New results on the formation of the Moon

Julien Salmon[1], Robin M. Canup[1]

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[1]Southwest Research Institute, Boulder CO, USA

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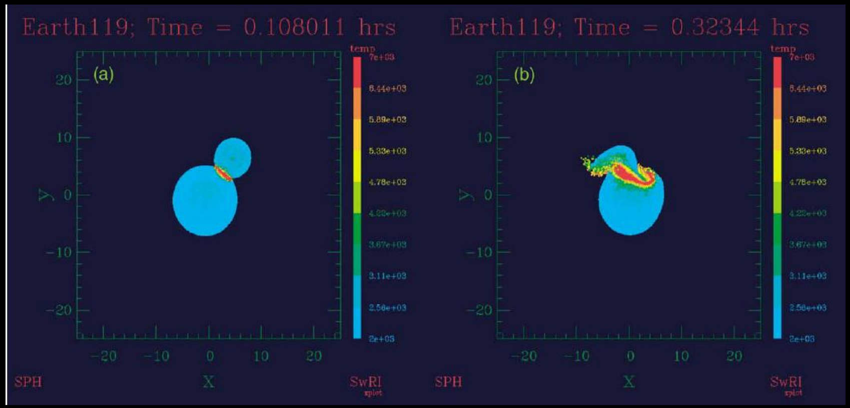
Giant impact hypothesis

- Impact of a ~Mars-size object on proto-Earth (Hartmann & Davis 1975 ; Cameron & Ward 1976)

- Formation of a circumterrestrial disk from impactor debris and ejected Earth mantle

- Accretion of the Moon from the disk

Previous work



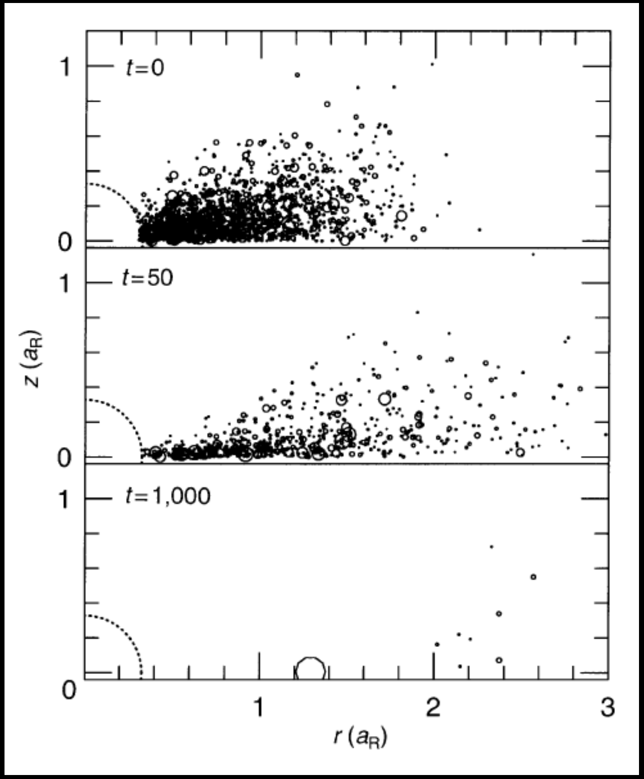
Giant impact simulations: formation of a 1.5-2 M_L disk (e.g. Benz et al. 1986, Canup 2004, 2008)

Moon accretion: N-body simulations of protolunar disk (Ida et al. 1997, Kokubo et al. 2000)

- Accretion of the Moon in < 1 year

BUT…

- Disk = mostly impactor debris
  - $\Rightarrow$ Earth-Moon isotopic similarities ?
- Such fast accretion implies completely molten Moon



Issues with pure N-body model

- Within Roche limit: gravitational instabilities + tidal disruption

  $\Rightarrow$ high collision rates

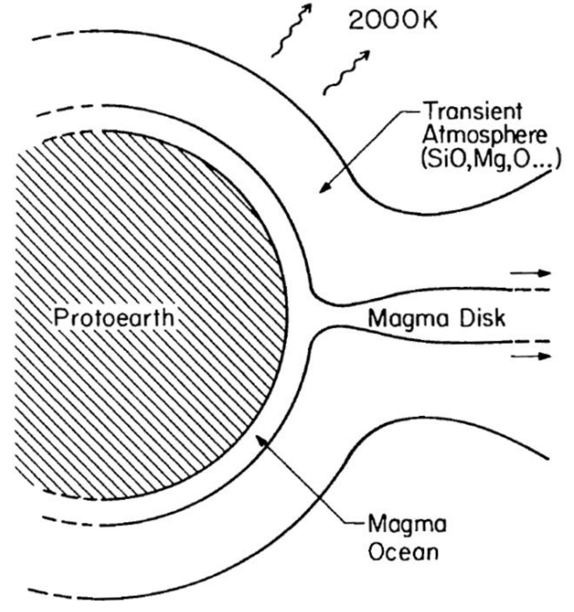
  $\Rightarrow$ a particle disk would rapidly vaporize
- Post-impact disk is melt + vapor

  $\neq$ individual particles

A more accurate modeling is needed

– Fluid disk within Roche limit

– Disk thermodynamics



From Stevenson (1987)

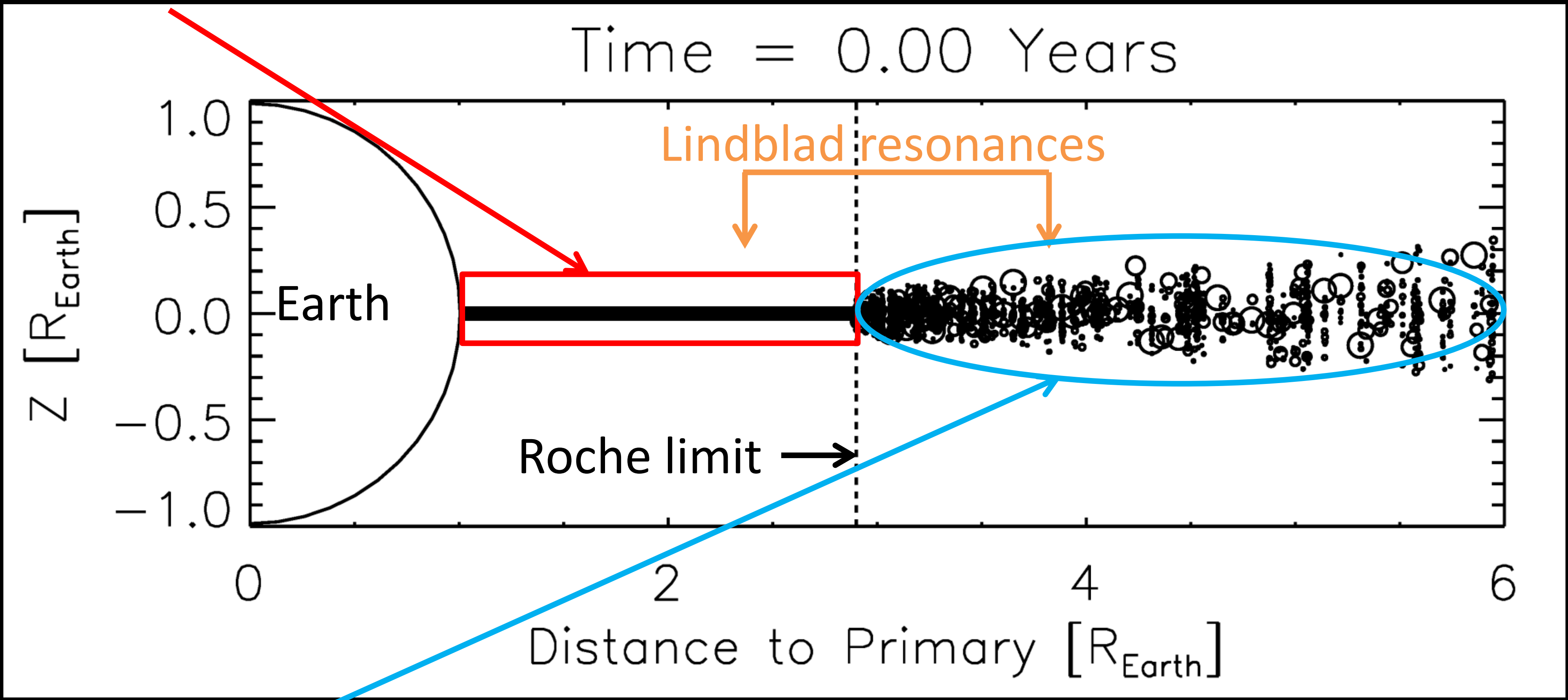
Question

Dynamics of lunar accretion from a fluid disk?

- Can we still form a ~ lunar mass object ?
- Accretion timescales ?
- Influence of the disk's thermodynamics ?
- Implications for Earth-Moon isotopic similarities ?

Our concept model

within Roche limit: uniform fluid disk



beyond Roche limit : individual particles tracked with N-body code SyMBA

See also Canup & Ward (2000)

Physical processes

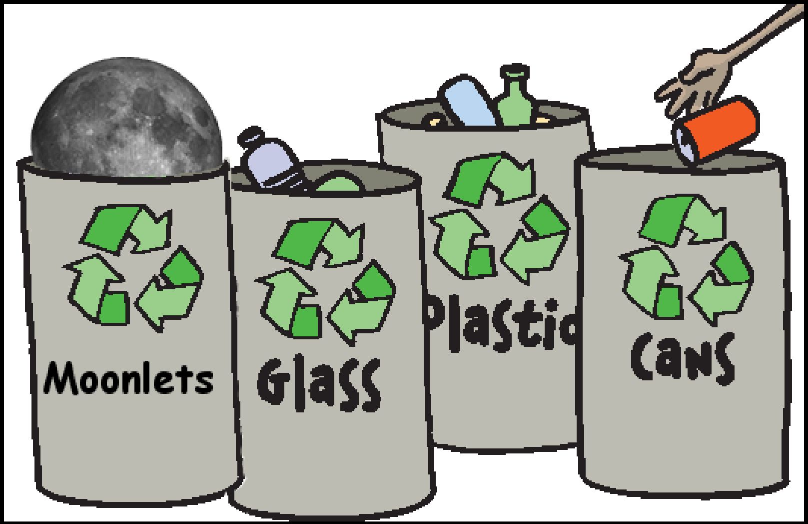
- Roche-interior disk spreads viscously
  - Physically motivated viscosity model (Ward & Cameron 1978; Thompson & Stevenson 1988)
  - Disk loses mass as it spreads onto planet
  - As material spreads beyond Roche limit, new moonlets added to N-Body code

- N-body outer disk: collisions treated with tidal accretion criteria

- Inner disk and outer moonlets interact through strongest Lindblad resonances
  - Moonlets orbits recede away from disk
  - Inner disk confined within Roche limit

Recycling moonetesimals

- Close encounters between outer moonlets can lead to scattering toward the Earth $\Rightarrow$ tidal disruption



- Tidal disruption criteria
  - Mass < $10^{-5} M_{\oplus}$
  - Position $< 2\ R_{\oplus}$
  - Body removed from N-body code
  - Mass and angular momentum added to inner disk

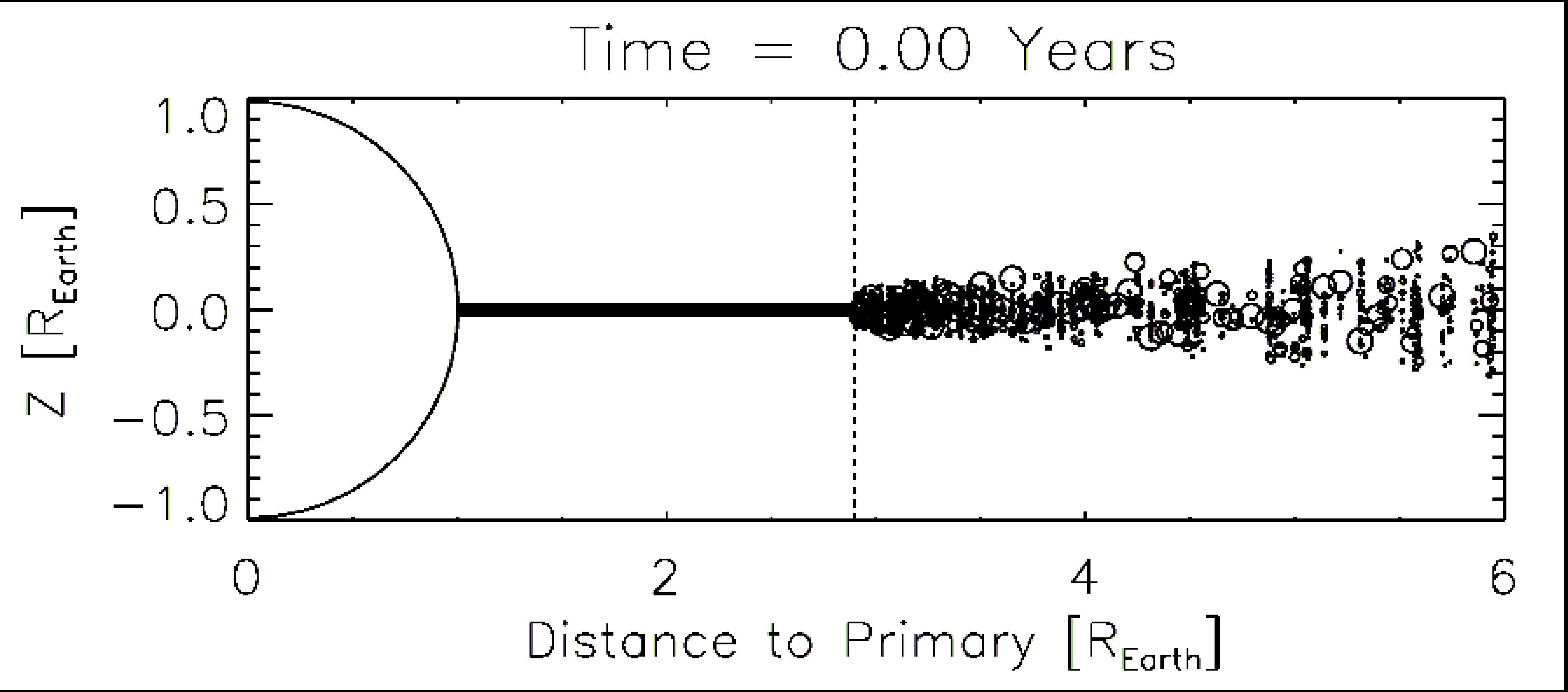
Initial setups

Table 3. Hybrid simulations parameters.

Run	L_d/M_d ($\sqrt{GM_\oplus a_R}$)	L_d (L_{EM})	M_d ($M_☾$)	M_{in} ($M_☾$)	M_{out} ($M_☾$)	q	a_{max} (a_R)
1	0.843	0.304	2.00	2.00	0.00	N/A	1
2	0.843	0.365	2.40	2.40	0.00	N/A	1
3	0.955	0.345	2.00	1.00	1.00	5	1.4
4	0.960	0.347	2.00	1.00	1.00	3	1.4
5	0.965	0.348	2.00	1.00	1.00	1	1.4
6	0.955	0.414	2.40	1.20	1.20	5	1.4
7	0.960	0.416	2.40	1.20	1.20	3	1.4
8	0.965	0.418	2.40	1.20	1.20	1	1.4
9	0.899	0.325	2.00	1.50	0.50	5	1.4
10	0.901	0.326	2.00	1.50	0.50	3	1.4
11	0.904	0.326	2.00	1.50	0.50	1	1.4
12	0.899	0.390	2.40	1.80	0.60	5	1.4
13	0.901	0.391	2.40	1.80	0.60	3	1.4
14	0.904	0.392	2.40	1.80	0.60	1	1.4
15	0.888	0.401	2.50	2.00	0.50	5	1.4
16	0.890	0.402	2.50	2.00	0.50	3	1.4
17	0.892	0.403	2.50	2.00	0.50	1	1.4
18	0.880	0.477	3.00	2.50	0.50	5	1.4
19	0.882	0.478	3.00	2.50	0.50	3	1.4
20	0.884	0.479	3.00	2.50	0.50	1	1.4
21	0.986	0.356	2.00	1.00	1.00	5	2.1
22	1.009	0.365	2.00	1.00	1.00	3	2.1
23	1.036	0.374	2.00	1.00	1.00	1	2.1
24	0.986	0.427	2.40	1.20	1.20	5	2.1
25	1.009	0.437	2.40	1.20	1.20	3	2.1
26	1.036	0.449	2.40	1.20	1.20	1	2.1
27	0.914	0.330	2.00	1.50	0.50	5	2.1
28	0.926	0.335	2.00	1.50	0.50	3	2.1
29	0.940	0.339	2.00	1.50	0.50	1	2.1
30	0.914	0.396	2.40	1.80	0.60	5	2.1
31	0.926	0.401	2.40	1.80	0.60	3	2.1
32	0.940	0.407	2.40	1.80	0.60	1	2.1
33	0.900	0.406	2.50	2.00	0.50	5	2.1
34	0.909	0.411	2.50	2.00	0.50	3	2.1
35	0.920	0.416	2.50	2.00	0.50	1	2.1
36	0.890	0.482	3.00	2.50	0.50	5	2.1
37	0.898	0.487	3.00	2.50	0.50	3	2.1
38	0.907	0.492	3.00	2.50	0.50	1	2.1
39	1.068	0.386	2.00	1.00	1.00	1	2.4
40	1.068	0.463	2.00	1.20	1.20	1	2.4
41	0.998	0.361	2.00	1.00	1.00	5	2.8
42	1.043	0.377	2.00	1.00	1.00	3	2.8
43	1.099	0.397	2.00	1.00	1.00	1	2.8
44	0.998	0.433	2.40	1.20	1.20	5	2.8
45	1.043	0.452	2.40	1.20	1.20	3	2.8
46	1.098	0.476	2.40	1.20	1.20	1	2.8

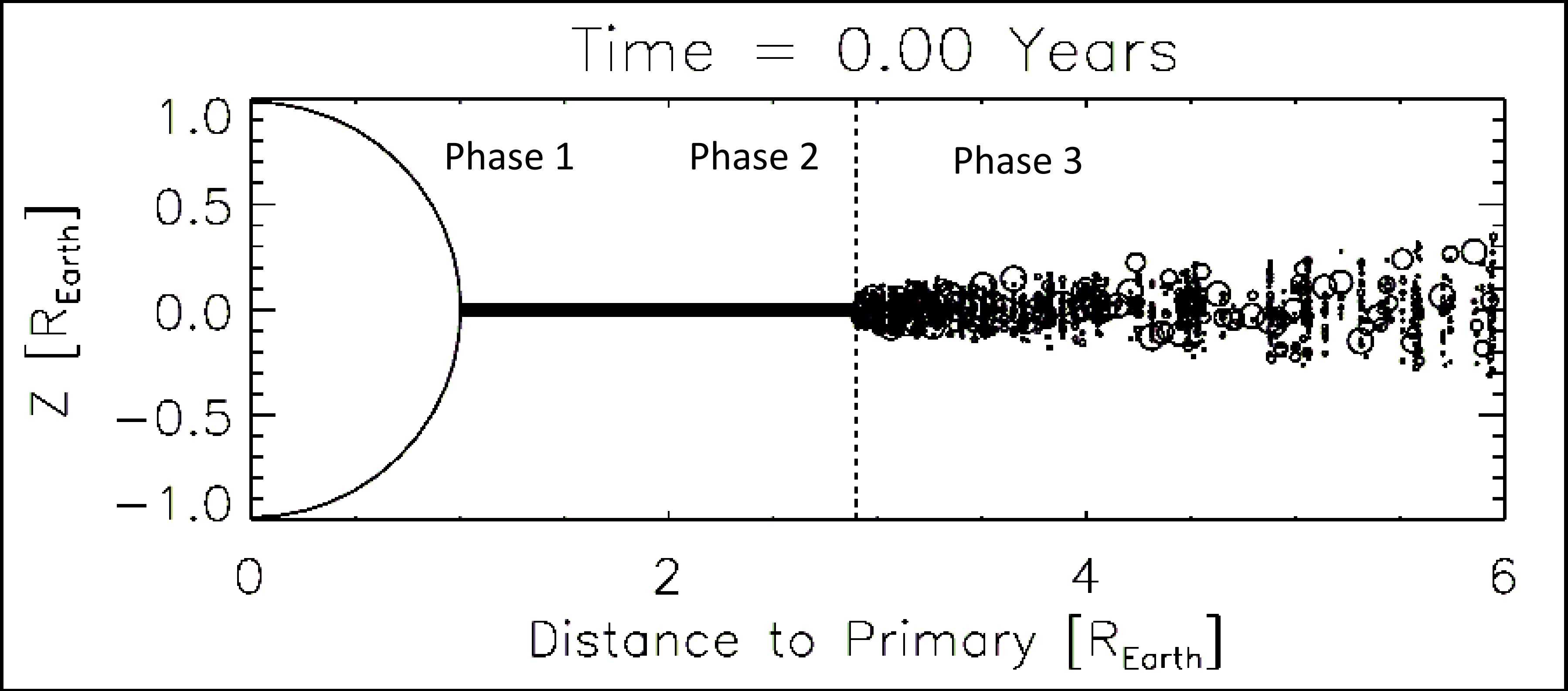
- 46 initial configurations using parameters from impact simulations
  - Total disk mass: 2 to 3 M_L
  - Inner disk mass: 50 to 100% of total mass
  - Outer disk edge: 4 to 8 $R_\oplus$
- 1500 initial particles in outer disk

A typical simulation



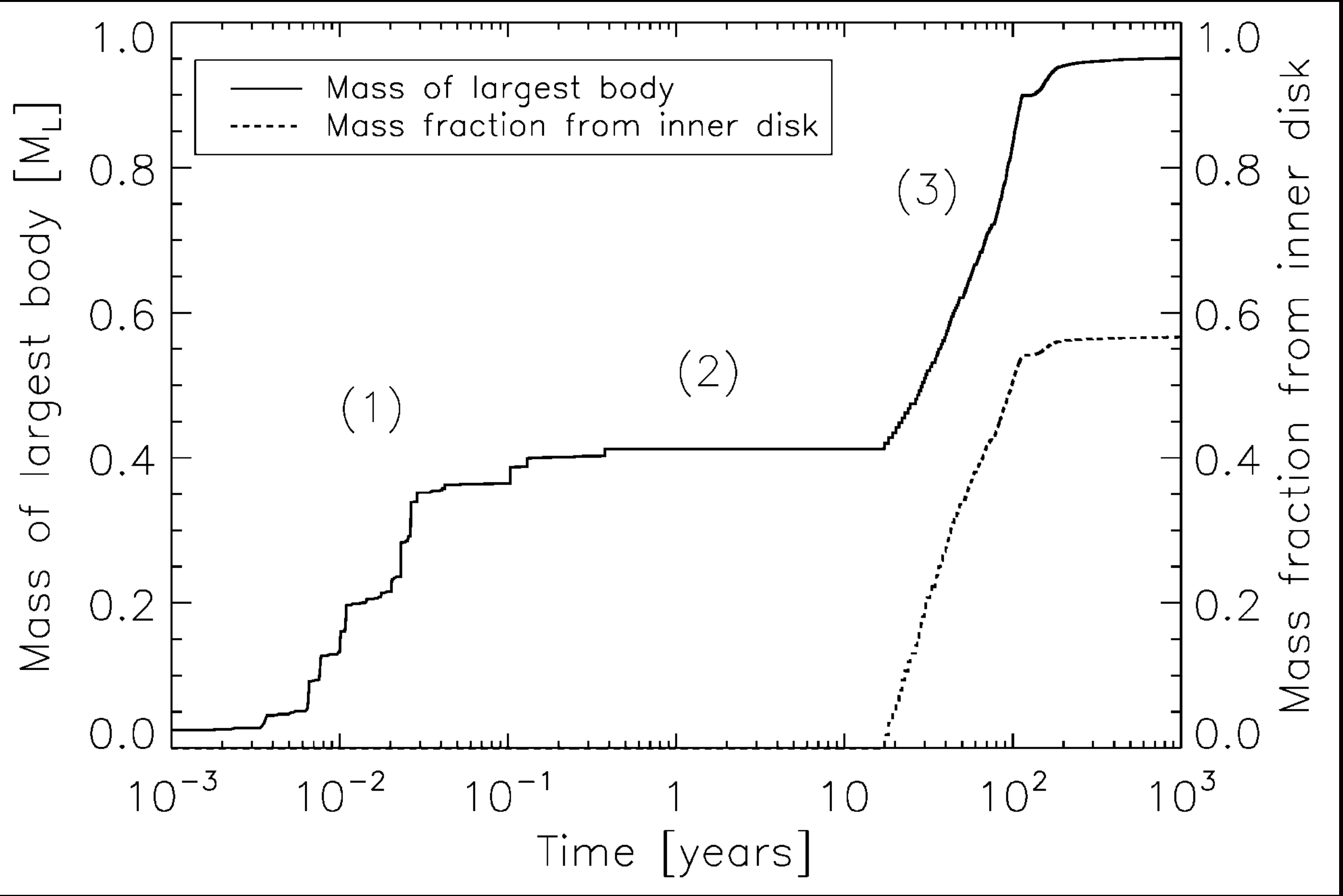
- Mass inner disk: 2 M_L
- Mass outer disk: 0.5 M_L
- Outer edge: 6 $R_\oplus$

A typical simulation

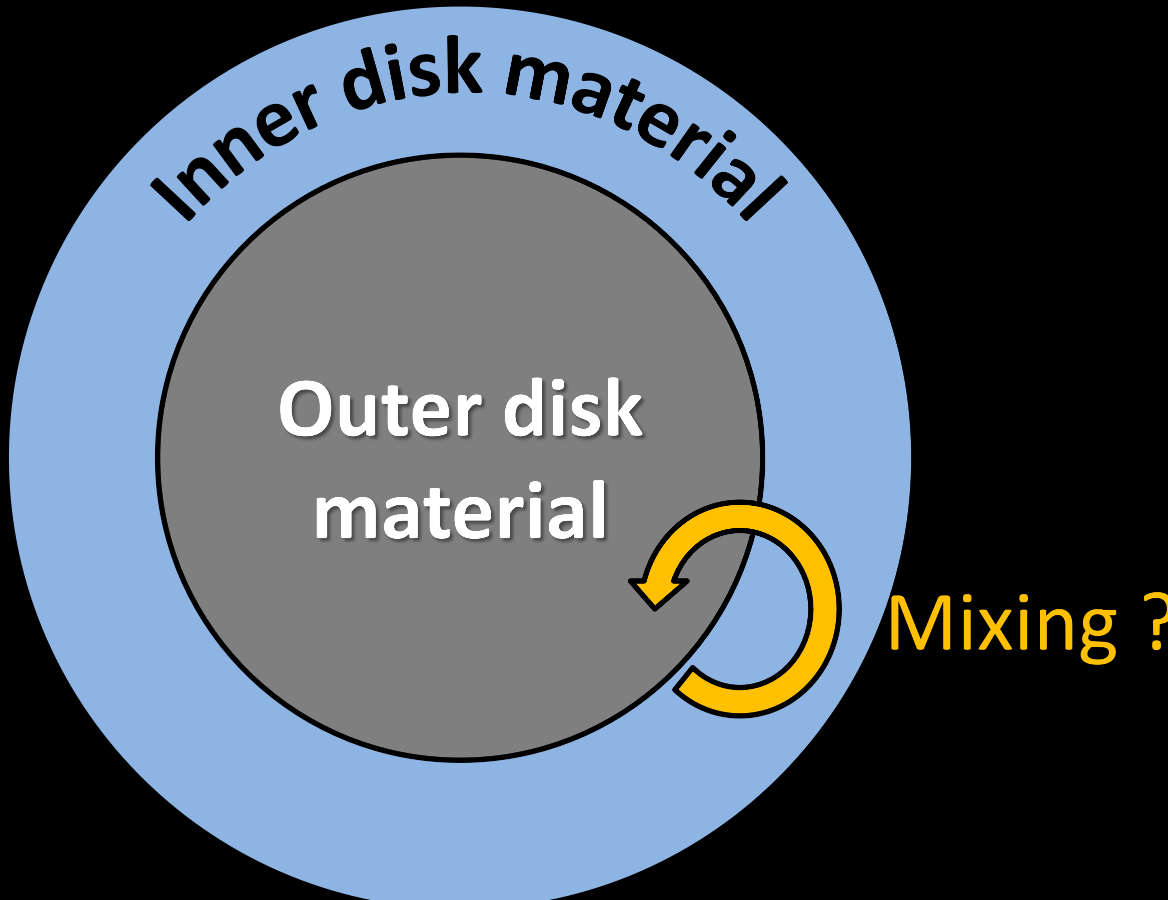


- Phase 1: outer bodies accrete and confine inner disk inside Roche limit
- Phase 2: inner disk slowly viscously spreads back out
- Phase 3: new bodies accrete at Roche limit and continue growth of the moon + serve as relay with inner disk causing moon orbit to expand

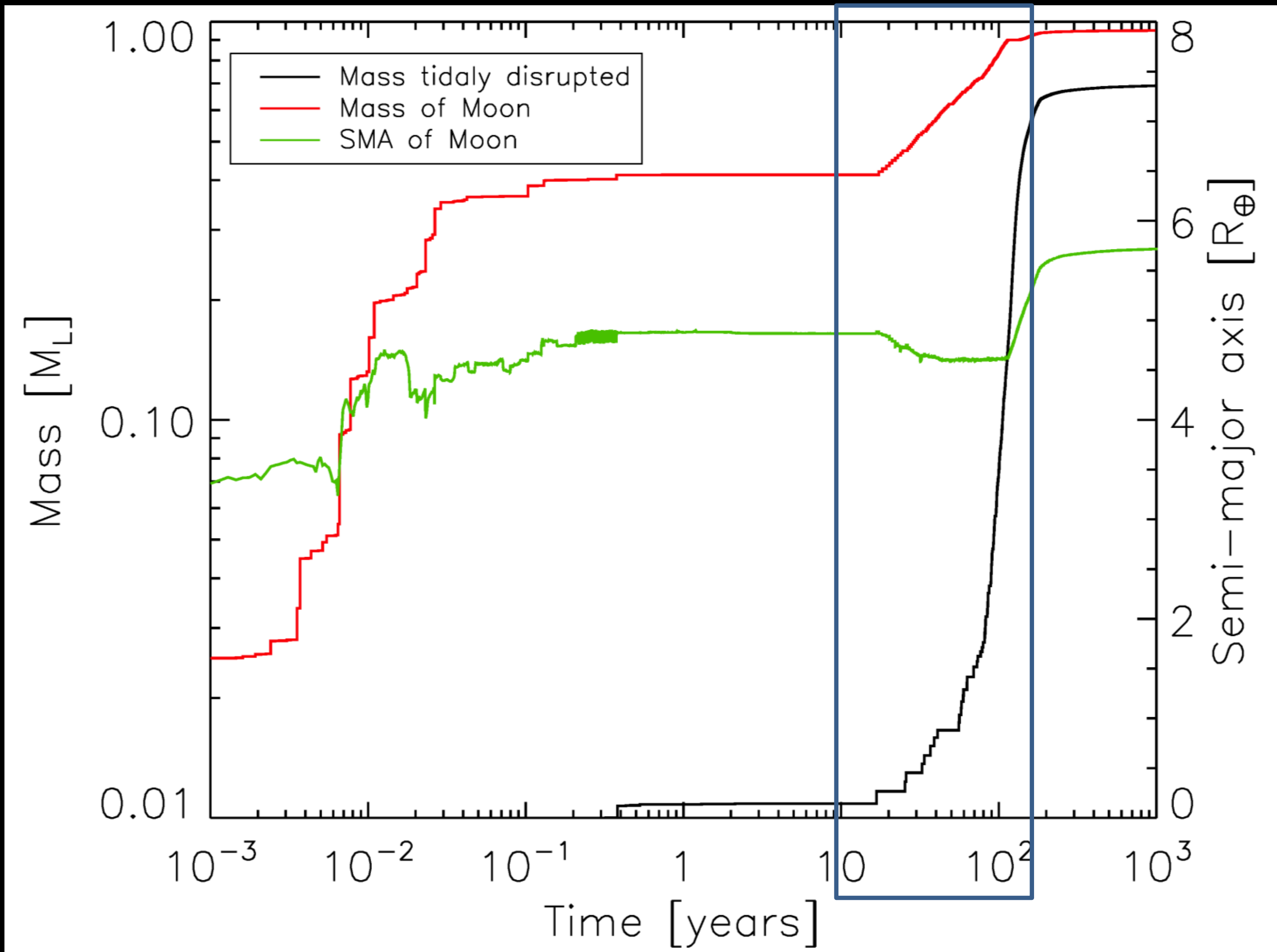
A long 3-step accretion



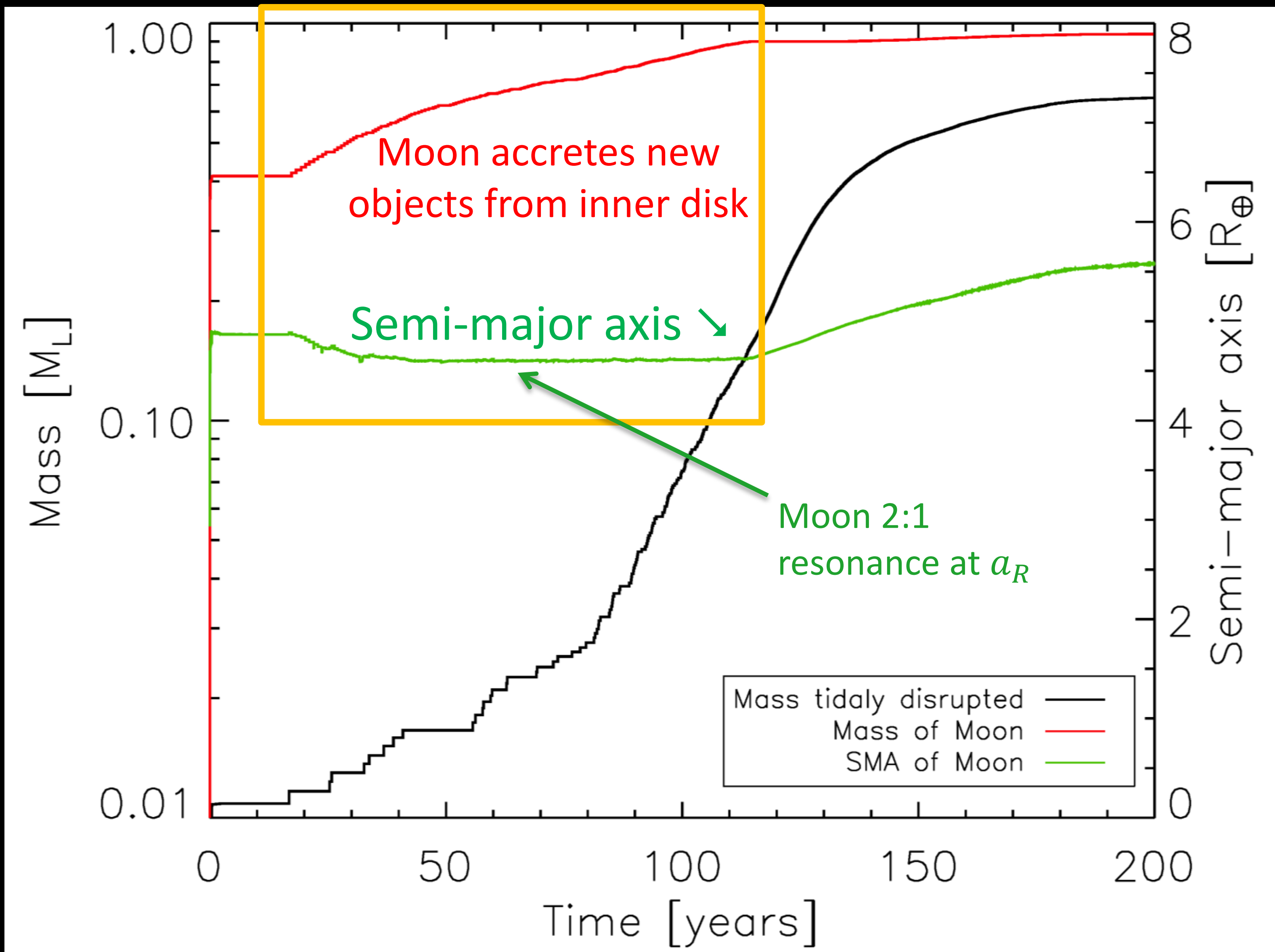
Resulting Moon structure ?



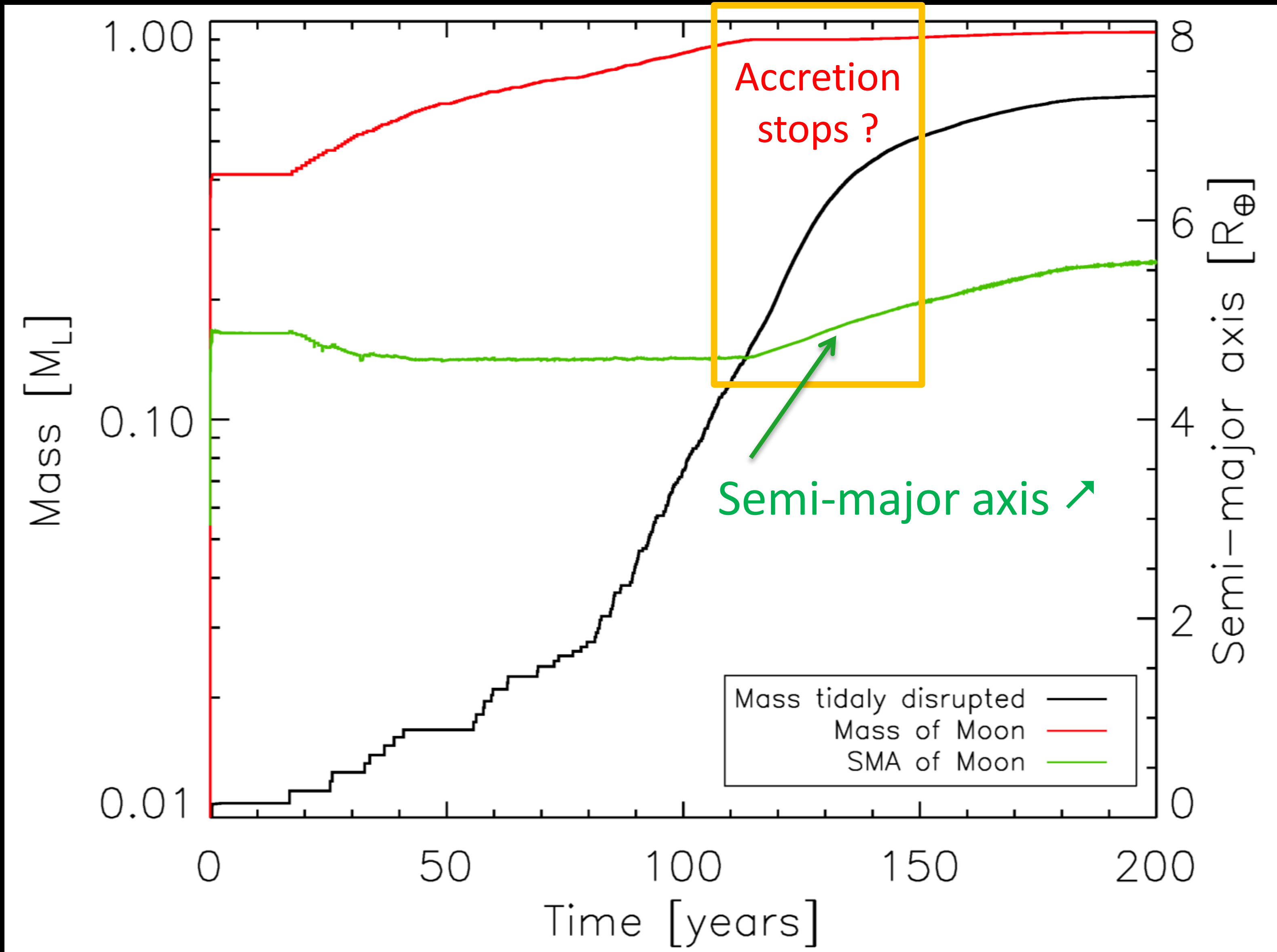
Moon mass and position



Moon mass and position



Moon mass and position



Conditions for accretion

- To accrete on Moon, bodies spawned at Roche limit must get on moon-crossing orbits

  $\Rightarrow$ expand sma and/or increase eccentricity

  Disk resonant torque

  Close encounter with Moon

- If particles gets high ecc before sma is expanded
  - Pericenter $< 2R_\oplus \Rightarrow$ Tidal disruption

- Each scattering event leads to increase of Moon semi-major axis (cf. planetesimal driven migration)

Conditions for accretion

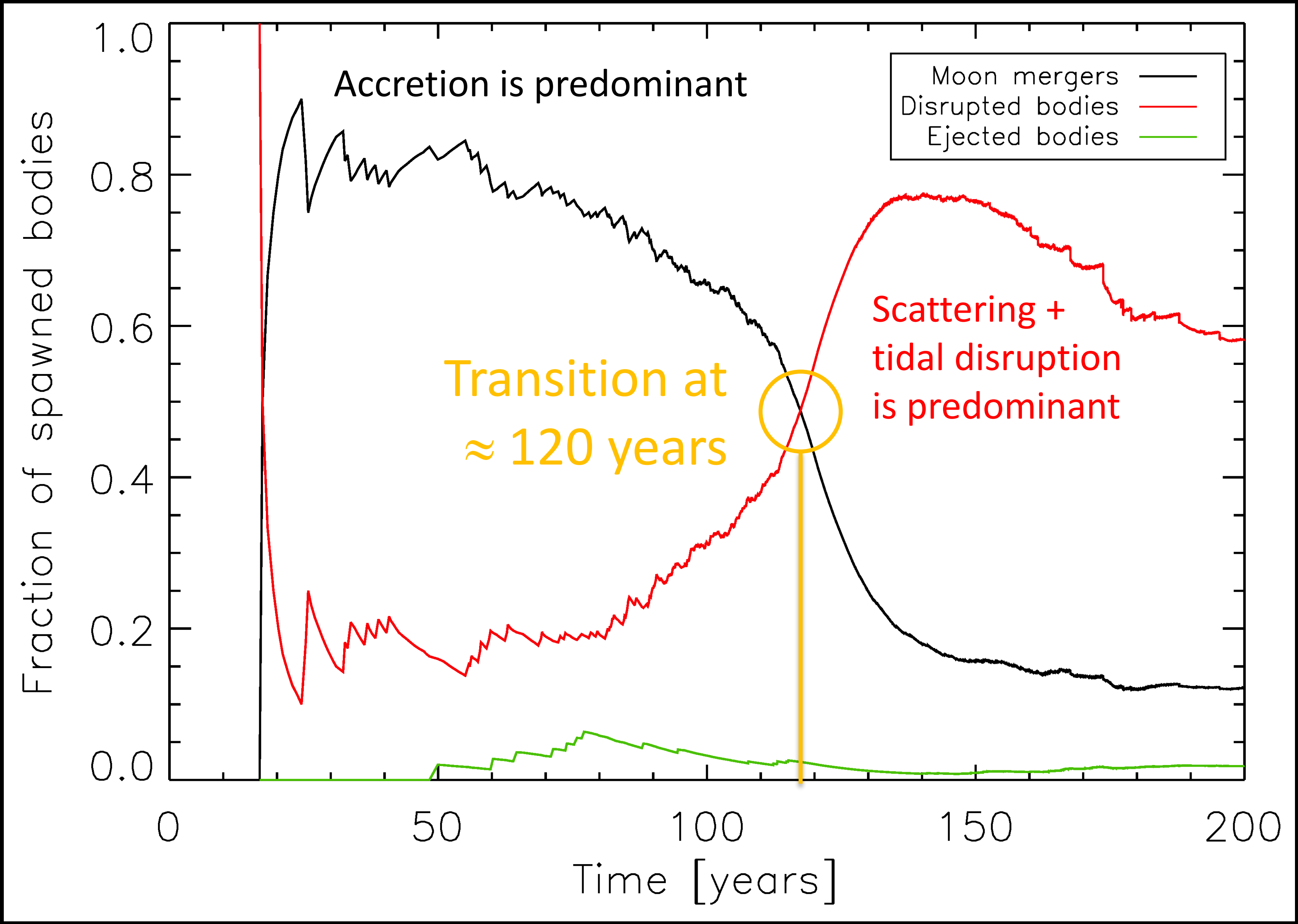
As time goes by:

1. inner disk mass decreases
   - Resonant torque decreases
   - Moonlets sma expansion timescale increases

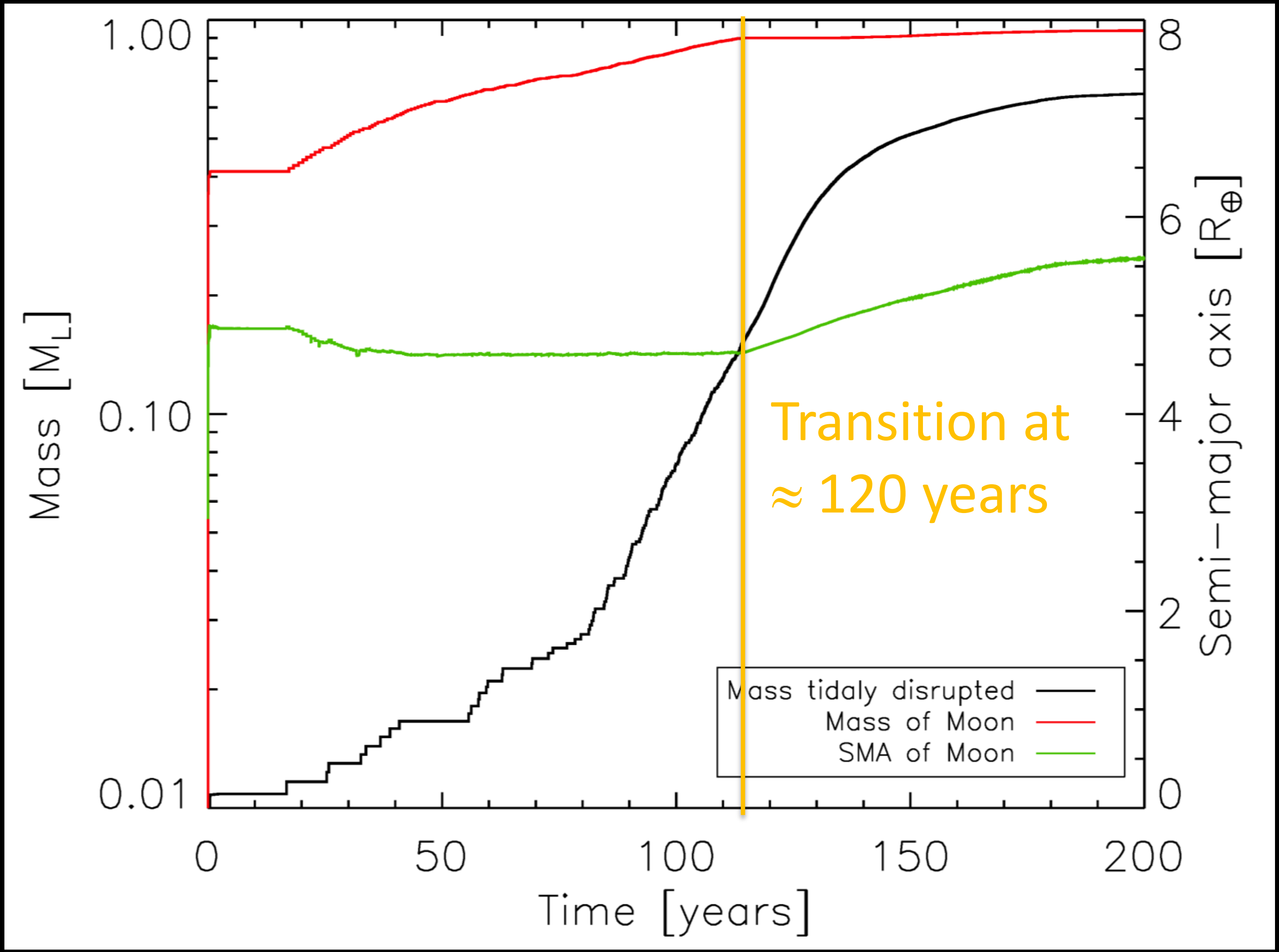
2. Moon mass increases
   - Scattering efficiency increases
   - Moonlets eccentricity excited more rapidly

It becomes increasingly difficult for new objects to collide with the Moon before being tidally disrupted

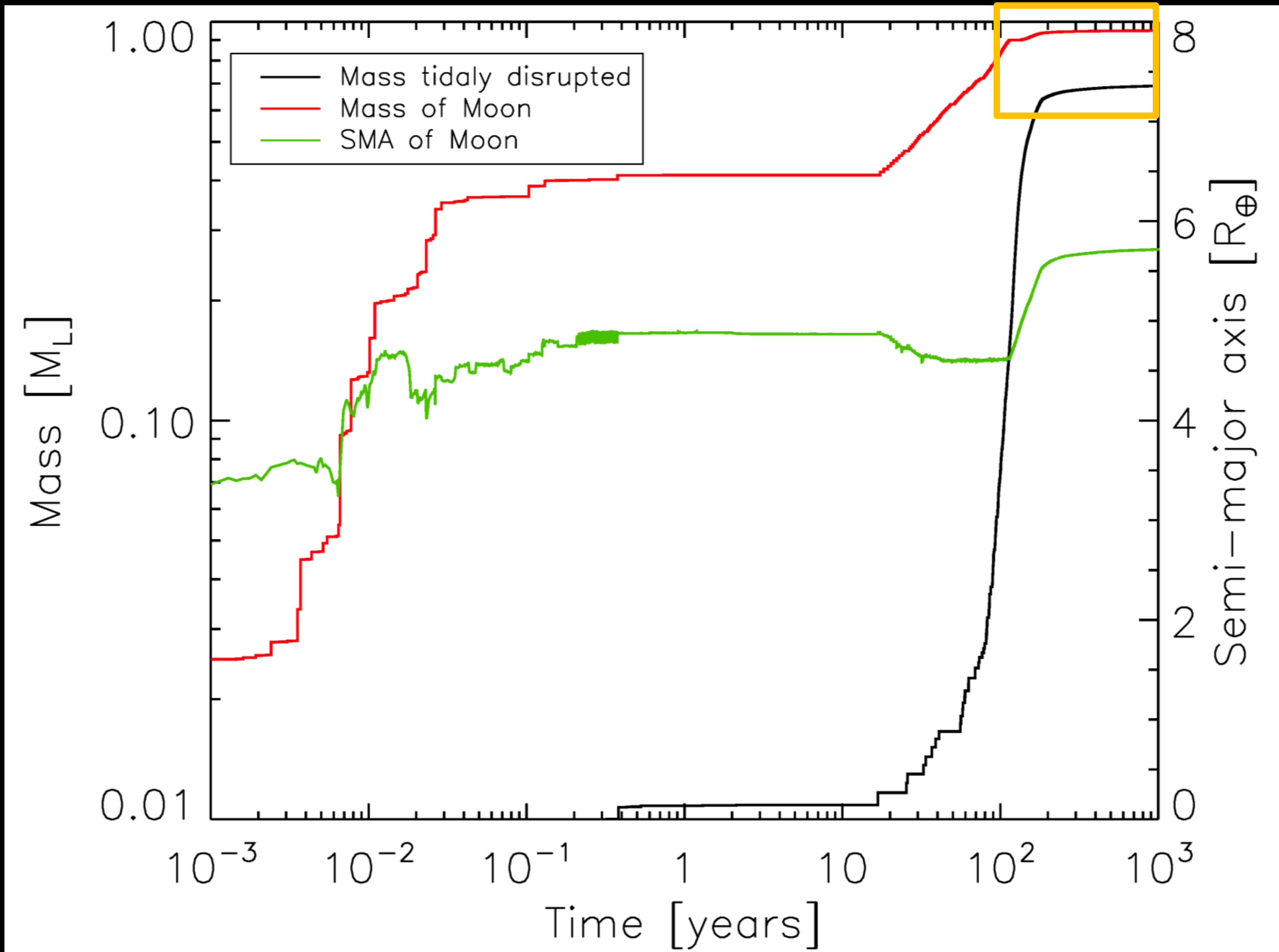
Fraction of new objects merging with Moon



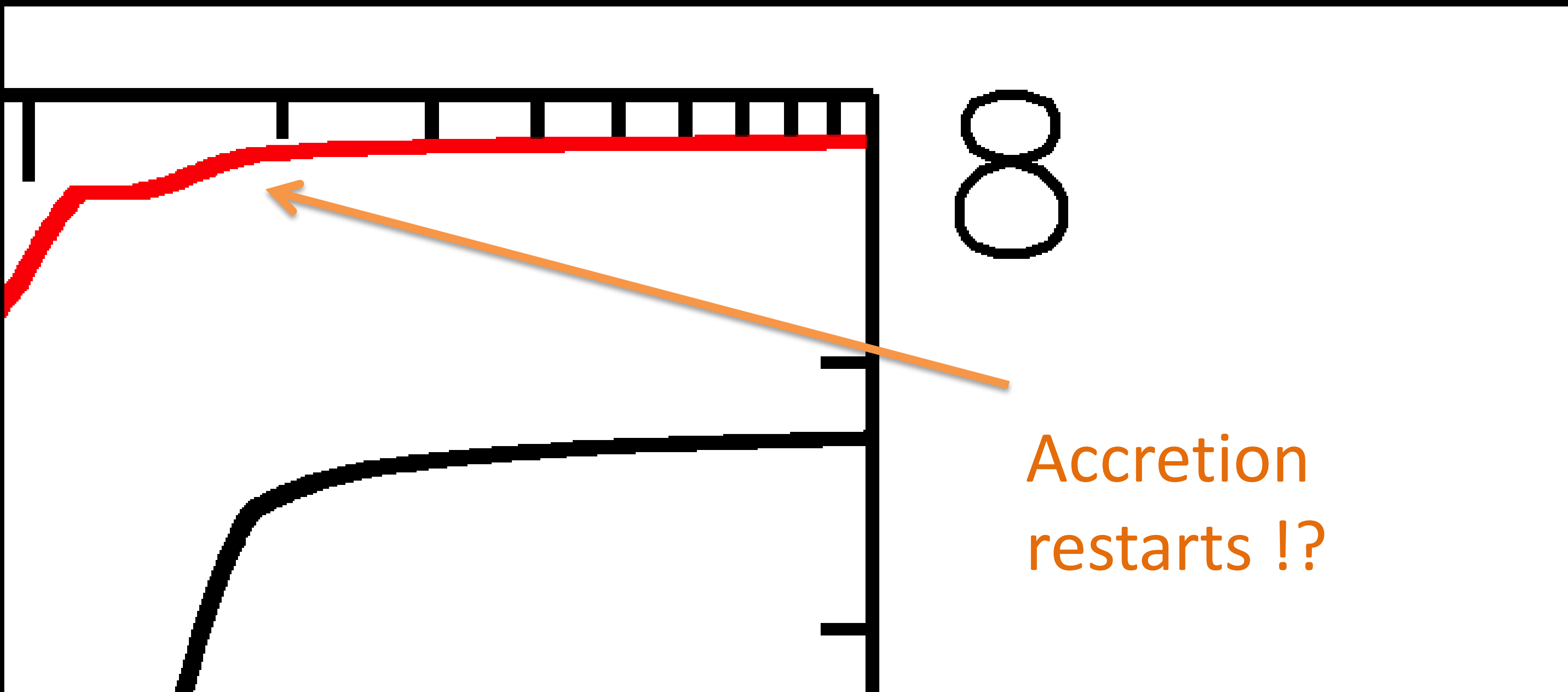
Moon mass and position



Late evolution



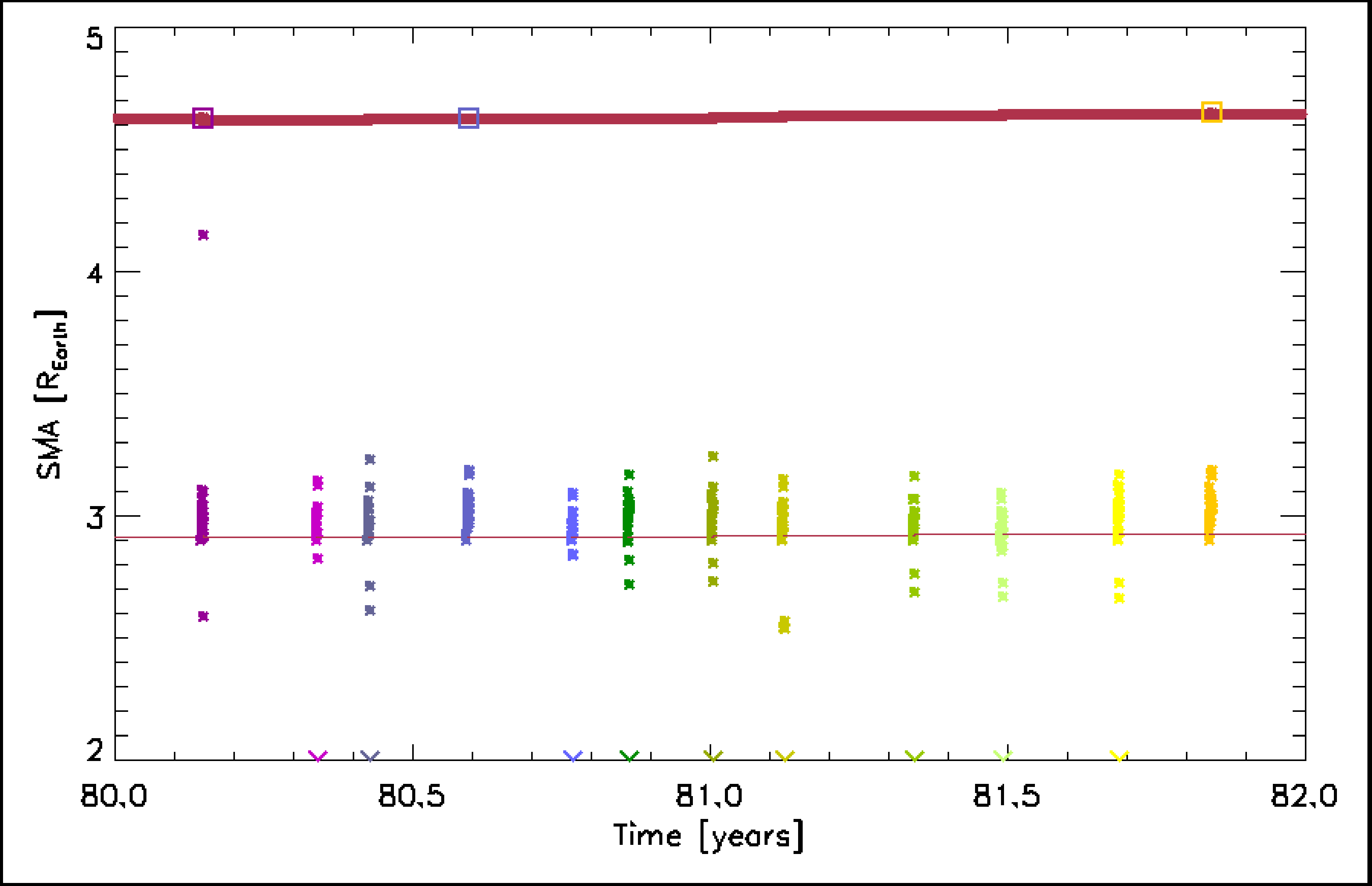
Late evolution



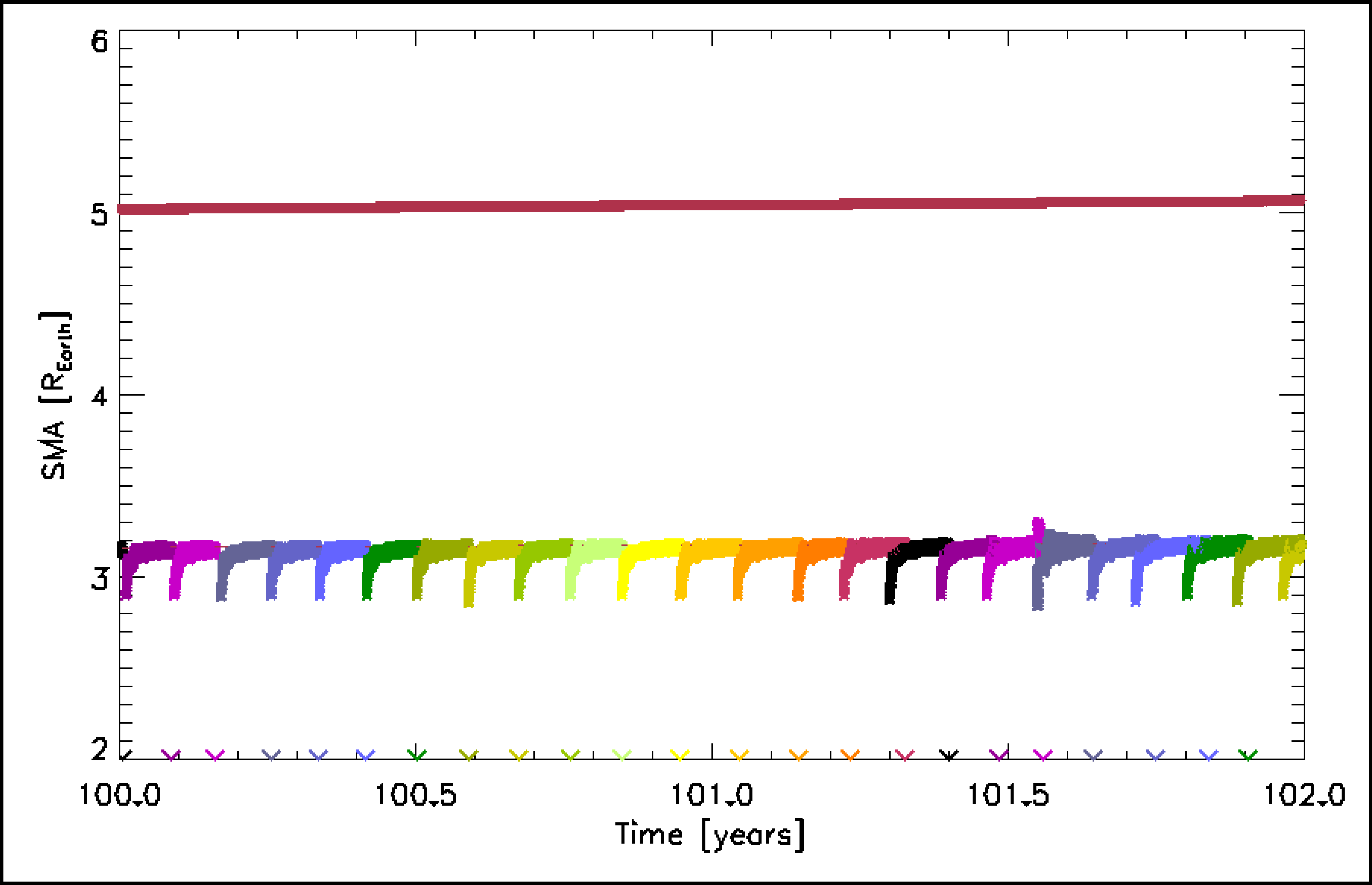
Capture in resonance

- At end of Phase (1), Moon's 2:1 mean motion resonance lies just outside of inner disk
- First new moonlets move outward rapidly and cross the resonance
- Later, disk push less efficient + Moon farther away $\Rightarrow$ capture

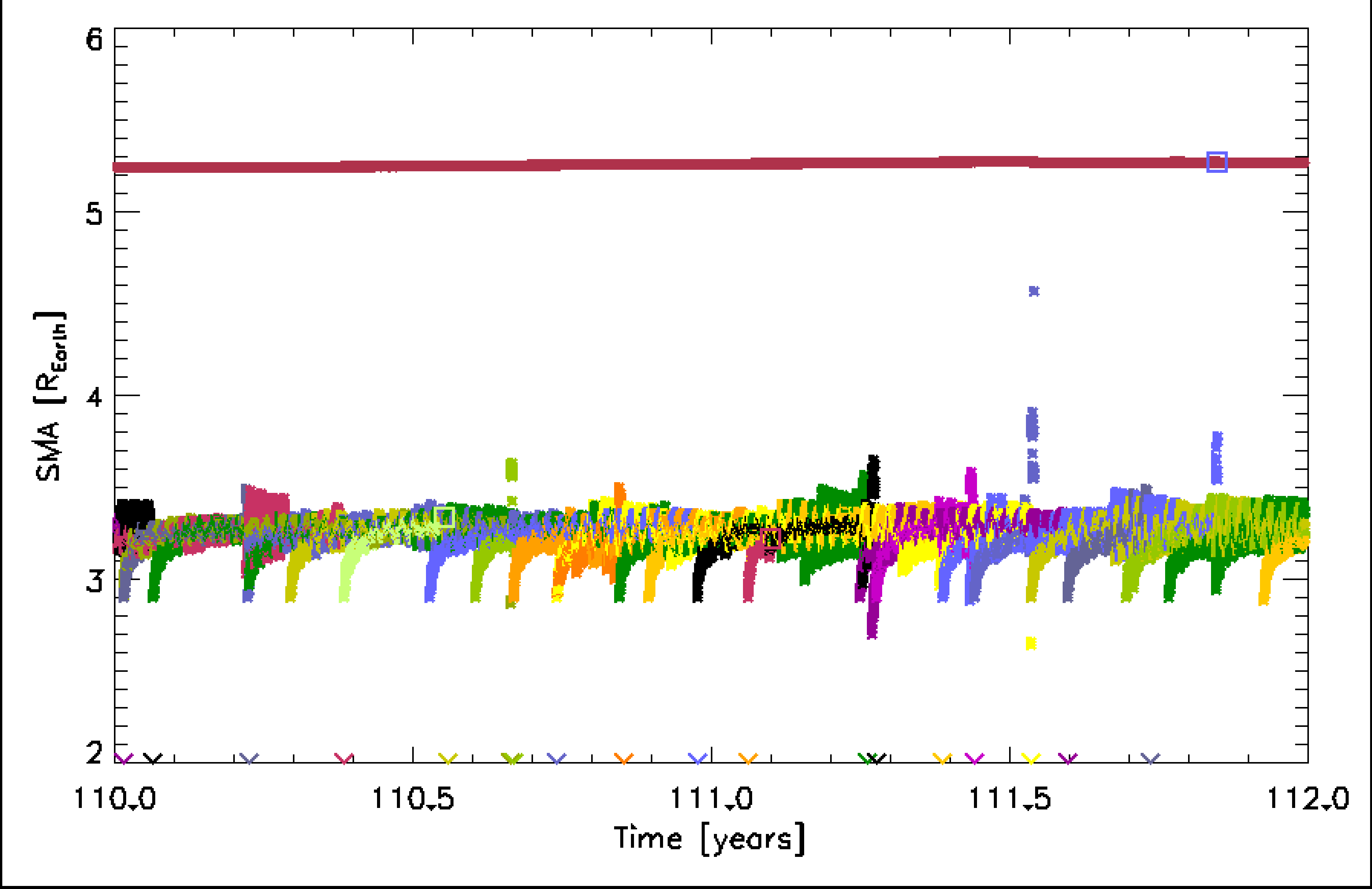
First moonlets cross the resonance



Capture into resonance



Ejection from the resonance



Summary

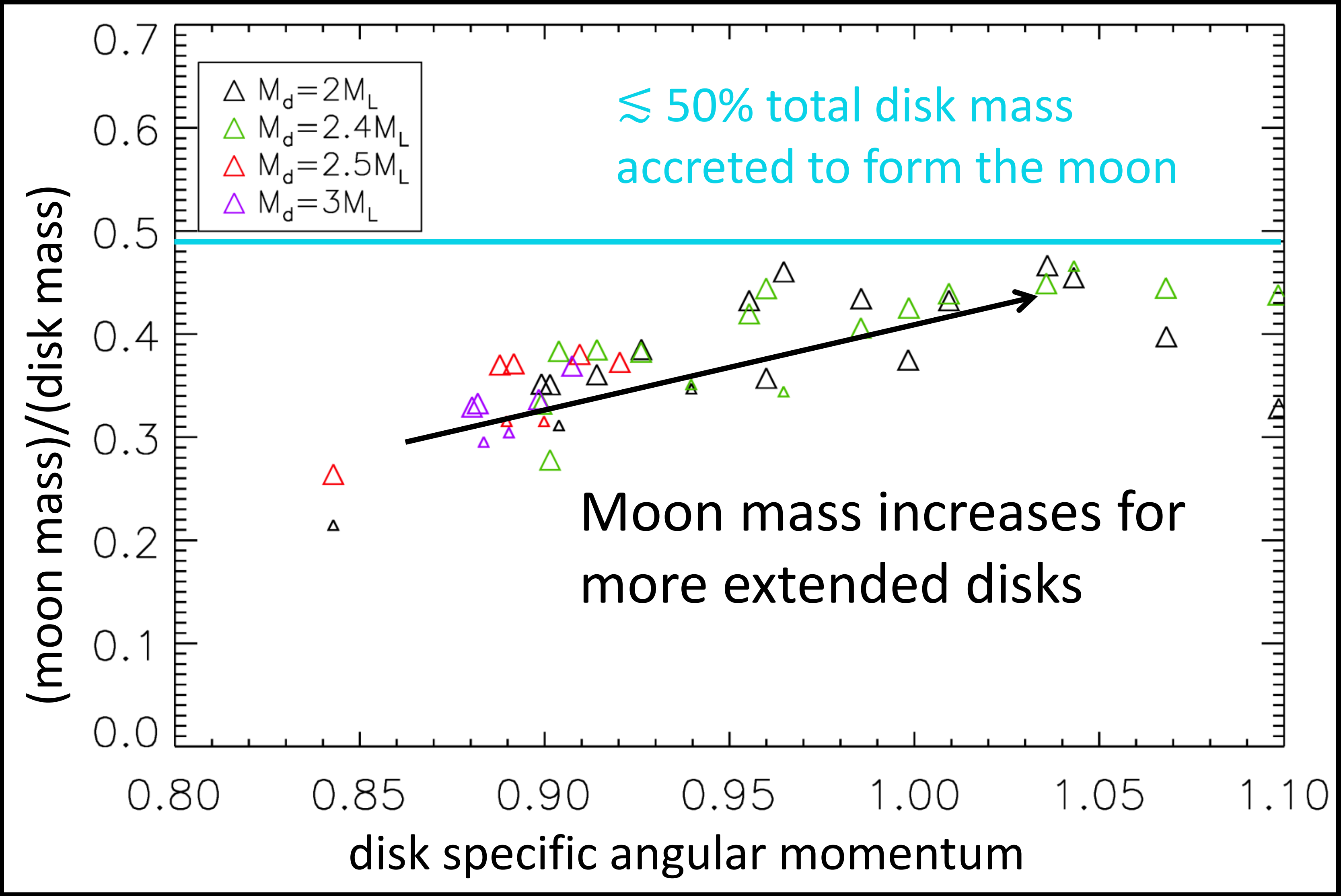
1. Initial outer bodies form a lunar « core »
2. New bodies formed at Roche limit pushed by disk and accrete on moon
3. Disk push becomes less efficient
   a. Moonlets scattered inward
   b. Moon migrates outward
4. Moonlets get captured into moon resonance
   a. Scattering continues
   b. moonlets ejected from resonance through mutual interactions can accrete on moon

Global results

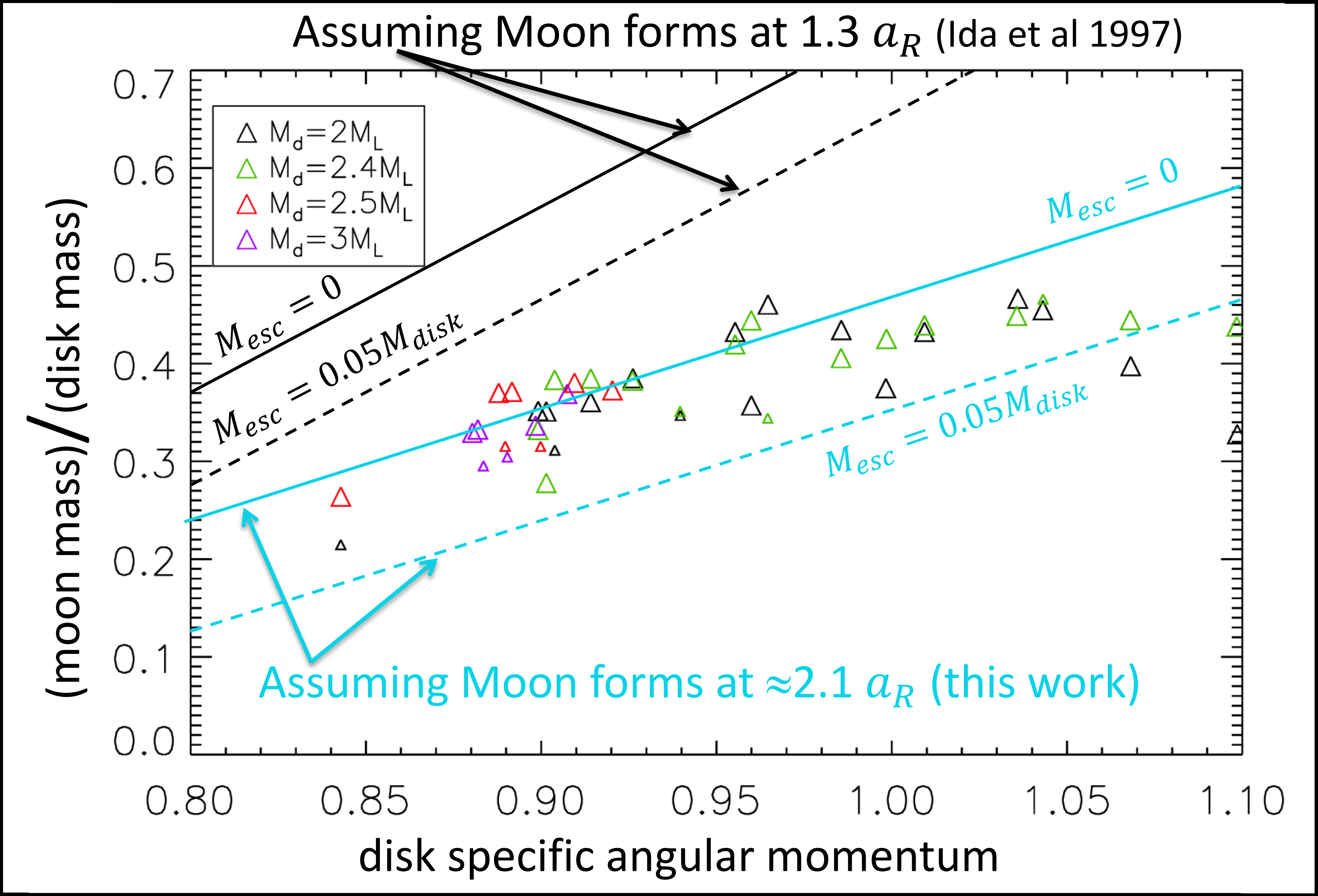
Average moon properties at t=1000 years

- Mass: 0.81 ± 0.21 M_L
- Semi-major axis: 2.15 ± 0.3 a_R, > 1.3 a_R in N-body
- Accretion timescale $\sim 10^2$ years, ≫ 1 year in N-body
- Mass fraction of inner disk material: 5 to 65%

Moon mass Vs. disk specific angular momentum

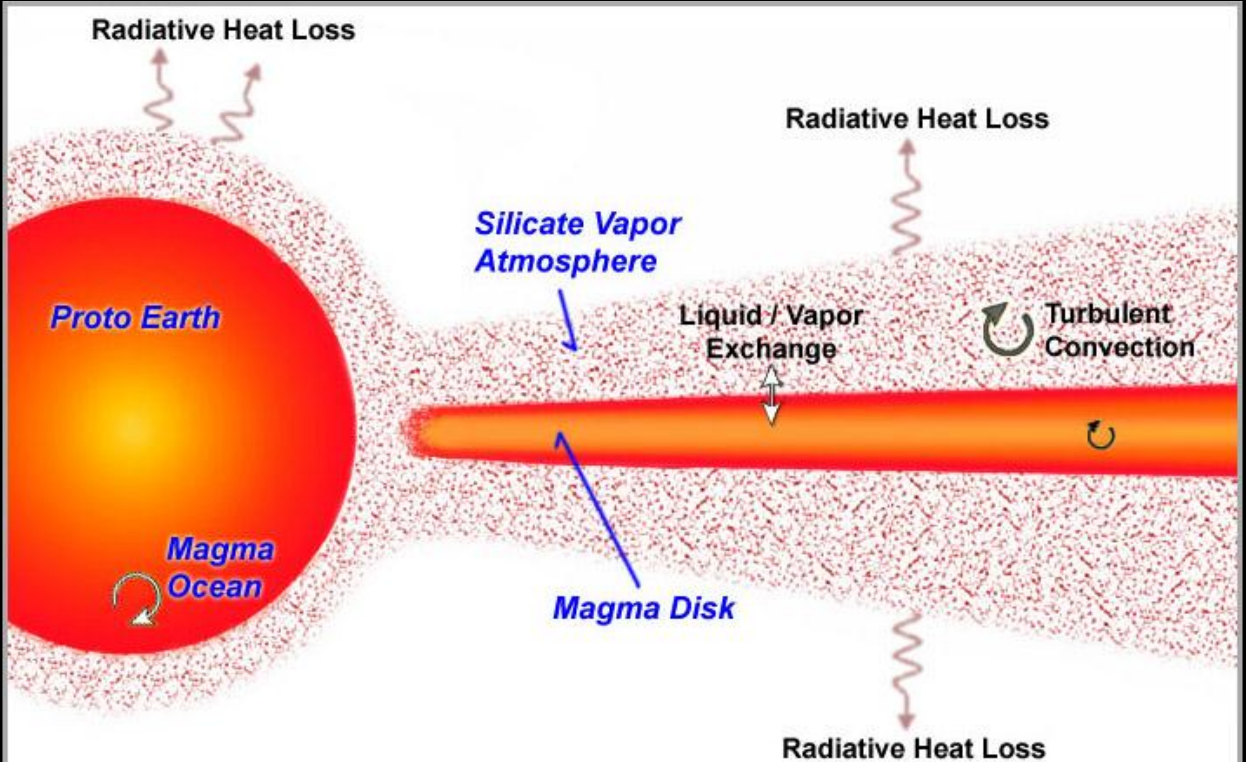


Analytical estimates



Equilibration

- Earth and Moon share striking isotopic similarities (O, Ti, W, …)
- Impact simulations: disk is mostly impactor material ≠ Earth ?



(PSRD graphic based on Pahlevan and Stevenson, 2007, *EPSL*, v. 262, p.438-449, Fig. 3.)

- Material exchange between Earth and disk's atmospheres
- Compositional equilibration in ~100-1000 years (Pahlevan & Stevenson 2007)

What our results imply

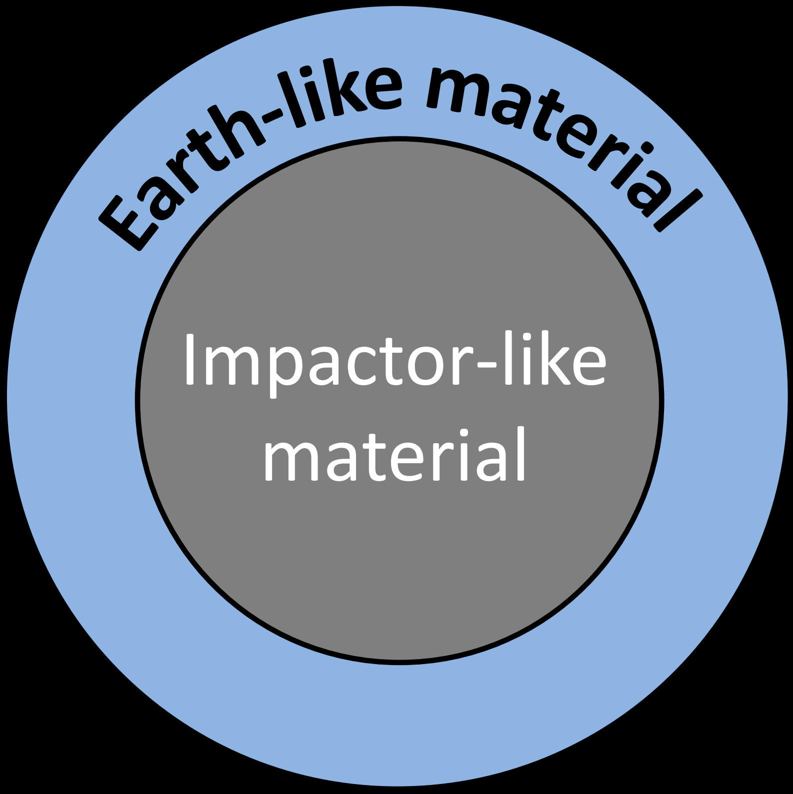
- Accretion timescales ~ 200 years

  ⇒ compatible with estimated equilibration timescales
- 3-steps accretion: "Earth-like" material accreted last

A 1 M_L object with 60% inner disk material

=> ~ 460km-deep "Earth-like" outer layer

Mare basalts estimated to have formed at ~ 500km



Conclusion

Consideration of a fluid inner disk drastically changes the dynamics of Moon accretion

- 3-stage accretion
- Longer timescales ~200 years
- Moon forms farther away

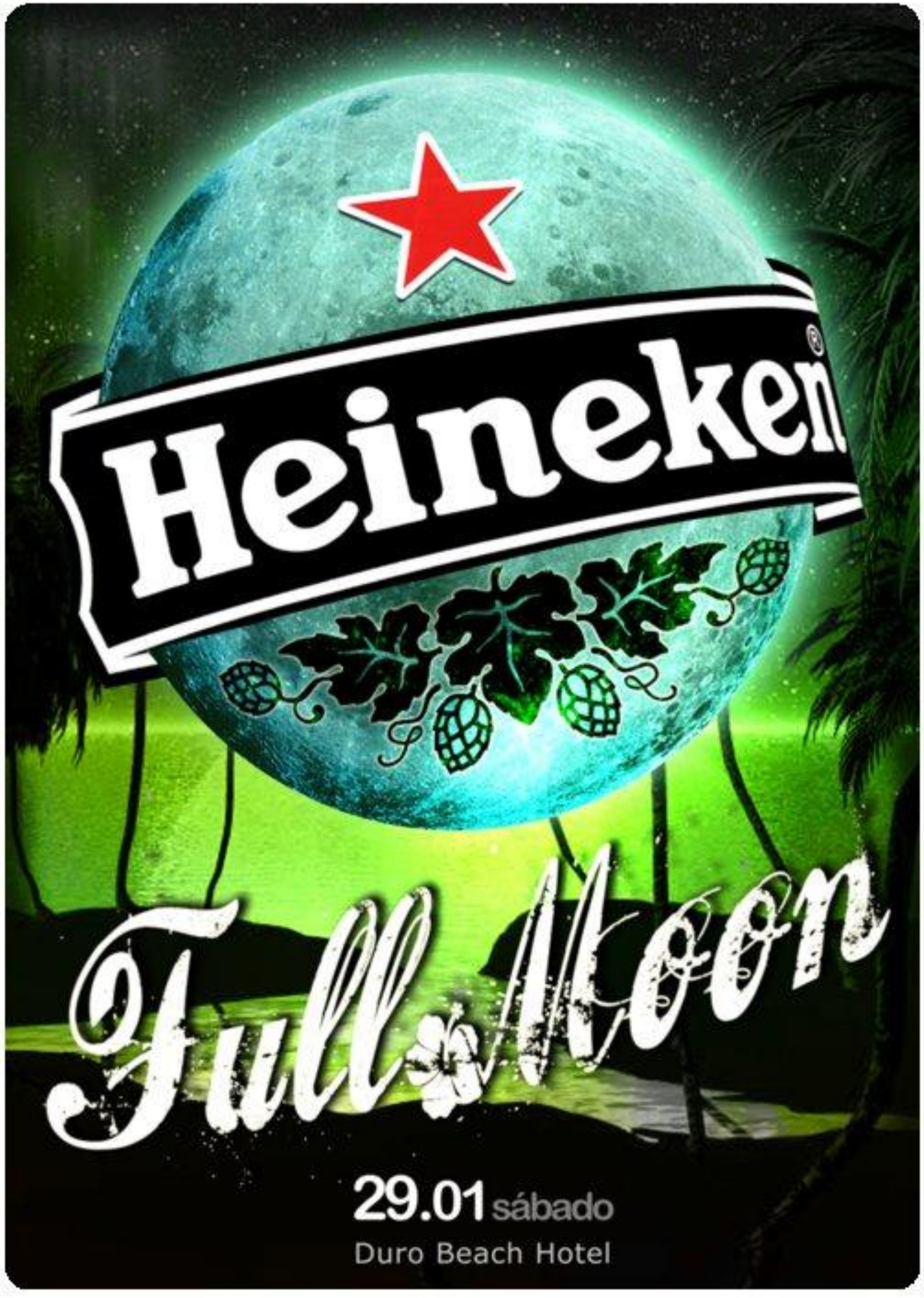
Accretion limited by confinement of inner disk + scattering/capture in resonance of moonlets

Positive implications regarding isotopic similarities

Paper submitted to ApJ

Future work

- Full hydro simulation of the inner disk (e.g. Charnoz, Salmon & Crida 2010)
- Improved inner disk model from recent theoretical studies (Ward 2012)
- Further explore the range of initial parameters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