RWI in MHD: inner and outer active/dead zone boundaries

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The magneto-rotational instability confronts the observations

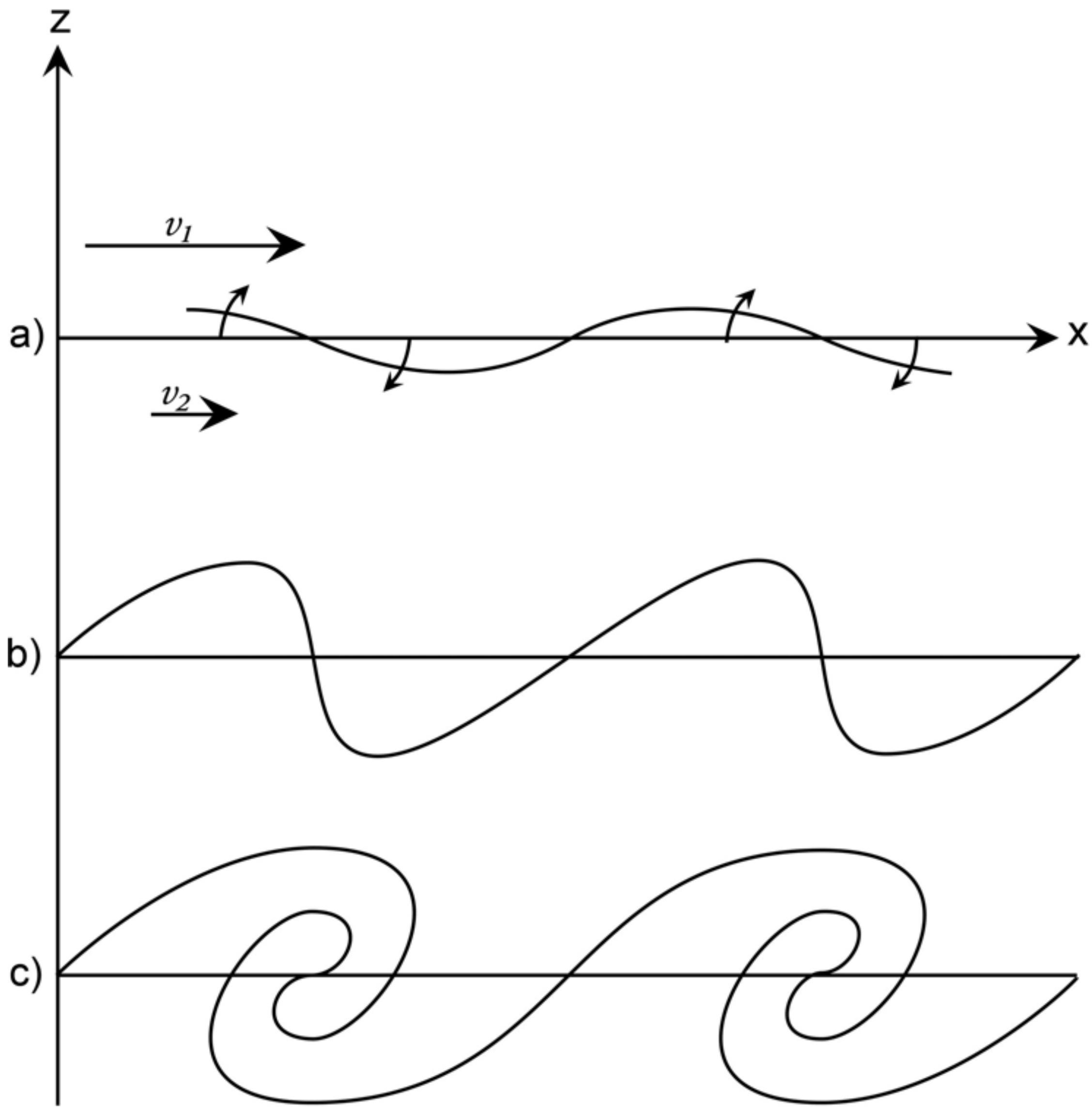
Ringberg, April 16th, 2015

Outline

- Rossby Wave Instability
    - History
    - Occurrence in disks

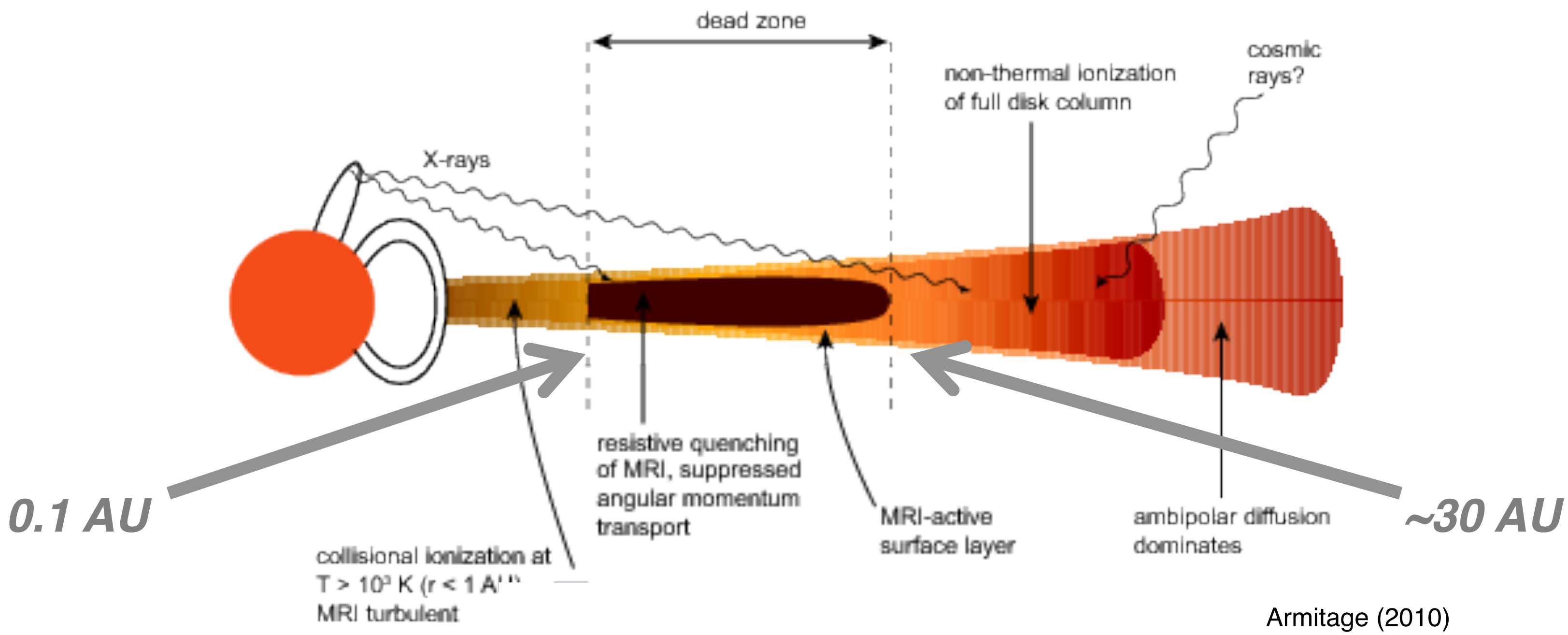
- Active/dead boundary in MHD models
    - Sharp inner active/dead boundary
    - Effect of magnetization
    - Smooth outer dead/active boundary

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



RWI-KHI connection: Tagger & Melia 2006

Dead zones are robust features of protoplanetary disks



Armitage (2010)

Disks are cold and thus poorly ionized

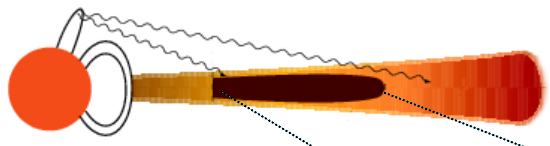
(Blaes & Balbus 1994)

Therefore, accretion is **layered**

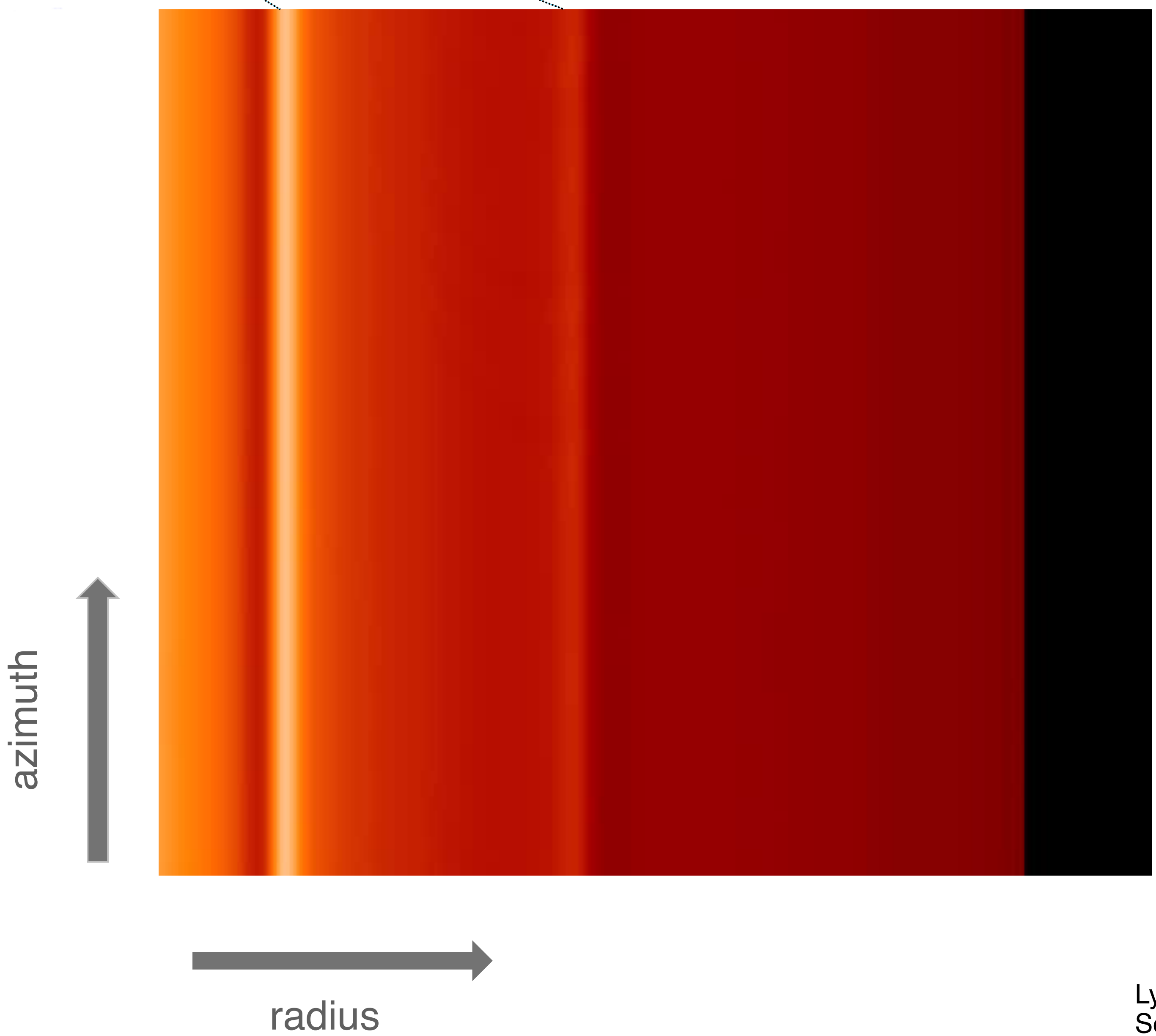
(Gammie 1996)

There should be a **magnetized, active zone**,

and a **non-magnetic, dead zone.**



A simple (2D alpha) dead zone model



Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

(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)

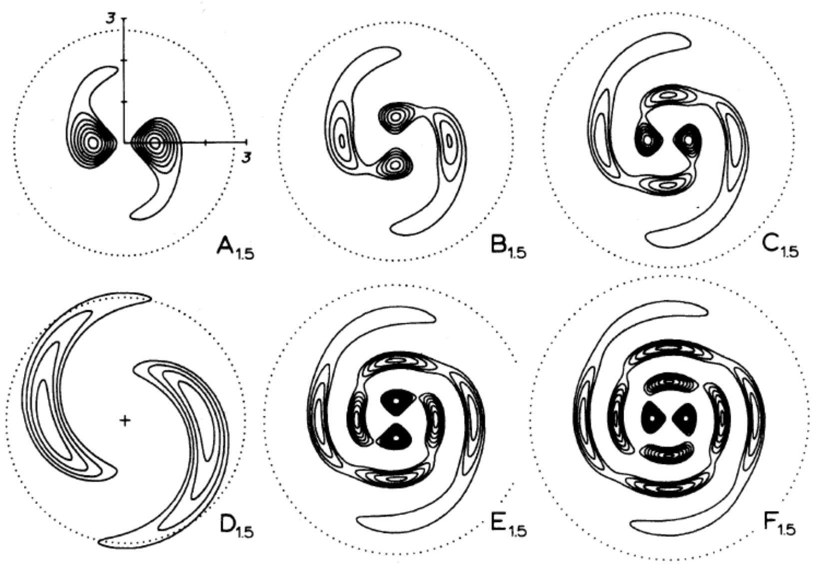


Fig. 12 Comparison of modes A-F for that Gaussian disk in which only 2/3 of the density remains "active". Their eigenfrequencies were reported at location 1.5 in Fig. 11. The corotation circles are again shown dotted; they have expanded markedly from Fig. 10.

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 edge mode which (a) arises only if the disk density drops off abruptly enough with radius, and yet (b) does not 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 $V = \text{const}$ 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)

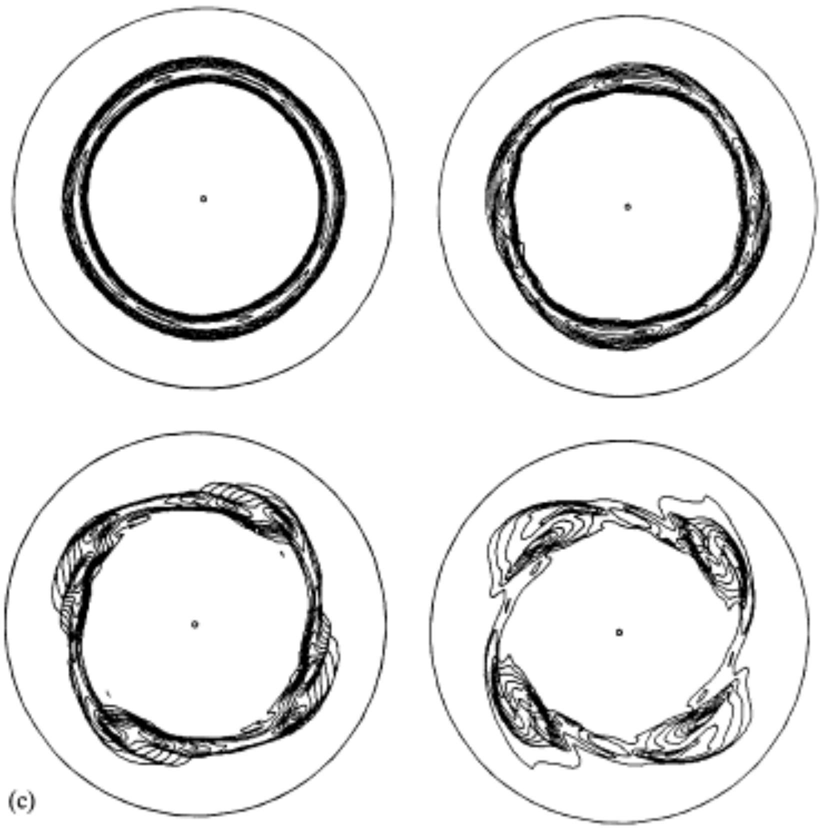


Figure 5–*continued*

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

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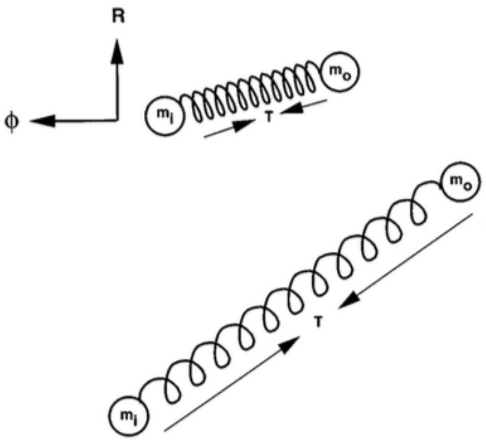
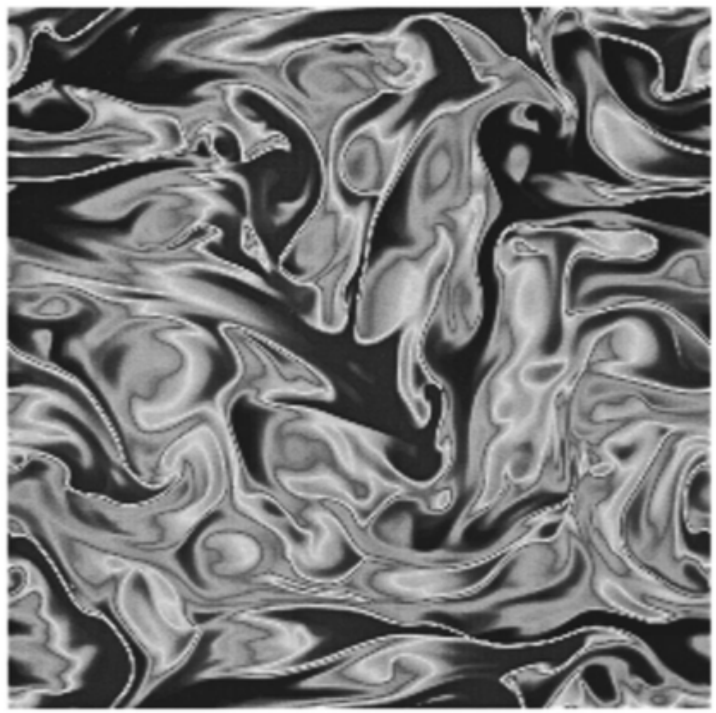
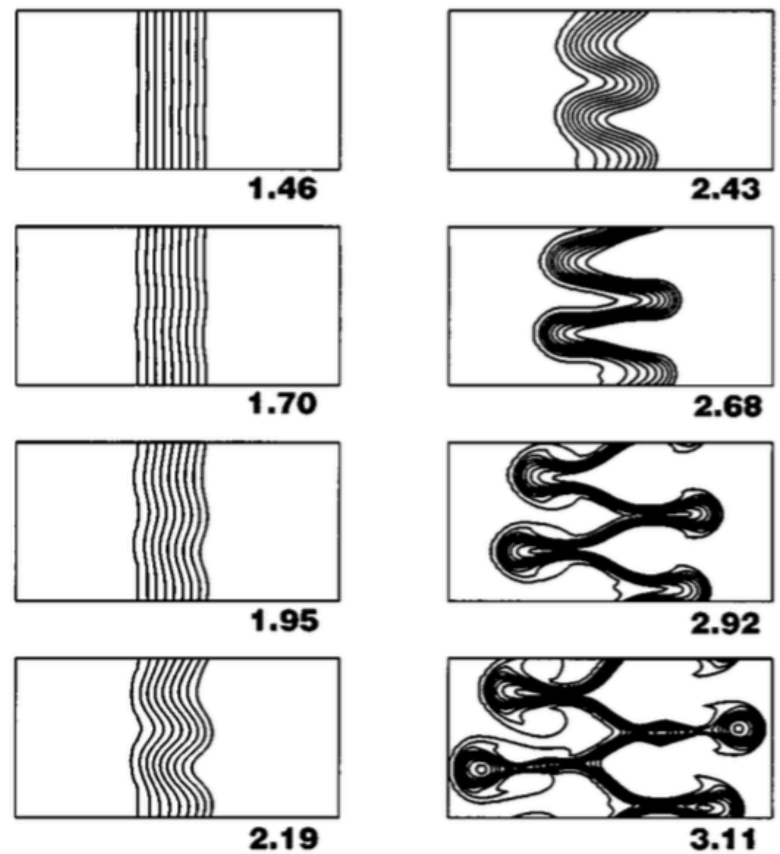
Accepted 1984 November 26. Received 1984 November 23; in original form 1984 October 1

1991: The MRI Revolution





(a)



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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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).

Koller et al. (2003)
RWI at planetary gap

THE ASTROPHYSICAL JOURNAL, 596:L91–L94, 2003 October 10

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VORTICES IN THE CO-ORBITAL REGION OF AN EMBEDDED PROTOPLANET

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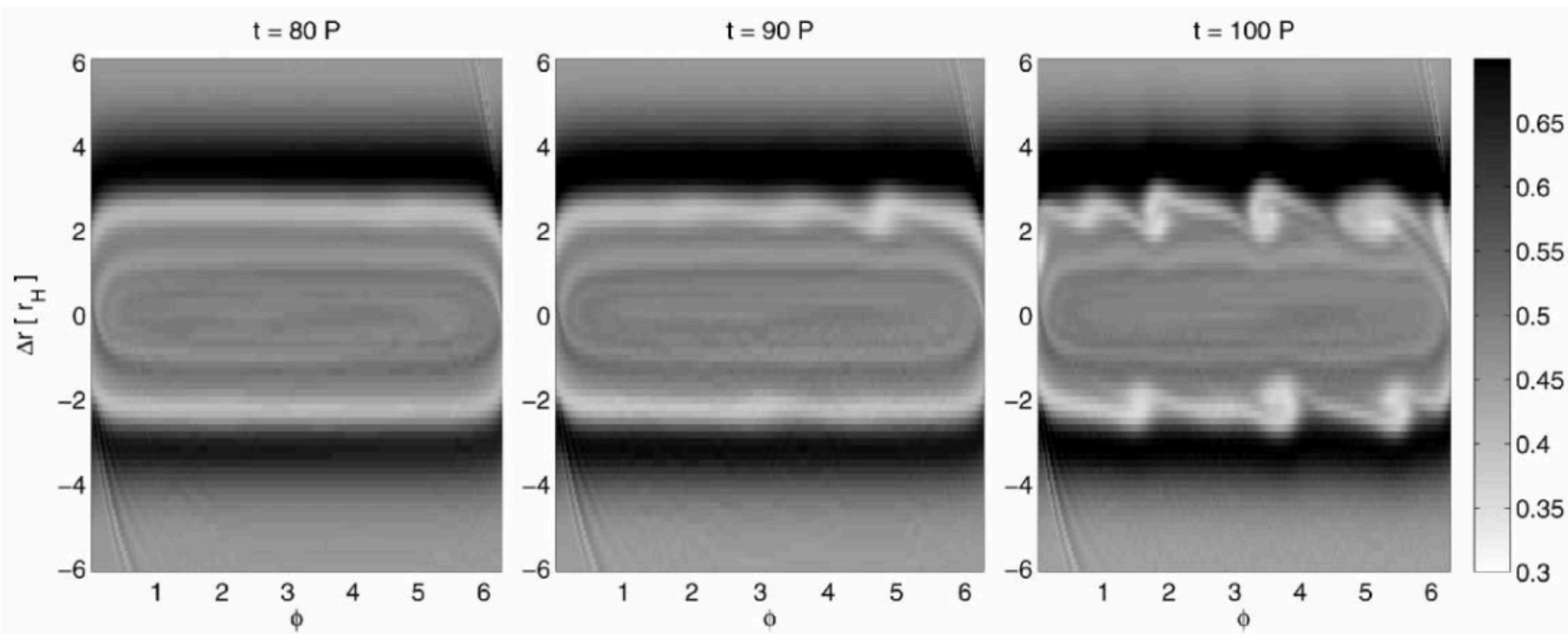
ABSTRACT

We present global two-dimensional inviscid disk simulations with an embedded planet, emphasizing the nonlinear dynamics in its co-orbital region. We find that the potential vorticity of the flow in this region is not conserved because of the presence of two spiral shocks produced by the planet. As the system evolves, the potential vorticity profile develops extrema (inflection points) that eventually render the flow unstable. Vortices are produced in association with the potential vorticity minima. Born in the separatrix region, these vortices experience close encounters with the planet, consequently exerting strong torques on the planet. The existence of these vortices have important implications for understanding the migration rates of low-mass planets.

Subject headings: accretion, accretion disks — hydrodynamics — planetary systems: protoplanetary disks



Peggy Varnière & Michel Tagger
RWI at dead zone boundary

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

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[3] Service d'Astrophysique (UMR Astroparticules et cosmologie) CEA/Saclay F-91191 Gif sur Yvette e-mail: tagger@cea.fr

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

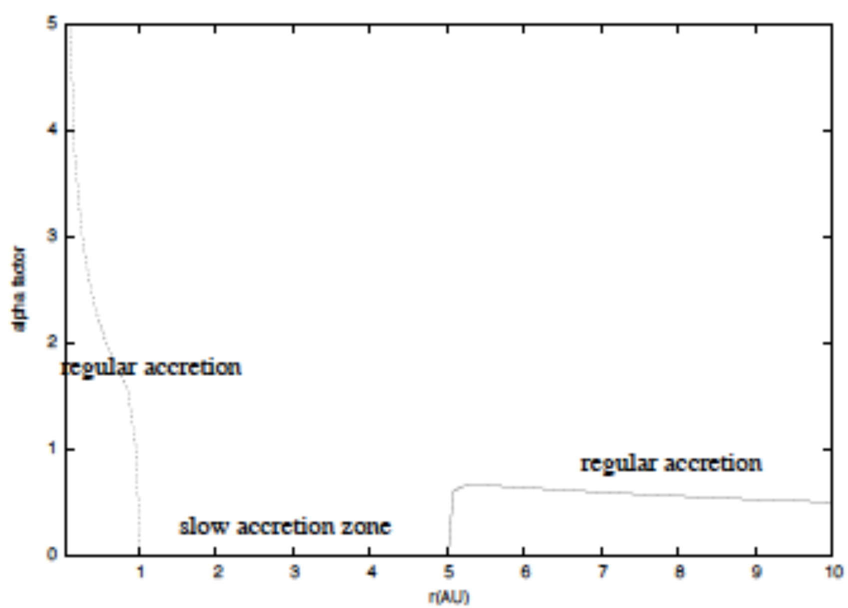


Fig. 1. Profile of the α-viscosity implemented to represent a Dead Zone between 1 and 5 AU with $(\epsilon, \delta_r) = (10^{-5}, 50)$.

Varnière & Tagger (2006)

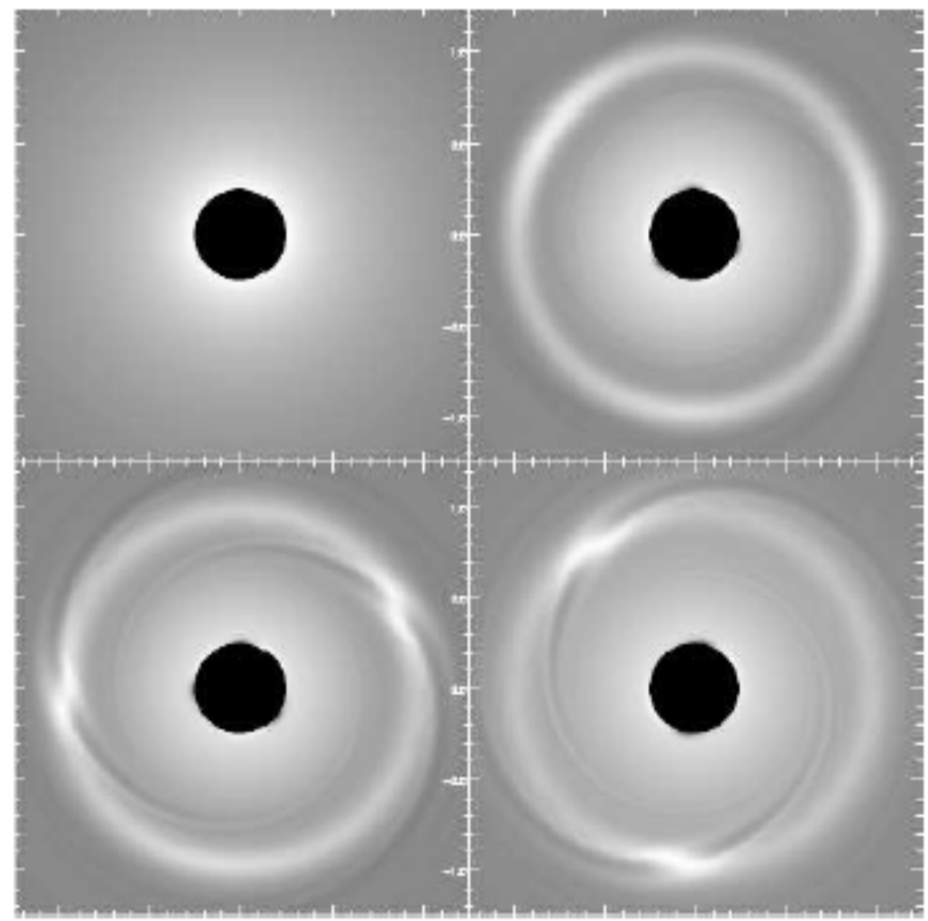


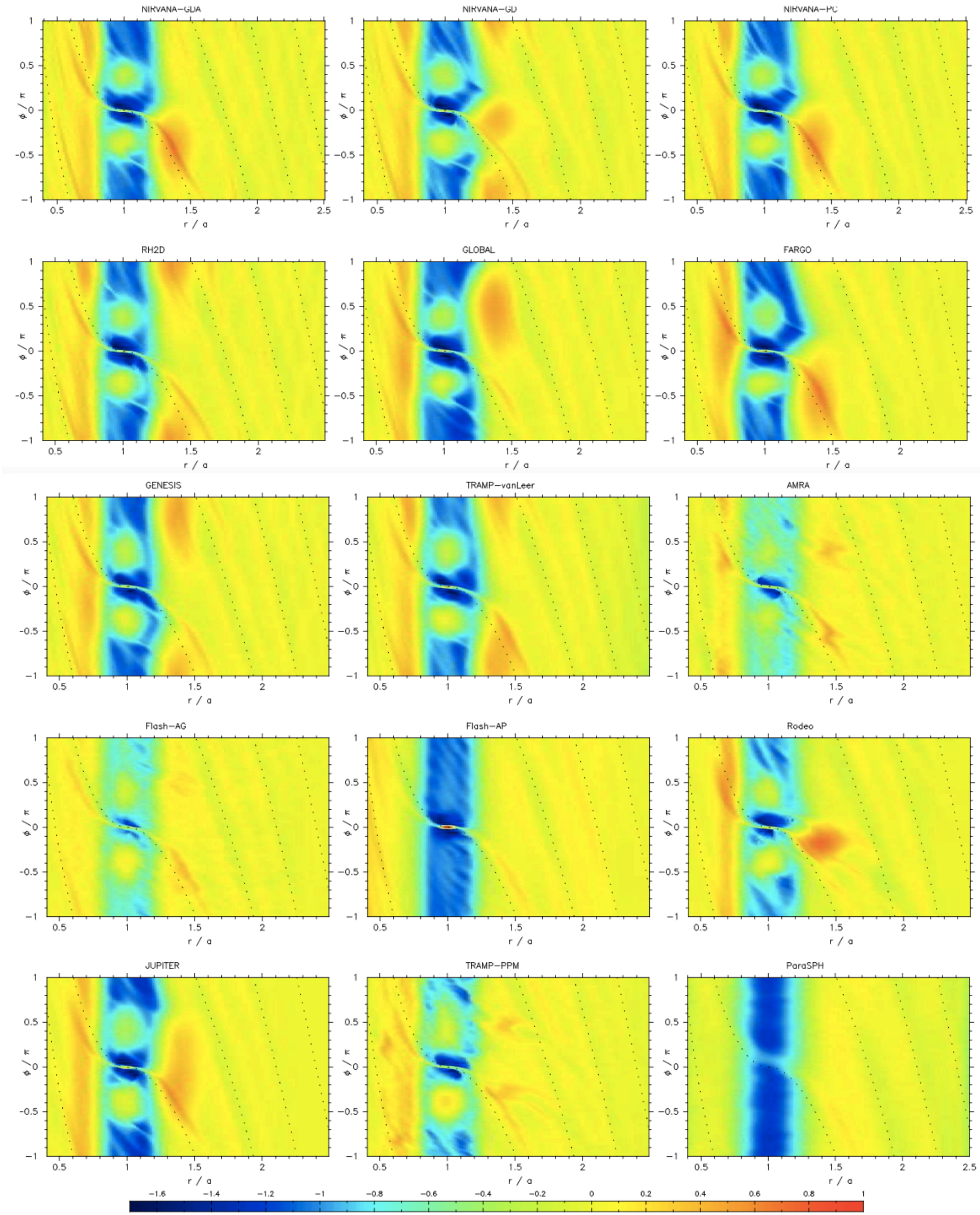
Fig. 3. Zoom of the first 2 inner AU of the simulation at $t = 0, 100, 200, 300$ years, showing the density. One sees three vortices forming, later evolving to two vortices, near the outer edge of the Dead Zone.

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

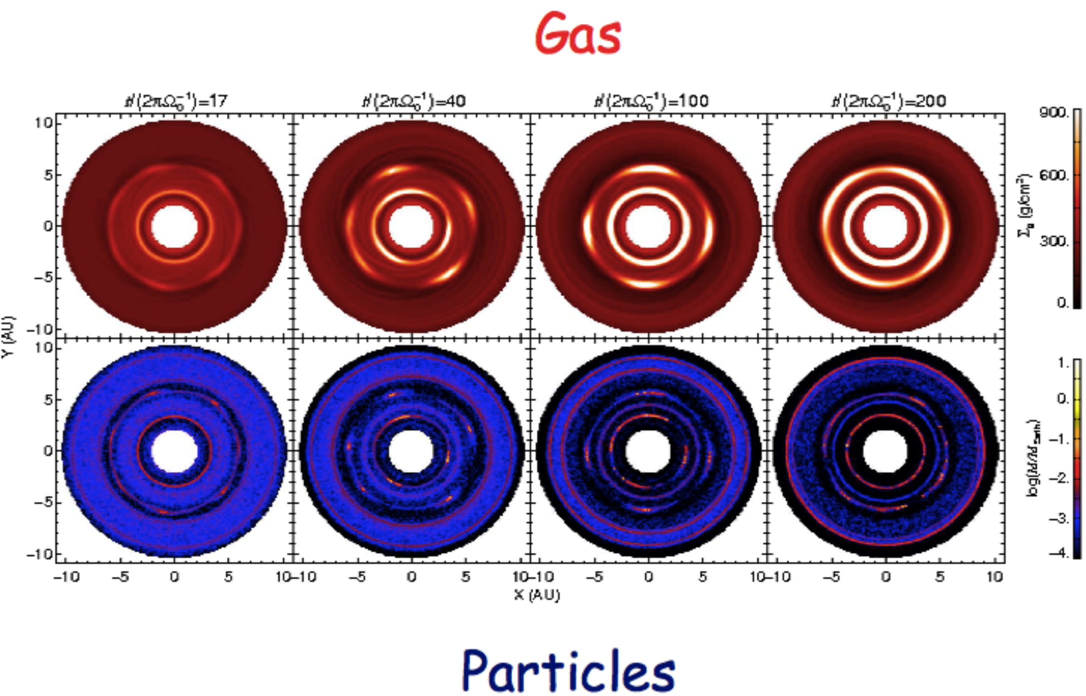
Problem of choice:
2D ‘vanilla’ planet-disk interaction.

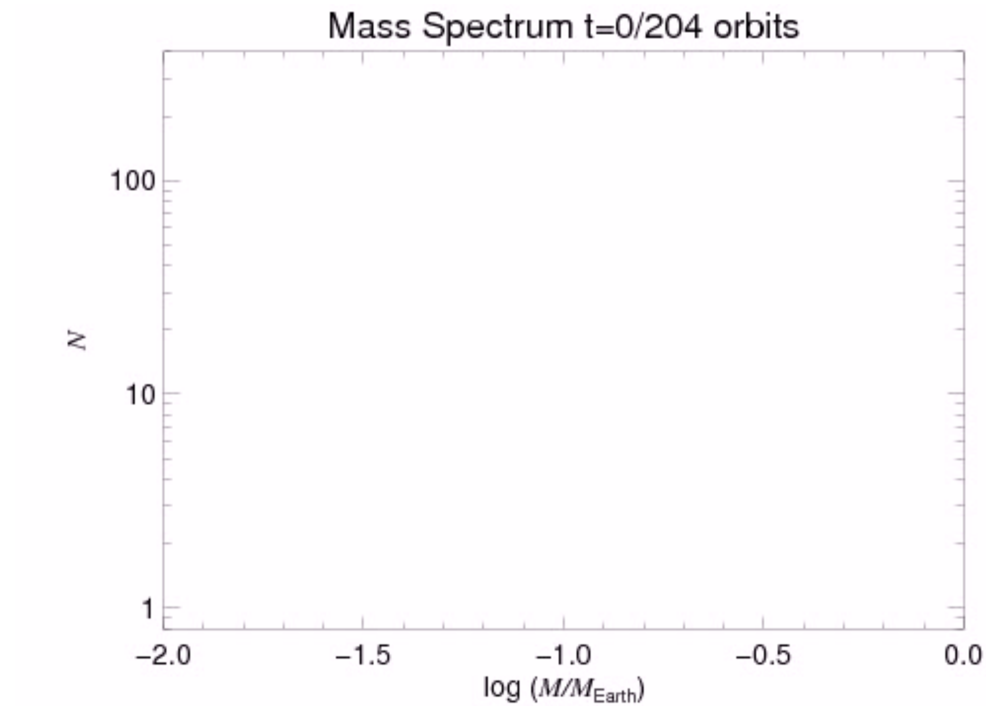
Several codes showed gap-edge vortices.

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



RWI and Planet Formation

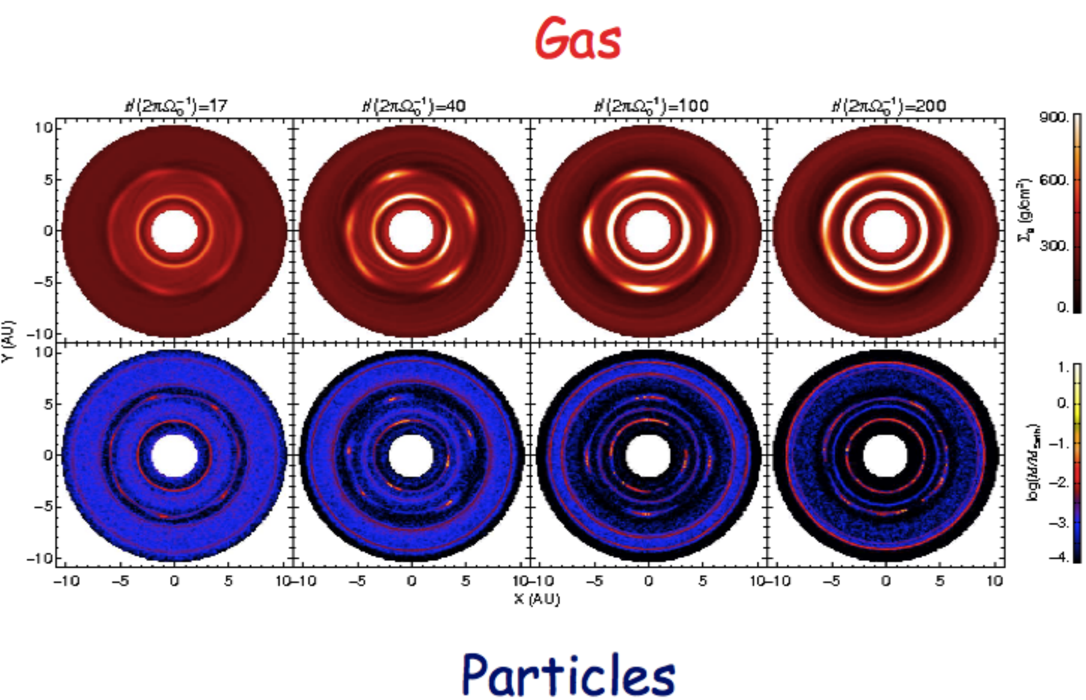


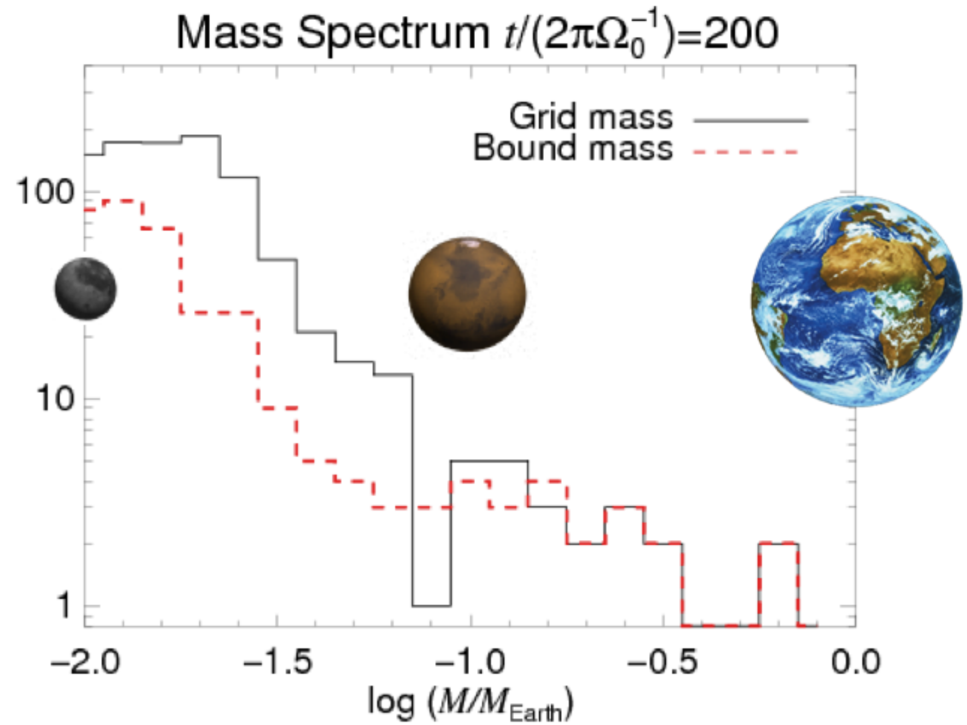


Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a,
see also Lambrechts & Johansen 2012)

RWI and Planet Formation





Collapse into Mars mass objects

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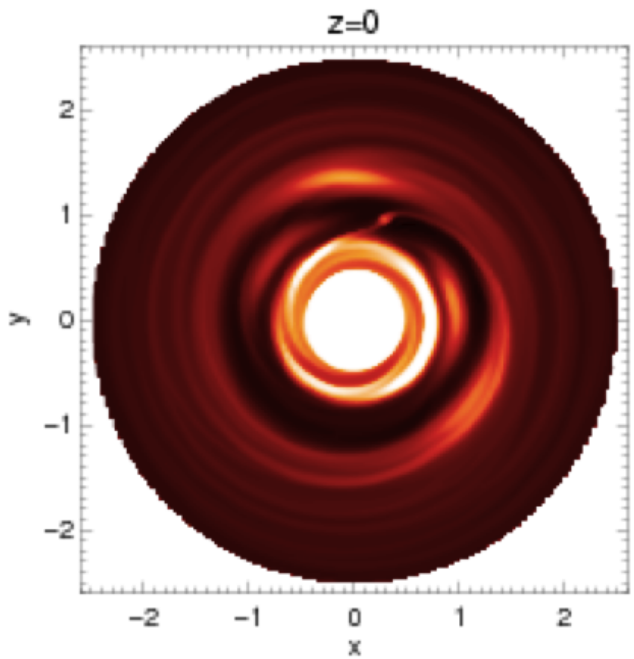
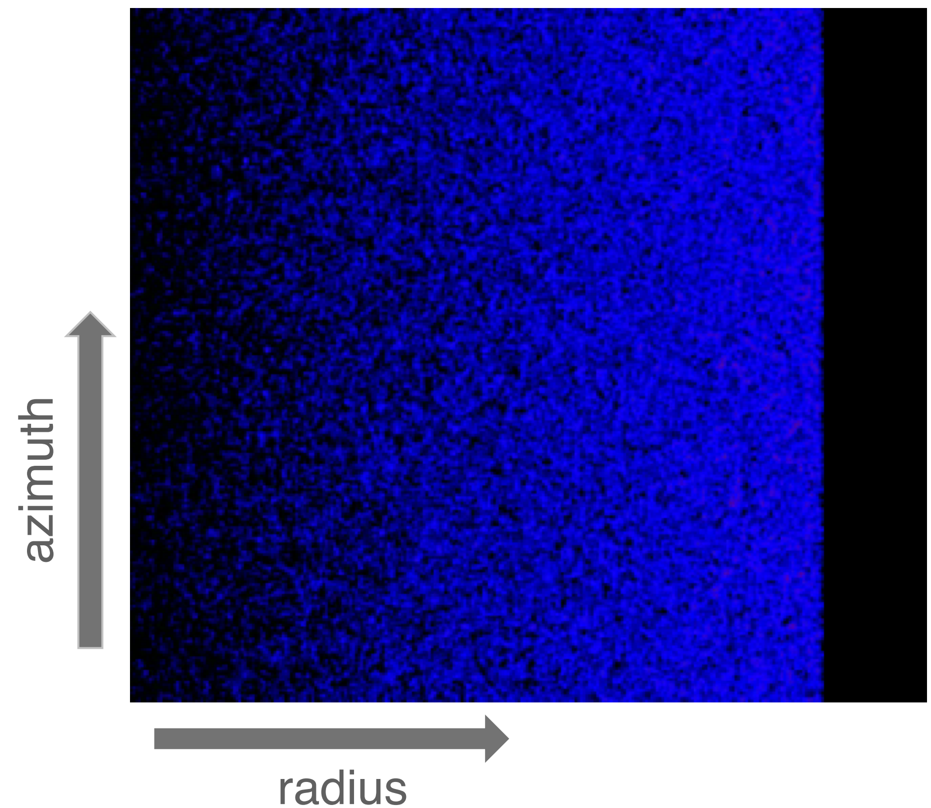
see also Lambrechts & Johansen 2012)

Planetary gap RWI



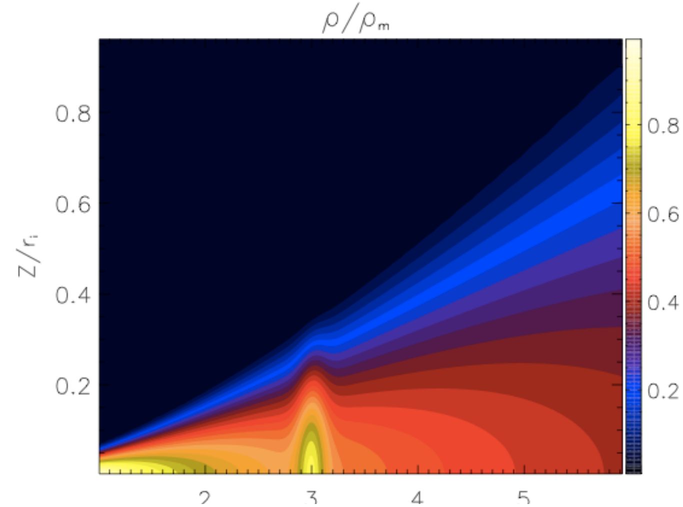
Lyra et al. (2009b),
see also de Val-Borro et al. (2007)



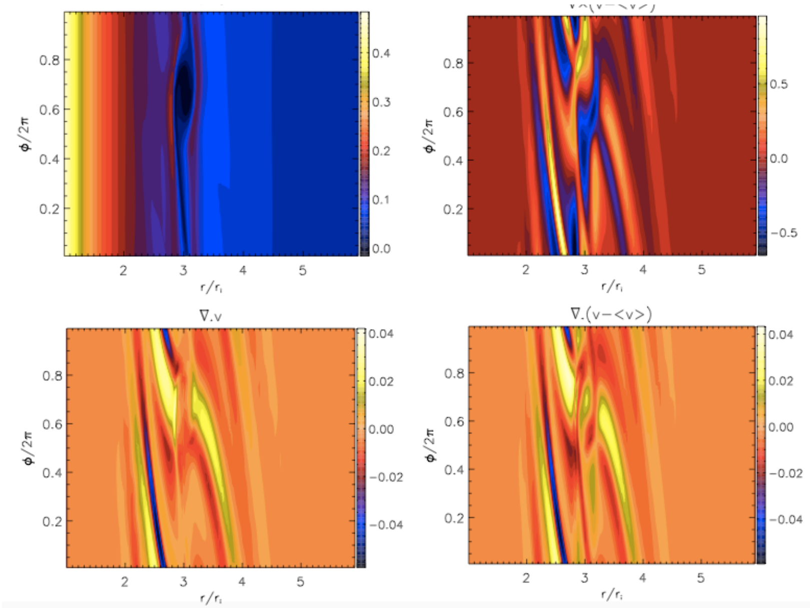
Burst of formation in gap vortices

Plus Trojan planets in Lagrangian clouds

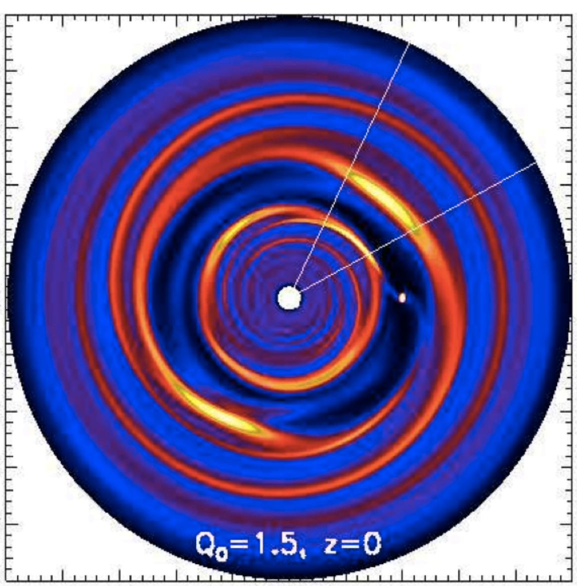
3D strat RWI



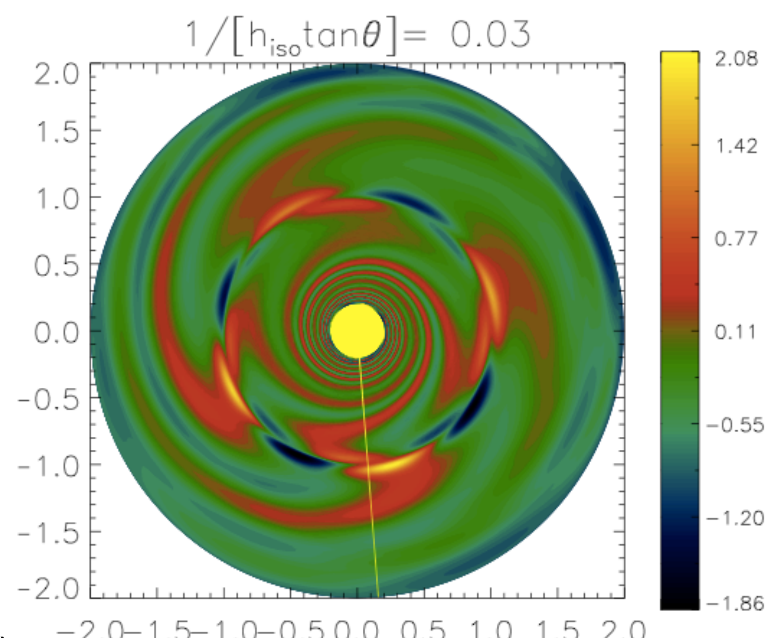
Meheut et al. (2010, 2012abc, 2013)



3D strat RWI self-gravity

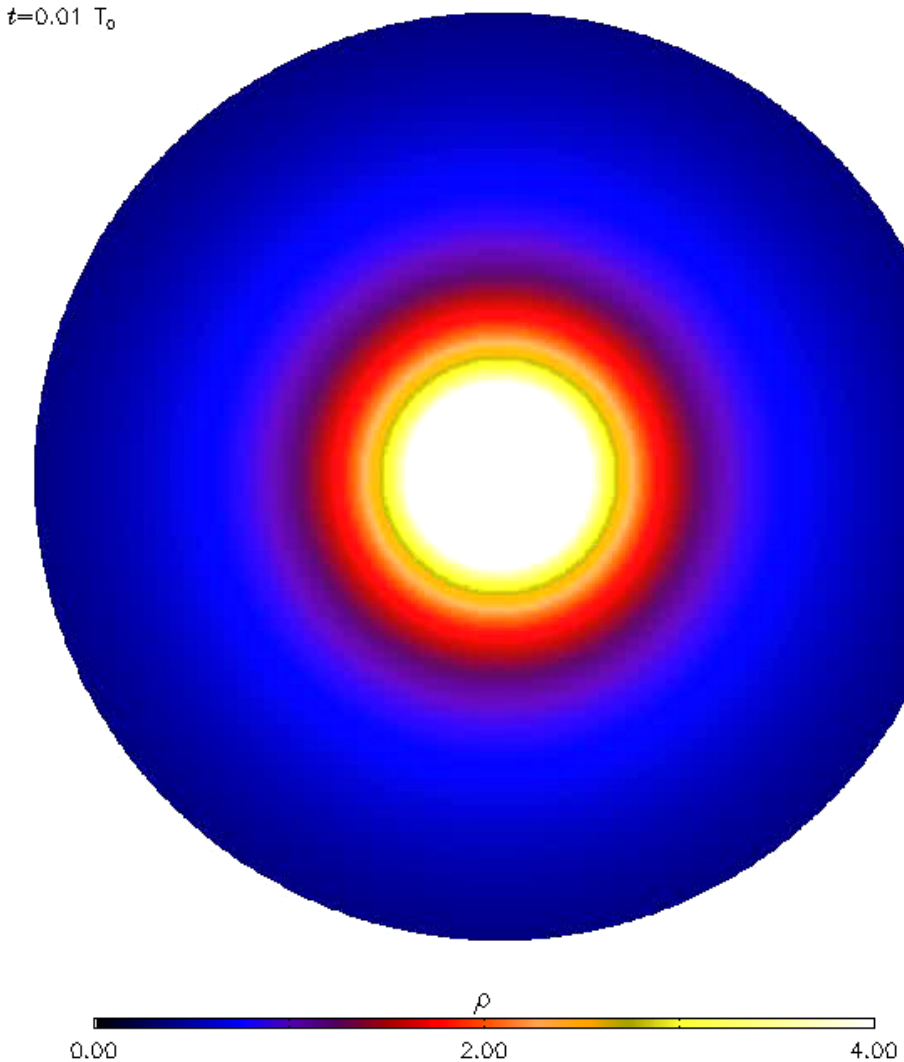


3D strat RWI polytropic



Lin (2012ab, 2013, 2014)

Inner Active/Dead zone boundary



Unstratified isothermal MHD
with static Ohmic resistivity jumps.

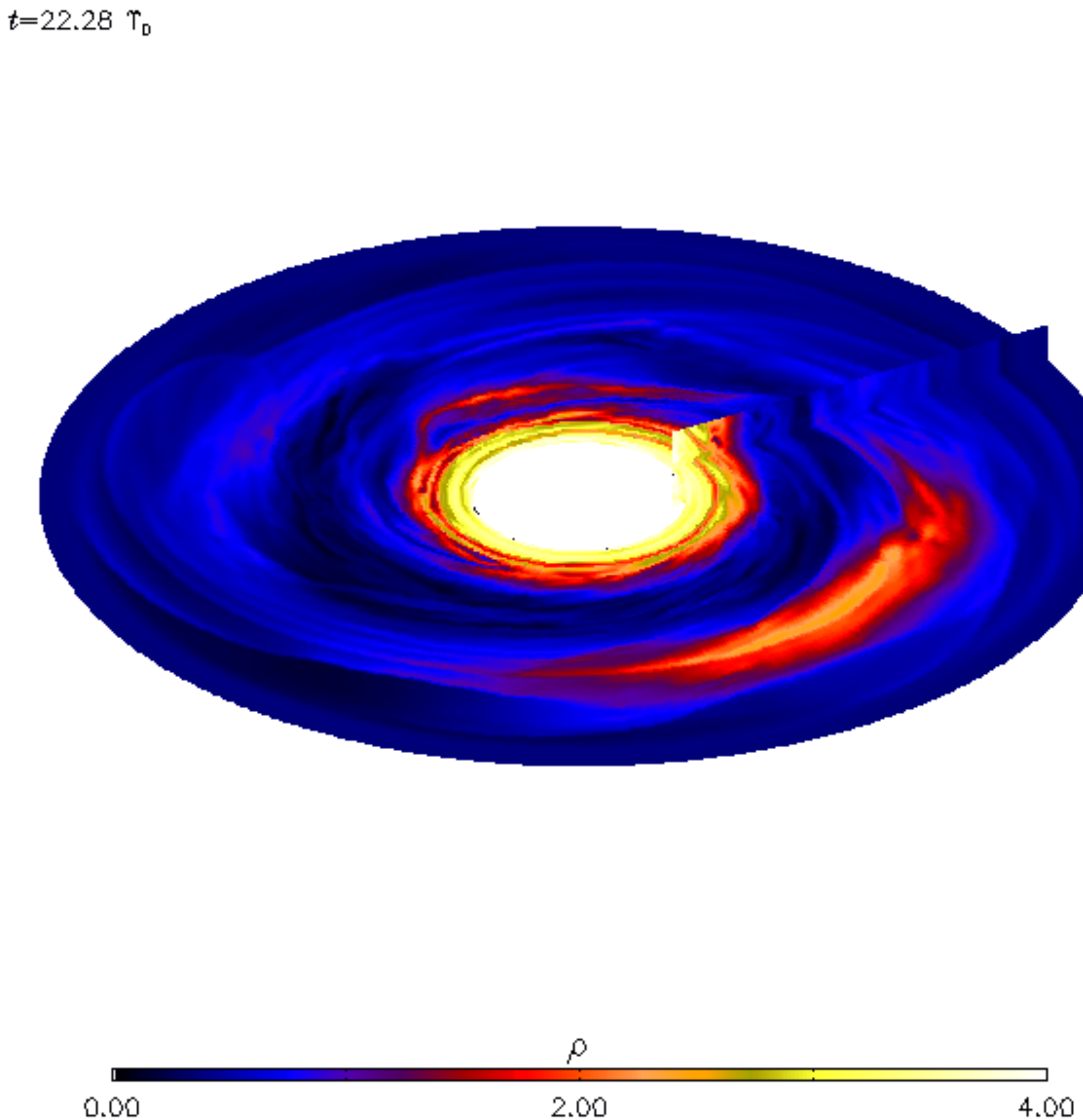
$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho - \rho\boldsymbol{\nabla}\cdot\boldsymbol{u},\\
\frac{\partial \boldsymbol{u}}{\partial t} &= -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\boldsymbol{u} - \frac{1}{\rho}\boldsymbol{\nabla} p - \boldsymbol{\nabla}\Phi + \frac{\boldsymbol{J}\times\boldsymbol{B}}{\rho},\\
\frac{\partial \boldsymbol{A}}{\partial t} &= \boldsymbol{u}\times\boldsymbol{B} - \eta\mu_0\boldsymbol{J}\\
p &= \rho c_s^2.
\end{aligned}
$$

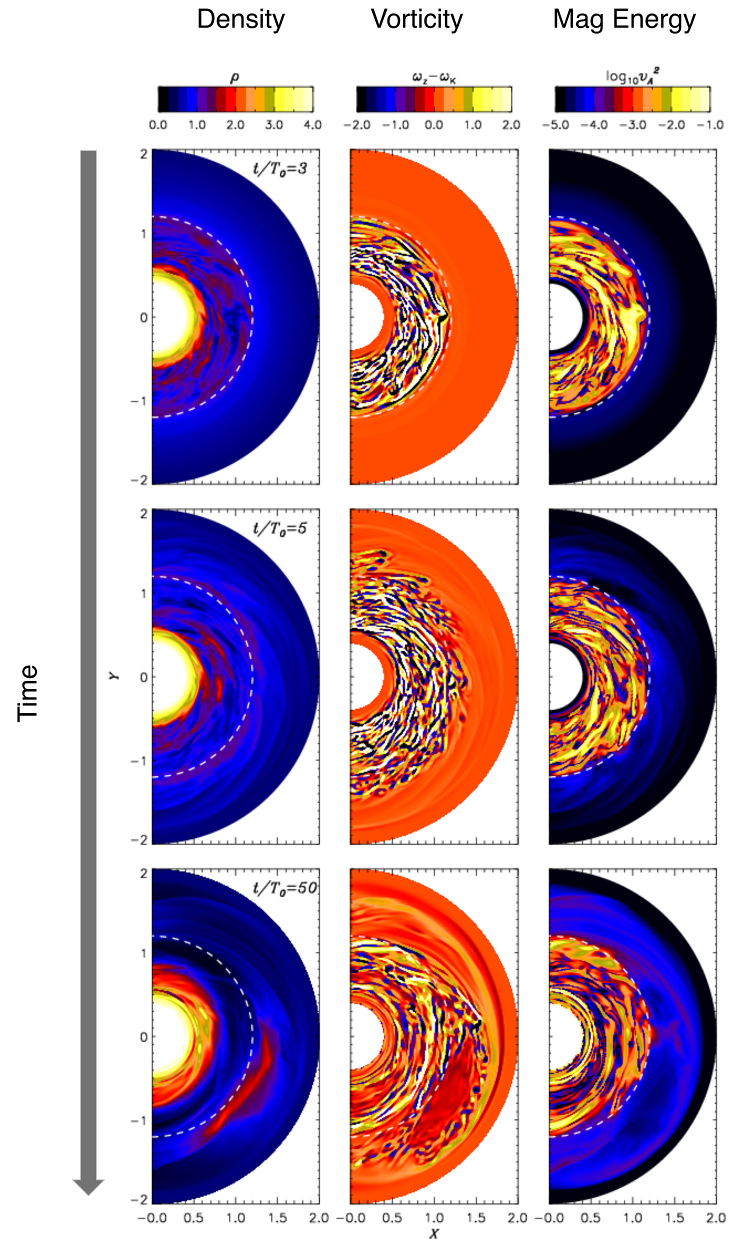
$$\eta(r) = \eta_0 - \frac{\eta_0}{2}\left[\tanh\left(\frac{r-r_1}{h_1}\right) - \tanh\left(\frac{r-r_2}{h_2}\right)\right]$$

Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012);
see also Faure et al. (2015)

Active/dead zone boundary

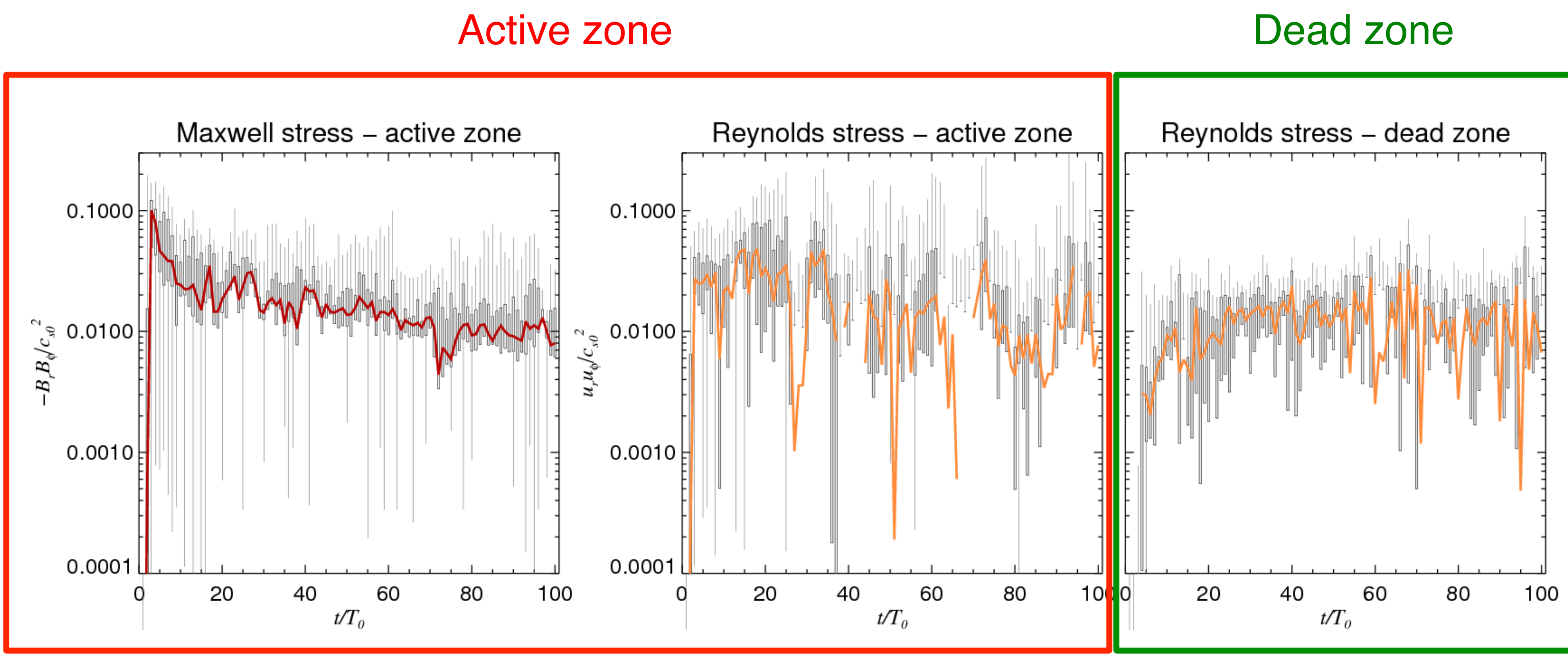




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Significant angular momentum transport



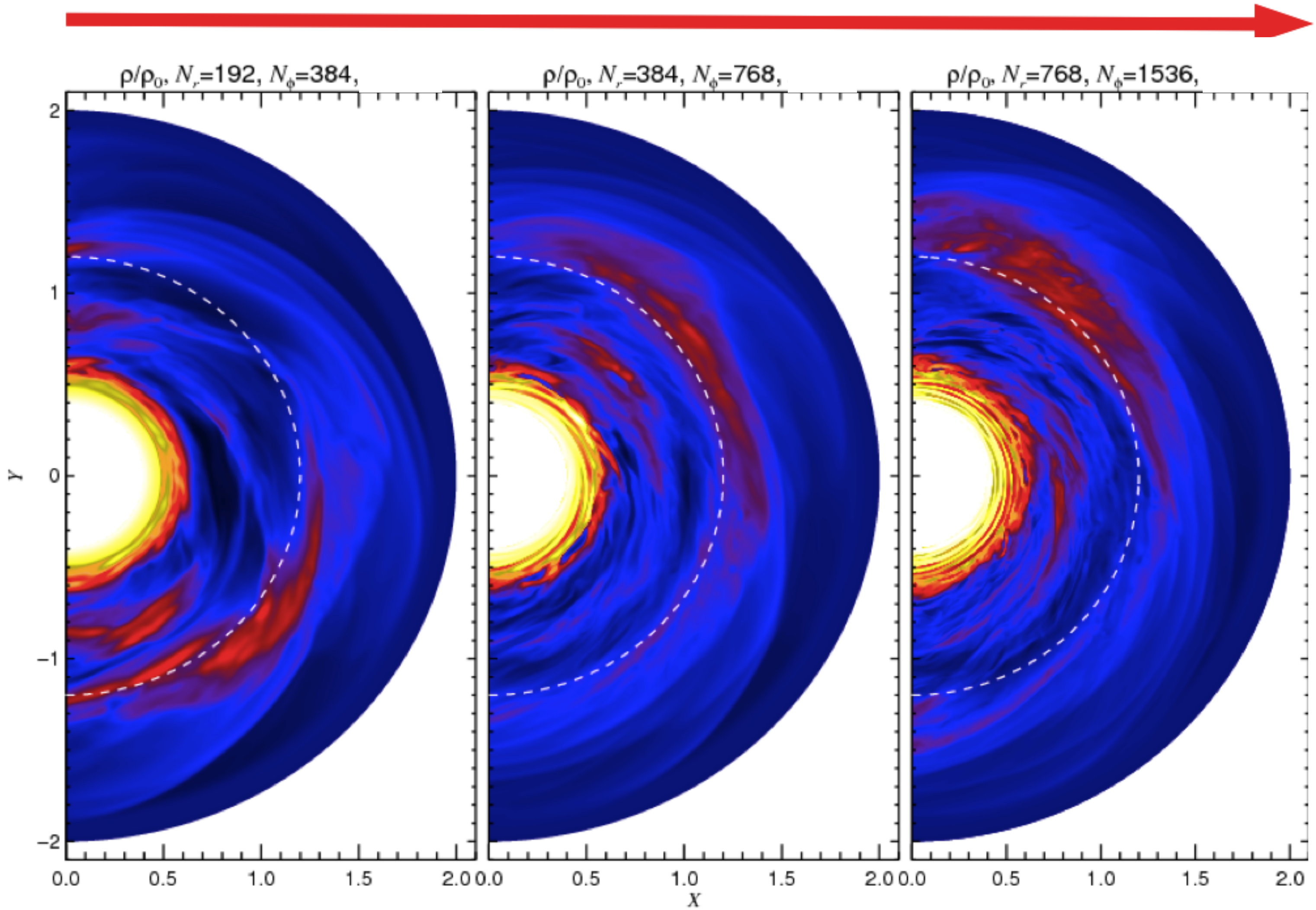
Large mass accretion rates in the dead zone,

comparable to the MRI in the active zone

Lyra & Mac Low (2012)

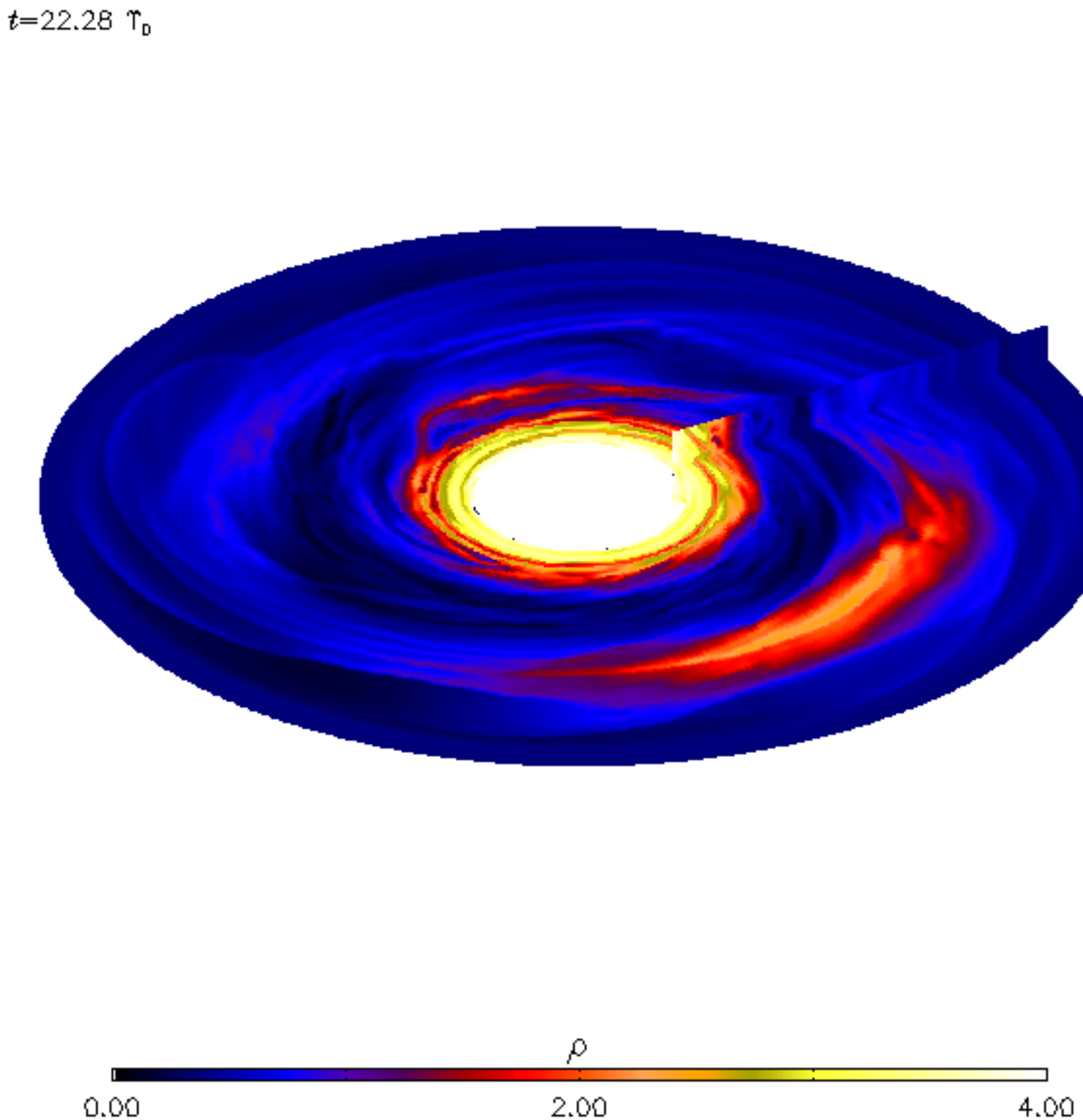
Convergence

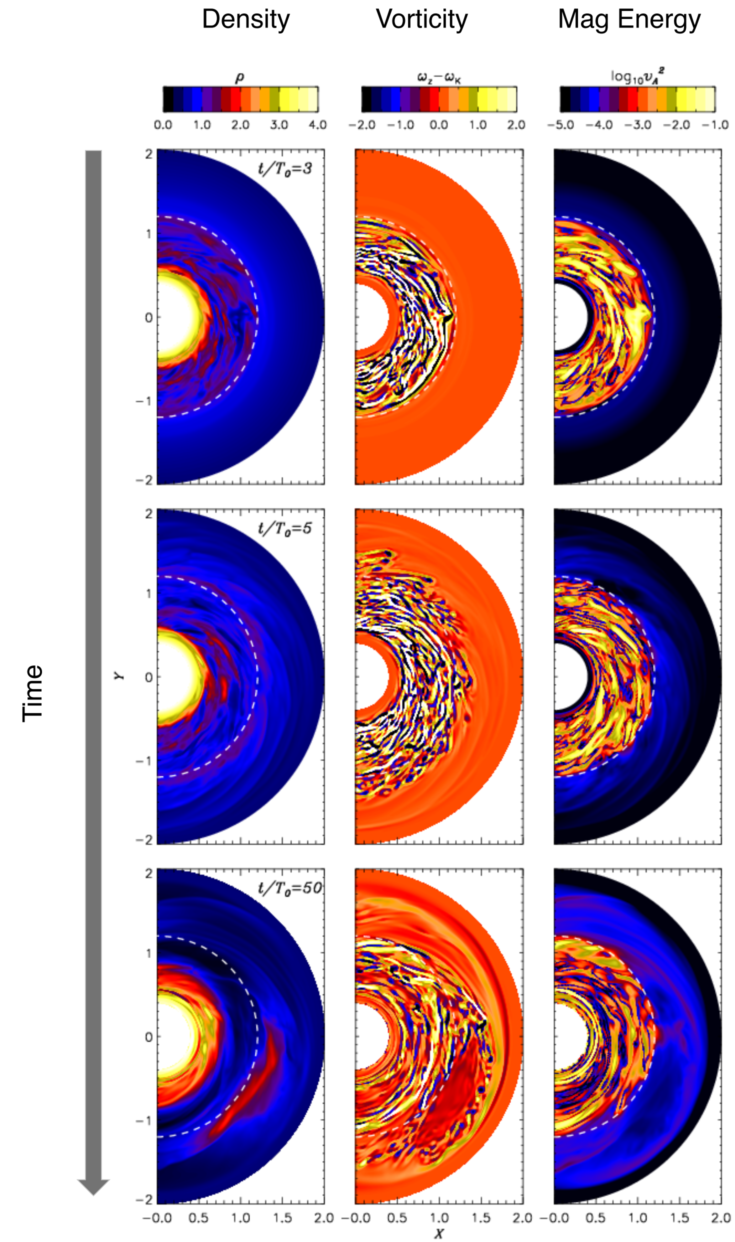
Resolution



Lyra & Mac Low (2012)

Active/dead zone boundary

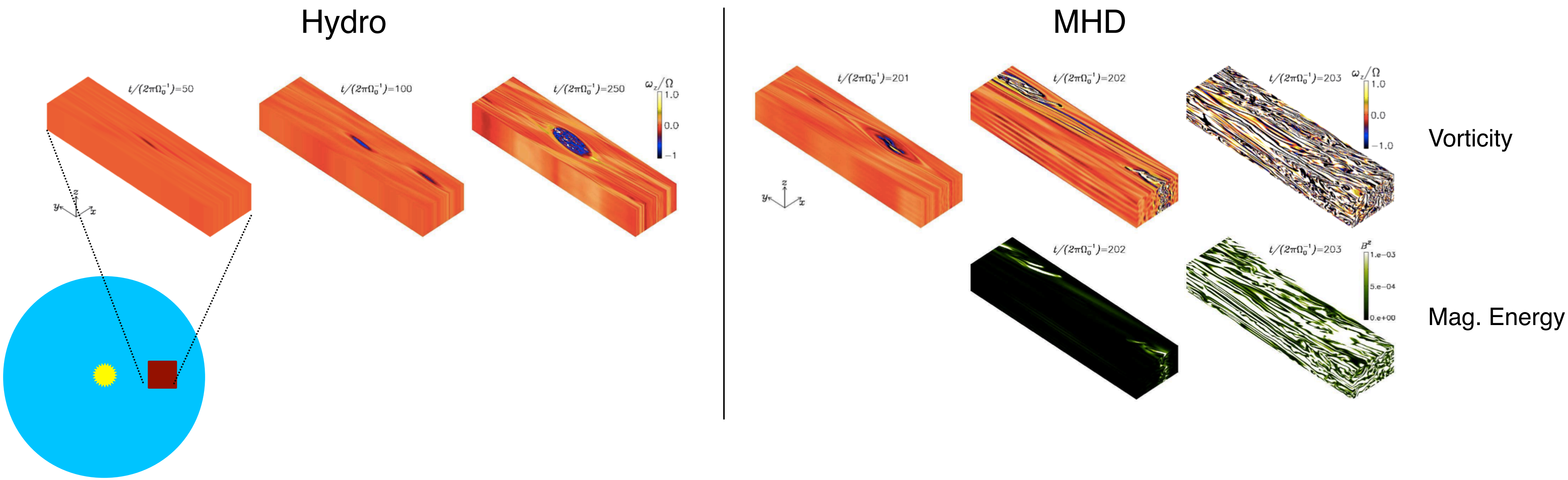




Magnetized inner disk + resistive outer disk

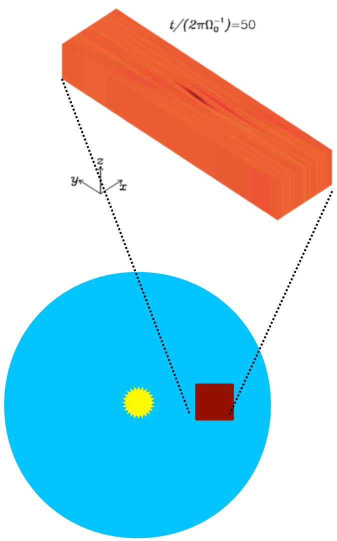
Lyra & Mac Low (2012)

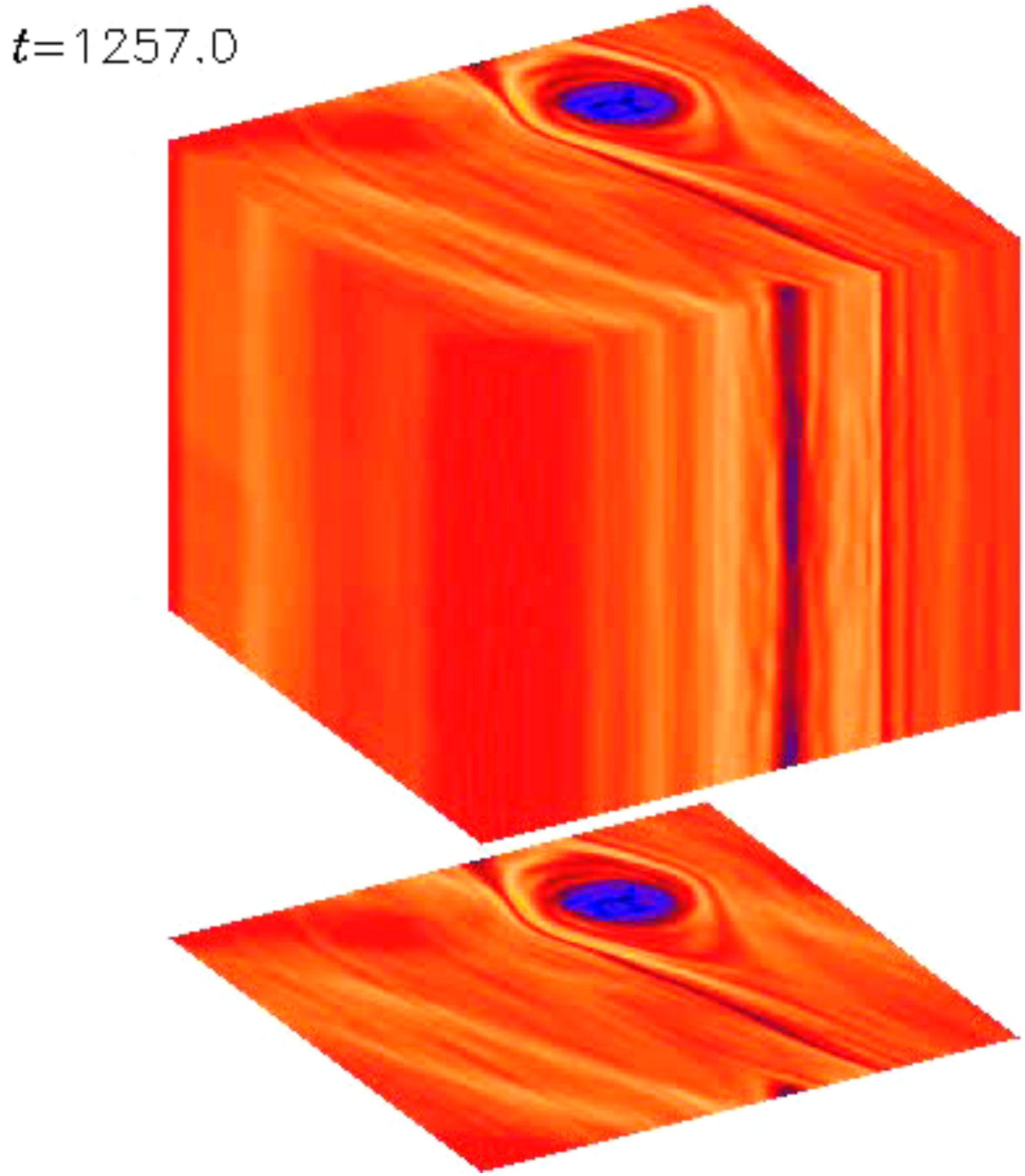
Magnetization

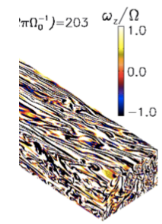


Lyra & Klahr (2011)

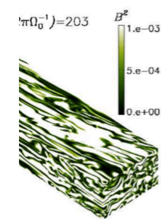
Magnetization





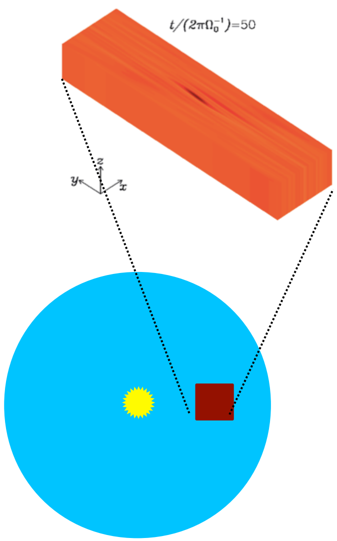


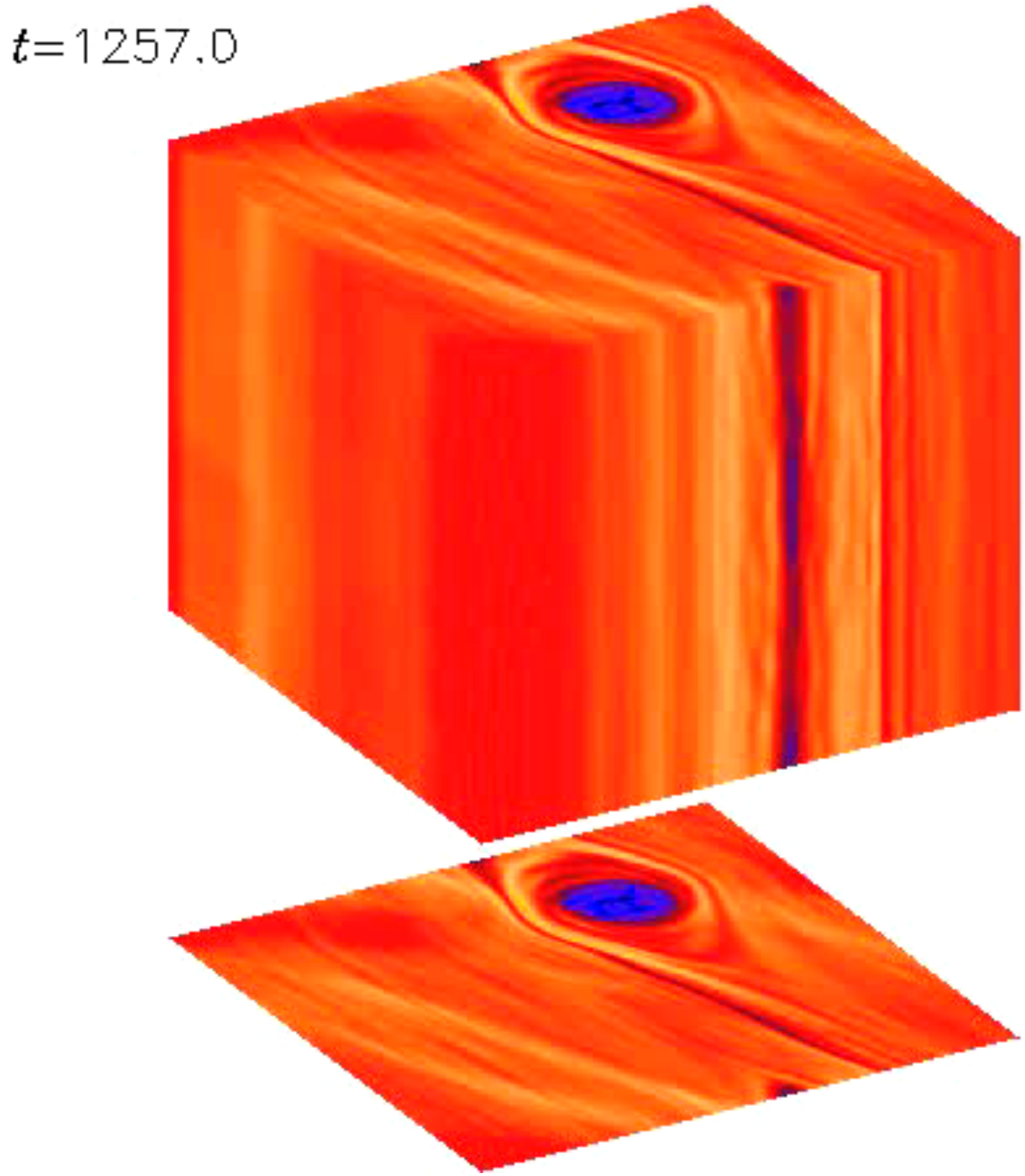
Vorticity

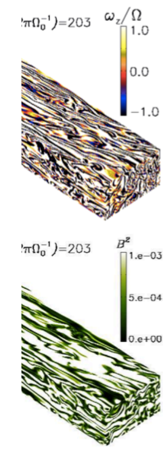


Mag. Energy

Magnetization





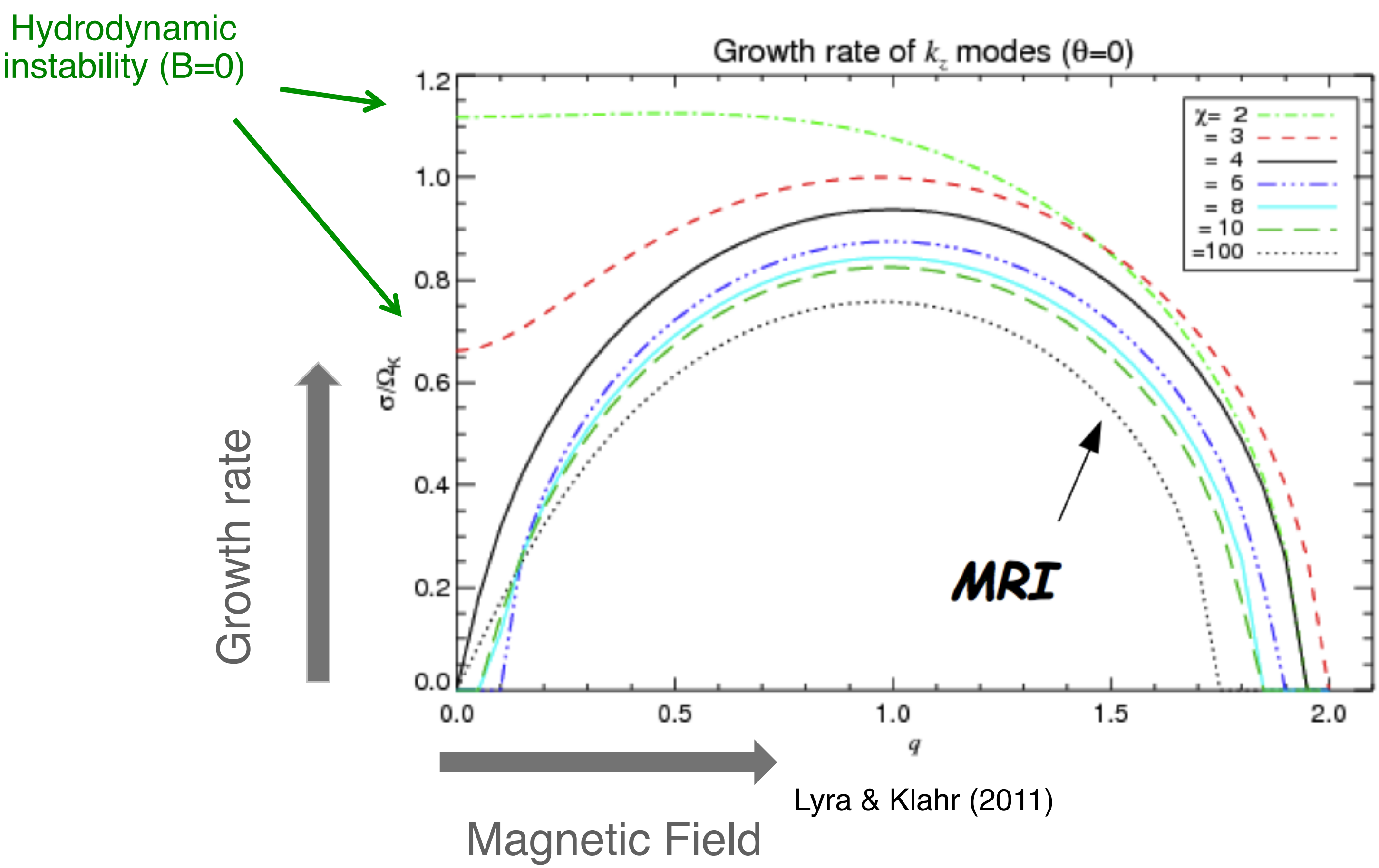


Vorticity

Mag. Energy

Lyra & Klahr (2011)

Magneto-Elliptic Instability

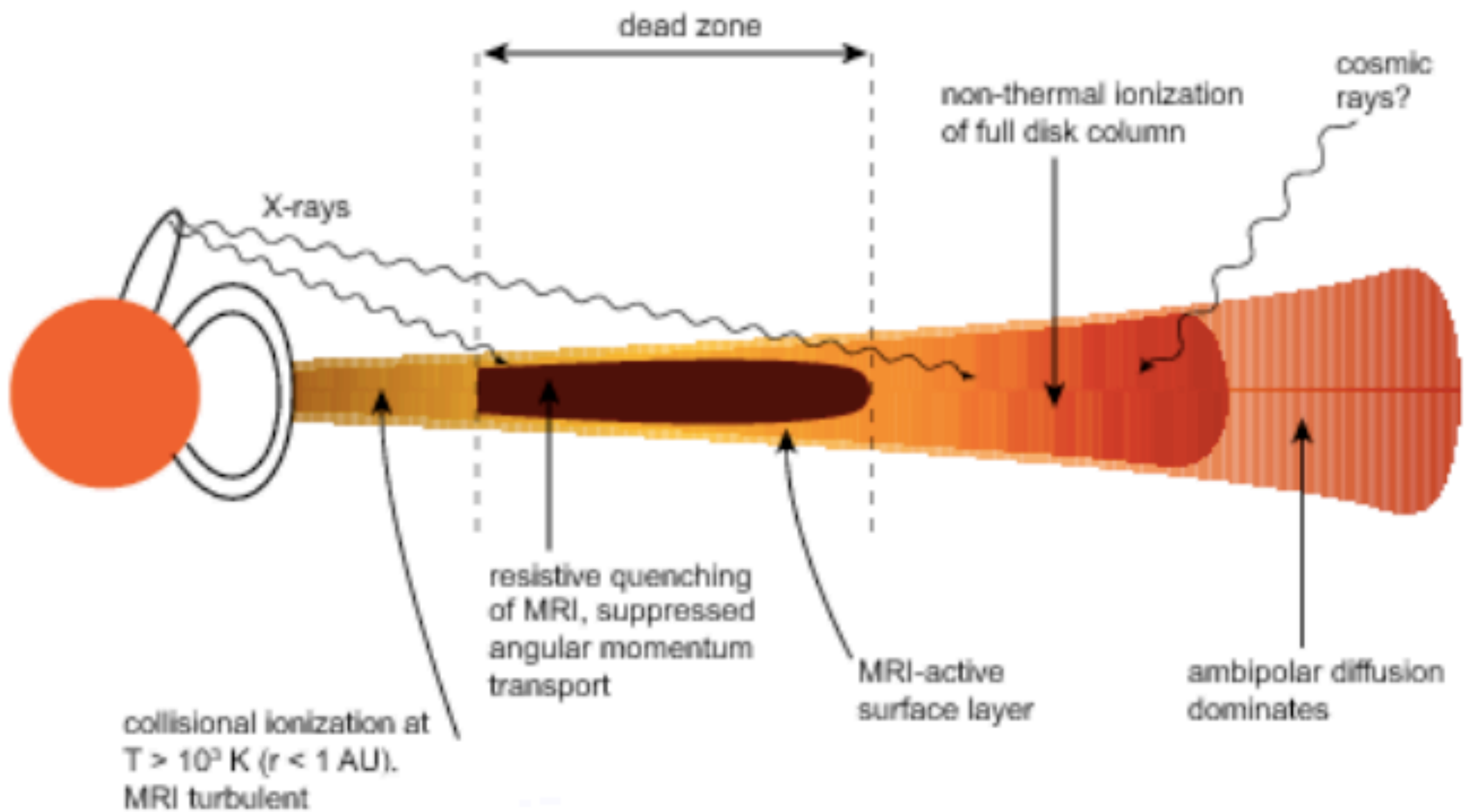


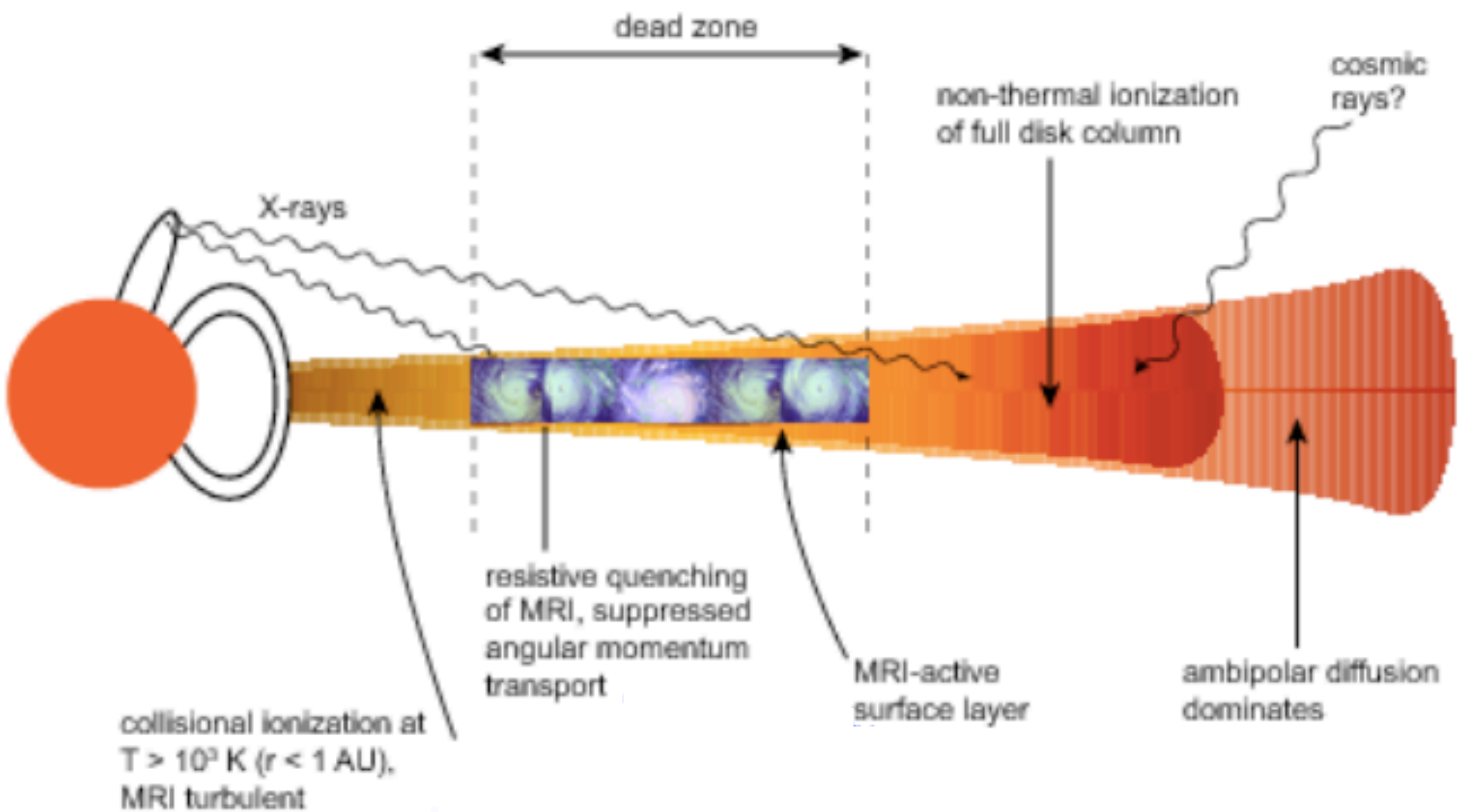
Lyra & Klahr (2011)

see also:
Mizerski & Bajer 2009,
Mizerski & Lyra 2012,
Lyra 2013

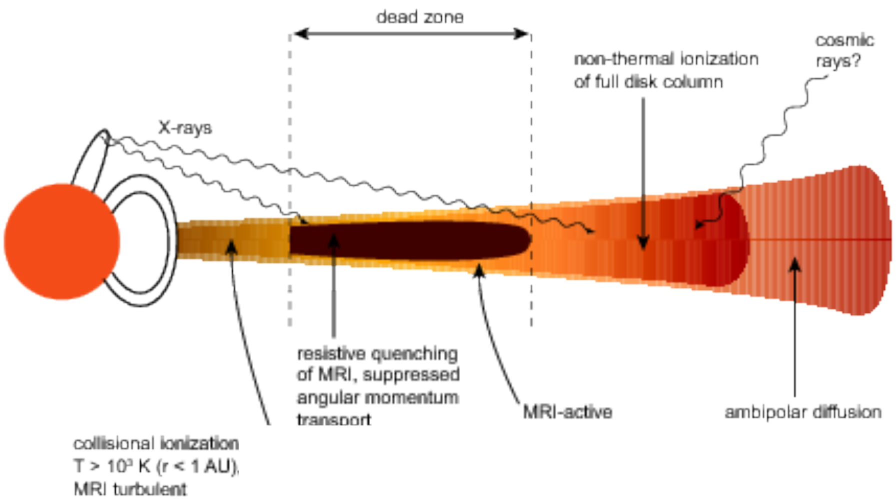
Infinitely elongated vortices are equivalent to **shear flows**.

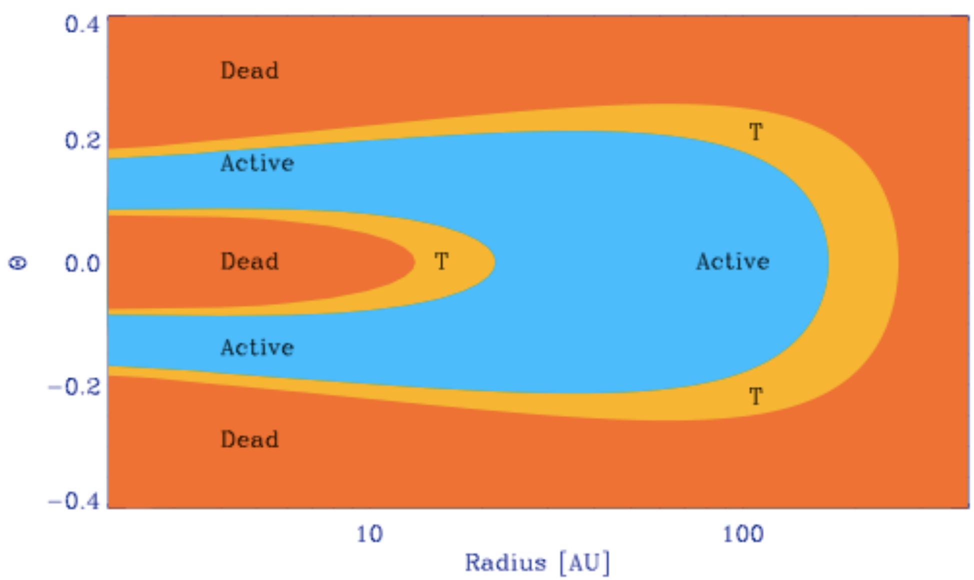
They are subject to an MRI-like instability when magnetized.


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

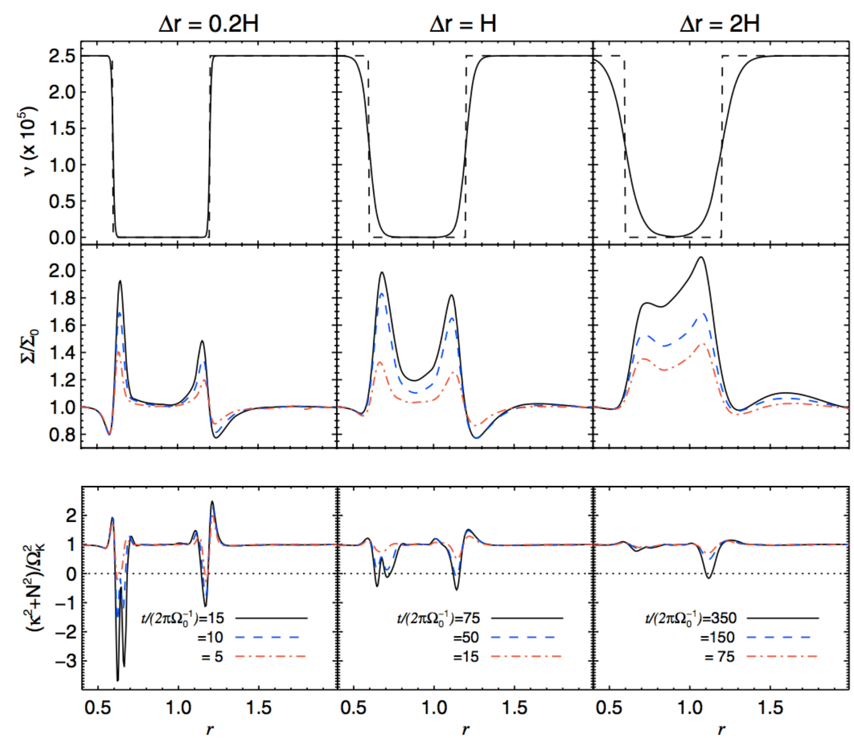

dead zone
cosmic rays?
non-thermal ionization of full disk column
X-rays
resistive quenching of MRI, suppressed angular momentum transport
MRI-active surface layer
ambipolar diffusion dominates
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent

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



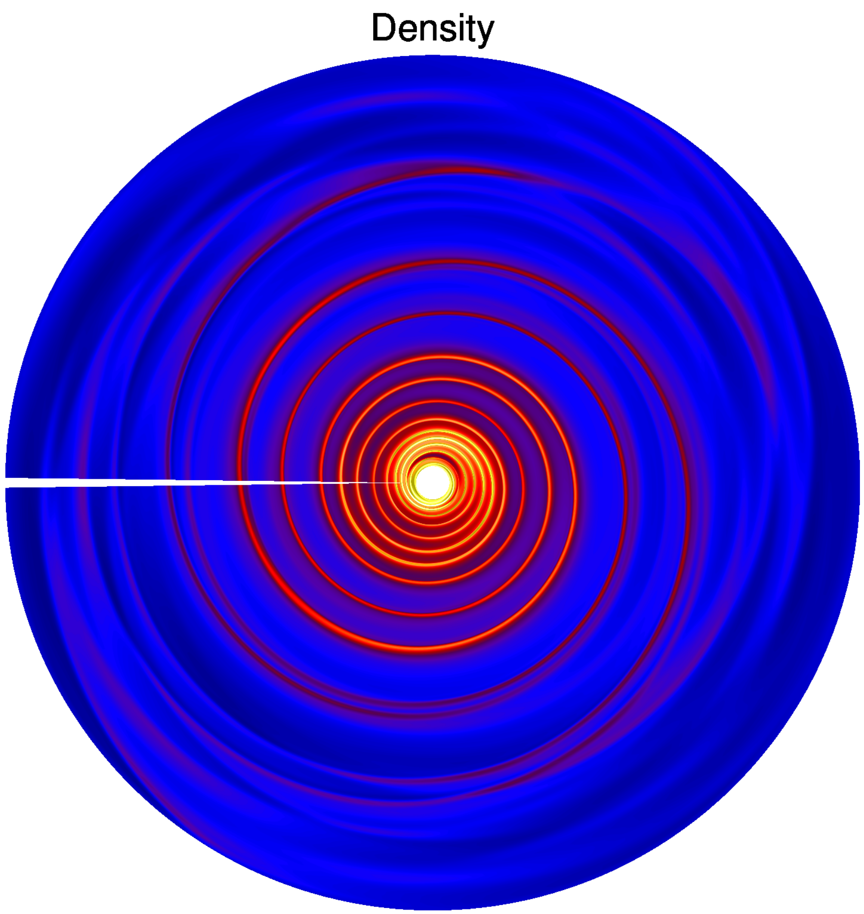


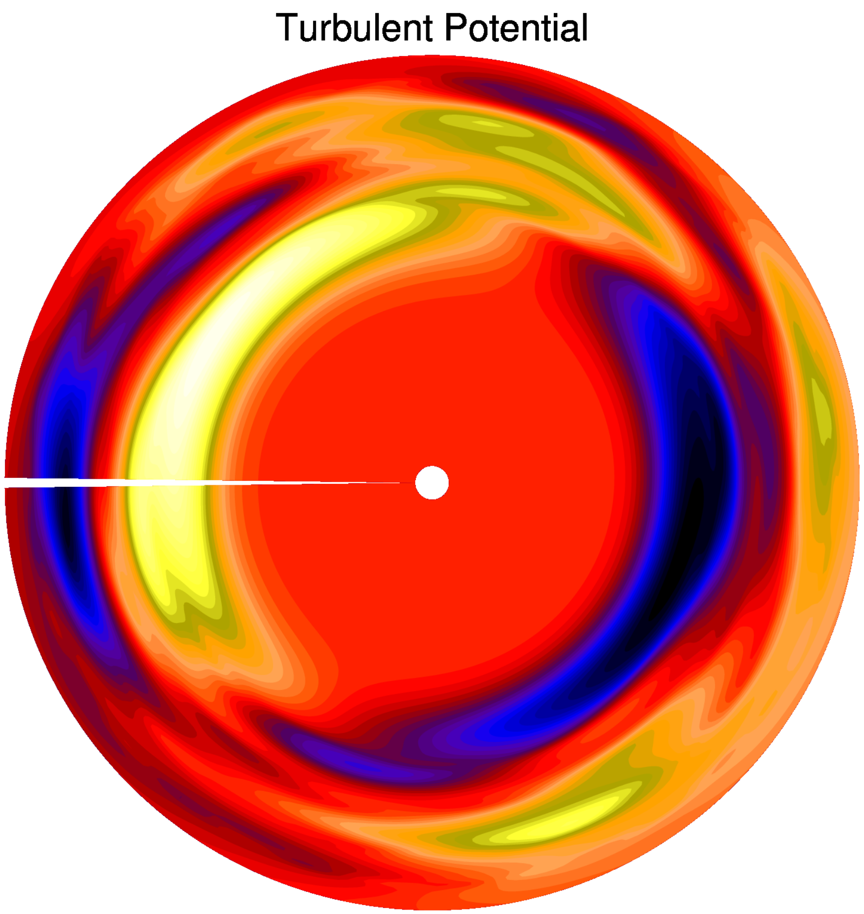
Dzyurkevitch et al (2013,
and poster just outside)



Lyra et al. (2009)

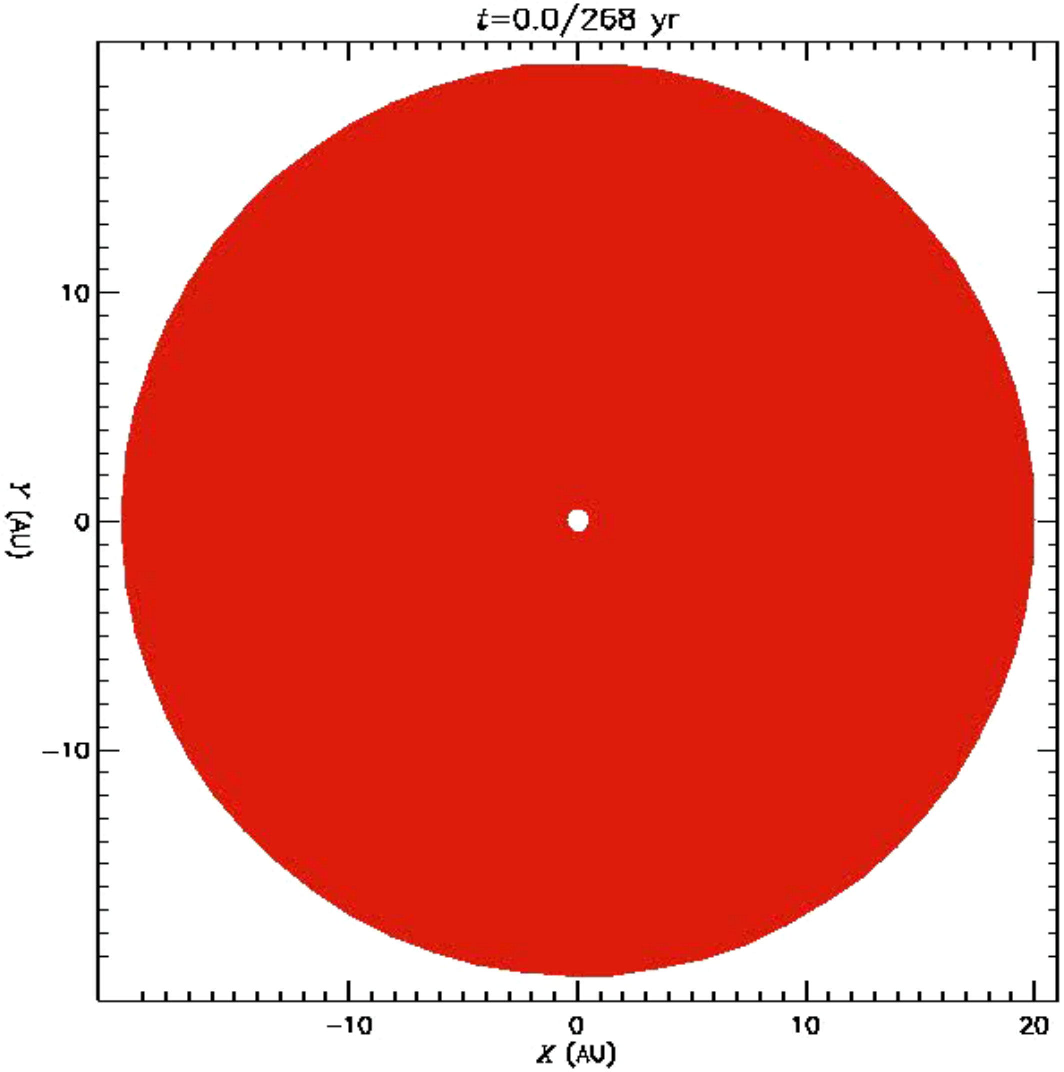
Outer Dead/Active zone transition: Spirals without planets





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

Turbulent Potential

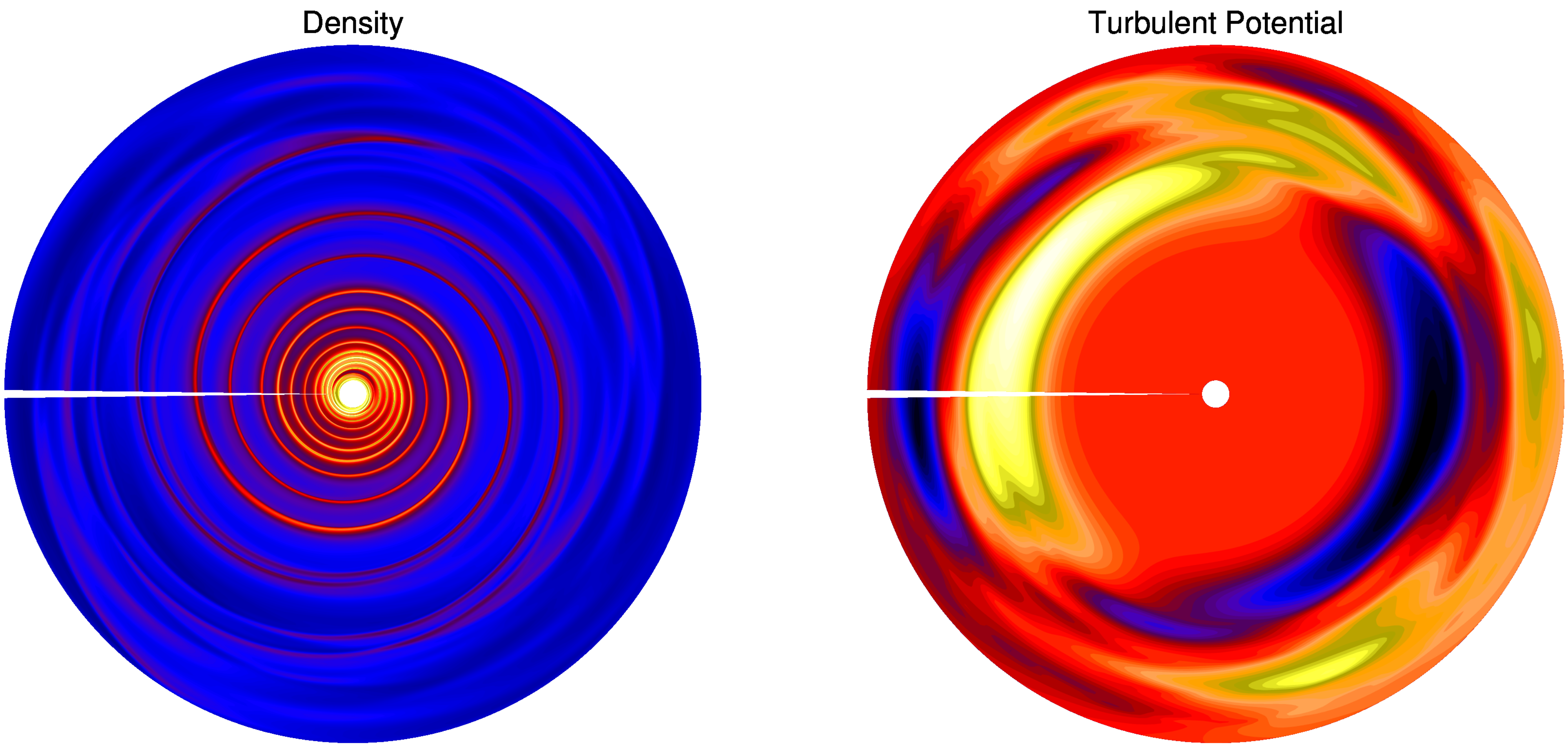


Stochastic forcing:
Laughlin et al. (2007)
Baruteau & Lin (2010)

$$\Phi = A r^2 \Omega^2 \sum_{i=1}^{n} \Lambda_{c,m}$$

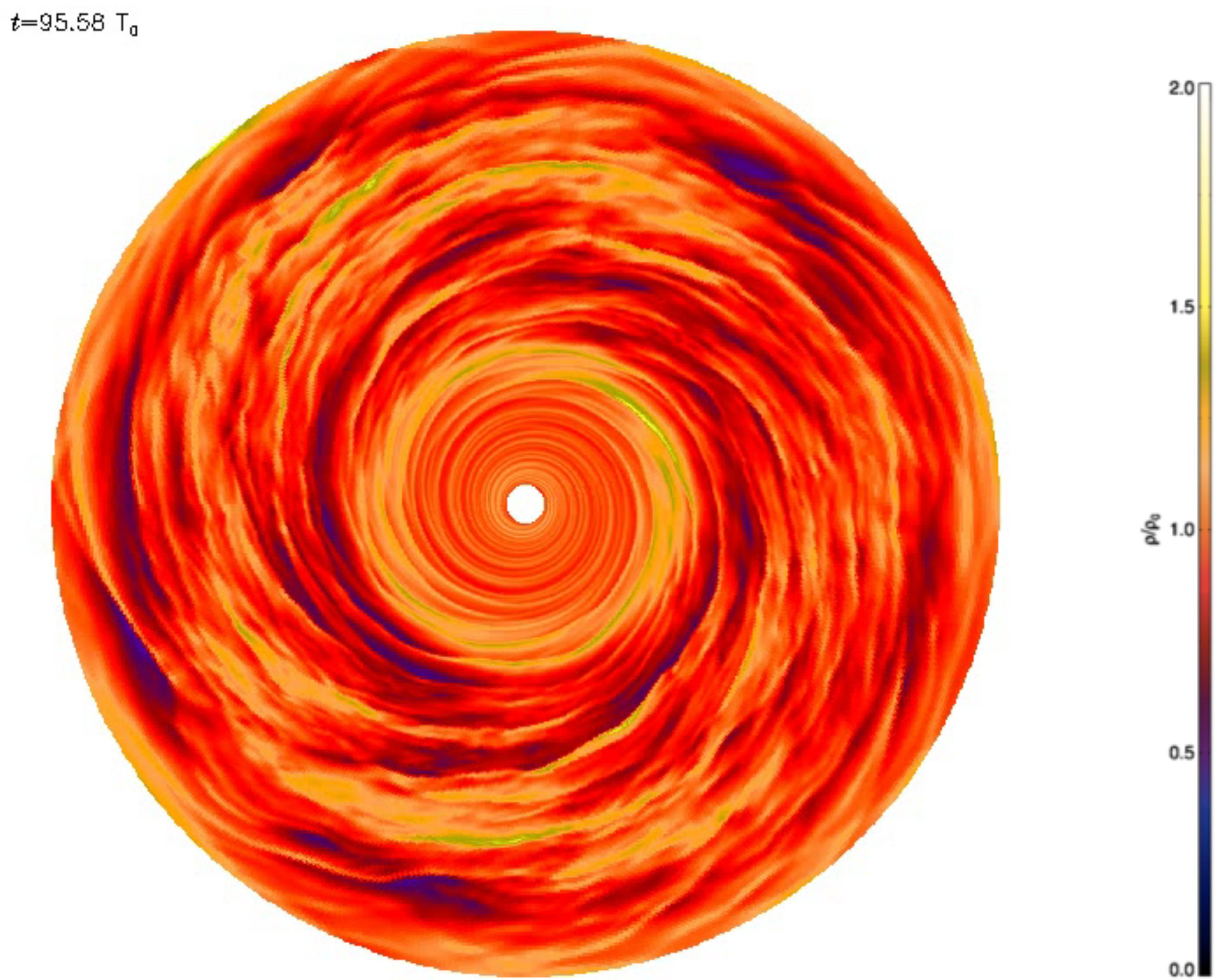
$$\Lambda_{c,m} = e^{-(r-r_c)^2/\sigma^2} \cos(m\theta - \phi_c - \Omega_c \tilde{t}) \sin(\pi \tilde{t} / \Delta t)$$

Outer Dead/Active zone transition: Spirals without planets



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

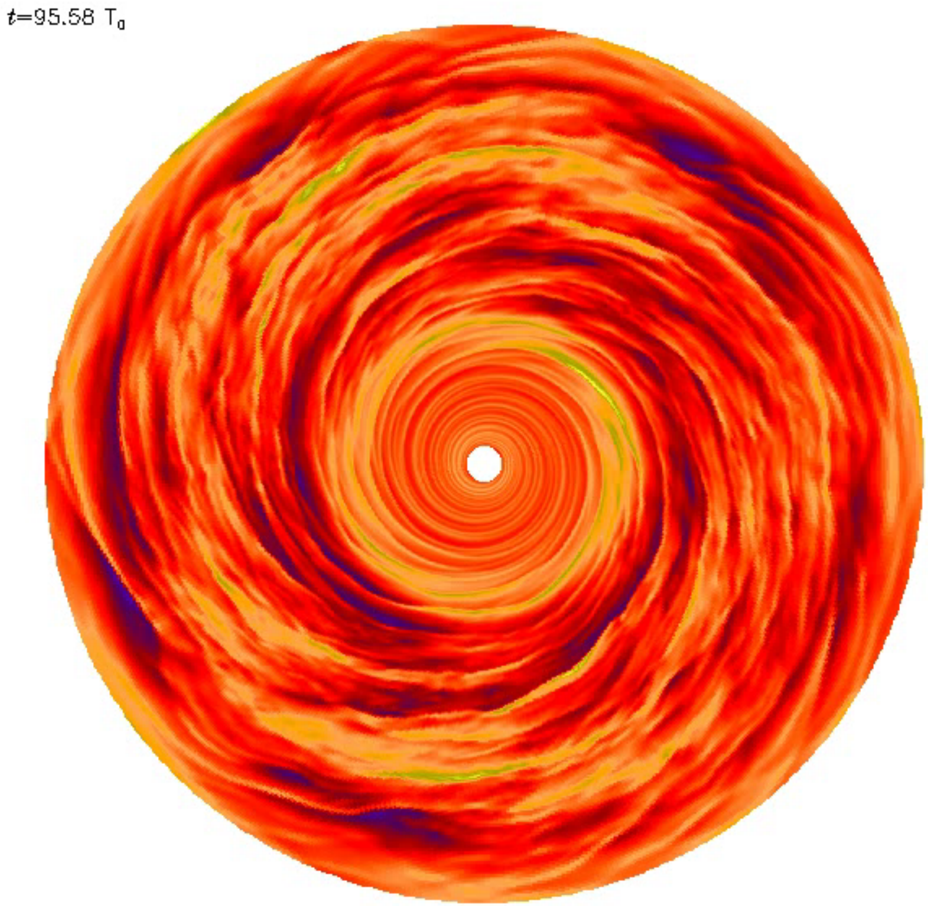
Outer Dead/Active zone transition: 3D MHD

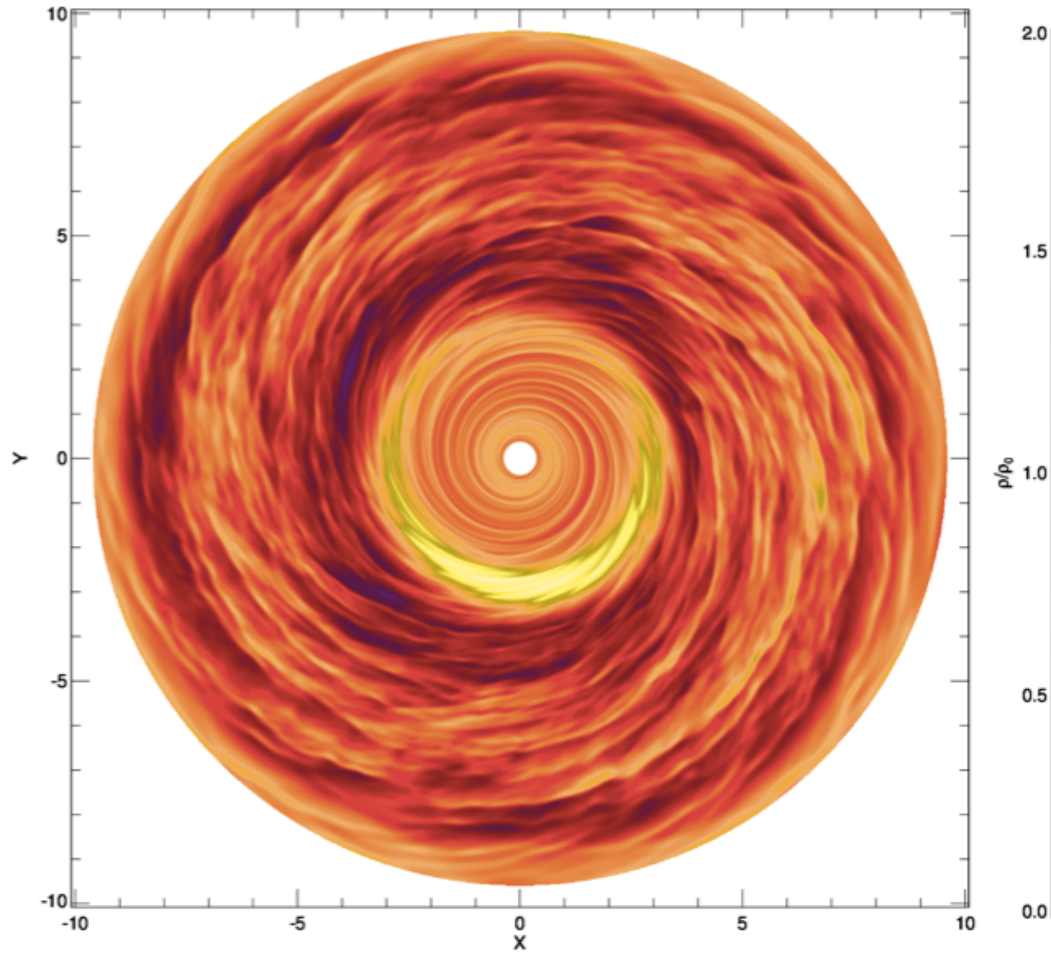


Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition: Spiral + Vortex

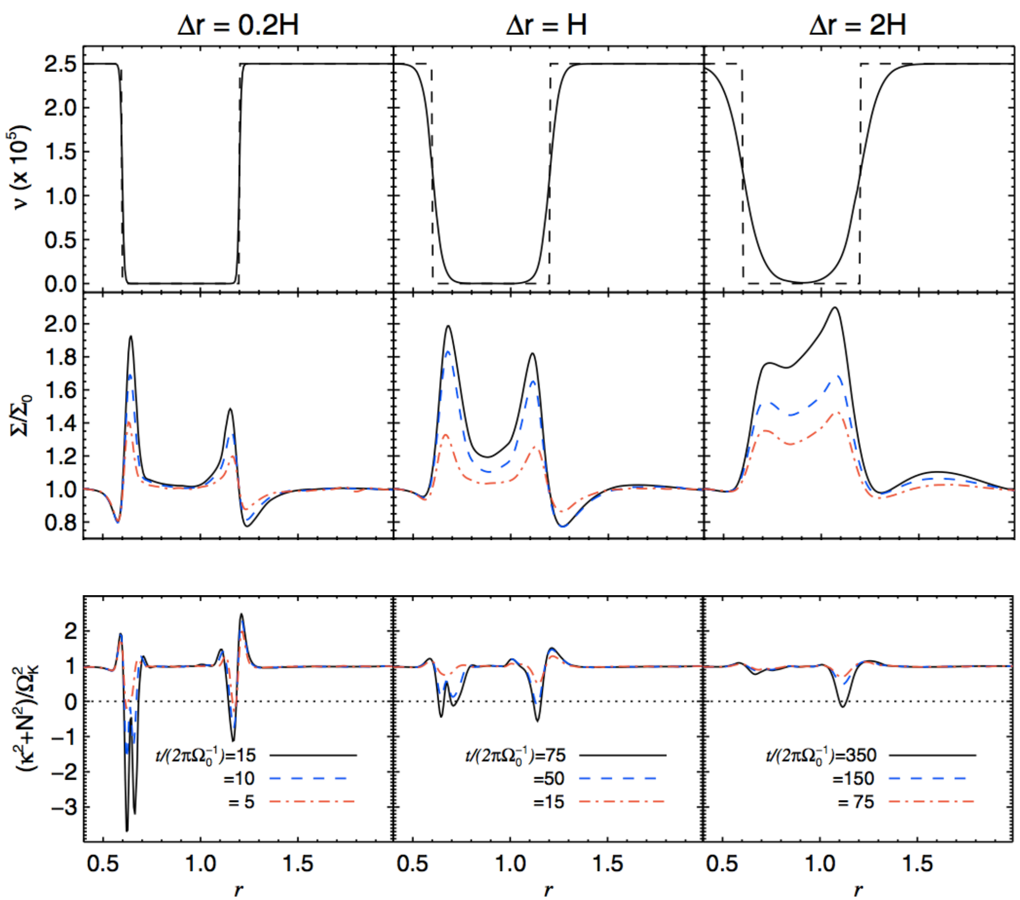




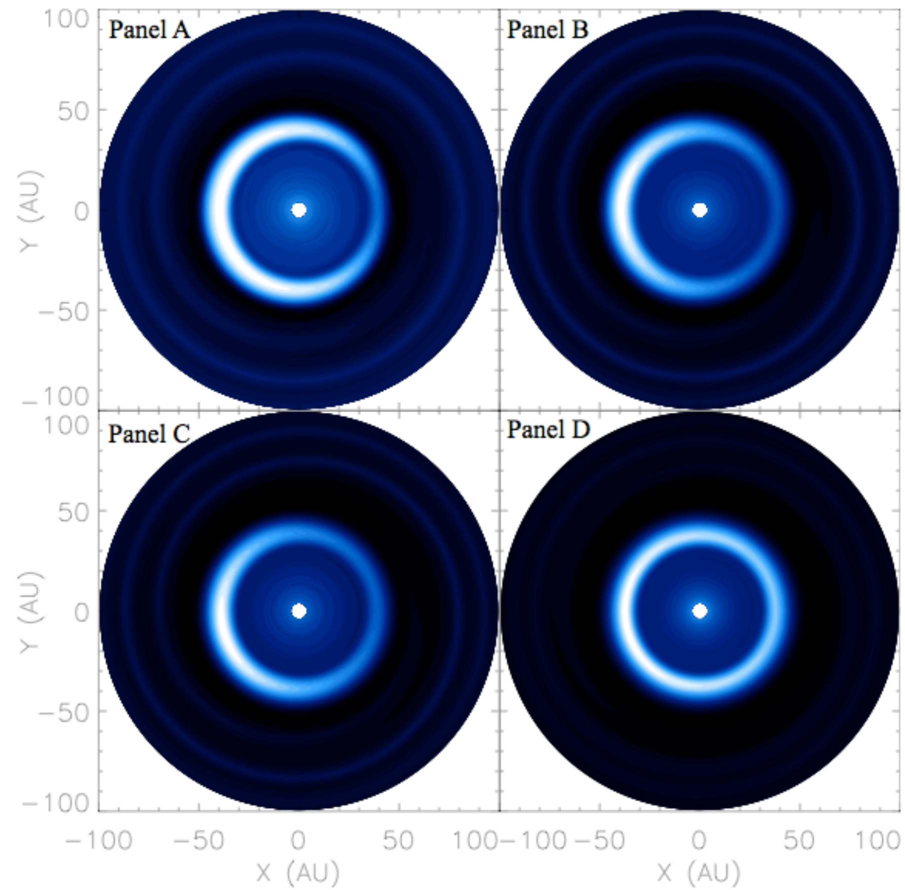
Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

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

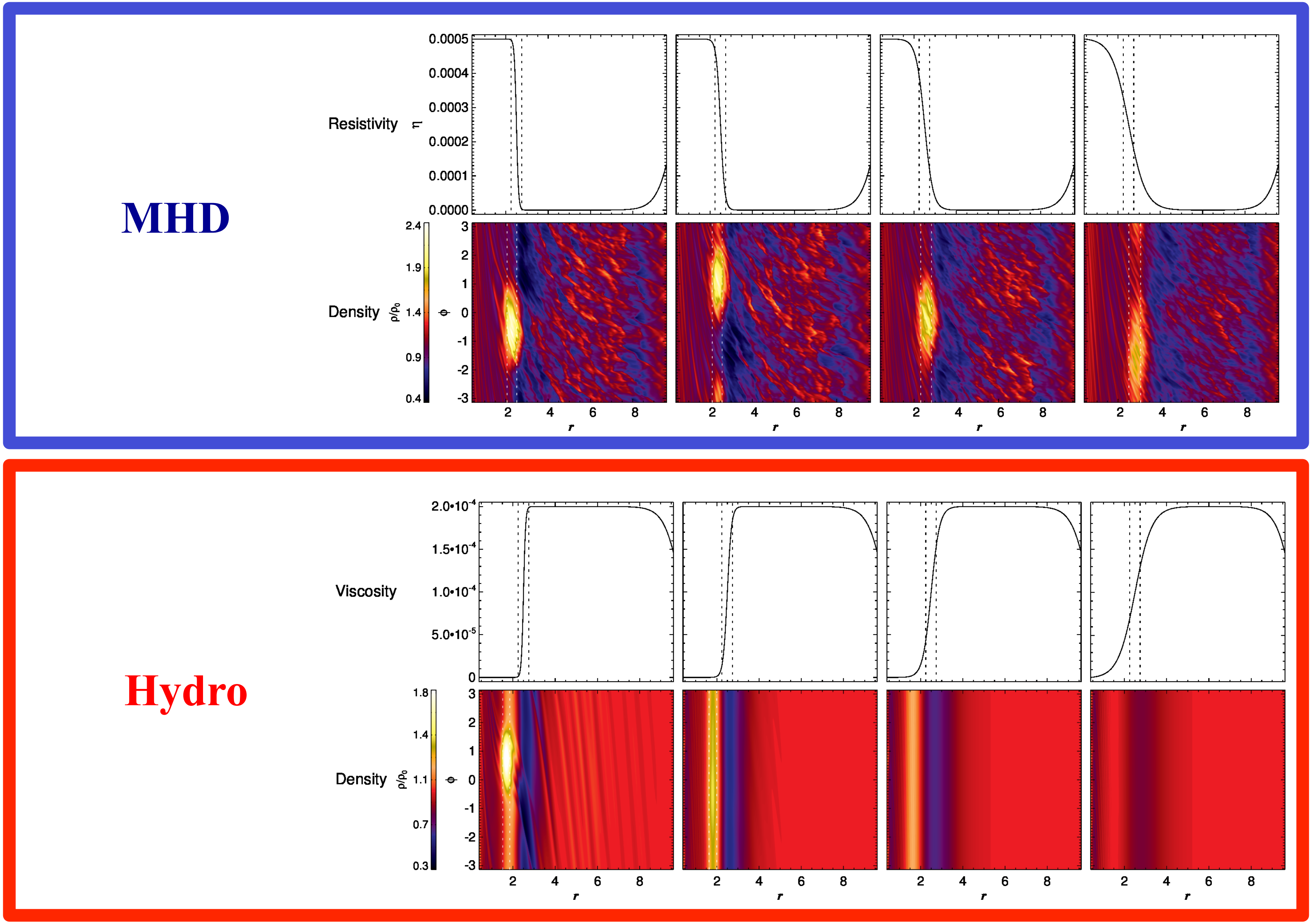


Lyra et al. (2009)



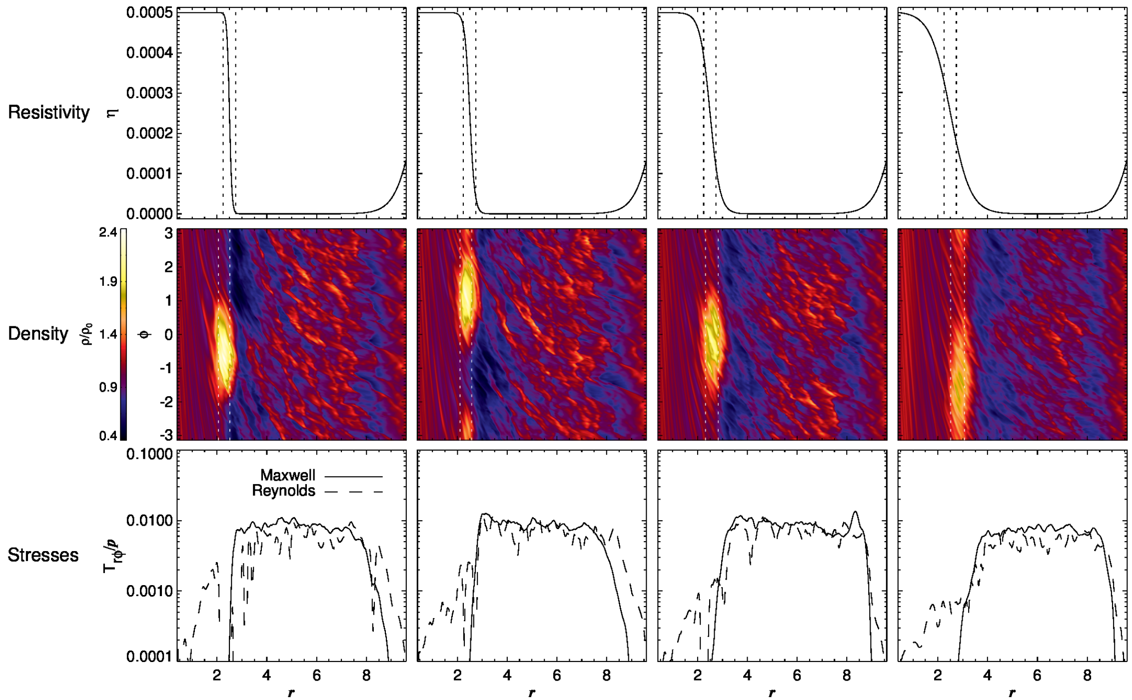
Regaly et al. (2012)

Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

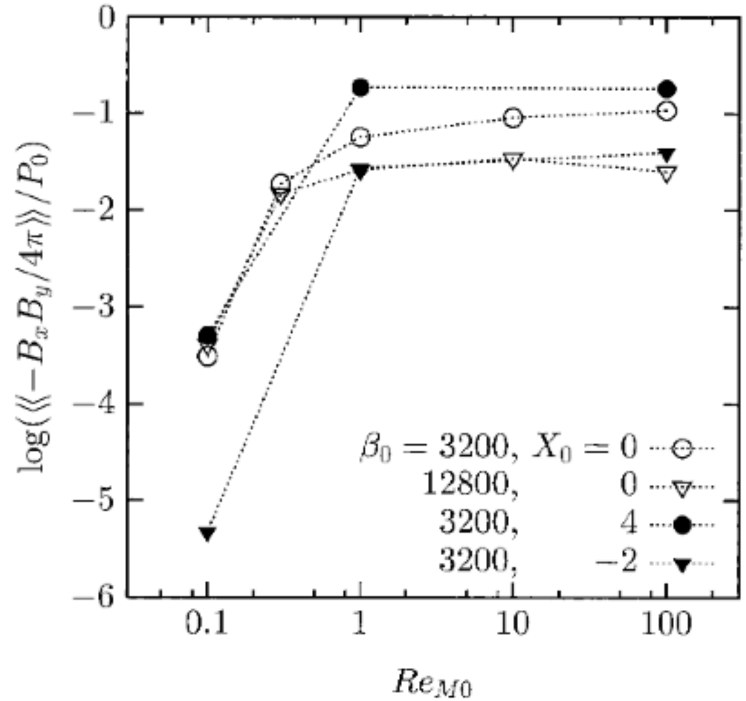
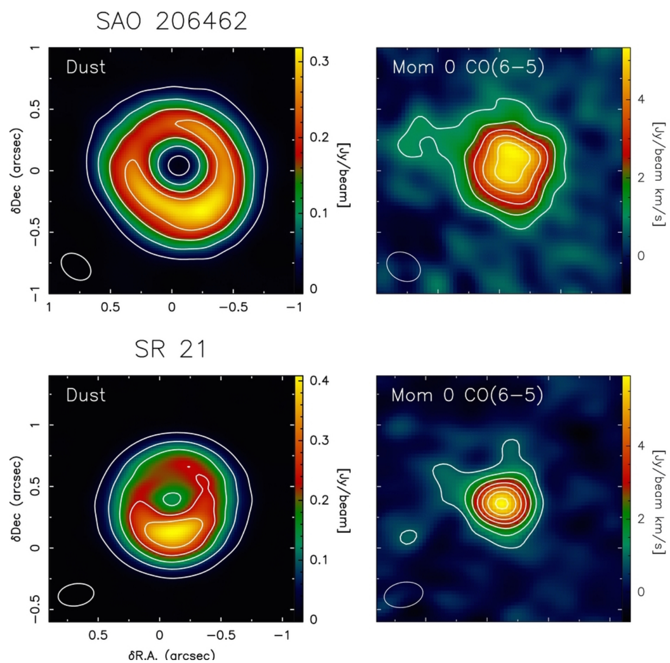
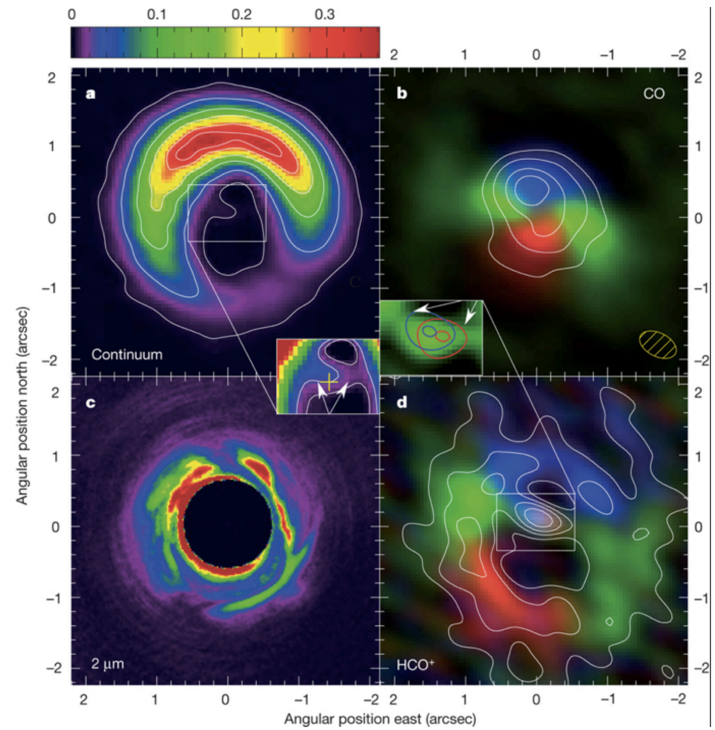
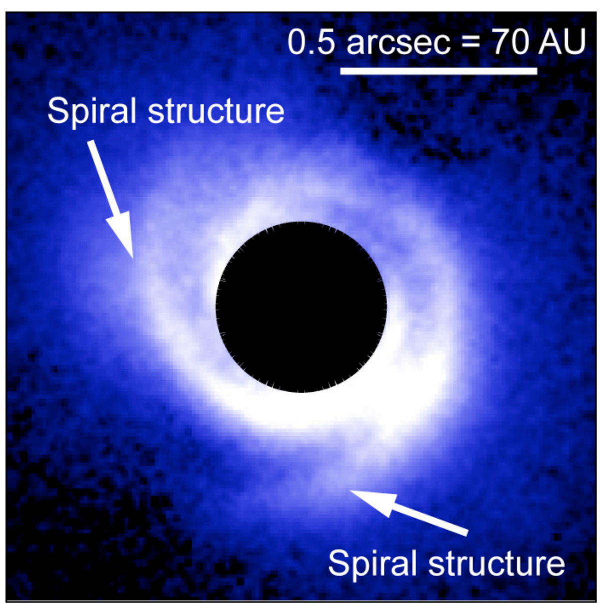


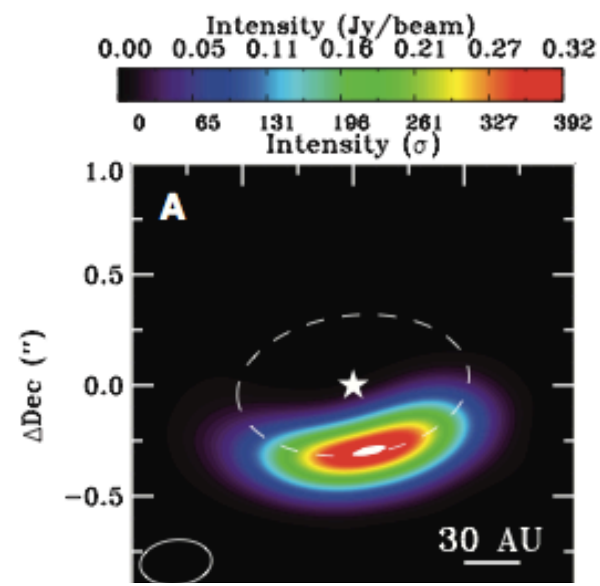
FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number Re_{M0}. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and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

Sano and Stone (2002)


SAO 206462
Dust
Mom 0 CO(6–5)
SR 21
Dust
Mom 0 CO(6–5)
δDec (arcsec)
δR.A. (arcsec)
[Jy/beam]
[Jy/beam km/s]


a
Continuum
b
CO
c
2 µm
d
HCO+
Angular position north (arcsec)
Angular position east (arcsec)


0.5 arcsec = 70 AU
Spiral structure
Spiral structure


Intensity (Jy/beam)
0.00 0.05 0.11 0.16 0.21 0.27 0.32
0 65 131 196 261 327 392
Intensity (σ)
A
ΔDec (")
30 AU

Conclusions

- Should we drop the name RWI in favor of simply Kelvin-Helmholtz?

- RWI can occur in 3D MHD disks
- Inner active/dead transition is a robust location for RWI
- RWI happens at the dead side of the transition (magneto-elliptic instability)
- Outer dead/active also triggers the RWI: although the resistivity gradient is weak, the transition in Maxwell stress is abrupt.