Planetary Growth with Fragmentation and Gas Drug

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Fragmentation

- Asteroids, Edgeworth-Kuiper belt
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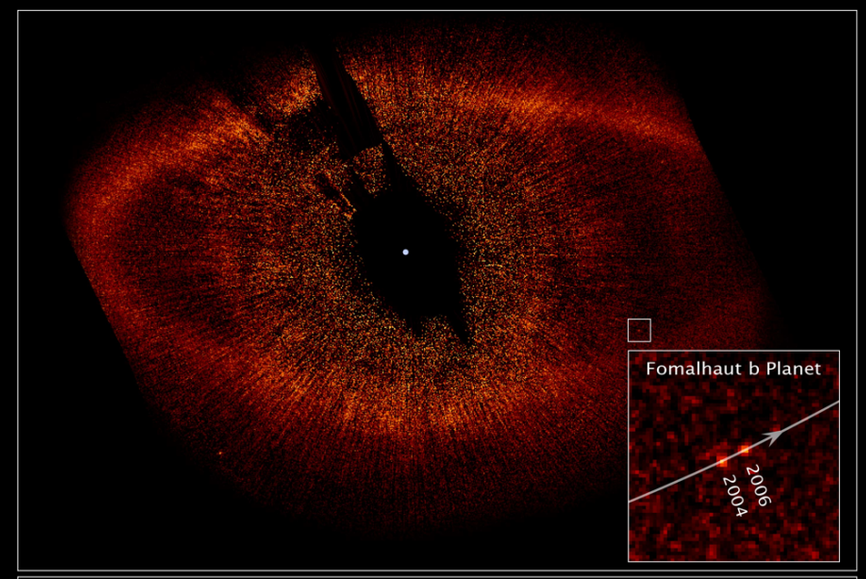
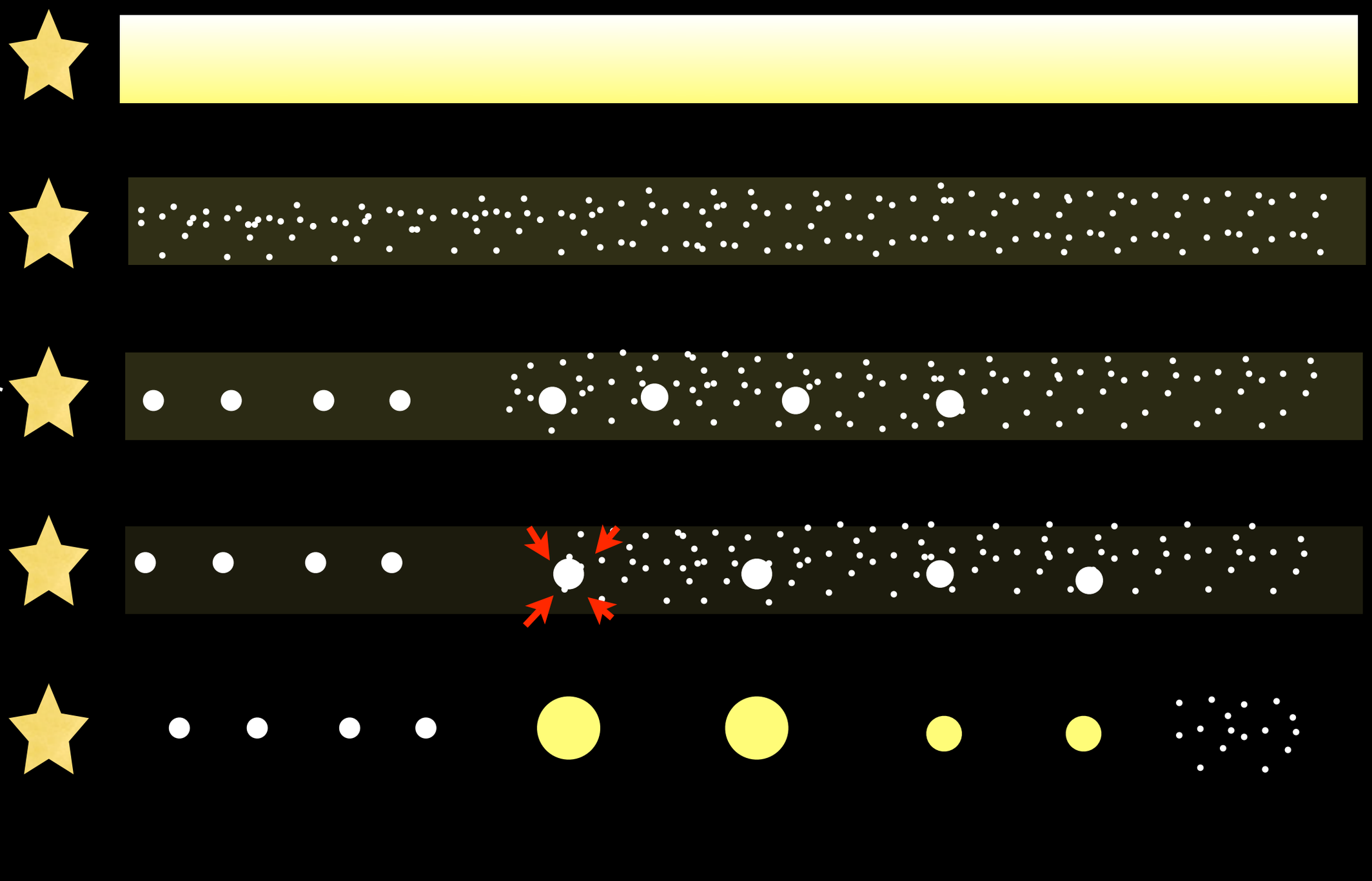


Fomalhaut System
Hubble Space Telescope • ACS/HRC

NASA, ESA, and P. Kalas (University of California, Berkeley) STScI-PRC08-39a

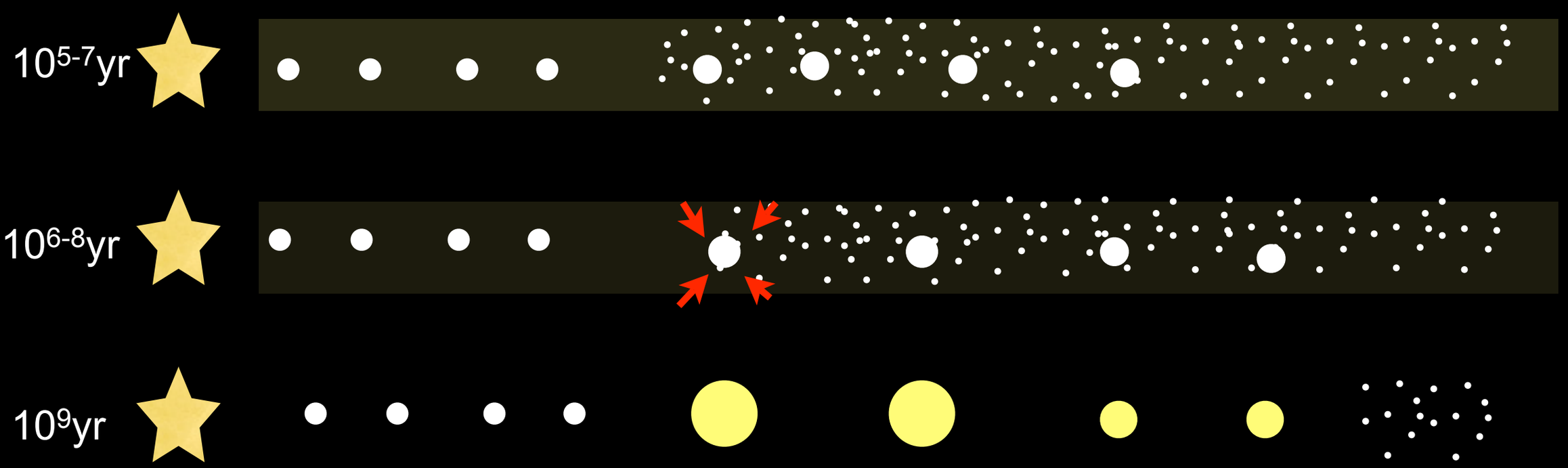
Standard Model



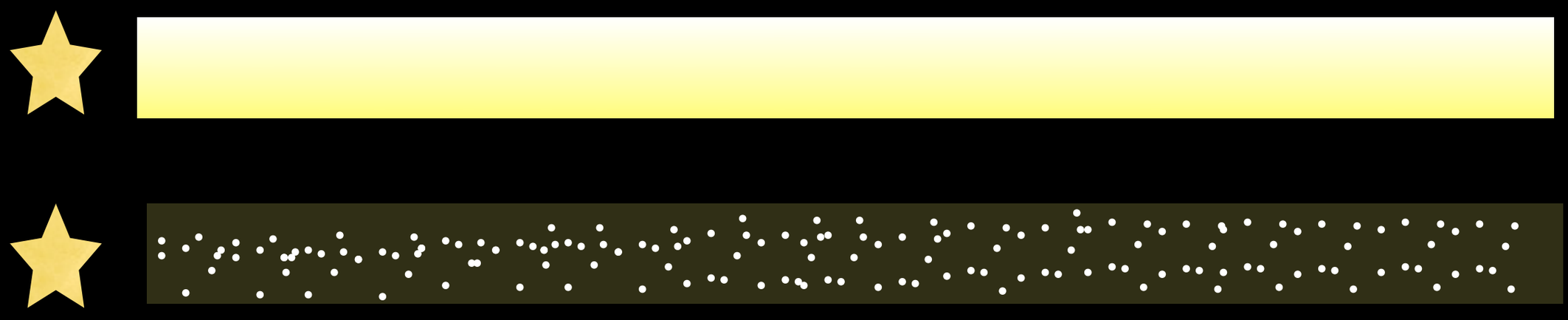
Standard Model

$10^{5\text{-}6}$yr

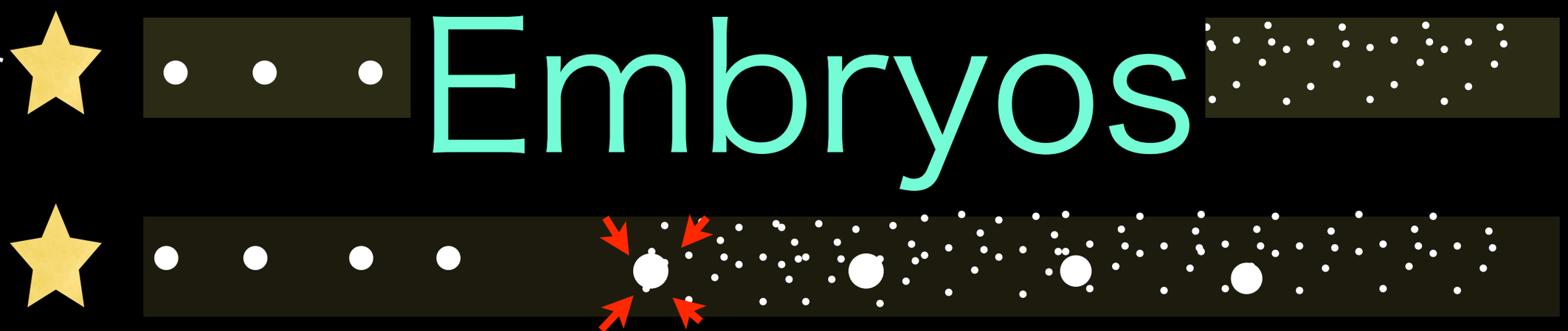
Planetesimals



Standard Model



$10^{5\text{-}6}$yr

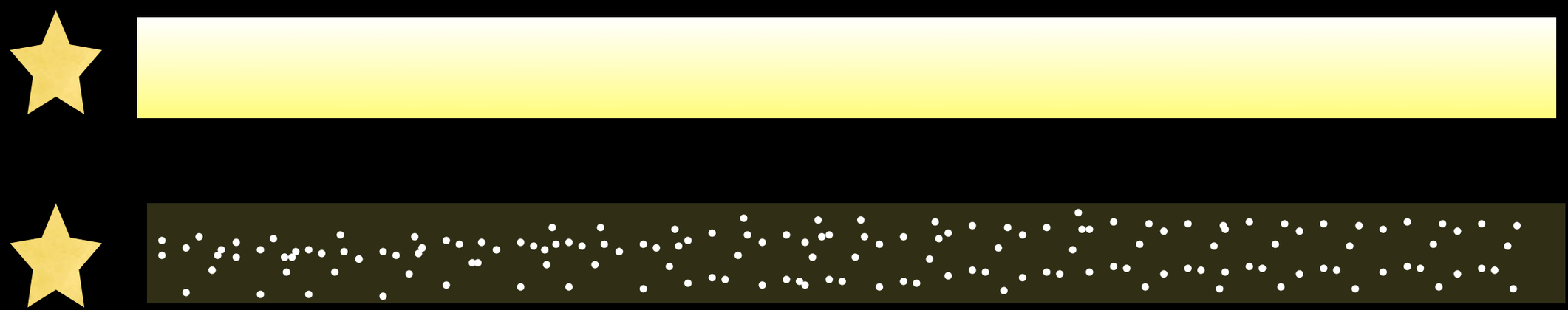


$10^{5\text{-}7}$yr

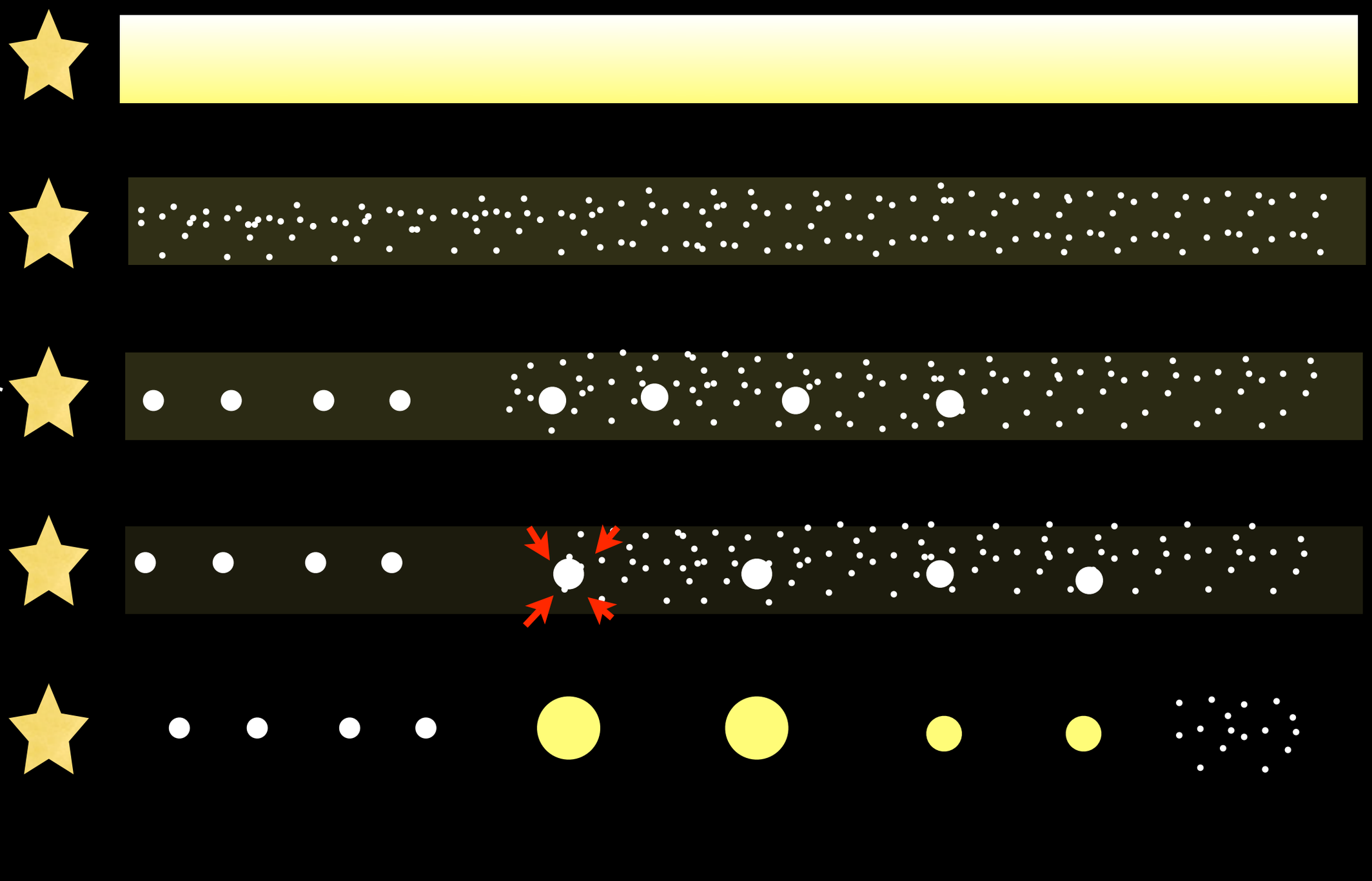
$10^{6\text{-}8}$yr

10^{9}yr

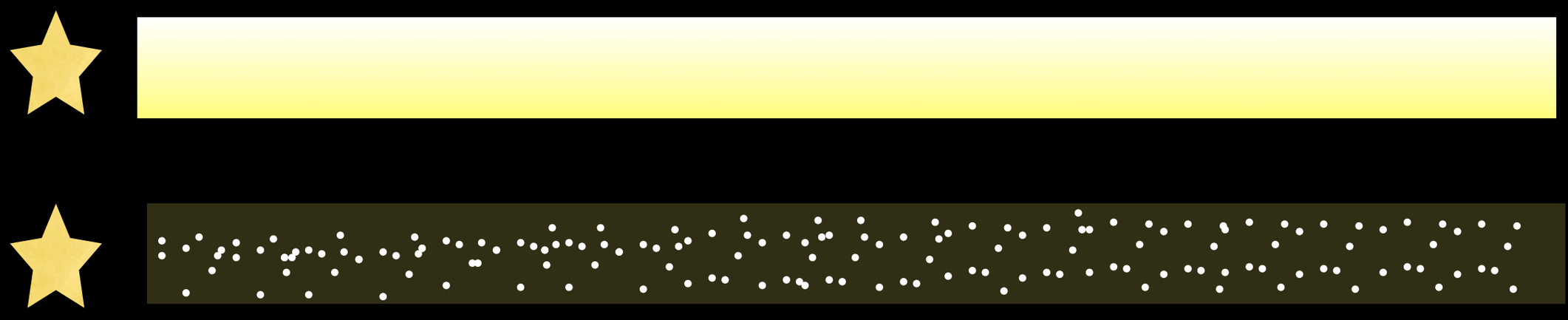
Standard Model



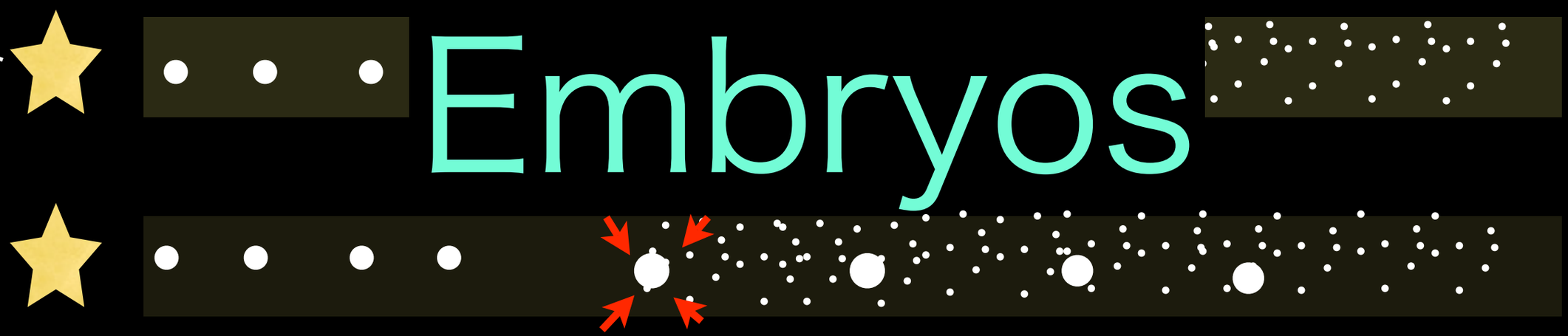
Standard Model



Standard Model



$10^{5\text{-}6}$yr



$10^{5\text{-}7}$yr

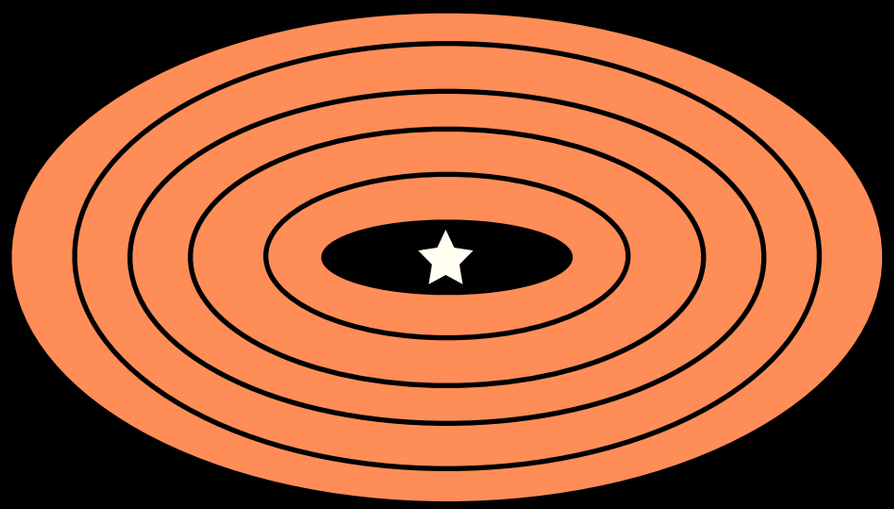
$10^{6\text{-}8}$yr

10^{9}yr

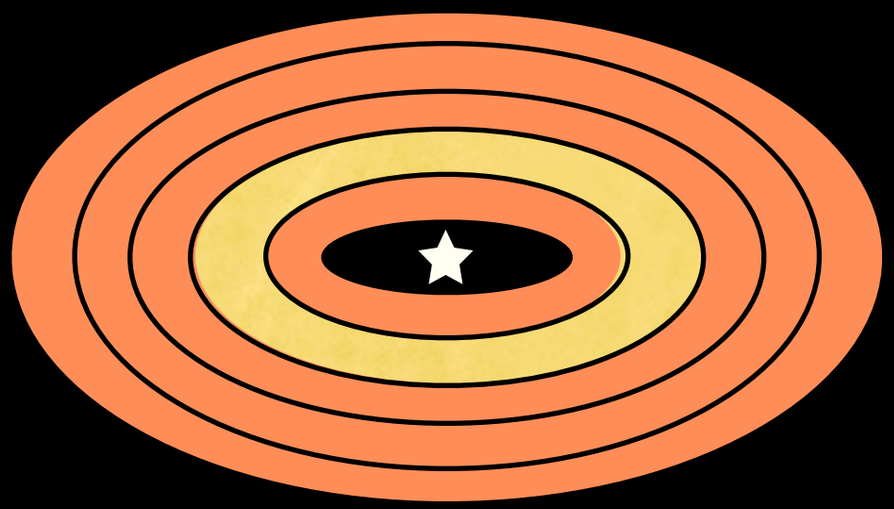
Embryo Growth with Fragmentation

- Planetary embryos grows by accretion with planetesimals.
- Massive embryos induce distractive collisions between planetesimals.
- Fragmentation reduces the final embryo mass.

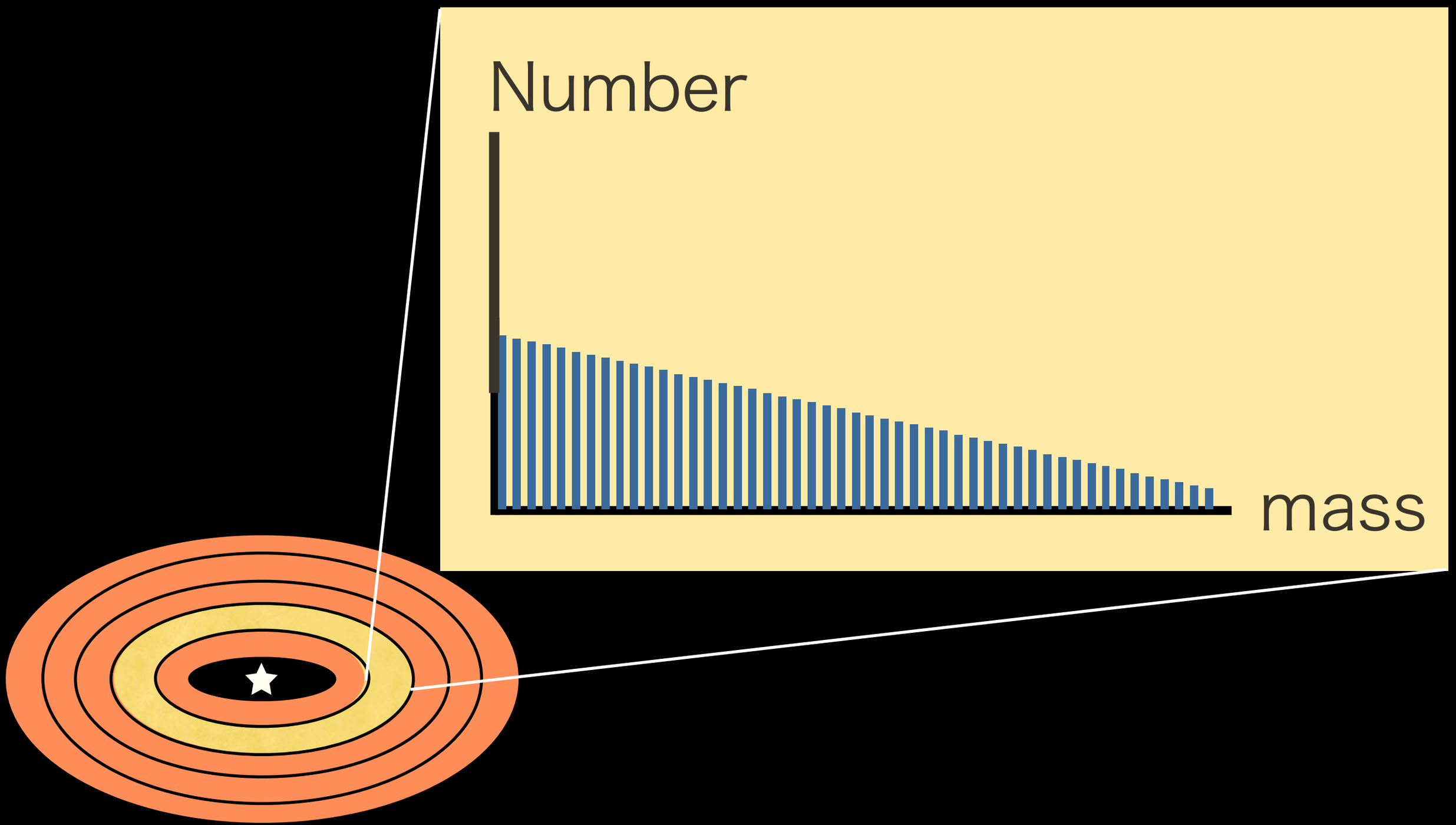
Calculation Model



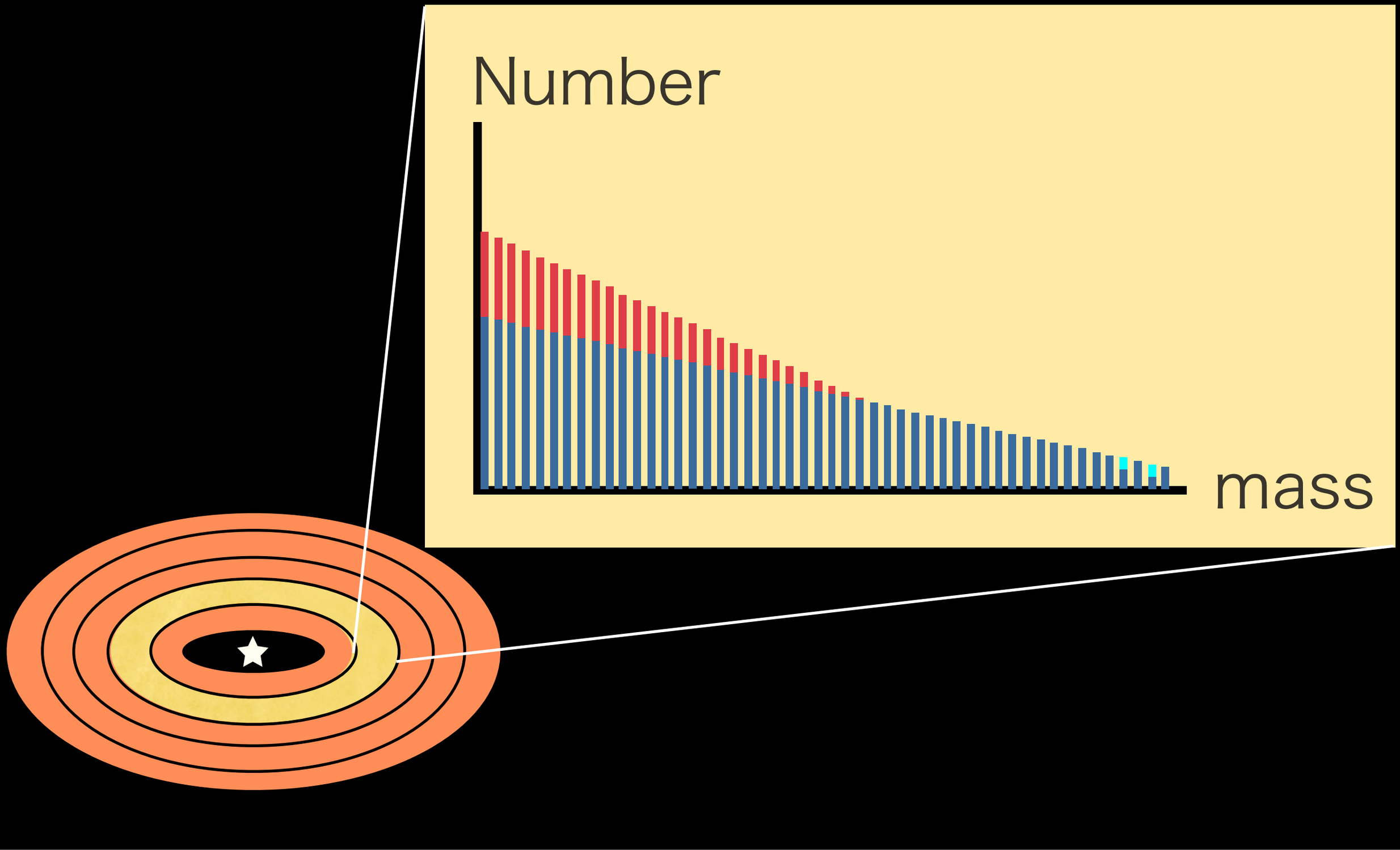
Calculation Model



Calculation Model



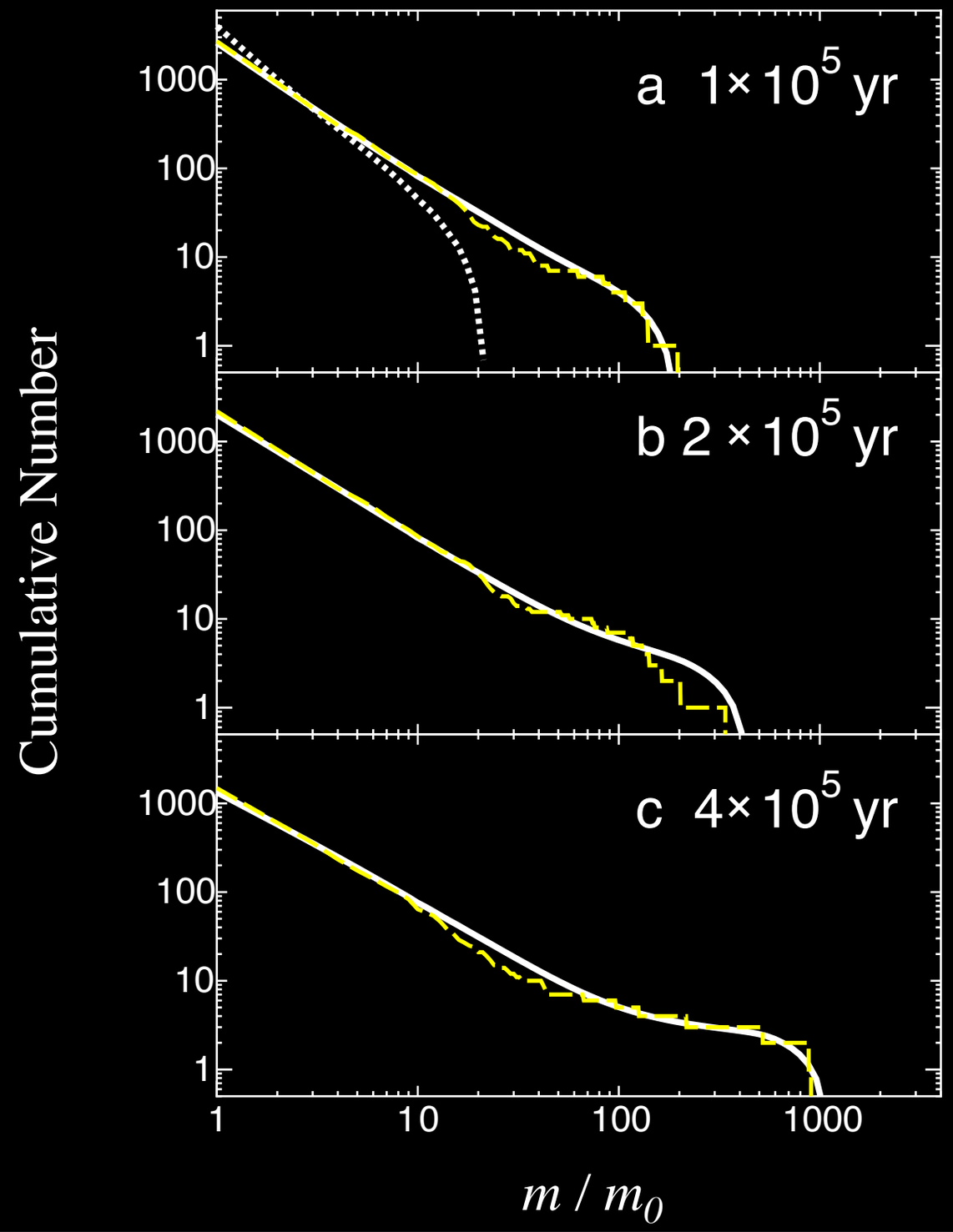
Calculation Model



N-Body Simulation

- Direct N-body simulation is most reliable for the embryo growth.
- If fragmentation is neglected.
- Comparison with N-body simulation for the case without fragmentation to validate our simulation.

Validation



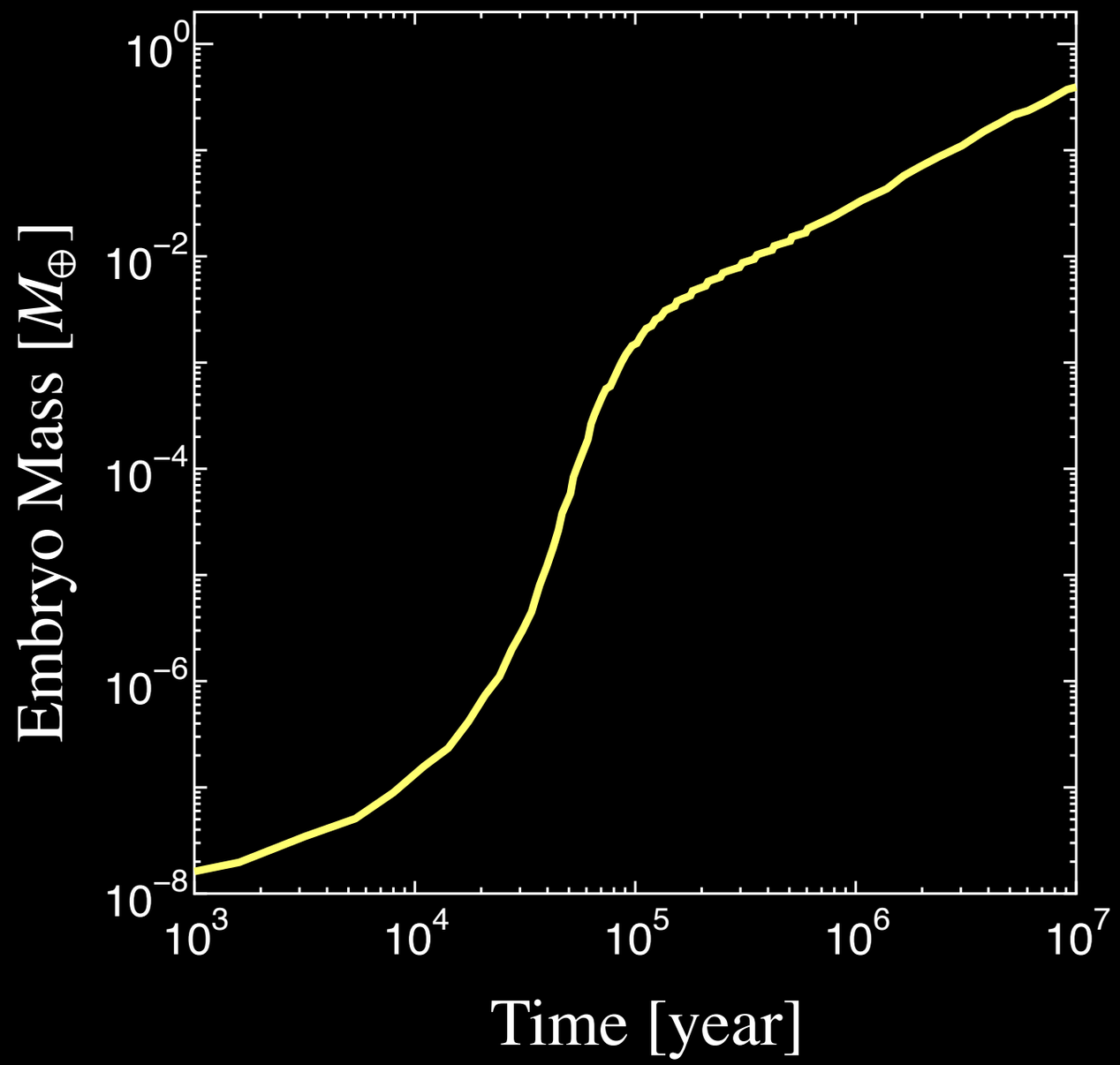
..... initial

— ours

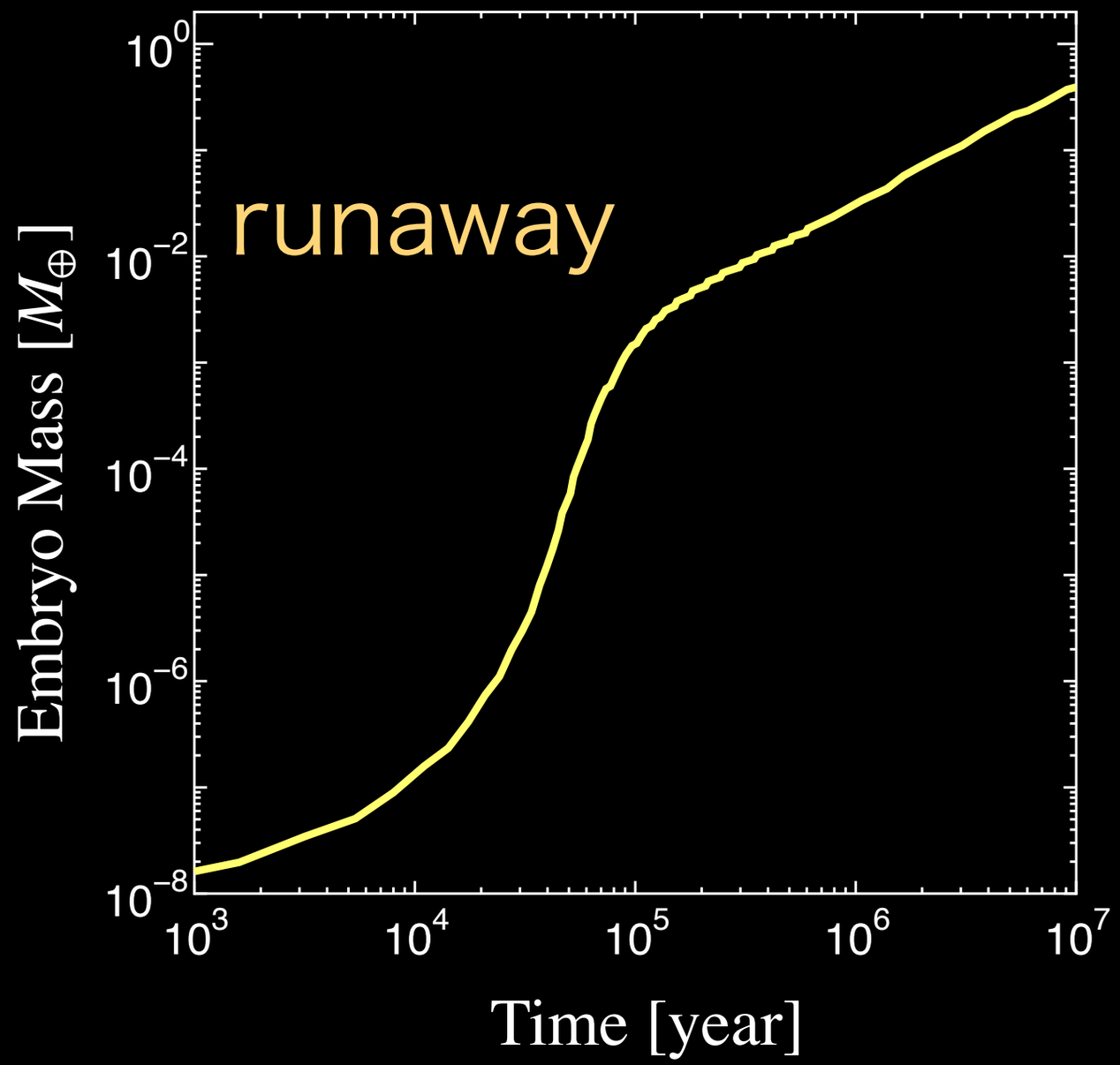
--- *N*-body

Embryo Growth without Fragmentation

at 3.2AU
MMSN

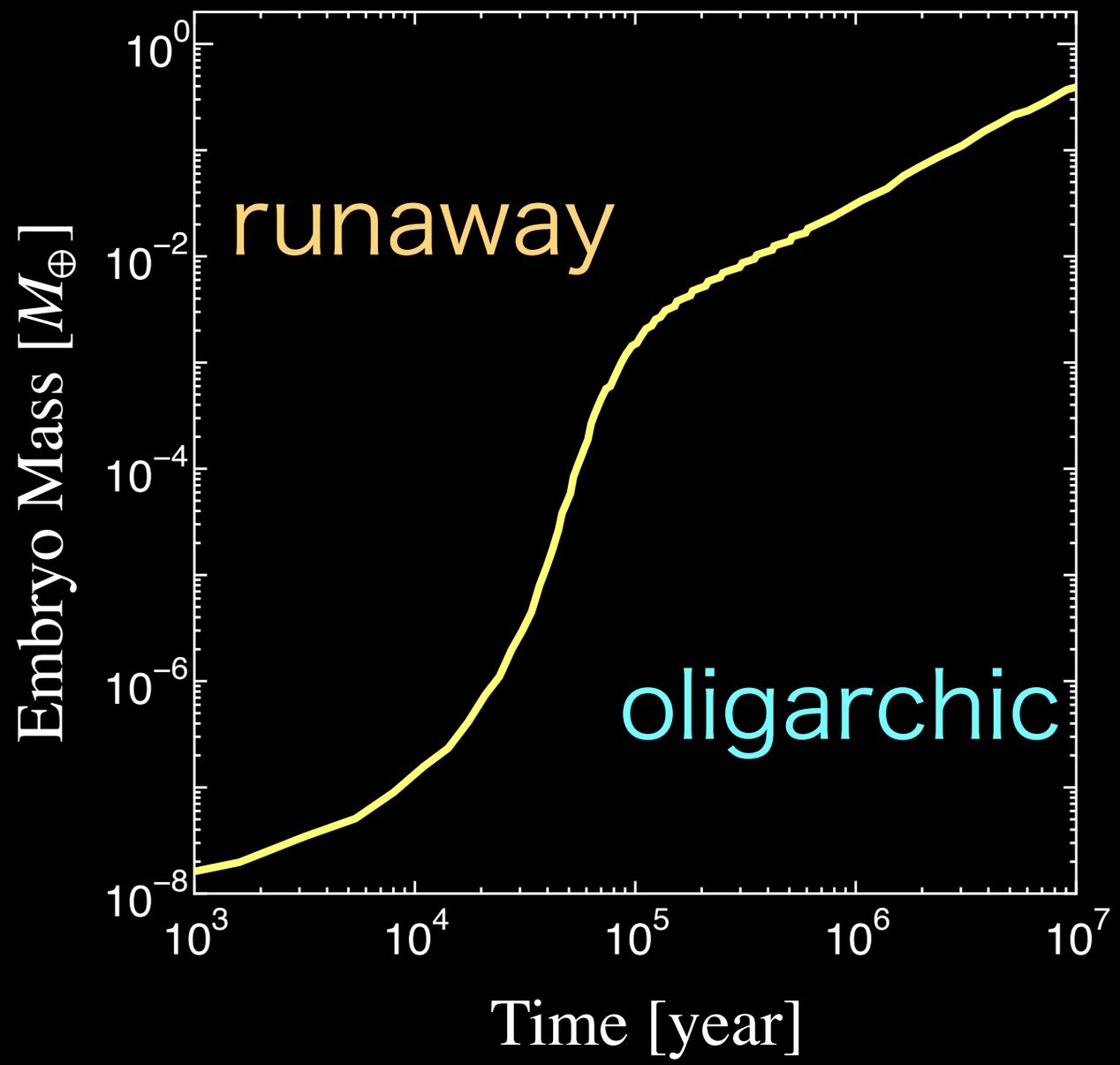


Embryo Growth without Fragmentation



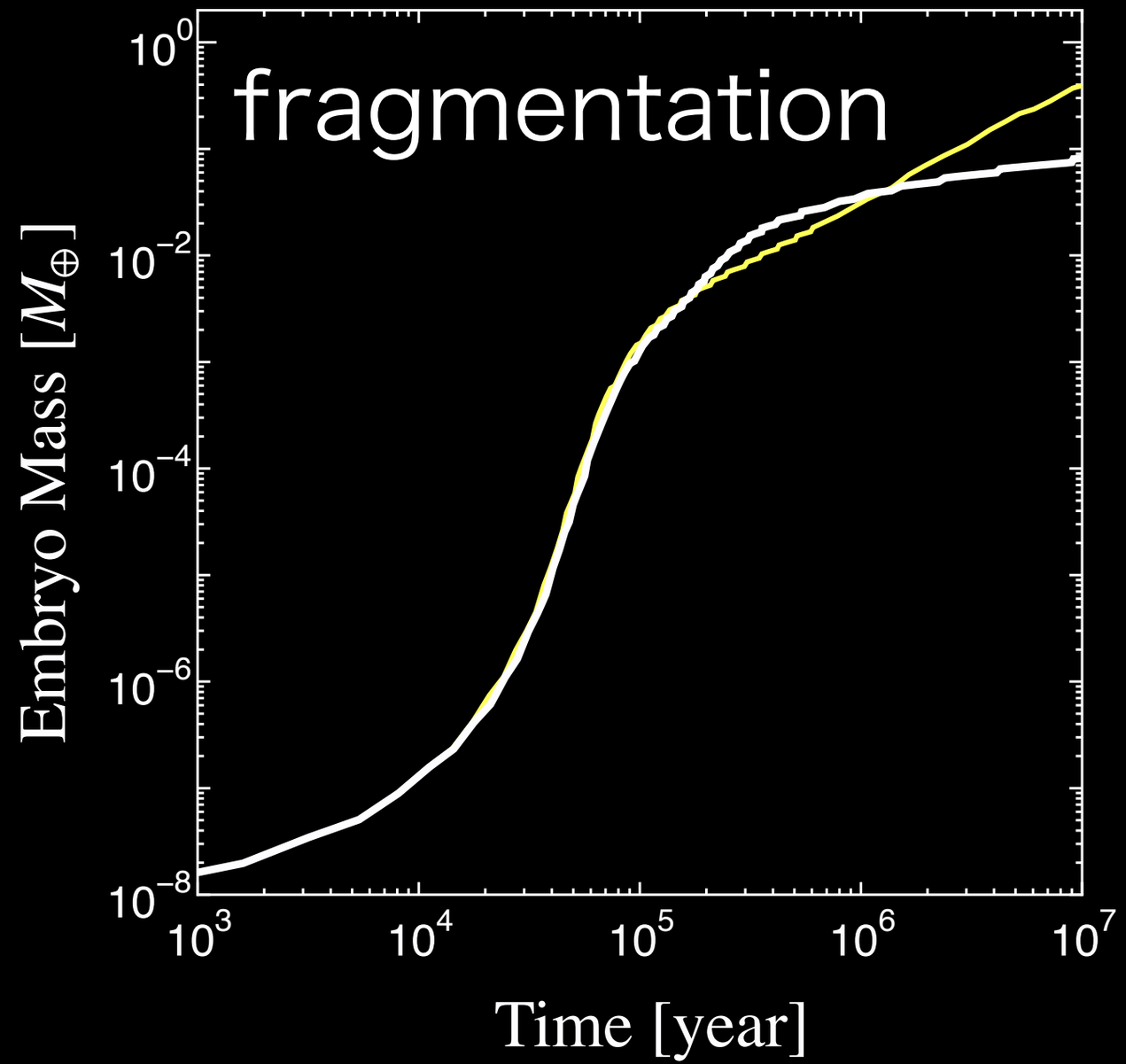
at 3.2AU
MMSN

Embryo Growth without Fragmentation



at 3.2AU
MMSN

Embryo Growth



no frag.

at 3.2AU
MMSN

Analysis

Embryo

Fragments

Planetesimals

mass

Analysis

Embryo

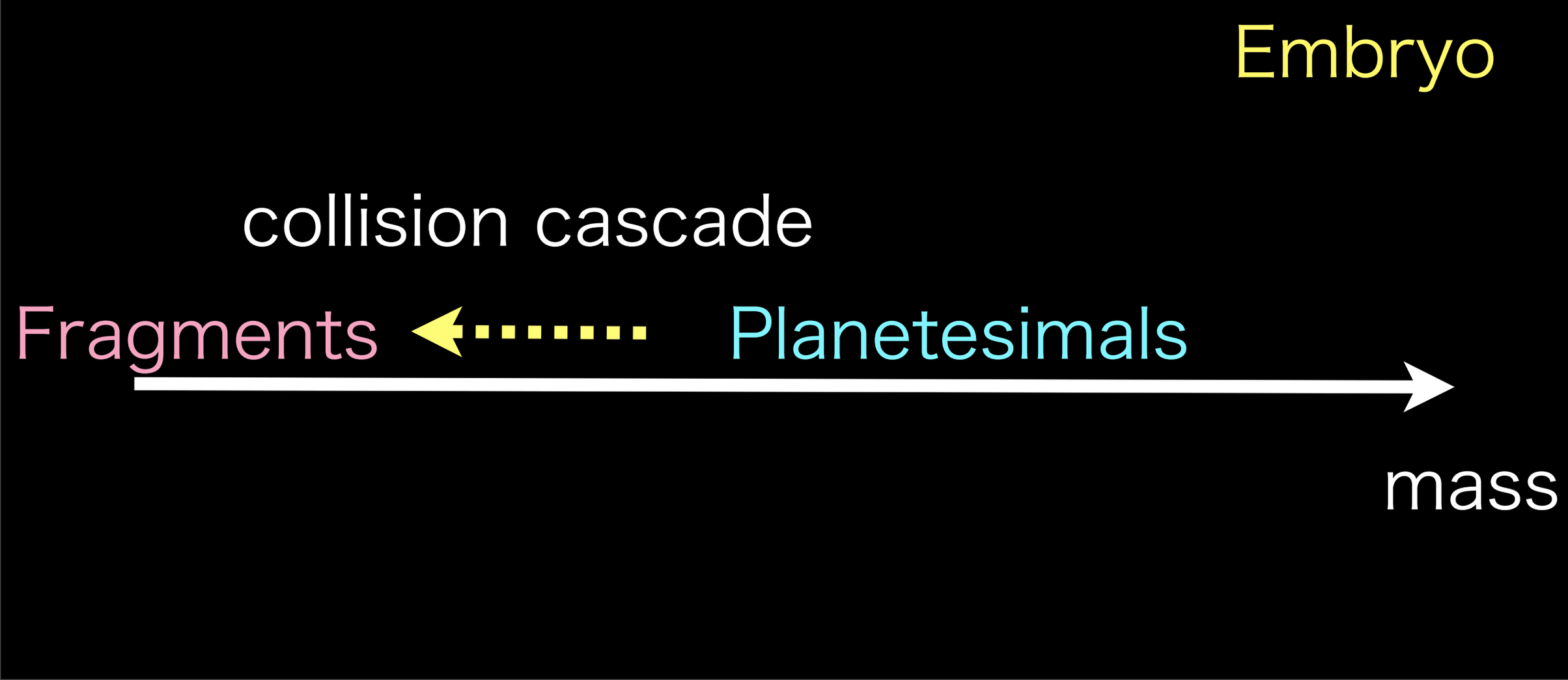
collision cascade

Fragments

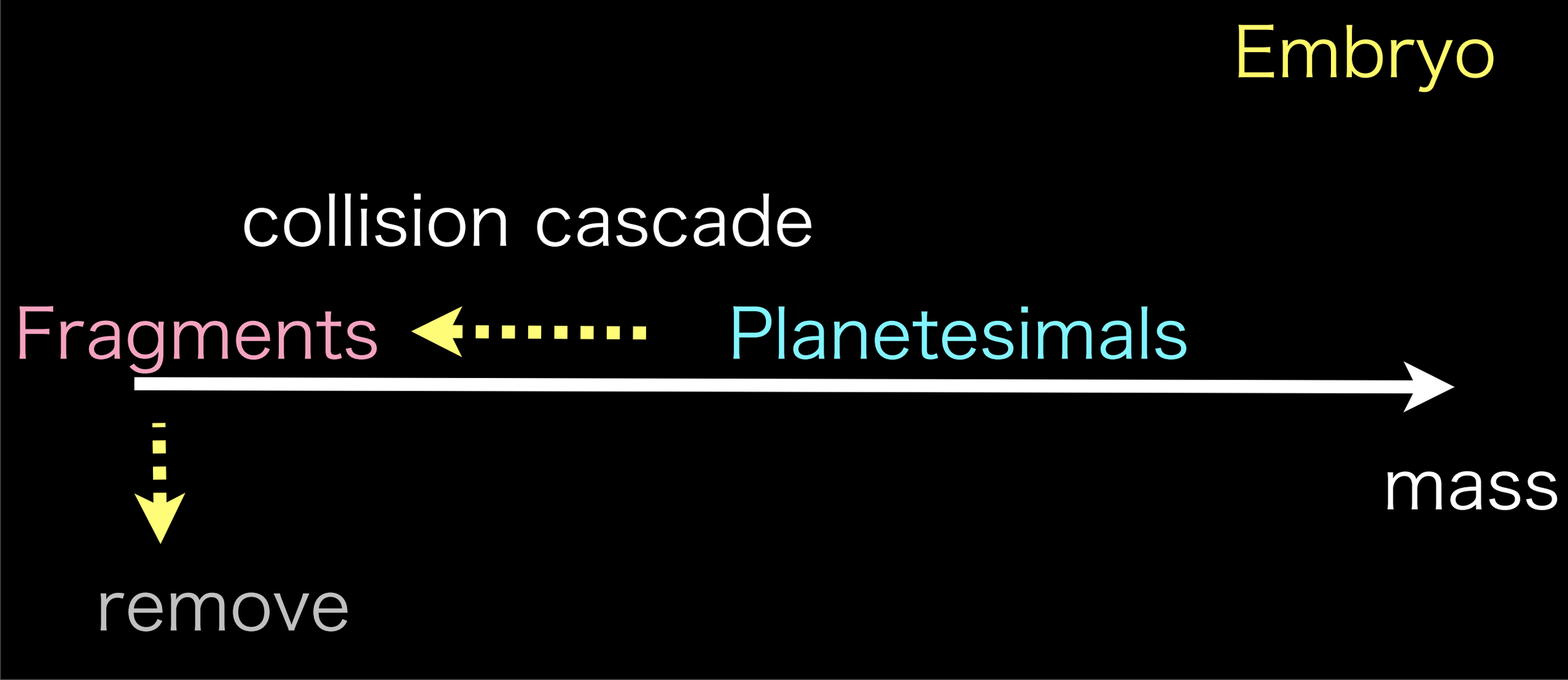
Planetesimals

mass

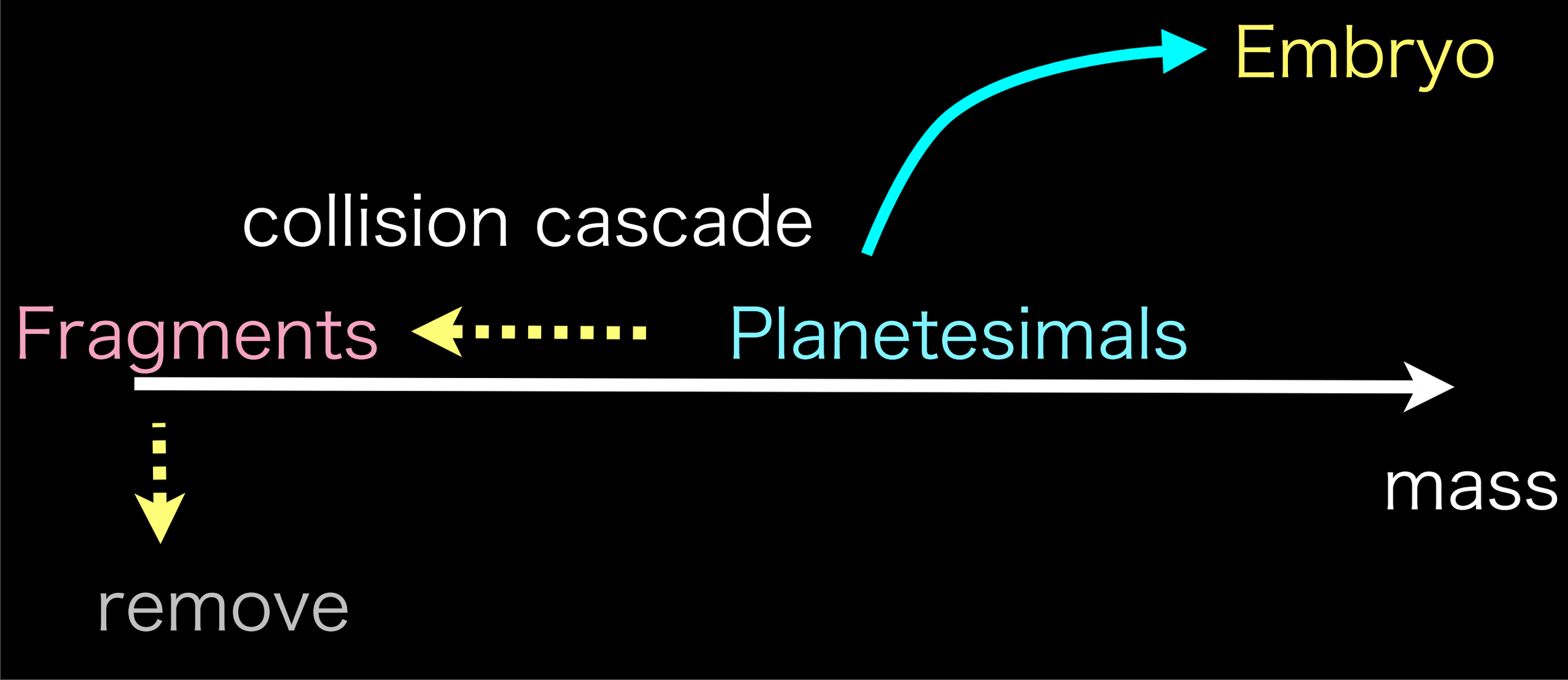
Analysis



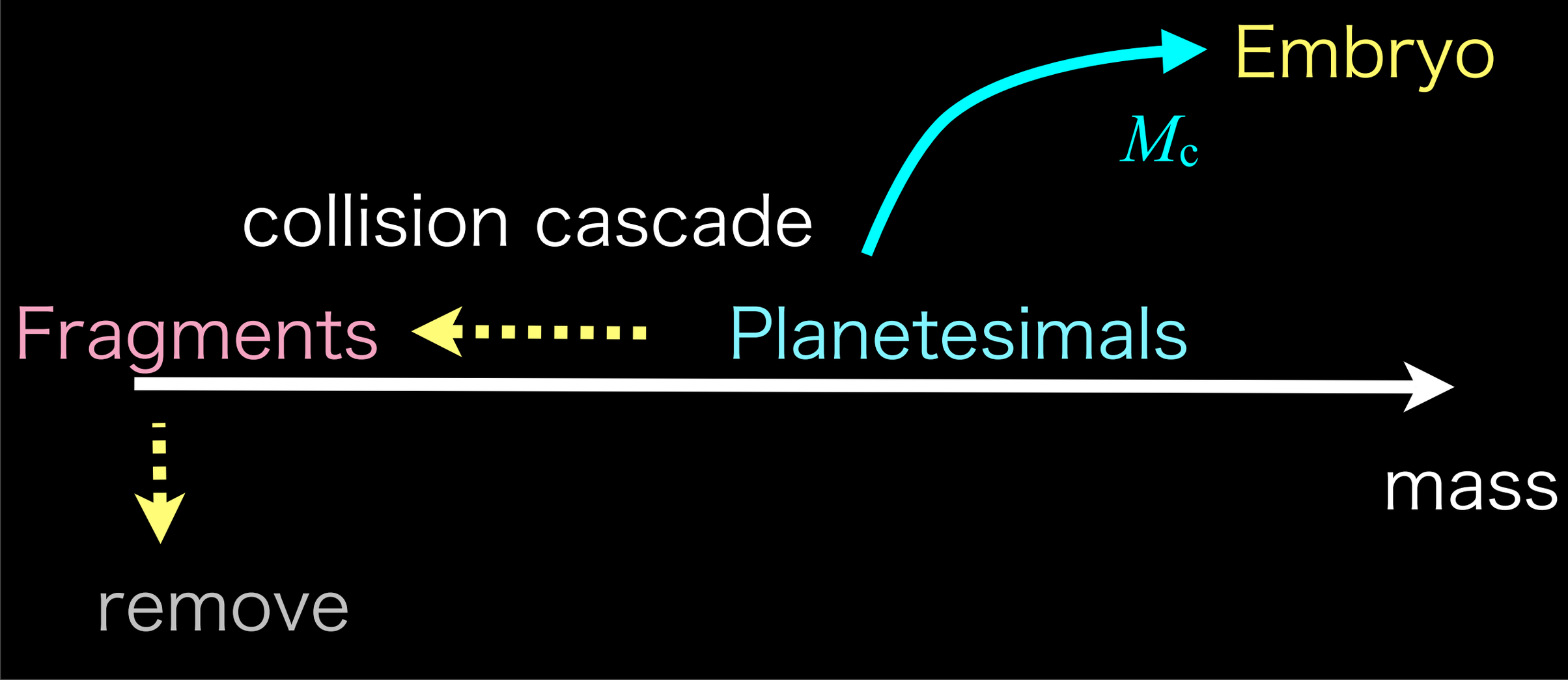
Analysis


Embryo
collision cascade
Fragments
Planetesimals
mass
remove

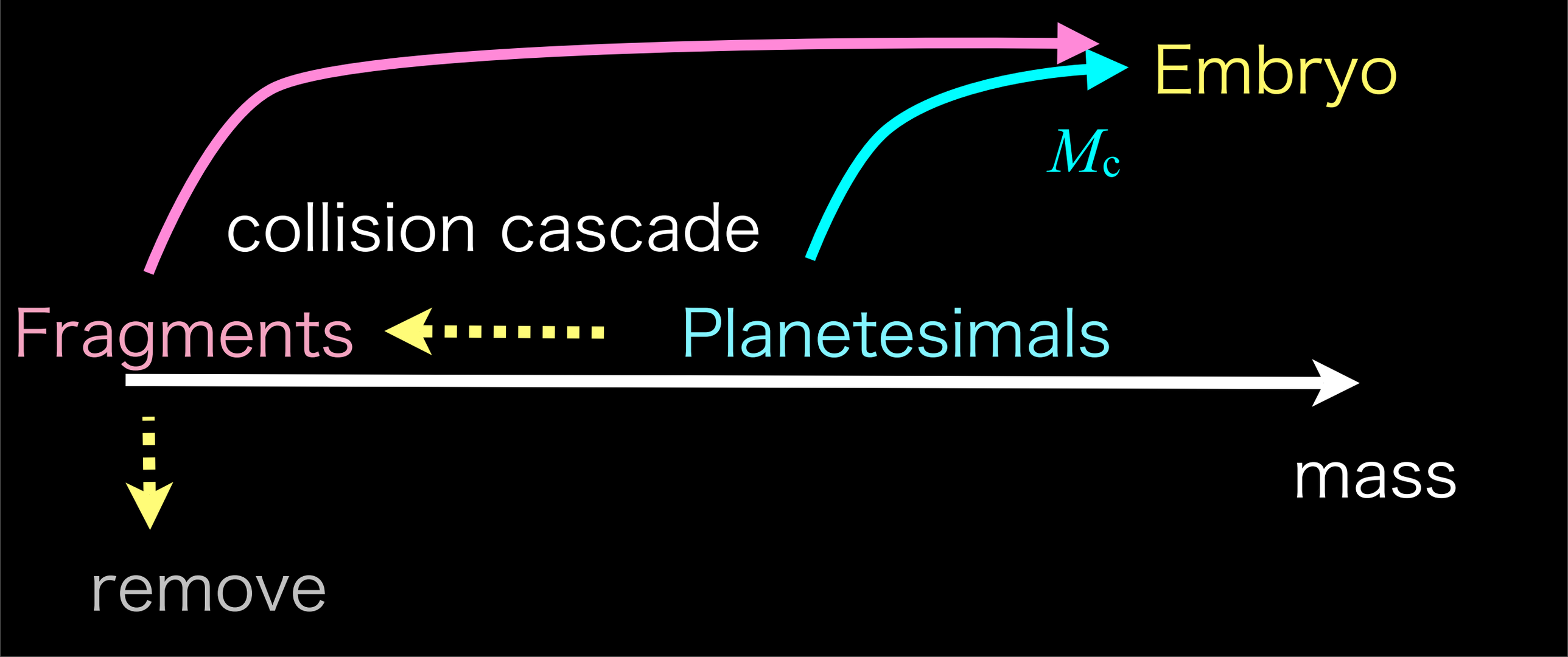
Analysis


Embryo
collision cascade
Fragments
Planetesimals
mass
remove

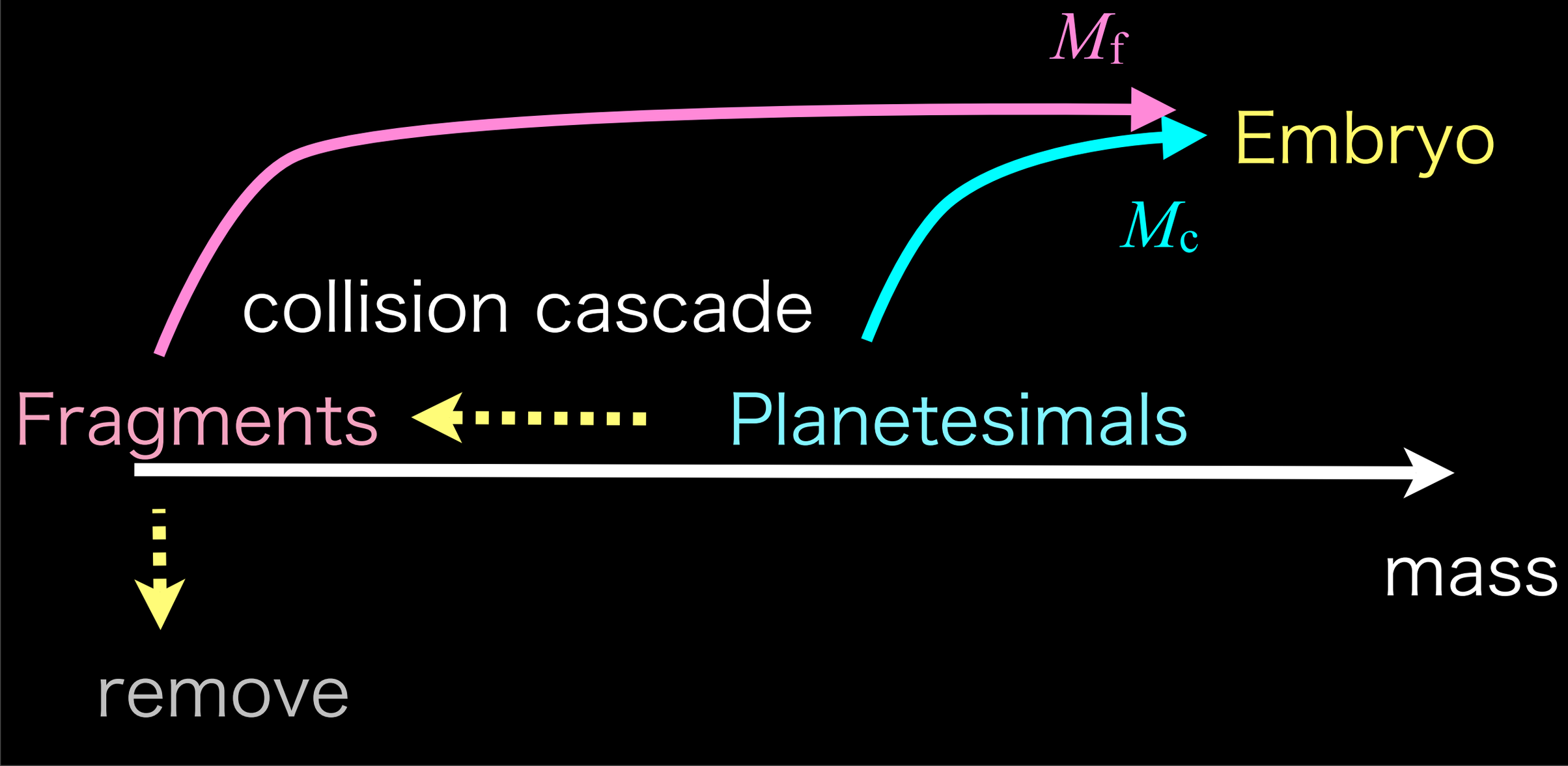
Analysis


Embryo
M_c
collision cascade
Fragments
Planetesimals
mass
remove

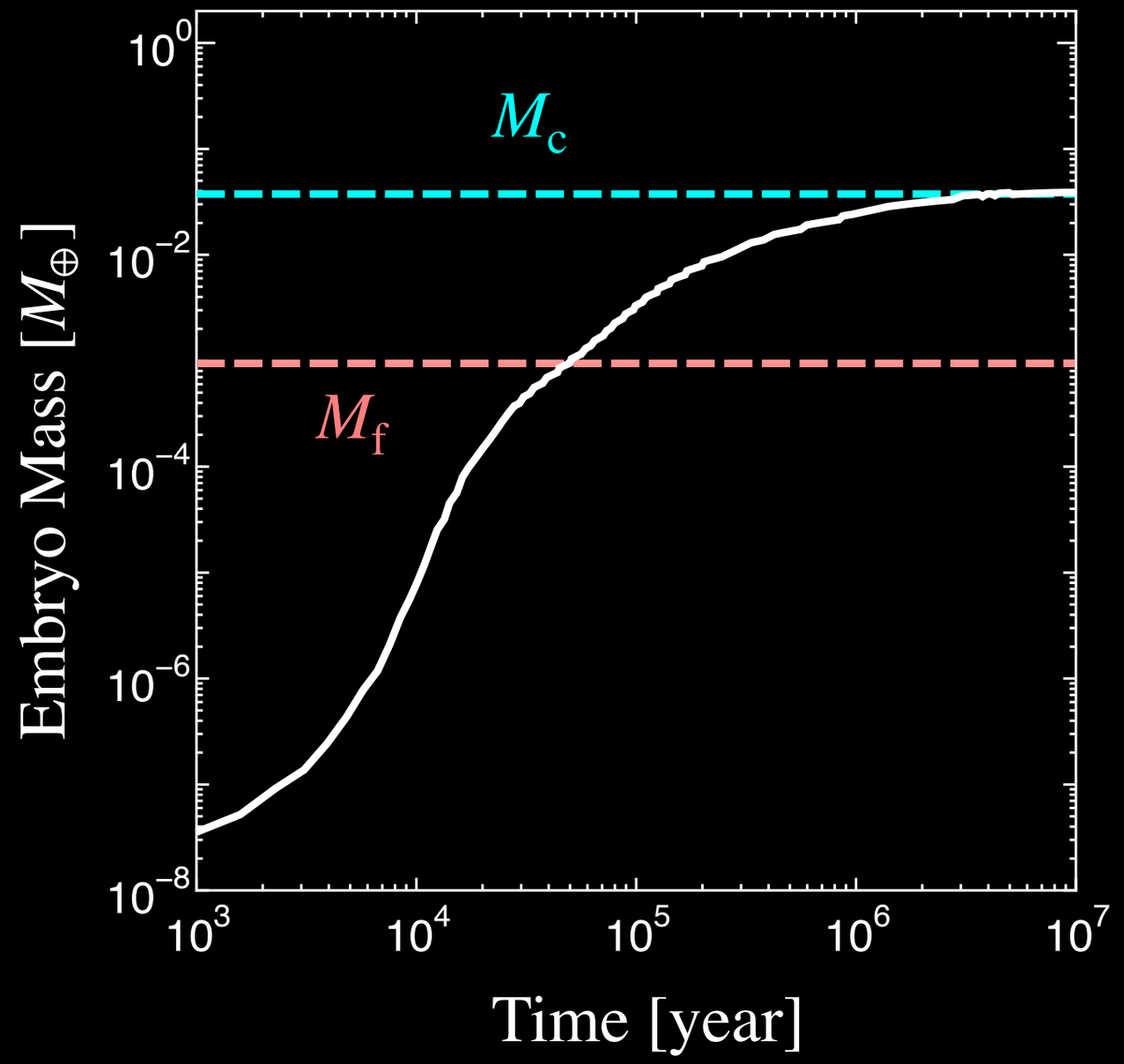
Analysis


Embryo
M_c
collision cascade
Fragments
Planetesimals
mass
remove

Analysis


$M_{\rm f}$
Embryo
$M_{\rm c}$
collision cascade
Fragments
Planetesimals
mass
remove

Final Embryo Mass

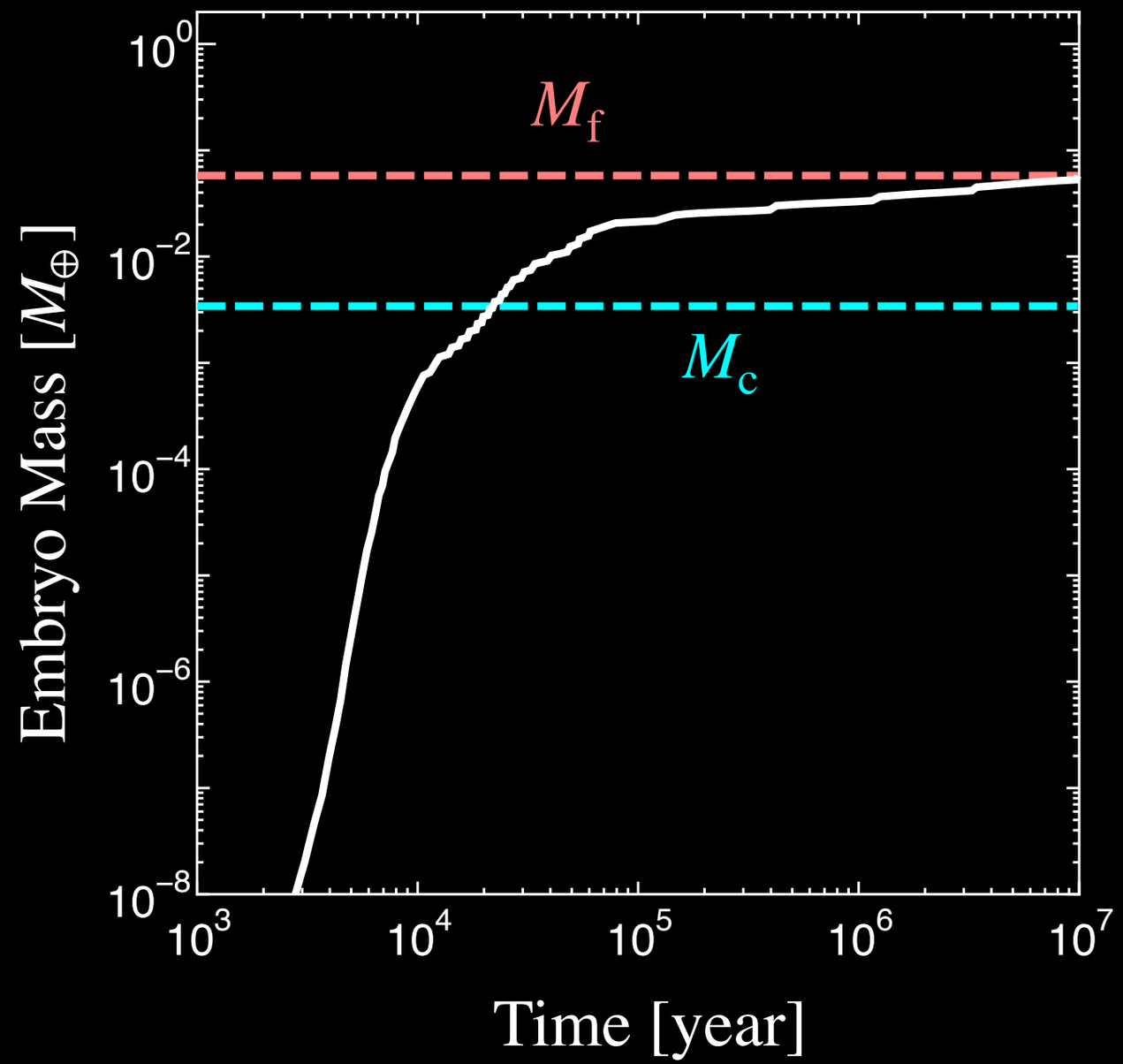


$r_0 = 10$ km

at 1 AU

MMSN

Final Embryo mass

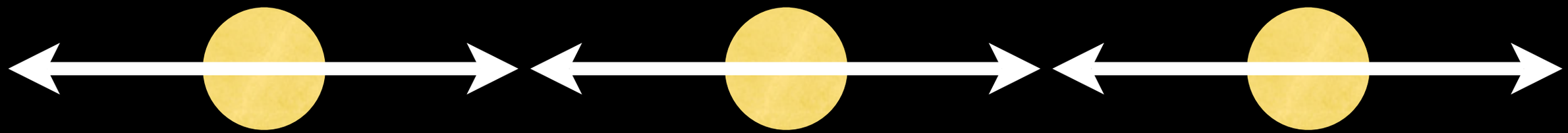


$r_0 = 1$ km

at 3.2 AU

MMSN

Isolation Mass



$$M_{\rm iso} = 2\pi a b \Sigma$$

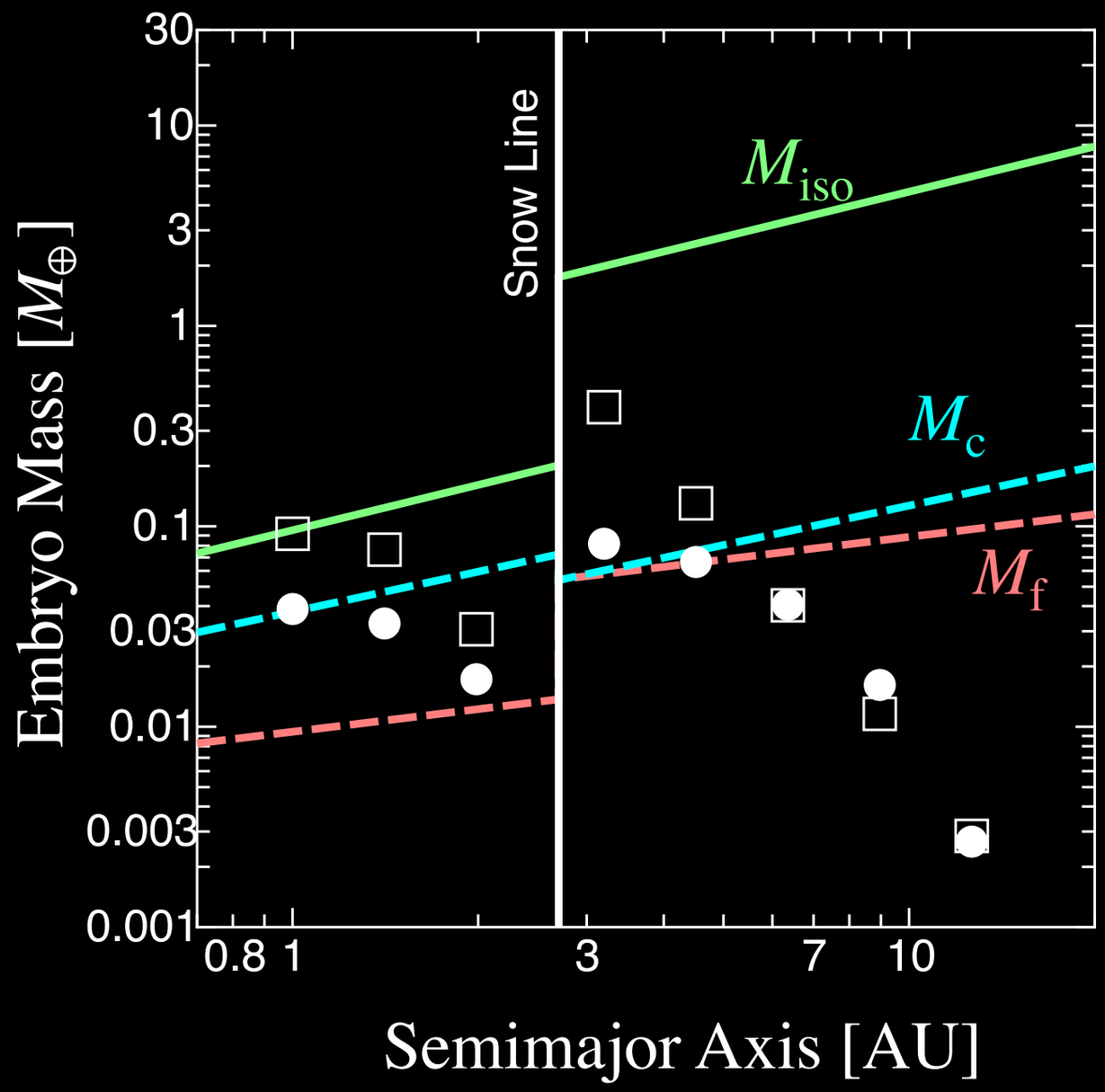
a: distance
b: separation
Σ: surface density

Distance

Sim. in10^7 yr

Frag.

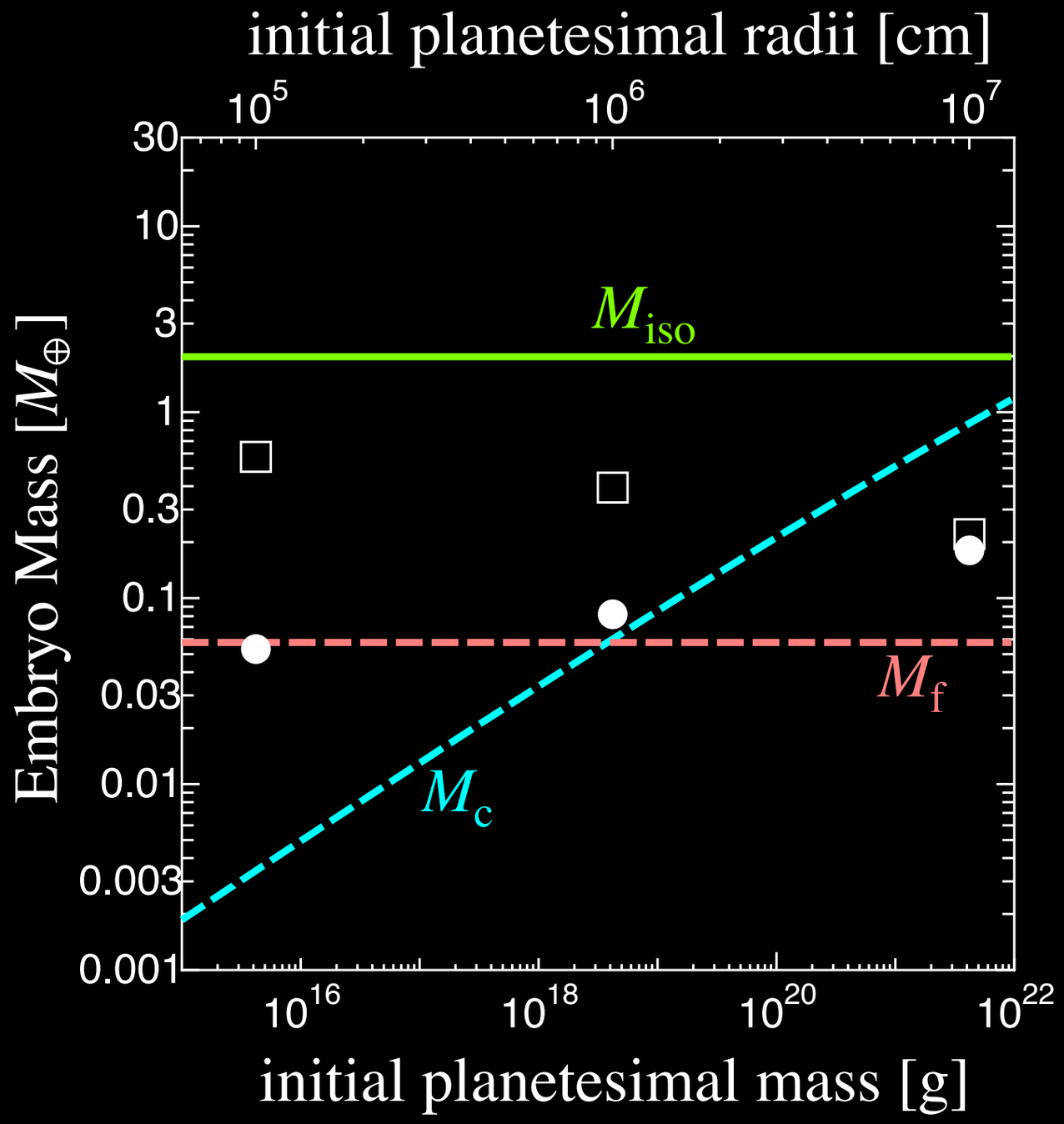
- ● Yes
- □ No



$r_0 = 10$ km

MMSN

Initial Planetesimal

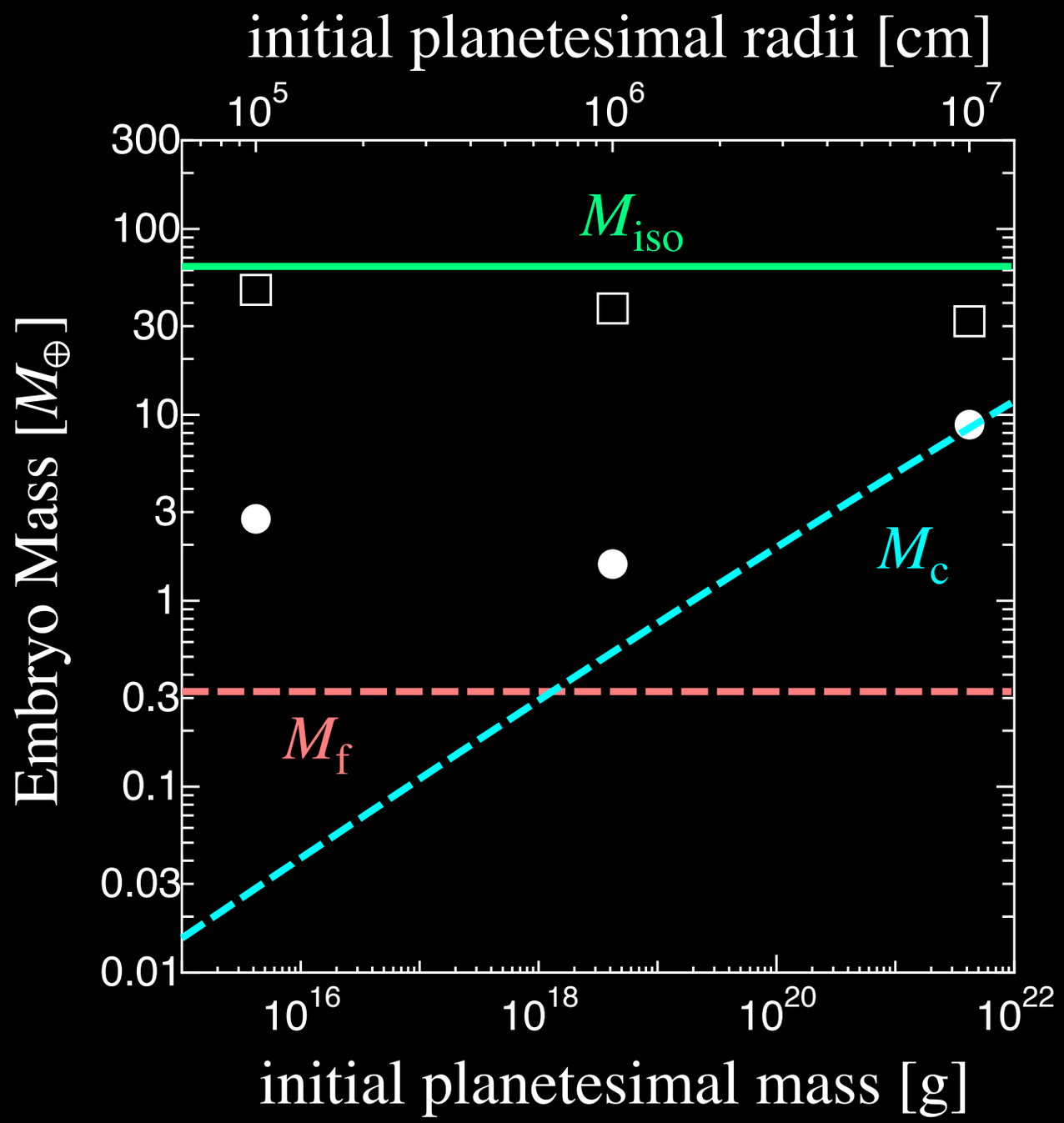


10^7 yr

at 3.2AU

MMSN

Massive Disk



10^7 yr

at 3.2AU

10MMSN

Conclusion

- The final embryo mass is much smaller than the isolation mass.
- Our analytical formulae are consistent with the final mass.
- Embryo mass reaches the critical core mass at 3-4AU for $r_0 > 100\ \mathrm{km}$ and > 10MMSN