Vortices and spirals at gap edges in 3D self-gravitating disk-planet simulations [P21B-1843]

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Introduction

The interaction between a giant planet and a gaseous protoplanetary disk leads to the formation of an annular gap in the disk. Planetary gaps can become dynamically unstable because they are associated with local potential vorticity (PV) extrema. Gap edges may undergo vortex formation in weakly self-gravitating disks (associated with PV minima) similar to the Kelvin-Helmholtz instability; or develop a spiral instability (associated with PV maxima) in strongly self-gravitating yet Toomre-stable disks. These instabilities can significantly affect orbital migration of planets and dust evolution in the disk. Previous studies of planetary gap stability employed 2D disk models. In this work, direct numerical simulations of disk-planet systems are performed to study gap stability in 3D.

Disk-planet model

The 3D disk embedded with a planet is described by the Euler equations coupled with the Poisson to account for self-gravity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho}\nabla p - \nabla \Phi_{\mathrm{ext}} - \nabla \Phi_{\mathrm{gas}},$$

$$\nabla^2 \Phi_{\mathrm{gas}} = 4\pi G \rho.$$

Φ_{ext} includes the stellar and planetary potentials considered as point masses M_* and M_p respectively. Φ_{gas} is the disk potential.

- Locally isothermal disk: $\sqrt{p/\rho} \equiv c_s = hR\Omega_k$, where h is the disk constant aspect-ratio, $\Omega_k^2 = GM_*/R^3$ and R is the cylindrical radius from the star.
- Self-gravity characterized by

$$Q_0 = \left.\frac{c_s \Omega_k}{\pi G \Sigma}\right|_{\text{outer boundary}},$$

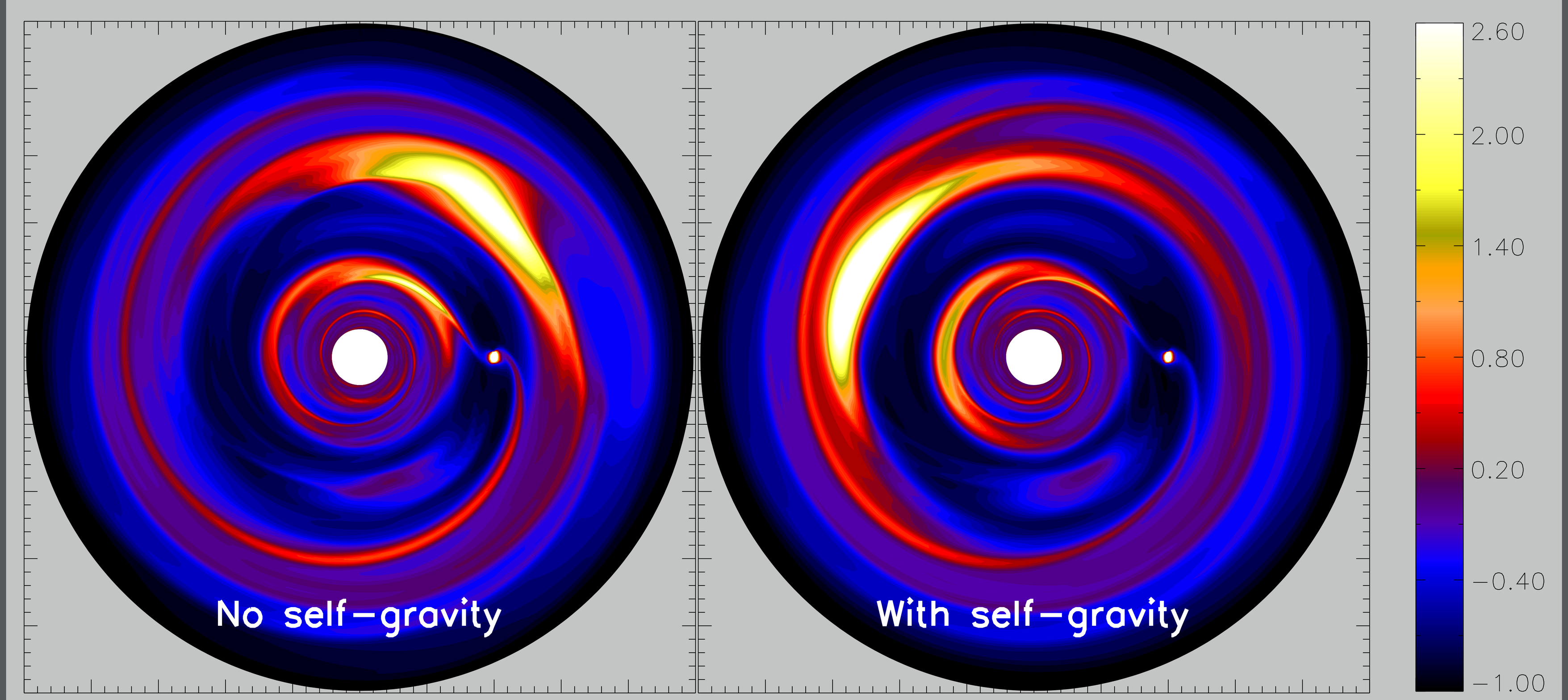
  where Σ is the surface density. *Smaller* Q_0 *imply stronger self-gravity.*
- Planet fixed on circular orbit with radius r_p in the midplane.

Numerical simulations

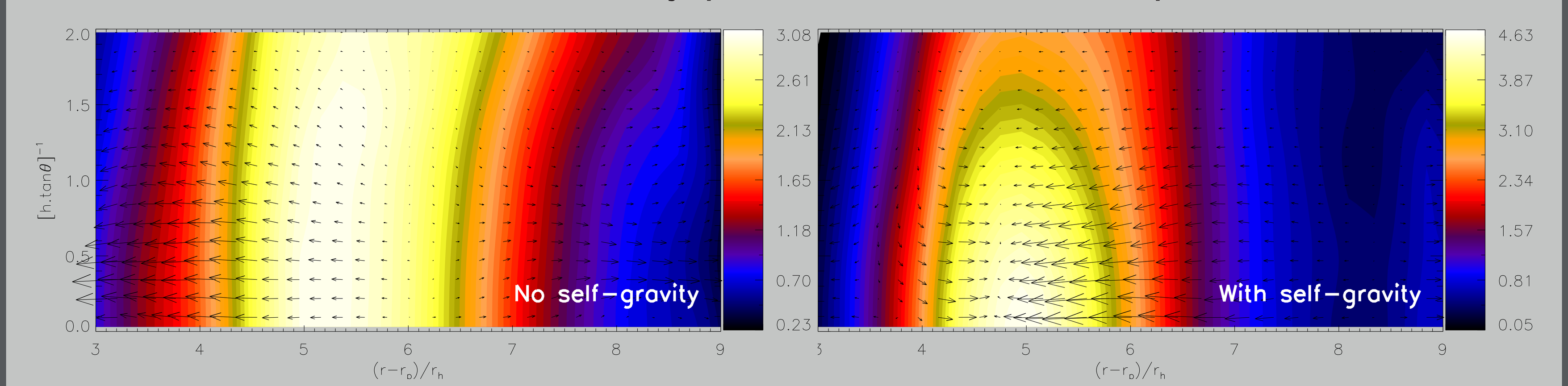
The self-gravitating hydrodynamic equations are evolved using the ZEUS-MP finite-difference code on a fixed spherical grid. The resolution in (r, θ, ϕ) is $256 \times 32 \times 512$. The vertical dimension covers 2 scale-heights.

Weakly self-gravitating disks

Parameters: $Q_0 = 8$, $h = 0.07$, $M_p = 0.002M_*$



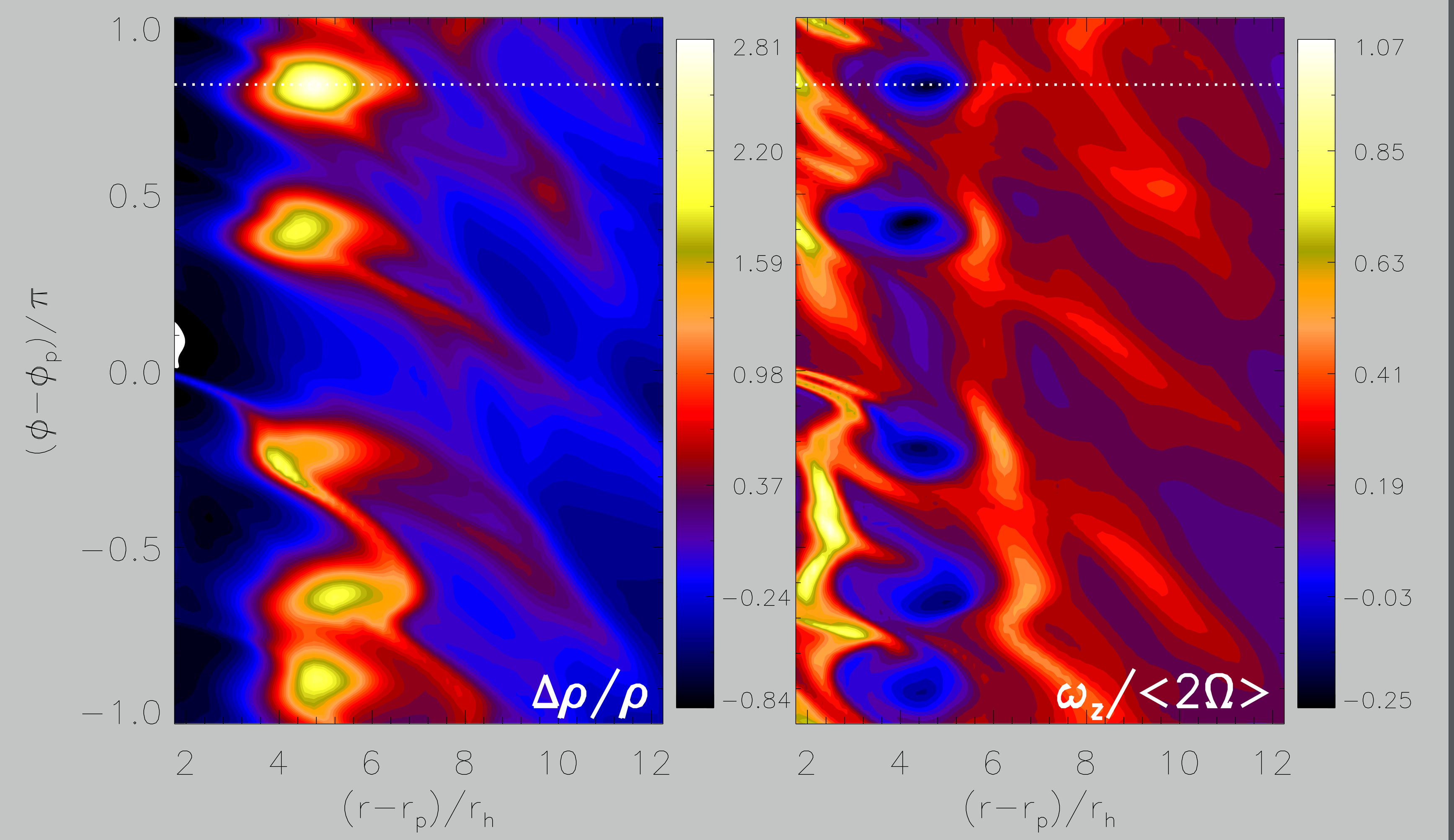
- No difference in relative density perturbation in the midplane.



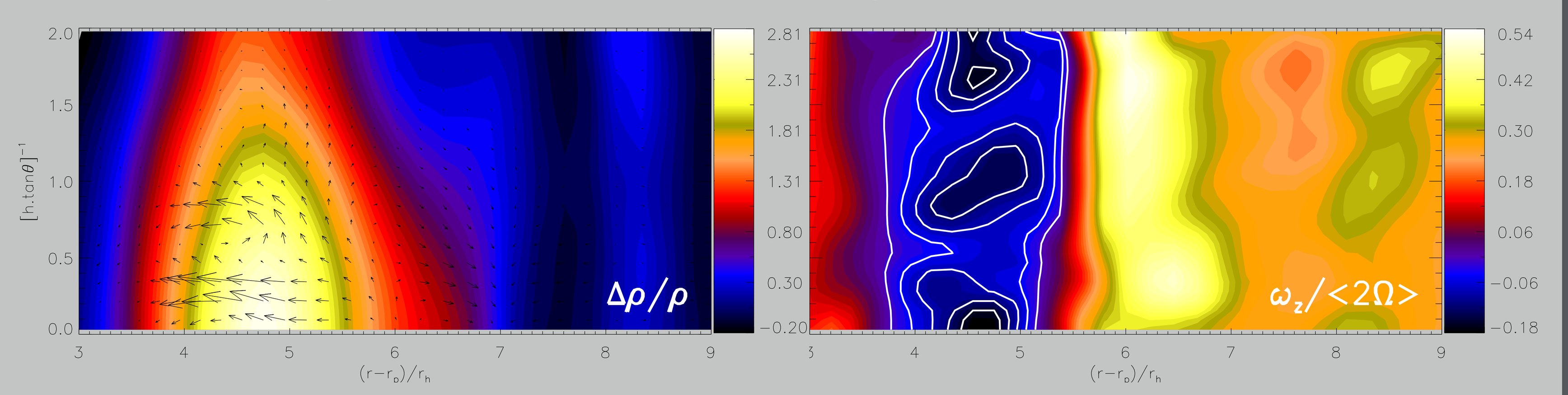
- Enhancement of vertical stratification in relative density perturbation. Self-gravity causes the vortex to be more condensed towards the midplane, even when self-gravity is negligible for horizontal dynamics.
- Typical vertical Mach number $\sim$ few per cent $\longrightarrow$ instability is 2D.

Moderately self-gravitating disk

Parameters: $Q_0 = 3$, $h = 0.07$, $M_p = 0.002M_*$



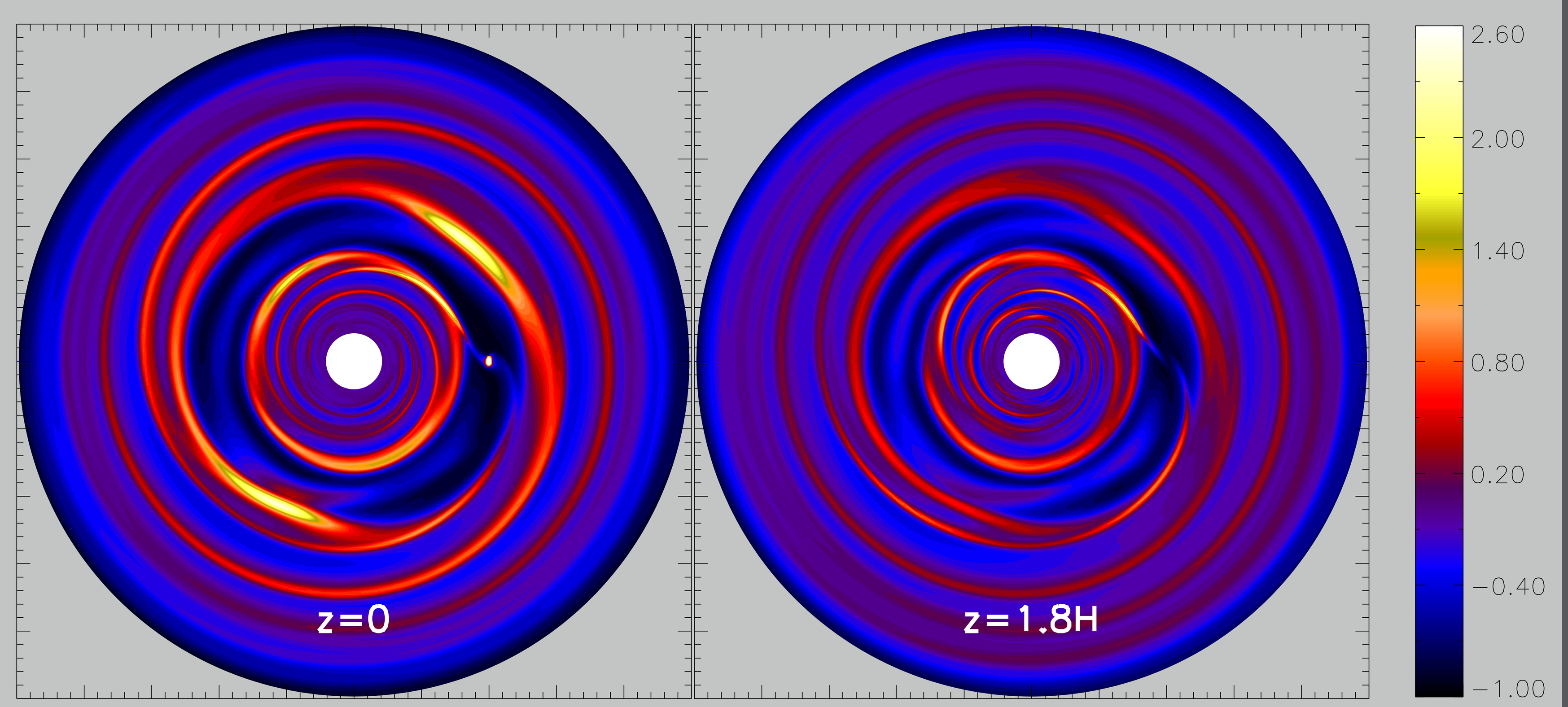
- Self-gravity favors vortex modes with higher azimuthal wavenumber **m** (partly by stabilizing low **m** modes).
- Time-scale for vortex merging increases with strength of self-gravity because they can execute horseshoe turns upon encountering one another.
- Result: stronger, multiple vortices for longer time, as in 2D.



- Vortex density is significantly enhanced at the midplane, over-density is large even before merging.
- Vertical vorticity has complicated dependence in meridional plane (cf. columnar in weakly self-gravitating disks).

Strongly self-gravitating disk

Parameters: $Q_0 = 1.5$, $h = 0.05$, $M_o = 0.001M_*$



- Unstable interaction between disturbance at the gap edge and the exterior smooth disk $\longrightarrow$ *global instability* (cf. outer disk plays no role in vortex formation).
- Density perturbation confined near the midplane.
- Edge disturbance provides *positive* disk-planet torques during gap formation $\longrightarrow$ outward migration possible.

Discussion

Explicit numerical simulations of self-gravitating disk-planet systems confirm the basic properties of gap stability, previously studied in 2D, persists in 3D. Vortex and spiral instabilities, associated with PV extrema, are two-dimensional in that vertical velocities are small compared to radial motion. However, vertical self-gravity can noticeably enhance the midplane over-density. This may mitigate upper disk boundary effects, and favor vortices to concentrate dust toward the midplane.

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