古い恒星系で探る天の川銀河の化学進化と元素の起源

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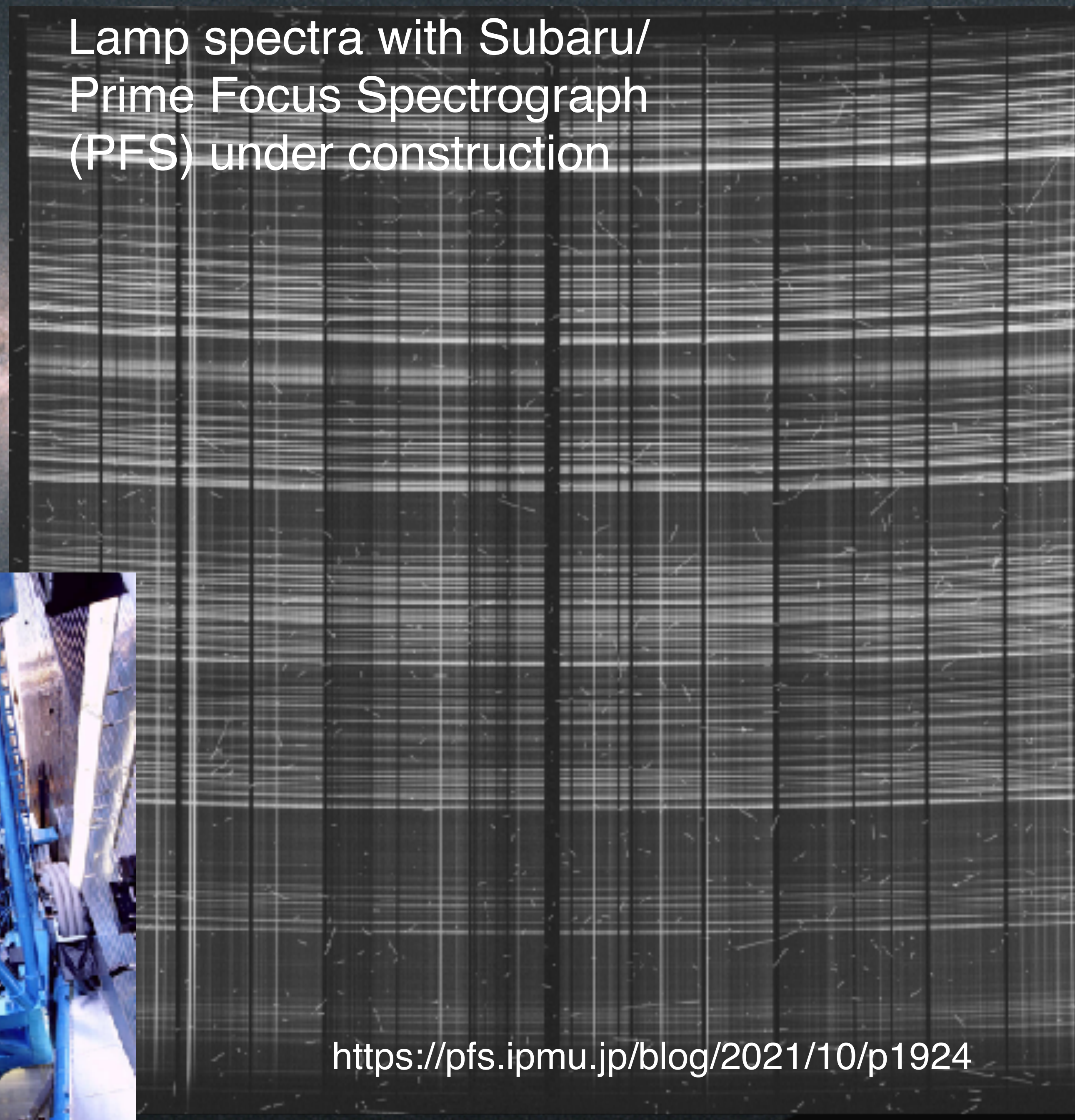

Credit: ESA/Gaia/DPAC, Acknowledgement: A. Moitinho.

Outstanding questions

What old stellar populations in the Milky Way tell us?

- Where does the Solar-system came from?
- How galaxies formed and evolved?
- The nature of dark matter
- The origin of metals

Beers & Christlieb05, Nomoto+13, Frebel & Norris15, Kobayashi+20

See Freeman & Bland-Hawthorn 2002

THE NEW GALAXY: Signatures of Its Formation

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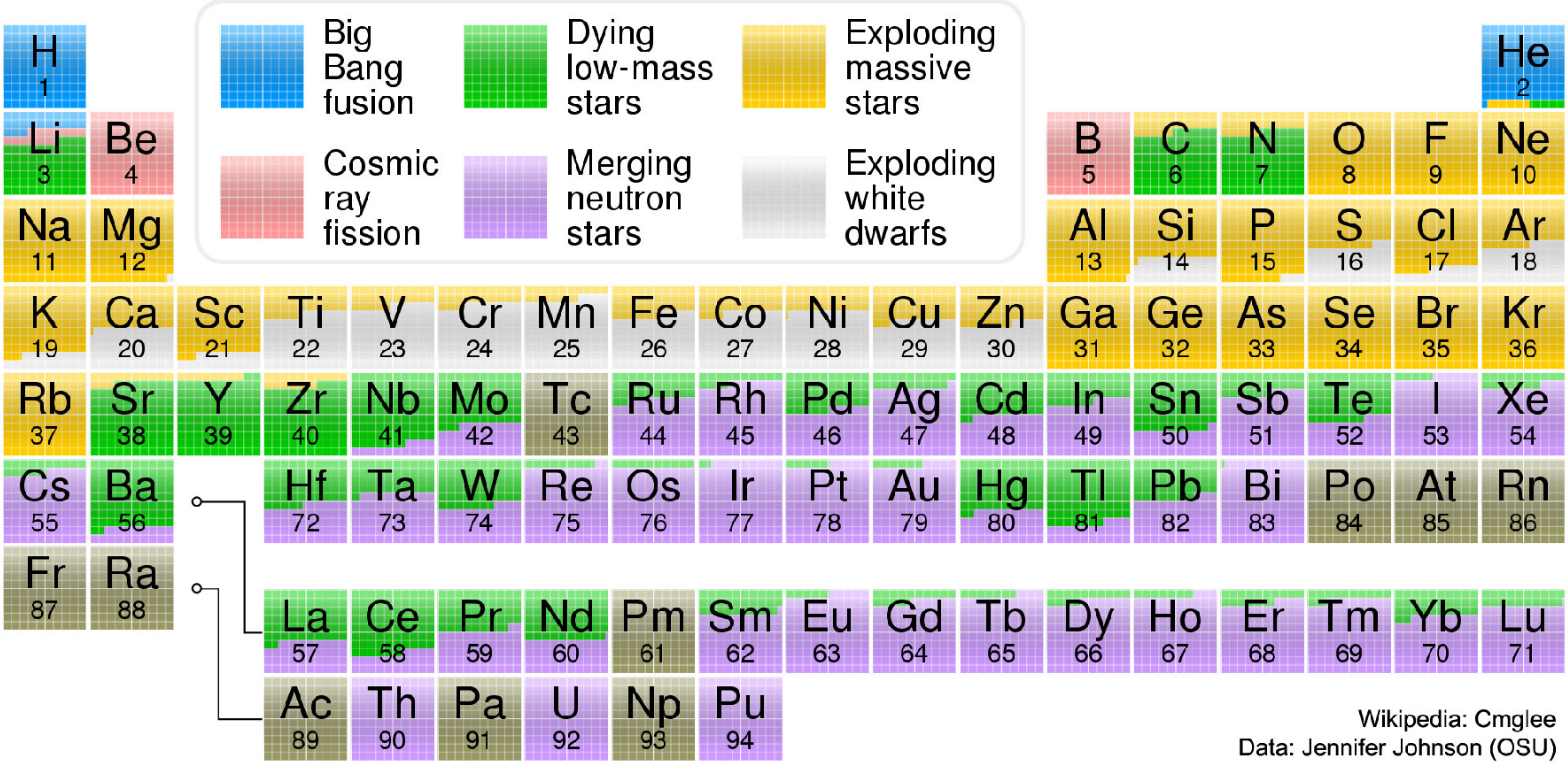
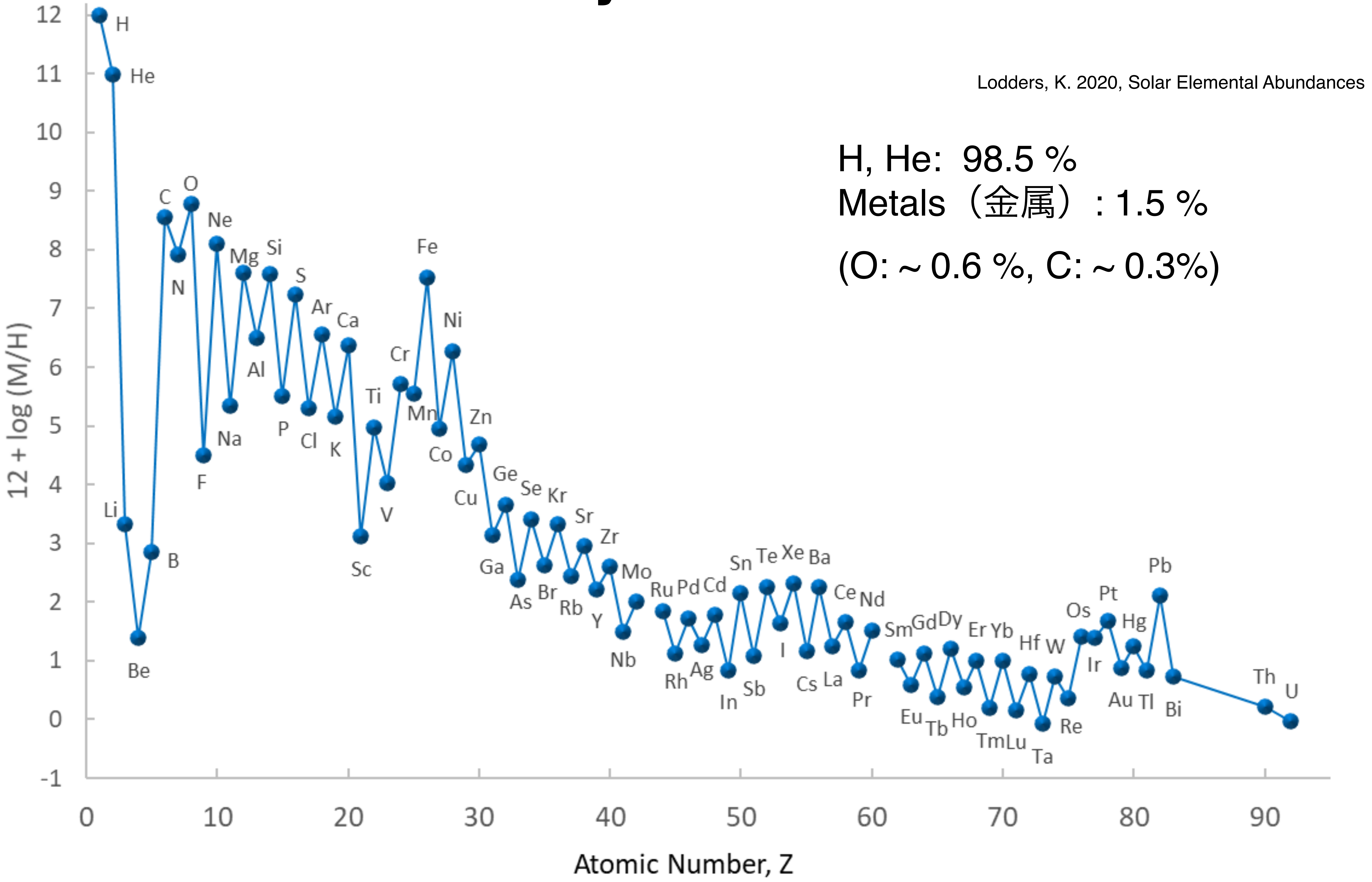
Origin of metals in the Universe



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

Solar system abundance



H, He: 98.5 %

Metals（金属）: 1.5 %

(O: ~ 0.6 %, C: ~ 0.3%)

The chemical evolution of the Universe

Old/metal-poor stars: fossil records of the synthesis of metals in the early Universe

Contents

- How to find “old” or metal-poor stars in the Milky Way?
  - Wide-field imaging and spectroscopic surveys
- What metal-poor stars tell us?
  - The origin of elements in the early Universe
- Open questions about the origin of elements
  - Prospects with new instruments and telescopes

Contents

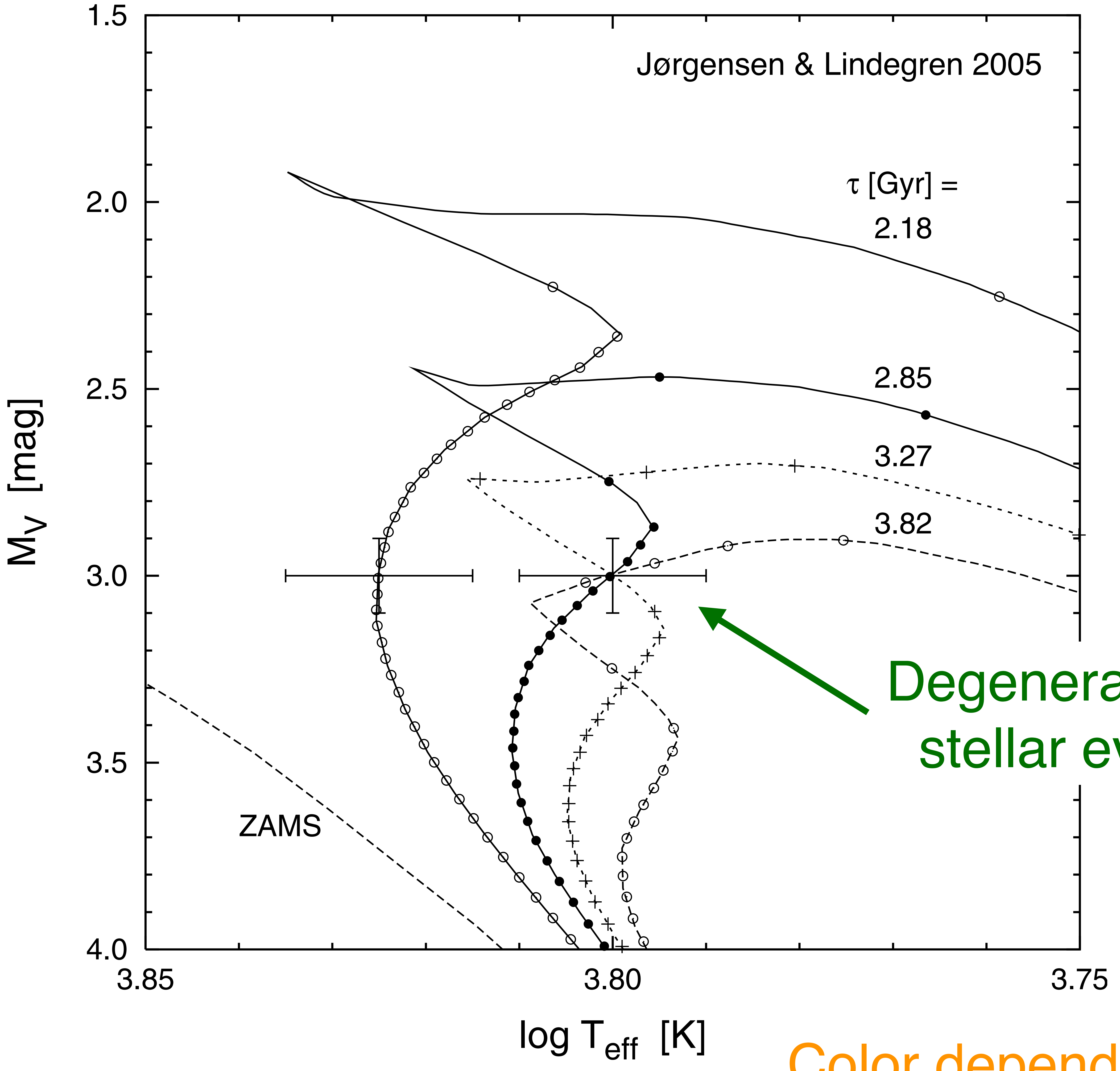
Why “old” stars matter

- Low-mass stars are long-lived: > 10 Gyrs for low-mass ($< 1 M_{\odot}$) stars
- Kinematics of stars are largely conserved: Inference on the initial orbit
- The surface chemical composition is preserved during the main-sequence phase of stellar evolution: Chemical composition of the birth cloud

Excellent probe of the star formation in the early Universe
e.g. the first (Population III or Pop III) stars

Challenges in stellar age estimates

Distance uncertainty



Degeneracy/uncertainty in stellar evolution models

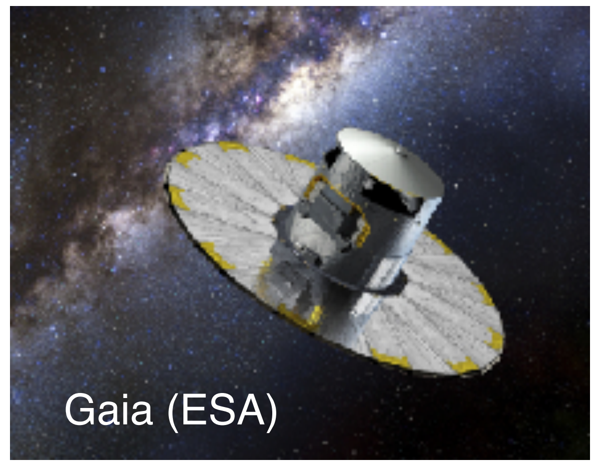
Color depends on chemical composition

The revolution of Galactic Archaeology with surveys

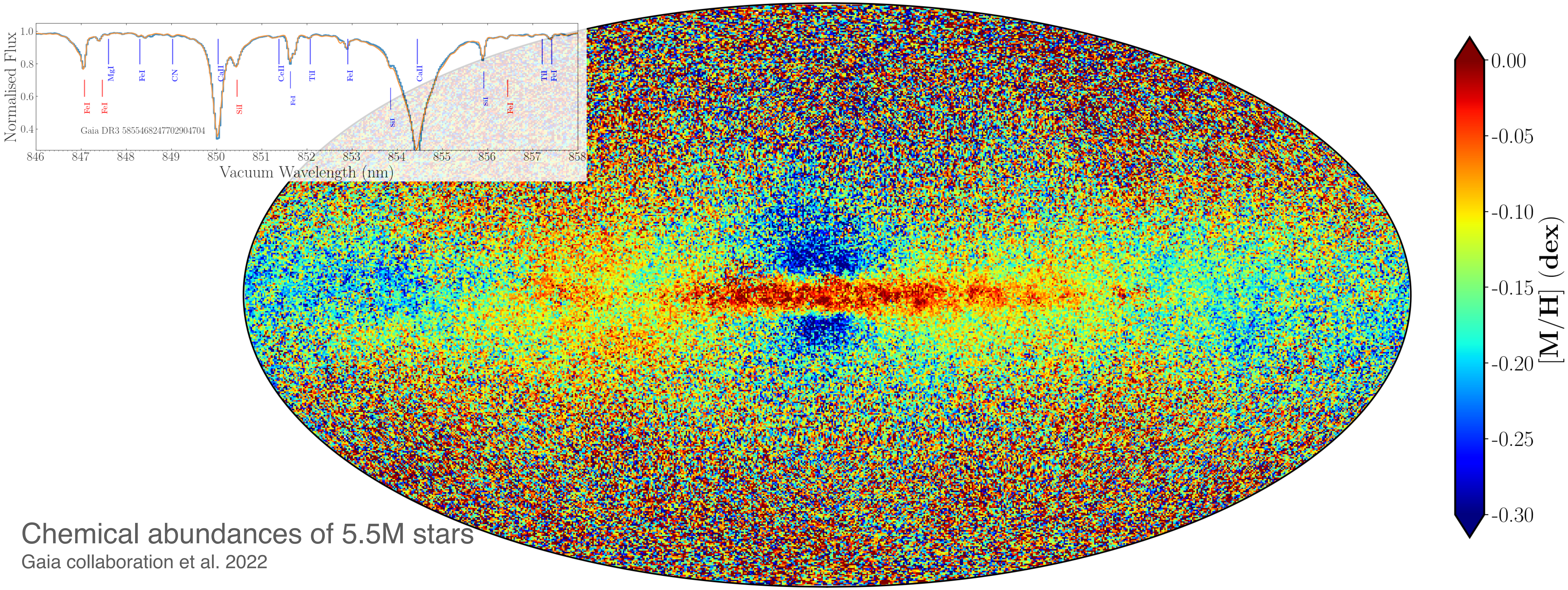
Parallax (distance)/proper motion: Gaia

Chemical abundance: LAMOST, GALAH, APOGEE, etc.

Asteroseismology: TESS, Kepler, K2



➡ a chronological table of the chemical enrichment history of our Galaxy

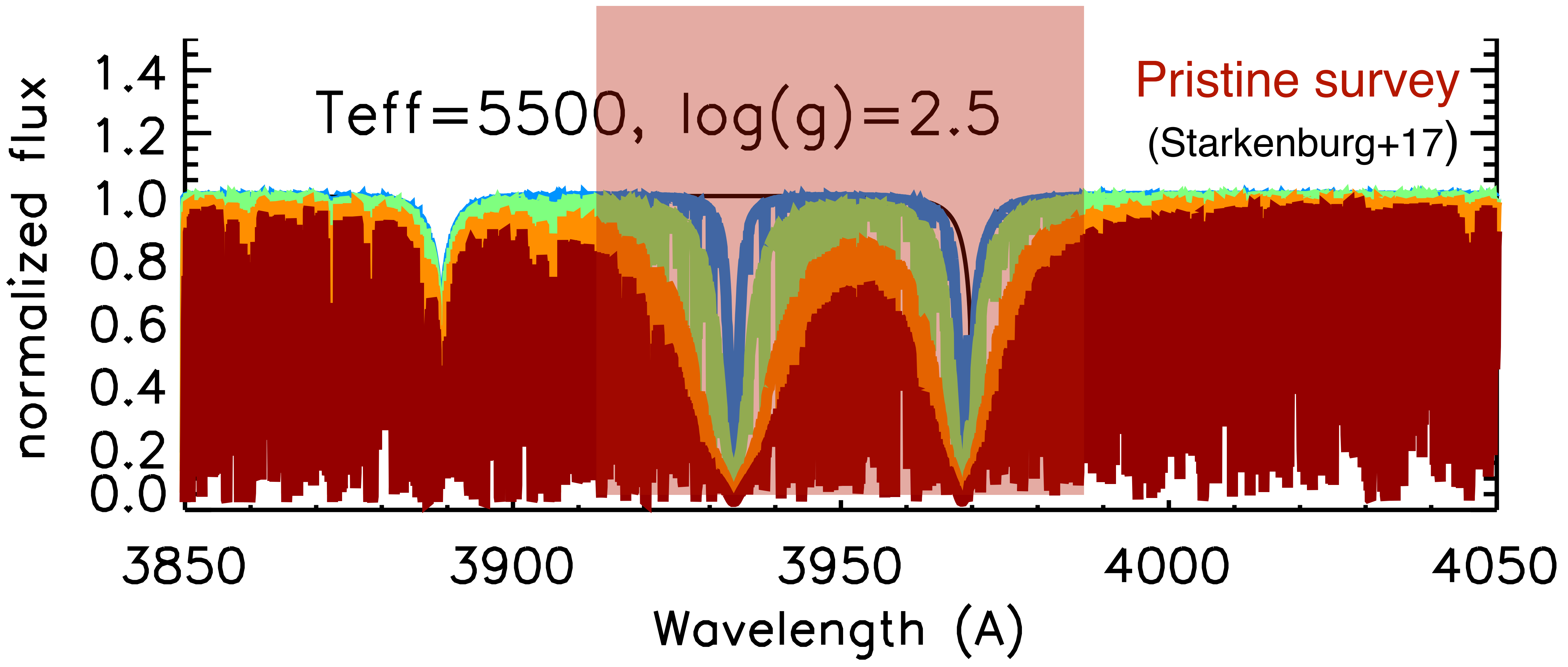


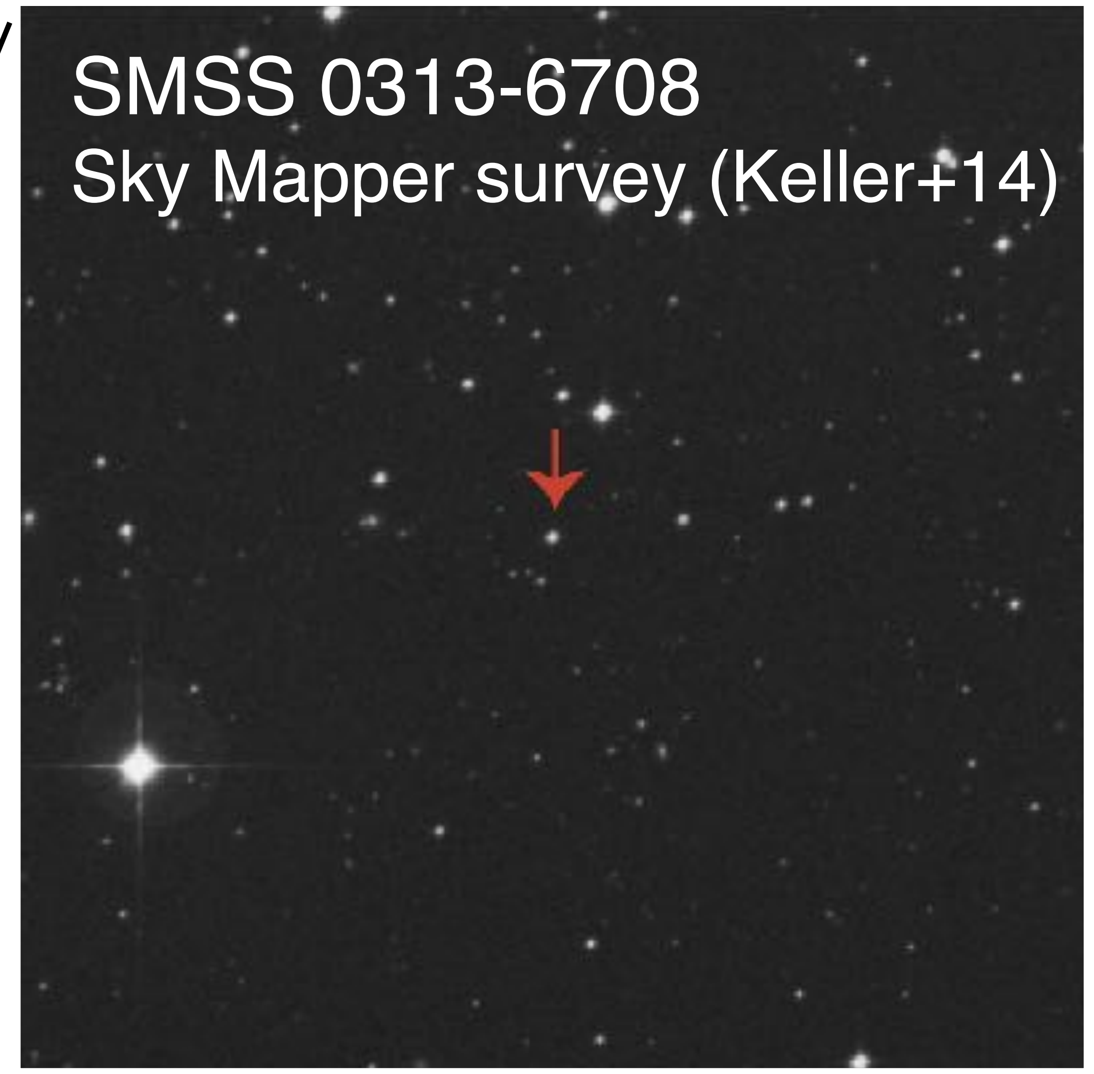
Chemical abundances of 5.5M stars

Gaia collaboration et al. 2022

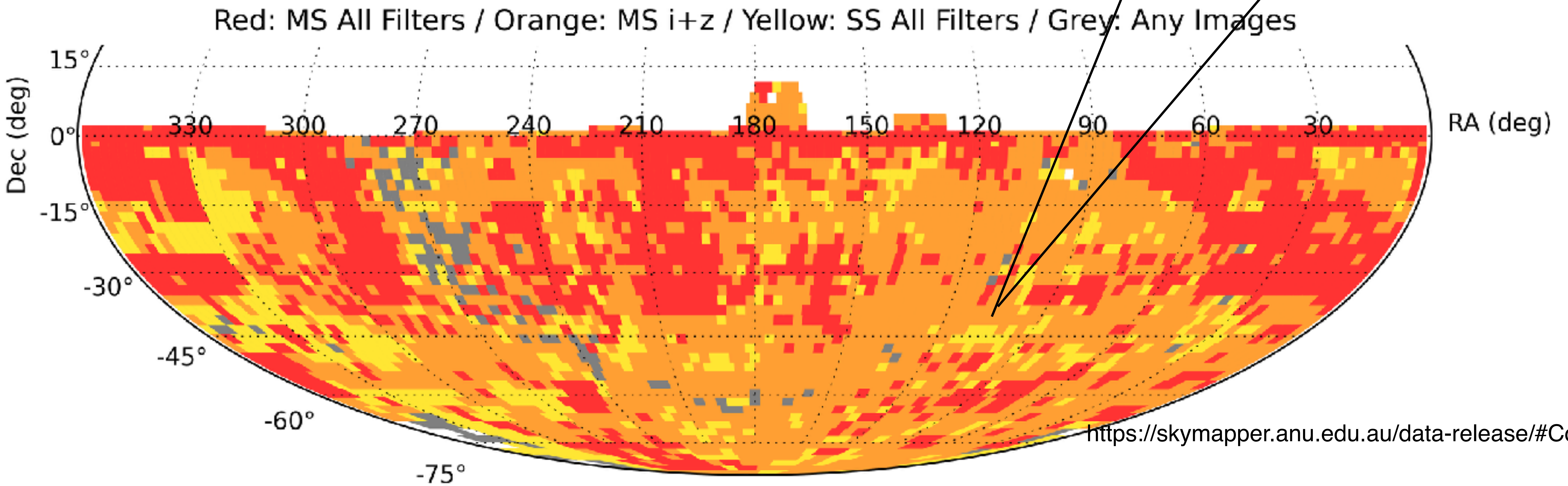
Search for the most chemically pristine stars; Narrow-band surveys

A narrow-band filter covering Ca H+K lines



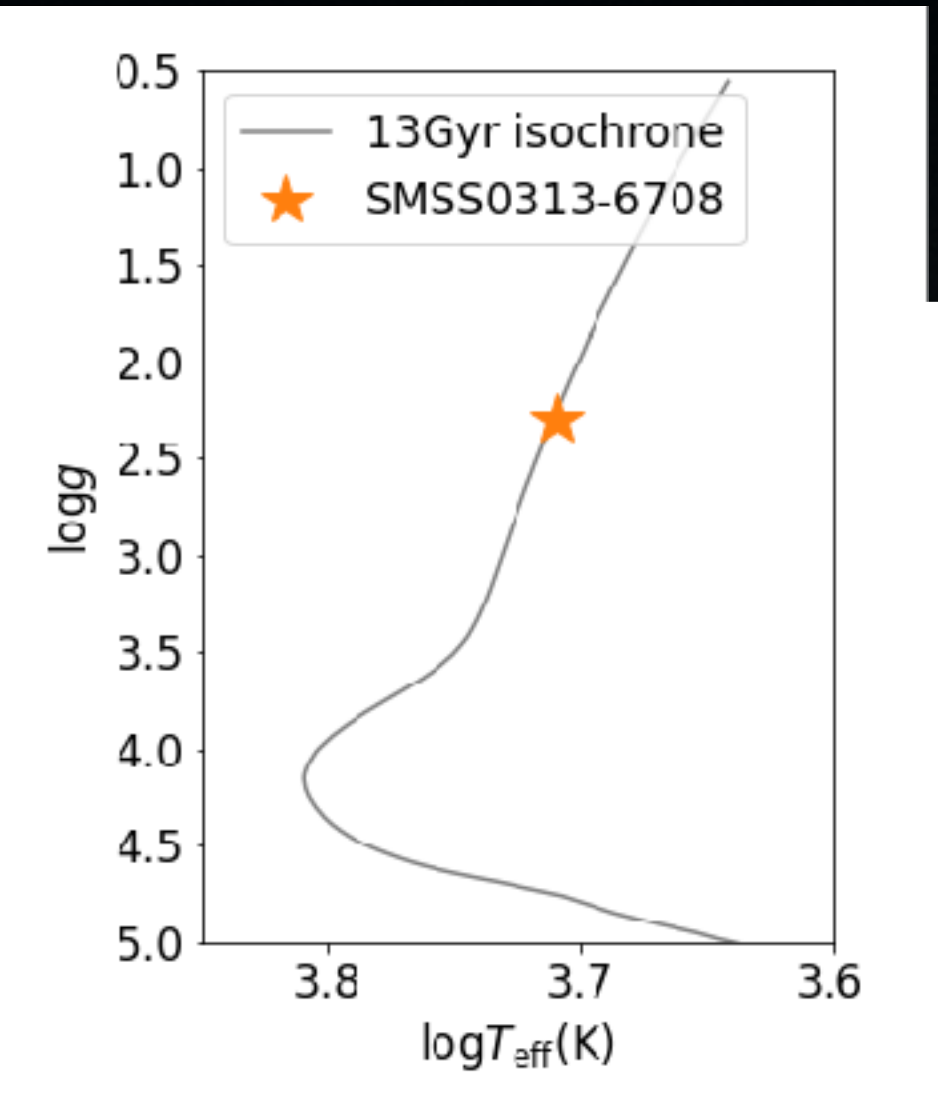


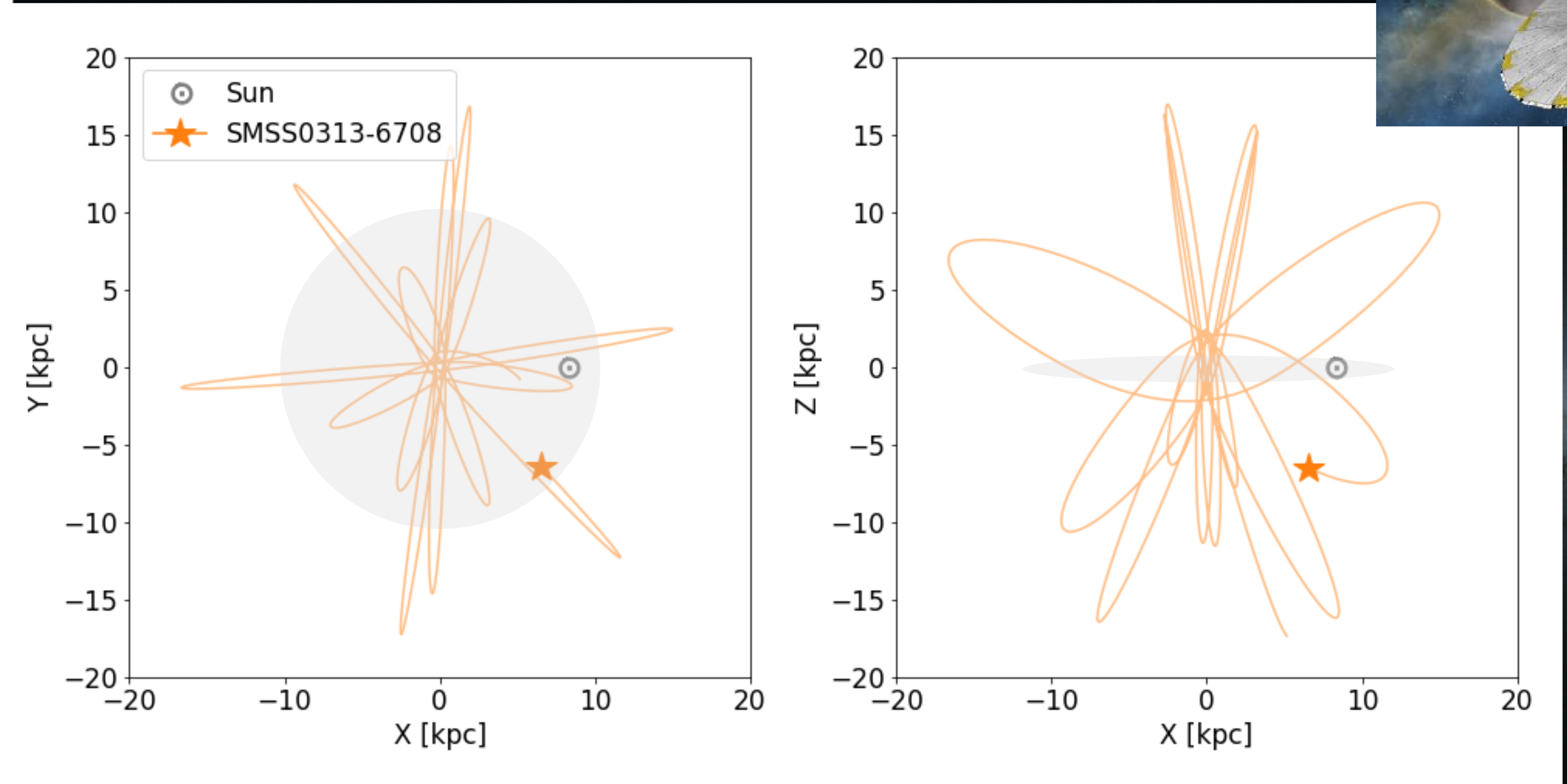
Footprint of the Sky Mapper survey



https://skymapper.anu.edu.au/data-release/#Coverage

The record holder of the lowest Fe abundnce: SMSS 0313-6701 Galactic location and kinematics





Steps in stellar chemical abundance analysis

Continuum, line strengths, line shape…

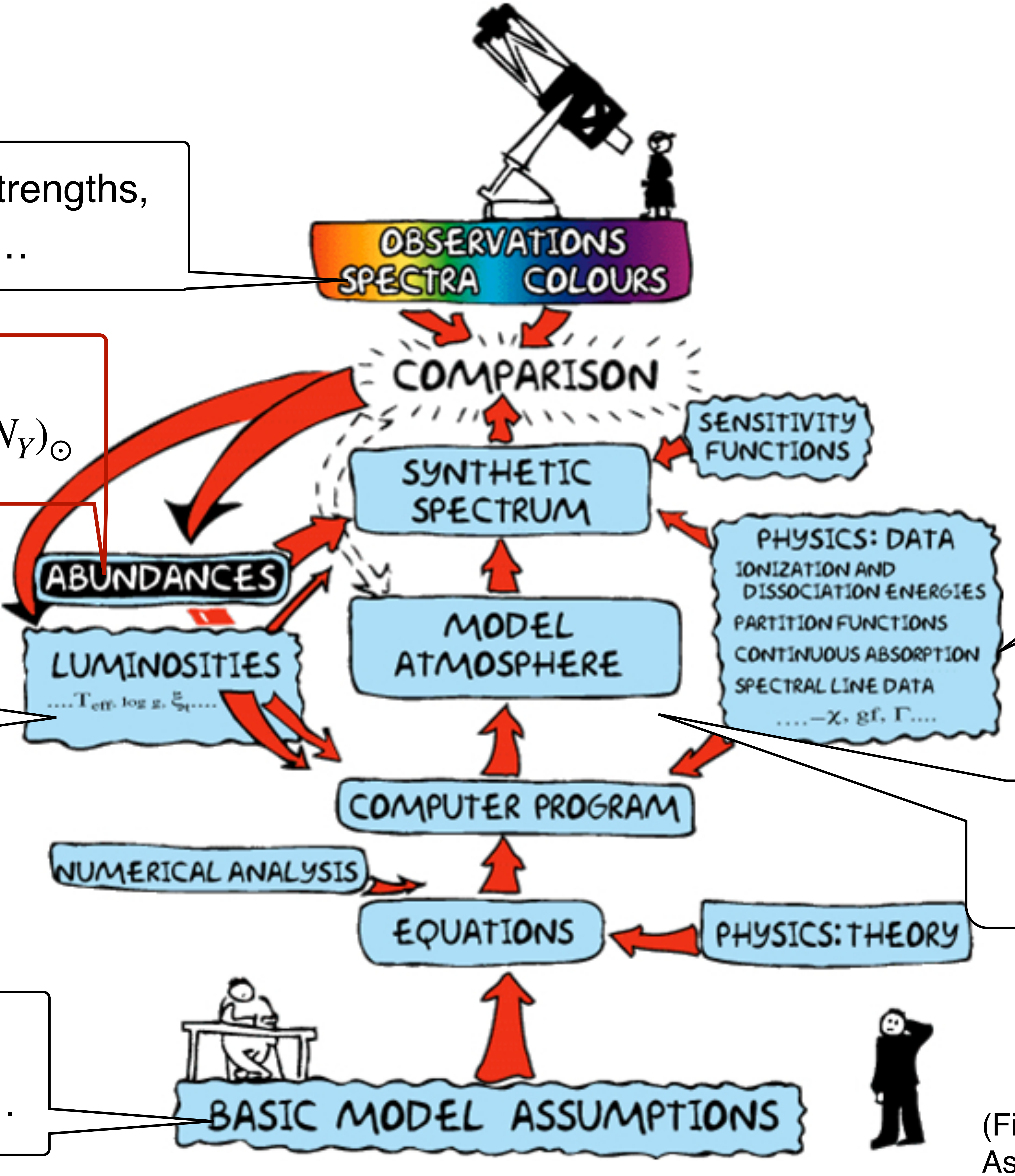
Abundance

$[X/Y] = \log(N_X/N_Y) - \log(N_X/N_Y)_\odot$

Physical properties of the star

$T_{\rm eff}$, $\log g$, [M/H] . . .

static, plane parallel, local thermo-dynamic equilibrium…



Atomic data (excitation potential, partition function, transition probability)

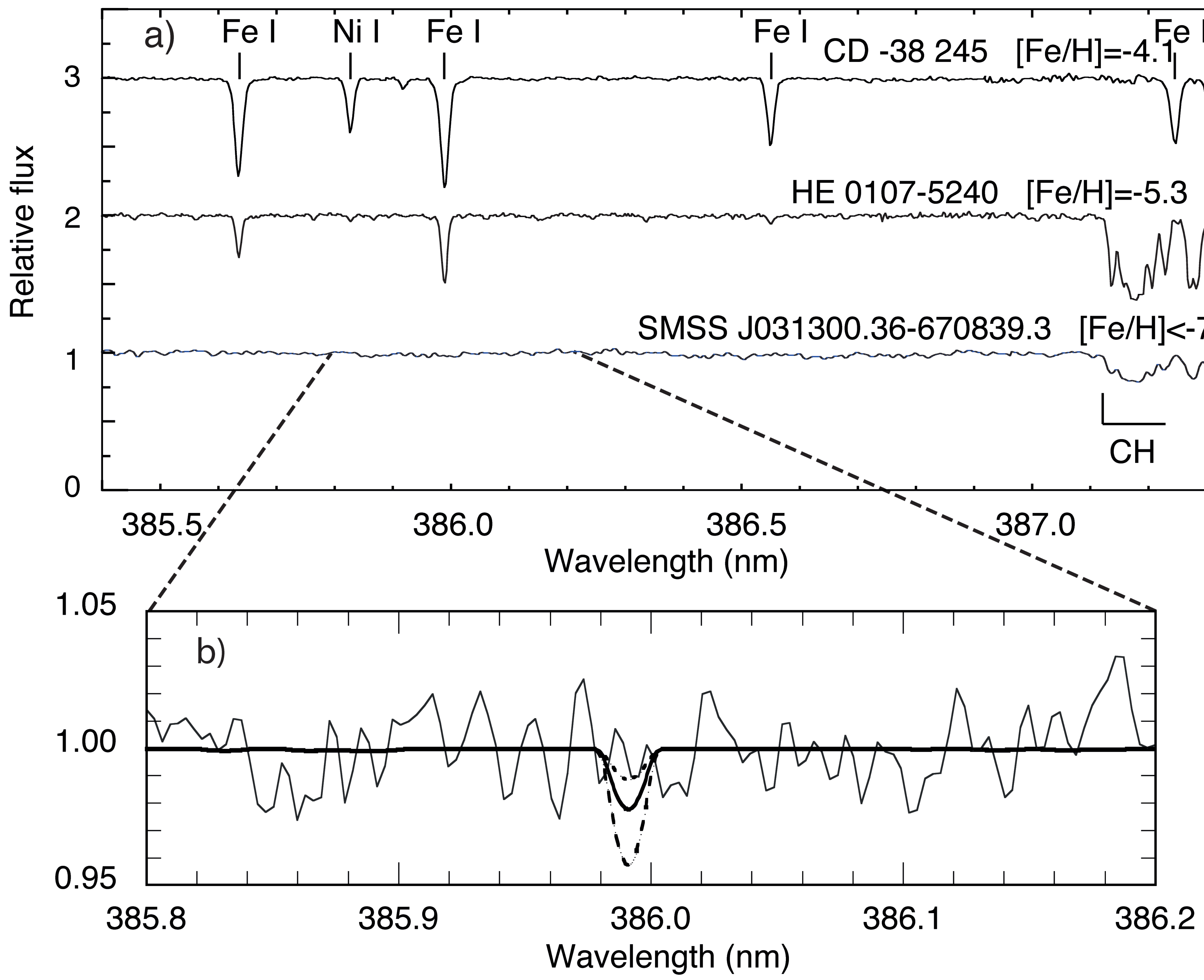
$T(\tau)$, $P(\tau)$, $\rho(\tau)$…

τ: optical depth

(Figure by Bengt Gustafsson, Astronomical Observatory, Uppsala)

The chemical composition: Extremely Fe-poor and carbon enhanced

Keller+14



$[\mathrm{Fe/H}] < -6.53\ (3\sigma)$

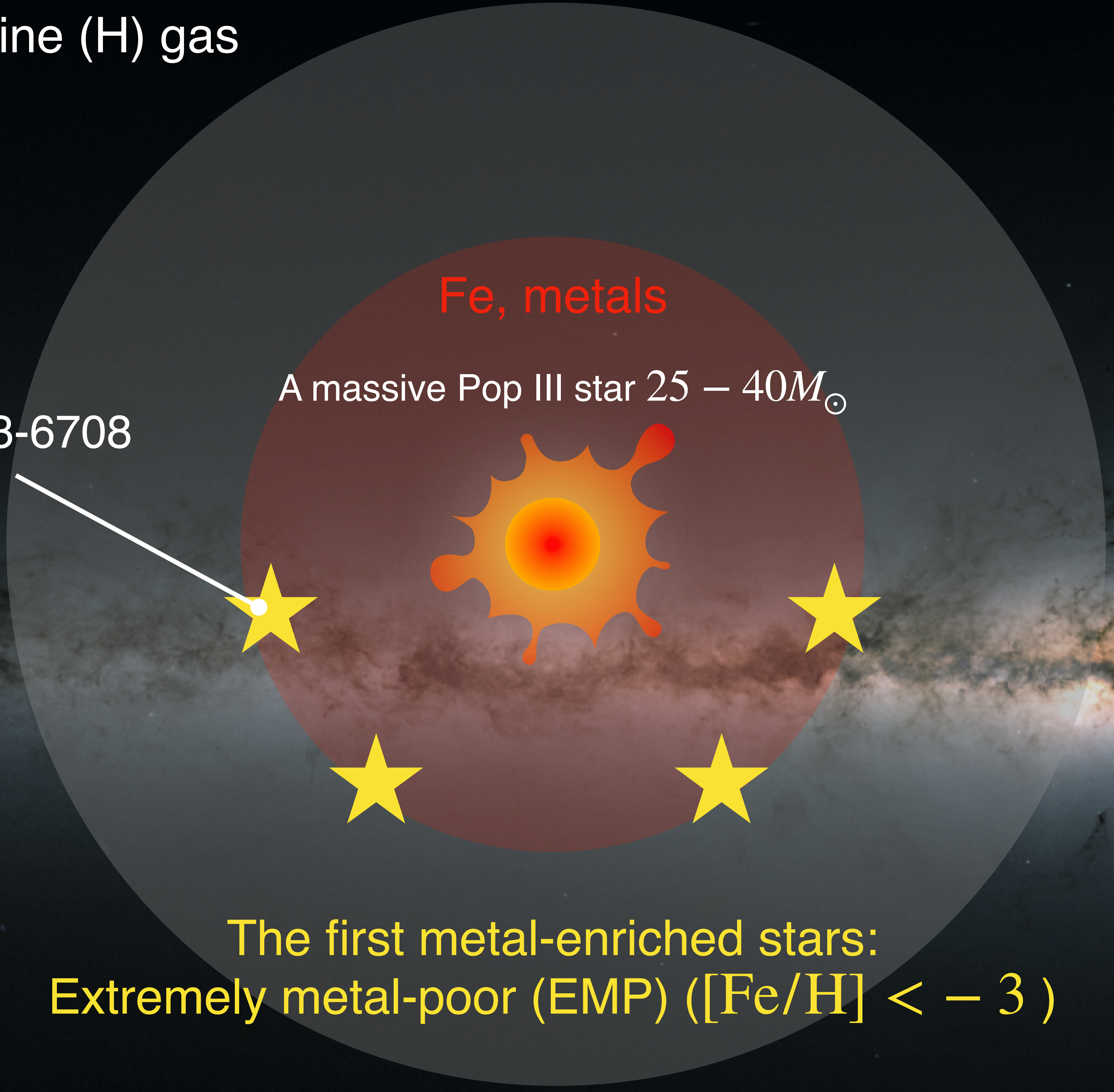
Bessel+15, Nordlander+17

- Ca abundance : 10^{-7} of the Sun
  ➡ Formed under extremely pristine environment
- C/Ca ratio $>10^4$ of the Sun
  ➡ Unusual source of metals

A scenario for the metal-enrichment source

In a dark matter mini-halo ($\sim 10^6 M_\odot$) at $z \gtrsim 20$

Pristine (H) gas

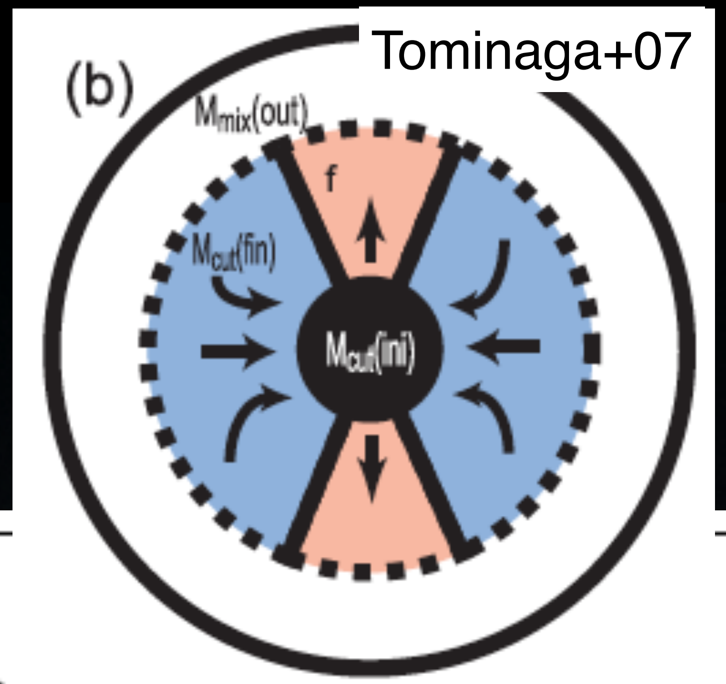


e.g., SMSS 0313-6708

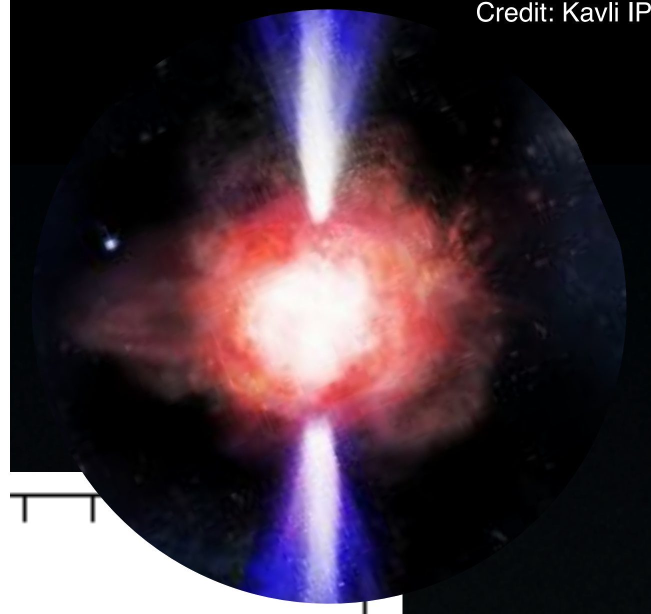
The first metal-enriched stars:
Extremely metal-poor (EMP) ($[\mathrm{Fe/H}] < -3$)

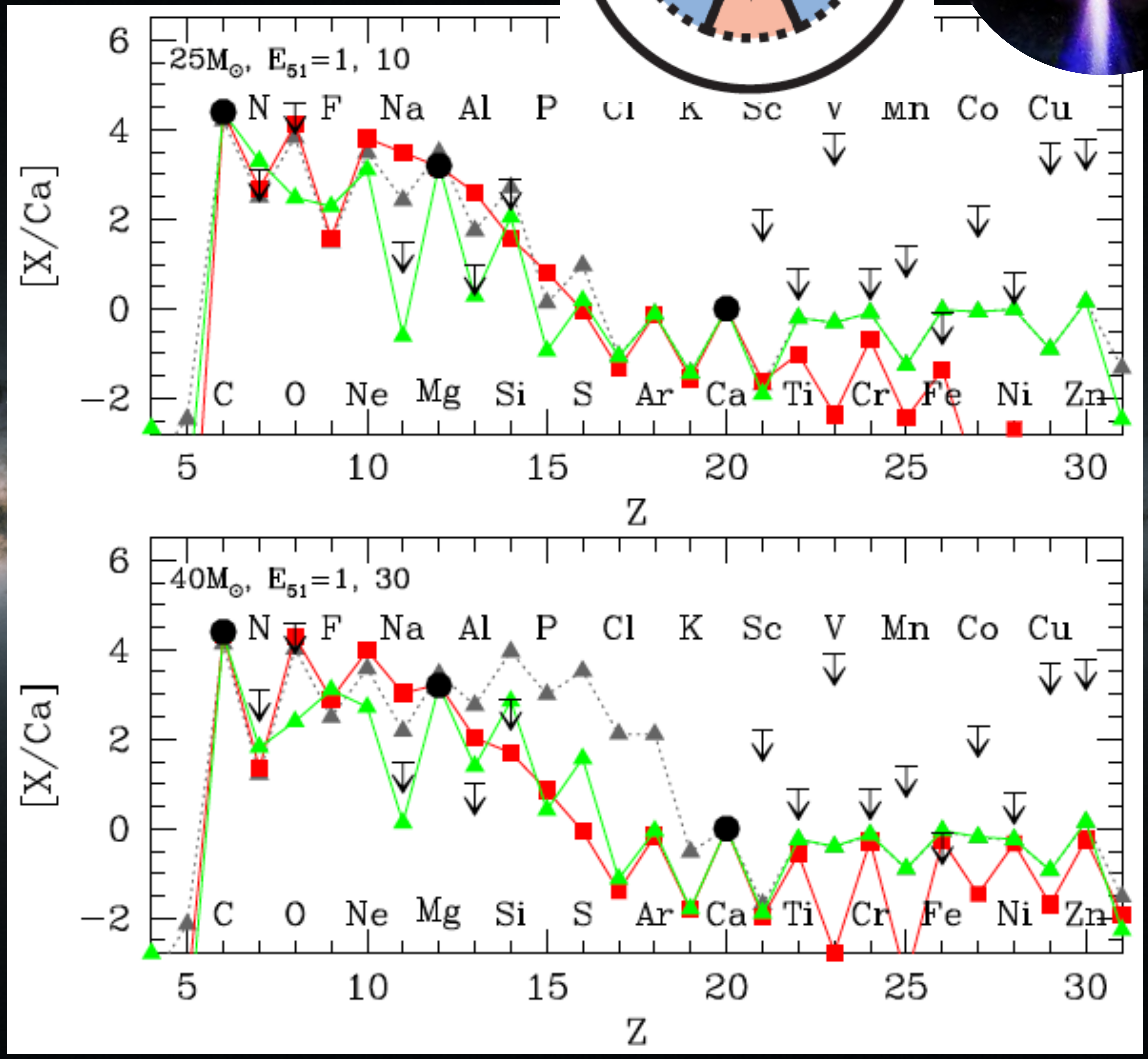
Keller+14, Takahashi+14, Chan+17, Choplin+19, Chan+20

Metal yields of a Pop III star experiencing large fallback leaving a $\sim 5-6M_\odot$ black hole.



Credit: Kavli IPMU

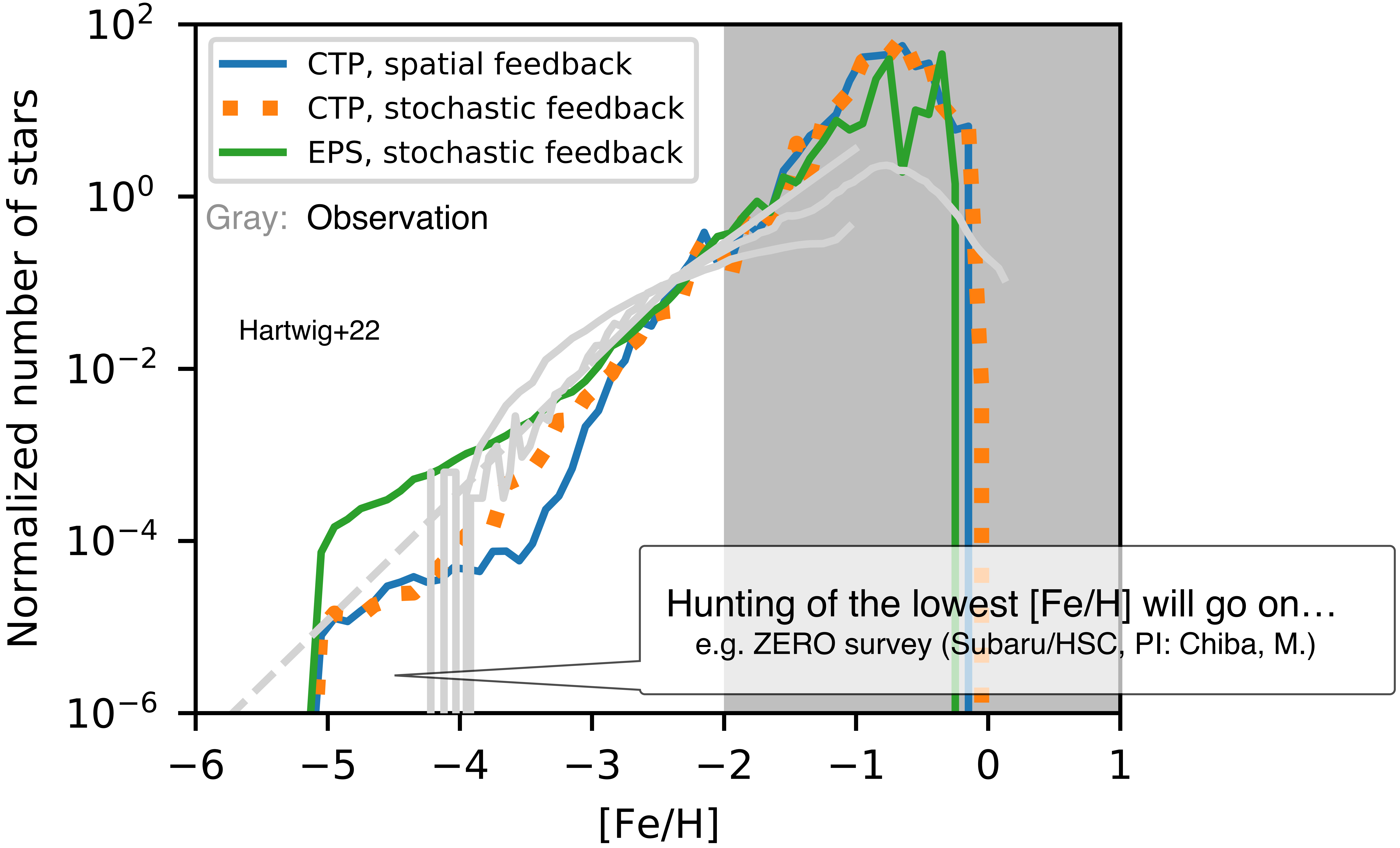




Umeda&Nomoto05, Tominaga+07, MI, Tominaga, Kobayashi & Nomoto14

The metallicity distribution function at lowest metallicities

A smoking gun of the nature of the first stars and their metal enrichment process



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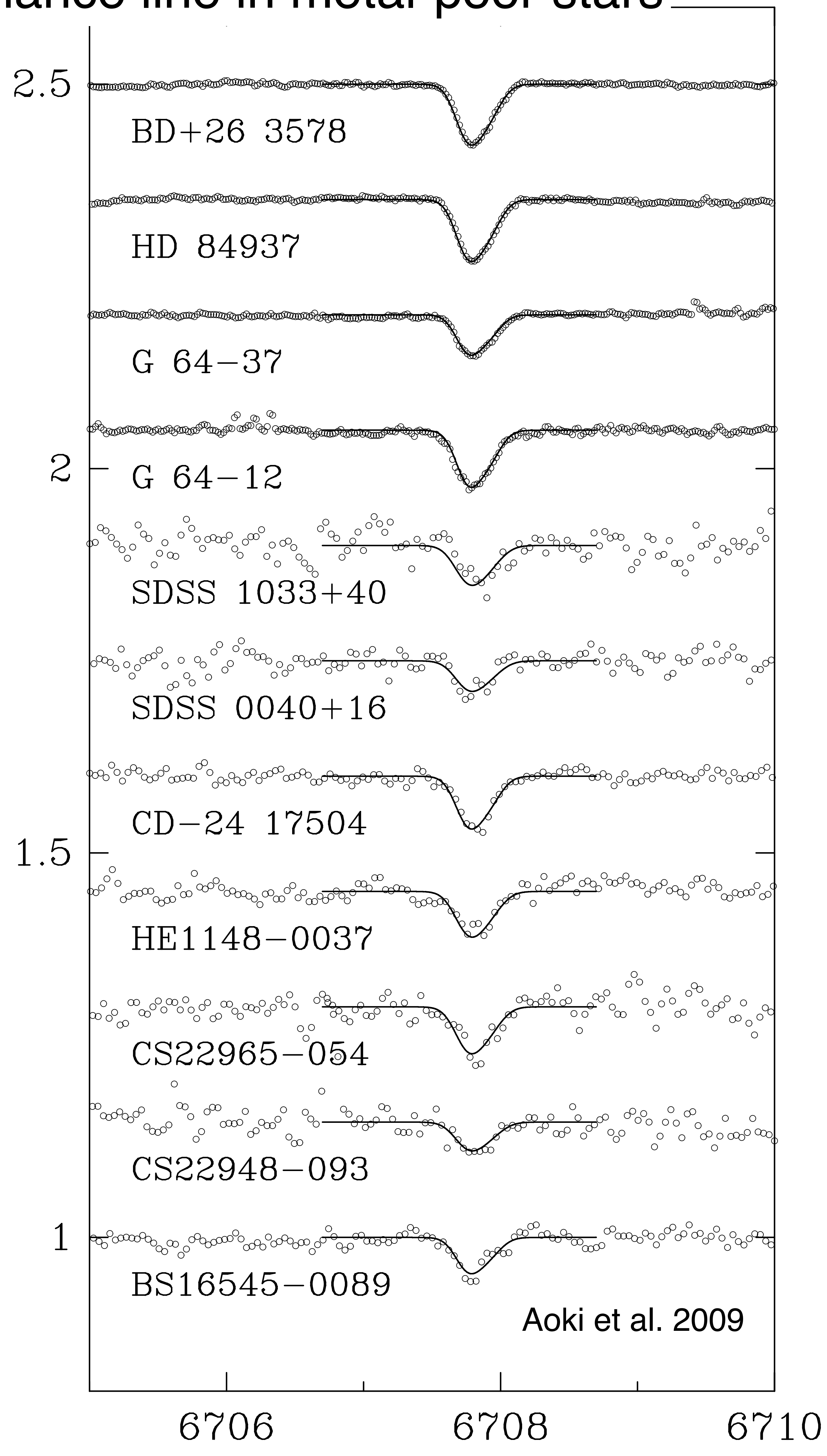
The origin of metals in the early Universe

- Big Bang nucleosynthesis
  - Is the standard theory of BBN correct? Are the stellar evolution models correct?
- The hydrostatic burning of massive stars, including the first stars
  - Is the nature of the first stars different from massive stars at present?
- Core-collapse supernovae
  - How the massive stars explode? Were the explosion energy and/or geometry different?
- Type Ia supernovae
  - How white dwarfs explode?
- Neutron capture (s- or r-process) elements
  - Astrophysical sites of s- and r-processes in the early Universe?

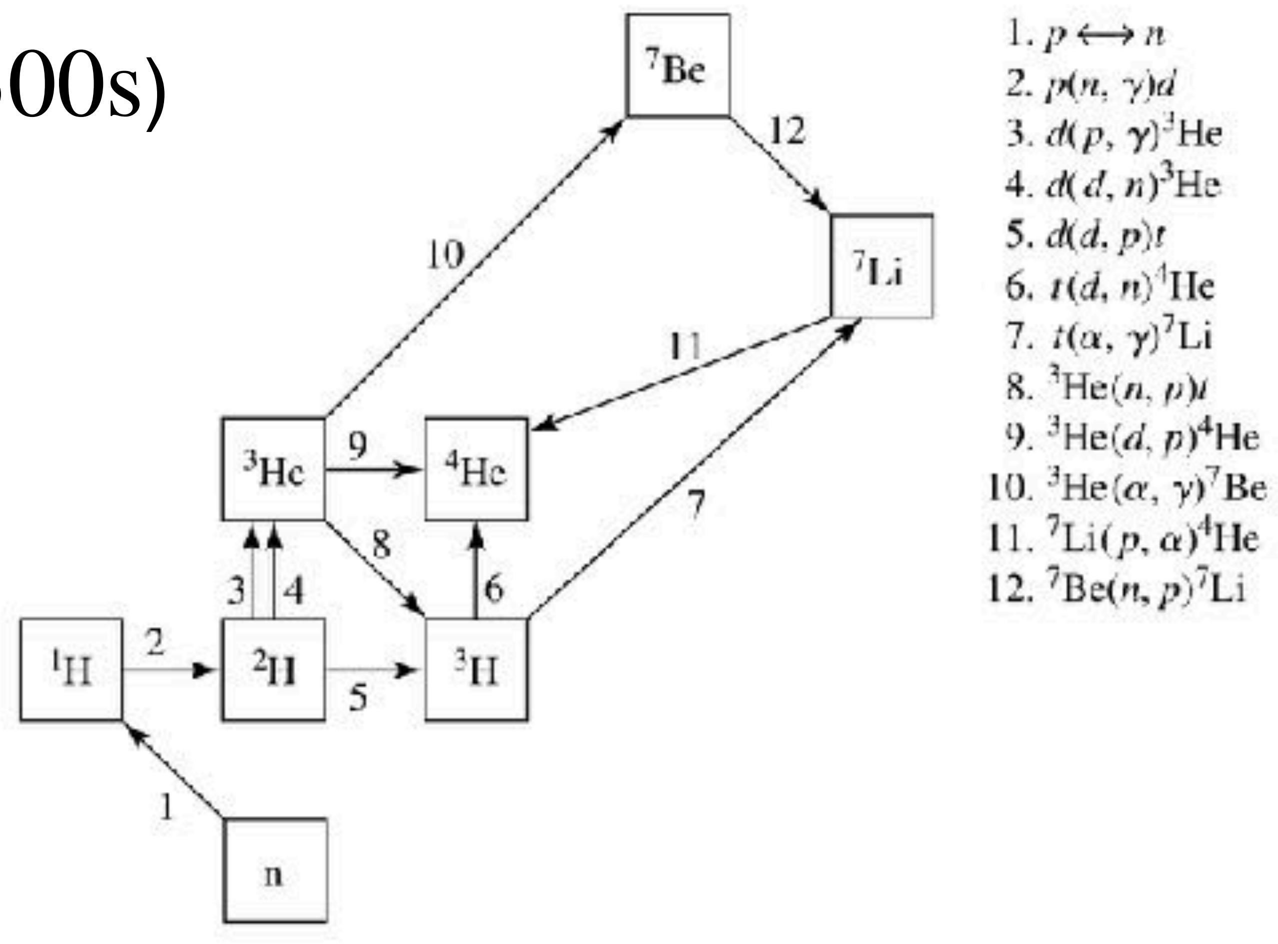
Lithium and Big-Bang nucleosynthesis

The Li resonance line in metal-poor stars

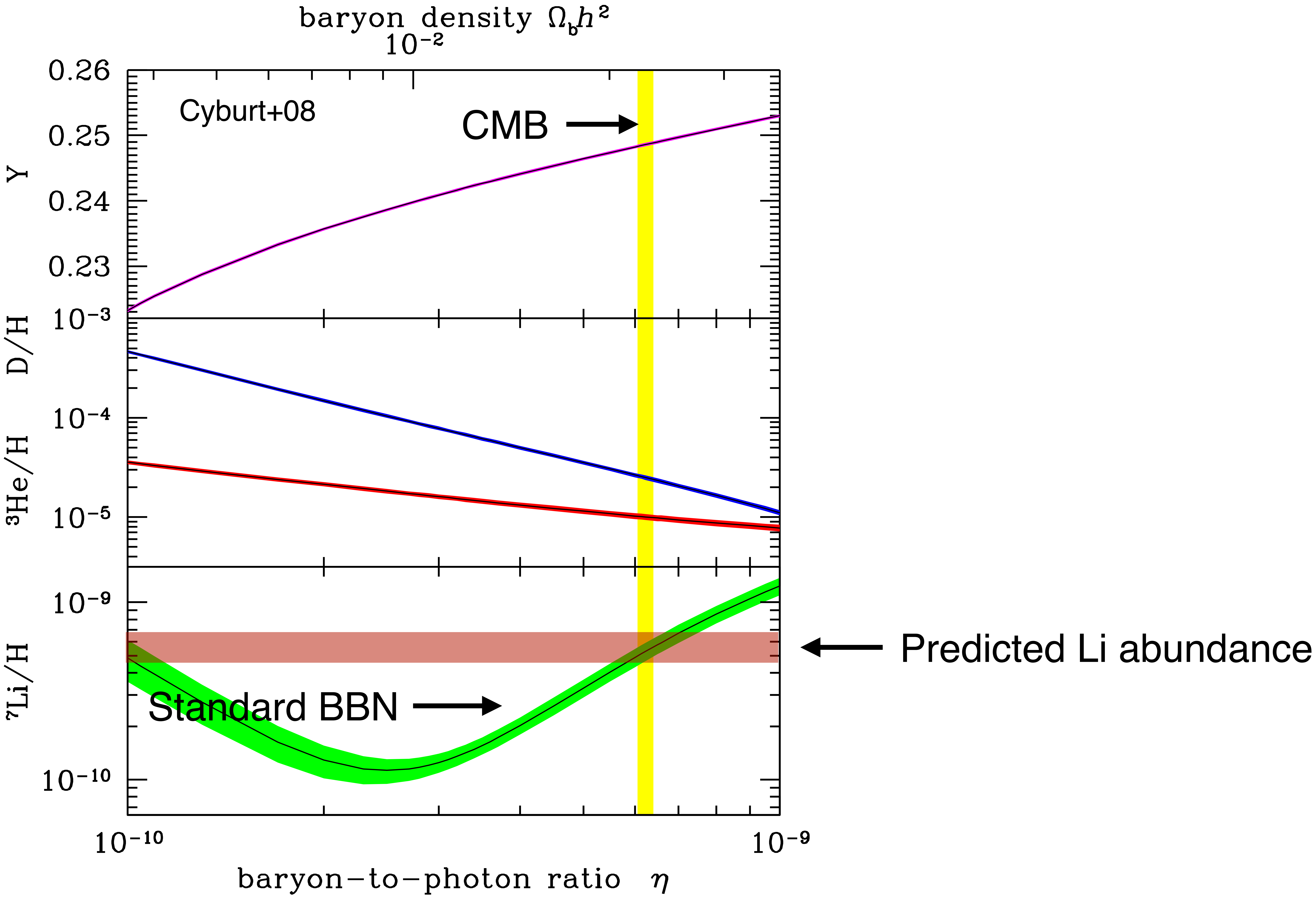


- Production of Li in the Universe
  - Big Bang nucleosynthesis (BBN)
  - Cosmic-ray spallation
  - Stellar interiors
  - Nova
- Fragile
  - Destroyed at ~10^6 K (e.g., Hydrogen burning ~ 10^7 K)

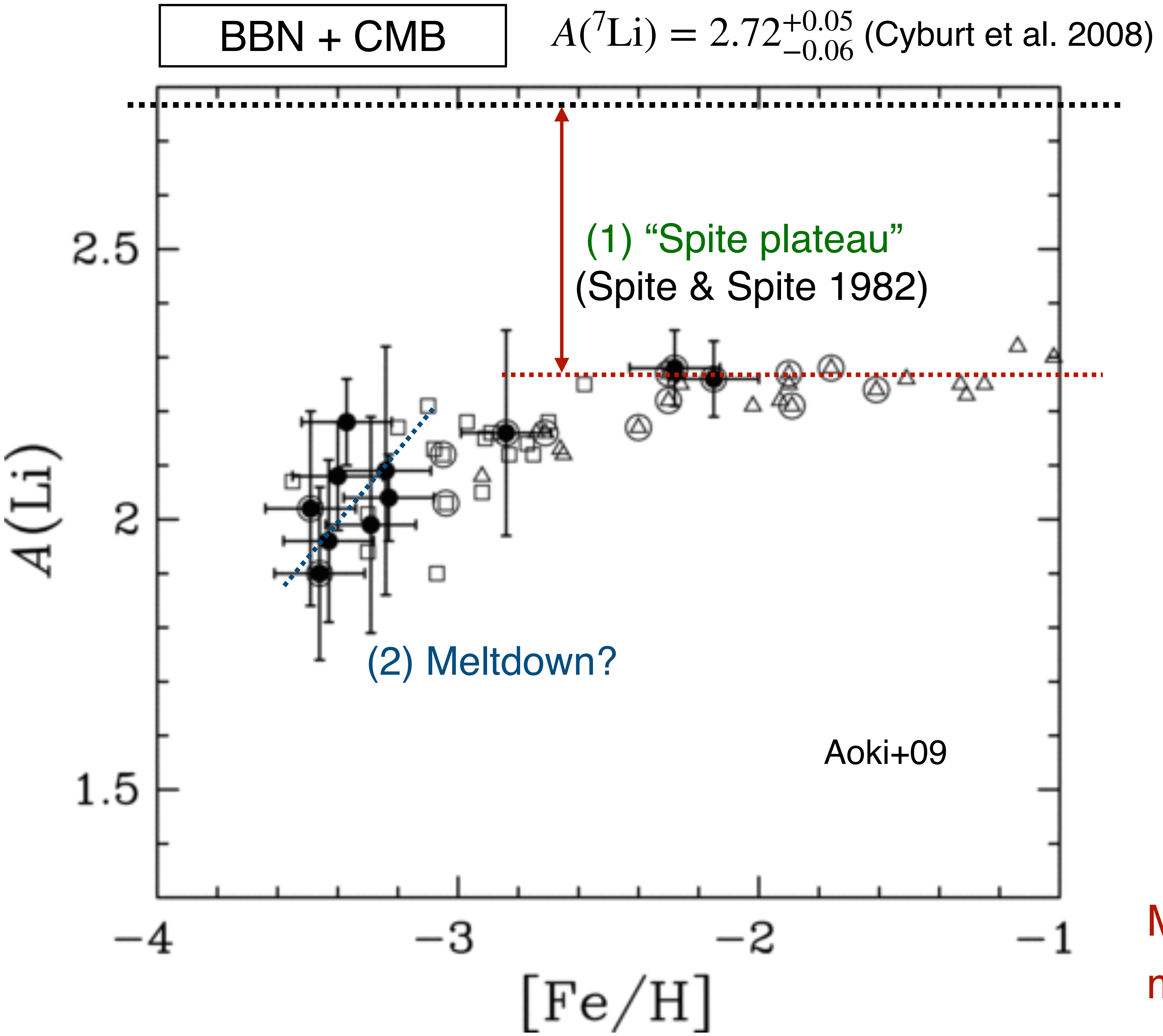
BBN ($t \lesssim 300$s)



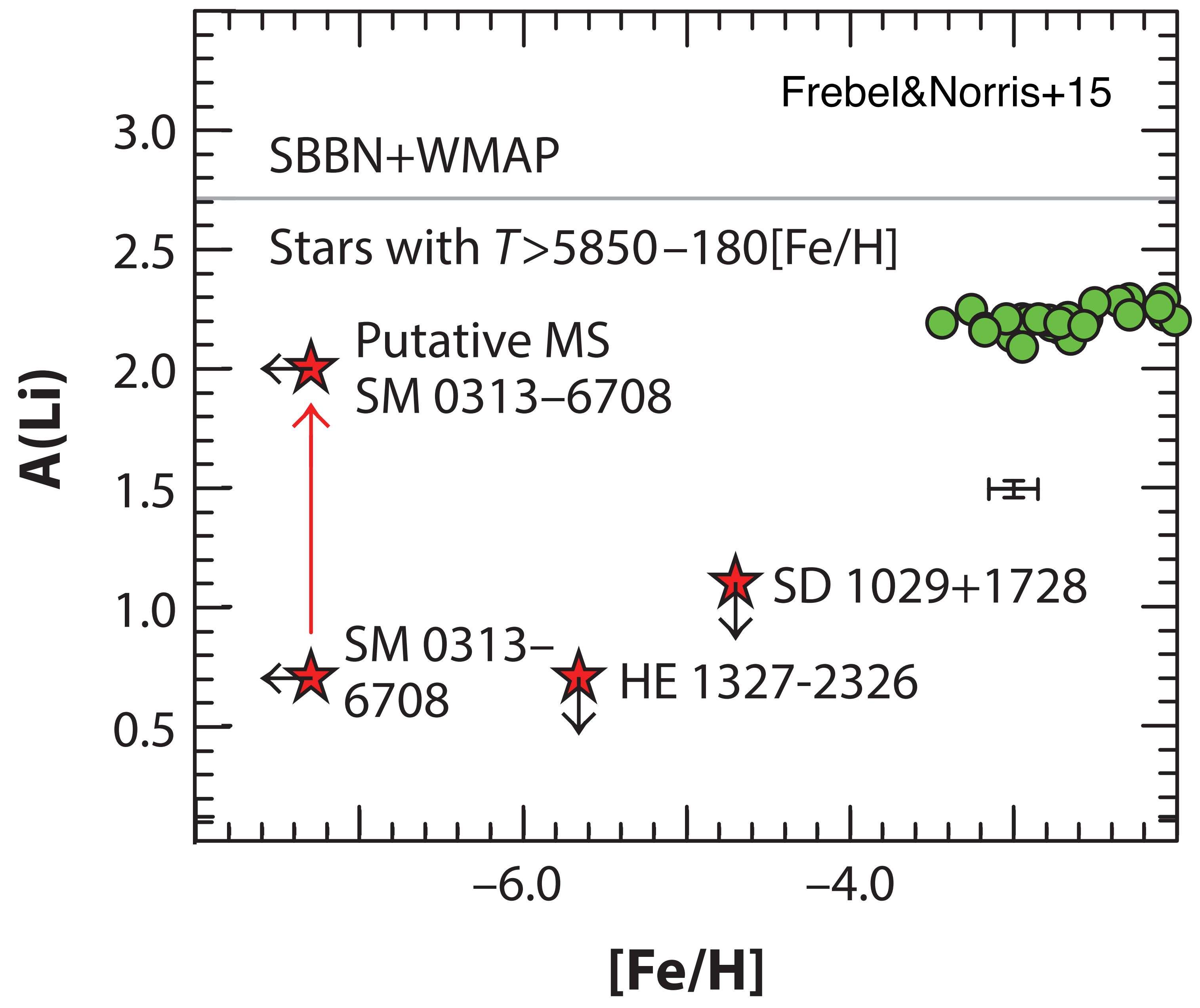
The predictions of the primordial Li abundance



The cosmological Li problem



- Incomplete understanding in Li production/ destruction in stars?
- Non-standard theories for the BBN?



Measurement of Li abundances in the most metal-poor stars is the key!

Synthesis of CNO in stars

- Hydrogen burning through the CNO cycle
  - Main-sequence stars with $\gtrsim 1M_\odot$
  - $T \sim 1.5 \times 10^7$ K

$$
\begin{aligned}
{}^{12}\mathrm{C} + \mathrm{p} &\rightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + \mathrm{e}^+ + \nu \\
{}^{13}\mathrm{C} + \mathrm{p} &\rightarrow {}^{14}\mathrm{N} + \gamma \\
\boxed{{}^{14}\mathrm{N} + \mathrm{p} \rightarrow {}^{15}\mathrm{O} + \gamma} & \\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + \mathrm{e}^+ + \nu \\
{}^{15}\mathrm{N} + \mathrm{p} &\rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He} \\
&\rightarrow {}^{16}\mathrm{O} + \gamma \\
{}^{16}\mathrm{O} + \mathrm{p} &\rightarrow {}^{17}\mathrm{F} + \gamma \\
{}^{17}\mathrm{F} &\rightarrow {}^{17}\mathrm{O} + \mathrm{e}^+ + \nu \\
{}^{17}\mathrm{O} + \mathrm{p} &\rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}
\end{aligned}
$$

Bottle neck: most of the ^{12}C are converted to ^{14}N

©天文学辞典

- Helium burning through the triple alpha process
  - The core of the red giant tip
  - $T \sim 1 \times 10^8$ K

$$
{}^4_2\mathrm{He} + {}^4_2\mathrm{He} \rightleftharpoons {}^8_4\mathrm{Be}
$$

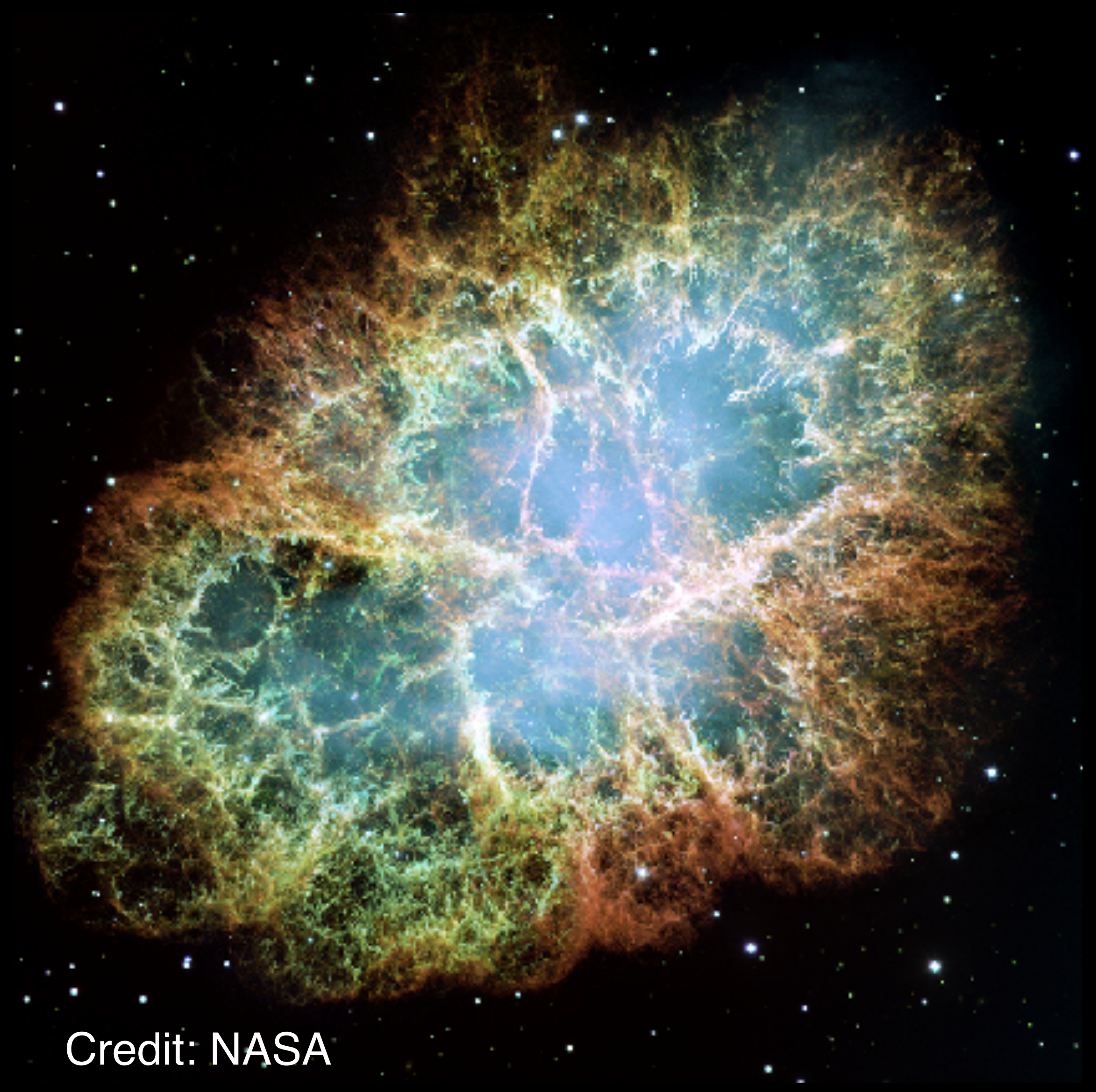
$$
{}^8_4\mathrm{Be} + {}^4_2\mathrm{He} \rightarrow {}^{12}_6\mathrm{C} + \gamma.
$$

- Carbon burning
  - Massive stars
  - $T \sim 6 \times 10^8$ K

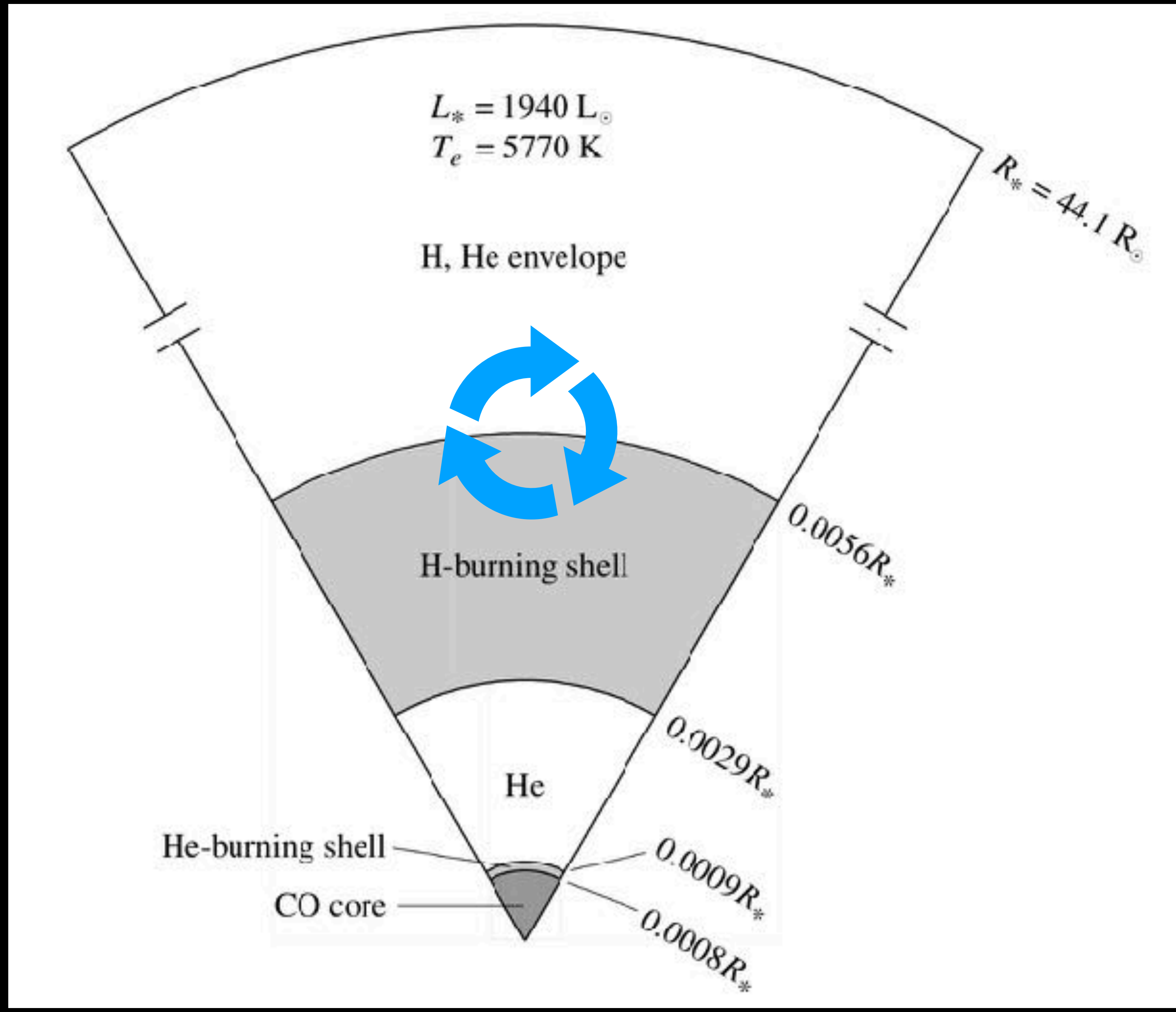
$$
{}^{12}_6\mathrm{C} + {}^4_2\mathrm{He} \rightarrow {}^{16}_8\mathrm{O} + \gamma
$$

CNO enrichment in the early Universe

Core-collapse supernova

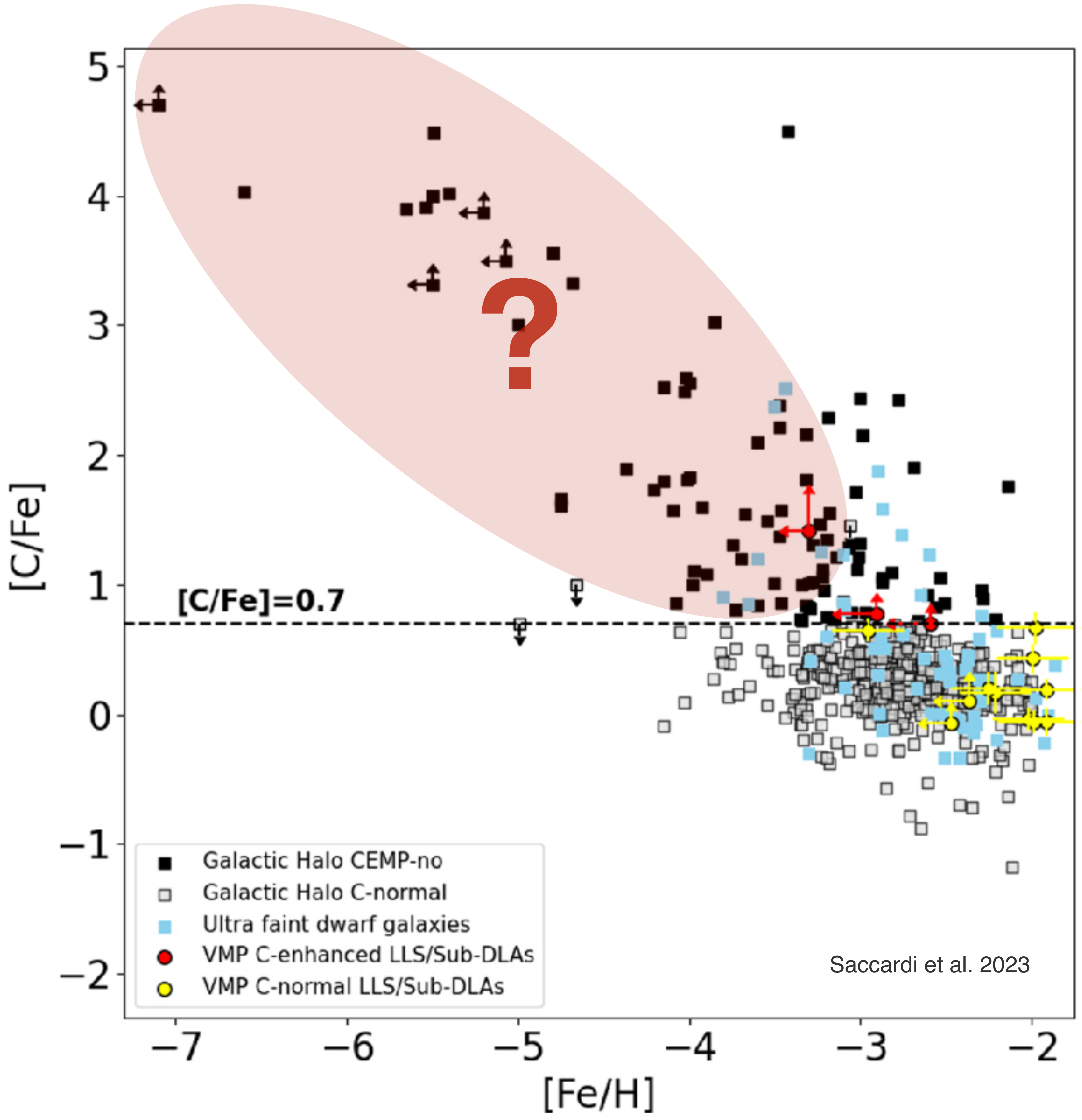


Asymptotic Giant Branch (AGB) stars



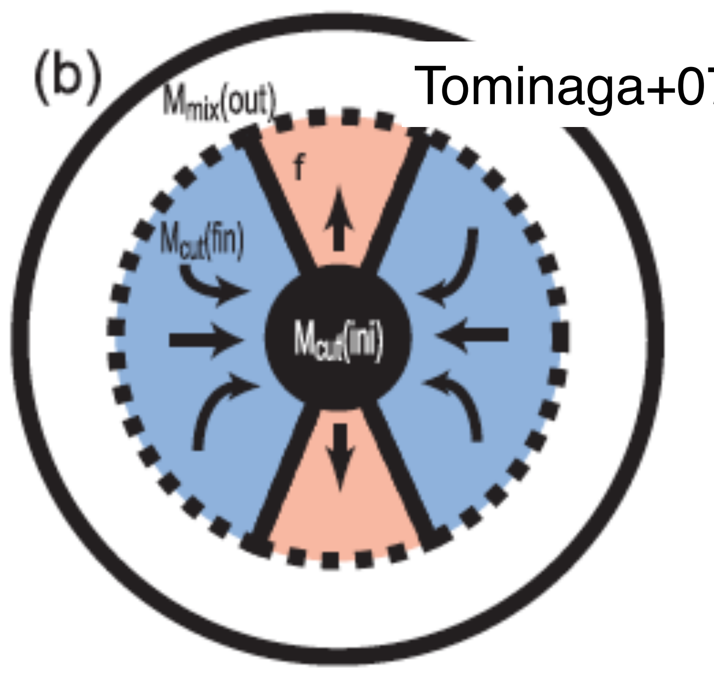
Winds from rotating massive stars

The origin of carbon-enhanced metal-poor (CEMP) stars



- More metal-poor stars show higher [C/Fe] ratios
- Possible explanation
  - Supernovae of the first stars
  - Mass transfer from an AGB companion
  - Dust cooling in the formation of low-mass second-generation stars
  - Rotating massive stars

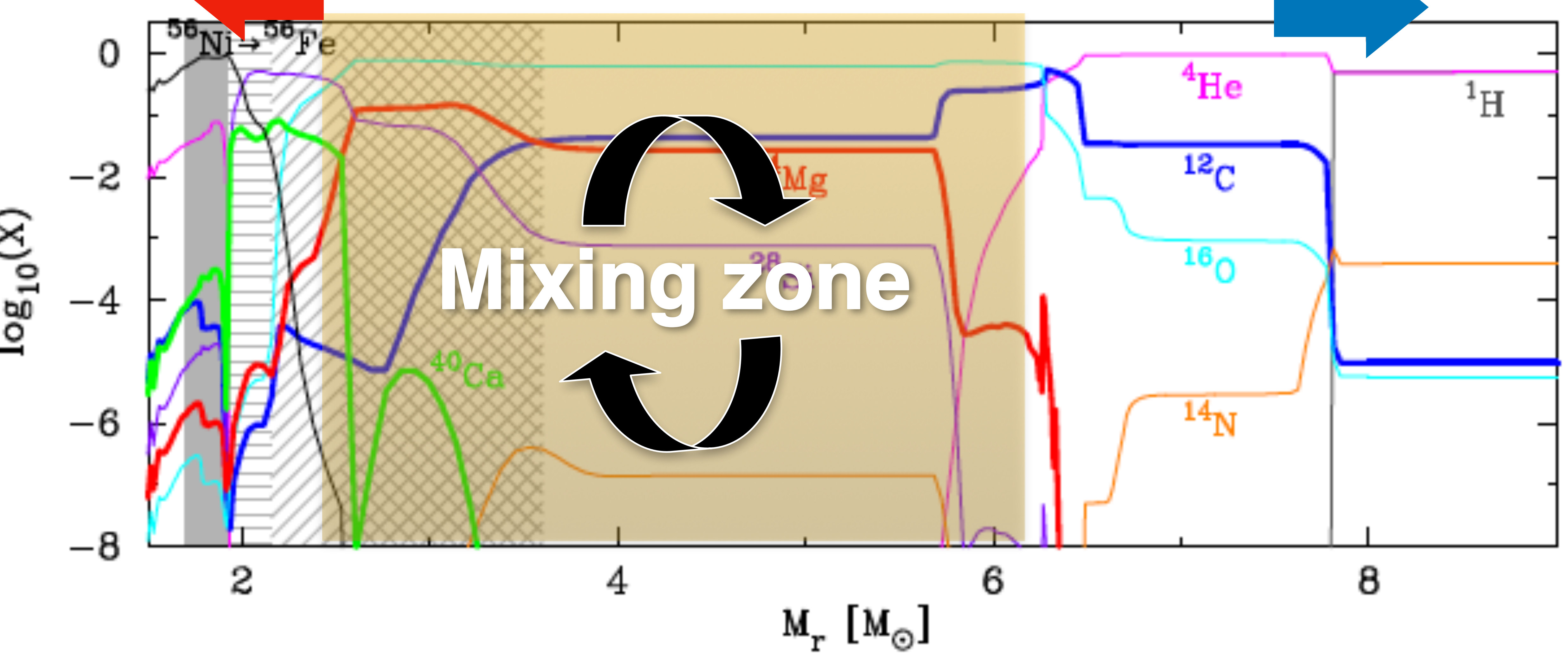
Faint supernovae of the first stars



The carbon enhancement as the result of fallback of Fe or Ca to the compact remnant

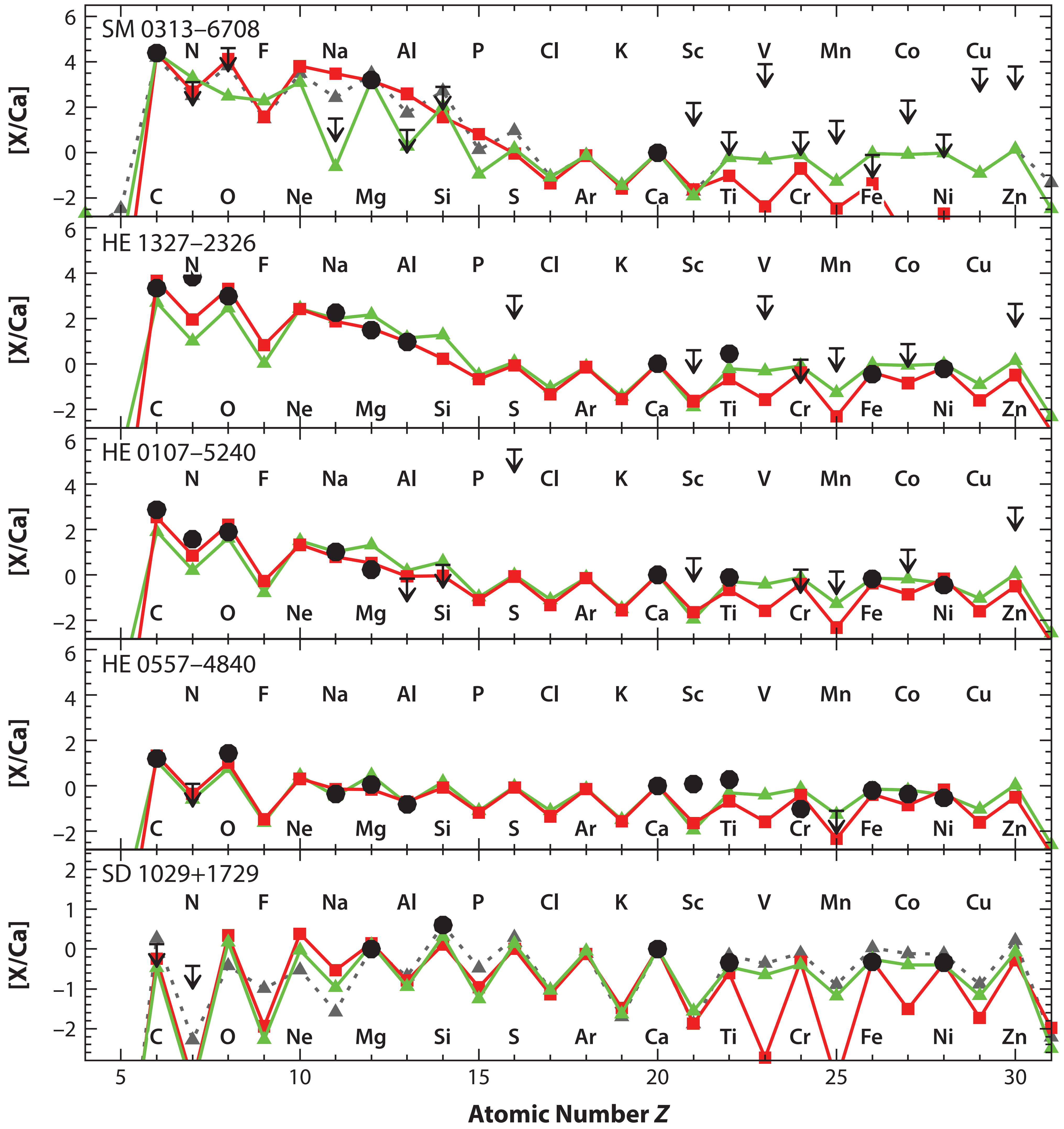
Fallback

Ejection



Umeda&Nomoto02, 03, Iwamoto+05, Tominaga+07, Ishigaki+14

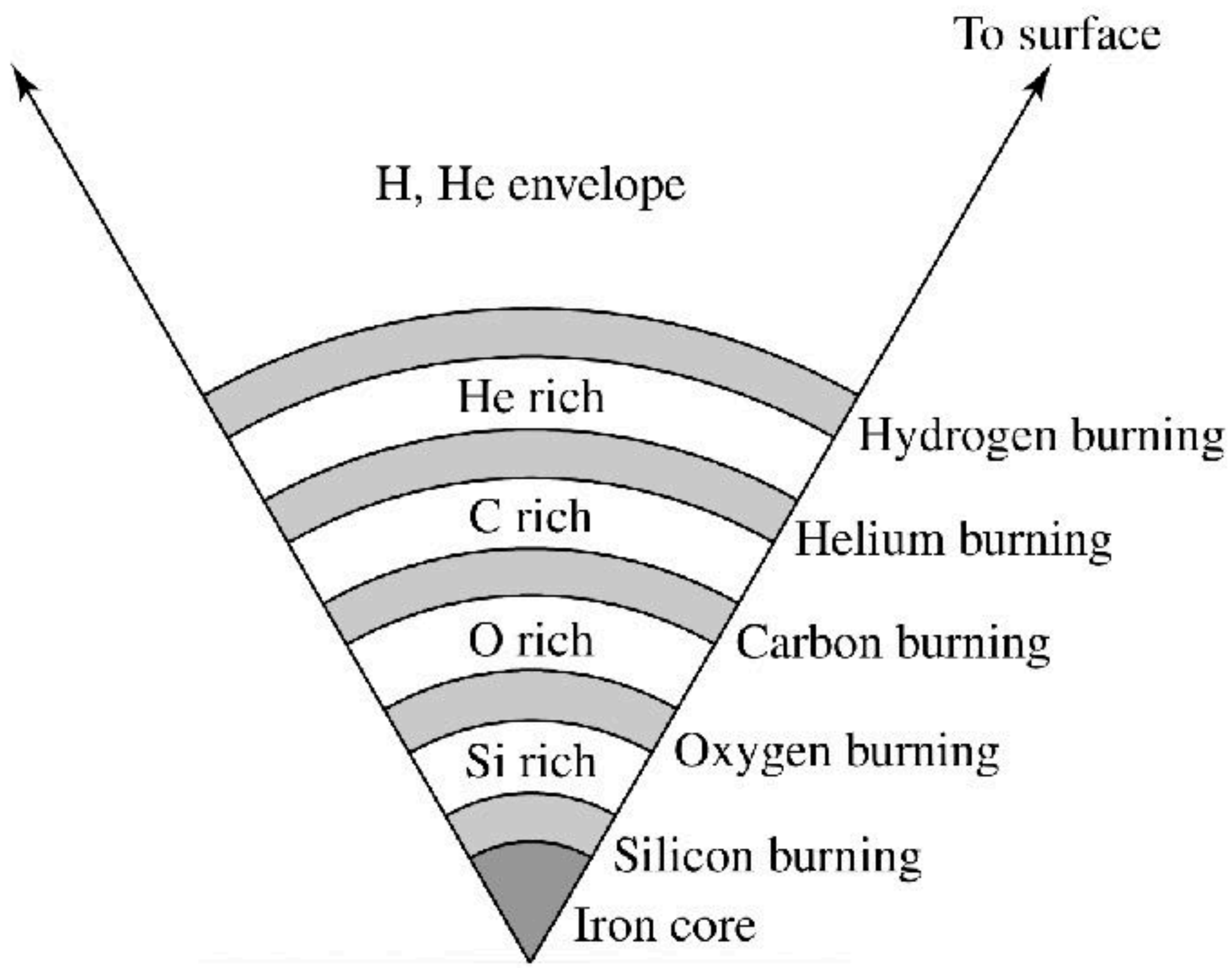
Ishigaki+14, Frebel & Norris 2015



The origin of CEMP stars remain unclear… Larger samples of elemental abundances in EMP stars are needed.

α-element: the most popular tracer of galactic chemical evolution

Massive stars with $\sim 10 - 100 M_\odot$ → The core is hot enough to ignite carbon



* α-element

- Carbon and Neon burning $(T \sim 10^9 \ [\mathrm{K}],\ t \sim 600 \ [\mathrm{yr}])$

  → Na、Mg、Ne、O

- Oxygen burning $(T \sim 2 \times 10^9 \ [\mathrm{K}],\ t \sim \frac{1}{2} \ [\mathrm{yr}])$

  → Si、S

- Silicon burning $(T \geq 3 \times 10^9 \ [\mathrm{K}],\ t \sim 1 \ [\mathrm{day}])$

  → Fe、Ni (F-peak elements)

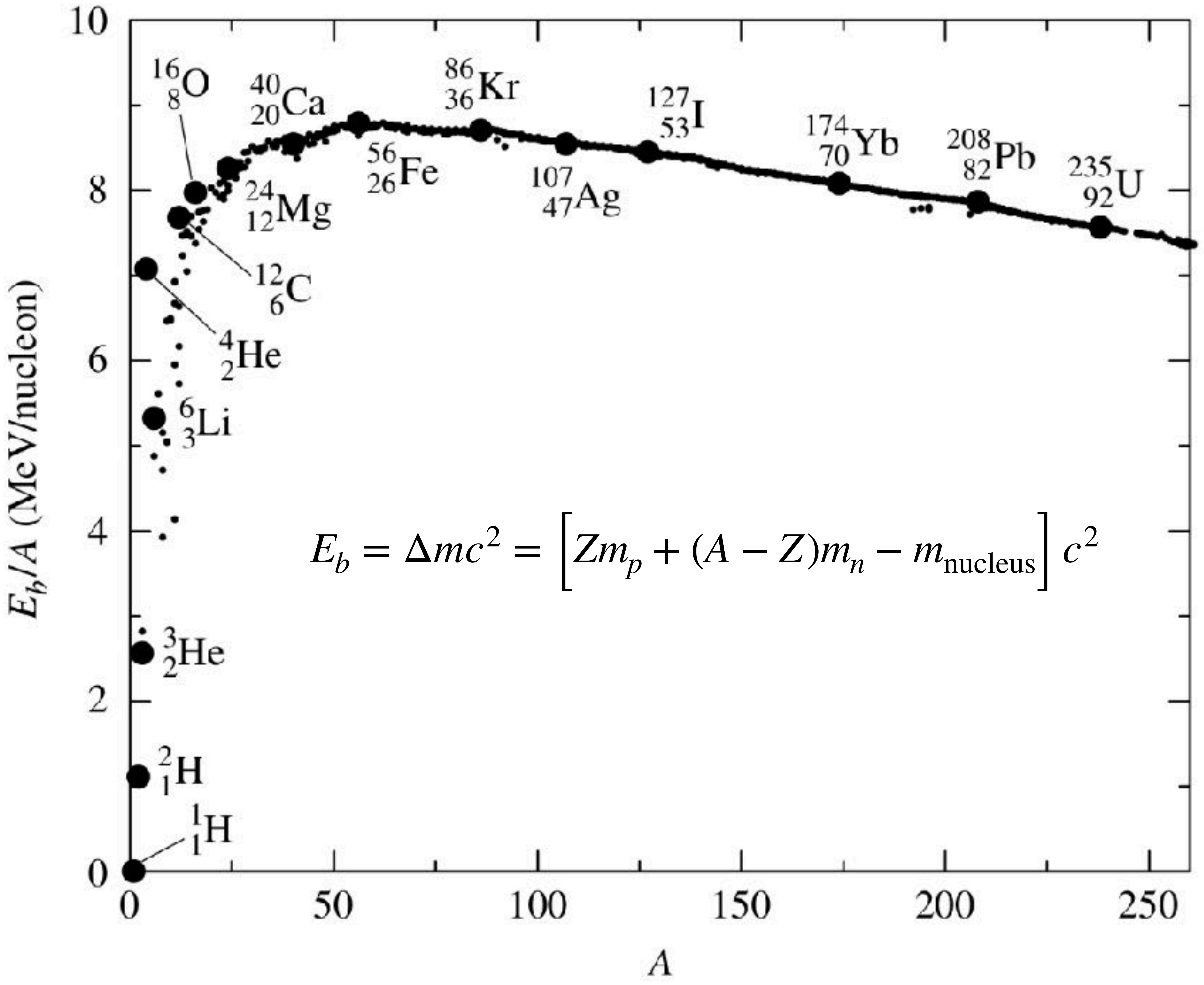
Abundance of nuclei determined by the temperature and density (thermal equilibrium)

→ Onion-skin-like structure with an iron core

The fate of massive stars

Extremely high temperature and density $(T \sim 8 \times 10^9\ [\mathrm{K}],\ \rho \sim 10^{13}\ [\mathrm{kg\ m^{-3}}])$

Binding energy per nuclei



Presence of high-energy photon

→ Photo-dissociation of Fe (endothermic)

An electron and a proton to produce neutrons

→ Lose electron degenerate pressure

➡ Losing pressure support leads to Fe core-collapse

➡ Core-collapse supernova → supernova nucleosynthesis

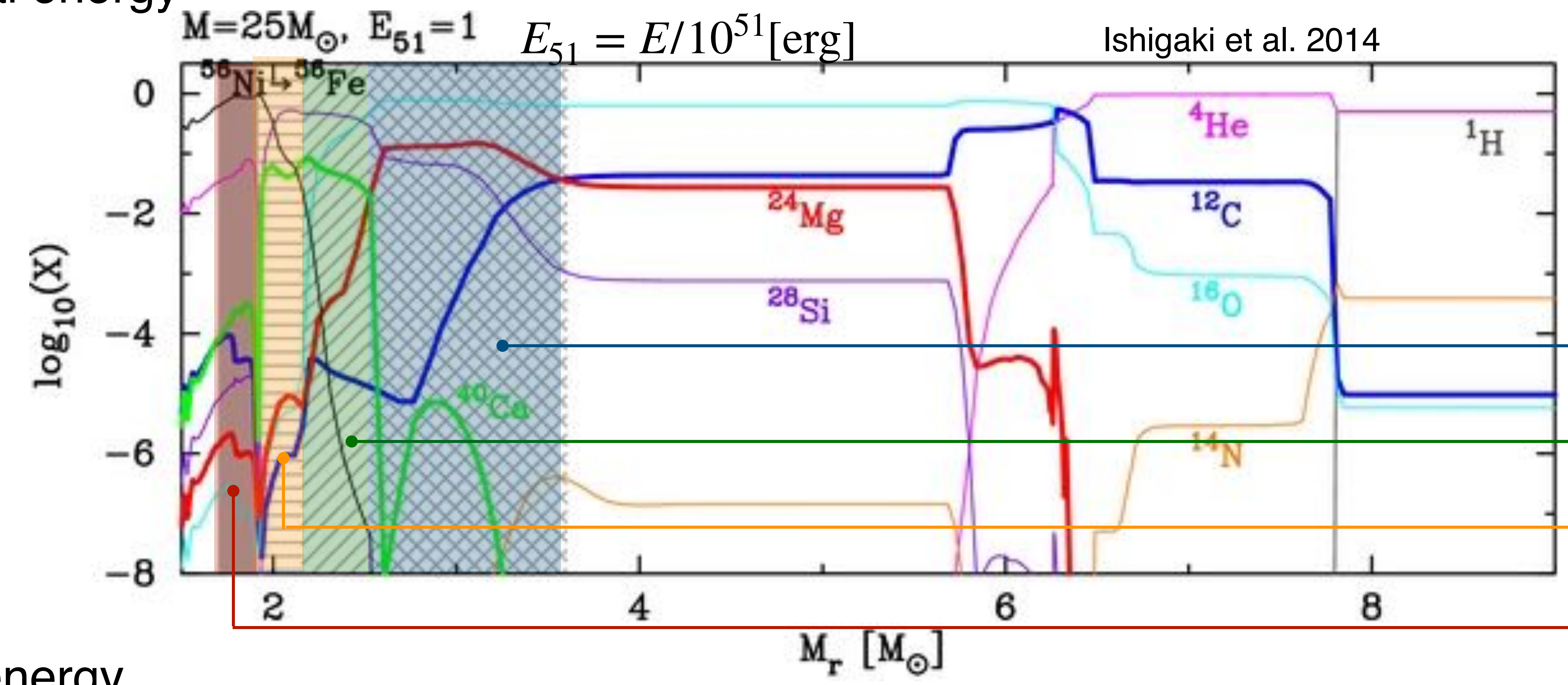
Explosive nucleosynthesis in core-collapse supernovae (CCSNe)

More elements are created at the time of explosion

Normal energy

$E_{51} = E/10^{51}$[erg]

Ishigaki et al. 2014



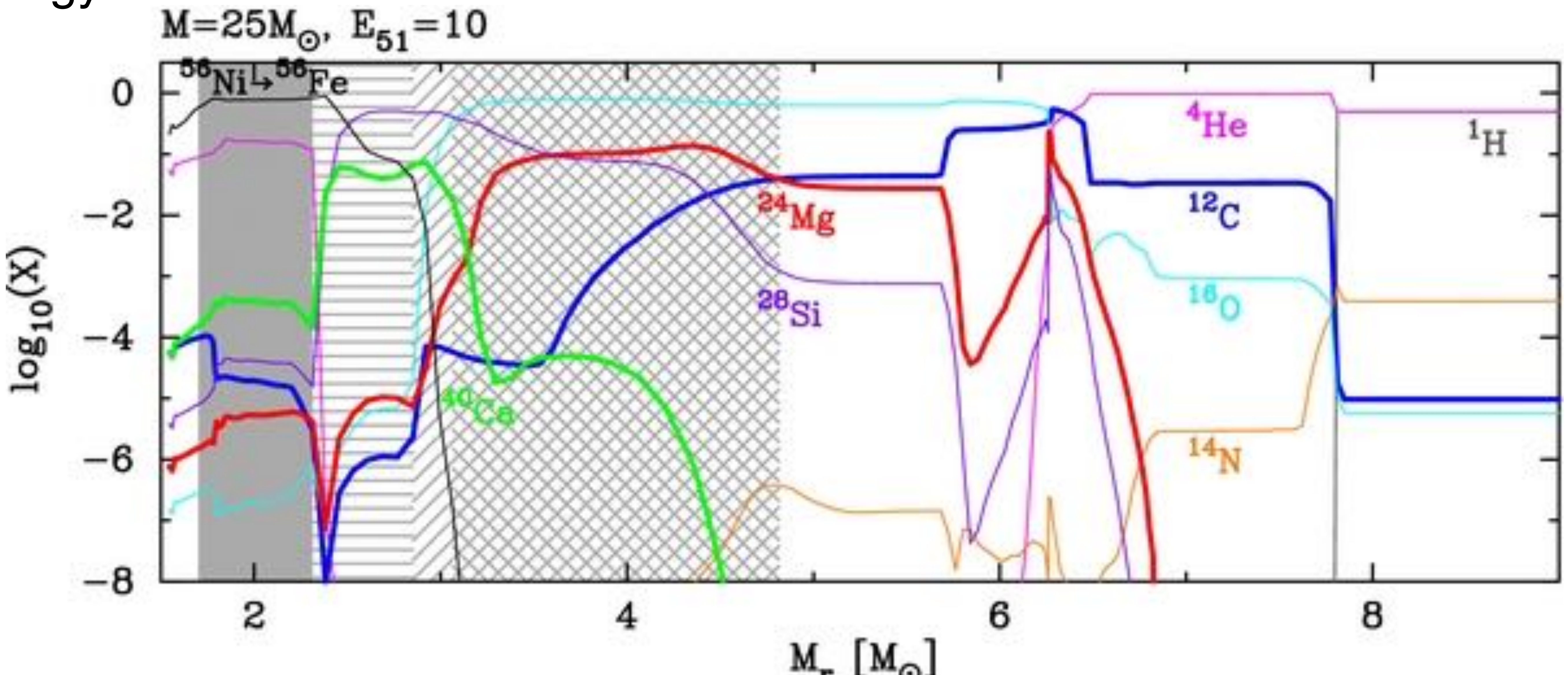
Explosive C burning: Ne, Mg

Explosive Ne burning: O, Si

Incomplete Si burning: Cr, Mn

Complete Si burning: Fe, Ni, Co, Zn

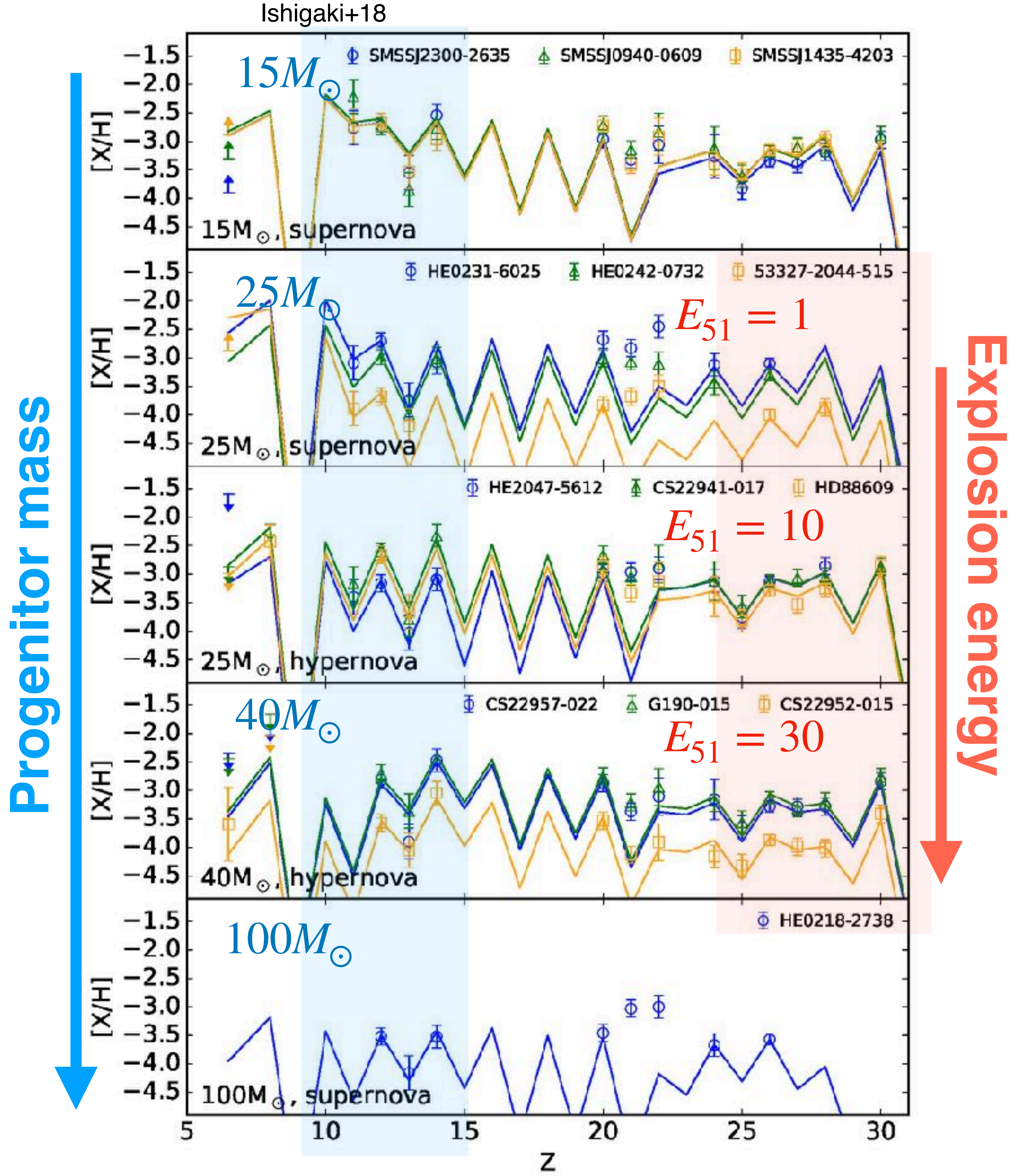
High energy



Nucleosynthesis products depends on

- Explosion energy
- Mass cut

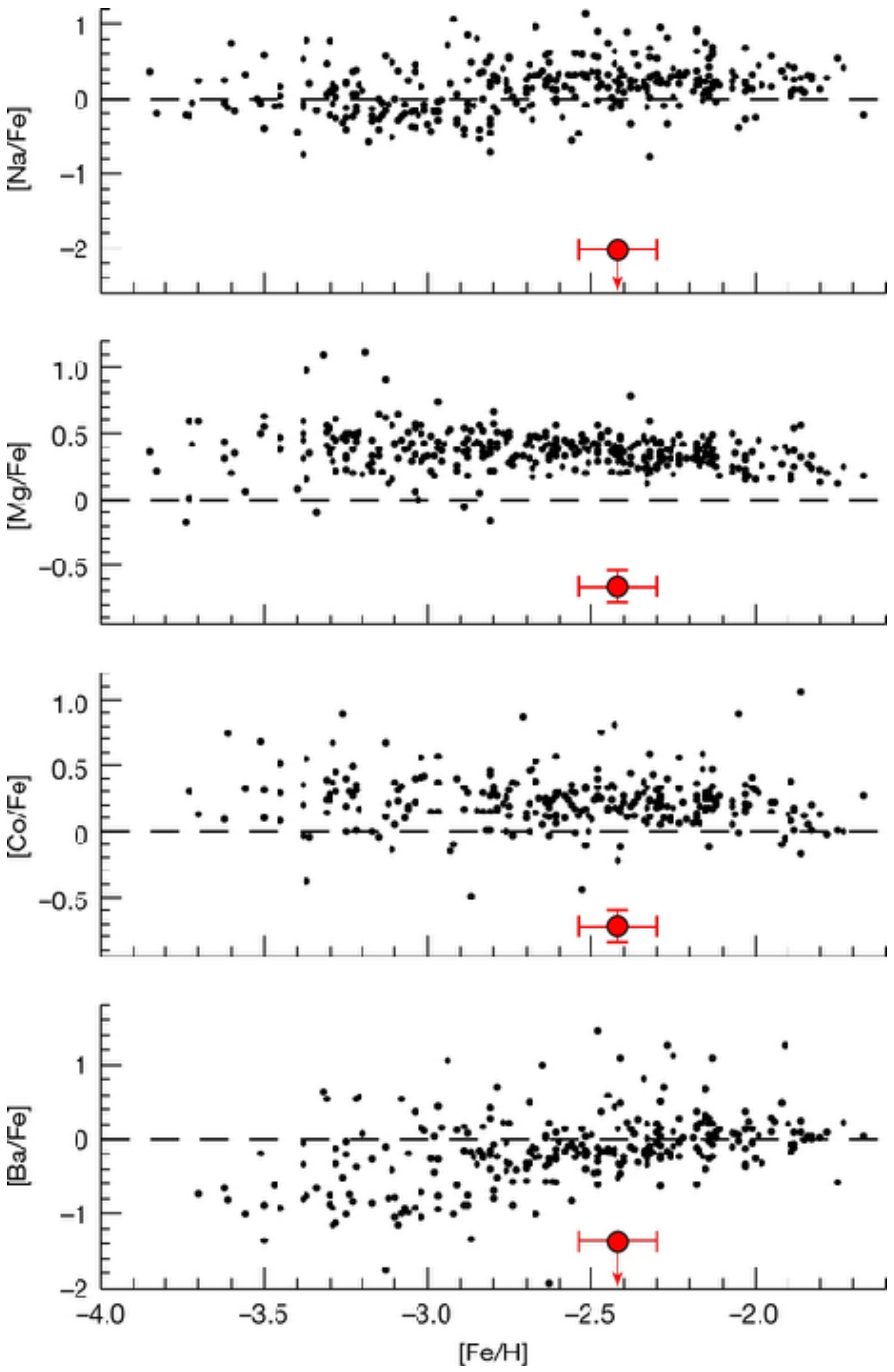
Chemical abundances of EMP stars as a tracer of Pop III CCSN yields

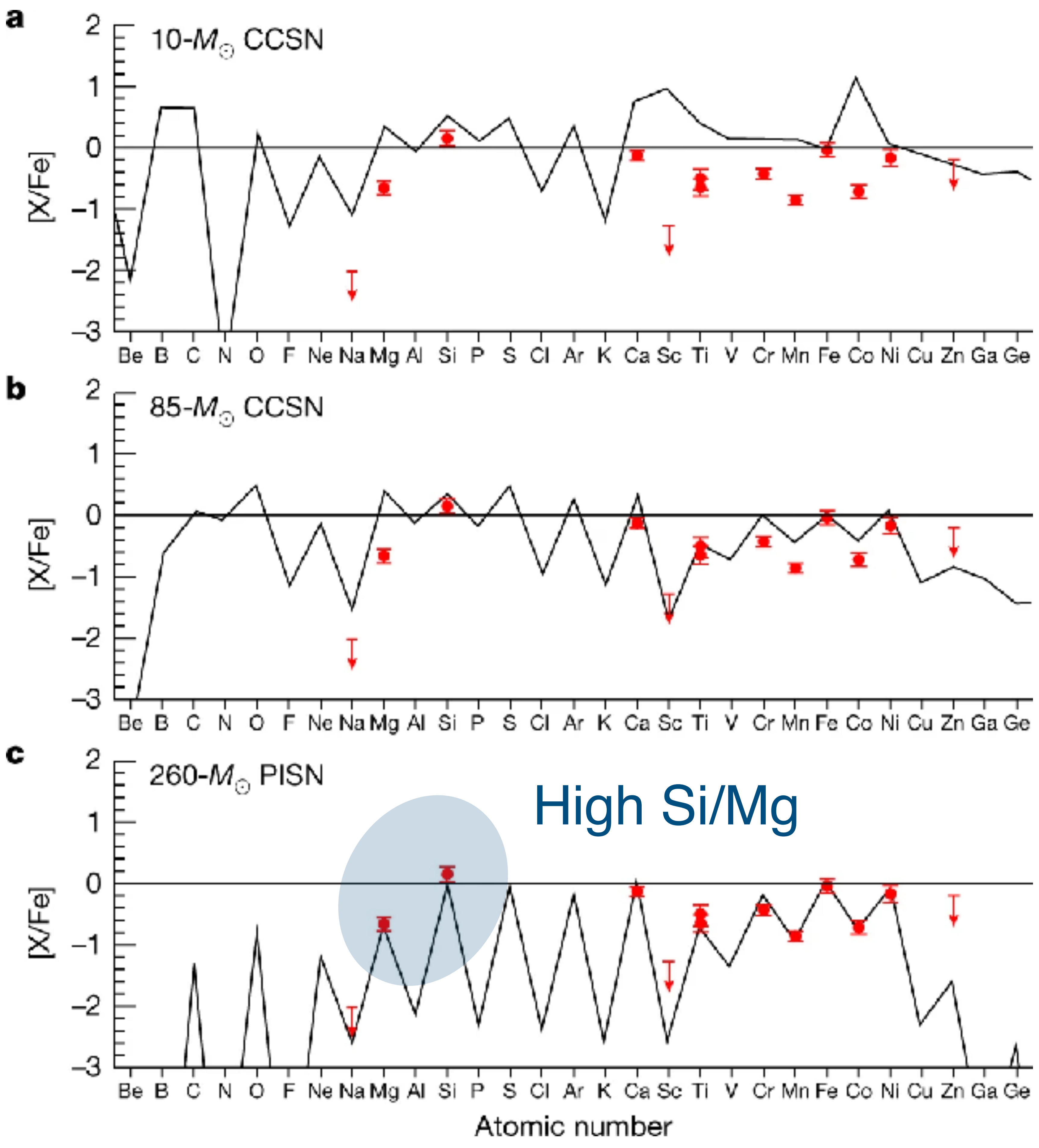


- Extremely metal-poor (EMP) stars: The chemical abundance pattern reflects a single or a few Pop III CCSN yields
- The α-element abundances in particular depend on the progenitor masses
- The initial mass function (IMF) of the Pop III stars

A possible chemical signature of an extremely massive Pop III star

Xing+23, Nature





A new evidence of the presence of extremely massive ($> 100 M_\odot$) Pop III stars as a source of metals in the early Universe

Type Ia supernovae: the production of Fe-peak elements

A thermonuclear explosion of a C-O white dwarf with $M \sim M_{\mathrm{Ch}}$

A white dwarf accreting mass from the companion

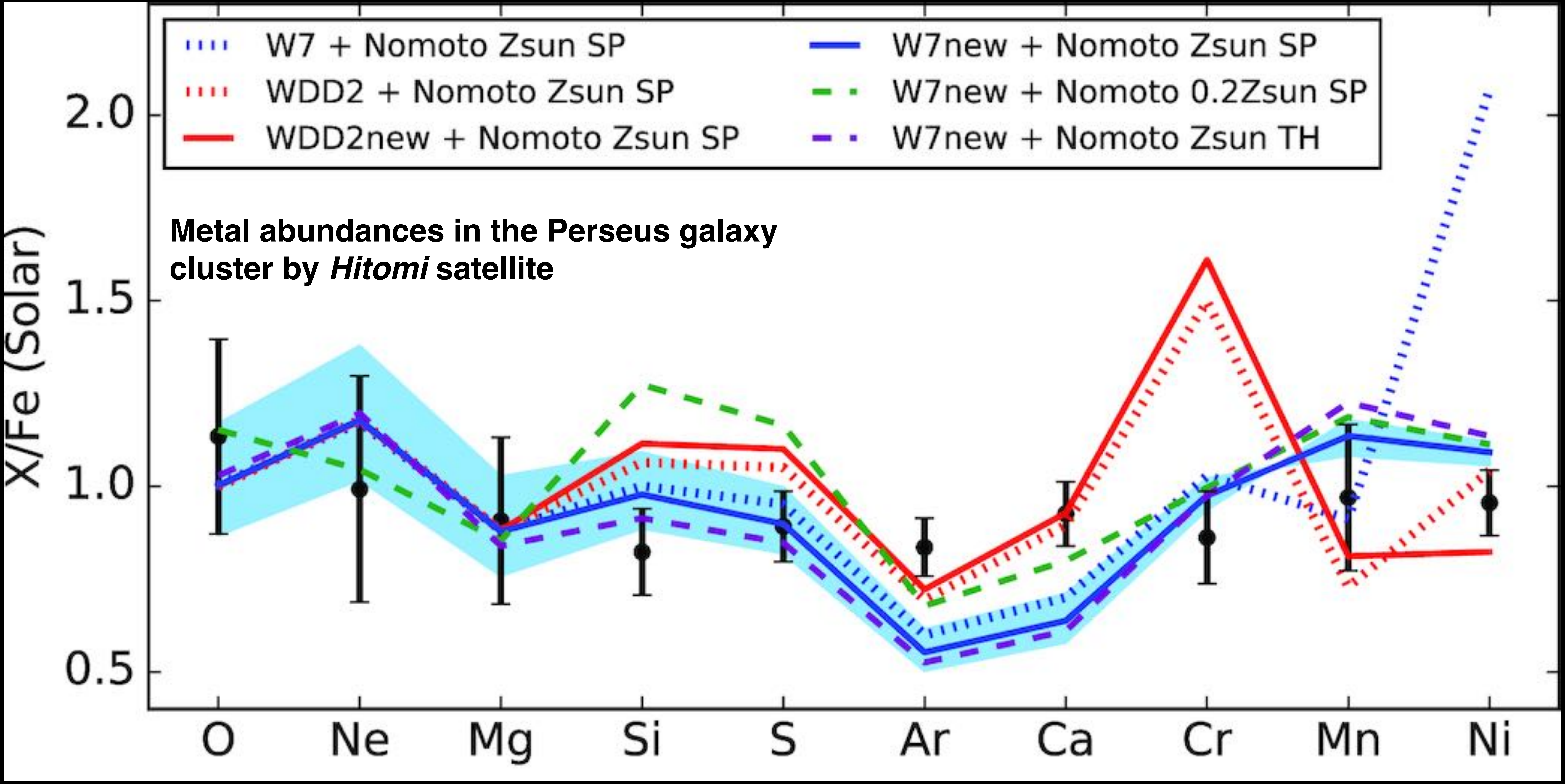
Merger of two white dwarfs

- Products
  - Fe-peak elements (Mn, Fe, Ni)
- Nucleosynthesis yields depend on
  - Central density of the white dwarf $\sim 10^{7}$-10^{9} g/cm^{3}
  - Initial chemical composition

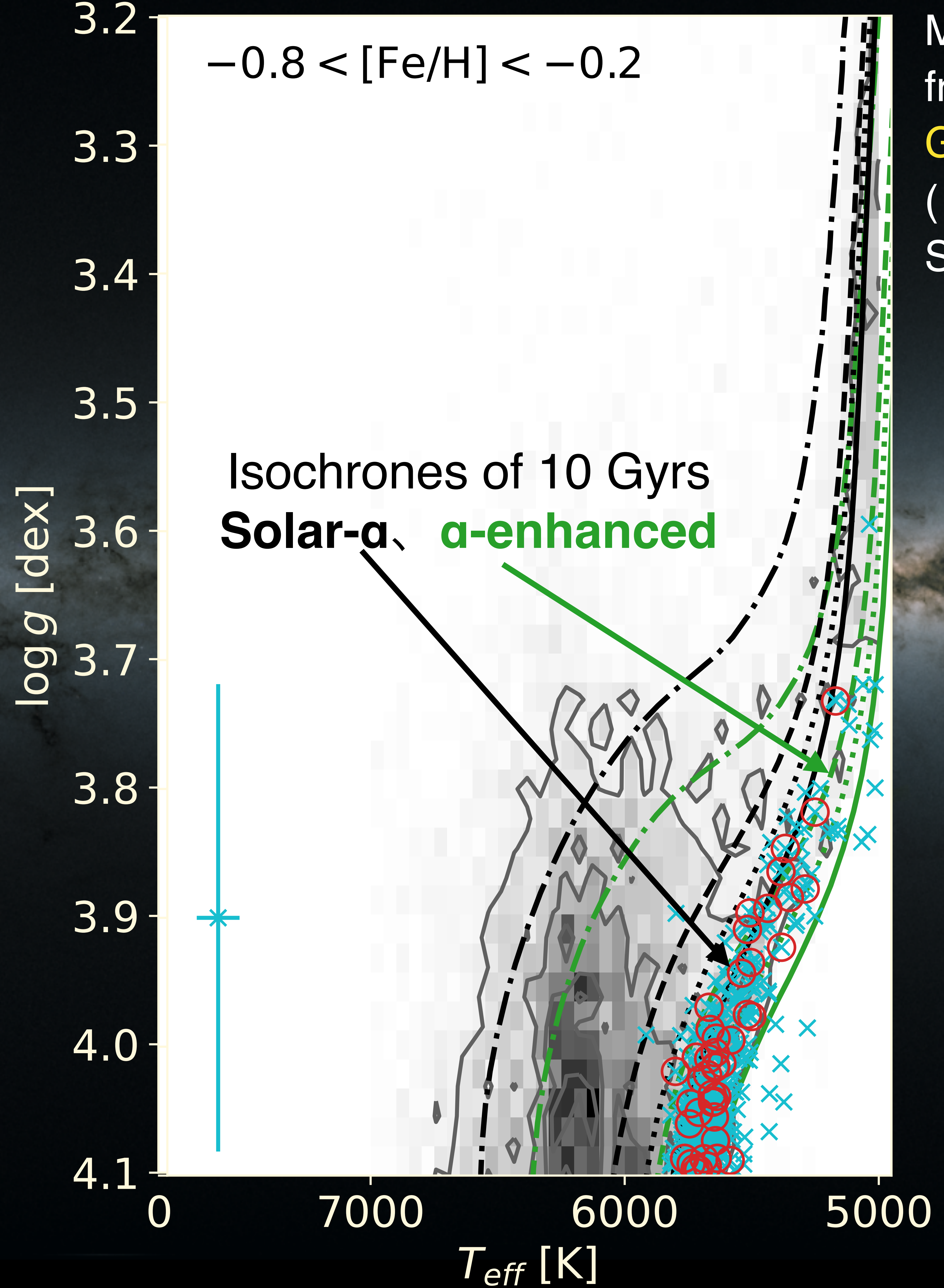
Present-day probes of the chemical evolution of the Universe

Solar system material, Solar photosphere, galaxy clusters

Tsujimoto+95, Mernier+18, Simionescu+19

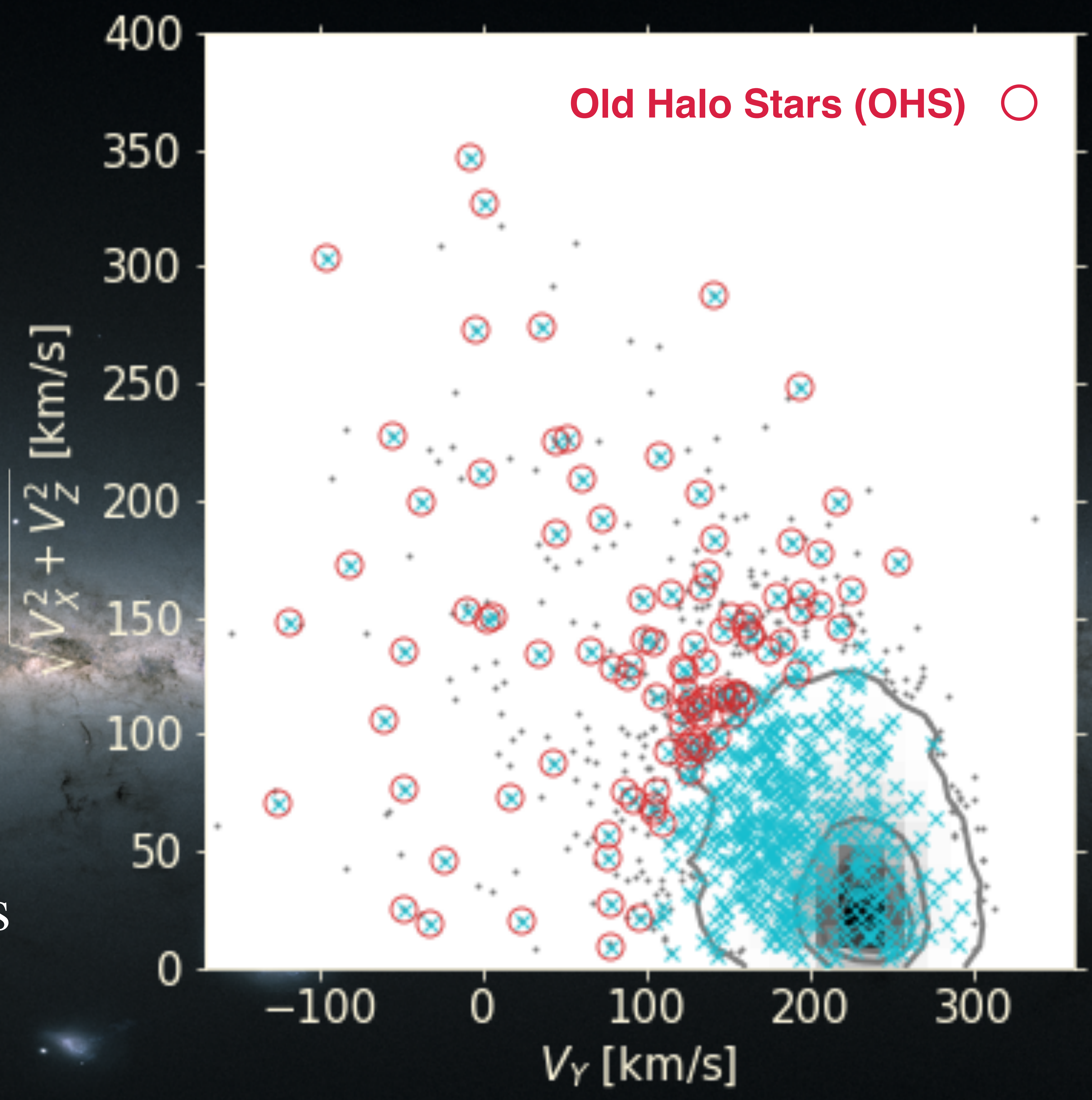


Selecting nearby old stars by kinematics + elemental abundances + ages



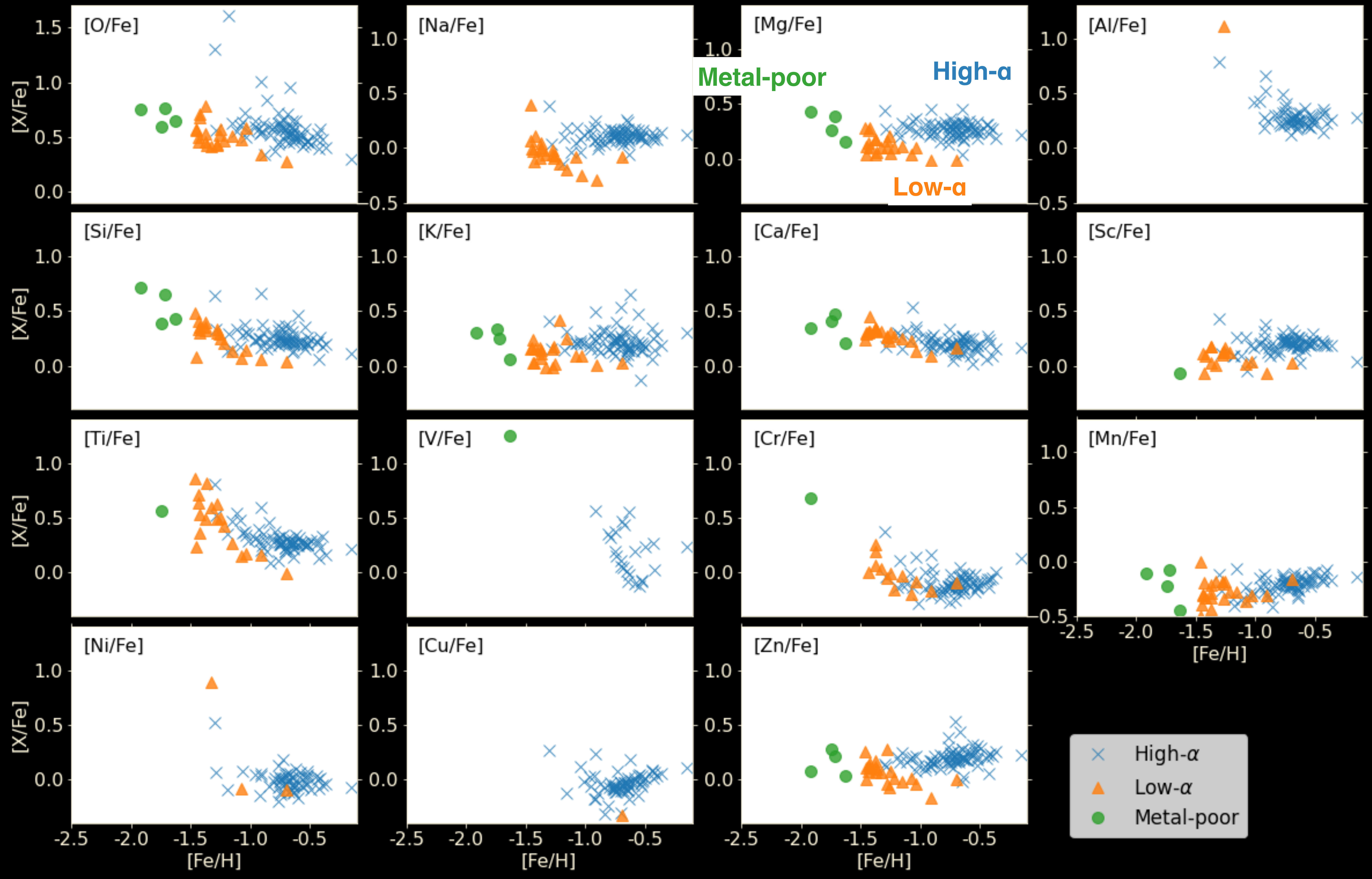
MSTO stars with age > 12 Gyrs (×) from Value-added catalog of GALAH DR3 ($\sim 600{,}000$ stars) (Sharma+18; Buder+20; see also Sanders&Das18)

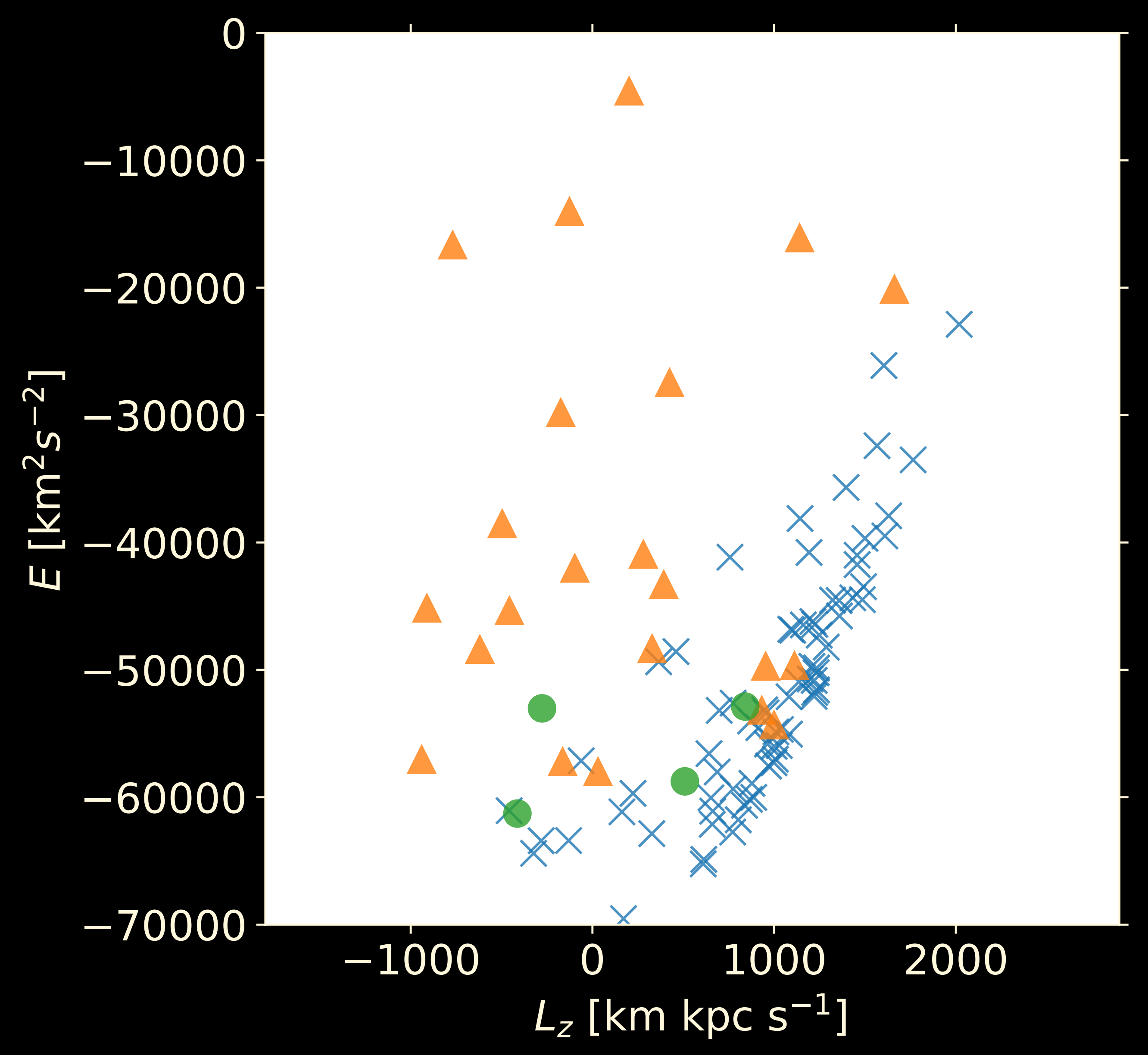
Stars with halo-like kinematics ($|v - v_{\odot}| > 150$km/s) from GALAHxGaia EDR3



"**Old Halo Stars**" : candidate of stars belonging to the old stellar population in the Solar neighborhood (e.g., Di Matteo+19, Gallart+19)

[X/Fe]-[Fe/H] subgroups





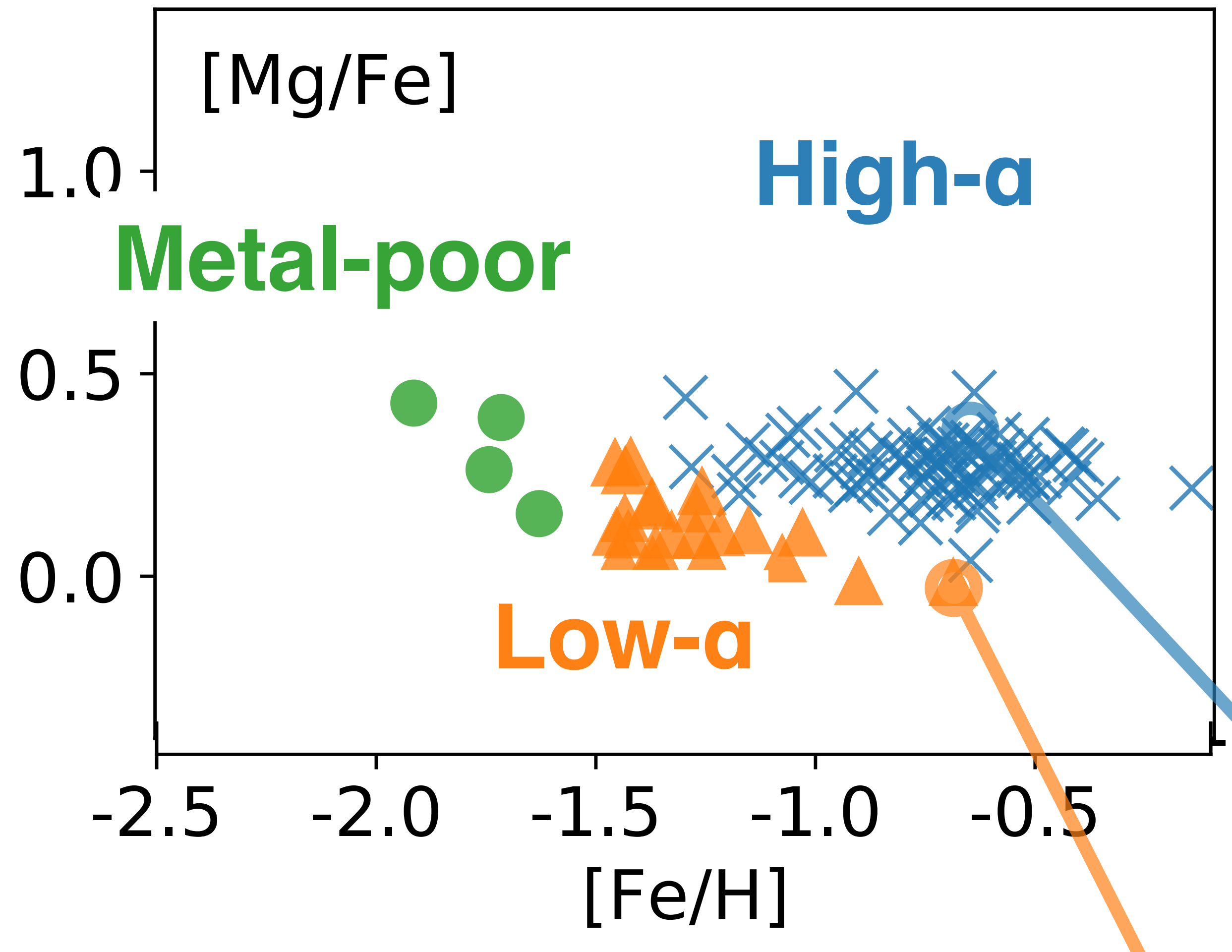
e.g., Nissen&Schuster10, Hawkins+15, Hayes+18, Helmi+18, Belokurov+18, Koppelman+18, Simpson+20

- High-α: rotation along the disk
- Low-α: high-eccentricity, Gaia-Sausage-Enceladus
- Metal-poor: small L_Z (zero net rotation)

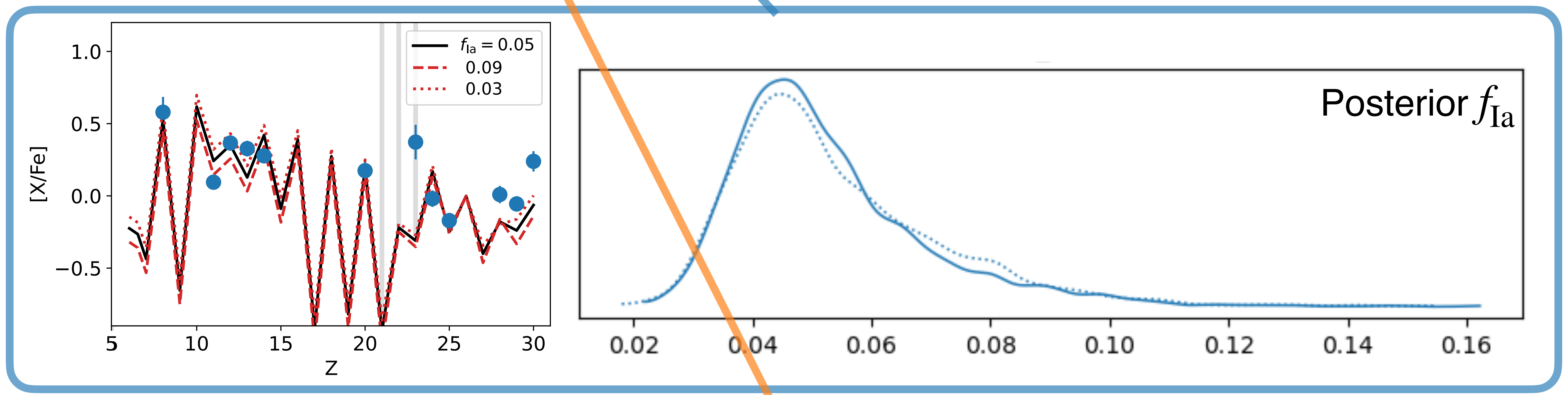
Constraints on the contribution of SN Ia to the metals in old halo stars

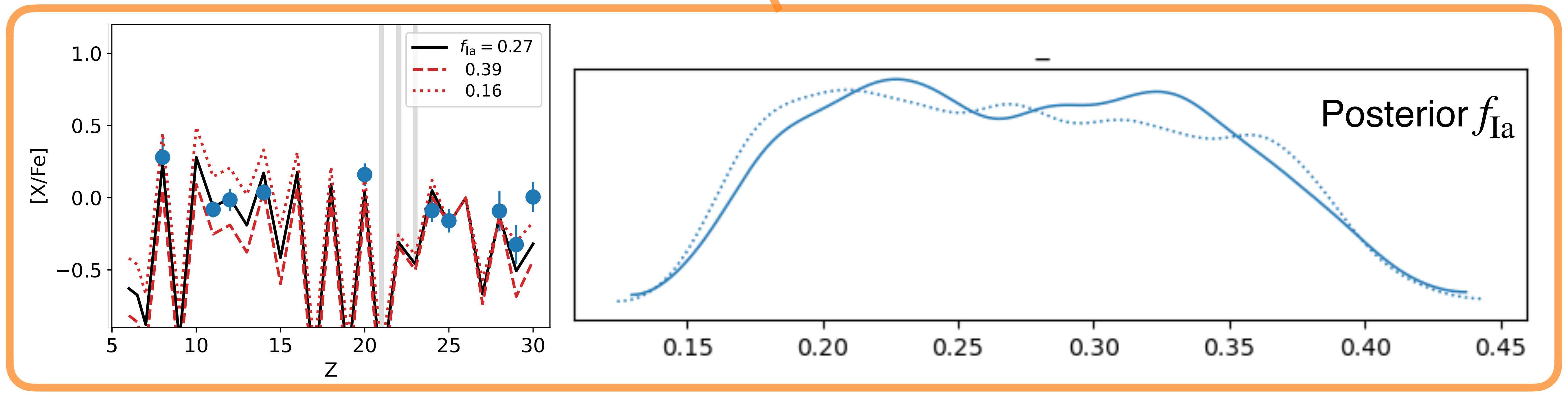
The relative fraction of SNIa of 5-10% best explain
the abundances in old halo stars

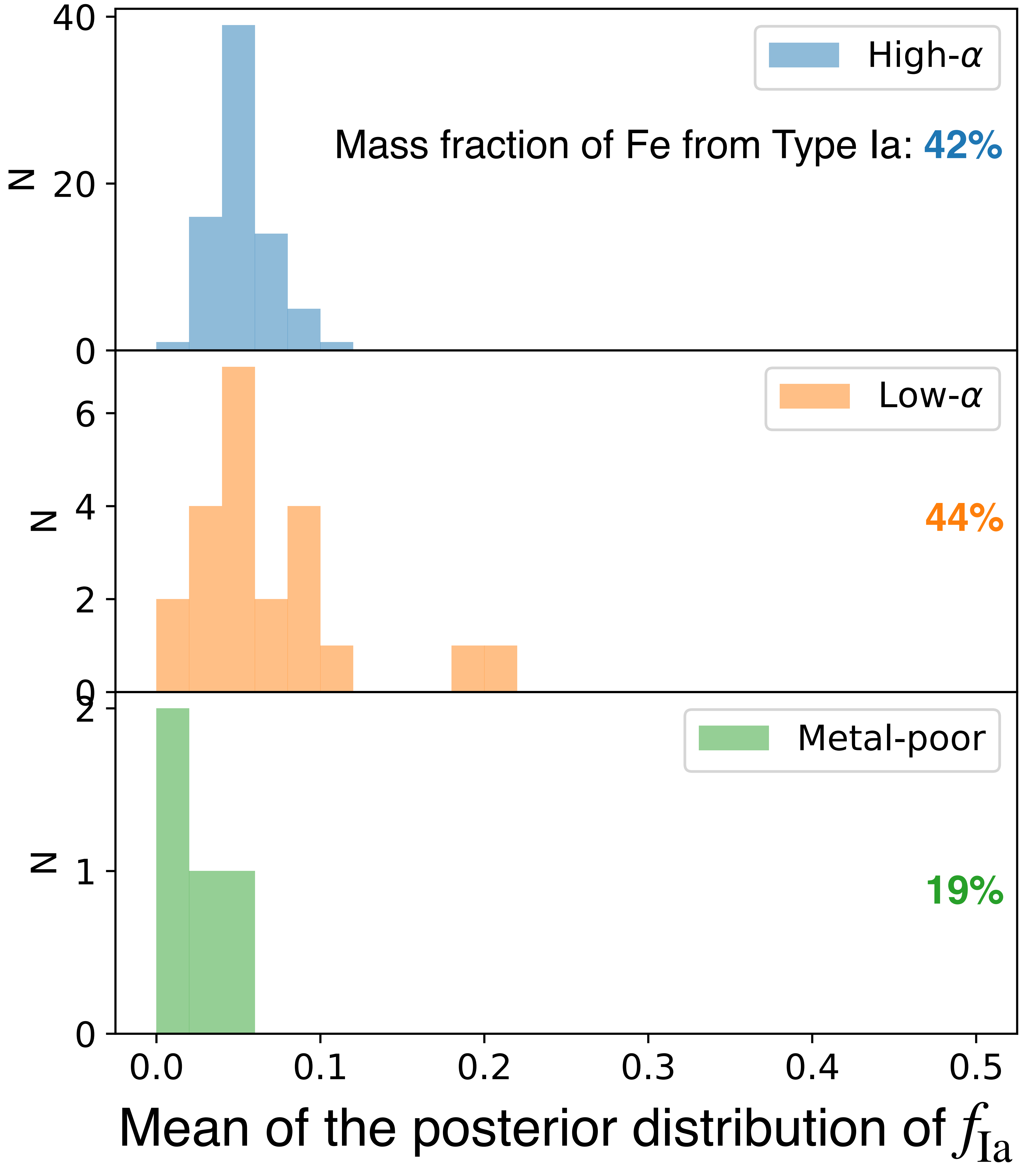
Ishigaki+21



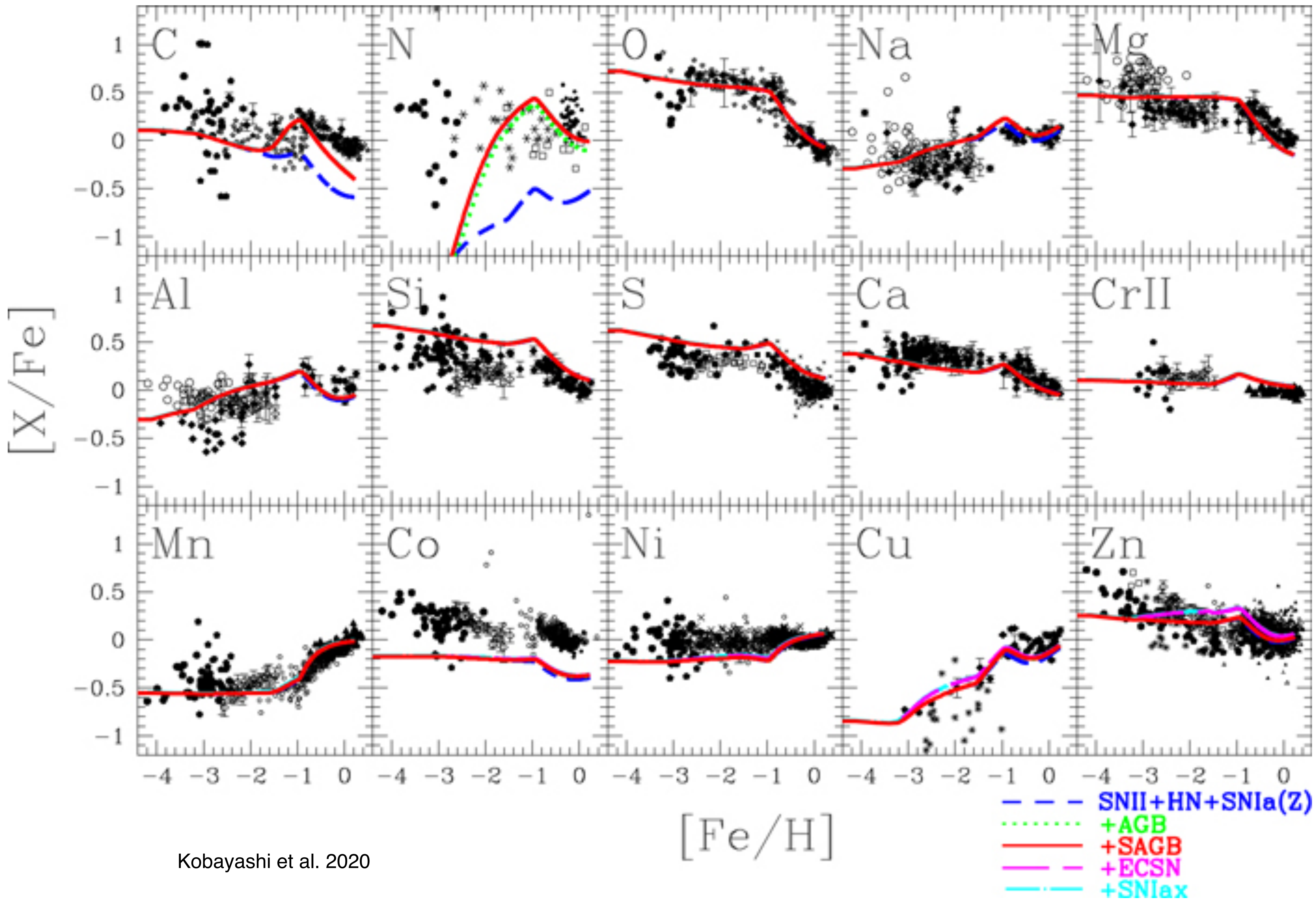
About 20-40% of the mass of Fe
from SNIa in the early Universe







Chemical evolution models with all the possible channels



Kobayashi et al. 2020

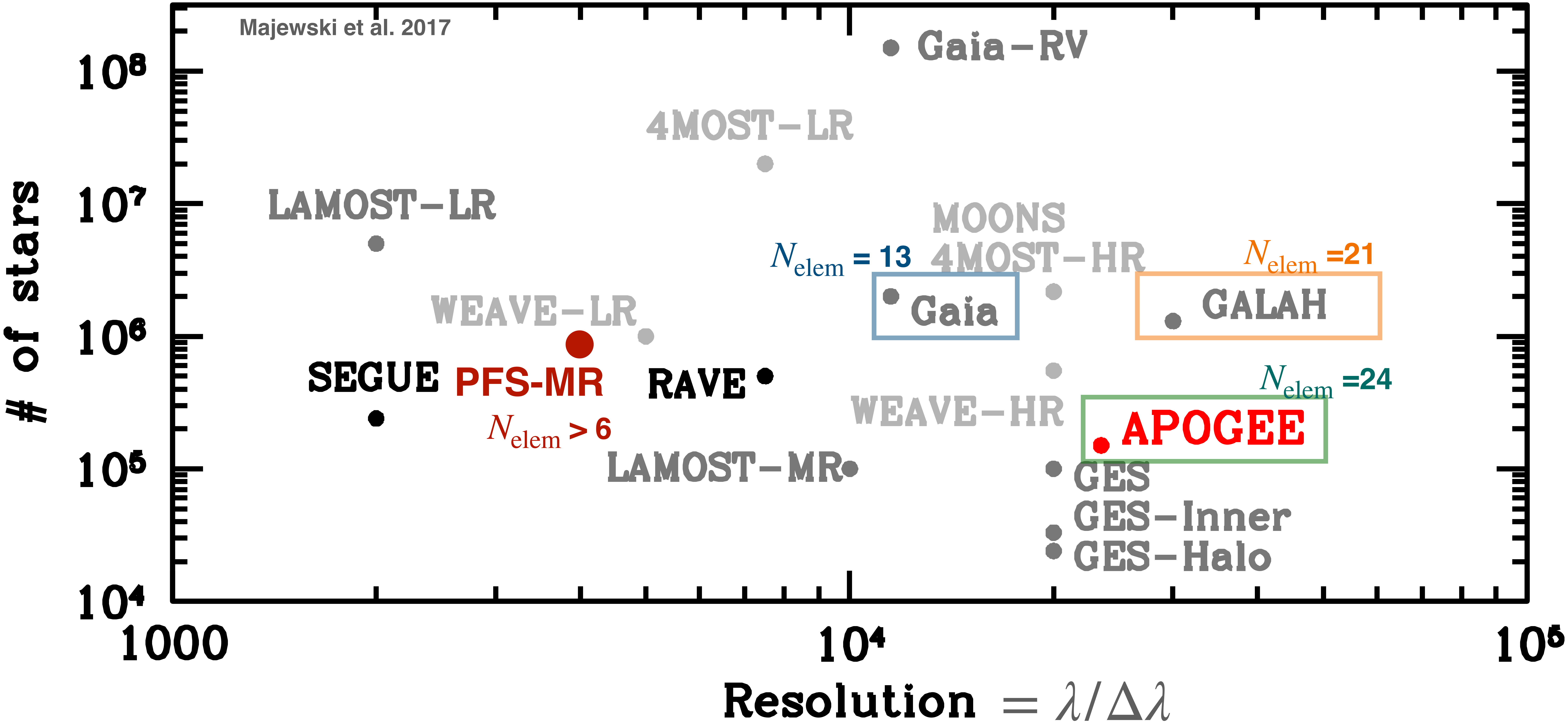
Contents

- How to find “old” or metal-poor stars in the Milky Way?
  - Wide-field imaging and spectroscopic surveys
- What metal-poor stars tell us?
  - The origin of elements in the early Universe
- Open questions about the origin of elements
  - Prospects with new instruments and telescopes

Summary of the open questions in the next decade

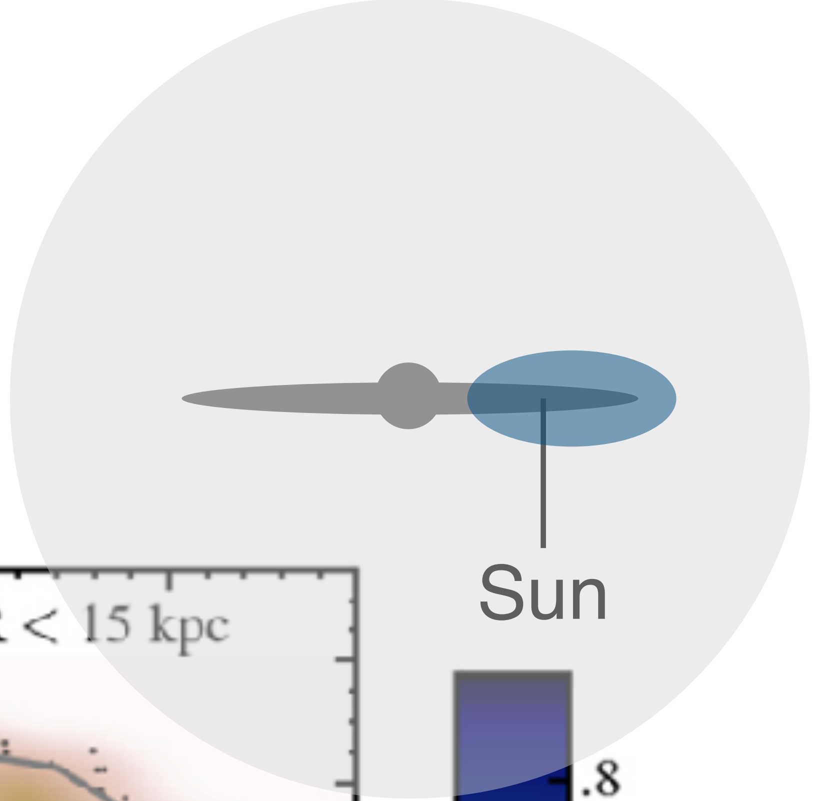
- The nature of the very first (PopIII) stars in the Universe
  - Diversity in chemical abundances in the outer Milky Way halo
  - Consistency with the high-z observations (e.g. JWST)
- Supernova explosion mechanisms
  - Elements produced by explosive nucleosynthesis
- The complete explanation of the Solar-system abundances
  - Chemical evolution and the formation of the Milky Way

Recent and future multi-element surveys of Galactic stellar populations

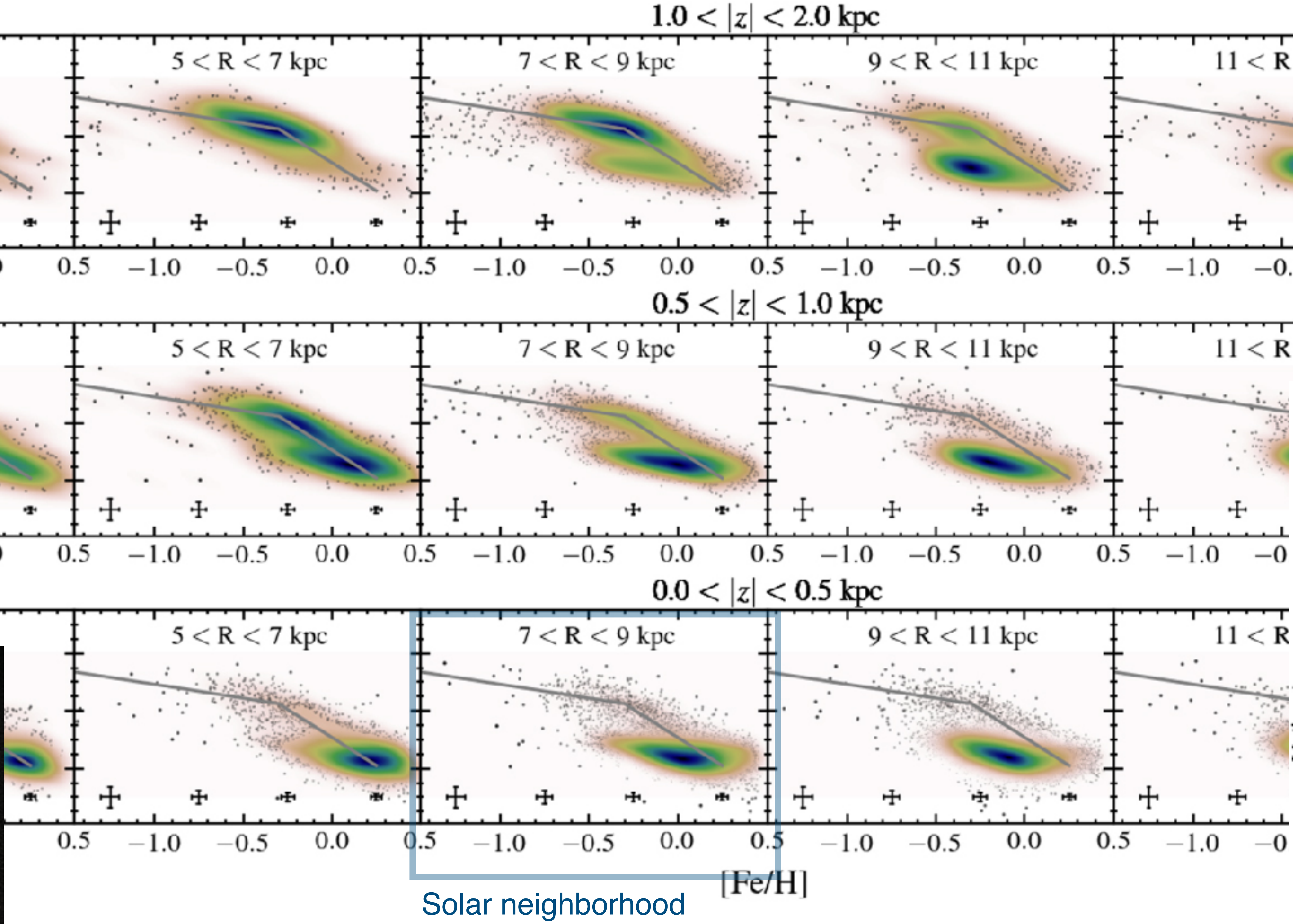


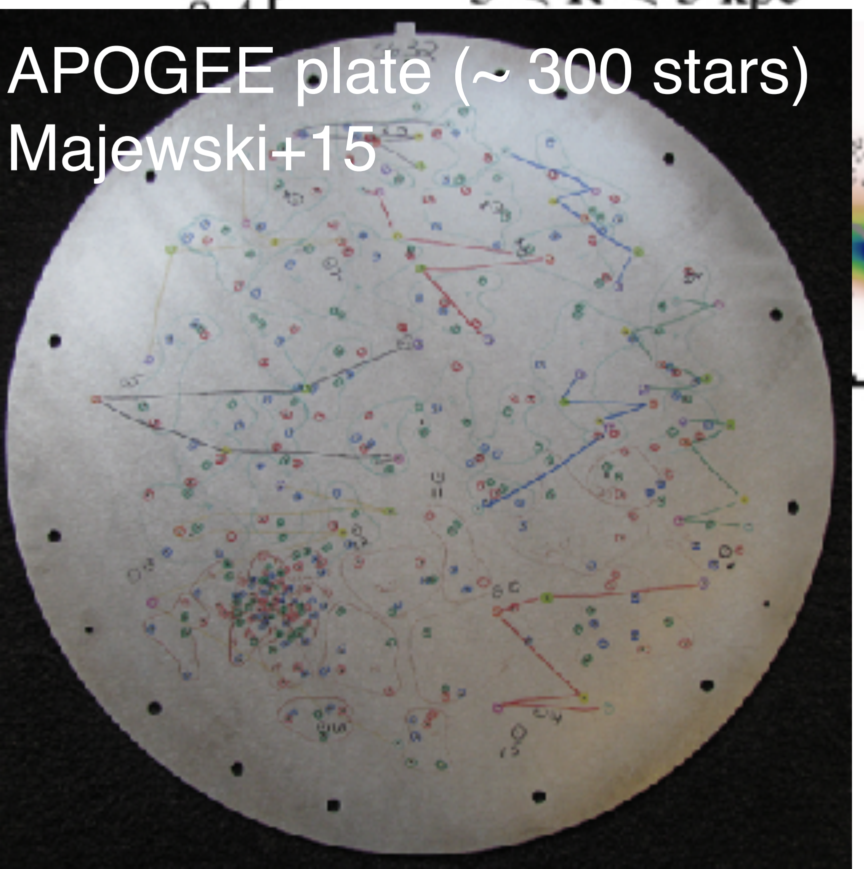
Probing multiple nucleosynthesis channels: core-collapse SNe, SNIa, s/r/i process, etc.

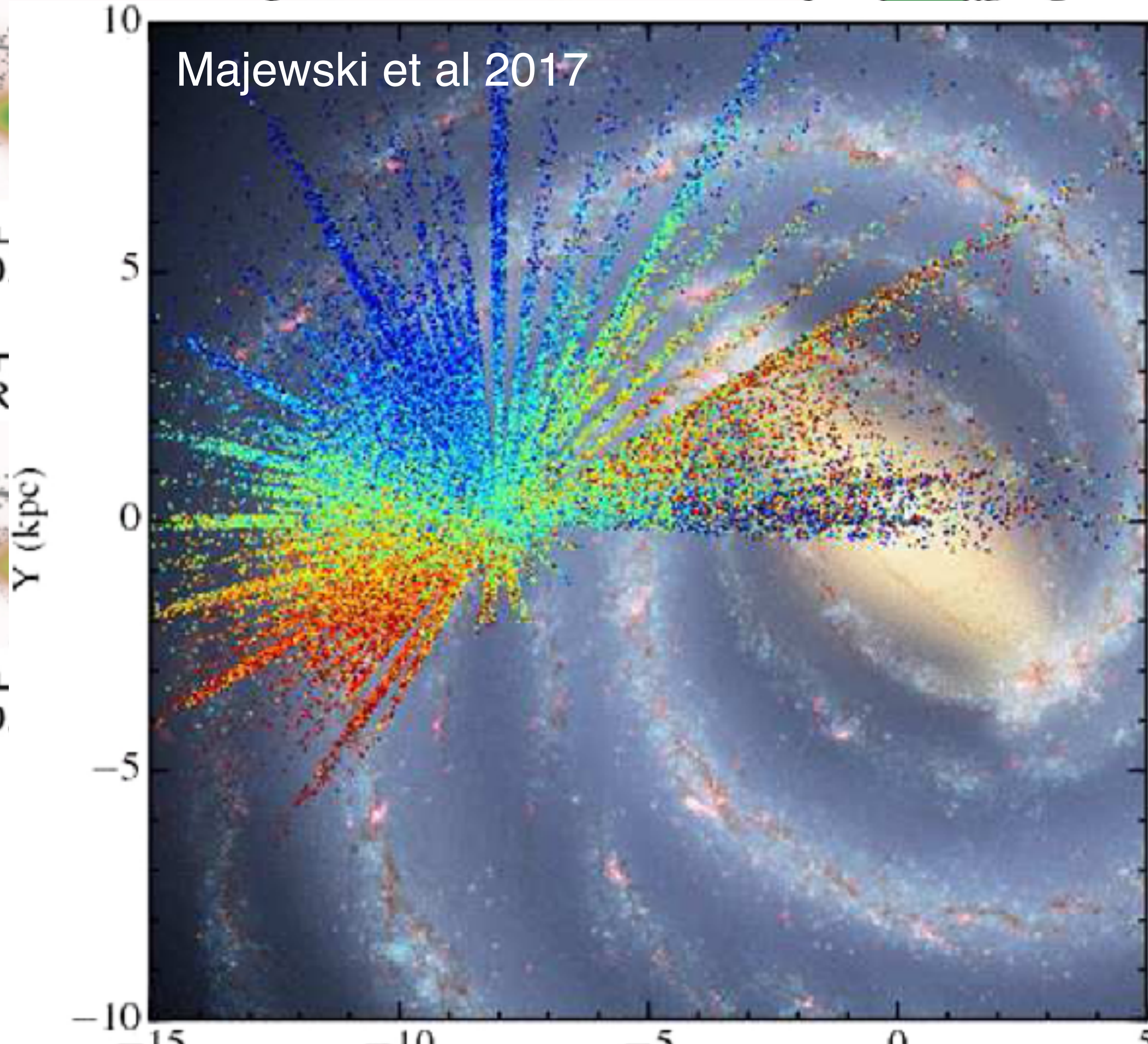
Covering large volumes



Hayden et al. 2015



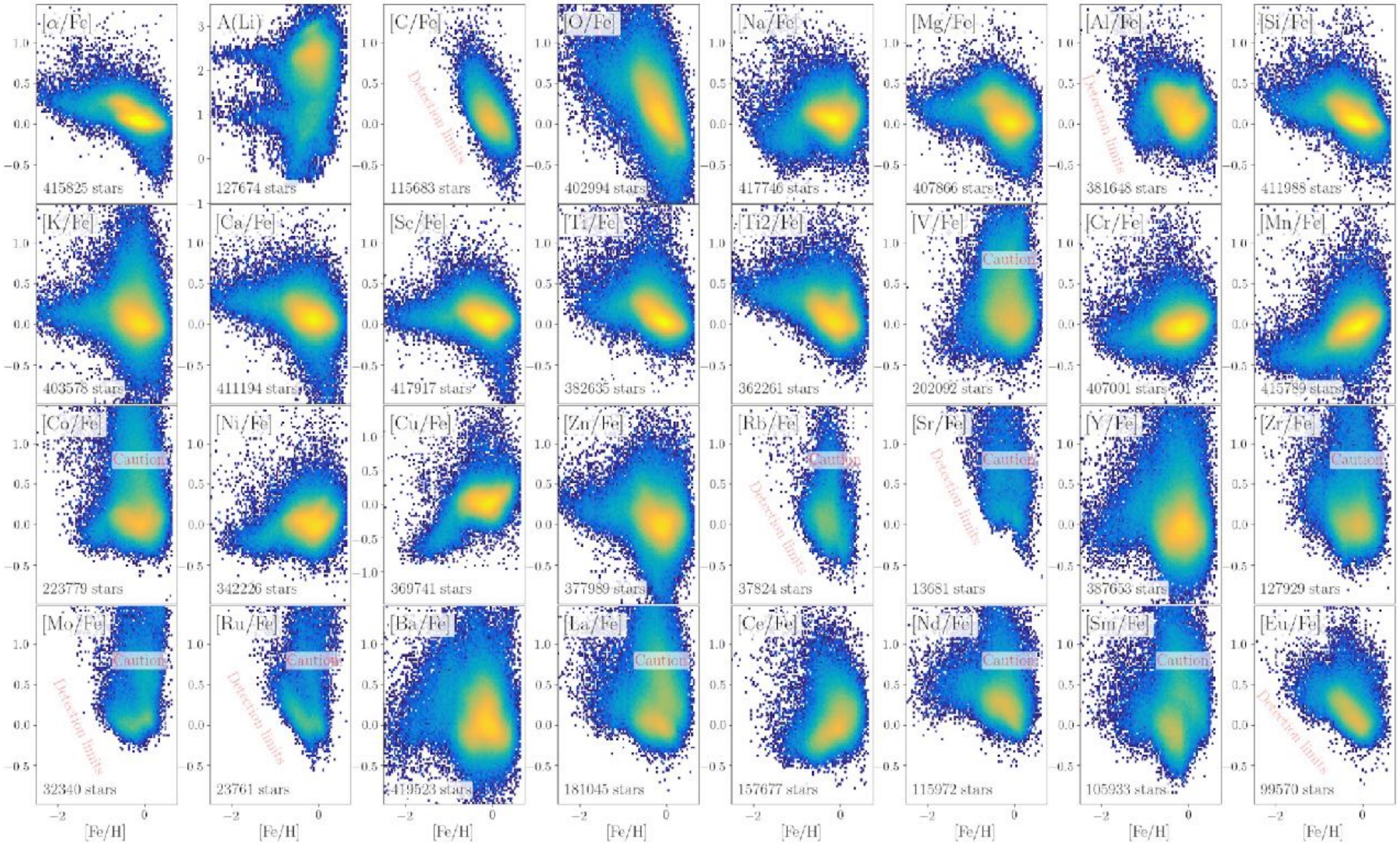


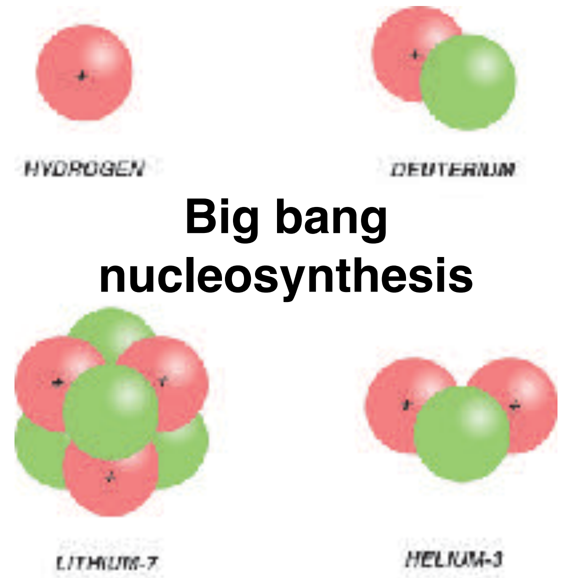


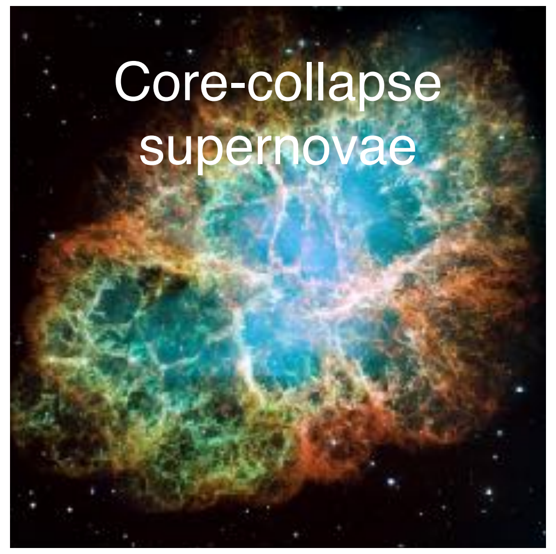
Multi-element abundances: probe of multiple nucleosynthesis channels

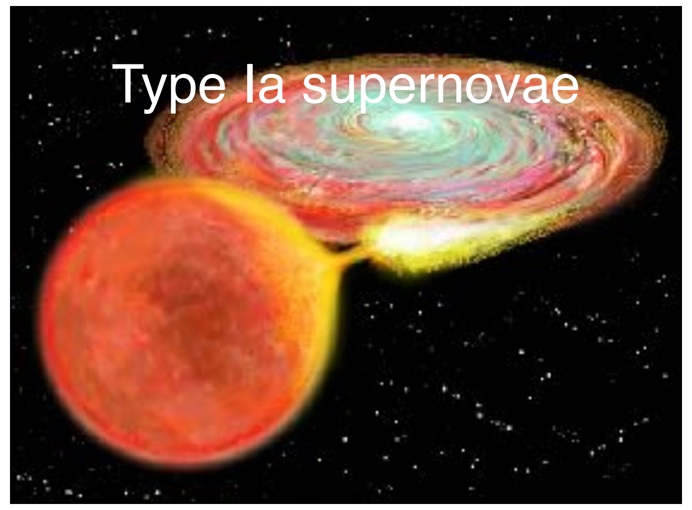
Elemental abundance distribution from GALAH survey

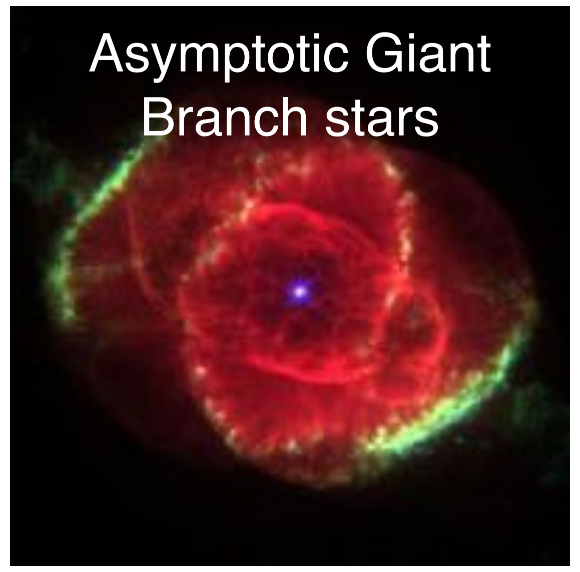
Buder et al. 2021









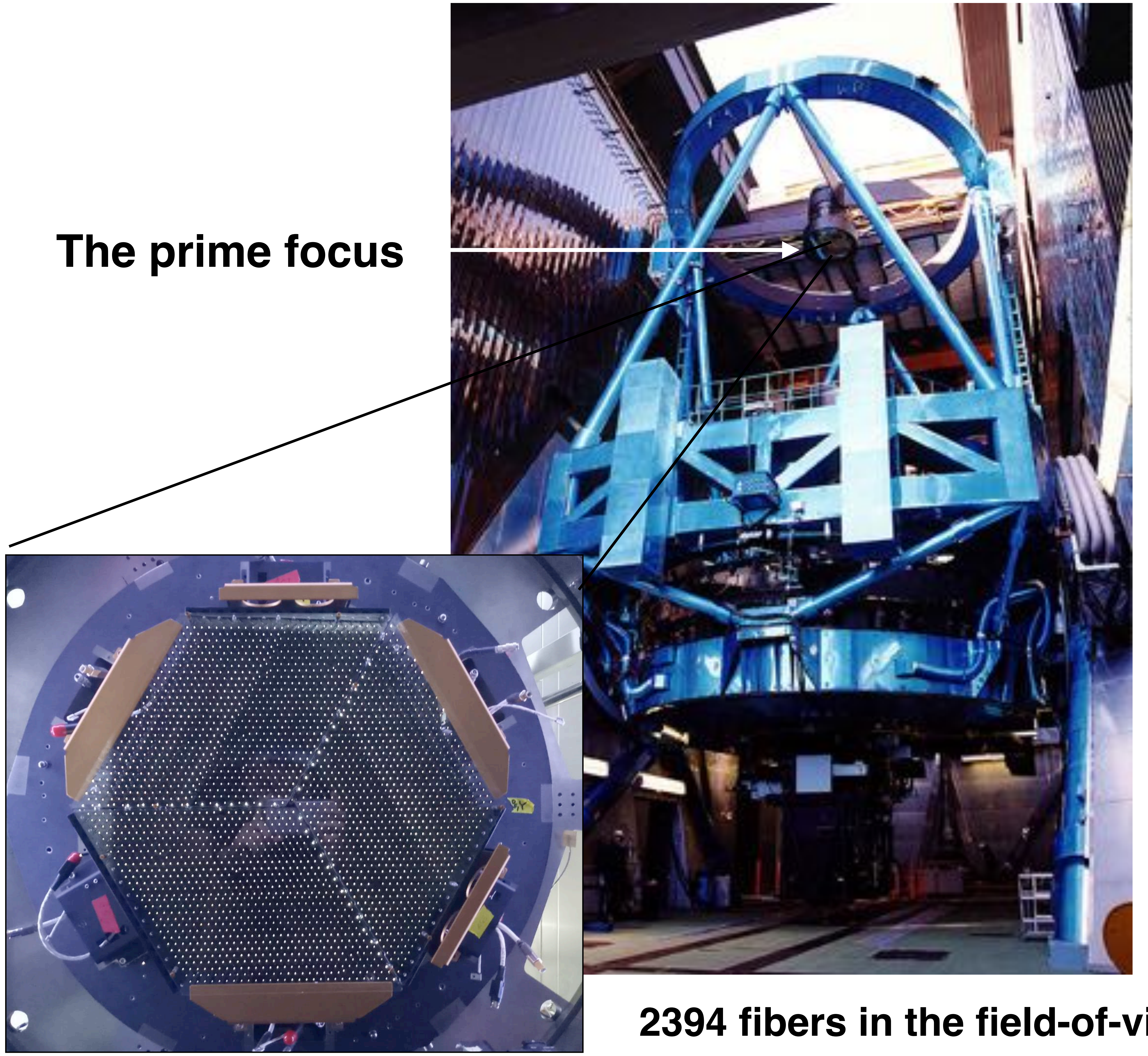


The next generation instruments

- Prime Focus Spectrograph (PFS)/Subaru
  - Wide field (1.3deg^2), >2 3 0 0 fibers
  - Identification of chemically pristine stars in the dwarf satellite galaxies and field halo stars.
- HROS/TMT
  - Detailed elemental abundance estimates of the most metal-poor stars
  - Test theories of supernova/stellar nucleosynthesis

➡ Nature of the first stars and their metal yields

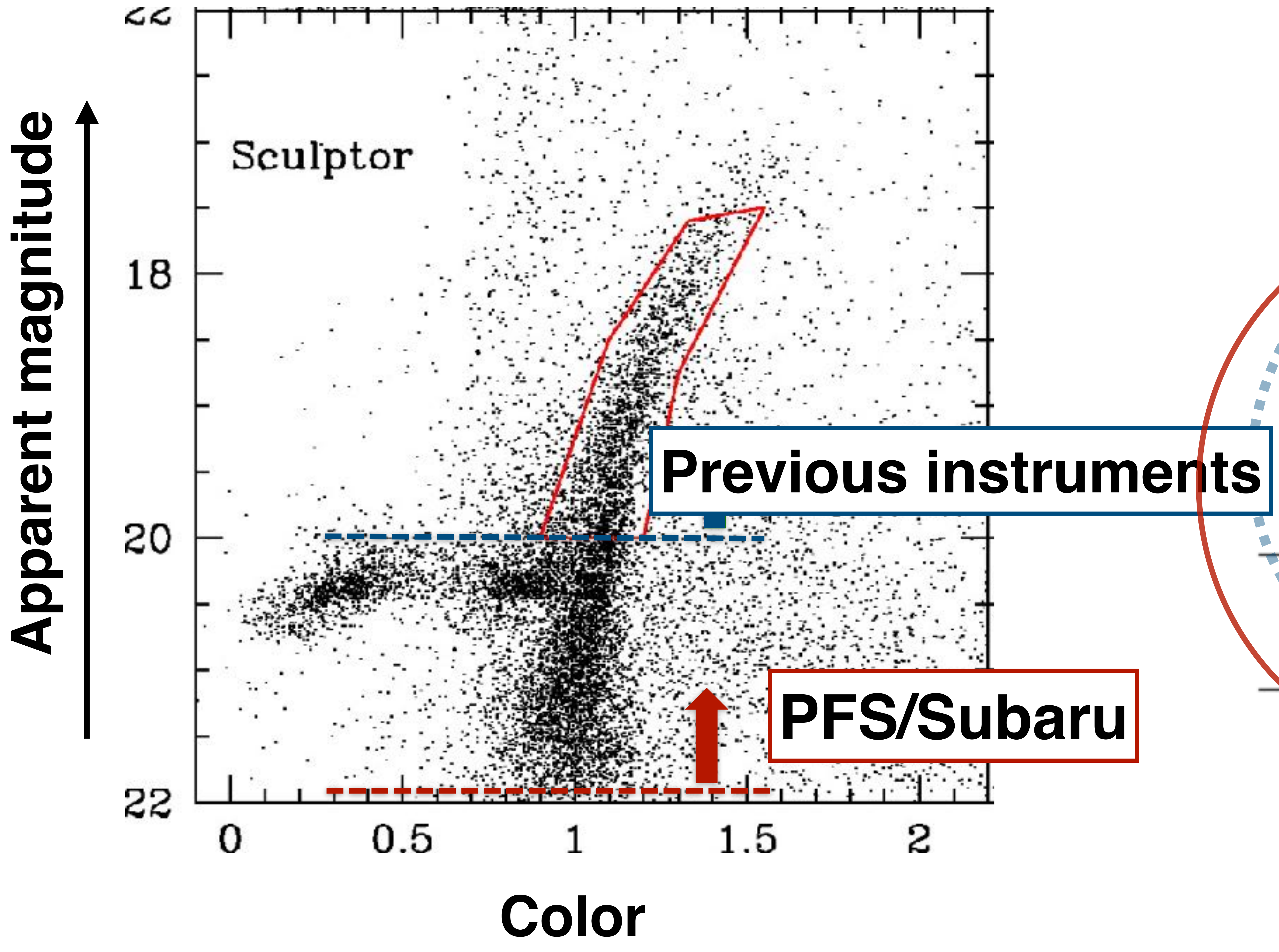
The prime focus

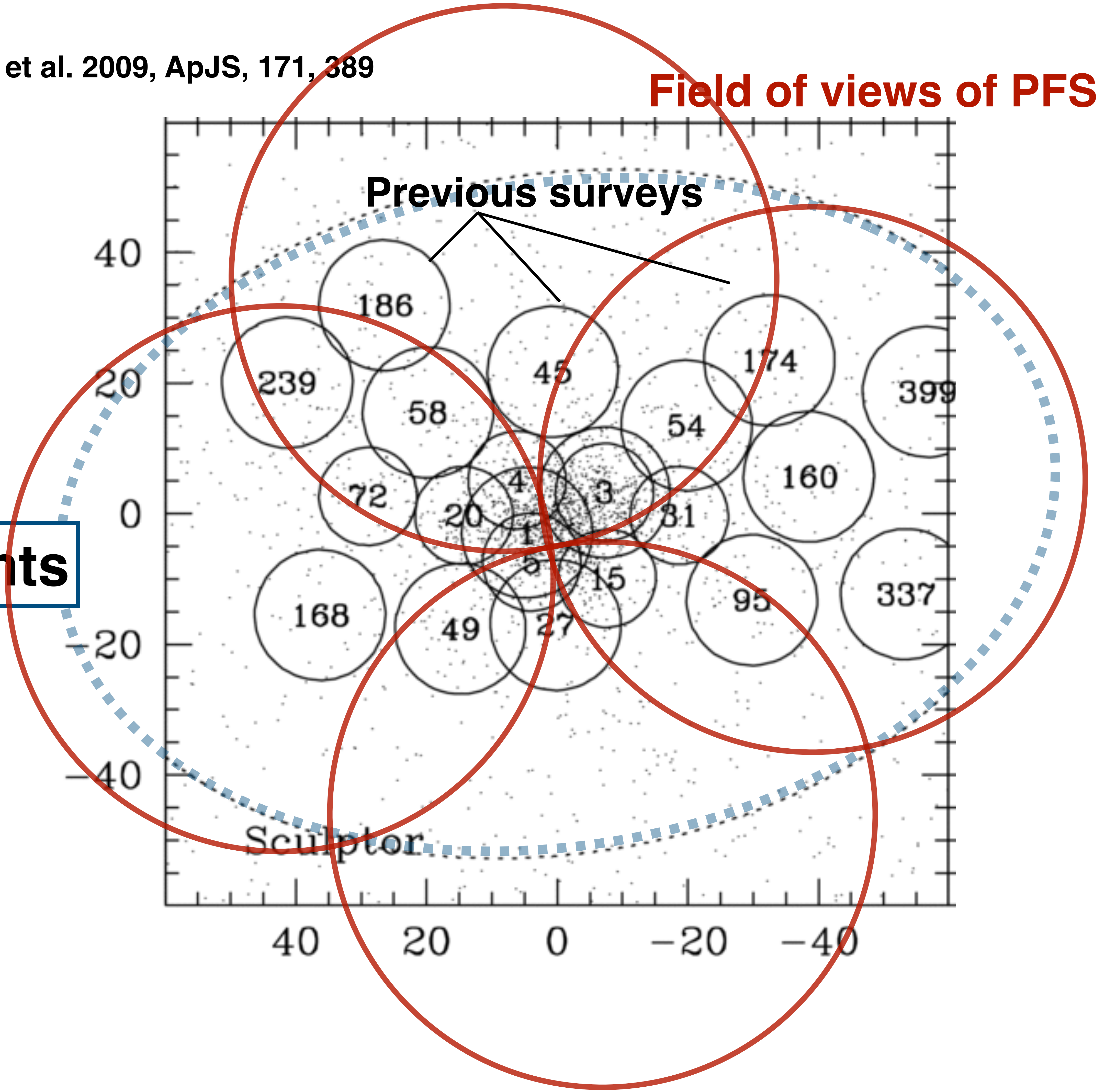


2394 fibers in the field-of-view

PFS: wide-field and deep spectroscopic surveys of the dwarf satellites

Sculpter dwarf satellite Walker et al. 2009, AJ, 137, 3100; Walker et al. 2009, ApJS, 171, 389



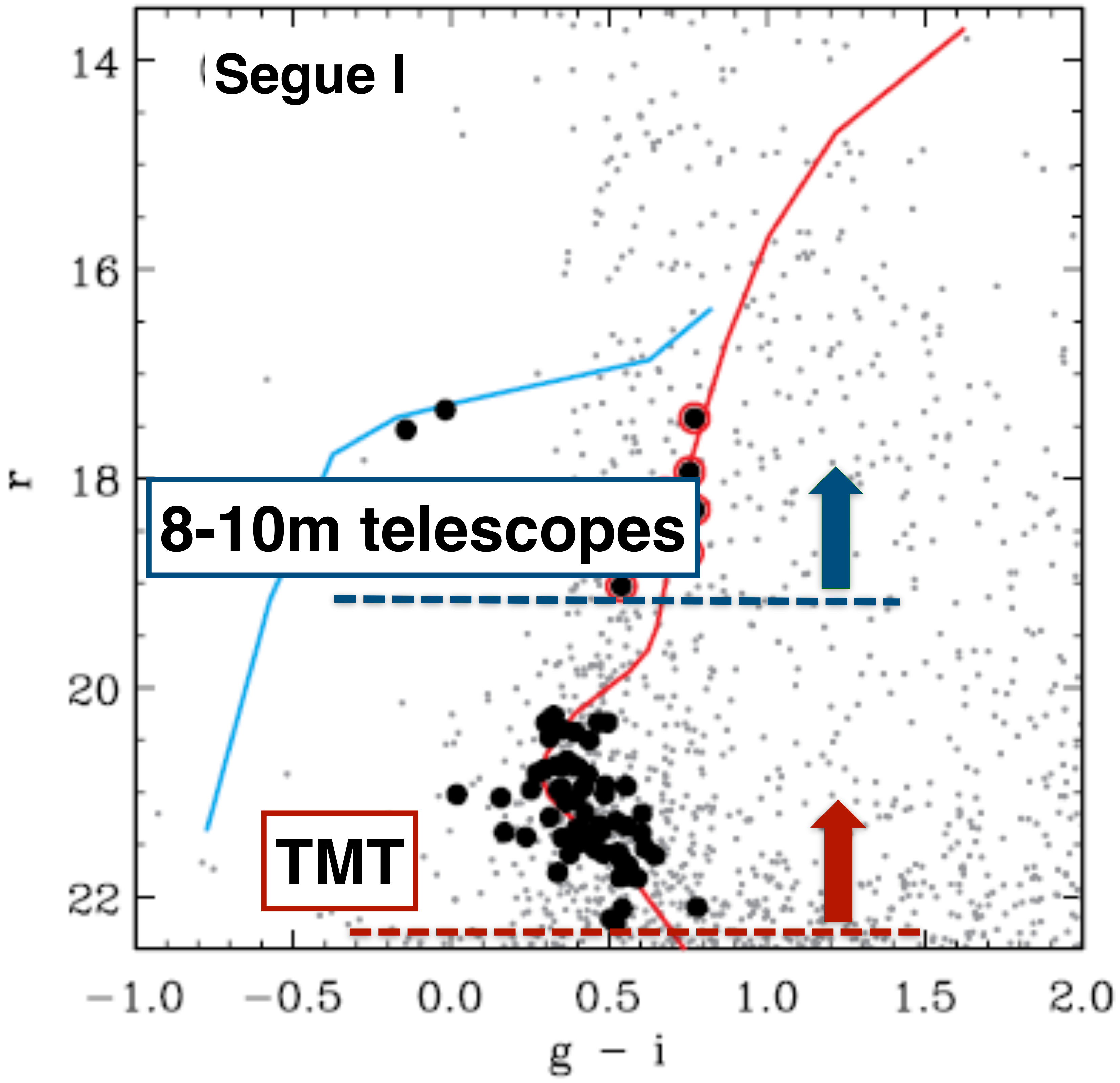


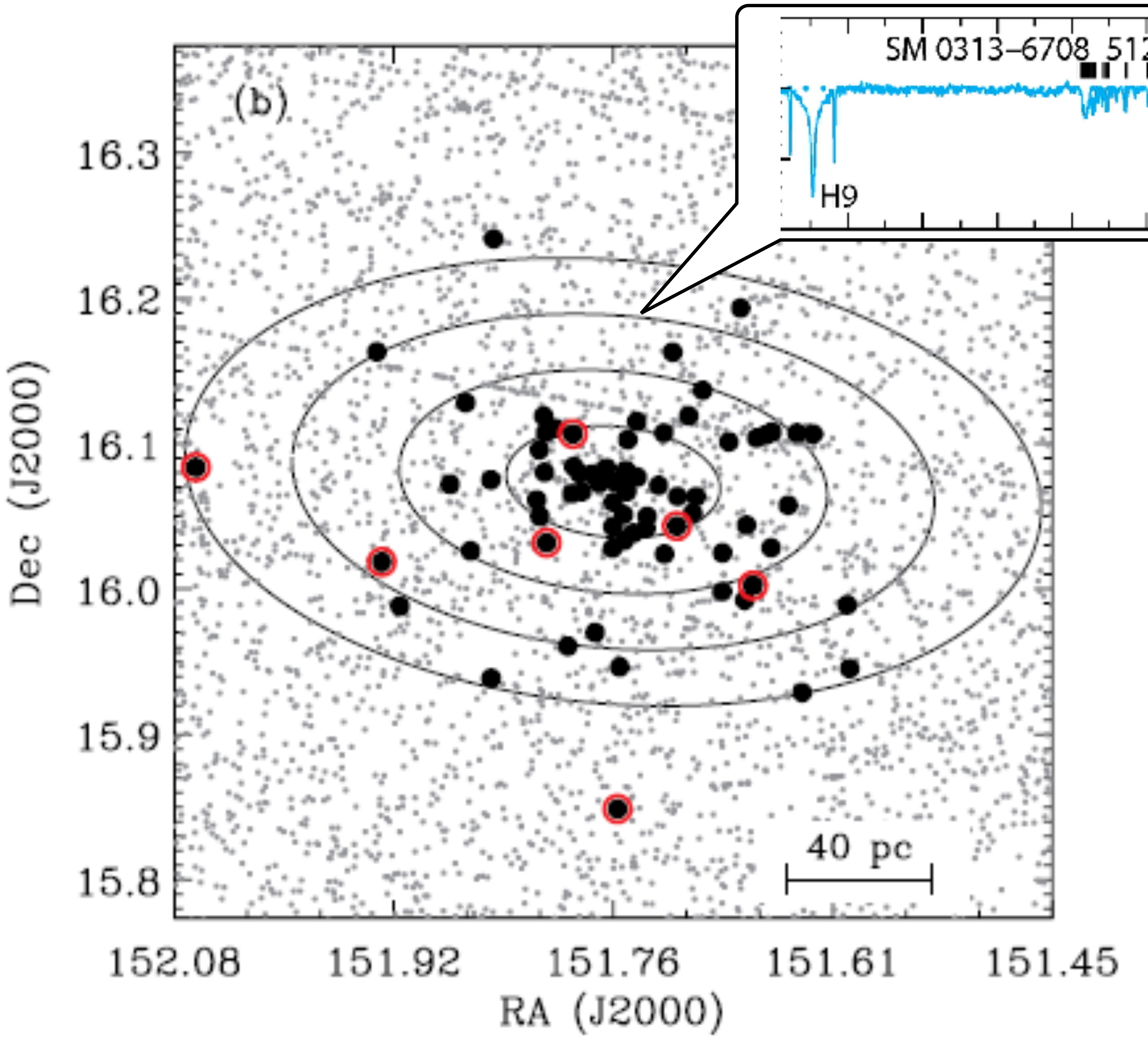
TMT：High-resolution spectroscopy of stars in ultra-faint dwarf

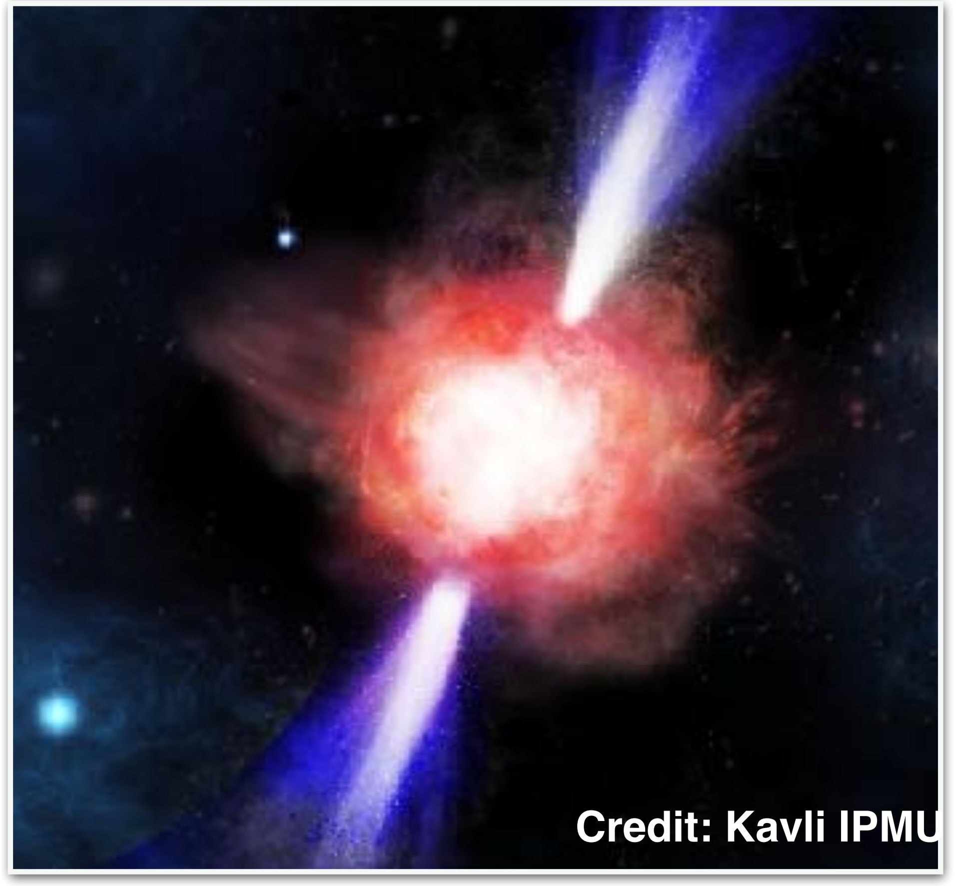
Ultra-faint dwarf galaxies: A large fraction of CEMP and r-rich stars

➡ Best suited to constrain the astrophysical sources responsible for producing the metals

Frebel et al. 2014







The nature of the first stars

Summary

- How to find "old" or metal-poor stars in the Milky Way?
  - Wide-field imaging and spectroscopic surveys have been successful in finding chemically pristine stars and constraining their metallicity distribution function (MDF).
  - The MDF at the lowest [Fe/H] range is important, but missing.
- What metal-poor stars tell us?
  - The origin of elements in the early Universe have been constrained by chemical abundance patterns in metal-poor stars.
    - The primordial abundance and BBN
    - The nature and explosion mechanisms of the Pop III stars
    - Progenitors of SNIa
- Open questions about the origin of elements
  - Prospects with new instruments and telescopes: a larger volume including the Milky Way outer halo and more detailed elemental abundances to constrain supernova yields in the early Universe.