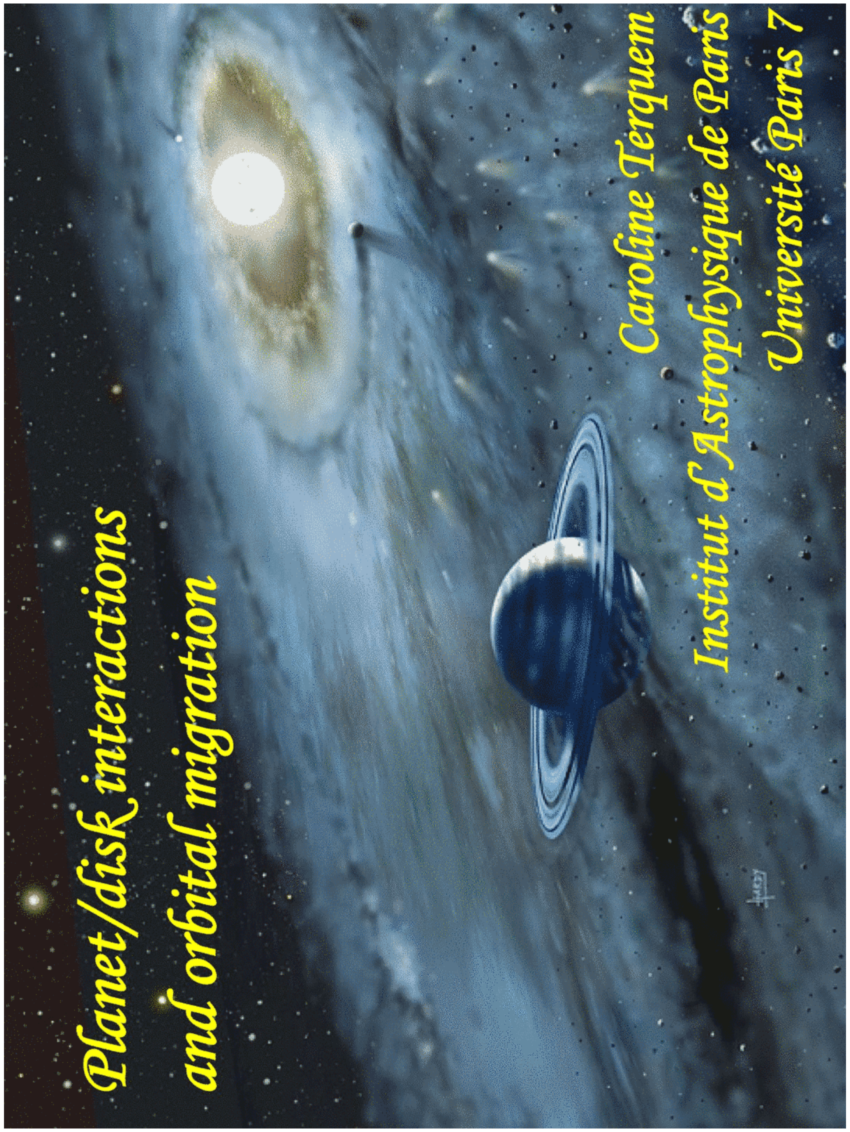
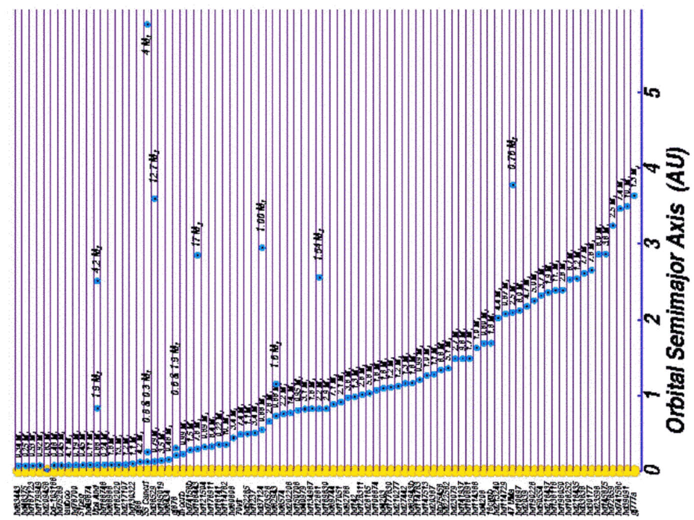
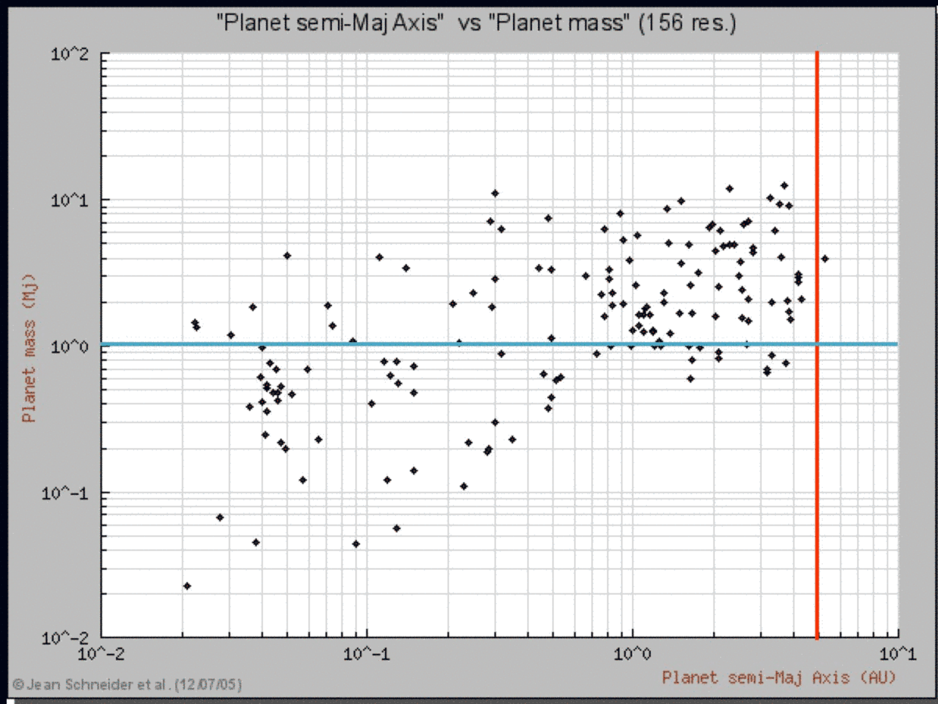


Extrasolar Planets

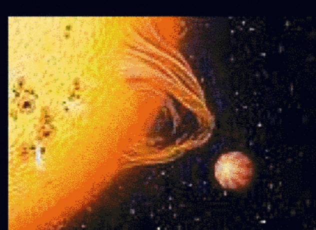
161 planetary systems
137 planets
18 multiple systems



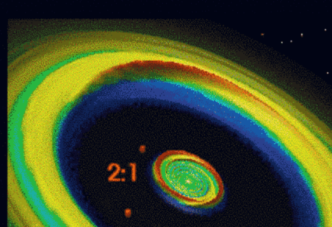
Characteristics of extrasolar planets



What do we need migration for ?


(L. Cook)

✓ Hot Jupiters: forming planets at small distances:
too hot
not enough material



(G. Bryden)

✓ Planets in resonances: capture

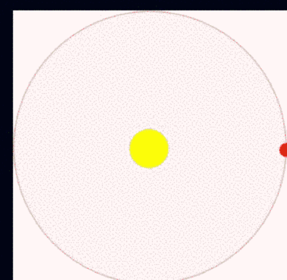
Planet migration

✓ Interaction between 2 or more Jupiter-mass planets —> orbit crossing —> collision or ejection

(Rasio & Ford '96, Weidenschilling & Marzari '96)

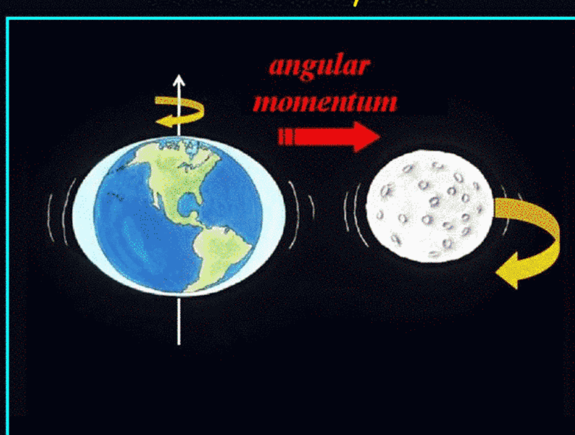
✓ "Migration instability": resonant interaction between planet and planetesimals —> ejection of planetesimals.
Requires massive disks…

(Murray et al. '98)

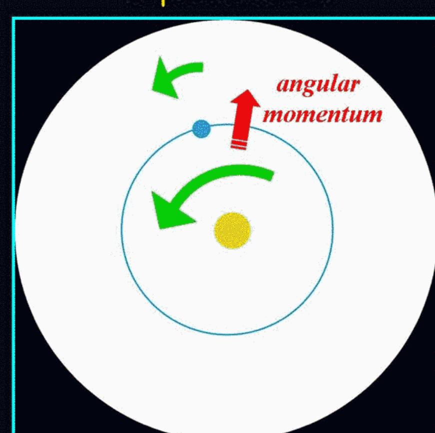


Tidal torques

Earth-Moon system



Keplerian disk



(Goldreich & Tremaine '79)

Type I migration

Difference between the torque exerted by the disk interior and the disk exterior

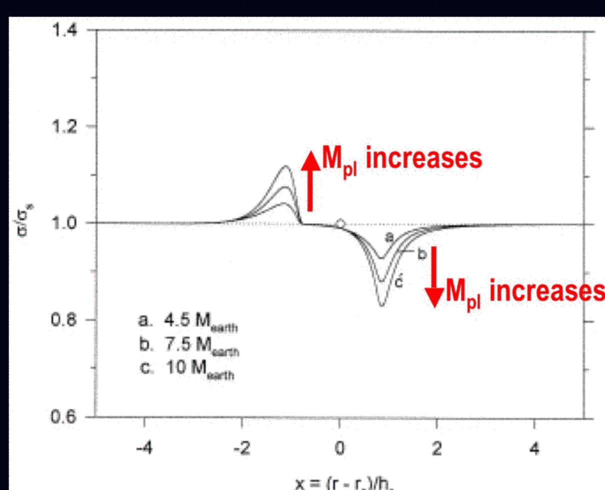
—> the planet migrates **with respect to** the disk on a **very short timescale ~ 10^4-10^5 ans**

$$t(yr) = 10^8 \left(\frac{M_{pl}}{M_{earth}} \frac{\Sigma}{g/cm^2} \right)^{-1} \left(\frac{r}{au} \right)^{-1/2} 10^2 \left(\frac{H}{r} \right)^2$$

(Goldreich & Tremaine '79, Ward '97)

Type I migration

Surface density perturbation

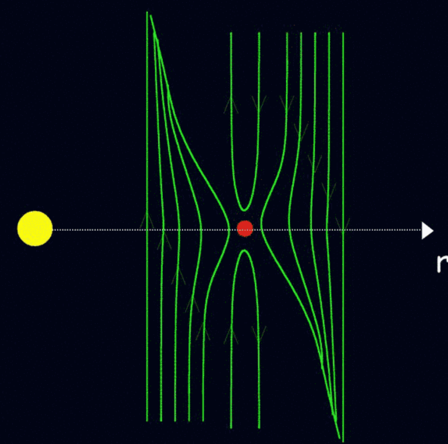


(Ward '97)

Type II migration

The planet opens up a ***gap*** and is locked into the disk viscous evolution process

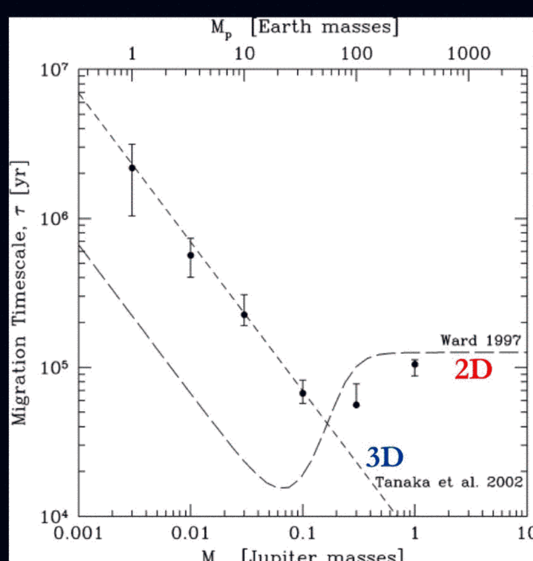
—> migration occurs on **the viscous timescale ~ 10^5 ans**



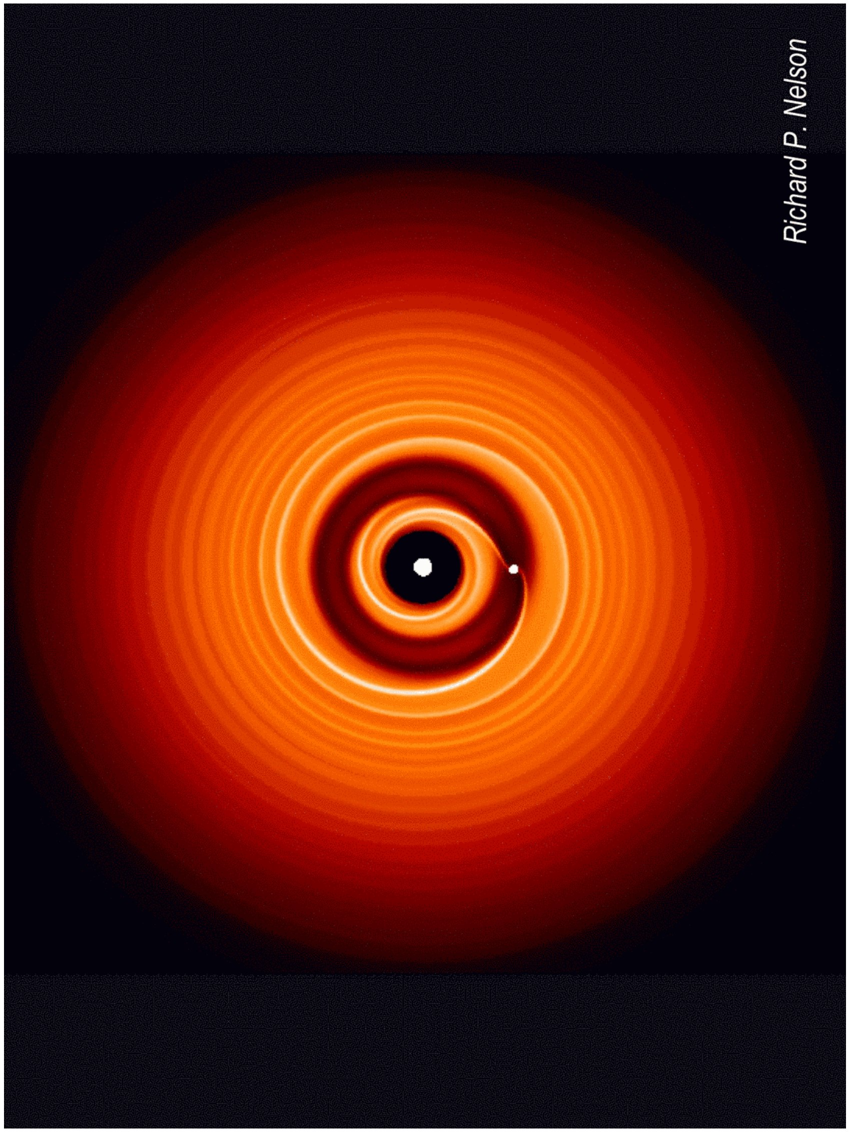
$$t(yr) = \frac{1}{\alpha}\left(\frac{r}{H}\right)^2 \Omega^{-1} = \frac{0.2}{\alpha}\left(\frac{r}{H}\right)^2 \left(\frac{r}{au}\right)^{3/2}$$

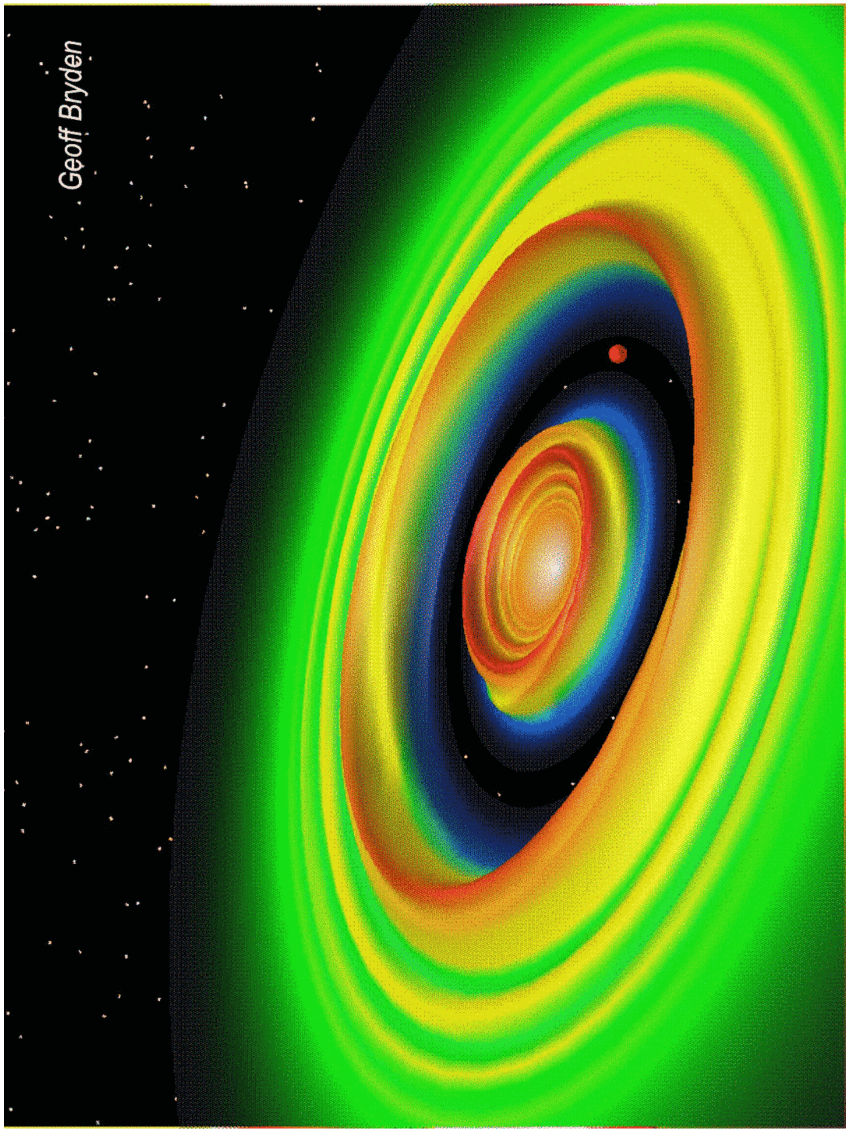
(Goldreich & Tremaine '80, Papaloizou & Lin '84)

Migration rate

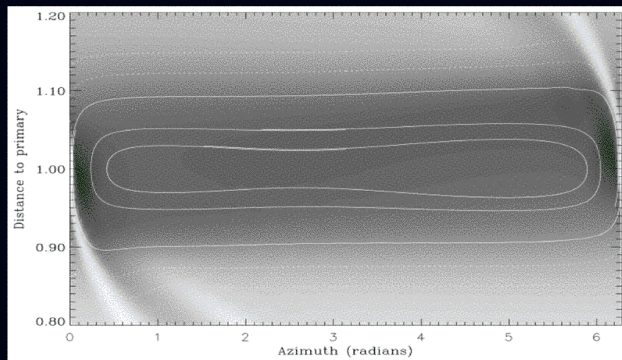


(Bate et al. '03)


Richard P. Nelson


Geoff Bryden

Runaway migration

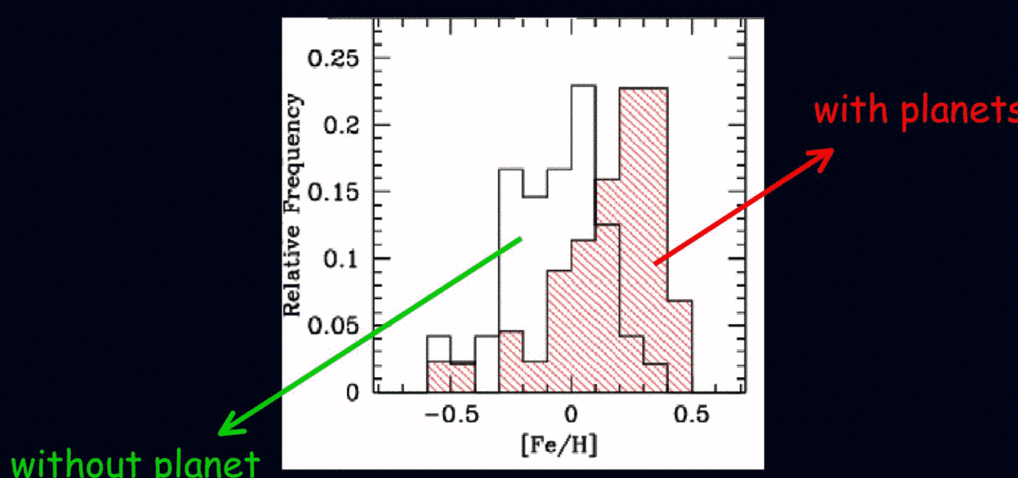


(Masset & Papaloizou 2003)

- Librating fluid elements: migrate with the planet —> lose angular momentum —> positive torque on the planet
- Fluid elements that cross the horseshoe region —> gain angular momentum —> negative torque on the planet
- If partial gap —> net negative torque on the planet which scales with da/dt and the mass deficit

Do planets fall onto their host star ?

Metallicity distribution of stars:



(Santos et al. 2001)

Tidal torque

$$T = -\iiint_{disk} \rho' \mathbf{r} \times \nabla \psi'$$

Exerted mainly at **Lindblad** and **corotation** resonances

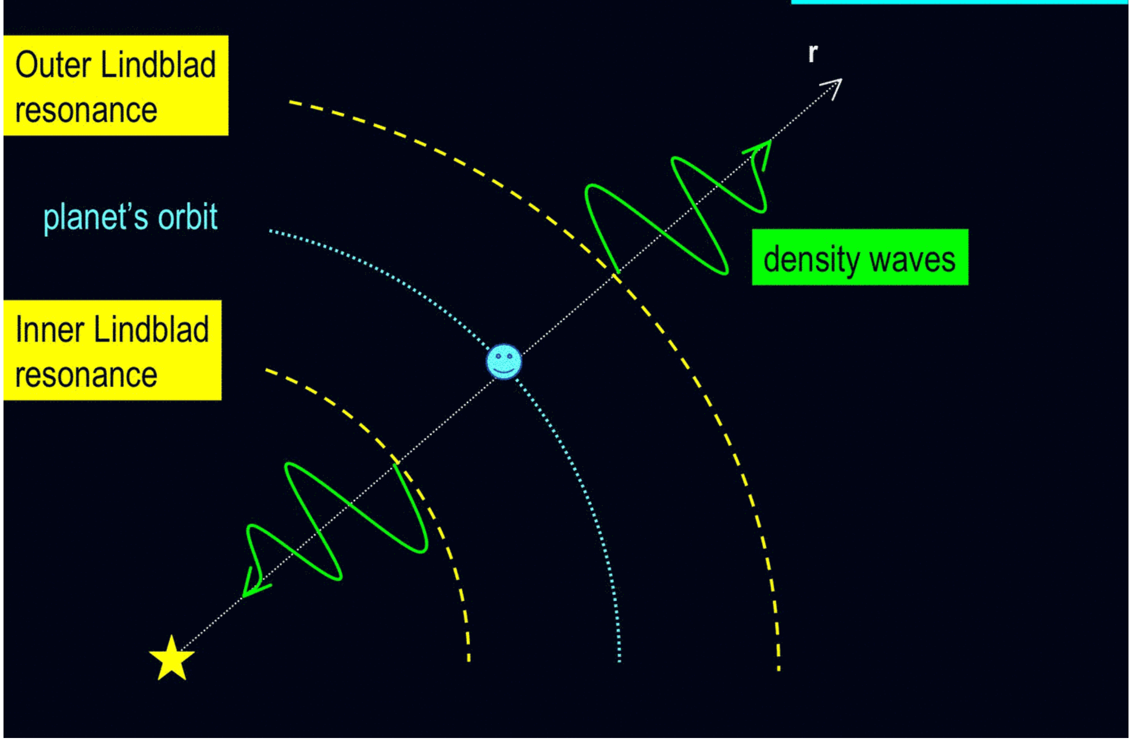
$T_{Lindblad}$: advected by waves

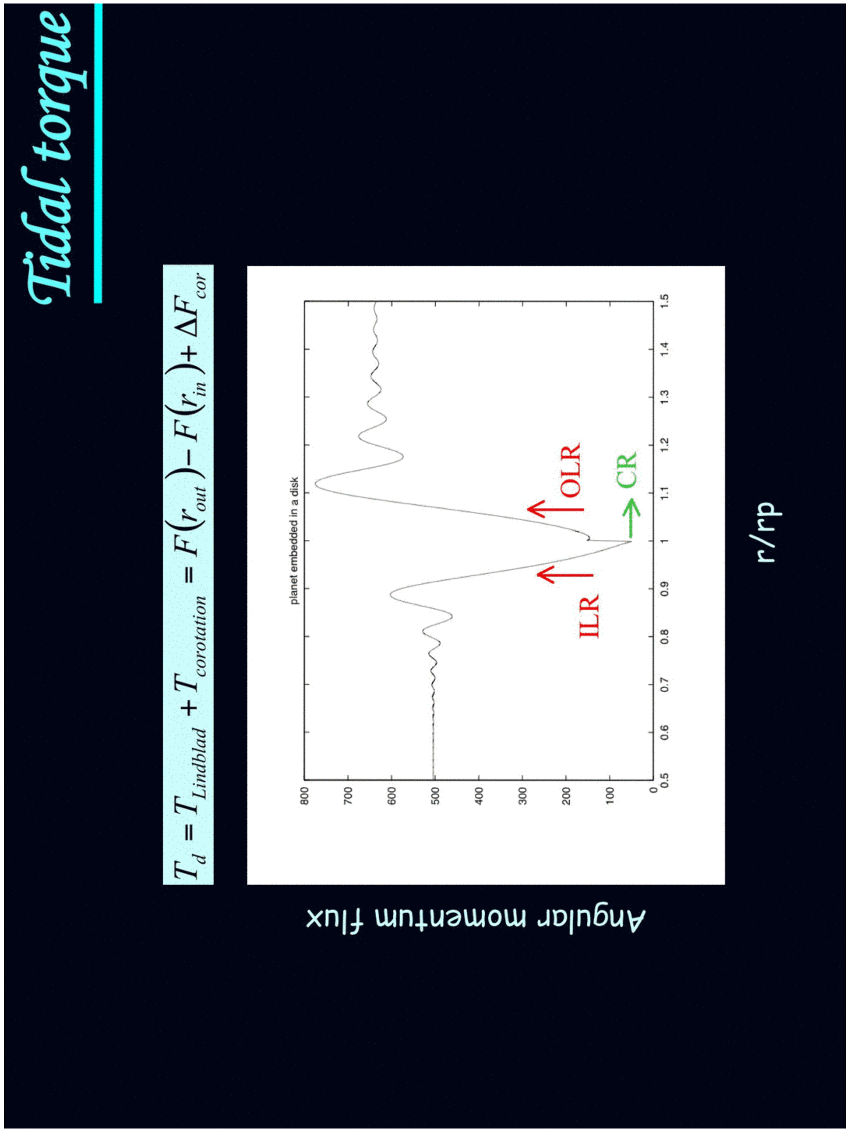
—> angular momentum flux

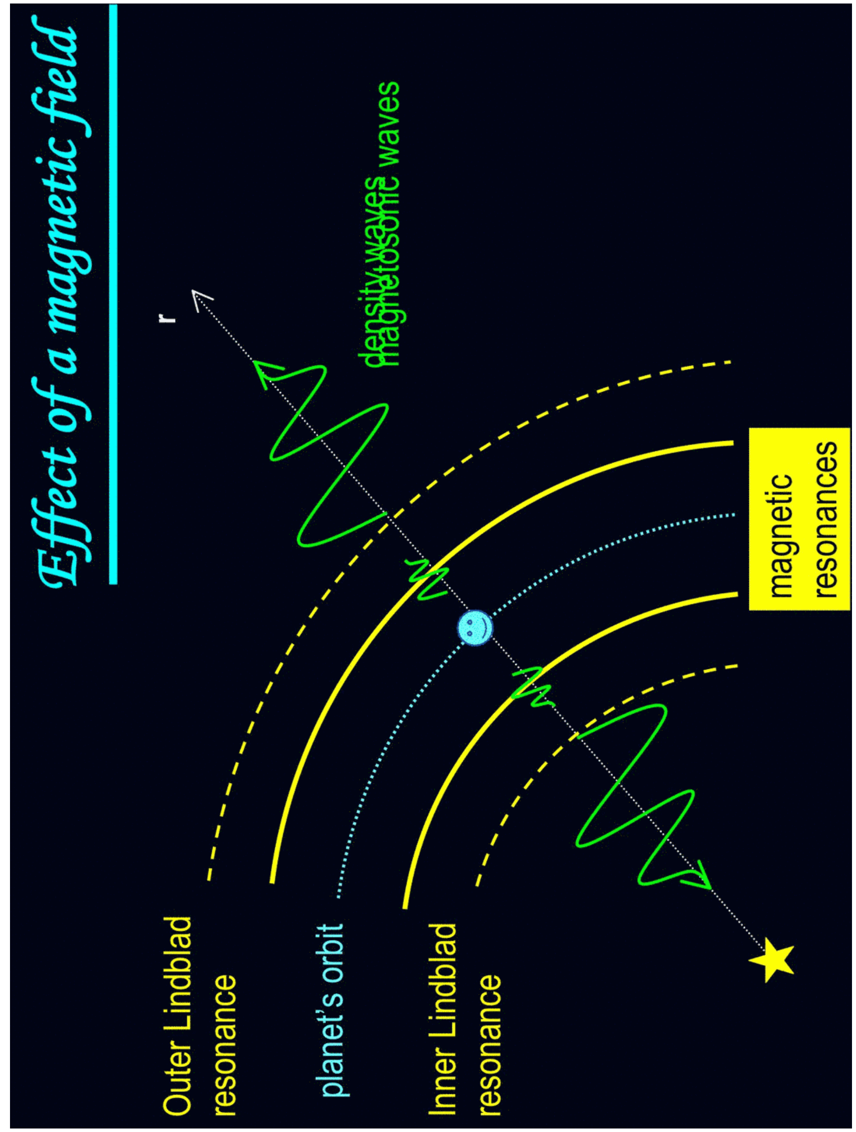
$T_{corotation}$: transferred to the fluid

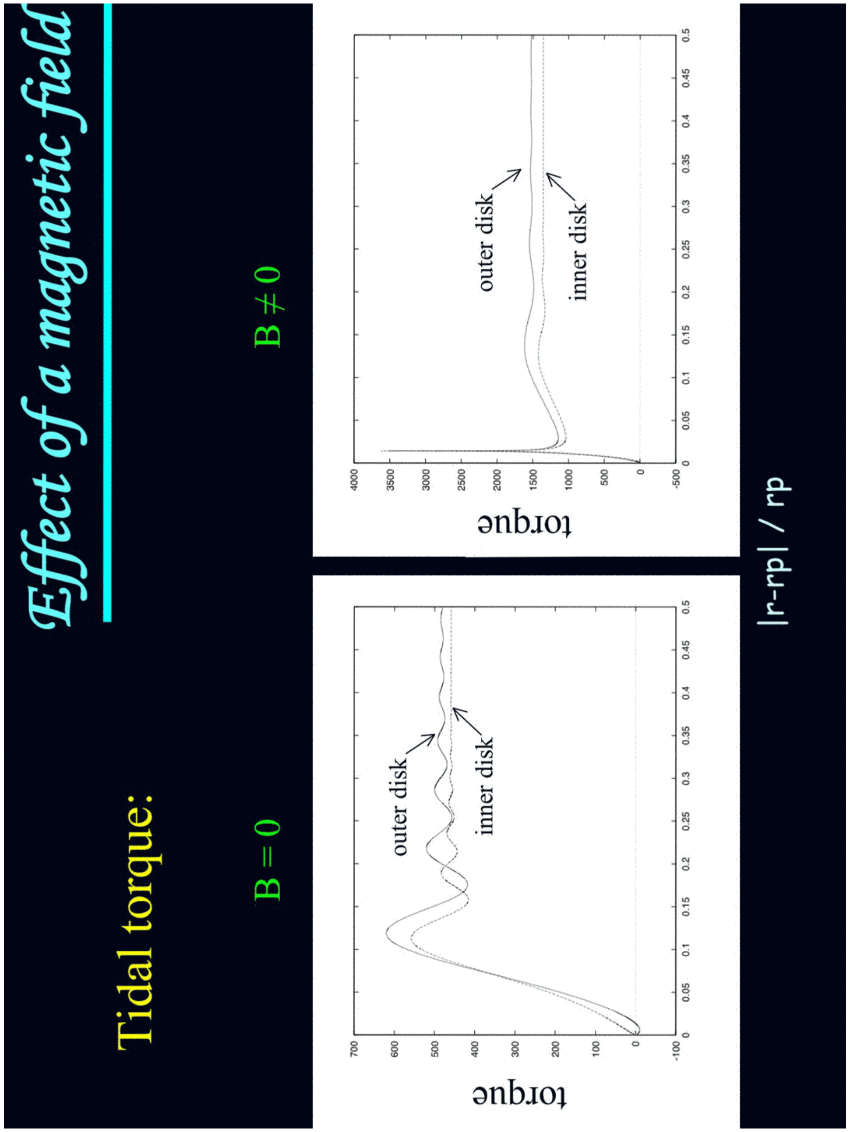
(cf. Landau damping)

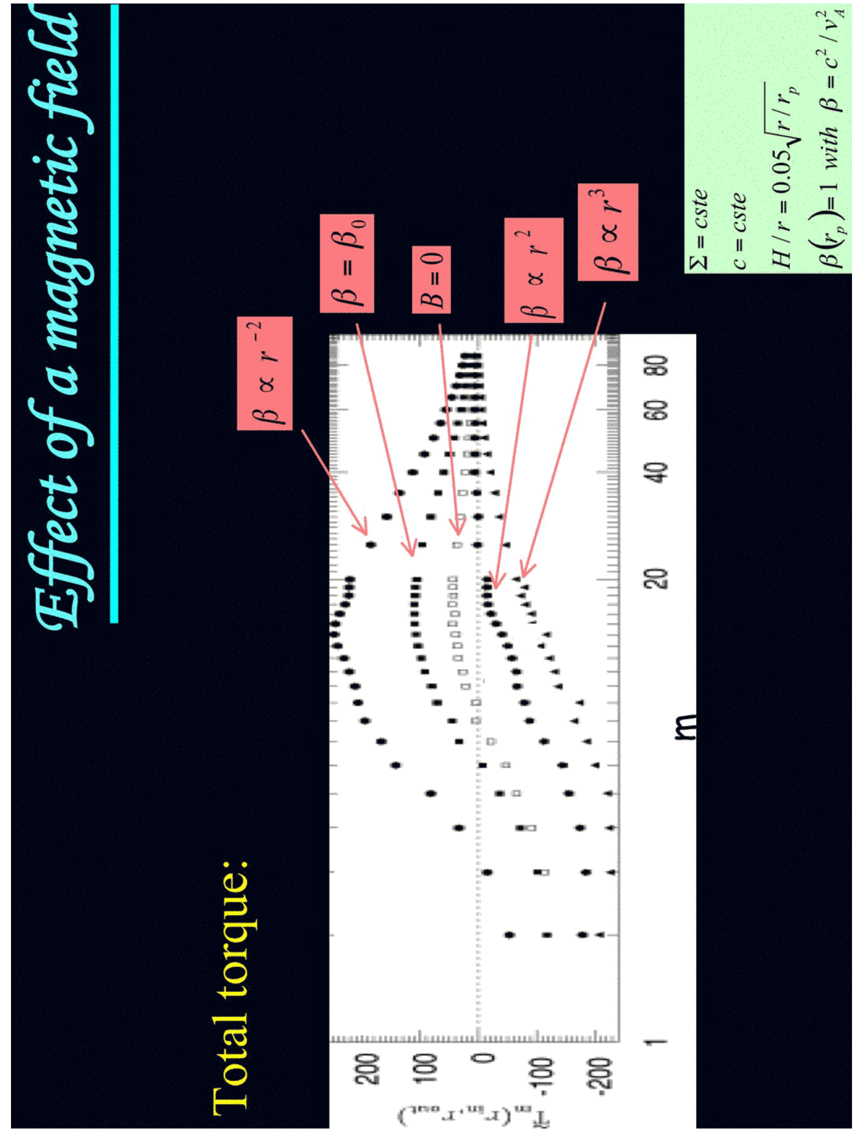
Disk response




Tidal torque
$T_d = T_{Lindblad} + T_{corotation} = F(r_{out}) - F(r_{in}) + \Delta F_{cor}$
planet embedded in a disk
Angular momentum flux
r/rp
ILR
OLR
CR


Effect of a magnetic field
r
density waves
magnetosonic waves
magnetic resonances
Outer Lindblad resonance
planet's orbit
Inner Lindblad resonance

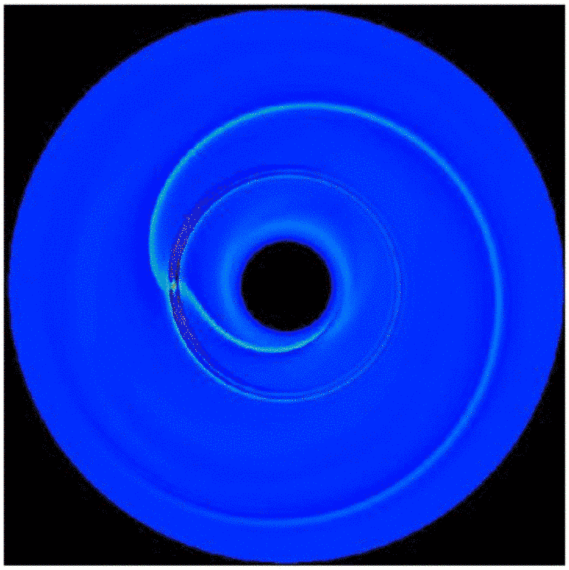

Effect of a magnetic field
Tidal torque:
B = 0
B ≠ 0
outer disk
inner disk
torque
|r-rp| / rp


Effect of a magnetic field
Total torque:
$\beta \propto r^{-2}$
$\beta = \beta_0$
$B = 0$
$\beta \propto r^2$
$\beta \propto r^3$
$\Sigma = cste$
$c = cste$
$H/r = 0.05\sqrt{r/r_p}$
$\beta(r_p)=1$ with $\beta = c^2/v_A^2$
m

Numerical Simulations

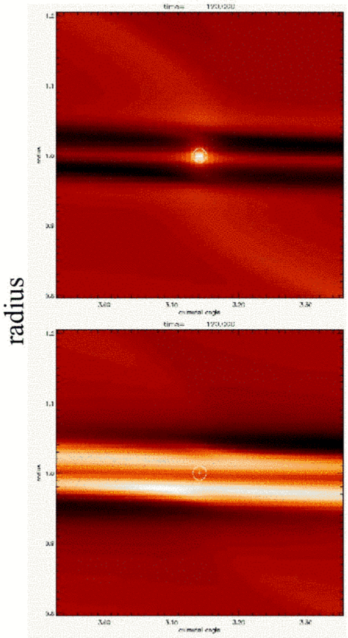
$M_{planet} = 5\ M_{earth}$
$\beta = c^2/v_A^2 = 2$

density at t=10



(Fromang, Terquem, Nelson 2005)

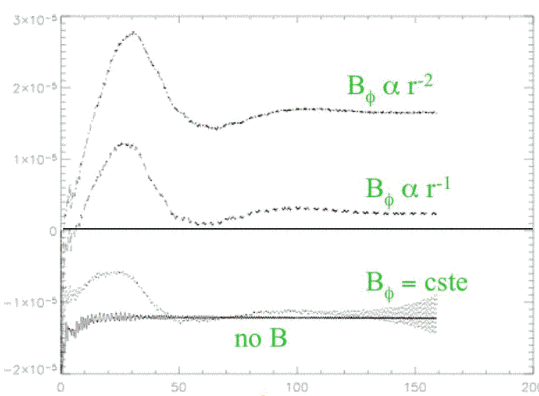
t=120



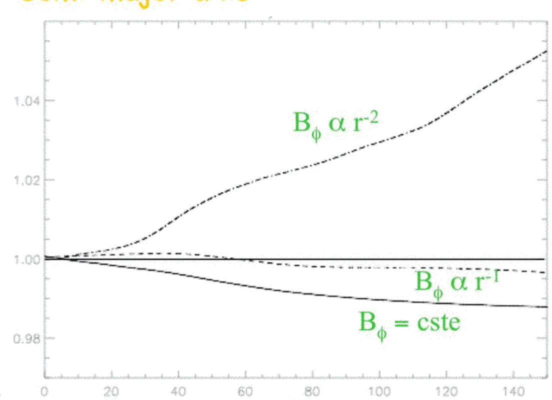
Numerical Simulations

$M_{planet} = 5\ M_{earth}$
$\beta = c^2/v_A^2 = 2$

torque



semi-major axis



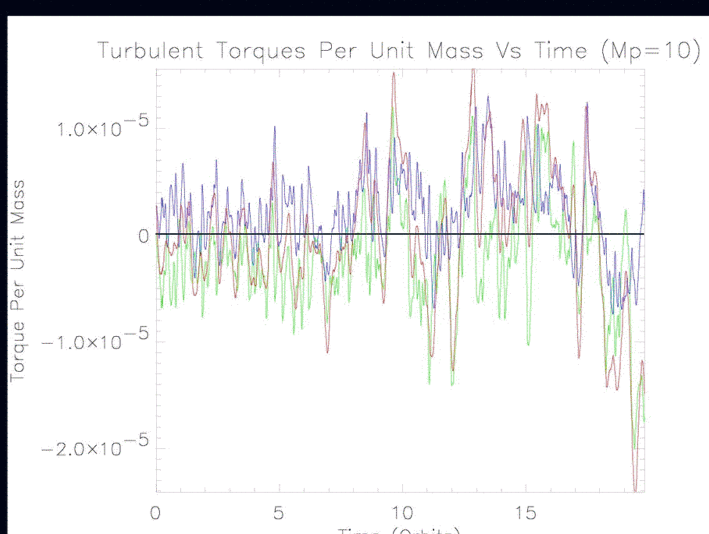
(Fromang, Terquem, Nelson 2005)

Effect of a magnetic field

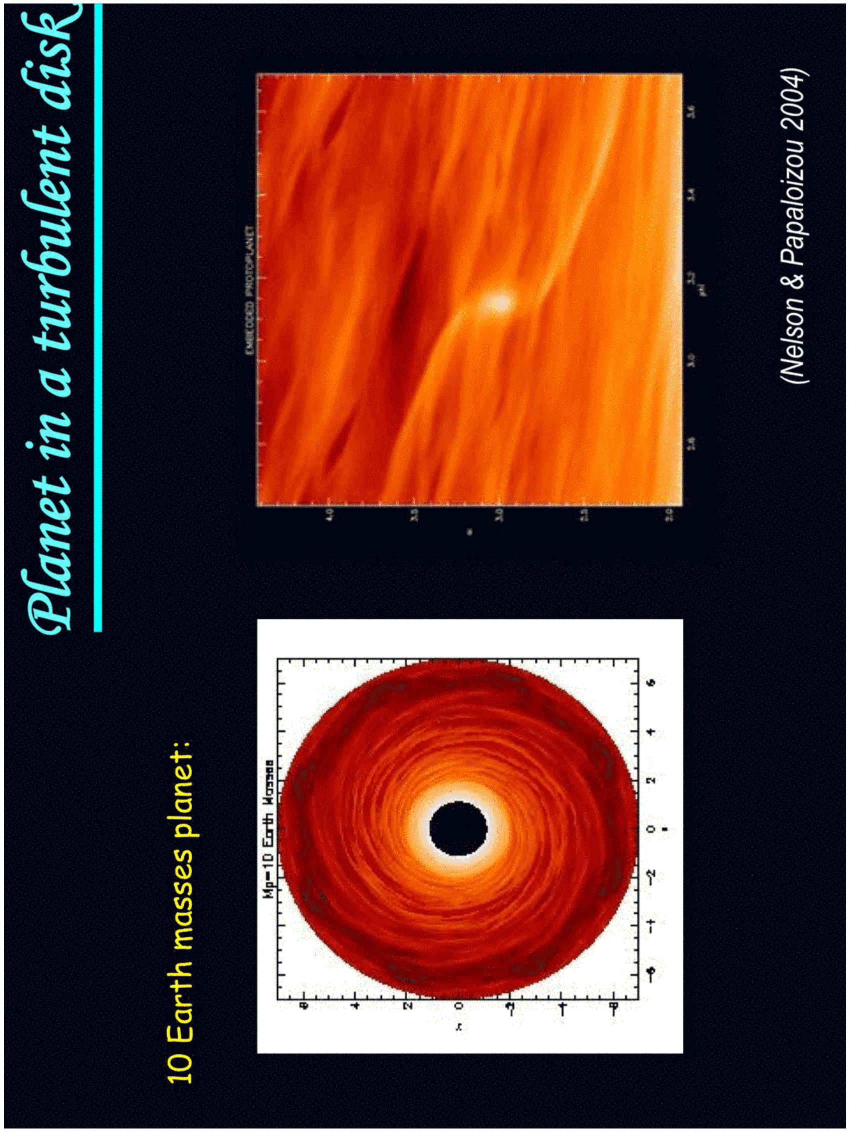
- Diffusive migration in a turbulent disk if the resonances still exist
- Migration stops at the border between magnetized and non magnetized zones

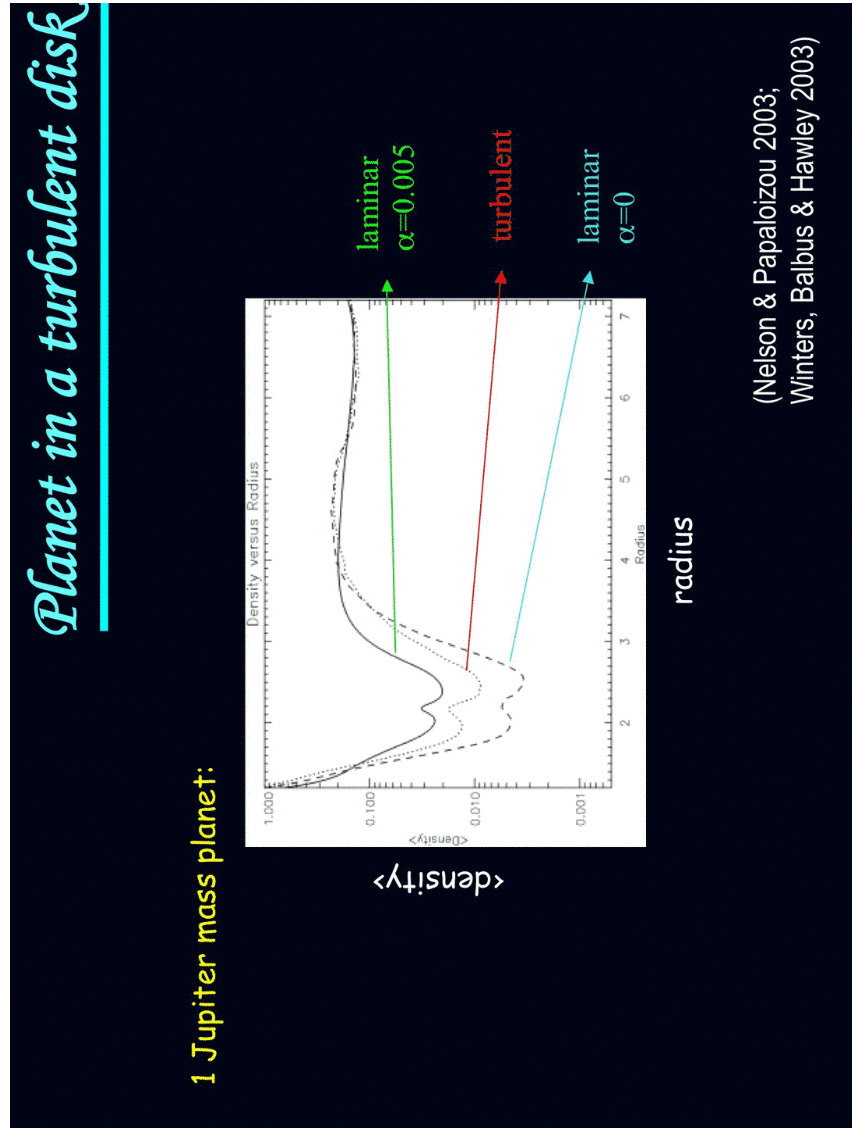
Planet in a turbulent disk

10 Earth masses planet:



(Nelson & Papaloizou 2004)


Planet in a turbulent disk
10 Earth masses planet:
(Nelson & Papaloizou 2004)


Planet in a turbulent disk
1 Jupiter mass planet:
laminar
α=0.005
turbulent
laminar
α=0
<density>
radius
(Nelson & Papaloizou 2003;
Winters, Balbus & Hawley 2003)