The initial mass function of the first stars inferred from elemental abundances in extremely metal-poor stars

Miho N. Ishigaki（Kavli IPMU/University of Tokyo）

N. Tominaga (Konan-U. /IPMU), C. Kobayashi (U. Hertfordshire/IPMU), K. Nomoto (IPMU)

Thanks to discussions with Tilman Hartwig (Kavli IPMU), Shing-Chi Leung (Kavli IPMU)

Stellar archaeology as a Time Machine to the First Stars

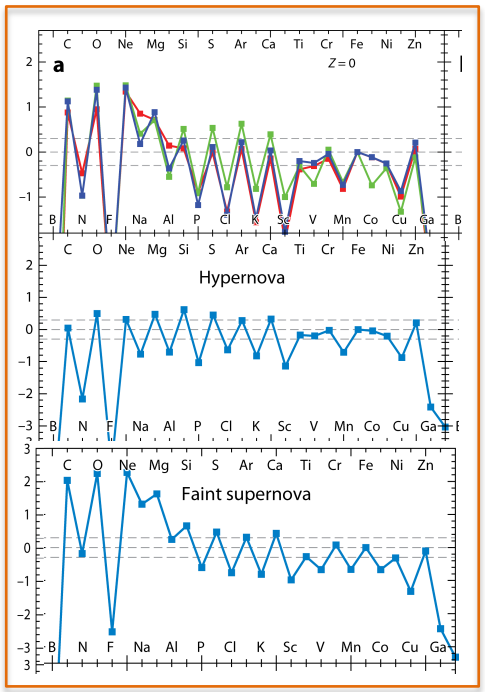
Kavli IPMU, December 3-8, 2018

Nucleosynthesis by Pop III stars

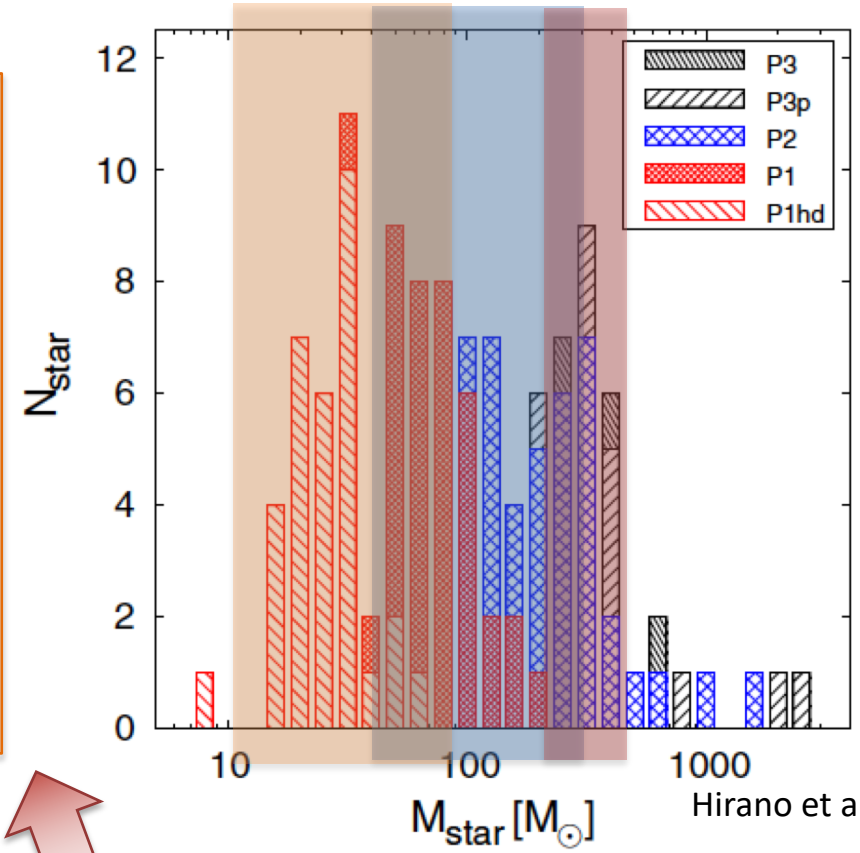
Theoretical predictions of Pop III mass distributions

Pulsational Pair Instability SNe or direct collapse

Core-Colapse SNe

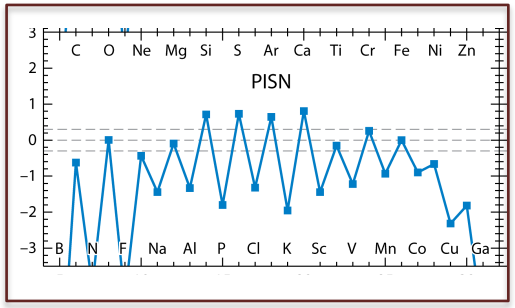


Nomoto et al. 2013



Hirano et al. 2014

Pair Instability SNe



Nomoto et al. 2013

Chemical abundance patterns of long-lived stars

Which stellar samples best traces the Pop III masses?

Stars that are formed out of gas predominantly enriched by a single or a few Pop III supernovae (see Hartwig et al. 2018, 2019)

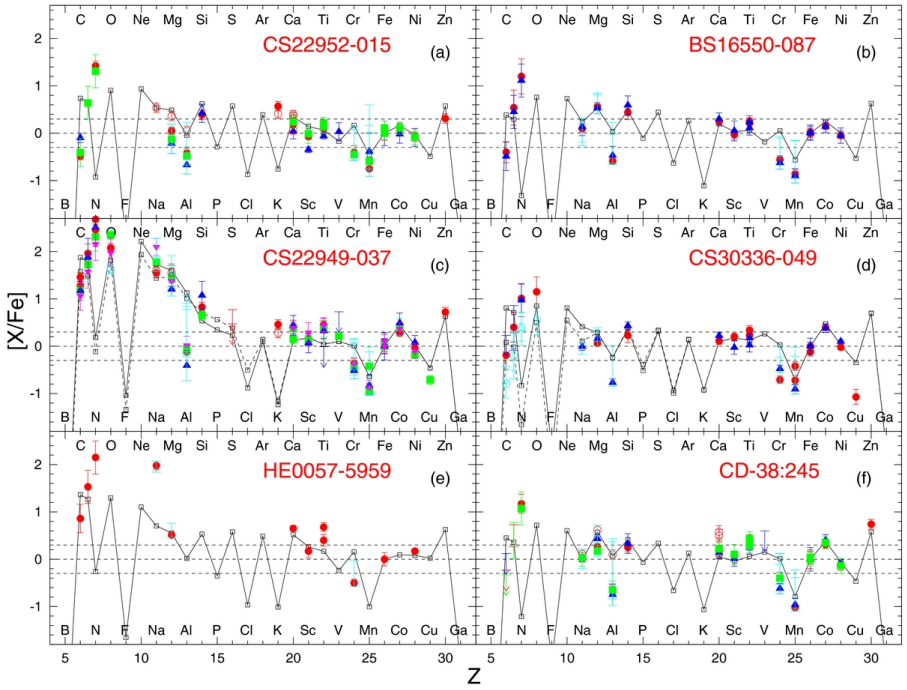
1) Stars with low Fe abundance

2) Stars in dwarf spheroidal galaxies

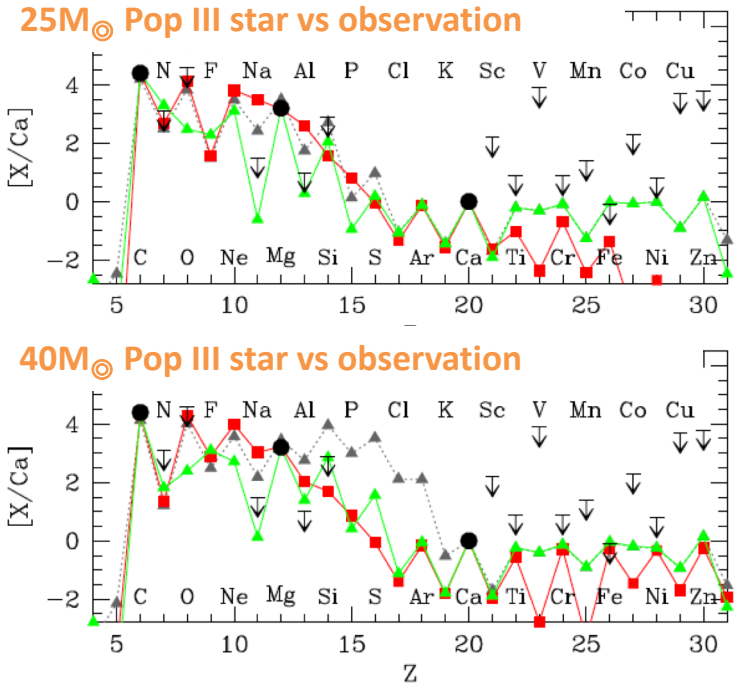
3) Old stars in the Milky Way halo

1) Stars with low Fe abundance

➡ Natural candidate of stars formed out of gas enriched with only a few (Pop III) supernovae



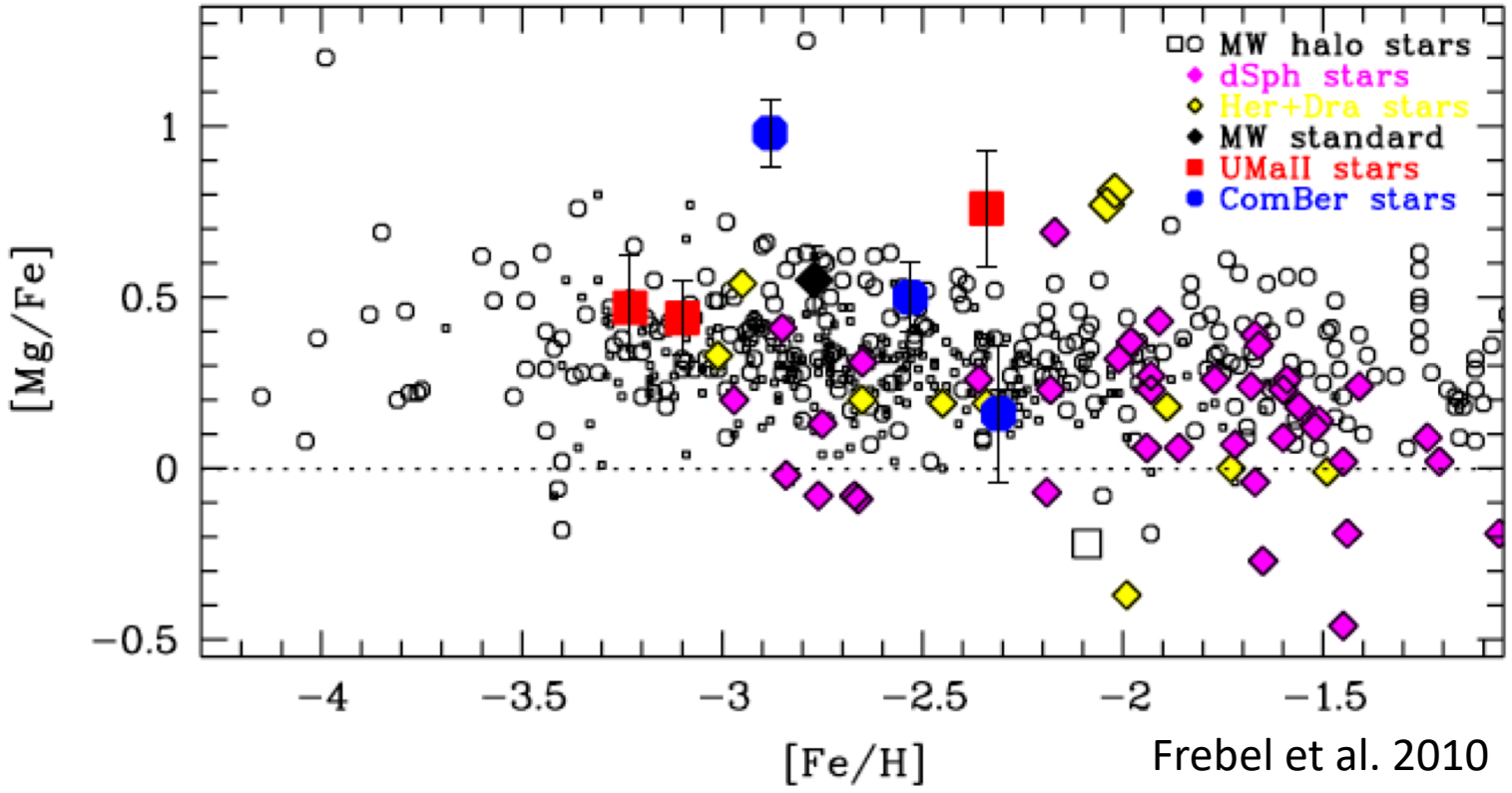
Stars with [Fe/H]<-3.5
(Tominaga et al. 2014)



SMSS 0313-6708
(Ishigaki et al. 2014)

2) Stars in dwarf spheroidal galaxies

Birth environments of individual stars are better constrained

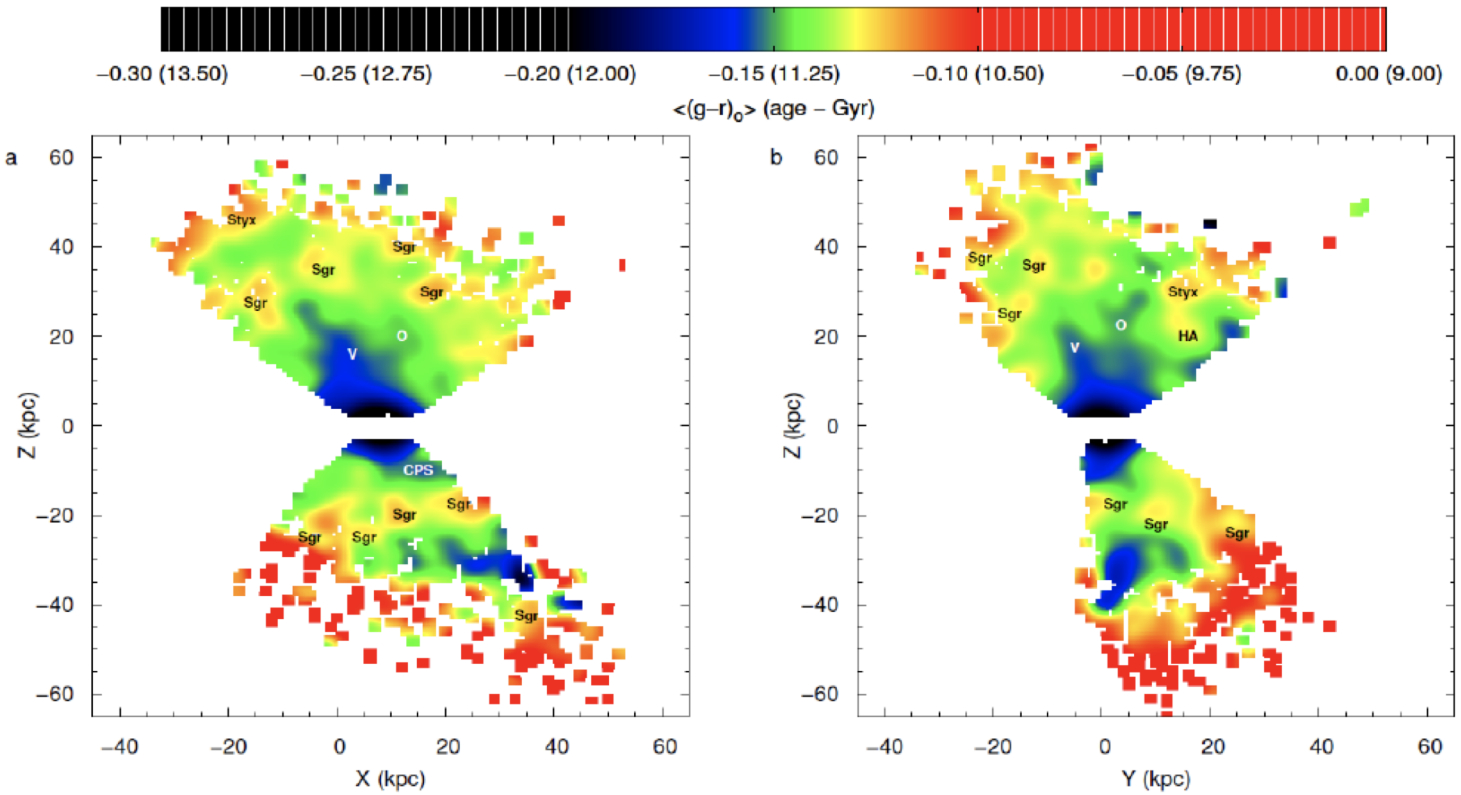


Frebel et al. 2010

Large scatter in elemental abundance ratios

3) Old stars in the halo

Stars NOT selected by [Fe/H] but with *kinematics and age*



"The age structure of the Milky Way halo" based on BHB (Carollo et al. 2017)

Gaia enables improved age estimation for a larger number of stars

Which stellar samples best traces the Pop III masses?

In this study

1) Stars with low Fe abundance

   ~200 extremely metal-poor stars ([Fe/H]<-3; Ishigaki+18)

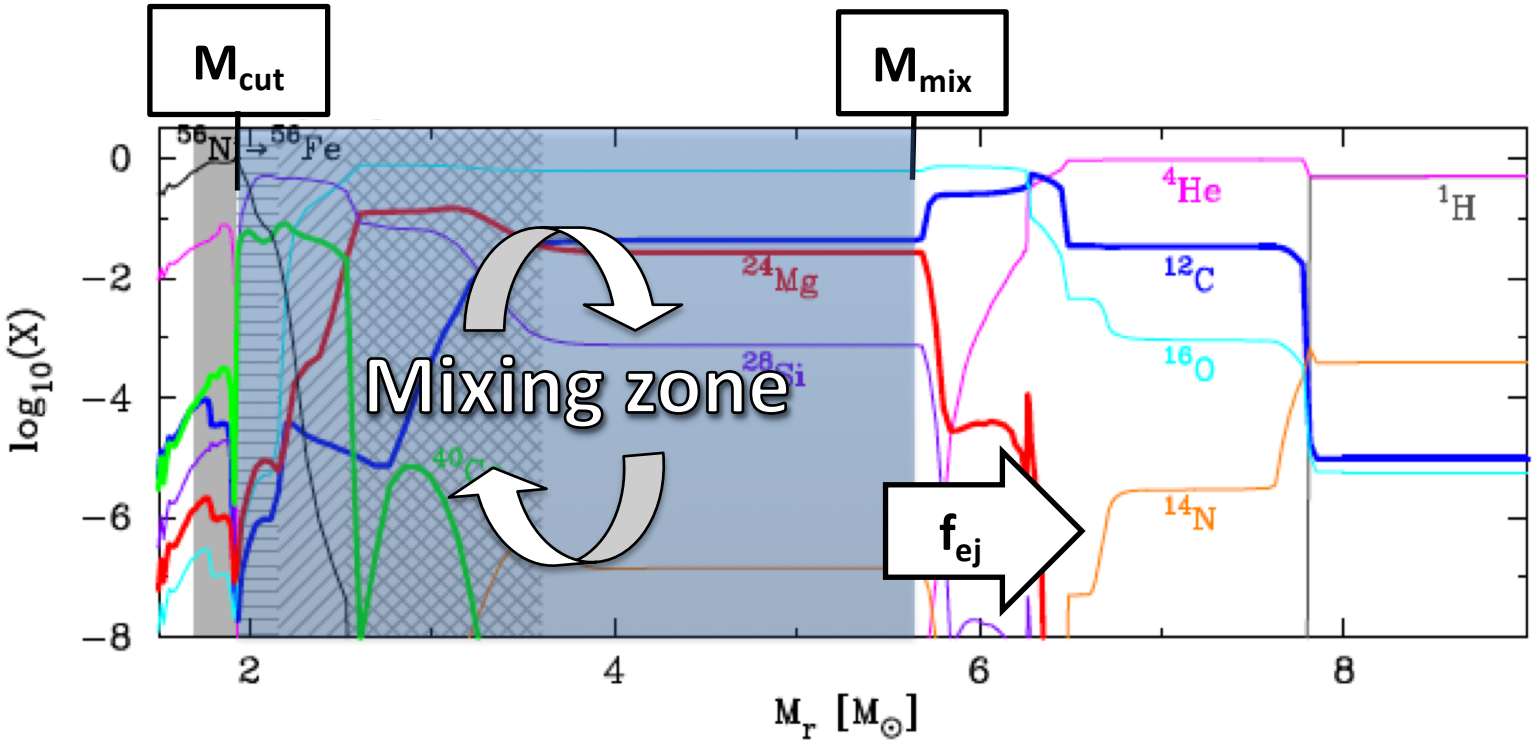
2) Stars in dwarf spheroidal galaxies

   5 stars in Sculptor dSph with [Fe/H]<-3 (Simon et al. 2015)

3) Old stars in the Milky Way halo

   Stars selected based on Gaia DR2 kinematics and age (Sanders and Das 2018)

The mixing-fallback model



e.g. Umeda & Nomoto 2002, 2003, Tominaga et al. 2007

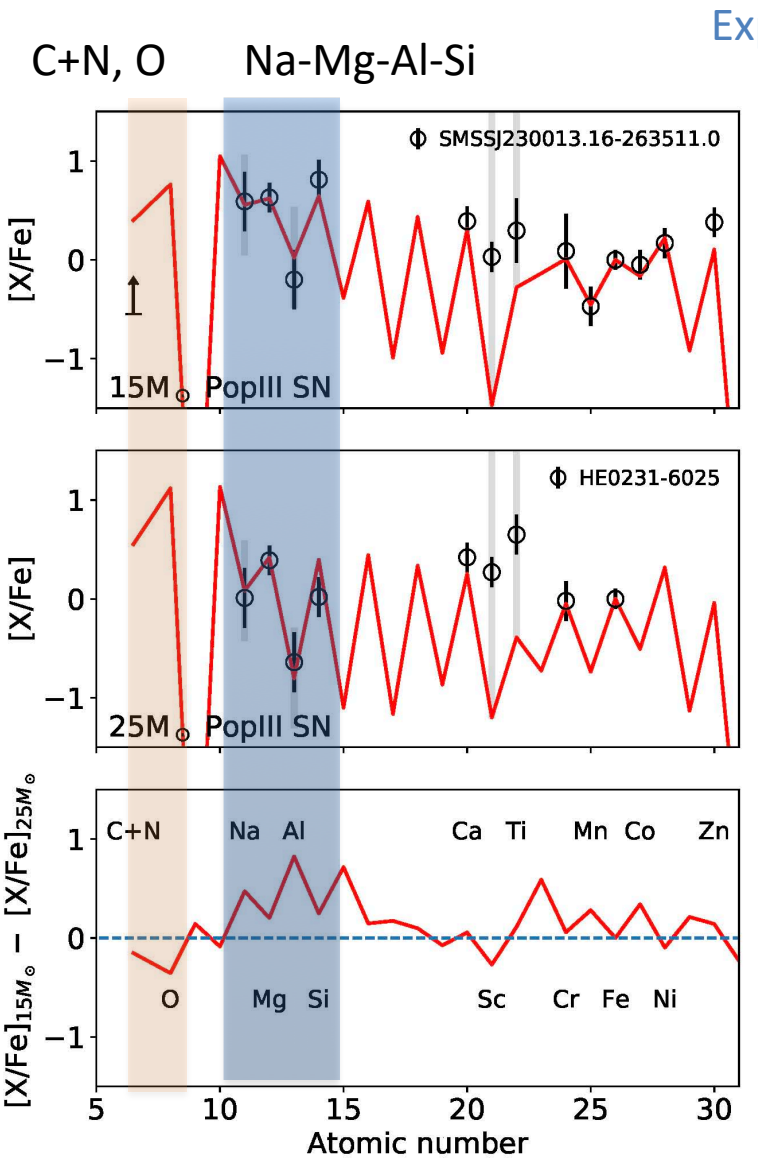
- M_{cut}: Inner boundary of the mixing zone
- M_{mix}: Outer boundary of the mixing zone
- f_{ej}: ejected fraction (fraction of mass ejected in the mixing zone)

The grid of supernova yields

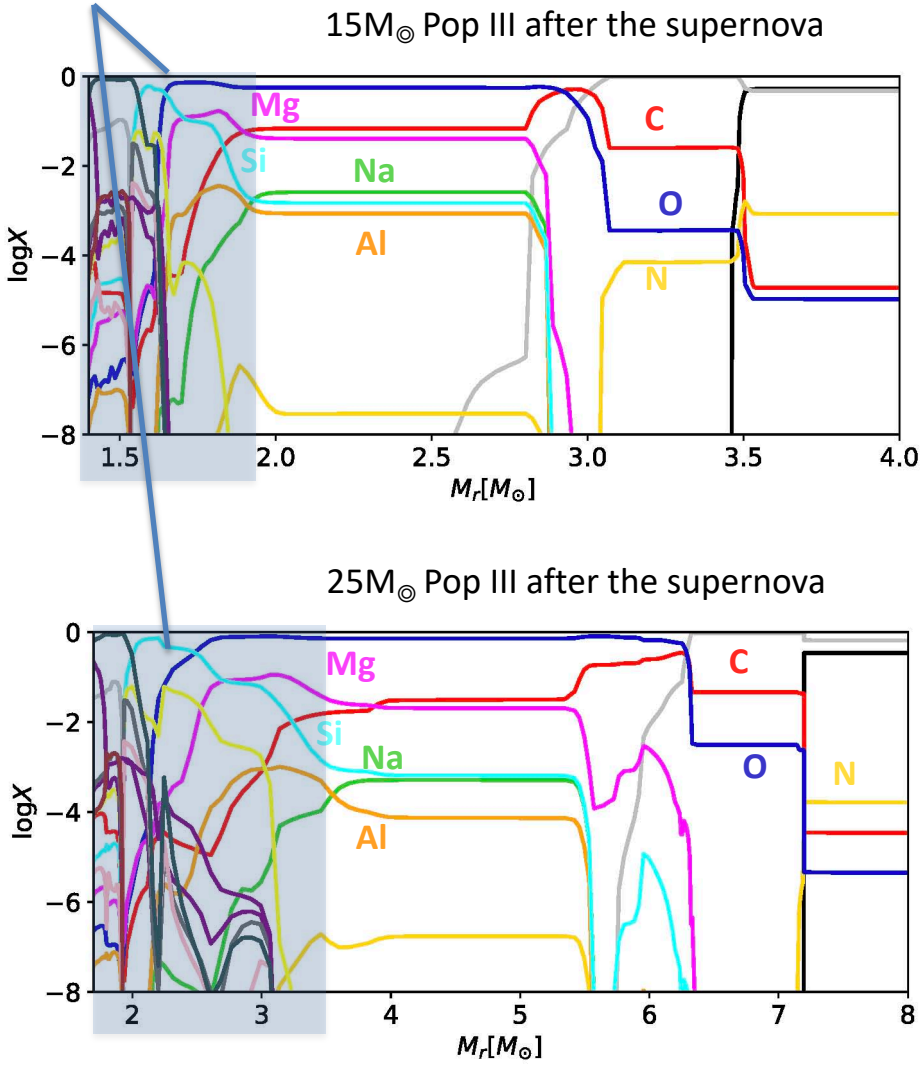
Model ID	Mass [$M_\odot$]	Explosion energy* [10^{51} erg]	M_{cut}	M_{mix} range	log(f_{ej}) range
13LE	13	0.5	1.47	1.47-3.30	-7 - 0
13SN	13	1	1.47	1.47-3.30	-7 - 0
15SN	15	1	1.41	1.41-4.64	-7 - 0
25SN	25	1	1.69	1.69-10.90	-7 - 0
25HN	25	10	1.69	1.69-10.90	-7 - 0
40SN	40	1	2.42	2.42-25.36	-7 - 0
40HN	40	30	2.42	2.42-25.36	-7 - 0
100SN	100	1	3.63	3.63-80.37	-7 - 0
100HN	100	60	3.63	3.63-80.37	-7 - 0

*Low-energy explosion (LE): 0.5 [10^{51} erg], Supernova (SN): 1 [10^{51} erg], Hypernova (HN): >1 [10^{51} erg]

Abundance ratios sensitive to the mass

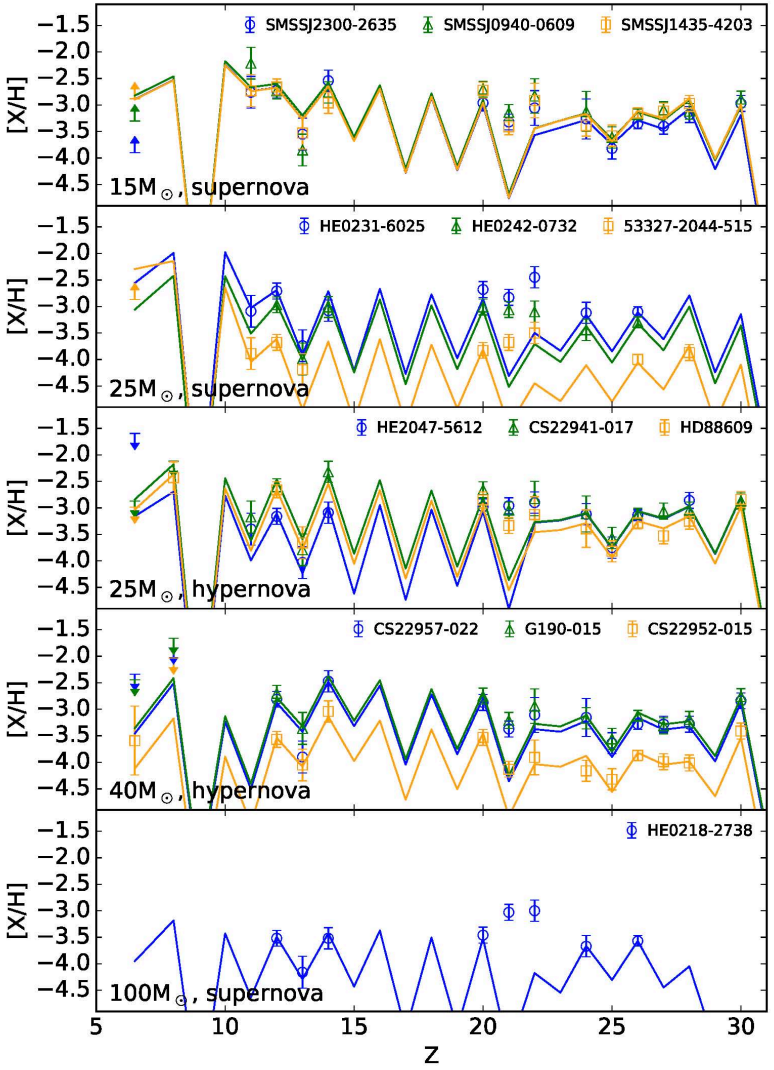


Explosive burning



Extremely metal-poor stars

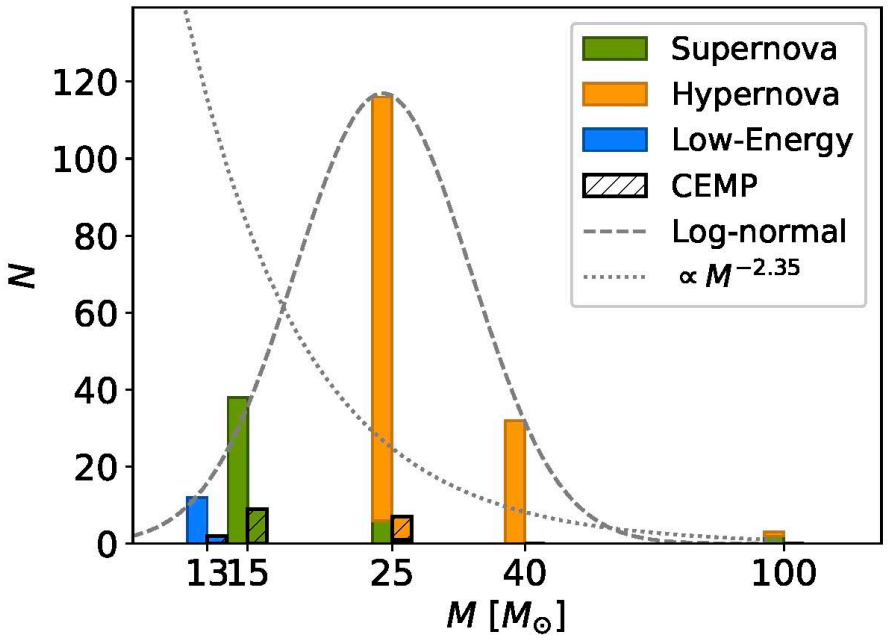
- Elemental abundance measurements for *~200 EMP stars* ([Fe/H]<-3) based on high-resolution spectroscopy available from recent literature (Yong et al. 2013; Cohen et al. 2013; Roederer et al. 2014; Jacobson et al. 2015; Hansen et al. 2014; Placco et al. 2015, 2016; Frebel et al. 2015; Melendez et al. 2016)
- Multiple abundance measurements (at least 7) of C, N, O, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Fe, Co, Ni, and Zn



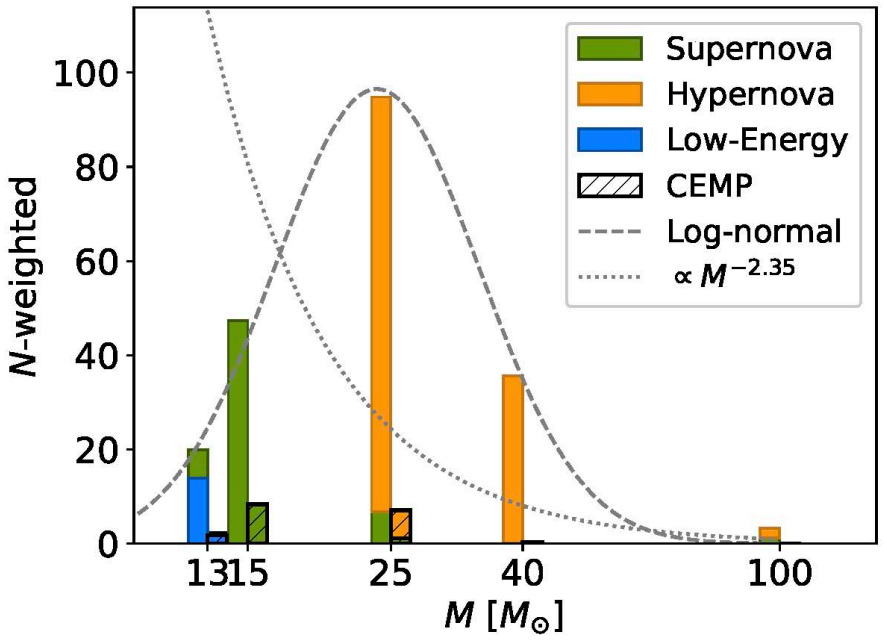
Ishigaki et al. 2018

Masses of the best-fit Pop III models

The best-fit models

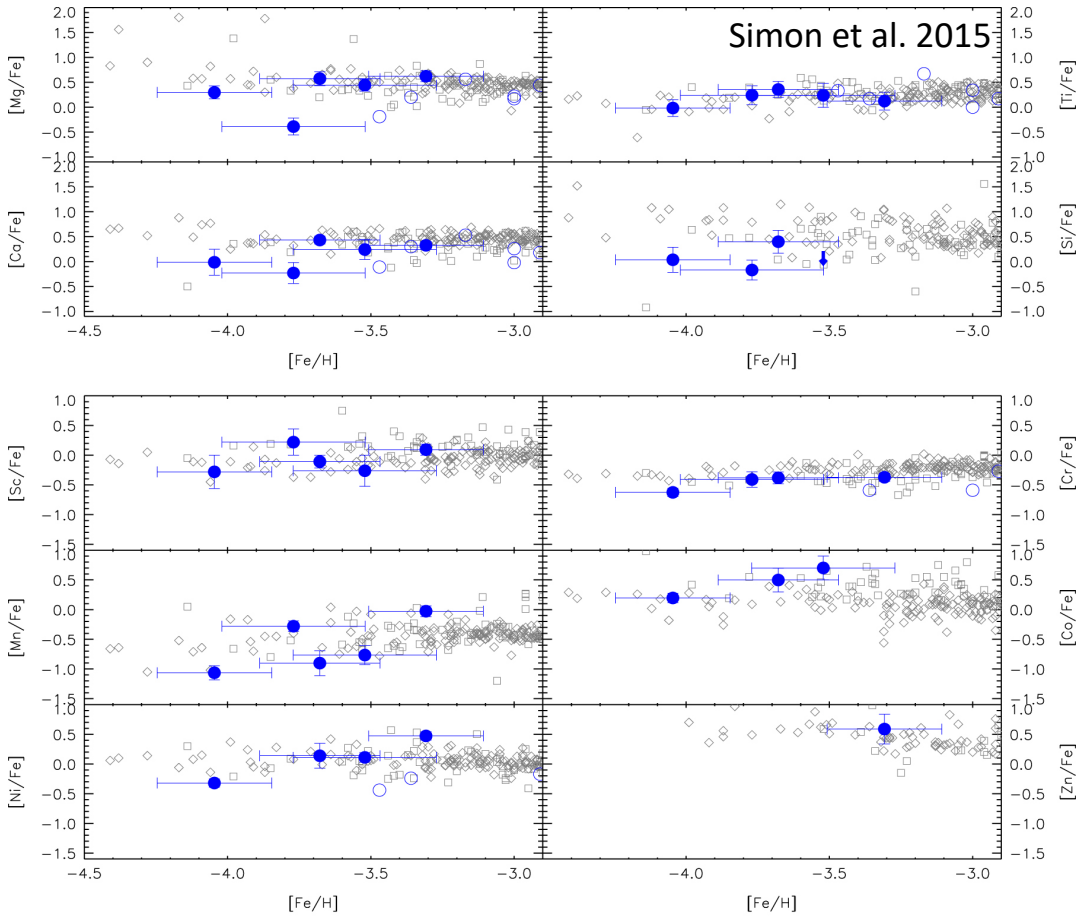


Counting also the non-best-fit models weighted according to χ^2



- Peaked at the Pop III models with M=25$M_\odot$
- ~ 80% of the EMP stars are best-fitted with the Pop III models with M<40$M_\odot$

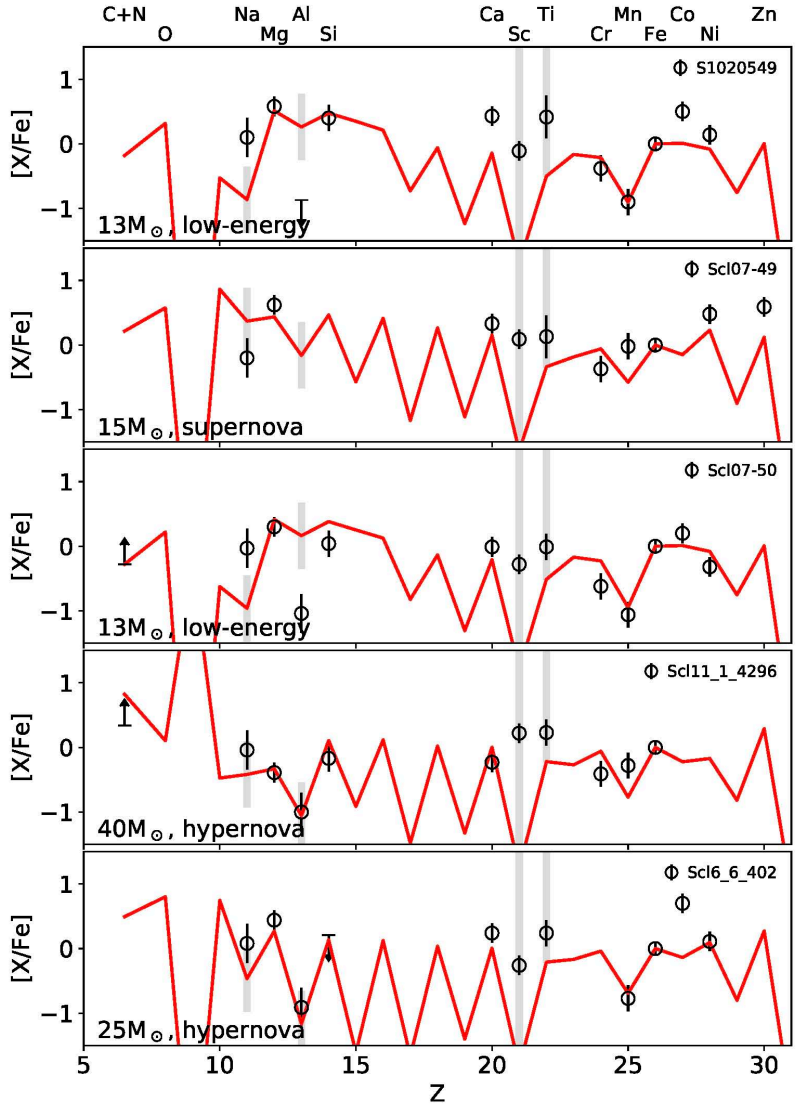
Metal-poor stars in Sculptor dSph



Large star-to-star scatter in elemental abundance ratios

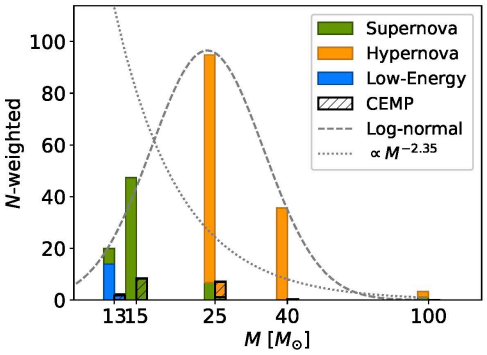
➡ Signature of stochastic enrichment

Abundance patterns



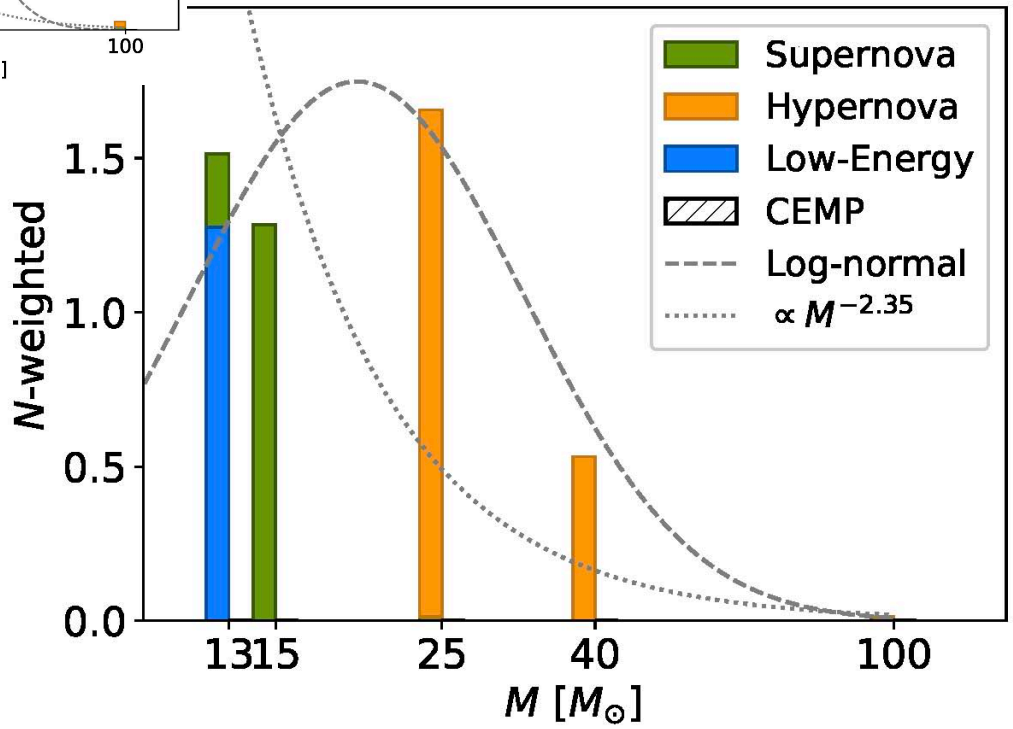
- Best-fit models range from 13-40M◎
- Some stars are not fitted well with the Pop III SN yield models

Masses of the best-fit Pop III models



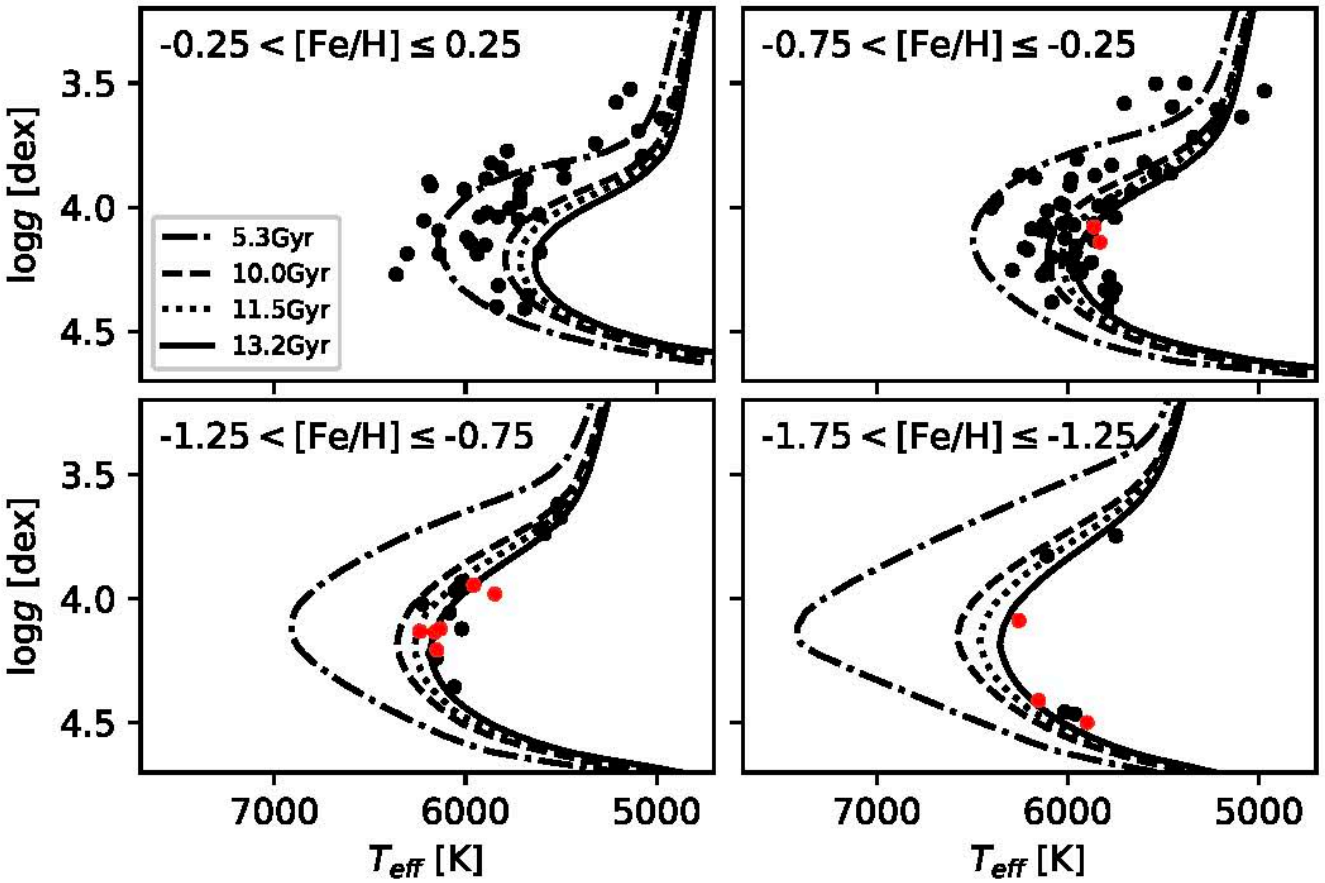
Extremely metal-poor stars

Sculptor dwarf spheroidal galaxy



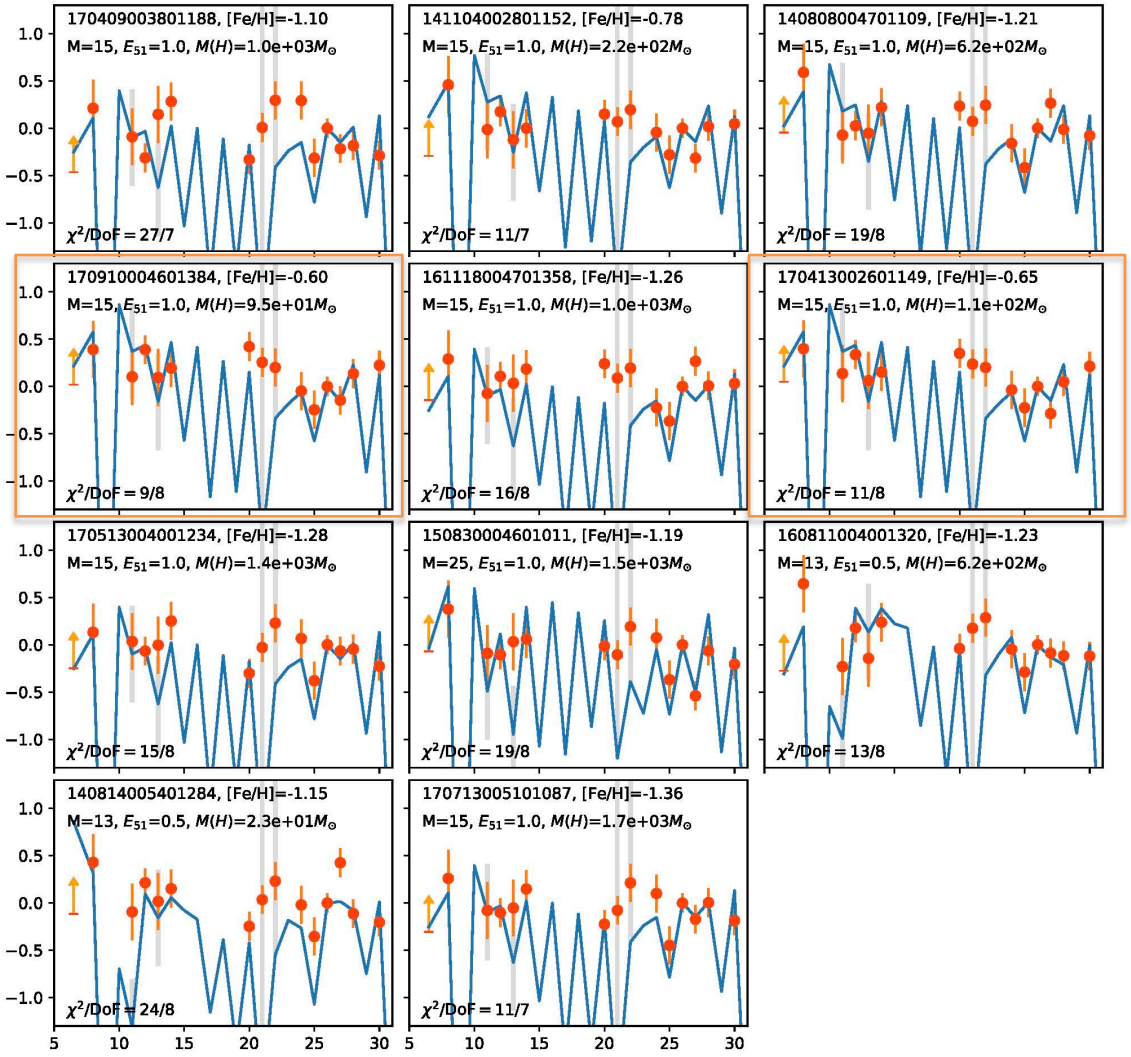
Old halo stars selection

Main sequence Turnoff (MSTO)stars with halo-like kinematics selected from Sanders & Das (2018) + GALAH DR2



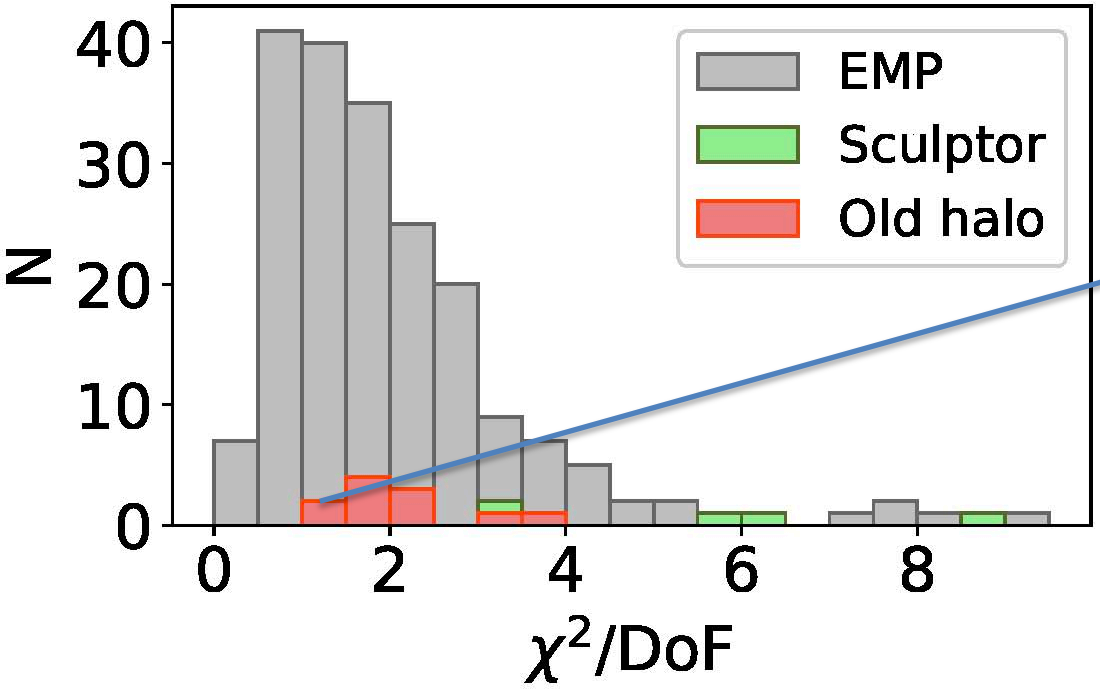
Red: 11 Stars with age greater than 12 Gyr, with relative age uncertainty < 50%, only modestly metal-poor (-1.8<[Fe/H]<-0.5)

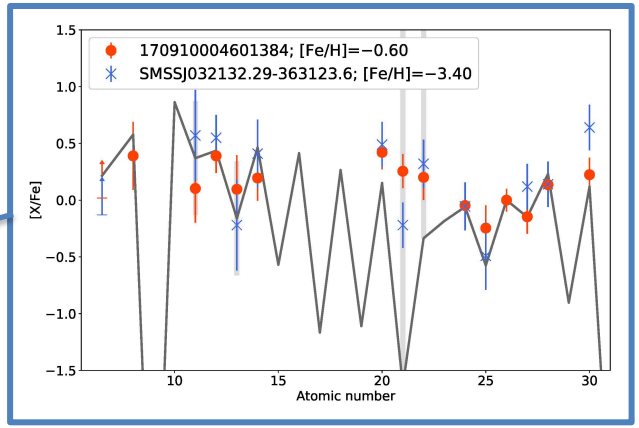
Abundance patterns



- χ^2/DoF : Larger than the EMP sample
- Fitting is as good as that of the EMP stars for a few [Fe/H]>-1 stars

χ^2/DoF distribution





- The Sculptor sample have much larger χ^2/DoF compared to the EMP
- The old halo sample have slightly larger χ^2 /DoF compared to the EMP

Summary

- We fit Pop III supernova yield models to the three different sample of stars to evaluate their relative similarity to the yield models.
  - EMP stars with [Fe/H]<-3
  - 5 stars in Sculptor dSph
  - 11 stars selected according to kinematics and age
- Stars in Sculptor show the largest χ^2/DoF on average
- Some of the old but only modestly metal-poor stars show abundance patterns fitted with Pop III yields, similar to some of the EMP stars with [Fe/H]<-3