Gap formation and stability in non-isothermal protoplanetary disks [2014 CITA Summer Student Program]

Min-Kai Lin and Robert Les†

Canadian Institute for Theoretical Astrophysics, 60 St George Street, Toronto, M5S 3H8, Canada

†student: all simulations, data analysis and figures

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Introduction

Large-scale vortex formation at planetary gap edges has been suggested to explain observations of transition disks with lopsided dust distributions. Thus far, theoretical models have employed locally isothermal disks, while the linear theory of the vortex-formation instability was originally developed for adiabatic disks. We generalize the study of planetary gap edge instabilities to non-isothermal disks by including an energy equation with variable cooling rate, and study its effect on the formation and evolution of gap-edge vortices.

Disk-planet model with simple cooling

We numerically evolve the 2D fluid equations including a gap-opening giant planet, treated as an external potential on a fixed circular orbit. We include in the energy equation a simple source term in the form

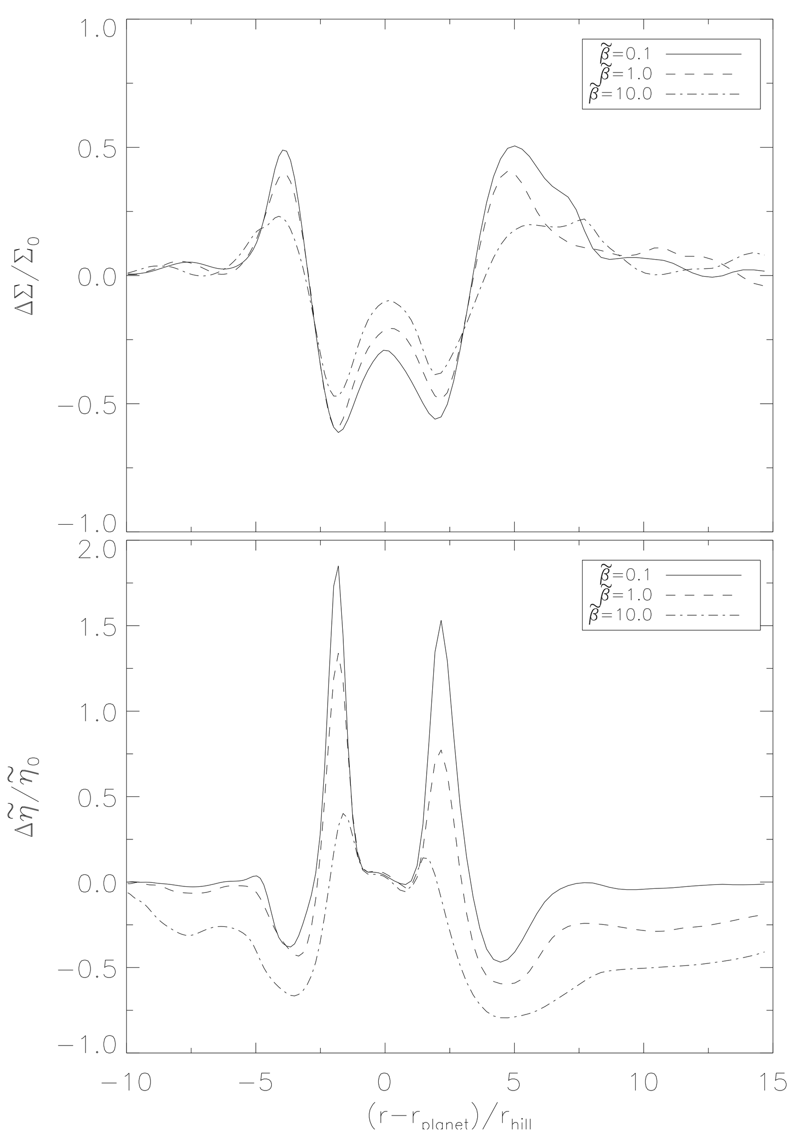
$$\frac{\partial e}{\partial t} = \cdots + \frac{e - e_{t=0}}{t_{\mathrm{cool}}},$$

and $t_{\mathrm{cool}} = \beta\Omega_k^{-1}$, where Ω_k is the Keplerian frequency. The energy density $e = p/(\gamma - 1)$ where p is the pressure field and $\gamma = 1.4$ is the adiabatic index. We choose β indirectly through $\tilde{\beta}$ such that

$$t_{\mathrm{cool,gap\,edge}} = \tilde{\beta} t_{\mathrm{lib,gap\,edge}},$$

- $t_{\mathrm{lib,gap\,edge}} = 2\pi/|\Omega_k(r_p) - \Omega_k(r_{\mathrm{edge}})|$ is the time in between successive encounters of a fluid element at the gap edge and the planet's azimuth
- $\tilde{\beta} \ll 1 \Rightarrow$ fluid at the gap edge returns to its initial temperature in between going through planet-induced shocks

Planetary gap profiles and cooling rate



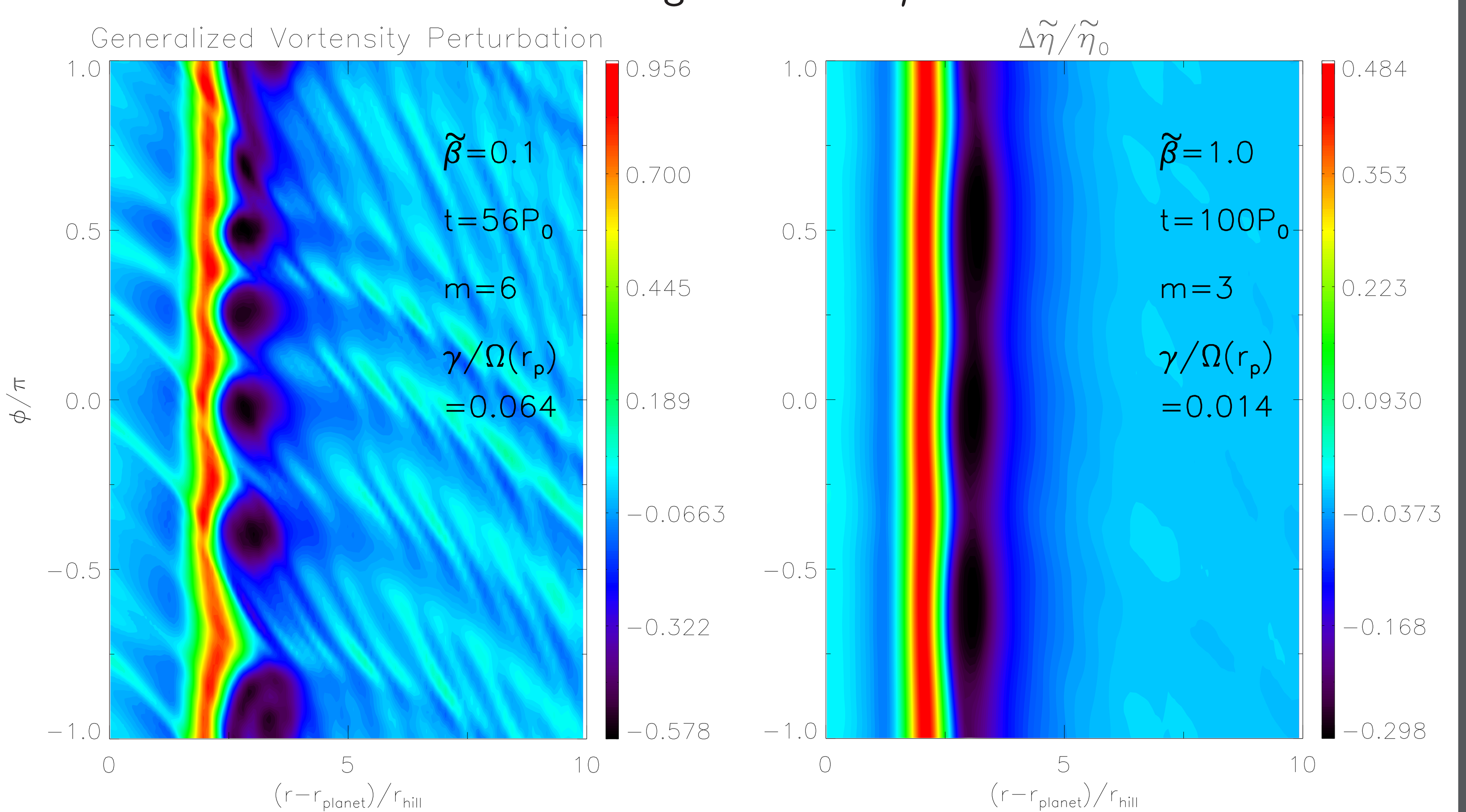
- Top panel: shallower gaps with increasing t_{cool} but no strong dependence
- Lower panel shows the generalized vortensity

$$\tilde{\eta} = \frac{\omega_z}{\Sigma} \times S^{-2/\gamma},$$

where ω_z is the vertical vorticity and $S \equiv p/\Sigma^\gamma$ is the entropy.
- Extrema in $\tilde{\eta}$ associated with instability (Lovelace et al. 1999, Li et al. 2000)
- Entropy-production across planet-induced shocks weakens extrema in $\tilde{\eta}$, so increasing t_{cool} may stabilize the system by making gap edges less sharp

Numerical linear stability simulations

In these simulations we switch off the planet potential after it is fully introduced and a partial gap is formed. An azimuthal average is performed, and the system is subject to random density perturbations. We then use Fourier analysis to find the dominant mode number m and growth rate γ.

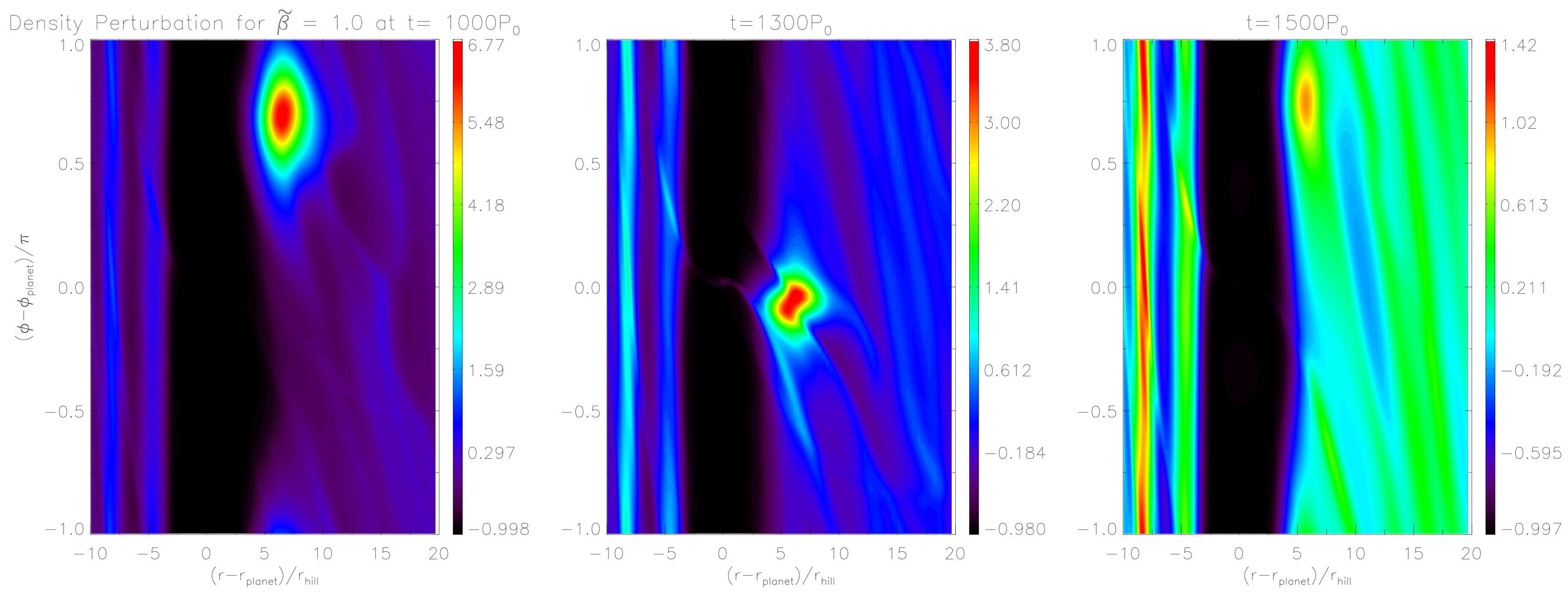


- Slower cooling rate increases *linear* stability and favors lower-m modes

Non-linear evolution of gap edge vortices

We include the planet throughout. Generic evolution independent of t_{cool}:

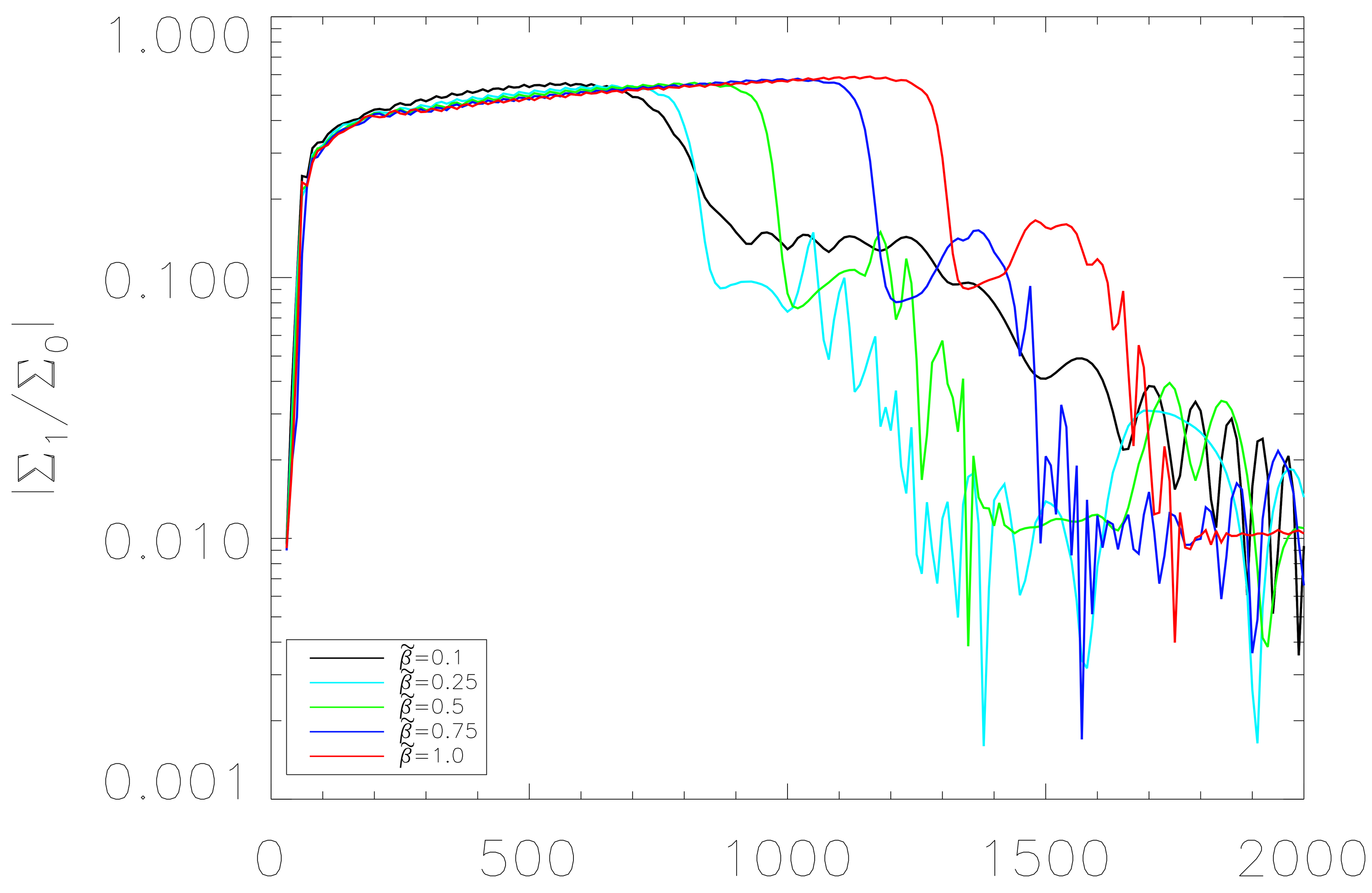
- Single vortex in quasi-steady state from vortex merging
- Continuous vorticity source from disk-planet interaction $\longrightarrow$ vortex intensifies
- Vortex dissipates quickly after its Rossby number **Ro** minimizes, due to vortex-induced shocks and/or smoothing out the gap edge



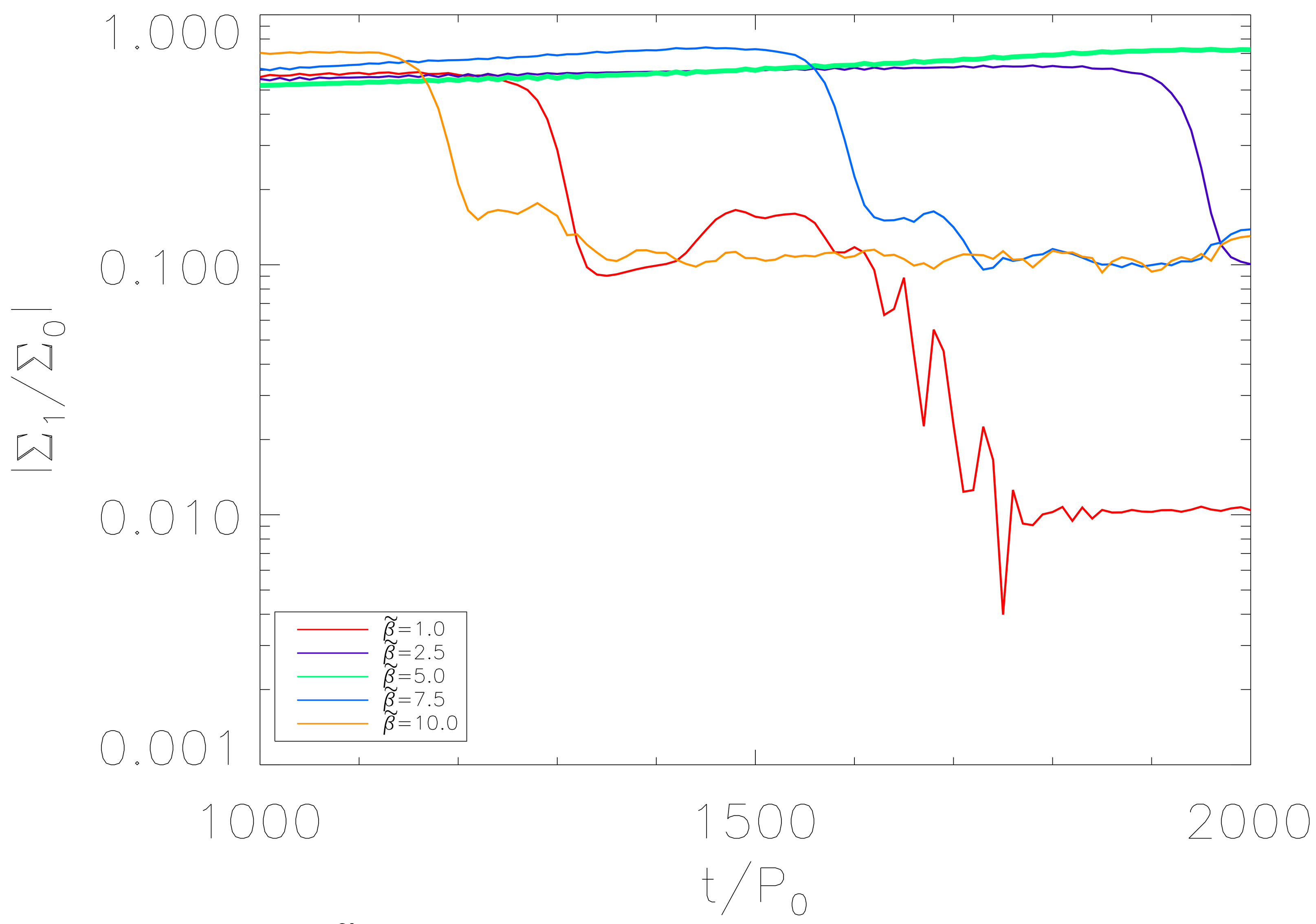
$Ro = -0.15$ $\quad$ $Ro = -0.43$ $\quad$ $Ro = -0.05$

Vortex lifetimes and cooling rate

- Vortices typically live longer with increasing cooling time:



- However, for very long t_{cool} vortex lifetimes shorten again:



- A cooling time of $\tilde{\beta} \sim 5$ maximizes vortex lifetime (thick line)

Summary

The stability of planetary gaps in gaseous protoplanetary disks is affected by disk thermodynamics. A slower cooling rate, which permits more heating, tends to stabilize the system, but also enables longer vortex lifetimes unless the cooling time is extremely long. Our simulations suggest there exists an optimal t_{cool} that maximizes vortex lifetimes, a result consistent with recent isothermal simulations by Fu et al. (2014,ApJ,788,L41) with variable disk aspect-ratio.

http://www.cita.utoronto.ca/∼mklin924 mklin924@cita.utoronto.ca, robert.les@mail.utoronto.ca