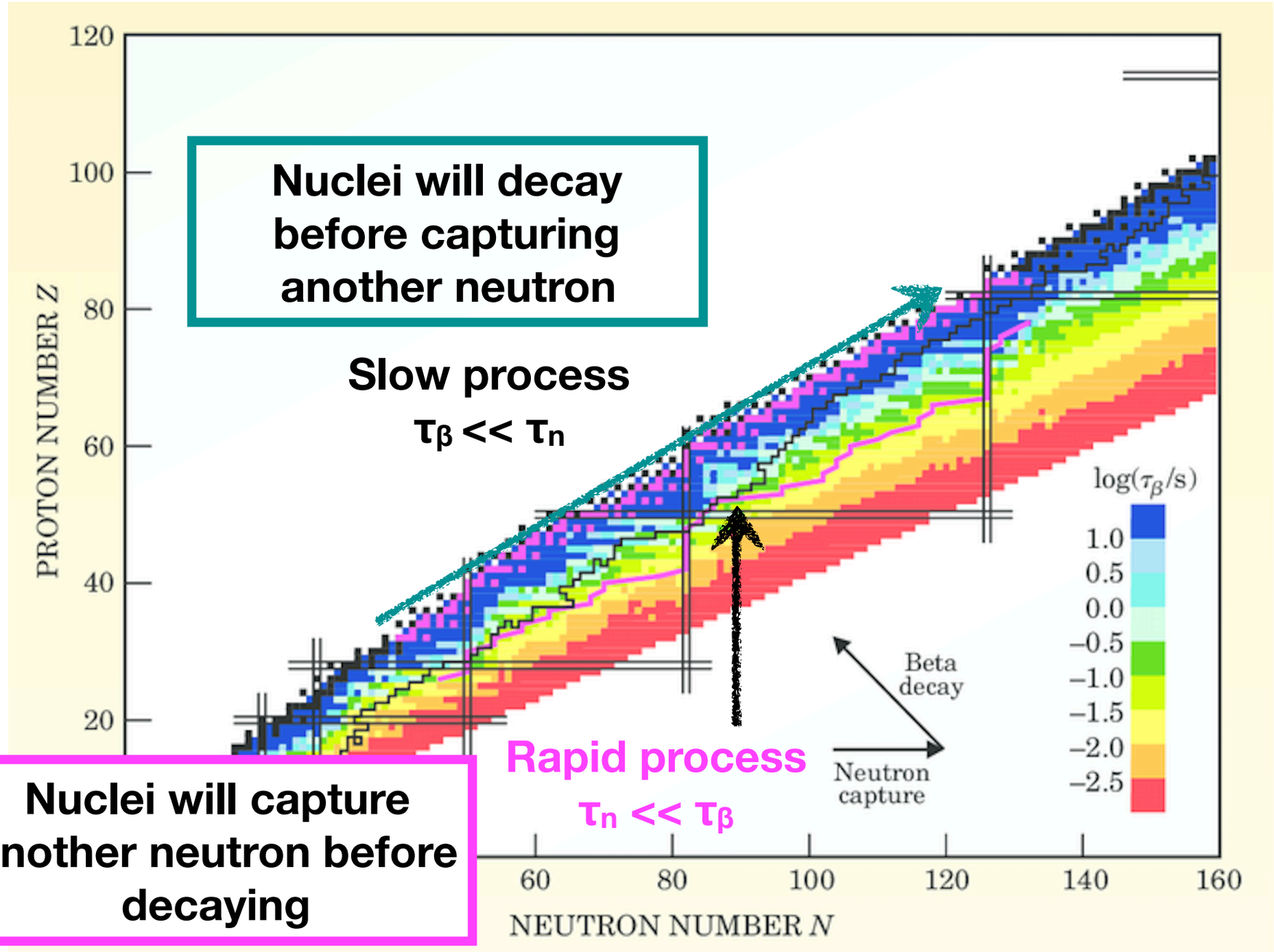
Dwarf galaxies' view of the heavy elements

Ása Skúladóttir
University of Florence / INAF

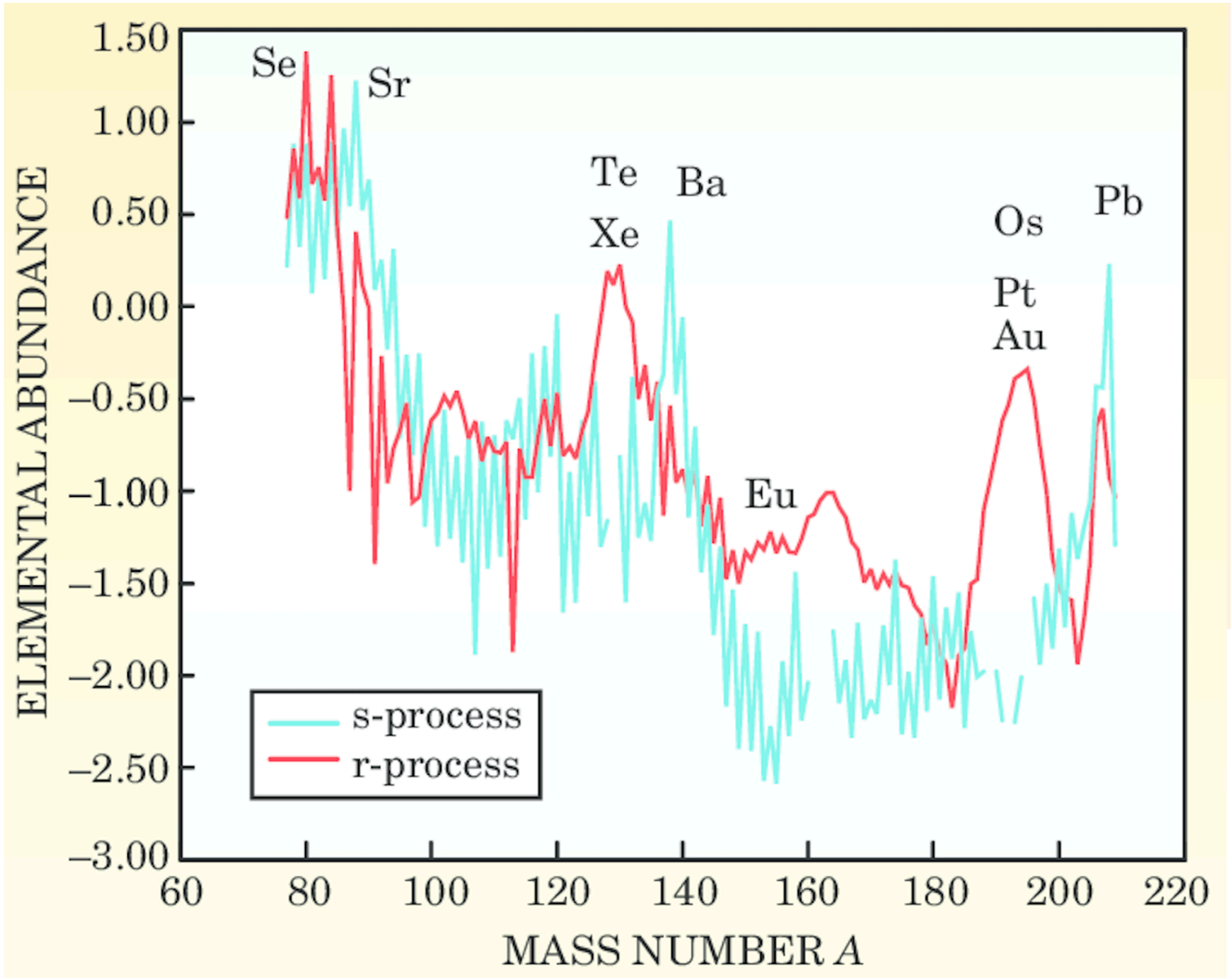
Heavy elements

Elements heavier than Zn (Z>30) form through series of neutron captures



Cowan & Thielemann 2004

Neutron capture



Solar system abundances of the s- and r-processes

Typical neutron densities:

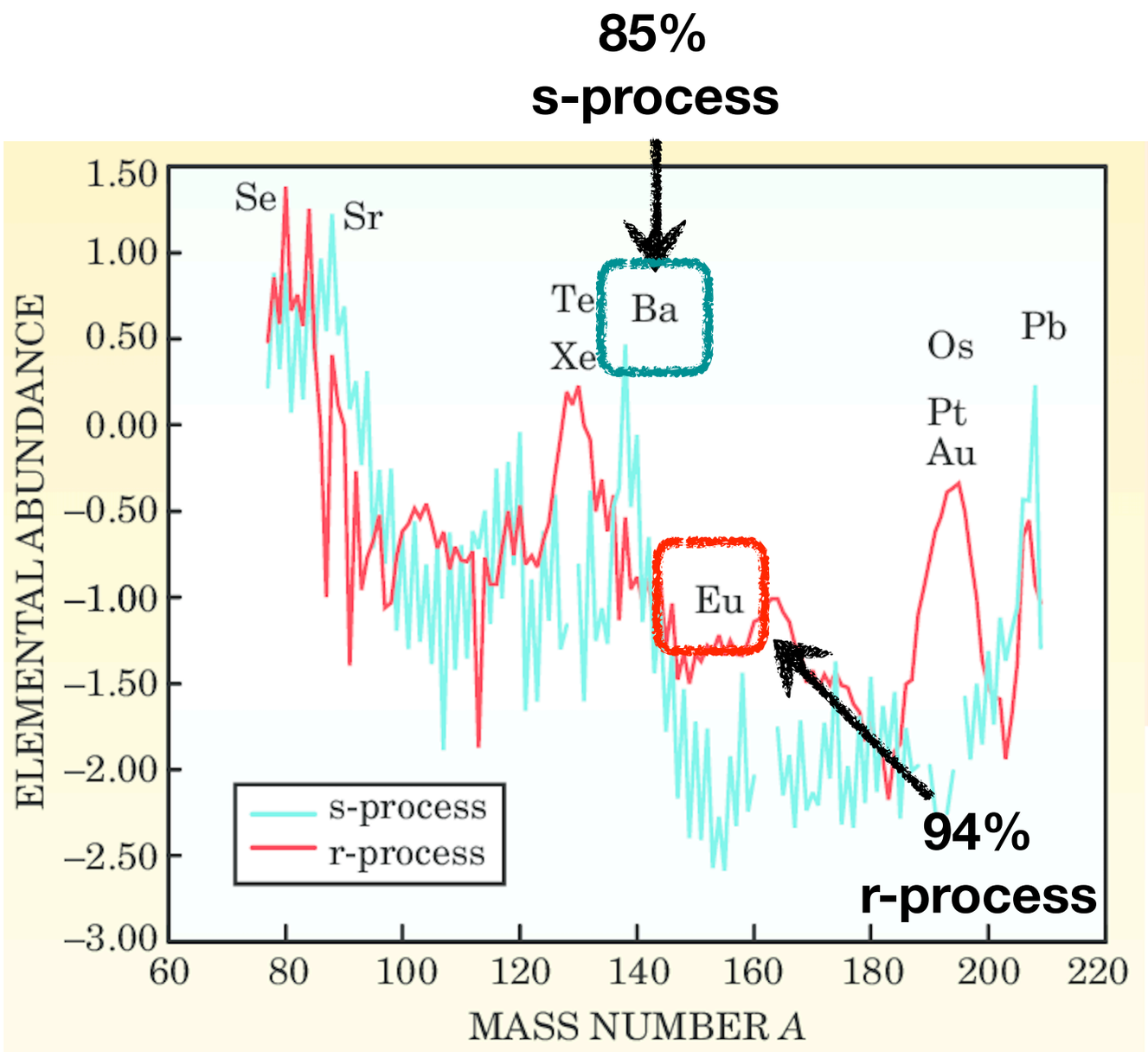
s-process n_d~$10^{6\text{-}12}$ cm^{-3}

r-process n_d>10^{22} cm^{-3}

Cowan & Thielemann 2004

Sneden et al. 2008

Neutron capture



Solar system abundances of the s- and r-processes

Typical neutron densities:

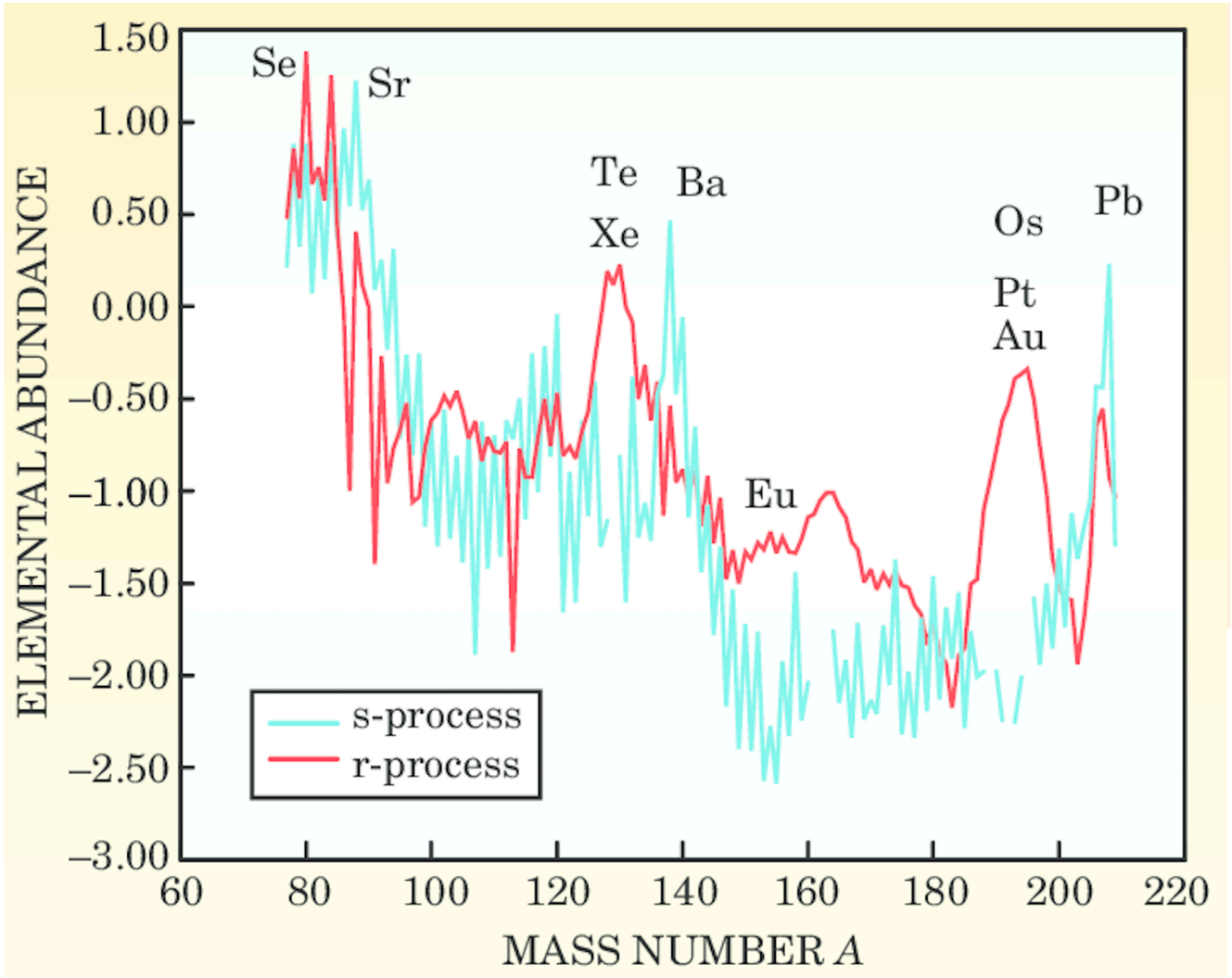
s-process n_d~$10^{6\text{-}12}$ cm^{-3}

r-process n_d>10^{22} cm^{-3}

Cowan & Thielemann 2004

Sneden et al. 2008

Neutron capture



Solar system abundances of the s- and r-processes

Typical neutron densities:

s-process n_d~$10^{6\text{-}12}$ cm^{-3}

- AGB stars

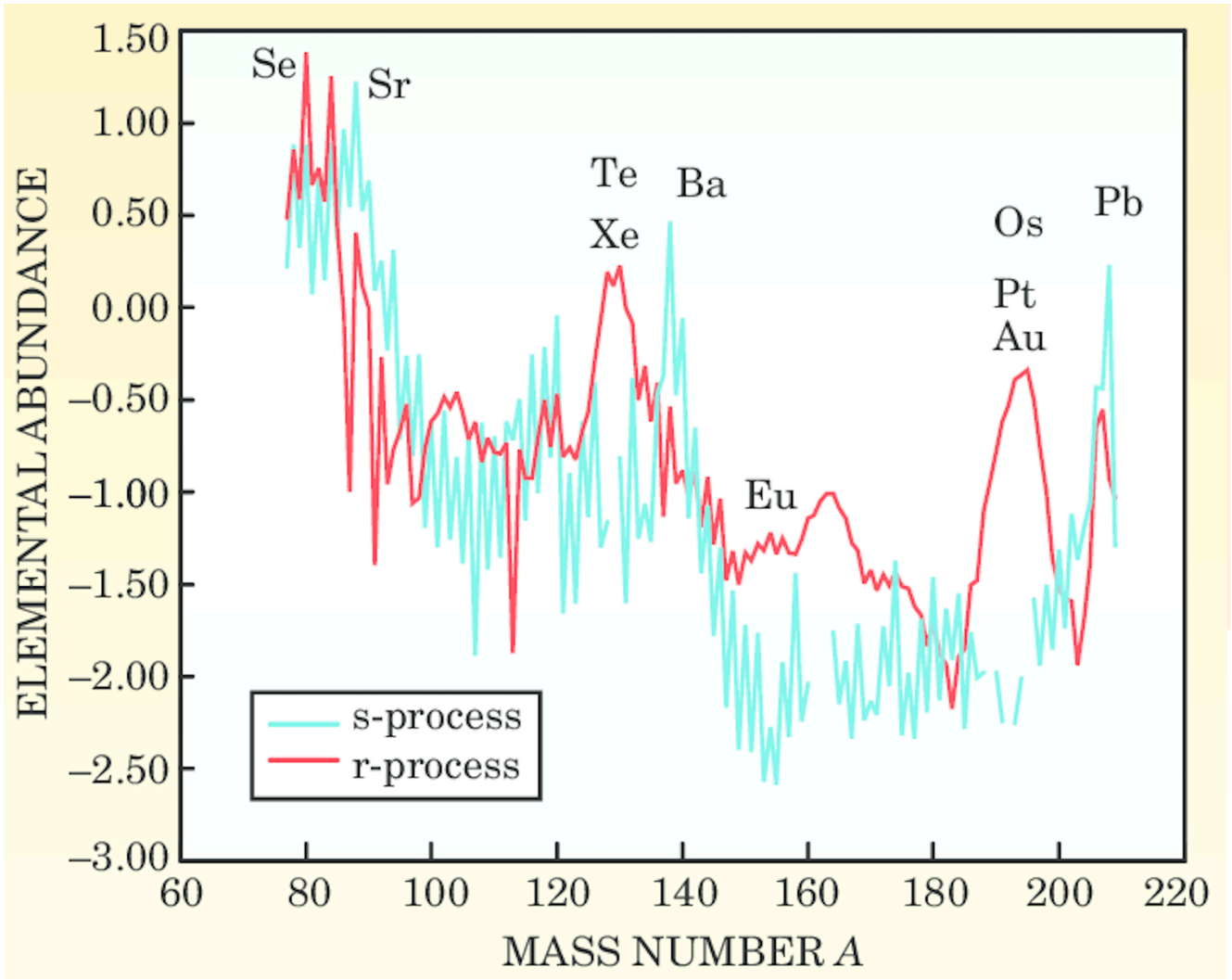
r-process n_d>10^{22} cm^{-3}

- Neutron star mergers
- Certain types of supernovae?

Cowan & Thielemann 2004

Sneden et al. 2008

Neutron capture



Solar system abundances of the s- and r-processes

Typical neutron densities:

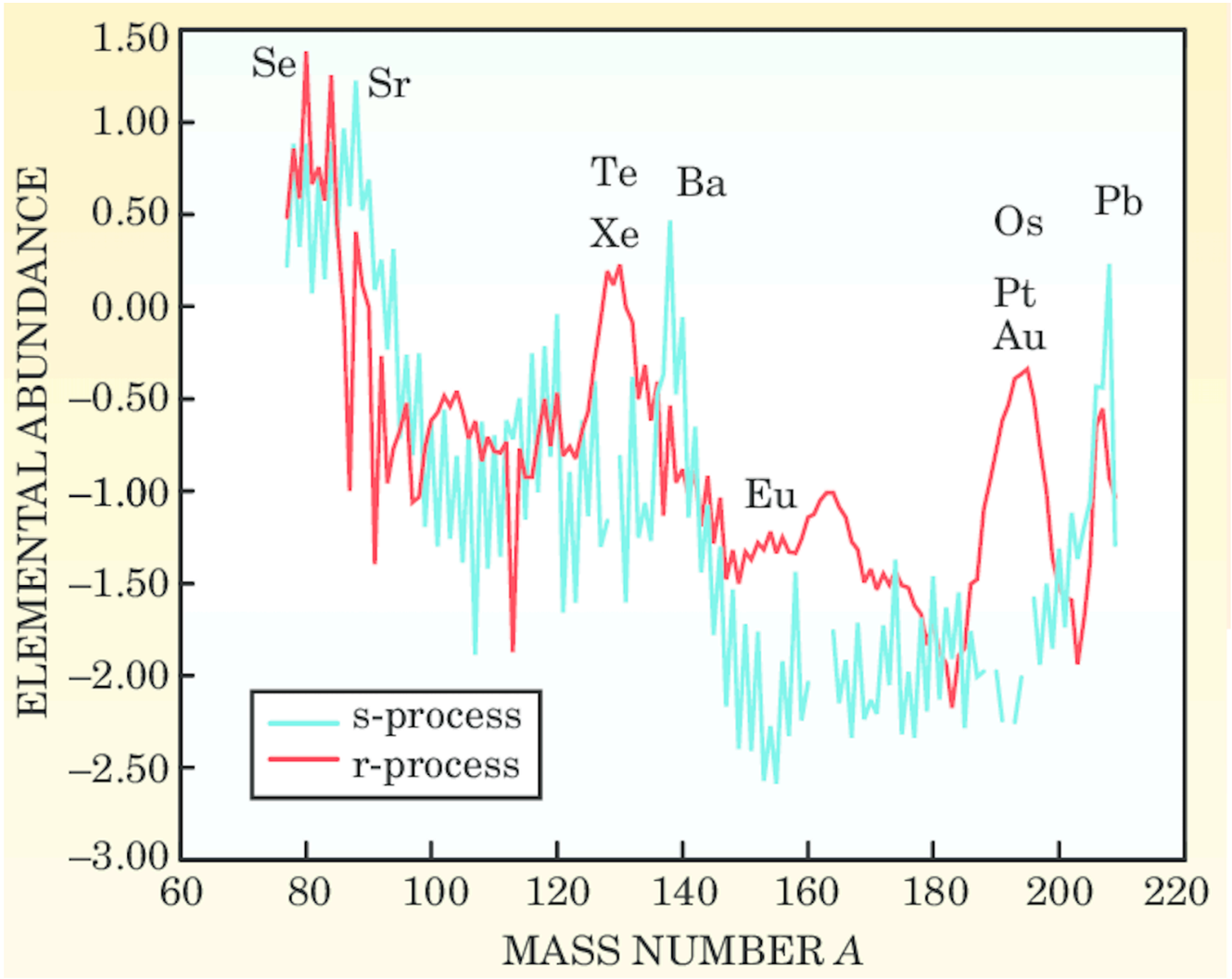
s-process $n_d \sim 10^{6\text{-}12}$ cm^{-3}

r-process $n_d > 10^{22}$ cm^{-3}

Cowan & Thielemann 2004

Sneden et al. 2008

Neutron capture



Solar system abundances of the s- and r-processes

Typical neutron densities:

s-process $n_d \sim 10^{6\text{-}12}$ cm^{-3}

i-process!

r-process $n_d > 10^{22}$ cm^{-3}

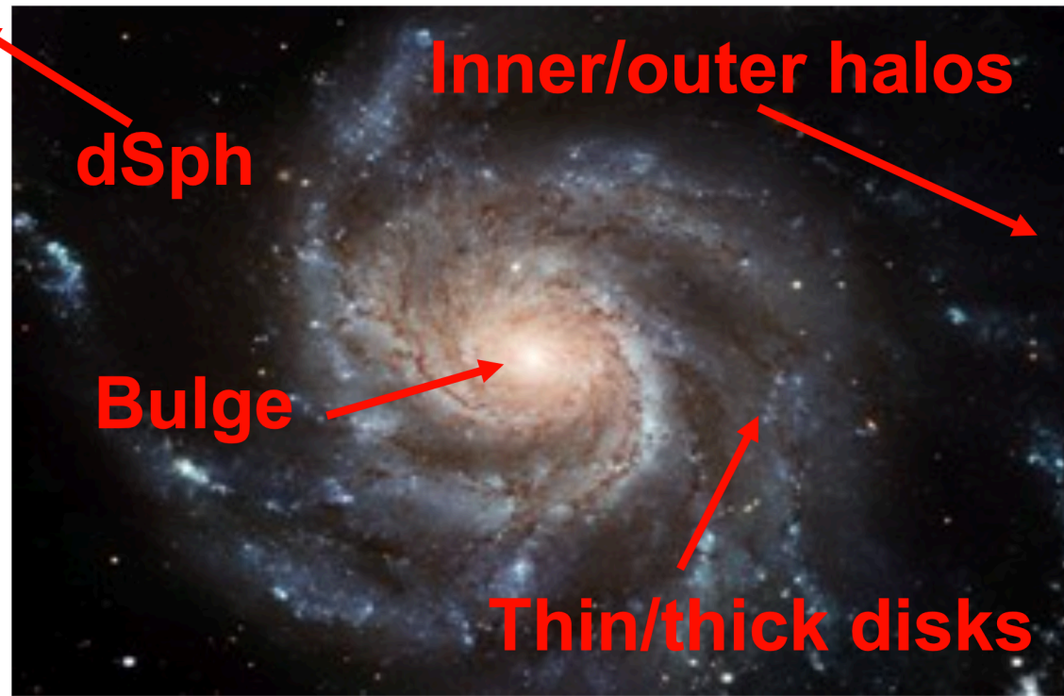
Cowan & Thielemann 2004

Sneden et al. 2008

Galactic Archaeology

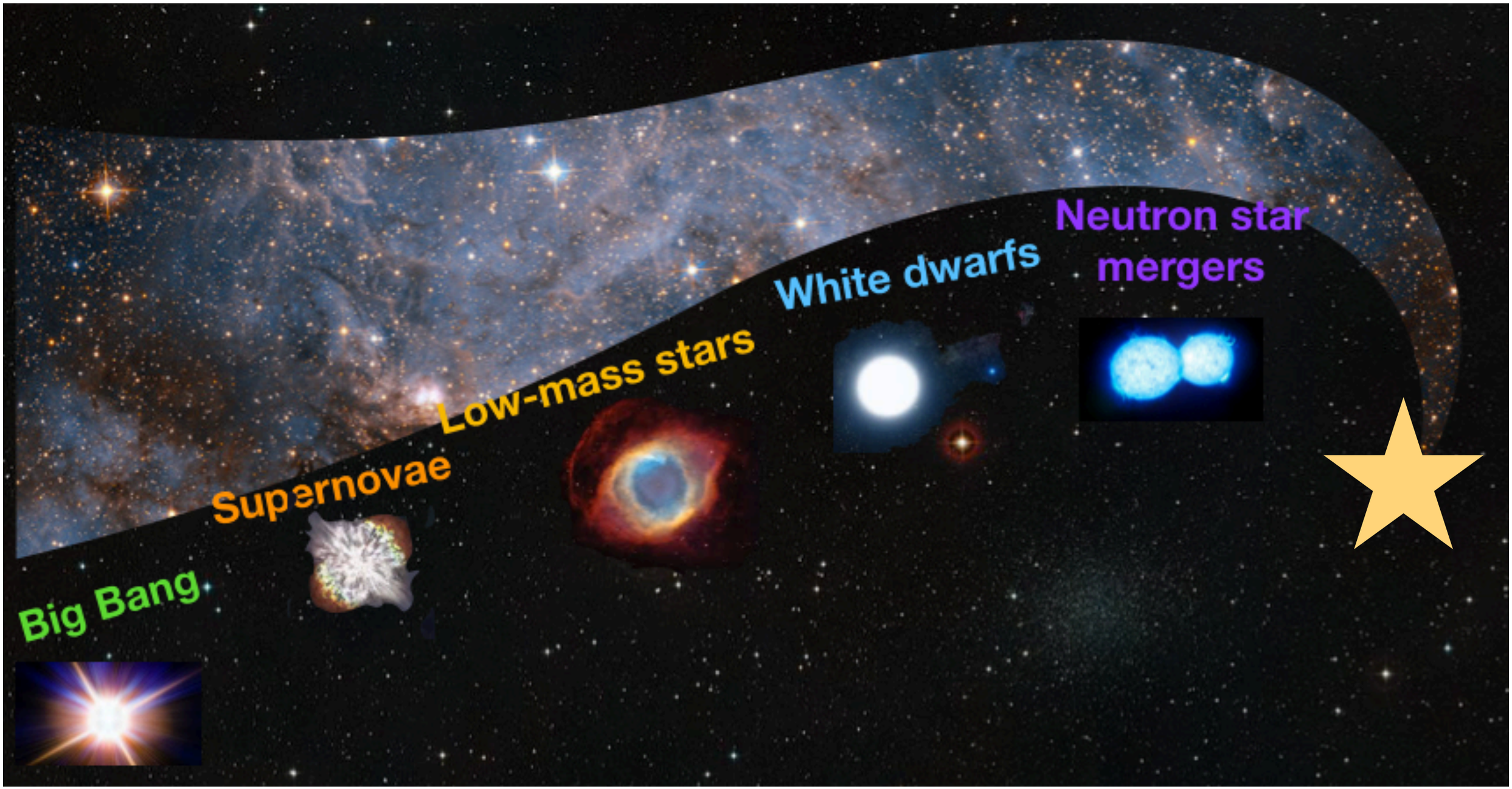
What is Galactic Archeology?

- Galactic Archeology uses kinematics 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.**



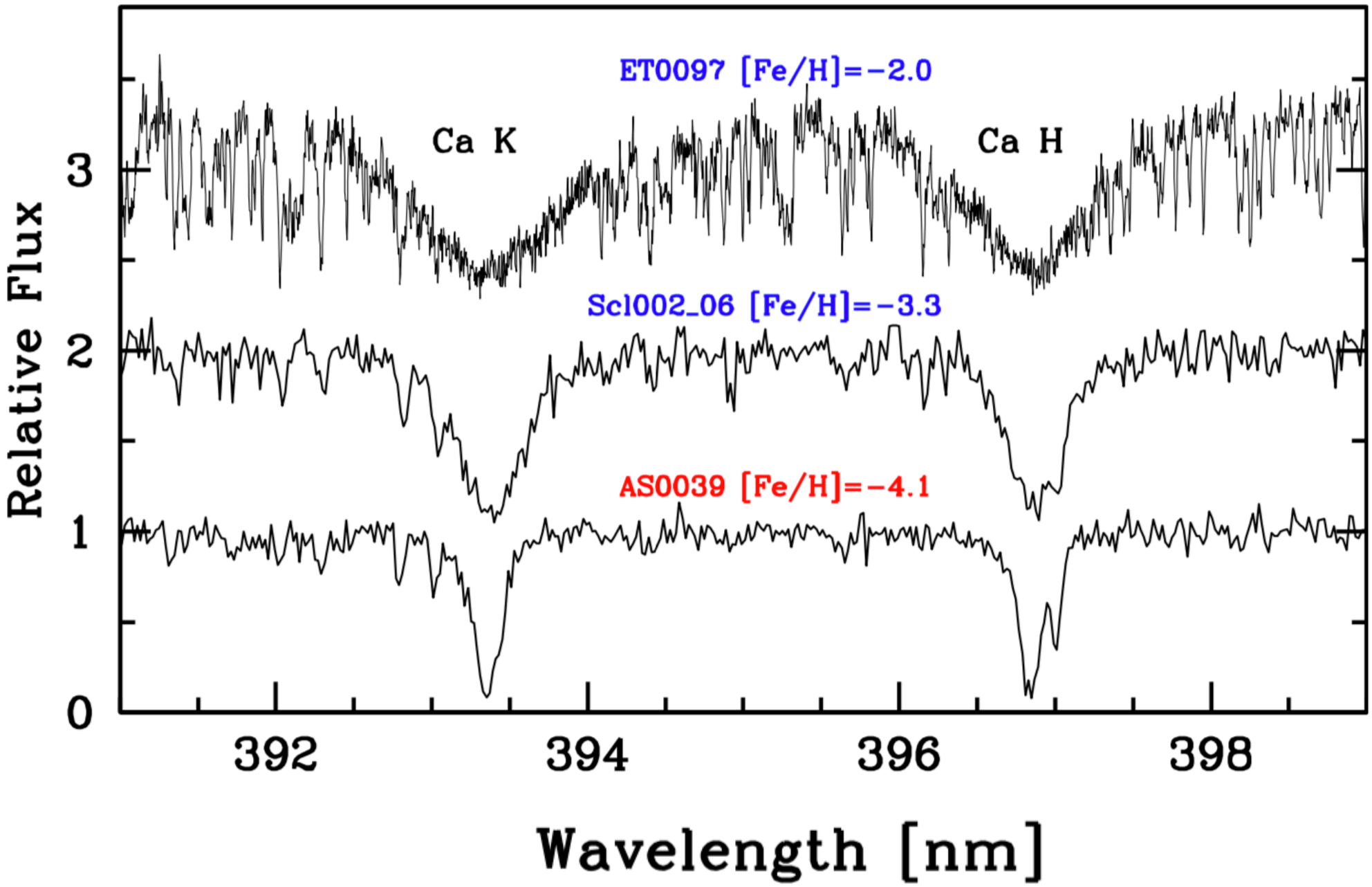
Galactic Archeology

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



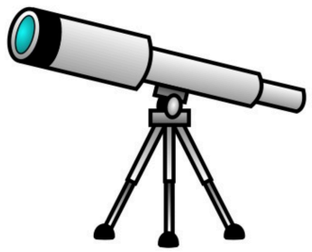
Galactic Archeology

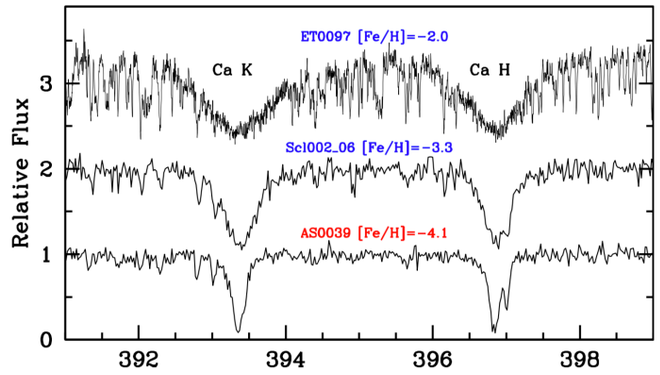
- Abundances of stars depend on **where** and **when** they were born!



Skúladóttir et al. 2021

Stellar abundances





Fe

Eu

Mg

Ba

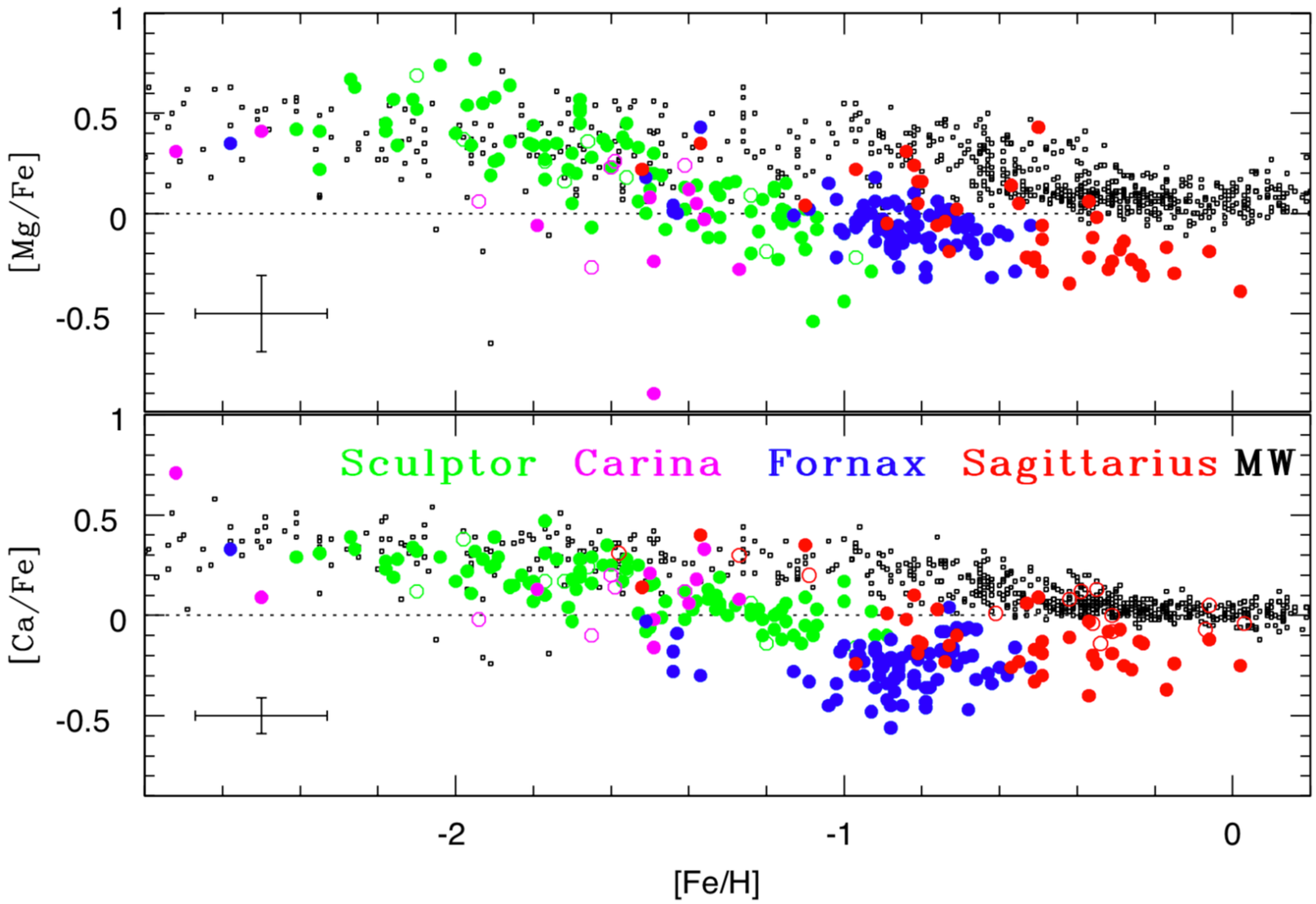
C

Stellar models

Atomic data

Galactic Archeology

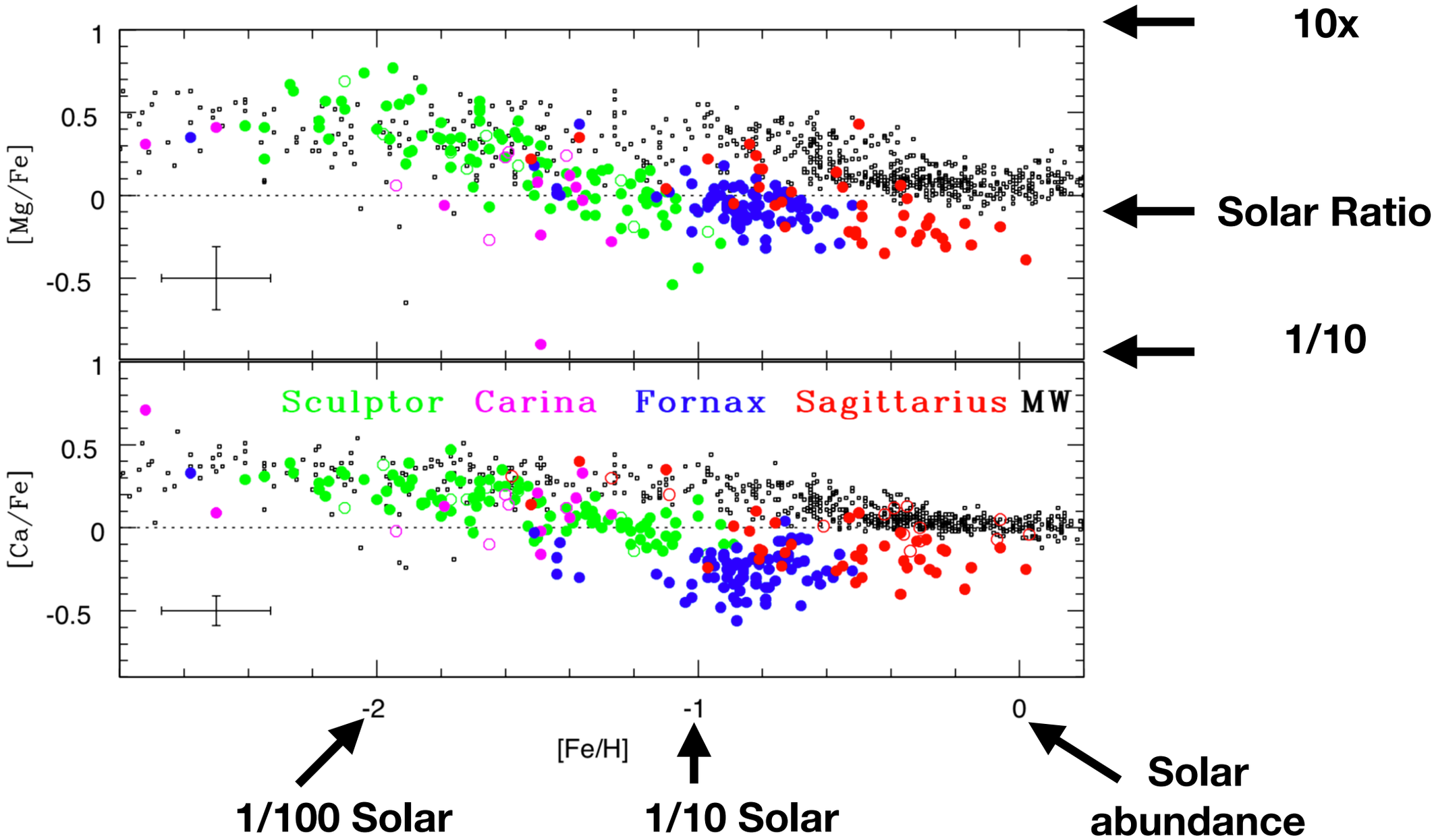
- Abundances of stars depend on **where** and **when** they were born!



Tolstoy et al. 2009

Galactic Archeology

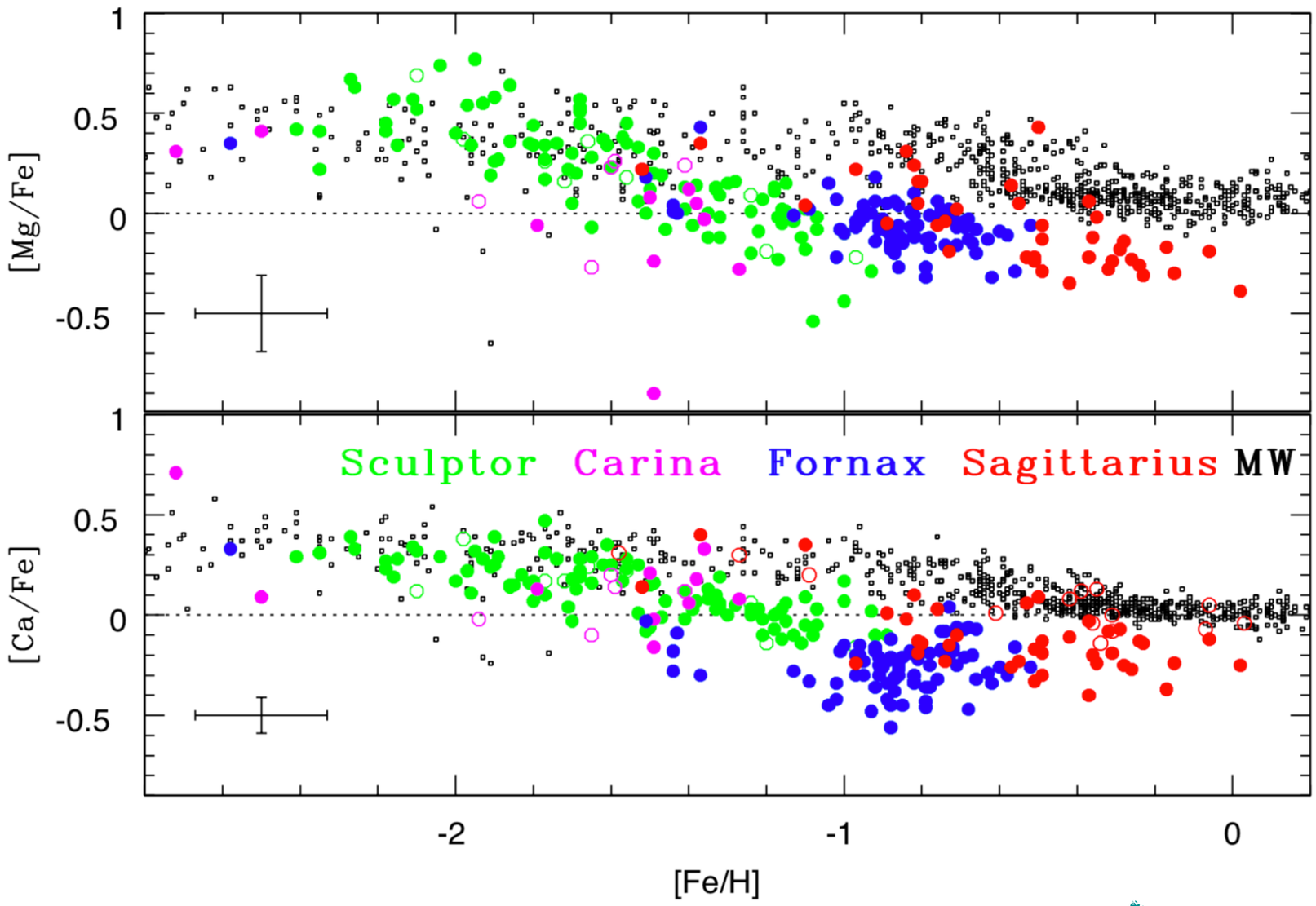
- Abundances of stars depend on **where** and **when** they were born!



Tolstoy et al. 2009

Galactic Archeology

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



“Time”

Tolstoy et al. 2009

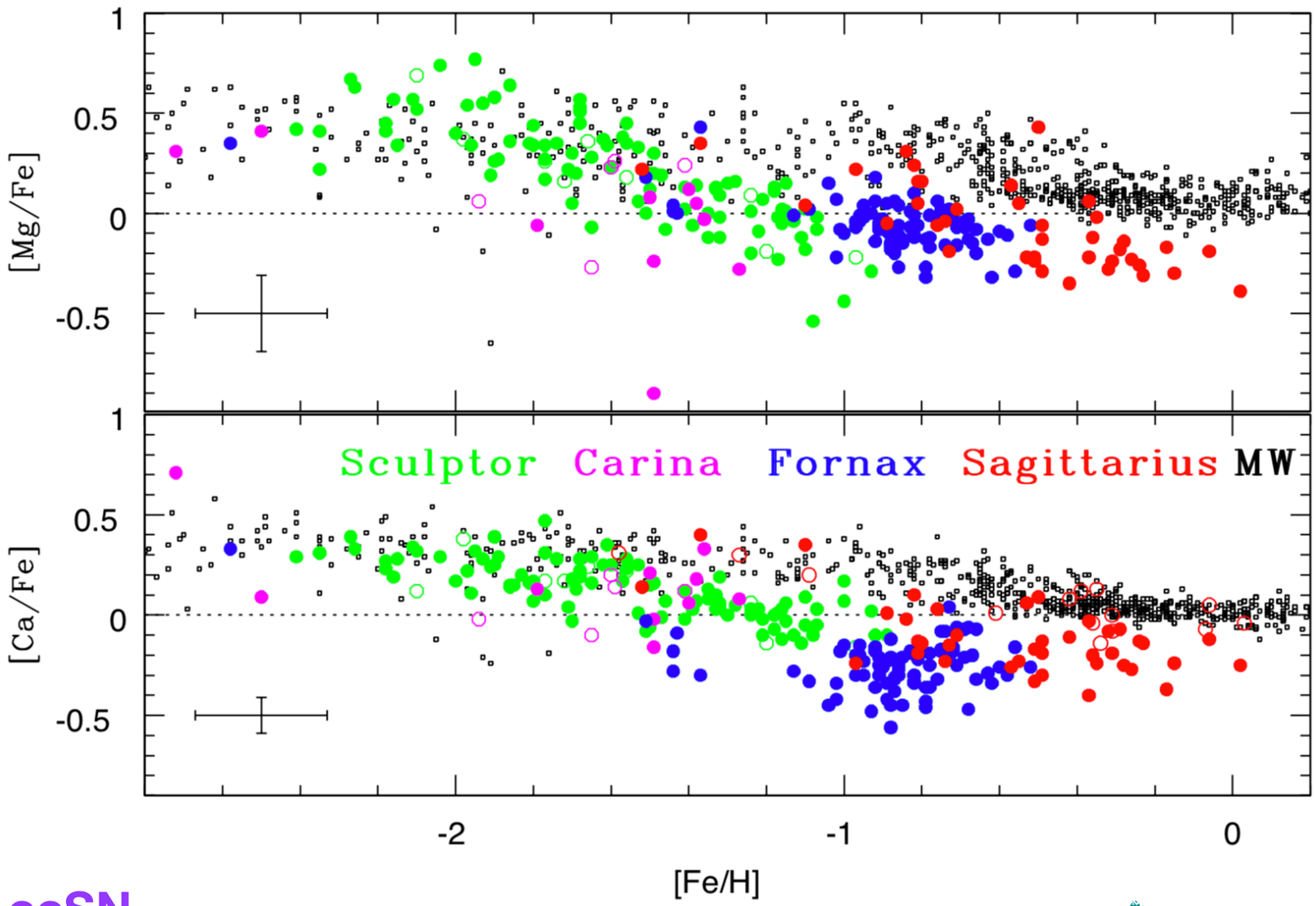
Galactic Archeology

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

ccSN **ccSN + SNIa**

Mg: ccSN

Ca: mostly ccSN



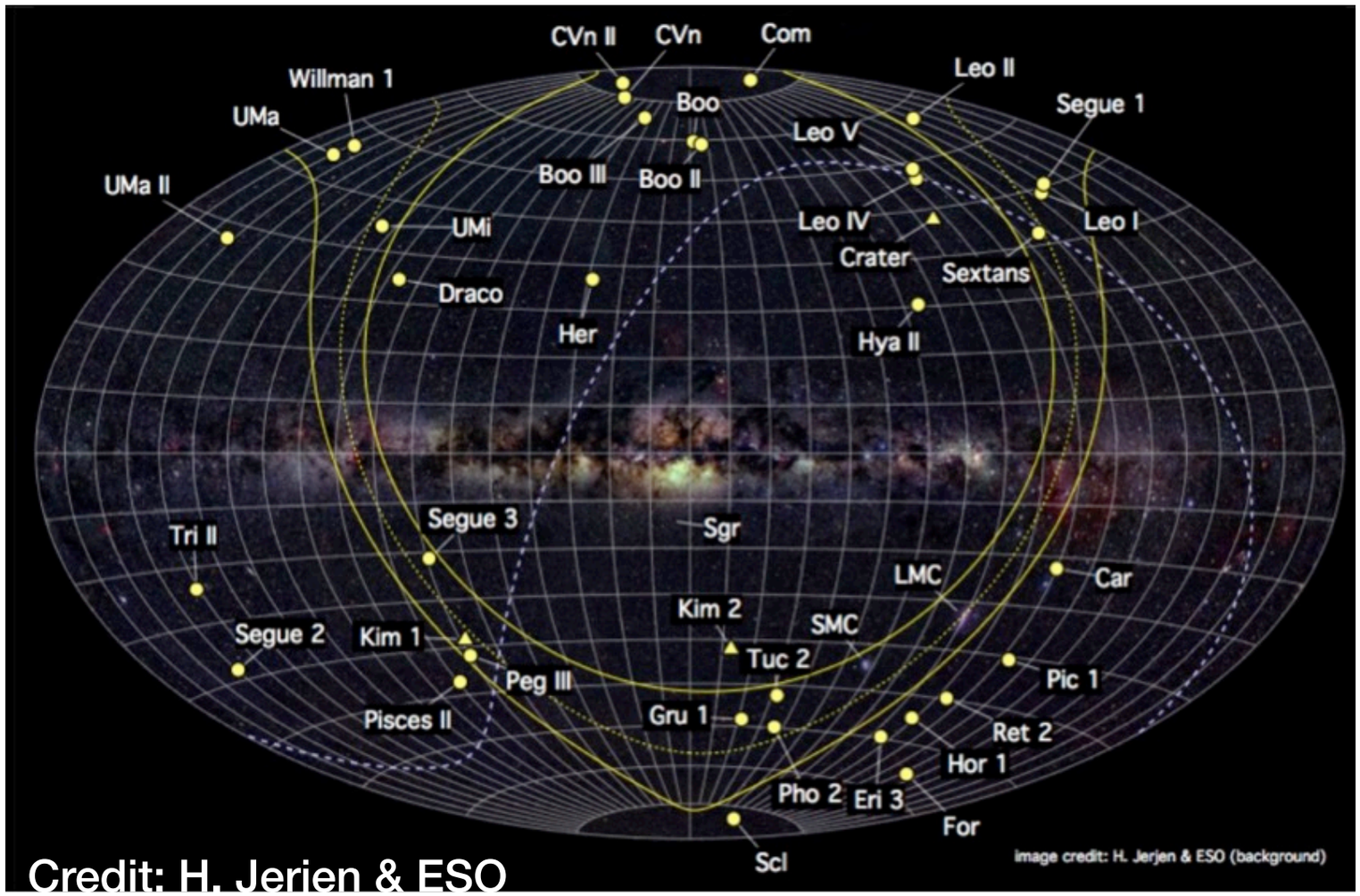
Fe: ccSN and SNIa

"Time"

Tolstoy et al. 2009

The Milky Way + satellites

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



Credit: H. Jerjen & ESO

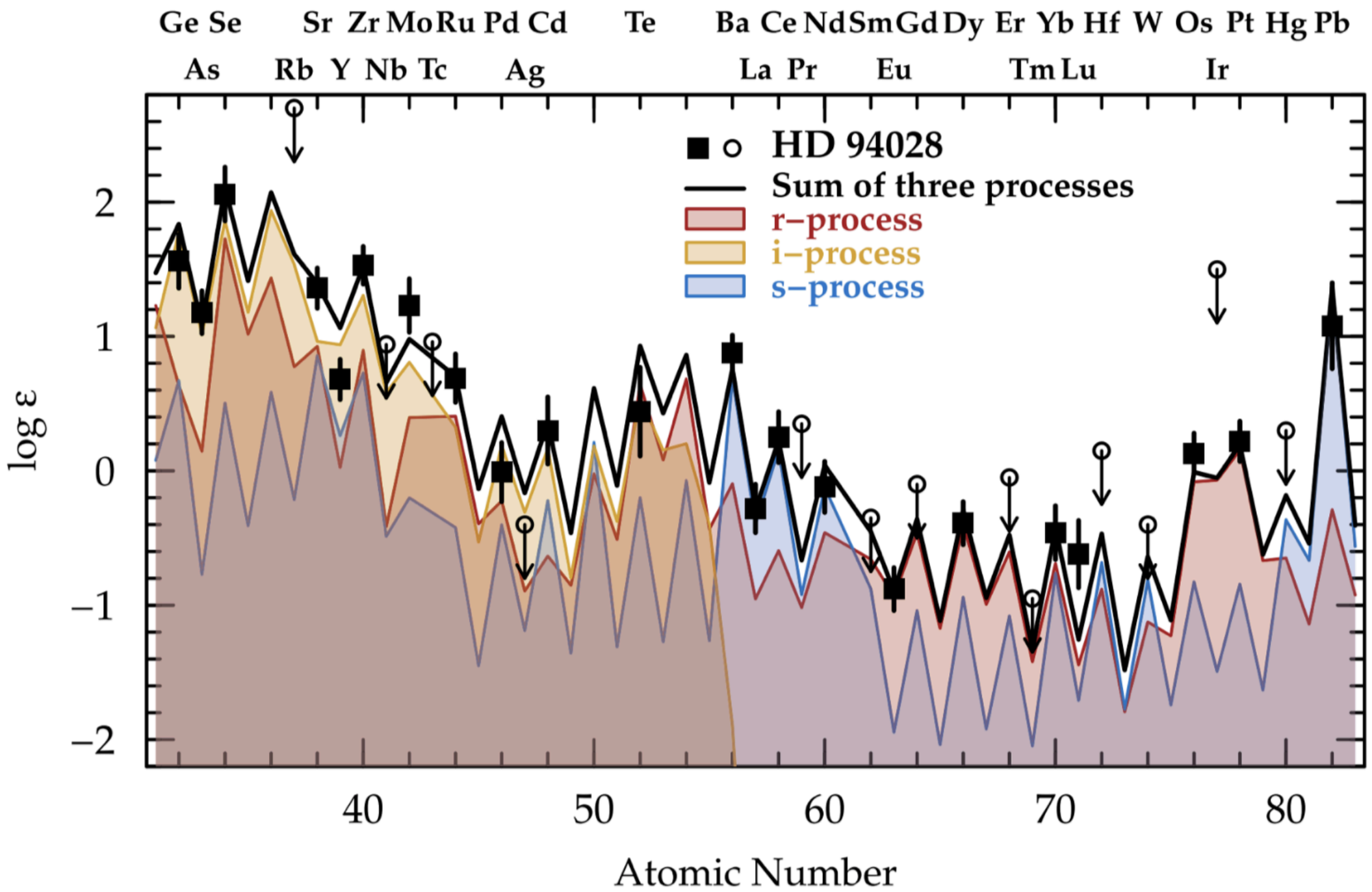
The i-process

The i-process

The i-process: Proposed by Cowan & Rose in 1977

Recent interest: Several metal-poor stars in the Milky Way cannot be explained by a combination of the r- and s-processes - **the i-process is needed!**

The i-process



Roederer et al. 2016

The i-process

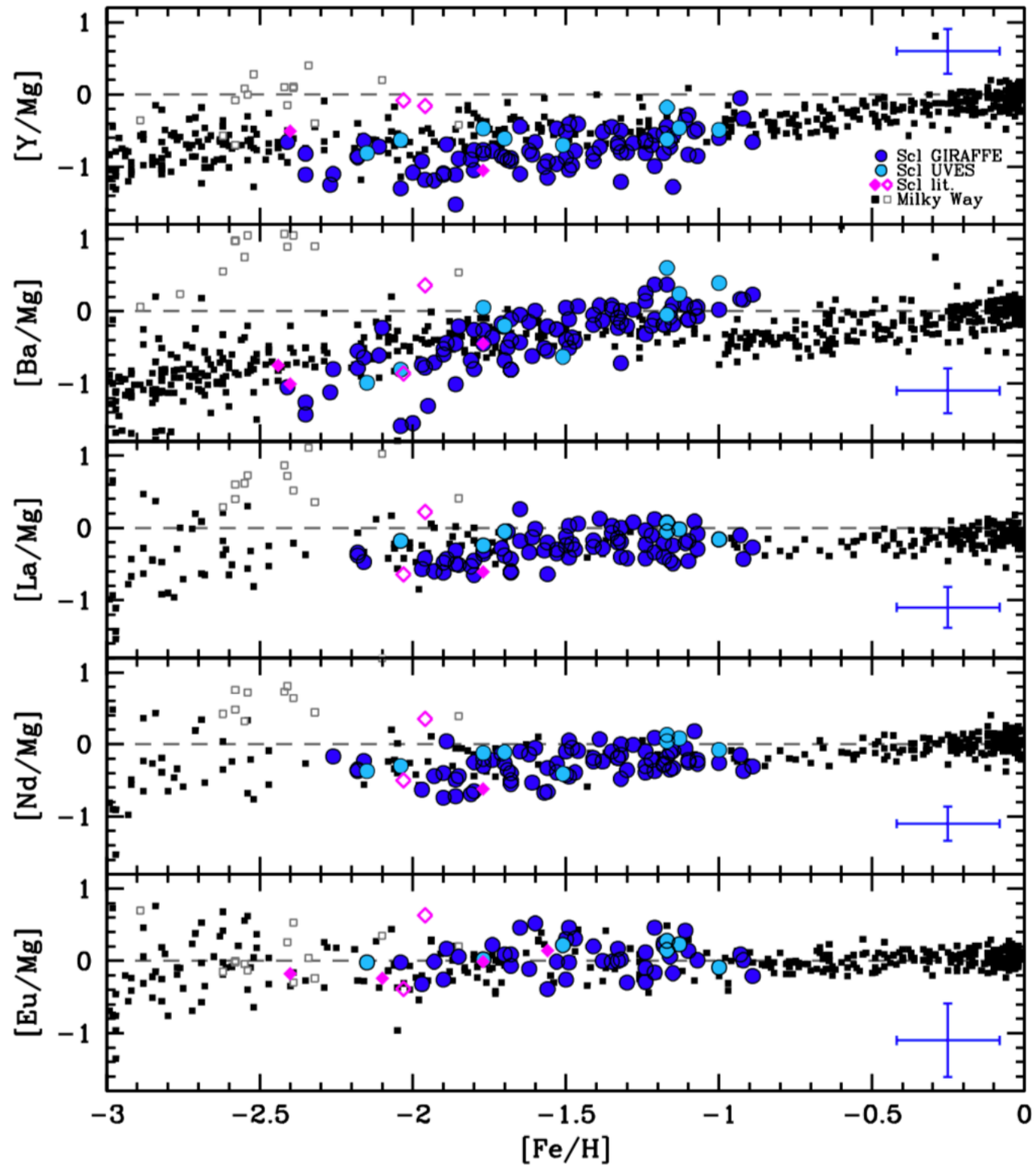
The i-process: Proposed by Cowan & Rose in 1977

Recent interest: Several metal-poor stars in the Milky Way cannot be explained by a combination of the r- and s-processes - **the i-process is needed!**

Possible sites: low-metallicity stars, massive (5–10 $M_\odot$) super-AGB stars; evolved low-mass stars; and rapidly accreting white dwarfs…

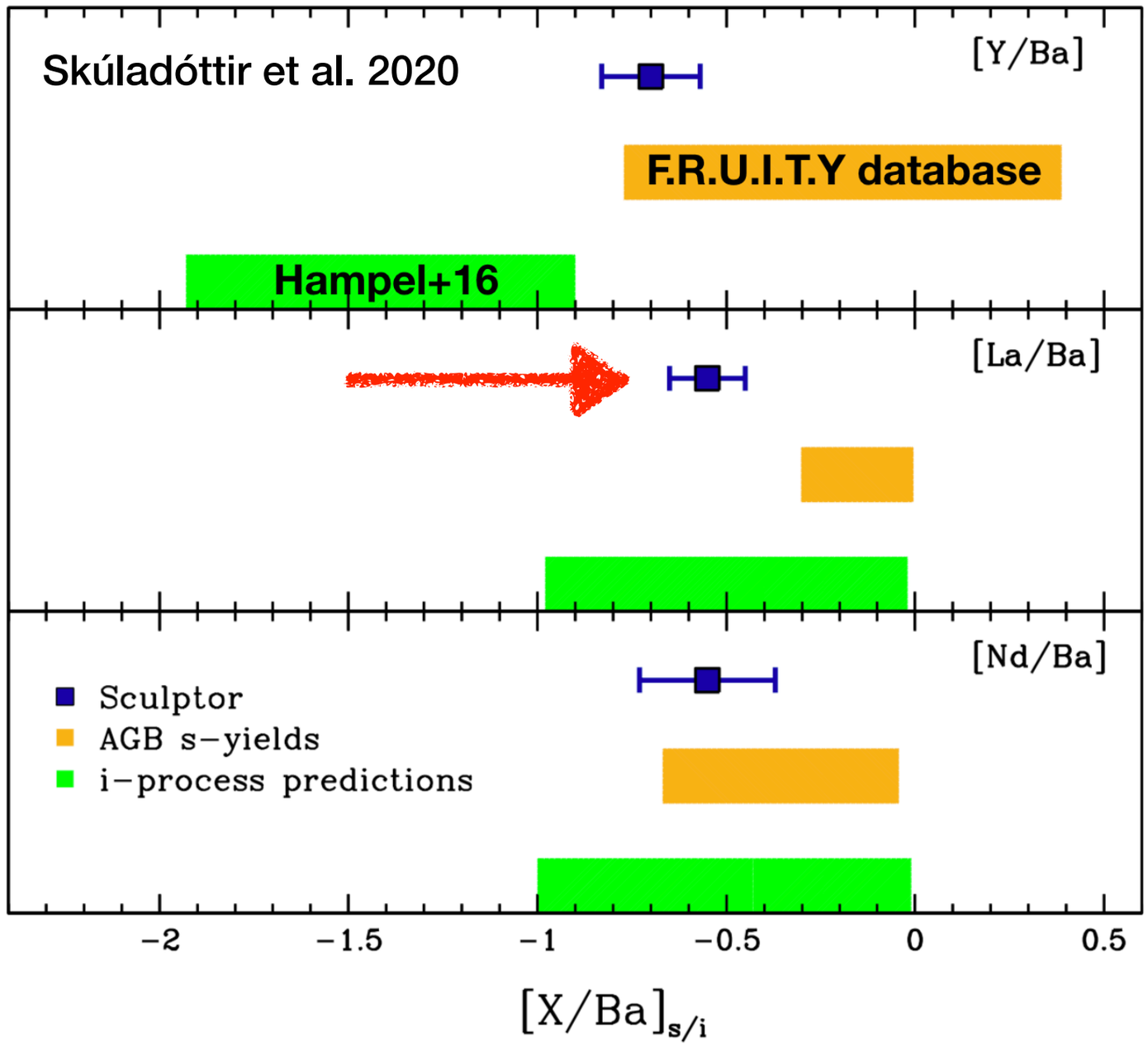
The s/i process in Sculptor

Skúladóttir et al 2019



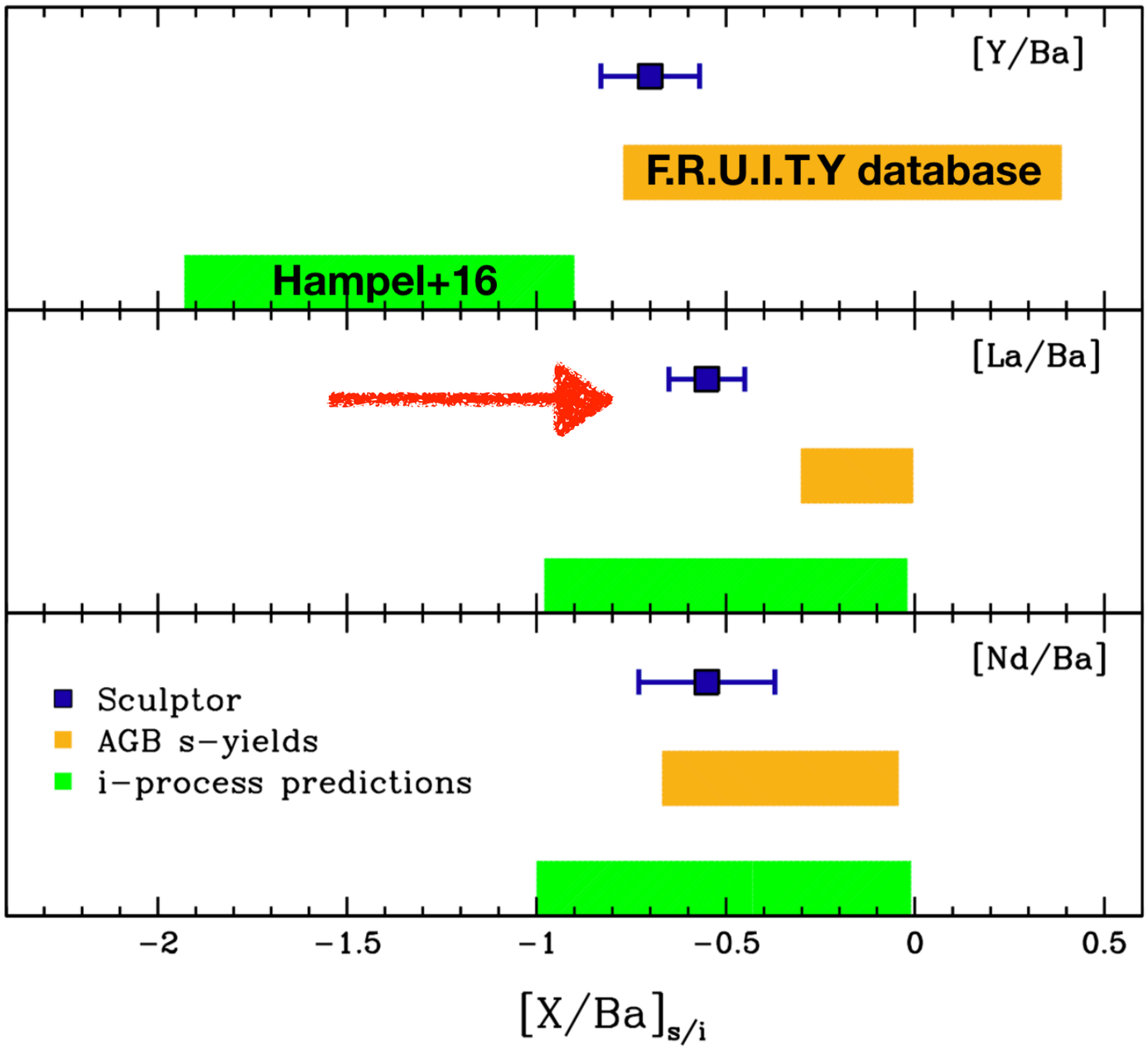
Importance of the i-process

- Heavy elemental abundance ratios in Sculptor (after removing the r-process)



Based on Skúladóttir et al. 2020

Importance of the i-process



The low [La/Ba] in Sculptor suggests significant i-process contribution

More data!

Based on Skúladóttir et al. 2020

The r-process

What about the r-process?

The possible production sites of the r-process

- **Neutron star mergers - delayed time scale**
  - GW170817 estimated to have >6.8 Gyr delay (Blanchard et al. 2017)
  - One third of short gamma ray bursts found in early type galaxies (Berger 2014)
- **Massive stars - short time scales**

Delayed processes

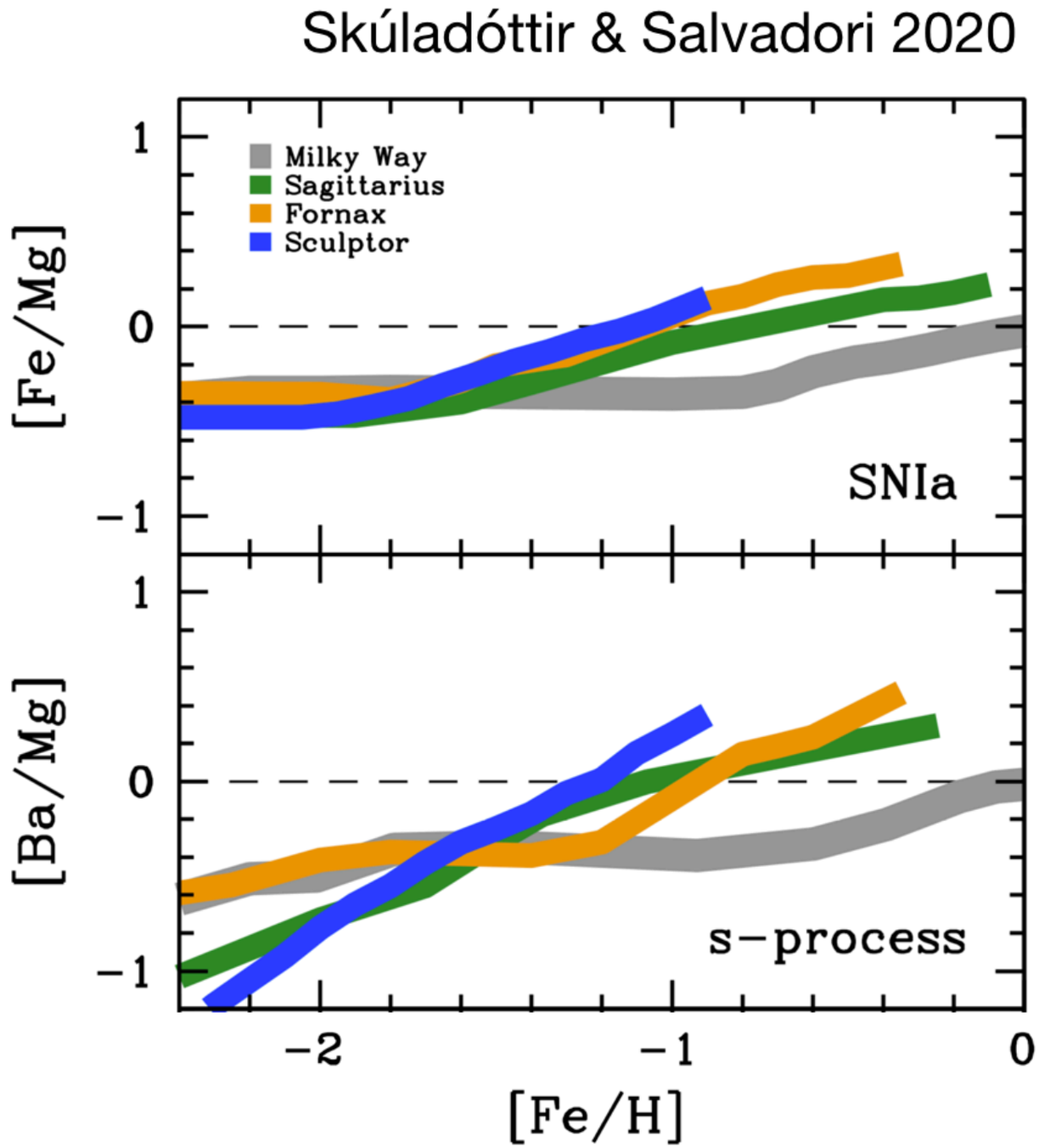
Mg almost exclusively made by core collapse SN

Supernovae type Ia

~60% of Fe in the Sun

AGB stars

~85% of Ba in the Sun



Delayed processes

Mg almost exclusively made by core collapse SN

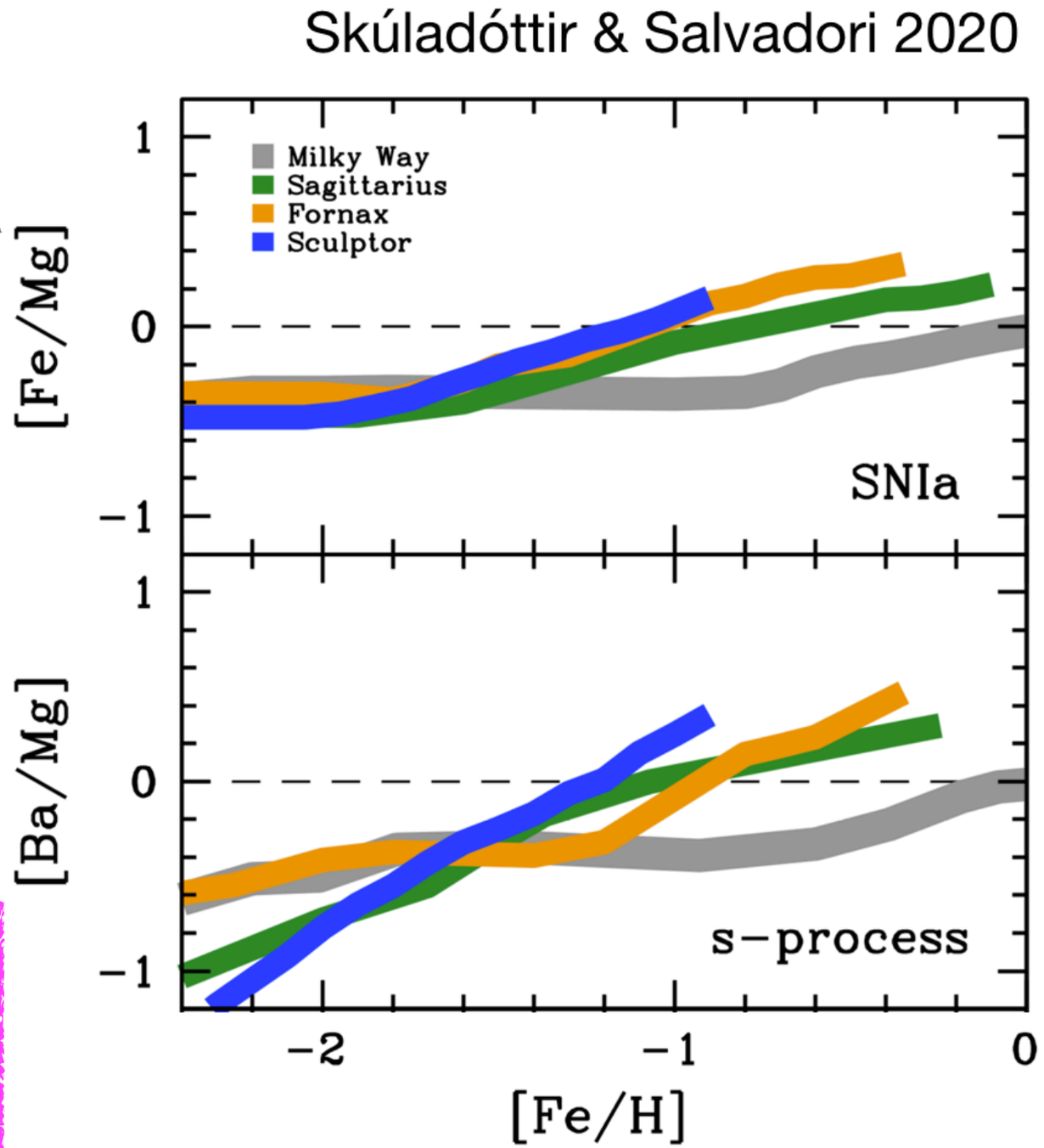
Supernovae type Ia

~60% of Fe in the Sun

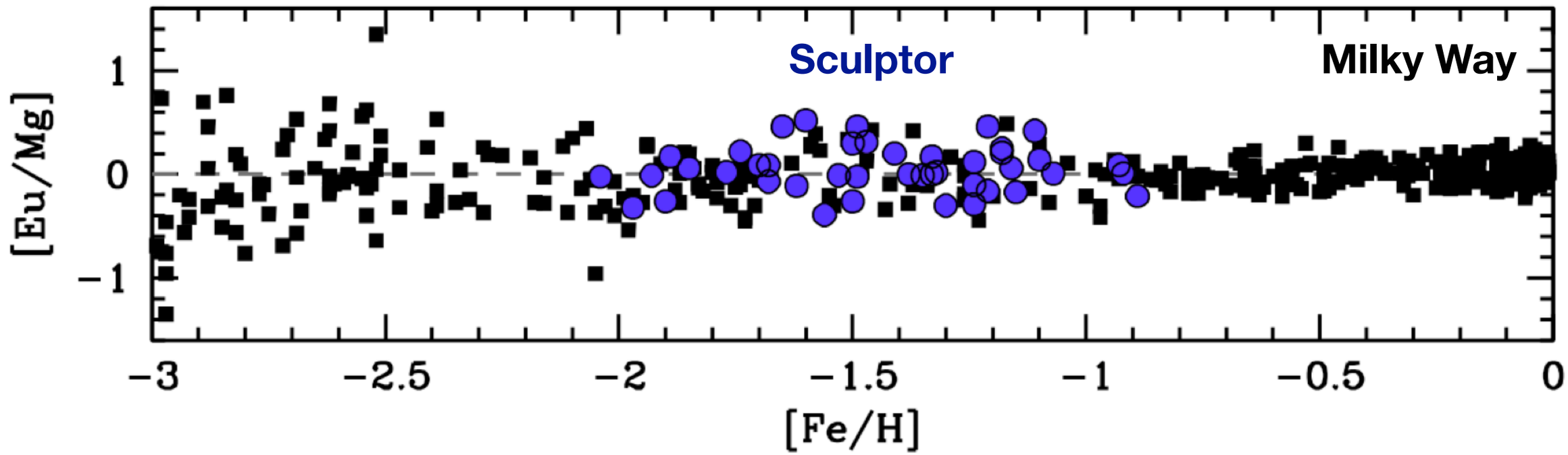
AGB stars

~85% of Ba in the Sun

What about the r-process?

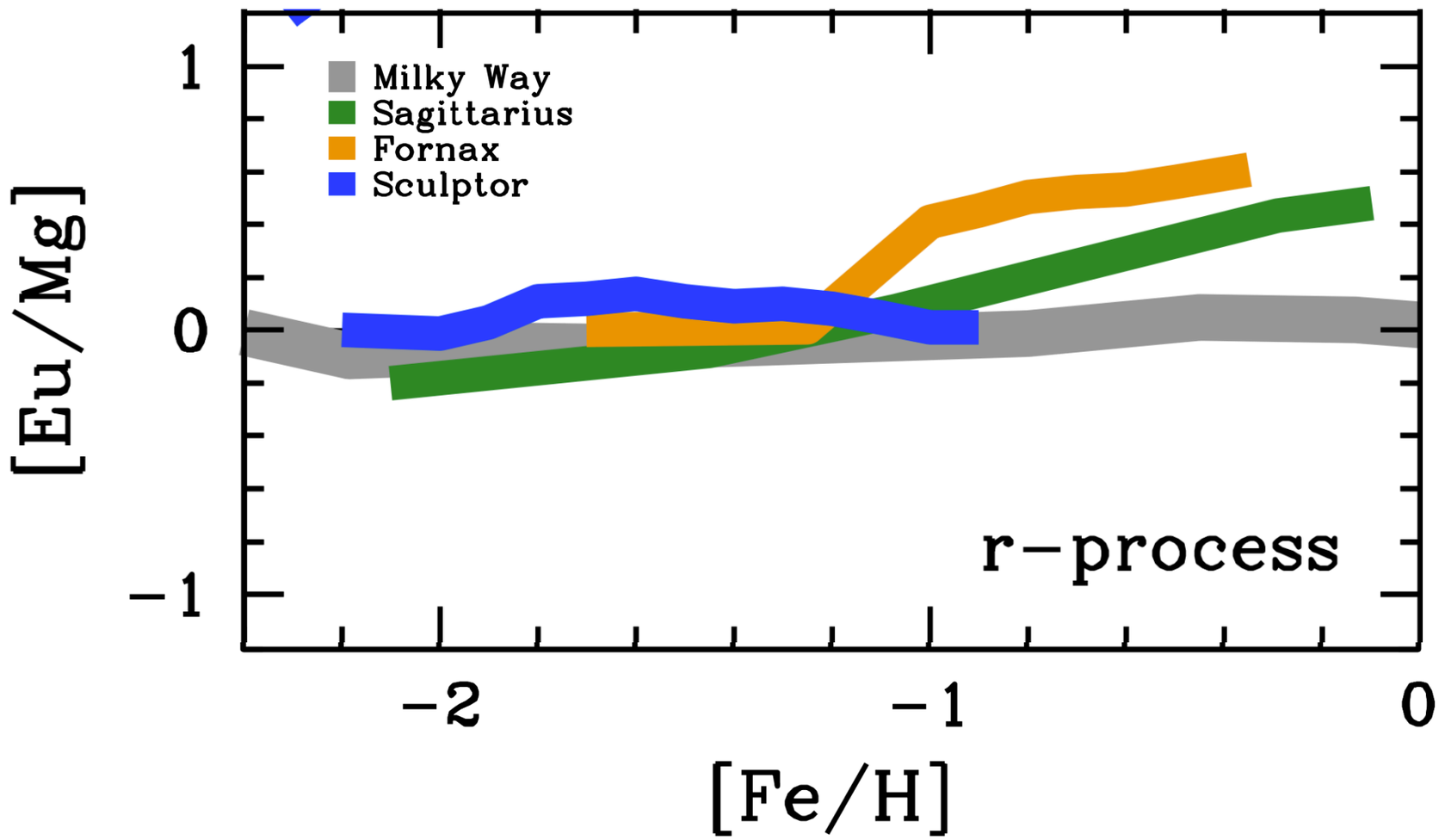


[Eu/Mg] in two galaxies



- No clear evidence of time delay!
- Observations suggest massive stars are the dominant source!

The r-process

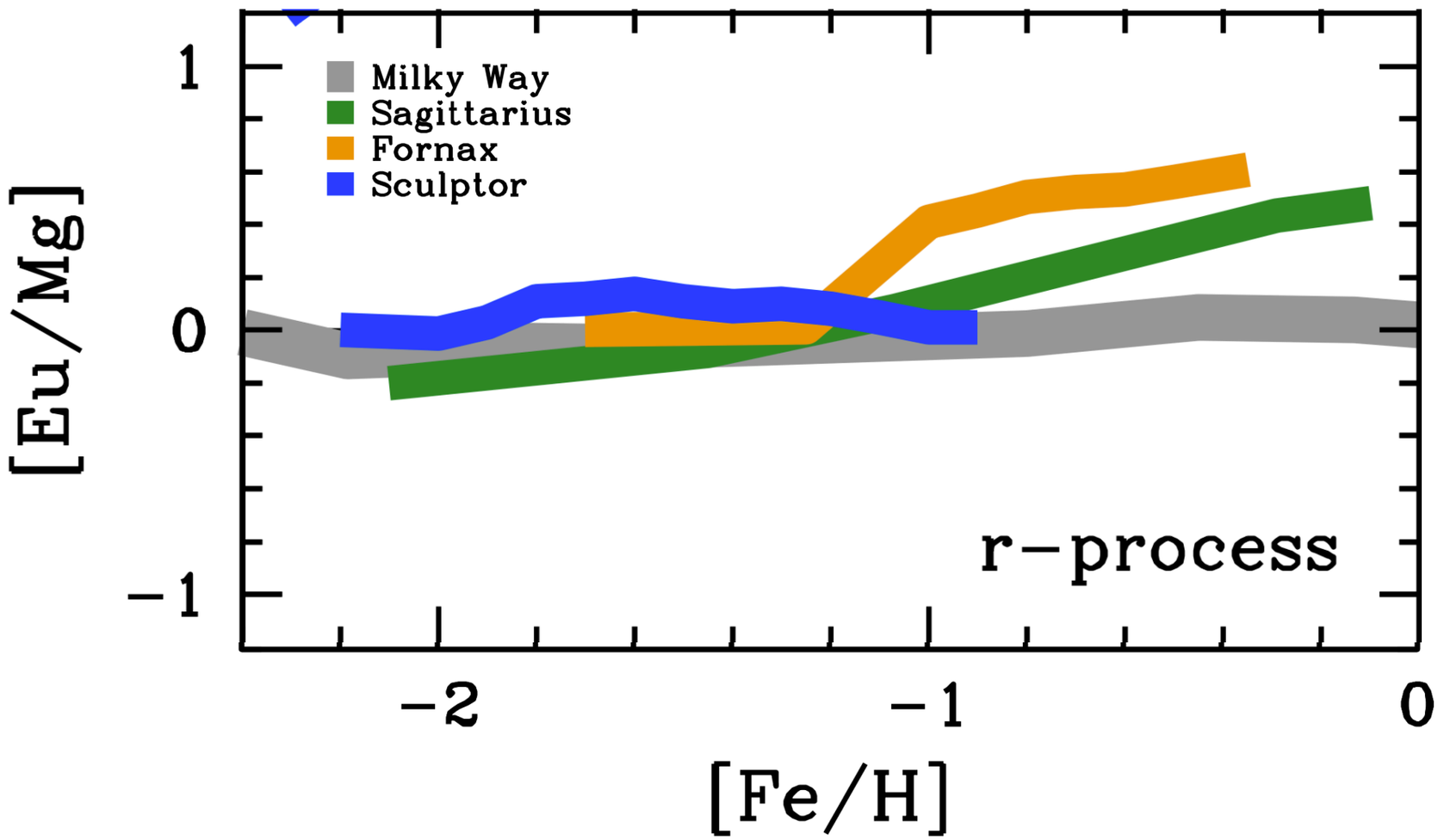


The r-process

~94% of Eu in the Sun

Skúladóttir & Salvadori 2020

The r-process



The r-process

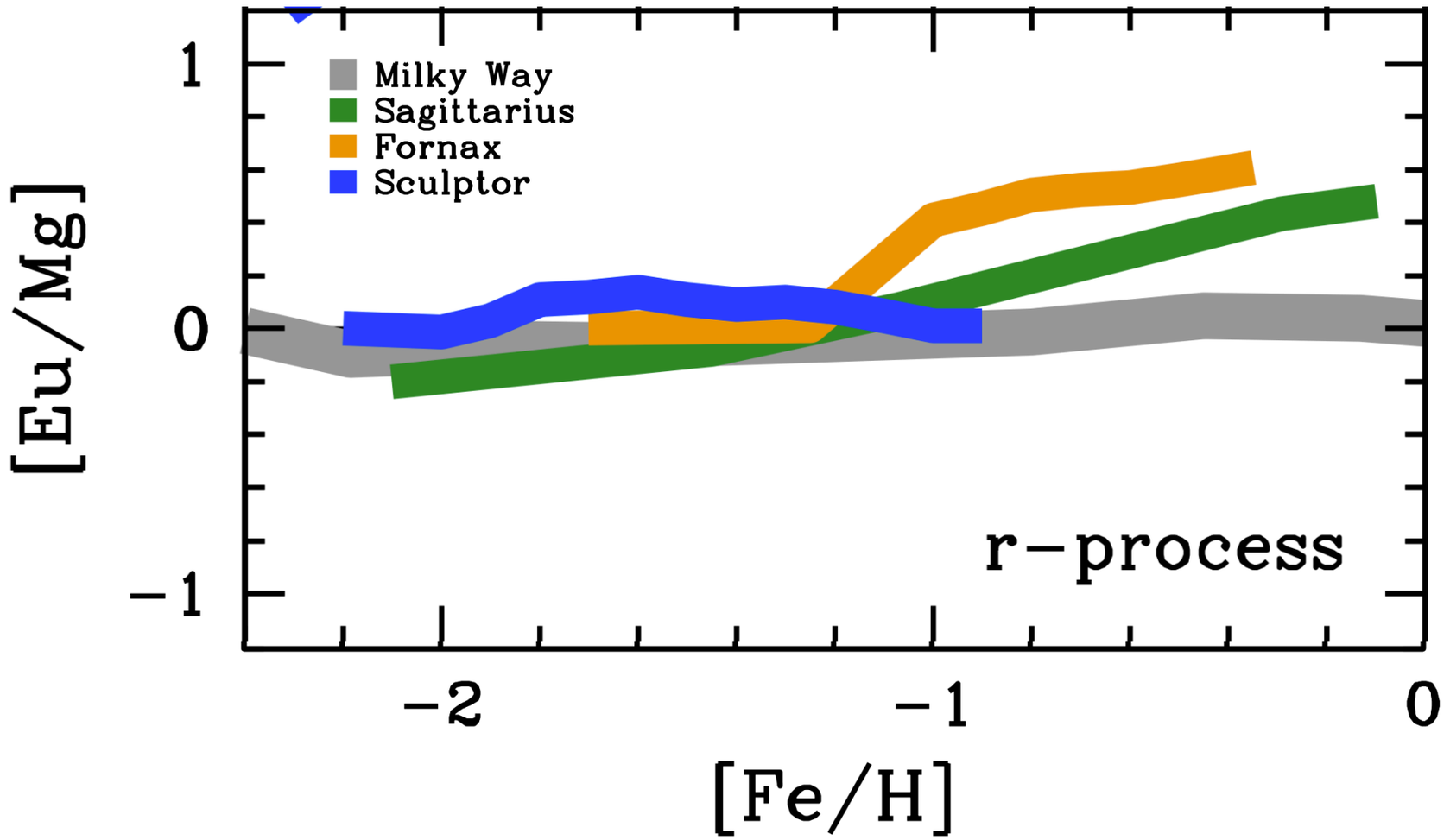
~94% of Eu in the Sun

Accreted systems such as Gaia Enceladus have also be shown to be r-process rich, with high [Eu/Mg], see e.g. Aguado et al. 2021.

Skúladóttir & Salvadori 2020

The r-process

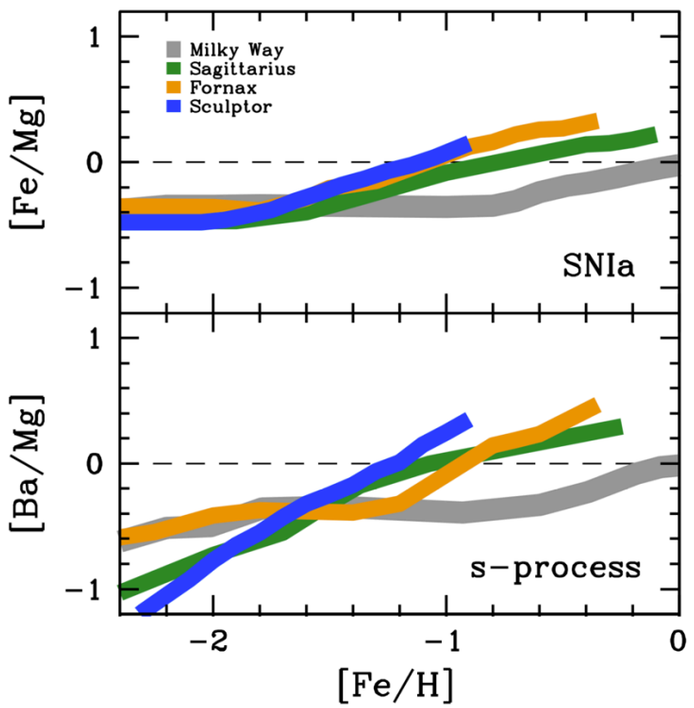
Skúladóttir & Salvadori 2020



The r-process

~94% of Eu in the Sun

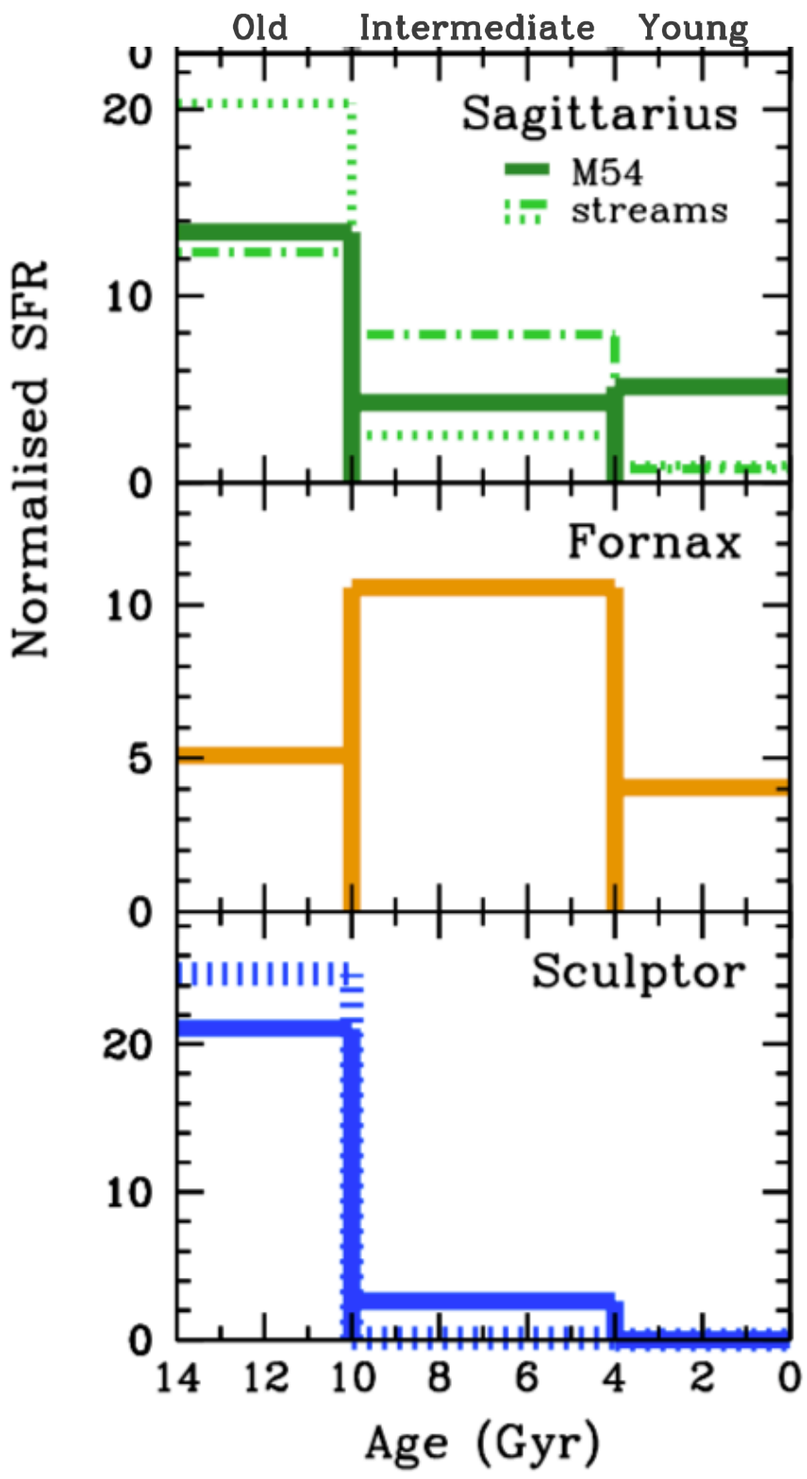
Skúladóttir & Salvadori 2020



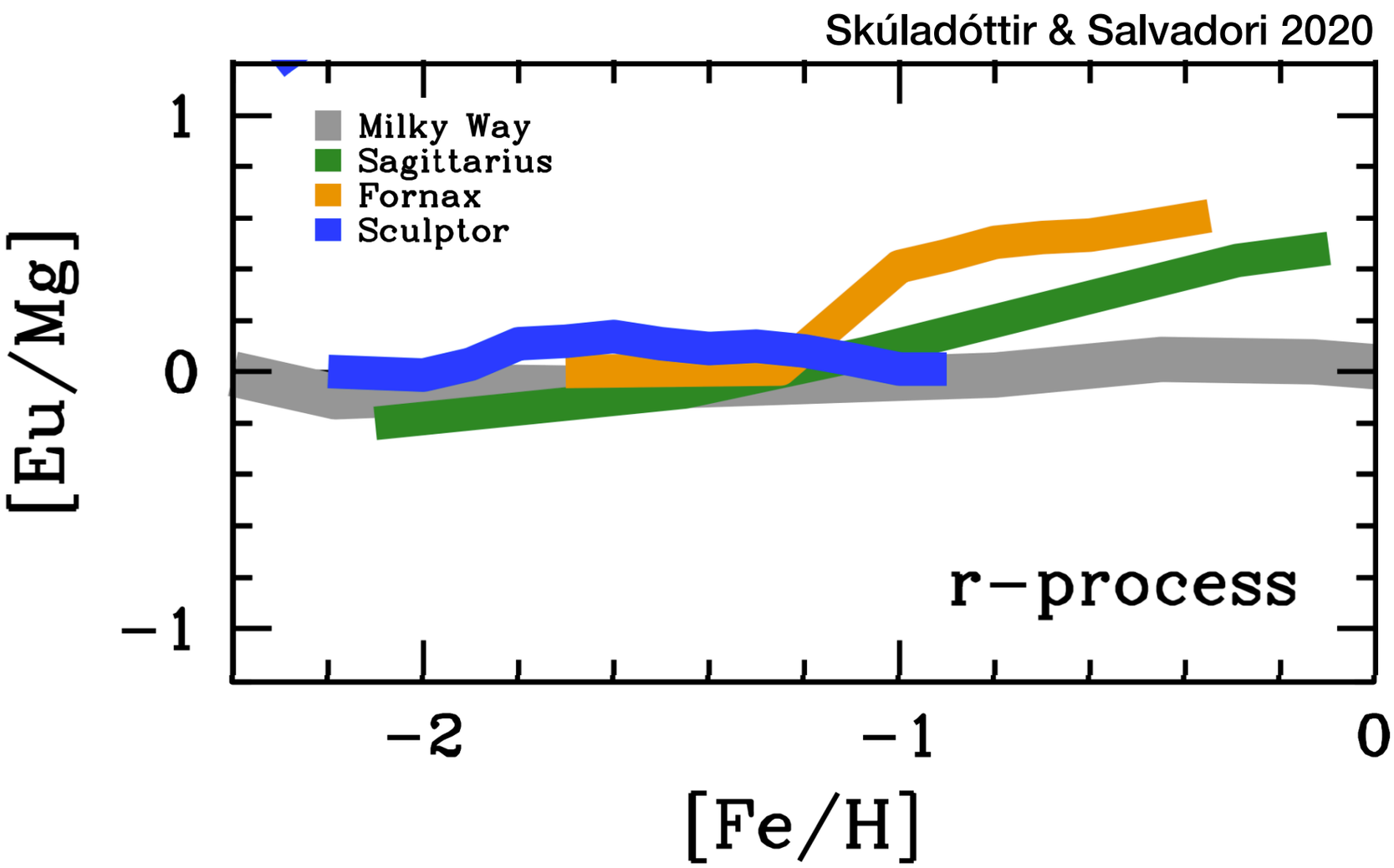
This can only be explained with two sources: Quick + Delayed

Star Formation Histories

- Fornax and Sagittarius have extended star formation histories
- Sculptor stopped forming stars ~10 Gyr ago.
- A delayed source with timescales >4 Gyr can explain abundances in all three galaxies!
- Old population dominates in all dwarf galaxies: more than 60% of stars older than 6 Gyr.



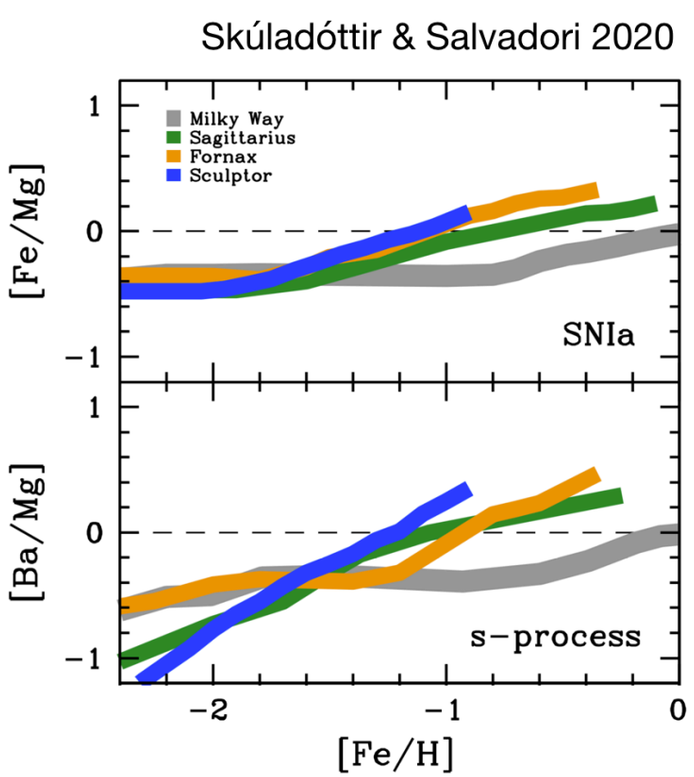
The r-process



The r-process

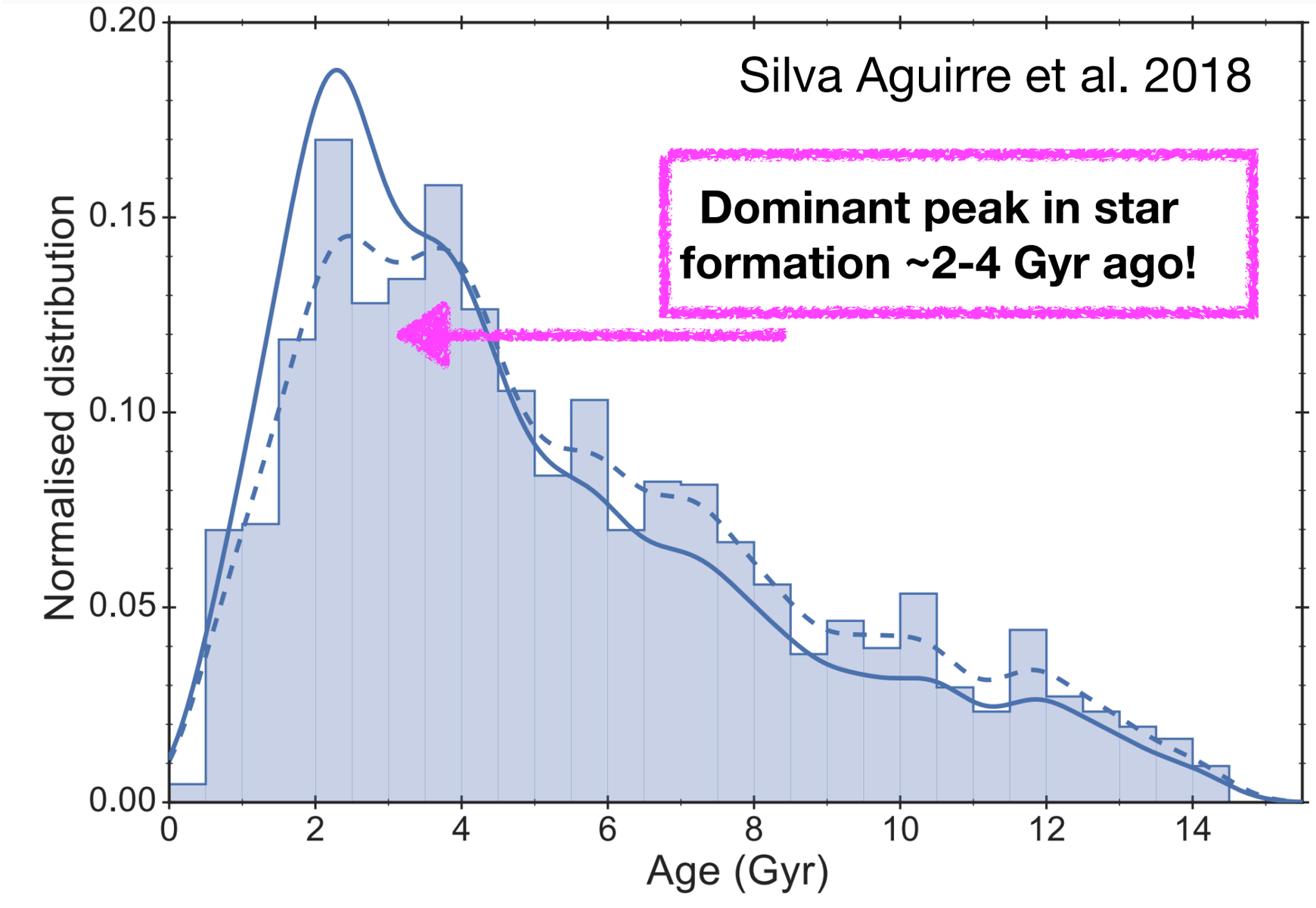
~94% of Eu in the Sun

But what about our Milky Way?



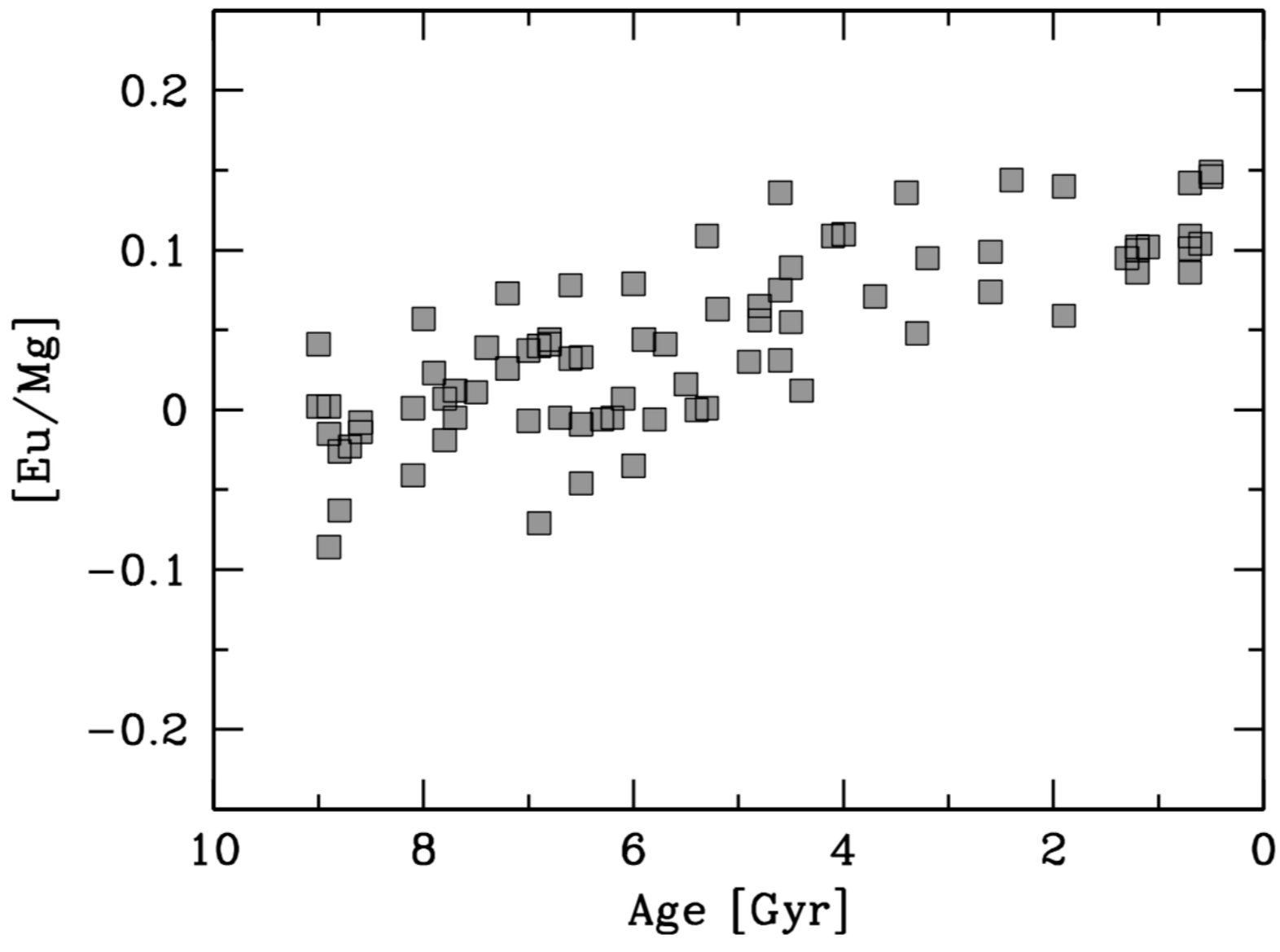
What about the Milky Way?

Ages of stars in the Solar neighbourhood, as proxy for its star formation history



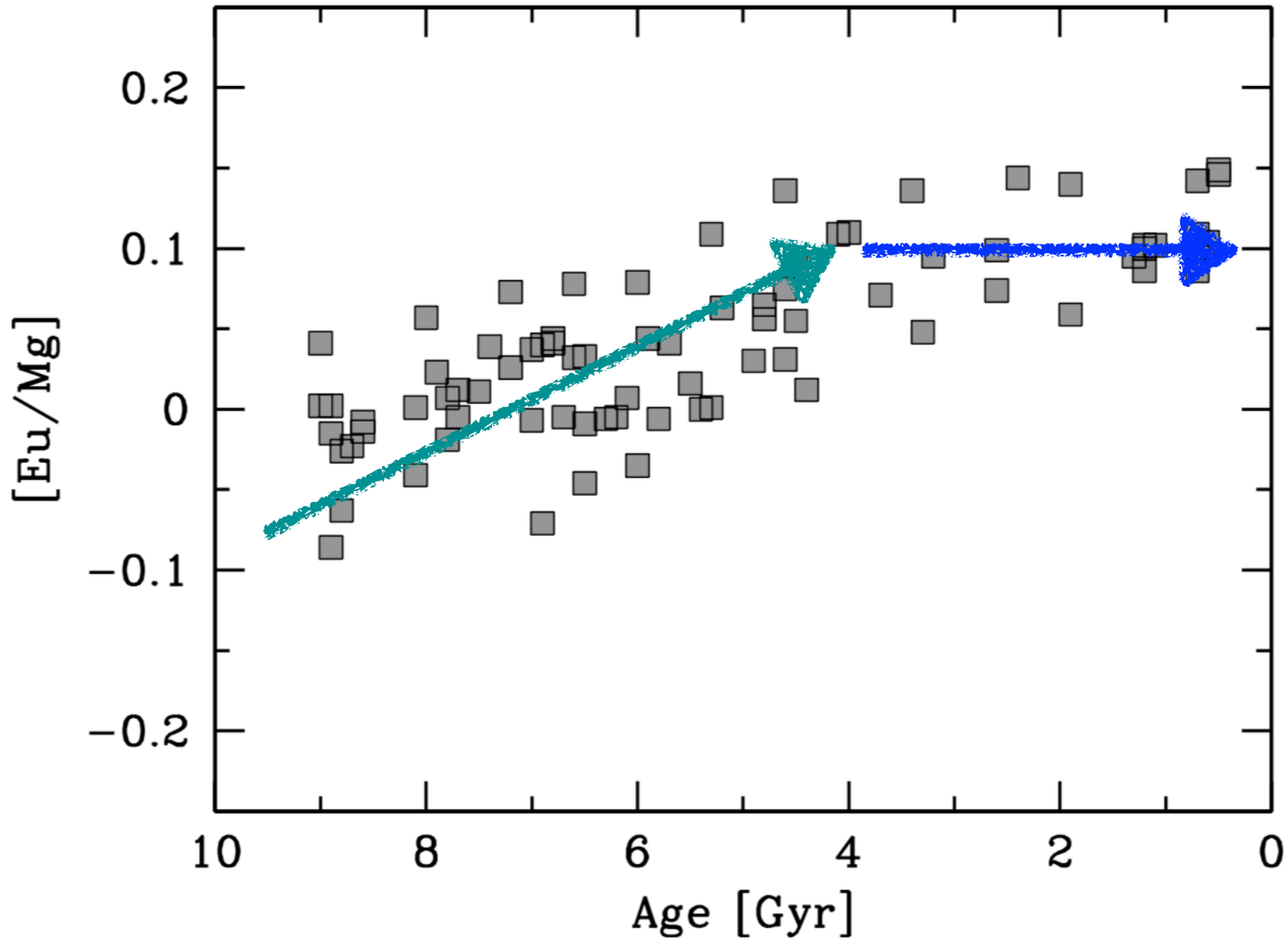
What about the Milky Way?

Change in slope of [Eu/Mg] ~4 Gyr ago in Solar twins.



What about the Milky Way?

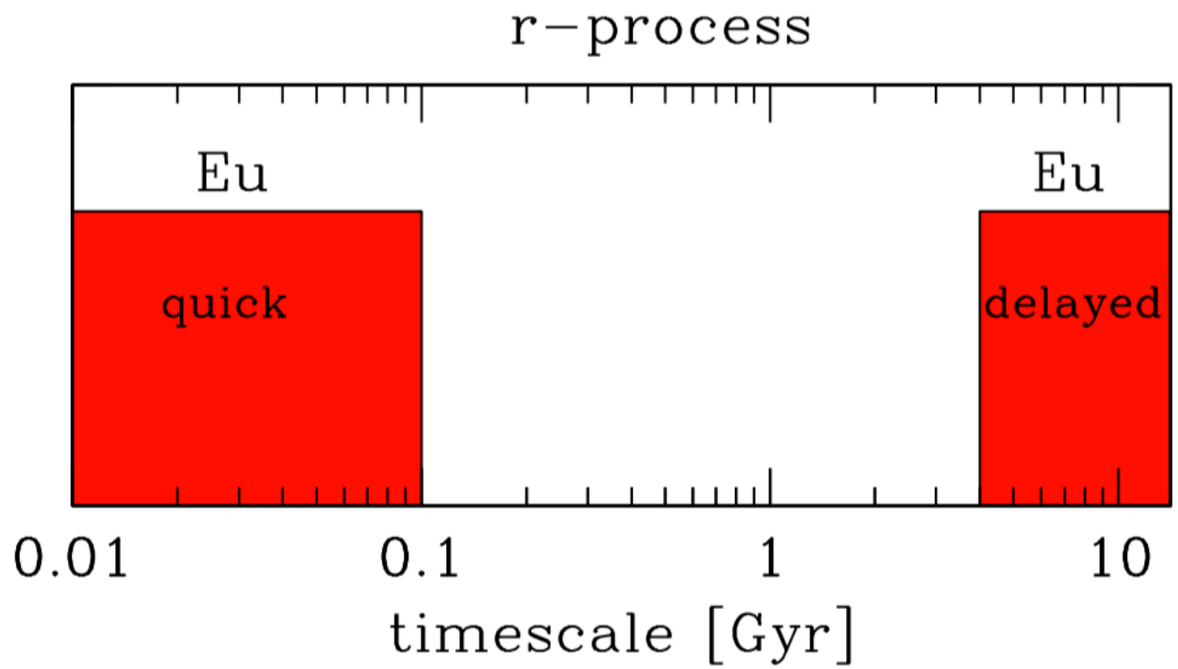
Change in slope of [Eu/Mg] ~4 Gyr ago in Solar twins.



Our proposed timescales

Skúladóttir & Salvadori 2020

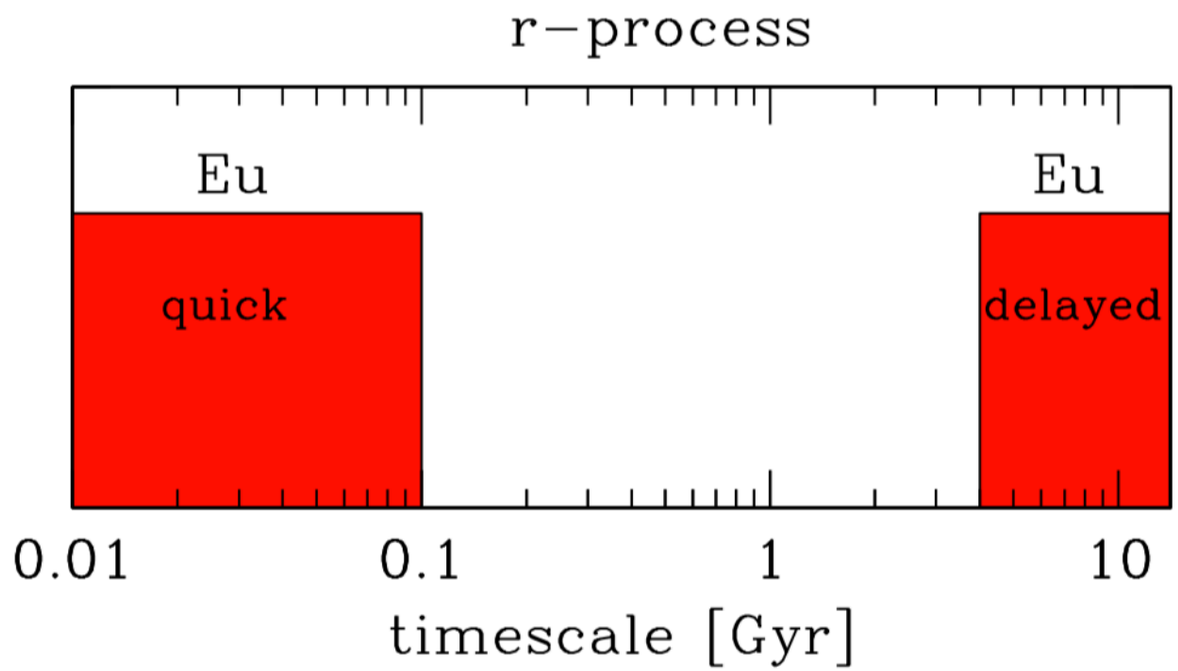
- Two distinct r-process sites are able to explain all the data:
  - A ***quick*** source <10^8 yr
    likely massive stars
  - A ***delayed*** source ≳4 Gyr
    likely neutron star mergers



Our proposed timescales

Skúladóttir & Salvadori 2020

- Two distinct r-process sites are able to explain all the data:
  - A ***quick*** source <10^8 yr
    likely massive stars
  - A ***delayed*** source ≳4 Gyr
    likely neutron star mergers

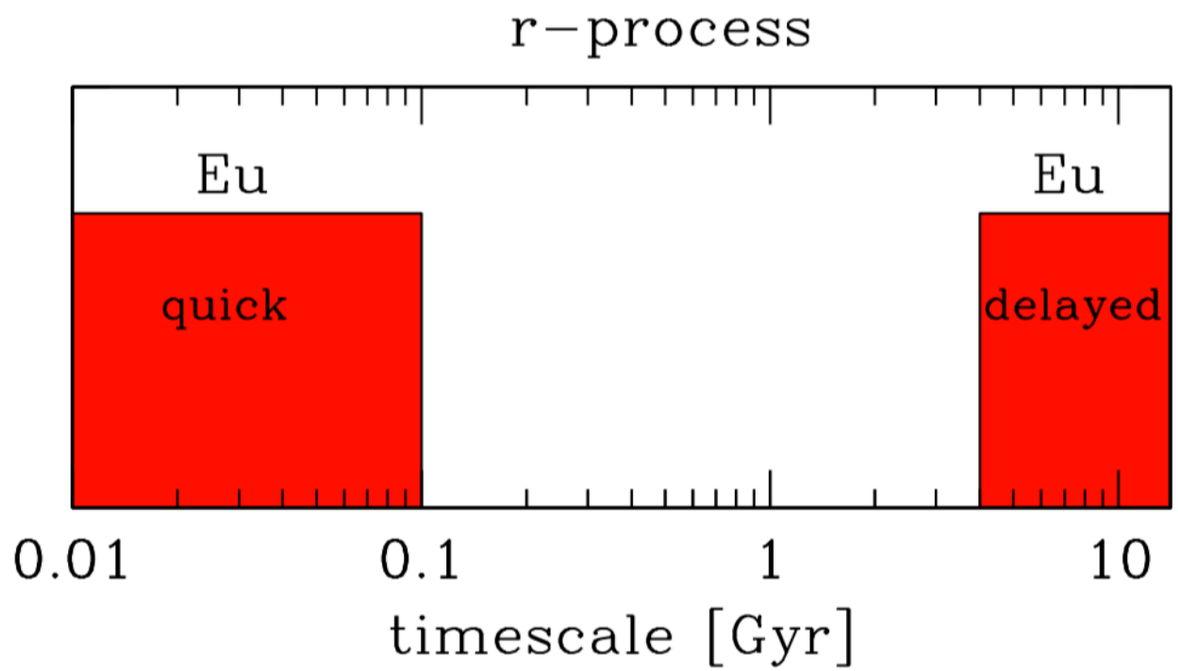


Observations require two distinct r-process sites: a quick and a delayed source!

Our proposed timescales

- Two distinct r-process sites are able to explain all the data:
  - A ***quick*** source <10^8 yr
    likely massive stars
  - A ***delayed*** source ≳4 Gyr
    likely neutron star mergers

Skúladóttir & Salvadori 2020



More data!

The Future


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

4MOST

- Public survey of the Southern Hemisphere.
- 4m VISTA telescope, Paranal, Chile.
- 5 year survey - first light in 2023.
- Public call for survey proposals!

4DWARFS

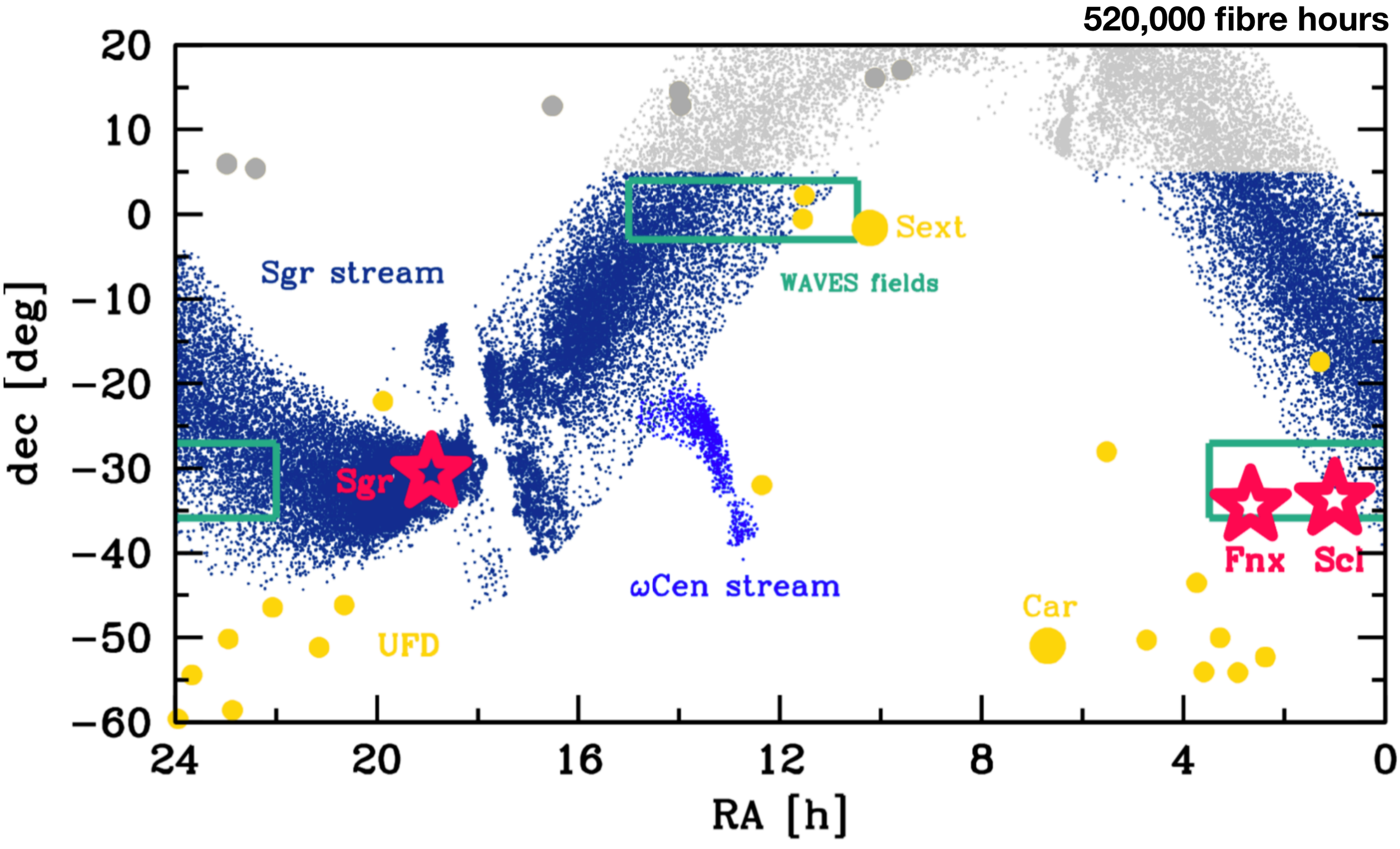
ESO Public Spectroscopic Survey Phase 1 LoI

4MOST survey of dwarf galaxies and their stellar streams (4DWARFS): Small but fundamental

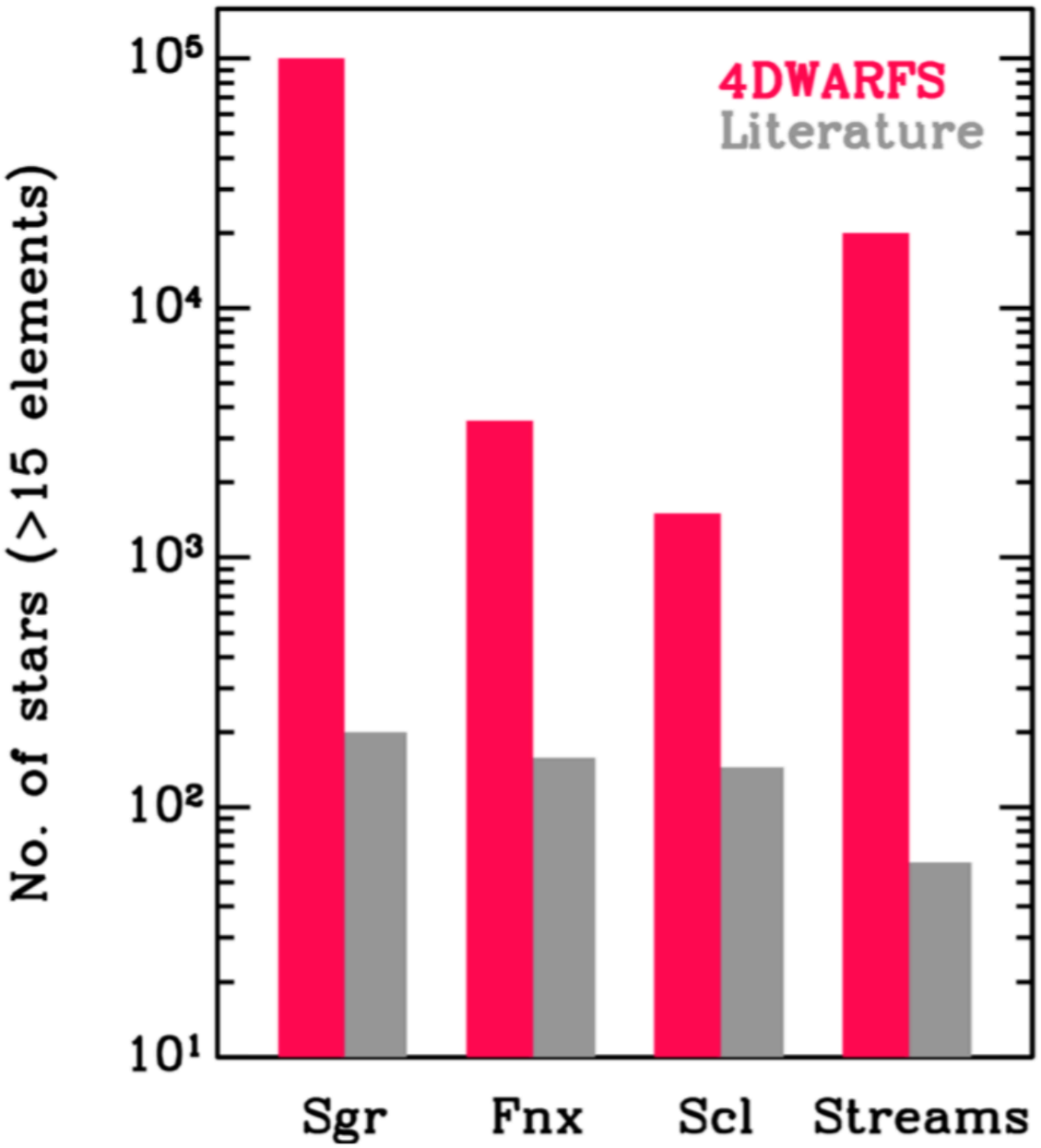
PI: Ása Skúladóttir [1,2] e-mail: asa.skuladottir@unifi.it

Cols: Anish M. Amarsi [3], Almudena Arcones [4,5], Giuseppina Battaglia [6,7], Sven Buder [8], Benoit Côté [9], Simon W. Campbell [10], Marius Eichler [4], Diane Feuillet [11], Andrew J. Gallagher [12], Viola Gelli [1,2], Melanie Hampel [10], Michael Hanke [13], Camilla J. Hansen [12], Sten Hasselquist [14,15], Vanessa Hill [16], Rodrigo Ibata [17], Nikolay Kacharov [12], Amanda Karakas [10], Andreas Koch [13], Karin Lind [18], Maria Lugaro [9], Davide Massari [19,20,21], Thomas Nordlander [8,22], Moritz Reichert [4], Martina Rossi [1,2], Ashley Ruiter [23], Stefania Salvadori [1,2], Ivo Seitenzahl [23], Eline Tolstoy [21], Theodora Xilaki-Dornbusch [24].

4DWARFS


520,000 fibre hours
Sext
WAVES fields
Sgr stream
Sgr
ωCen stream
UFD
Car
Fnx
Scl
dec [deg]
RA [h]
20
10
0
−10
−20
−30
−40
−50
−60
24
20
16
12
8
4
0

4DWARFS



- ~120,000 stars with detailed chemical abundance measurements (>15 elements) in dwarf galaxies + the Sagittarius stream

- Currently available: <1,000

Conclusions

- **Dwarf galaxies** are excellent systems to learn about nucleosynthesis.
- The **i-process is essential** to the overall production of n-capture elements in the Sculptor dwarf spheroidal galaxy.
- Two sources are required to explain the r-process: a **quick** source (likely SN) and a **delayed** source (likely NSM).
- **Data are coming!**

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 804240).