Physics of Planets

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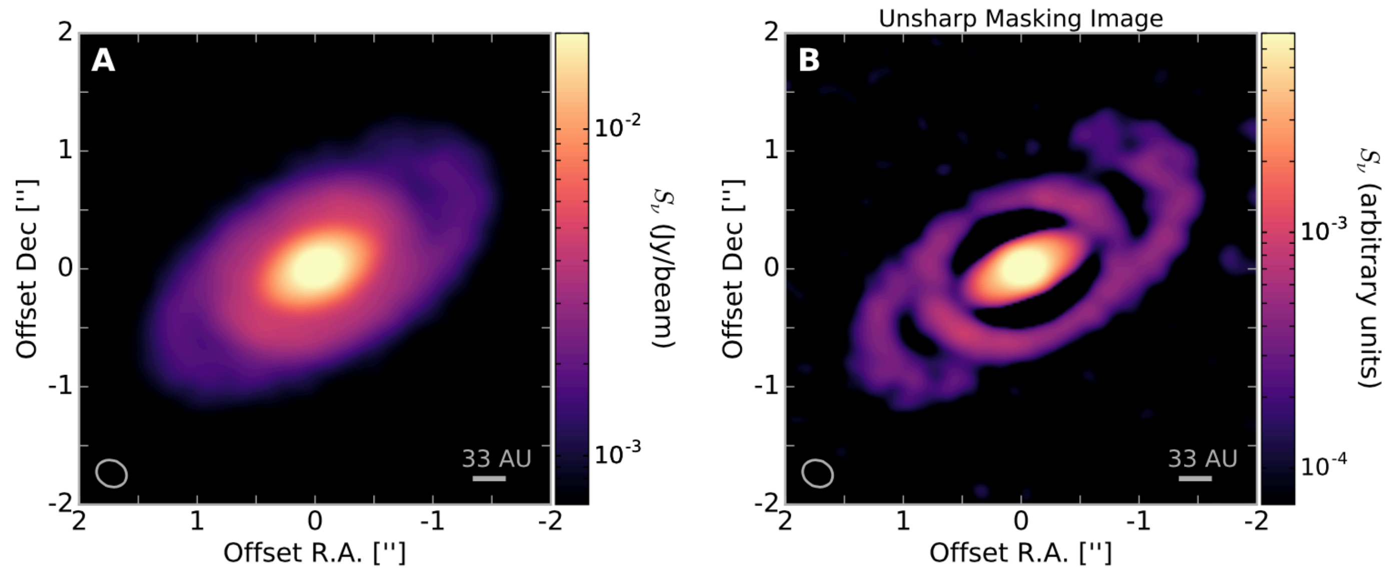


Fig. 1. Thermal dust emission from the protoplanetary disk surrounding Elias 2-27. The disk was imaged at a wavelength of 1.3 mm with ALMA reaching an angular resolution of $0.26'' \times 0.22''$ (indicated by the ellipse in the bottom-left corner), which corresponds to 36×31 AU at the distance of the star (where AU is the astronomical unit). The field of view center (at 0,0) corresponds to the disk emission peak located at Right Ascension (J2000) = 16h 26m 45.024s, Declination (J2000) = –24d 23m 08.250s and coincidental with the position of the star Elias 2-27. **(A)** 1.3 mm dust continuum image from the Elias 2-27 protoplanetary disk over a $4'' \times 4''$ area. The color-scale represents flux density measured in units of Jansky per beam ($1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$). **(B)** Increased contrast image from processing the original ALMA observations shown in panel (A) with an unsharp masking filter (*17*).

Perez et al. (2016)

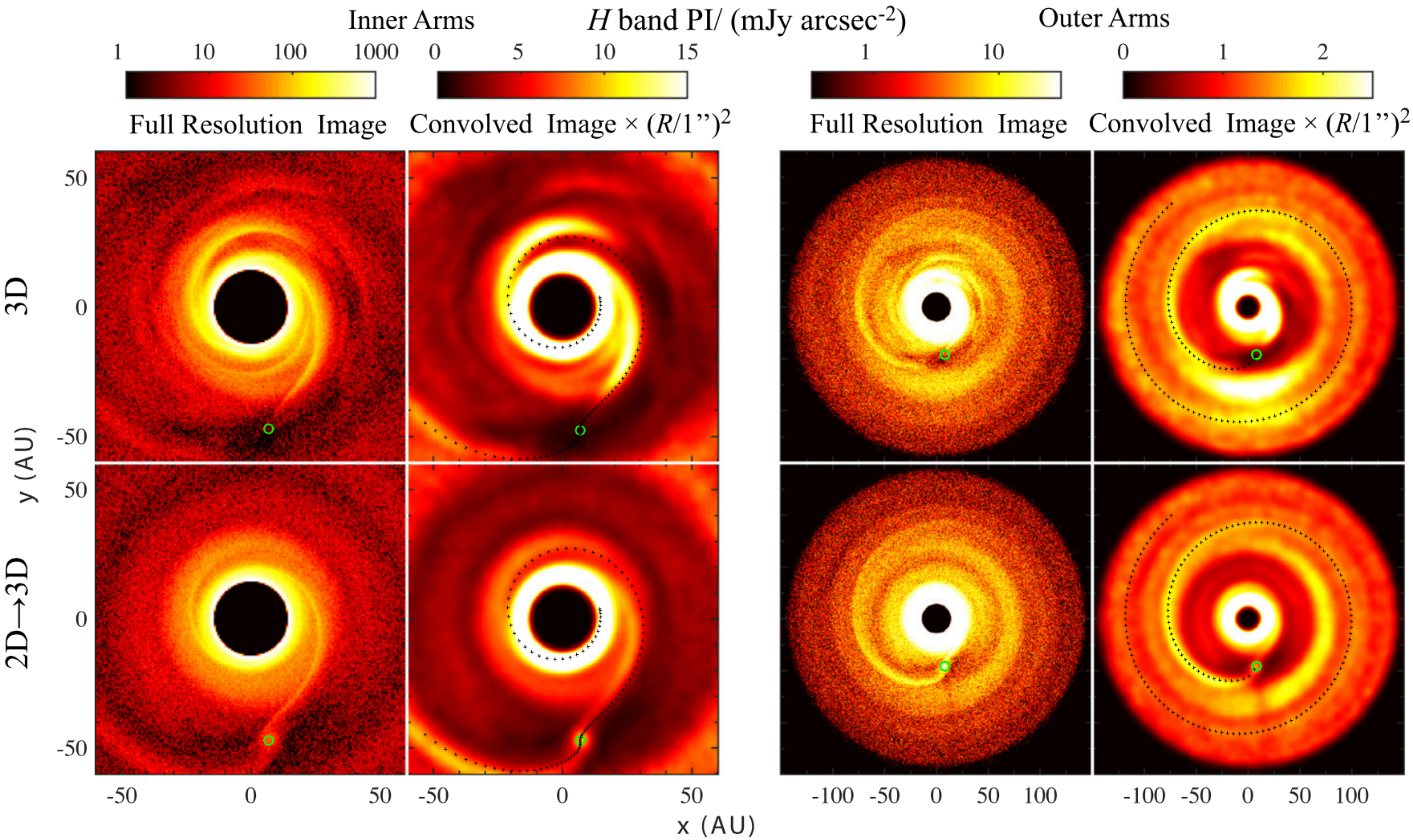
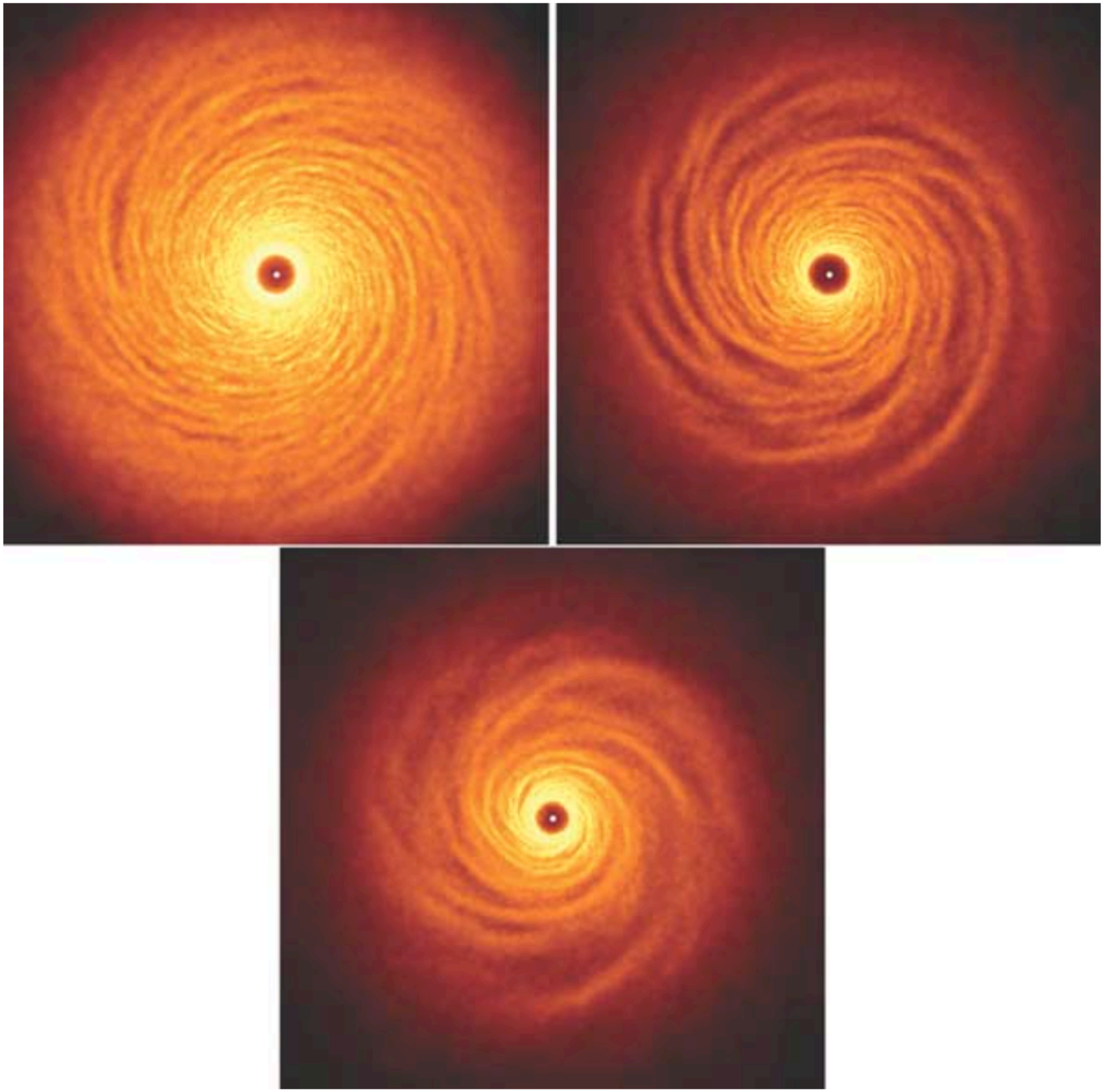
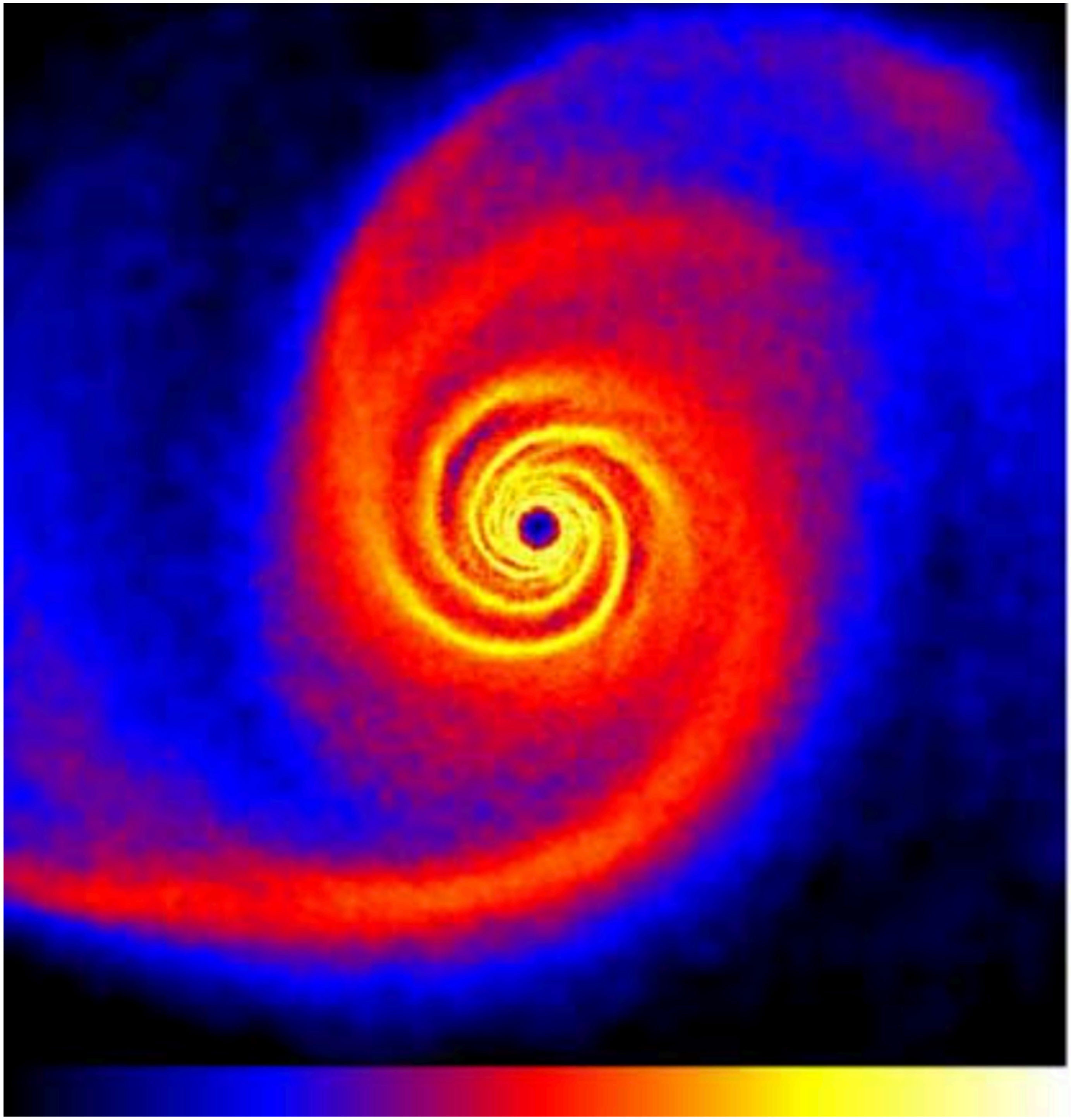


Figure 19. Similar to Figure 18 but for SM3ISO ($M_p = 6\ M_J$).

Zhu, Dong et al. (2015)



Lodato & Rice (2004)



Lodato & Rice (2005)

What types of transient structures might form spontaneously in turbulent disks?

General expectations

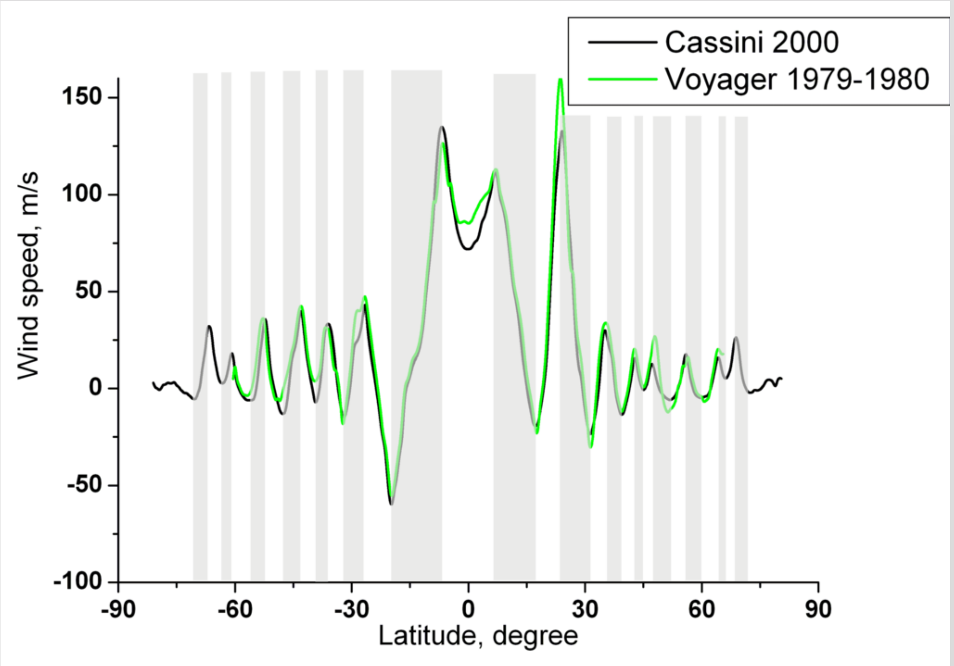
- three-dimensional turbulence is described by a cascade of energy from large to small scales, where dissipation occurs
- two-dimensional turbulent systems also support an “inverse cascade”, where energy flows to the largest scale accessible to the system

Protoplanetary disks are three-dimensional, **but** strongly flattened… so not clear which regime is better for gaining an intuitive understanding

What types of transient structures might form spontaneously in turbulent disks?

General expectations – in "nearly 2D" systems, form

Long-lived vortices



Zonal flows

Zonal flows

Johansen, Youdin & Klahr ‘09 found zonal flows in ideal MHD simulations of disk turbulence

- an inverse cascade leads to large-scale magnetic field structures
- the variation in the magnetic stress leads to peaks and troughs in disk surface density
- resulting pressure gradient is balanced by radial variations in the azimuthal velocity

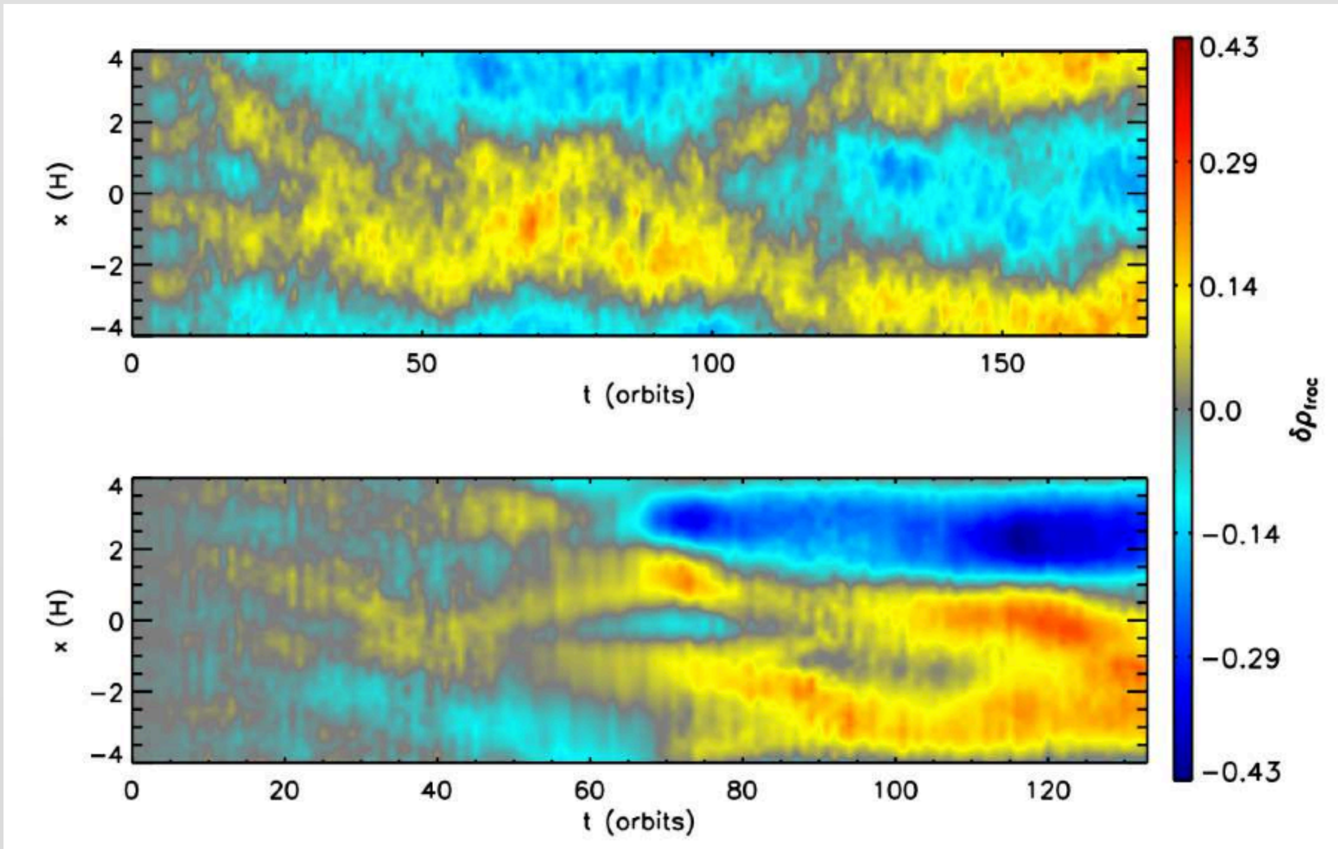
$$\frac{v_\phi^2}{r} = \frac{GM_*}{r^2} + \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r}$$

“geostrophic balance”

Appear to form generically in local simulations of MHD disk turbulence

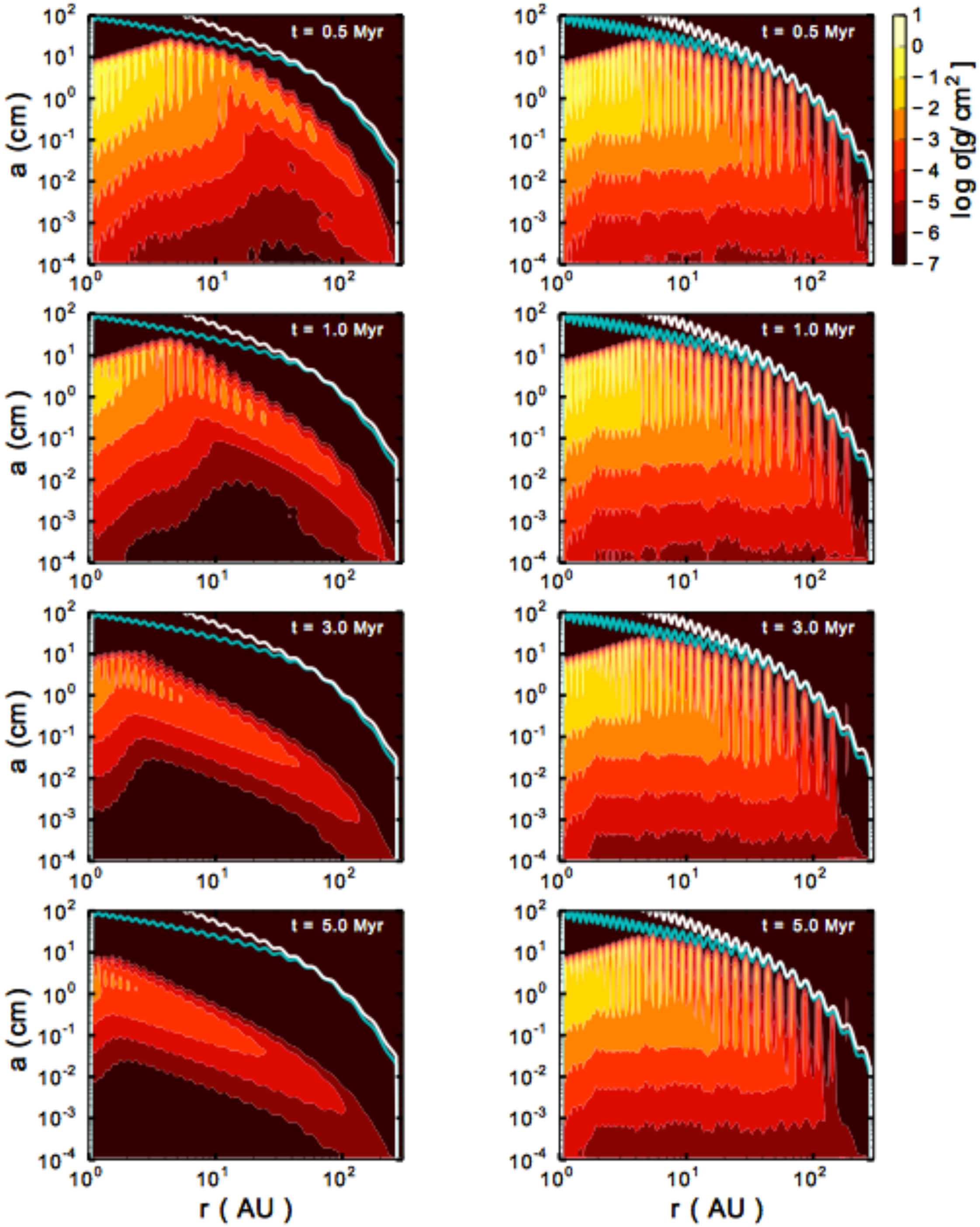
Ideal MHD

Disk model at 30AU with ambipolar diffusion and net field



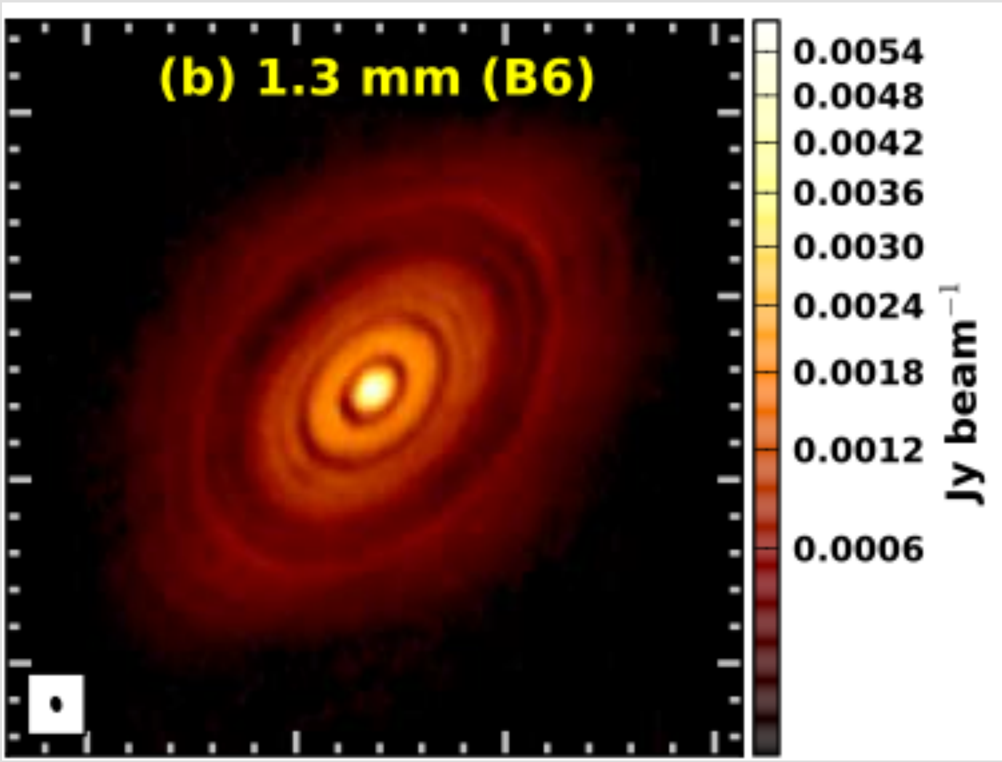
Simon & Armitage '14

- amplitudes of 10s of percent in Σ
- lifetimes of 10s-100s of orbits



Zonal flows that are strong enough to trap particles could assist in the collisional growth of solids in the outer disk

Pinilla et al. '12



Axisymmetric ring-like structures, in principle detectable through concentration of small particles

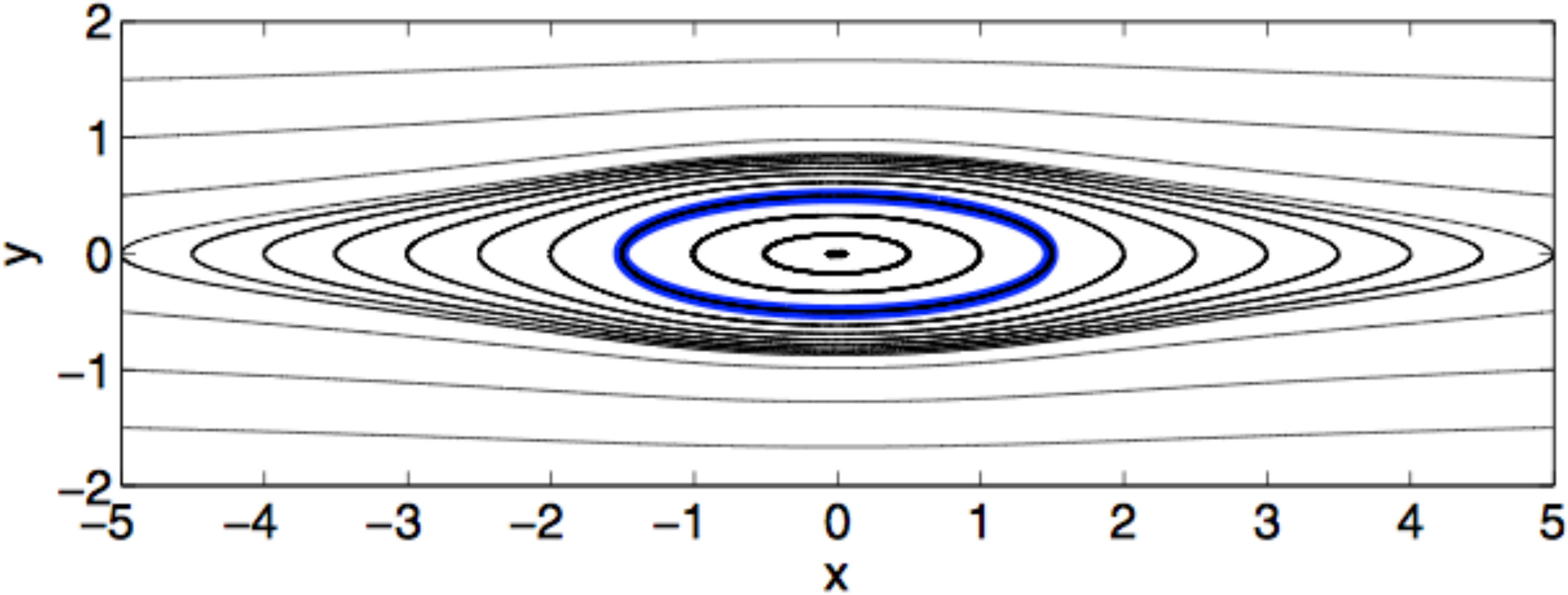
Uncertainties

- what is the characteristic radial scale?
- in regions where ambipolar diffusion dominates, structures also depend on strength (and evolution?) of net magnetic fields threading the disk *(Bai & Stone '14)*

Vortices

Several related issues concerning role of vortices in disks:

- how to form them
- their long-term stability and migration
- efficiency at angular momentum transport
- role in particle concentration



Vortices - rotating structures superimposed on the background Keplerian shear. Simple model – *Kida '81* solution

Velocity field for vortex core: vorticity ω, aspect ratio χ, in disk with background vorticity S *(Lesur & Papaloizou '09)*

$$v_x = S\frac{1}{\chi - 1}\chi y$$

$$v_y = -S\frac{1}{\chi - 1}\frac{1}{\chi}x$$

Only anticyclonic vortices are stable in disks

Particles tend to spiral in toward center of a disk vortex *(Barge & Sommeria '95)*

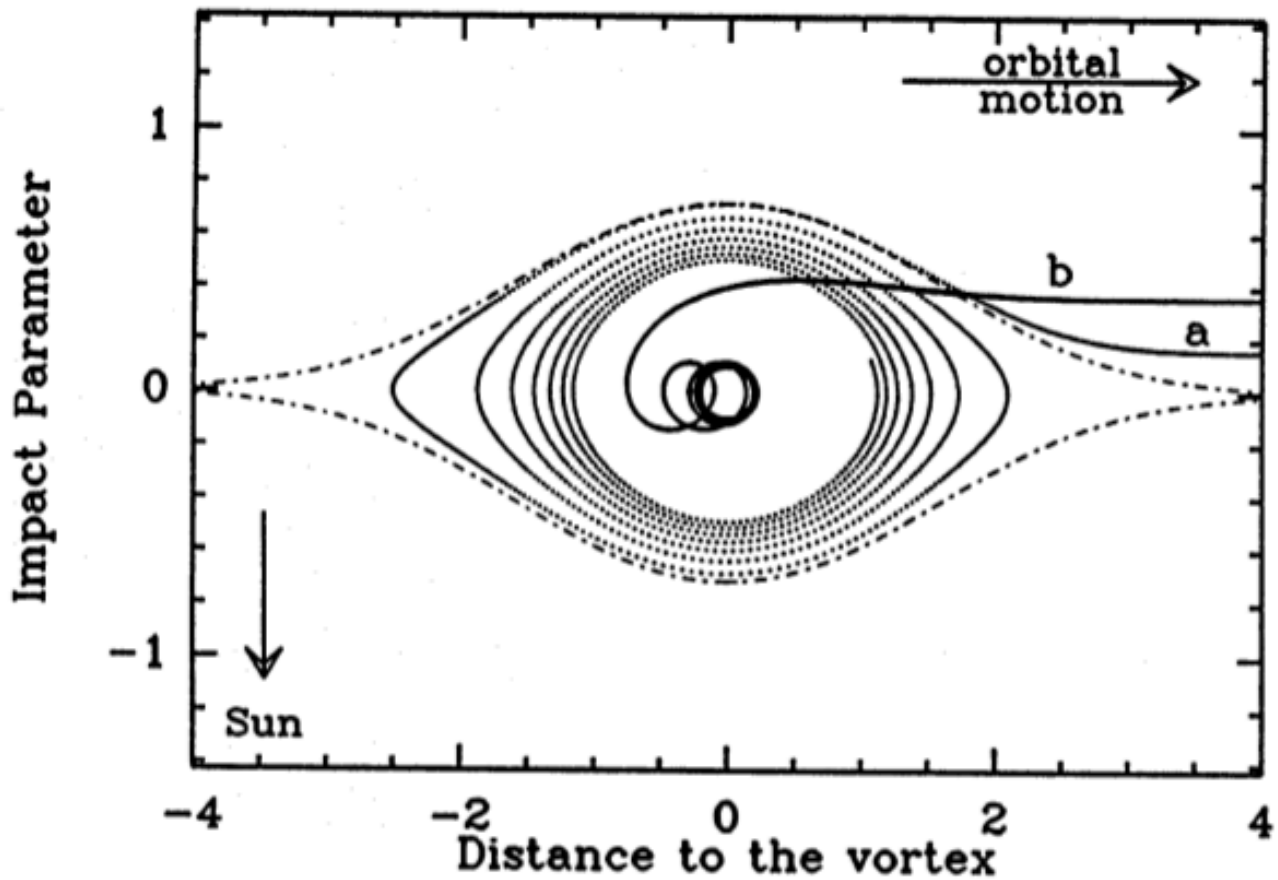


Fig. 1. Trajectories of the particles captured in a gaseous vortex, sketched by the separatrix (dashed line) between open and closed streamlines. The particles penetrate into the vortex and spiral inward toward its center; they tend to reach purely epicyclic motion with a transient behaviour strongly dependent on the friction parameter: light particles ($\tau_S = 0.05$ in case (a)) remain near the edge of the vortex, whereas heavy ones ($\tau_S = 3$ in case (b)) first sink deeply into the inner regions. It must be noted that, for clarity of the figure, the ordinates have been expanded by a factor of two.

How to form vortices?

Are axisymmetric bumps in the surface density stable?

$$\mathcal{L} \equiv \frac{\Sigma}{(\nabla \times \mathbf{v}) \cdot \hat{z}}$$

unstable to **Rossby Wave Instability** if the vortensity has an extremum *(Li et al. '99)*

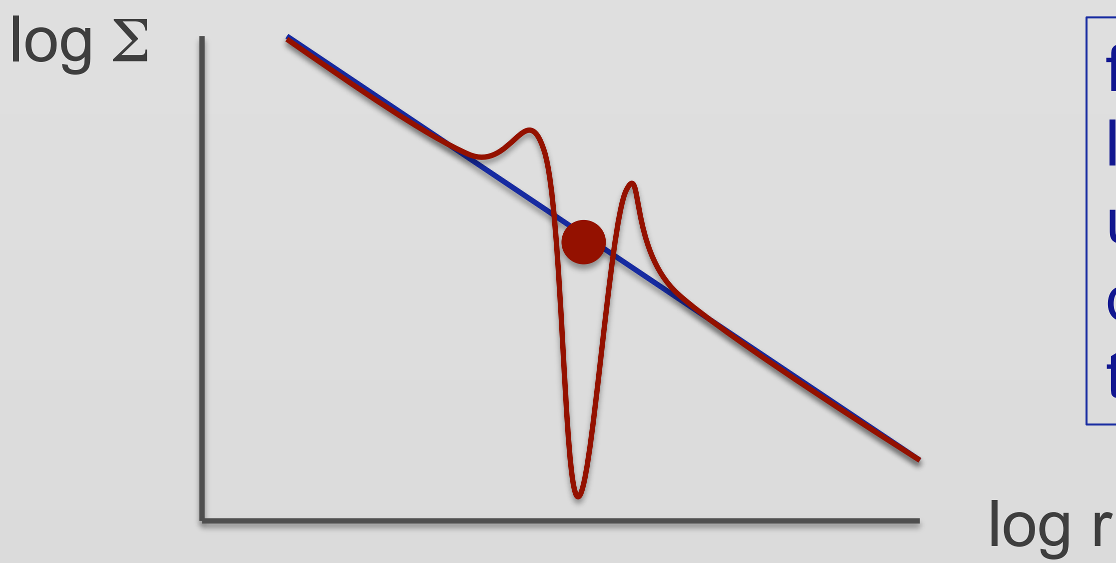
(a more complete criterion involves the entropy gradient)

Type of inertial wave (restoring force: Coriolis force)

Roughly, need 10-20% variation in Σ over scales ~h

How to form vortices?

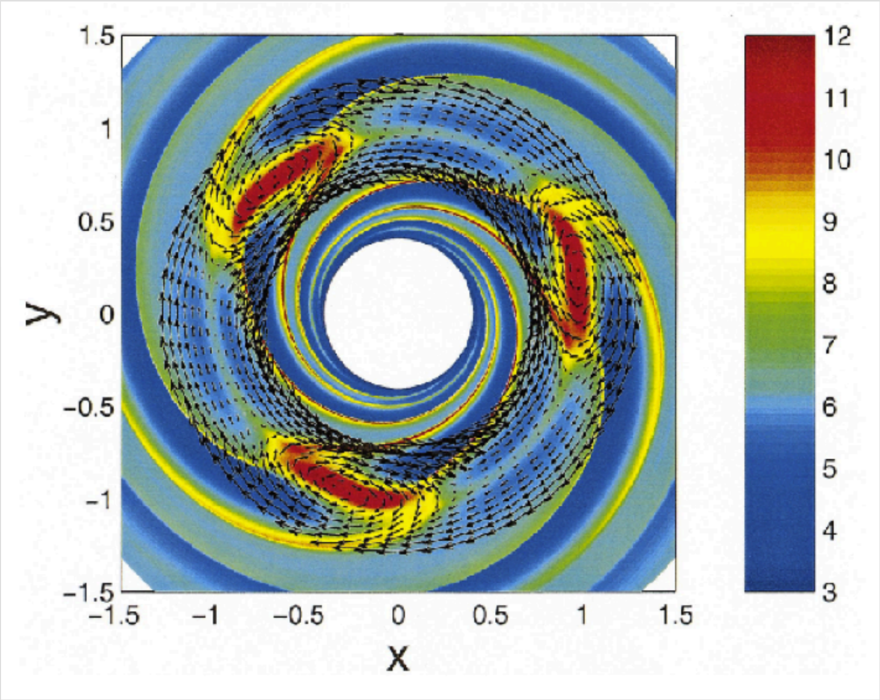
Rossby wave instability – this can be triggered by the growth of a massive planet in a low viscosity disk



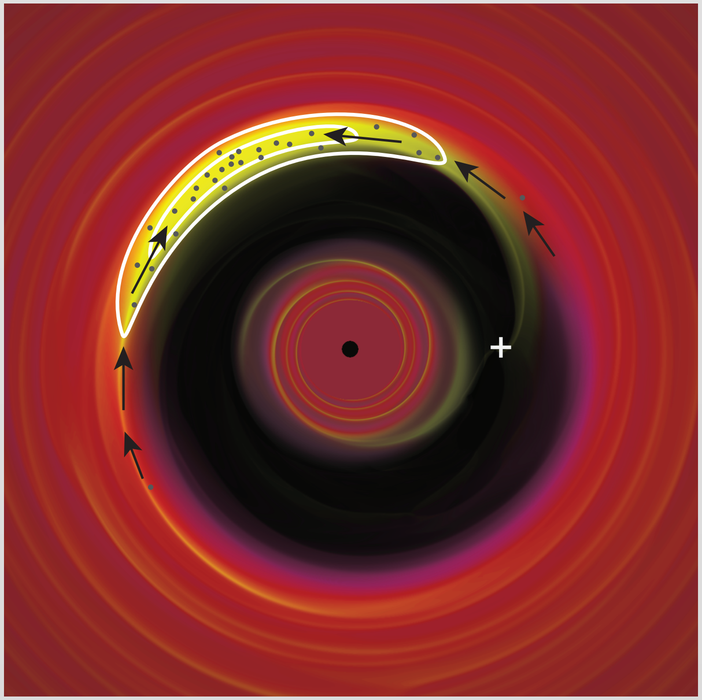
formation of the gap leads to potentially unstable surface density maxima at the gap edges

Any other process that leads to an unstable surface density profile would spawn vortices in the same way

Rossby wave instability leads to the formation of **vortices** at the edges of the rings



Li et al. '01

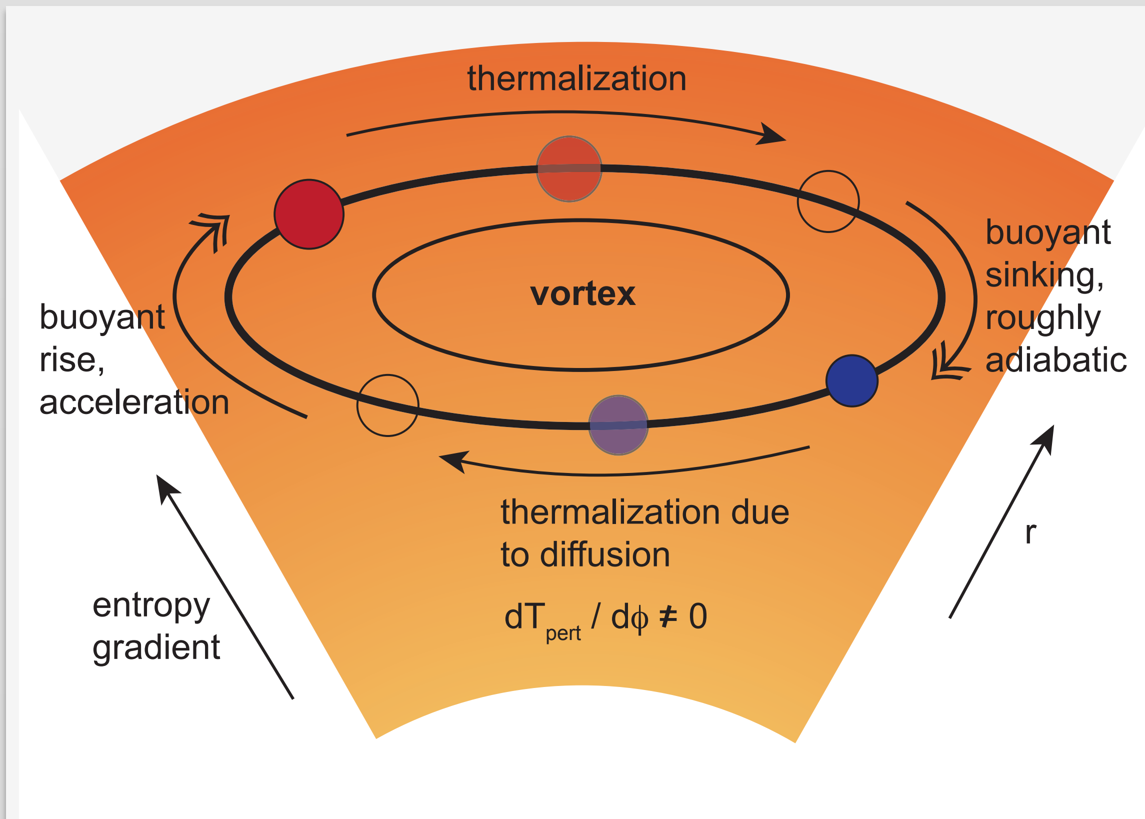


Armitage '13

Physics and outcome is very similar whether the cause of the ring is a planet, or a sharp transition with some other origin

How to form vortices?

Baroclinic instability – in the disk context (*not* in atmospheres) this usually refers to a non-linear entropy-driven instability that drives vortices in disks with an appropriate S(r)



Requires entropy profile that is Schwarzschild unstable

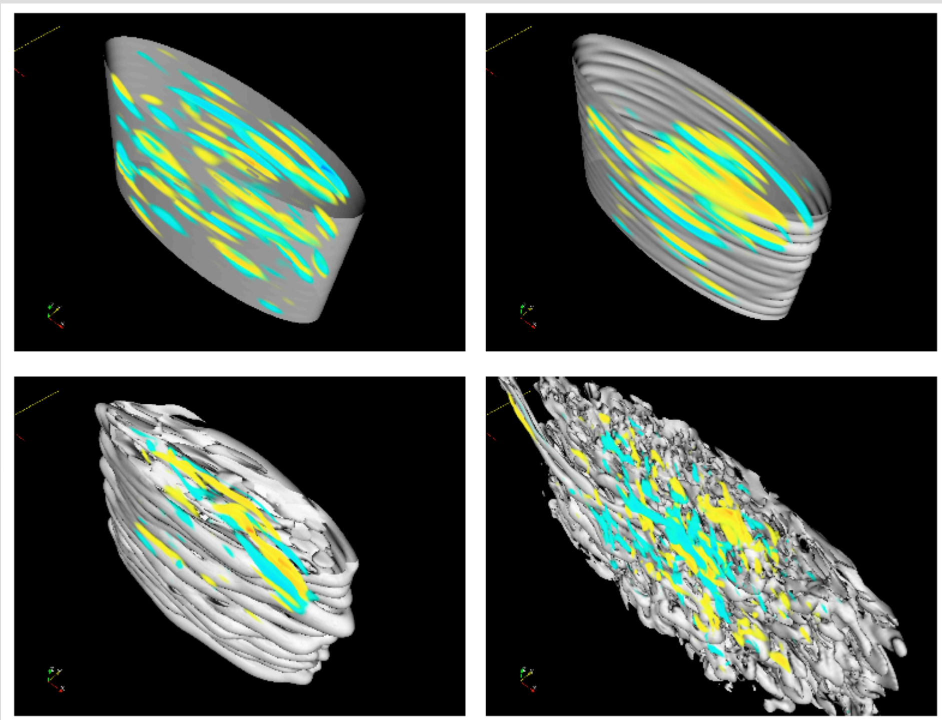
References:

Klahr & Bodenheimer '03; Lesur & Papaloizou '10

Armitage, ARA&A '11

Stability of vortices

Vortices in inviscid, 2D gas disks are stable indefinitely

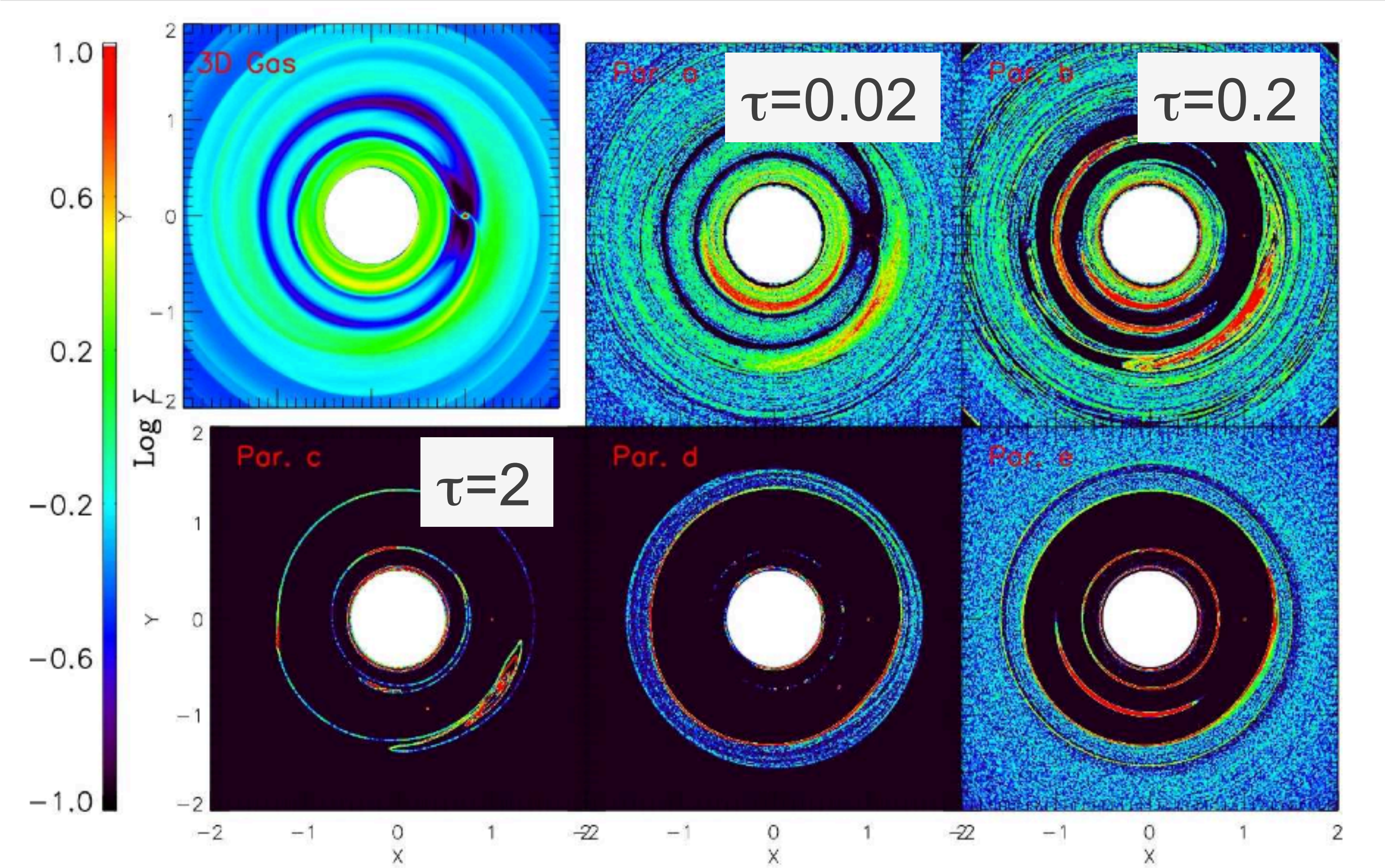


- in 3D, destroyed by the **elliptical instability** (a resonance between the turnover of the vortex and epicyclic frequency)
- **vertical shear** in the disk may also affect vortices

Lesur & Papaloizou '09

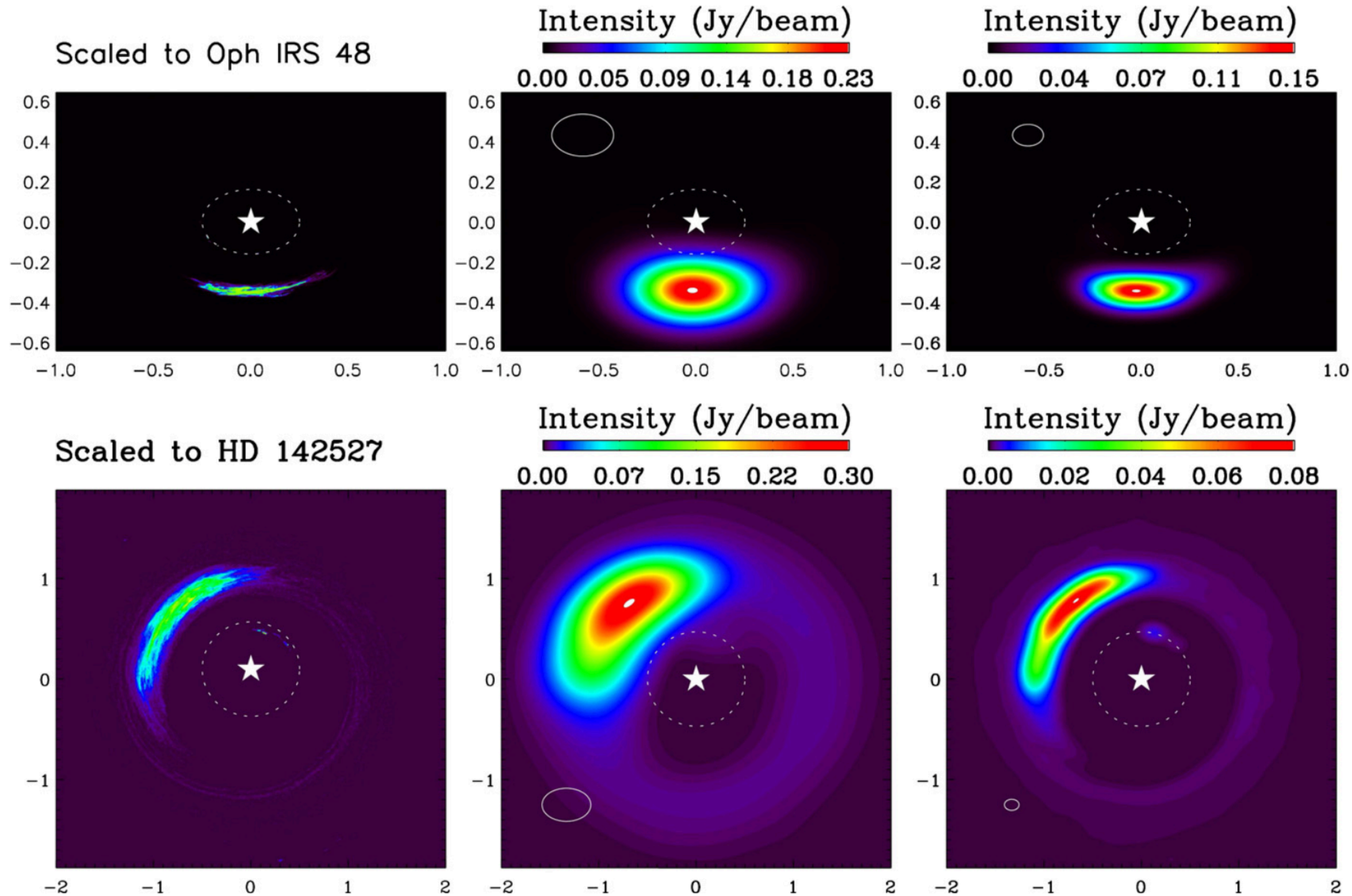
However – **growth rate** of these instabilities is slow… may take hundreds of orbits to grow to large amplitude

Trapping of particles



Zhu et al. 14

Vortices strongly concentrate particles with stopping time $\tau \sim 1$, *physical size* of these particles depends on radius from star



Zhu & Stone (2014)

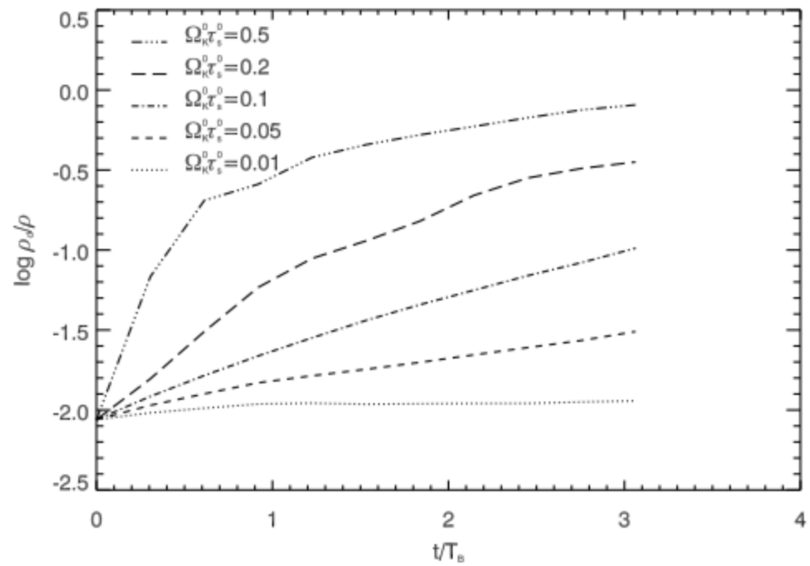
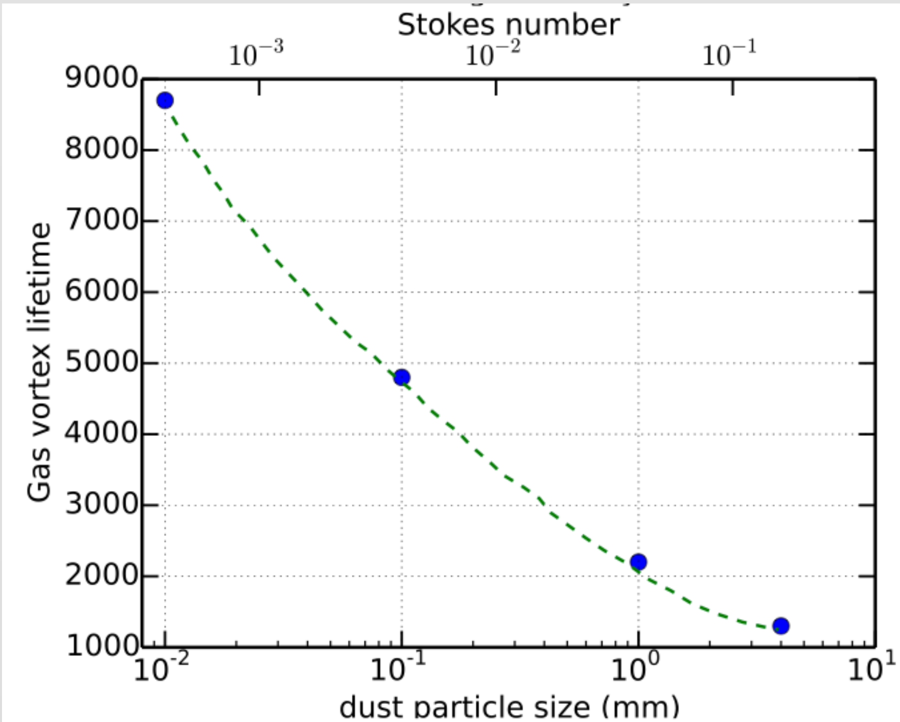


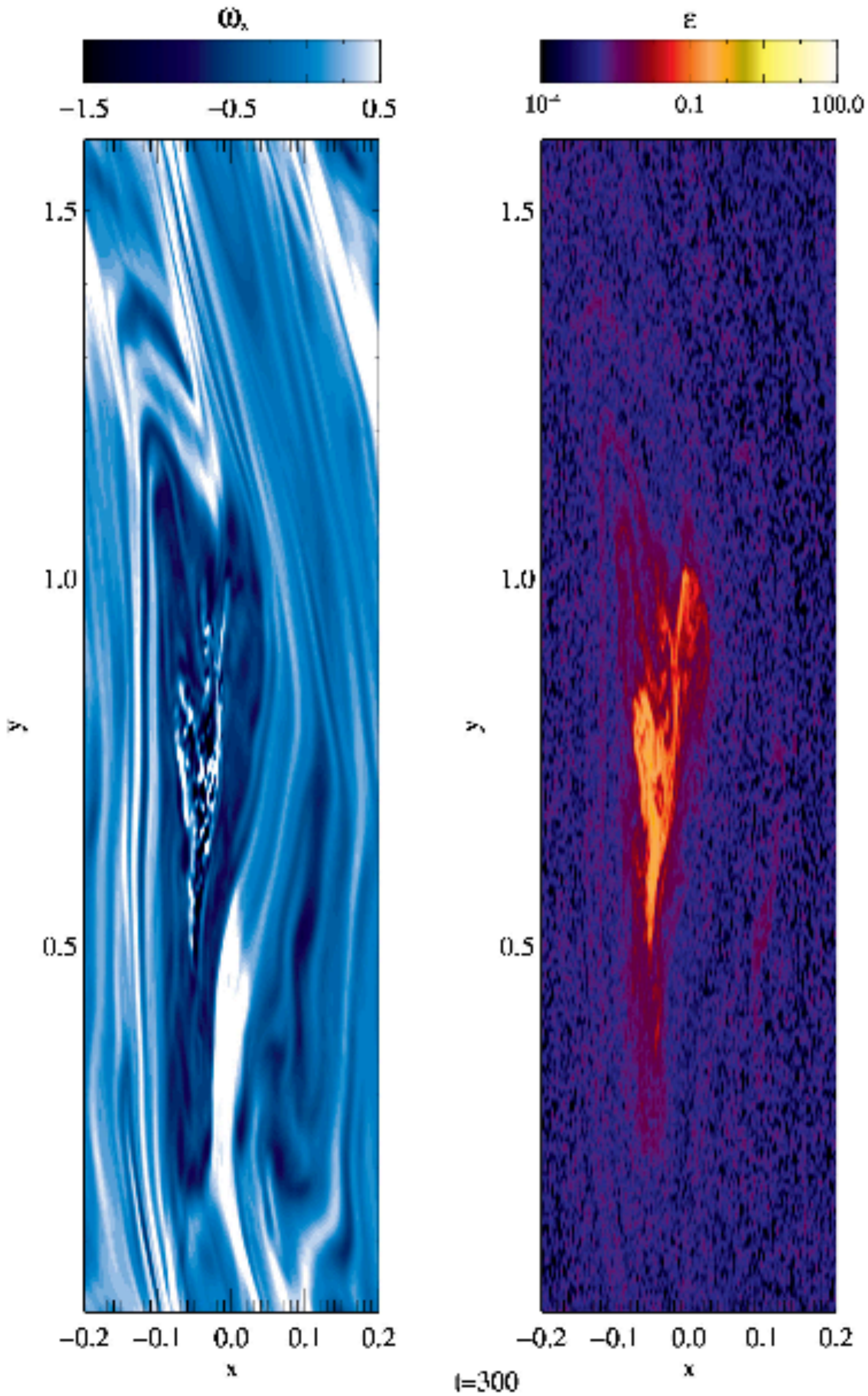
Fig. 4. Maximum dust density relative to maximum gas density in the midplane and in a logarithmic scale as a function of time for different solid sizes.



Meheut et al. '12

Fu et al. '14

Concentration of solids within vortex cores can be strong **BUT** too high a density of solids leads to feedback on the gas that destroys the vortex *(Chang & Oishi '10)*



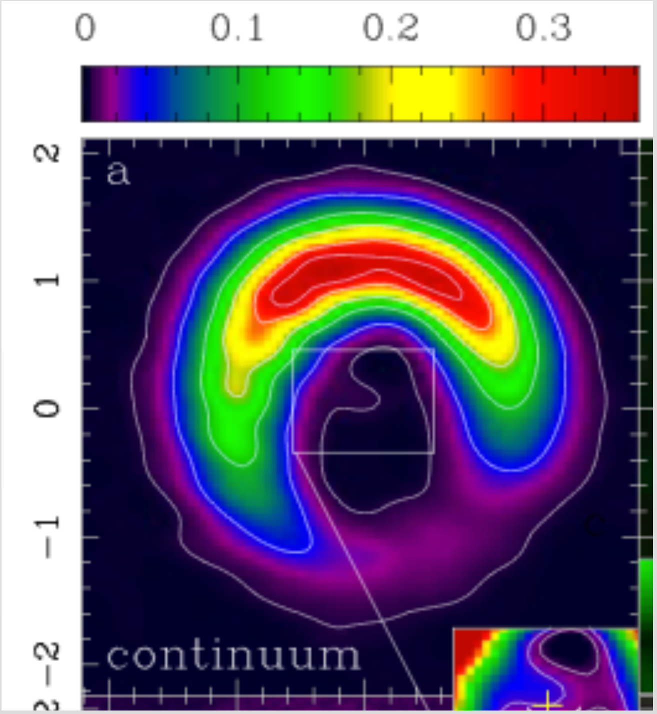
Possible scenario:

- vortices form
- particles with $\tau \sim 1$ concentrate in core
- streaming instability and gravitational collapse is triggered
- **before** feedback of solids on gas destroys the vortex

Raettig et al. '15

1. Application to asymmetry in transition disks

Interpretation of observed asymmetries in transition disks as vortices trapping particles is plausible

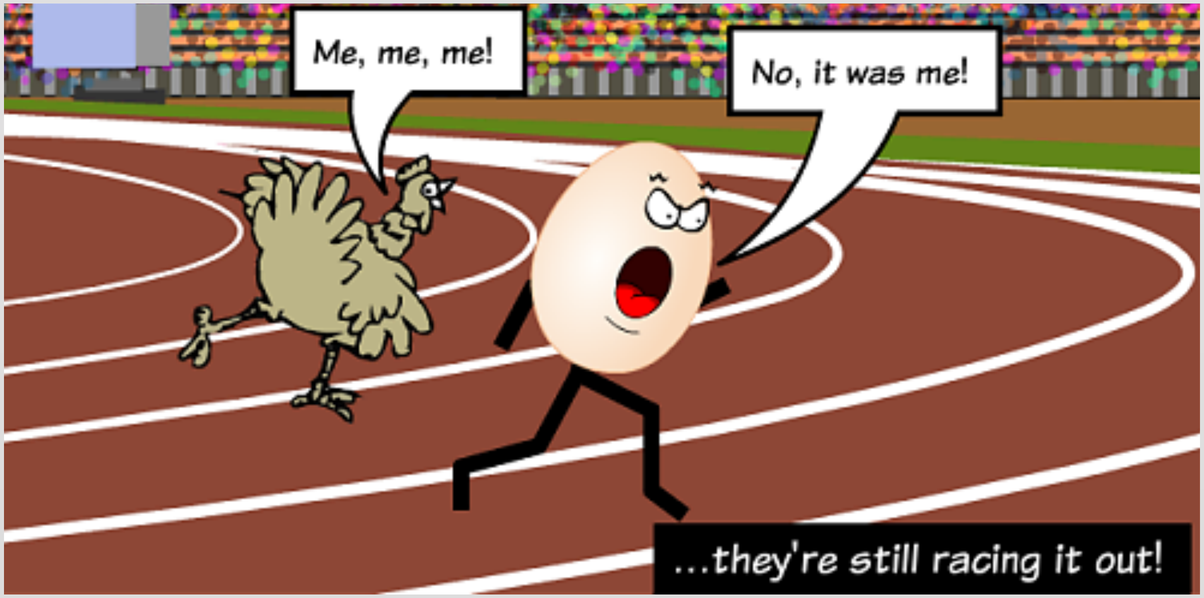


Casassus et al. 13

- vortices in disks merge into a single large vortex
- a vortex in the outer disk traps particles of ~mm size strongly
- smaller dust particles are not trapped
- long time scales mean that destruction processes do not have time to operate

Requires low viscosity (e.g. from ambipolar damping of MRI turbulence). A planet would work to spawn the vortex, but is not strictly *necessary*

2. A general role in planet formation?



For vortices to be important for *all* planet formation:

- need vortices to be present and survive in the inner disk, where time scales >> vortex destruction times
- require ongoing **source** of vorticity
- …which cannot be pre-existing planets
- baroclinic instability is one possibility