How super-Earths migrate in low-turbulence radiative disks

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Motivation: challenges in type-I migration

More than 5500 exoplanets have been discovered so far, and their population shows remarkable diversity in orbital parameters, masses, and multiplicity [1]. Low-mass planets migrate in the type-I regime before settling to their observed locations [2], and their interaction with the surrounding disk is rich in both physics and complexity [3].

As observational data constrains turbulence to very low levels in the disk dead zone (~1-30 au), traditional models of viscous type-I migration give way to dynamic or stochastic processes [4]. Here, radiative effects are critically important to understanding how, where, and when planets form.

With state-of-the-art radiation hydrodynamics models, we investigate the migration of super-Earths in low-turbulence protoplanetary disks.

The dynamical corotation torque

Spiral arms exert a **negative torque** on the planet:

$$\Gamma_\mathrm{L} \sim -3\left(\frac{q}{h}\right)^2 \Sigma_\mathrm{p} R_\mathrm{p}^4 \Omega_\mathrm{p}^2, \quad q = \frac{M_\mathrm{p}}{M_\star}$$

The vortensity contrast between the corotating region (ϖ_c) and the background flow (ϖ_p) results in a **dynamical corotation torque** [5]:

$$\Gamma_\mathrm{C} = 2\pi\left(1-\frac{\varpi_\mathrm{p}}{\varpi_\mathrm{c}}\right) \Sigma_\mathrm{p} R_\mathrm{p}^2 x_\mathrm{h} \Omega_\mathrm{p} \frac{\mathrm{d}R_\mathrm{p}}{\mathrm{d}t}, \quad x_\mathrm{h} \approx \sqrt{\frac{q}{h}} R_\mathrm{p}$$

The trapped vortensity would be conserved for a barotropic flow...

$$\frac{\mathrm{d}\varpi}{\mathrm{d}t} = \frac{\nabla\Sigma \times \nabla P}{\Sigma^3}$$

... so the planet should eventually stall as a vortensity contrast builds.

But planet–disk interaction is full of baroclinic processes. How does **radiative cooling** affect migration?

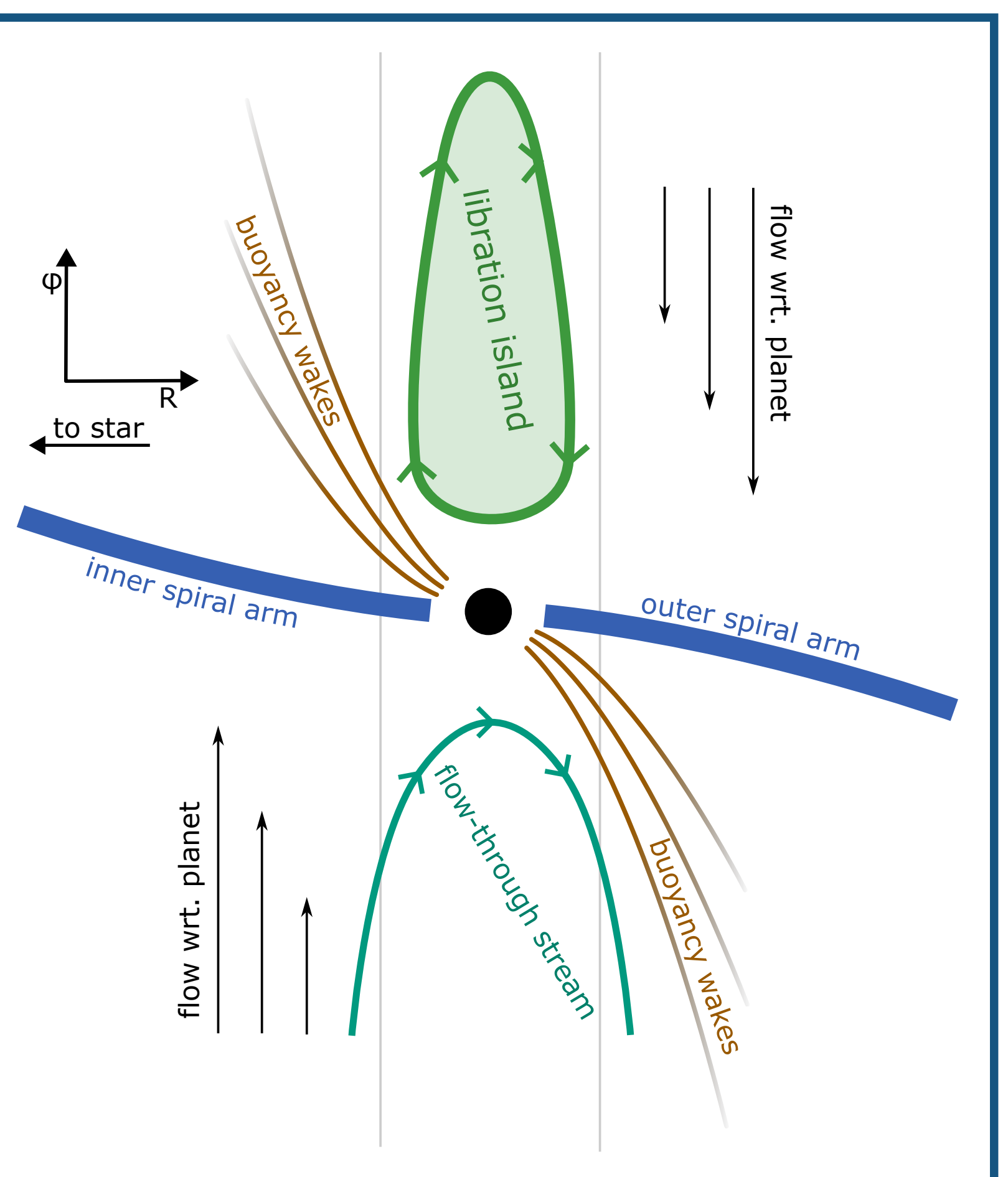

Figure 1: Sketch of the flow around a migrating planet [2]. Material trapped **ahead of the planet** corotates with it, exerting a positive torque (drag) that scales with the vortensity contrast to the background flow. The drag eventually matches the **Lindblad torque** and the planet stalls. The dissipation of **buoyancy** oscillations [6,7] and/or radiative effects can reduce this vortensity contrast, however.

Our disk model

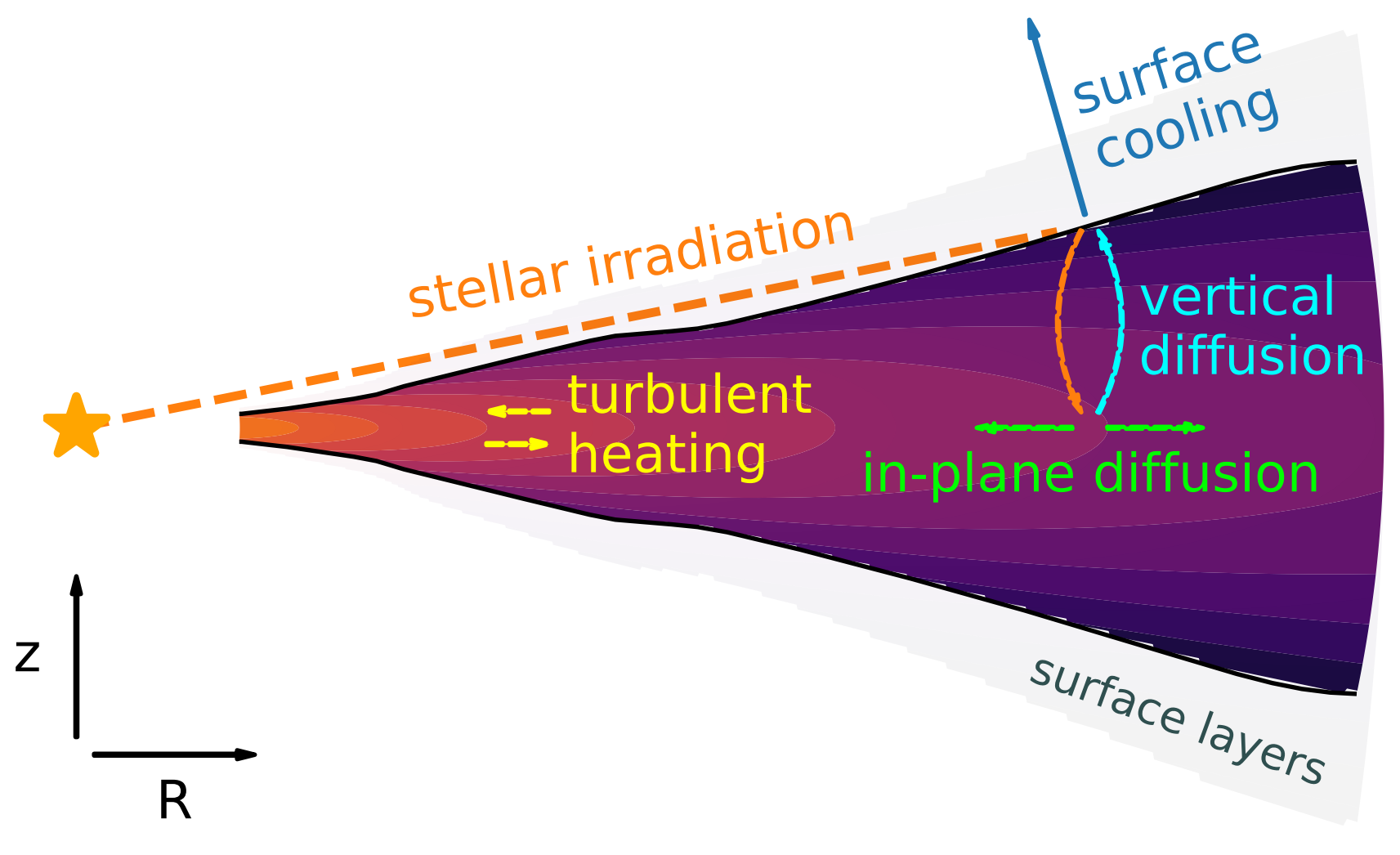

Figure 2: Radiative processes in a protoplanetary disk. The thermal structure reaches equilibrium through a balance of heating and cooling mechanisms that can redistribute heat within the disk.

We solve the **radiation hydrodynamics** equations in a laminar global protoplanetary disk with a **migrating embedded planet**. We include a full treatment of radiation transport using **flux-limited diffusion** (FLD) [8], and ρ- and T-dependent dust opacities. We also compare to simplified, local cooling.

A: planet–gas interaction in the corotating region

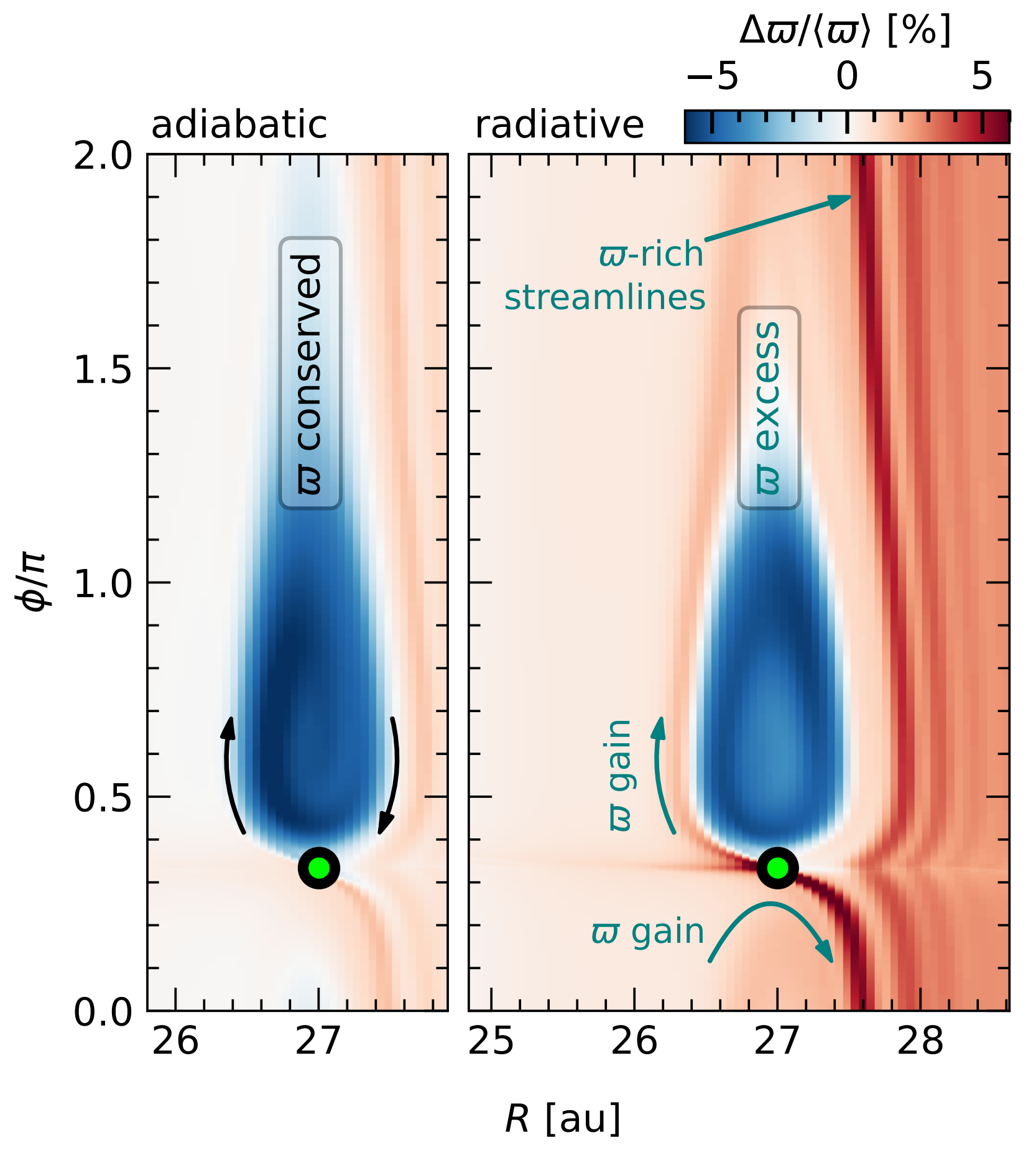

Figure 3: In an adiabatic disk (left), a U-turn near the planet (black arrows) conserves vortensity (white background). In a radiative disk (right), the same U-turn generates vortensity instead (red features in libration island and on streamlines).

Cooling induces a baroclinic forcing as gas U-turns near the planet.

Consider a blob of gas U-turning near the planet (Fig. 3). By allowing the blob to cool/diffuse its excess heat (see Fig. 2) at the U-turn point, its pressure changes. This results in a baroclinic effect, **generating vortensity**.

This vortensity excess collects in the libration island, **weakening the dynamical corotation torque** and **accelerating migration** (Fig. 5). The effect is strongest when the cooling time matches the U-turn time, but remains active for a **large radial extent of the disk** (Fig. 4).

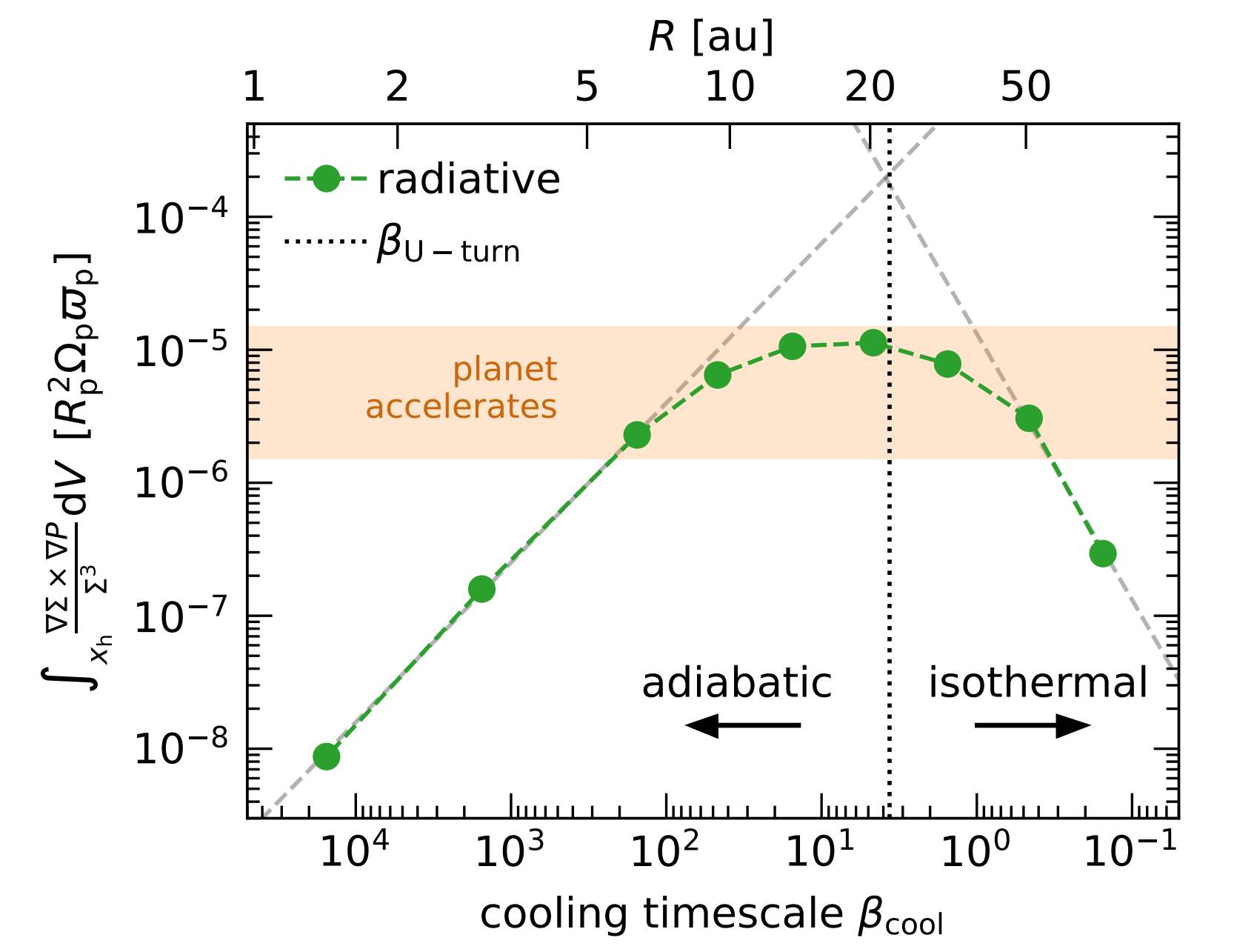

Figure 4: The baroclinic source term in the horseshoe region, used to gauge the strength of this effect. It operates efficiently for the bulk of the disk, peaking for intermediate cooling timescales.

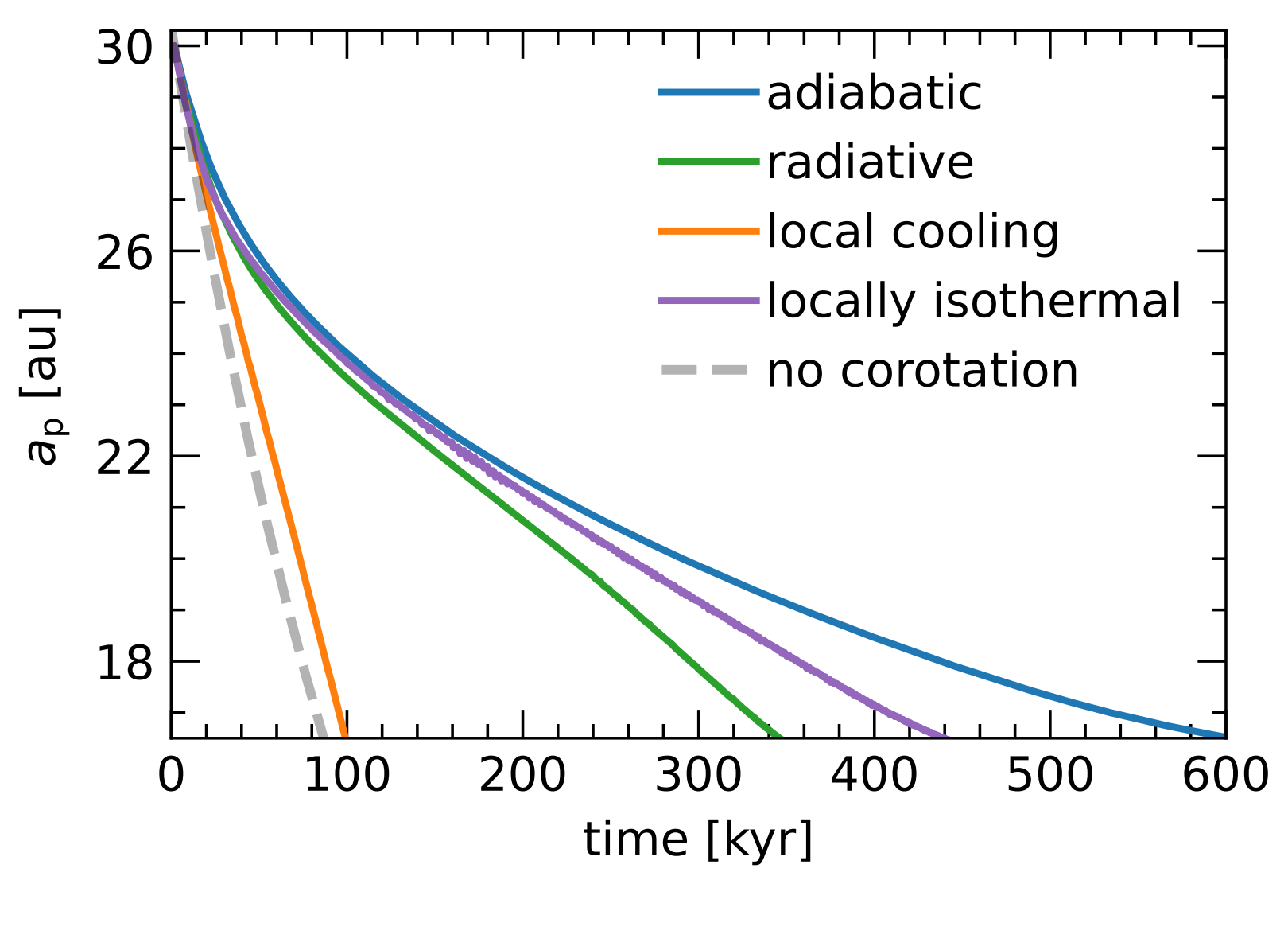

Figure 5: Migration tracks for models with different cooling prescriptions. The dynamical corotation torque slows the planet down, but it accelerates inwards in models with cooling. A local cooling prescription wrongly overestimates the vortensity growth and the planet's migration rate.

B: exciting the disk buoyancy response

In 3D, the **disk buoyancy response** excites vertical oscillations that dissipate in the corotating region, **generating vortensity**.

Radiative cooling suppresses this effect by damping the buoyancy response of the disk when the Brunt–Väisälä (buoyancy) frequency exceeds the cooling rate [9].

Can the buoyancy response still **quench the dynamical corotation torque** in the optically thick, inner few au of the disk?

It heavily depends on the disk model (Fig. 8), but typically **yes**. The planet then **migrates inwards rapidly** (Fig. 7).

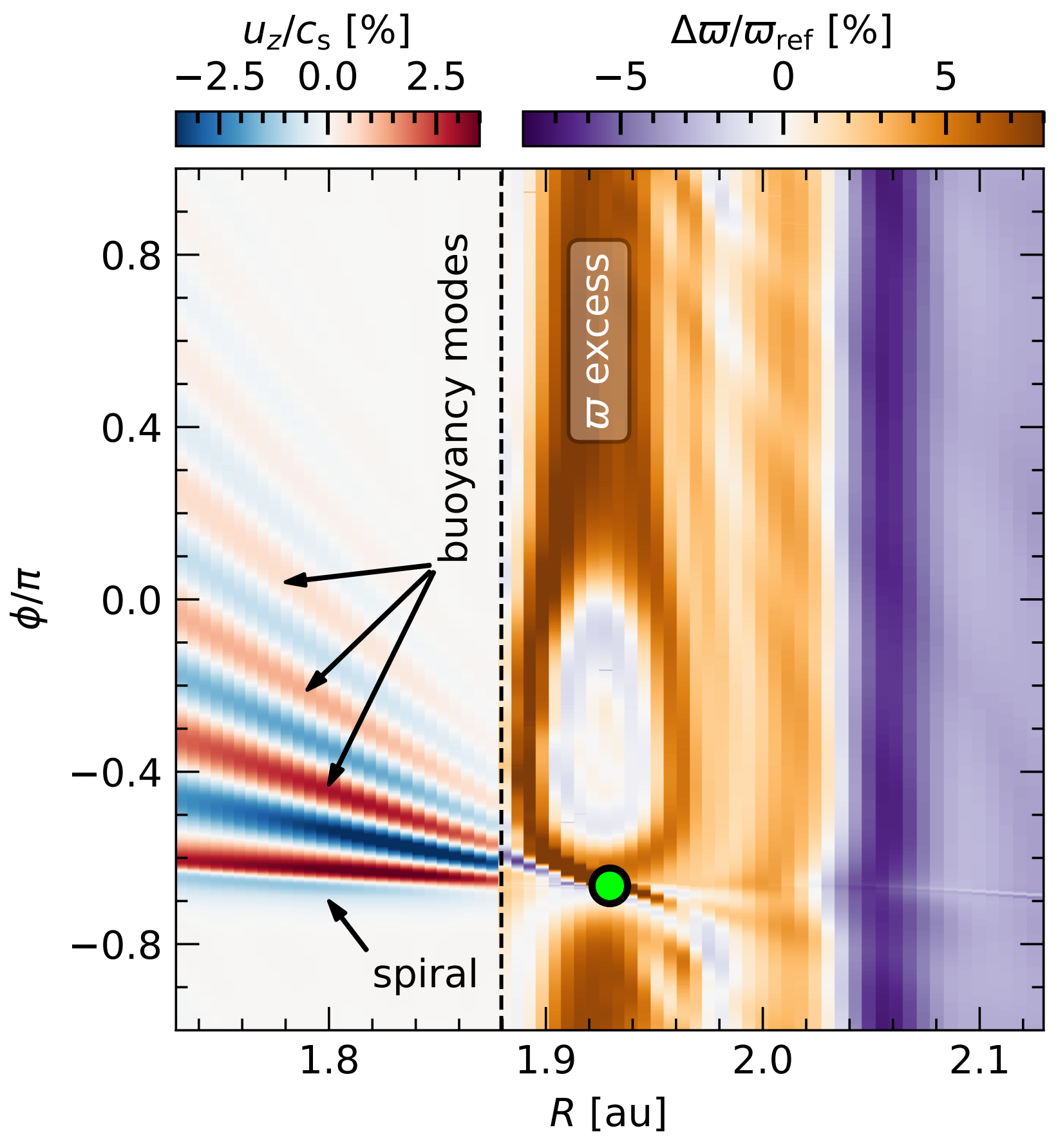

Figure 6: The planet excites vertical buoyancy oscillations (left) which induce a baroclinic forcing in the corotating region, generating vortensity (right). The result is rapid migration.

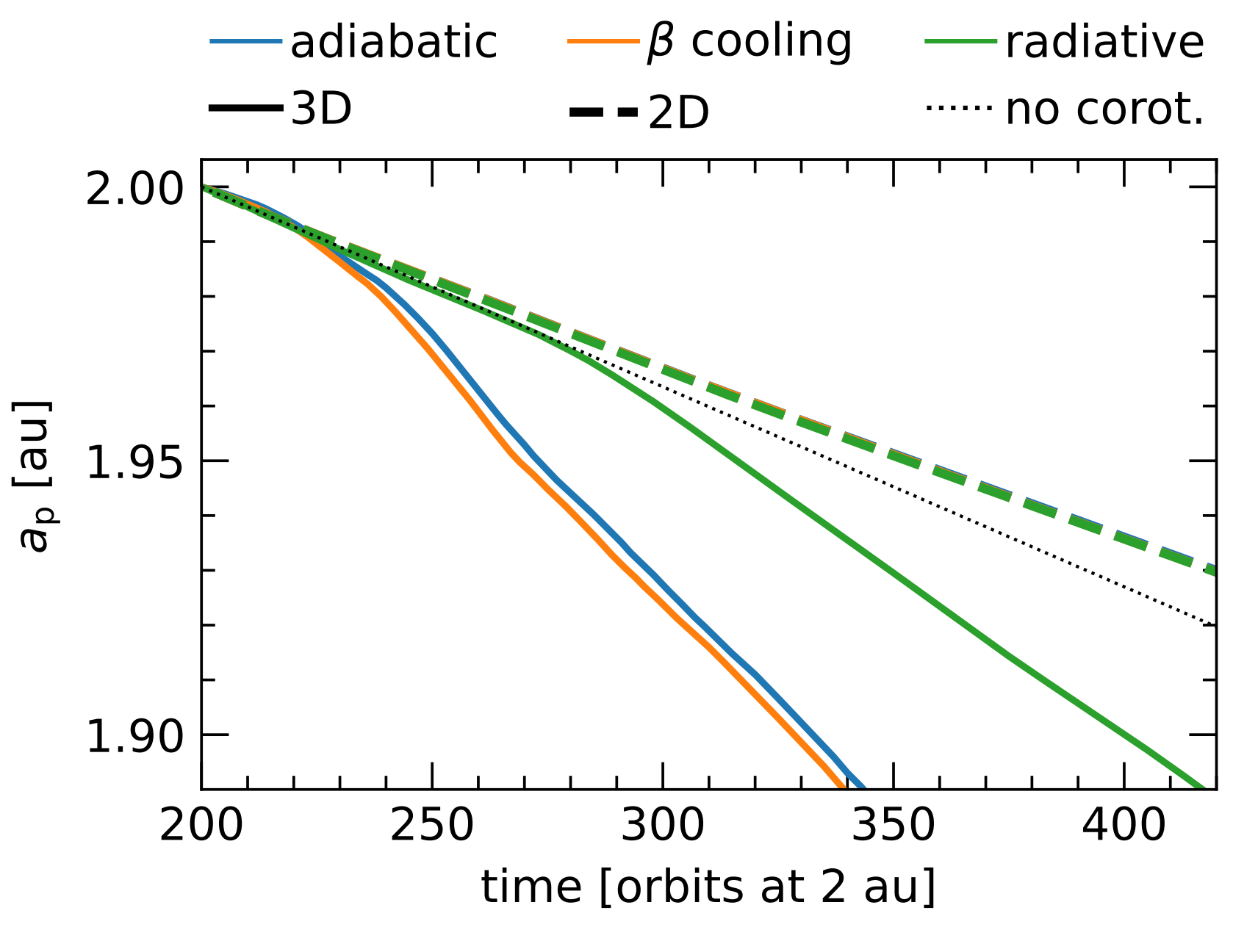

Figure 7: Migration tracks for 3D vs 2D models and with different cooling prescriptions (no/local/self-consistent cooling). The buoyancy response is active in 3D. Radiative cooling tends to damp its activity, but the planet continues to migrate rapidly. Local cooling does not capture this damping correctly, however.

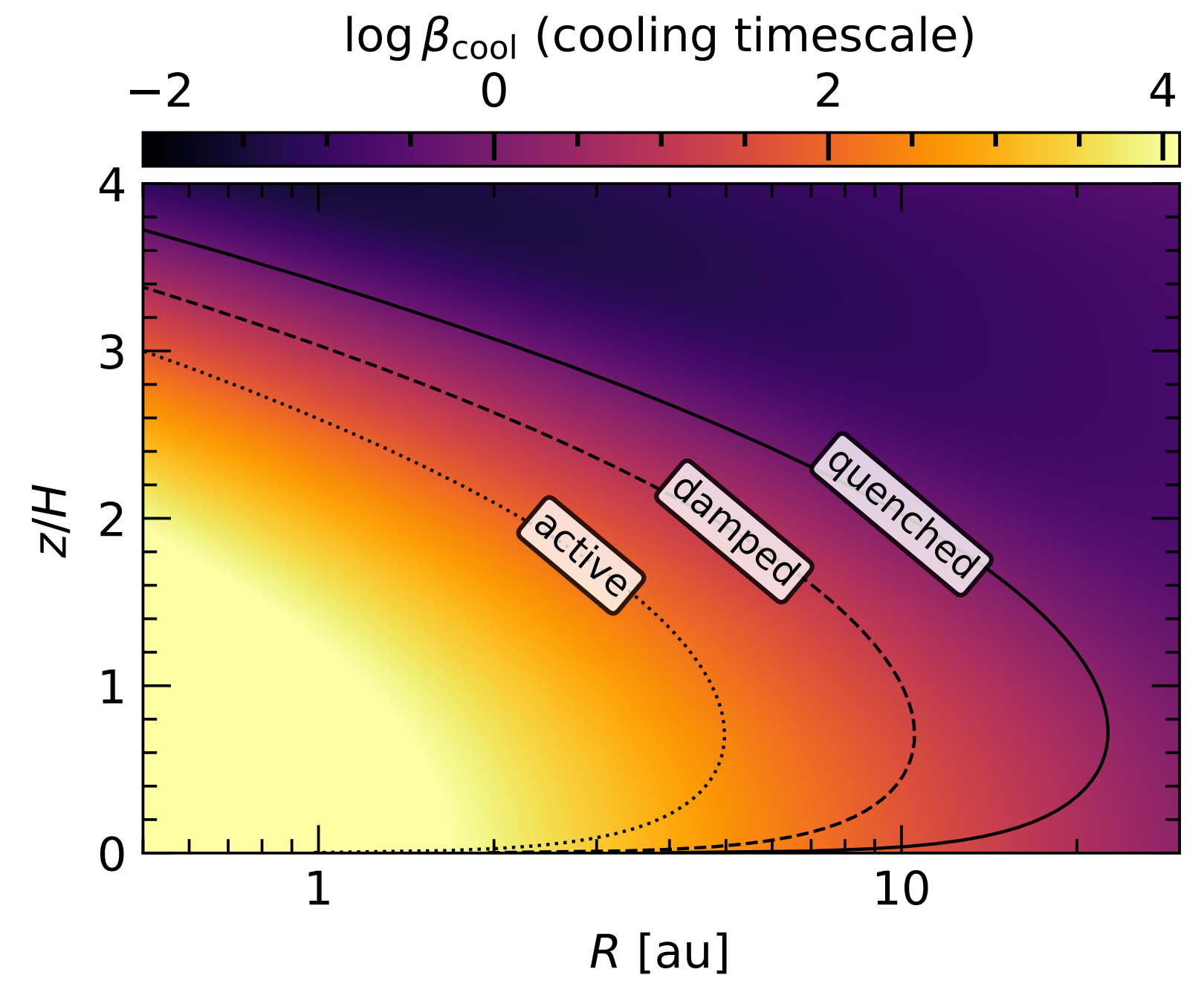

Figure 8: Cooling timescale map for a typical passive disk. Contours mark regions where buoyancy torques would operate. In the inner few au, planets would migrate rapidly inwards.

Summary

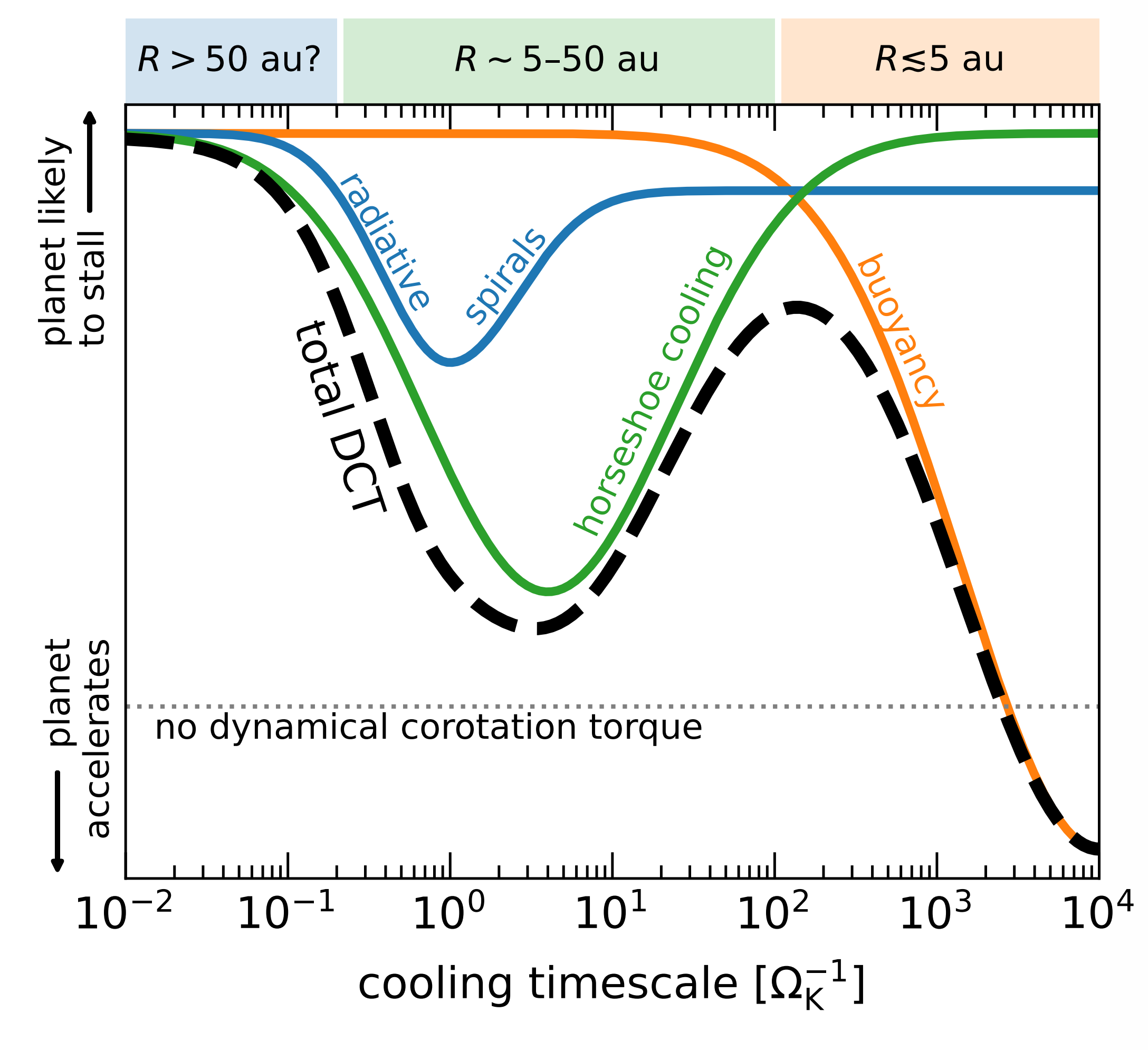

Figure 9: Map of different baroclinic terms and how they affect the dynamical corotation torque. The combined effect of cooling-induced vortensity growth and the disk buoyancy response cover a large extent of the protoplanetary disk.

The takeaway messages

- The **dynamical corotation torque** (DCT) is expected to **slow down** low-mass planets.
- **Radiative cooling** induces a baroclinic forcing for intermediate cooling timescales, weakening the DCT and **promoting inward migration**.
- For longer cooling timescales the disk **buoyancy response** can also eliminate the DCT. Radiative cooling constrains this effect to the **inner disk**.
- A **simplified local cooling** prescription strongly **over/underestimates** radiative effects. As a result, a treatment of **radiative diffusion** is necessary.

References

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