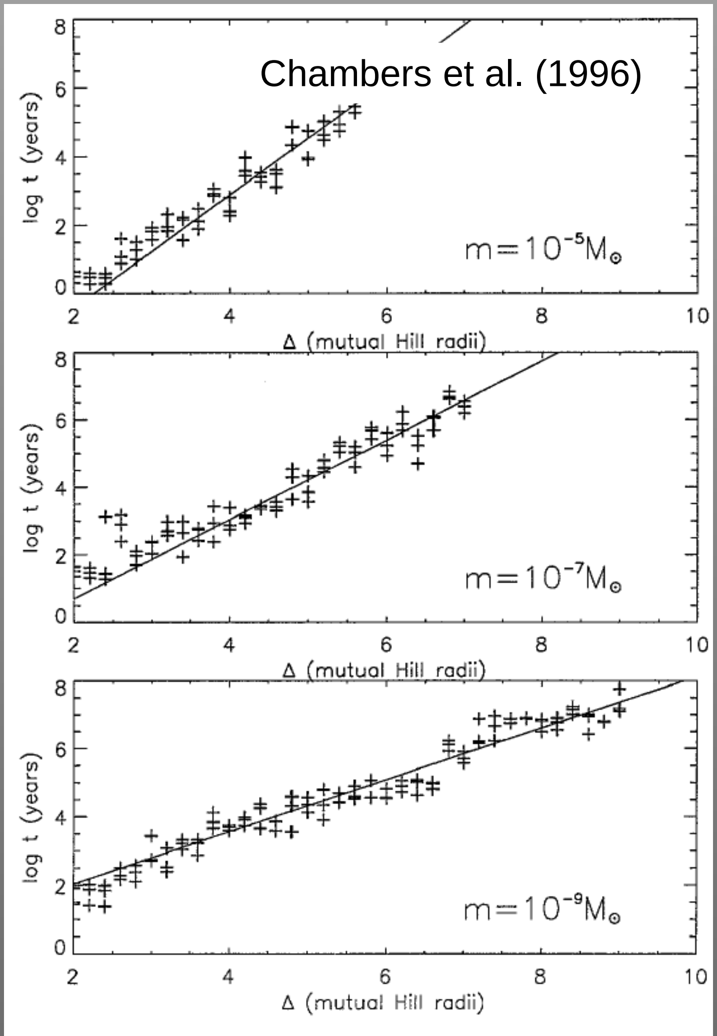
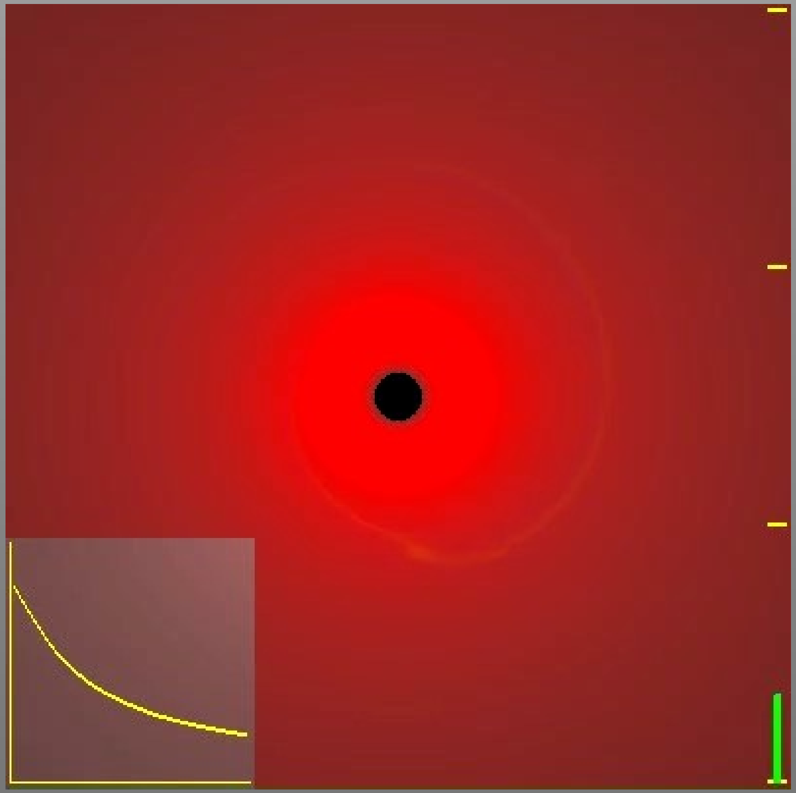
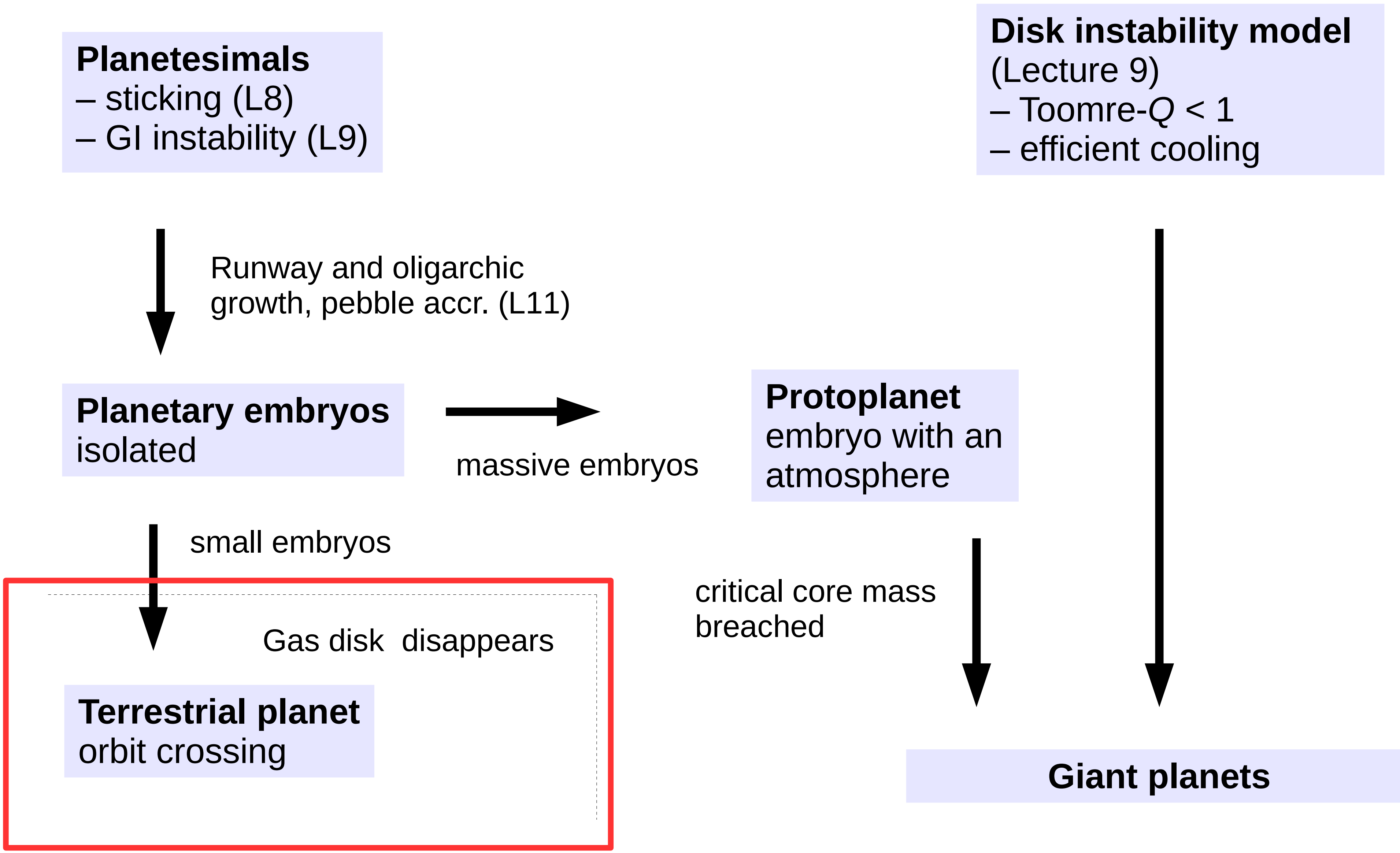
L13: Orbit crossing & Planet migration





Armitage

Core accretion model



Orbital stability

Chambers et al. (1996)

Hill stability criterion
from circular restricted 3-body problem, we can find allowed/forbidden regions..

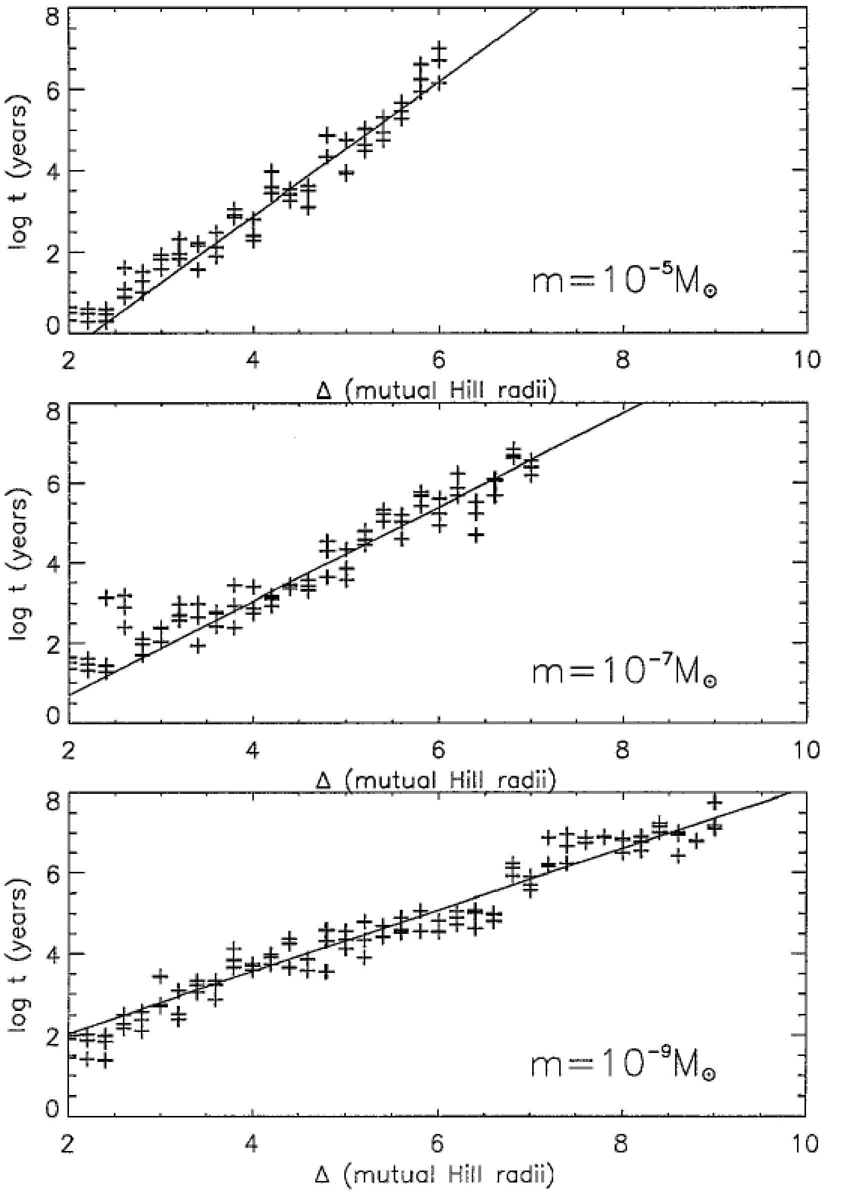
→ $\Delta > 3.46\ R_{Hill}$ stable (no orbit crossing)

For general 3-body systems:

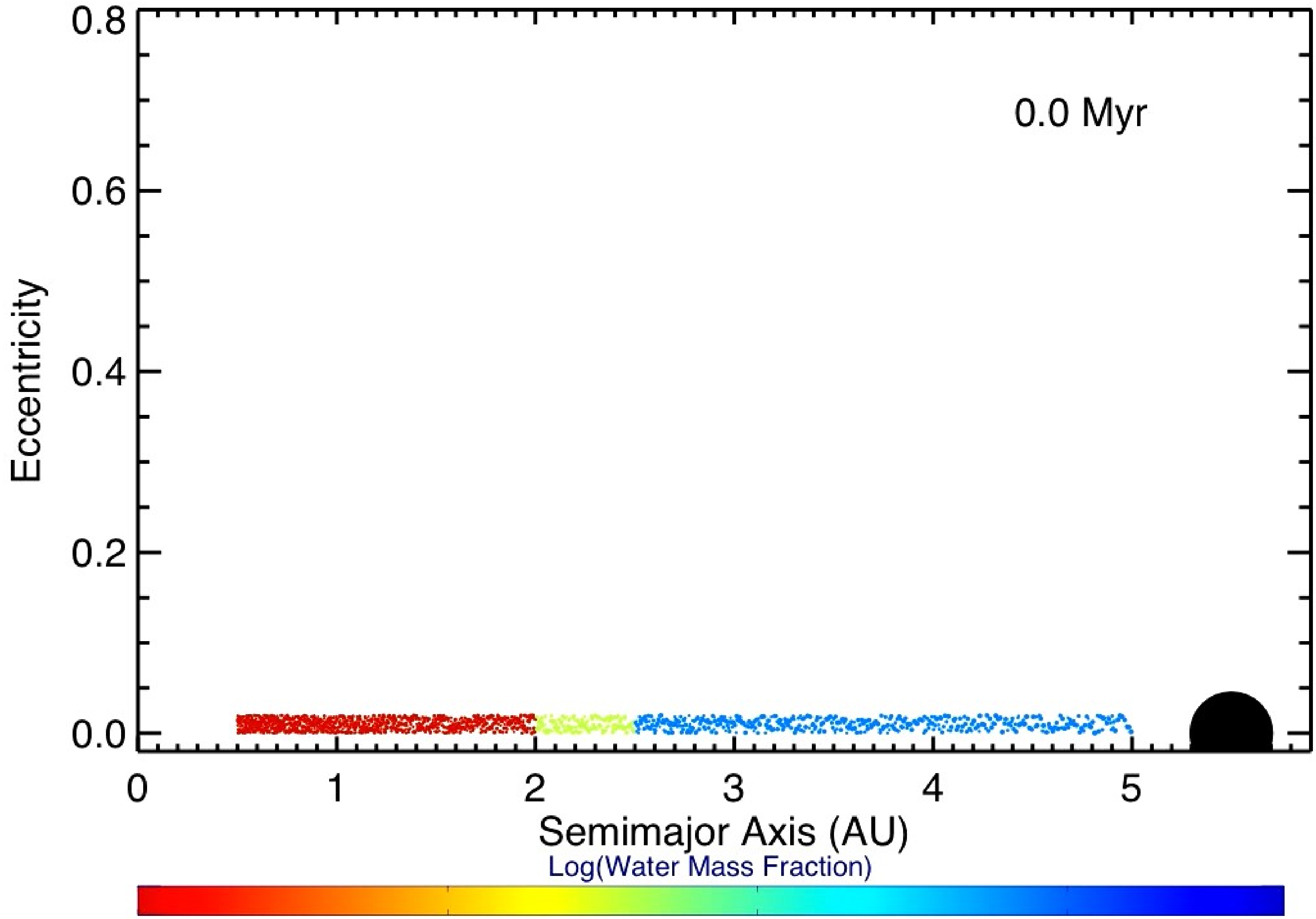
$$\Delta > 2.4 a_{in} (q_{in} + q_{out})^{1/3}$$

For true N-body systems there is no analytic theory. They are unstable, with the crossing time fitted as:

$$t_{cross} = a \exp[\ b*\Delta\ ]$$



Orbit crossing



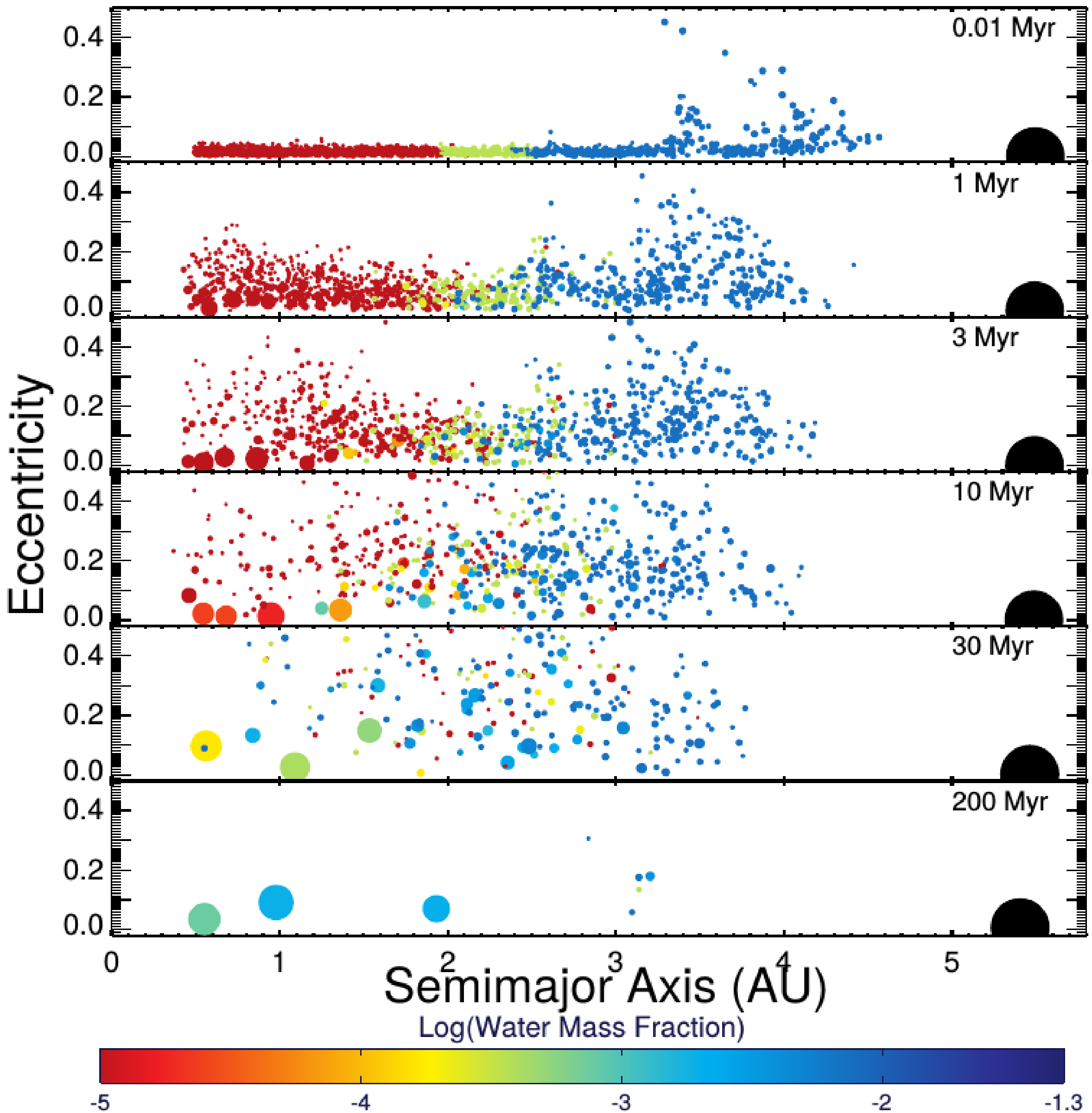
Evolution

Initial conditions
(Raymond et al. 2006)
– no gas
– around 2,000 embryos
– separated by <1 R_{Hill}

Q: What is wrong with this initial setup?
(authors improved initial conditions in later work)

Nevertheless, outcome is very similar to solar system

Q: except for....

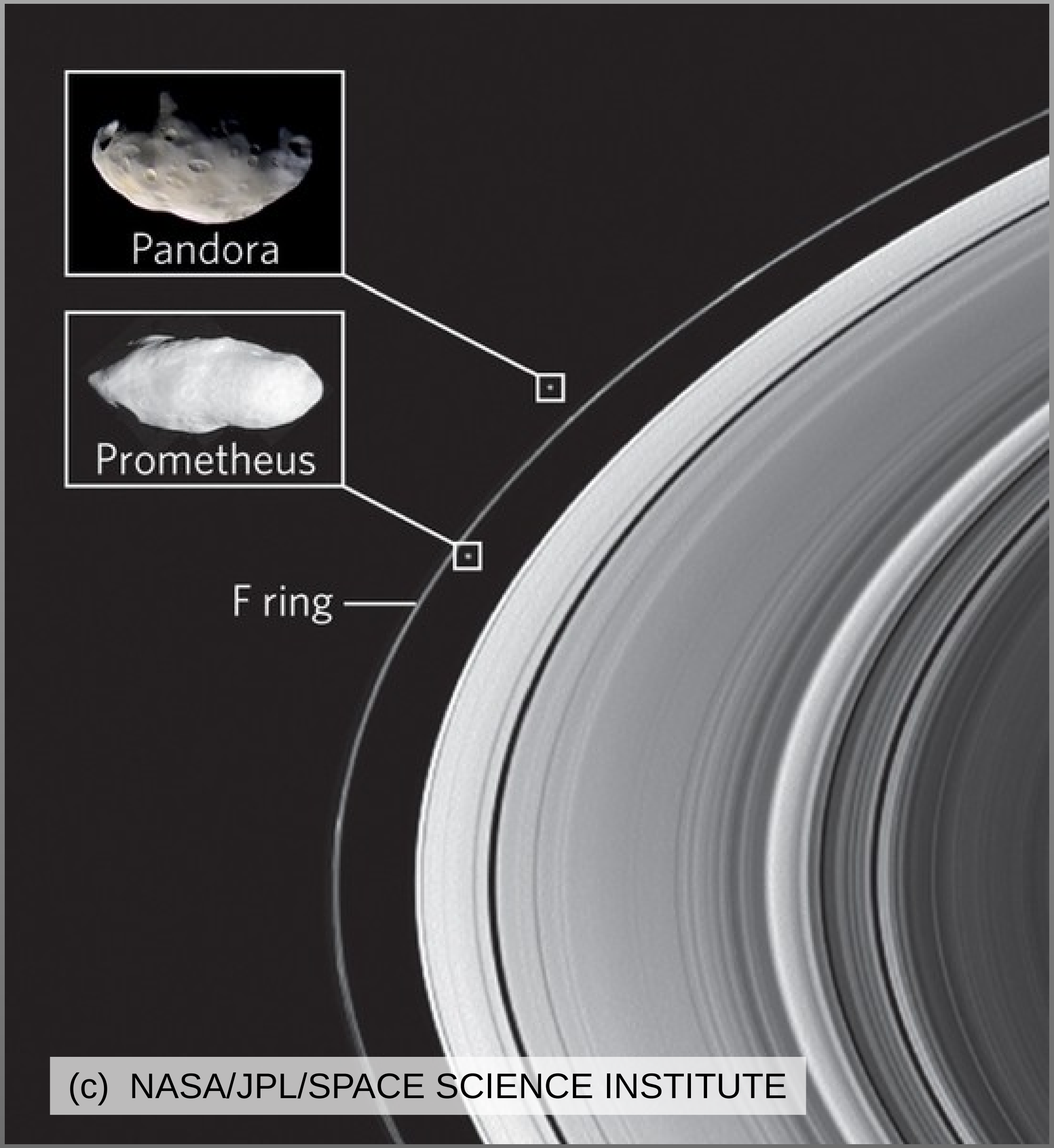


Blackboard

– Planet migration: Impulse approximation

– Gap opening & Type-I migration

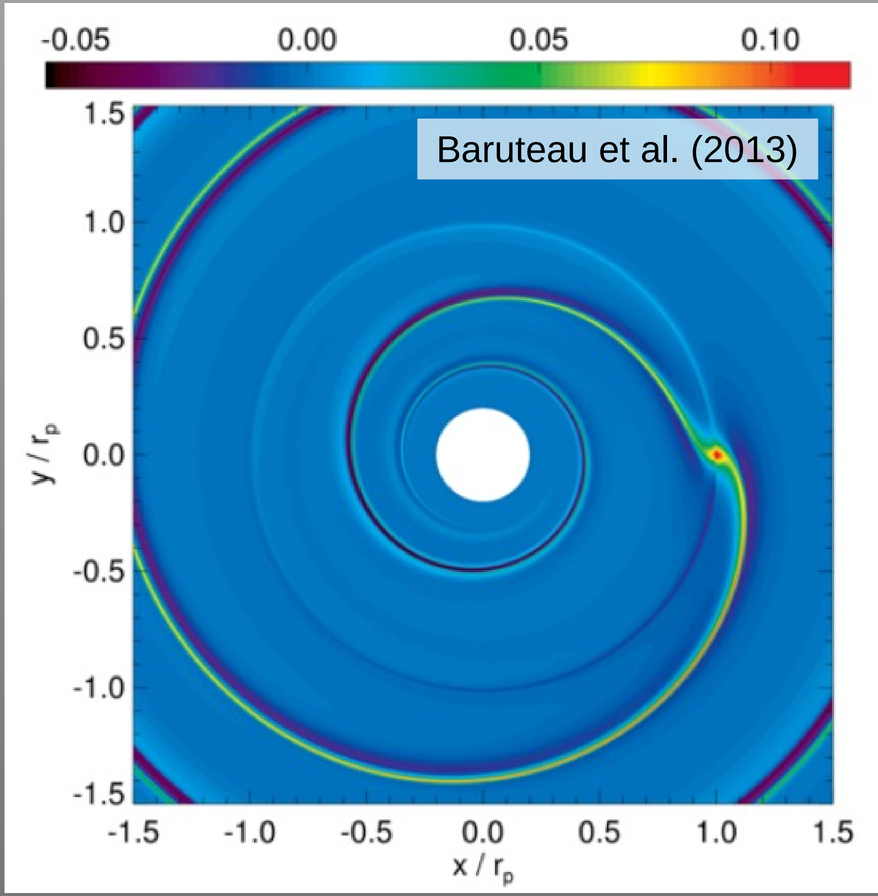
Impulse approximation exists!

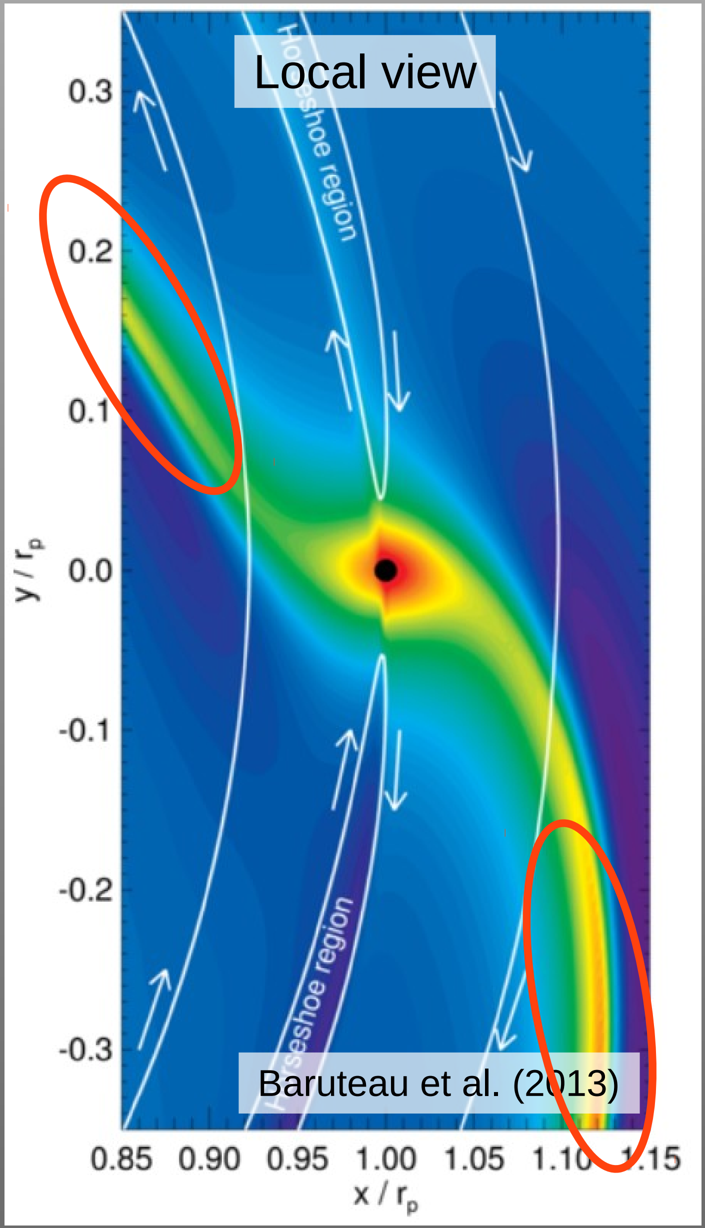


(c) NASA/JPL/SPACE SCIENCE INSTITUTE


(c) wikipedia

Gaseous disks



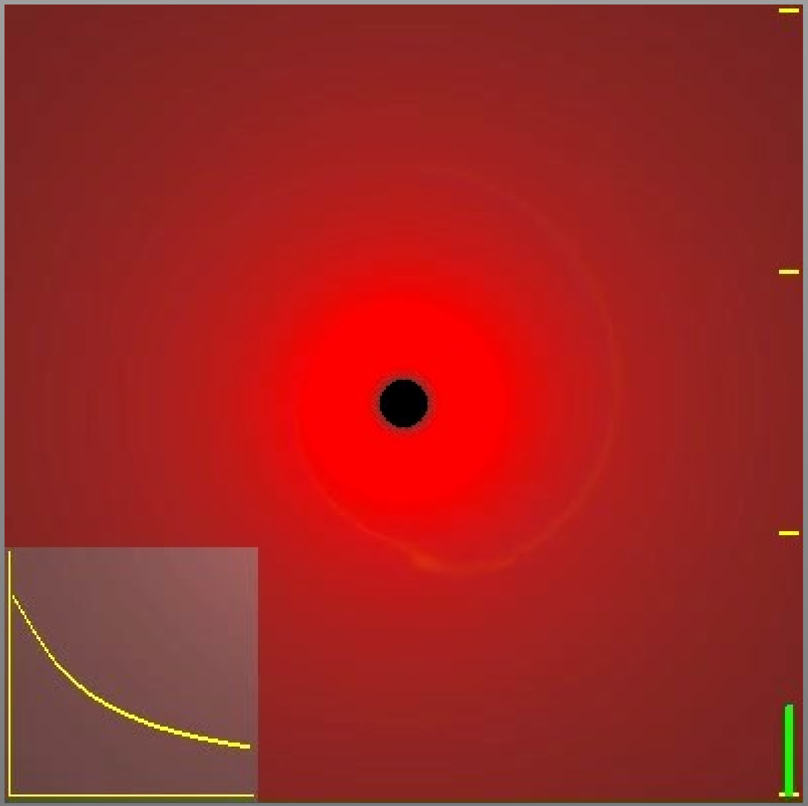


Type I, Type II

Type I migration
planets are embedded

Type II migration
planets open a gap in the disk; migration slows down

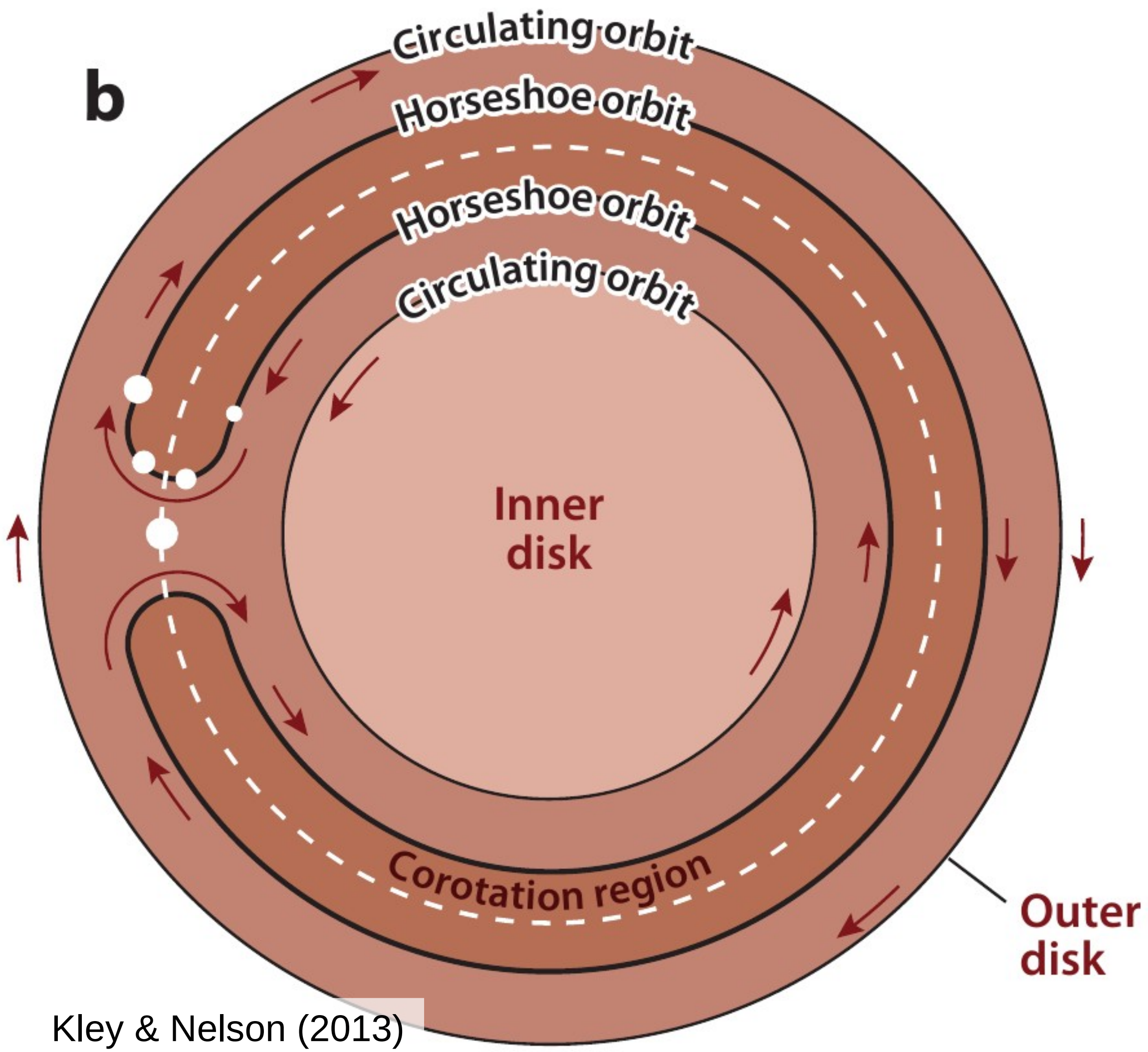
→ (c) Phil Armitage; the movie shows 600 orbits



10 M_{Jup}

3 M_{Earth}

Disk-planet topology

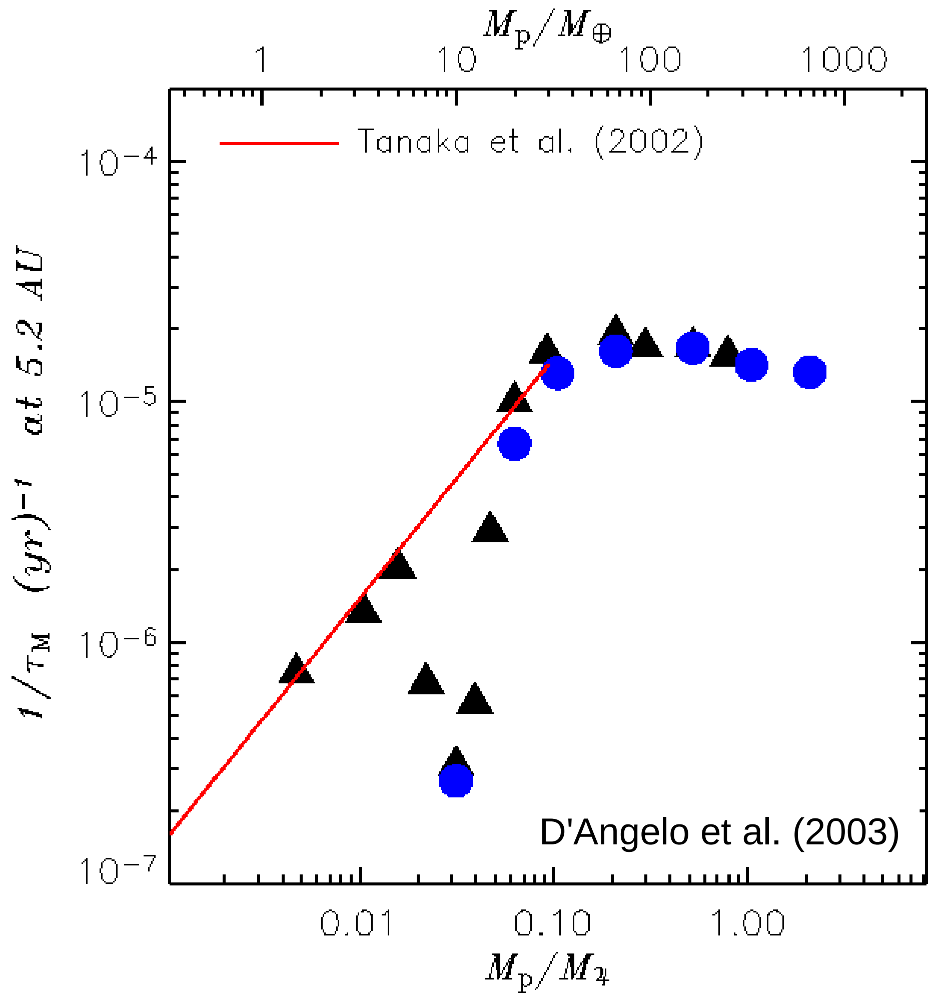


Kley & Nelson (2013)

Lindblad torque(s)
circulating orbits the star; distant encounters & small-angle delections; impulse approximation valid (until b~h_{gas}); more thoroughly described with resonance theory.

Corotation torques(s)
make U-turn (librate); subsonic velocities. Hydro- & thermo-dynamics very important in determining the torque.

Migration time



Red curve
Type I, 2-sided isothermal EOS migration rate according to theory (Tanaka et al. 2002)

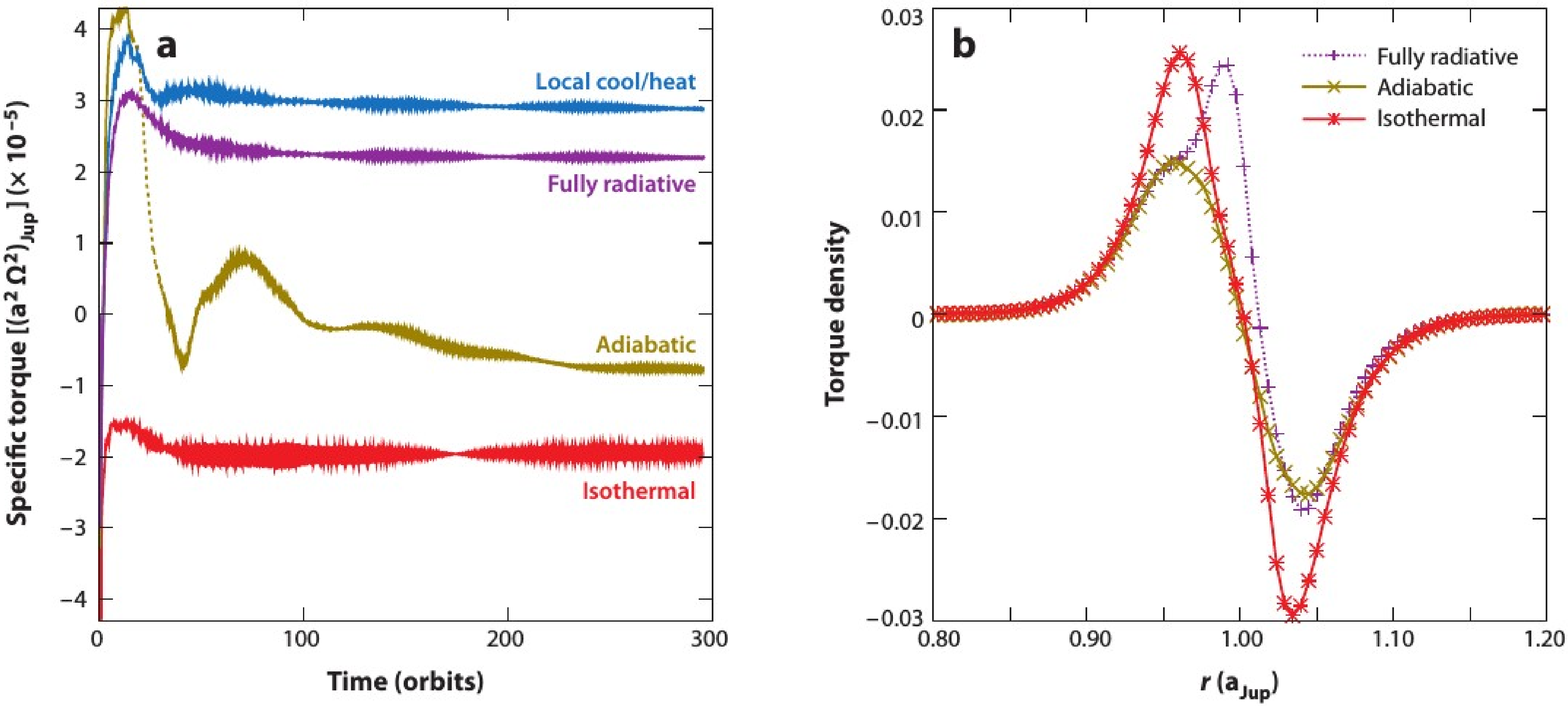
$$\tau = (2.7 + 1.1\alpha)^{-1} \frac{M_c}{M_p} \frac{M_c}{\sigma_p r_p^2} \left(\frac{c}{r_p \Omega_p}\right)^2 \Omega_p^{-1} \ .$$

Symbols
Simulations (D'Angelo et al. 2003)

There is a good perfect match b/w theory and simulations

→ **migration very efficient!**

Two-sided



Kley & Nelson (2013)

Migration

- **Planet migration**
  - **Gas-free migration**
  - **Disk migration**

Migration

Planet migration

Gas-free migration

– Kozai cycles
– planet-planet scattering
Usually invokes tidal interactions with star to shrink planet's orbit

Disk migration

Migration

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    will greatly depend on
    flow pattern in vicinity planet
    (hydro- *and* thermodynamics)

Migration

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Problem setup

- **2D or 3D?**
- **E.O.S. ?**
- **Planet atmosphere** **(smoothing length)**
- **1-sided or 2-sided?** (differential)
- **Linear or non-linear?** (high mass planets, eccentric planets, gap opening?)

Disk migration takeaways

- Features
  - result of near-cancellation of two opposing torques
  - Type I and II
  - rapid
- Usually inward

  key exception: positive co-orbital torque may dominate over (negative) Lindblad torque
- Good for explaining hot-Jupiters

  … and other close-in systems, but not solar system
- Missing physics

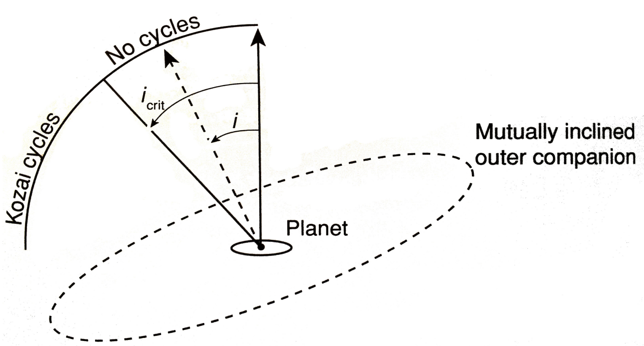
  Two-planet migration; flow w/i atmosphere, etc...

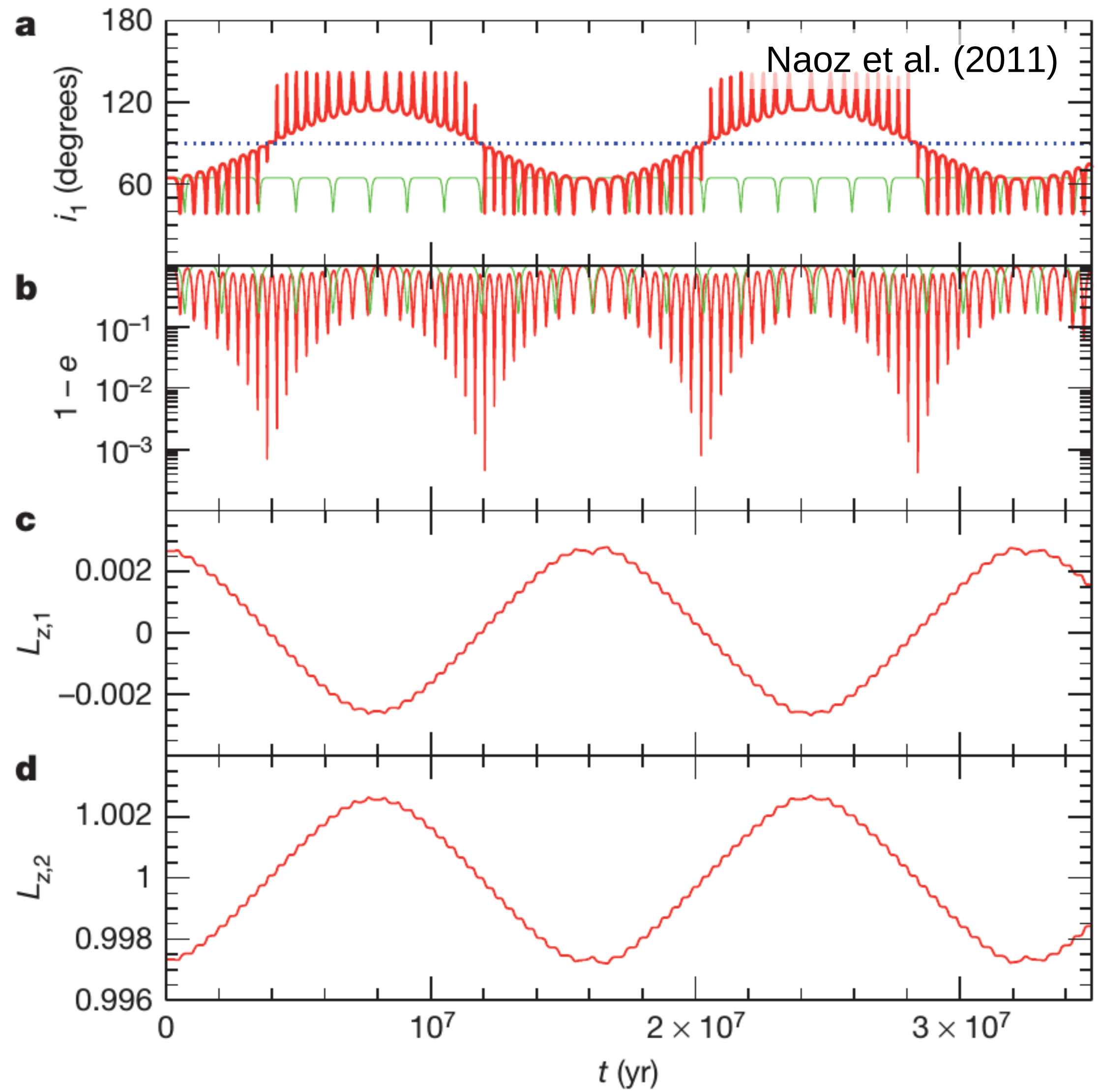
Gas disk-free migration mechanisms

Solid (planetesimal)-driven migration
in rings or early solar system

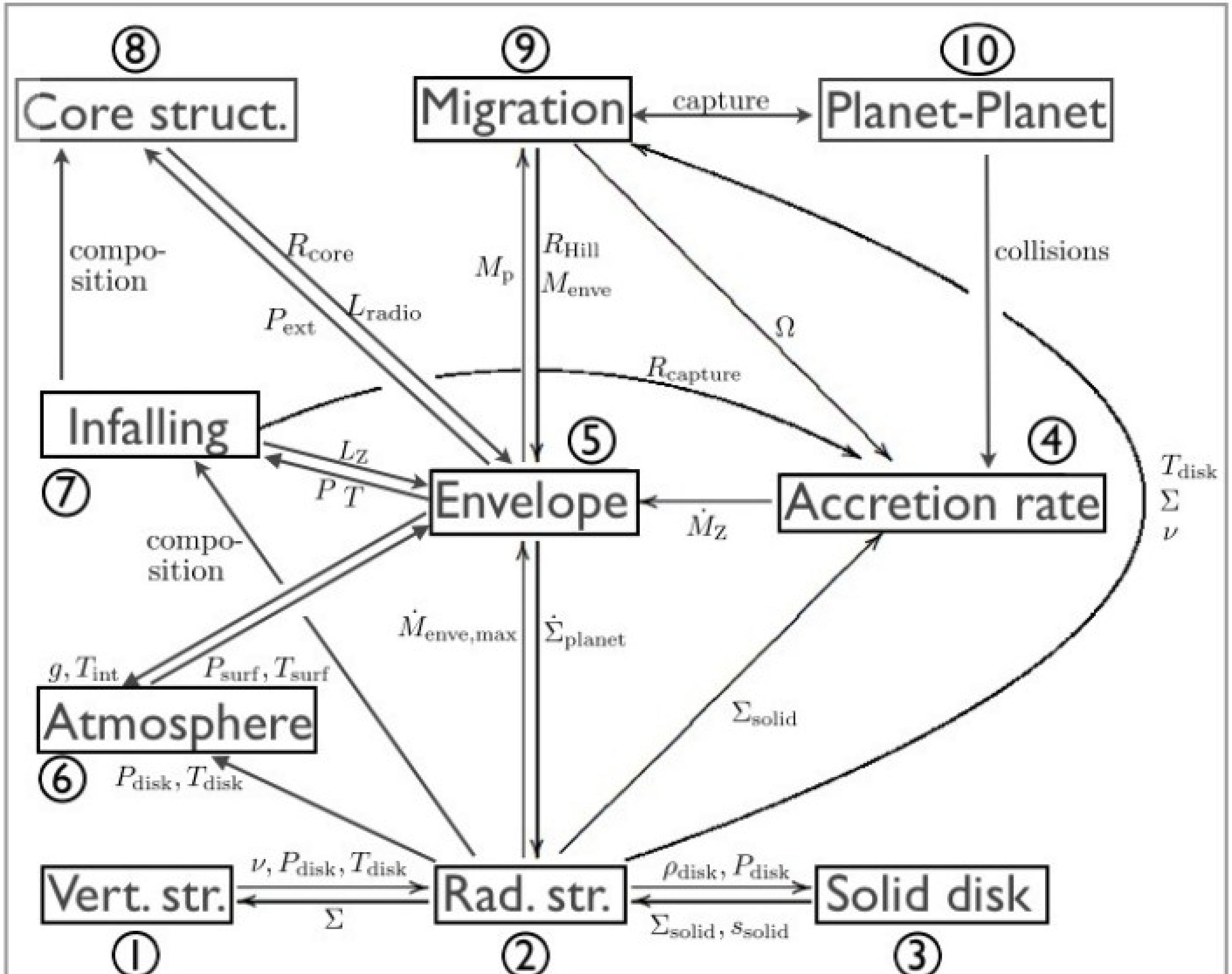
Planet-planet scattering

Kozai-Lidov cycles
binary perturber





Planet Population synthesis models



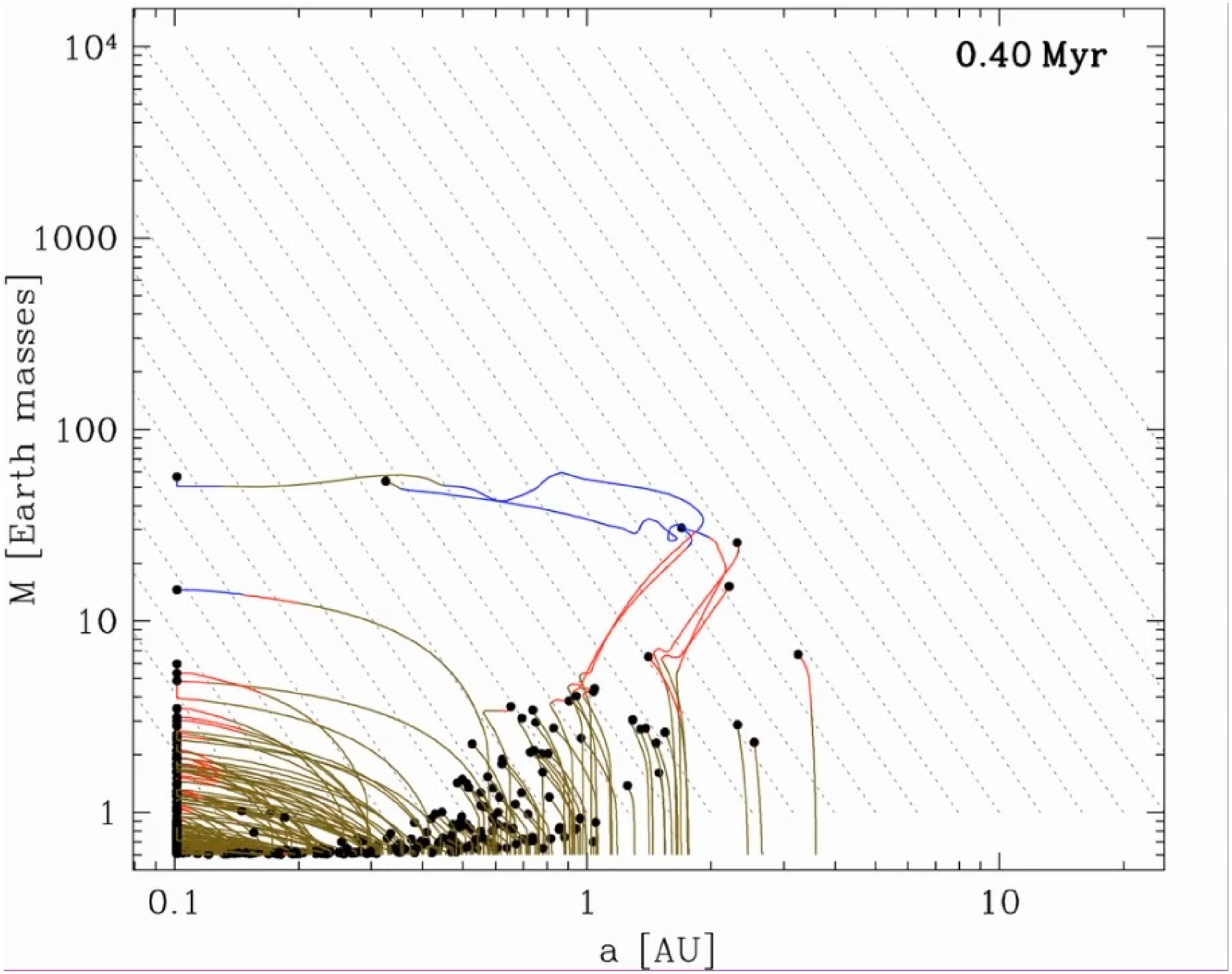
Benz et al. (2013)

Planet Population Synthesis

Planet pop. synthesis
each of these line represents an evolving planet in a *different* disk.

Key advantage
This exercise attempts to match the observed exoplanet distribution

Key disadvantage
It's a weakest link game



Mordasini et al.

Exoplanet zoo

Exoplanets
Certainly much more diverse than the solar system!

A complete planet formation theory still awaits us!