Giant Planet Formation:

episodic impacts vs. gradual core growth

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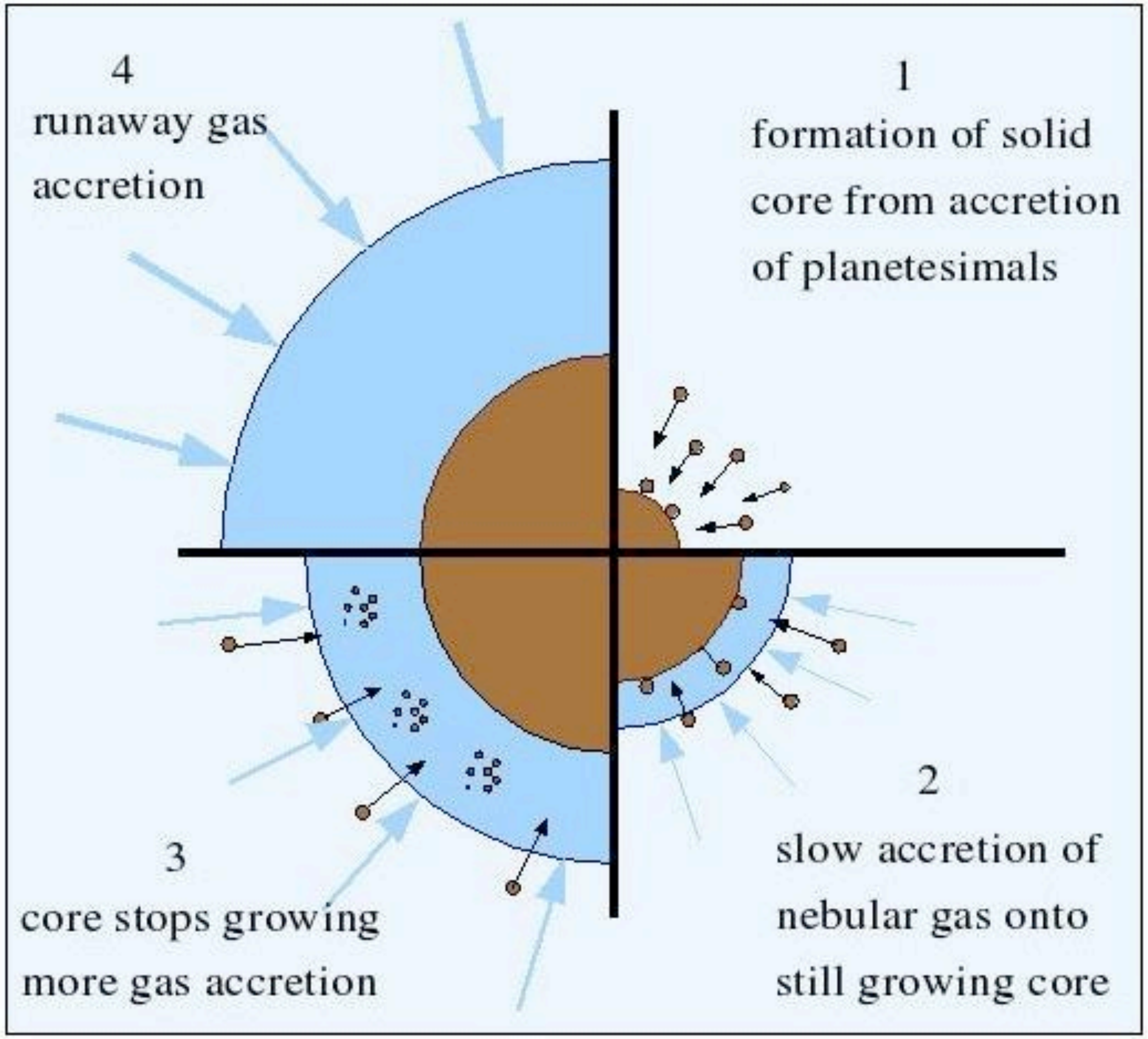
Outline

- Motivation:
  core growth by giant impacts important for giant planet formation?
- Methods
  impact modeling and numeric scheme
- Validation
- Results
- Conclusion

the core accretion paradigm

- This model could be called the standard model and has been first worked out by Mizuno (1980, Progress of Theoretical Physics, 64, 544) and Bodenheimer & Pollack (1986, Icarus, 67, 391). It was refined in great detail by Pollack et al. (1996, Icarus, 124, 62) and extended recently by Alibert et al. (2004, AA, 434, 343).
- In these models a solid core accretes first. Once this core reaches a critical mass (of order 10 Mearth) the gaseous envelope is accreted in a runaway process.



Motivation

- The planetesimal accretion rate is an important parameter in the core accretion scenario
- For numerical convenience, formation models use gradual core growth modelled by a rate equation
- However, in the oligarchic growth regime, possibly:
  - the core growth is dominated by large impacts
  - the mass ratio is large, e.g. 0.1

Does this change the current picture of giant planet growth?

Methods

Procedure

- Replace constant dM_z/dt with „impacts“
- Impacts are modelled as Gaussian dM_z/dt curve: width gives timescale
- Parameters:
    - impact mass
    - impact timescale
    - (initial & background rate)
- Study thermal response on impact

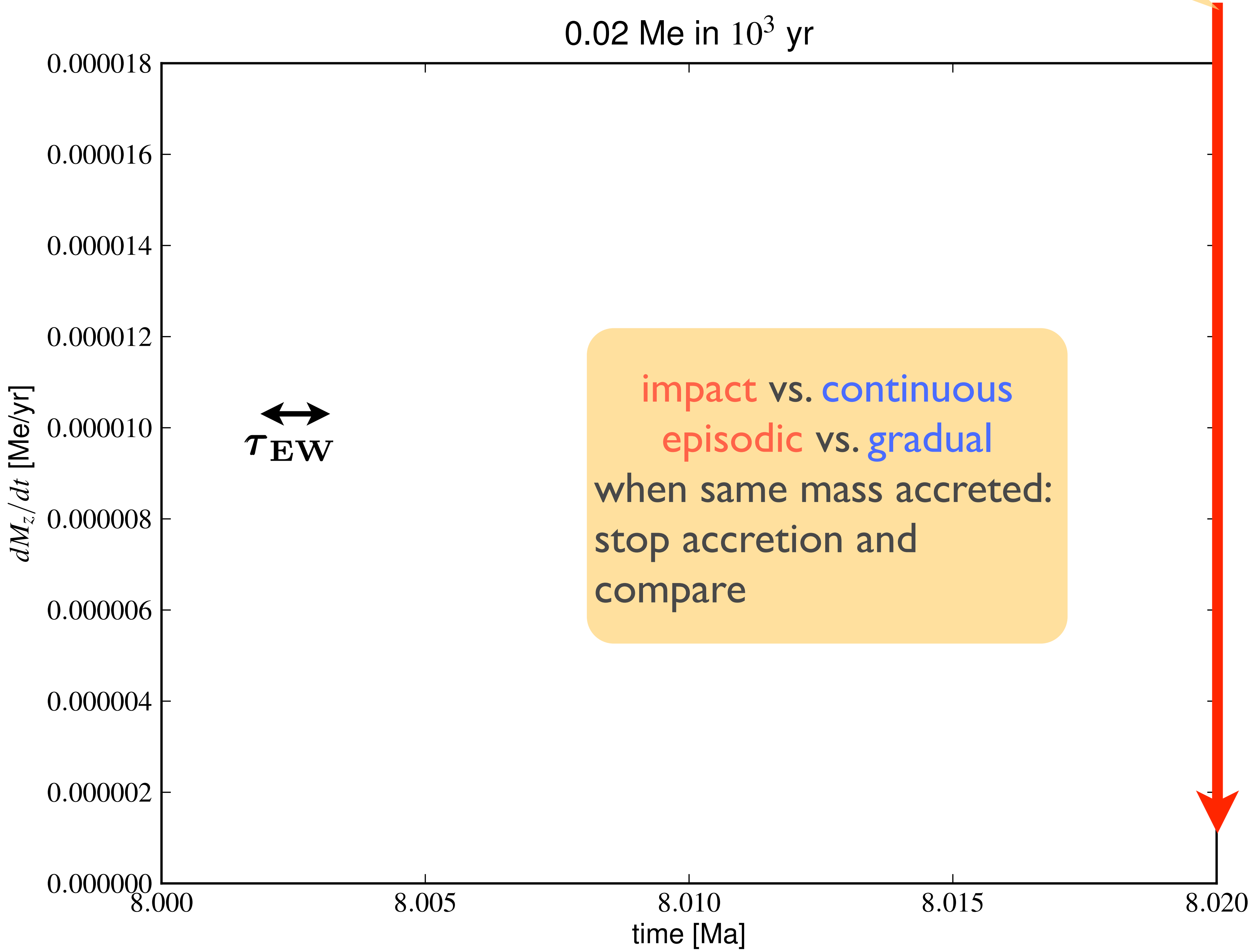
impact model

core growth rate

compare here!

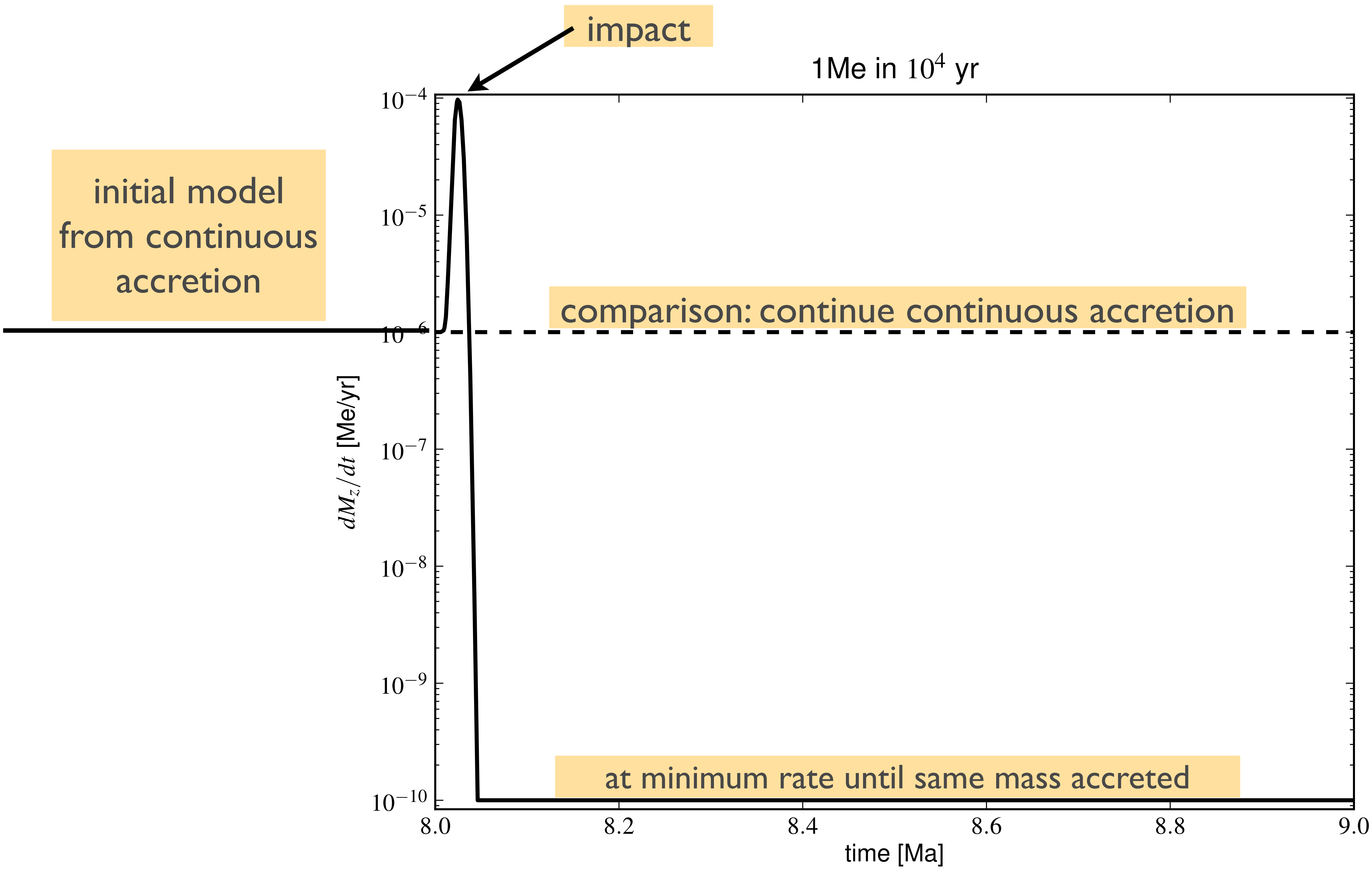
parameters:
- impact mass
- impact timescale

$$\tau_{EW} = \sigma\sqrt{2\pi}$$



impact vs. continuous
episodic vs. gradual
when same mass accreted:
stop accretion and
compare

core growth rate log scale



impact

initial model from continuous accretion

comparison: continue continuous accretion

at minimum rate until same mass accreted

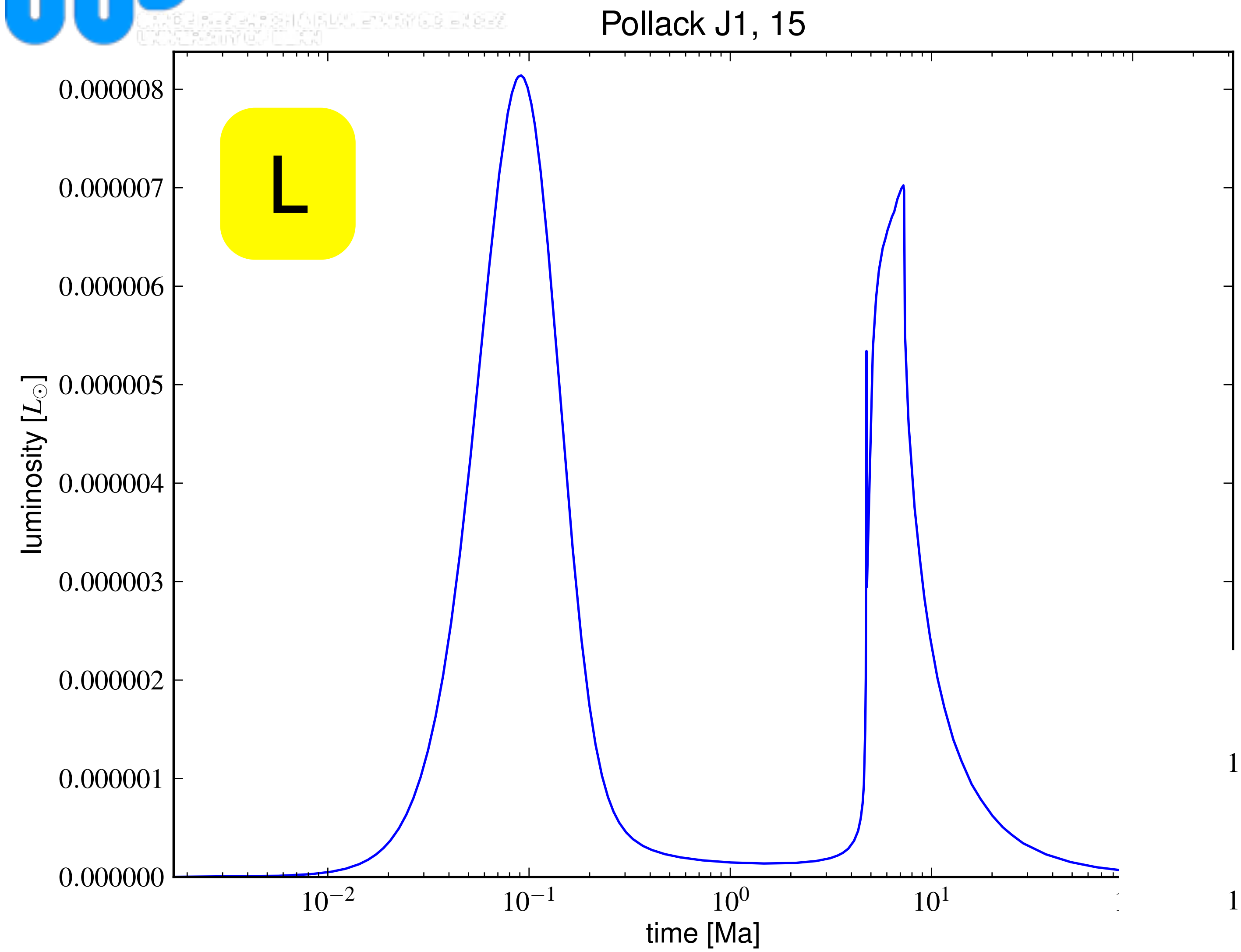
Calculation

- Henyey type code with self-adaptive 1D grid
- Stellar structure equations
- Quasi-hydrostatic equilibrium
- Impact timescale t_{imp}: $t_{\mathrm{dyn}} \ll t_{\mathrm{imp}} \ll t_{\mathrm{KH}}$
- Neglect energy deposition in atmosphere
- Material
  - Saumon et al. (1995) EOS
  - Opacities: [Bodenheimer & Pollack (1986) + Alexander & Ferguson (1994) + weiss et al. (1990)] bzw. [Ferguson et al. (2005)]

code verification

Verification: Jupiter formation (Pollack J1)

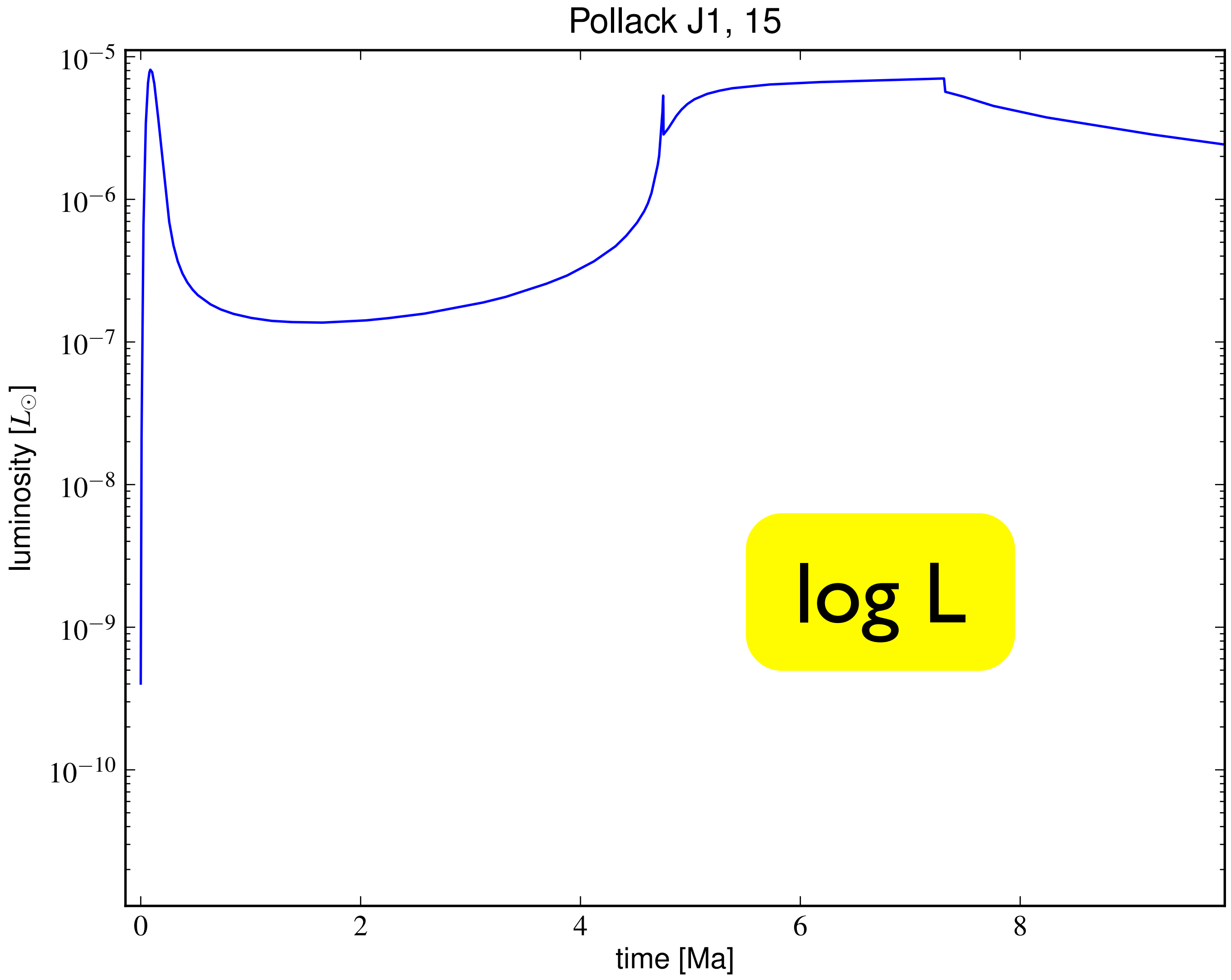
- Model
  - feeding zone: left and right of planet
  - give Sigma_0
  - no migration
- Simplifications / differences:
  - capture radius = core radius
  - feeding zone width = 4 hill radii
  - const. grav. focussing: $F_g=10^5$
  - outer BC: hill radius
- Maximum gas accretion rate 10^{-4} M_e/yr



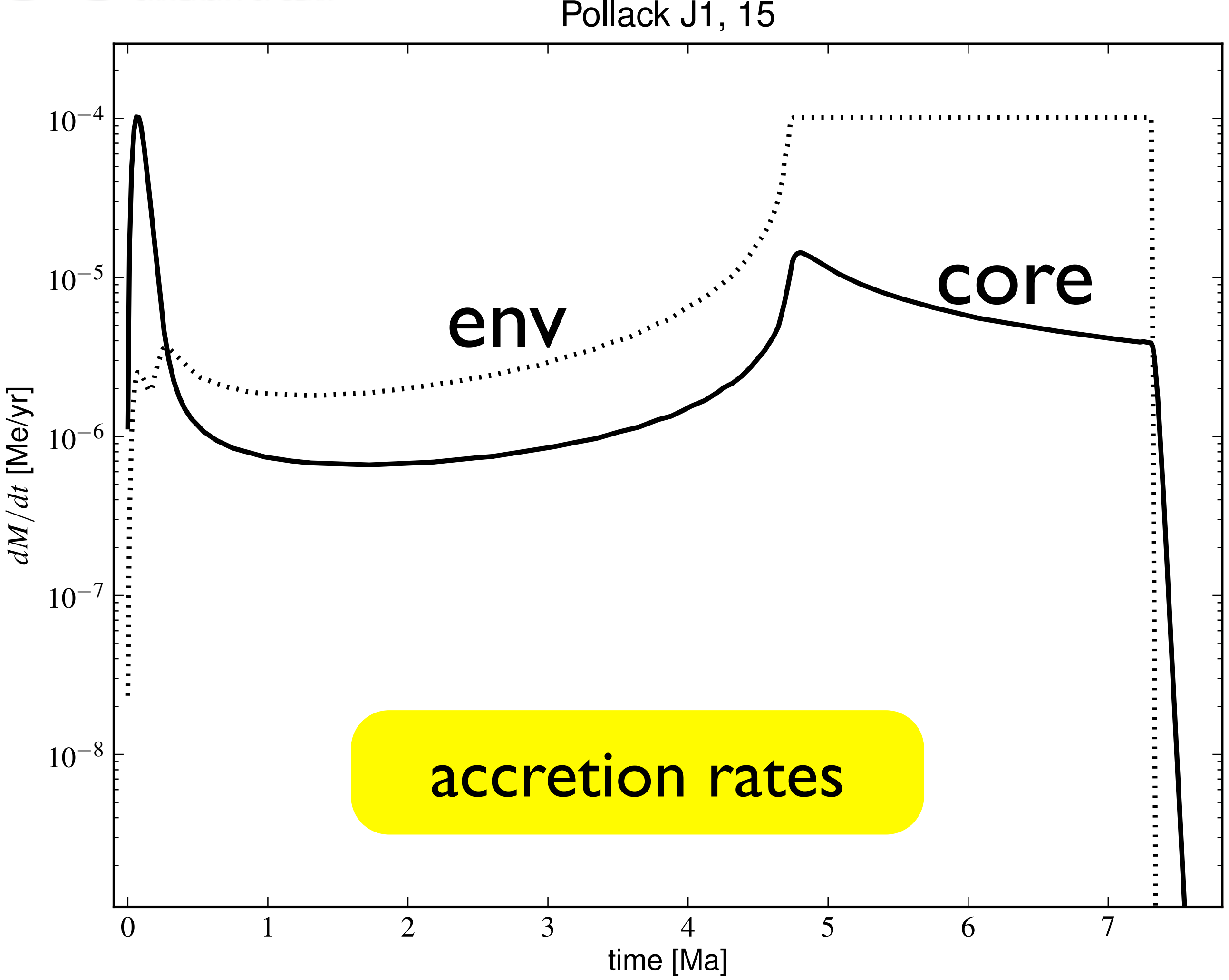
L

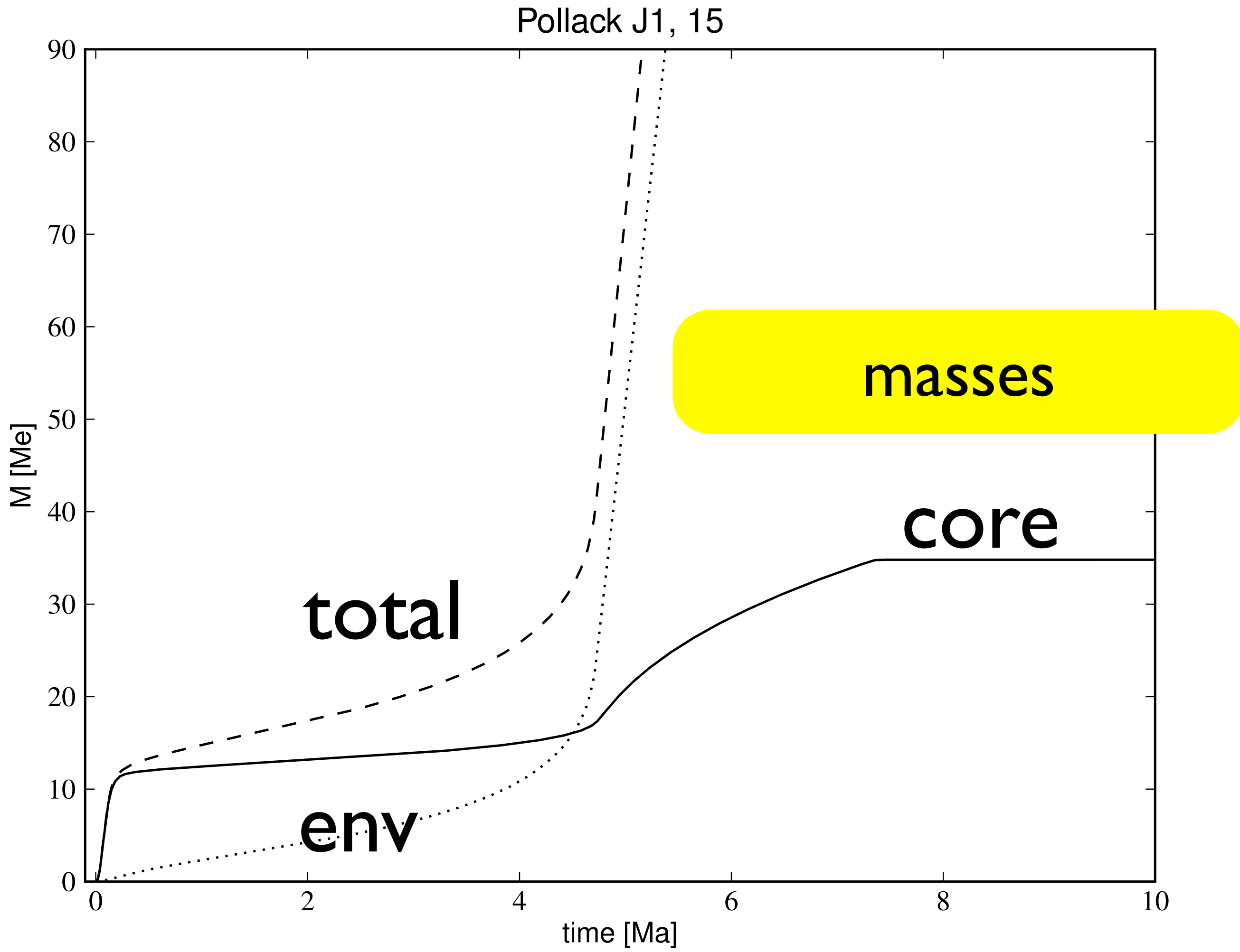
time [Ma]

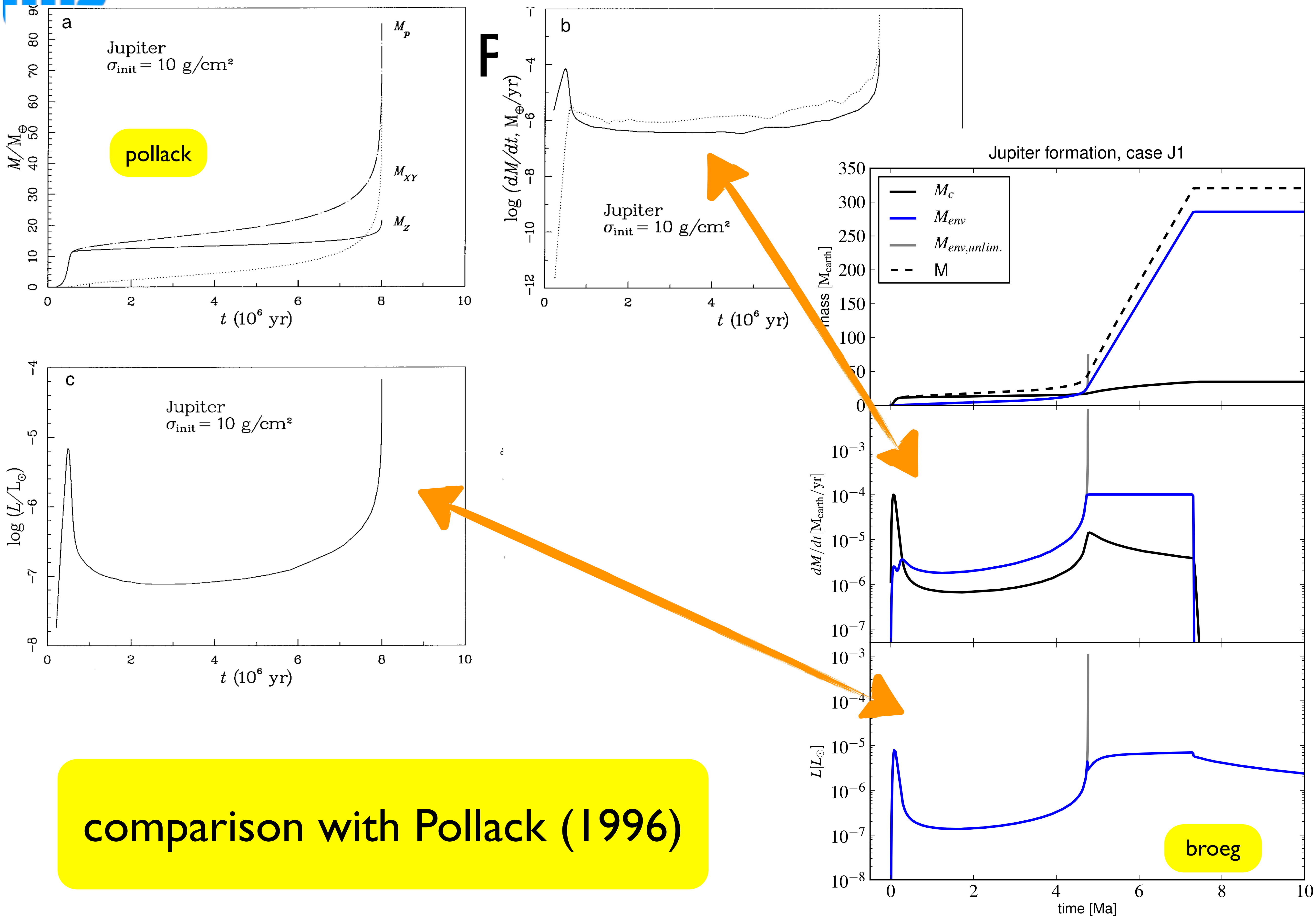
luminosity



log L


Pollack J1, 15
dM/dt [Me/yr]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
1
2
3
4
5
6
7
time [Ma]
env
core
accretion rates


Pollack J1, 15
M [Me]
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
time [Ma]
masses
core
total
env



pollack

broeg

comparison with Pollack (1996)

Verification summary

- Good agreement with Pollack
- L_max = 10^{-5} L_{sun}
  (10^{-3} when limiting accretion to 0.01 instead of 10^{-4} Me/yr)
- Jupiter values at 4.5 Gyr:
  - Mass: 1.008 Mjup (by construction)
  - Radius (4.5 Ga) = 1.03 R_{Jup}
  - M_z = 34 M_{earth}
  - L = 0.76 L_jup_internal
- Mach number of inflow: -0.4
- Further tests:
  - static (Mizuno 1980),
  - CoRoT-9b,
  - HD209458b (all verification successful)

Results:
impact vs gradual growth

- 1 example case: 1 M_e impact on 10 M_e target core
  envelope mass, gas accretion rate, luminosity
- all targets for 1 M_e impact

Scenario

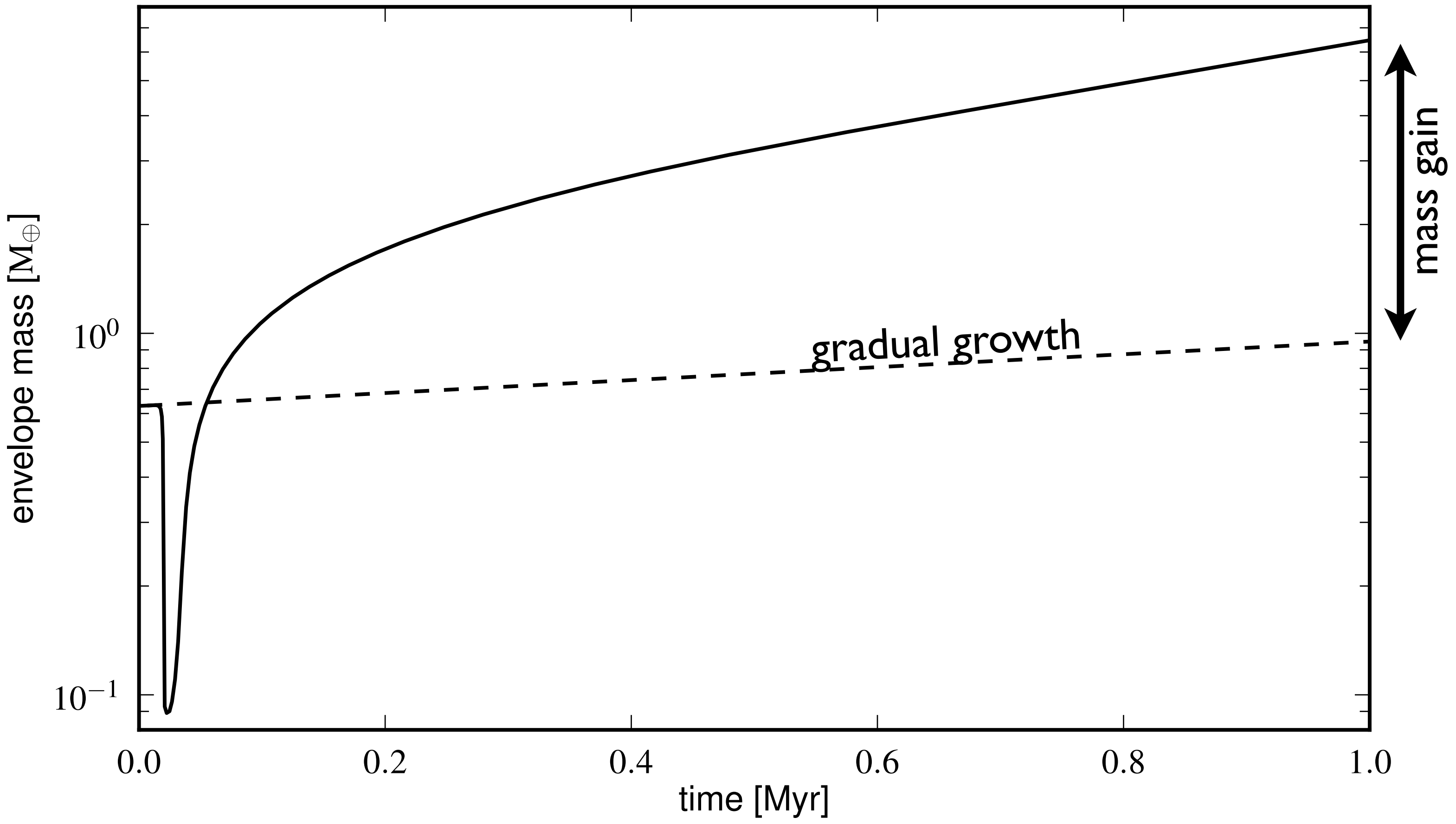
- Growing proto-planet core at 3 AU in MMSN, solar host star
- Nominal core accretion rate: 10^{-6} Earth masses / yr
- At desired impact core mass:
  - impact followed by no solid accretion
  - compare to gradually growing case
- Parameter study:
  - different impact masses 0.02, 0.1, 0.5, and 1 Earth masses
  - different target masses M_c=1,2,3,…,15 Earth masses

envelope mass (impact 1 on 10 M_e)

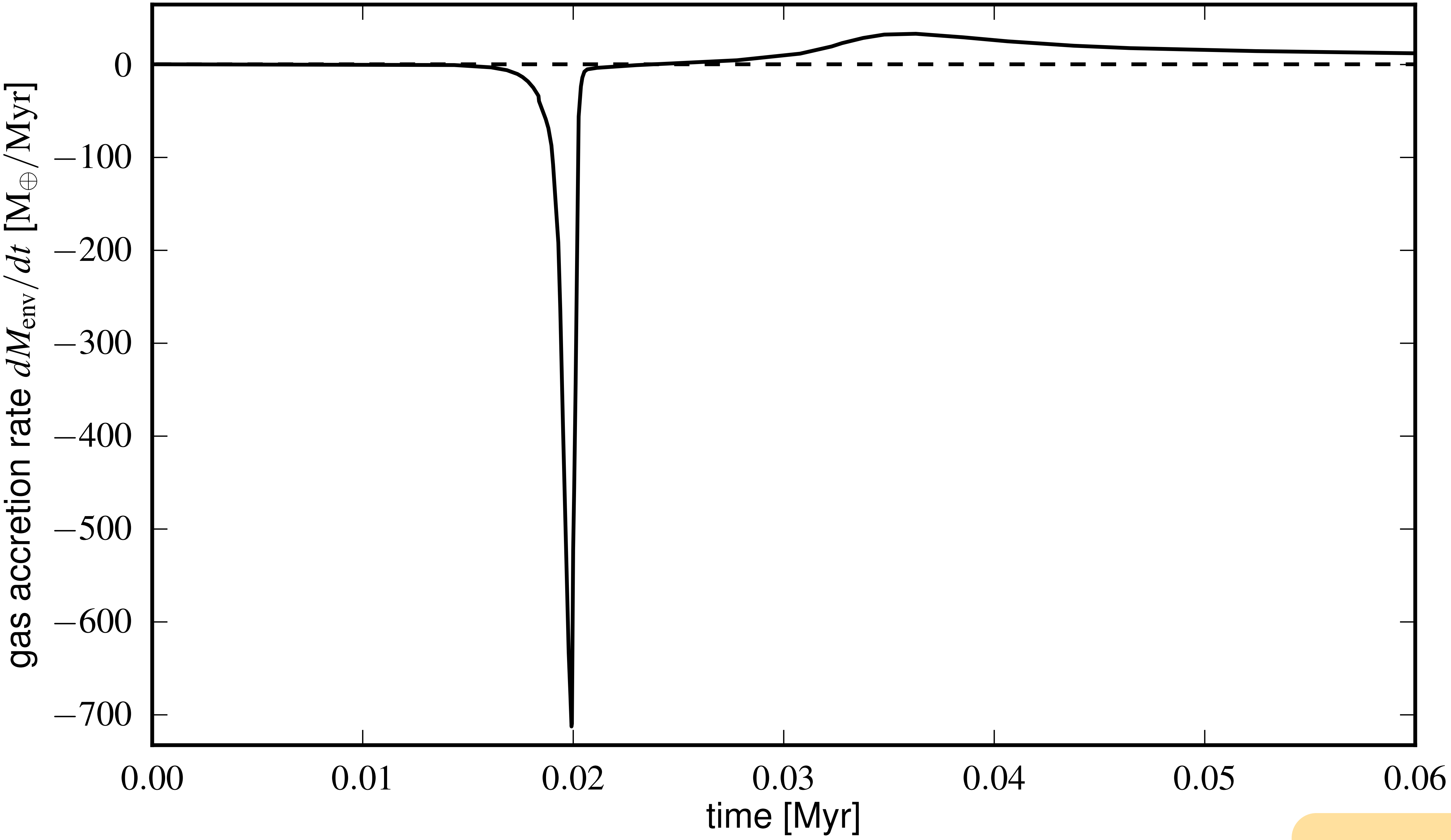
sequence:

1. gas ejection
2. fast accretion
3. gas replenished after 0.055 Myr
4. gas accretion slows down

➡ net more gas accreted

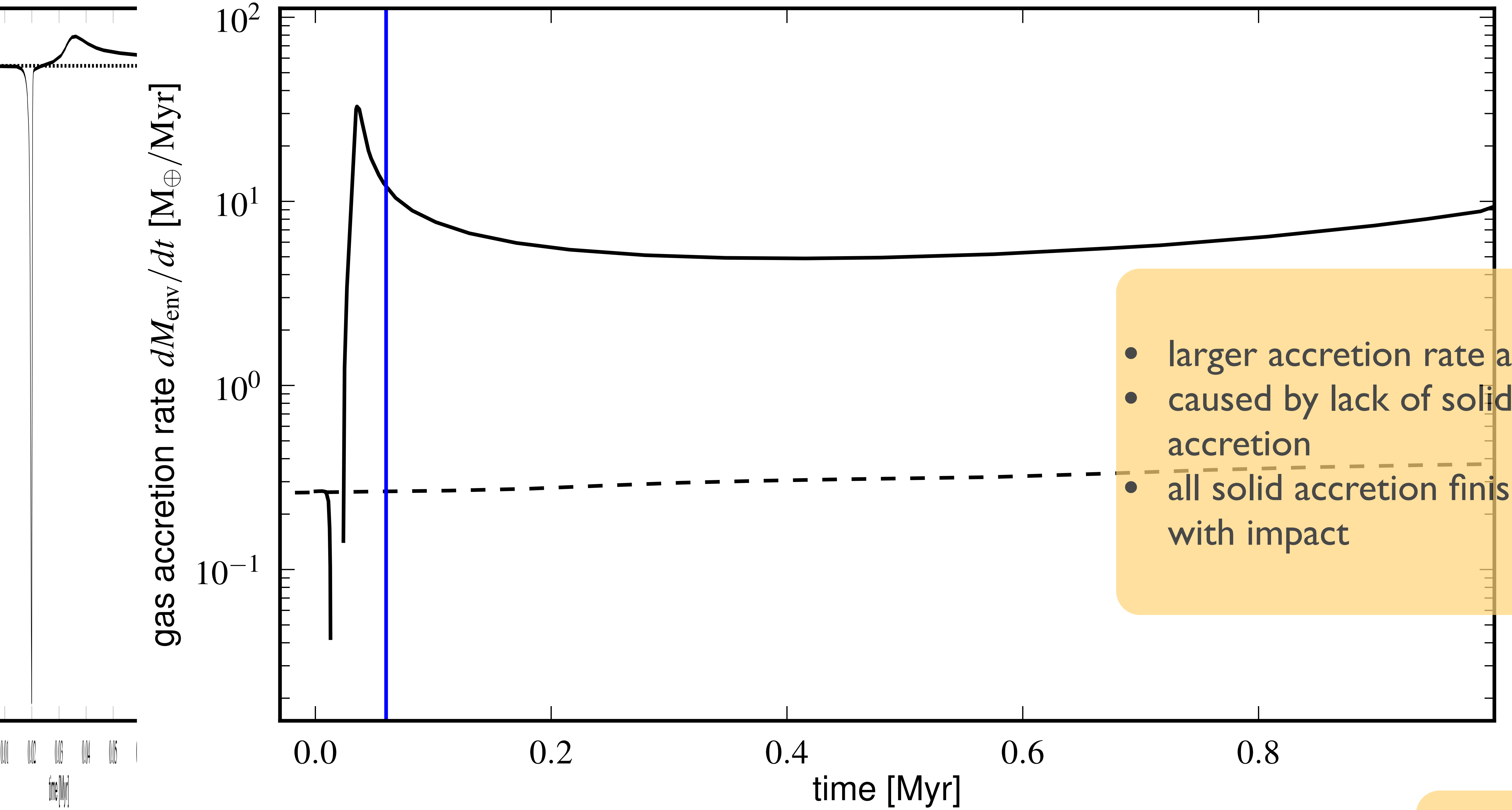


gas accretion rate



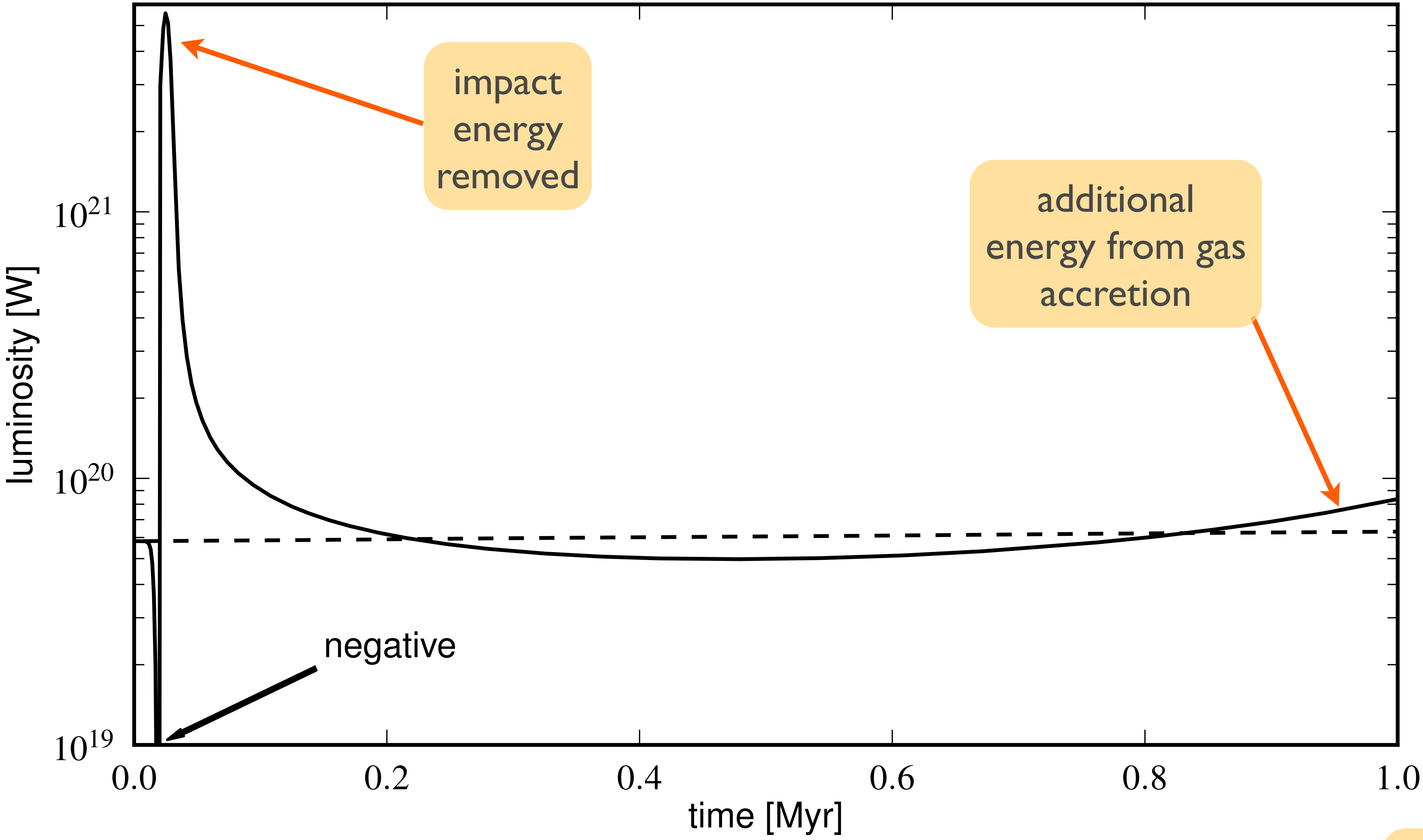
1 / 10

gas accretion rate



- larger accretion rate at end
- caused by lack of solid accretion
- all solid accretion finished with impact

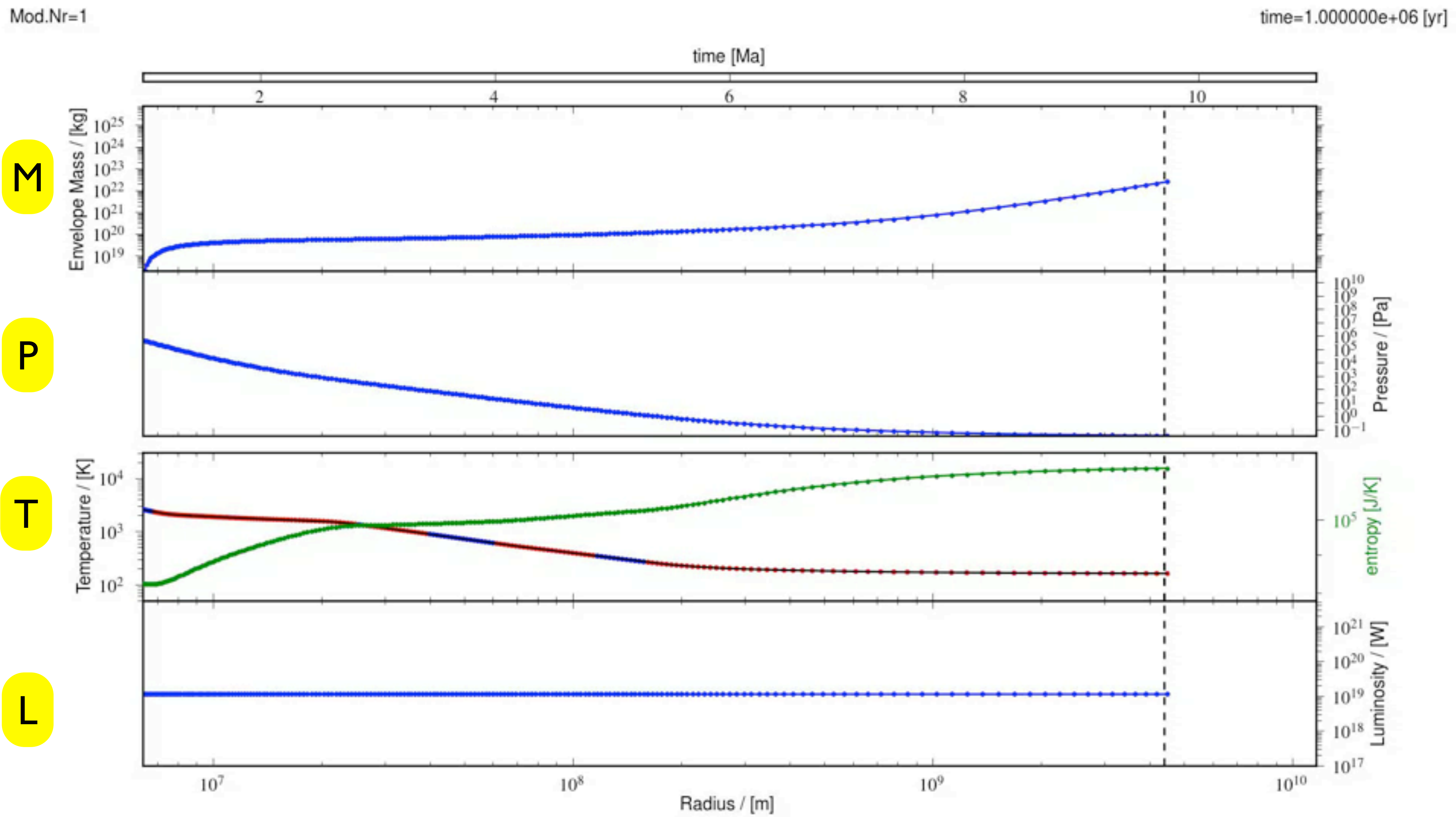
luminosity



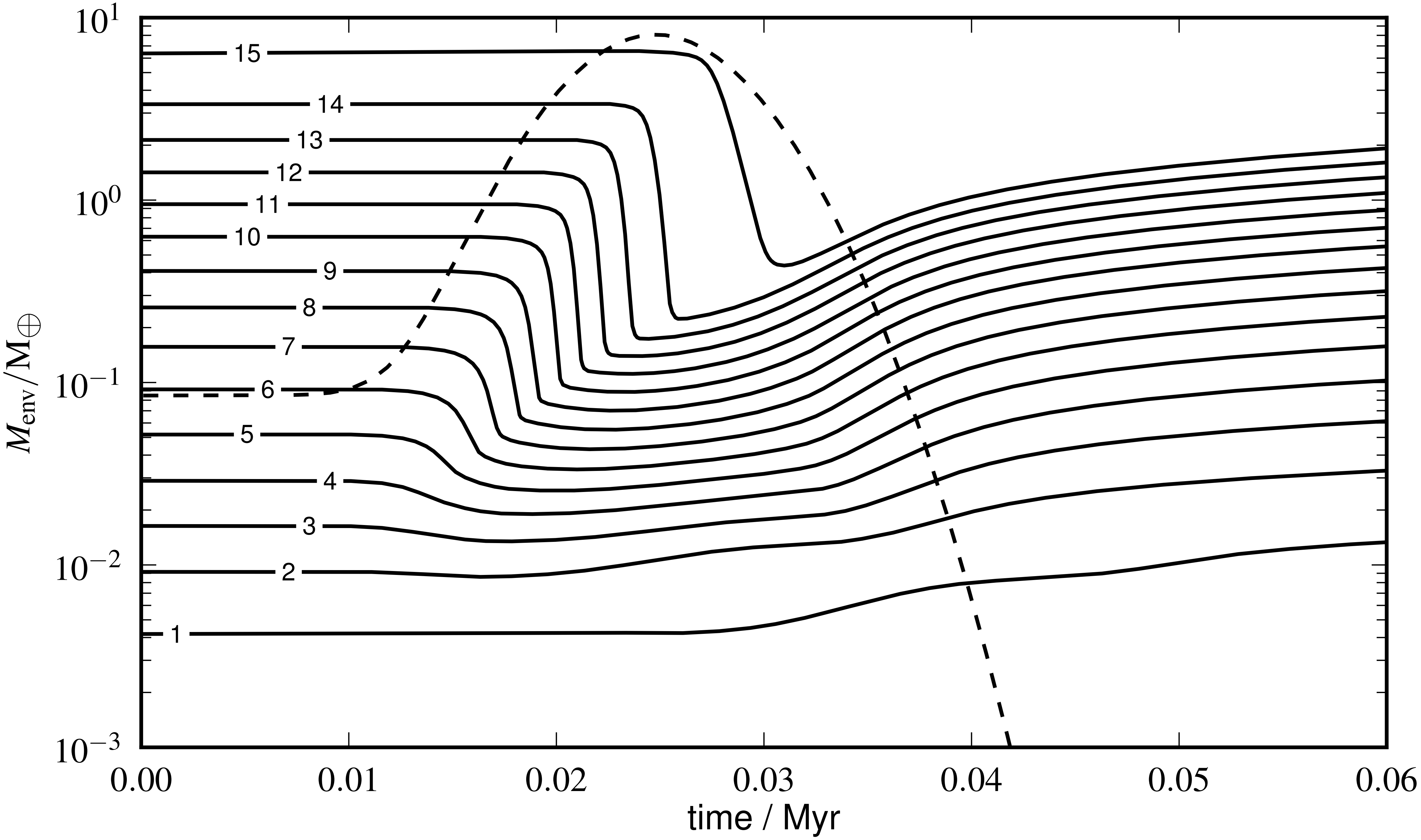
impact energy removed

additional energy from gas accretion

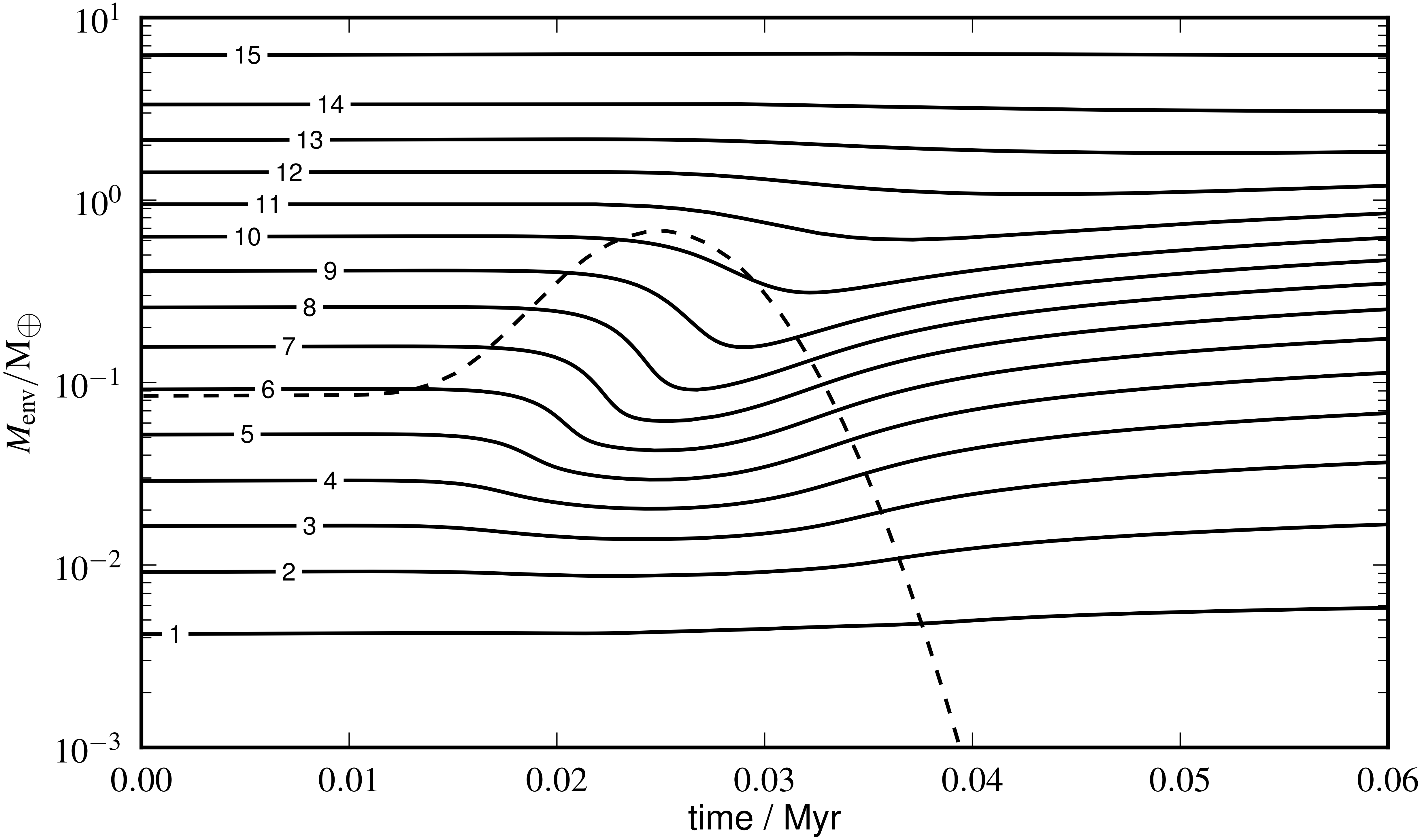
10 M_e target, 1 M_e impact



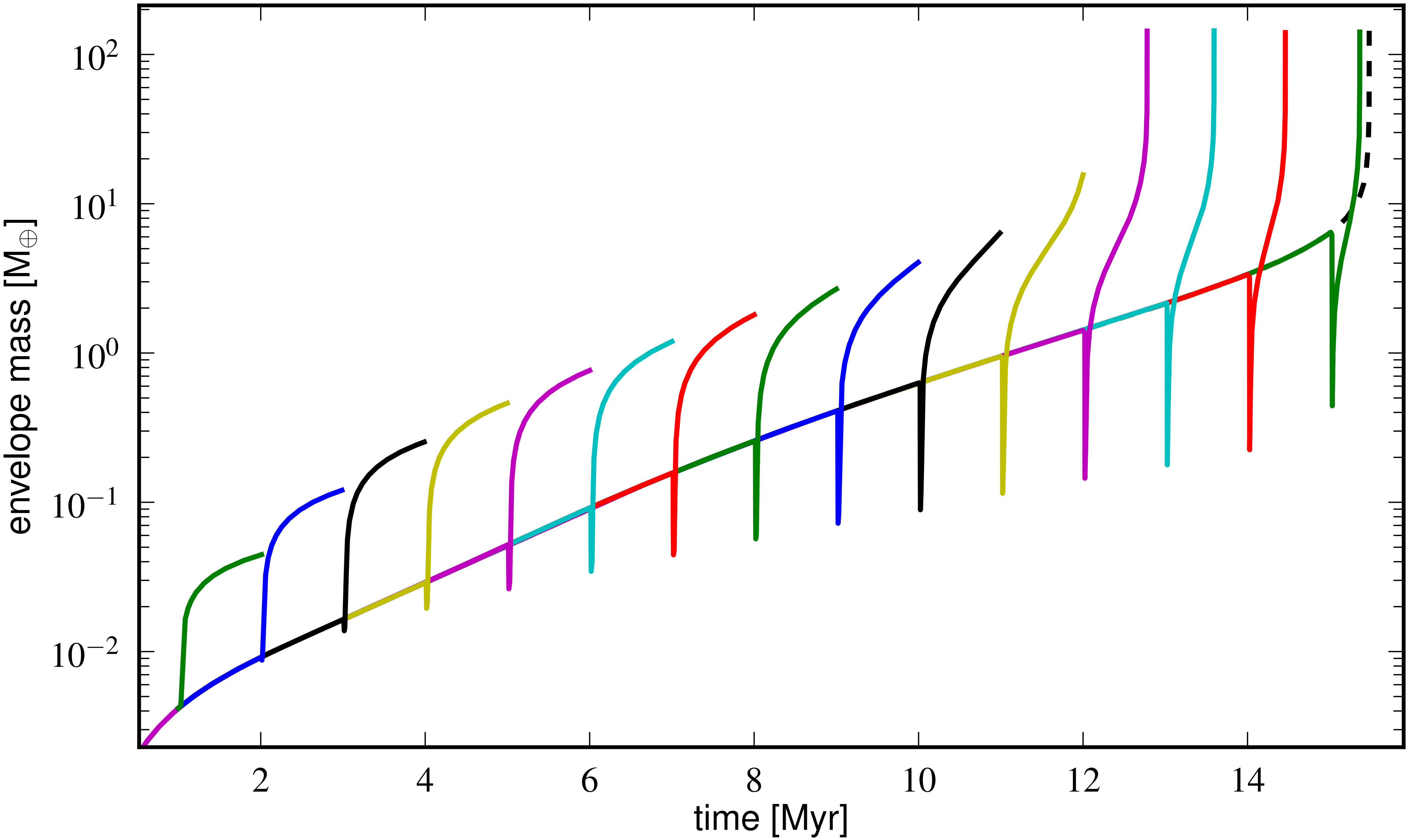
envelope mass during 1 M_e impact



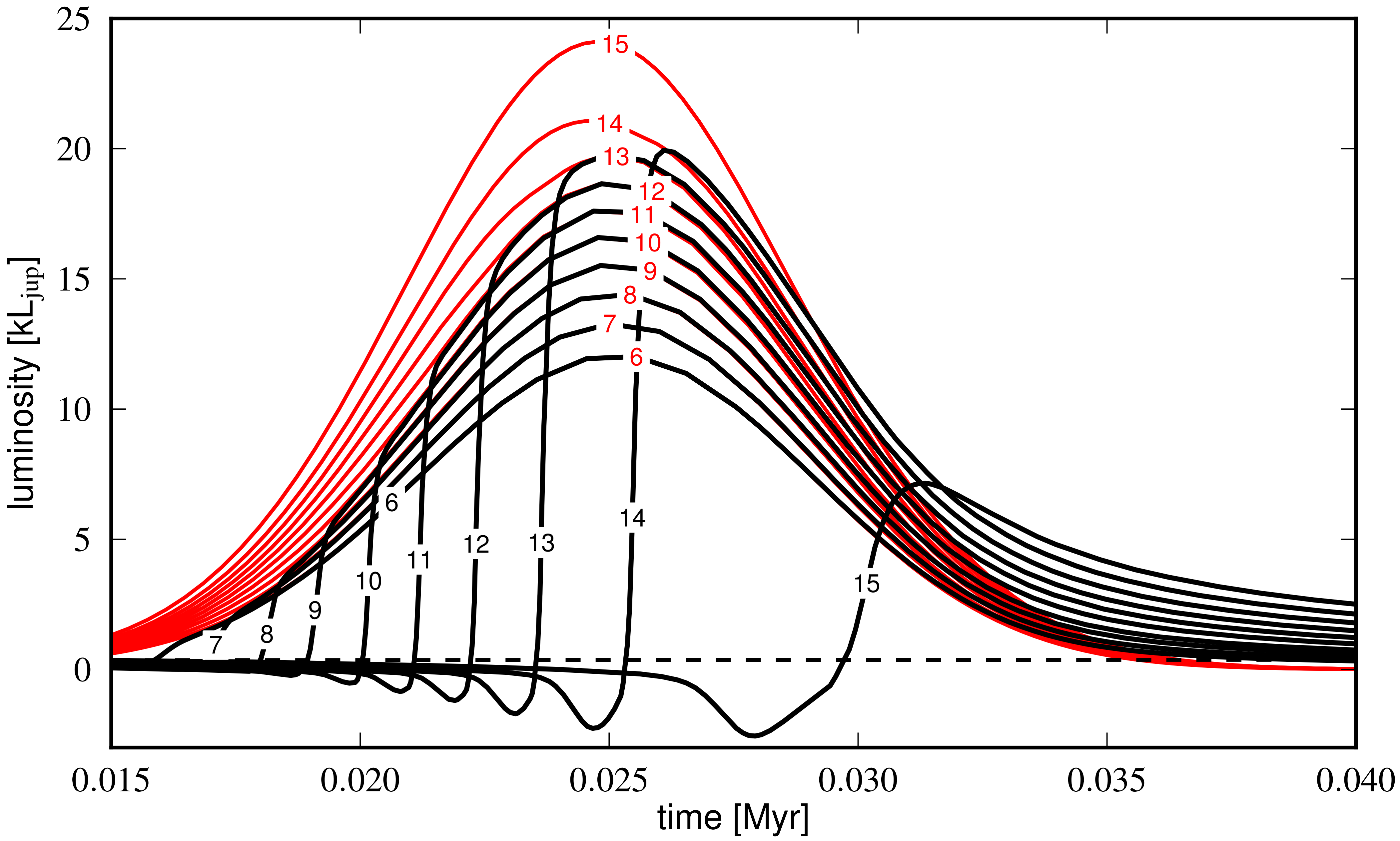
envelope mass during 0.1 M$_e$ impact



envelope mass after 1 M_e impact

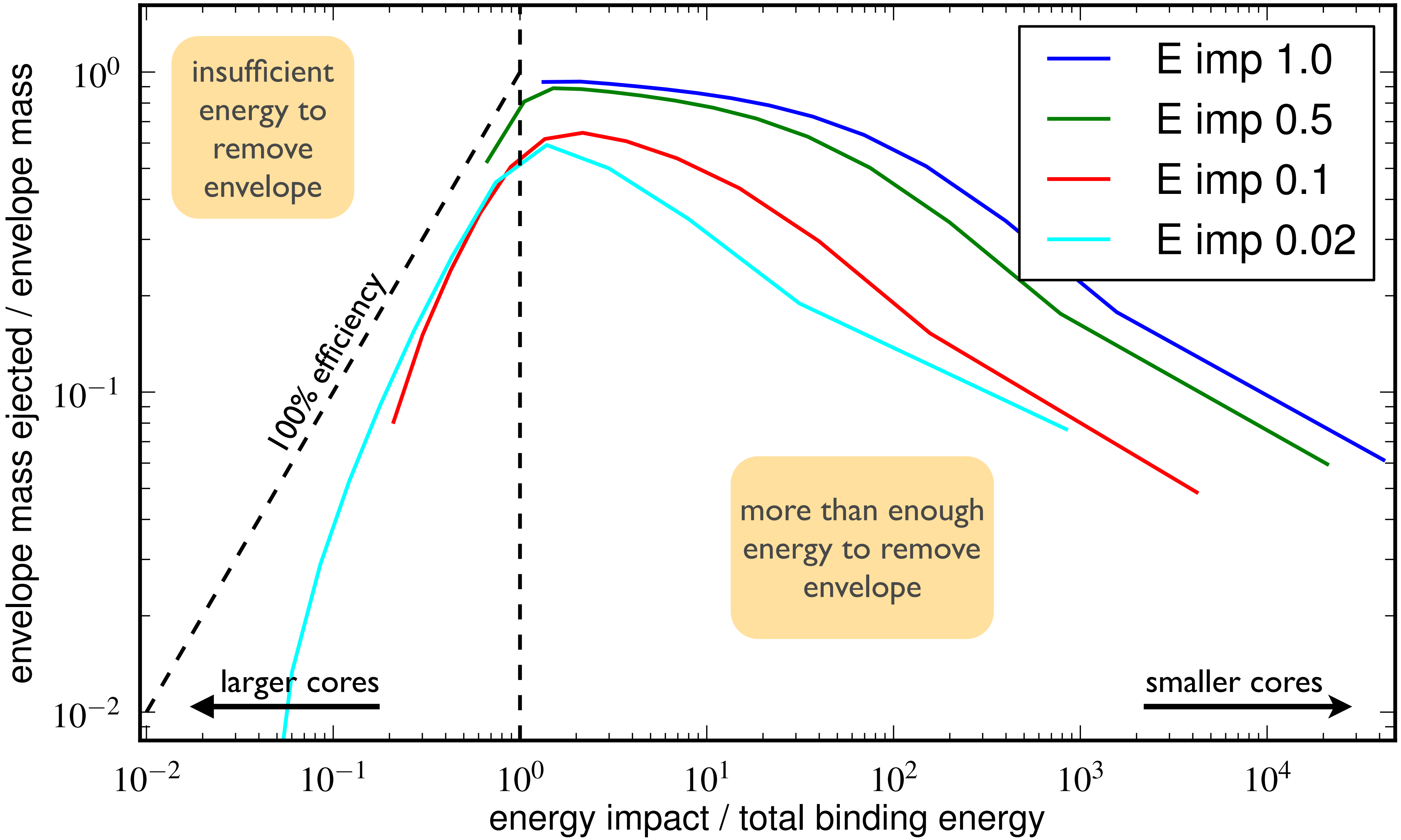


luminosity evolution 1Mₑ impacts

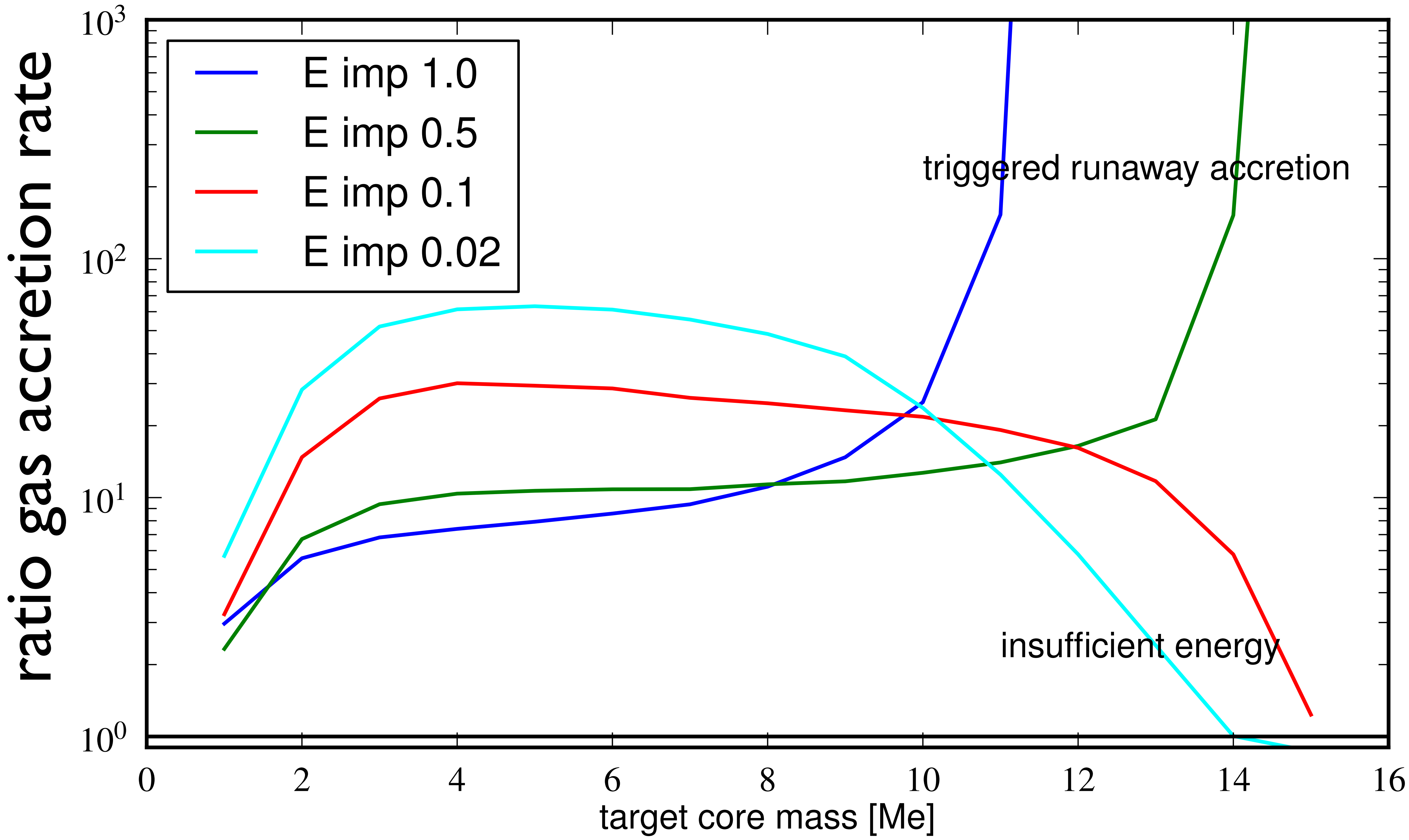


core luminosity luminosity

ejected envelope mass as a function of target size for 4 different impact sizes



envelope accretion rate: ratio episodic vs continuous



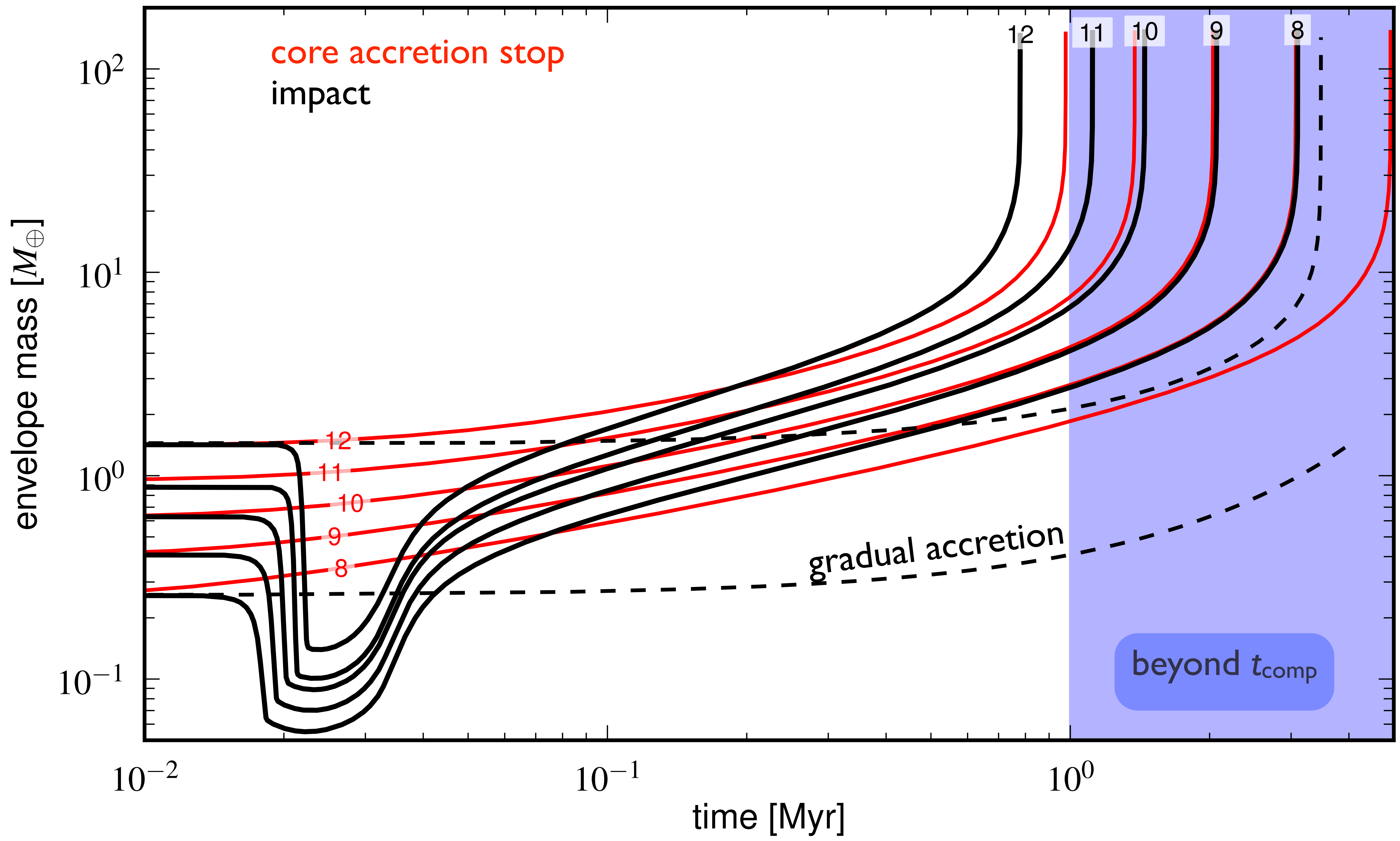
(corrected y-axis label from talk)

Discussion

- Results show that the impact scenario yields more massive envelopes compared to gradual core growth
- Most of the energy can be transported at very high luminosity immediately after envelope ejection
- The Kelvin-Helmholtz timescale becomes very small during the impact and the energy from solid accretion can be shed quickly (For a 10 M_e core: before: 0.2 Myr; during: **200 yr**; after: 1.6 Myr)
- The subsequent phase without solid accretion quickly accumulates a large envelope

comparison with stopped core accretion

impact accretion vs. no accretion



see Ikoma et al. 2000, ApJ

Summary & Conclusion

- We were able to calculate episodic large impacts in the quasihydrostatic approximation
- Results show that the impact scenario yields more massive envelopes compared to the gradual core growth
- The impact itself leads to a very rapid loss of the deposited energy
- Gas accretion as fast as the shut-off case with the larger (post-impact) core
- In the oligarchic growth regime, this effect can be very important
- With this method, formerly sub-critical cores can accrete large amounts of gas

Broeg & Benz 2010, in prep.