Planetary Formation with Fragmentation

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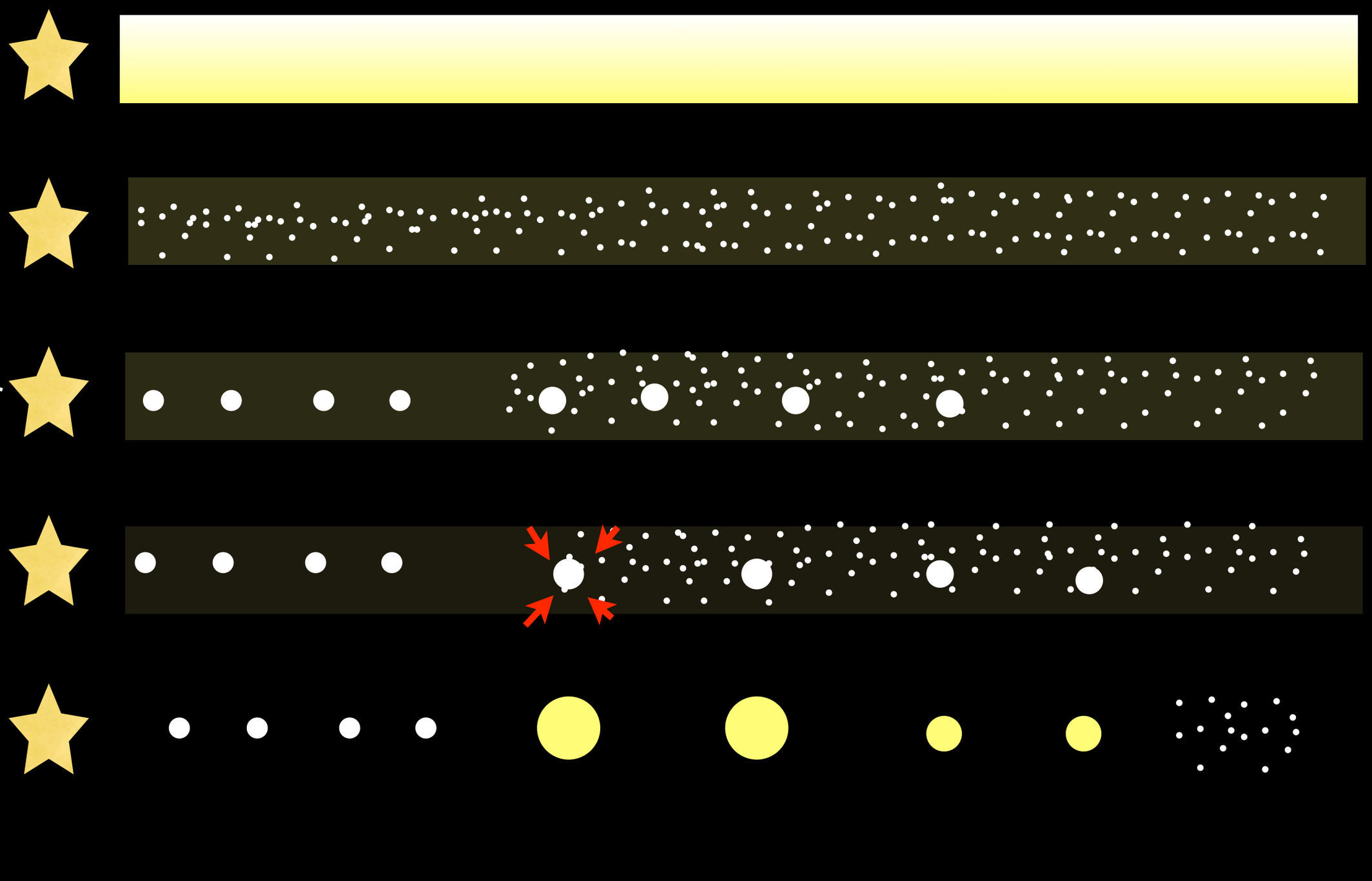
Collaborator:
A. Krivov, H. Tanaka

Contents

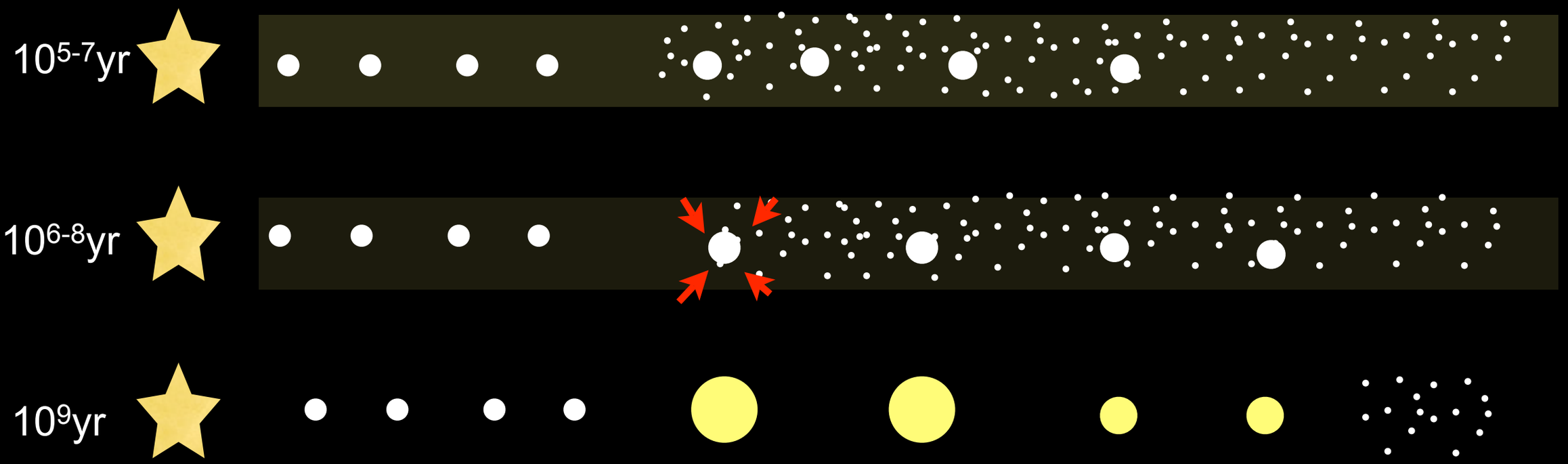
Standard Model



Standard Model

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

Planetesimal



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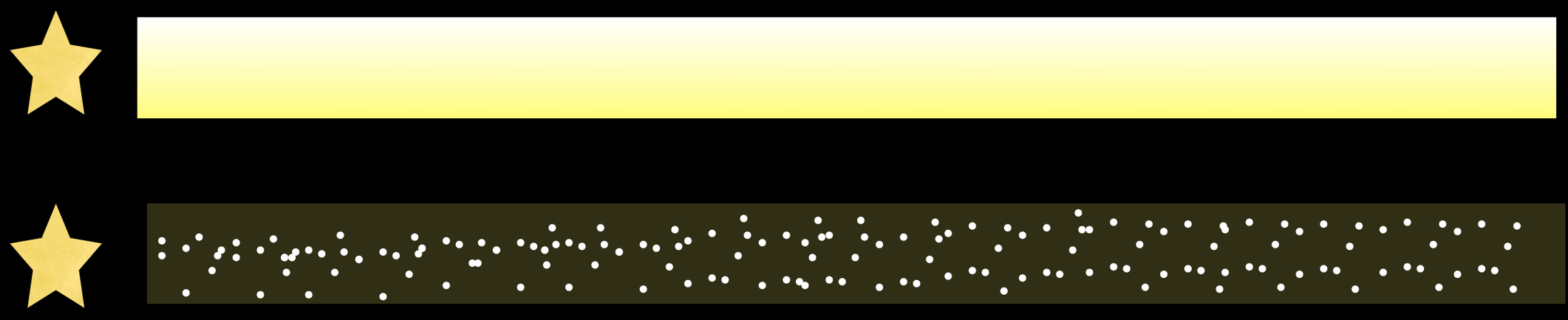
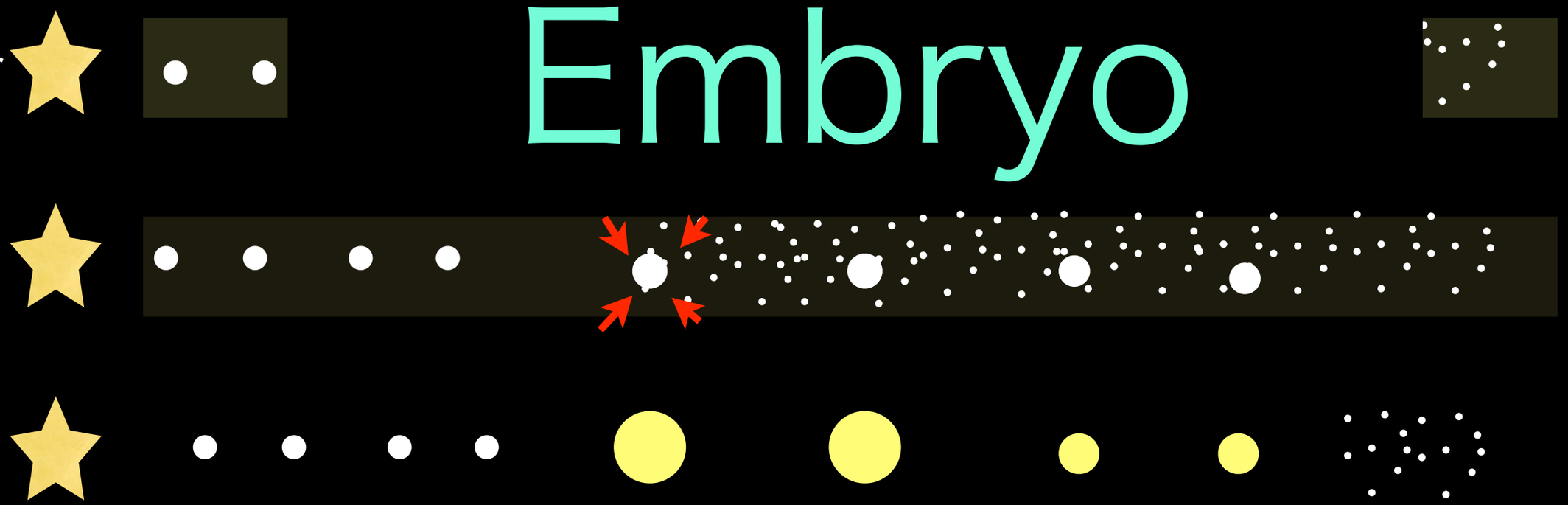


$10^{5\text{-}6}$yr

Embryo

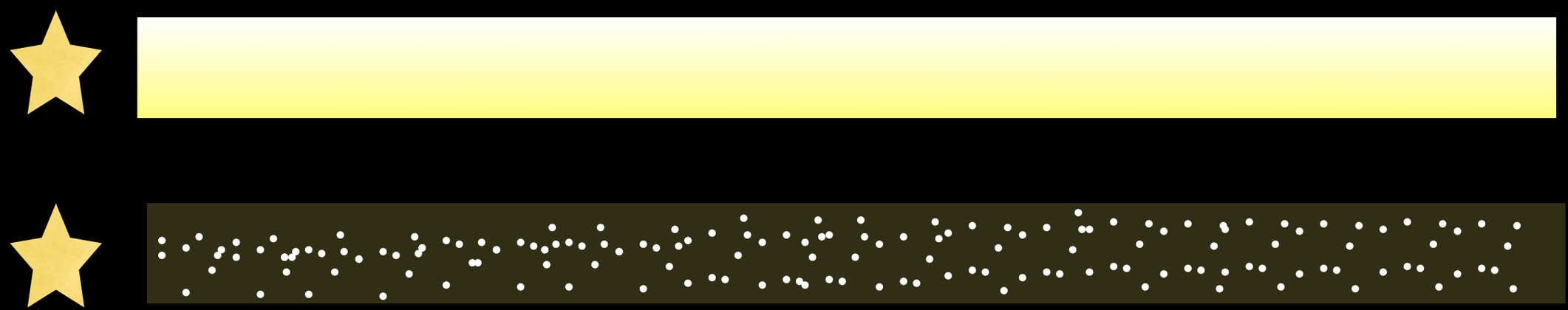


$10^{5\text{-}7}$yr

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

10^{9}yr

Standard Model



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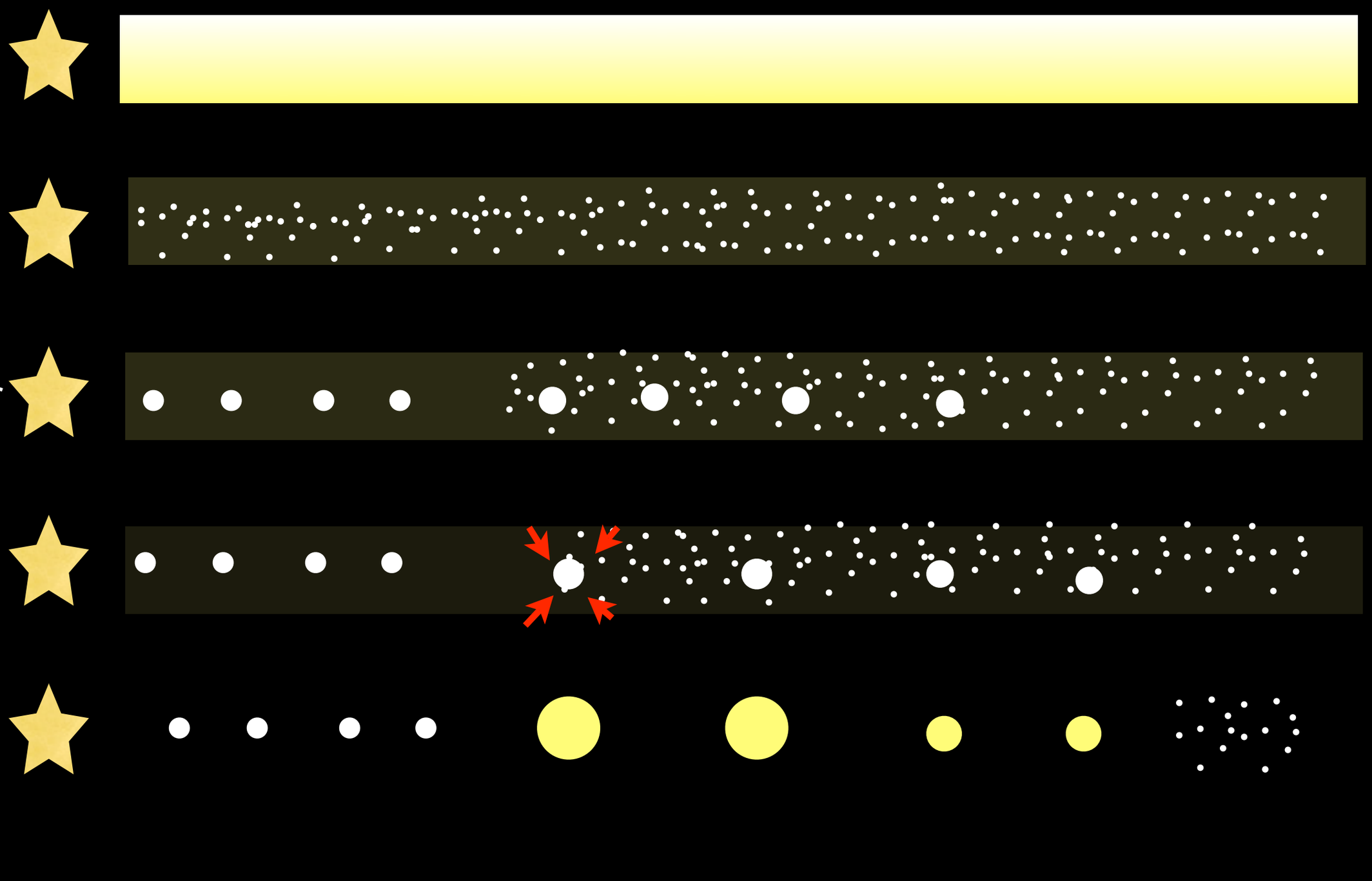
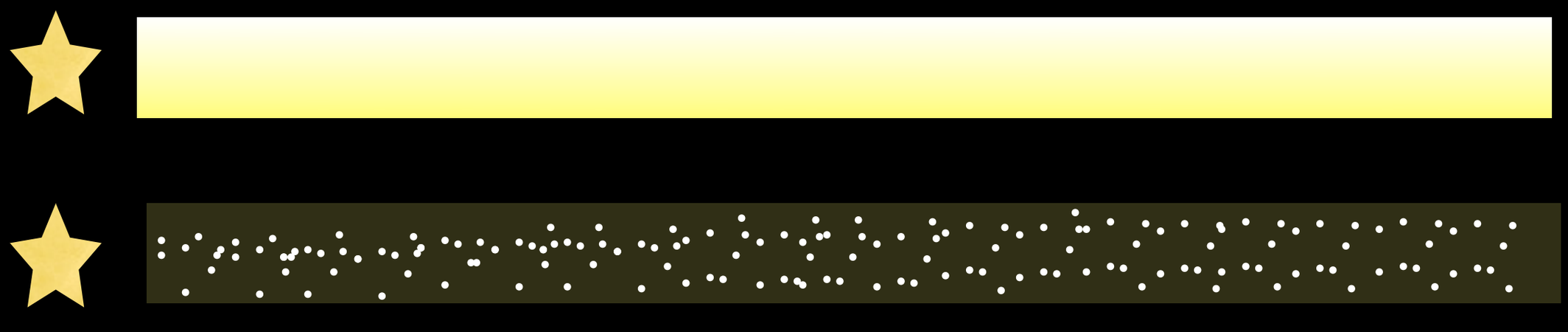
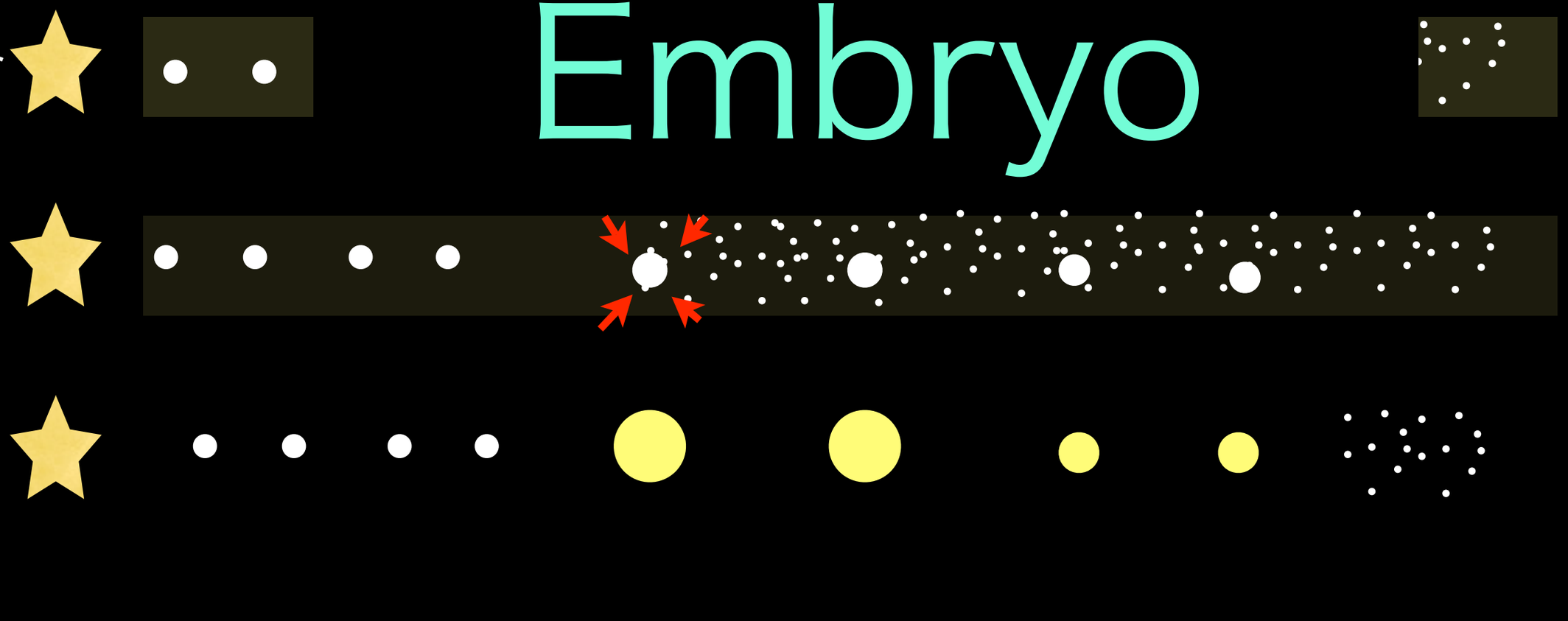


Standard Model



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

Embryo



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

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

10^{9}yr

Fragmentation

- Embryos grow through accretion with planetesimals.
- The embryos become massive and then start to dynamically stir up planetesimals.
  - Planetesimals are ground down by successive collisions,
- until very small bodies are removed by gas drag.

Fragmentation

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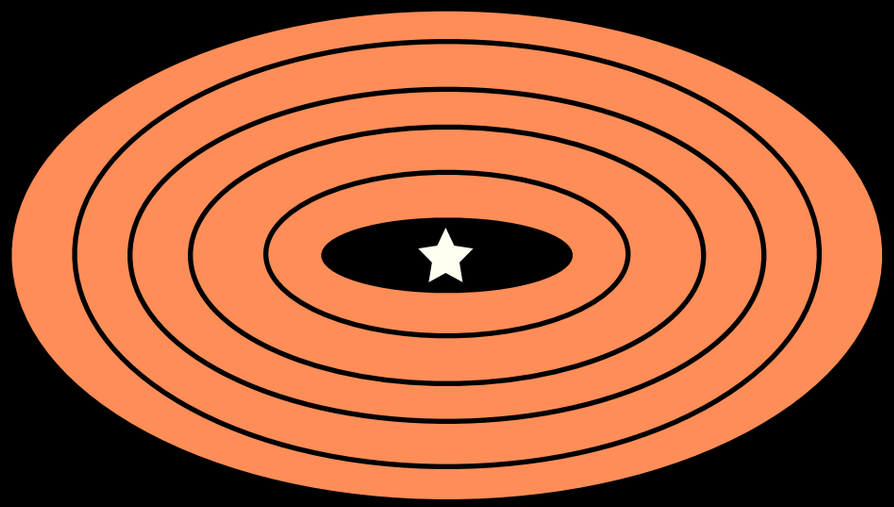
- The embryos become massive and then start to dynamically stir up planetesimals.
  - Planetesimals are ground down by successive collisions,
- until very small bodies are removed by gas drag.

The final mass is estimated to be the Mars mass.
(Kobayashi and Tanaka 2010)

Aim

- Embryo growth with fragmentation.
  - Calculation of the coupled velocity and mass evolution (e.g., Wetherill and Stewart 1993).
  - Inward drift by gas drag.
- What determines the final mass?

Model



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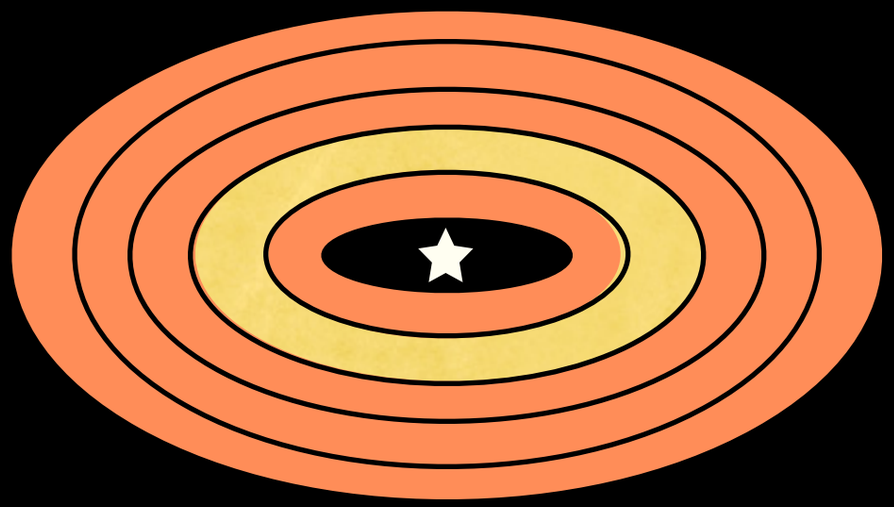

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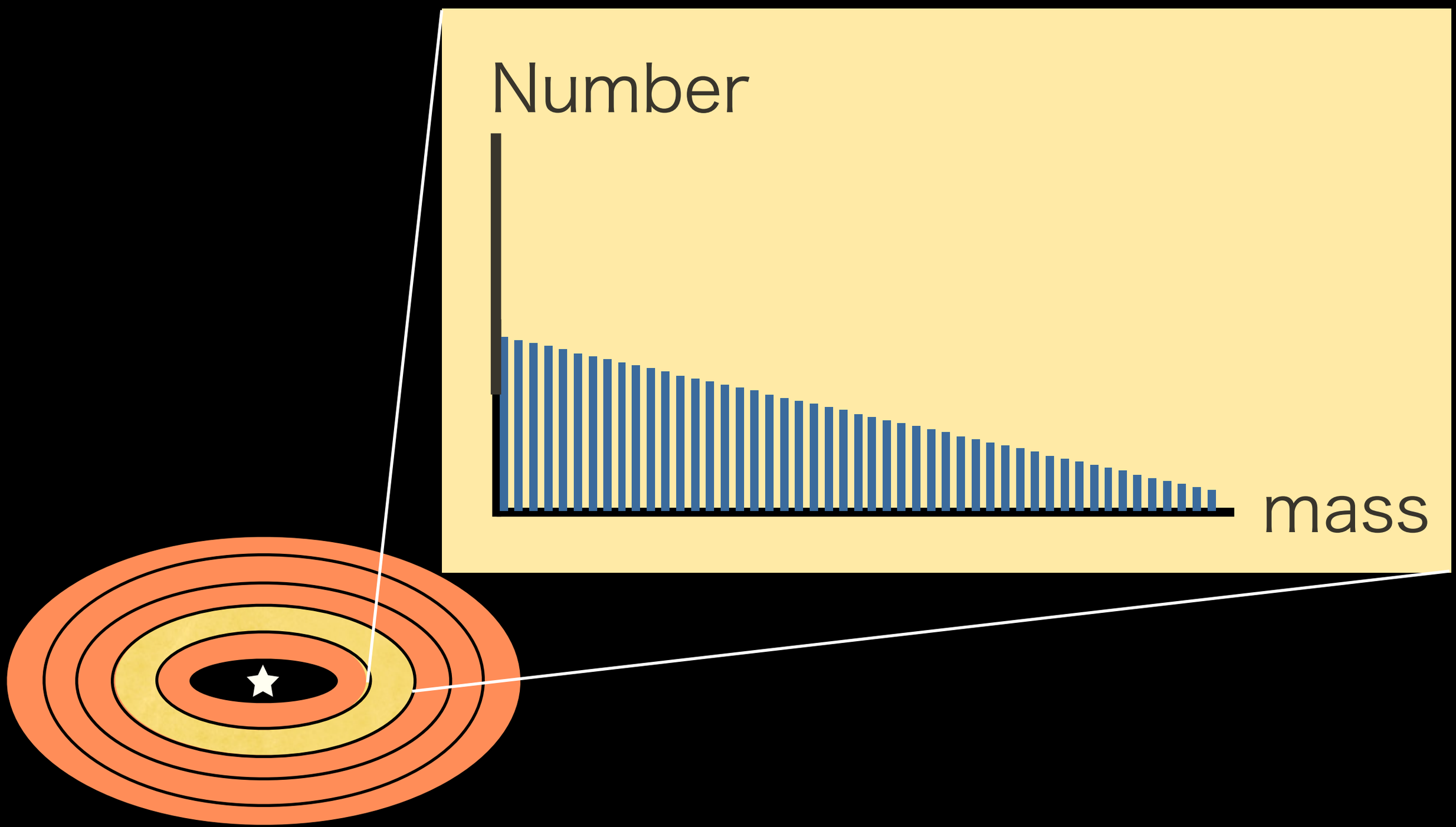

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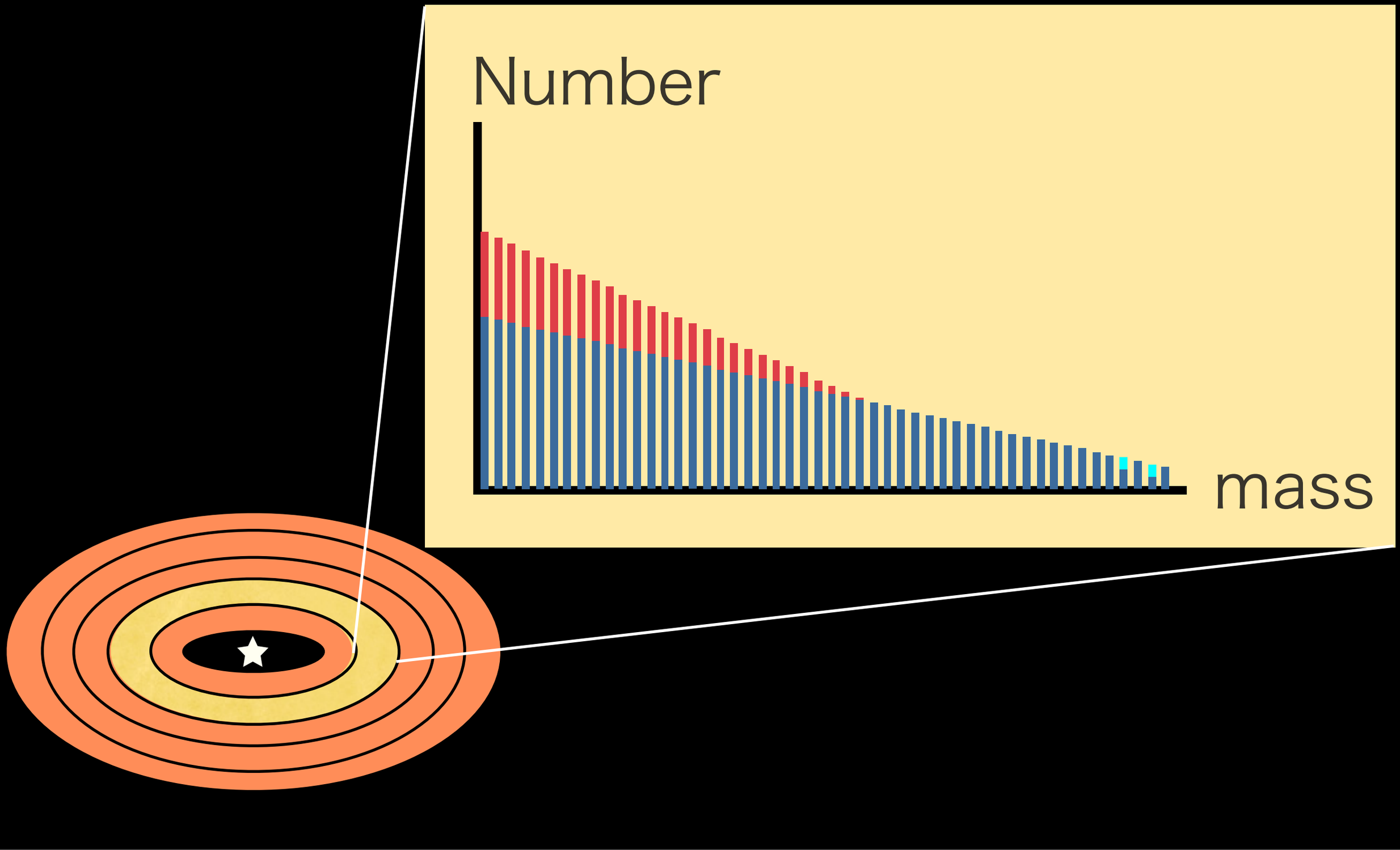
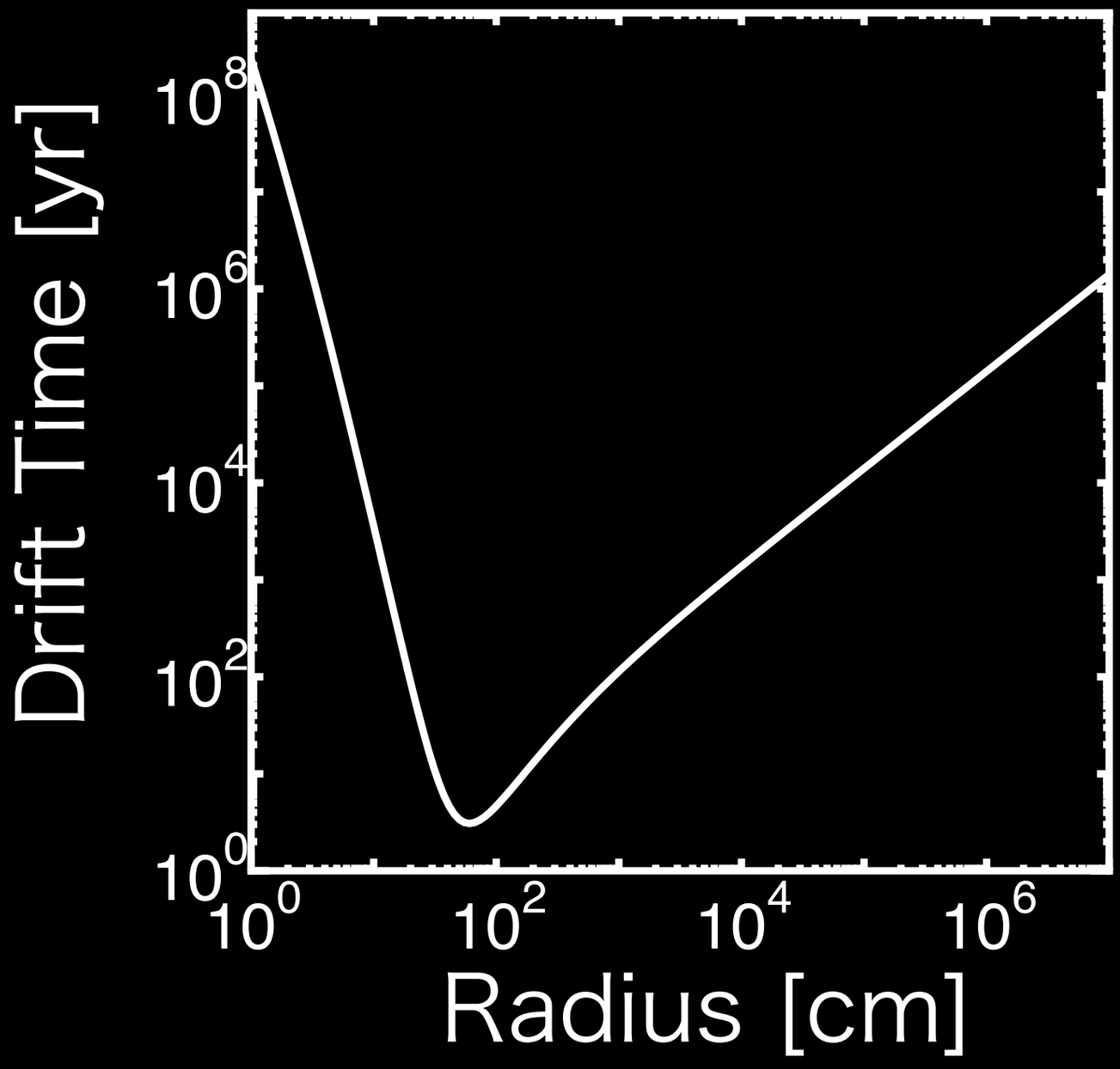


Drift by Gas Drag

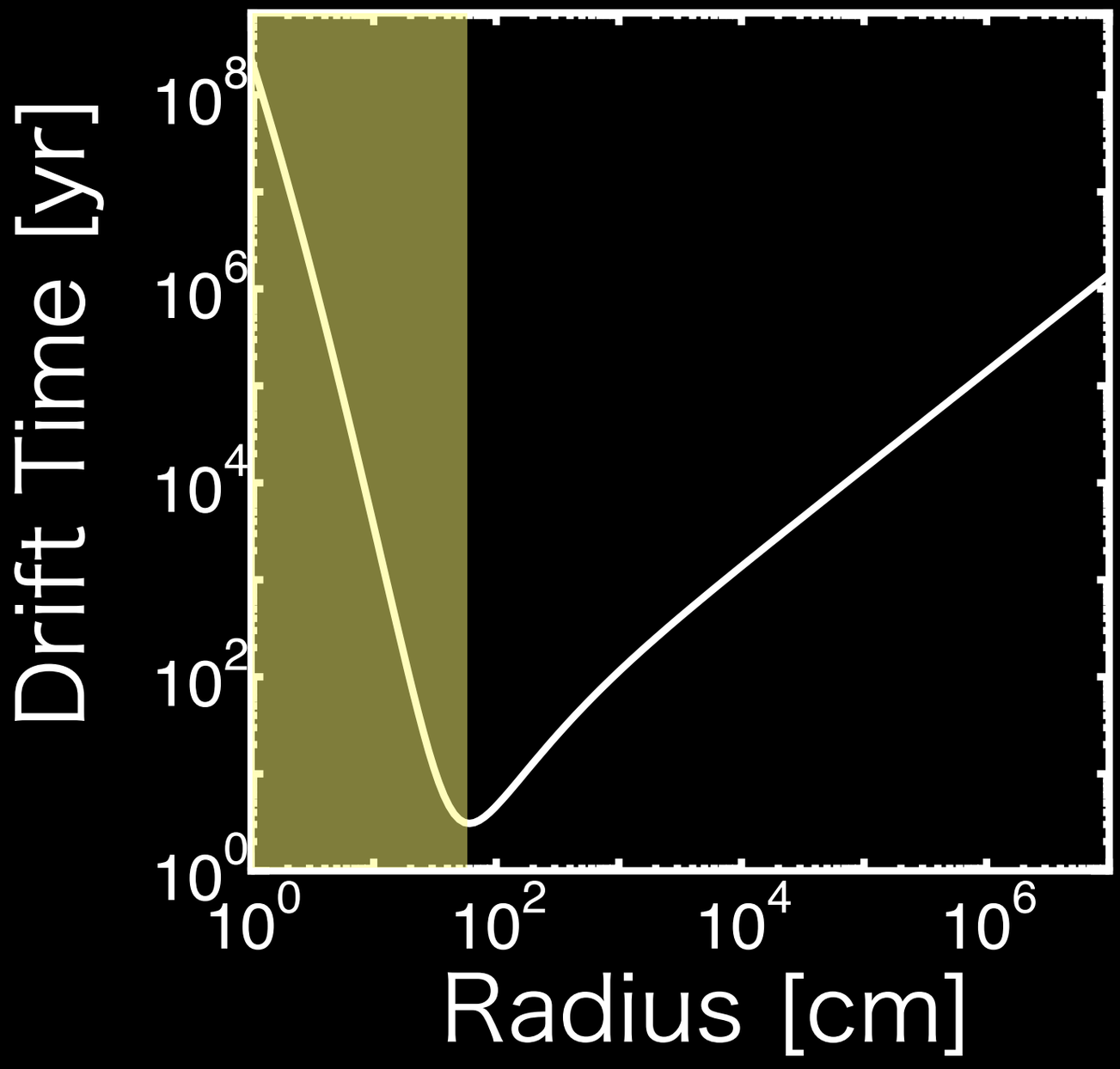


at 5 AU

$s_{\min} = 1\,\mathrm{cm}$

The coupled bodies may help the embryo growth to some extent (Kenyon and Bromley 2009).

Drift by Gas Drag



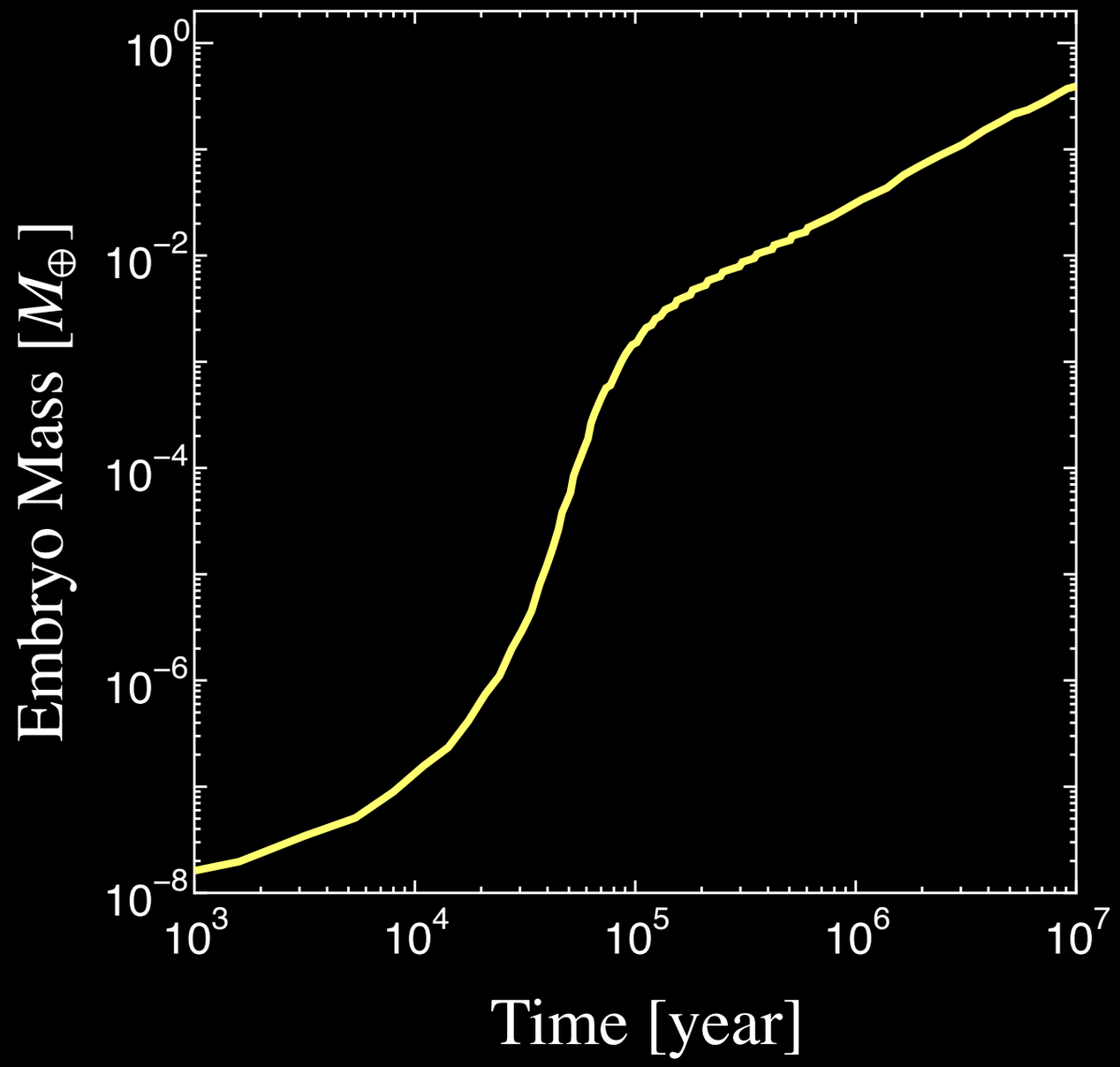
at 5 AU

$s_{\min} = 1\,\mathrm{cm}$

The coupled bodies may help the embryo growth to some extent (Kenyon and Bromley 2009).

Embryo Growth

No Fragmentation

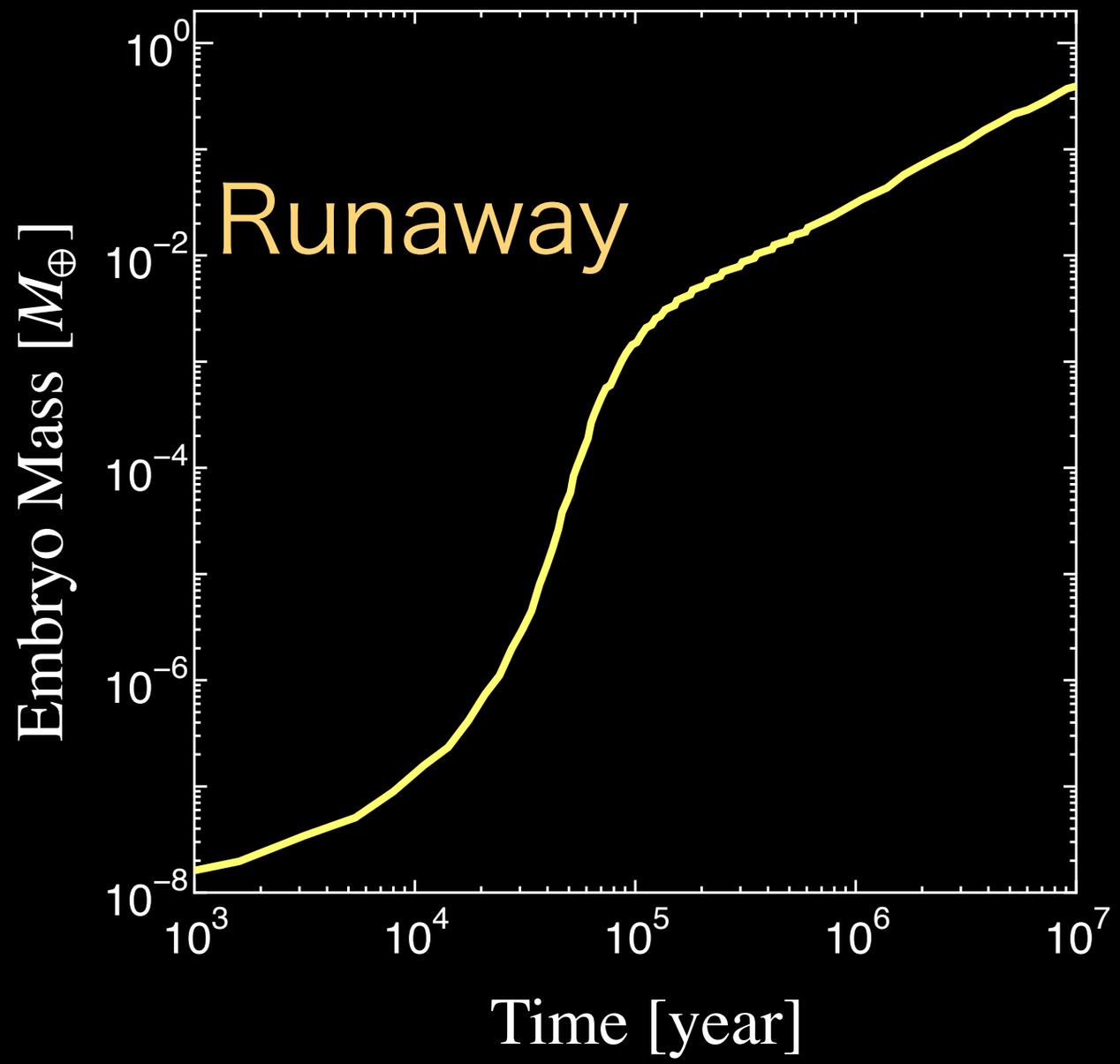


at 3.2AU
MMSN

(Wetherill and Stewart 1989)

(Kokubo and Ida 1998)

No Fragmentation



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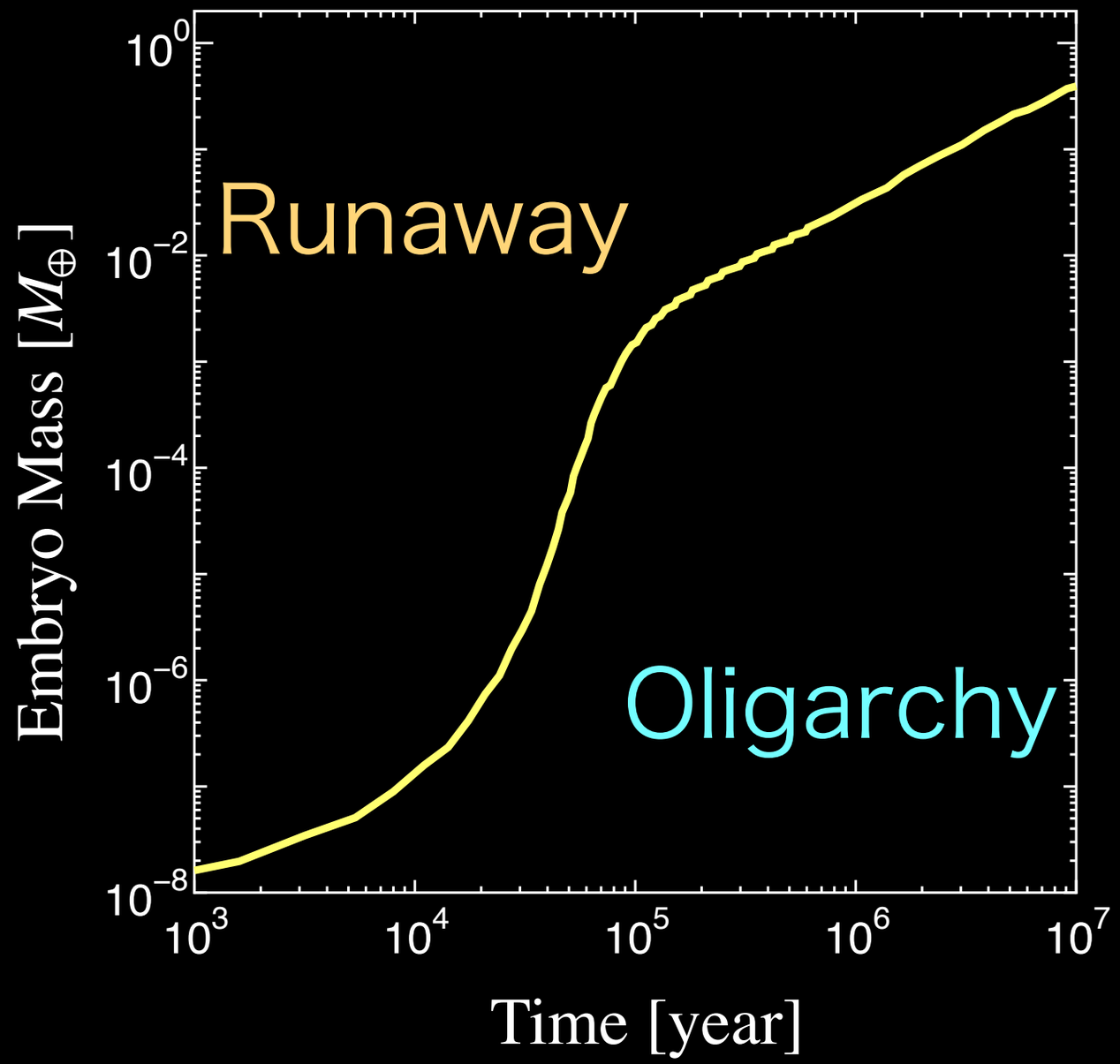
(Wetherill and Stewart 1989)

(Kokubo and Ida 1998)

No Fragmentation

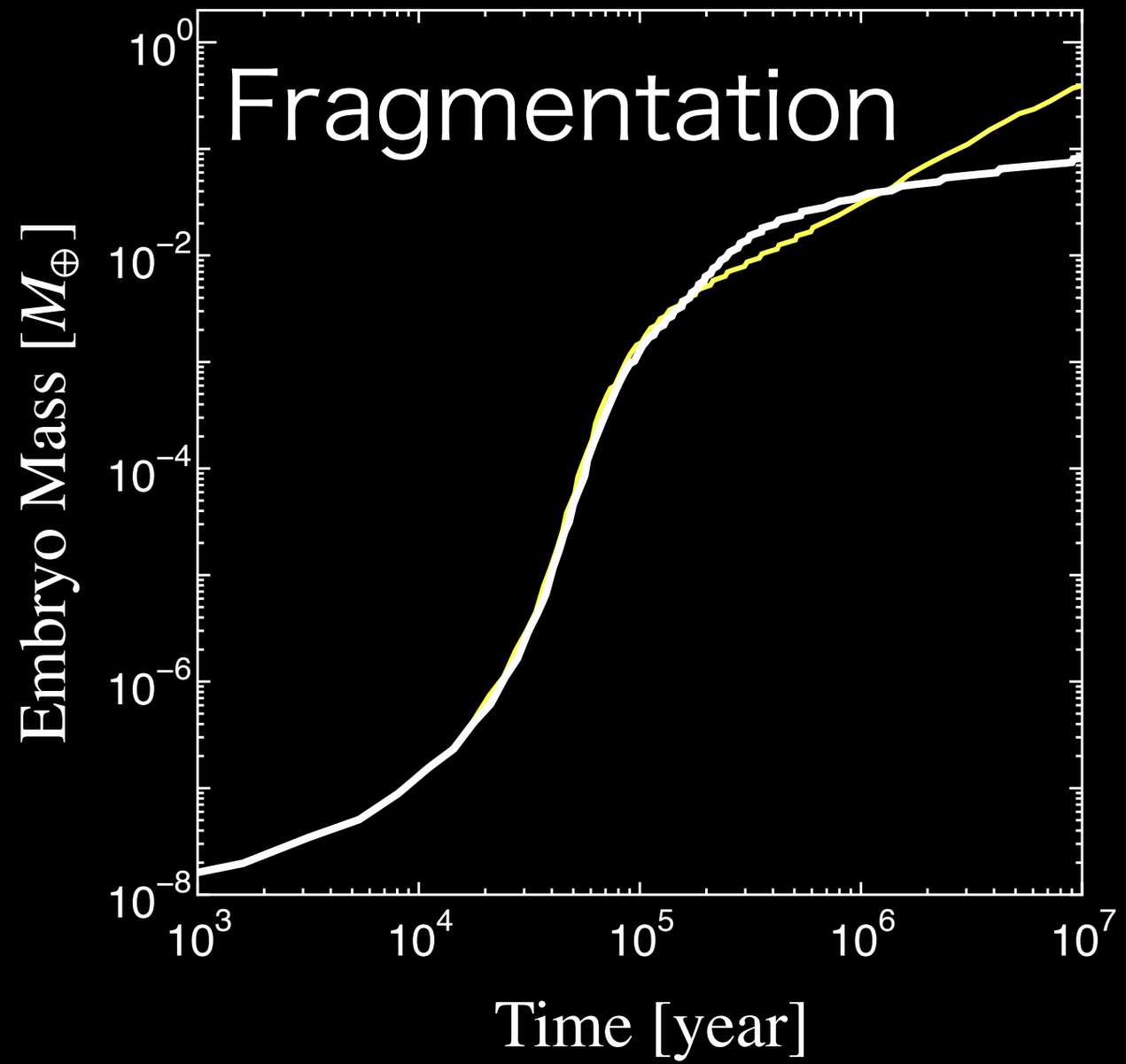


at 3.2AU
MMSN

(Wetherill and Stewart 1989)

(Kokubo and Ida 1998)

With Fragmentation

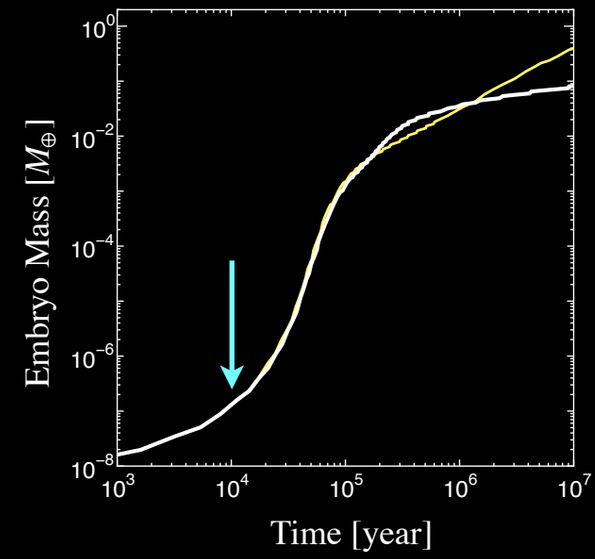


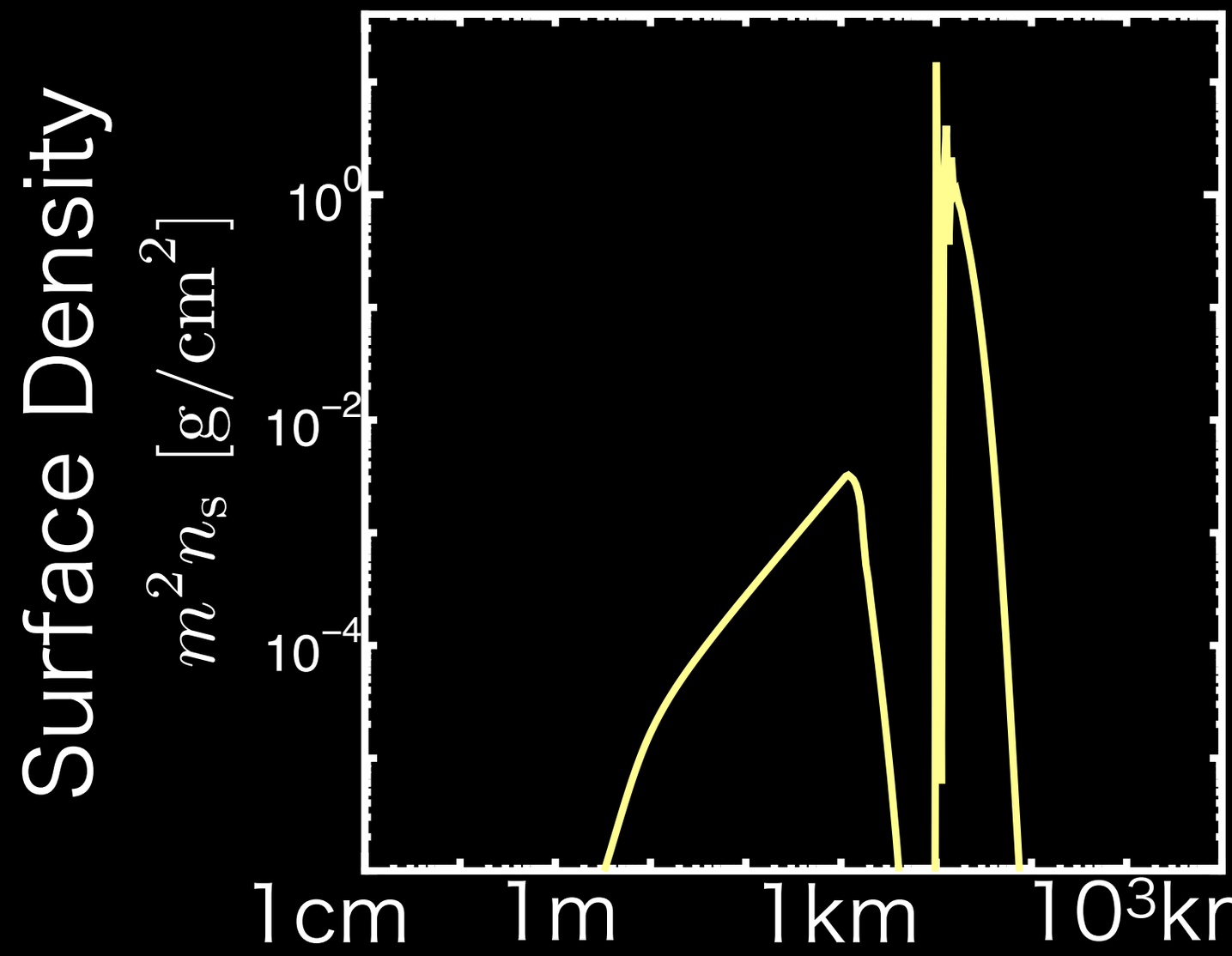
No fragment

at 3.2AU
MMSN

Mass Distribution

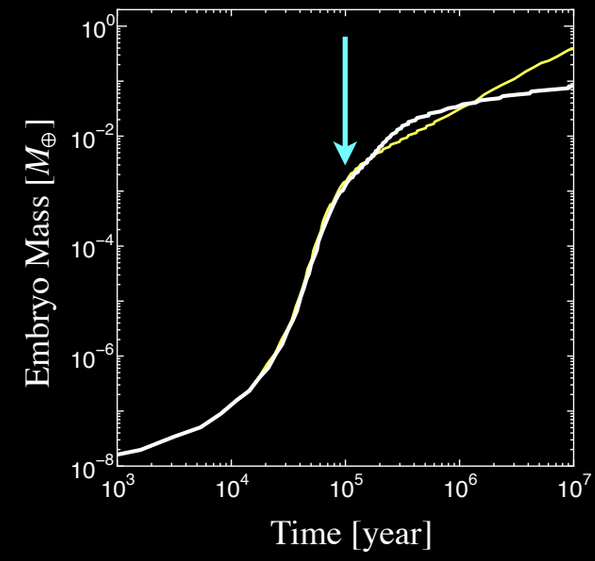
$t = 10^4$ yr

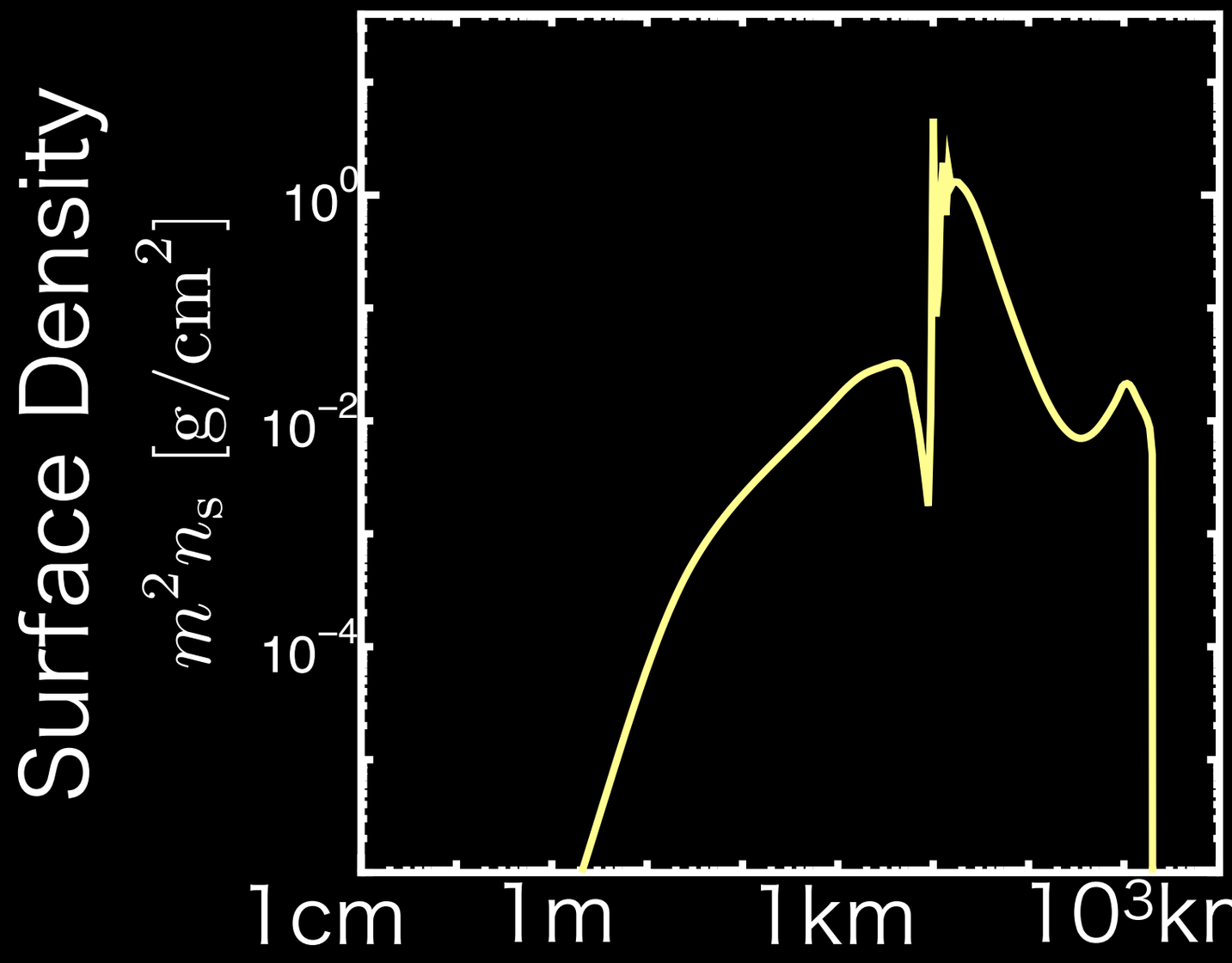

Embryo Mass [$M_\oplus$]
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Time [year]


Surface Density
$m^2 n_s$ [g/cm^2]
10^{0}
10^{-2}
10^{-4}
1cm
1m
1km
10^3km
Radius

3.2AU

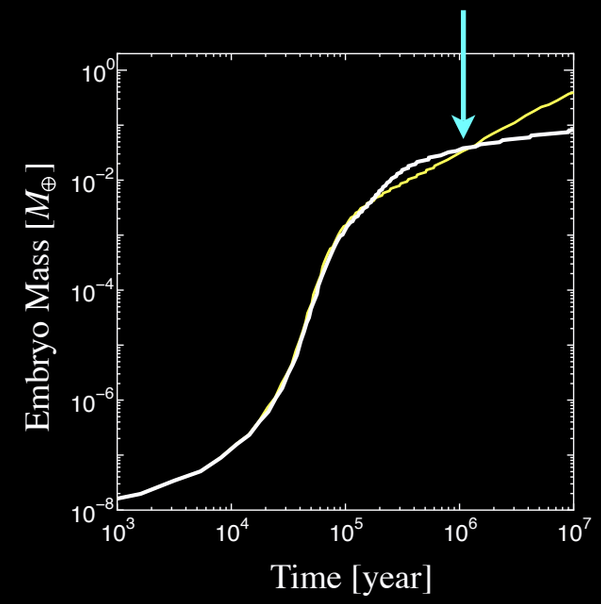
$t = 10^5$ yr

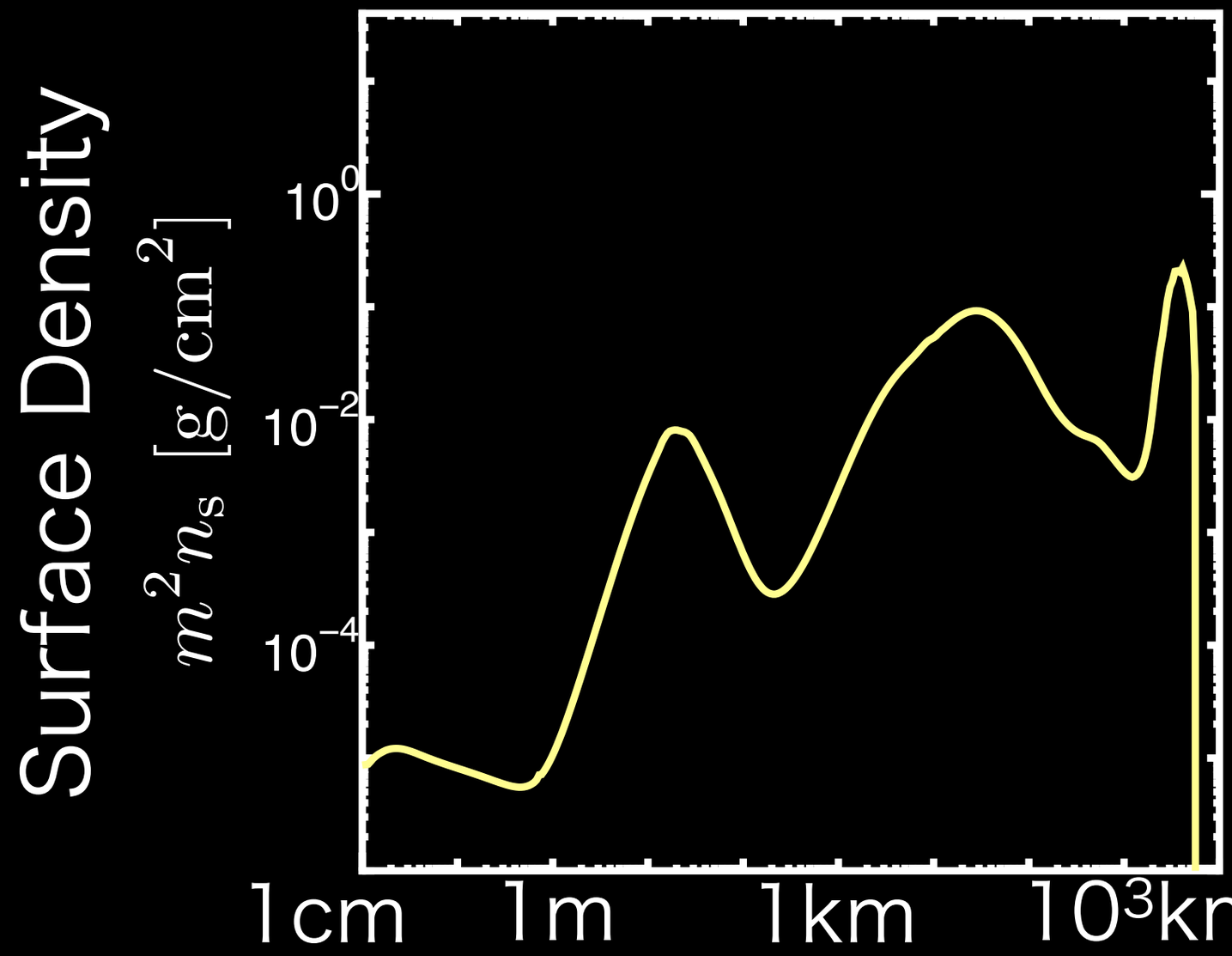

Embryo Mass [$M_\oplus$]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^3
10^4
10^5
10^6
10^7
Time [year]


Surface Density
$m^2 n_s$ [g/cm^2]
10^0
10^{-2}
10^{-4}
1cm
1m
1km
10^3km
Radius

3.2AU

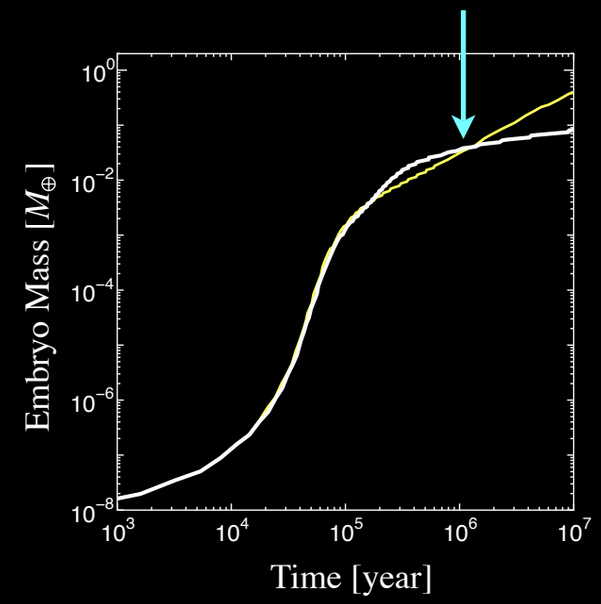
$t = 10^6$ yr

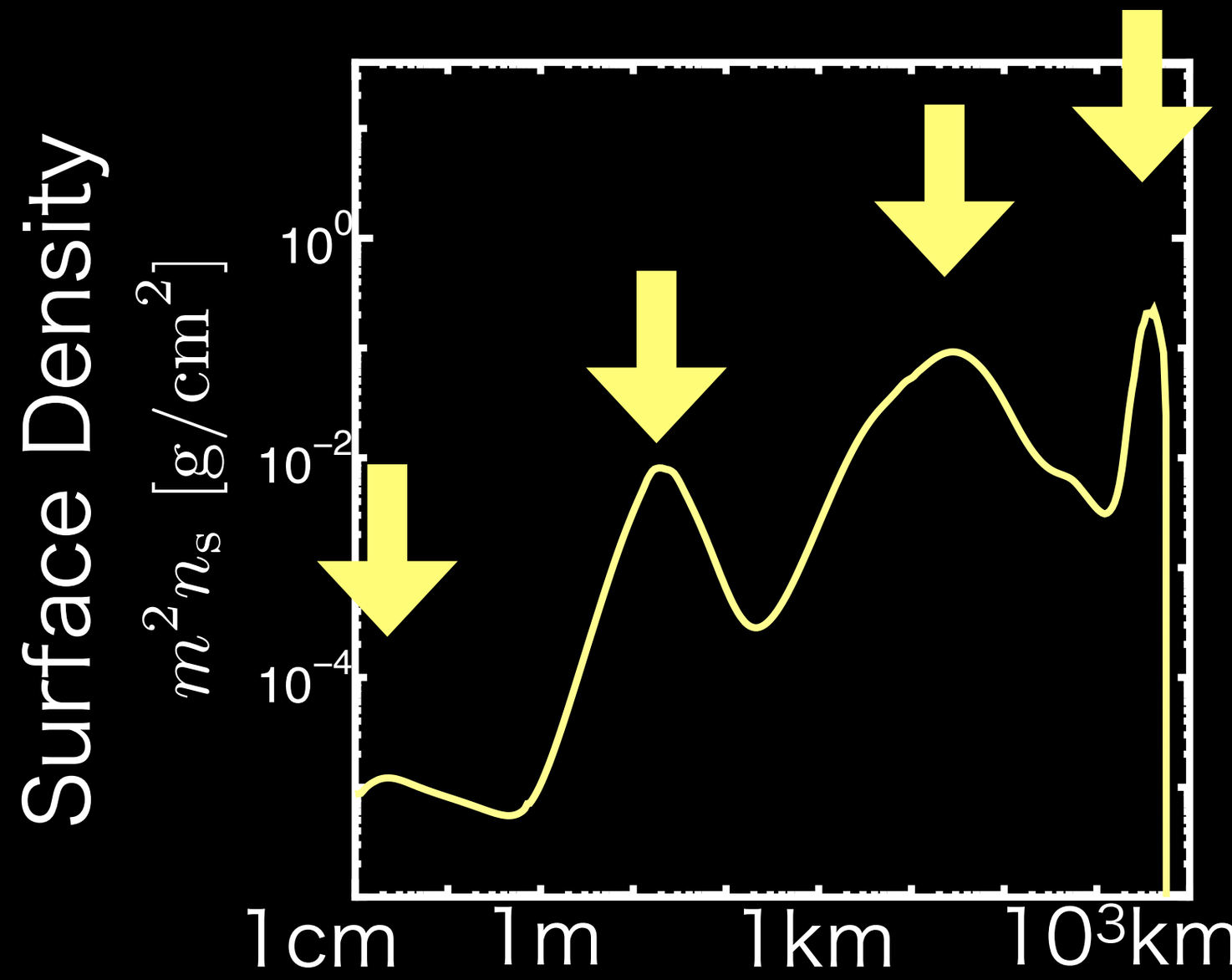

Embryo Mass [$M_\oplus$]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^3
10^4
10^5
10^6
10^7
Time [year]


Surface Density
$m^2 n_s$ [g/cm^2]
10^0
10^{-2}
10^{-4}
1cm
1m
1km
10^3km
Radius

3.2AU

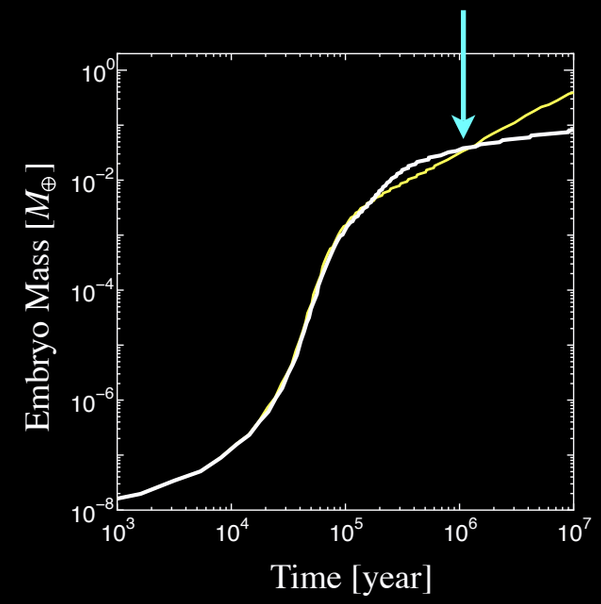
$t = 10^6$ yr

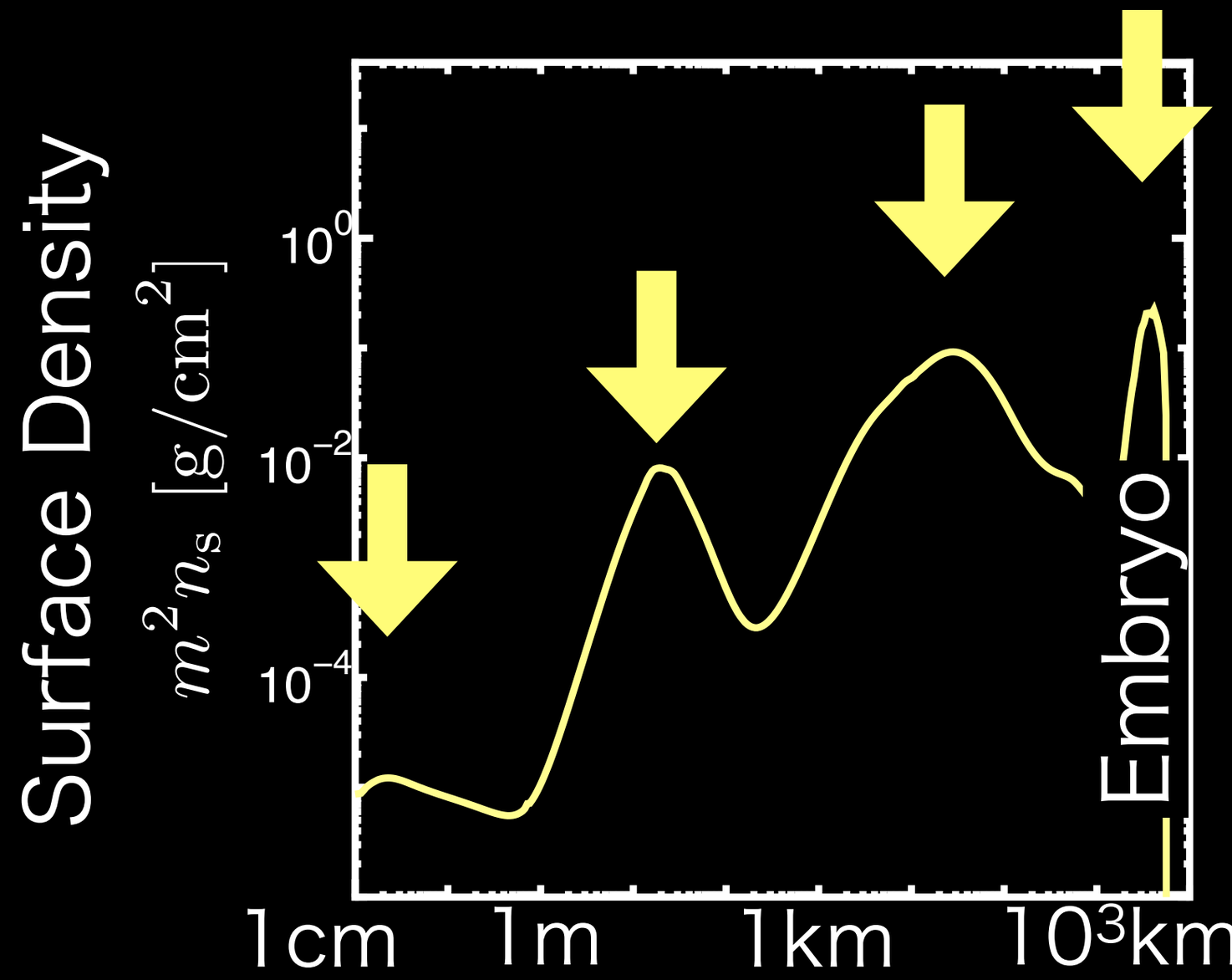

Embryo Mass [$M_\oplus$]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^3
10^4
10^5
10^6
10^7
Time [year]


Surface Density
$m^2 n_s$ [g/cm^2]
10^0
10^{-2}
10^{-4}
1cm
1m
1km
10^3km
Radius

3.2AU

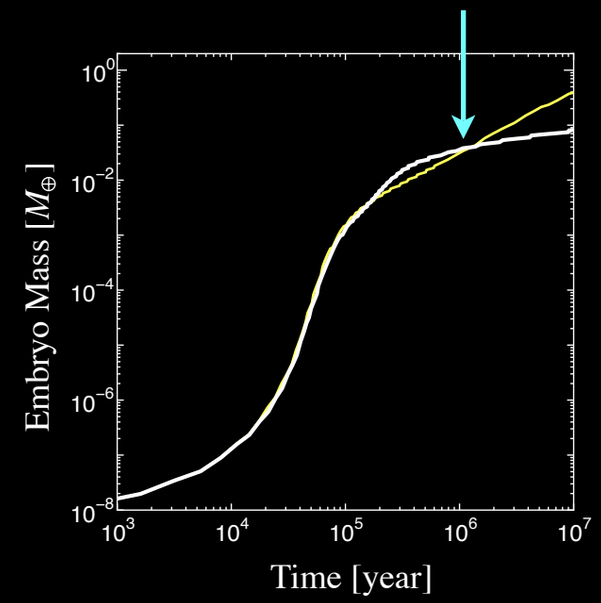
$t = 10^6$ yr

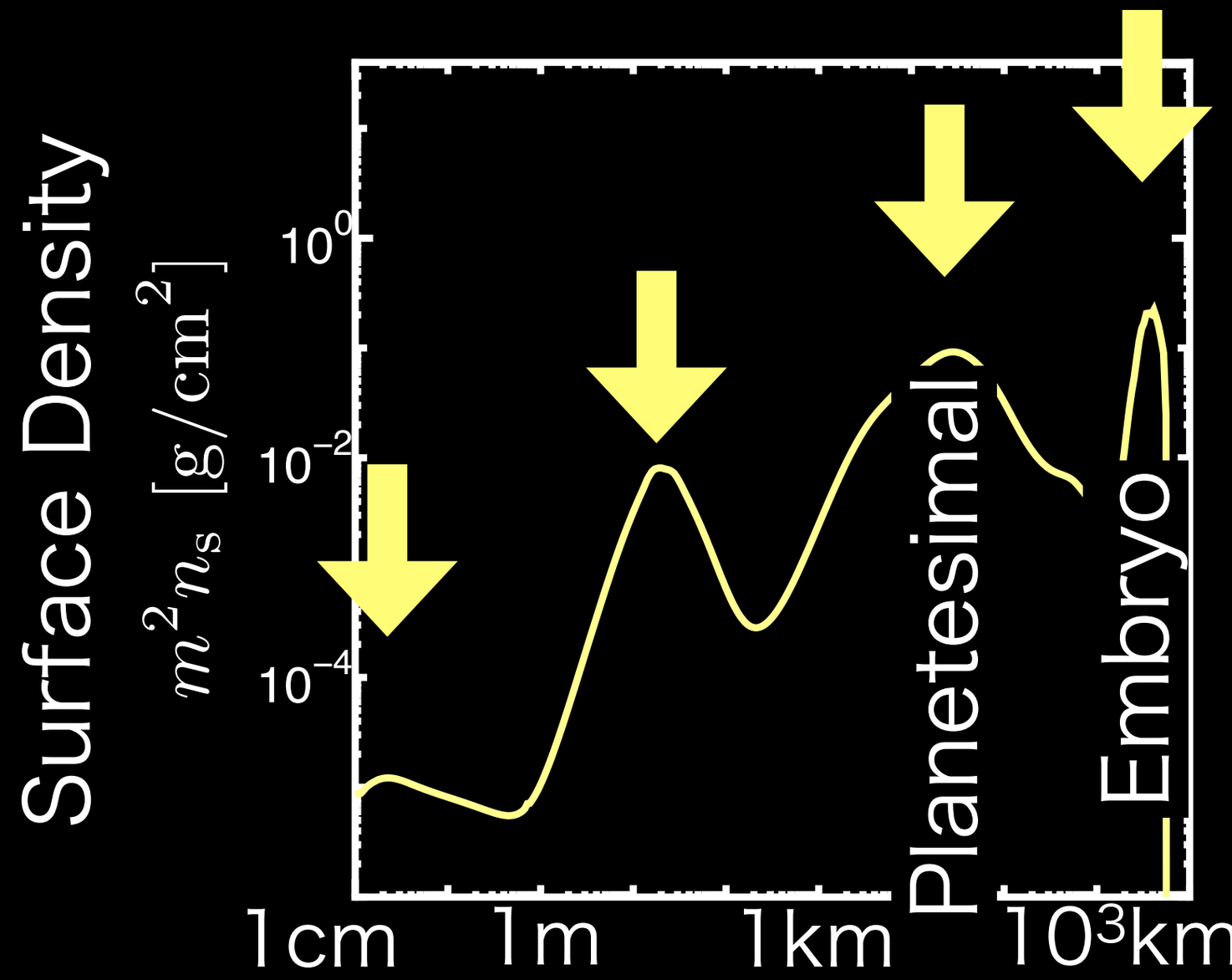

Embryo Mass [$M_\oplus$]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^3
10^4
10^5
10^6
10^7
Time [year]


Surface Density
$m^2 n_s$ [g/cm^2]
10^0
10^{-2}
10^{-4}
Embryo
1cm
1m
1km
10^3km
Radius

3.2AU

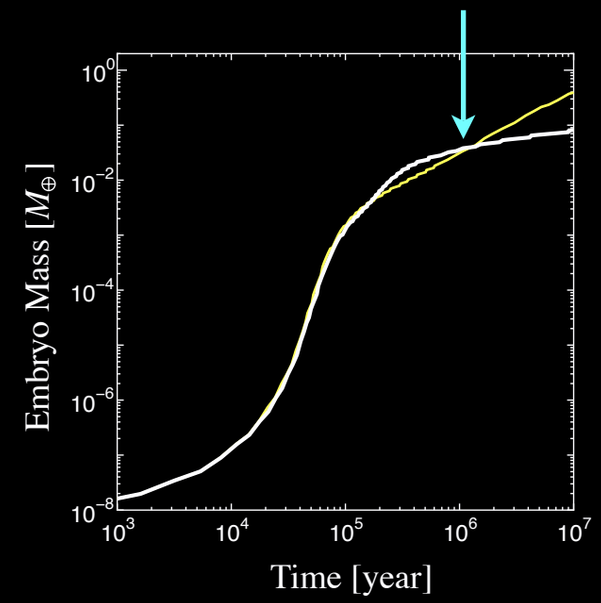
$t = 10^6$ yr

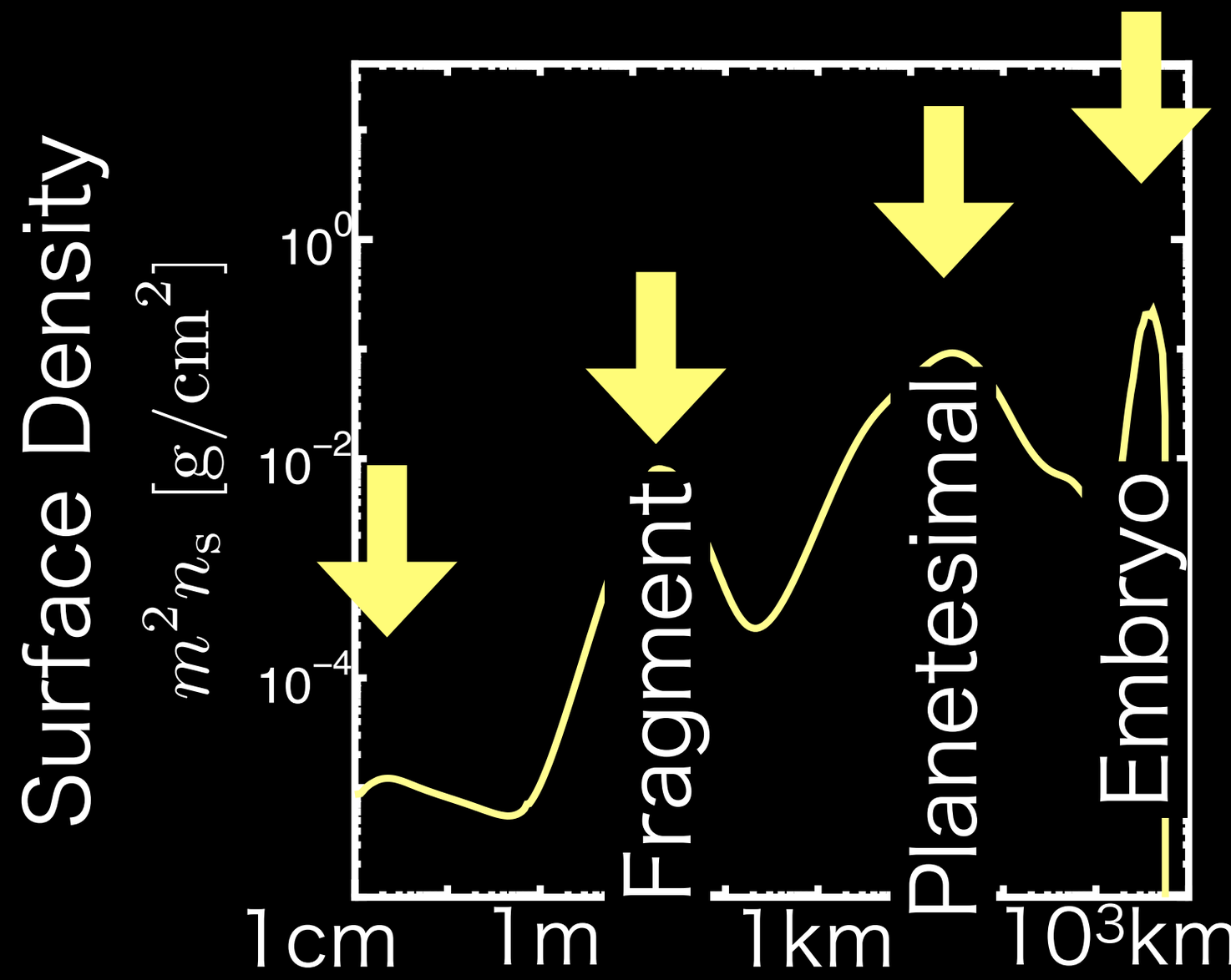

Embryo Mass [$M_\oplus$]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^3
10^4
10^5
10^6
10^7
Time [year]


Surface Density
$m^2 n_s$ [g/cm^2]
10^0
10^{-2}
10^{-4}
1cm
1m
1km
Planetesimal
10^3km
Embryo
Radius

3.2AU

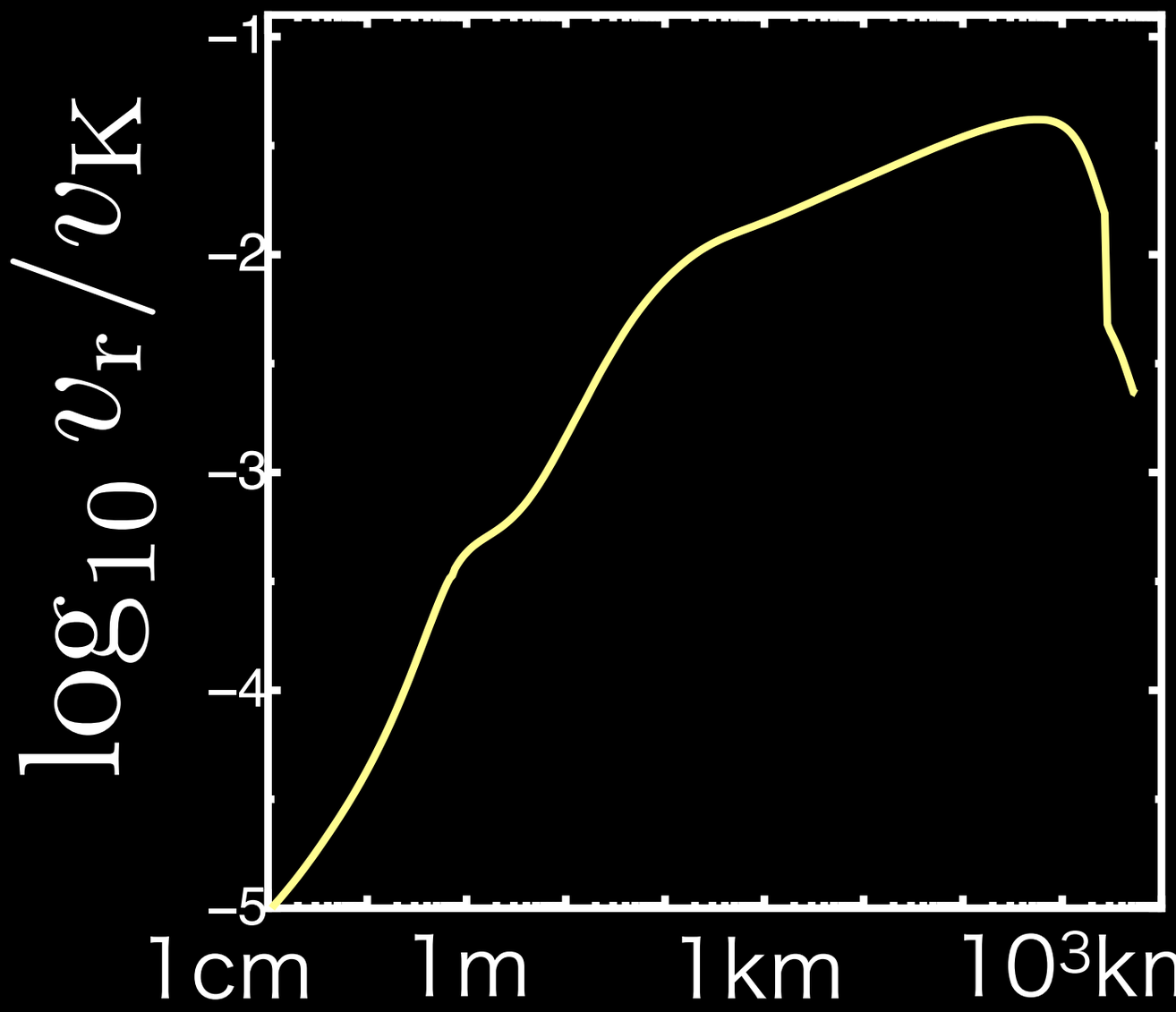
$t = 10^6$ yr


Embryo Mass [$M_\oplus$]
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Time [year]


Surface Density
$m^2 n_s$ [g/cm^2]
10^{0}
10^{-2}
10^{-4}
Fragment
Planetesimal
Embryo
1cm
1m
1km
10^3km
Radius

3.2AU

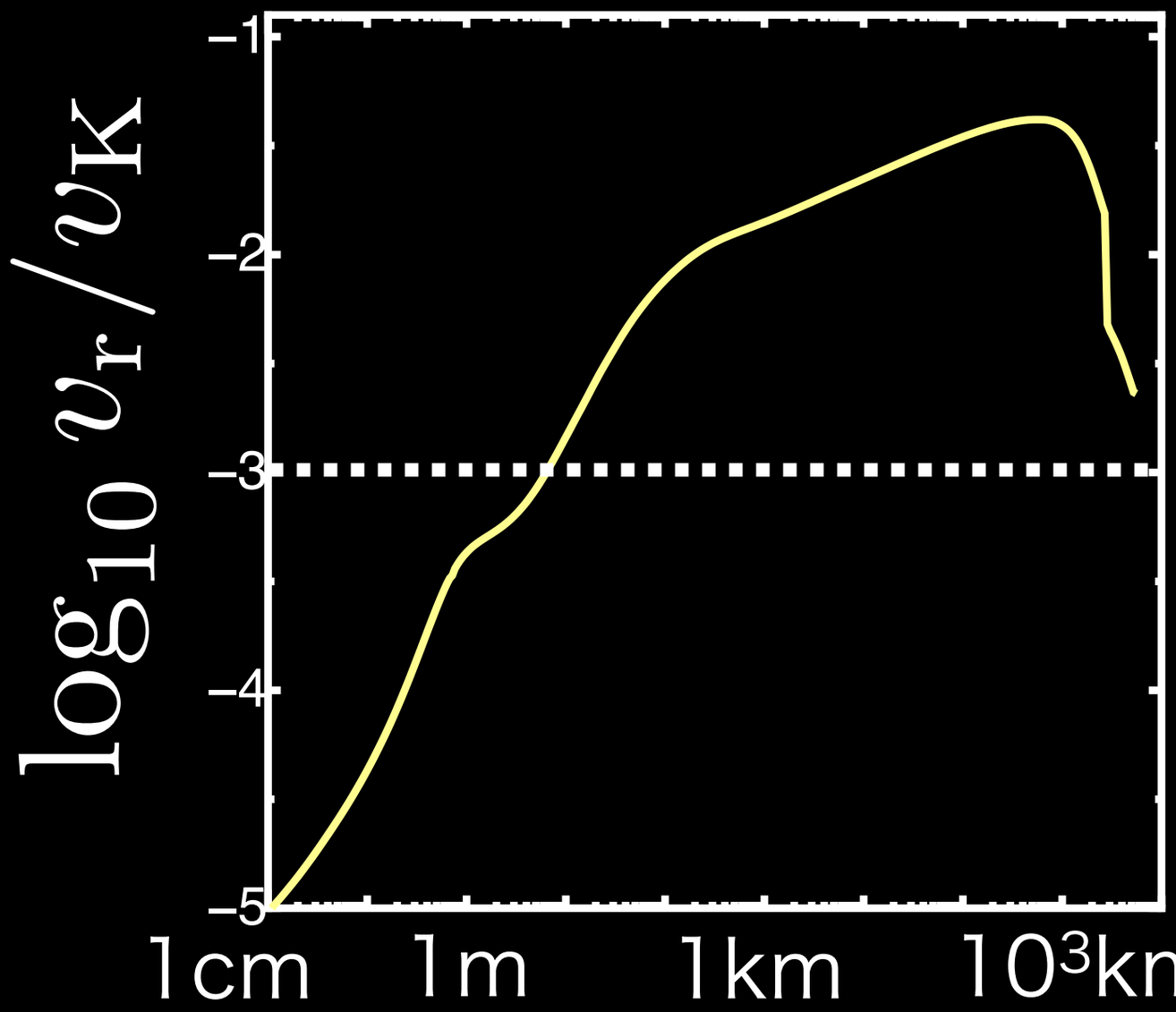
Fragment Size



1x10⁶yr

3.2AU

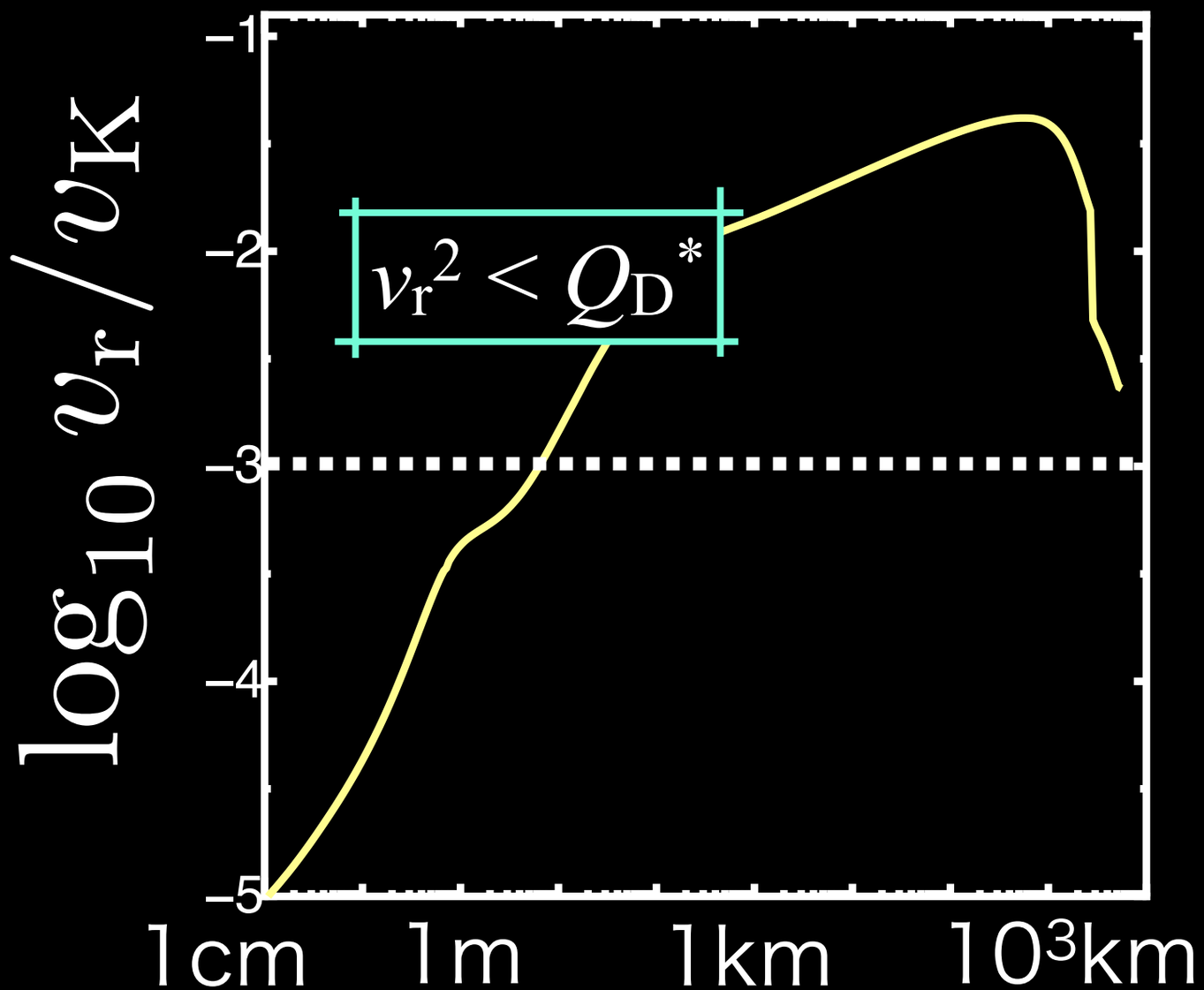
Fragment Size



1x10⁶yr

3.2AU

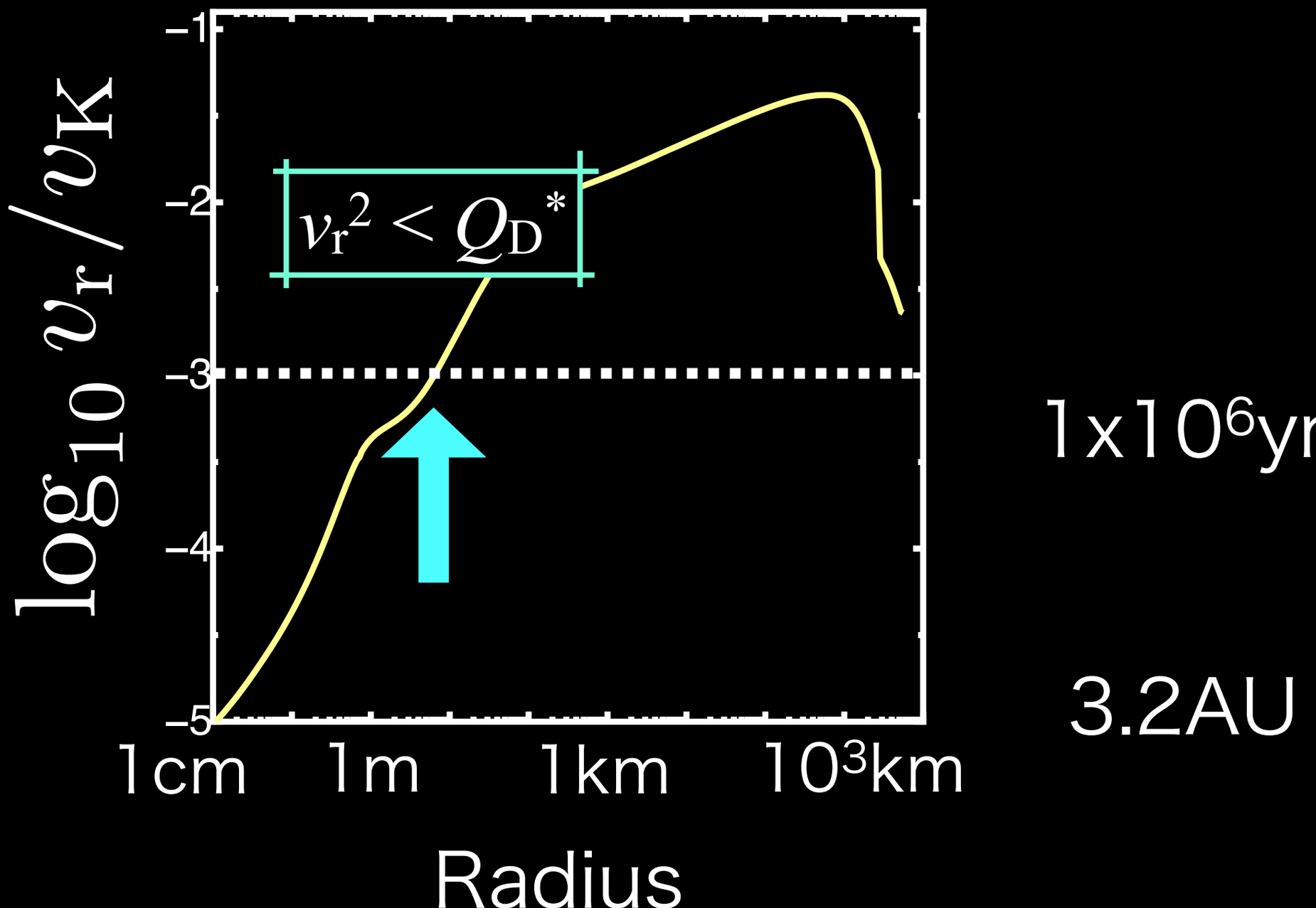
Fragment Size



1x10^{6}yr

3.2AU

Fragment Size



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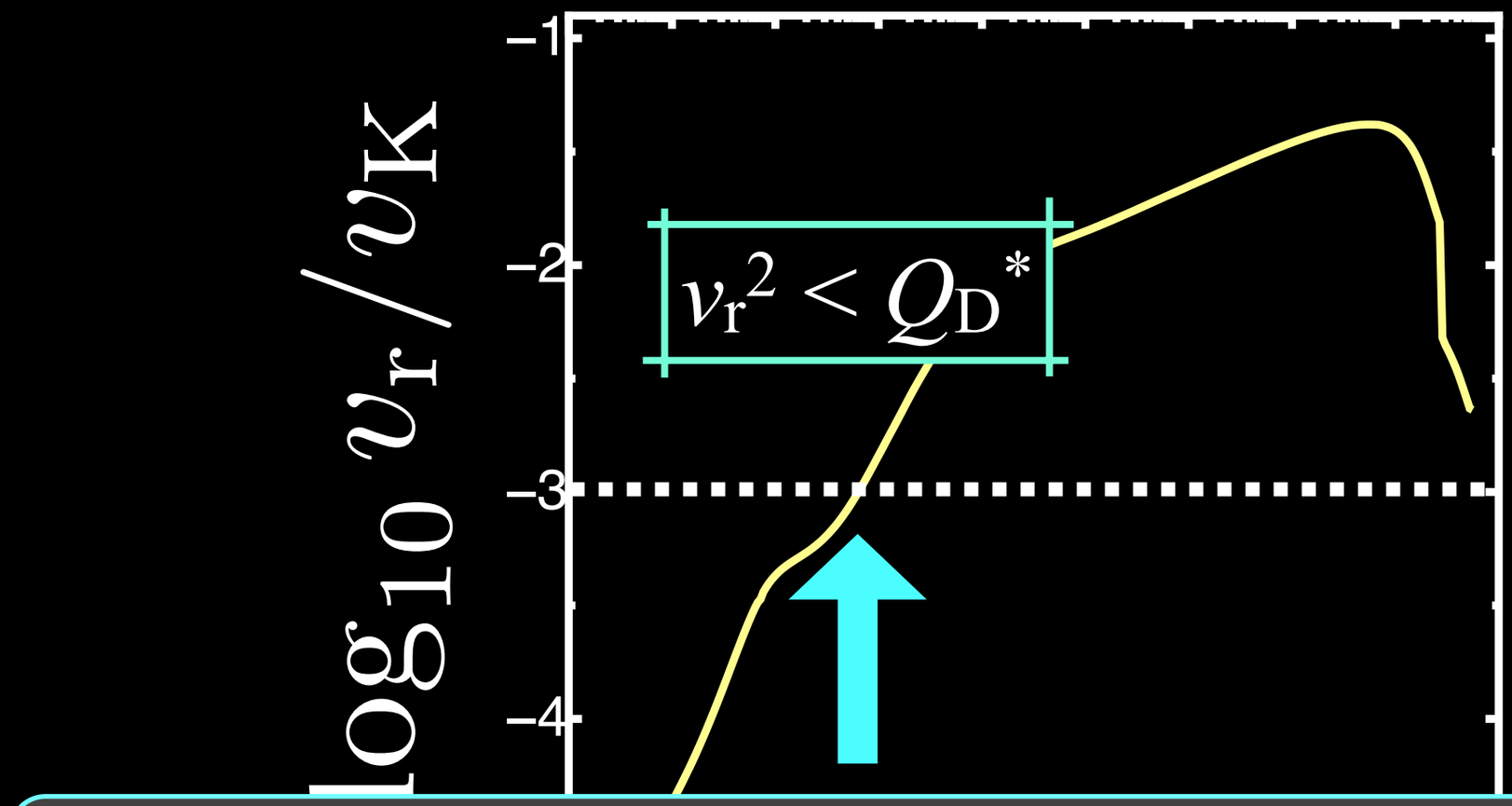


$$4.0 \left(\frac{M}{0.1 M_\oplus} \right)^{-1/2} \left(\frac{a}{3.2\,\mathrm{AU}} \right)^{1/2} \left(\frac{Q_\mathrm{D}^\star}{3 \times 10^6\,\mathrm{erg/g}} \right)^{1/2} \mathrm{m}$$

Radius

Final Embryo Mass

Growth Rate

The growth rate of embryo with M

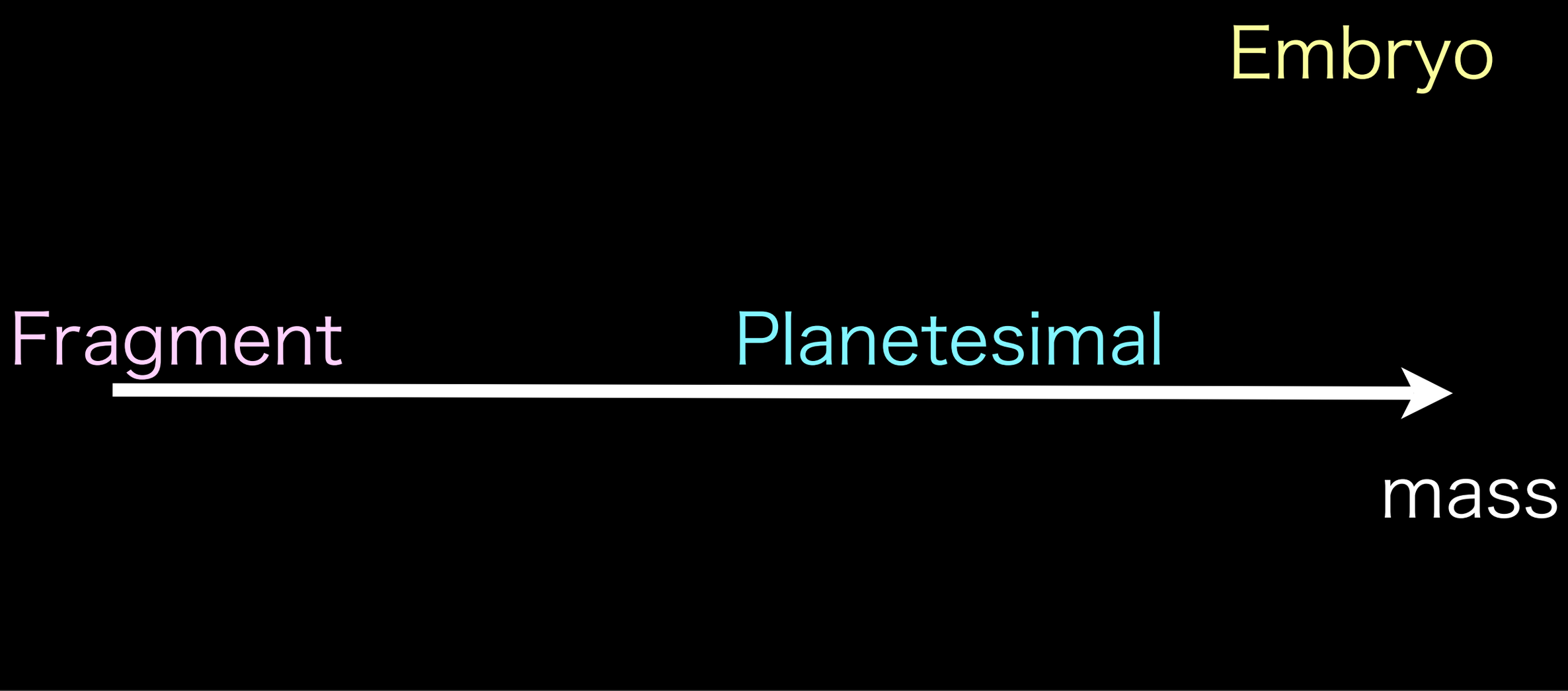
$$\frac{dM}{dt} = \Sigma_{\rm s} P_{\rm col}(e, i, M, m)\, \Omega_{\rm K}$$

$\Sigma_{\rm s}$: Solid surface density

$$P_{\rm col}(e, i, M, m) \sim \sigma_{\rm col} \frac{\sqrt{(e^2 + i^2)}}{2i}$$

for planetesimals(Greezweig and Lissauer 1990,1992)
for fragments (Ida and Nakazawa 1989)

Accretion Diagram



Accretion Diagram

Embryo

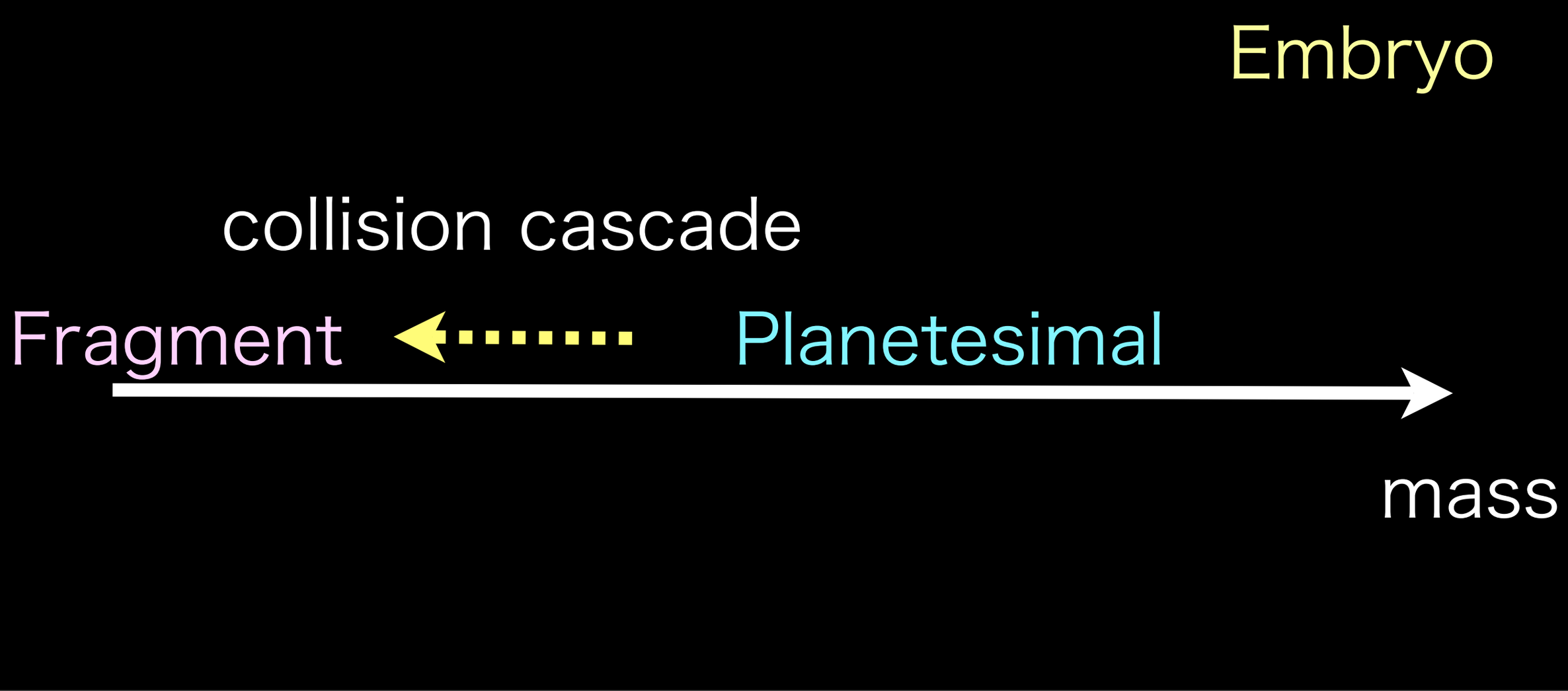
collision cascade

Fragment

Planetesimal

mass

Accretion Diagram



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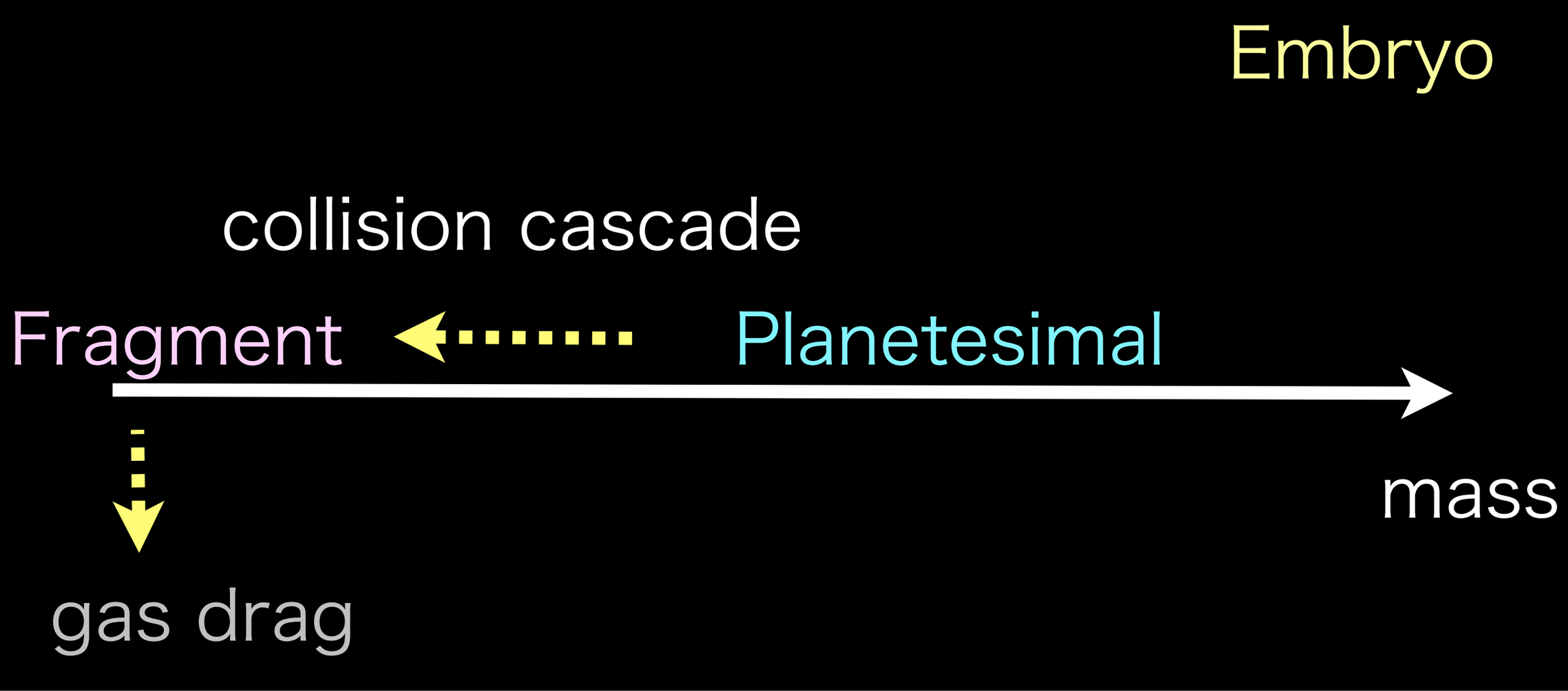
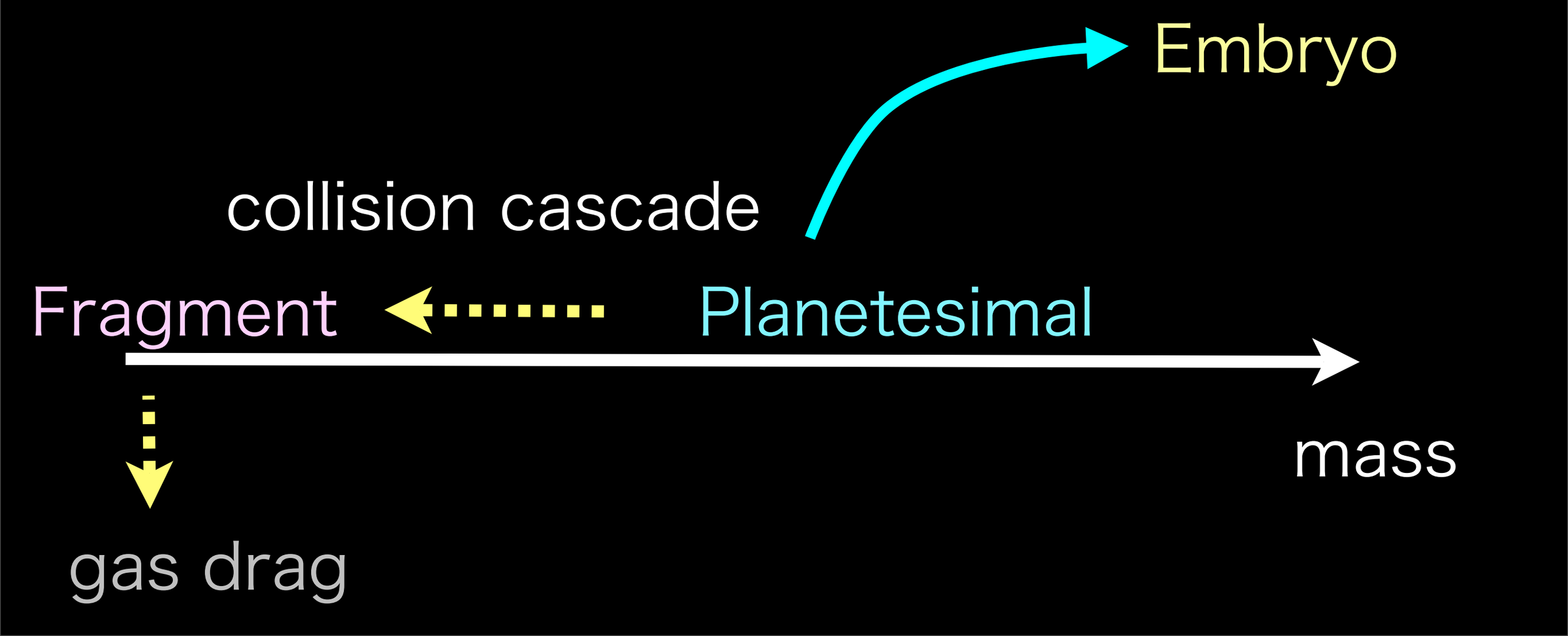
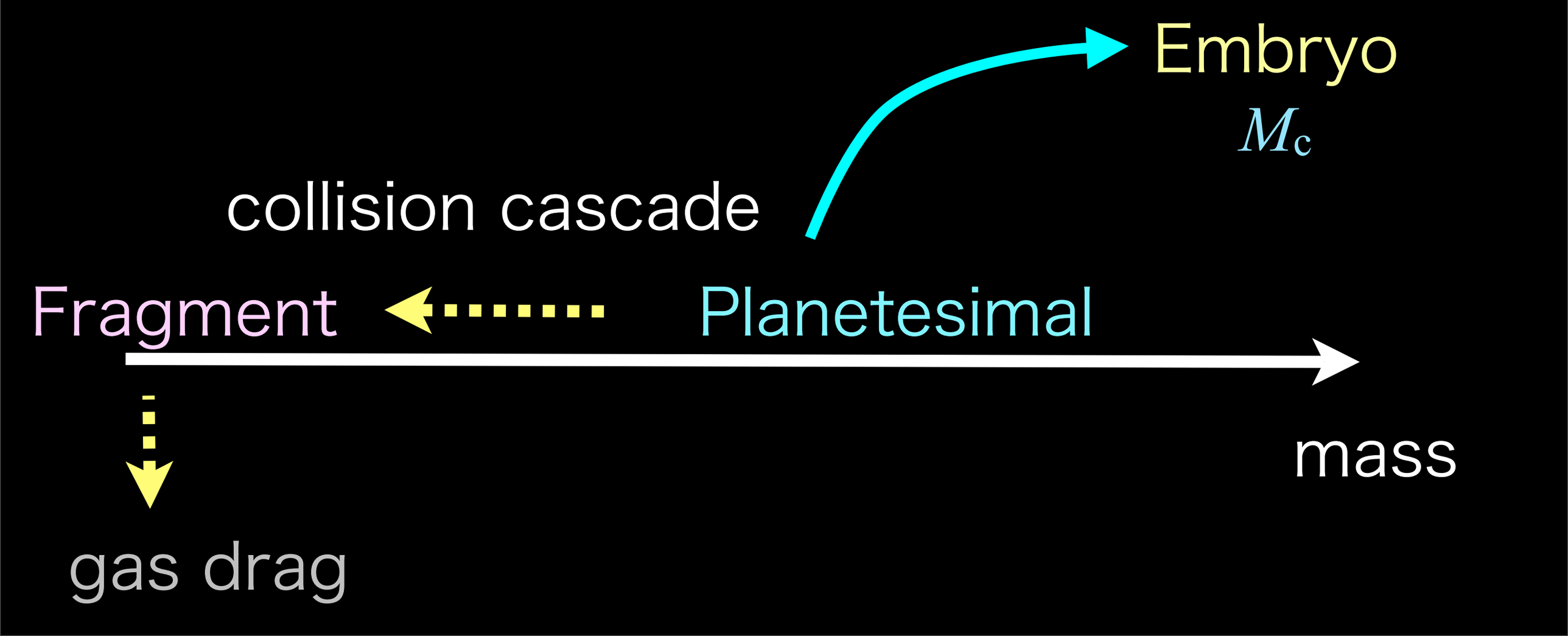


Accretion Diagram



Accretion Diagram



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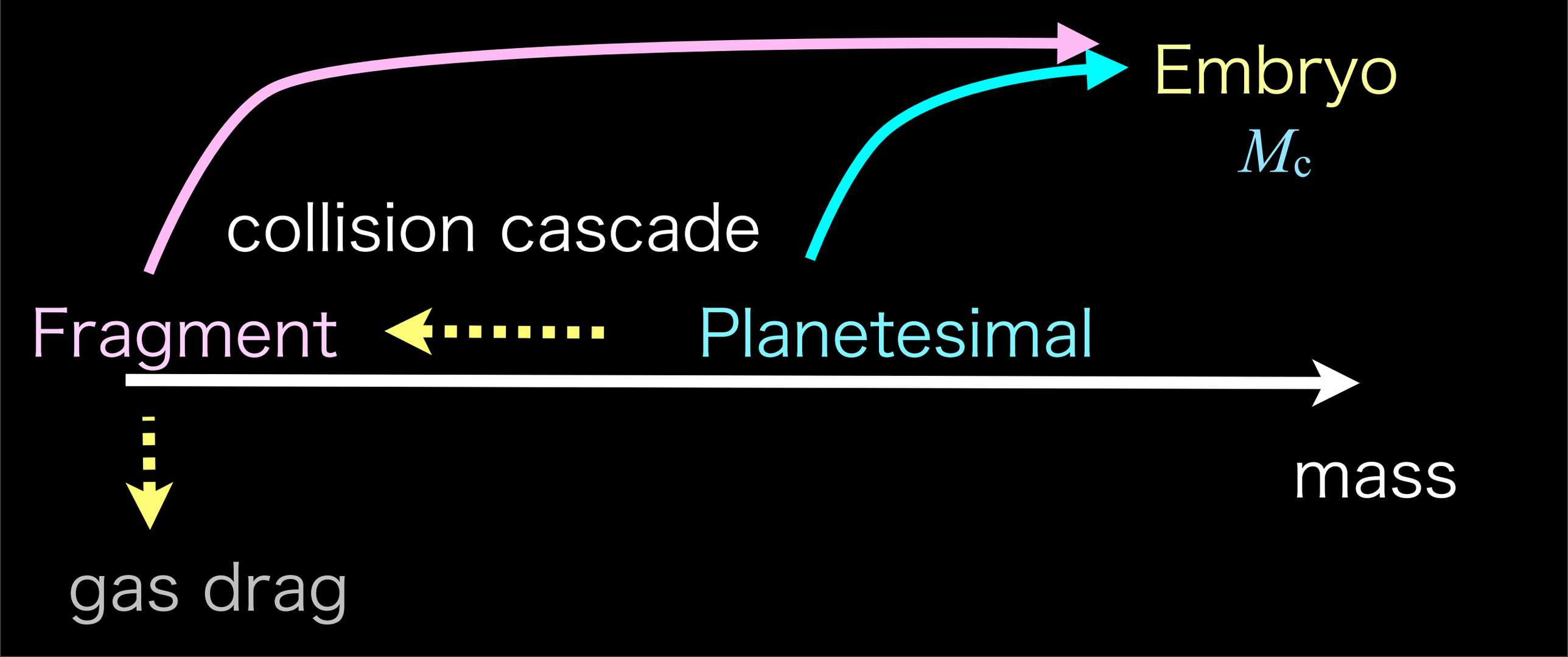
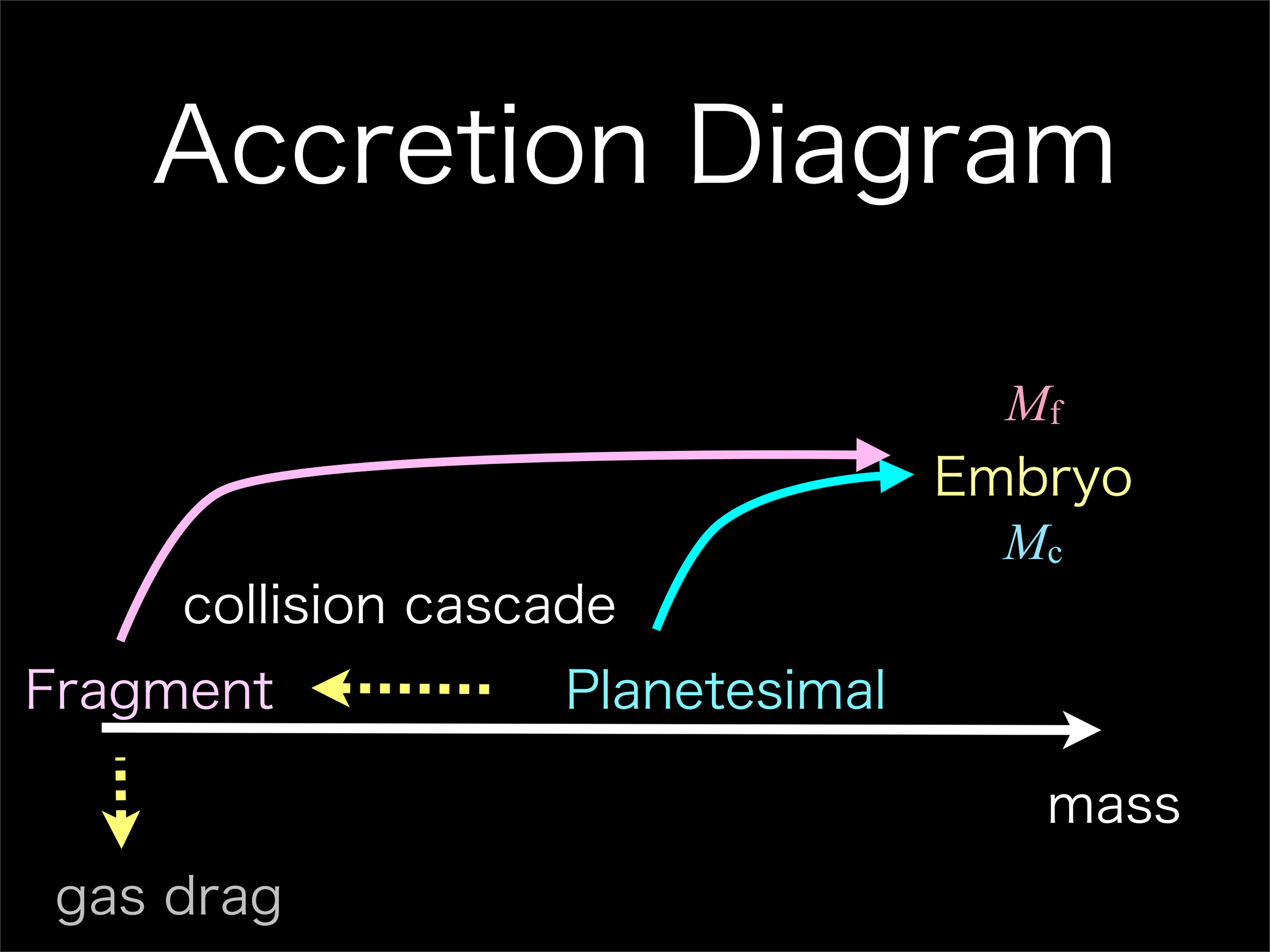
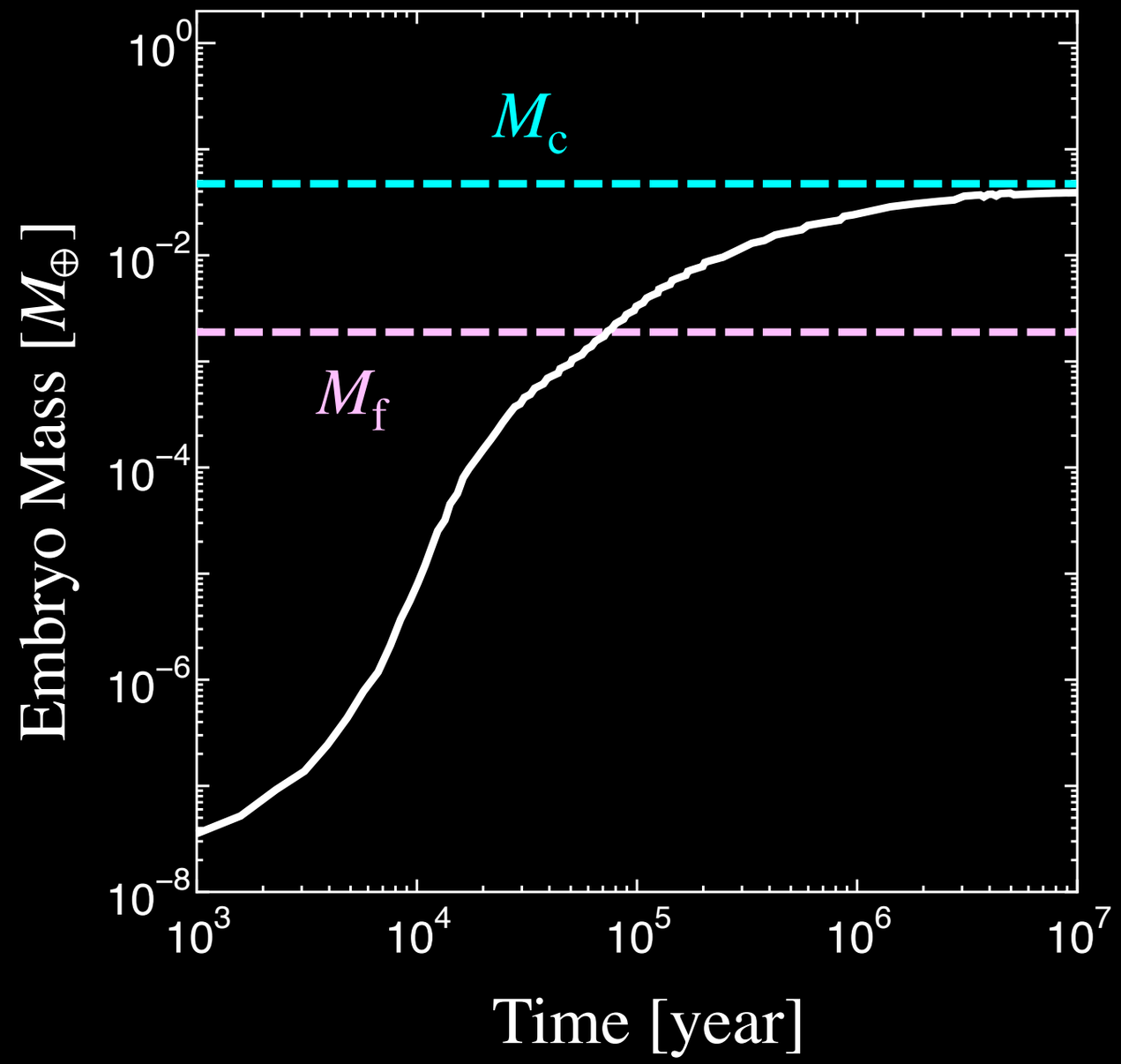


Accretion Diagram



Planetesimal Accretion

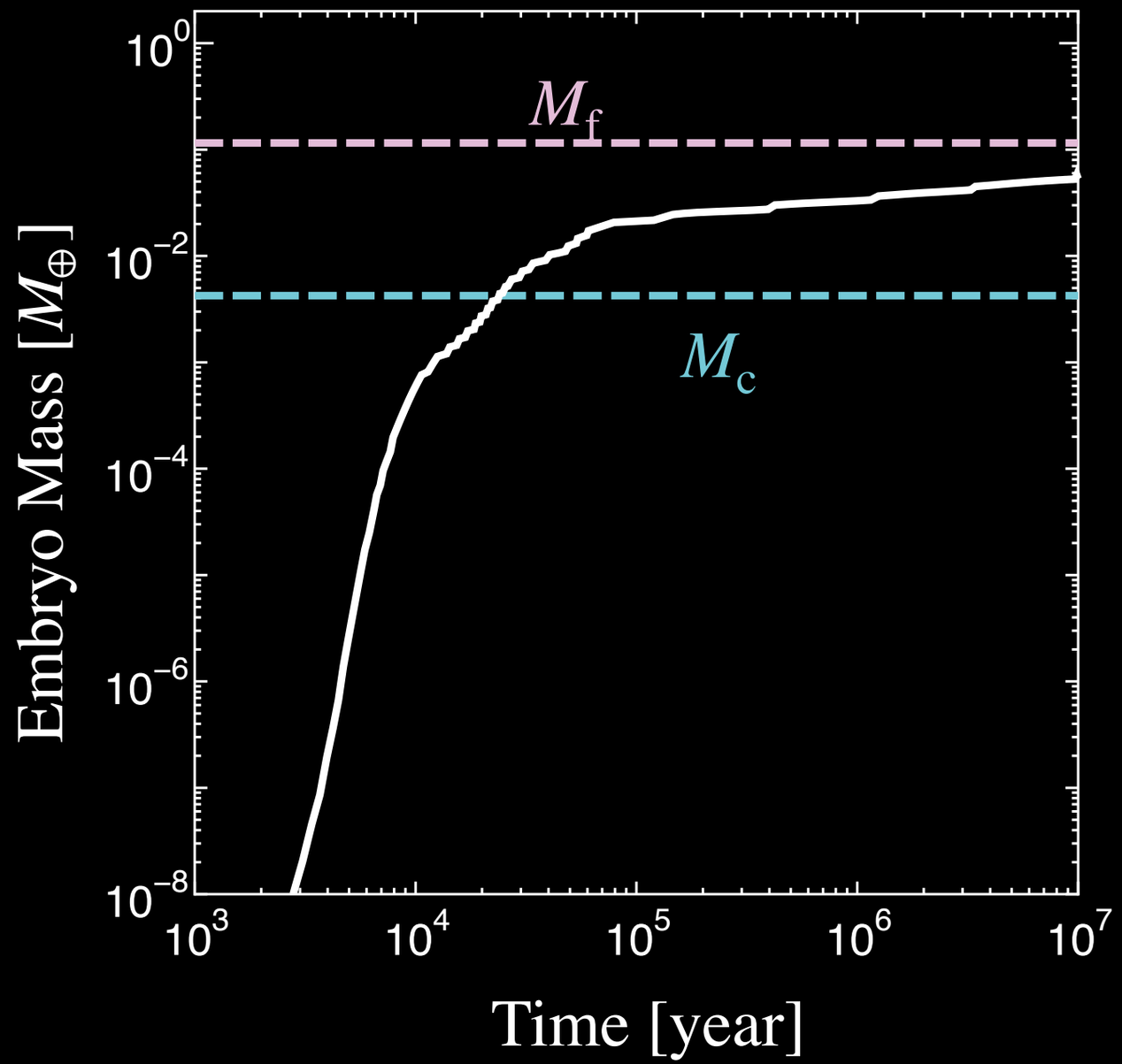


$r_0 = 10$ km

at 1 AU

MMSN

Fragment Accretion



$r_0 = 1$ km

at 3.2 AU

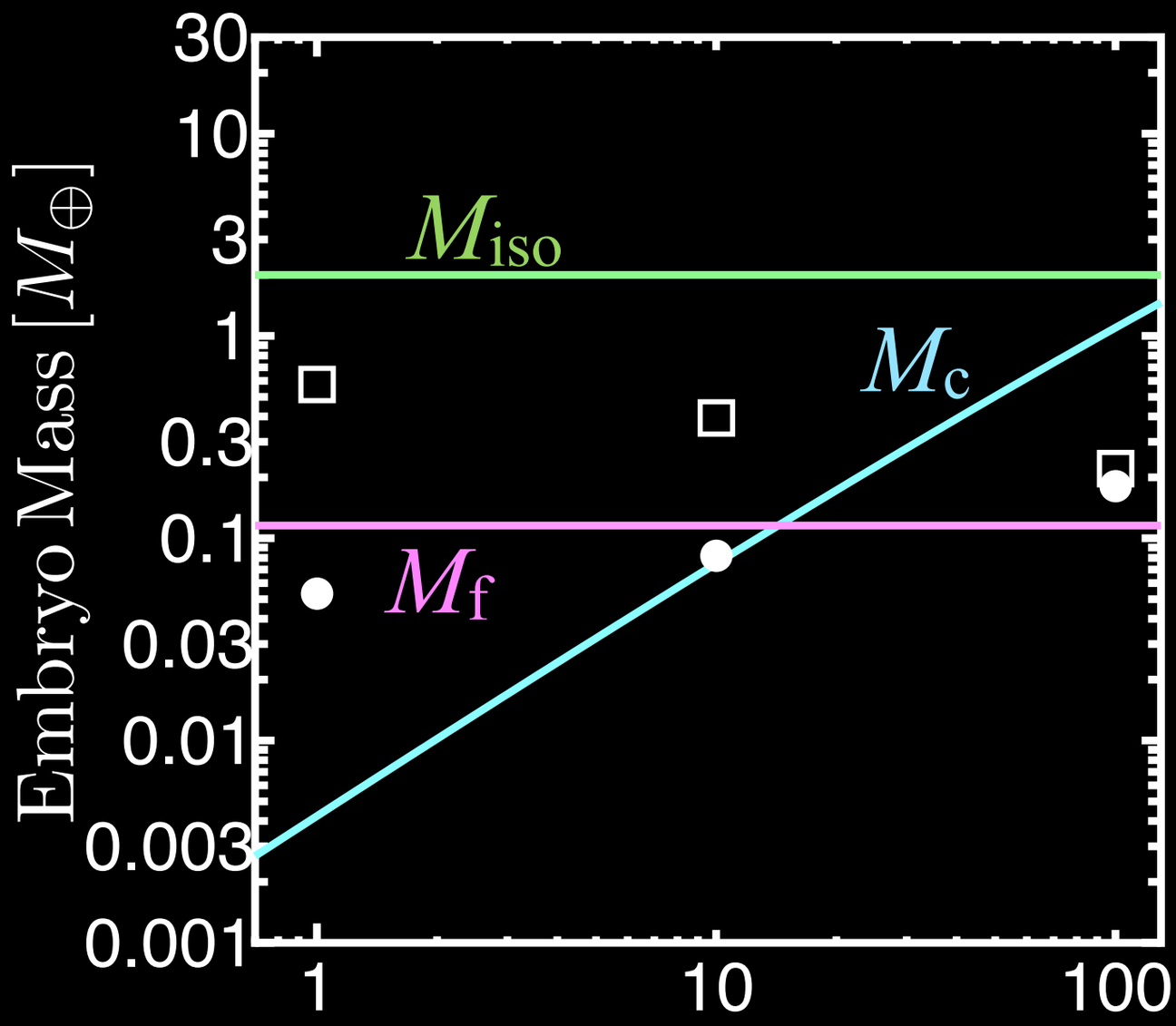
MMSN

Radius Dependence

In 10^7 years

Frag.

- ● Yes
- □ No



at 3.2AU

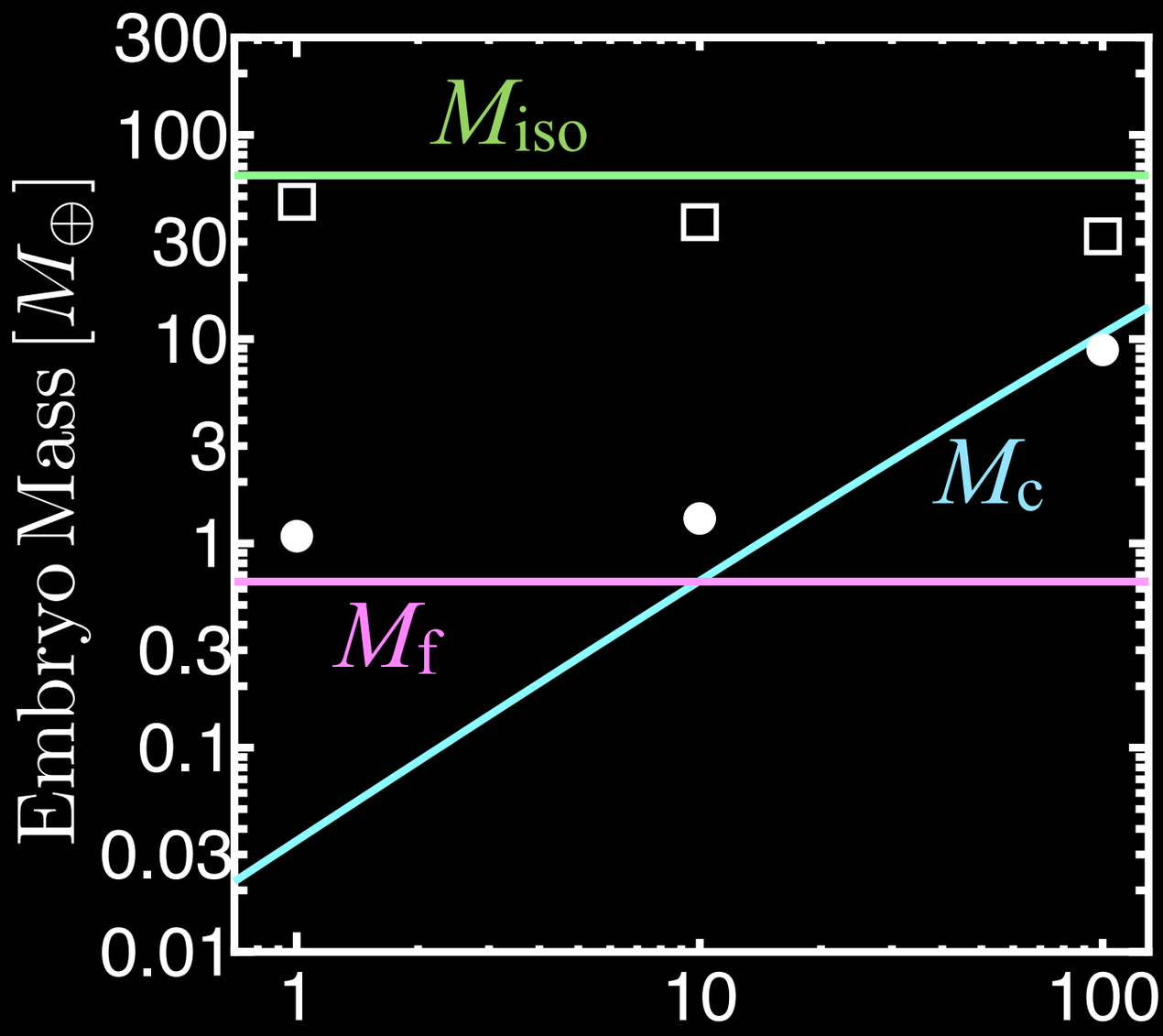
MMSN

Massive Disk

In 10^7 years

Frag.

- ● Yes
- □ No



at 3.2AU

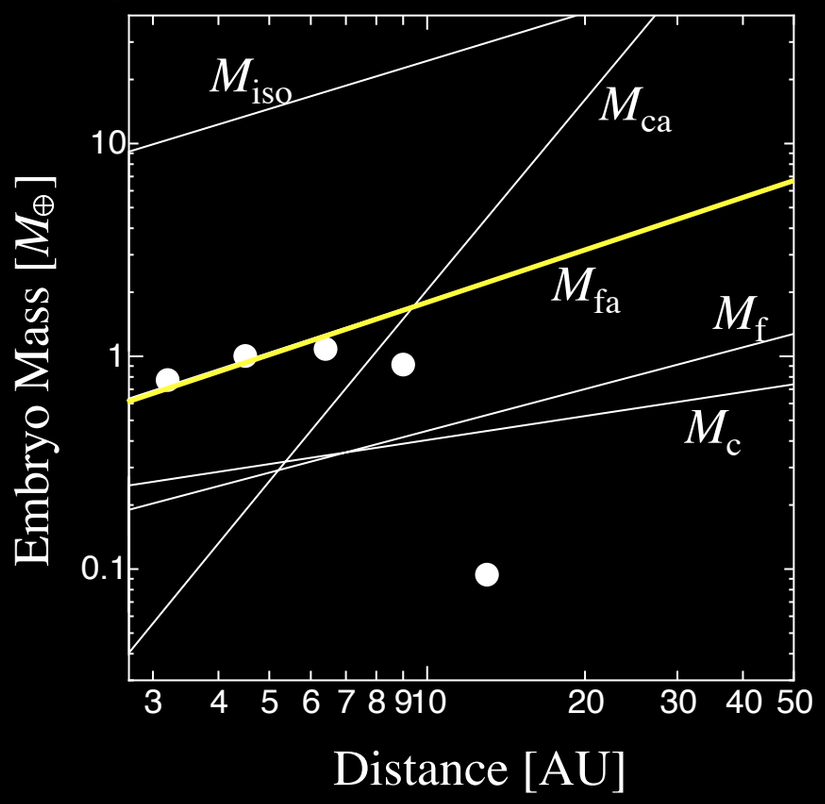
10 x MMSN

Conclusion

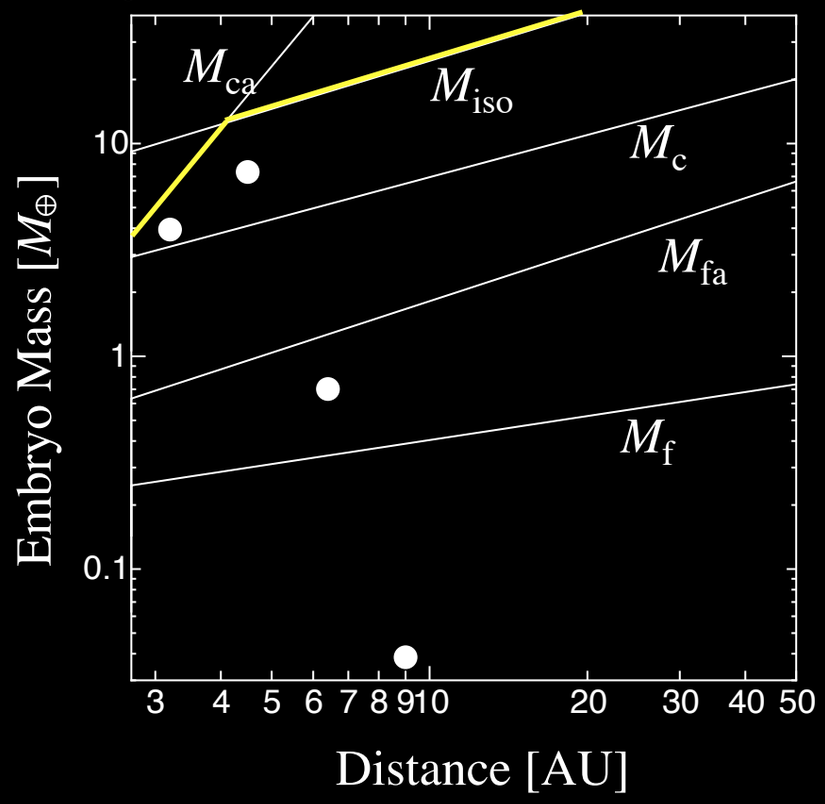
- The final mass is smaller due to fragmentation.
  - The embryo grows by the accretion with planetesimals or fragments.
- Embryo can be large for larger initial planetesimals.
  - Embryo reaches 10 Earth masses if initially 100km-sized or larger planetesimals.
  - However, the location is only at 3-4 AU.
- Necessary effects.
  - Atmosphere (Inaba & Ikoma 2003; Tanigawa & Ohtsuki 2010).
  - Collisional enhancement for drifting bodies (Ormel & Klahr 2010).

Atmosphere

$r_0 = 10$ km



$r_0 = 100$ km



10^7 years
3 x MMSN
at 3.2 AU

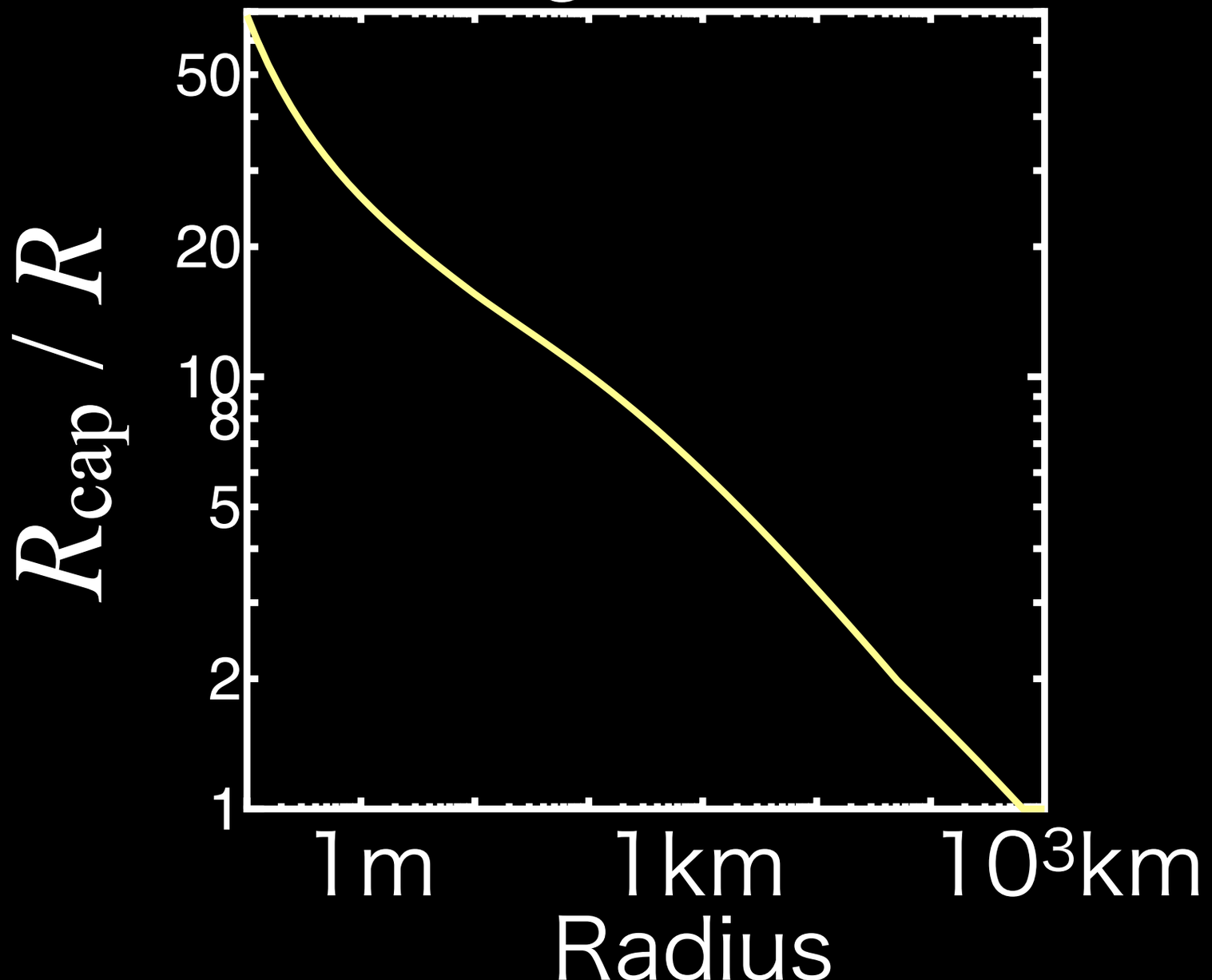
The subscript “a” means the solutions of final masses including the atmosphere effect.

- Embryos can be larger than those without atmosphere.
- Large planetesimals still tend to form a large embryo.

Planetary Atmosphere

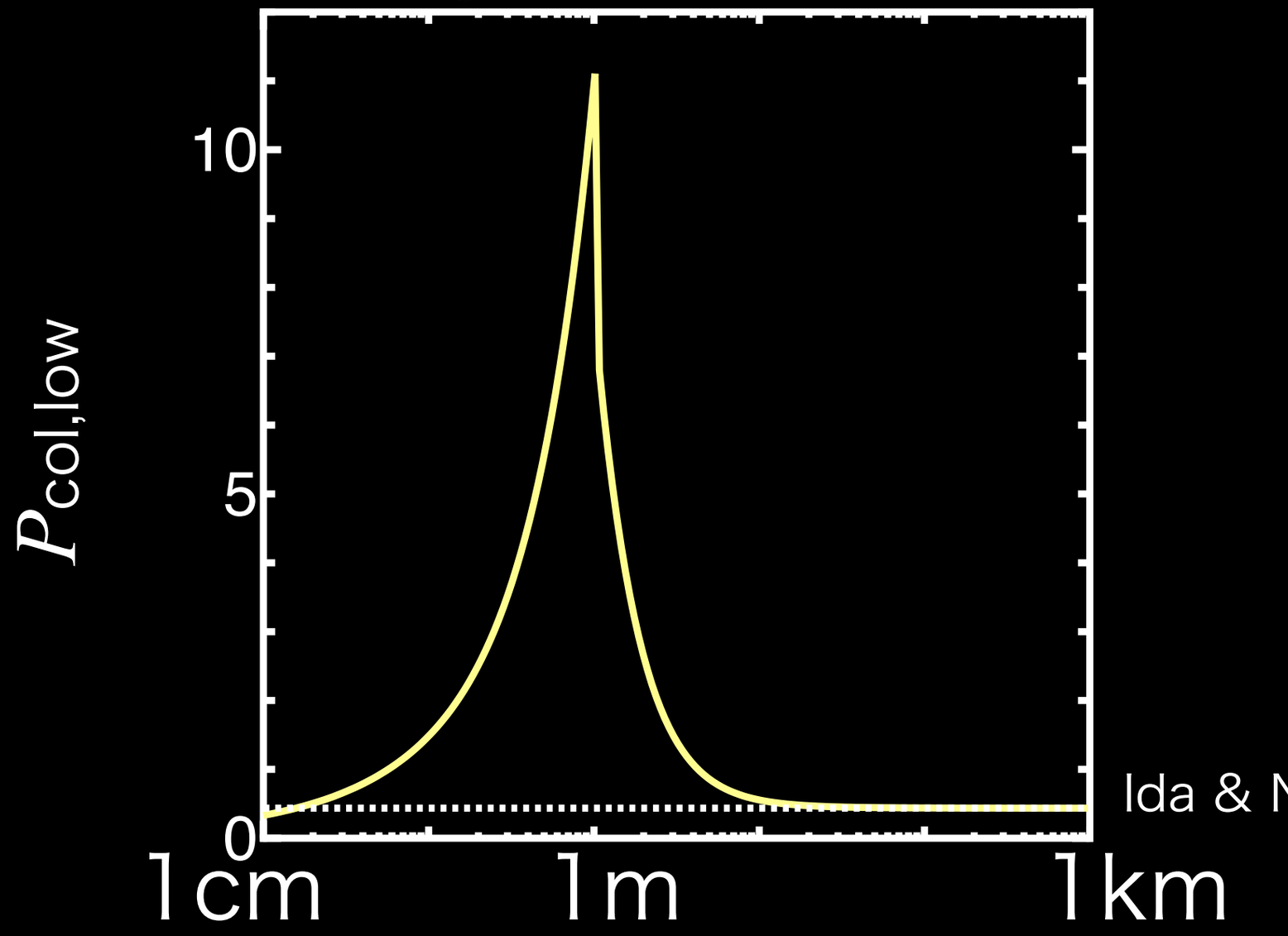
Inaba and Ikoma (2003)

Tanigawa & Ohtsuki (2010)



Collisional Enhancement

By Ormel and Klahr (2010)



It is effective after M reaches the Mars mass.

Gap around Embryo

- The planetary embryos can open gaps in a solid disk, which would affect the accretion of fragments on the embryo and their removal by the gas drag (Levison et al. 2009).

- The condition for gap formation(Tanaka & Ida 1999);

$$r \geq r_{\rm g} \simeq 1.0 \times 10^2 \left(\frac{M}{0.1 M_\oplus}\right)^{-1/3} \left(\frac{a}{5\,{\rm AU}}\right)^{3/8} {\rm m},$$

- At the end of collision cascade,

$$r_{\rm e} \simeq 5.0 \left(\frac{M}{0.1 M_\oplus}\right)^{-1/2} \left(\frac{a}{5\,{\rm AU}}\right)^{1/2} {\rm m}$$

The gap does not affect the embryo growth.