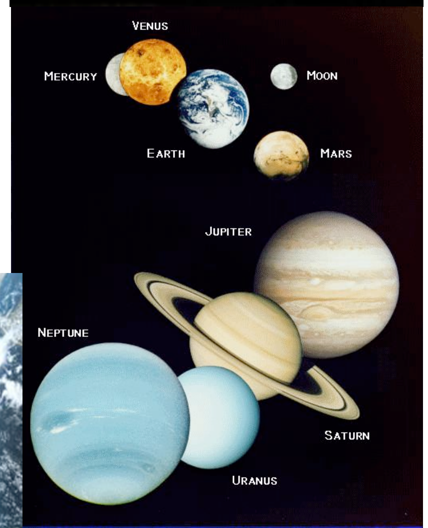
Definitions

- Stars: $M>0.07M_s$ — Burn H
  - cosmic composition (H+He)

- Brown dwarfs: $M<0.07M_s$ — No Burning
  - degenerate
  - cosmic composition (H+He)

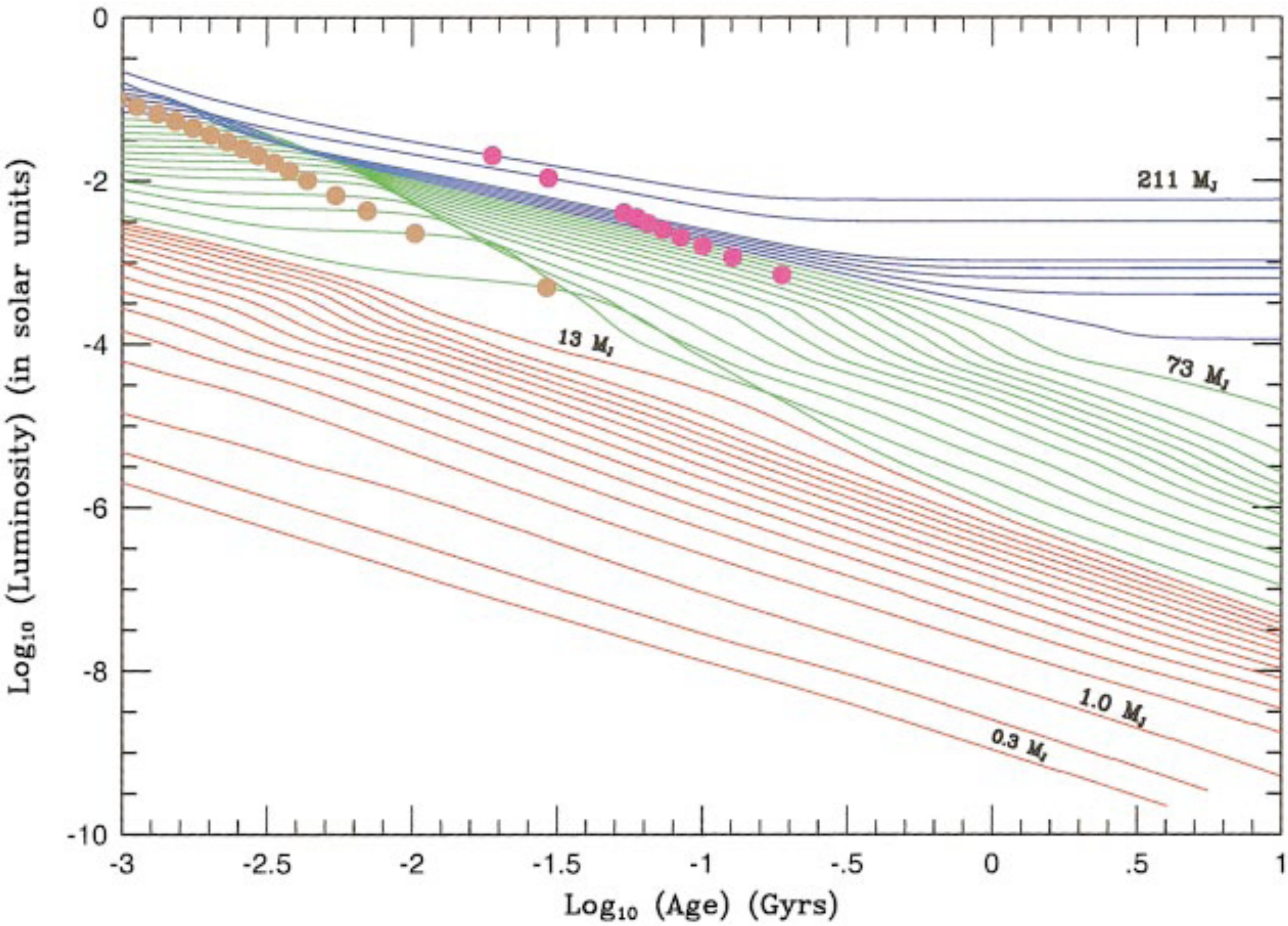
- Planets — No Burning
  - orbit stars
  - not cosmic composition (more metals)
  - form in gas/dust disks

- Dwarf planets
  - Pluto, Eris, Ceres



Definition ?

Burrows et al. 1997 ApJ 491 856



Questions

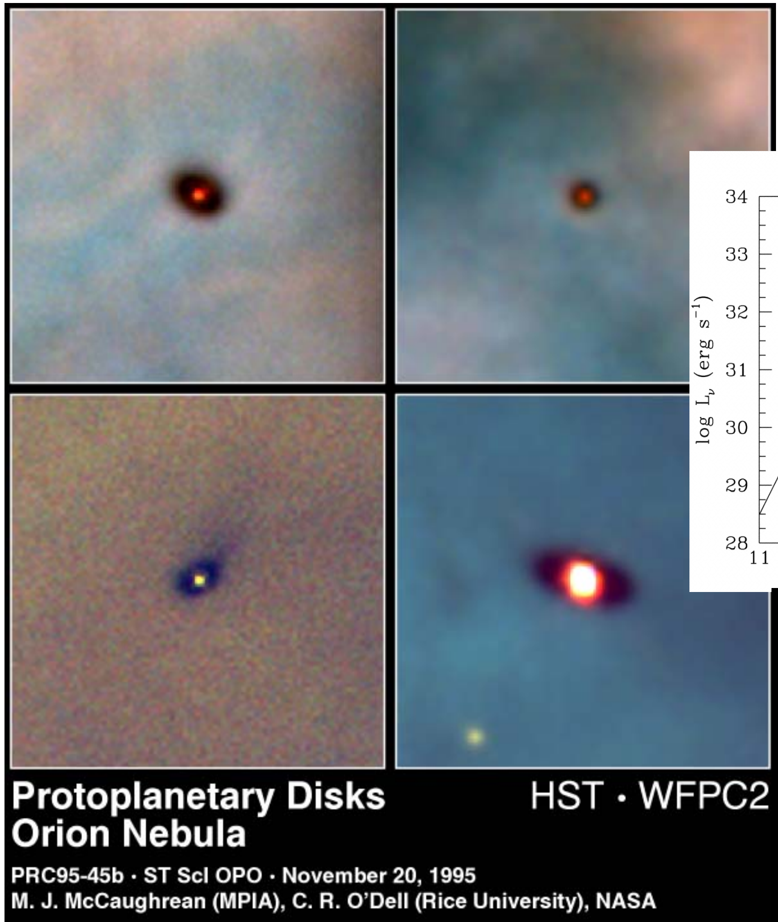
- What set the number of solar system planets?
- How long did it take them to form?
- Why are their orbits circular and coplanar?
- What set the planetary spins?

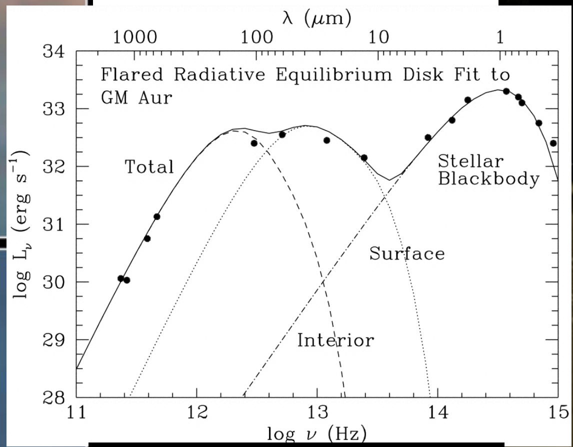
- Binaries in the Kuiper Belt and new moons.

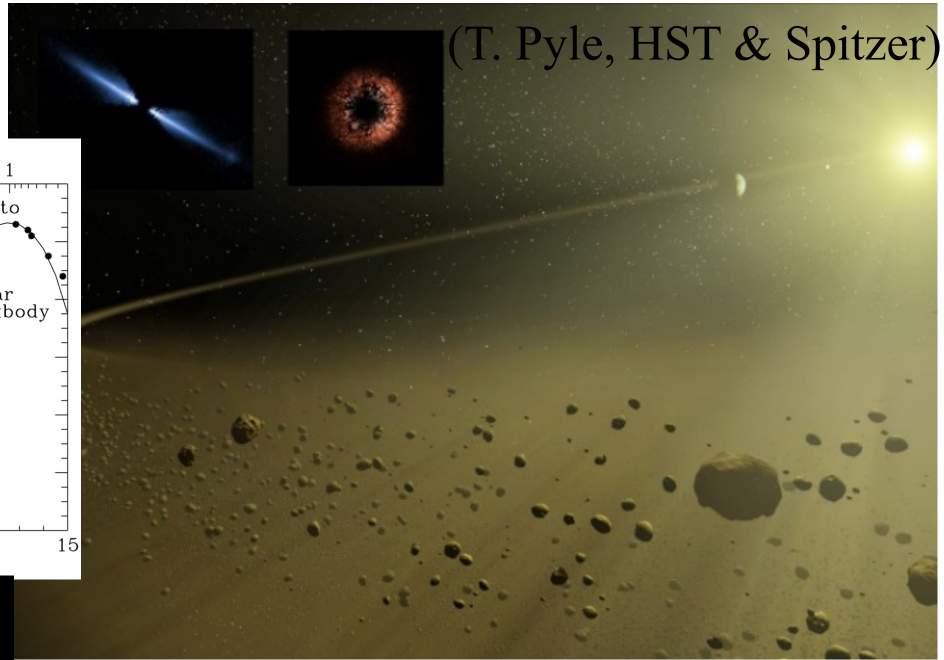
- Binary Planets?

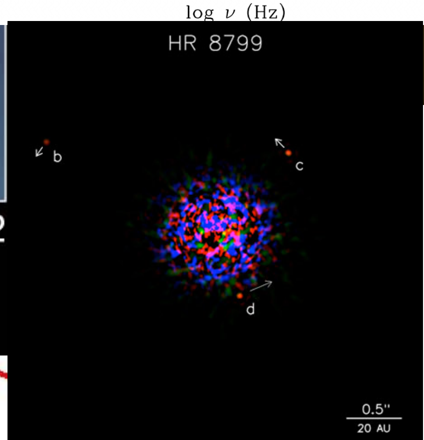
- What happens after planet formation?
- When and how did the Oort cloud form?
- How long do debris disks live?

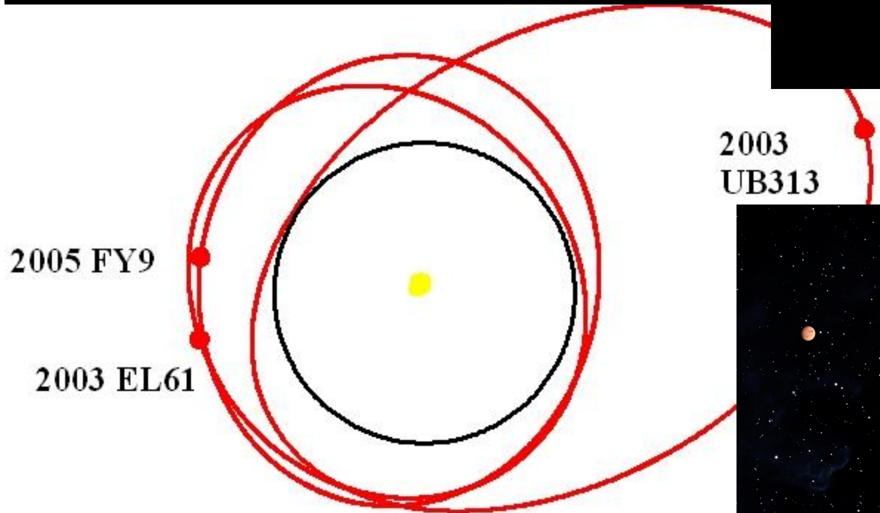
Amazing Observations

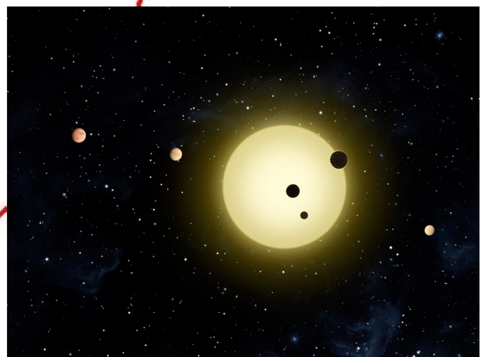


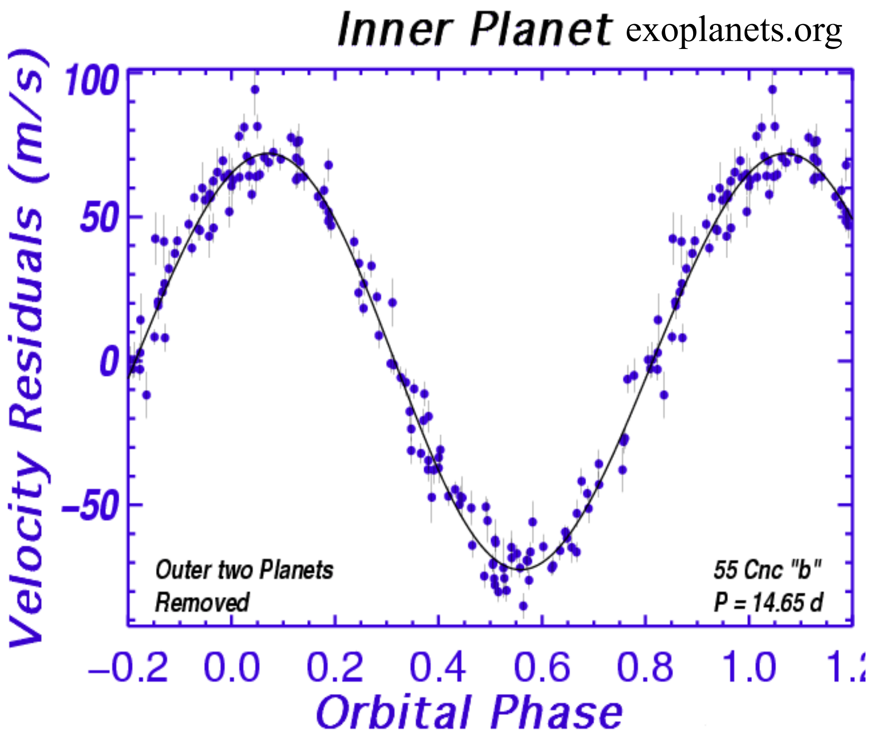




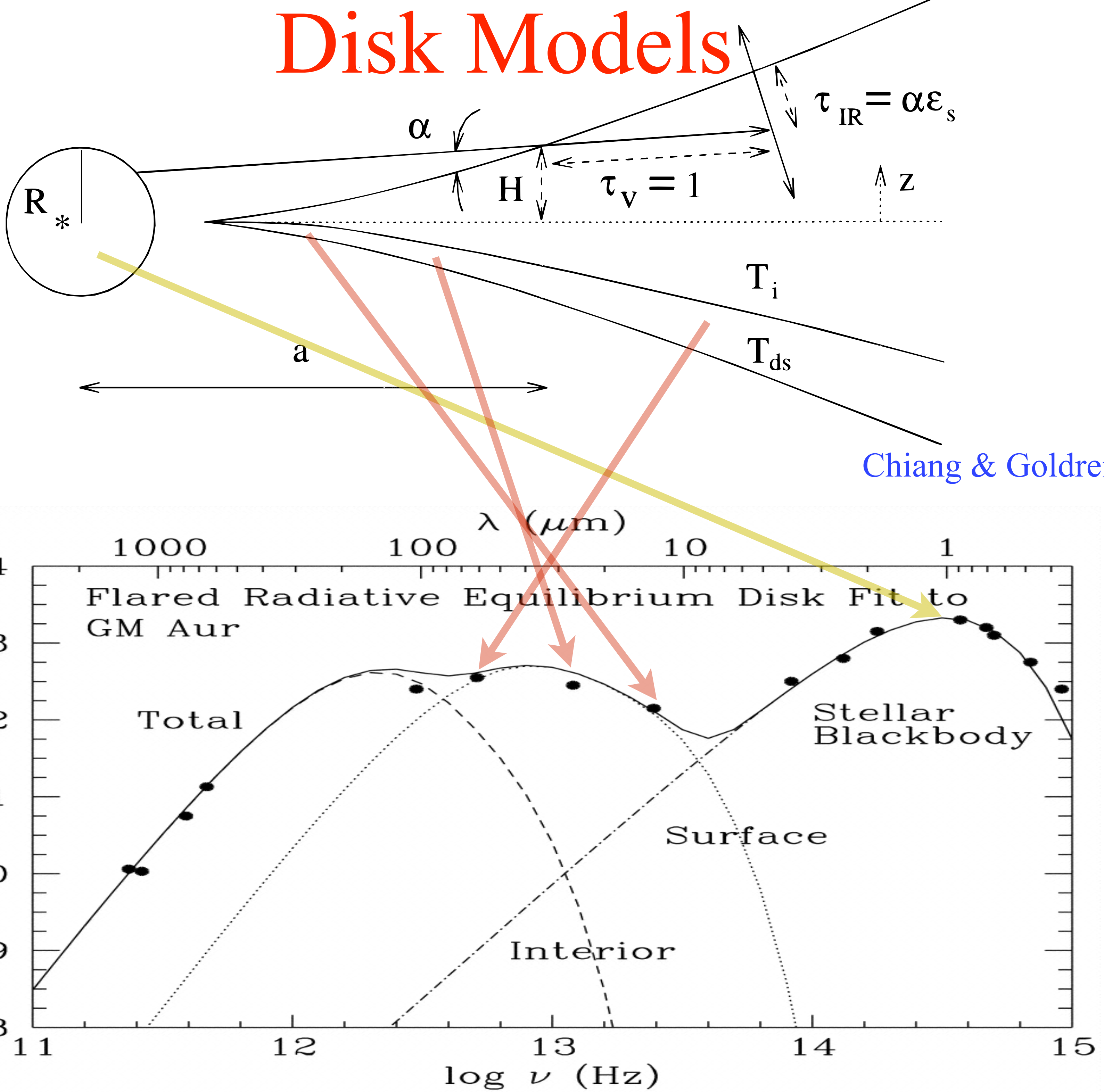






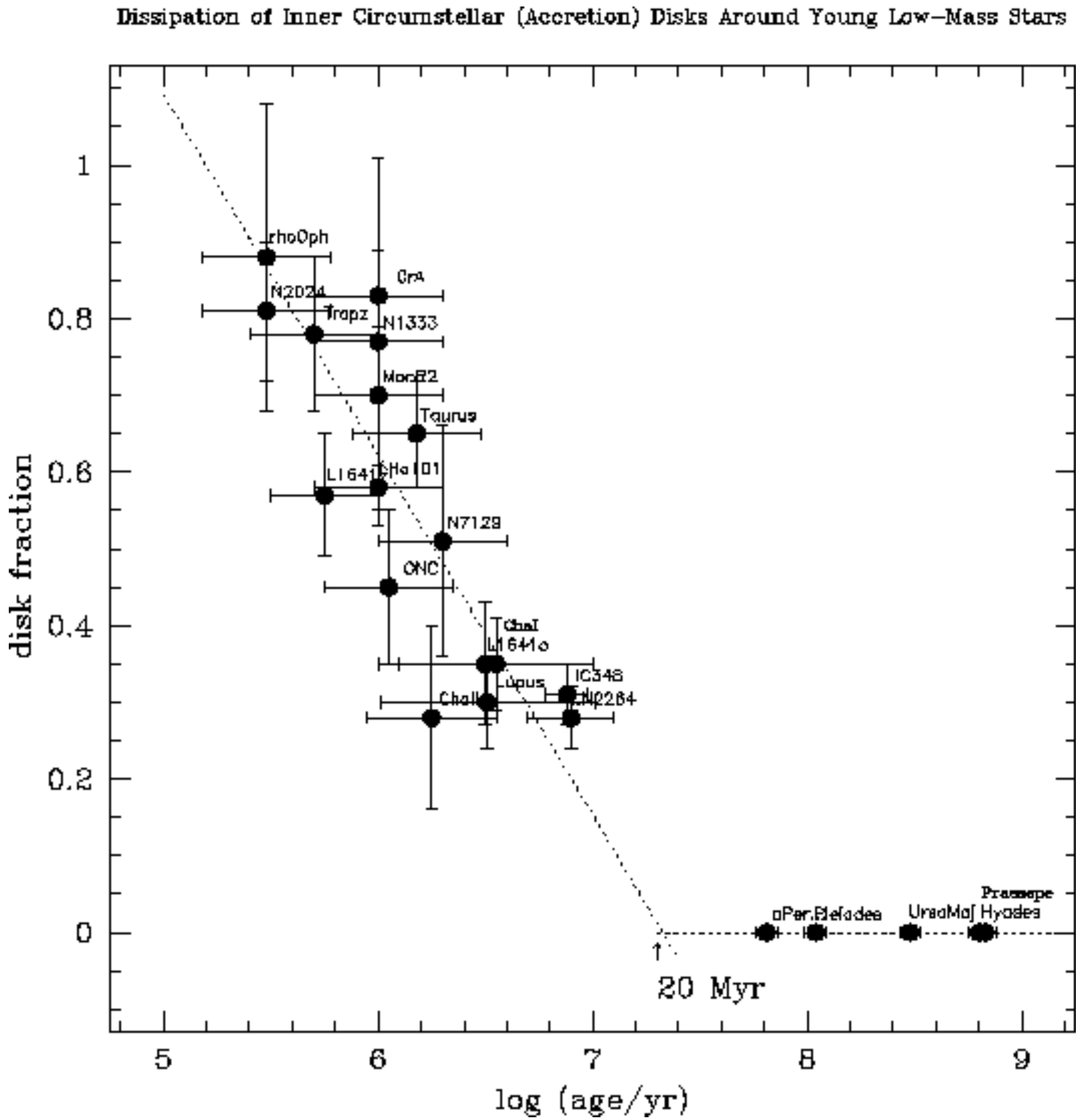


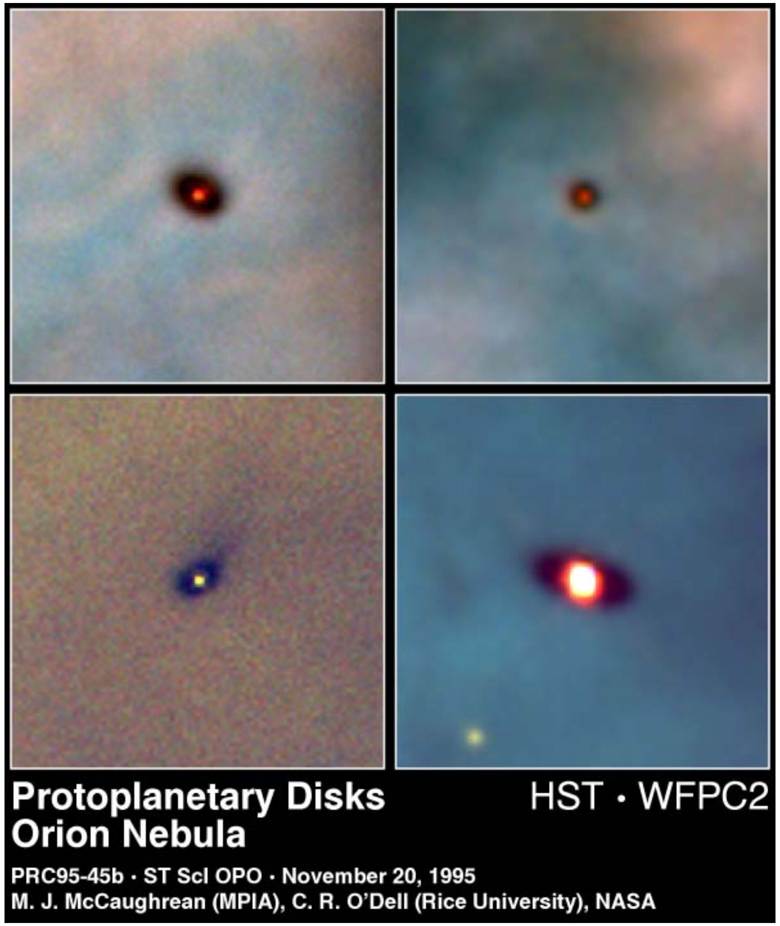
Disk Models



Chiang & Goldreich 97

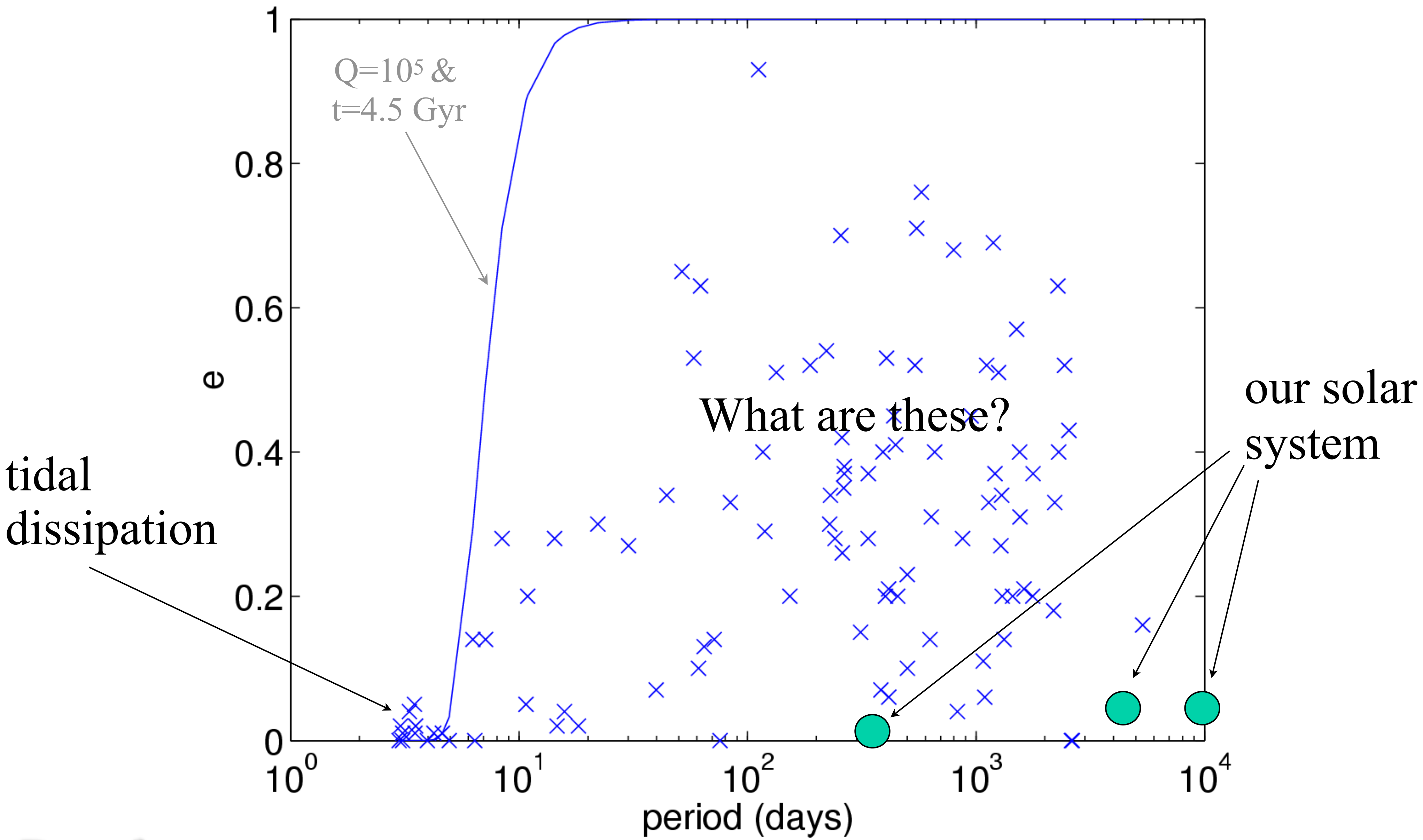
Disks - Results: 1-10Myr lifetime





Giant planet formation must be fast!

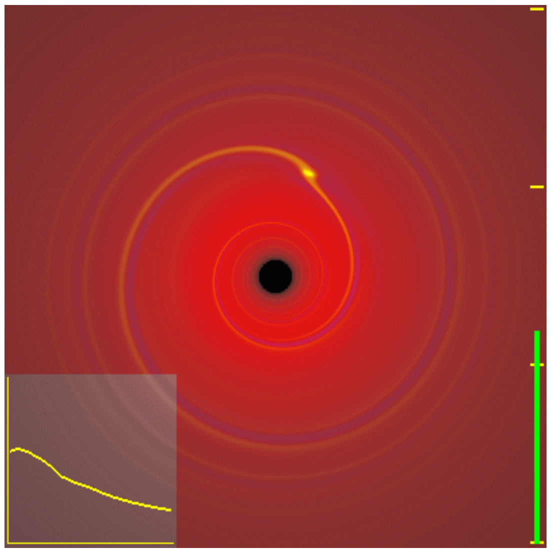
Eccentricities & Periods

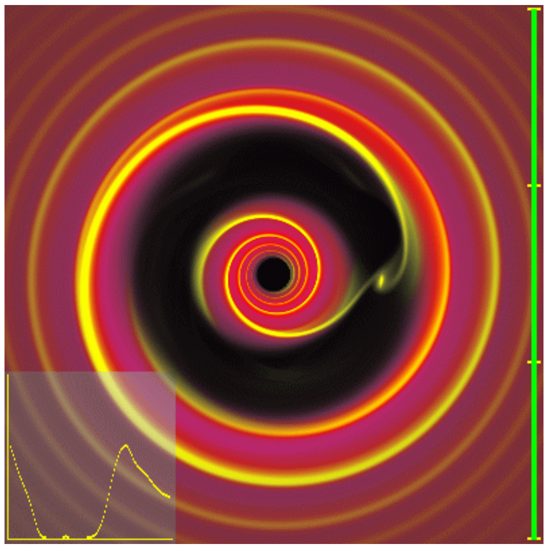


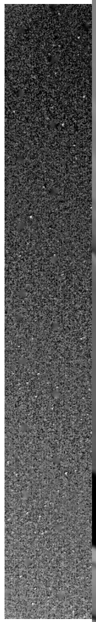
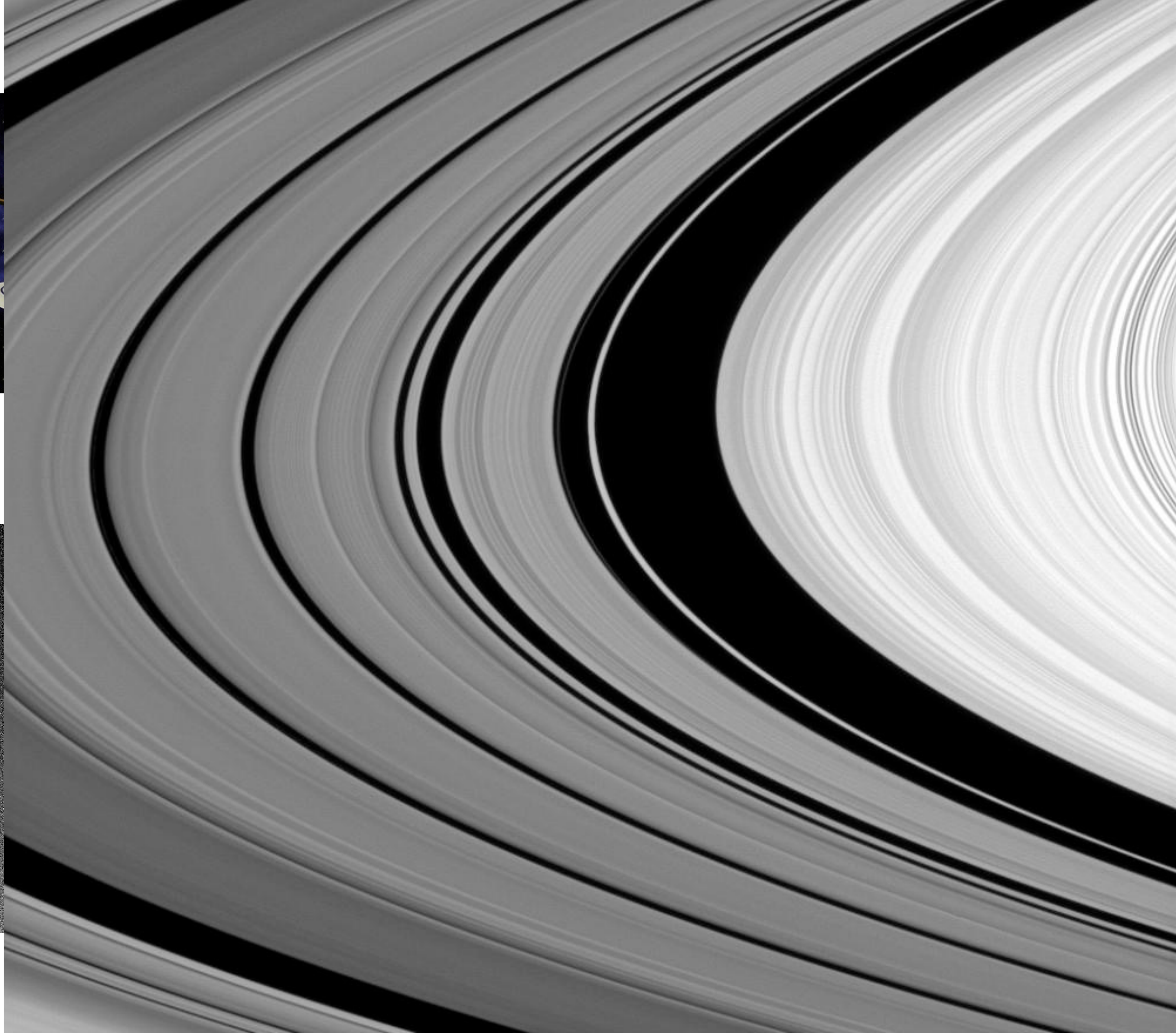
Data from http://exoplanets.org/almanac.html

Theories for strange orbits

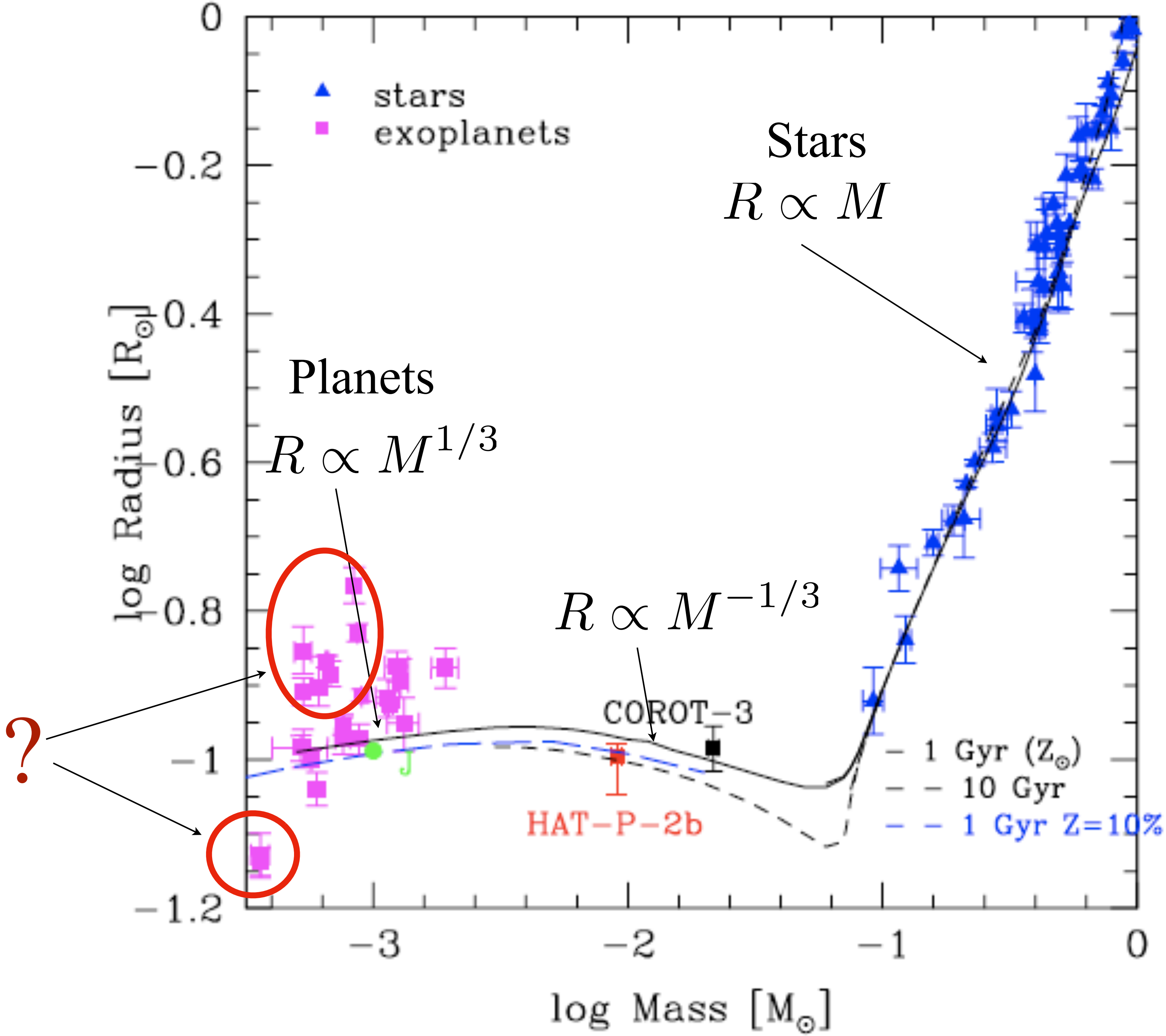
- Disk Migration
- Planet-Planet interaction - Migration and e
- Does disk excite eccentricities?
- Tides?






Transits - Radius Mass Relation - Surprise



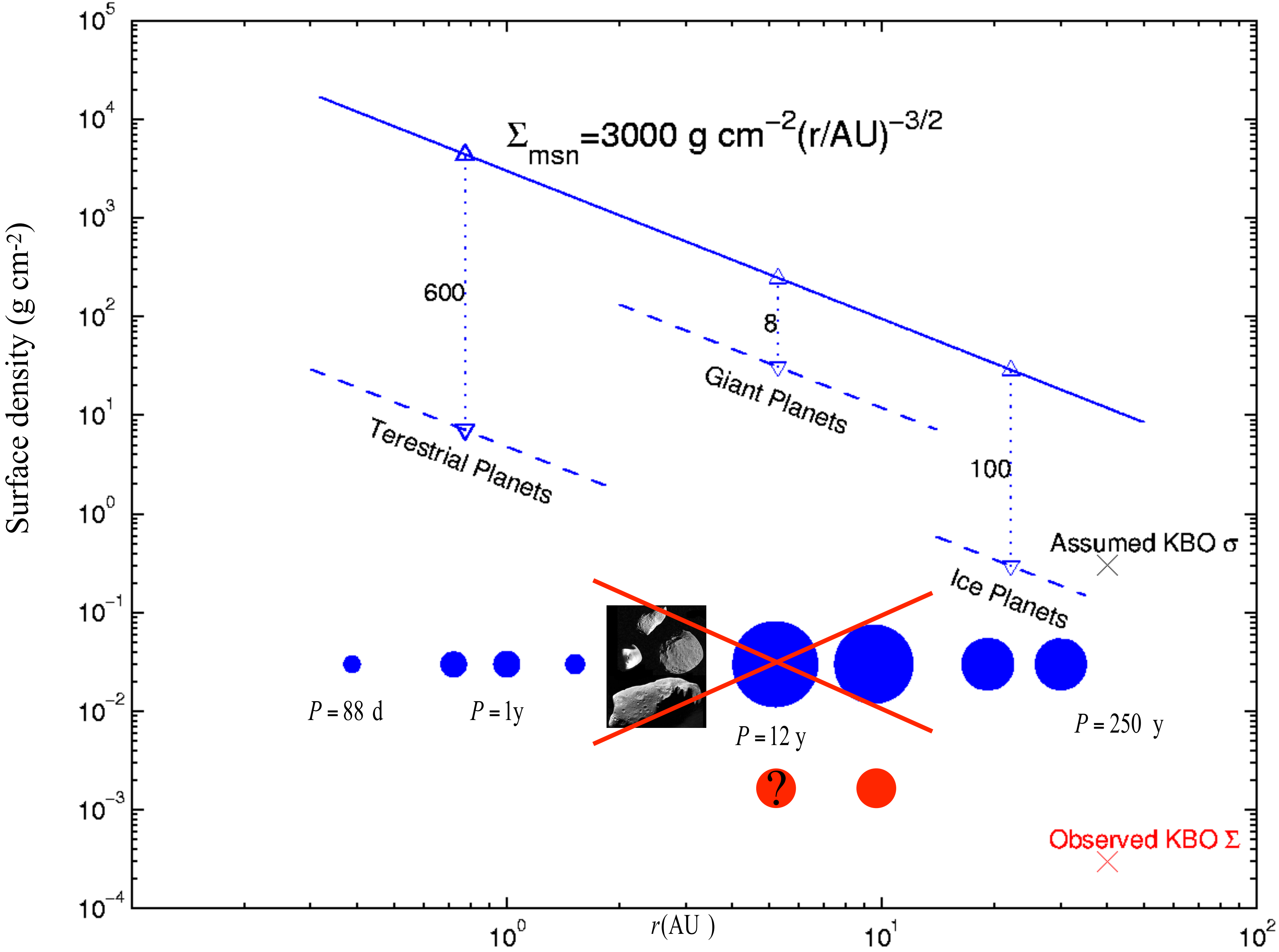
Inflated Hot Jupiters - Theories

- Why are hot (short period) Jupiters inflated?
- Possible for hot objects only.
- 1% inflation for each 1,000 degrees.
- Planets form with 100,000 degrees.

- Short cooling time. Why they did not get cold?

- Solar flux slows cooling. Not sufficient.
- Internal heating!

Minimum Mass Solar Nebula



Geometric Accretion

- If collision cross section is geometric

$$collision\ rate = n\pi R^2\,\mathrm{v}$$

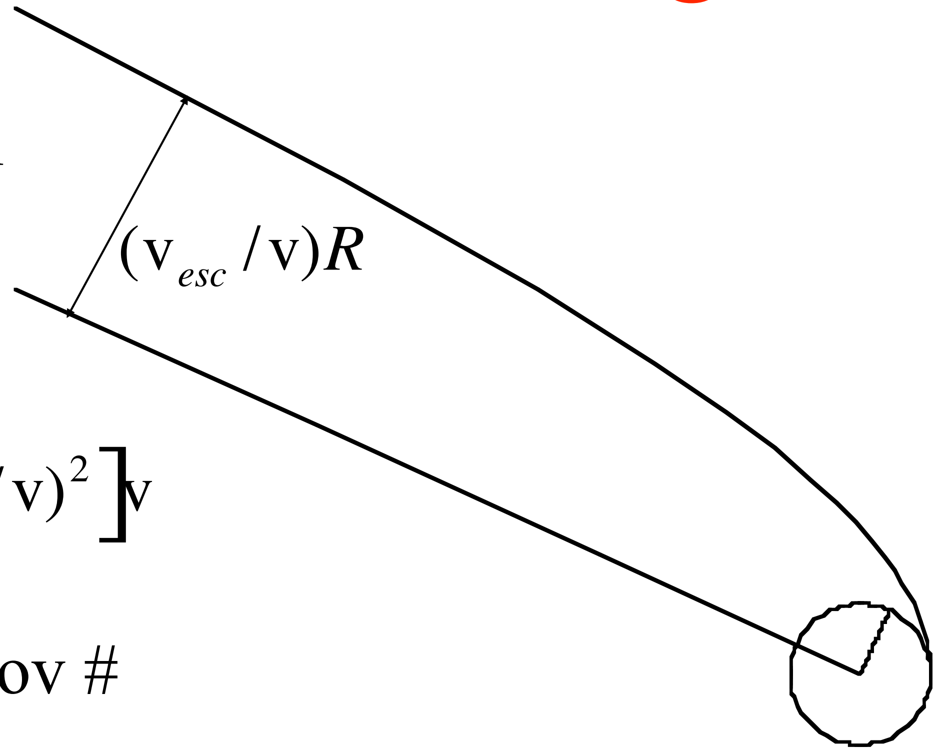
- Scale height h~v/Ω
  - n ∝σ/h
- In terms of surface density:
  - Independent of velocity

$$\frac{dR}{dt} = \frac{\sigma\Omega}{8\rho} \approx 3\frac{cm}{yr}(a/AU)^{-3}$$

- For Minimum Mass Solar Nebula (MMSN):
  - Earth (6,400km) 10^8 yr
  - Jupiter's core 10^9 yr
  - Neptune (25,000km) 10^{12} yr

Need Gravitational Focusing

- Larger collision cross section

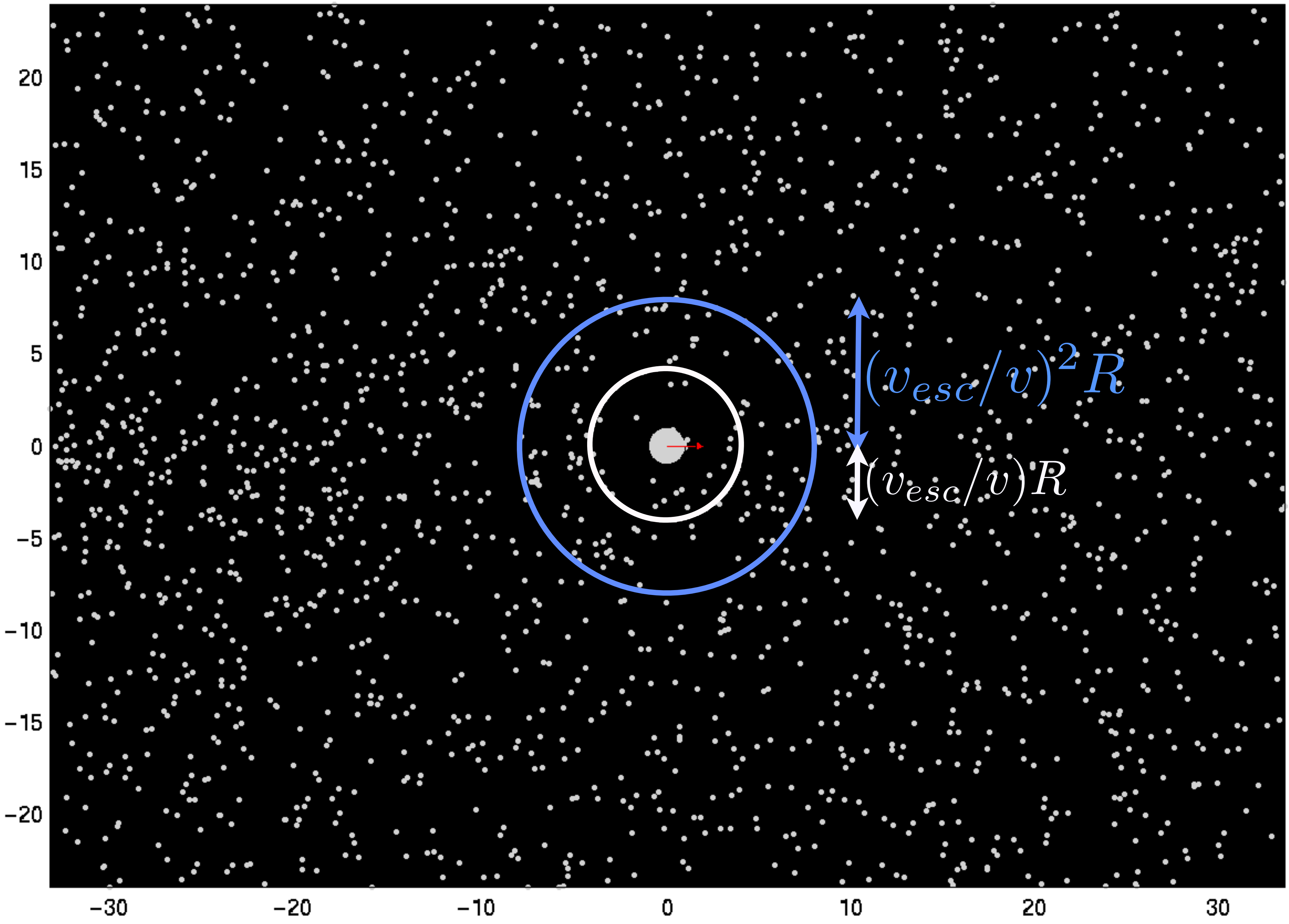


$$collision\ rate = n\pi R^2\left[1 + (v_{esc}/v)^2\right]v$$

Safronov #

	size (km)	geometric time	required time (yr)	implied eccentricity
Earth	6,400	10^8 yr	$<10^8$	$e<1$
Jupiter's core	10,000?	10^9 yr	$<10^7$	$e<0.1$
Neptune	25,000	10^{12} yr	$10^7<t<10^9$	$0.03<e<0.4$

תאוריות ליצירת פלנטות Planet Formation



Early Times: Runaway Accretion

- Without gravitational focusing

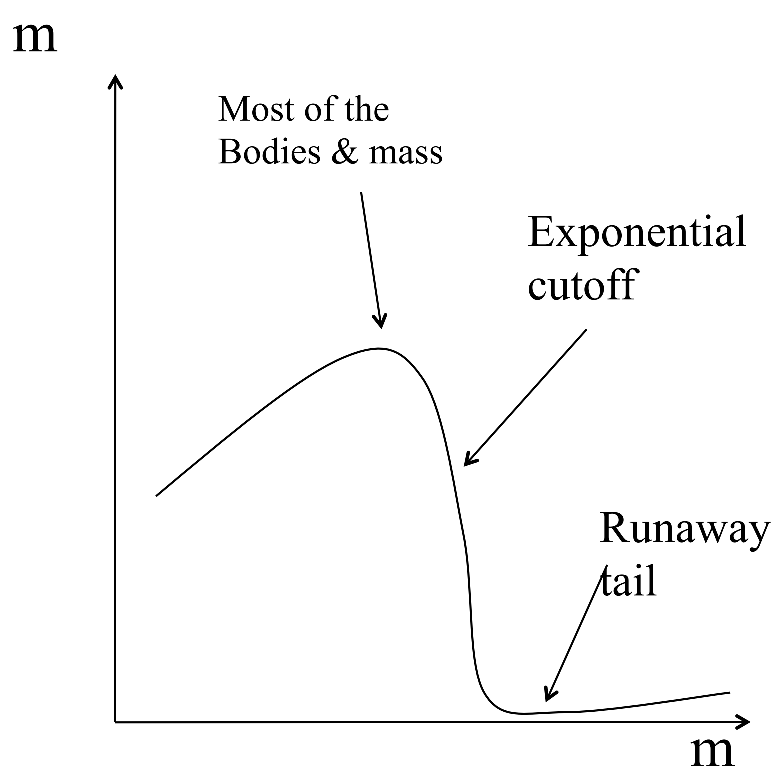
$$\frac{1}{R}\frac{dR}{dt} \propto \frac{1}{R}$$

  - 3 cm/year @ 1AU
  - too slow @ 30 AU
  - Bodies tend to become of equal size
  - Orderly growth

- With focusing

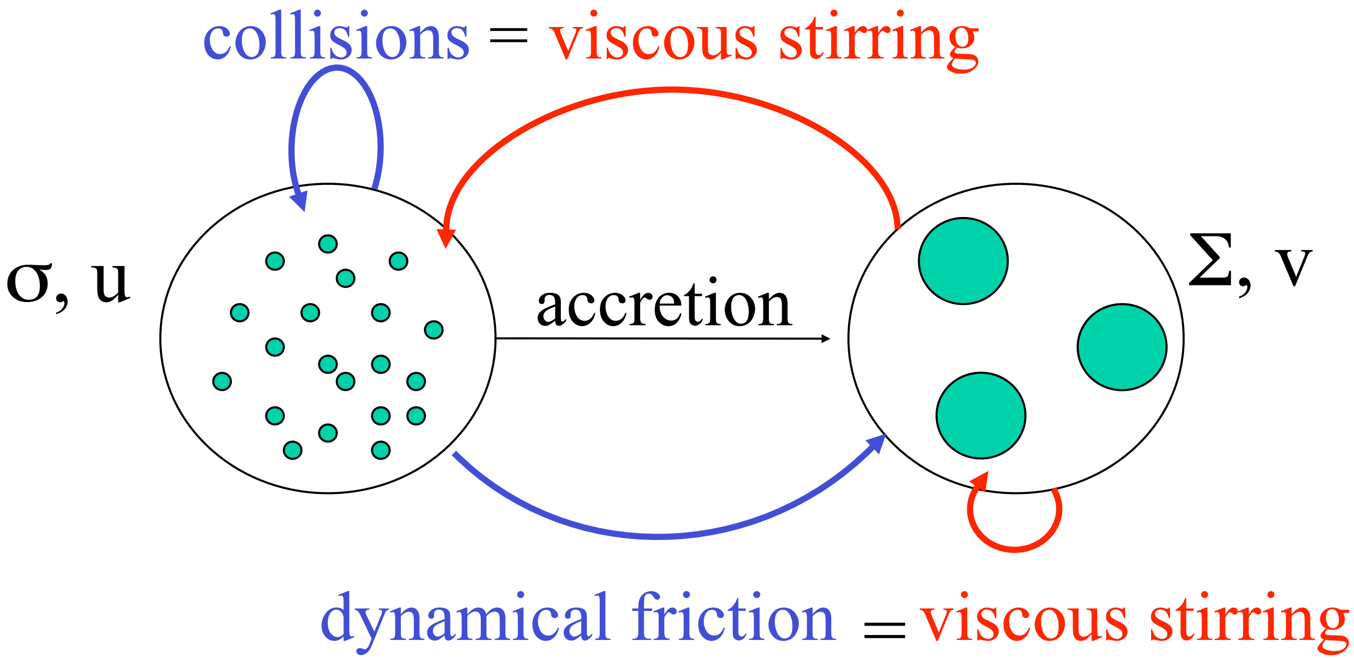
$$\frac{1}{R}\frac{dR}{dt} \propto \frac{1}{R}\left(\frac{v_{esc}}{v}\right)^2 \propto R^{+1}$$

  - Few large bodies become larger than their peers.
  - Runaway accretion



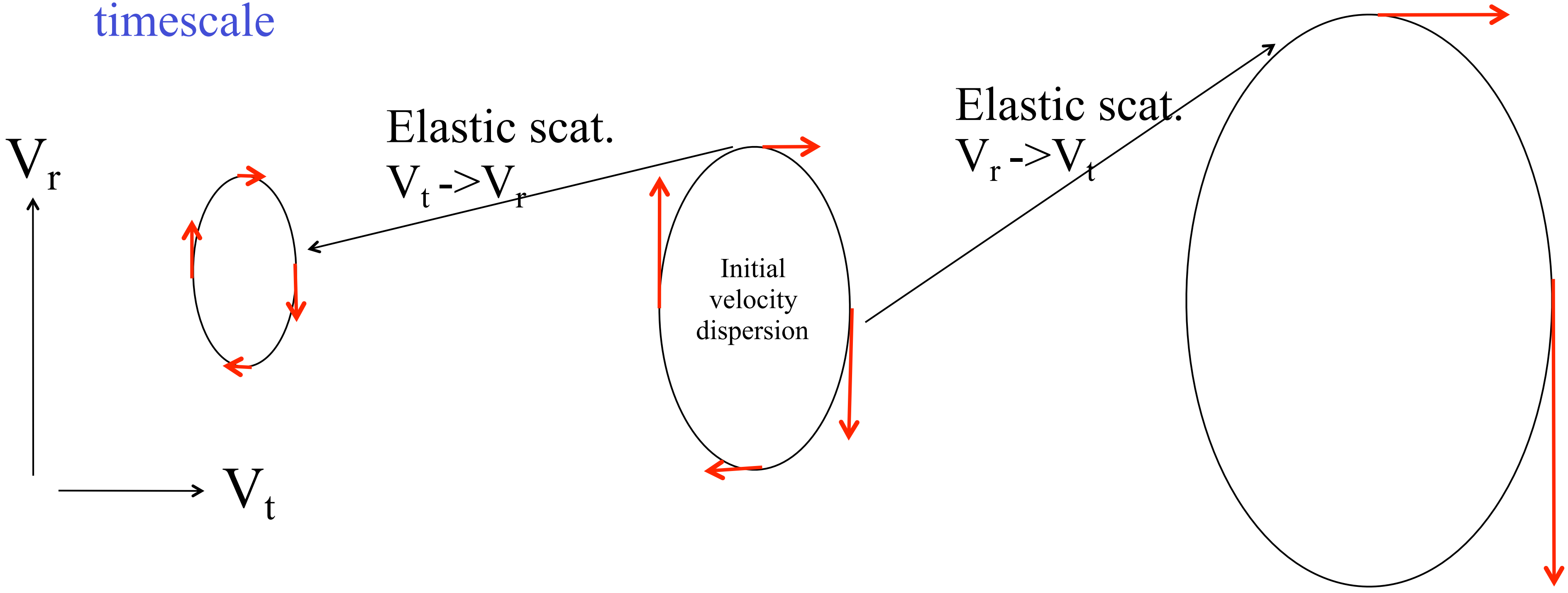
Physical Processes

- Setup: many small bodies, few big bodies



Disk Effects

- Hill sphere
  - Tidal effects from the Sun
  - Sets a minimum drift velocity
  - Sets the maximum binary separation
- Viscous stirring
  - Radial and tangential velocity are coupled - eccentricity
  - Even elastic deflections increase velocity dispersion
  - Results in much faster heating: temperature doubles in one deflection timescale

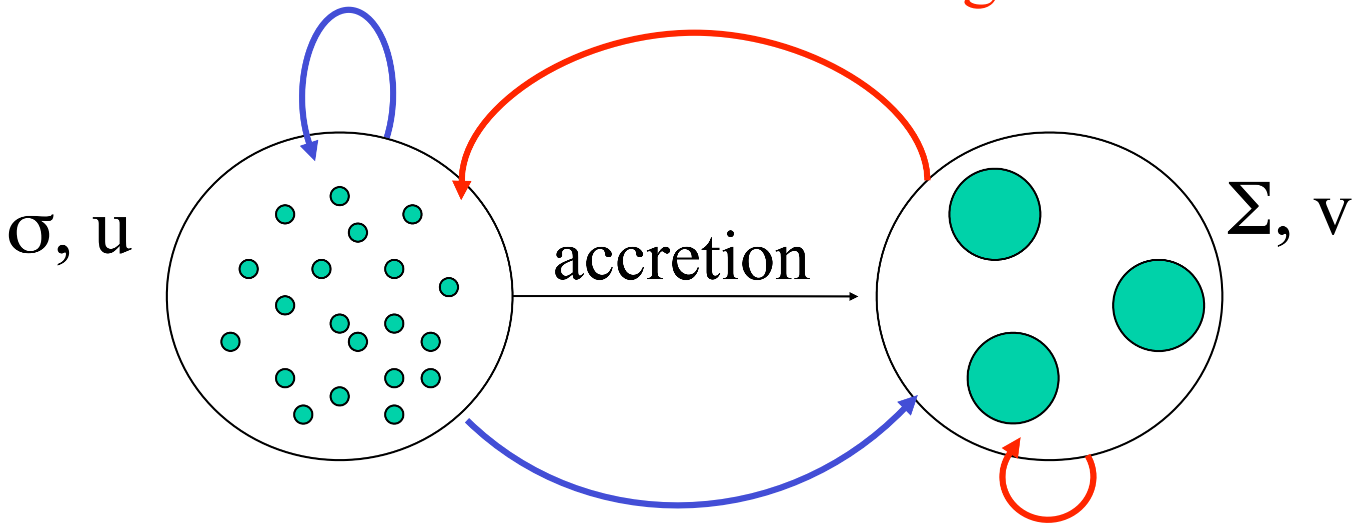


Physical Processes: velocities

- Setup: many small bodies, few big bodies

$$\frac{\sigma\Omega}{\rho s} \sim \frac{\Sigma\Omega}{\rho R}\left(\frac{v_{\rm esc}}{u}\right)^4 \quad \Rightarrow u \sim v_{\rm esc}\left(\frac{\Sigma}{\sigma}\frac{s}{R}\right)^{1/4}$$

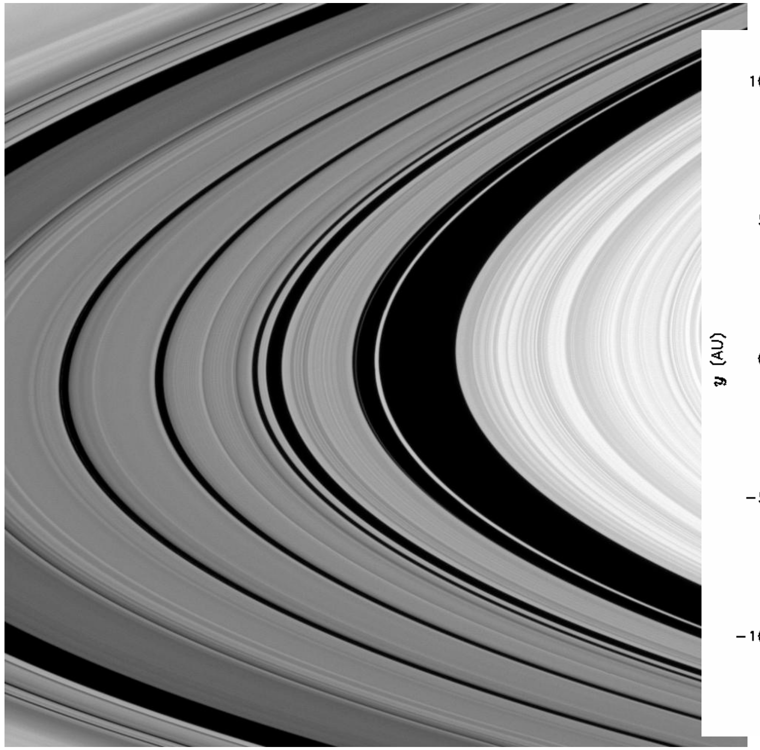
collisions = viscous stirring

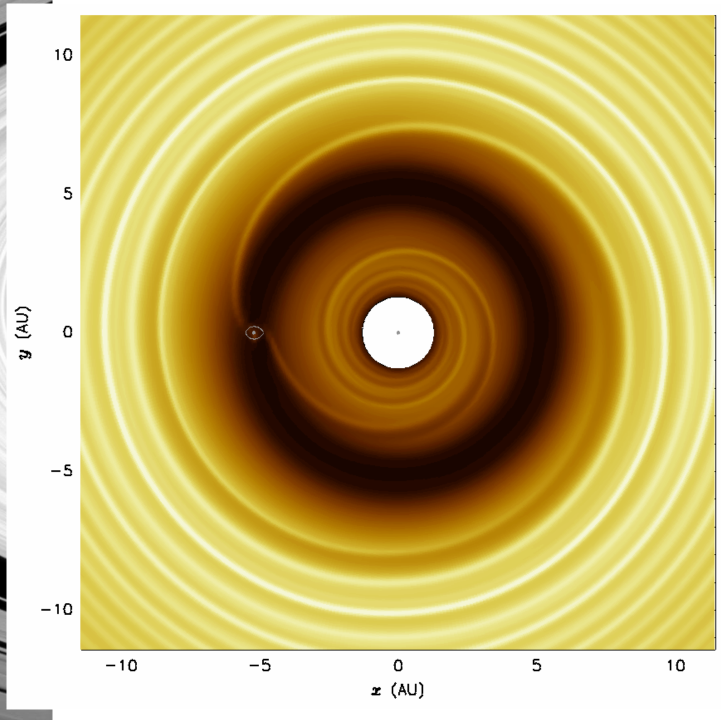


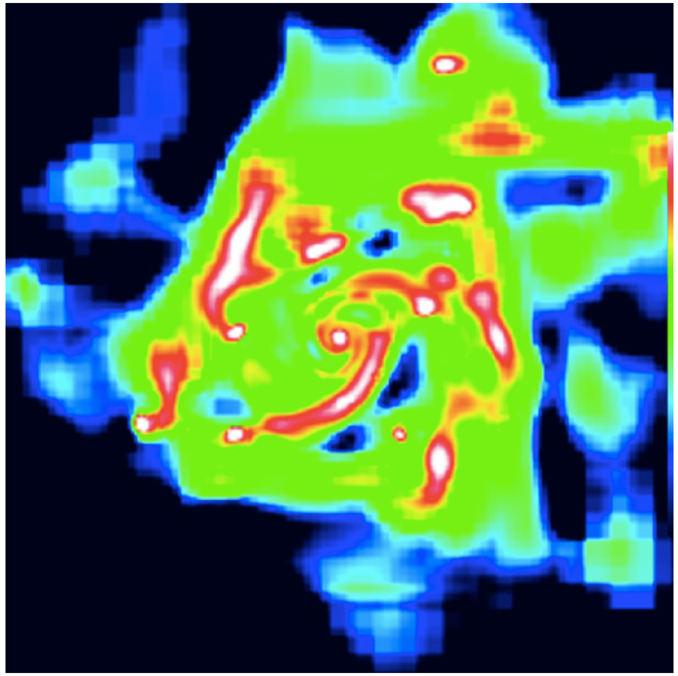
dynamical friction = viscous stirring

$\Rightarrow$ solve for v

From Clean to Dirty







$h/r = 10^{-6}$ $\quad$ $h/r = 1/30$ $\quad$ $h/r = \delta \approx 1/4$

Late Times: Oligarchic Growth

"Classical" oligarchy:

- Big bodies heat their own food

  $\Rightarrow$ larger u around bigger bodies

  $\Rightarrow$ bigger bodies grow more slowly

  $\Rightarrow$ big bodies are:

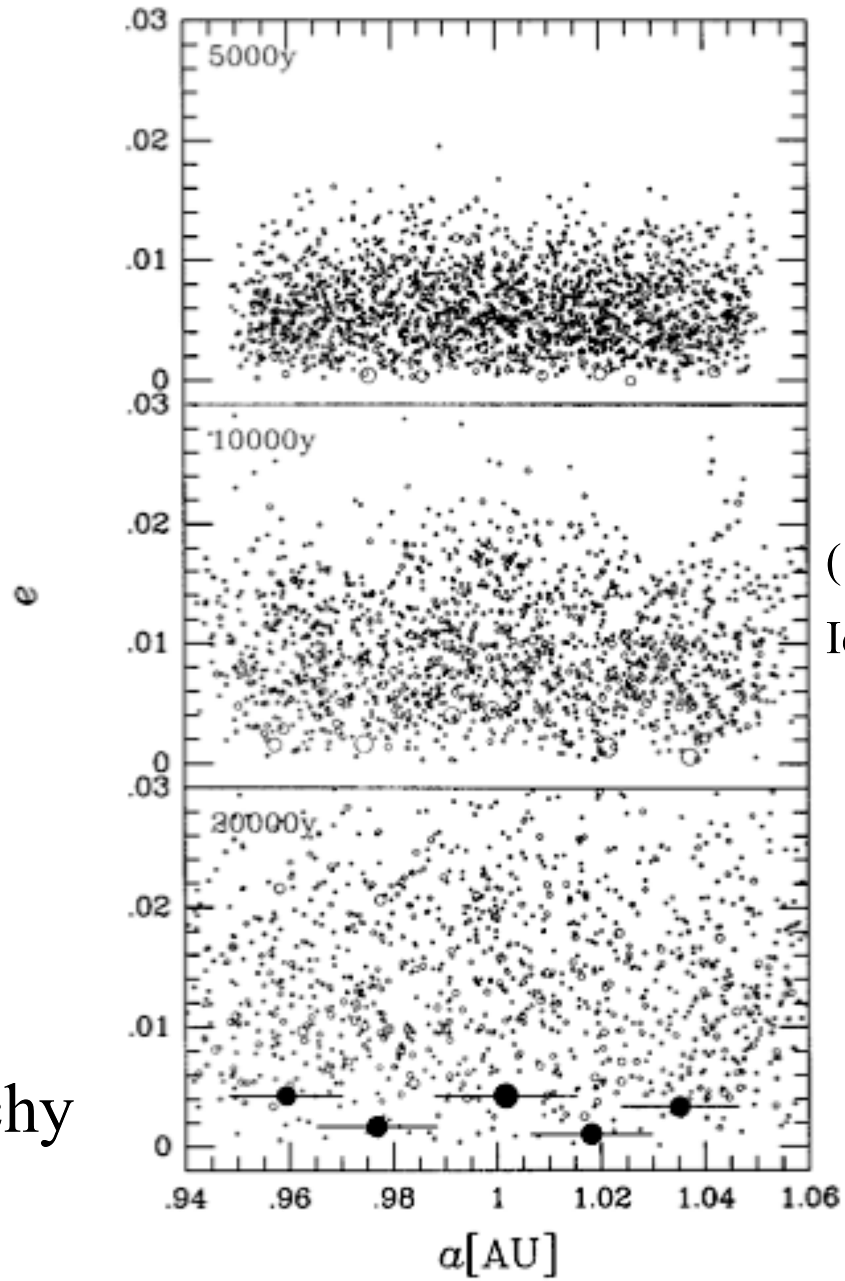
  equal mass,

  uniformly spaced

- Number of big bodies decreases as they grow

More refined oligarchy - battles:

- Super Hill - win by competition
- Sub Hill - large-large accretion
- Thin disk - No sustained Oligarchy



(Kokubo & Ida 1998)

End of Oligarchy: Isolation

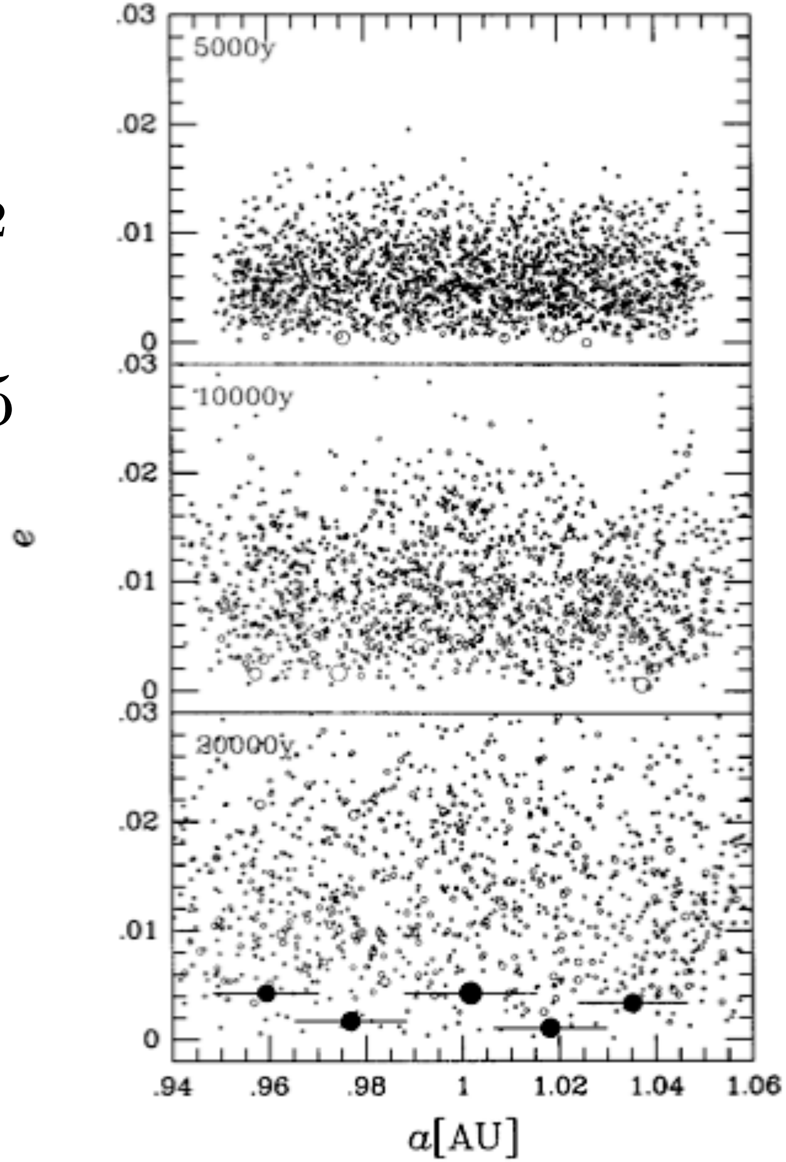
- Definition:
  - A large body has all the mass in annulus of ~5R$_H$

$$M_{iso} = (2\pi a)(5R_H)\Sigma$$

$$M_{iso}/M_* = 6.5(M_{disk}/M_*)^{3/2}$$

$$M_{disk}/M_* = (M_{iso}/M_*)^{2/3}/3.5$$

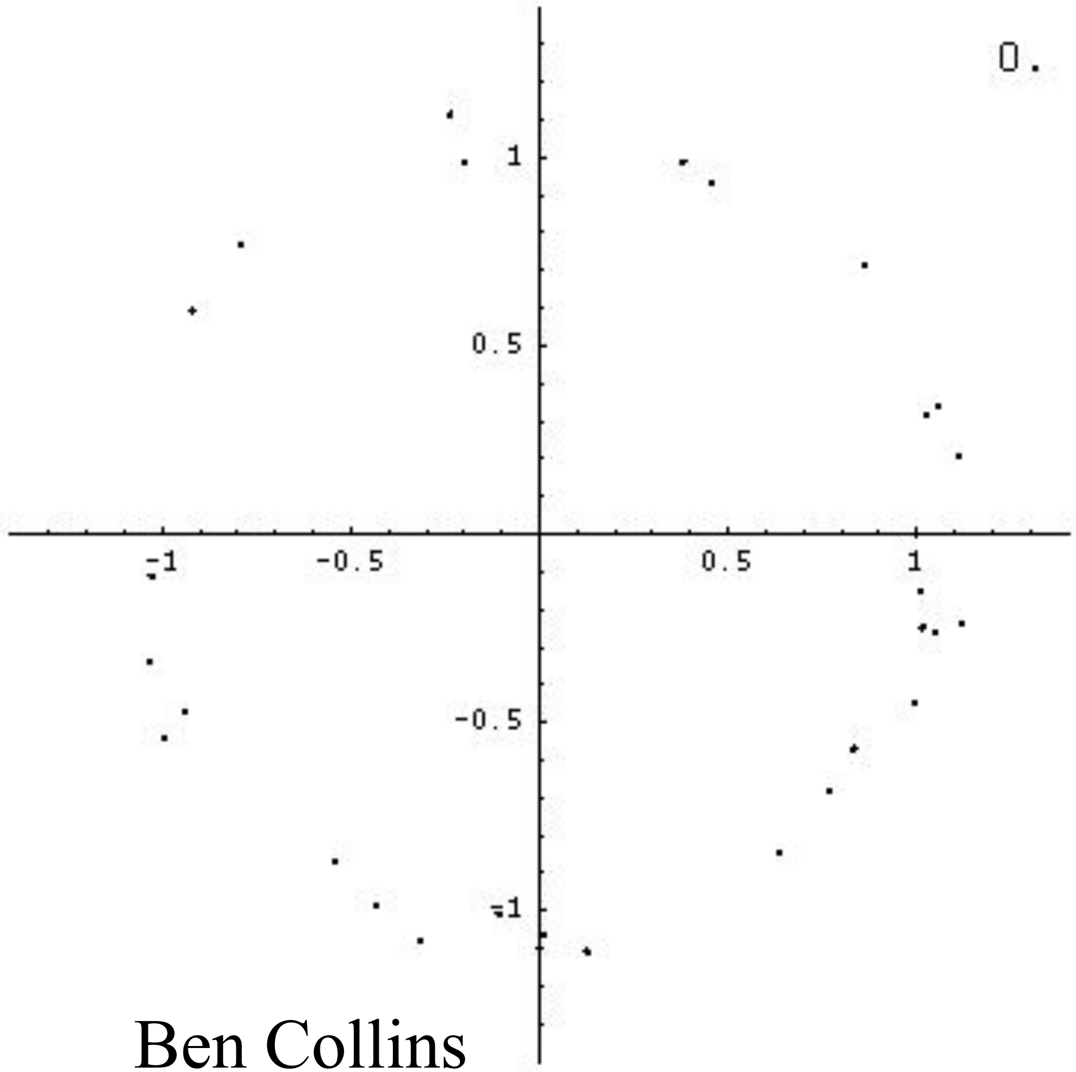
  - For earth region
    - Use mass of disk
    - N ~ 50 => GIANT IMPACTS
  - For outer solar system
    - Use known M_{iso}
    - x5 Minimum mass solar nebula
    - N ~ 5



Numerical N-body Simulation

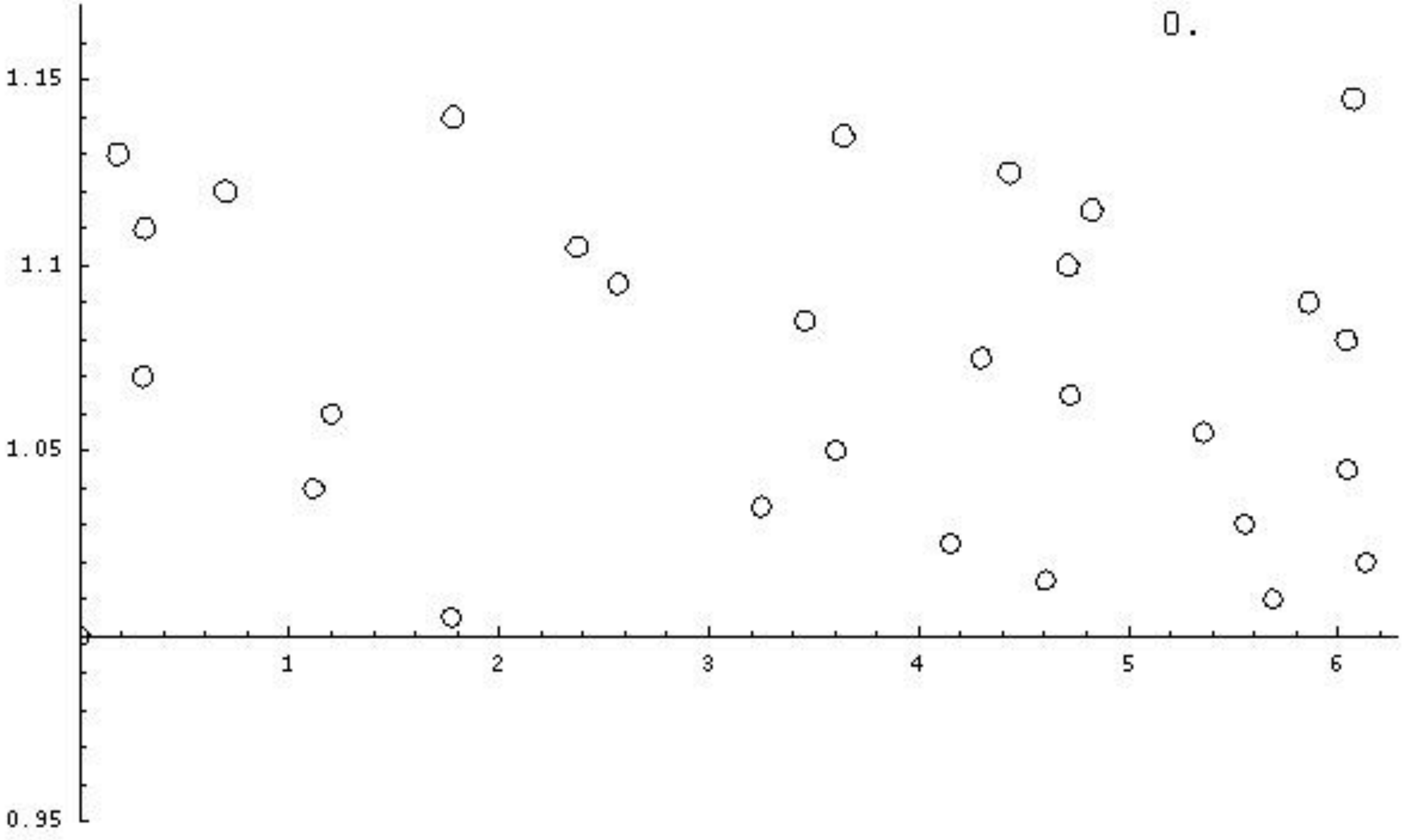
- New N-body code
- Accretion
- Dynamical friction

- Questions:
  - Σ/σ at transition.
  - Are all planets excited?
  - Timescale
  - How many survivors?



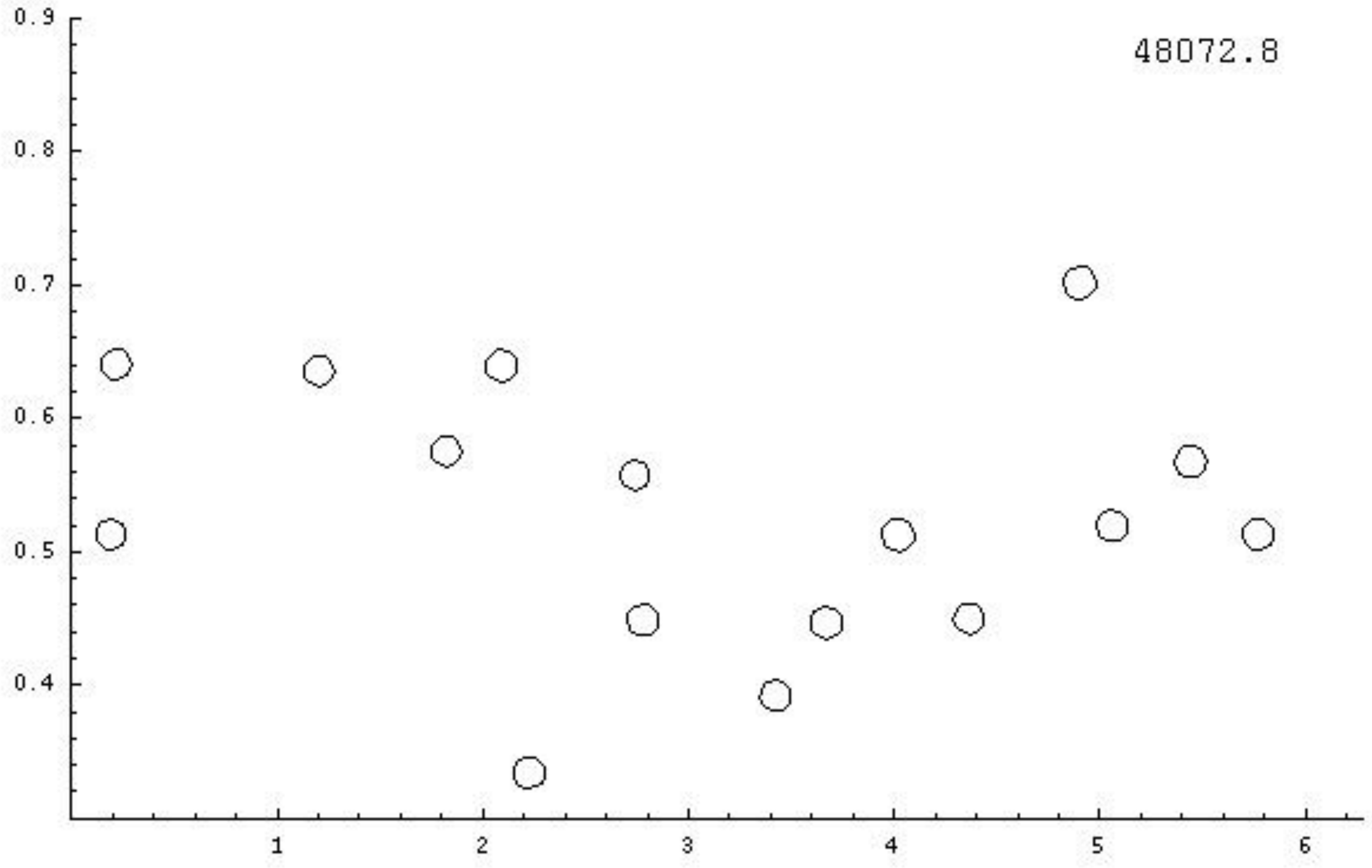
Ben Collins

Beginning of Oligarchy



- Radius of circle = Hill sphere ~ 3000R

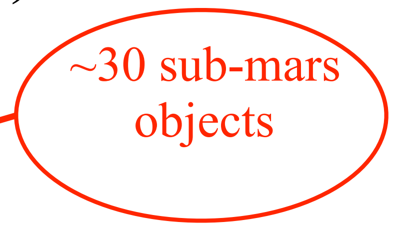
End of Oligarchy

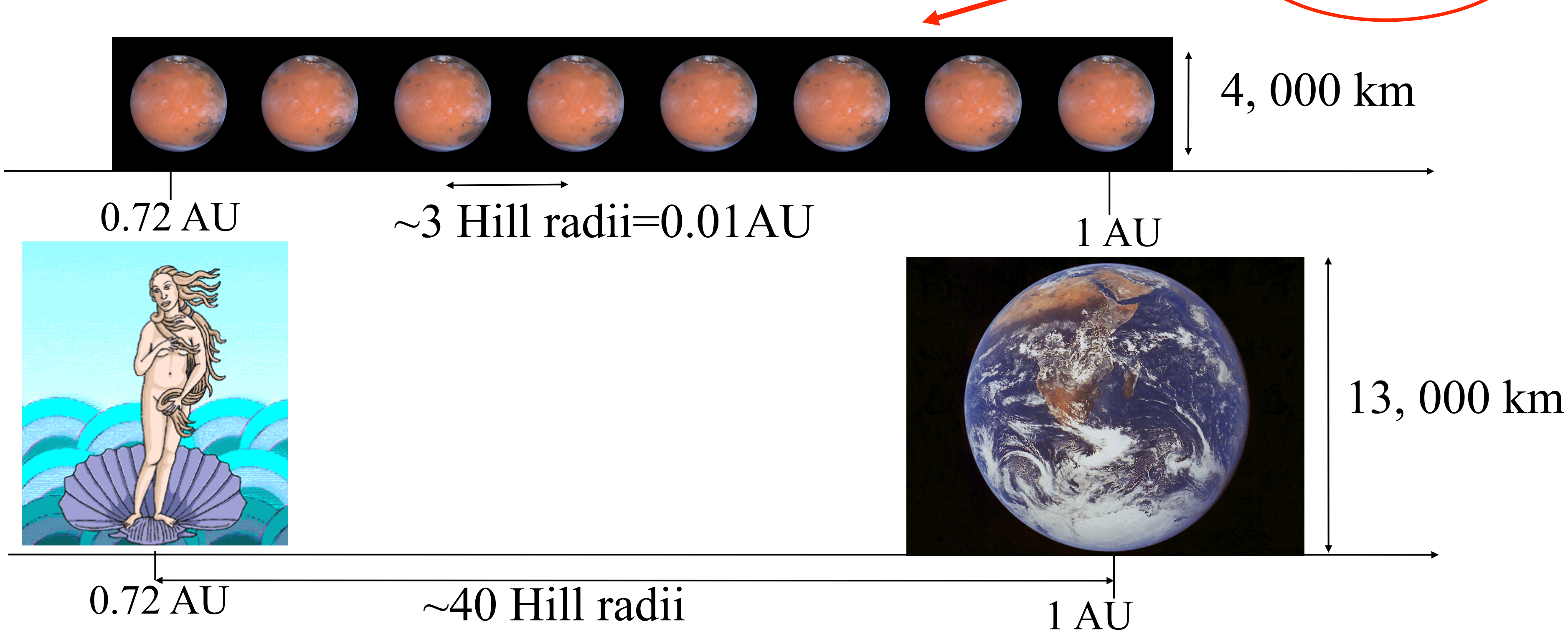


- Radius of circle = Hill sphere ~ 3000R
- At end of oligarchy $\Sigma \sim \sigma$, $v \sim V_H$

Venus & Earth: Beyond Isolation

- $V_{esc} < V_{orbit}$ ejection unlikely - MMSN sufficient
- Collisions
- Formation on geometric timescale (100 Myr)
- Giant impacts!





Summary

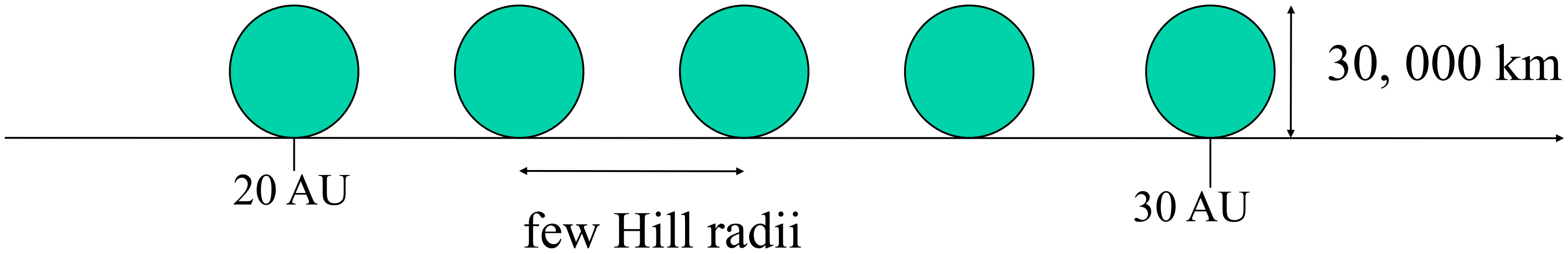
- Planetesimals Impacts & Giant impact are expected.
- Strange planets w/extended atmospheres: Kepler 11
- Evidence for older & newer magma:
  implies several atmospheric losses.

What should we find out

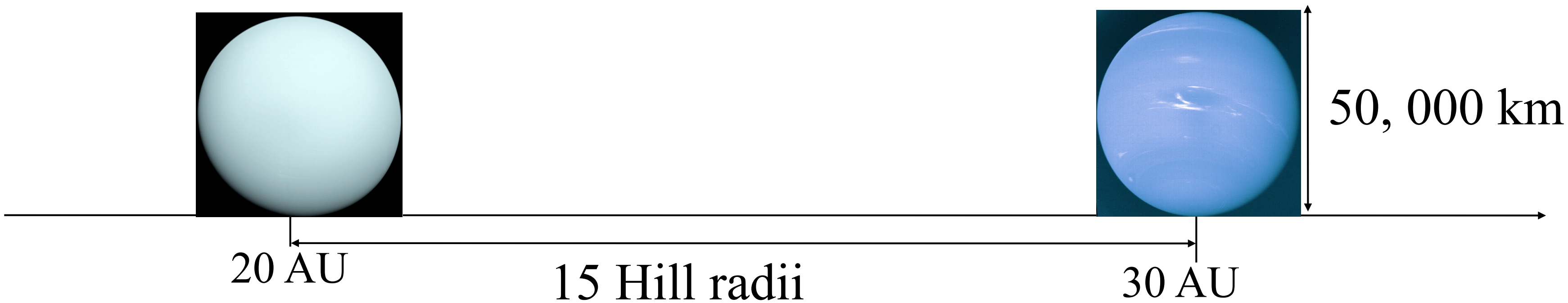
- What happens to atmospheres during impacts?
- Giant vs. small (planetesimals) impacts
- Is it all consistent?

Uranus & Neptune = End of Oligarchy

- Fast formation of Uranus & Neptune (<10 Myr) if small bodies are very small (<1 m)
- In cold accretion with MMSN:



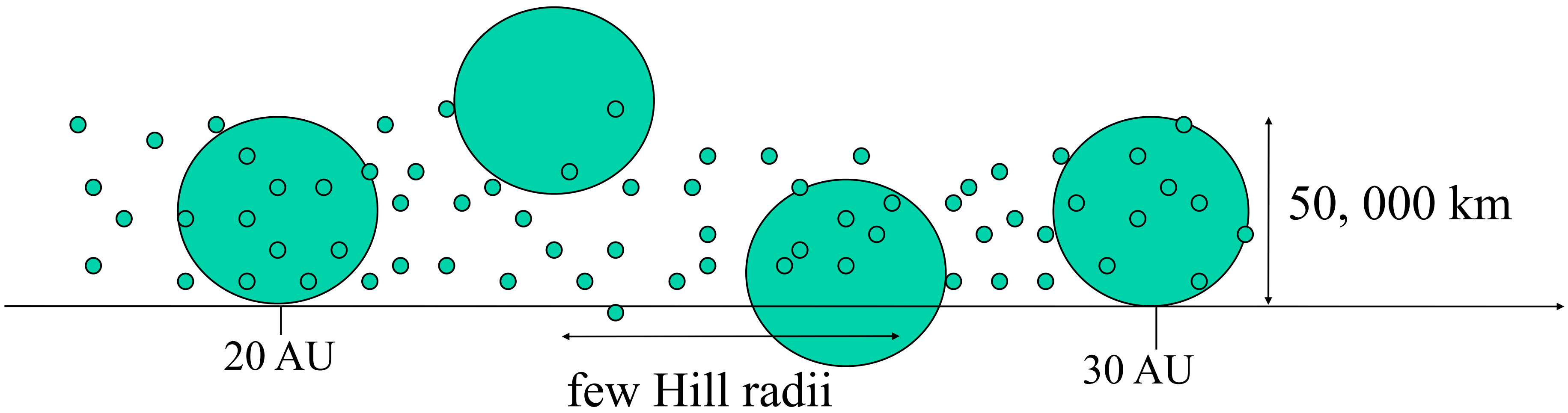
- Observed:



Uranus & Neptune: Isolation

- Isolation when $\Sigma \sim \sigma$.
- we assume $u \sim v_H$

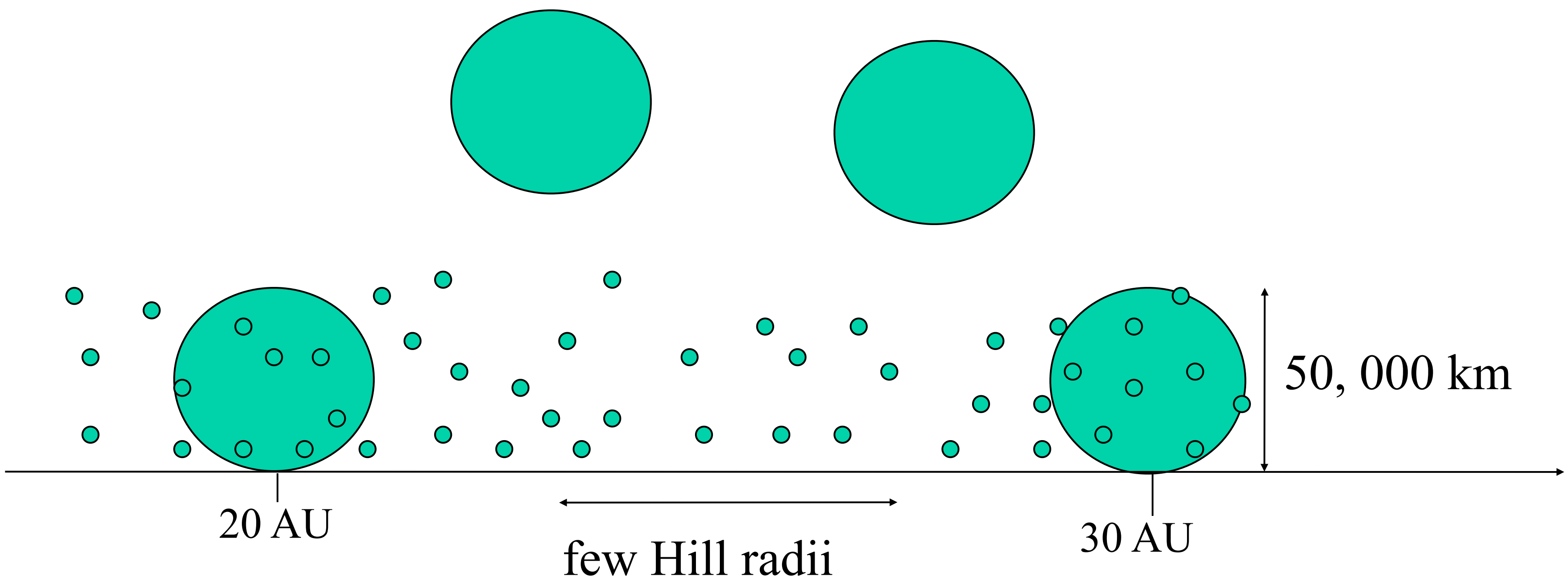
$$T_{\text{isolation}} \sim \Omega^{-1} \frac{\alpha \rho R}{\sigma} \sim 10 \text{ million years}$$



Uranus & Neptune: Ejection

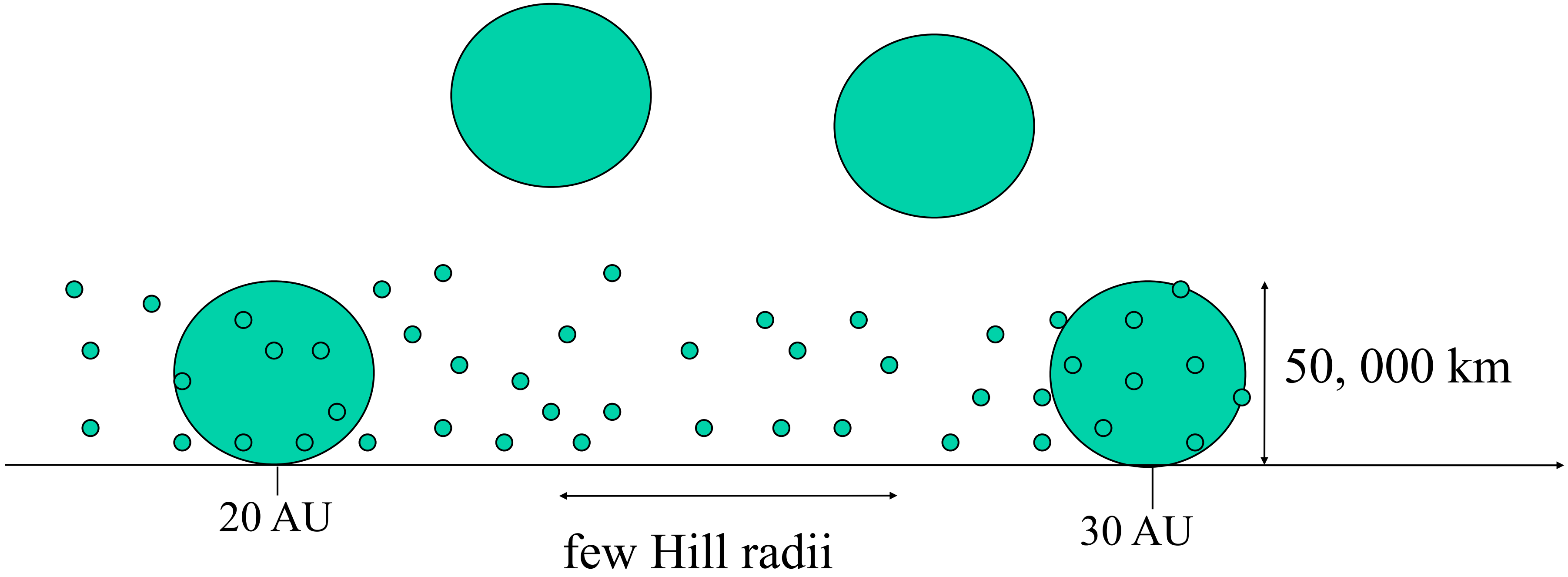
- After <10 million years, $\Sigma > \sigma$
- Heating > Cooling $\Rightarrow$ **runaway heating**
- Planets are ejected $v_{esc} > v_{orbit}$, collisions unlikely.

$$T_{\rm eject} \sim \frac{1}{10}\Omega^{-1}\left(\frac{M_\odot}{M_{\rm Neptune}}\right)^2 \sim \text{billion years}$$



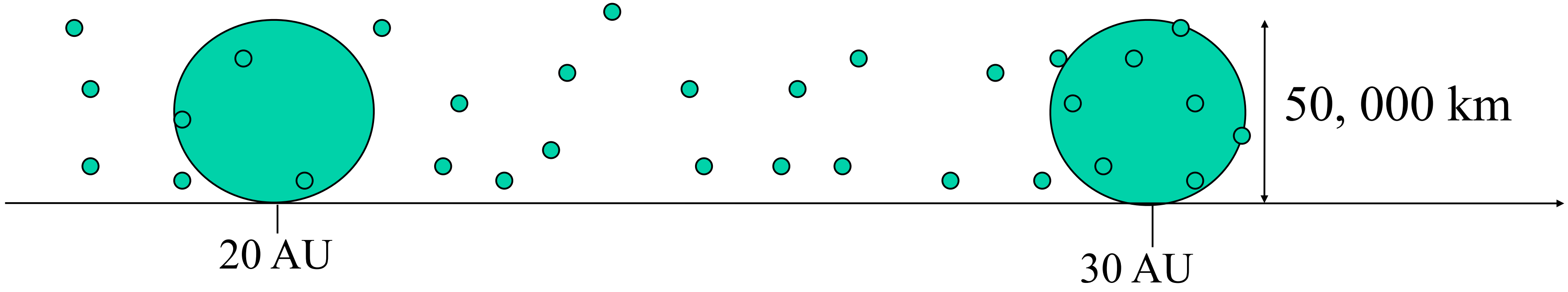
Uranus & Neptune: required mass

- Planets are ejected $v_{esc} > v_{orbit}$, collisions unlikely.
- Uranus & Neptune already form at end of oligarchy (<10Myr).
- About 5 x MMSN is needed. Otherwise
  - Mass of individual objects too small.
  - Ejection too long.



Uranus & Neptune: regularization

- Only a few remaining bodies (Uranus & Neptune)
- No Chaos = no heating - **sets # of planets**
- Cooled by remaining small bodies (explains current small eccentricity)



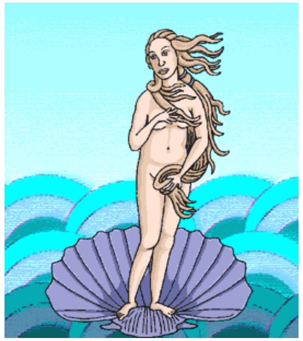
Collide or Eject?

$$\frac{V_{esc}}{V_{orbit}} \sim \alpha^{-3/2}\left(\frac{\sigma}{\rho a}\right)^{1/3} \sim \begin{cases} 0.16 & a = 1\text{AU} \\ 3 & a = 25\text{AU} \end{cases}$$

$$V_{esc} = V_{orb} \quad at \quad a \sim 3AU$$

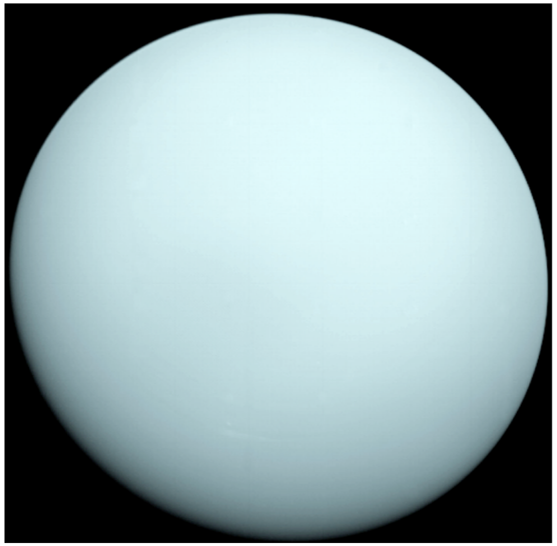
a<3AU

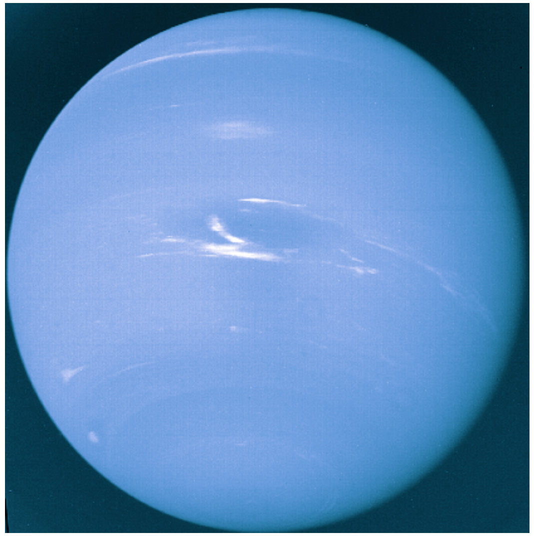
Collision



a>3AU

Ejection





Orbital Regularization

- Eccentricity decays due to leftover small bodies.
  - Initial timescale = ejection (outer) or collision (inner) timescale
- Gas effects?
  - Could have helped in cooling the small bodies during oligarchy
  - Unlikely to be present at the final stages
    - 100Myr for inner solar system
    - 10Myr-1Gyr after ejection in outer solar system
  - Must rely on small bodies.
- Residual mass (of small bodies) during regularization?
  - Of order the initial mass in outer solar system
    - Uncertainties: separation and instability onset
  - Perhaps somewhat smaller in inner solar system
    - delicate balance between accretion and shattering