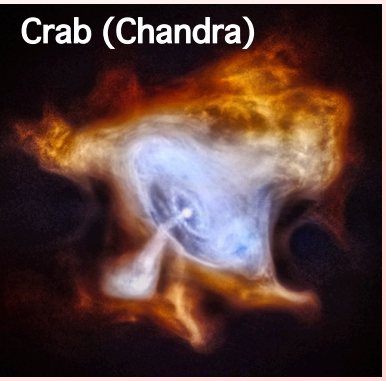
Tanaka, Chiaki, Tominaga, & Susa, ApJ, 844, 137 (2017)

KONAN

Blocking metal accretion onto low-mass PopIII stars by stellar wind

低質量初代星への星間金属降着に対する恒星風の影響



Shuta J. Tanaka(1) -> (2)

with

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(1) Konan Univ., (2) AGU

(3) Georgia Tech., (4) Univ. of Tokyo, IPMU

Introduction

Low-mass Population III Stars

- Study the initial mass function (IMF) of PopIII stars.
- Top-heavy PopIII IMF has been predicted, while some might have < 1 $M_\odot$

e.g., Nakamura&Umemura01

- Low-mass PopIII stars < 0.8$M_\odot$ are still in Main-sequence phase, if they exist.

Machida+13

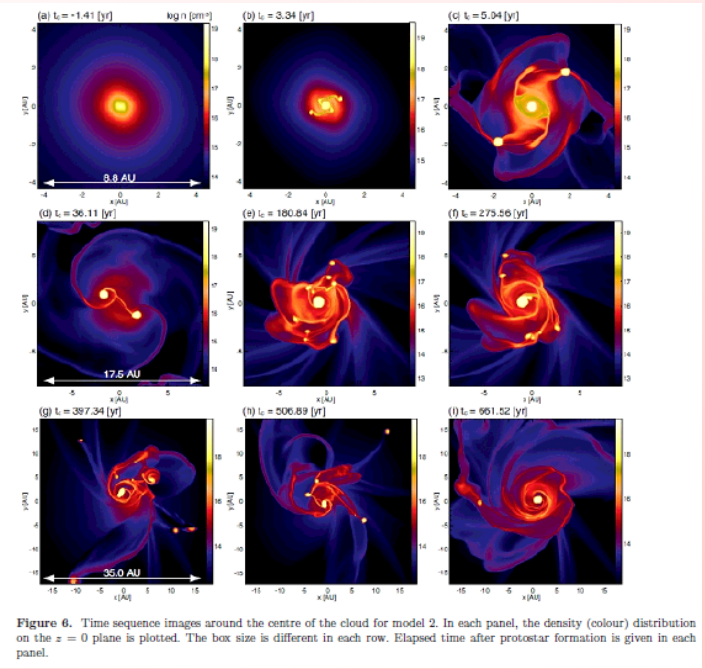
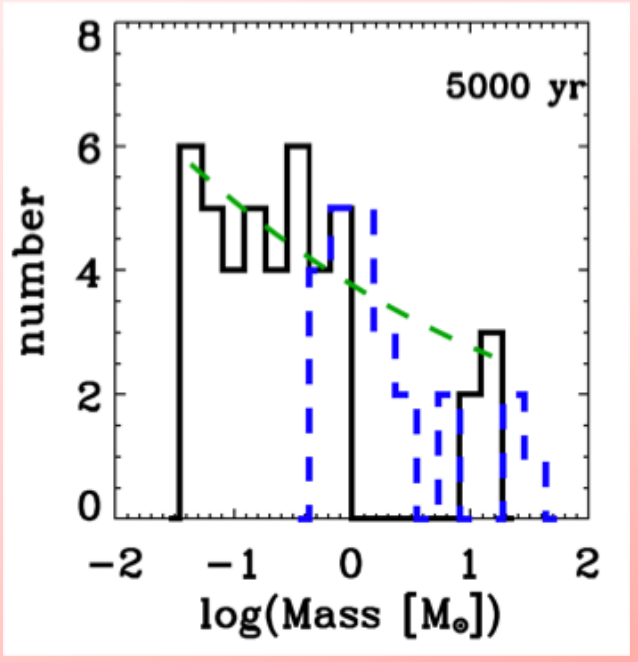
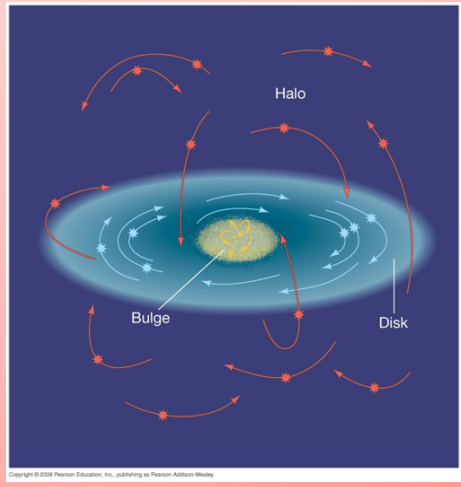


Figure 6. Time sequence images around the centre of the cloud for model 2. In each panel, the density (colour) distribution on the $z = 0$ plane is plotted. The box size is different in each row. Elapsed time after protostar formation is given in each panel.

Stacy+16



?

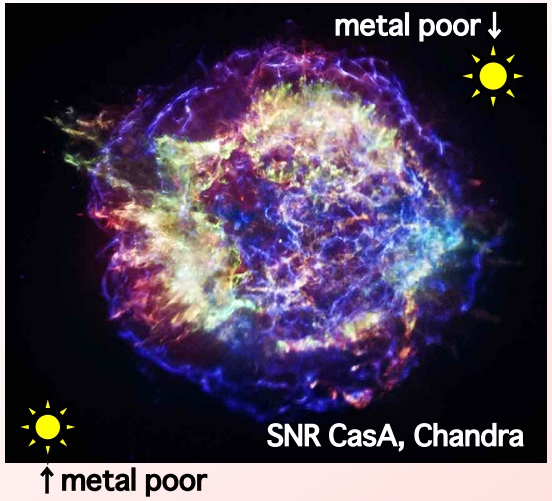


http://pages.uoregon.edu/jimbrau/astr123/

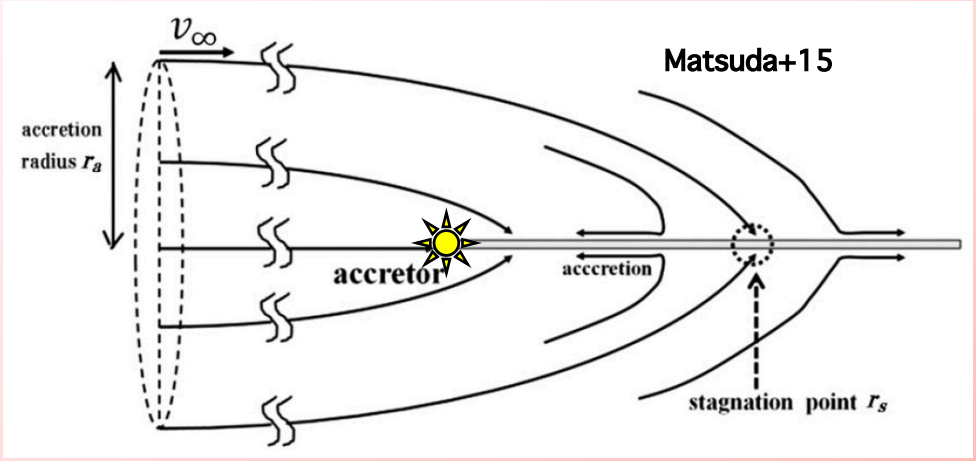
Can we find **low-mass PopIII stars as metal free star** in our Galactic halo?

Origin of Metal Poor Stars

1. Second generation stars?

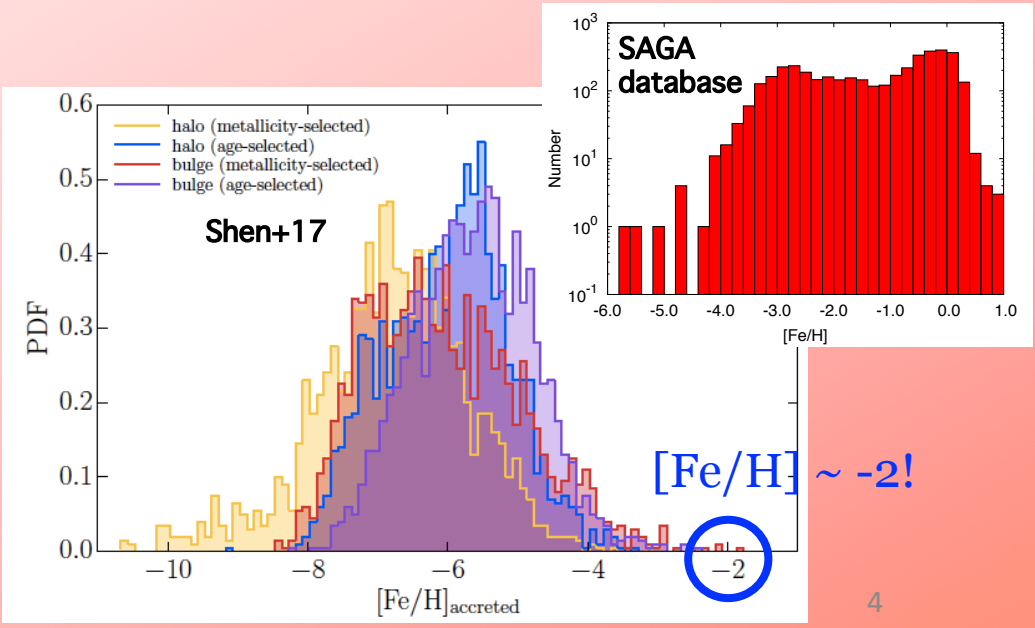


2. Chemically enriched PopIII stars?



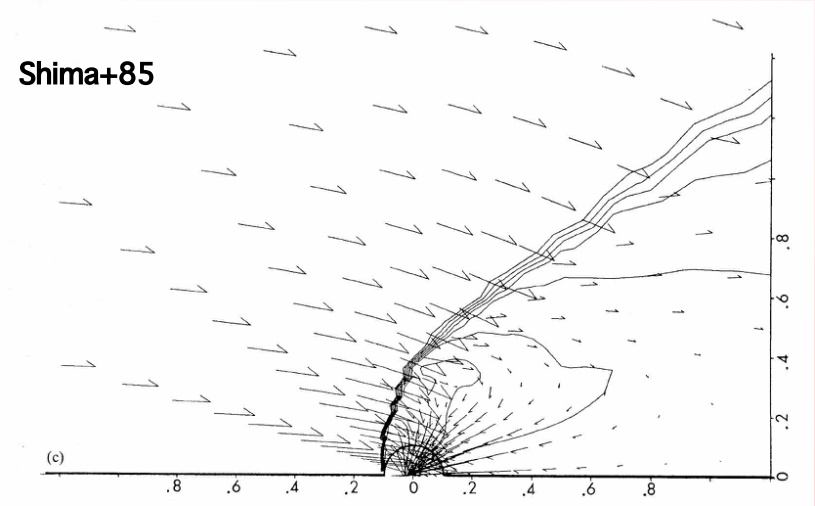
Study of scenario 2 predicts [Fe/H] ~ -2 in an extreme case.

Contamination for study of low-mass PopIII stars.



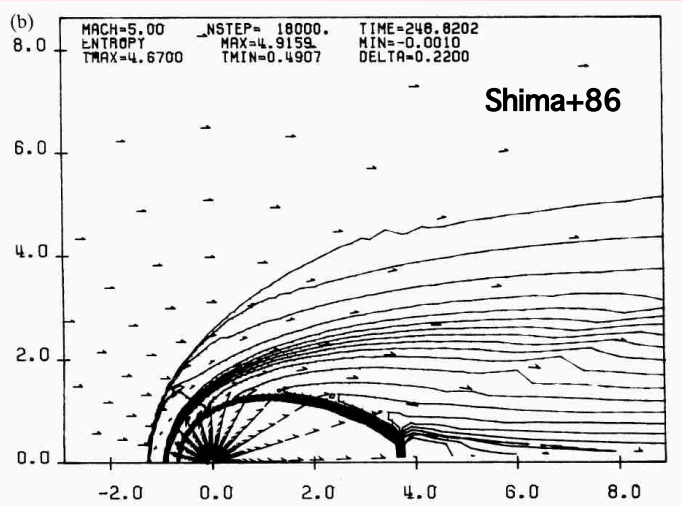
Accretion or Wind?

Bondi-Hoyle-Lyttleton accretion

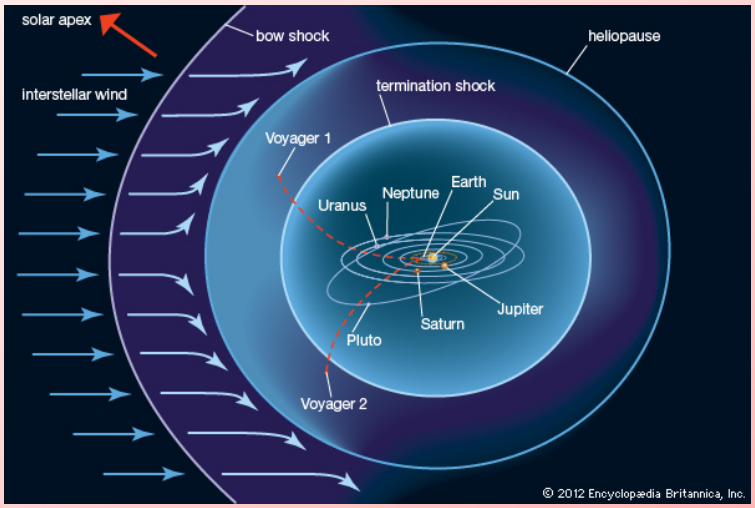


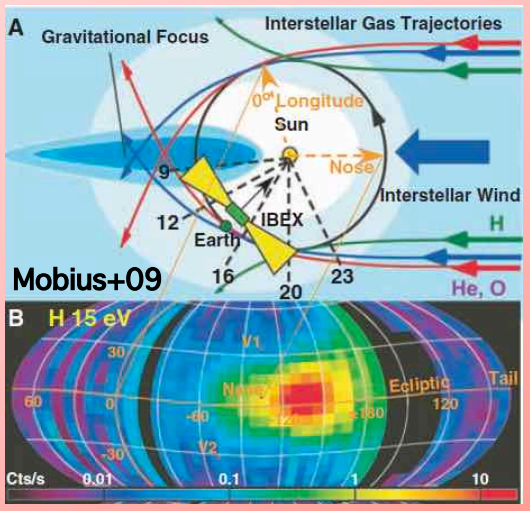
VS.

Formation of astrosphere



Case of our Sun: interstellar particles are picked up by the solar wind!!



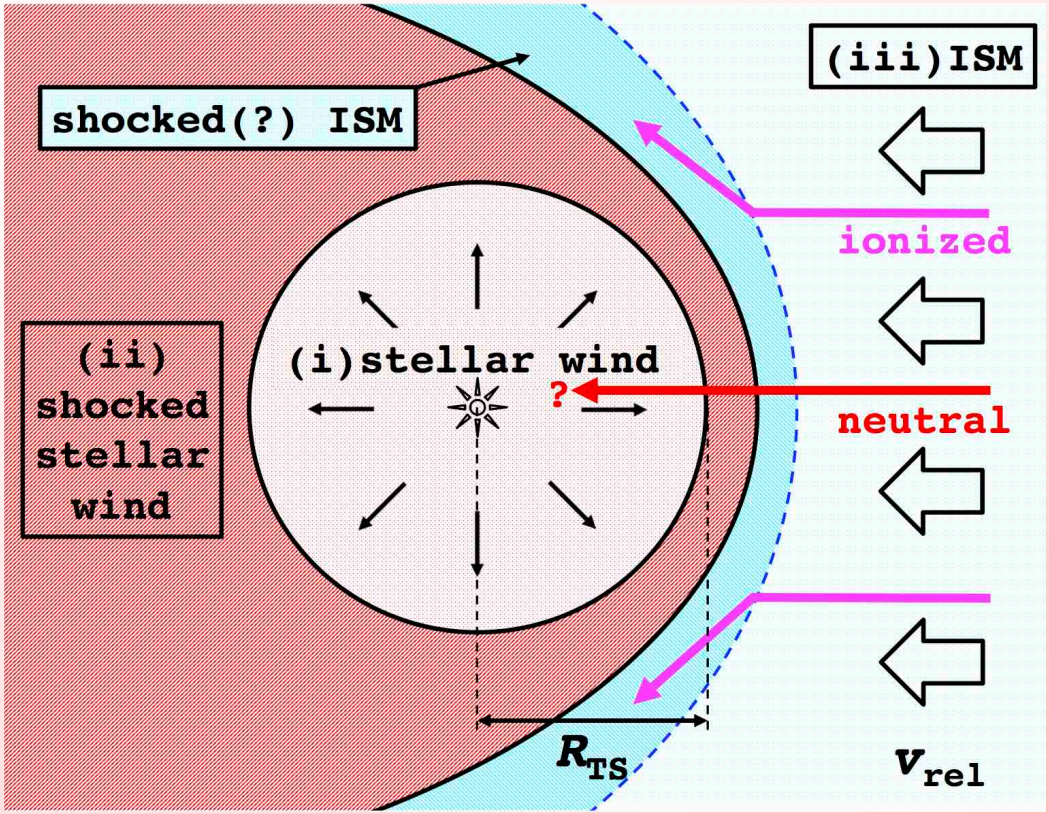


Can interstellar heavy elements accrete onto low-mass PopIII stars against their wind?

Model

Stellar Wind & ISM

The parameters of stellar wind are set to the Solar values.



(i) Thermal driven supersonic flow

$$n_{\rm sw}(r) = n_{\rm sw\star}\left(\frac{r}{R_\star}\right)^{-2}$$

$$v_{\rm sw}(r) = v_{\rm sw\star},$$

(iii) Bondi-Hoyle-Lyttleton accretion flow

$$n_{\rm HL}(r,\theta,\xi) = \frac{n_{\rm ISM}\xi^2}{r\sin\theta(2\xi - r\sin\theta)},$$

$$v_{{\rm HL},r}(r,\theta,\xi) = -\sqrt{v_{\rm rel}^2 + \frac{2GM_\star}{r} - \frac{\xi^2 v_{\rm rel}^2}{r^2}},$$

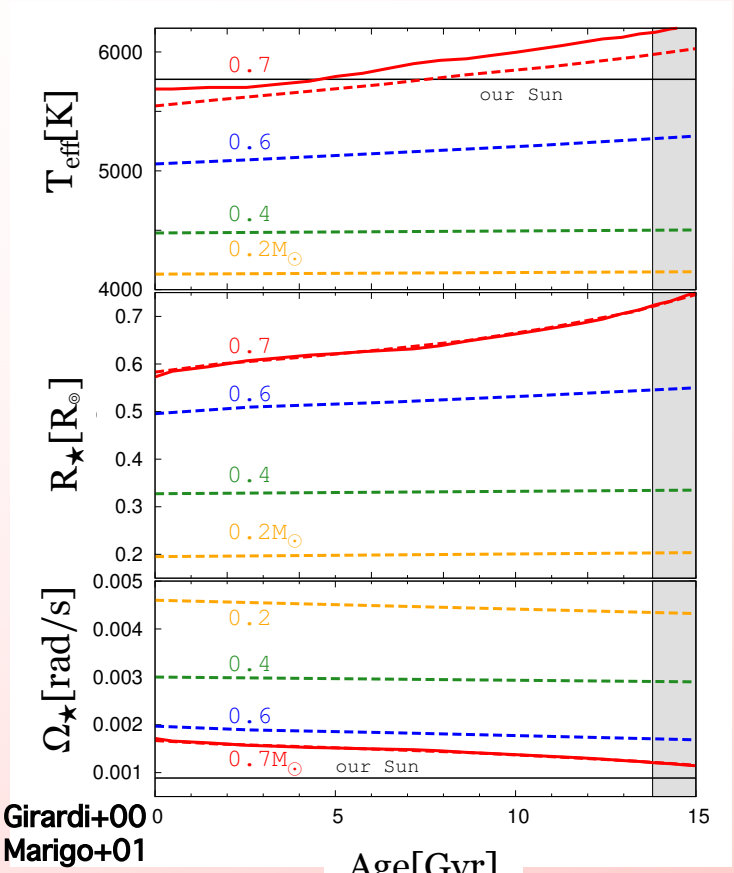
Conditions for astrosphere formation around low-mass star?

Neutrals in the ISM behave different from ionized ones!!

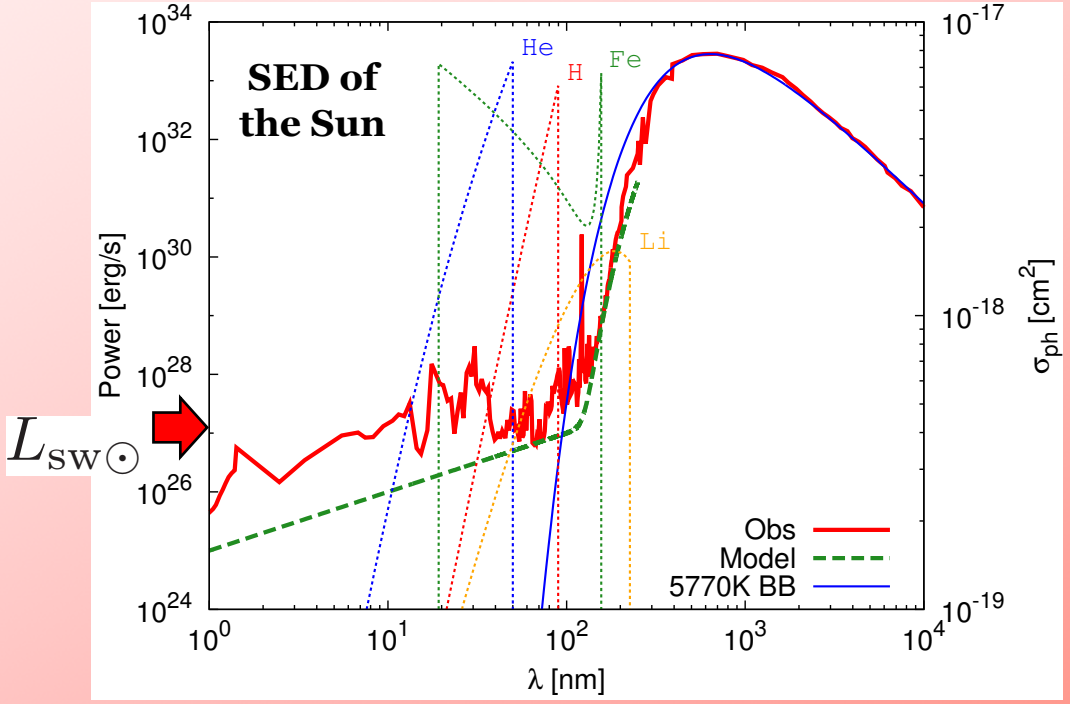
Stellar Model

$$\frac{r_{\mathrm{g,FeII}}(R_\star)}{R_\star} \approx 10^{-5} \left(\frac{B_{\mathrm{sw}\star}}{1\ \mathrm{G}}\right)^{-1} \left(\frac{\Omega_{\mathrm{K}\star}}{10^{-3}\ \mathrm{rad\ s^{-1}}}\right),$$

B-field of $\ll$ Gauss at surface is enough to trap ionized Fe.



Stellar parameters (effective temperature, radius of low-mass PopIII stars



For photoionization, SED is taken from the Sun.

Rate Equation

What fraction of Neutral ISM attains to stellar surface before photoionized?

$$v(r)\frac{dn_i(r)}{dr} = -\beta_{\mathrm{ph},i}(r)n_i(r) + \alpha_{\mathrm{rec},i}n_{\mathrm{e}}n_i^+(r)$$

Recombination processes can be neglected.

$$v(r) = -\sqrt{v_{\mathrm{rel}}^2 + \frac{2GM_\star}{r}}$$

Motion of neutrals in gravitation field

$$\beta_{\mathrm{ph},i} \propto r^{-2}$$

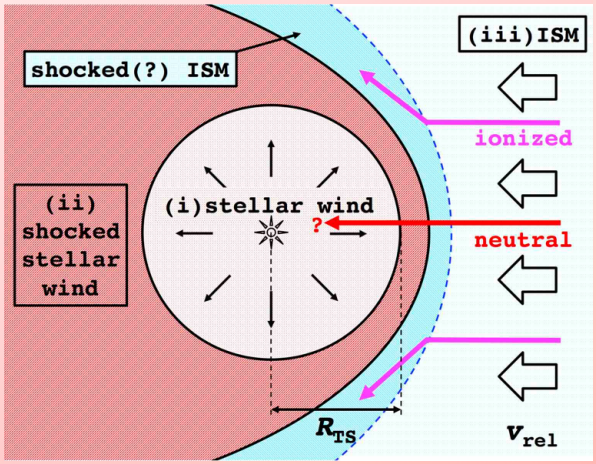
$$\frac{n_i(r)}{n_{\mathrm{ISM},i}} = \exp\left[-\frac{\sqrt{2}\beta_{\mathrm{ph}\star,i}}{\Omega_{\mathrm{K}\star}}\left(\sqrt{\frac{v_{\mathrm{rel}}^2}{v_{\mathrm{esc}\star}^2} + \frac{R_\star}{r}} - \frac{v_{\mathrm{rel}}}{v_{\mathrm{esc}\star}}\right)\right]$$

Results

Formation of Magnetosphere

Pressure balance between accretion and wind flows.

$$n_{\rm sw\star} v_{\rm sw\star}^2 \left(\frac{R_\star}{R_{\rm TS}}\right)^2 \approx n_{\rm ISM}\left(v_{\rm rel}^2 + v_{\rm esc\star}^2 \frac{R_\star}{R_{\rm TS}}\right).$$



For ($R_\star$ <) $\xi_{\rm BHL} < R_{\rm TS}$

c.f., Talbot&Newman77

$$\xi_{\rm BHL} = \frac{2GM_\star}{v_{\rm rel}^2} = R_\star \frac{v_{\rm esc}^2}{v_{\rm rel}^2}$$

$$n_{\rm crit} \equiv \frac{n_{\rm sw\star}}{2}\frac{v_{\rm sw\star}^2 v_{\rm rel}^2}{v_{\rm esc\star}^4}$$

$$\approx 10^4\ {\rm cm}^{-3}\left(\frac{n_{\rm sw\star}}{7.0\times10^5\ {\rm cm}^{-3}}\right)\left(\frac{v_{\rm sw\star}}{400\ {\rm km\ s}^{-1}}\right)^2\left(\frac{v_{\rm rel}}{200\ {\rm km\ s}^{-1}}\right)^2\left(\frac{v_{\rm esc\star}}{680\ {\rm km\ s}^{-1}}\right)^{-4}$$

Solar wind value

Average of halo stars

e.g., Chiba&Beers00

0.7 $M_\odot$ PopIII star

$$\dot{M}_{\rm BHL} = \frac{2\pi G^2 M_\star^2 \rho_{\rm ISM}}{(c_{\rm s}^2 + v_{\rm rel}^2)^{3/2}}$$

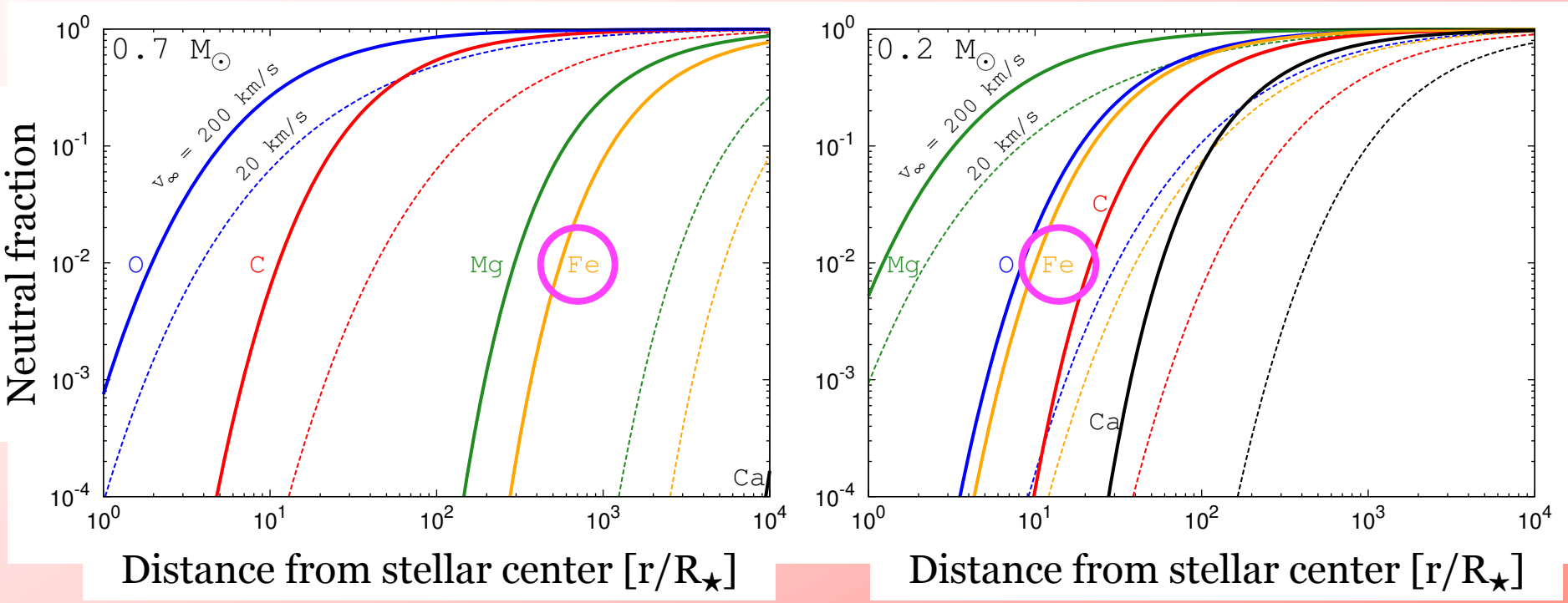
Volume fraction of $n_{\rm ISM} > n_{\rm crit}$ is very small even at Gal. disk.

=> **Magnetosphere is sustained!!**

Survival Probability

Neutral fraction at given radius.

$$\frac{n_i(r)}{n_{\mathrm{ISM},i}} = \exp\left[-\frac{\sqrt{2}\beta_{\mathrm{ph}\star,i}}{\Omega_{\mathrm{K}\star}}\left(\sqrt{\frac{v_{\mathrm{rel}}^2}{v_{\mathrm{esc}\star}^2}+\frac{R_\star}{r}}-\frac{v_{\mathrm{rel}}}{v_{\mathrm{esc}\star}}\right)\right]$$



Iron hardly attains stellar surface

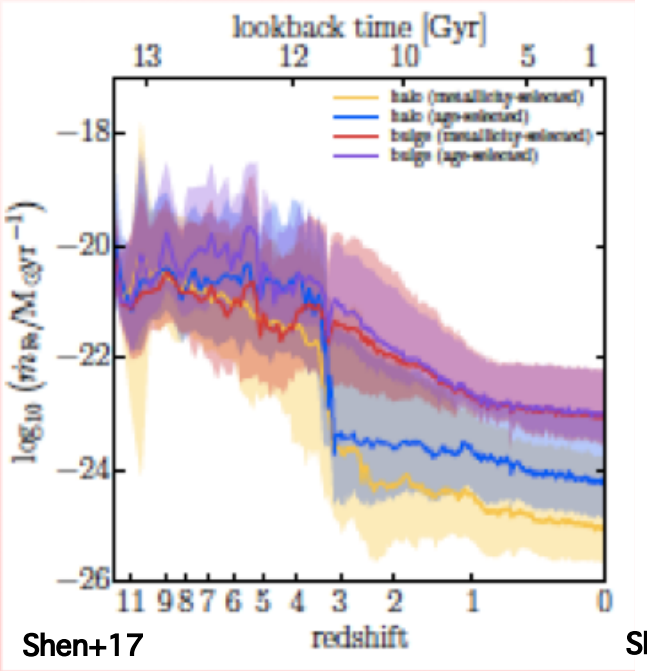
Discussion & Conclusions

Accretion from $n > n_{\rm crit}$

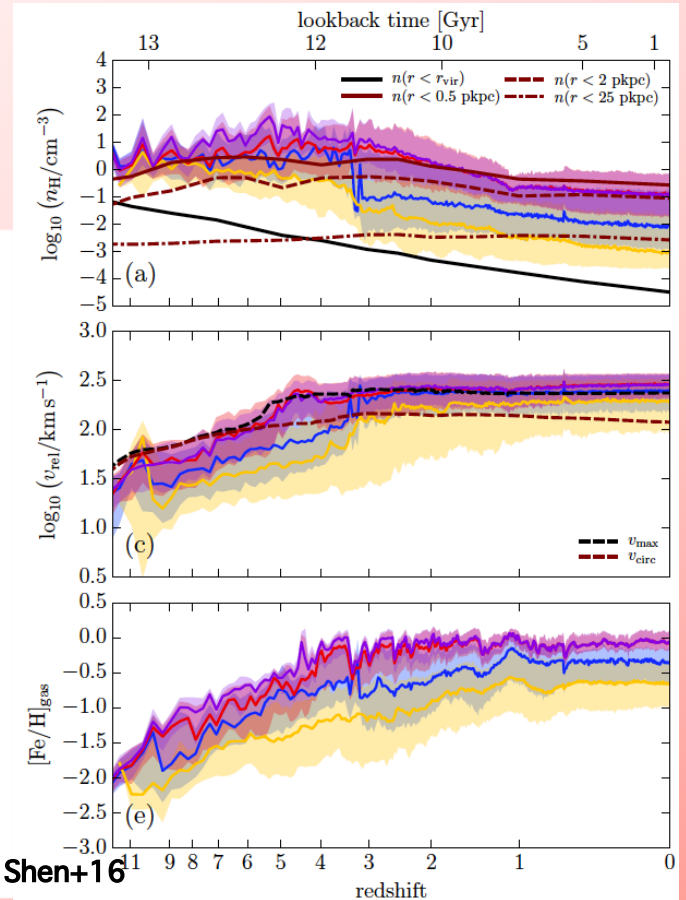
Density probability distribution $P(n, t)$ and metallicity distribution $Z(n, t)$

$$M_{Z,\rm acc} = \int dt \int_{n_{\rm crit}(t)}^{\infty} dn P(n,t) Z(n,t) \dot{M}_{\rm BHL}(n,t).$$

Accretion @ high-z is dominant because $\dot{M}_{\rm BHL} \propto (v_{\rm rel})^{-3}$



Shen+17



Shen+16

Shen+16 set $n_{\rm crit} = 0$, i.e., no wind and always $n < 10^2$ cc^{-1}! (difficult to resolve $n > 10^2$ cc^{-1} numerically.)

Johnson & Khochfar11 estimated that the probability of encounter of a star and a cloud at high-z is less than 0.1. [Fe/H]~-6 for one encounter.

Conclusions & Further Studies

Conclusions

- [Fe/H] is reduced by photoionization ([Fe/H] < -14 even for extreme case).
- Currently observed metal poor stars are not low-mass PopIII stars.
- Low-mass PopIII stars will be found as metal free stars or current observations have already constrained PopIII IMF.
- Metal poor stars preserve their initial metallicity.

Further Studies

- Metal accretion in dust phase (however, Johnson2015).
- Binary case.
- Stellar wind from low-mass PopIII stars (Suzuki17)
- Bondi-Hoyle-Lyttleton accretion with stellar wind
  - Used n_{crit} may be over-simplified because we consider 1D trajectory.