Understanding the Migration of Gas Giant Planets

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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
- Works of Chen+ (2020): Effect of Rogue Lindblad Torques at Gap Edges
- Summary

2019 Nobel Prize in Physics

木星质量

A Jupiter-mass companion to a solar-type star

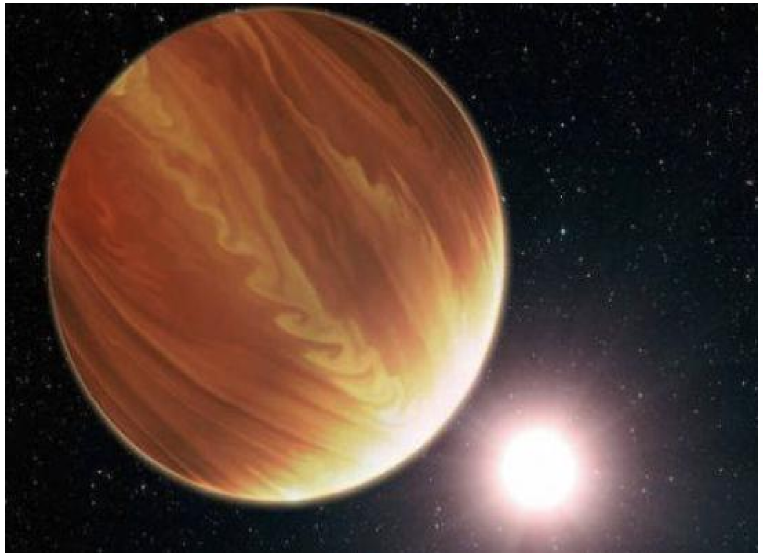
Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

abstract of Mayor & Queloz (1995) article in Nature

–for the discovery of a planet around a solar-type star–



Doug, 1:21

BTW, in the NB Prize committee's essay on this year's winners, 3 of my papers were cited.

Migration (迁移) of the planet, predicted by theorists ages ago (e.g. Lin & Papaloizou 1986), was backed up by observation.

Migration plays a large role after gas giants form, leading to shrinking of their orbital radius

Cause of Migration

There are two ways to understand migration of planet: The easy way, and the hard way.

The HARD way:

- Calculate fluid equations with Fourier expansion of potential -> density waves (密度波) that transport angular momentum

The EASY way:

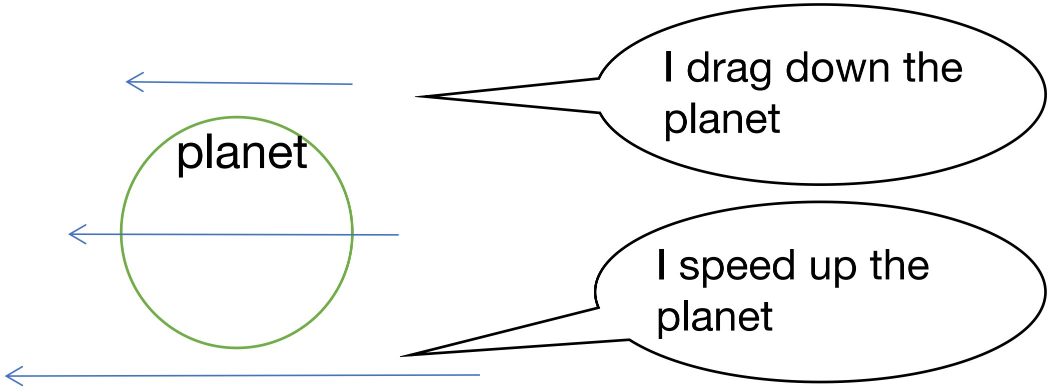
- planet gravity pulls passing gas and planet together.

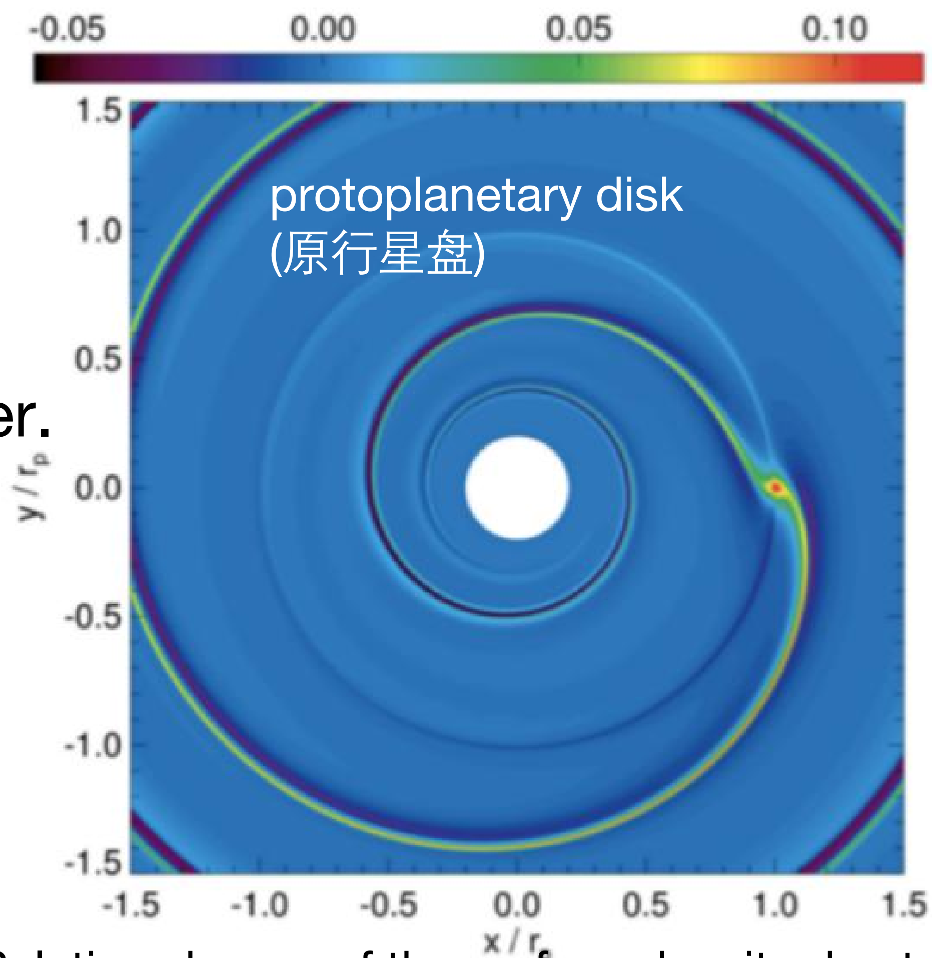
Gas in the outer disk (farther from planet) rotates slower than the planet, and drag it down; Gas in the inner disk rotates faster, and speeds it up

Outer disk

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

Inner disk



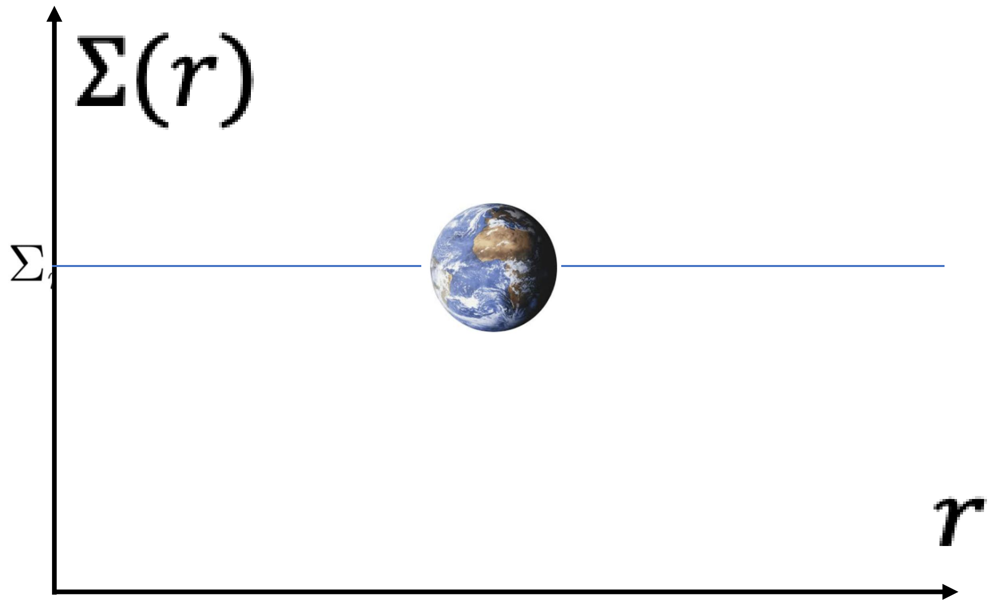


Relative change of the surface density due to the planet-disk interaction, Baruteau+2014

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 (Type I)**

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



How to calculate the torque from the disk?
Most of the torques arise from Lindblad resonance (林德布拉德共振) locations, where the period of gas is ~ (1+-1/m) of planet period -> gives a secular (长期) perturbation

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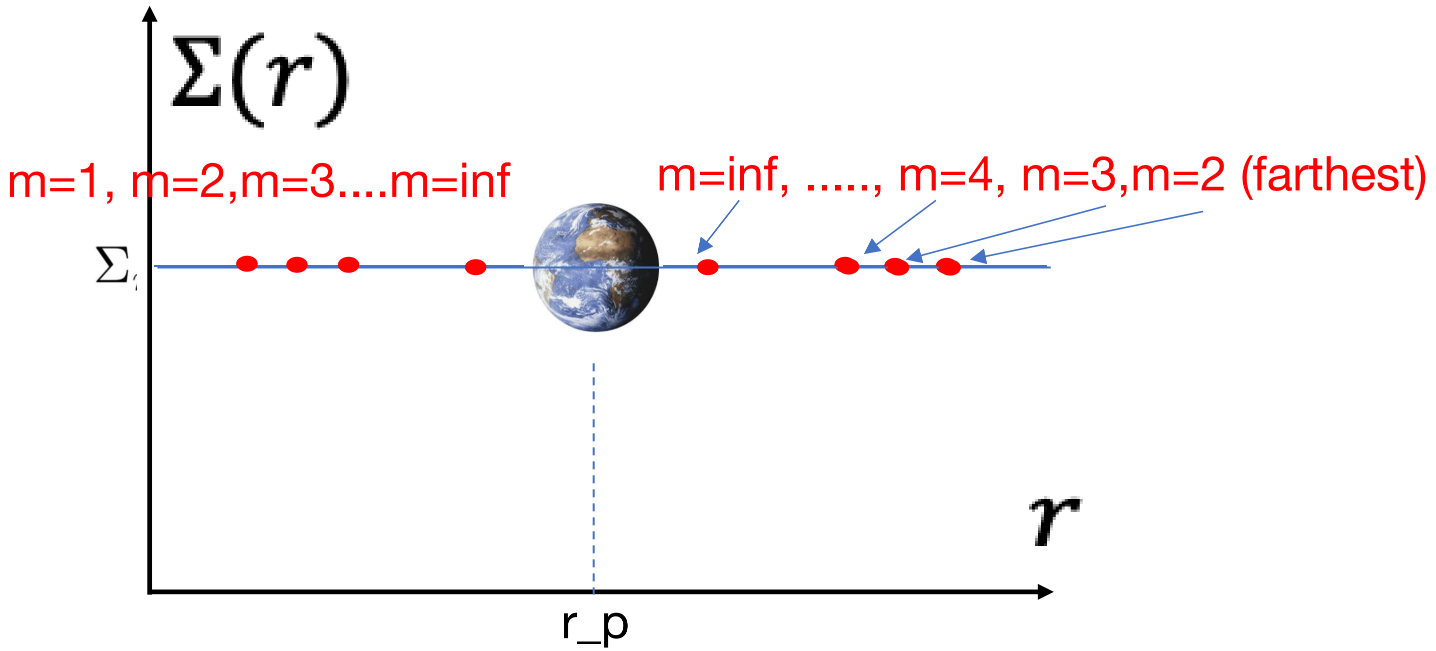


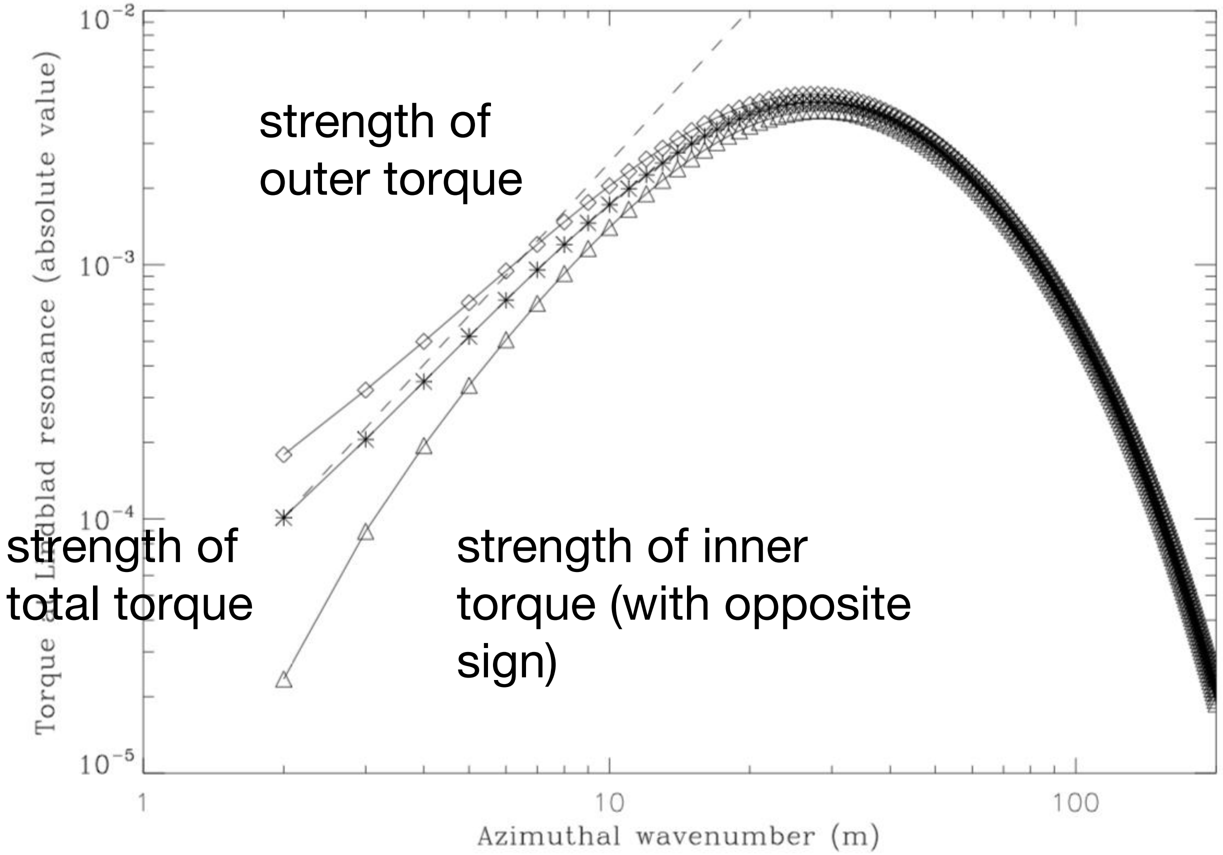
How to calculate the torque from the disk?
Most of the torques arise from sum of m-th order Lindblad resonance locations, where the period of gas is ~(1+-1/m) the planet period -> gives a secular (长期) perturbation

Cause of Migration: Type I

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

Each m-th order torque is determined by values of distance, surface density, gas rotation velocity..... evaluated at the PARTICULAR RESONANCE LOCATION

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)



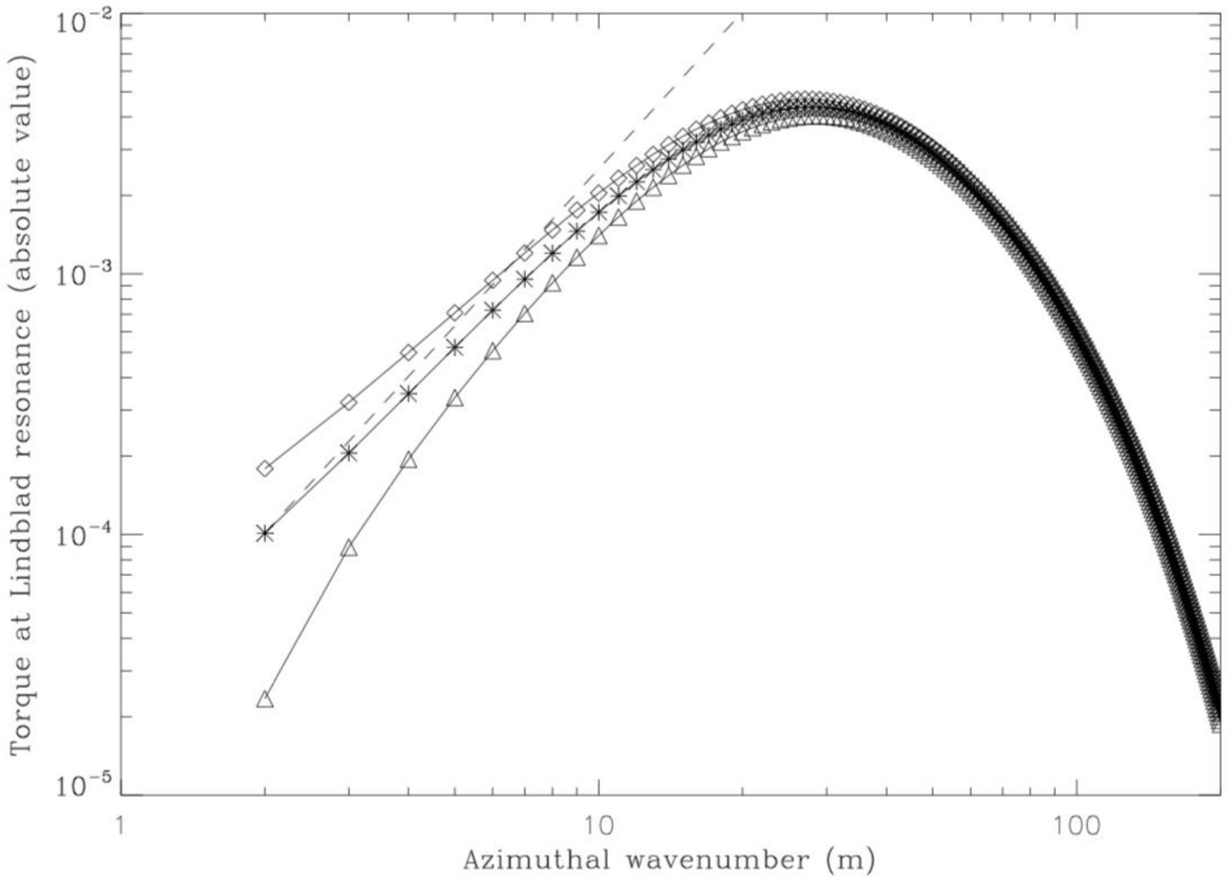
Cause of Migration: Type I

Total torque:

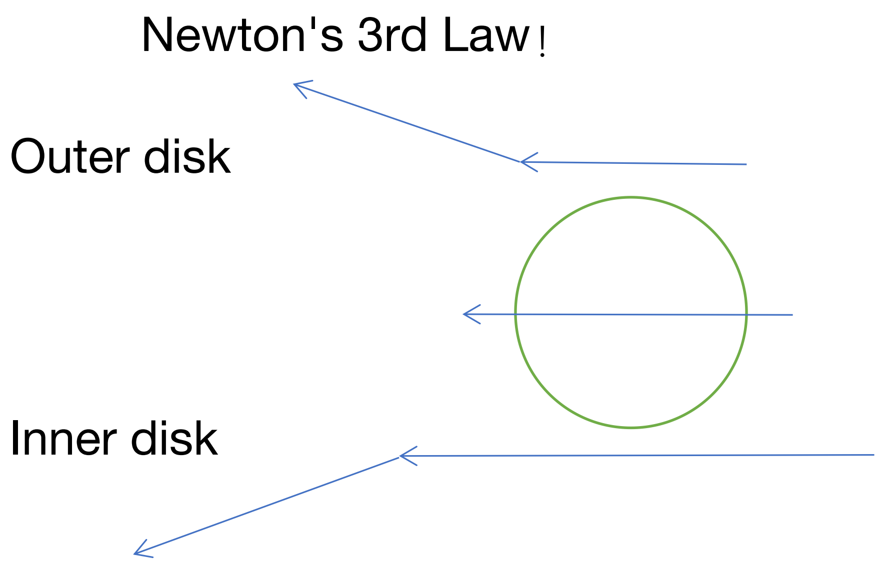
$$\Gamma_{typeI} \propto q^2\Sigma, q = M_p/M_*$$

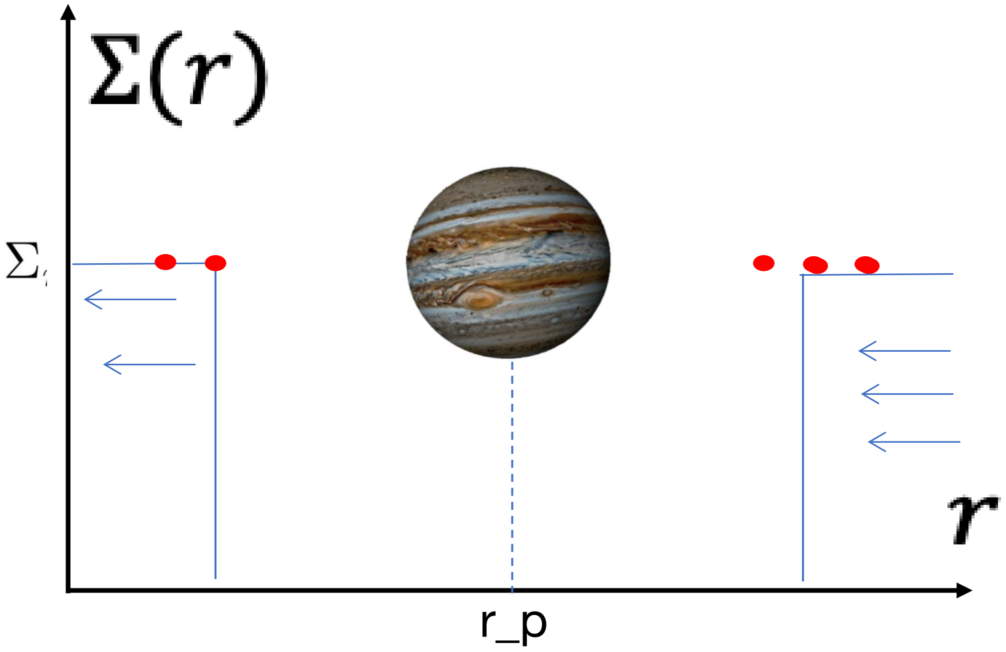
Migration radial speed:

$$\dot{r_p} = -\frac{\Gamma_{typeI}}{r_p\Omega_p M_p}$$



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

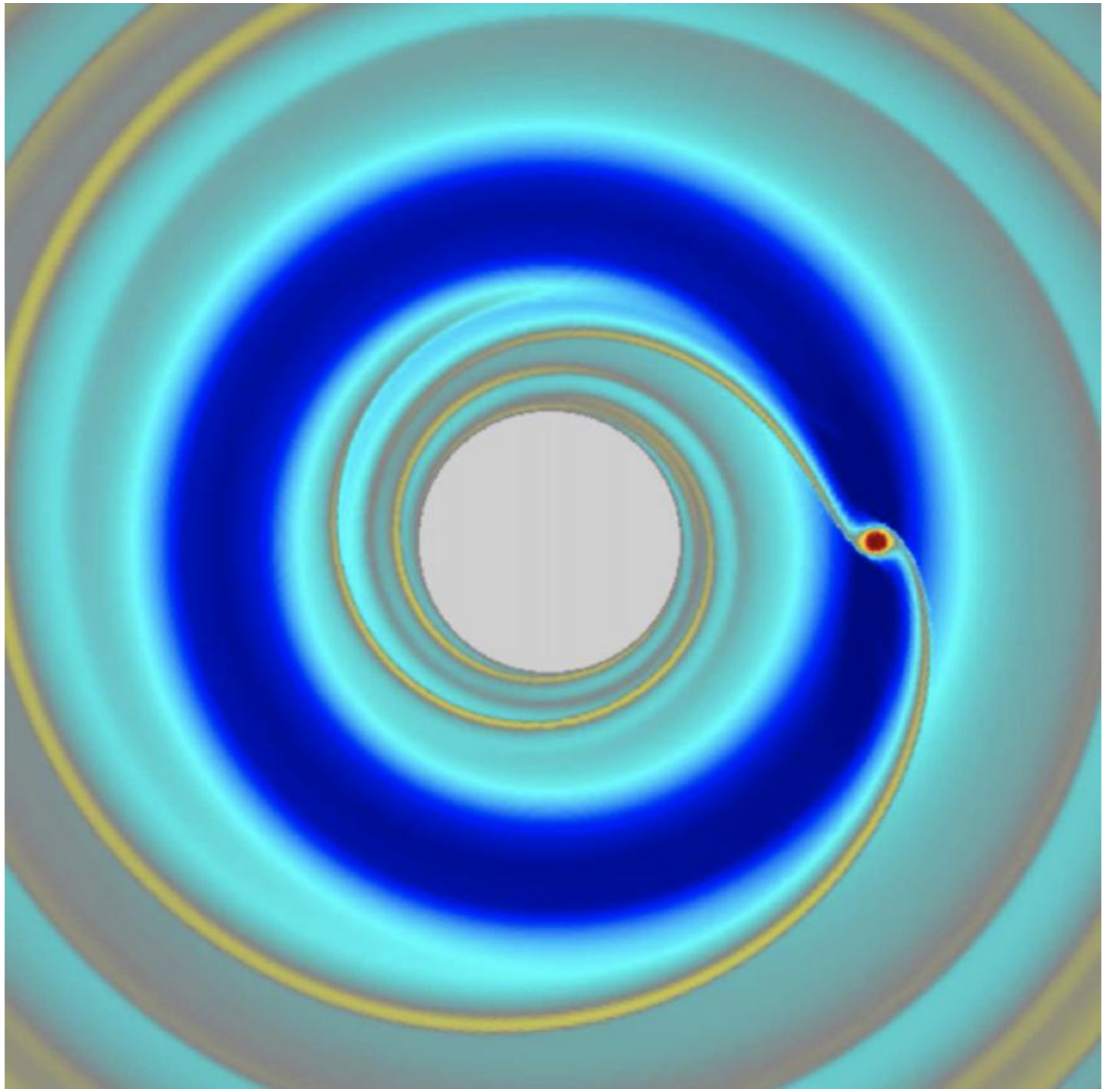
Most resonances are gone (with density/torque at r_m nearly 0)!

But the disk gas, due to angular momentum transportation mechanisms, has an inward accretion 吸积 velocity, when this is blocked, gas accumulates to push on the planet until it reaches same radial speed as gas (go with the flow 随波逐流).

New Type II Migration

However, 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



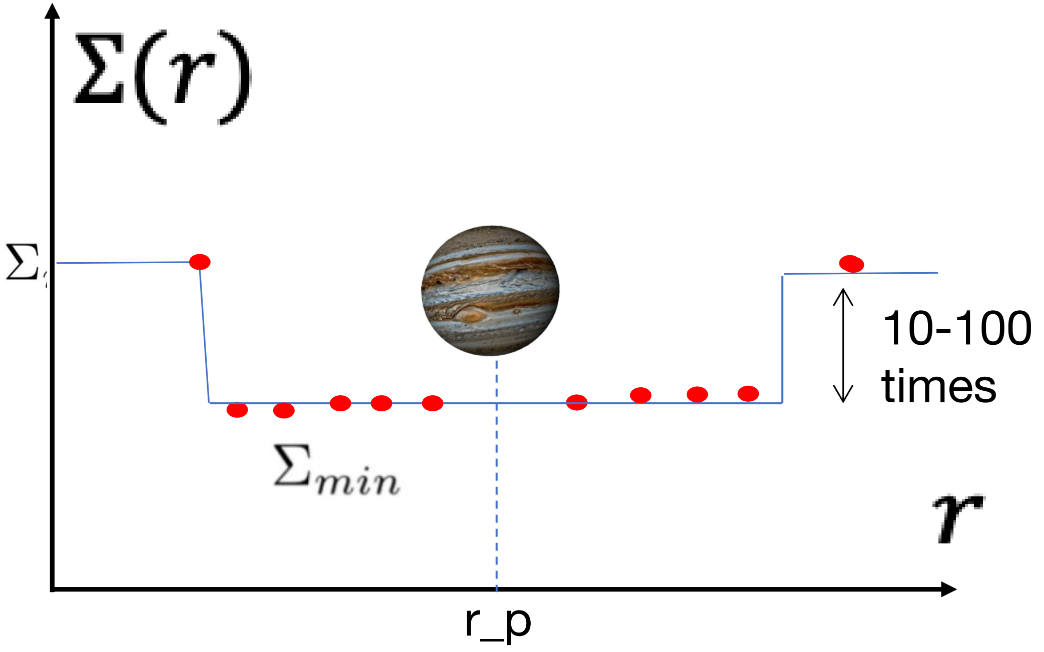
New Type II Migration

In the new gap models, the gap maintains some non-zero bottom density. This challenges the classical theory.

$$\frac{\Sigma_{min}}{\Sigma} \approx \frac{1}{1+0.04K} \qquad \text{where} \qquad K \propto q^2$$

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

We only have to replace the density in the Type I torque expression!



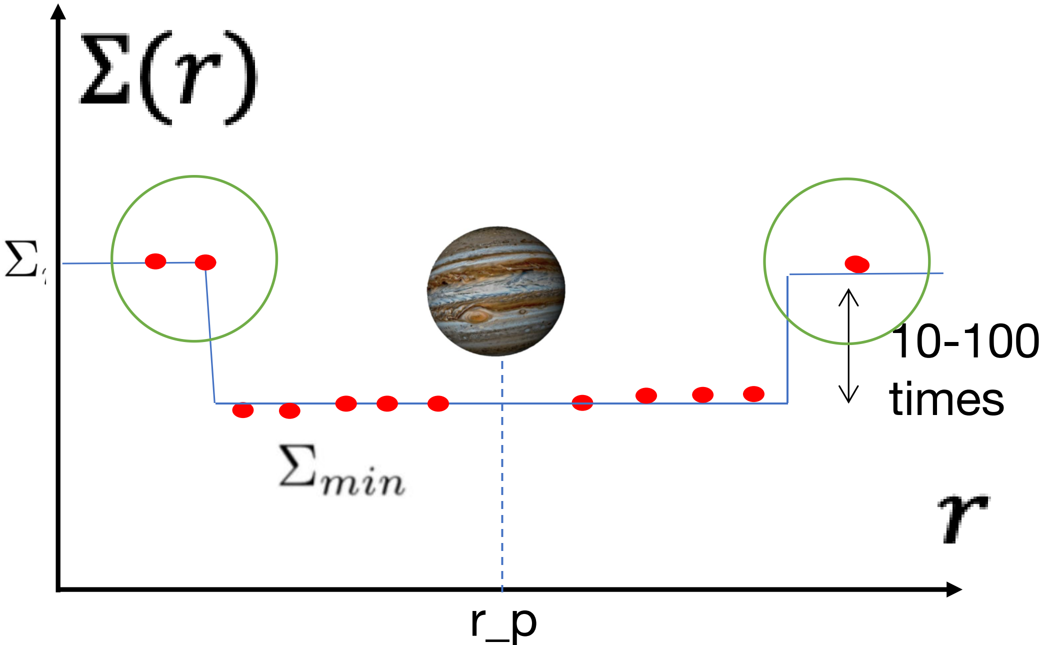
$$\Gamma_{typeI} \propto q^2\Sigma \longrightarrow \Gamma_{typeII} \propto q^2\Sigma_{min}$$

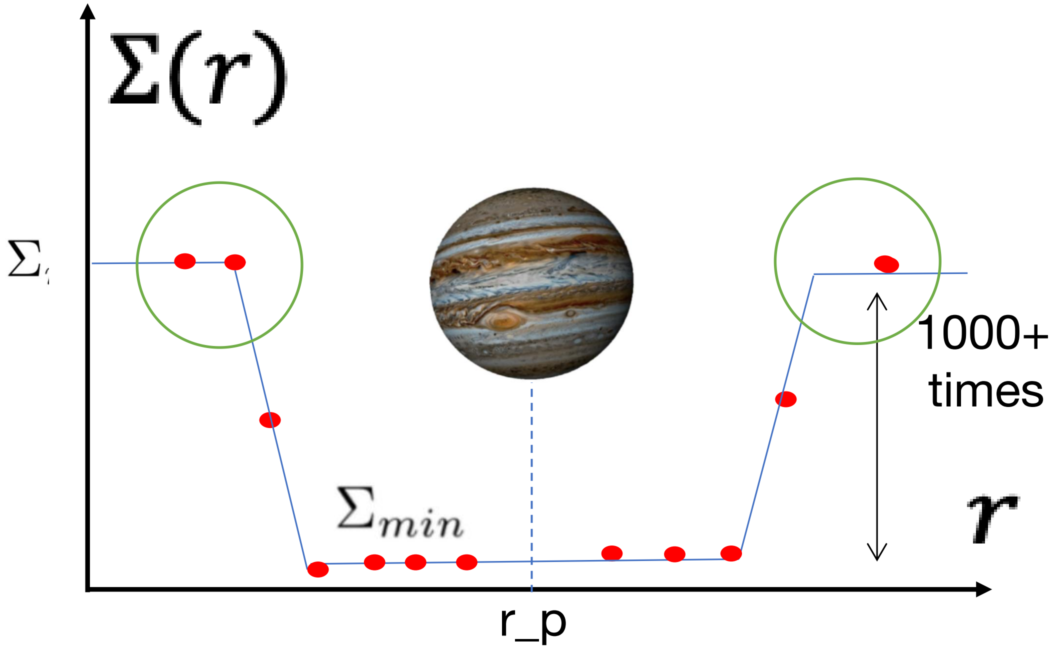
Effect of Gap Edges

However, it fails to predict migration rates for even larger planets than open up very deep gaps. Chen + (2020, ApJ) studied this process, and one of our main finding is the exact reason for this discrepancy.

Hypothesis: 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(I personally call them rogue torques 野蛮力矩)

Therefore, the case of shallow gap and deep gap will be very different, according to how large is the depletion factor (whether it gives the Rogue torques dominance)



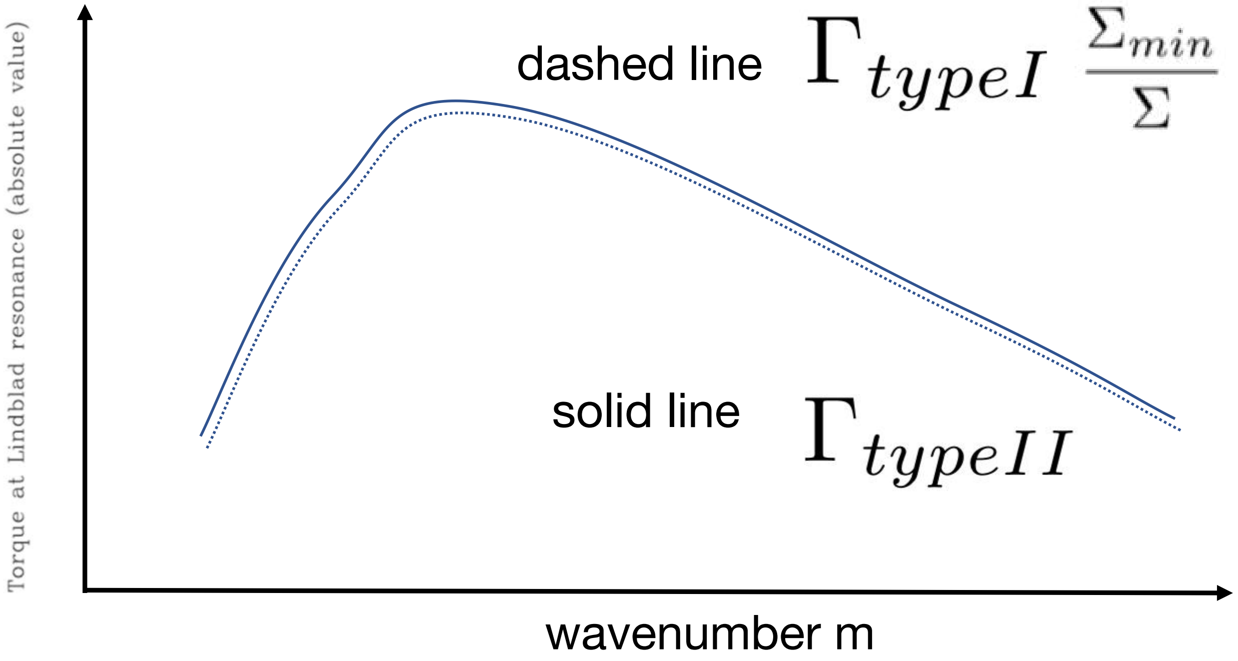


Effect of Gap Edges

Method:

1. We perform computer 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)

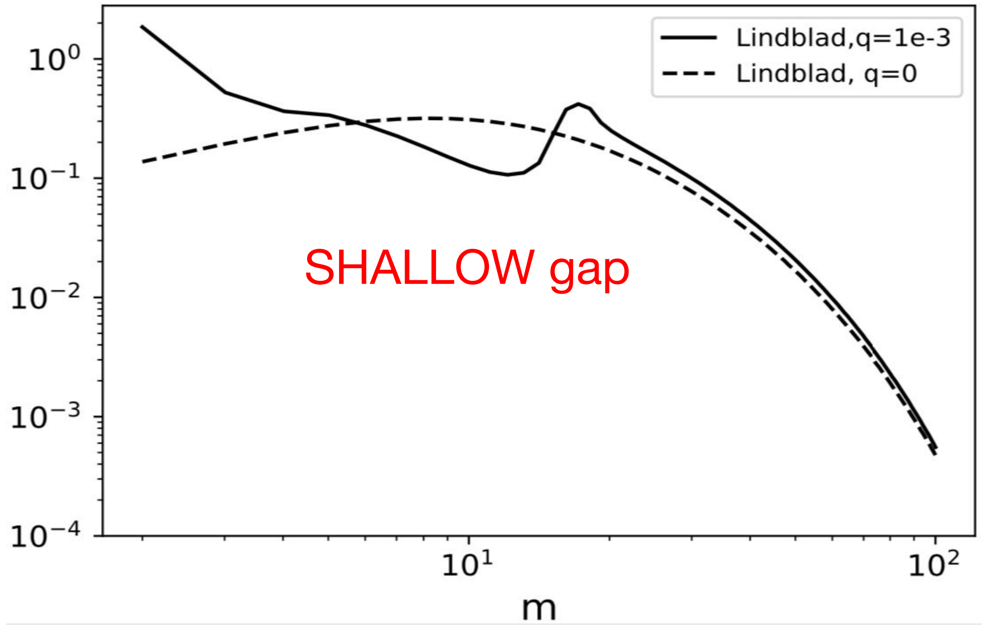
2. We calculate each m-th order torque for the perturbed profile and compare with the unperturbed torque **times the depletion factor**, if all torques are uniformly dropped to a lower density:

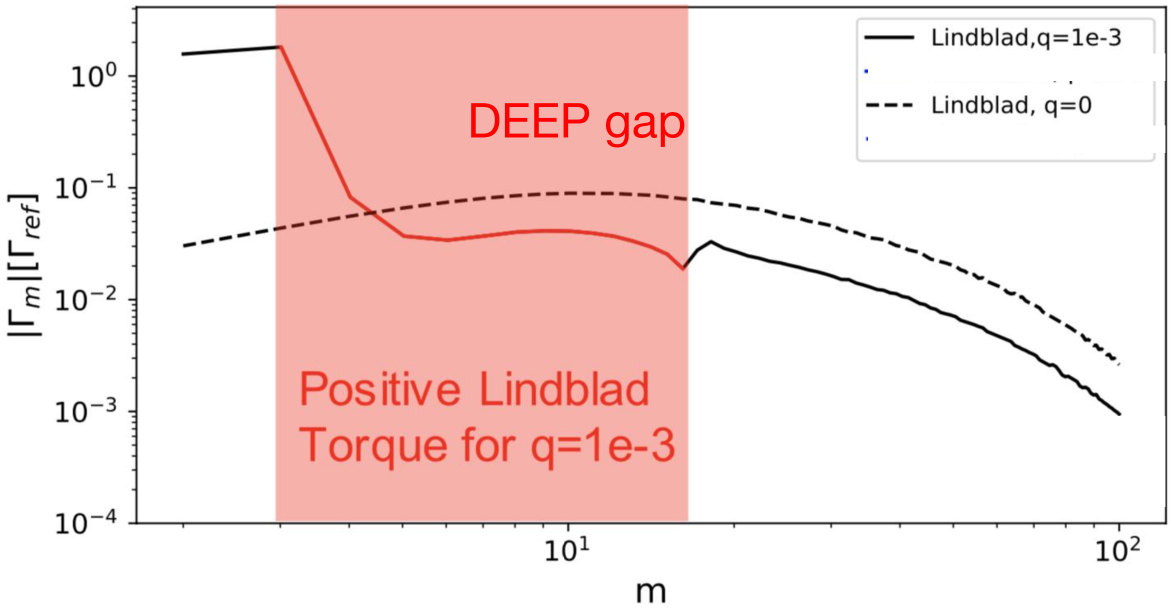


We not only expect the total torque to only differ in a density factor, but ALL the individual torques should overlap in comparison!

Effect of Gap Edges

What is our results in reality?



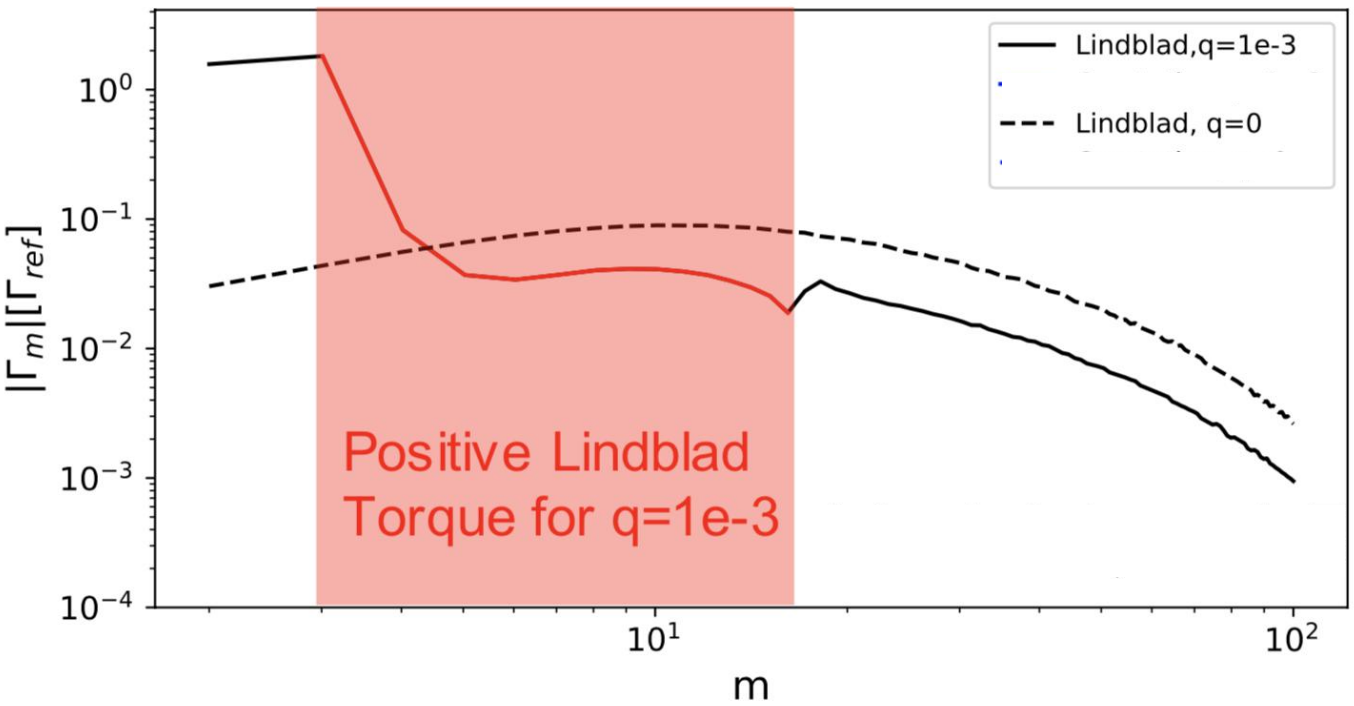


When the gap is shallow, the low-order torques from the gap edges is negligible compared to the sum of all other torque in the bottom, and the approximation is valid

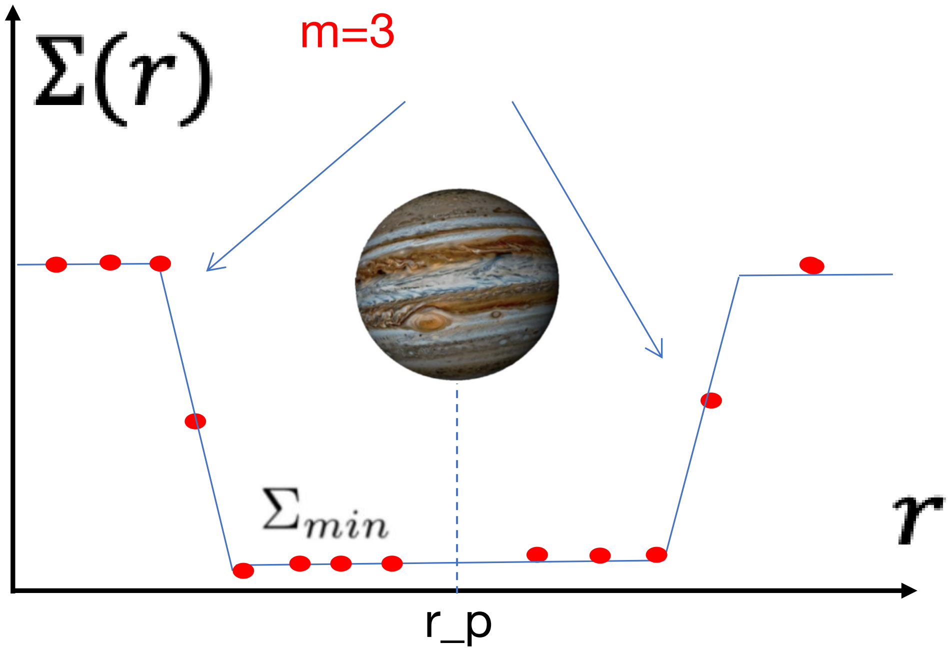
When the gap is deep, the low-order torques from the gap edges will dominate the total torques since the gap density is larger by 2 or 3 orders of magnitude.

Effect of Gap Edges

DEEP gap



e.g. relative magtitude of m=3



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 “go with the flow”

- 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

- Works of Chen+ (2020): Effect of Rogue Lindblad Torques at Gap Edges
  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 (addressed many other issues, see https://arxiv.org/abs/2007.14905)