Understanding the Migration of Gas Giant Planets

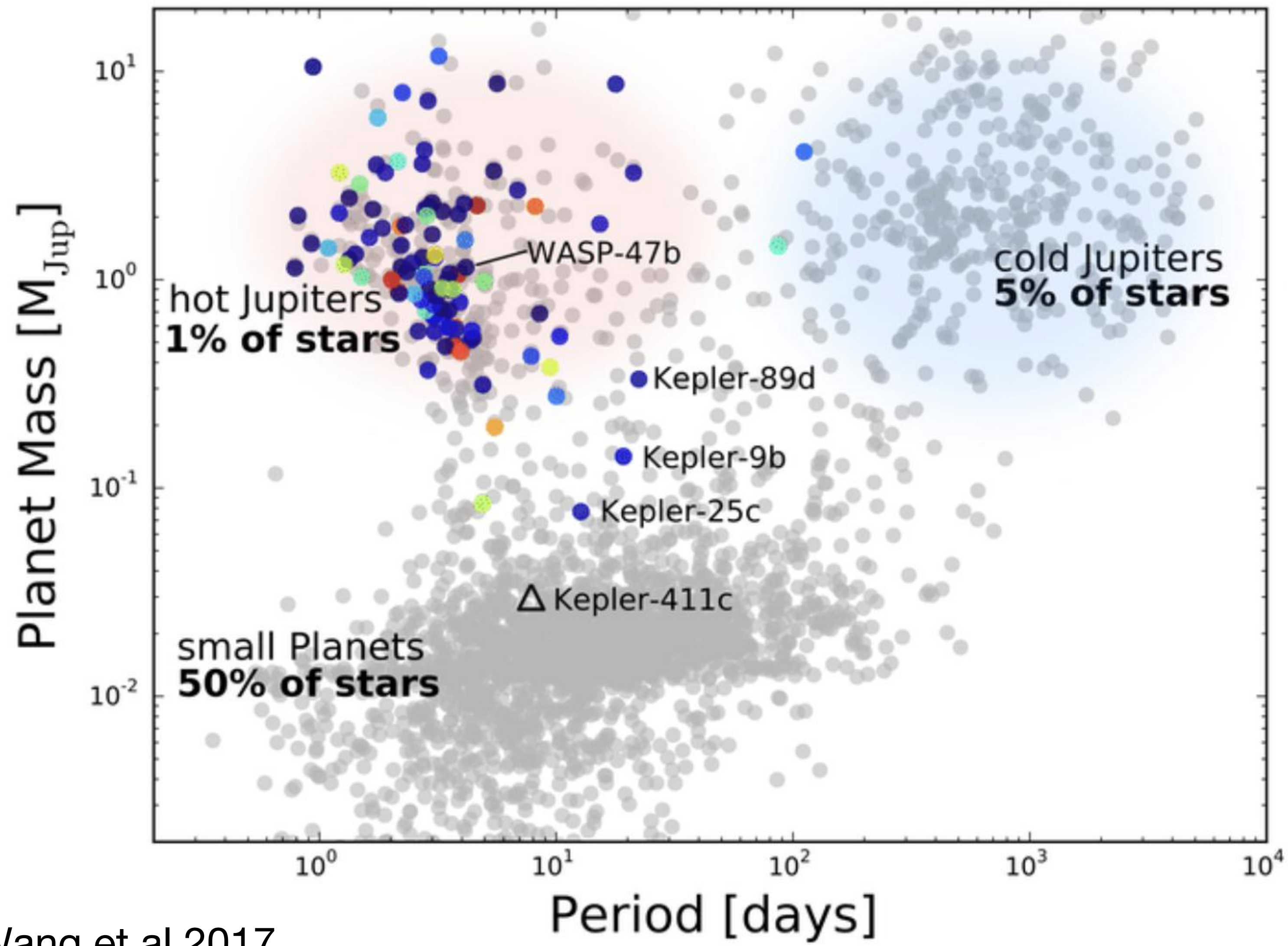
Yi-Xian Chen
With Xiaojia Zhang, Ya-Ping Li, Douglas Lin

Princeton

Outline

- Type I Migration in Ideal Protoplanetary Disk
- Gap-opening and the Classical Type II Migration
- The New Paradigm of Type II Migration: Extrapolation of Type I
- Effect of Rogue Lindblad Torques at Gap Edges
- Summary

Motivations



Wang et al 2017

Migration may be important in the evolution of both Super Earths & Hot Jupiters

Cause of Migration from Disk Interaction

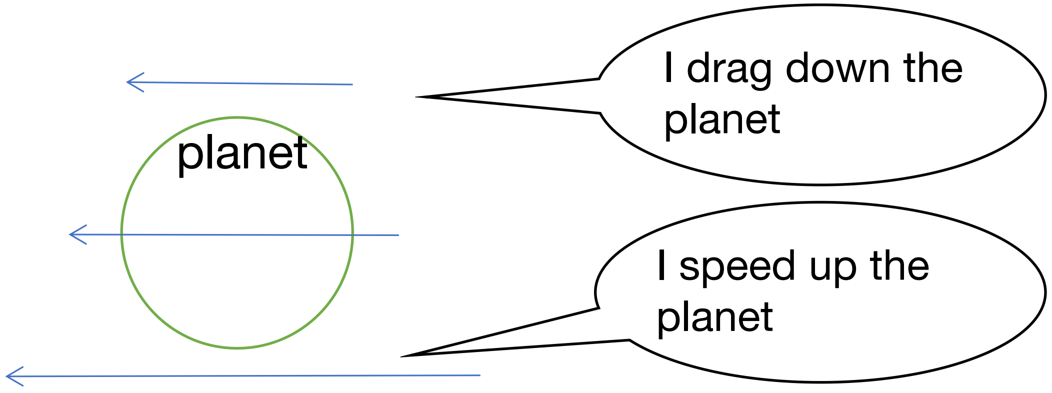
planet gravity pulls passing gas and planet together.

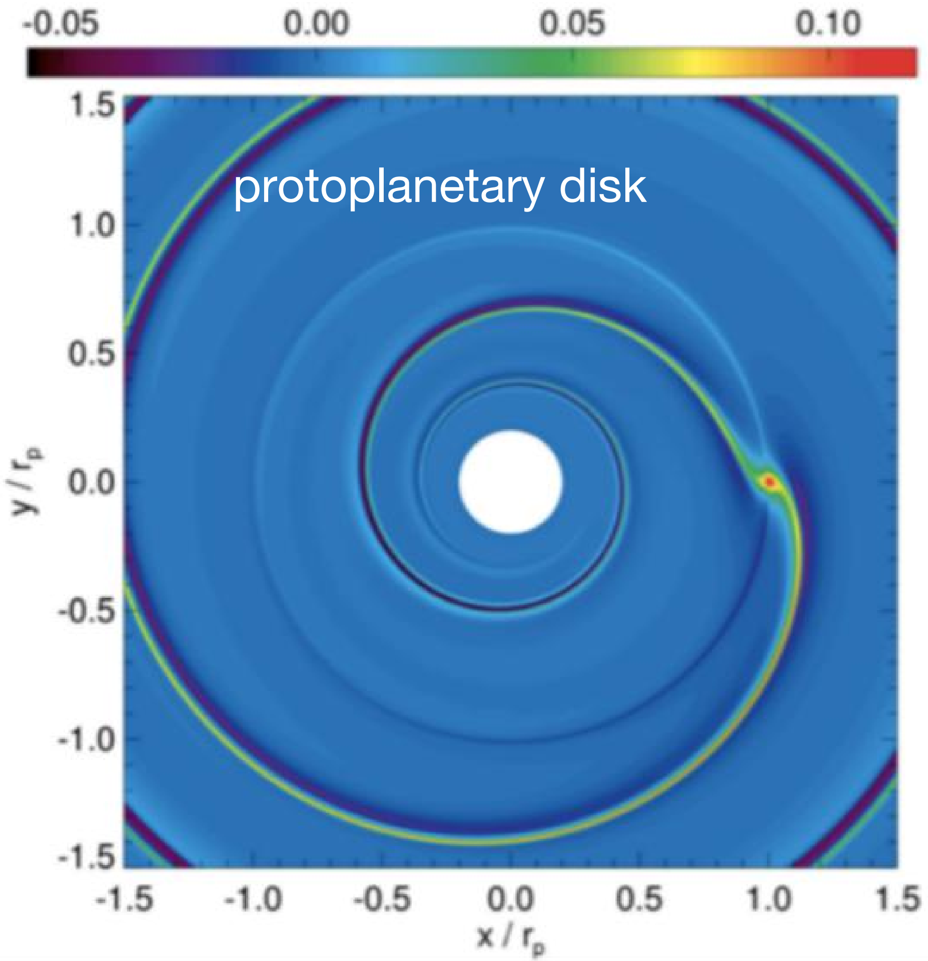
- Gas in the outer disk (farther from star) rotates slower than the planet, and drag it down;
- Gas in the inner disk rotates faster, so speeds it up

Outer disk

$$v_K = \sqrt{\frac{GM_*}{r}}$$

Inner disk



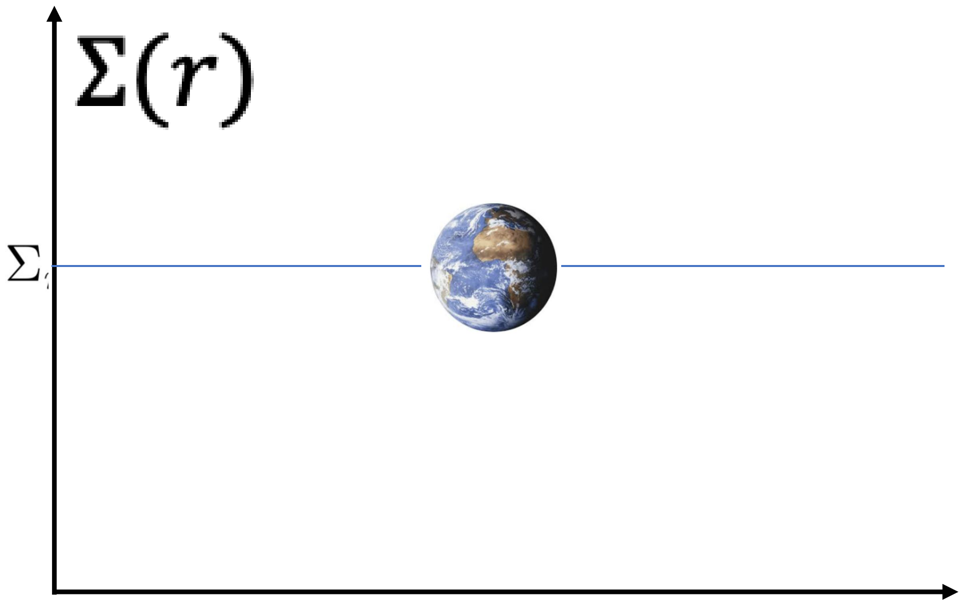


Relative change of the surface density due to the planet-disk interaction, Baruteau+2014

Cause of Migration: Type I

Question that needs further scrutiny: Which side of the disk WINS?
First consider a small planet that does not perturb the disk gas profile

azimuthally averaged surface density of gas (nearly symmetric except density wave regions)

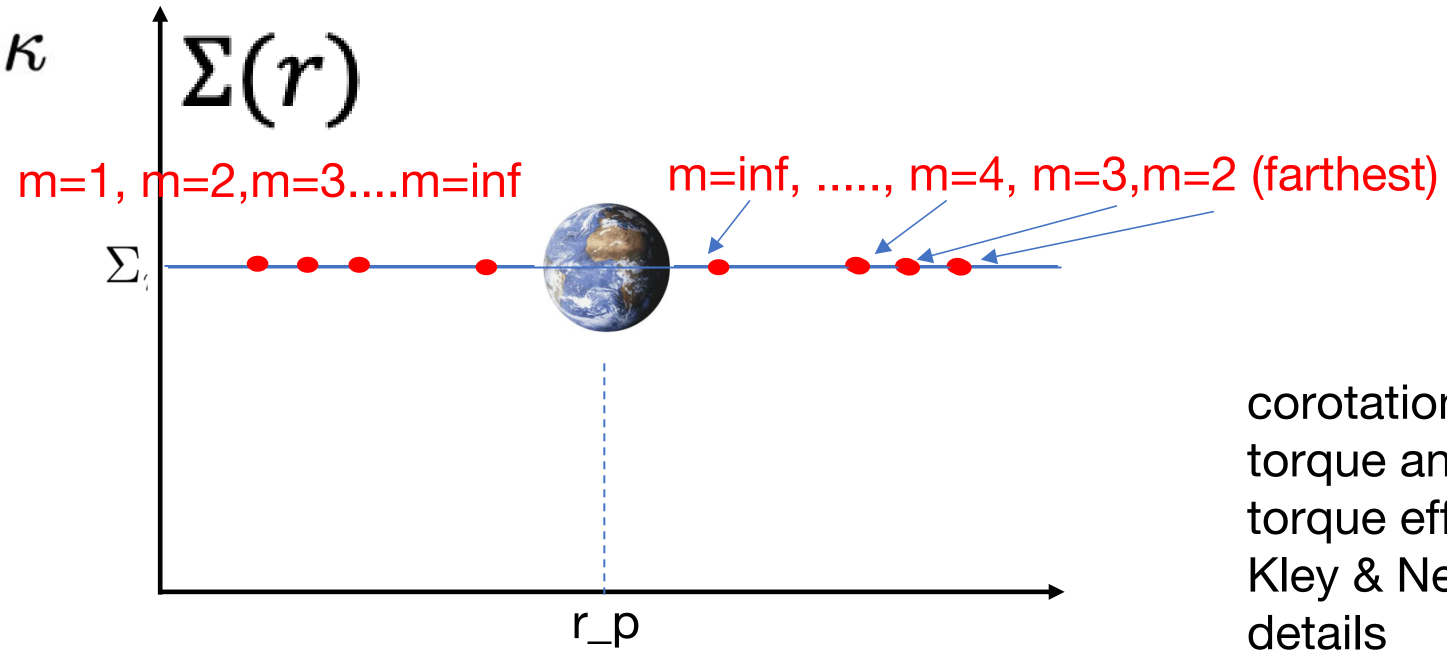


Most of the torques are launched from Lindblad resonance locations, where the period of gas is ~ (1+-1/m) of planet period -> gives an accumulating perturbation

Cause of Migration: Type I

Question that needs further scrutiny: Which side of the disk WINS?
First consider a small planet that does not perturb the disk gas profile

$$m[\Omega(r) - \Omega_{\rm p}] = \pm\kappa$$



corotation/horseshoe torque and thermal torque effects see Kley & Nelson 2012 for details

Most of the torques are launched m-th order Lindblad resonance locations, where the period of gas is ~(1+-1/m) the planet period

Cause of Migration: Type I

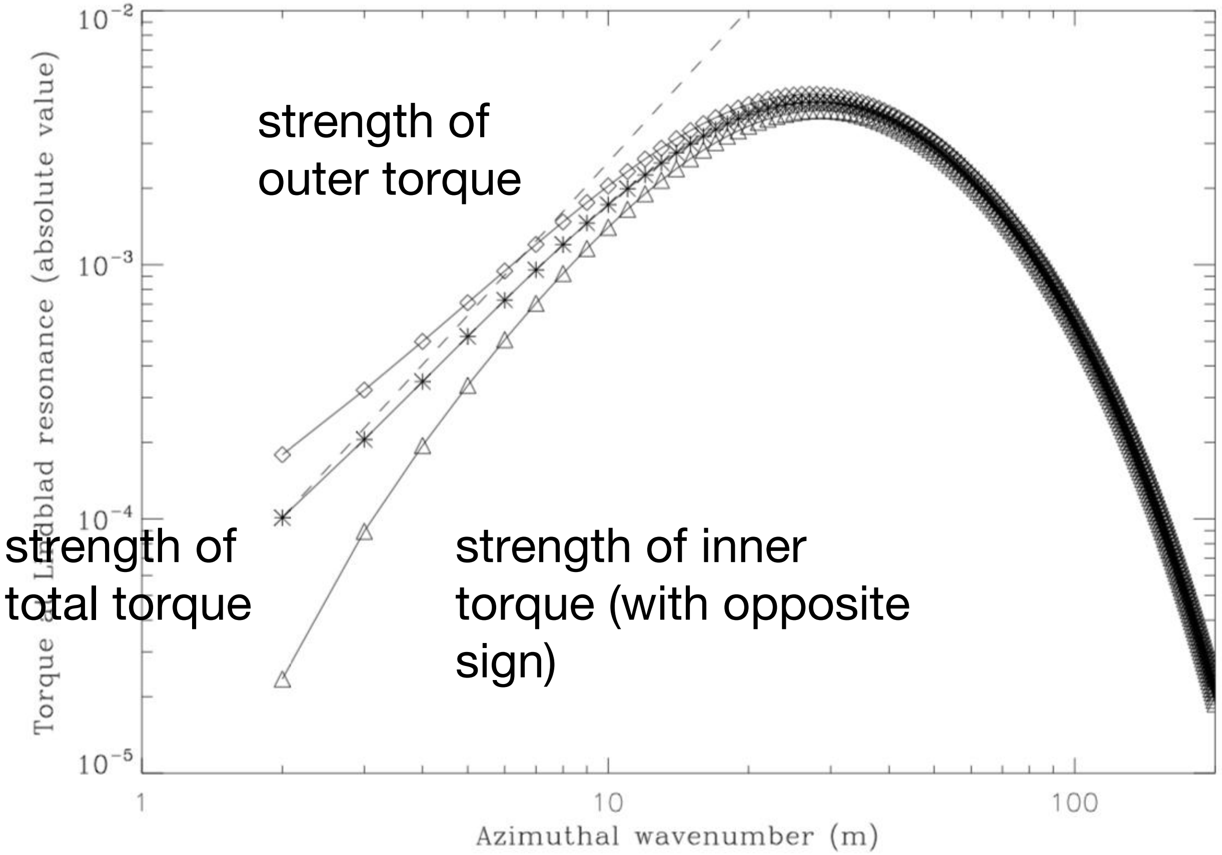
$$\Gamma_m = \frac{m\pi^2\Sigma}{r\mathrm{d}D/\mathrm{d}r}\left[r\frac{\mathrm{d}\phi_m}{\mathrm{d}r} + 2m^2(1-\frac{\Omega_p}{\Omega})\phi_m\right]^2 f_L\Bigg|_{r_m}$$

e.g. Artymowicz 1993
Kley & Nelson 2012

Each m-th order torque is evaluated at RESONANCE LOCATION r_m

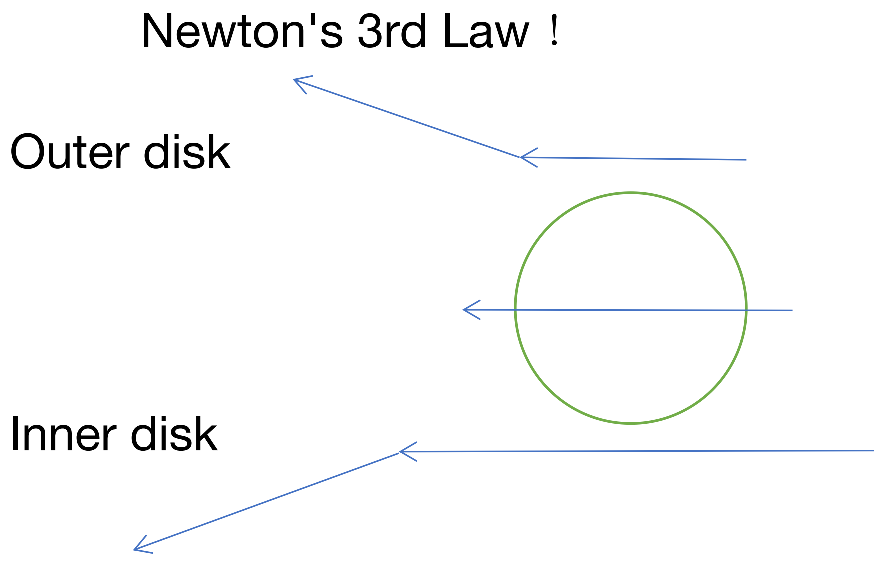
Ideally, the outer m-th resonance is always closer to the planet than m-th inner resonance -> net torque drives planet inwards! (Goldreich & Tremaine 1980)

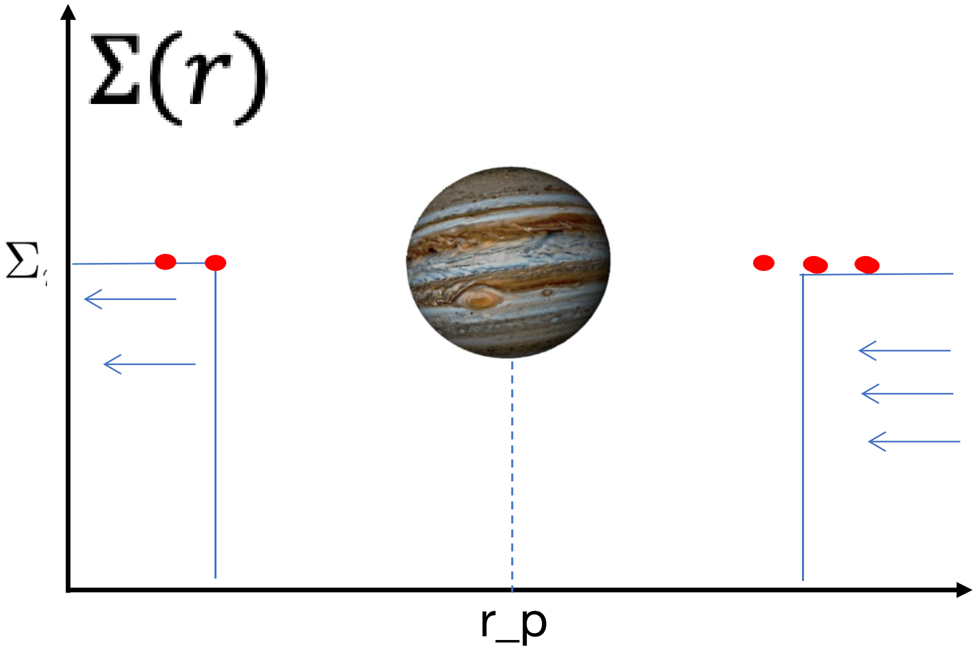
$$\Gamma_{typeI} \propto \left(\frac{q}{h_\mathrm{p}}\right)^2 \Sigma\,\Omega_\mathrm{p}^2 r_\mathrm{p}^4$$



Expression used commonly in N-body simulations

Classical Type II Migration



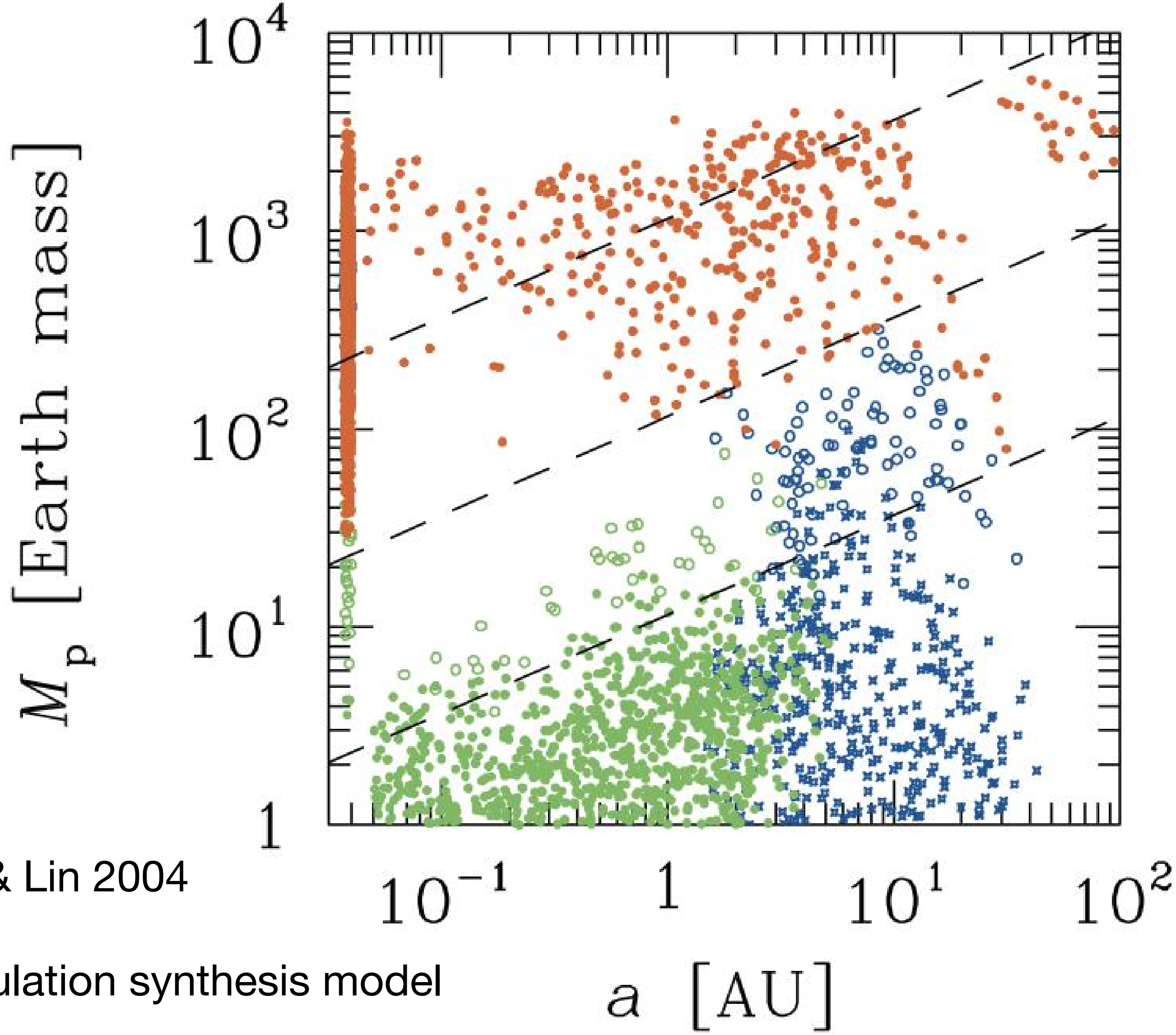


In the old model (Lin& Papaloizou 1986), a giant planet pushes away the gas around its vicinity, and opens a clean gap

Most resonances are gone (with density/torque at r_m nearly 0)!

But the disk gas has inward viscous velocity, when this is blocked, gas accumulates to push on the planet until it reaches viscous speed as gas.

Problem: Too much Hot Jupiters



Ida & Lin 2004

population synthesis model

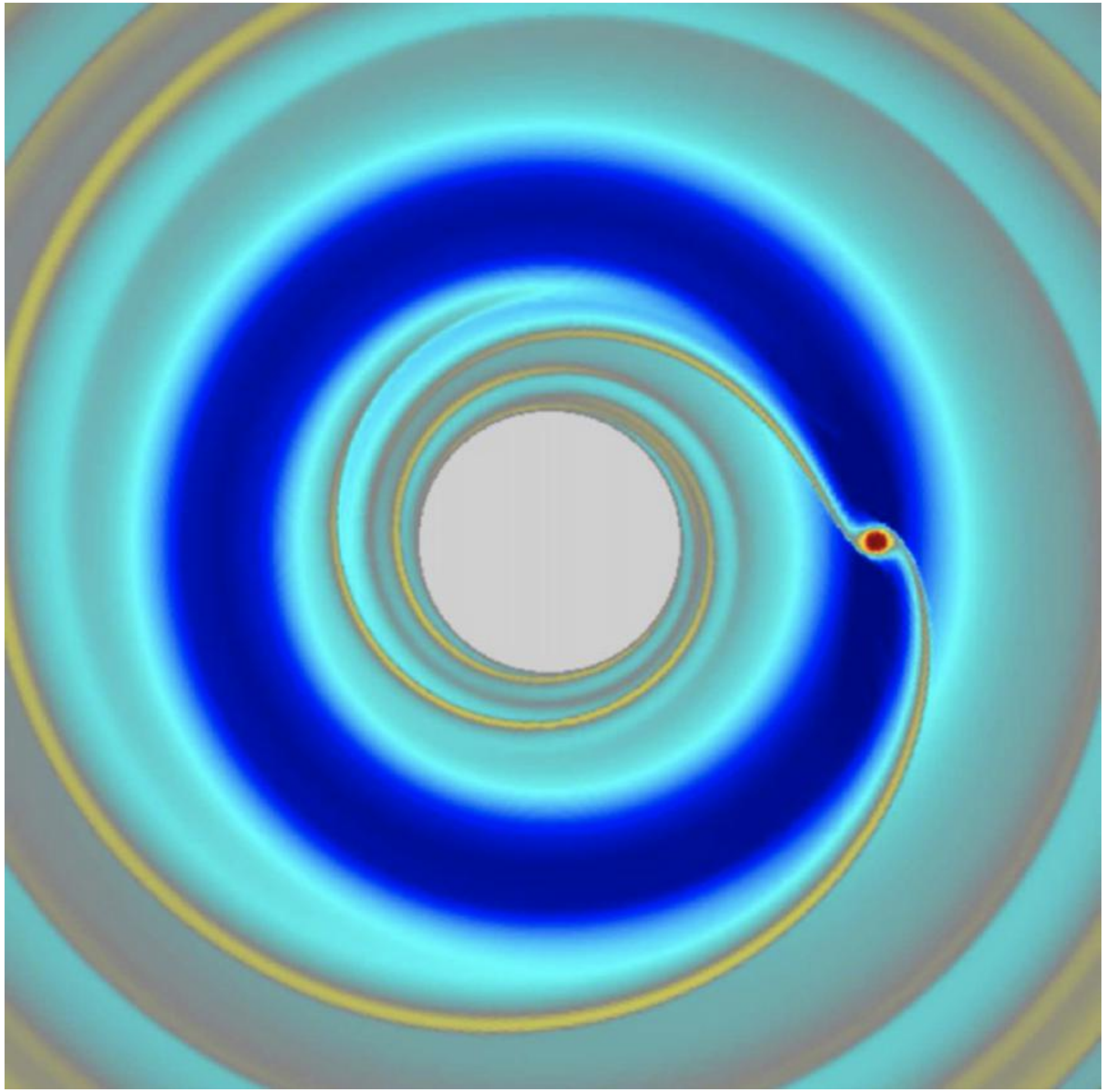
Classical Type II migration is quick

will make most gas giants migrate inwards to become hot Jupiters

New Type II Migration

Recent simulations show the gap is never quite totally depleted.

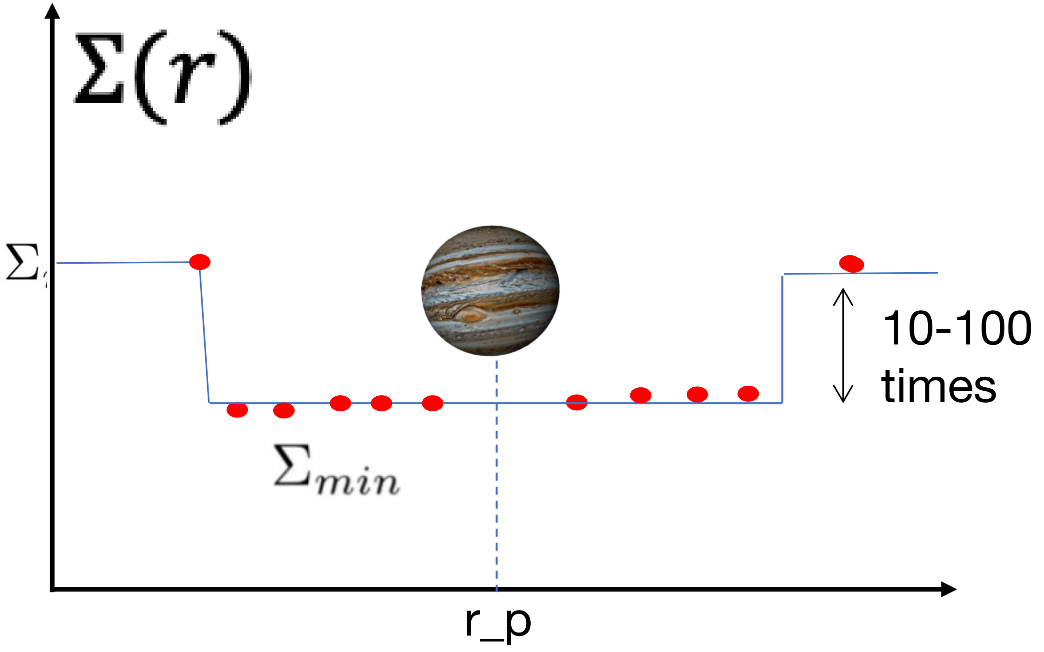
In a typical gap carved out by a giant planet: materials can still flow inwards and is not cut off



New Type II Migration

The gap maintains some non-zero bottom density. This challenges the classical theory.

$$\frac{\Sigma_{min}}{\Sigma} \approx \frac{1}{1+0.04K} \qquad \text{where} \quad K \equiv q^2 h_p^{-5} \alpha^{-1}.$$



Kanagawa+ (2015,2018) makes the assumption that most of the resonances are not lost, just “dropped” to the bottom

Then only have to replace the density in the Type I torque expression

Usually slower than classical Type II, but still not enough

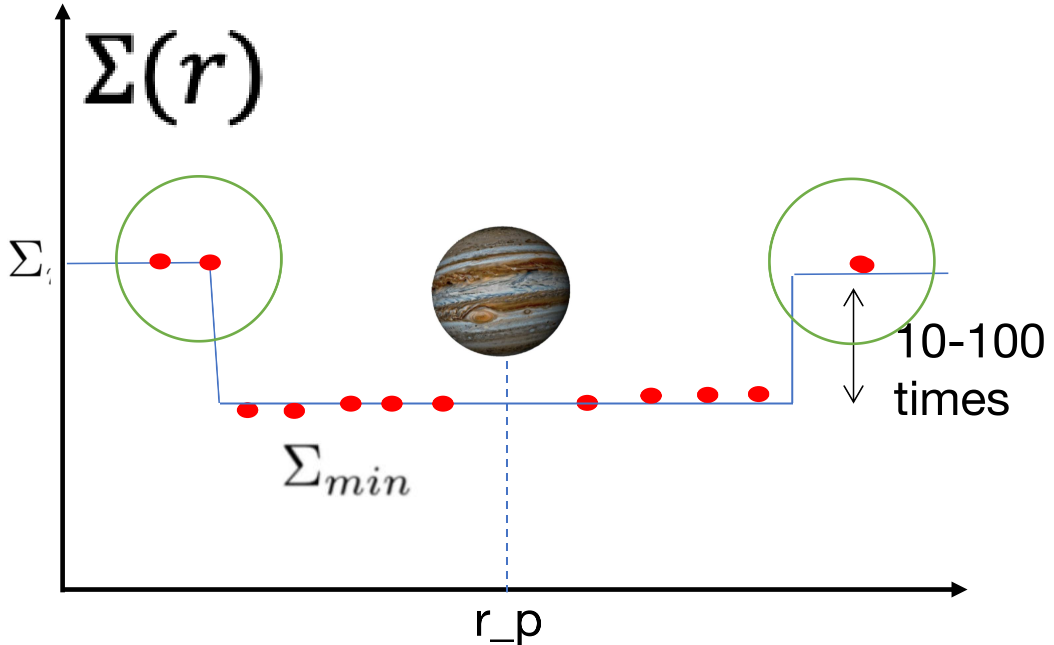
$$\Gamma_{typeI} \propto q^2 \Sigma \quad \Longrightarrow \quad \Gamma_{typeII} \propto q^2 \Sigma_{min}$$

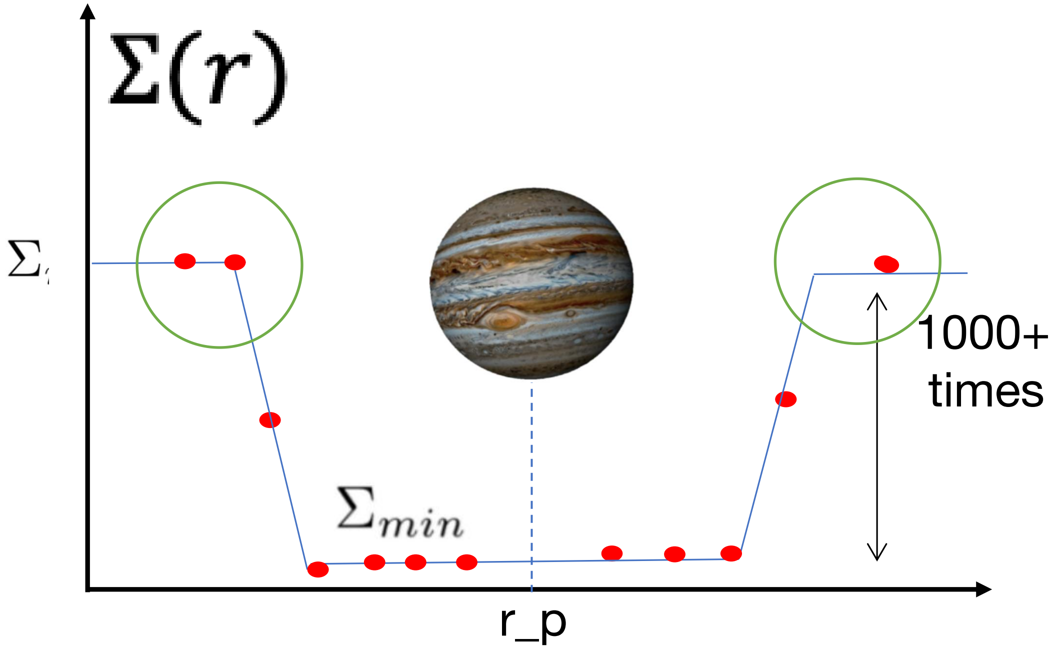
Effect of Gap Edges

However, it fails to predict migration rates for even larger planets than open up very deep gaps.

Problem:
The radial width of the gap depends sensitively on the planet mass, and some of the few torques are left out in the gap edges, where gas density is not ~ Σ_{min} but rather ~ Σ (rogue torques)

Shallow gap and Deep gap will be very different



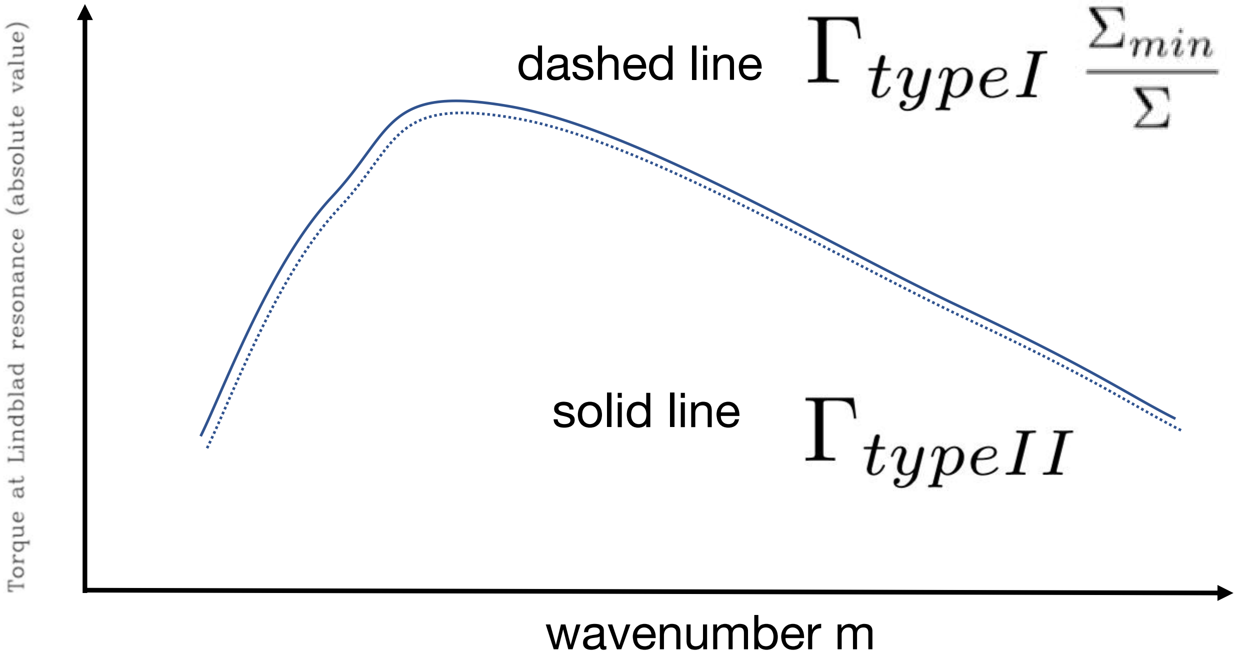


Effect of Gap Edges

Method:

1. We perform hydro simulation of gas giant (Jupiter mass, or q=0.001) migration in the disk, until the surface density profile becomes quasi-steady (using two codes to cross-check)

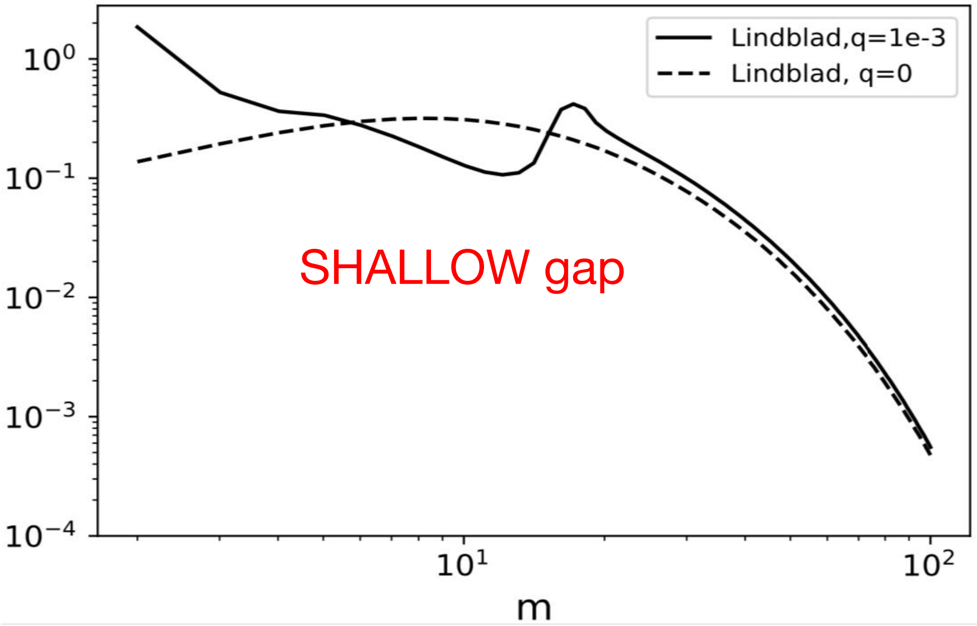
2. We calculate each m-th order torque for the perturbed profile and compare with the unperturbed torque times the depletion factor, if all torques are uniformly dropped to a lower density:

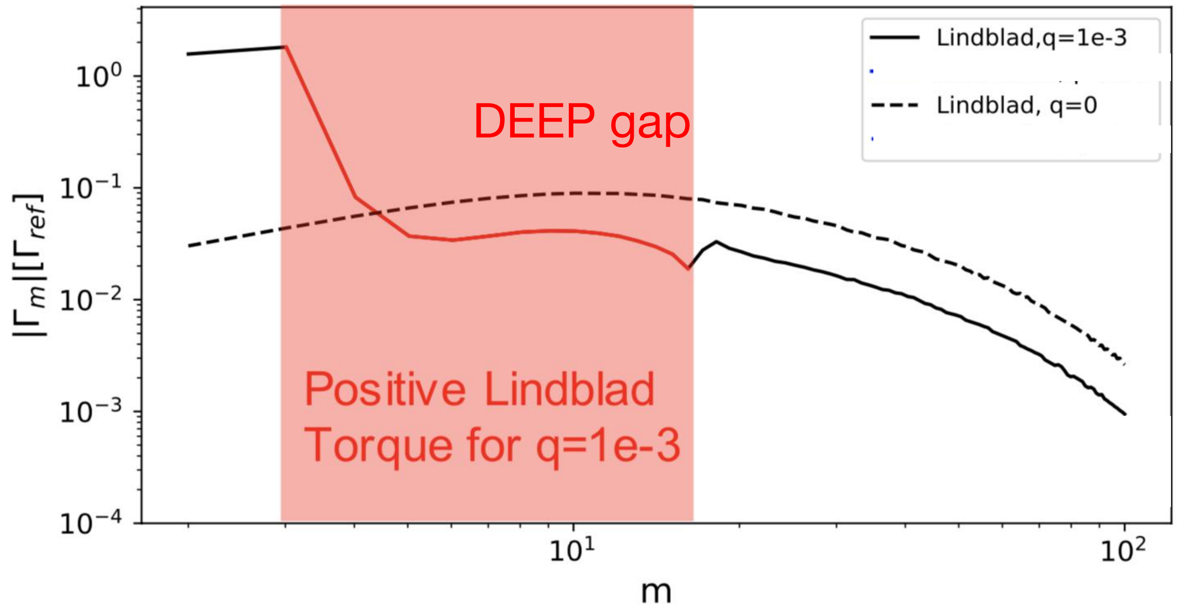


If the "uniform drop"hypothesis is valid, we not only expect the total torque to only differ in a density factor, but all/most the individual torques should overlap in comparison

Effect of Gap Edges

What is our results in reality?

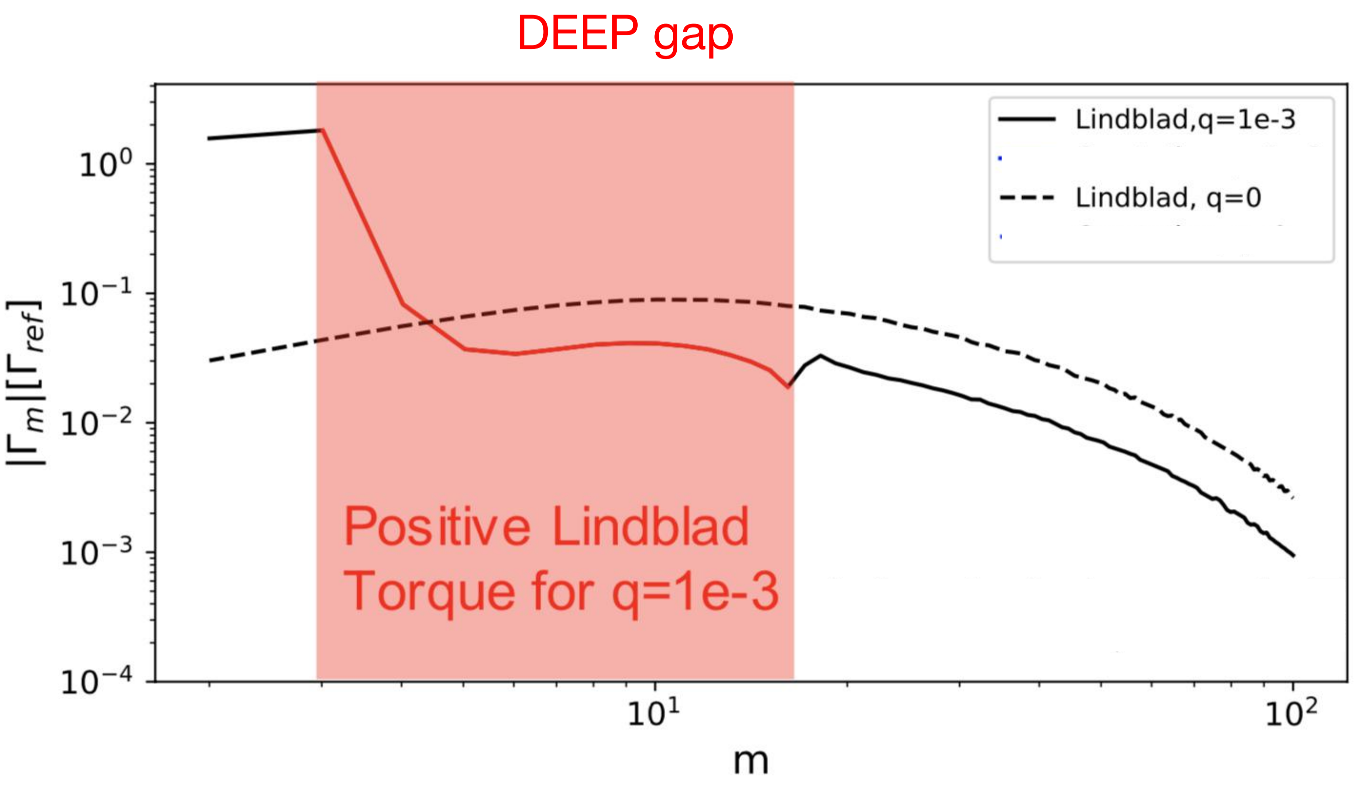


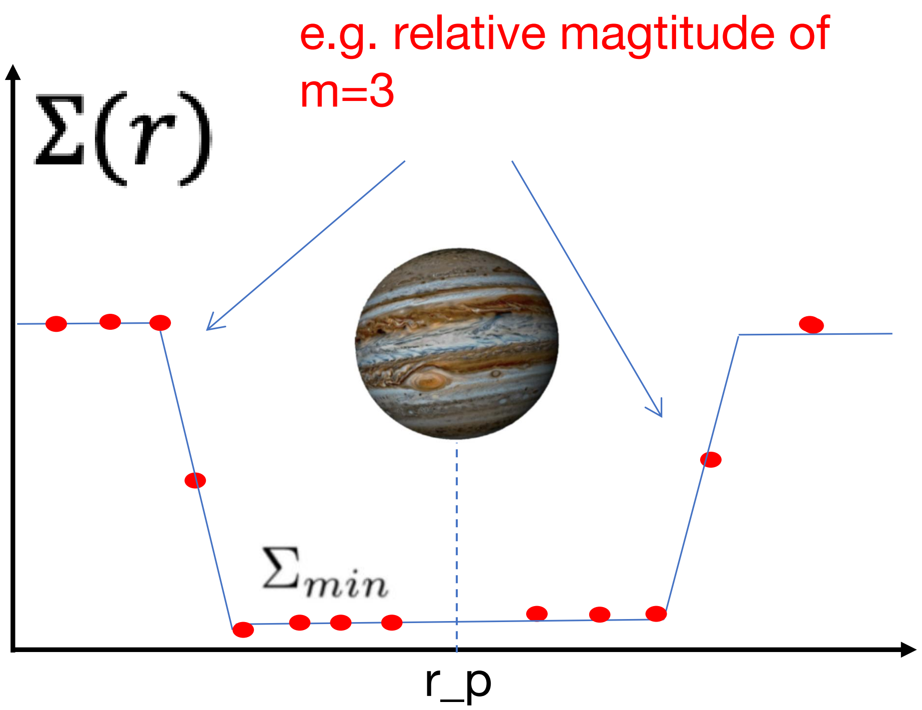


When the gap is shallow, the low-order torques from the gap edges is negligible compared to the sum of all other torque in the bottom, and the approximation is valid

When the gap is deep, the low-order torques from the gap edges will dominate the total torques since the gap density is larger by 2 or 3 orders of magnitude.

Effect of Gap Edges





Why is the sign reversed in some places?

Inner torques usually are farther from the planet -> but higher surface density of the gas at distance farther from the planet makes up for this loss
(E.g. m=3 outer resonance is closer, but density much smaller!)

Summary

- Type I Migration in Ideal Protoplanetary Disk

  Outer Lindblad torques have more influence because closer to planet

- Gap-opening and the Classical Type II Migration

  If gas flow is cut off, then planet will follow viscous evolution

- The New Paradigm of Type II Migration: Extrapolation of Type I

  If gap is shallow, most of contributing resonances just drop down uniformly, and can extrapolate type I -> type II

- Effect of Rogue Lindblad Torques at Gap Edges (Chen Y-X et al. 2020)

  If gap is deep, the torques at gap edges will contribute most of the torque, and they depend delicately on the exact density profile.
  In this case the “uniform drop” assumption cannot be applied and migration could be much slower, helping retain cold gas giants