Formation of planets in turbulent accretion disks

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CASCA, Calgary June 2012

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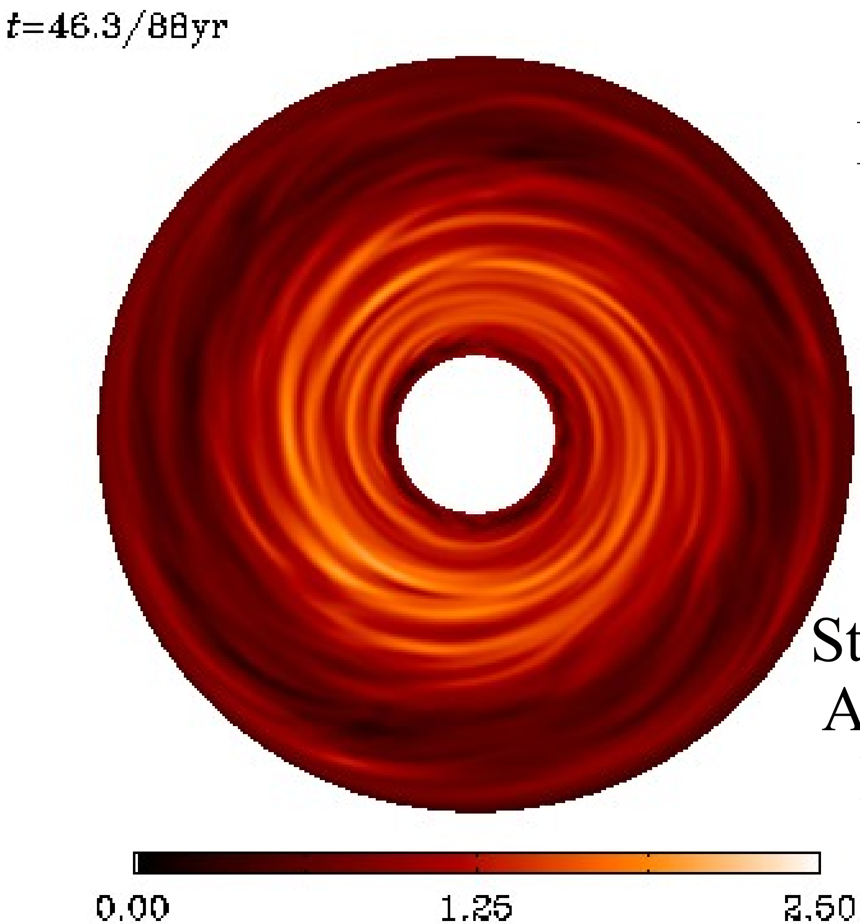
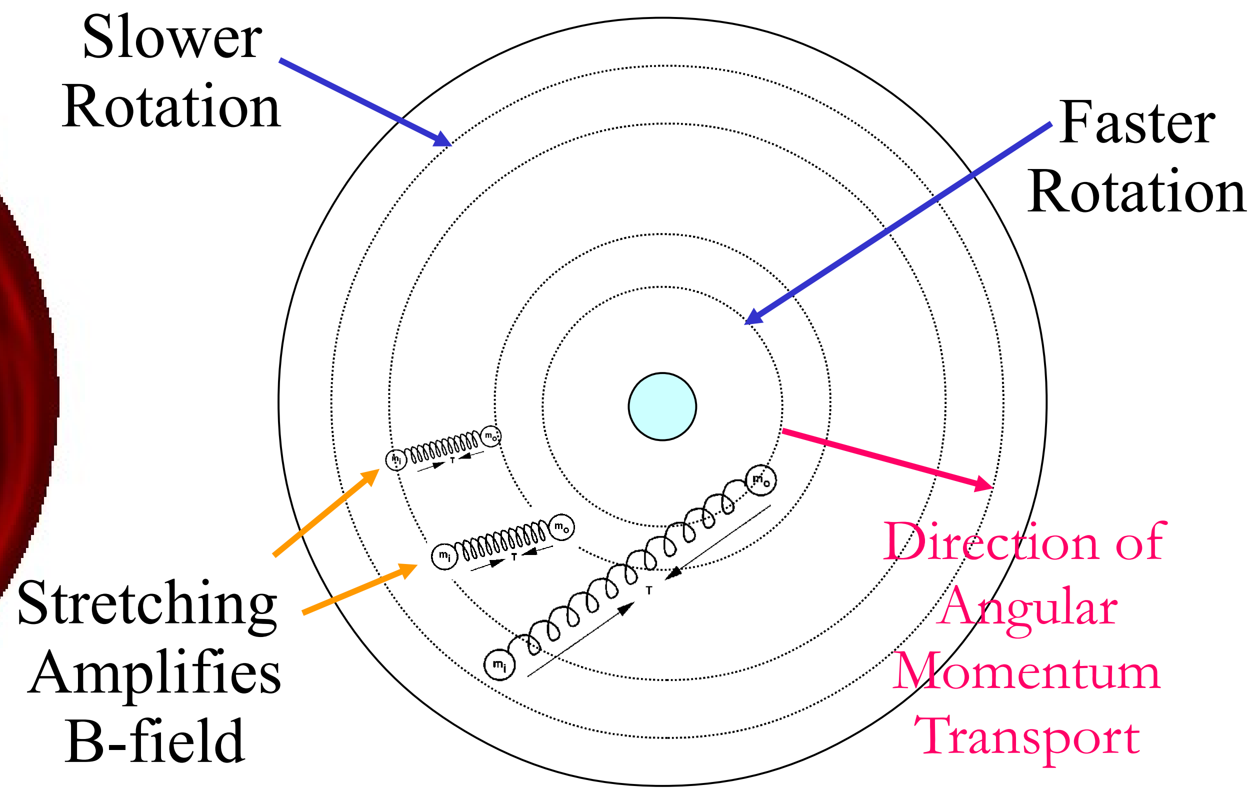
Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability



Source: Lyra et al (2008a)

MRI sketch



Unstable if angular velocity decreases outward

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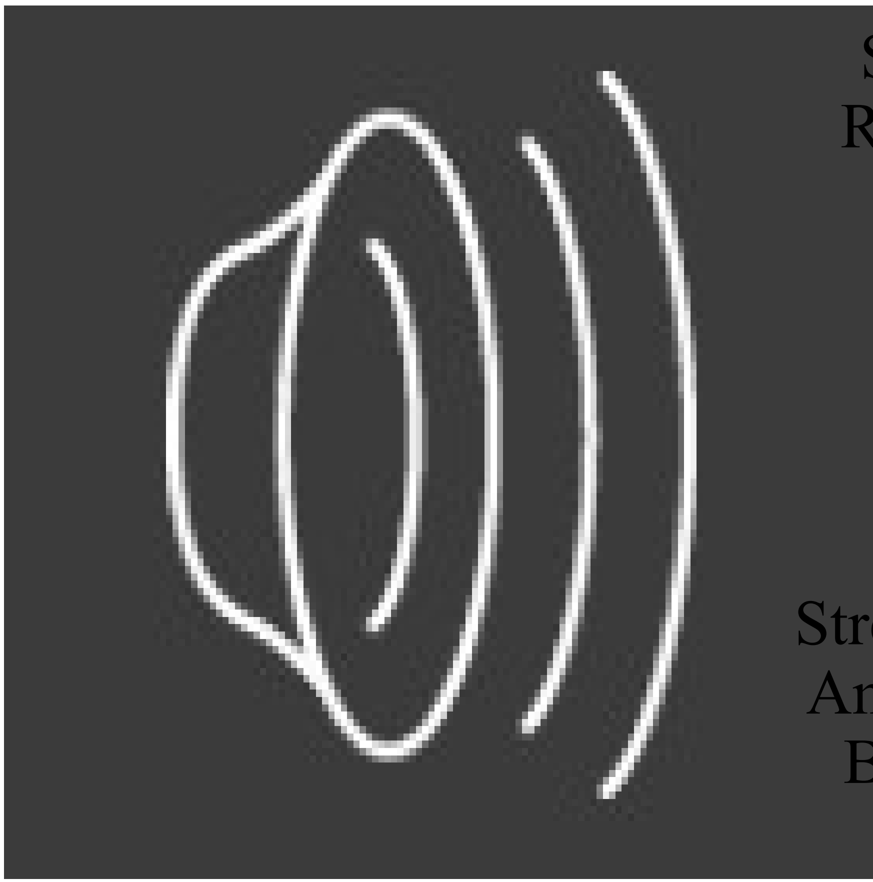
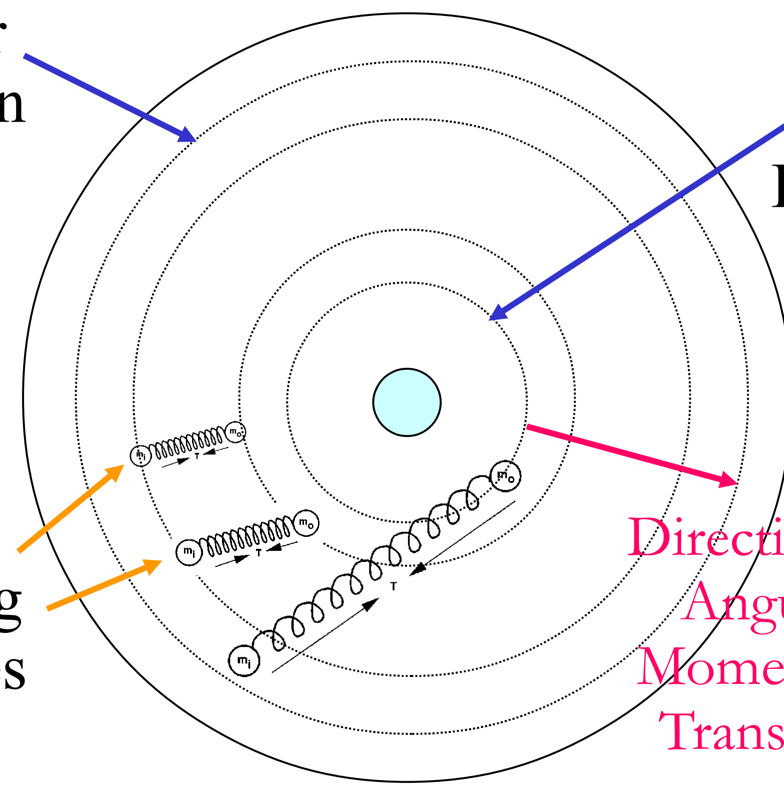
MRI sketch

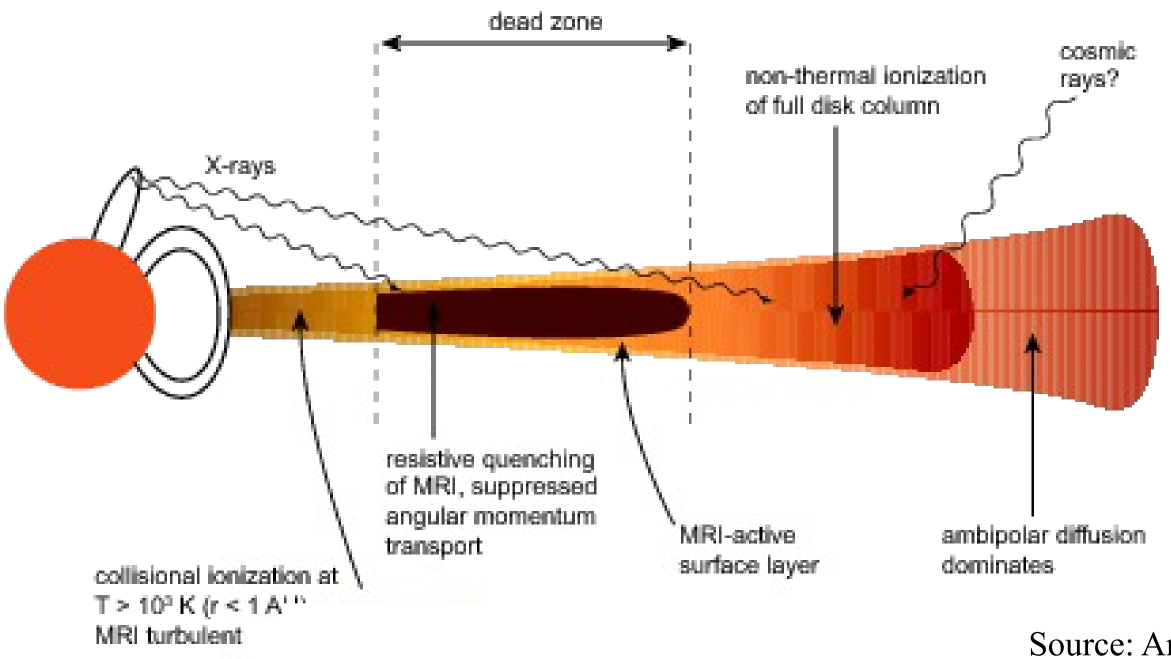




Unstable if angular velocity decreases outward

Source: Lyra et al (2008a)

Alas... Dead zones are robust features of accretion disks

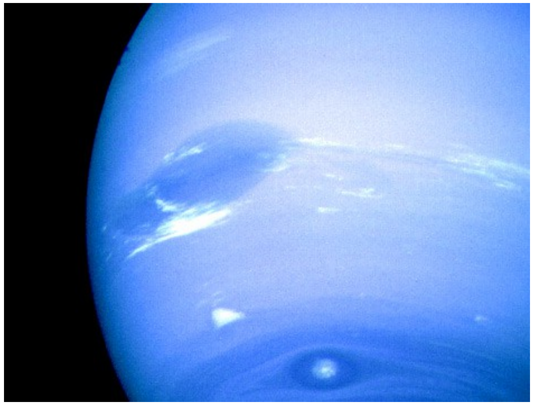


Source: Armitage (2010)

Therefore....

The search for **hydrodynamical routes**
for turbulence **continues**.

A possibility: Baroclinic Instability

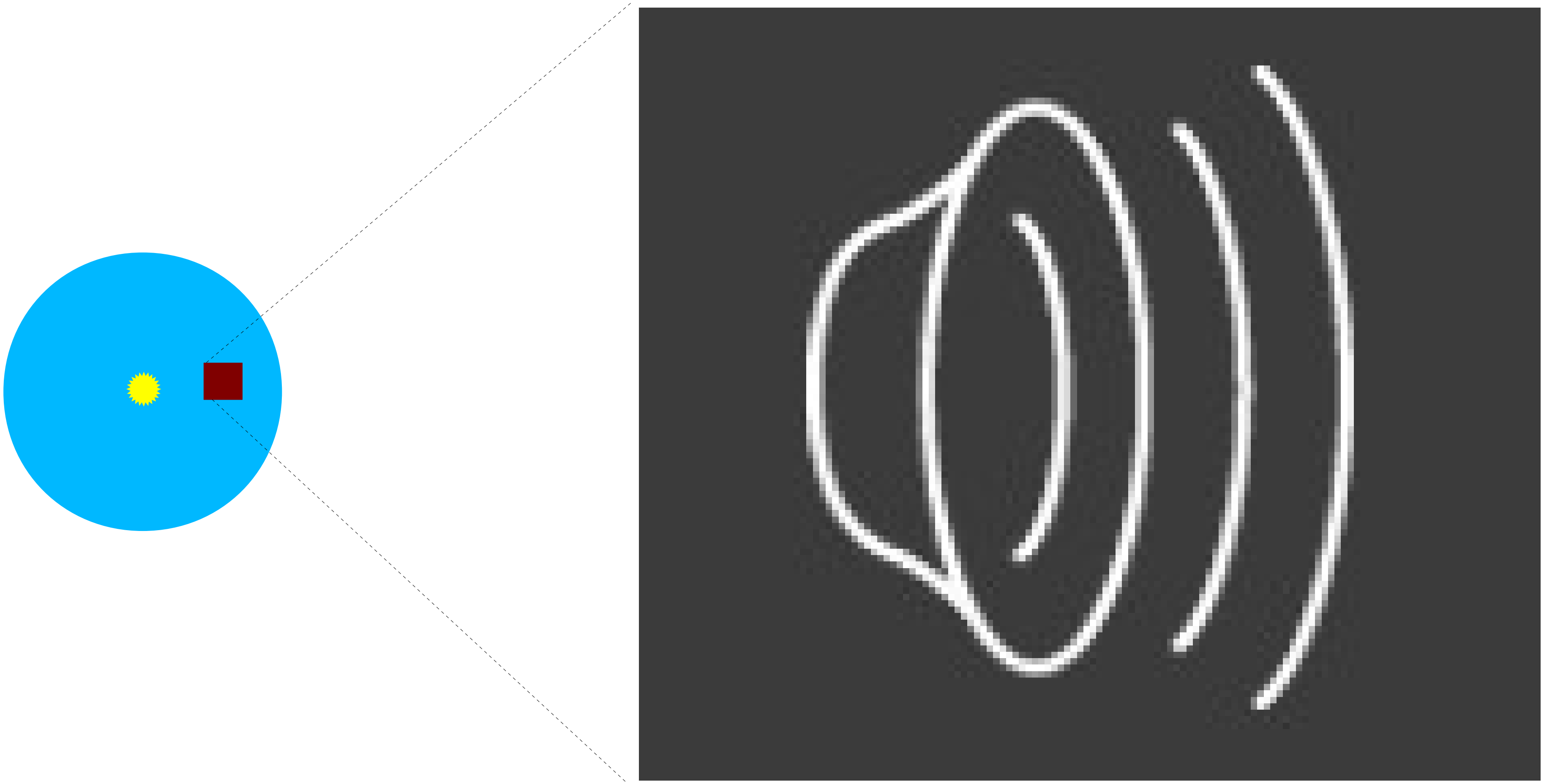


- Well known in planetary atmospheres

And vortices are:

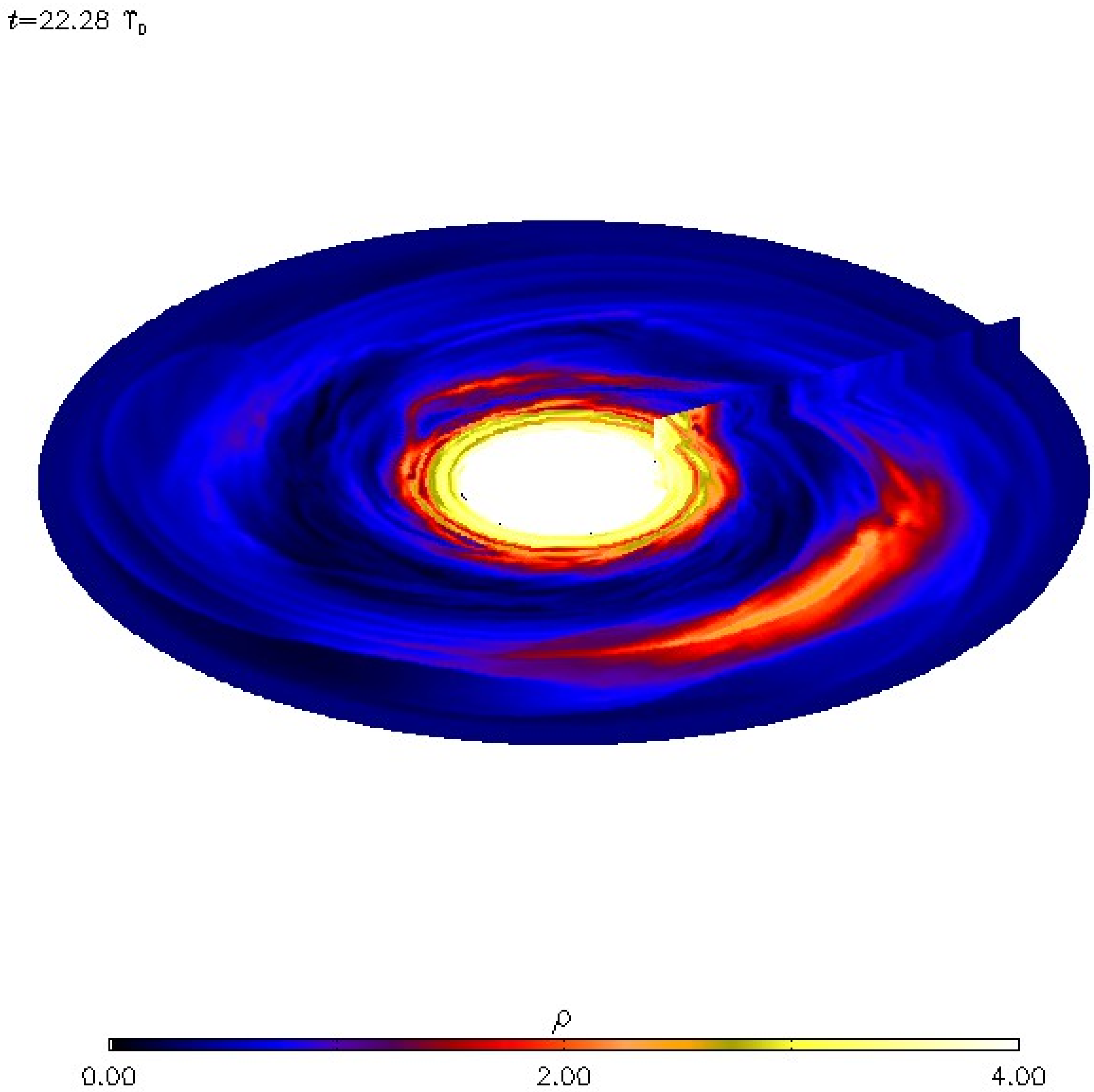
- A solution of the NS equations: persistent structures
- Very interesting for planet formation:

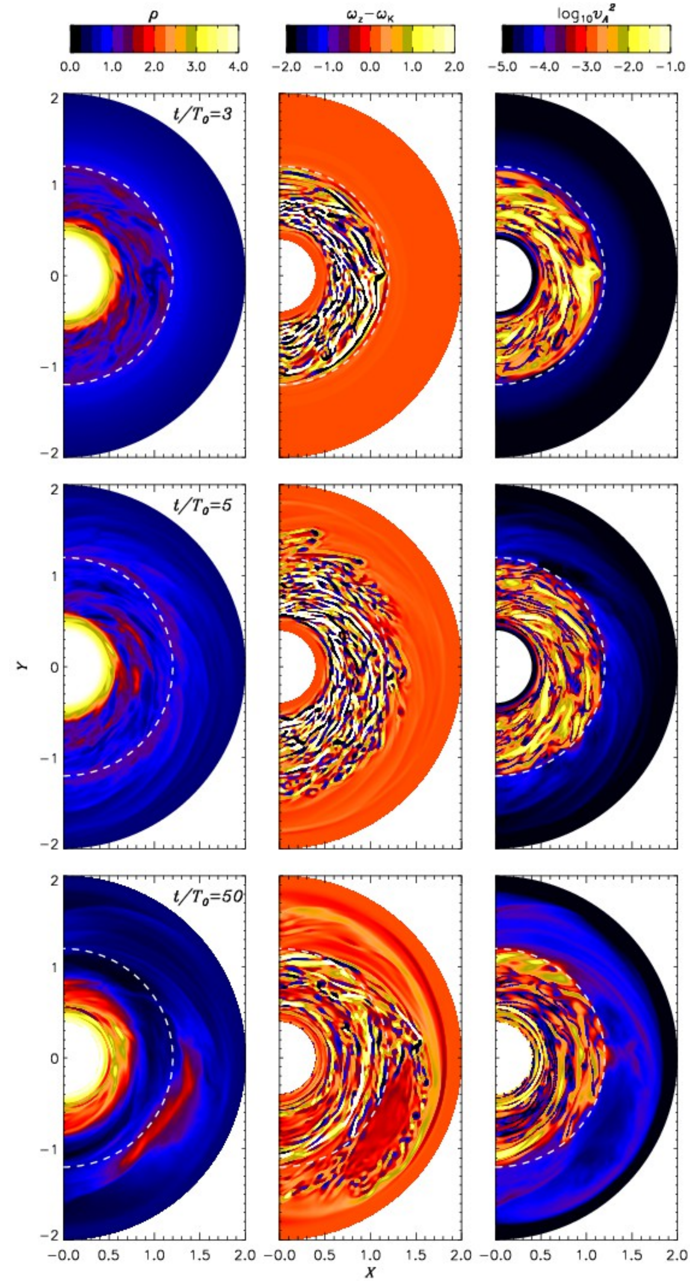
Baroclinic Instability - Excitation and self-sustenance of vortices



Source: Lyra & Klahr (2011)

Active/dead zone boundary

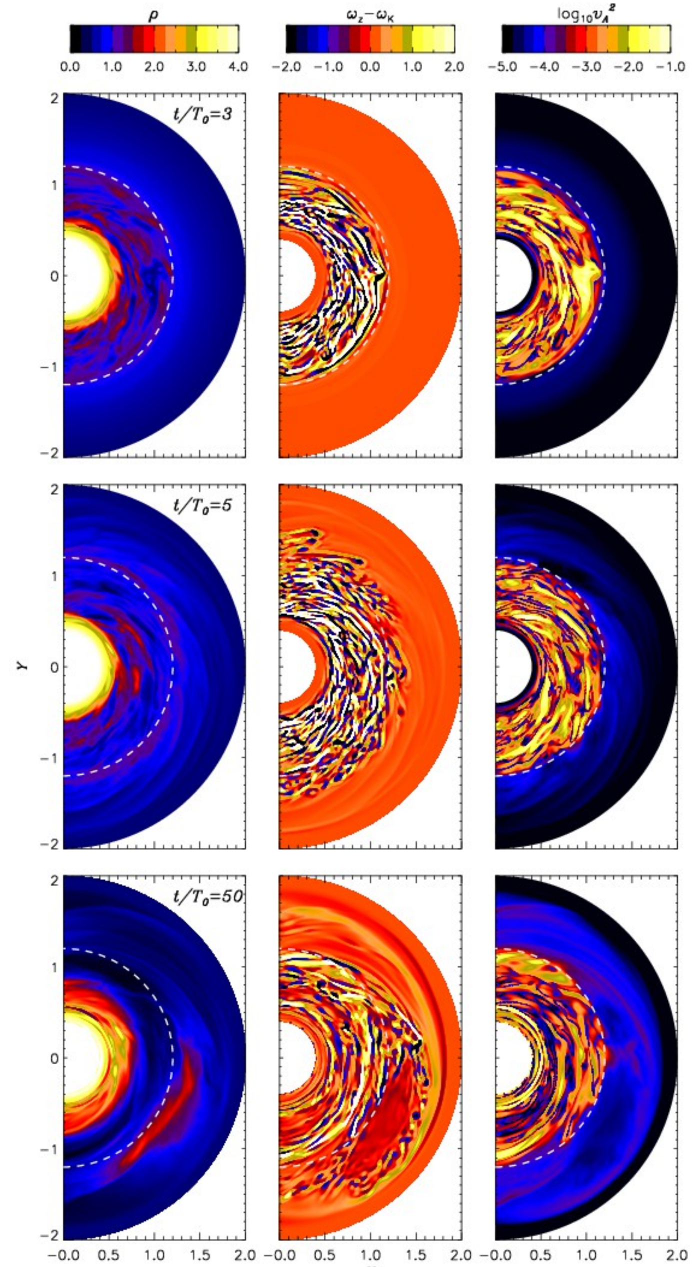




Magnetized inner disk + resistive outer disk

Source: Lyra & Mac Low (2012, submitted)

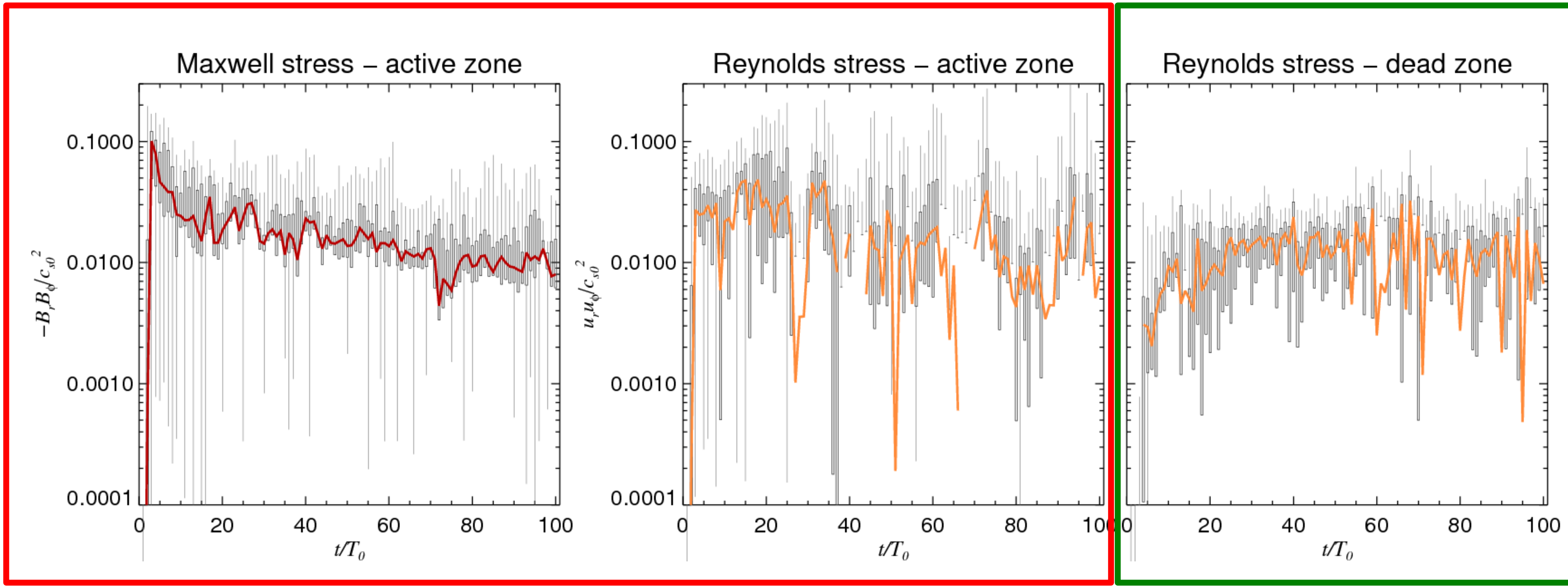
Active/dead zone boundary



Magnetized inner disk + resistive outer disk

Source: Lyra & Mac Low (2012, submitted)

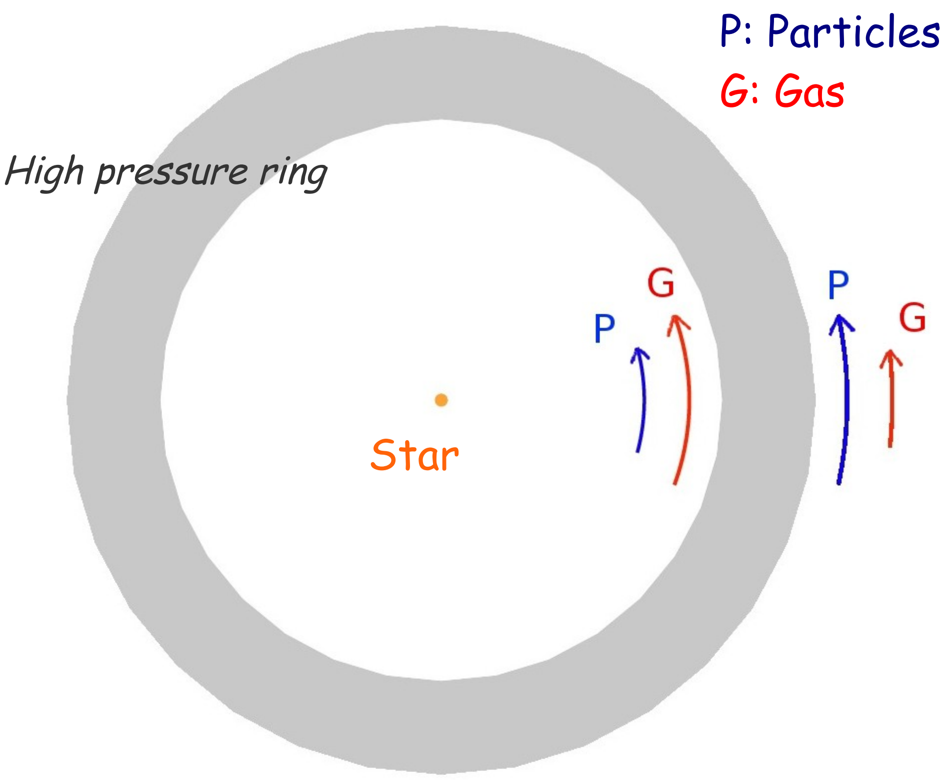
Significant angular momentum transport



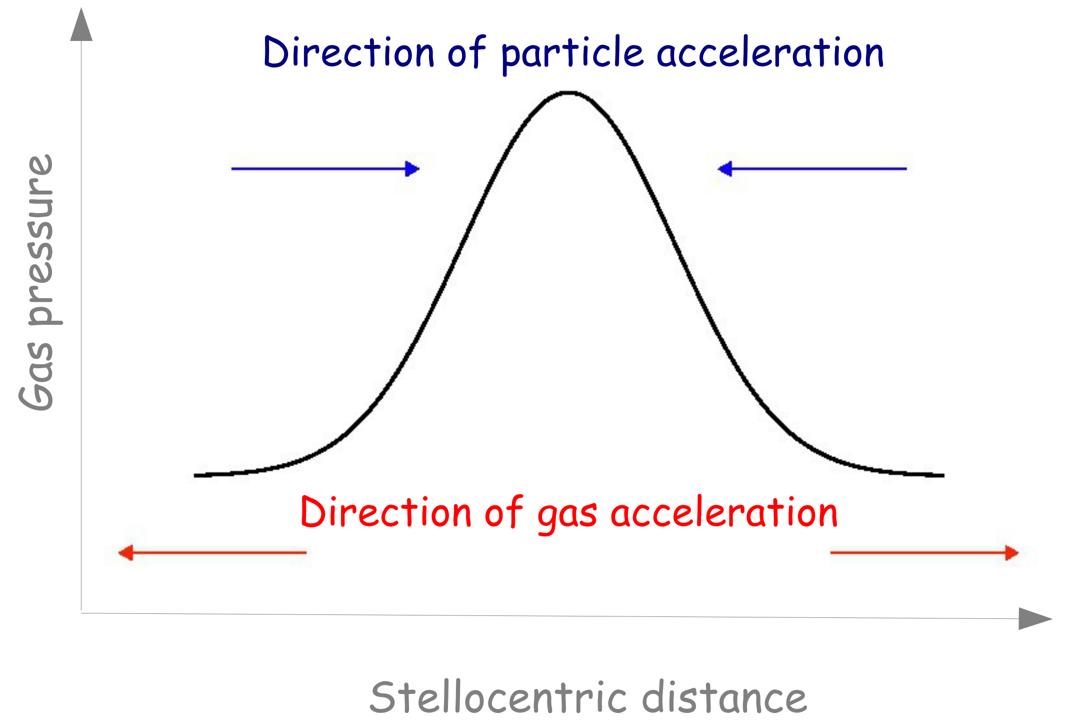
Large mass accretion rates in the dead zone,
comparable to the MRI in the active zone!

Source: Lyra & Mac Low (2012, submitted)

Forming planets in a turbulent disk



Adapted from Whipple (1972)



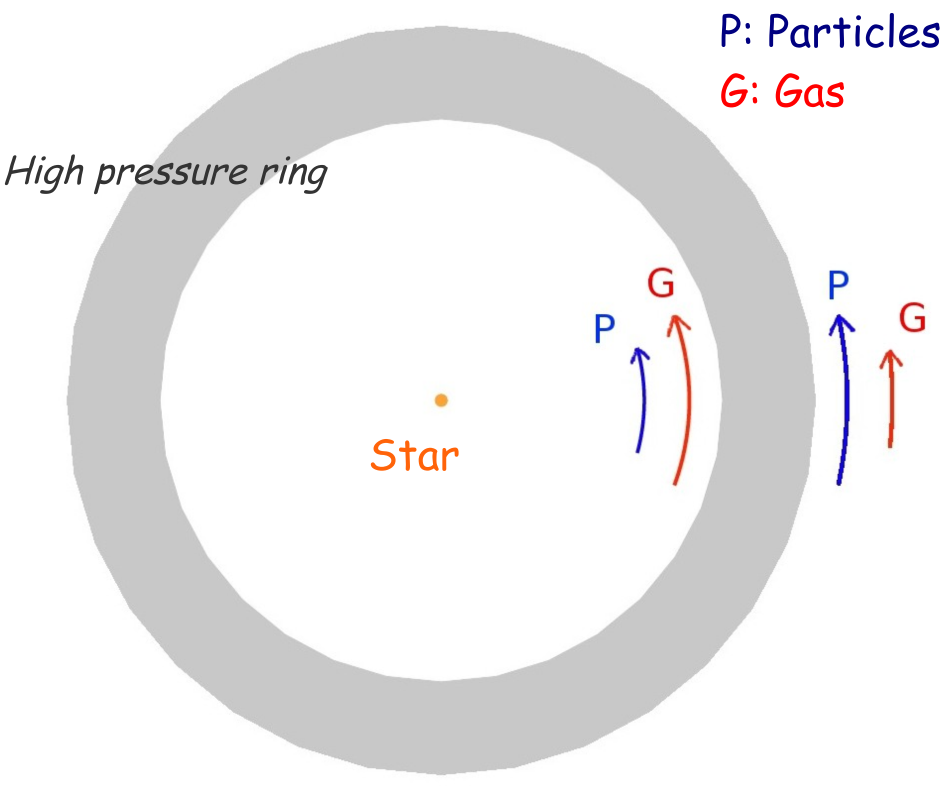
Forming planets in a turbulent disk

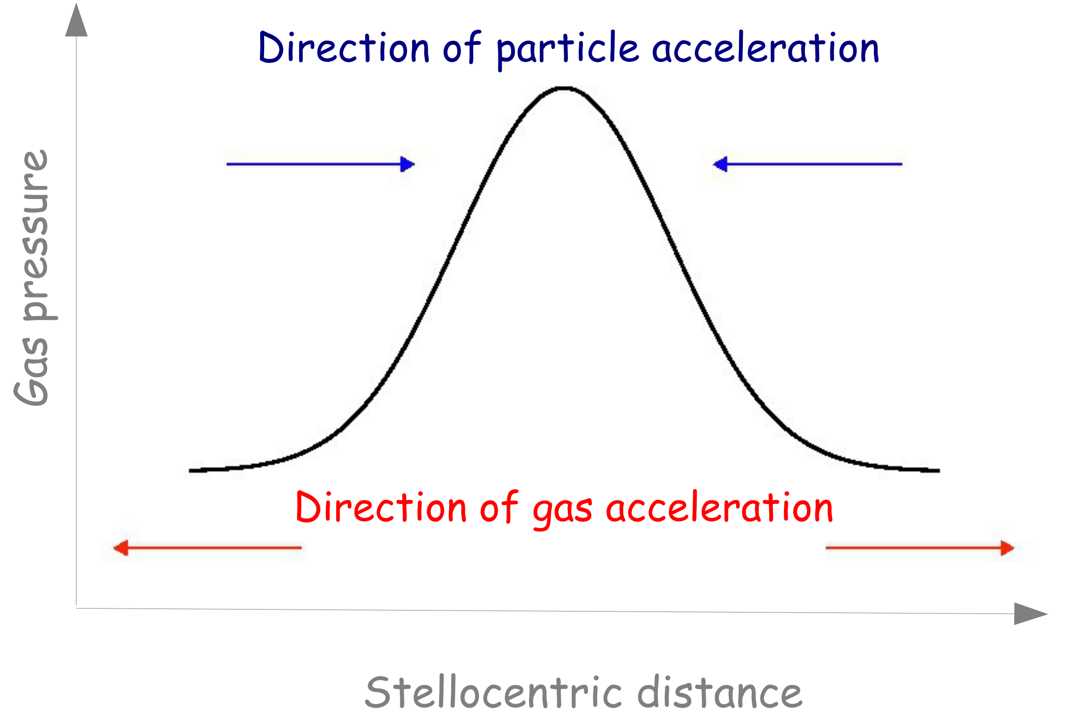
Gas $\frac{D\boldsymbol{u}}{Dt} = -\nabla\Phi - \rho^{-1}\nabla p$

Particles $\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - \frac{(\boldsymbol{w}-\boldsymbol{u})}{\tau}$

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

The drag force pushes the solids *towards* the pressure gradient





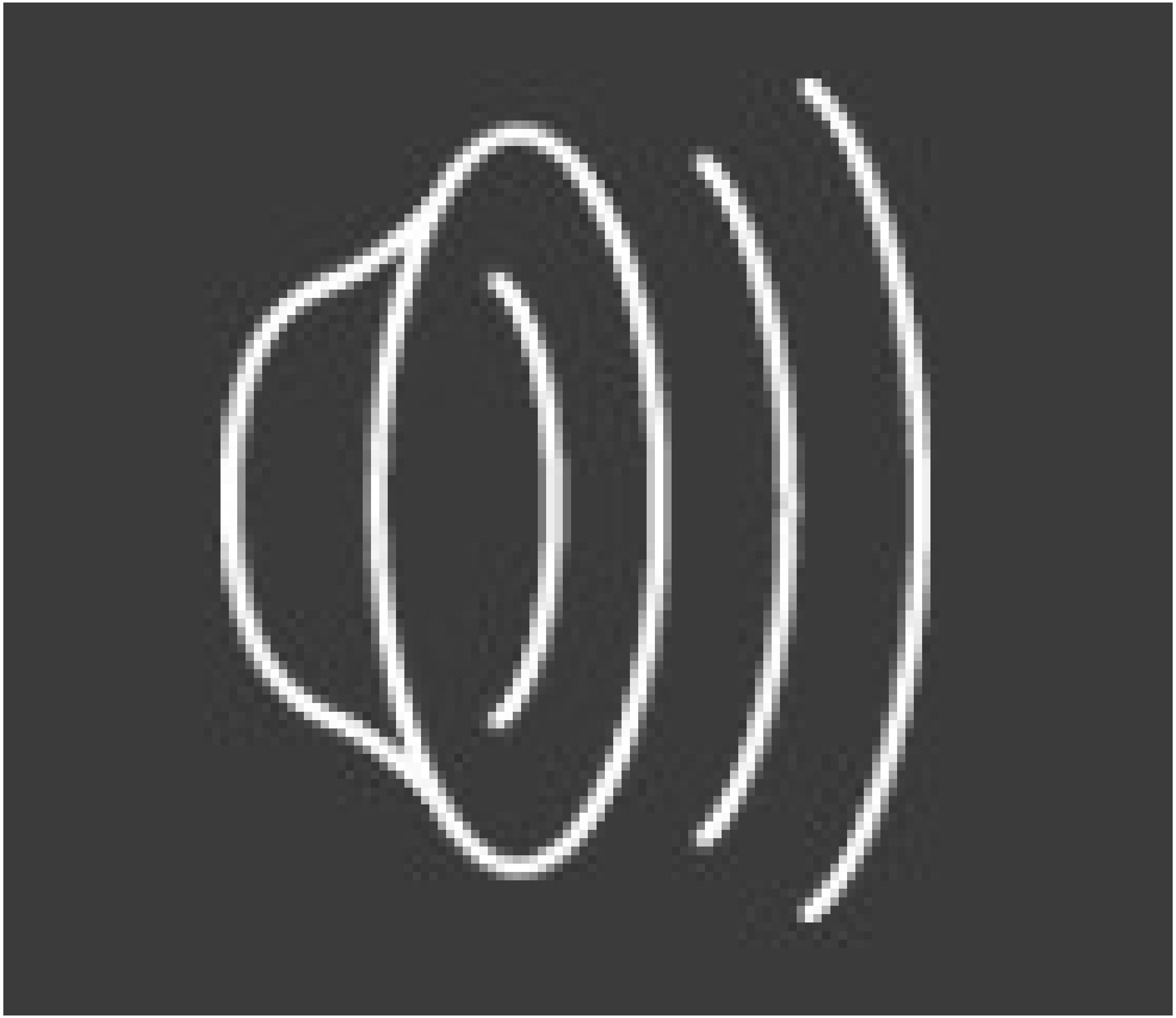
Adapted from Whipple (1972)

Solid particles

move **toward**

pressure maxima

Turbulence concentrates solids mechanically in pressure maxima



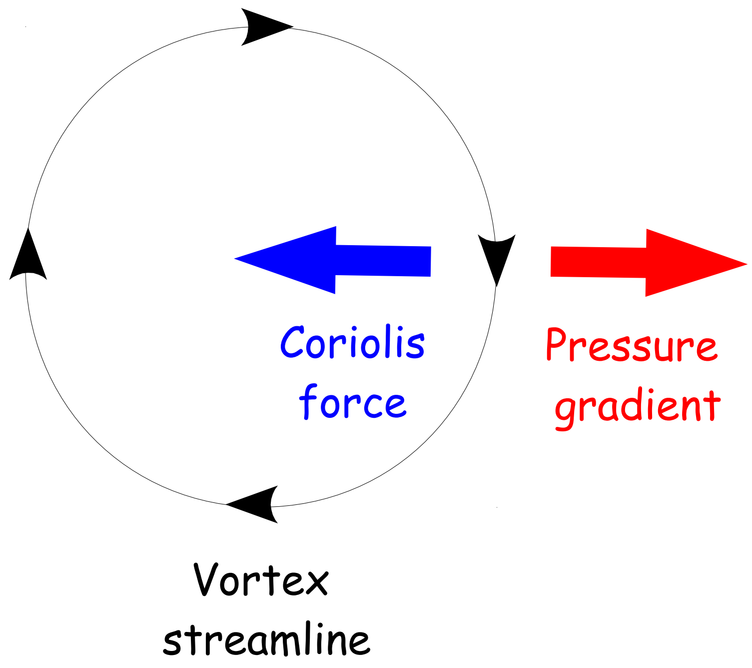
Gravitational collapse into planetesimals

Source: Johansen et al. (2007)

Turbulent eddies concentrate solids,
turning them into planetesimals...

...and vortices are **huge** eddies!

Vortex Equilibrium



Geostrophic balance:

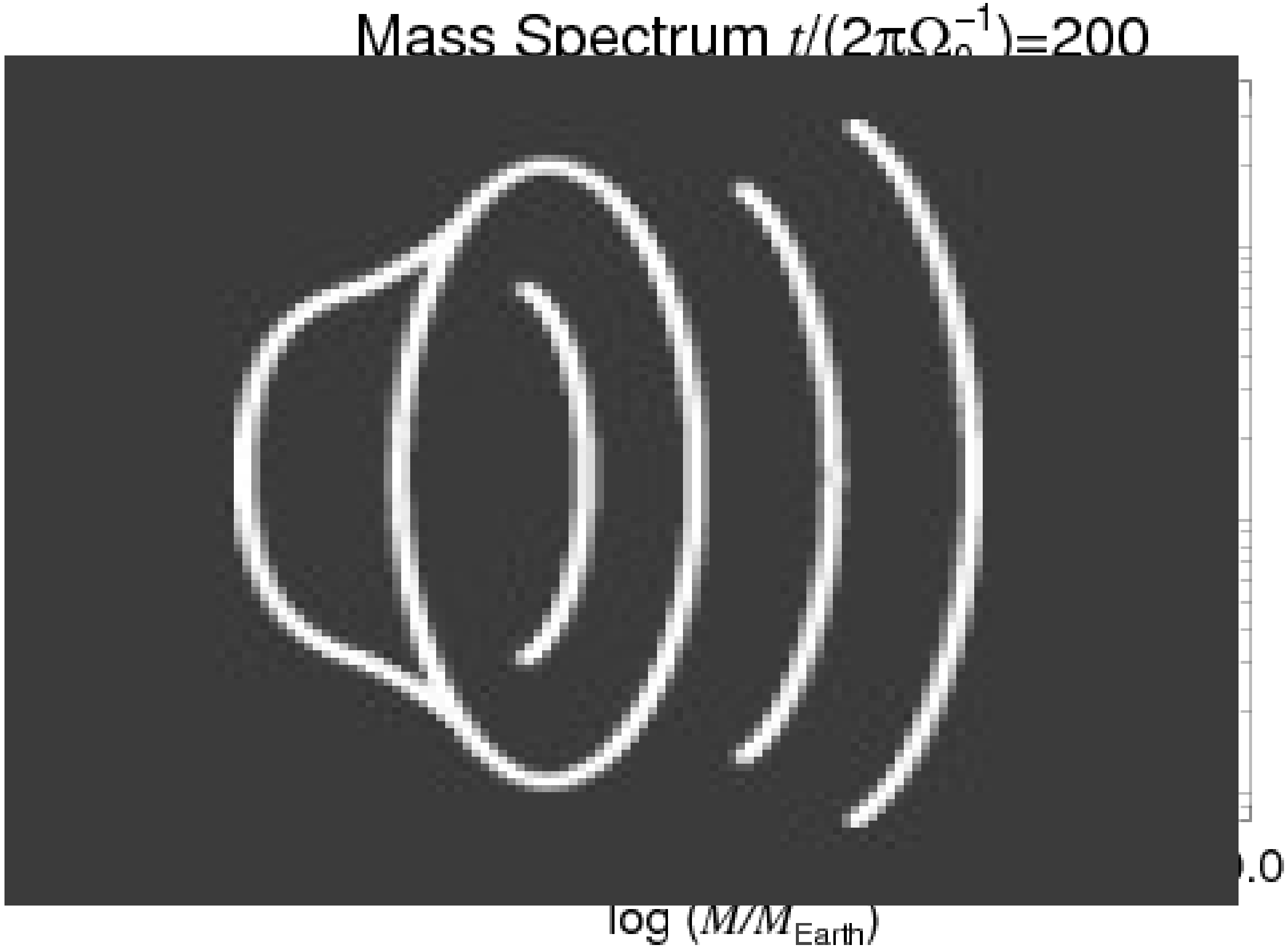
$$2\boldsymbol{\Omega}\times\boldsymbol{u}=-\rho^{-1}\boldsymbol{\nabla}p$$

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

Aid to planet formation (Barge & Sommeria 1995)

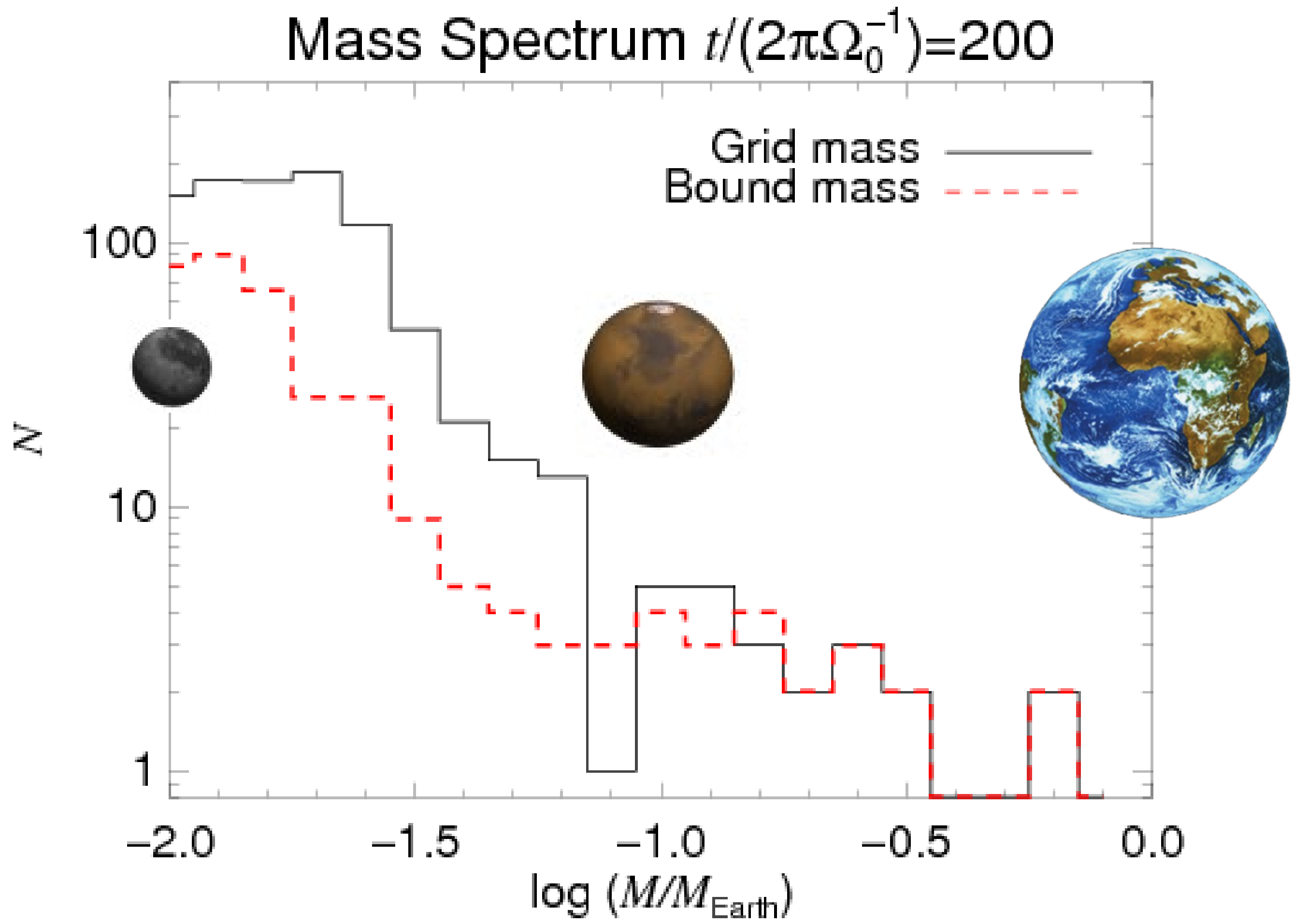
Speed up planet formation enormously
(Lyra et al. 2008b, 2009a, 2009b, Raettig, Lyra & Klahr 2012)

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

The Initial Mass Function of planets



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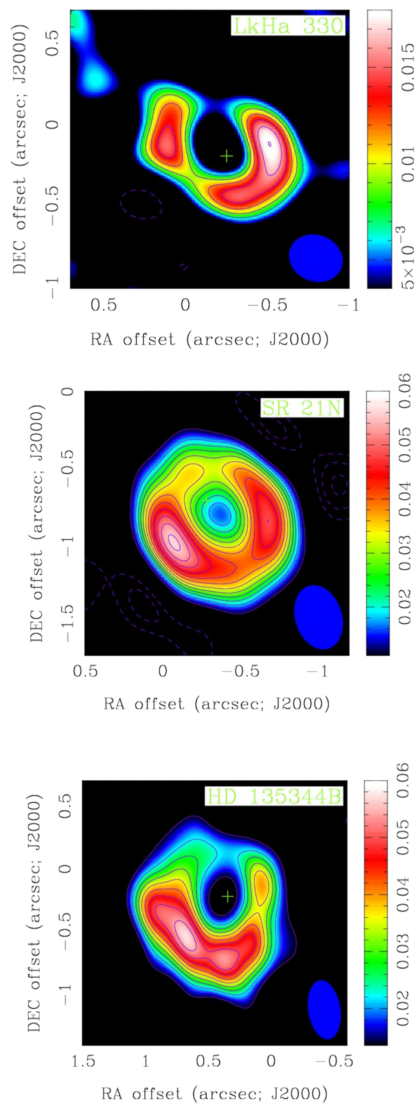
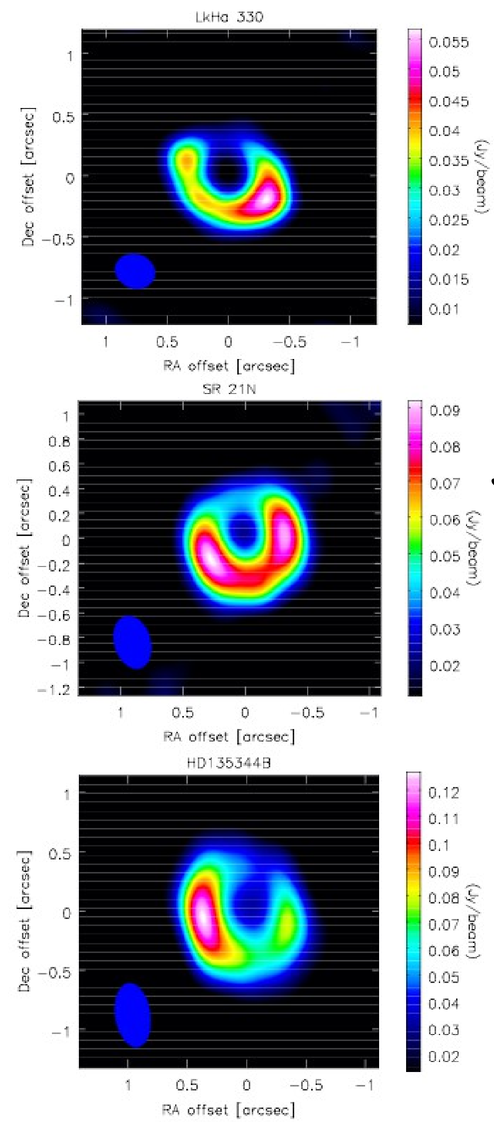
A possible detection of vortices in disks

Observations

Brown et al. (2009)

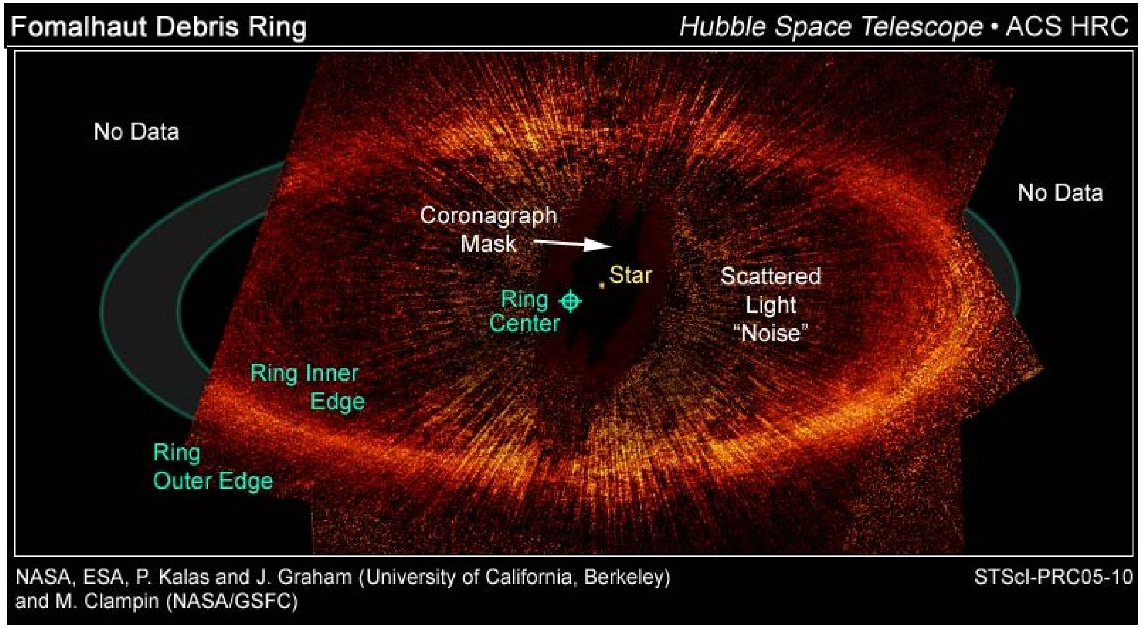




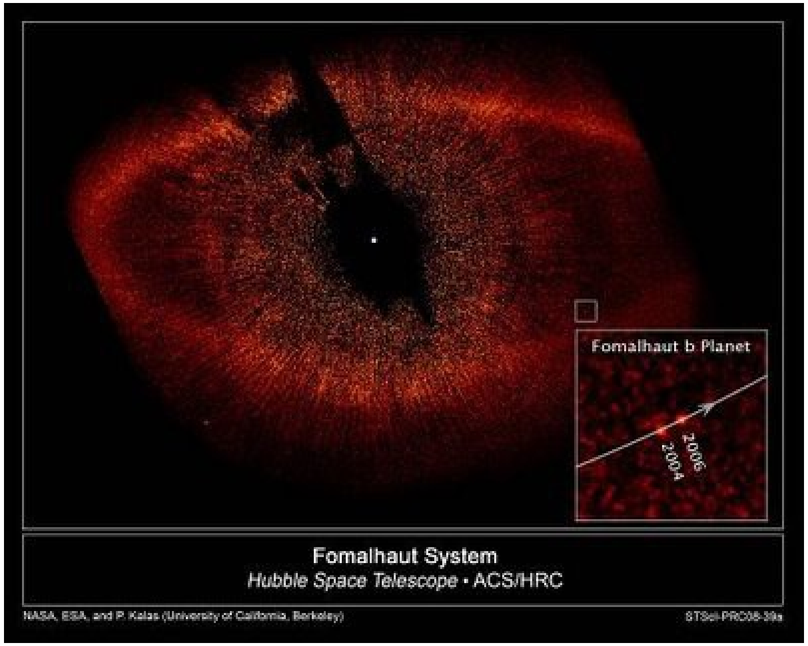
Simulated observations of Rossby vortices

Regaly et al. (2012)

Sharp and eccentric rings in debris disks



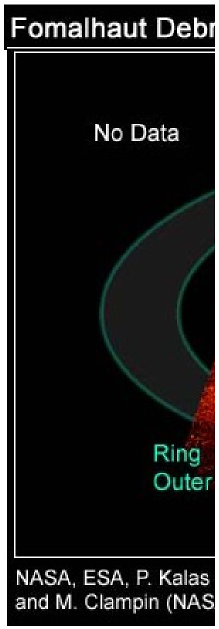
Narrow sharp eccentric ring



Detection of a source quickly heralded as a planet Fomalhaut b

Sharp and eccentric rings in debris disks

However.....



The Astrophysical Journal, 747:116 (7pp), 2012 March 10
doi:10.1088/0004-637X/747/2/116

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

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Received 2011 December 16; accepted 2012 January 12; published 2012 February 23

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 μm, 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

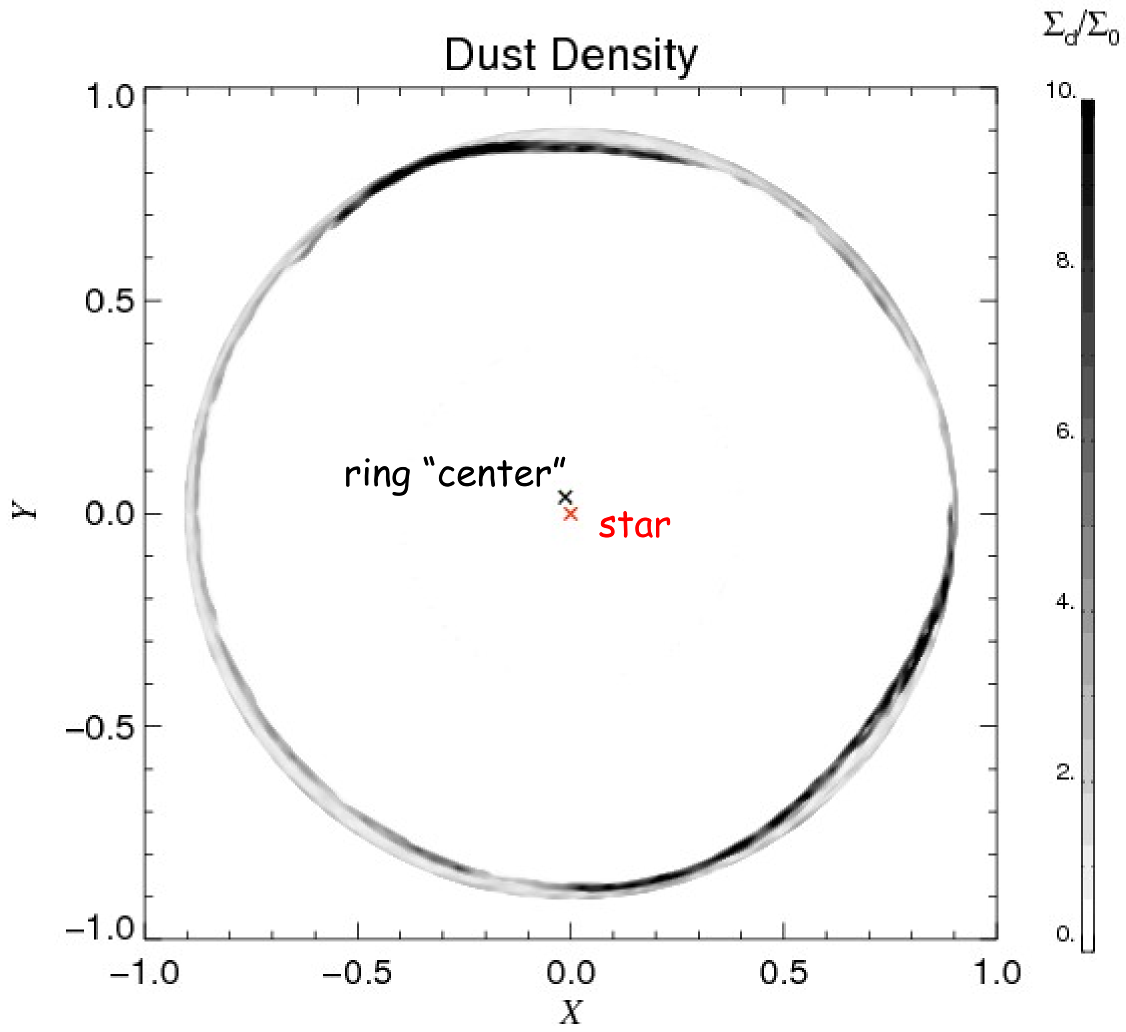
Dust heats gas

Heated gas = high pressure region

High pressure concentrates dust

Lyra & Kuchner (2012)

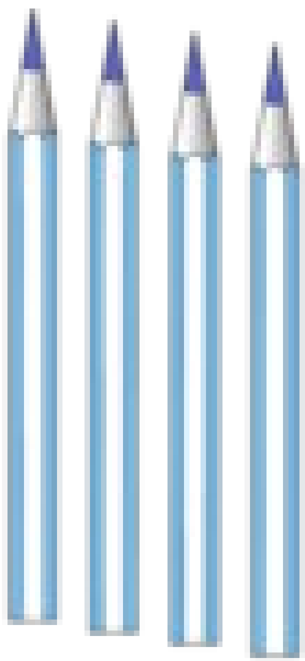
Sharp and eccentric rings in debris disks without planets



Eccentricity e=0.04

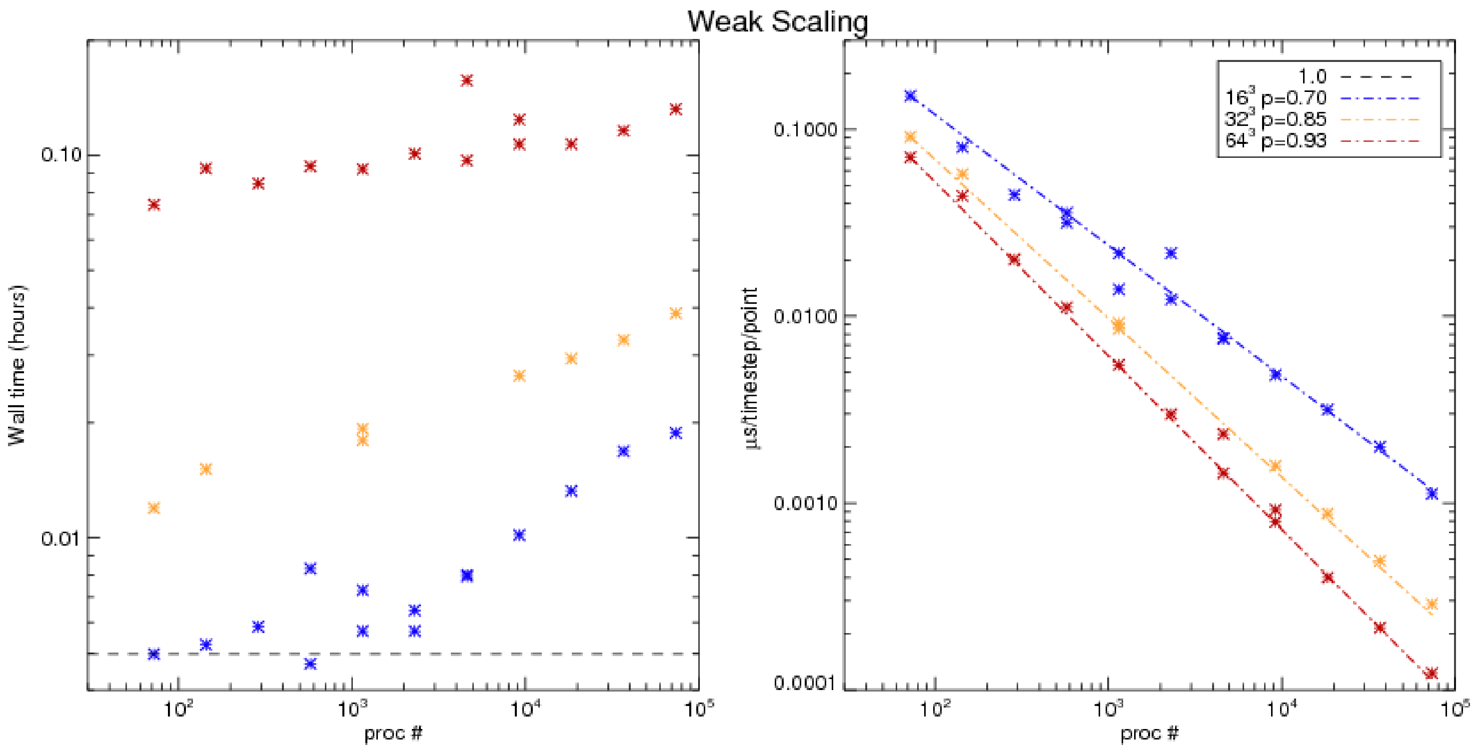
Lyra & Kuchner (2012)

High end computing



The Pencil Code

Brandenburg & Dobler (2002)



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

(At NICS - Kraken)

Thanks for your attention!!!