恒星間天体による初代星の金属汚染に関する研究

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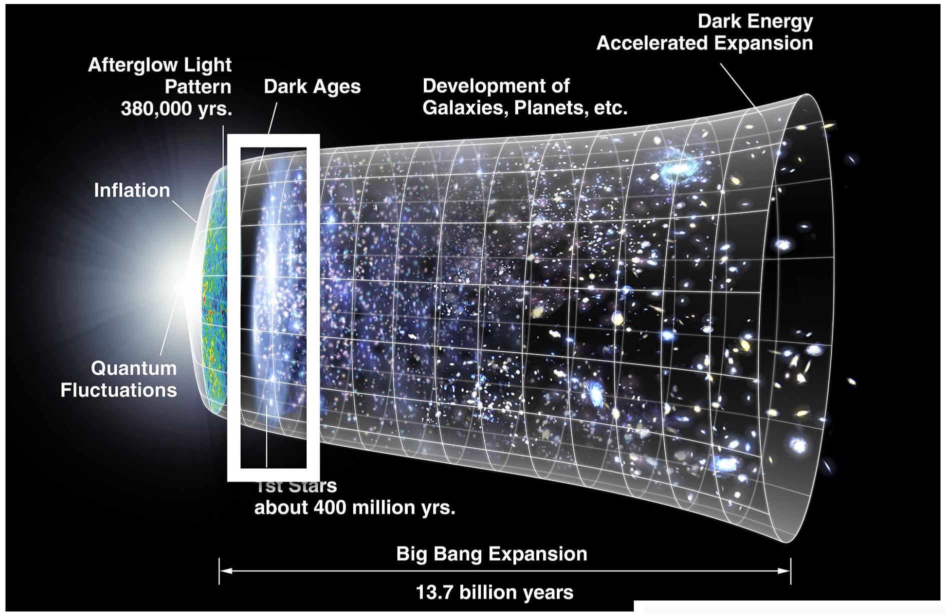
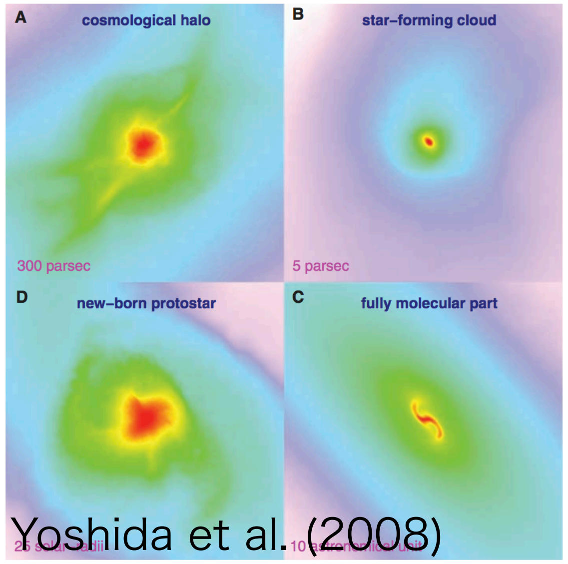
Tanikawa, Suzuki, Doi (2018, PASJ, 70, 80)

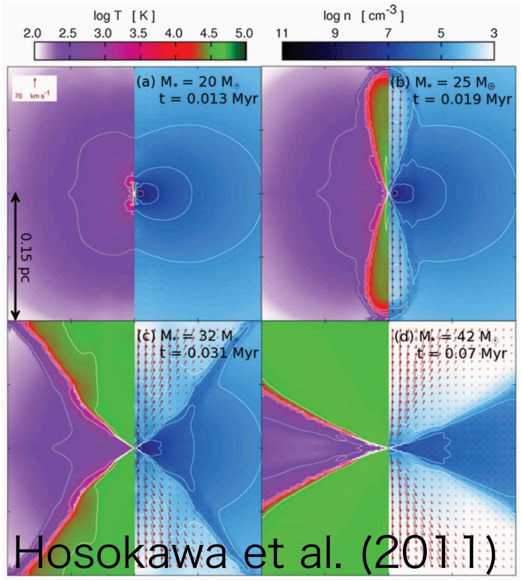
Pop. III stars

- 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

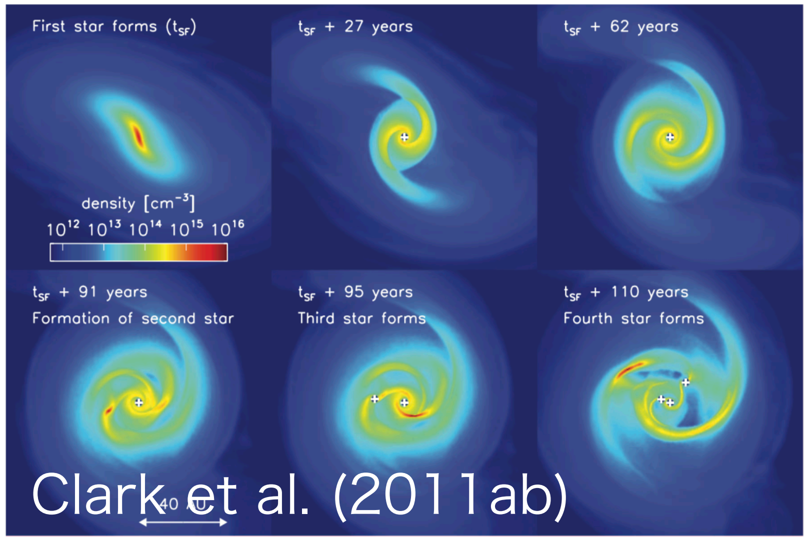




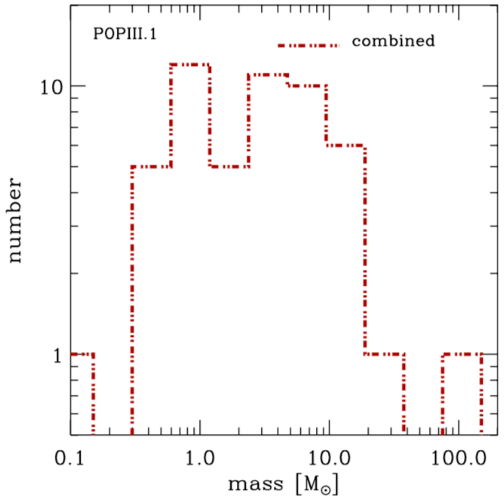
Yoshida et al. (2008)



Hosokawa et al. (2011)

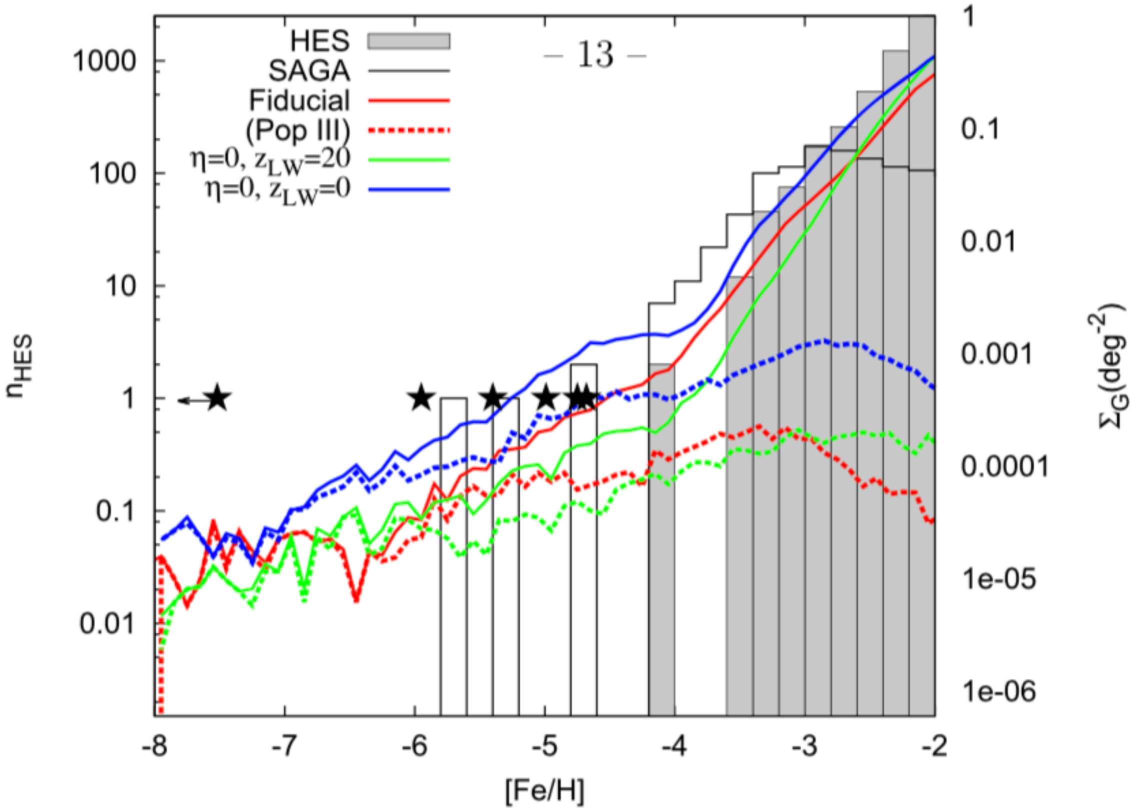


Clark et al. (2011ab)

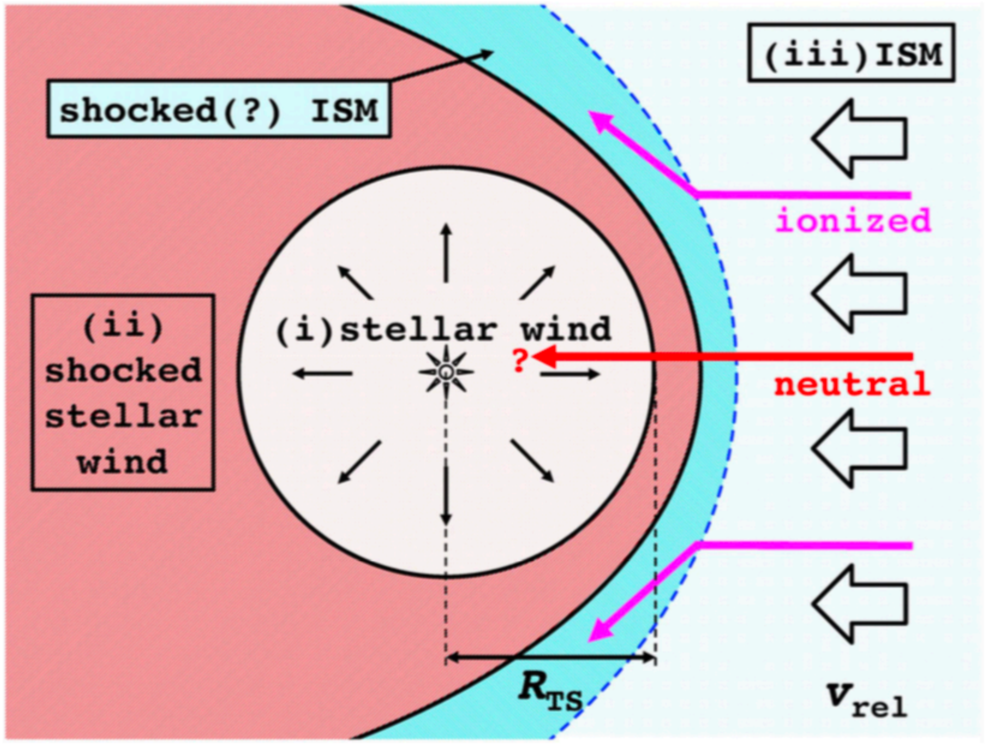


Metal pollution

- 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



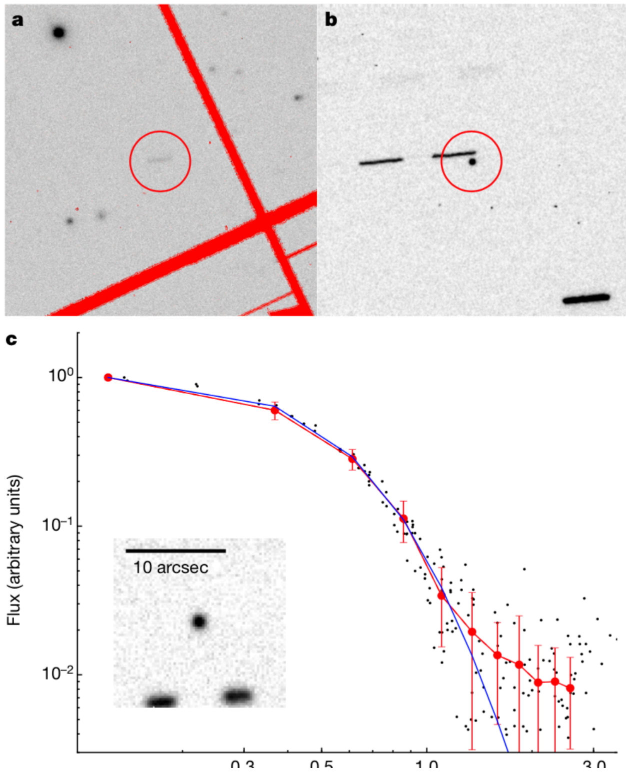
Komiya et al. (2015)



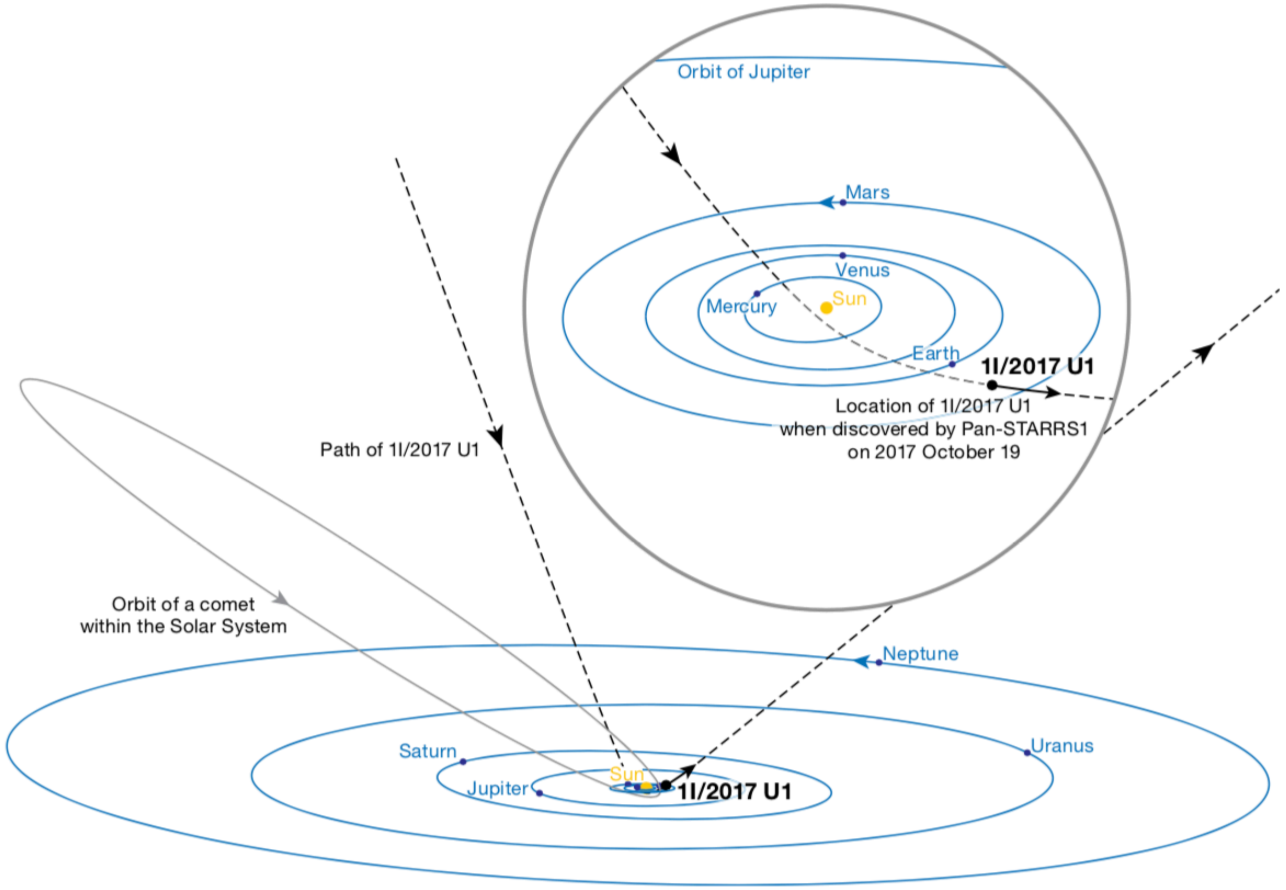
Tanaka et al. (2017), Suzuki (2018)

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



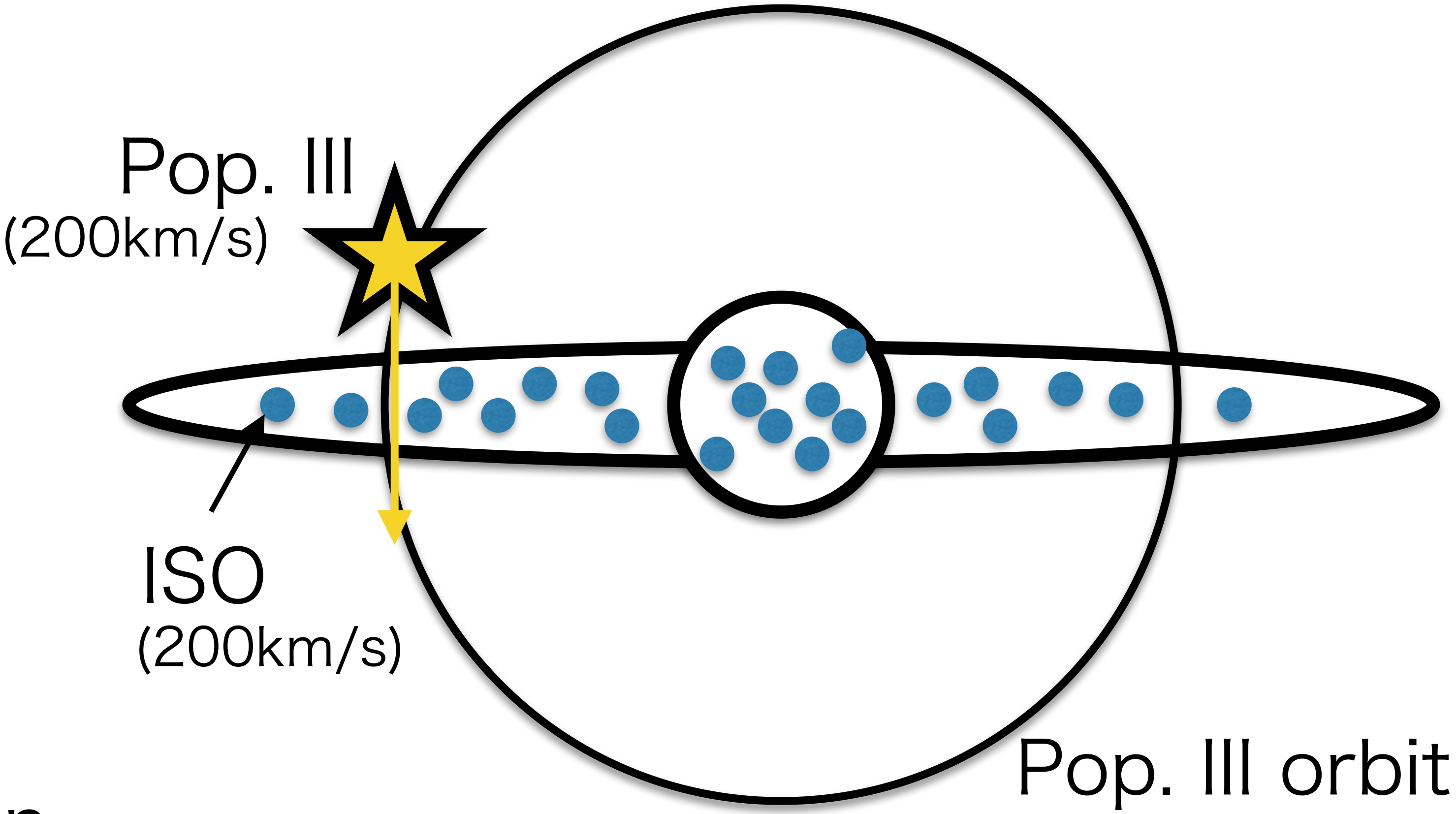
Meech et al. (2017)



Collision rate

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

- 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



Pop. III
(200km/s)

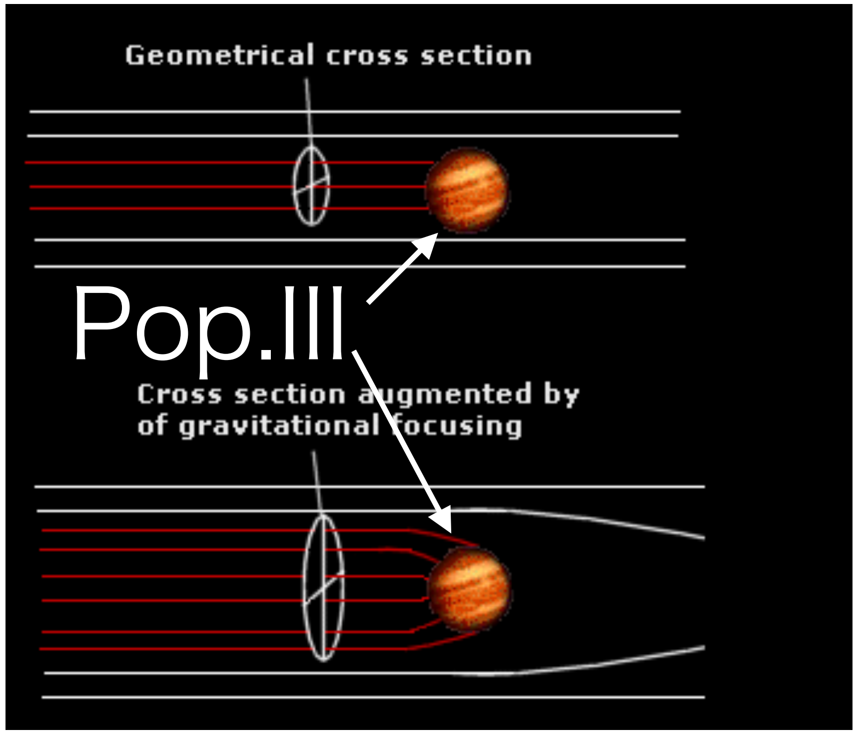
ISO
(200km/s)

Pop. III orbit

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

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

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



Cross section

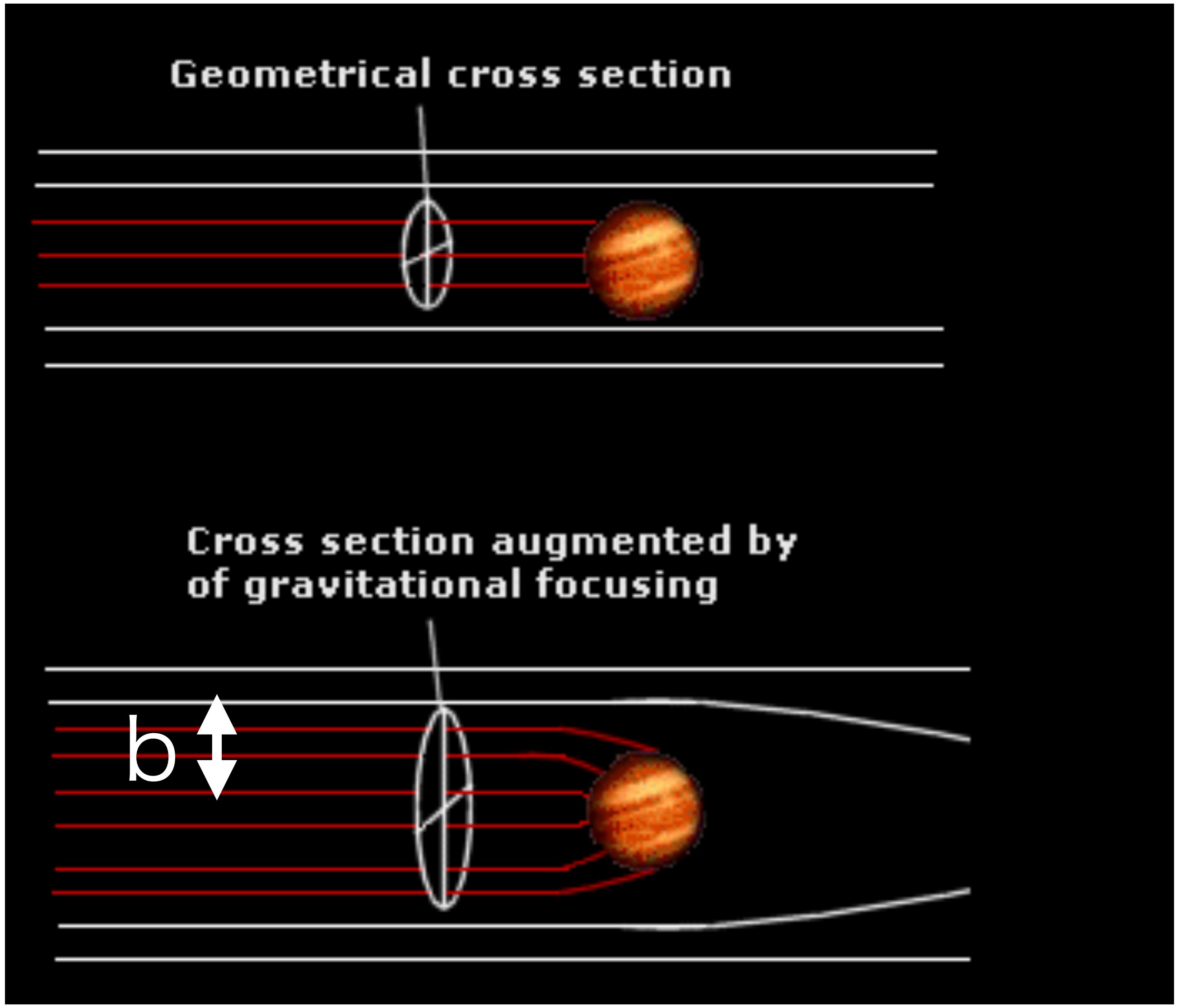
$$\sigma = \pi r_*^2 \left(1 + \frac{2GM_*}{r_* v^2}\right)$$

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

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

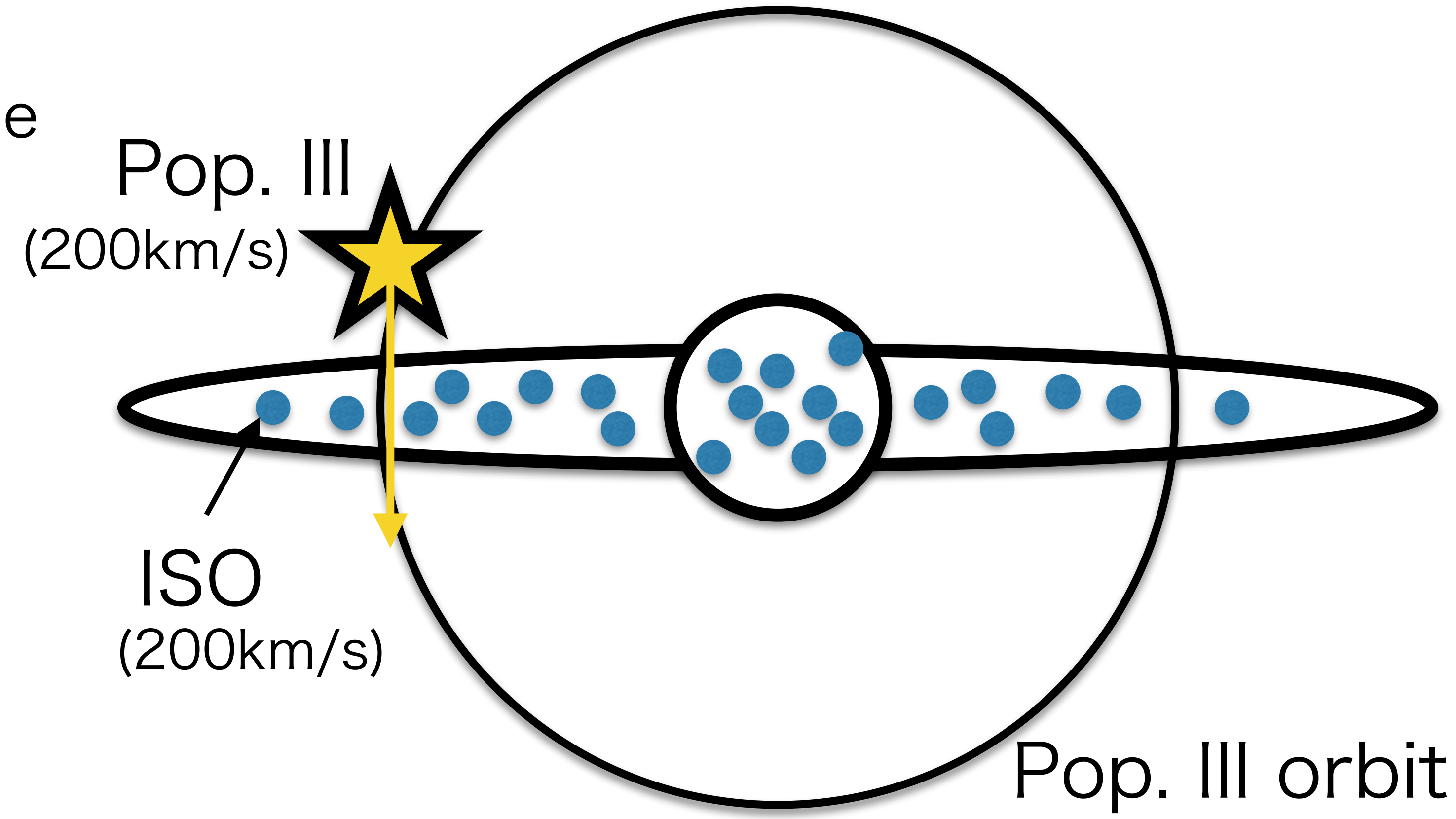
$$bv = r_* v_{\mathrm{p}}$$

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



Pop. III and ISO orbits

- f ~ 0.032 at R_g = 8kpc
  - Disk thickness ~ 400pc
  - Orbital inclination ~ 30 degree
- v ~ 310 kms^{-1}
  - circular velocity ~ 220kms^{-1}
  - $2^{1/2}$ x circular velocity
- σ ~ 7.6x10^{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: $n_{\rm star}$ ~ 0.1 pc^{-3} … 8.8×10^{-12} Gyr^{-1} … no chance
- Free floating planet: $n_{\rm ffp}$ ~ 200 pc^{-3} … 1.8×10^{-8} Gyr^{-1} … no chance

Tidal disruption

- The solar density is1.4 g/cm^3.
  - If ISOs are asteroids, they can survive at the solar surface, since their density is 3 g/cm^3.
  - If ISOs are comets, they will be tidally disrupted, since their density is 0.5 g/cm^3.
    - However, they can plunge into the Sun because of the short times of the events (Brown et al. 2015).

Sublimation of ISOs

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

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

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

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

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

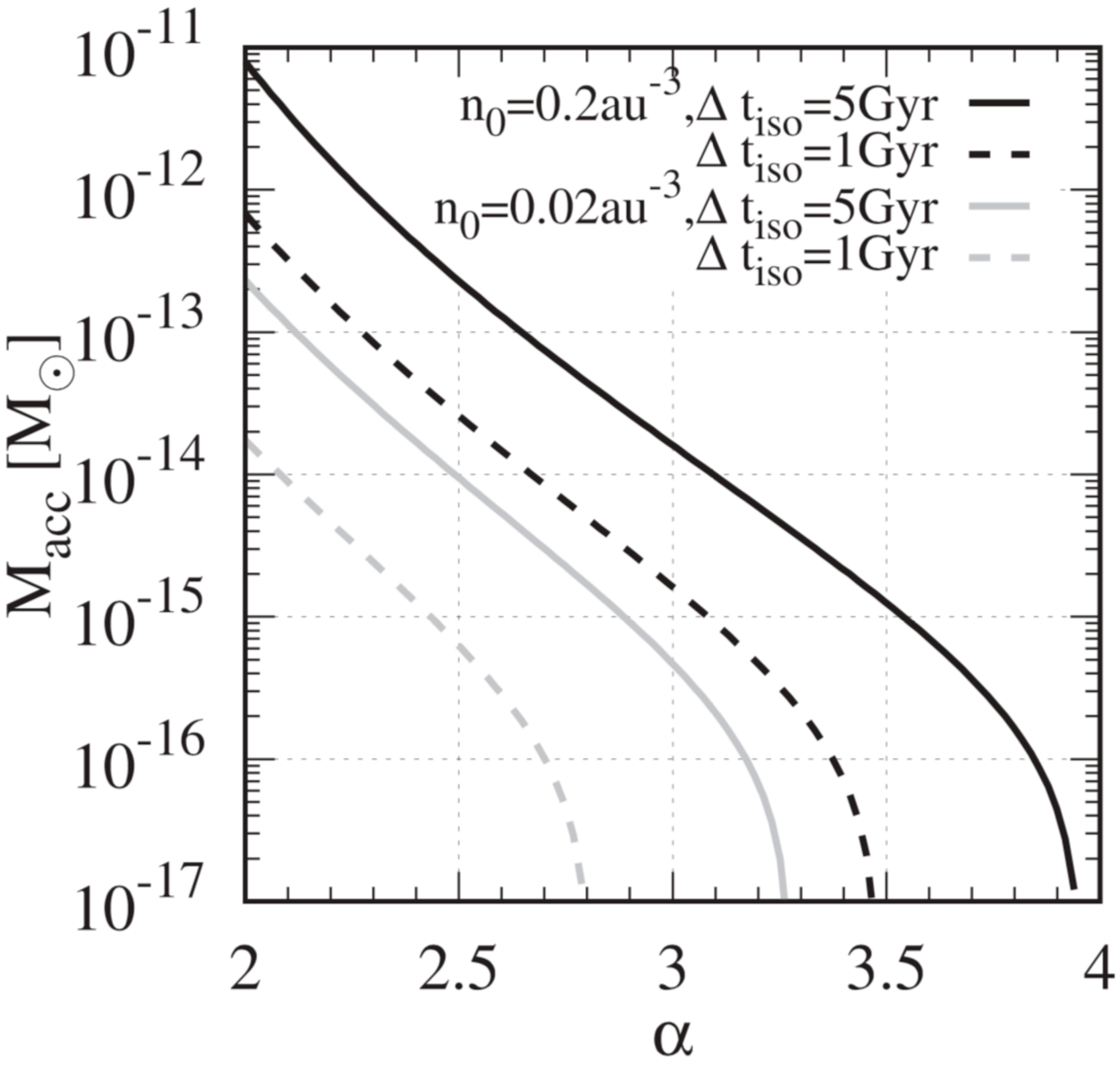
Cumulative size distribution of ISOs

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

- 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)

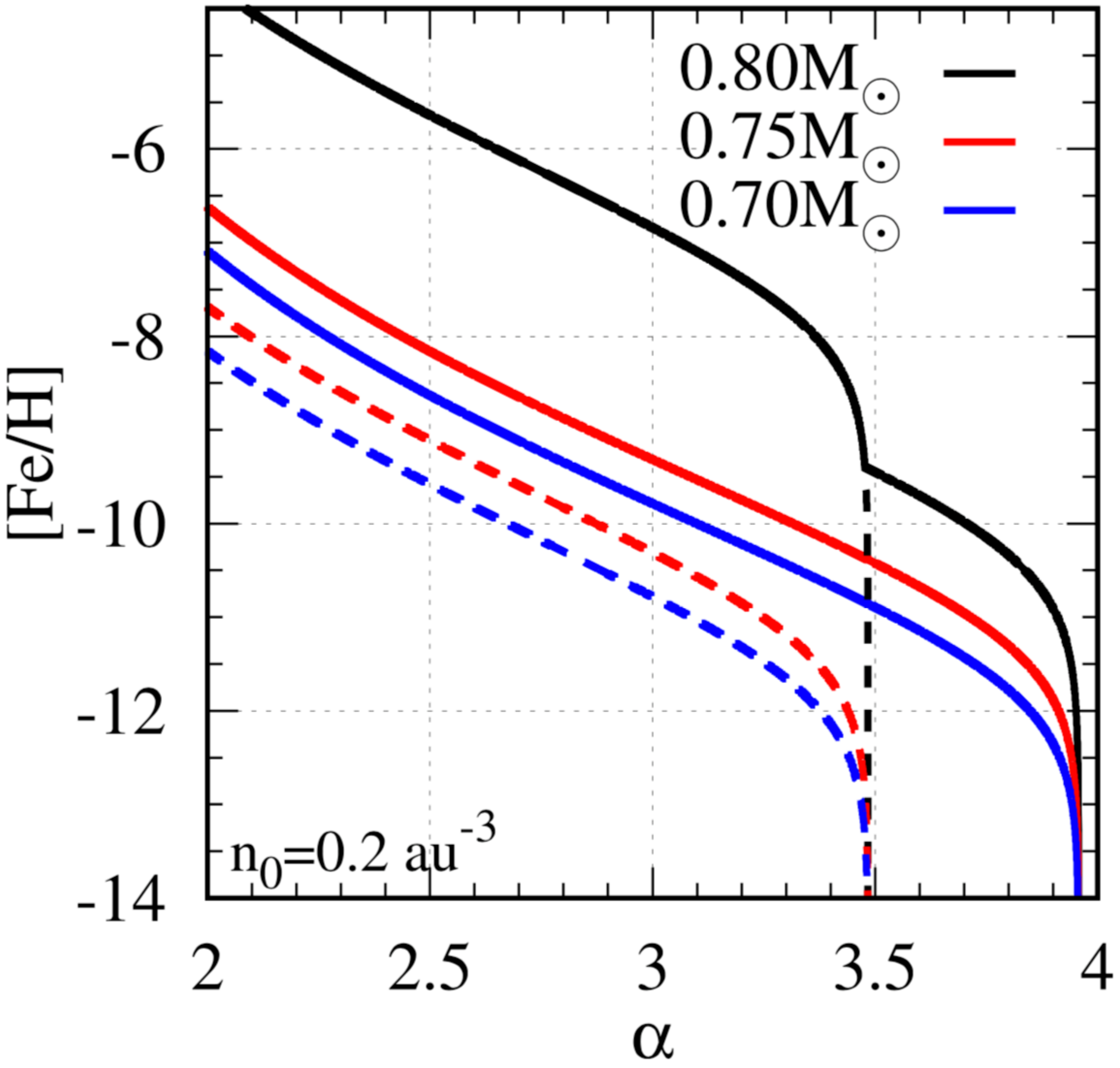
Accreting mass of ISOs

- 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:
  - $0.80M_\odot$: $10^{-6.0}$
  - $0.75M_\odot$: $10^{-2.5}$
  - $0.70M_\odot$: $10^{-2.0}$
- 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)