Vortices and spirals at gap edges in 3D self-gravitating disk-planet simulations

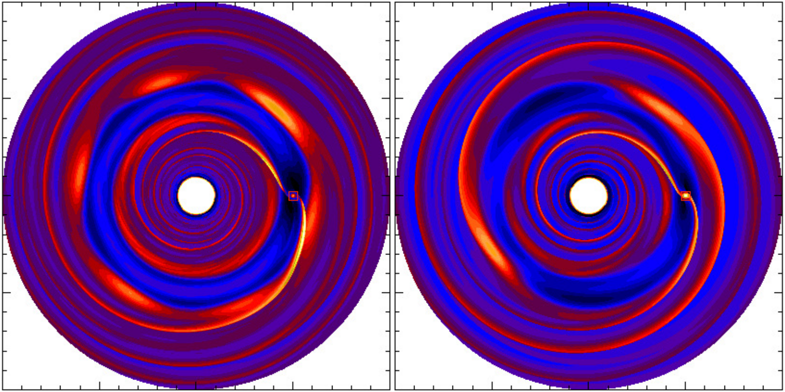
Min-Kai Lin

Canadian Institute for Theoretical Astrophysics

September 20 2012

Unstable planetary gaps

- Giant planets in self-gravitating disks.



- Low mass disk → VORTICES (Koller et al., 2003; Li et al., 2005; Ou et al., 2007; Li et al., 2009; Yu & Li, 2009; Lin & Papaloizou, 2010, 2011a)
- High mass disk → SPIRALS (Meschiari & Laughlin, 2008; Lin & Papaloizou, 2011b, 2012)

Outline

- Review
- Examples in 3D
- Discussion
- Upcoming

Non-axisymmetric instabilities in structured 2D disks

- Potential vorticity (vortensity) extrema is neccessary for instability:

$$\eta \equiv \frac{\kappa^2}{2\Omega\Sigma}$$

- Note: barotropic, non-magnetized
- Nearly-Keplerian disk: $\kappa \sim \Omega$ so $\eta \sim \kappa/\Sigma \propto Q$

Non-axisymmetric instabilities in structured 2D disks

- Potential vorticity (vortensity) extrema is neccessary for instability:

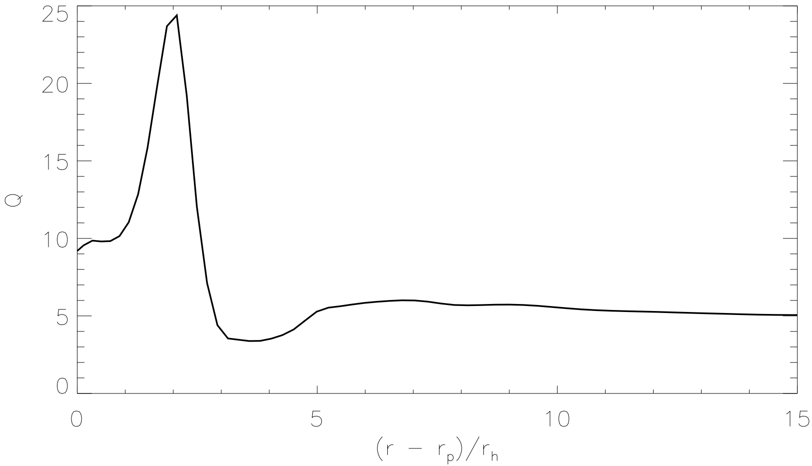
$$\eta \equiv \frac{\kappa^2}{2\Omega\Sigma}$$

- Note: barotropic, non-magnetized
- Nearly-Keplerian disk: $\kappa \sim \Omega$ so $\eta \sim \kappa/\Sigma \propto Q$

$$Q \equiv \frac{c_s \kappa}{\pi G \Sigma} = \frac{c_s}{\pi G} \left(\frac{2\Omega\eta}{\Sigma} \right)^{1/2}$$

- Planet gaps: Q and η look similar

Planetary gaps in terms of Q



- Local $\min(Q) \rightarrow$ vortices
- Local $\max(Q)$ plus $Q(r_{\rm out}) \lesssim 2 \rightarrow$ spirals

Checklist for 3D simulations

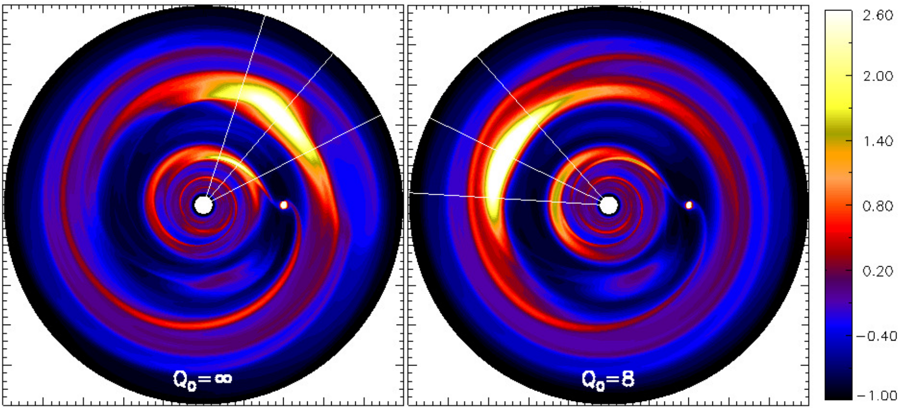
2D results:

- Vortex formation in low M_d, fast merging
- More vortices with inceasing M_d, resisted/delayed merging
- Spirals with large M_d

3D setup:

- Inviscid 3D disk in spherical polars
- Locally isothermal (now with energy equation)
- Self-gravity parametrized by $Q_0 = Q(r_{\mathrm{out}})$ or M_d
- Giant planet: 1 or 2-Jupiter mass

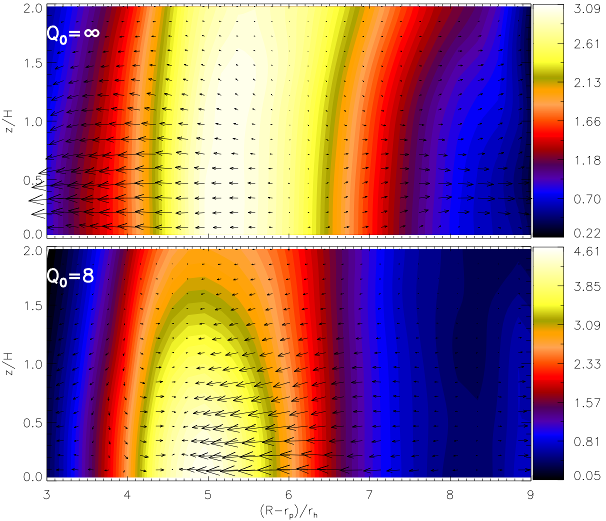
$Q_0 = \infty$ verses $Q_0 = 8$



- Vortex formation, checked.

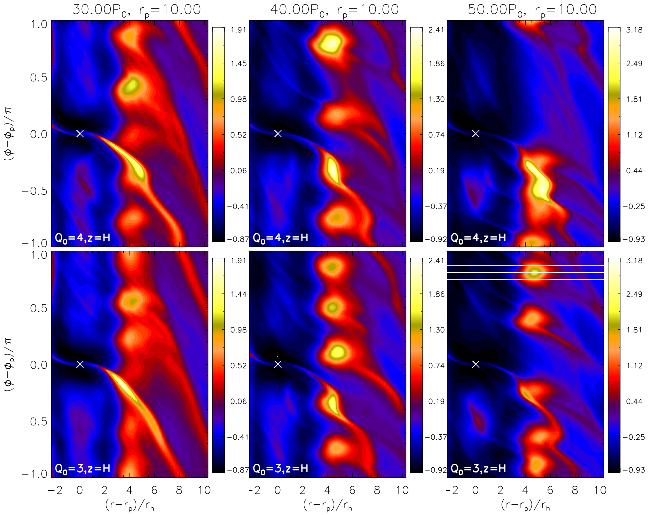
$Q_0 = \infty$ verses $Q_0 = 8$

Vortex vertical structure (relative density perturbation)



- Initially $Q \sim 10$ in this region $\rightarrow$ but $\Delta\rho/\rho$ is stratified

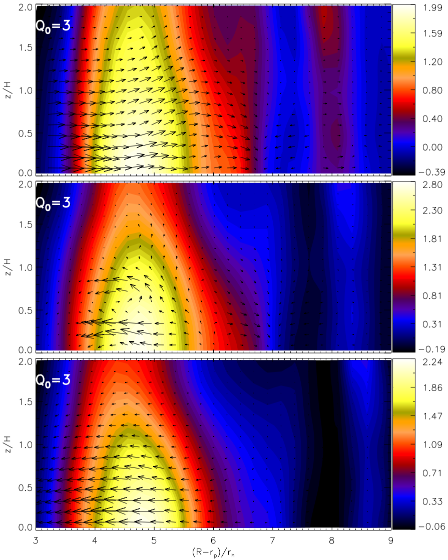
$Q_0 = 4$ and $Q_0 = 3$



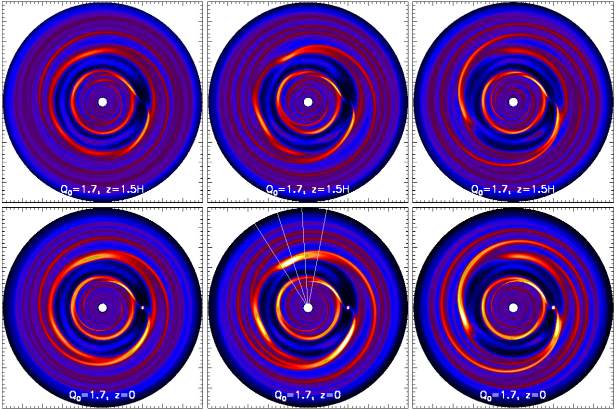
- More vortices and resisted merging, checked.
- Caution: boundary potential needs $m >$ vortices

$Q_0 = 3$

- Unperturbed $Q \sim 4$
- No merging yet
- Most stratified at vortex core
- Unable to identify 'typical' vertical flow pattern (cf. anti-cyclonic horizontal flow)

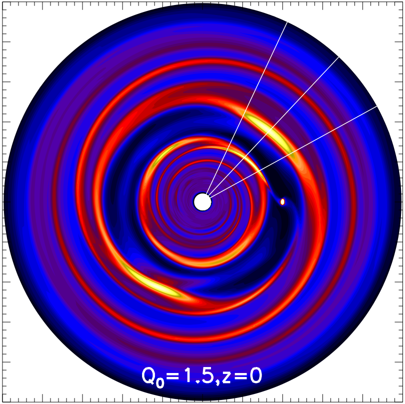


$Q_0 = 1.7$ and $Q_0 = 1.5$



- Spirals in massive disks, checked.
- Sharp $\max(Q)$ circumvents need for low Q locally ($Q_{\rm edge} \sim 10$), but need exterior disk to feel the edge disturbance
- They provide *positive* co-orbital torques (outward migration possible)

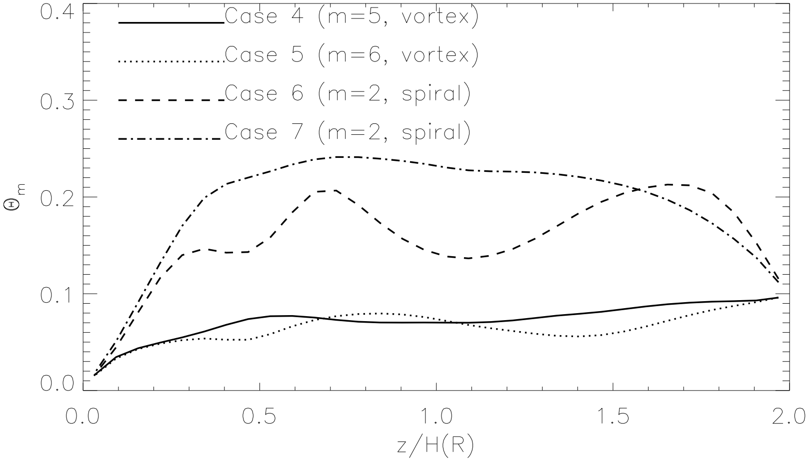
$Q_0 = 1.7$ and $Q_0 = 1.5$



- Spirals in massive disks, checked.
- Sharp $\max(Q)$ circumvents need for low Q locally ($Q_{\rm edge} \sim 10$), but need exterior disk to feel the edge disturbance
- They provide *positive* co-orbital torques (outward migration possible)

Three-dimensionality

- Empirical measure: $\sqrt{v_z^2/(v_R^2+v_z^2)}$



- Approximately 2D disturbance
- Vertical Mach number $\sim$ few per cent

Discussion

- Confirmed that most 2D results persist in 3D, long term 3D evolution unknown (H. Li's talk)
- Strongest 3D effect: vertical self-gravity

Speculations:

- Vortex stability ('flattened' under its own weight)
- Reduction of vertical boundary effects: avoid complicated physics at upper and lower active layers
  (failed to find linear vortex modes with, e.g. $\delta v_{\parallel} = 0$ or $\delta\rho = 0$ at upper disk boundary)

Back to linear stability

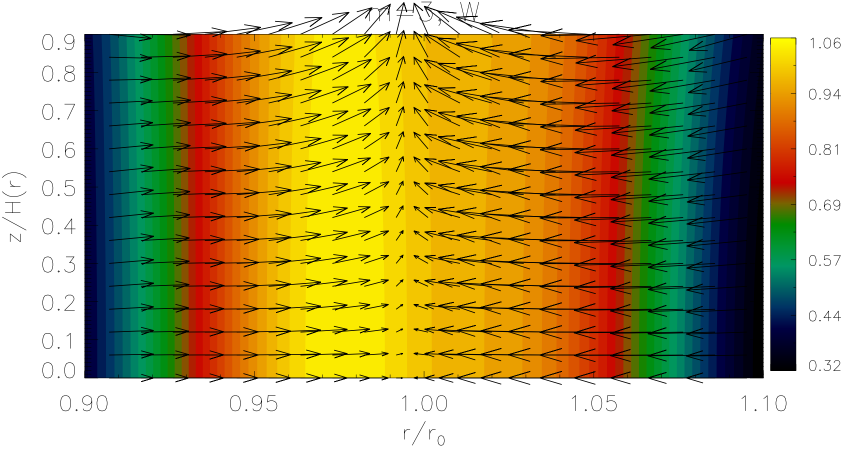
- Linear 3D adiabatic disturbances governed by PDE eigenvalue problem

$$U(W) = 0,$$

  where $W \equiv \delta p/\rho$. (freedom to implement vertical b.c.)
- Equilibrium: $p \propto \rho^\Gamma$ and $\gamma \geq \Gamma \geq 1$.
- Solve for nonhomentropic 3D thin disks with a density bump $\rightarrow$ Rossby wave instability.
- Thick tori version (harder) done by Frank & Robertson (1988) and Kojima et al. (1989) $\rightarrow$ clues.
- Difficult in general, but brute force works OK for RWI.

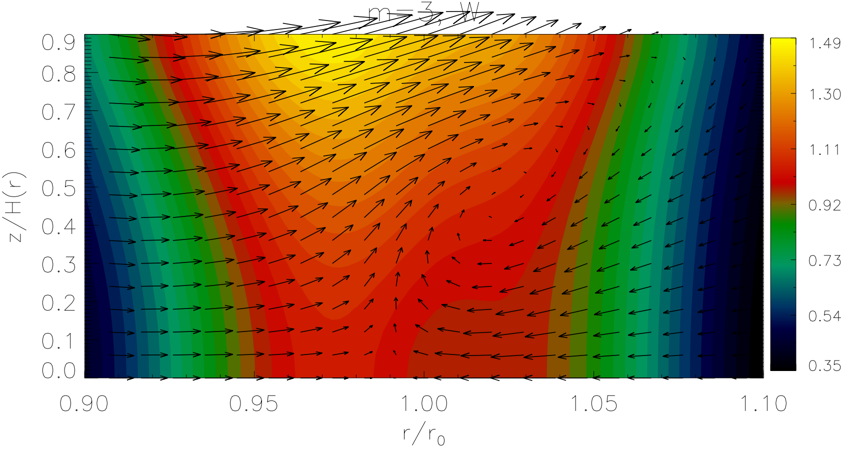
Homentropic verses nonhomentropic

- $\gamma/\Gamma = 1$ (polytrope)



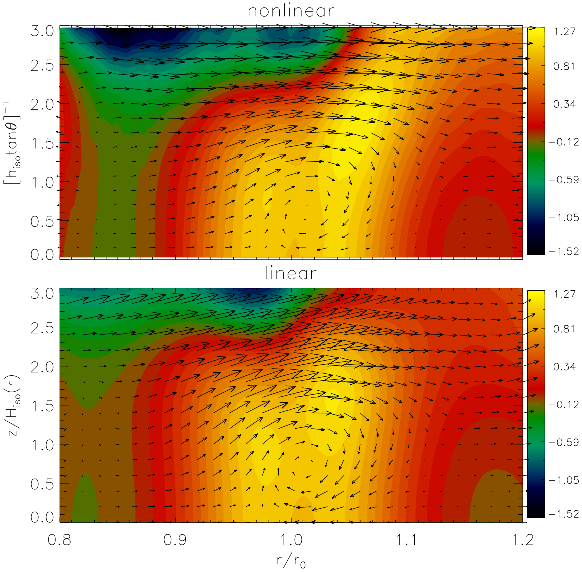
Homentropic verses nonhomentropic

- $\gamma/\Gamma = 1.8$



Linear verses nonlinear

- Strictly isothermal equilibria, $\gamma = 1.4$



More details

- *'Vortex and spiral instabilities at gap edges in three-dimensional self-gravitating disc-satellite simulations'*: Lin, M-K., 2012, MNRAS, in press, astro-ph: 1205.4034
- *'Effects of upper disc boundary conditions on the linear Rossby wave instability'*: Lin, M-K., 2012, MNRAS, accepted (Sept 17), look out on astro-ph (PDE solver demo)
- *'Non-barotropic linear Rossby wave instability in three-dimensional disks'*: Lin, M-K., 2012, ApJ, submitted, astro-ph: 1209.0470

References

Frank J., Robertson J. A., 1988, MNRAS, 232, 1

Kojima Y., Miyama S. M., Kubotani H., 1989, MNRAS, 238, 753

Koller J., Li H., Lin D. N. C., 2003, ApJL, 596, L91

Li H., Li S., Koller J., Wendroff B. B., Liska R., Orban C. M., Liang E. P. T., Lin D. N. C., 2005, ApJ, 624, 1003

Li H., Lubow S. H., Li S., Lin D. N. C., 2009, ApJL, 690, L52

Lin M.-K., Papaloizou J. C. B., 2010, MNRAS, 405, 1473

Lin M.-K., Papaloizou J. C. B., 2011a, MNRAS, 415, 1426

Lin M.-K., Papaloizou J. C. B., 2011b, MNRAS, 415, 1445

Lin M.-K., Papaloizou J. C. B., 2012, MNRAS, 421, 780

Meschiari S., Laughlin G., 2008, ApJL, 679, L135

Ou S., Ji J., Liu L., Peng X., 2007, ApJ, 667, 1220

Yu C., Li H., 2009, ApJ, 702, 75