# Covered Ideas

- Solar system observations
  - diversity in object types: giants, terrestrial, moons, KBOs, asteroids
- Exoplanet observations
  - Observational techniques, various observational biases
- Orbital dynamics
  - Basic equations, resonances, stability, evolution in mass losing star, etc.

# Covered Ideas (Continued)

**Stars Forms**
star
+
protoplanetary disk

→

**Planets form in the disk**
variety in length scales and types of planets

↓

**Subsequent evolution of planetary orbits**

**planet-planet/ planetesimal interaction**
no disk, stochastic evoltuion

**planet-disk interaction**
migration

→

**Observed systems**

# Covered Ideas (Continued)

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→ **Observed systems**

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# Covered Ideas (Continued)

- Planet formation
  - Protoplanetary disks
    - Passive
    - Steady state acretion
  - Core accretion scenario
  - GI model

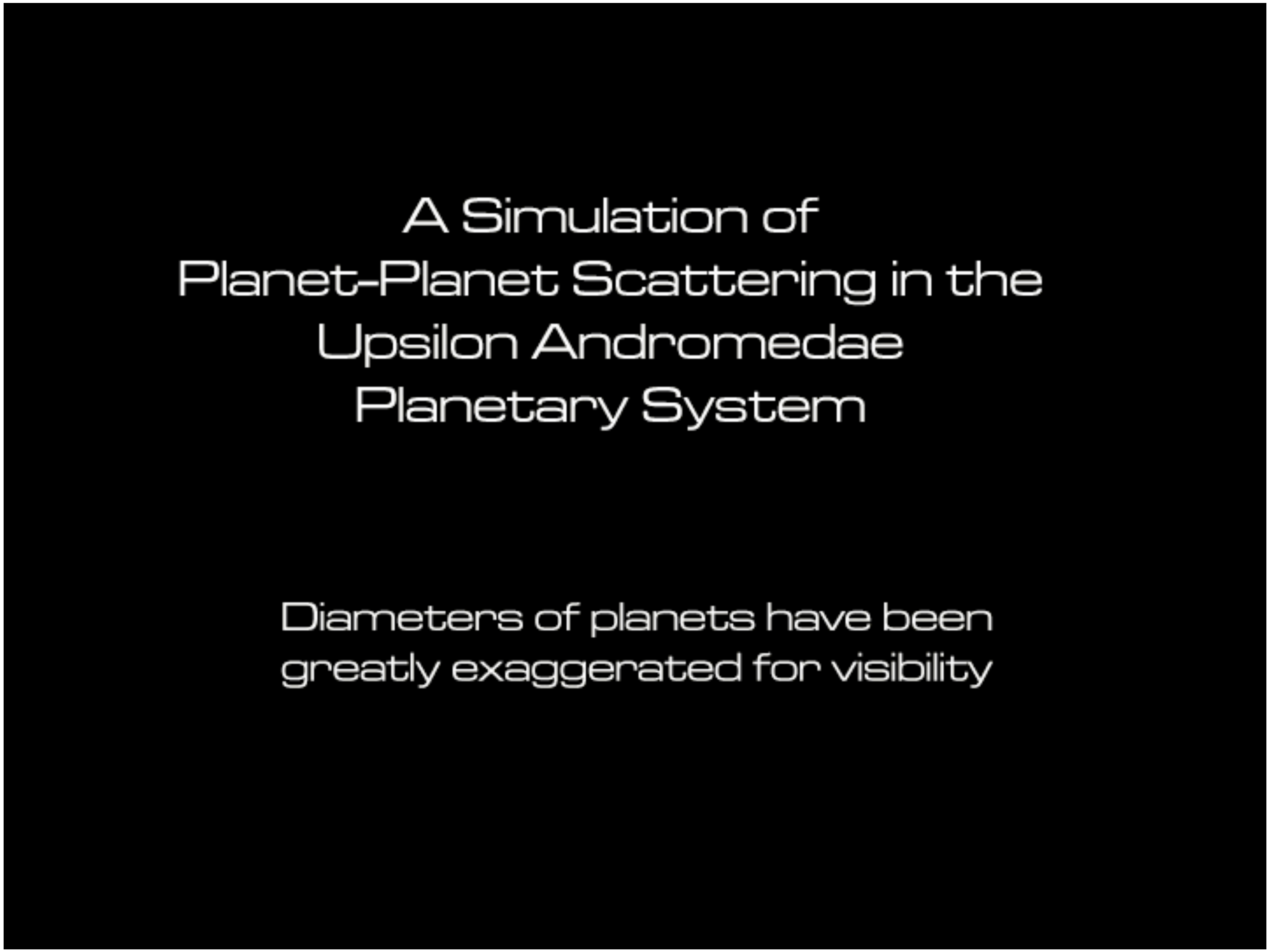
# Covered Ideas (Continued)

- Planet formation
  - Core accretion scenario
    - Dust (μm) -> rocks (cm - m)
      - collisional growth, problem of the radial drift speed
    - Rocks (cm-m) -> planetesimals (1-10 km)
      - Goldreich-Ward mechanism
        - Gravitational instability- Toomre criteria
        - Streaming instability
        - Turbulance
    - Planetesimals -> rocky planets/planetary cores
      - Collisional growth
        - strength-dominated vs gravity-dominated
        - isolation mass, coagulation equation (mass-spectra)
    - Gas giant formation
      - Accretion of atmosphere

# Covered Ideas (Continued)

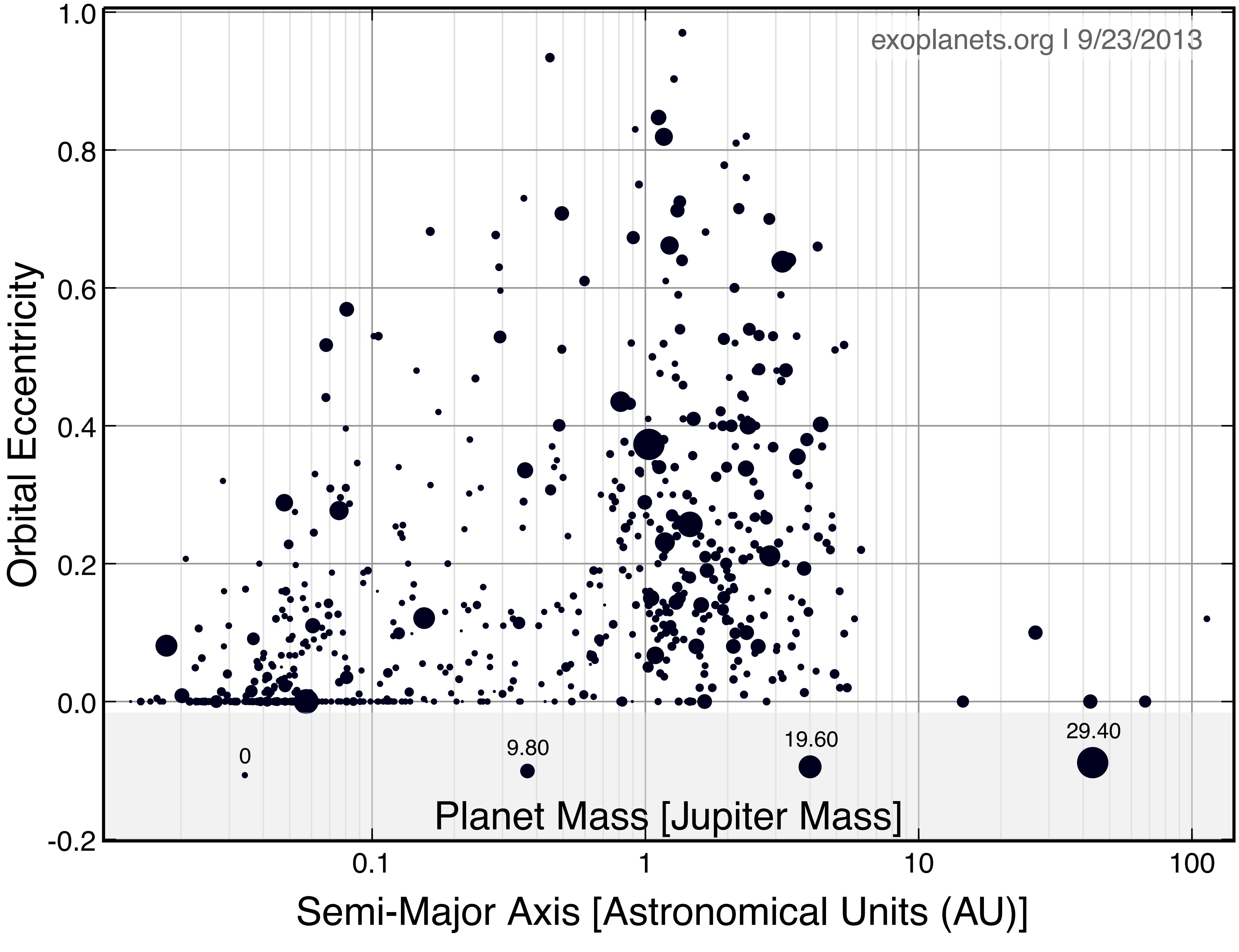
- After planet formation
  - Migration
    - Type I
      - Impulse approximation picture based on Lin & Papaloizou (1979)
      - Gravity torques, dependence on $\Sigma$-profile, T-profile, magnetic field
      - Lindblad and coorbital resonances
    - Type II
      - Tidal torques after gap opening
      - Slower than Type I
    - Type III
      - Runaway coorbital migration due to asymmetries in coorbital region

# Planet-Planet Scattering



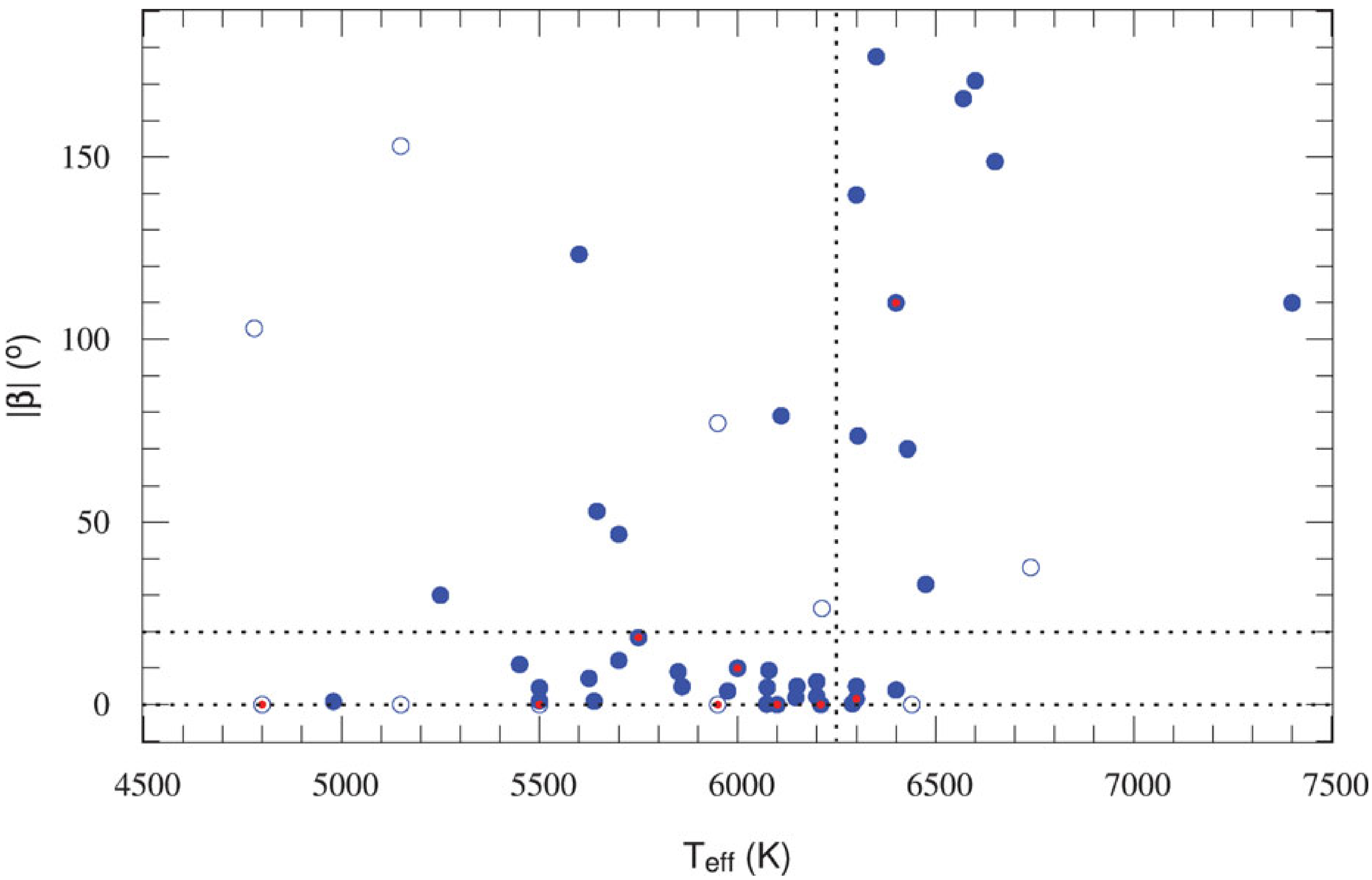
# Planet-Planet Scattering

Eccentric Giants



# Planet-Planet Scattering

## High Inclination




Triaud et al. 2011

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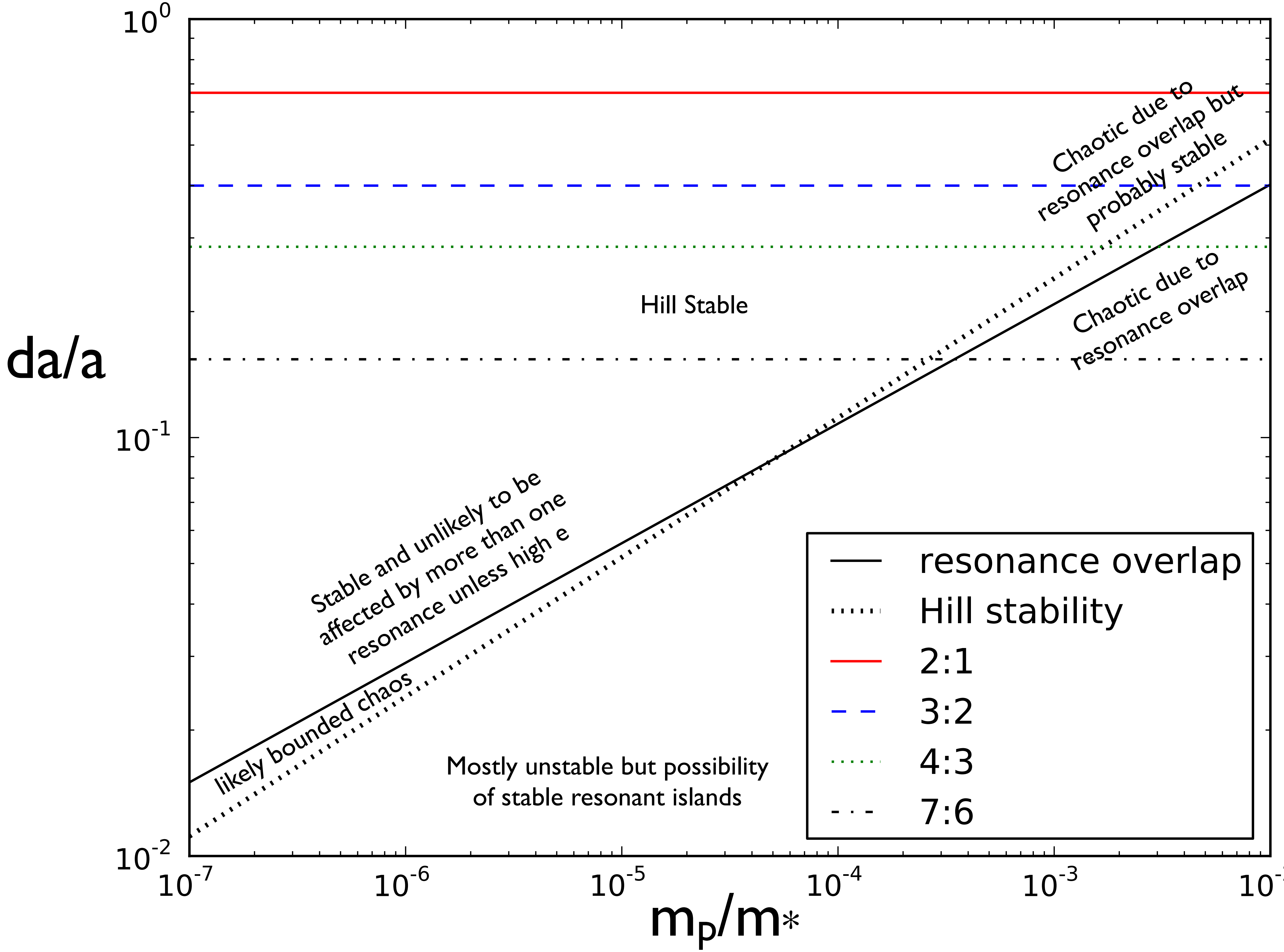

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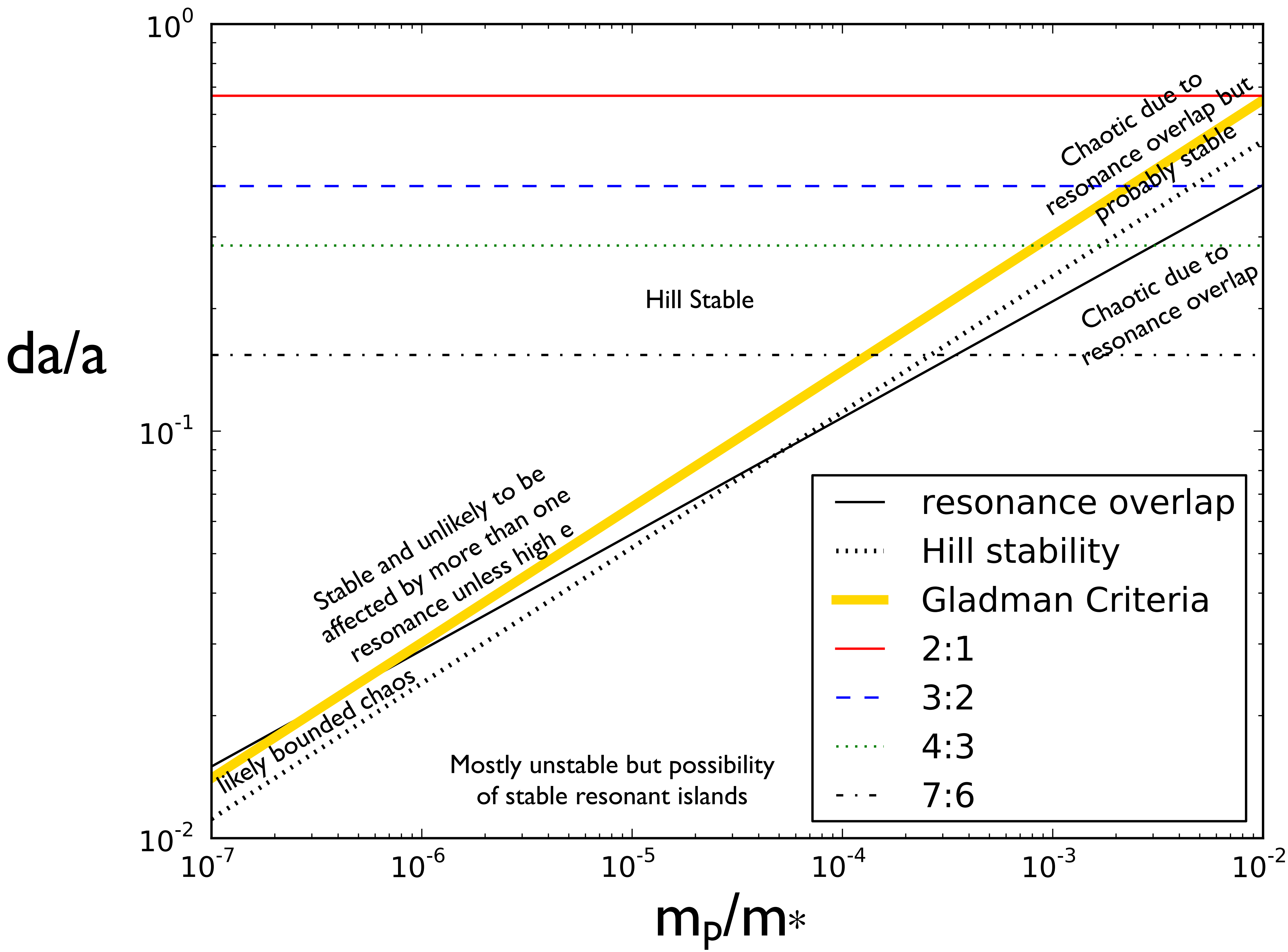
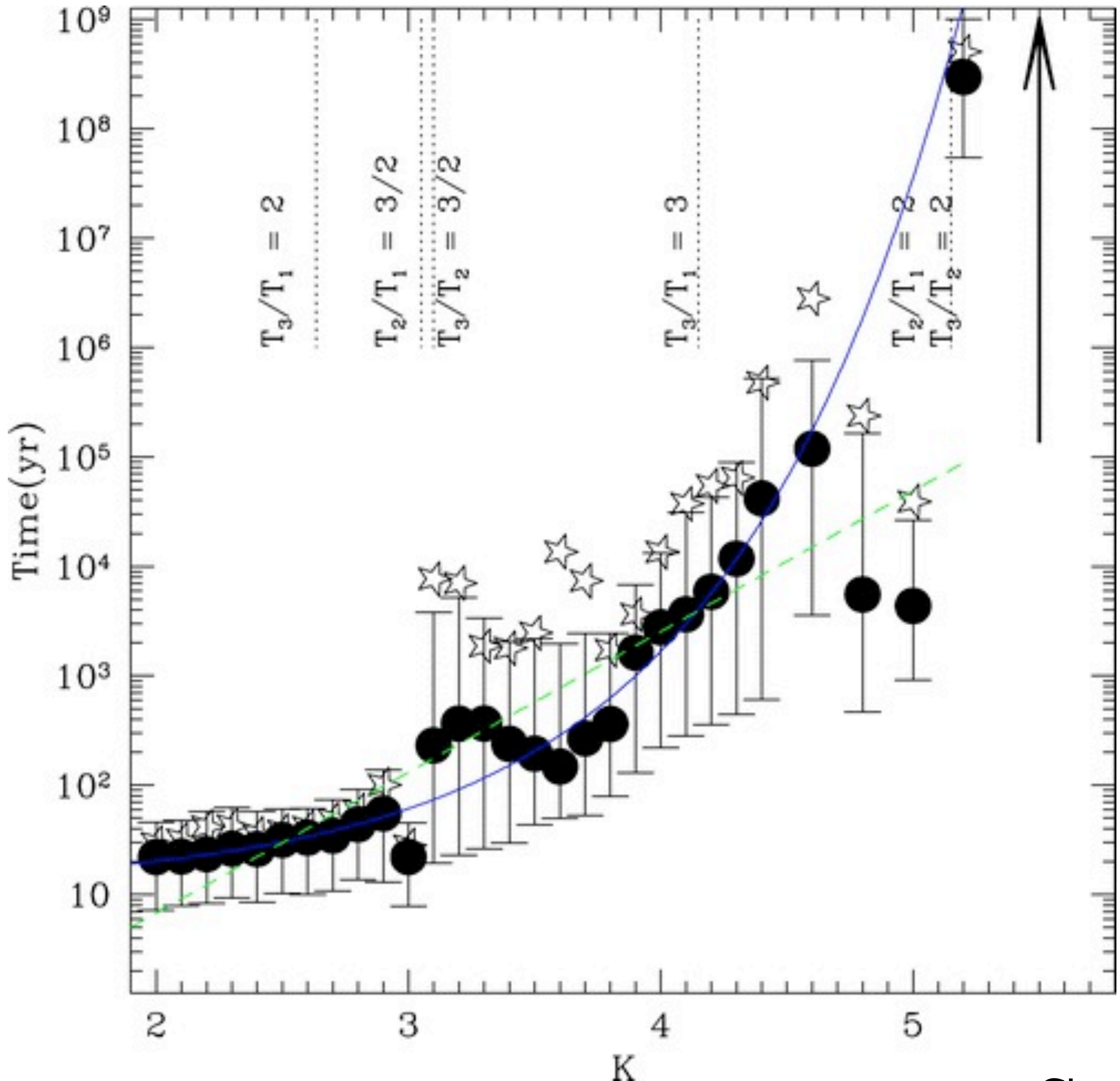


# Planet-Planet Scattering

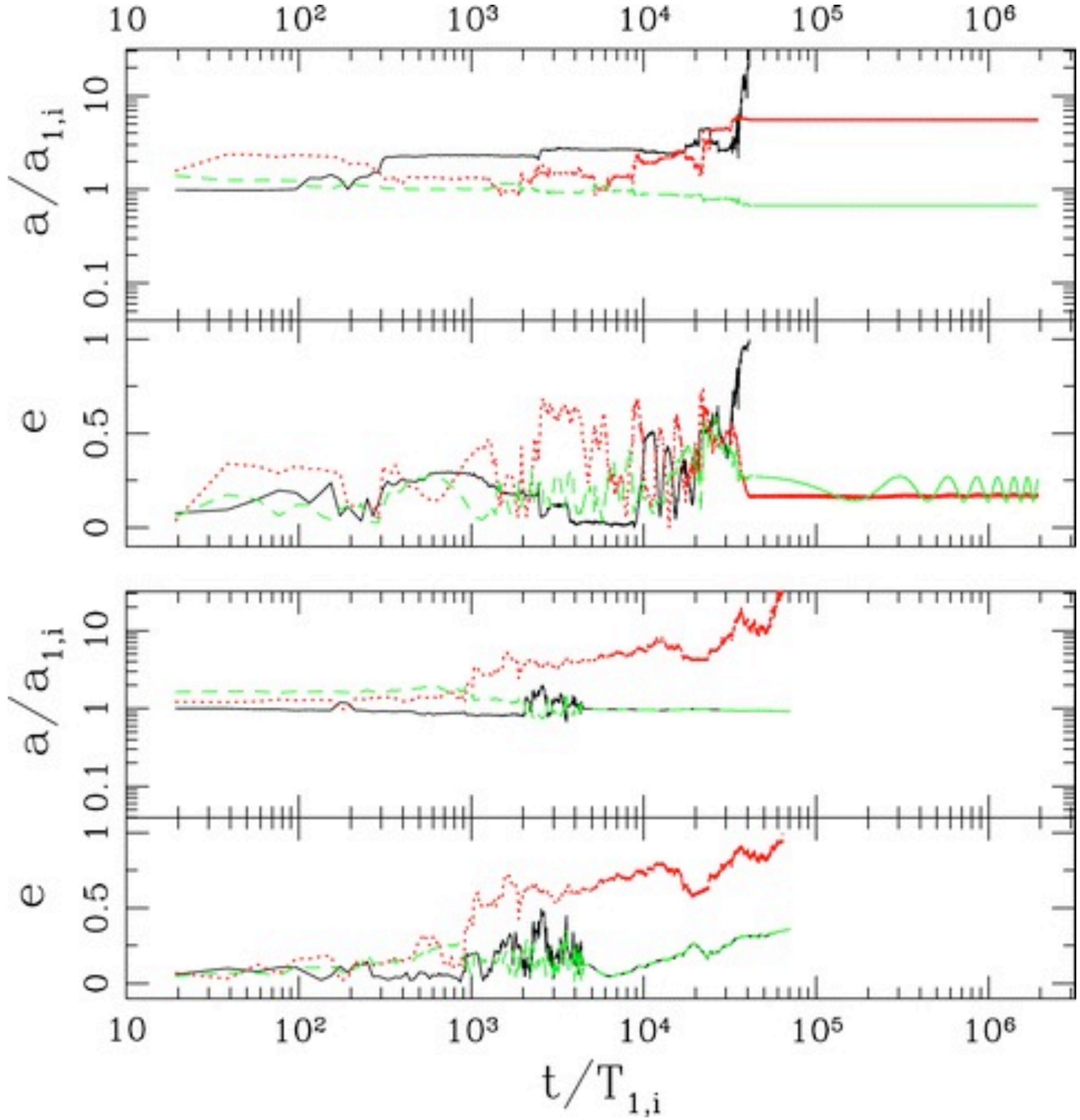
Instability Timescale




Chatterjee et al. 2008

# Planet-Planet Scattering

Evolution




Chatterjee et al. 2008

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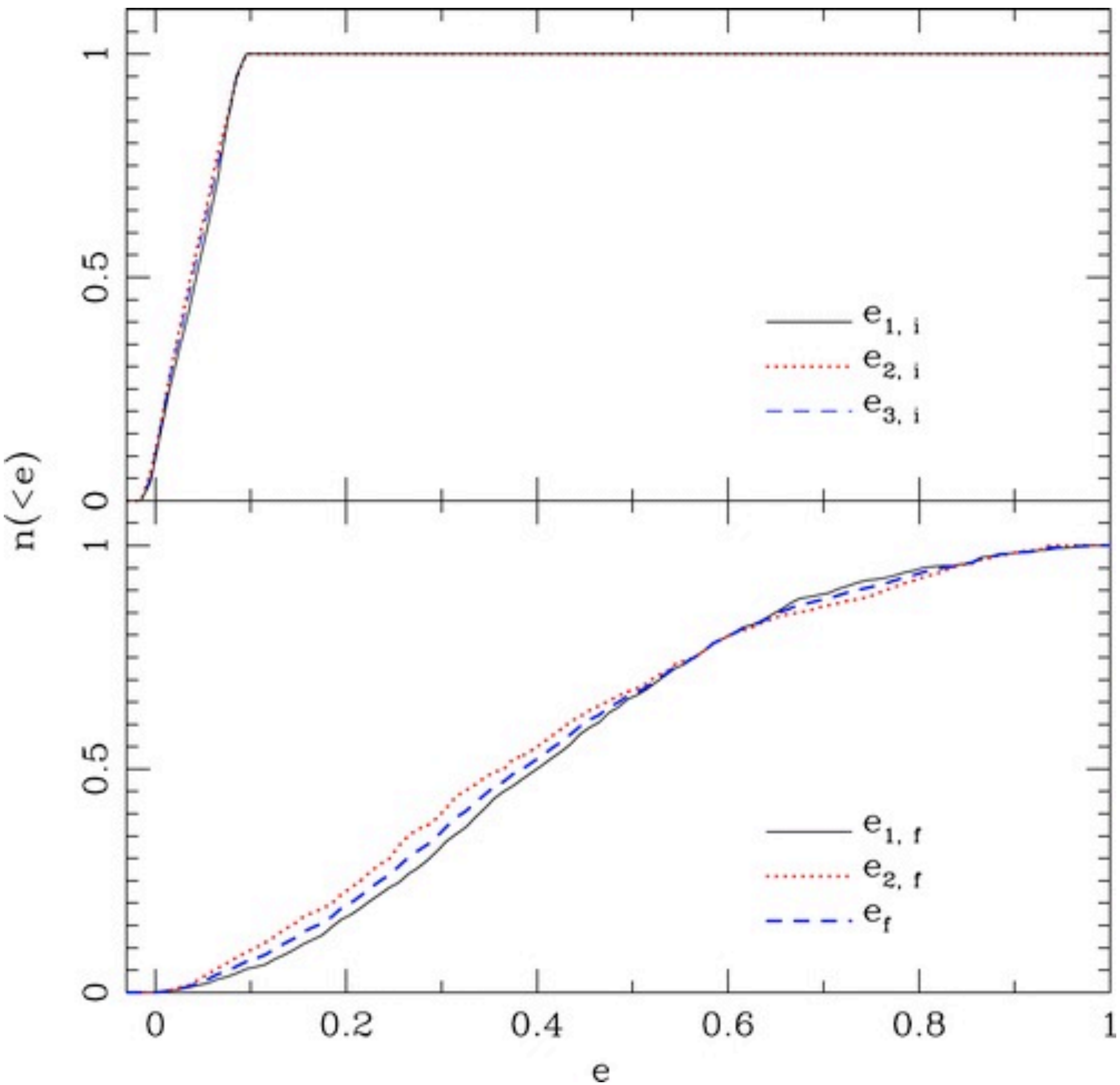
Eccentricity

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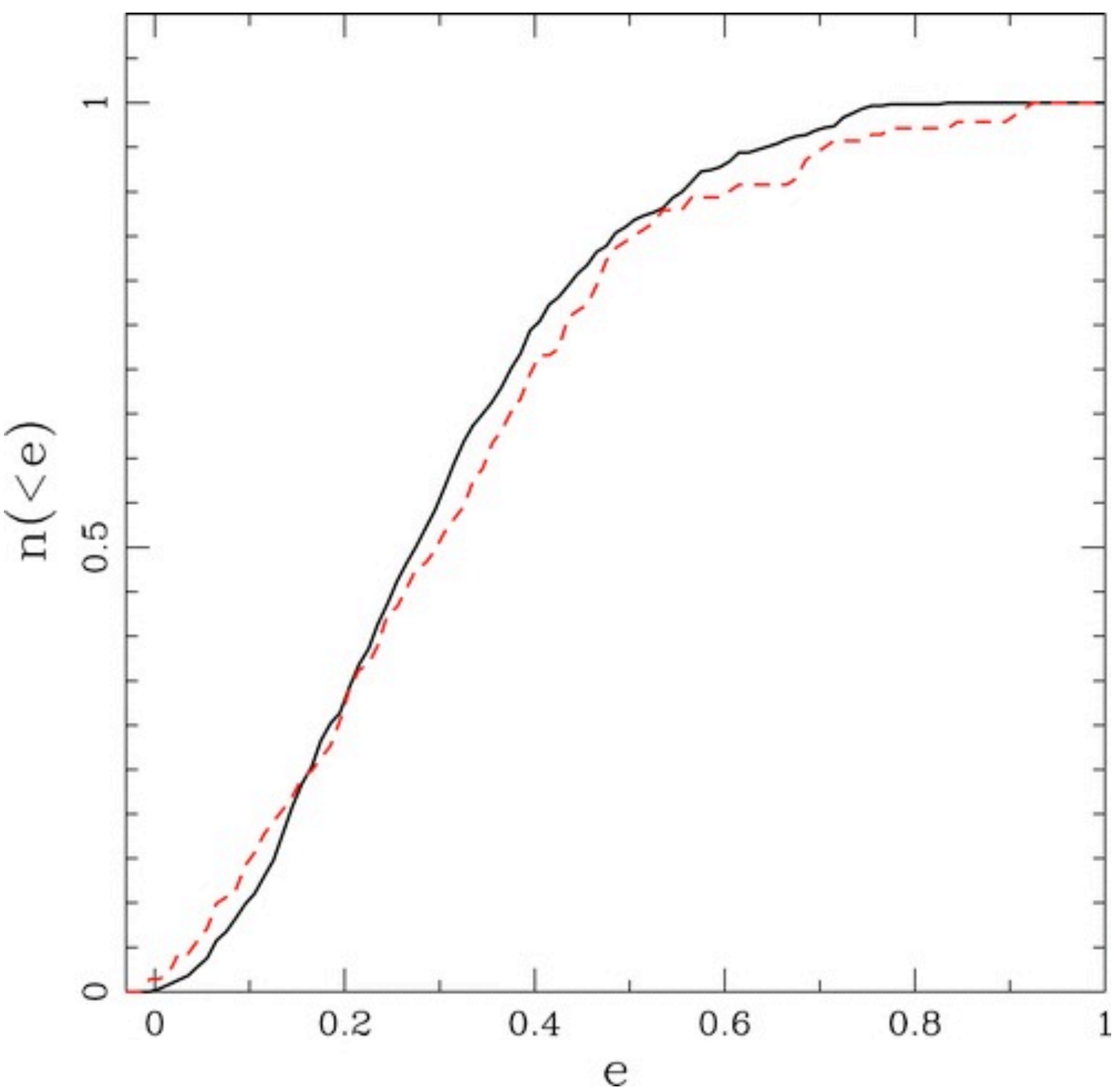


Chatterjee et al. 2008

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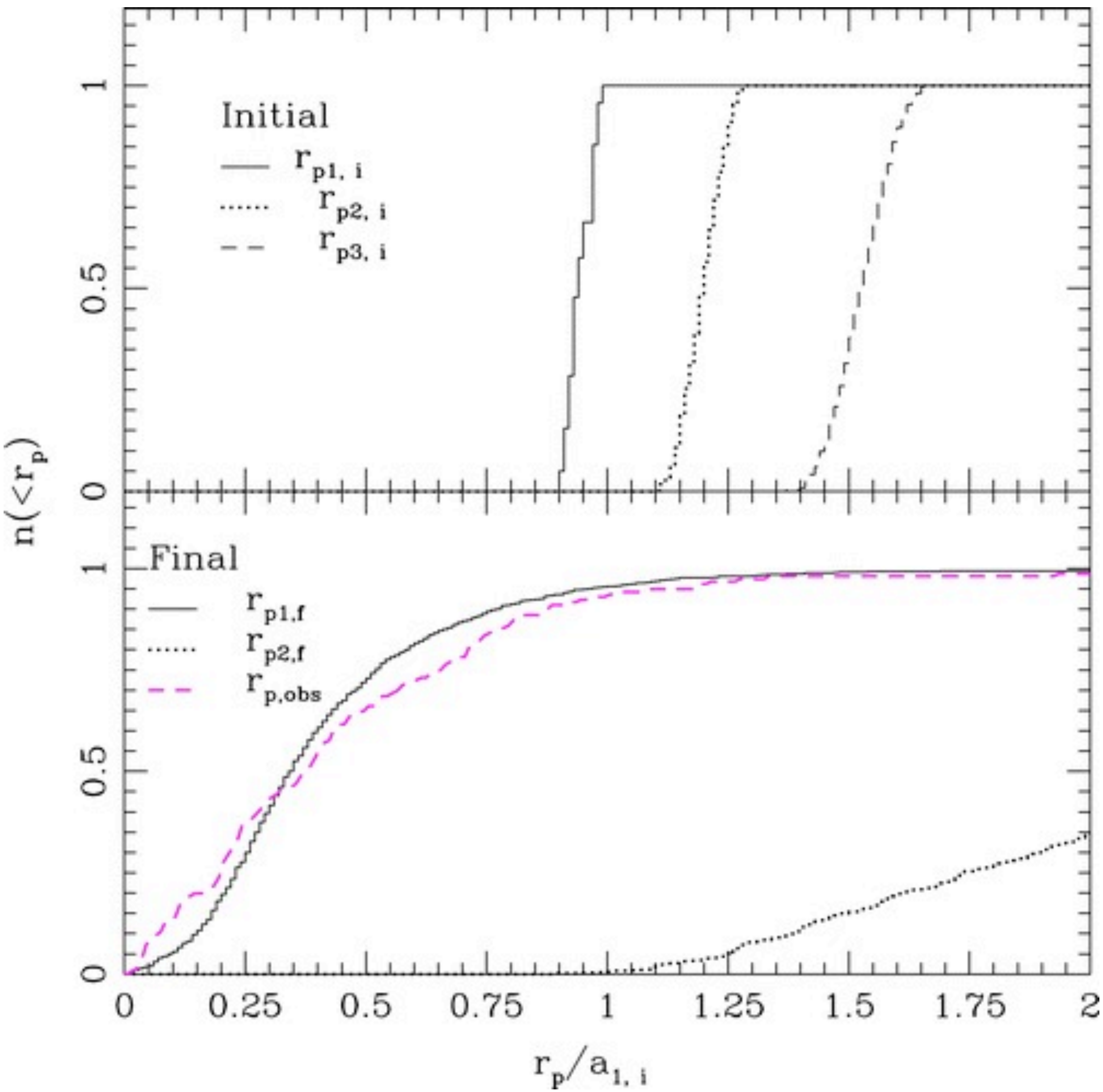
Pericenter Distance




Chatterjee et al. 2008

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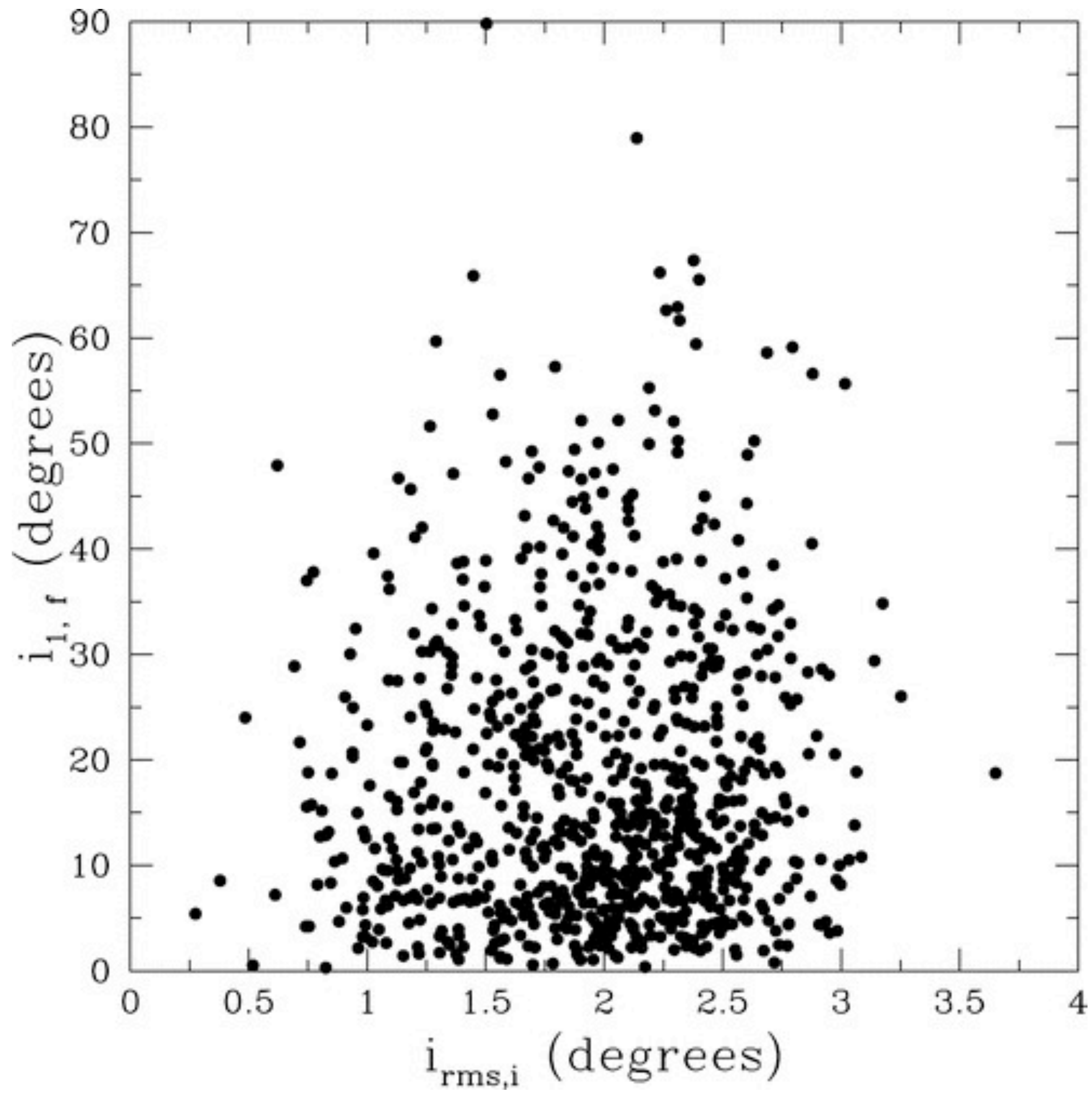
Inclinations

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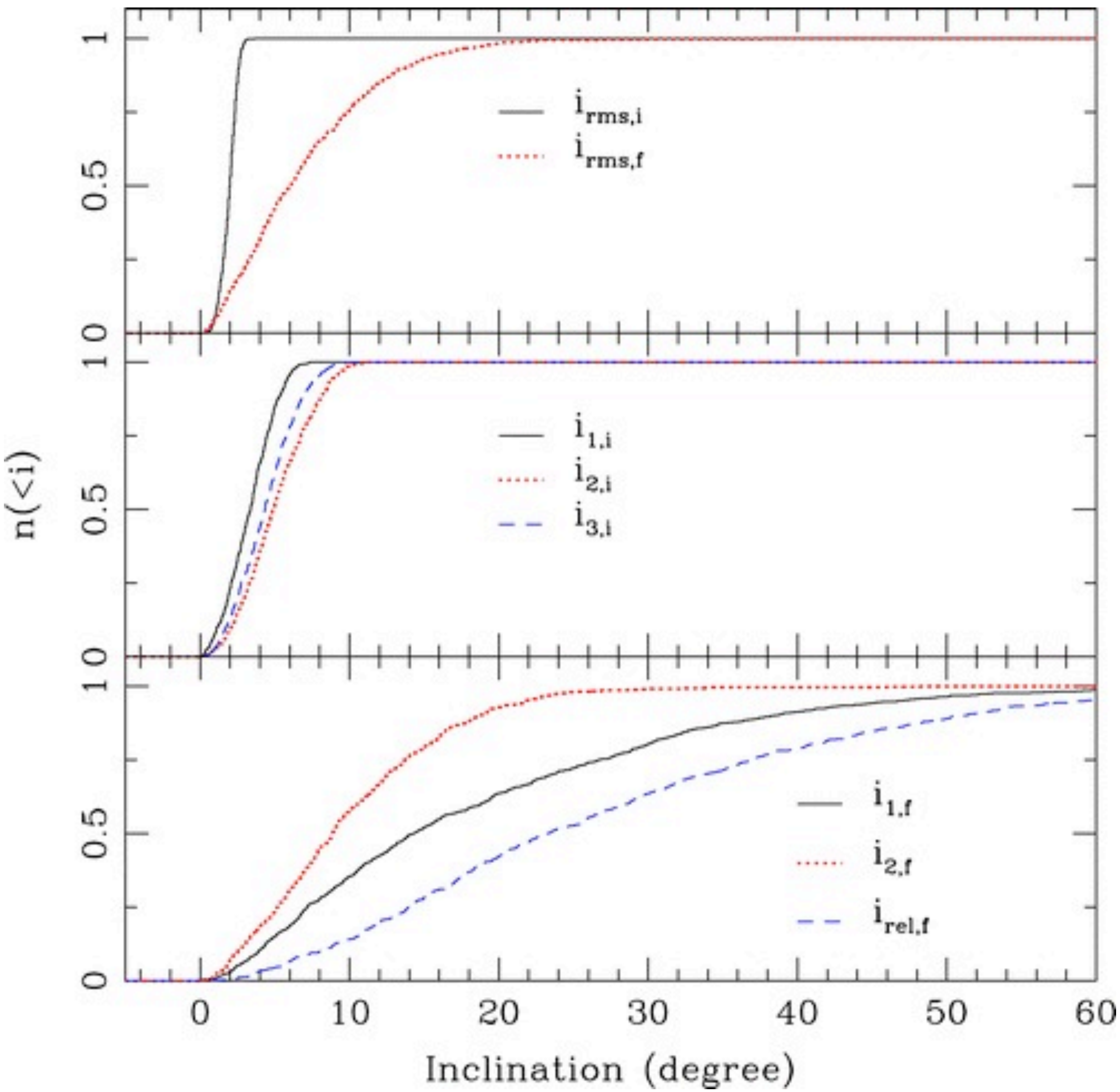


Chatterjee et al. 2008

# Planet-Planetesimal Scattering

# Planet-Planetesimal Scattering

## Analytical Expectations

- Planet scatters planetesimal
  - $da/a \sim dm/m_p$ (Can you show this assuming conservation of angular momentum?)
  - For order one change the total mass in planetesimals needs to be ~ planet mass
    - Much larger change is expected in the planetesimal disk and planetesimal orbits
    - Compared to planet-planet scattering changes are slow and less violent
    - Empirical evidence in the Solar system that this has occured at some point.

# Planet-Planetesimal Scattering

## Nice Model 2

- Giant planets were close to each other
- Overlapping gaps
- Trapped in some resonance (3:2) leads to excited eccentricity
- Late instability in the planetesimal disk due to this eccentricity
  - Late heavy bombardment
- Outward migration due to Jupiter-Saturn mass ratio

Morbidelli & Crida 2007

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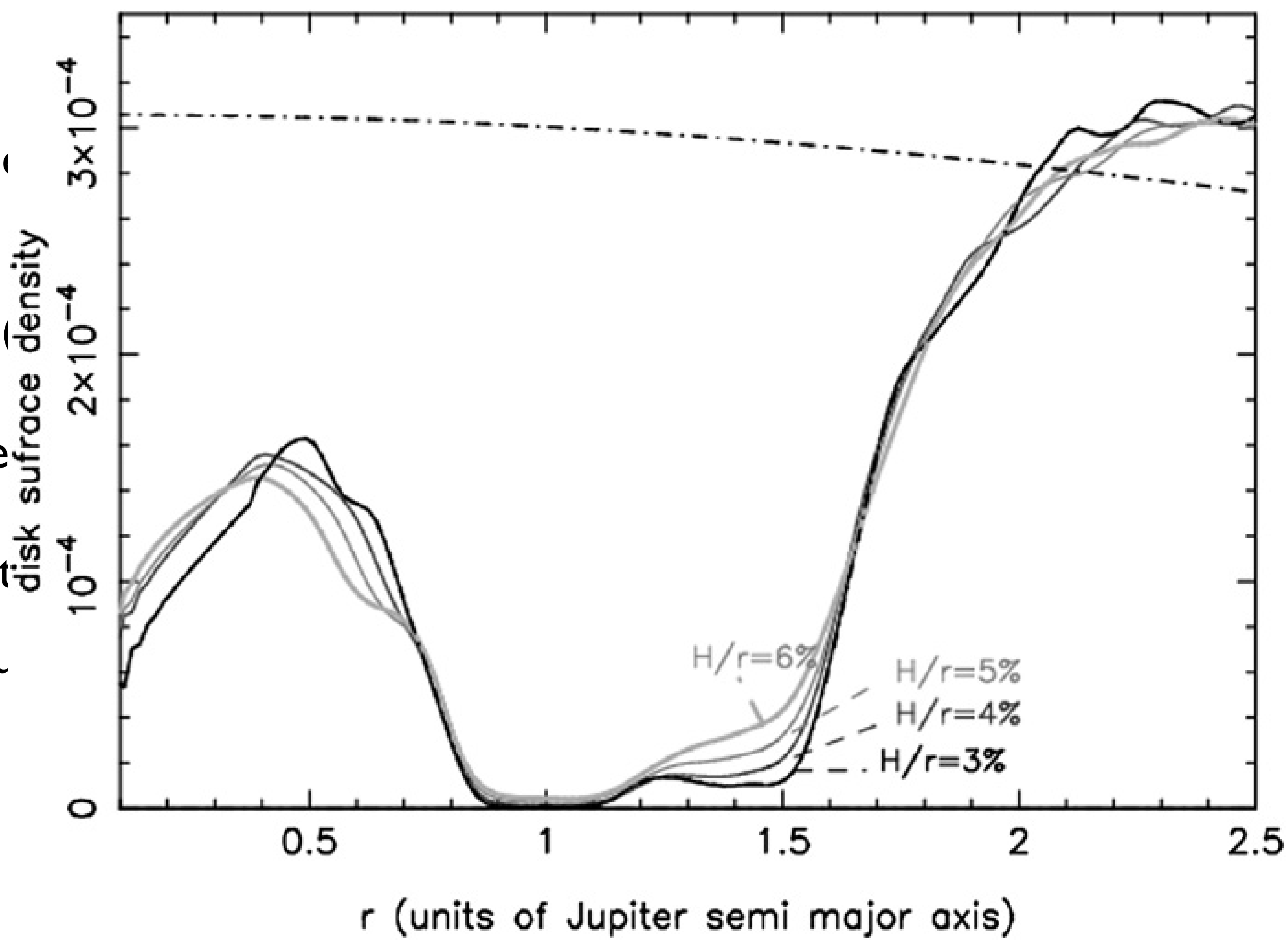


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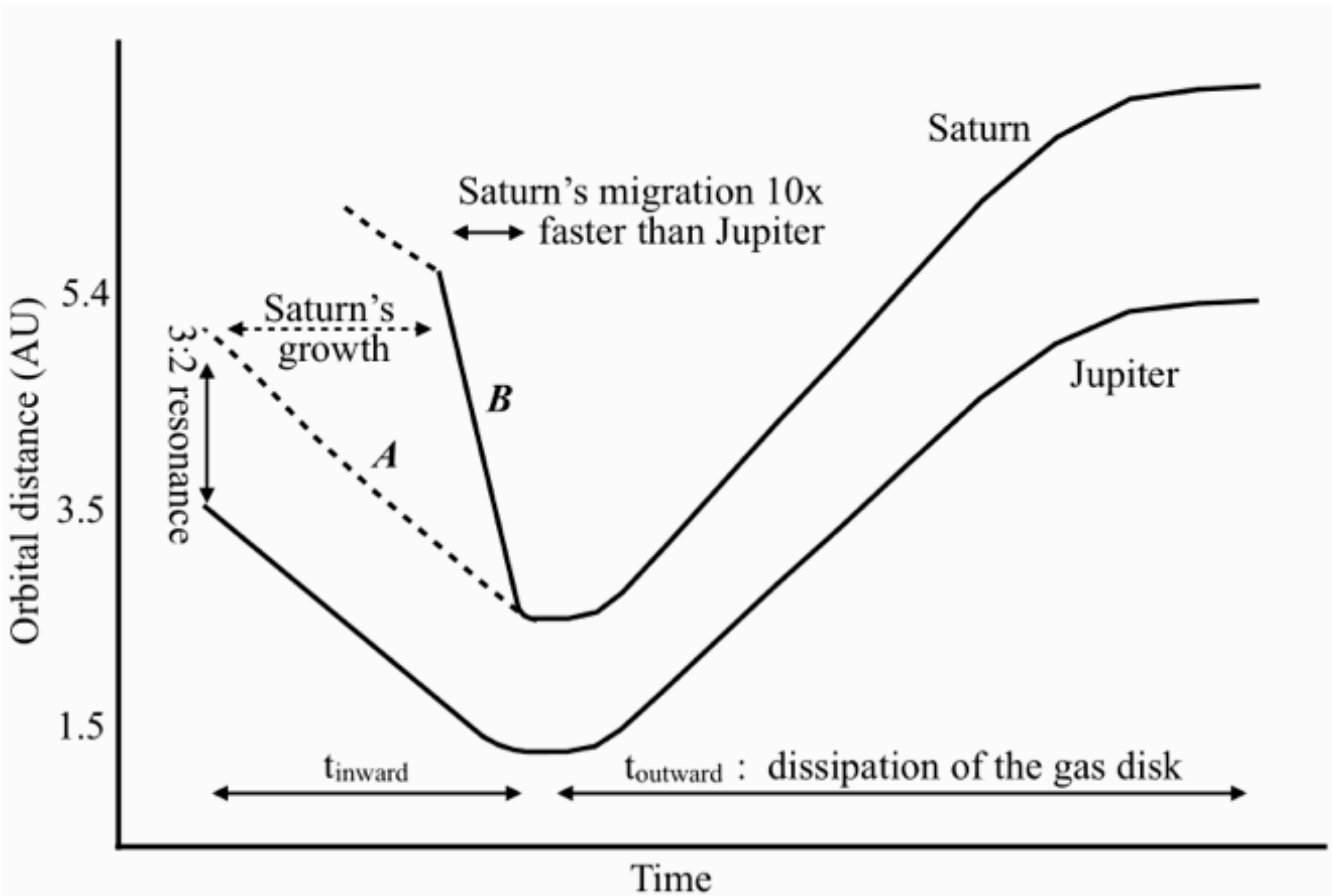
# Planet-Planetesimal Scattering

Grand Tack model (Walsh et al. 2011)



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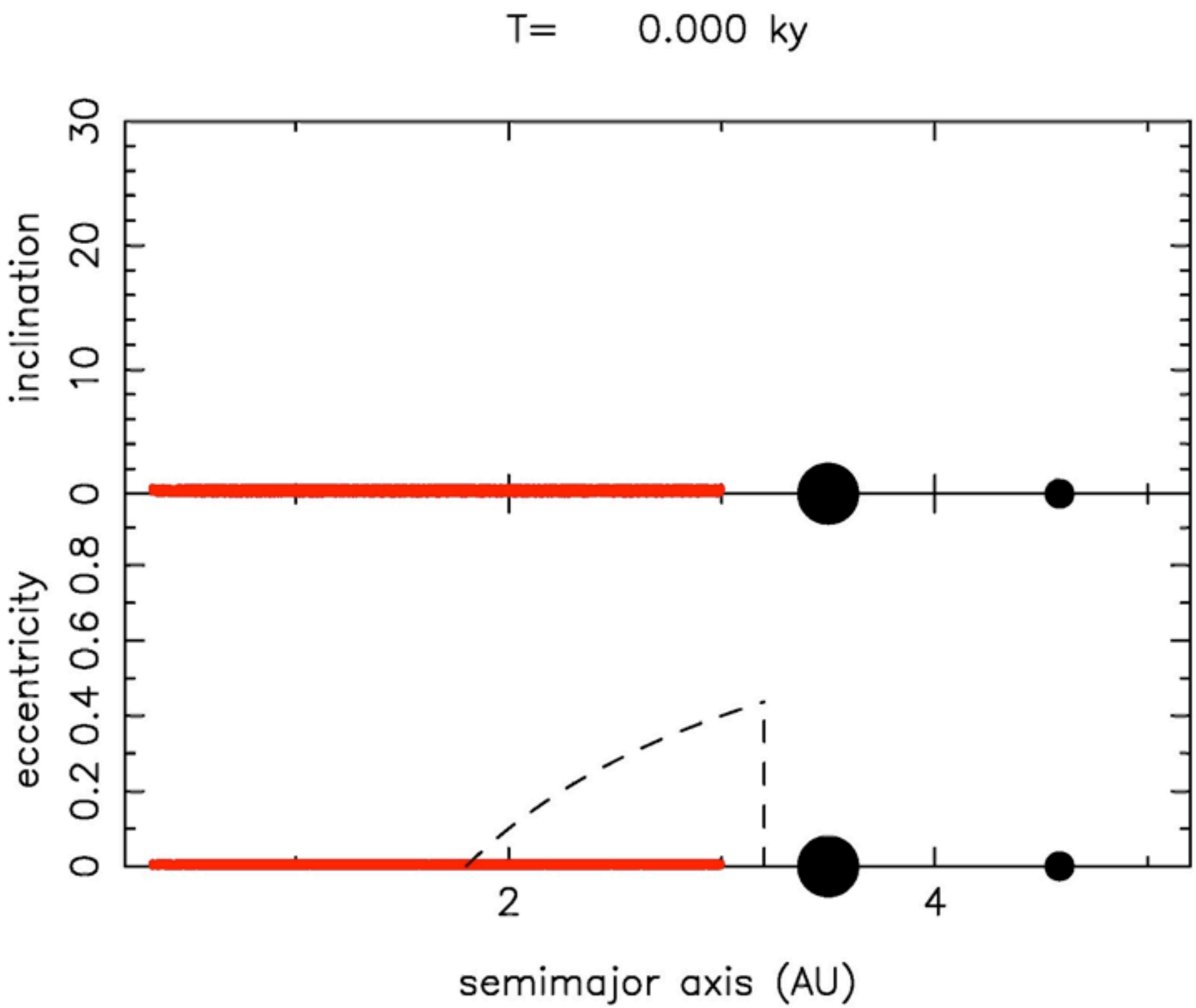

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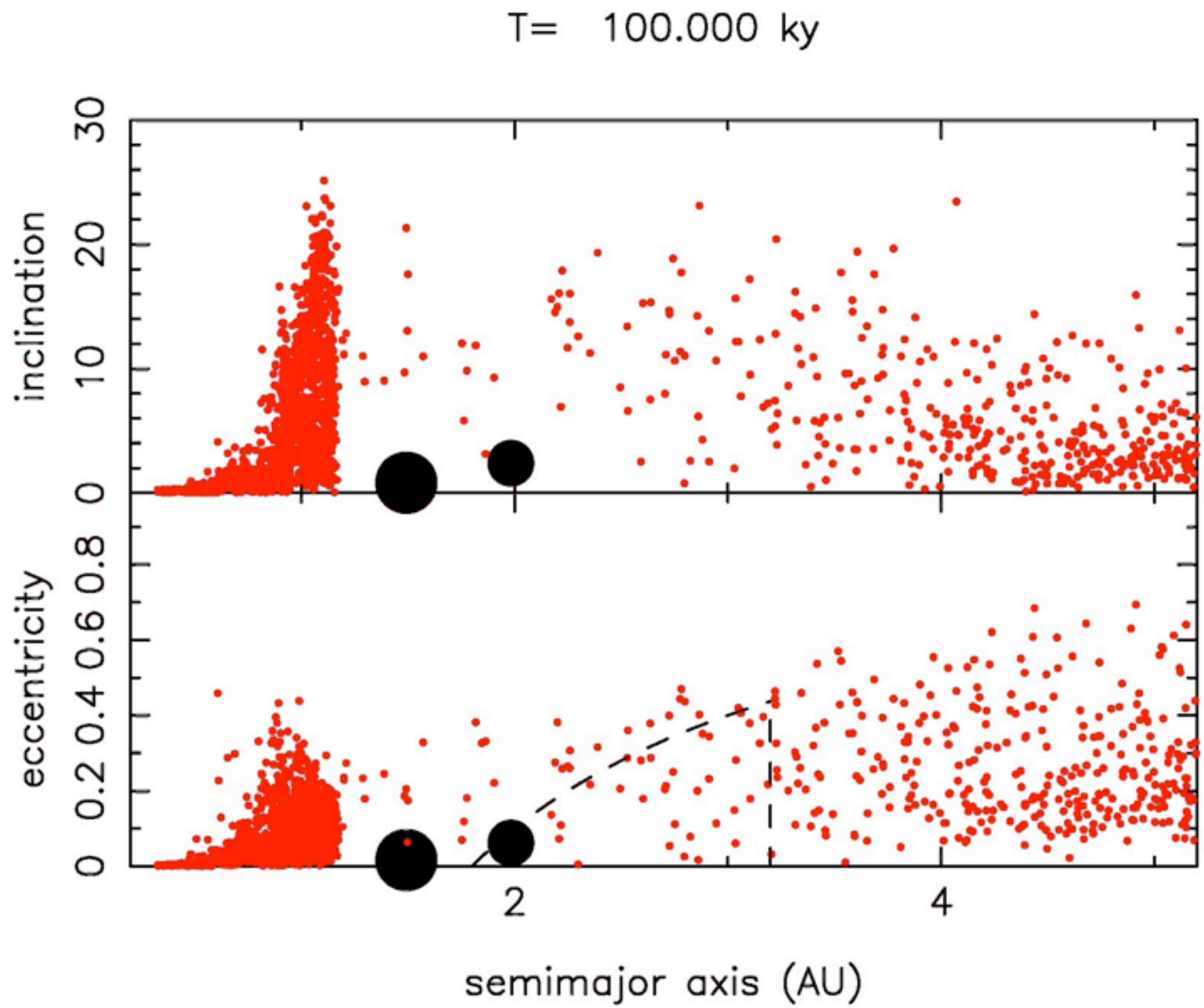

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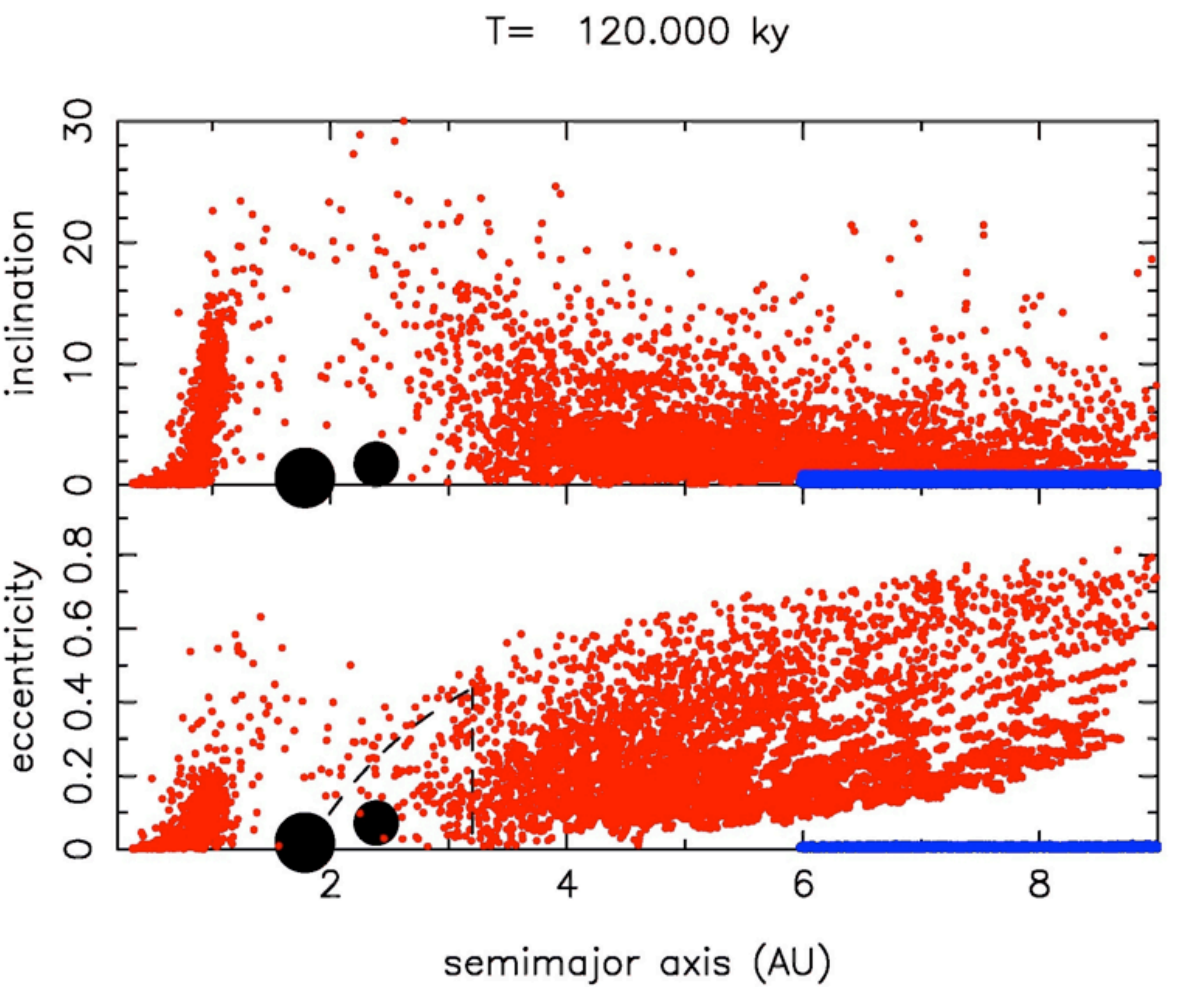

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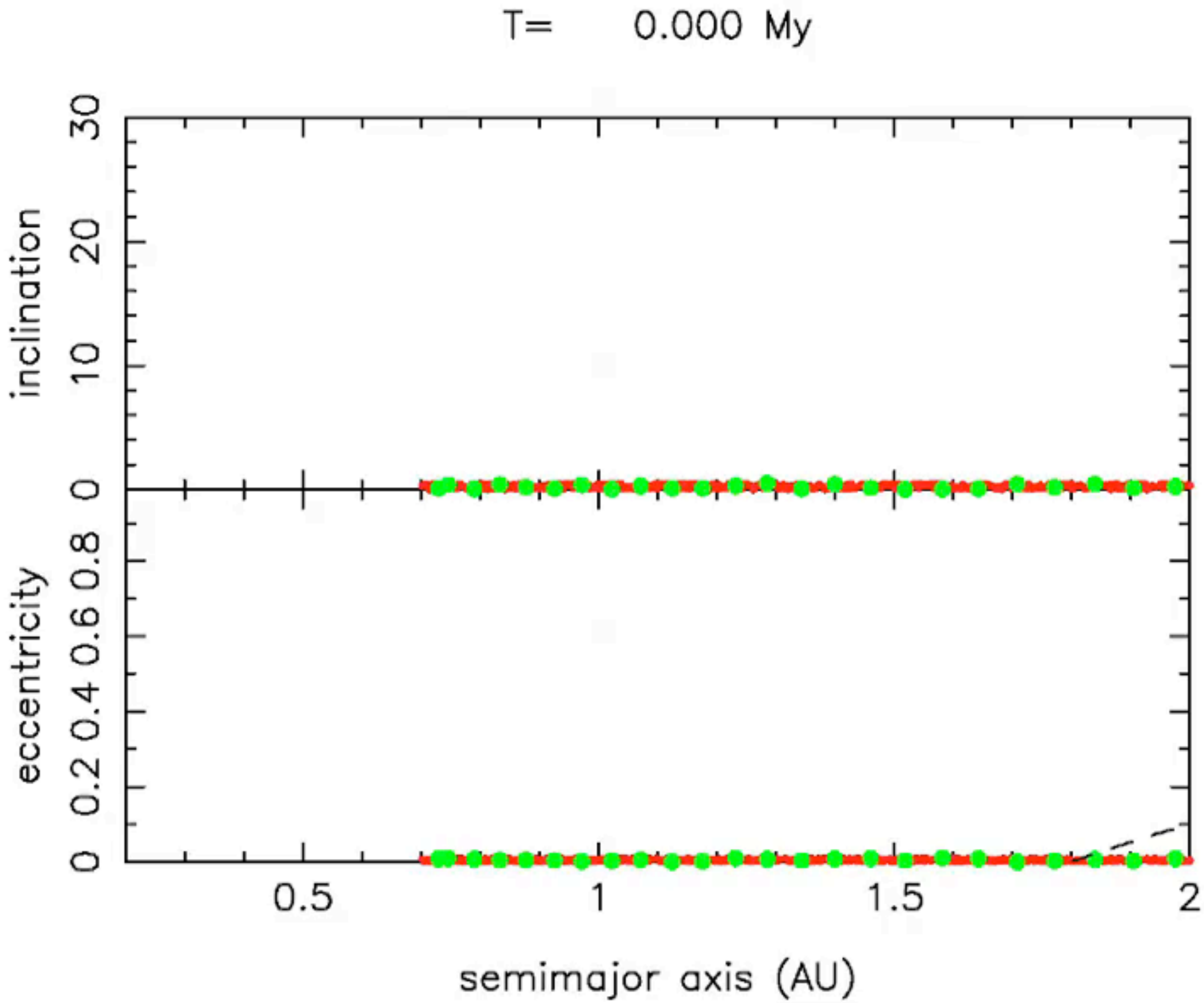

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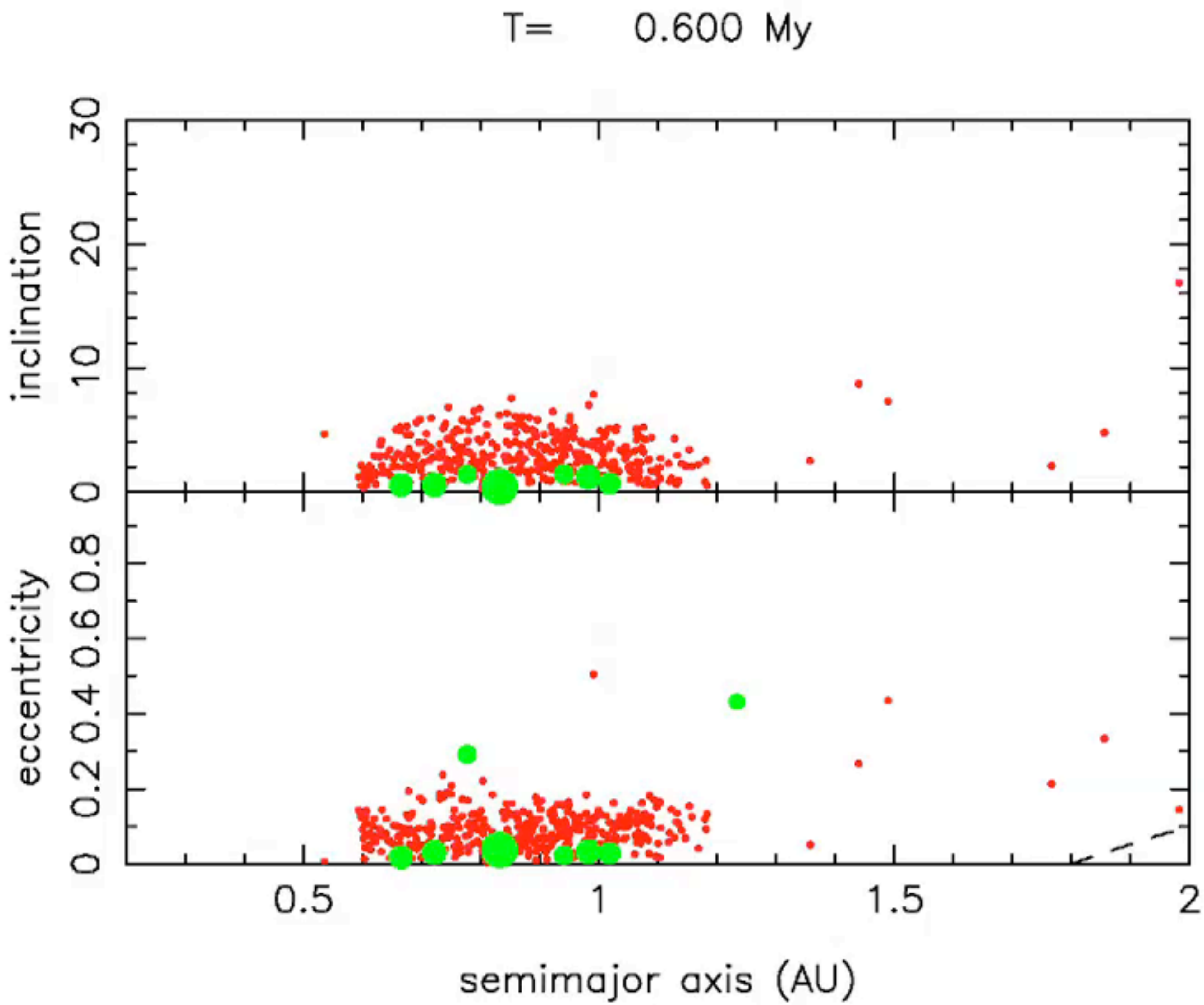

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