恒星間天体による初代星の金属汚染について

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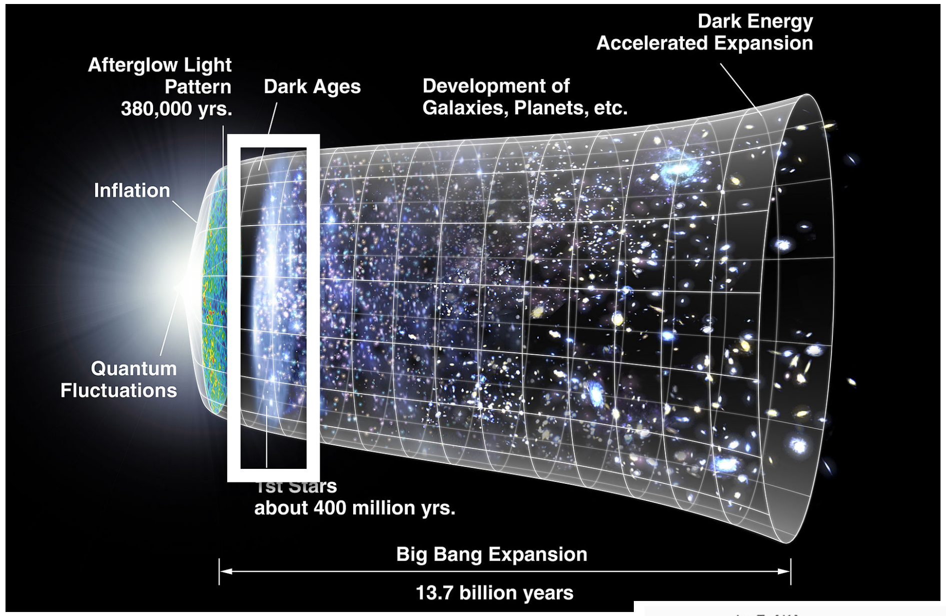
Tanikawa, Suzuki, Doi (2018, PASJ, 70, 80)

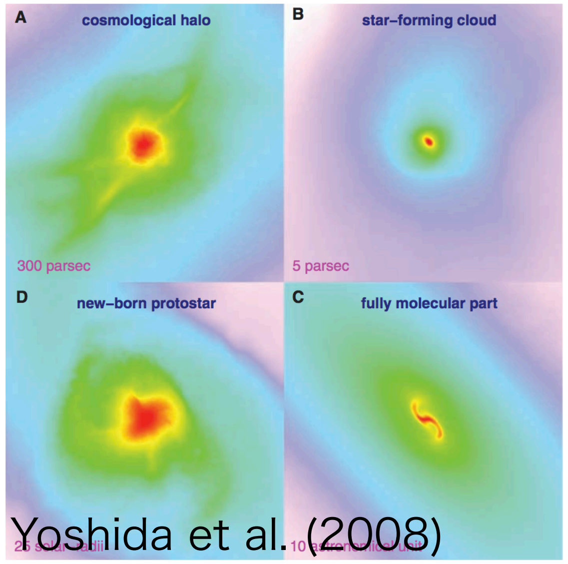
2009.04 - 2012.09

Watabe ->
Akahori ->
Tanikawa

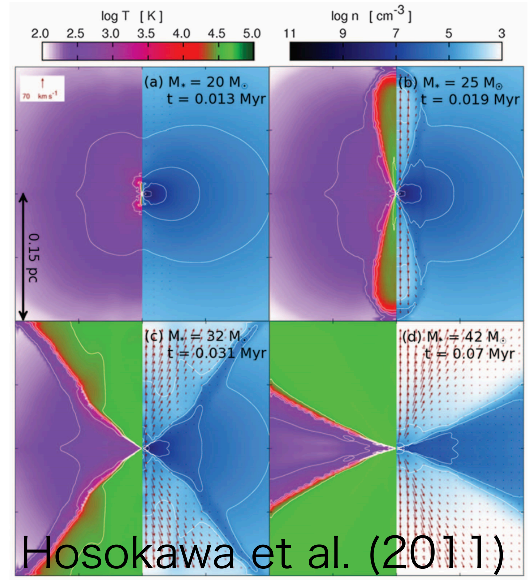
Pop. III stars

- Importance
  - Reionization
  - Nucleosynthesis
- Mass
  - Massive stars (~100$M_\odot$) formed in the typical mode
  - Low-mass stars (~0.8$M_\odot$) (Nakamura, Umemura 01; Machida+ 08; Clark+ 11ab; Greif+ 11, 12; Machida, Doi 13; Susa+ 14; Chiaki+ 16)
- Low-mass stars (Pop. III survivors)
  - Long lifetime (~ 10Gyr)
  - Should-be observed in the Milky Way galaxy
- No discovery of metal-free stars

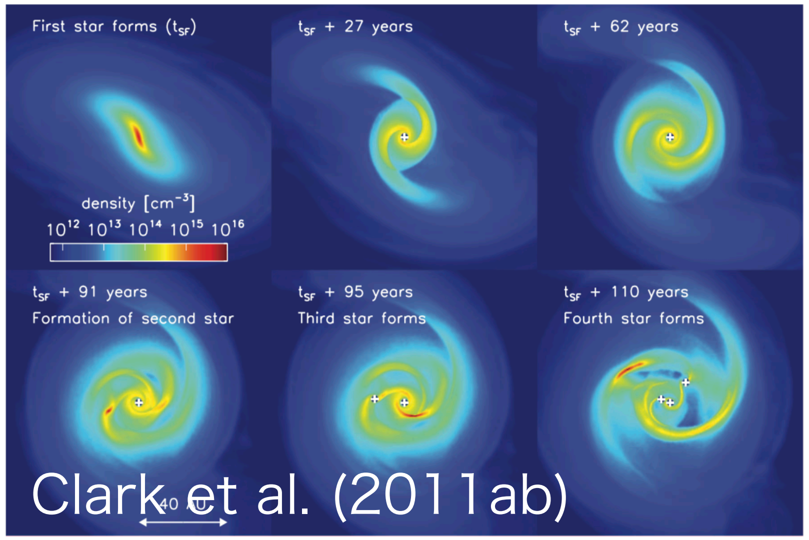




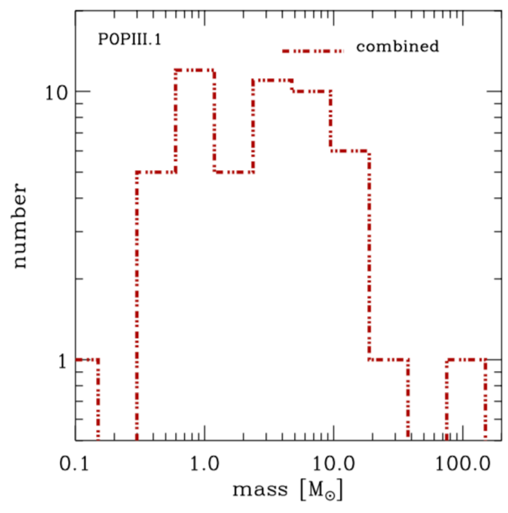
Yoshida et al. (2008)



Hosokawa et al. (2011)

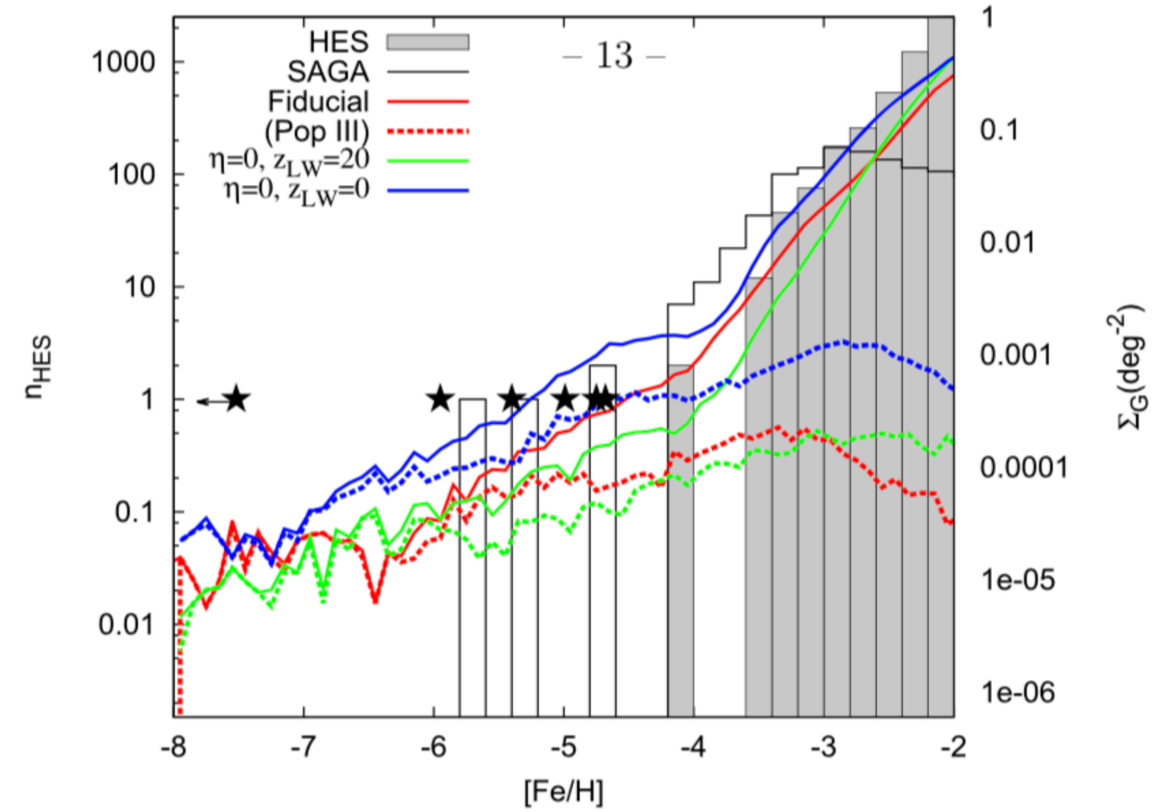


Clark et al. (2011ab)

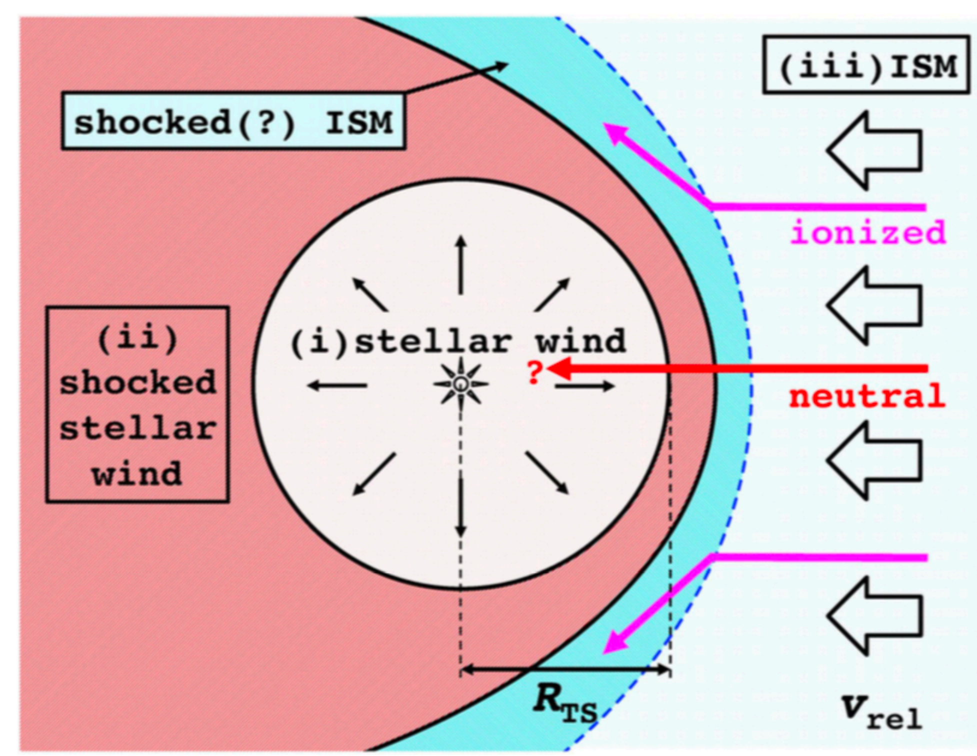


Metal pollution

- By ISM
    - Pop. III survivors have wandered in the MW for 10Gyr.
    - They may have accreted ISM through Bondi-Hoyle-Lyttleton accretion.
- ISM gas
    - Blocked by stellar wind
    - [Fe/H] ~ -14 (<< [Fe/H] of EMP stars)
- ISM dust
    - Sublimated by stellar radiation
    - Also blocked by stellar wind



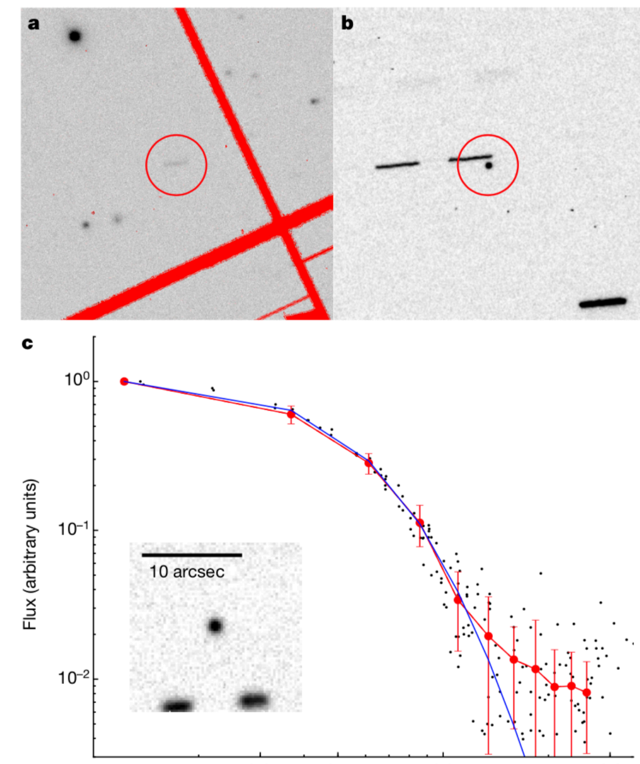
Komiya et al. (2015)



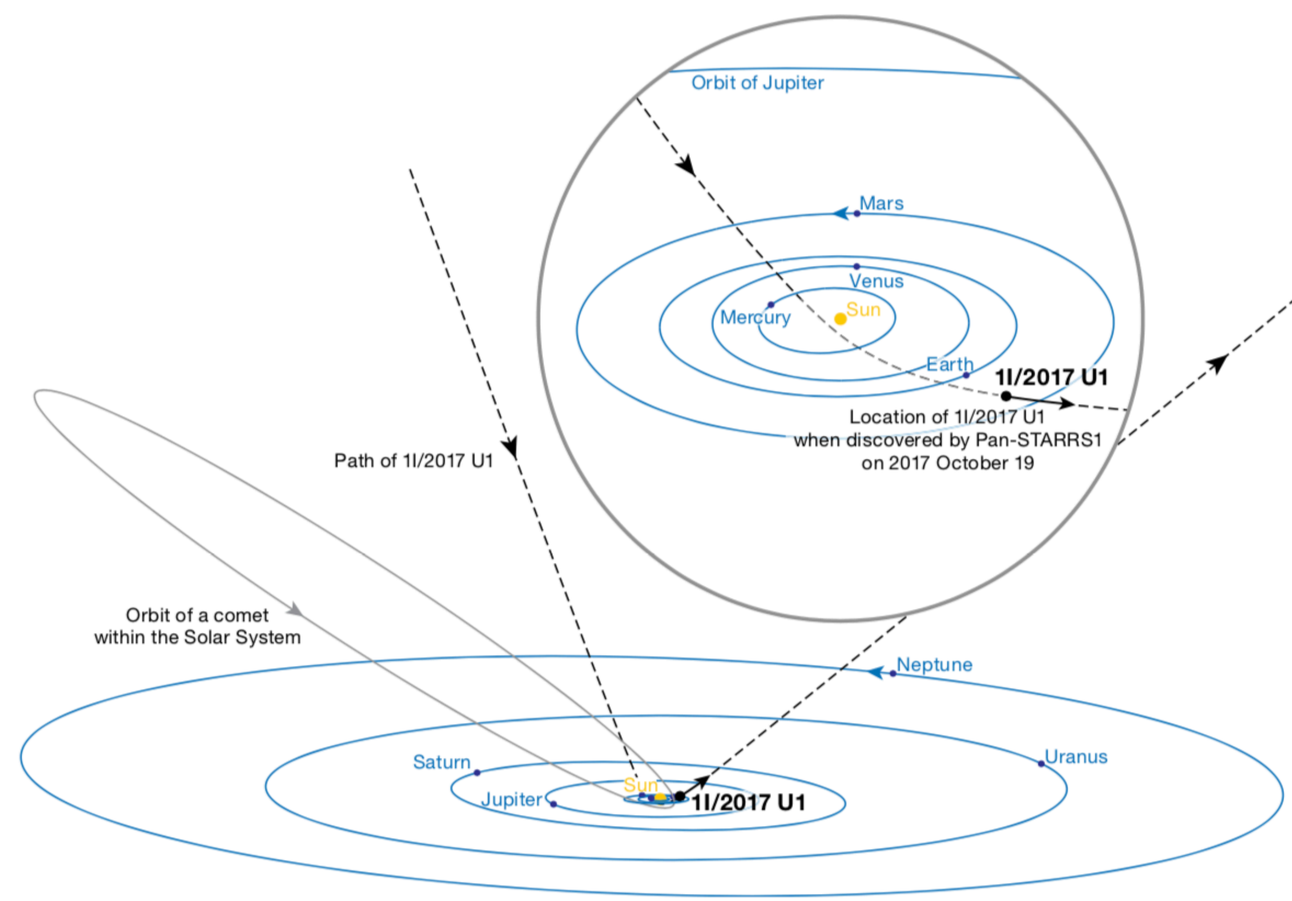
Tanaka et al. (2017), Suzuki (2018)

Interstellar objects (ISOs)

- The discovery of 1I/2017 U1 `Oumuamua
- The first ISO
- No hint of cometary activity (asteroid or comet nucleus)
- Size ~ 100m
- High number density ~ 0.2 au^{-3} (Do et al. 2018)
- Metal pollution of Pop. III through collision with ISOs



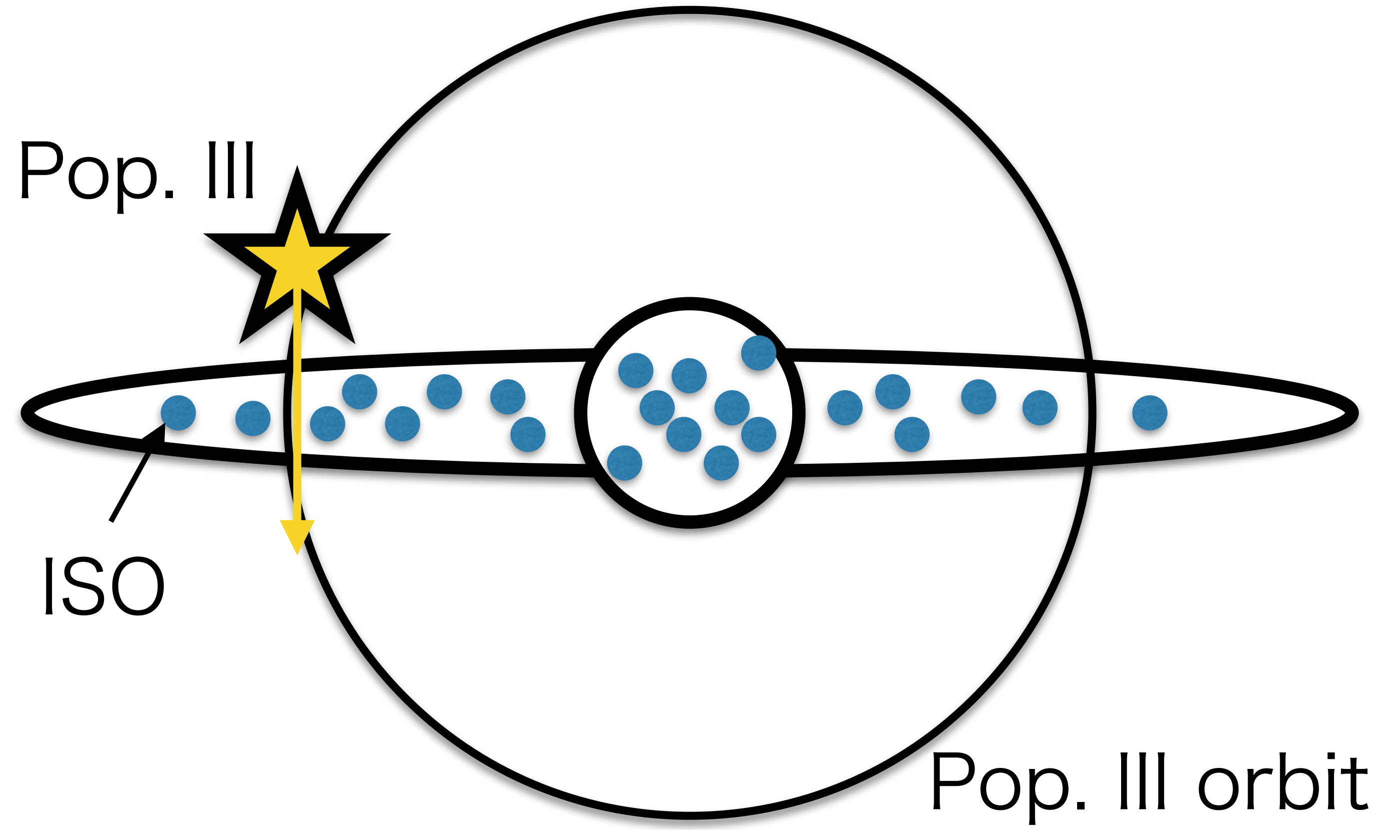
Meech et al. (2017)



Collision rate

$$\dot{N}_{\rm coll} = fn\sigma v$$

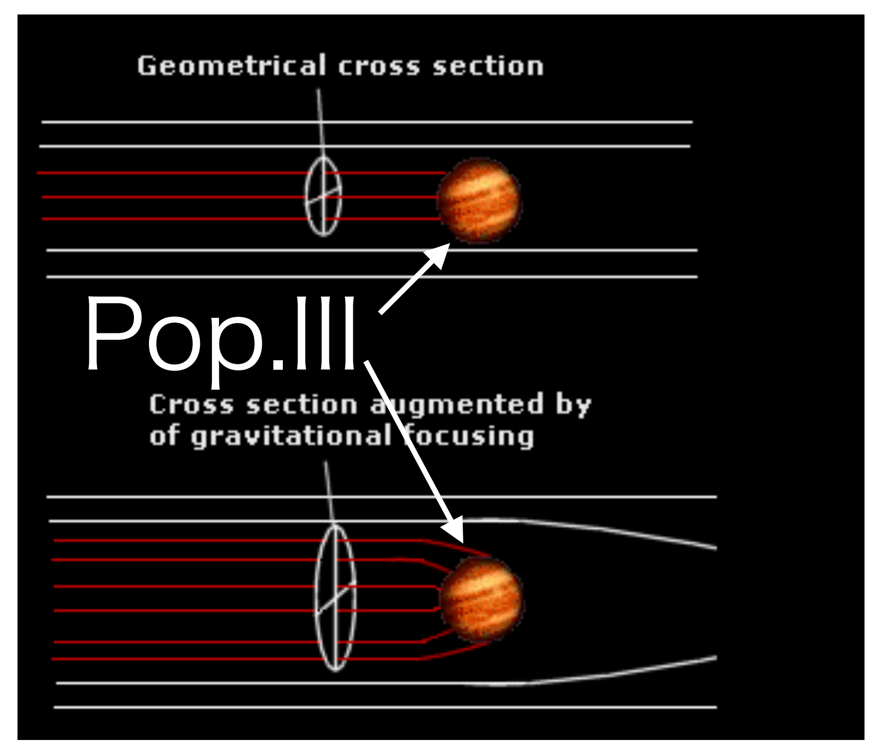
- f: fraction of ISO-rich regions in a Pop. III orbit
- n: ISO number density
- σ: cross section
- v: relative velocity between Pop. III and ISOs



ISO $\dot{N}_{\rm coll,iso} \sim 10^5 \left(\frac{n}{0.2{\rm au}^{-3}}\right)[{\rm Gyr}^{-1}]$

Pop. I stars $\dot{N}_{\rm coll,star} \sim 10^{-11} \left(\frac{n}{0.1{\rm pc}^{-3}}\right)[{\rm Gyr}^{-1}]$

Free floating planets $\dot{N}_{\rm coll,ffp} \sim 10^{-8} \left(\frac{n}{200{\rm pc}^{-3}}\right)[{\rm Gyr}^{-1}]$



Cross section

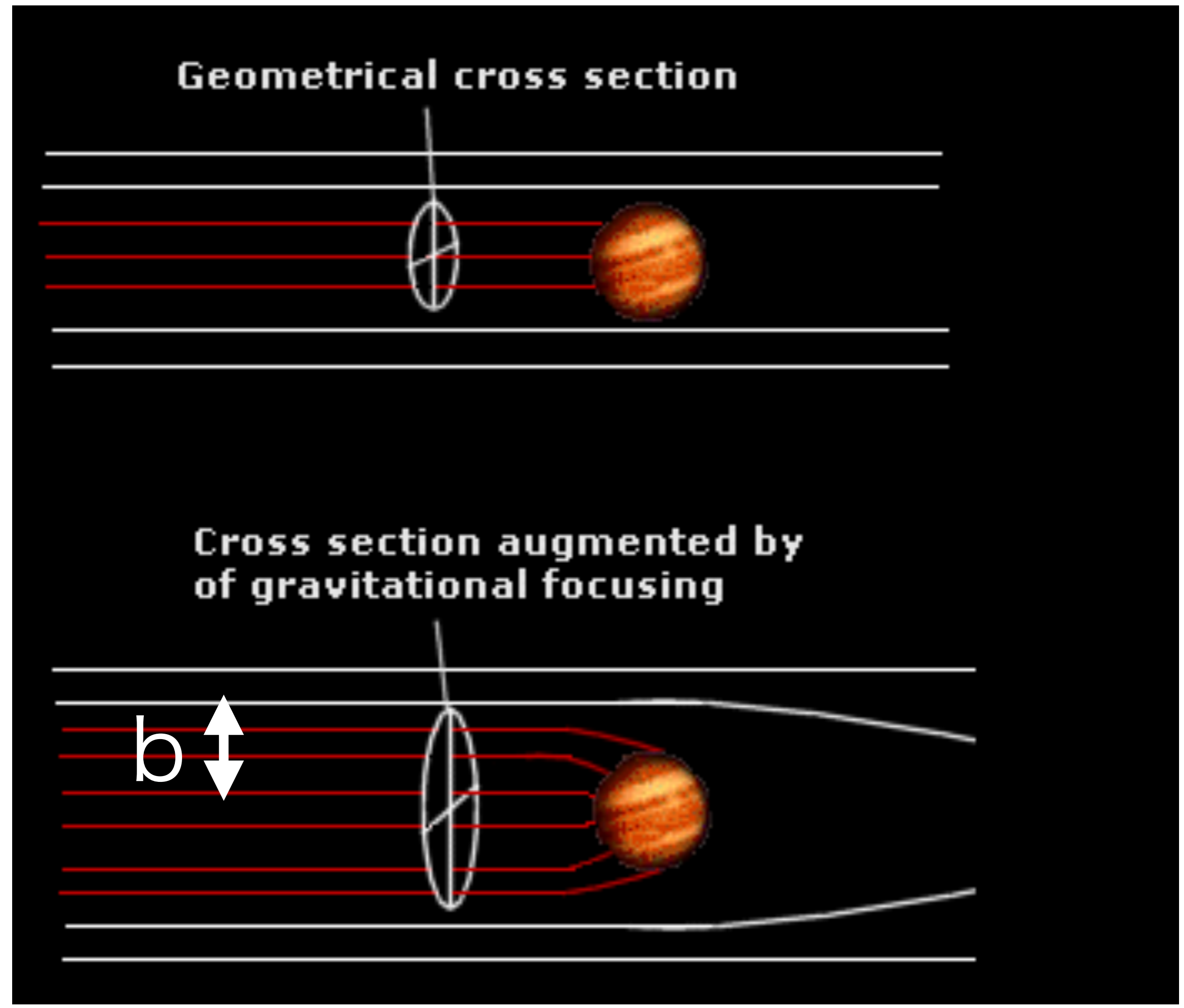
$$\sigma = \pi r_*^2 \left(1 + \frac{2GM_*}{r_* v^2}\right)$$

- r*: Pop. III radius
- M*: Pop. III mass
- Derived from conservation law of energy and angular momentum

$$\sigma = \pi b^2$$

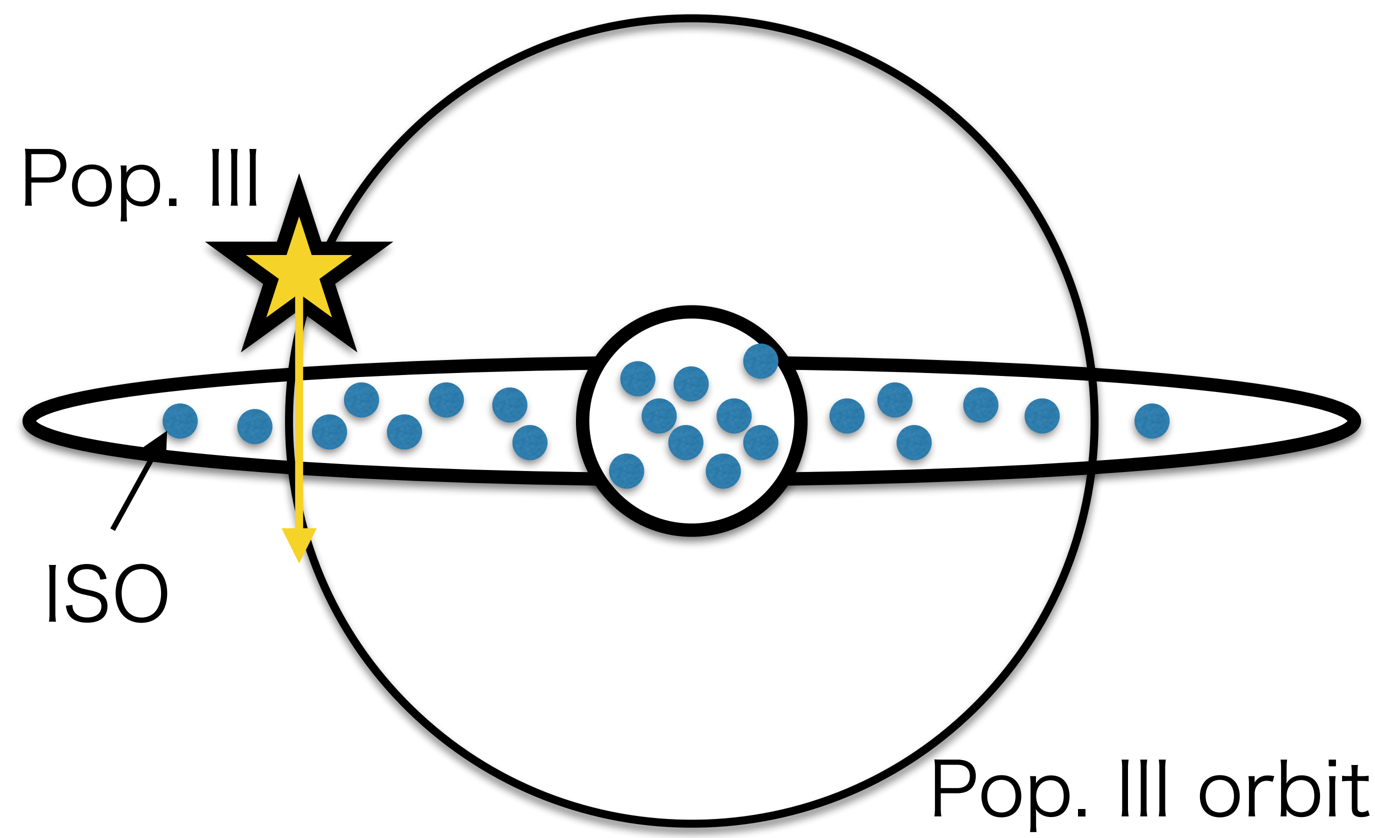
$$bv = r_* v_\mathrm{p}$$

$$\frac{1}{2}v^2 = \frac{1}{2}v_\mathrm{p}^2 - \frac{GM_*}{r_*}$$



Pop. III and ISO orbits

- $f \sim 0.032$ at R_g = 8kpc
  - Disk thickness ~ 400pc
  - Orbital inclination ~ 30 degree
- $v \sim 310$ kms^{-1}
  - circular velocity ~ 220kms^{-1}
  - $2^{1/2}$ x circular velocity
- $\sigma \sim 7.6 \times 10^{22}$ cm^2
  - 4.9 x the solar cross section
  - $M^* = M_\odot$
  - $r^* = r_\odot$



ISO collision rate

$$N_{\rm acc} \sim 1.4 \cdot 10^5 \left(\frac{n}{0.2\ \mathrm{au}^{-3}}\right) [\ \mathrm{Gyr}^{-1}]$$
$$\sim 1.4 \cdot 10^5 \left(\frac{n}{1.6 \cdot 10^{15}\ \mathrm{pc}^{-3}}\right) [\mathrm{Gyr}^{-1}]$$

- Star: n_{star} ~ 0.1 pc^{-3} … 8.8×10^{-12} Gyr^{-1} … no chance
- Free floating planet: n_{ffp} ~ 200 pc^{-3} … 1.8×10^{-8} Gyr^{-1} … no chance

Sublimation of ISOs

Distance to start sublimated $$R = \left(\frac{L_*}{4\pi\sigma_s T^4}\right) \sim 6.9 \cdot 10^{-2} \left(\frac{L_*}{L_\odot}\right)^{1/2} \left(\frac{T}{1500\mathrm{K}}\right) \text{ [au]}$$

Velocity at the distance $$v_R = \left(v^2 + \frac{2GM_*}{R}\right) \sim 3.5 \cdot 10^2 \text{ [km s}^{-1}\text{]}$$

Time to reach a Pop. III survivor $$t_{\mathrm{orbit}} \sim 3.0 \cdot 10^4 \text{ [s]}$$

Conduction time $$t_{\mathrm{cond}} \sim \frac{D^2}{\kappa}$$ (D: ISO size, κ: Thermal conductivity)

$$t_{\mathrm{cond}} > t_{\mathrm{orbit}} \;\Rightarrow\; D_{\mathrm{min}} \sim 3.0 \left(\frac{\kappa}{3 \cdot 10^6 \text{ erg cm}^{-1}\text{ K}^{-1}}\right)^{1/2} \text{ [km]}$$

Cumulative size distribution of ISOs

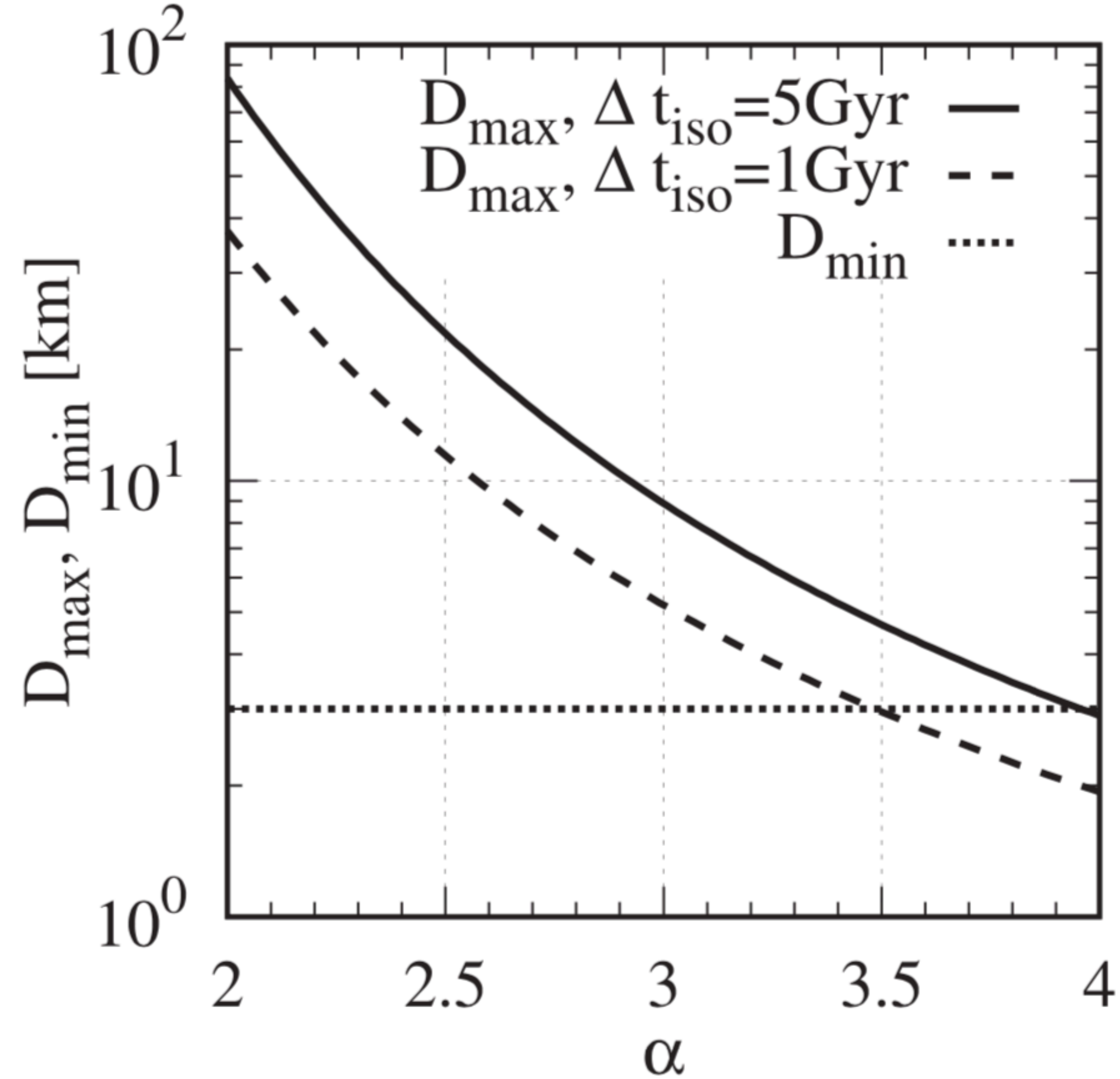
$$n = n_0 \left(\frac{D}{D_0} \right)^{-\alpha} \quad (n_0 = 0.2\ \mathrm{au}^{-3},\ D_0 = 100\ \mathrm{m})$$

- The main belt: α~1.5 for D>200m (Gladman et al. (2009)
- Long-period comet: α~3 for 0.1-10km (Fernandez et al. 2012)
- The Edgeworth-Kuiper belt: α~2.5-3.5 for 0.1-100km (Kenyon et al. 2004)

The maximum size of ISOs

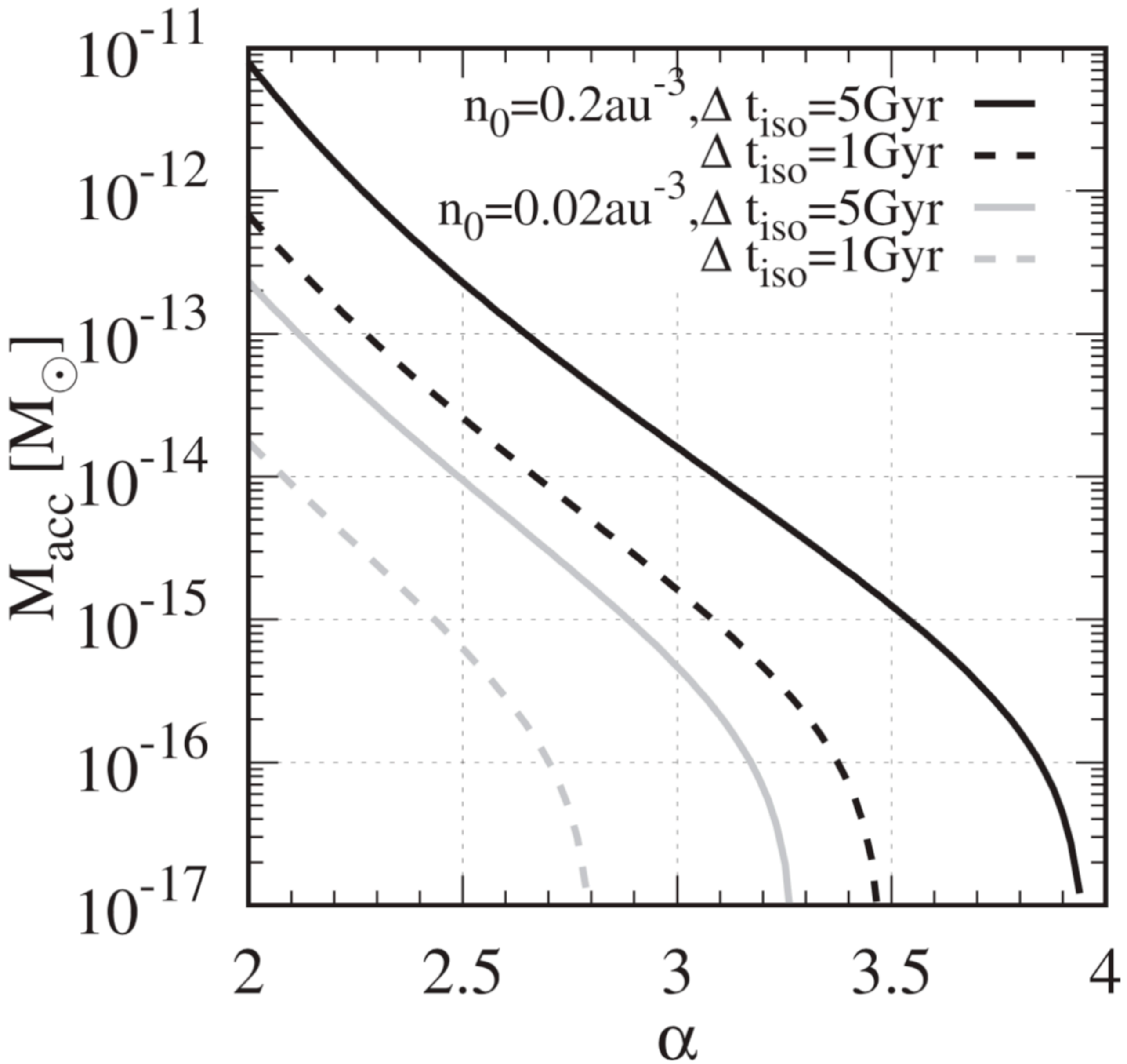
- The maximum size of ISOs which a Pop. III survivors has at least one chance to collide with.

- ISOs have kept the number density of 0.2 au^{-3} for 5Gyr (or 1Gyr).



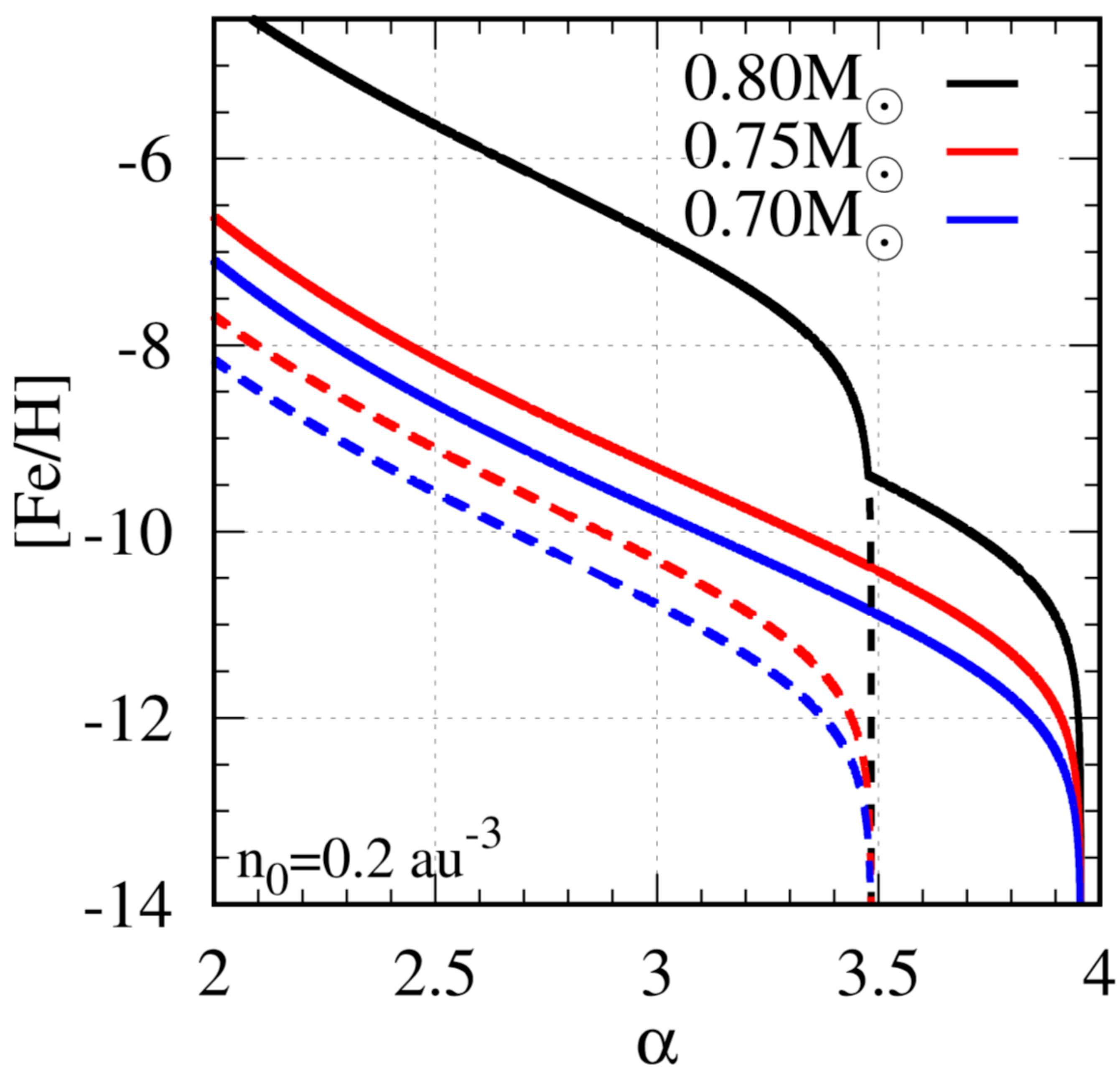
Accreting mass of ISOs

- Total accreting mass is 10^{-15}-$10^{-13} M_\odot$ in the fiducial model.
- ISM accreting mass is $10^{-19} M_\odot$, much smaller than ISO accreting mass.
- Even if ISO number density is smaller than estimated by an order of magnitude, ISO mass is much larger than ISM mass.
- ISOs are the most dominant polluter of Pop. III survivors.



Metallicity

- We assume the mass fraction of a surface convection zone as follows:
  - $0.80 M_{\odot}$: $10^{-6.0}$
  - $0.75 M_{\odot}$: $10^{-2.5}$
  - $0.70 M_{\odot}$: $10^{-2.0}$
- Metallicity is comparable to EMP stars ([Fe/H] > -7) in the extreme case.
- Metallicity is less than EMP stars by several orders of magnitude in non-extreme cases.



Summary

- We have estimated metal pollution of Pop. III survivors by ISOs, or interstellar asteroids.
- We have found ISOs can be the most dominant polluters of Pop. III survivors.
- In the extreme case, Pop. III survivors could hide in EMP stars so far discovered.
- These results are published in Tanikawa, Suzuki, Doi (2018, PASJ, 70, 80)