Vortex (and spiral) instabilities in structured protoplanetary disks

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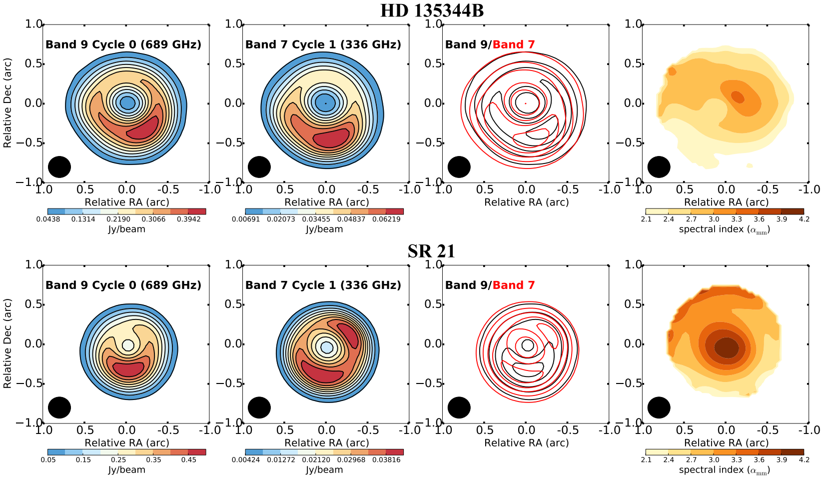
Outline

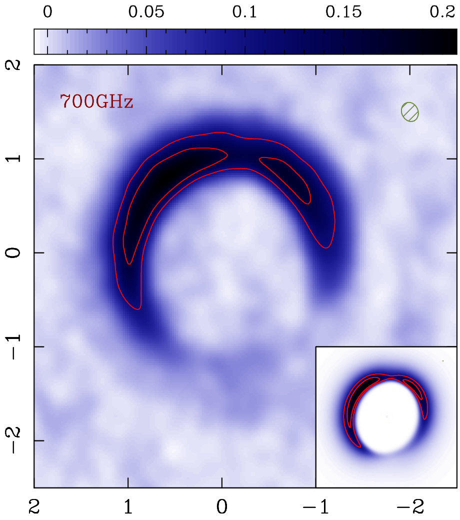
1. Vortices at planetary gap edges (recap)
2. Self-gravity, disk mass $\leftrightarrow$ asymmetric morphology
3. 3D effects, vertical structure/boundary conditions
4. Advertisement & mystery slide

Disk asymmetries are not uncommon



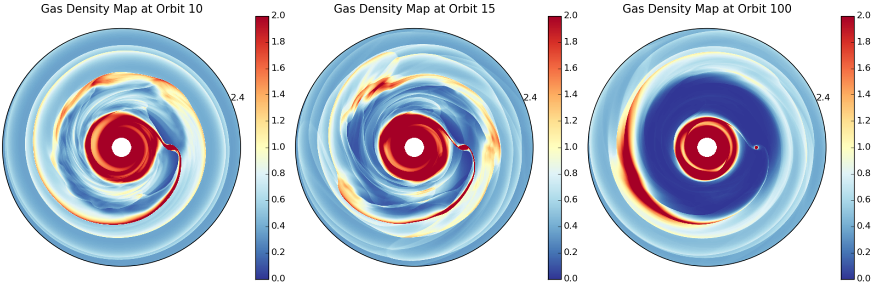
(Pinilla et al., 2015)

Disk asymmetries are not uncommon



(HD142527, Casassus et al., 2015)

Gap edges as sites for vortex formation



(2D simulations by M. Hammer, 'Vortices and orbital migration')

- Disk-planet interaction $\rightarrow$ gaps
- Surface density maxima at gap edges, or PV minima due to strong shear
- 'Roll up' into vortices (think: Kelvin-Helmholtz)

Basic theory :

Lovelace et al. (1999); Li et al. (2000)

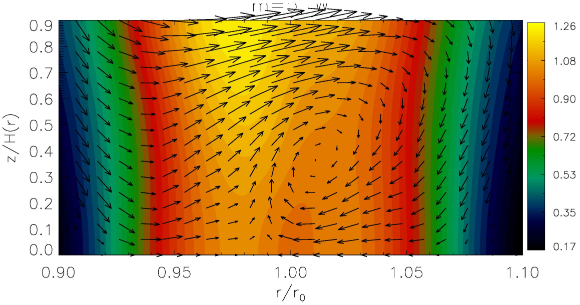
Poster: 5O [T. Ono] $\rightarrow$ new criteria for Rossby wave instability

Recent extensions to linear theory

3D :

Meheut et al. (2012); Lin (2012, 2013b)

- Instability is physically 2D
- Increased vertical/structure flow with stiffer equation of state, or when buoyancy forces are present

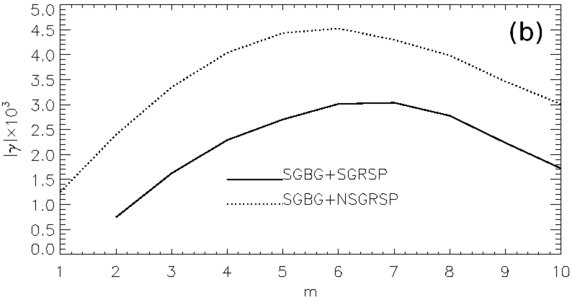


($\gamma = 2.5$, $P \propto \rho^{3/2}$, Lin, 2013b)

Recent extensions to linear theory

Self-gravity tends to stabilize against vortex formation

Lin & Papaloizou (2011a,b); Lovelace & Hohlfeld (2013); Yellin-Bergovoy et al. (2015) Poster: 5J [R. Yellin-Bergovoy , E. Heifetz]



Growth rates v.s. azimuthal mode number (Lin & Papaloizou, 2011a)

Self-gravity: when should you care?

Classic Toomre-like criterion:

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim 2$$

BUT

- Toomre Q does not account for global disk structure, like gaps/edges

Self-gravity: when should you care?

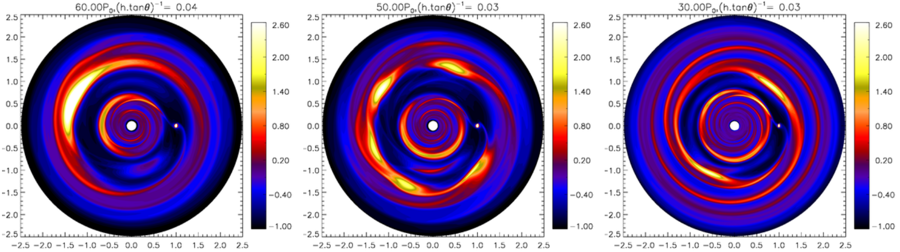
Vortex formation (Lovelace & Hohlfeld, 2013):

$$\boxed{Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim \frac{r}{H}}$$

Confirmed numerically by Zhu & Baruteau (2015): vortex weakens

- Disk aspect-ratio $H/r \ll 1$ in protoplanetary disks
- $H/r \sim 0.05 \rightarrow$ should include SG when $Q \lesssim 20$

No extended vortices in massive disks

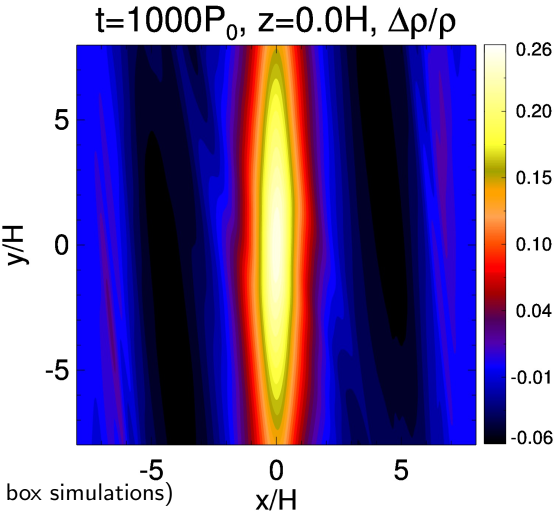


$M_d = 0.02M_*$ $\quad$ $M_d = 0.06M_*$ $\quad$ $M_d = 0.08M_*$

- Multi-vortex confirguation in quasi-steady state for moderately massive disks (Lin & Papaloizou, 2011a)

Do massive vortices behave like planets?

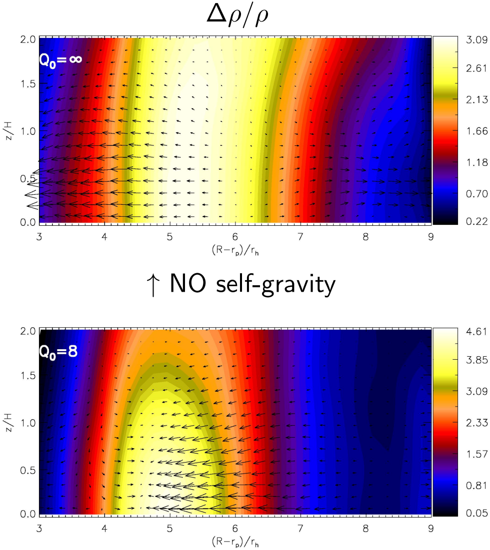
(See also talk by Z. Zhu)



(Athena shearing box simulations)

- Gap-opening by vortices/ellipsoidal potentials

These vortices are vertically global



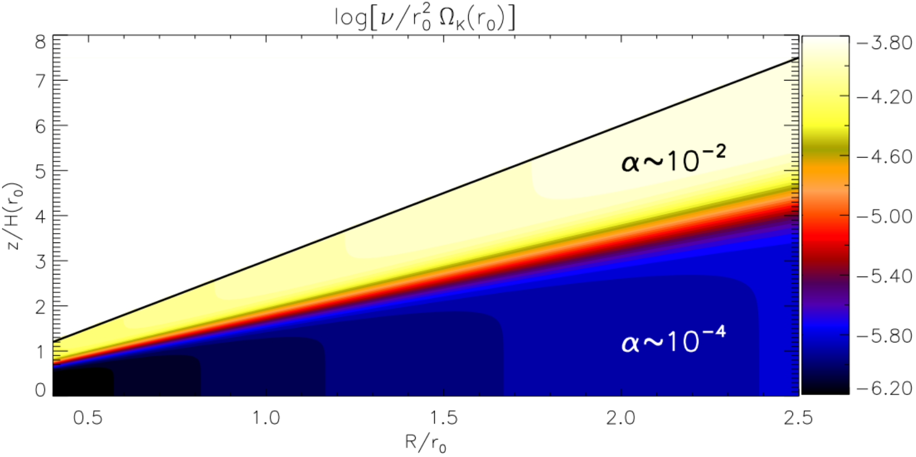
↑ NO self-gravity

↑ WITH self-gravity

- $Q_{\rm planet} \simeq 15$ initially
- SG → more stratified
- $|v_z/c_s| \sim$ few %

So vertical boundary conditions matter

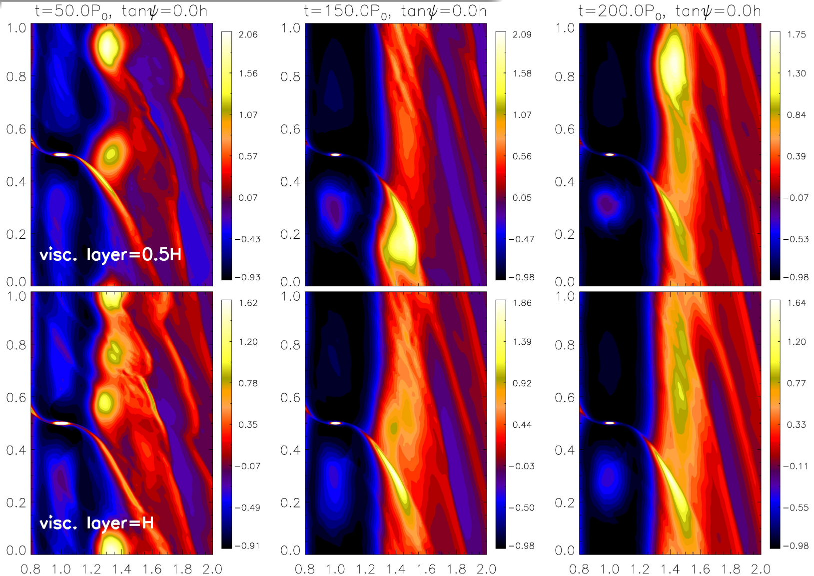
Vortex formation with layered viscosity (Lin, 2014)



- cf. Lin (2013a) $\rightarrow$ unstable only for proper choice of B.C.

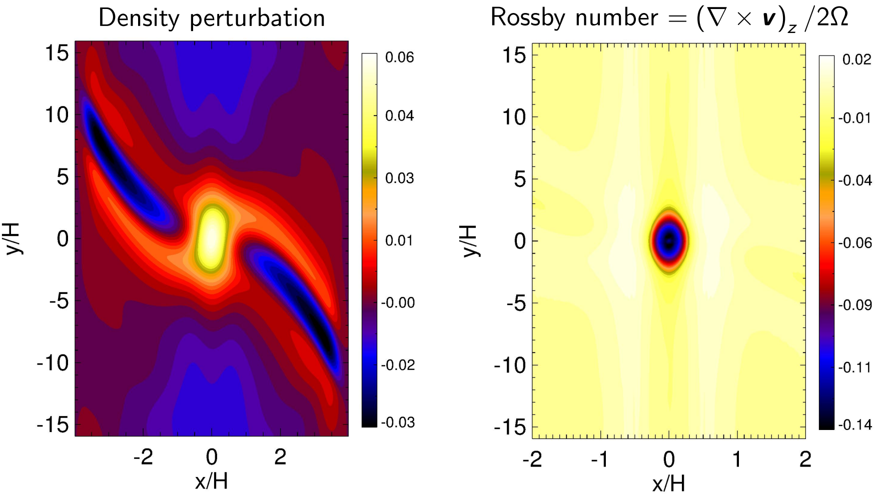
So vertical boundary conditions matter

Vortex formation with layered viscosity (Lin, 2014)



An even simpler example

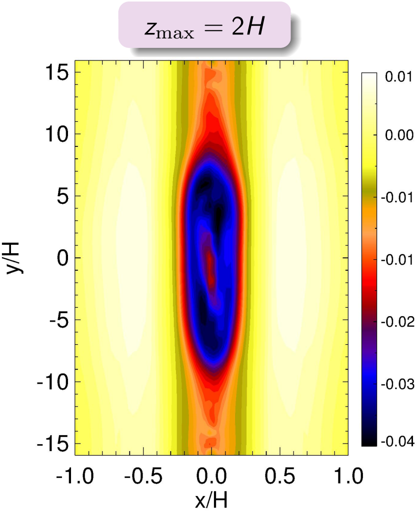
- Isothermal shearing box initialized with a vortex

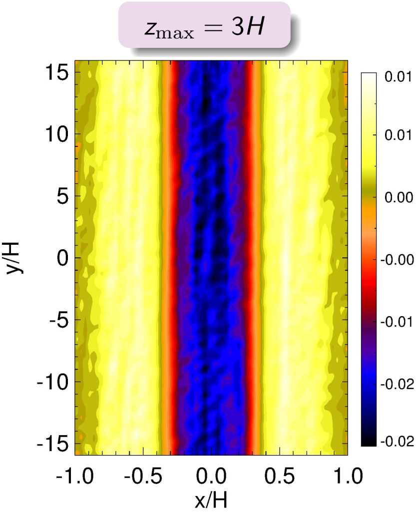


Athena simulations (Lin & TBC, in prep.)

An even simpler example

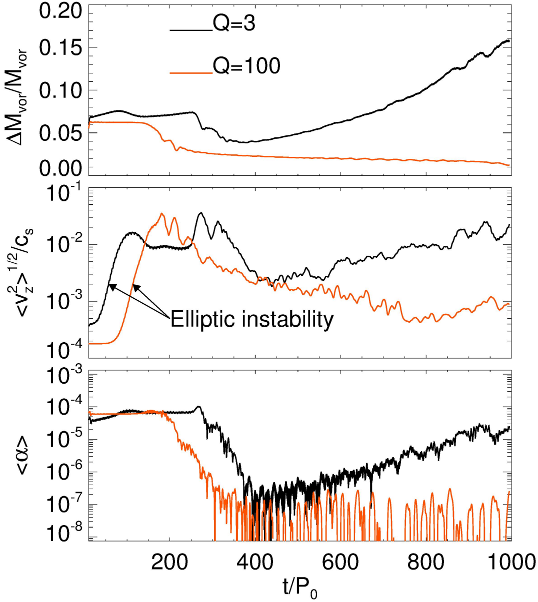
- Short vortices survive, tall vortices die
  ('elliptic instability', Lesur & Papaloizou, 2009; Lithwick, 2009)





Athena simulations (Lin & TBC, in prep.)

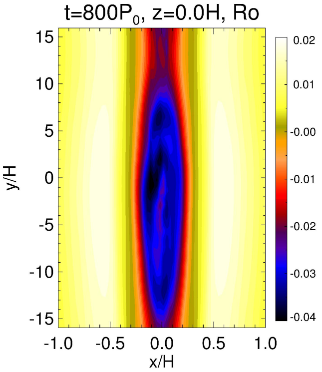
Elliptic instability & self-gravity



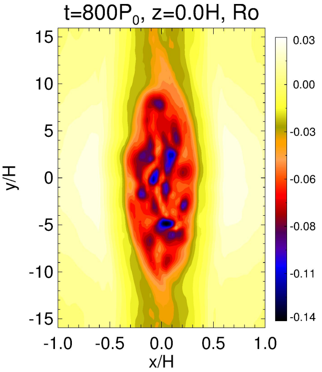
- Athena shearing box with self-gravity

Elliptic instability & self-gravity

$Q = 100$



$Q = 3$



$$\text{elliptic instability} \underset{\text{adds rotation}}{\overset{\text{removes rotation}}{\rightleftarrows}} \text{gravitational collapse}$$

Lessons

- Azimuthally-extended, single vortex only exist in low mass disks
  (Detailed quantitative parameter study needed)
- Vertical disk structure is important for columnar vortex survival
  (Back-reaction of vortex formation on vertical structure?)

Advertisement

- *Poster 5L: Vertical shear instability in protoplanetary disks* (Lin & Youdin, 2015)
- Disk eccentricity growth through external irradiation (Lin, 2015)
- Thermodynamics $\leftrightarrow$ vortex evolution/lifetimes (Les & Lin, 2015; Lobo Gomes et al., 2015)
- Stability of massive disks with resistive MHD (Lin, 2014)

If you're into disk fragmentation...

$$t_{\mathrm{cool},*} = \left(\sqrt{\gamma} - 1\right)^{-3/2} \Omega^{-1}$$

$$\alpha_* = \frac{4}{9} \frac{\sqrt{\sqrt{\gamma} - 1}}{\gamma(\sqrt{\gamma} + 1)}$$

γ	α_*	$t_{\mathrm{cool},*}\Omega$	Sim., $t_{\mathrm{cool,frag}}\Omega$	Reference
7/5	0.062	12.75	12—13	Rice et al. (2005)
1.6	0.063	7.33	8	Rice et al. (2011)
5/3	0.063	6.37	6—7	Rice et al. (2005)
2	0.059	3.75	3	Gammie (2001)

(Lin & Kratter, submitted, arXiv:1603.01613)

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