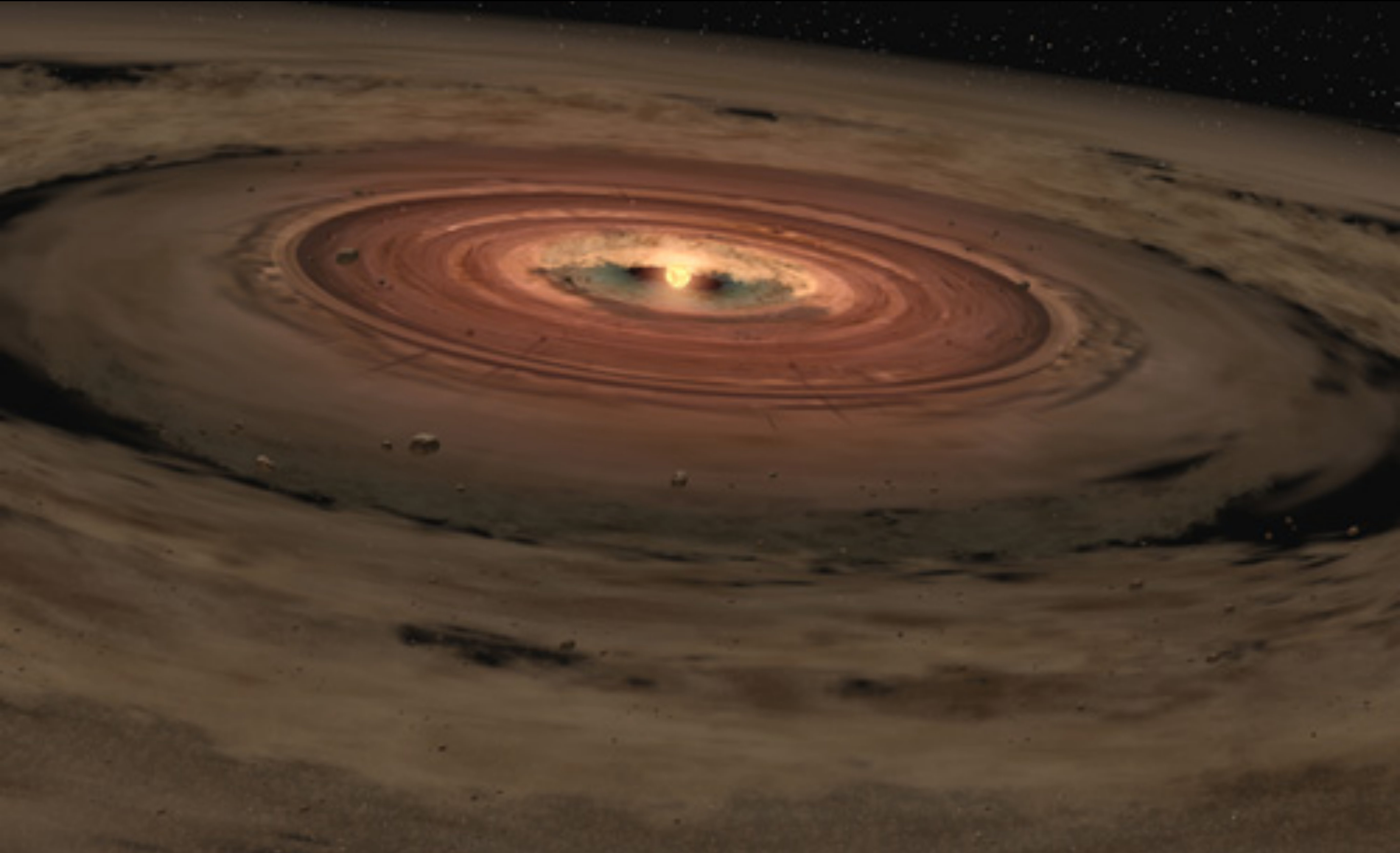
Astrophysics of Planet Formation

Lecture 5 - Planet migration



Course Outline

- 5 Lectures, 2 hours each (with a break in the middle!).
    1) Observations of planetary systems
    2) Protoplanetary discs
    3) Dust dynamics & planetesimal formation
    4) Planet formation
    5) Planetary dynamics
- Notes for each lecture will be placed on the course home page *in advance* - you may find it useful to annotate these as we go.
- These slides will also be posted online.
- Textbooks: Armitage - *Astrophysics of planet formation* (CUP).
  Protostars & Planets series (*VI* - 2014; *VII* - 2023)

Course home-page: `rdalexander.github.io/planets_2023.html`

Resonant Torques

- Full perturbation analysis finds that the total torque is the sum of the torques at ***resonances***.
- Co-rotation resonance:

$$\Omega(R) = \Omega_{\rm p}$$

- Lindblad resonances:

$$m[\Omega(R) - \Omega_{\rm p}] = \pm\kappa(R)$$

$$R_{\rm L} = \left(1 \pm \frac{1}{m}\right)^{2/3} a$$

Resonant Torques

- Circular disc has one co-rotation resonance and a "comb" of Lindblad resonances:

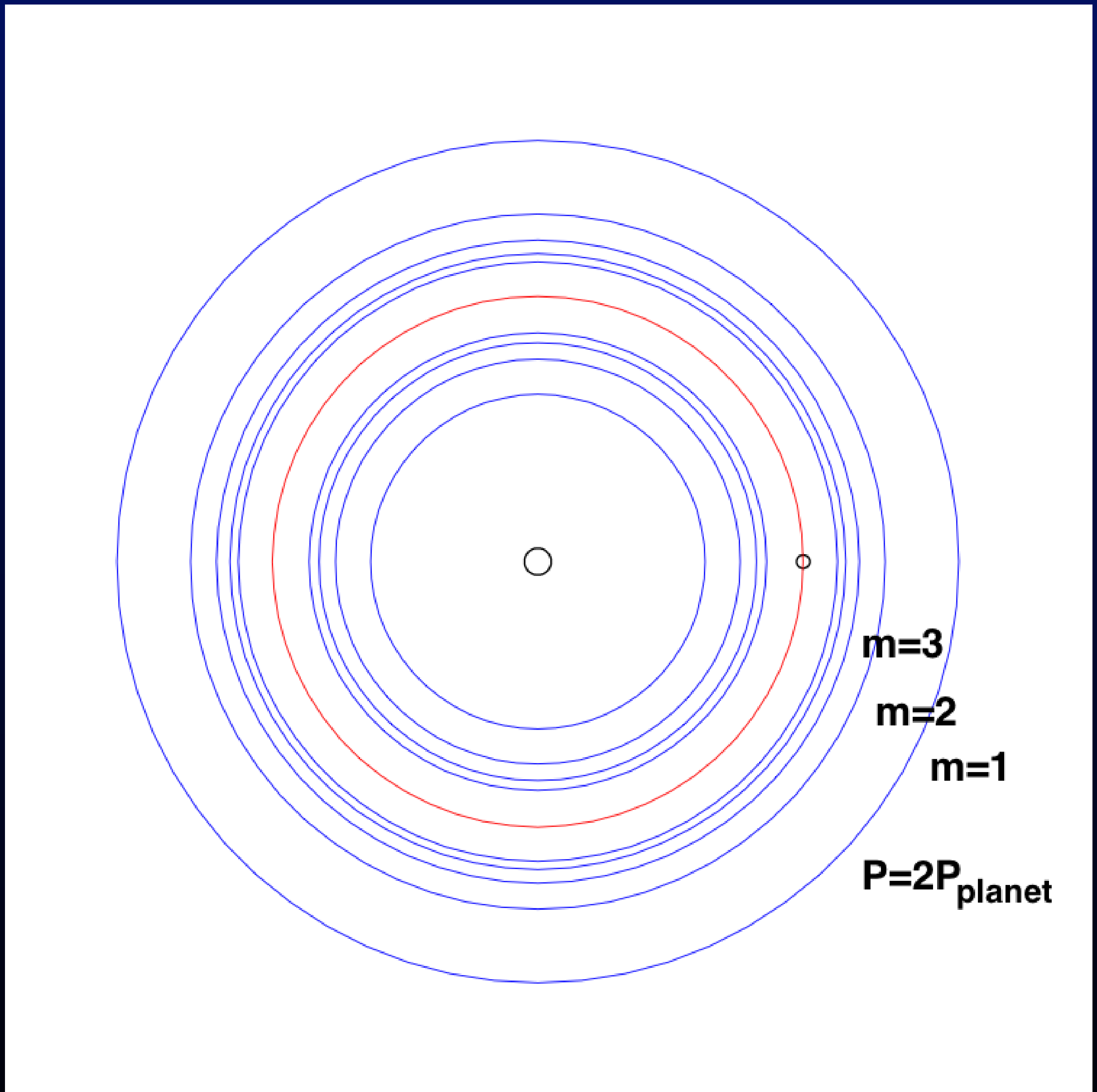


Figure from Armitage (2007)

$$R_{\rm L} = \left(1 \pm \frac{1}{m}\right)^{2/3} a$$

Resonant Torques

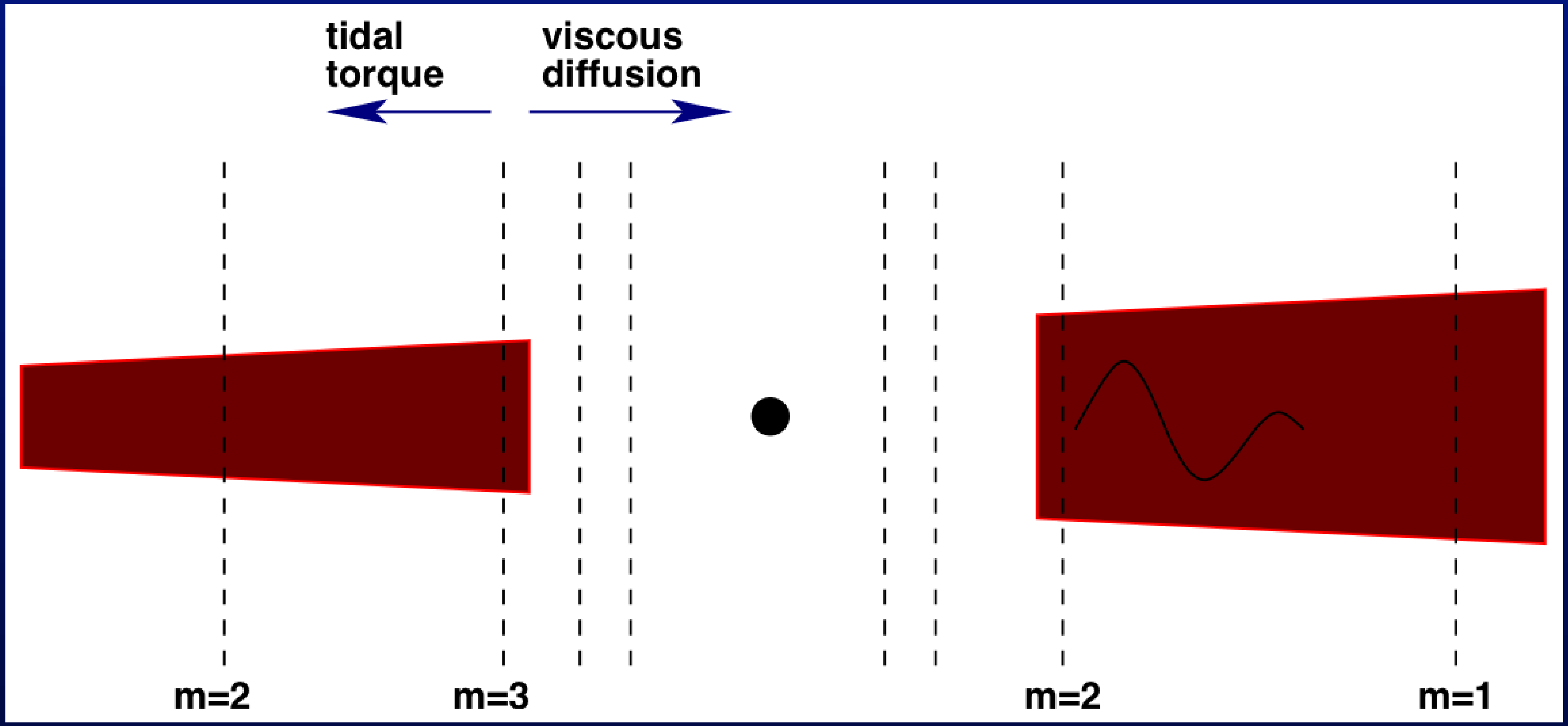


Figure from Armitage (2007)

- Torques repel disc gas from region close to planet, but viscosity opposes this. A sufficiently massive planet can open a gap in the disc.
- For typical disc parameters, the gap-opening mass is a few times the mass of Saturn.

No gap = Type I migration

Gap = Type II migration

Gap-opening conditions

- Thermal condition:

$$R_{\rm h} = R q^{1/3} \gtrsim H$$

$$q \gtrsim \left(\frac{H}{R}\right)^3$$

- Viscous condition:

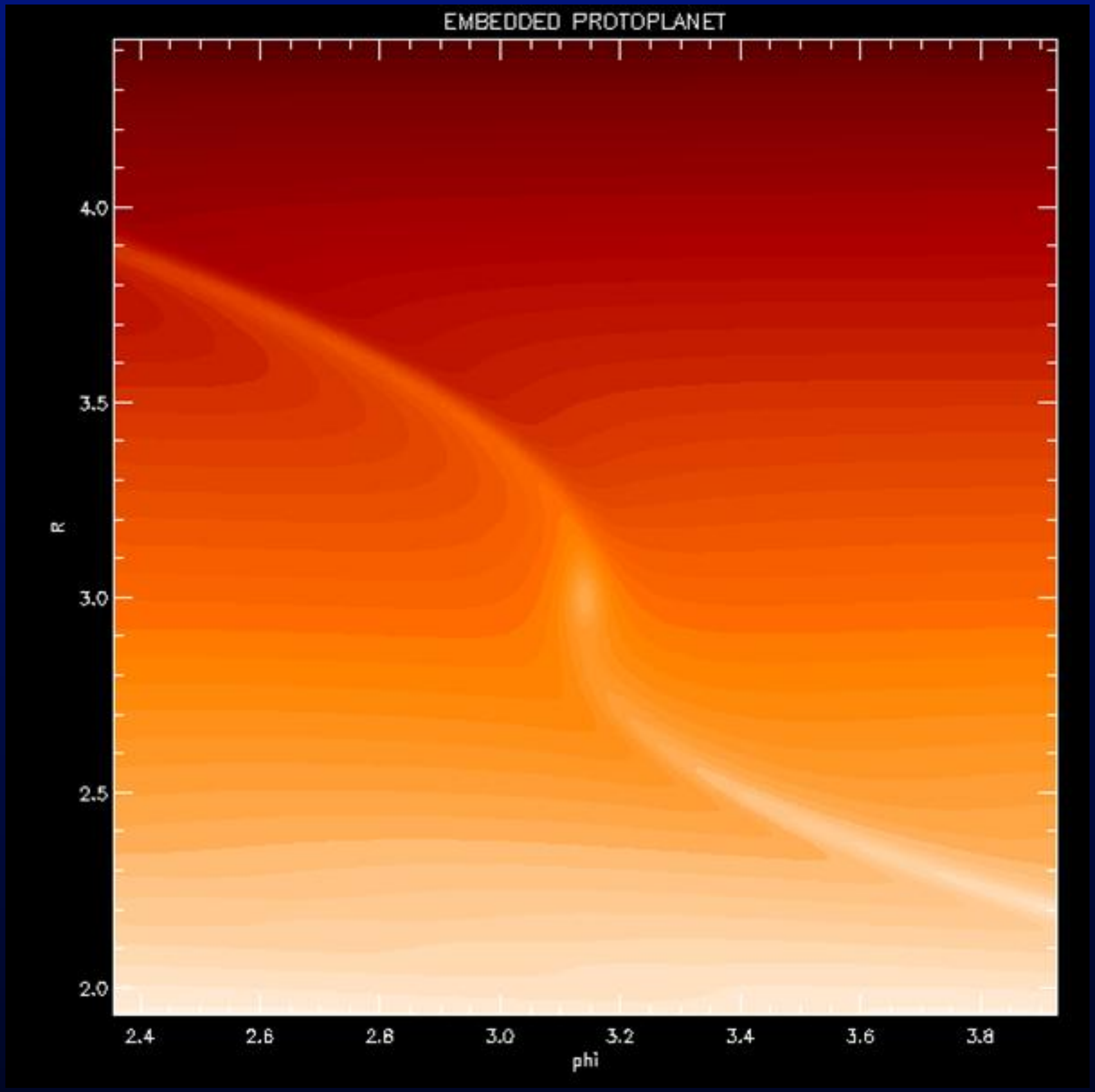
$$q \gtrsim \left(\frac{c_{\rm s}}{a_{\rm p}\Omega_{\rm p}}\right)^2 \alpha^{1/2}$$

- Combined condition (e.g., Crida+ 2006):

$$\frac{(H/R)}{q^{1/3}} + \frac{50\alpha(H/R)^2}{q} \lesssim 1$$

Type I migration in real discs

Figures/movies from Nelson et al. (2003,2004)

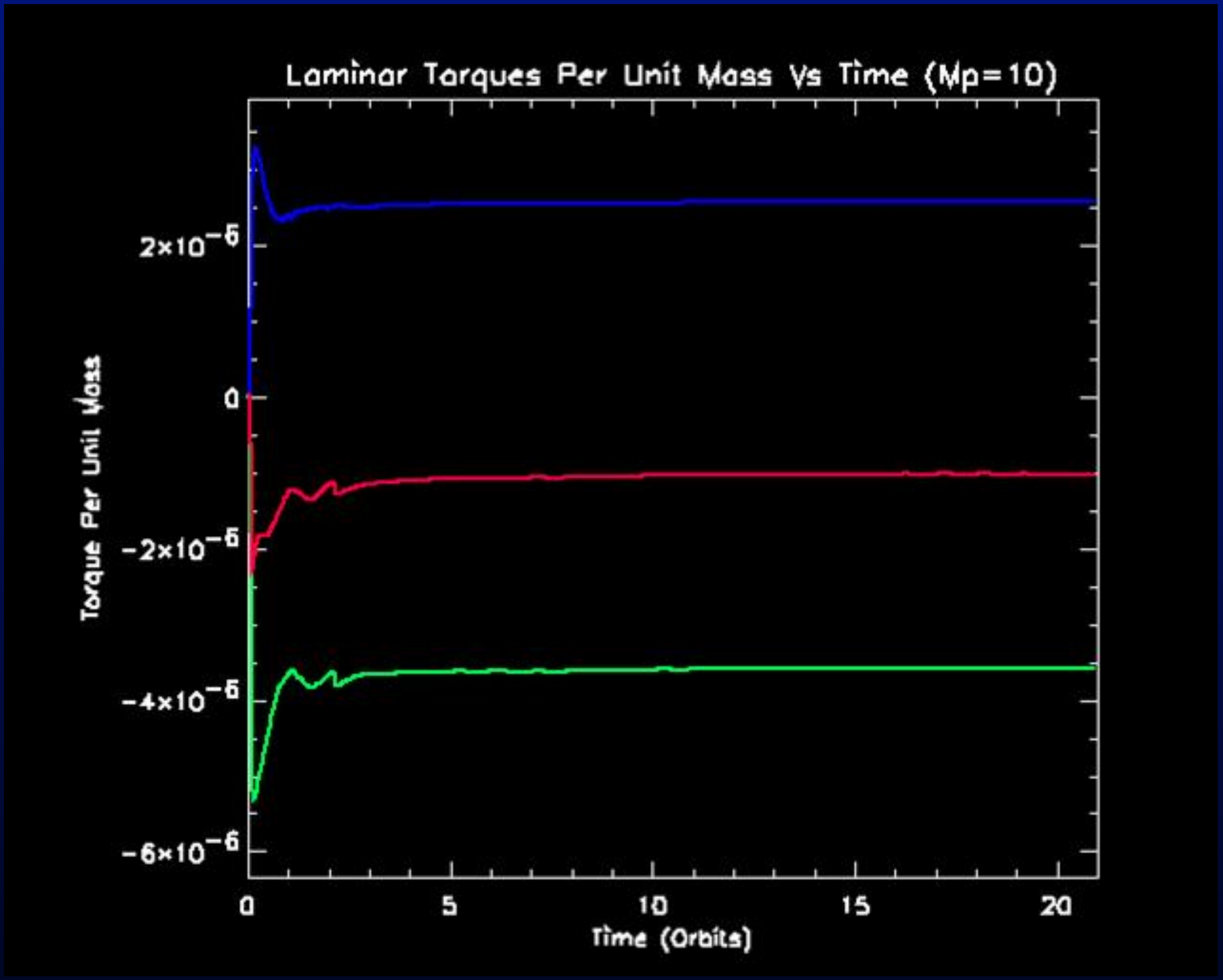


10M$_\oplus$ planet in laminar disc:

Spiral density waves launched from resonances. Well-defined, stable torques drive steady migration.

Type I migration in real discs

Figures/movies from Nelson et al. (2003,2004)



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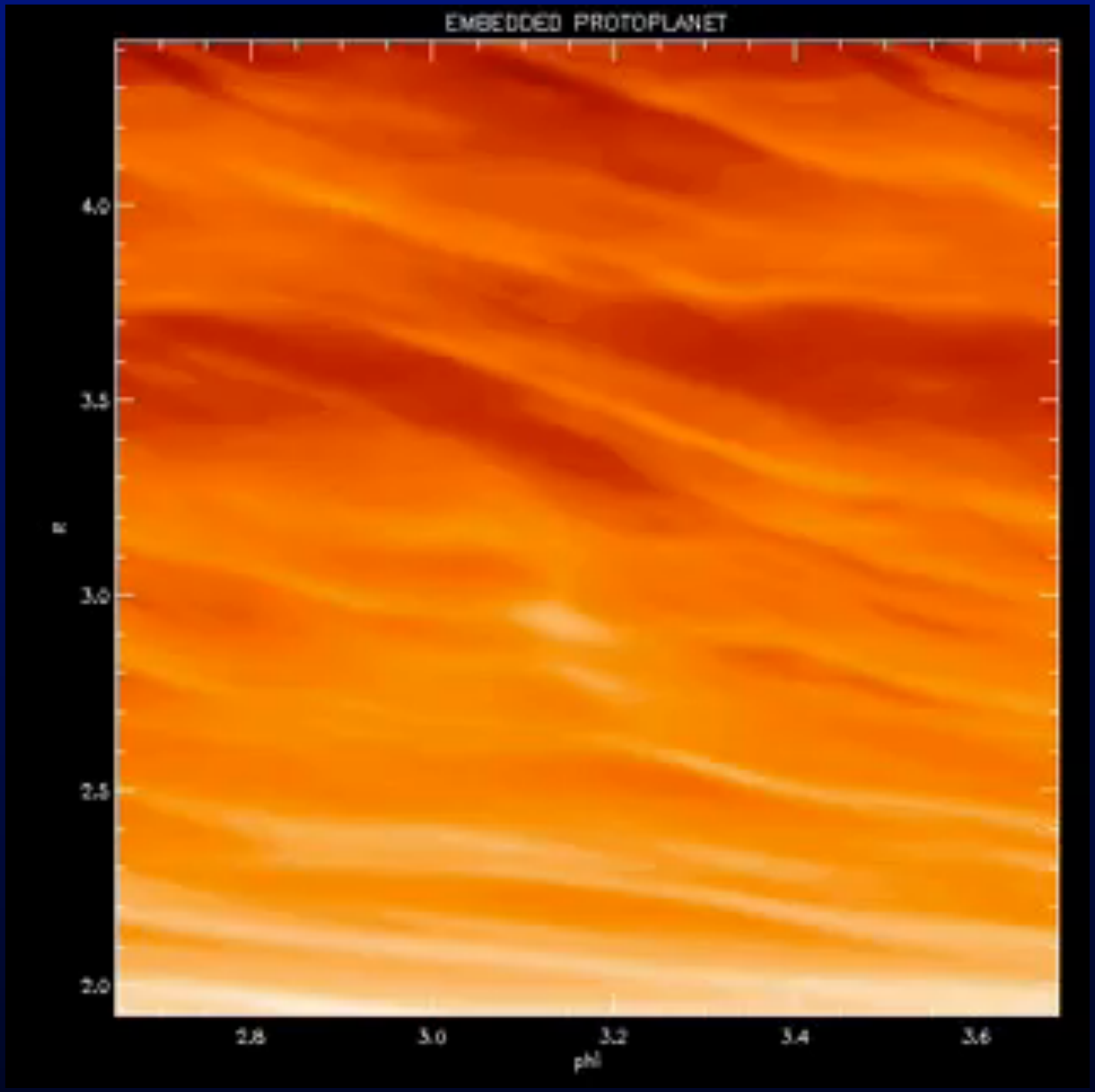
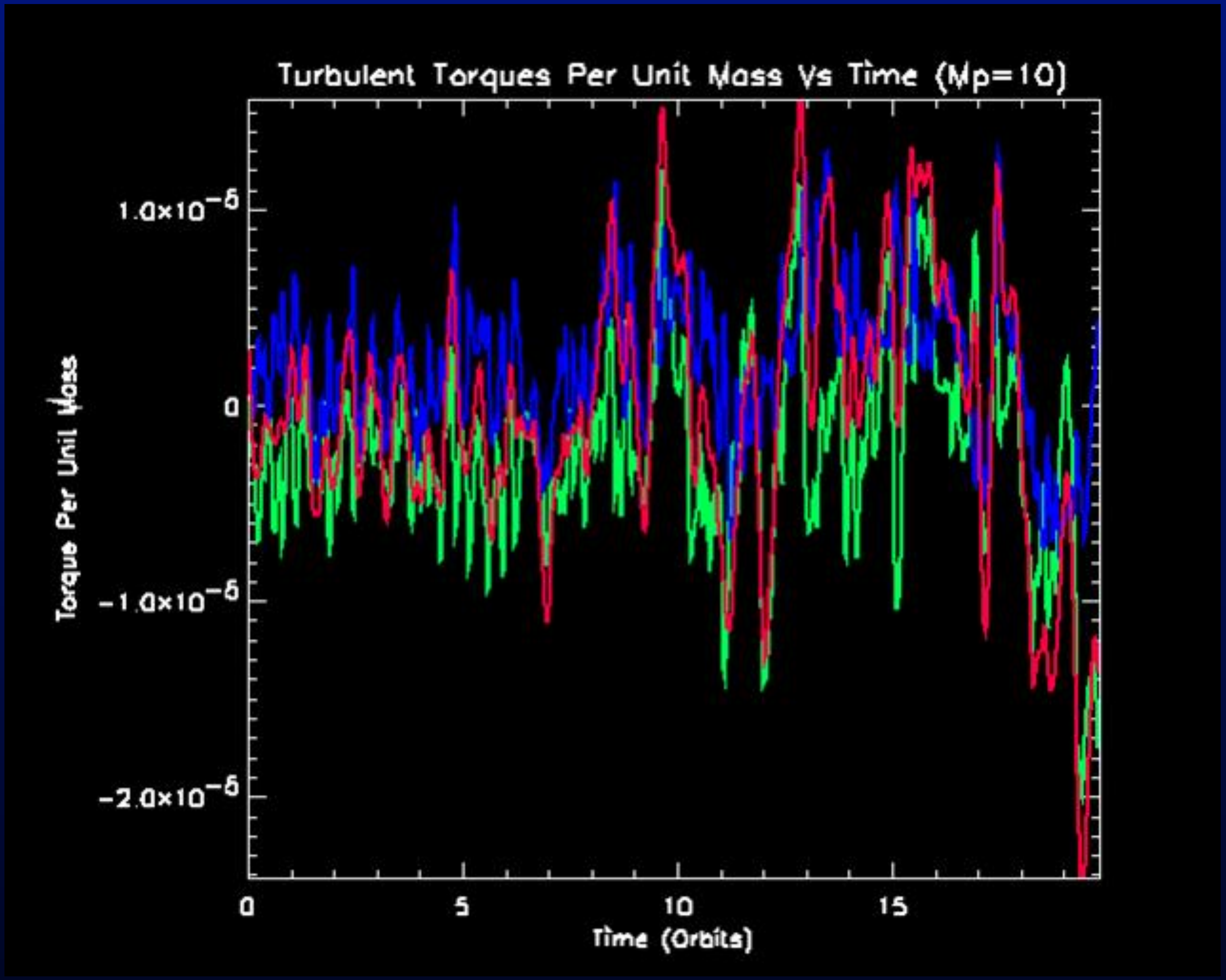


10M$_{\oplus}$ planet in MRI-turbulent disc:

Spiral density waves dwarfed by turbulent fluctuations.
Torques are very variable, leading to stochastic migration.

Type I migration in real discs

Figures/movies from Nelson et al. (2003,2004)



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Spiral density waves dwarfed by turbulent fluctuations.
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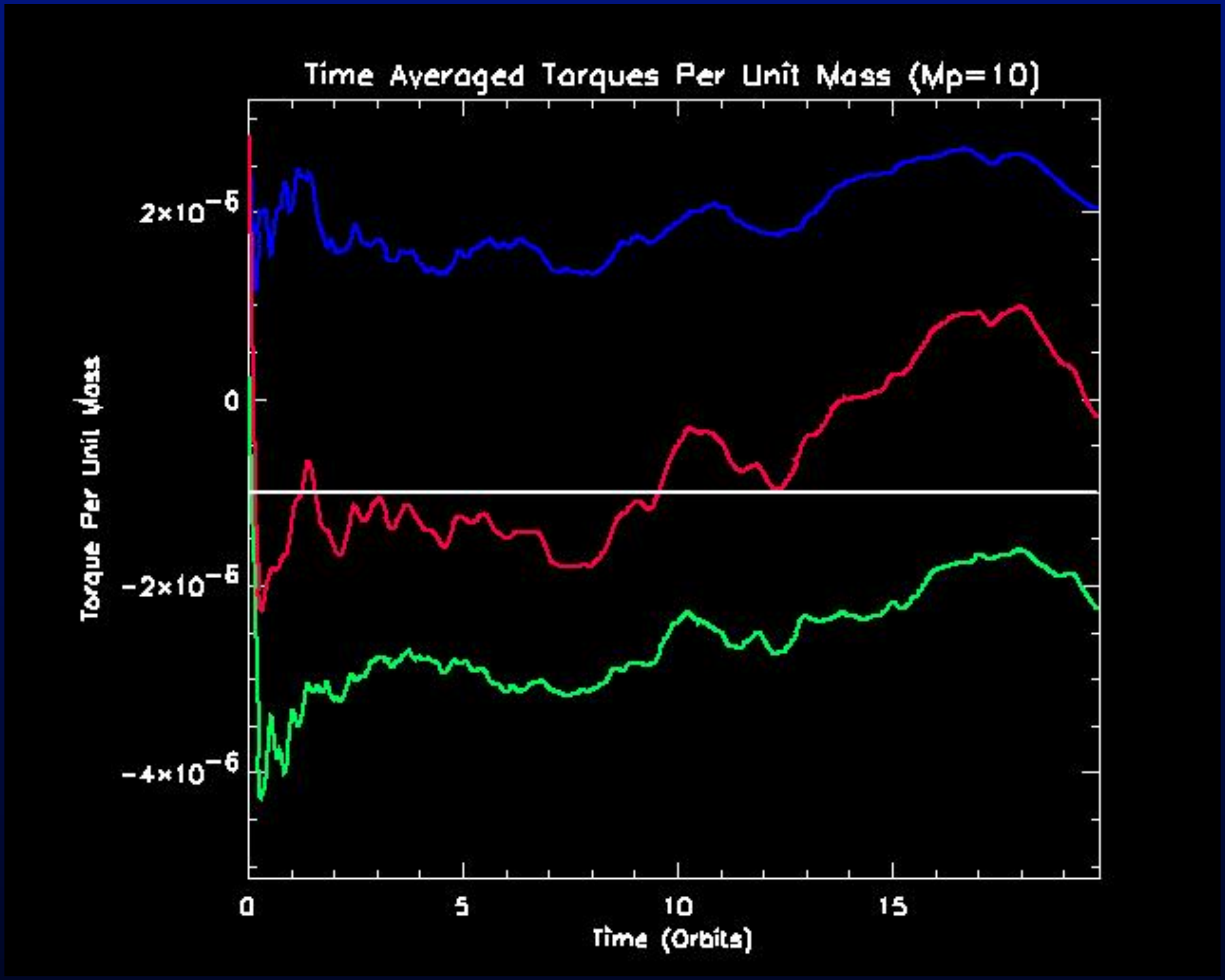
Type I migration in real discs

Figures/movies from Nelson et al. (2003,2004)

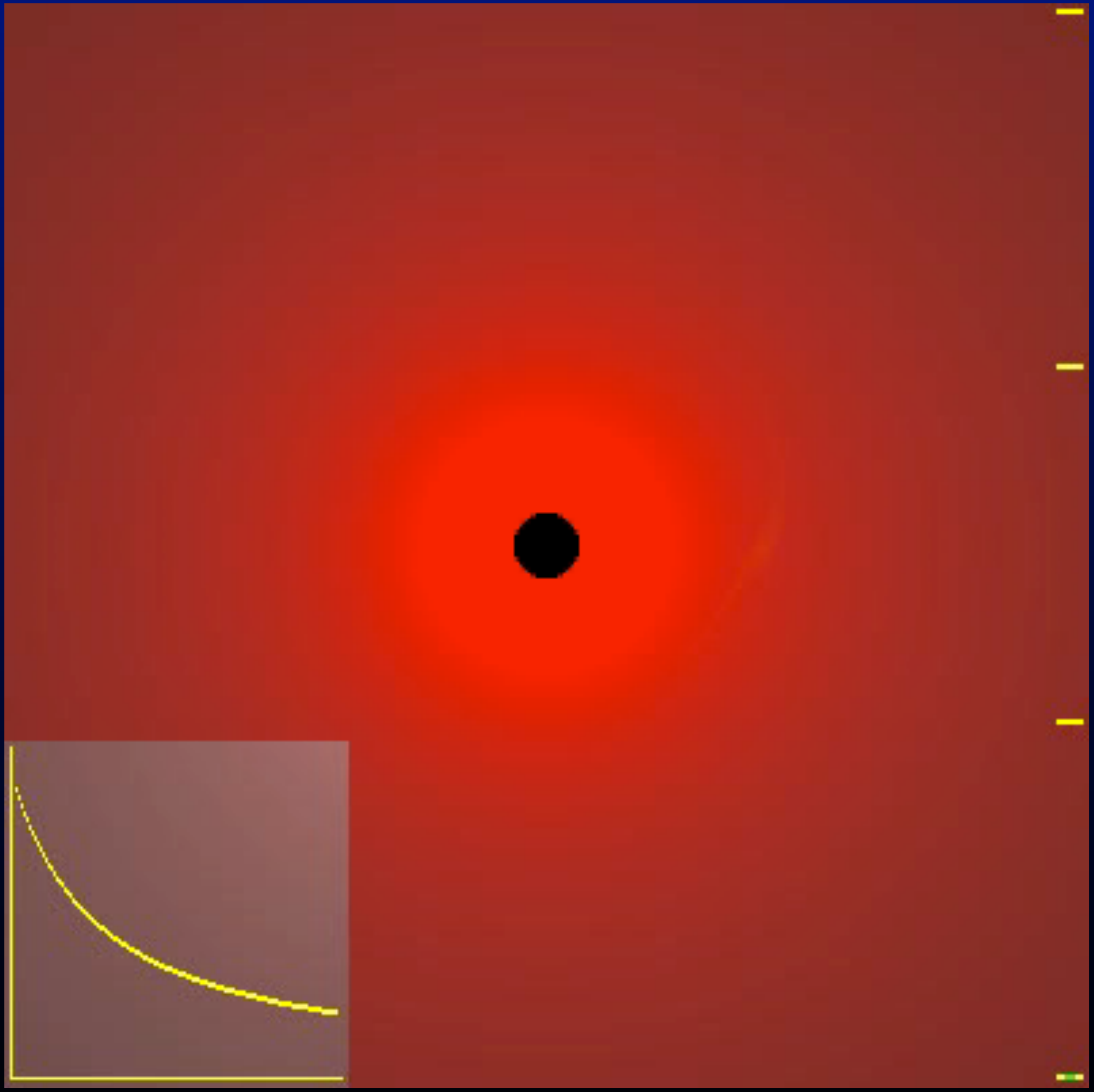


$10M_\oplus$ planet in MRI-turbulent disc:

Spiral density waves dwarfed by turbulent fluctuations.
Torques are very variable, leading to stochastic migration.

Type I/II migration

Animation from Armitage (2005)



Resonant capture

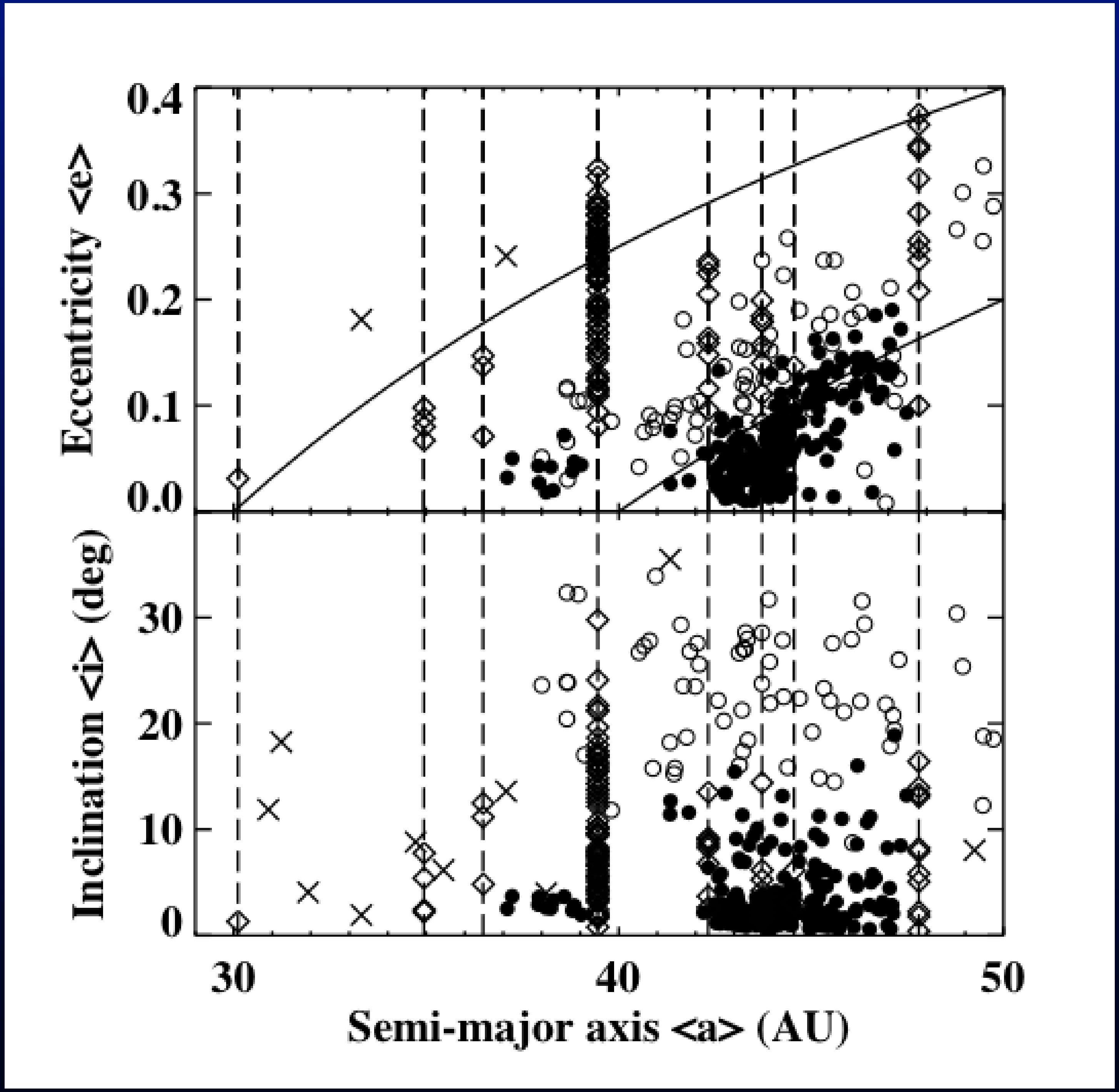
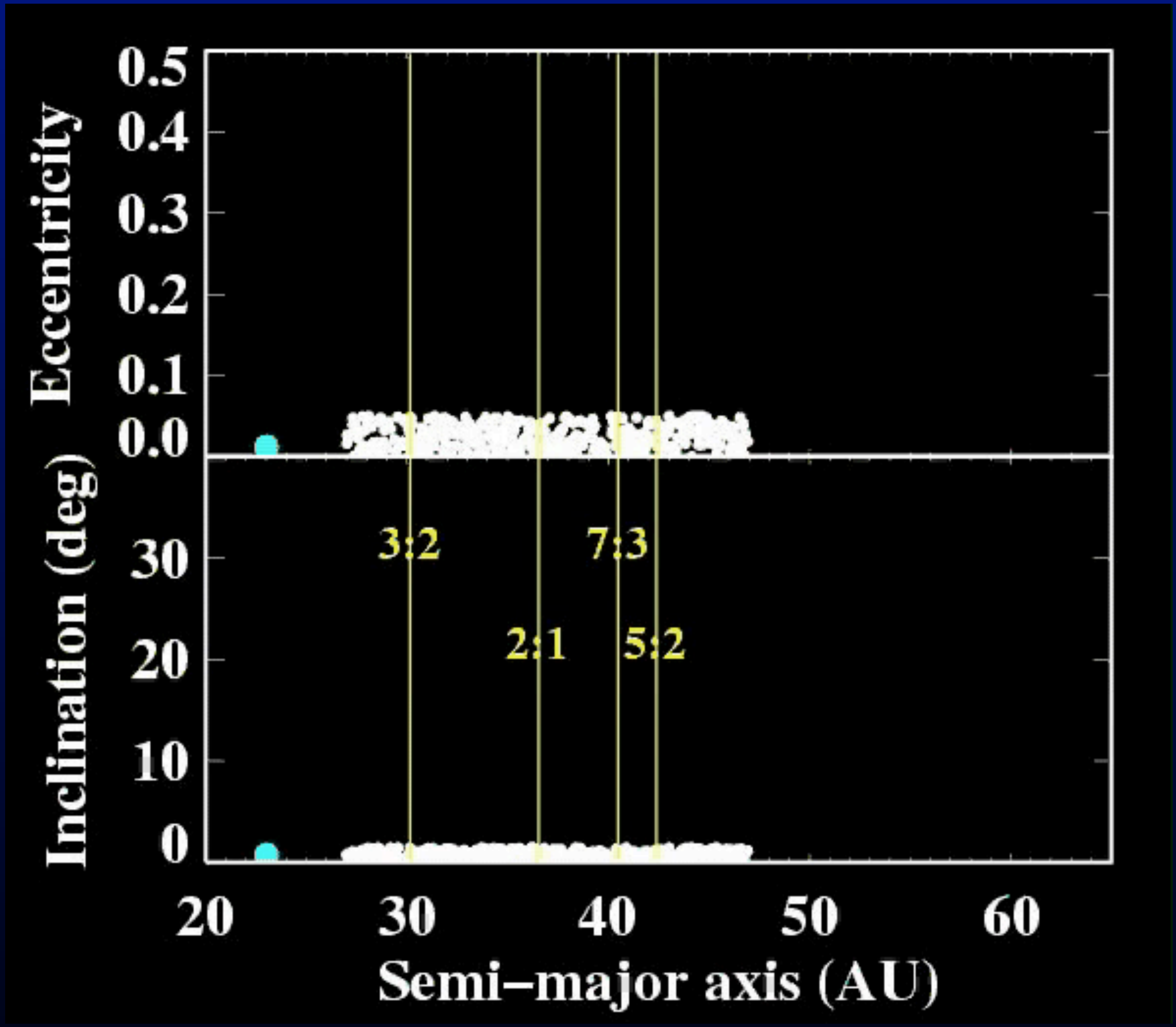


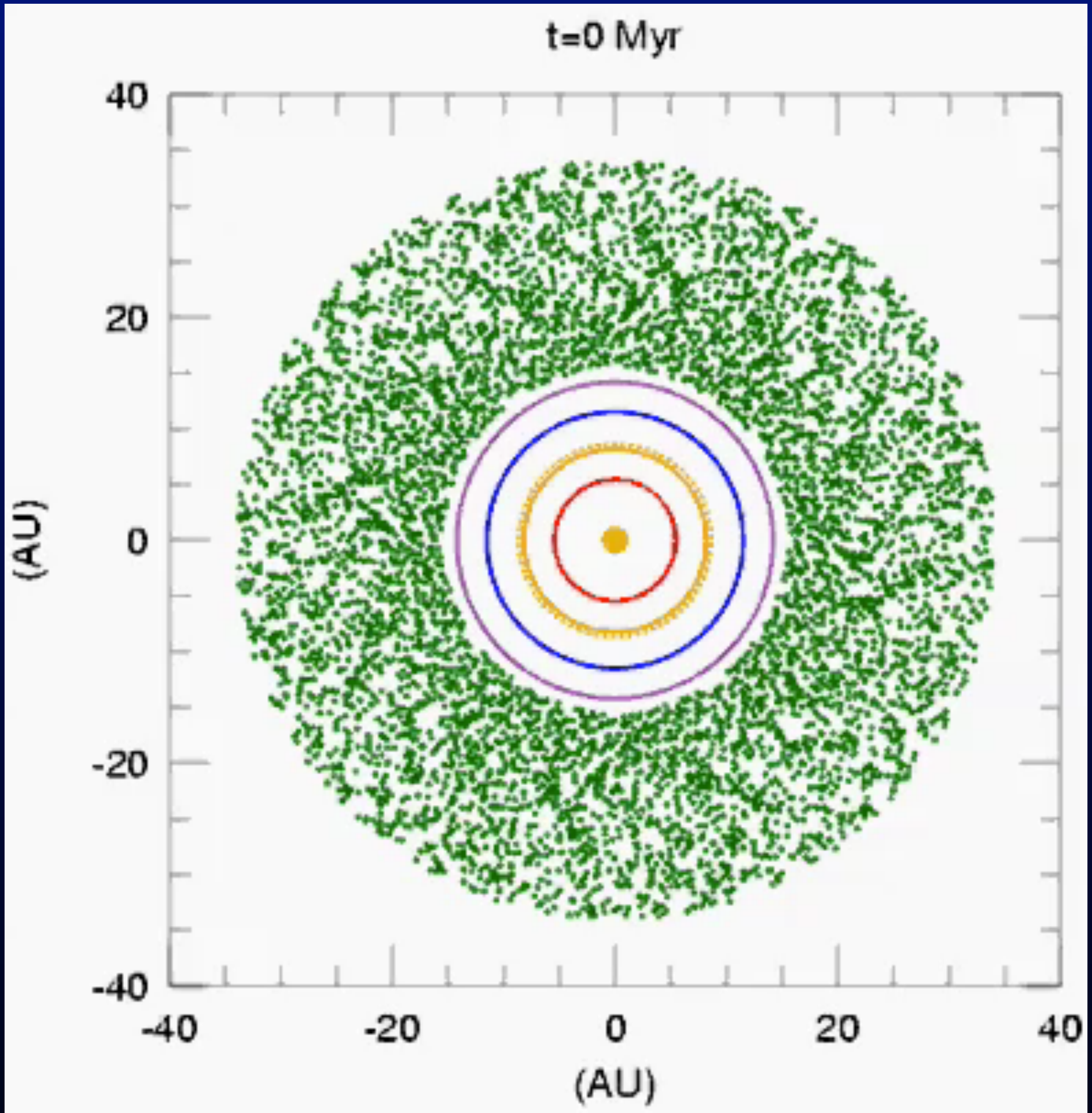
Figure from Chiang et al. (2007)

Resonant capture



Animation courtesy of Eugene Chiang

The Nice Model



Animation courtesy of Hal Levison

The Nice Model

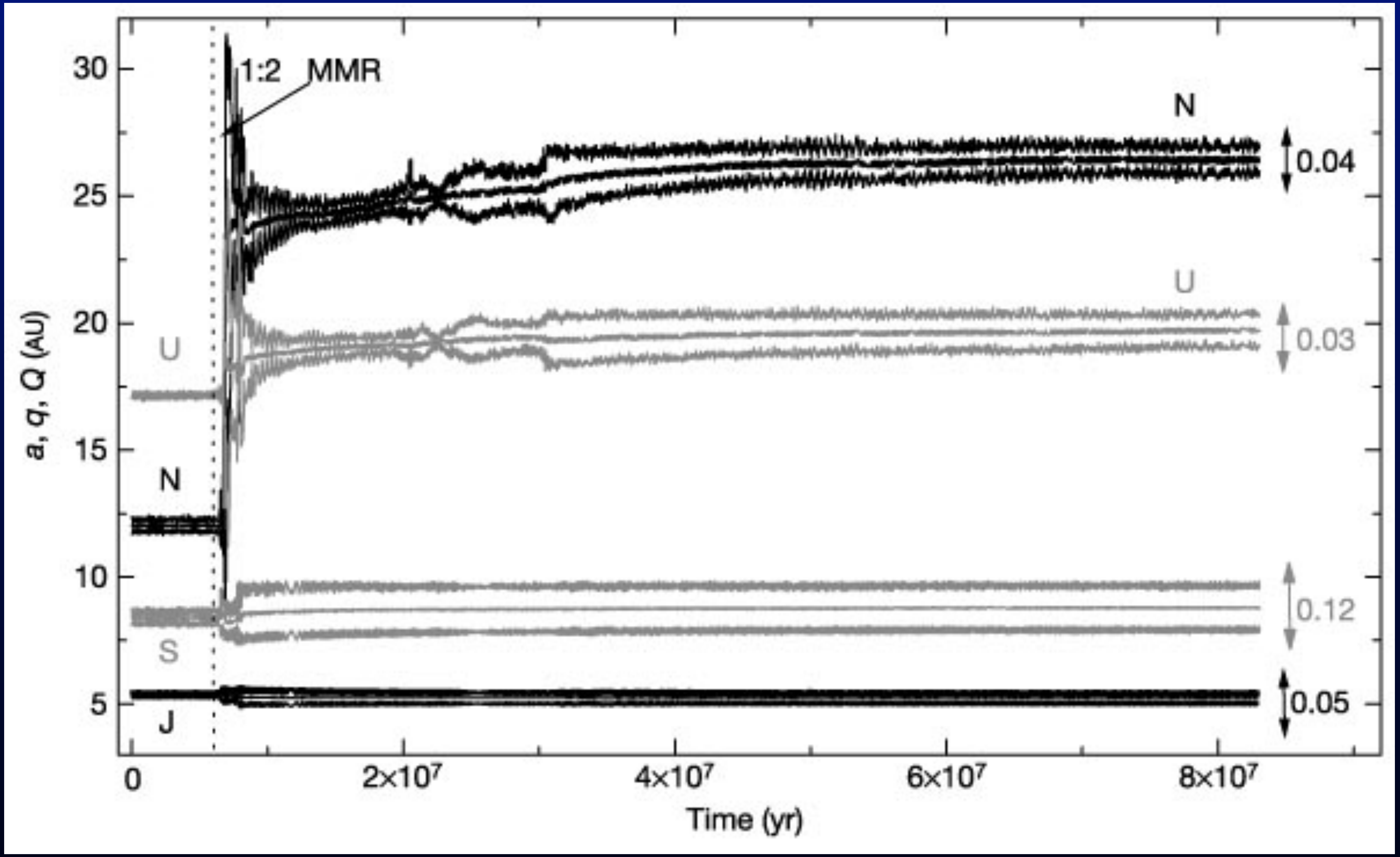
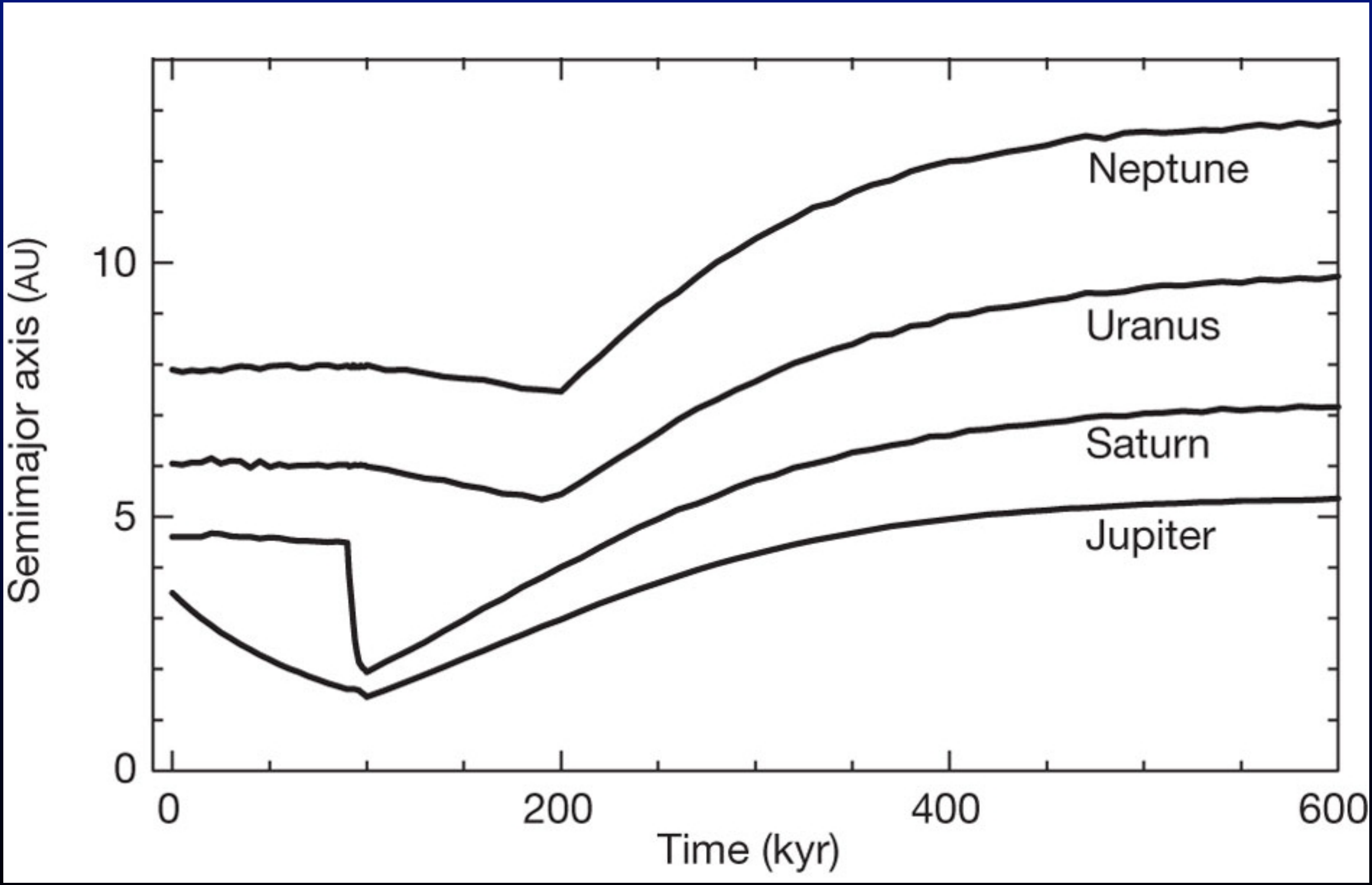


Figure from Tsiganis et al. (2005)

The "Grand Tack"

Walsh et al. (2011)



Movies courtesy of Sean Raymond

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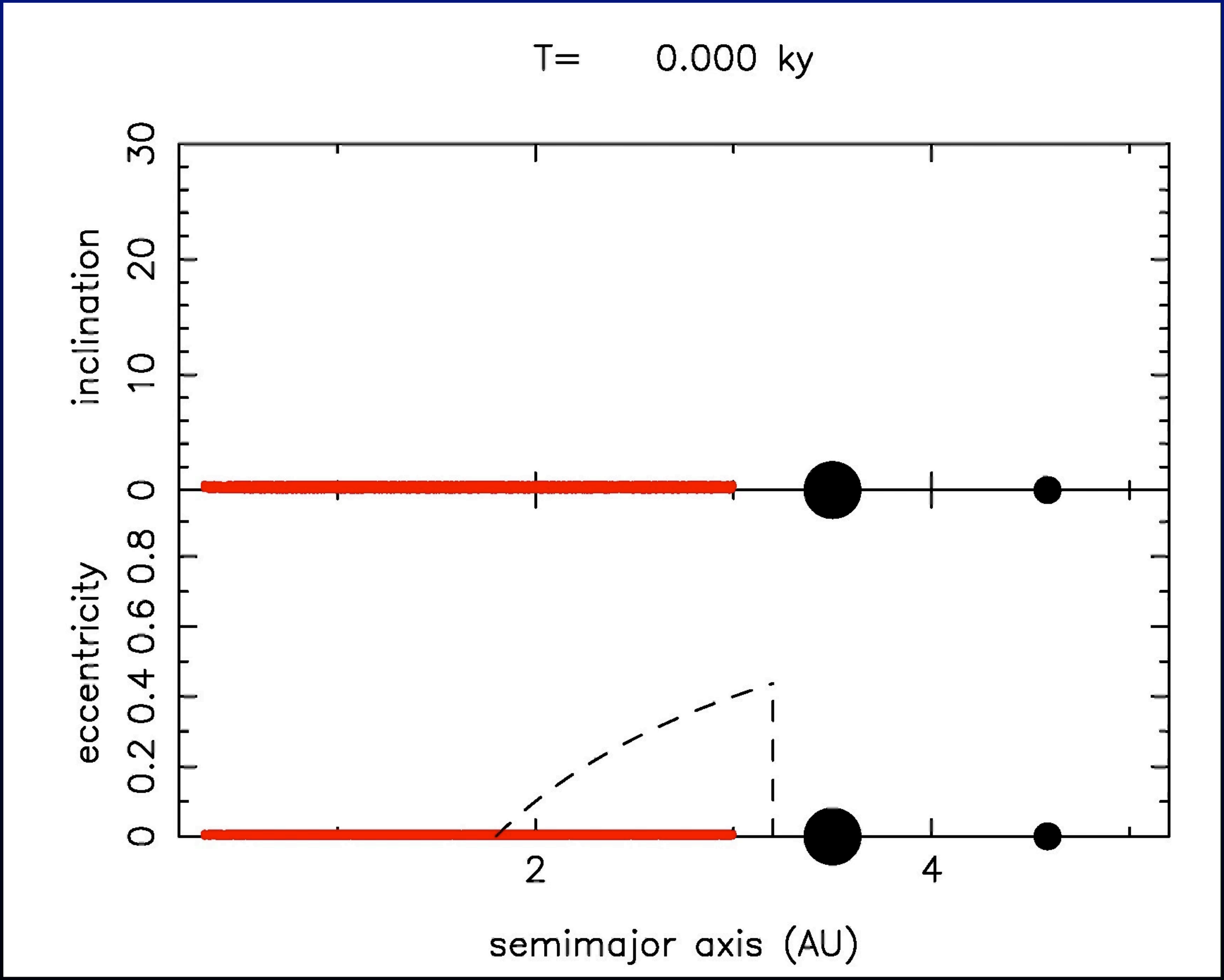

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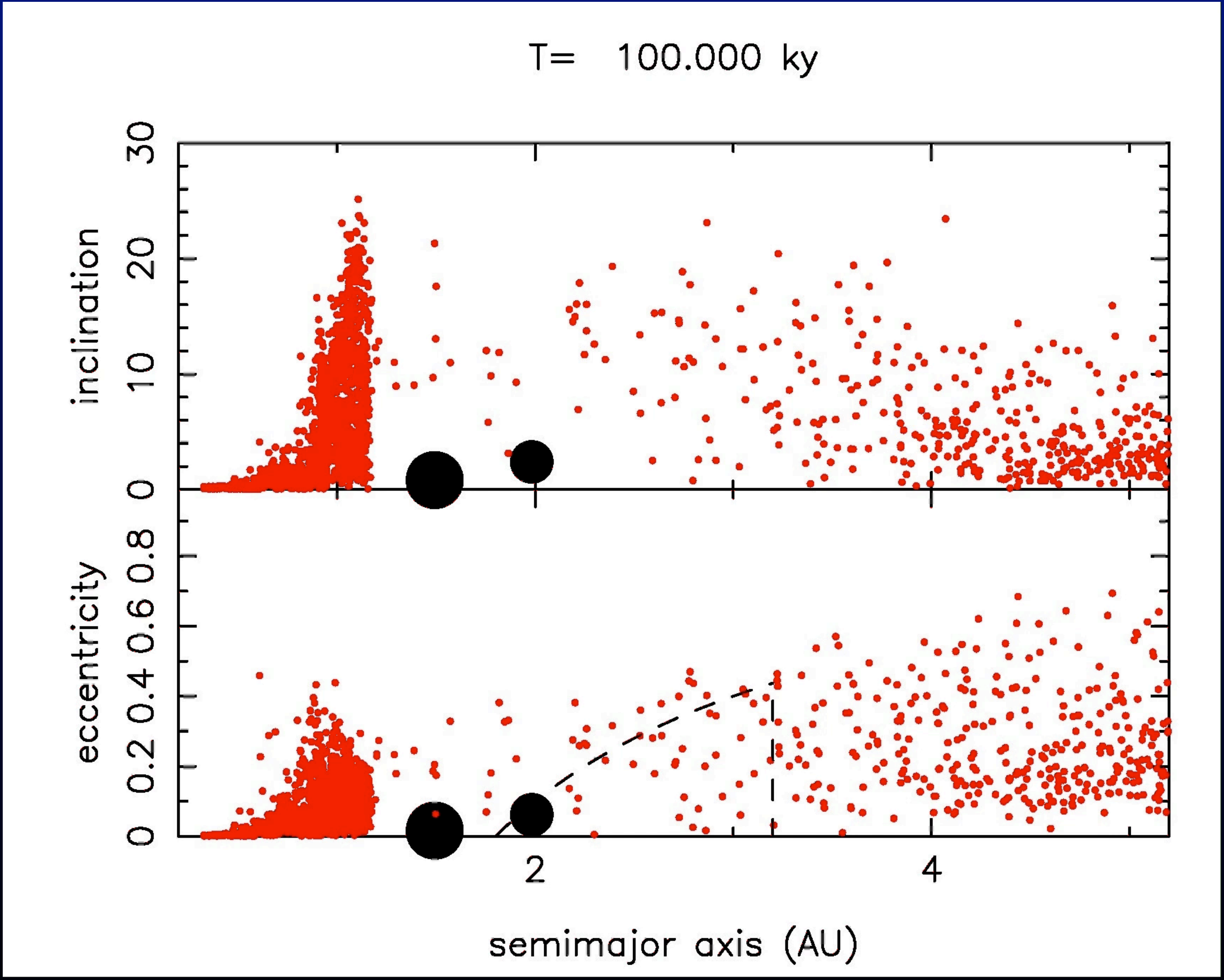

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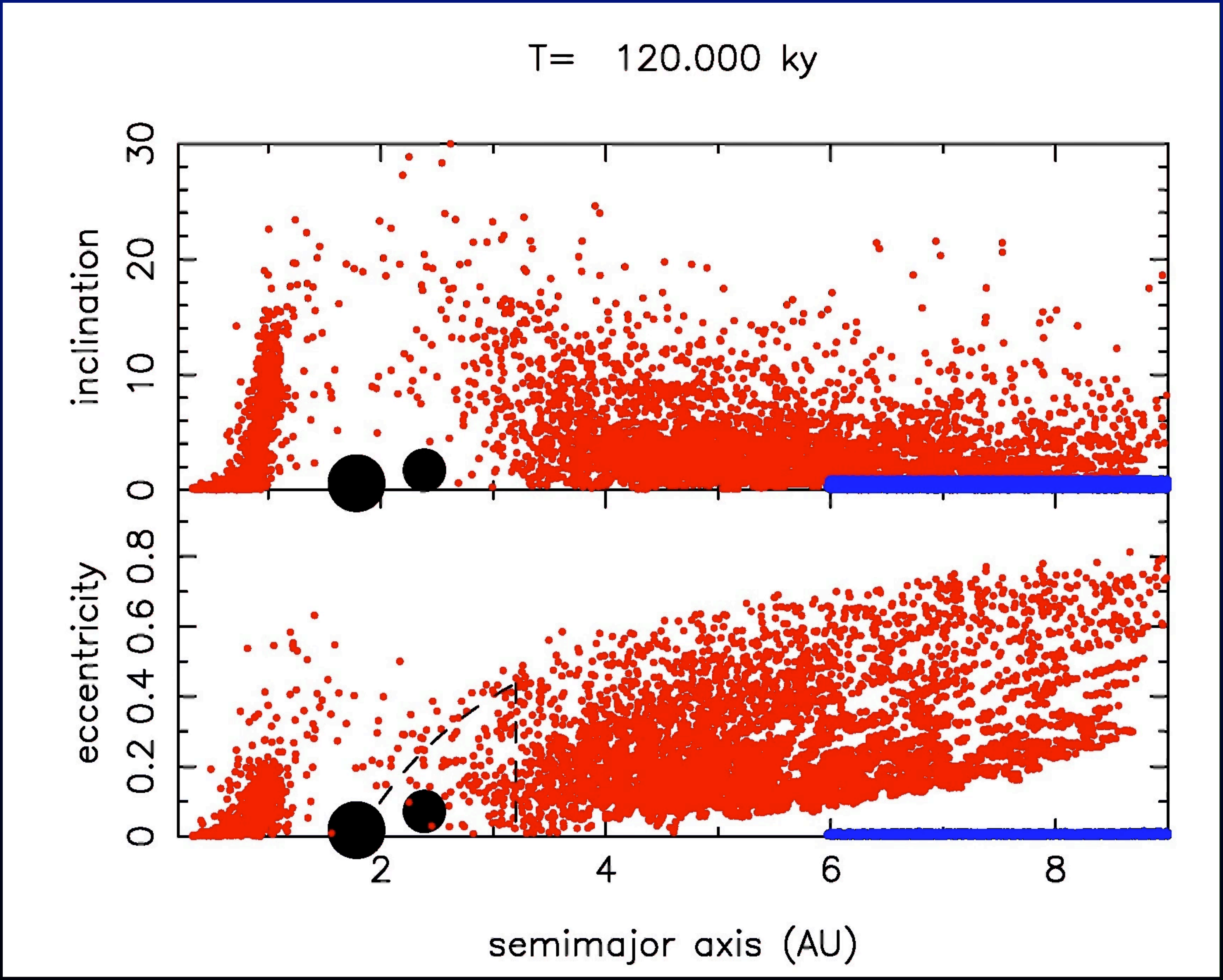

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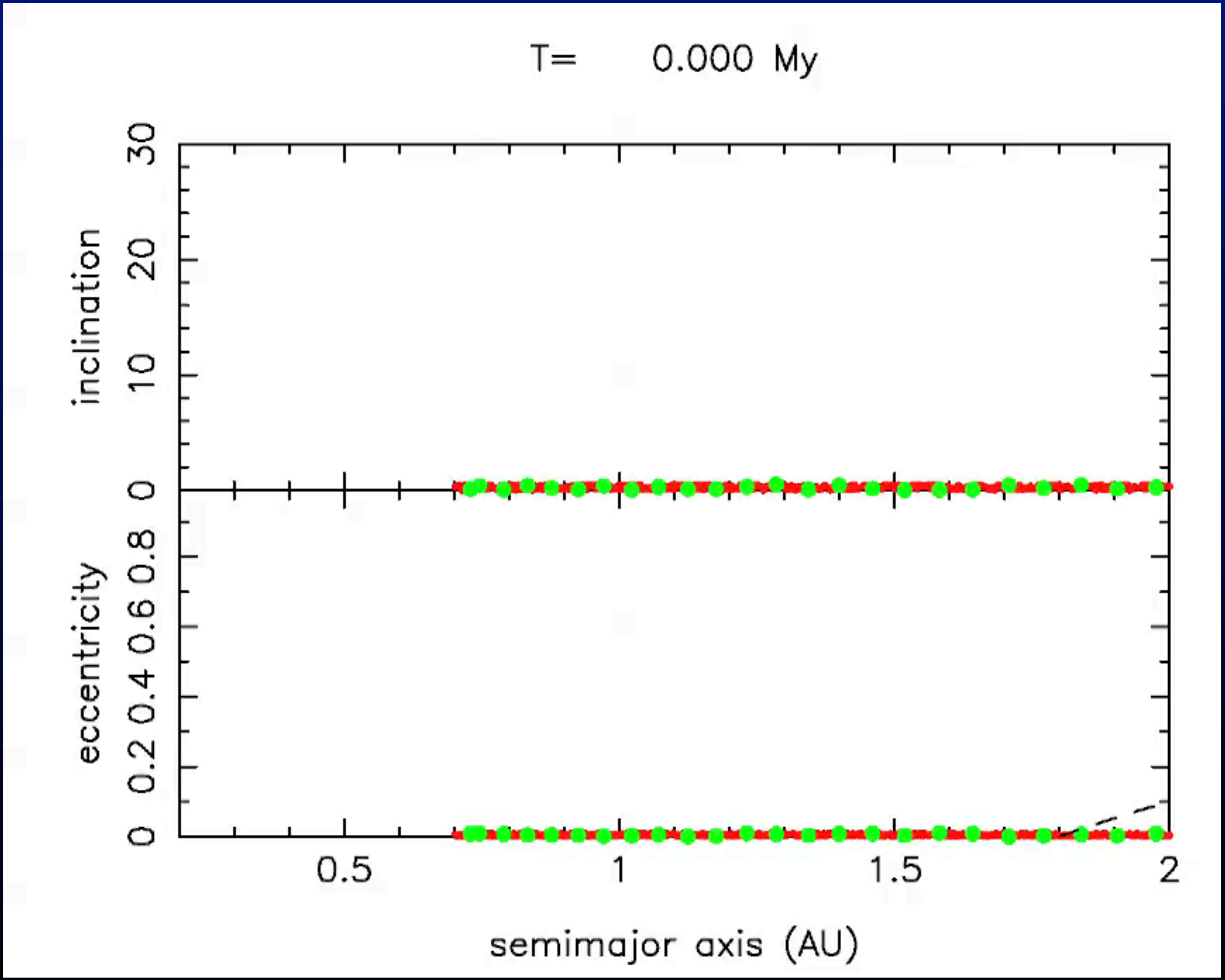

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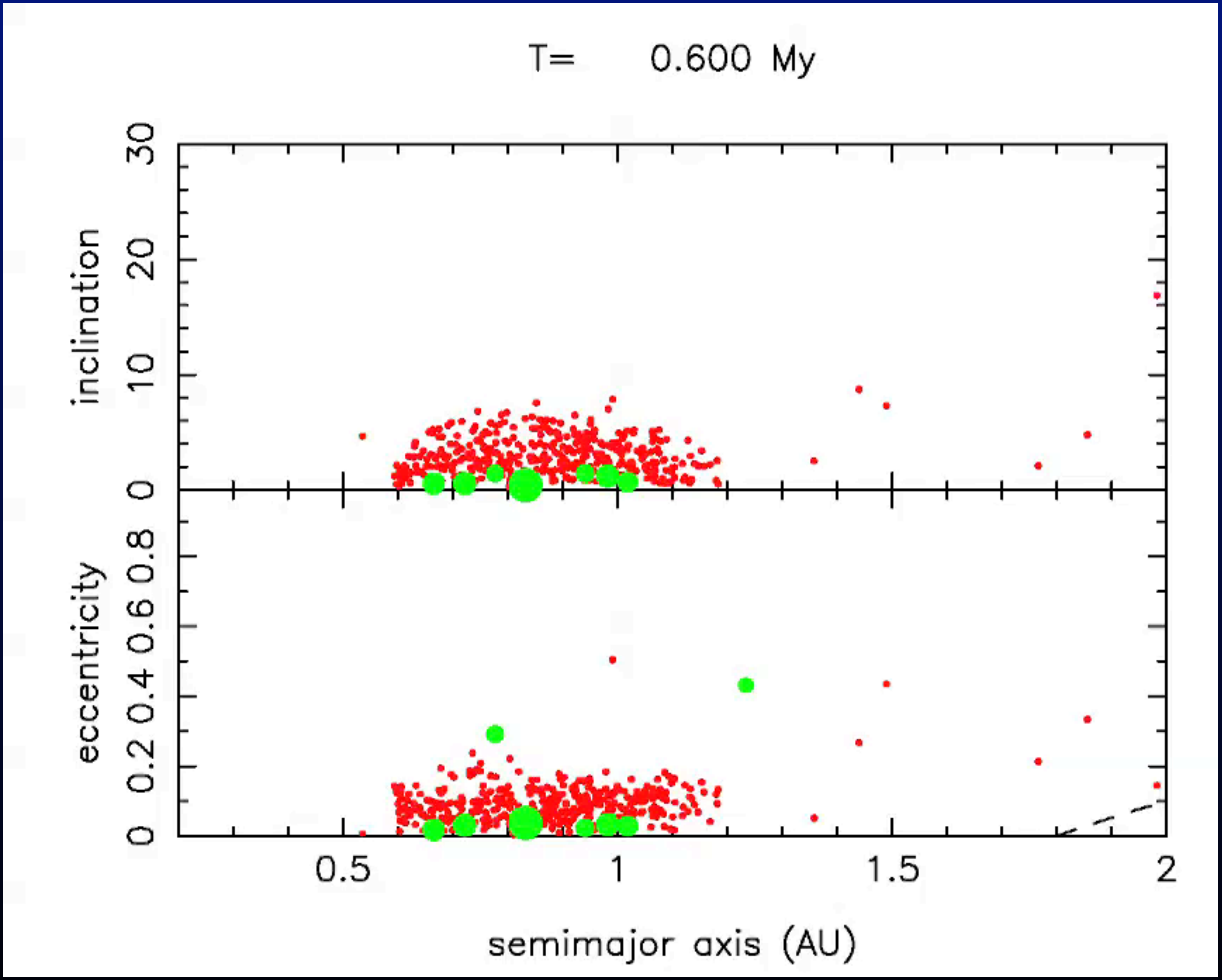

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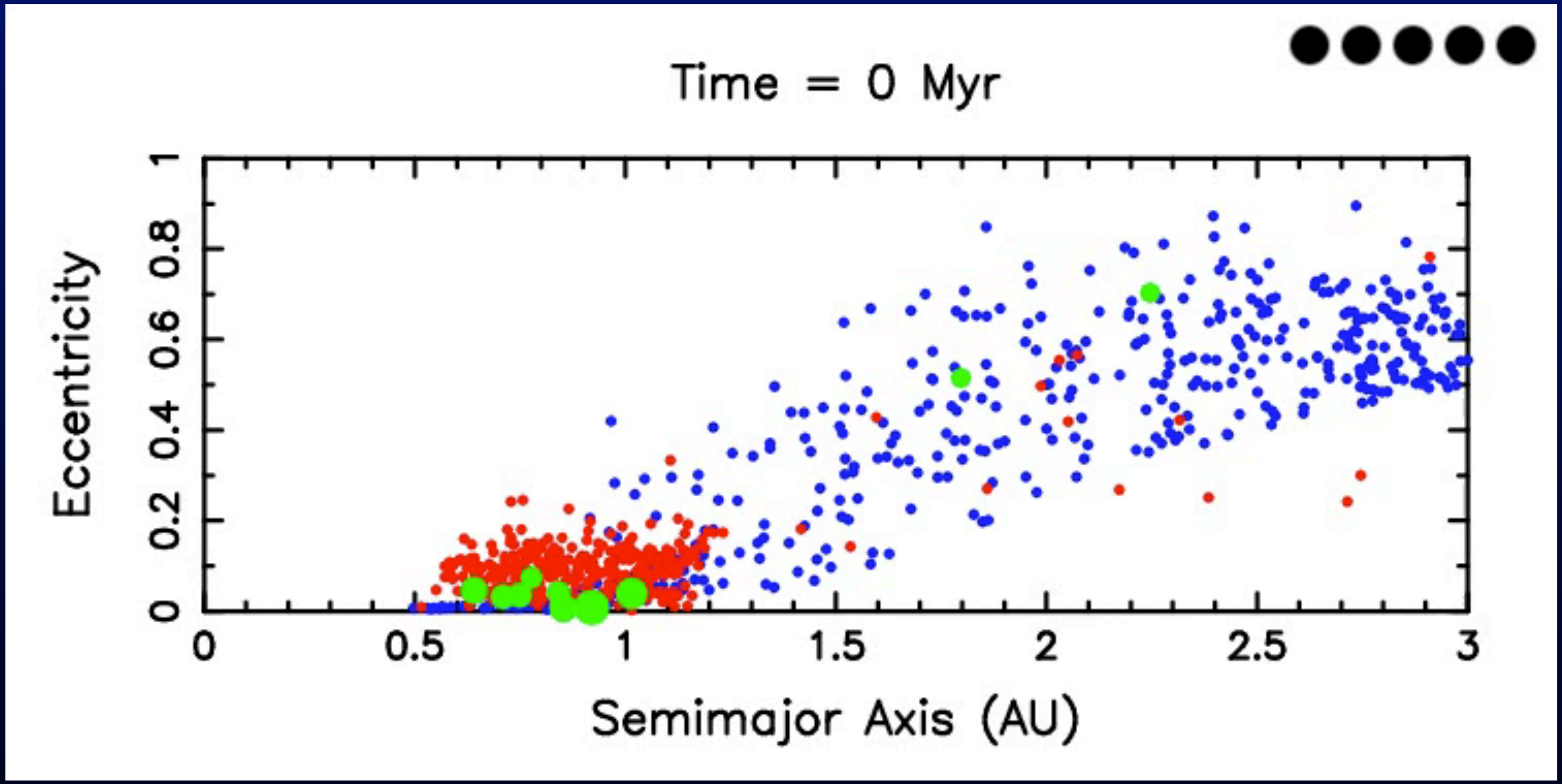

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