On the Death of Type II Migration & What Might Replace It

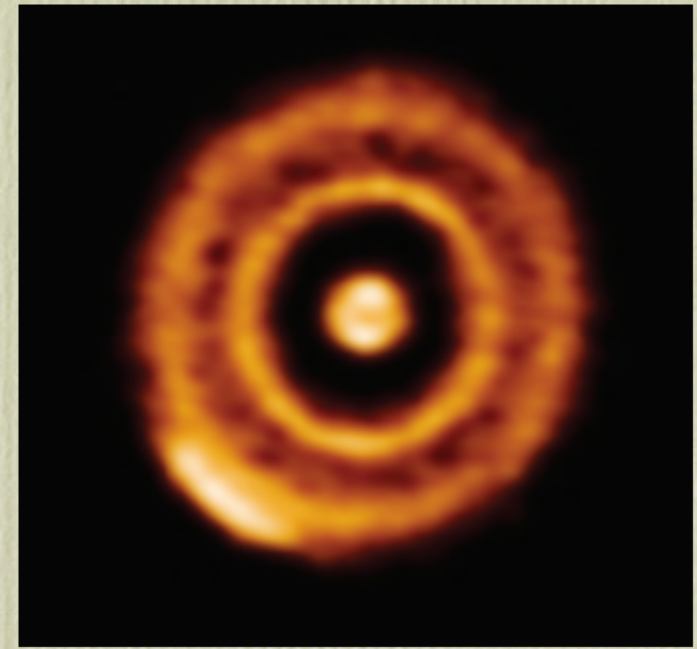
Yoram Lithwick

Northwestern University/ CIERA

with Adam Dempsey, Wing-Kit Lee, and Diego Munoz

Motivation #1

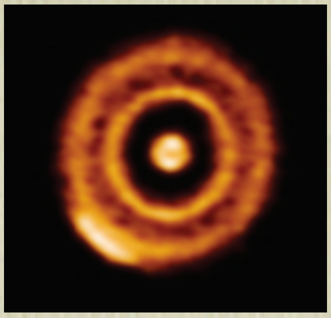
- Protoplanetary disks with large inner holes (a.k.a. "transitional disks")

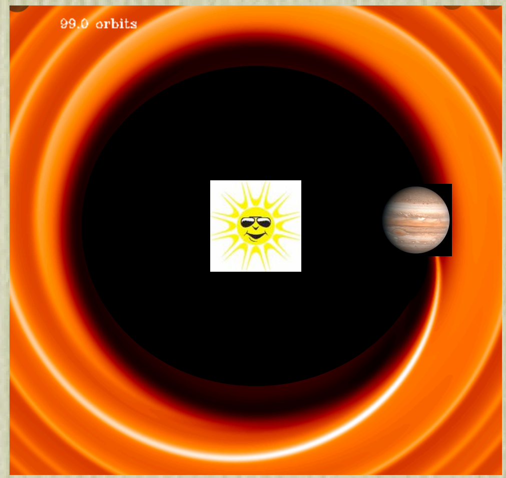


ALMA image
(Andrews et al. '19)

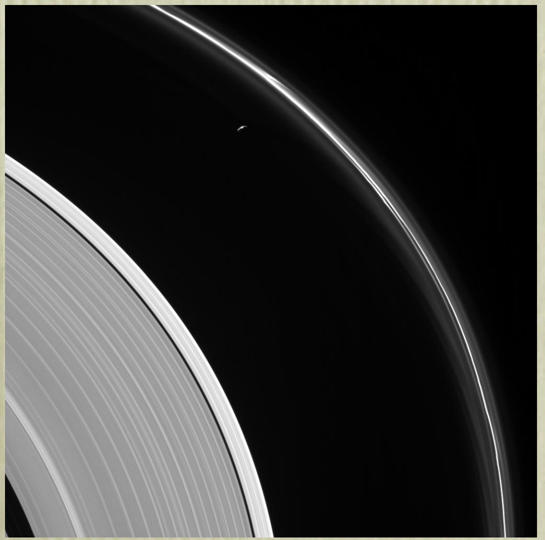
- ~10% of disks have large inner holes
  - appears true for dust *and* gas

- Can inner holes be caused by a planet?



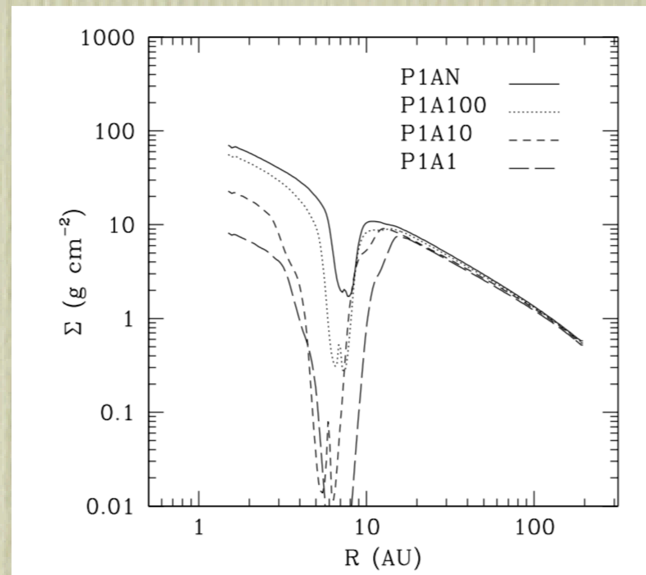


Planet could shut off accretion from the outer disk, leading to an inner hole.



Saturn ring&moon

- But: simulations show narrow gap & no hole



(Zhu et al. ’11)

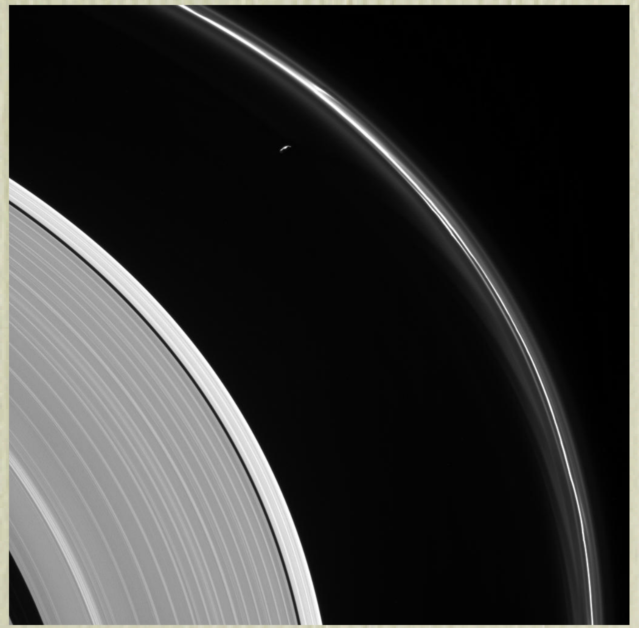
- Planets are (at best) leaky dams

- see also: (Lubow & d'Angelo '06, Crid & Morbidelli ’07, Duffell et al. ’14, Fung et al. ’14, Durmann & Kley ’15, Kanagawa ’17, ’18)

- What if the planet is very massive (or a brown dwarf or binary star)?

- What if the viscosity is very small?
  Then inflow is slower => easier for planet to dam it

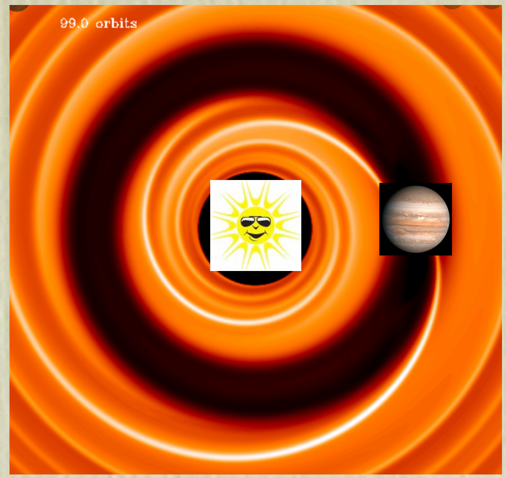
  (But have to run simulations for longer.)



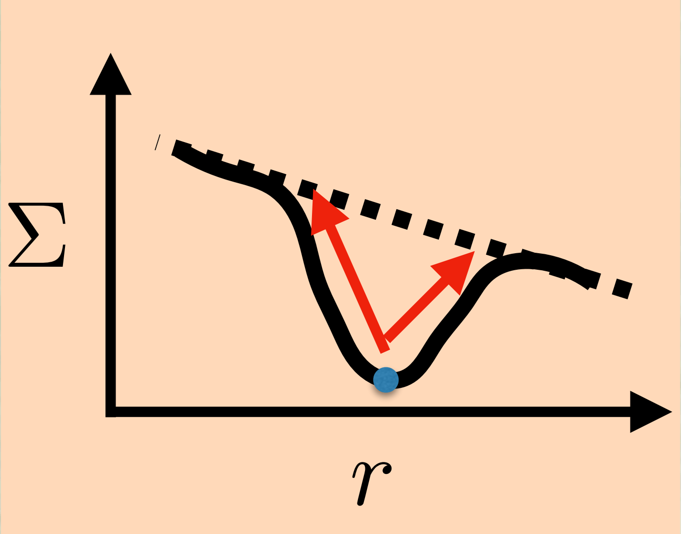
1D Model of Planet+Disk

- Planets torque the disk by launching spiral density waves

(Lin & Papaloizou, '79), (Goldreich & Tremaine, '80)



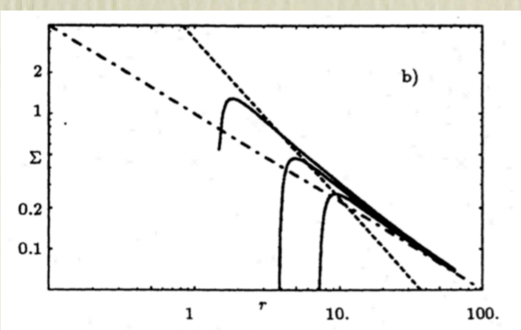
- "Standard torque formula": determines the disk's viscous evolution in 1D (and backreaction onto planet => migration)



1D Model: results

- 1D models predict Jupiter-mass planets are *very* strong dams

- Syer & Clarke (1995): massive planet in disk (with migration)



- Ward (1997): for planets mass > Jupiter, planet gap exponentially deep

  => planet locked into disk

Type II migration

(~800 citations)

Type II paradigm also predicts migration rates

- Could explain hot Jupiters (Lin et al. '96)

- Disk migration of close binary stars
  - Binary stars thought to form at ≳50AU. Observed binaries at ≲ 50 AU, should thus have been migrated inwards by disk

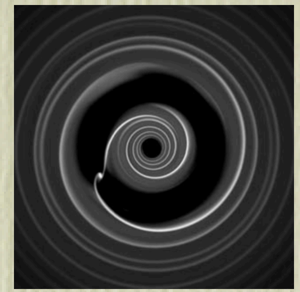
    (Bonnell & Bate '94, Kratter et al. '08)

- Disk migration of supermassive black hole binaries
  - Could solve the "final parsec problem"

Simulation Setup

(Dempsey, Lee & Lithwick, '20)

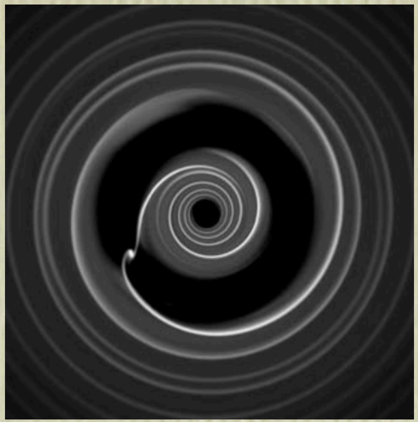
- Place planet on *fixed* orbit in viscous disk & run to viscous steady state



- Parameters: $q = M_{planet}/M_{star}$
  α
  h/r

1: What is effect of planet on disk?

2: What is effect of disk on planet (especially: migration rate)?



Assumptions:

1: Neglect migration

- ok when disk mass < planet mass

2: Disk has lived for a viscous time

3: 2D

4: α viscosity

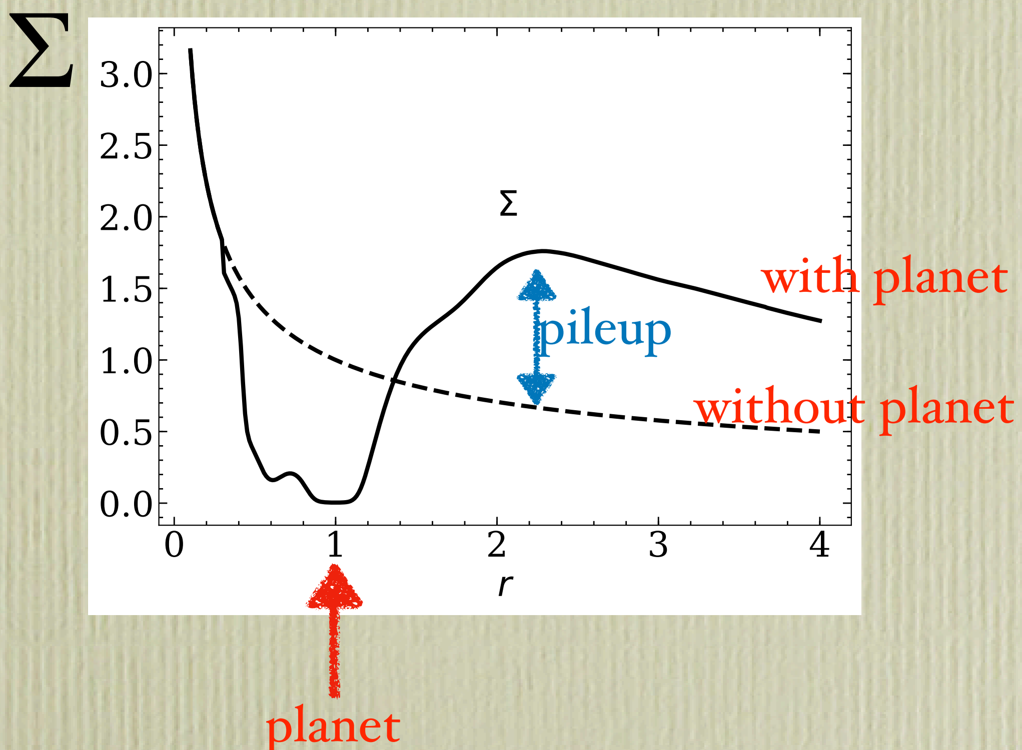
5: etc. (locally isothermal equation of state, softening radius)

Result: Leaky dam

FARGO sim

$q = 10^{-3}$

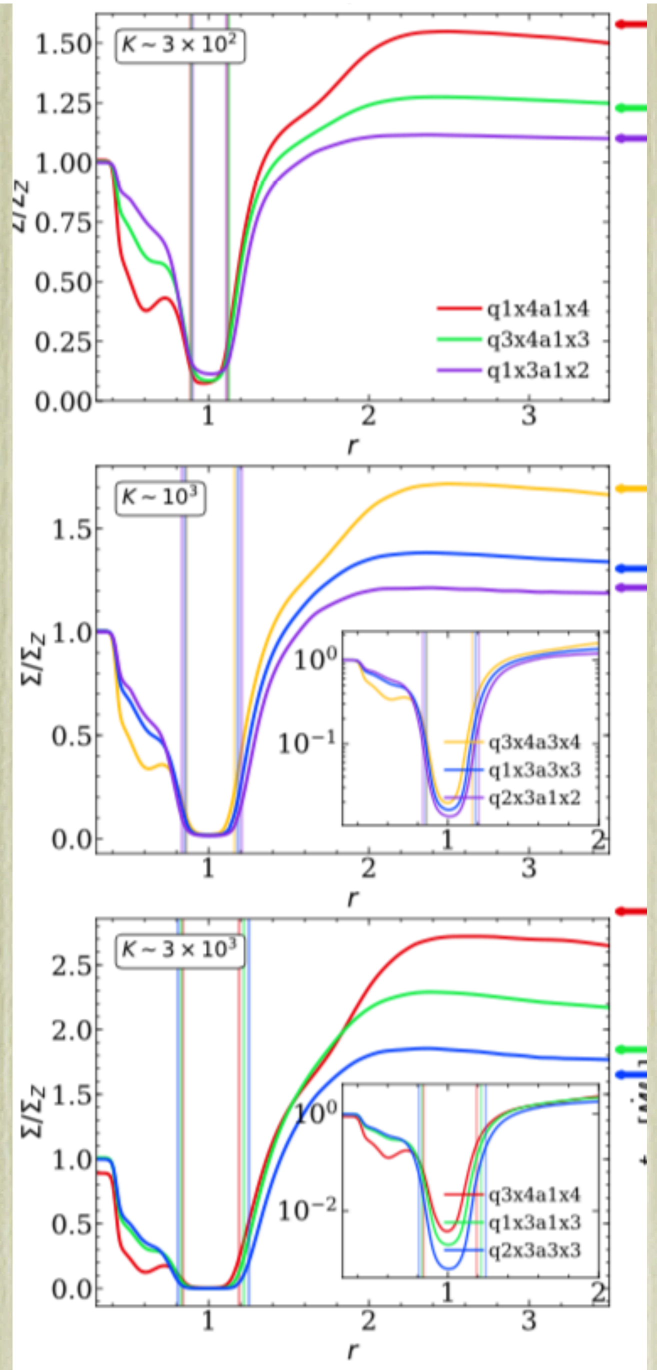
$\alpha = 10^{-3}$



Increase mass, decrease viscosity

$$K = \frac{q^2}{\alpha}\frac{1}{h^5}$$

- Larger K ⇒ deeper gaps & larger pileups
- Pileups up to ~3



$q = 10^{-3}$
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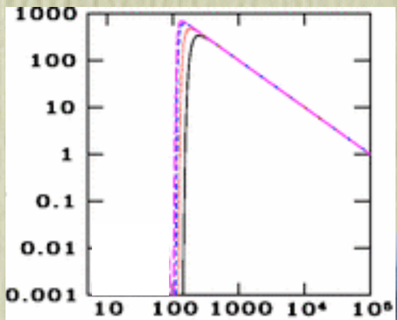
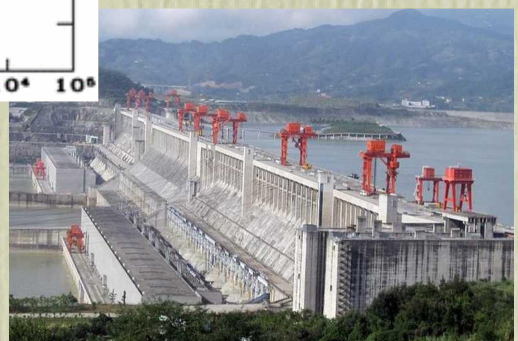
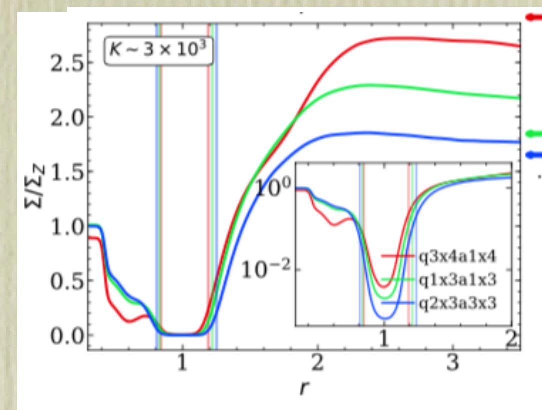
1D Models: what went wrong?

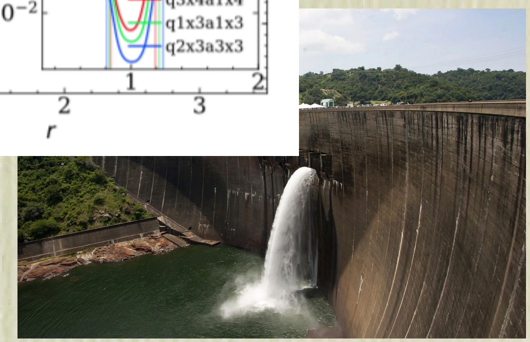
1D models → 2D simulations



gap depth $\sim e^{-0.1K}$





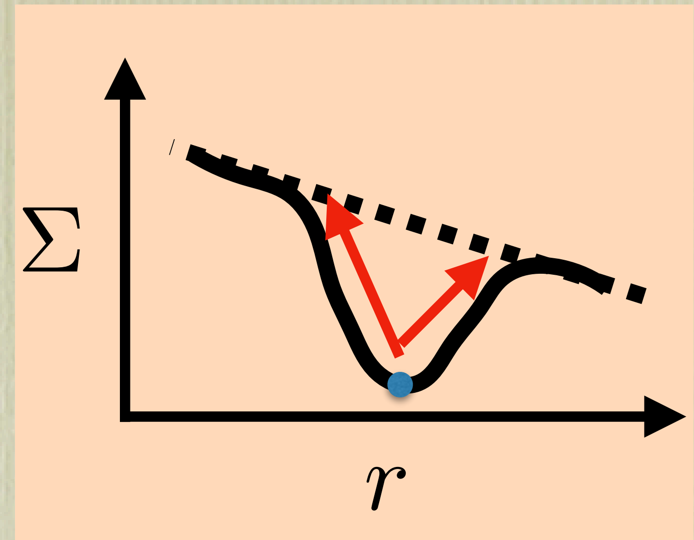


- Important for surface density profile

- Less important for migration rate (e.g., Scardoni et al. '20)

(Because when pileup ~order unity, planet moves at ~ disk drift rate)

- What really happens:



planet $\Rightarrow$ waves

t_{ex} = standard torque formula

(Lin & Papaloizou, '79, Goldreich & Tremaine, '80)

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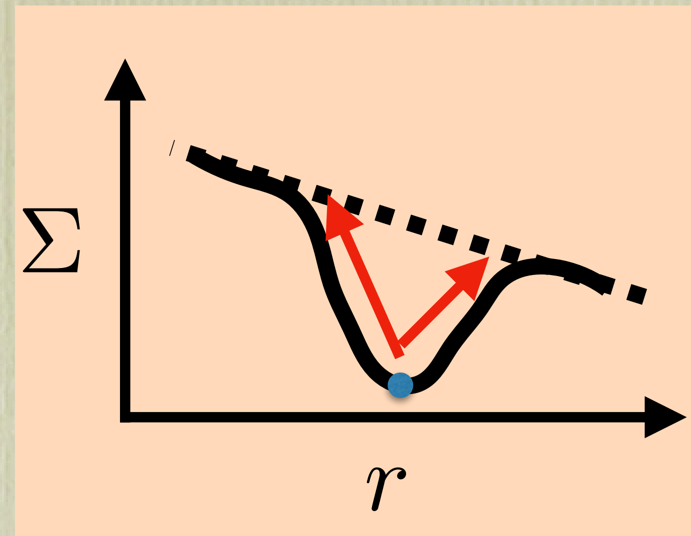


planet $\Rightarrow$ waves $\Rightarrow$ waves travel $\Rightarrow$ waves damp (viscosity/shocks)

$t_{\rm ex}$ = standard torque formula

(Lin & Papaloizou, '79, Goldreich & Tremaine, '80)

$t_{\rm dep}$

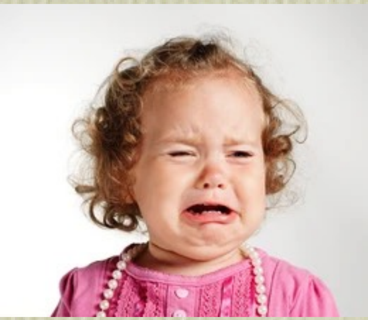
$$\frac{\partial}{\partial t}\left(\text{disk angular momentum}\right) = t_{\rm ex} \rightarrow t_{\rm dep}$$

- Distance waves travel is small. But has huge impact on gap depth

- Theory for wave damping is an unsolved problem

  (for Jupiter-mass planets. For lower-mass planets, see Goodman & Rafikov '01, Ginzburg & Sari, '18)

- Need simulations(?)



What happens at even higher K? (Dempsey et al, ’21)

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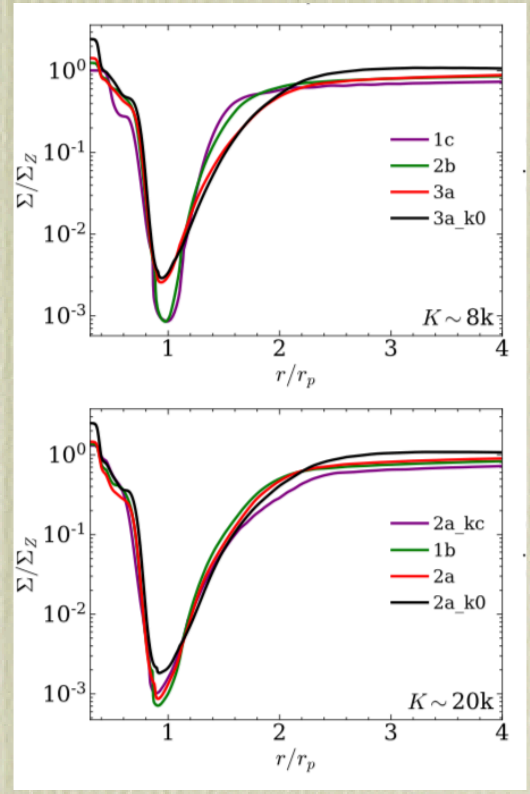
- Disk becomes eccentric for $q \gtrsim 2 \times 10^{-3}$ due to excitation by resonances

  [e.g., Kley & Dirksen '06, Teyssandier & Ogilvie '17]

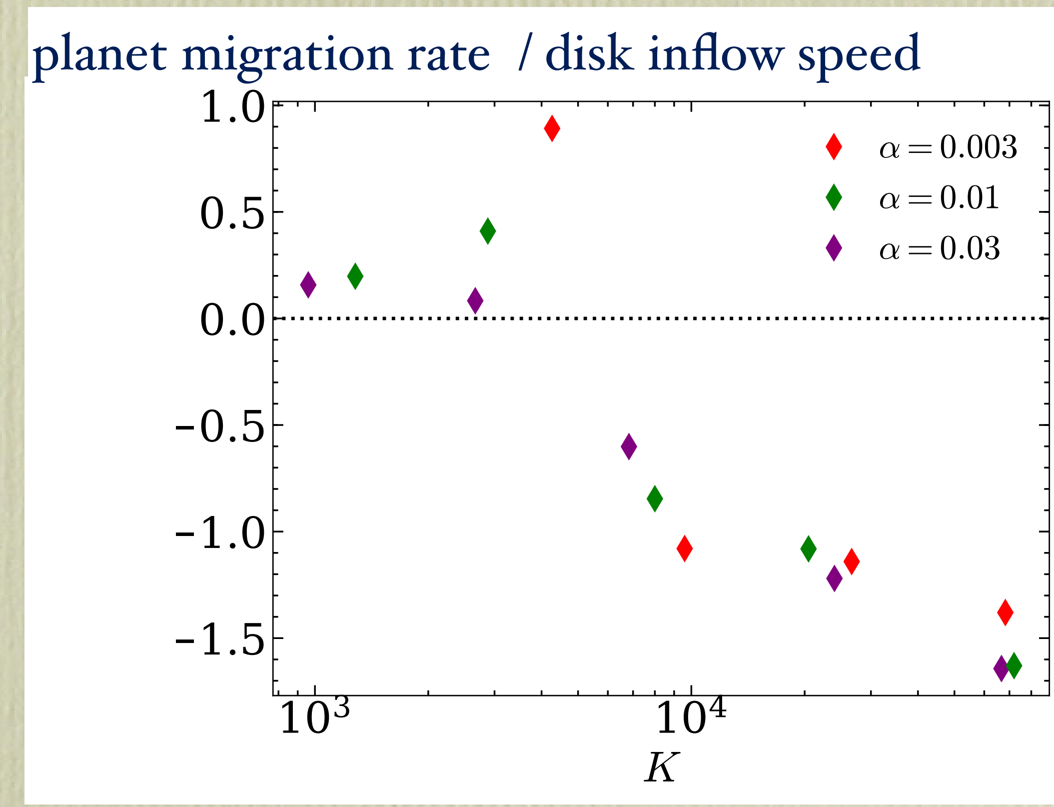
- Pileup goes away!

  (eccentric outer disk overflows planet's orbit)



What happens at even higher K?

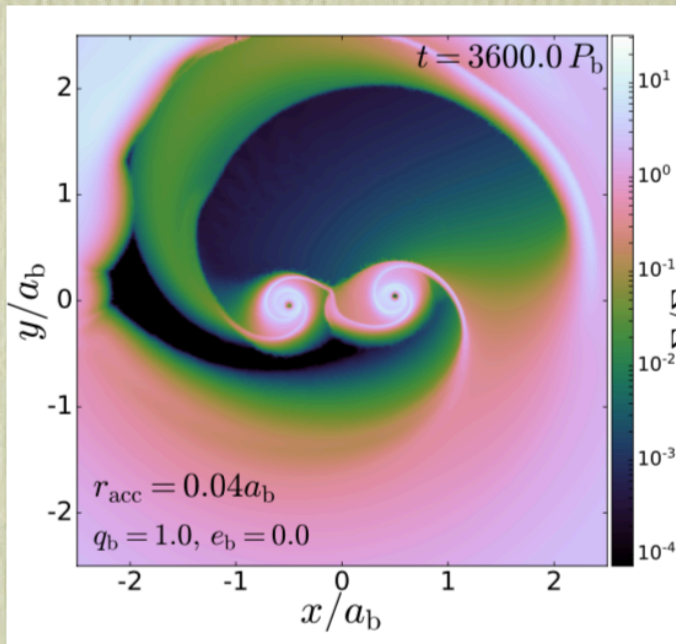
- super-Jupiters migrate *outwards!*

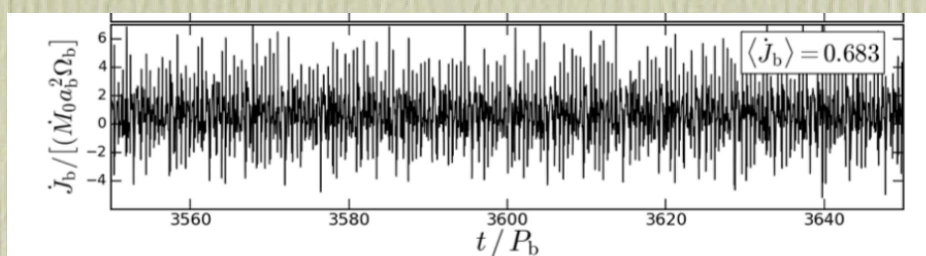


- Can perhaps explain: why hot Jupiters lower mass (Patzold & Rauer '02, Zucker & Mazeh '02)

  far out Jupiters (i.e., directly imaged)

Binary stars also found to migrate *outwards*





[Munoz et al. '19]

Also found by: [Miranda et al. '17], [Tang et al. '17], [Moody et al. '19], [Duffell et al '19]

Caveats

Assumptions:

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- ok when disk mass < planet mass

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3: 2D   Wave damping and disk eccentricity could be different in 3D. But simulations costly.

4: α viscosity

5: etc. (locally isothermal equation of state, softening radius)

Caveats

Assumptions:

1: Neglect migration

- ok when disk mass < planet mass

2: Disk has lived for a viscous time

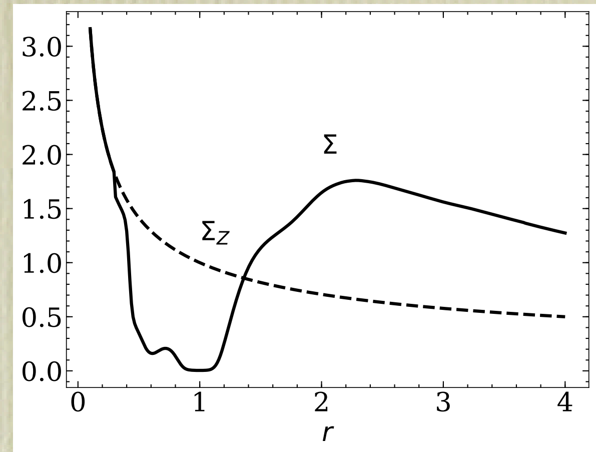
3: 2D — Wave damping and disk eccentricity could be different in 3D. But simulations costly.

4: α viscosity — Unsolved problem.

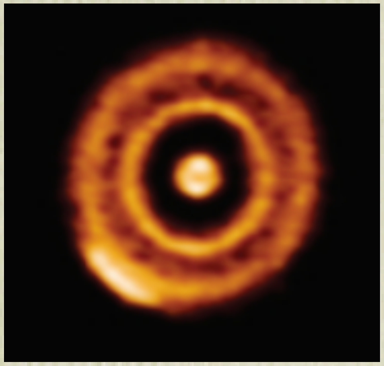
Super-important, but super-difficult

5: etc. (locally isothermal equation of state, softening radius)

Summary



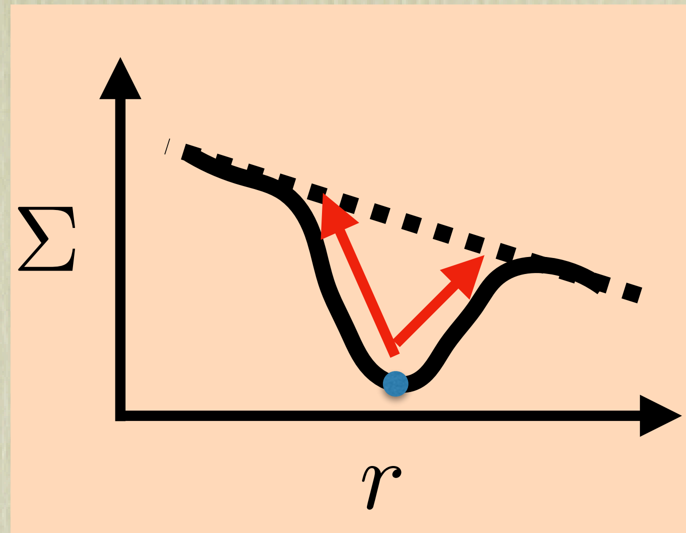
- From simulations:
  - Jupiter-mass planets produce modest pileups of gas density outside of their orbit
  - Super-Jupiters produce no pileup & migrate outwards



  - Pileups likely too small to explain transition disks

Summary

- Need better theory for wave damping



- Need 3D & other kinds of viscosity