First Stars - The importance of accurate stellar abundances

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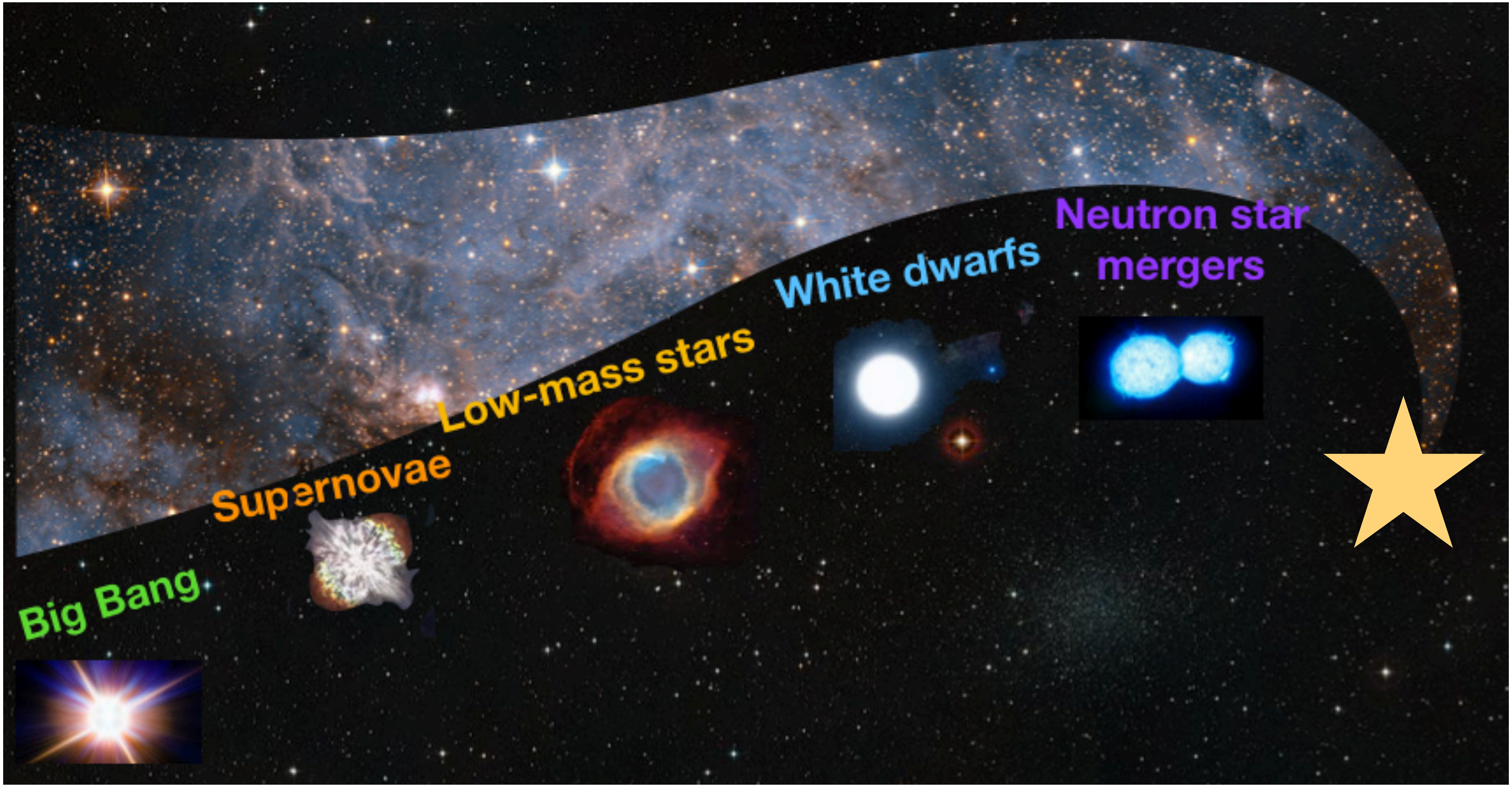
The Chemical Elements

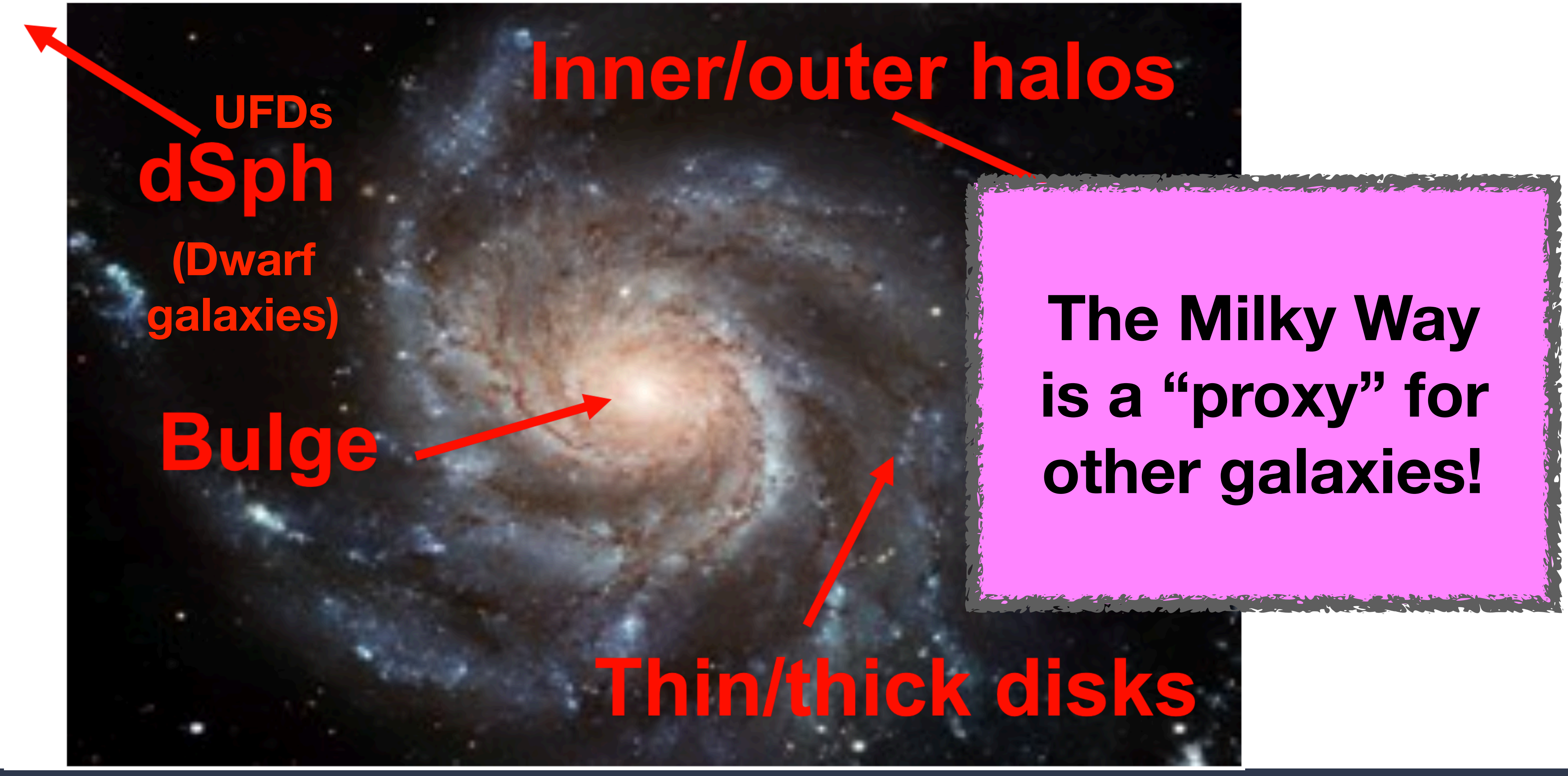
- The origin of the Chemical elements: **Where** and **when**



Galactic Archaeology

Galactic Archeology

- Galactic Archeology uses **kinematics**, **stellar ages** and **chemical abundances** of old (and young) stars to learn about the evolution of our Milky Way and its stellar populations.

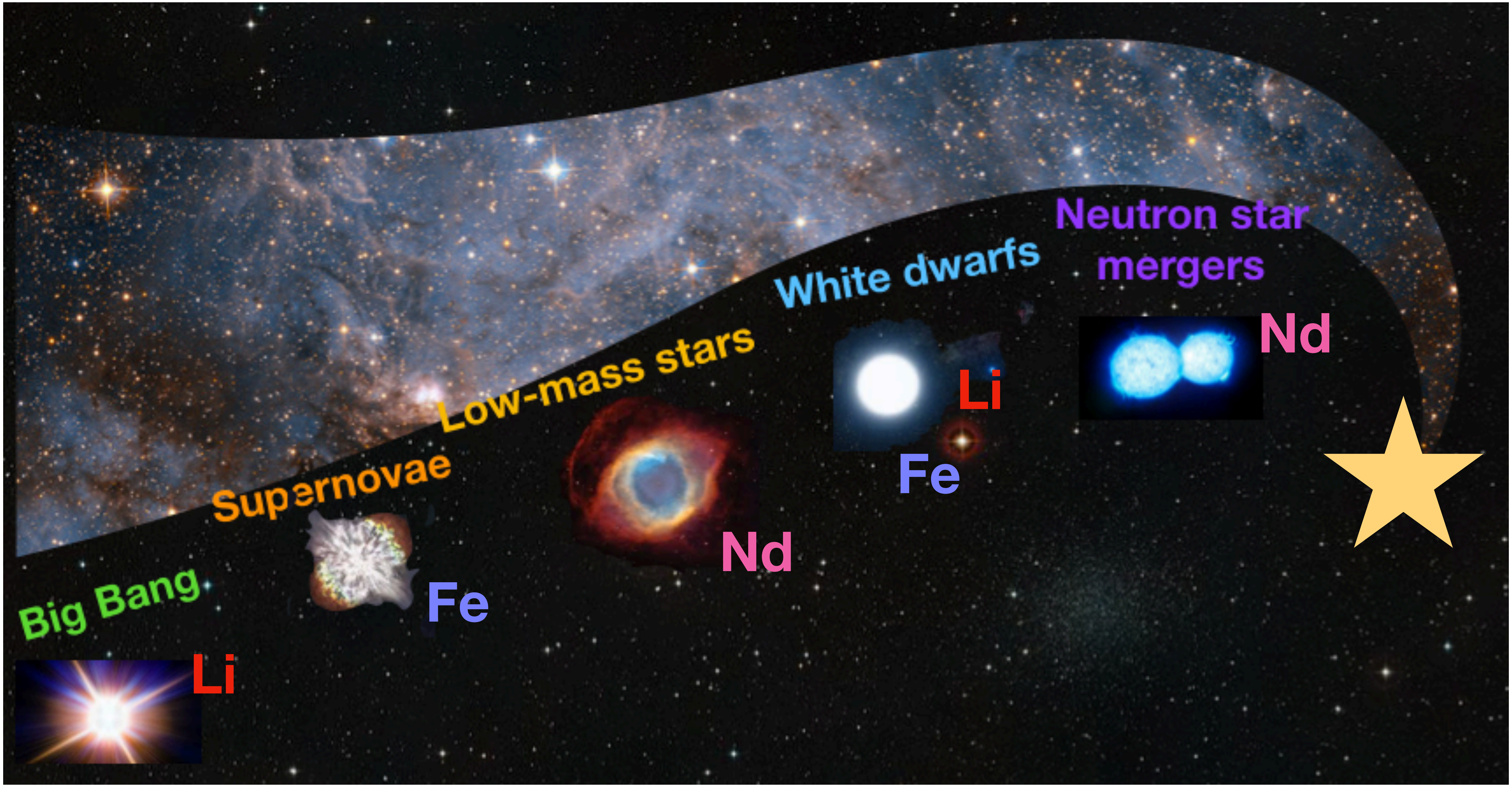


Galactic Archeology

- Galactic Archeology uses **kinematics**, **stellar ages** and **chemical abundances** of old (and young) stars to learn about the evolution of our Milky Way and its stellar populations.
  - Dynamical evolution (bulge, disks, halo)
  - Accretion history (mergers with smaller galaxies)
  - Chemical evolution (infall/outflows, IMF, SFR, migration, first stars)
  - **Nucleosynthesis - The origin of the chemical elements**

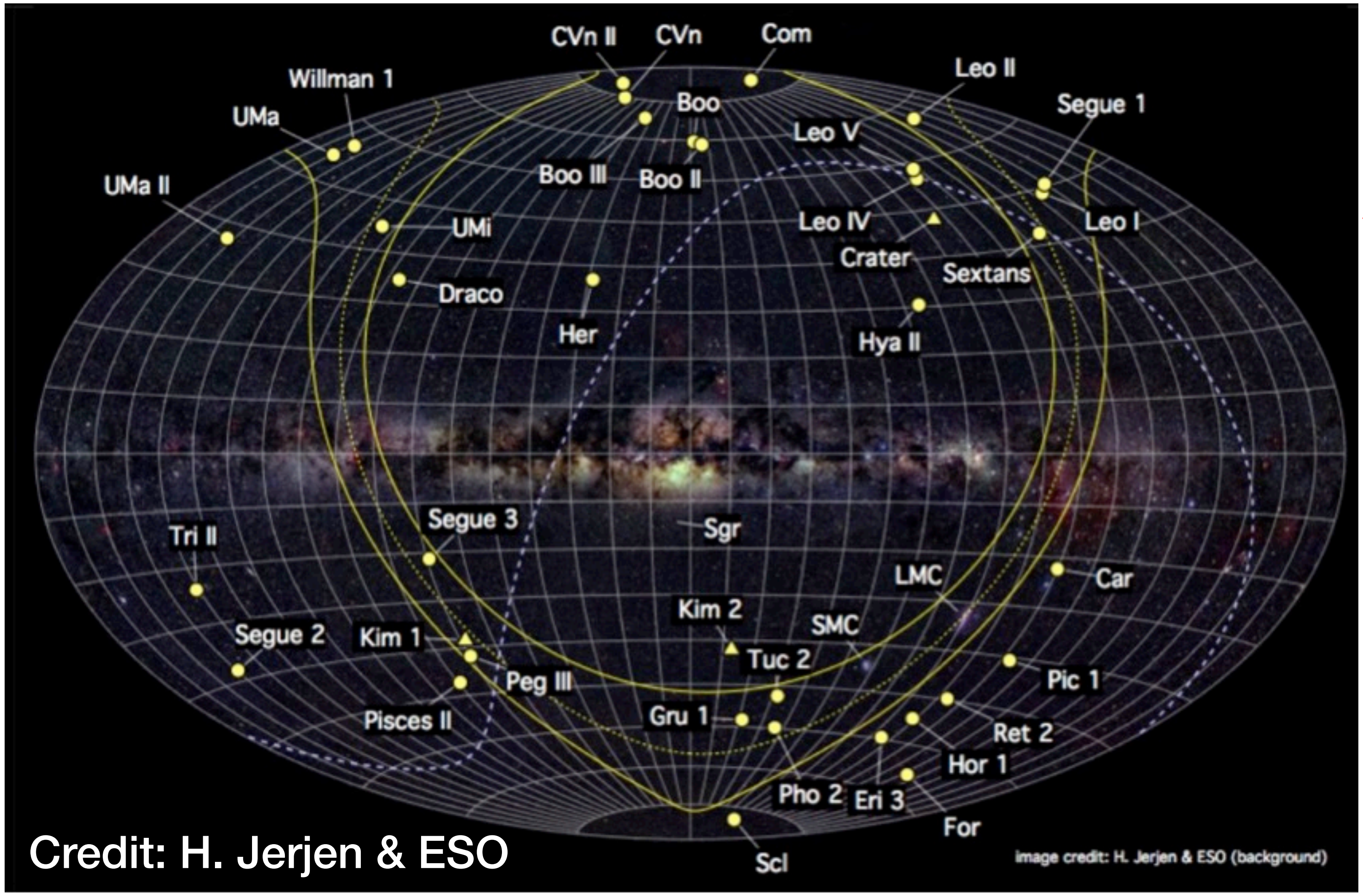
The Chemical Elements

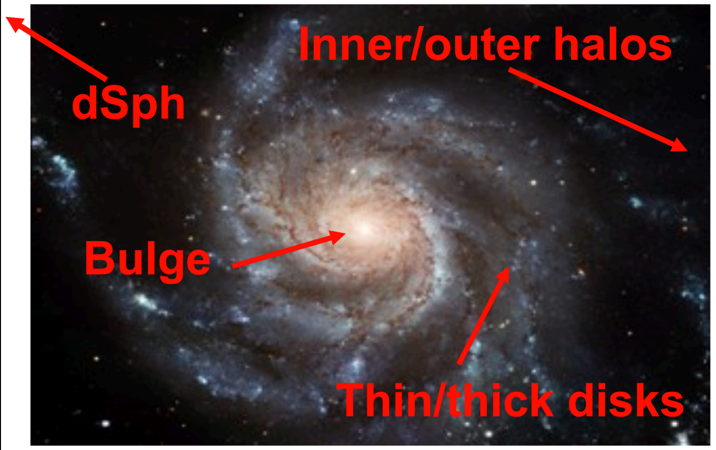
- Many **degeneracies:** Most elements formed in more than one place!



The Milky Way + satellites

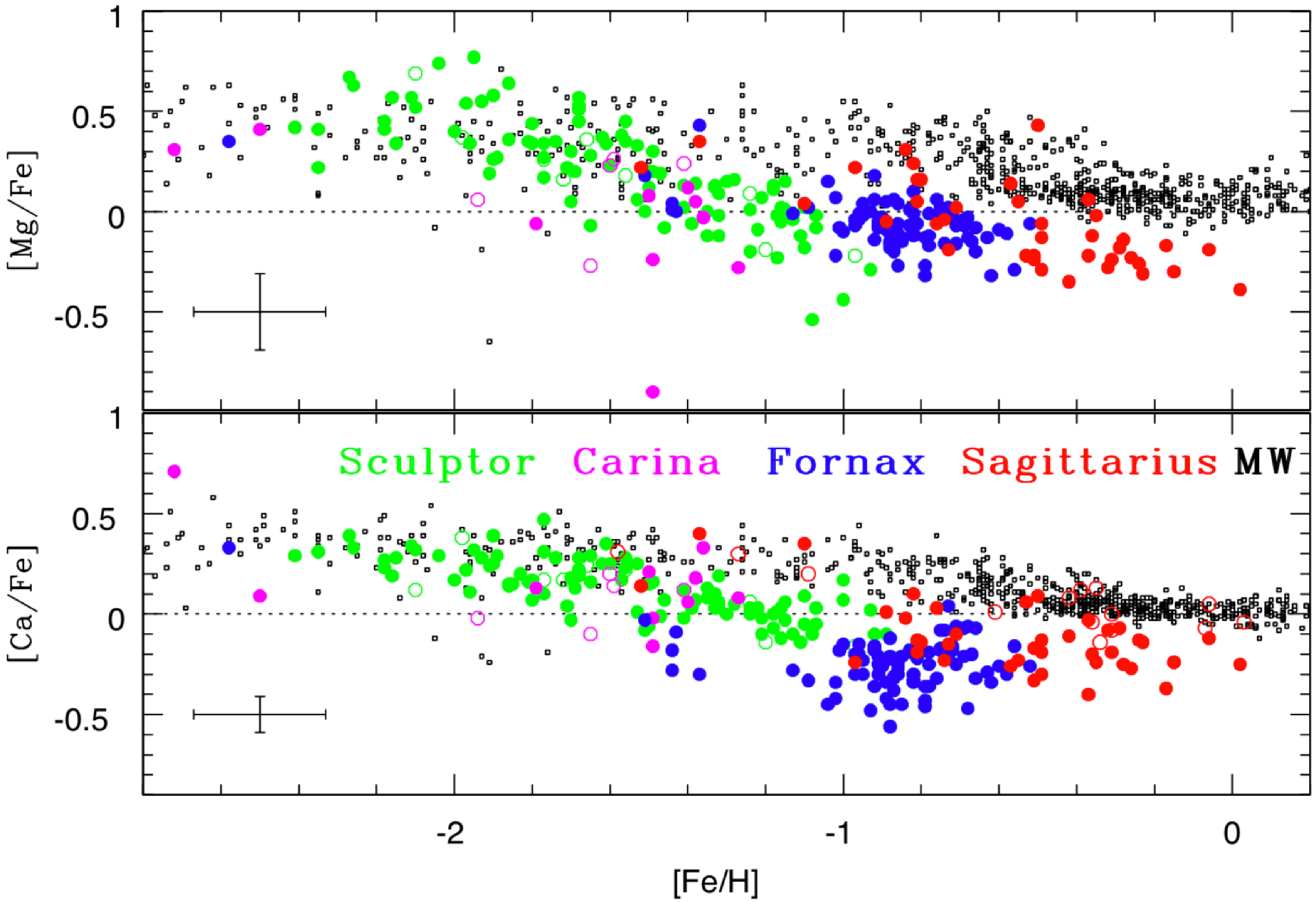
- The Milky Way has ≈50 known dwarf galaxy satellites (McConnachie 2012 + updates)
- Various environments to study the chemical enrichment!





Galactic Archeology

- Abundances of stars depend on **where** and **when** they were born!



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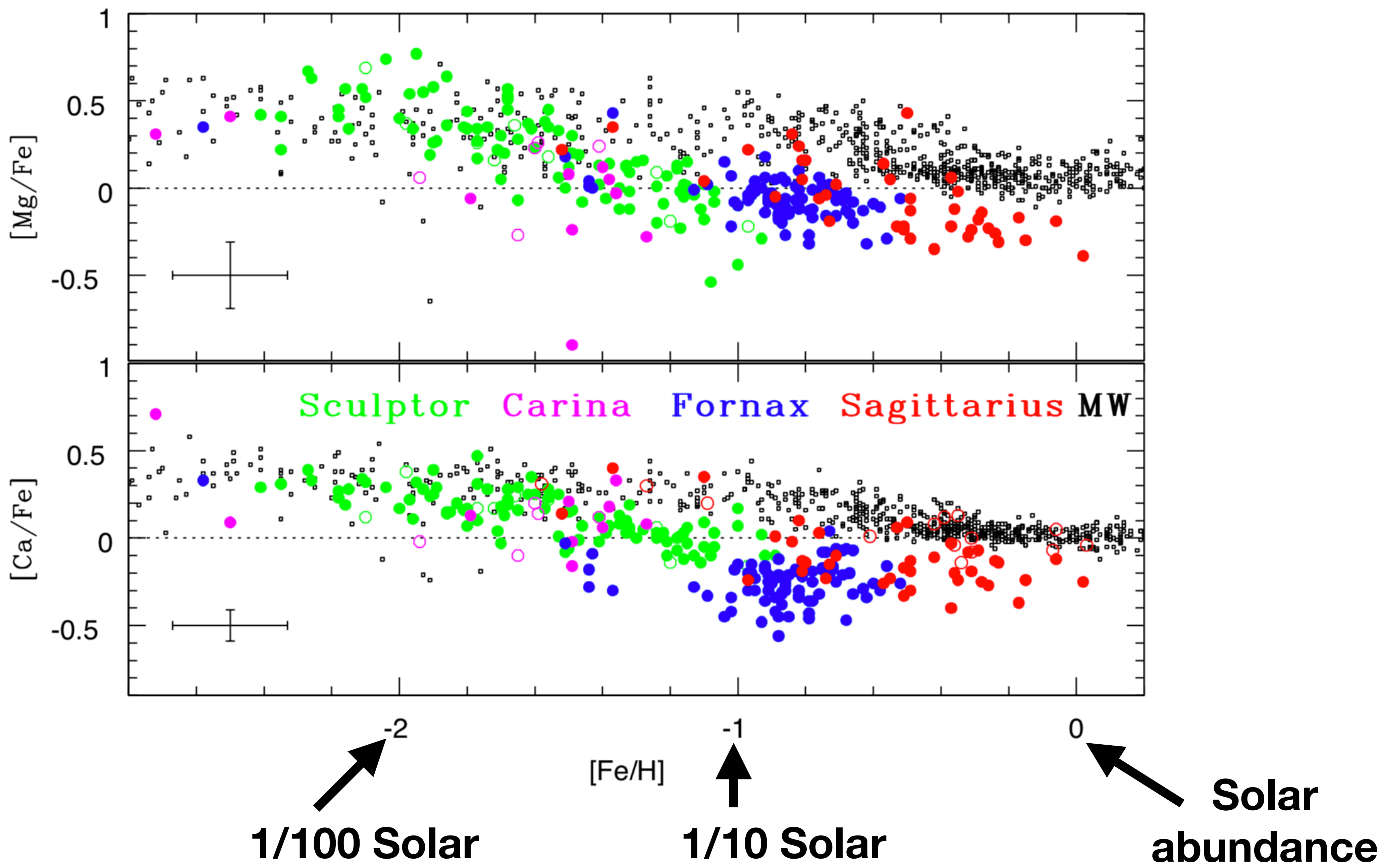

Tolstoy et al. 2009

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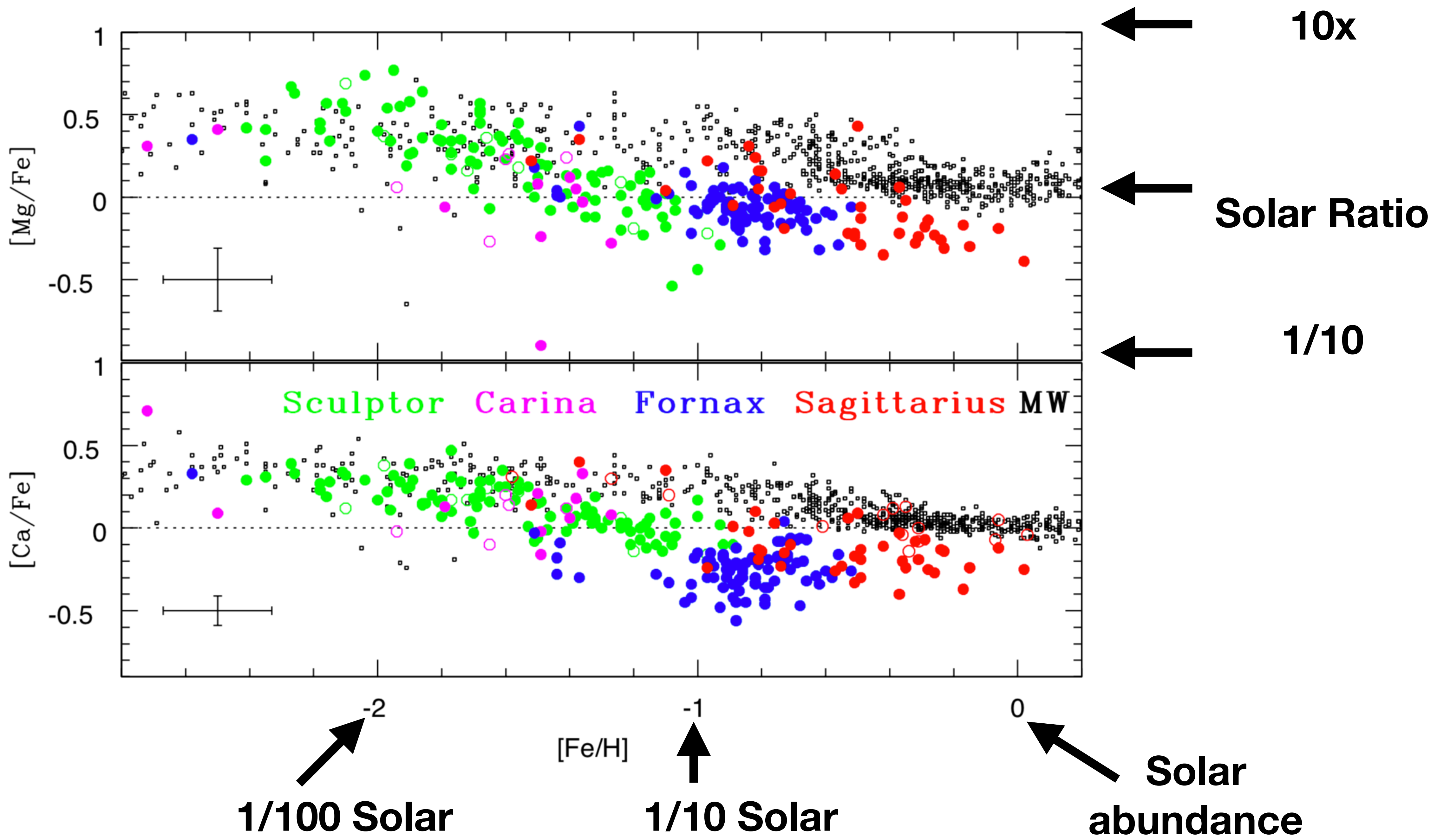

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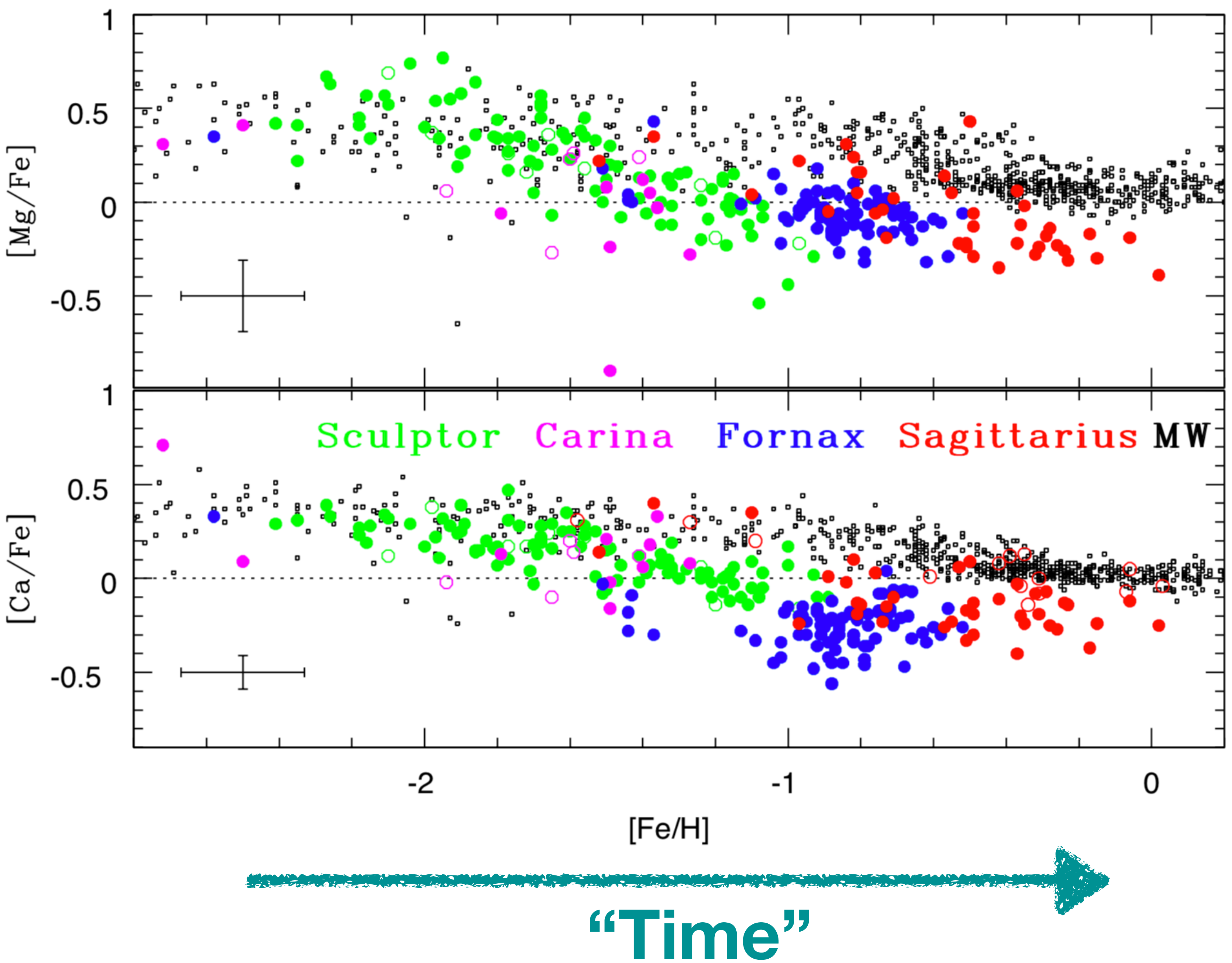

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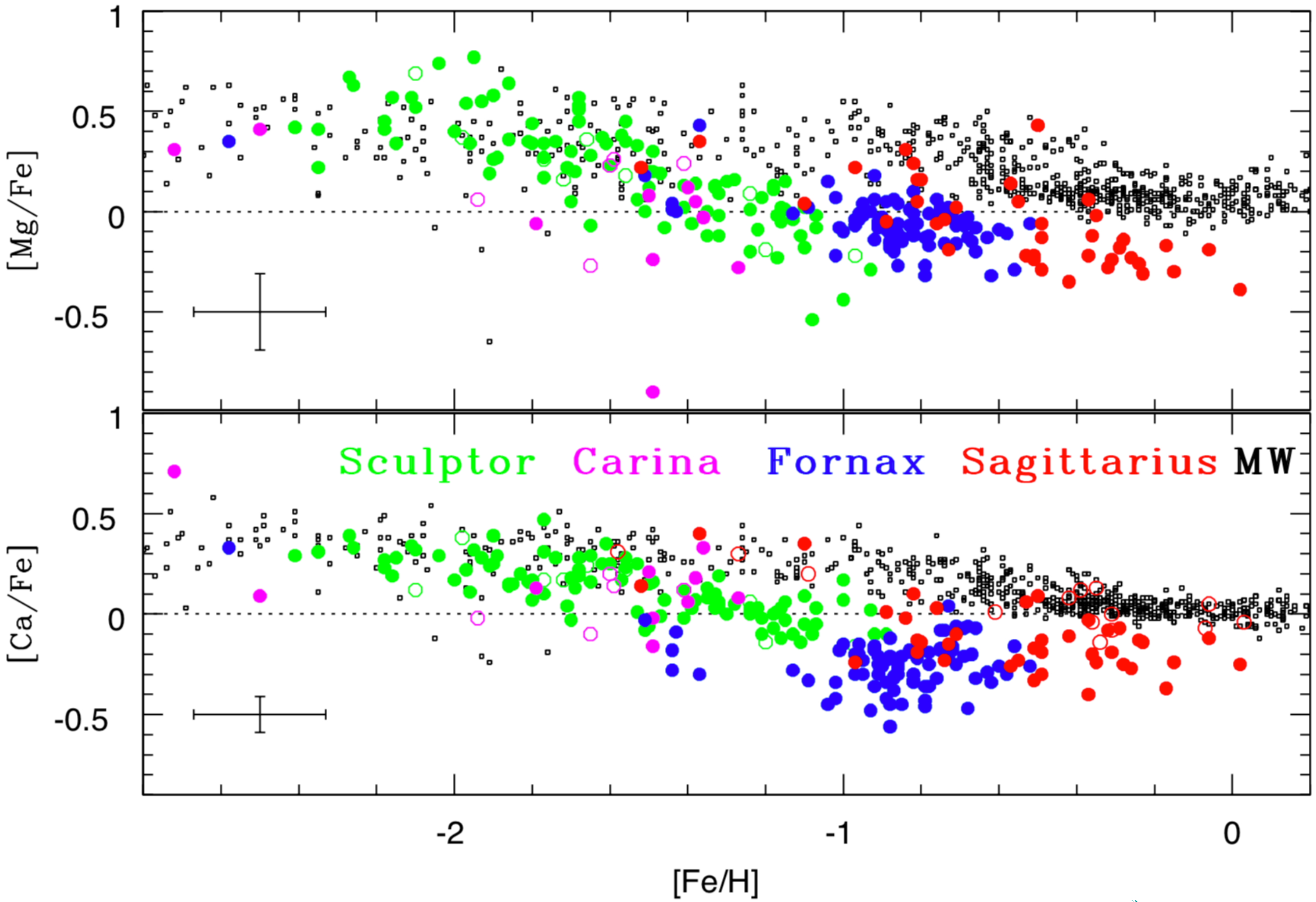

ccSN: core-collapse Supernovae - end of the life of massive stars

SNIa: Supernovae Type Ia - white dwarf in binary system

Tolstoy et al. 2009

Galactic Archeology

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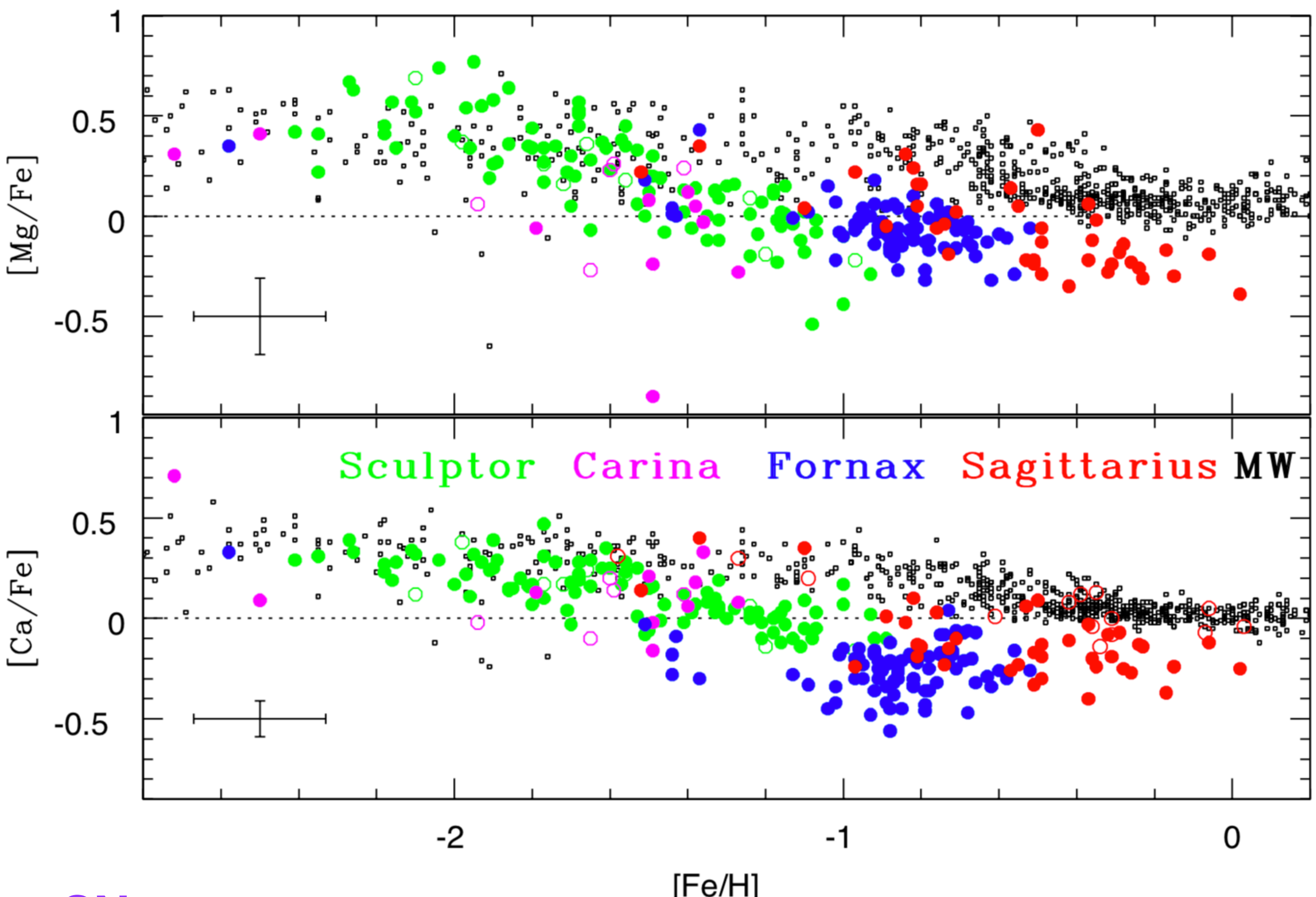
ccSN **ccSN + SNIa**

Mg: ccSN

Ca: mostly ccSN



ccSN: core-collapse Supernovae - end of the life of massive stars

SNIa: Supernovae Type Ia - white dwarf in binary system

Fe: ccSN and SNIa

"Time"

Spectroscopic Surveys of Stars

- **Ongoing:**

APOGEE

SDSSIII

GALAH

- **Upcoming (very soon!)**

WEAVE

4MOST

MOONS

Multi Object Optical and Near-infrared Spectrograph

Spectroscopic Surveys of Stars

Each survey has their own website!

APOGEE

SDSS III

GALAH

- **Upcoming (very soon!)**

WEAVE

4MOST

MOONS

Multi Object Optical and Near-infrared Spectrograph

Spectroscopic Surveys of Stars

Having many spectra is one thing - interpreting them correctly is another!

First Stars


Xe
Tin
Ce
Samarium
Niobium
Sodium
Vanadium
Manganese
Zinc
Oxygen
Promethium
Carbon
Palladium
K
Iron
Magnesium
Sulphur
Argon
Nitrogen
Silver
Silicon
Zirconium
Zn
Lead
Sulphur
Lithium
Beryllium
Helium
Nickel
Hydrogen
Gold
C
Zinc
Lanthanum
Aluminium
Fluorine
Chromium
Nitrogen
Barium
Lutetium
Europium
Neon
Strontium
Yttrium
Oxygen
Cobalt
Phosphorus
S
Praseodymium
Copper
Krypton
Cerium
Arsenic
Sc
Copper
Neodymium
Calcium
Scandium
Potassium
Silver
Nickel
Titanium
Beryllium
Nitrogen
Cerium
Titanium
Zinc
Cobalt
Indium
Scandium
Molybdenum
Oxygen
Iron
Cobalt

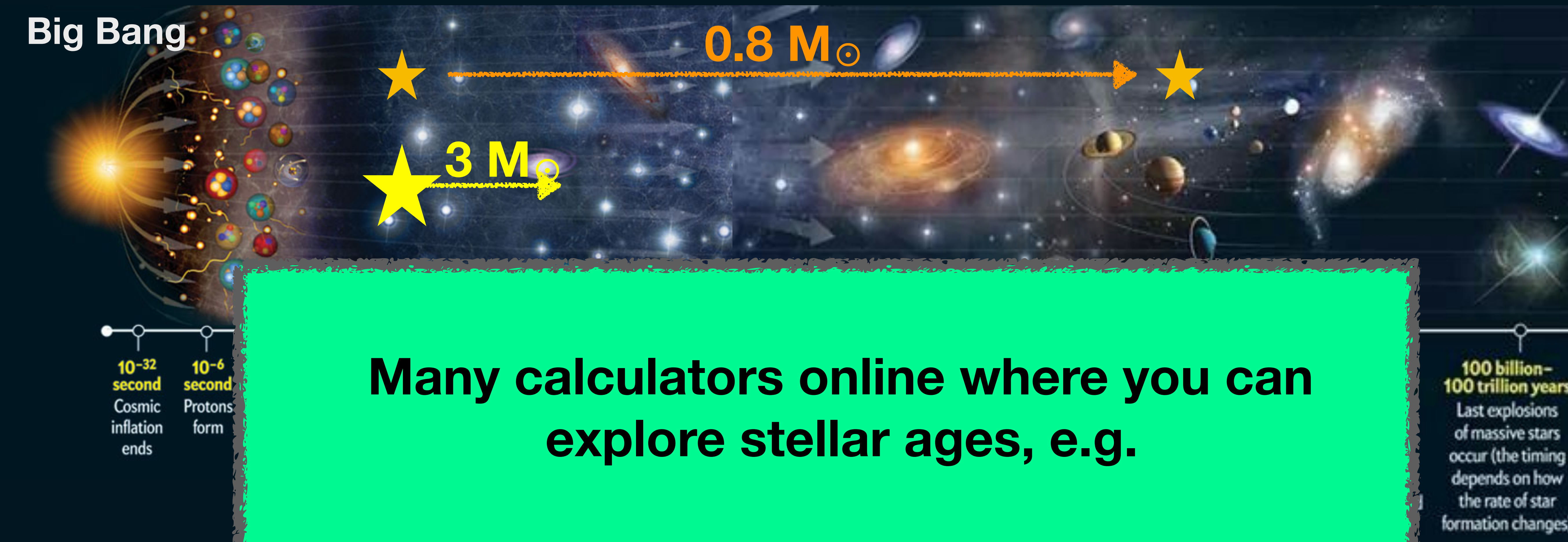
The First Stars

Many calculators online where you can explore stellar ages, e.g.

https://rechneronline.de/planets/lifespan-star.php

- The first stars after the Big Bang only made of H and He (and a dash of Li)
- Likely more massive than the stars formed today.
- First stars with M < 0.8 M⊙ can survive until today

The First Stars



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  (a …
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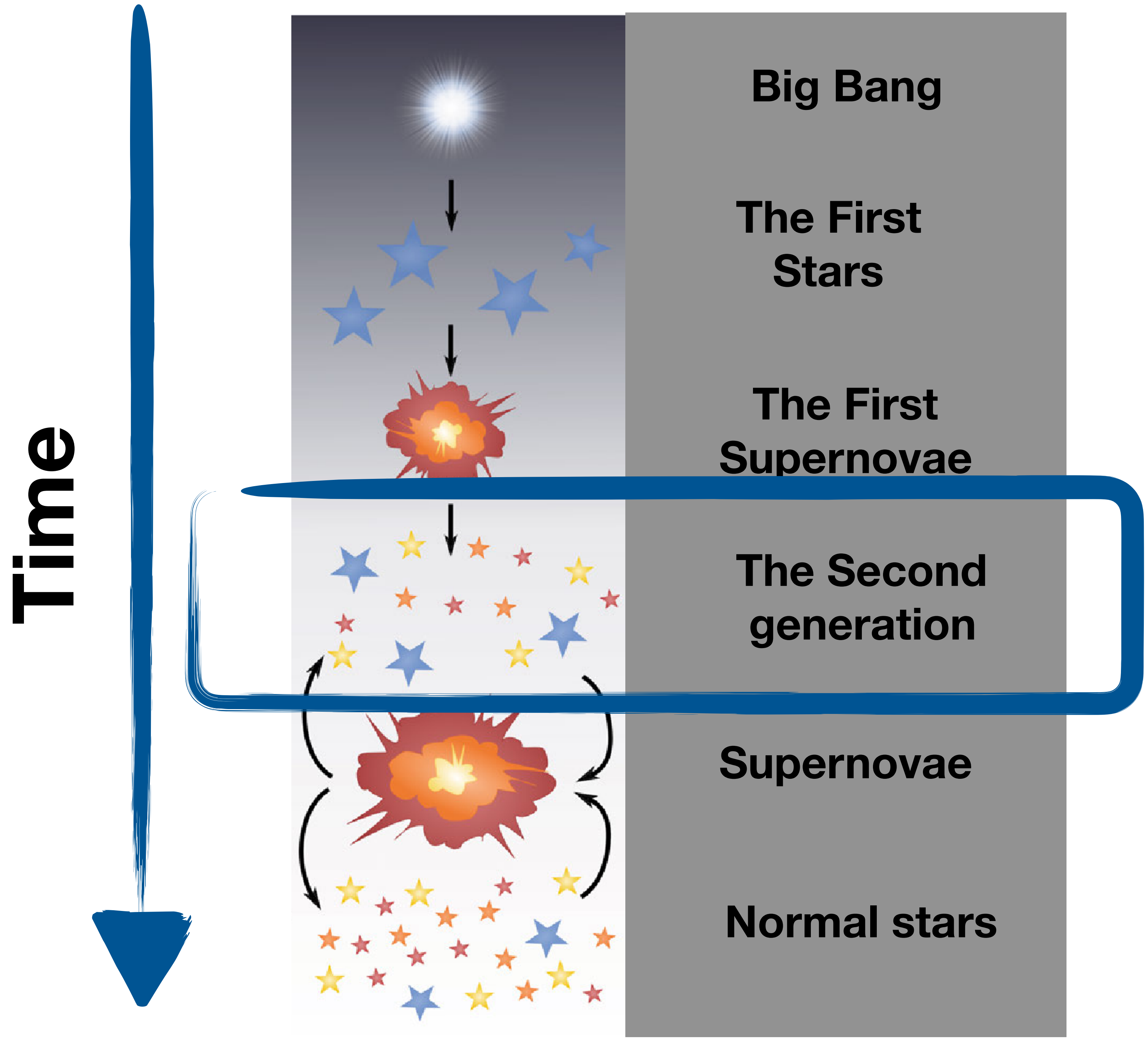
First Stars

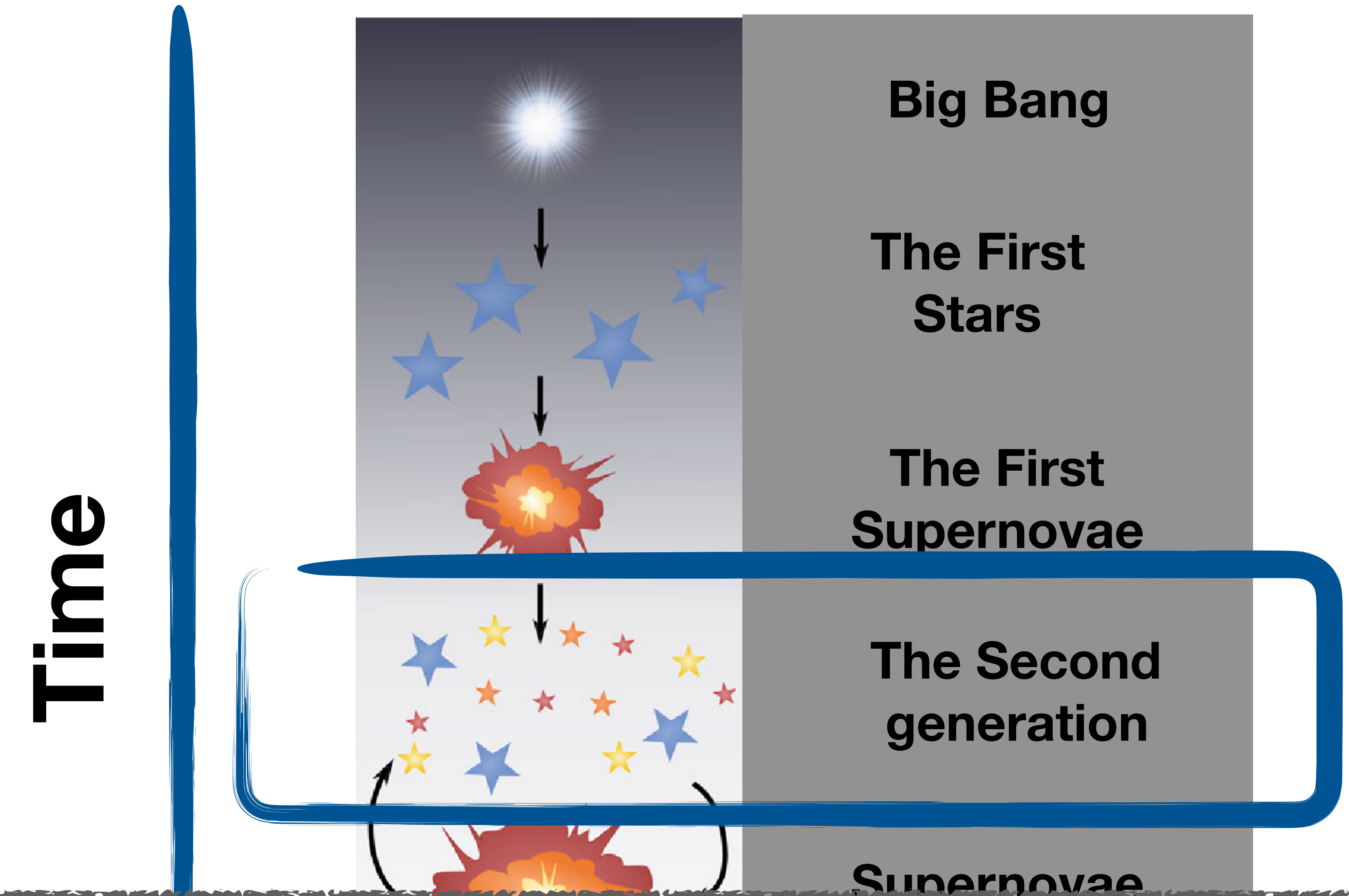
- **If first stars were more massive**
  - More ionizing radiation.
  - Higher fraction of Supernovae (end of massive stars) - more production of chemical elements.
  - Less likely that there is a surviving first star in the Milky Way - **None found yet!**

Fig. credit: https://www.universetoday.com/24776/what-were-the-first-stars/

Second Generation!



Second Generation!

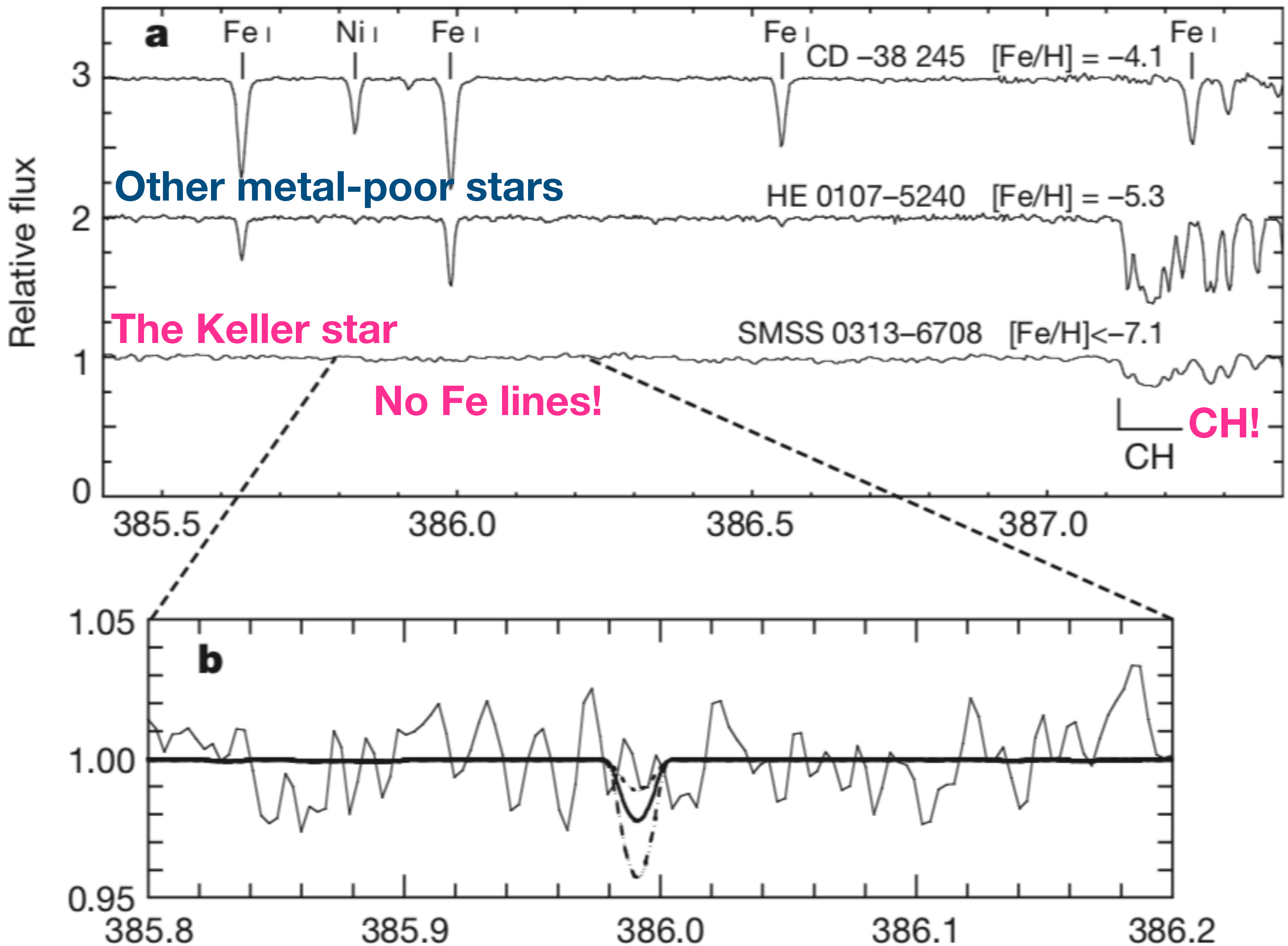


Second generation stars guard the products of the First Stars

The most iron-poor star

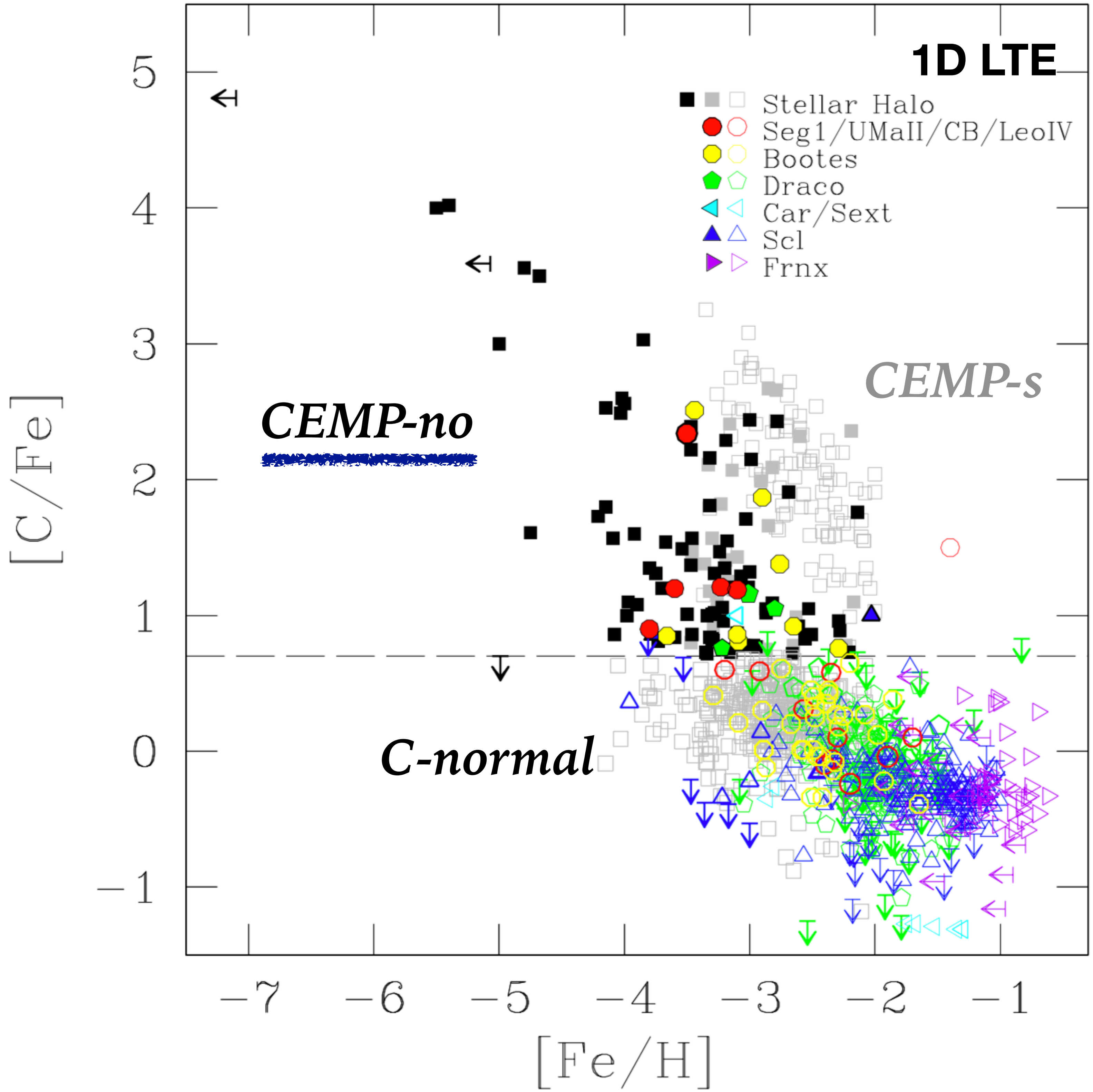
- The most iron-poor star known to date has
  - [Fe/H]<-7.1 when estimated in 1D LTE (Keller et al. 2014).
  - [Fe/H]<-6.5 when estimated with 3D NLTE, **~4 times higher** (Nordlander et al. 2017)
- That is less than 1/3,000,000 solar!

The most iron-poor star



Keller et al. 2014

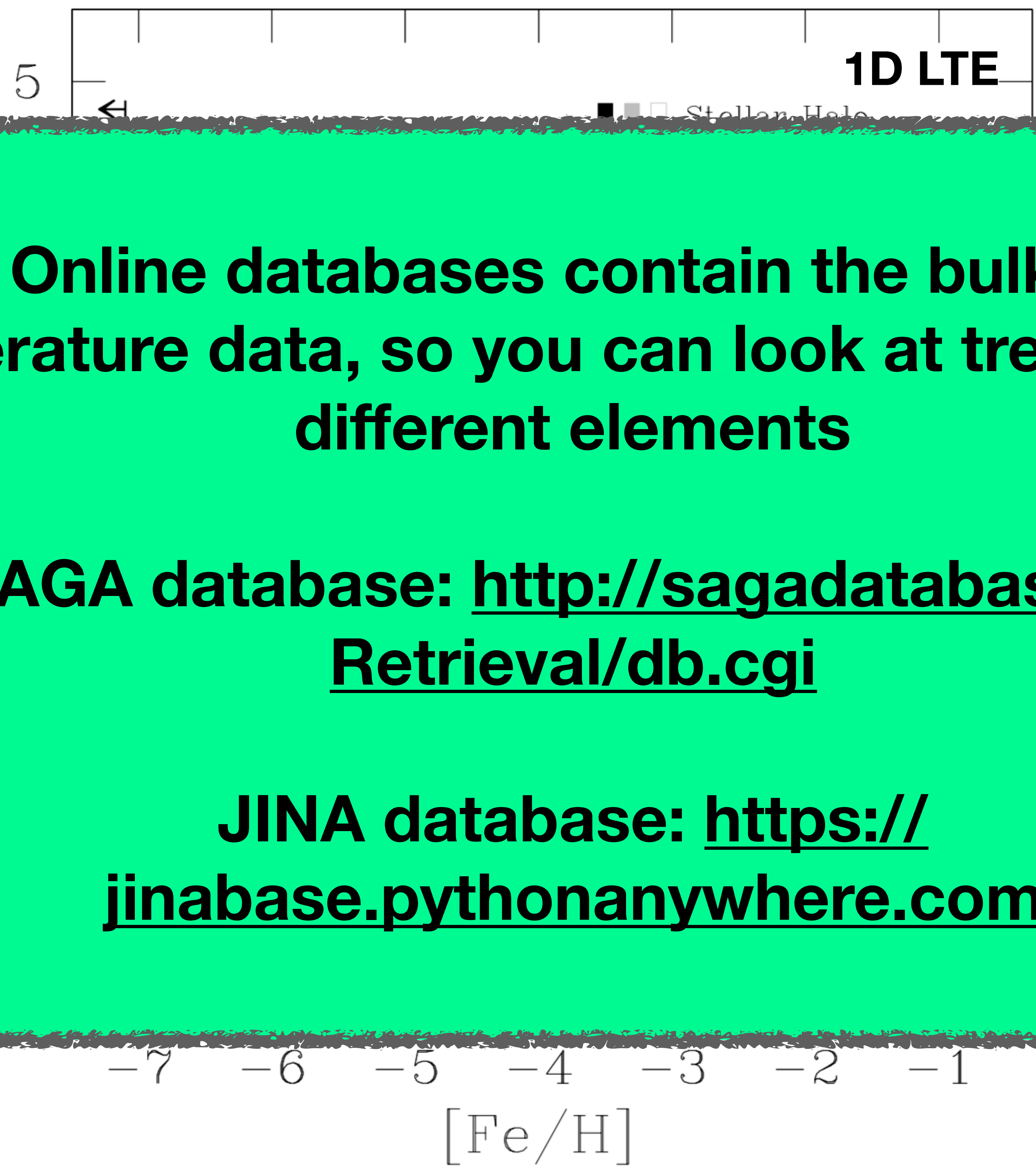
CEMP stars



CEMP-no star: Carbon-enhanced metal-poor star (no Ba, Eu enhancement)

Keller et al. 2014

CEMP stars



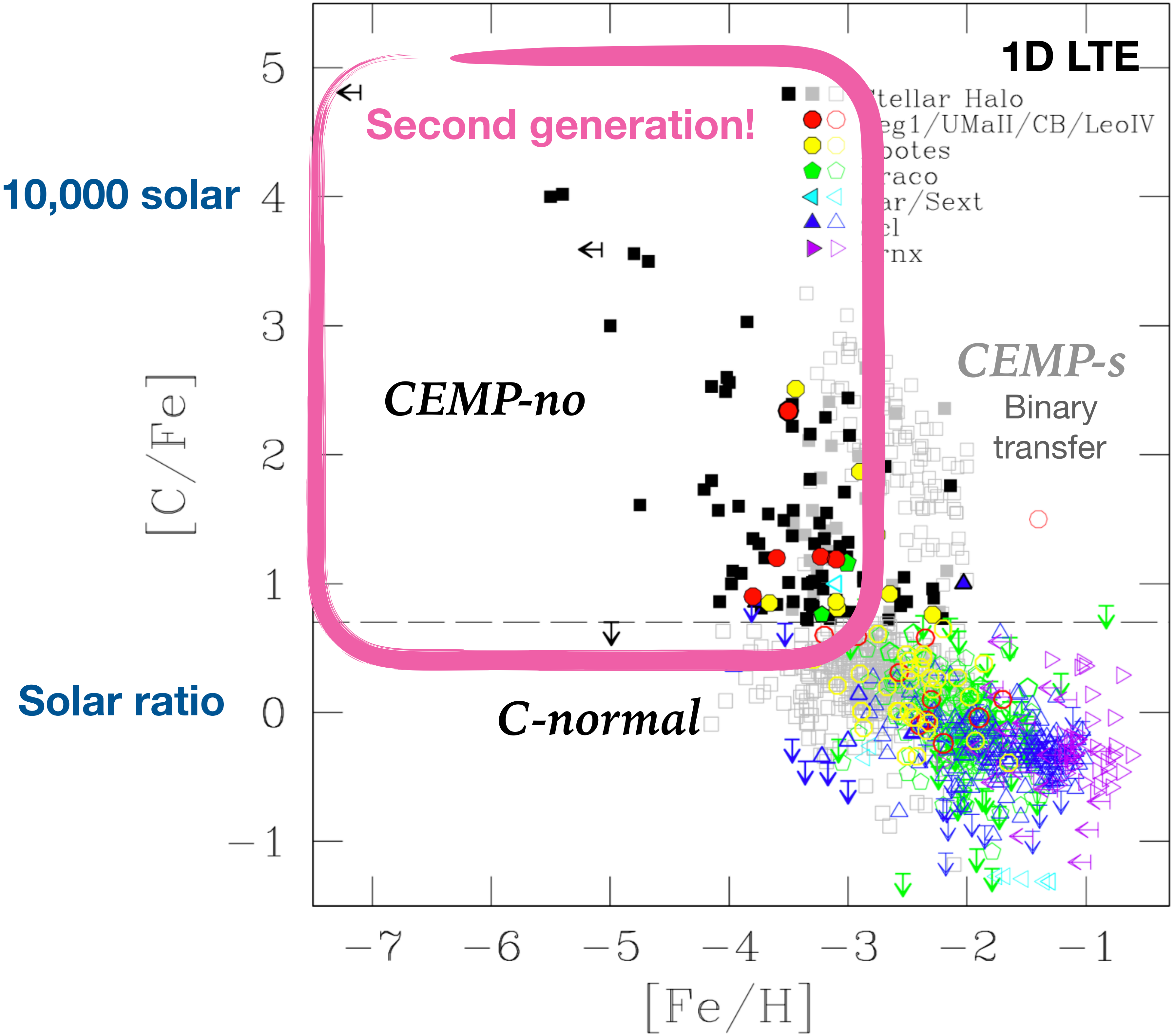
Online databases contain the bulk of literature data, so you can look at trends of different elements

SAGA database: http://sagadatabase.jp/Retrieval/db.cgi

JINA database: https://jinabase.pythonanywhere.com

o star:
on-
l metal-
(no Ba,
cement)

CEMP stars



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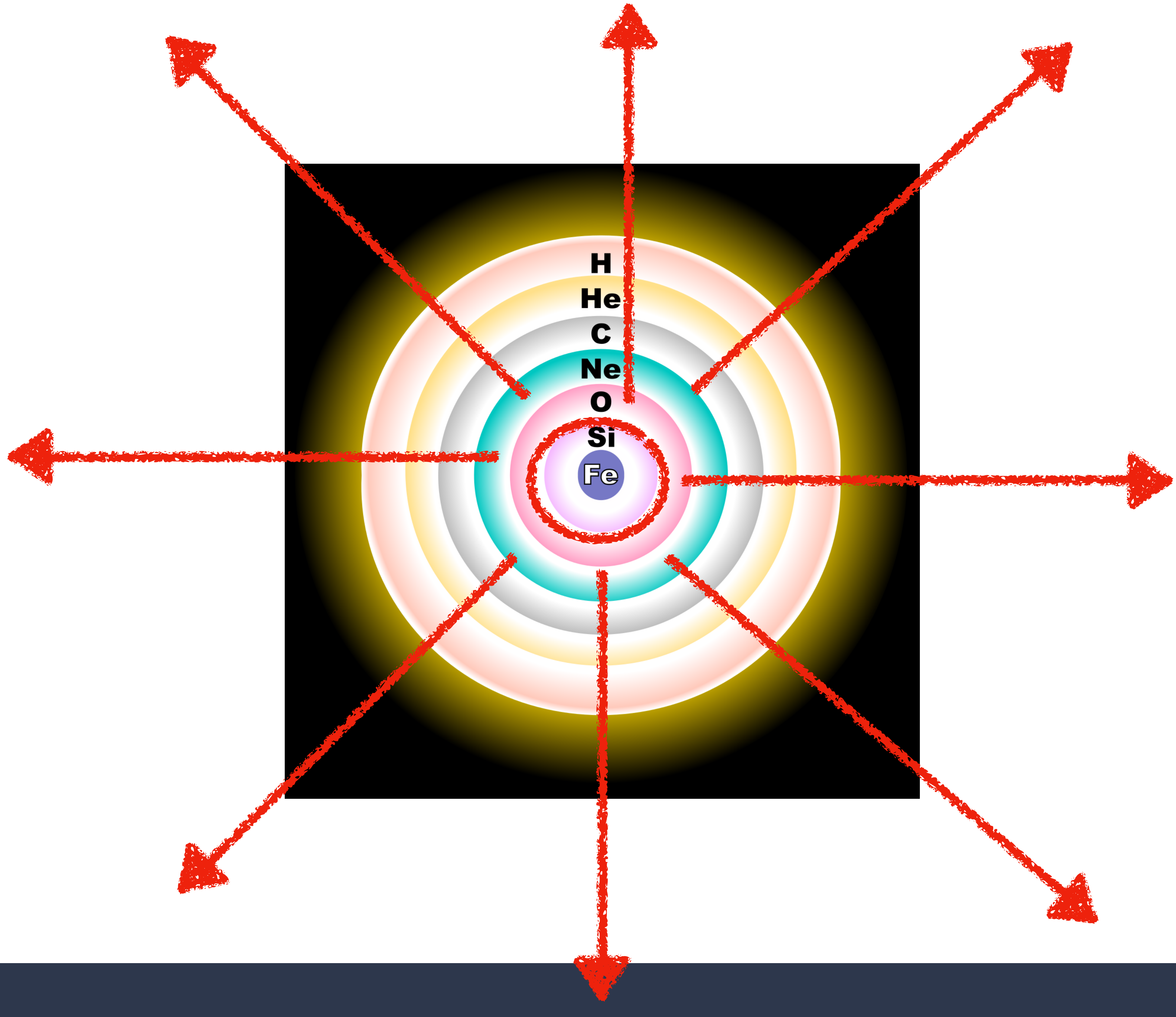
CEMP stars - Faint SN fallback



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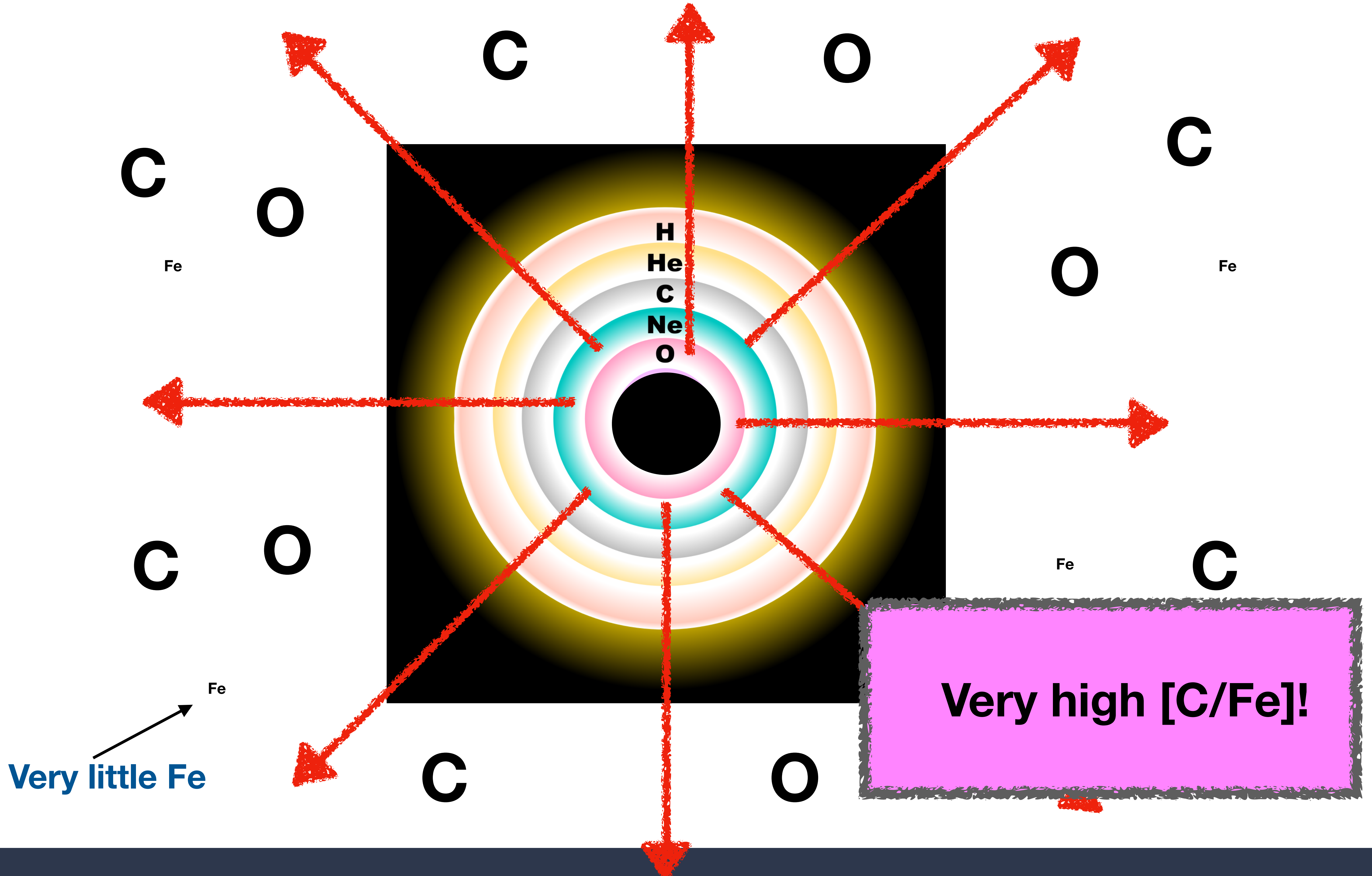
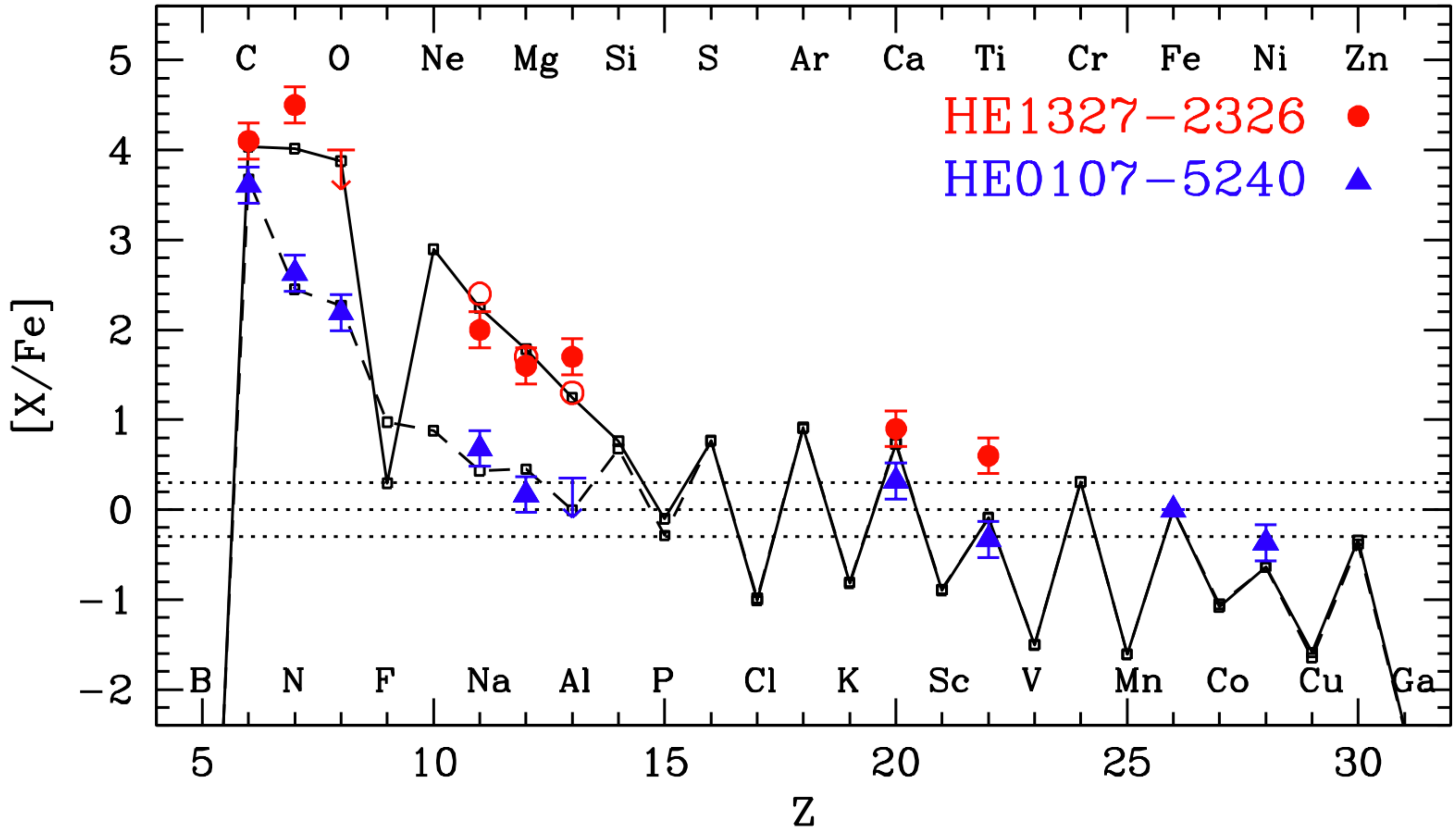


CEMP-no stars!

- CEMP-no stars are our best observational evidence for the first stars!
  - Their composition tell us about the products of the first stars!
  - The products of their first stars tell us about their properties, e.g. mass and explosion energy.

The products of the first stars

Two 25 $M_\odot$ models with different explosion energies



Iwamoto et al. 2005

The products of the first stars

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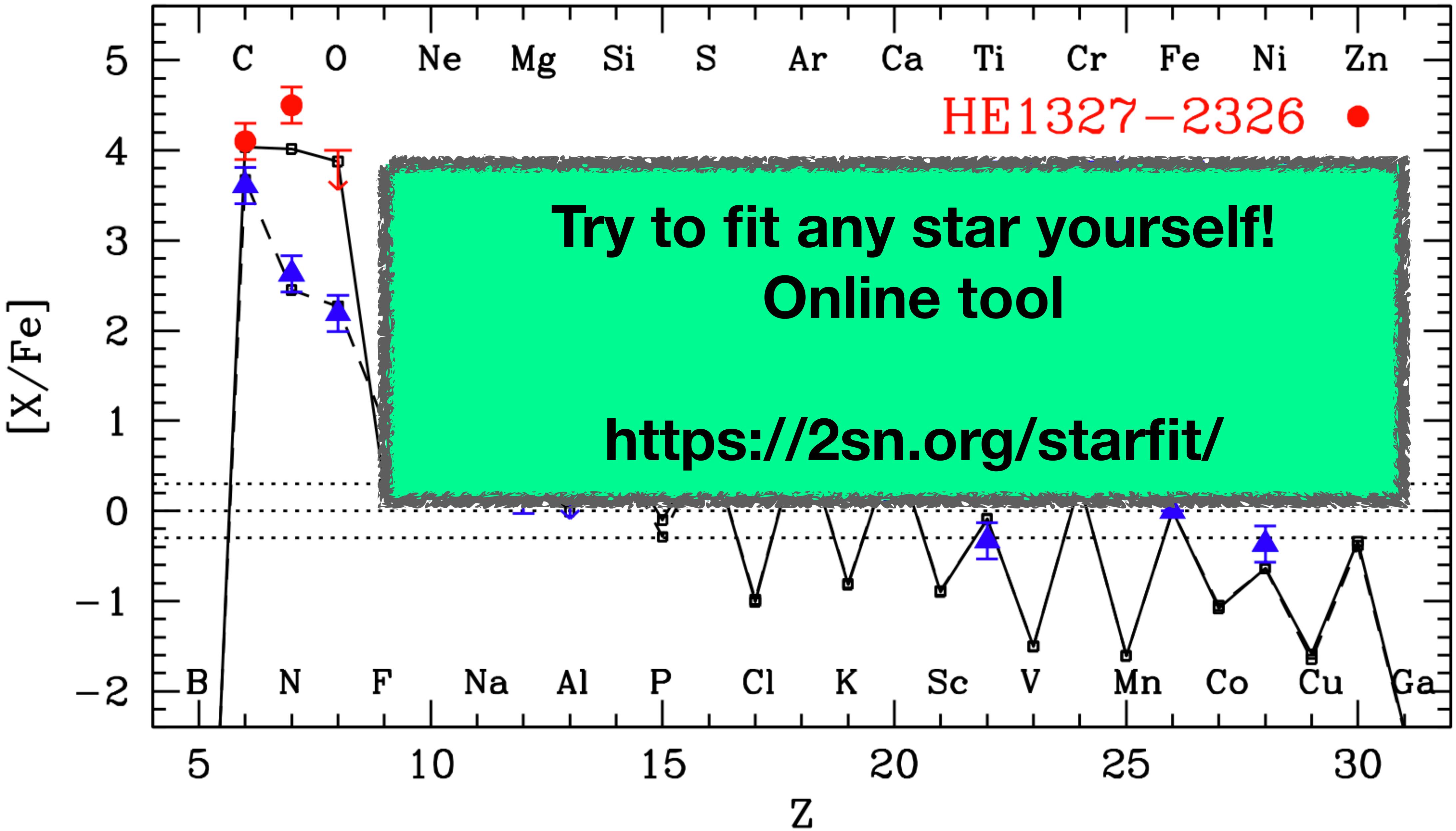

Try to fit any star yourself!
Online tool

https://2sn.org/starfit/

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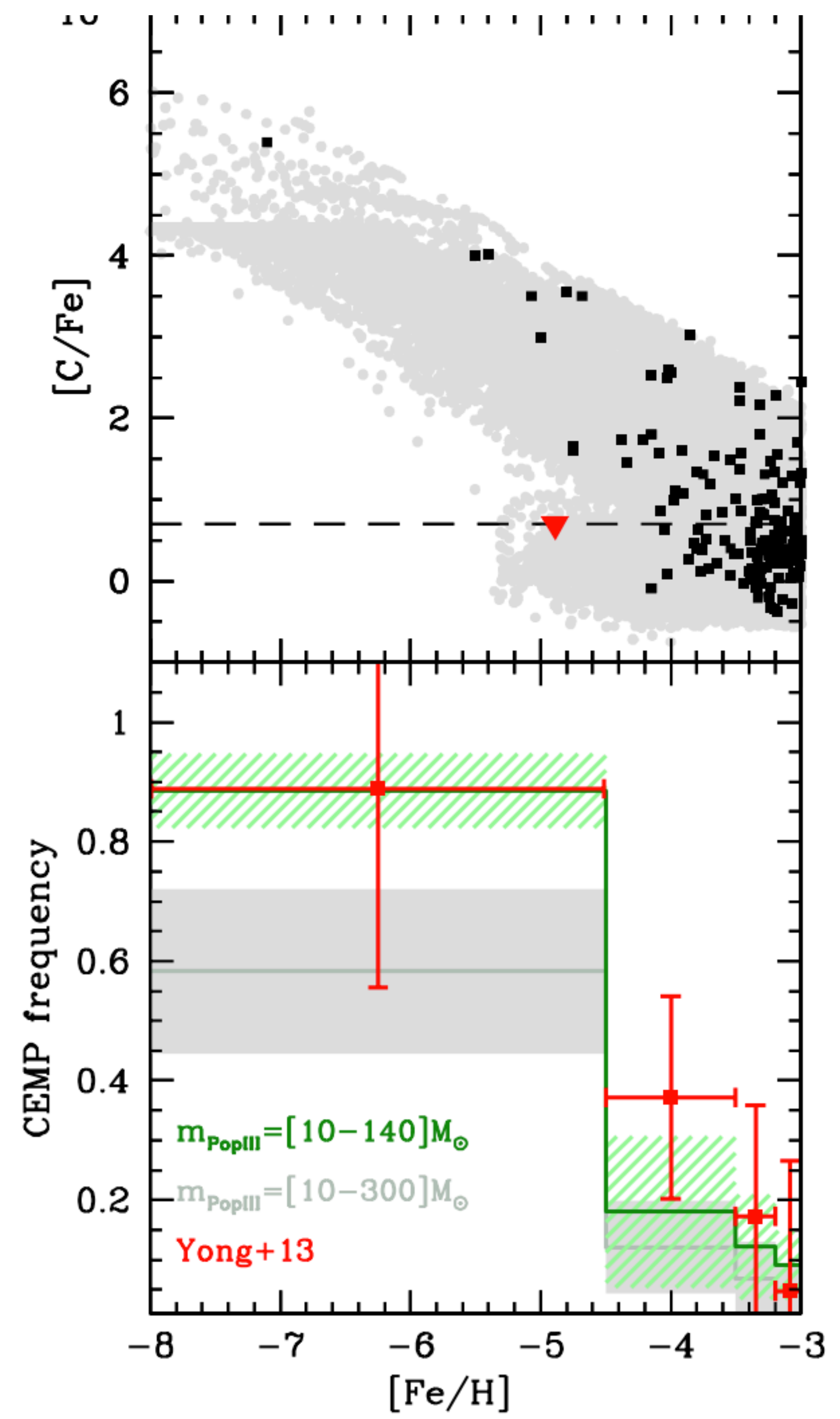
  - **The CEMP-no frequency tells us about the earliest chemical enrichment.**

CEMP-no stars!

- Model with different mass distribution of stars compared with observed fraction of CEMP-no stars (de Bennassuti et al. 2017)



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- **However…**

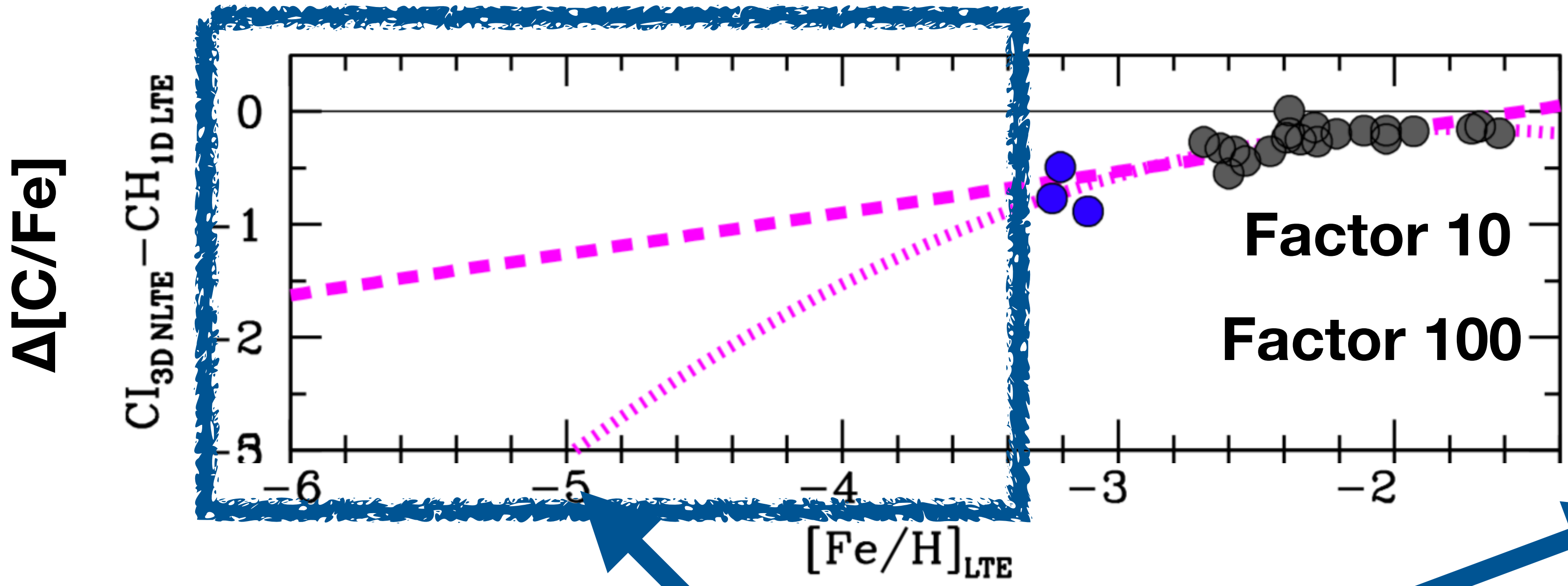
[C/Fe] measurements

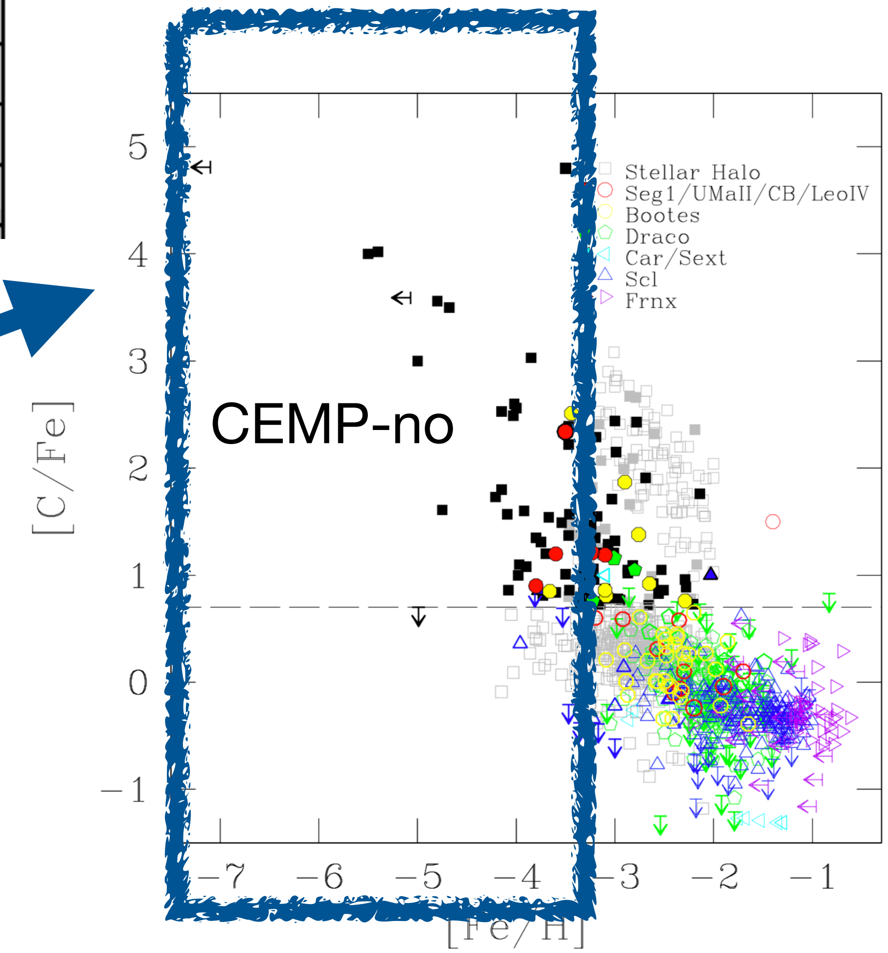
- Carbon is typically measured from molecular CH lines, which are sensitive to temperature and thus 3D effects. Thus Carbon is typically **overestimated.**
- Fe measured using 1D LTE **underestimates** the Fe compared to 3D NLTE.
- The 1D LTE [C/Fe] is overestimated by as much as **1 dex** at the lowest metallicities!

Amarsi et al. 2019, Amarsi, Nissen & Skúladóttir 2019

[C/Fe]-measurements

- Comparison of 1D LTE CH lines, and 3D NLTE atomic C I lines.





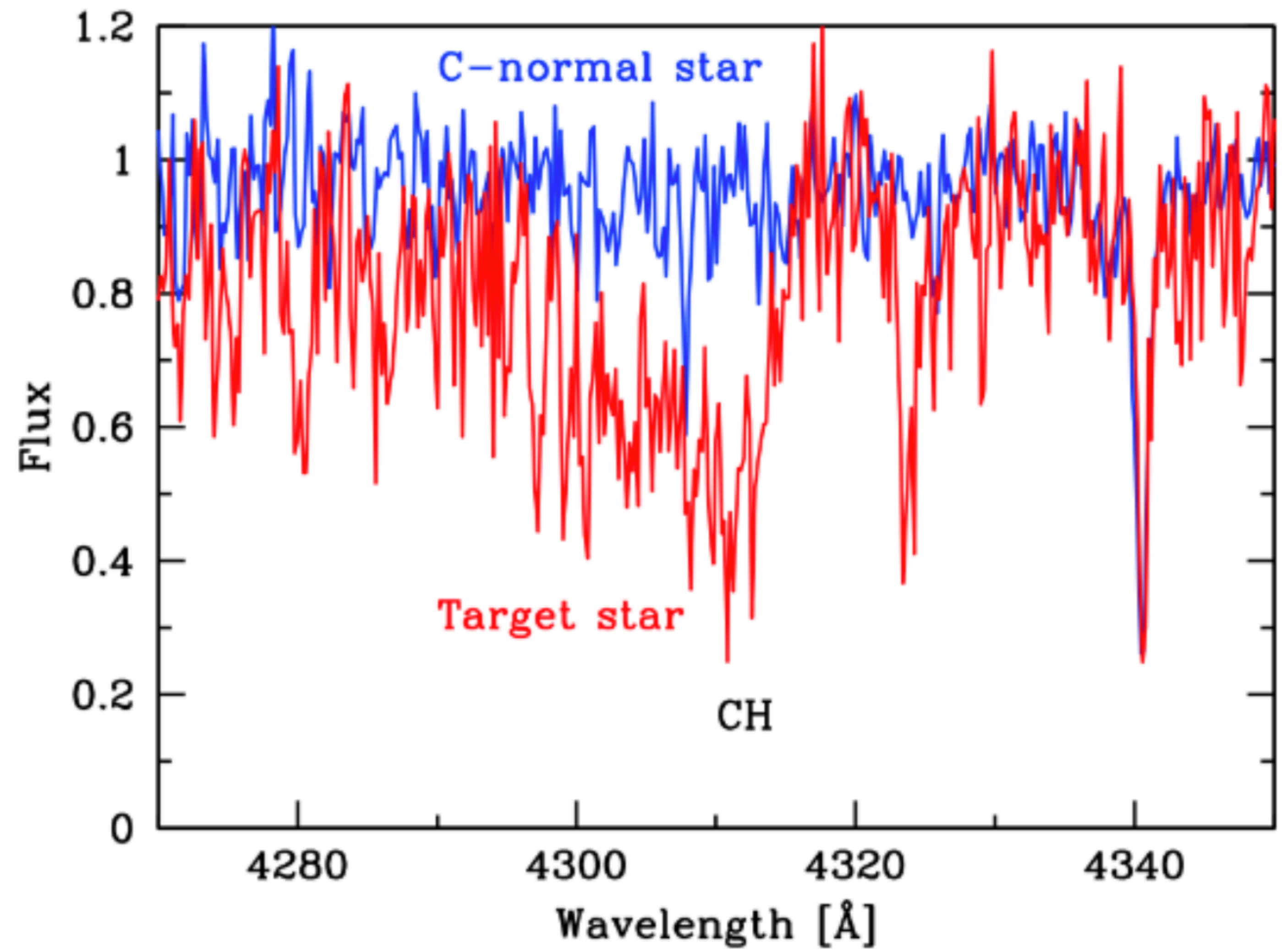
Unknown region

Work in progress!

(CEMP-no stars do exist)

- From directly comparing the spectra of similar stars with different C abundances we know the the dispersion is real, but it is still poorly quantified.

Example: A recently discovered CEMP-no star in a dwarf galaxy.



Skúladóttir et al in prep.

Beyond CEMP-no stars

- Not all first stars are expected to explode as faint supernovae.
- If we want to study different kinds of First Stars, e.g. hypernovae, pair-instability supernovae, massive rotating zero-metallicity stars etc. Accurate abundances are still very important.
- Carbon is not the only element with high 3D and/or NLTE corrections.
  - Aluminum corrections can be as high as 1 dex (Nordlander et al. 2017).
  - Manganese corrections can be as high as 1 dex (Bergemann et al. 2019).
  - etc…

Conclusions

- Chemical abundances of stars are currently the best (and often only) observational evidence of the properties of the first stars.
- The 3D NLTE abundances can differ up to (and maybe beyond) 1 dex from the 1D LTE abundances.
- **Accurate chemical abundances are of utmost importance if we want to understand the first stars!**
- **Still work in progress.**

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