# Planet formation through vortices in turbulent accretion disks


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***American Museum of Natural History***

***Max-Planck Institute for Astronomy***

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Hamilton, June 2012


Collaborators:

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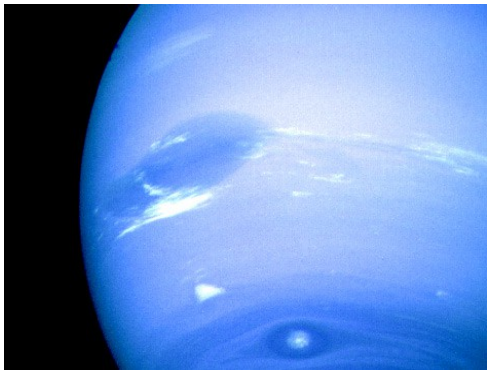
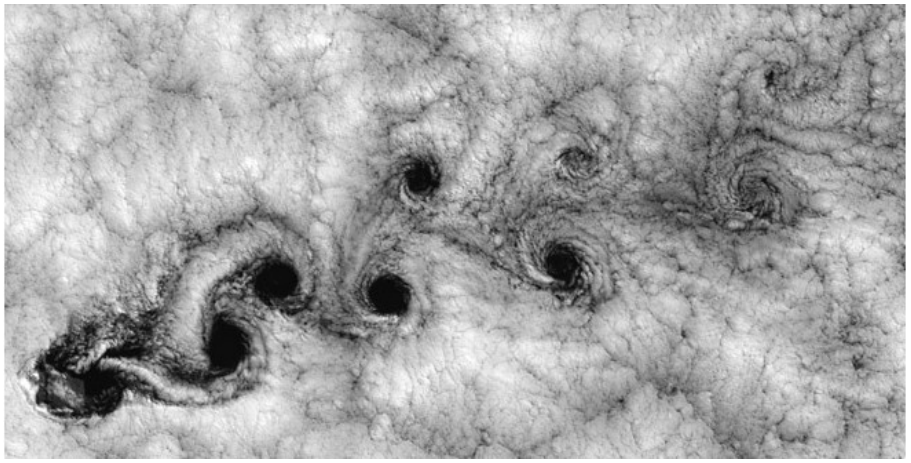
# Vortices – An ubiquitous fluid mechanics phenomenon

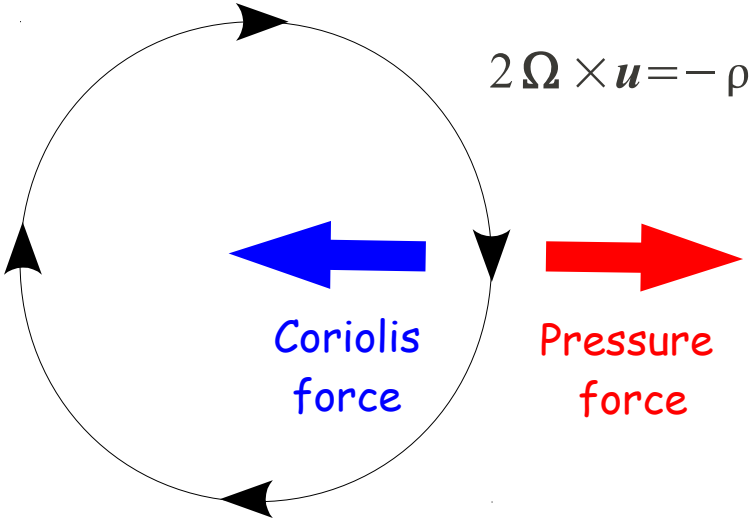


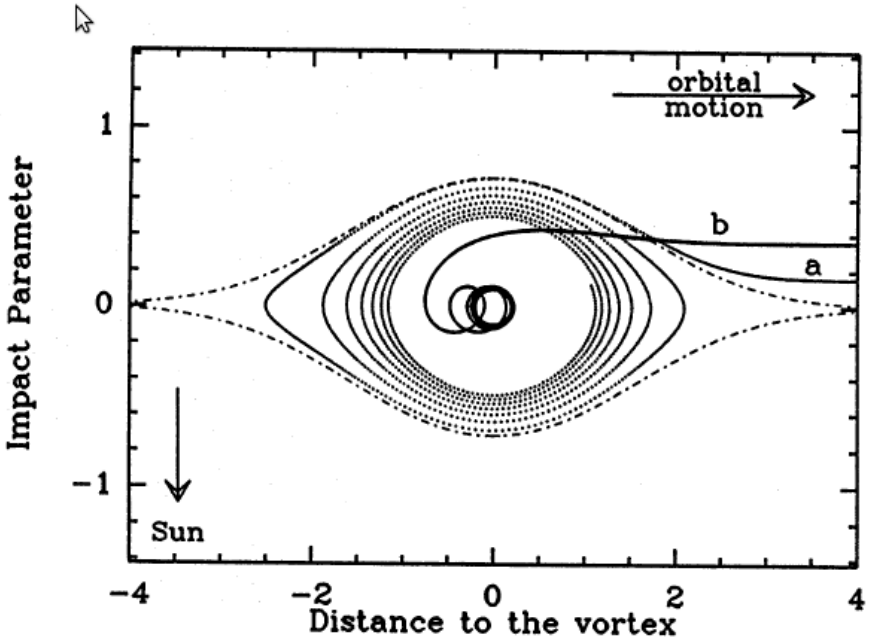


# Vortices and Planet Formation

Geostrophic balance:

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



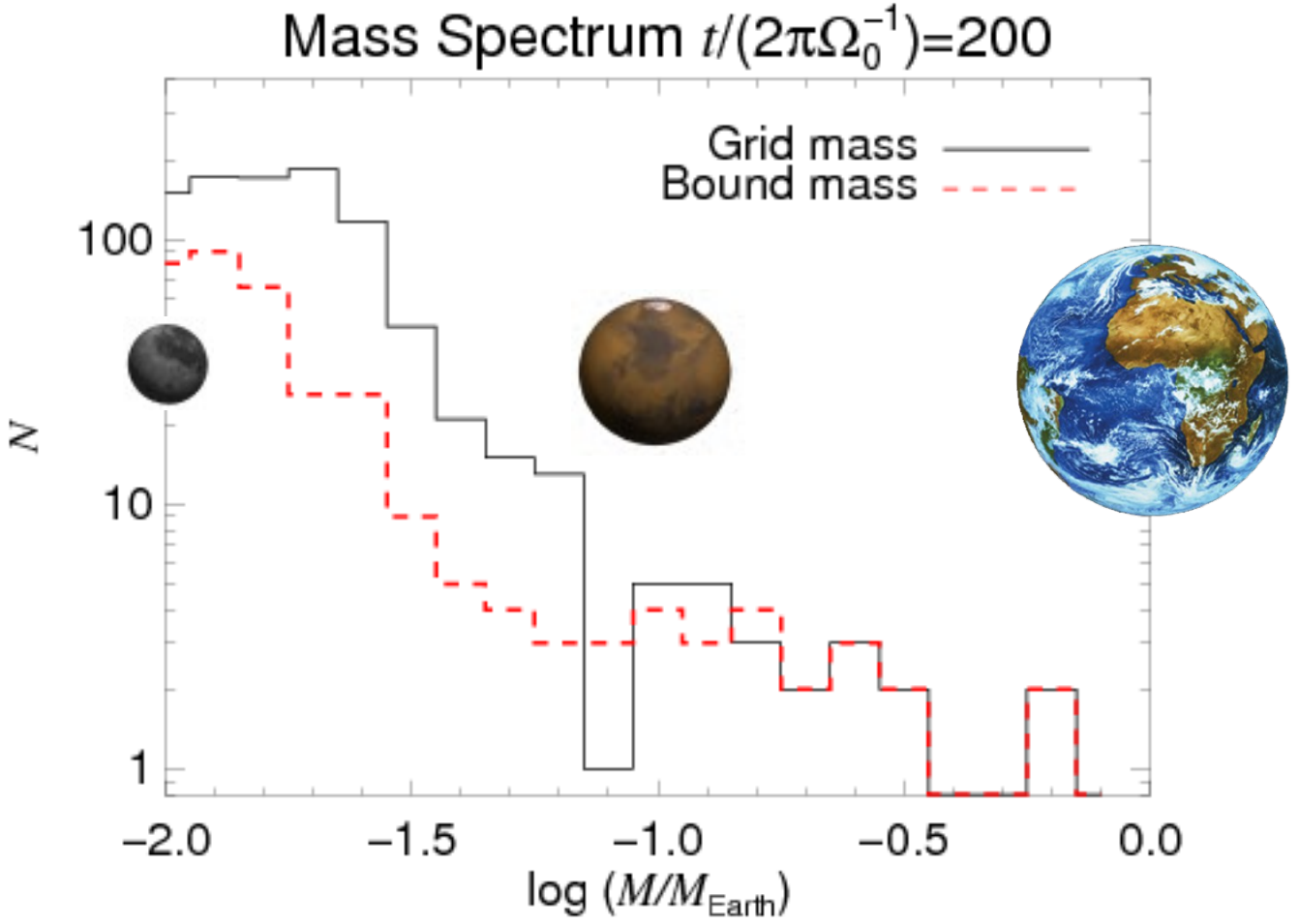

Source: Barge & Sommeria (1995)

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

Aid to planet formation (Barge & Sommeria 1995)

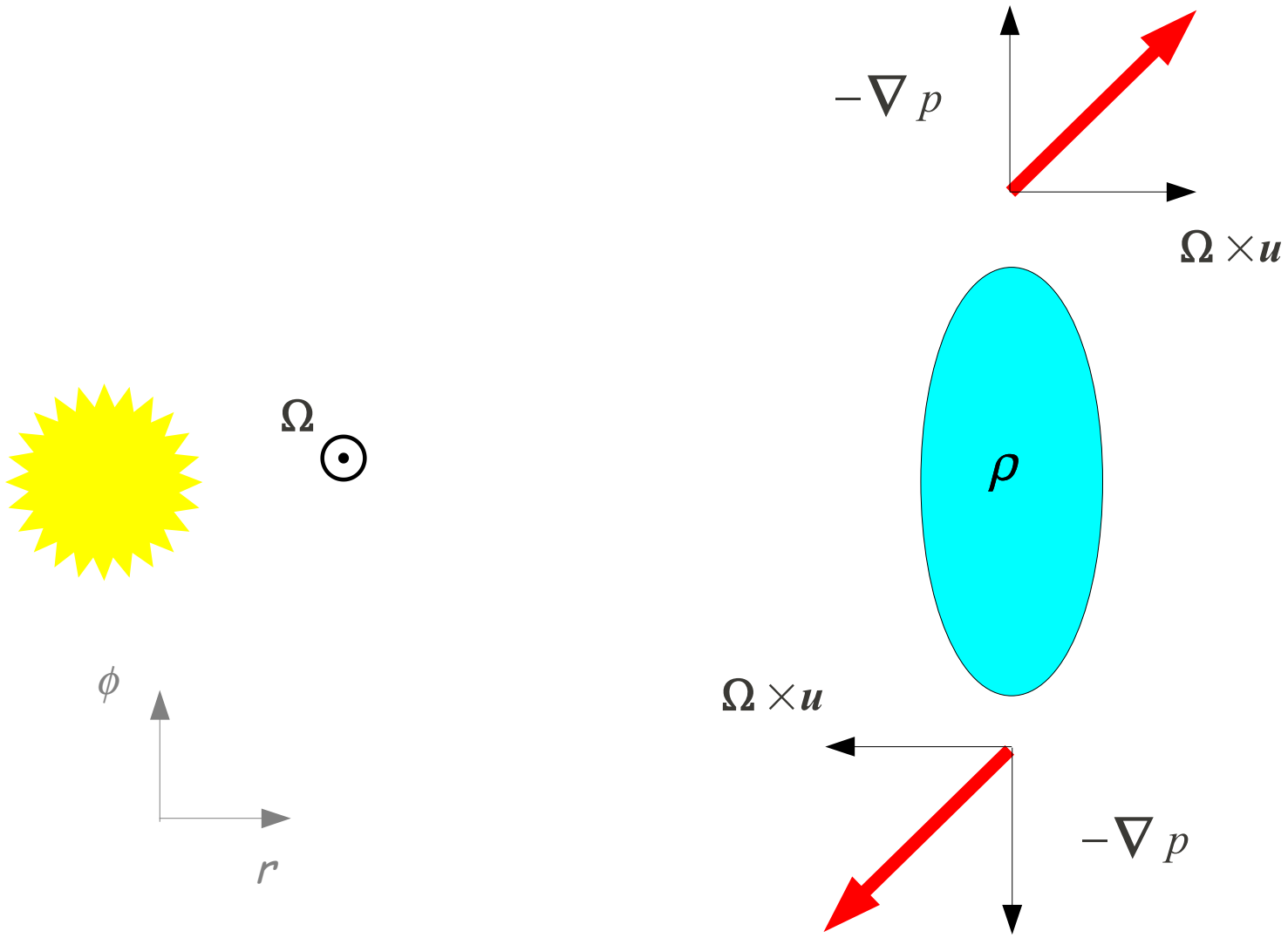
Speed up planet formation enormously
(Lyra et al. 2008b, 2009a, 2009b, Raettig, Lyra & Klahr 2012)

# The Initial Mass Function of planets

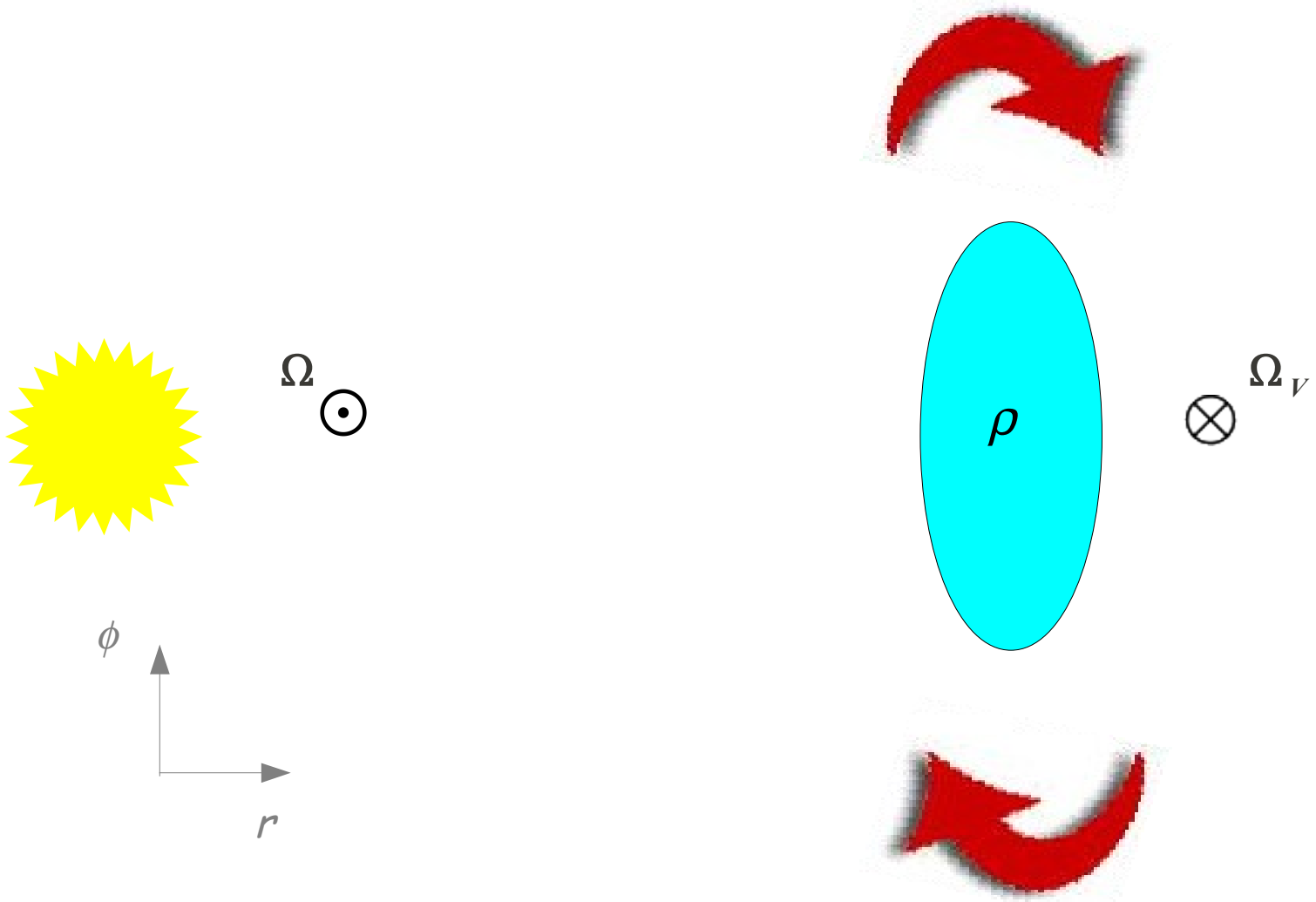



•Mass spectrum by the end of the simulation
•300 bound clumps were formed
•Power law d(log *N*)/d(log *M*)=-2.3 +/- 0.2
•20 of these are more massive than Mars

# Vortices in disks

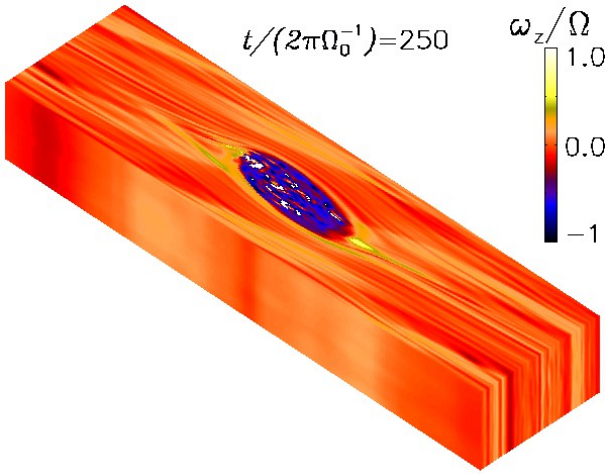


# Vortices in disks



So how to sustain vortices in disks?

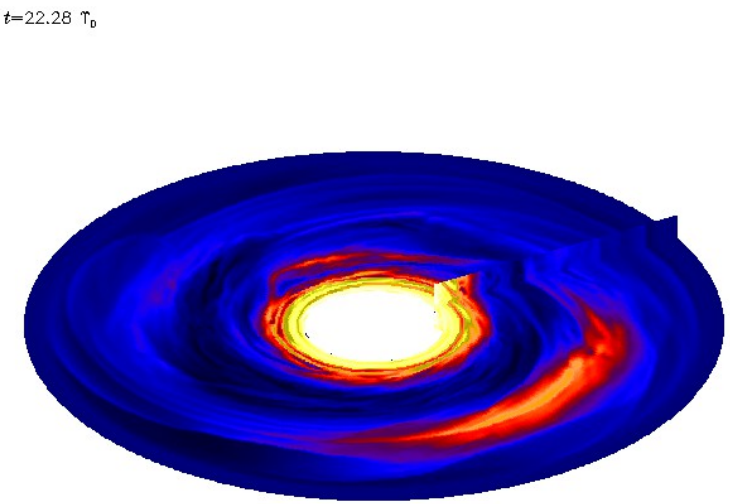
## Baroclinic Instability




Nonlinear

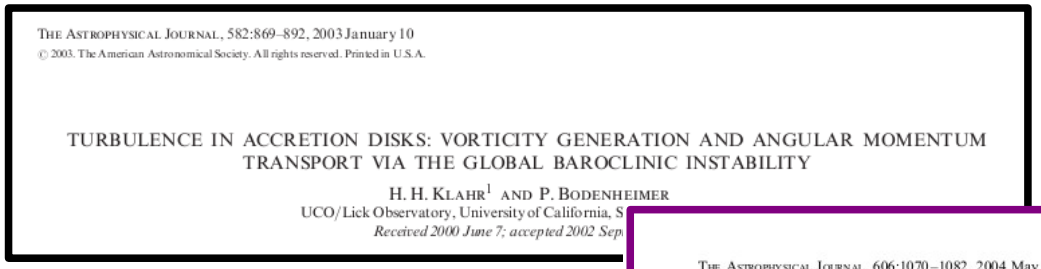
Powered by:
buoyancy, thermal diffusion

## Rossby Wave Instability




Linear
Non-axissymmetric

Powered by:
Modification of shear profile



THE ASTROPHYSICAL JOURNAL, 582:869–892, 2003 January 10
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TURBULENCE IN ACCRETION DISKS: VORTICITY GENERATION AND ANGULAR MOMENTUM TRANSPORT VIA THE GLOBAL BAROCLINIC INSTABILITY

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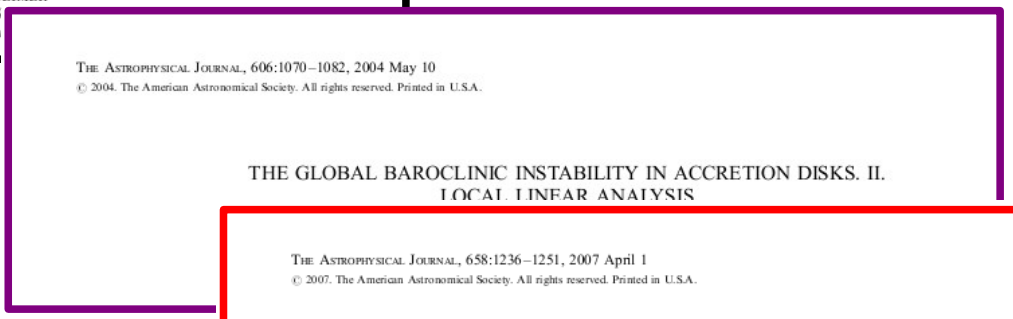
UCO/Lick Observatory, University of California, S
*Received 2000 June 7; accepted 2002 Sep*

Klahr & Bodenheimer (2003)

Klahr (2004)



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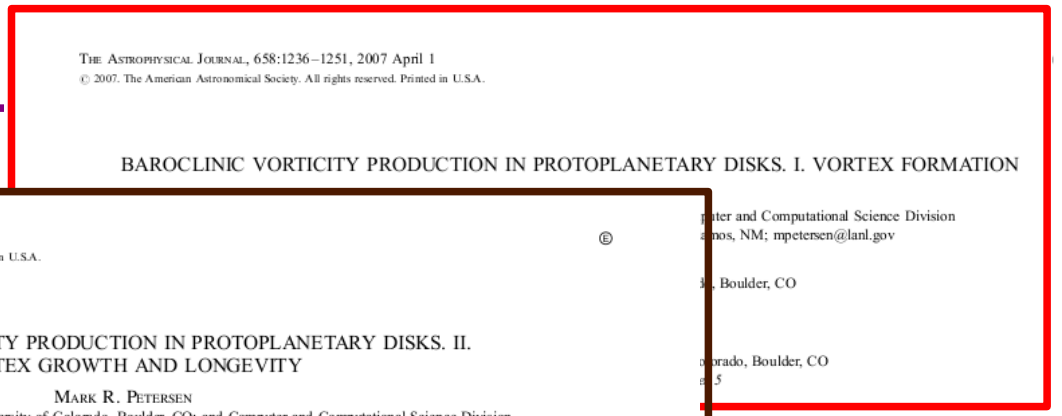
THE GLOBAL BAROCLINIC INSTABILITY IN ACCRETION DISKS. II.
LOCAL LINEAR ANALYSIS

Petersen et al. (2007a)



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BAROCLINIC VORTICITY PRODUCTION IN PROTOPLANETARY DISKS. I. VORTEX FORMATION

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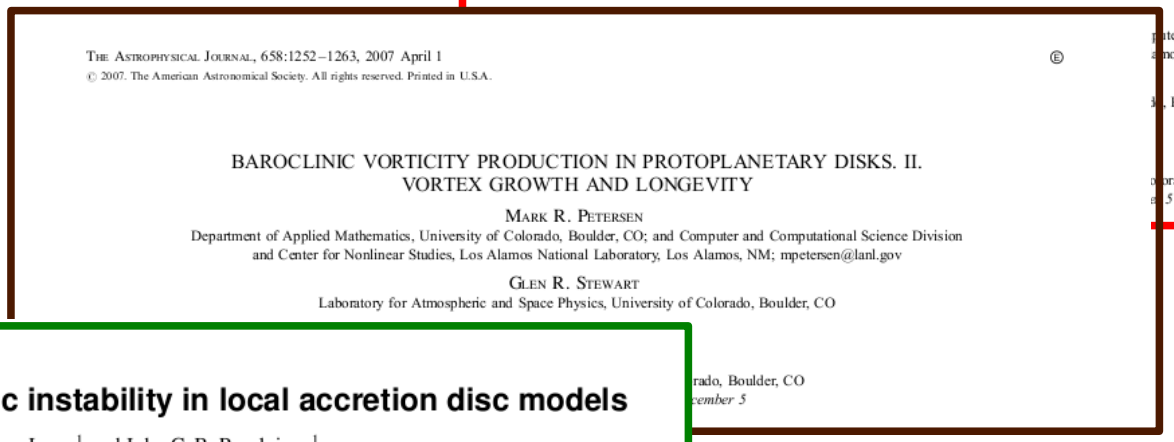
Petersen et al. (2007b)



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BAROCLINIC VORTICITY PRODUCTION IN PROTOPLANETARY DISKS. II.
VORTEX GROWTH AND LONGEVITY

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Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO

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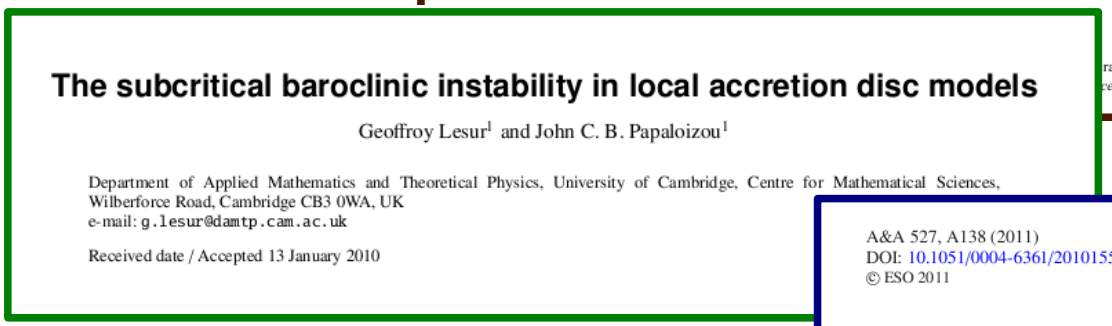

**The subcritical baroclinic instability in local accretion disc models**

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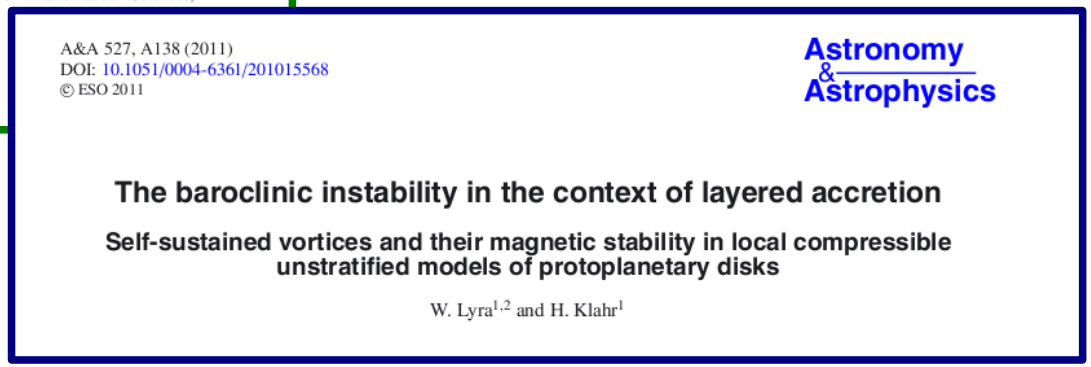
Received date / Accepted 13 January 2010

Lesur & Papaloizou (2010)



A&A 527, A138 (2011)
DOI: 10.1051/0004-6361/201015568
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Astronomy & Astrophysics

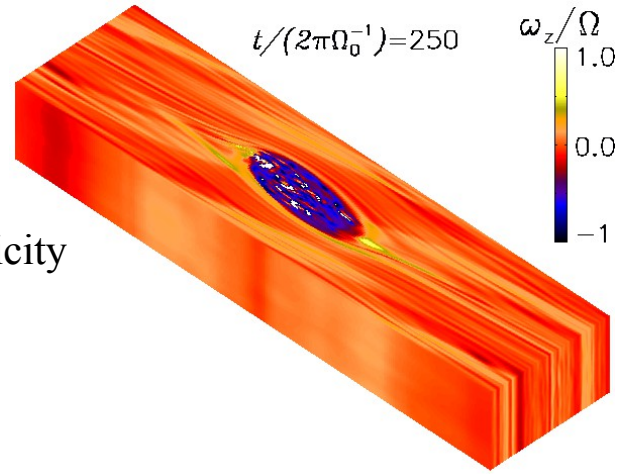
**The baroclinic instability in the context of layered accretion**

**Self-sustained vortices and their magnetic stability in local compressible unstratified models of protoplanetary disks**

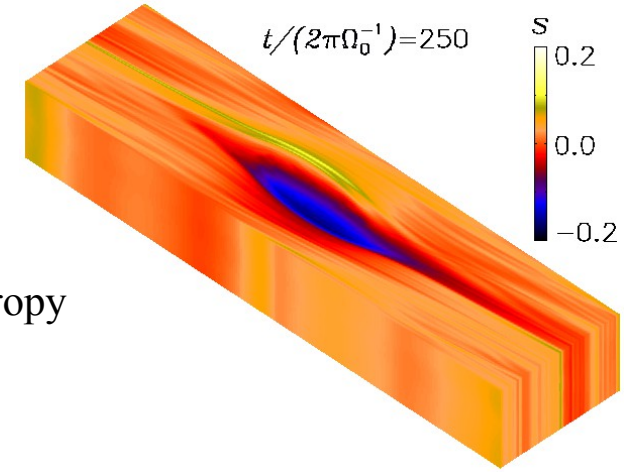
W. Lyra[1,2] and H. Klahr[1]

Lyra & Klahr (2011)

# Baroclinic Instability – Excitation and self-sustenance of vortices



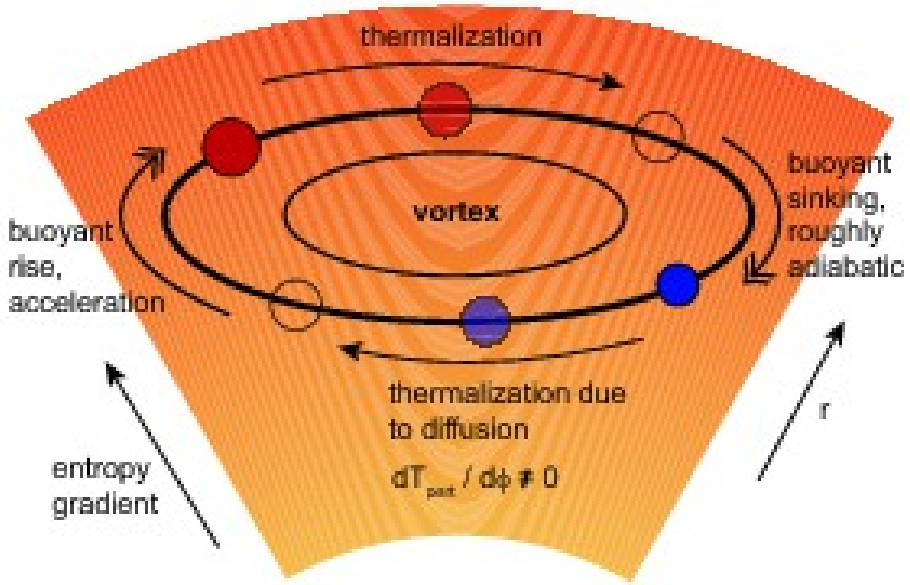

Vorticity




Entropy

Source: Lyra & Klahr (2010)

## Sketch of the Baroclinic Instability

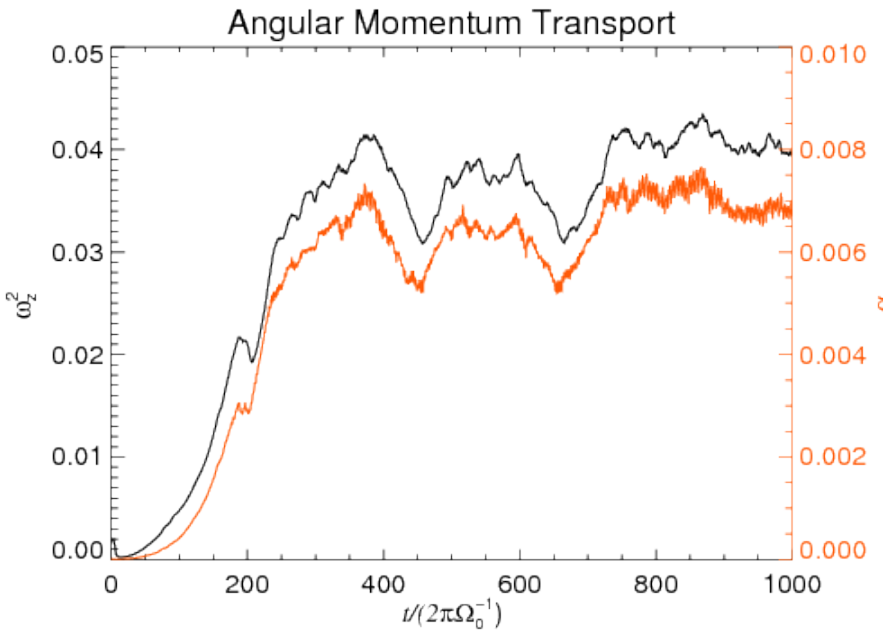



Source: Armitage (2010)

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

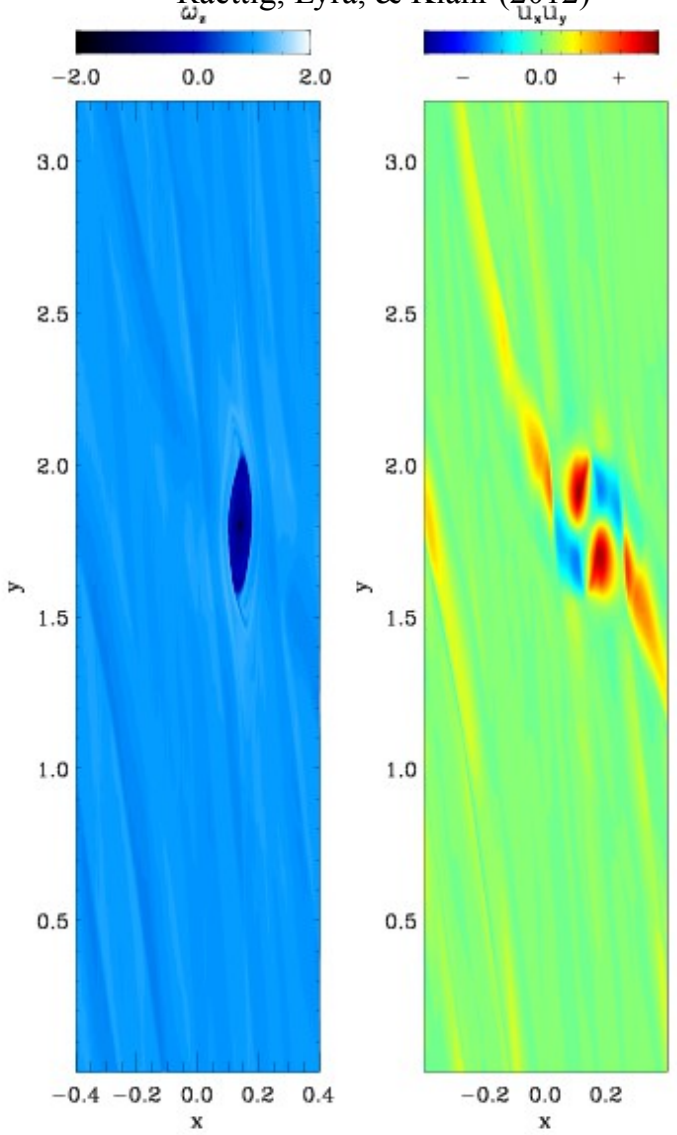
# Baroclinic Instability and Accretion

**Large mass accretion rates**, comparable to the MRI!




Lyra & Klahr (2011)

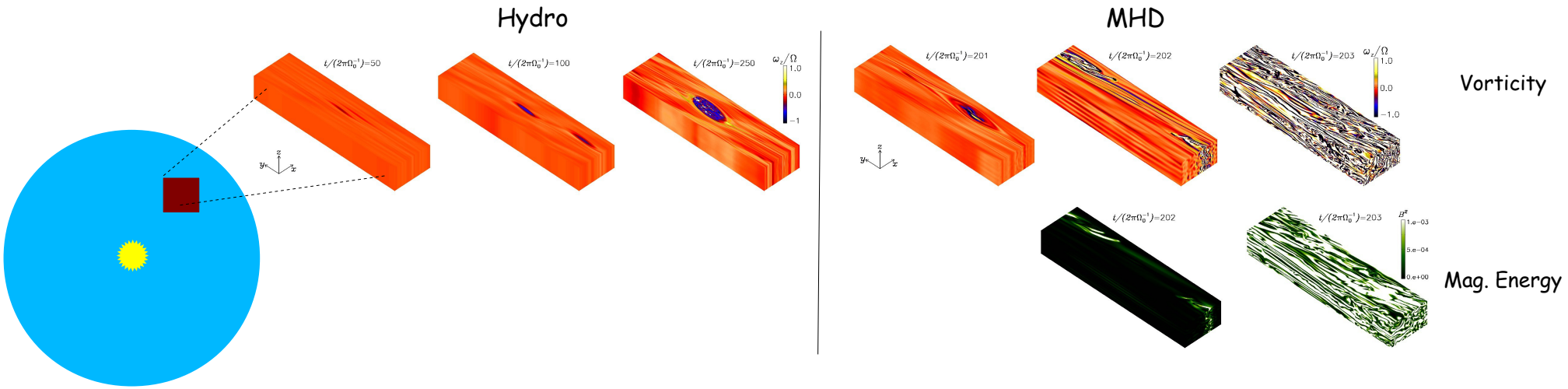
Raettig, Lyra, & Klahr (2012)




The angular momentum is carried by ***waves*** excited by the vortex

# Interaction of Baroclinic and Magneto-Rotational Instabilities

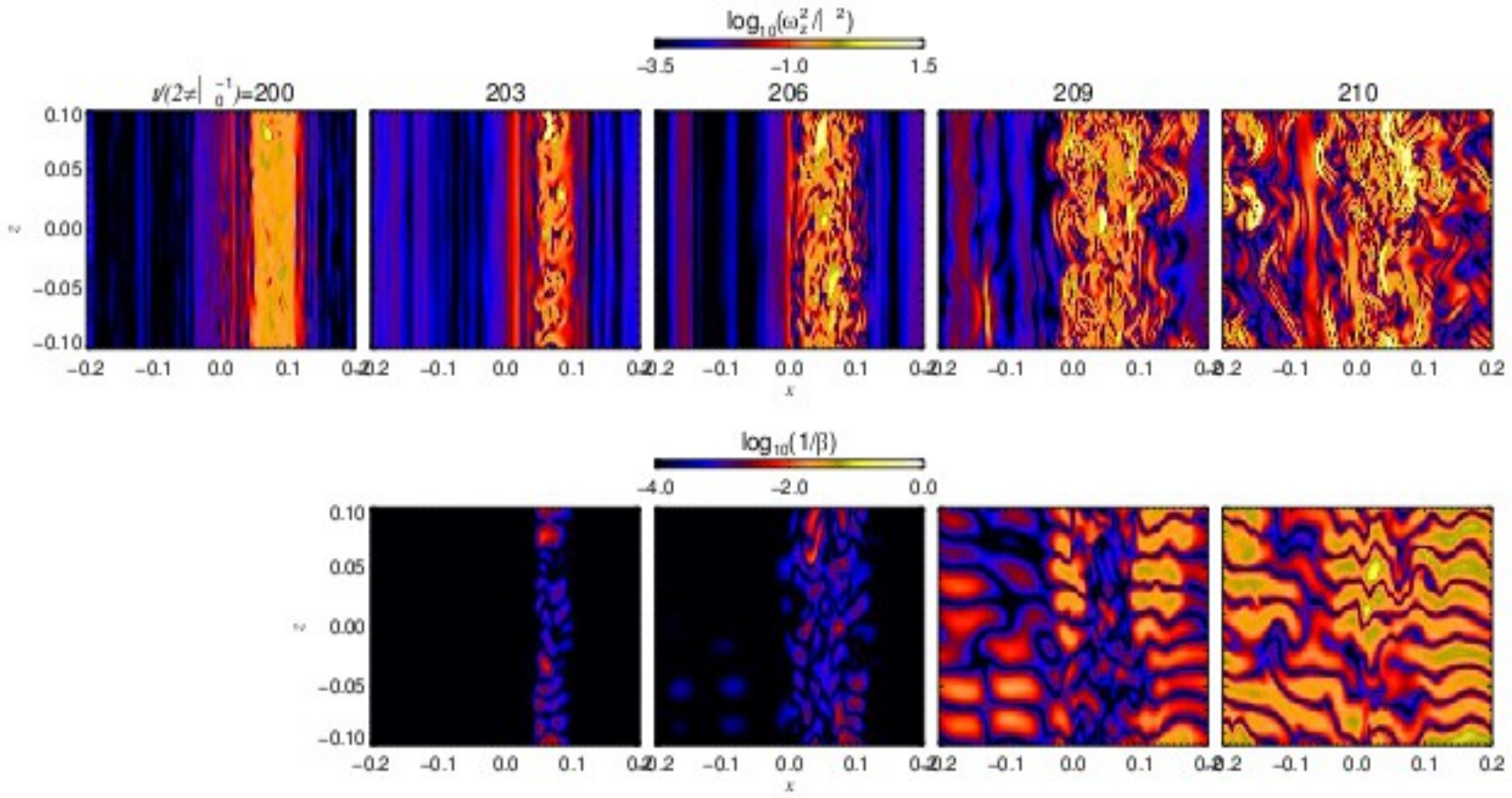
What happens when the vortex is magnetized?




Vortex gone!

Lyra & Klahr (2011)

# Interaction of Baroclinic and Magneto-Rotational Instabilities



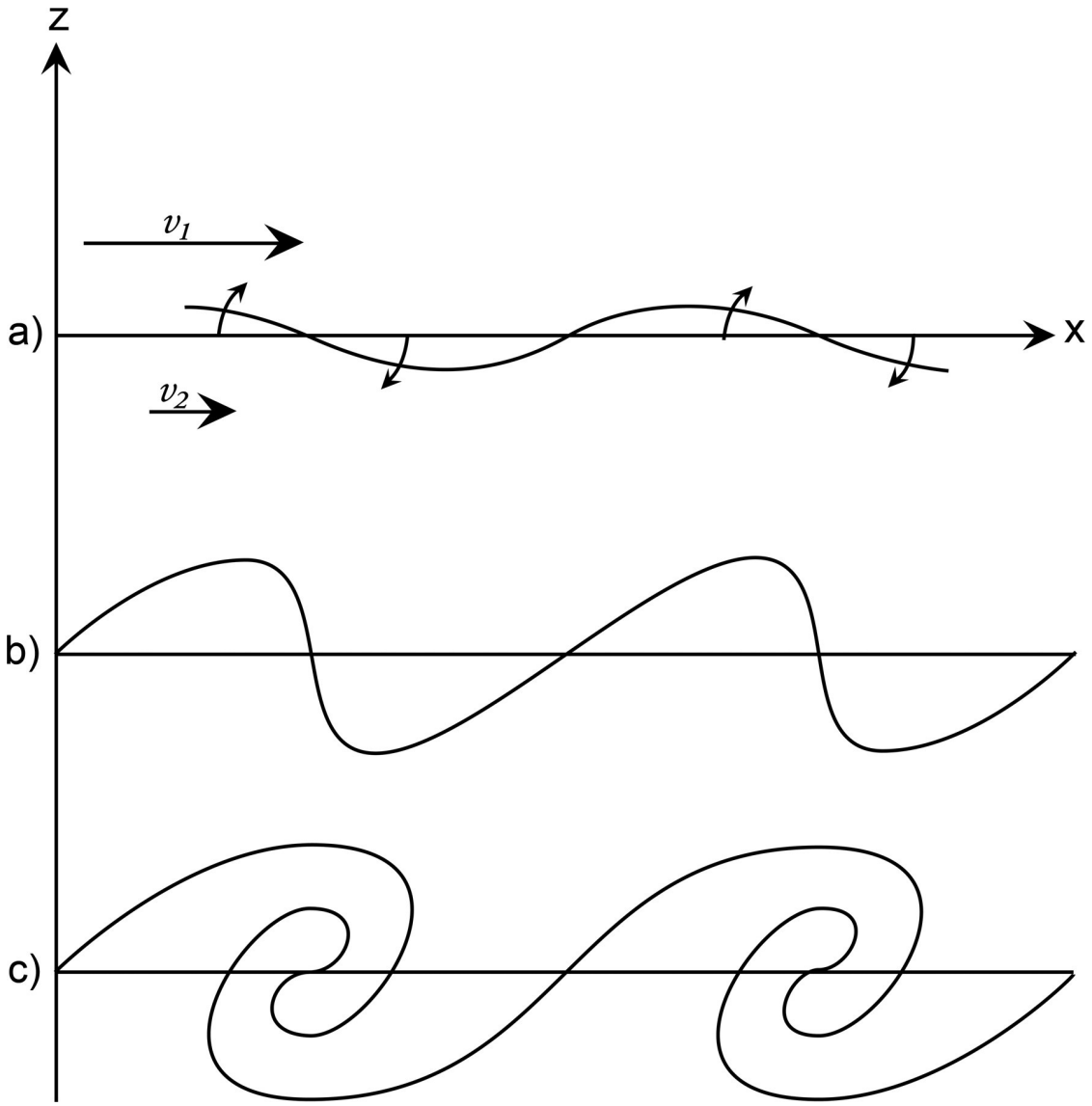

*Enstrophy (Vorticity squared)*

*Mag. Energy*

Vortices do not survive magnetization.
Restricted to dead zones.

# Rossby Wave Instability

(or…. **Kelvin-Helmholtz** in rotating disks)

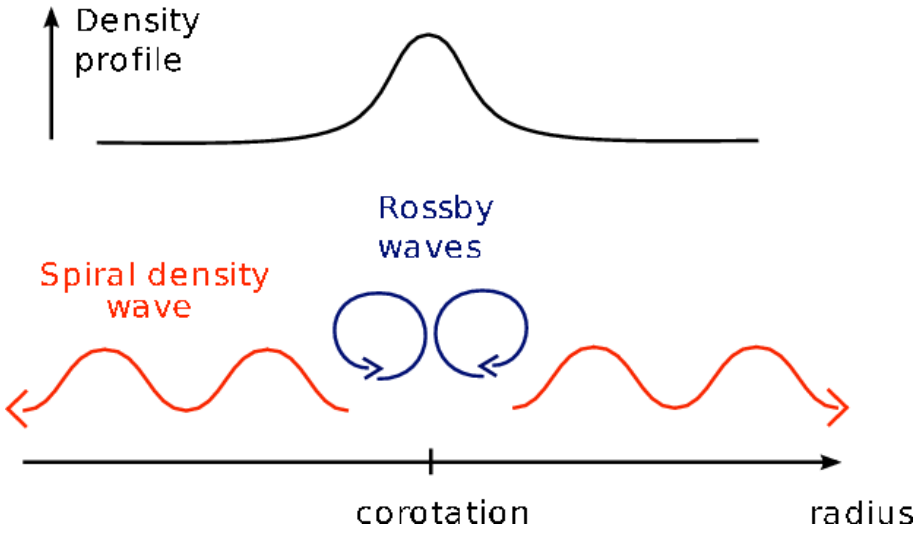




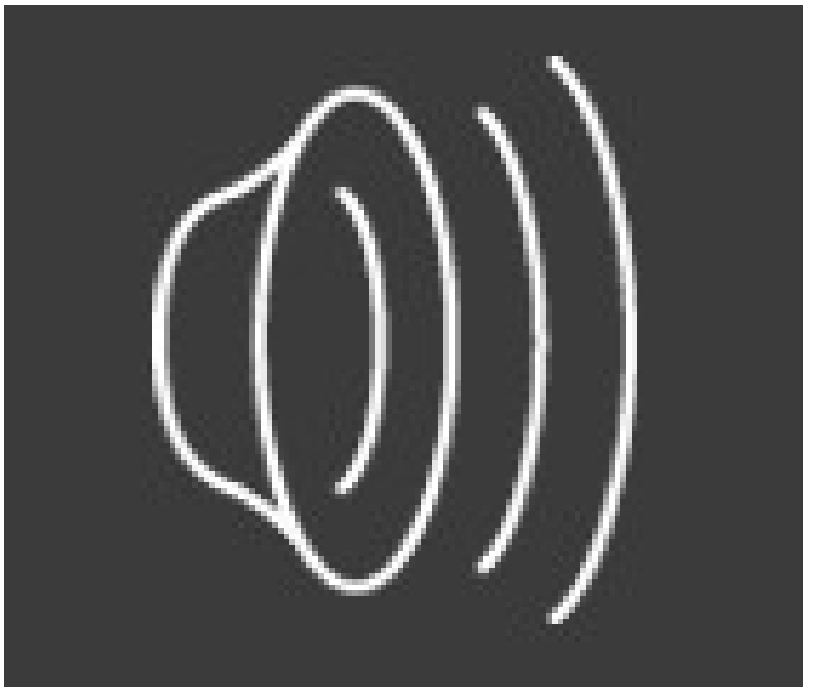
# Rossby Wave Instability

(or.... **Kelvin-Helmholtz** in rotating disks)

Sketch of the
Rossby Wave Instability

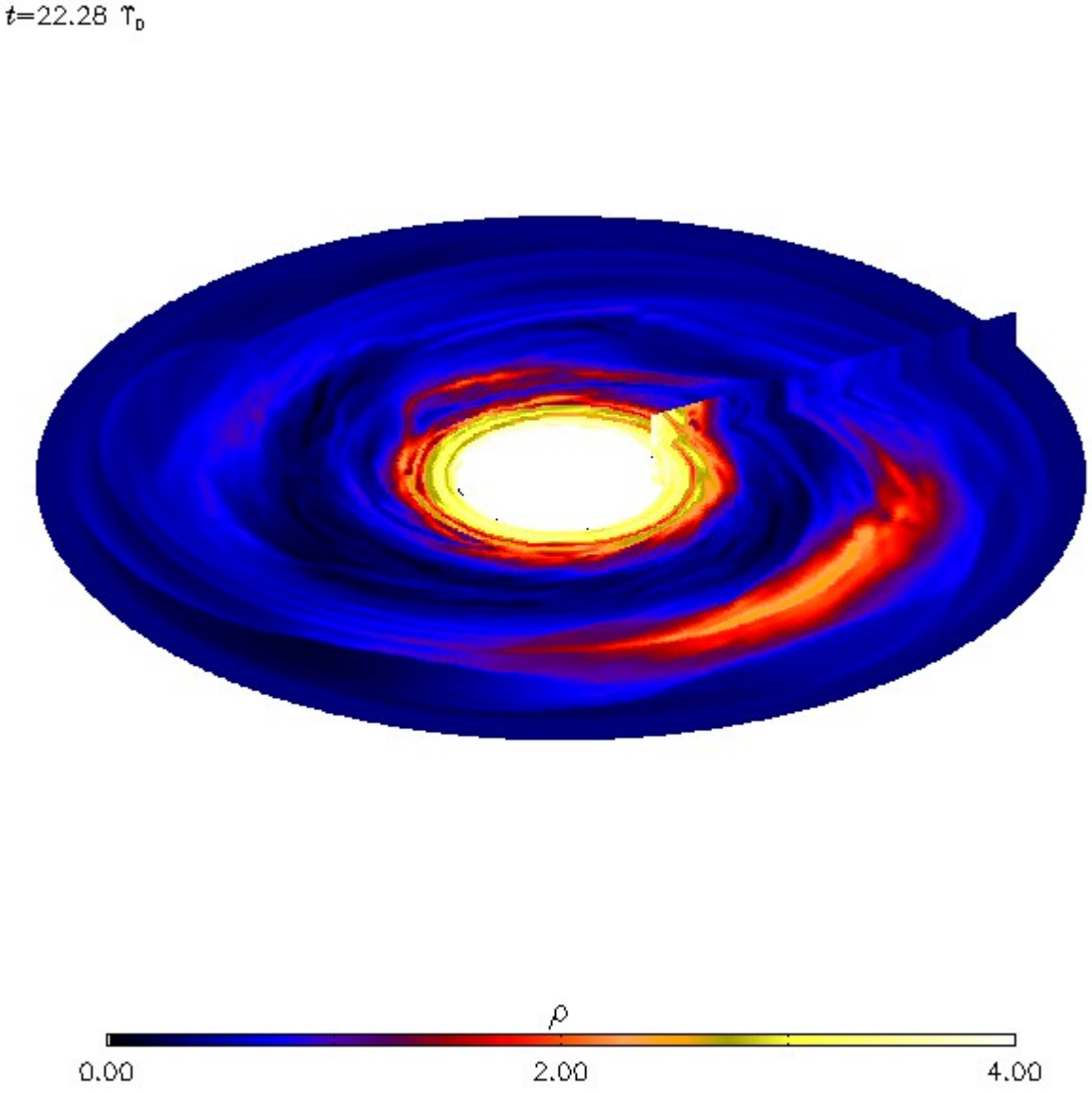


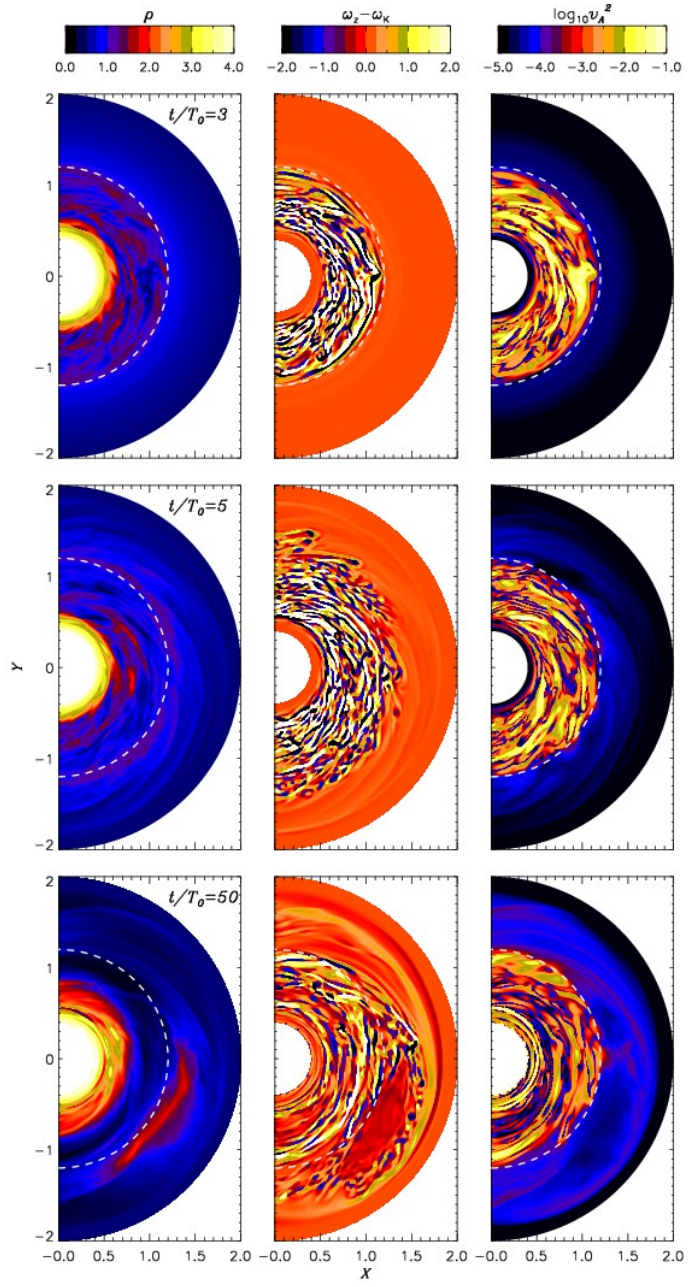

Source: Meheut et al. (2010)



Source: Lyra et al. (2008b)

# Active/dead zone boundary

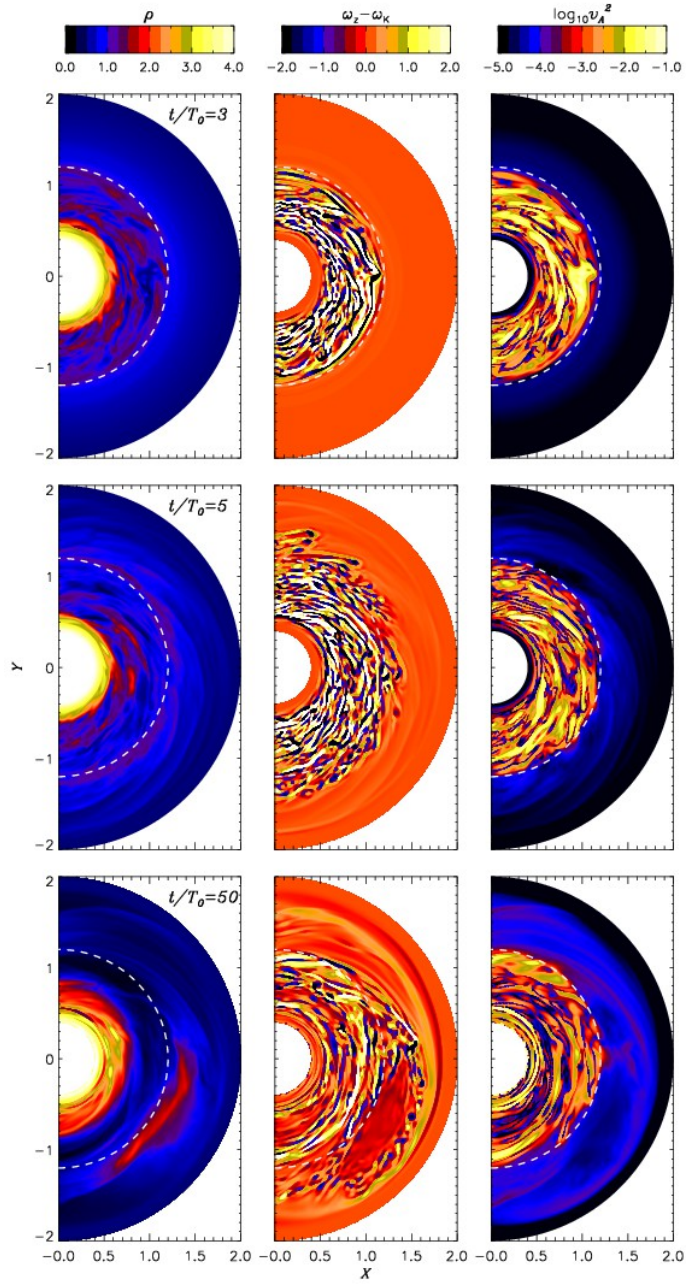



Magnetized inner disk + resistive outer disk

Source: Lyra & Mac Low (2012, submitted)

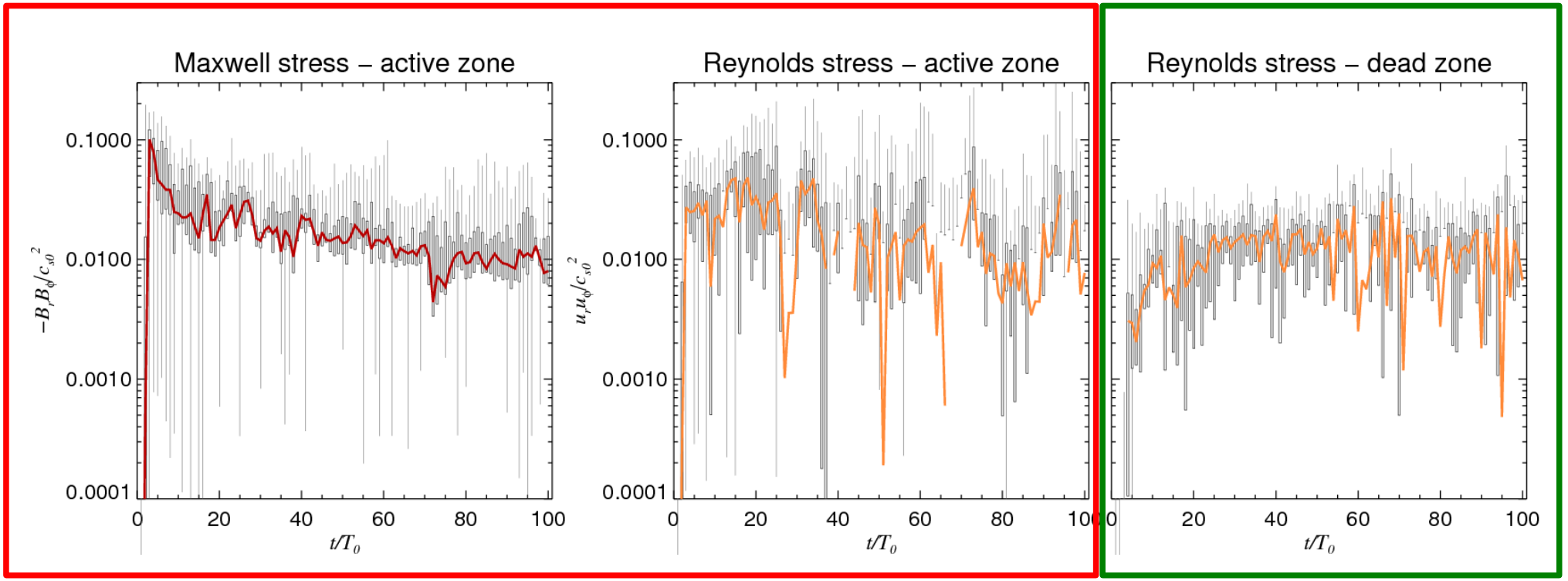
# Active/dead zone boundary




Magnetized inner disk + resistive outer disk

Source: Lyra & Mac Low (2012, submitted)

# ***Significant angular momentum transport***

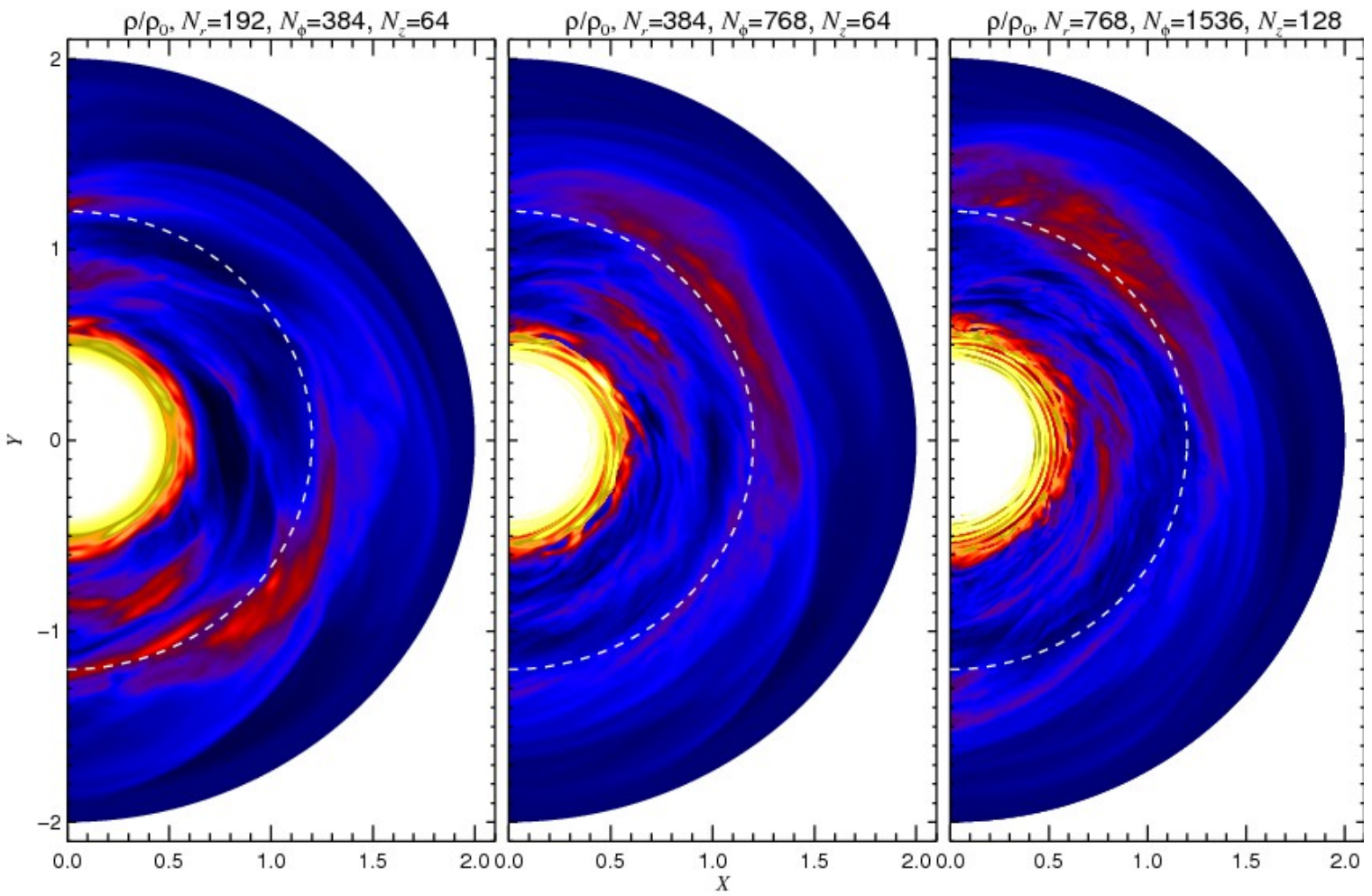



**Large mass accretion rates in the dead zone,**
comparable to the MRI in the active zone!

Source: Lyra & Mac Low (2012, submitted)

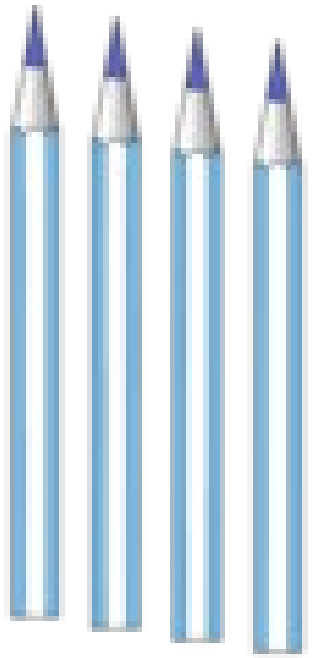
# Fishy vortex in the active zone...

Resolution



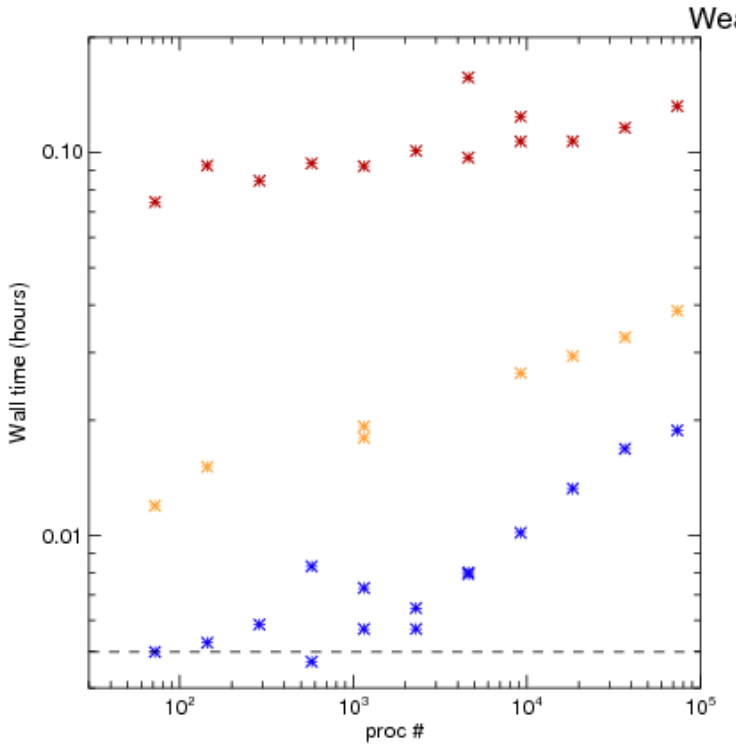

Δ/H = 10 Δ/H = 20 Δ/H = 40

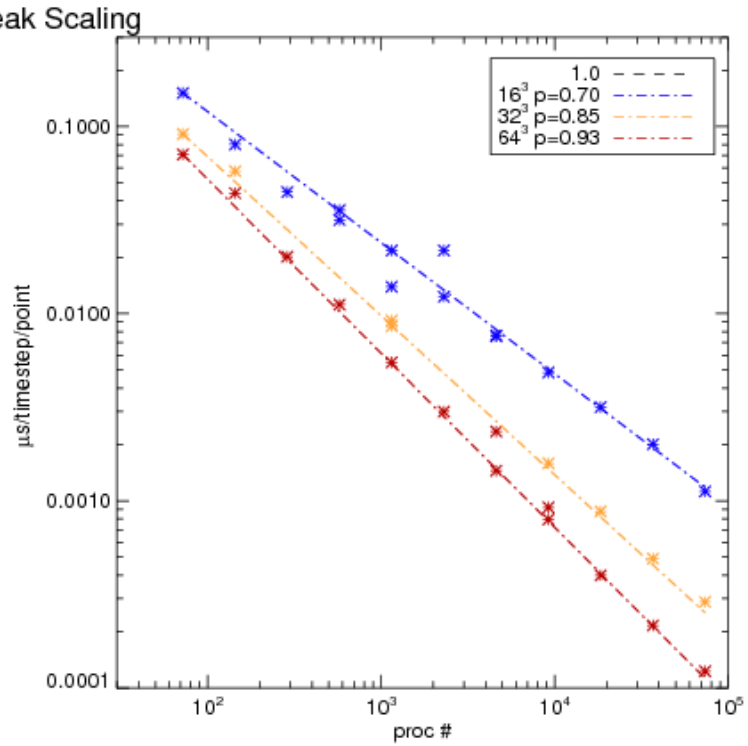
# *High end computing*



**The Pencil Code**

Brandenburg & Dobler (2002)



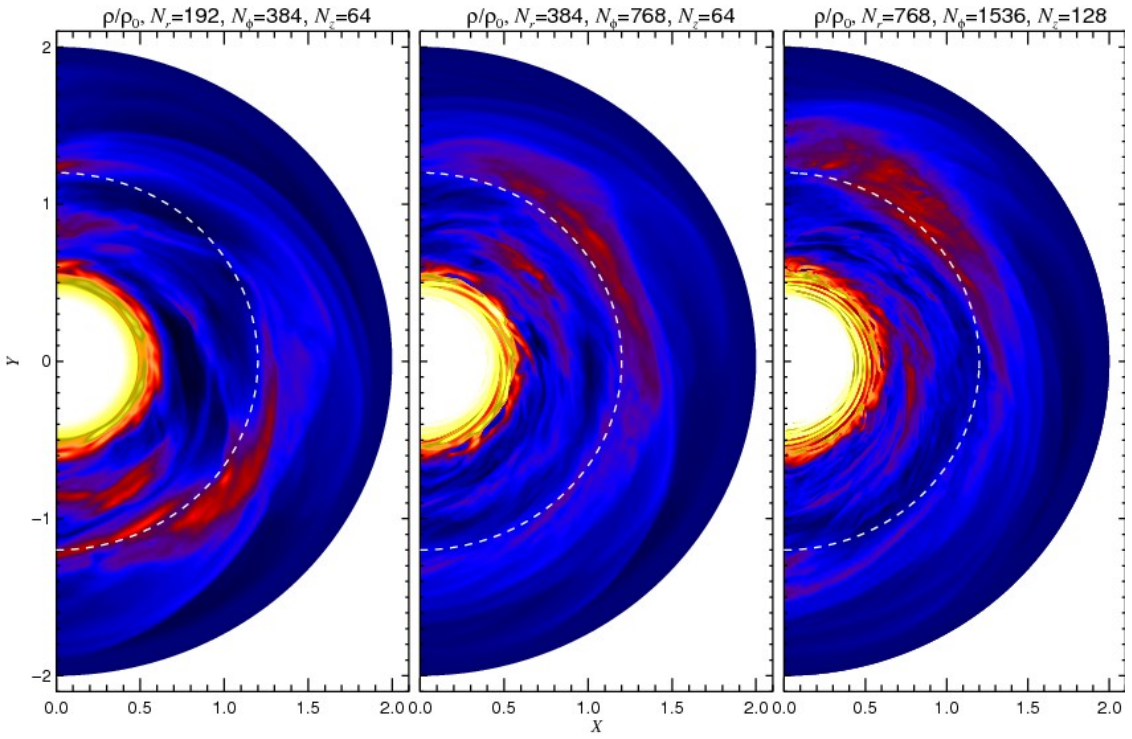




Good scaling up to > **70,000 processors !**

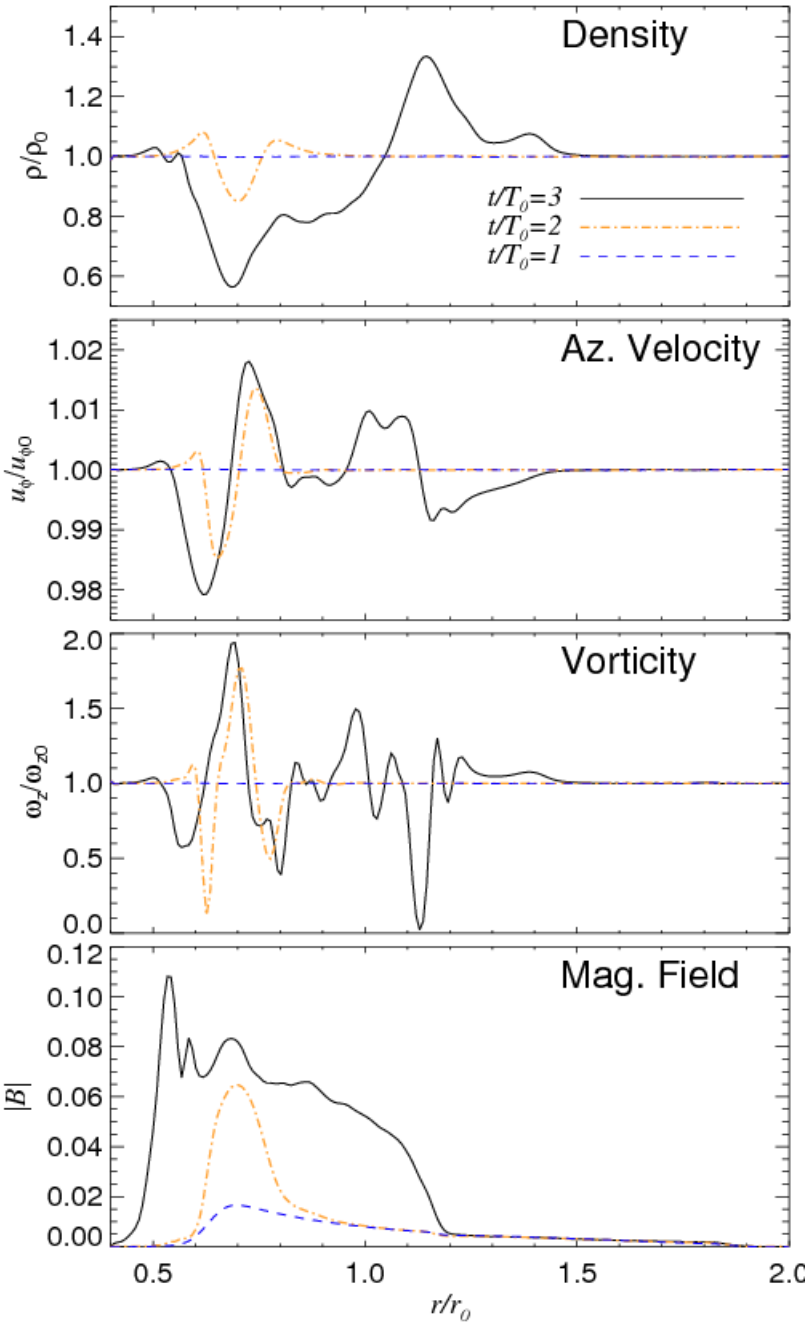
(At NICS - Kraken)

# Fishy vortex in the active zone...

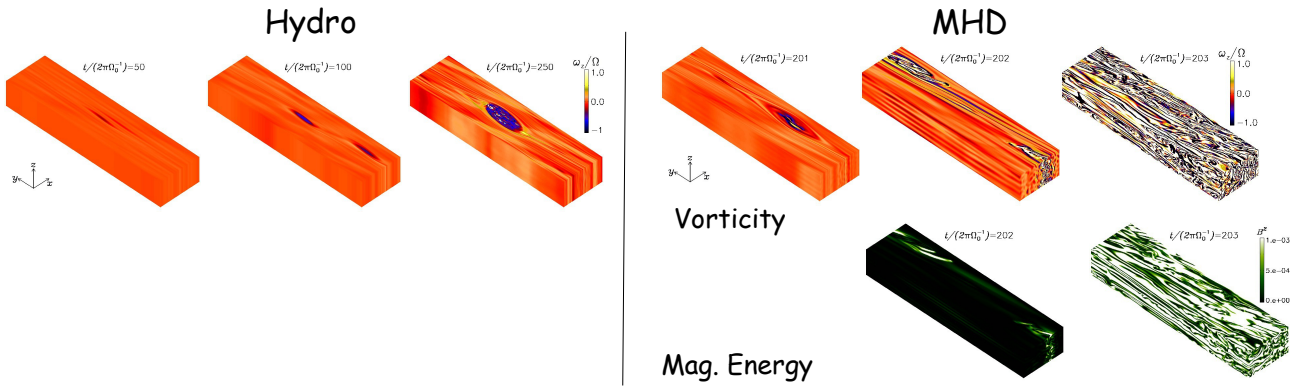
Resolution



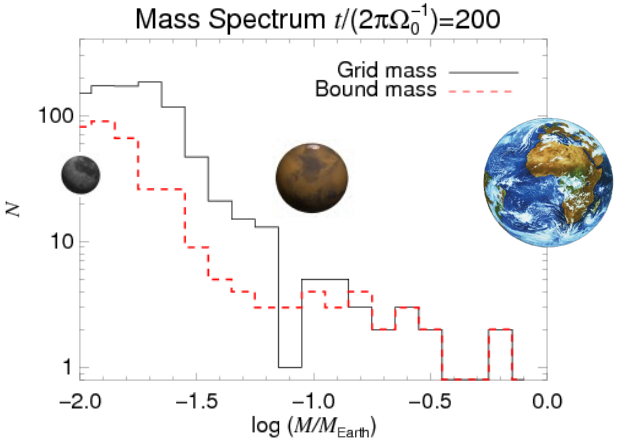

$\Delta/H = 10$ $\Delta/H = 20$ $\Delta/H = 40$



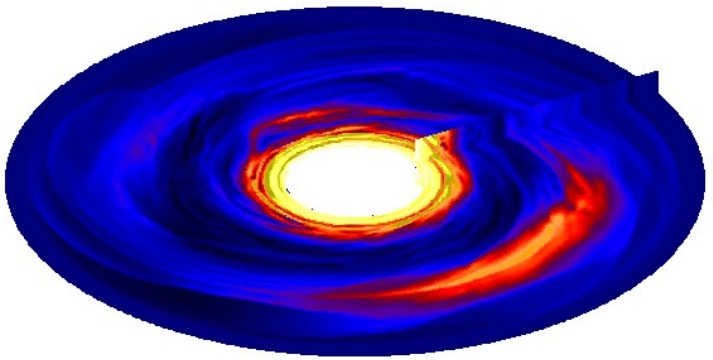
Baroclinic vortices do not survive magnetization: restricted to dead zones. (Lyra & Klahr 2011)



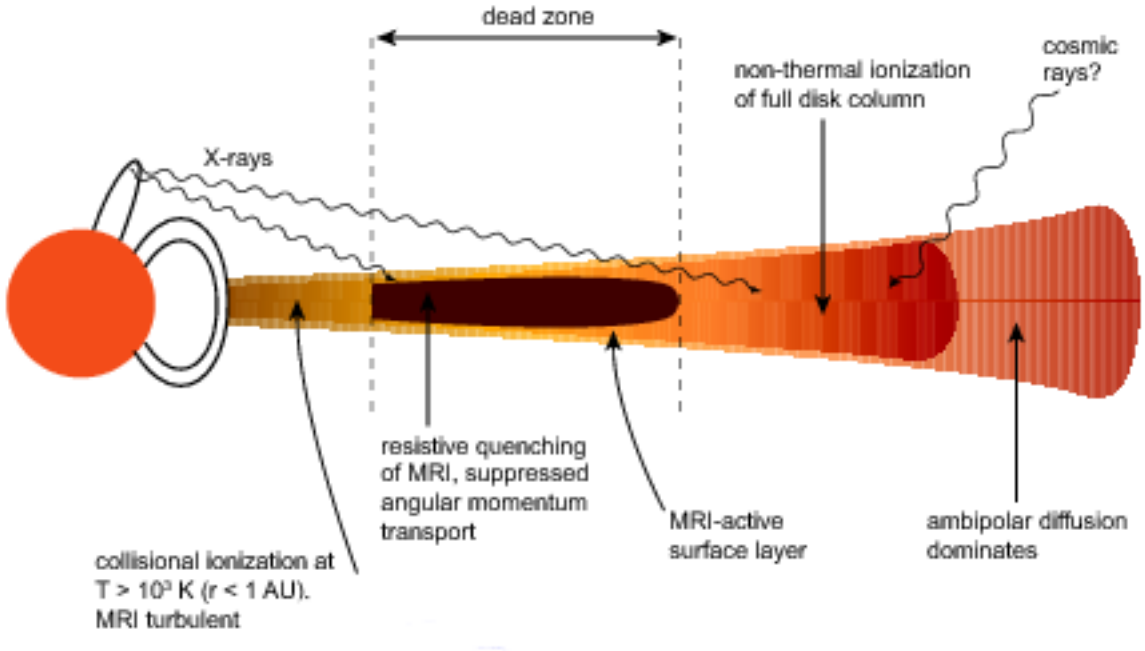

Vortices form planets (Lyra et al. 2009)



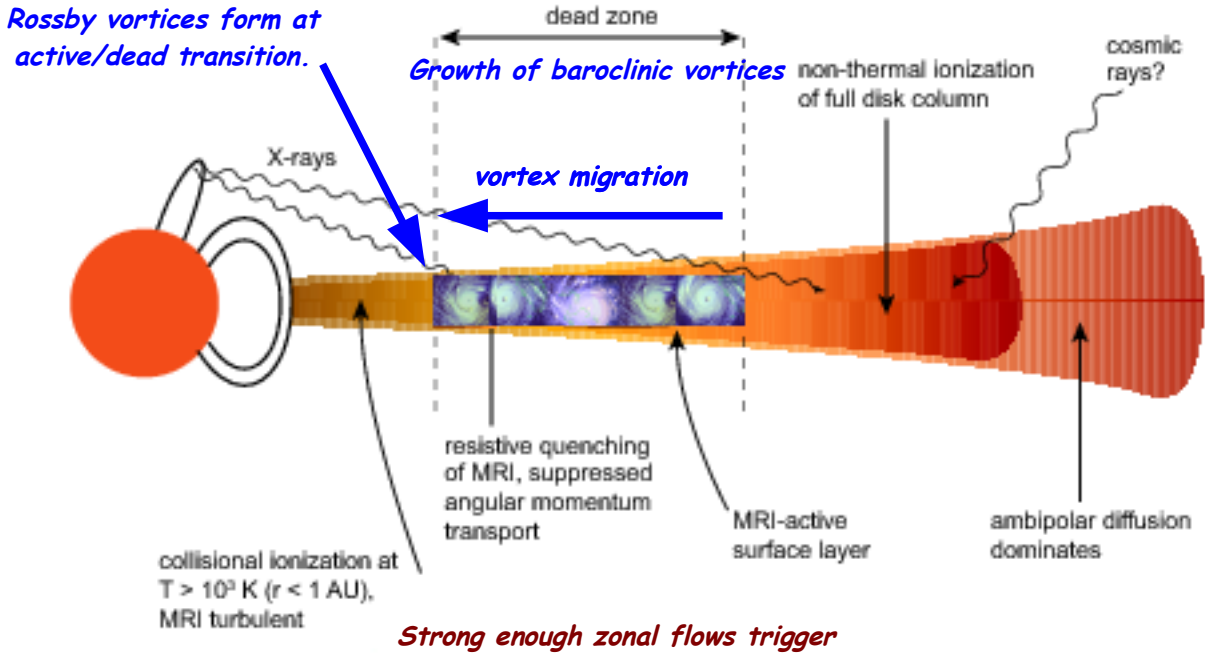

Rossby vortices form at the dead/active transition, possibly survive magnetization. (Lyra & Mac Low 2012)



# Suggested large-scale phenomenology



# Suggested large-scale phenomenology



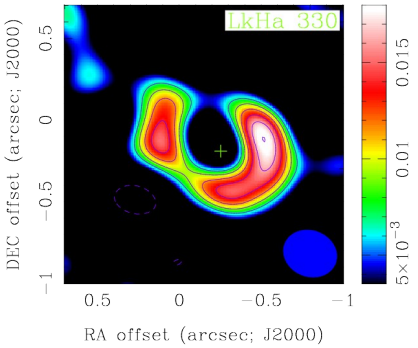

*Vortices assist the formation of planets.*

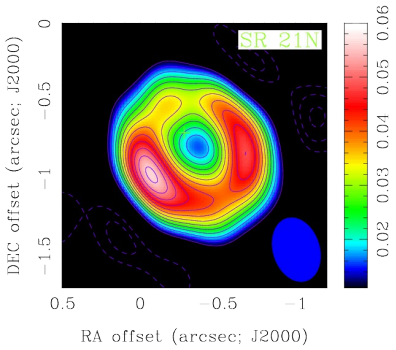
# A possible detection of vortices in disks

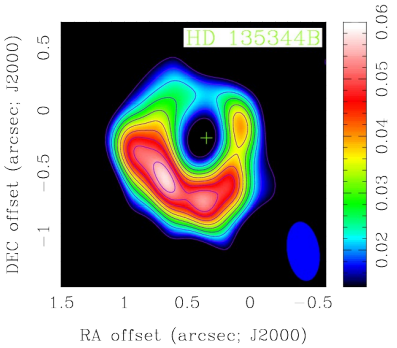
Observations

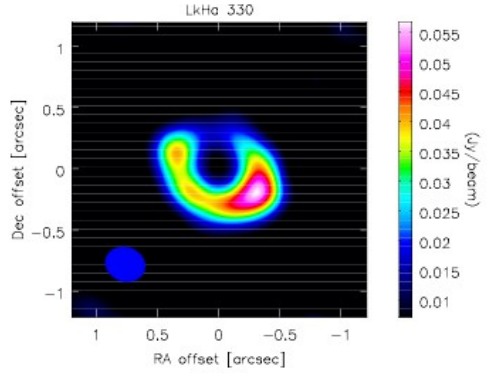
Brown et al. (2009)

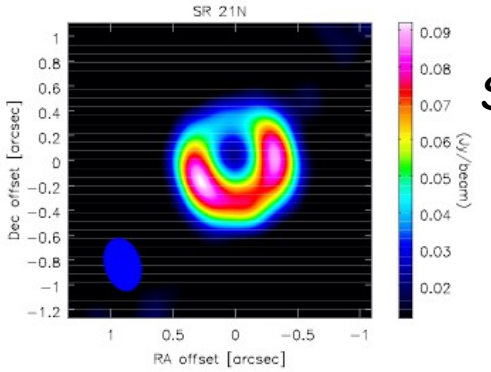
(see also Sean Andrews' talk)

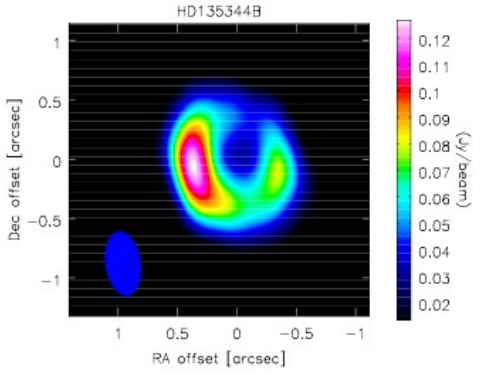


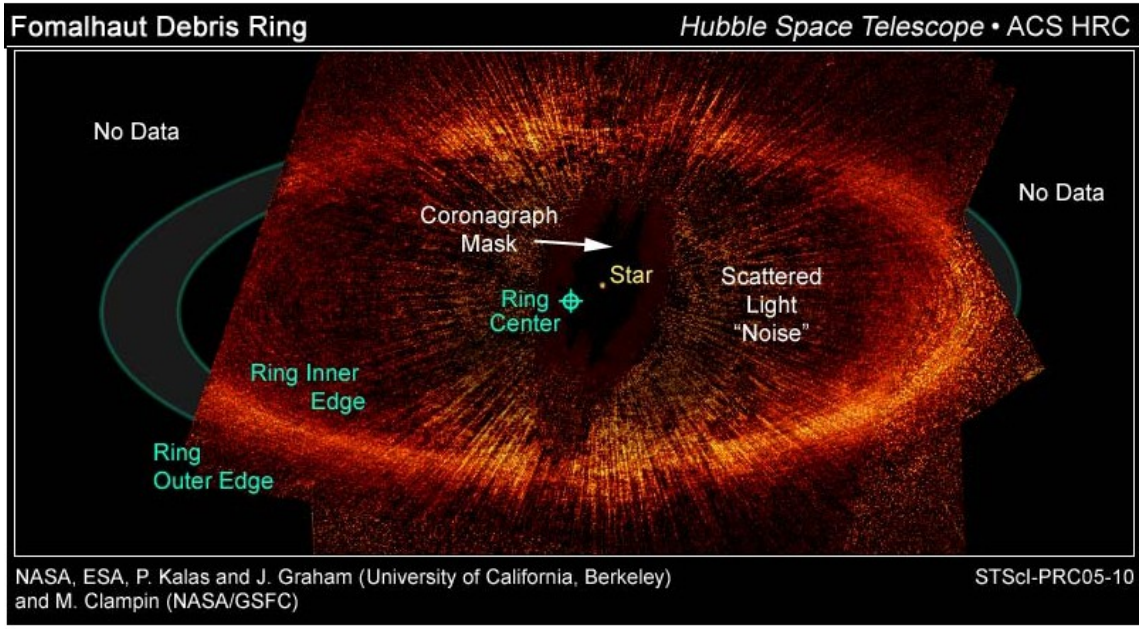



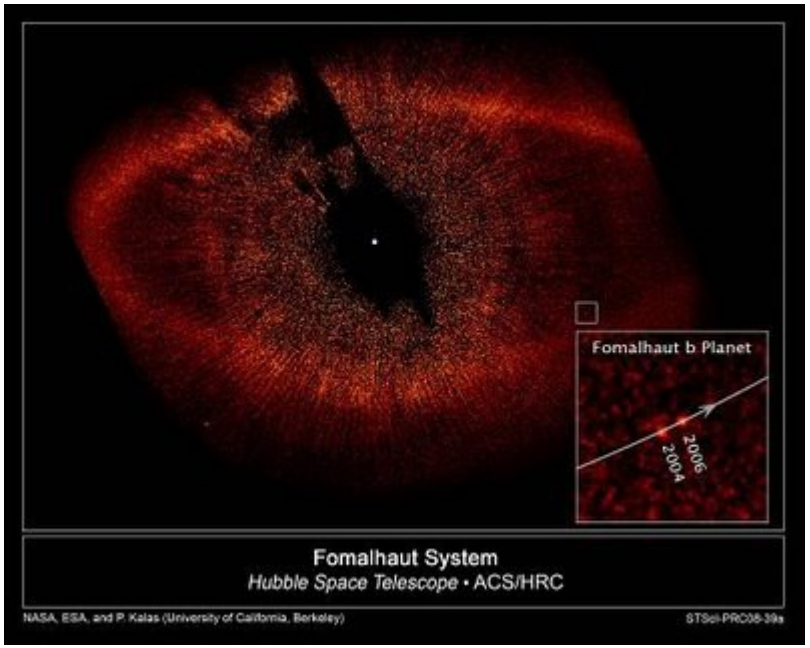

Simulated observations of Rossby vortices

Regaly et al. (2012)

# Sharp and eccentric rings in debris disks



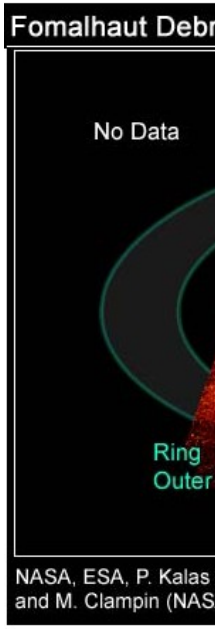

Narrow sharp eccentric ring




Detection of a source quickly heralded as a planet Fomalhaut b

# Sharp and eccentric rings in debris disks

## However.....

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### INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

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ABSTRACT

The nearby A4-type star Fomalhaut hosts a debris belt in the form of an eccentric ring, which is thought to be caused by dynamical influence from a giant planet companion. In 2008, a detection of a point source inside the inner edge of the ring was reported and was interpreted as a direct image of the planet, named Fomalhaut b. The detection was made at ~600–800 nm, but no corresponding signatures were found in the near-infrared range, where the bulk emission of such a planet should be expected. Here, we present deep observations of Fomalhaut with *Spitzer*/IRAC at 4.5 $\mu$m, using a novel point-spread function subtraction technique based on angular differential imaging and Locally Optimized Combination of Images, in order to substantially improve the *Spitzer* contrast at small separations. The results provide more than an order of magnitude improvement in the upper flux limit of Fomalhaut b and exclude the possibility that any flux from a giant planet surface contributes to the observed flux at visible wavelengths. This renders any direct connection between the observed light source and the dynamically inferred giant planet highly unlikely. We discuss several possible interpretations of the total body of observations of the Fomalhaut system and find that the interpretation that best matches the available data for the observed source is scattered light from a transient or semi-transient dust cloud.

*Key words:* circumstellar matter – planetary systems – stars: early-type

*Online-only material:* color figures


**Planet not detected in infrared**

# Sharp and eccentric rings in debris disks without planets

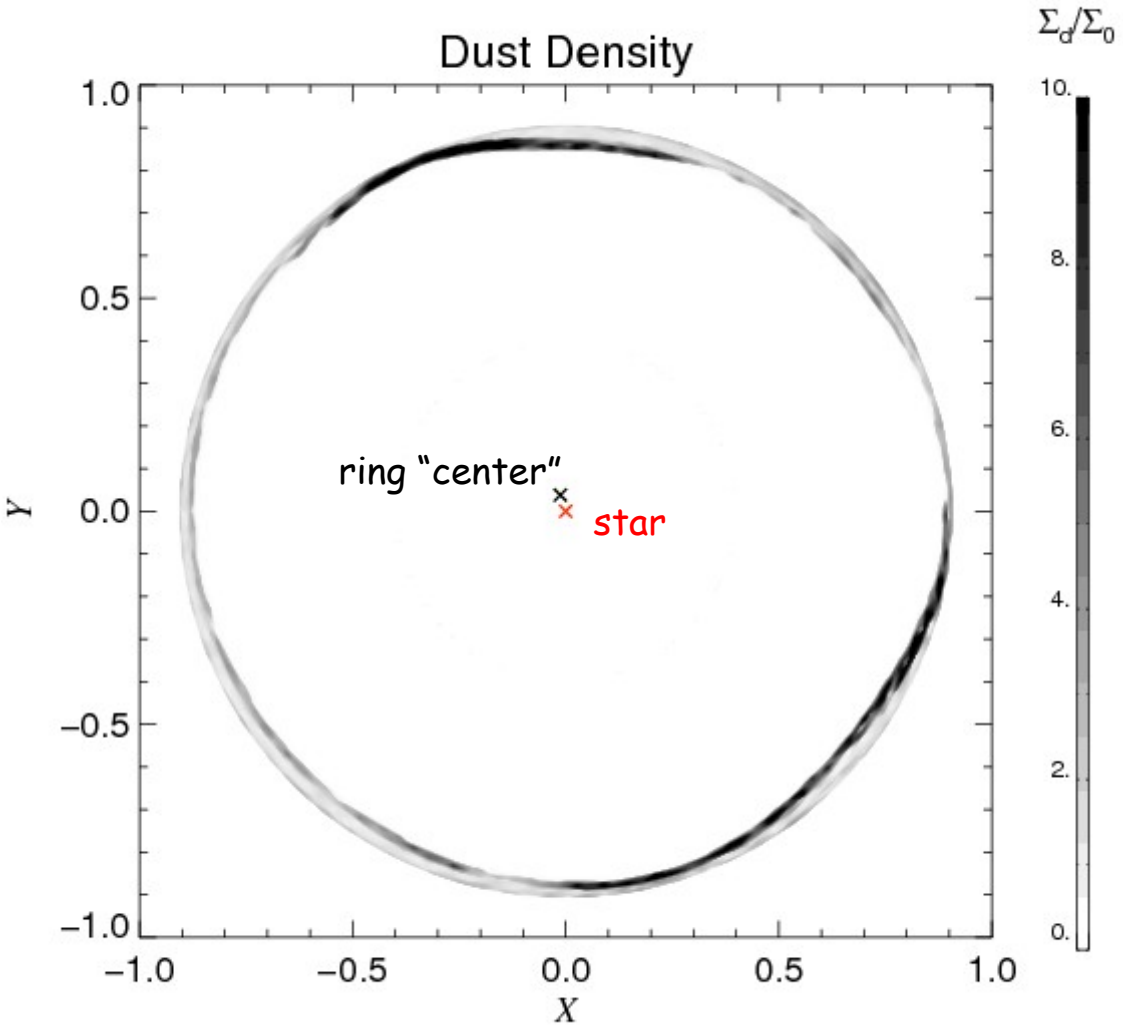
Dust heats gas

Heated gas = high pressure region

High pressure concentrates dust

Lyra & Kuchner (2012)

# Sharp and eccentric rings in debris disks without planets




Eccentricity e=0.04

Lyra & Kuchner (2012)

Thanks for you attention!!!