Evolution of circumstellar disks and planet formation

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Leiden Observatory, The Netherlands

Mar 9th, 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

Protoplanetary Disks

PP disk fact sheet

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

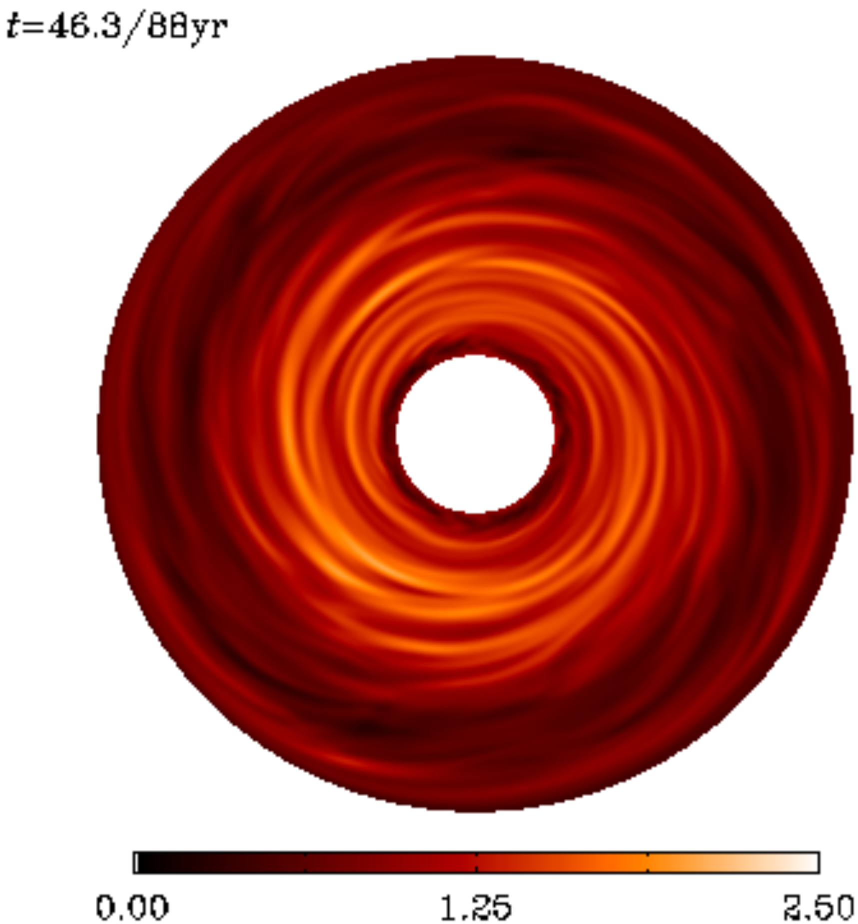
Temperature: 10-1000 K

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

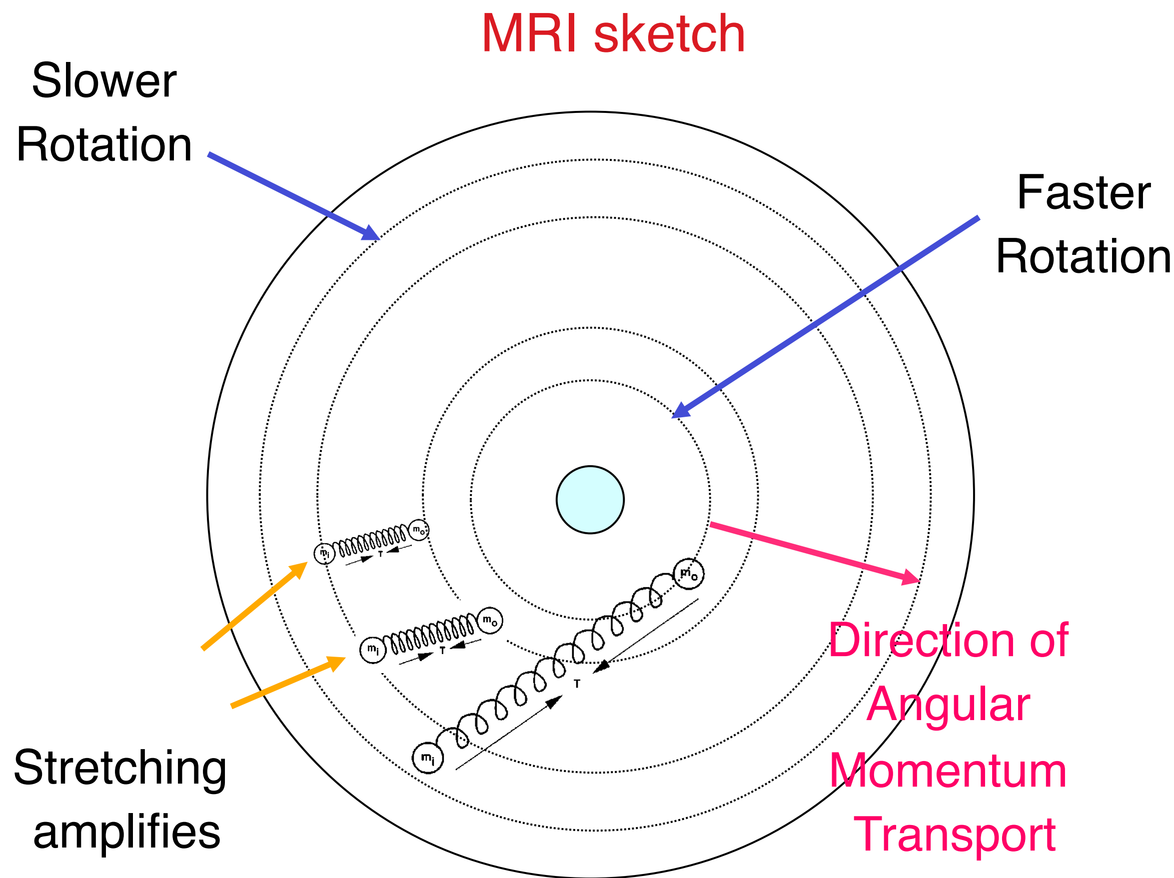
Mass: $10^{-3} – 10^{-1}$ M_{sun}
(1 M_{sun} = 2×10^{33} g)

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability

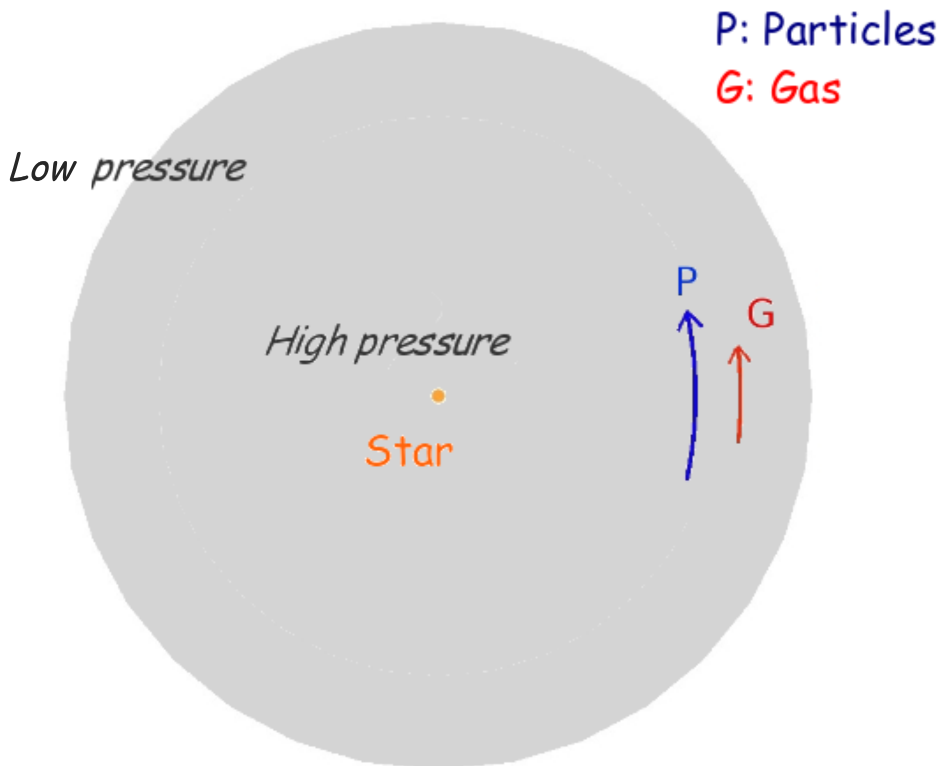


Magnetized disk
Lyra et al. (2008a)

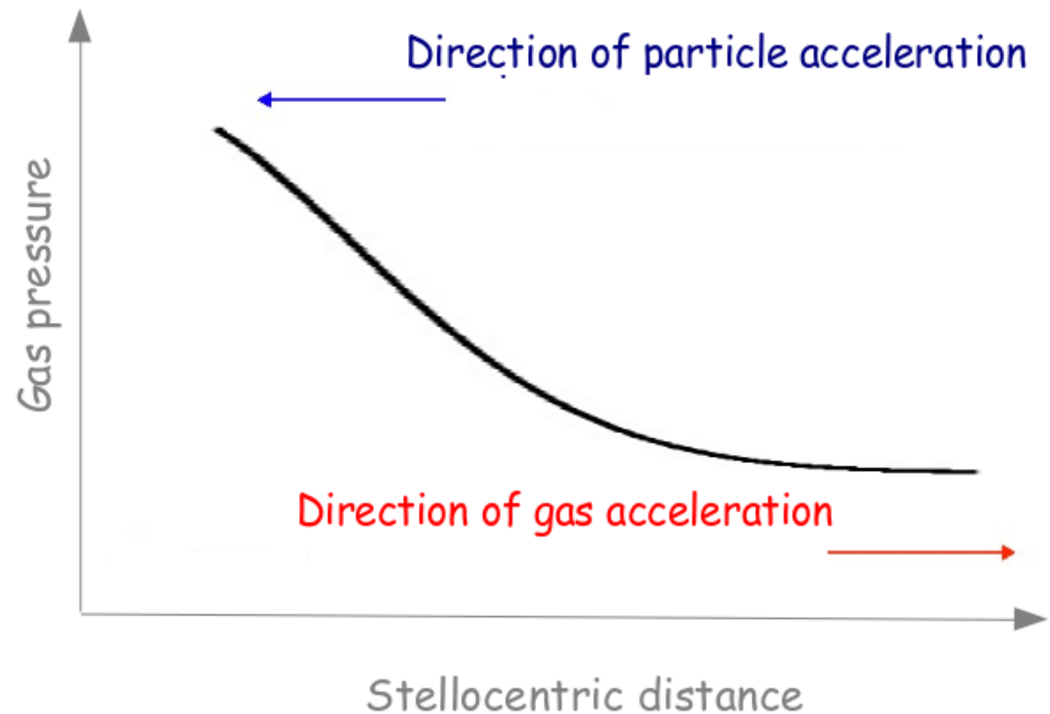


Unstable if angular
velocity decreases
outward

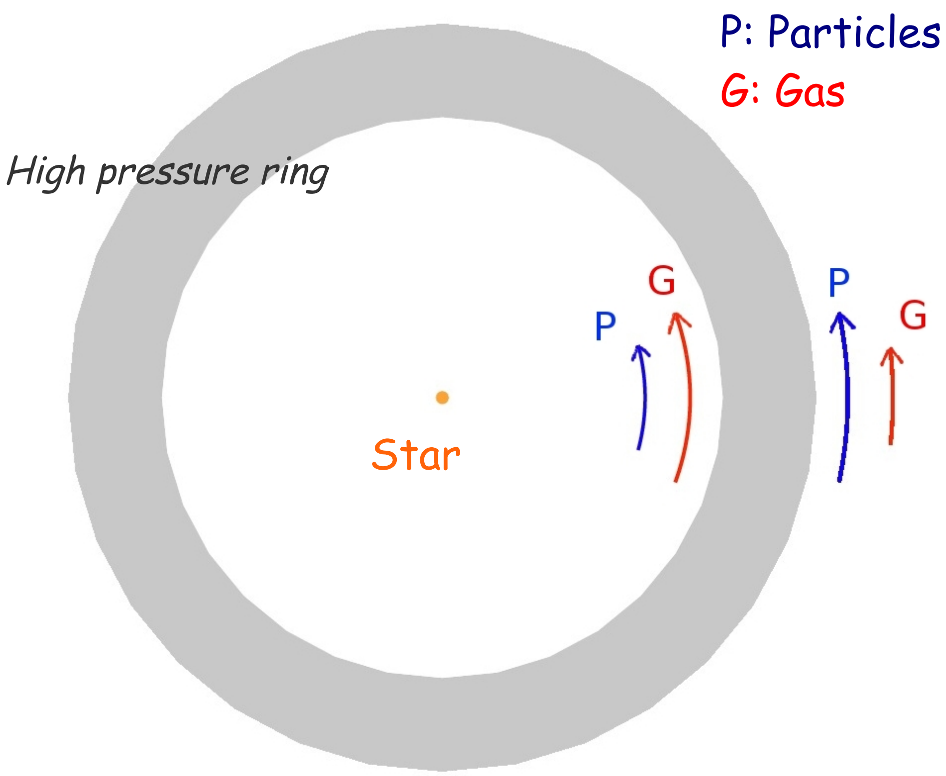
Particle drift



Adapted from Whipple (1972)



Pressure Trap



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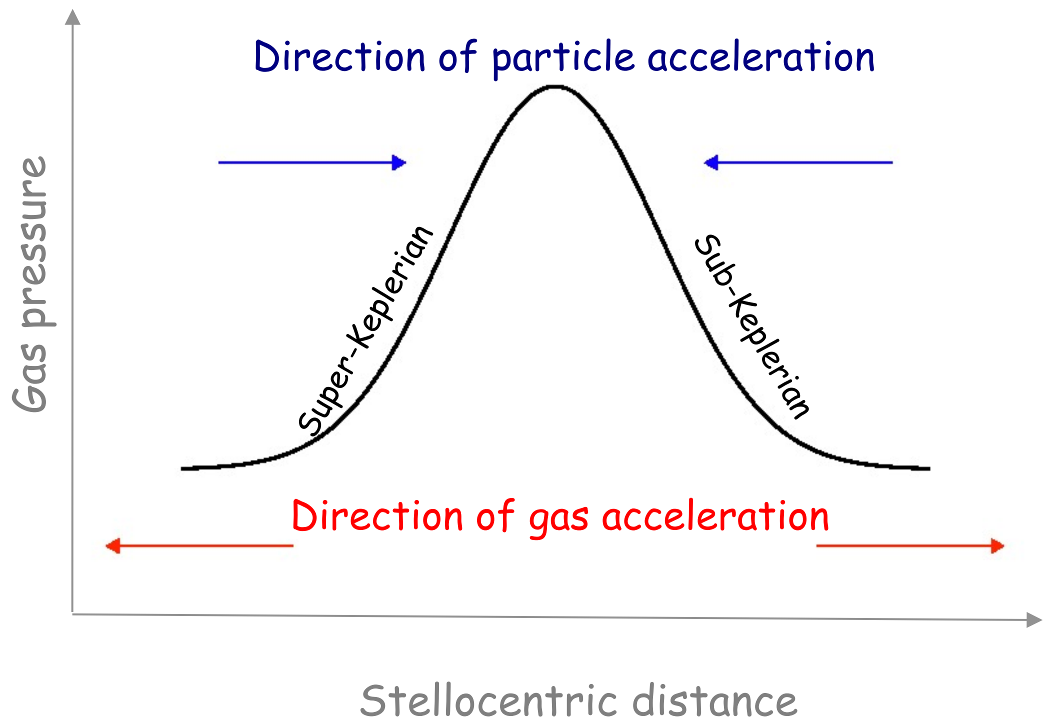

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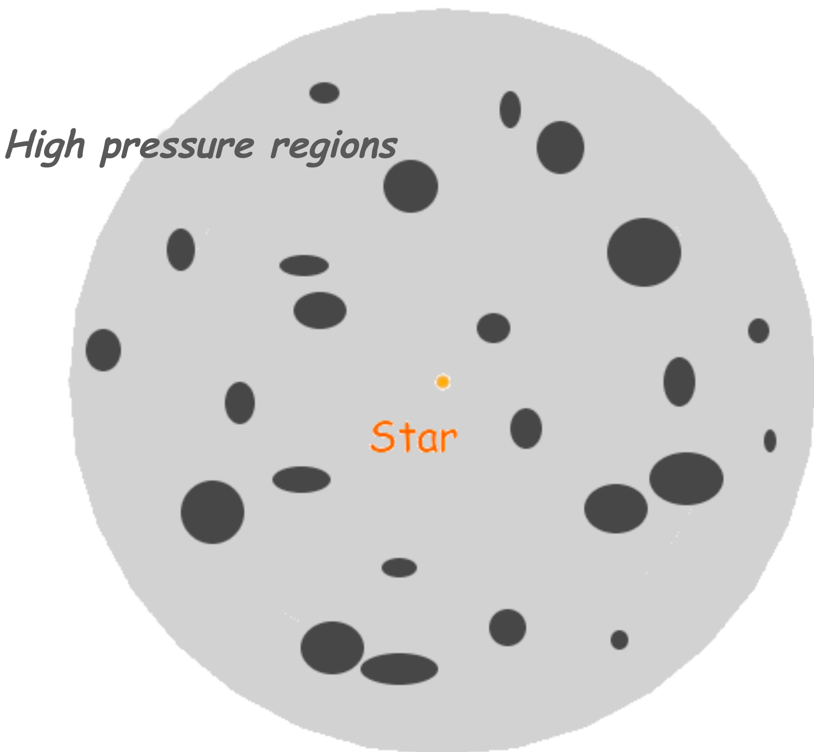
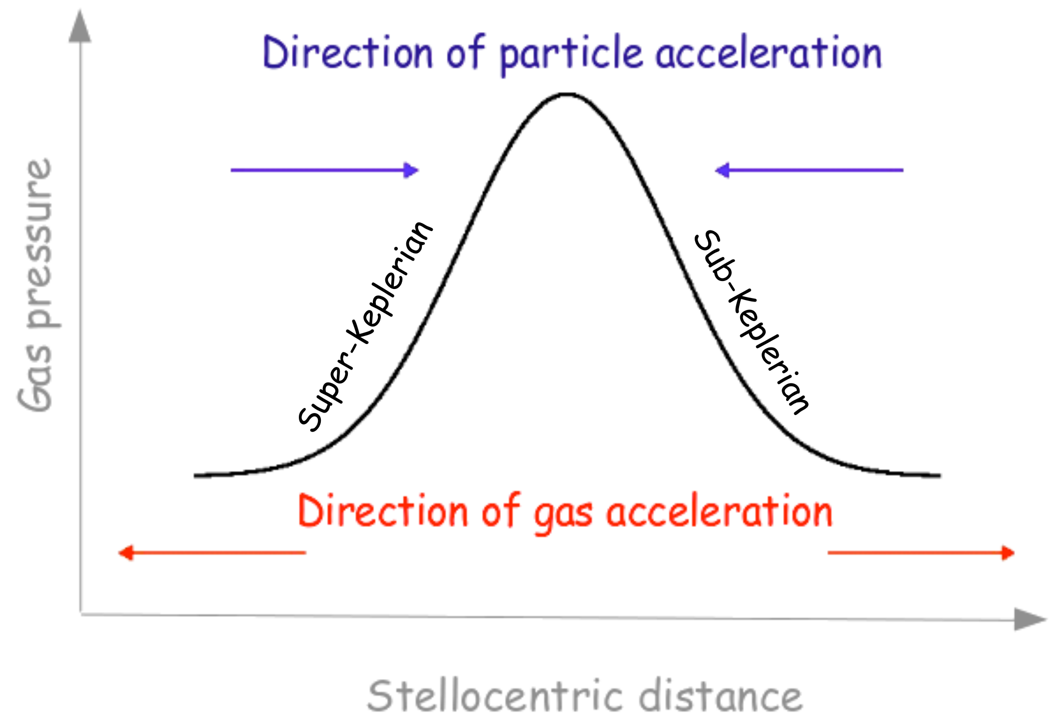
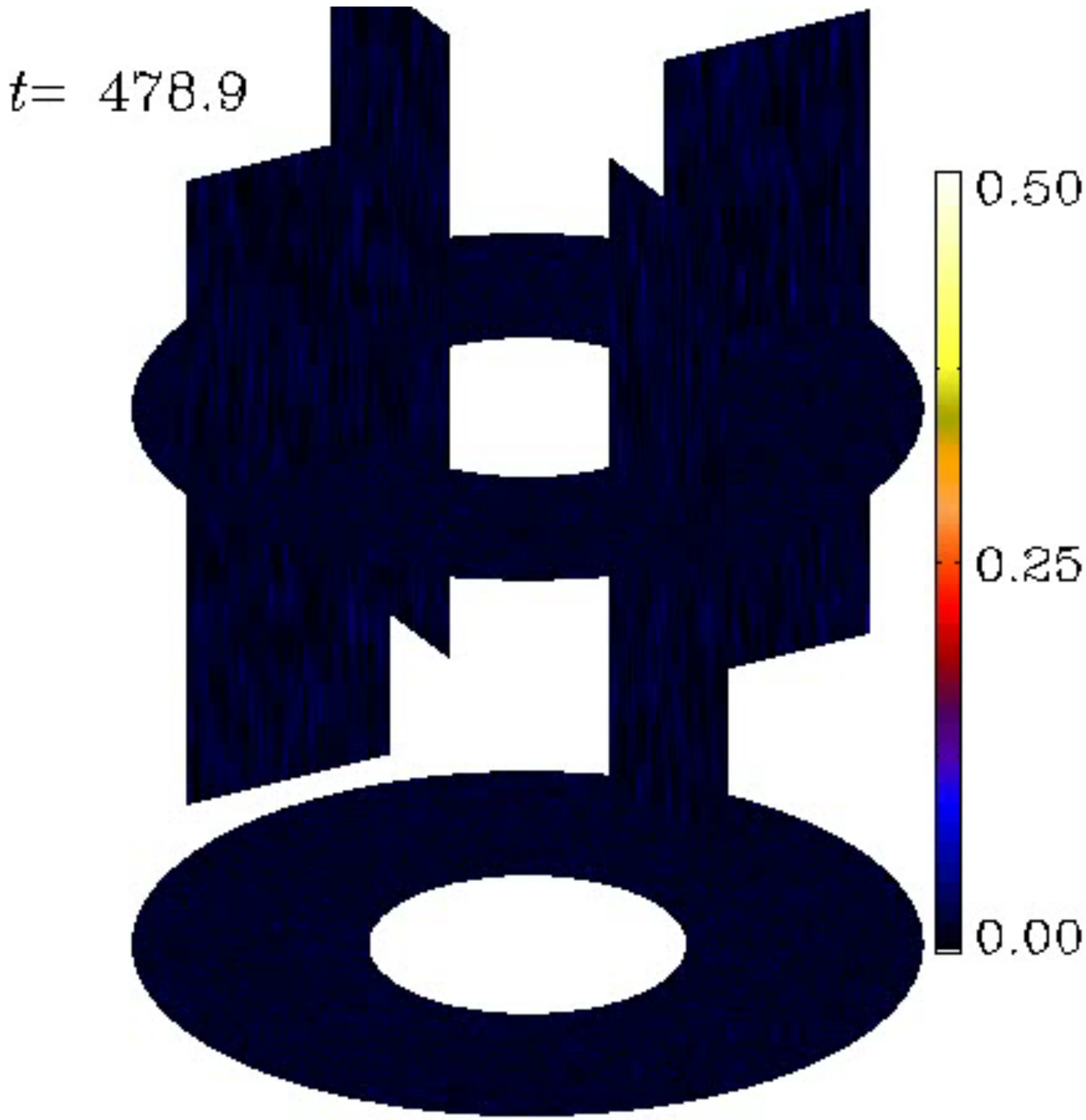


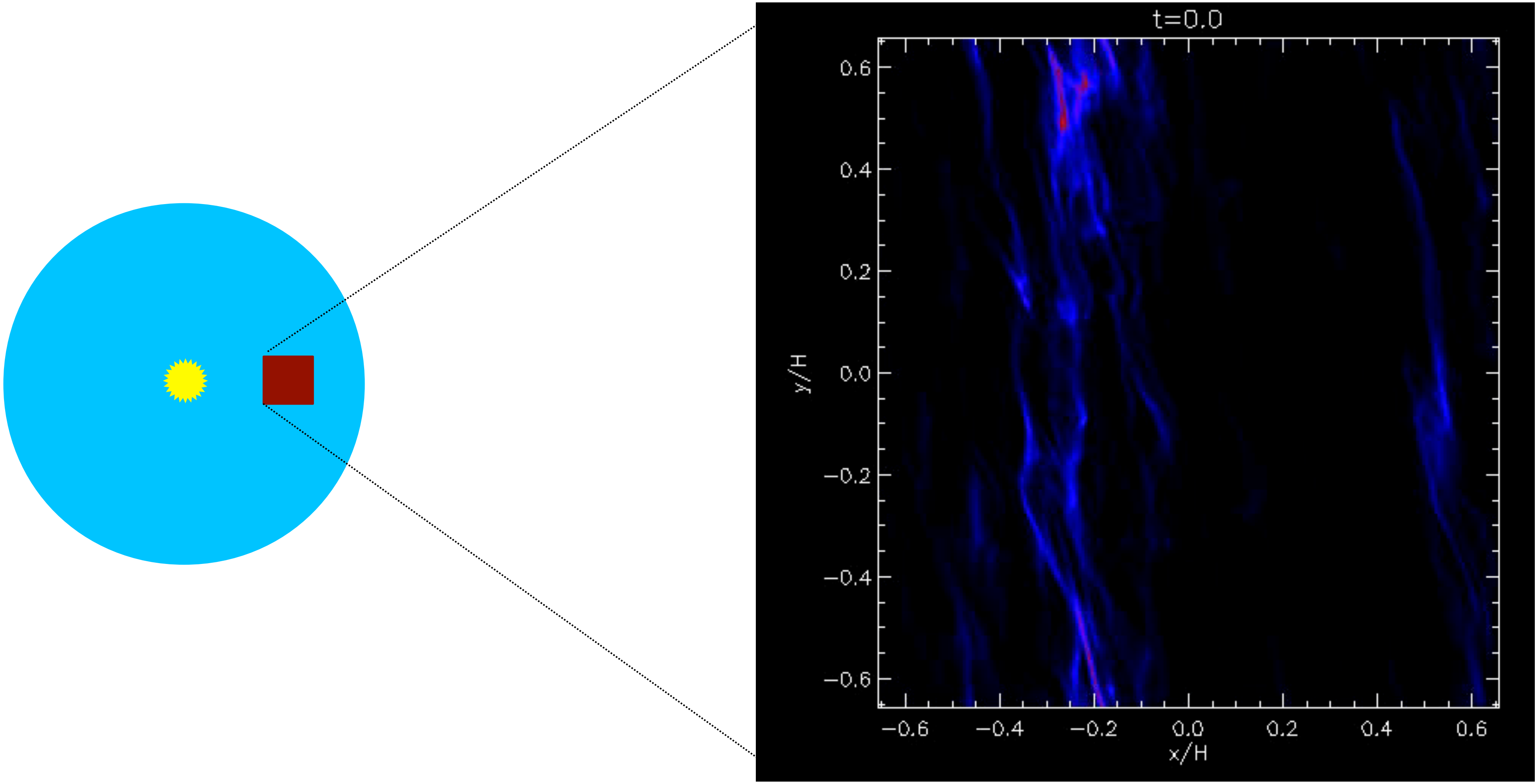


Turbulence concentrates solids mechanically in pressure maxima



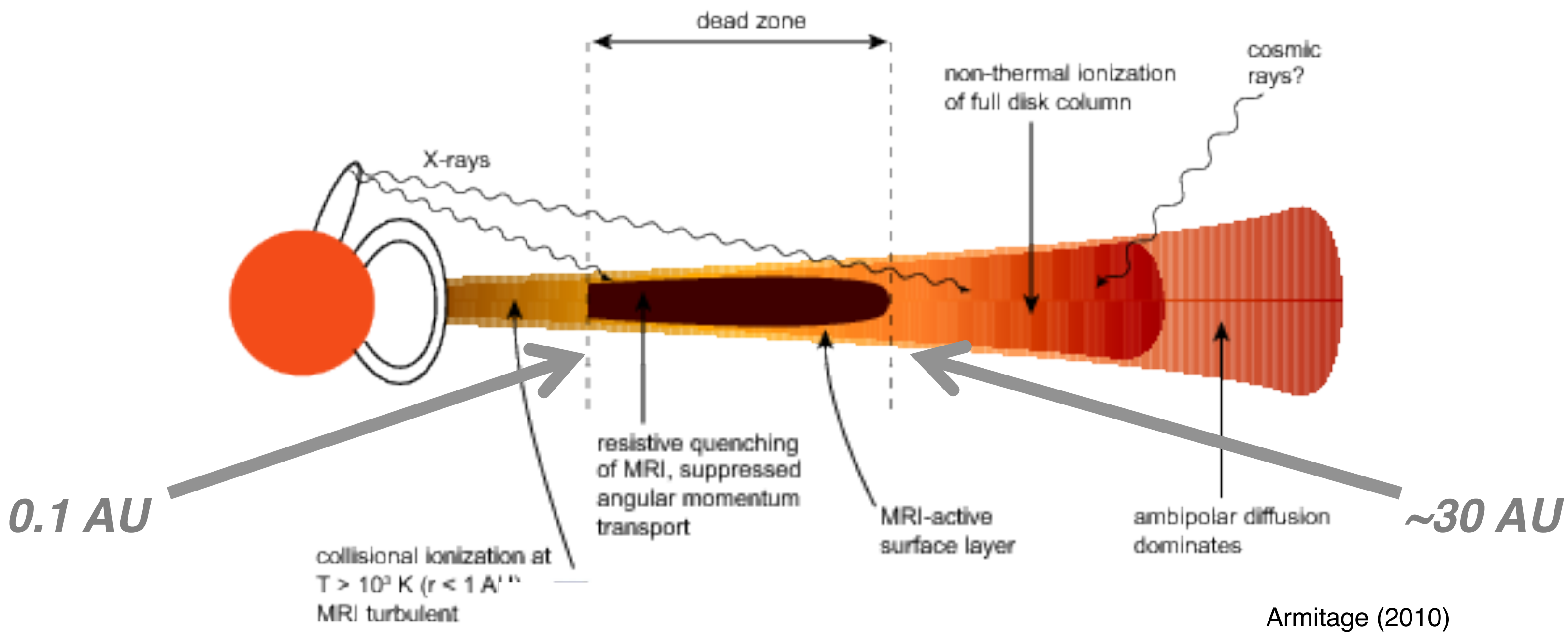
Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

Dead zones are robust features of protoplanetary disks



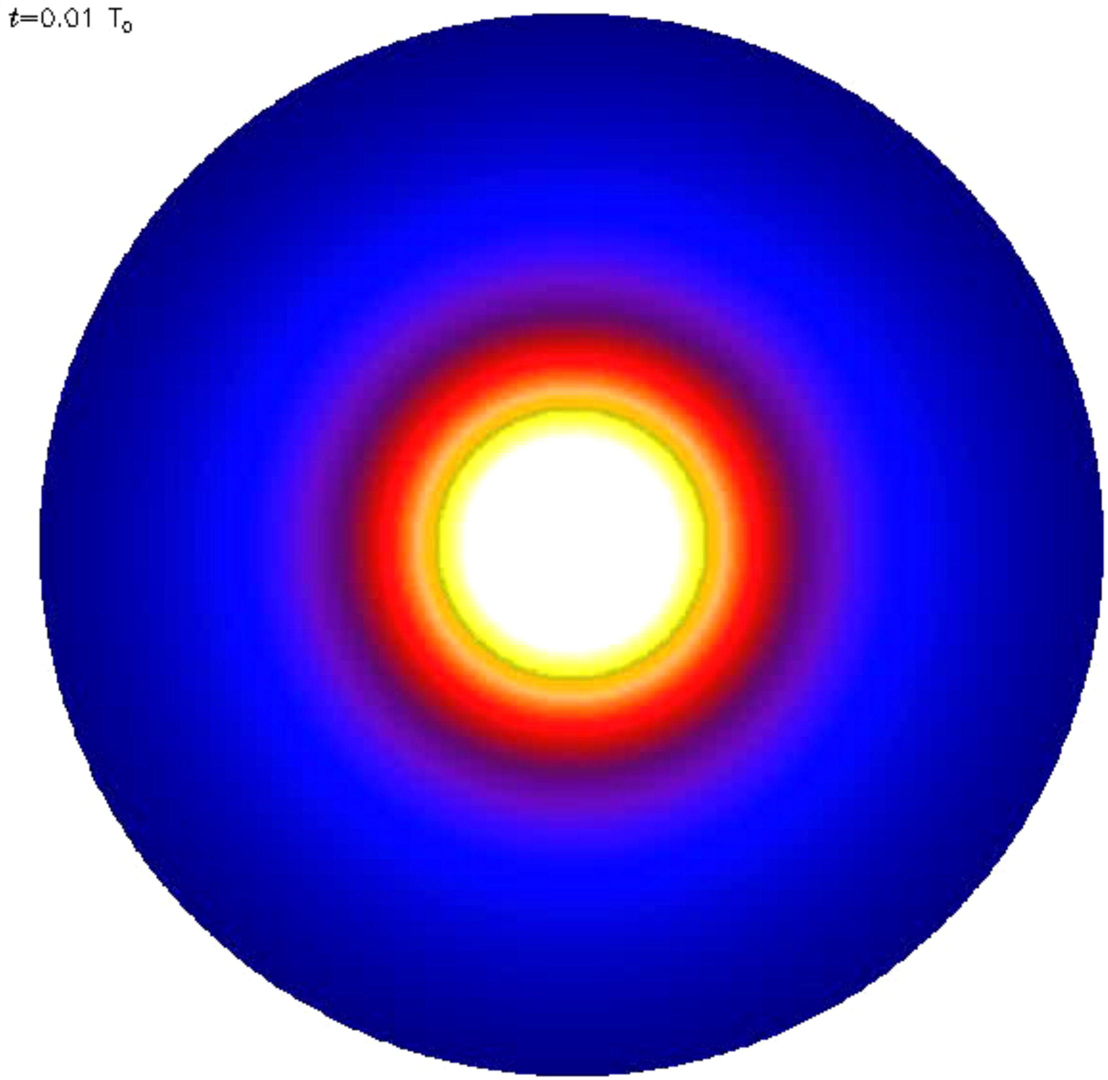
Armitage (2010)

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.**

Active/dead zone boundary

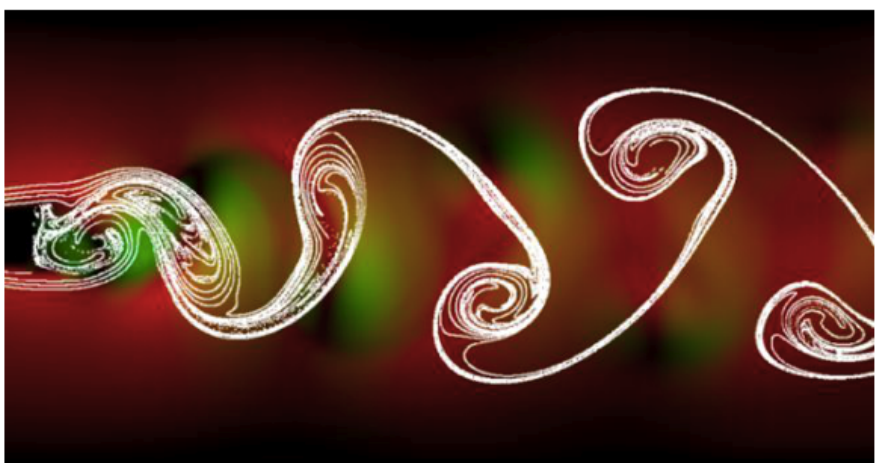
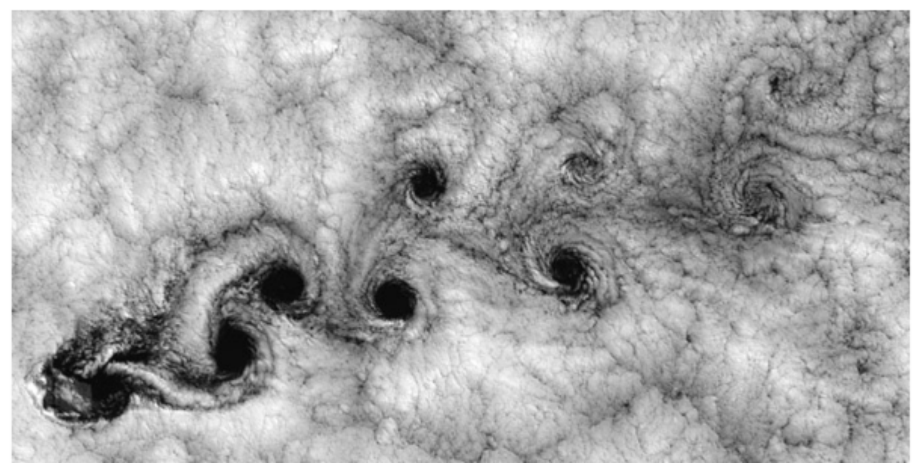


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

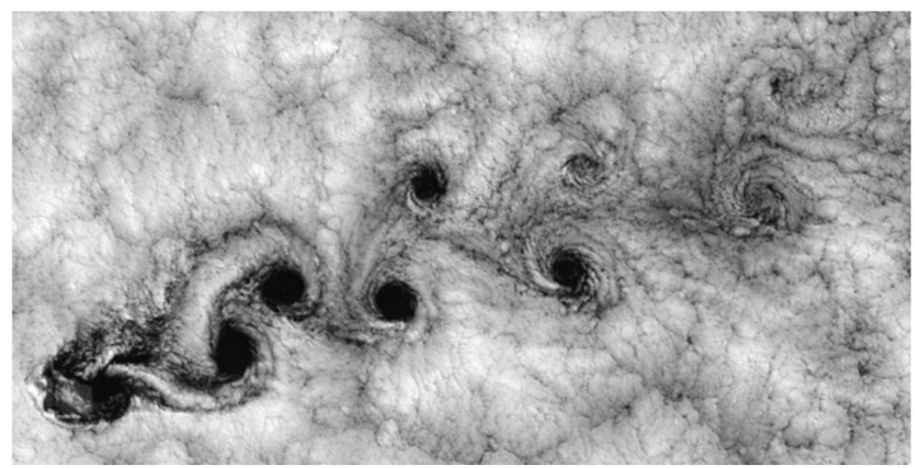
Vortices – an ubiquitous fluid mechanics phenomenon



Vortices – an ubiquitous fluid mechanics phenomenon

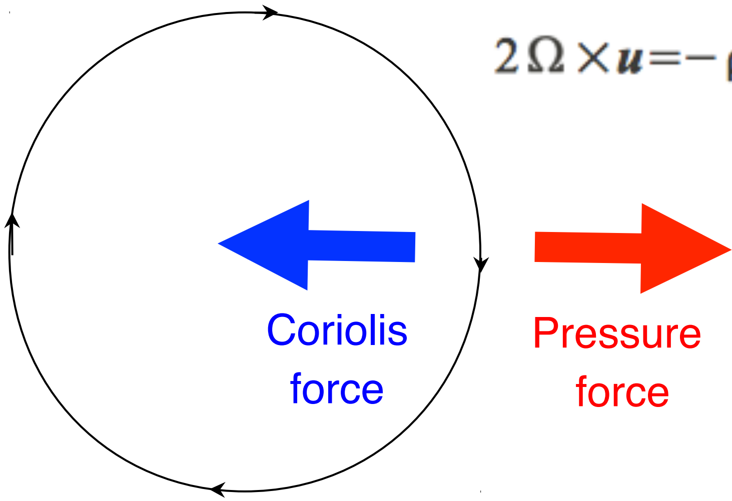
Von Kármán *vortex street*



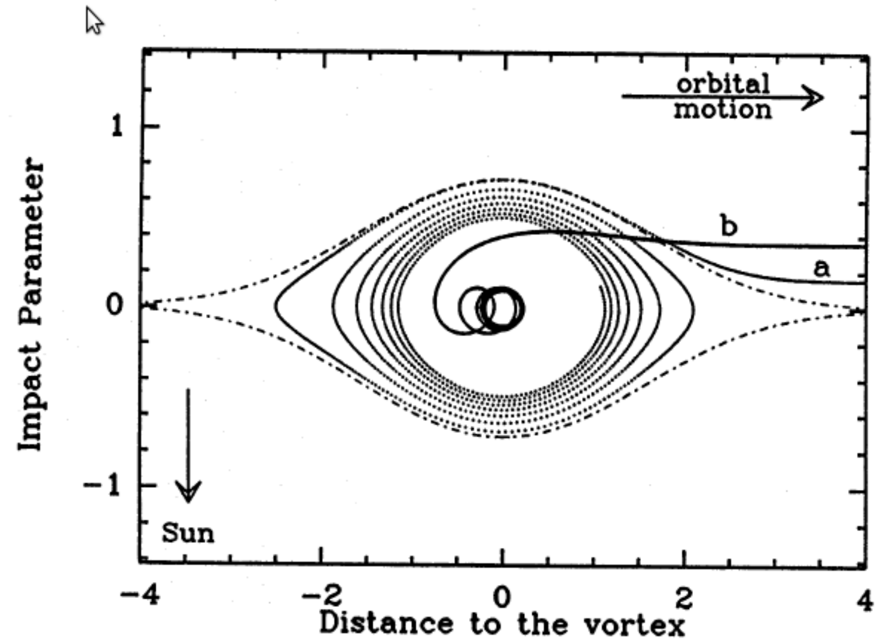
The Tea-Leaf effect

Geostrophic balance:

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



Vortex streamline



Barge & Sommeria (1995)

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

Aid to planet formation

(Barge & Sommeria 1995, Adams & Watkins 1996, Tanga et al. 1996)

Speed up planet formation enormously

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

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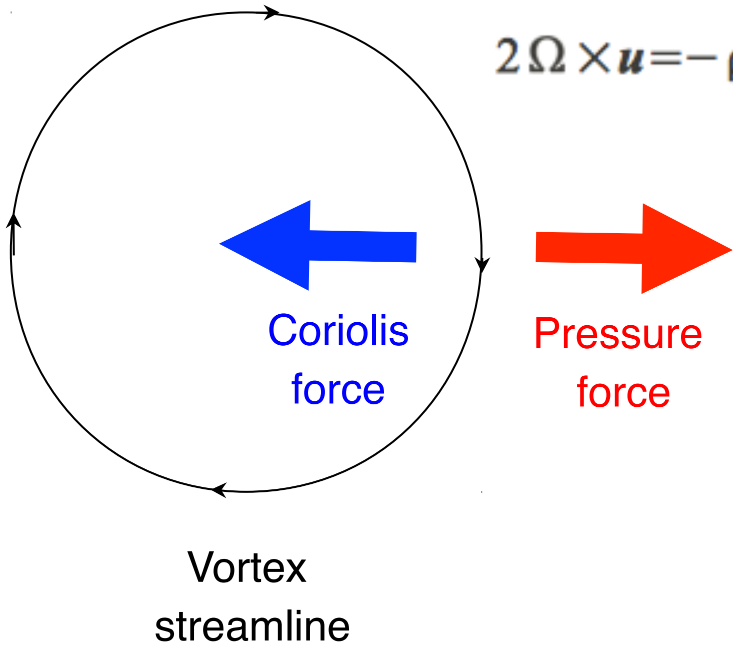

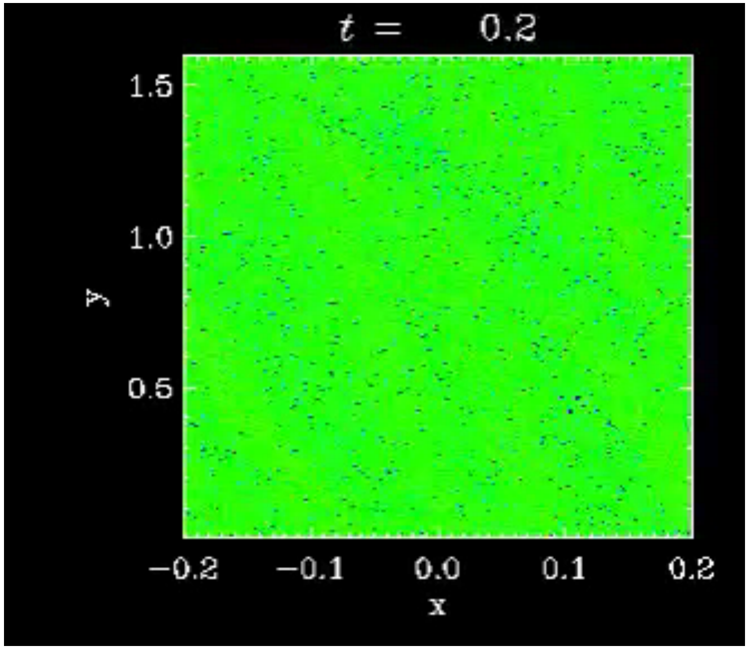

Raettig et al. (2012)

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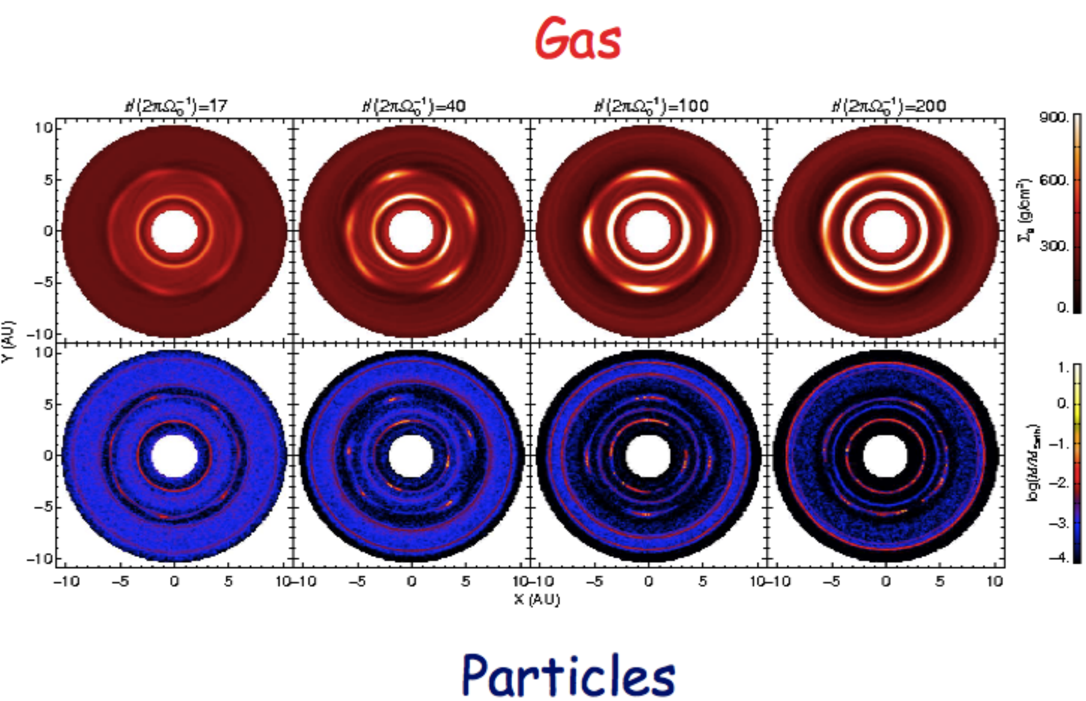
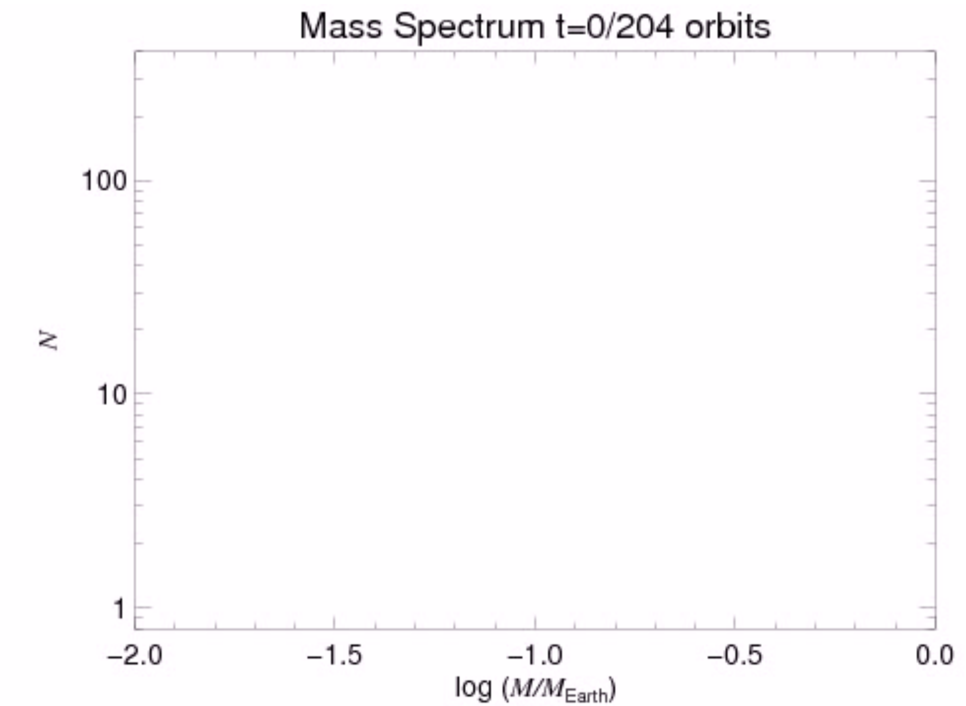
Vortices and Planet Formation

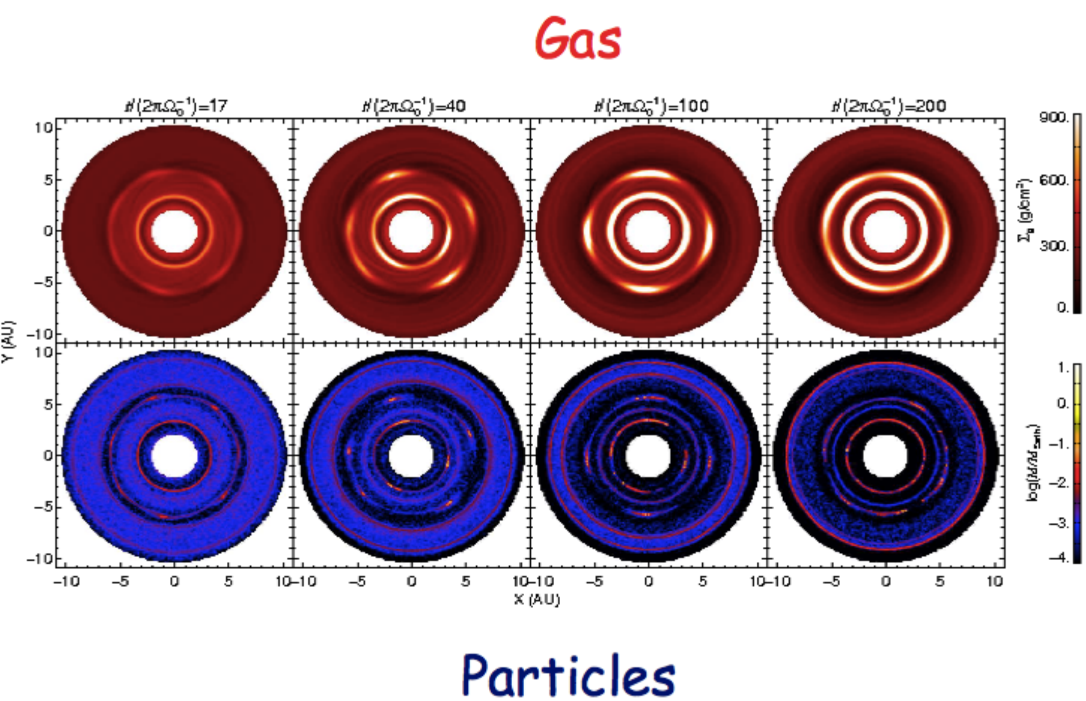


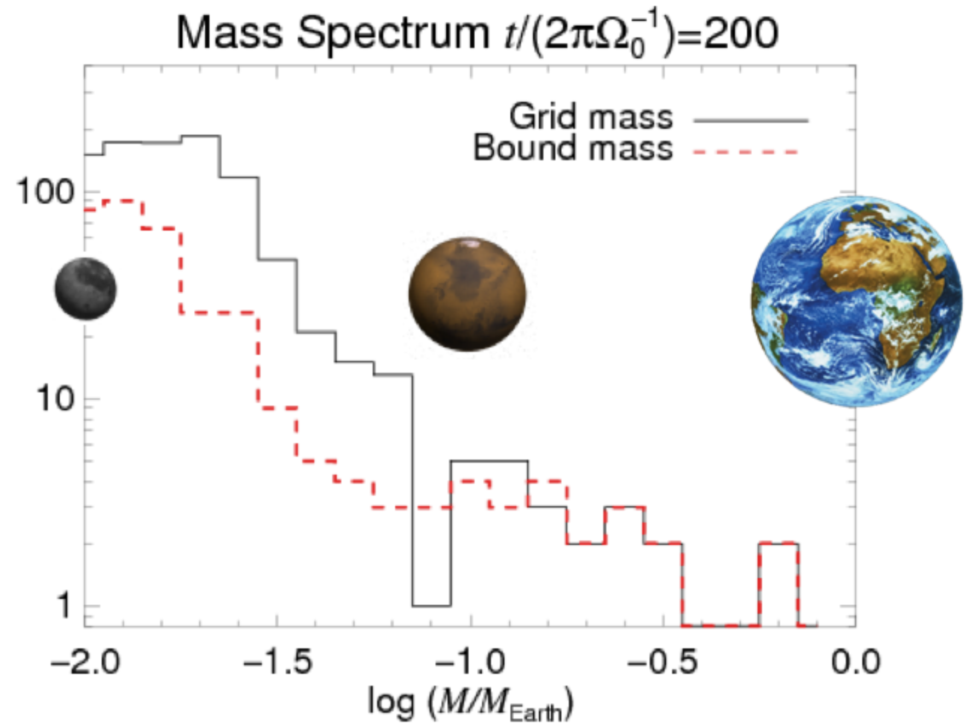


Collapse into Mars mass objects

(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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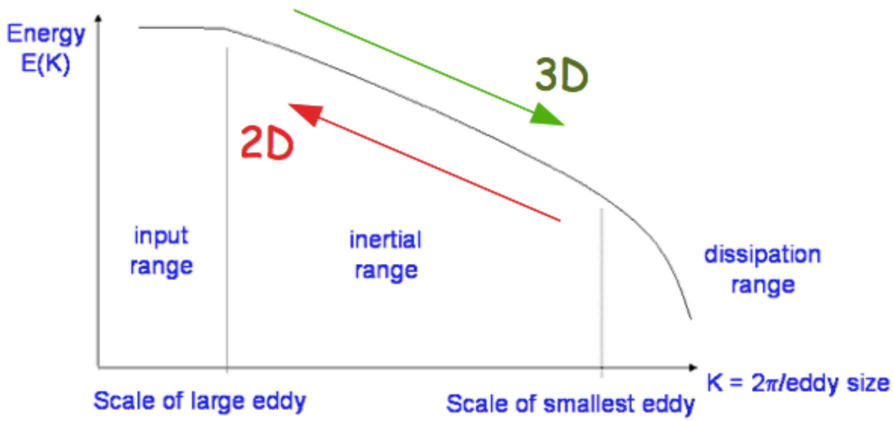
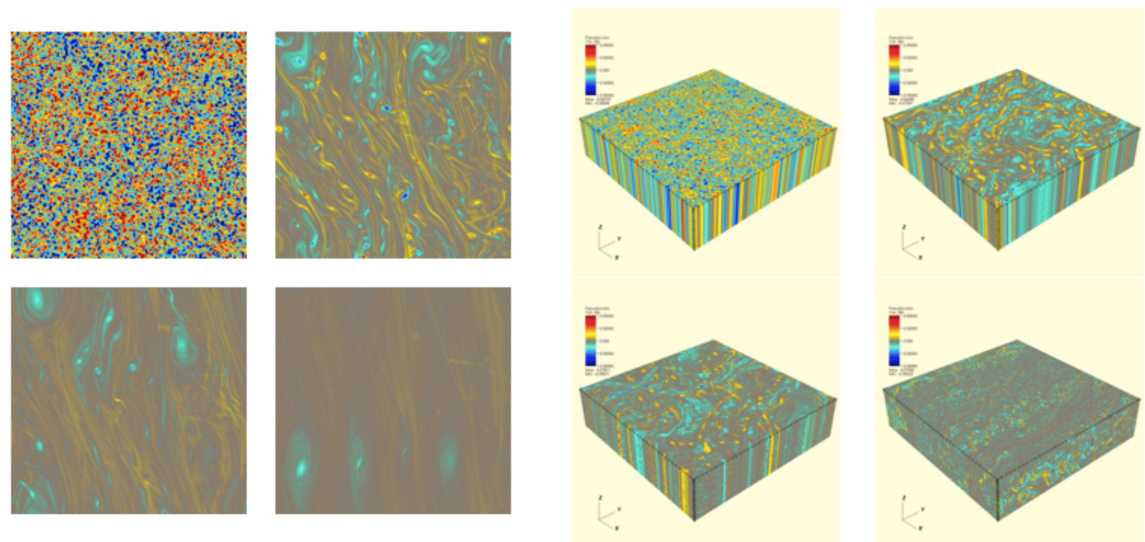
The energy cascade



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



2D

3D

Inverse cascade

No 3D instability
Eddies merge

Direct cascade

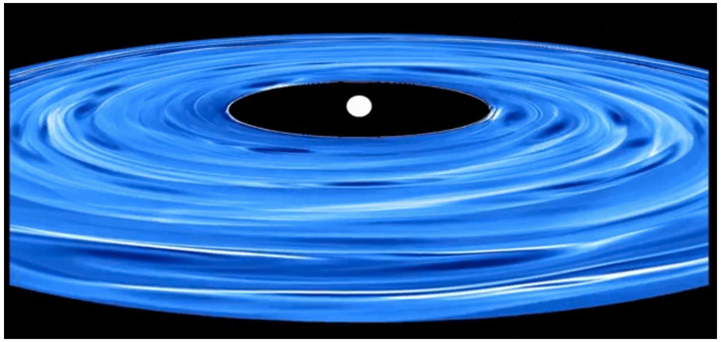
Destruction occurs
faster than merging

Sustaining vortices in disks

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

Baroclinic instability

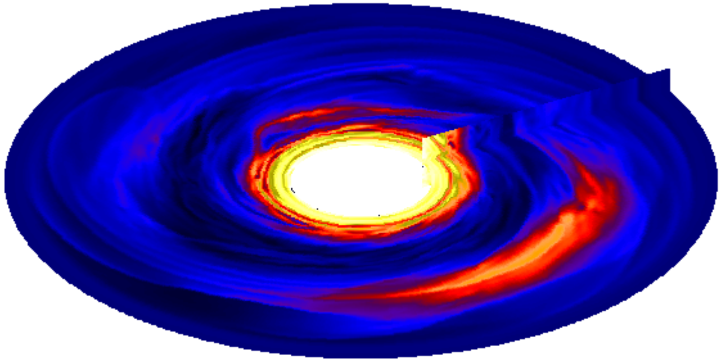
(Convective overstability)



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)

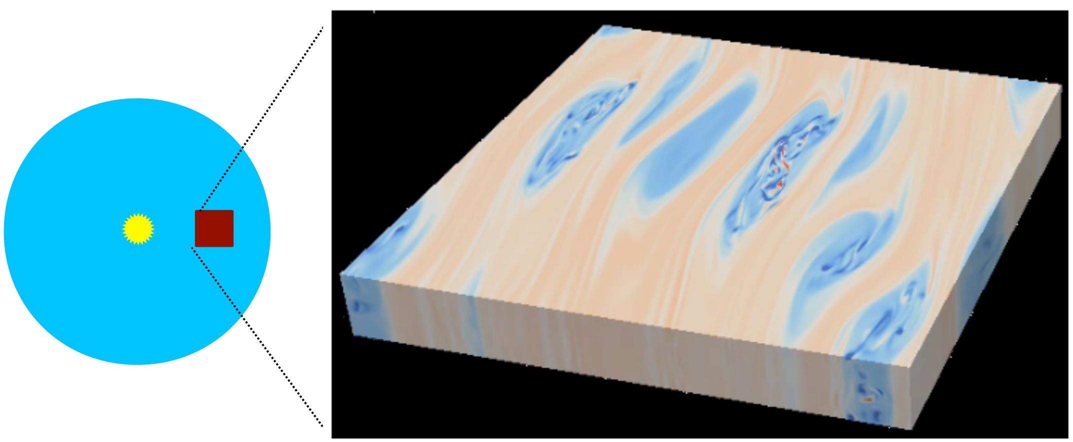
Rossby wave instability



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)

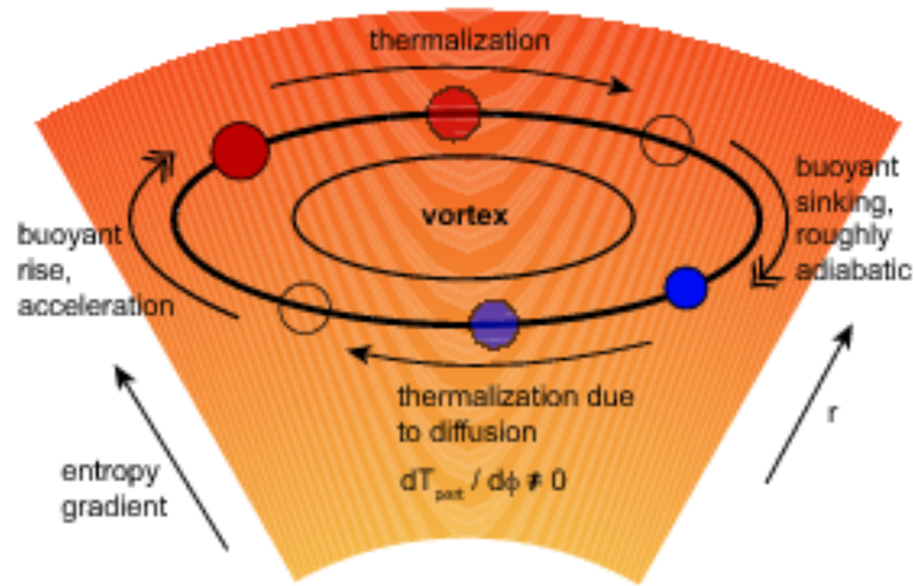
Powered by:
Modification of shear profile
(external vorticity reservoir)

Baroclinic Instability – Excitation and self-sustenance of vortices



Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability

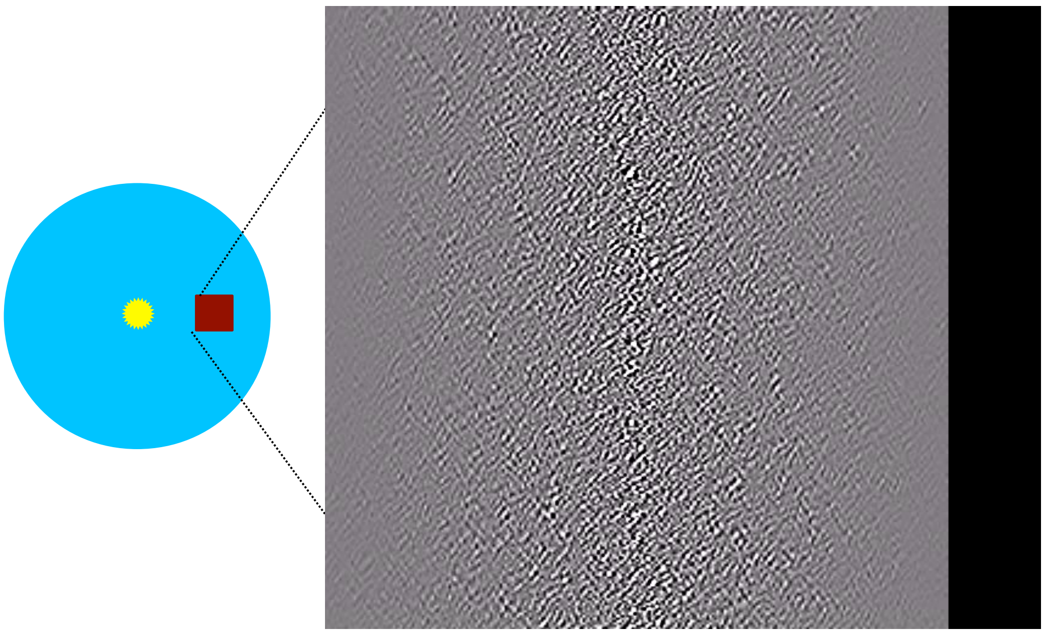


Armitage (2010)

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

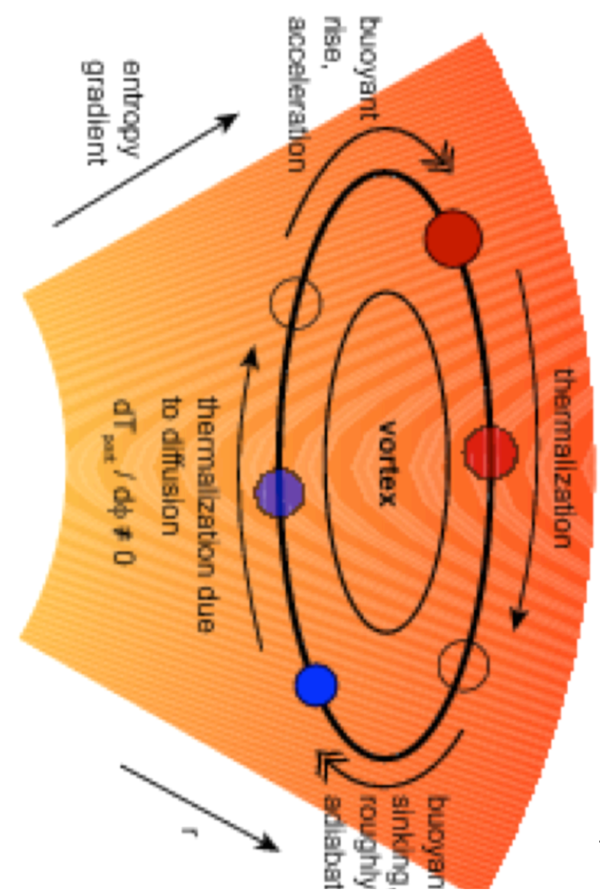
advection | compression | stretching | baroclinicity | dissipation

Baroclinic Instability – Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

Sketch of the Baroclinic Instability



Armitage (2010

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advection

compression

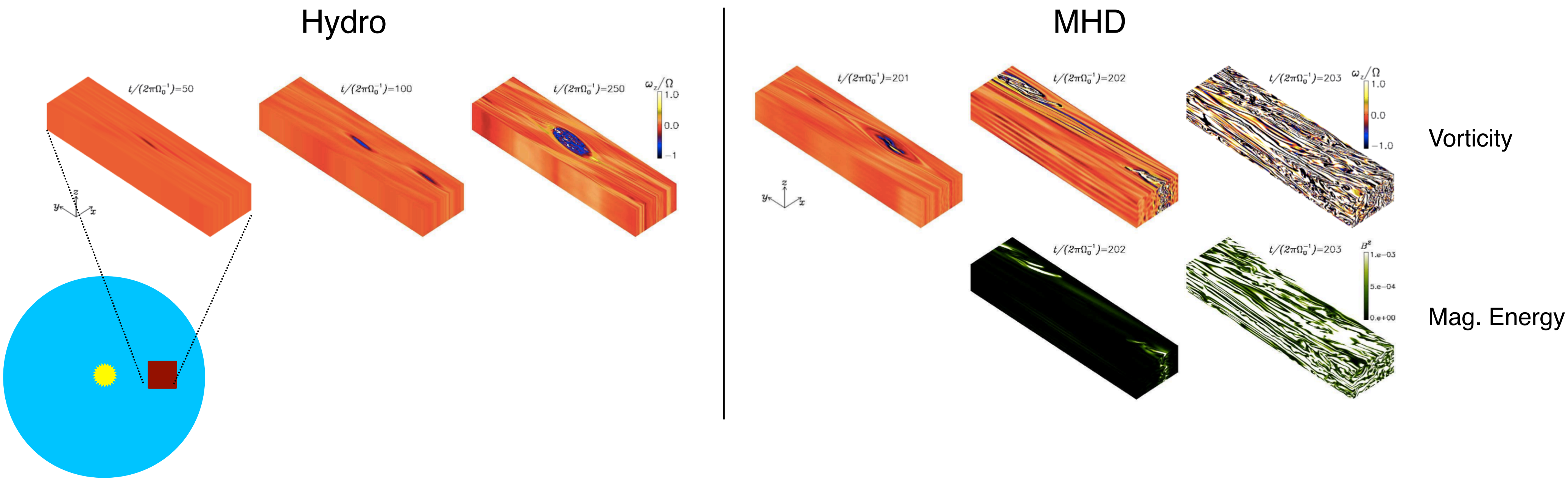
stretching

baroclinicity

dissipation

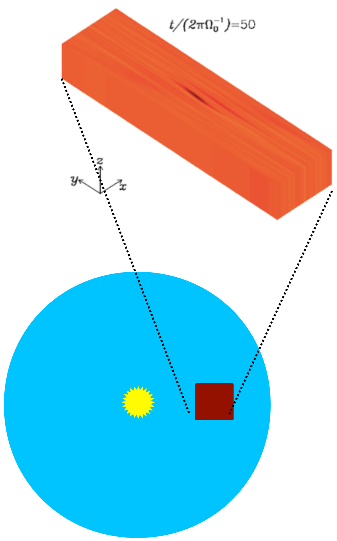
Baroclinic instability and layered accretion

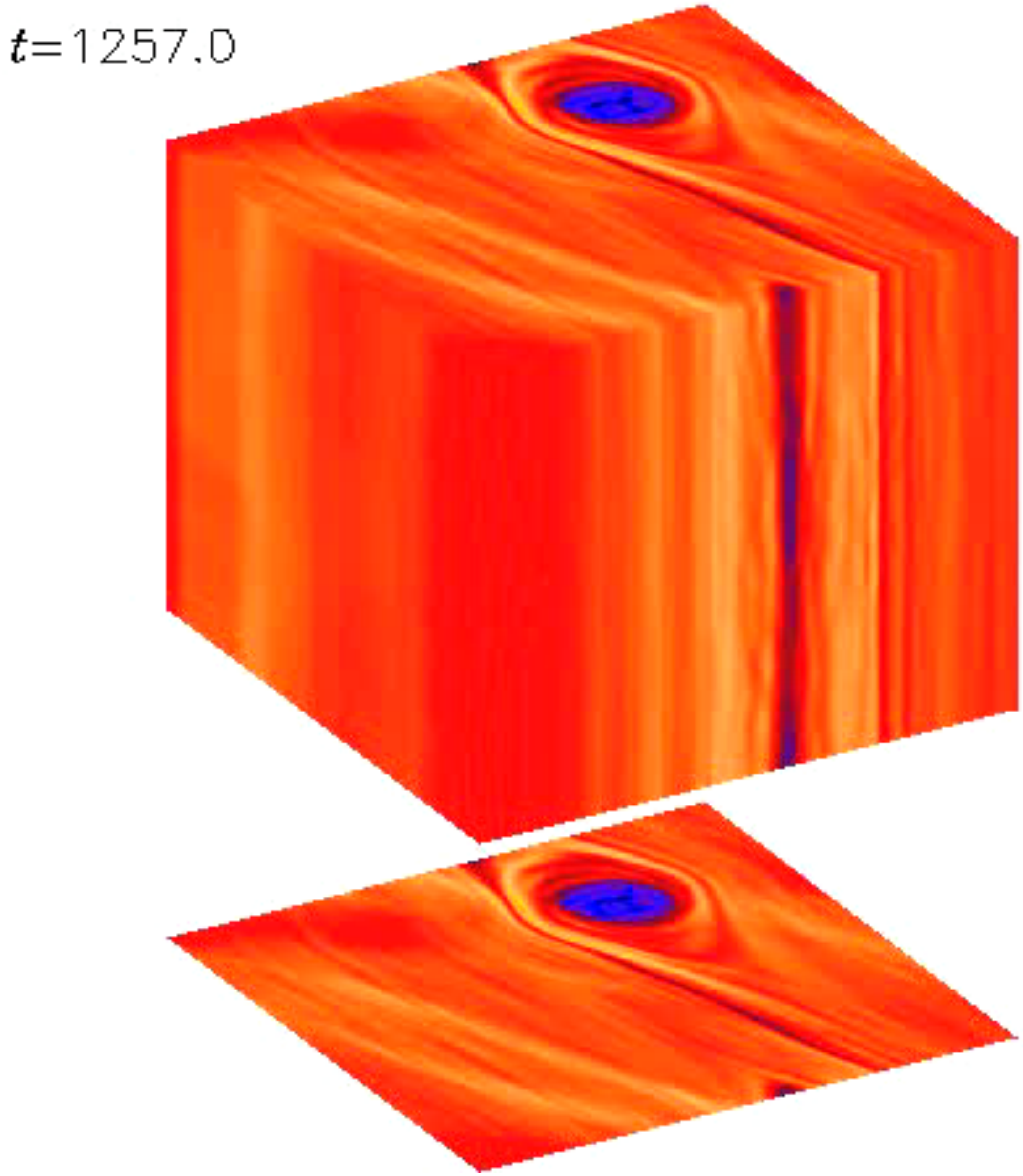
What happens when the vortex is magnetized?

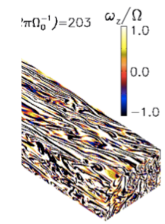


Lyra & Klahr (2011)

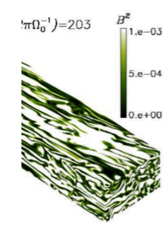
Baroclinic instability and layered accretion







Vorticity



Mag. Energy

Baroclinic instability and layered accretion

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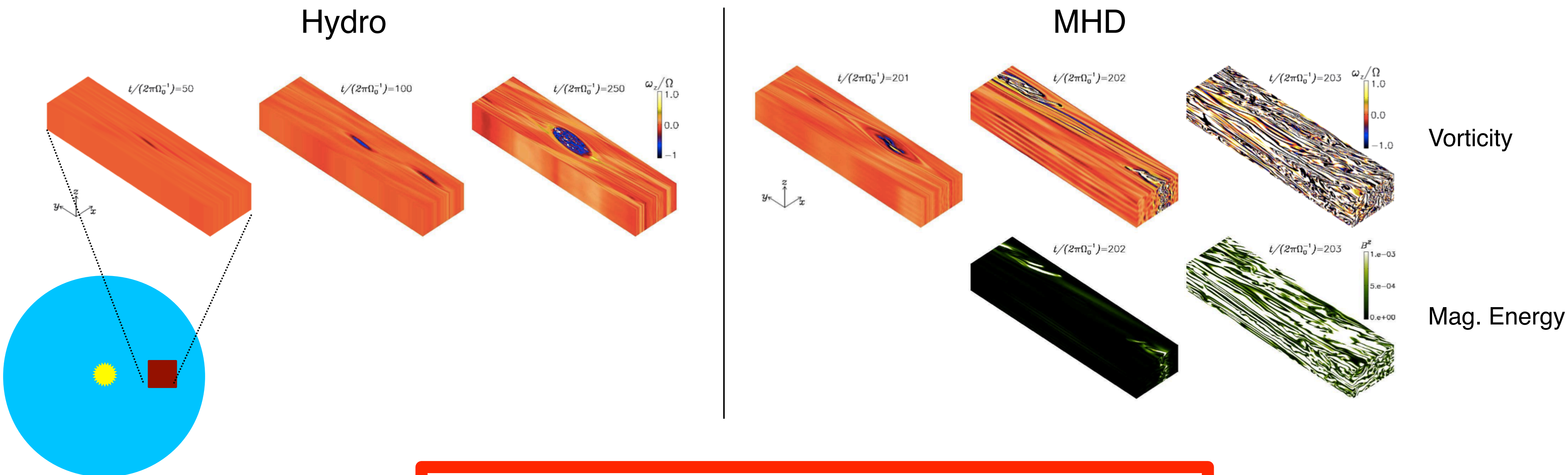
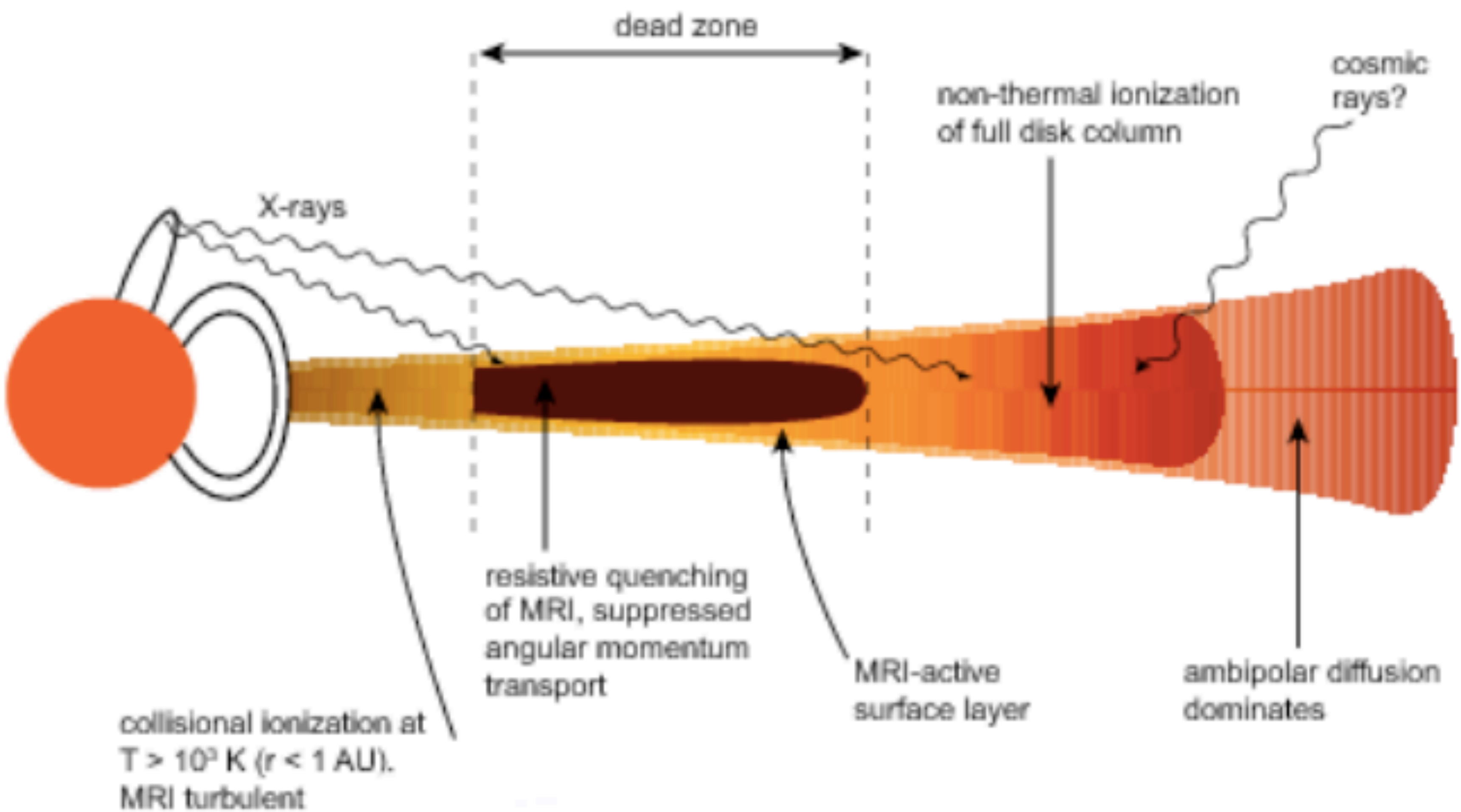
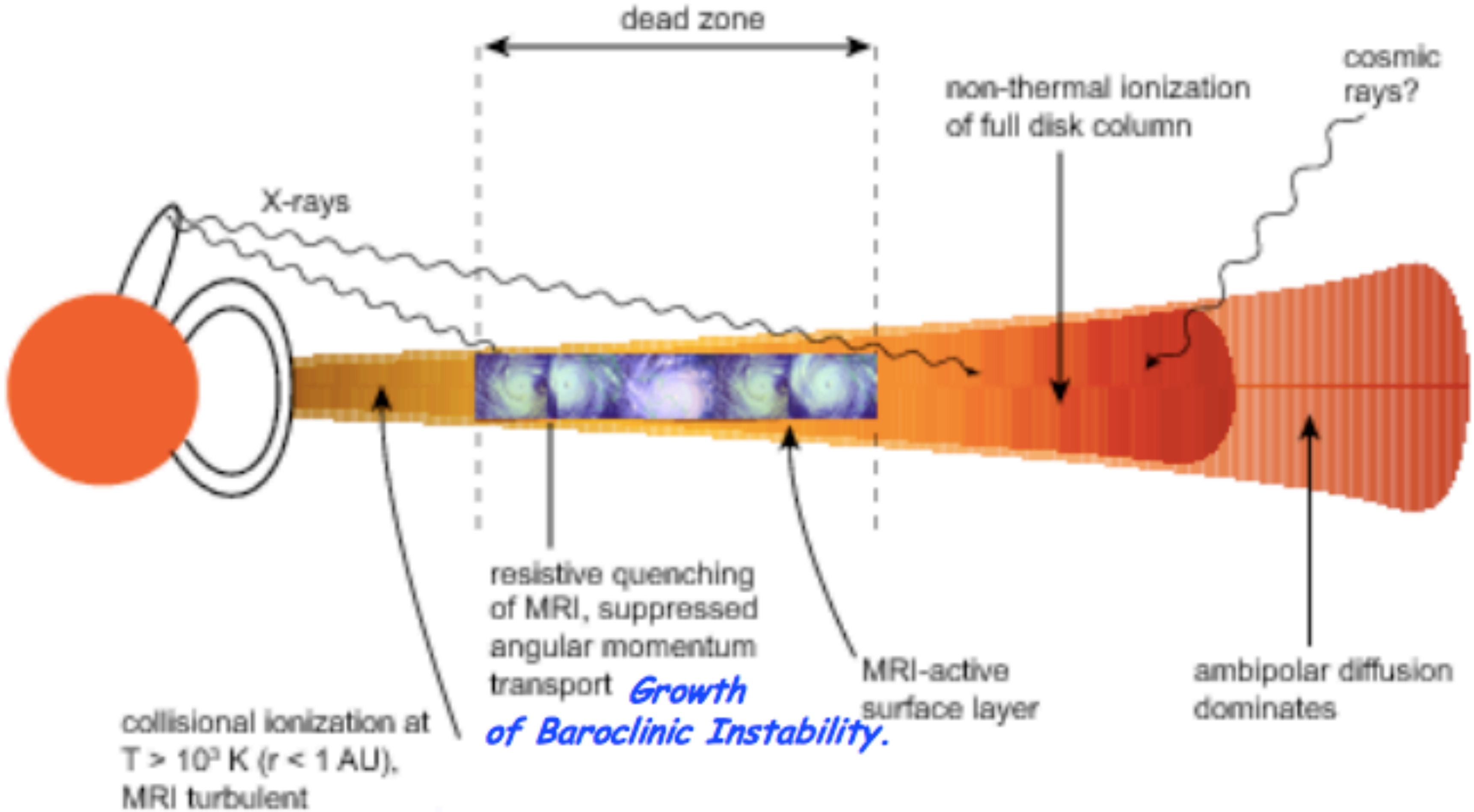


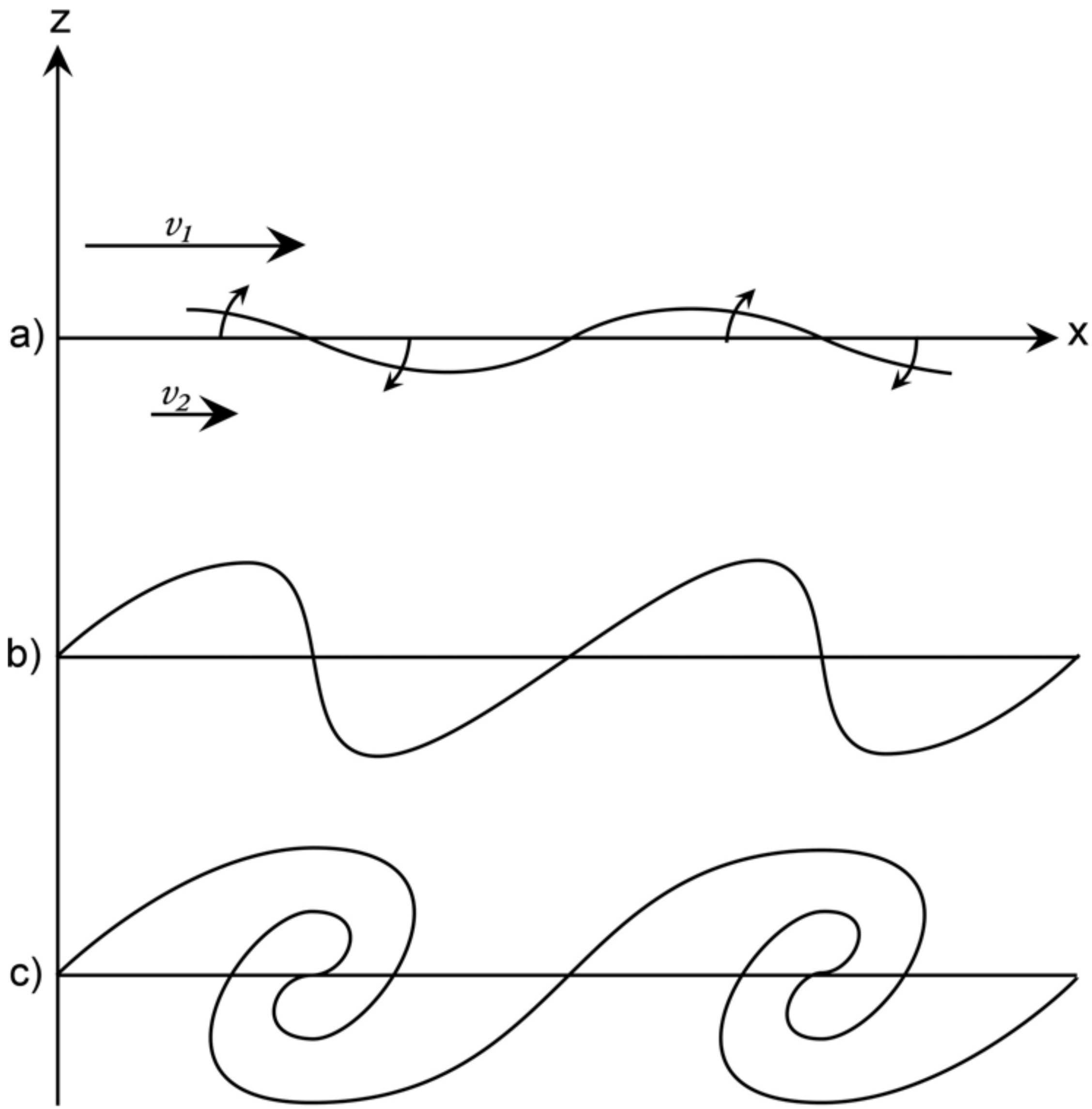
Baroclinic vortices
do ***not*** survive magnetization

Lyra & Klahr (2011)

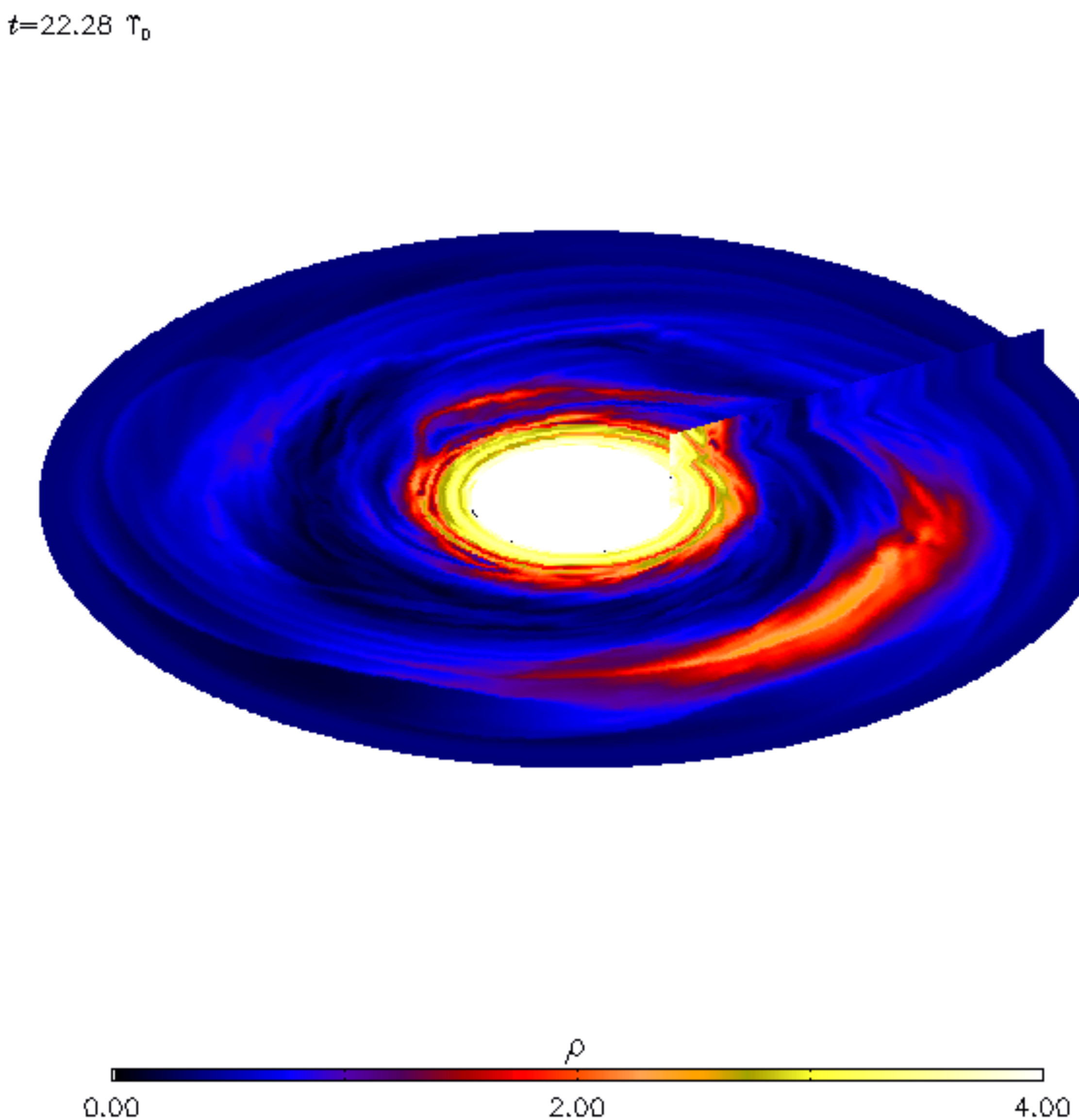

dead zone
cosmic
rays?
non-thermal ionization
of full disk column
X-rays
resistive quenching
of MRI, suppressed
angular momentum
transport
MRI-active
surface layer
ambipolar diffusion
dominates
collisional ionization at
T > 10³ K (r < 1 AU).
MRI turbulent

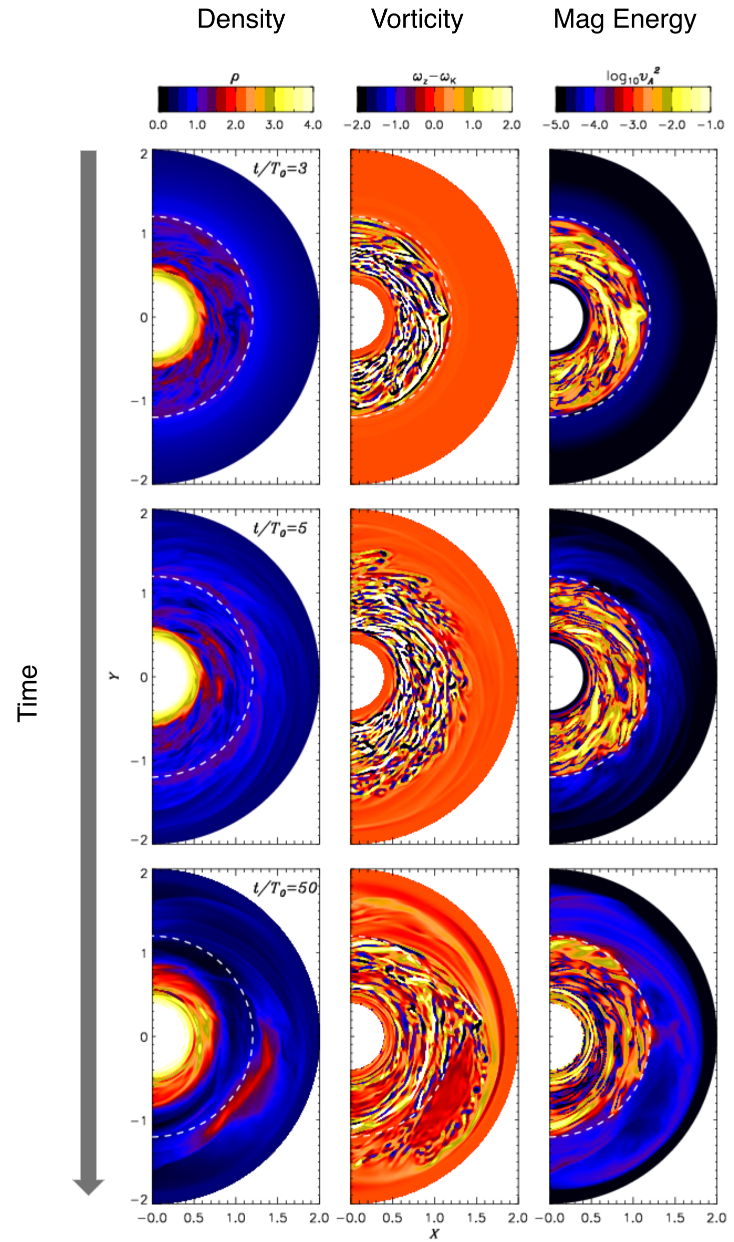

dead zone
cosmic rays?
non-thermal ionization of full disk column
X-rays
resistive quenching of MRI, suppressed angular momentum transport
Growth of Baroclinic Instability.
MRI-active surface layer
ambipolar diffusion dominates
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent

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



Active/dead zone boundary

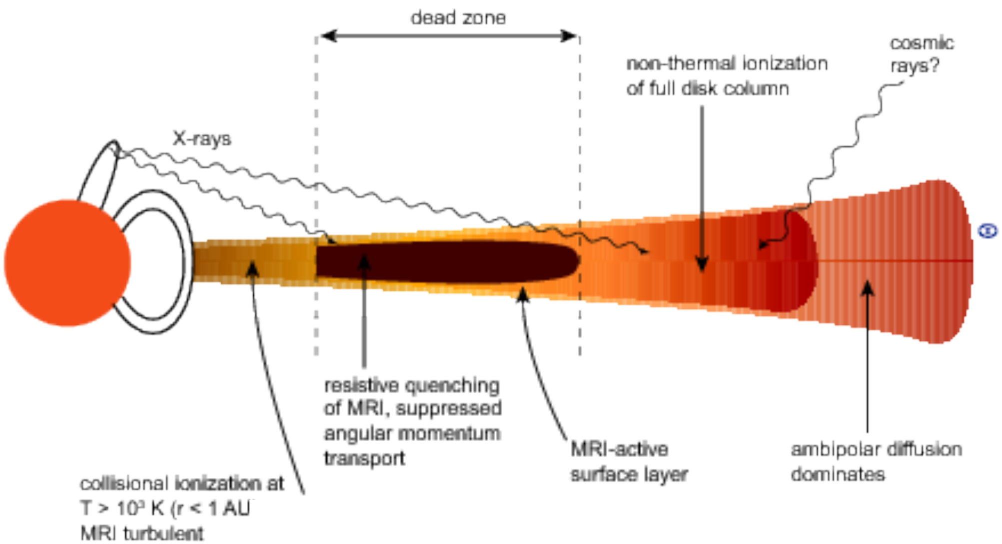




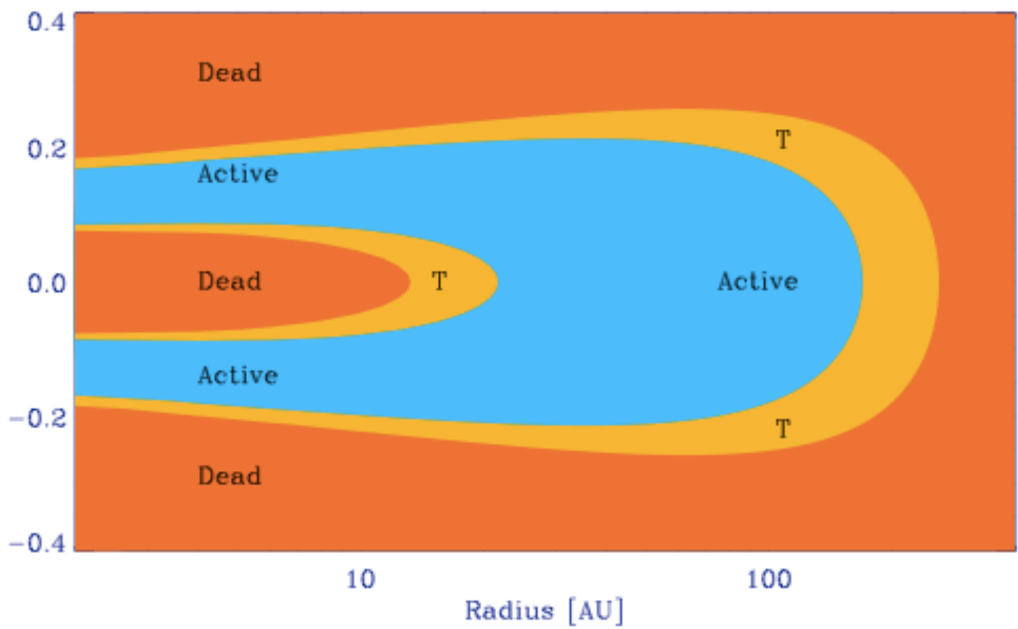
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Outer Dead/Active zone transition RWI



Armitage (2010)



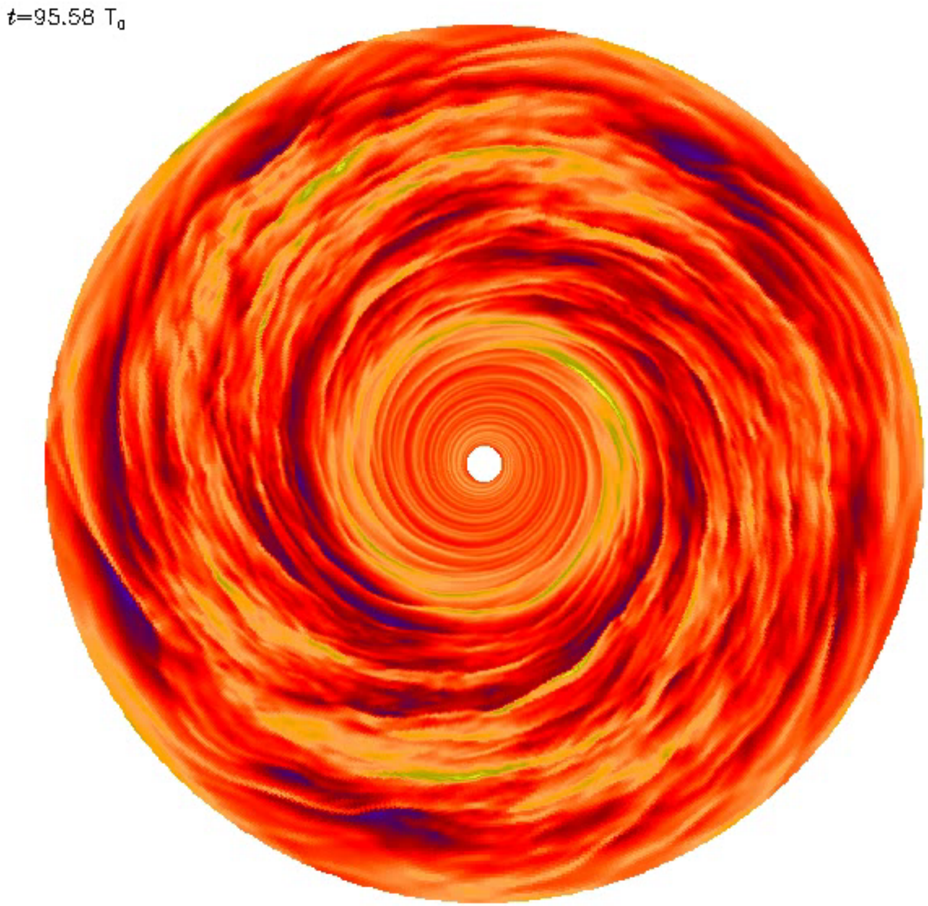
Dzyurkevitch et al (2013)

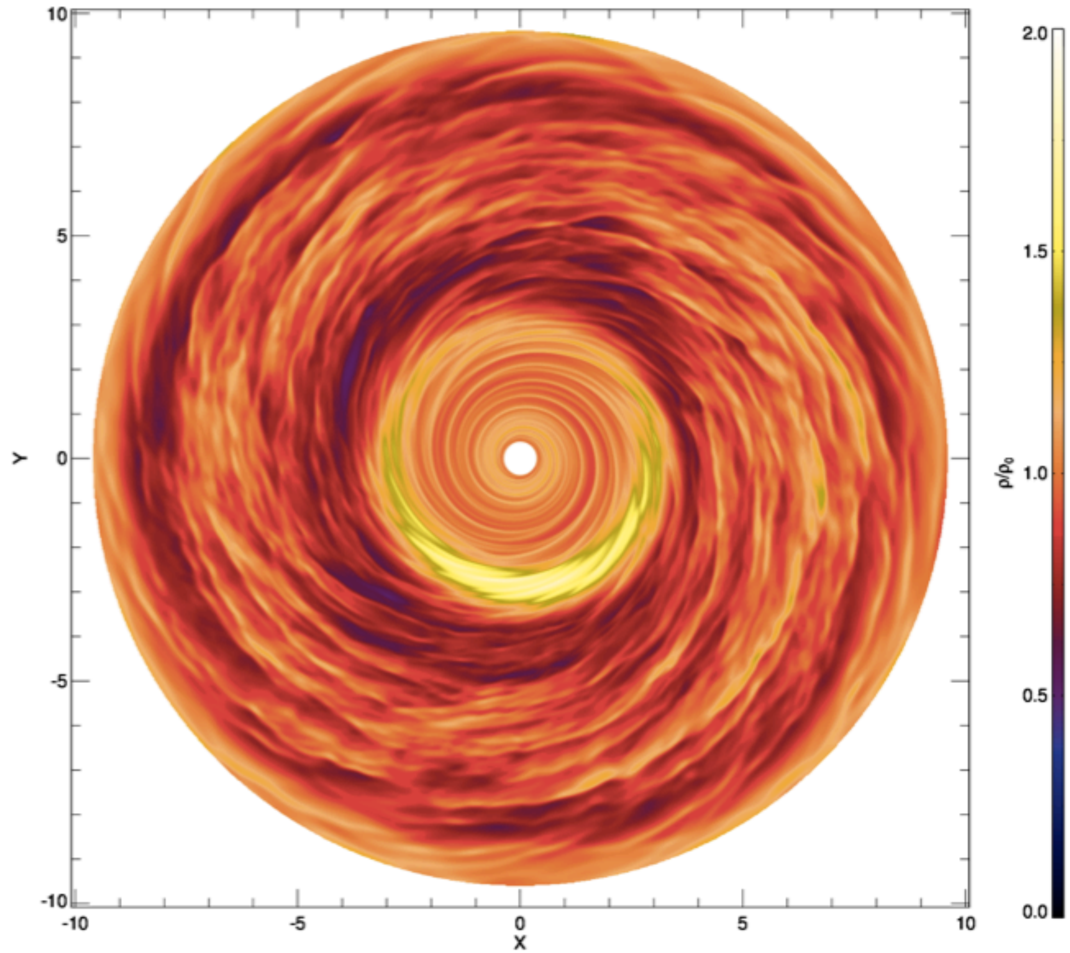
The **outer** dead zone transition in ionization supposed

TOO SMOOTH

to generate an RWI-unstable bump.

Outer Dead/Active zone transition RWI

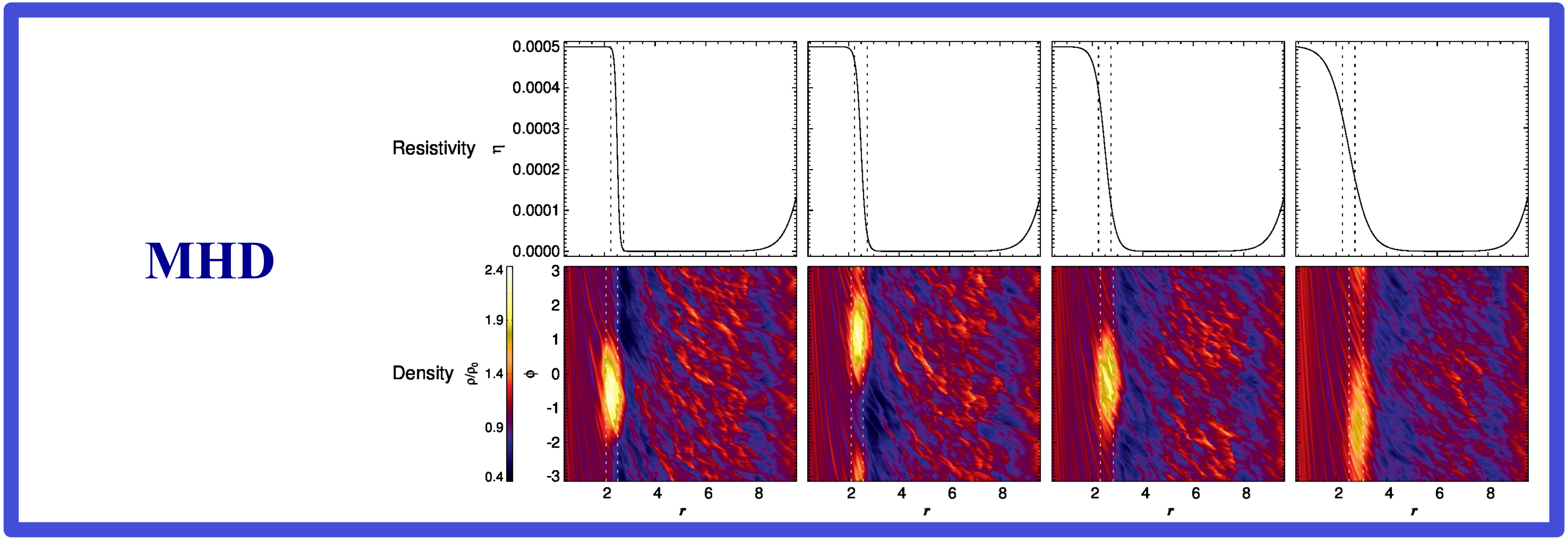


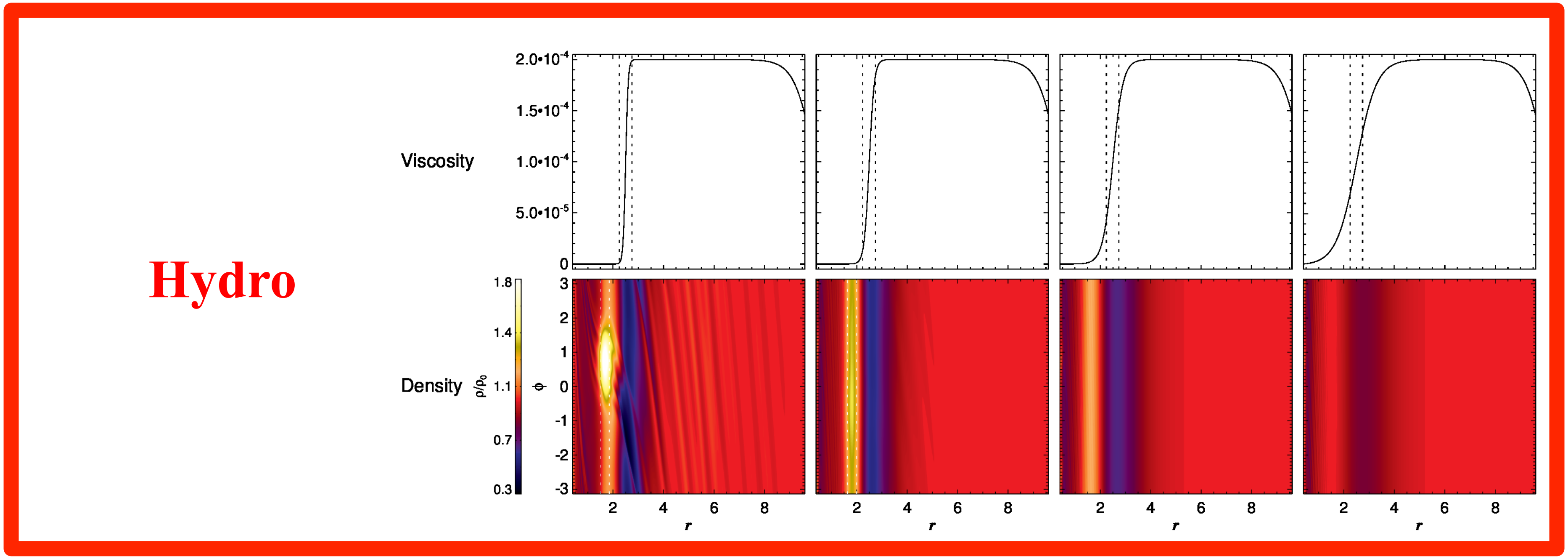


Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI





Lyra, Turner, & McNally (2015)

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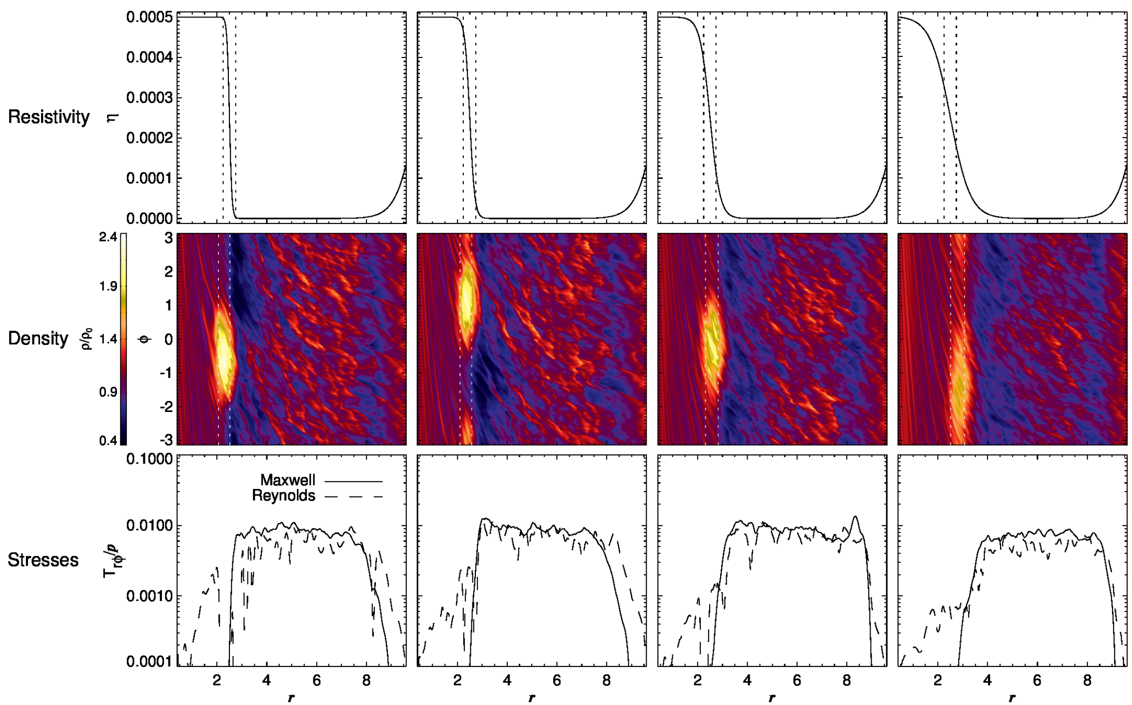


Lyra, Turner, & McNally (2015)

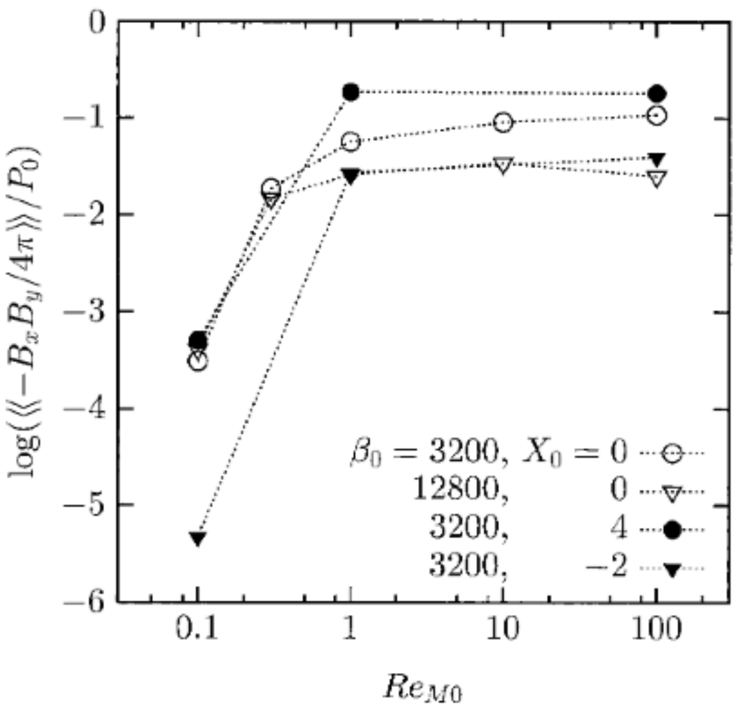


FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number Re_{M0}. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and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

Sano and Stone (2002)

(Pre-)History of Rossby Wave Instability

Lovelace & Hohlfeld (1978)

NEGATIVE MASS INSTABILITY OF FLAT GALAXIES

R. V. E. Lovelace and R. G. Hohlfeld
Center for Radiophysics and Space Research, and Department of Applied Physics, Cornell University
Received 1977 May 4; accepted 1977 September 15

ABSTRACT

A study is made of the linear initial value problem of a flat, low-"temperature," self-gravitating disk for perturbations which are radially localized with $|\omega - n\Omega|^2 \ll \Omega^2$, where ω is the angular frequency and n the azimuthal mode number ($\neq 0$) of the perturbation, and where $\Omega(r)$ is the angular velocity of the differentially rotating disk matter at a radial distance r. We find that instability is possible in situations where the distribution function for angular momentum, $f(r) \equiv \sigma\Omega\kappa^{-2}$, has a maximum or minimum as a function of r and $(d/dr)\Omega \neq 0$ at the extremum of f, where $\sigma(r)$ is the surface mass-density of the disk, and $\kappa(r)$ is the epicyclic frequency. Approximate growth rates are derived. The mechanism of the instability is related to that of the negative mass instability of charged-particle rings. We propose that the instability may drive a disk toward a state in which $f(r)$ is approximately constant.

Values of $\Omega(r)$, $\kappa(r)$, and $\sigma(r)$ derived from observations are used to calculate $f(r)$ for two cases: For our Galaxy we find $3.8 < f(r) < 4.5$ for $0.3 \leq r \leq 10$ kpc, with f in units of $M_\odot$ pc^{-2} (km s^{-1} kpc^{-1})$^{-1}$. For M31, $3.2 < f(r) < 5.6$ for $3 \leq r \leq 30$ kpc.

Subject headings: galaxies: internal motions — galaxies: structure — stars: stellar dynamics

Vorticity criterion already derived back then

(Pre-)History of Rossby Wave Instability

WHAT AMPLIFIES THE SPIRALS?

Alar Toomre

Massachusetts Institute of Technology

Toomre (1981)

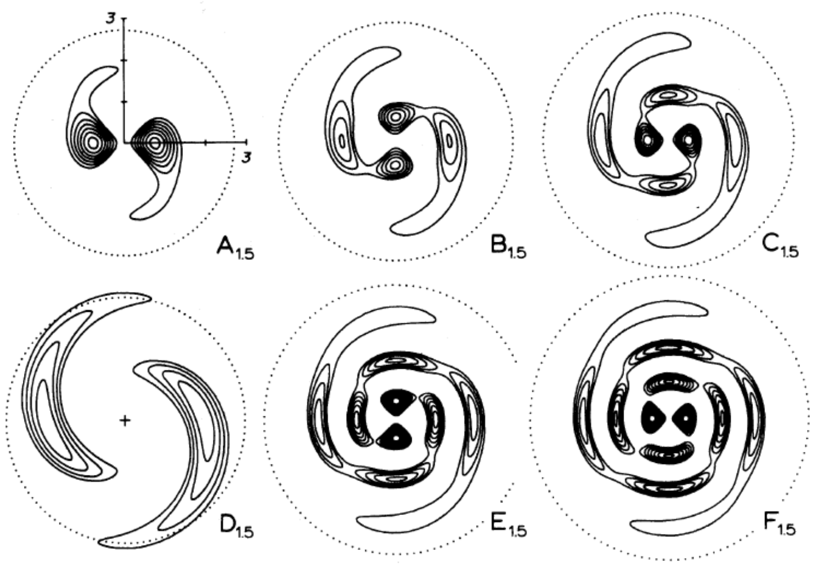


Fig. 12 Comparison of modes A-F for that Gaussian disk in which only 2/3 of the density remains "active". Their eigenfrequencies were reported at location 1.5 in Fig. 11. The corotation circles are again shown dotted; they have expanded markedly from Fig. 10.

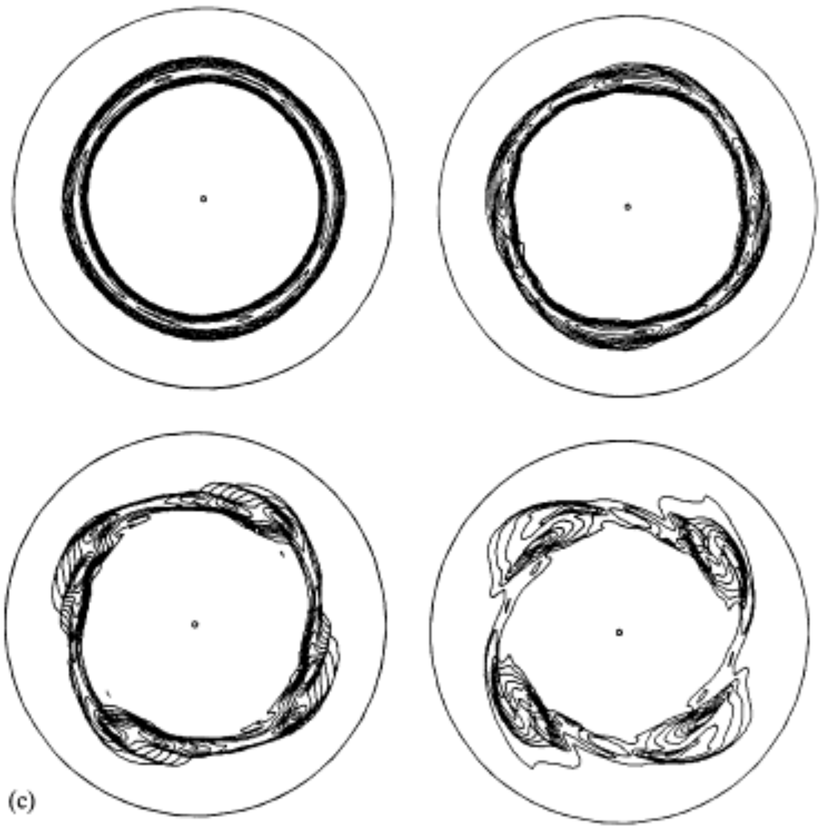
One black sheep still needs to be dealt with. I am referring, of course, to the mode marked D in Figs. 10-12. As luck has it, the pattern speed (and even the growth rate) of this mode lands it smack amidst the swing-amplified modes in the full-mass Fig. 10. And it is there somewhat contaminated by the latter — as if only to confuse us! **That mode D is a wolf in sheep's clothing becomes clear,** however, once we weaken those rival modes in Figs. 11-12 by reducing the active disk mass. Its shape and hefty growth rate then point firmly to a different kind of animal.

What is mode D? It seems genuinely to be an <u>edge mode</u> which (a) arises only if the disk density drops off abruptly enough with radius, and yet (b) does <u>not</u> require any wave transport into or through the central regions. Kalnajs and I can support claim (a) with some experimental findings that any analogue of mode D occurs at most very weakly in the yet more soft-edged exponential disk — and it is altogether absent from Zang's V = const disk — whereas it can be aroused to fresh fury by artificially truncating either of those disks in a smooth but sudden enough manner. We can also vouch for claim (b) with the little discovery that any "freezing" of our Gaussian disk inward of (say) r = 1 hardly alters the eigen-

(Pre-)History of Rossby Wave Instability

Papaloizou-Pringle Instability (1984ab)

(Goldreich & Narayan 1985, Blaes 1985, Blaes & Glatzel 1986, Hawley 1987, Narayan et al. 1987, Goldreich et al. 1987, 1988)



(c)

Figure 5–*continued*

Numerical model by Hawley (1987)

The dynamical stability of differentially rotating discs with constant specific angular momentum

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J. E. Pringle *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

Received 1983 August 10

The dynamical stability of differentially rotating discs – II

J. C. B. Papaloizou *Theoretical Astronomy Unit, School of Mathematical Sciences, Queen Mary College, London E1 4NS*

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Accepted 1984 November 26. Received 1984 November 23; in original form 1984 October 1

History of Rossby Wave Instability

Lovelace et al. (1999) resurrect the process;
call it "Rossby Wave" Instability

ROSSBY WAVE INSTABILITY OF KEPLERIAN ACCRETION DISKS

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Received 1998 March 19; accepted 1998 October 15

disk quantities, such as surface density and entropy have steep radial gradients. The conditions we consider are in general nonbarotropic which distinguish our work from that of Papaloizou and Pringle (1984, 1985; Goldreich, Goodman, & Narayan 1986; Narayan, Goldreich, & Goodman 1987). Also, in contrast with the work of Papaloizou and Pringle, the modes we consider are trapped at least initially in a narrow range of radii and therefore do not depend on reflections from inner and outer radii of the disk (or tori).

Peggy Varnière & Michel Tagger
RWI at dead zone boundary

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

P. Varnière[1,2] & M. Tagger[3]

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[2] LAOG, Université J. Fourier UMR 5571 France, e-mail: pvarni@pas.rochester.edu
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the date of receipt and acceptance should be inserted later

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

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

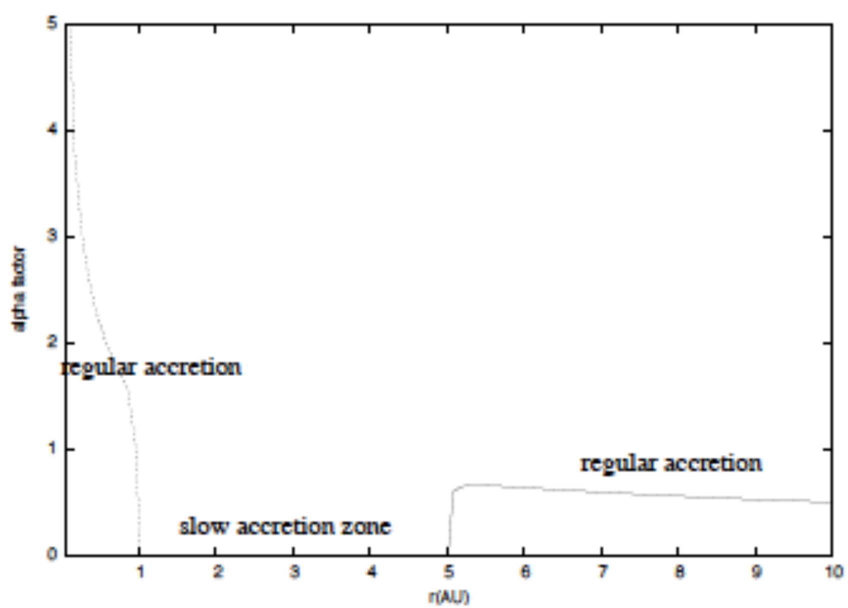


Fig. 1. Profile of the α-viscosity implemented to represent a Dead Zone between 1 and 5 AU with $(\epsilon, \delta_r) = (10^{-5}, 50)$.

Varnière & Tagger (2006)

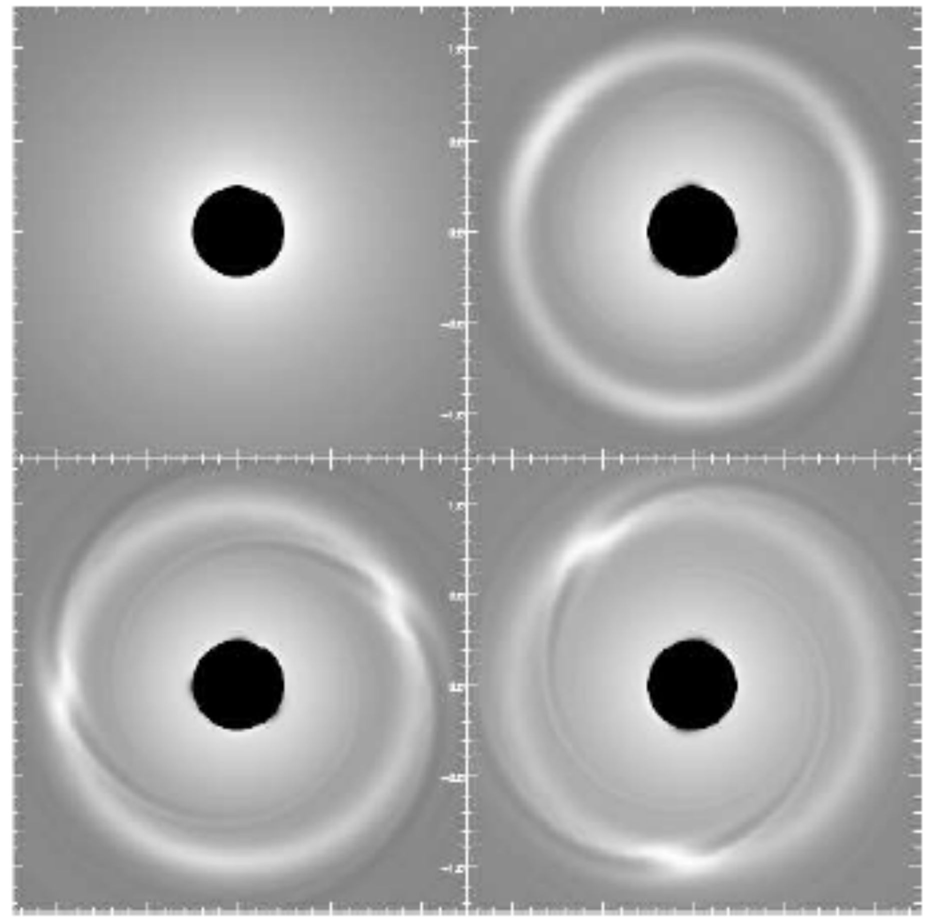


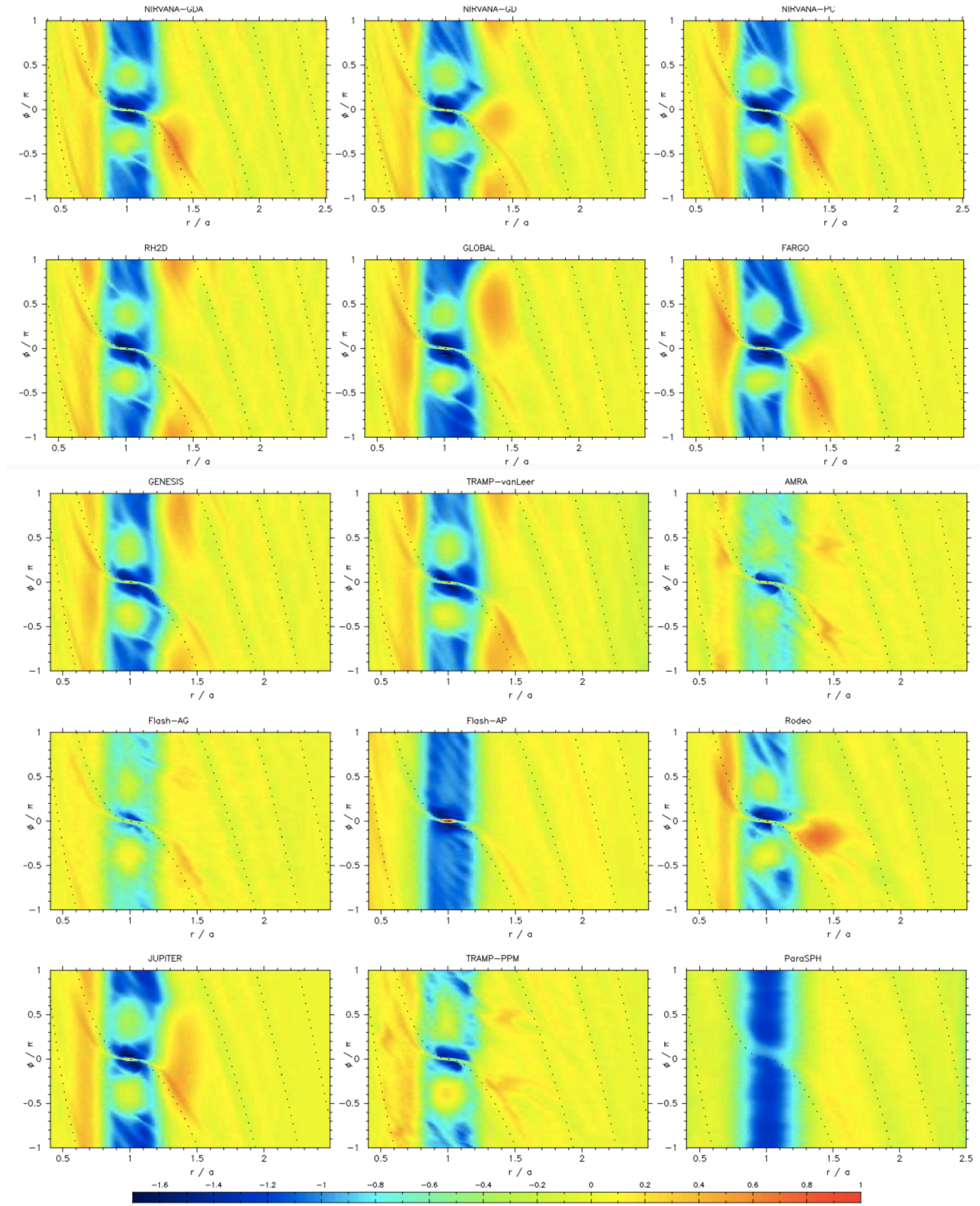
Fig. 3. Zoom of the first 2 inner AU of the simulation at $t = 0, 100, 200, 300$ years, showing the density. One sees three vortices forming, later evolving to two vortices, near the outer edge of the Dead Zone.

The code comparison project of 2006 (de Val-Borro et al. 2006)

Problem of choice:
2D ‘vanilla’ planet-disk interaction.

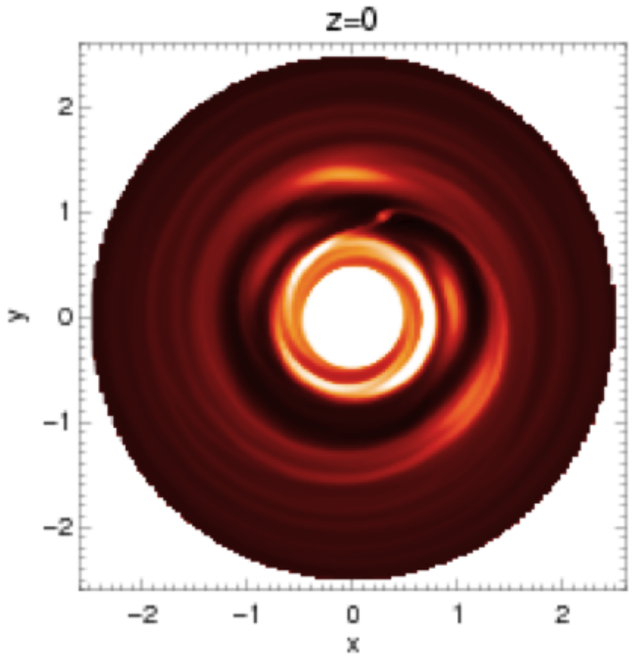
Several codes showed gap-edge vortices.

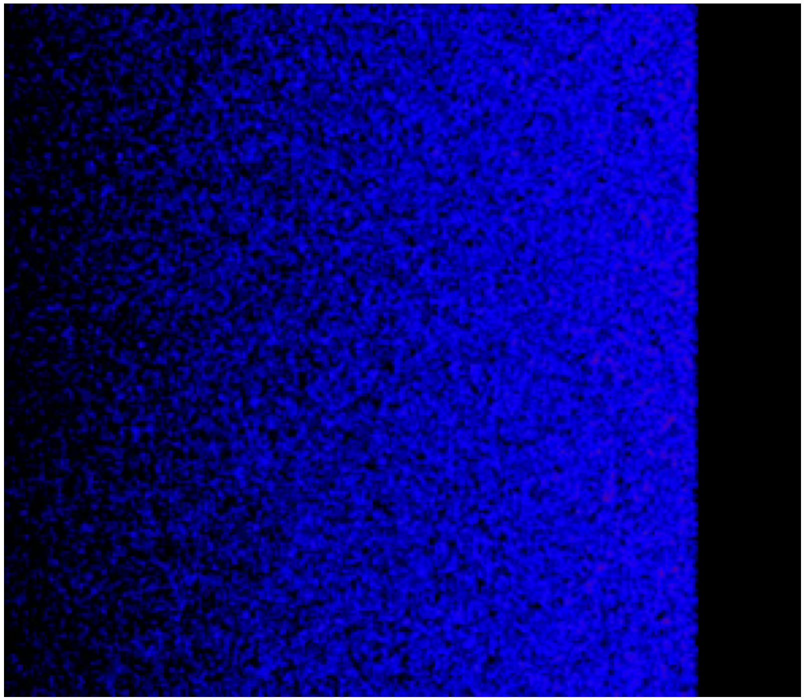
Follow-up work
(de Val-Borro et al. 2007)
showed that to be
the result of RWI



Planet Formation in gap edge vortices

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

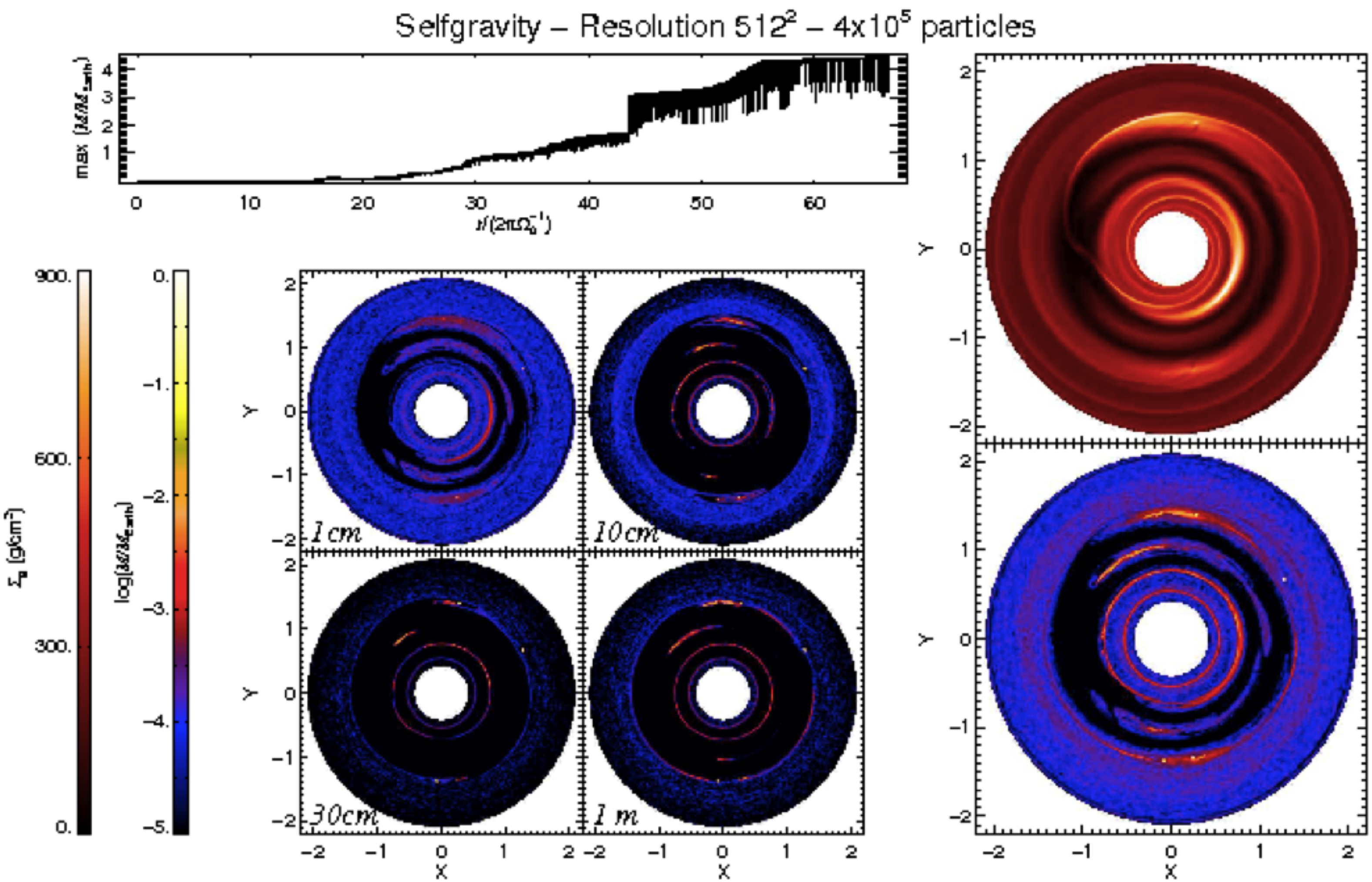




Burst of formation in gap vortices

Plus Trojan planets in Lagrangian clouds

Vortex trapping



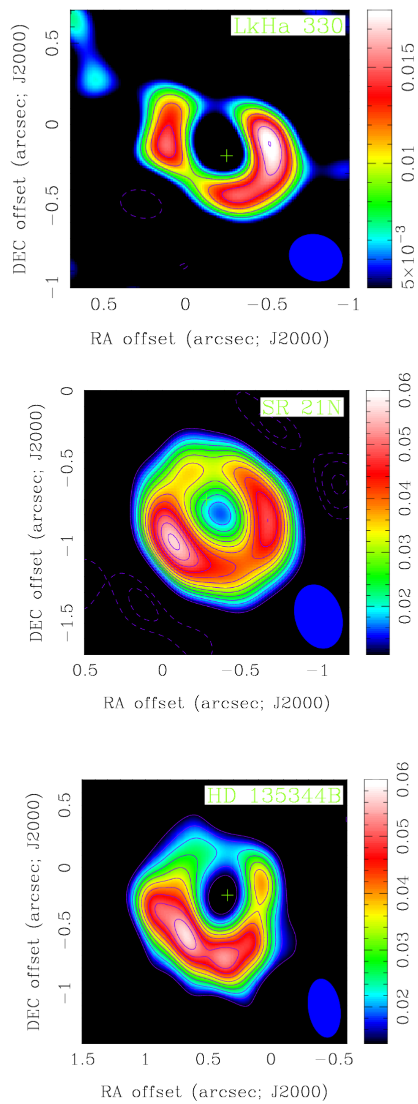
3 Super-Earths formed + Mars mass Trojans

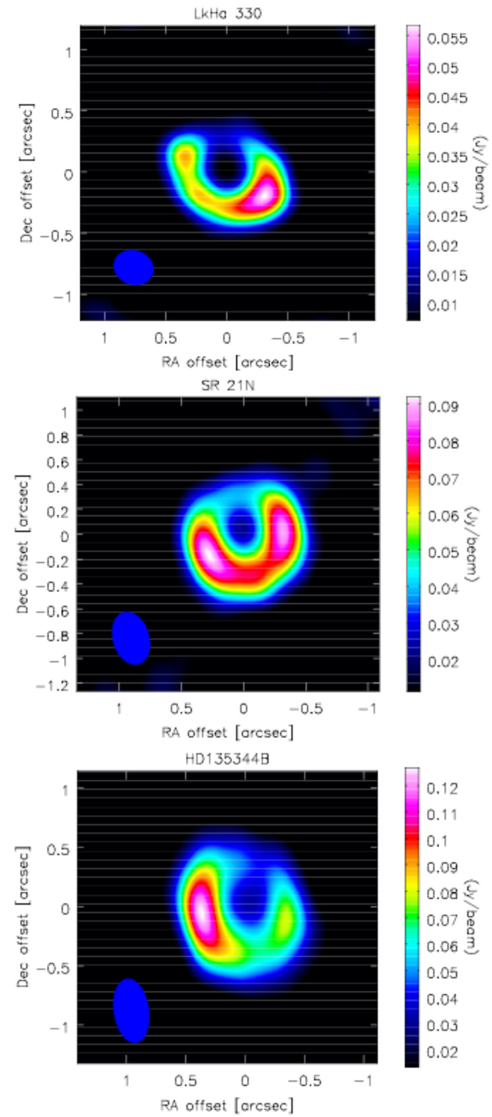
Lyra et al. (2009b)

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.

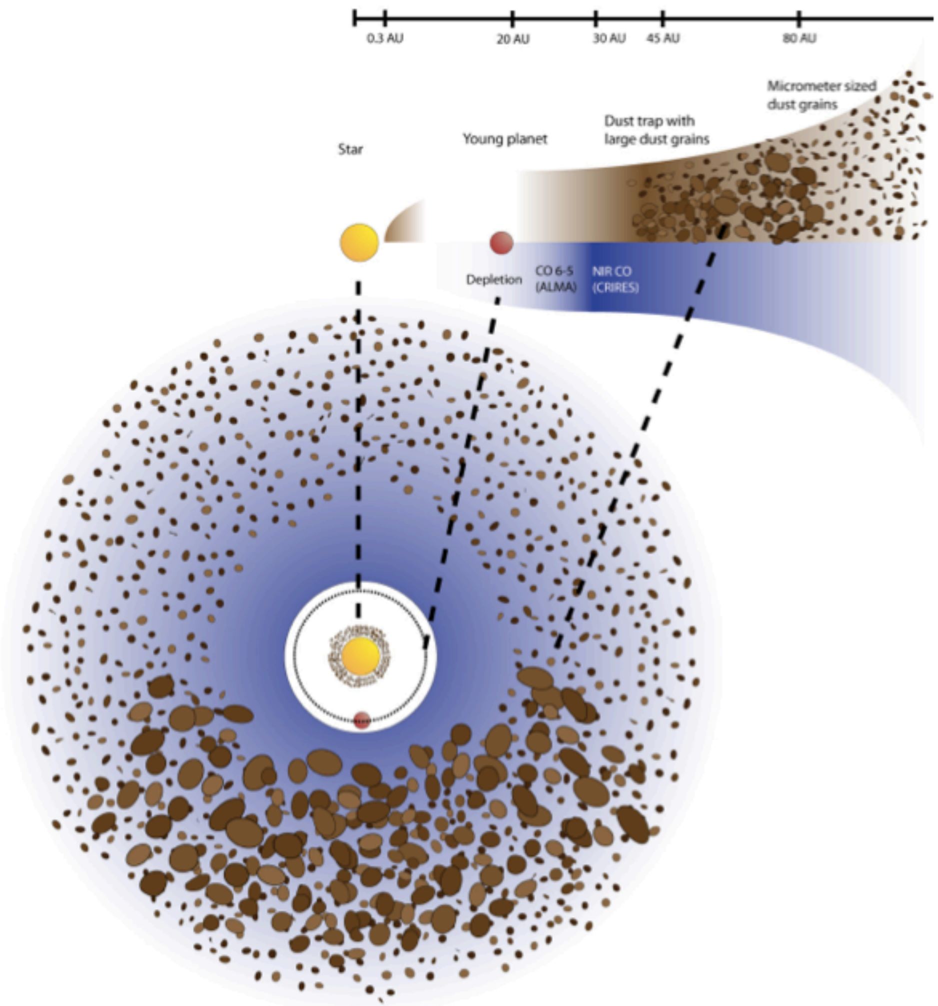
Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

Down

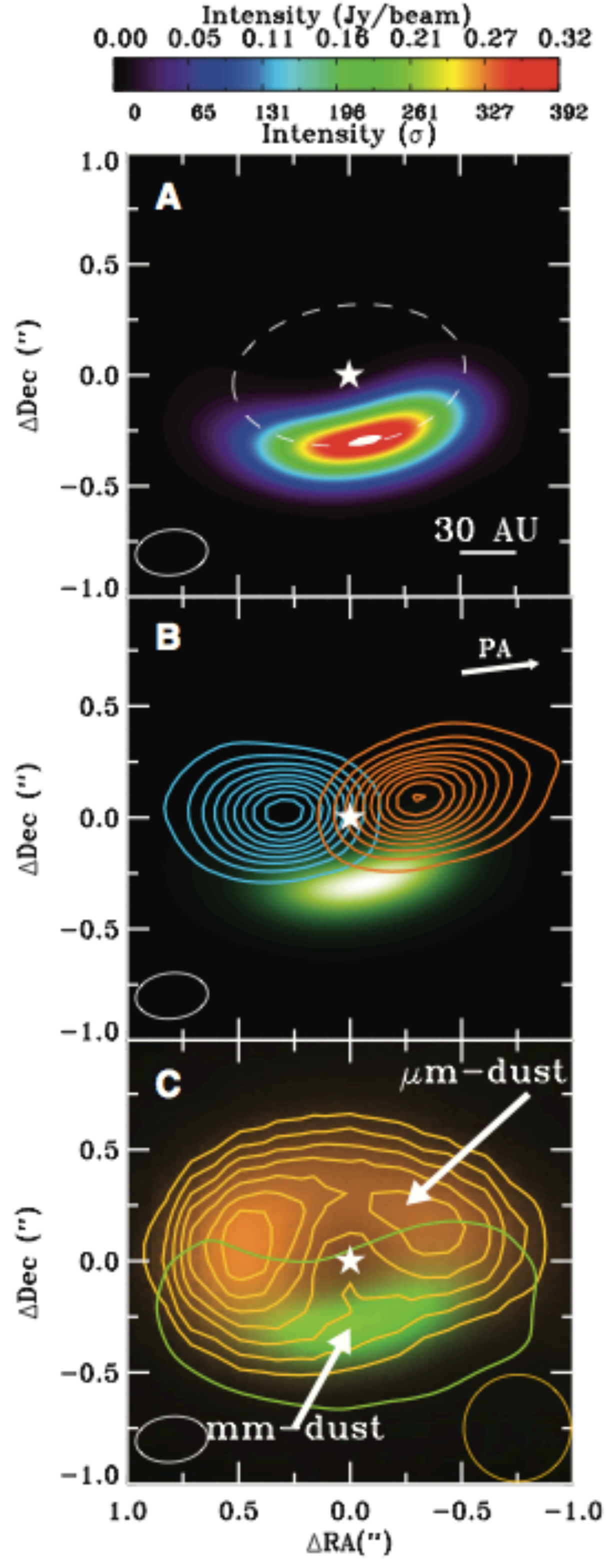
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

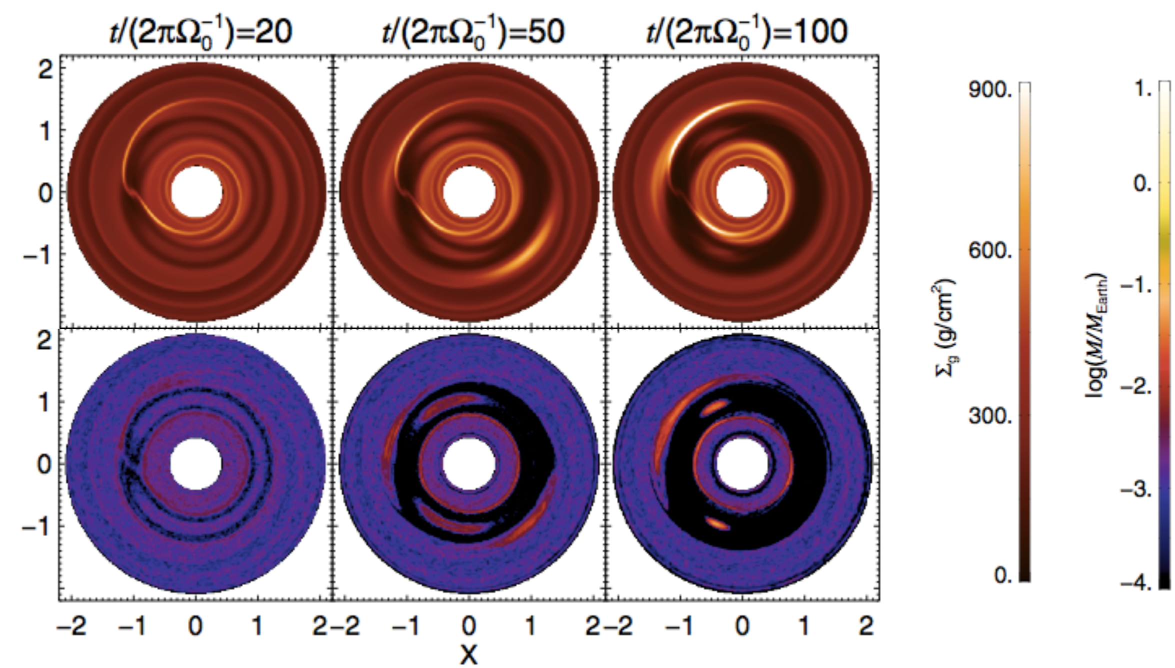


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

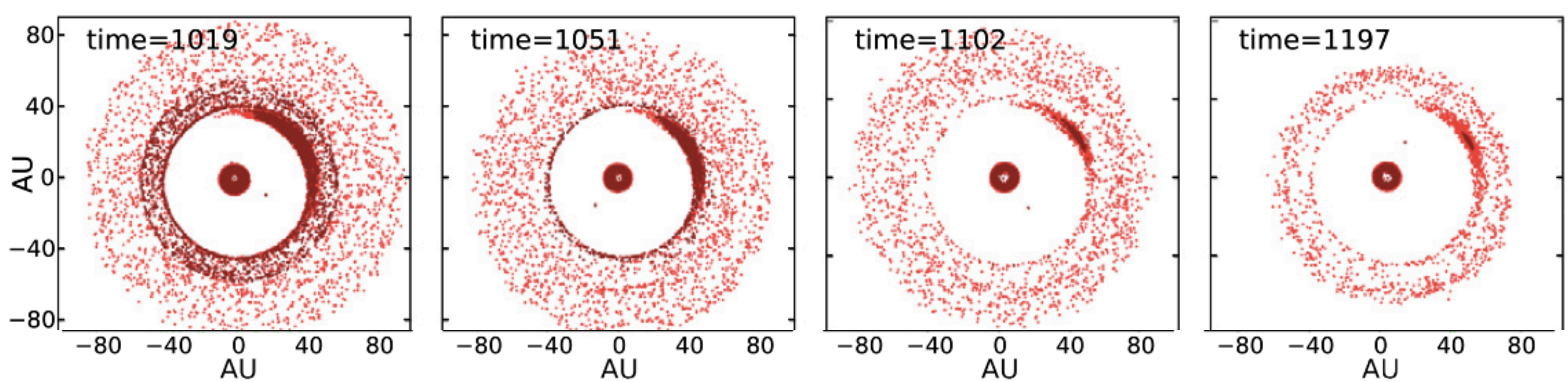
Micron-sized dust follows gas

Dust Trapping



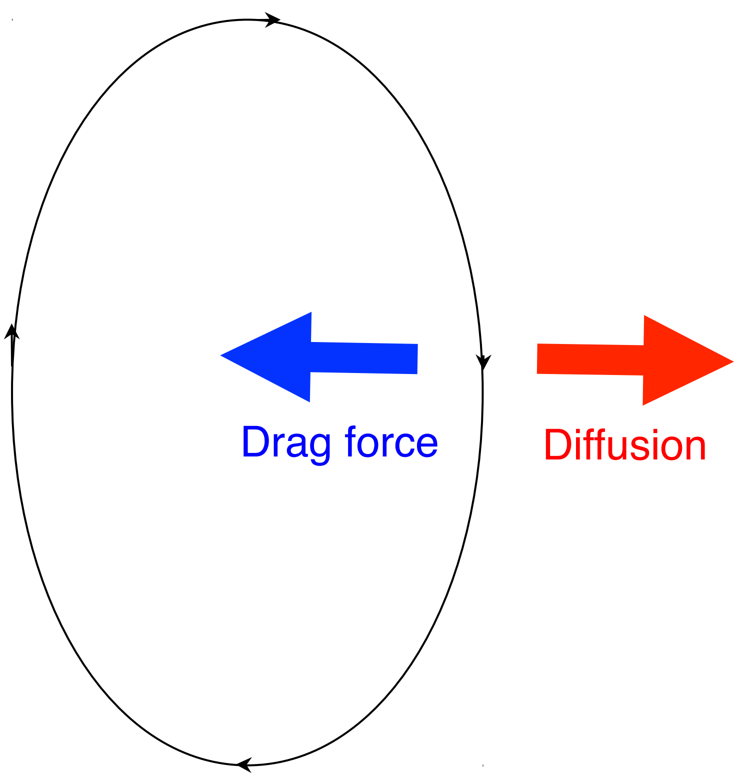
Lyra et al (2009b)

Turbulent “kicks” lead to steady state



Ataiee et al. (2013)

Drag-Diffusion Equilibrium



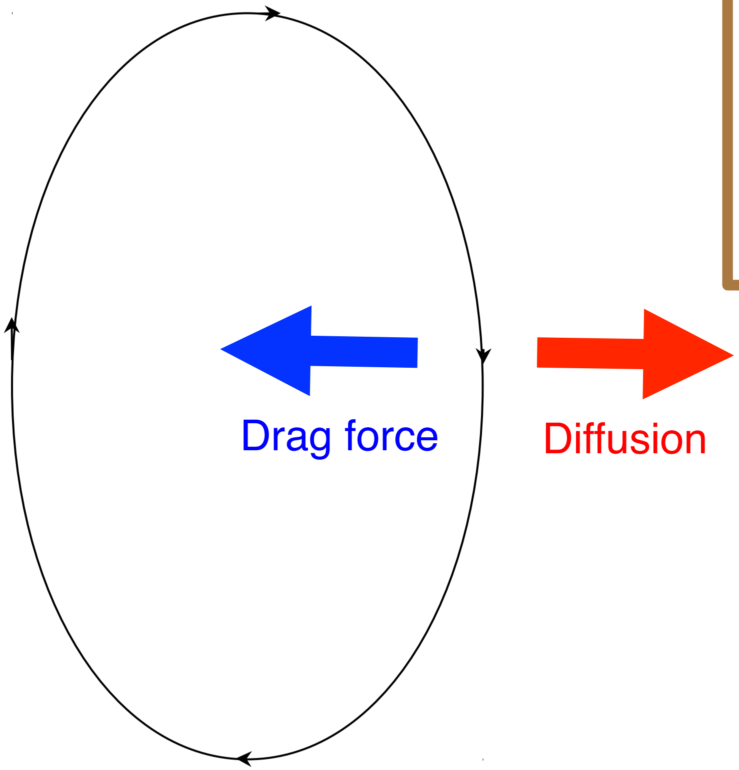
Trapped particle

Dust continuity equation

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

advection — compression — diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

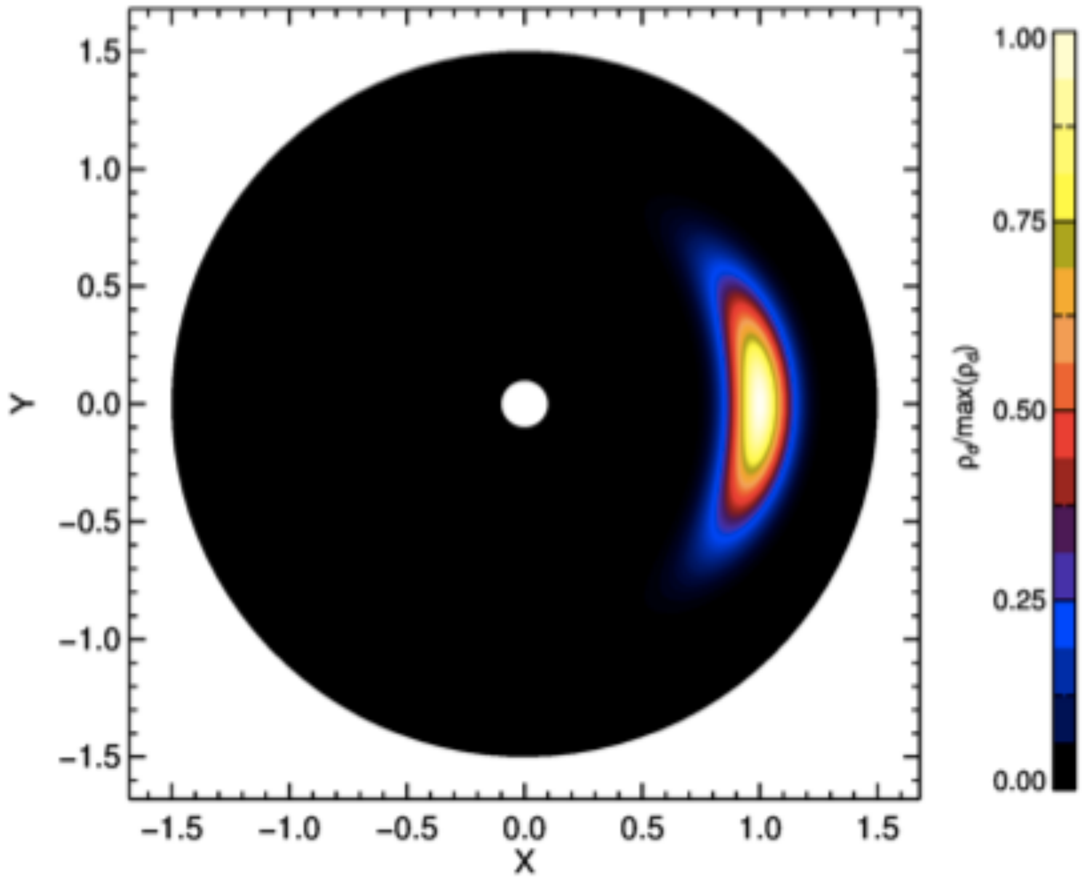
Lyra & Lin (2013)

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

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

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

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

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

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

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

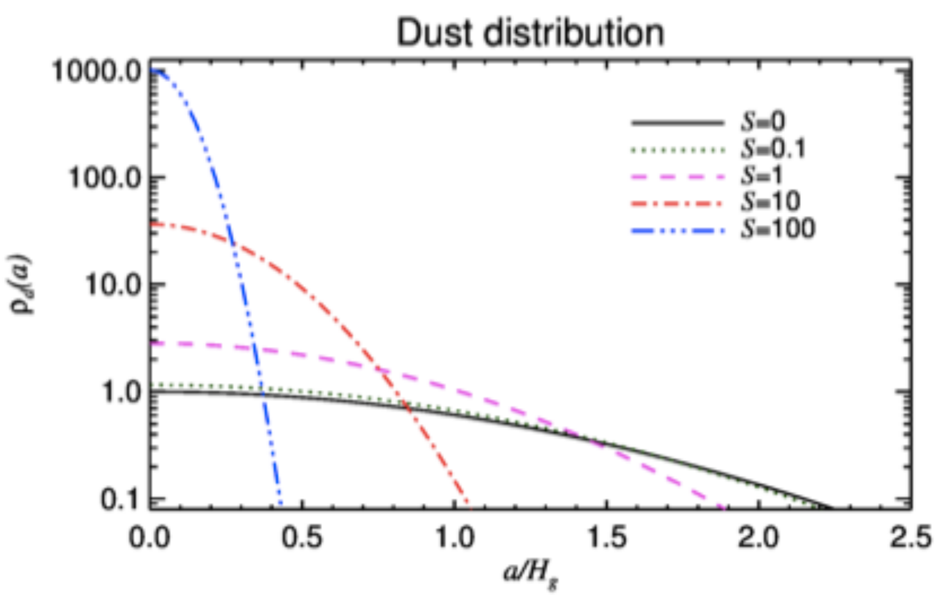
a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

Solution for

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

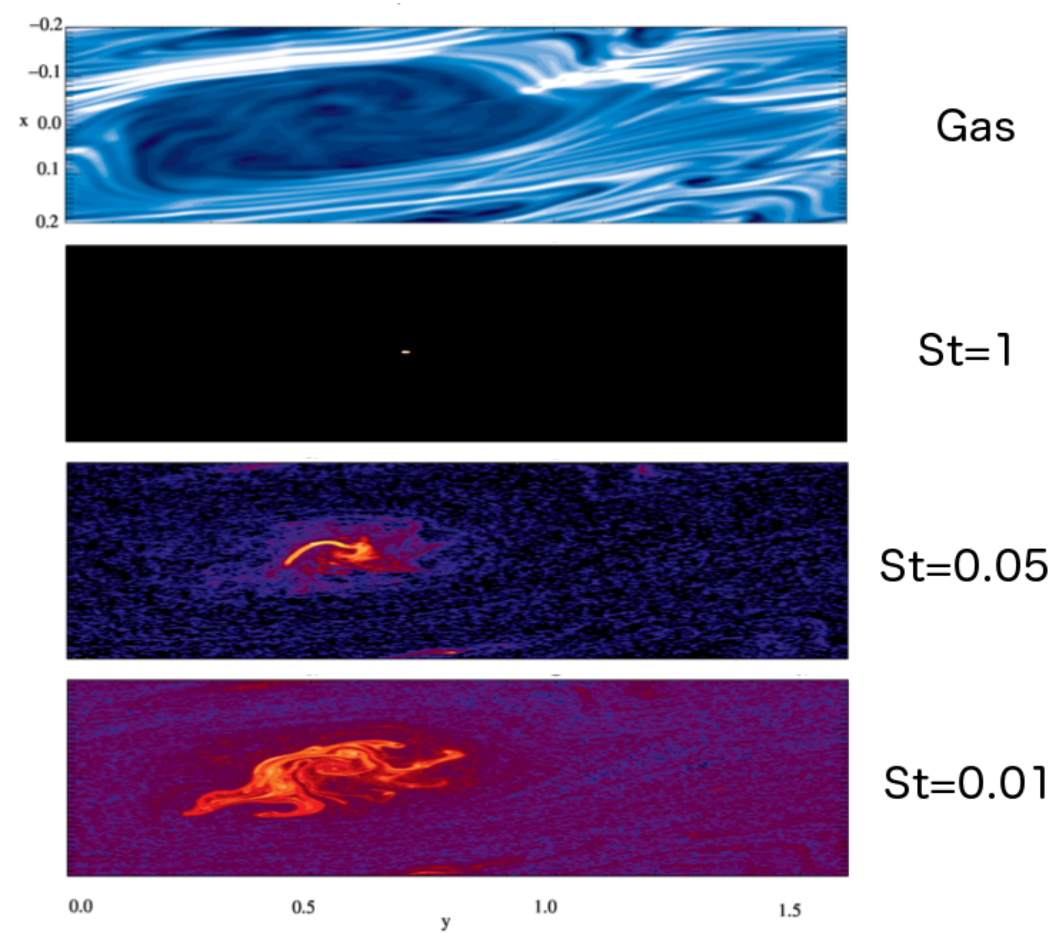
Lyra & Lin (2013)

Analytical vs Numerical



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

Lyra & Lin (2013)



Raettig et al (2015)

Derived quantities

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

Lyra & Lin (2013)

Gas distribution

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

Maximum dust density

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

Gas contrast

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

Dust contrast

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

Total trapped mass

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

Vortex size

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

H = disk scale height (temperature)
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}

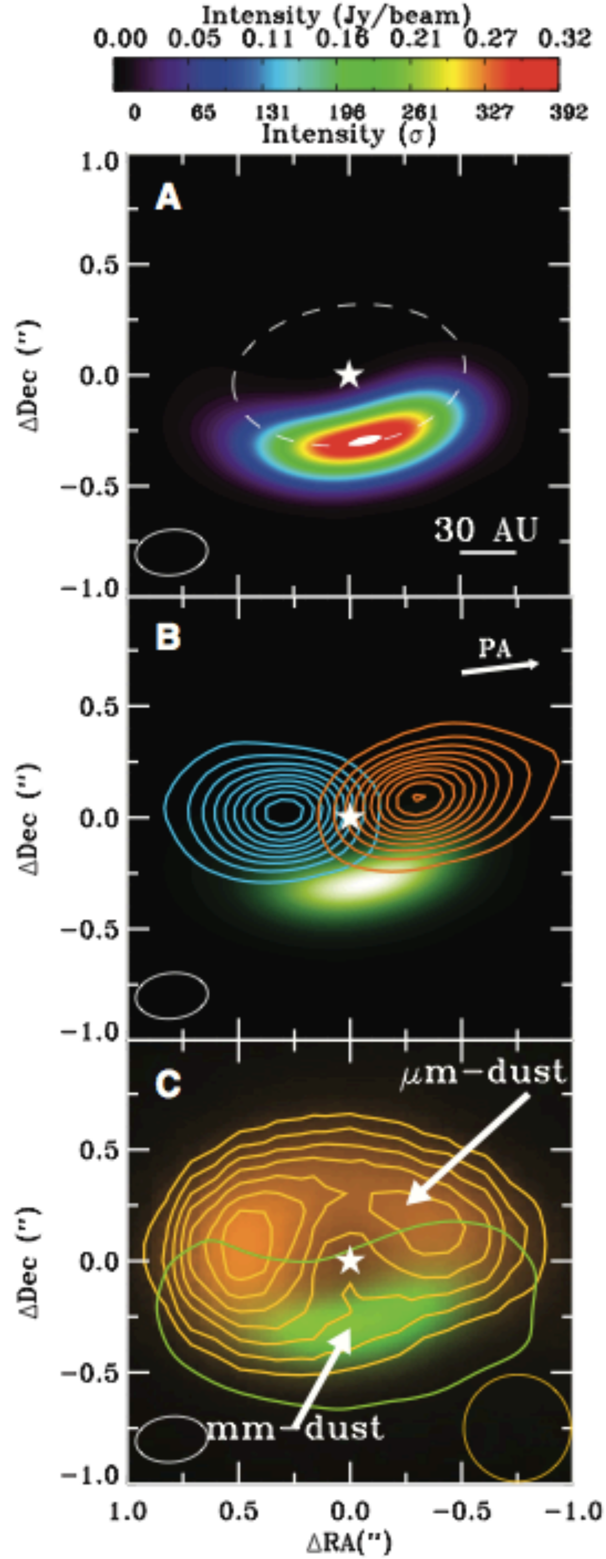
Derived parameters

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

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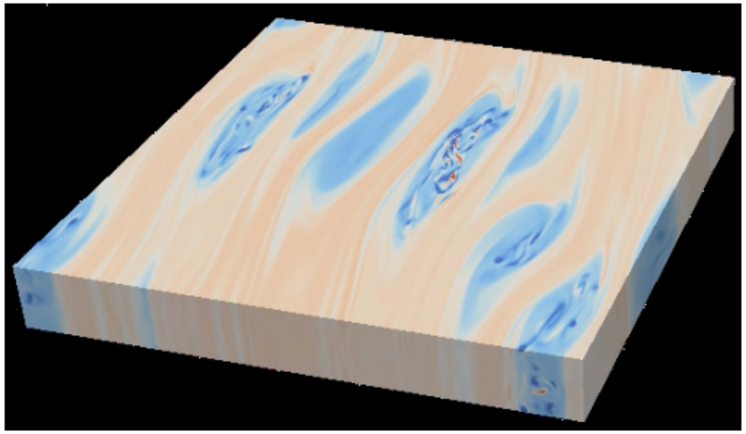
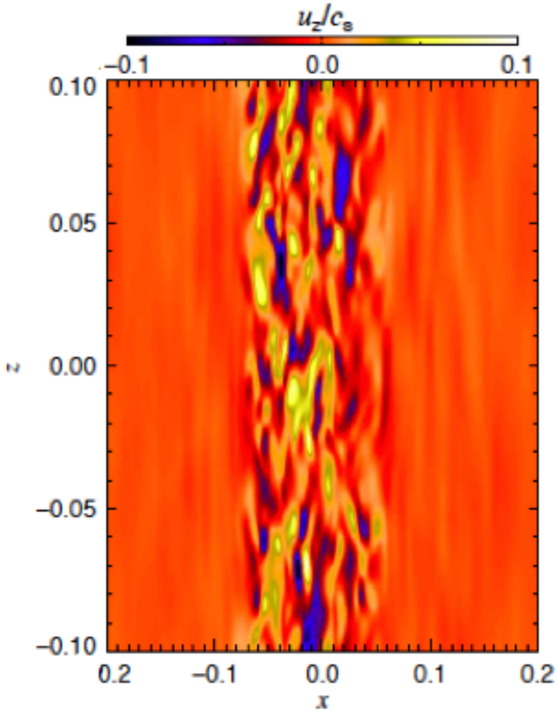
Micron-sized dust follows gas

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

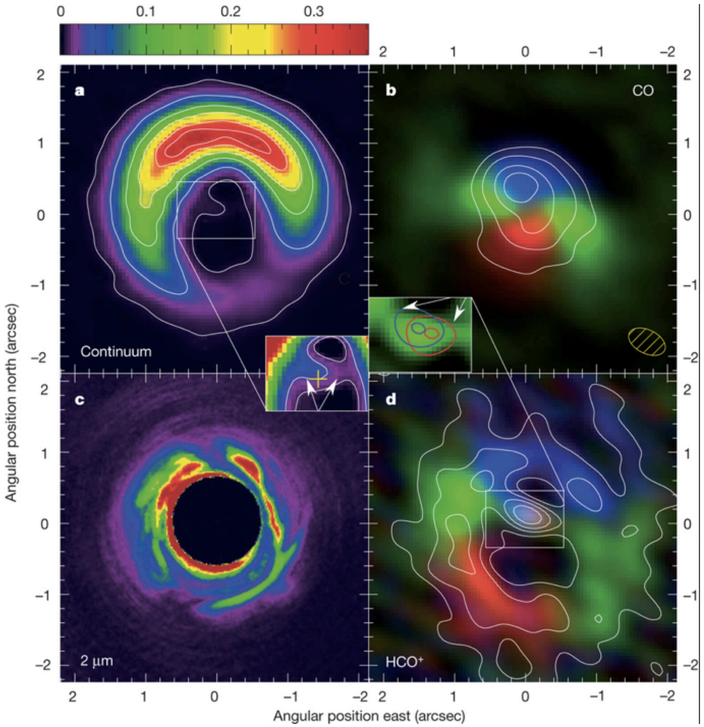
HD 142527

Observed parameters

Aspect ratio: 10

Dust contrast: 30

Temperature: 25K

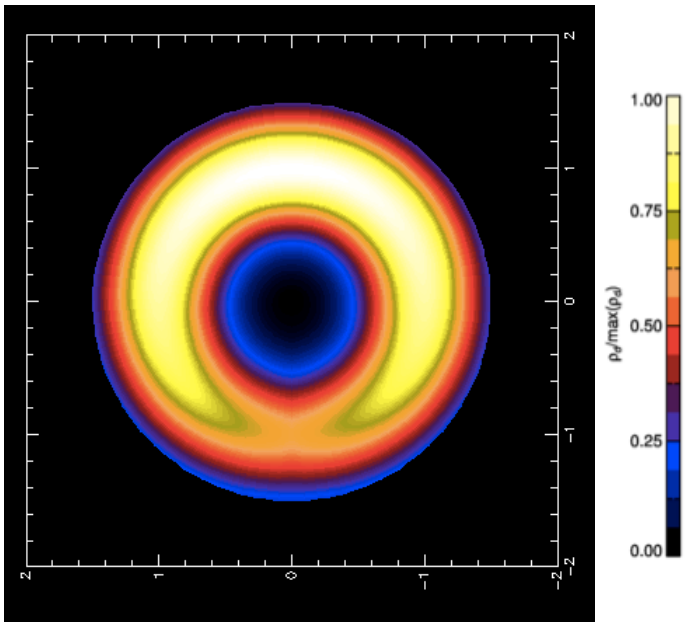


Derived parameters

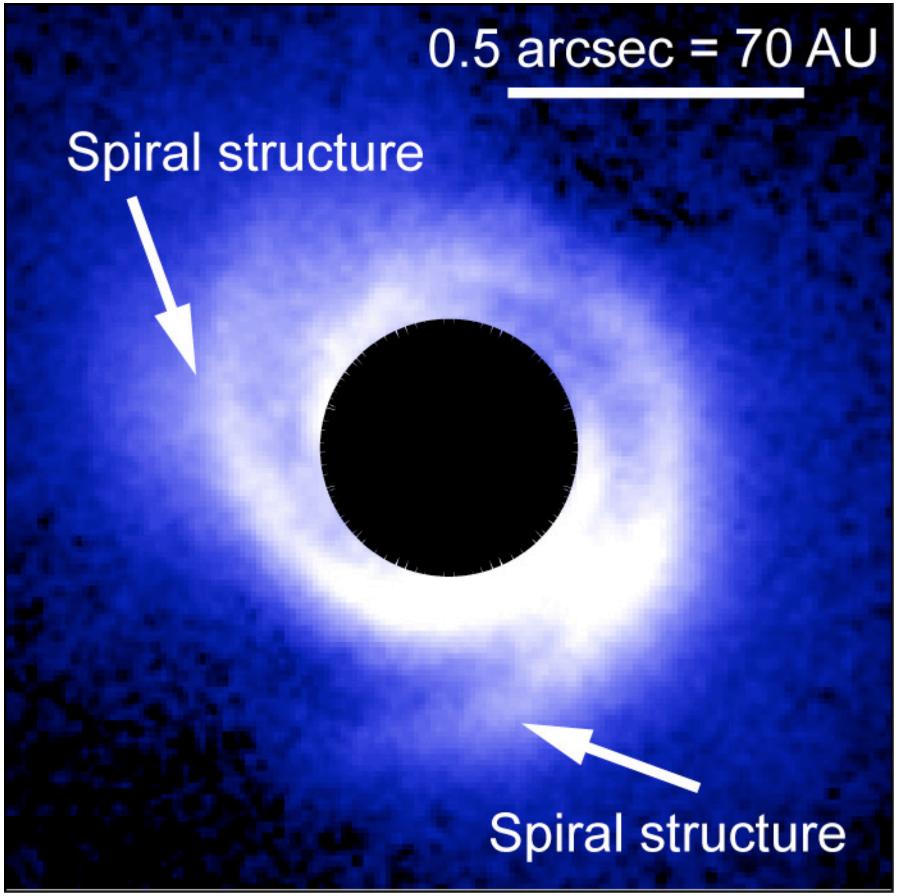
S=3.5

Stokes number, St=0.004

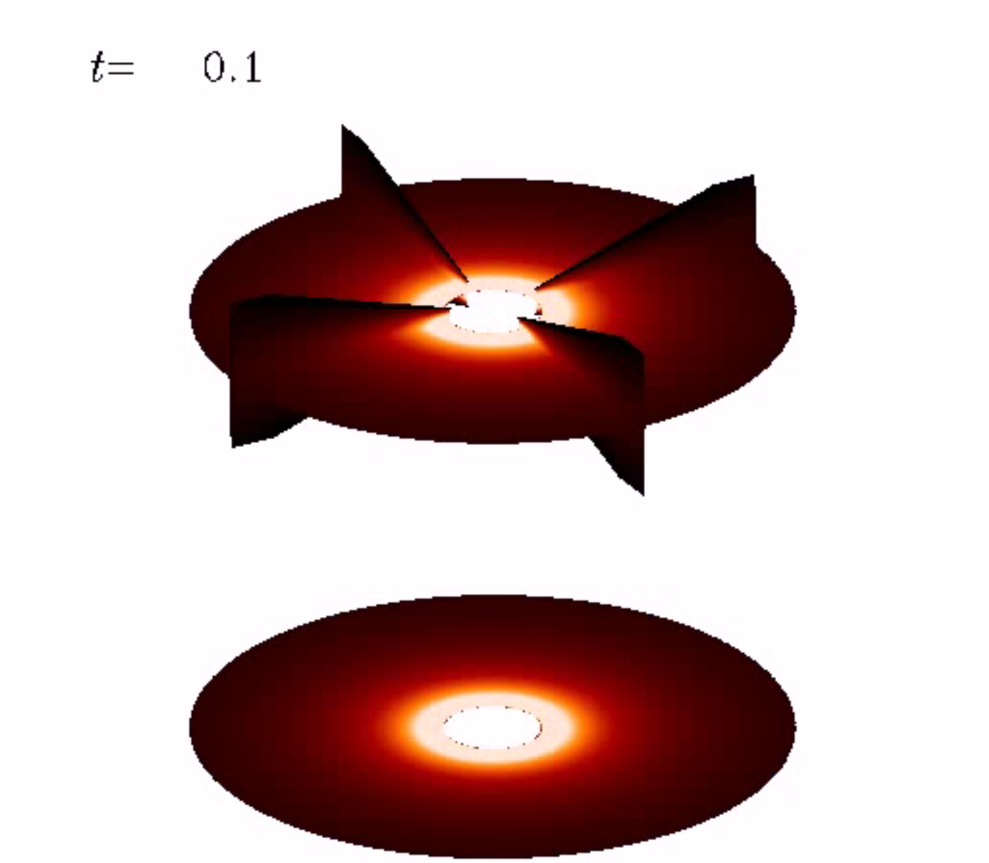
δ *= 0.001,* v_{rms} = 4% c_s



Spirals in transition disks



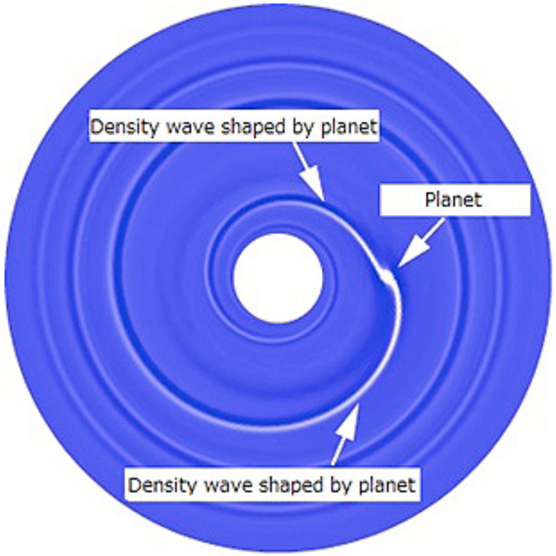
Muto et al. (2012)



Lyra (2009)

Spiral arm fitting leads to problems

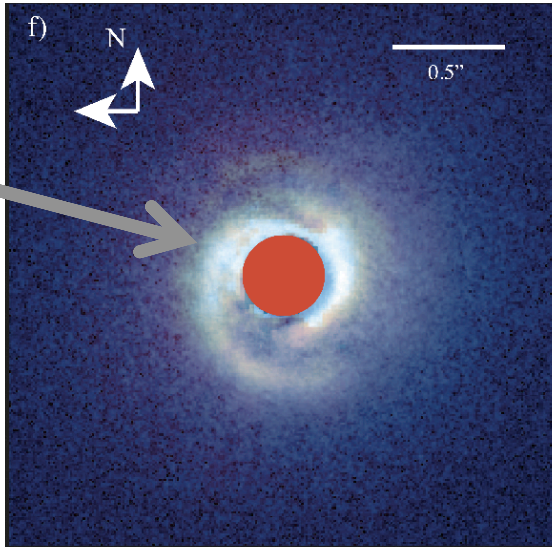
Analytical spiral fit



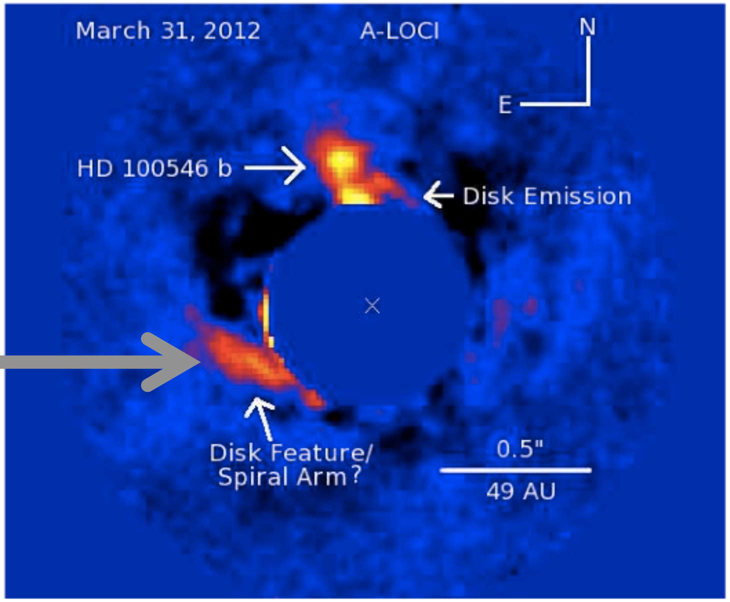
$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \left(\frac{r}{r_c}\right)^{-\alpha} \right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \right) \right\},$$

Rafikov (2002)
Muto et al. (2012)

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

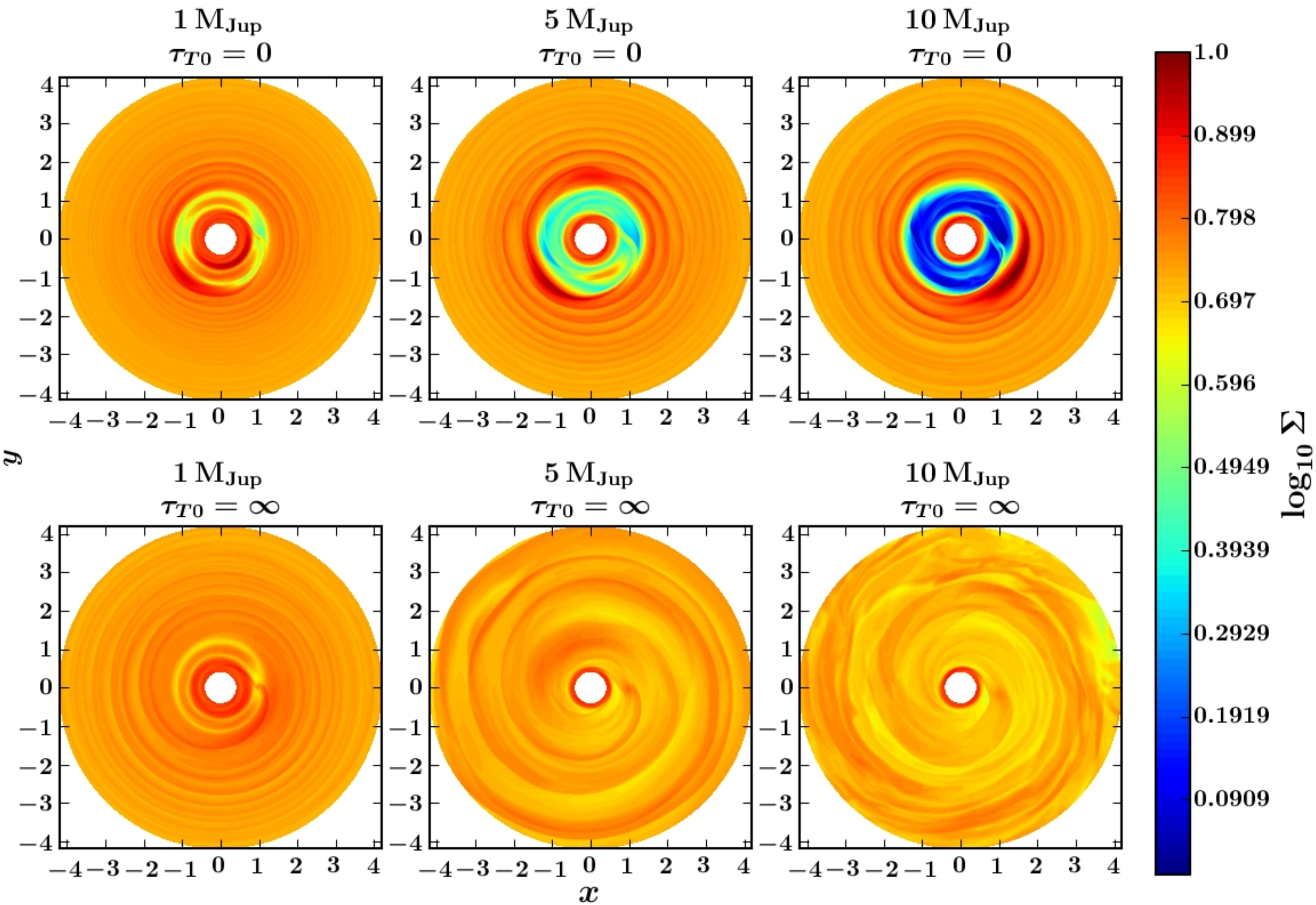


Spiral has little polarization. Must be thermal emission at 1000K.



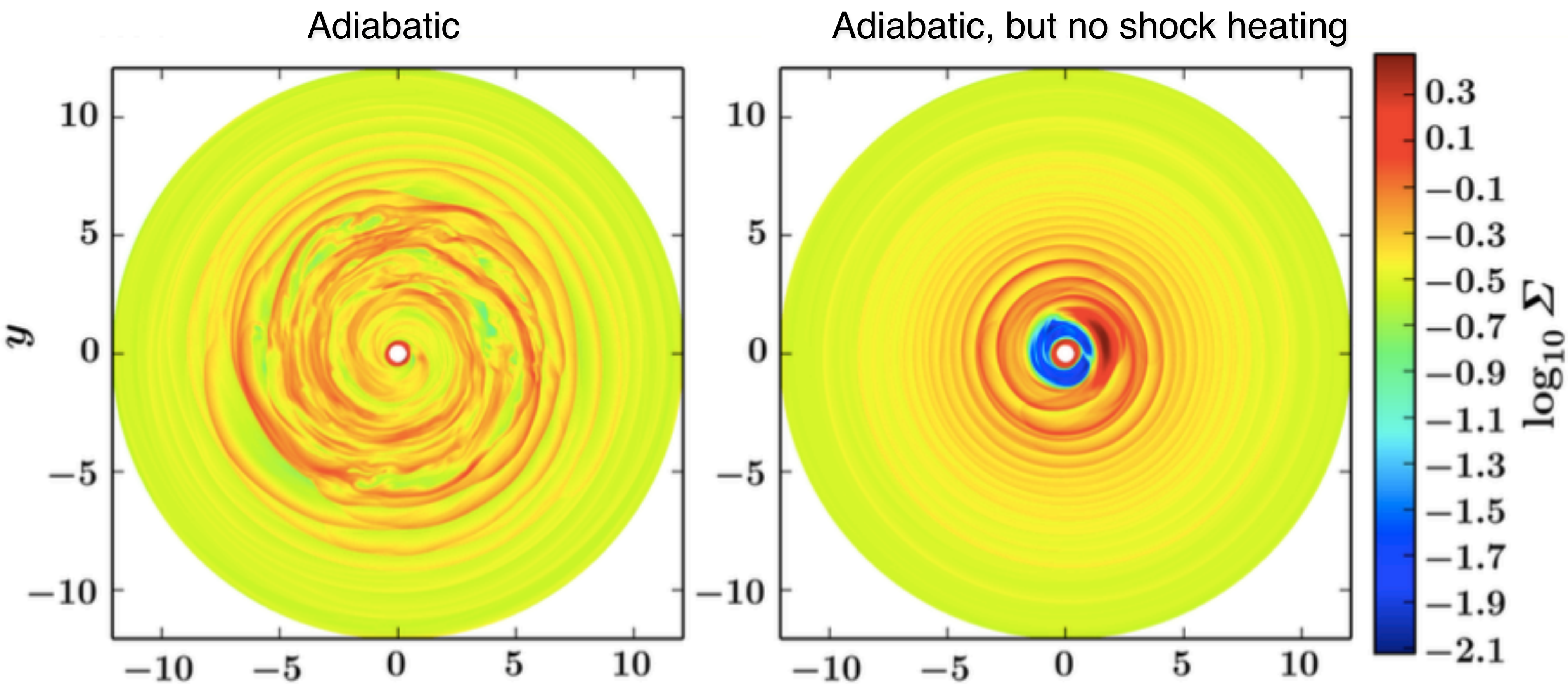
Currie et al. (2014)

Isothermal vs Adiabatic



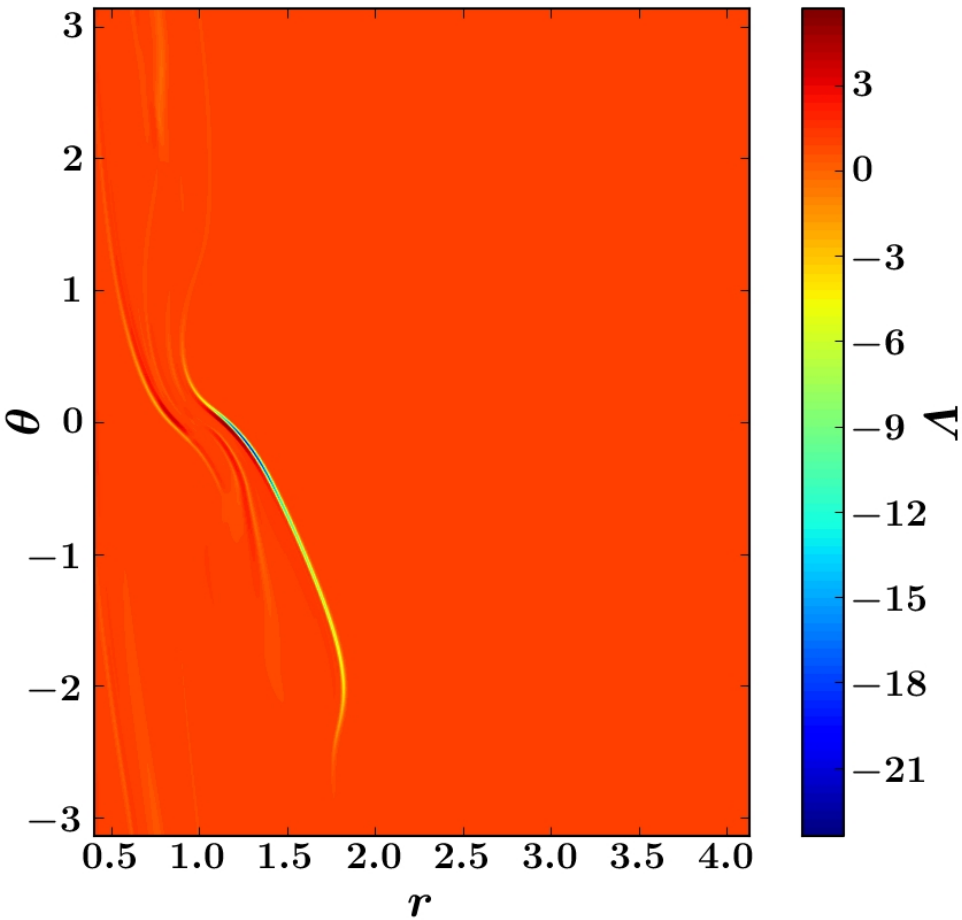
Richert et al. (2015, submitted)

The energy source: shock heating!

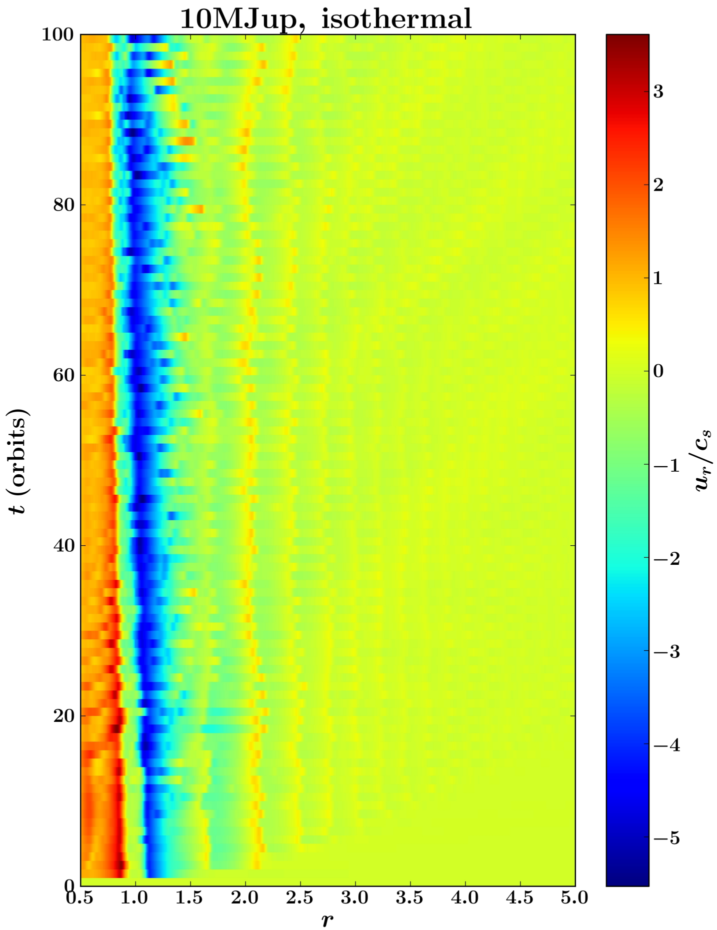


Richert et al. (2015, submitted)

The spiral is buoyantly unstable



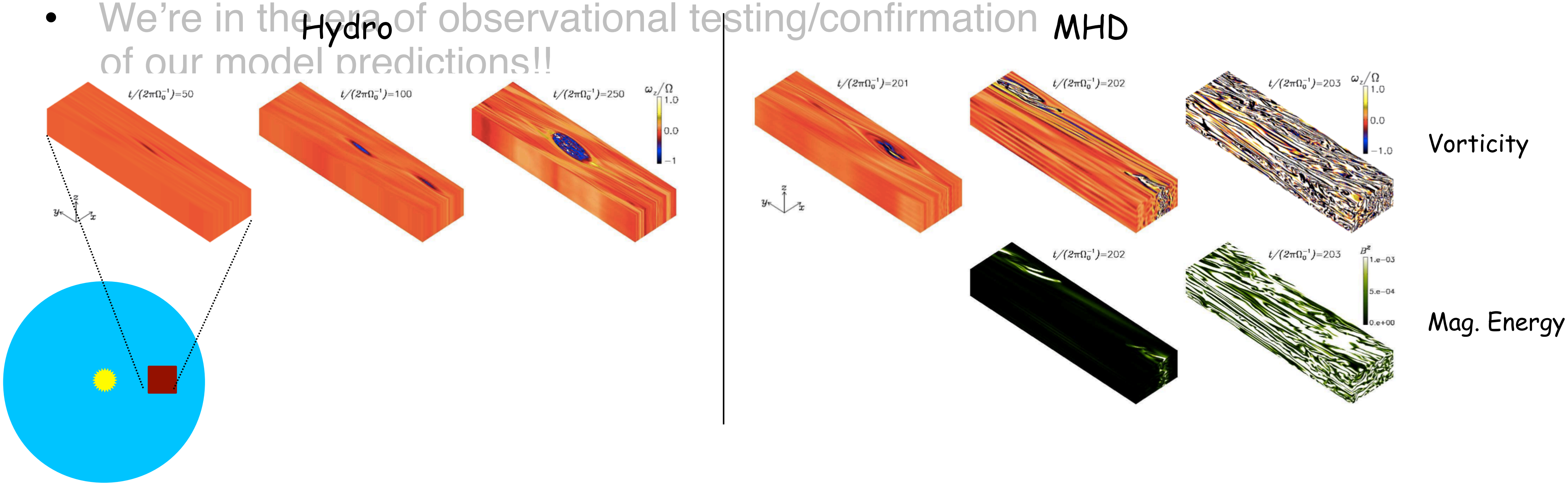
The spiral has Ma >~ 1



Richert et al. (2015, submitted)

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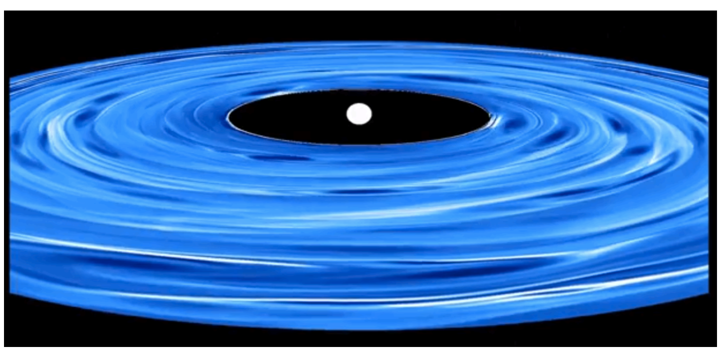
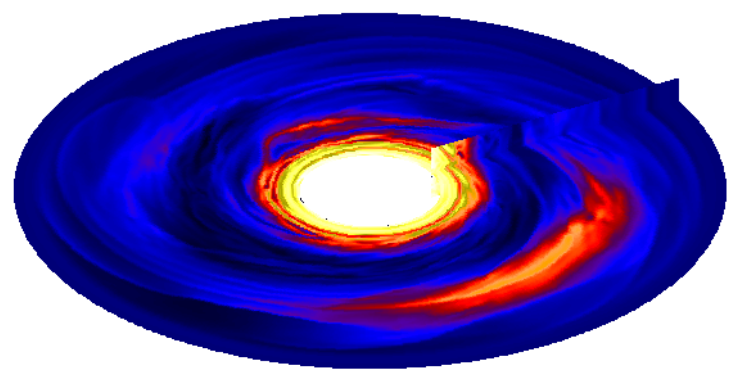
- Two sustenance modes: Rossby Wave Instability and Convective Overstability
- Vortex-assisted is a complementary formation mode to streaming instability
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Rossby wave instability may be the culprit of these dust traps
- We're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

Baroclinic instability



Rossby wave instability



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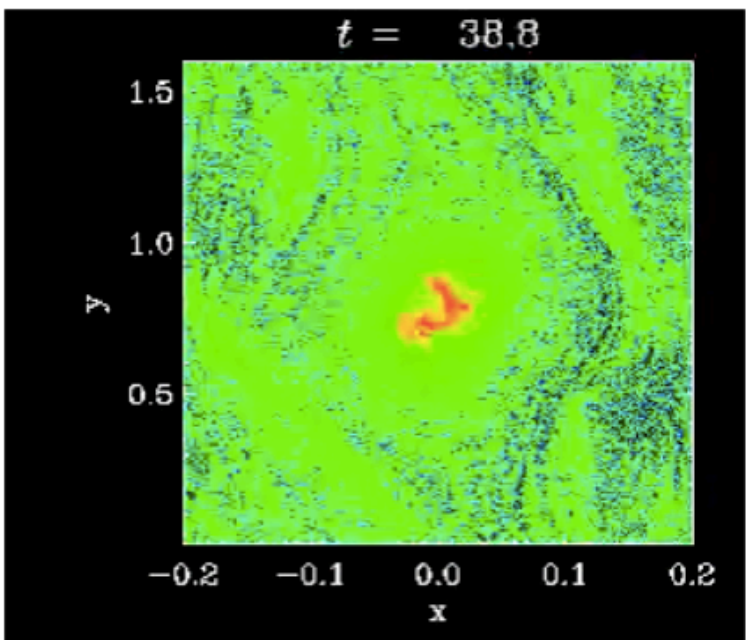

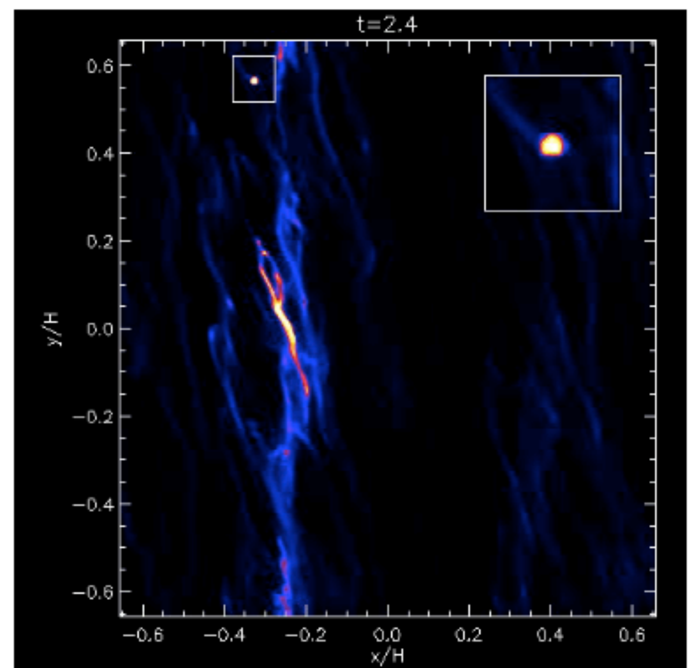

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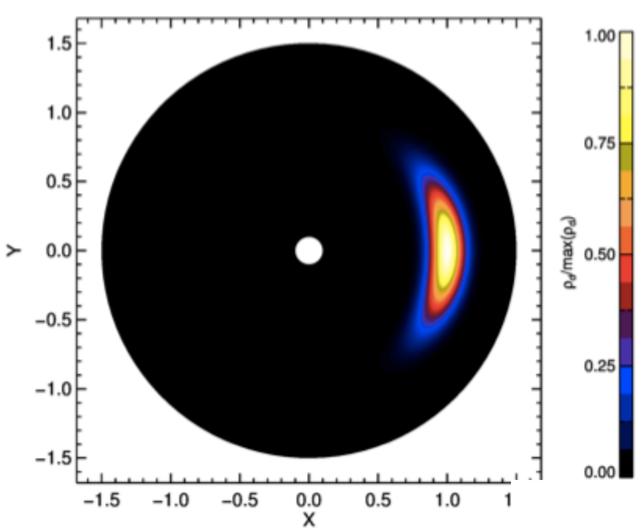
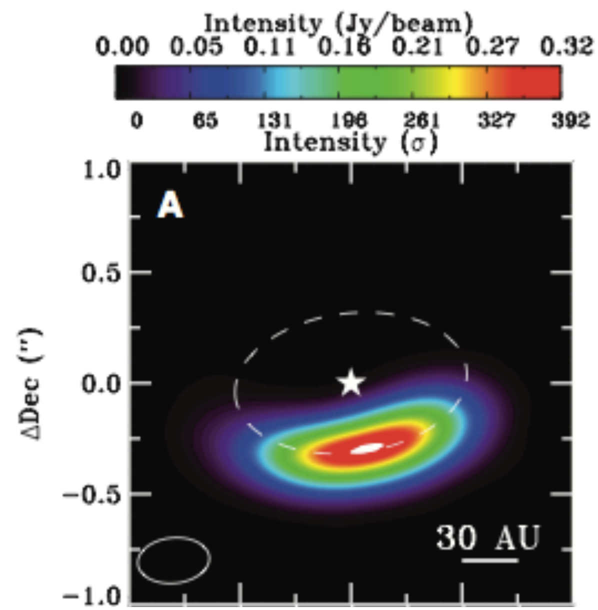
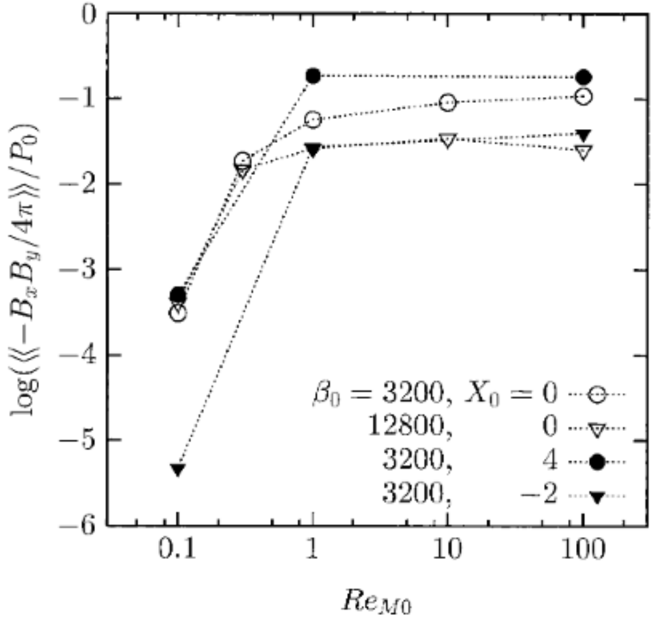
Lyra & Lin (2013)







Conclusions

zone only

Rossby Wave Instability and Convective Overstability

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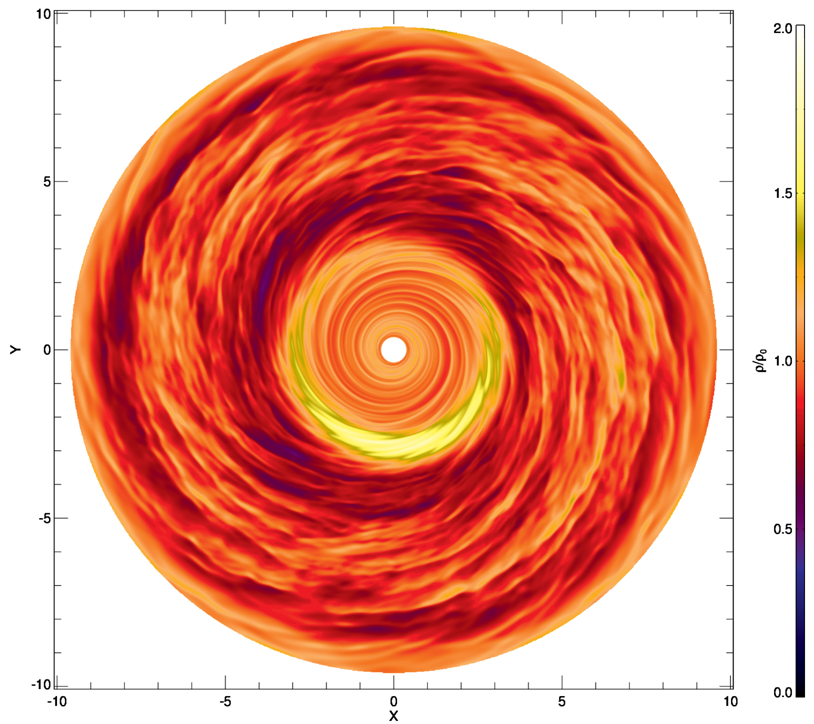
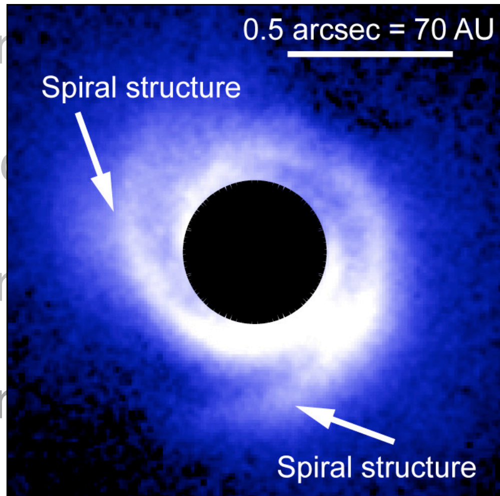
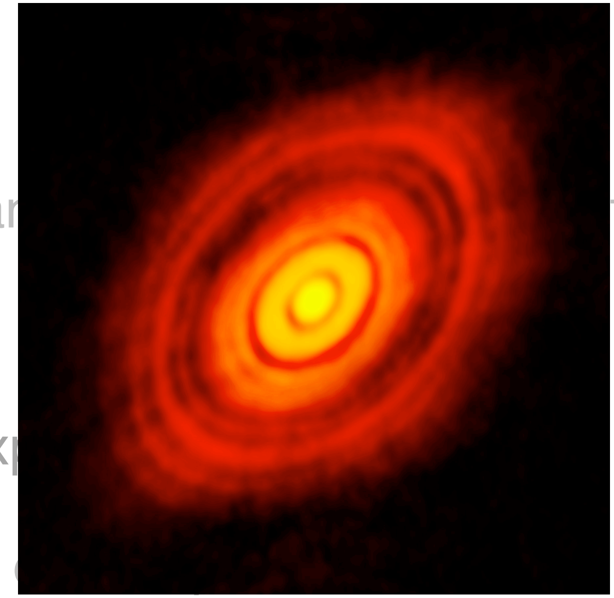
ıg-diffusion equilibrium explains the observations

- Rossby wave instability may be the culprit of these dust traps
- We're in the era of observational testing/co of our model predictions!!



Conclusions





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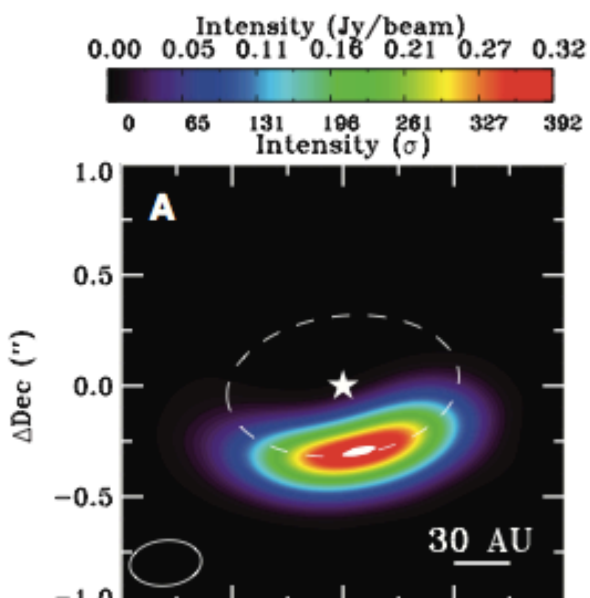
- Rossby wave instability may be the culprit of these c
- We're in the era of observational testing/confirmation of our model predictions!!



Conclusions

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- Rossby w
- We're in th
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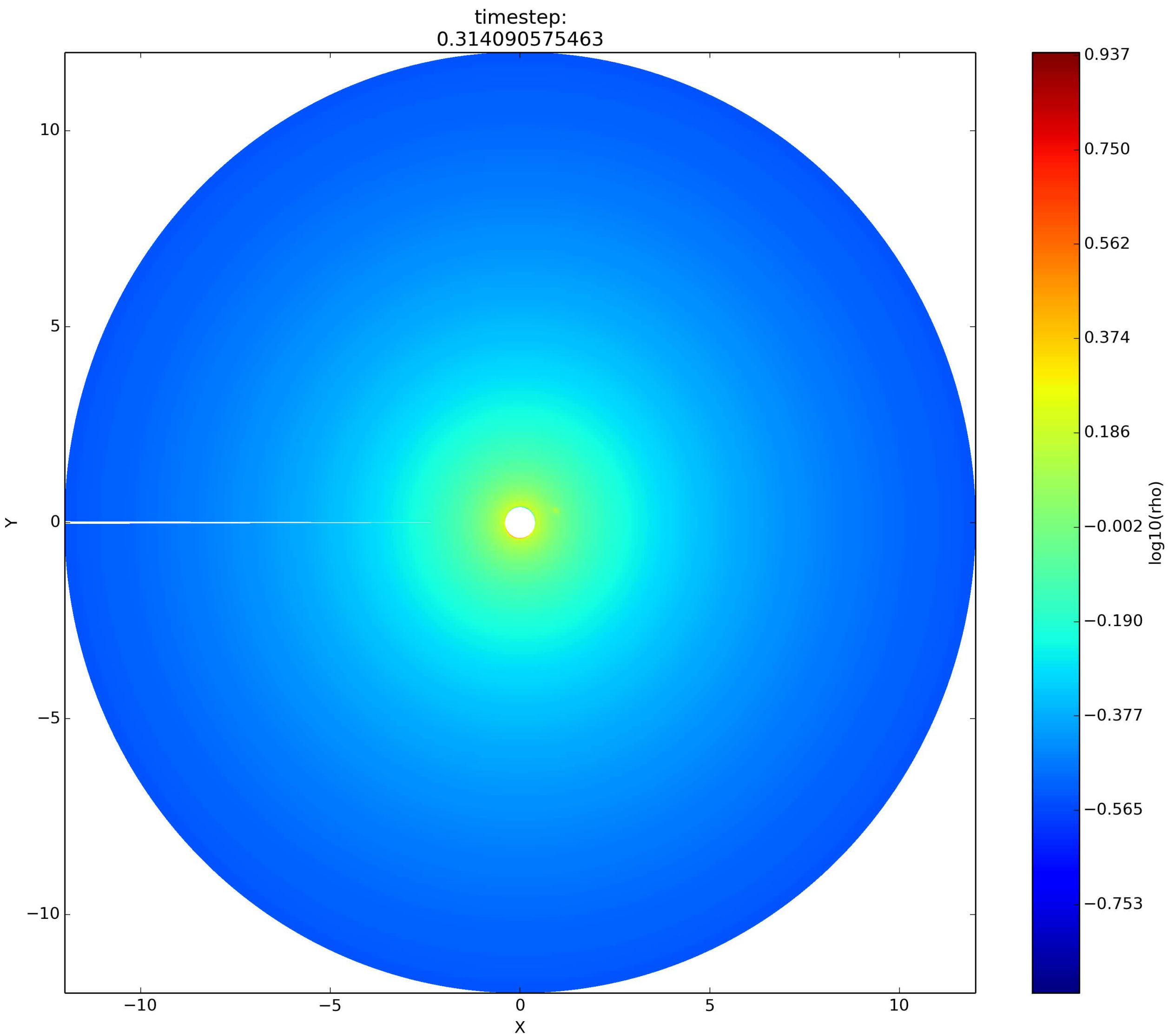

Richert et al. (2015, submitted)