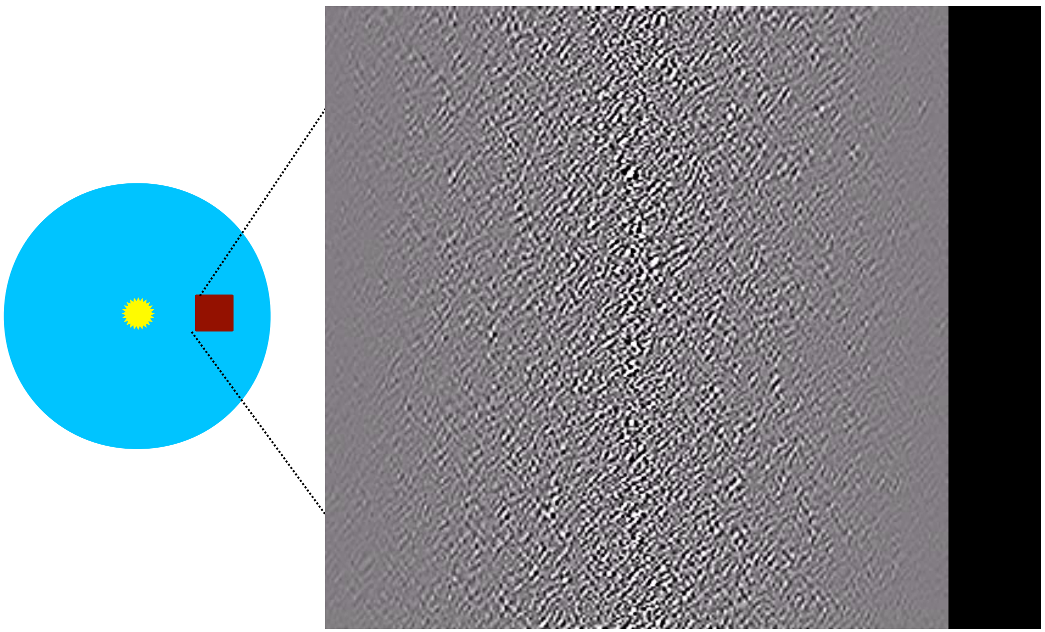
Lesur & Papaloizou (2010)



Armitage (2010)

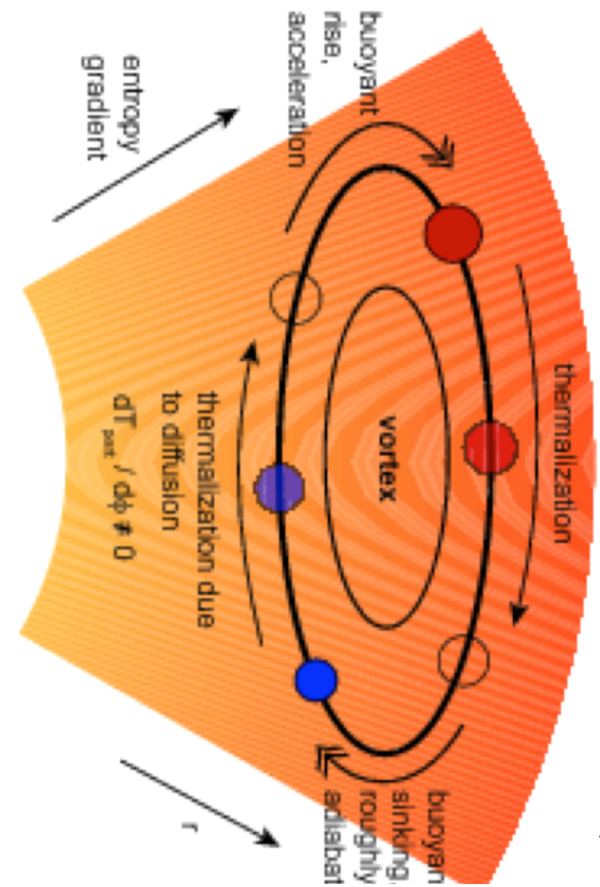
$$\frac{\partial \omega}{\partial t} = \underbrace{-(\boldsymbol{u}\cdot\nabla)\omega}_{\text{advection}} \underbrace{-\omega(\nabla\cdot\boldsymbol{u})}_{\text{compression}} + \underbrace{(\omega\cdot\nabla)\boldsymbol{u}}_{\text{stretching}} + \underbrace{\frac{1}{\rho^2}\nabla\rho\times\nabla p}_{\text{baroclinicity}} + \underbrace{\nu\nabla^2\omega}_{\text{dissipation}}$$

Baroclinic Instability - Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

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

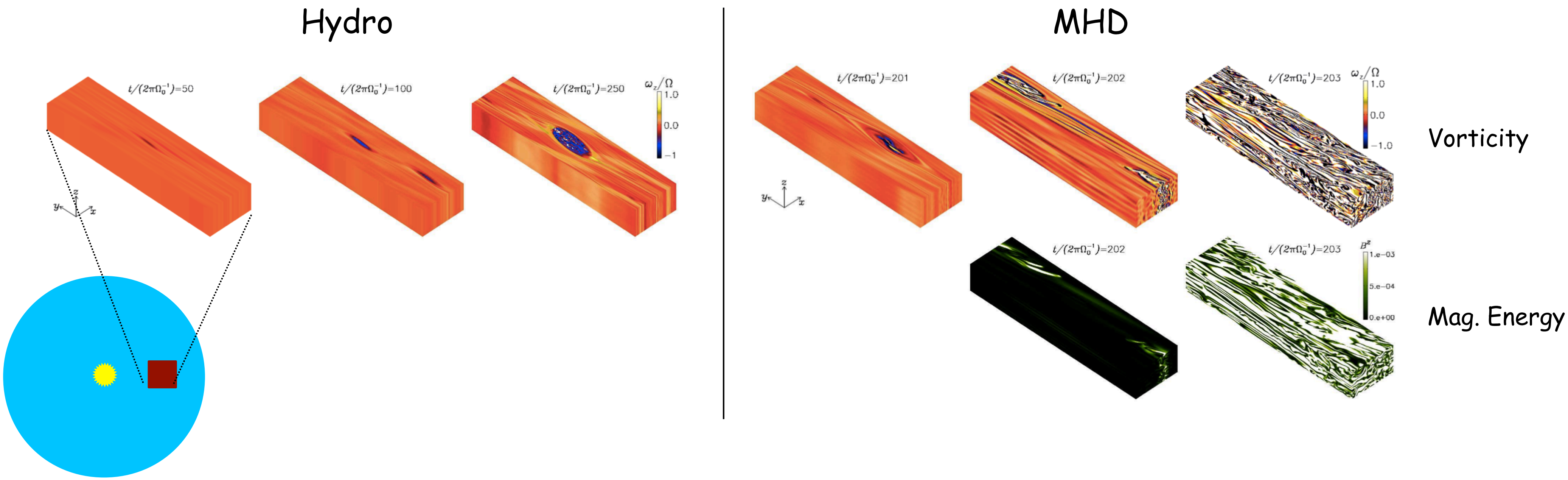
stretching

baroclinicity

dissipation

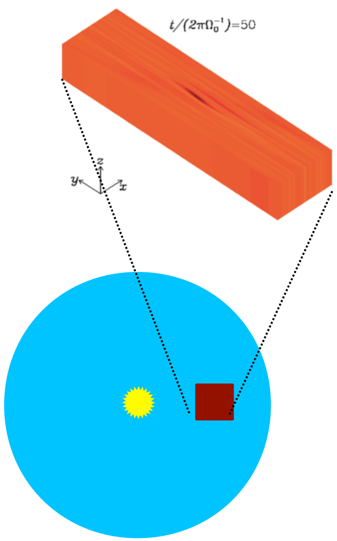
Baroclinic instability and layered accretion

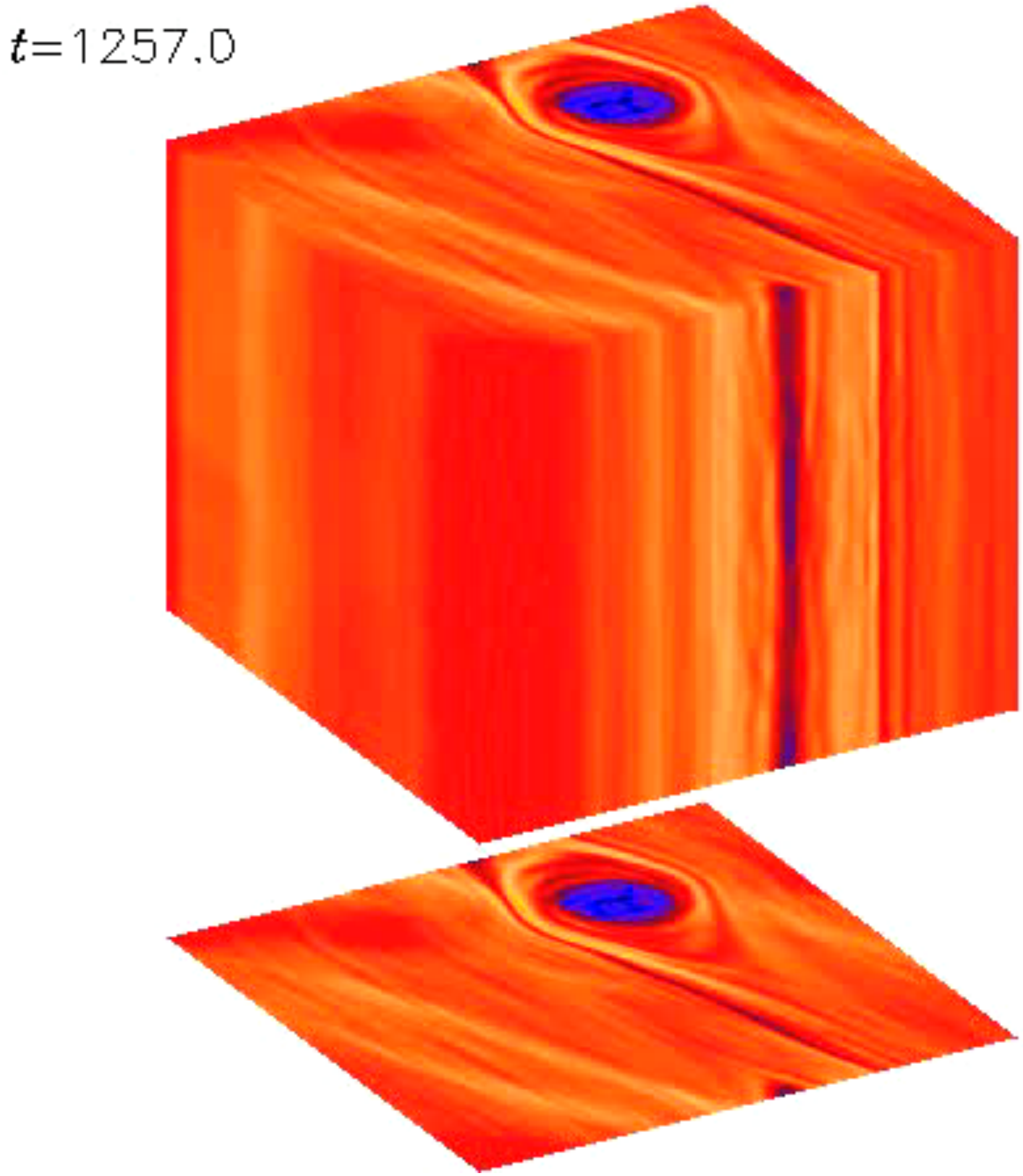
What happens when the vortex is magnetized?

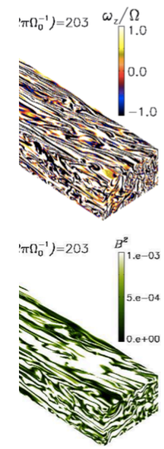


Lyra & Klahr (2011)

Baroclinic instability and layered accretion







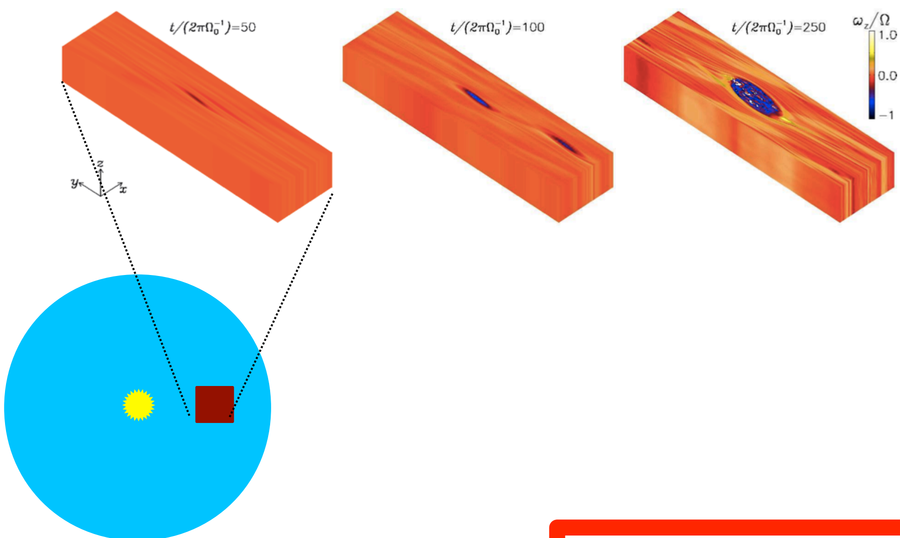
Vorticity

Mag. Energy

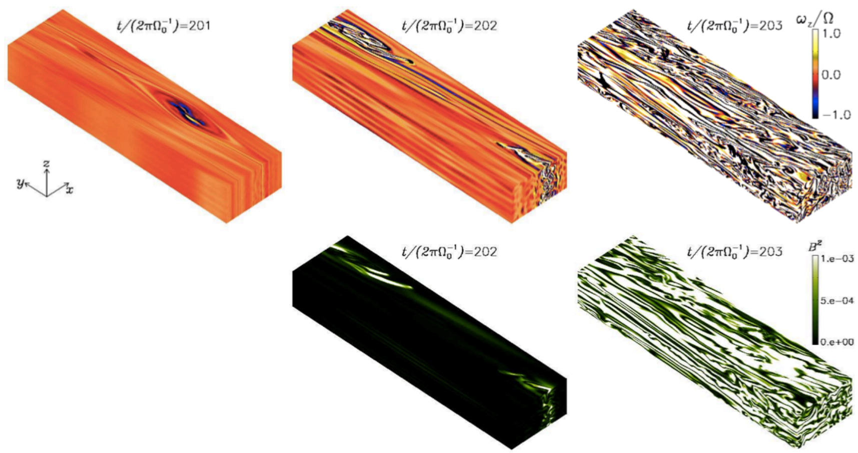
Baroclinic instability and layered accretion

What happens when the vortex is magnetized?

Hydro



MHD



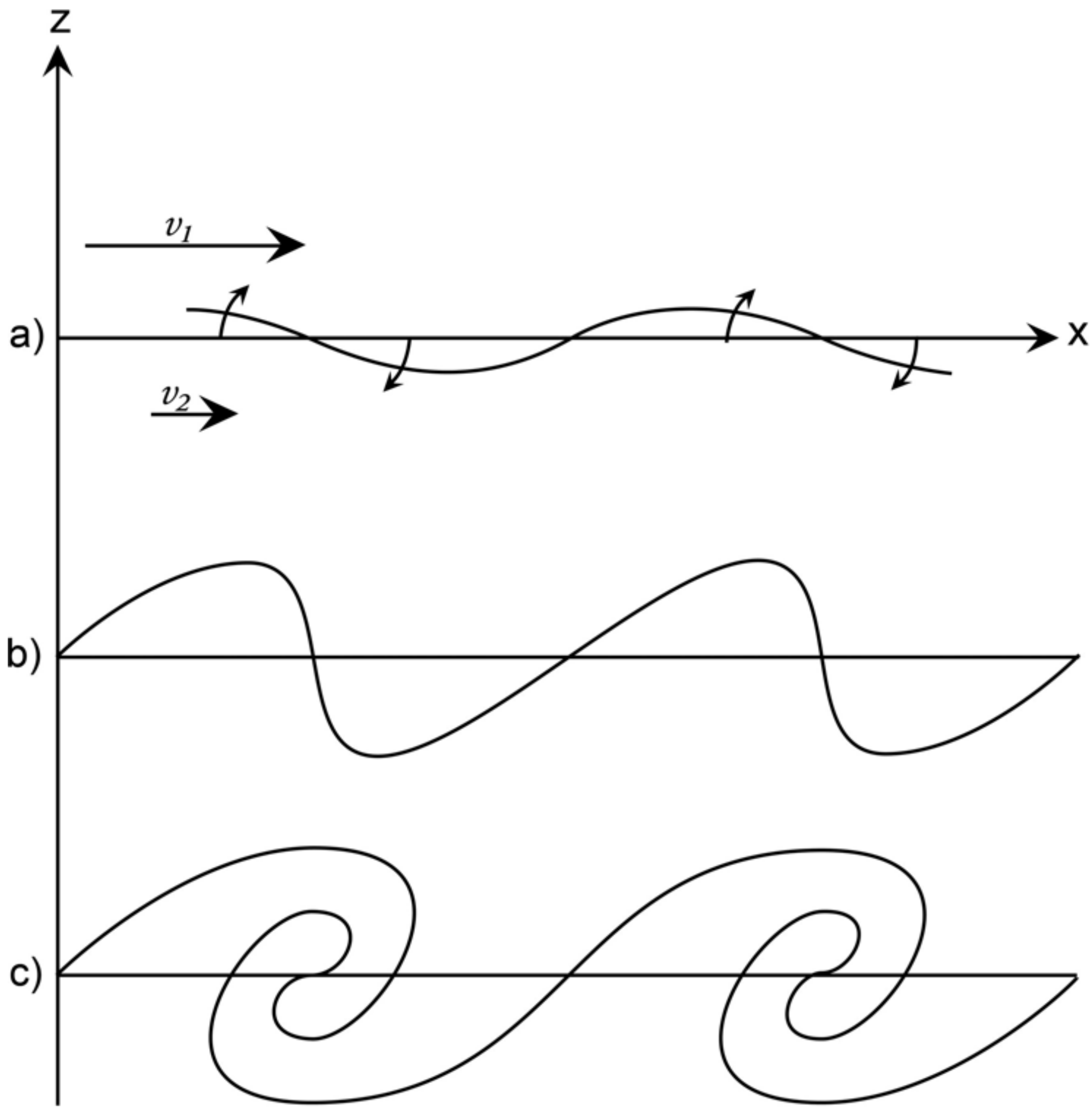
Vorticity

Mag. Energy

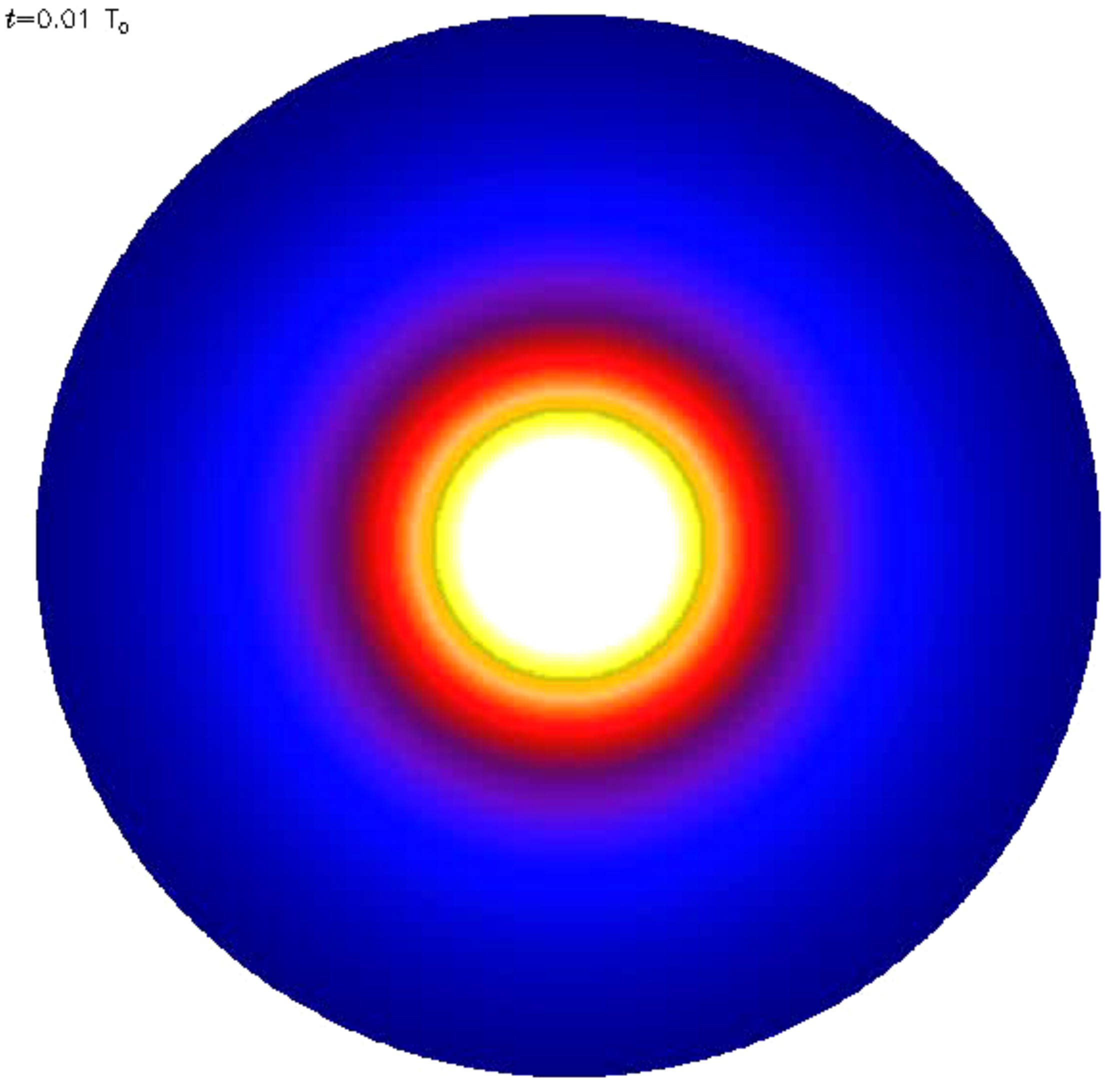
Lyra & Klahr (2011)

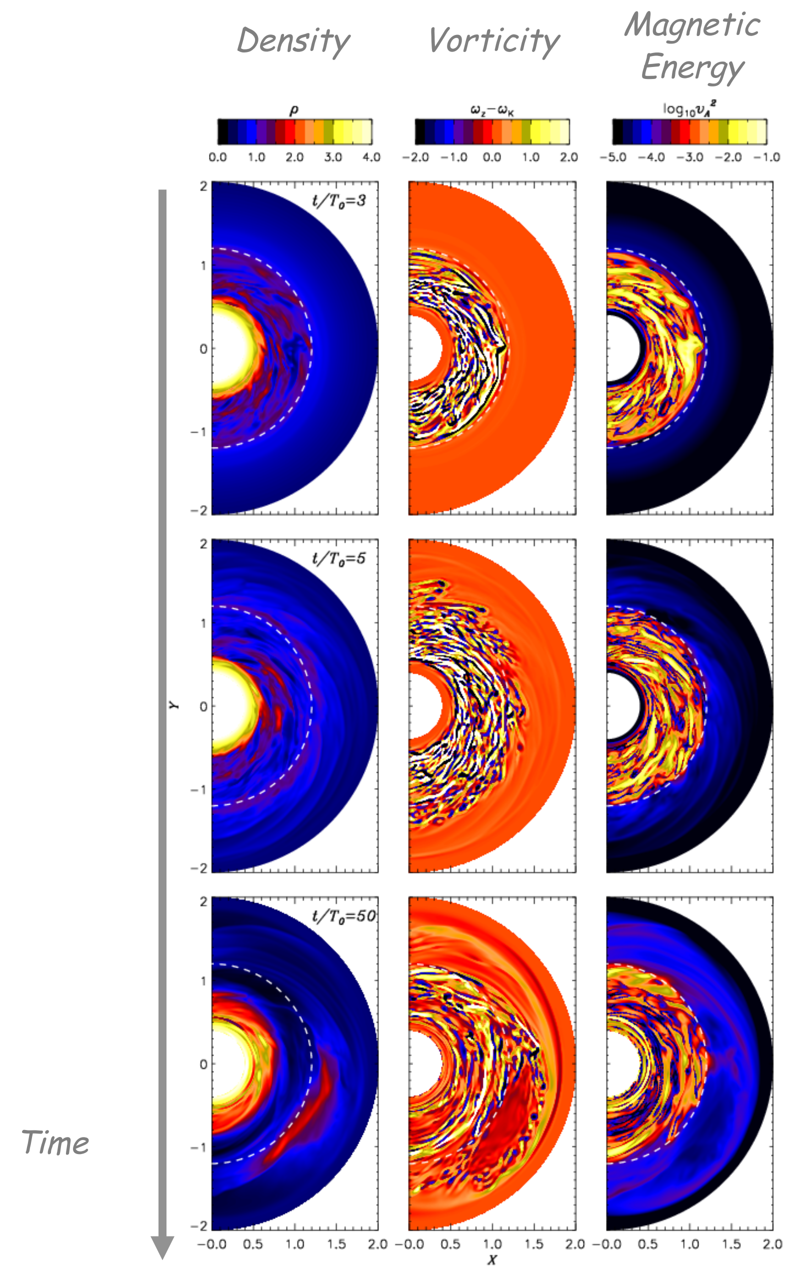
Baroclinic vortices
do ***not*** survive magnetization

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



Active/dead zone boundary





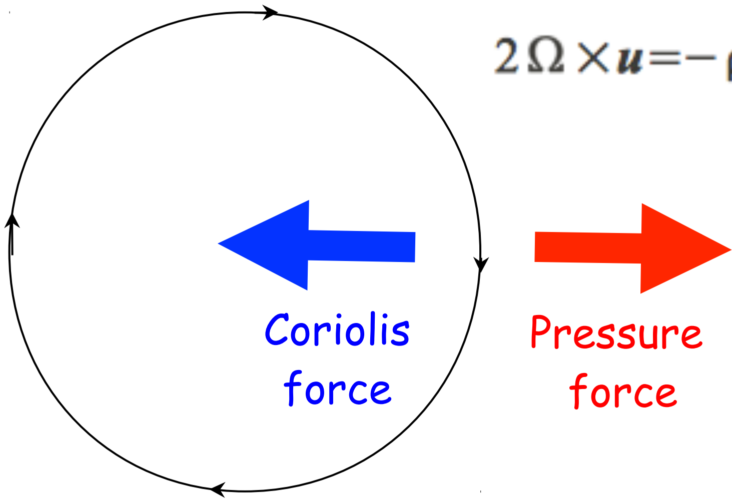
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

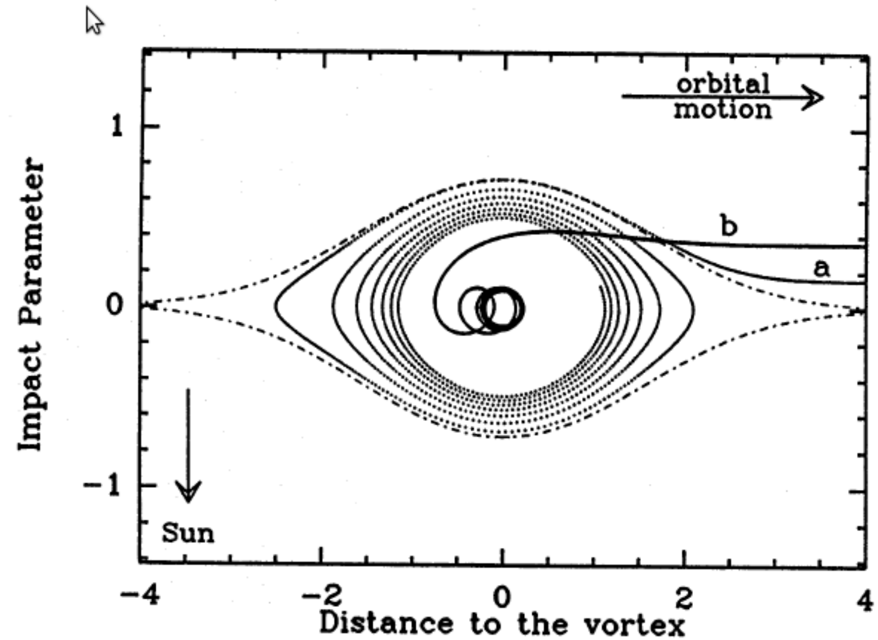
The Tea-Leaf effect

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.

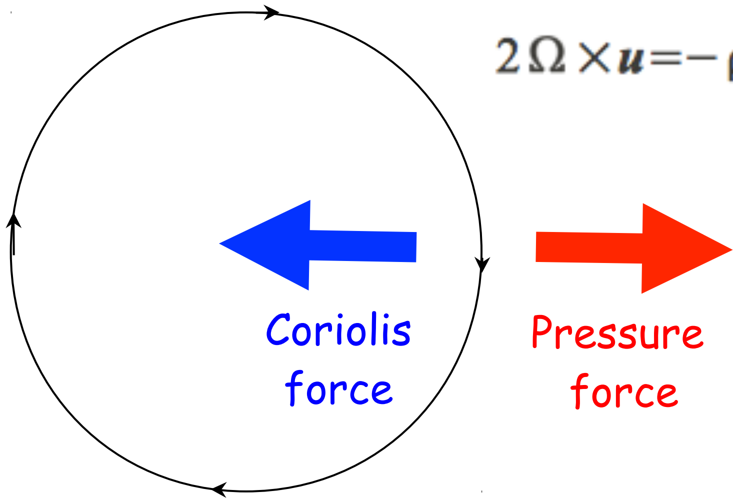
Aid to planet formation (Barge & Sommeria 1995)

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

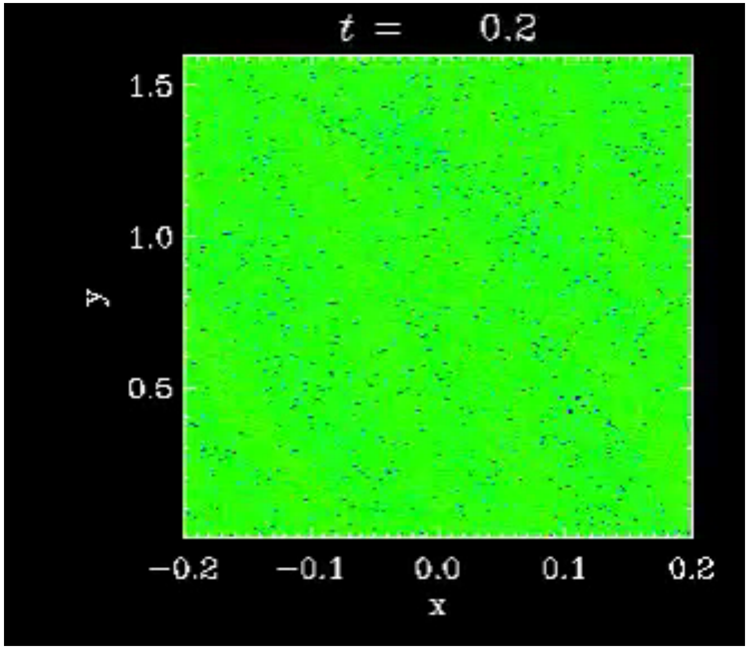
The Tea-Leaf effect

Geostrophic balance:

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



Vortex streamline



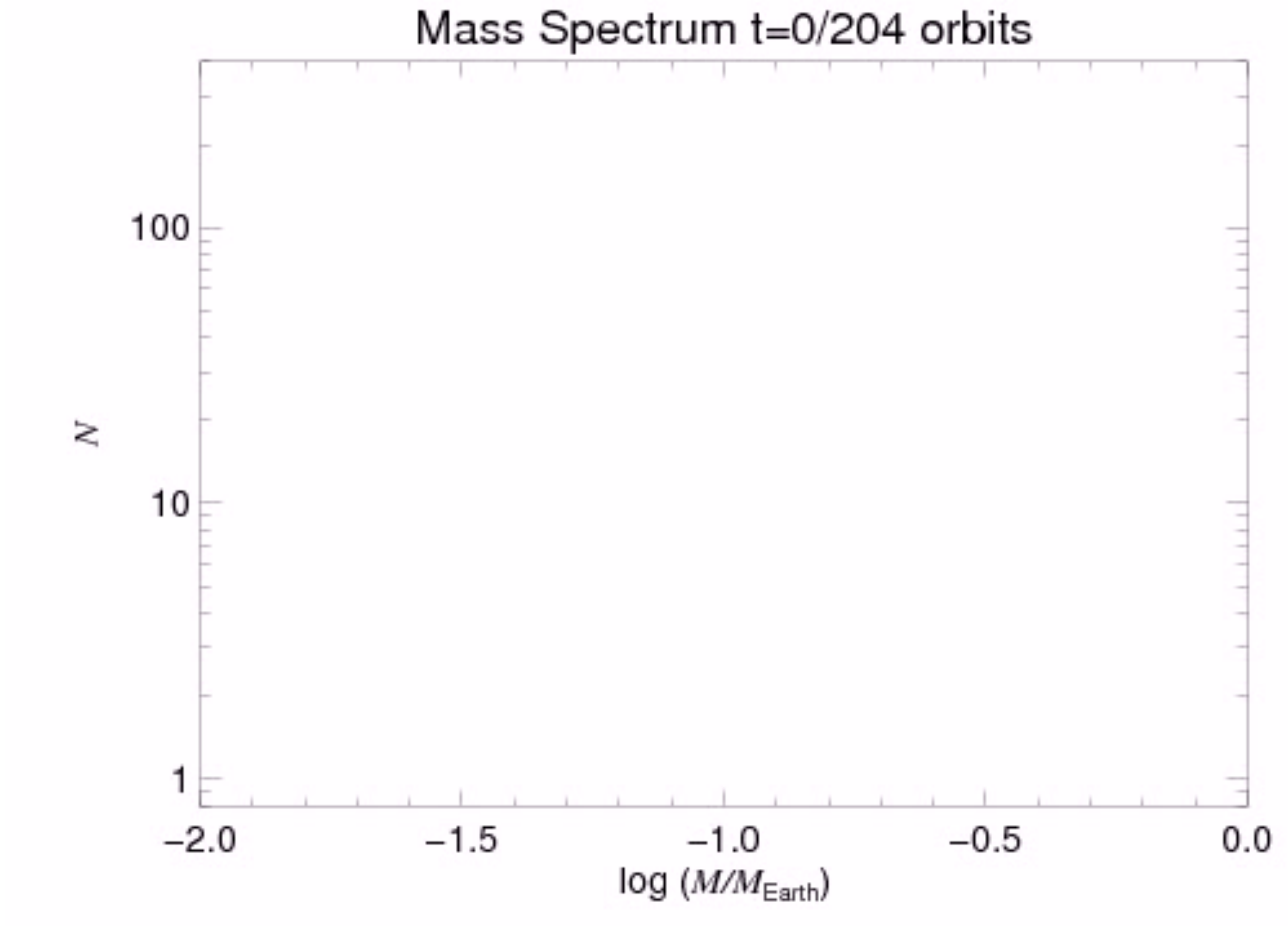
Raettig et al. (2012)

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

Aid to planet formation (Barge & Sommeria 1995)

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

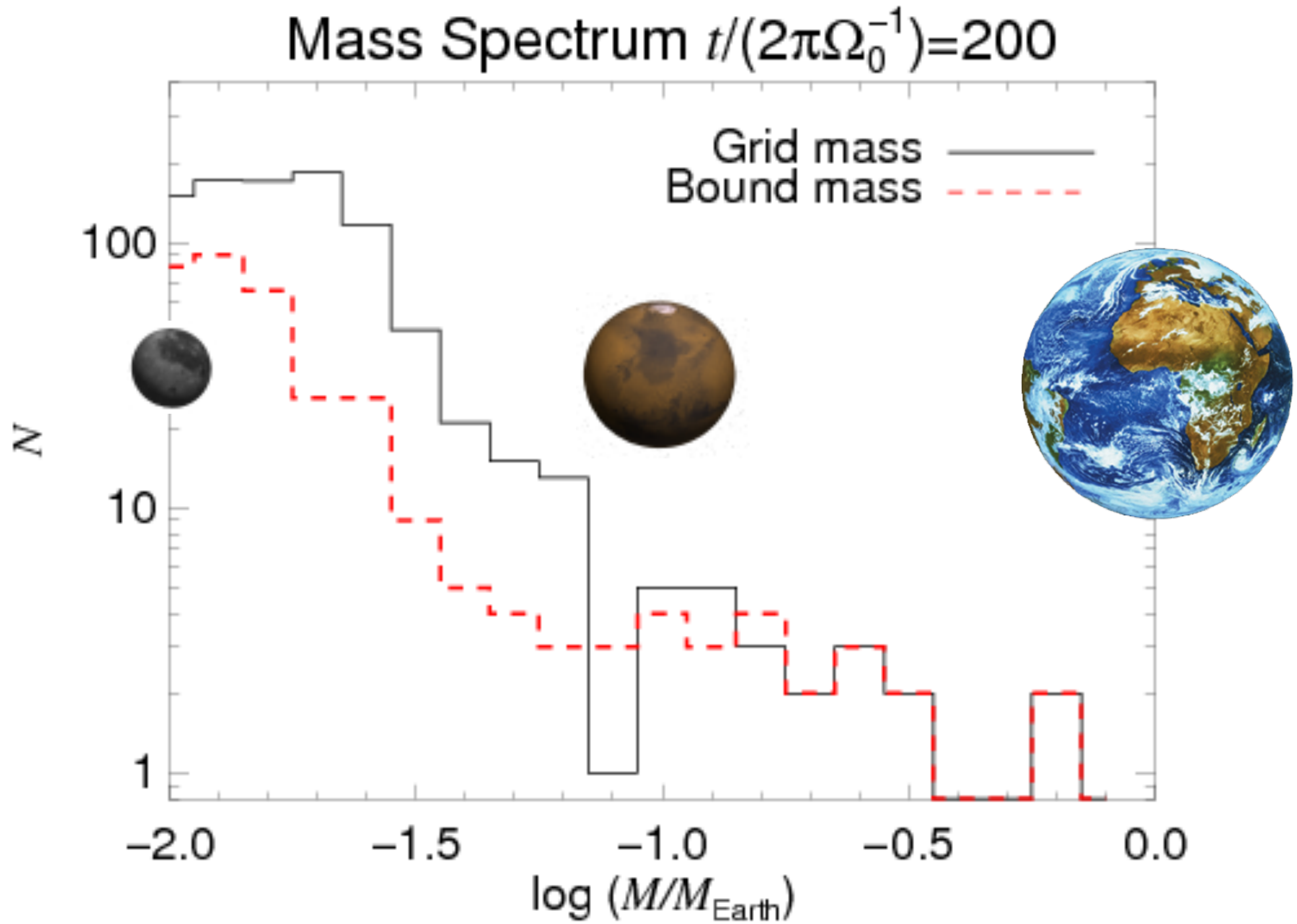
The Initial Mass Function of planets



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

Lyra et al. (2009)

The Initial Mass Function of planets



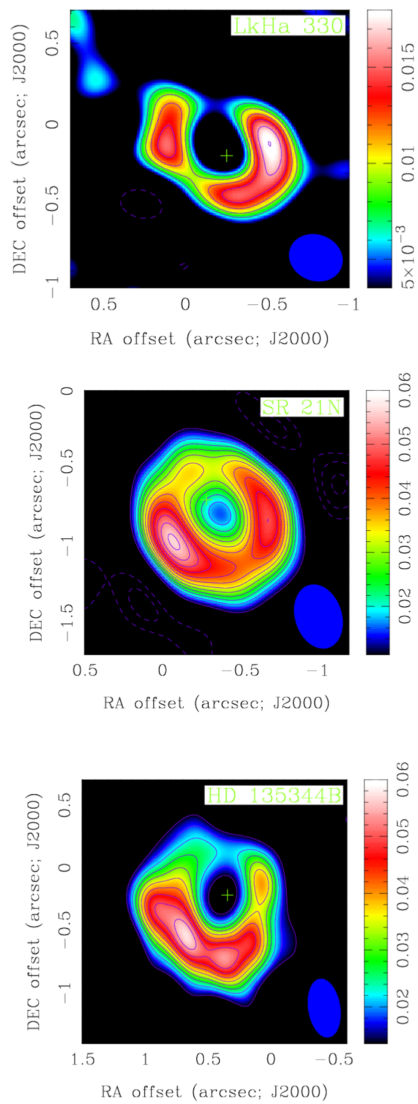
- Mass spectrum by the end of the simulation
- 300 bound clumps were formed
- Power law d(log N)/d(log M)=-2.3 +/- 0.2
- 20 of these are more massive than Mars

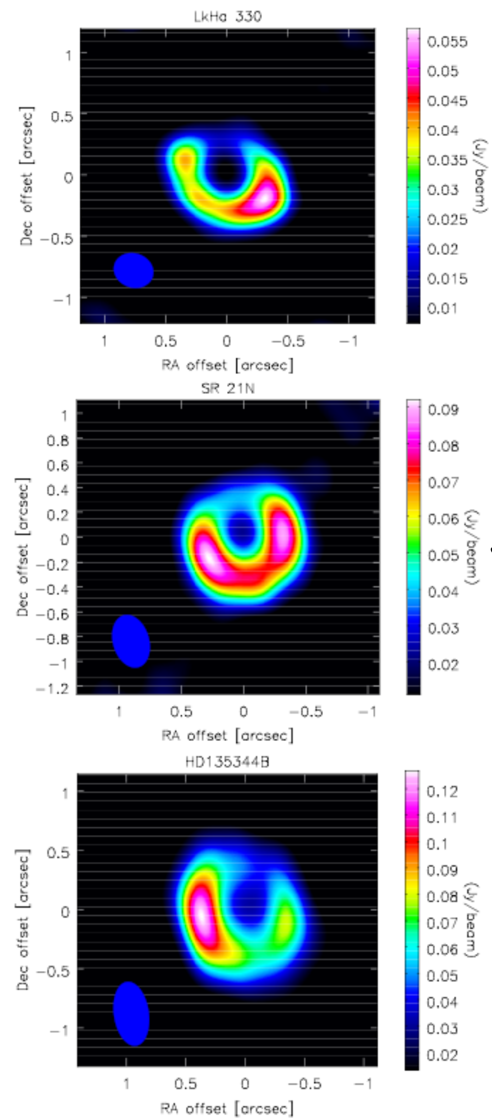
Lyra et al. (2009)

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]

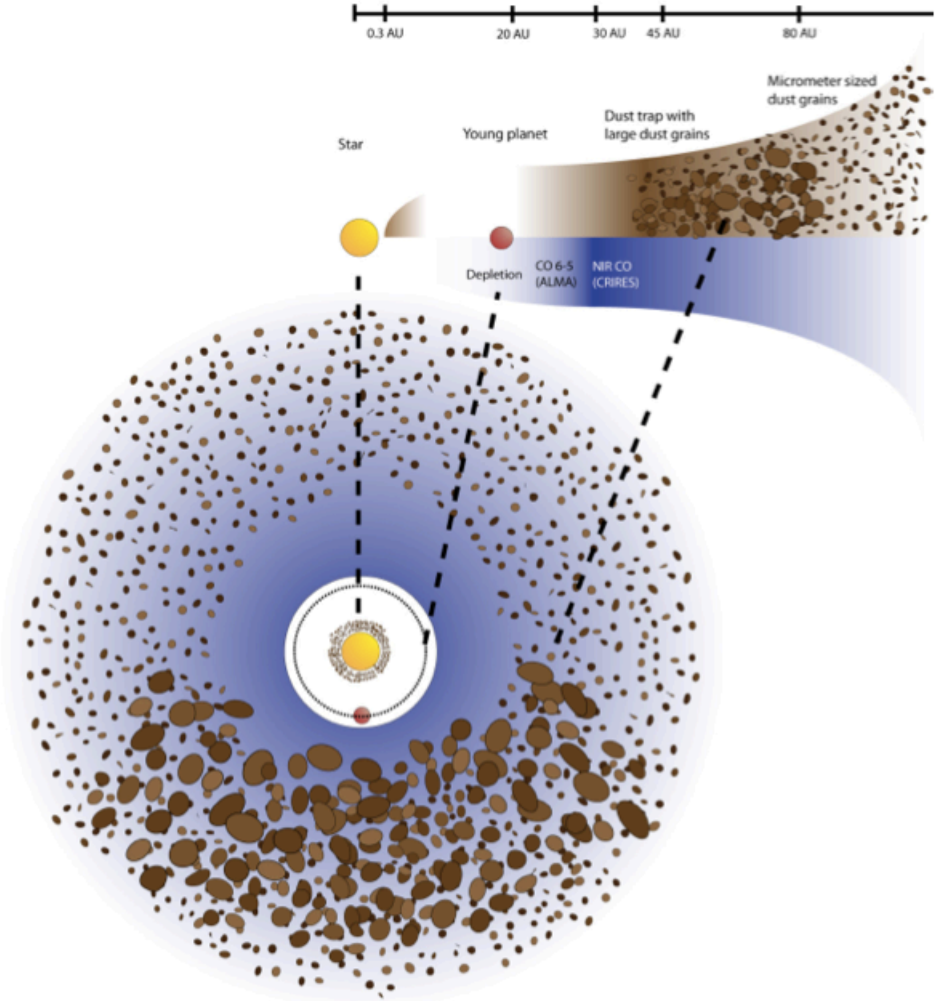
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection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

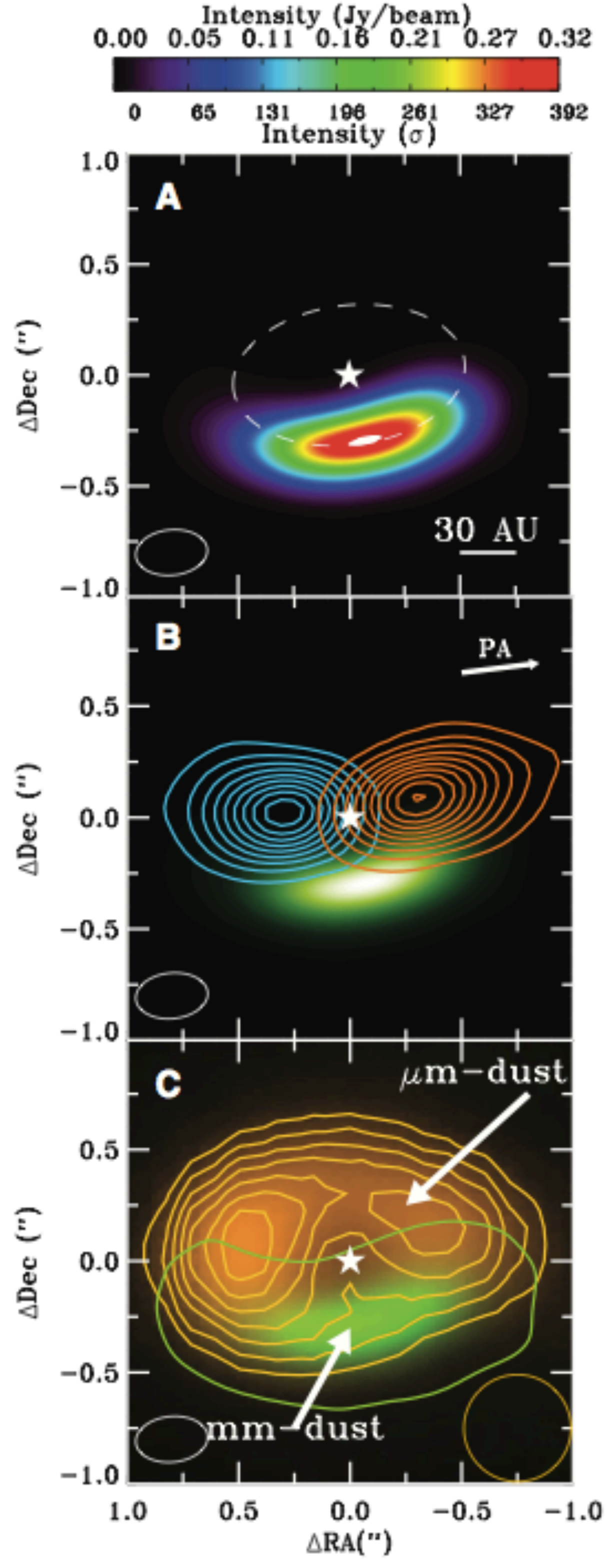
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

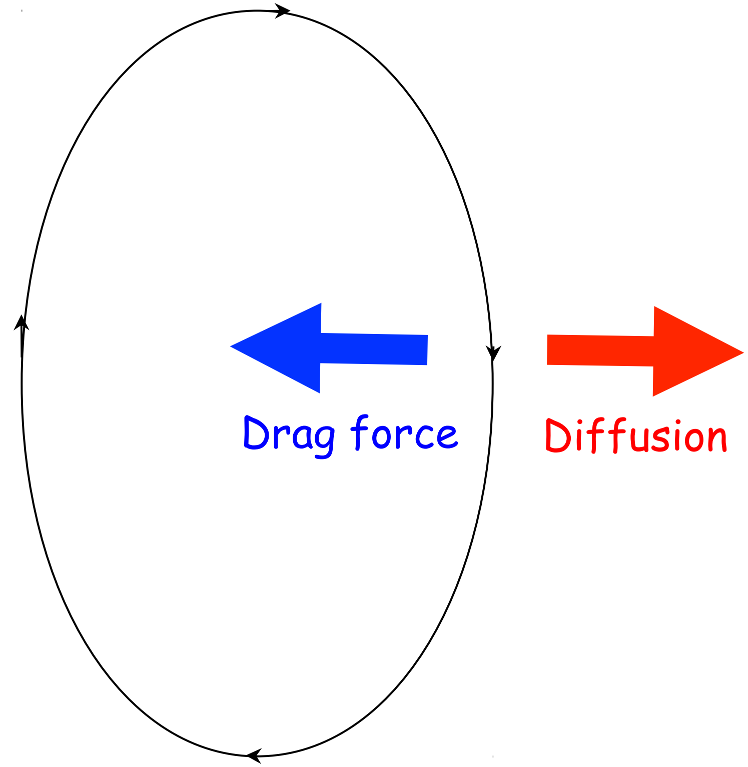


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

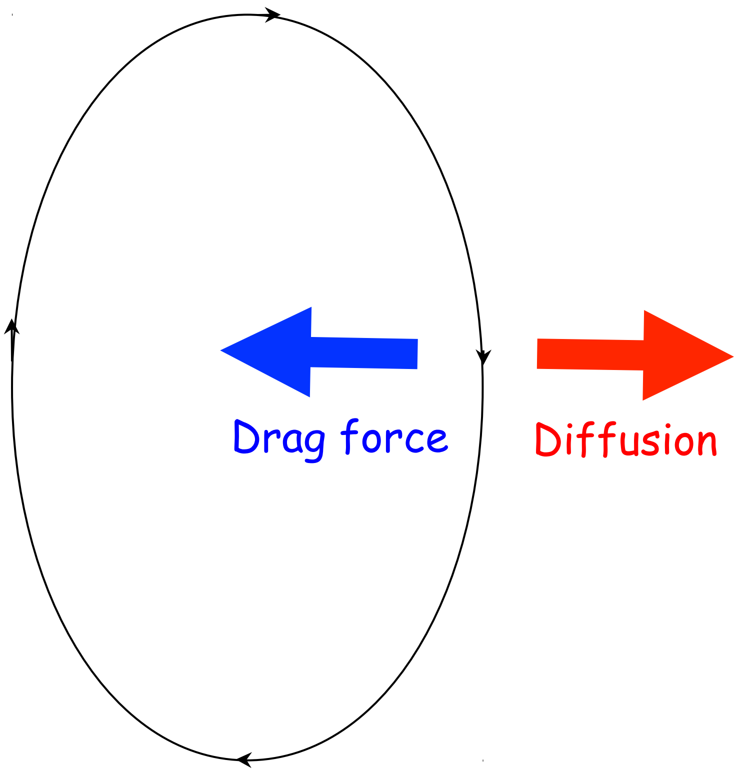
Micron-sized dust follows gas

Drag-Diffusion Equilibrium



Trapped particle

Drag-Diffusion Equilibrium



Trapped particle

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

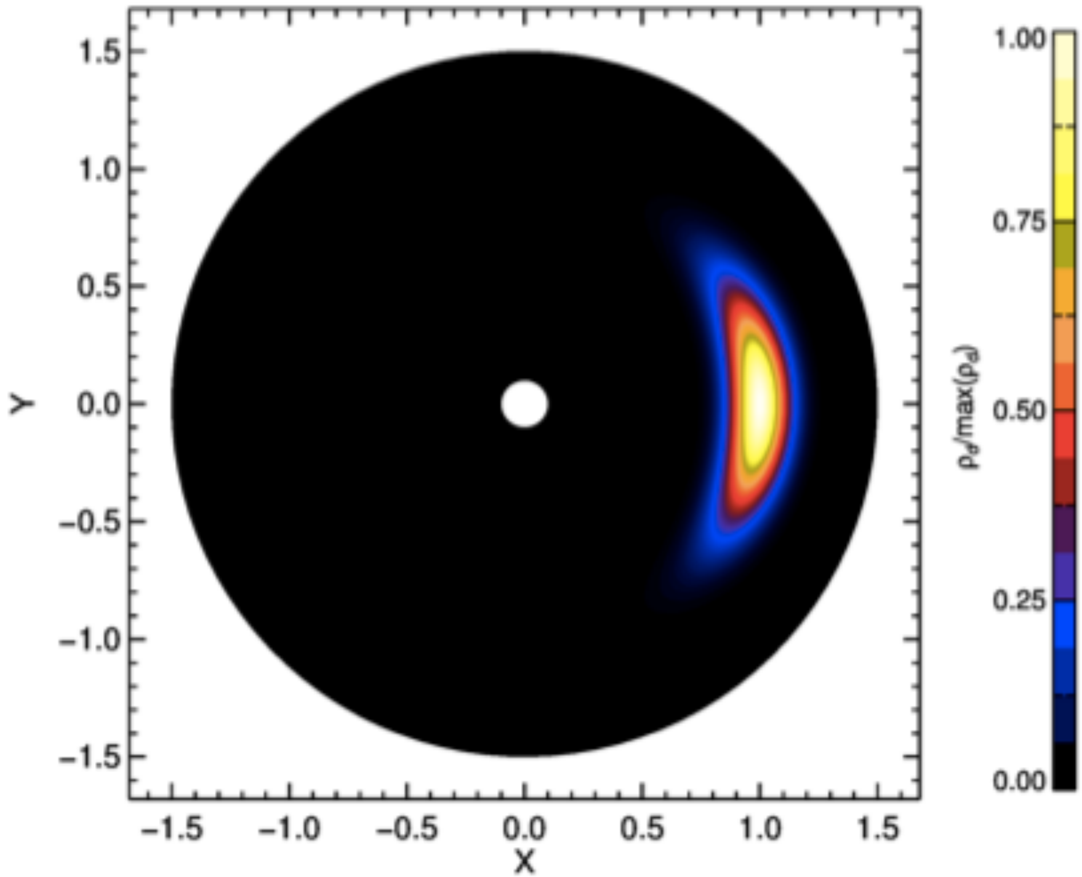
Lyra & Lin (2013)

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

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

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

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

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

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

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

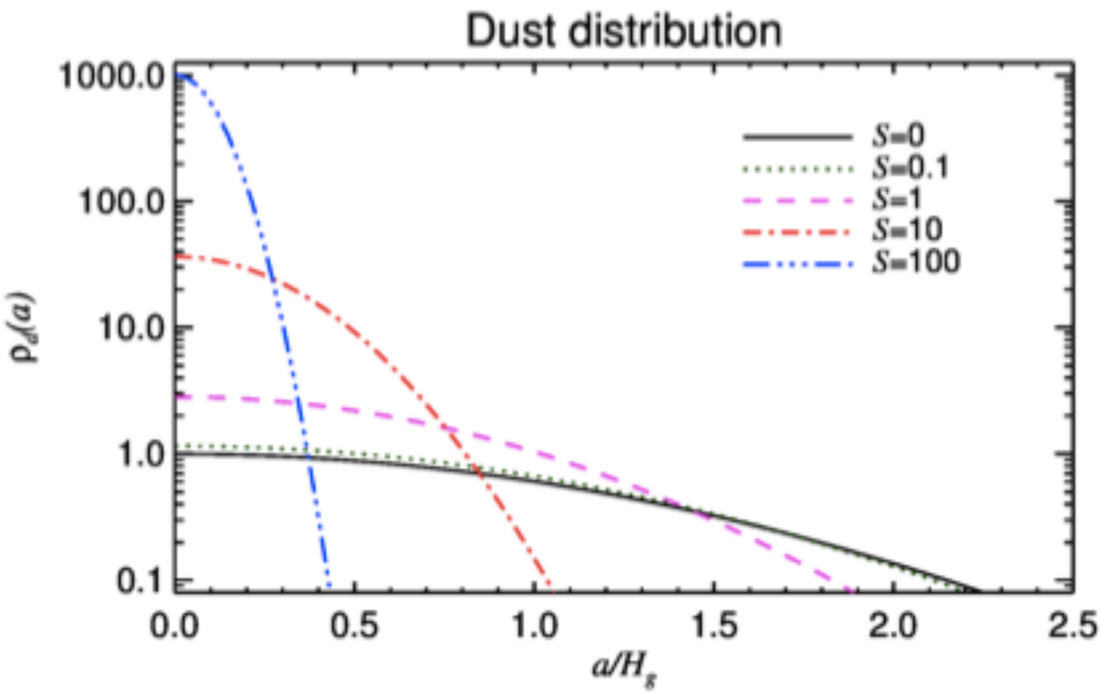
a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

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)

Derived quantities

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

Lyra & Lin (2013)

Gas distribution

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

Maximum dust density

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

Gas contrast

$$\frac{\rho_{g\,\mathrm{max}}}{\rho_{g\,\mathrm{min}}} = \exp\left[\frac{f^2(\chi)}{2\chi^2\omega_V^2}\right],$$

Dust contrast

$$\frac{\rho_{d\,\mathrm{max}}}{\rho_{d\,\mathrm{min}}} = \frac{\rho_{g\,\mathrm{max}}}{\rho_{g\,\mathrm{min}}} \exp(S),$$

Total trapped mass

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

Vortex size

$$a_s = H(\chi\omega_V)^{-1}$$

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

Applying the model to Oph IRS 48

Observed parameters

Aspect ratio: 3.1

Dust contrast: 130

Temperature: 60K

Trapped mass: 9 M_{Earth}

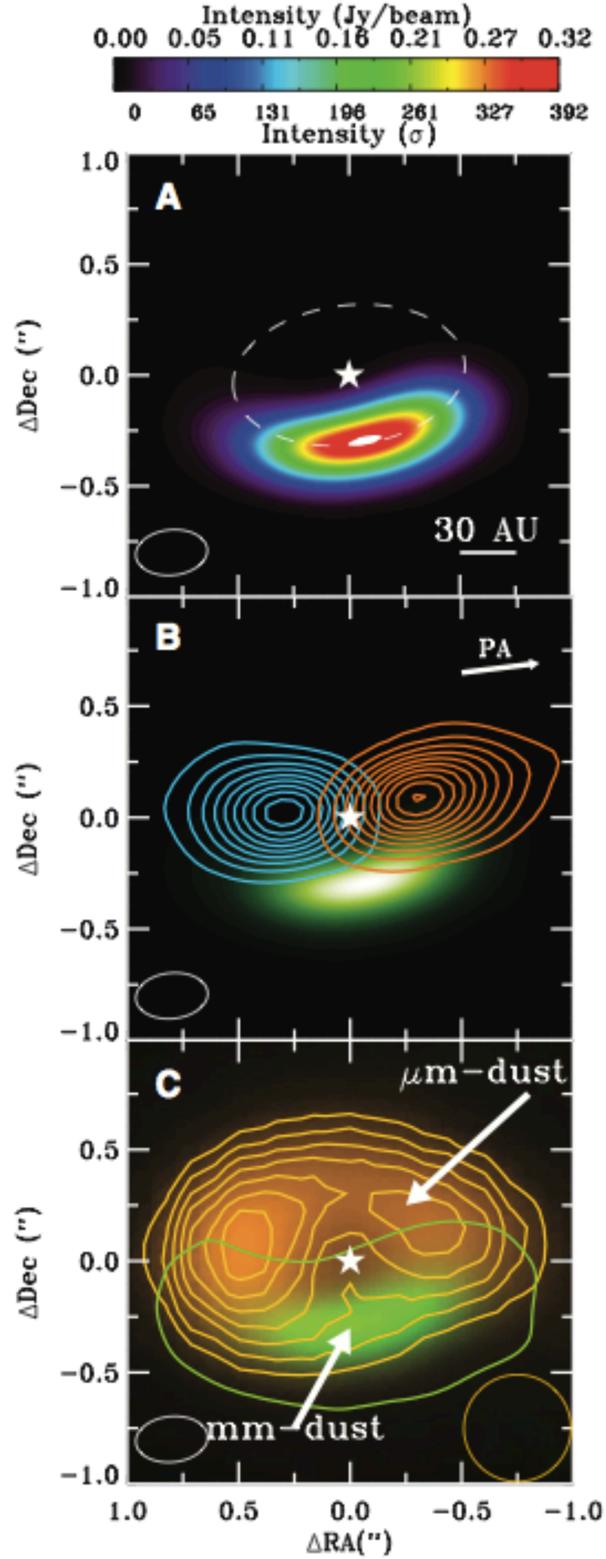
Derived parameters

S=4.8

Stokes number, St=0.008

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

Trapped mass: 11 M_{Earth}



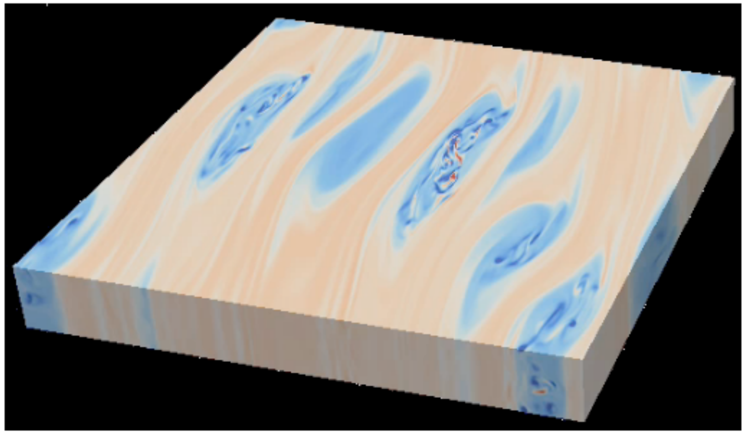
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

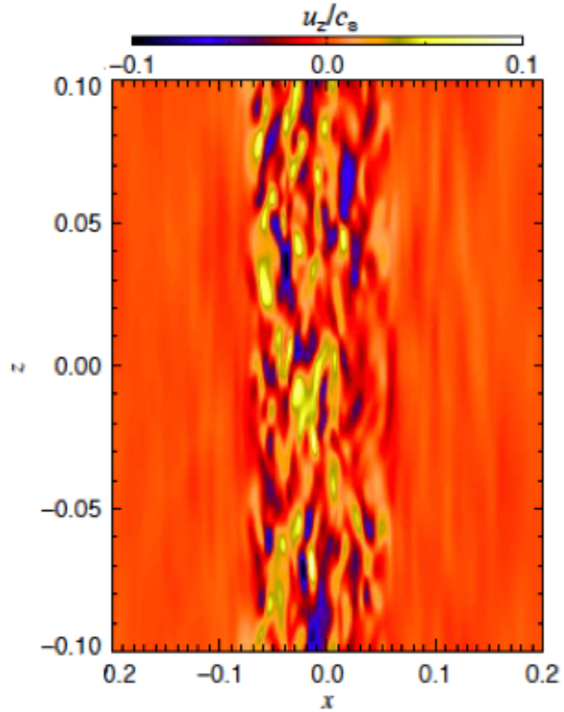
Micron-sized dust follows gas

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

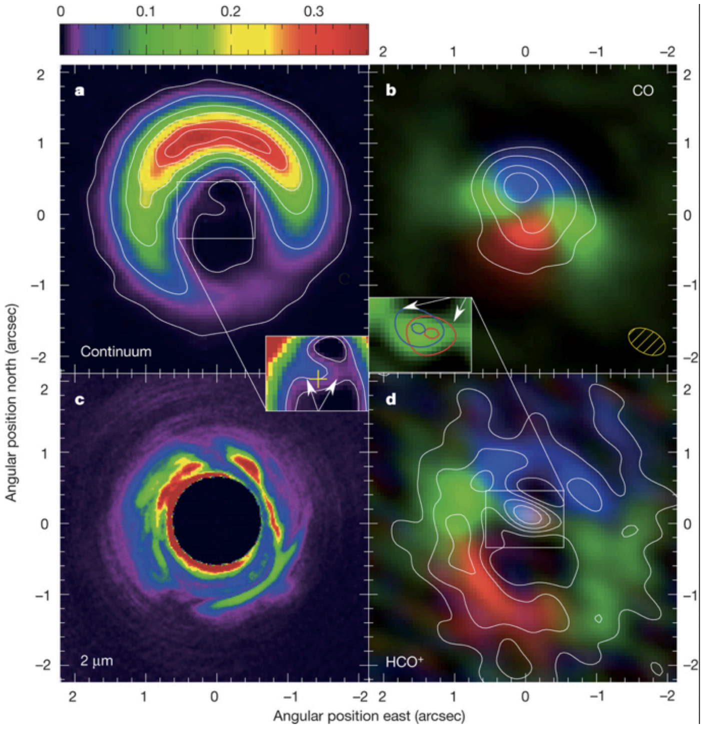
Temperature: 25K

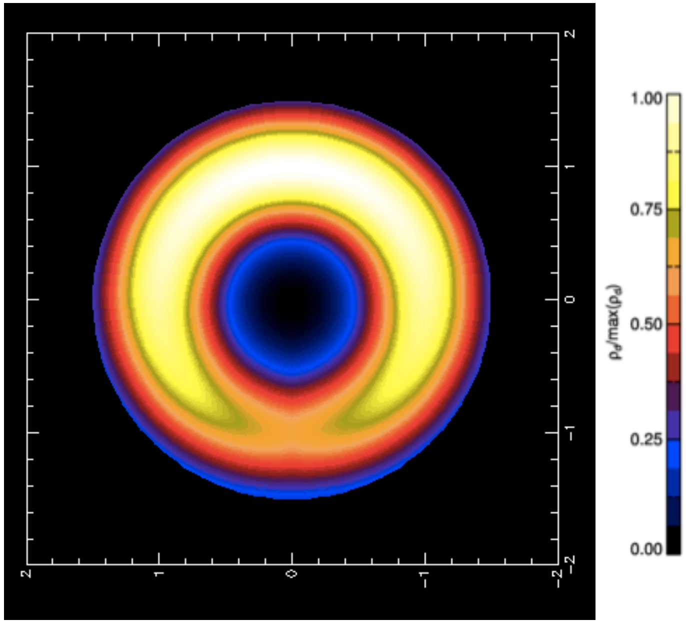
Derived parameters

S=3.5

Stokes number, St=0.004

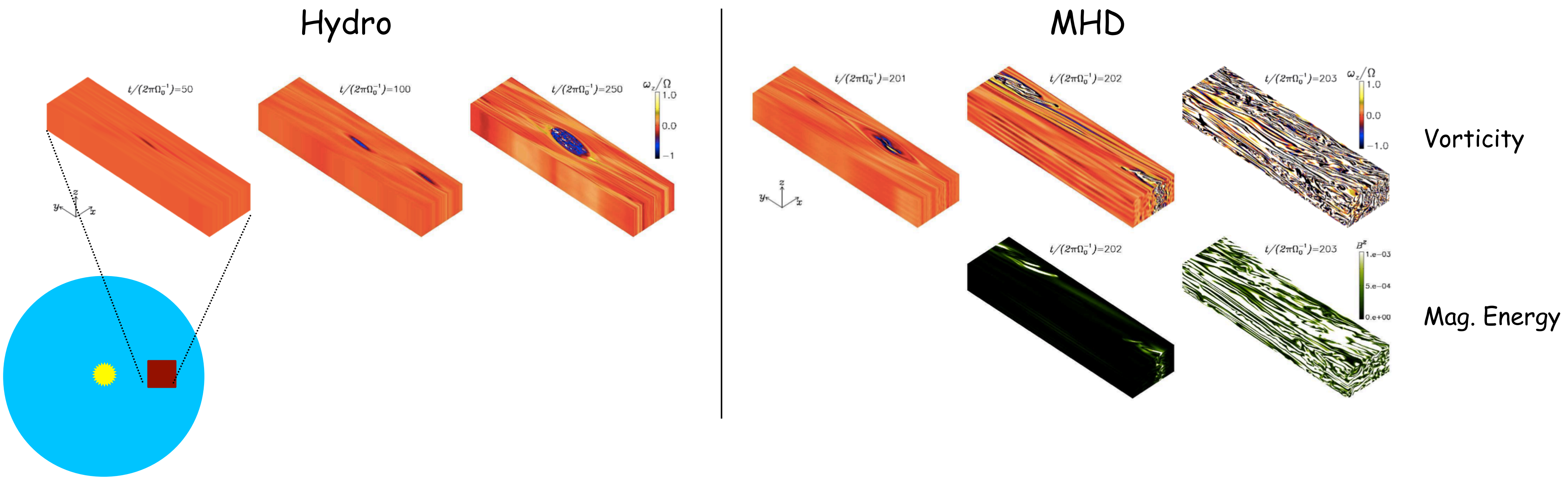
$\delta = 0.001$, $v_{rms} = 4\%\ c_s$





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

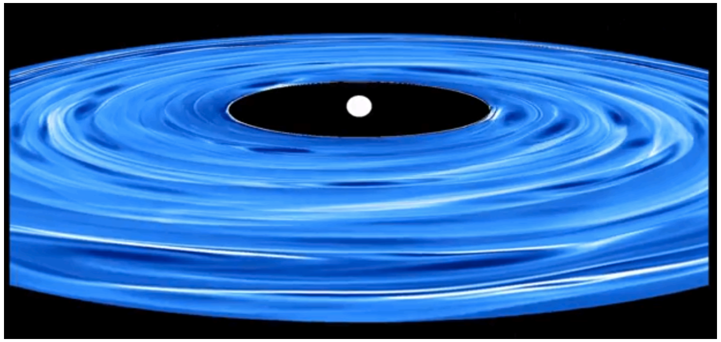


Lyra & Klahr (2011)

Conclusions

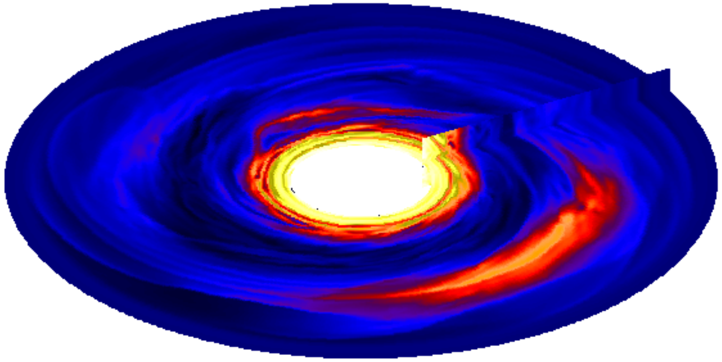
- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted is a complementary formation mode to streaming instability
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- We're in the era of observational testing/confirmation of our model predictions!!

Baroclinic instability



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

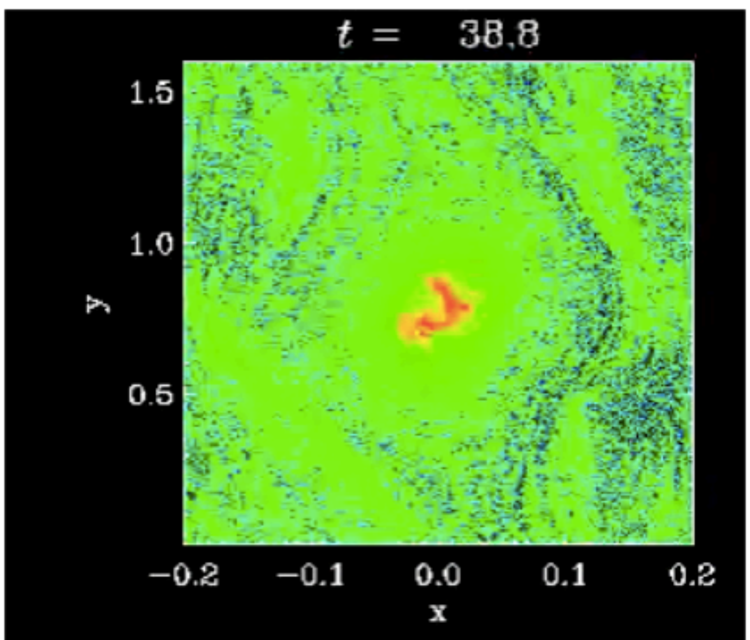
Rossby wave instability

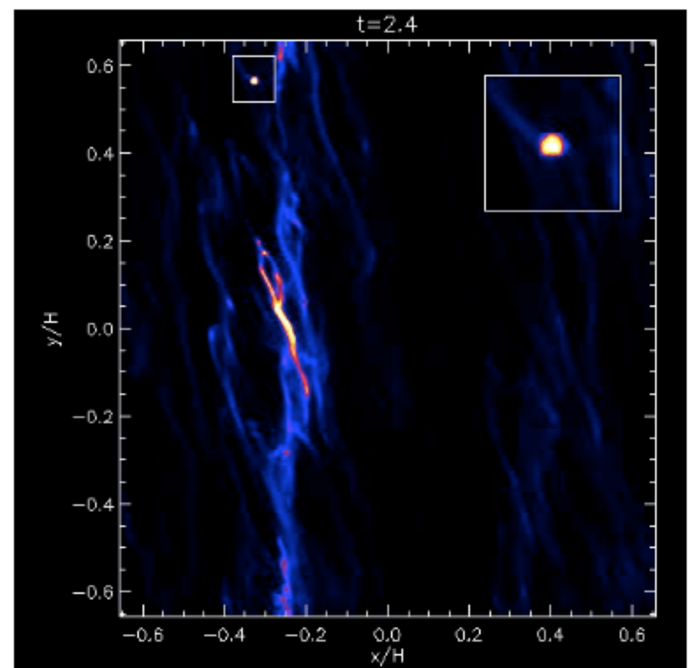


Lovelace et al. (1999)
Lyra et al. (2008b,2009ab)
Lyra & Mac Low (2012)

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





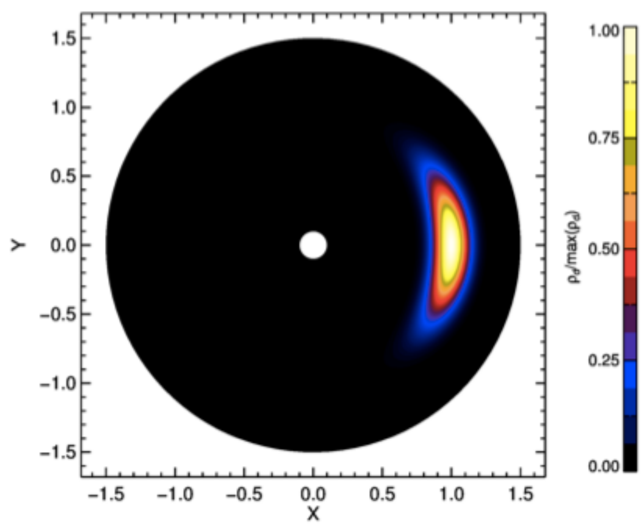
Conclusions

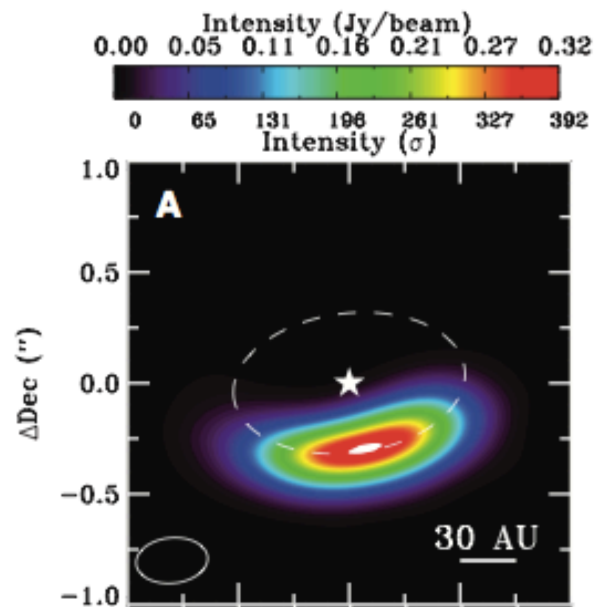
- Vortices exist in the dead z
- Two sustenance modes: Ros
- Vortex-assisted and strea

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

Lyra & Lin (2013)

- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- We're in the era of observational testing/confirmation of our model predictions!!





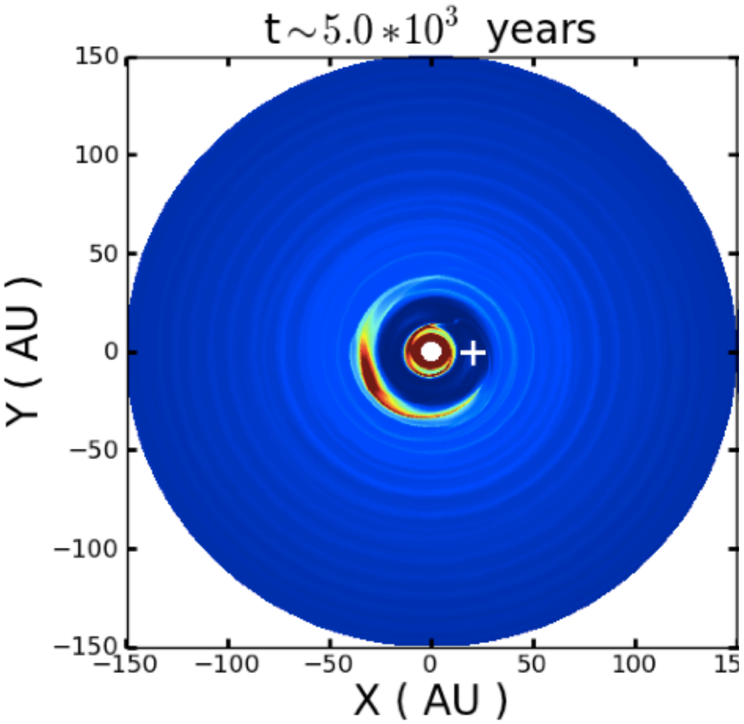
Conclusions

- Vortices exist in the dead zone only
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted and strea
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- We're in the era of observational testing/confirmation of our model predictions!!

It seems to have the properties of vortices.

But… is it really a vortex?

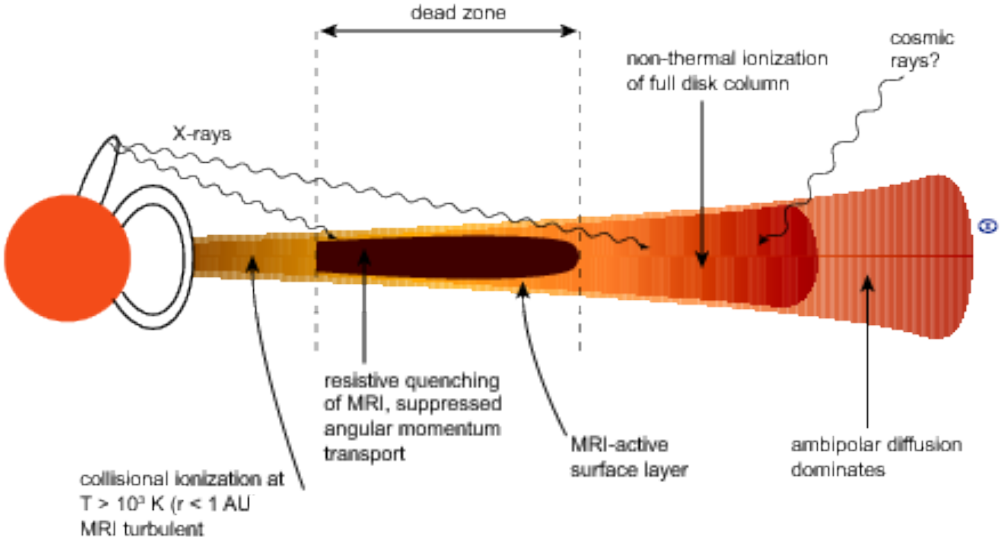
The dust trap is too far from the planet!



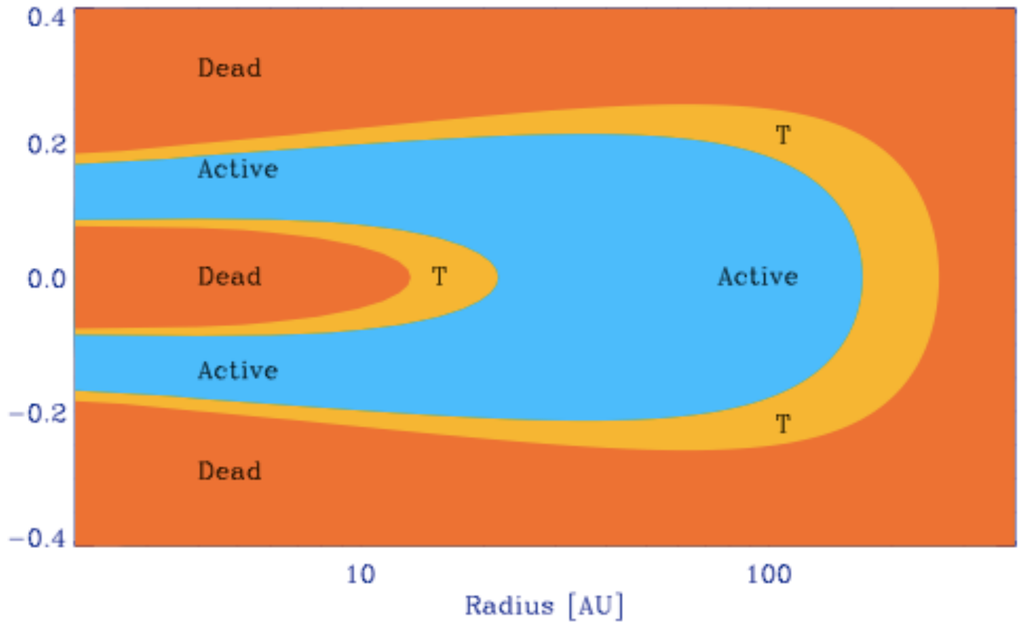
A gap in gas emission suggests a 10 MJ planet at **15-20 AU**.

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

Dead zone RWI fails!



Armitage (2010)



Dzyurkevitch et al (2013)

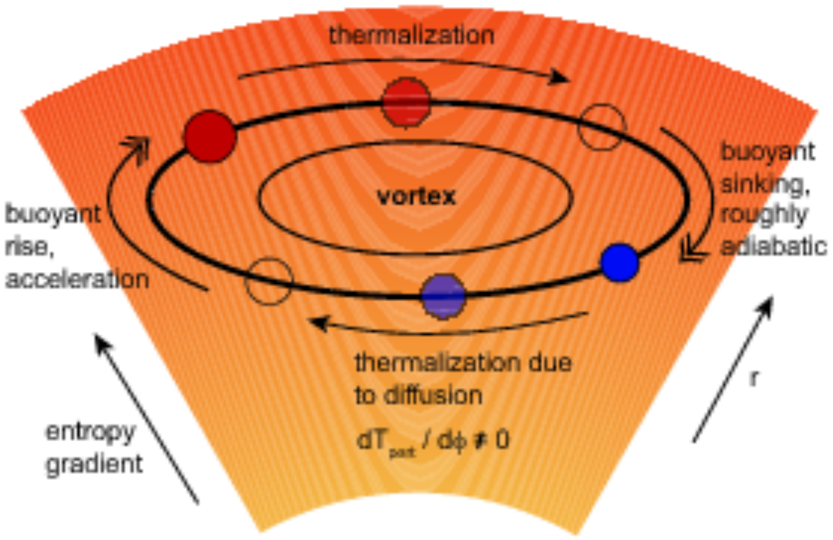
The **outer** dead zone transition in ionization is
TOO SMOOTH
to generate an RWI-unstable bump.

Baroclinic instability

1. Radial entropy gradient

2. Thermal diffusion

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

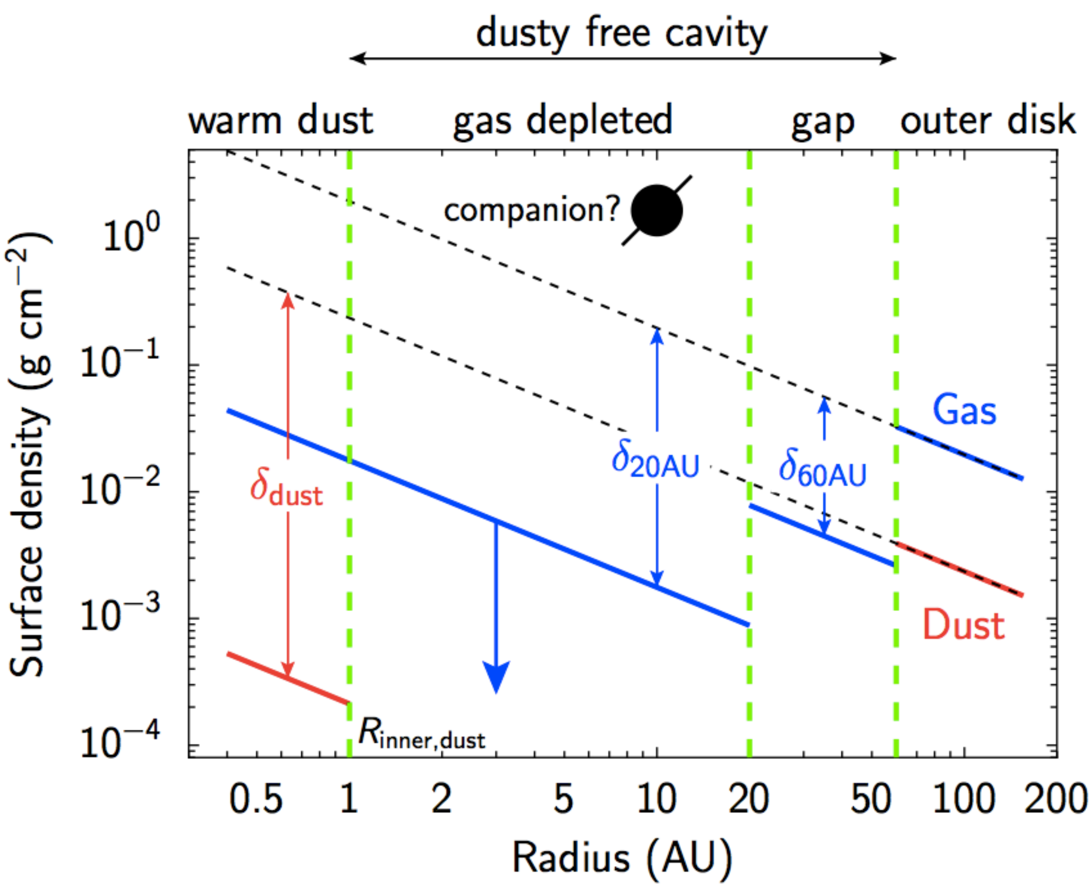


The thermal diffusion time for the gas in IRS Oph 48 is **0.1 orbits**.

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.