Morphology of spirals in gravito-turbulent disks

Prakruti Sudarshan[1,2], William Béthune[1], Mario Flock[2]
[1]University of Tübingen, [2]Max Planck Institute for Astronomy

Introduction

Young, massive gaseous disks are prone to gravitational instabilities (GI). GI-driven accretion can have implications on early grain growth and planet formation. Depending on the cooling time, gravitationally unstable disks can **fragment** or settle into a system of **stable angular momentum transport** by generating large-scale **spiral arms**. We study the spiral structure and the thermal saturation of GI under slow, parametrized cooling with 2D global simulations. We compare to theory and 3D global models without smoothing.

Disk evolution and stability criterion

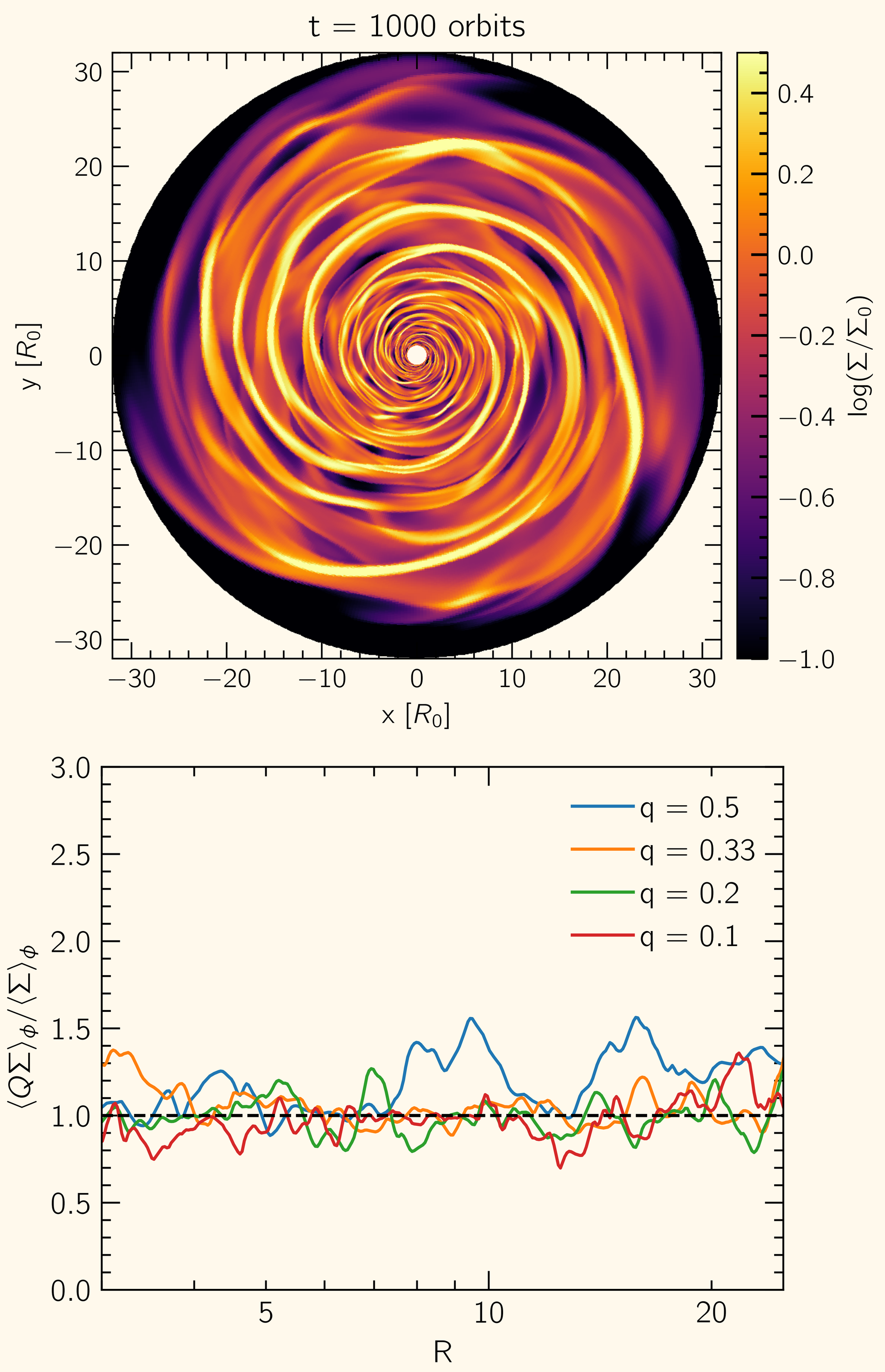


Figure 1: top: Normalized surface density after 1000 orbits at R_0 for the model $q = 0.2$, $\beta = 10$.
bottom: Density-weighted Toomre parameter Q for different disk–star mass ratios q.

- The interplay between heating from spiral-driven angular momentum transport and cooling causes the disk to **settle into a steady state**.
- Spirals are oriented with roughly **constant pitch angles**.
- The disk does not fragment for slow cooling.
- Disk self-regulates to **marginal stability** with Toomre criterion $Q \approx 1$

$$Q = \frac{\kappa c_s}{\pi G \Sigma} \sim \frac{M_*}{M_d}\left(\frac{H}{r}\right) \quad [1]$$

- Profiles of Q in our models indicate that thermodynamics (**radiative cooling** in particular) controls the disk state.

Turbulent stresses and accretion

- The radial flux of angular momentum consists of contributions from both Reynolds [3] and gravitational stresses [4],

$$R_{R\phi} = \Sigma(u_R - \langle u_R\rangle_\Sigma)(u_\phi - \langle u_\phi\rangle_\Sigma) \qquad G_{R\phi} = \int \frac{g_R g_\phi}{4\pi G} dz$$

- Angular momentum transport is **dominated by gravitational stress**, and values of turbulent stress **match the local prescription** in [5] and 3D runs with a reasonable error margin.
- An increase in Reynolds stresses in our higher-resolution models might indicate additional parametric features being resolved.

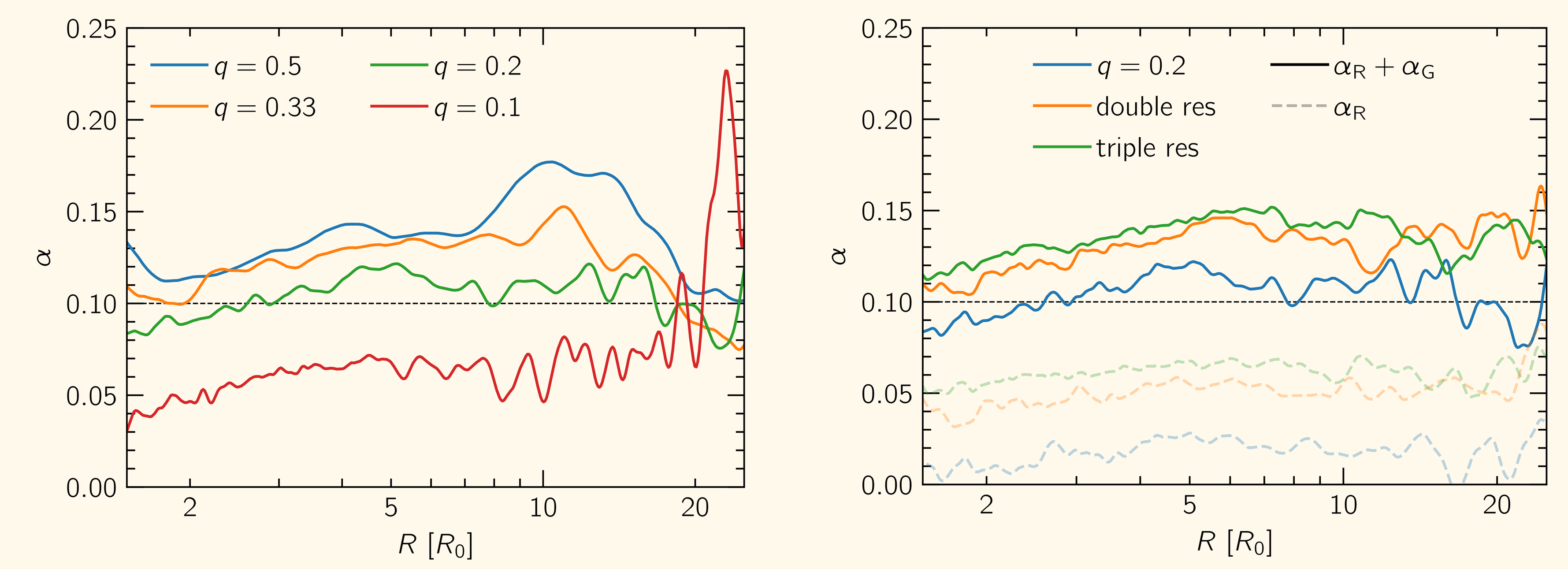
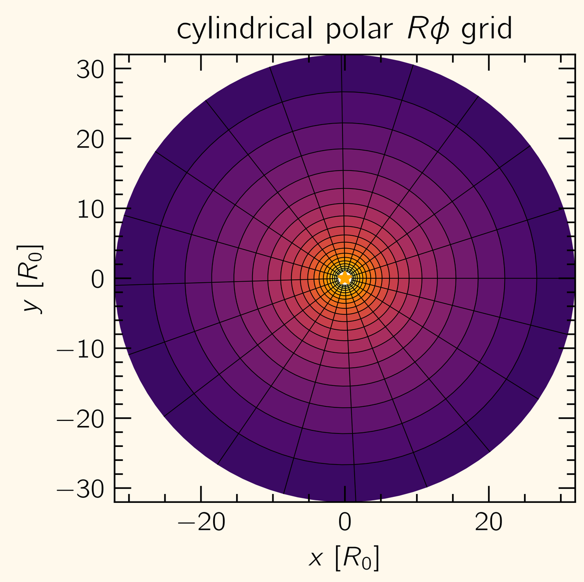


Figure 3: left: Turbulent stress α for models with different disk–star mass ratios q. right: Total turbulent stress for different resolutions for models with $q = 0.2$. The faint, dashed lines indicate the Reynolds stress.

Methods



- GPU-**PLUTO** in 2D with a self-gravity module and a **modified smoothing length** $\varepsilon(h^a)$ to correct short-range forces.
- res: 518×512, ×2–3.
- Models are **scale free**.

Pitch angles and linear theory

The spiral pitch angle i is quantified by the radial and azimuthal wavenumbers (k,m) satisfying the linear dispersion relation

$$\frac{dR}{d\phi} = -\frac{m}{k} = -R\tan(i)$$

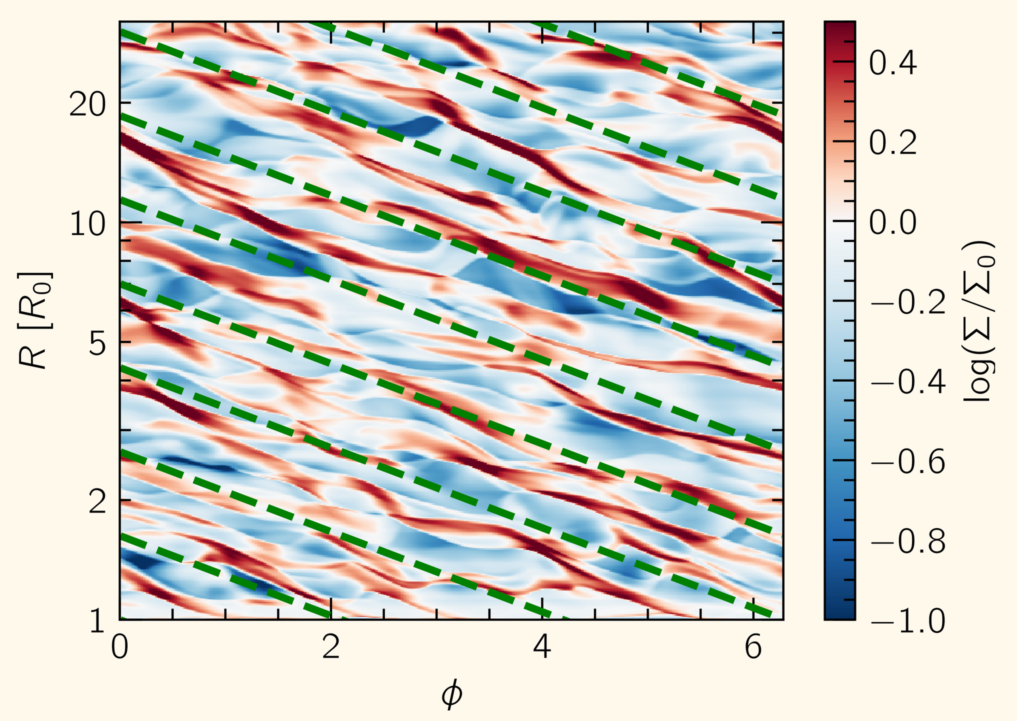


Figure 2: Two-dimensional density fluctuations for the model q = 0.2, β = 10. The dashed diagonal lines fit the spirals and the slope of the family of lines is the mean pitch angle tan(i) = 0.232.

- Linear fits of mean pitch angles are **close to 3D models** [2] with values ranging between 12–14° for the least to most massive disks.
- We found radial wavenumbers $k \approx k_0 = \pi G\Sigma/c_s^2$, the wavenumber **most strongly influenced** by self-gravity according to linear theory.

Summary

- Models agree with theory in [5]: GI unstable disks in the $Q \approx 1$ regime are well-modeled locally.
- Spirals show **self-similarity** and are constant in radius and time with wavenumbers of the order predicted by linear theory.

Future work

- Explore the origins of the increased **Reynolds stresses** in simulations with a higher resolution.
- Sensitivity to **smoothing length** and its effects in 2D (with smoothing) vs 3D global models.

References

[1] Kratter K., Lodato G., 2016, ARA&A, **54**, 271
[2] Béthune W., Latter H., Kley W., 2021, A&A, **650**, A49
[3] Balbus, S. A., & Papaloizou, J. C. B. 1999, ApJ, **521**, 650
[4] Lynden-Bell D., Kalnajs A. J., 1972, MNRAS, **157**, 1
[5] Gammie, C. F. 2001, ApJ, **553**, 174

About me

Prakruti Sudarshan ("Kruti")
PhD student at MPIA
(she/her) sudarshan@mpia.de
www.ufos-project.eu/