Planet migration in protoplanetary disks

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an astrophysical migrant crisis? Part III

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Selected Chapters on Astrophysics
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Today's plan

- Finish the discussion of Type I migration
  - corotation torque
  - migration maps, migration traps & implications
  - (too many) additional regimes of Type I migration - thermal torques, torques from pebbles, turbulent disks, low-viscosity disks
- Gap opening
- Type II migration of giant planets
  - classical paradigm (and its problems)
  - beyond the classical paradigm
  - additional regimes of Type II migration - dust-loaded outer gap edge, irradiated outer gap edge, low-viscosity disks

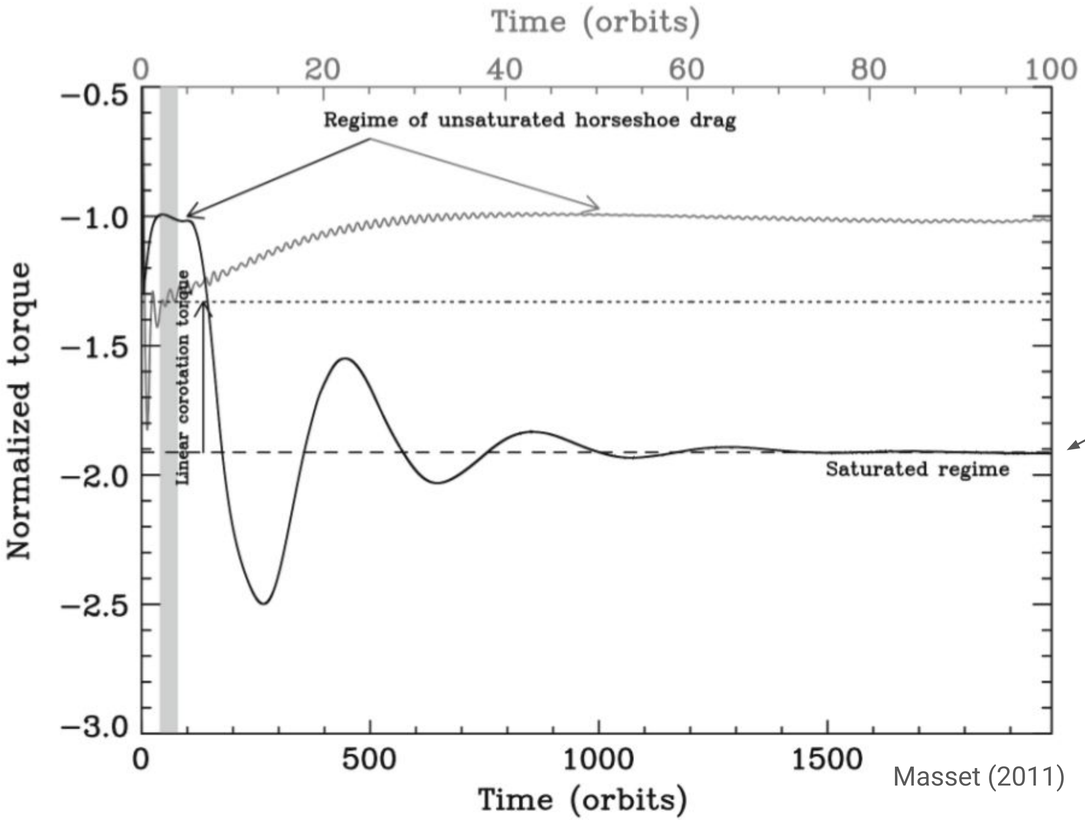
Corotation torque

- corotation resonance condition: $[\Omega(r) - \Omega_{\rm p}] = 0$
- rich behaviour: can be positive/negative, dominant/negligible w.r.t. the Lindblad torque
- regimes:
  - linear
  - non-linear (a.k.a. horseshoe drag <- this is related to our calculations in the impulse approx.)
    - unsaturated
    - saturated
- components:
  - driven by the vortensity gradient across corotation
  - driven by the thermal gradient across corotation

Corotation torque - regimes

Normalized to

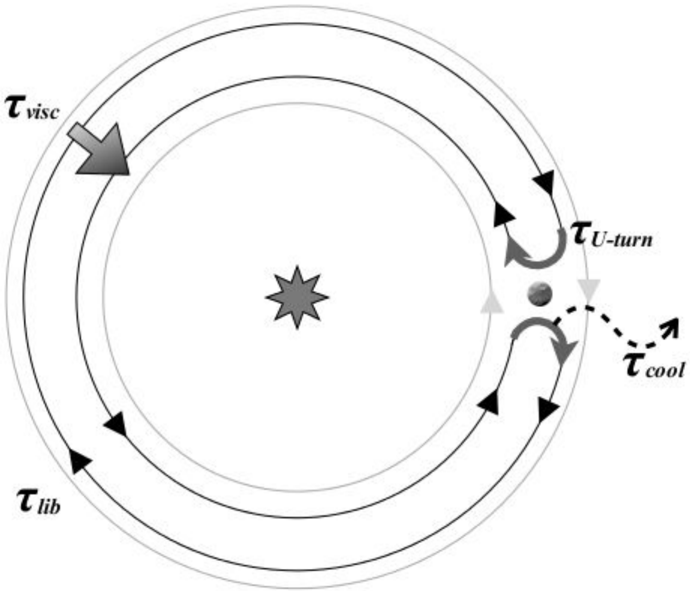
$$\Gamma_0 = \Sigma_p a_p^4 \Omega_p^2 \left(\frac{q}{h_p}\right)^2$$



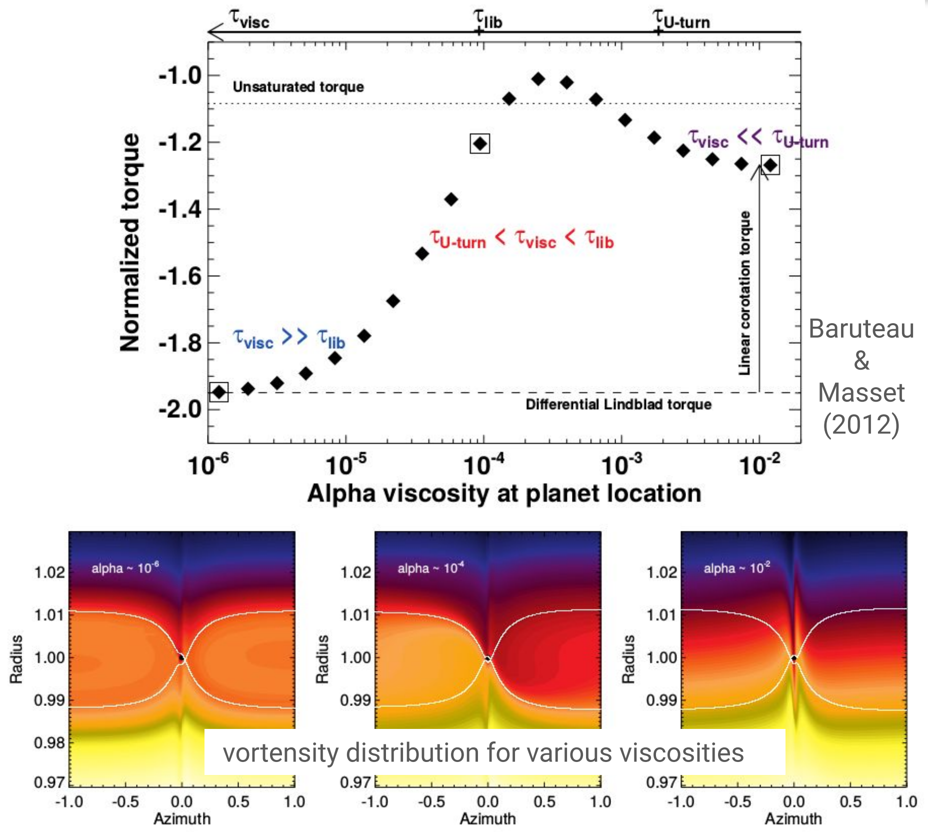
Lindblad torque remains

Masset (2011)

Corotation torque - question of saturation



Mordasini et al. (2011)



Baruteau & Masset (2012)

vortensity distribution for various viscosities

Corotation torque - components

- full formula for the corotation torque includes linear and non-linear regimes, their blending, and saturation of the non-linear regime
- for simplicity, let us assume that the torque operates in the non-linear unsaturated regime (i.e. the maximum possible corotation torque):

$$\gamma_{\mathrm{eff}}\Gamma_{\mathrm{c}} = \left[\underbrace{1.1\left(\frac{3}{2}-\alpha\right)}_{\text{Vortensity-related component}} + \underbrace{7.9\frac{\xi}{\gamma_{\mathrm{eff}}}}_{\text{Entropy-related component}}\right]\Gamma_0$$

Paardekooper et al. (2011)

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Paardekooper et al. (2011)

- compare to the impulse approximation:

$$\Gamma_{\rm hs} = \frac{3}{4}\left(\frac{3}{2}-\alpha\right)\Sigma_{\rm p} x_{\rm s}^4 \Omega_p^2$$

half-width of the horseshoe region has to be determined accurately, Paardekooper & Papaloizou (2009) suggest: $x_{\rm s} = a_{\rm p}\frac{1.1}{\gamma_{\rm eff}^{1/4}}\sqrt{\frac{q}{h}}$

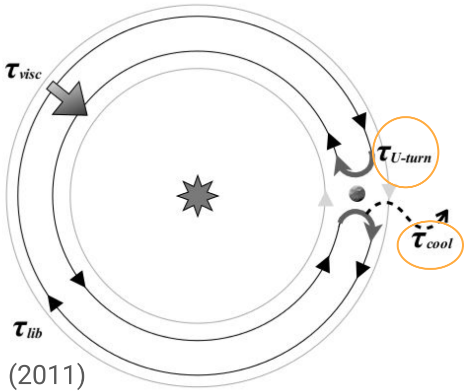
but then: $\Gamma_{\rm hs} \simeq 1.1\left(\frac{3}{2}-\alpha\right)\Sigma_{\rm p} a_{\rm p}^4 \Omega_{\rm p}^2 \frac{q^2}{h^2\gamma_{\rm eff}} = 1.1\left(\frac{3}{2}-\alpha\right)\frac{\Gamma_0}{\gamma_{\rm eff}}$

Corotation torque - components

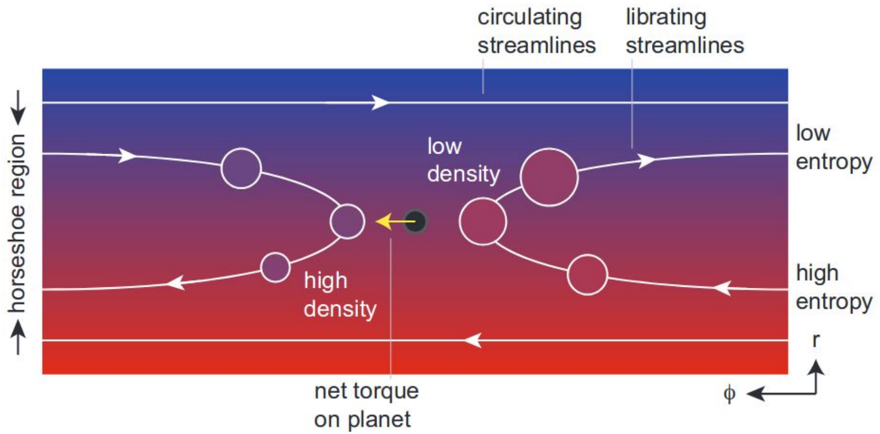
$$\gamma_{\rm eff}\Gamma_{\rm c} = \left[1.1\left(\frac{3}{2}-\alpha\right) + 7.9\frac{\xi}{\gamma_{\rm eff}}\right]\Gamma_0$$

Paardekooper et al. (2011)

- reasoning for the entropy-related component:
  - we consider a measure of the specific entropy $\mathcal{S} = \frac{P}{\Sigma^\gamma} \propto \frac{\Sigma T}{\Sigma^\gamma} \propto r^{-\xi}$ with the slope $\xi = \beta - (\gamma - 1)\alpha$
  - after a U-turn, a blob of gas finds itself surrounded by material with different entropy and can produce density variations
  - again, question of timescales:



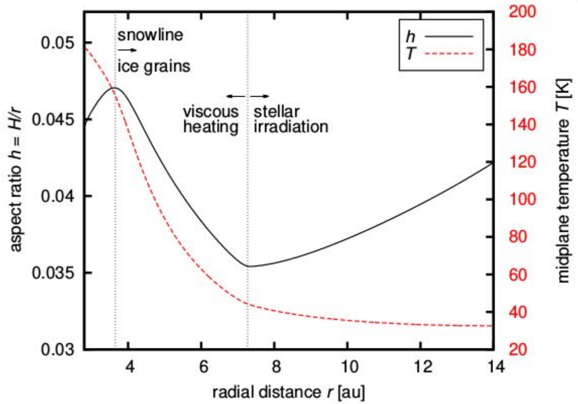
Mordasini et al. (2011)

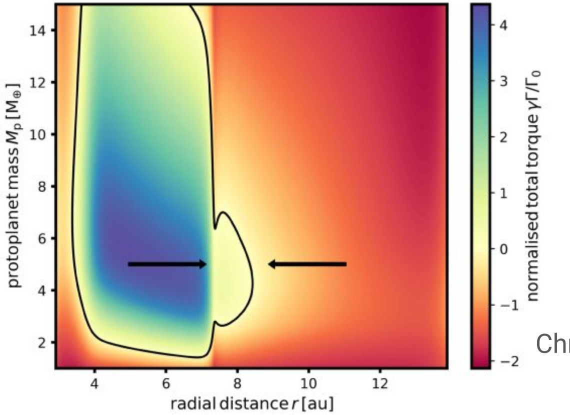


Credit: P.J. Armitage

Migration maps & traps

- planets can migrate outwards if disk conditions (profiles of surface density & temperature) allow for a corotation torque which is (i) positive, (ii) unsaturated, (iii) larger than the Lindblad torque
- planets migrate inwards otherwise
- traps and deserts occur at the transition radii
- e.g. a **trap in the giant-planet formation zone:**

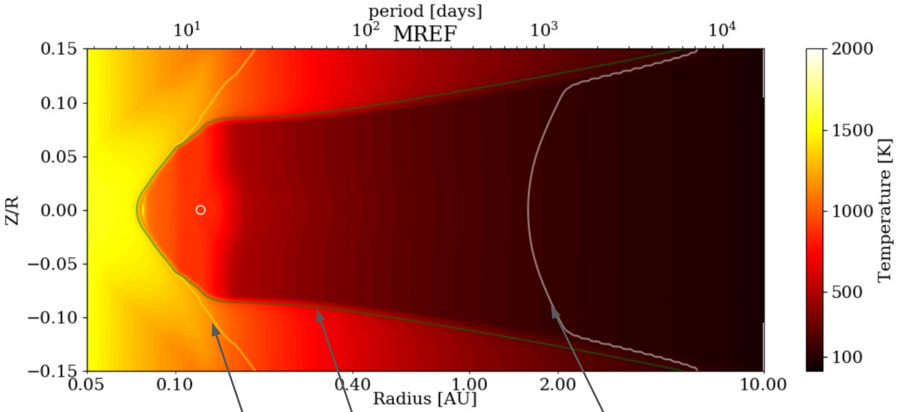


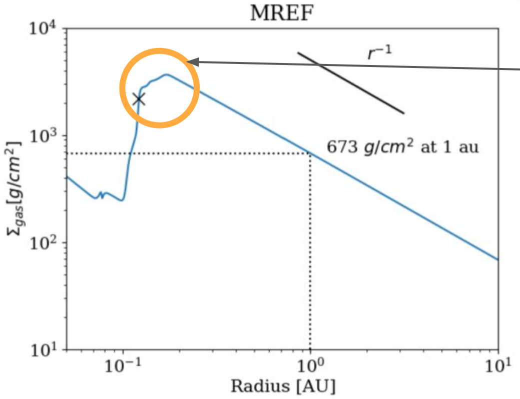


Chrenko et al. (2017)

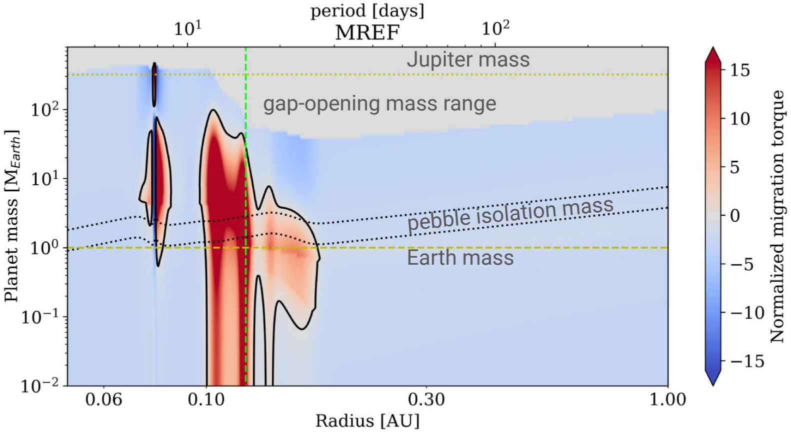
Migration maps & traps

- a **trap at the inner disk rim:**





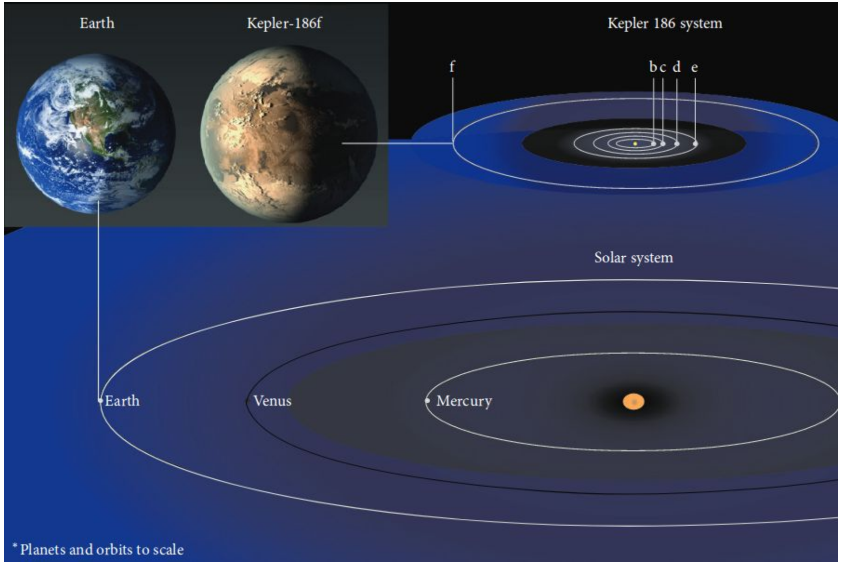
With increasing T (towards smaller r), there is a viscosity transition (the magneto-rotational instability becomes active). The surface density drops to conserve the mass flux of viscously transported gas.



model & figs. from Flock et al. (2019)

(Possible) origin of low-mass planets

- **close-in low-mass exoplanets:**
  progenitor embryos migrated all the way to the inner rim where they were trapped (e.g. Izidoro et al. 2018)
- **solar-system terrestrial planets:**
  - either: only Mercury- to Mars-sized embryos formed during the disk phase to prevent too fast inward migration; final formation through mutual collisions after the disk dispersal (e.g. Hansen 2009)
  - or: full formation during the disk phase + one extra planet to facilitate the Moon-forming impact (Brož et al. subm.)

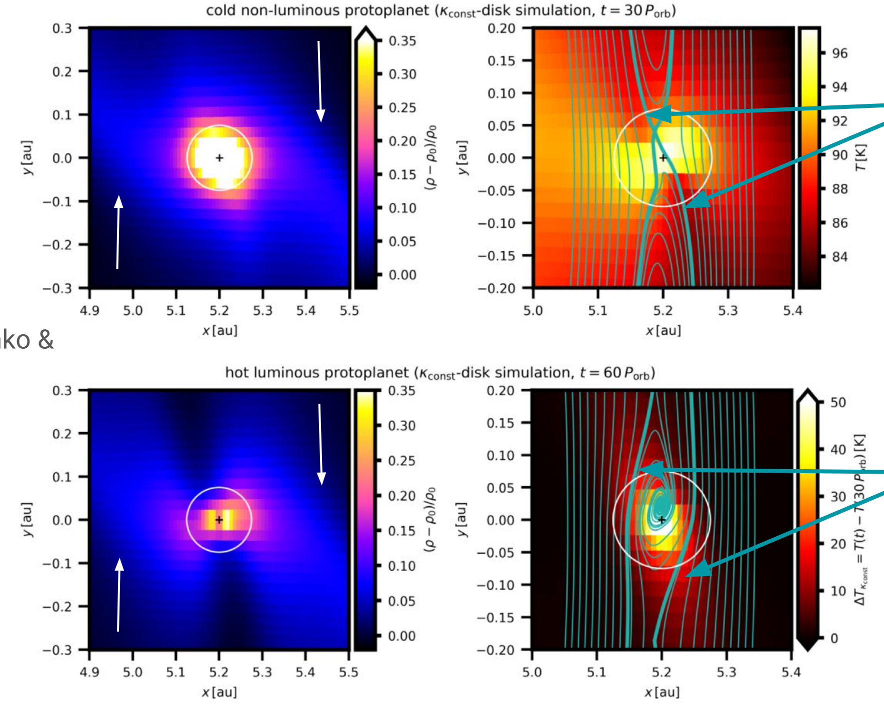


credit: NASA/JPL

Thermal torques (additional regimes of Type I)

- additional torques due to radiative effects on local scales close to the planet

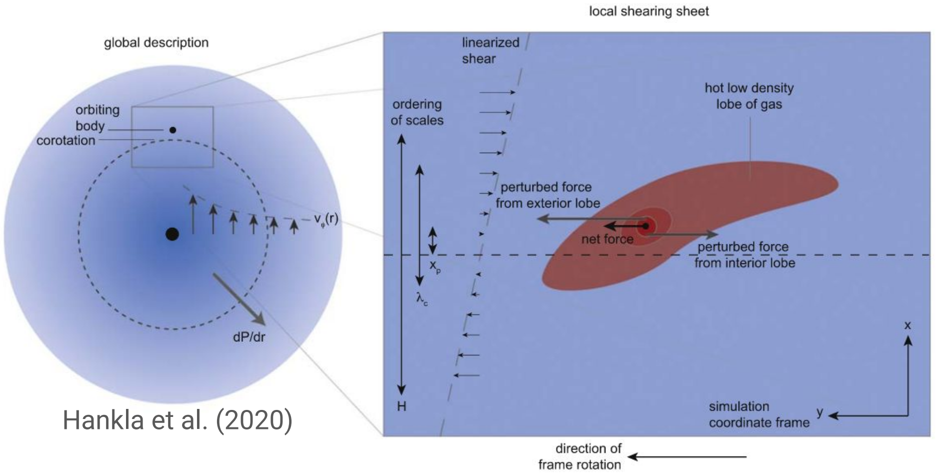
simulations from Chrenko & Lambrechts (2019):



cold gas becomes overdense ->
the **cold-finger torque**
(Lega et al. 2014)

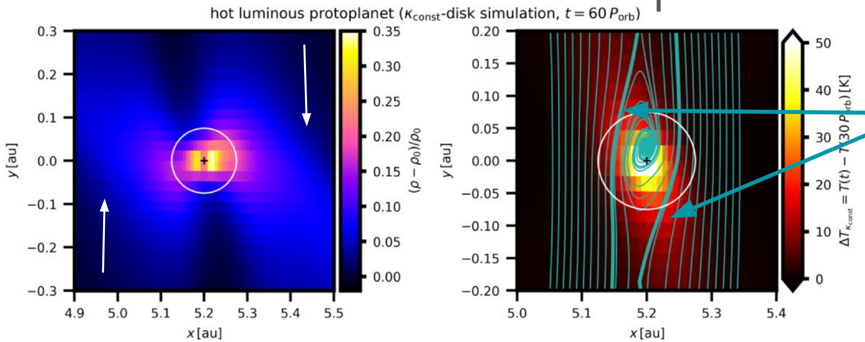
hot gas becomes underdense ->
the **heating torque**
(Benítez-Llambay et al. 2015)

Thermal torques (additional regimes of Type I)



Hankla et al. (2020)

basic **illustration** of the mechanism

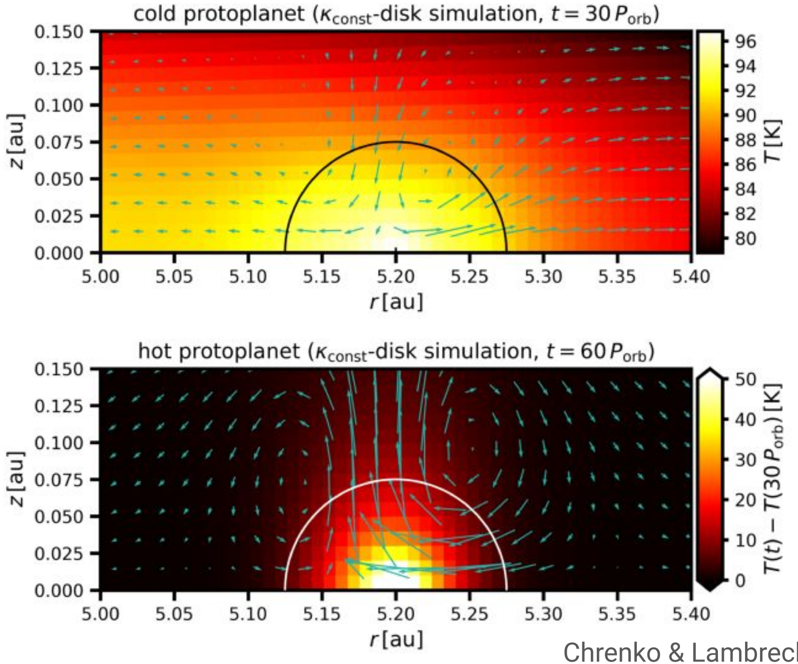


hot gas becomes underdense -> the **heating torque**

(Benítez-Llambay et al. 2015)

Thermal torques (additional regimes of Type I)

- the **vertical flow** differs for non-luminous and luminous planets!



Chrenko & Lambrechts (2019)

Thermal torques (additional regimes of Type I)

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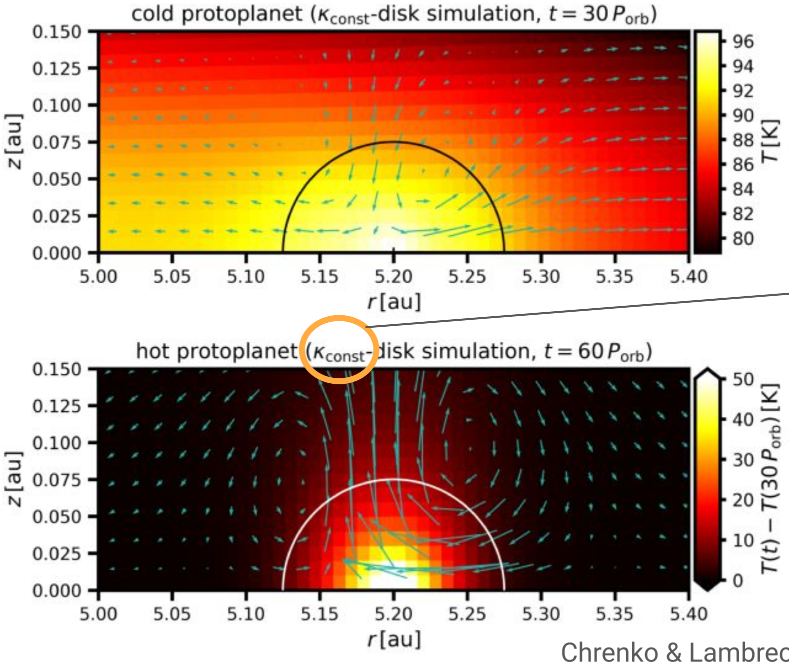
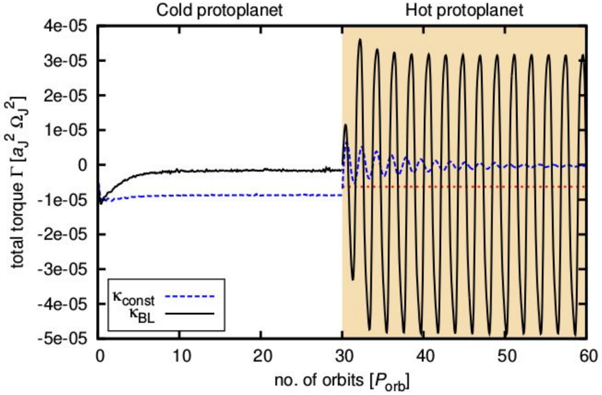


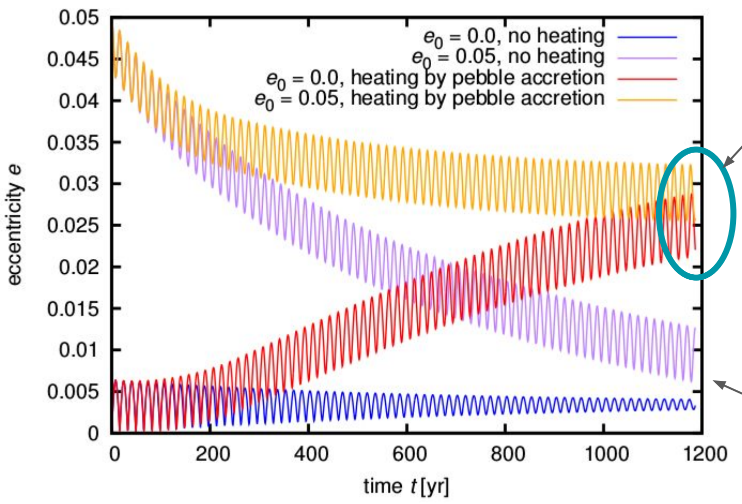
If the opacity is changed from constant to temperature-dependent, the torque might start to **oscillate**



Chrenko & Lambrechts (2019)

Thermal torques (additional regimes of Type I)

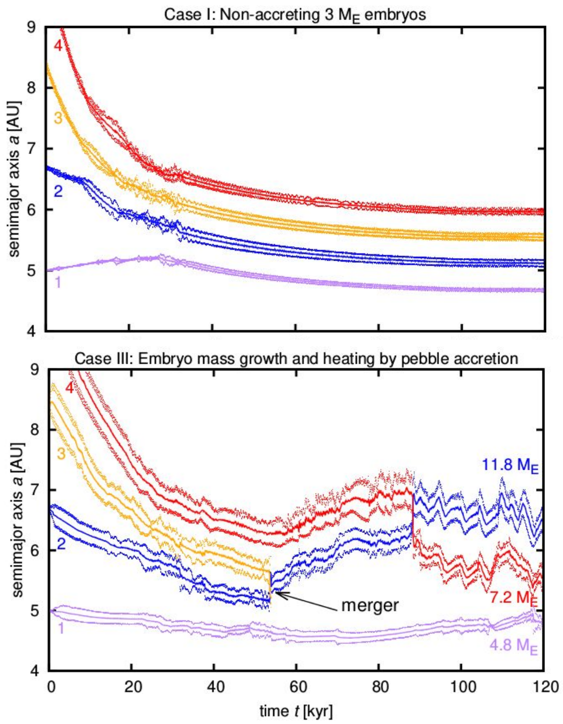
- luminous planets are also subject to the eccentricity and inclination growth = the **hot-trail effect**



Chrenko et al. (2017), see also Eklund & Masset (2017)

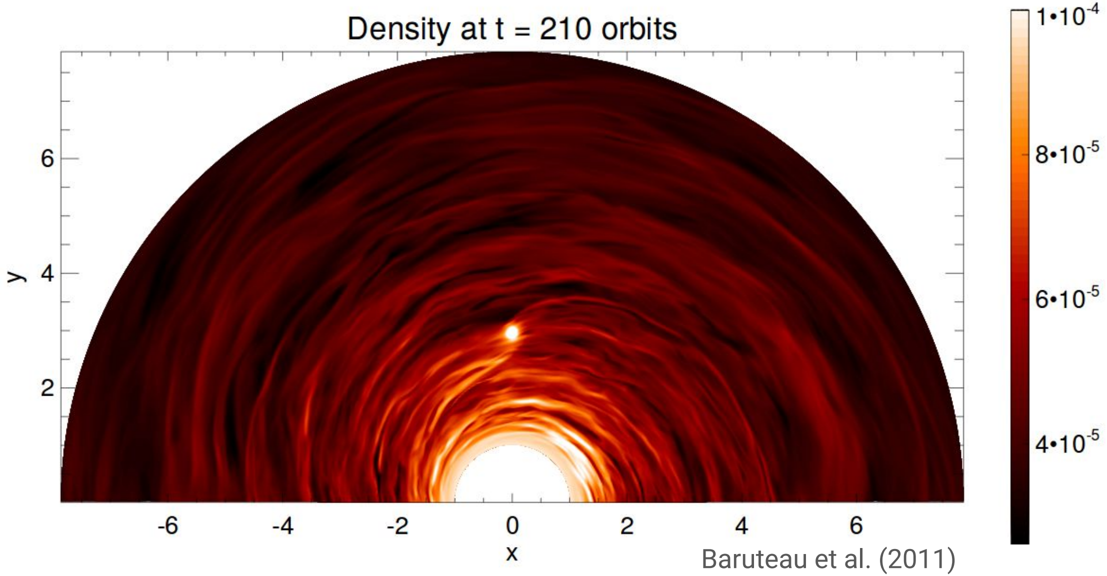
Without accretion heating (=zero planetary luminosity), the orbit remains almost circular.

The hot-trail changes the dynamics of multiple interacting planets:



Torques in turbulent disks (additional regimes of Type I)

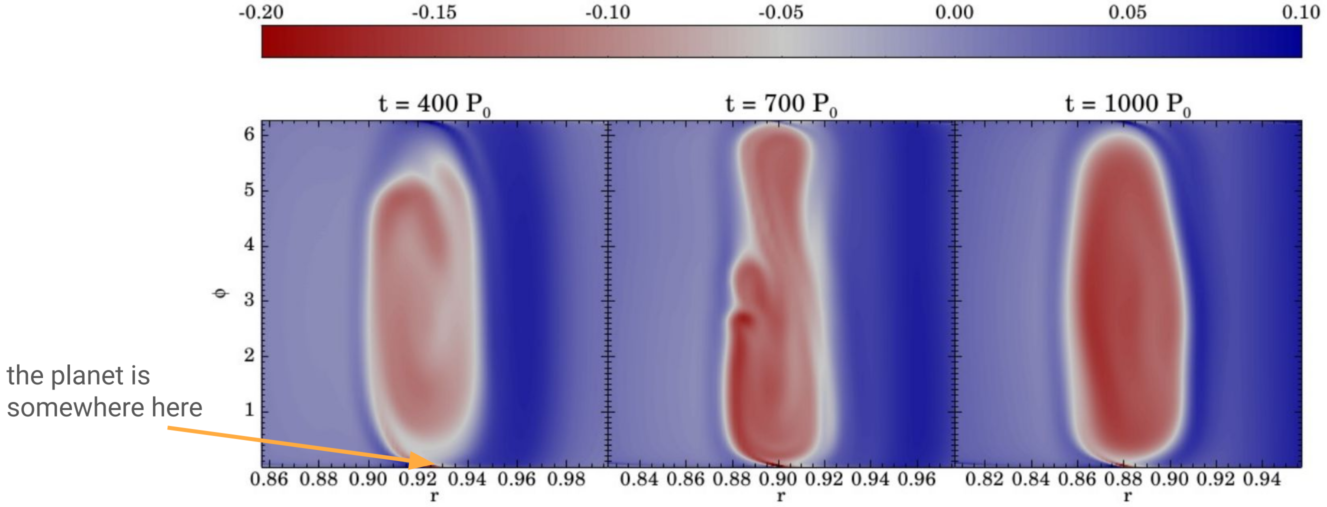
- a turbulent disk is threaded by multiple vortices and the arising density fluctuations lead to a **stochastic forcing** (Nelson 2005, Baruteau et al. 2011, Pierens et al. 2012)



Baruteau et al. (2011)

Torques in low-viscosity disks *(additional regimes of Type I)*

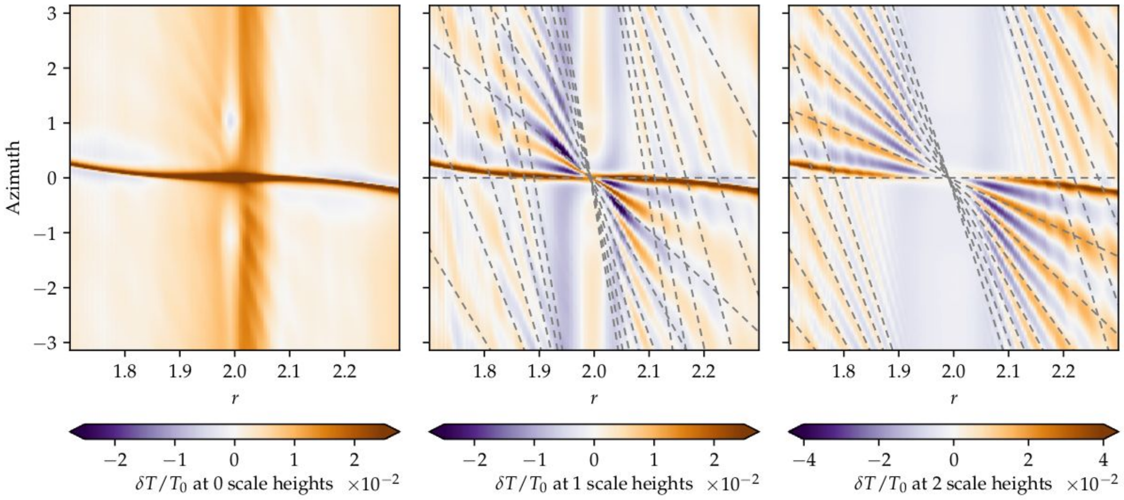
- **dynamical torques:** when the planet starts to migrate, the horseshoe region becomes deformed. The deformation is stronger in low-viscosity disks where it is often accompanied by vortices.



Paardekooper (2014)

Torques in low-viscosity disks (additional regimes of Type I)

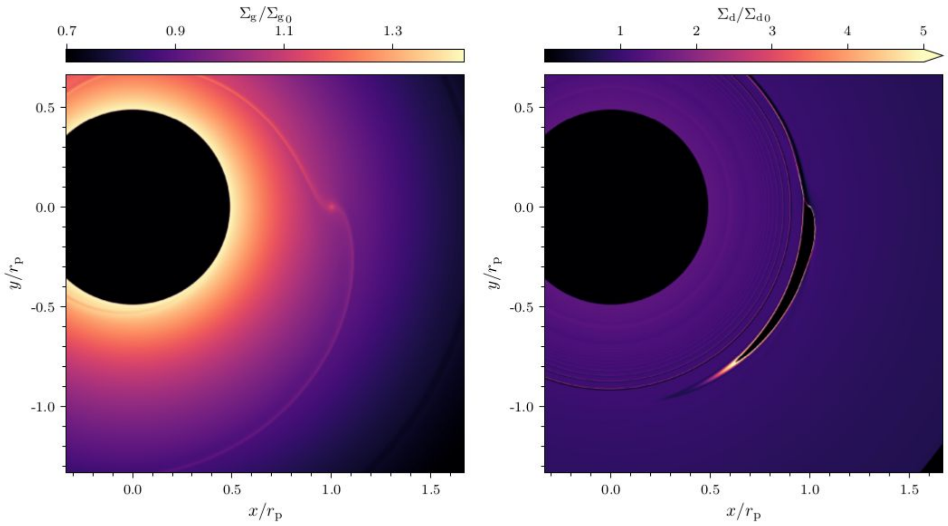
- **buoyant resonances:** appear when vertical oscillations of disk elements perturbed by the planet resonate with the frequency of the restoring buoyant force (Zhu et al. 2012, 2015)
- they can again change the vortensity in the corotation region; the dynamical torque becomes negative in this case



McNally et al. (2020)

Torques from pebbles (additional regimes of Type I)

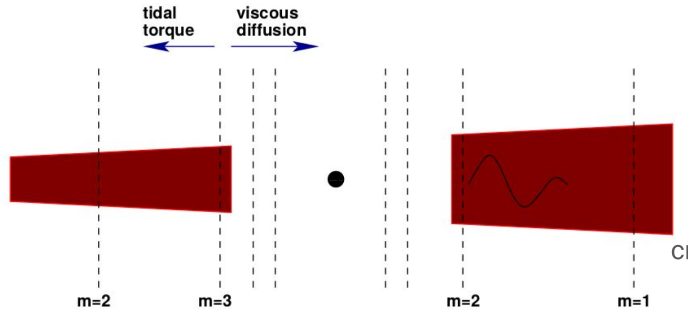
- a disk of **pebbles** affected by the **gas drag** exhibits complex perturbations when interacting with a planet
- strong azimuthal asymmetries can produce additional (usually positive) torques, but relatively large pebble-to-gas mass ratios (~0.01) are required



Benítez-Llambay & Pessah (2018)

Gap opening

- Type I->II transition is usually attributed to the ability of the planet to open a gap in the gas disk
- (**Thermal**) **criterion 1**: the planet must overcome restoring pressure forces (satisfied when $R_\mathrm{H} = a_\mathrm{p}\left(\frac{M_\mathrm{p}}{3M_\star}\right)^{1/3} \gtrsim H_\mathrm{p} = \left(\frac{c_\mathrm{s}}{\Omega}\right)_\mathrm{p}$)
- (**Viscous**) **criterion 2**: the timescale of gap opening must be shorter than that of viscous spreading

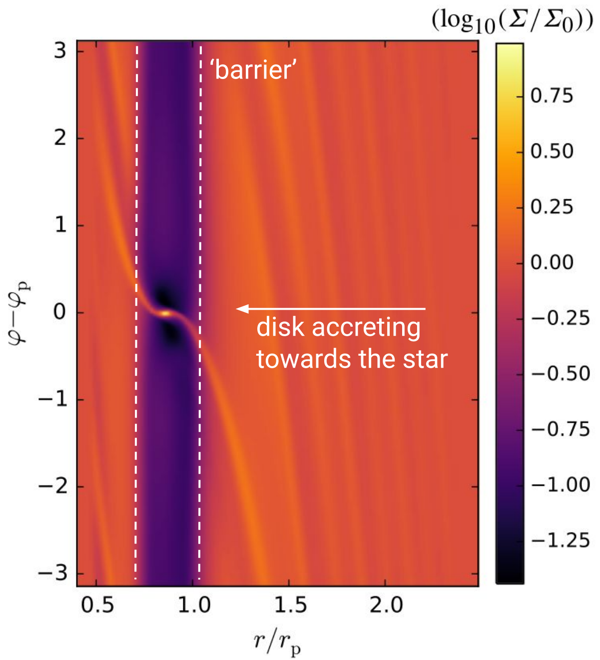


credit: P. J. Armitage

- **combined criterion:** $\frac{3H_\mathrm{p}}{4R_\mathrm{H}} + \frac{50\nu_\mathrm{p}}{q\Omega_\mathrm{p} r_\mathrm{p}^2} \lesssim 1$ (Crida et al. 2006, but cf. Kanagawa et al. 2018)

Type II - classical picture (and its problems)

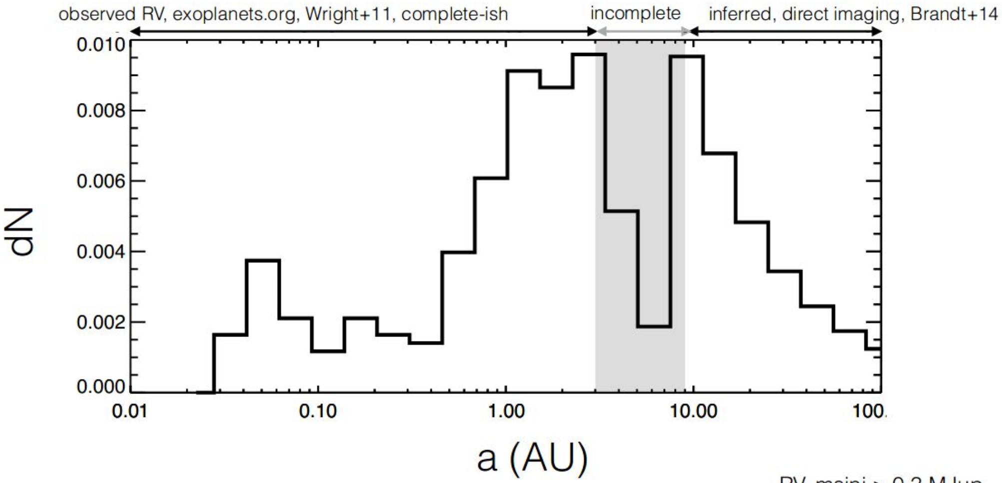
- Lin & Papaloizou (1986): the gap-opening mechanism creates an impenetrable barrier to the gas inflow, the planet is ‘frozen’ in the gap centre and has to drift at the same velocity as the surrounding disk
- in a viscous accretion disk, the radial gas velocity is $v_{r,\mathrm{visc}} = -\frac{3\nu}{2r}$ and the torque can be deduced from $v_{r,\mathrm{visc}} \simeq \frac{\mathrm{d}a_\mathrm{p}}{\mathrm{d}t} = \frac{2\Gamma}{M_\mathrm{p} a_\mathrm{p} \Omega_\mathrm{p}}$
- Type II is thus inward and related to the local viscous evolution timescale



(Paardekooper & Johansen 2018)

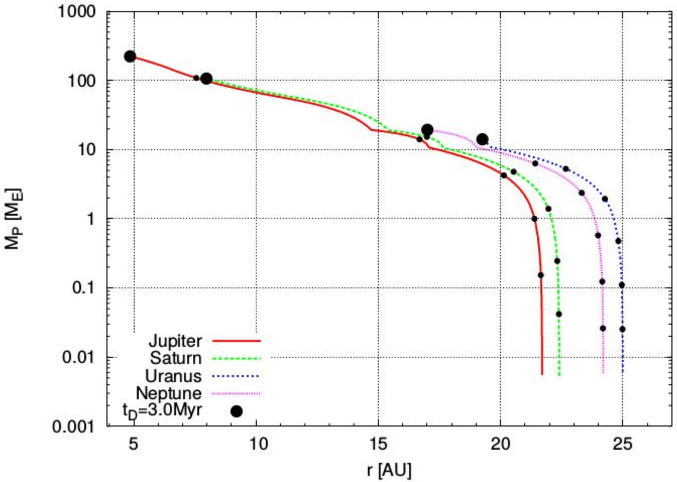
Type II - classical picture (and its problems)

- if giant planets migrate inwards on a viscous timescale, there is an inconsistency between observations (prevalence of ‘cold Jupiters’) and planet accretion scenarios



credit: R. Dawson (2015)

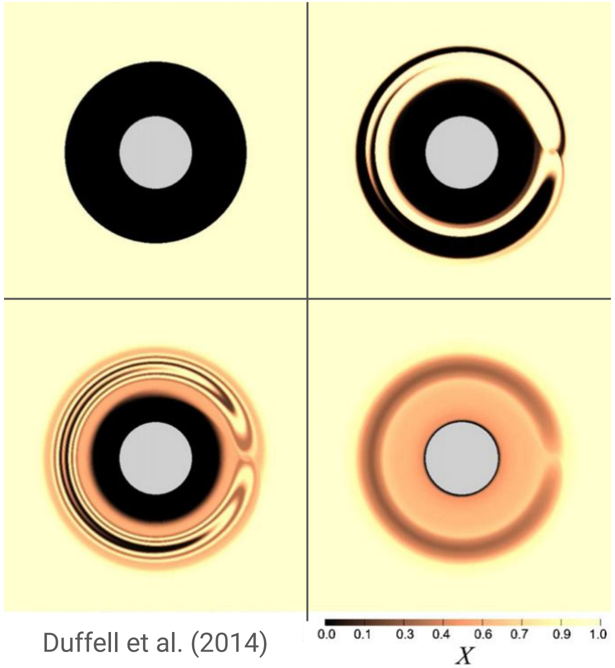
RV, msini > 0.3 MJup



Bitsch et al. (2015)

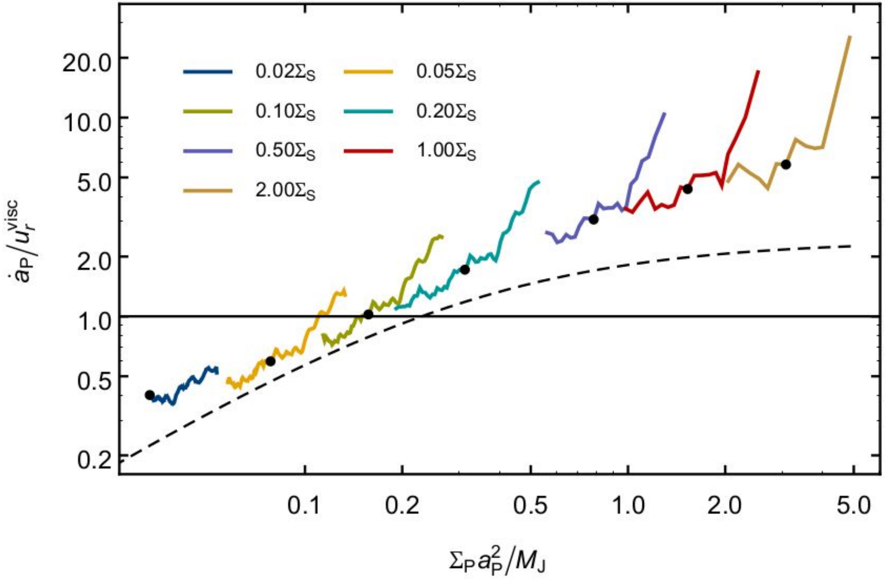
Type II - beyond the classical picture

- there is evidence for **gap-crossing flows:**



Duffell et al. (2014)

- **migrating planet can decouple** from the viscous drift rate:



Durmann & Kley (2015)

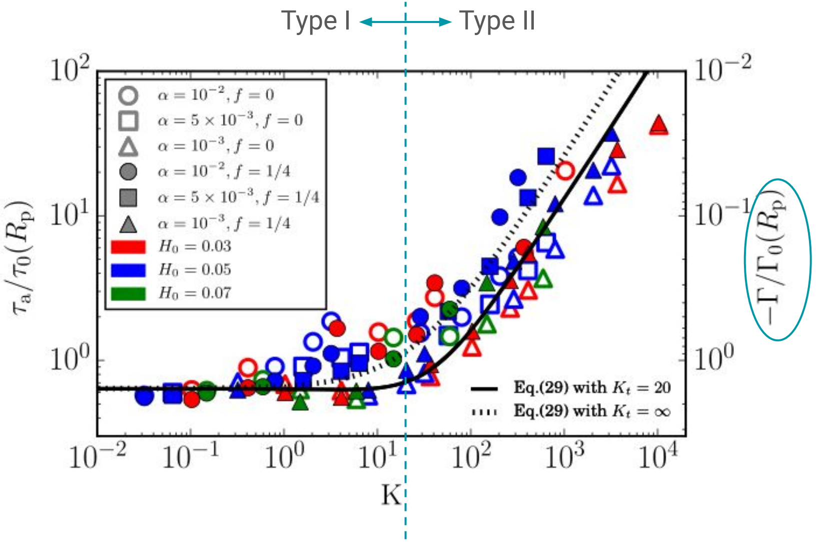
Type II - beyond the classical picture

- **Kanagawa et al. (2018)** suggests a new picture: Type II can be characterized with the same Lindblad + corotation torque as Type I, only taking into account the decreased gas density within the gap
- formulae:

$$\Gamma = \frac{\Gamma_{\rm L} + \Gamma_{\rm C}\exp\left(-K/K_{\rm t}\right)}{1 + 0.04K}$$

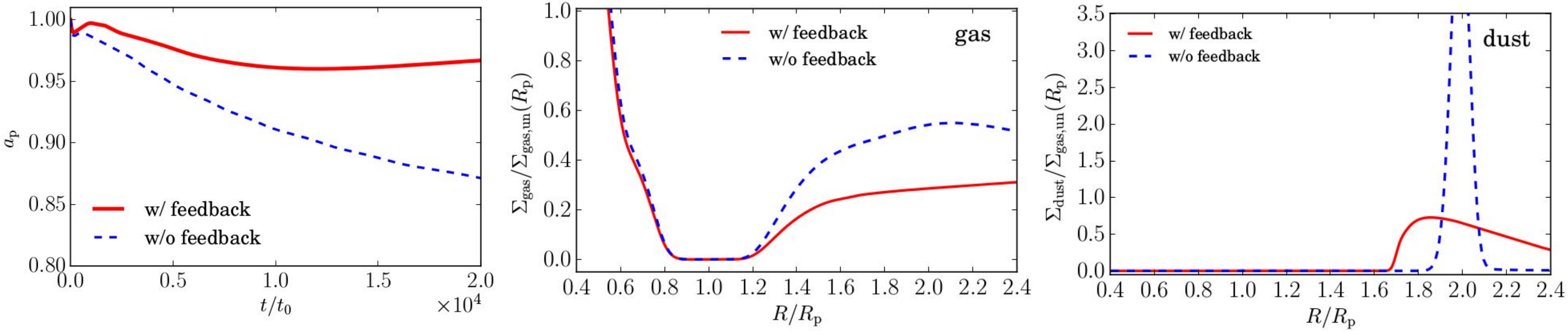
$$K_{\rm t} \simeq 20$$

$$K = \left(\frac{M_{\rm p}}{M_\star}\right)^2 \left(\frac{H_{\rm p}}{r_{\rm p}}\right)^{-5} \alpha^{-1}$$



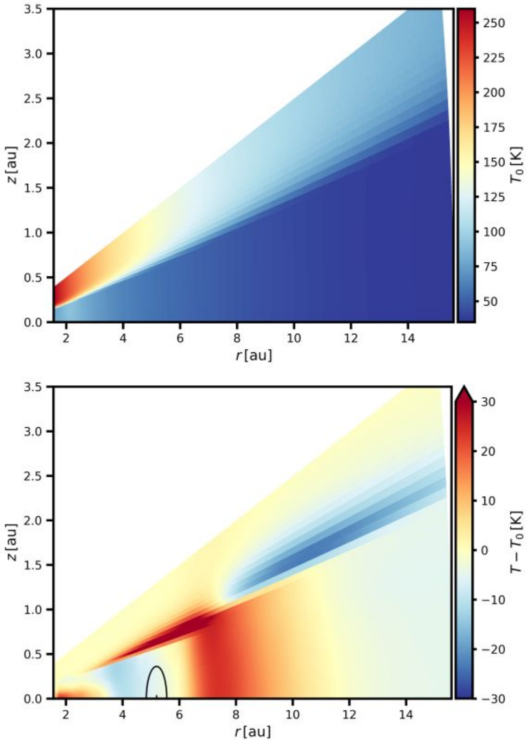
Type II with gap edge effects

- if Type II is governed by the Lindblad torque (as suggested by Kanagawa et al. 2018), changes of the outer gap edge structure can affect the outer spiral arm
- Kanagawa (2019): **dust** concentrates at the outer gap edge -> if its aerodynamic **back-reaction** is taken into account, it can reduce the gas density near the outer gap edge

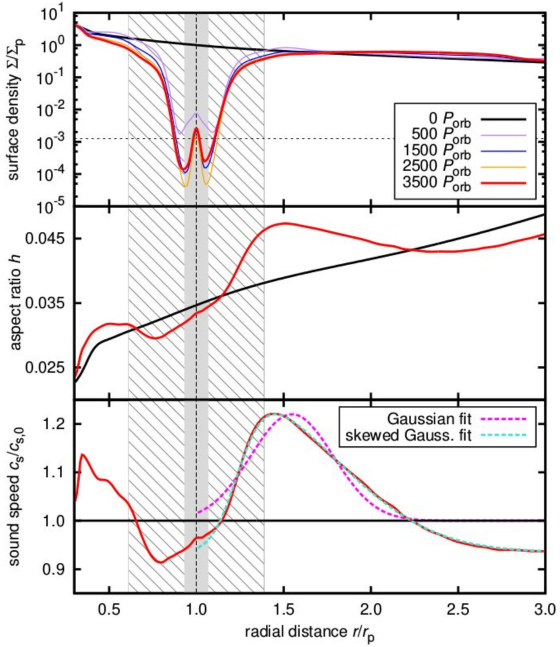


Type II with gap edge effects

- Hallam & Paardekooper (2018), Chrenko & Nesvorný (2020): **irradiation of the outer gap edge** can boost the local scale height -> affect the outer one-sided Lindblad torque (which scales as ~h^{-3})



Chrenko & Nesvorný (2020)



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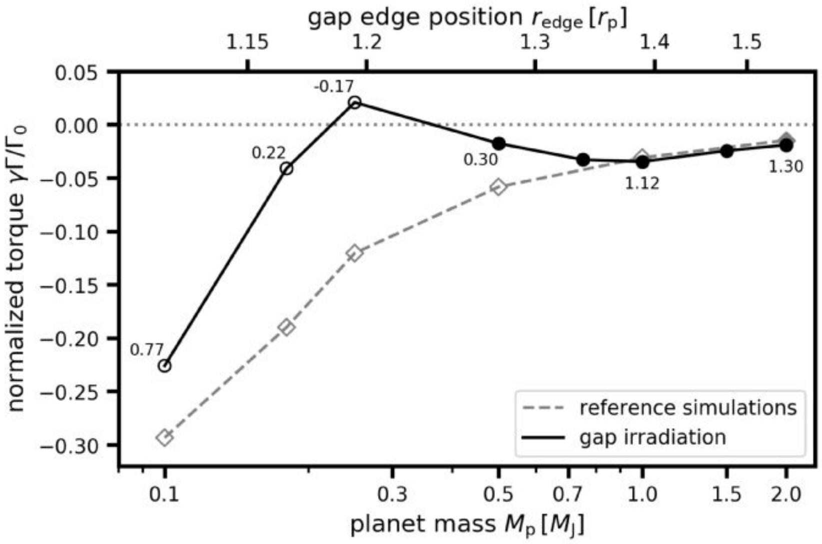
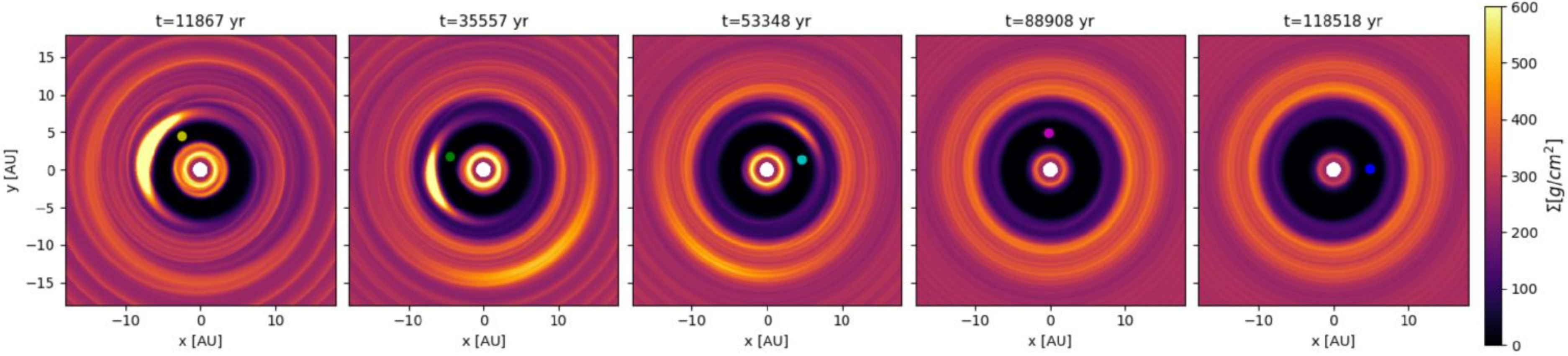


Chrenko & Nesvorný (2020)

Type II in inviscid disks

- Lega et al. (2021): if the viscosity is low, Type II is first regulated by a neighbouring Rossby vortex -> then the vortex decays and the migration is stalled due to reduced gas density in the outer disk



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