Vortex dynamics in protoplanetary disks

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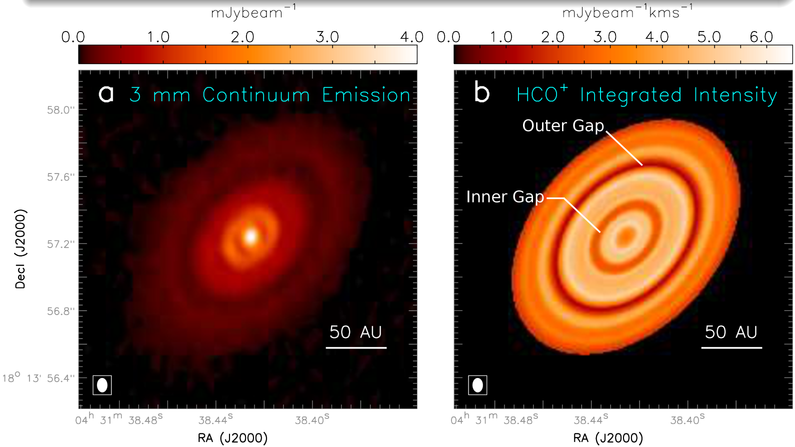
A new era for planet formation

Planets form in protoplanetary accretion disks around young stars



(Yen et al., 2016, HL Tau)

- Planet-induced gaps?
- Dust-gas instability rings (Takahashi & Inutsuka, 2016)?

A new era for planet formation

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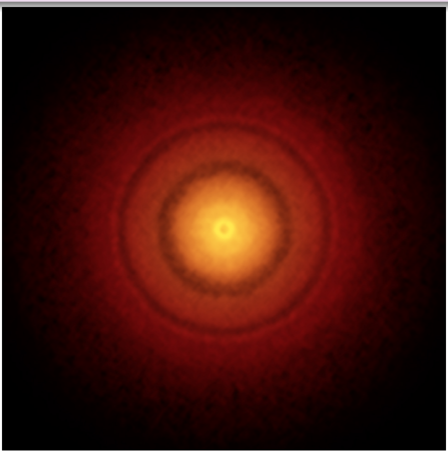

(TW Hydrae, Andrews et al., 2016)

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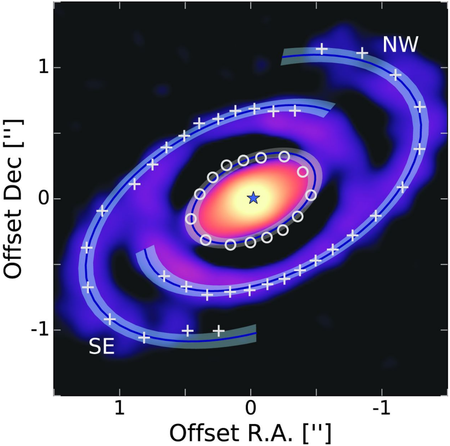
Spiral arms in protoplanetary disks (cf. galaxies)

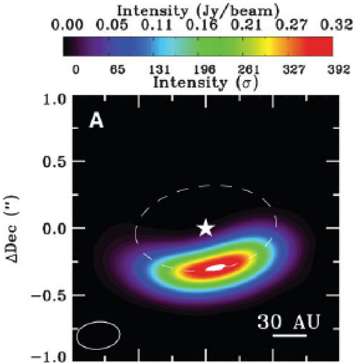


(Elias 2-27, Pérez et al., 2016)

- Gravitational instability on 100AU scales?

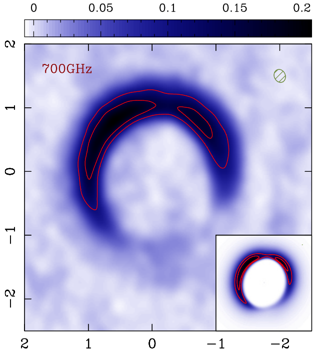
Lopsided protoplanetary disks

Oph IRS 48



(van der Marel et al., 2013)

HD142527



(Casassus et al., 2015)

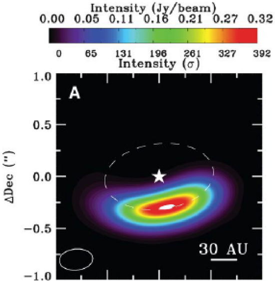
- Dust particles are concentrated on one side of the disk only

Sub-structures in protoplanetary disks

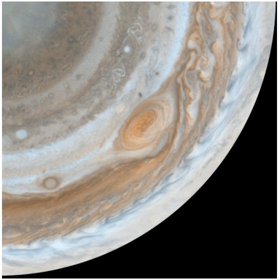
BIG QUESTIONS

- Mechanisms to form rings, spirals, lopsidedness?
- Can we extract the underlying disk properties by observing these sub-structures?
- Disk-planet interaction are known to structure disks. Can we predict the properties of the unseen planet?
- How do these structures affect solids' evolution in the disk?

Lopsidedness as vortices



IRS 48



Jupiter

Why may vortices explain observations?

- Dust-trapping by vortices

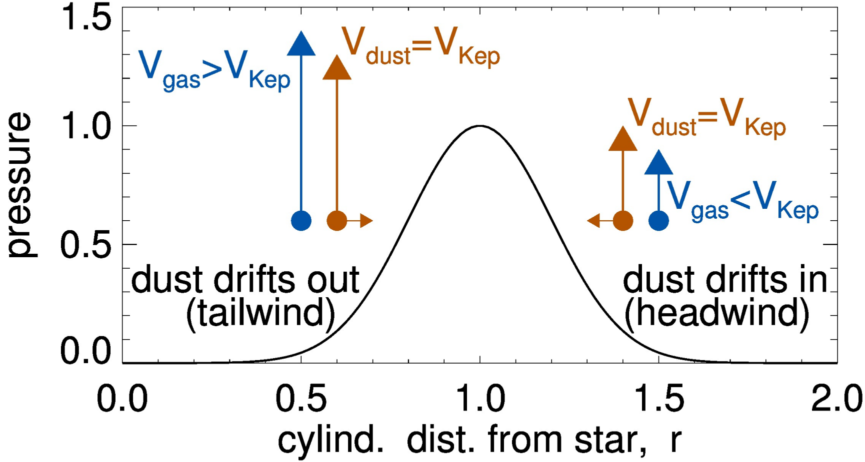
How are vortices formed?

- Planet-induced vortices

What are the important physics?

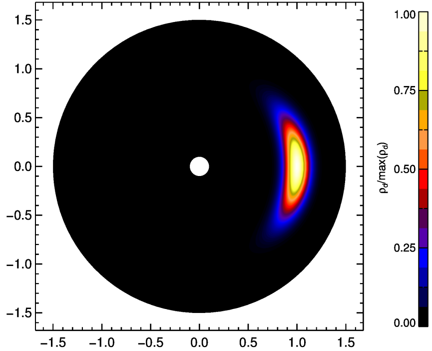
- The effect of 3D and self-gravity in vortex dynamics

Dust-trapping at pressure maxima



- Drag forces cause dust to accumulate at pressure bumps

Dust distribution in disk vortices



Lyra & Lin (2013):

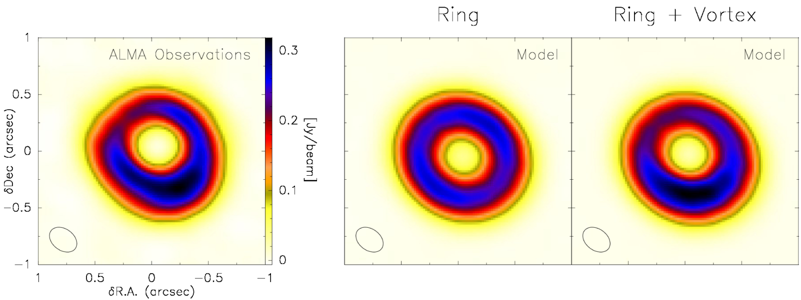
$$\rho_d(a) \propto \exp\left(-\frac{a^2}{2H_v^2}\right)$$

- a: distance from the vortex center

$$H_V = H_v(\chi, \delta, \mathrm{St}, H_g)$$

- χ: vortex aspect-ratio, geometry
- δ: gas turbulence in the vortex
- St: Stokes number $\sim$ particle size
- H_g: gas scale height, disk temperature

Extracting disk properties from observations



(SAO 206462, Pérez et al., 2014)
$\chi_{\rm obs} \sim 7$, model+ data $\rightarrow v_{\rm turb} \sim 0.22 c_s$.

Vortices in planet formation theory

- Concentrate dust particles → accelerated planetesimal formation → planet formation
- Angular momentum transport → disk accretion
- Hydrdodynamic origins:
  - Rossby wave/Kelvin-Helmholtz instabilities (Li et al., 2000)
  - Sub-critical baroclinic instability (Lesur & Papaloizou, 2010)
  - Convective overstability (Lyra, 2014)
  - Zombie vortex instability Marcus et al. (2015)
  - Vertical shear instability (Richard et al., 2016)

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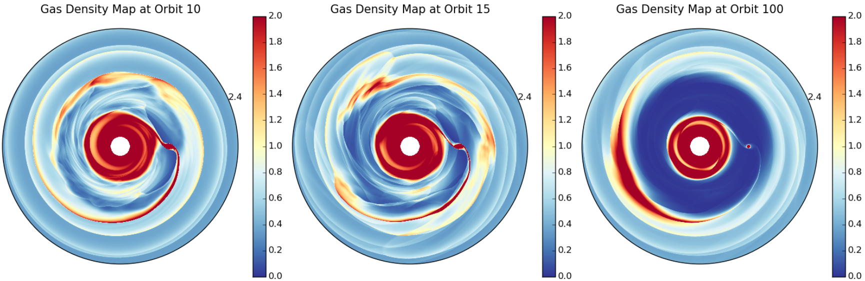
Vortices should be common in protoplanetary disks

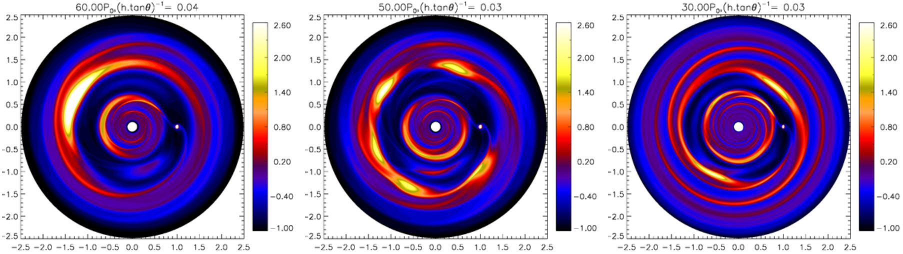
Gap edges as sites for vortex formation



(Credits: UA grad. student M. Hammer; FARGO 2D simulations)

- Disk-planet interaction → gaps
- Surface density maxima at gap edges, or PV minima due to strong shear
- Rossby wave instability → edges 'roll up' into vortices (Li et al., 2001) if disk self-gravity is not too strong

Gap edges as sites for vortex formation



$M_{\rm disk} = 0.02 M_*$ $M_{\rm disk} = 0.06 M_*$ $M_{\rm disk} = 0.08 M_*$

(Zeus-MP simulations Lin, 2012b)

- Disk-planet interaction $\rightarrow$ gaps
- Surface density maxima at gap edges, or PV minima due to strong shear
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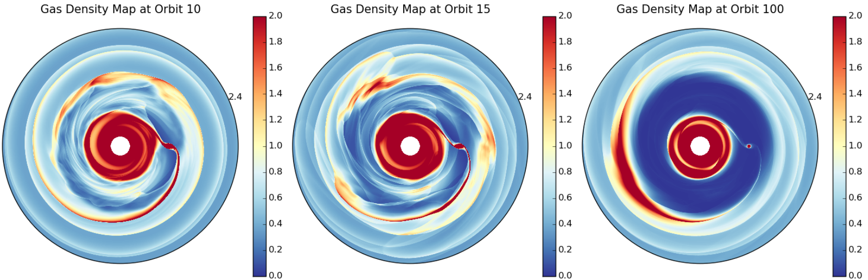
Gap edges as sites for vortex formation



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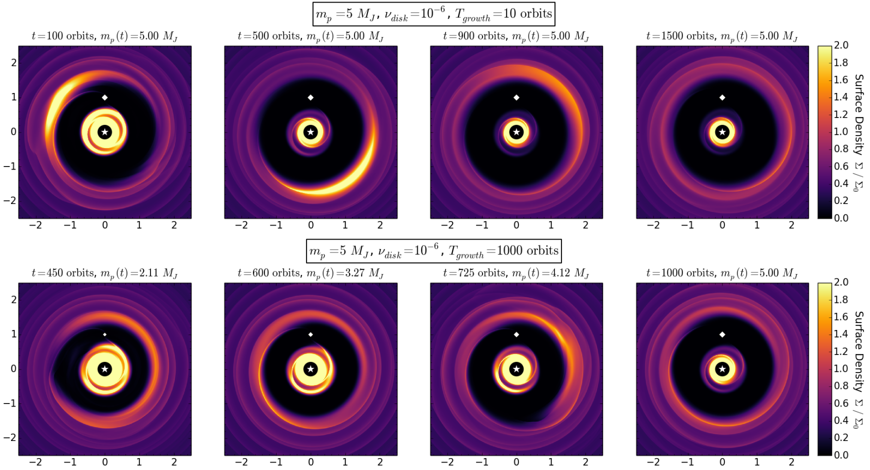
Many studies confirm this (some with e.g. self-gravity, 3D, dust particles):

- Li et al. (2005); Lin & Papaloizou (2010); Lin (2012b); Zhu et al. (2014)...

However, these simulations introduce the planet *quickly* — much shorter than expected growth times from planet formation models!

Slowly-growing planets make weaker vortices

(Hammer, Kratter & Lin, 2016, submitted, arXiv:1610.01606)



- Vortex forms *before* the planet reaches full mass, and back-reacts on the gap structure: self-limited vortex growth

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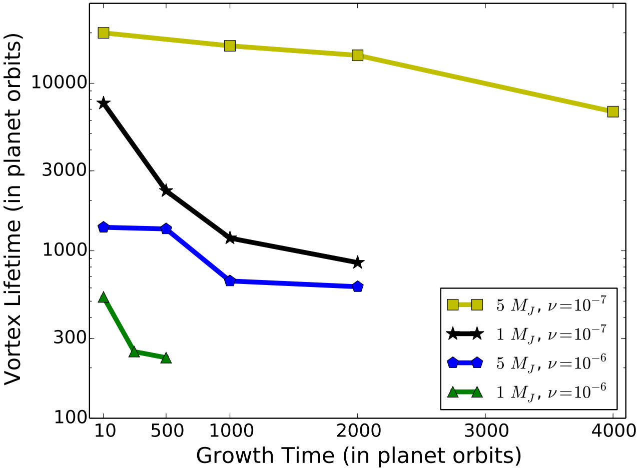
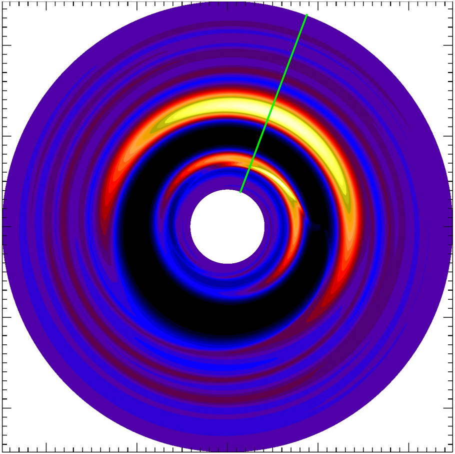


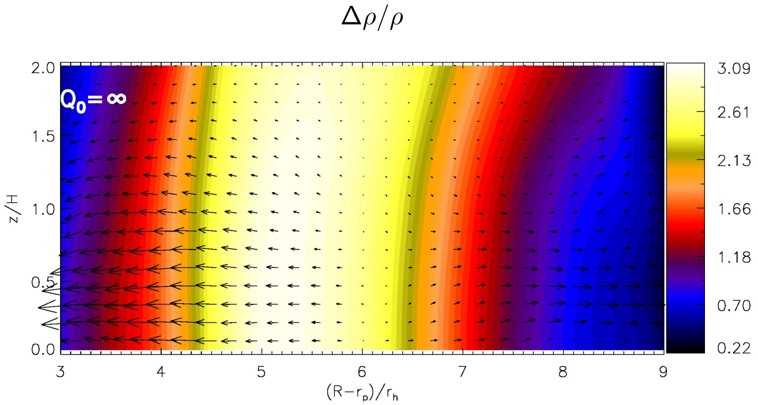
- Vortex lifetime/observability depends on planet formation time-scale

Basic theory is 2D, but PPDs are 3D



Take a look in the (r, z) plane through the vortex

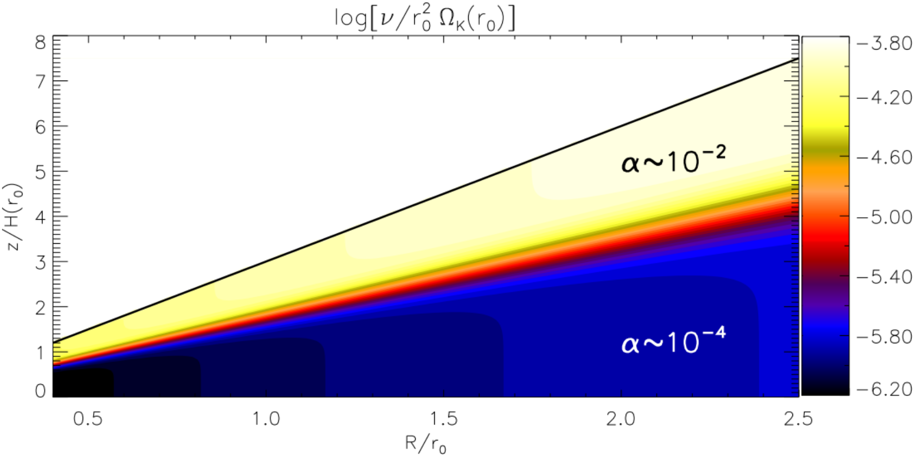
Rossby vortices are vertically global



- Global 3D Zeus-MP simulations (Lin, 2012b)
- Consistent with 3D linear theory (Lin, 2012a, 2013a,b)
- Vortex evolution is sensitive to disk vertical structure (Lin, 2014)

So vertical disk structure matters

Vortex formation with layered viscosity (Lin, 2014)

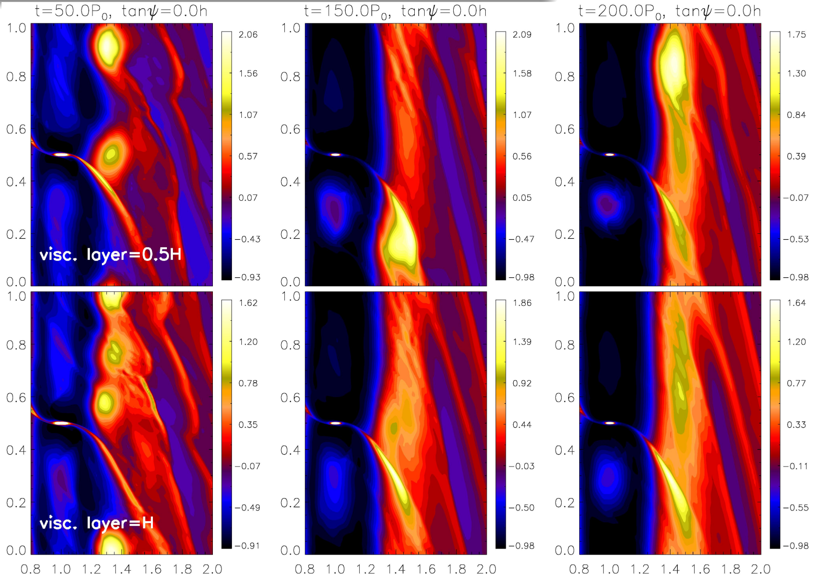


- cf. Lin (2013a) → Rossby wave unstable only for proper choice of B.C.

So vertical disk structure matters

Rossby vortices may not survive in layered disks

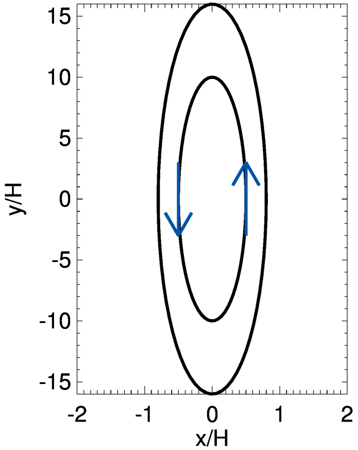
(Pluto sims., Lin, 2014)



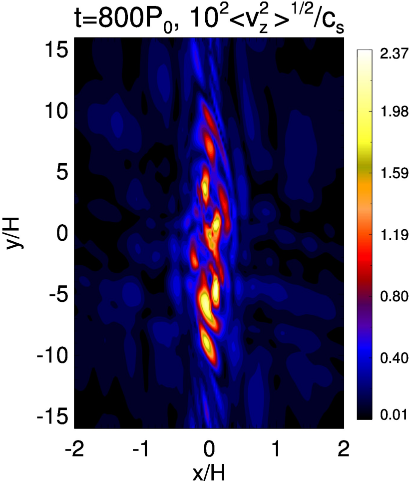
Elliptic instability of 3D vortices

(Ryu & Goodman, 1994; Lesur & Papaloizou, 2009)

- In plane ($v_z = 0$) elliptical flow about the vortex center



- Instability → small-scale 3D turbulence ($v_z \neq 0$)

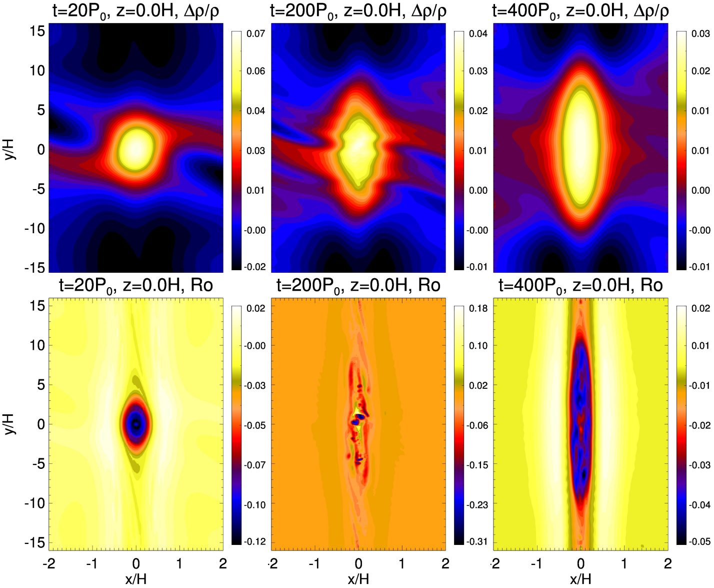


Athena sims. (Lin, in prep.)

Elliptic instability of 3D vortices

Density pert.

Vort./2Ω



Athena simulations (Lin, in prep.)

Vortices should survive long enough to be observable

Without external driving, vortices die in $O(100)$ orbits

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Can the self-gravity of vortices help them survive?

Self-gravity

When is disk self-gravity important?

Textbook answer:

$$Q \equiv \frac{\Omega c_s}{\pi G \Sigma} \lesssim 1 \text{ to } 2$$

Assumptions:

- 2D, razor-thin disk, axisymmetric
- Circular flow
- Laminar

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Vortices: non-axisymmetric, with elliptical streamlines, and likely turbulent

Self-gravity

Lin & Papaloizou (2011):

- Self-gravity stabilizes the Rossby wave instability (analytically proved & numerically verified)

Lovelace & Hohlfeld (2013); Zhu & Baruteau (2016):

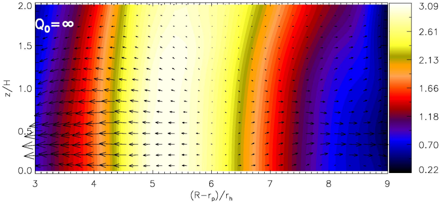
- Self-gravity affects 2D vortex evolution when $Q \lesssim 10 - 20$ in protoplanetary disks

Self-gravity

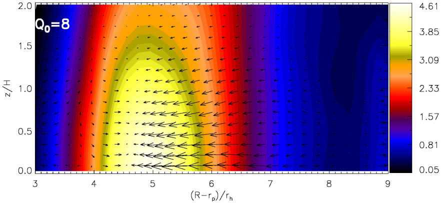
Should include SG when modeling vortices even in low mass disks

3D global Zeuz-MP simulations

$\Delta\rho/\rho$



↑ NO self-gravity

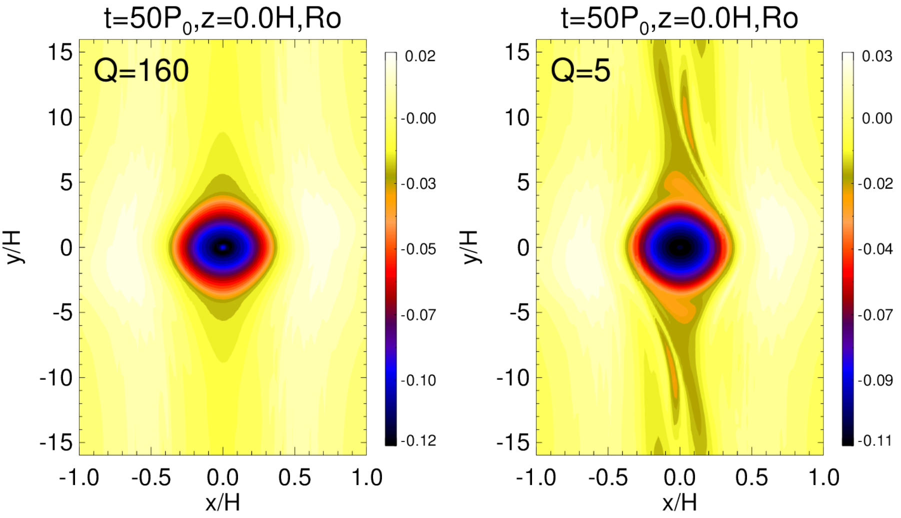


↑ init. $Q \sim 10$

(low res. $\sim$ 4 cells per H in r, ϕ)

Vortices & self-gravity in 3D

Athena 3D shearing box simulations



(small box, high res. 16 to 64 cells/H)

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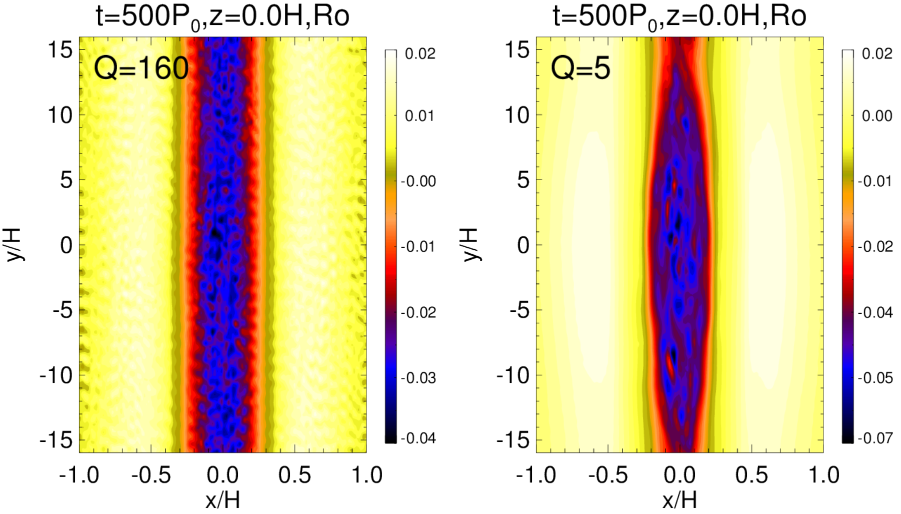

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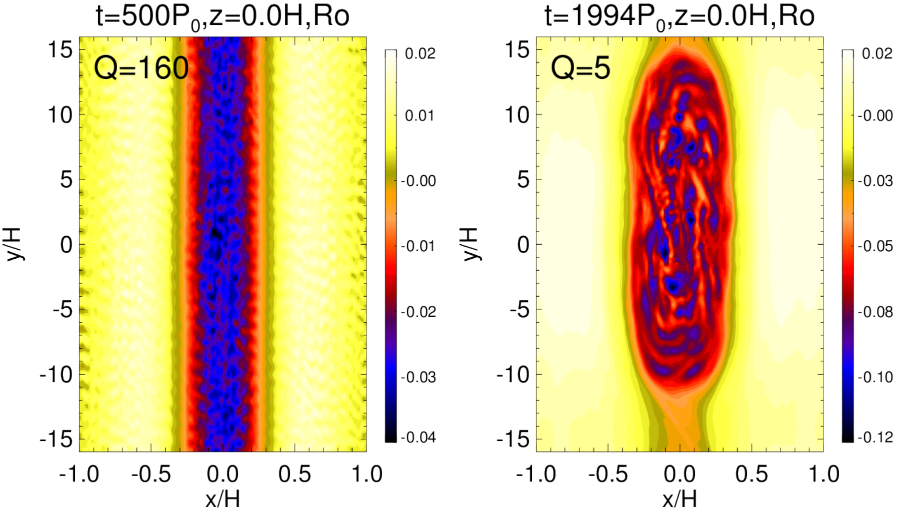

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Vortices & self-gravity in 3D

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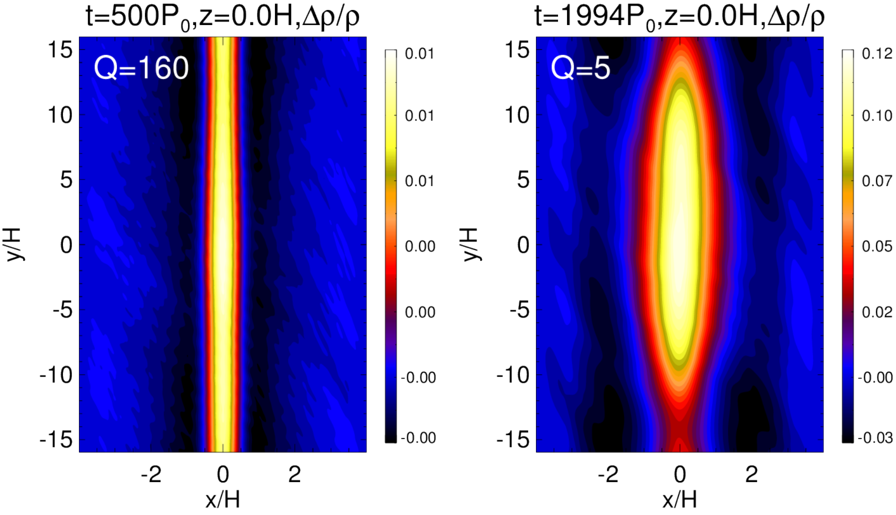


(small box, high res. 16 to 64 cells/H)

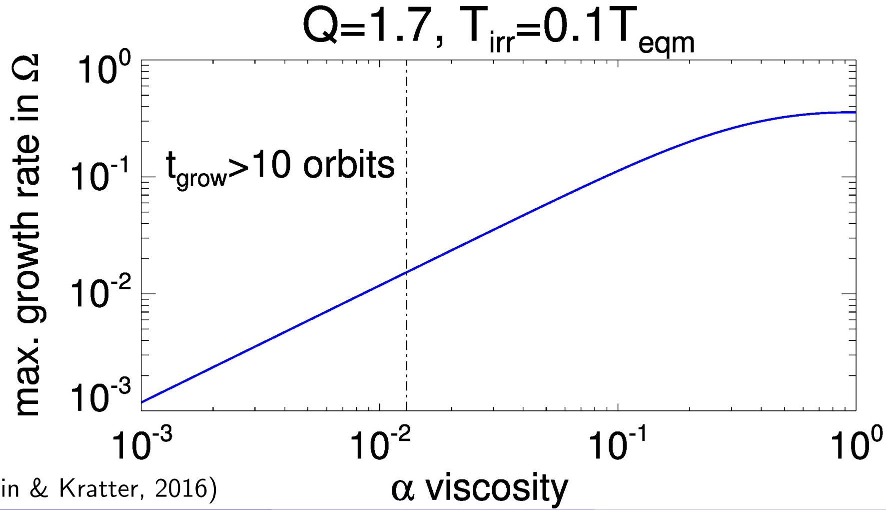
Turbulence and self-gravity

Is turbulence enhancing self-gravity?

If turbulence ∼ viscosity

Viscous/secular gravitational instabilities

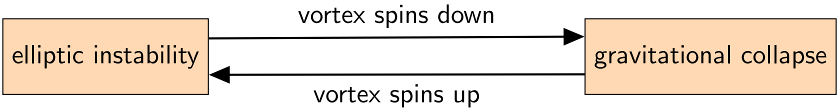
- Friction reduces rotational stabilization (Lynden-Bell & Pringle, 1974)



(Lin & Kratter, 2016)

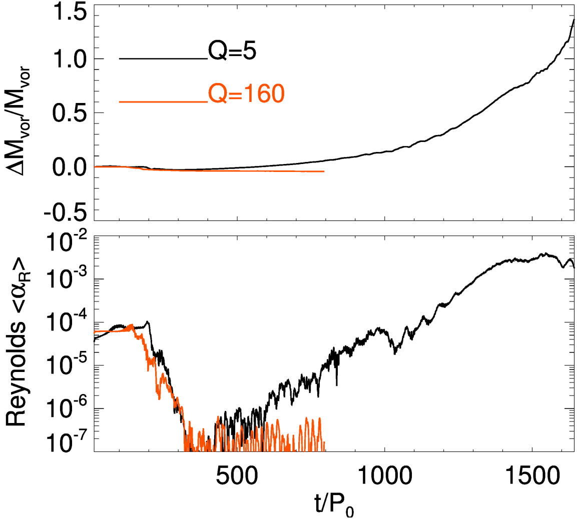
Gravito-elliptic feedback

Conjecture:



- Elliptic instability $\rightarrow$ hydrodynamic turbulence/viscosity
- Viscosity removes rotational support $\rightarrow$ vortex collapses
- Vortex spins up $\rightarrow$ Elliptic instability

Runaway 3D vortex collapse



- Large box, low resolution (still 32 cells/H in x)
- EI strength limited $\rightarrow$ vortex remains intact with turbulent core
- Secular growth in mass

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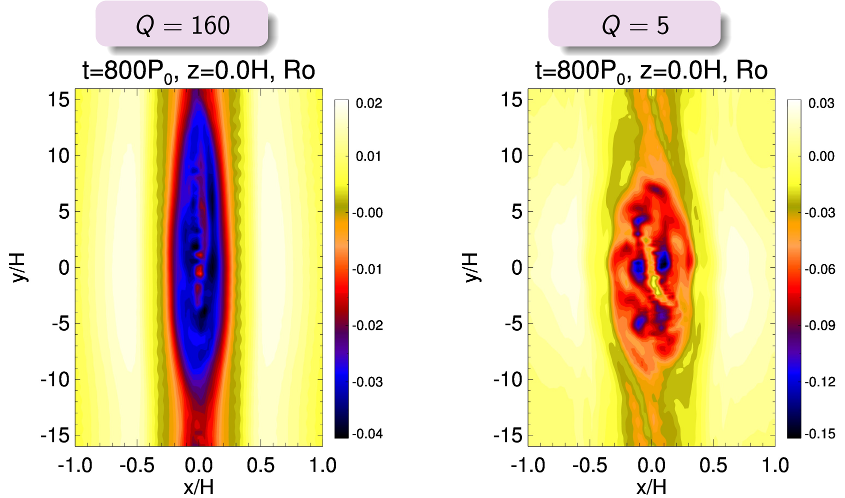

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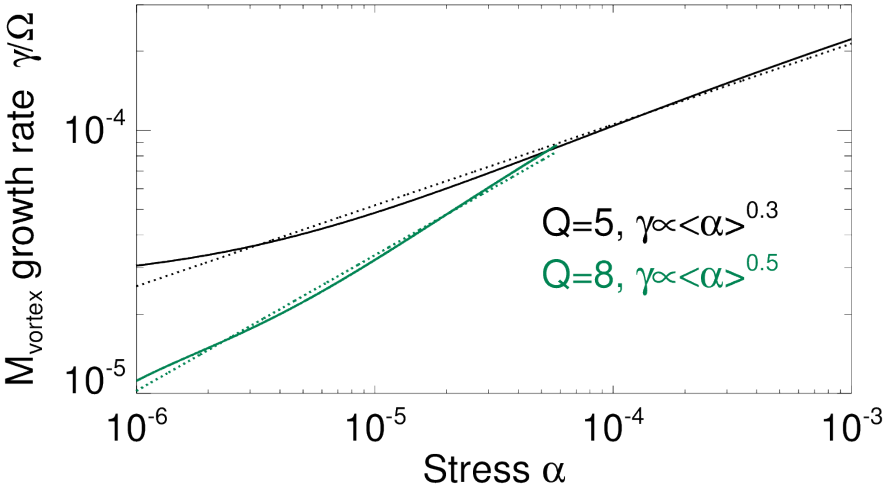
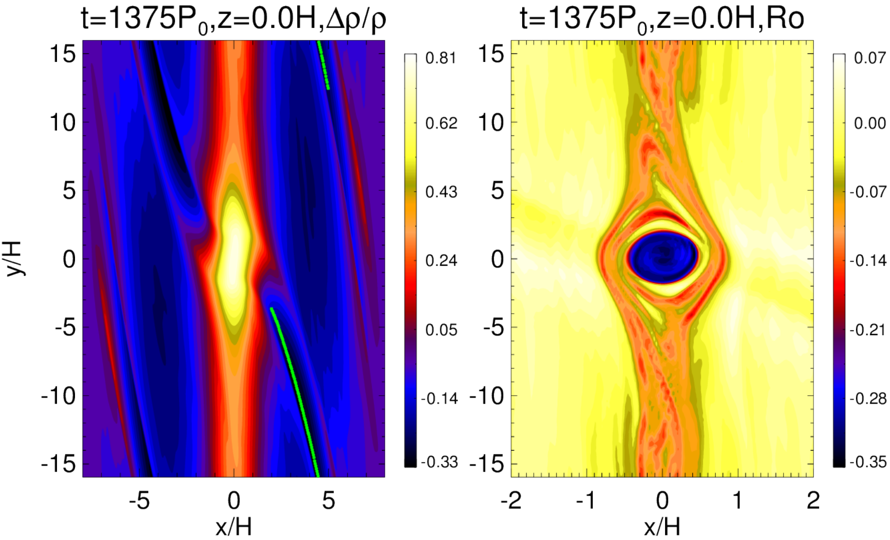
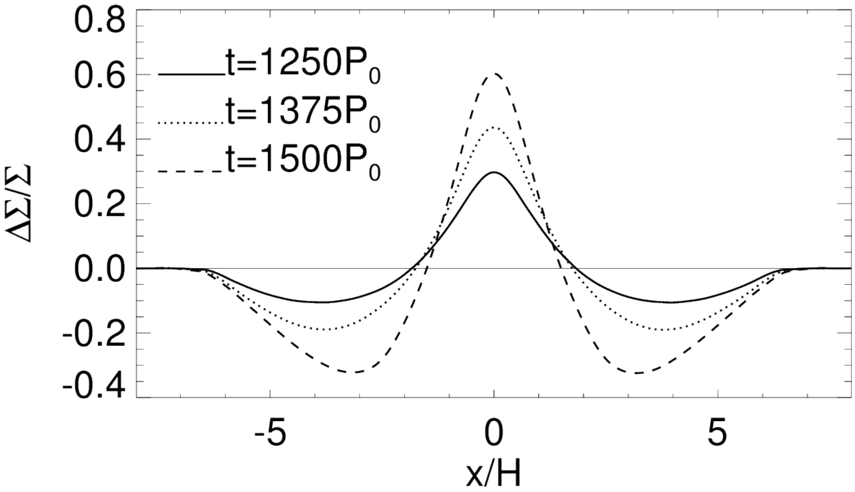
Growth rates and turbulent viscosity



Vortex gap-opening



Vortex gap-opening



Summary

- Protoplanetary disk sub-structures reflect disk and/or unseen planet properties
- Large-scale lopsidedness may be produced by vortices
- Rossby vortices should be modeled in 3D to account for elliptic instabilities
- Vortex self-gravity could help survival against EI

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Some future topics

- Gap-opening by ellipsoidal density distributions
- Gas/dust accretion onto ellipsoidal perturbers in the disk
- Dust dynamics within elliptical flow

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We need:

- Global disk models
- Cylindrical/spherical Poisson solver for self-gravity (no modern public code)
- High resolution, > 32 cells per scale-height H in 3D

If you have such a code, I'd be interested!

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