New insights in planet migration

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Outline

- Planet migration: why, when and how
- Type 0, I, II and III
- Migration by waves
- The maze that is corotation
- Thermodynamics
- Outlook

A Jupiter-mass companion to a solar-type star

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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.

For more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions[1-5]. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m s^{-1}. As the reflex motion of the Sun due to Jupiter is 13 m s^{-1}, all current searches are limited to the detection of objects with at least the mass of Jupiter (M_J). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s^{-1}. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years[6,7]. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 M_J, orbiting at 0.05 AU around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 M_J for the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

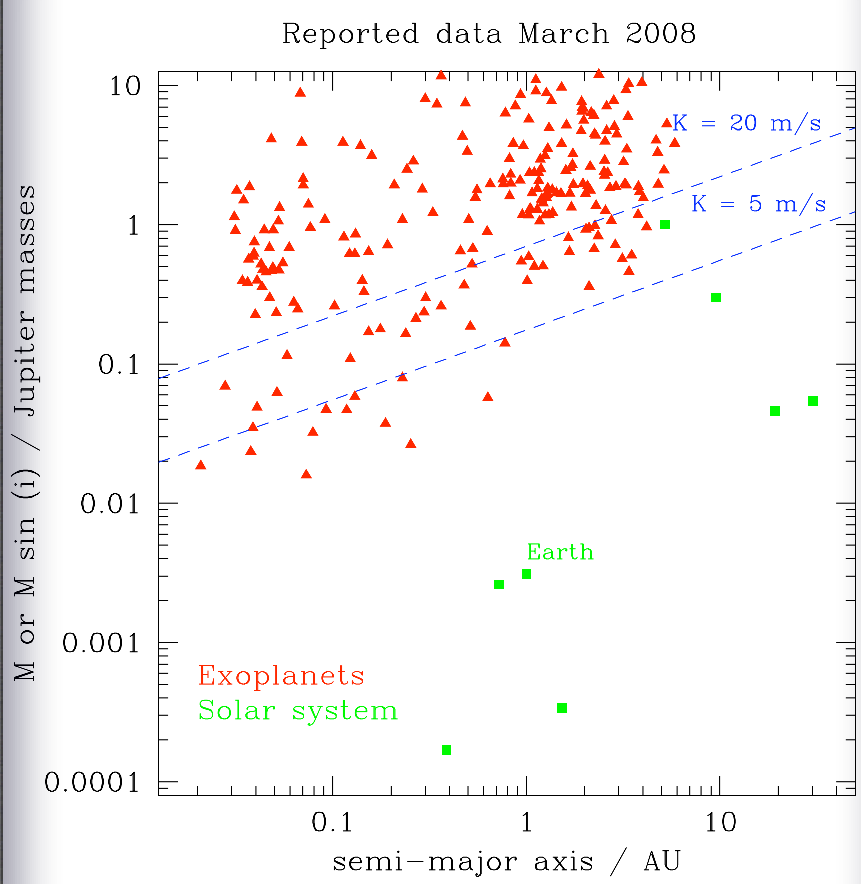
The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation[8]. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant[9] over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

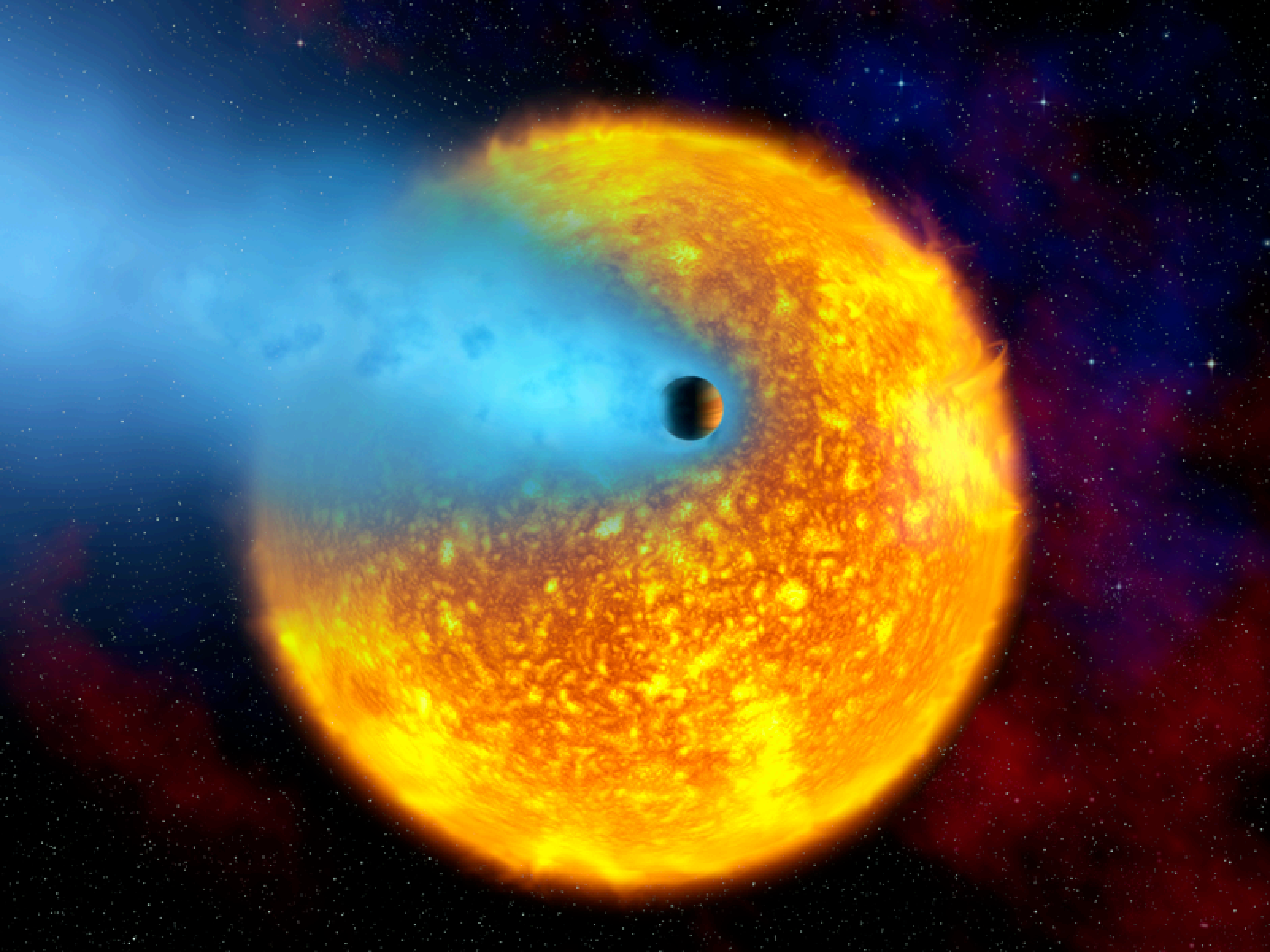
Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODIE of the Haute-Provence Observatory, France[10]. This instrument permits measurements of radial velocity with an accuracy of about 13 m s^{-1} of stars up to 9 mag in an exposure time of <30 min. The radial velocity is computed

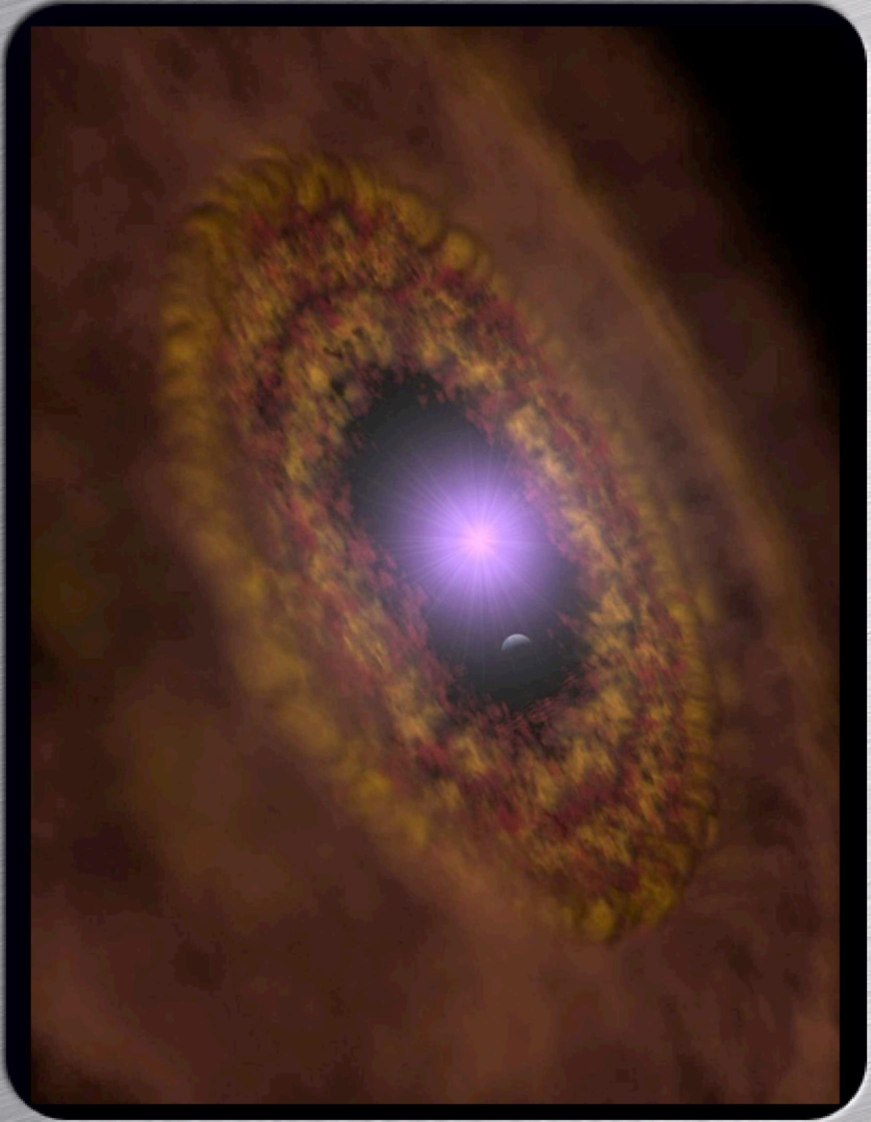
Case for migration



- Close-in giant planets: Hot Jupiters
- Can probably only form at ~5 AU
- Must have migrated inward



Planet migration



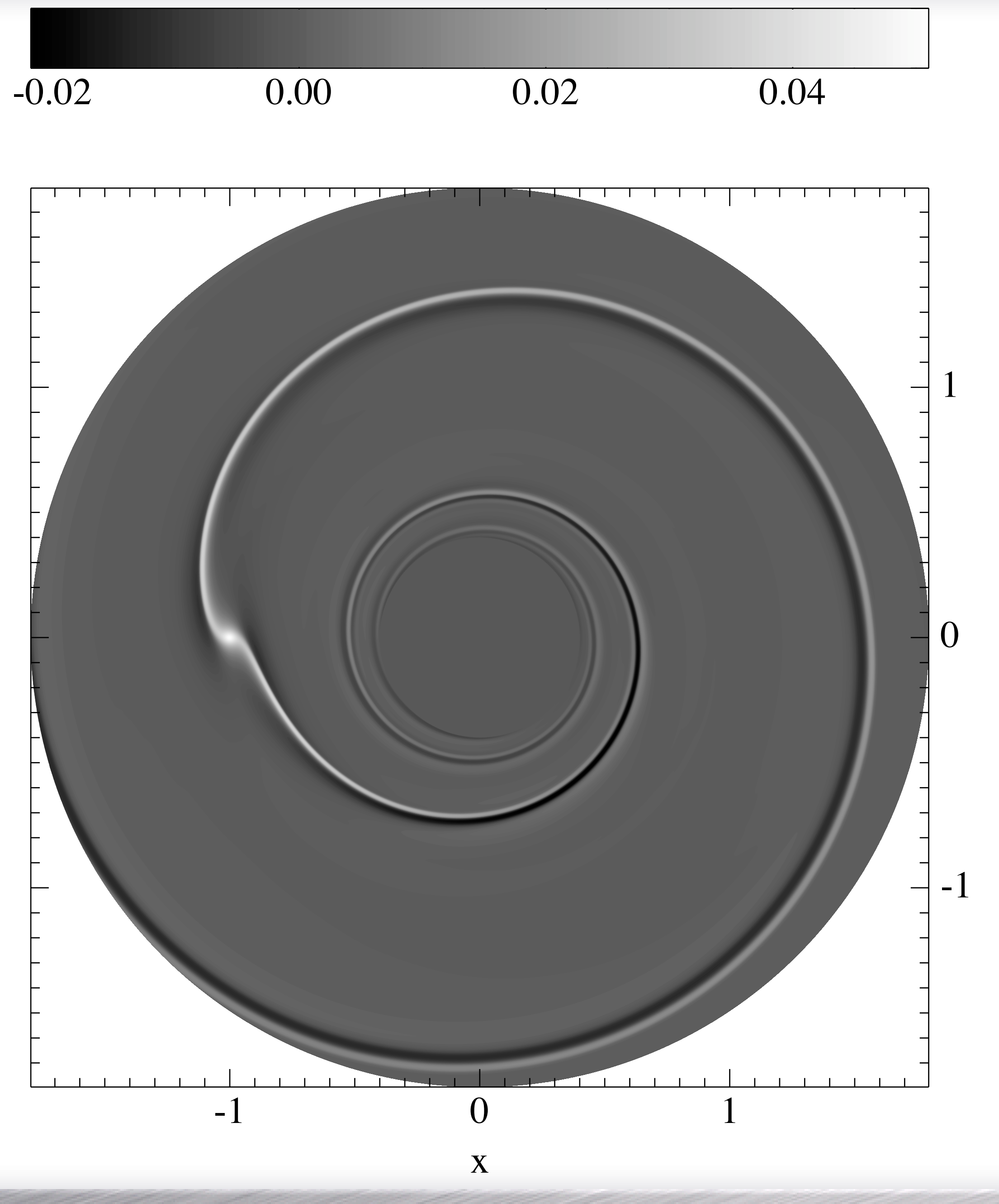
- Planets form inside circumstellar discs
- Gas disc exerts force (torque) on the planet
- Result: orbital migration

Type 0, I, II, III

- *All* embedded bodies subject to migration
- Type 0: aerodynamic drag causes small particles to drift inward (Weidenschilling 1977)
- Type I: low-mass planets excite linear waves causing inward migration (Ward 1997)
- Type II: massive planets undergo 'accretion' onto the central star (Lin & Papaloizou 1986)
- Type III: intermediate-mass planets embedded in massive discs undergo runaway migration (Masset & Papaloizou 2003)

Migration by waves

- Planets up to a few $M_\oplus$ excite linear waves in the disc (Goldreich & Tremaine 1979)
- Asymmetries in disc (density, rotation) lead to an exerted torque
- Semi-analytic torque formula (Tanaka et al. 2002): inward migration



-0.02
0.00
0.02
0.04
1
0
-1
-1
0
1
x

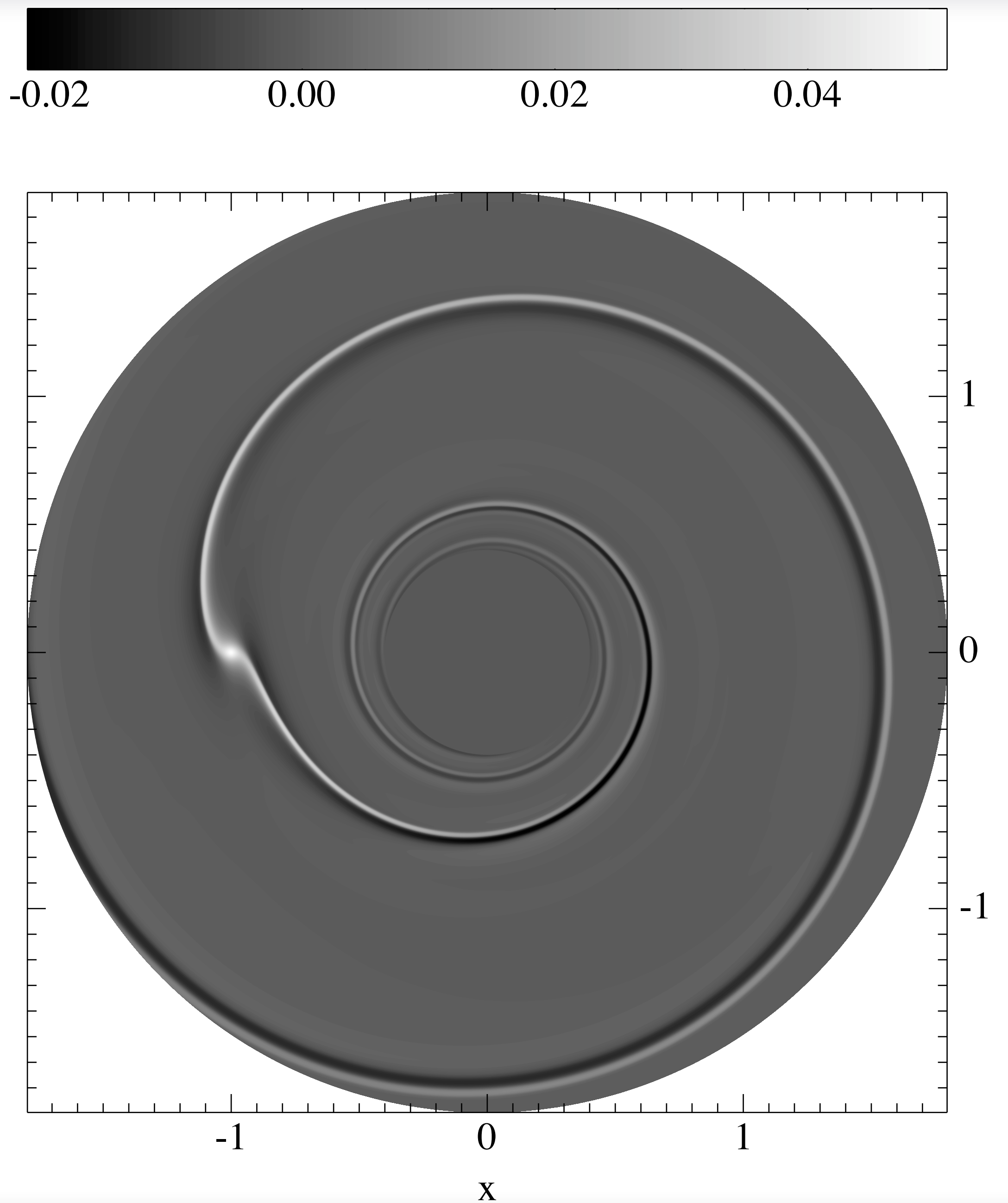
Migration by waves

$$m(\Omega - \Omega_{\mathrm{p}}) = \pm\Omega$$

$$\Omega/\Omega_{\mathrm{p}} = \frac{m}{m \mp 1}$$

$$r/r_{\mathrm{p}} = \left(\frac{m}{m \mp 1}\right)^{-2/3}$$

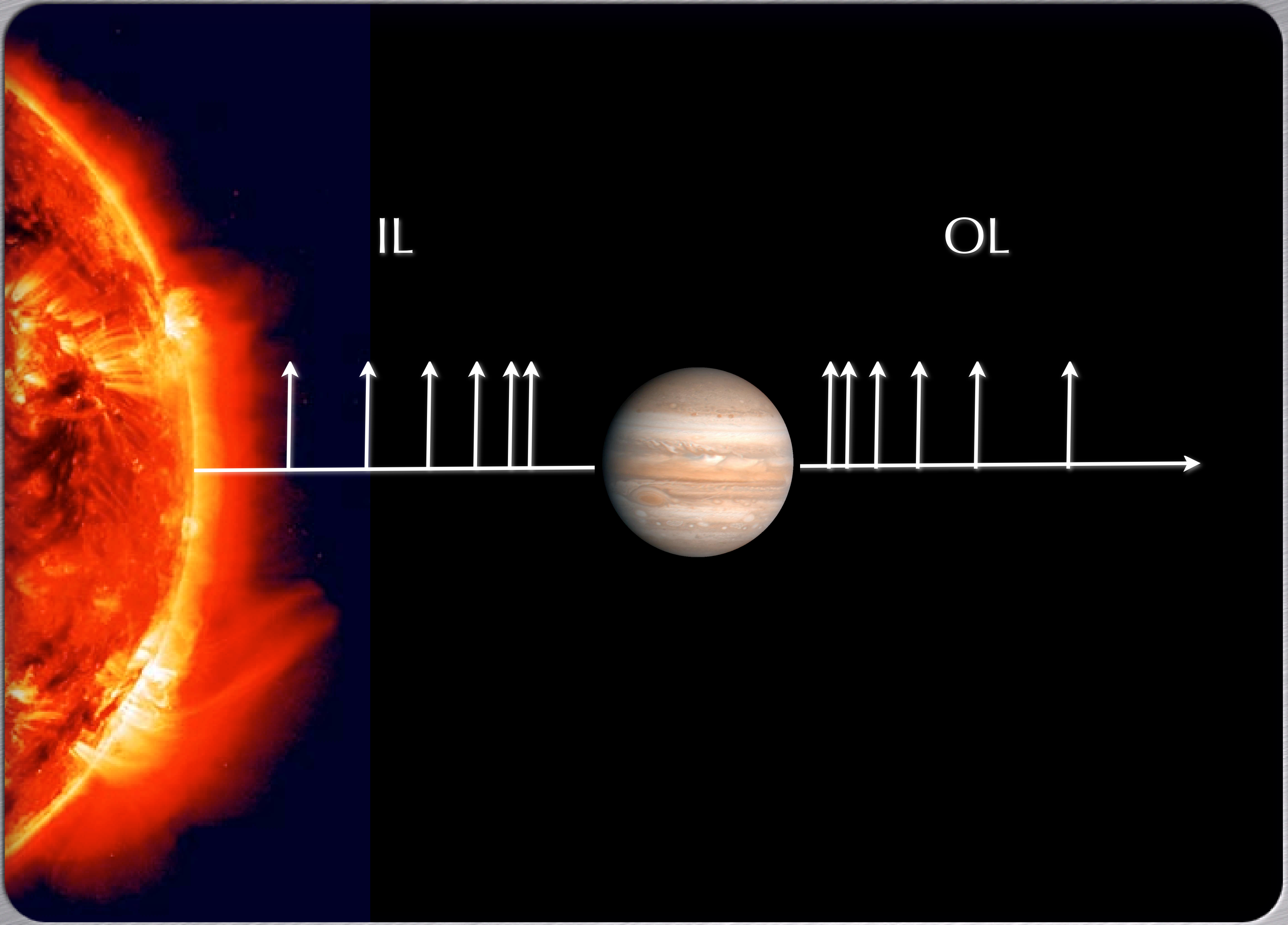
- Waves are launched at Lindblad resonances (Goldreich & Tremaine 1979)
- Wake is sum of all waves



-0.02
0.00
0.02
0.04
1
0
-1
-1
0
1
x

Migration by waves

- Competition between inner and outer wake
- Outer resonances push planet inward, inner resonances push planet outward
- Outer resonances closer to planet: they win in general, planet moves inward


IL
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Migration by waves

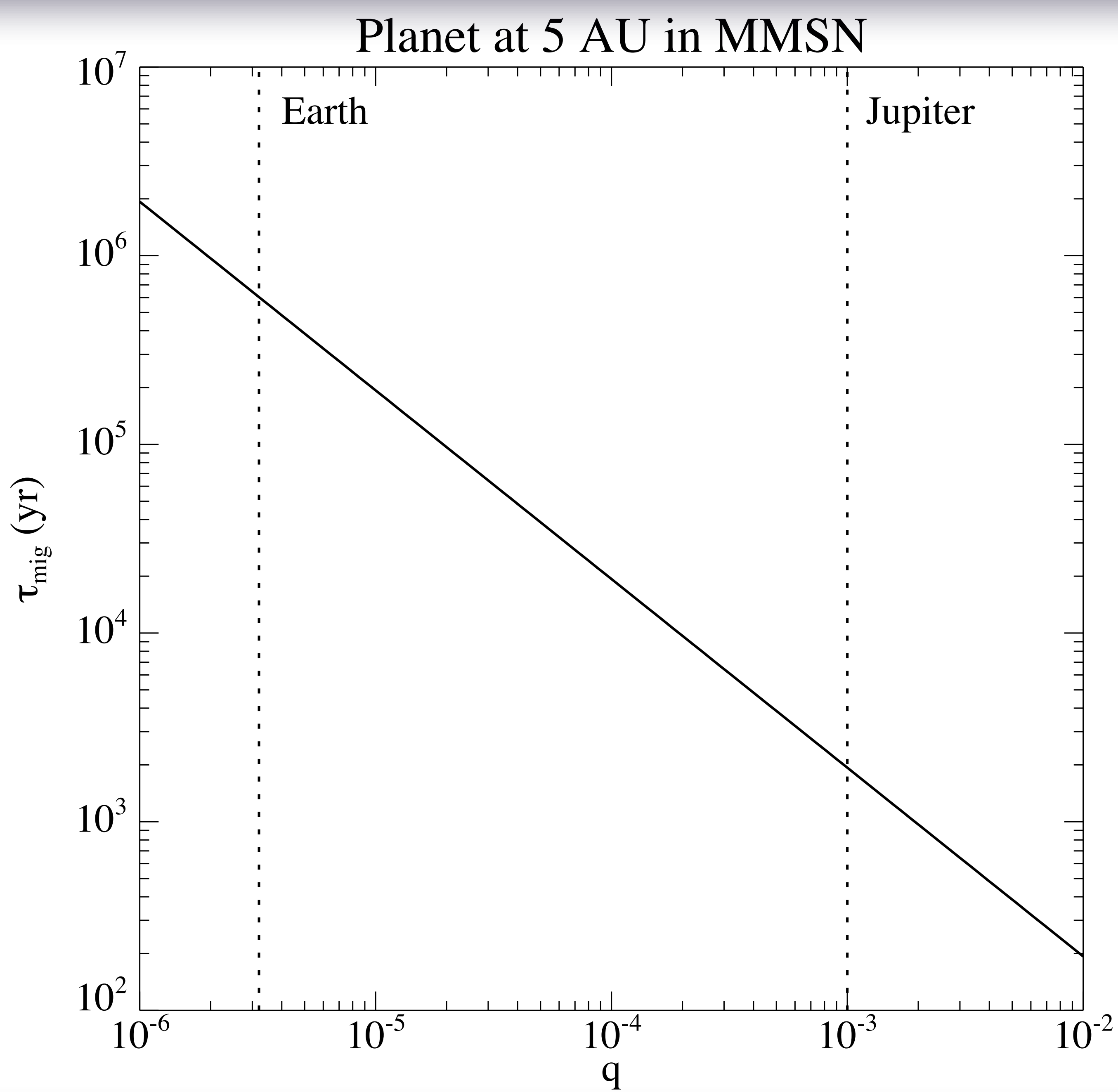
$$\Gamma_{\rm L} = -(2.34 - 0.1\alpha)\frac{q^2}{h^2}\Sigma_{\rm p} r_{\rm p}^4 \Omega_{\rm p}^2$$

$$\Sigma \propto r^{-\alpha} \qquad q = \frac{M_p}{M_*}$$

Disc thickness $h \ll 1$

$$\dot{r}_{\rm p} = -2(2.34 - 0.1\alpha)\frac{q}{h^2}\frac{\Sigma_{\rm p} r_{\rm p}^2}{M_*} r_{\rm p}\Omega_{\rm p}$$

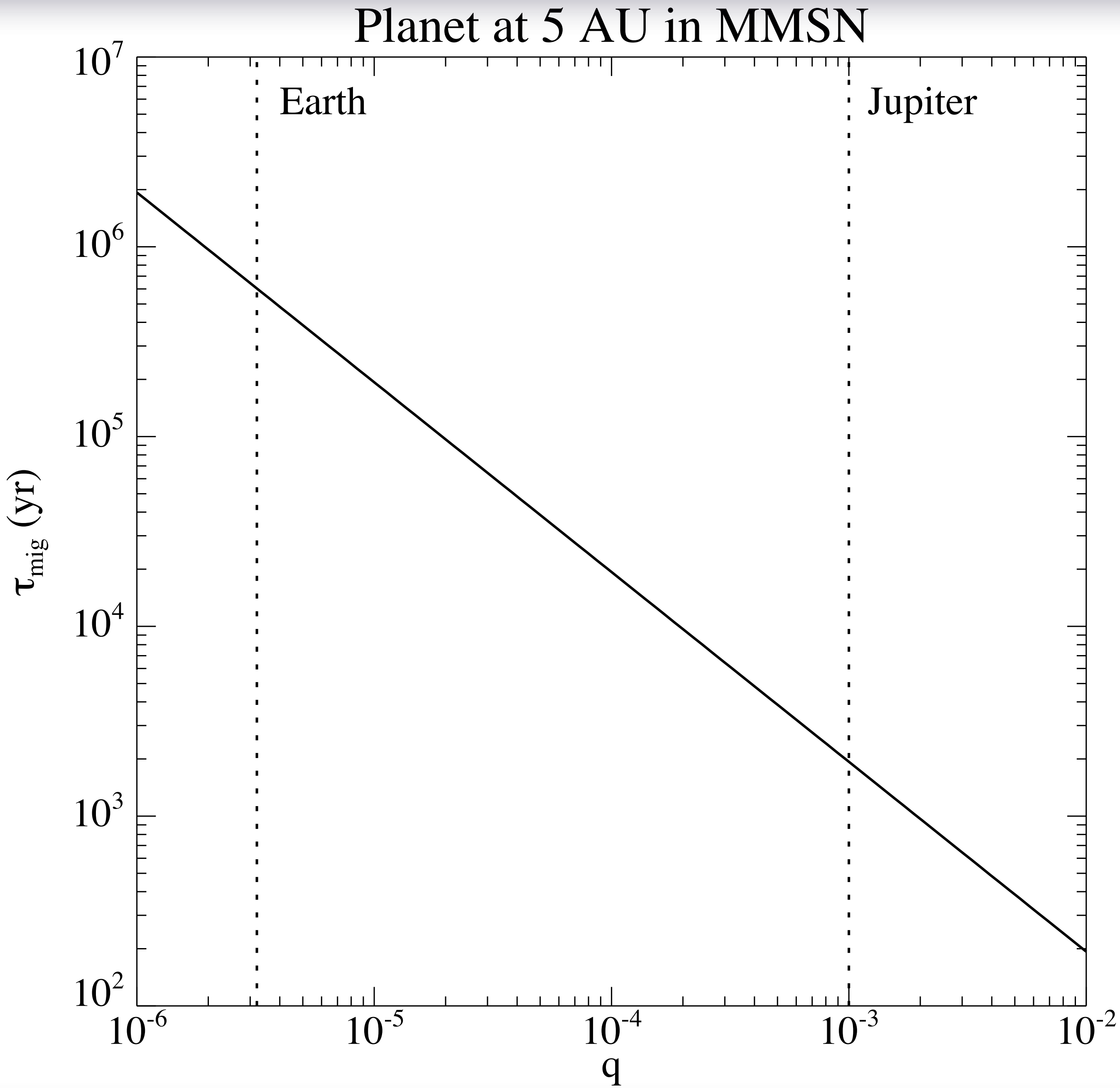
- Inward migration is robust for reasonable disc parameters
- Linear calculations: Tanaka et al. (2002)
- Bigger planets move faster



Planet at 5 AU in MMSN
Earth
Jupiter
10^7
10^6
10^5
10^4
10^3
10^2
τ_{mig} (yr)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
q

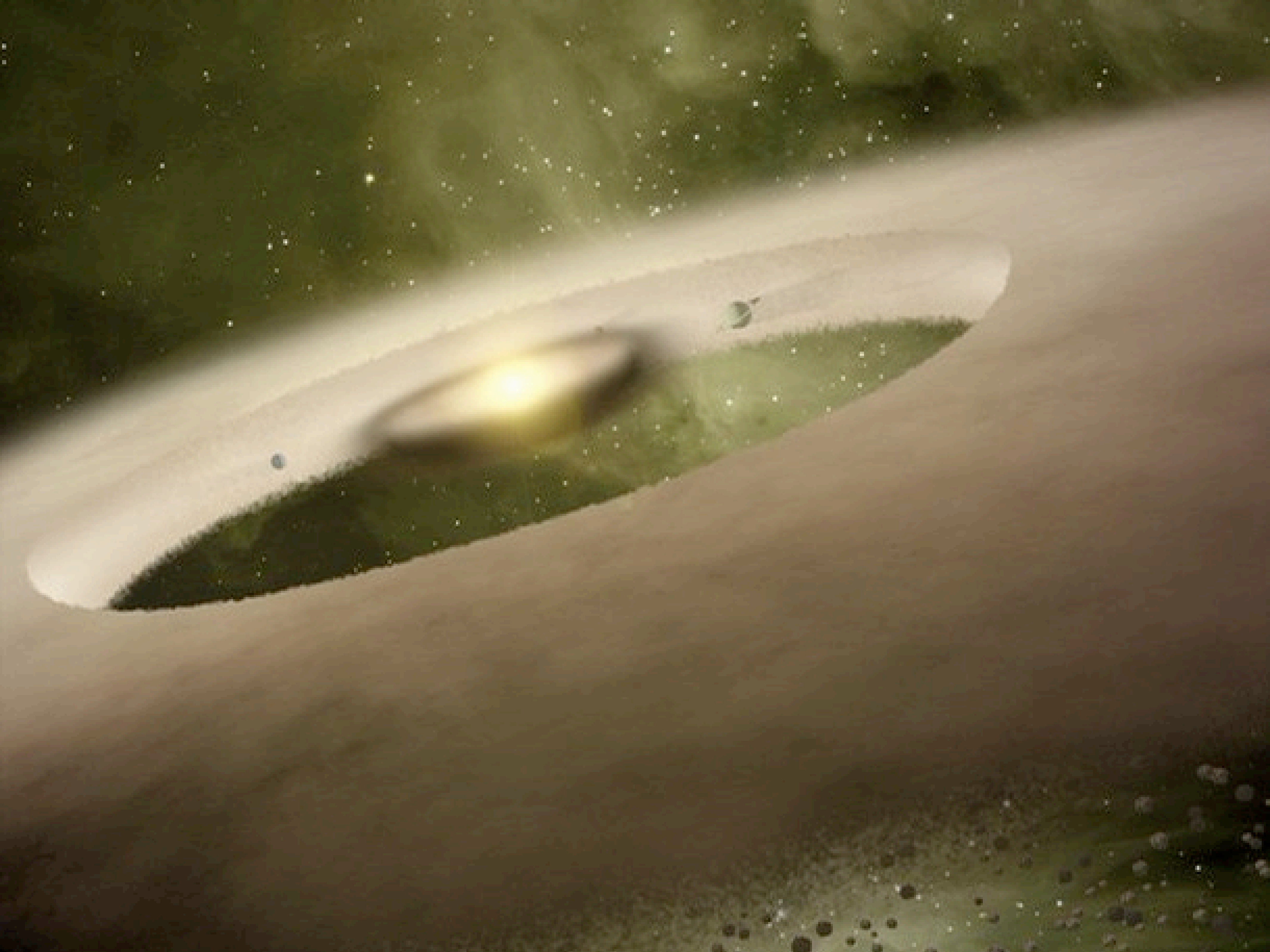
Type I problem

- Migration can be *very* efficient
- Type 0: m-sized bodies migrate into the central star in ~100 years
- Type I: Earth-sized planets migrate inward in ~10^5 years
- Disc lifetime: 10^6-10^7 yr
- Population synthesis models usually include a fudge factor of order 10^x

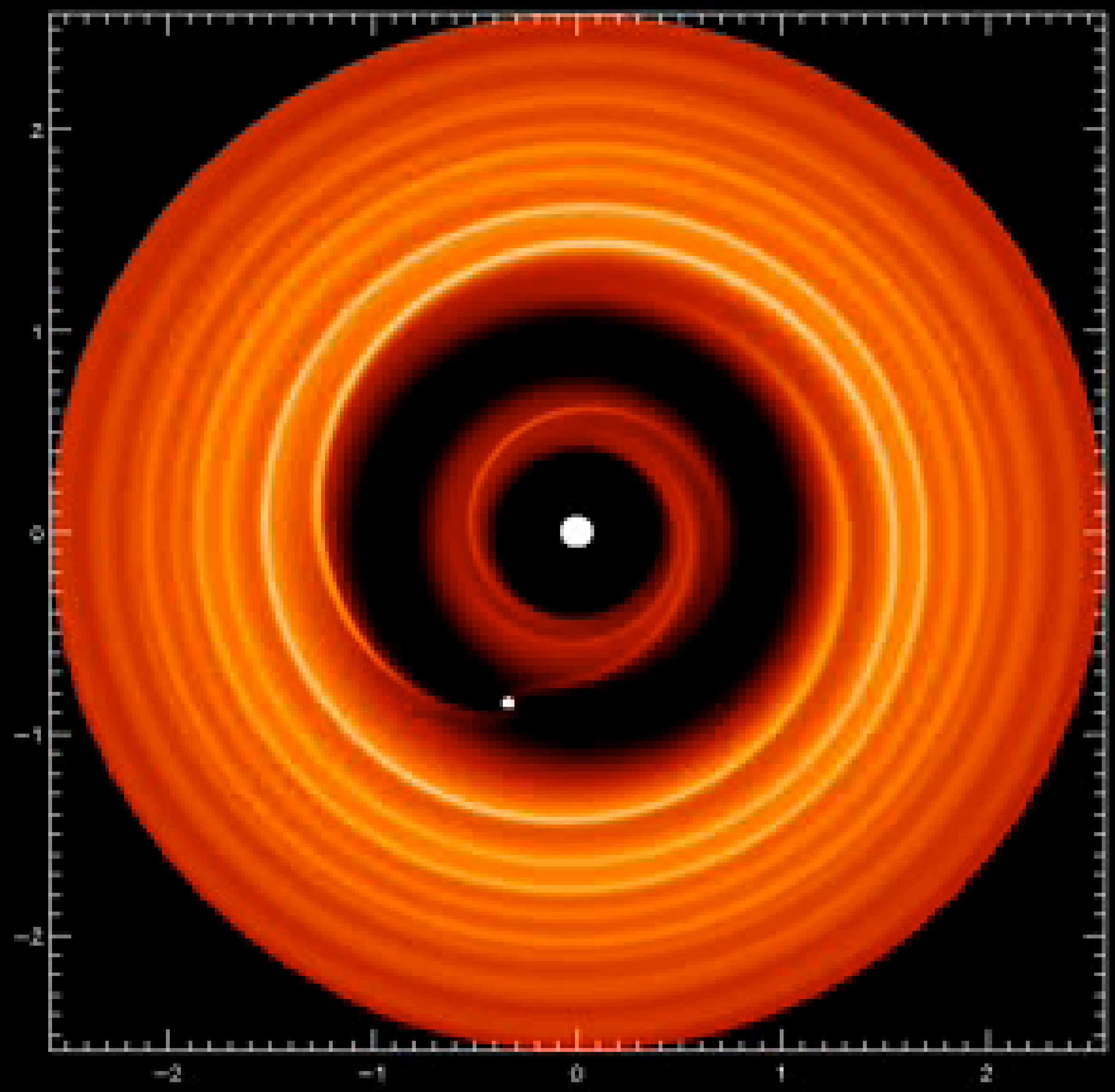

Planet at 5 AU in MMSN
Earth
Jupiter
τ_{mig} (yr)
10^7
10^6
10^5
10^4
10^3
10^2
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
q

Gap formation

- High-mass planets induce a non-linear disc response
- Angular momentum flux too large to be compensated by viscous flow
- Annular gap forms

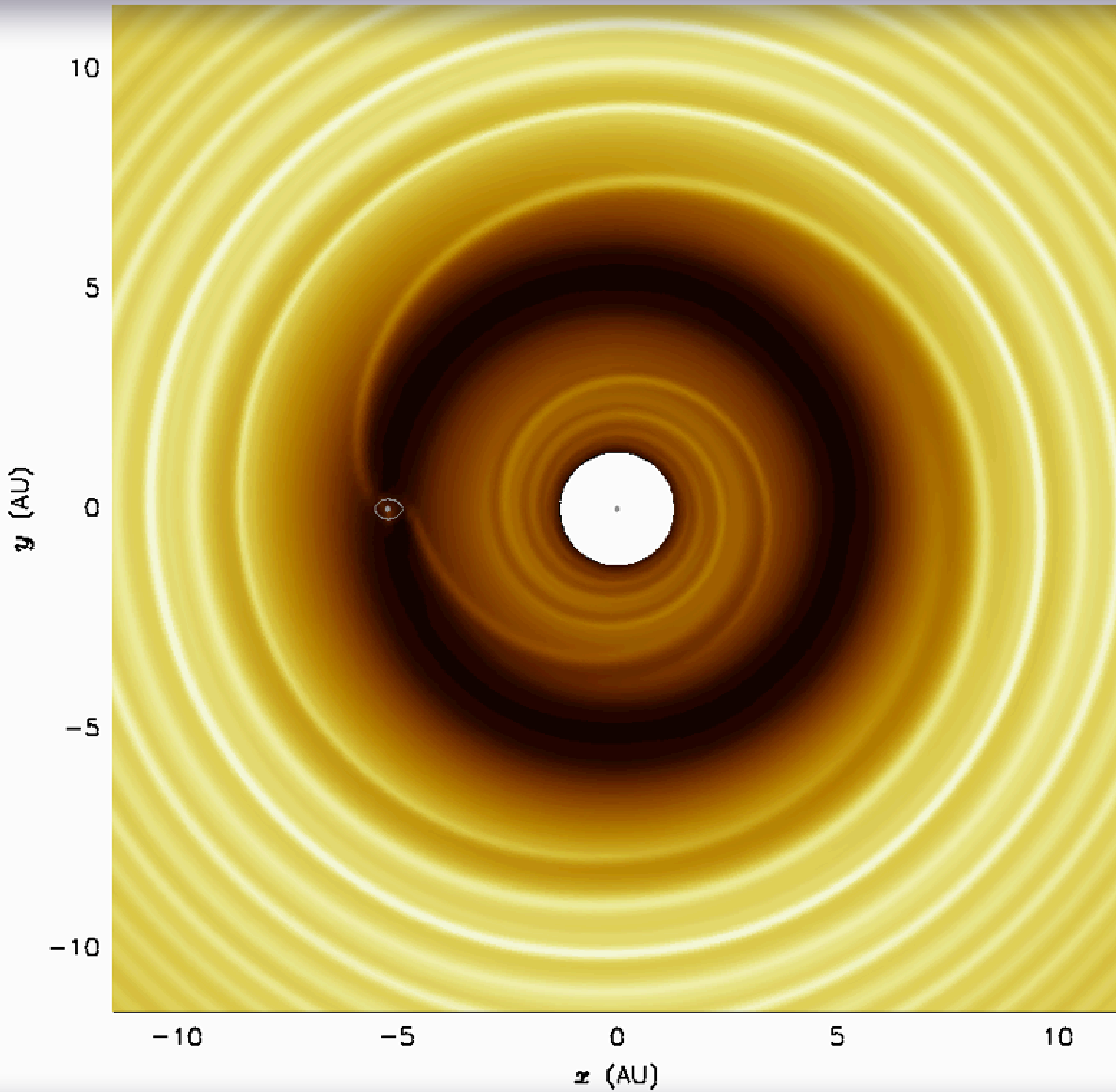


R.P. Nelson, QMUL, London



Gap formation

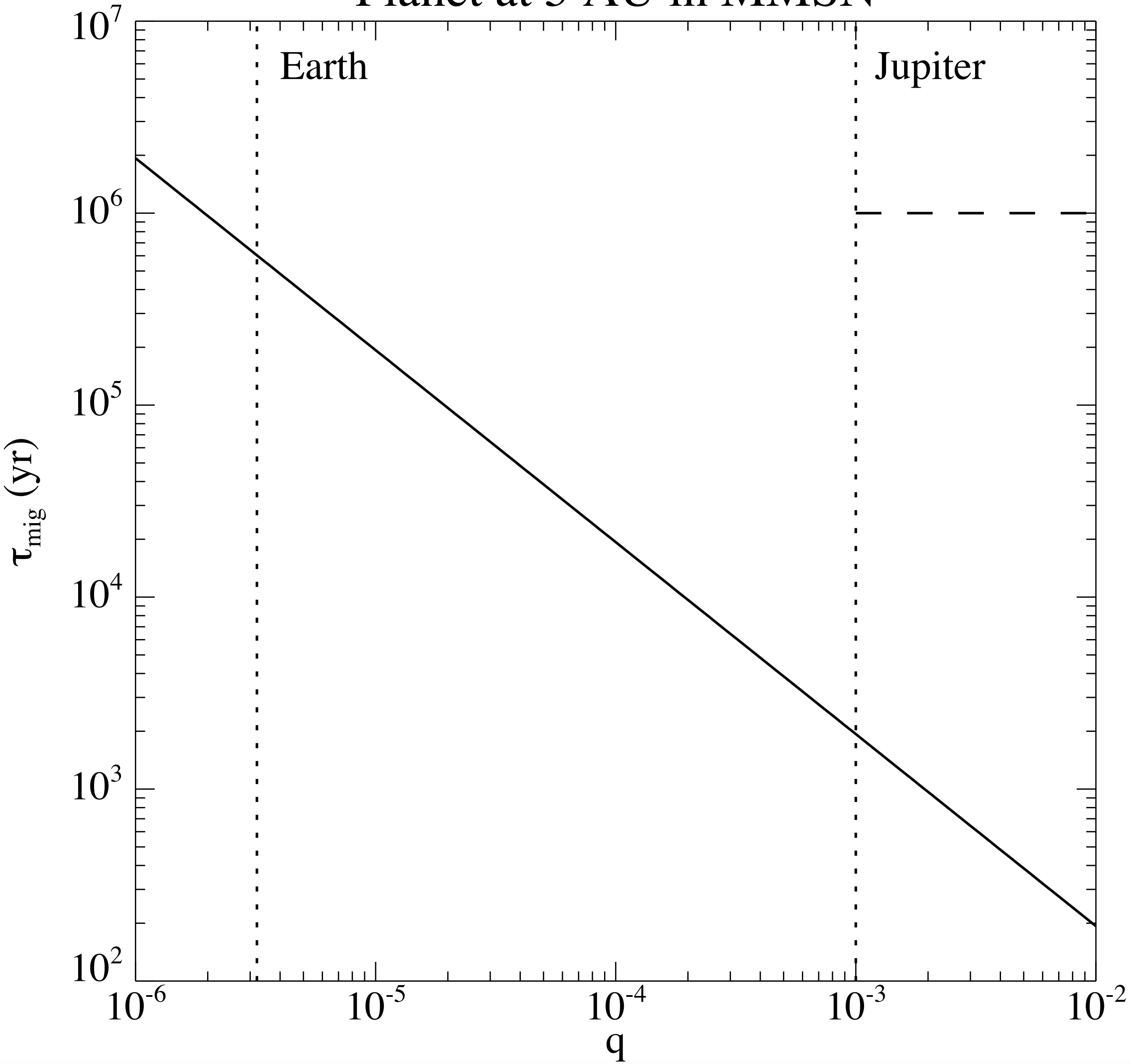
- Crida et al. (2006): minimum planet mass depends on disc scale height and viscosity
- Typically $M > M_{Jup}$
- Different mode of migration: Type II


10
5
0
−5
−10
y (AU)
−10
−5
0
5
10
x (AU)

Type II migration

- Planet opens up deep annular gap
- It can not move with respect to the gap
- Gap accretes with rest of disc
- Planet accretes onto star
- Time scale: viscous

Planet at 5 AU in MMSN



Type II migration

- Independent of planet mass (unless planet much more massive than disc)
- Requires a VERY clean gap
- Otherwise, residual wave torque drives planet inward faster

Migration by waves

- Embedded planets launch tidal waves
- Resulting torque pushes planets inward at an alarming rate: Type I migration
- Cut-off at high mass due to gap formation: Type II migration
- Wave theory is quite robust
- Verified to within 10% by numerical simulations

Enter: corotation

$$m(\Omega - \Omega_{\mathrm{p}}) = 0$$

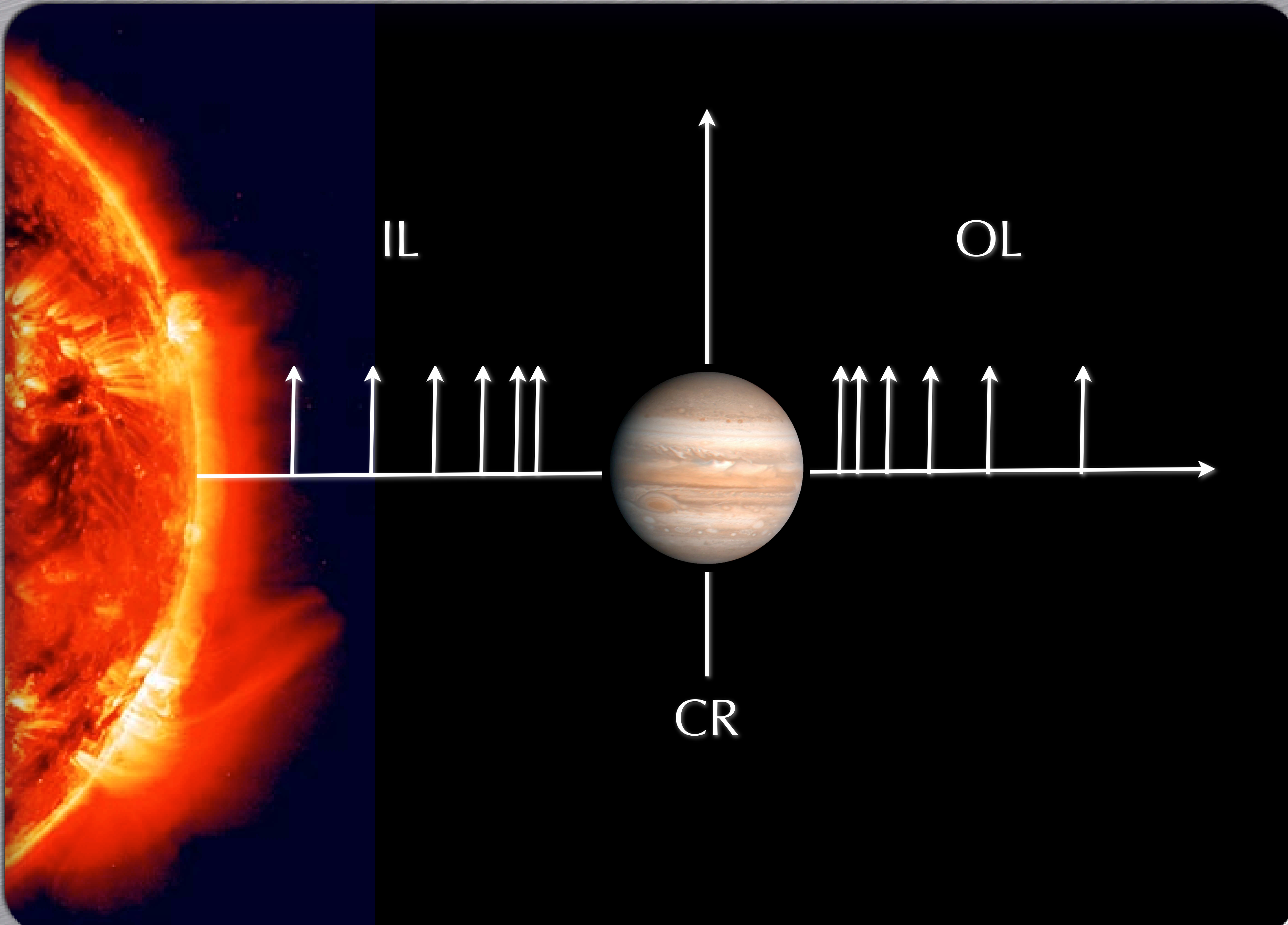
$$\Omega = \Omega_{\mathrm{p}}$$

$$r \approx r_{\mathrm{p}}$$

- Waves originate approximately one scale height from the planet
- Additionally, gas that corotates with planet also feels strong perturbation

Corotation resonance

- Apply successful resonance theory to corotation
- No waves at corotation
- Perturbation carried away by viscous flow
- Torque is sum of contribution from all corotation resonances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OL
CR

Corotation Torque

$$\omega = \frac{\nabla \times \vec{v}}{\Sigma}$$

$$\Sigma \propto r^{-\alpha}$$

$$\frac{d\omega}{dr} = \frac{\omega}{r}\left(\frac{3}{2} - \alpha\right)$$

$$\Gamma_C \propto \left(\frac{3}{2} - \alpha\right)$$

- Goldreich & Tremaine (1979): resonances at corotation radius
- Proportional to radial vortensity gradient
- Always smaller than Lindblad torque

Total Torque

$$\Gamma = -(1.364 + 0.541\alpha)\frac{q^2}{h^2}\Sigma_p r_p^4 \Omega_p^2$$

$$\Sigma \propto r^{-\alpha} \qquad q = \frac{M_p}{M_*}$$

Disc thickness $h \ll 1$

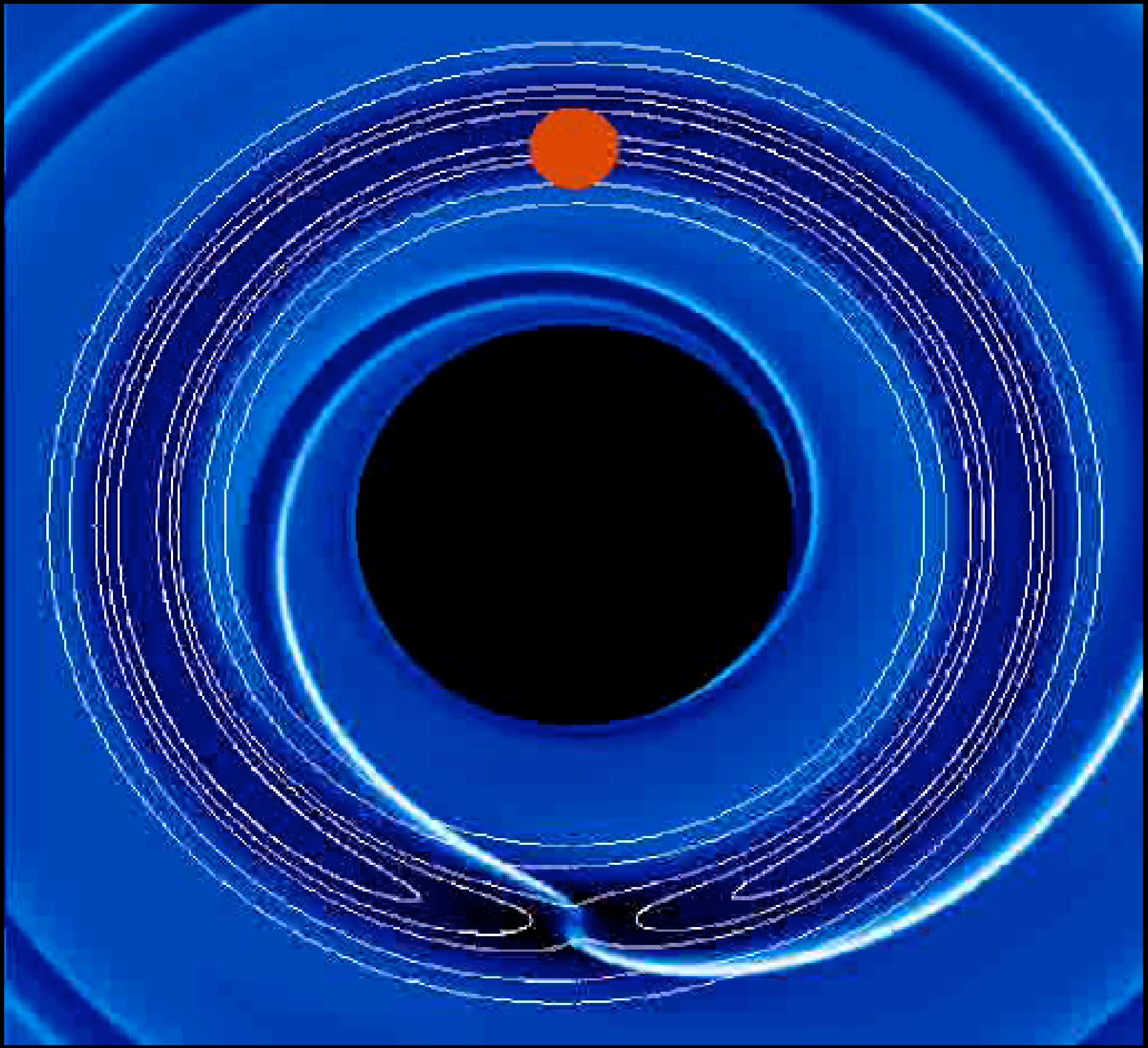
$$p = p(\Sigma)$$

- Tanaka et al (2002)
- Widely used
- Low-mass planets
- Usually negative
- Barotropic disc

The maze of corotation

- Ward (1991) provides an alternative formulation of corotation torque
- Based on streamline analysis
- Material on horseshoe orbits exerts torque on planet

F. Masset, CEA Saclay



Horseshoe drag

$$\omega = \frac{\nabla \times \vec{v}}{\Sigma}$$

$$\Delta\Sigma = \left.\frac{d\omega}{dr}\right|_{r_p} \Delta r$$

- In 2D, barotropic flow, vortensity is conserved along streamlines
- After making the turn, density must change

The maze of corotation

$$\Gamma_{\rm c,HS} = \frac{3}{4}\left(\frac{3}{2}-\alpha\right) x_{\rm s}^4 \Sigma_{\rm p} r_{\rm p}^4 \Omega_{\rm p}^2$$

- Horseshoe drag

$$\Gamma_{\rm c,lin} = 1.36\left(\frac{3}{2}-\alpha\right) \frac{q^2}{h^2} \Sigma_{\rm p} r_{\rm p}^4 \Omega_{\rm p}^2$$

- Linear corotation torque

Horseshoe drag

- Alternative view on corotation torque
- Inherently non-linear
- Relation to linear (resonant) torque?
- Both proportional to vortensity gradient
- ‘Free’ parameter: horseshoe width x_s

Linear horseshoes?

- So which of the two approaches is correct?
- This issue has never been settled...
- Linear theory: perturbed circular orbits
- Horseshoe drag: horseshoe bends
- These cannot co-exist...

What determines x_s?

$$\Gamma_{\mathrm{c,HS}} = \frac{3}{4}\left(\frac{3}{2} - \alpha\right) x_{\mathrm{s}}^4 \Sigma_{\mathrm{p}} r_{\mathrm{p}}^4 \Omega_{\mathrm{p}}^2$$

$$x_{\mathrm{s}} = C\sqrt{\frac{4q}{3h} E\left(\frac{3}{2}\right)} \approx 1.68C\sqrt{\frac{q}{h}}$$

- Critical for calculating horseshoe drag
- Simple model (C<1 accounts for gravitational softening)
- Paardekooper & Papaloizou (2009)

Horseshoe vs Linear

$$\Gamma_{\rm c,HS} = 5.97 \left(\frac{3}{2} - \alpha\right) \frac{q^2}{h^2} \Sigma_{\rm p} r_{\rm p}^4 \Omega_{\rm p}^2$$

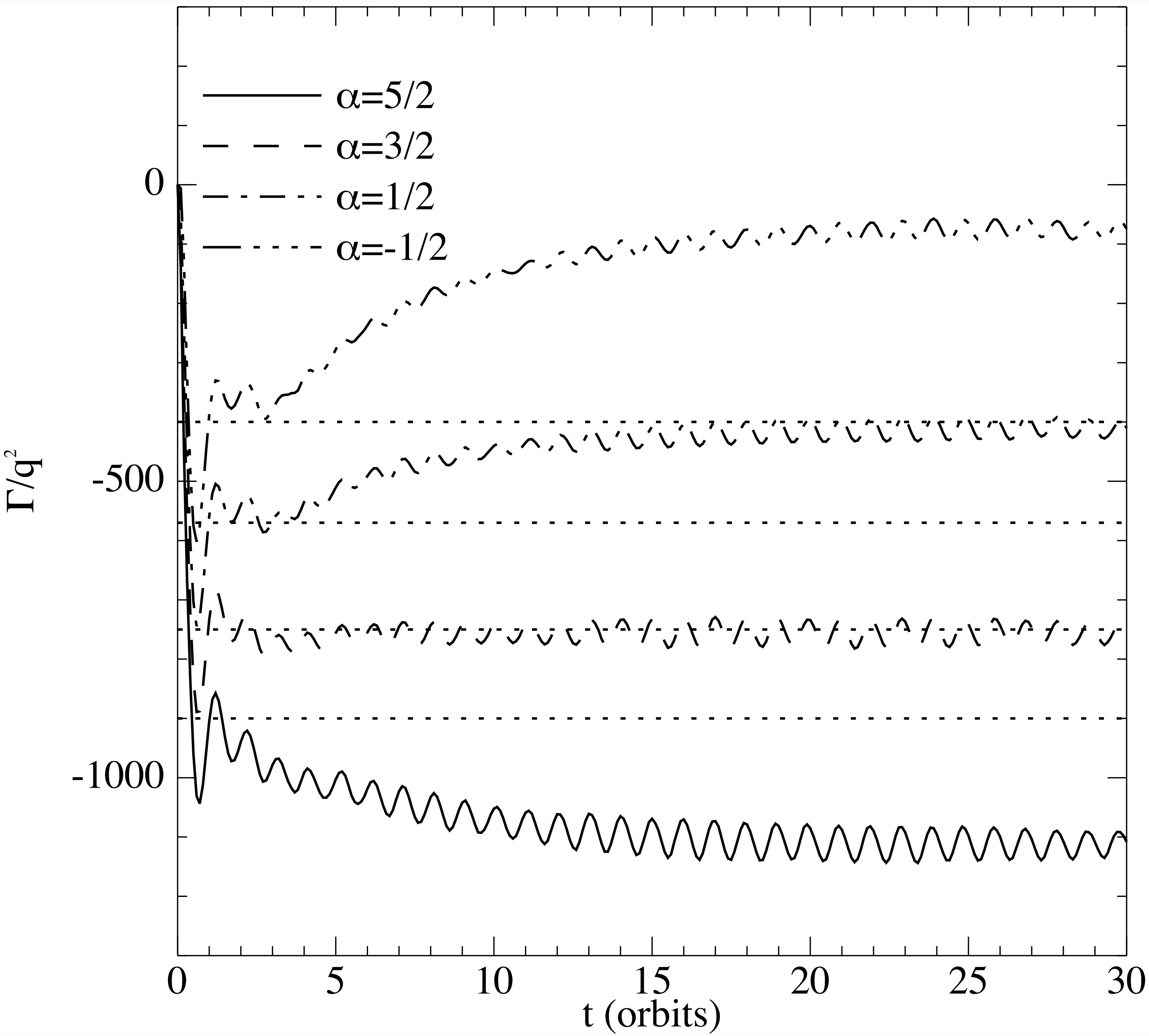
$$\Gamma_{\rm c,lin} = 1.36 \left(\frac{3}{2} - \alpha\right) \frac{q^2}{h^2} \Sigma_{\rm p} r_{\rm p}^4 \Omega_{\rm p}^2$$

- This value of x_s gives a horseshoe drag that is much larger than the linear corotation torque!
- They only differ in magnitude

Numerical simulations

- 2D isothermal disc
- Low-mass planet (4 $M_{\oplus}$)
- Different surface density profiles

Paardekooper & Papaloizou 2009



The maze of corotation

- Numerical hydrodynamical simulations show departure from linear theory whenever the vortensity gradient is non-zero
- Linear corotation torque is replaced by (stronger) horseshoe drag
- Migration may be slowed down by an order of magnitude for $\alpha<0$

Extension

$$p = p(\Sigma)$$

$$p = c^2\Sigma$$

$$p = \Sigma\mathcal{R}T$$

- Applies to barotropic fluid (isothermal)
- Releasing this assumption means solving the energy equation

Adiabatic simulations

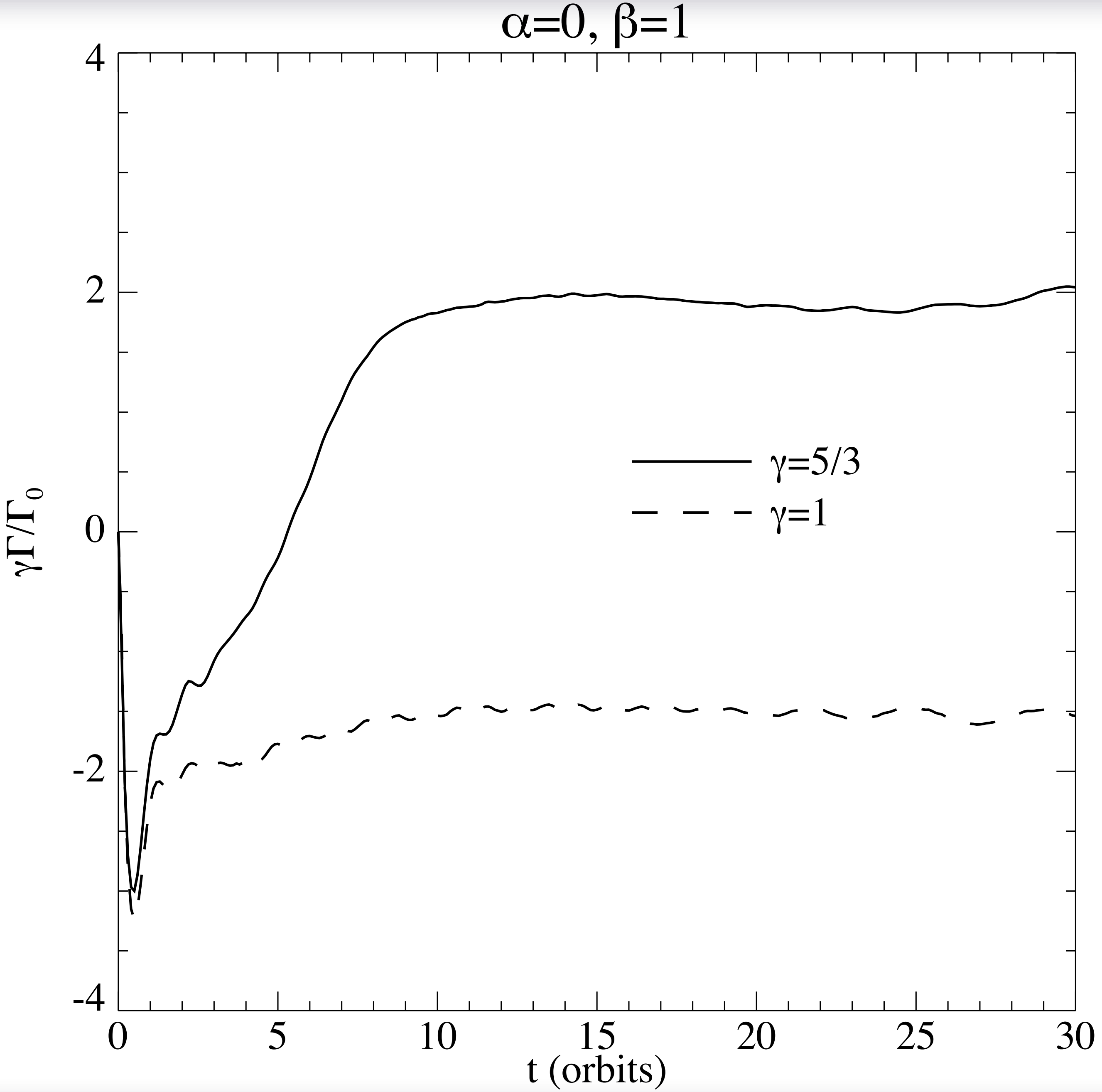
$$s = \frac{p}{\Sigma^\gamma}$$

$$\Sigma \propto r^{-\alpha},\ T \propto r^{-\beta}$$

$$s \propto r^{(\gamma-1)\alpha-\beta}$$

$$\Gamma \propto (\beta - (\gamma - 1)\alpha)$$

- Add conservation of entropy to (2D) equations
- Gives rise to additional horseshoe torque
- Wave torque smaller by factor γ


α=0, β=1
γΓ/Γ0
t (orbits)
γ=5/3
γ=1
4
2
0
-2
-4
0
5
10
15
20
25
30

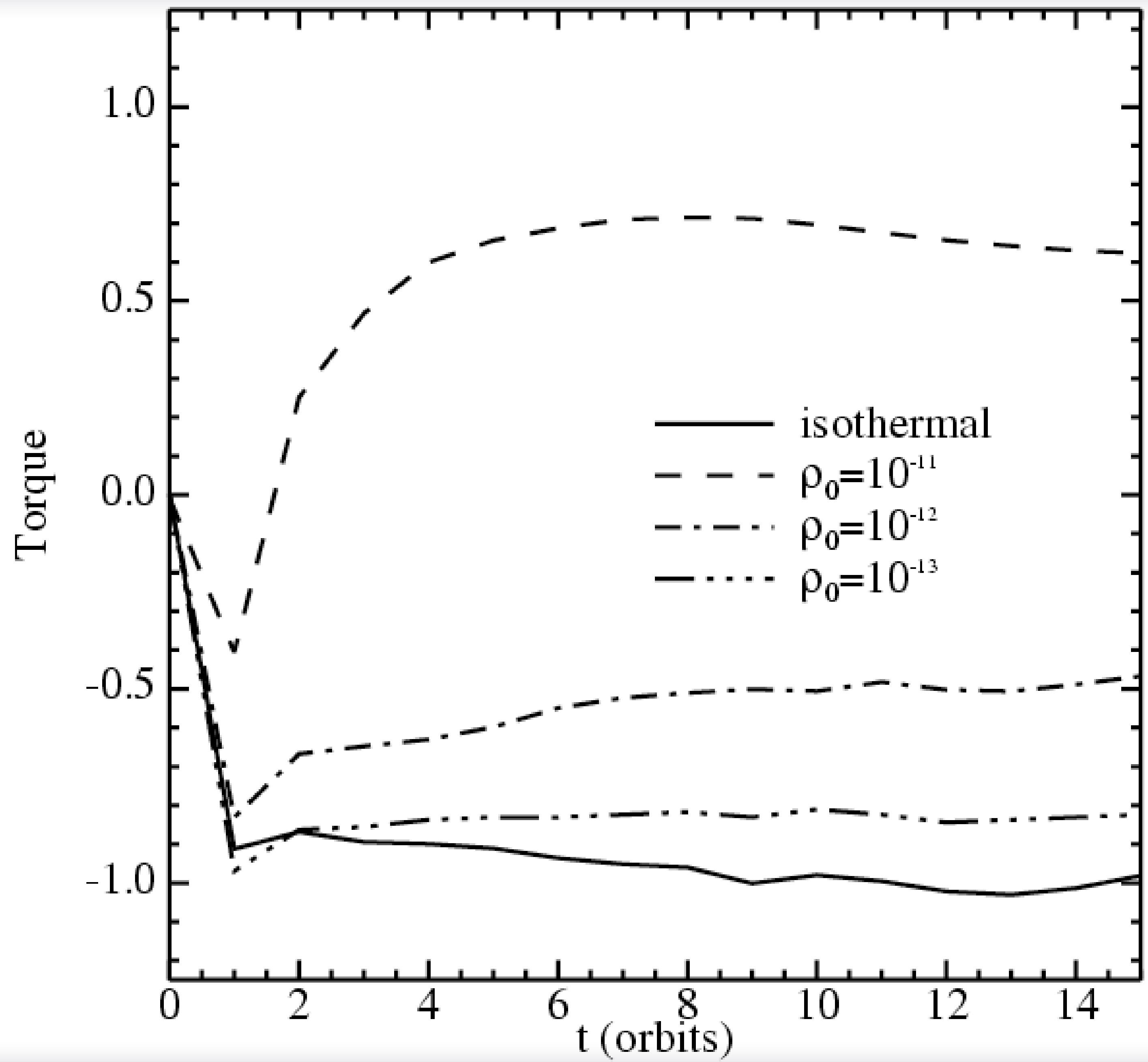
Adiabatic simulations

- Extra horseshoe drag changes sign of torque!
- Low-mass planets move *outward* for negative entropy gradients
- Since the temperature usually decreases with r, this is not unrealistic
- This behaviour can *not* be understood from linear theory!

Cooling efficiency

- Isothermal: cooling very efficient
- Adiabatic: no cooling
- Depending on local opacity, expect adiabatic or isothermal result
- 3D, radiation hydrodynamical simulations

Paardekooper & Mellema 2006



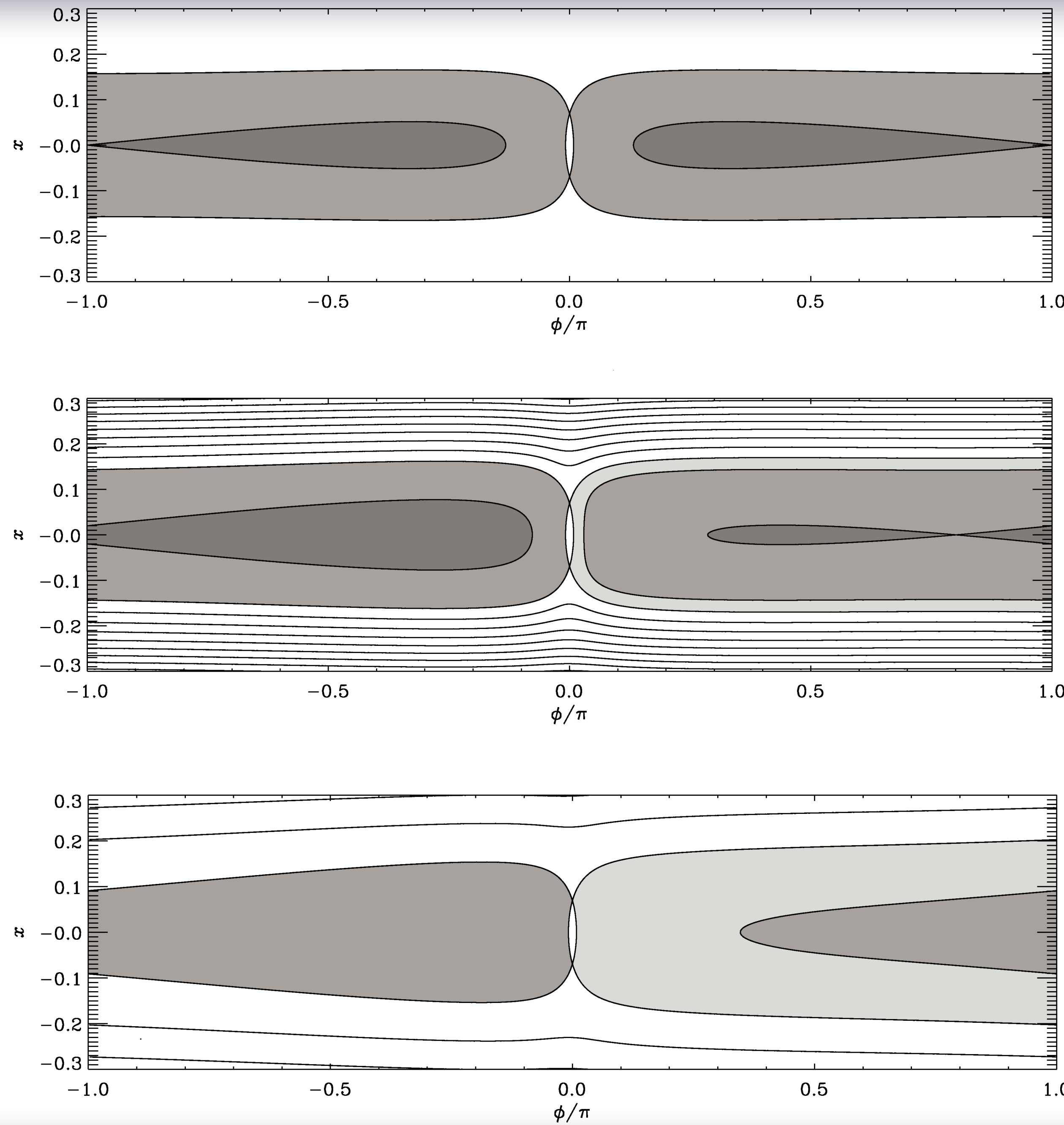
Radiation-hydrodynamics

- High density (opacity): adiabatic result, planet moves *outward*.
- Low density (opacity): isothermal result, planet moves *inward*.
- Safety net for low-mass planets

Torques and migration

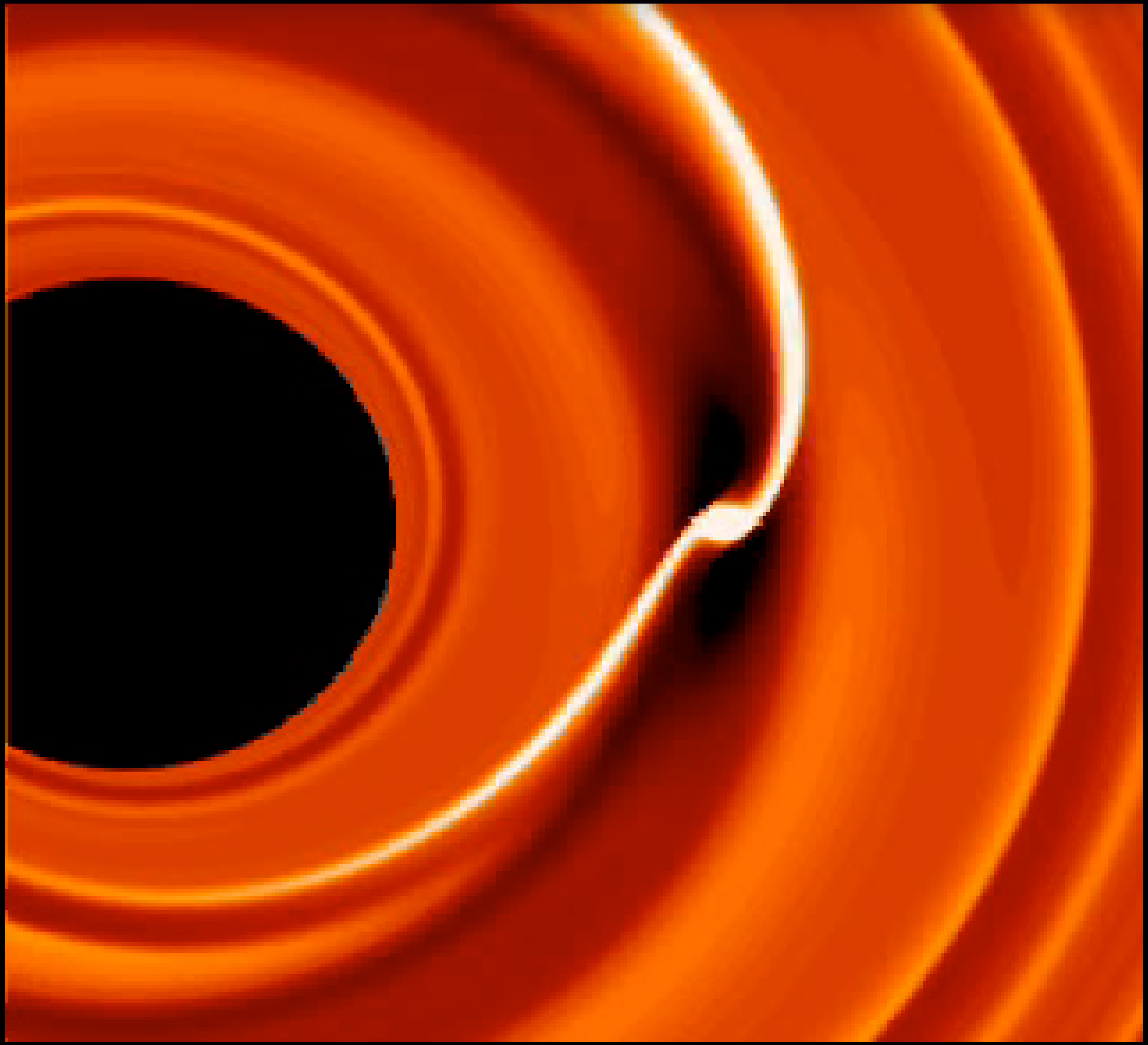
- Wave torque is independent of migration rate
- Horseshoe region is no longer closed
- Inflow of fresh material drives additional migration

Ogilvie & Lubow 2006



Type III migration

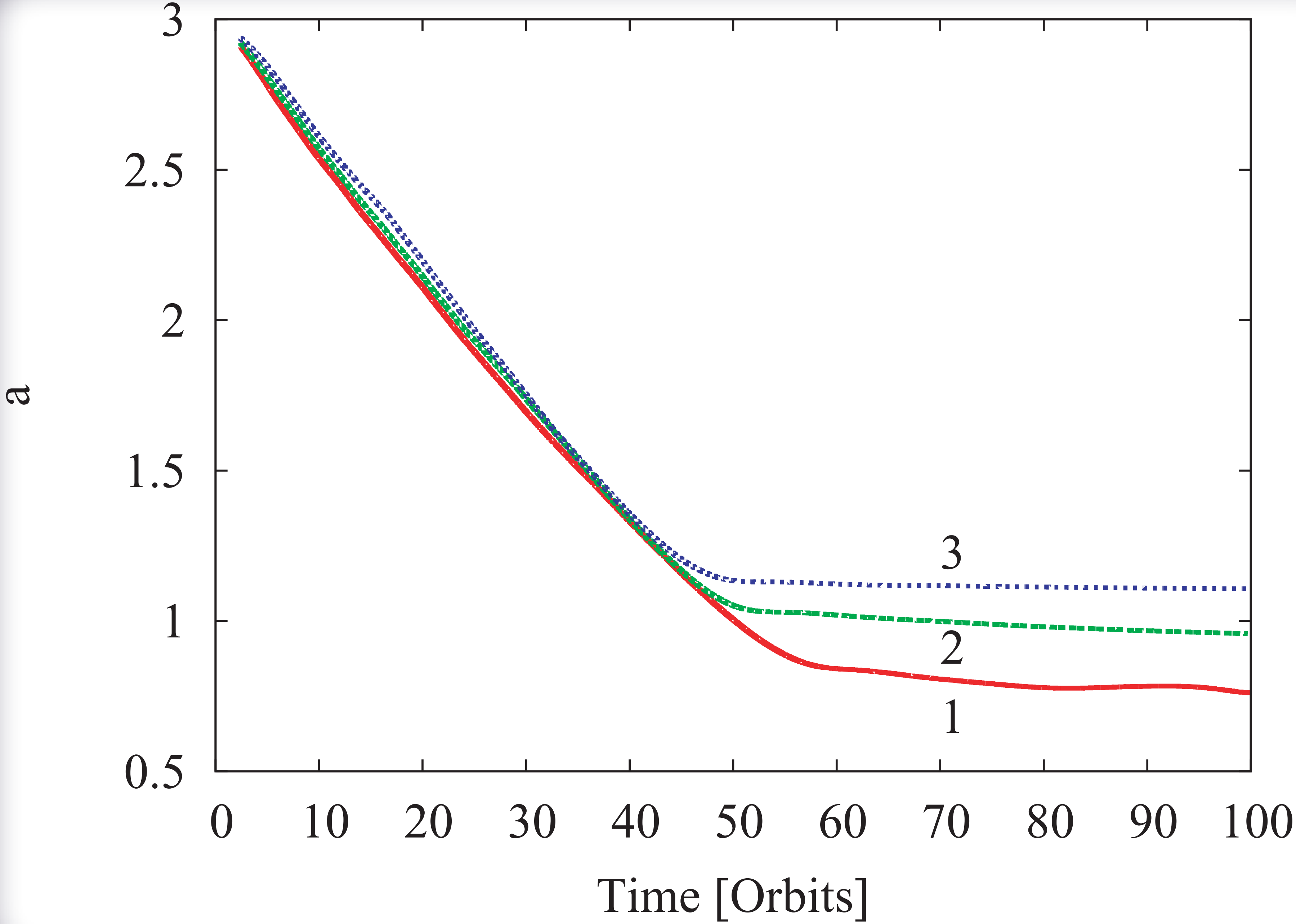
- Corotation torque is proportional to migration rate
- Positive feedback: runaway migration (Masset & Papaloizou 2003)
- Time scale: 10-100 orbits (!)



Type III migration

- Can be both inward and outward, depending on initial conditions (Peplinski et al. 2008)
- Inward migration is limited due to shrinking of horseshoe region
- Outward migration is limited due to rapid growth of planet (Peplinski et al. 2008)

Peplinski et al. 2008



Type III migration

- Disc mass in horseshoe region needs to be comparable to planet mass
- Important in massive discs
- Driven by corotation torques

The maze of corotation

- Disc planet interactions are less linear than previously thought
- In absence of an enormously strong viscosity, non-linear corotation torques slow down inward migration for shallow density gradients
- Torque reversal for cases with background entropy gradient

Conclusion

- Planets are very mobile
- One should be careful when applying linear formula
- Proper thermodynamics is critical

Future work

- Understand 3D horseshoe dynamics
- Turbulence and horseshoes
- Is there a simple formula capturing all this?

What was not discussed

- Magnetic fields: magnetic resonances, MRI turbulence (Nelson & Papaloizou 2003)
- Self-gravity (Baruteau & Masset 2008)
- Saturation (Paardekooper & Papaloizou 2008)
- Multiple planets