GIANT PLANETS IN PROTOPLANETARY DISKS

GAP FORMATION AND MIGRATION

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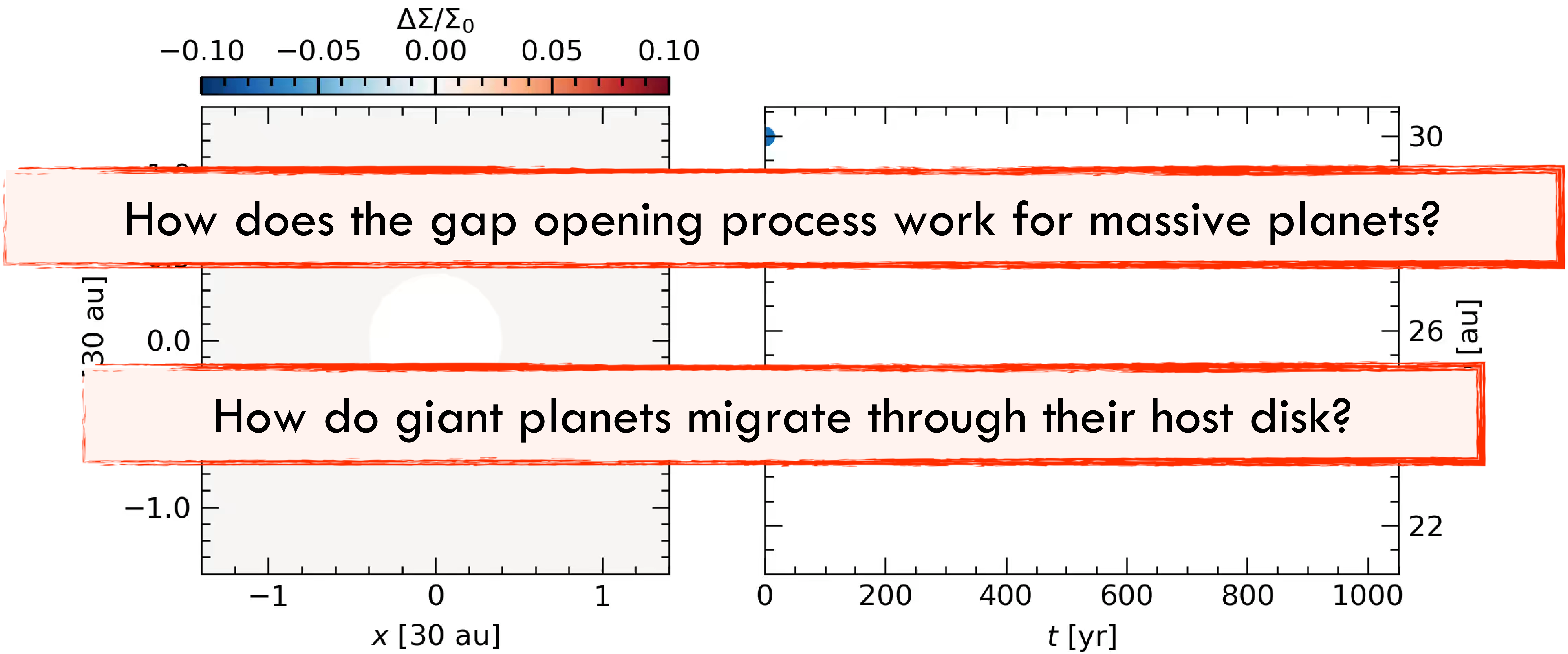
Planet–disk interaction: gap opening and planet migration



Planet interacts with its surrounding disk → the disk exerts a torque on the planet

PLANET → DISK: GAP FORMATION

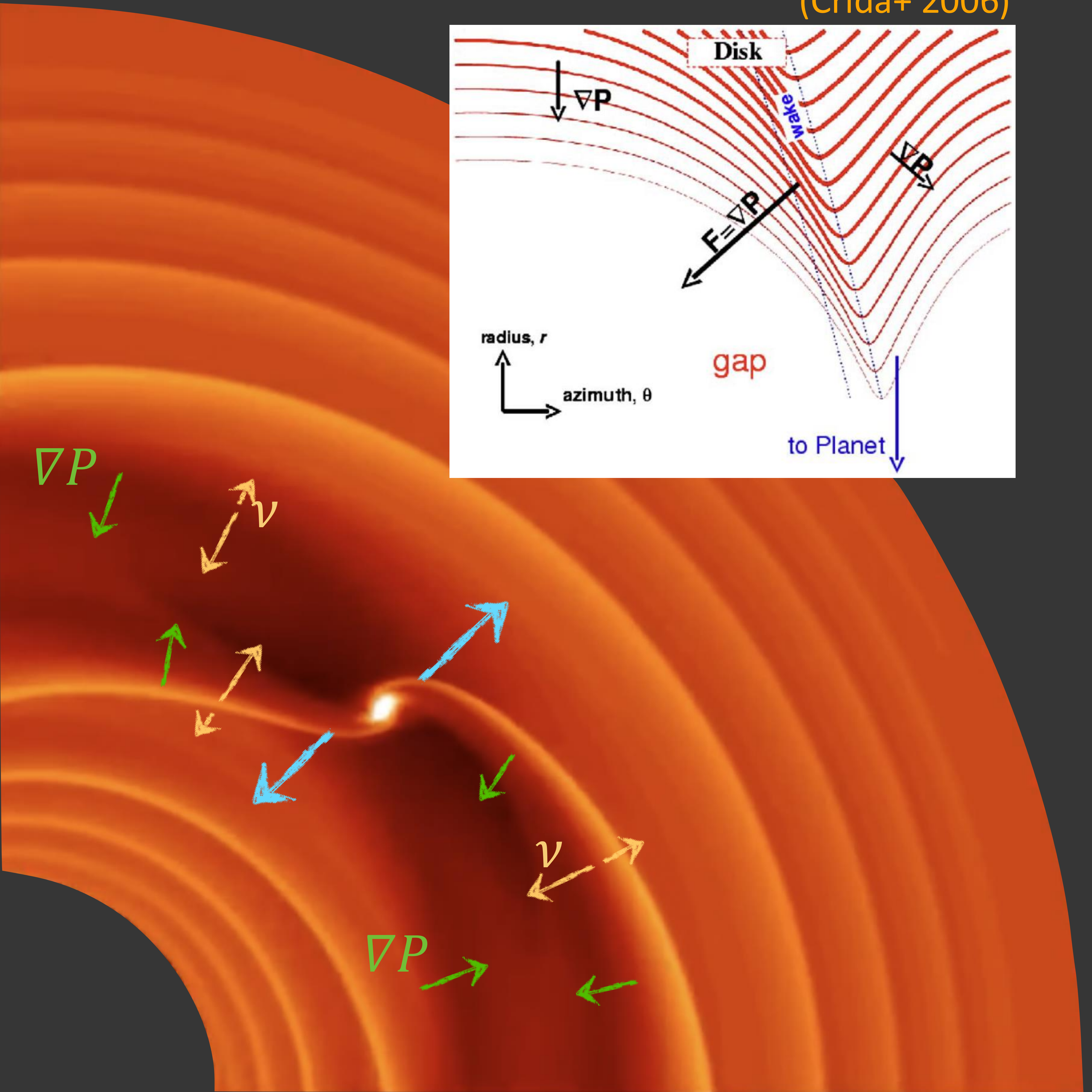
(image: Kley & Nelson 2012)

Gap opening in action

(Kley & Nelson 2012)

(See also Kanagawa+ ’15, Dong & Fung ’17, Duffel ’20)

Gap opening in action: torque balance



(Crida+ 2006)

- Spiral shocks ($\propto M_\mathrm{p}$) torque the gas away
- Pressure gradient ($\propto H$) pushes back in
- Viscous forces ($\propto \nu$) smear the gap edges

Balance between the 3: a *gap opening* criterion

$$\frac{3}{4}\frac{H}{R_\mathrm{Hill}} + \frac{50\nu}{\Omega R^2}\frac{M_\star}{M_\mathrm{p}} \lesssim 1$$

(Crida+ 2006)

Related to the definition of the *thermal mass*:

$$M_\mathrm{th} \approx \frac{2h^3}{3} M_\star$$

(Goodman & Rafikov 2001)

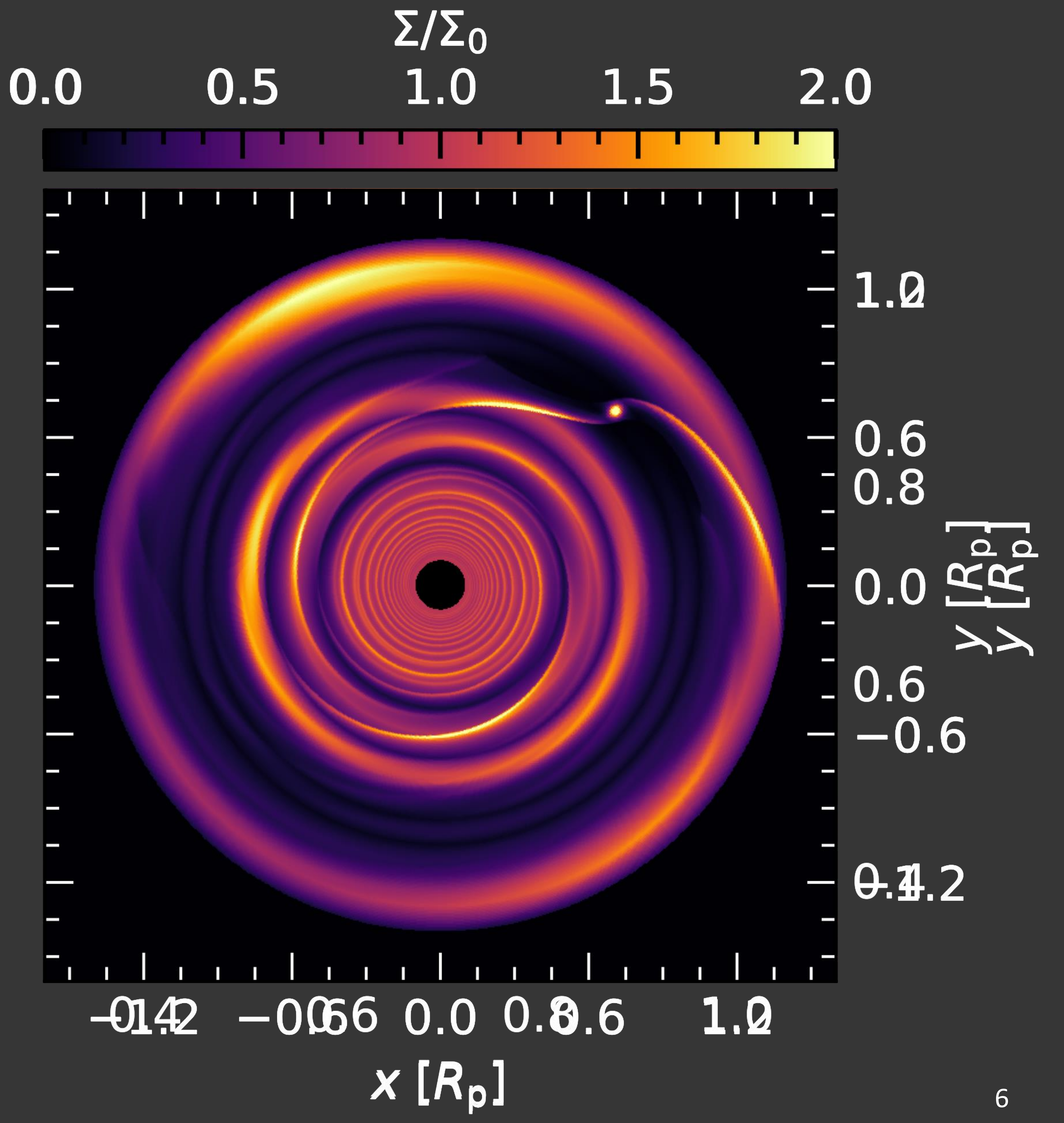
Planets as the cause of substructure

1. Planet launches spiral arms
   (Ogilvie & Lubow 2002)

2. Spirals steepen as they go
   → shocks! (Rafikov 2001)

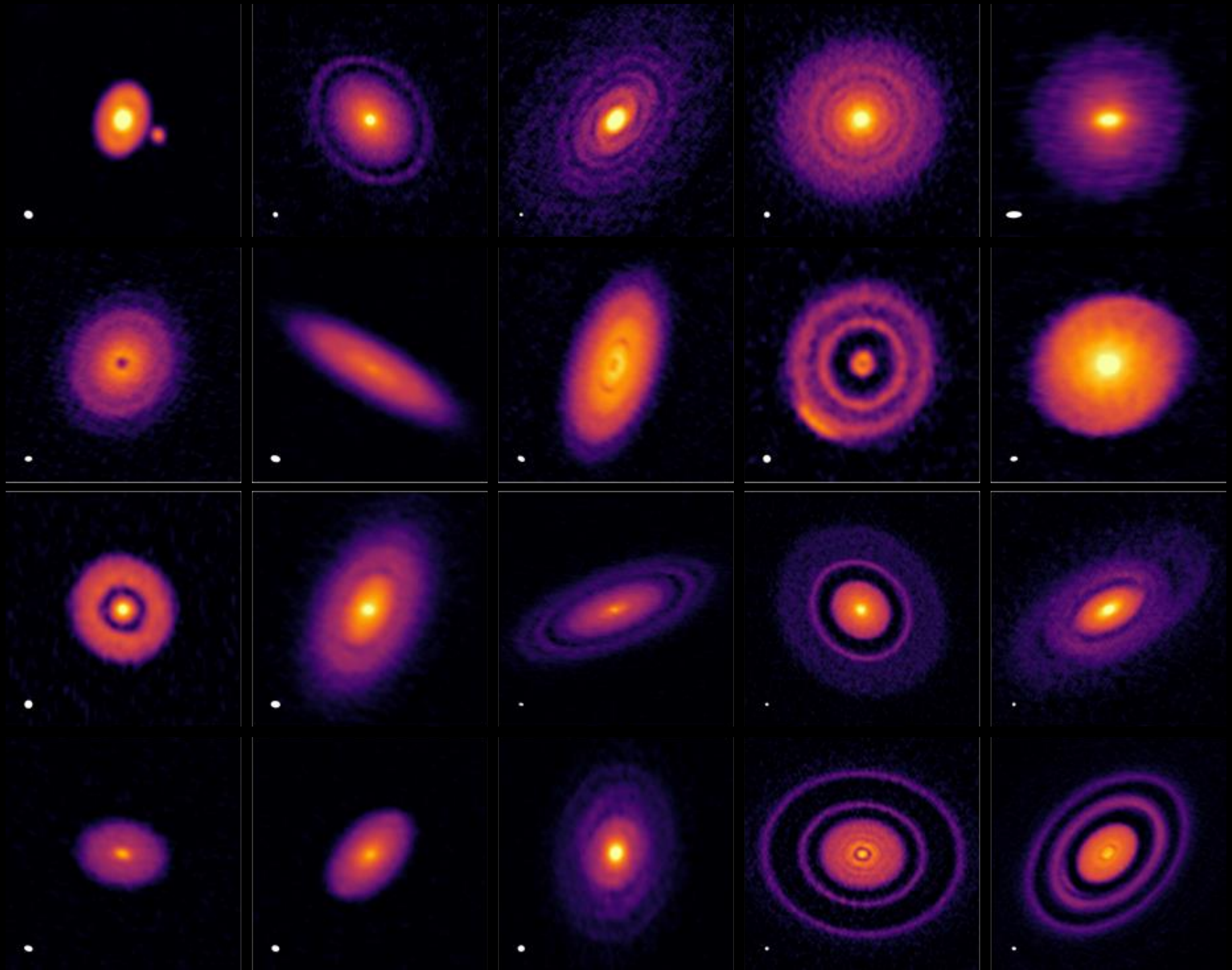
3. Local angular momentum deposition
   → gap opening!

4. Repeat for secondary/tertiary spirals…



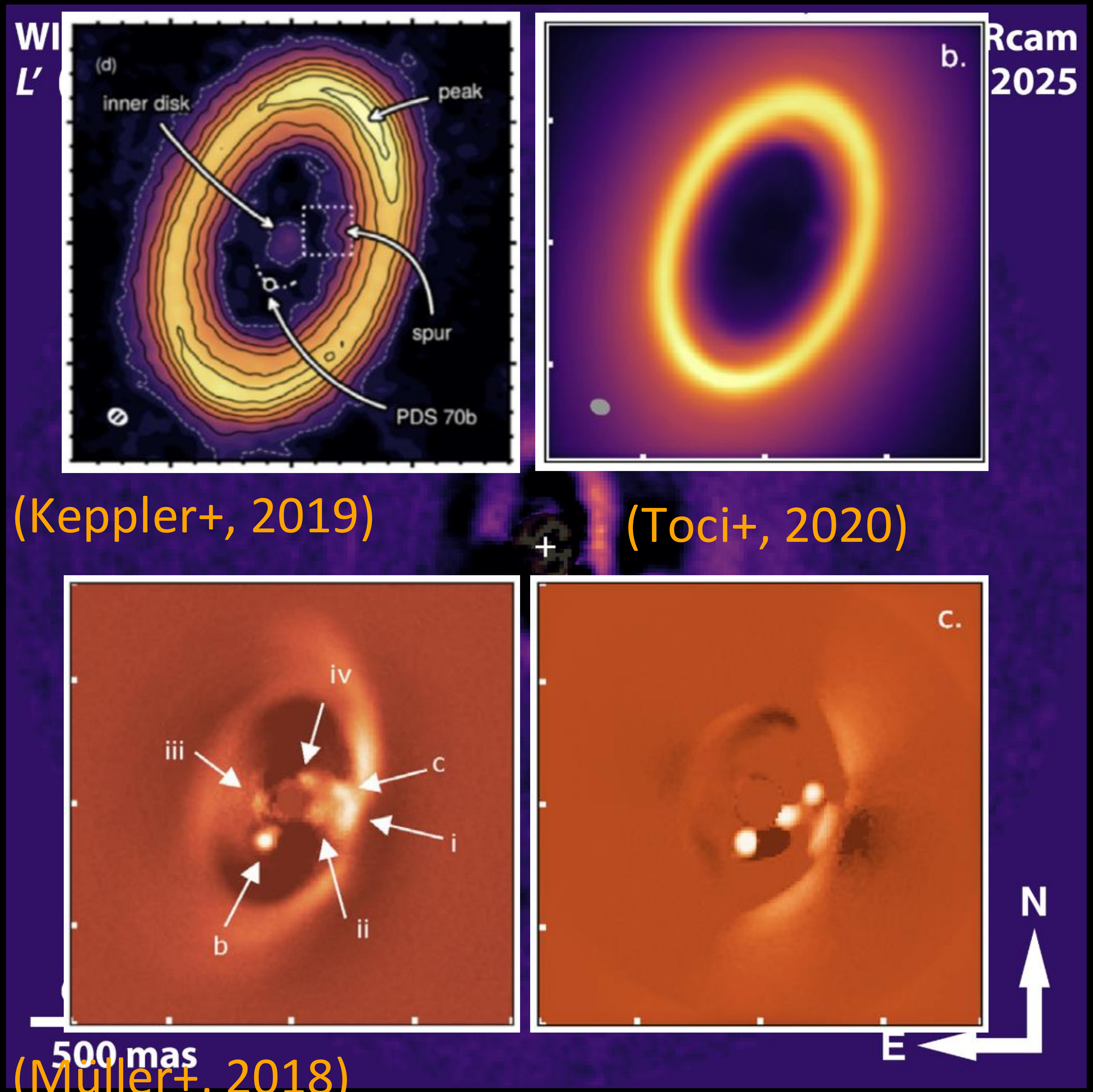
Could (some of) these be planets?

(DSHARP survey, Andrews+ 2018)



Models match observations!
We've seen planet gaps!
We've seen planets live!

Observations | Simulations



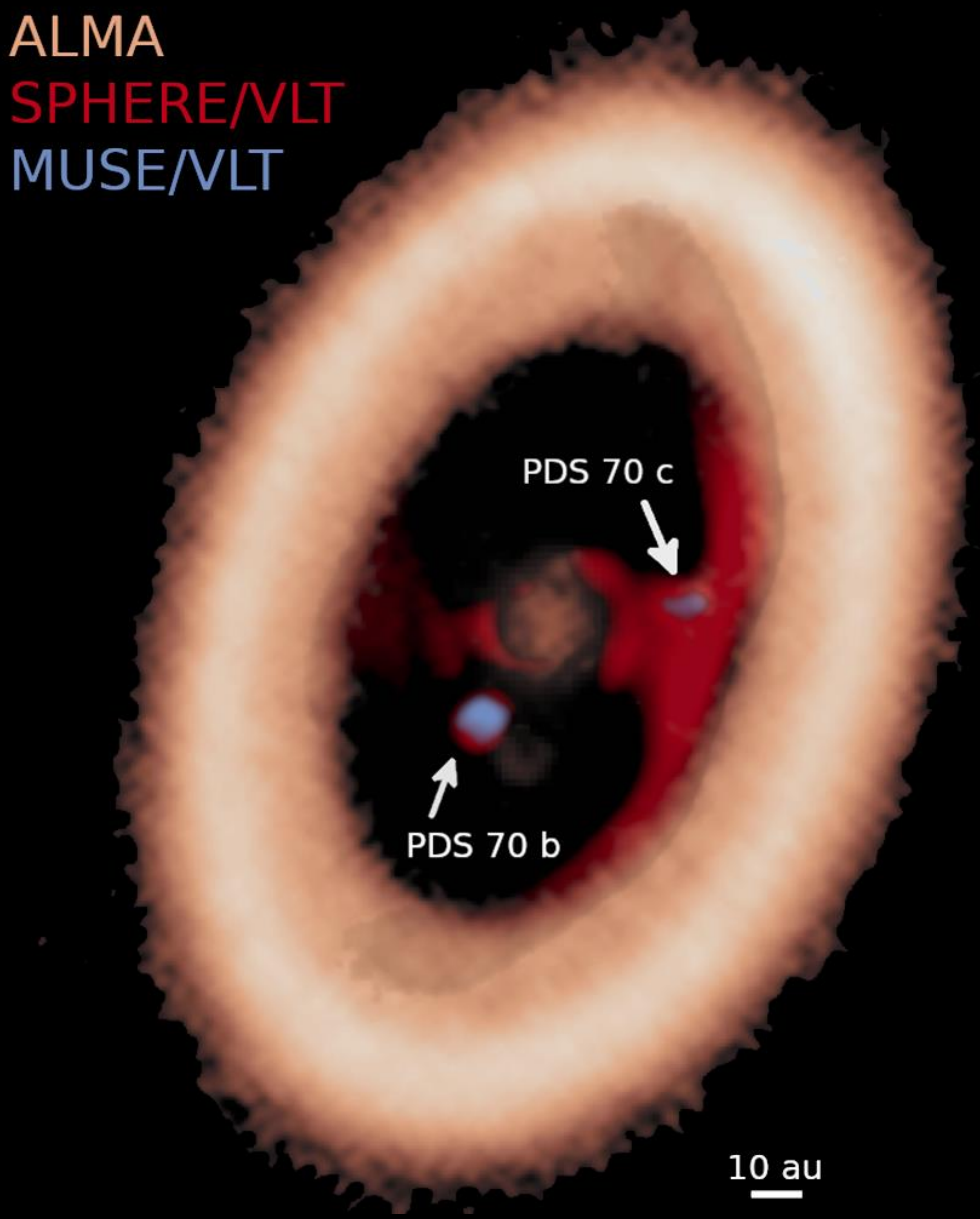
(Keppler+, 2019)

(Toci+, 2020)

(Müller+, 2018)

(van Capelleveen+ '25; Close+ '25)

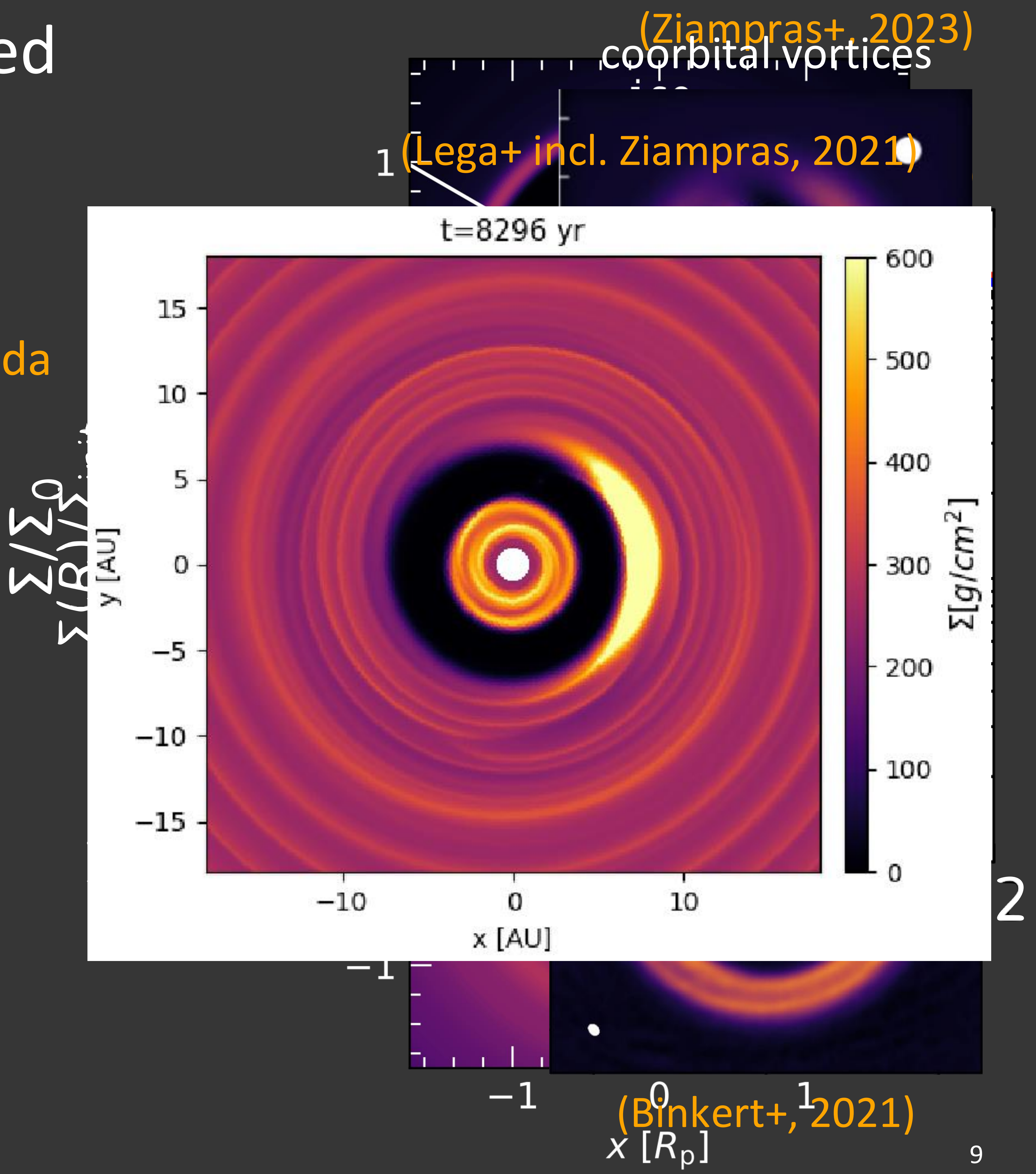
(See also Bae+, 2019)



(Keppler+ '18; Haffert+ '19; Benisty+ '19)

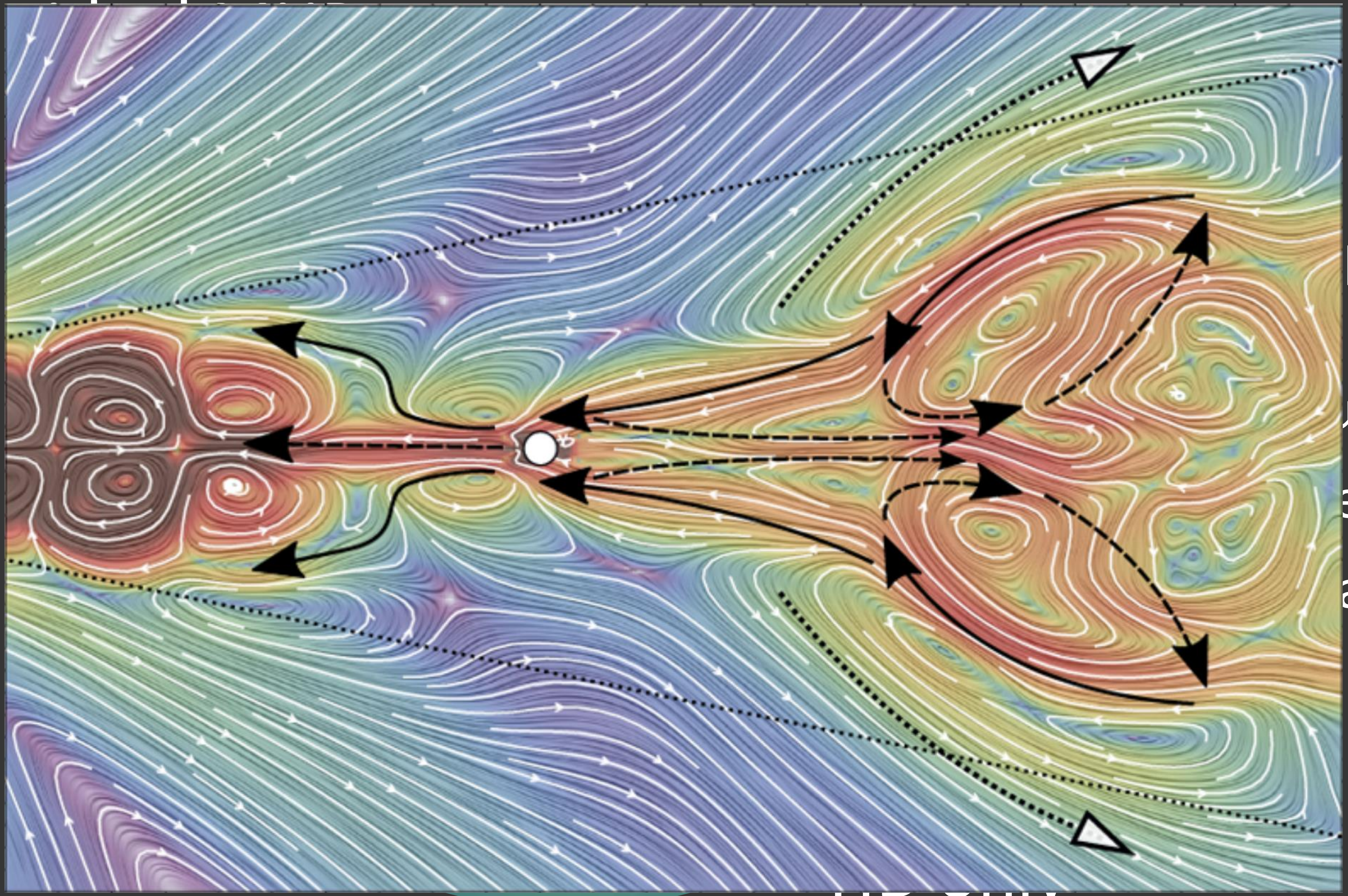
… but reality is much more complicated

- Radiative cooling "focuses" planetary torques (Miranda & Rafikov '20a,b, Ziampras+ ’23, '25c)
- Non-ideal MHD processes can promote gap opening (Aoyama & Bai '23; Hu+ '25)
- Turbulent diffusion decides gap edge stability (Rometsch, Z+ '20; Lega+ '21; Hammer & Lin '23)
- Dust–gas dynamics can drive additional features (Binkert+ '21, '23; Ziampras+ '25a)



Recent developments: radiation/non-ideal MHD models

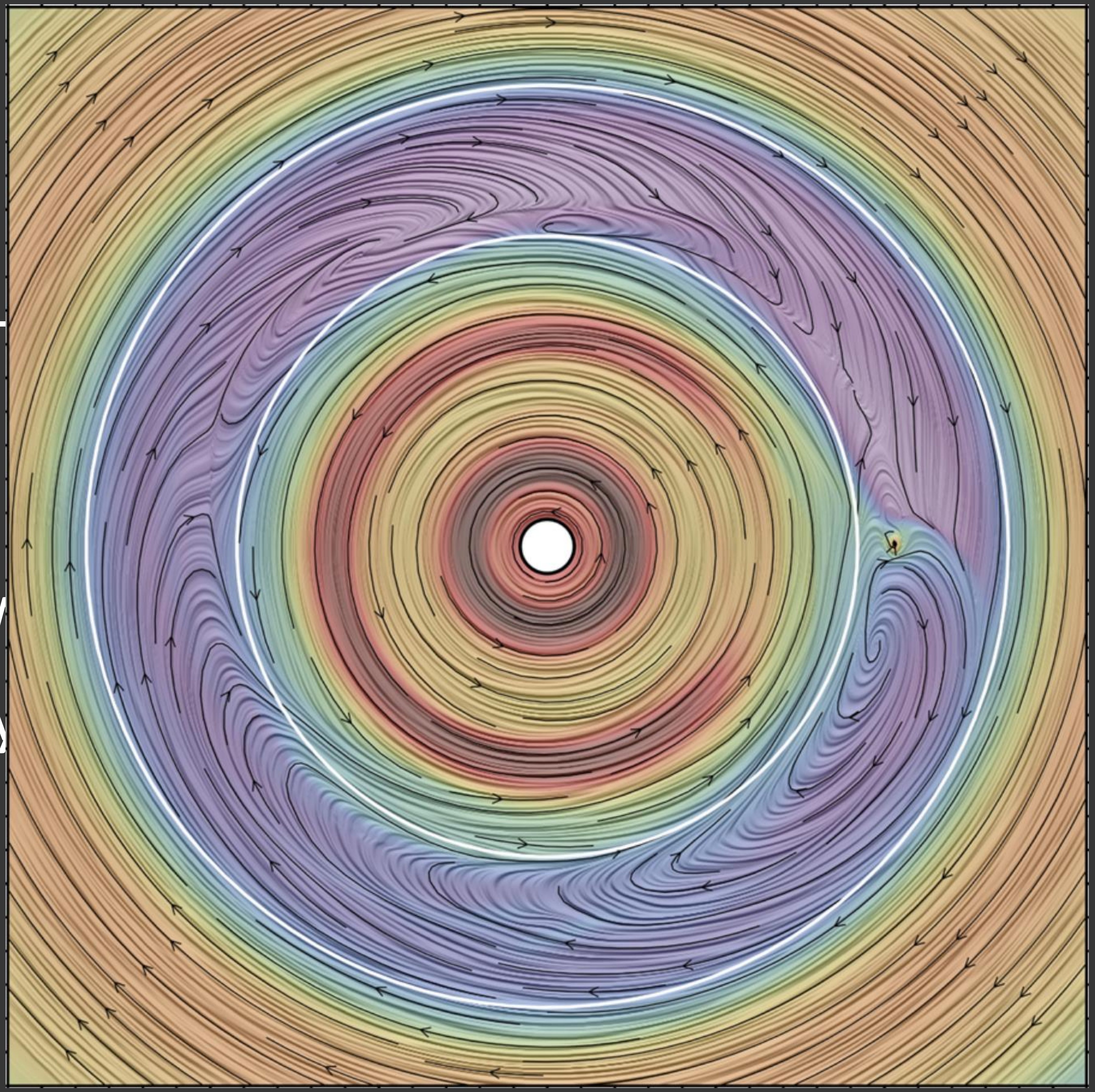
Complex 3D flows, accretion channels, and winds



(Cilibrasi+ 2023)

(Wafflard-Fernandez+ 2023)

Non-ideal MHD quenches MRI



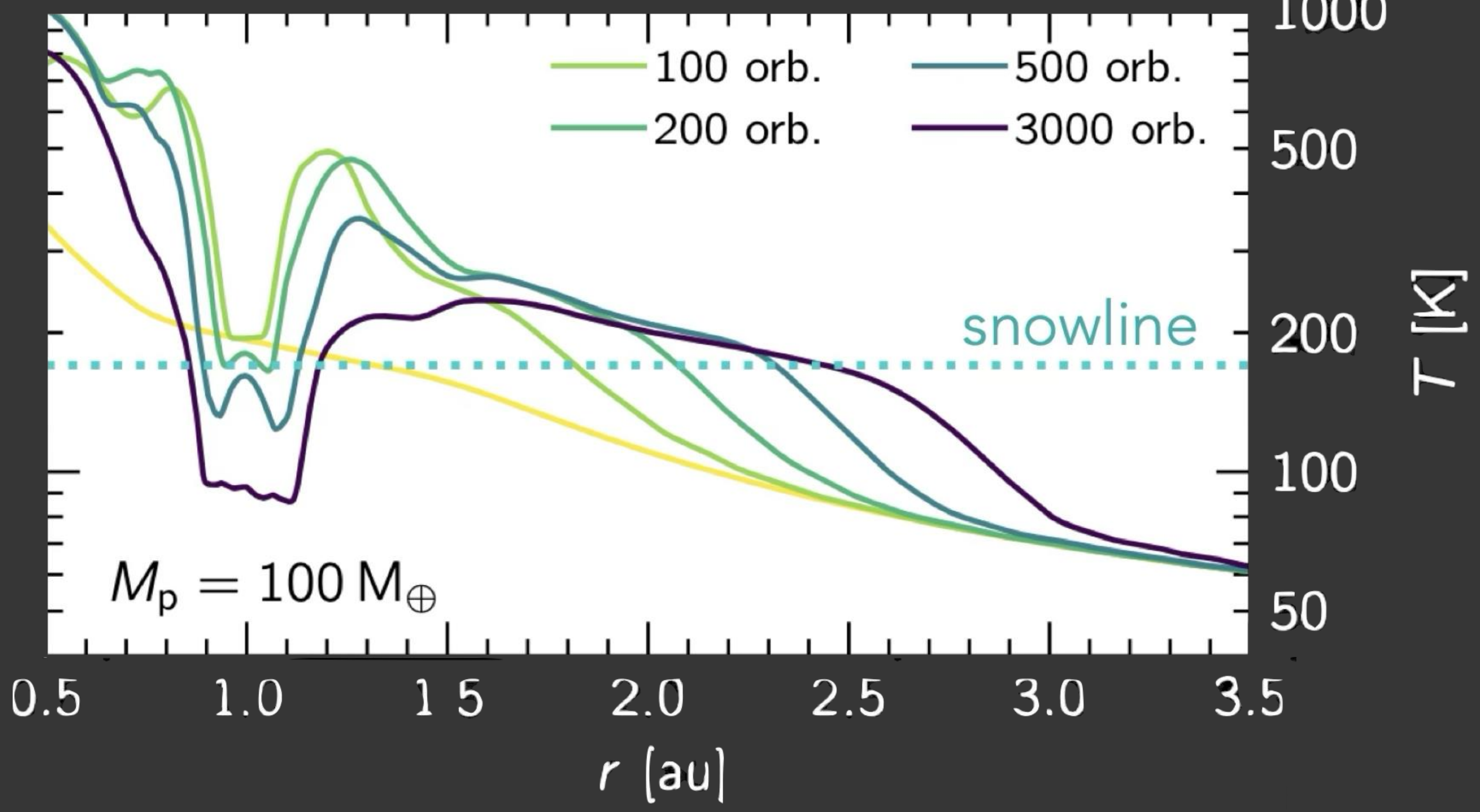
(Wafflard-Fernandez & Lesur 2025)

(On 3D flows, see also Morbidelli+ 2014; Fung+ 2014; Szulagyi+ 2021)

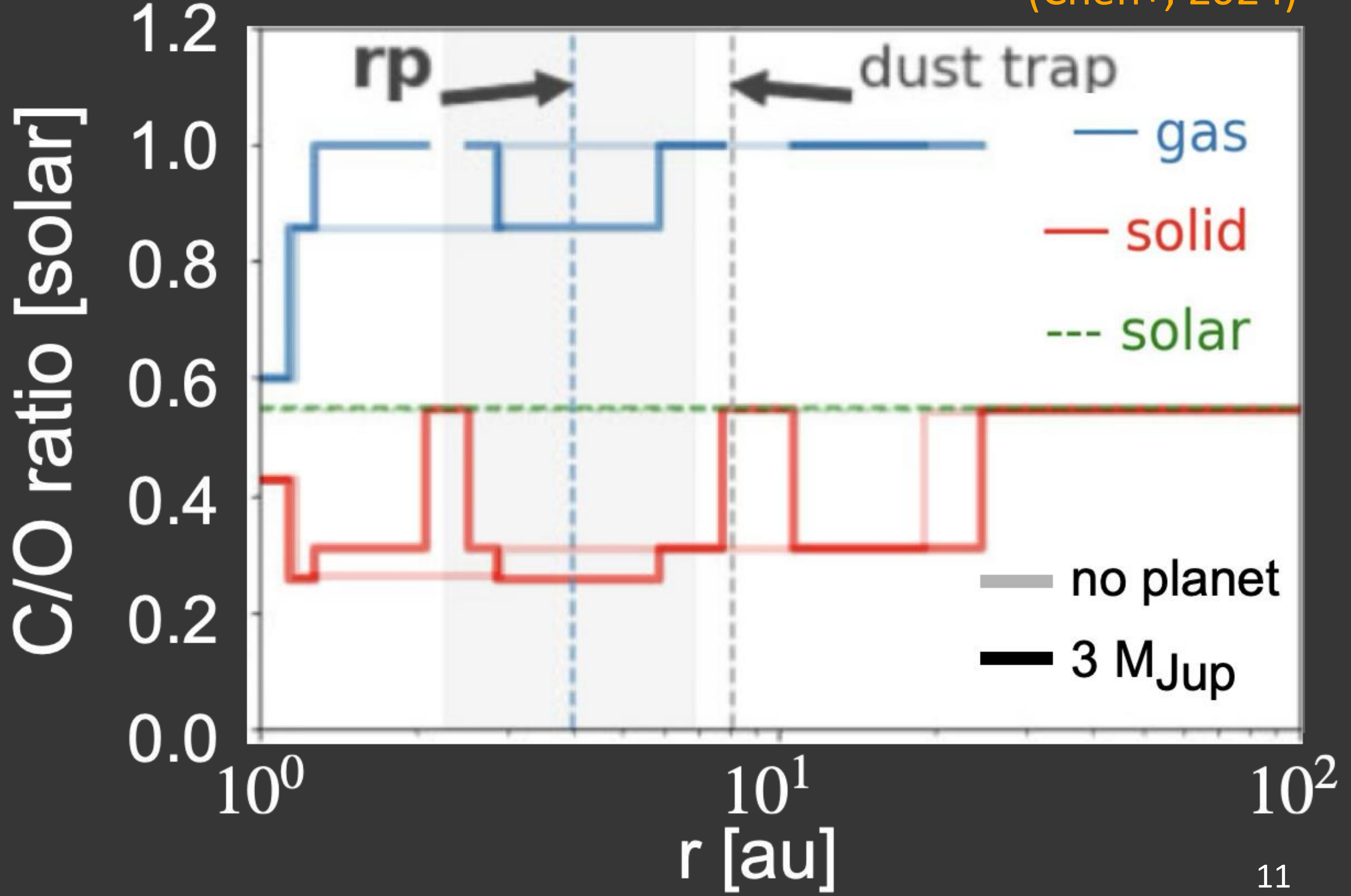
Changes in chemistry due to giant planets

- Spiral shocks heat up the disk (Rafikov ’16; Ziampras+ '20, Ono+ ’25; Okuzumi+ '25)
- Combination of gap opening, shock heating, and shadows (Chen+ ’24; Akansoy+ '25)
  → multiple snowlines, changes in gas composition!

(Ziampras+, 2020)



(Chen+, 2024)



The takeaways, part I

Giant planets sculpt their disk

- they carve gaps that promote grain growth and create observable substructure
- their spiral shocks can heat up the gas and influence the disk chemistry

Gap opening is sensitive to the underlying physics

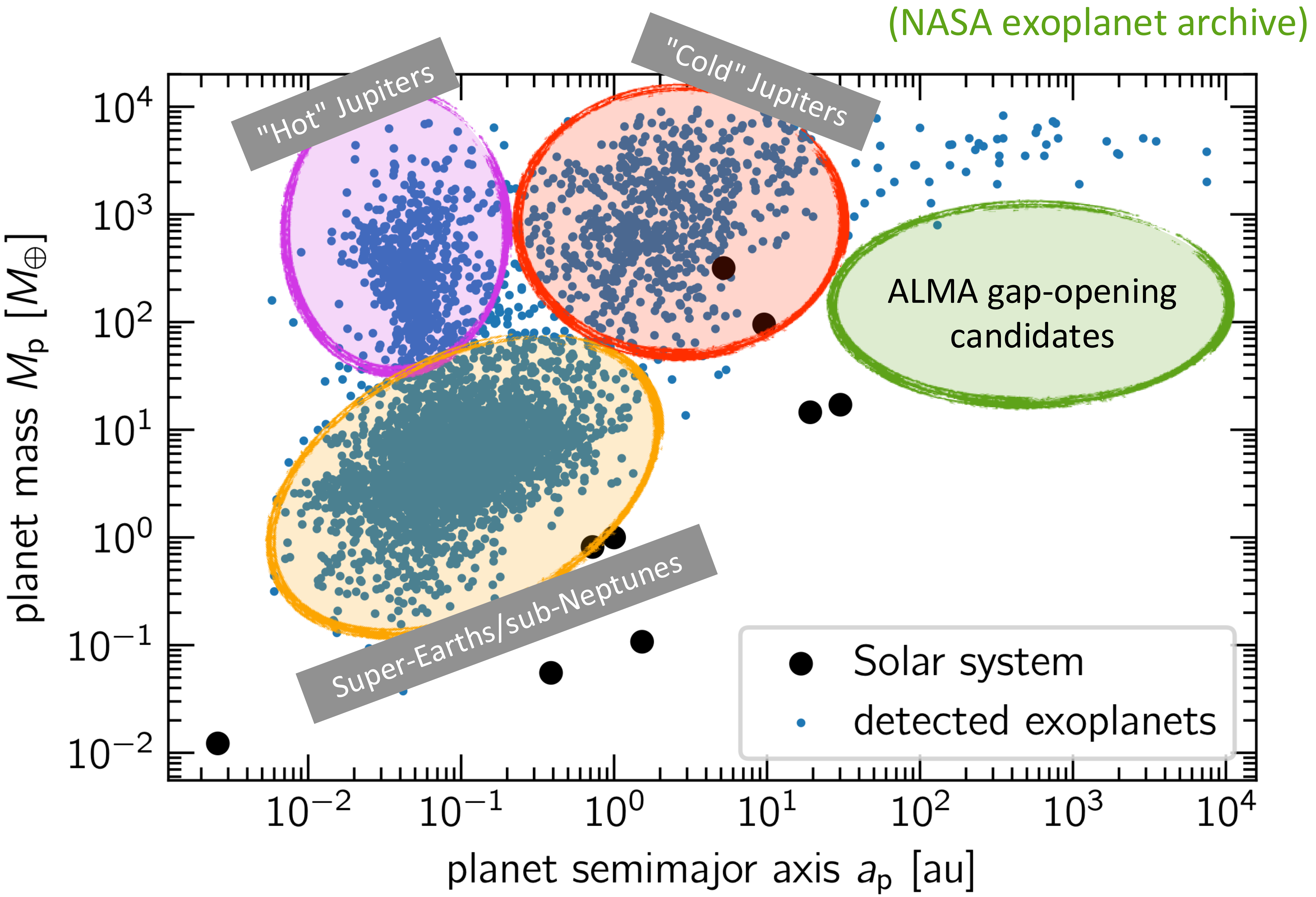
- radiative cooling affects the shape and number of gaps
- MHD can promote or hinder gap opening depending on the disk conditions
- dust–gas dynamics can produce unexpected features

Current models can reproduce observations

- e.g.: multiple giants in PDS 70 → dust substructure, scattered light emission
- More work being done on gas kinematics!

DISK → PLANET:
GIANT PLANET MIGRATION

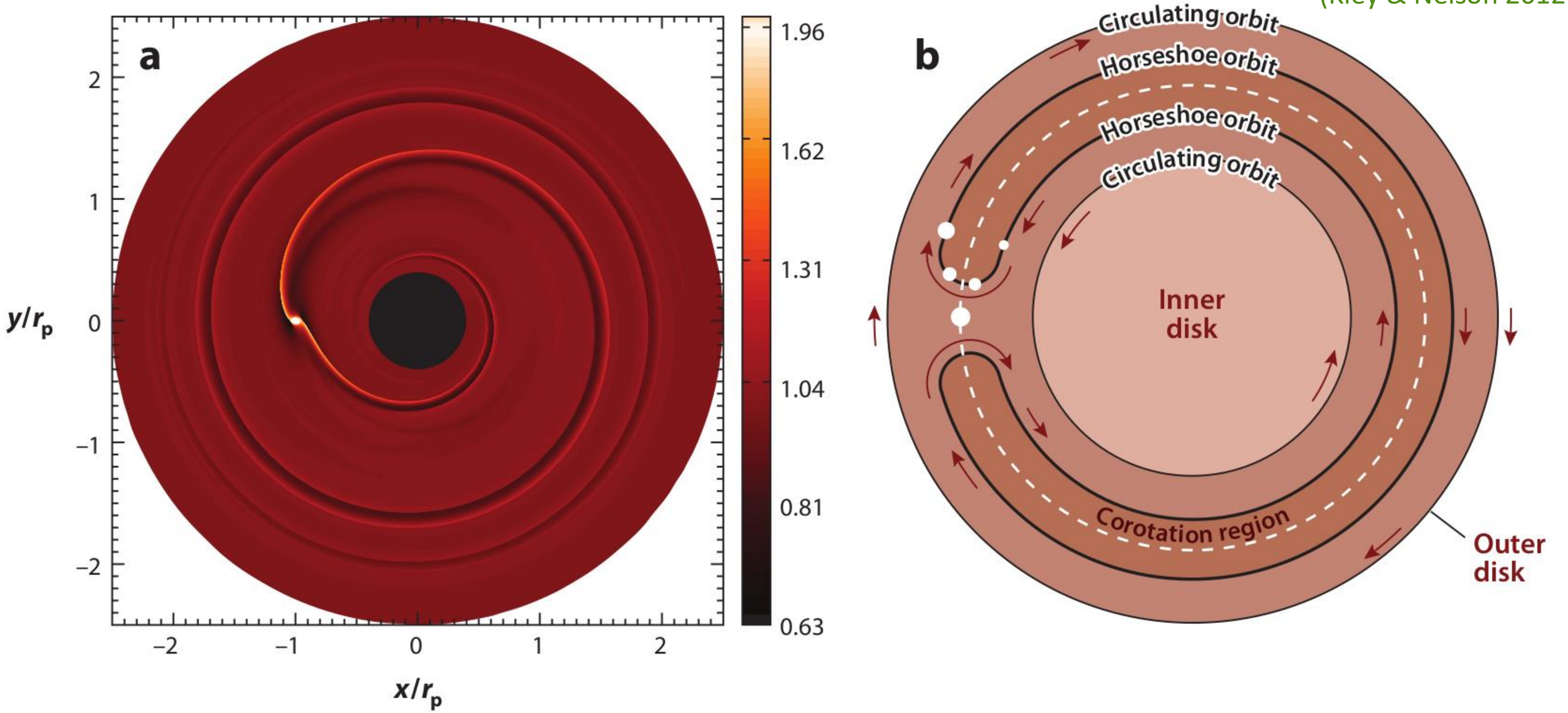
More than 6000 exoplanets!



How do we populate the groups involving massive planets? → planet migration!

Torques acting on a planet

(Kley & Nelson 2012)



Lindblad torque (inwards) vs corotation torque (outwards)

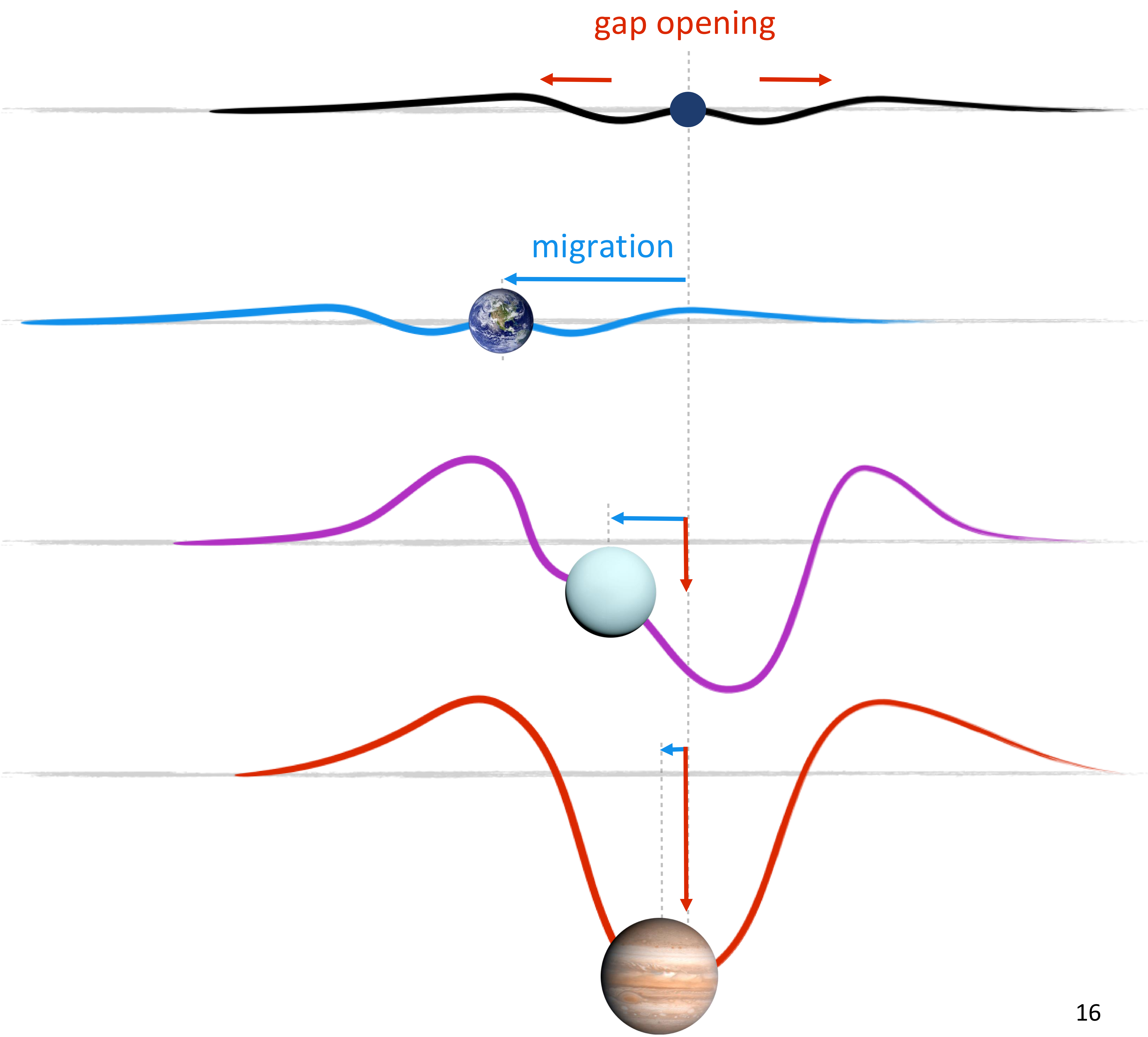
(See also Goldreich & Tremaine 1978, 1980; Lin+ 1986; Ward 1997)

Migration regimes

weak effects on the disk
("type I regime")

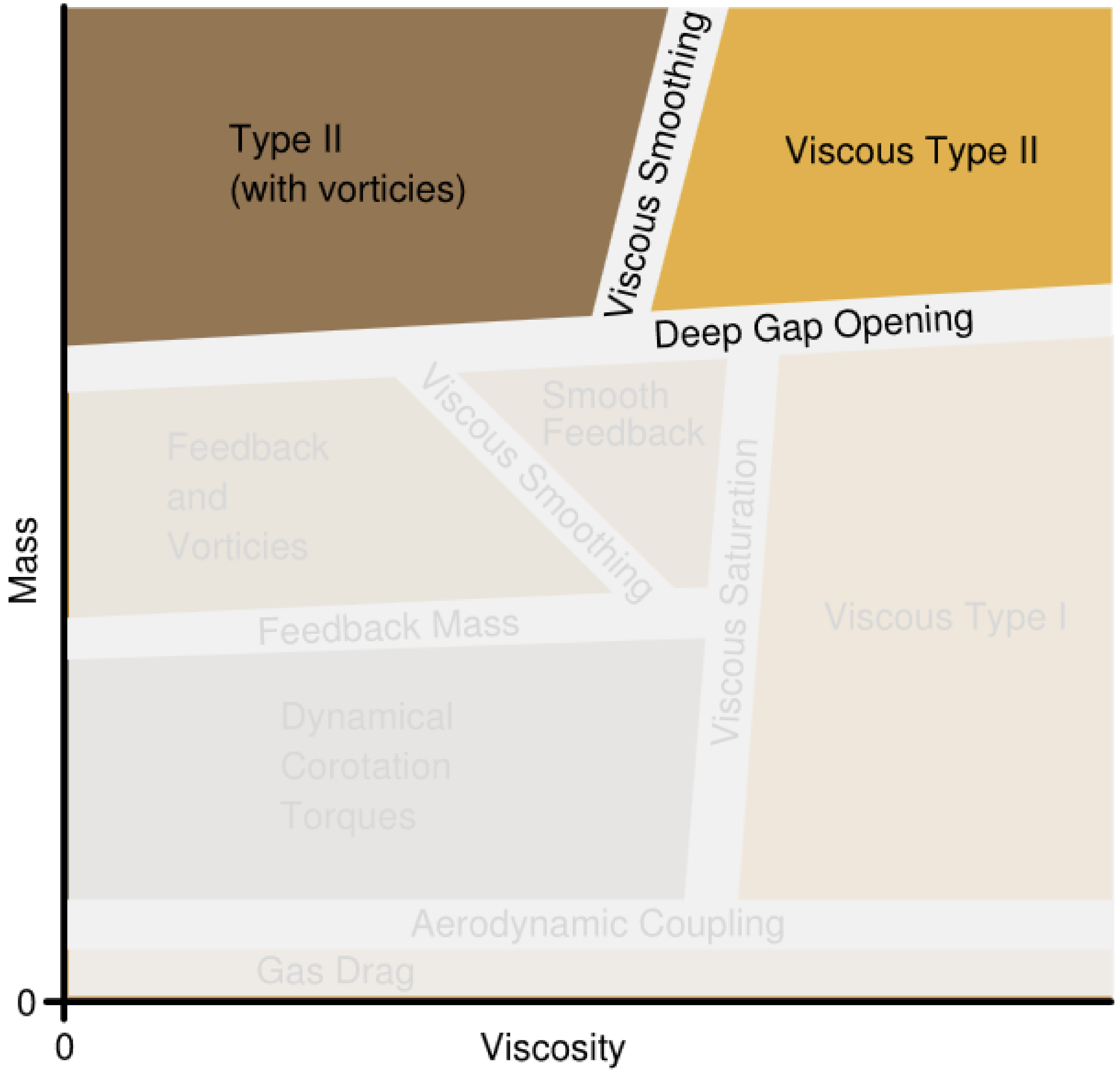
modification of local disk
("feedback regime")

deep gap opening
("type II regime")



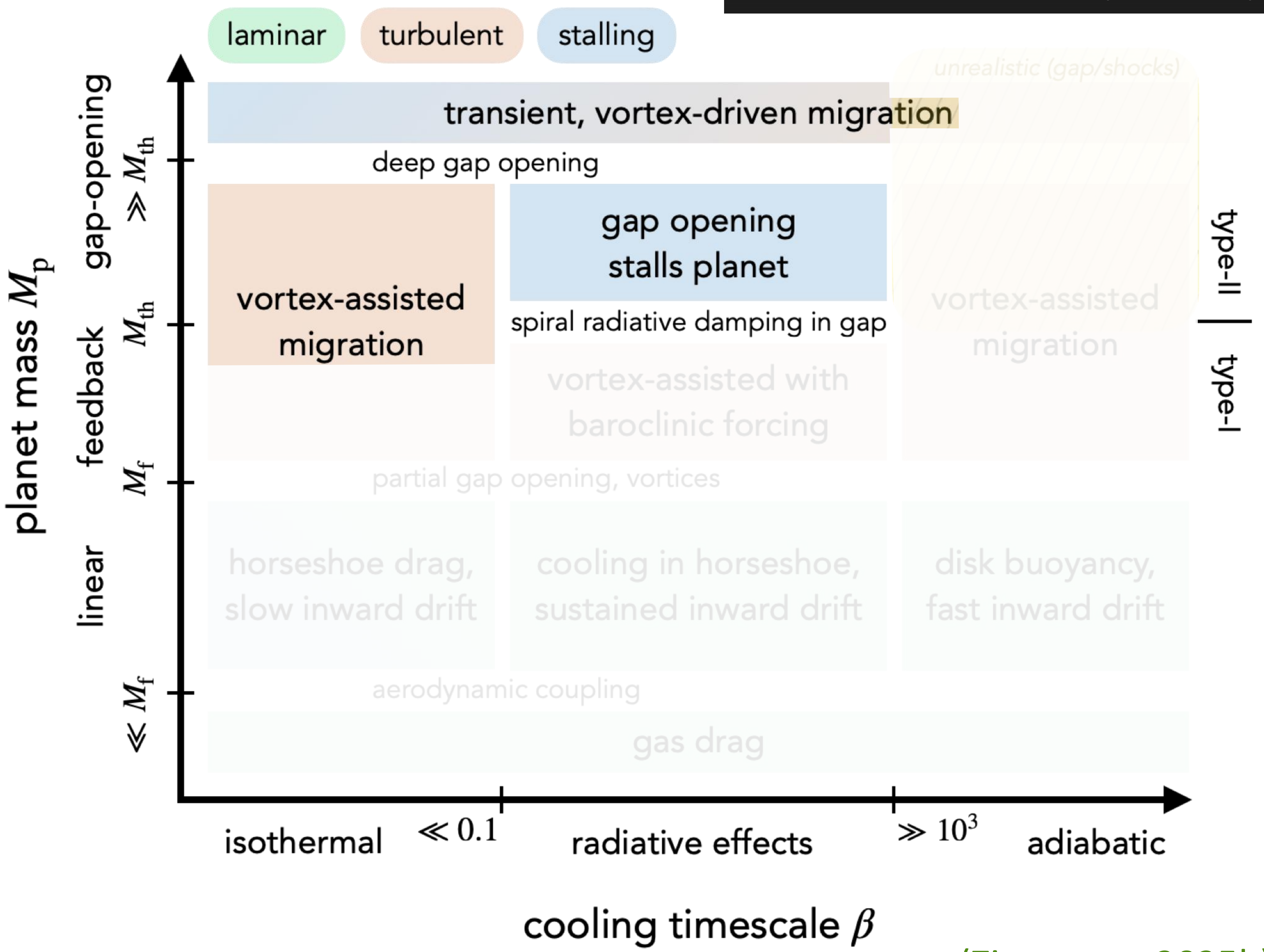
Maps of the different regimes of planet migration

ISOTHERMAL LIMIT ($\beta \to 0$)



(McNally+ 2019, Paardekooper+ 2023 [PPVII])

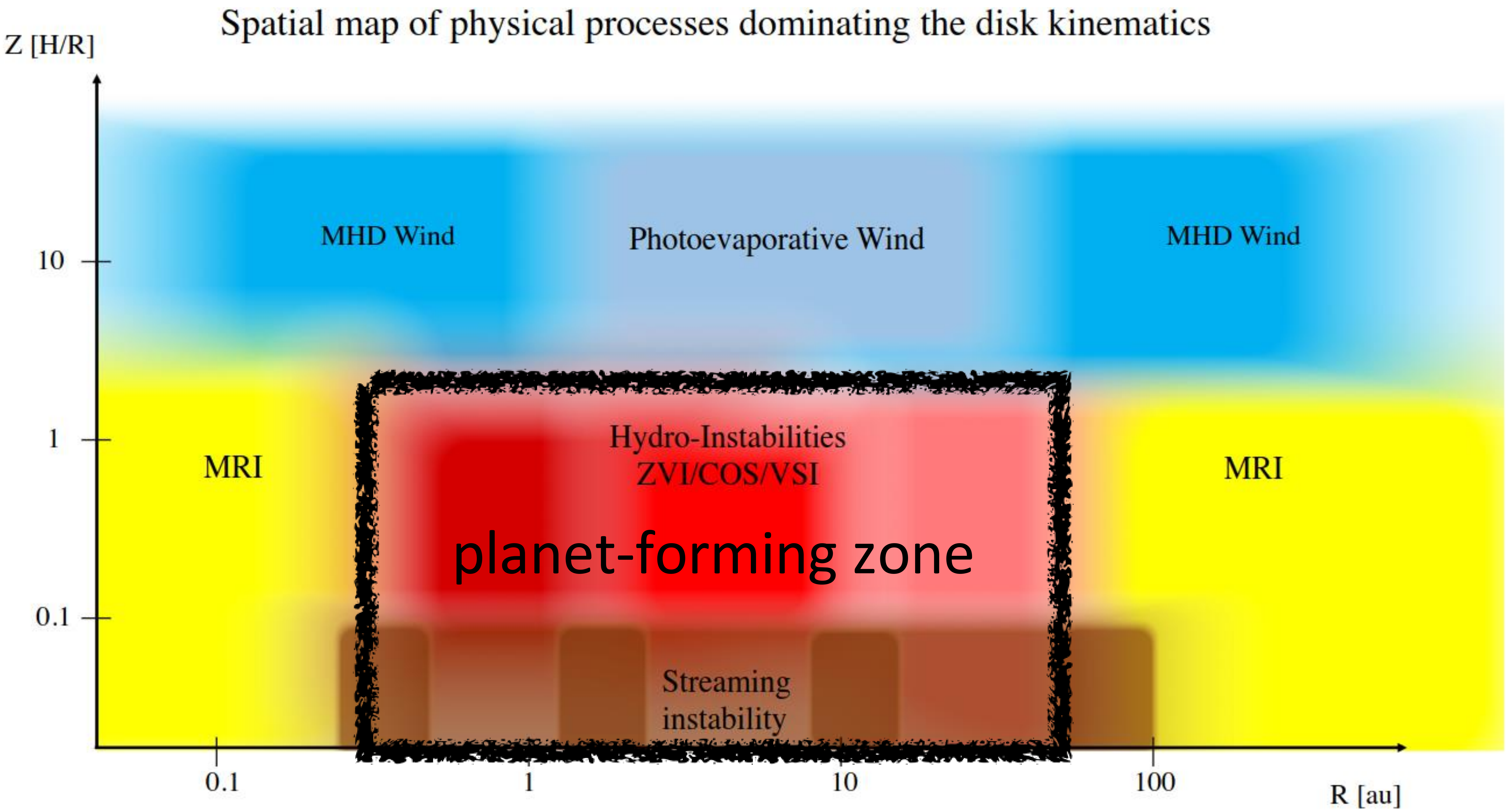
INVISCID LIMIT ($\alpha \to 0$)



(Ziampras+ 2025b)

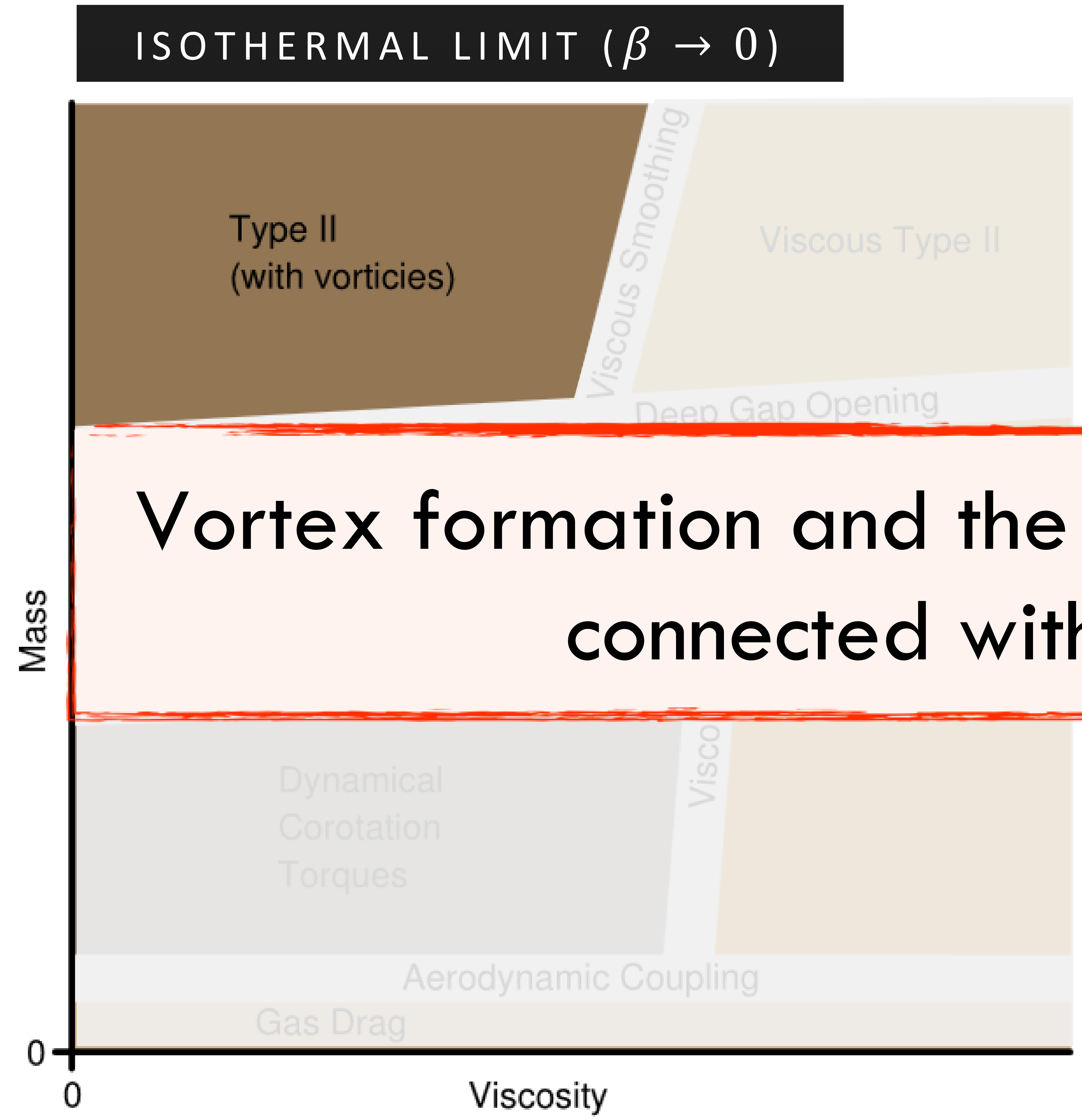
Turbulence is quite low in the bulk of the disk

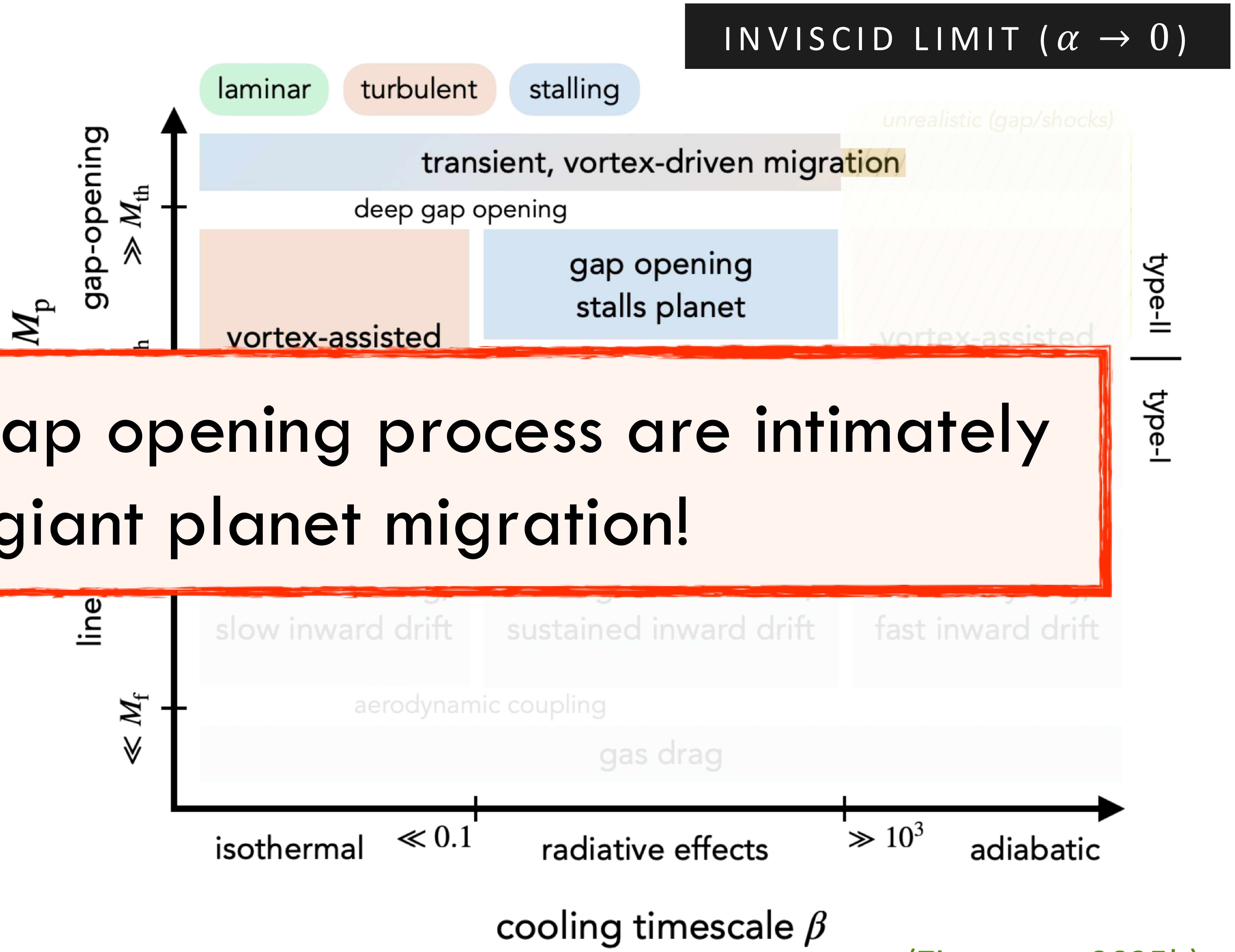
(Lesur+ 2023 [PPVII])



Observations (Pinte+ '16, Dullemond+ '18, Rosotti+ '23…) and modeling (Youdin & Johansen '07, Nelson+ '13, Bai & Stone '13...) suggest that disks are only weakly turbulent → low α regime

Maps of the different regimes of planet migration





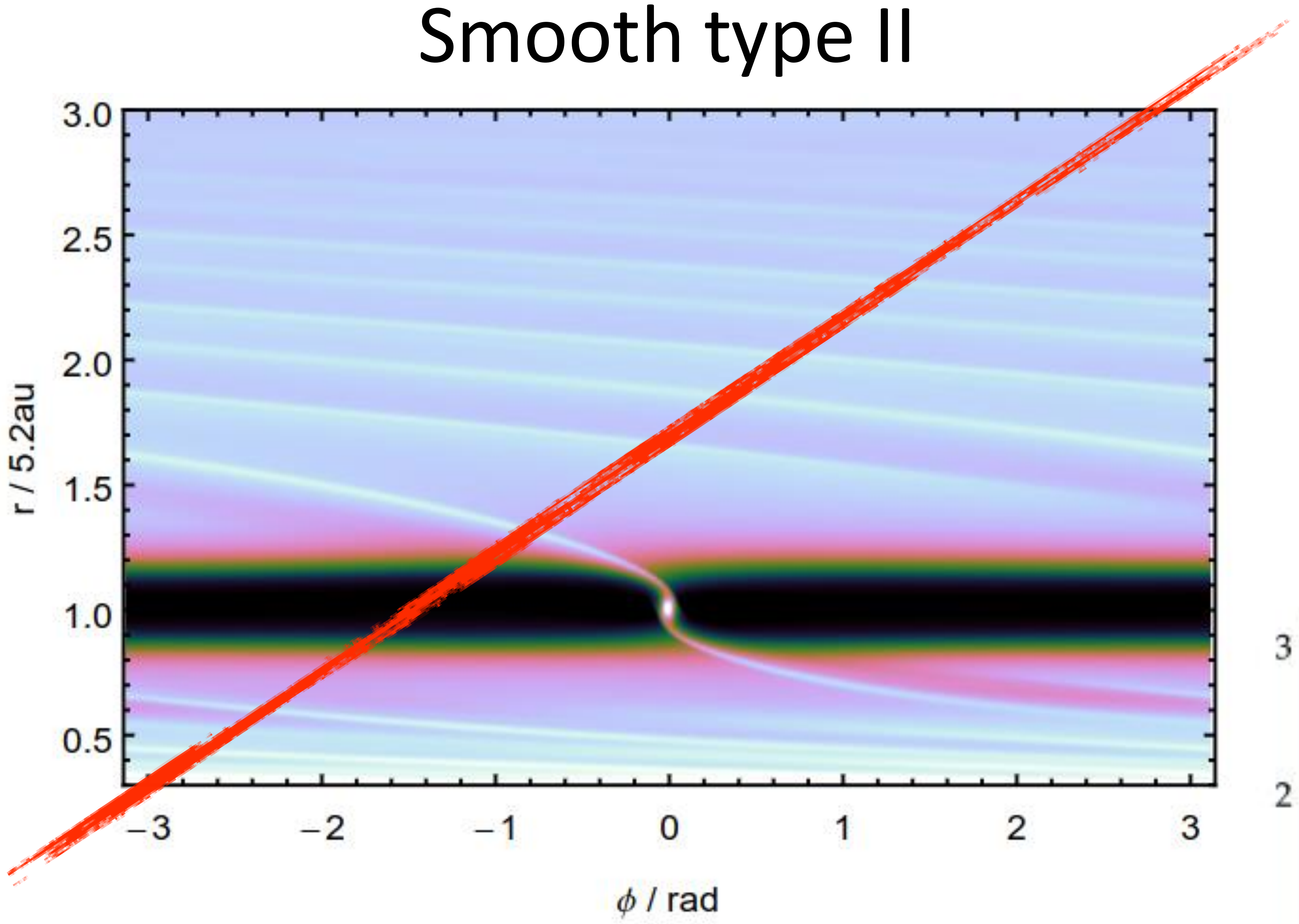
Vortex formation and the gap opening process are intimately connected with giant planet migration!

(Ziampras+ 2025b)

(McNally+ 2019, Paardekooper+ 2023 [PPVII])

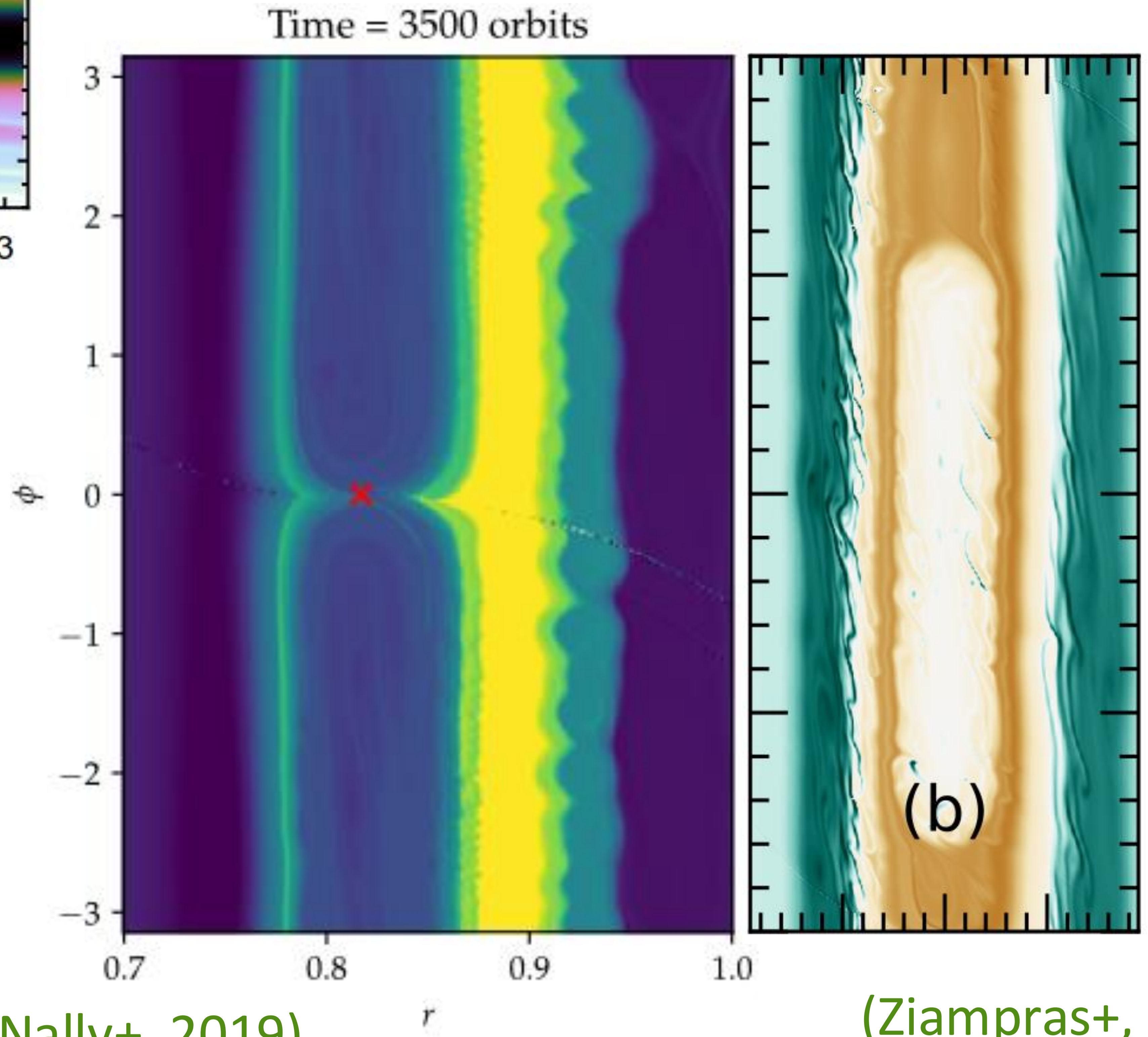
Planet migration likely looks more like this

Smooth type II



(Dürmann & Kley, 2015)

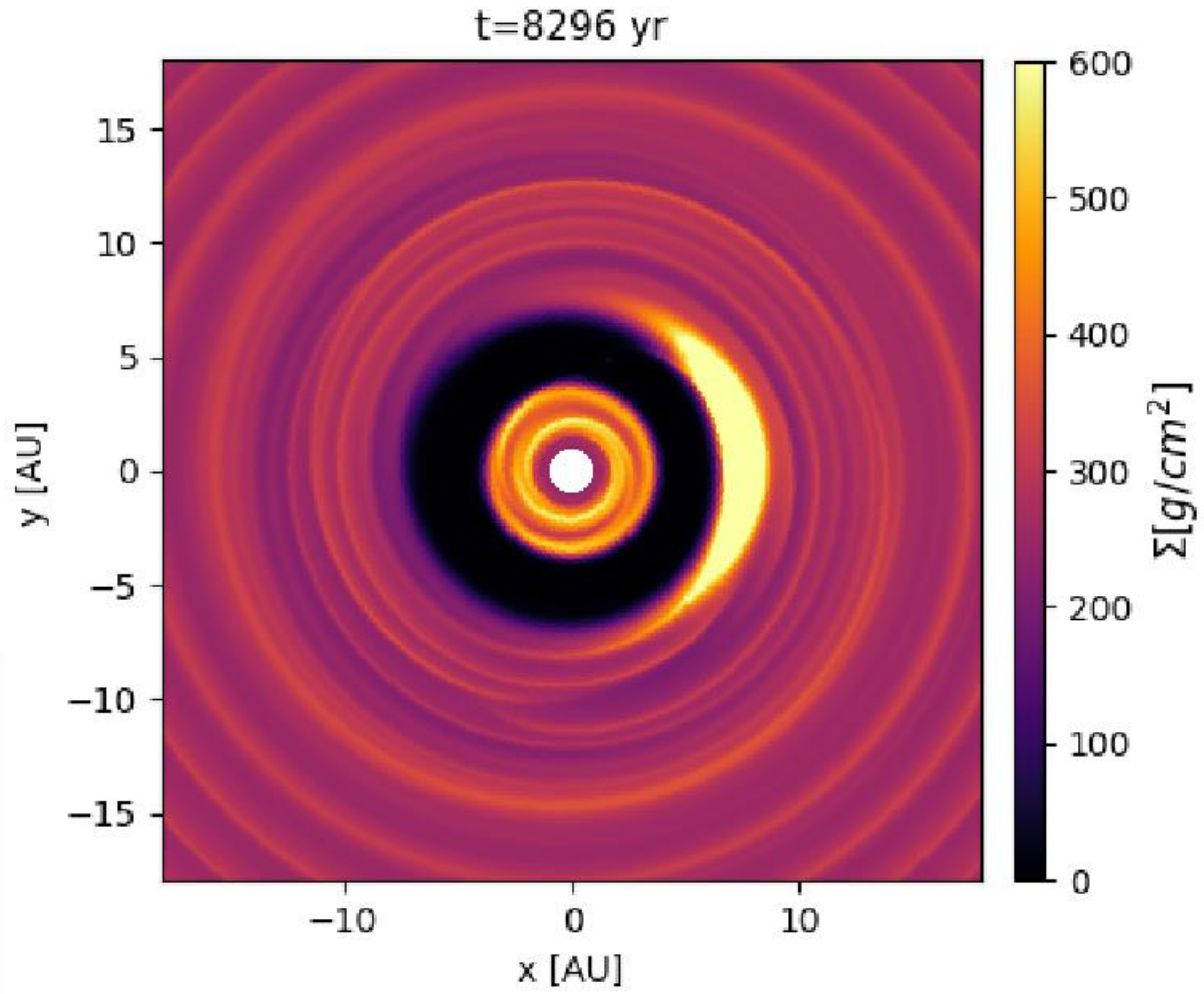
Feedback and vortices



(McNally+, 2019)

(Ziampras+, 2025)

Type II with vortices



(Lega+ incl. Ziampras, 2021)

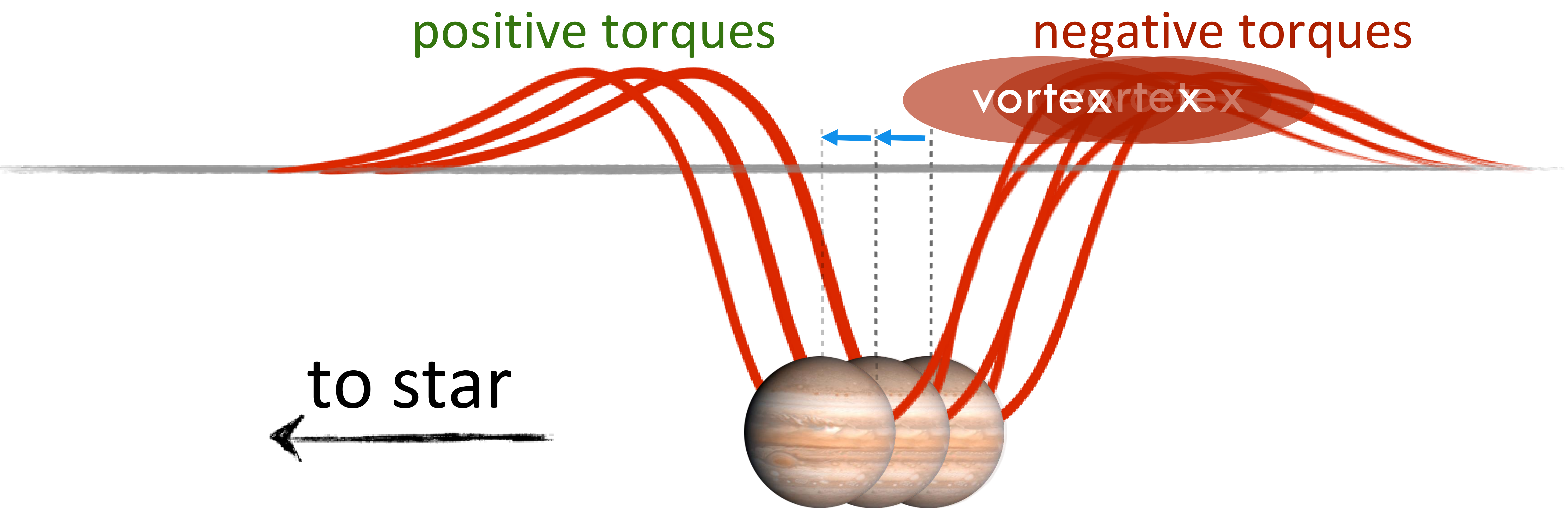
Beyond type-II: vortex-driven migration

The gap edge goes Rossby-wave unstable

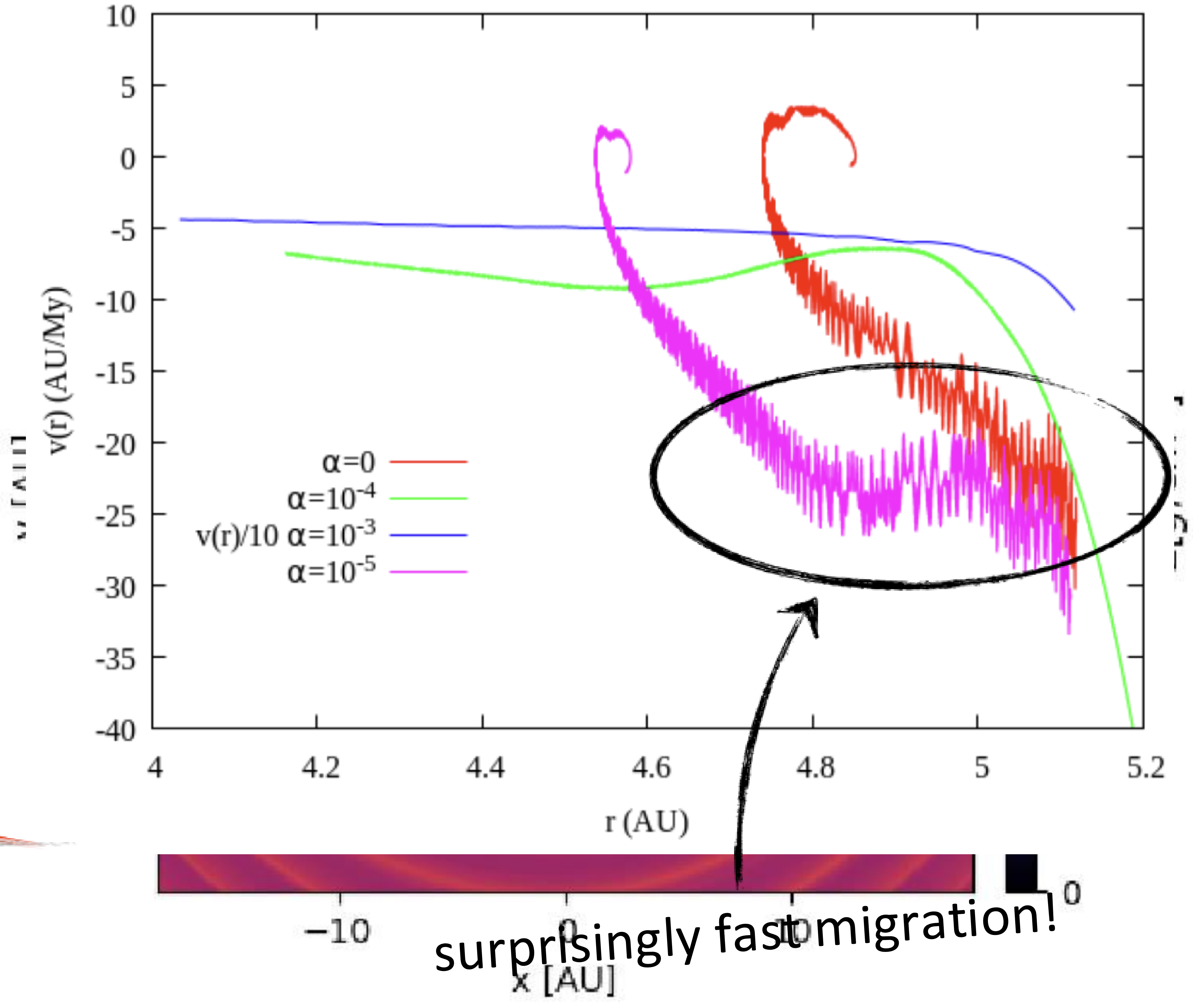
→ massive vortex forms!

→ vortex diffuses material inside the gap region

→ intermittent, *vortex-driven* migration



(Lega+ incl. Ziampras, 2021)



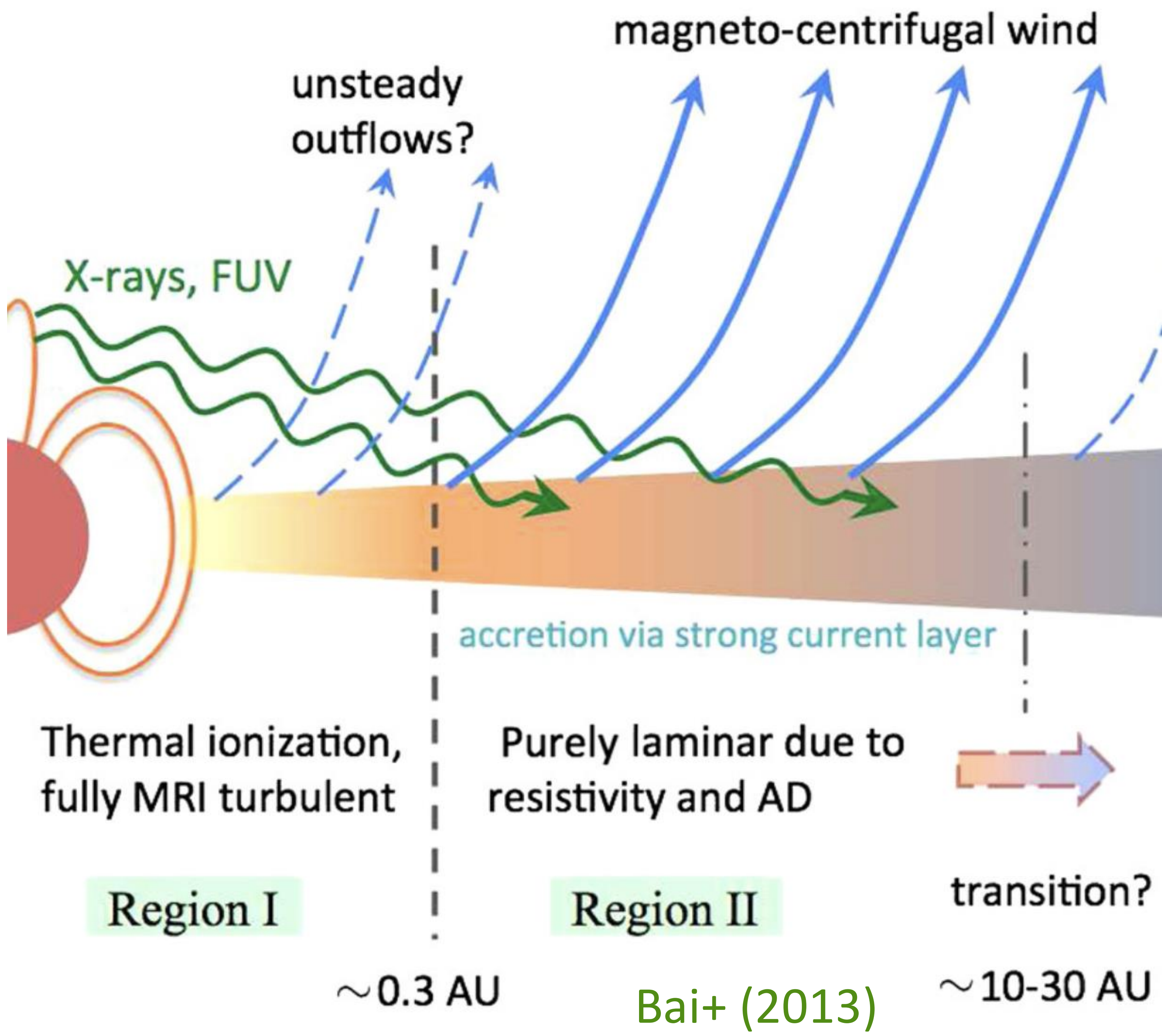
Beyond type-II: wind-driven migration

Wind-driven disks: a fast, surface accretion layer

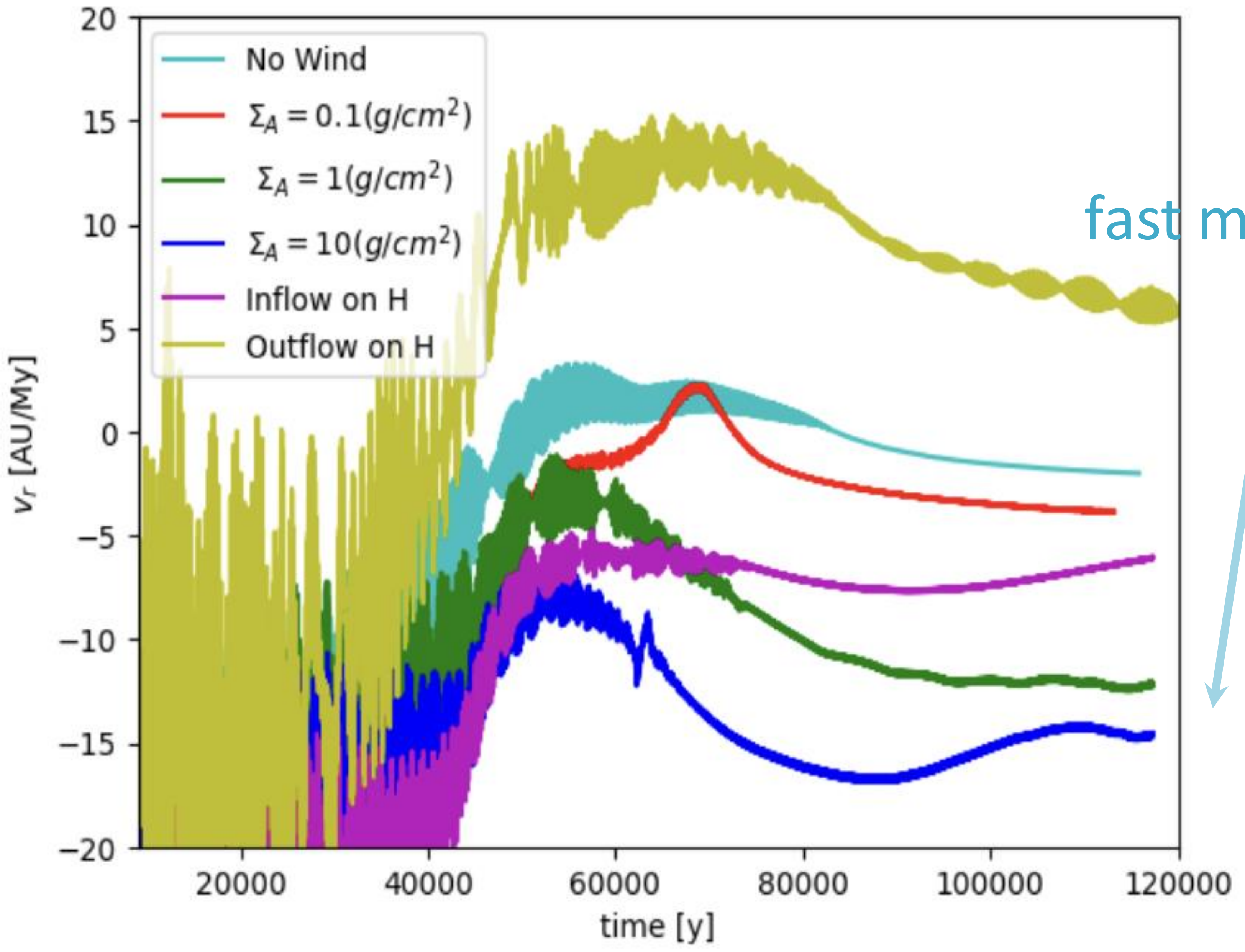
→ massive planets can intercept this flow

→ wind layer deposited on outer gap edge

→ sustained, *wind-driven* migration

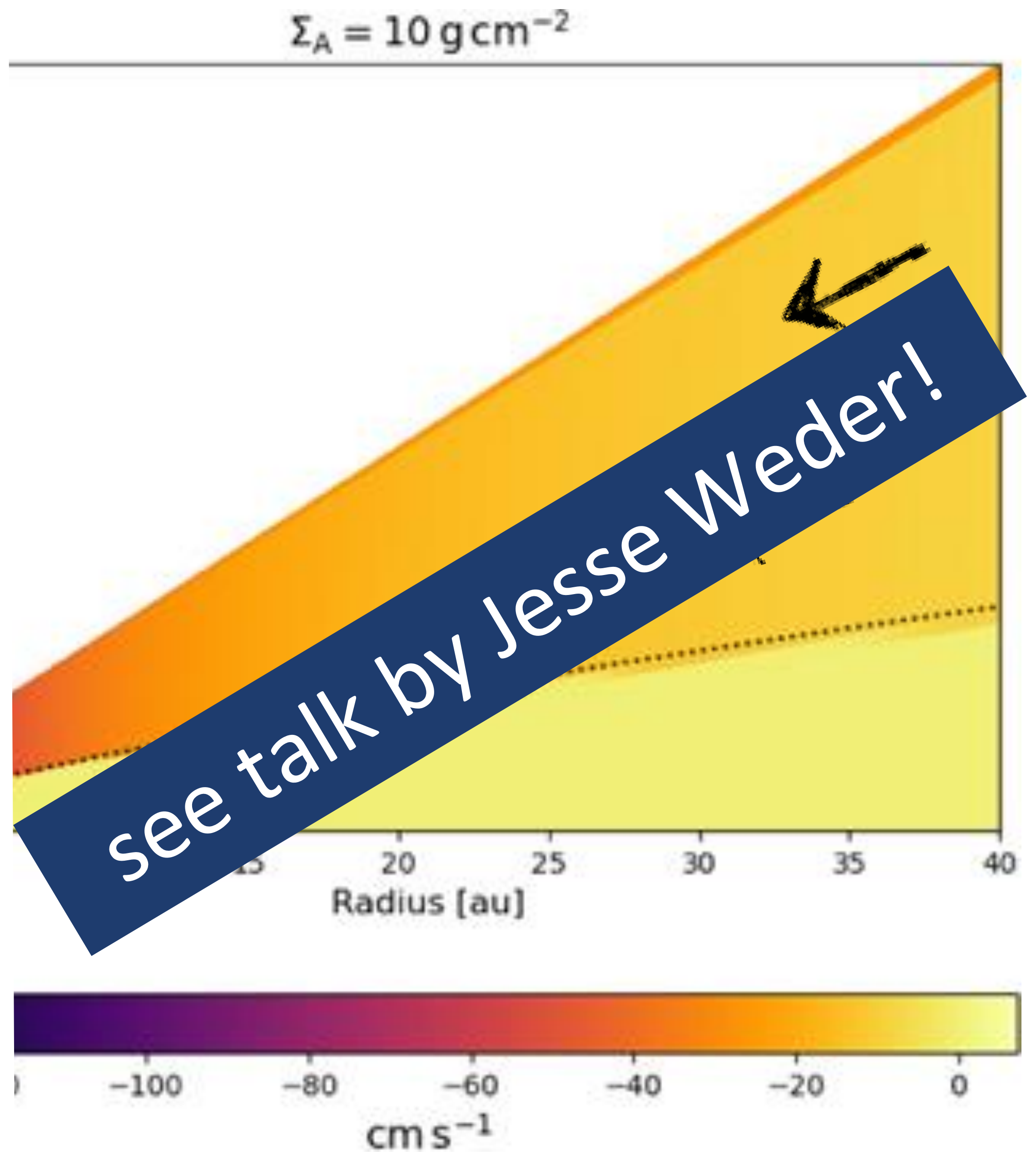


Bai+ (2013)



fast migration

Lega+ (2022), see also Nelson+ (2023), Kimmig+ (2020)



Non-ideal MHD: accretion + mass loss

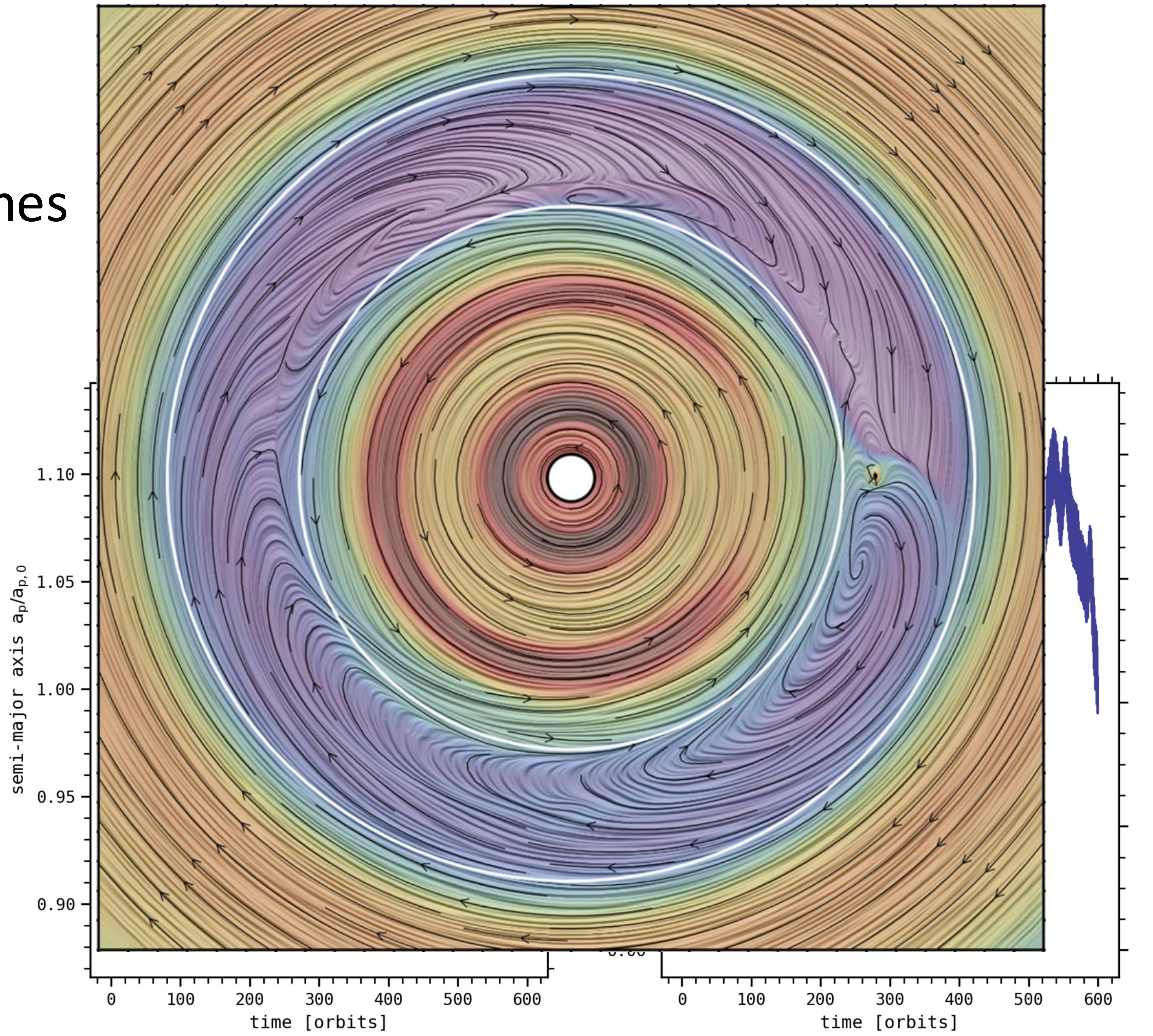
When including wind-powered mass loss, the gap becomes wider and strongly asymmetric:

→ empty outer Lindblad resonances: torque reversal

→ eccentricity growth near planet

→ outward migration possible!

⚠ more models must be run to validate this!



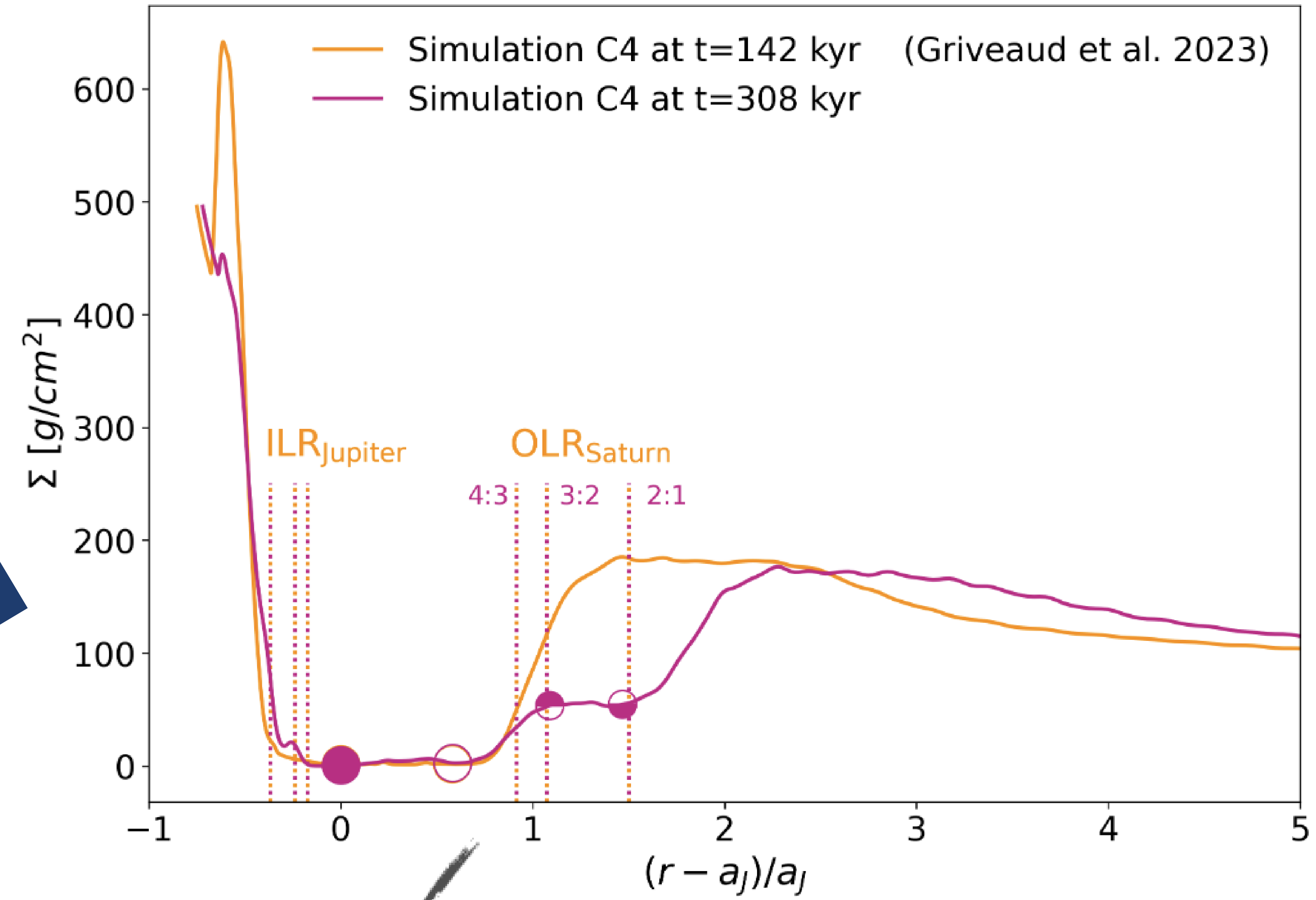
(Wafflard-Fernandez & Lesur 2025)

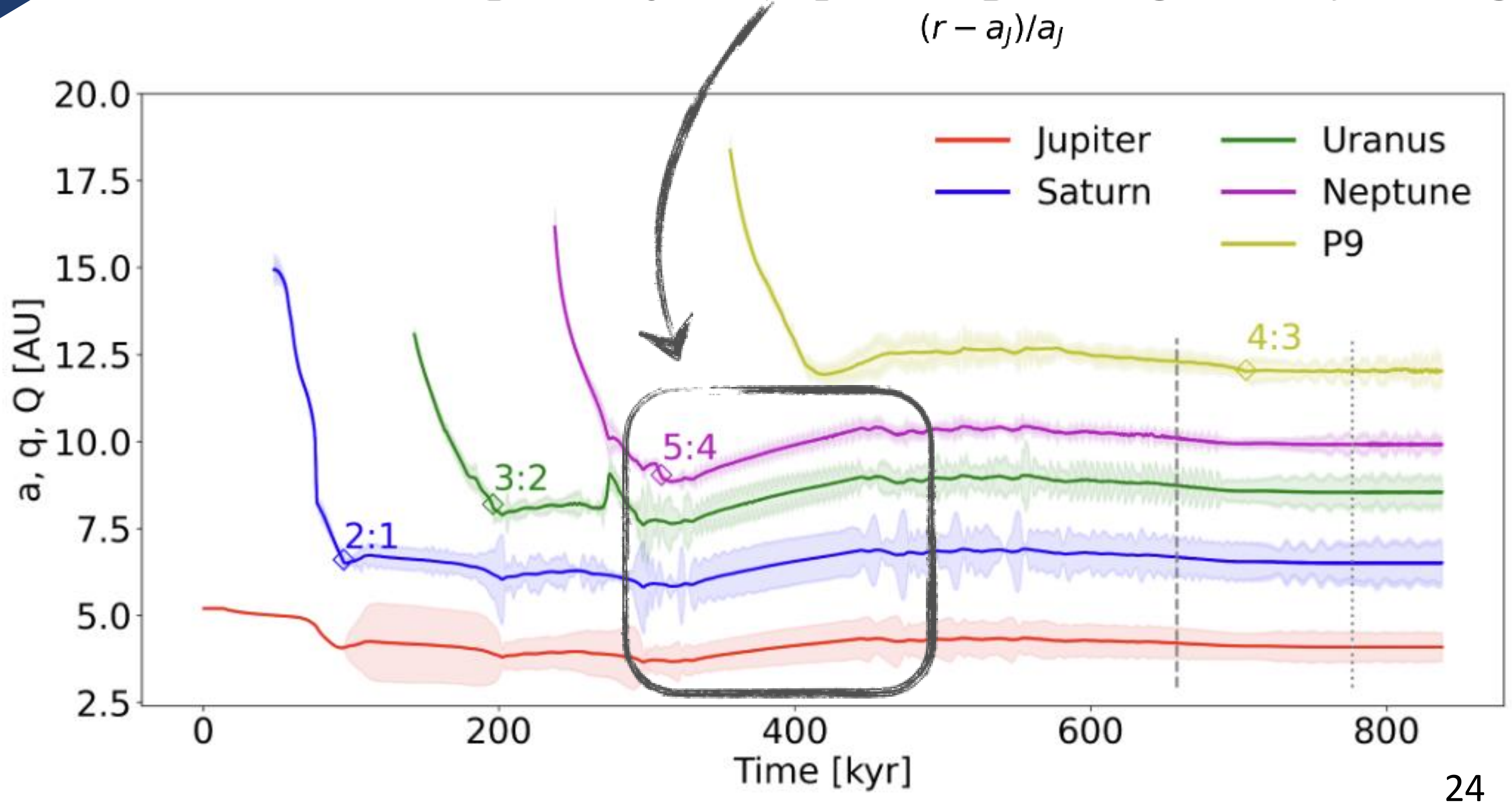
Migration in multi-planet systems

Planet–planet interactions enable all-new dynamics:

- Resonant trapping can push planets beyond their gaps
- Mutual-gap configurations can trigger MS-like behavior
- Eccentricity growth!

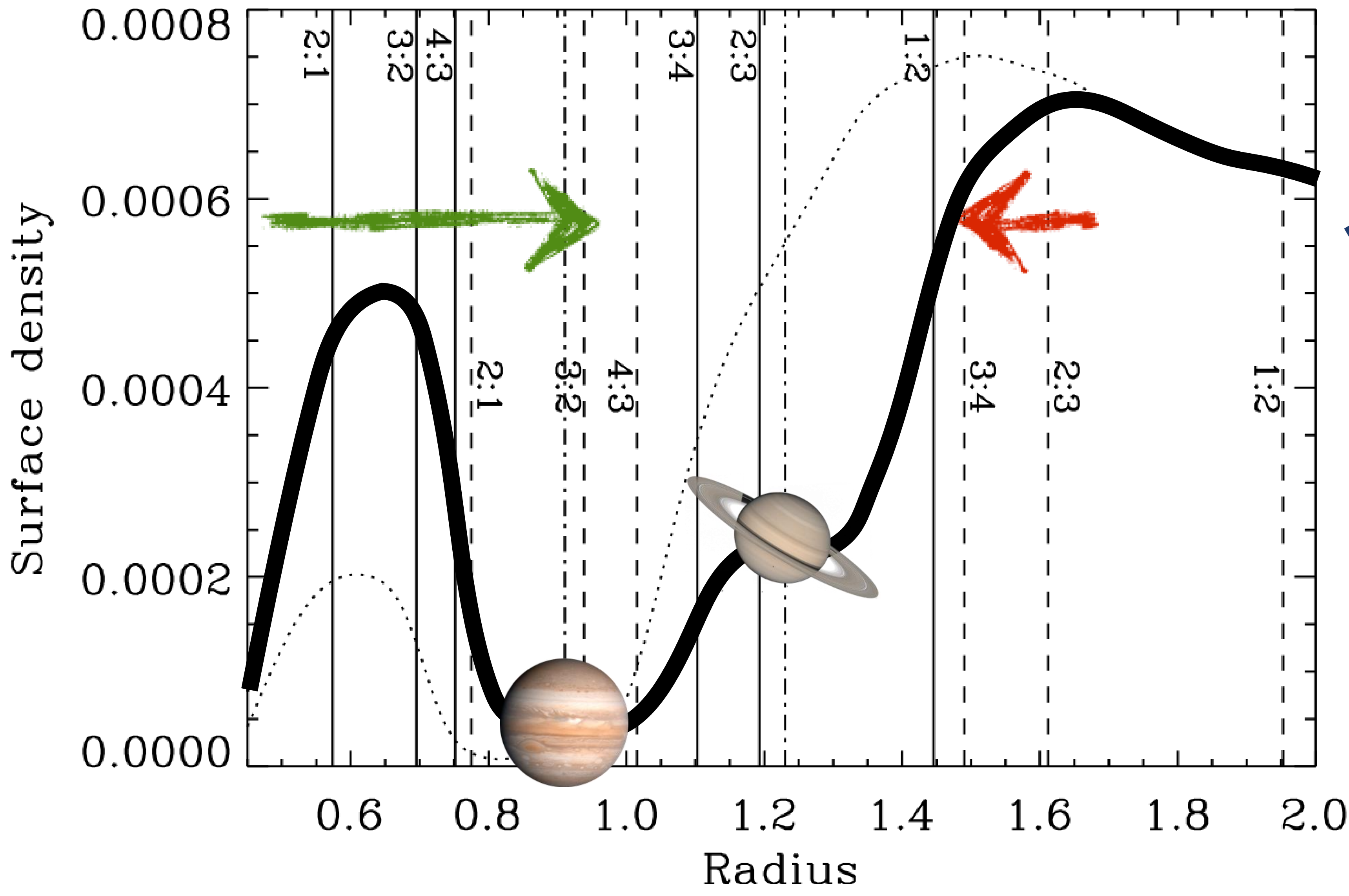
(Griveaud+, 2024)





see talk by Philippine Griveaud!

(Masset & Snellgrove, 2001)



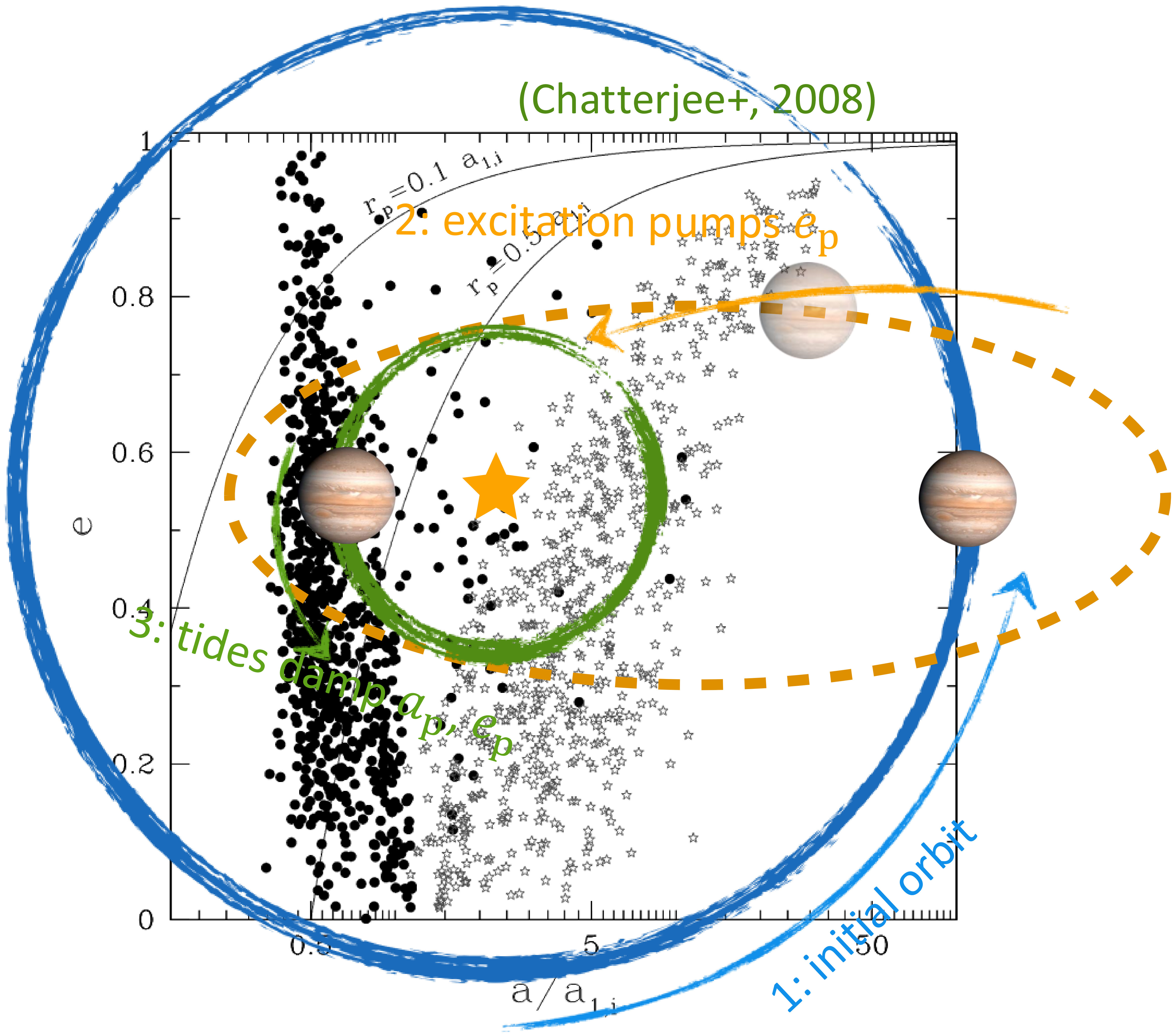
(See also Morbidelli+ 2007, Rometsch+ 2020, Griveaud+ 2023)

High-eccentricity migration

Eccentricity growth can come from many sources:

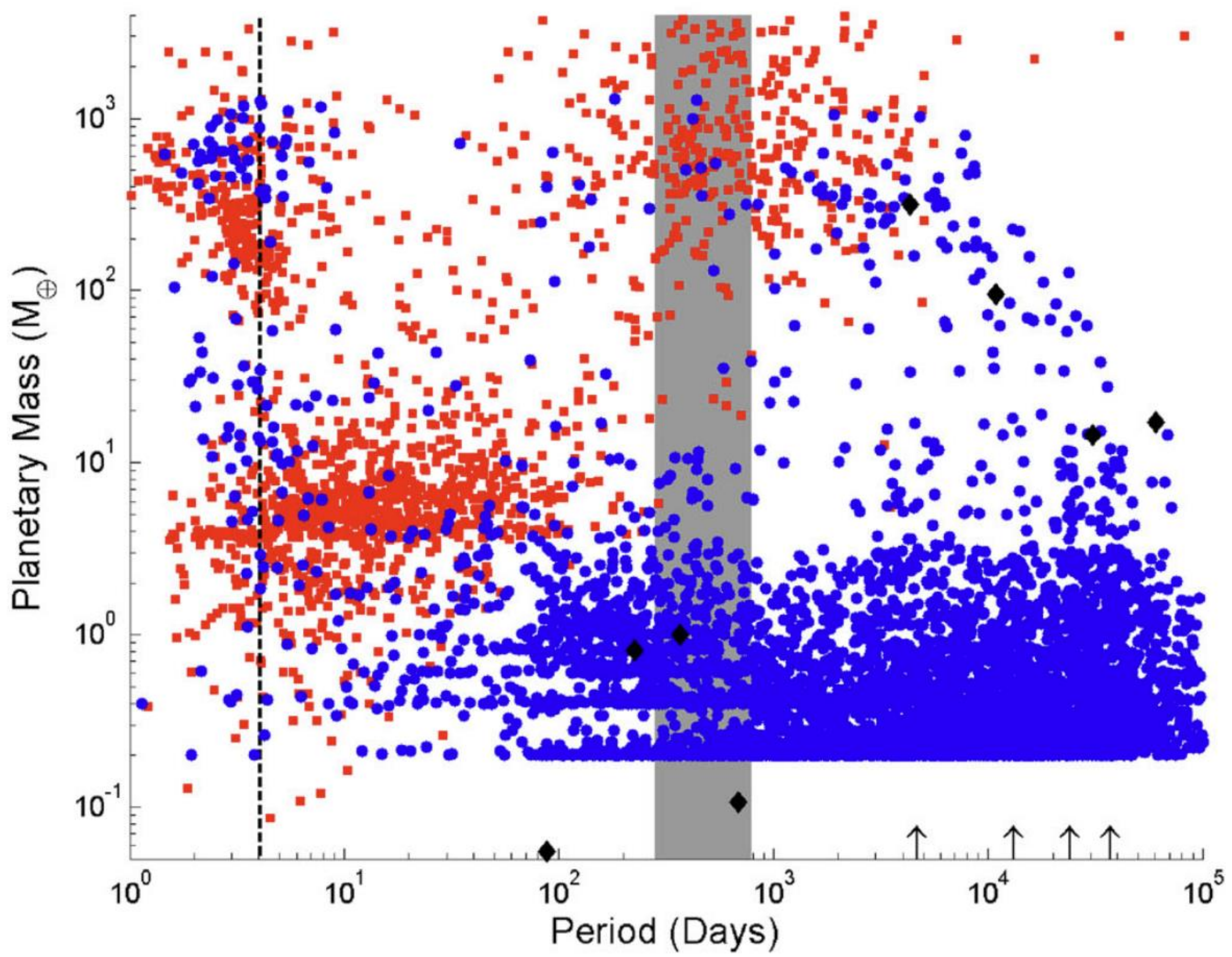
- Planet–planet interactions → scattering
- Kozai–Lidov excitation by a stellar companion

+ tidal circularization near periastron → Hot Jupiters!

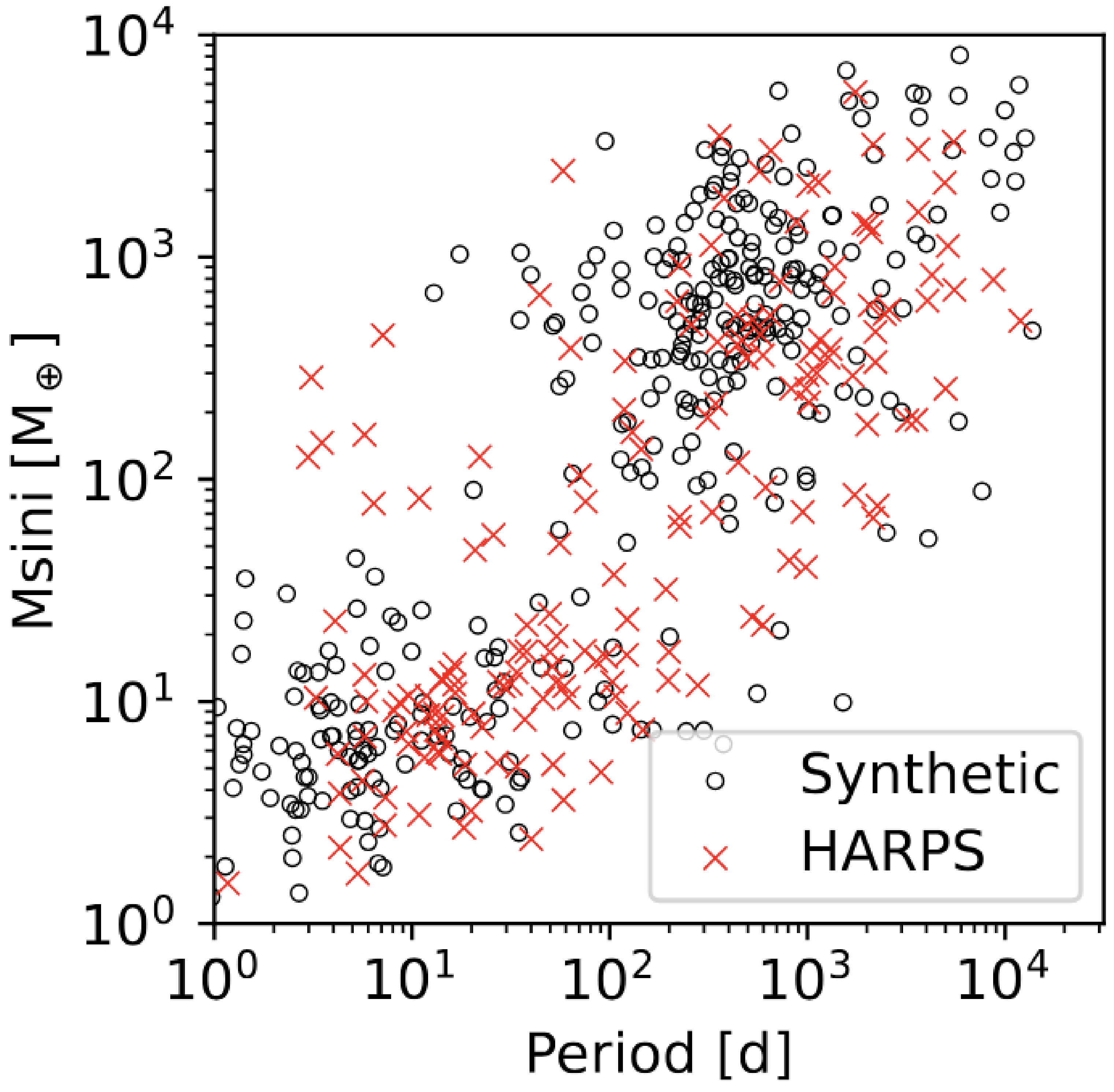


(See also Rasio & Ford+ ’96; Weidenschilling & Marzari ’96; Nagasawa+ ’08, Jurić & Tremaine ’08)

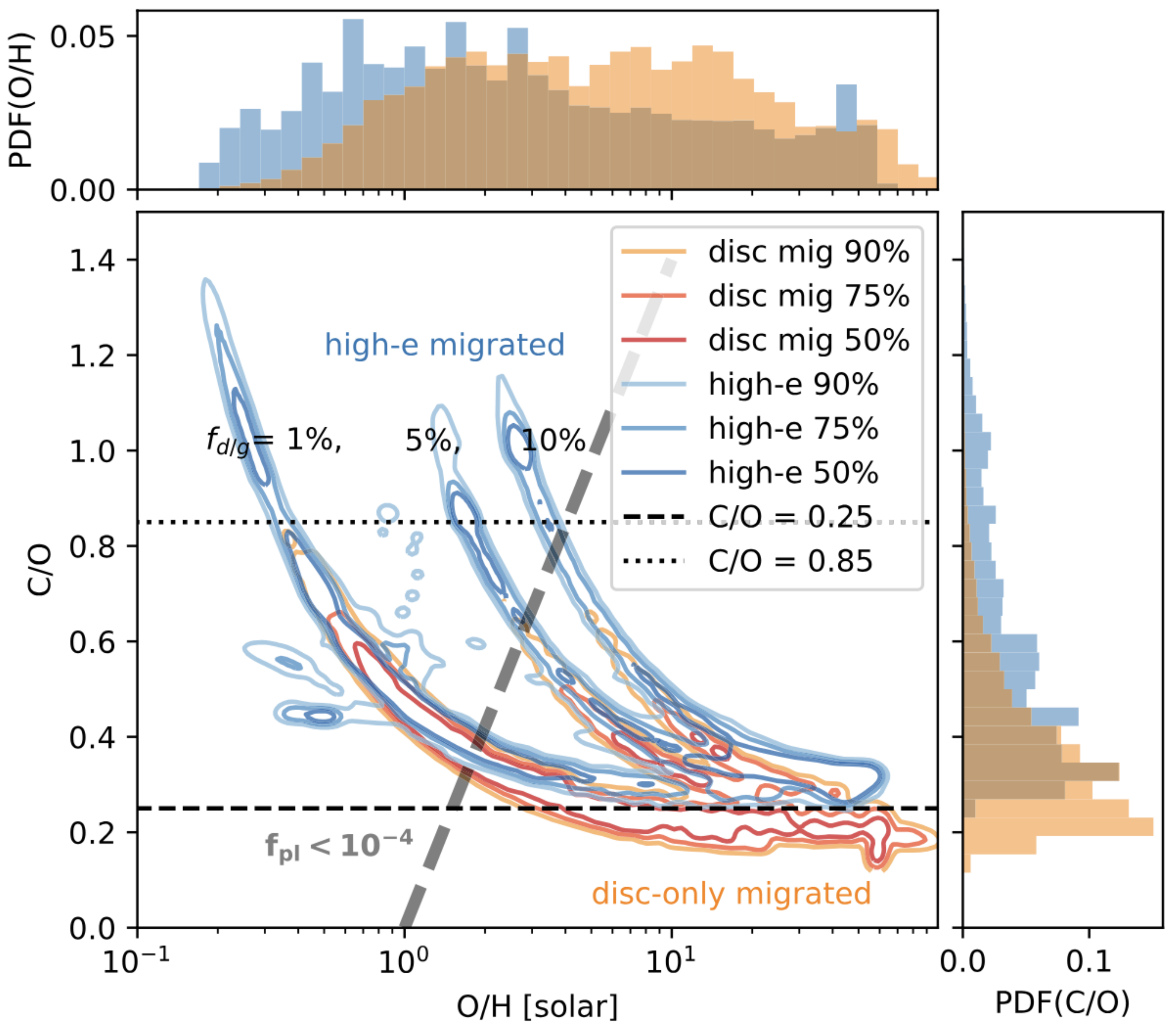
Towards population synthesis modeling



(Coleman & Nelson, 2016)



(Emsenhuber+, 2025)



(Penzlin & Booth+, 2024)

Parametrized "kitchen-sink" simulations → statistics on a population level

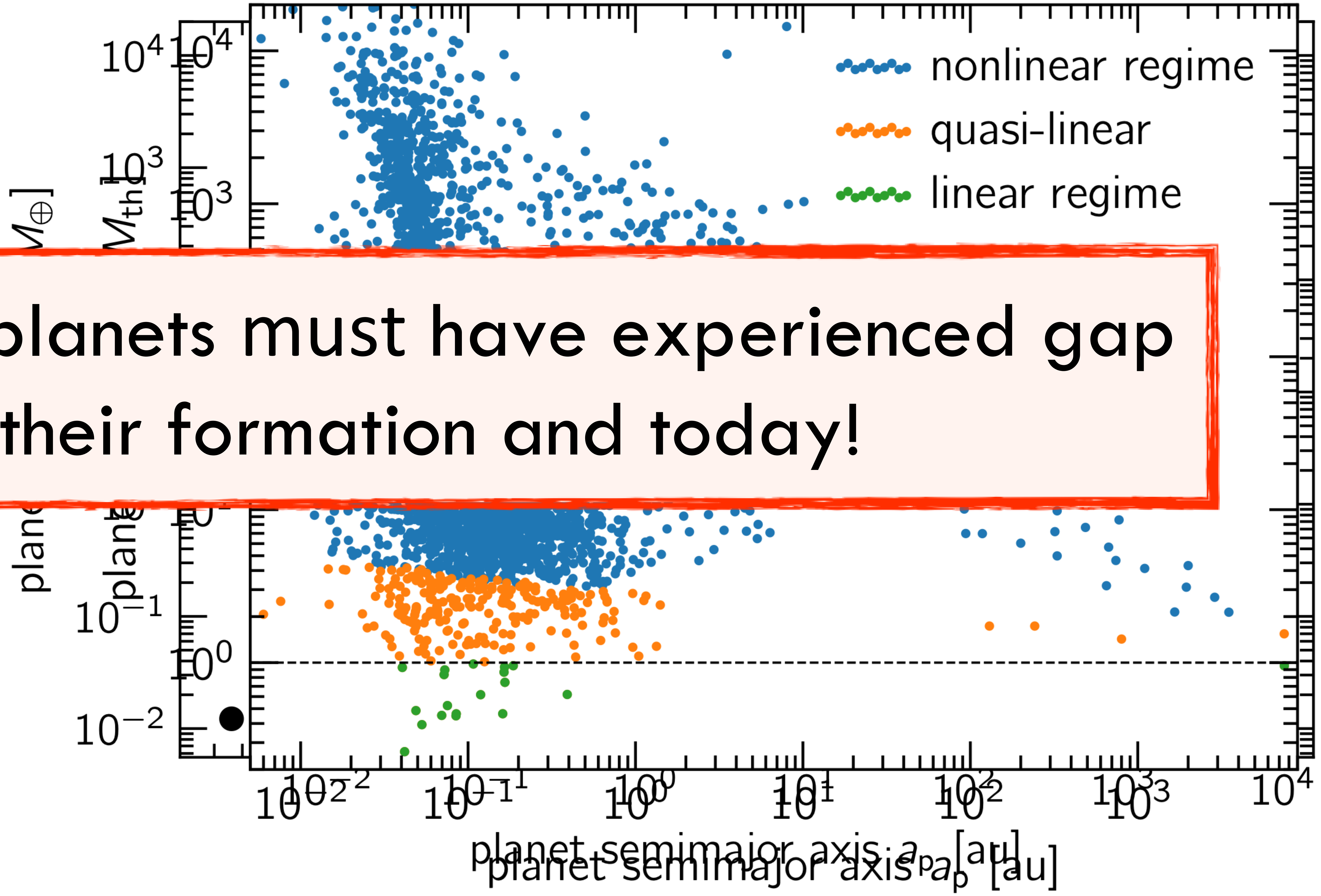
We can now make statements about the formation paths and composition of giant planets!

It's time to reconsider what "type-II migration" means!

$M_{\rm th}$ ...

Nearly all disk-formed exoplanets must have experienced gap opening between their formation and today!

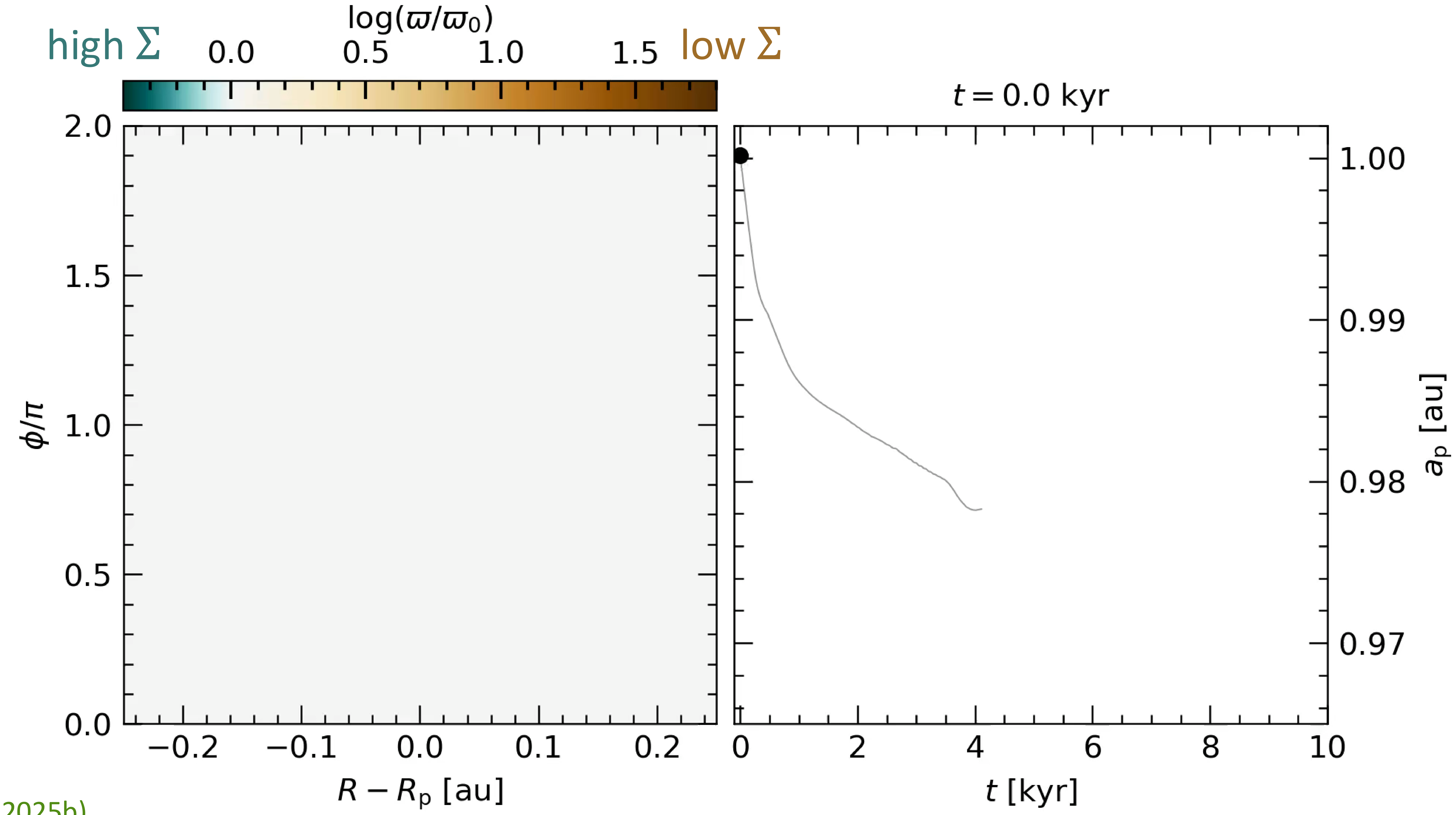
The "typical" (median) planet from the Kepler and K2 samples is 6 $M_\oplus$ at 0.1 au!



(Ziampras+, 2025b)

(Crida+ 2006; Rafikov 2002)

7 $M_\oplus$ planet, radiative: a deep gap forms, planet stalls



(Ziampras+, 2025b)

The takeaways, part II

Giant planet migration is tied to gap opening

- migration slows to the type-II regime → very sensitive to the dynamics at gap edges
- vortex formation and MHD winds can modify the torque balance, accelerating migration

Modeling giant planet migration requires complex simulations

- magnetothermal wind mass loss → asymmetric gap profiles
- planet–planet interactions → eccentricity growth, outward migration
- radiative transfer → easier gap opening, complex vortex stuctures

Current models can capture observational trends

- The planet migration scenario can reproduce giant planet populations
- We can now make predictions on their chemical composition and apply them to JWST data!

Summary

Giant planets play a central role in their disks, dominating the dynamics

Giant planet–disk interaction and pop-synth modeling has come a long way!

Some open questions…

What about the giant planets at tens of au?

Can we collapse 3D radiation multifluid non-ideal MHD models down to prescriptions?

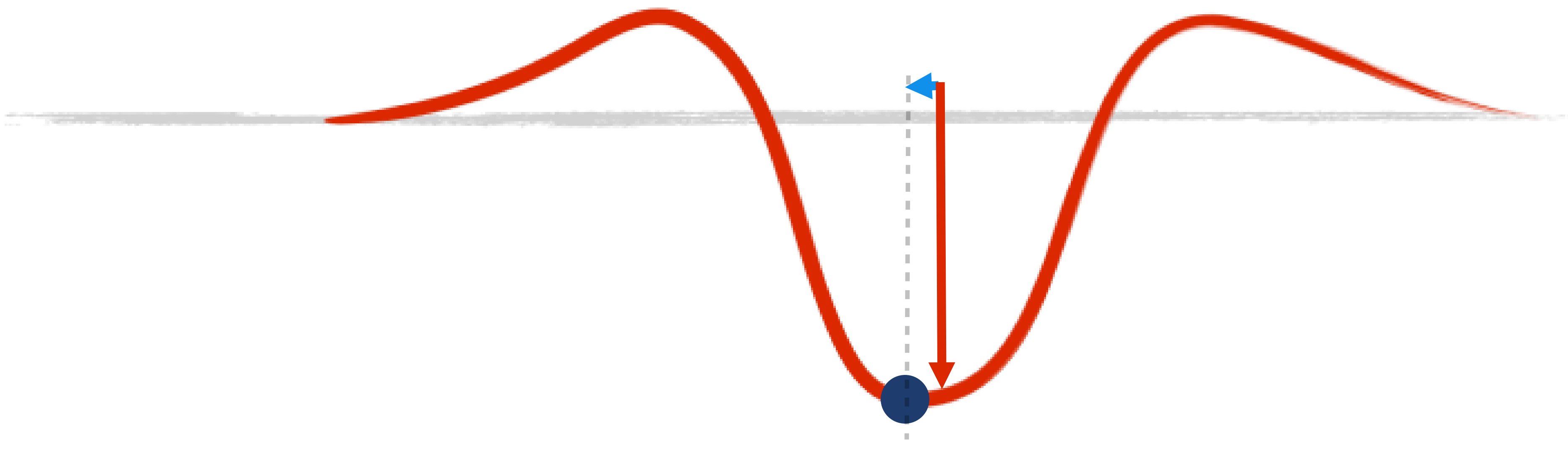
Your question goes here!

Back-up slides

Criteria for the feedback and gap-opening mass

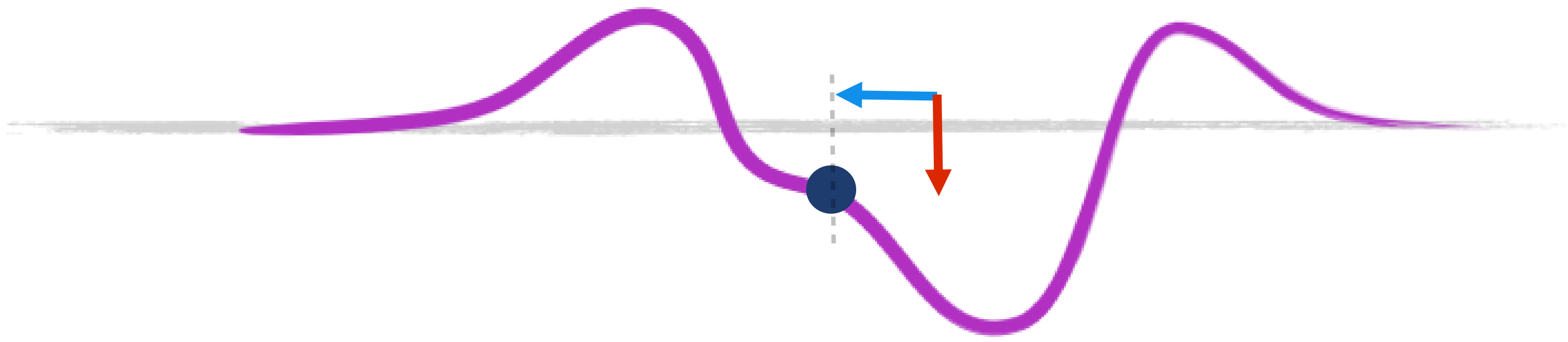
Deep gap opening is expected when planet-driven spirals shock within the planet's Hill radius → *thermal mass*:

$$M_{\rm th} = \frac{2h^3}{3} M_\star, h = \frac{c_{\rm s}}{u_{\rm K}} \sim 0.02 - 0.05$$



Feedback effects already happen when the planet can significantly perturb the gas on migration timescales → *feedback mass*:

$$M_{\rm f} \approx 3.8 \left(\frac{Q}{h}\right)^{-5/13} M_{\rm th}, Q = \frac{c_{\rm s}\Omega_{\rm K}}{\pi {\rm G}\Sigma} \gtrsim 100$$



(Rafikov 2002a,b)