Non-axisymmetric structures in transition disks: dynamical instabilities without planets?

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Caltech - JPL

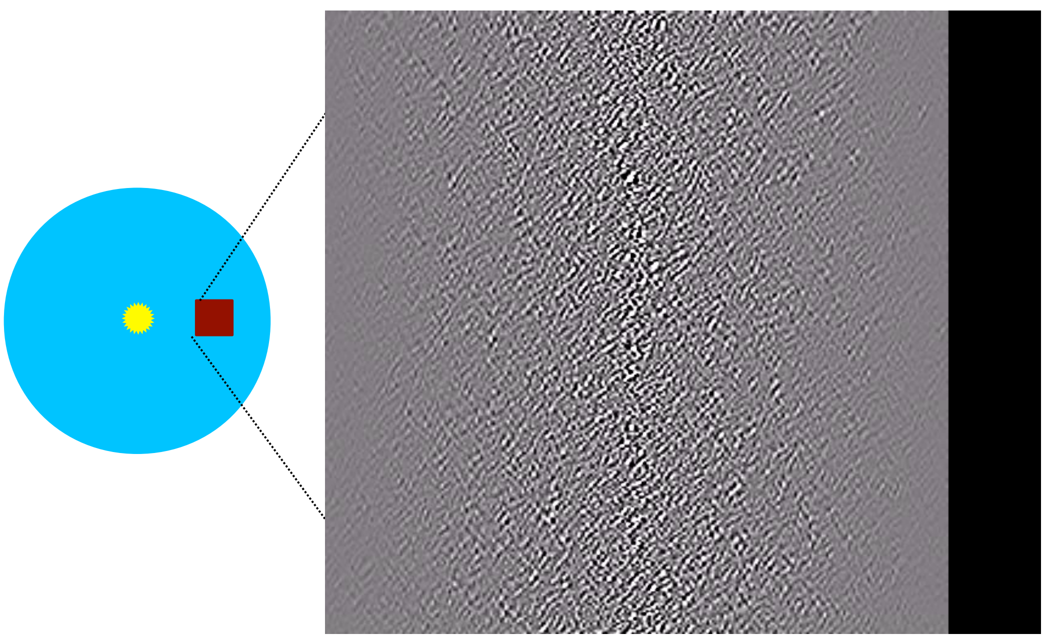
Transition Disks and Planet Formation workshop

Leiden, March 5th, 2015

Outline

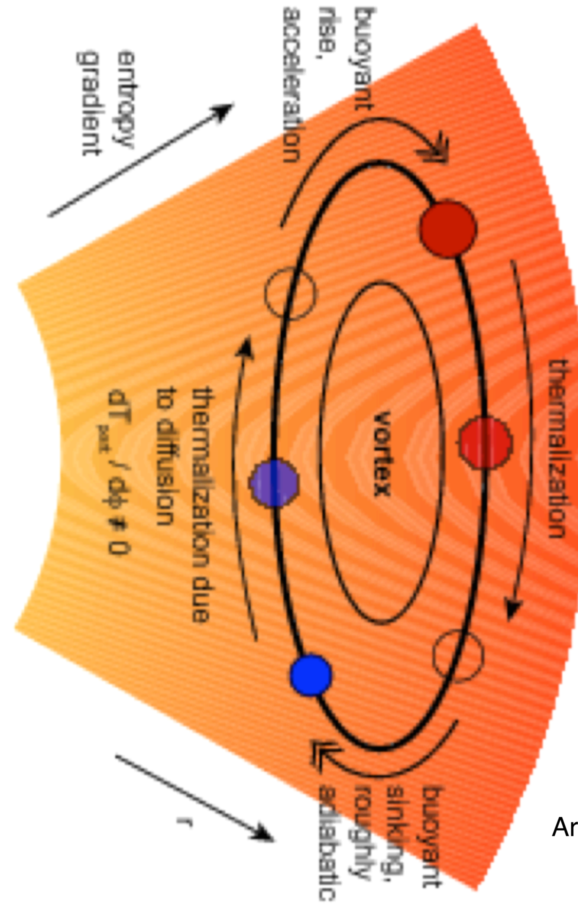
- Sustaining vortices
    - Convective Overstability and Rossby Wave Instability
- RWI at active/dead zone boundaries
- Spirals
- Rings and arcs: Photoelectric instability

Baroclinic Instability – Excitation and self-sustenance of vortices



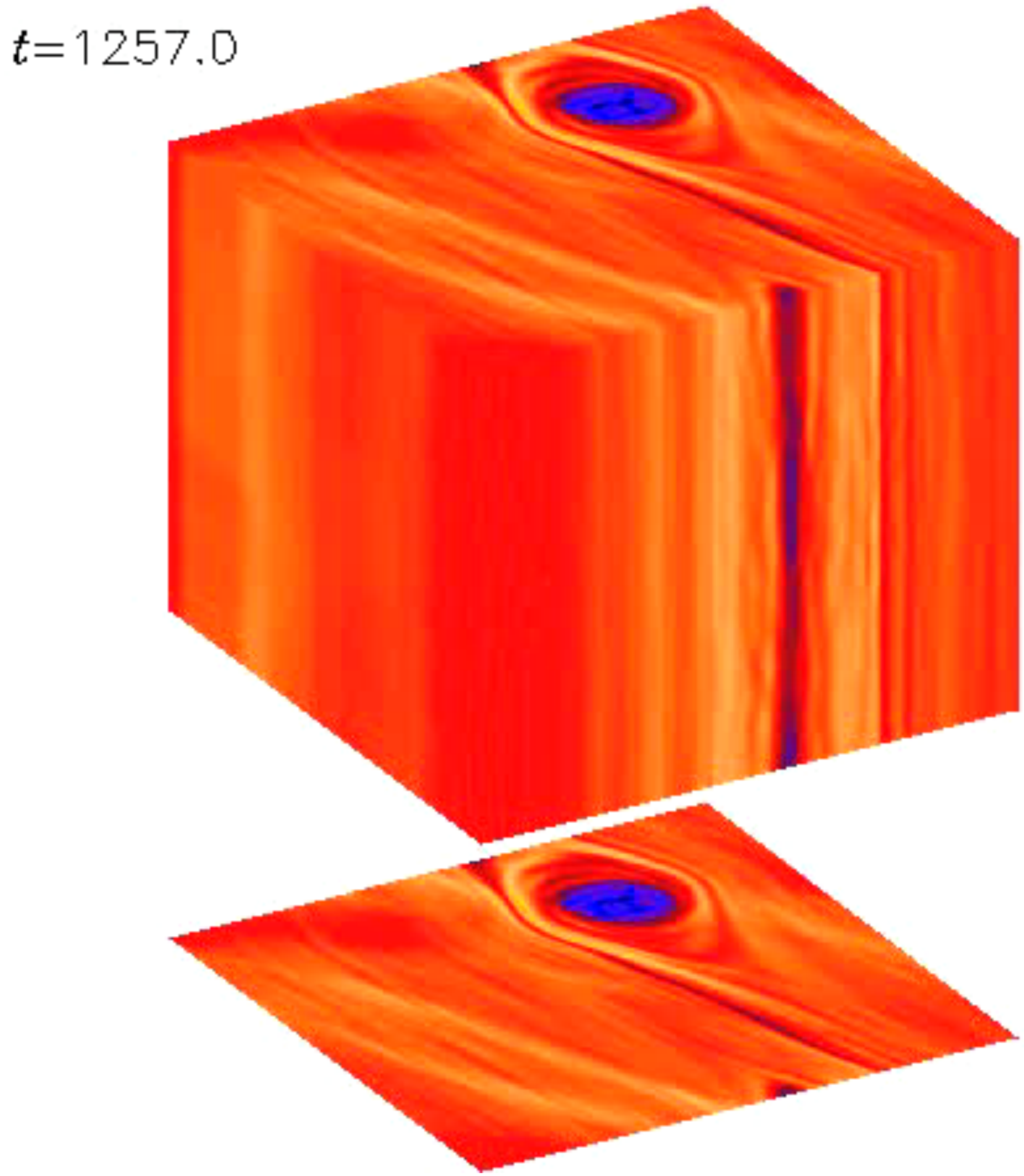
Lyra & Klahr (2011)

Sketch of the
Baroclinic Instability



Armitage (2010)

Baroclinic vortices do not survive magnetization



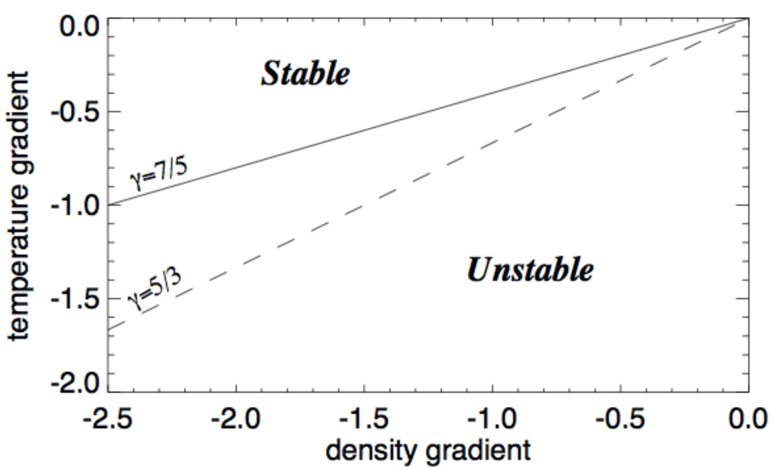
The "Baroclinic Instability" is LINEAR
(Convective Overstability)

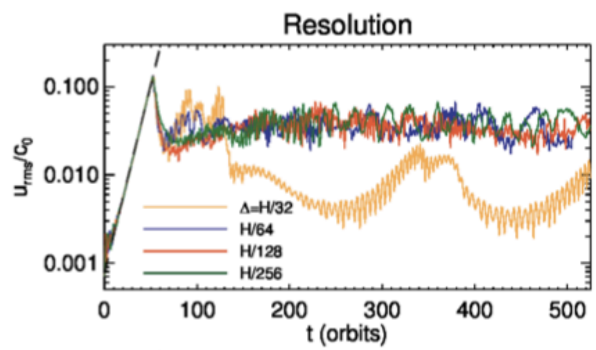
Klahr & Hubbard (2014), Lyra (2014)

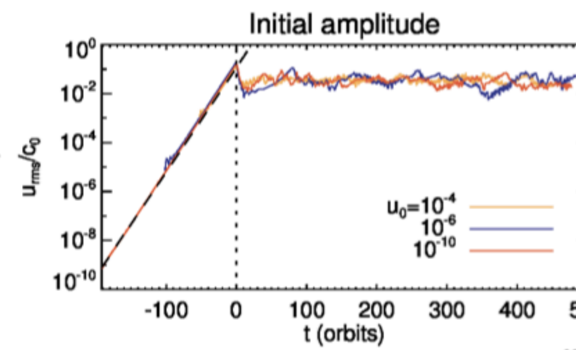
$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u},$$
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\boldsymbol{u} = -\frac{1}{\rho}\boldsymbol{\nabla} p + \boldsymbol{g},$$
$$\frac{\partial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

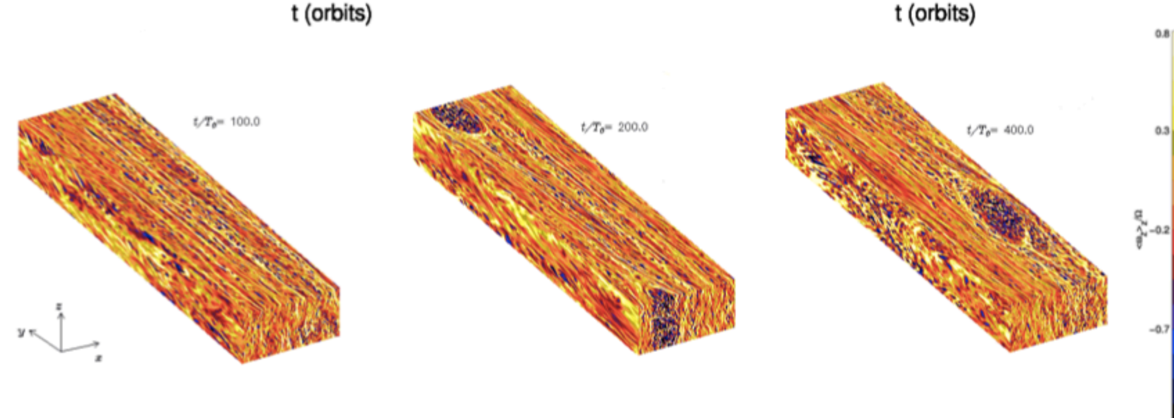
$$\bar{\omega}^3 + i\varsigma\bar{\omega}^2 - \bar{\omega}\mu^2(\kappa^2+N^2) - i\varsigma\kappa^2\mu^2 = 0,$$
$$\varsigma = 1/\gamma\tau \qquad \mu^2 = k_z^2/k^2.$$

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







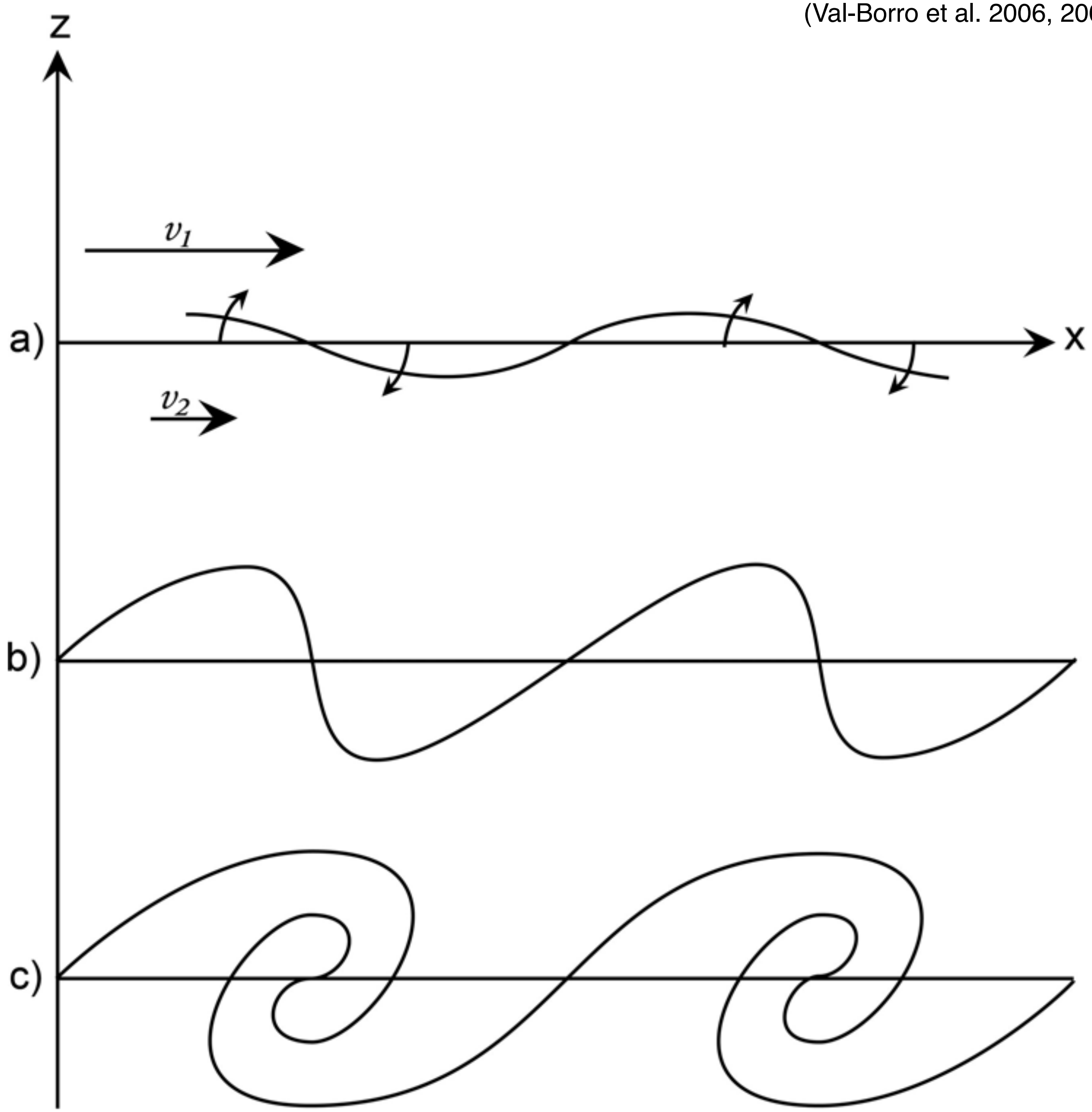


Lyra (2014)

Rossby Wave Instability

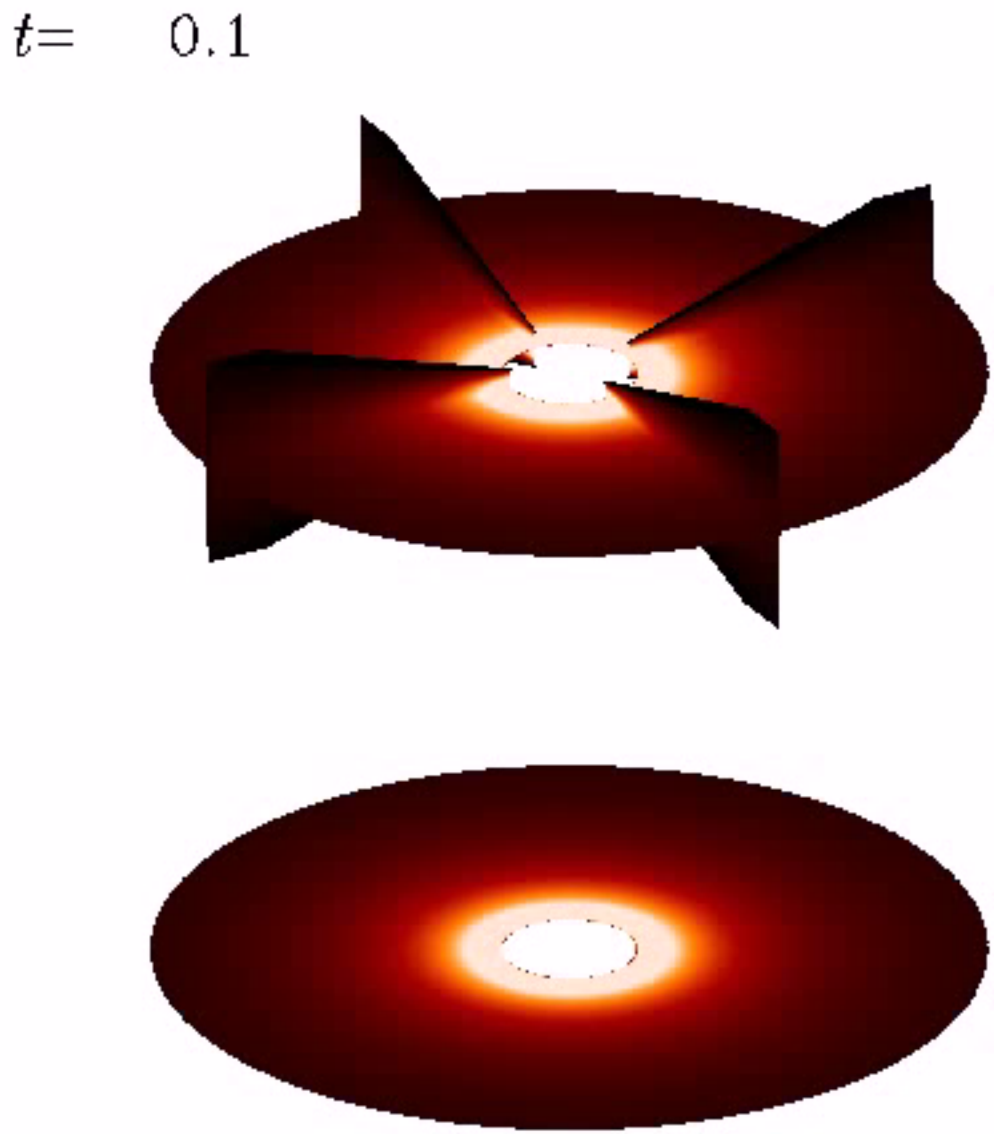
(or… Kelvin-Helmholtz in rotating disks)

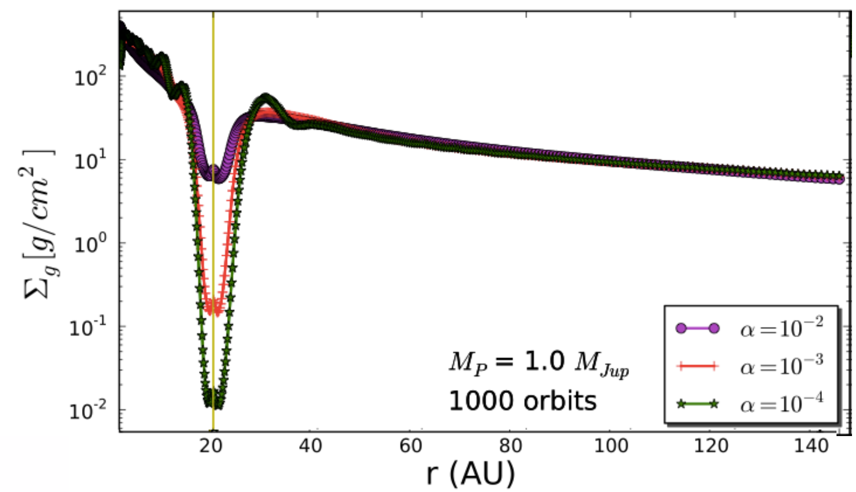
(Val-Borro et al. 2006, 2007)



Planetary gap RWI

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





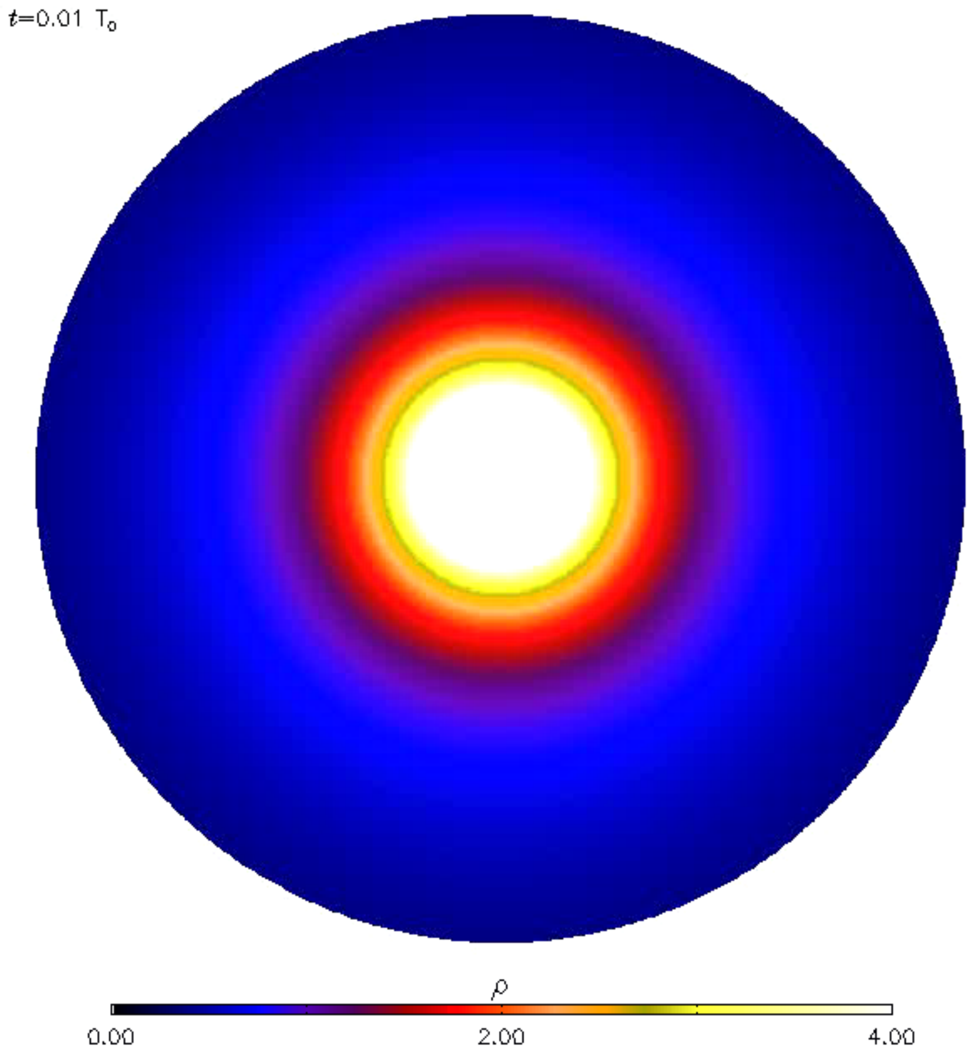
Pinilla et al. (2012)

Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

Lyra (2009)

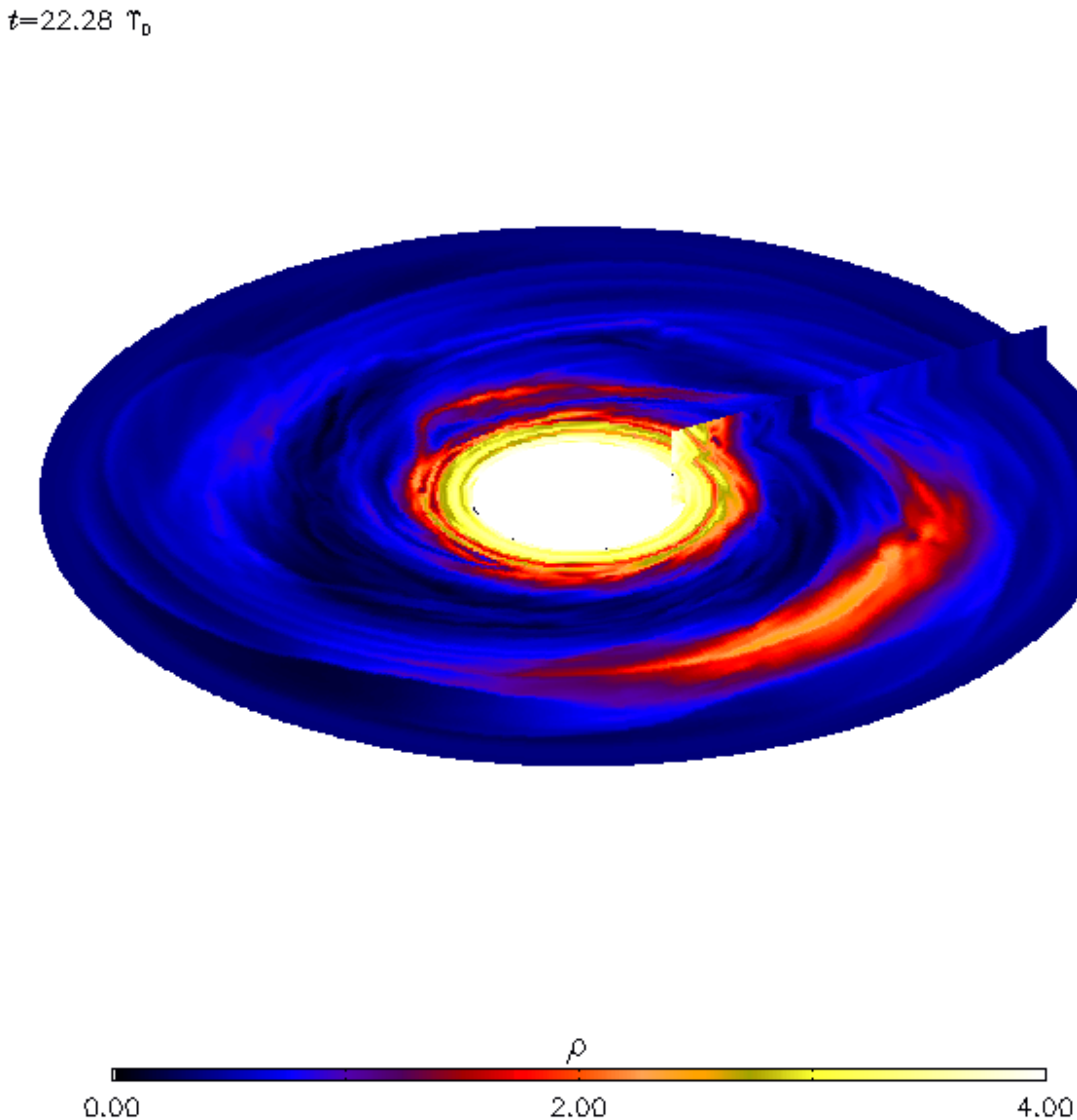
Inner Active/Dead zone boundary

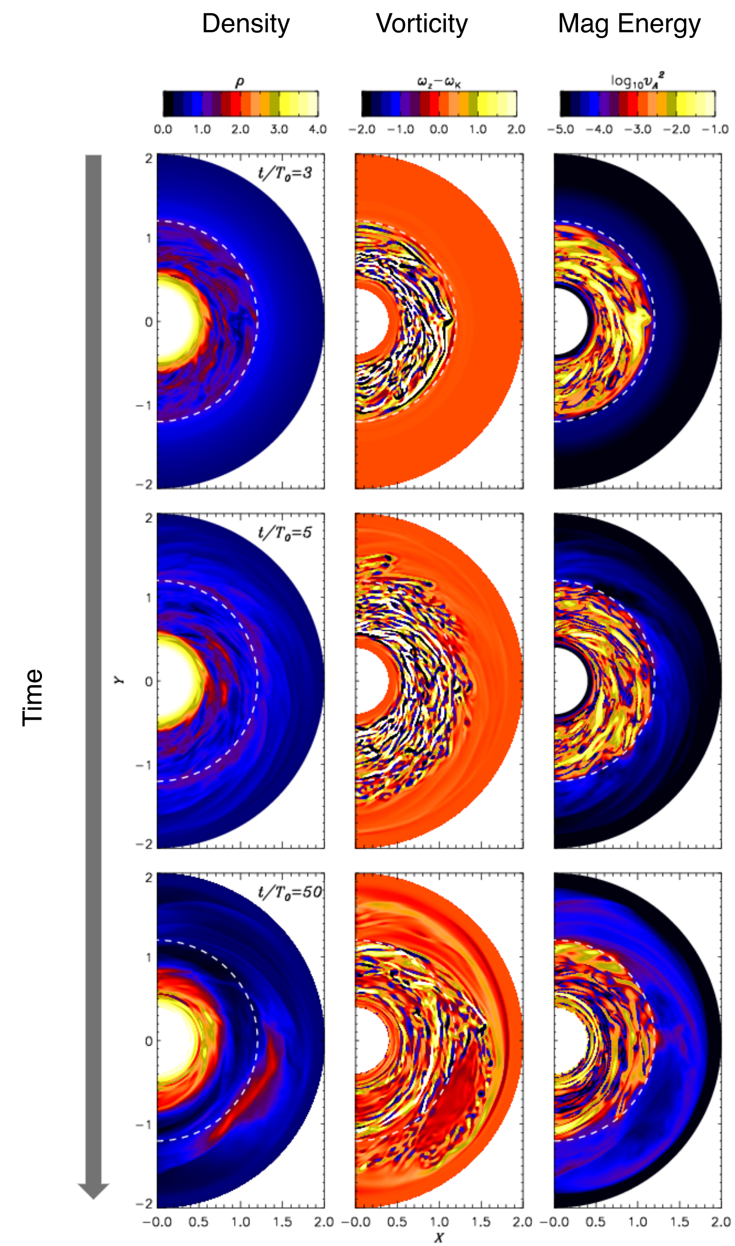


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Active/dead zone boundary

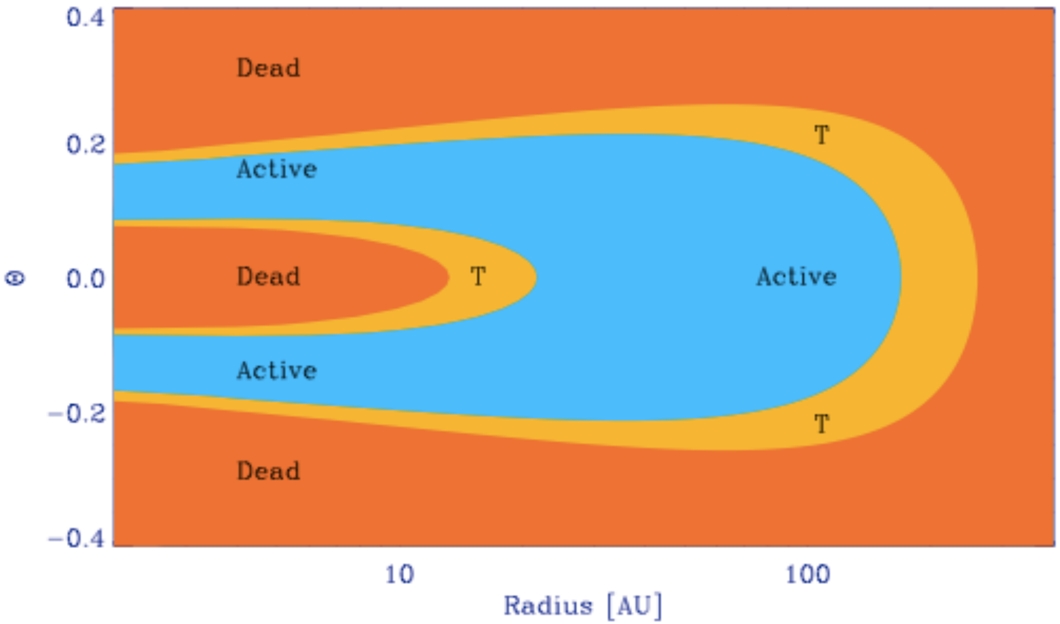




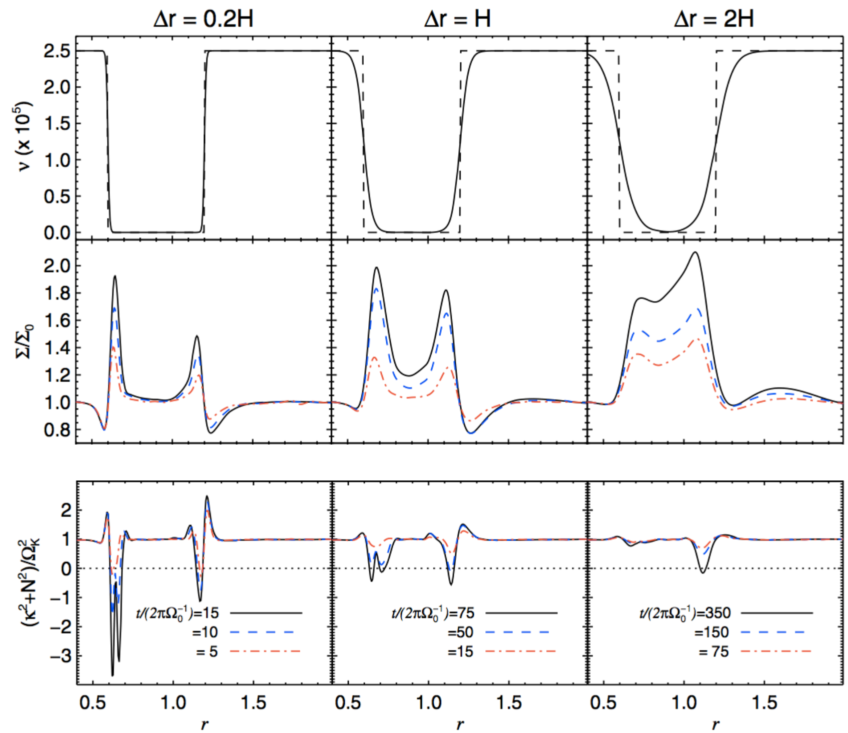
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Outer Dead/Active zone transition



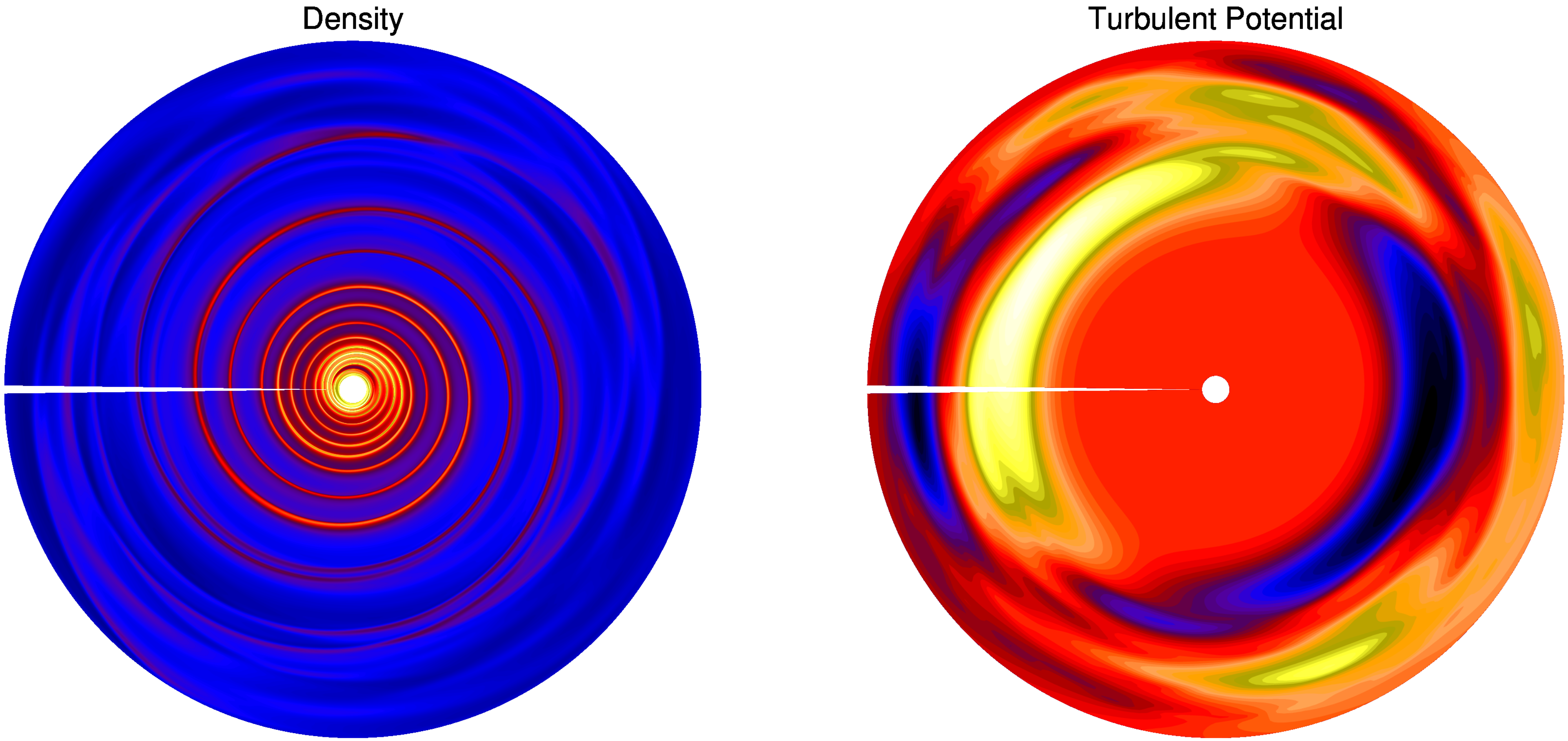
Dzyurkevitch et al (2013)



Lyra et al. (2009)

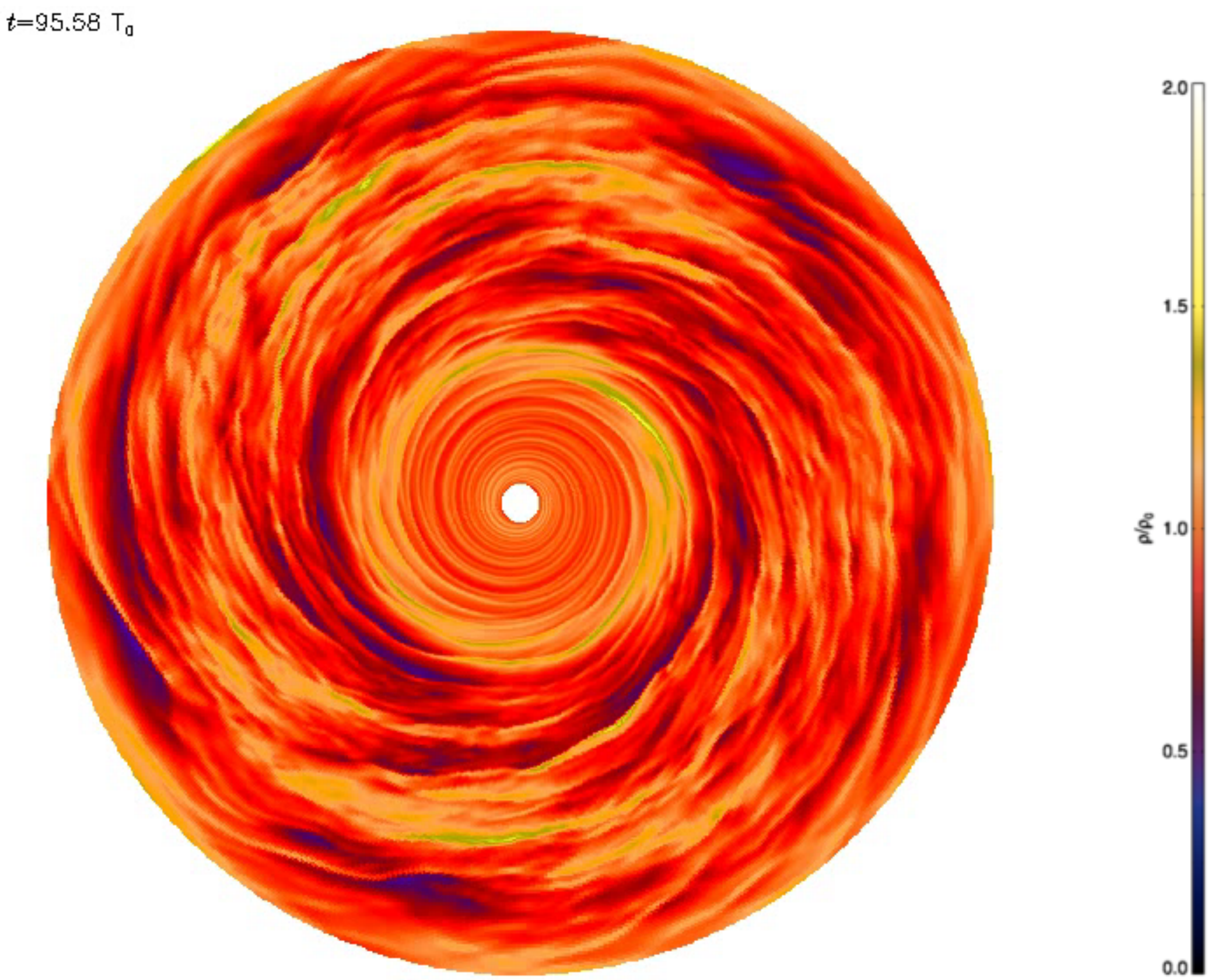
The **outer** dead zone transition in ionization is
TOO SMOOTH
to generate an RWI-unstable bump.

Outer Dead/Active zone transition: Spirals without planets



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

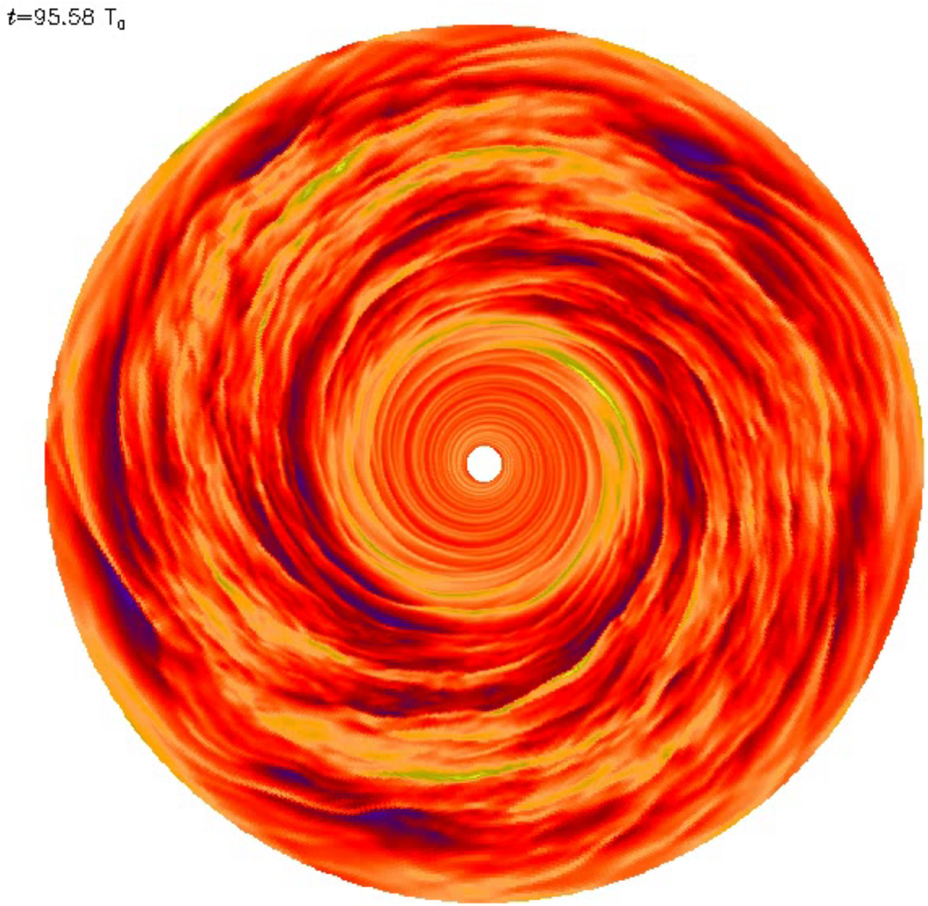
Outer Dead/Active zone transition: 3D MHD

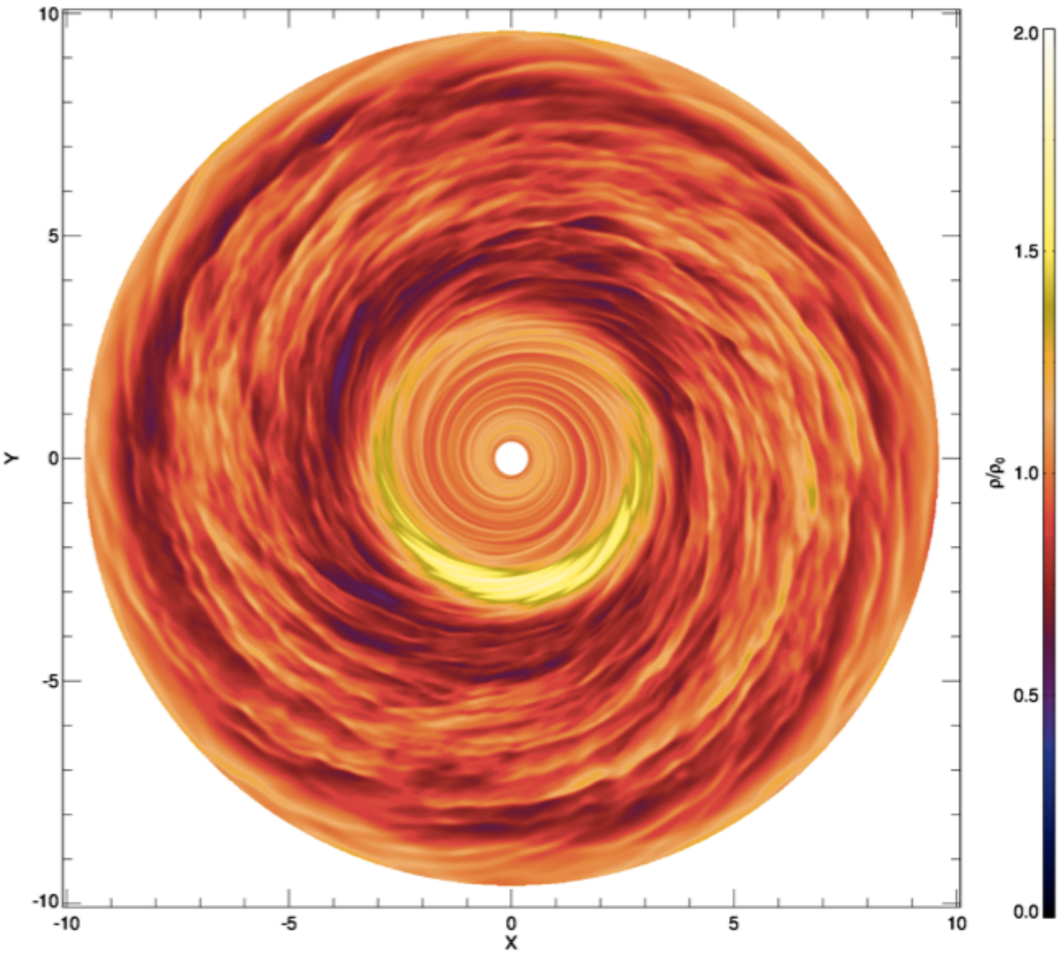


Resistive inner disk + magnetized outer disk

Lyra et al (2015)

Outer Dead/Active zone transition: Spiral + Vortex

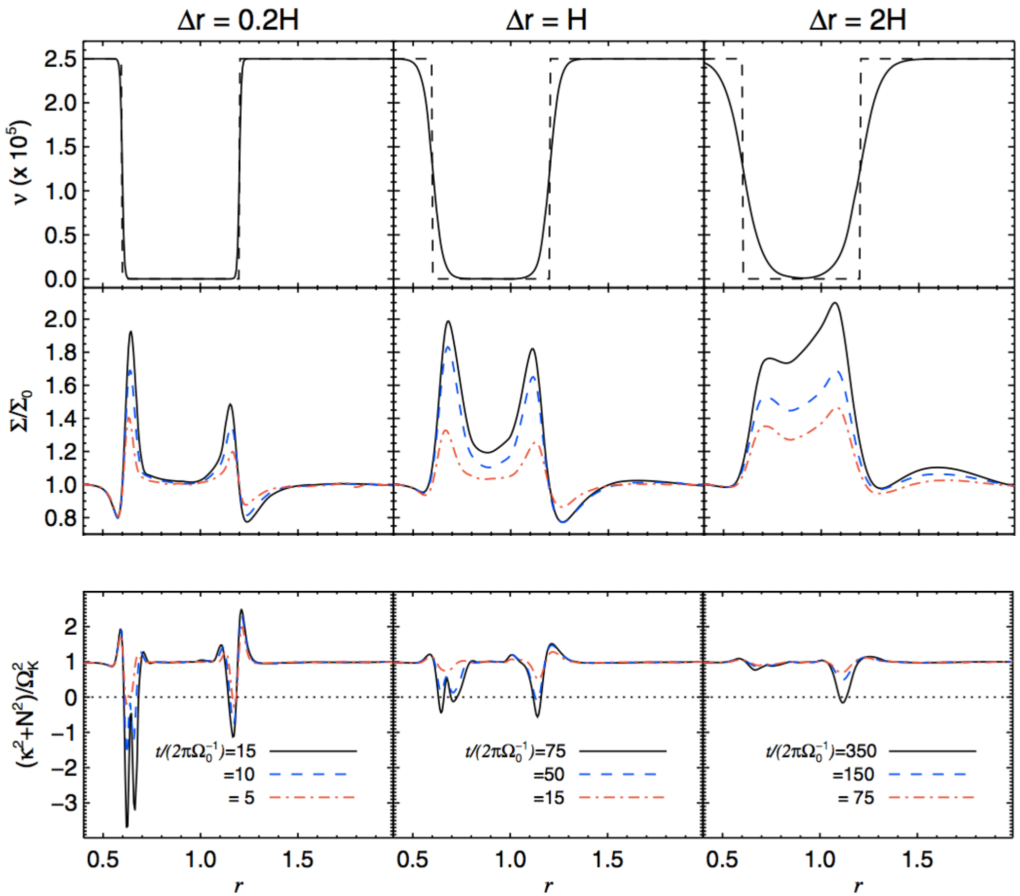




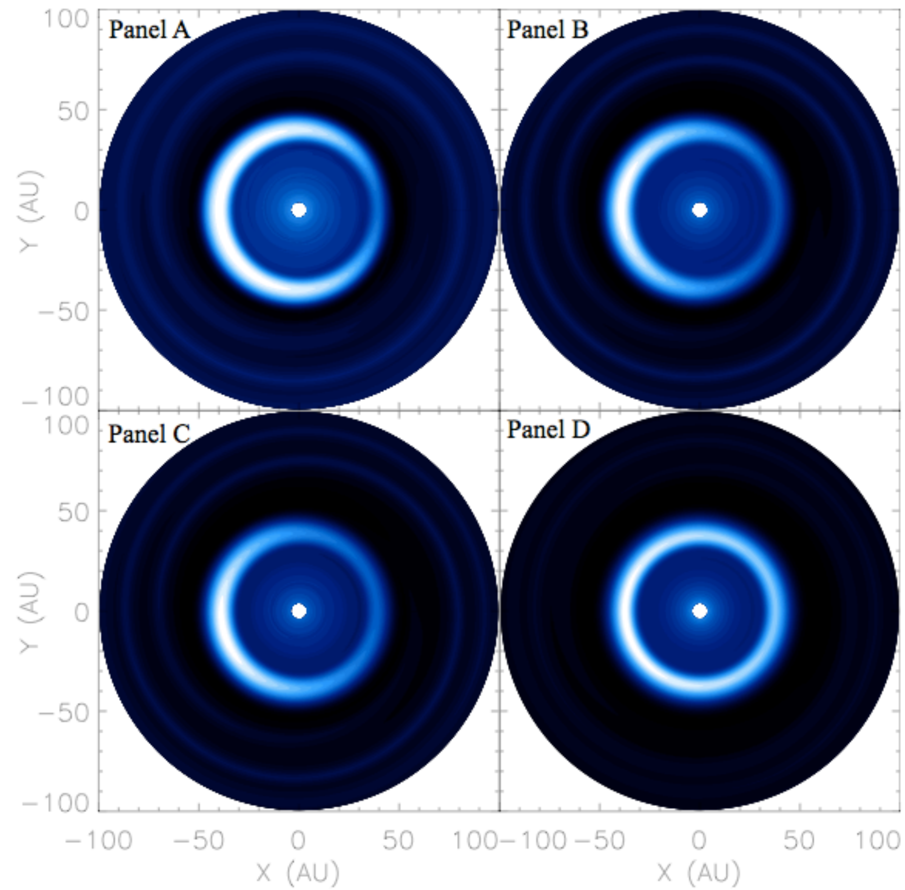
Resistive inner disk + magnetized outer disk

Lyra et al (2015)

What's going on? RWI should not occur for Δ > 2H

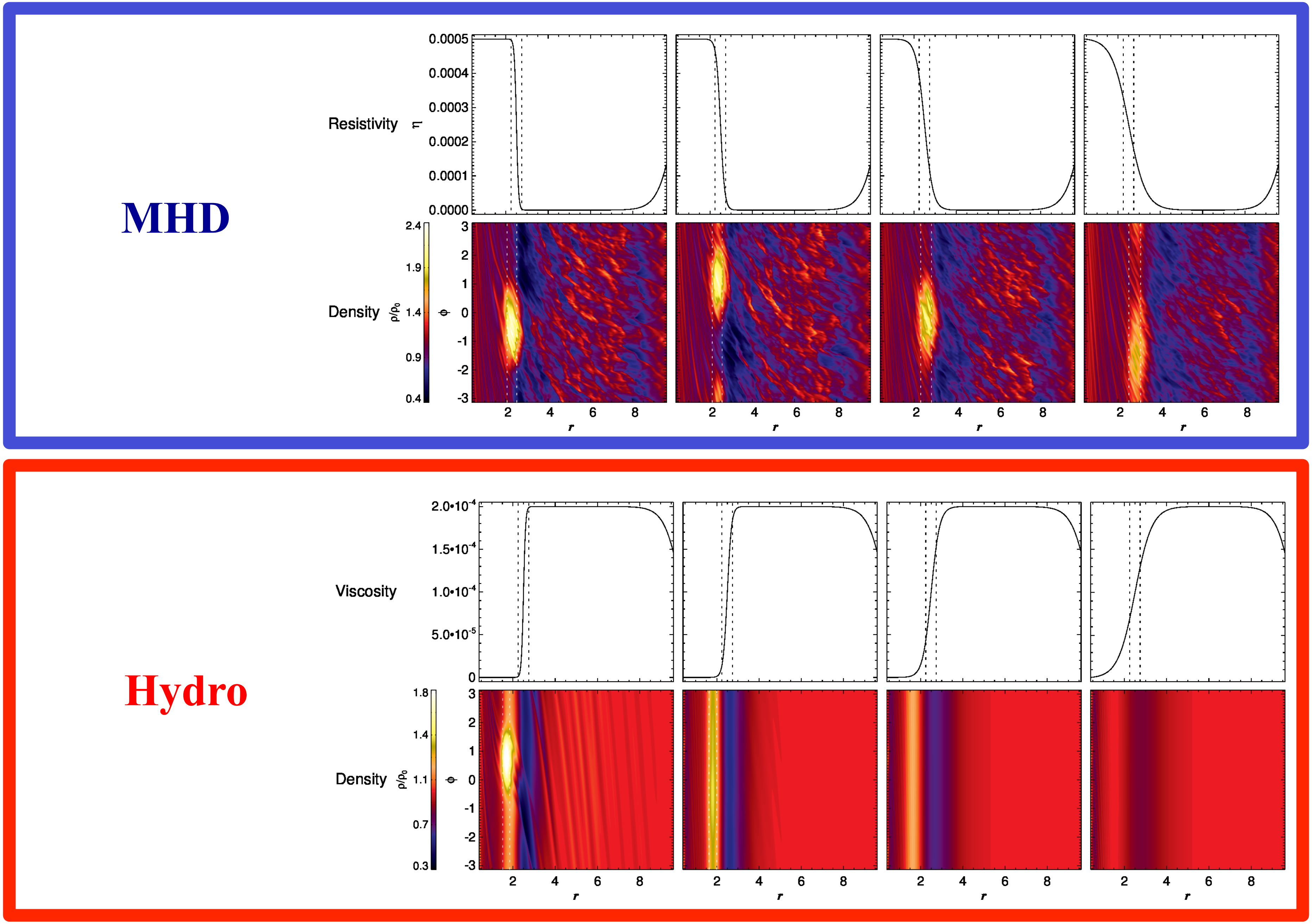


Lyra et al. (2009)



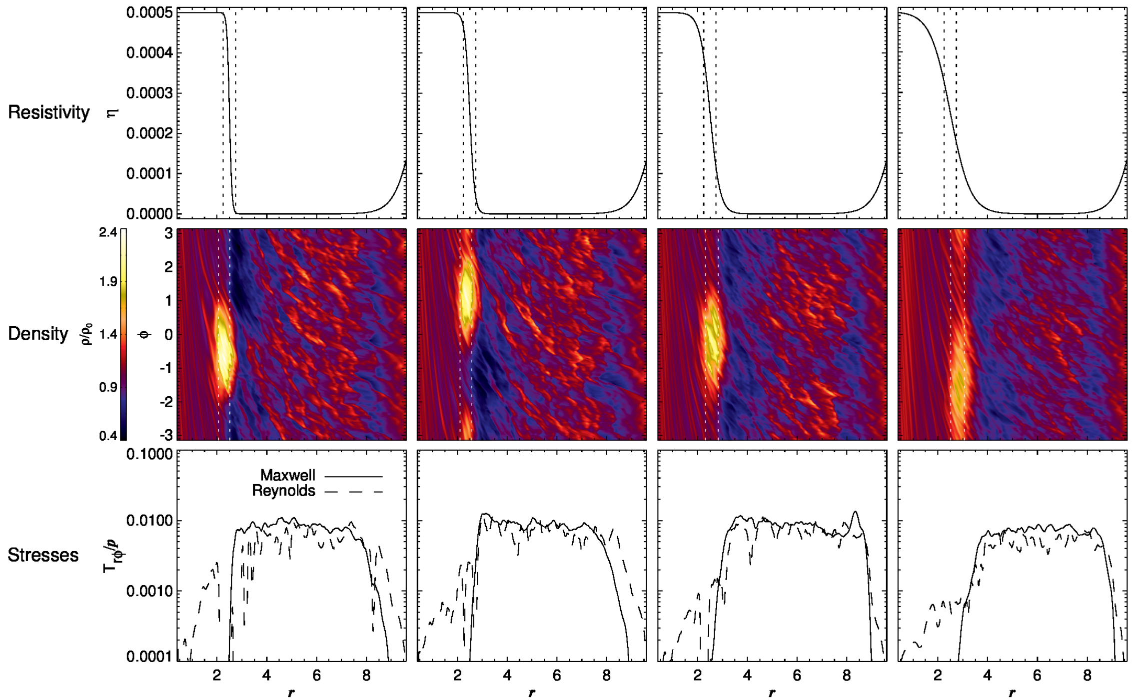
Regaly et al. (2012)

Outer Dead/Active zone transition RWI



Lyra et al (2015)

Outer Dead/Active zone transition RWI



Lyra et al. (2015)

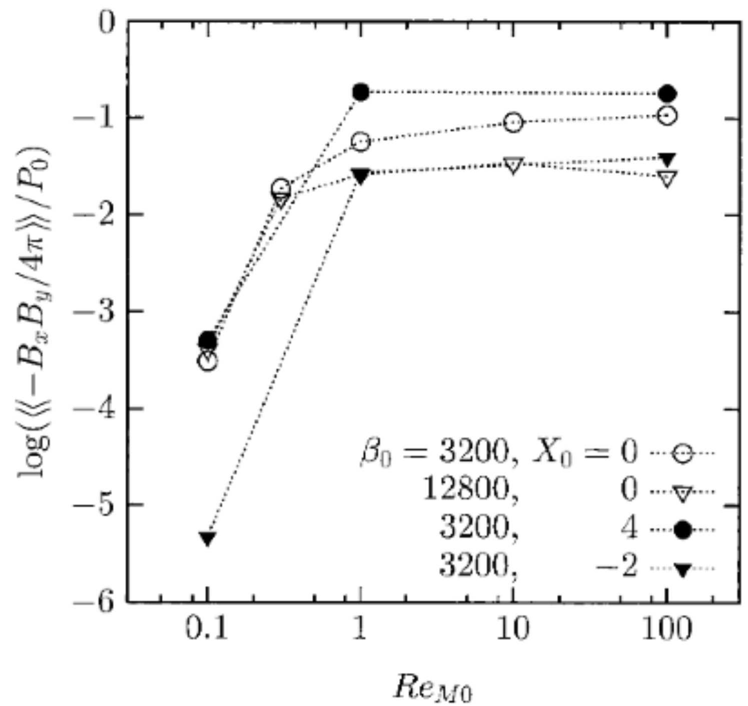
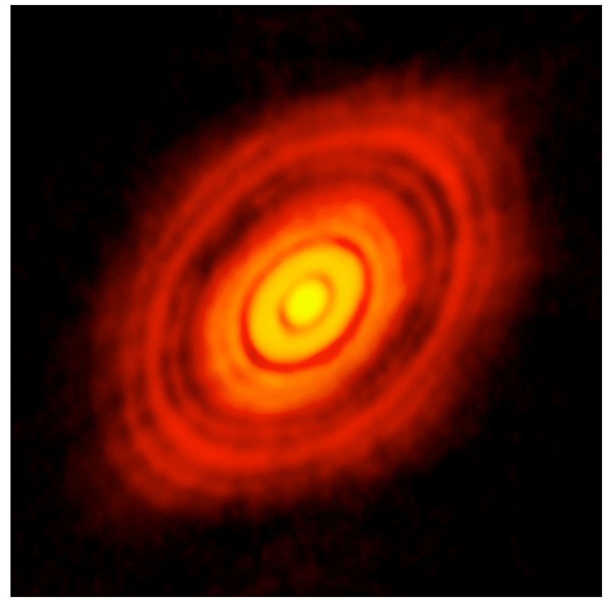


FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number Re_{M0}. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and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

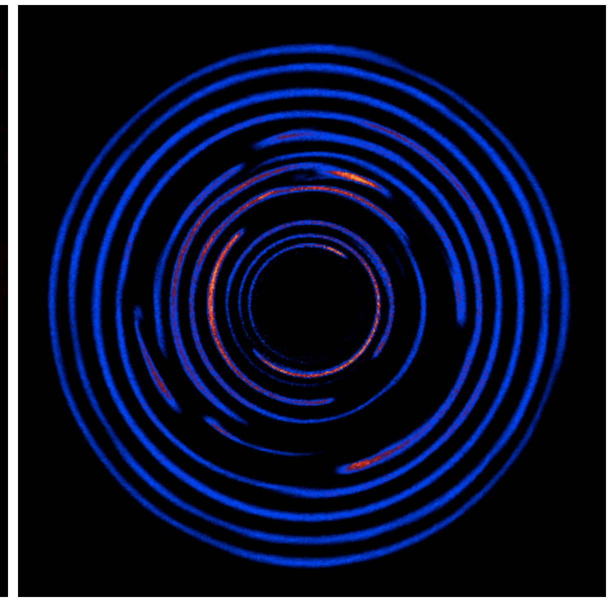
Sano and Stone (2002)

Photoelectric Instability

HL Tau



Lyra & Kuchner (2013)



LETTER

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Formation of sharp eccentric rings in debris disks with gas but without planets

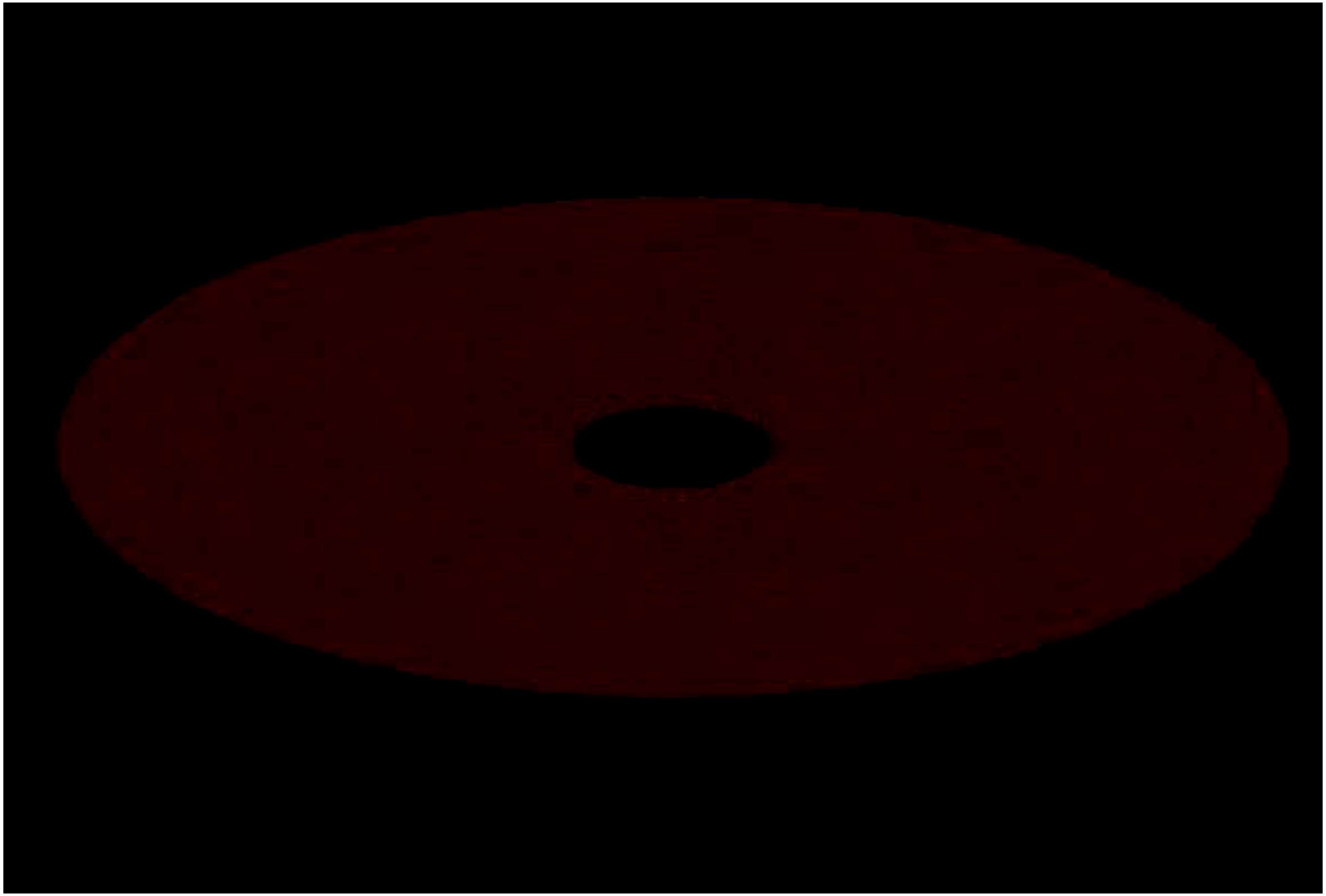
W. Lyra[1,2,3] & M. Kuchner[4]

'Debris disks' around young stars (analogues of the Kuiper Belt in our Solar System) show a variety of non-trivial structures attributed to planetary perturbations and used to constrain the properties of those planets[1–3]. However, these analyses have largely ignored the fact that some debris disks are found to contain small quantities of gas[4–9], a component that all such disks should contain at some level[10,11]. Several debris disks have been measured with a dust-to-gas ratio of about unity[4–9], at which the effect of hydrodynamics on the structure of the disk cannot be ignored[12,13]. Here we report linear and nonlinear modelling that shows that dust–gas interactions can produce some of the key patterns attributed to planets. We find a robust clumping instability that organizes the dust into narrow, eccentric rings, similar to the Fomalhaut debris disk[14]. The conclusion that such disks might contain planets is not necessarily required to explain these systems.

Disks around young stars seem to pass through an evolutionary phase when the disk is optically thin and the dust-to-gas ratio ε ranges from 0.1 to 10. The nearby stars β Pictoris[5,6,15–17], HD32297 (ref. 7), 49 Ceti (ref. 4) and HD 21997 (ref. 9) all host dust disks resembling ordinary debris disks and also have stable circumstellar gas detected in molecular CO, Na I or other metal lines; the inferred mass of gas ranges from lunar masses to a few Earth masses (Supplementary Information). The gas in these disks is thought to be produced by planetesimals or dust grains

We present simulations of the fully compressible problem, solving for the continuity, Navier–Stokes and energy equations for the gas, and the momentum equation for the dust. Gas and dust interact dynamically through a drag force, and thermally through photoelectric heating. These are parametrized by a dynamical coupling time τ_f and a thermal coupling time τ_T (Supplementary Information). The simulations are performed with the Pencil Code[21–24], which solves the hydrodynamics on a grid. Two numerical models are presented: a three-dimensional box embedded in the disk that co-rotates with the flow at a fixed distance from the star; and a two-dimensional global model of the disk in the inertial frame. In the former the dust is treated as a fluid, with a separate continuity equation. In the latter the dust is represented by discrete particles with position and velocities that are independent of the grid.

We perform a stability analysis of the linearized system of equations that should help interpret the results of the simulations (Supplementary Information). We plot in Fig. 1a–c the three solutions that show linear growth, as functions of ε and $n = kH$, where k is the radial wavenumber and H is the gas scale height ($H = c_s/\sqrt{\gamma}\Omega_K$, where c_s is the sound speed, Ω_K the Keplerian rotation frequency and γ the adiabatic index). The friction time τ_f is assumed to be equal to $1/\Omega_K$. The left and middle panels show the growth and damping rates. The



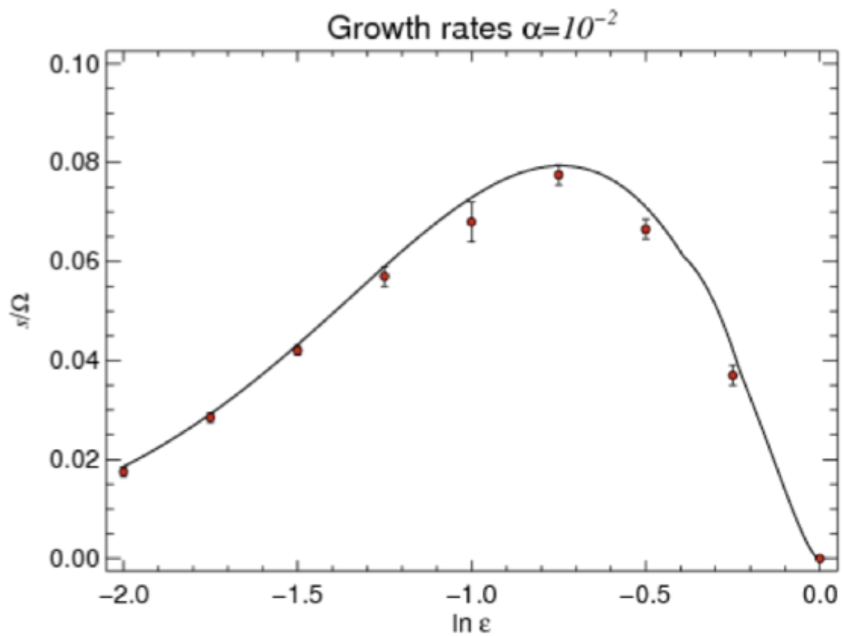
Runaway process: instability

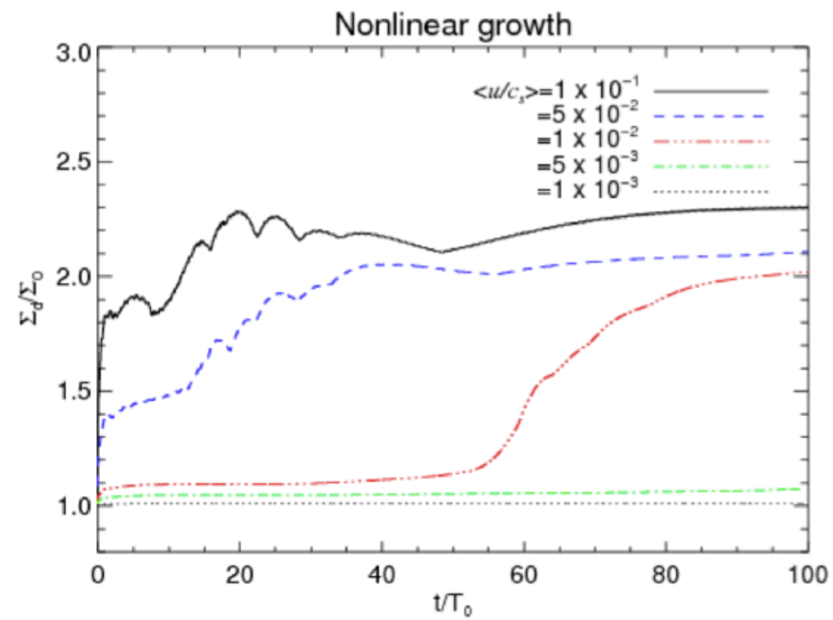
Dust heats gas

Heated gas = high pressure region

High pressure concentrates dust

Dependency on dust-to-gas ratio





Linear for ε < 1

Nonlinear for ε >= 1

Fastest for ε ~ 0.2

Conclusions

- Vortices and spirals without planets in the dead zone.
- RWI at outer dead/active transition may be the culprit for the observed vortices.
- Transition disks are prone to photoelectric instability (if the dust is optically thin)
- **Don't be too quick to shout *"Planet!"*. Rule out these possibilities first.**