Hydrodynamical simulations of circumbinary discs hosting circumbinary planets

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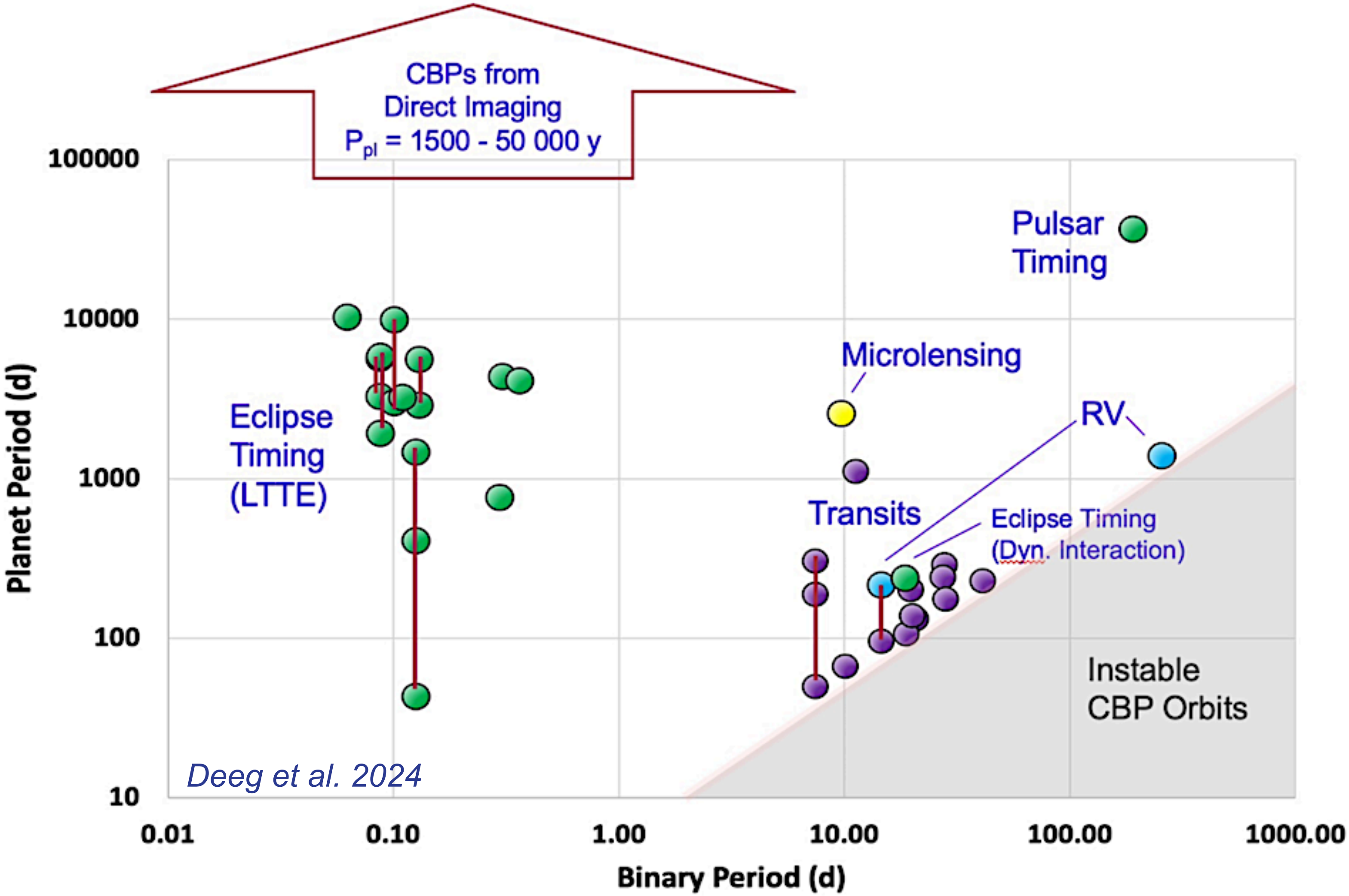
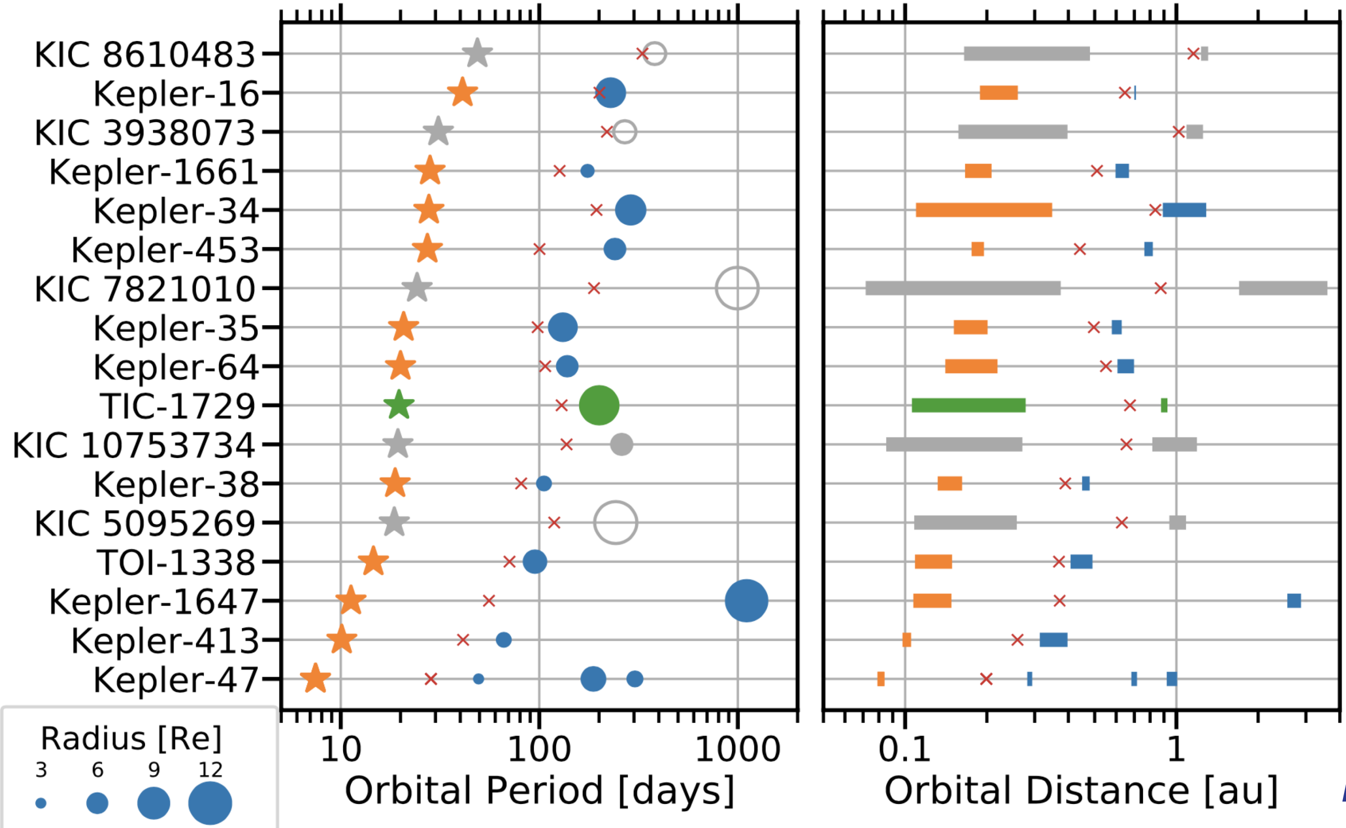
CBPs across the HR diagram

14 Jan 2025

Panorama of observed circumbinary planets



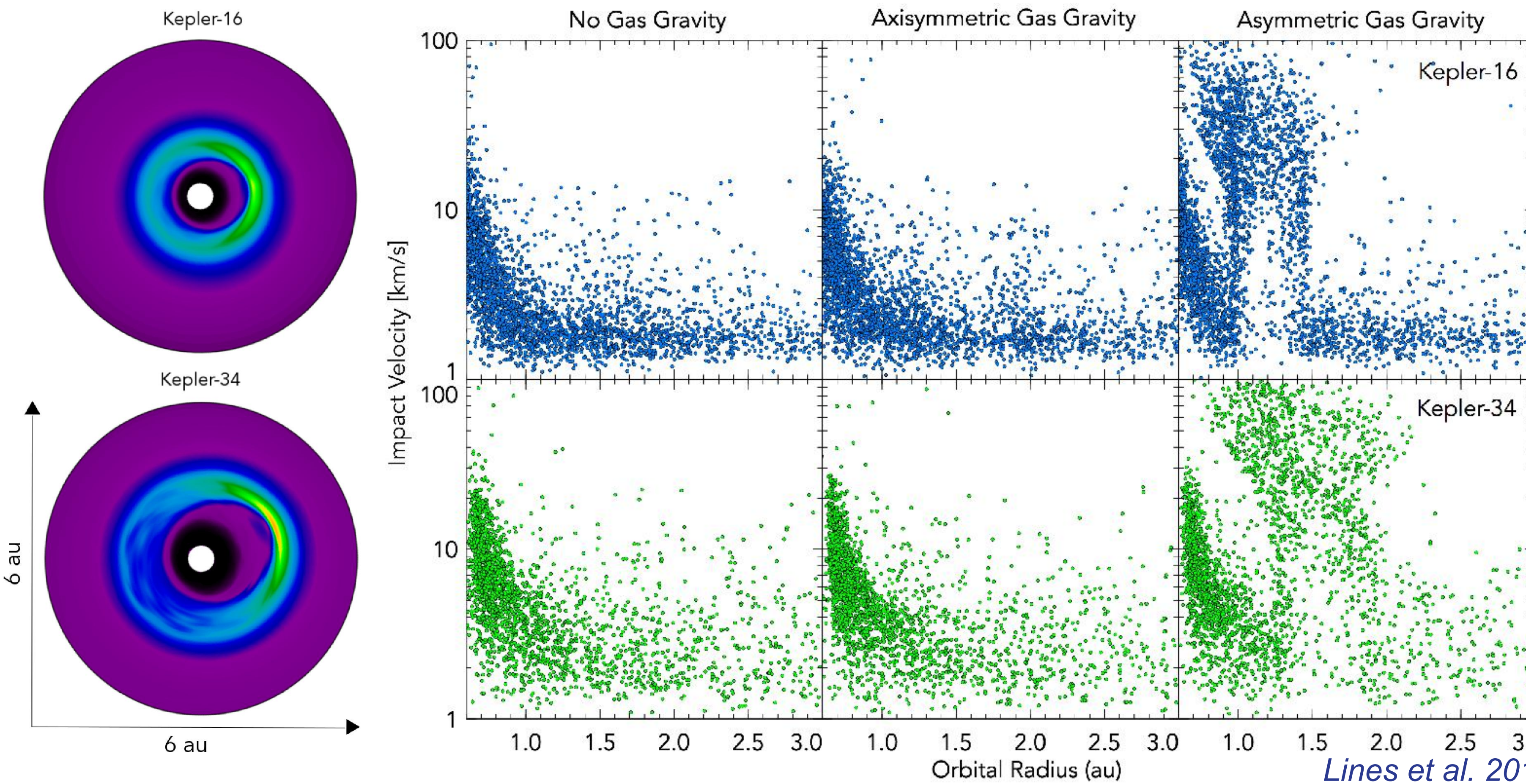
Transiting circumbinary planets



Kostov et al. 2023

- Most CPBs in the Neptune to sub-Jupiter mass range, and orbit around binaries with orbital periods > 7 days
- Interesting systems: Kepler-16 (close to the stability limit), Kepler-34 (high eccentricity), Kepler-47 (multiplicity), Kepler-1647 (long orbital period)
- low mutual inclination between planet and binary orbital planets → formation in a circumbinary disc

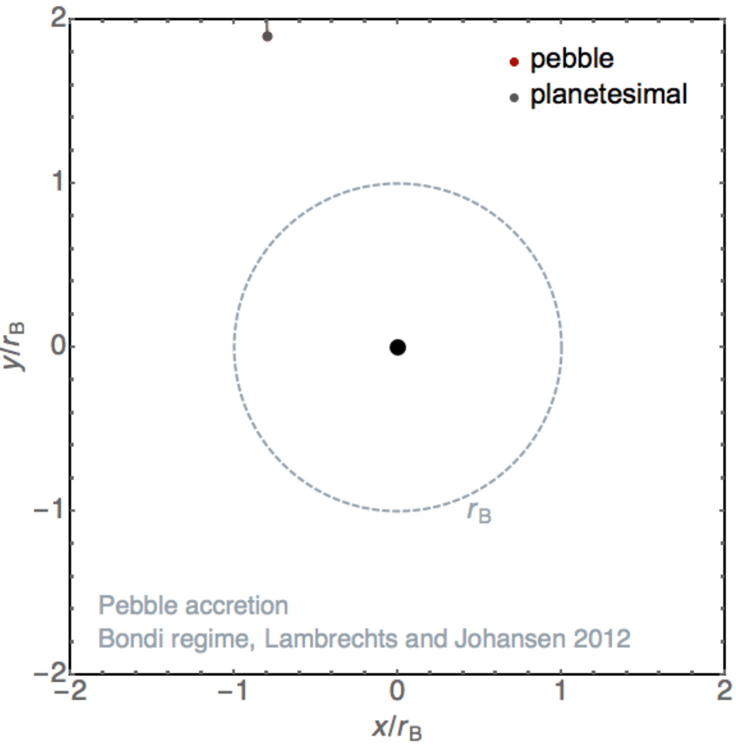
In-situ formation of CBPs:Planetesimal accretion



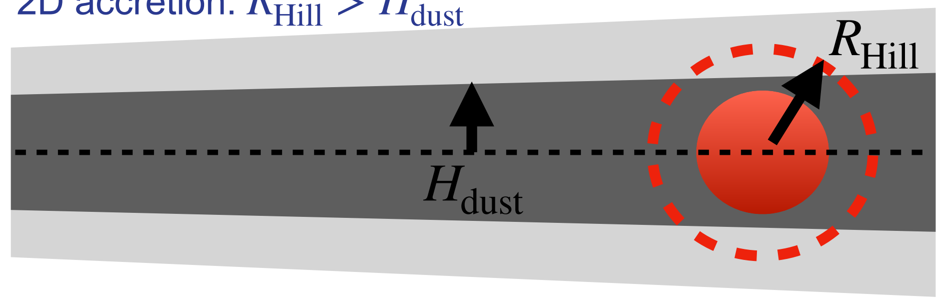
Lines et al. 2016

- Eccentric disc gravity inhibits accretion by increasing planetesimals eccentricities and removing their perihelia alignment *(Marzari et al. 2013, Lines et al. 2016)*
- Turbulence can also prevent planetesimal accretion *(Meschiari 2012)*

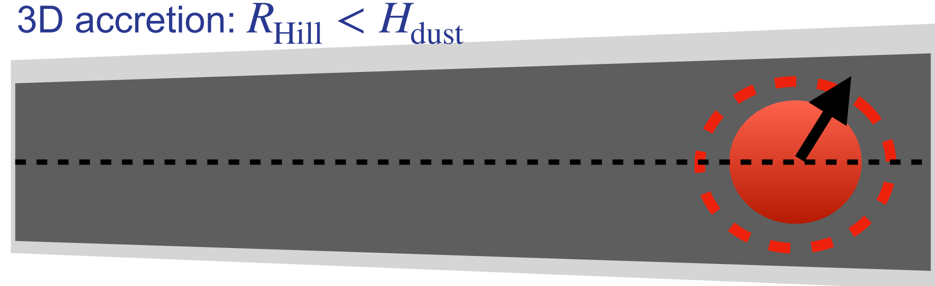
In-situ formation of CBPs: Pebble accretion



2D accretion: $R_{\rm Hill} > H_{\rm dust}$

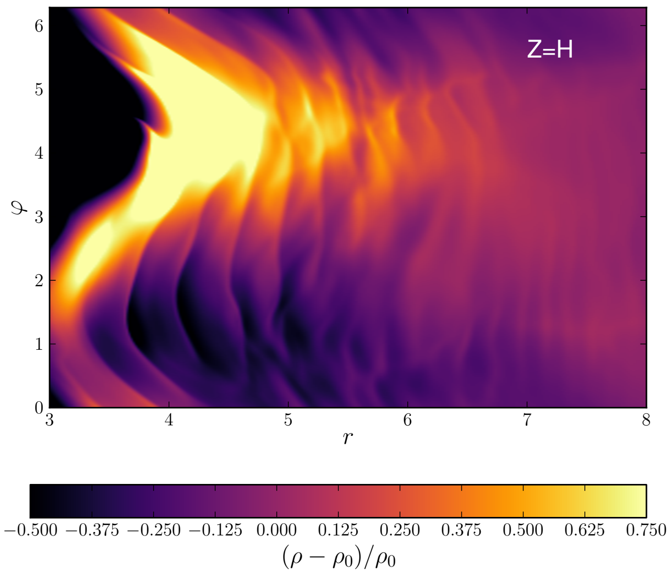


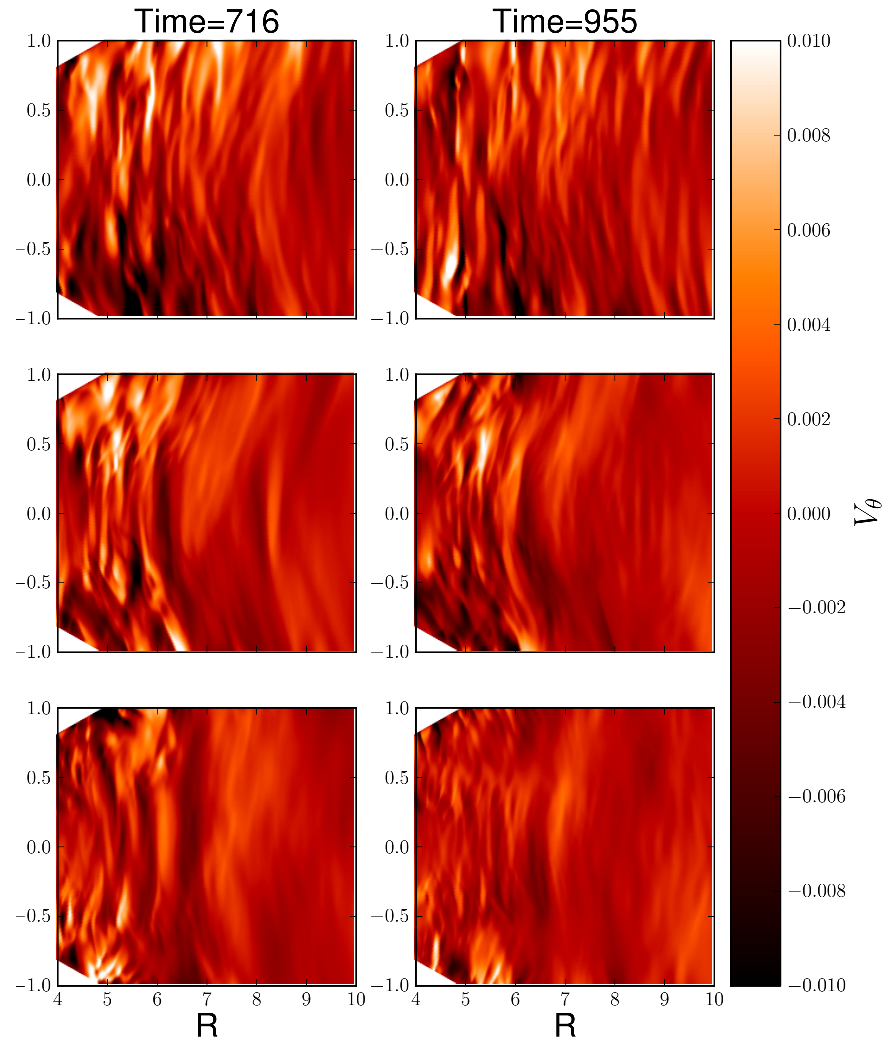
3D accretion: $R_{\rm Hill} < H_{\rm dust}$



- Examine alternative scenario in which 10^3km planetesimals are formed through SI and accrete pebbles
- Efficiency of SI and pebble accretion are reduced in turbulent discs (~ 50% in VSI-active discs)

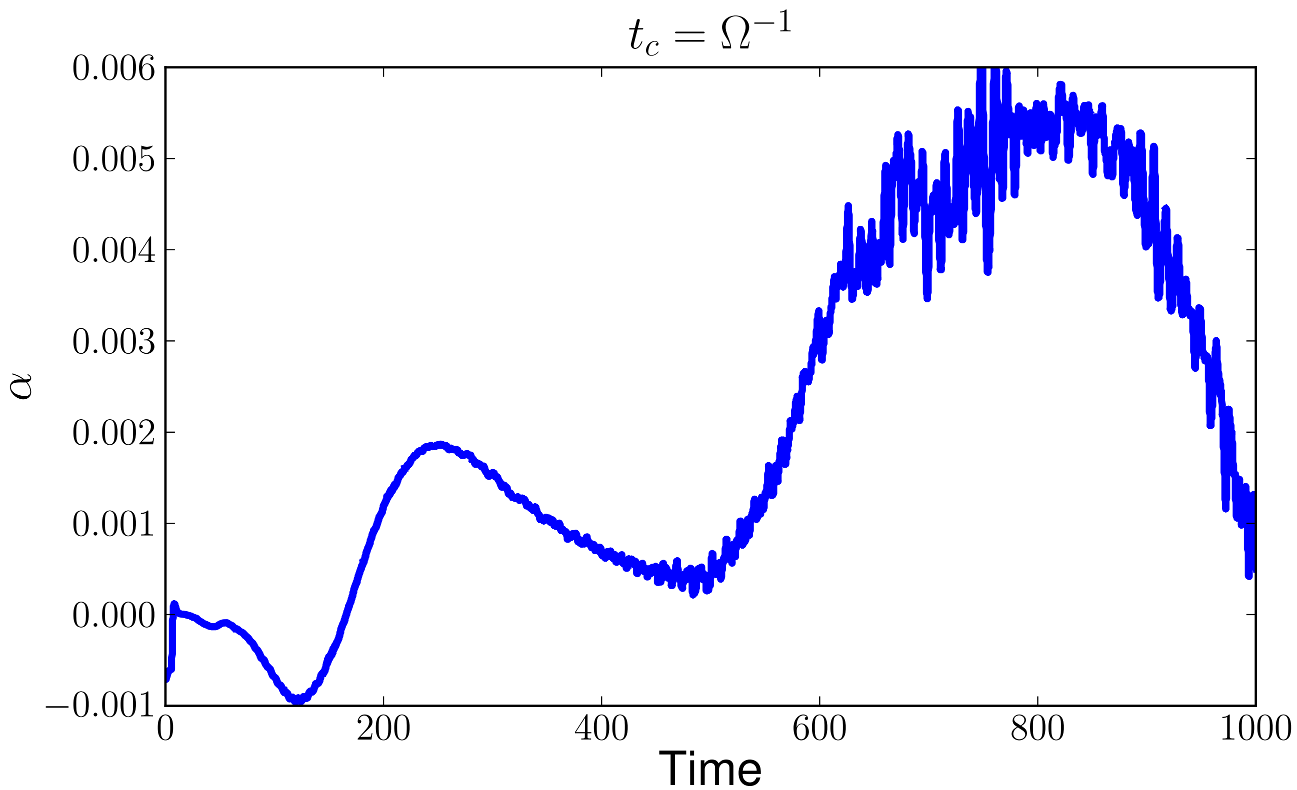
Hydrodynamical turbulence in CB discs





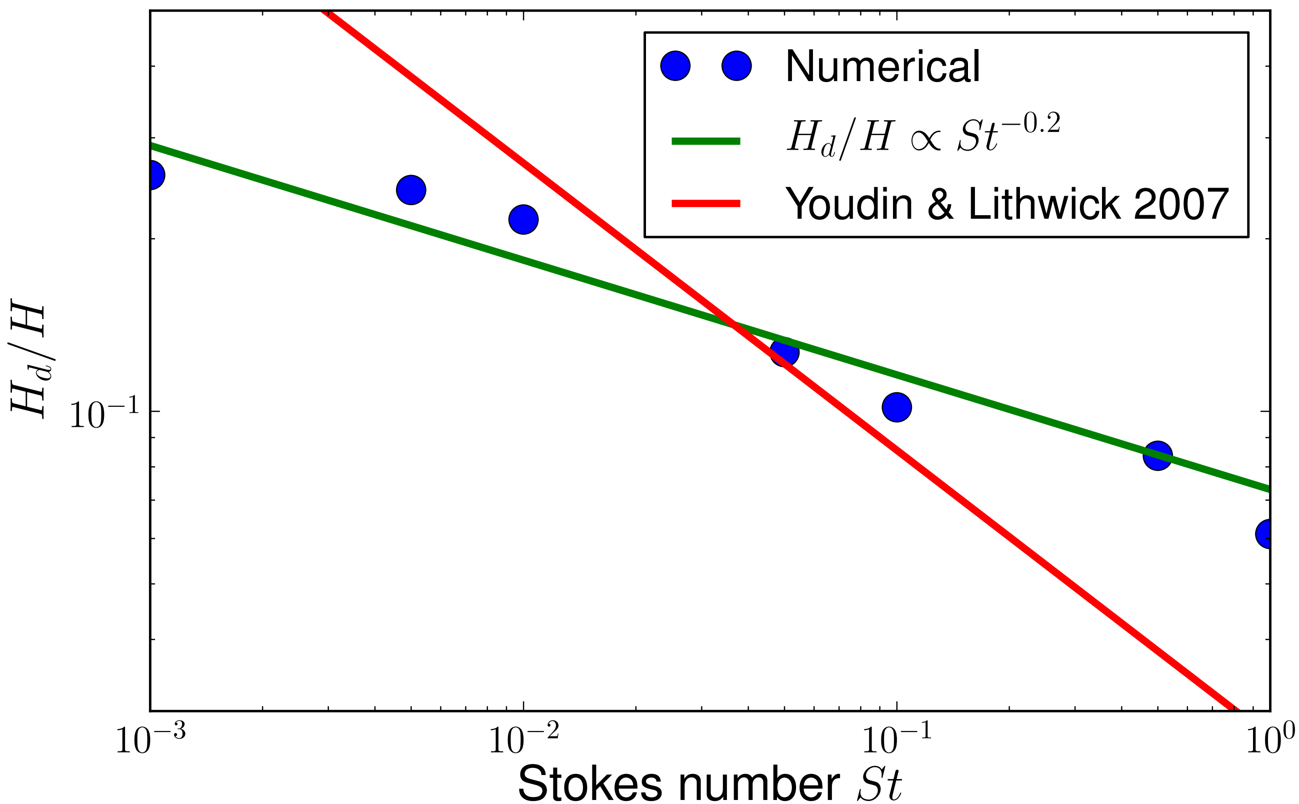
- Resonant mode coupling between inertial-gravity waves and m=1 eccentric modes *(Papaloizou 2005, Barker & Ogilvie 2014)*
- In standard discs, parametric instability leads to turbulence with $\alpha \sim 10^{-3} - 10^{-2}$

Hydrodynamical turbulence in CB discs



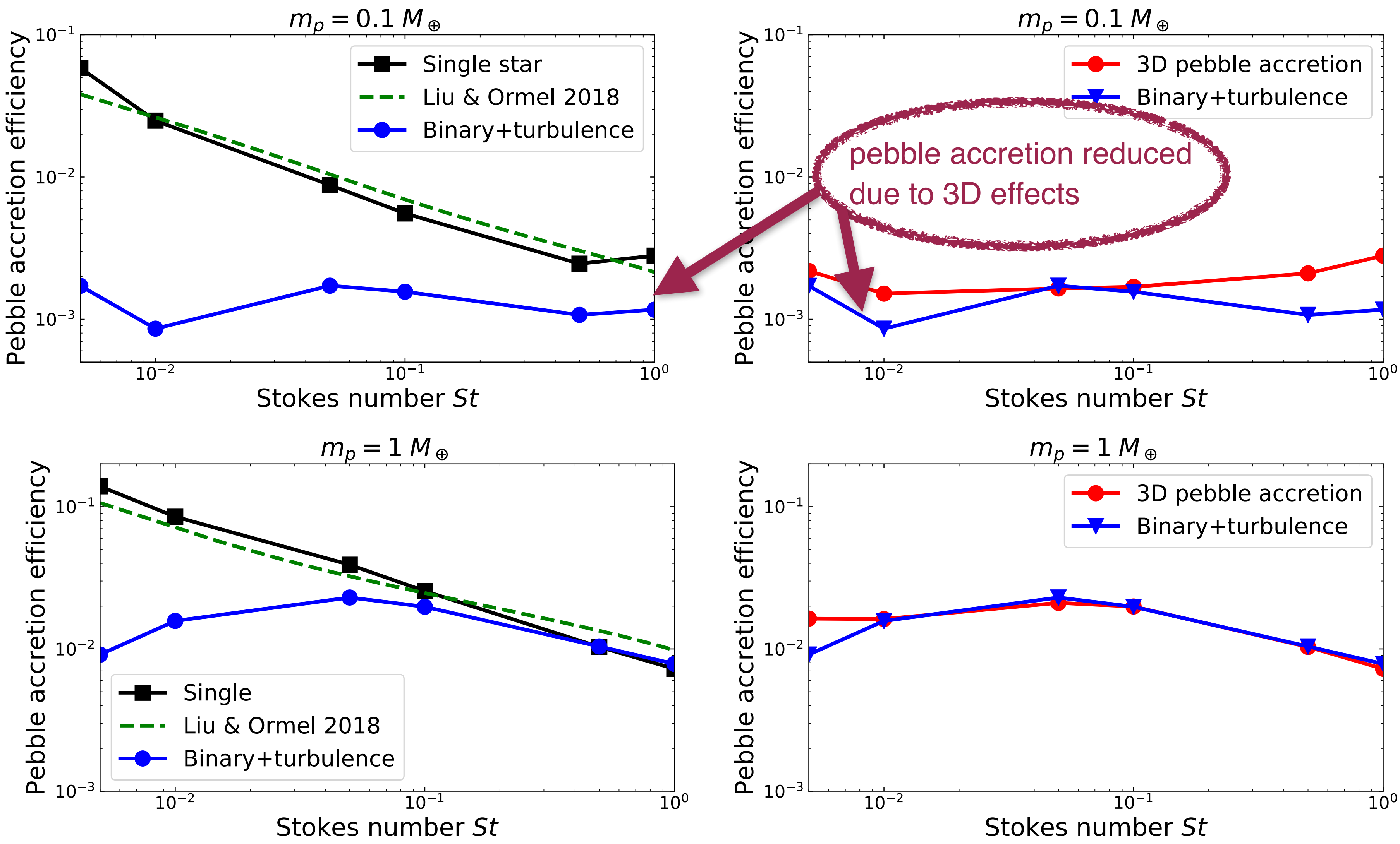
- parametric instability induces a Reynolds stress corresponding to $\alpha \approx 5.10^{-3}$

Consequences for dust settling

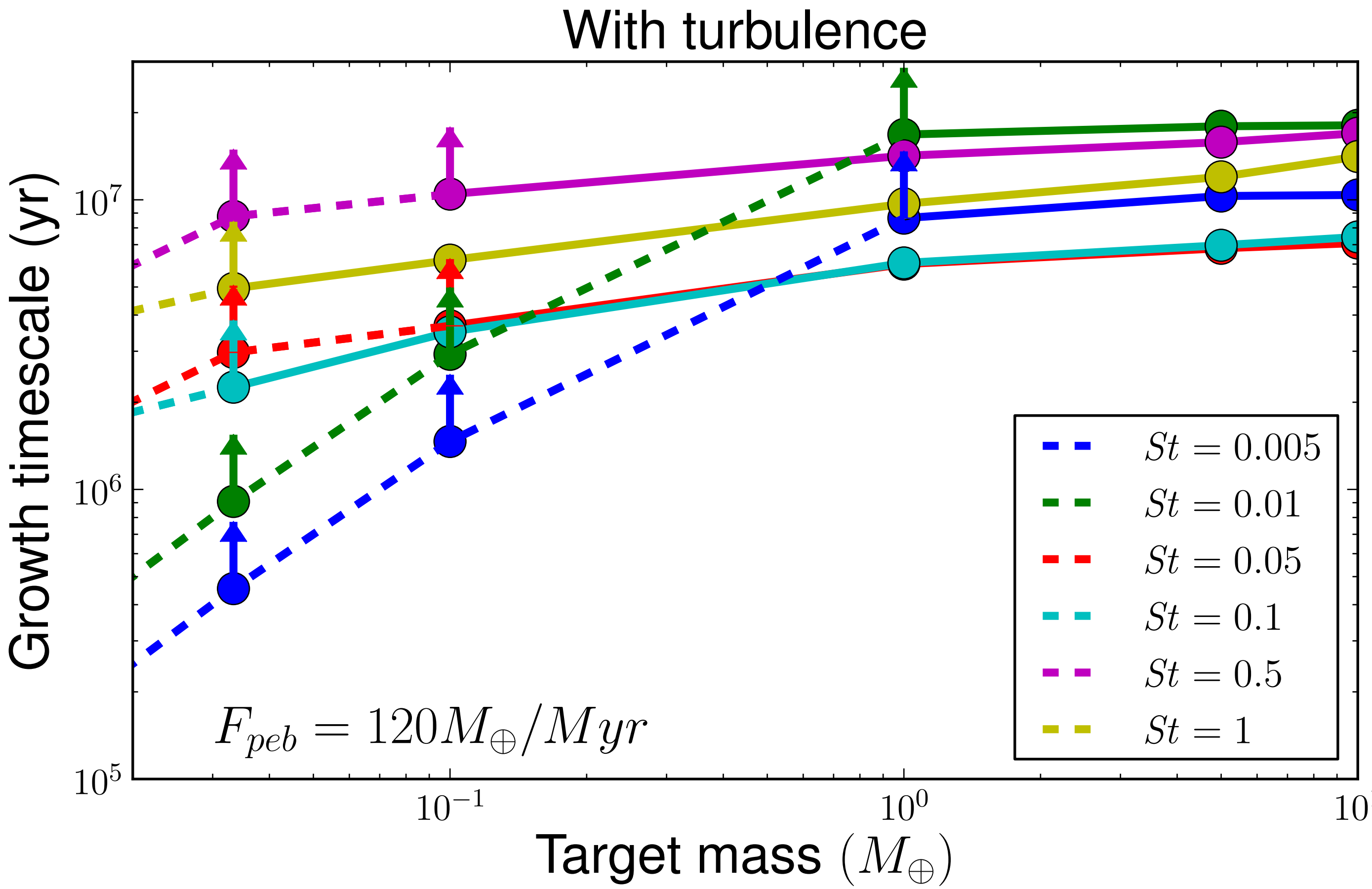


- significant settling of dust grains
- Deviation from the standard result $H_d \propto St^{-0.5}$ due to coherent vertical flows

Impact on pebble accretion rate

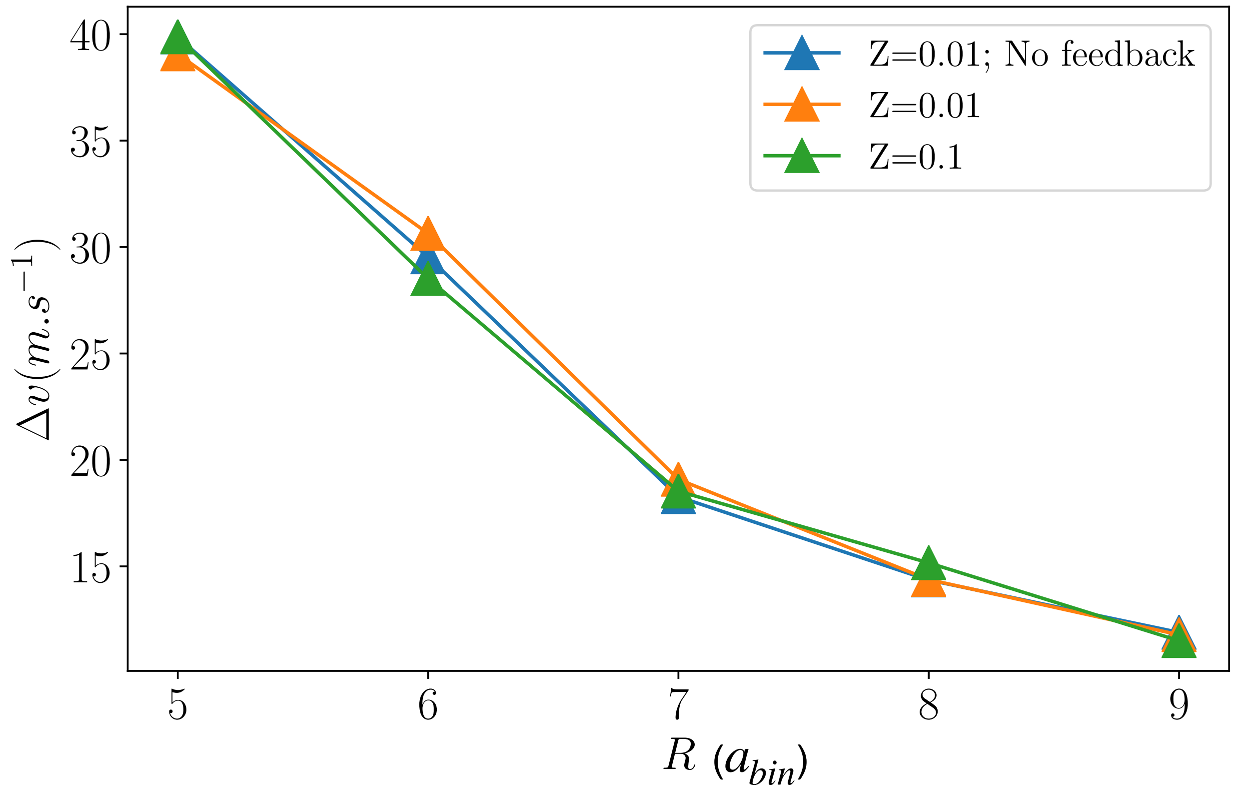


Consequence on the *in-situ* formation of CBPs



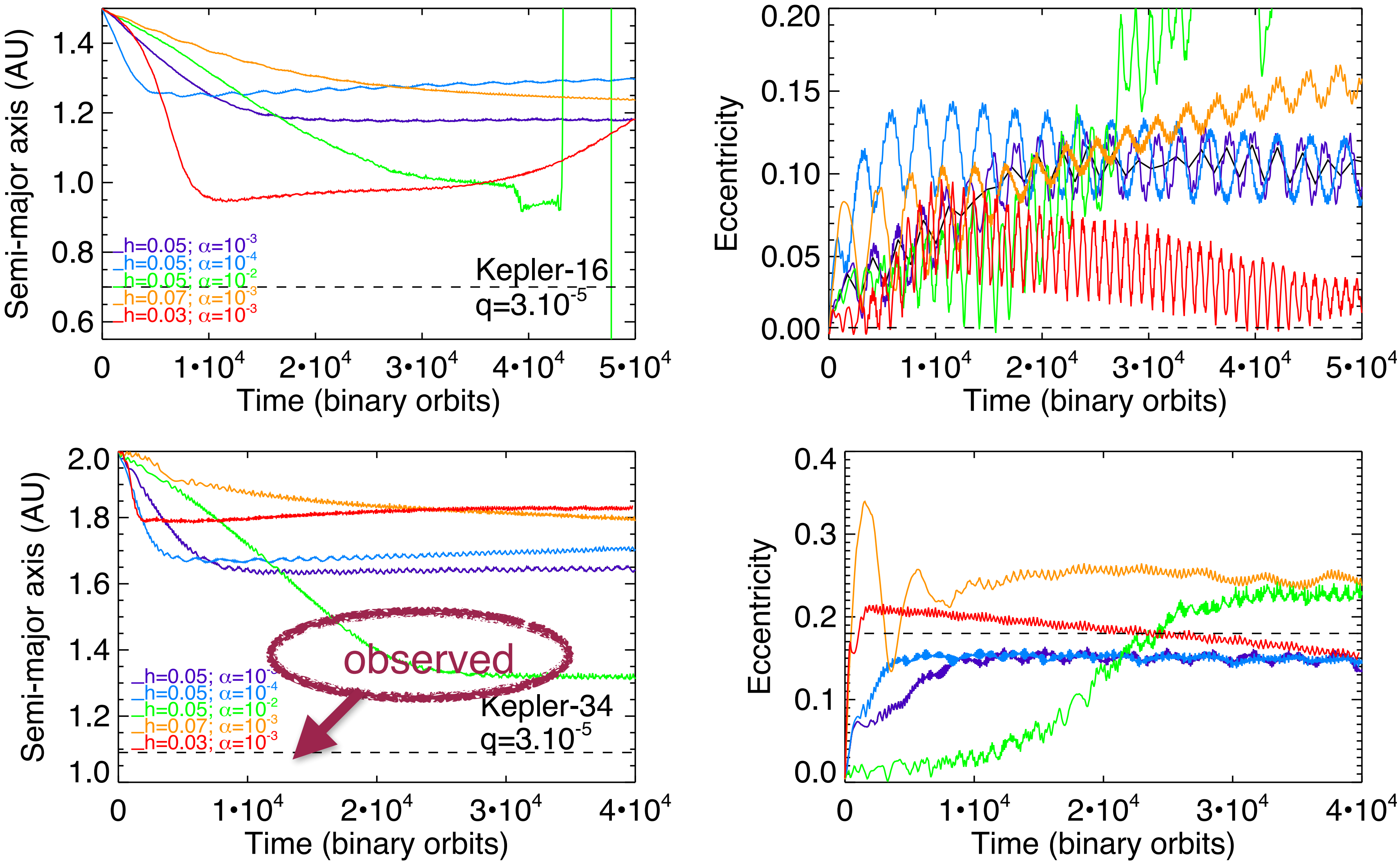
- 6-20 Myr are required to form a 10 $M_\oplus$ core from pebble accretion

Consequence on the *in-situ* formation of CBPs

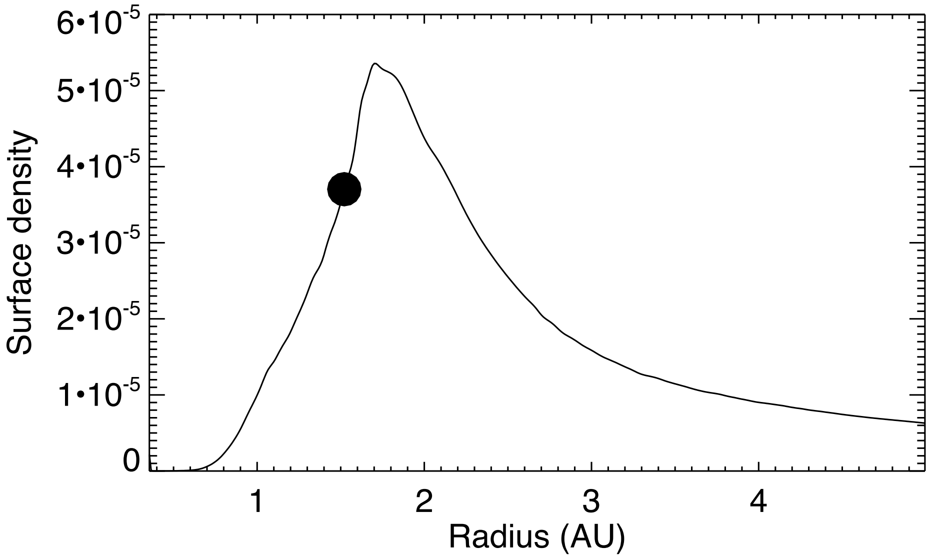


- Collisions velocities of silicate aggregates higher than fragmentation velocity close to the binary
- Forming a circumbinary planet *in-situ* at the cavity edge is difficult to achieve→ migration scenario

Migration of CBPs: *Kepler* systems

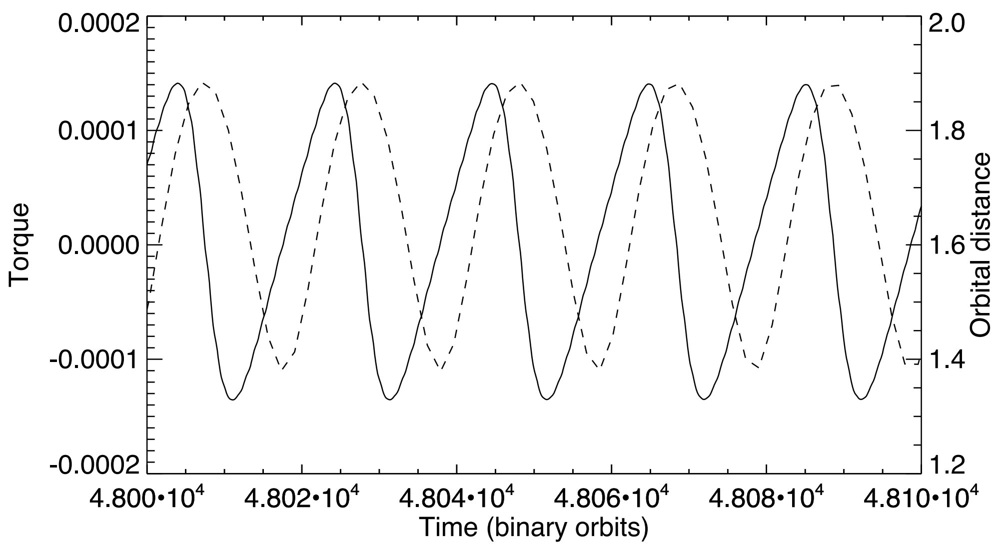


Stopping inward migration of CPBs



- CBPs get trapped near the cavity edge formed through different processes:

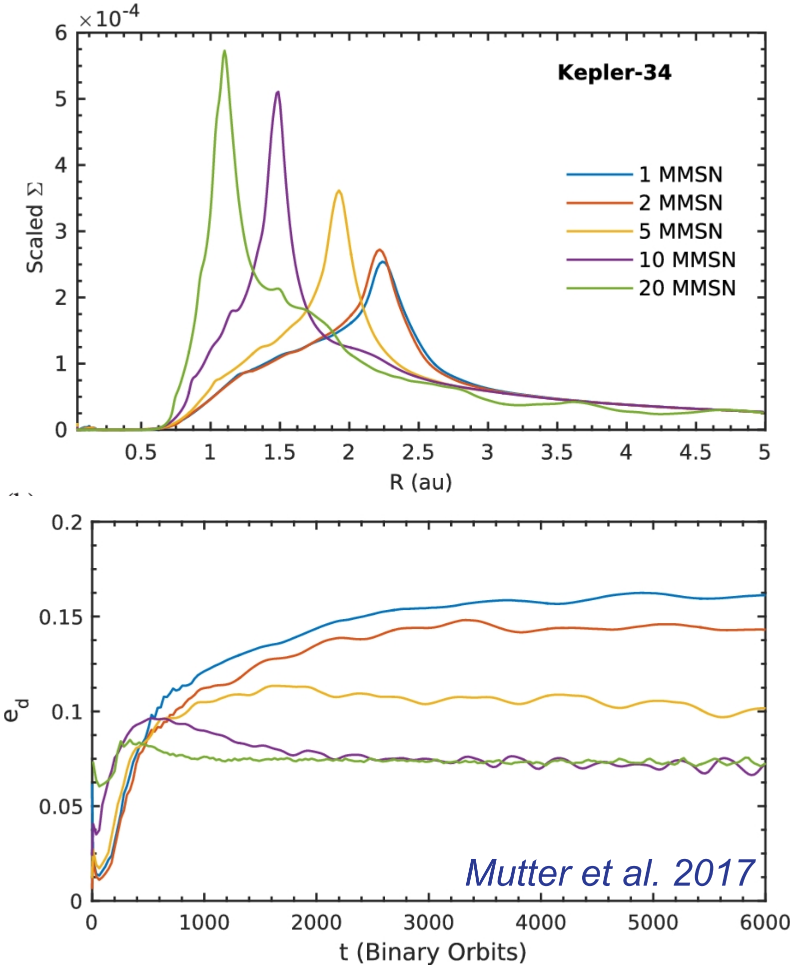
i) Strong positive (unsaturated) corotation torques

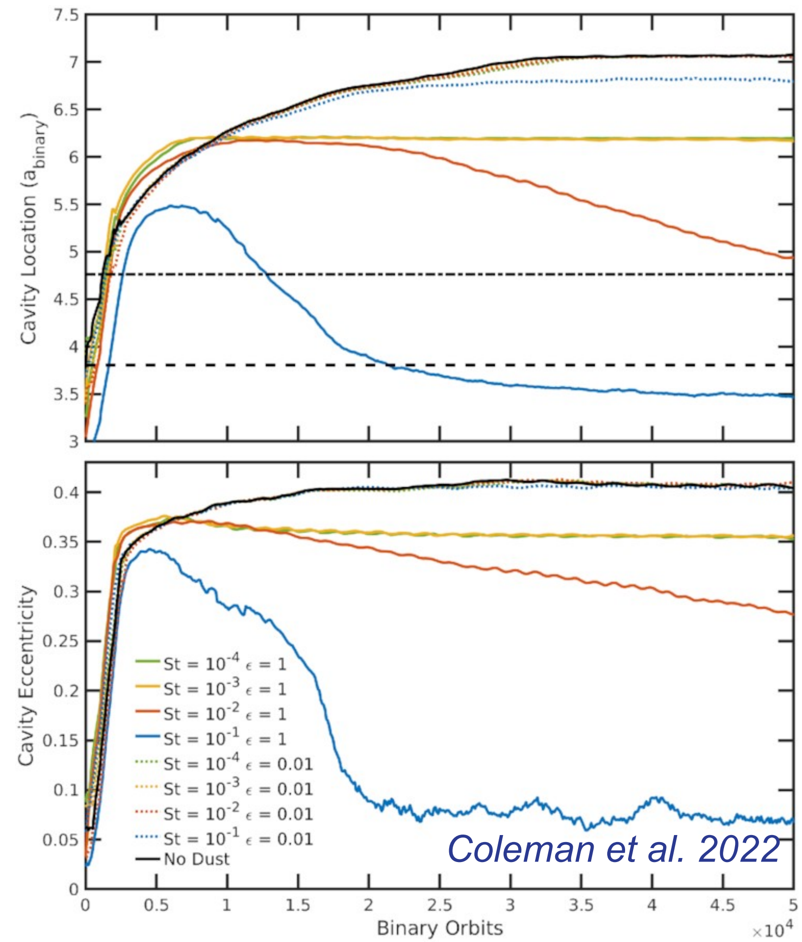


ii) Reversal of Lindblad torques due to significant planet eccentricity

- **As the eccentric disc is the main driver of eccentricity growth, disc models with small eccentricity are needed**

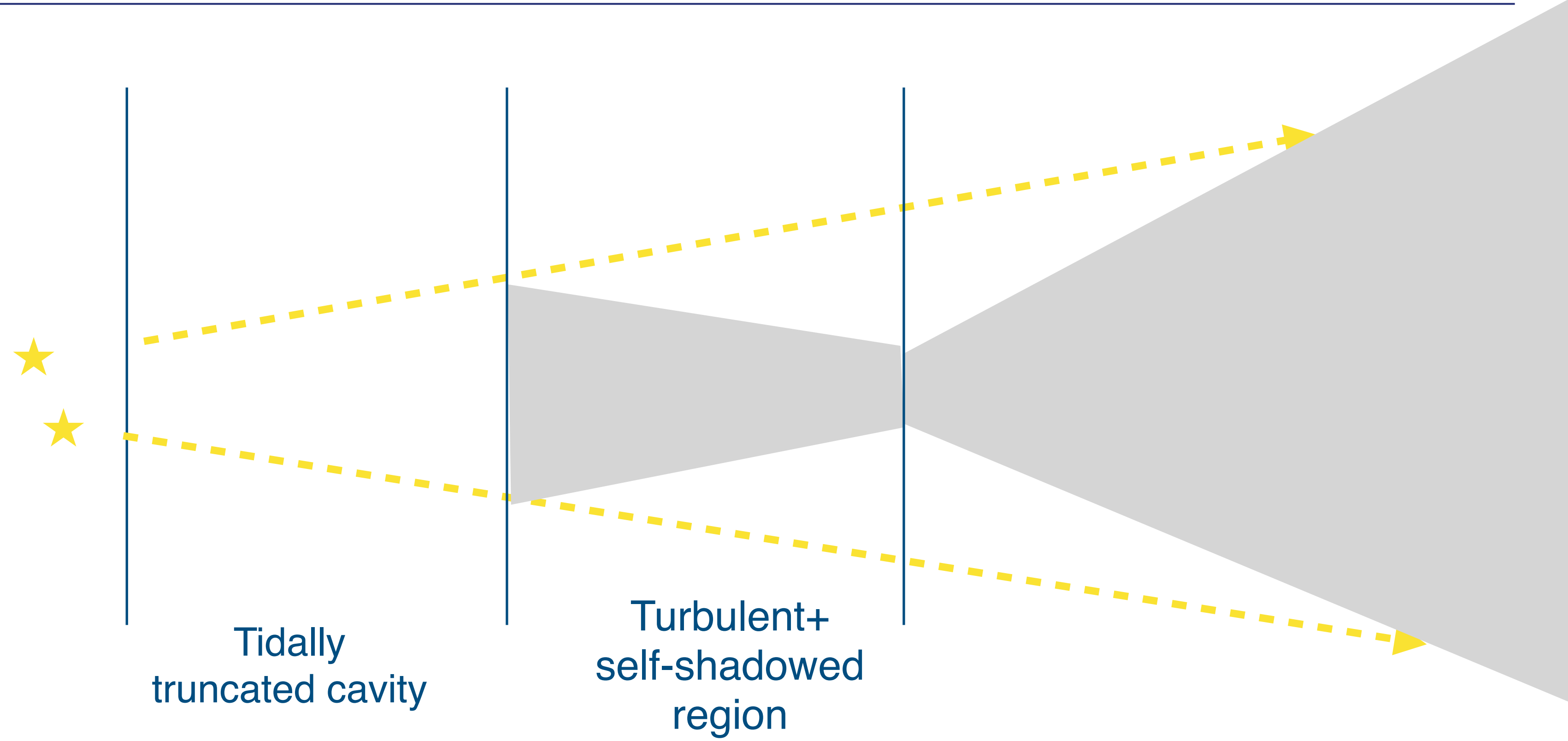
How to decrease disc eccentricity?





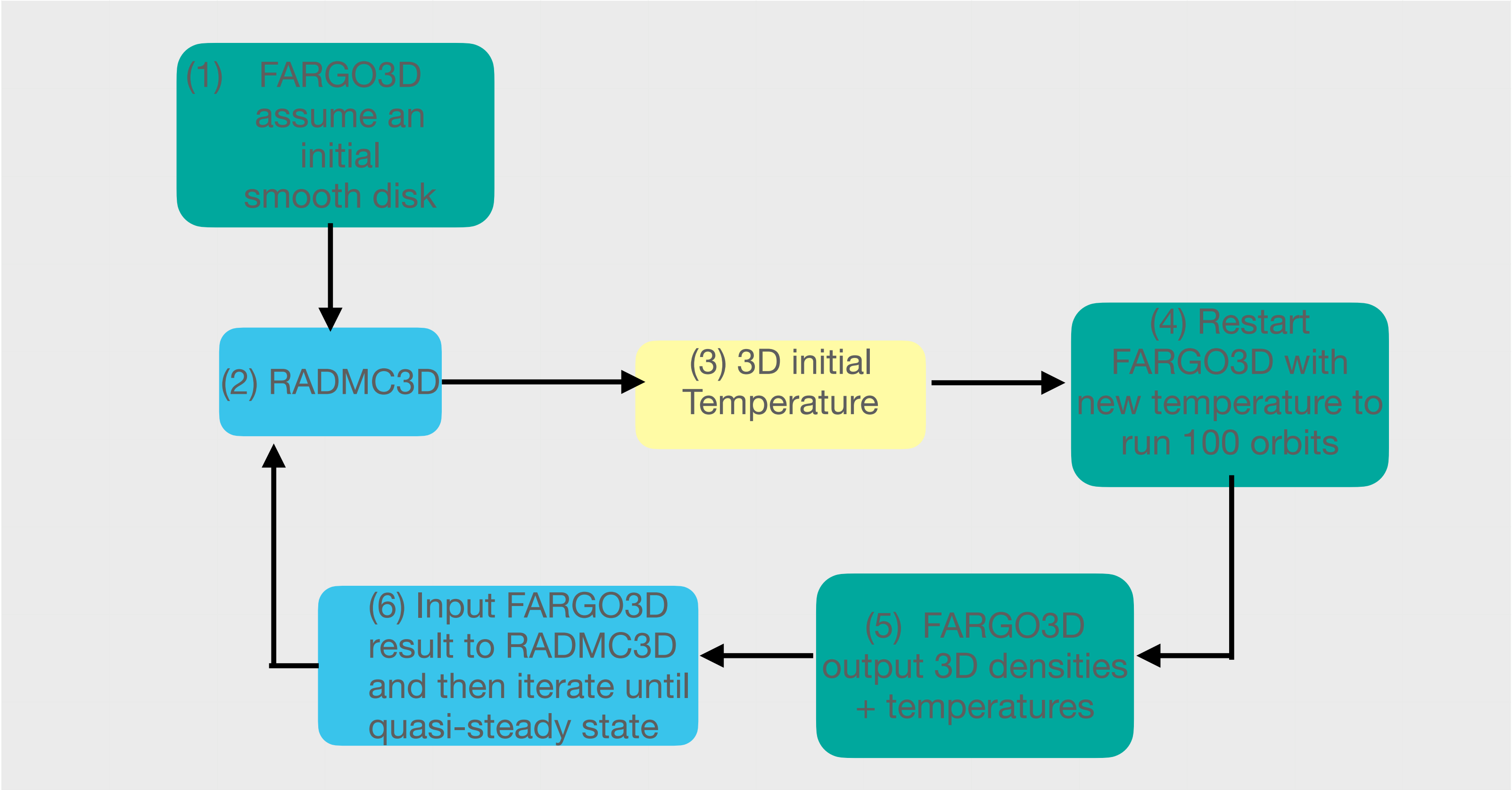
- Invoked mechanisms: self-gravity, effect of dust-back-reaction, partial gap opening

3D radiative models of circumbinary discs

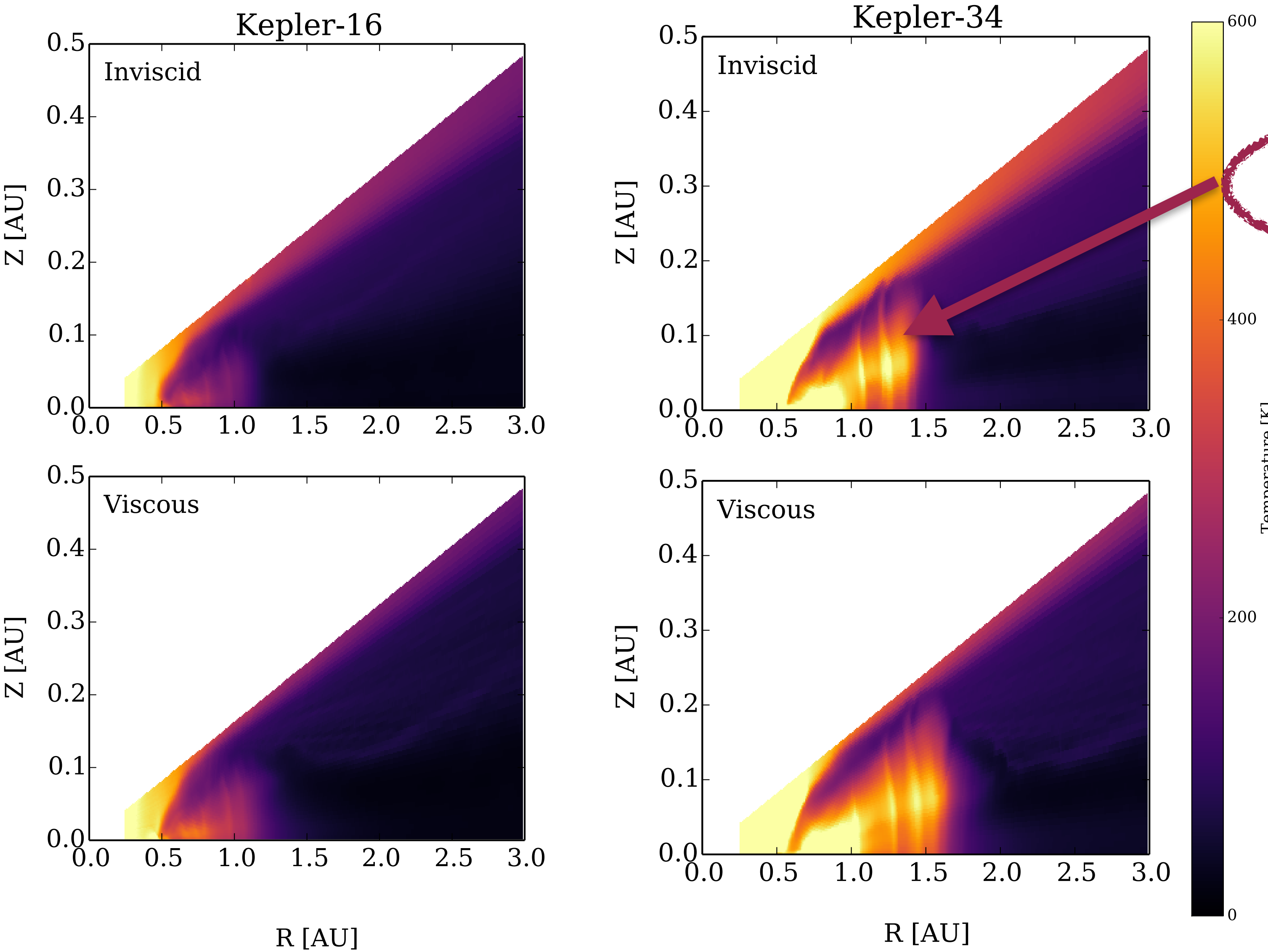


- Difficult to explain CB disc structure with isothermal, 2D viscous models
- More sophisticated modelling is needed to constraint disc physics+planet migration
- 3D models recently developed with thermodynamical structure obtained by coupling FARGO3D with radiative transfert code RADMC3D

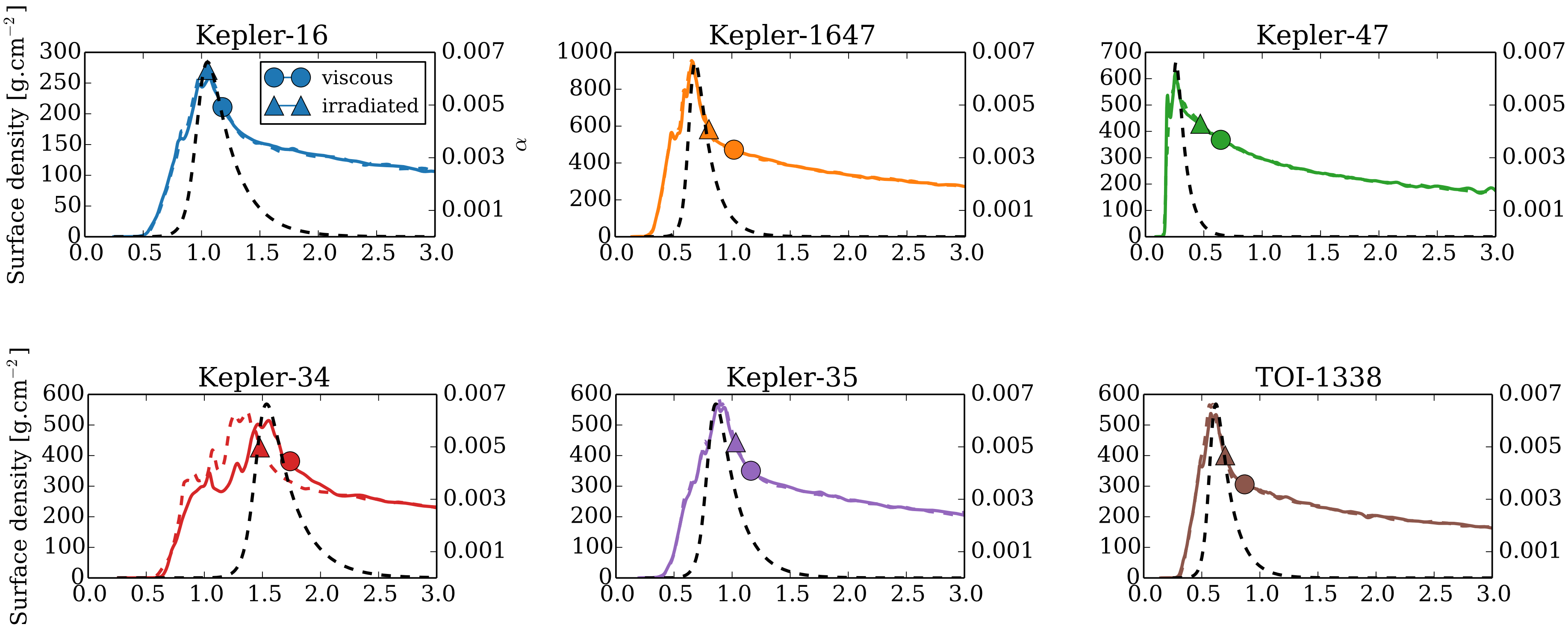
3D radiative models of circumbinary discs



3D radiative models of circumbinary discs

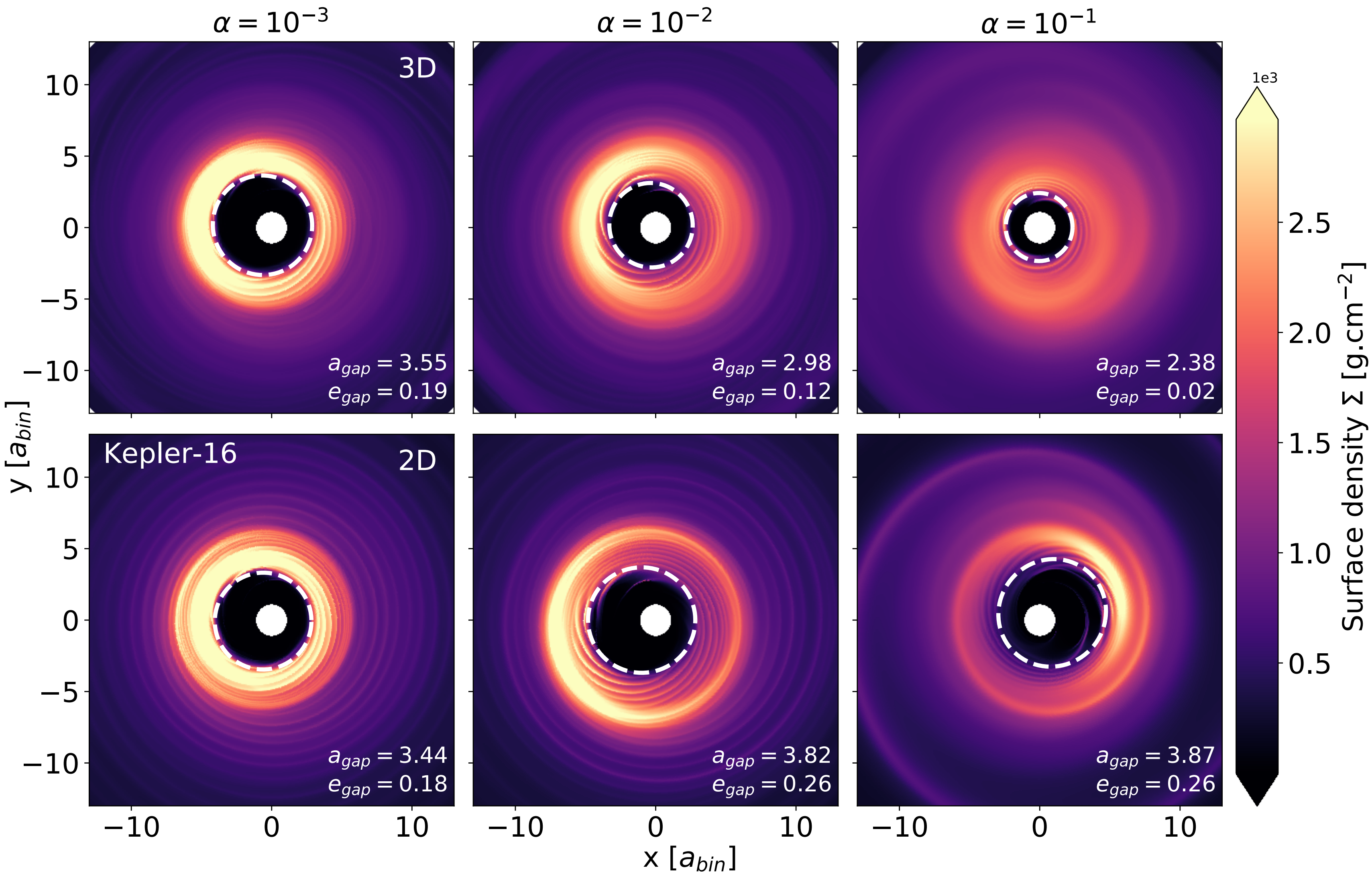


Location of snowlines in circumbinary discs

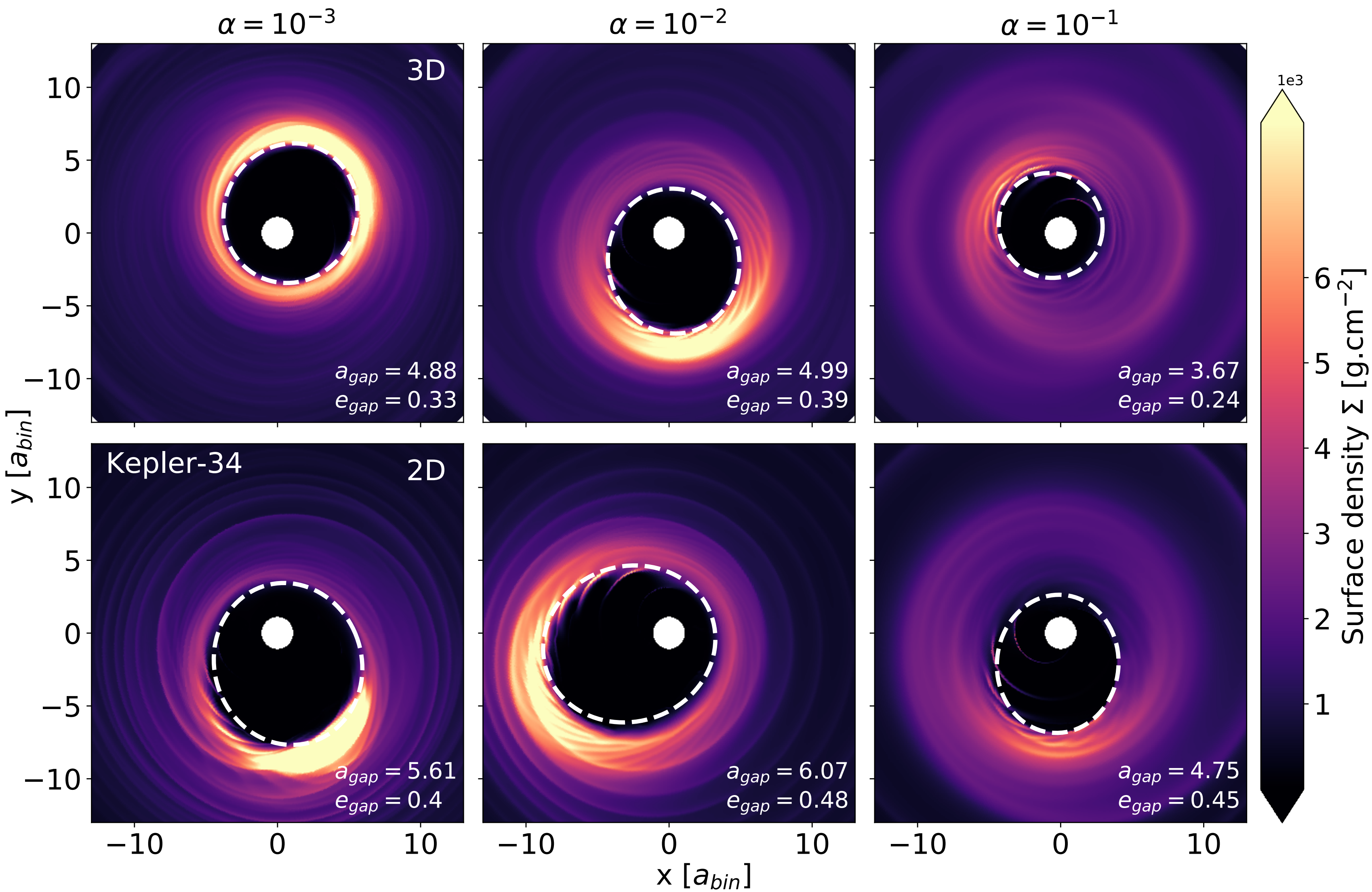


- snowlines located in narrow regions close to the inner cavity
- Difficult to form rocky planets there due to turbulence
- CBPs should therefore be preferentially icy

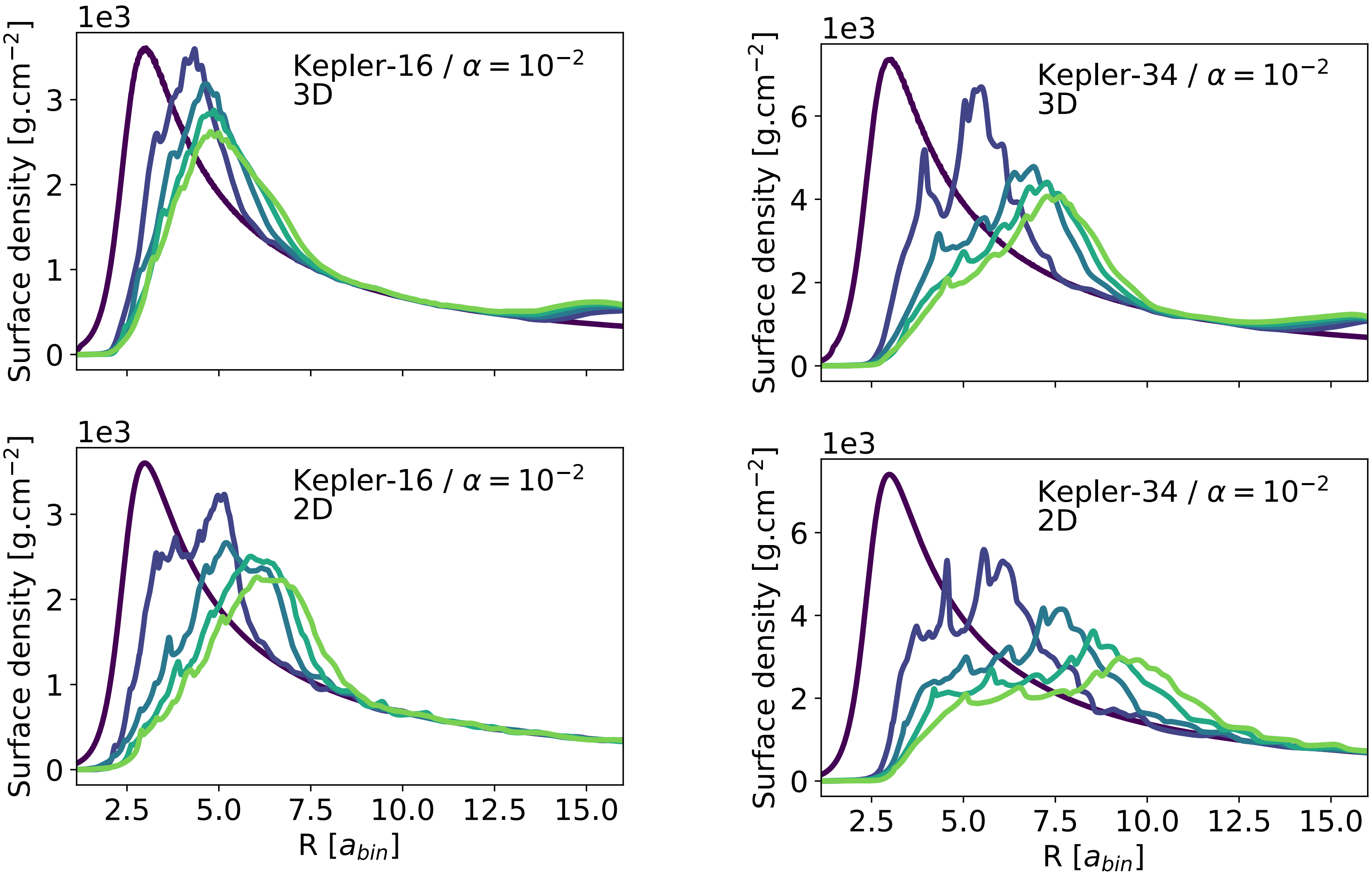
Cavity size in 3D: the case of Kepler-16



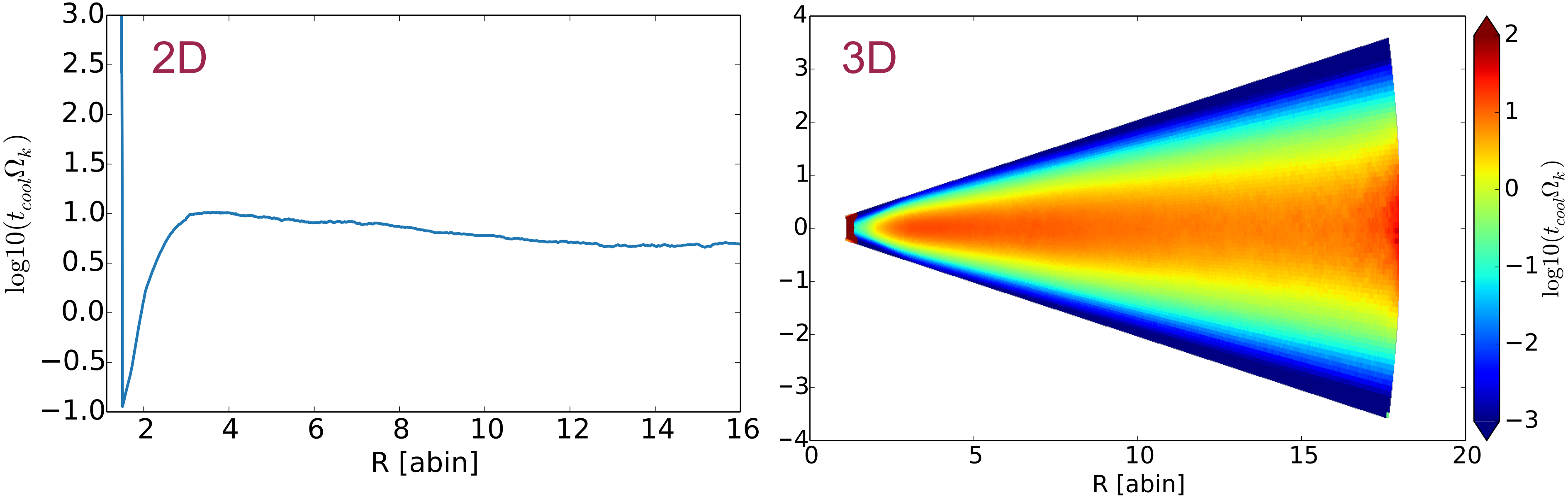
Cavity size in 3D: the case of Kepler-34



Sizes and eccenticities of the cavity smaller in 3D

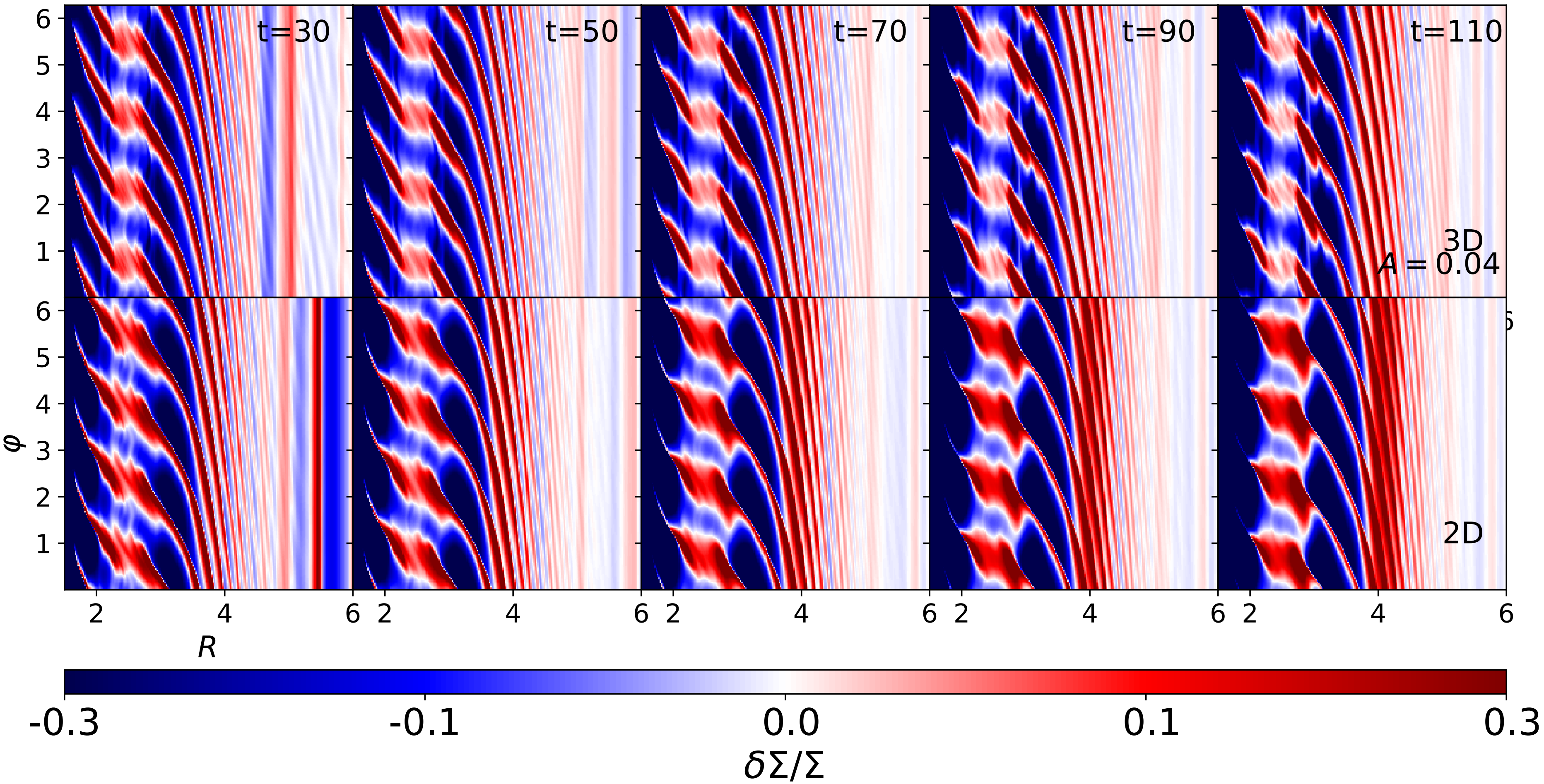


How to explain differences between 2D and 3D ?



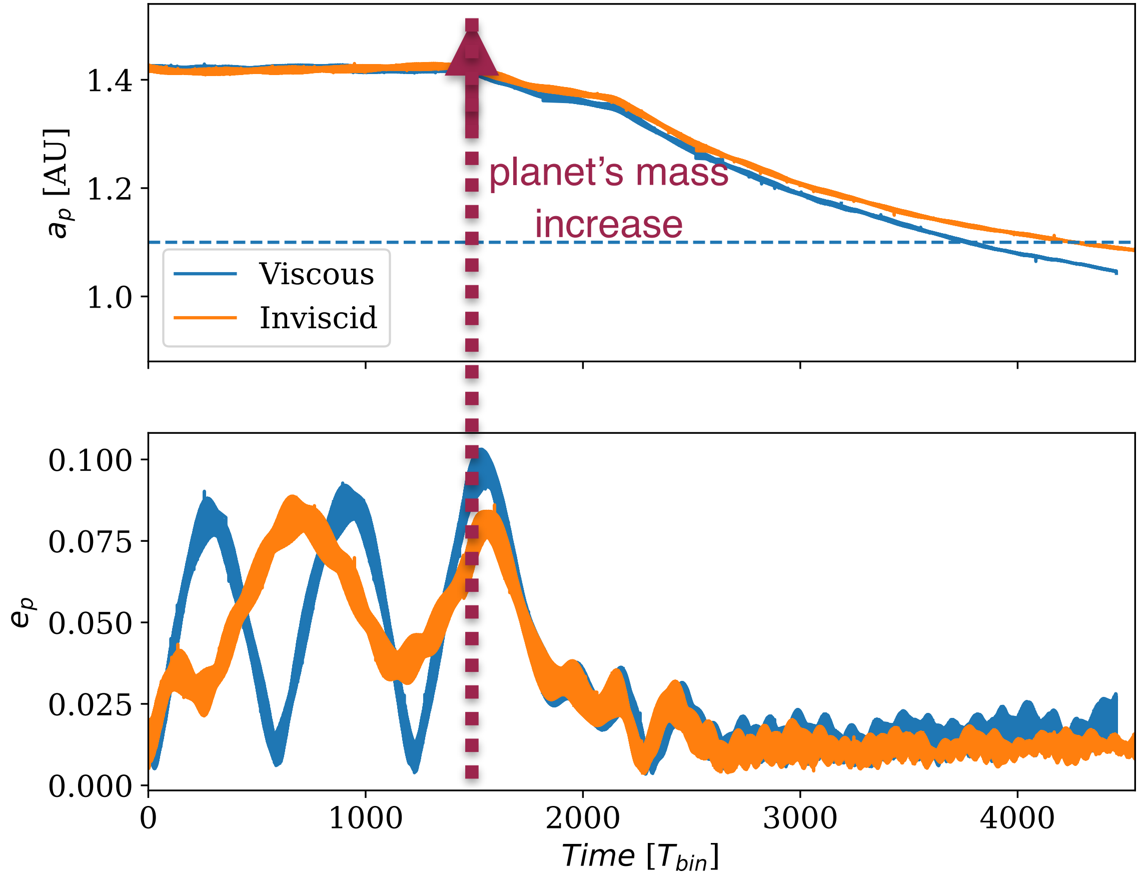
- Formation of inner cavity result from dissipation of spiral waves whose amplitude depend on cooling timescale
- In 2D, disc almost adiabatic → constant AMF
- In 3D, regions with shorter cooling timescales → significant radiative damping

Spiral wave dissipation in 2D and 3D



- Examine the disc response to a perturbing potential of amplitude A
- Spirals appear weaker in 3D→ smaller amplitudes of spirals→ smaller cavities

Evolution of planets in 3D discs: The case of Kepler-34b



- planets with mass corresponding to observed mass park too far from the binary
- planets with slightly higher mass have too small eccentricities

Summary

- Hydrodynamical turbulence renders both grain growth and pebble accretion inefficient close to the inner cavity → migration scenario is favoured
- 2D CB models tend to produce large cavities. This leads to migrating planets parking too far from the central binary
- In 3D, disc eccentricities and cavity sizes are smaller but fitting the orbital parameters of observed CBPs remains difficult.
- Result of missing physics ?

2025: Models of wind-driven CB discs