2015.1. 19
東北大学

銀河系の金属欠乏星探査と初代星

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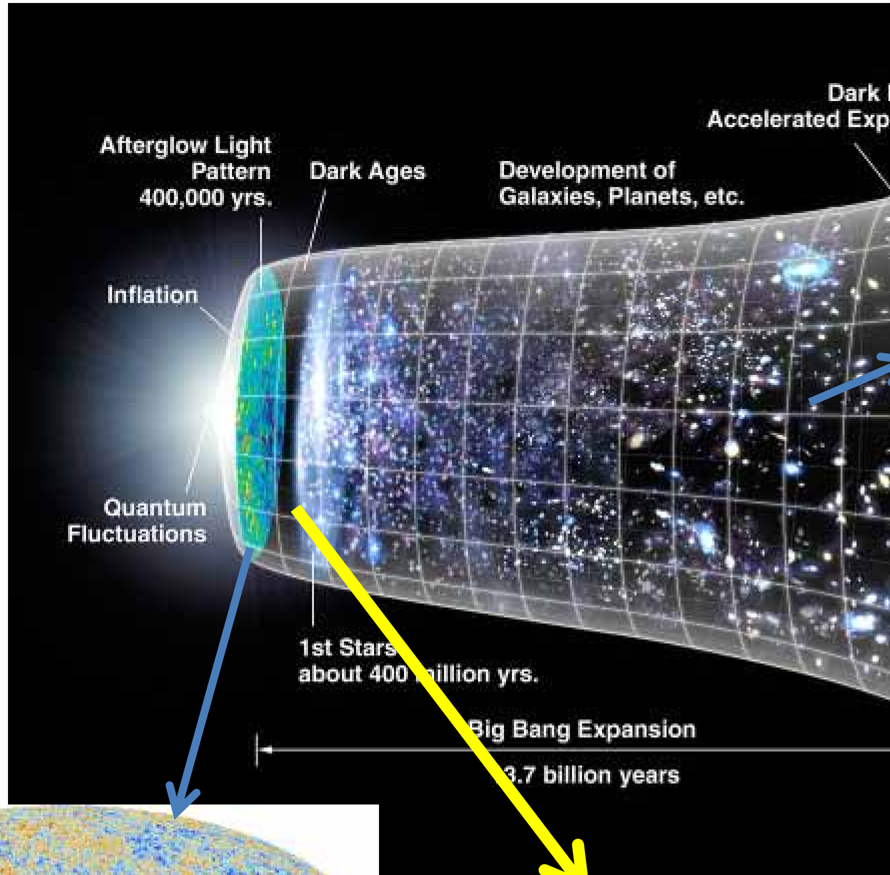
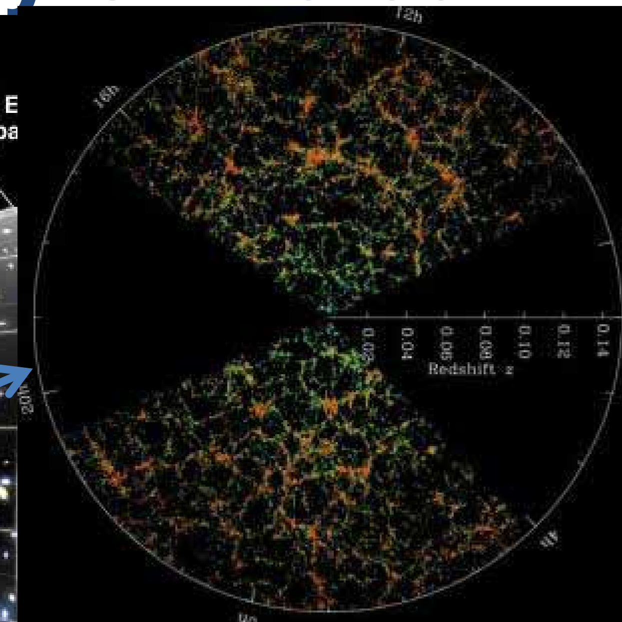
Mass distribution of first stars

- First stars as the first step of structure formation and chemical evolution
- Mass and the fate of first stars
- Constraints from chemical abundances of metal-poor stars
- Signature of very massive stars
- Future prospects

Structure formation and chemical enrichment in the early Universe





SDSS

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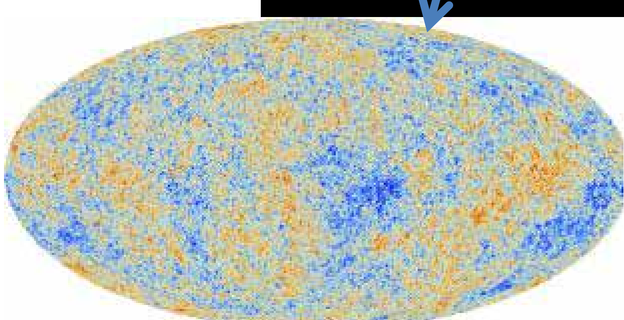
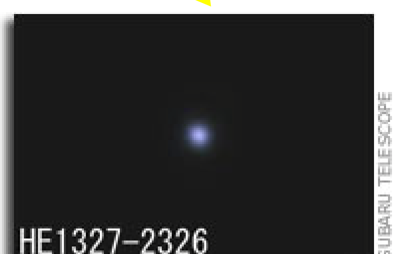


Planck/ESA



Low-mass stars with long lifetime can survive

Early generation stars in the Milky Way ... old and metal-poor stars

Halo structure

Globular clusters

Dwarf galaxies

What can we learn from early generation stars?

- Nucleosynthesis of individual stars and supernovae

➡ examination of nucleosynthesis models

- Nature of first-generation stars

  -no metal

  -mass distribution?

  -other characteristics (rotation, binarity, etc.)?

- Galaxy formation
  - From first-generation stars to early galaxies

Mass distribution of first stars

- Very-massive stars (>140 Msun)

  -formation is expected from clouds with zero metallicity

  -pair-instability supernovae or formation of black-hole
- Massive stars (8-140Msun)

  -dominant in first-generation stars?

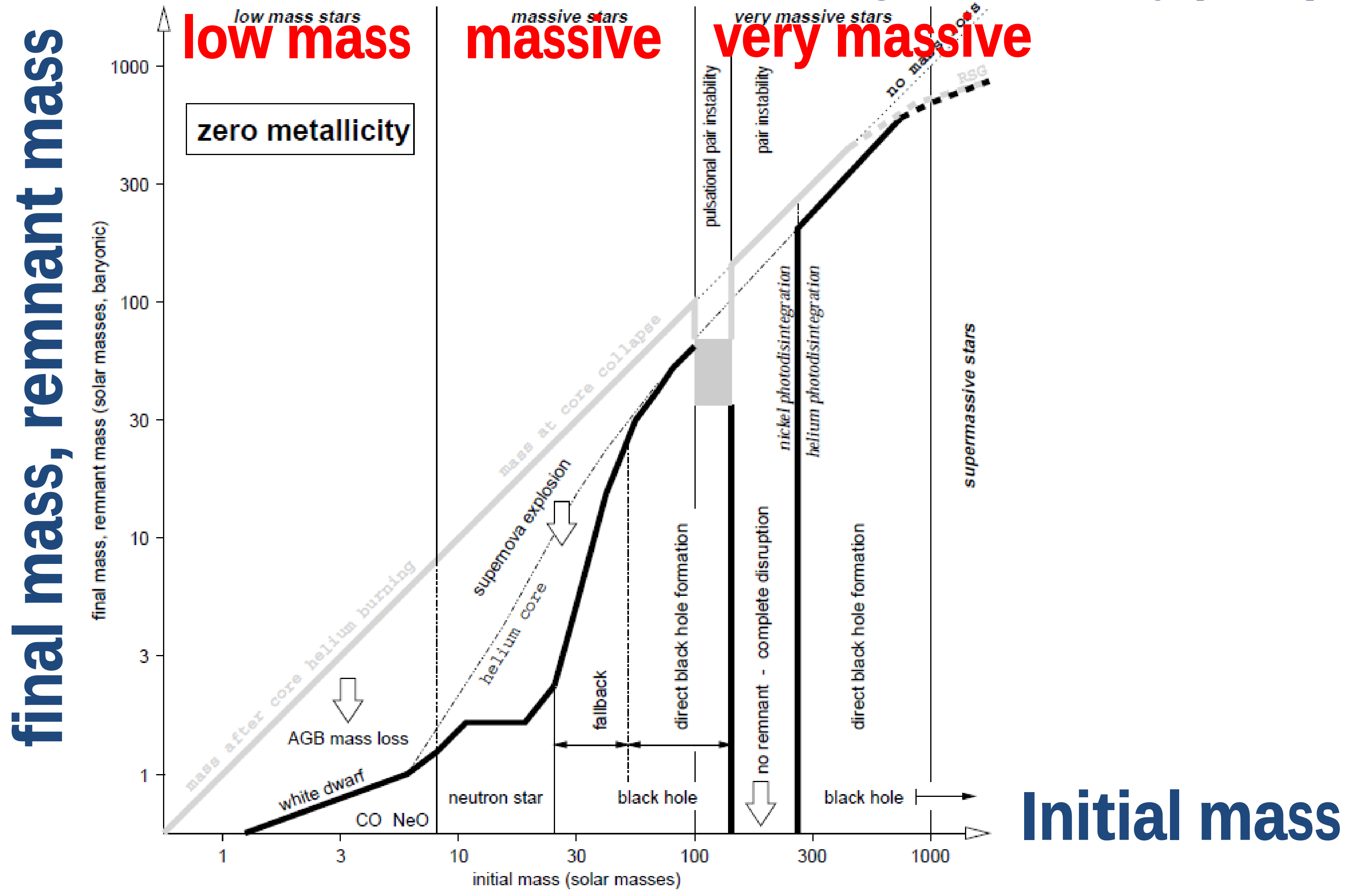
  -core-collapse supernovas forming black holes or neutron stars
- Low-mass stars (<8Msun)

  -not formed from clouds with zero metallicity?

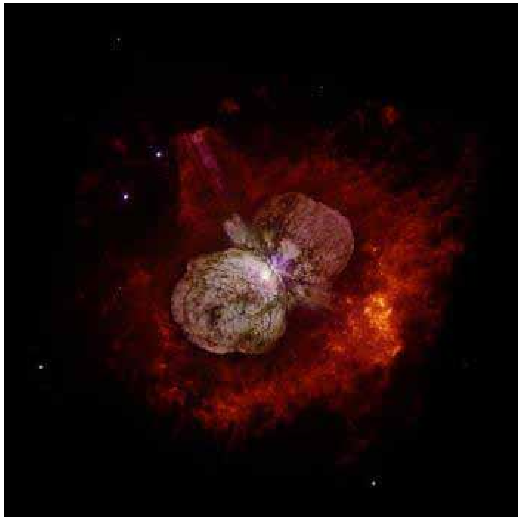
  -evolving to white dwarfs. Low-mass star with M<0.8Msun can be found in the current universe.

initial-final masses of primordial stars

Heger & Woosley (2002)



Candidates for very-massive stars in the current universe

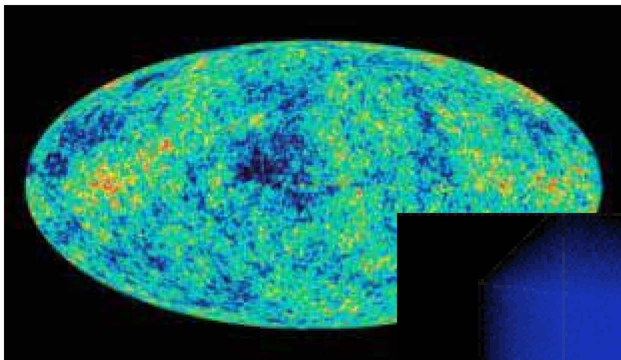


⇐eta Carina

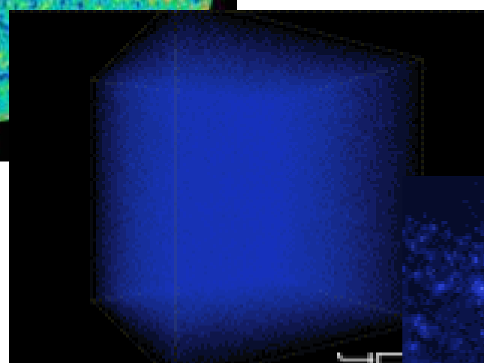
- One of the most massive stars in the Galaxy
- Nebulae by ejecta ... the star losing mass

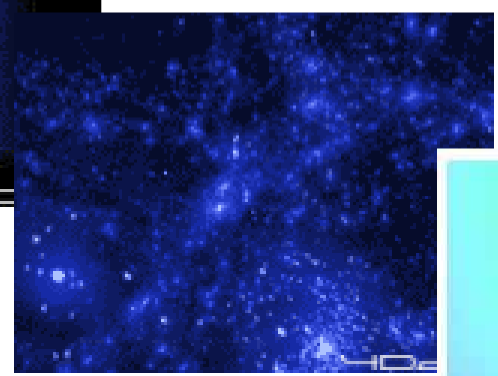
⇓stars with >150 solar masses in magellanic clouds

Numerical simulations of formation of first-generation stars

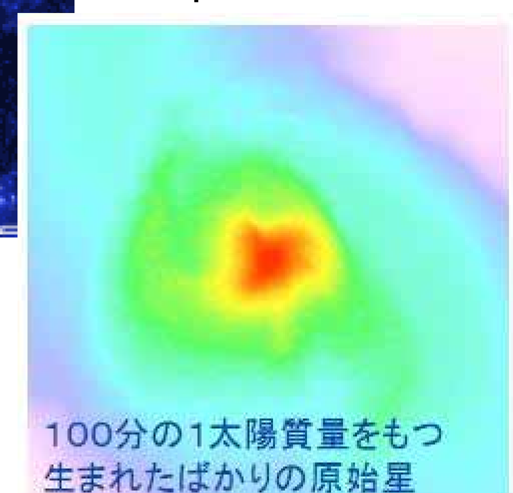


Structure formation





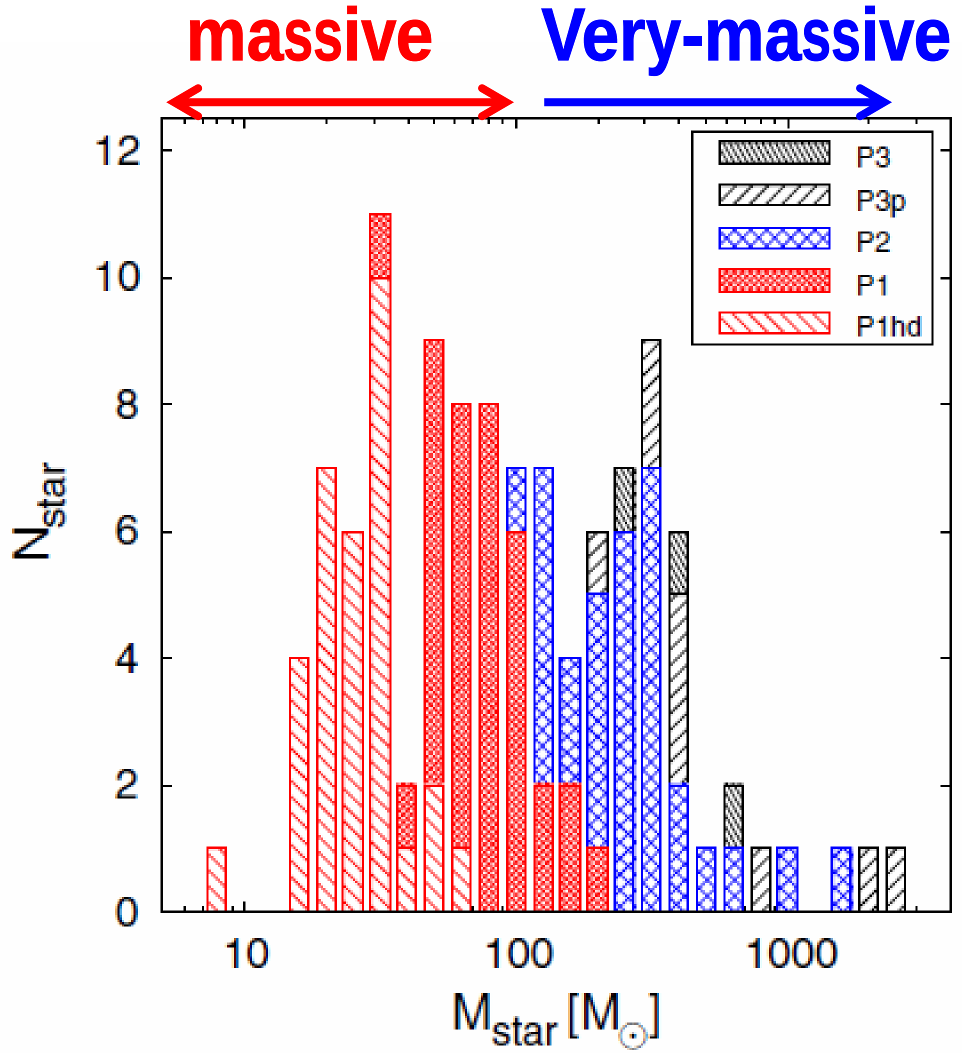
First proto-stars



200-300 Million years?

Mass distribution of first stars predicted by numerical simulations

Masses of first-generation stars
- Majority are massive stars
- some fraction of them are very-massive



Hirano et al. (2014, Astrophys. J. 781, 60)

Searches for metal-poor stars

cf. *Beers & Christlieb (2005, ARAA)*

- Bond (1981) "where is population III?"

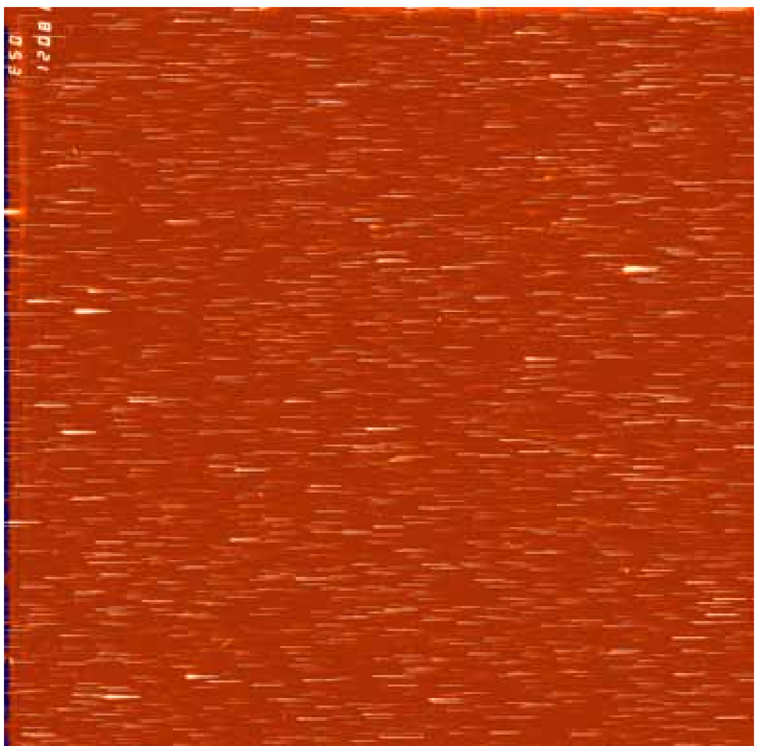
- HK survey (1980s-)
  Beers et al. 1985, 1992, etc.
  → e.g. BS12345-678, CS23456-789 ...

- Hamburg/ESO survey (1990s-)
  stellar content: *Christlieb et al. 2001* etc.
  → e.g. HE1234-5601

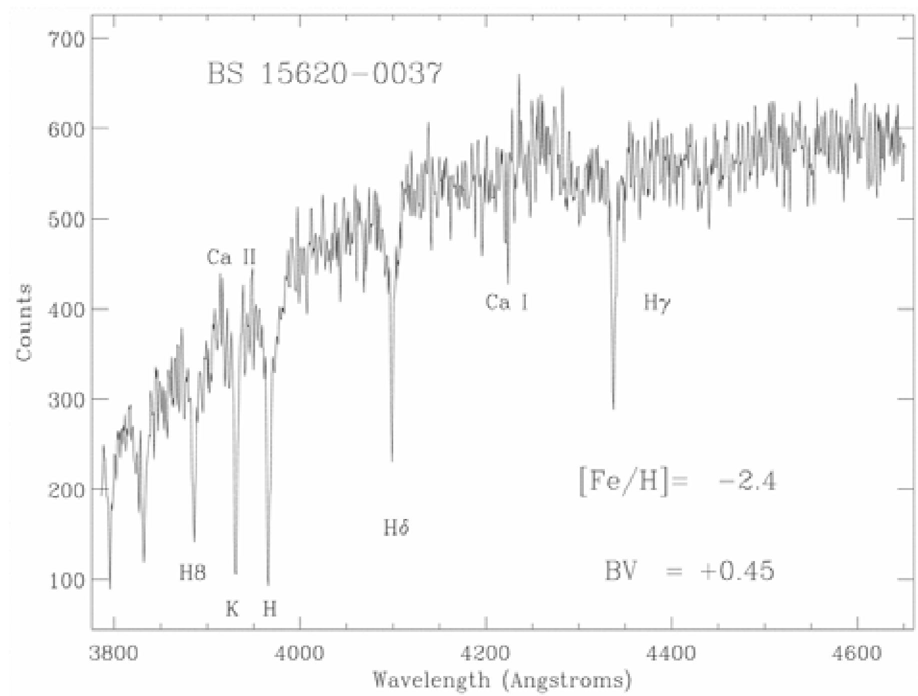
- SDSS/SEGUE (2006-)

Searches for early generation stars (metal-poor stars) in the Milky Way

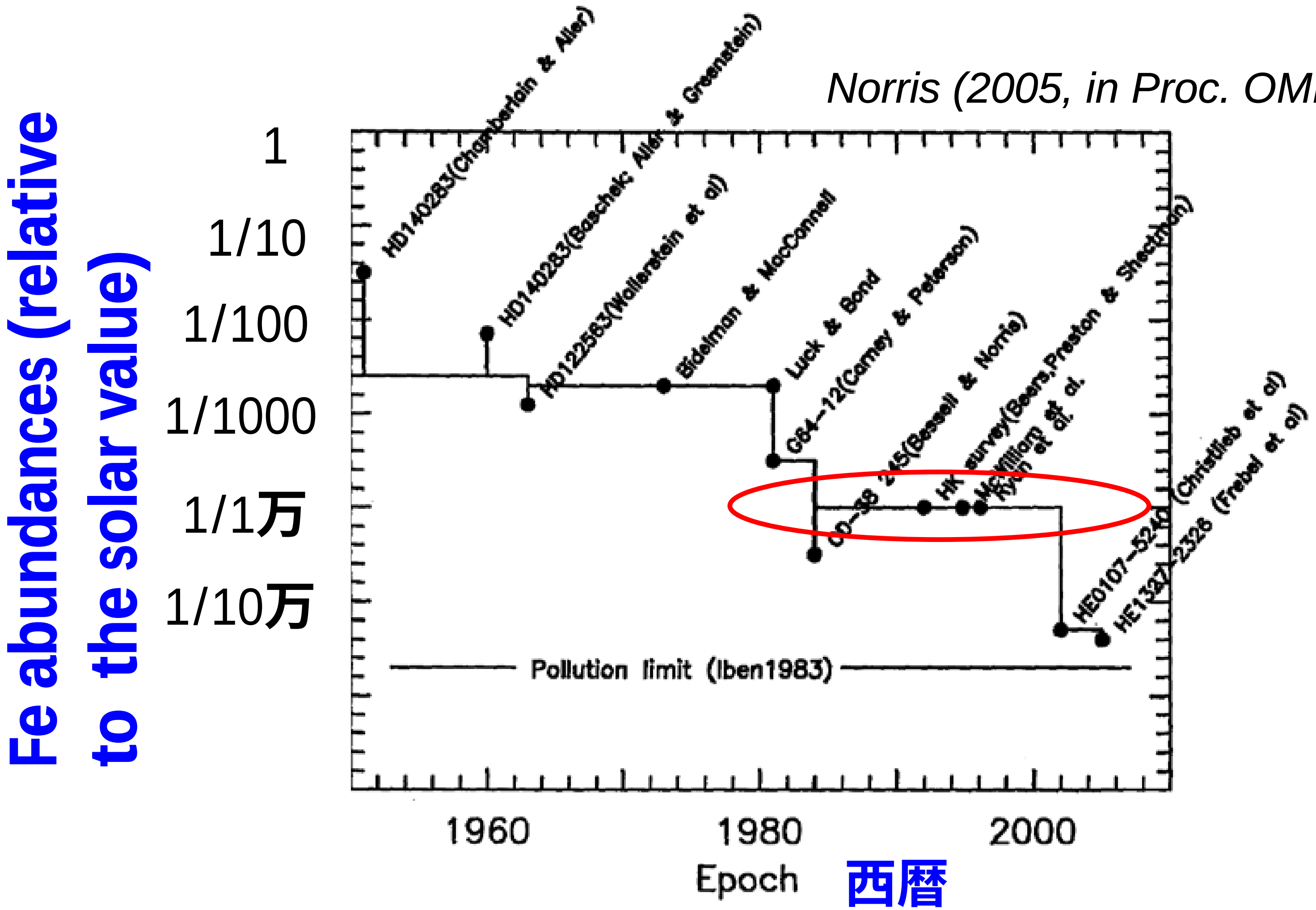
①wide-field spectroscopic survey



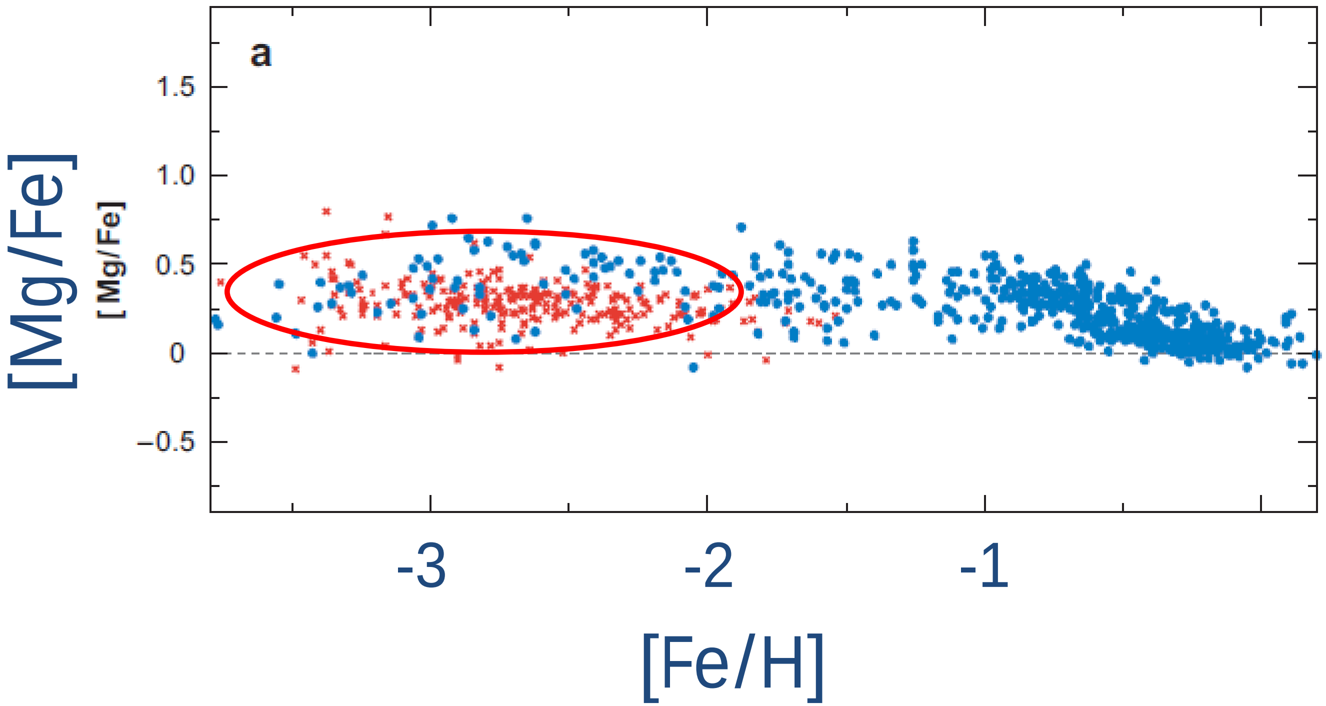
②follow-up medium resolution spectroscopy



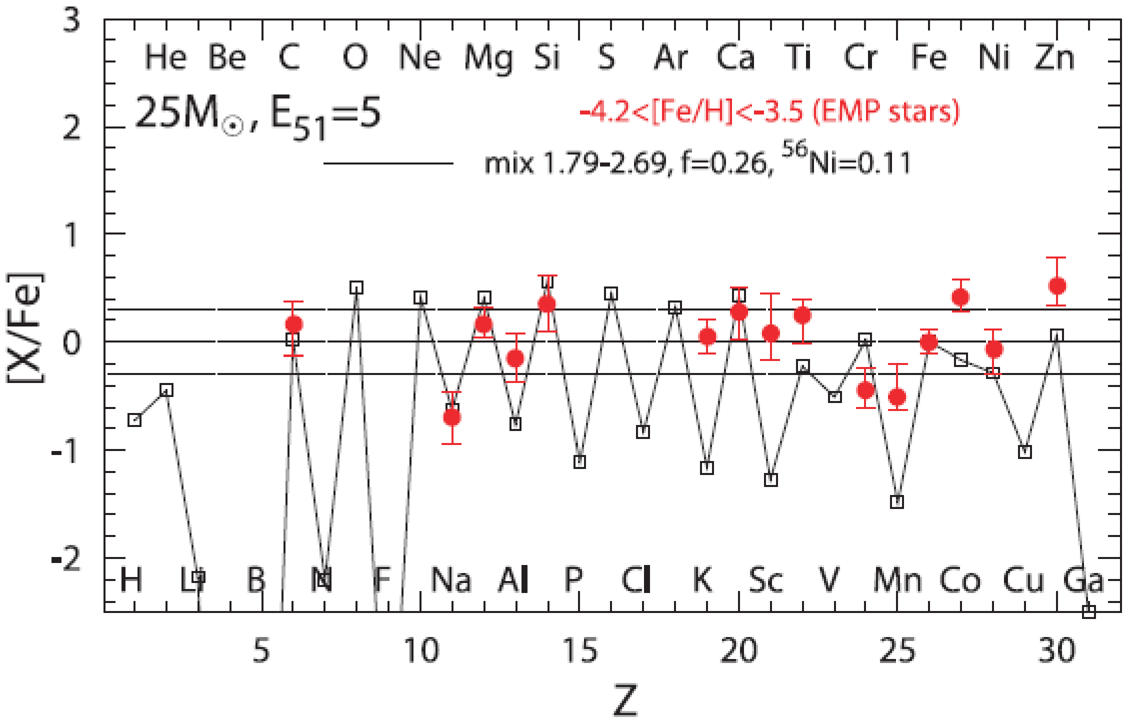
Progress of searches for most metal-poor stars



Extremely metal-poor stars with "normal" abundance pattern



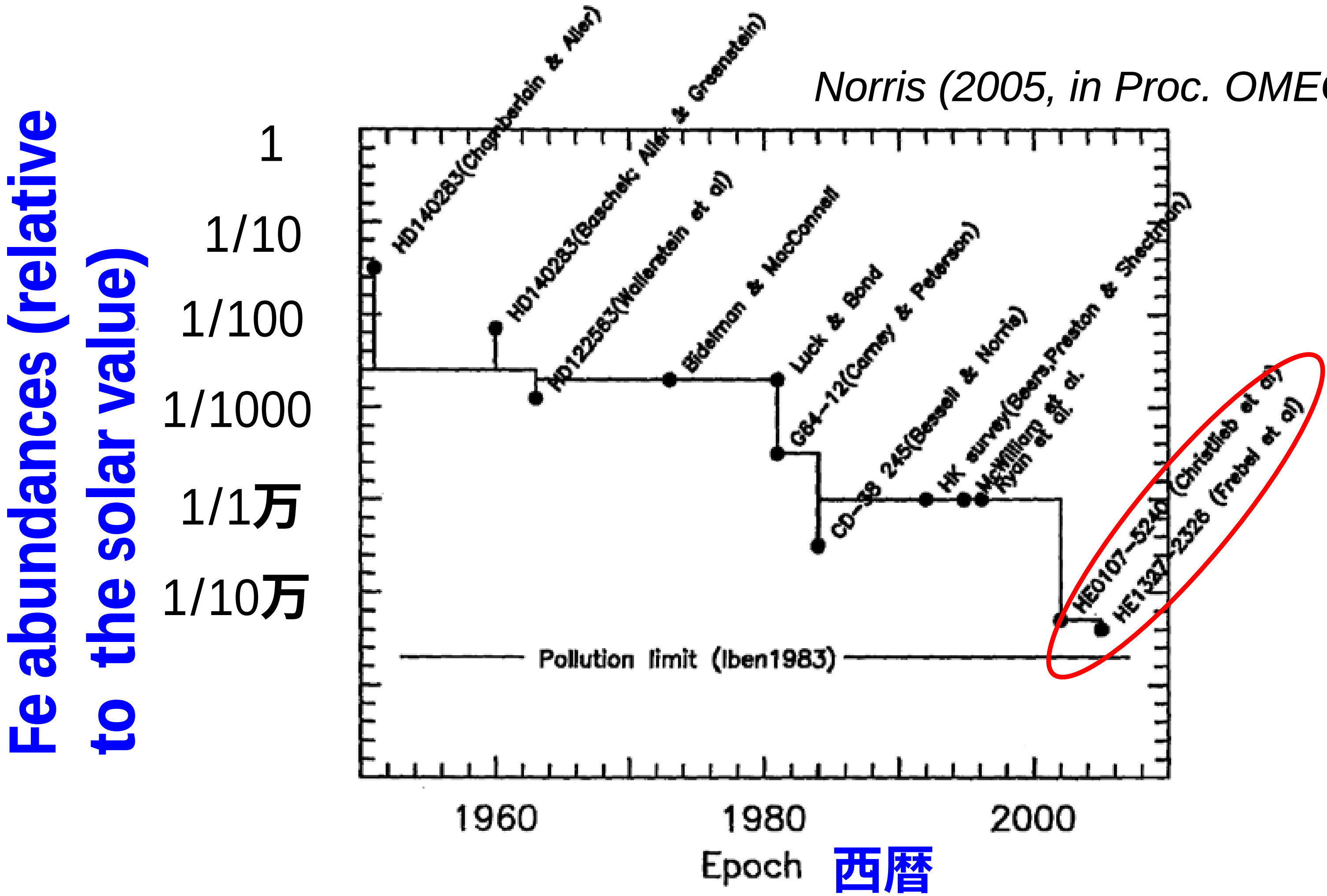
Extremely metal-poor stars with "normal" abundance pattern



Tominaga et al. (2007)

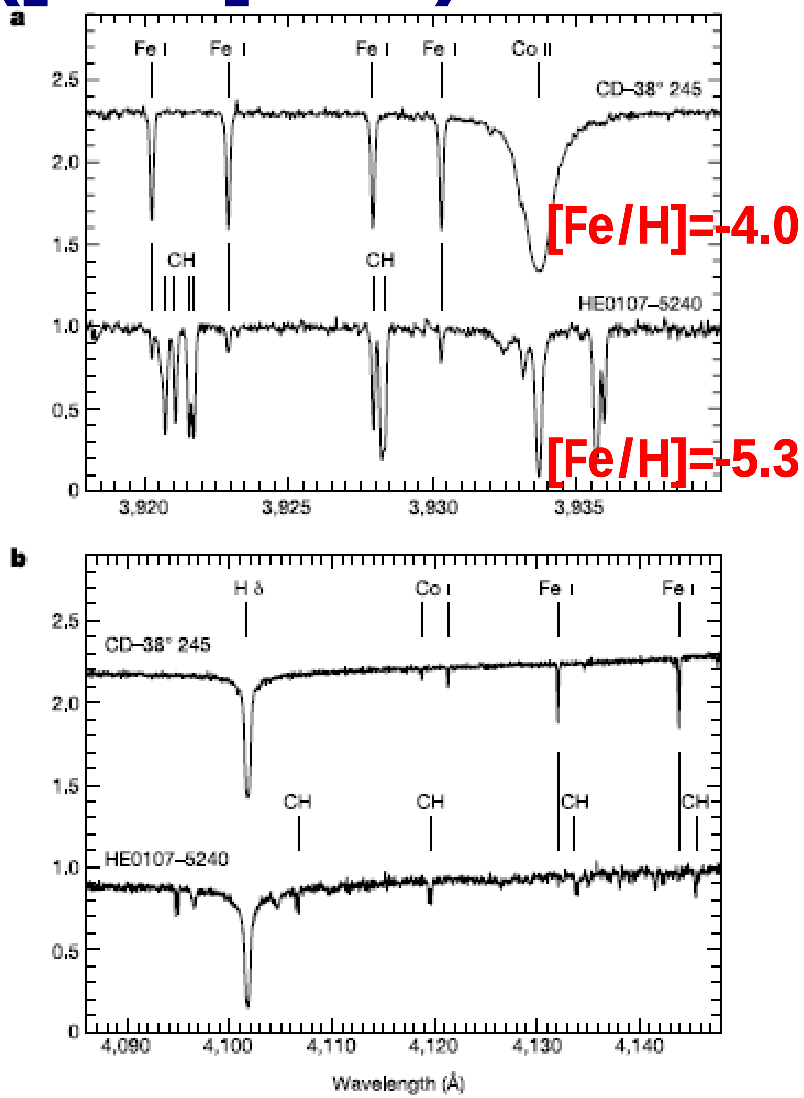
Progress of searches for most metal-poor stars

Norris (2005, in Proc. OMEG05)



Most metal-poor stars: discovery of HE0107-5240 ([Fe/H]=-5.3)

The first "Hyper Metal-Poor" (HMP) star
Christlieb et al. (2002)



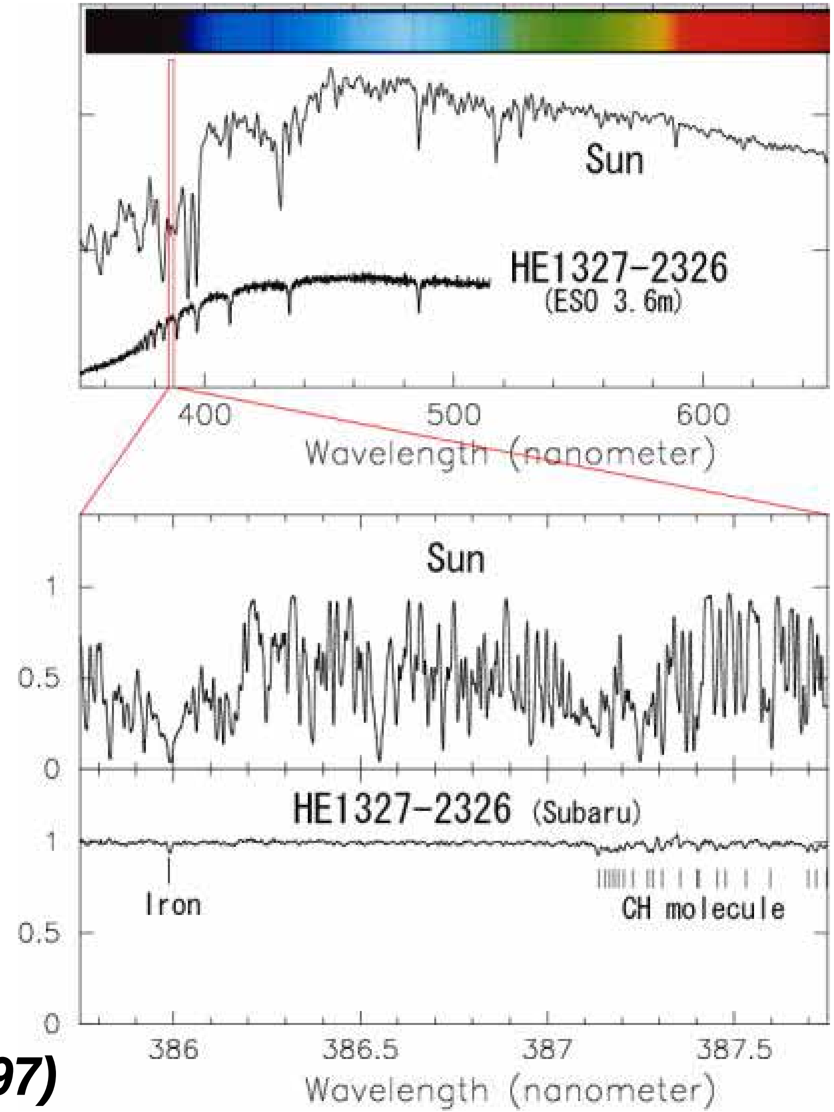
Beers & Christlieb (2005, ARAA)

TABLE 1 Nomenclature for stars of different metallicity

[Fe/H]	Term	Acronym
> +0.5	Super metal-rich	SMR
∼0.0	Solar	—
< −1.0	Metal-poor	MP
< −2.0	Very metal-poor	VMP
< −3.0	Extremely metal-poor	EMP
< −4.0	Ultra metal-poor	UMP
< −5.0	Hyper metal-poor	HMP
< −6.0	Mega metal-poor	MMP

"Ultra/Hyper Metal-Poor" stars found in the past 10 years

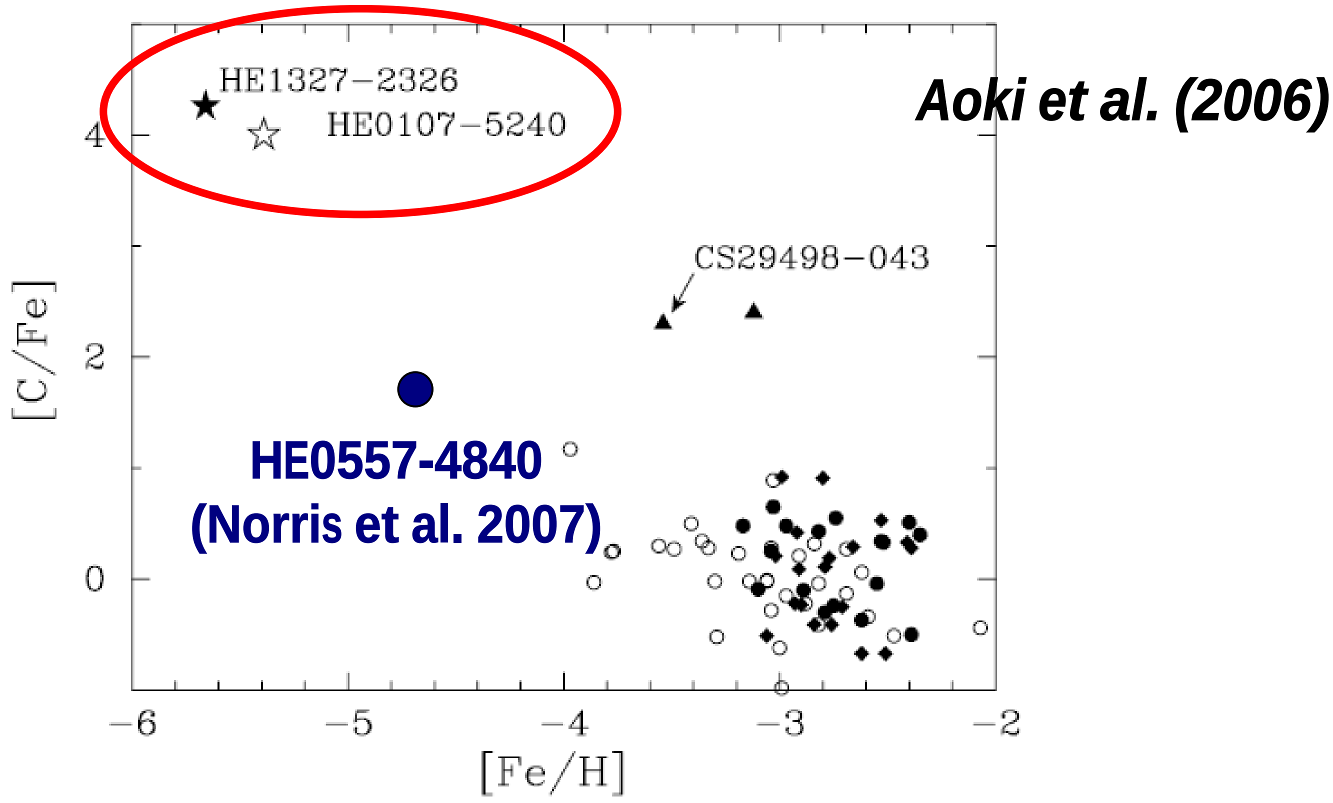
HE1327-2326 ([Fe/H]=-5.4)



Frebel et al. (2005, Nature, 434, 871)
Aoki et al. (2006, Astrophys. J. 639, 897)

Carbon-enhancement in HMP stars

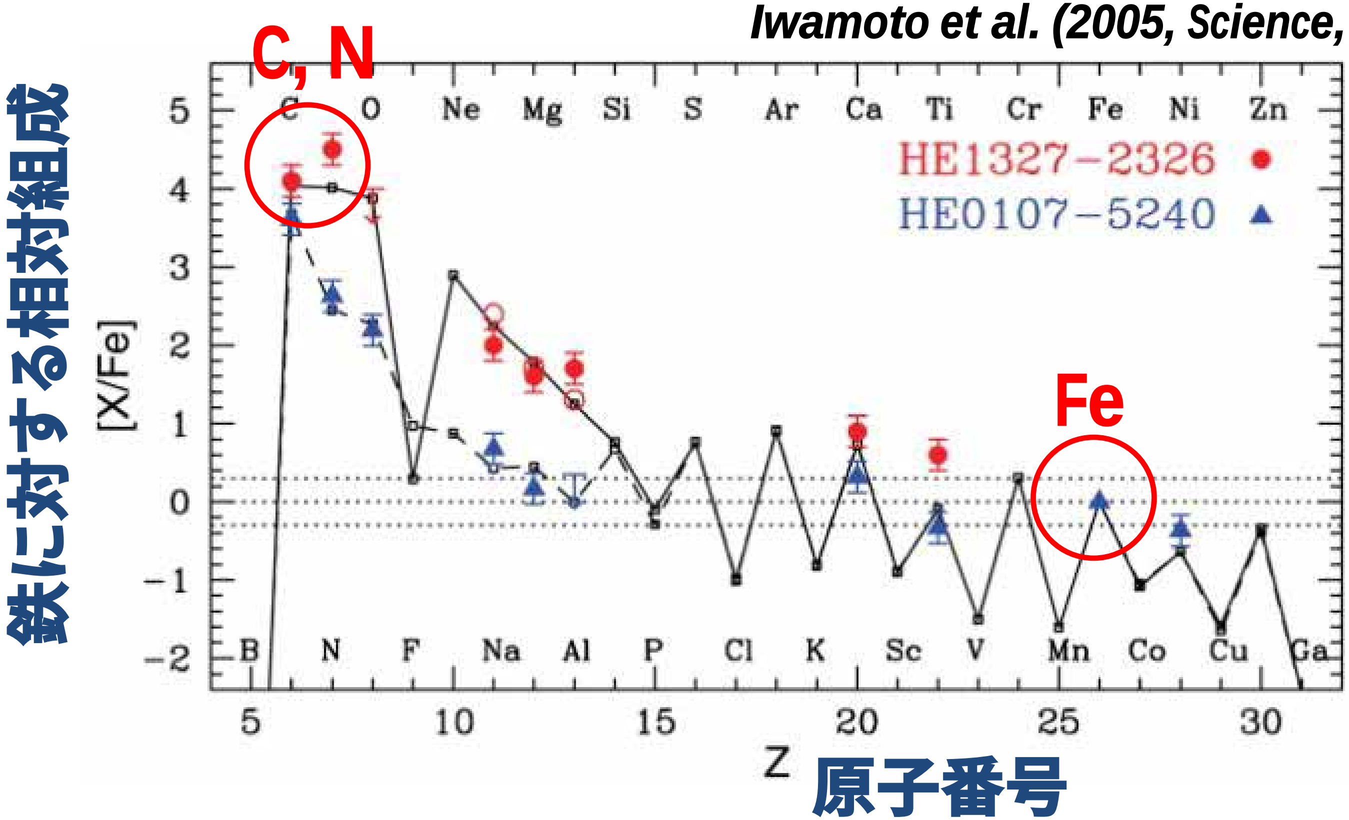
The two HMP stars show large excesses of C, (N) and O ... low-mass star formation from C and O-rich cloud?



Chemical abundance patterns of "Hyper Metal-Poor" stars

- [Fe/H]=-5.4, [C, N/Fe]>〜+4
- Faint supernova origin?

Iwamoto et al. (2005, Science, 309, 451)

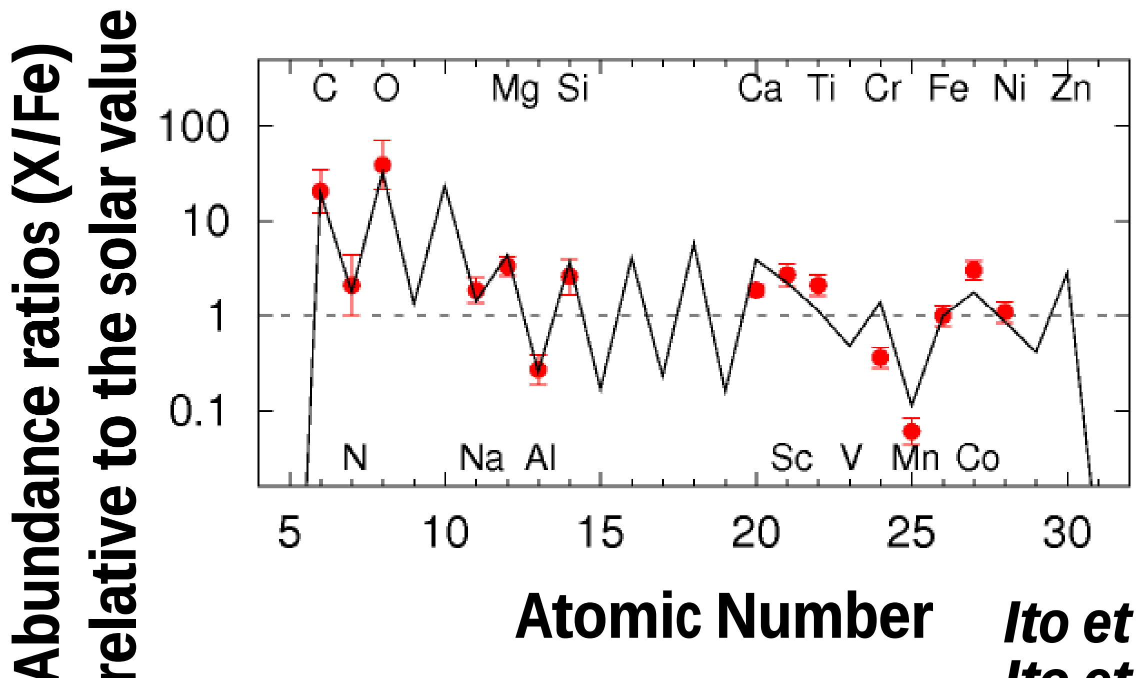


The carbon-enhanced star BD+44 493

Carbon-enhanced EMP star BD+44 493 ([Fe/H]=-3.7): another evidence for "faint supernovae"

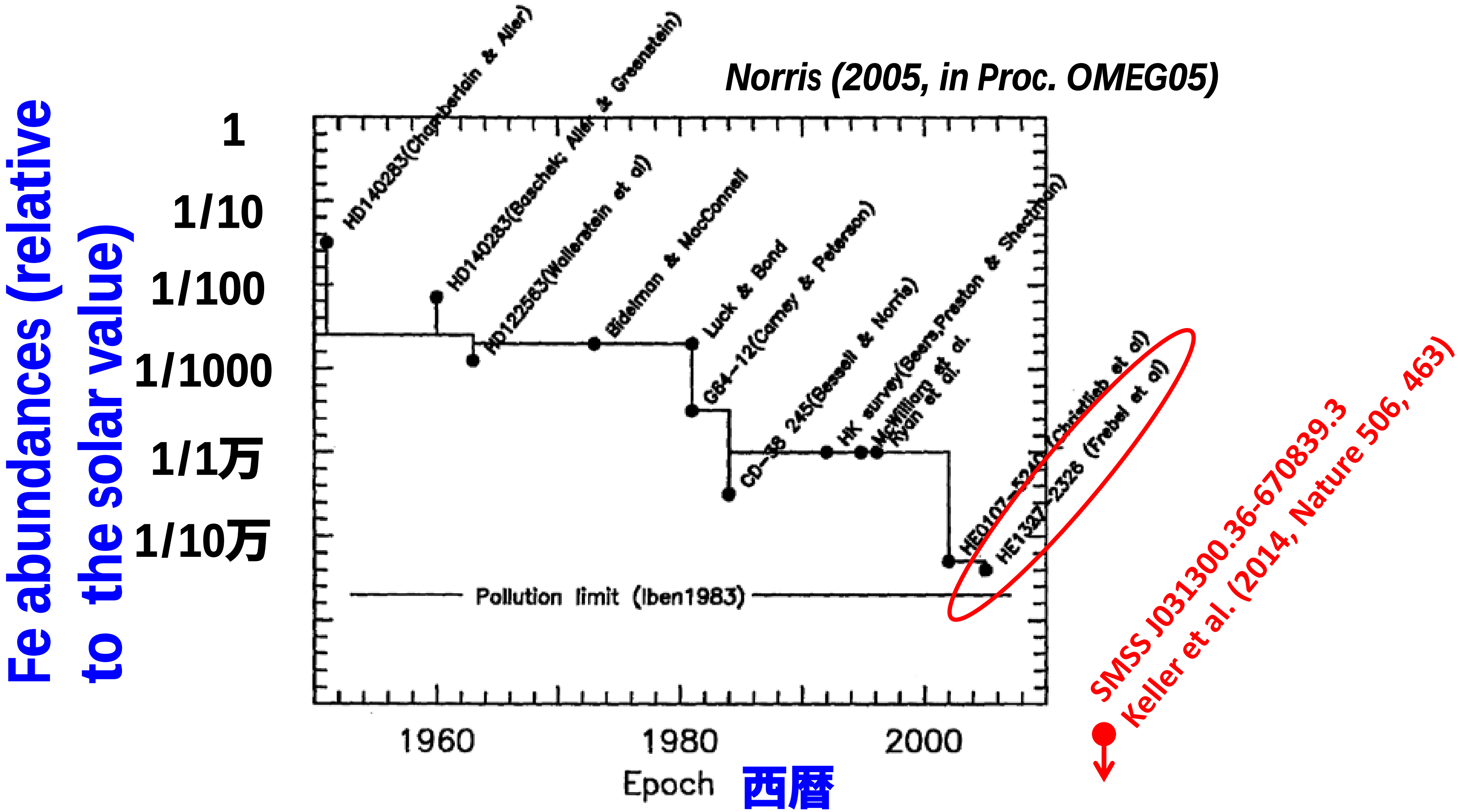
The normal Ba abundance, the high O/C, and the low N/C exclude the AGB and massive rotating stars as the progenitor

→ Faint supernova scenario is the remaining possibility.



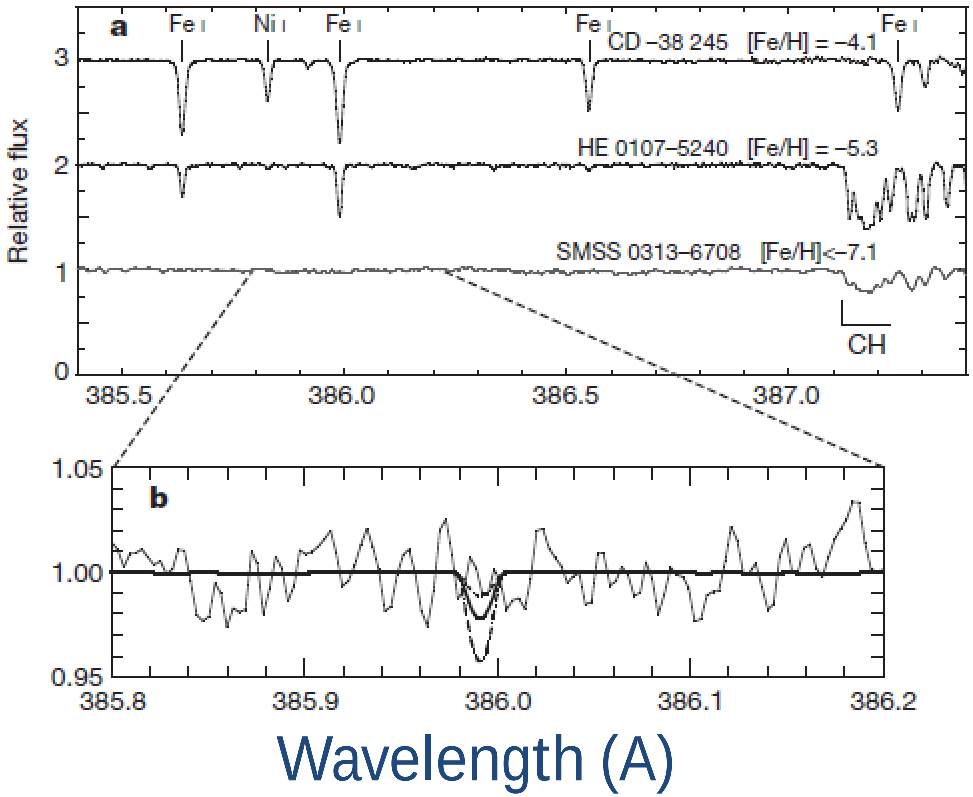
Ito et al. (2009)
Ito et al. (2013)

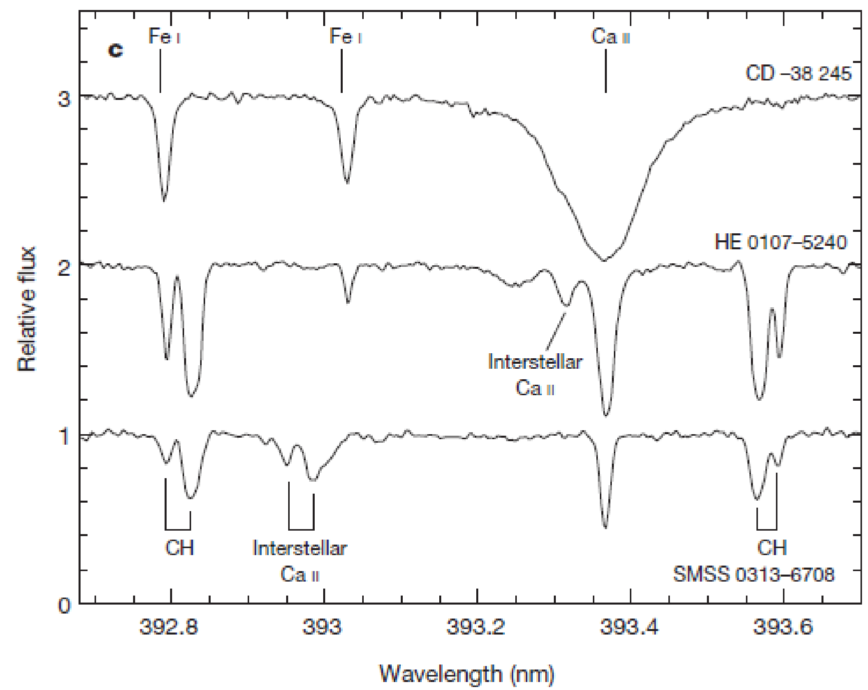
Progress of searches for most metal-poor stars



SMSS 0313-6708 (Keller et al. 2014)

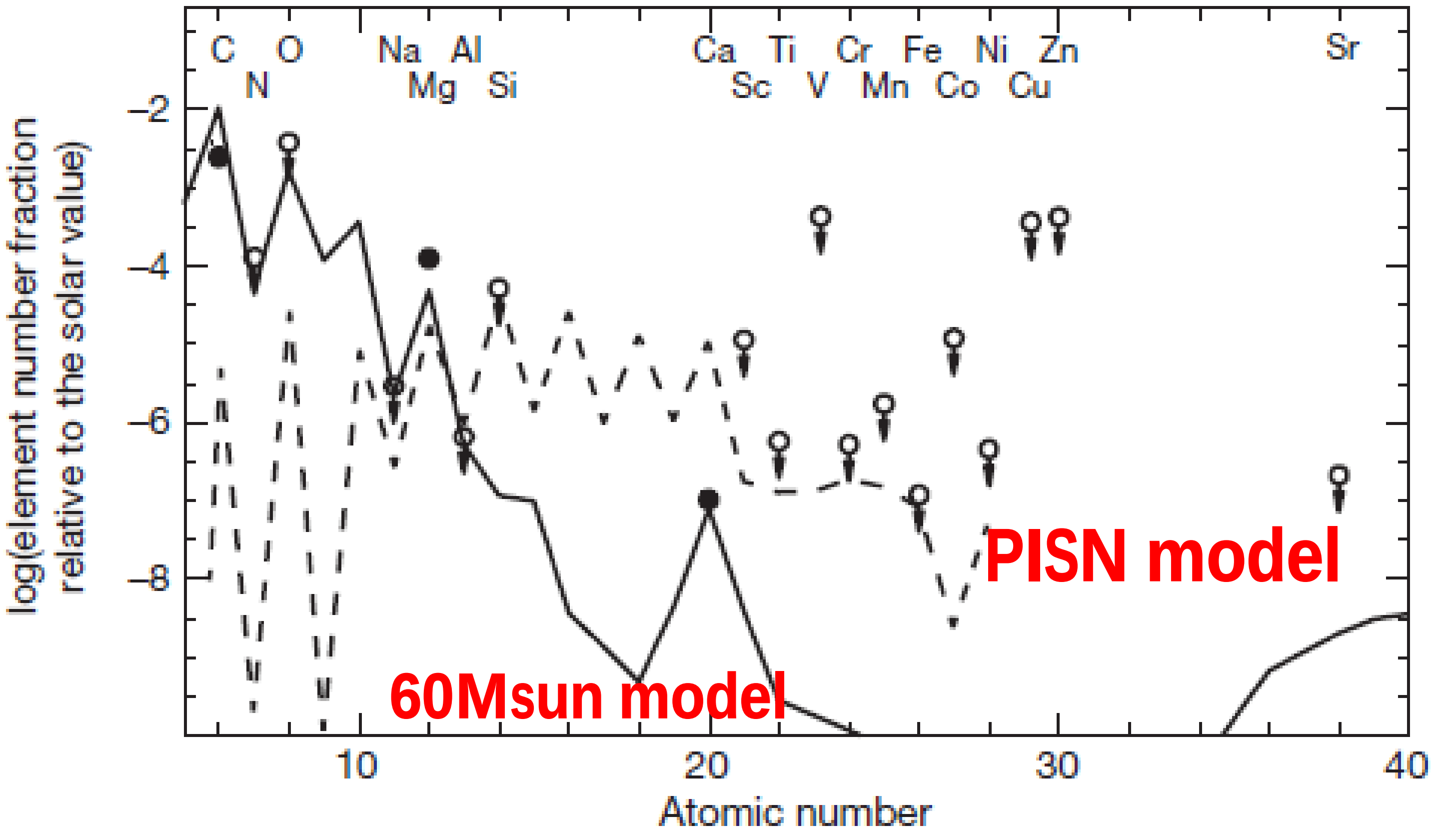
- [Fe/H]<-7
- red giant





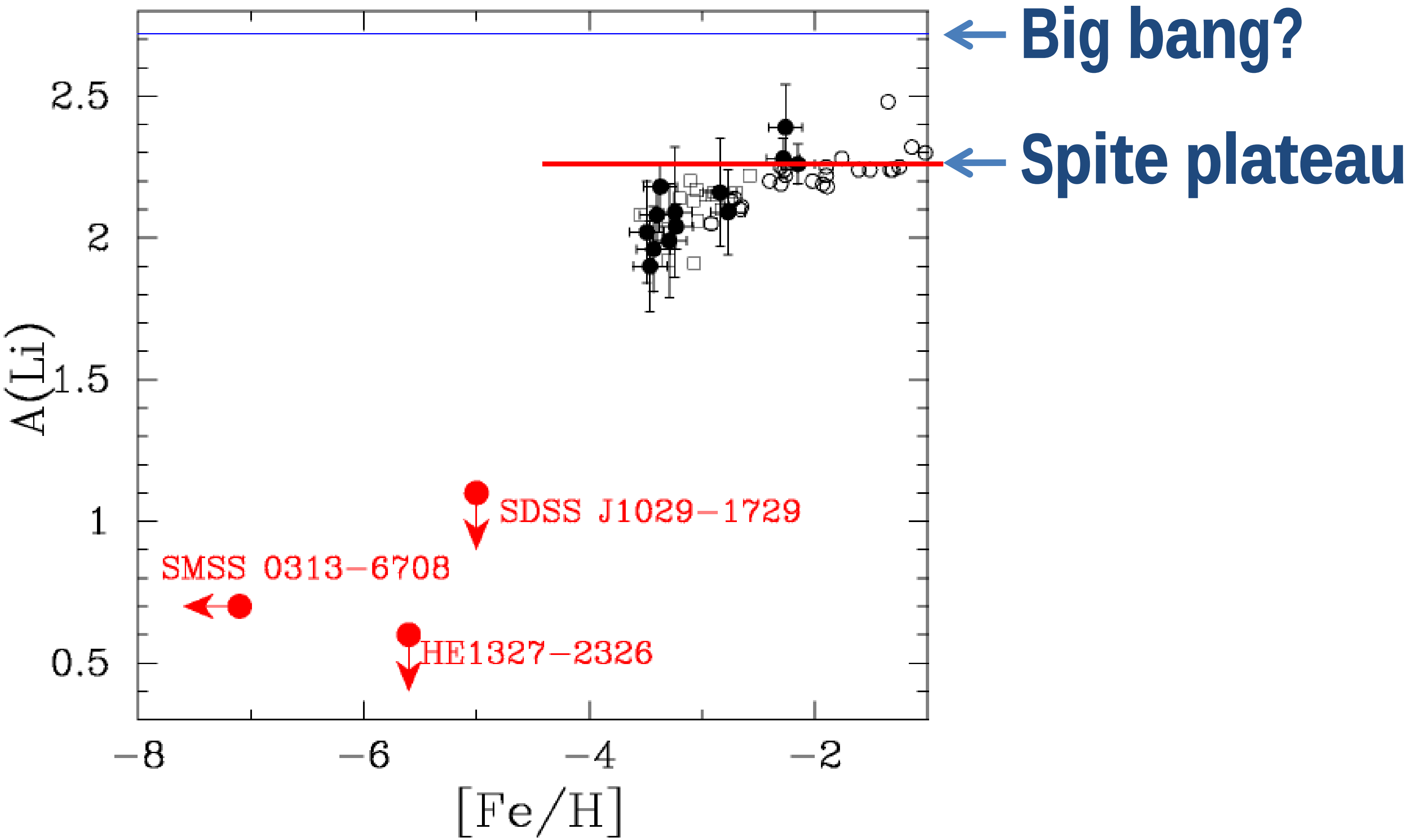
SMSS 0313-6708 (Keller et al.)

Abundance pattern is explained by a supernova from a 60 Msun star rather than PISN



SMSS 0313-6708 (Keller et al.)

Li is detected! ... *A*(Li)=log(Li/H)+12=0.7

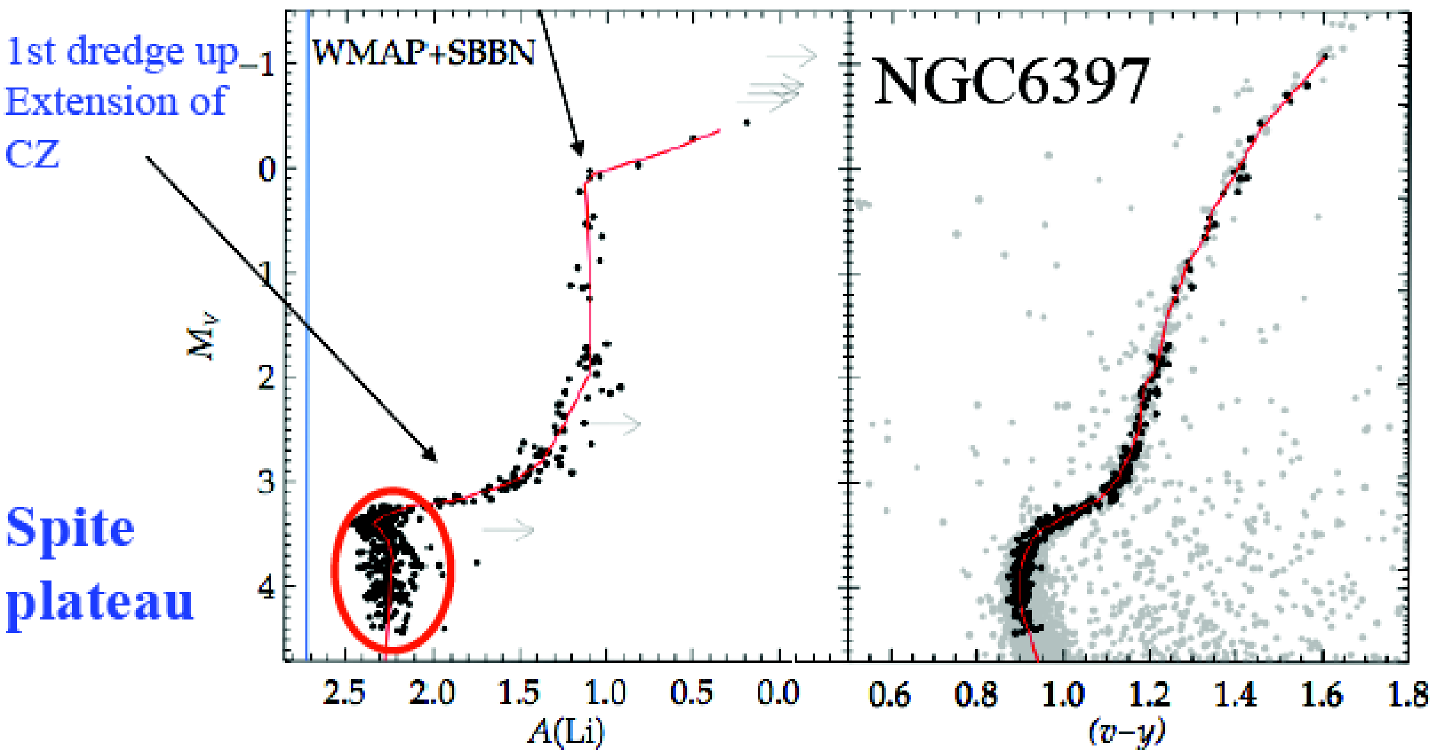


SMSS 0313-6708 (Keller et al.)

Li abundance is "normal" as a metal-poor red giant

A(Li)=0.7 in SMSS 0313-6708

A(Li)～1.0 in red giants in globular clusters

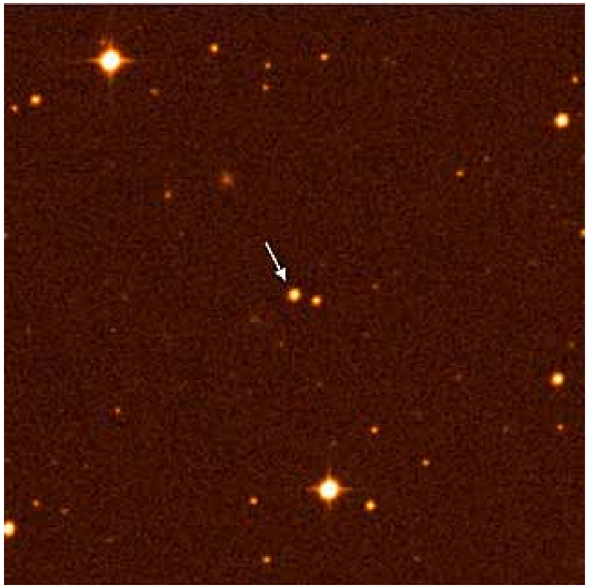


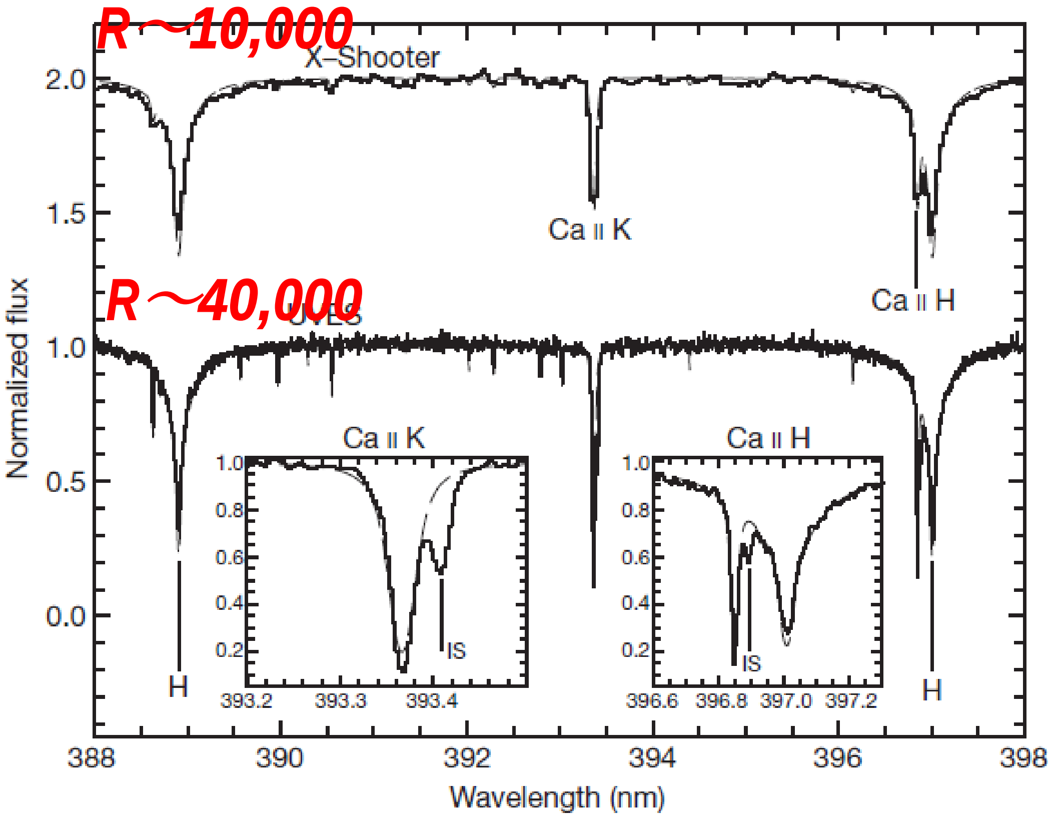
Lind et al. (2009)

Discovery of the [Fe/H]～-5 star with normal C abundance SDSS J1029+1729

Caffau et al. (2011, 2012)

[Fe/H]=-4.7 (1D LTE analysis) → Ultra-Metal-Poor (UMP) star





No very-massive stars among first-generation stars?

Second-generation stars affected by first PISN might be metal-poor, rather than extremely metal-poor

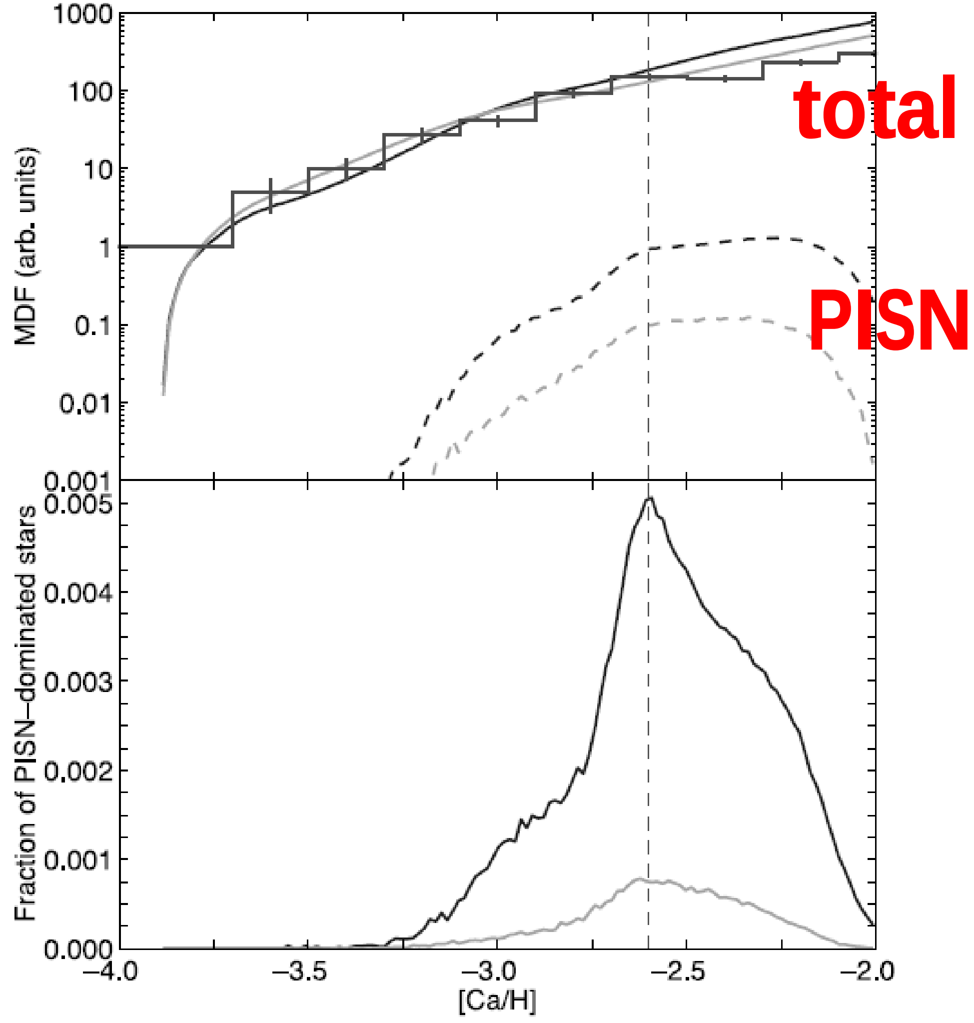
Karlsson et al. (2008, Astrophys. J. 679, 6)

...the evidence of very-massive stars and their explosions might only be found in moderate metal-poor stars

→chemical abundance analysis for a large sample of metal-poor stars is required...

Metallicity distribution function of stars formed following PISN

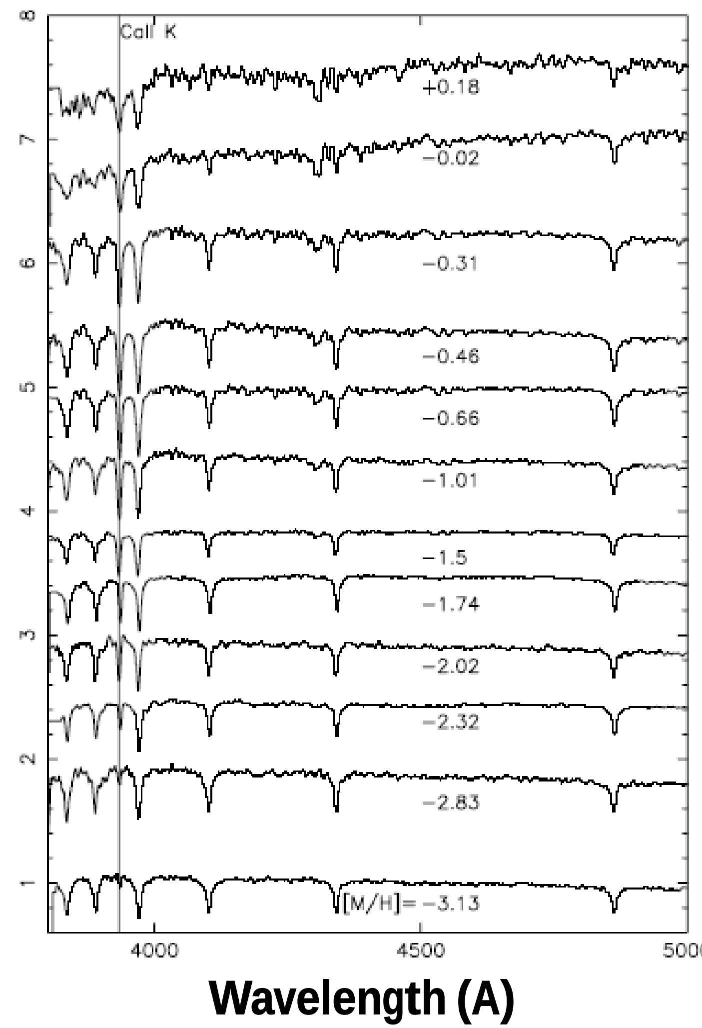
Karlsson et al. (2008)



Searches for very/extremely metal-poor stars in the Milky Way

The 2.5m telescope at Apache Point Observatory

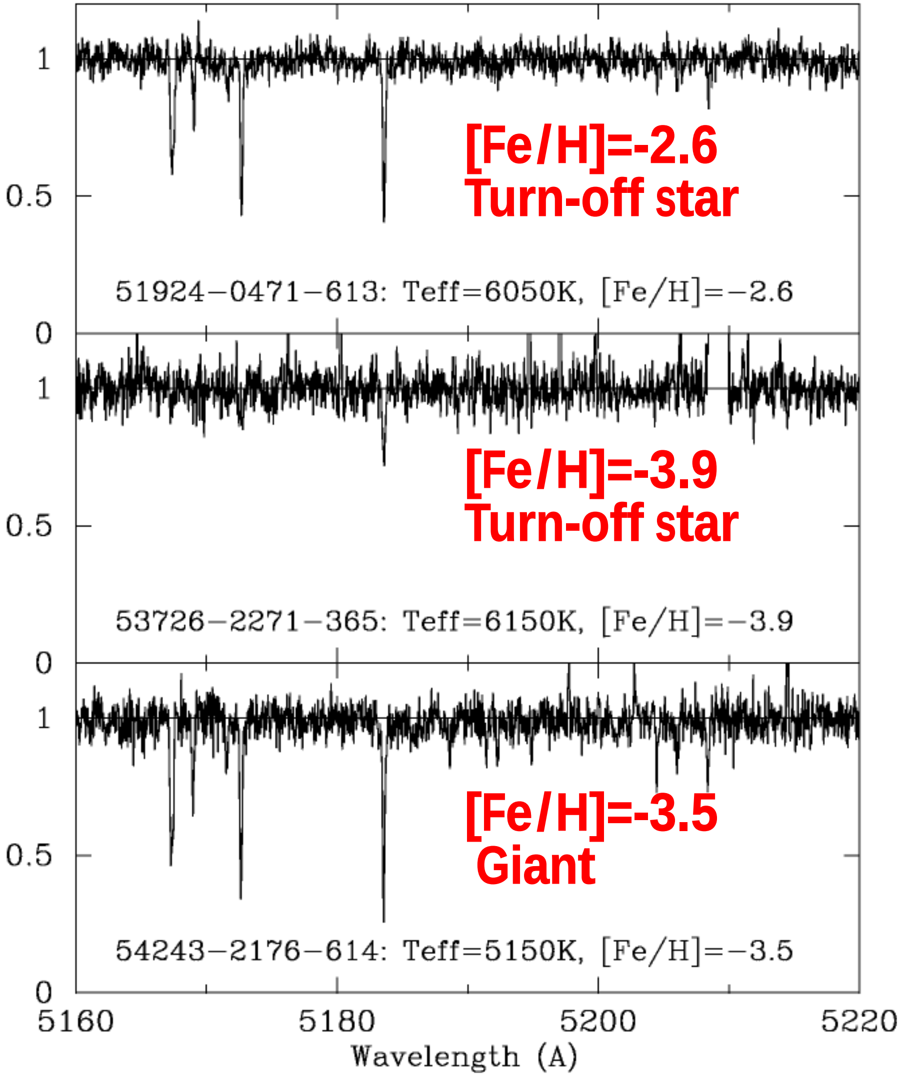
- **Imaging/spectroscopic surveys**
- **<u>Surveys of Galactic stars 240,000</u>**



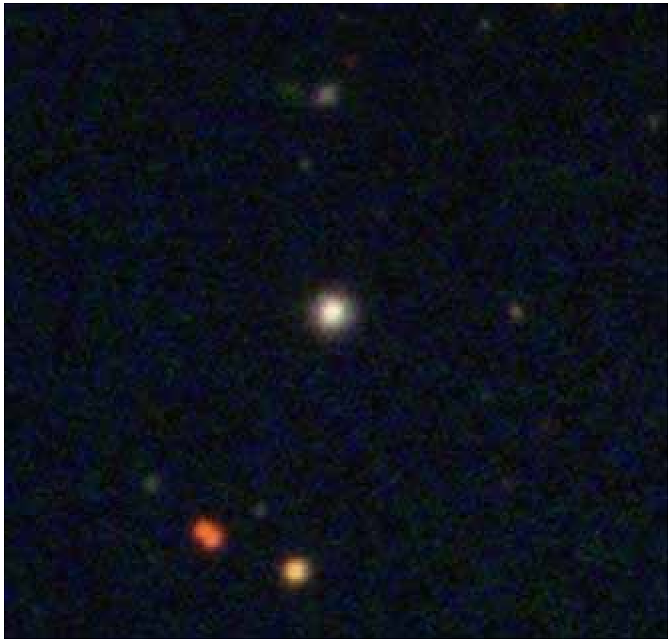
Cf. LAMOST

Follow-up high resolution spectroscopy with Subaru for selected SDSS objects

Follow-up spectroscopy with Subaru/HDS
150 objects(2008-2009)
→chemical compositions of 137 very/extremely metal-poor stars（*Aoki et al. 2013, Astron. J. 145, 13*)



Discovery of a low-mass star with peculiar chemical composition



Taken from SDSS

SDSS J001820.51-093939.2

- [Fe/H]=-2.5
- Low C and Mg abundances
- A low-mass main-sequence star

Aoki et al. (2013, Astron. J. 145, 13)

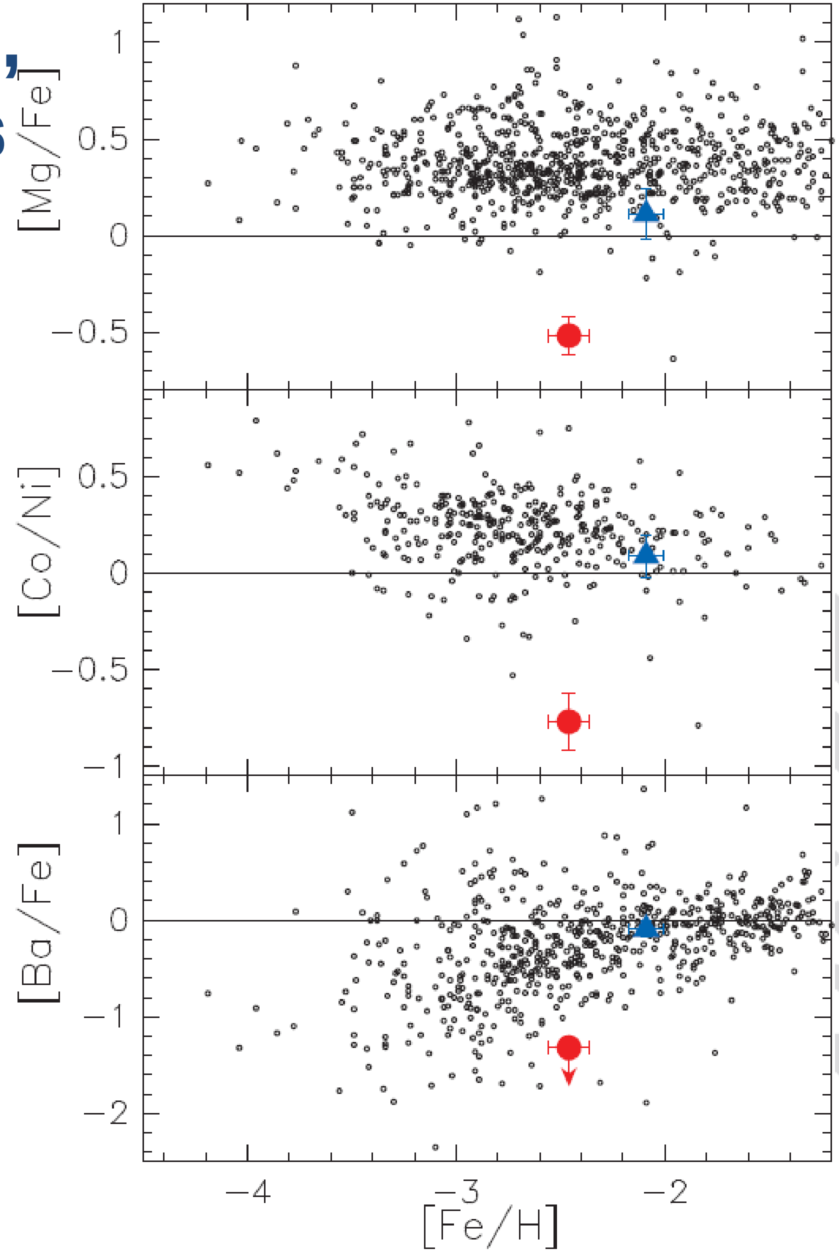
↓

Further follow-up spectroscopy with Subaru/HDS（August 2012）

Low abundances of alpha, odd, and neutron-capture elements of SDSS J0018-0939

Aoki, Tominaga, Beers, Honda, Lee (2014, Science)

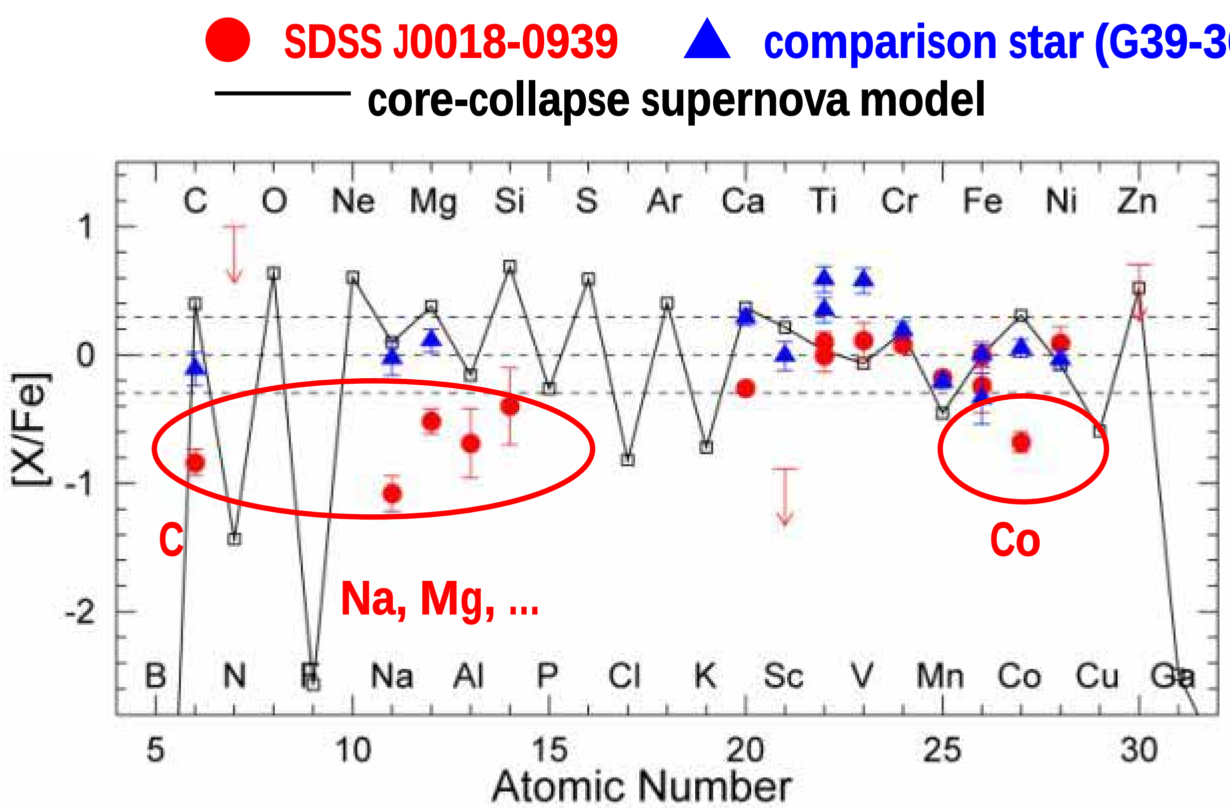
➡ **excess of Fe?**



SDSS J0018-0939 -- a low-mass star with a peculiar abundance pattern

The abundance pattern is not explained by normal core-collapse supernovae

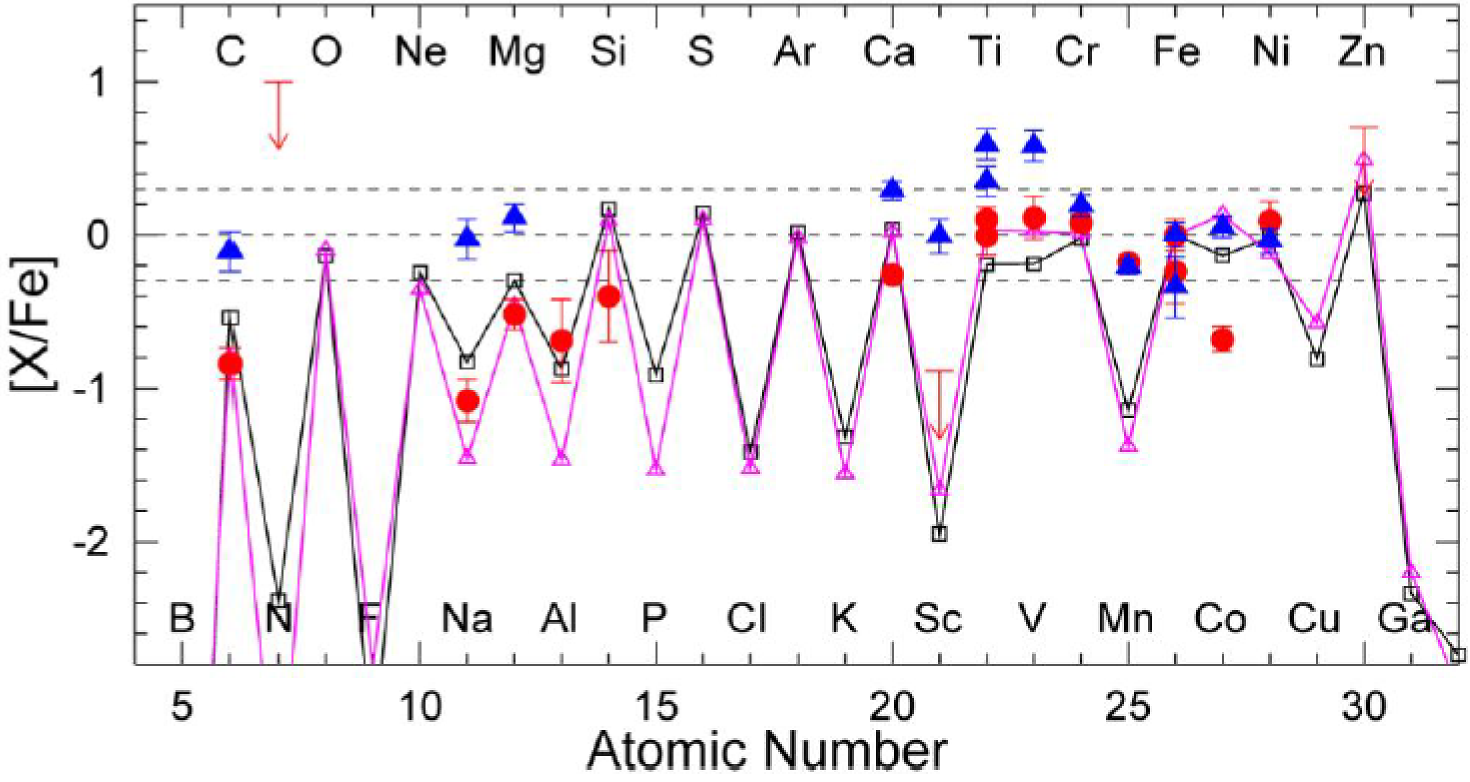
Aoki, Tominaga, Beers, Honda, Lee (2014)



SDSS J0018-0939 -- a low-mass star with a peculiar abundance pattern

The abundance pattern is not explained by variations of core-collapsed supernovae

Comparison with higher explosion energy models



SDSS J0018-0939 -- a low-mass star with a peculiar abundance pattern

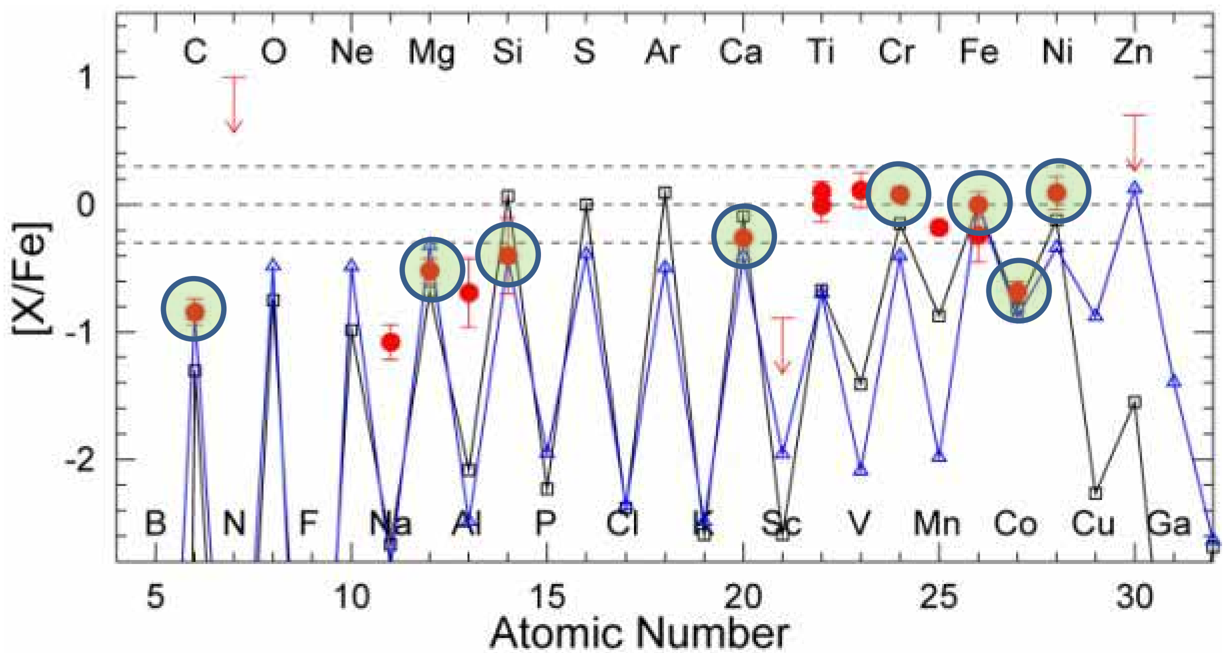
Aoki, Tominaga, Beers, Honda, Lee (2014)

Recording yields of a very-massive star?

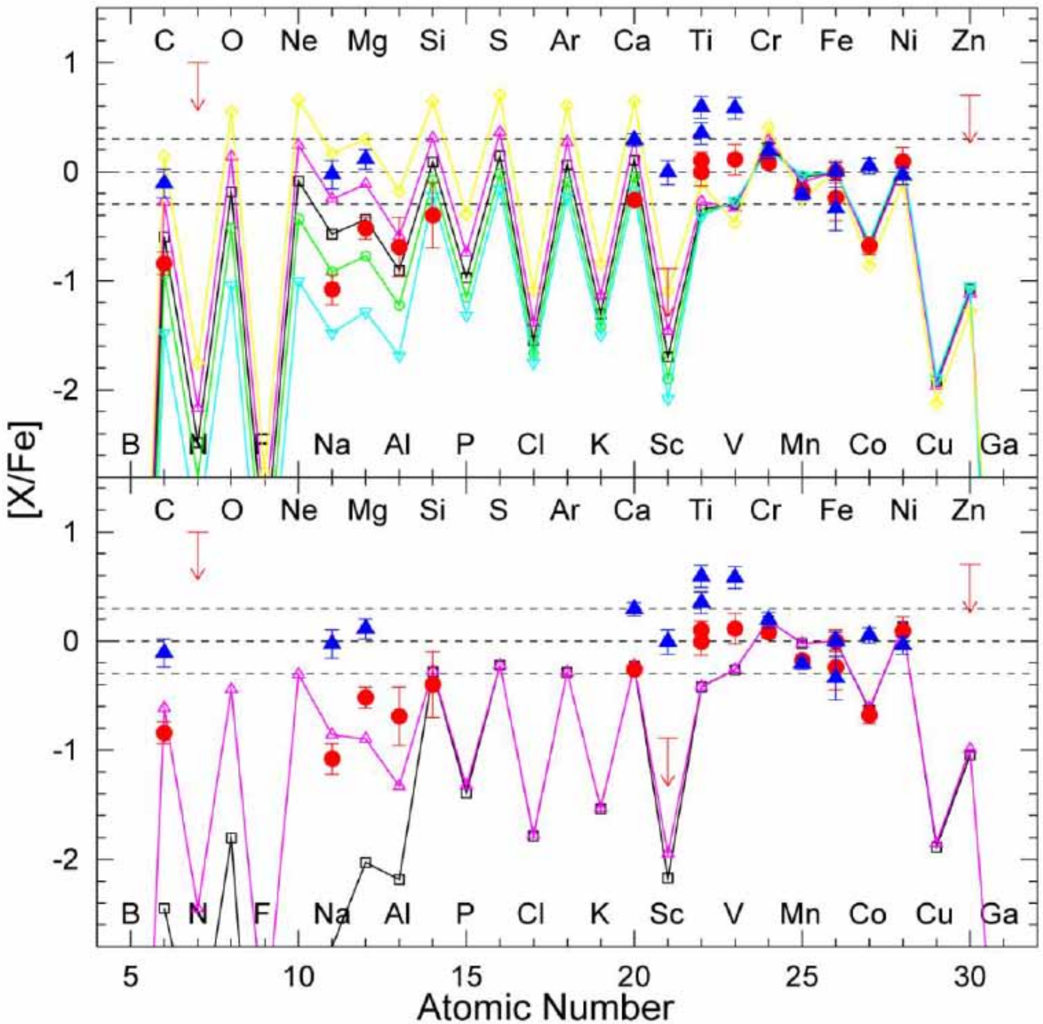
● SDSS J0018-0939

—— Pair-Instability Supernova

—— core-collapse supernova of very-massive stars



another possibility: Type Ia contamination?
... but a problem in time-scales



Current understanding of first stars from stellar observations

•Massive stars (10-100Msun) are dominant.

•Very massive stars (>100Msun) could exist and explode.

•Low mass stars were not formed or they are very rare

•Low-mass stars are formed from gas polluted by first supernovae, in particular carbon-rich environment

Extension of the study with LAMOST and Subaru

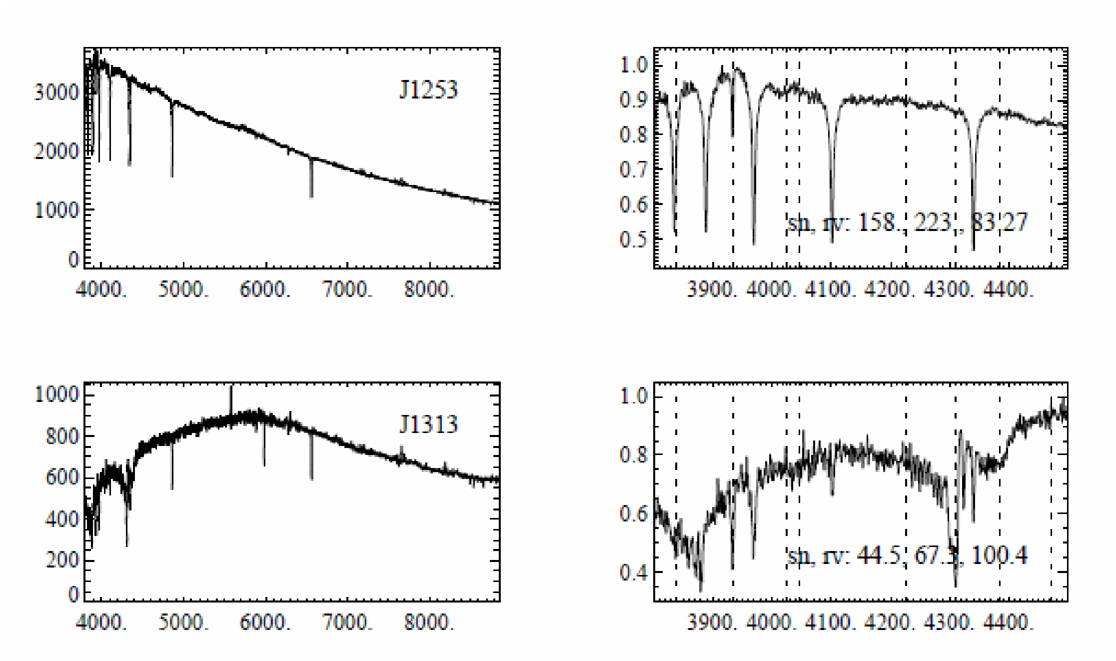
Aoki, Li, Zhao, Honda, Suda, Christlieb

Subaru/HDS follow-up spectroscopy for a large sample of candidate EMP stars found with LAMOST

LAMOST (中国、興隆)

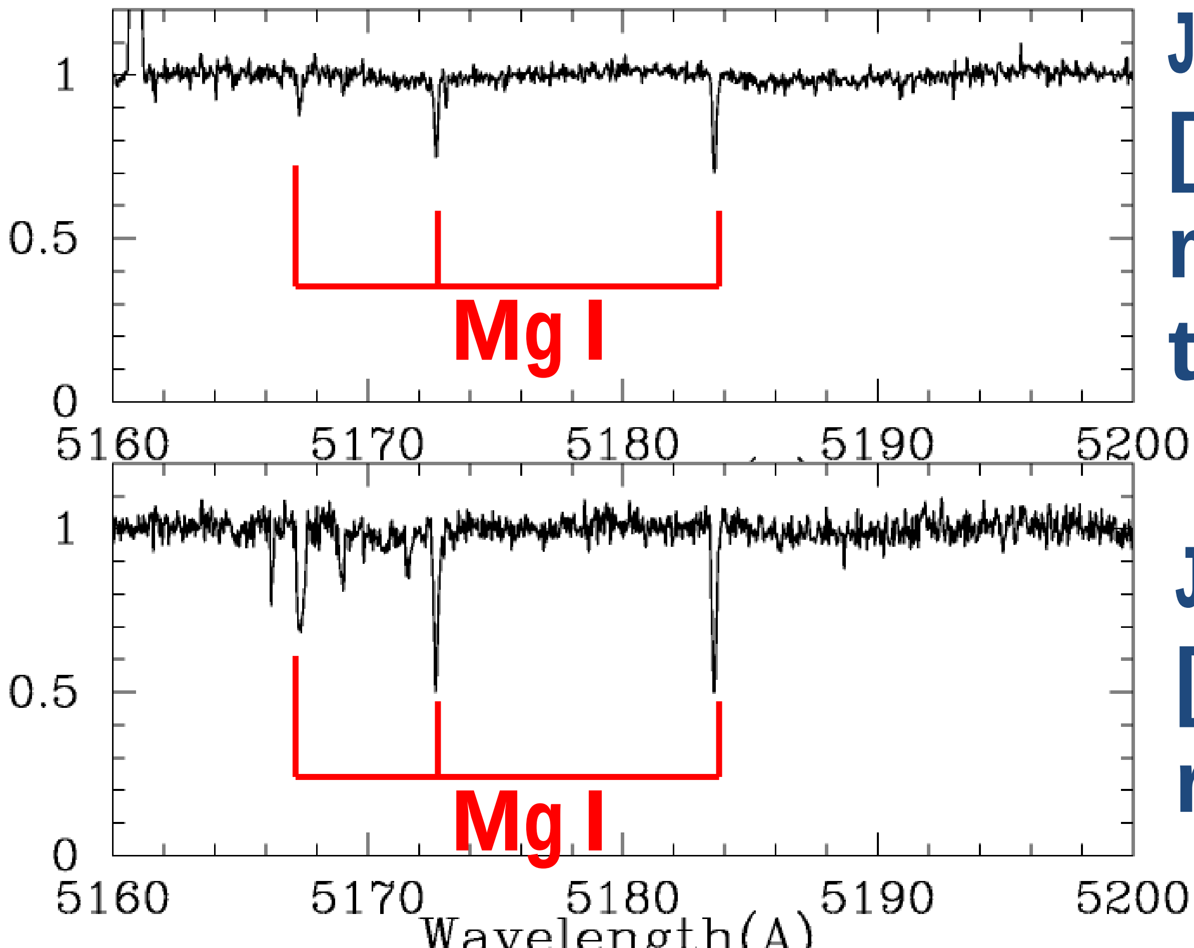
Target selection from LAMOST sample

LAMOST medium resolution spectra



Subaru high-resolution follow-up spectroscopy for 54 stars (May 2014, 2 nights)

High-resolution spectra obtained with Subaru/HDS (*R=36,000*)

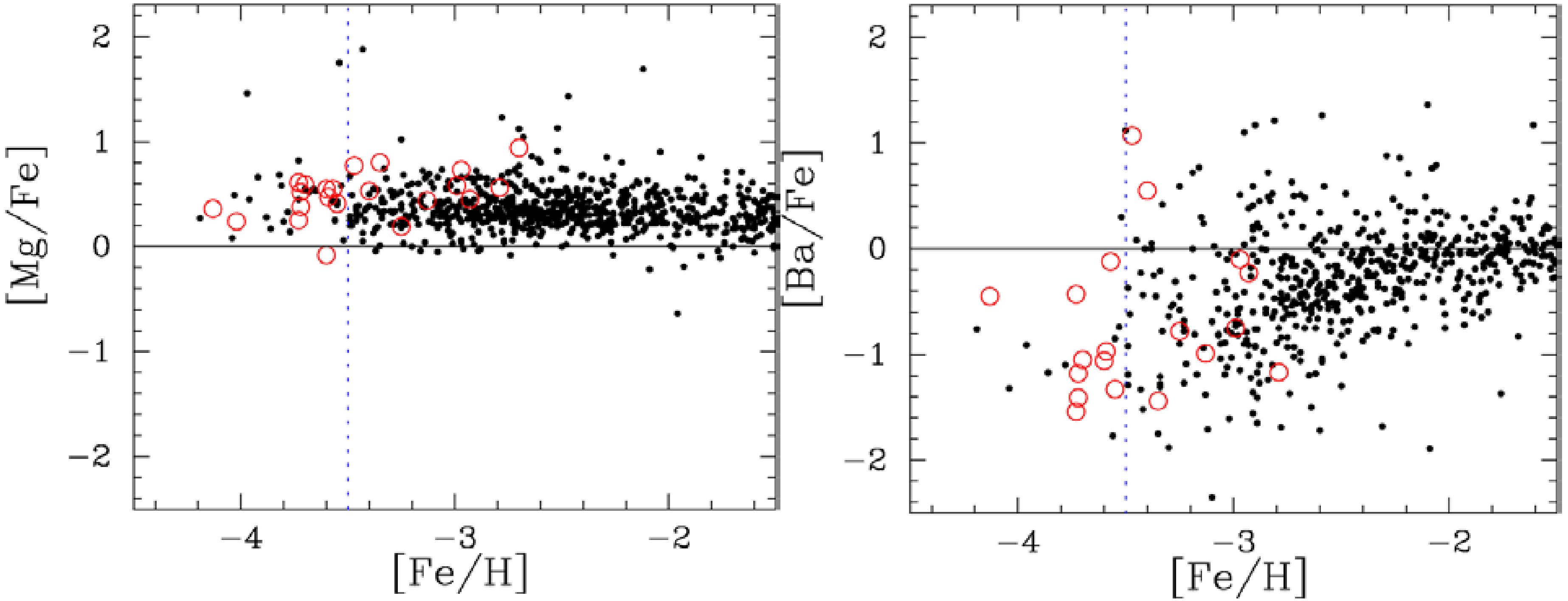


J1253+0753
[Fe/H]=-4.0
main-sequence turn-off

J1313-0552
[Fe/H]=-4.0
red giant

Many stars with [Fe/H]<-3.5 from LAMOST/Subaru!

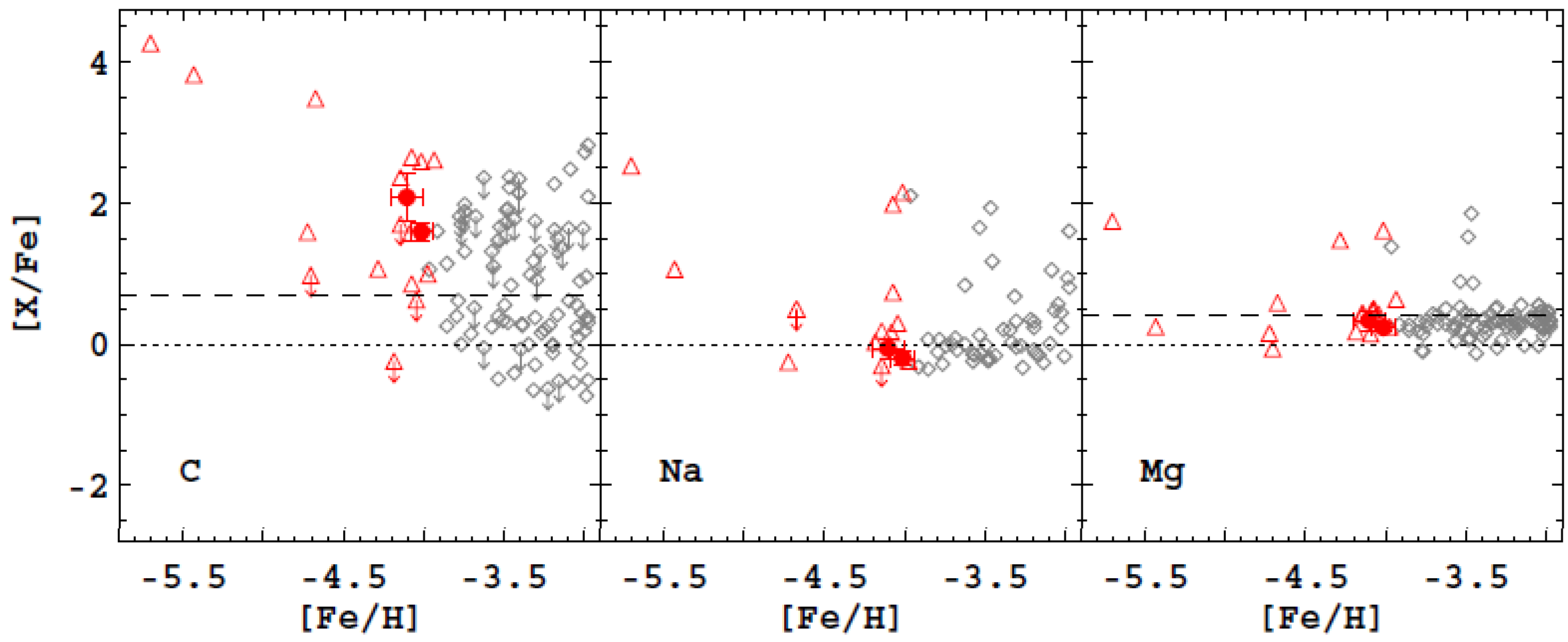
Li et al., preliminary results



Two ultra metal-poor stars ([Fe/H]<-4) from LAMOST measured with high S/N with Subaru

Li et al., in preparation

● LAMOST+Subaru



Searches for evidence of first stars in dwarf galaxies

Searches for metal-poor stars and chemical abundance measurements for individual stars in dwarf galaxies around Milky Way

SDSS/LAMOST + Subaru + TMT

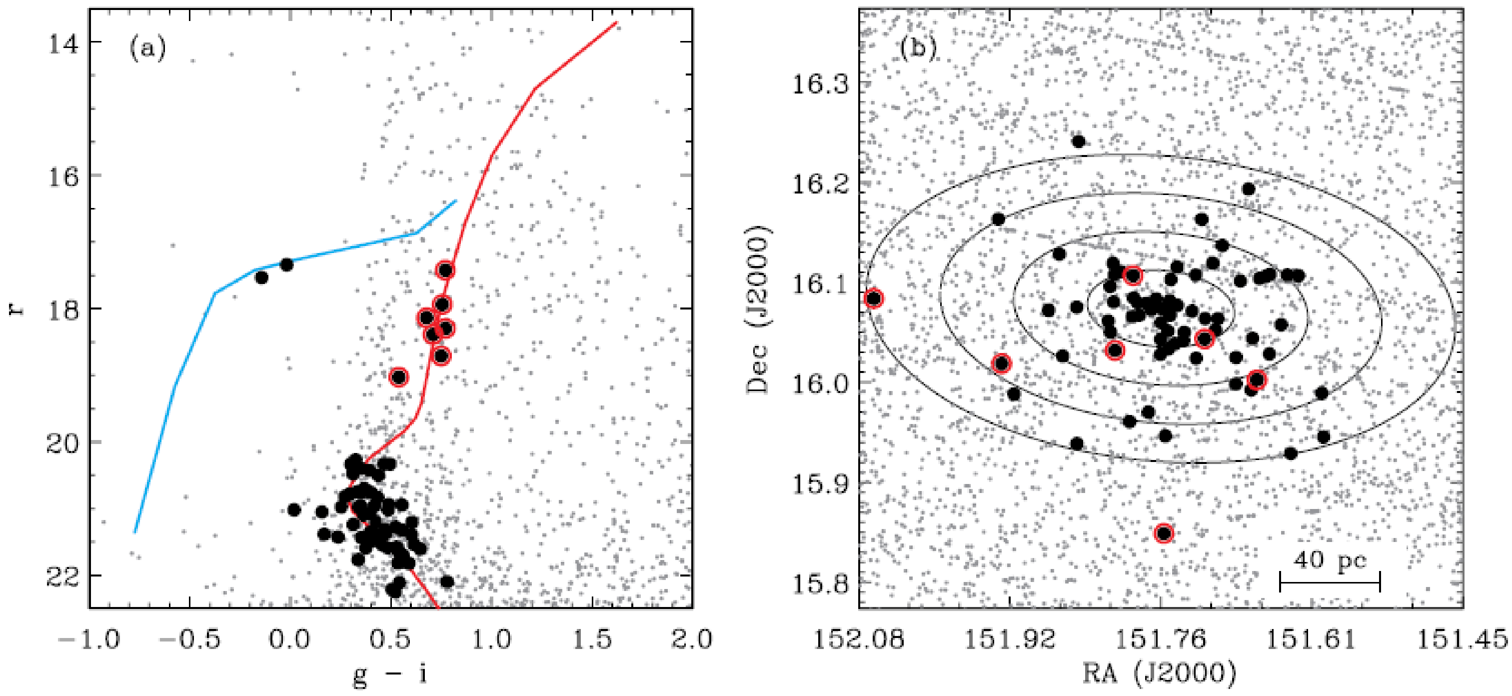
Dwarf irregular
Sextans A

TMT at Mauna Kea

The ultra-faint dwarf galaxy Segue 1

Frebel et al. (2014)

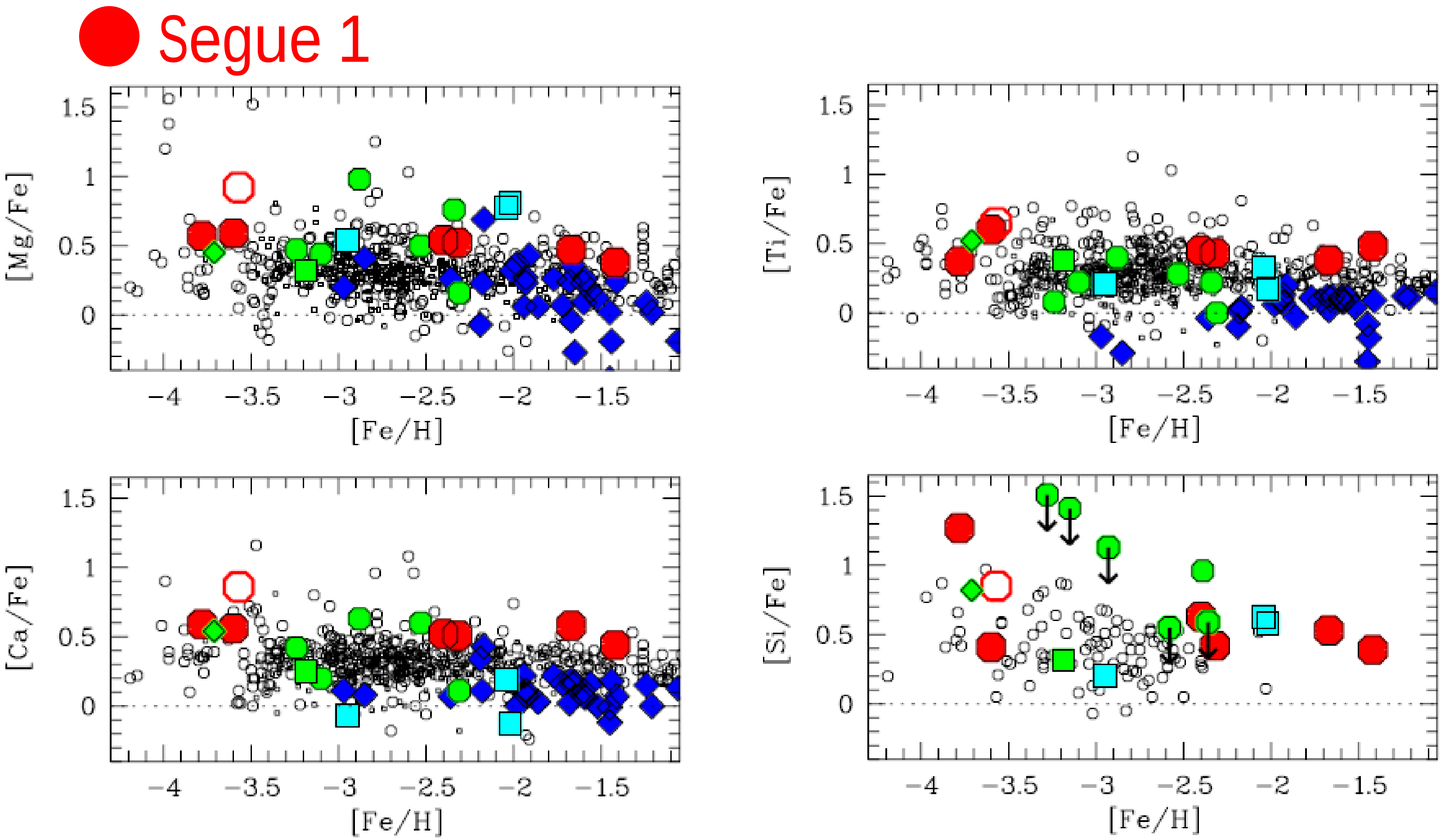
Only 7 red giants in the galaxy



The ultra-faint dwarf galaxy Segue 1

Frebel et al. (2014)

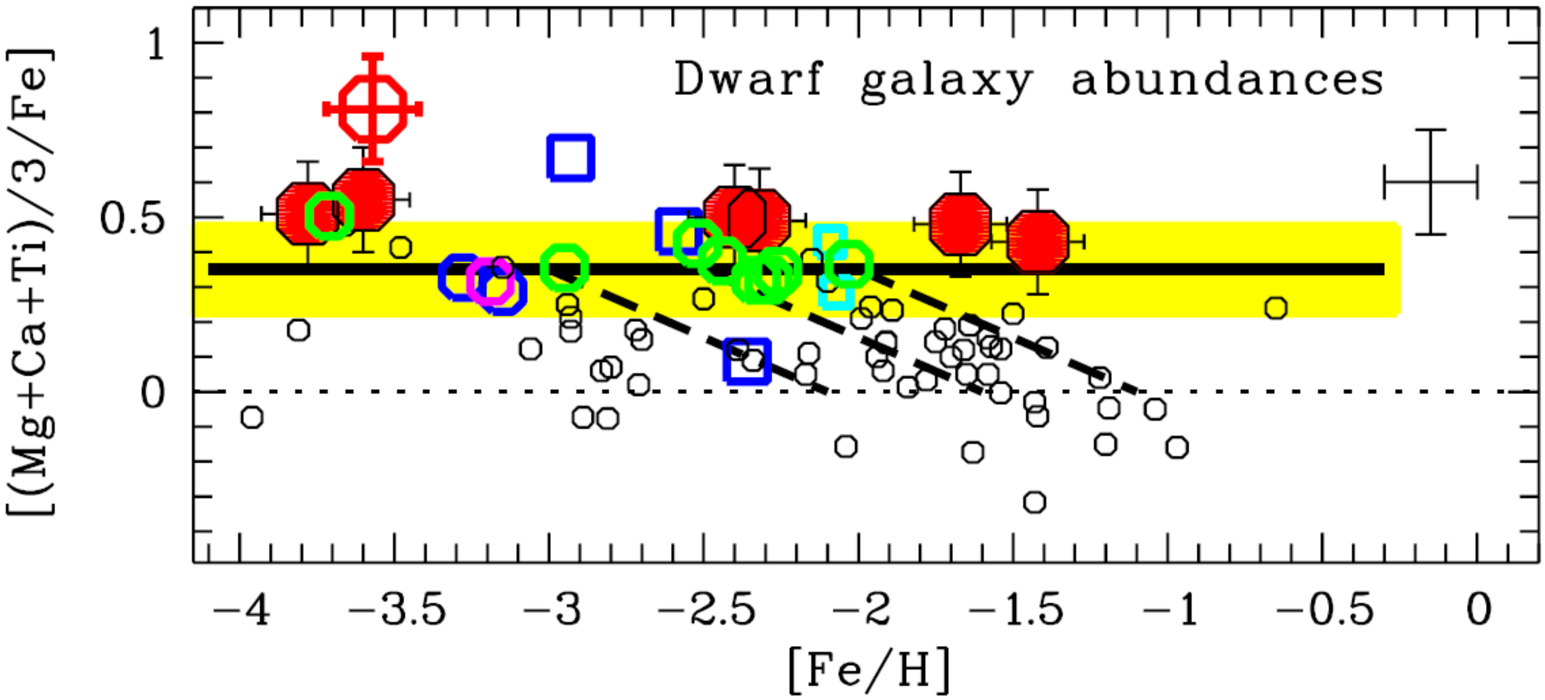
Constant α/Fe ratios



The ultra-faint dwarf galaxy Segue 1

Frebel et al. (2014)

Constant α/Fe ratios → "one-shot enrichment"



The ultra-faint dwarf galaxy Segue 1

Frebel et al. (2014)

No detectable heavy elements