Evolution of circumstellar disks and planet formation

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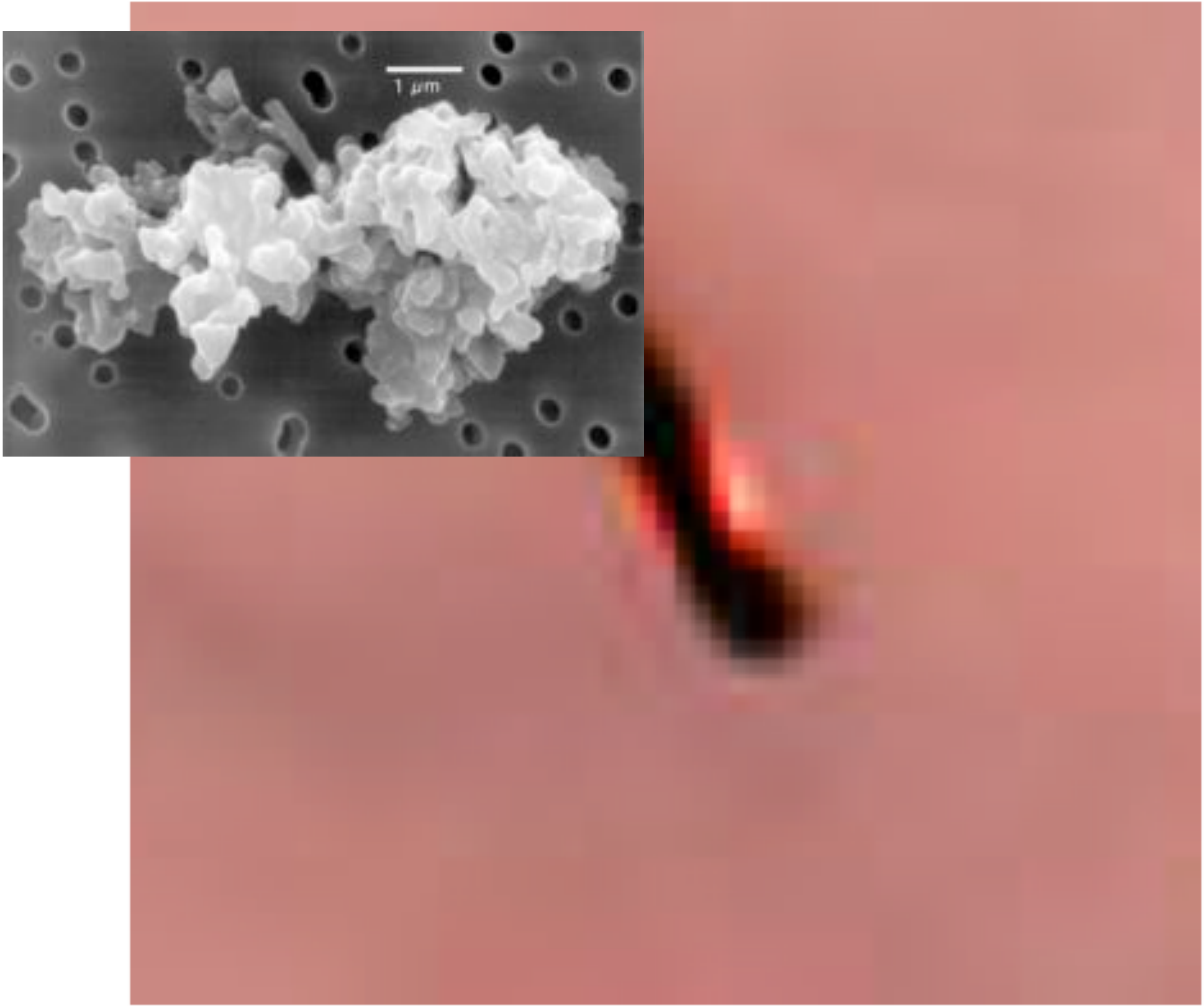
Princeton NJ

May 5th, 2015

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


1 μm

Protoplanetary Disks

PP disk fact sheet

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

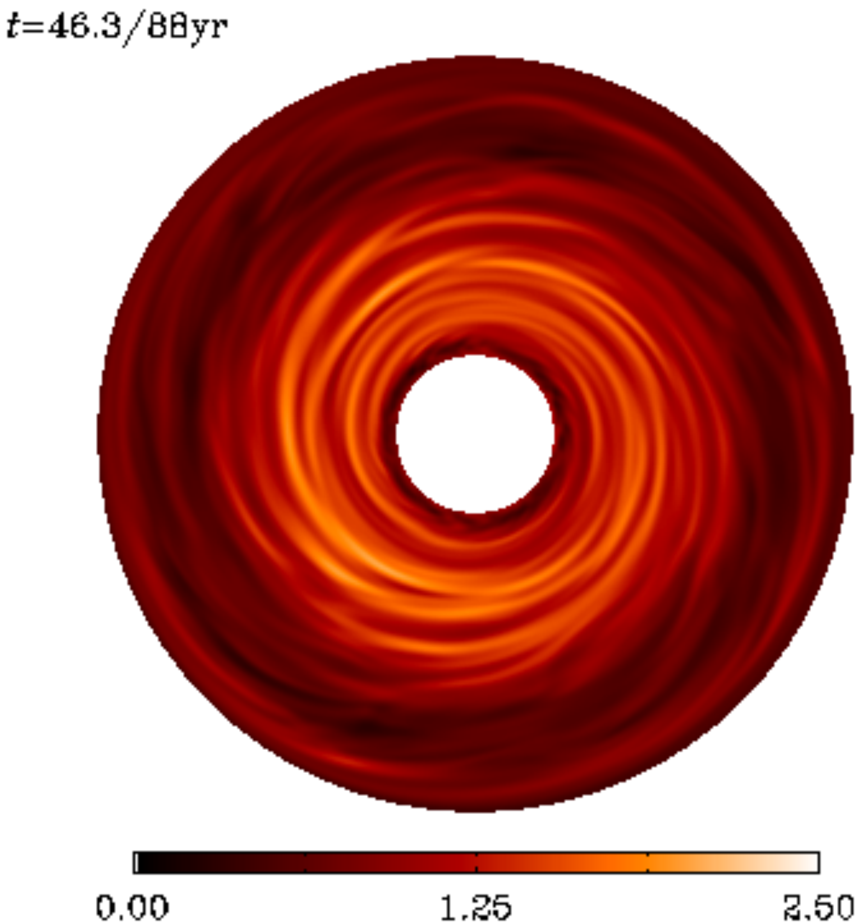
Temperature: 10-1000 K

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

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

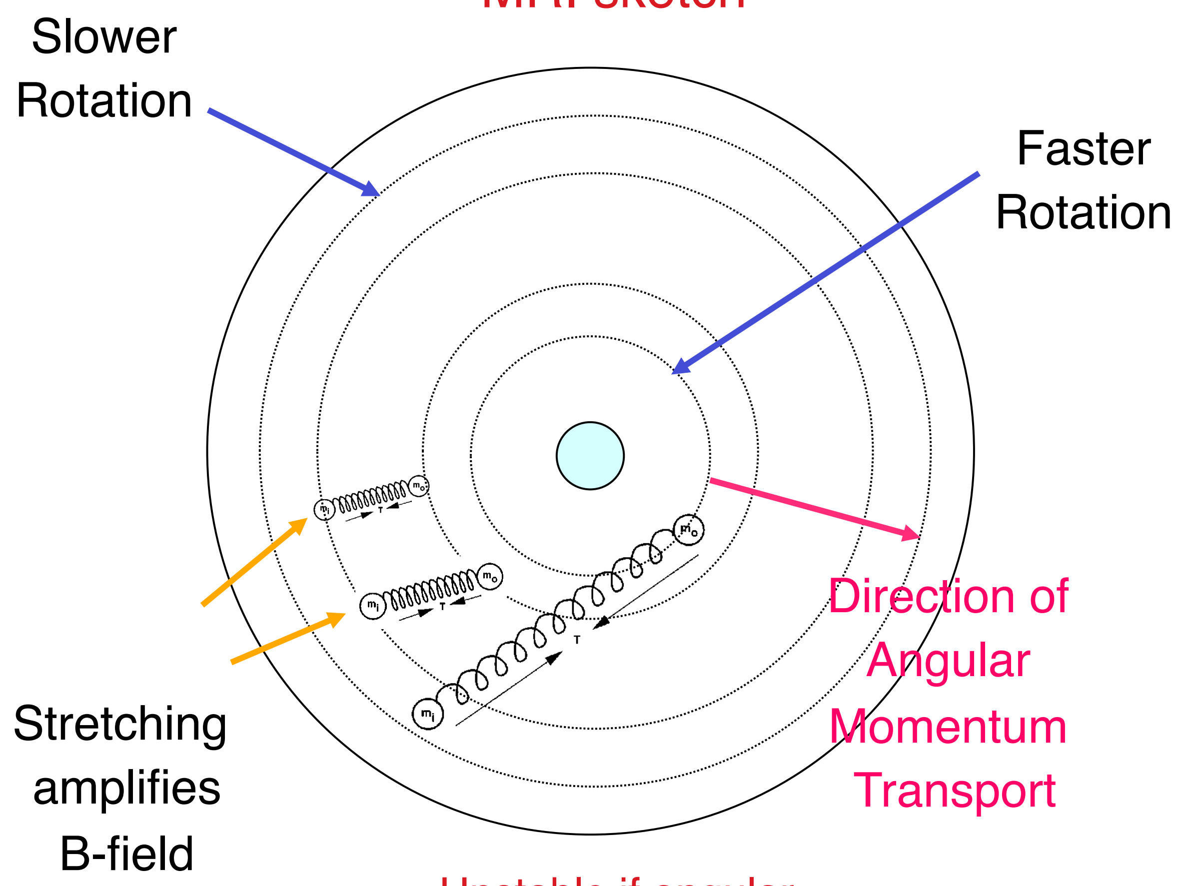
Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by the Magneto-Rotational Instability



Magnetized disk
Lyra et al. (2008a)

MRI sketch



Unstable if angular velocity decreases outward

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
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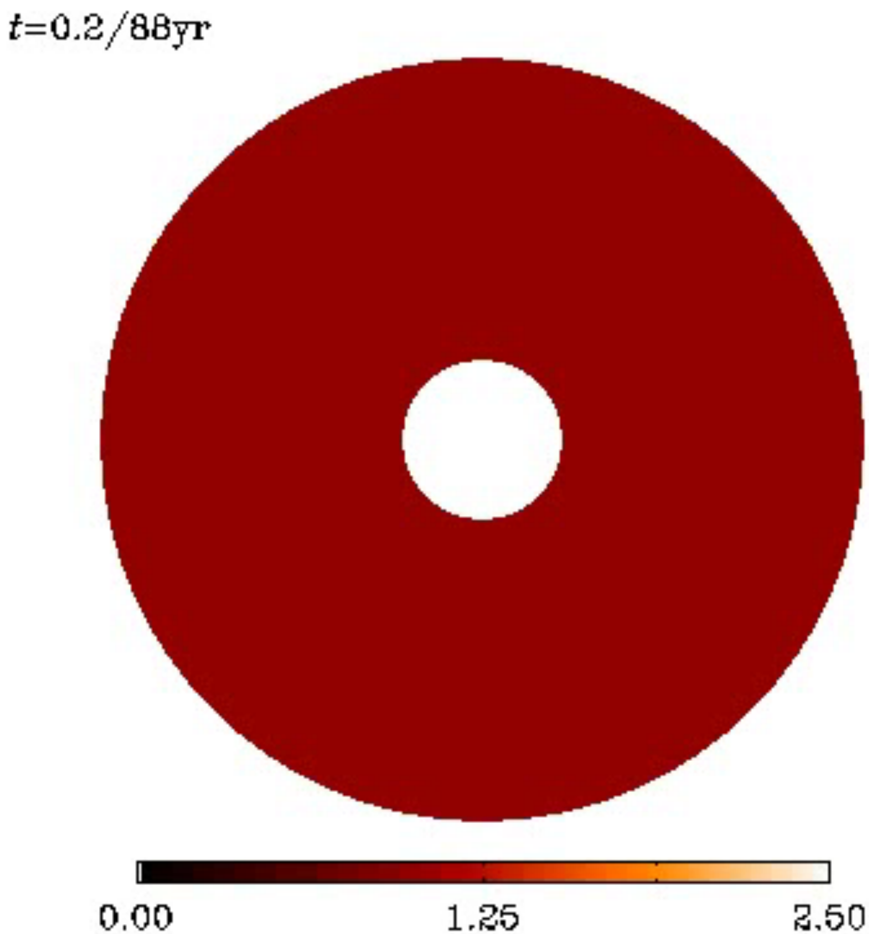

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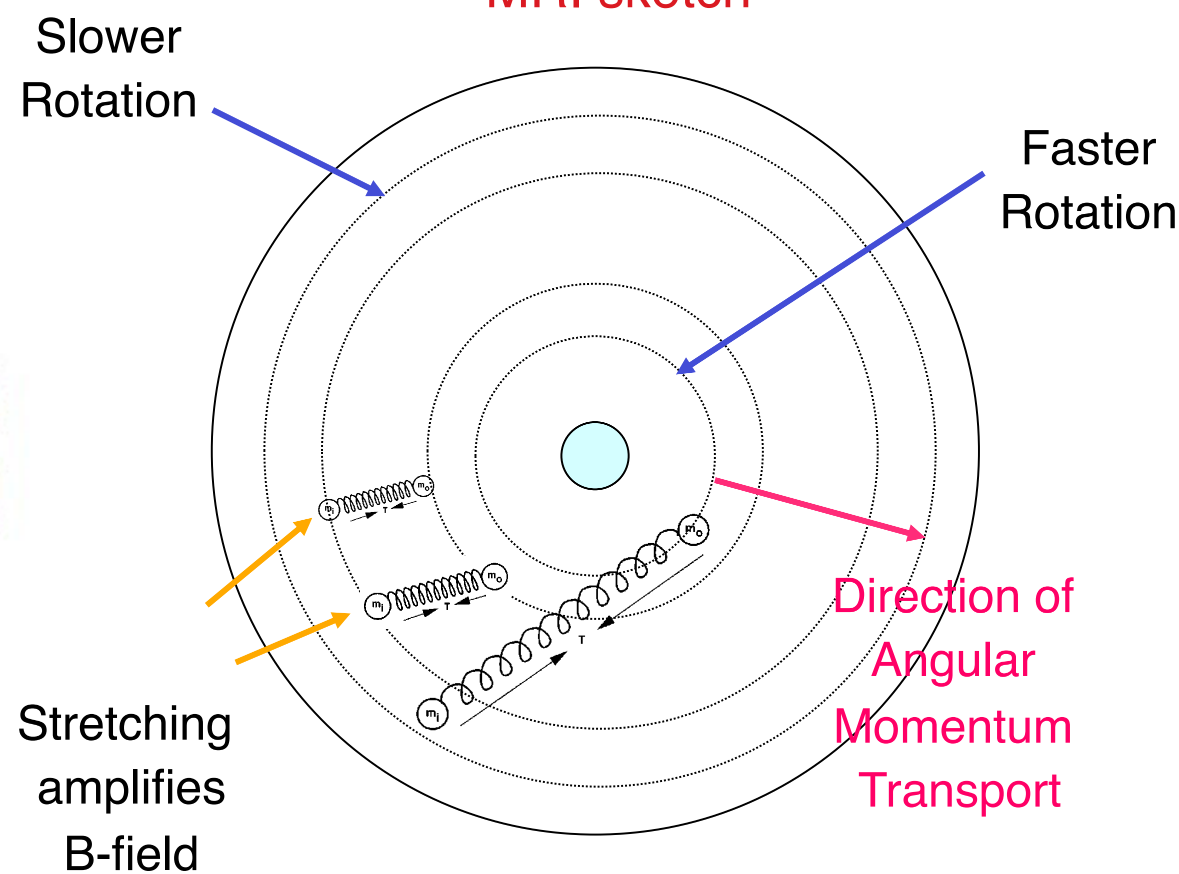
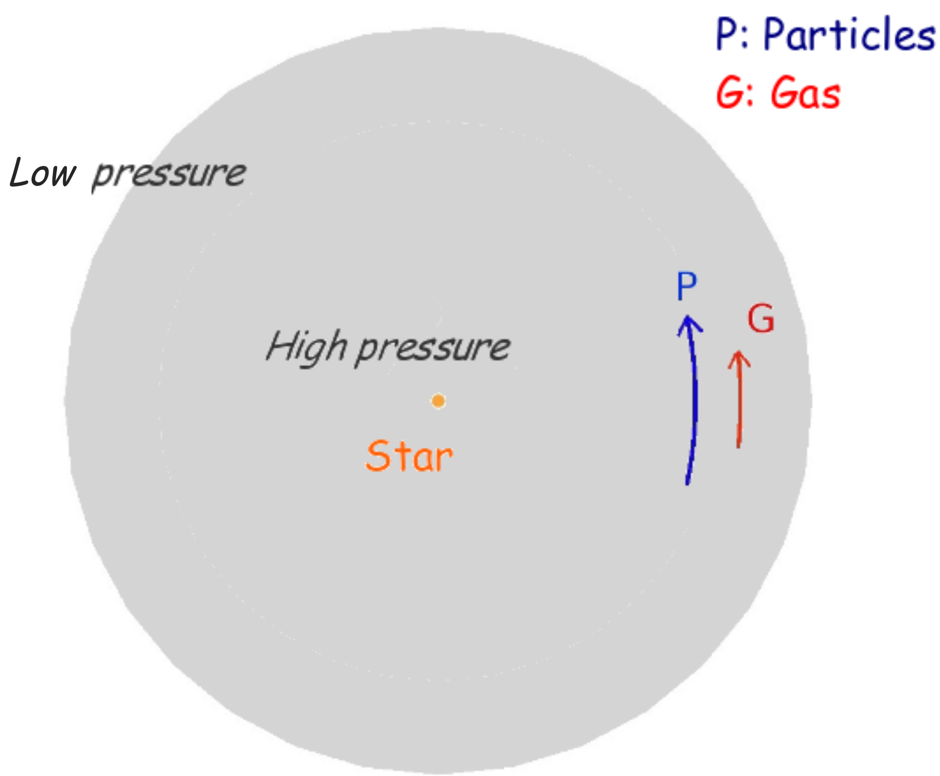
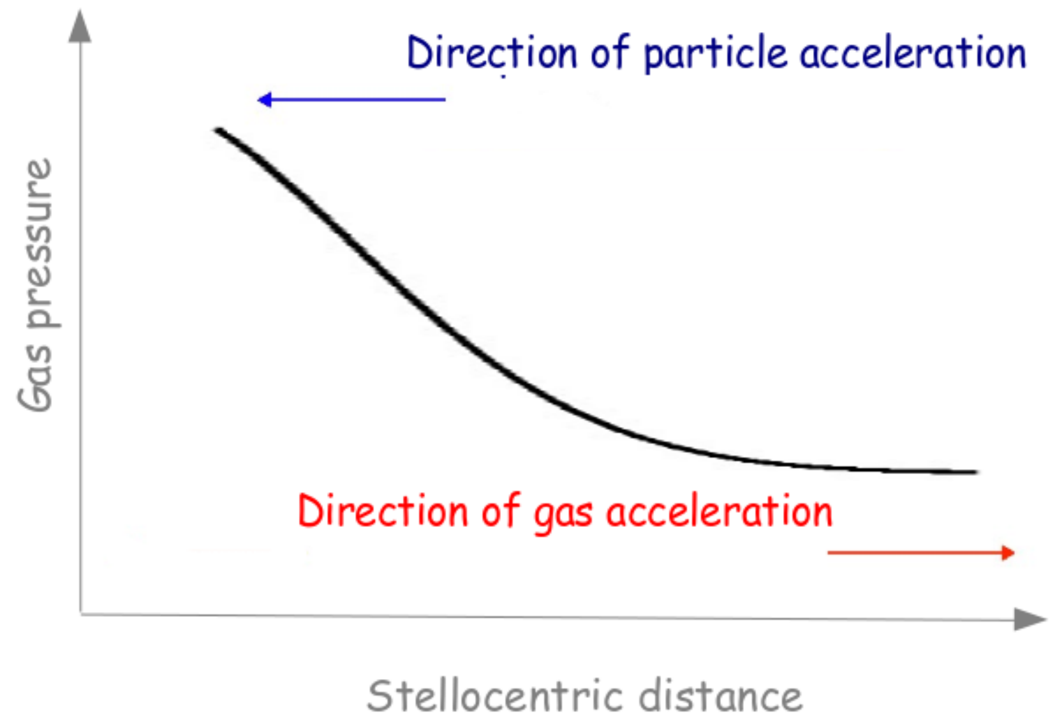


Unstable if angular velocity decreases outward

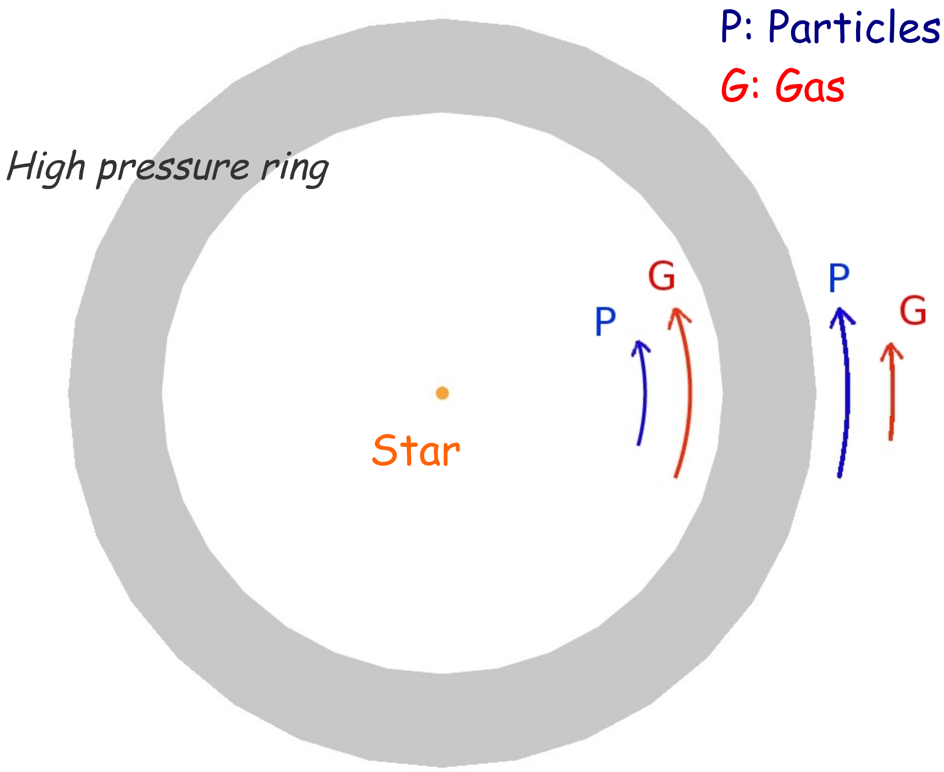
Particle drift



Adapted from Whipple (1972)



Pressure Trap



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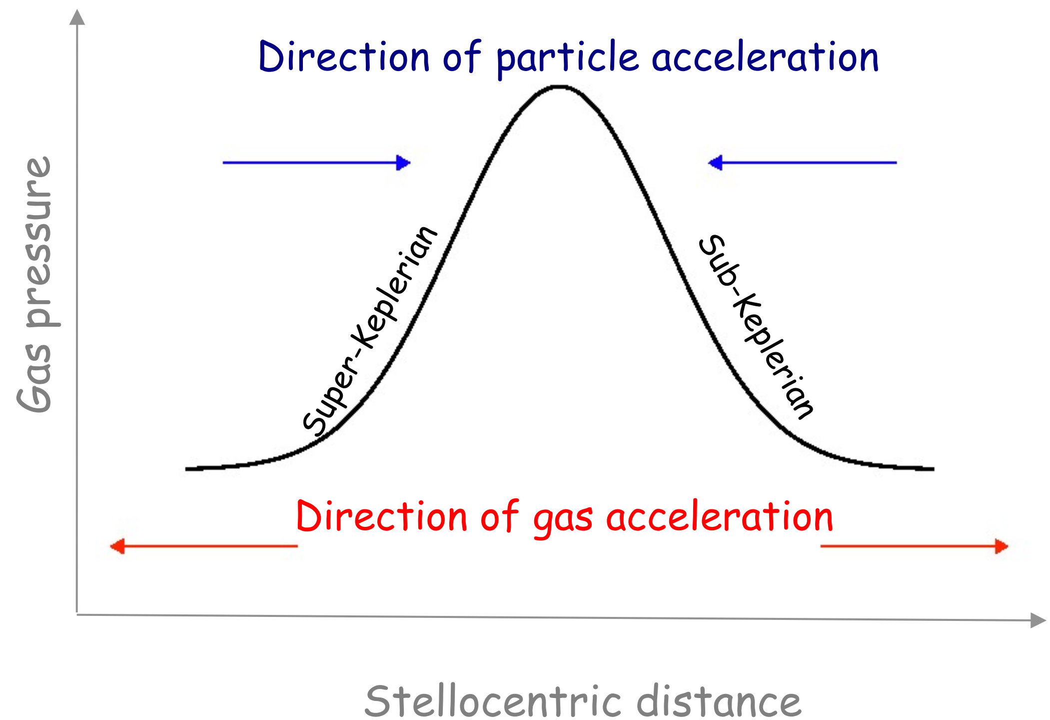

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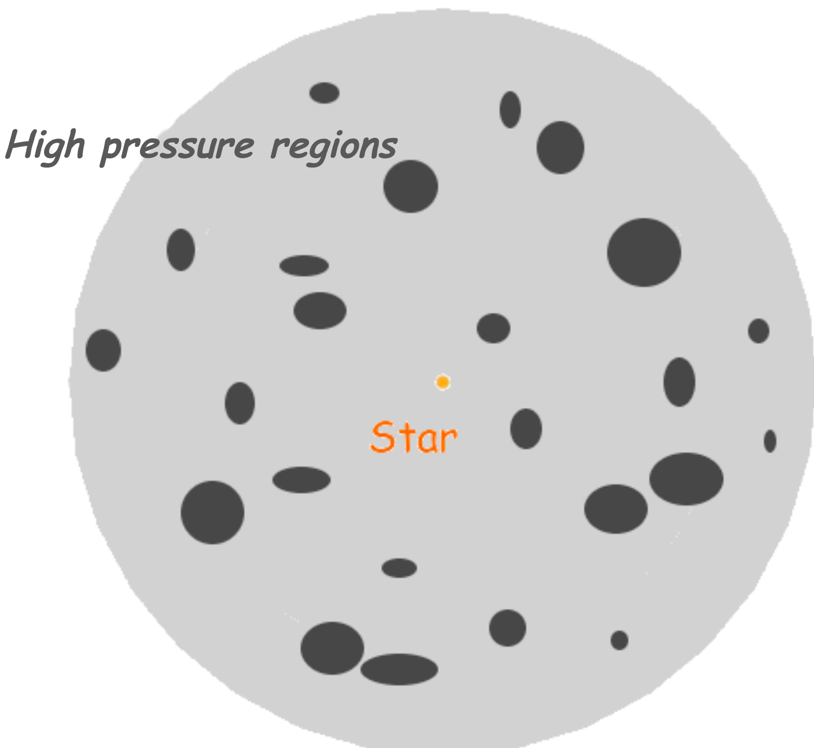
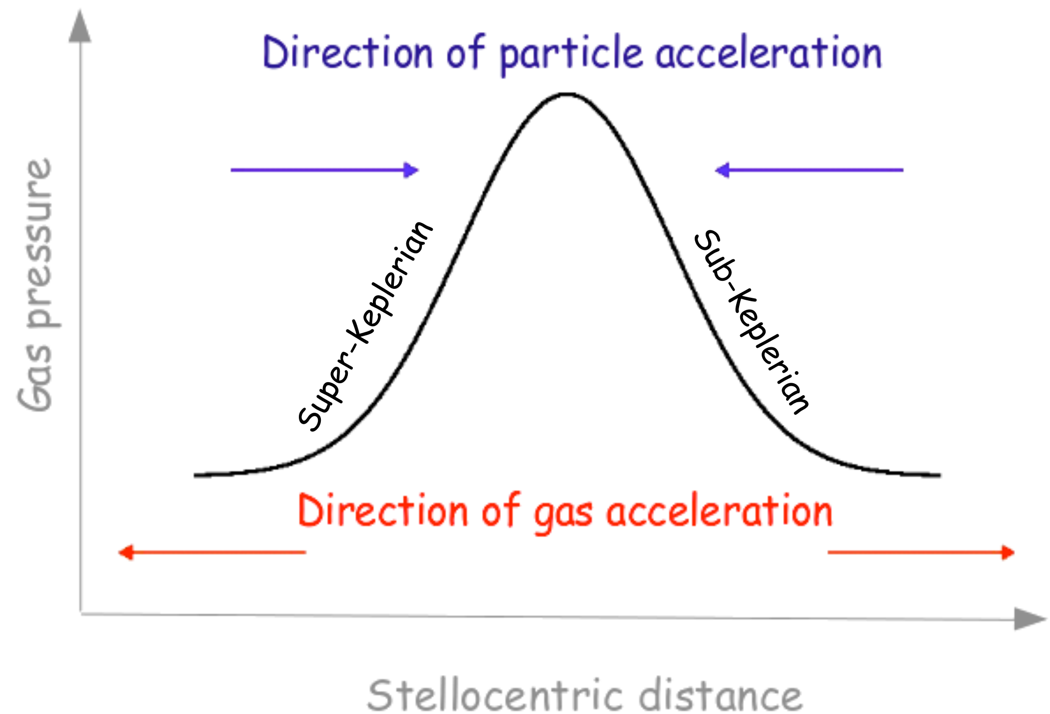
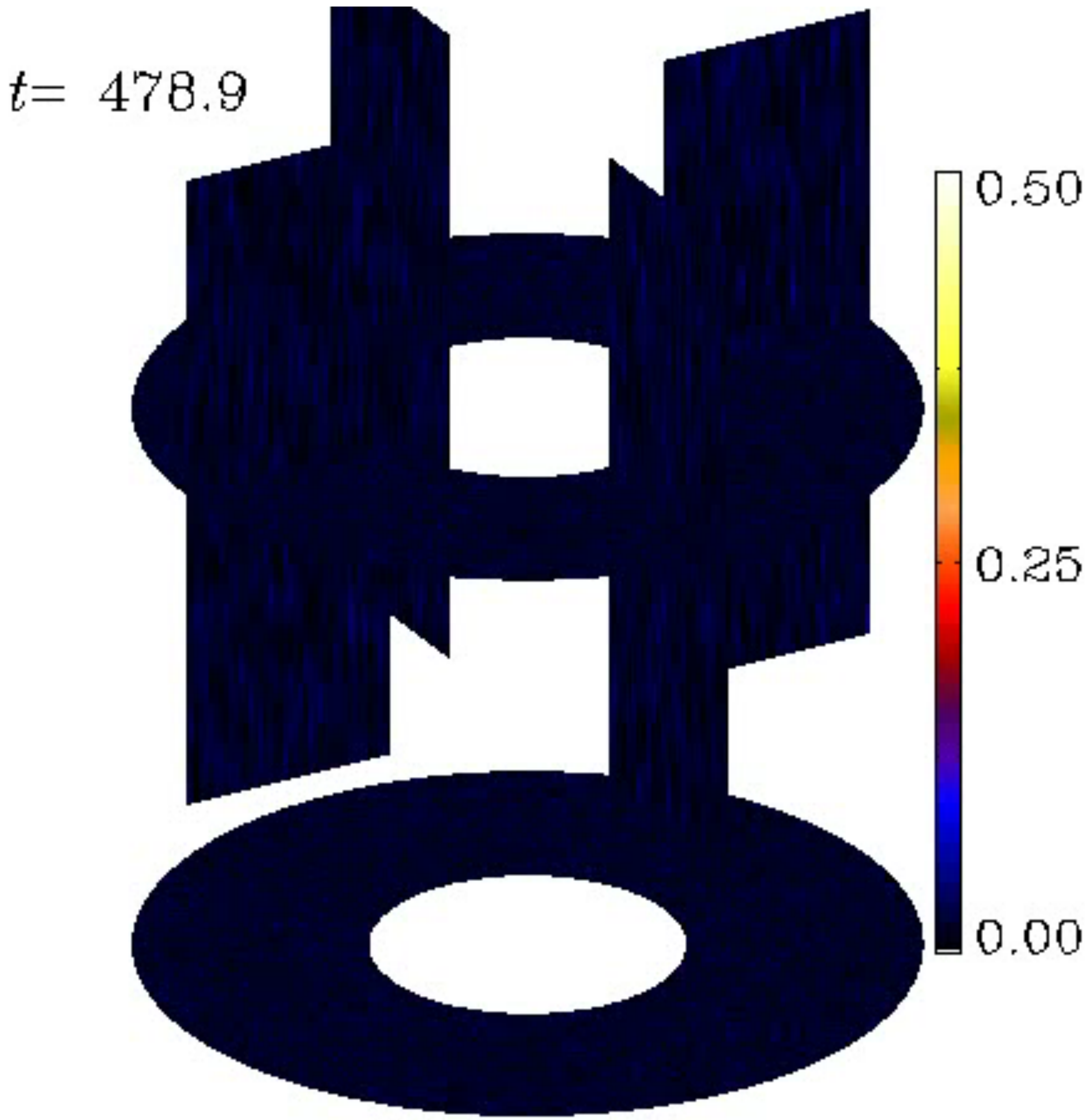


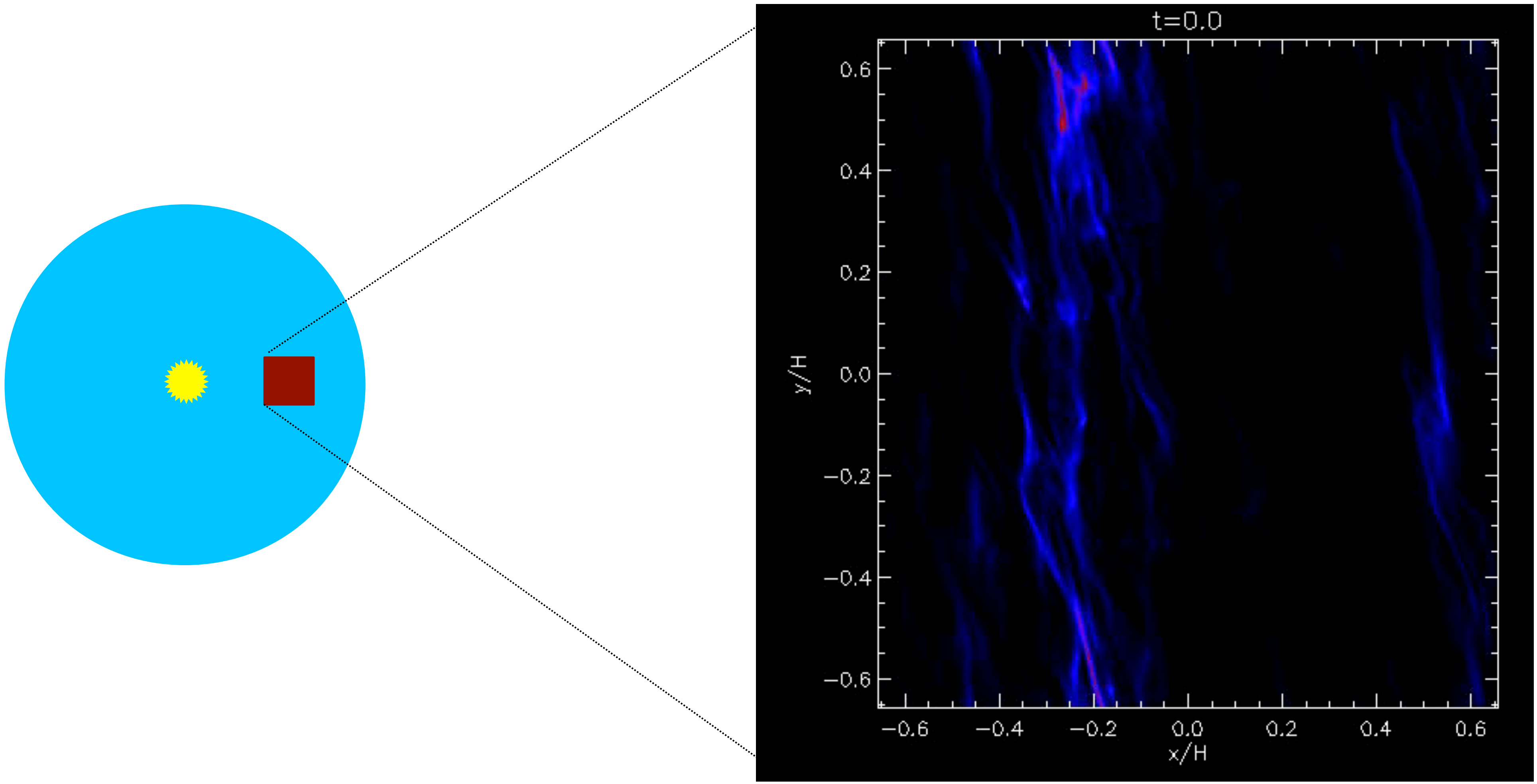


Turbulence concentrates solids mechanically in pressure maxima



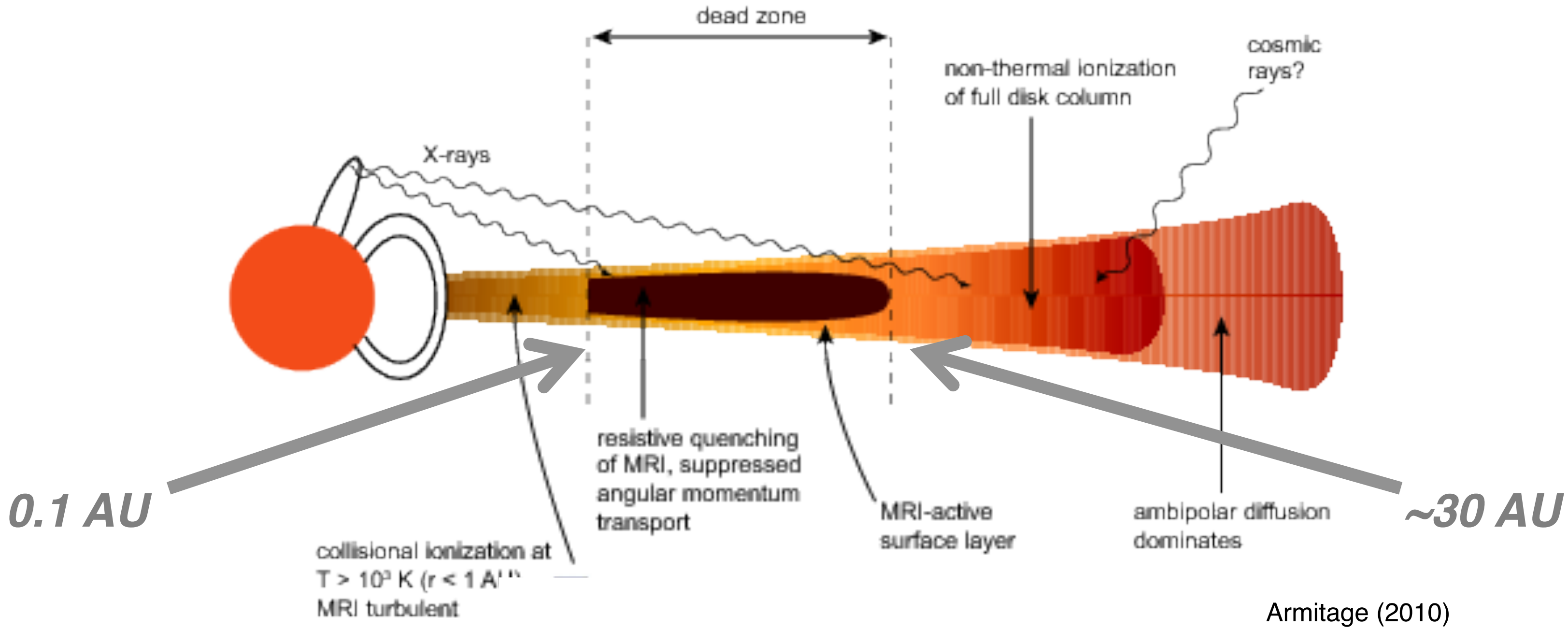
Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

Dead zones are robust features of protoplanetary disks



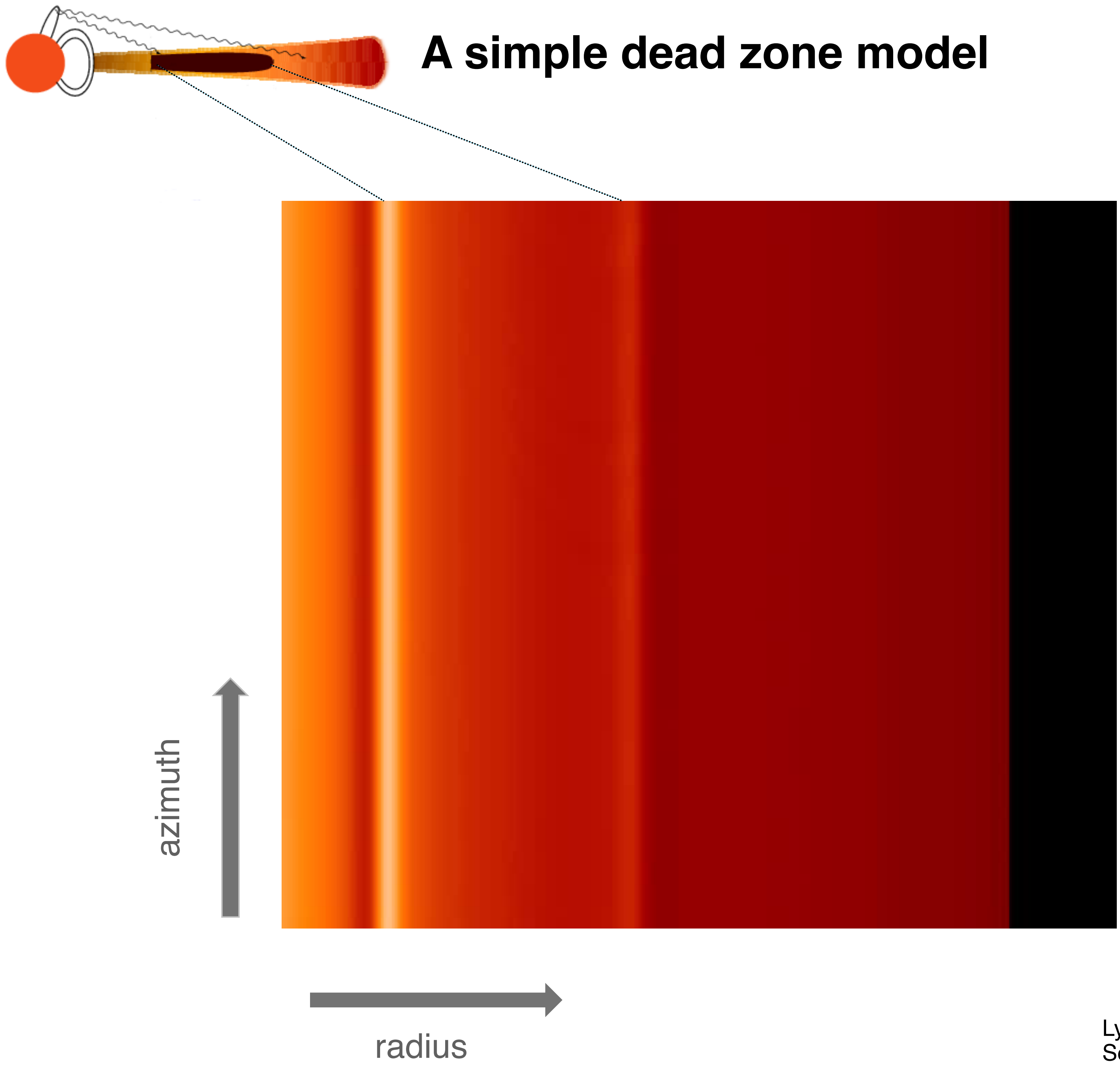
Armitage (2010)

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

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

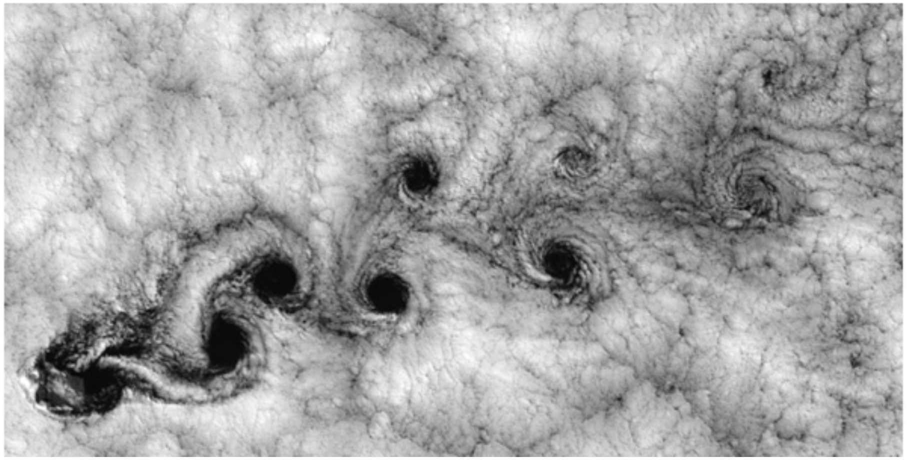
There should be a **magnetized, active zone**,
and a **non-magnetic, dead zone.**

A simple dead zone model



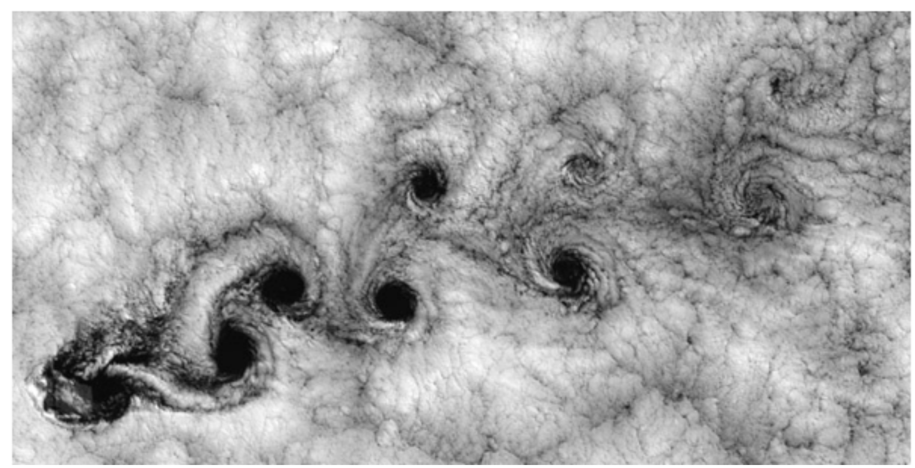
Lyra et al. (2008b);
See also Varniere & Tagger (2006)

Vortices – an ubiquitous fluid mechanics phenomenon



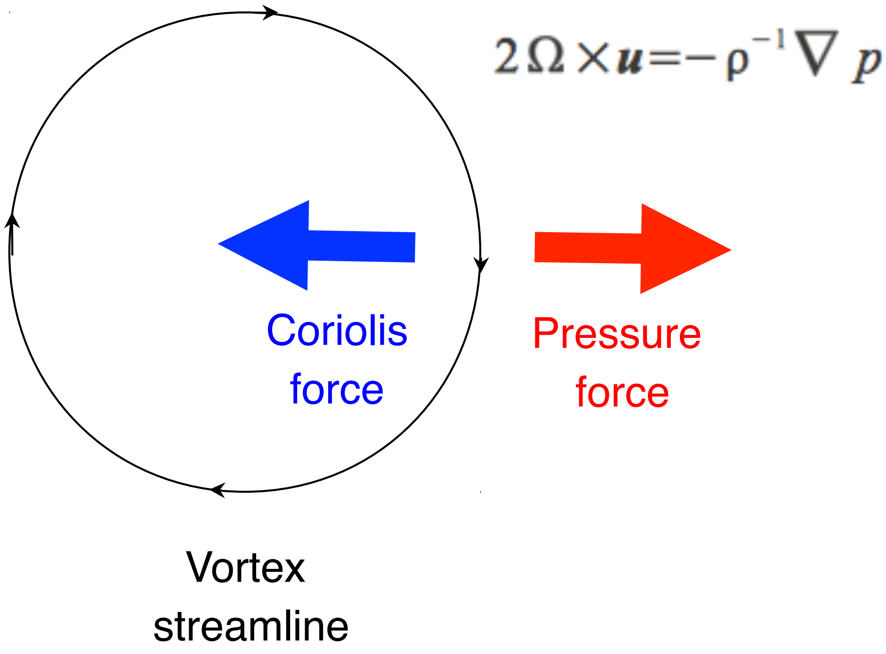
Vortices – an ubiquitous fluid mechanics phenomenon

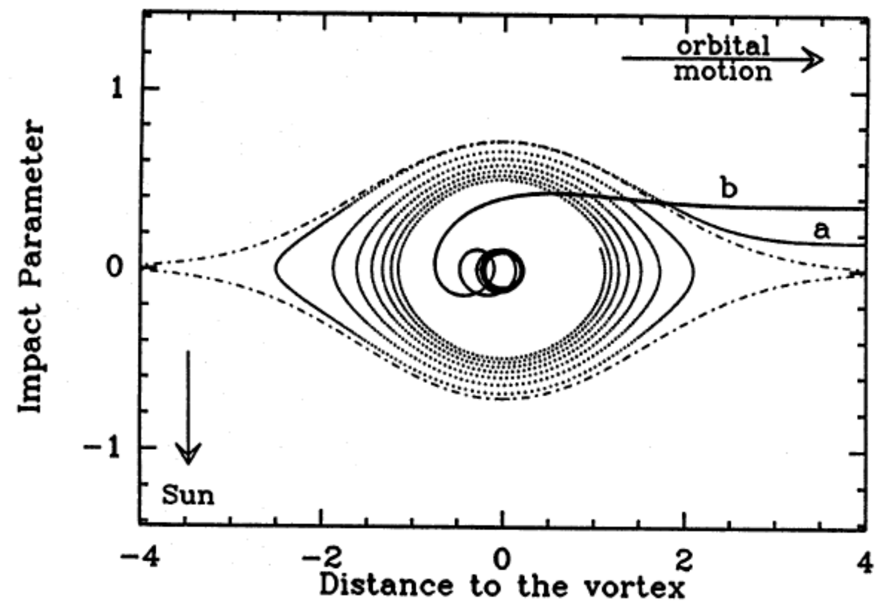
Von Kármán *vortex street*



The Tea-Leaf effect

Geostrophic balance:





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)

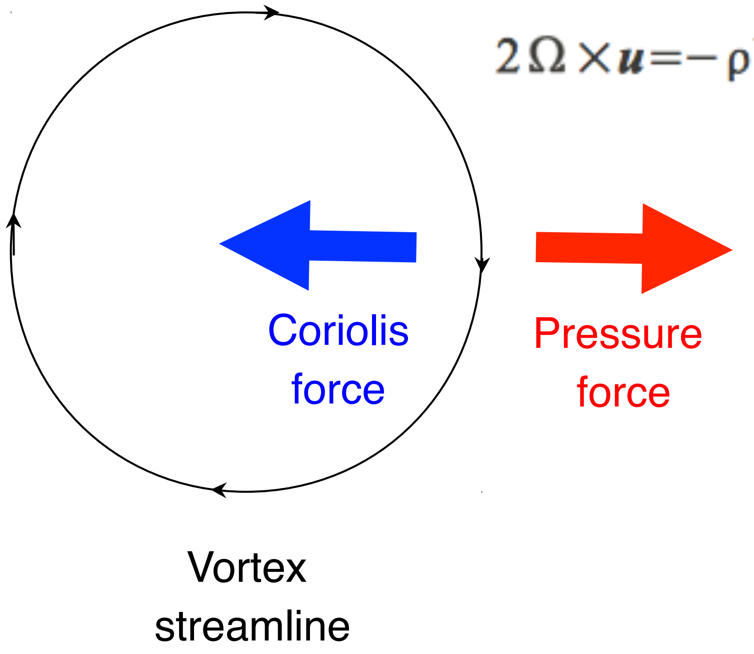
Speed up planet formation enormously

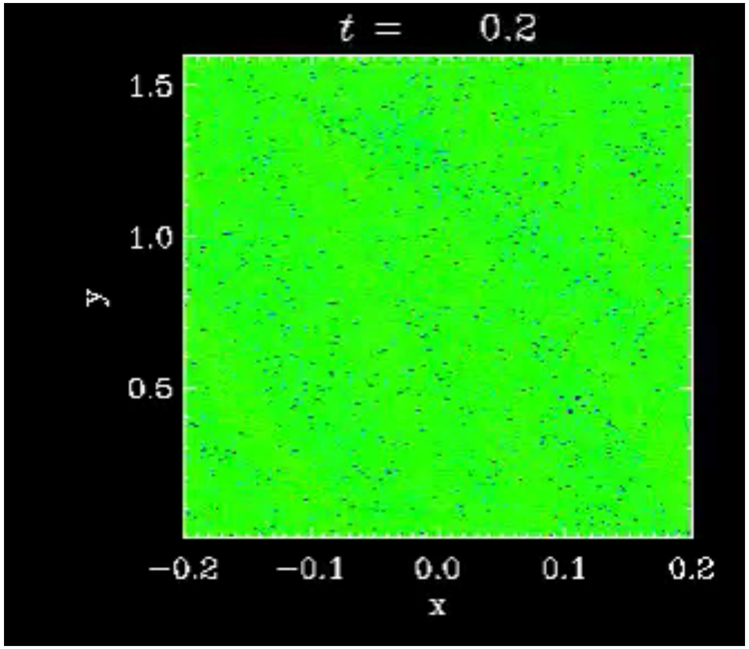
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

The Tea-Leaf effect

Geostrophic balance:

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





Raettig et al. (2012)

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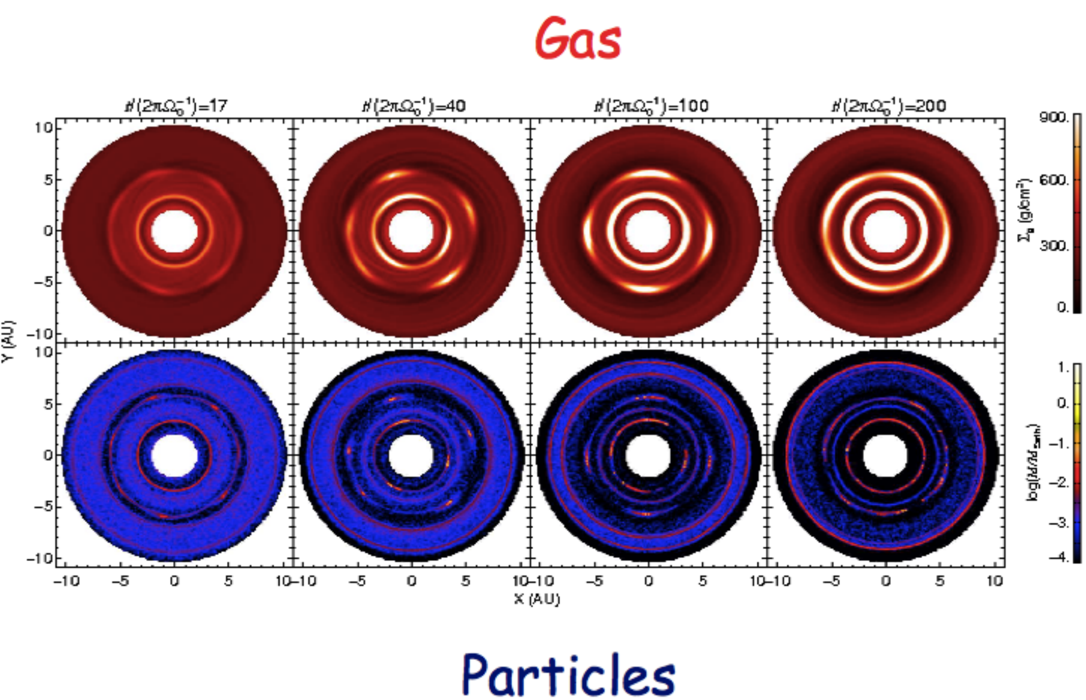
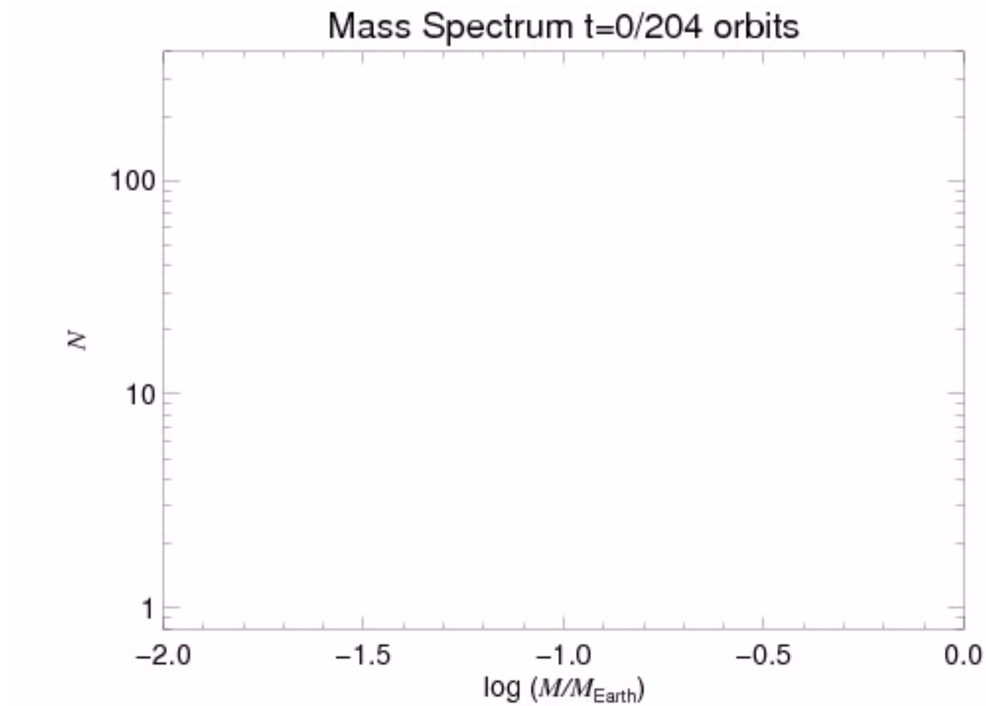
Vortices and Planet Formation

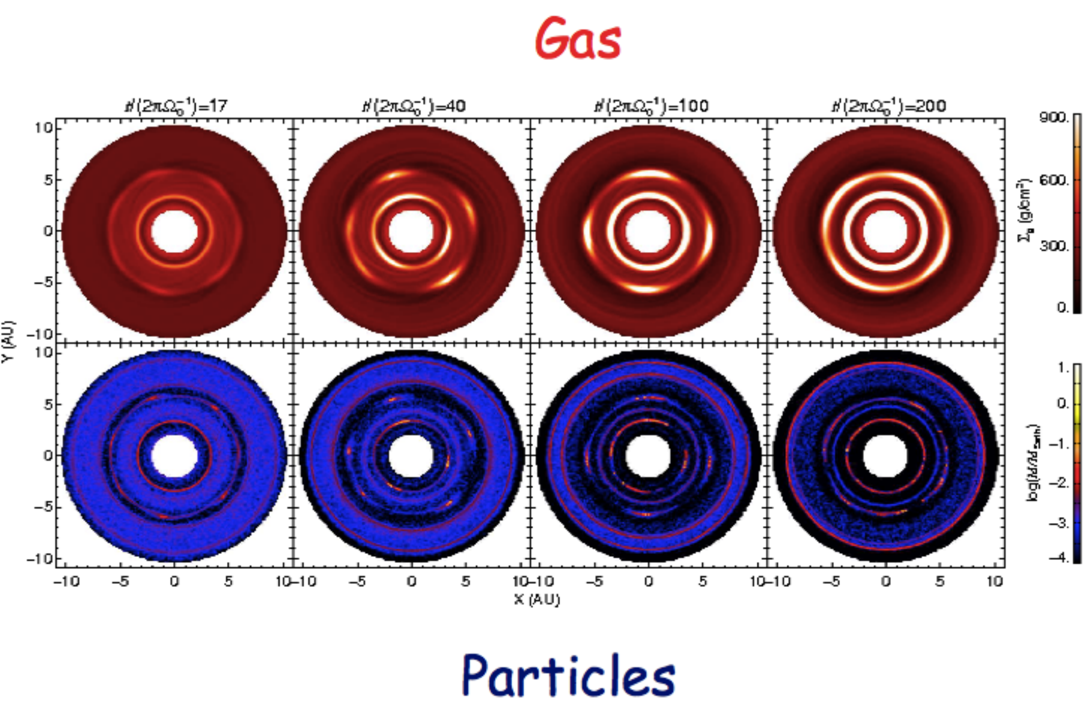


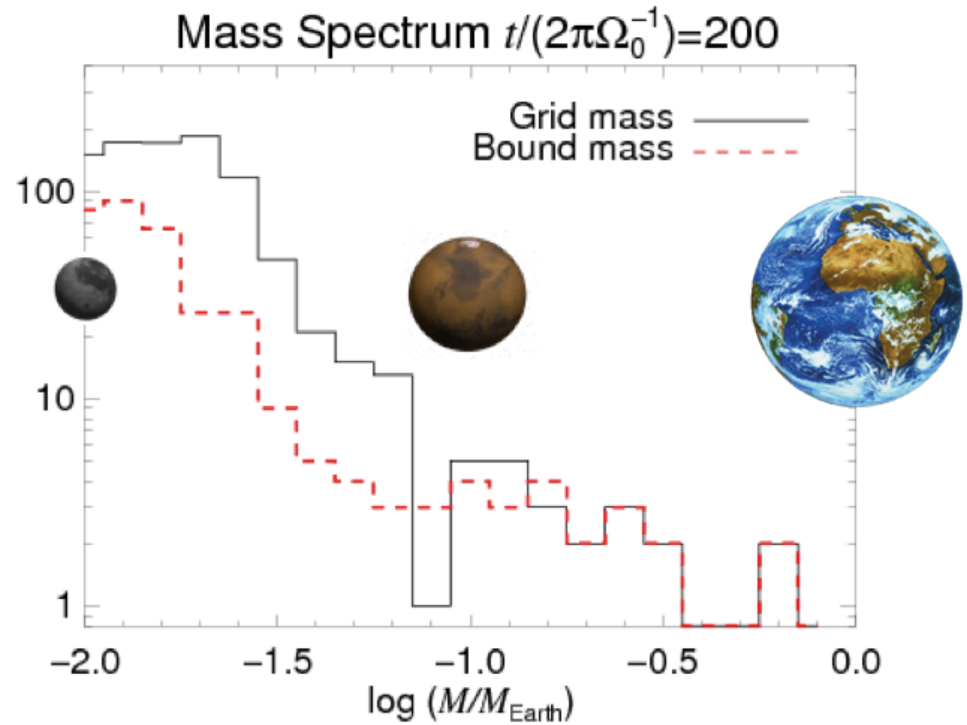


Collapse into Mars mass objects

(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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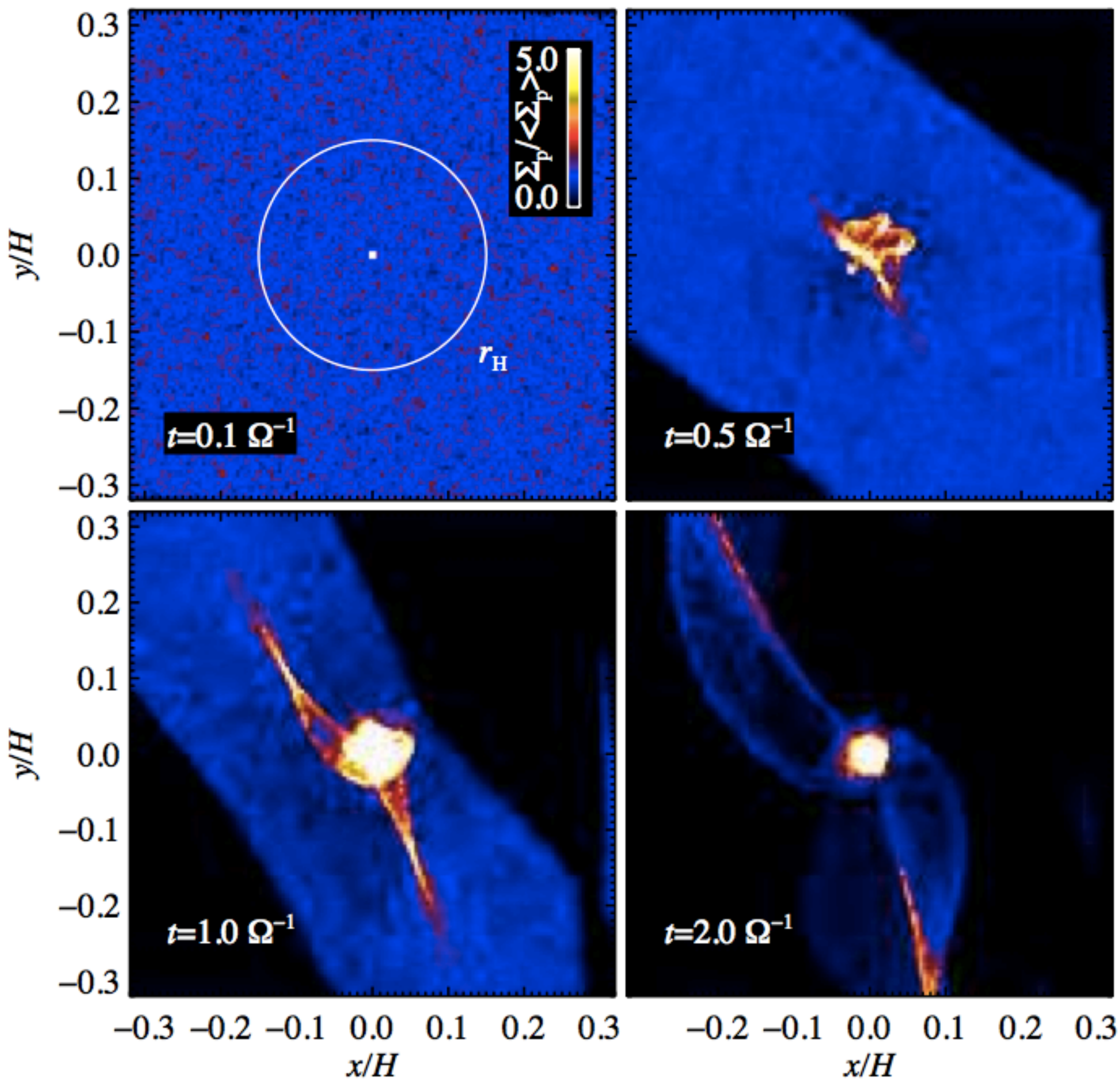
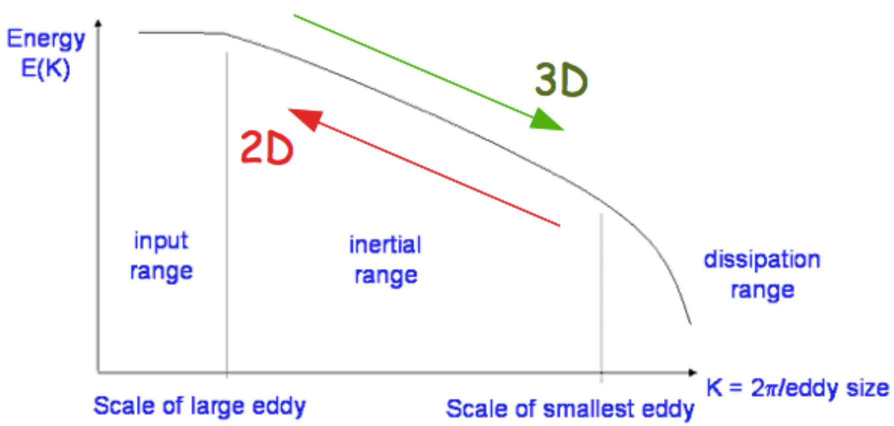
Rapid formation of planetary cores

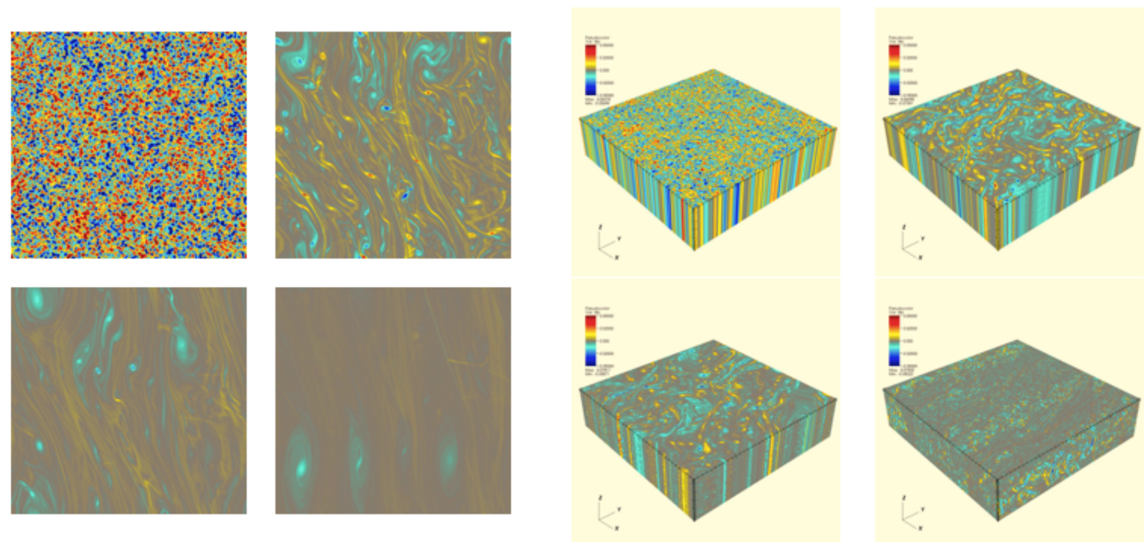


Lambrechts & Johansen (2012)

The energy cascade



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



2D

3D

Inverse cascade

No 3D instability
Eddies merge

Direct cascade

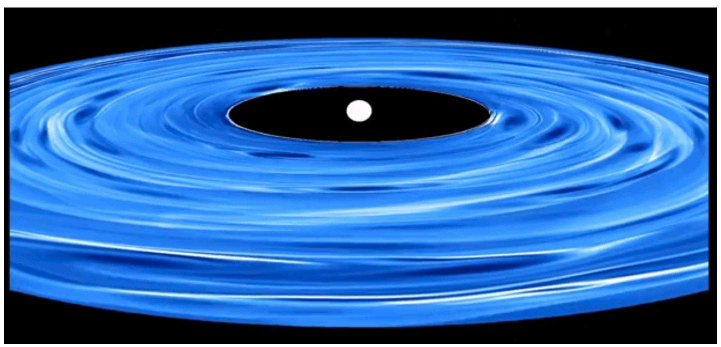
Destruction occurs
faster than merging

Sustaining vortices in disks

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

Baroclinic instability

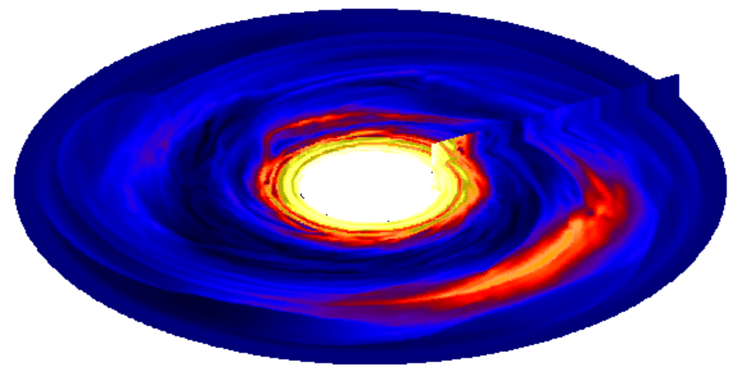
(Convective overstability)



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)

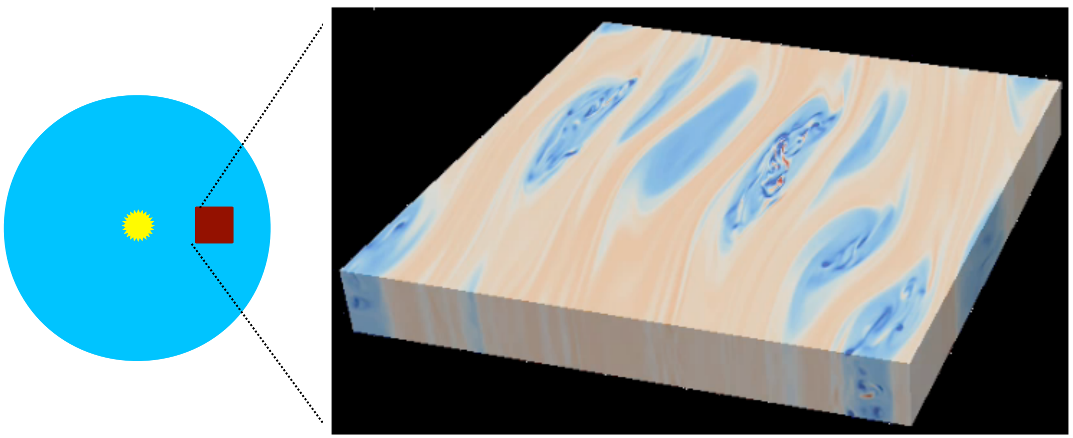
Rossby wave instability



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)

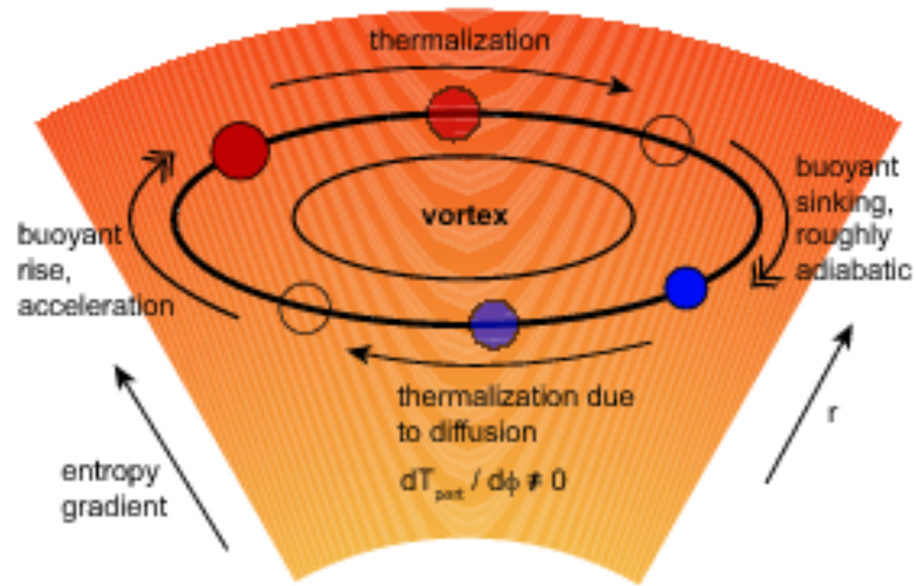
Powered by:
Modification of shear profile
(external vorticity reservoir)

Baroclinic Instability – Excitation and self-sustenance of vortices



Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability

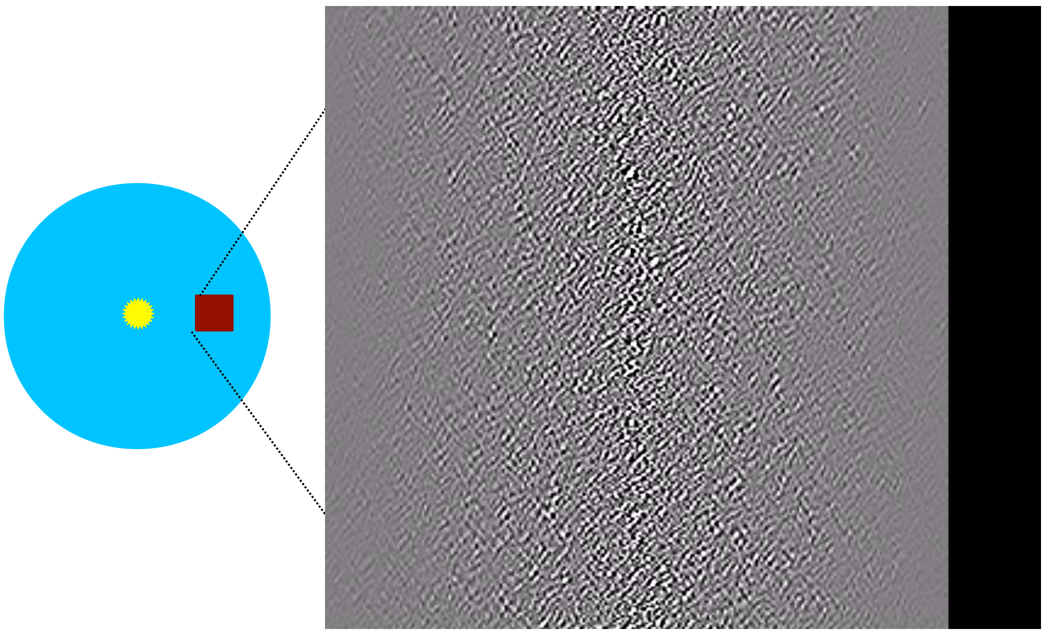


Armitage (2010)

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

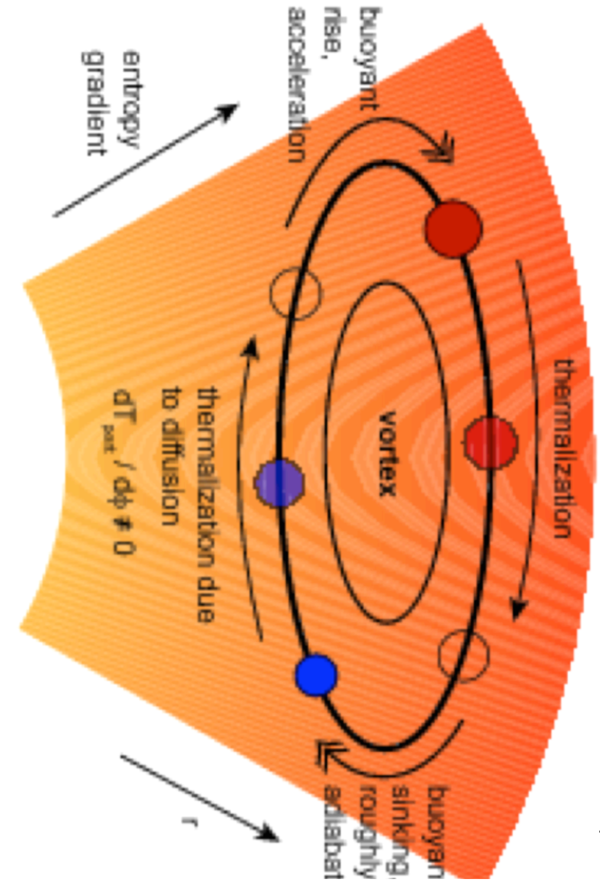
advection — compression — stretching — baroclinicity — dissipation

Baroclinic Instability – Excitation and self-sustenance of vortices



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

The "Baroclinic Instability" is LINEAR (Convective Overstability)

Klahr & Hubbard (2014), Lyra (2014)

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

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

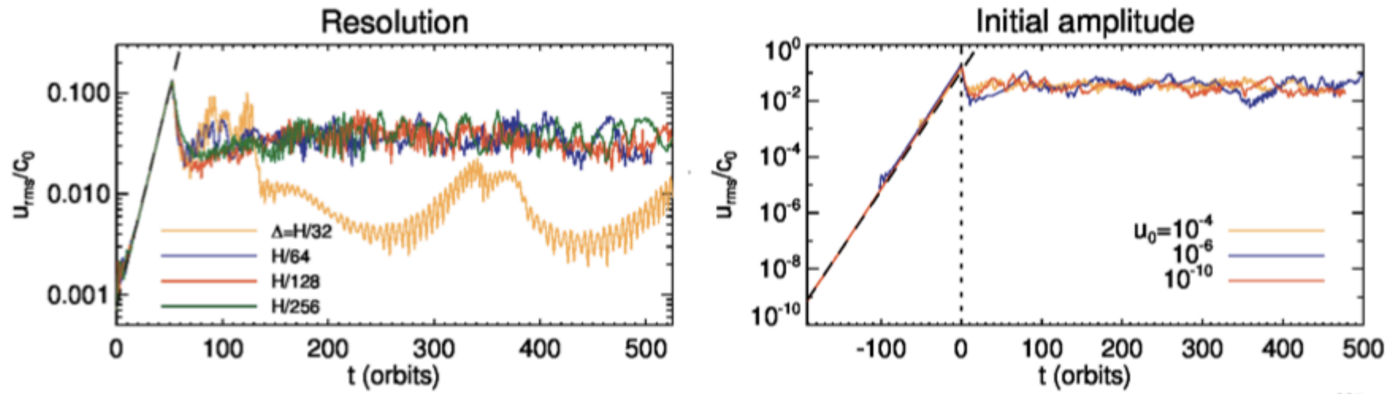
$$\frac{\partial p}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,p = -\gamma p\boldsymbol{\nabla}\cdot\boldsymbol{u} - \frac{p}{T}\frac{(T-T_0)}{\tau},$$

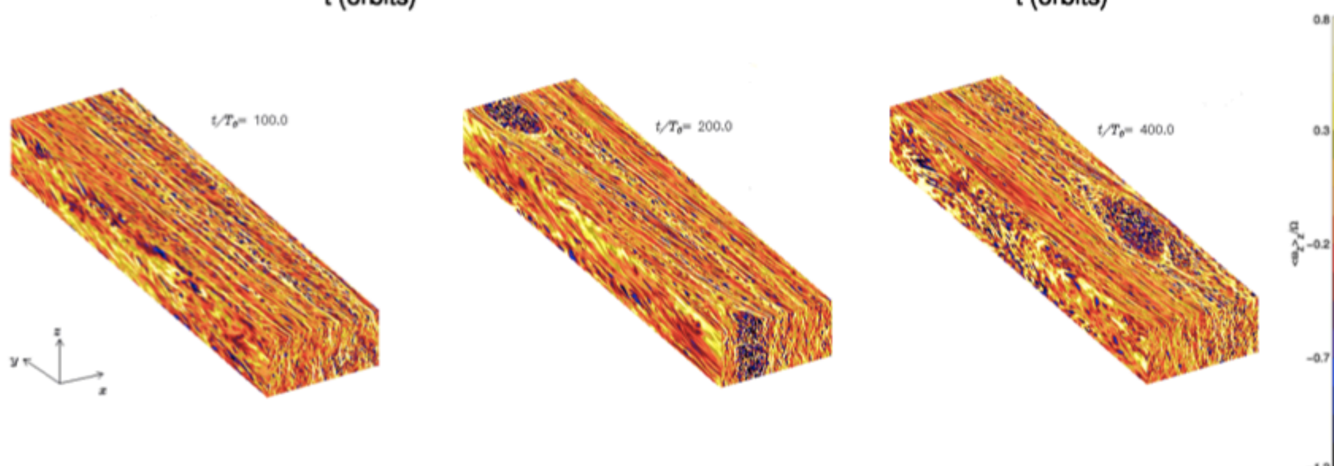
$$\bar{\omega}^3 + i\varsigma\bar{\omega}^2 - \bar{\omega}\mu^2(\kappa^2+N^2) - i\varsigma\kappa^2\mu^2 = 0,$$

$$\varsigma = 1/\gamma\tau \qquad \mu^2 = \quad k_z^2/k^2.$$

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

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

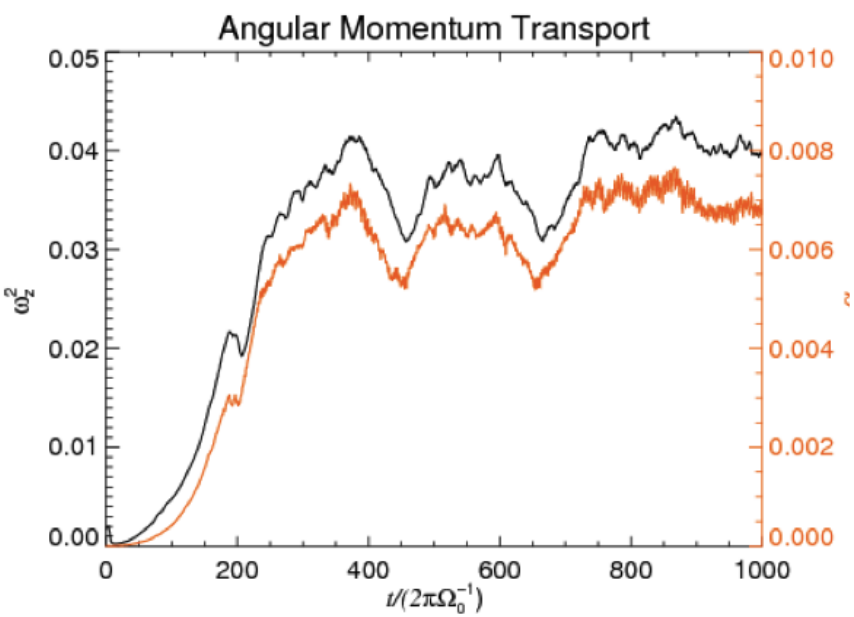




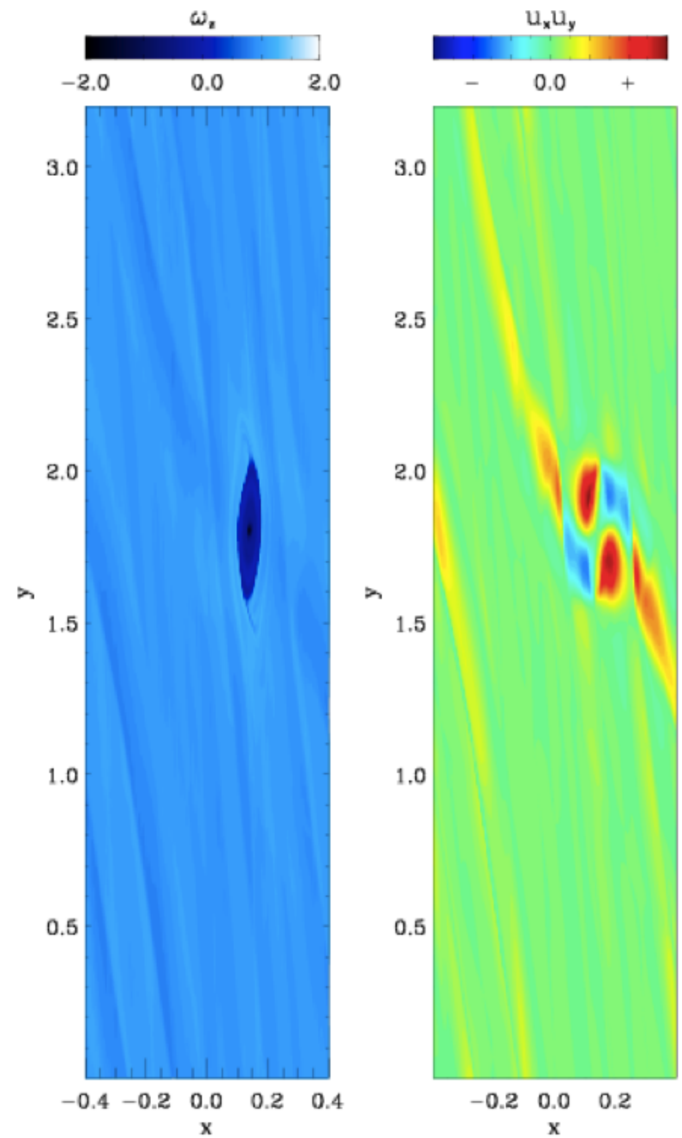
Lyra (2014)

Baroclinic Instability and Accretion

Large mass accretion rates, comparable to the MRI!



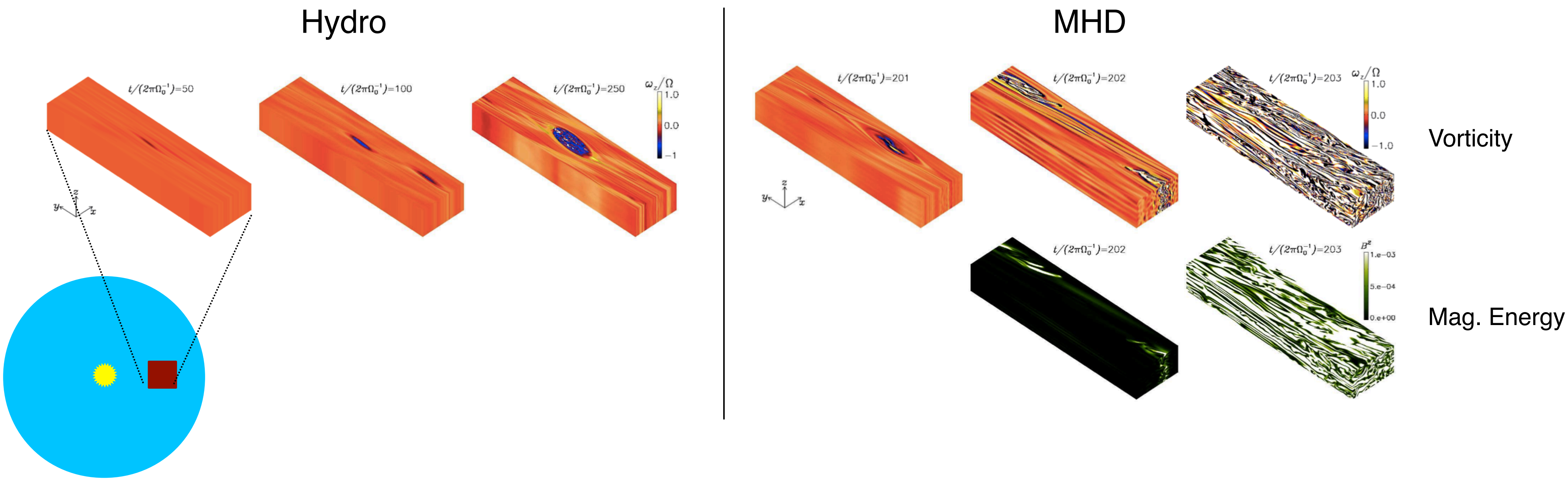
Raettig, Lyra, & Klahr (2012)



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

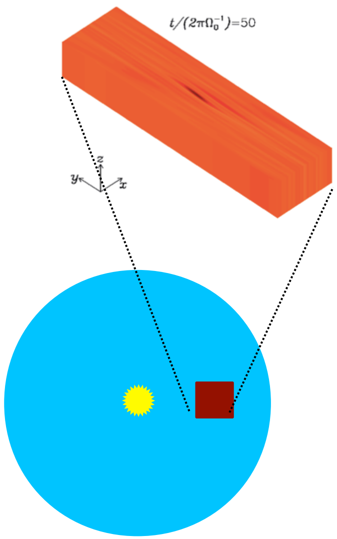
Baroclinic instability and layered accretion

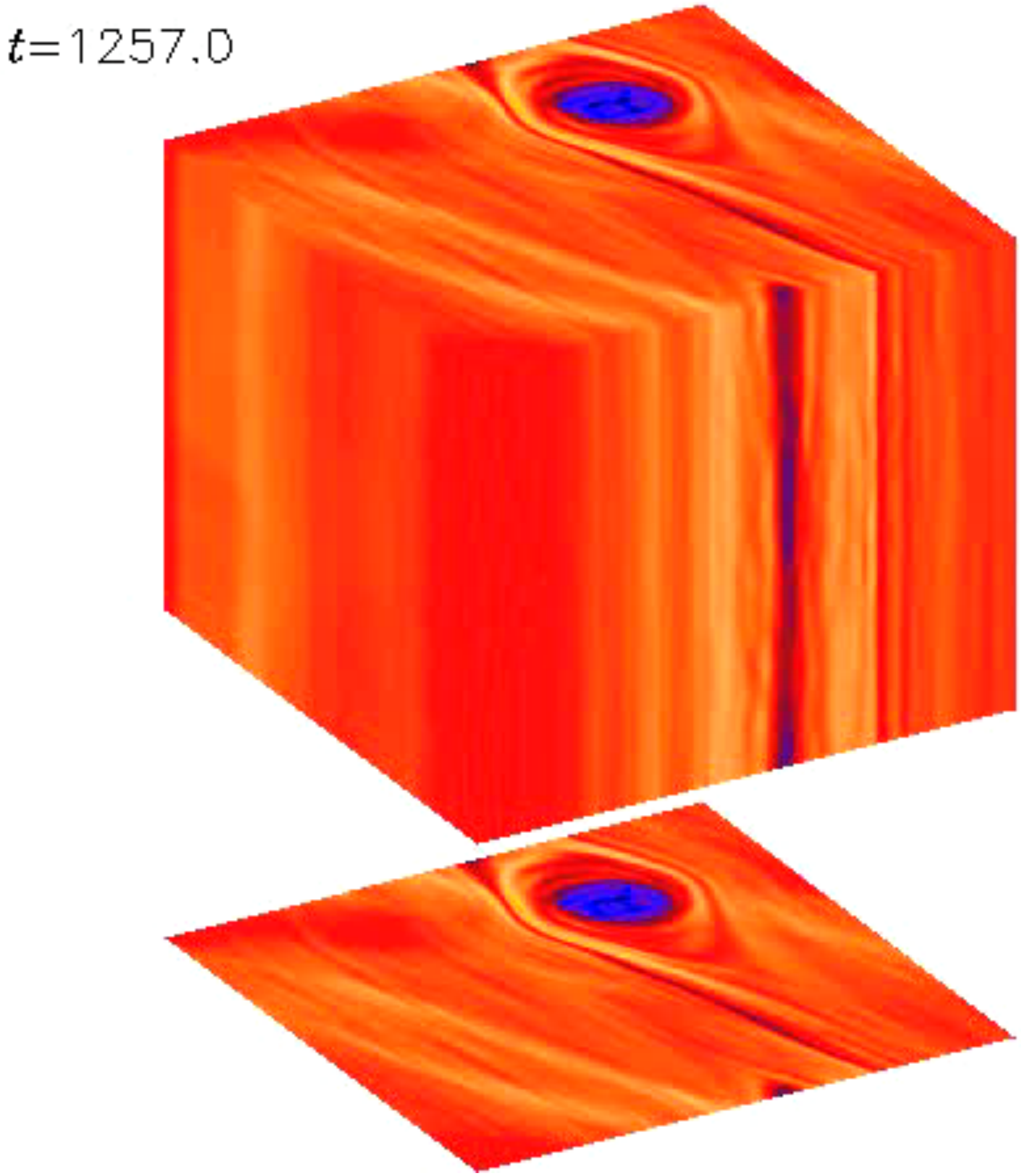
What happens when the vortex is magnetized?

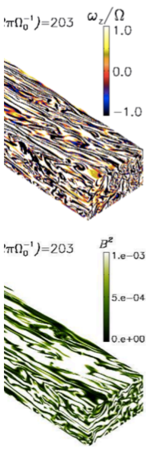


Lyra & Klahr (2011)

Baroclinic instability and layered accretion







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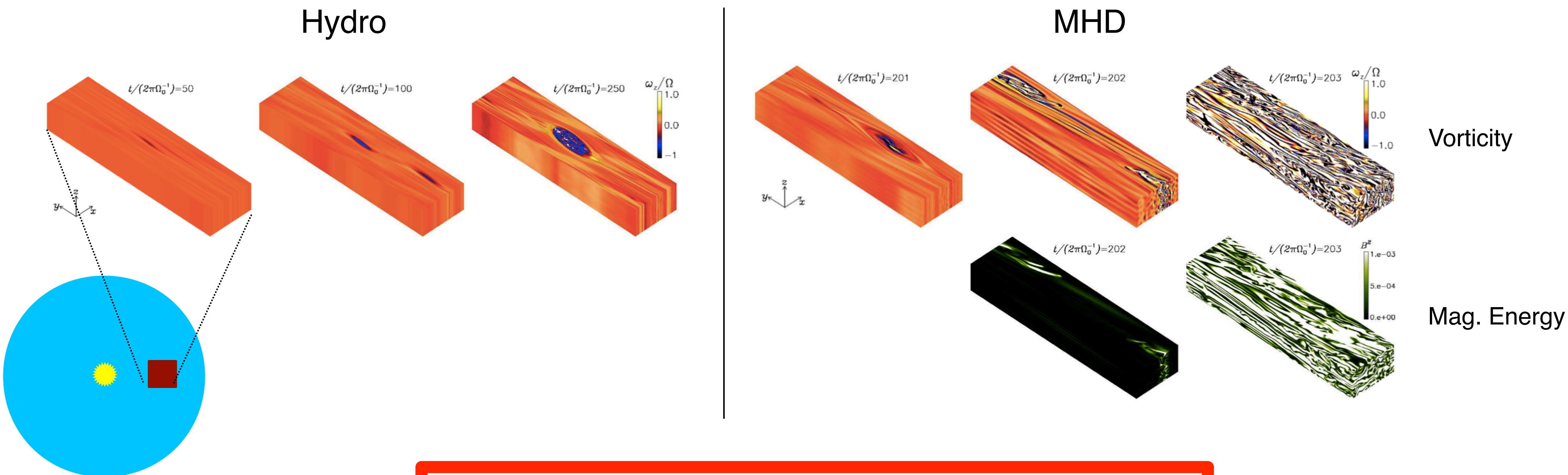
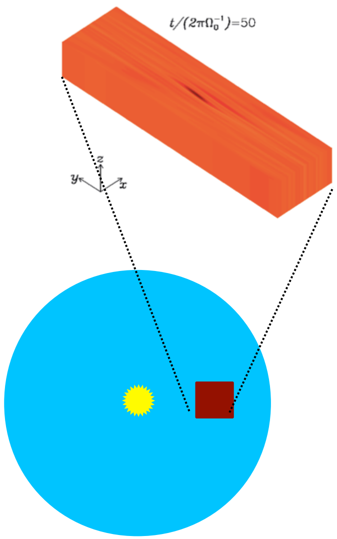


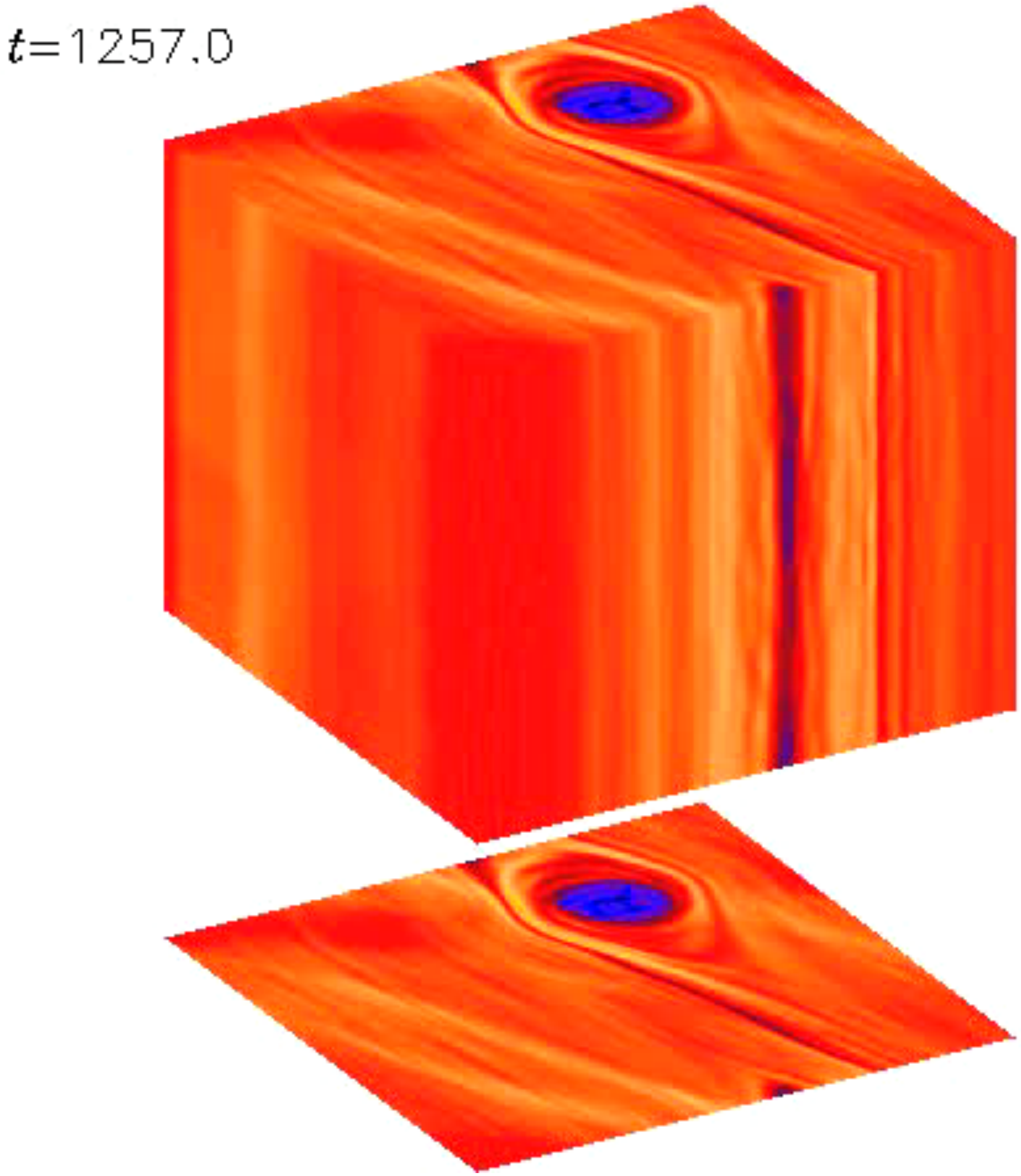
Lyra & Klahr (2011)

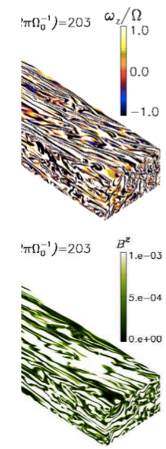
Baroclinic vortices

do ***not*** survive magnetization

Baroclinic instability and layered accretion





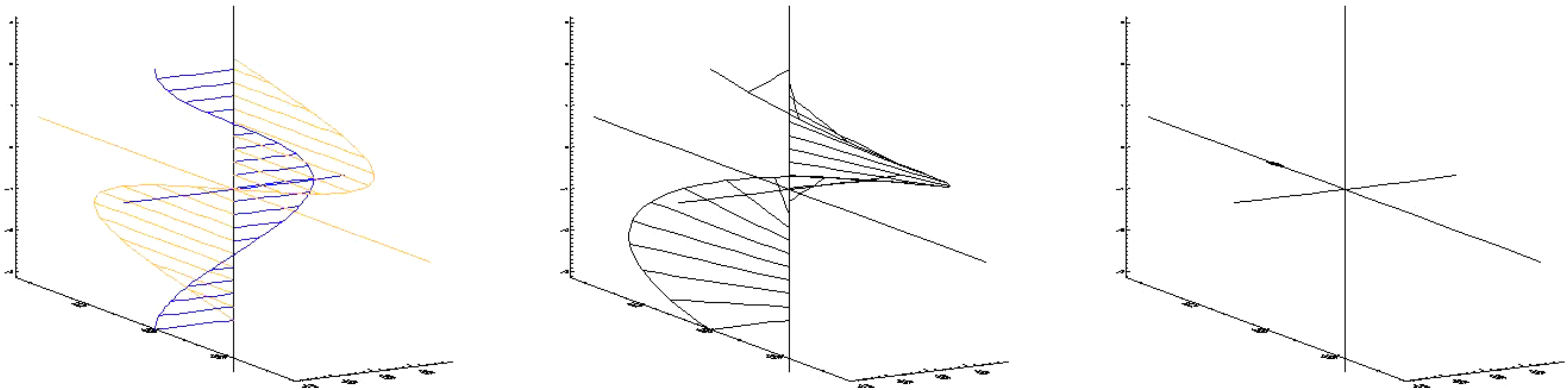


Vorticity

Mag. Energy

Lyra & Klahr (2011)

Fluid in rigid rotation supports a spectrum of oscillations



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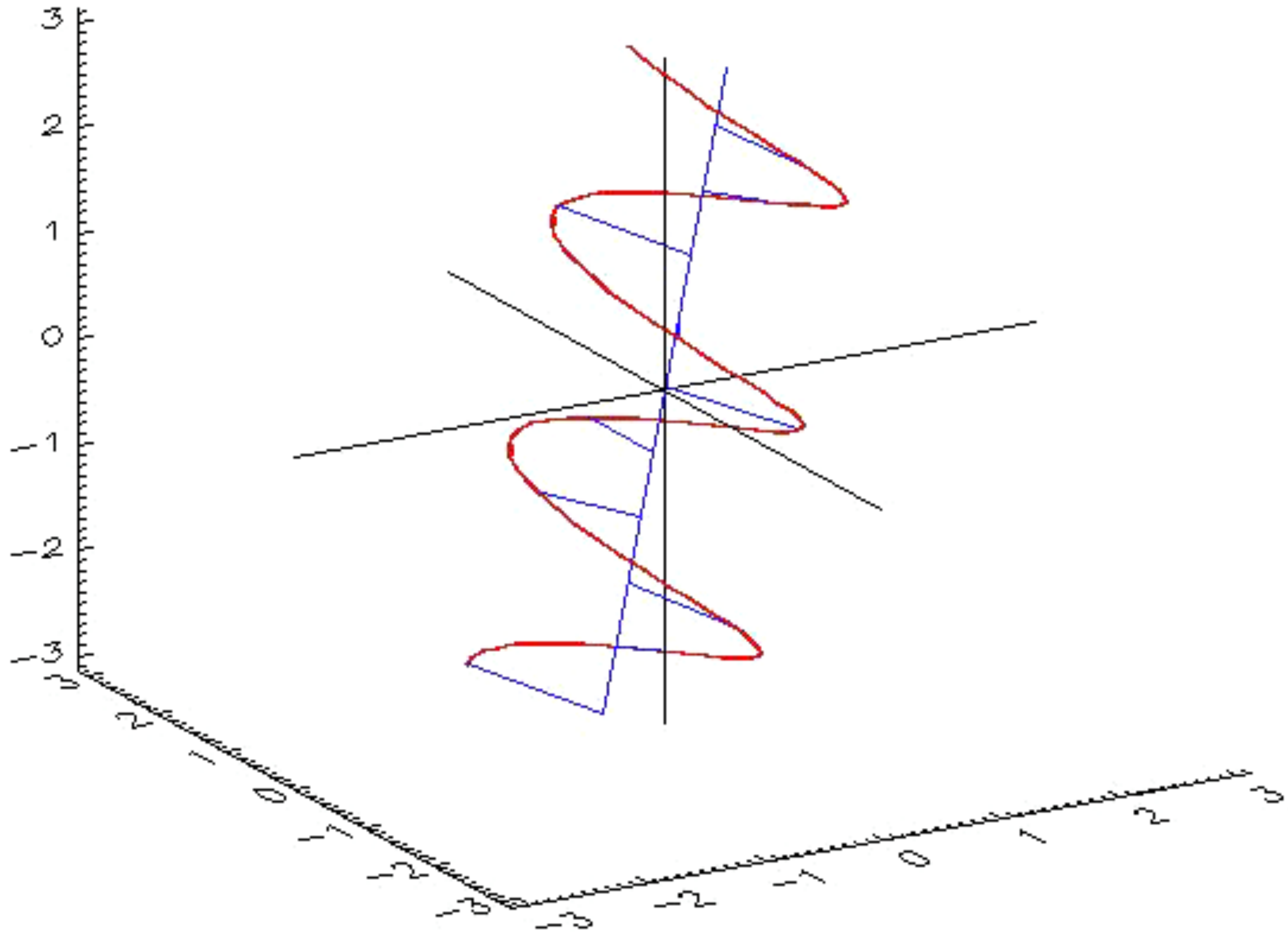
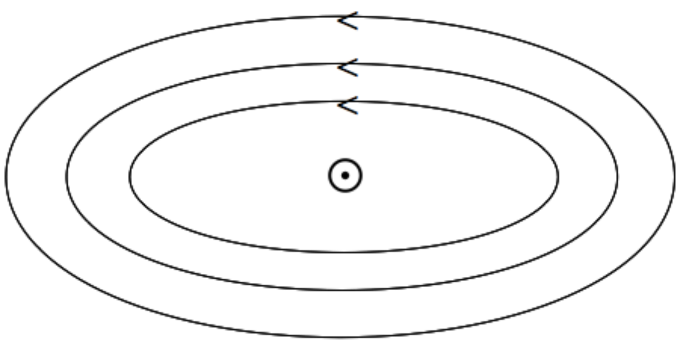


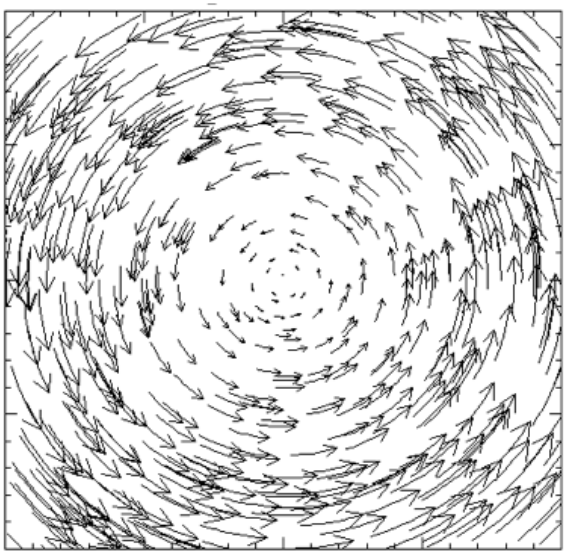
Introducing ellipticity: Strain



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

$=$

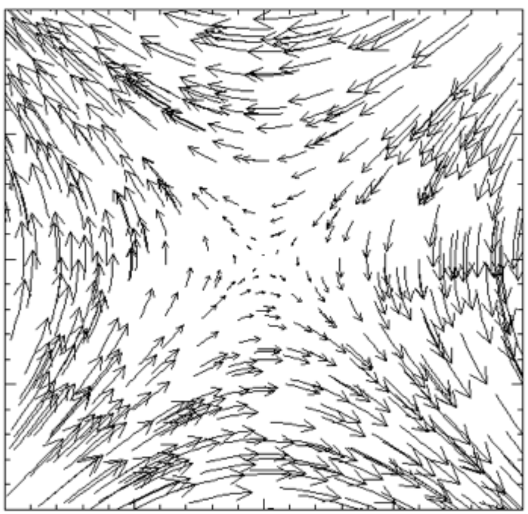
Rigid rotation



$[-y,x]$

$+$

Strain field

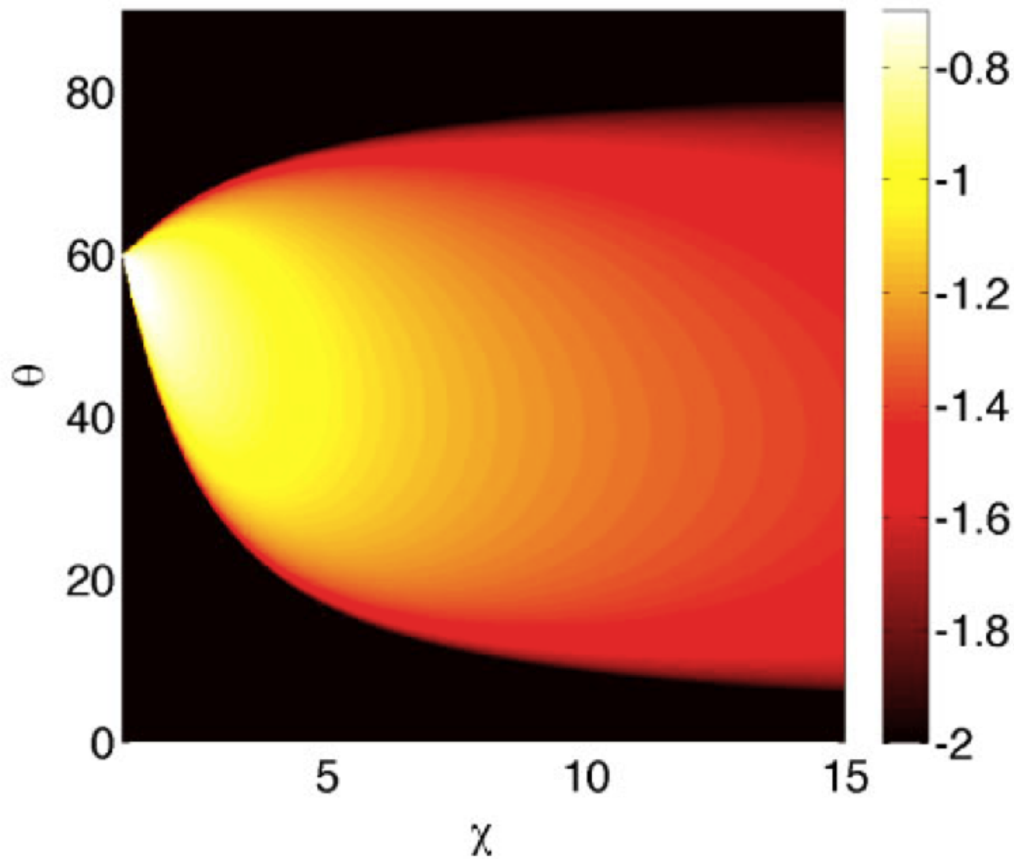


$-\epsilon[y,x]$

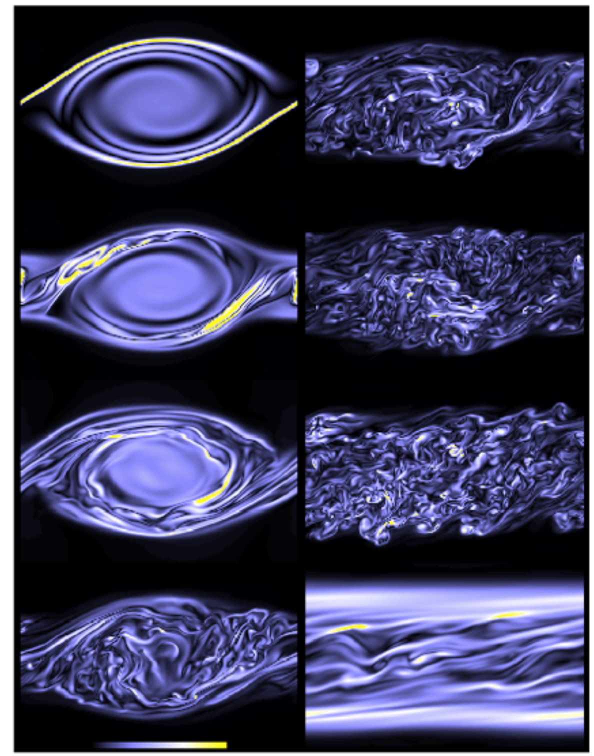
Rigid rotation is stable.

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

Elliptic Instability



Lesur & Papaloizou (2009)
After Bayly (1986)

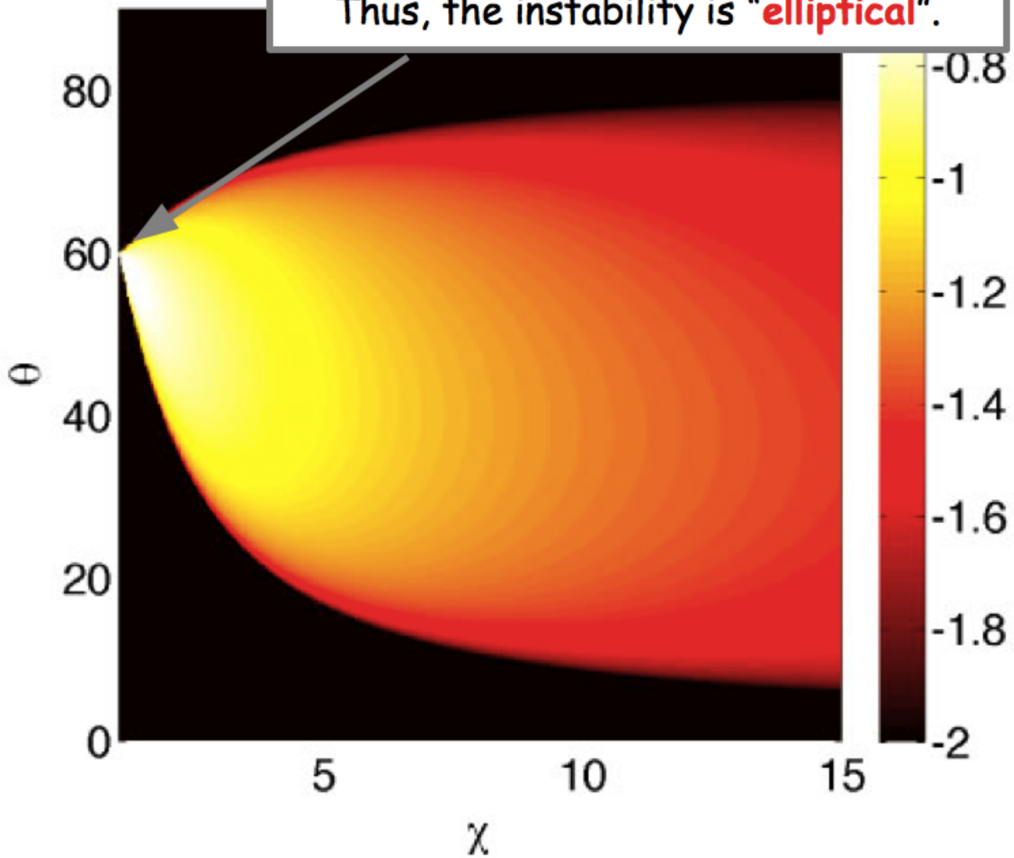


Vortex coherence is destroyed.
Energy cascades forward and dissipates.
The flow relaminarizes.

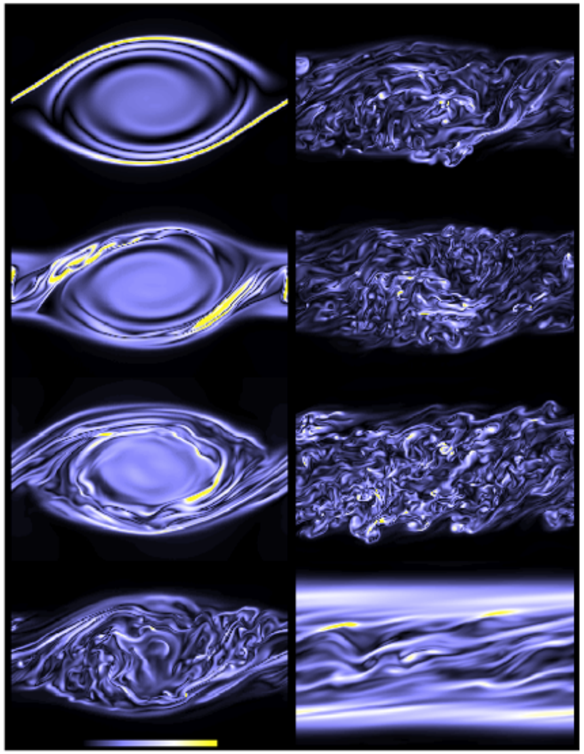
McWilliams (2010)

Elliptic Instability

No instability for circular streamlines.
Thus, the instability is "**elliptical**".



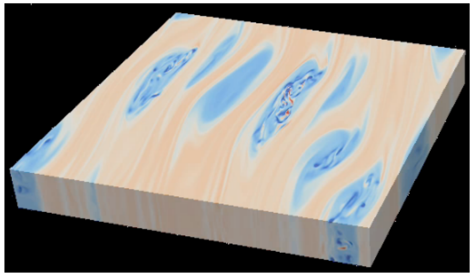
Lesur & Papaloizou (2009)
After Bayly (1986)



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

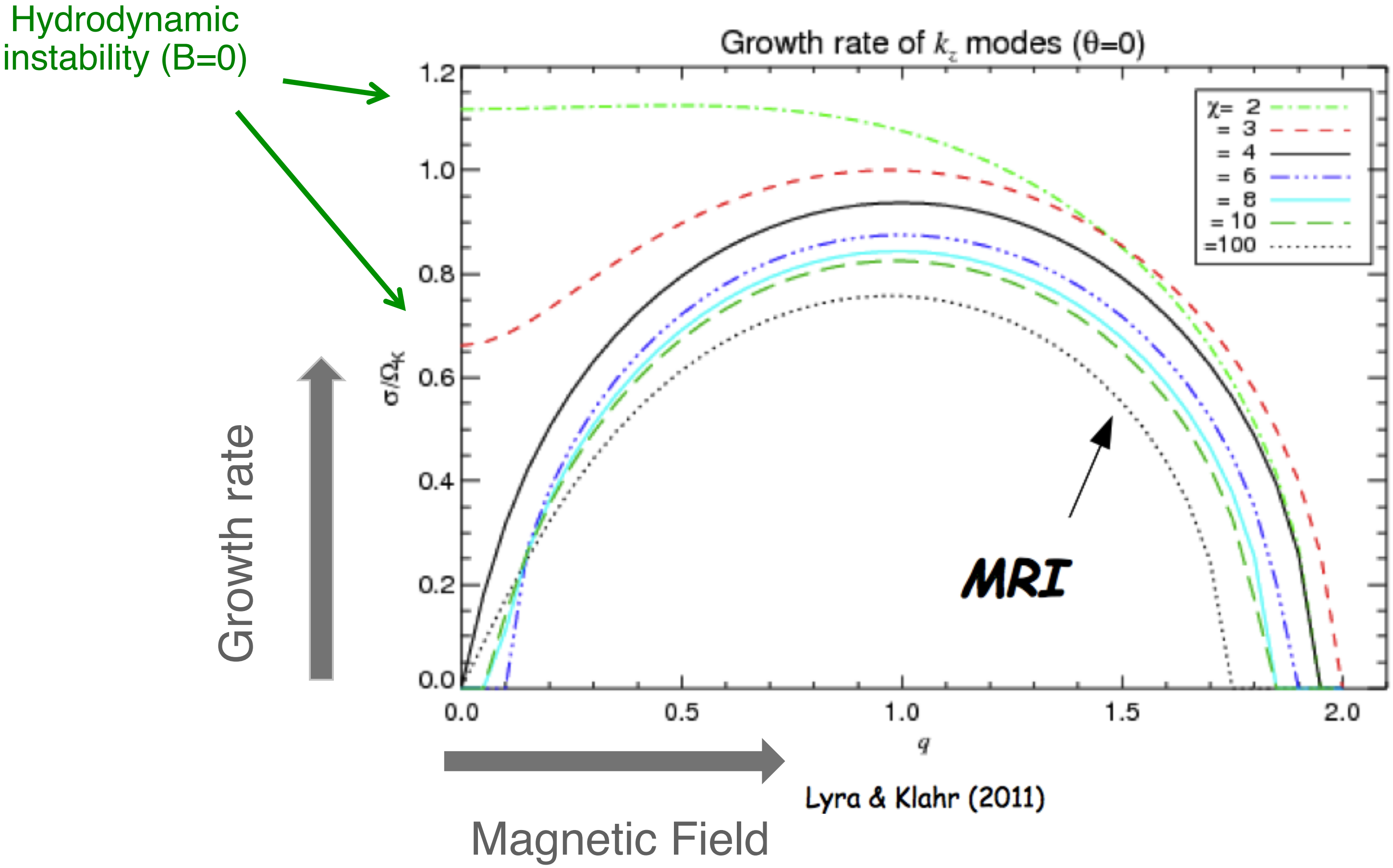
McWilliams (2010)

Magneto-Elliptic Instability



Lesur & Papaloizou (2010)

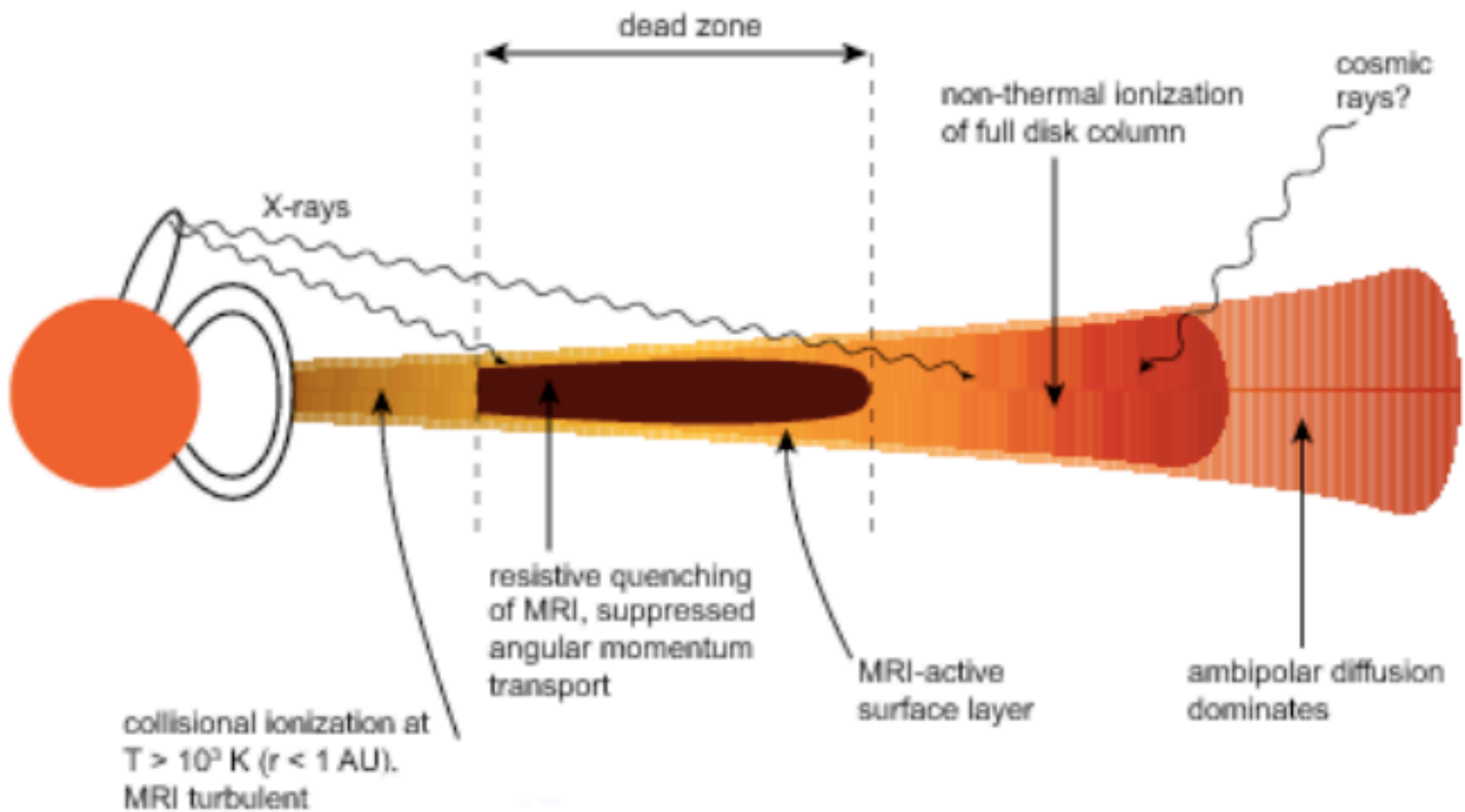
See also
Pierrehumbert 1986
Bayly 1986
Kerswell 2002
Lesur & Papaloizou 2009
Lesur & Papaloizou 2010
Lyra & Klahr 2011
Lyra 2013



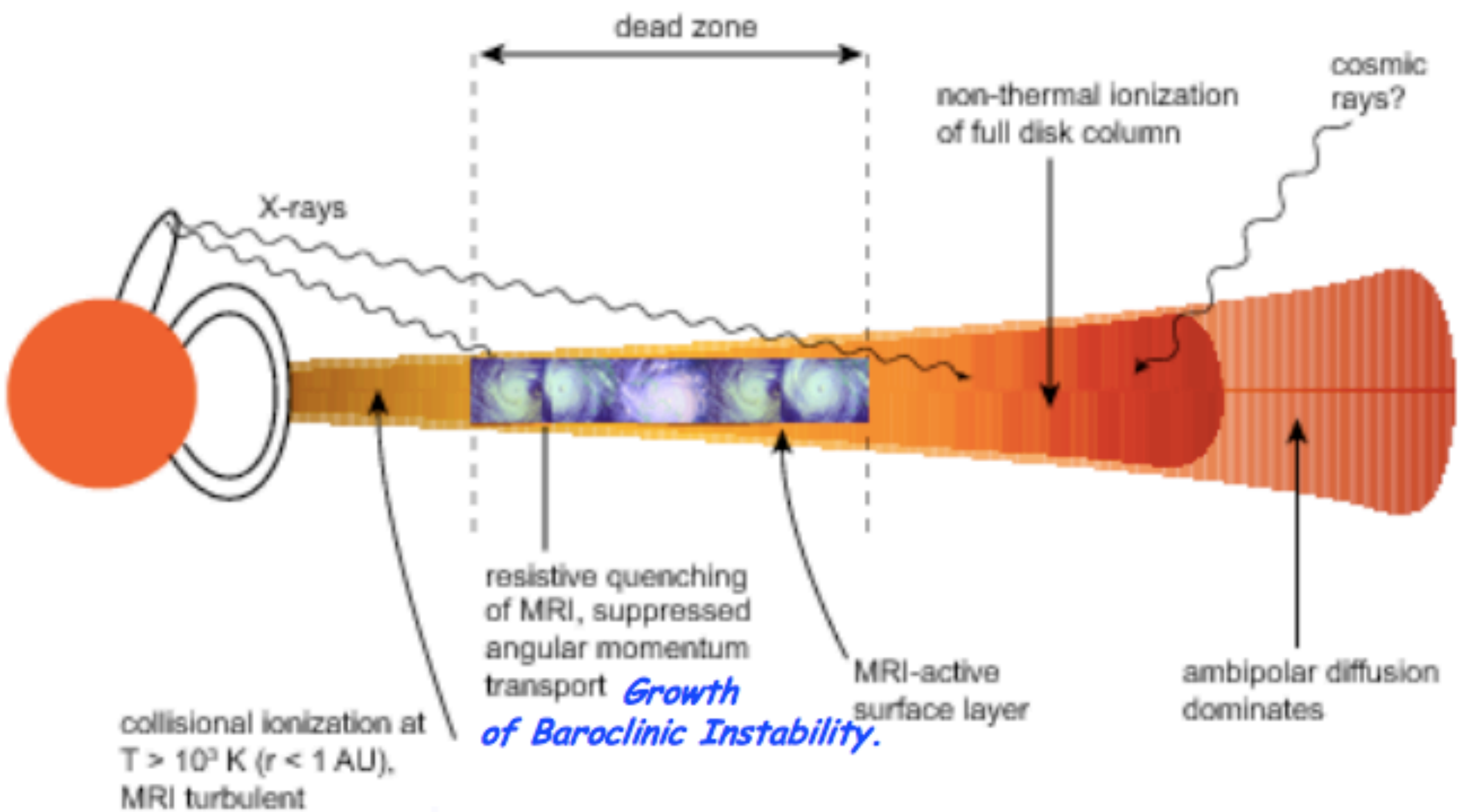
Lyra & Klahr (2011)

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

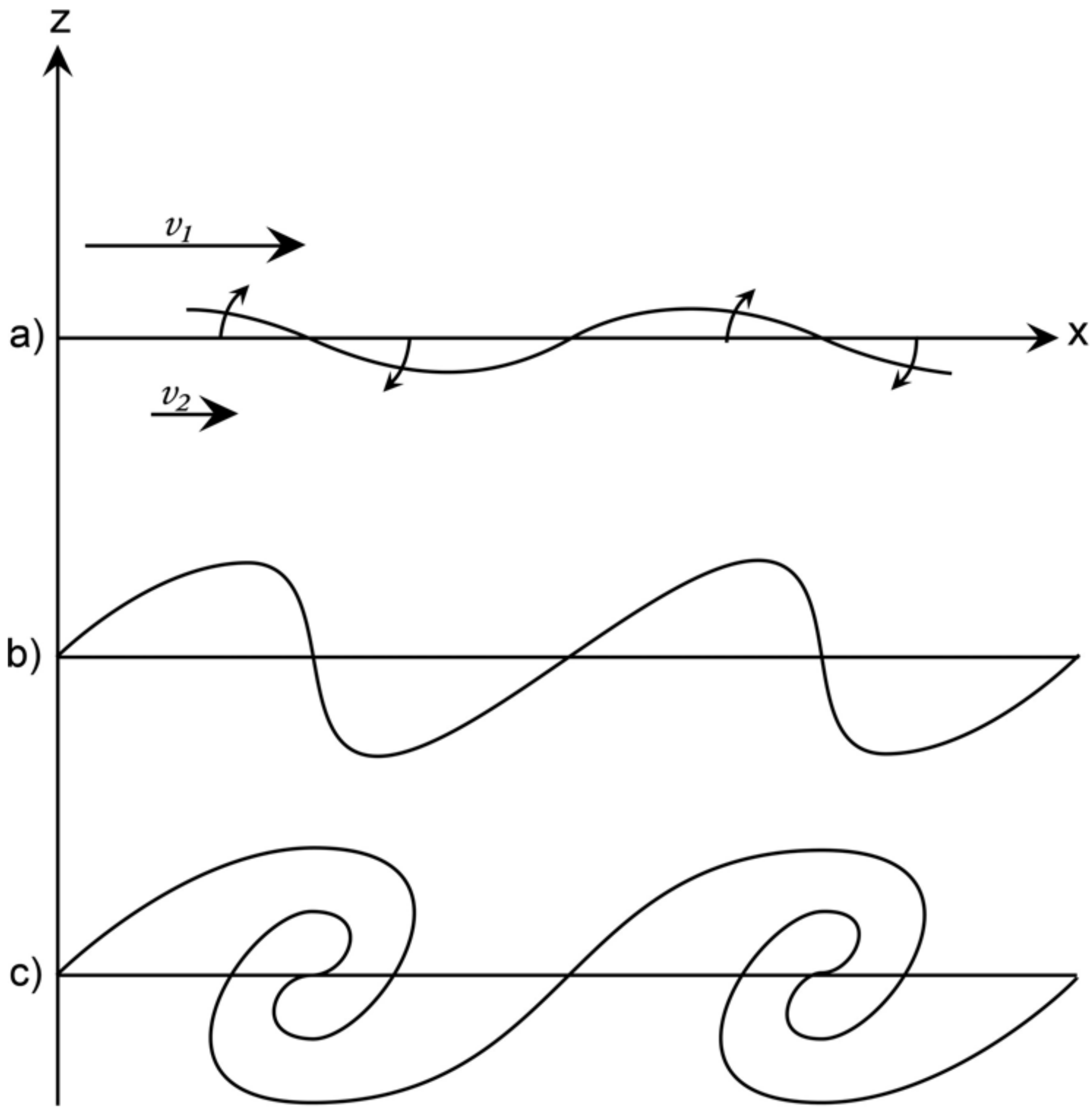
They are subject to an MRI-like instability when magnetized.



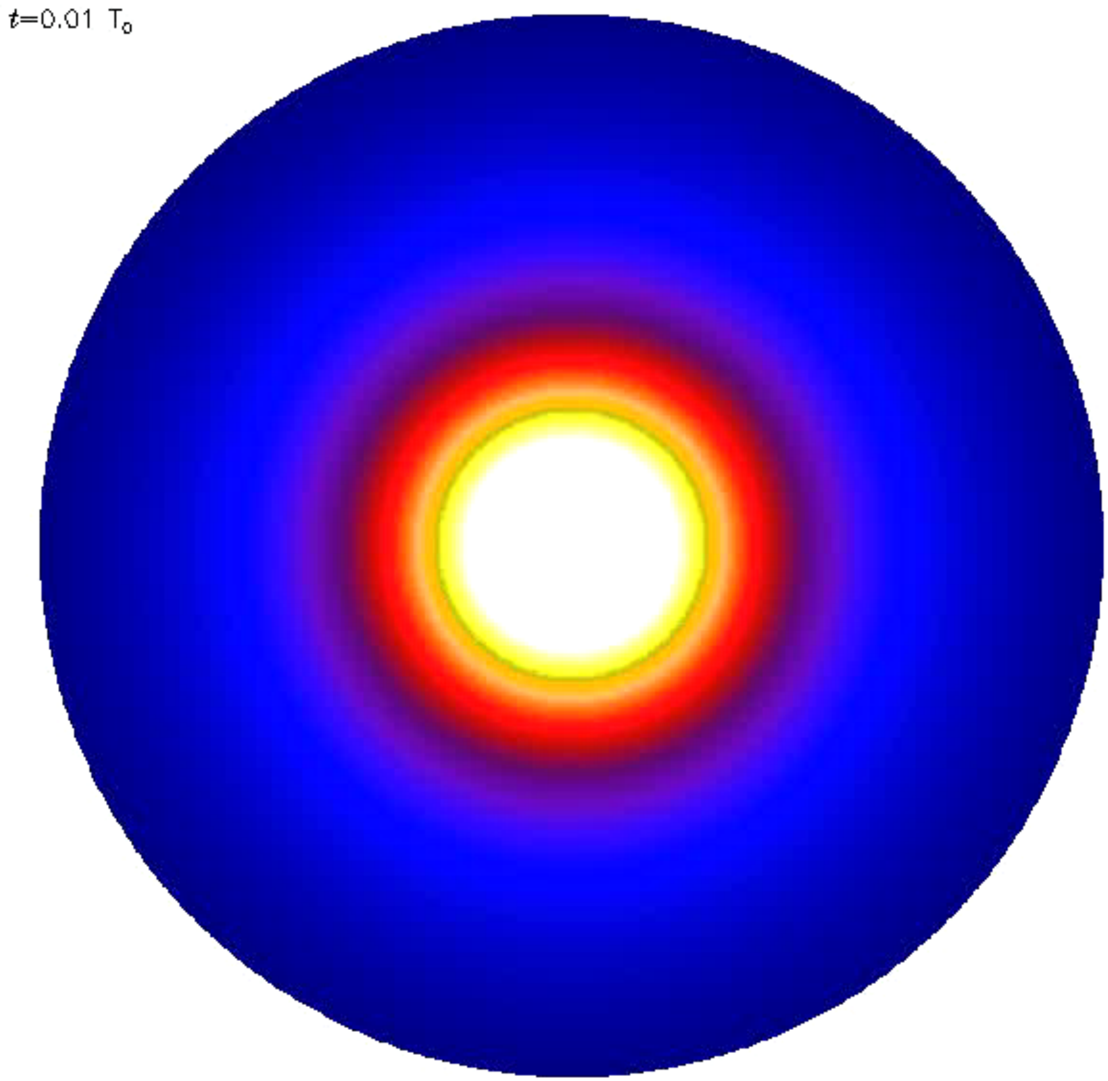
dead zone
cosmic rays?
non-thermal ionization of full disk column
X-rays
resistive quenching of MRI, suppressed angular momentum transport
MRI-active surface layer
ambipolar diffusion dominates
collisional ionization at T > 10³ K (r < 1 AU). MRI turbulent


dead zone
cosmic rays?
non-thermal ionization of full disk column
X-rays
resistive quenching of MRI, suppressed angular momentum transport
Growth of Baroclinic Instability.
MRI-active surface layer
ambipolar diffusion dominates
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent

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



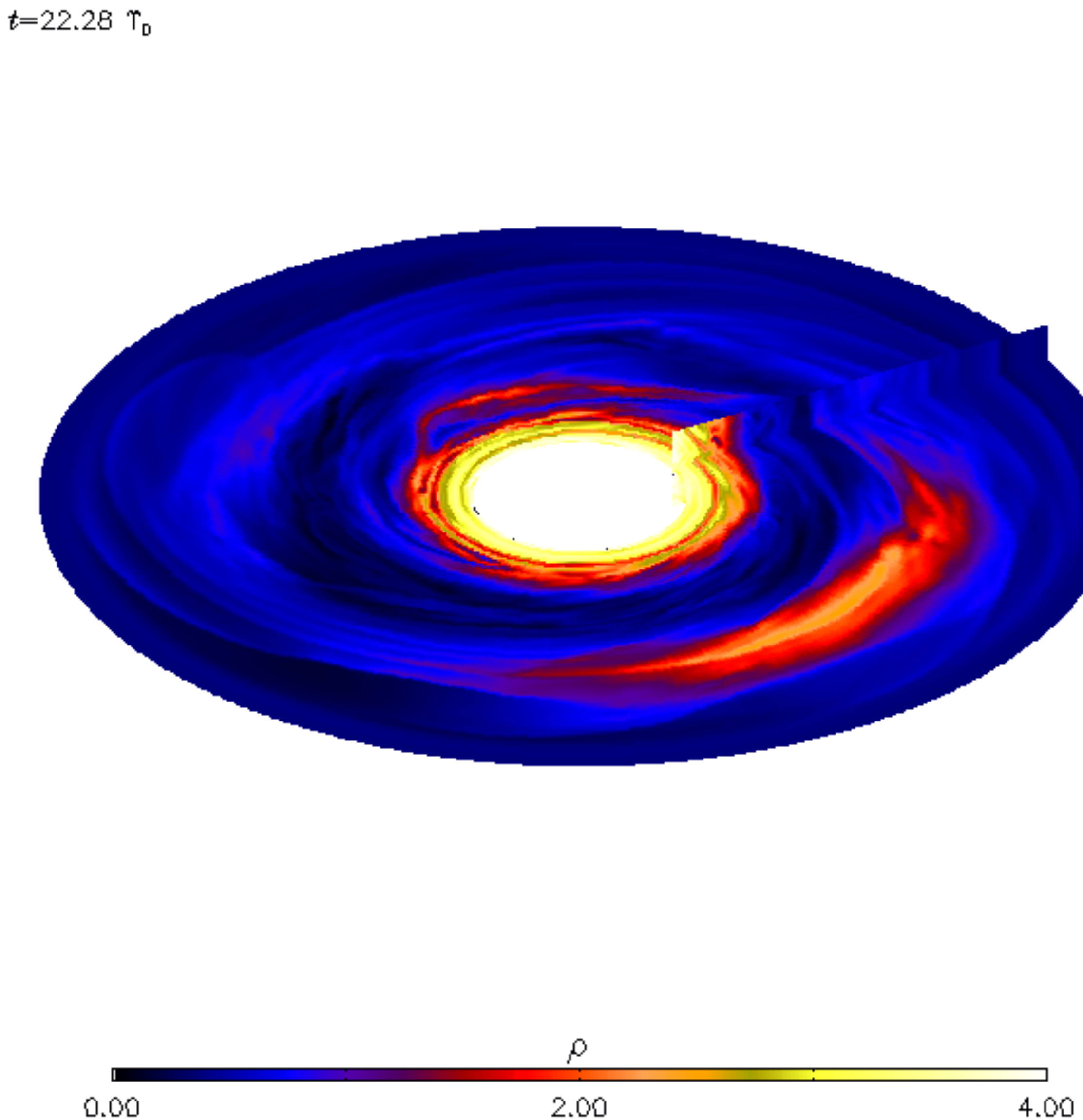
Active/dead zone boundary

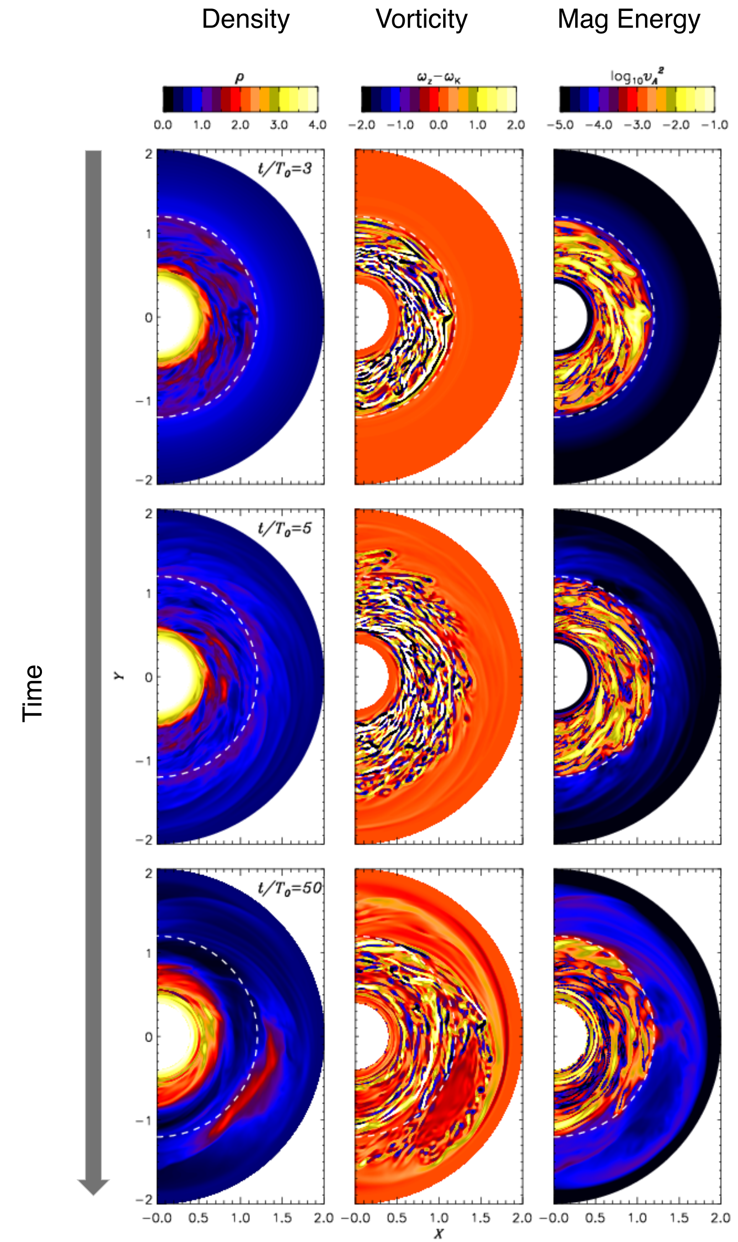


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Active/dead zone boundary

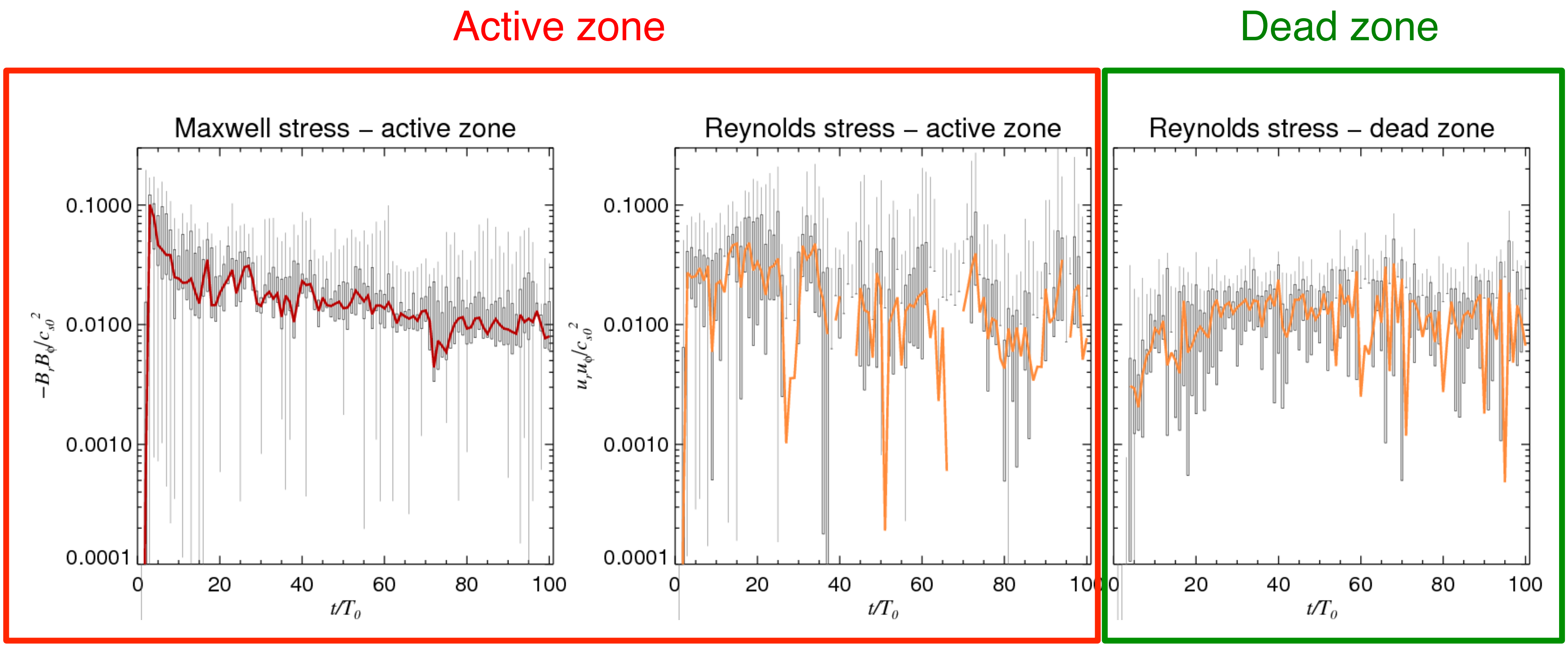




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Significant angular momentum transport

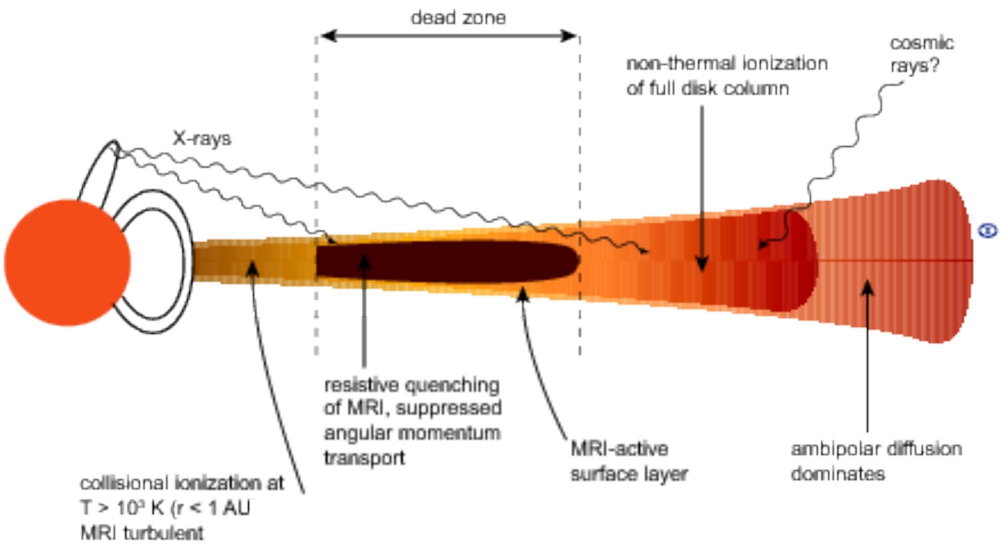


Large mass accretion rates in the dead zone,

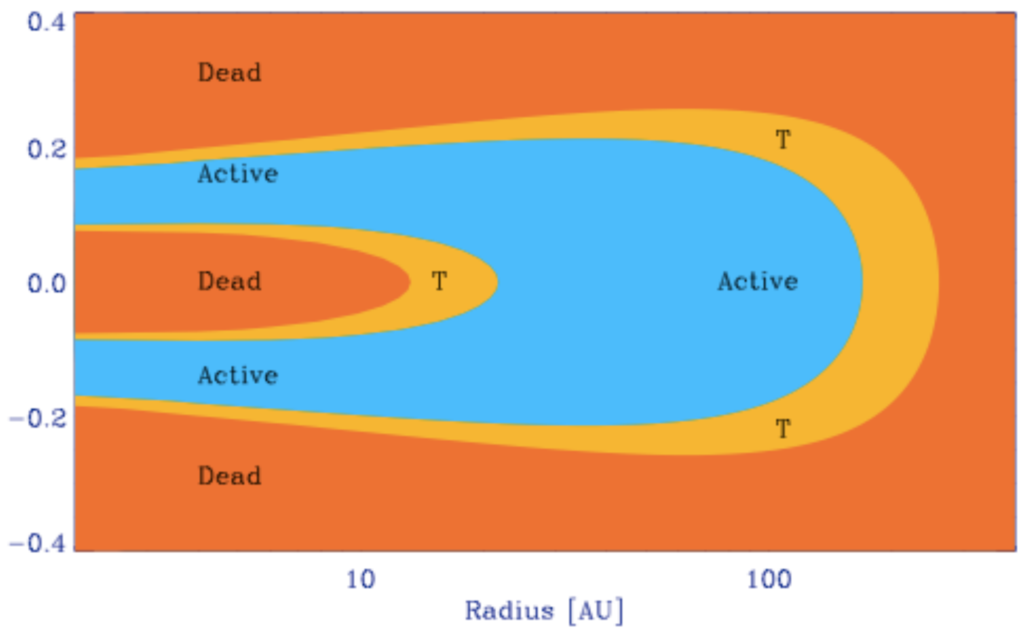
comparable to the MRI in the active zone!

Lyra & Mac Low (2012)

Outer Dead/Active zone transition RWI



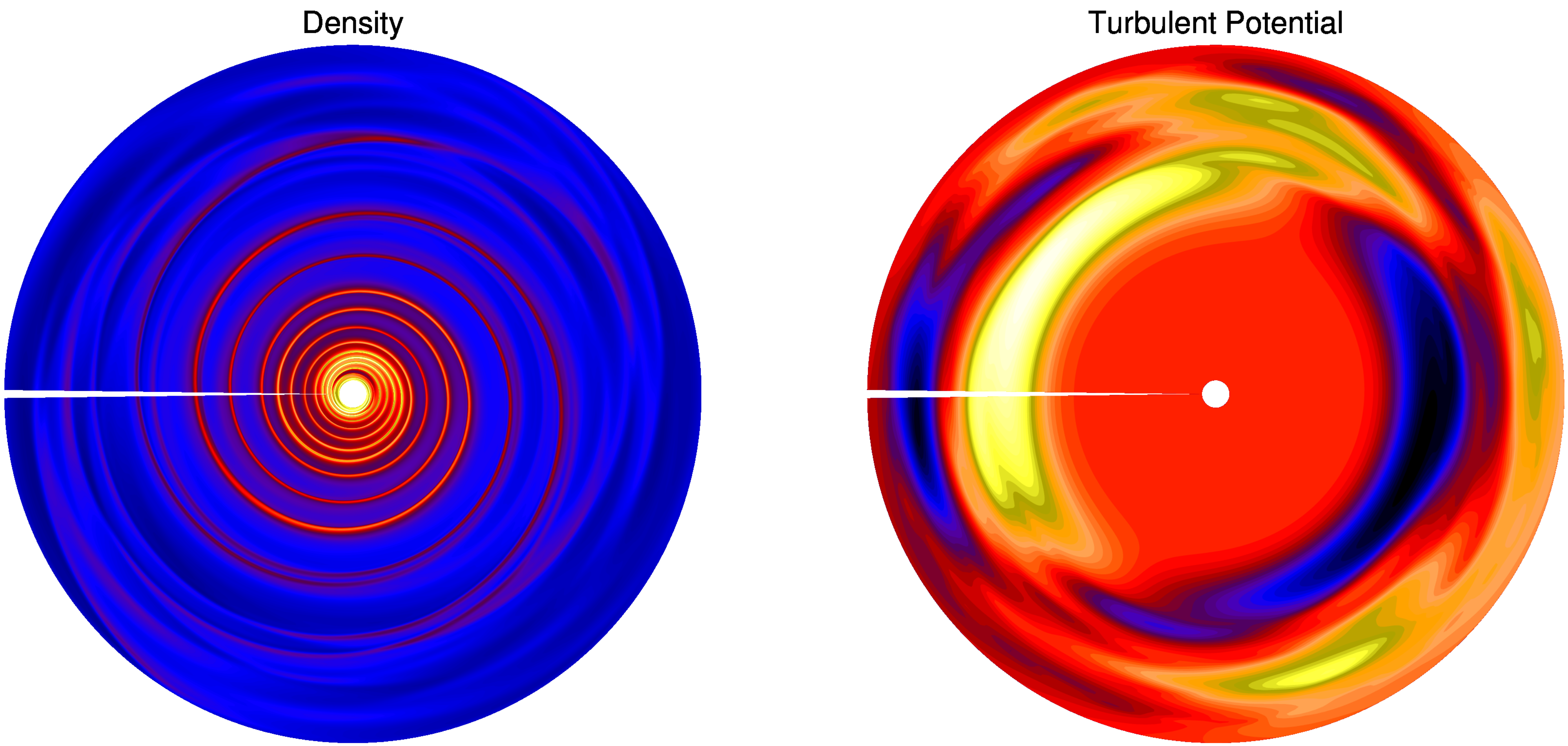
Armitage (2010)



Dzyurkevitch et al (2013)

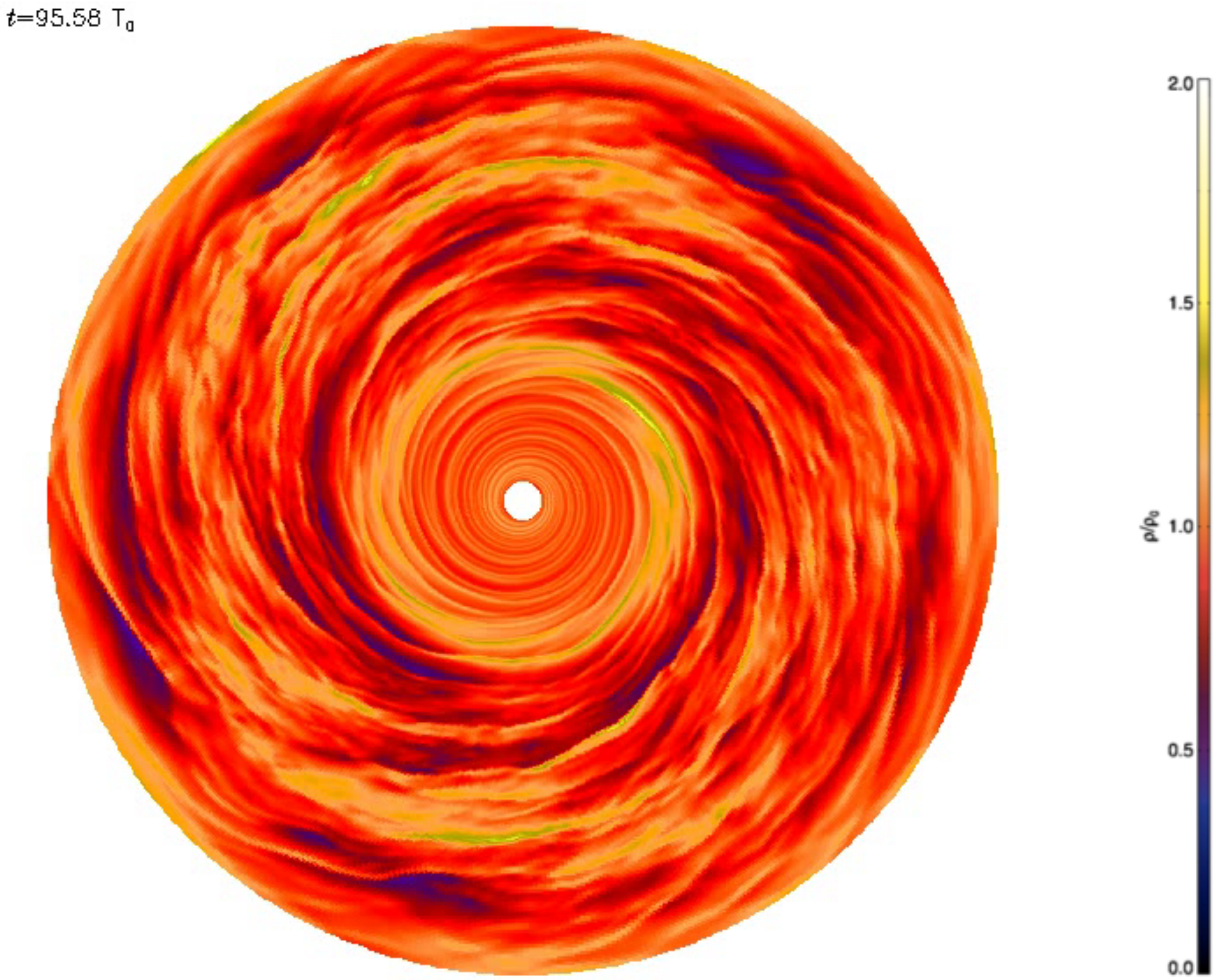
The **outer** dead zone transition in ionization supposed
TOO SMOOTH
to generate an RWI-unstable bump.

Outer Dead/Active zone transition: Spirals without planets



Waves launched at the active zone propagate into the dead zone as a coherent spiral.

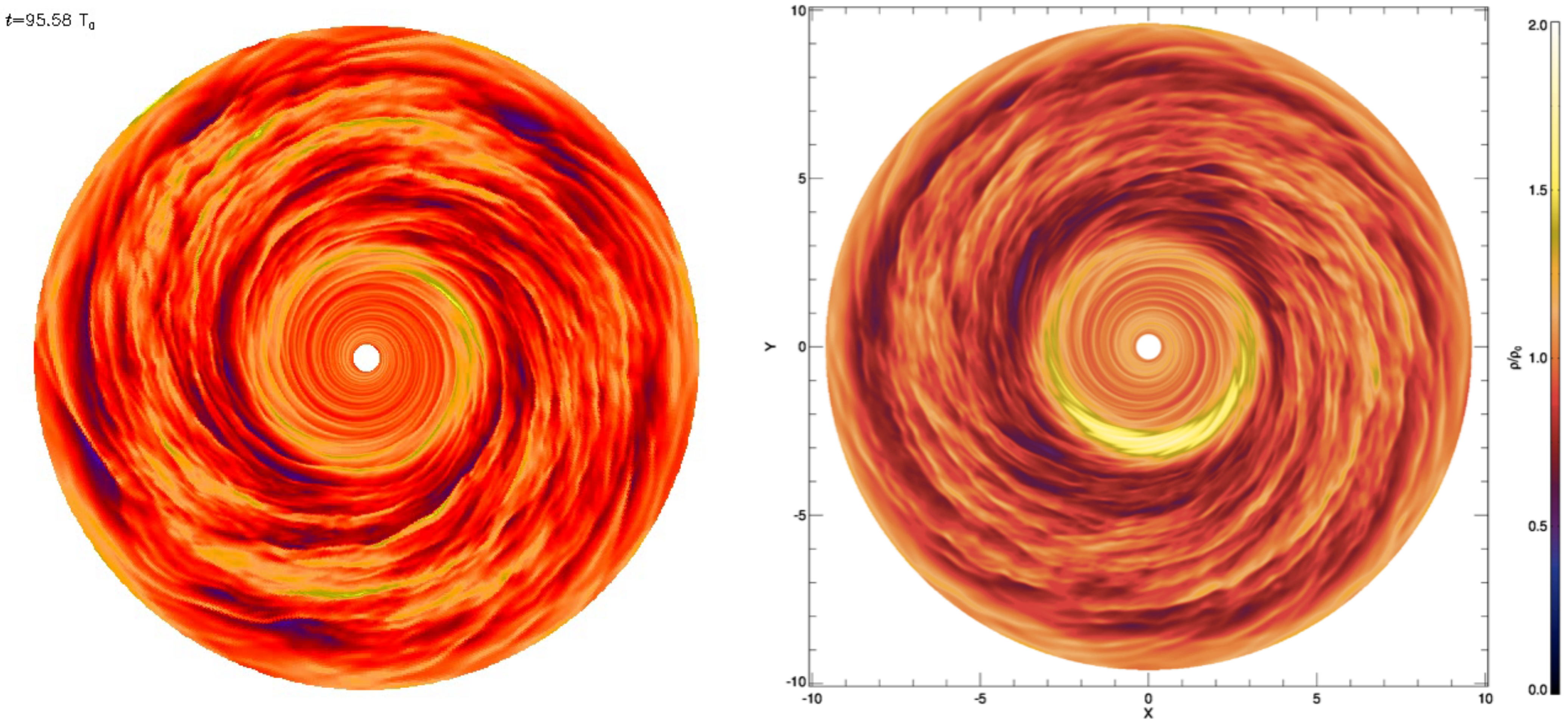
Outer Dead/Active zone transition: 3D MHD



Resistive inner disk + magnetized outer disk

Lyra et al (2015)

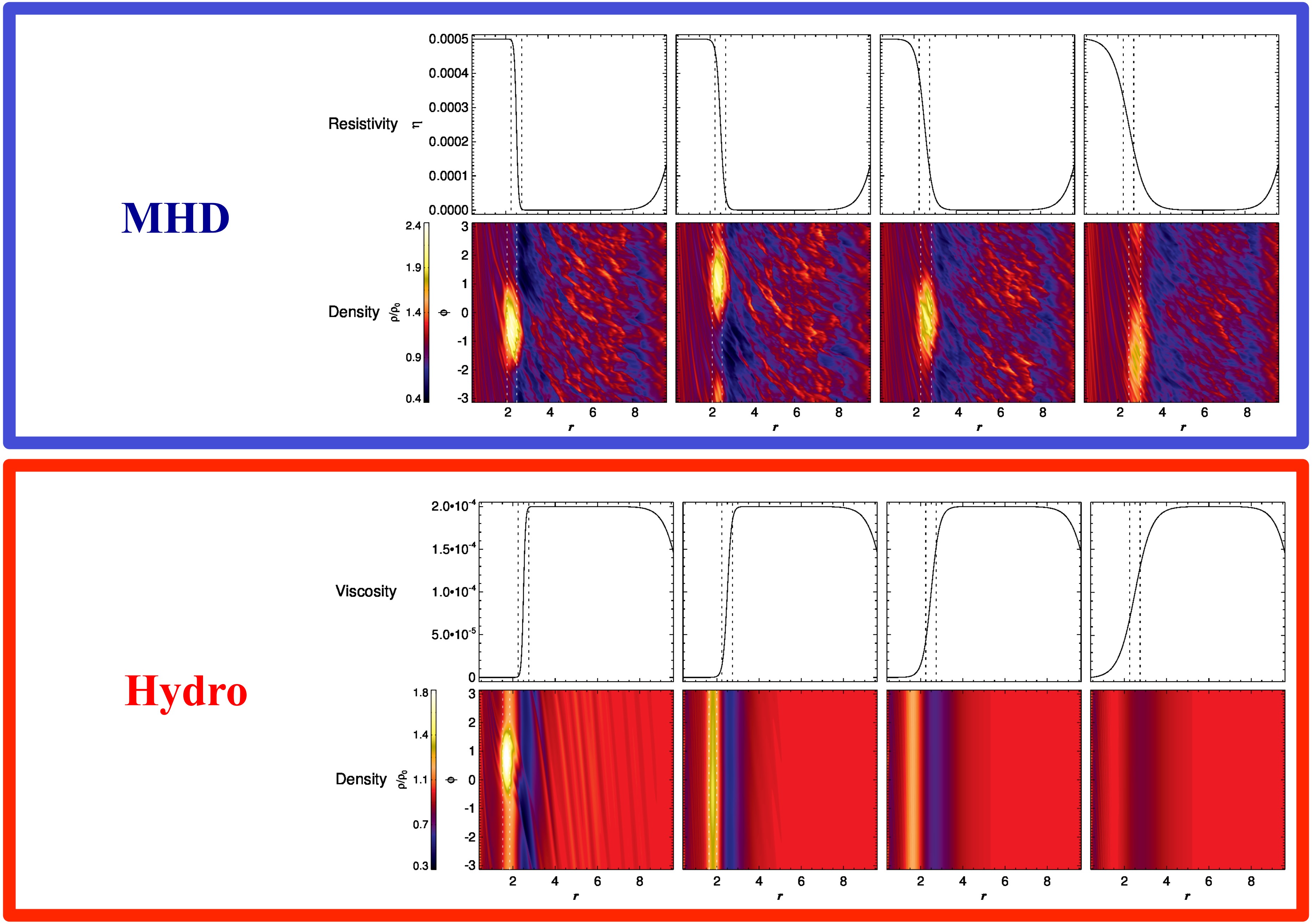
Outer Dead/Active zone transition RWI



Resistive inner disk + magnetized outer disk

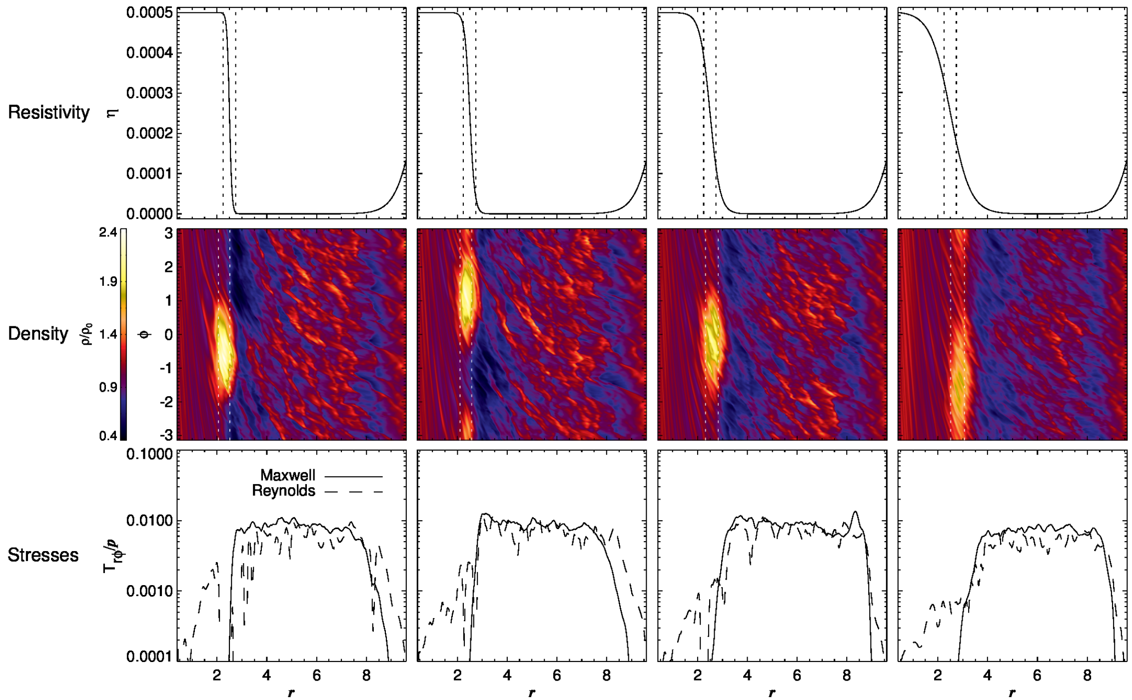
Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

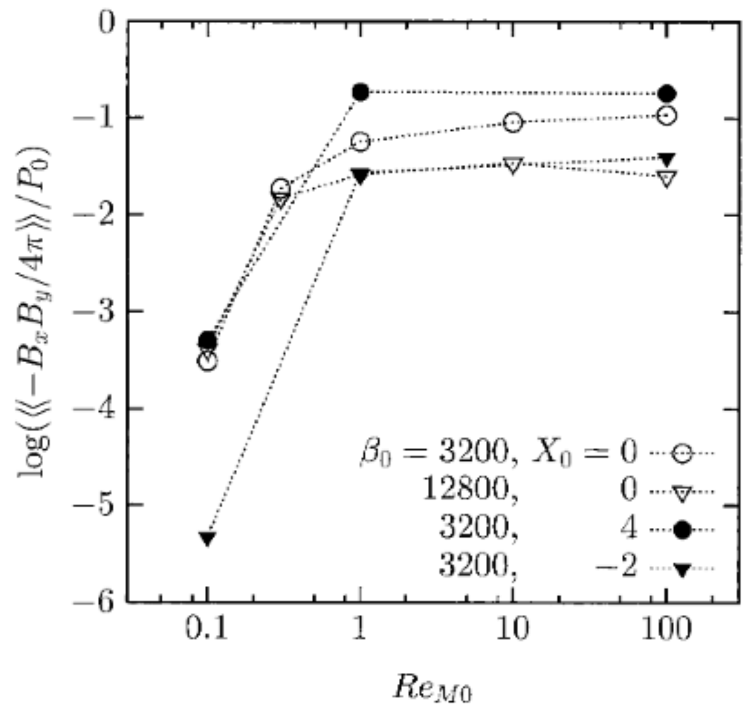


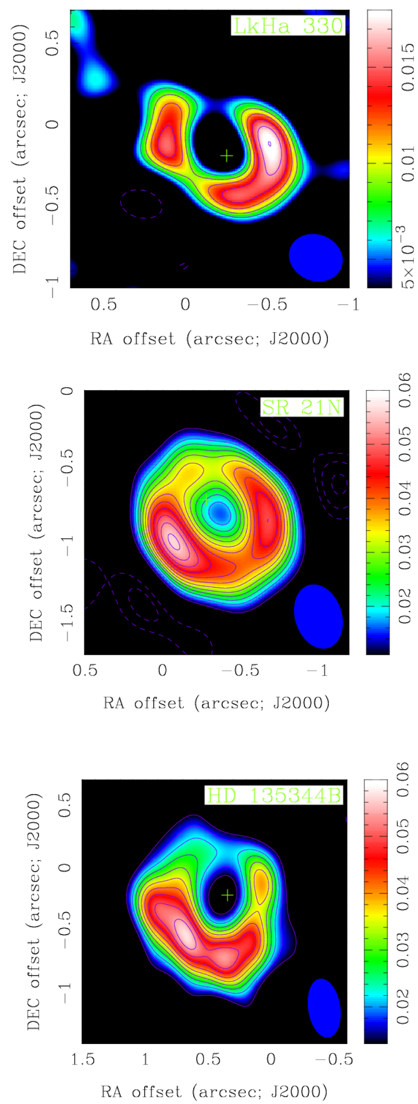
FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number Re_{M0}. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and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

Sano and Stone (2002)

A possible detection of vortices in disks?

Observations

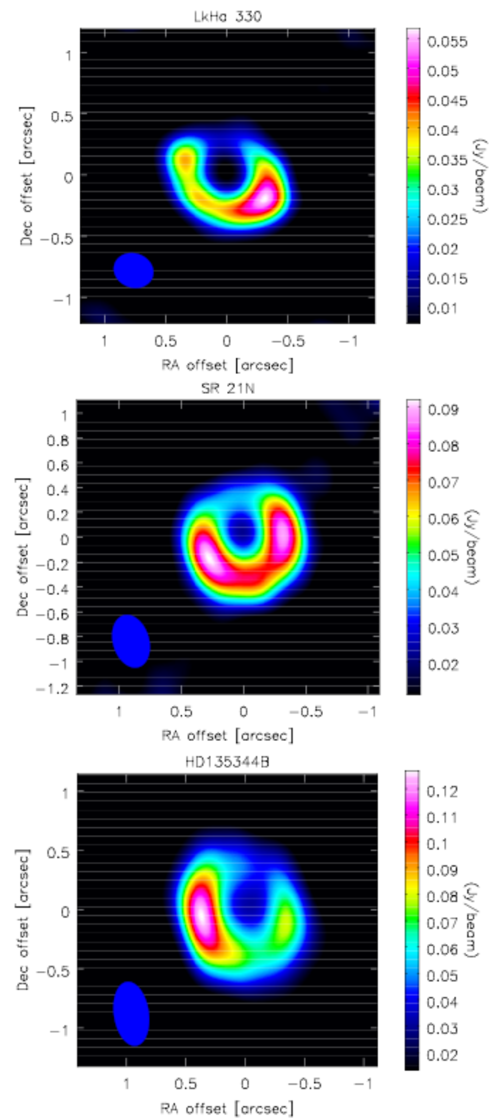
Brown et al. (2009)



Models

Simulated observations of Rossby vortices

Regaly, Sándor 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]

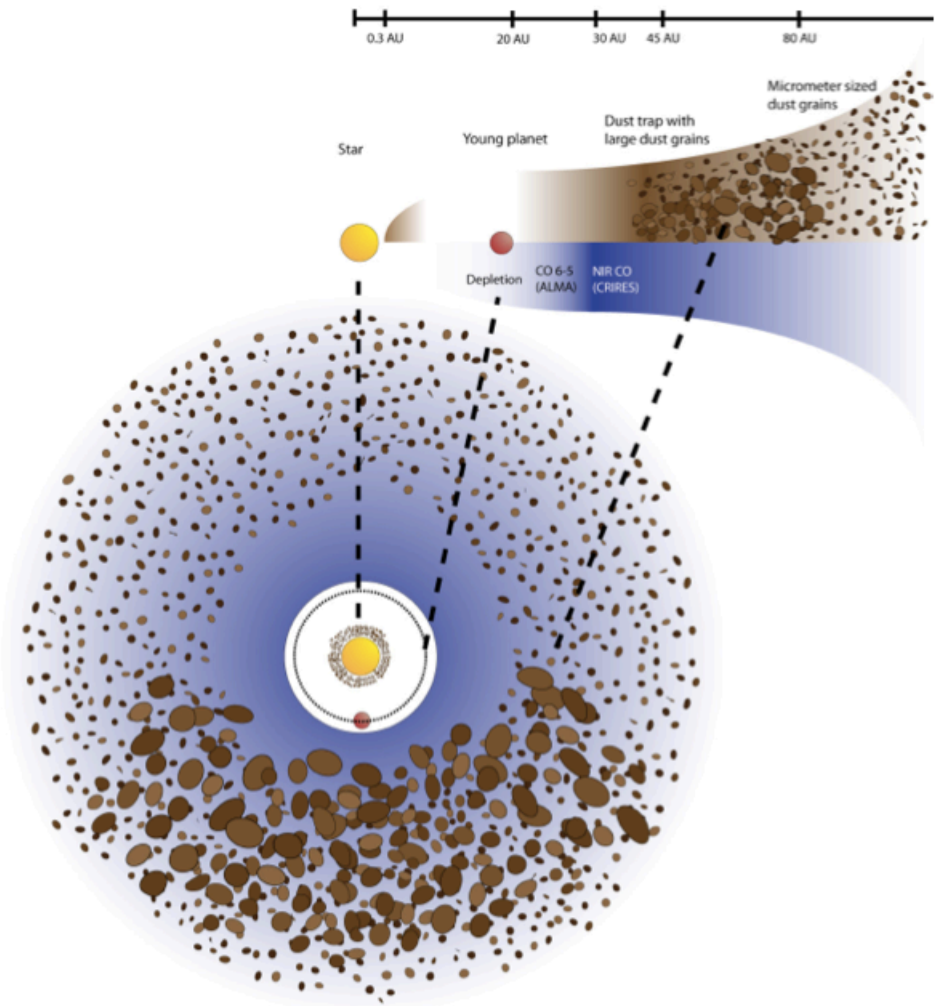
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection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

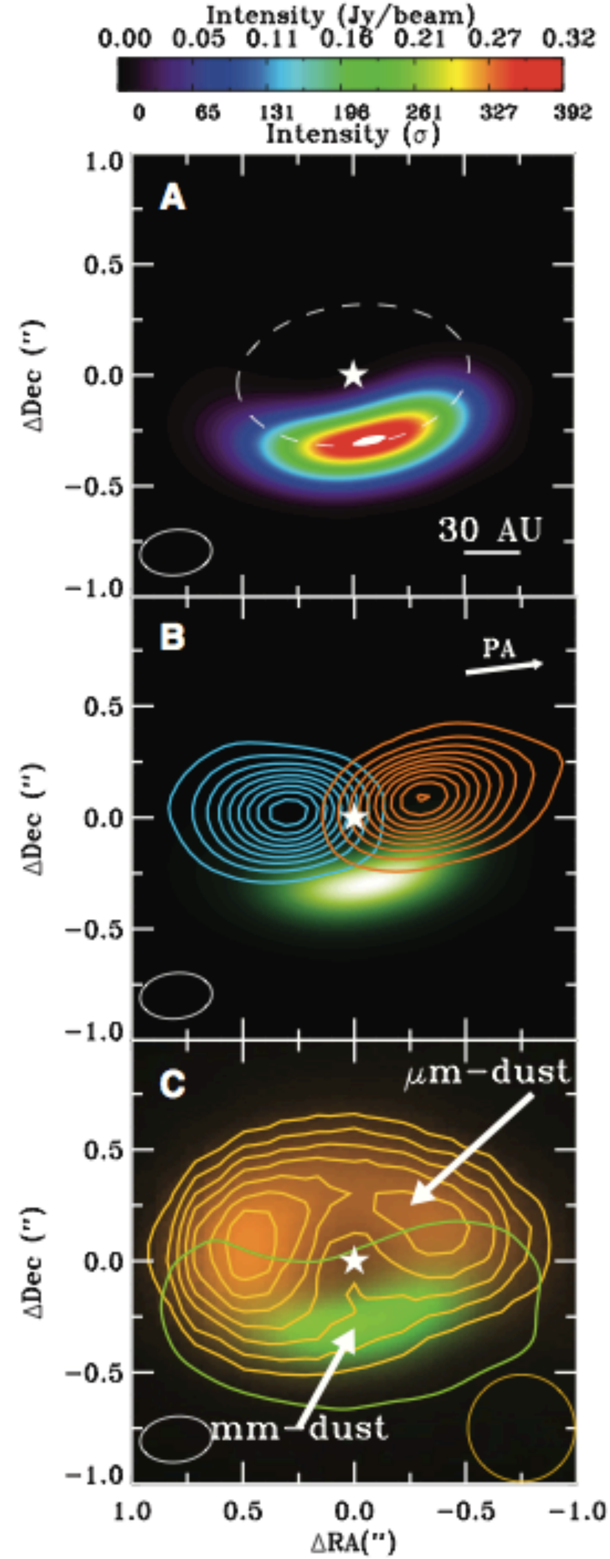
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

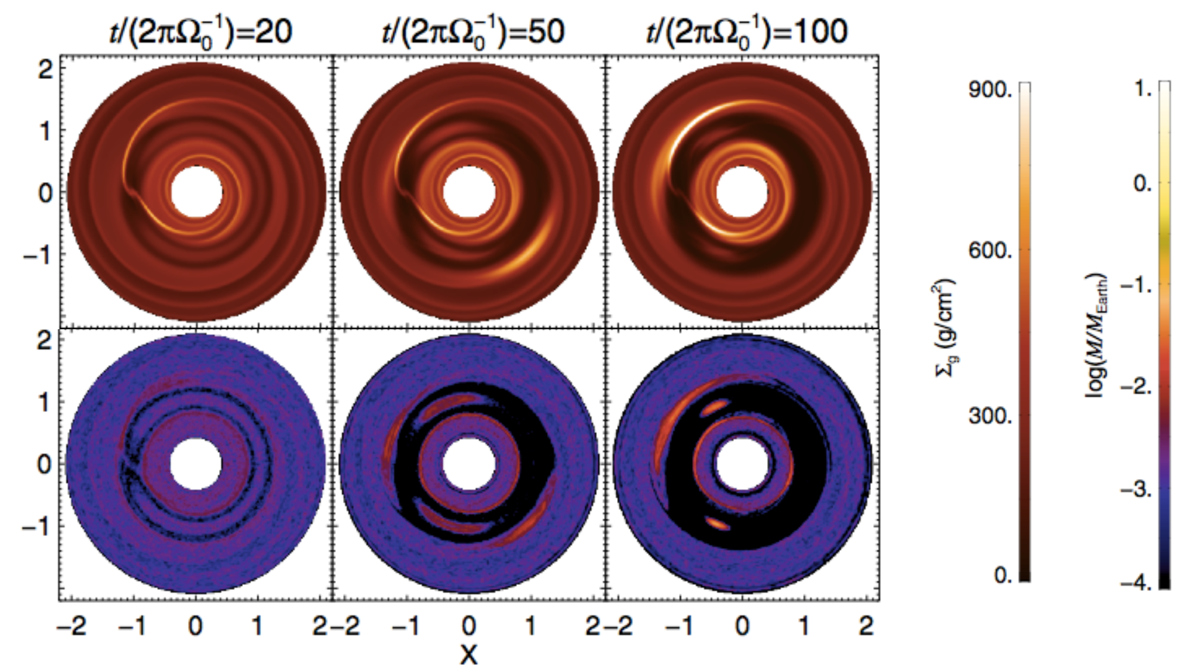


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

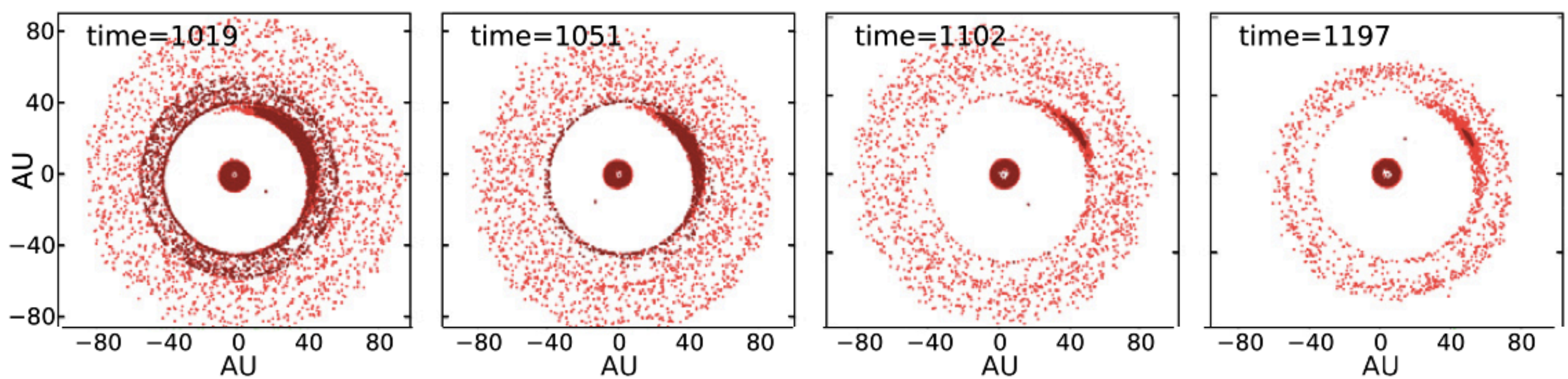
Micron-sized dust follows gas

Dust Trapping



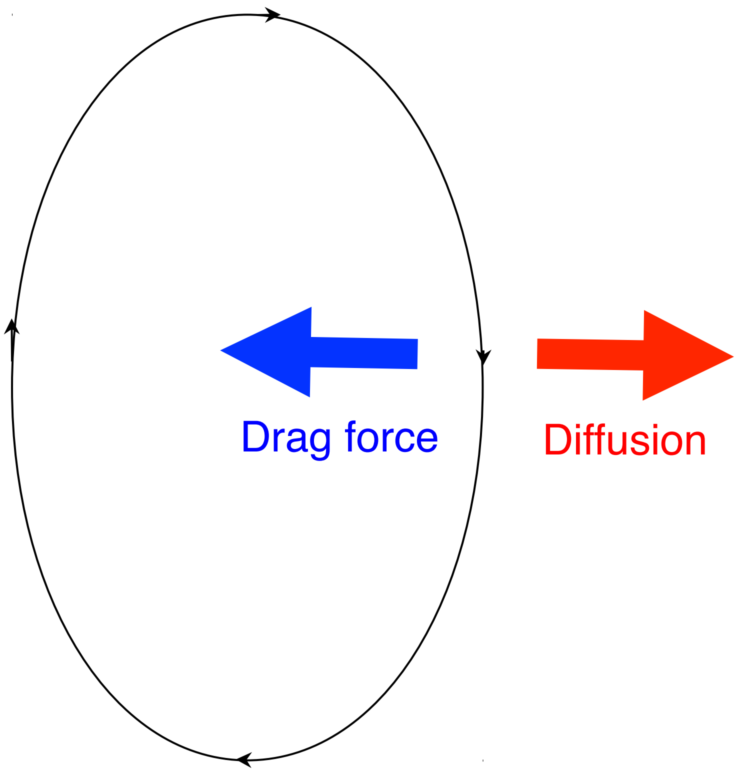
Lyra et al (2009b)

Turbulent "kicks" lead to steady state



Ataiee et al. (2013)

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

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

Looking for an analytical solution for the steady state

Dust continuity equation

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

Lyra & Lin (2013)

Looking for an analytical solution for the steady state

Dust continuity equation

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

Gas
$$\frac{D\boldsymbol{u}}{Dt} = -\nabla\Phi - \rho^{-1}\nabla p$$

Dust
$$\frac{D\boldsymbol{v}}{Dt} = -\nabla\Phi - \frac{(\boldsymbol{v} - \boldsymbol{u})}{\tau}$$

$$\boldsymbol{v} = \boldsymbol{u} + \tau\rho^{-1}\nabla p$$

Lyra & Lin (2013)

Looking for an analytical solution for the steady state

Dust continuity equation

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

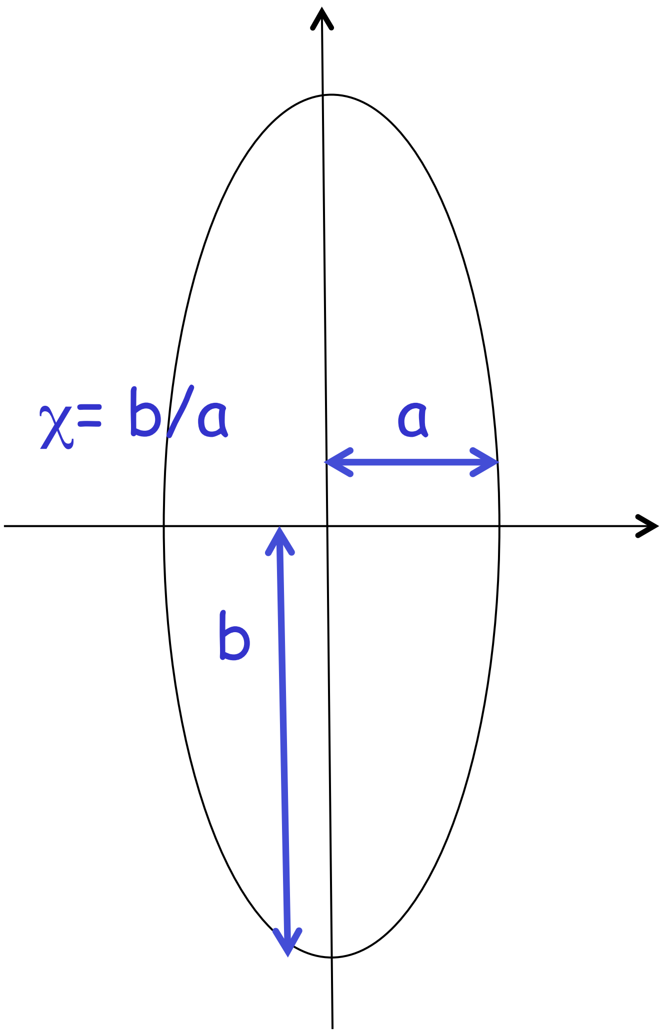
$$\boldsymbol{v} = \boldsymbol{u} + \tau \boldsymbol{\nabla} h,$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{v} = \tau \nabla^2 h,$$

Equilibrium between diffusion and drag

$$\left(D\nabla^2 - \boldsymbol{v} \cdot \boldsymbol{\nabla} + C\right) \rho_d = 0.$$

Analytical solution for dust trapping



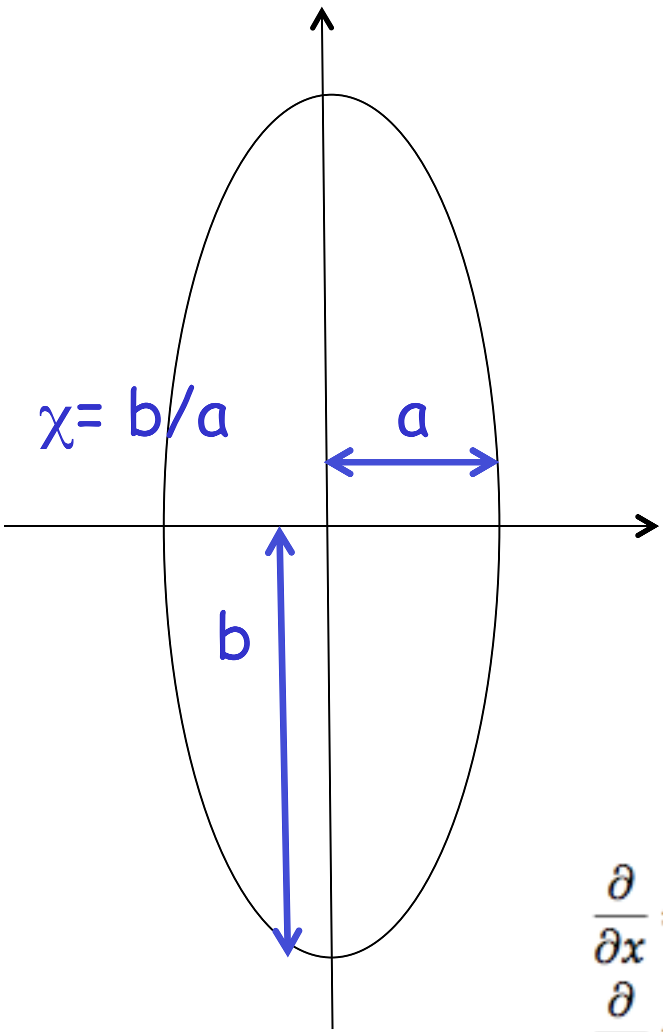
Equilibrium between diffusion and drag

$$\left(D\nabla^2 - v\cdot\boldsymbol{\nabla} + C\right)\rho_d = 0.$$

Transformation of Chang & Oishi (2010)

$$x = a\cos\nu,$$
$$y = a\chi\sin\nu.$$

Analytical solution for dust trapping



Equilibrium between diffusion and drag

$$\left(D\nabla^2 - v \cdot \boldsymbol{\nabla} + C\right)\rho_d = 0.$$

Transformation of Chang & Oishi (2010)

$$x = a\cos\nu,$$
$$y = a\chi\sin\nu.$$

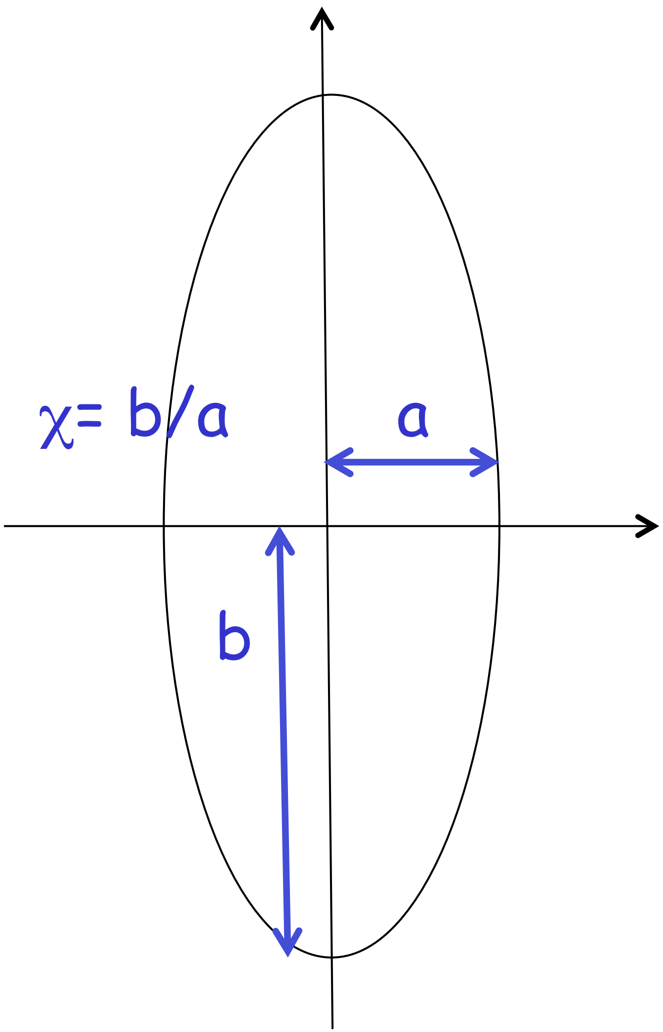
Derivatives

$$\frac{\partial}{\partial x} = \cos\nu\frac{\partial}{\partial a} - \frac{\sin\nu}{a}\frac{\partial}{\partial \nu},$$
$$\frac{\partial}{\partial y} = \frac{1}{\chi}\left(\sin\nu\frac{\partial}{\partial a} + \frac{\cos\nu}{a}\frac{\partial}{\partial \nu}\right),$$

Laplacian

$$\nabla^2 = \frac{1}{2}\left[\varepsilon_- \cos 2\nu + \varepsilon_+\right]\partial_a^2 + \frac{1}{2a^2}\left[\varepsilon_+ - \varepsilon_- \cos 2\nu\right]\partial_\nu^2 - \frac{\sin 2\nu}{a}\varepsilon_- \partial_{a\nu}^2 + \frac{1}{2a}\left[\varepsilon_+ - \varepsilon_- \cos 2\nu\right]\partial_a + \frac{\sin 2\nu}{a^2}\varepsilon_- \partial_\nu,$$

Analytical solution for dust trapping



$$\left(D\nabla^2 - v\cdot\nabla + C\right)\rho_d = 0.$$

$$\left[\partial_a^2 + \left(\frac{1}{a} + \frac{k^2}{2}a\right)\partial_a + k^2\right]\rho_d = 0,$$

Solution

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

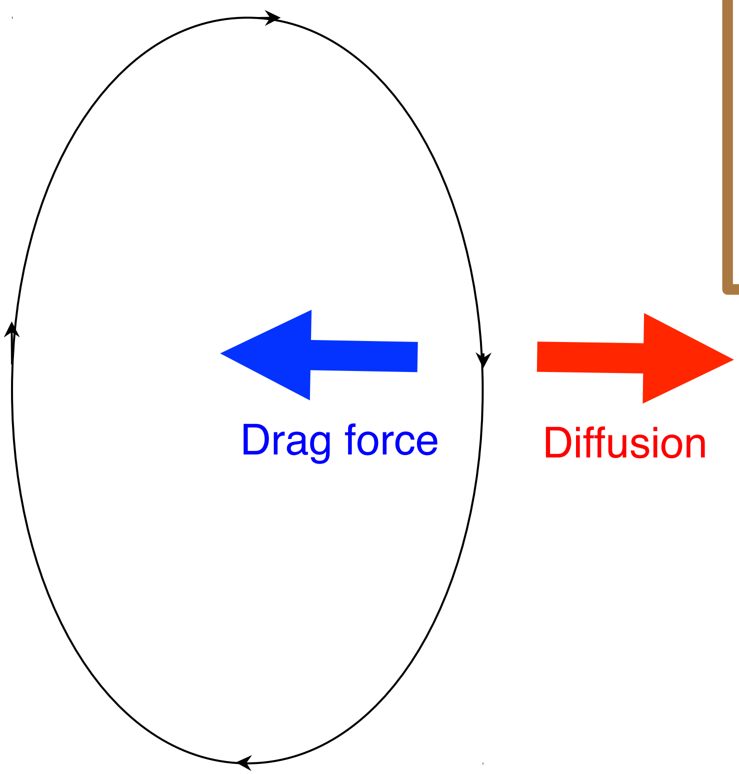
$$H_V = \frac{H}{f(\chi)}\sqrt{\frac{1}{S+1}}$$

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

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

Lyra & Lin (2013)

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

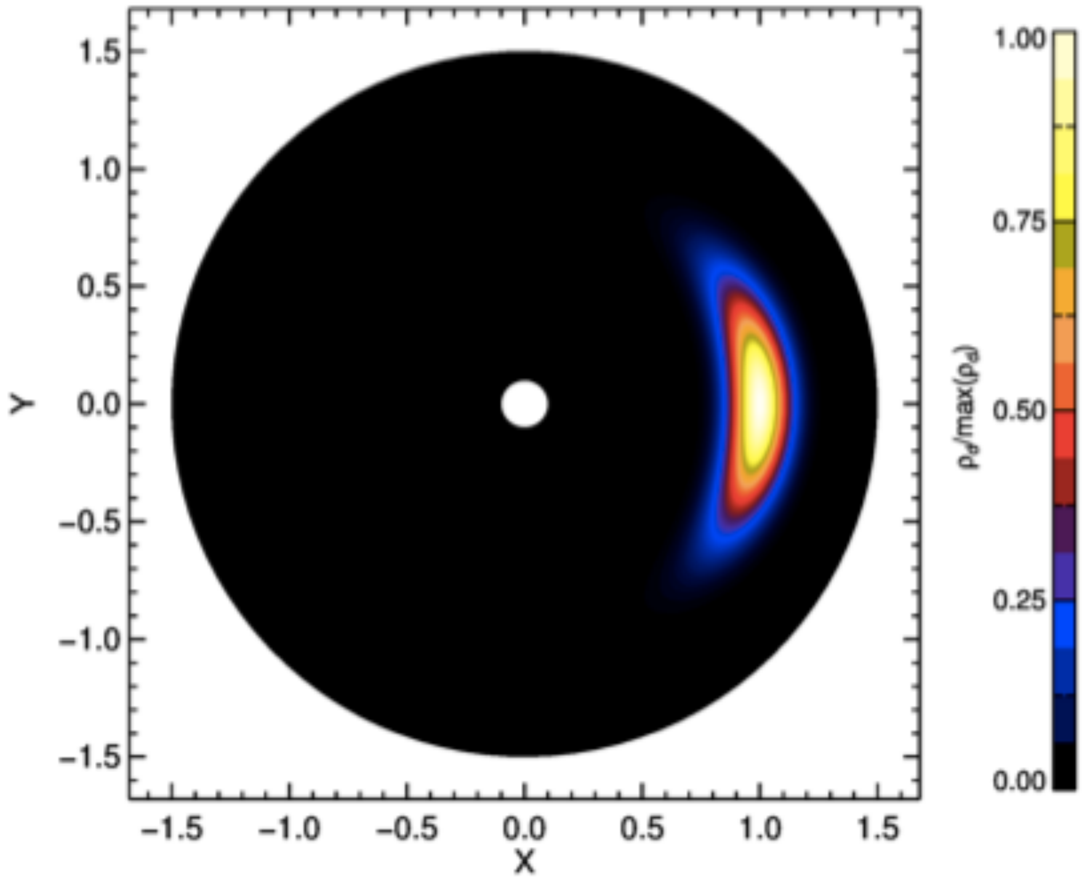
Lyra & Lin (2013)

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

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

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

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

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

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

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

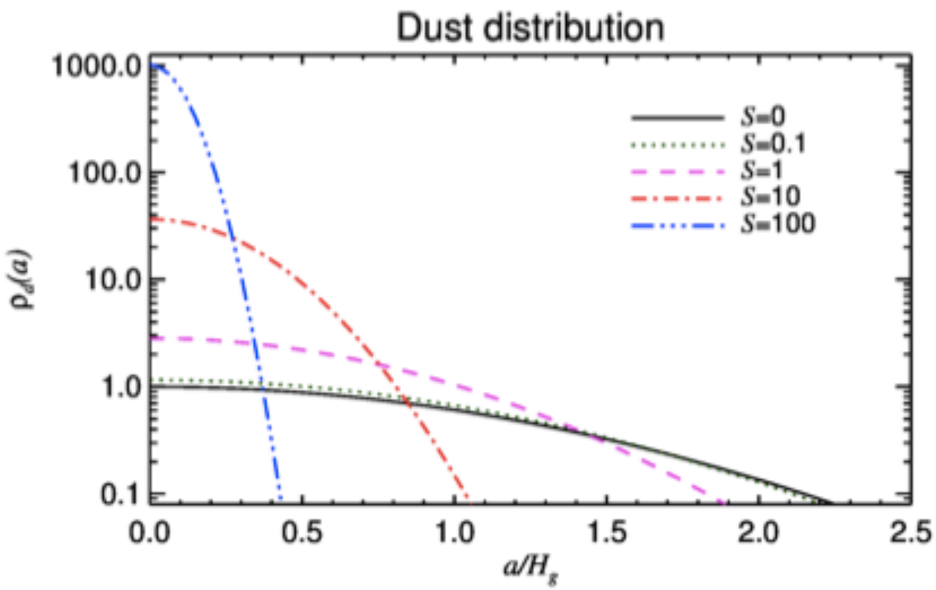
- a = vortex semi-minor axis
- H = disk scale height (temperature)
- χ = vortex aspect ratio
- δ = diffusion parameter
- St = Stokes number (particle size)
- $f(\chi)$ = model-dependent scale function

Solution for

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

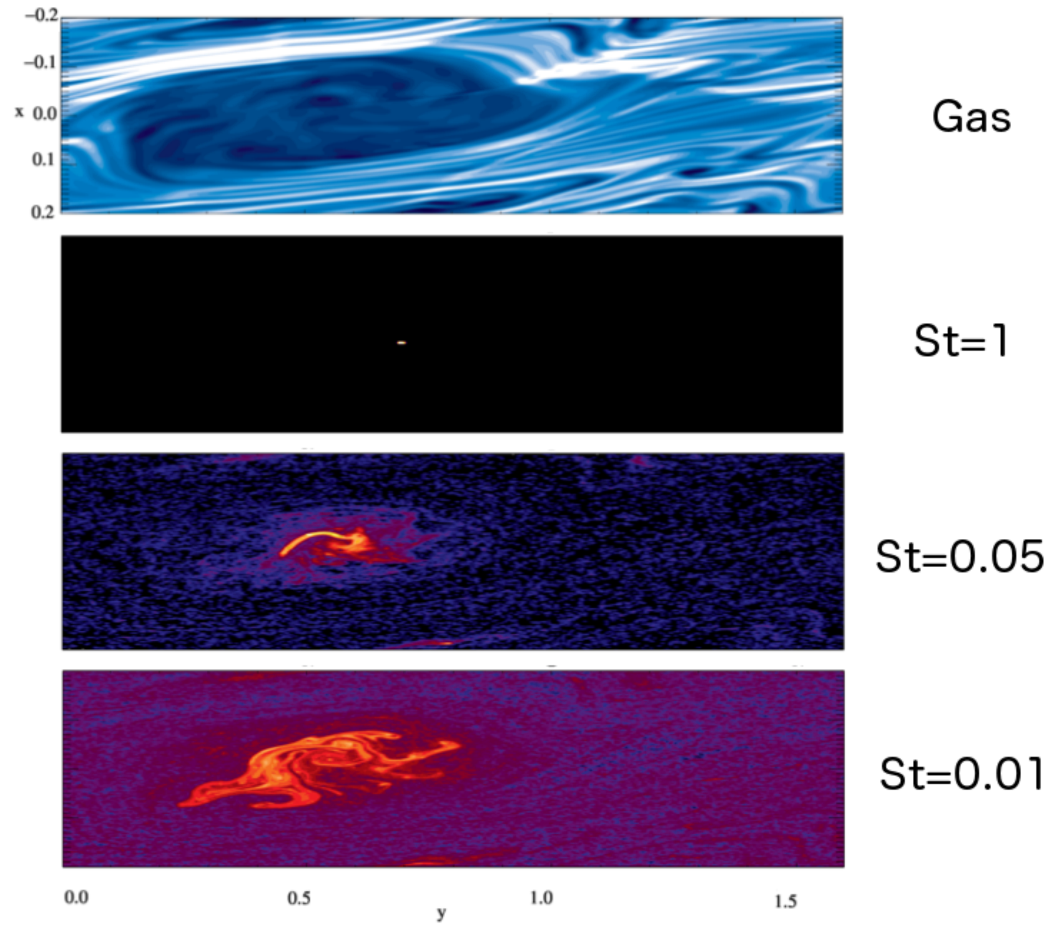
Lyra & Lin (2013)

Analytical vs Numerical



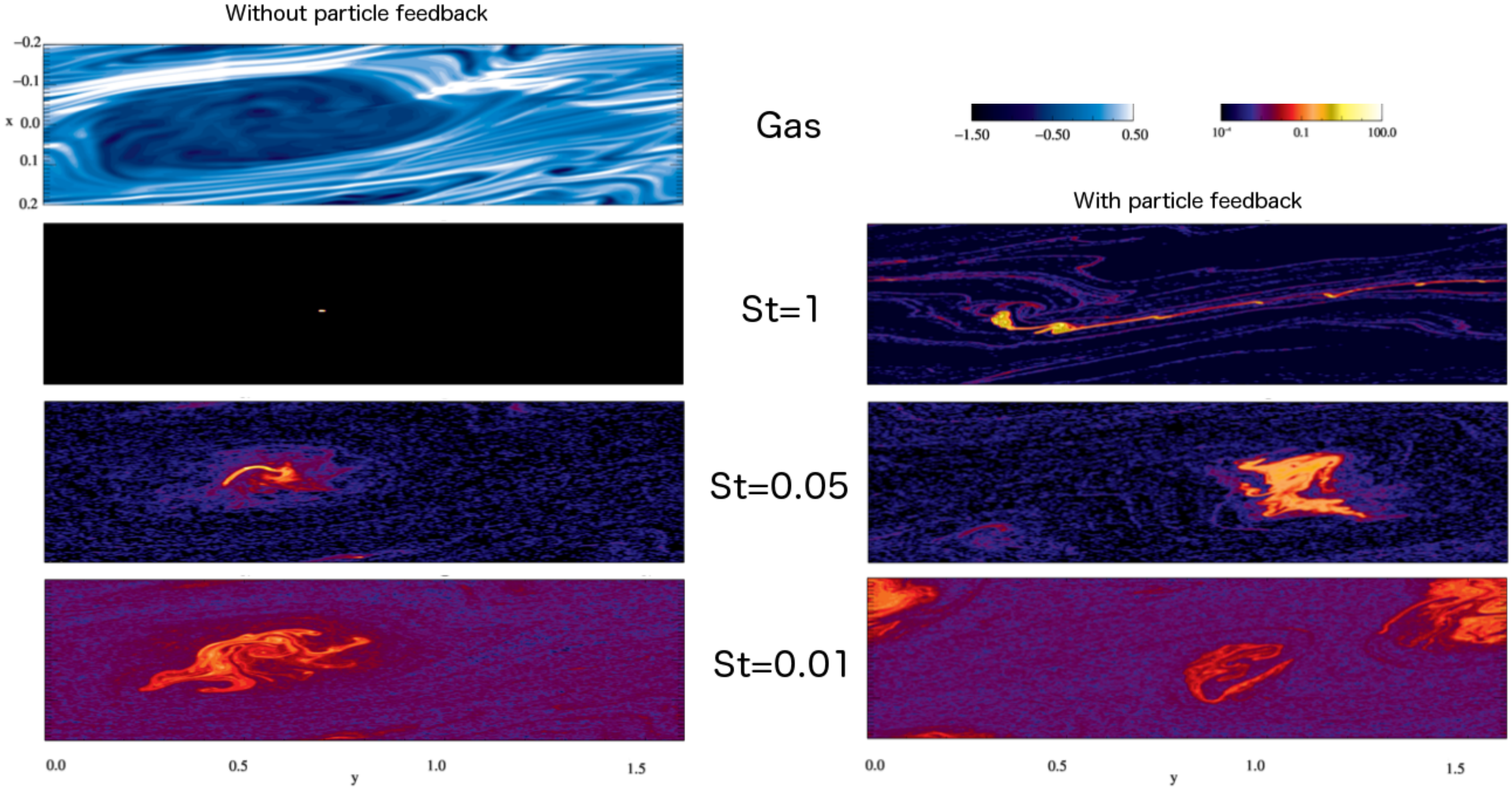
$$S = \frac{St}{\delta} \qquad \delta = v_{\mathrm{rms}}^2 / c_s^2,$$

Lyra & Lin (2013)



Raettig et al (2015)

Drag force backreaction



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

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

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}

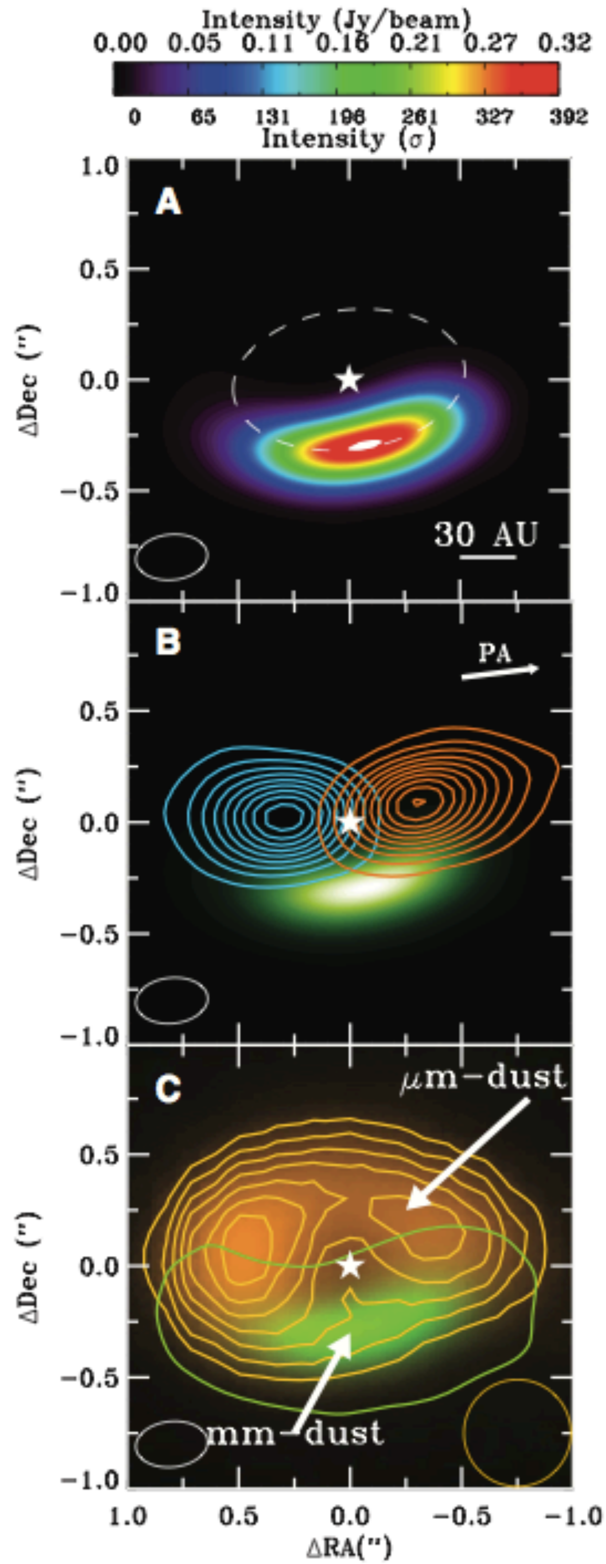
Derived parameters

S=4.8

Stokes number, St=0.008

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

Trapped mass: 11 M_{Earth}



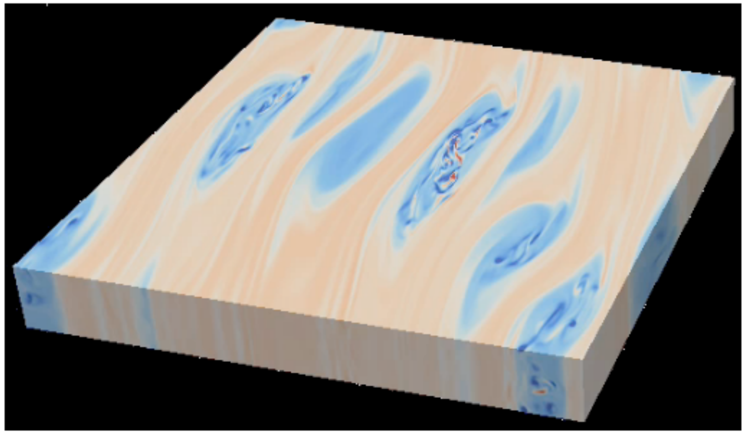
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

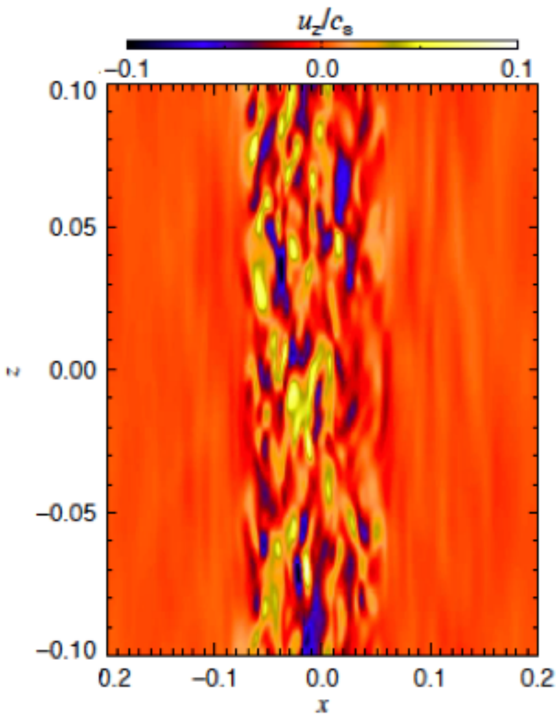
Micron-sized dust follows gas

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

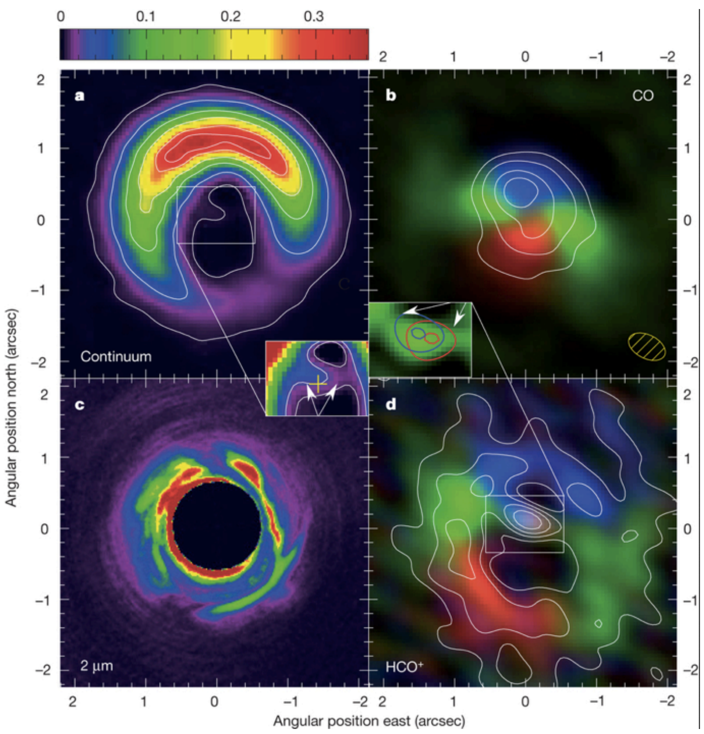
HD 142527

Observed parameters

Aspect ratio: 10

Dust contrast: 30

Temperature: 25K

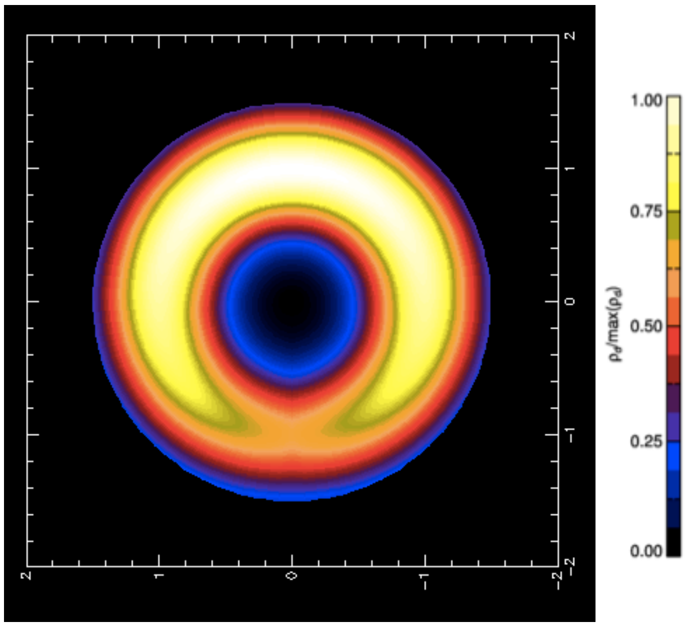


Derived parameters

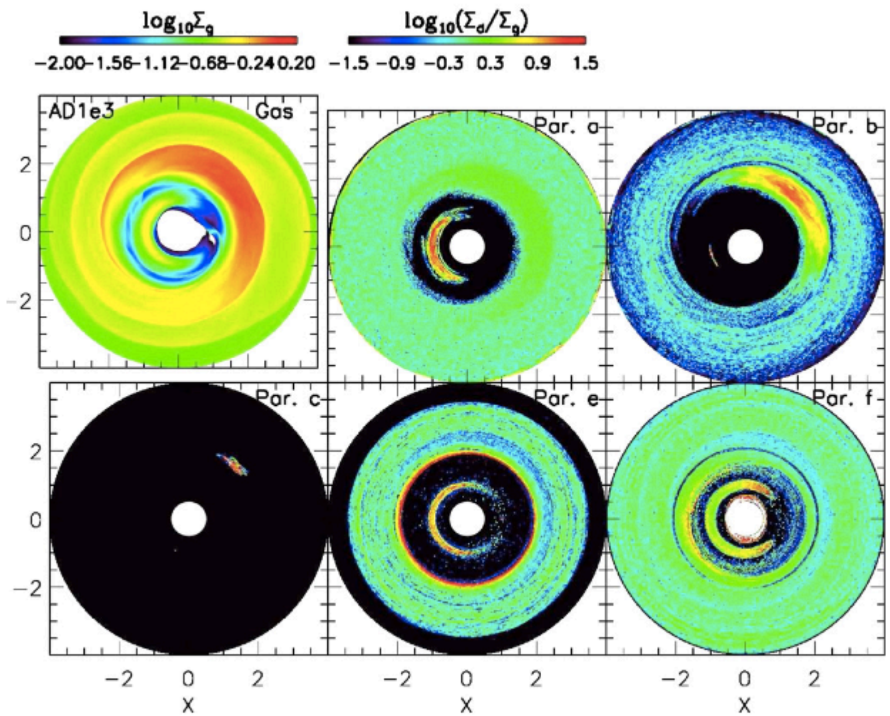
S=3.5

Stokes number, St=0.004

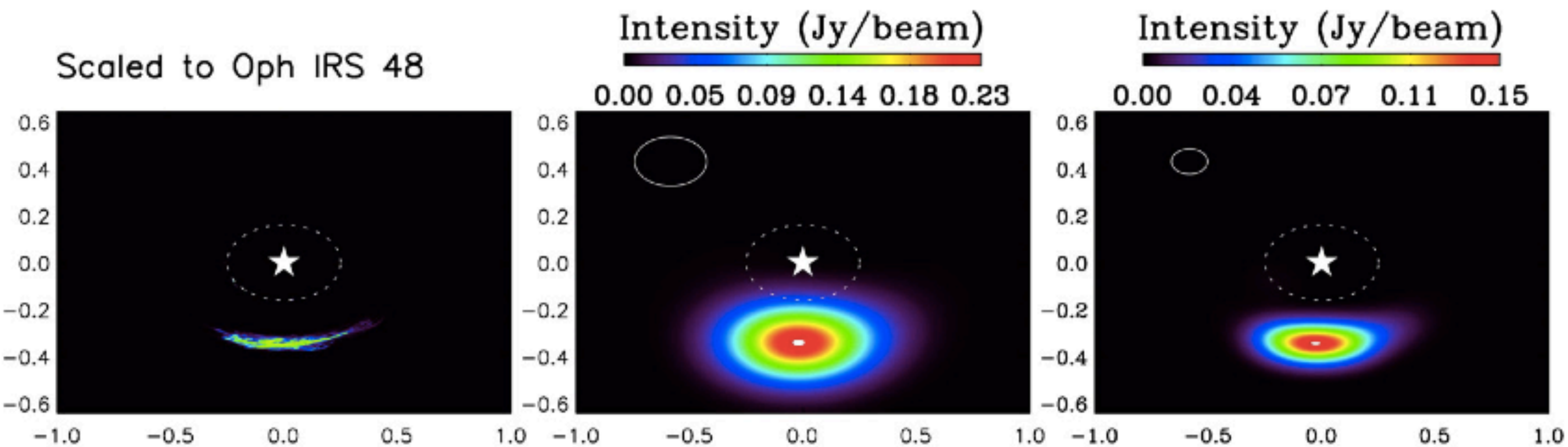
$\delta = 0.001$, $v_{rms} = 4\% \, c_s$



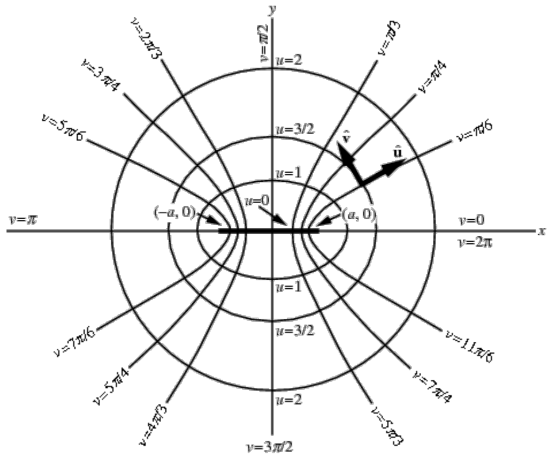
Waiting for ALMA cycle 3



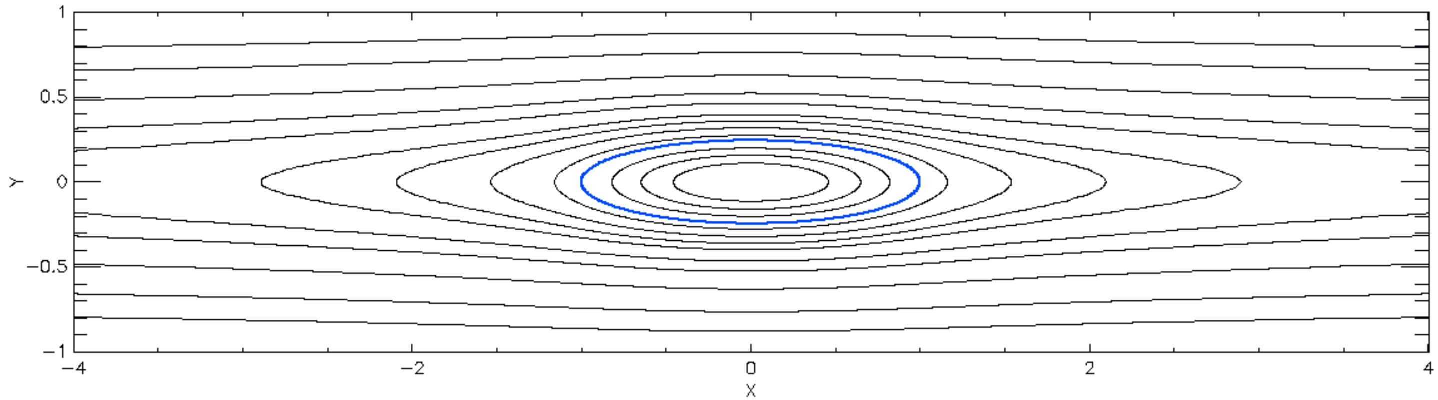
Zhu & Stone (2014)



Logarithmic tail



$$\nabla^2\psi = \begin{cases} -S & : \text{ outside the core} \\ -S + \omega_v & : \text{ inside the core} \end{cases}$$



Lesur & Papaloizou (2009)

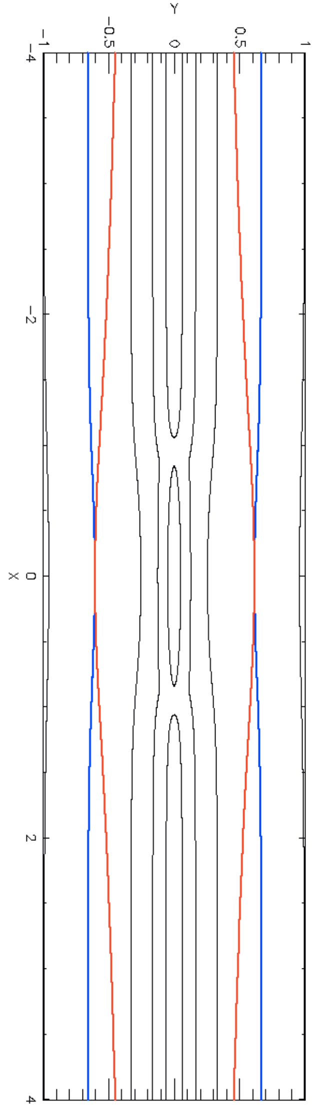
$$\psi_i = \frac{-Sf^2}{2(\chi-1)}\left[\chi^{-1}\cosh^2(\mu)\cos^2(\nu) + \chi\sinh^2(\mu)\sin^2(\nu)\right]$$

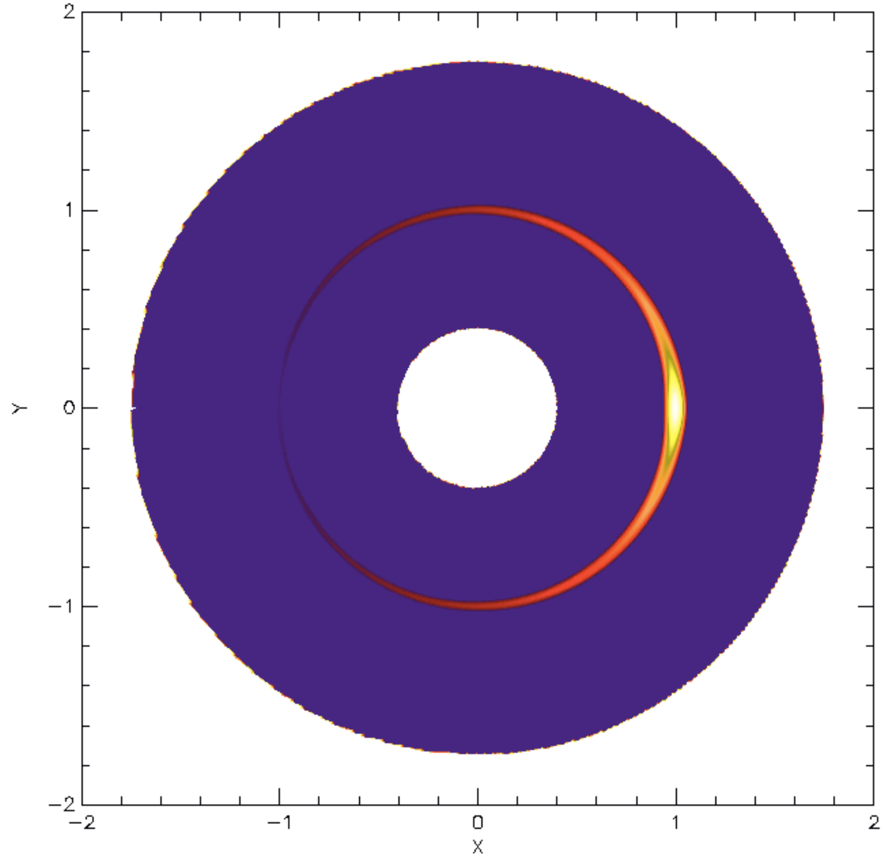
$$\psi_o = \frac{-Sf^2}{4(\chi-1)^2}\left\{1 + 2(\mu-\mu_0) + 2(\chi-1)^2\sinh^2(\mu)\sin^2(\nu) + \frac{\chi-1}{\chi+1}\exp[-2(\mu-\mu_0)]\cos(2\nu)\right\}$$

Tail trapping

Sonic perimeter
(Mach number = 1)

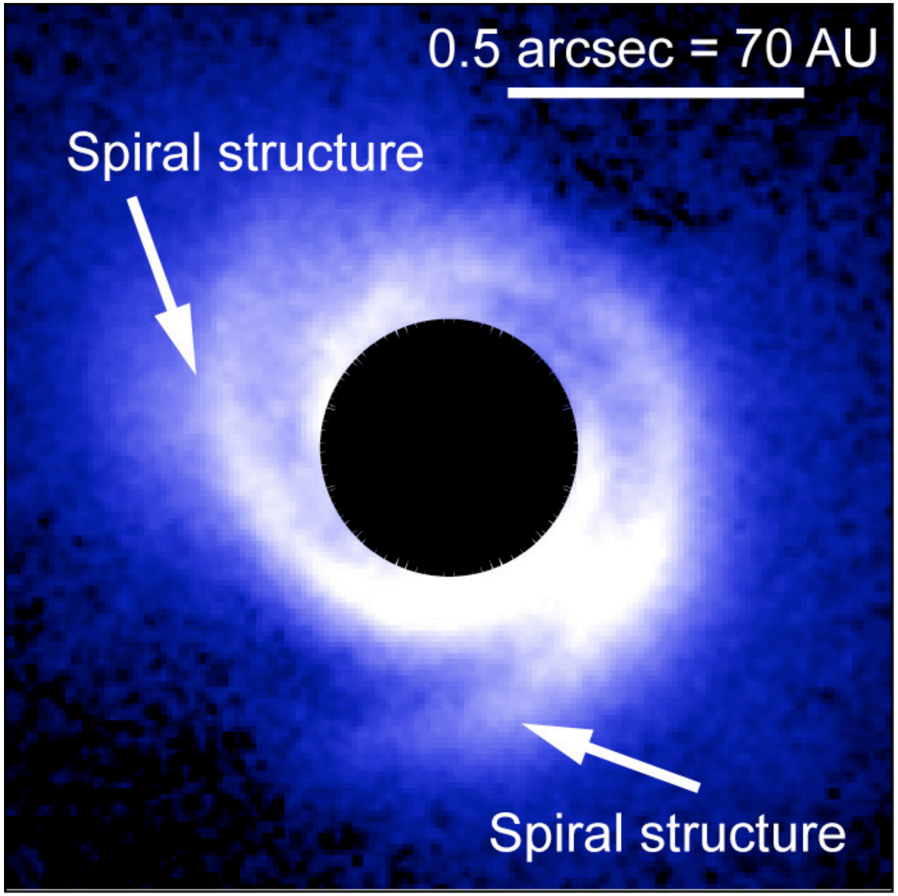
Streamline
tangent to
sonic perimeter



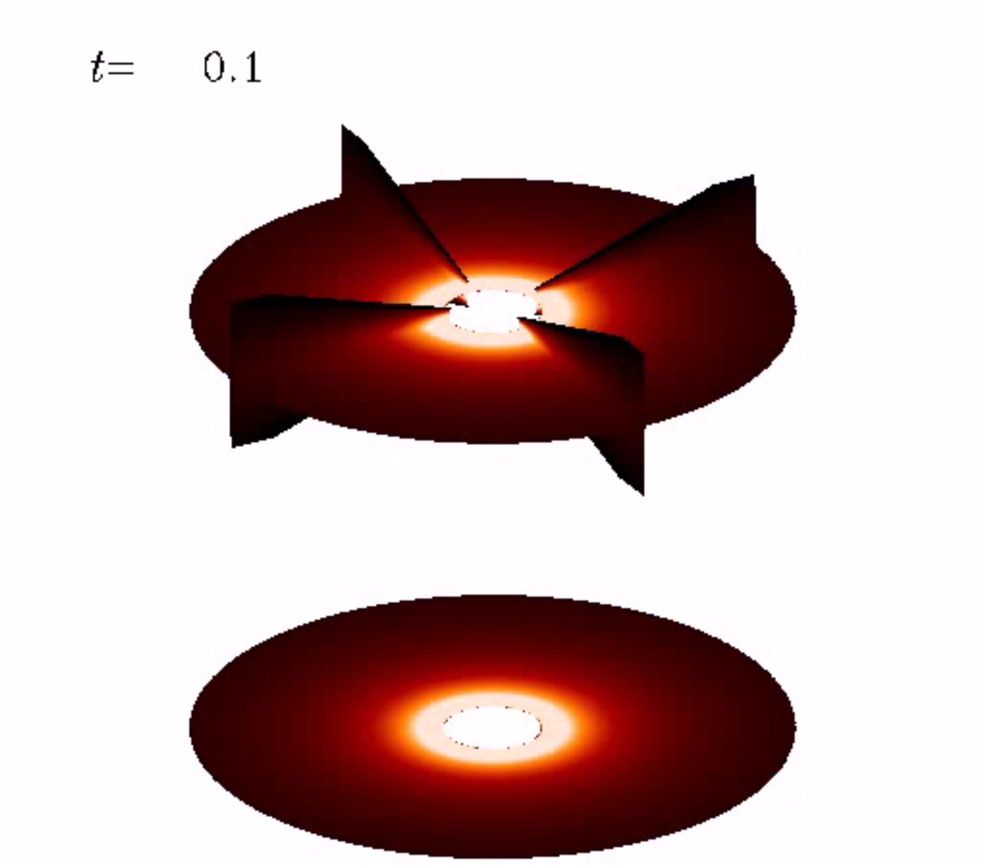


Global wrapping

Spirals in transition disks



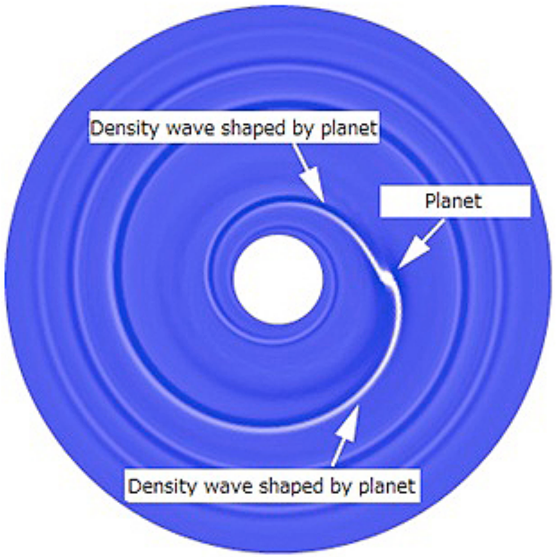
Muto et al. (2012)



Lyra (2009)

Spiral arm fitting leads to problems

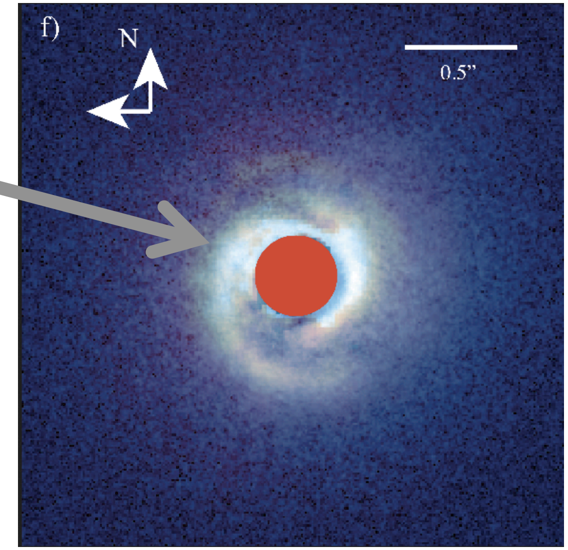
Analytical spiral fit



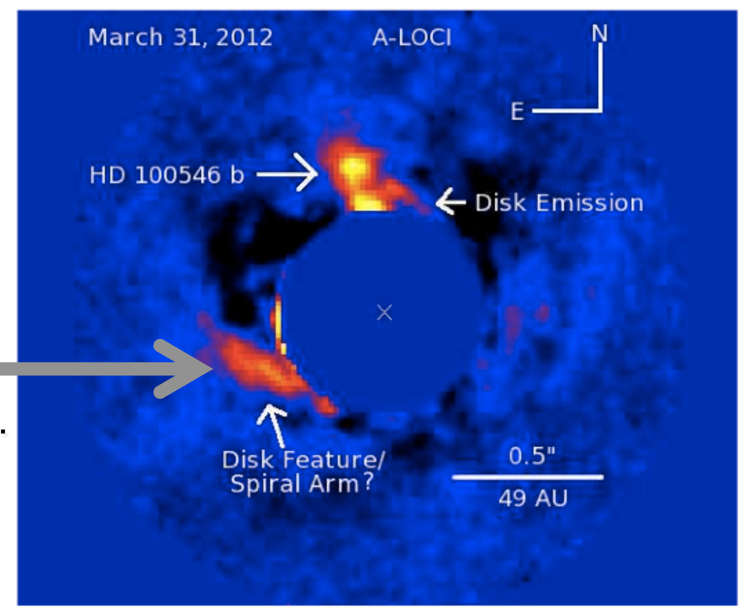
$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \left(\frac{r}{r_c}\right)^{-\alpha} \right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \right) \right\},$$

Rafikov (2002)
Muto et al. (2012)

Spiral is too wide, hotter (300K) than ambient gas (50K).

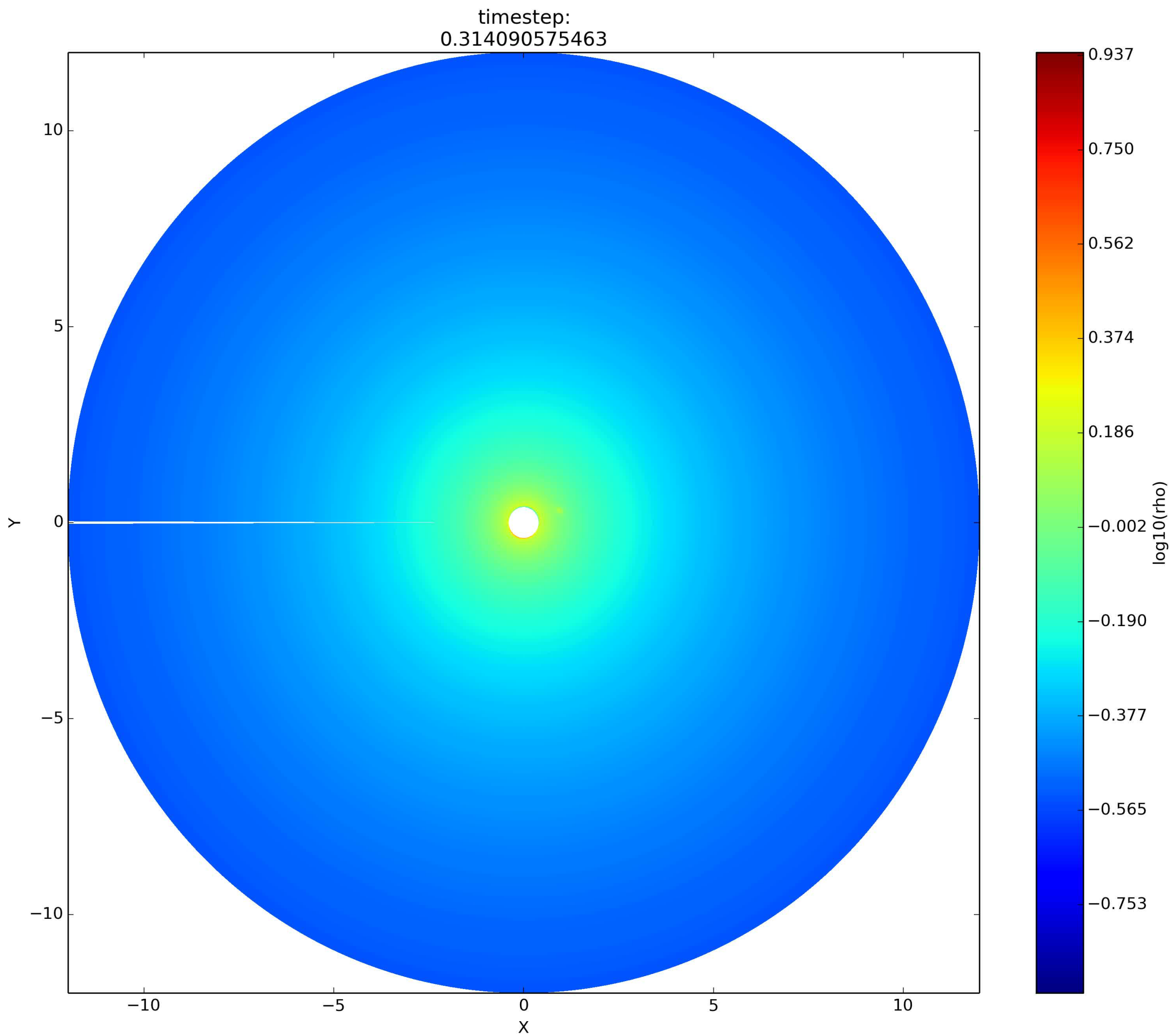


Spiral has little polarization. Must be thermal emission at 1000K.



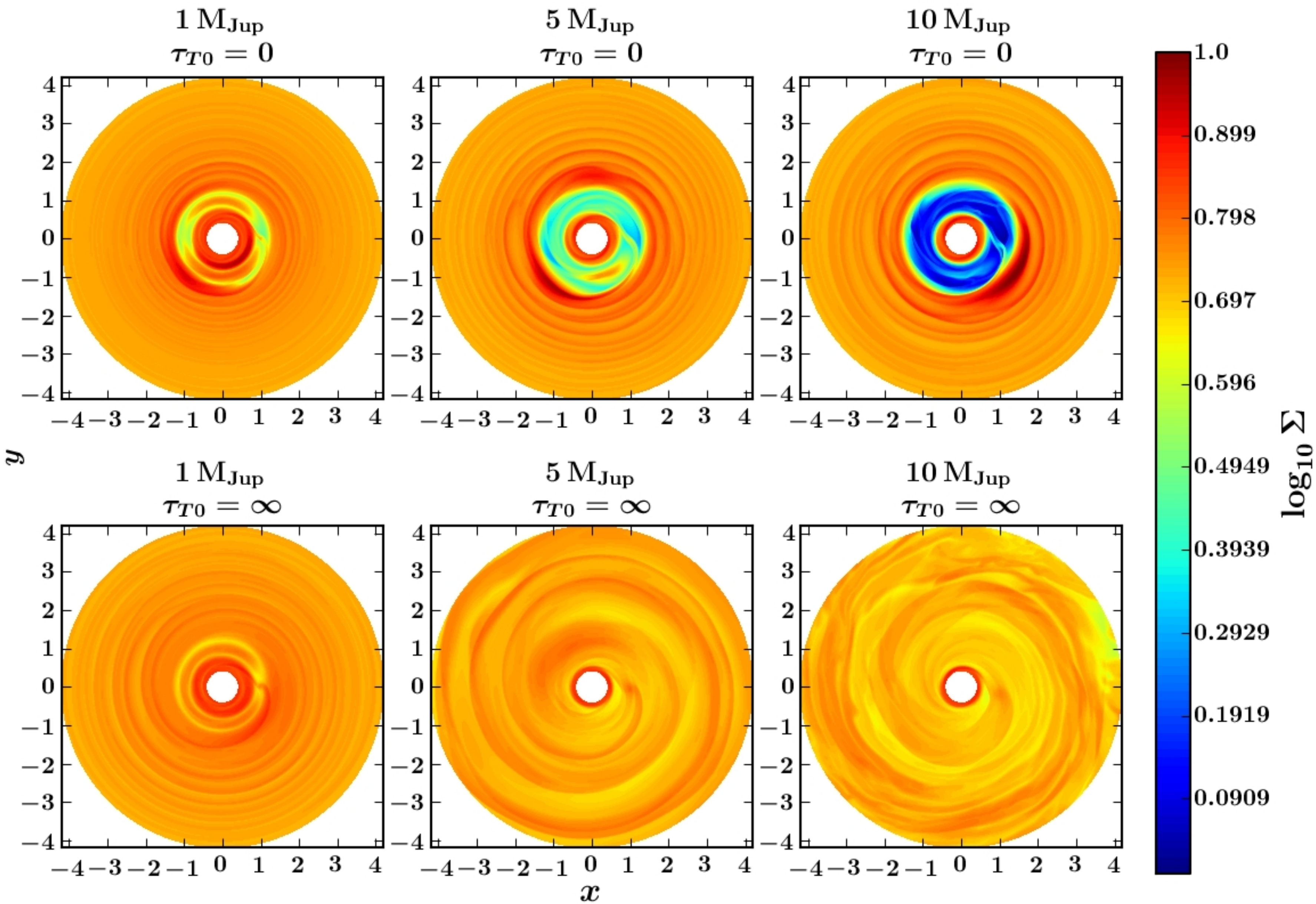
Currie et al. (2014)

Hot spirals



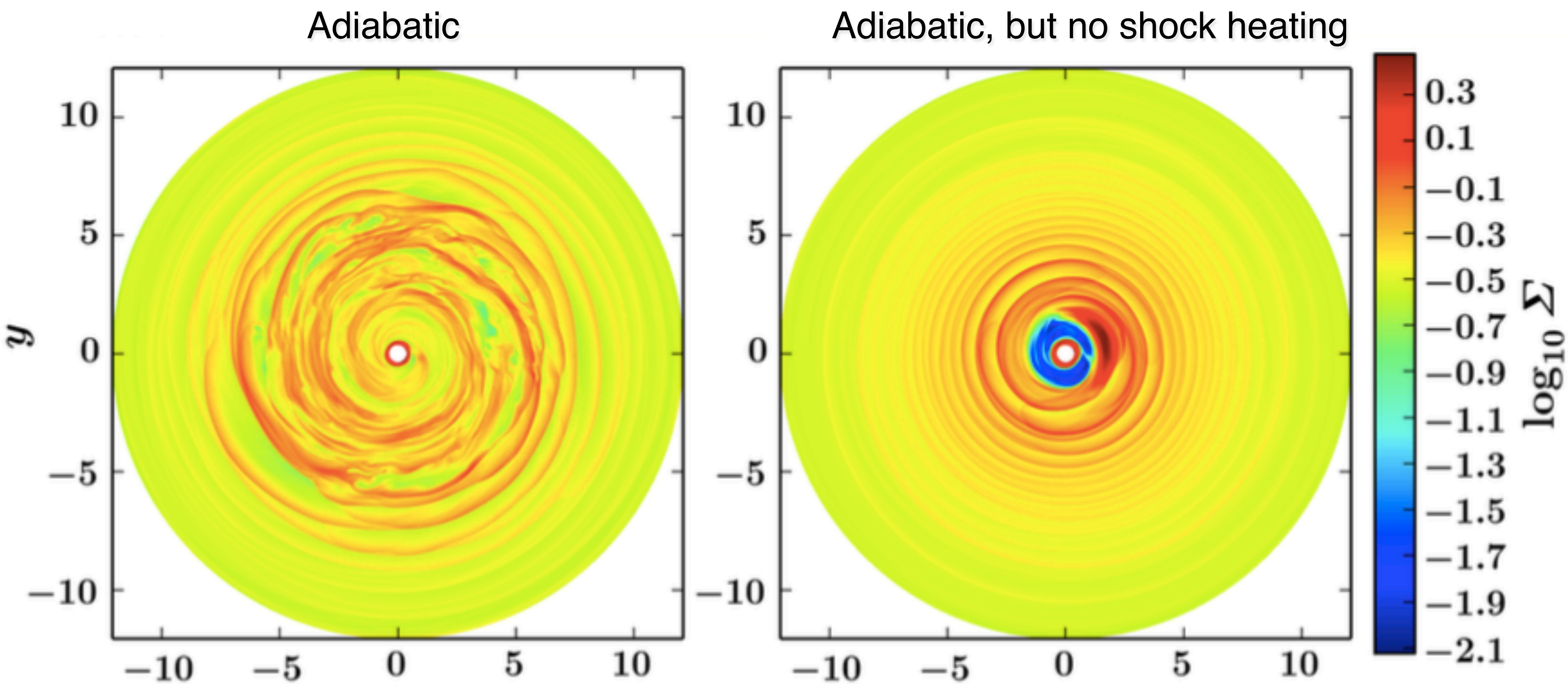
Richert et al. (2015)

Isothermal vs Adiabatic



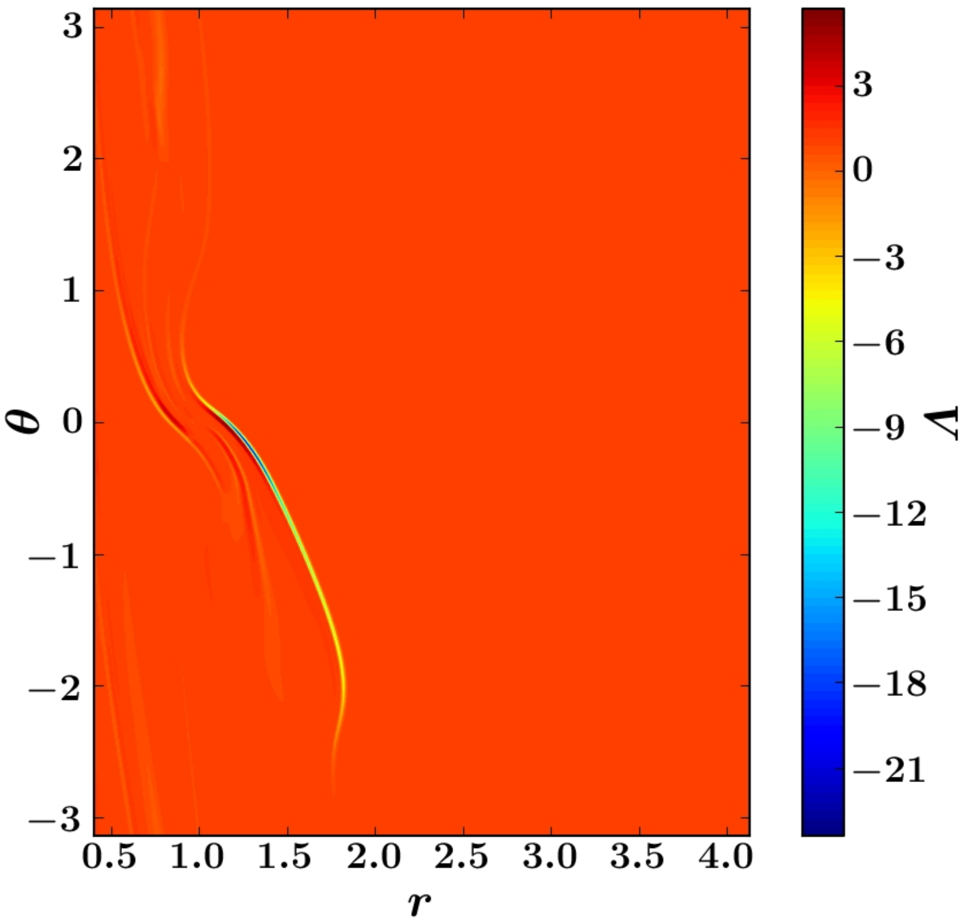
Richert et al. (2015)

The energy source: shock heating!

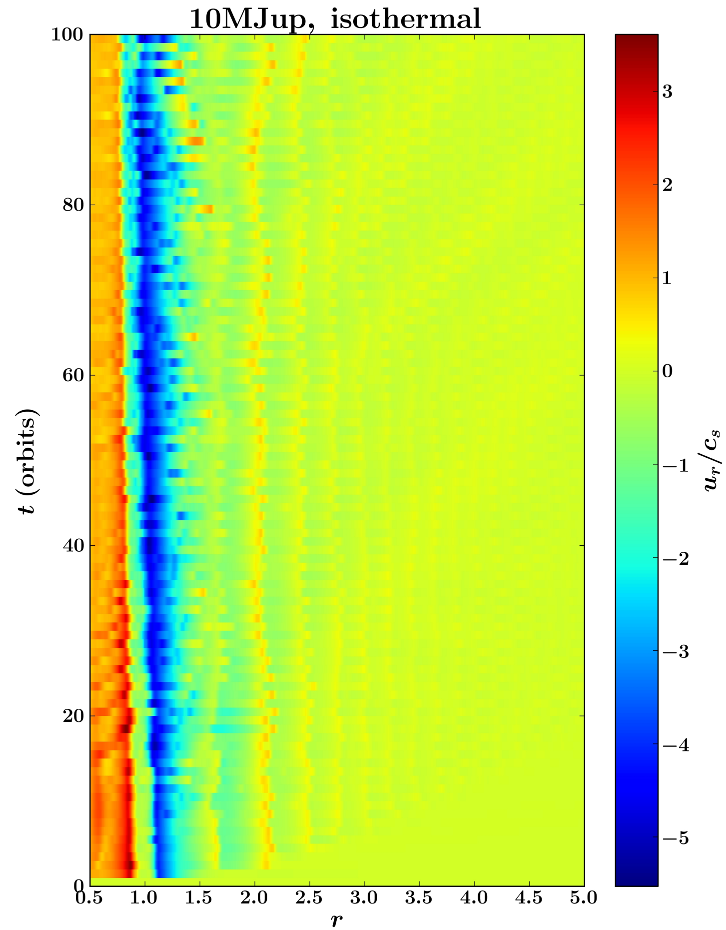


Richert et al. (2015)

The spiral is buoyantly unstable



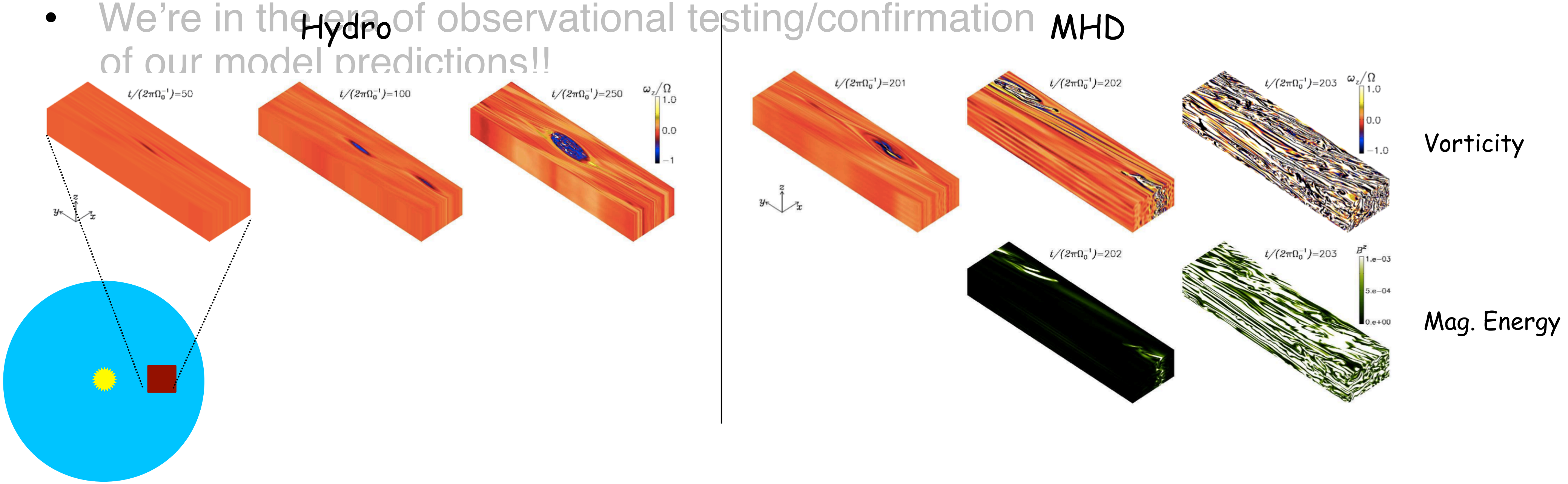
The spiral has Ma >~ 1



Richert et al. (2015)

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

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- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted is a complementary formation mode to streaming instability
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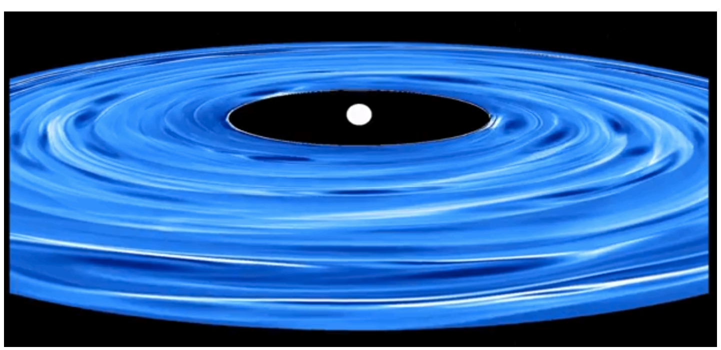
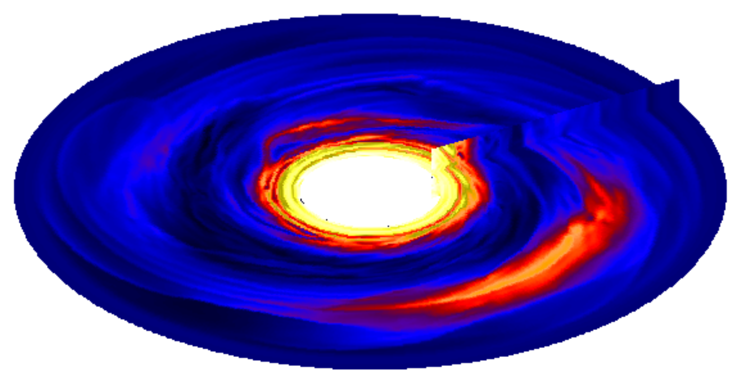
- Rossby wave instability may be the culprit of these dust traps
- We're in the era of observational testing/cor

Baroclinic instability



Rossby wave instability



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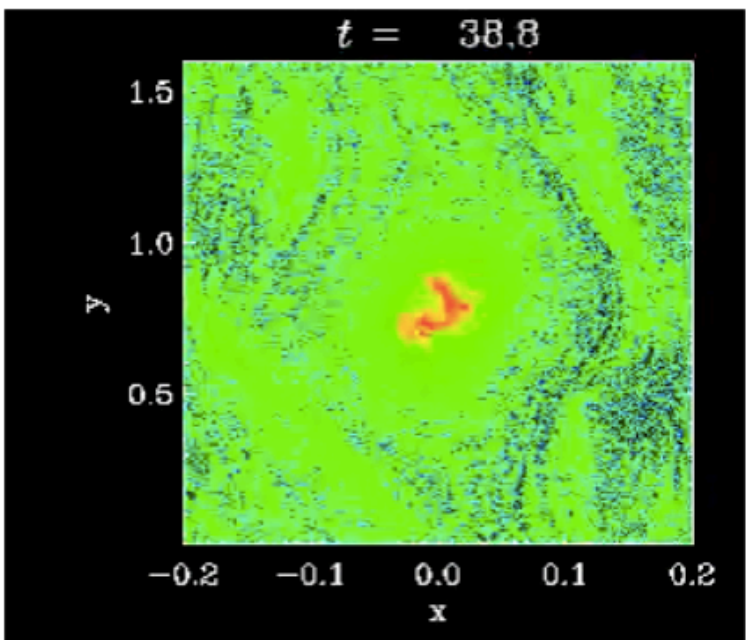

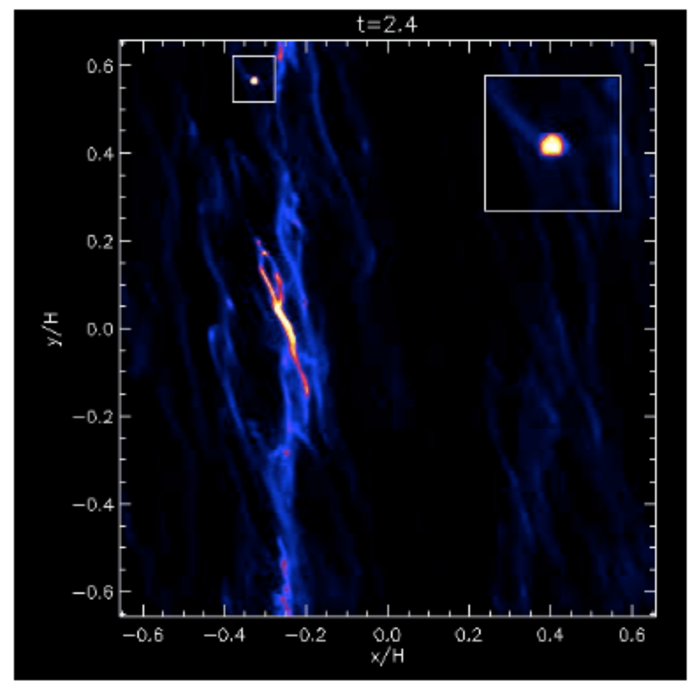

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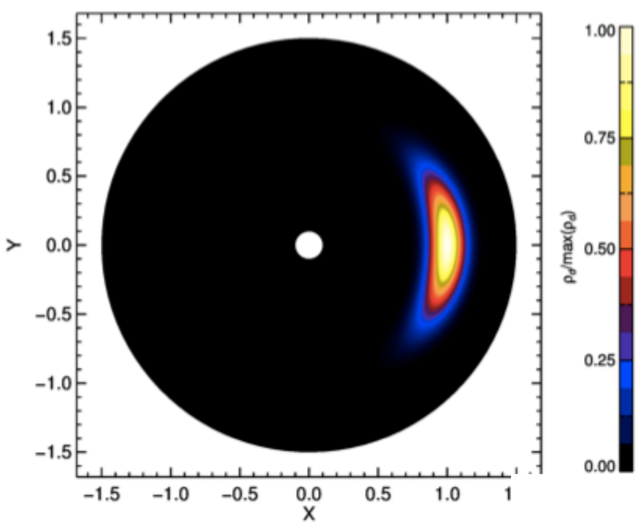
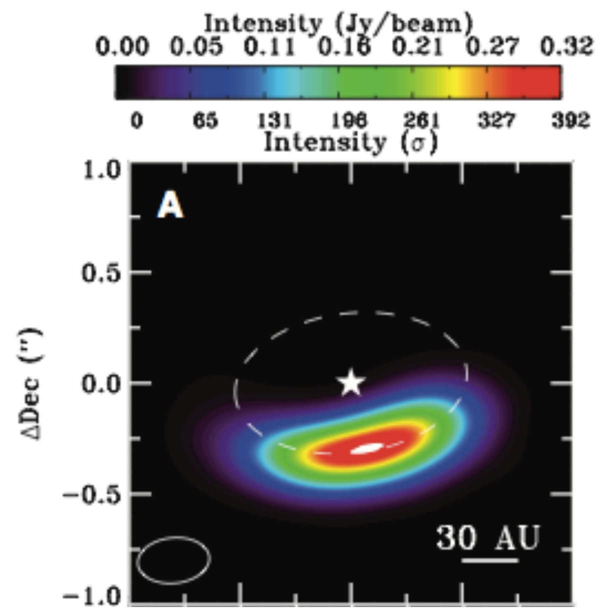
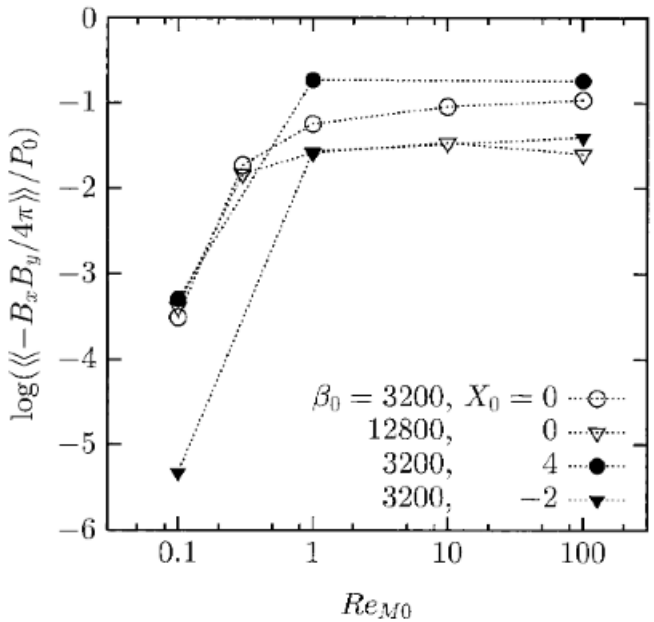
$$\rho_d(a,z) = \varepsilon\rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin (2013)





Conclusions



zone only

Rossby Wave Instability and Convective Overstability

mi

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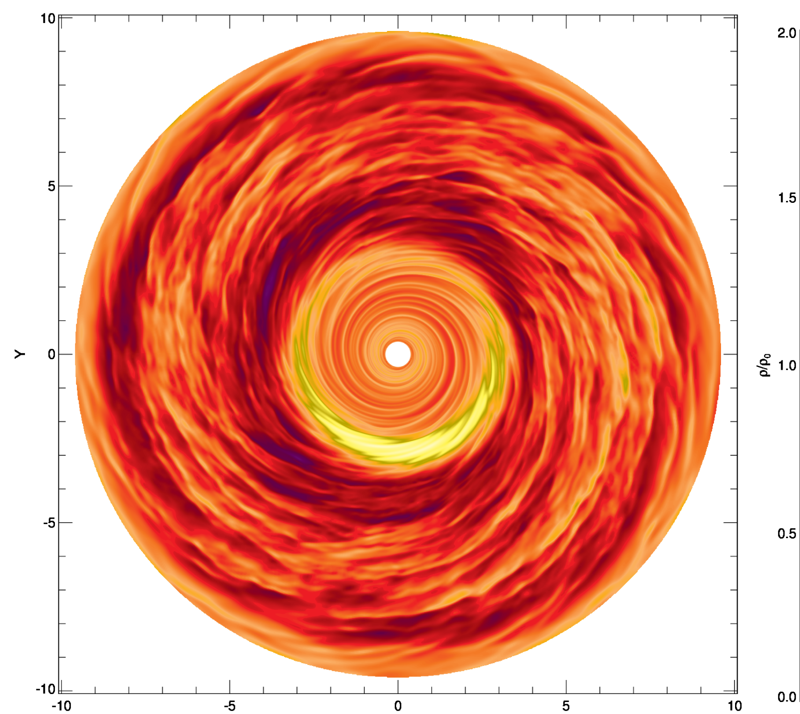

Conclusions

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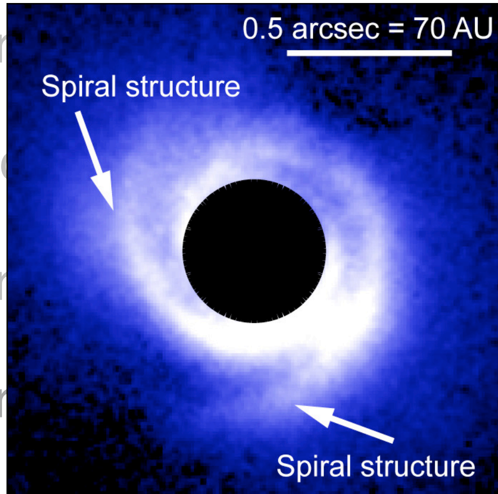

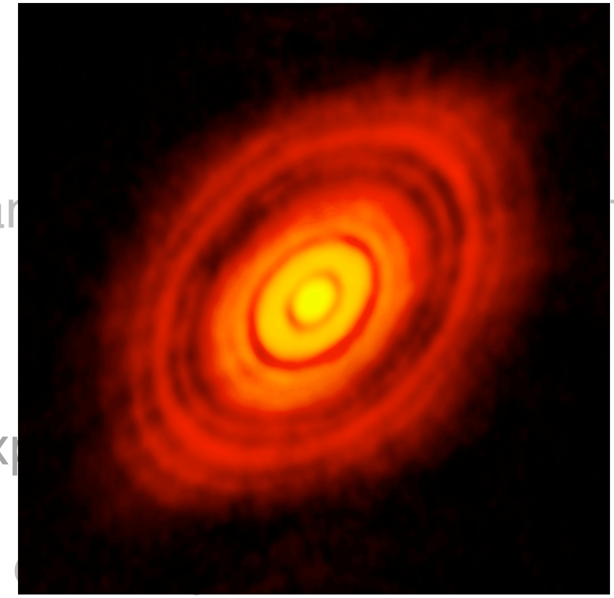

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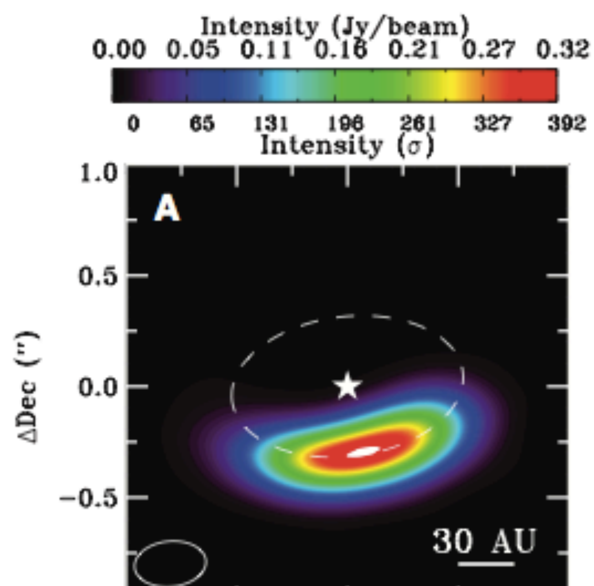

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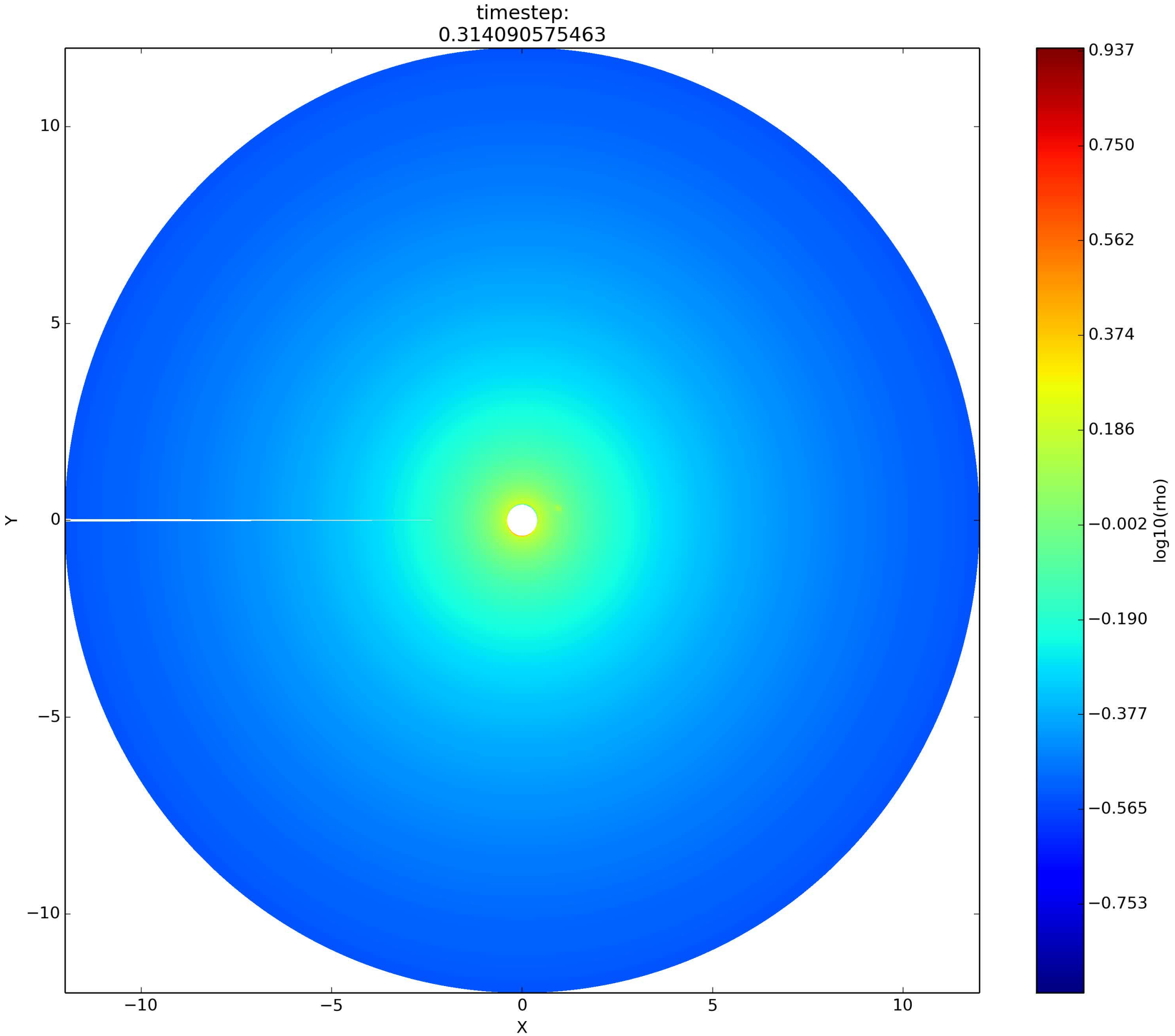

Richert et al. (2015)