Disc-planet interactions and migration during planet formation

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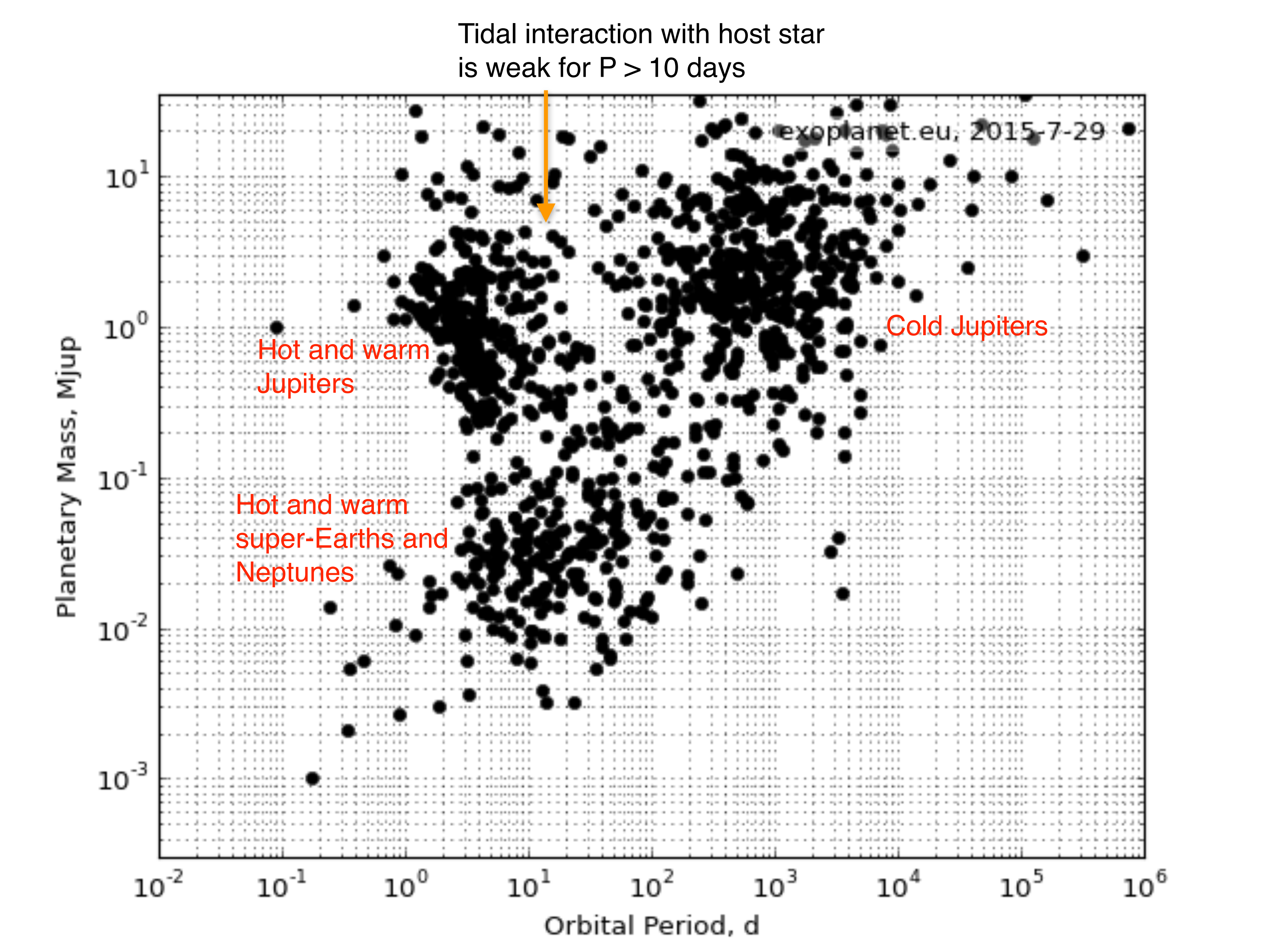
Evidence for disc-driven migration

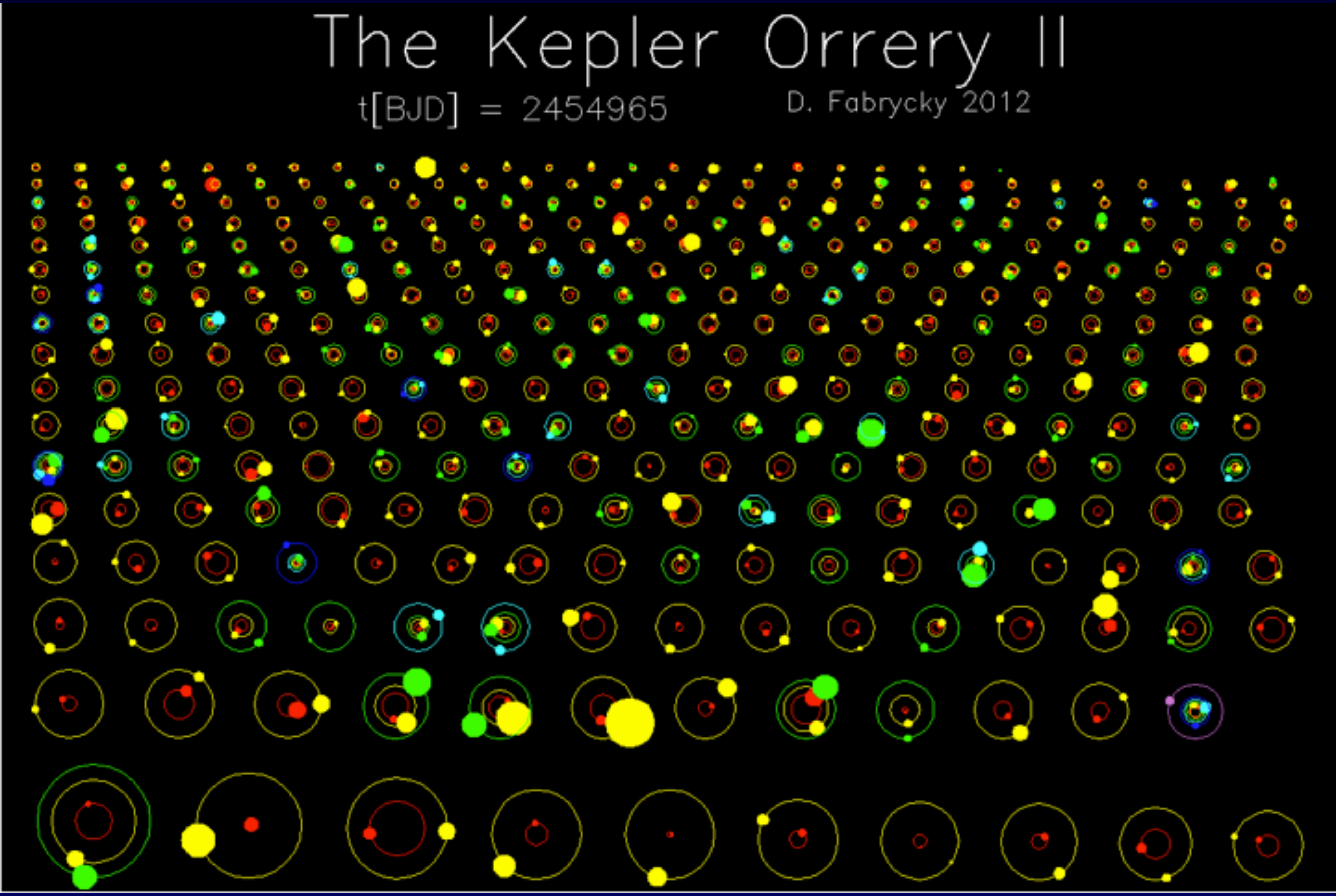
- Hot-Jupiters (e.g. 51 Peg) and the numerous “warm” Jupiters with periods ~ 10-20 days

- Short-period coplanar compact systems of super-Earths + Neptunes (e.g. Kepler 11)

- Systems in mean motion resonance (e.g. GJ 876)
  - convergent migration!

- Note: misaligned and eccentric systems also indicate that planet-planet scattering and/or Kozai-Lidov effect may also play an important role in post-formation orbital evolution. A brief discussion of the Kozai-Lidov effect will be given in the talk on planet formation in binary systems


Tidal interaction with host star
is weak for P > 10 days
exoplanet.eu, 2015-7-29
Hot and warm
Jupiters
Cold Jupiters
Hot and warm
super-Earths and
Neptunes
Planetary Mass, Mjup
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Orbital Period, d


The Kepler Orrery II
t[BJD] = 2454965
D. Fabrycky 2012

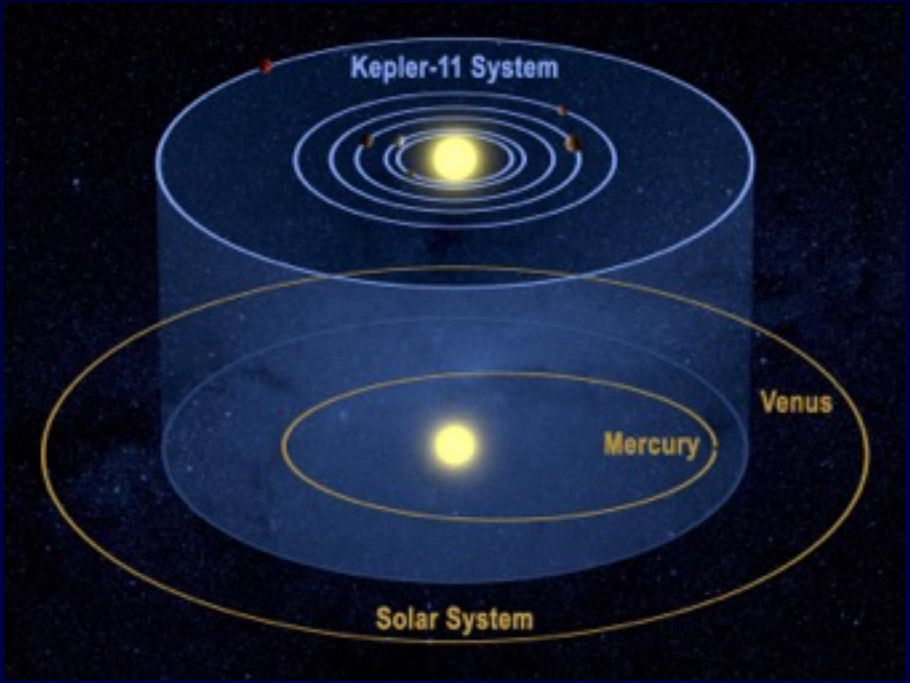
- *in situ* formation of Kepler multi-systems difficult because mass in solids for a MMSN disc interior to 1 AU ~ 3.6 Earth masses

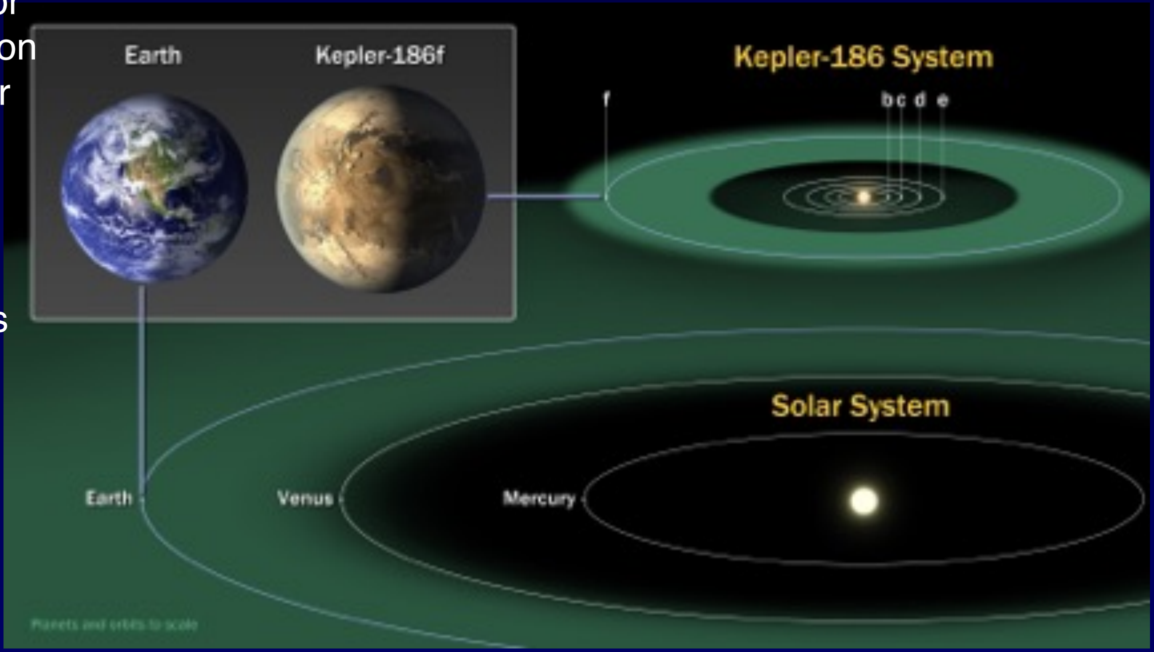
- Interior to Mercury's orbit the mass in solids is even smaller…

- Planets in Kepler 11-like systems form at larger distances where the mass reservoir is greater and migrate inwards

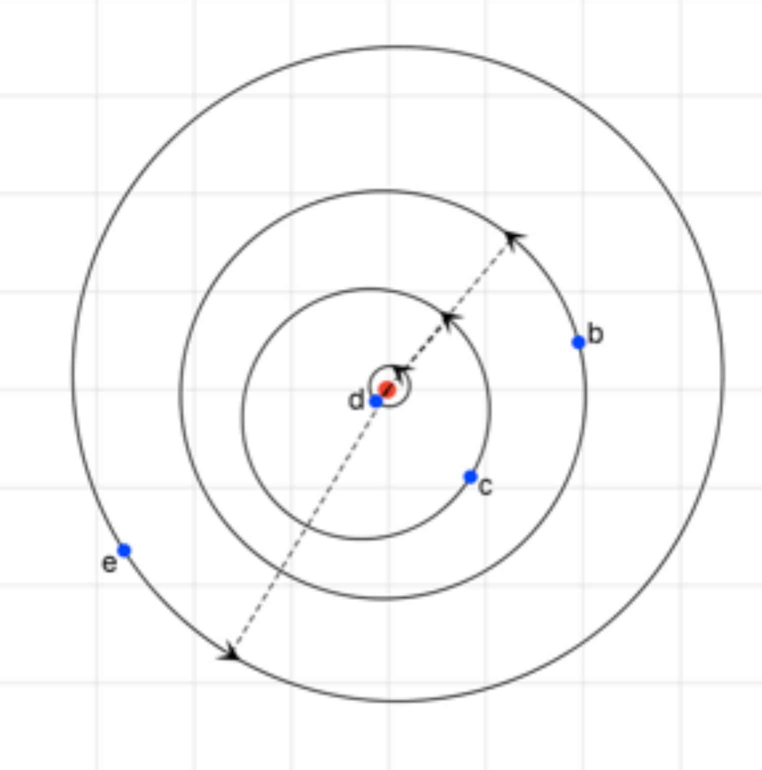
- Or there is large scale inwards drift of planetary building blocks (i.e. pebbles, boulders or planetesimals) that allow *in situ* formation after substantial enrichment of the inner disc

- We probably require more information about exoplanet interior structure to discriminate between these hypotheses





Gliese 876 - an exoplanet system displaying a Laplace-type mean motion resonance



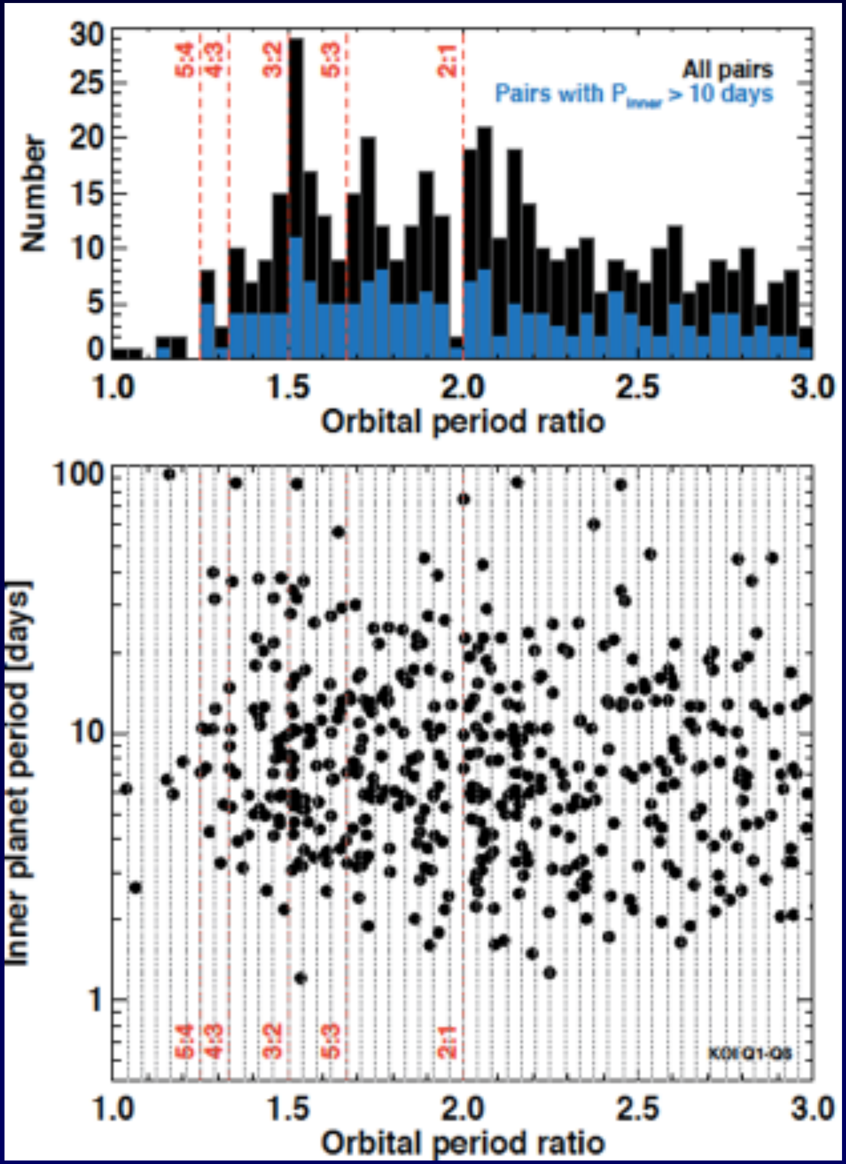
The Gliese 876 planetary system[25][note 5]

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity
Gliese 876 d	6.83 ± 0.40 $M_{\oplus}$	0.02080665 ± 0.00000015	1.937780 ± 0.000020	0.207 ± 0.055
Gliese 876 c	0.7142 ± 0.0039 M_J	0.129590 ± 0.000024	30.0081 ± 0.0082	0.25591 ± 0.00093
Gliese 876 b	2.2756 ± 0.0045 M_J	0.208317 ± 0.000020	61.1166 ± 0.0086	0.0324 ± 0.0013
Gliese 876 e	14.6 ± 1.7 $M_{\oplus}$	0.3343 ± 0.0013	124.26 ± 0.70	0.055 ± 0.012

Rivera et al (2010)

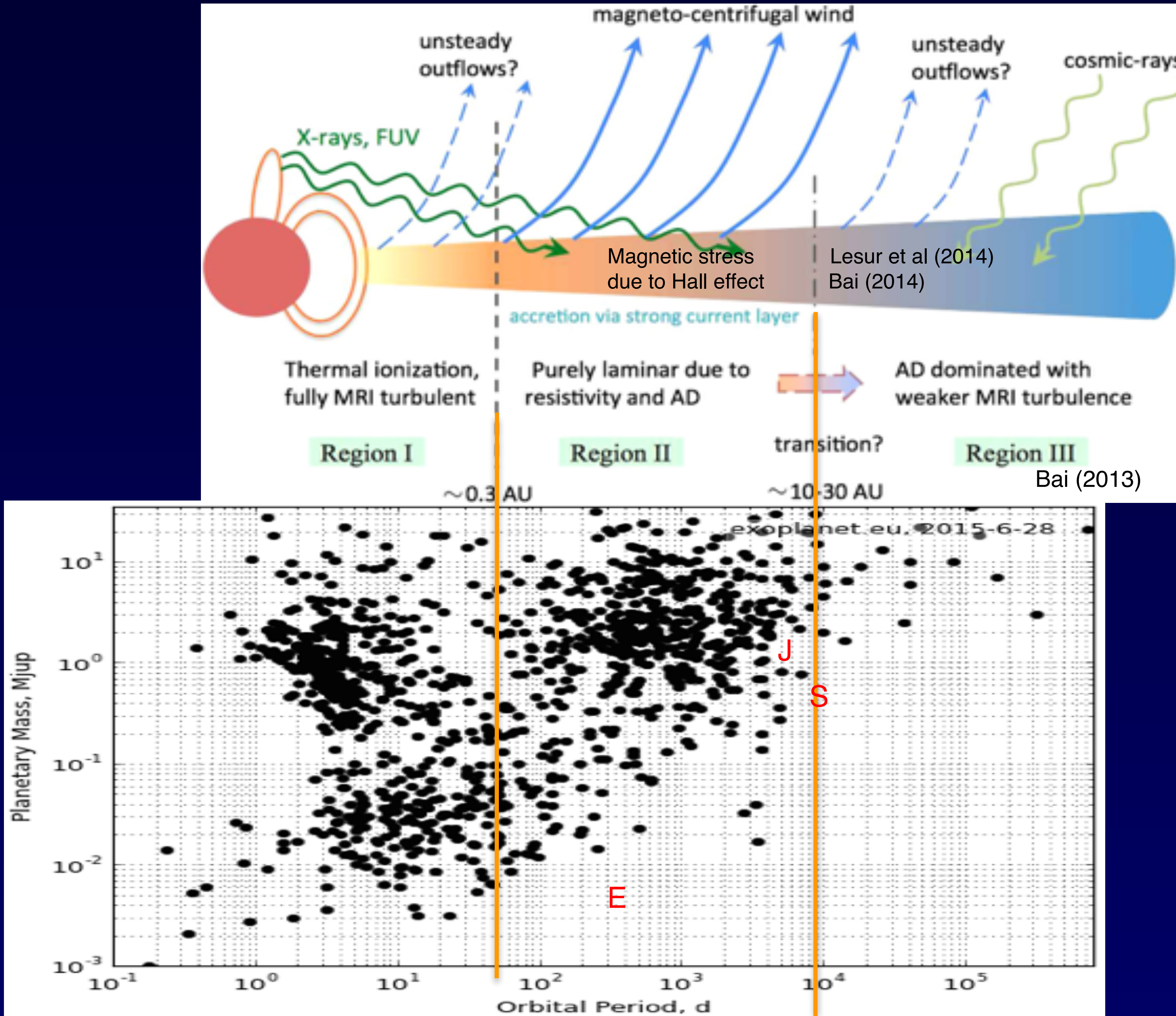
As discussed later, capture into the 2:1 MMR resonance requires slow, convergent migration

Kepler period ratios - evidence for physics beyond migration?



Baruteau & Papaloizou (2013)

Relation between currently favoured disc models and exoplanet orbital radii



Type I migration of low mass planets

Lindblad torque

- Gravitational interaction between planet and disc leads to the excitation of spiral density waves at Lindblad resonances (Goldreich & Tremaine 1978, 1980; Lin & Papaloizou 1979, 1984)

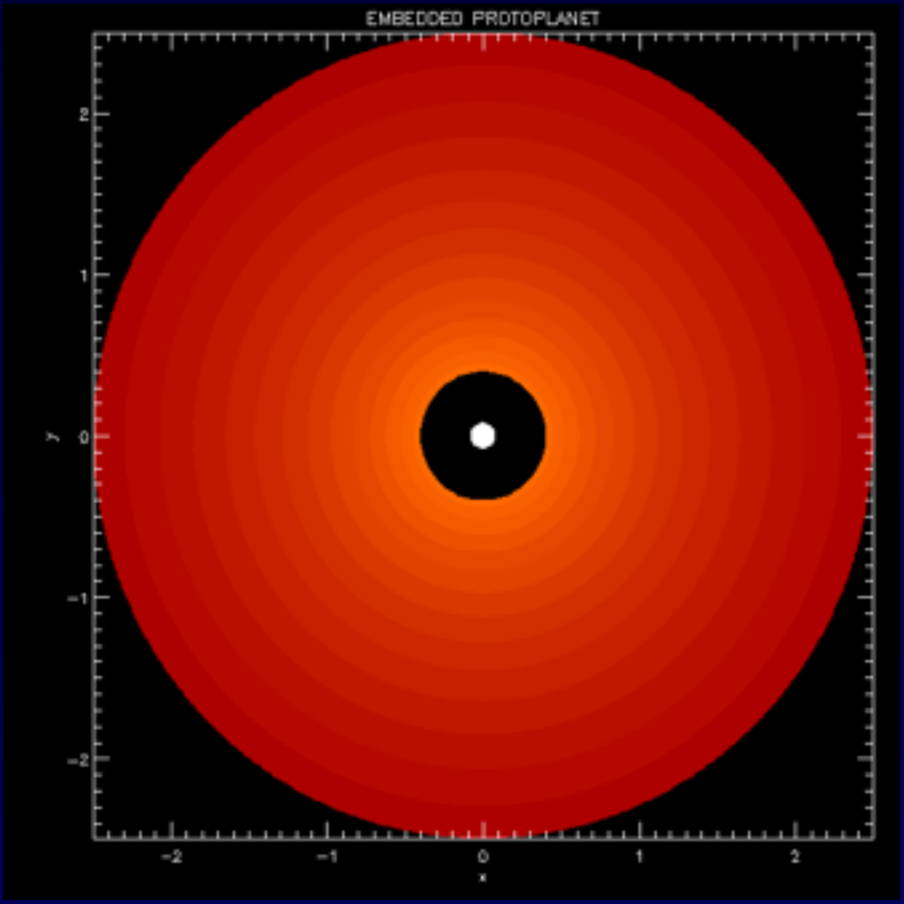
- Spiral wave exerts gravitational force on planet - removes angular momentum and drives inward migration

- Total Lindblad torque scales as:

$$\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2$$

q = M_p / $M_\star$ planet/star mass ratio
Σ = gas surface density
Ω = angular velocity
h = aspect ratio H/r
X_p = X at the planet location.

Σ(MMSN @1AU) =>
migration time [years] $\approx 1/q$
→ 300000 yrs for an Earth ,
→ 20000 yrs for a Neptune !



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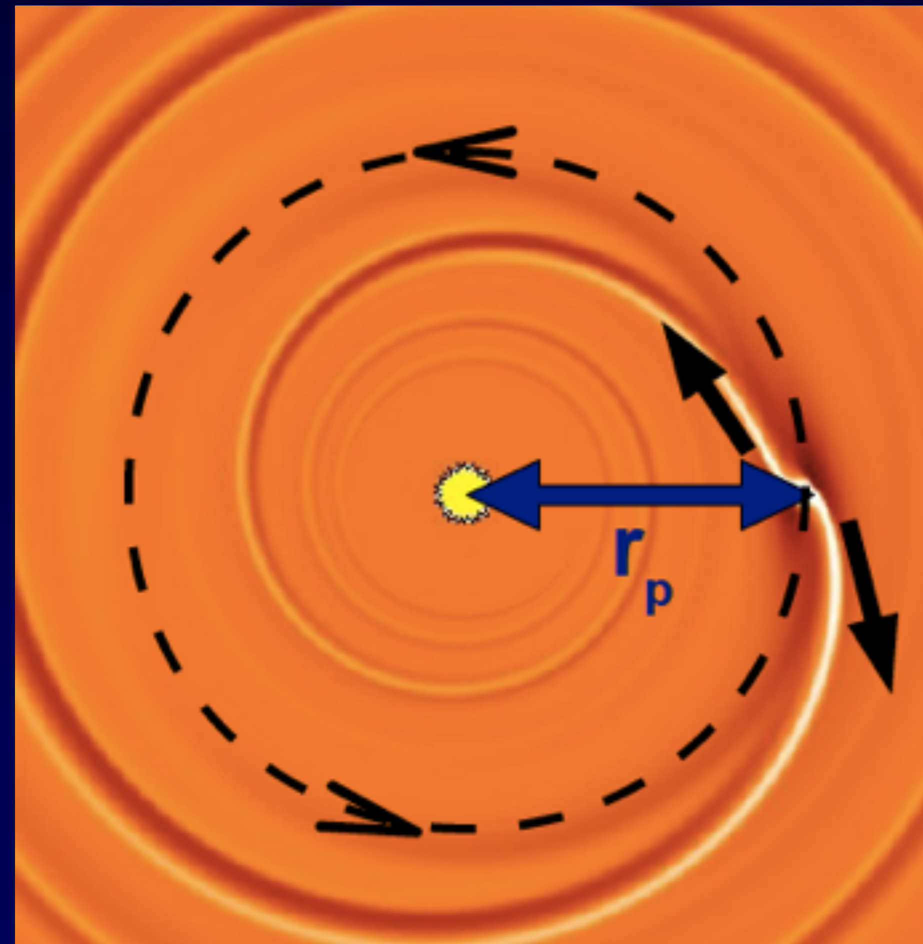

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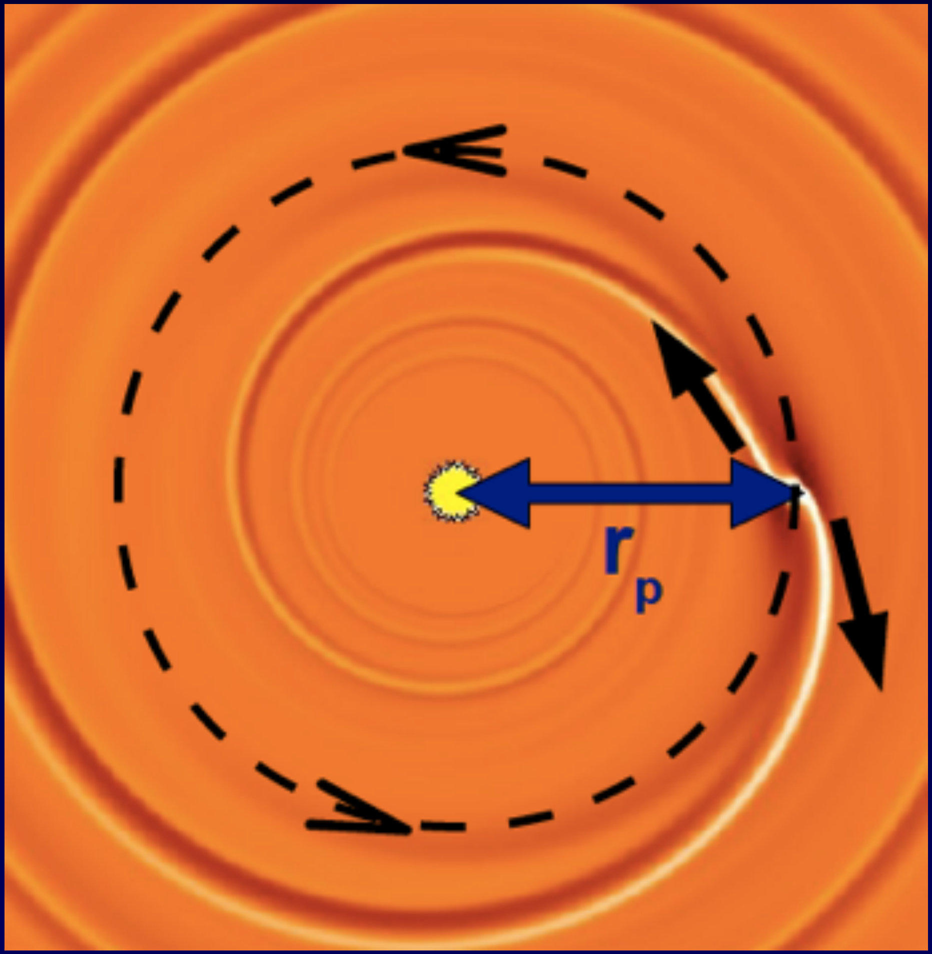
- Spiral wave exerts gravitational force on planet - removes angular momentum and drives inward migration
- Total Lindblad torque for a 2D adiabatic disc can be written as:

$$\boxed{\gamma\Gamma_L / \Gamma_0 = -2.5 - 1.7\beta_T + 0.1\alpha_\Sigma}$$

where γ = adiabatic index,
$\Sigma \sim r^{-\alpha_\Sigma}$, $T \sim r^{-\beta_T}$.
(Paardekooper et al. 2010)

In general, $0.5<\alpha_\Sigma<1.5$ and $\beta_T \approx 1$
$\rightarrow$ negative torque,
fast inward migration.



See blackboard notes for discussion about:

- Lindblad resonances

- Where torque formula scaling comes from (one-sided disc torque using impulse approximation from Lin & Papaloizou 1979) and simple argument about inner and outer Lindblad resonance torque imbalance

Corotation torque

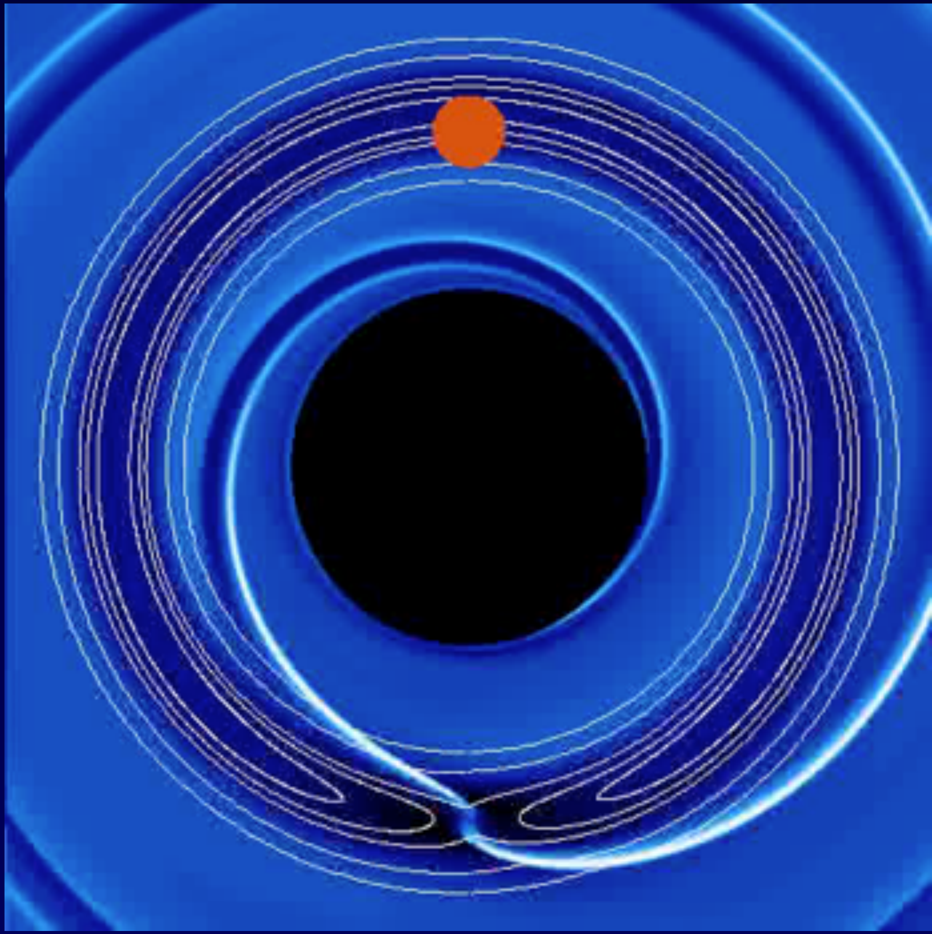
- Angular momentum is exchanged between planet and material that orbits in the horseshoe region (Goldreich & Tremaine 1980; Ward 1991, Masset 2001)

- Over one complete horseshoe orbit there is no net torque for a disc composed of ballistic particles

- Radial gradients in *entropy* and *vortensity* in a gaseous disc can give rise to a sustained corotation torque (e.g. Paardekooper et al 2010)

$$\boxed{\gamma\Gamma_c / \Gamma_0 = 1.1\,(3/2 - \alpha_\Sigma) + 7.9\,\xi/\gamma}$$

$$\xi = \beta_T - (\gamma-1)\alpha_\Sigma$$



$$\boxed{\gamma\Gamma_c / \Gamma_0 = 1.1\,(3/2 - \alpha_\Sigma) + 7.9\,\xi/\gamma}$$

First term comes from advection of vortensity (vorticity/**Σ**), and is proportional to the vortensity gradient across the horseshoe region. Note that this term disappears for surface density power law profile = -3/2

Second term comes from advection of the entropy. This term is proportional to the entropy gradient across the horseshoe region since:

$$\xi = -\,\mathrm{dlog(entropy)} / \mathrm{dlog(r)}$$

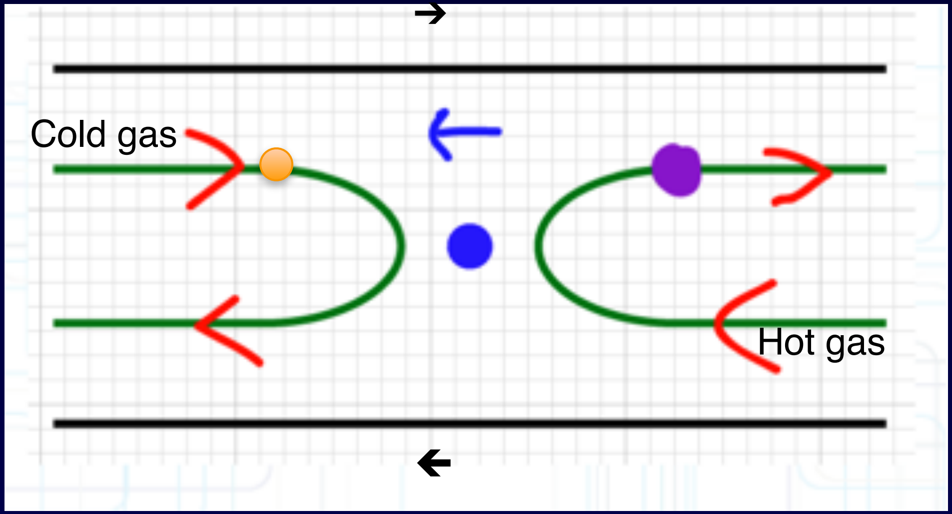
Note that the corotation torque is normally positive in protoplanetary discs and so opposes the inward migration associated with the Lindblad torques.

A positive corotation torque is maximised and outward migration may occur when

- Surface density profile increases outwards
- The disc has a large and negative entropy gradient

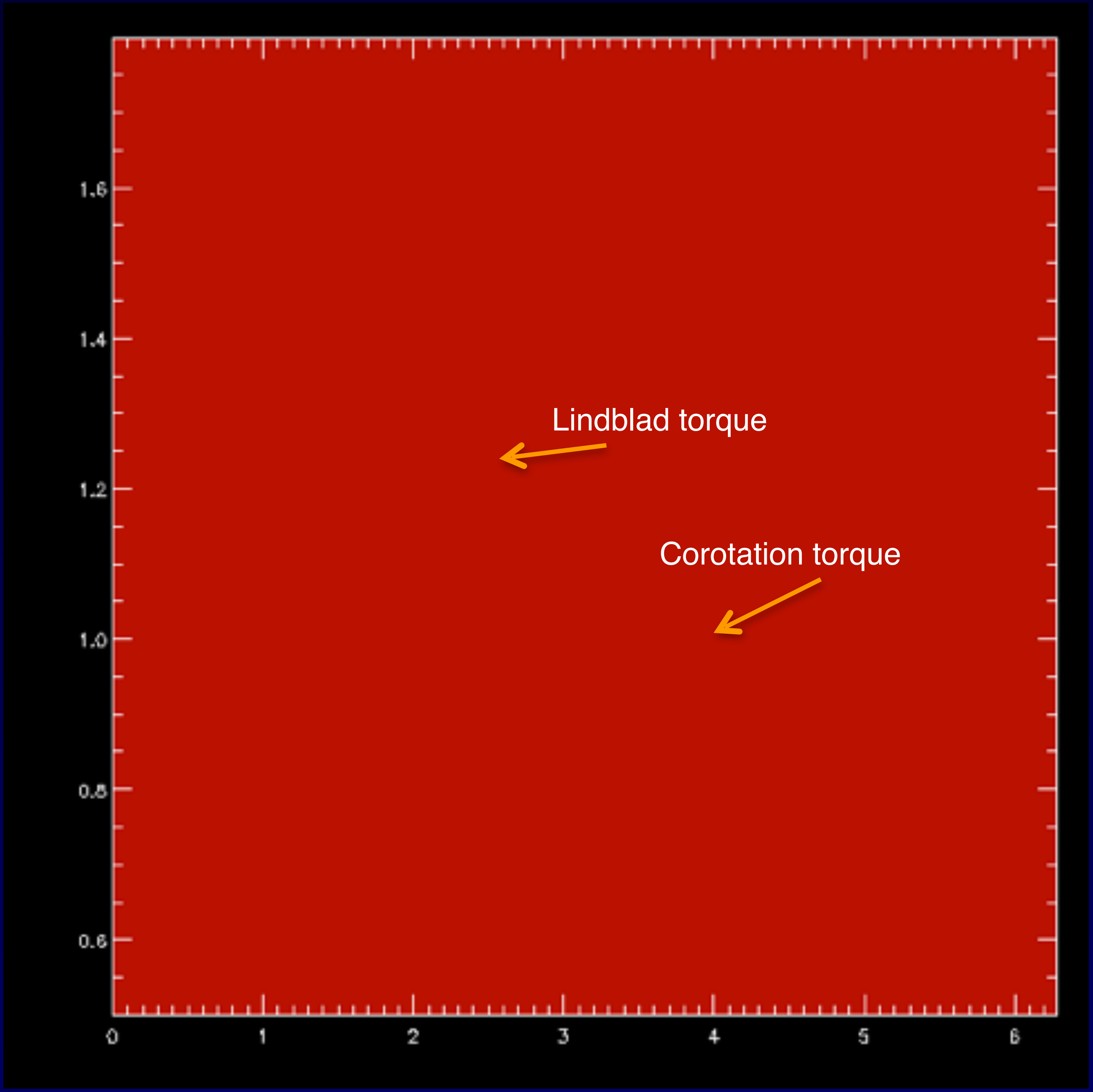
Note that corotation torques are prone to saturation

Corotation torque saturation - a simple argument



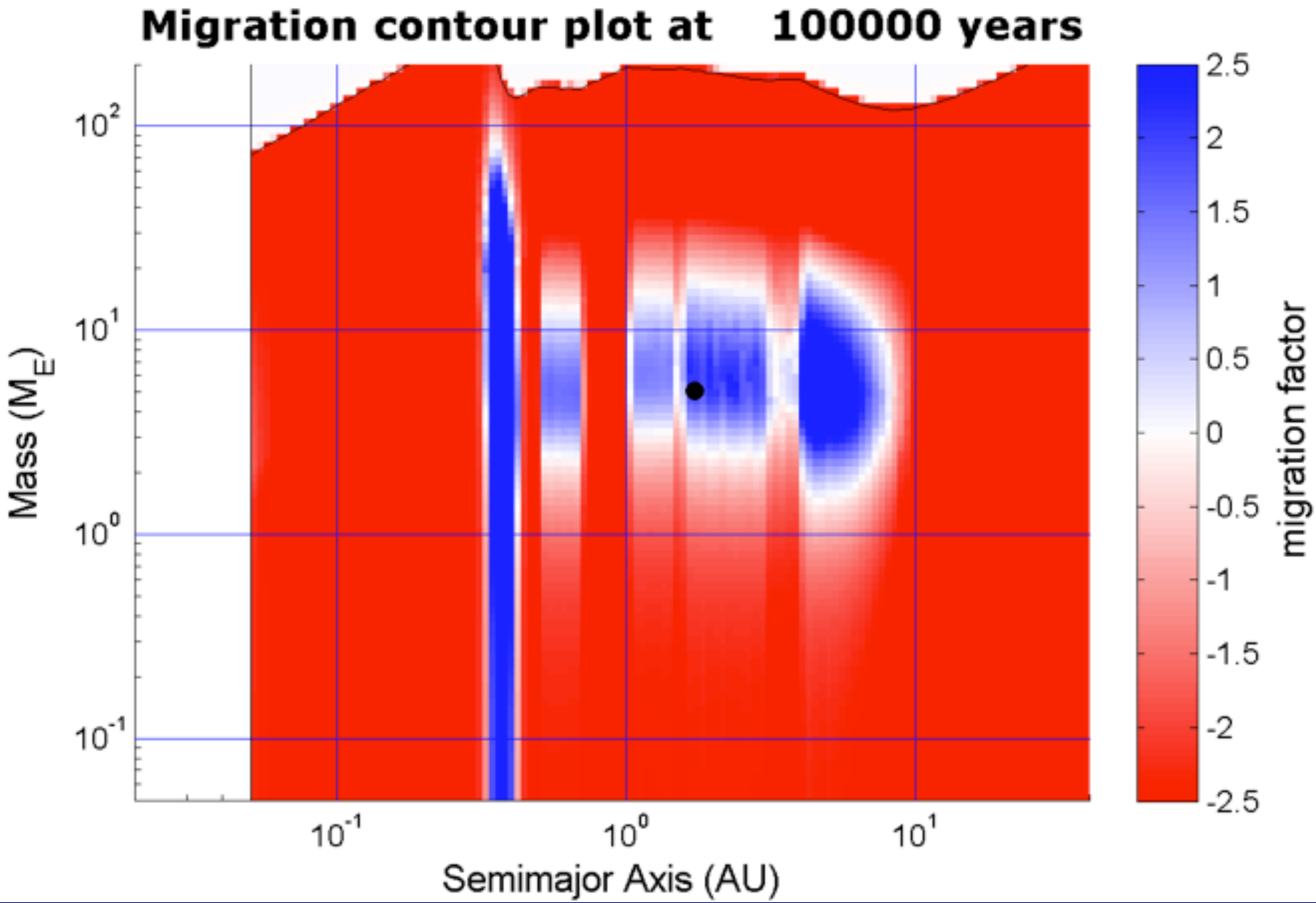
- We consider a disc with a negative radial entropy gradient.
- Case 1: Adiabatic evolution. The orange fluid element exchanges no heat with its surroundings - no horseshoe drag
- Case 2: Locally isothermal evolution. The orange fluid element instantaneously adjusts thermally to its surroundings - no horseshoe drag
- Case 3: Orange fluid element thermally equilibrates with its surroundings after 1/2 horseshoe orbit - optimal coronation torque
- See Paardekooper & Mellema (2006); Baruteau & Masset (2008); Pardekooper & Papaloizou (2008); Paardekooper et al (2010, 2011)
- A similar argument applies when a vortensity gradient is present in the disc where viscosity is required for unsaturating coronation torque

Note that viscosity is required to unsaturate both the vortensity and entropy related corotation torque. In the absence of viscosity the corotation region is a closed system and contains a finite amount of angular momentum that can be exchanged with the planet. Viscosity is required to resupply the corotation region with fresh angular momentum over long term evolution

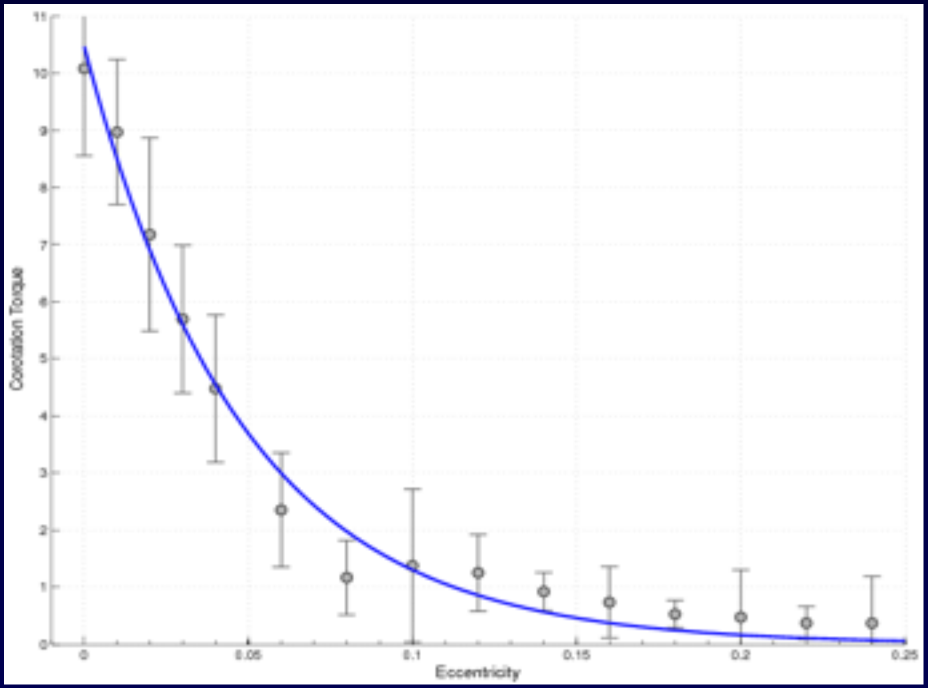


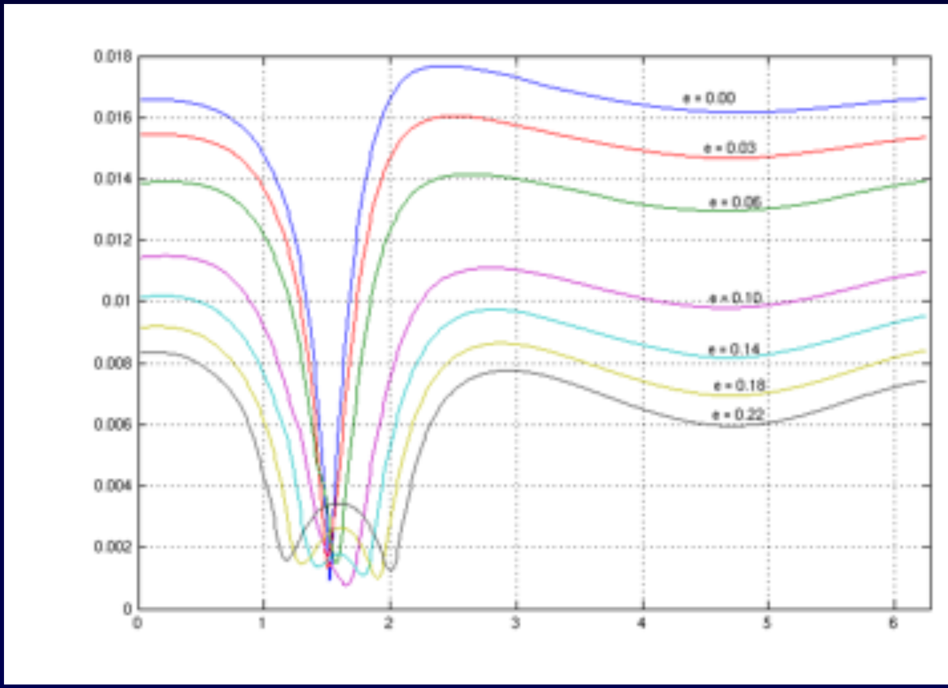
1.6
1.4
1.2
1.0
0.8
0.6
0
1
2
3
4
5
6
Lindblad torque
Corotation torque

Balance of Lindblad and coronation torques in a viscous irradiated disc



Corotation torque for an eccentric planet



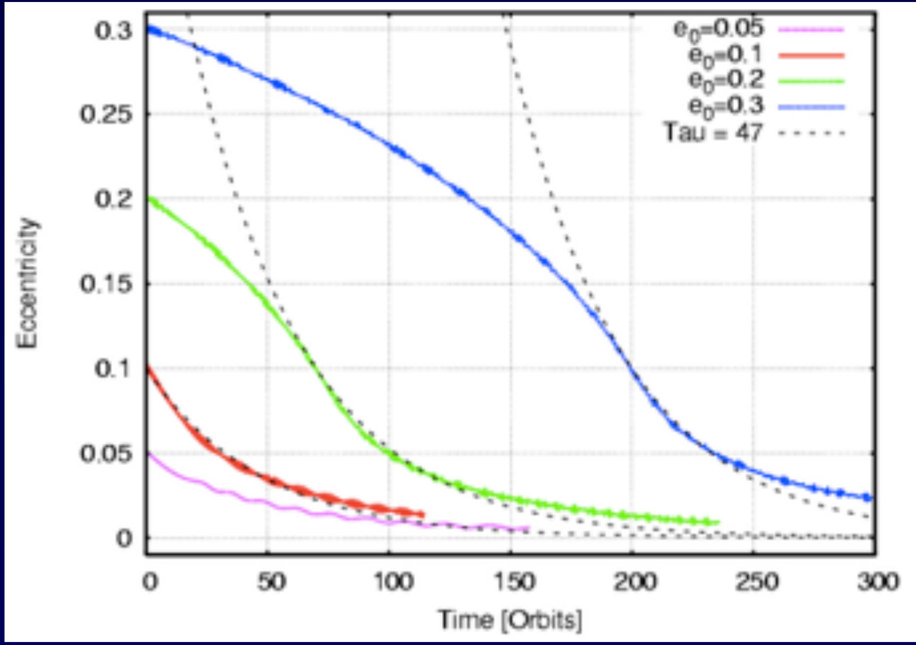


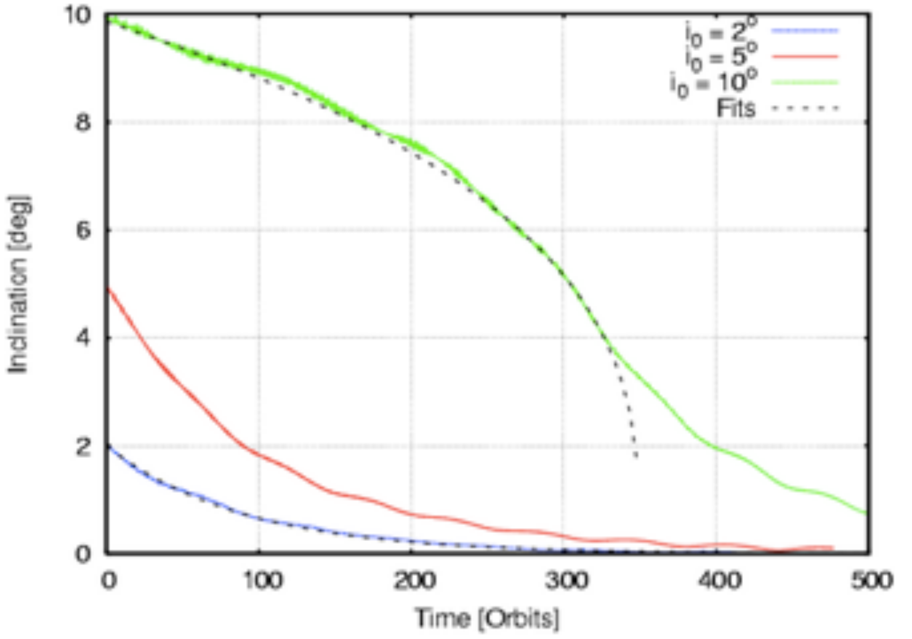
Corotation torques decrease with increasing eccentricity (Bitsch & Kley 2011)

This is due to reduction in width of horseshoe region as e increases (Fendyke & Nelson 2014)

Eccentricity and inclination evolution of low mass planets

- Eccentricity and inclination are damped rapidly for low mass planets - typically a factor ~ $(H/R)^2$ faster than migration time scale
- We expect low mass planets to migrate while maintaining ~ circular and non-inclined orbits

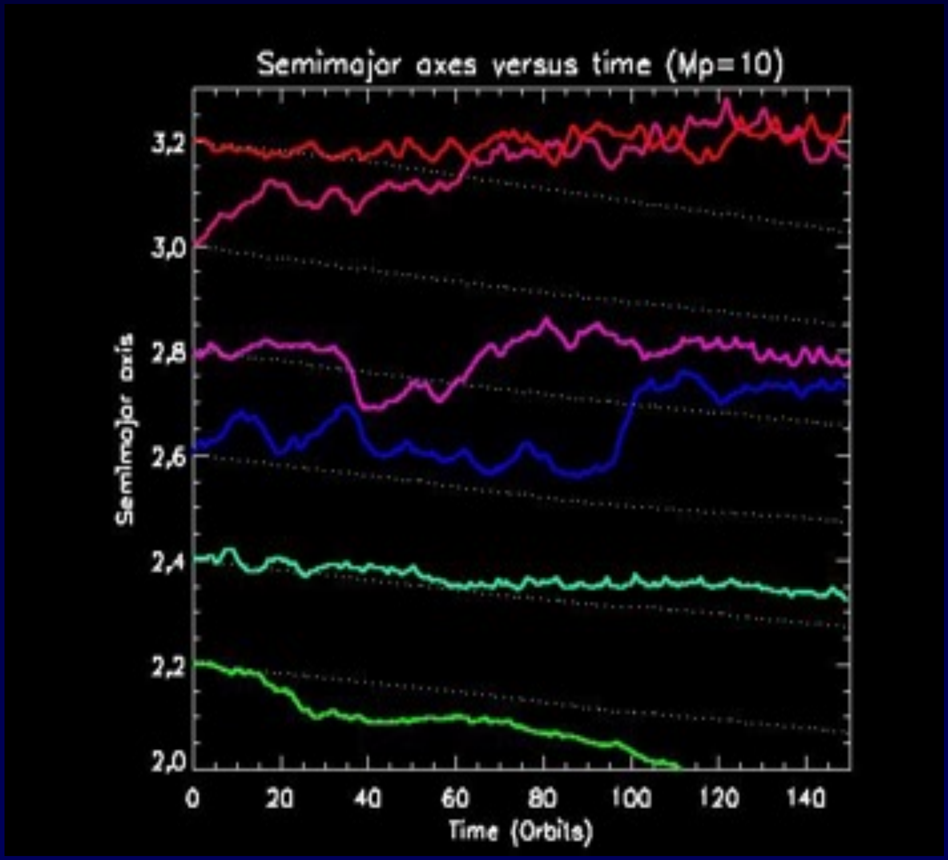


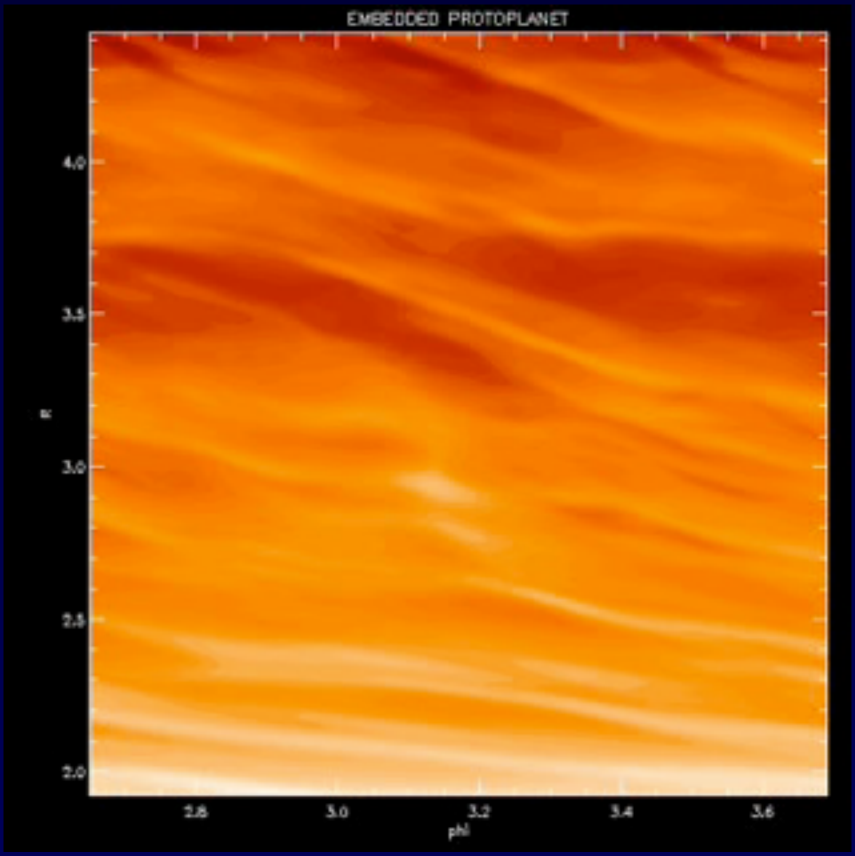


Cresswell et al (2007, 2008)

Type I migration - effect of magnetic fields

Stochastic migration





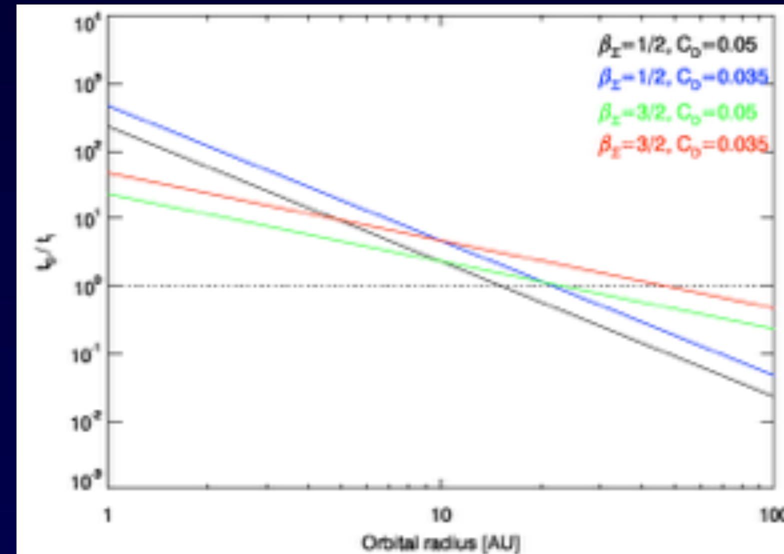
Nelson & Papaloizou (2004)
Papaloizou, Nelson & Snellgrove (2004)
Laughlin et al 2004,
Adams & Bloch 2009)

Treat as advection-diffusion problem to consider ensemble of planetary systems (Johnson, Goodman & Menou 2006, Adams & Bloch 2009)

$$\frac{\partial}{\partial t}P(J,t) = \frac{\partial}{\partial J}\left[\Gamma_{\rm I} P(J,t)\right] + \frac{\partial^2}{\partial J^2}\left[D_{\rm J} P(J,t)\right]$$

$$D_{\rm J} \simeq \sigma_{\rm T}^2 t_{\rm corr}$$

$$t_{\rm D} = J^2/D_{\rm J} \qquad t_{\rm I} = J/\Gamma_{\rm I}$$



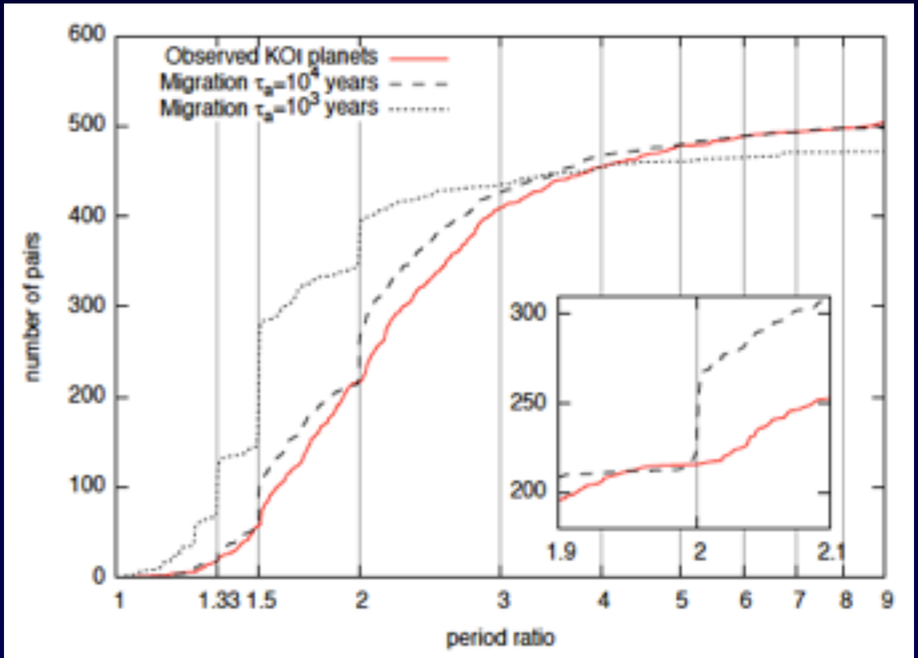
For stochastic forces to dominate evolution require $t_D < t_I$

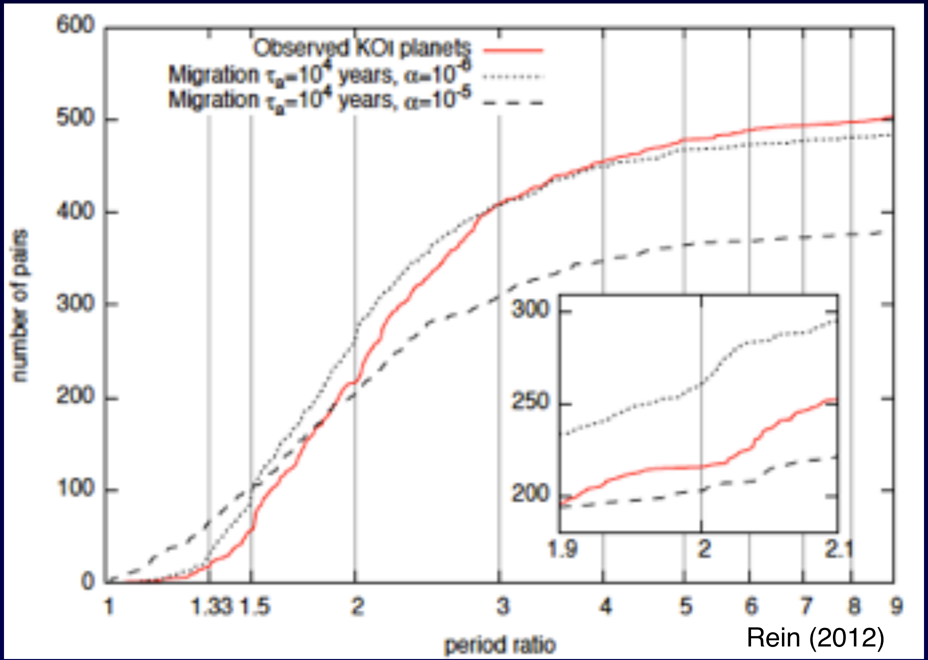
Stochastic forces become increasingly dominant in outer disc regions

For discs with α ~ 0.01 everywhere generated by MRI turbulence
➔ stochastic torques dominant only beyond 10-20 AU

⟶ Even for this optimising value of α stochastic torques cannot easily overcome type I migration

Stochastic torques in multiplanet systems





Migrating systems of low mass planets form mean motion resonances (e.g. 3:2, 4:3) (Papaloizou & Szuszkiewicz 2005) (Cresswel & Nelson 2006)

Stochastic torques diffuse planets out of resonance (Adams & Laughlin 2008; Rein & Papaloizou 2009)

Possible application to HD 128311 (Rein & Papaloizou 2009)

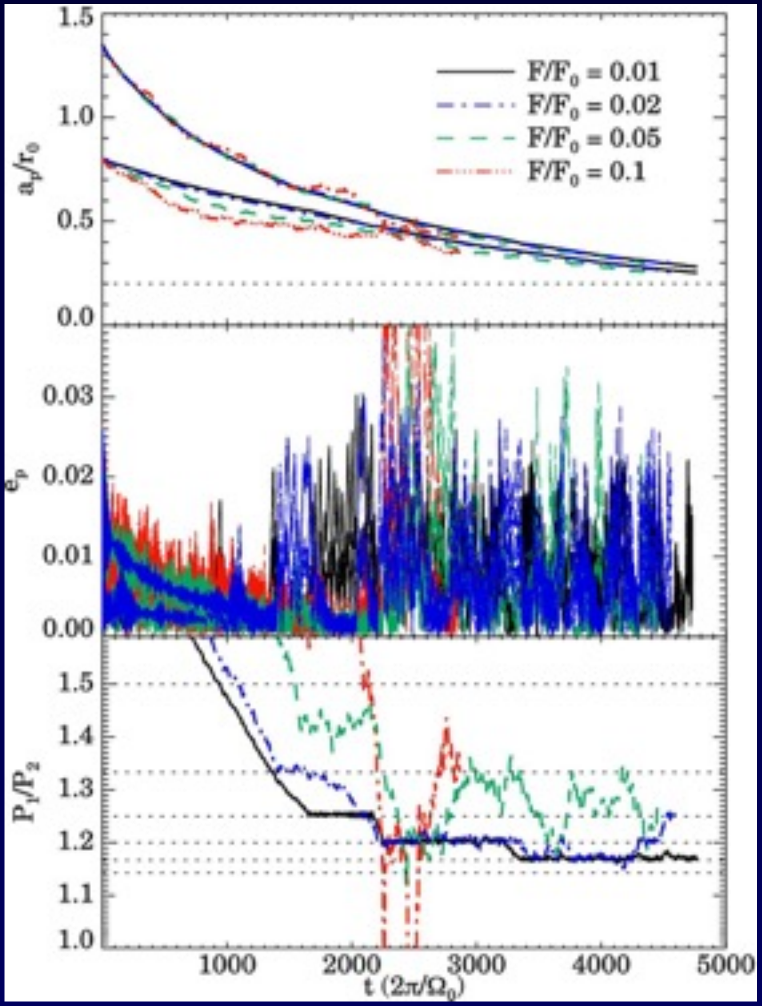
Kepler multiplanet systems show evidence for resonance breaking through stochastic torques (Rein 2012)

Kepler 36 – explaining a close-packed multiplanet system using stochastic torques

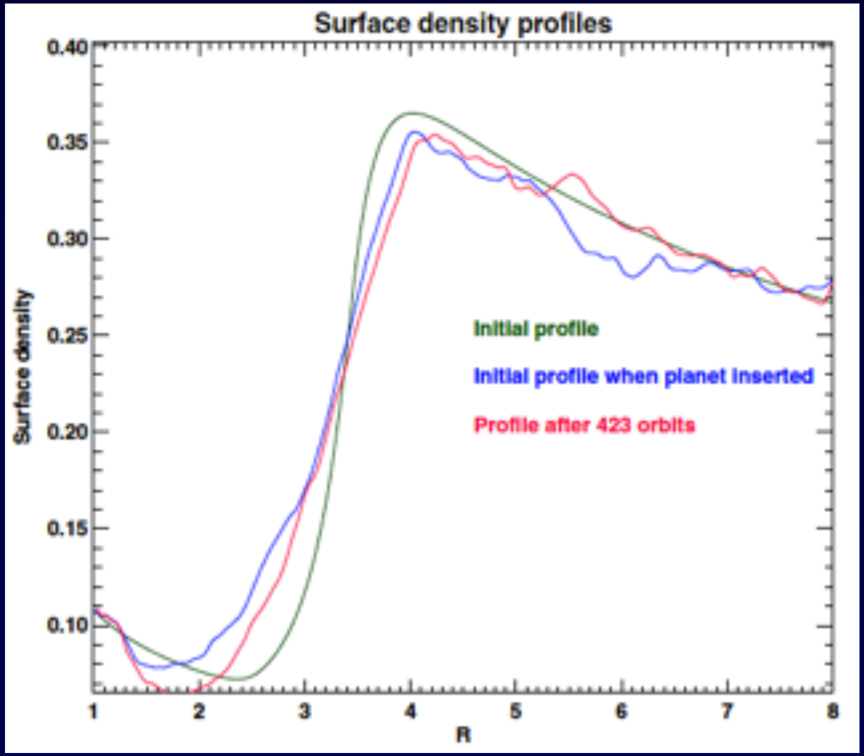
Pairs of convergently migrating planets with mass ratios ≤ 2 normally get trapped in 2:1 or 3:2 resonances in laminar discs

Kepler 36 is close to the 7:6 resonance

Migration in a disc with MHD turbulence allows planets to pass through 2:1, 3:2 , … resonances, arriving at 7:6 commensurability
(Pierens, Baruteau & Hersant 2011; Paardekooper, Rein & Kley 2013)



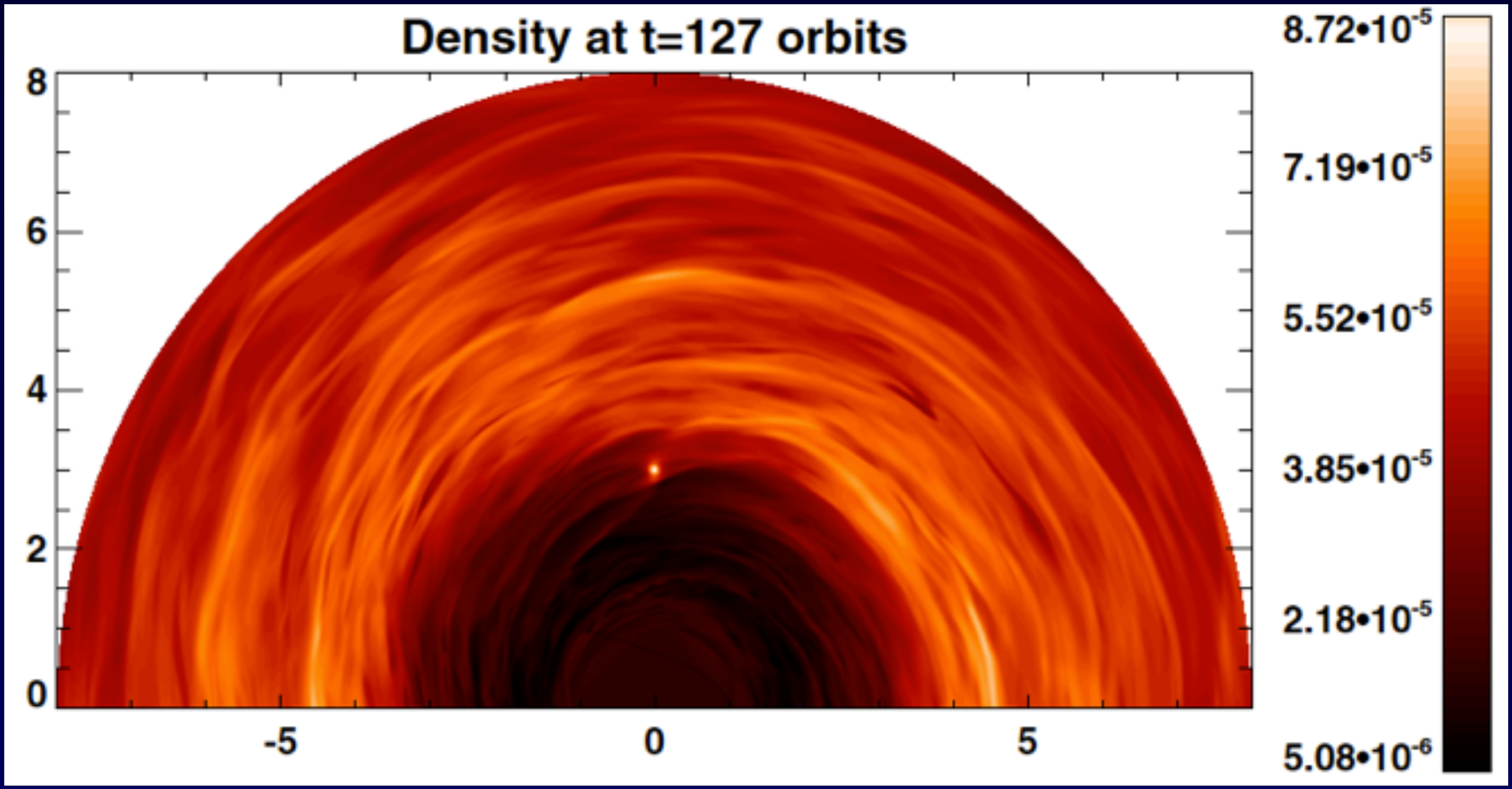
Unsaturating corotation torques with fully developed turbulence



Baruteau et al. (2011)

Locally isothermal models display unsaturated corotation torques for “planet trap” and power law Σ profiles

Unsaturating corotation torques with fully developed turbulence



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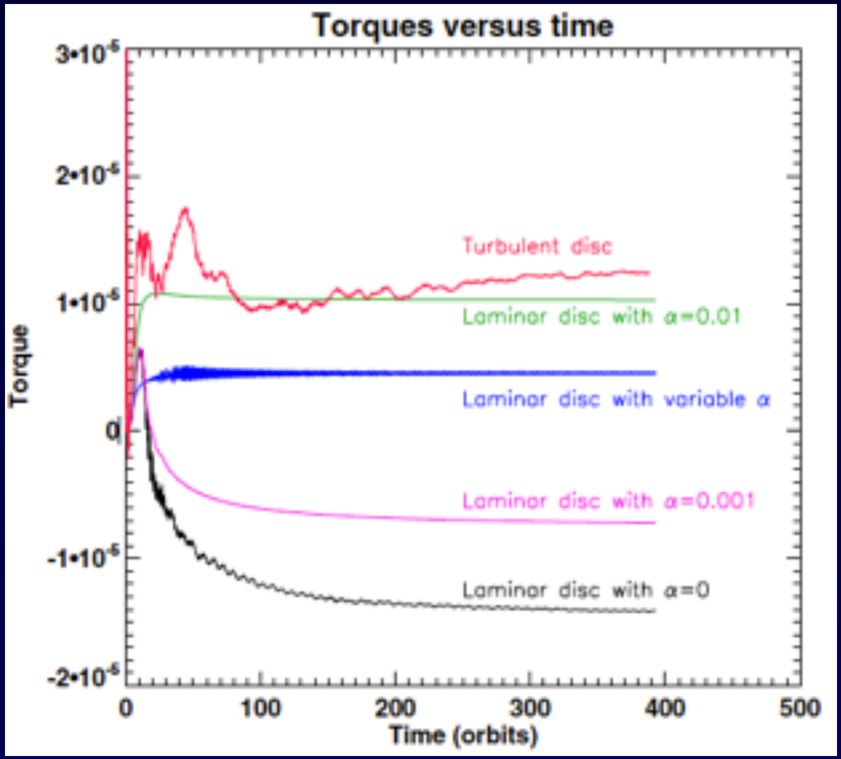

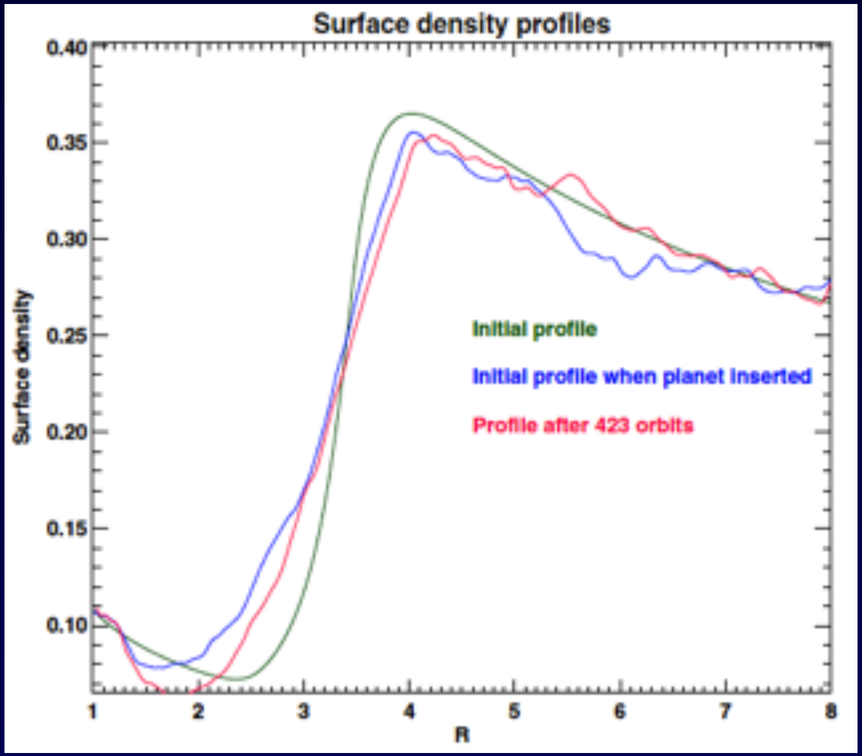

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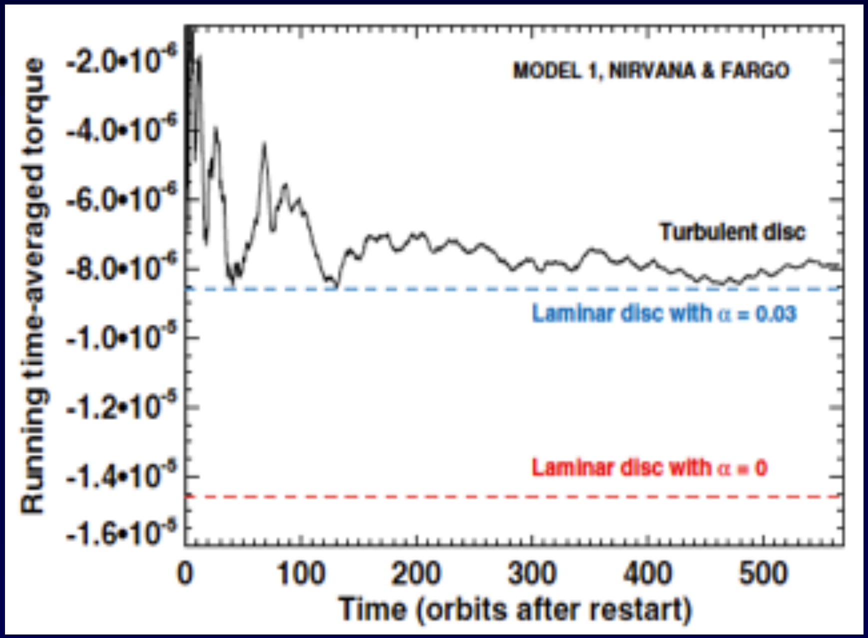
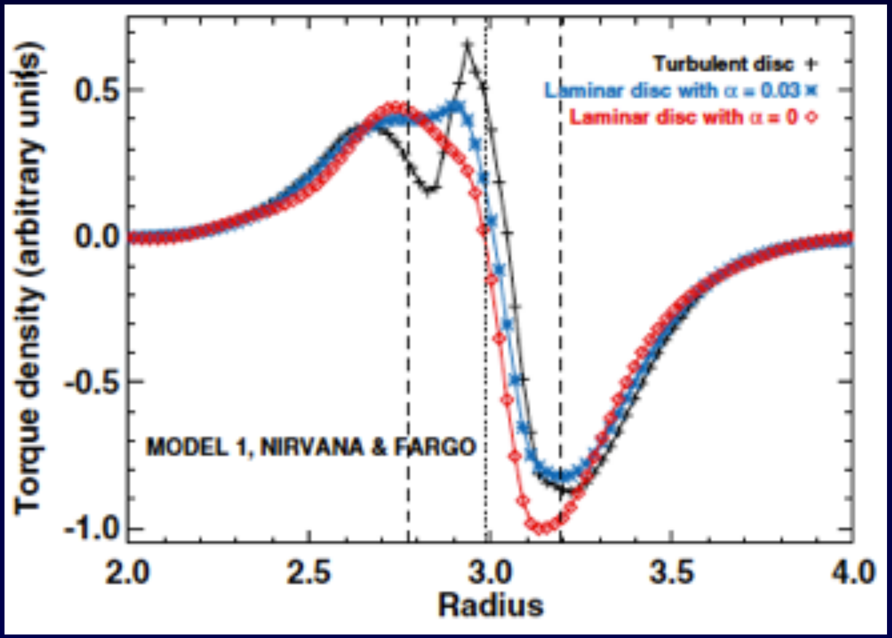




Baruteau et al. (2011)

Locally isothermal models display unsaturated corotation torques for “planet trap” and power law Σ profiles

Corotation torques in dead zones

- Global simulations of discs with dead zones performed using NIRVANA
(Nelson, Baruteau & Fromang 2015)

- Planets with masses m_p = 5 and 10 M_{earth} orbiting at 3 AU

- H/R=0.1 or H/R=0.05

- Disc mass varied between 0.1 – 2 x MMSN to vary dead zone depth

- $\Sigma \sim \Sigma_0 R^2$ ➔ strong and positive corotation torque

- $\nu = \alpha H^2 \Omega$ ➔ larger H requires smaller α value to prevent saturation

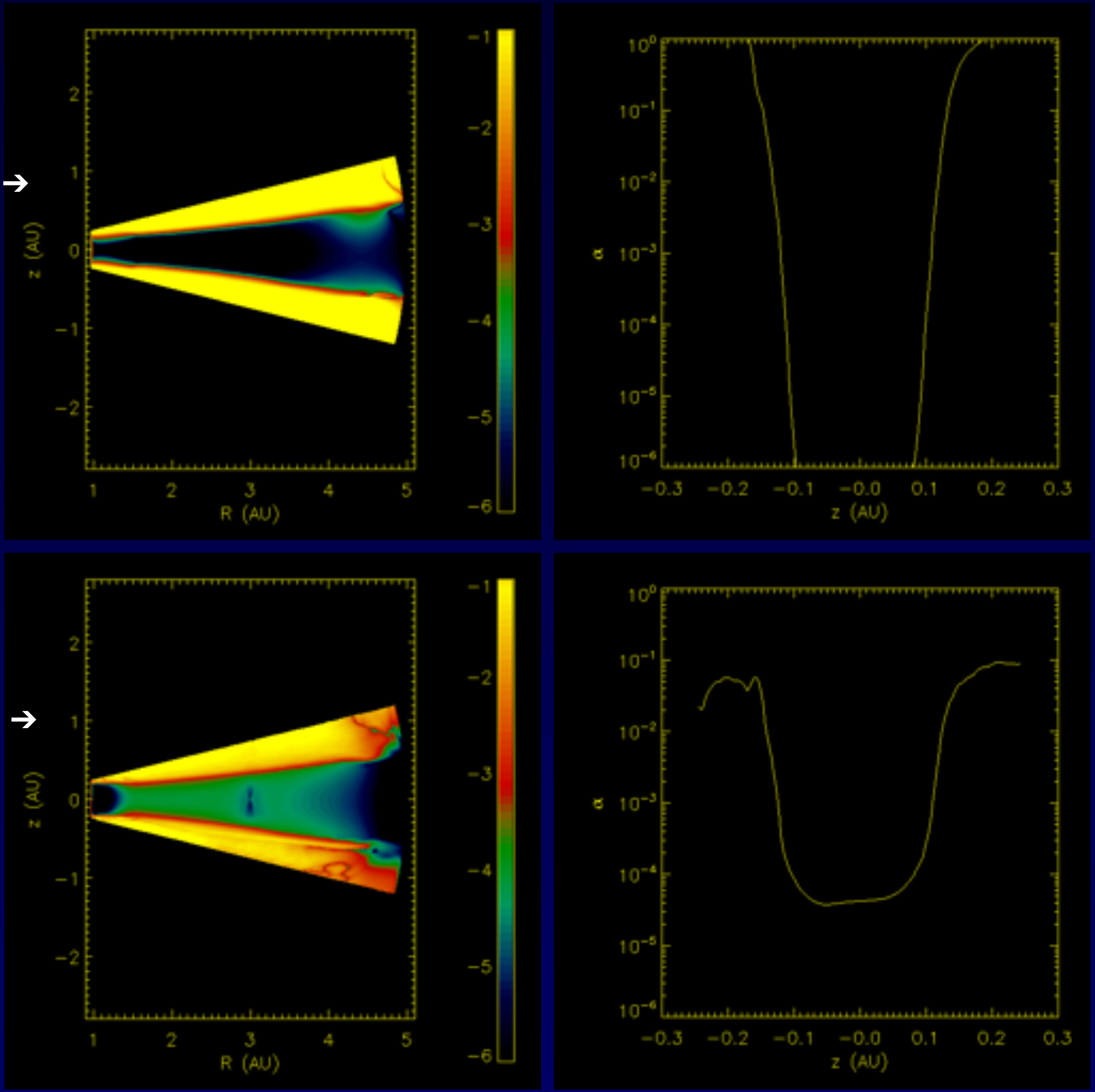
Preventing saturation:
m_p=10 M_{earth} and H/R=0.1 ➔ require $\alpha \sim 2 \times 10^{-4}$
m_p=5 M_{earth} and H/R=0.05 ➔ require $\alpha \sim 10^{-3}$

H/R=0.05 models

MMSN

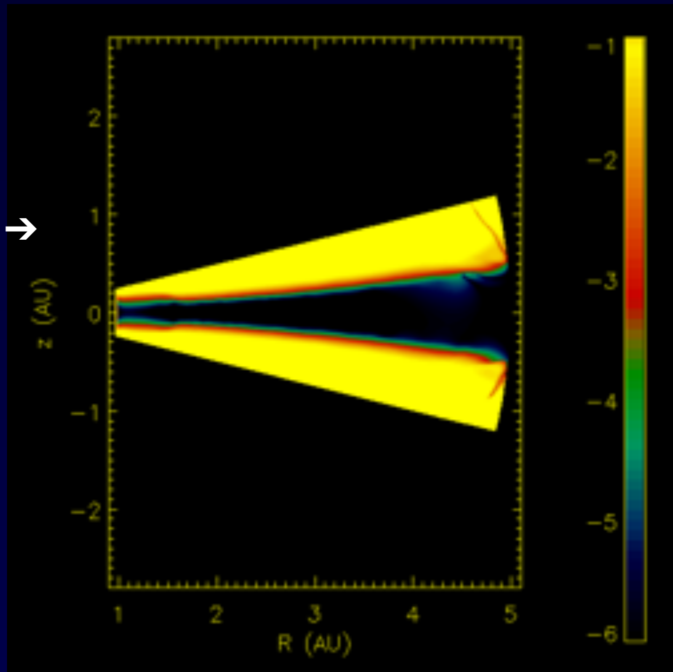
Maxwell stress →

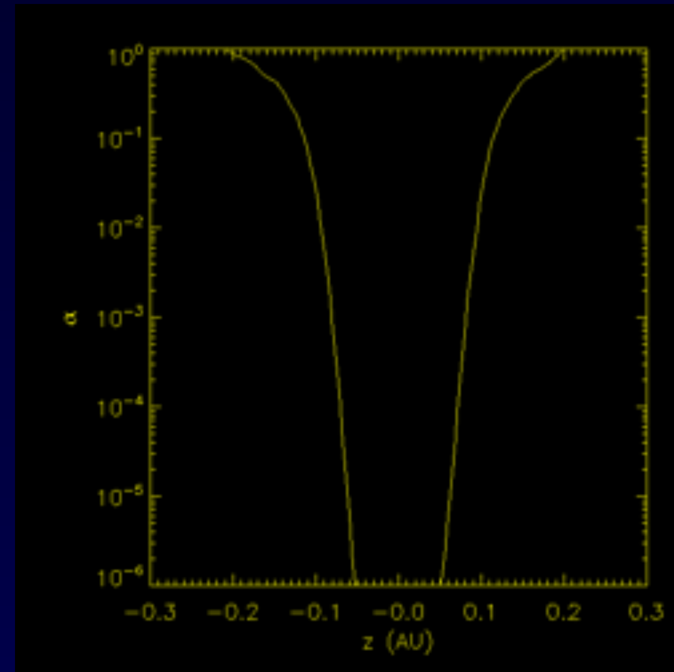
Reynolds stress →



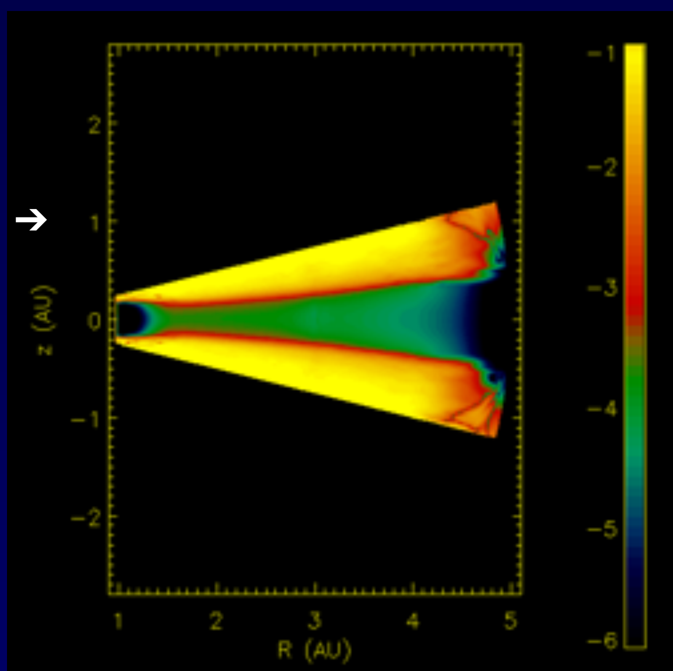
¼ MMSN

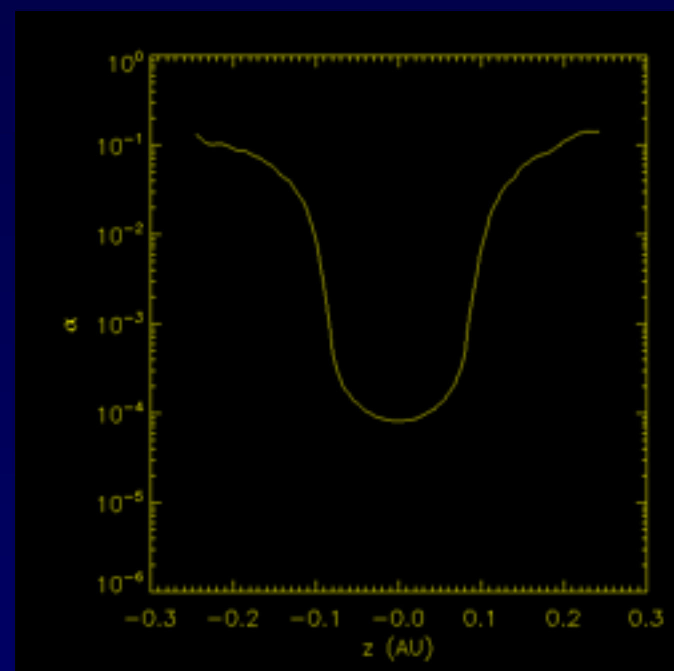
Maxwell stress →





Reynolds stress →

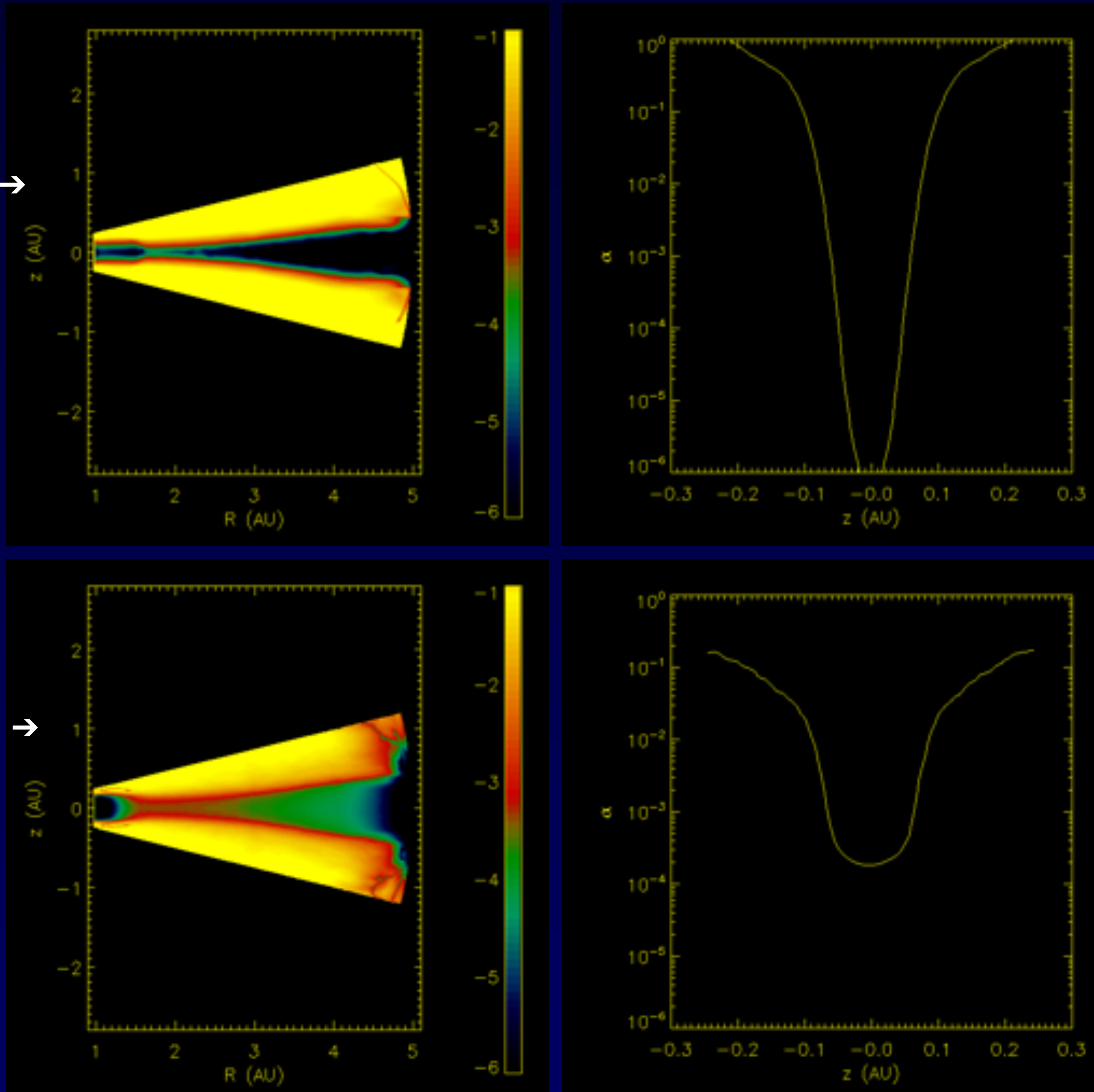


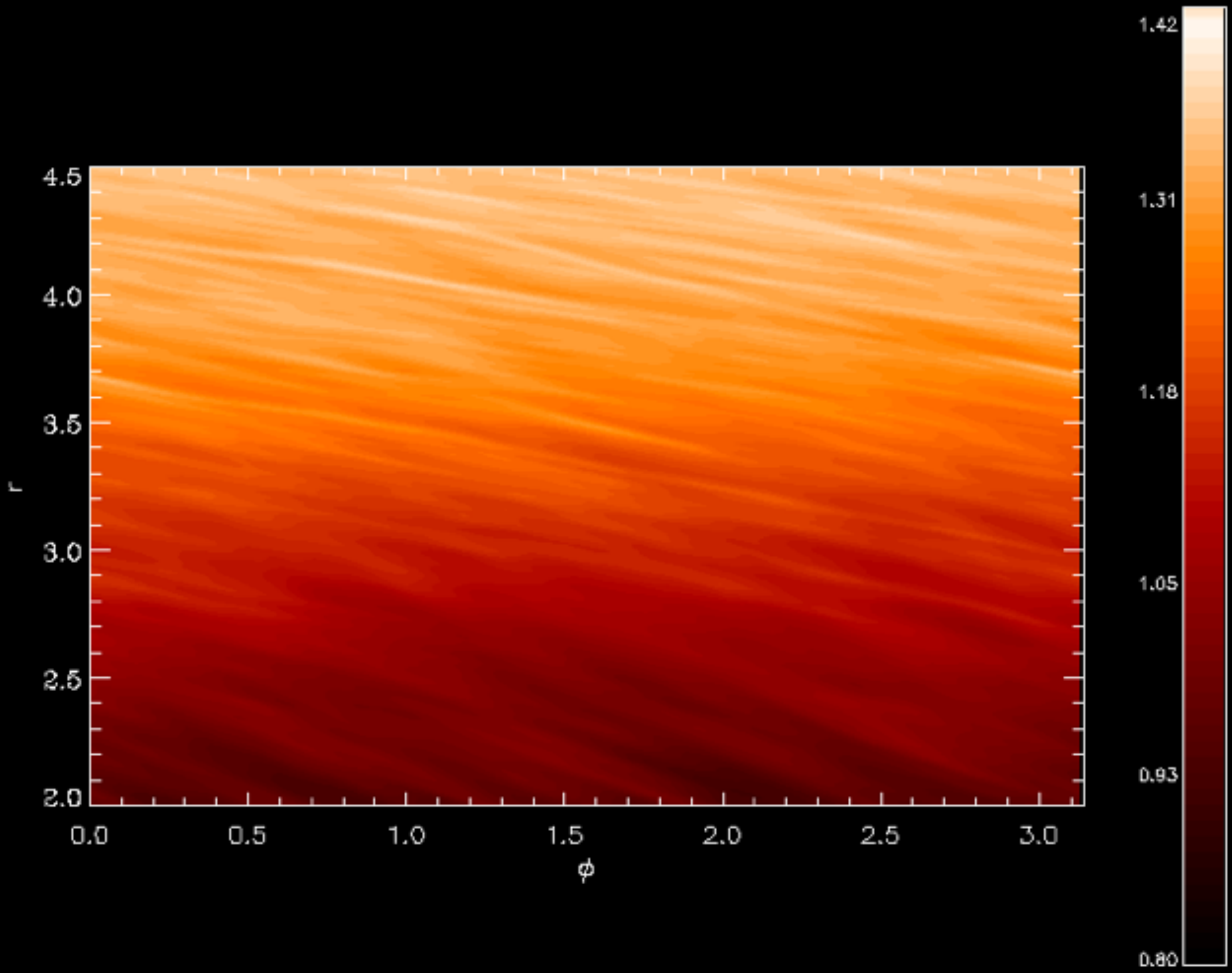


1/10 MMSN

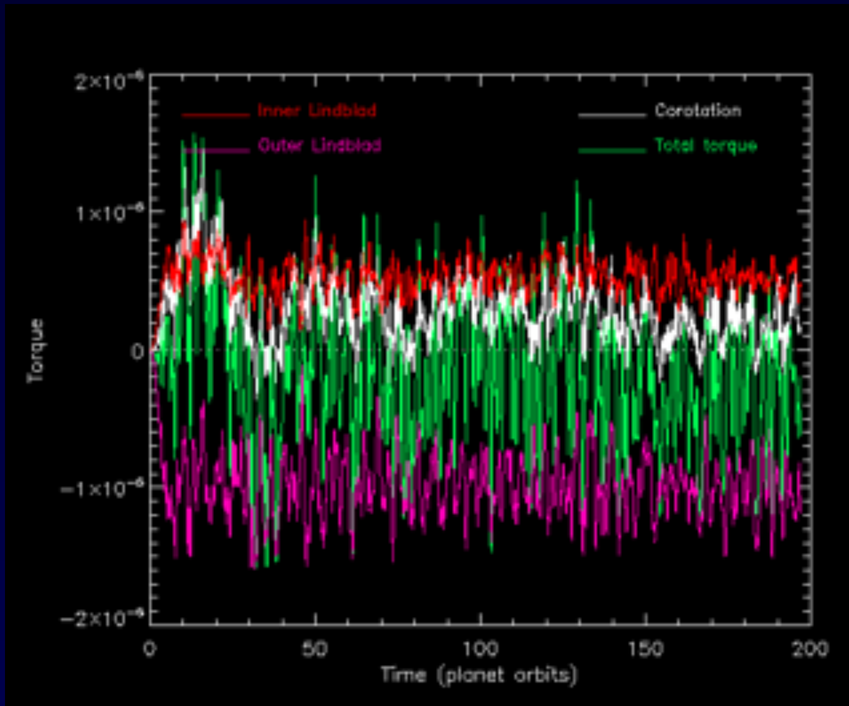
Maxwell stress →

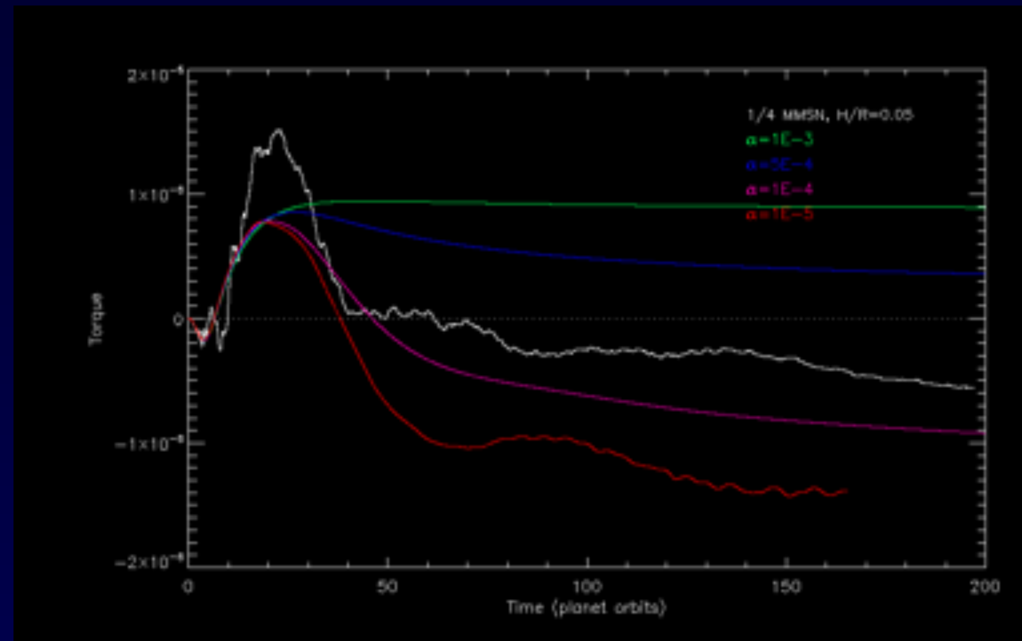
Reynolds stress →

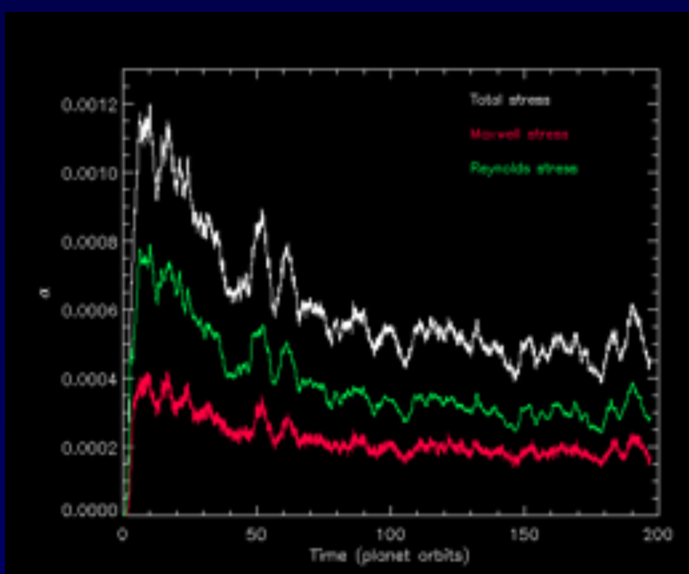




4.5
4.0
3.5
3.0
2.5
2.0
r
0.0
0.5
1.0
1.5
2.0
2.5
3.0
ϕ
1.42
1.31
1.18
1.05
0.93
0.80

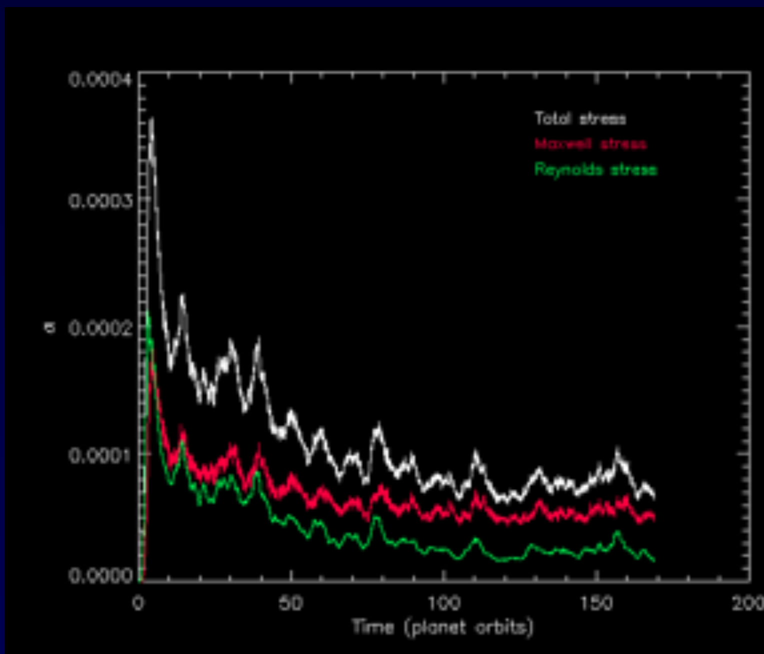


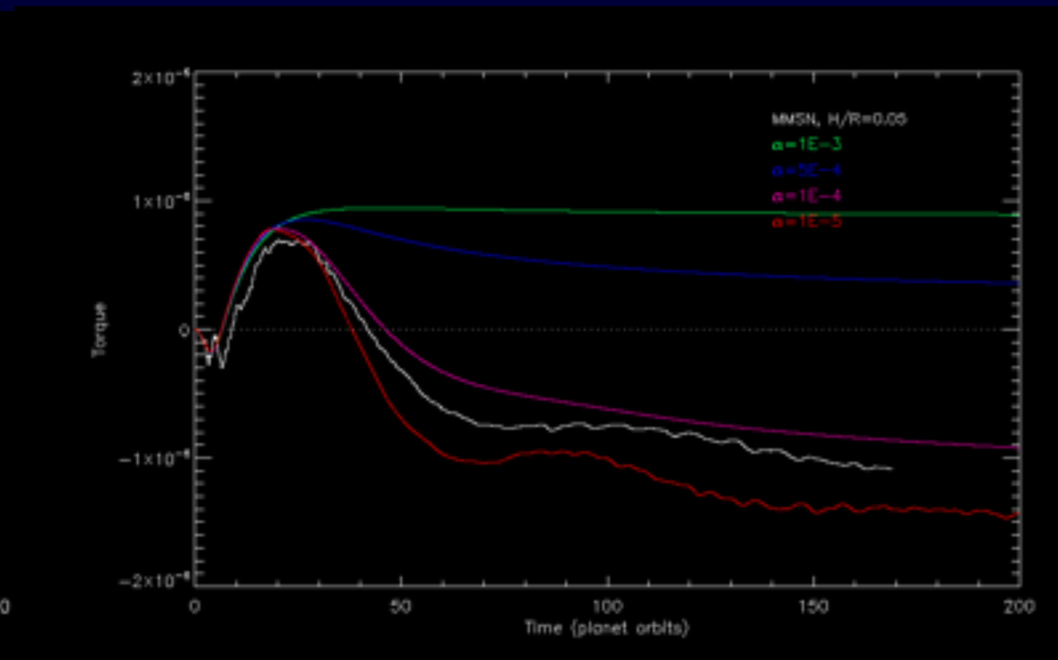




¼ MMSN model

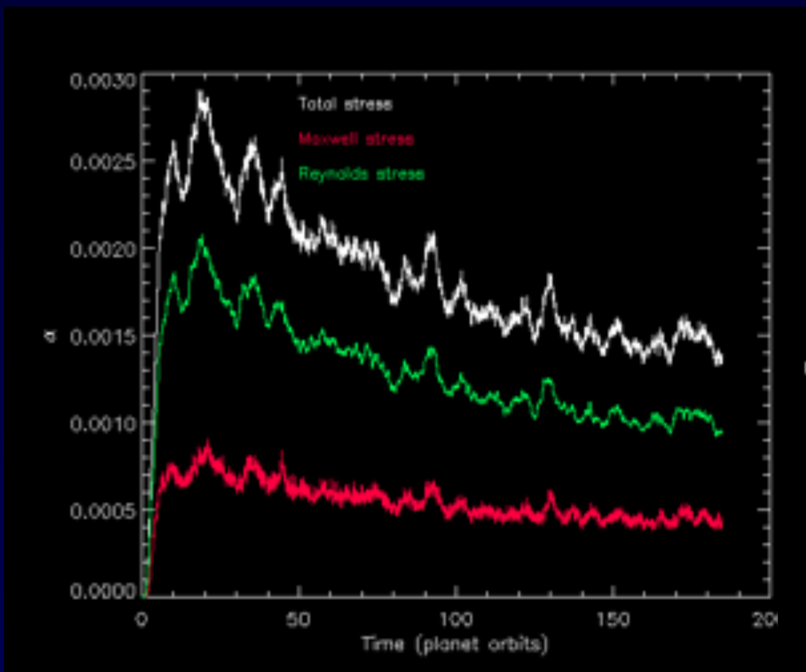
Midplane α ~ 8×10^{-5}
Volume averaged α ~ 5×10^{-4}
Model evolution corresponds to $10^{-4} \leq \alpha \leq 5\times10^{-4}$

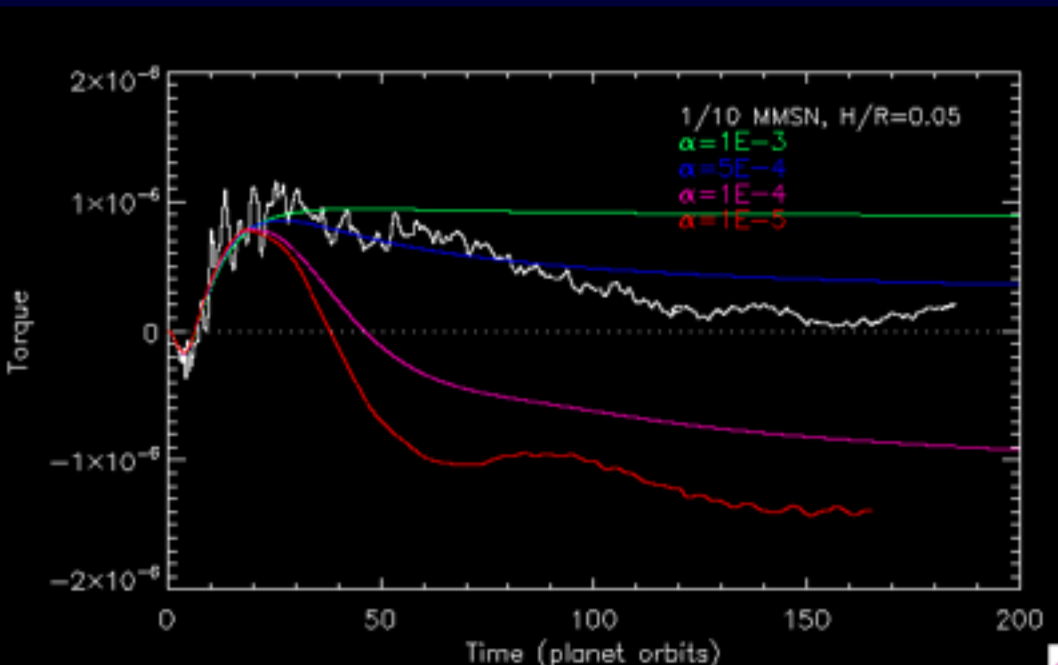




MMSN model

Midplane α ~ $3x10^{-5}$
Volume averaged α ~ $8x10^{-5}$
Model evolution corresponds to $10^{-5} \leq \alpha \leq 10^{-4}$





<u>1/10 x MMSN model</u>

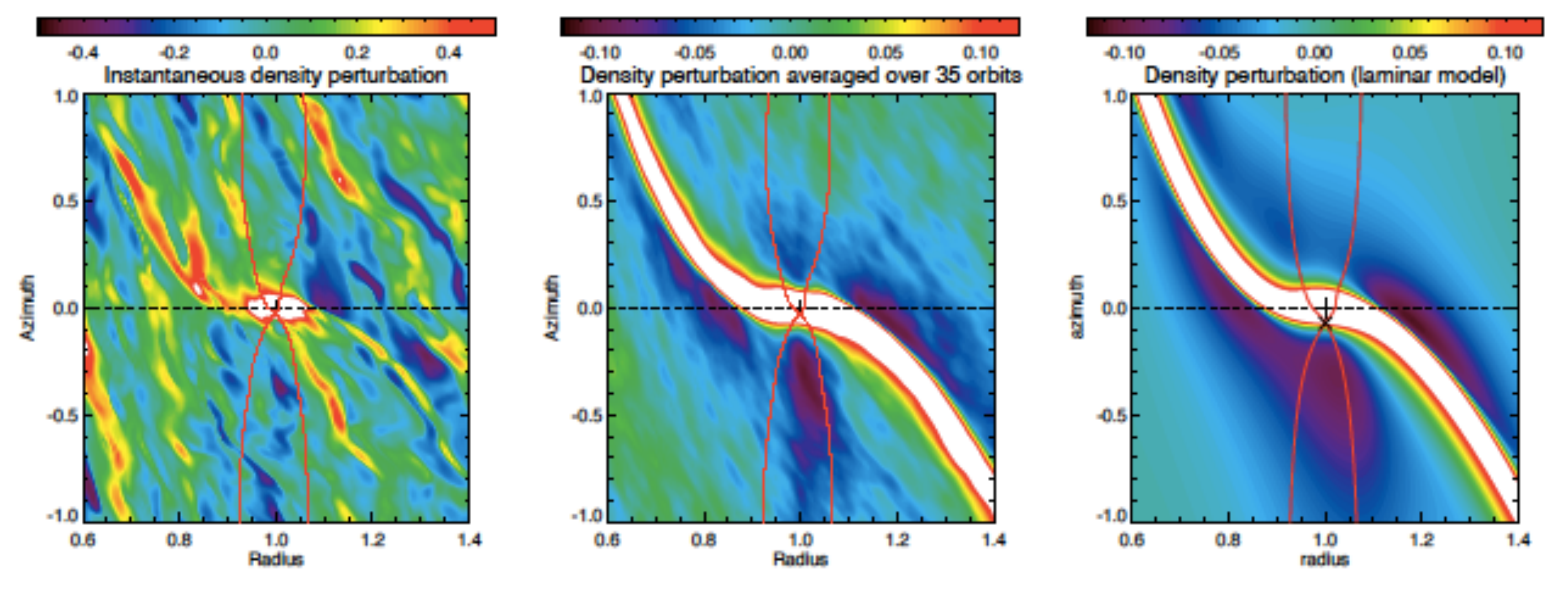
Midplane α ~ 2×10^{-4}
Volume averaged α ~ 1.5×10^{-3}
Model evolution corresponds to $10^{-4} \leq \alpha \leq 5\times10^{-4}$

Conclusion: cannot prevent saturation of corotation torque for low mass planets in dead zones unless at the end of disc life time ➔ require additional stresses to prevent catastrophic migration

Magnetic corotation torque - weak field

- Presence of a weak azimuthal magnetic field can create an additional corotation torque
  - advection of field by horseshoe motion creates low density region behind planet
  (Baruteau et al 2011; Guilet et al 2013)

- Horseshoe motion takes place when Alfven speed < shear velocity across separatrices of horseshoe region (otherwise get magnetic resonances as discussed below)



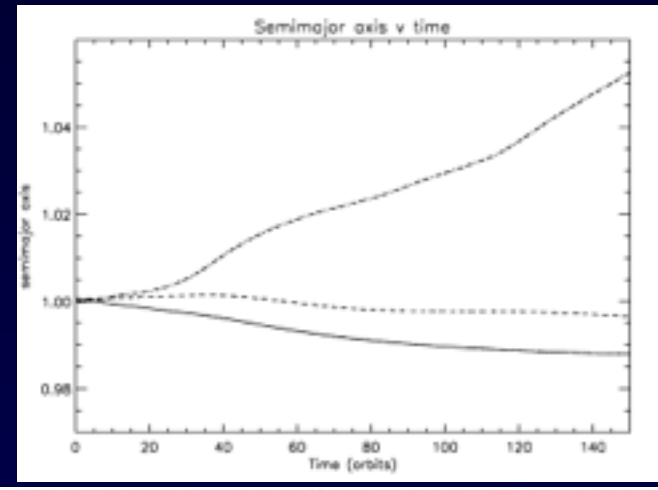
Baruteau et al (2014)

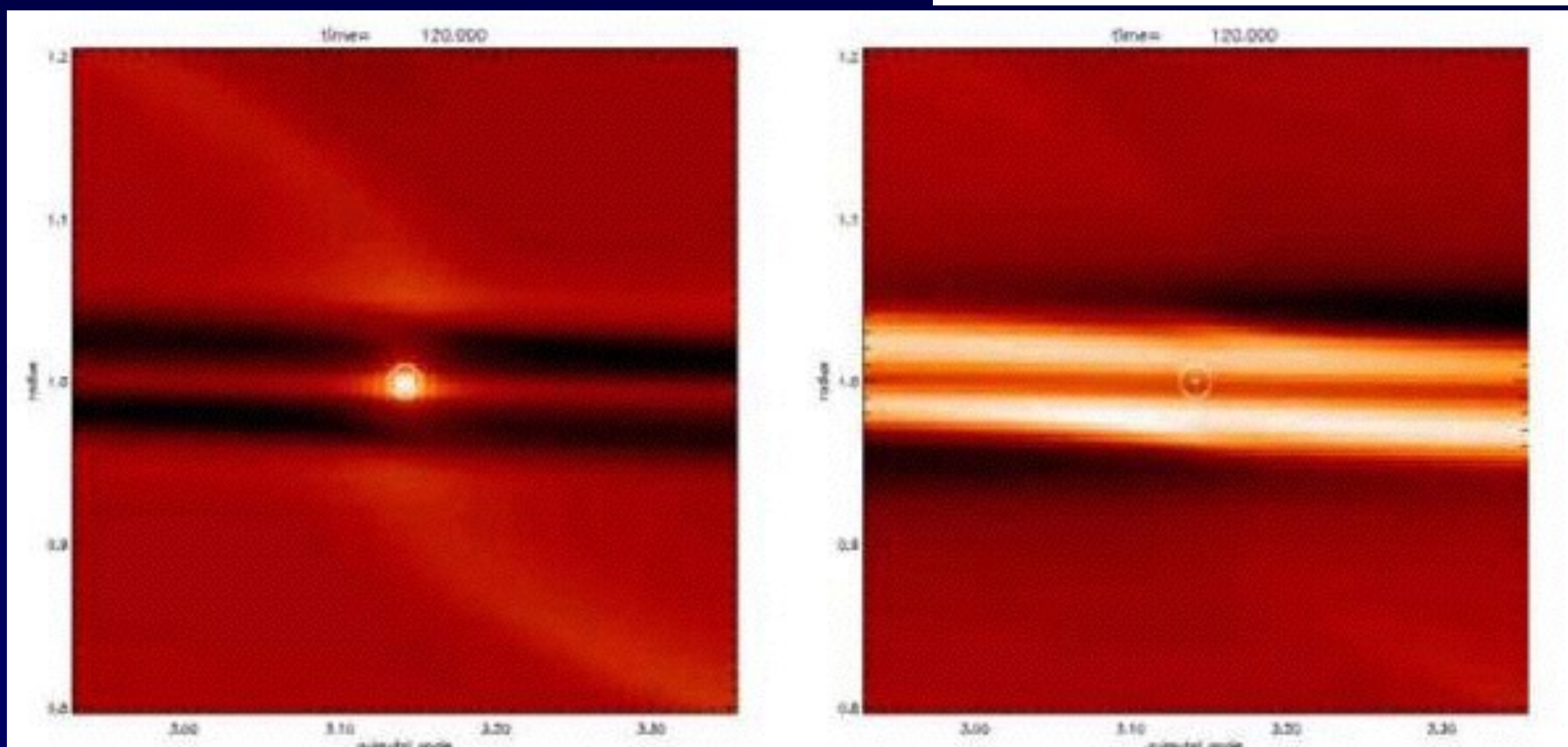
Magnetic resonances - strong field

A strong magnetic field prevents horseshoe motion

Magnetic resonances arise where the azimuthal velocity relative to planet = phase speed of slow magneto-sonic waves
(Terquem 2003; Fromang et al 2005)

For $\beta = 2$ we have outward migration when $B \sim r^{-2}$





Type I migration - other effects

- A planet may migrate more slowly than theory predicts in a disc with low viscosity - mismatch between vortensity in horseshoe region and local disc creates a drag on migration (Paardekooper 2014)

- The heating effect of a “hot planet” radiating its accretion luminosity into the disc may increase the corotation torque (Benitez-Llambay et al 2015)

- Corotation torques in 3D low viscosity discs may be enhanced compared to 2D (Fung et al 2015)

Type II migration of high mass planets

Gap formation

- Deep gap formation ($\delta\Sigma/\Sigma < 0.1$) occurs if:

$$R_{Hill} > H \quad (H\text{=disc thickness})$$

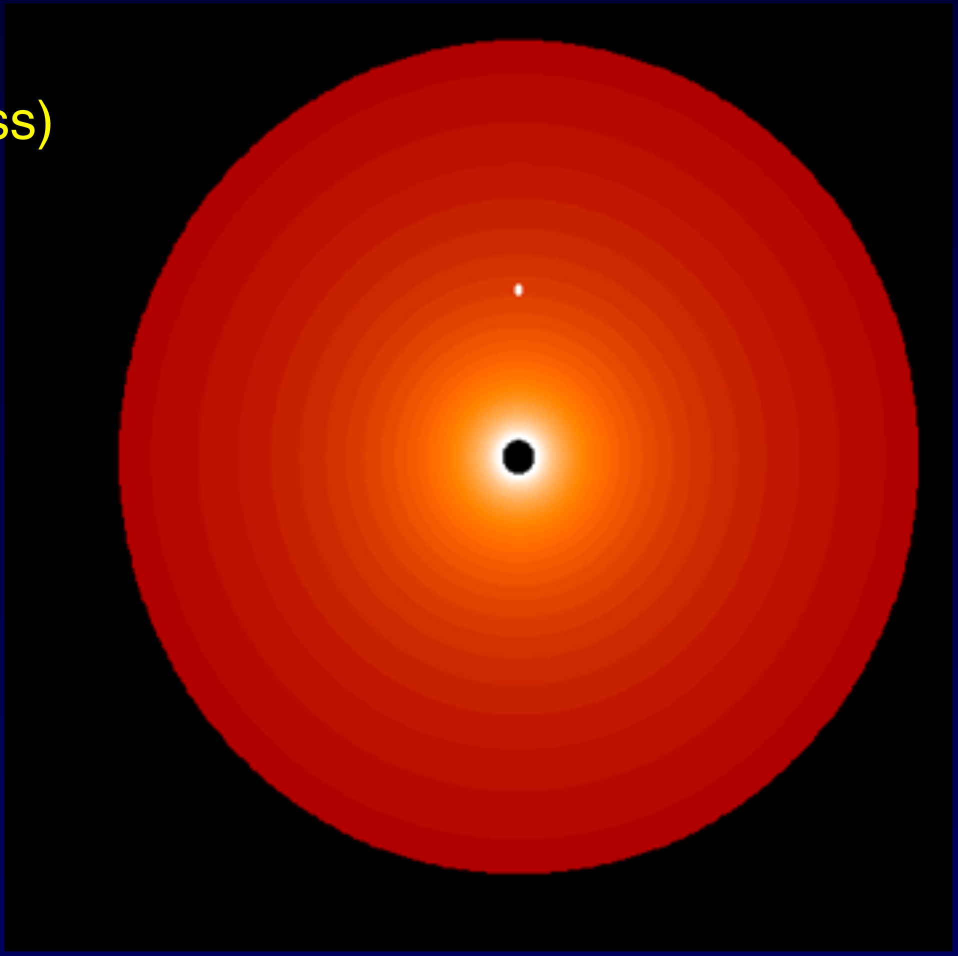
+

tidal torque > local viscous torque
(see exercises for discussion on this)

- Gap formation criterion:
(including pressure effects - Crida et al 2006)

$$h/q^{1/3} + 50\alpha_{visc}/qh^2 < \sim 1$$

q=Planet-star mass ratio
h= H/R (disc aspect ratio)



$h = 0.05$, $\alpha_{visc} = 0.004$
$\rightarrow$ gap if $q>10^{-3}$.

Deep gap formation for Jupiter mass planet

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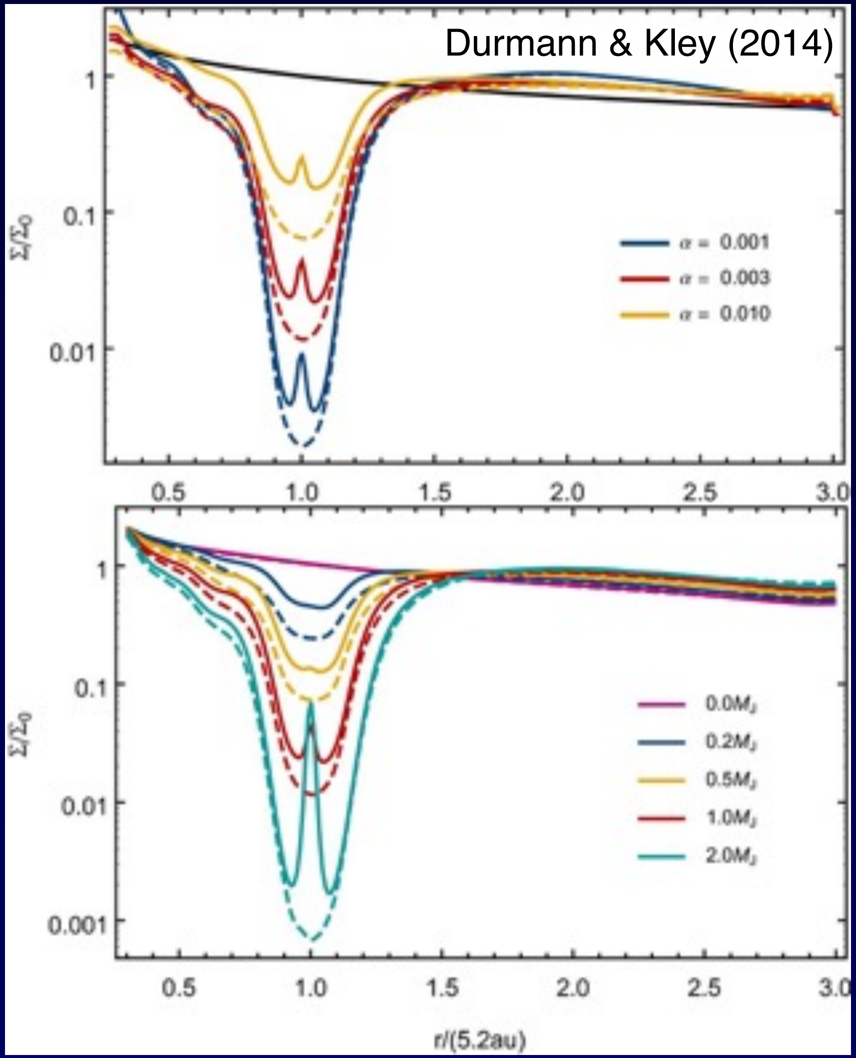

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Deep gap formation for Jupiter mass planet

Migration

- Type II migration occurs for a planet in a deep gap

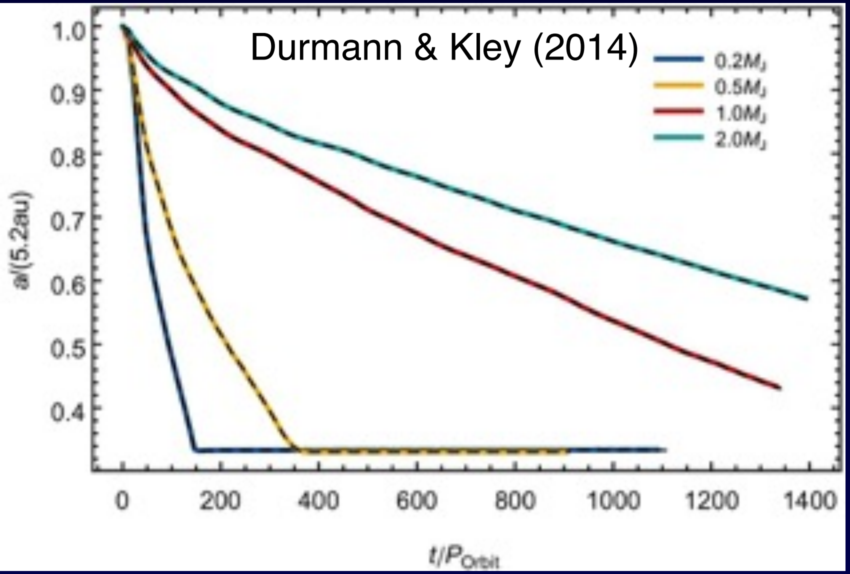
  migration at ~ disc viscous evolution rate (Lin & Papaloizou 1986)

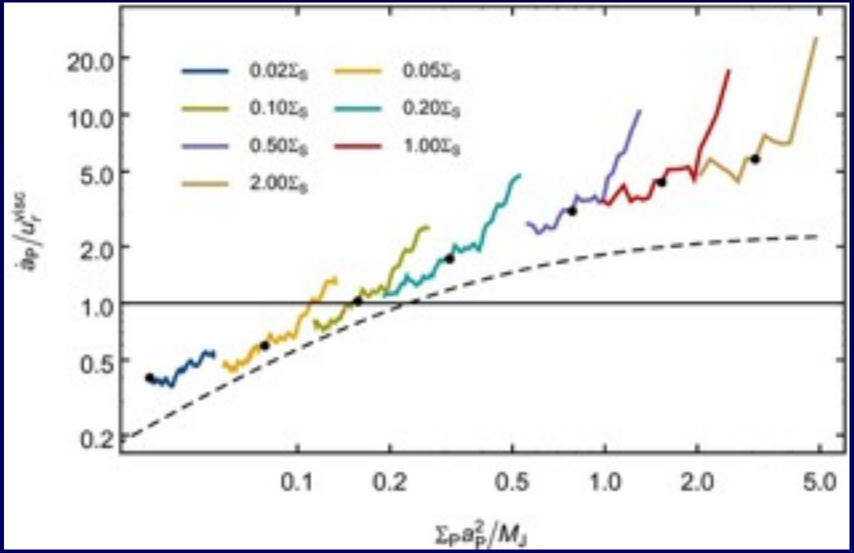
- Migration rates are not precisely equal to the viscous rate (Duffel 2014; Durmann & Kley 2014)

- For large disc masses migration rate > viscous rate

- For low disc masses migration rate < viscous rate

- Residual mass in the gap matters!





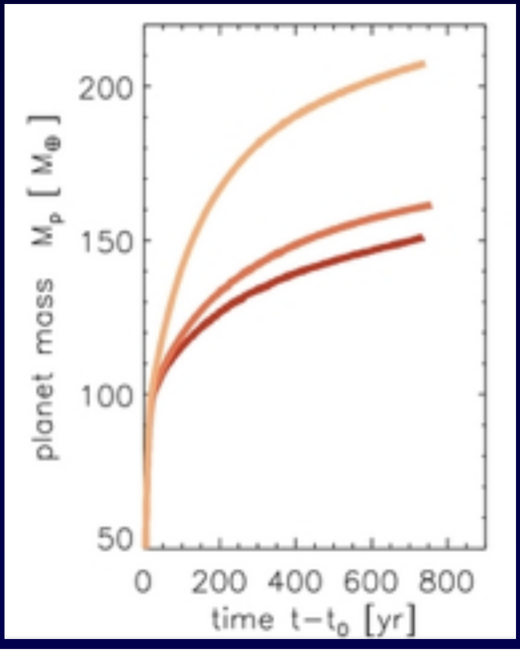
Gas accretion

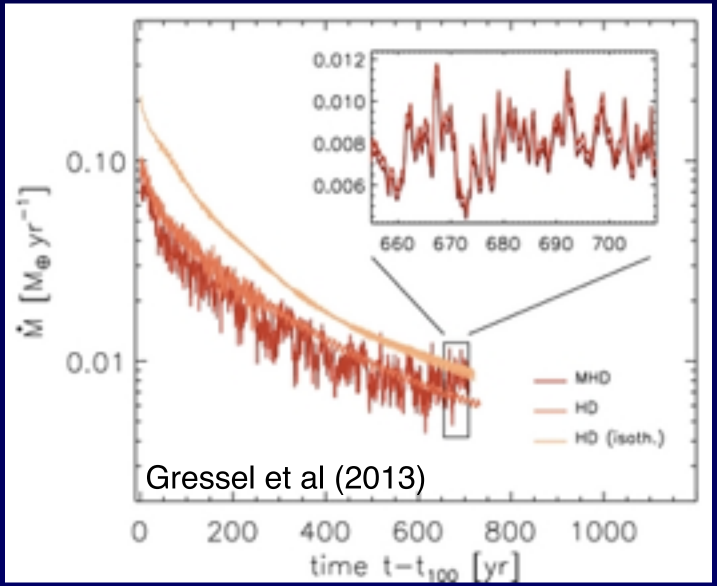
- Almost all simulations agree that the disc supplies gas through the gap to the planet at the viscous supply rate ~ 10^{-5} Jupiter / year (Bryden et al 1999; Kley 1999, Lubow et al 1999)

  - but note that numerical effects prevent accretion rate onto the planet being determined accurately! (Szulágyi 2014)

- During gap formation gas accretion can be at a much faster rate, building a Jovian planet in ~ 10^3 yr

- In 3D gas accretion onto planet largely occurs from high latitudes and not through a flat circumplanetary disc + the addition of magnetic fields makes life more interesting…





Gressel et al (2013)

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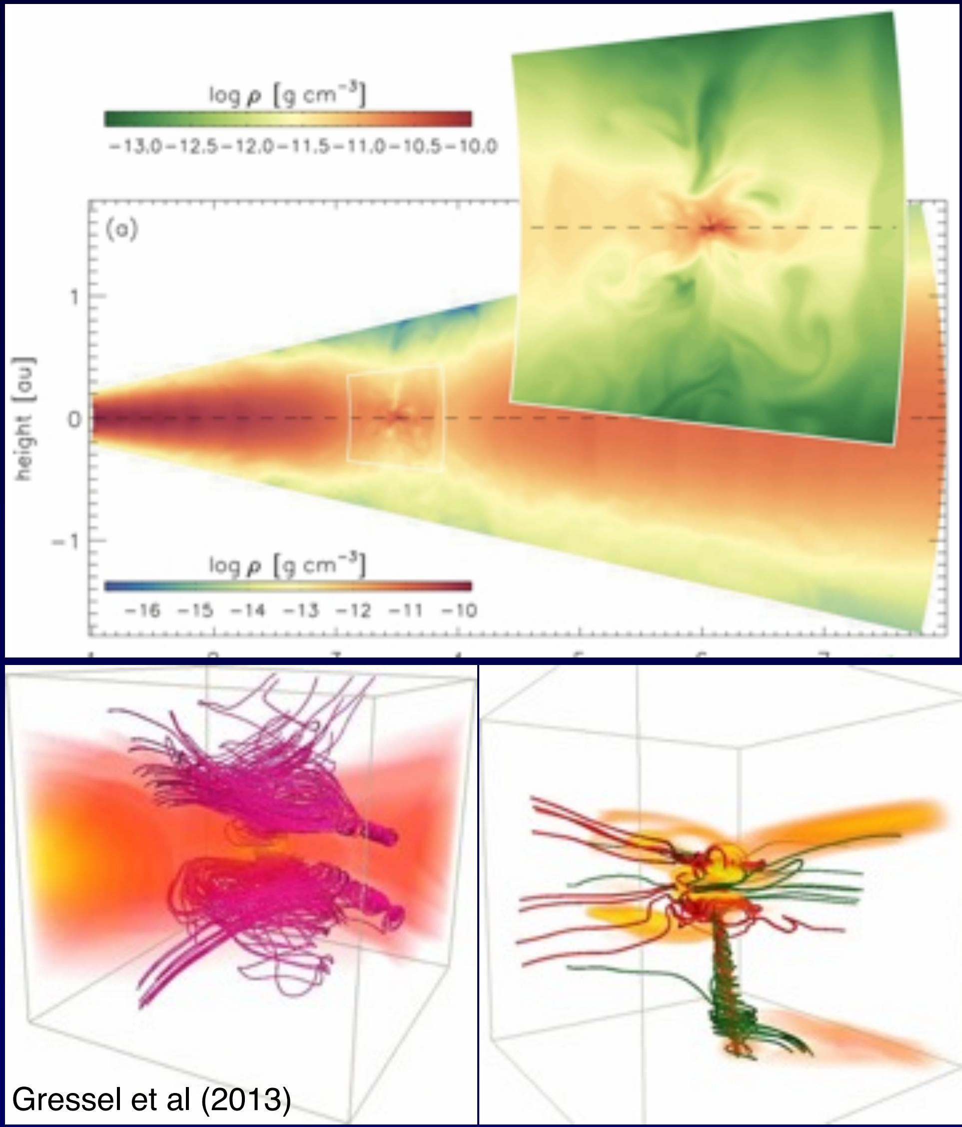
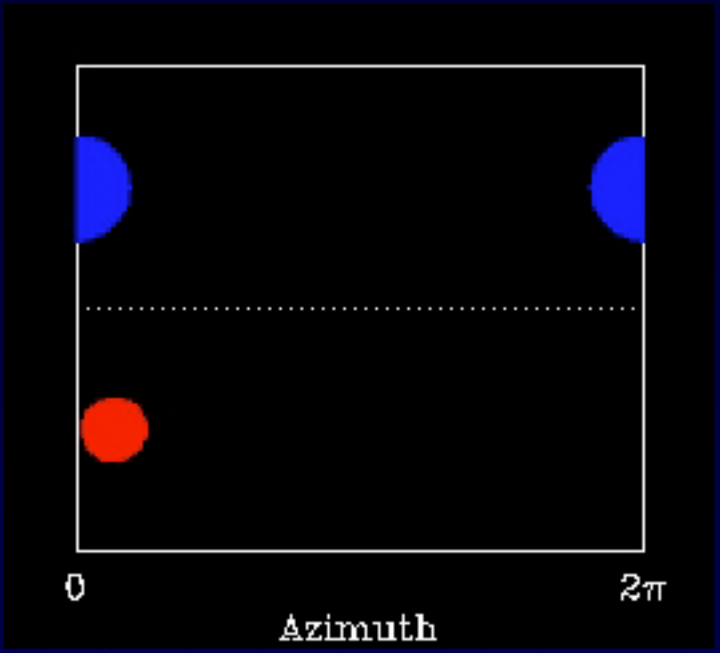


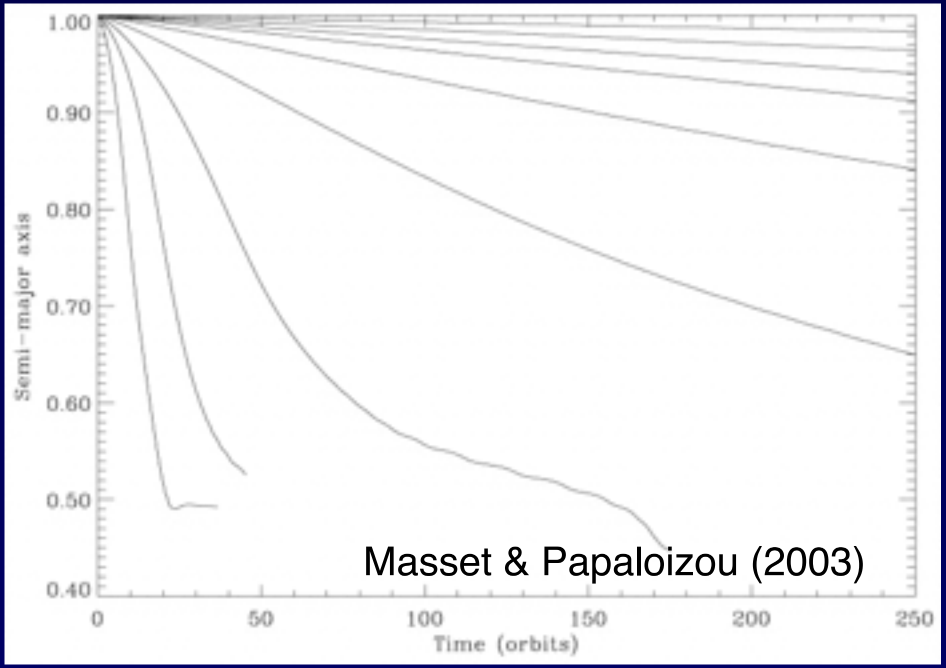
Gressel et al (2013)

Type III migration of intermediate mass planets

Type III migration

- Operates for ~ Saturn mass planets in disc models with mass ~ 3 x MMSN (Masset & Papaloizou 2003)
- Require partial gap
- Flow-through of gas past planet orbit during migration acts to propel planet inward at a rate that scales with the migration rate ⇨ runaway!
- Large scale migration can occur in a few 10s of orbits
- Forms an important part of the Grand Tack model for the Solar System





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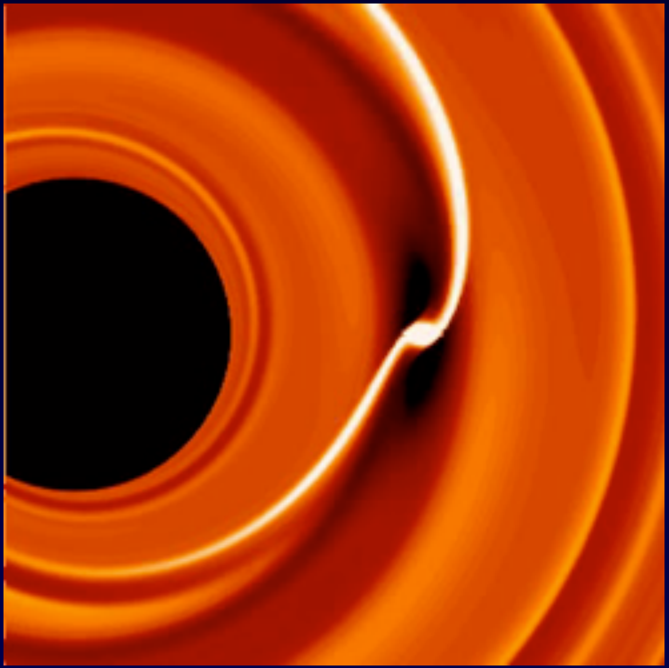

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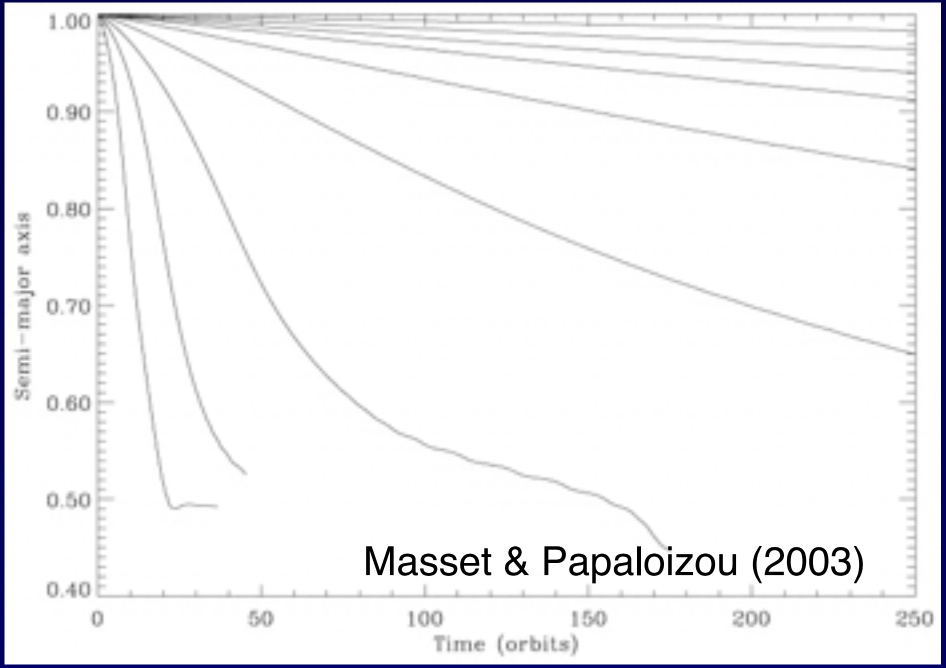

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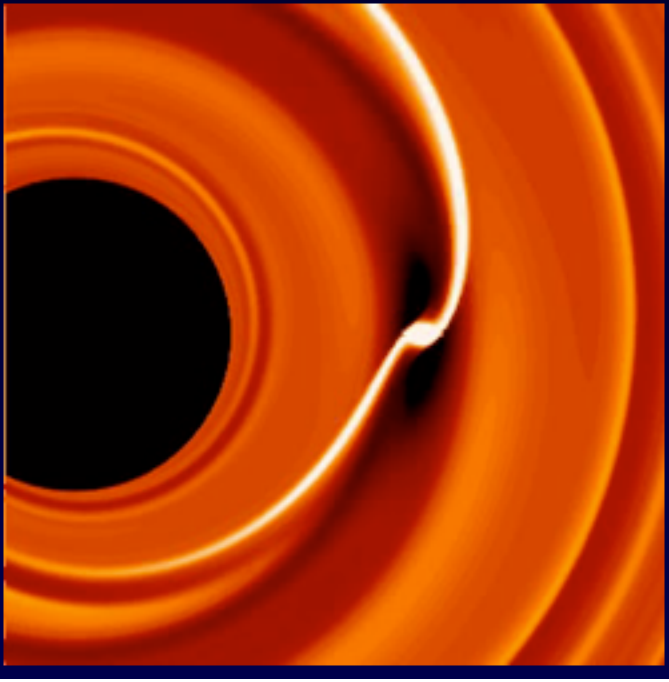
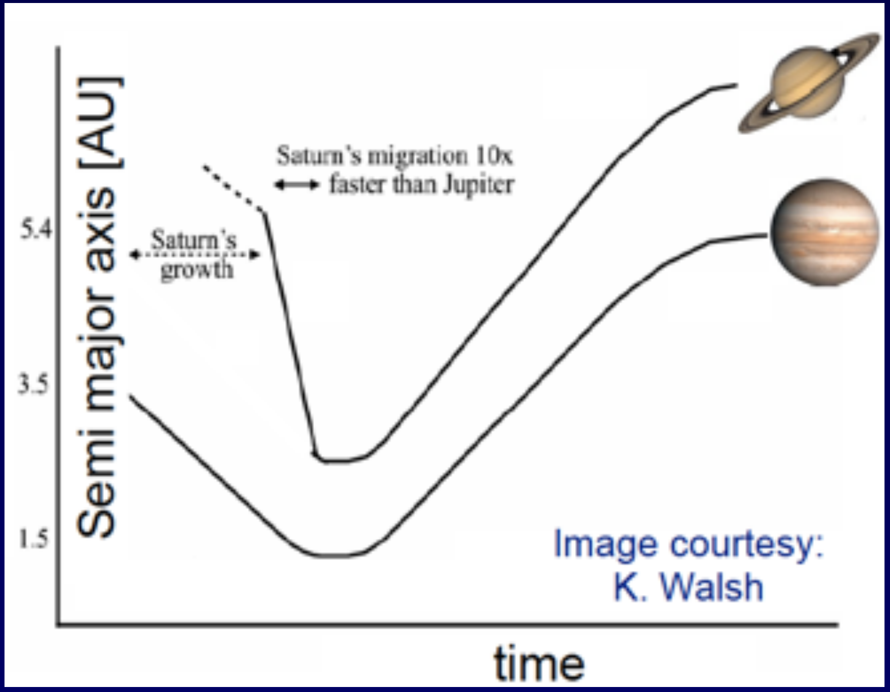


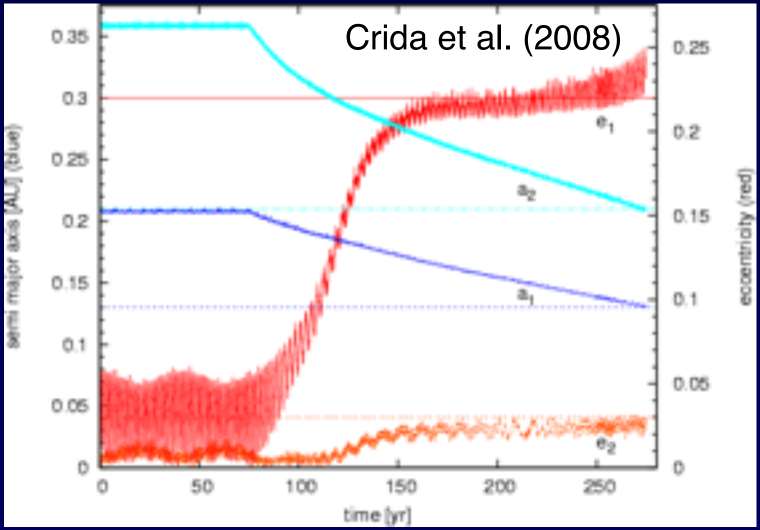


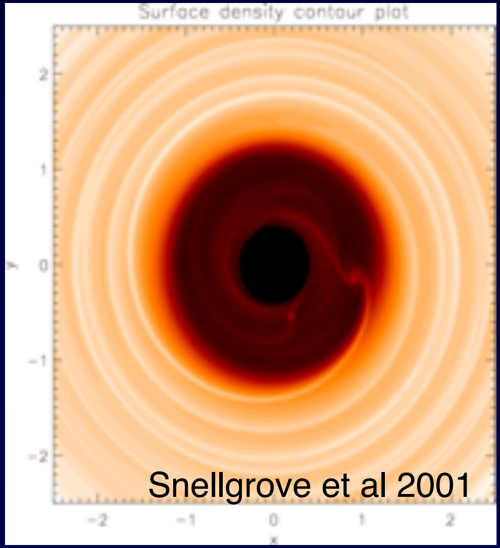
Multiple planets in a disc

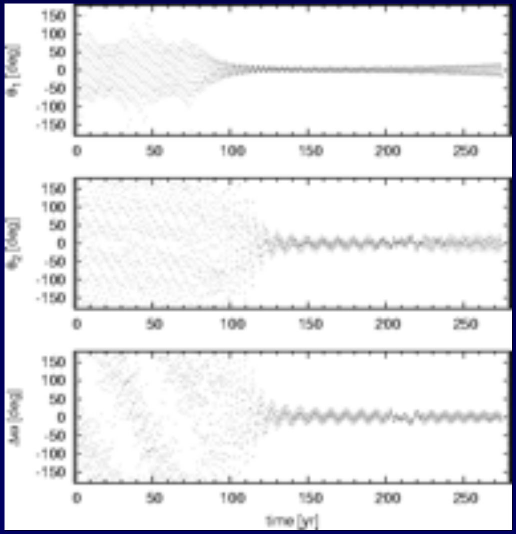
Capture in mean motion resonance - Gliese 876

Convergent type II migration of planet pair (b & c) leads to capture in 2:1 mean motion resonance (Snellgrove et al 2001; Lee & Peale 2002)

Hydro simulations where the inner boundary is close to star so that inner disc remains produce good agreement with observed system eccentricities (Crida et al. 2008)





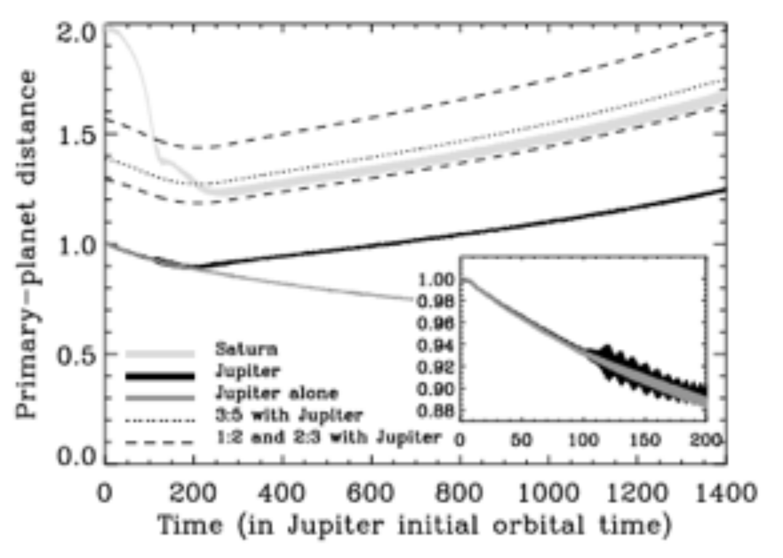


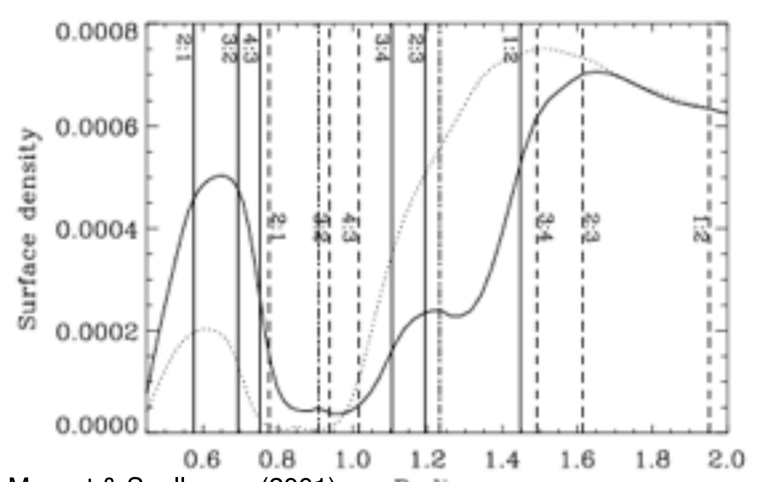
Capture into mean motion resonance and outward migration

Rapid type III migration of Saturn leads to capture in 3:2 resonance with Jupiter instead of 2:1 (Masset & Snellgrove 2001)

Total Lindblad torque acting on resonant planet pair is positive leading to outward migration

Capture in 3:2 also seen for HD 45364 (Rein et al 2010)



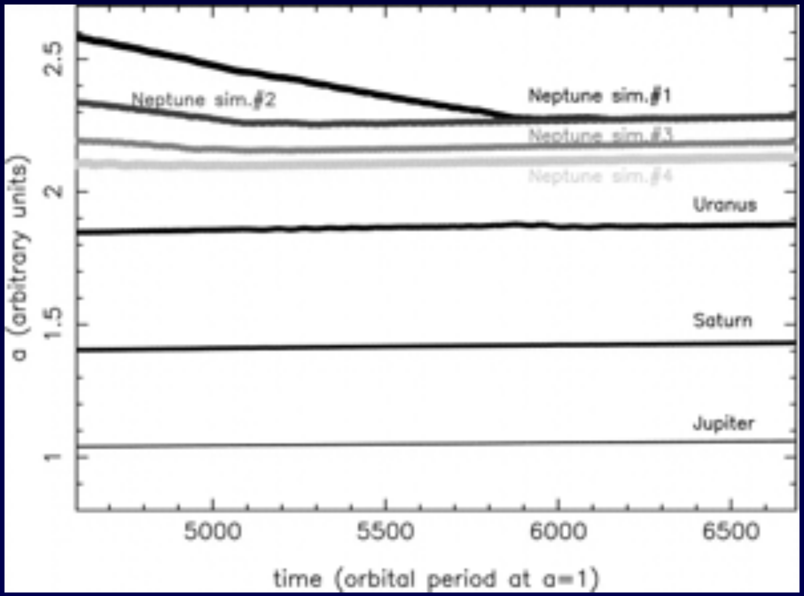


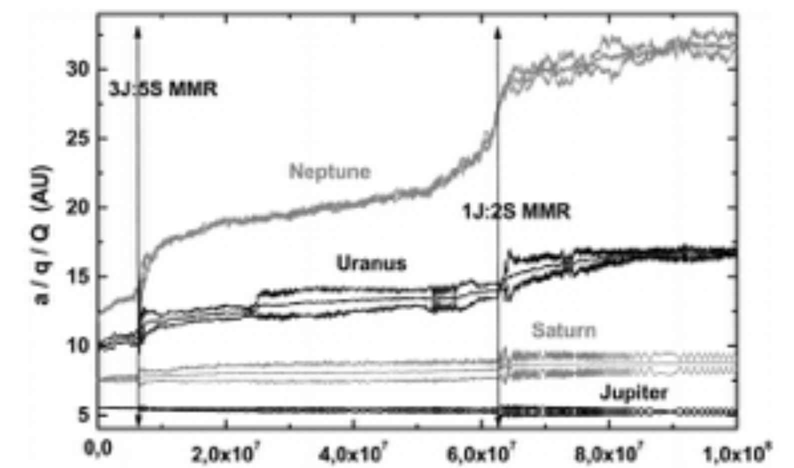
Masset & Snellgrove (2001)

Application to the Nice model - 4 planet resonance

With Jupiter & Saturn in 3:2 resonance it's possible to construct disc model in which outer planets of the solar system are in mutual resonance (3:2, 3:2, various for U+N) with no net migration (Crida et al 2007)

Long-term interactions with exterior planetesimal disc after gas disc removal results in instability among outer planets as required for Nice model





Crida et al (2007)

Concluding remarks

- Although we don’t have a complete understanding of protoplanetary discs or of disc-planet interactions, disc-driven migration of planets seems to be very difficult to avoid

- Major questions remain about how and where coronation torques operate
  - dead zones cannot sustain coronation torques due to the small viscosity there
  - does the activation of the disc by the Hall effect unsaturate the coronation torque?
  - does this really only occur in 50% of discs where field and disc rotation are aligned?

- What sets the rate at which giant planets accrete gas? Why are there so many Saturn mass planets when they should accrete gas so rapidly that they become Jupiters?

- Although recent focus of research has been on corotation torques and rapid type I migration, type II migration is also very rapid and delivers giant planets to the central star unless they form late in the disc life time and at large distances from the central star (see talk on Friday afternoon…)