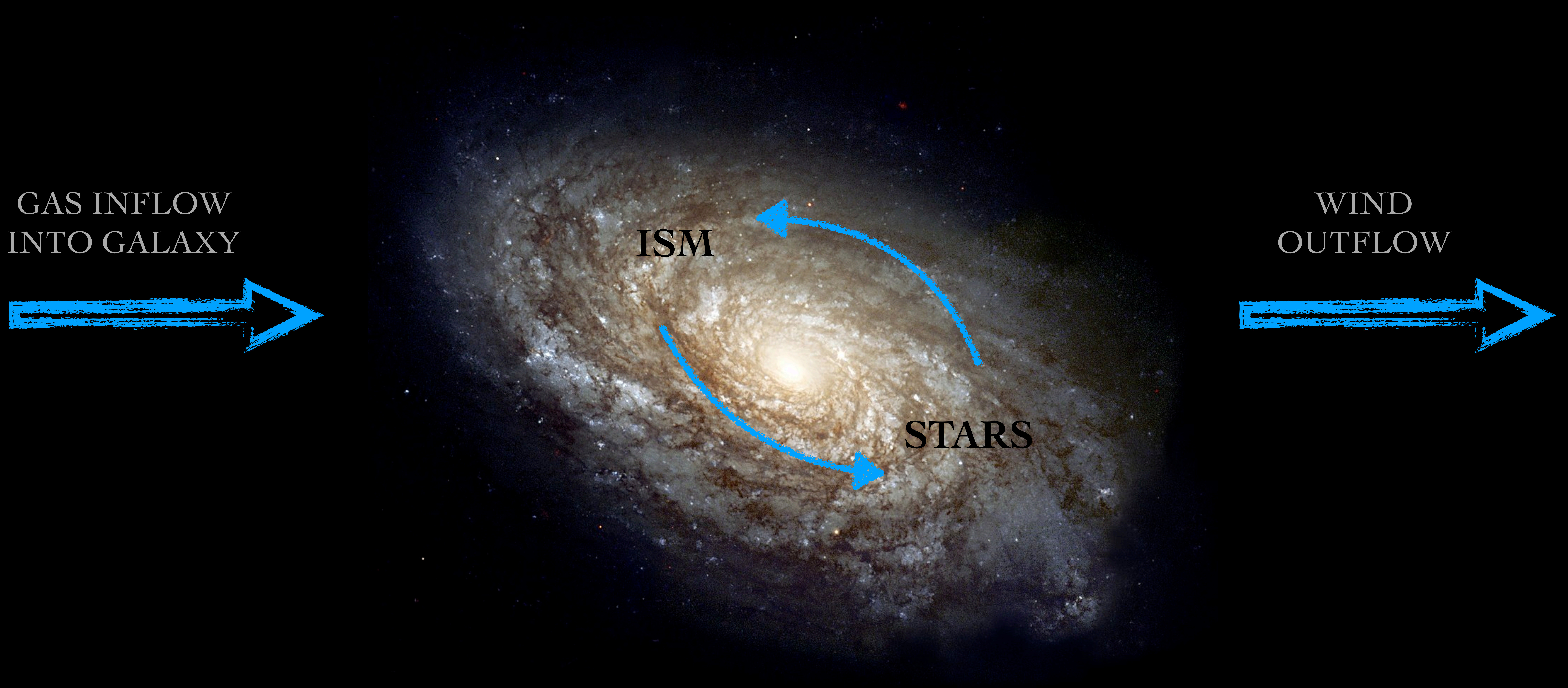
Evolution of neutron capture elements in dwarf galaxies

M. Molero, D. Romano, M. Reichert, F. Matteucci, A. Arcones, G. Cescutti, P. Simonetti, C. J. Hansen, G. Lanfranchi

17th Russbach School on Nuclear Astrophysics

M. Molero, 18/03/2022

Chemical evolution of galaxies



Equations of Chemical Evolution

$$\dot{M}_{\mathrm{gas},i}(t) = -\,\psi(t)X_i(t) + X_{i,A}A(t) - X_i(t)W(t) + \dot{R}_i(t)$$

Equations of Chemical Evolution

$$\dot{M}_{\mathrm{gas},i}(t) = -\boxed{\psi(t)X_i(t)} + X_{i,A}A(t) - X_i(t)W(t) + \dot{R}_i(t)$$

- Rate at which chemical elements are subtracted by the ISM to be included in star

Equations of Chemical Evolution

$$\dot{M}_{\mathrm{gas},i}(t) = -\boxed{\psi(t)X_i(t)} + \boxed{X_{i,A}A(t)} - X_i(t)W(t) + \dot{R}_i(t)$$

- Rate at which chemical elements are subtracted by the ISM to be included in star

- Rate at which chemical elements are accreted through infall of gas

Equations of Chemical Evolution

$$\dot{M}_{\mathrm{gas},i}(t) = -\boxed{\psi(t)X_i(t)} + \boxed{X_{i,A}A(t)} - \boxed{X_i(t)W(t)} + \dot{R}_i(t)$$

- Rate at which chemical elements are subtracted by the ISM to be included in star

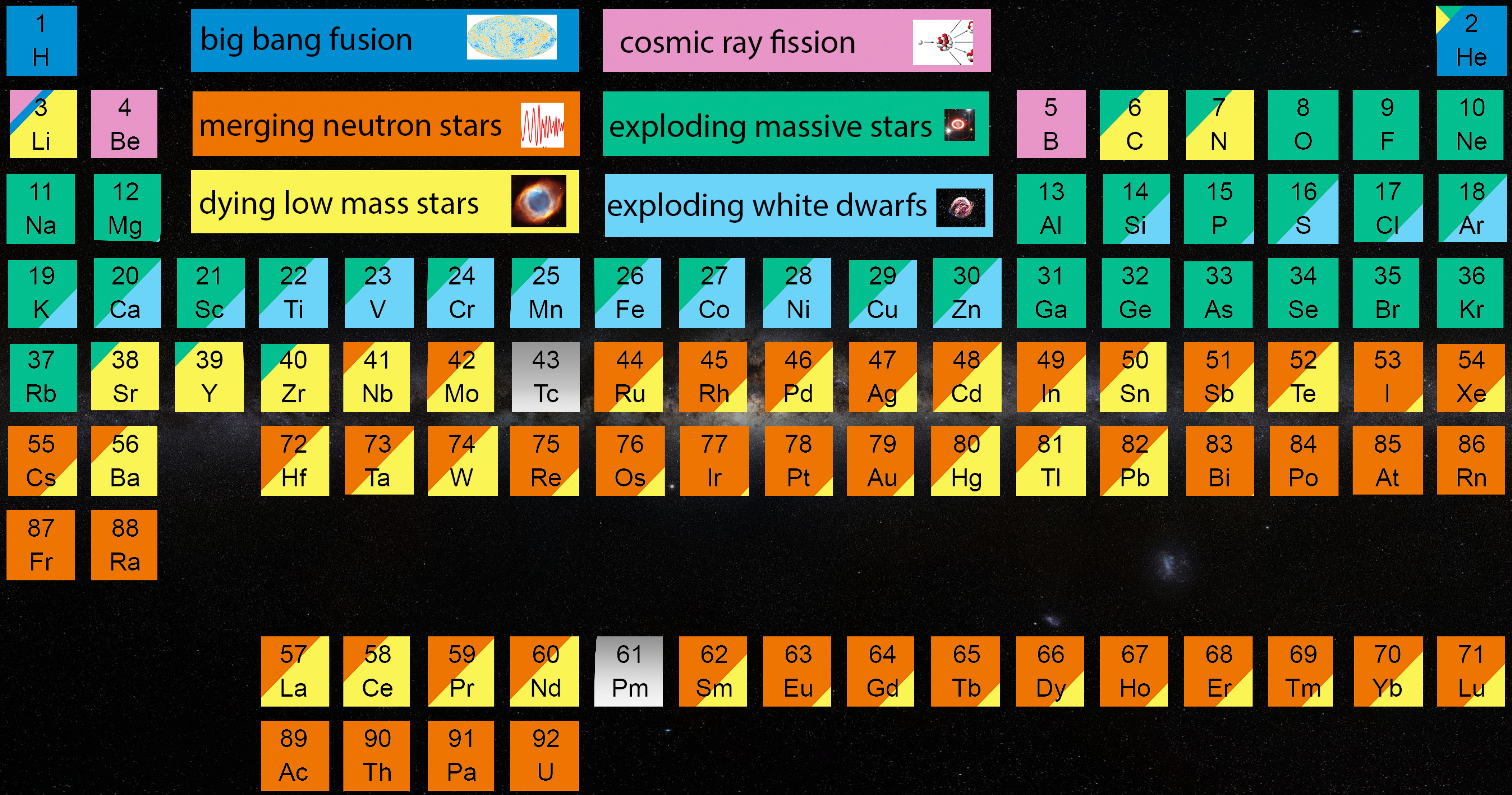
- Rate at which chemical elements are lost through galactic wind

- Rate at which chemical elements are accreted through infall of gas

Equations of Chemical Evolution

$$\dot{M}_{\mathrm{gas},i}(t) = -\boxed{\psi(t)X_i(t)} + \boxed{X_{i,A}A(t)} - \boxed{X_i(t)W(t)} + \boxed{\dot{R}_i(t)}$$

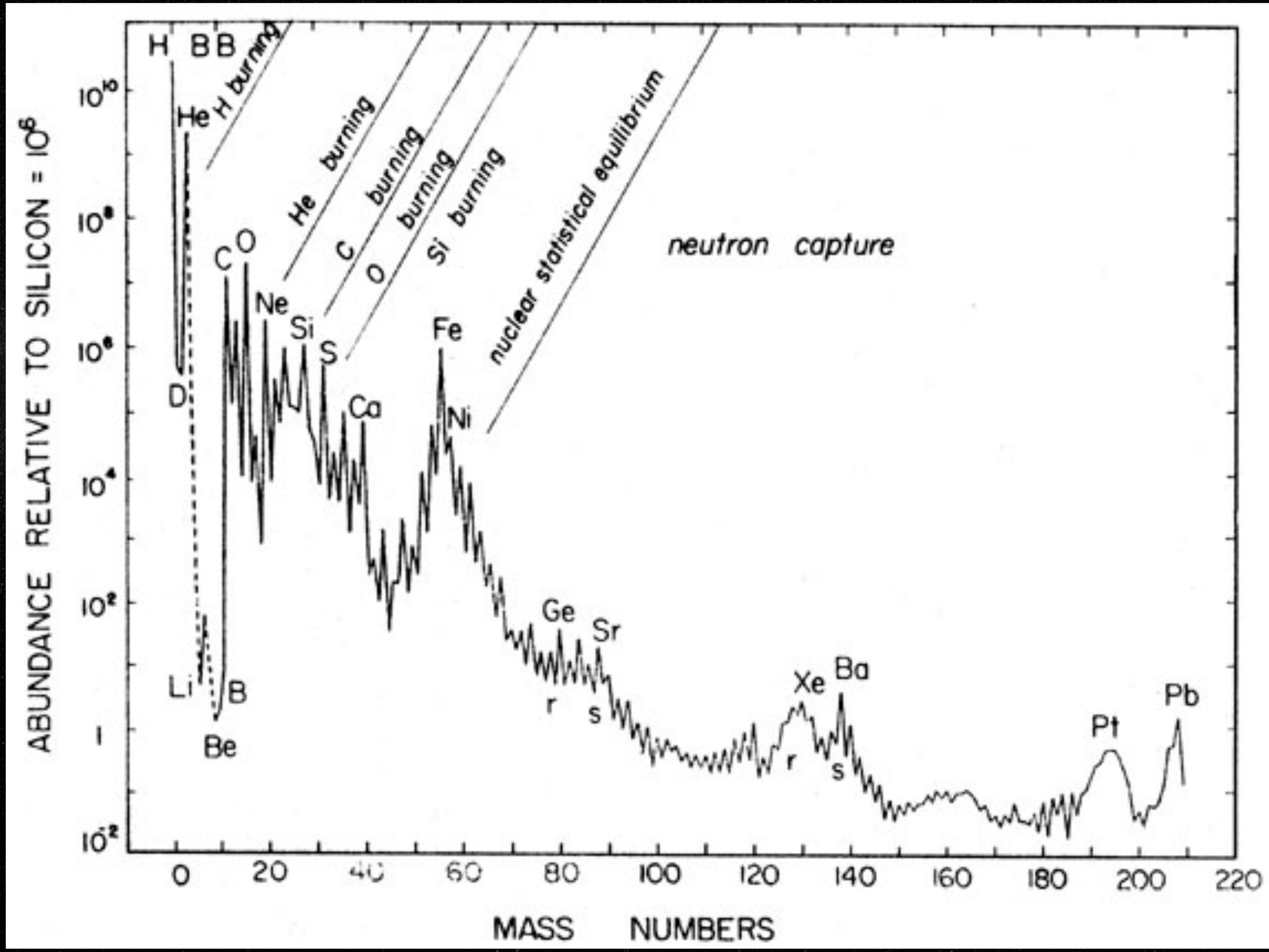
- Rate at which chemical elements are subtracted by the ISM to be included in star
- Rate at which chemical elements are lost through galactic wind
- Rate at which chemical elements are accreted through infall of gas
- Rate of restitution of matter from stars to the ISM



Graphic created by Jennifer Johnson

Astronomical image credits:
ESA/NASA/AASNova

Neutron capture elements nucleosynthesis

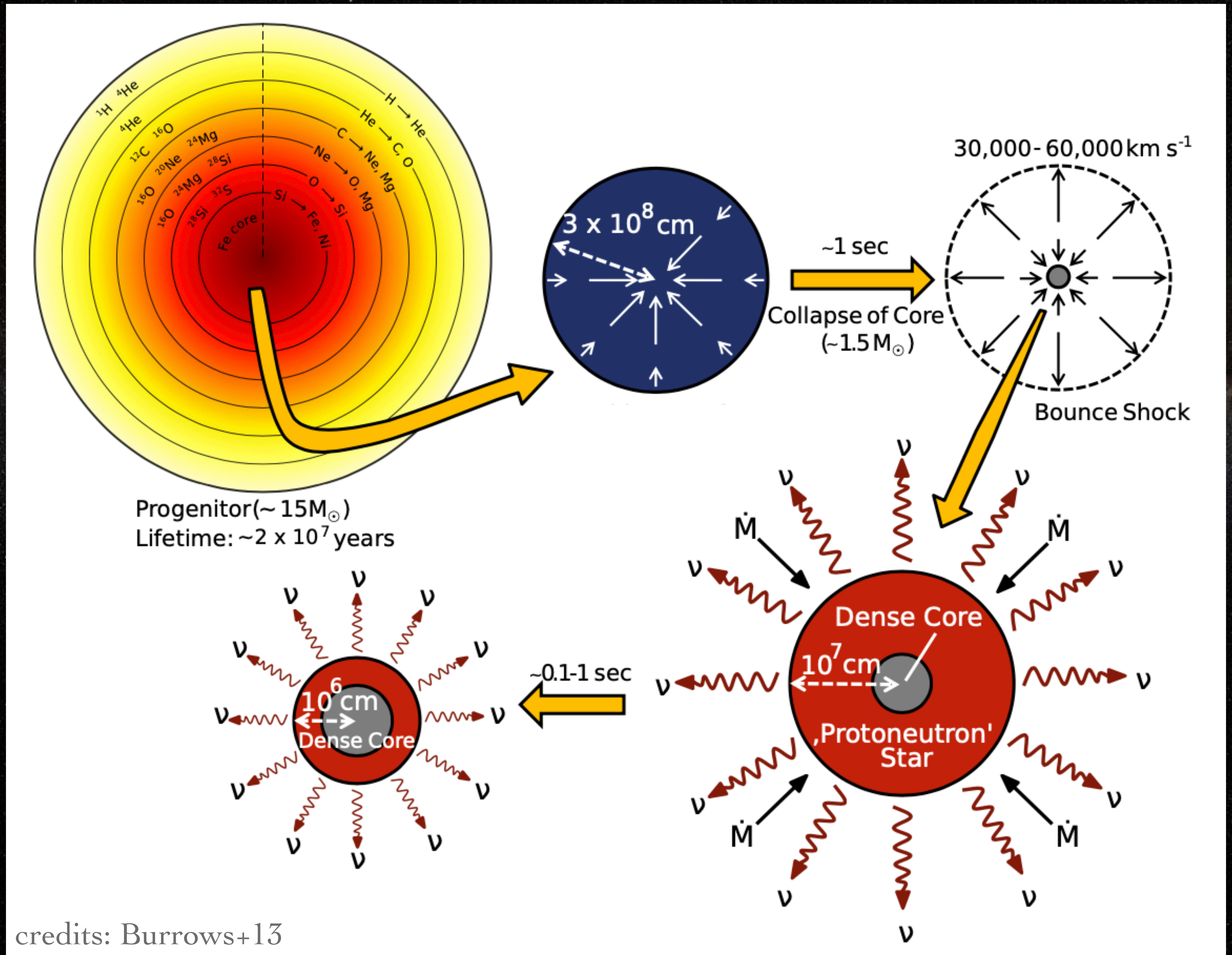


s-process: the unstable nuclide created by neutron capture will decay in a stable nuclide before it has time to capture another neutron

r-process: there is time for multiple neutron captures before the first β-decay occurs

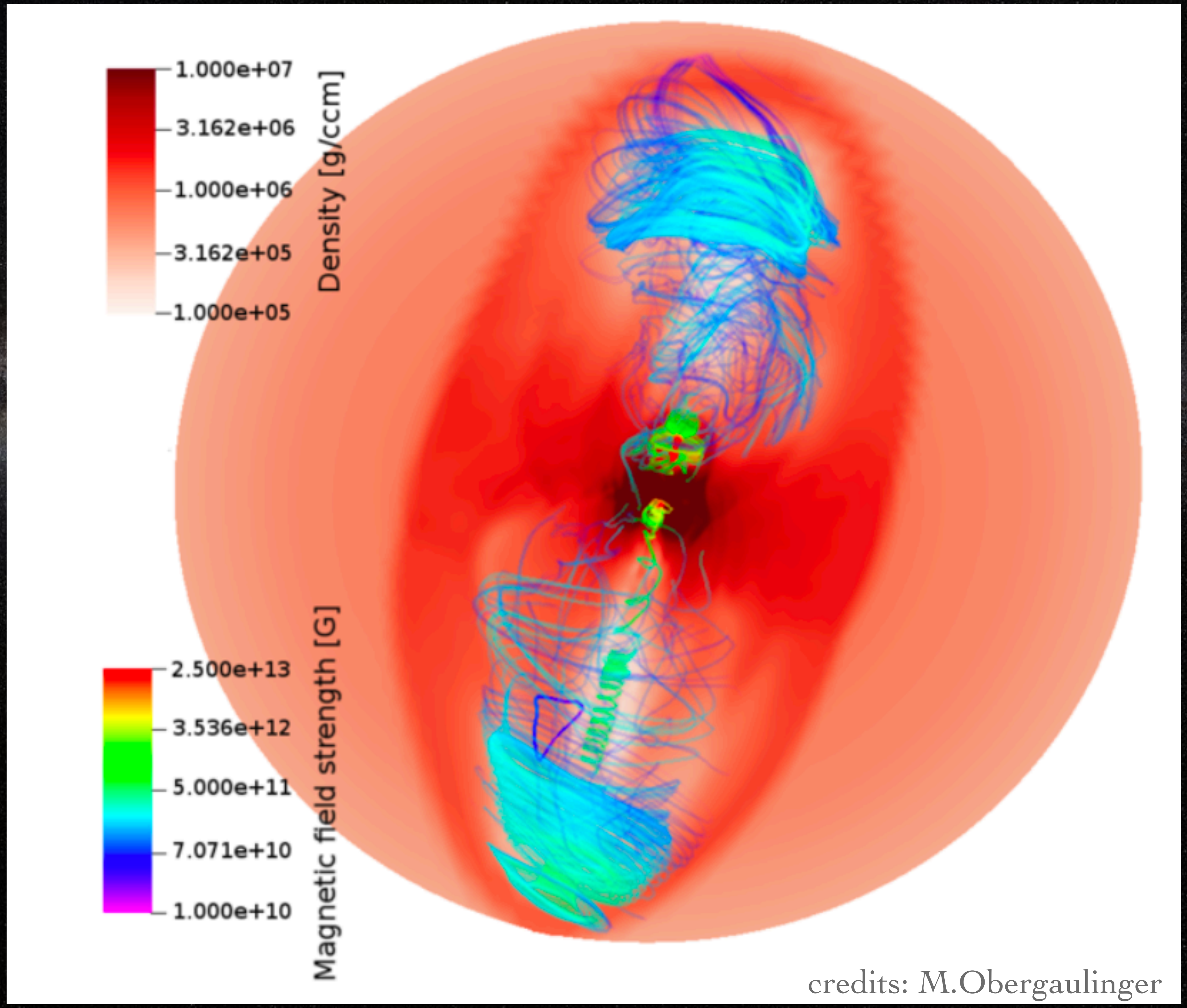
Neutron capture elements nucleosynthesis

CC-SNe



Standard supernovae cannot produce elements beyond the second r-process peak: the eject is often proton rich with some small clumps of slightly neutron-rich material

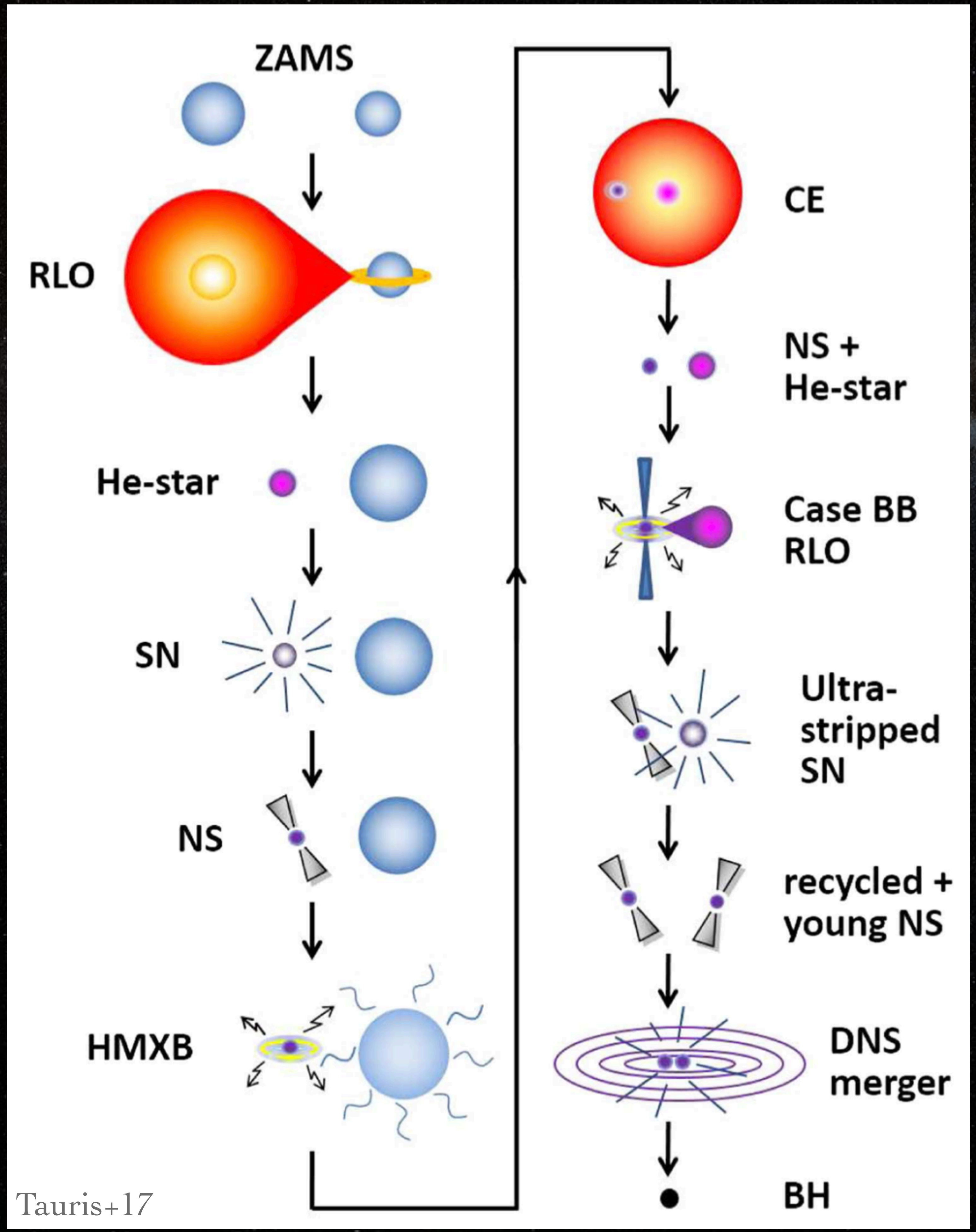
MRD-SNe

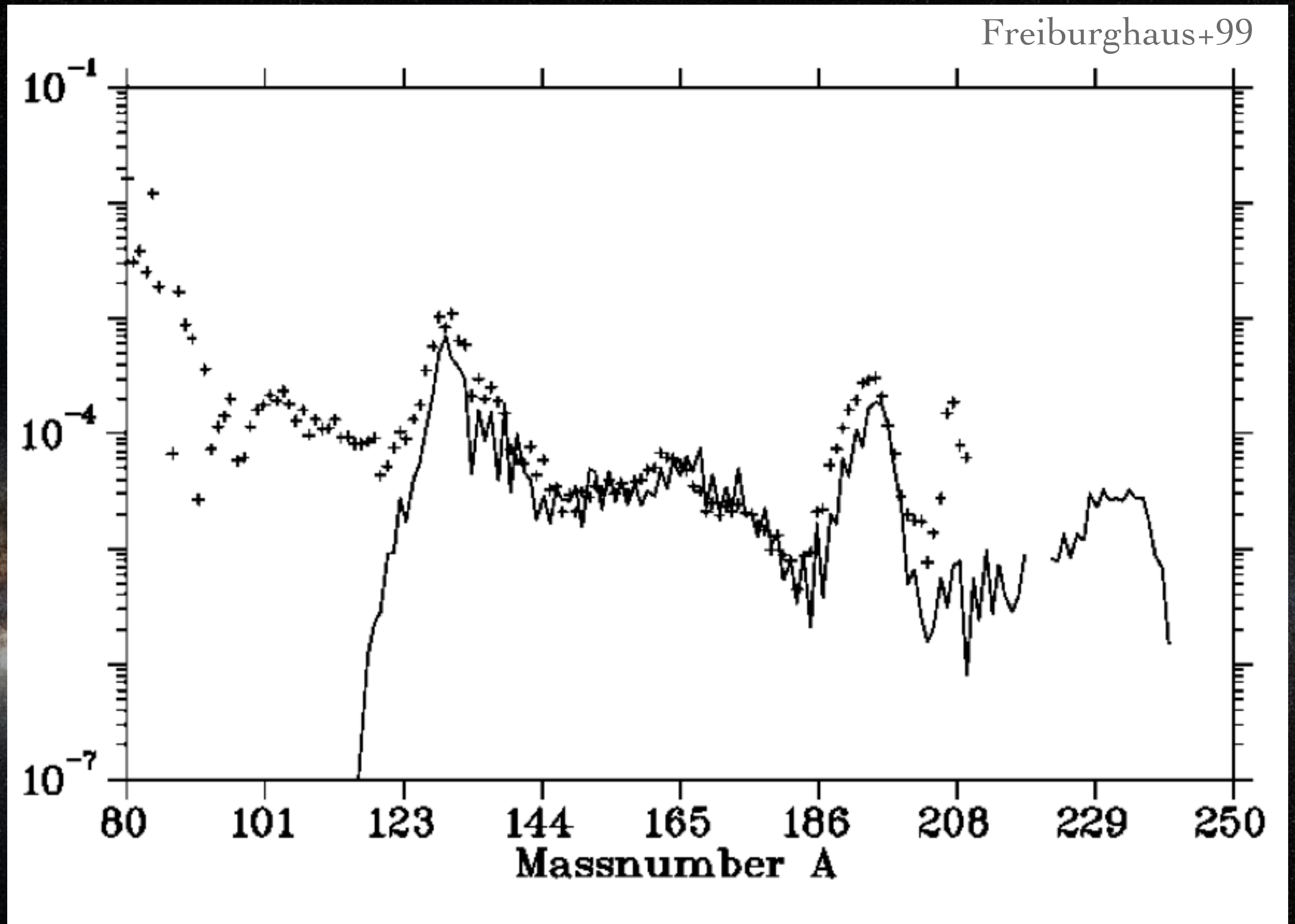


In contrast to "typical" neutrino-driven CC-SNe, where matter is processed by neutrinos and therefore neutrons can react to protons, MRD-SNe may eject matter that is dominantly driven by magnetic pressure and therefore conserve neutron rich conditions

Neutron capture elements nucleosynthesis

MNS





From the spectra of the kilonova AT2017gfo Watson et al. 2019 measure the yield of Sr: $(1-5)\times10^{-5}M_{\odot}$

Consisting mainly out of material from the neutron star itself and being located far away from the colliding neutron stars, the tidally ejected and unshocked matter is to a minimum processed by neutrinos, therefore it is very neutron rich and an ideal host of the r-process

Heavy Elements Nucleosynthesis

From the spectra of the kilonova AT2017gfo *Watson et al. 2019* measure the yield of Sr: $(1-5)\times 10^{-5} M_\odot$

Y_{Sr}^{MNS} ($M_\odot$)	Y_{Eu}^{MNS} ($M_\odot$)	Y_{Ba}^{MNS} ($M_\odot$)
$(1-5)\times 10^{-5}$	$3.0\times 10^{-7} - 1.5\times 10^{-6}$	$3.2\times 10^{-6} - 1.58\times 10^{-5}$
$(1-5)\times 10^{-4}$	$3.0\times 10^{-6} - 1.5\times 10^{-5}$	$3.2\times 10^{-5} - 1.58\times 10^{-4}$
$(1-5)\times 10^{-3}$	$3.0\times 10^{-5} - 1.5\times 10^{-4}$	$3.2\times 10^{-4} - 1.58\times 10^{-3}$

MNS

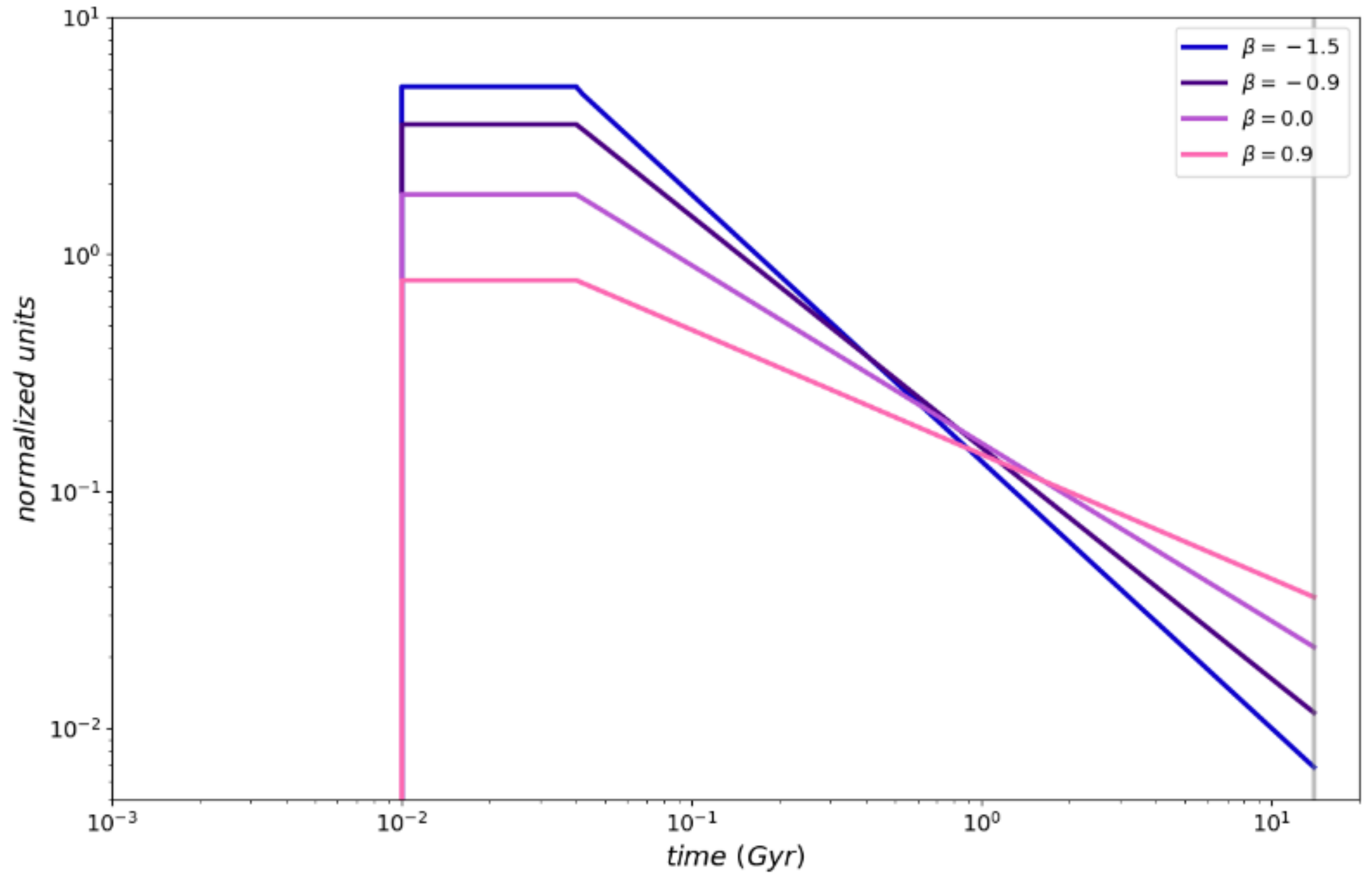
Y_{Eu}^{MRD} ($M_\odot$)	Y_{Ba}^{MRD} ($M_\odot$)	Model	Reference
1.11×10^{-5}	2.10×10^{-4}	–	Winteler et al. (2012)[1]
1.56×10^{-6}	2.72×10^{-6}	B12β0.25	Nishimura et al. (2015)
6.85×10^{-6}	2.58×10^{-4}	L0.10	Nishimura et al. (2017)
2.81×10^{-6}	1.23×10^{-4}	L0.60	"
4.69×10^{-7}	7.66×10^{-6}	L0.75	"
5.19×10^{-6}	2.07×10^{-5}	35OC-Rs	Reichert et al. (2021)

MRD-SNe

The Rate of Merging Neutron Stars

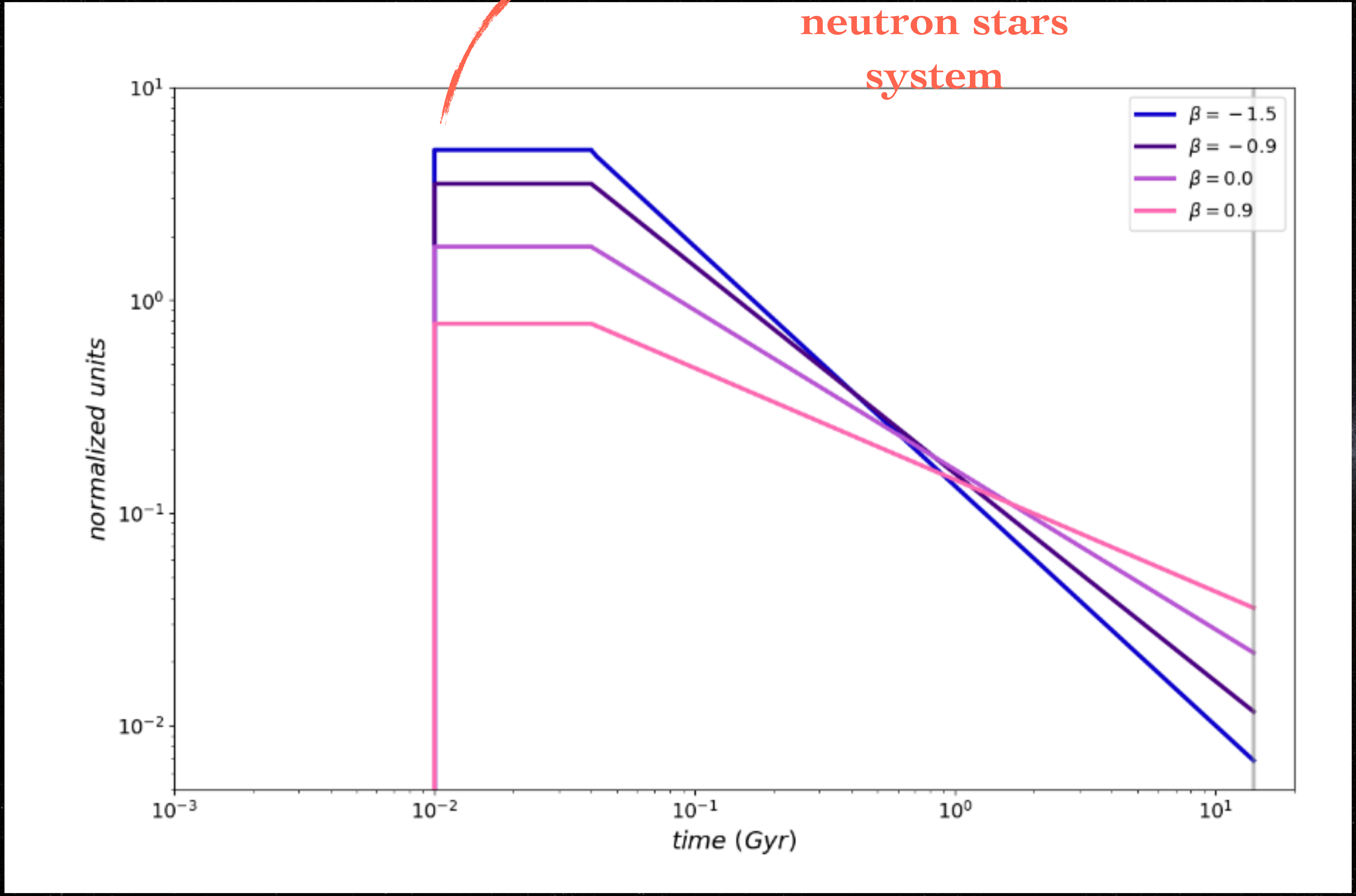
$$R_{MNS}(t) = k_\alpha \int_{\tau_i}^{min(t,\tau_x)} \alpha_{MNS}(\tau)\psi(t-\tau)f_{MNS}(\tau)\,\mathrm{d}\tau$$

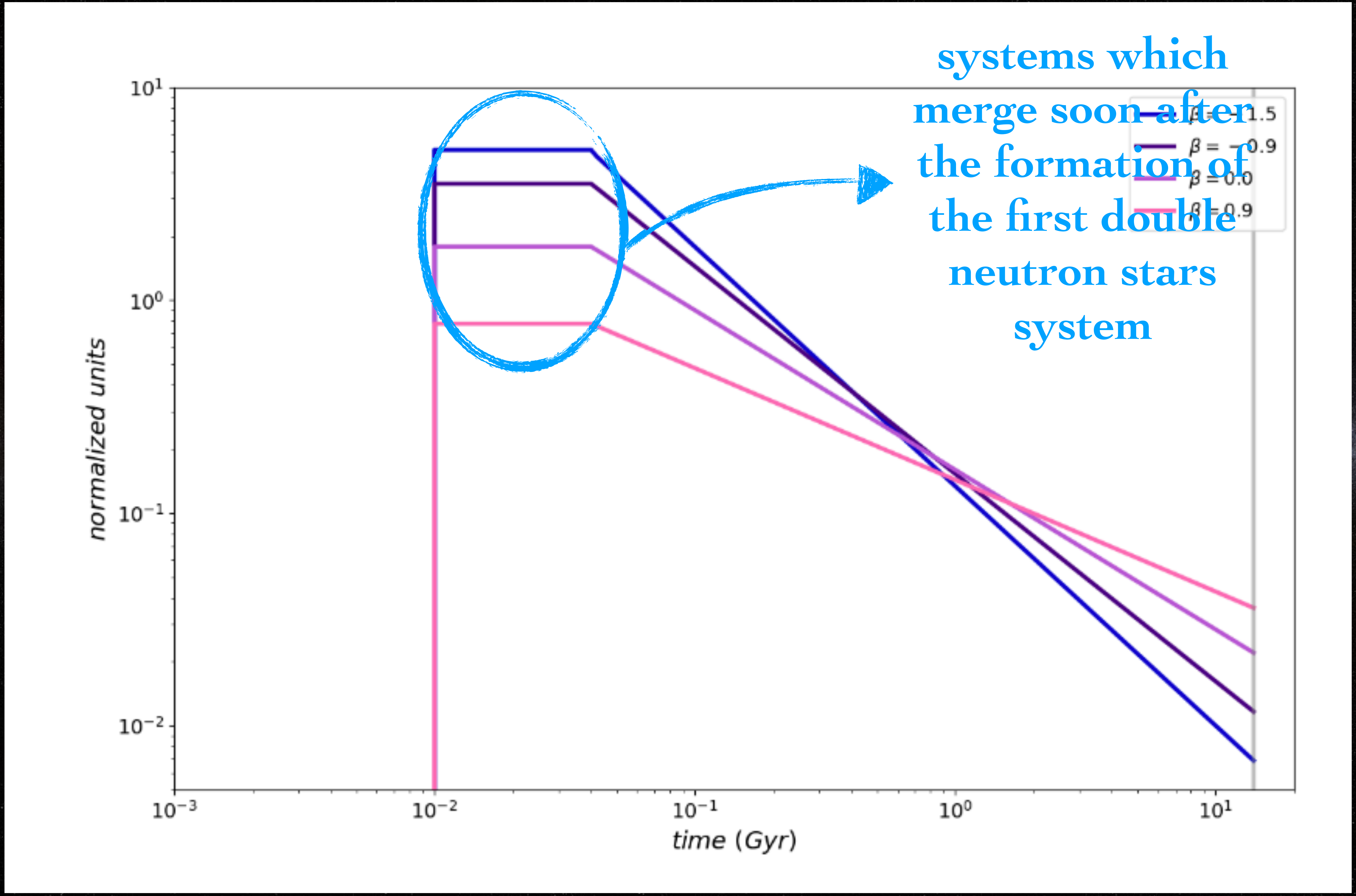
- α_{MNS} the fraction of stars which gives rise to a merging event (*Molero et al. 2021a, MNRAS*)
- $f_{MNS}(\tau)$ the delay time distribution (DTD) (*Simonetti et al. 2019, MNRAS*)
- $\tau = \tau_n + \tau_{gw}$ the delay time

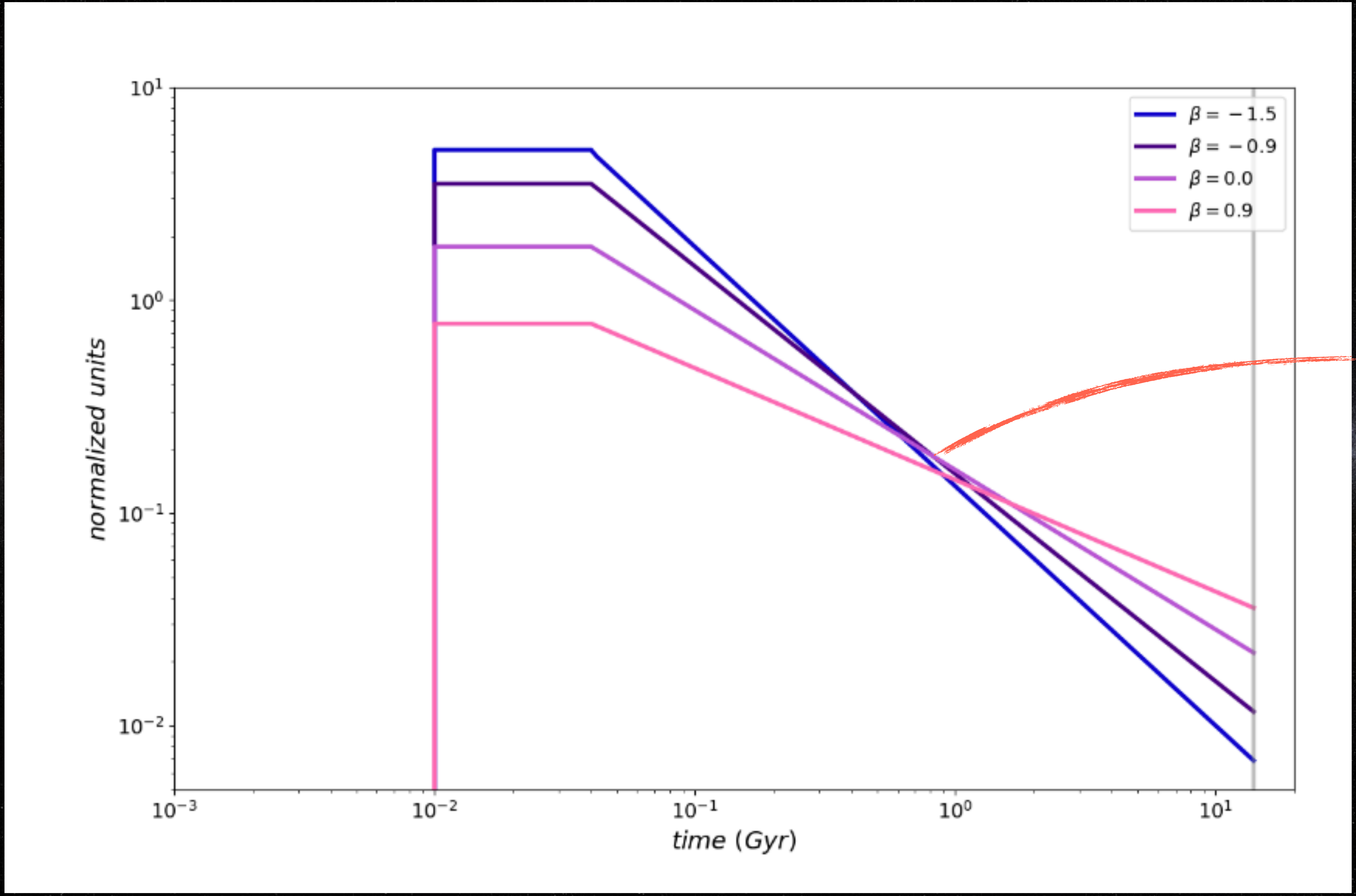


$\beta = -1.5$
$\beta = -0.9$
$\beta = 0.0$
$\beta = 0.9$
normalized units
time (Gyr)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

formation of the first double neutron stars system



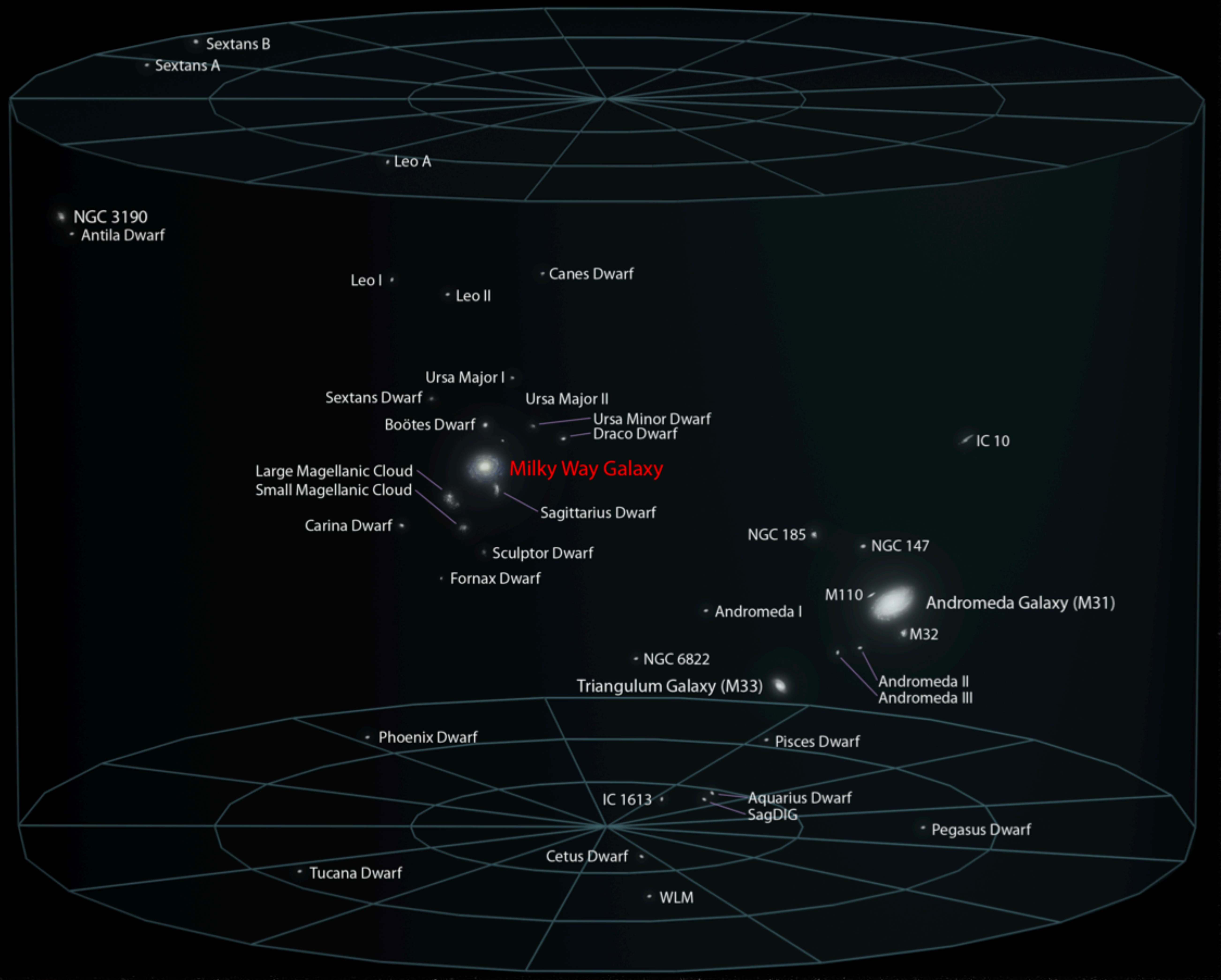

systems which merge soon after the formation of the first double neutron stars system
β = −1.5
β = −0.9
β = 0.0
β = 0.9
normalized units
time (Gyr)



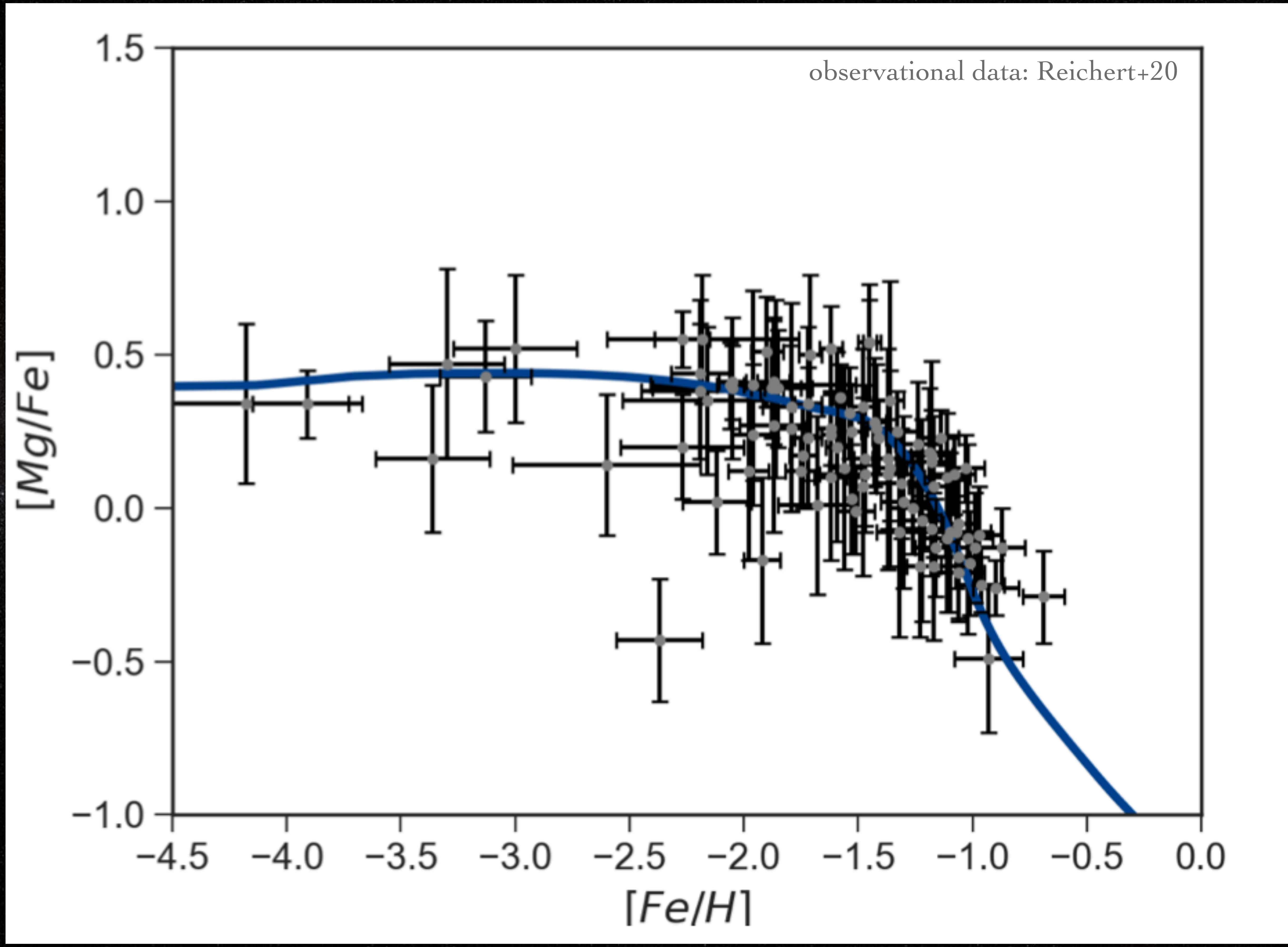
systems for which the delay is dominated by gravitational radiation

Classical dwarf spheroidal galaxies (dSphs): the least luminous and most dark matter dominated galaxies which are observed today in the Universe. Classified as early-type since they are observed to posses very low gas mass at the present time and their stars are very iron poor compared to the Sun

Ultra-faint dwarf spheroidal galaxies (UFDs): dwarf galaxies orbiting around the Milky Way with physical properties very similar to dSph galaxies but average surface brightnesses and effective radii even much smaller



Sculptor dSph - the time delay model



CC-SNe:

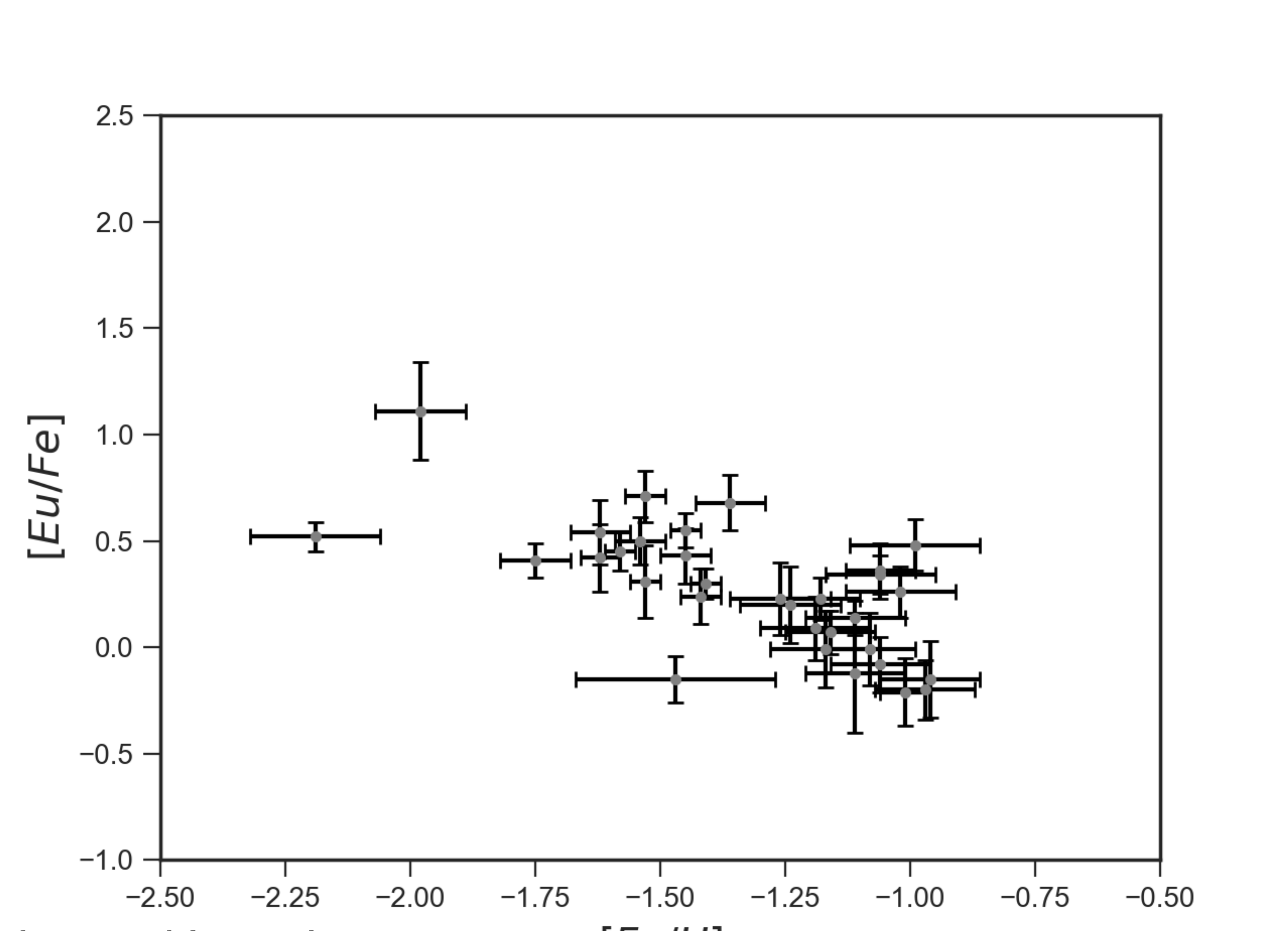
- Main producers of α-elements
- 1/3 of Fe producers
- From massive stars (short lifetime)

SNe Ia:

- Main producers of Fe
- From low-mass stars (long lifetime)

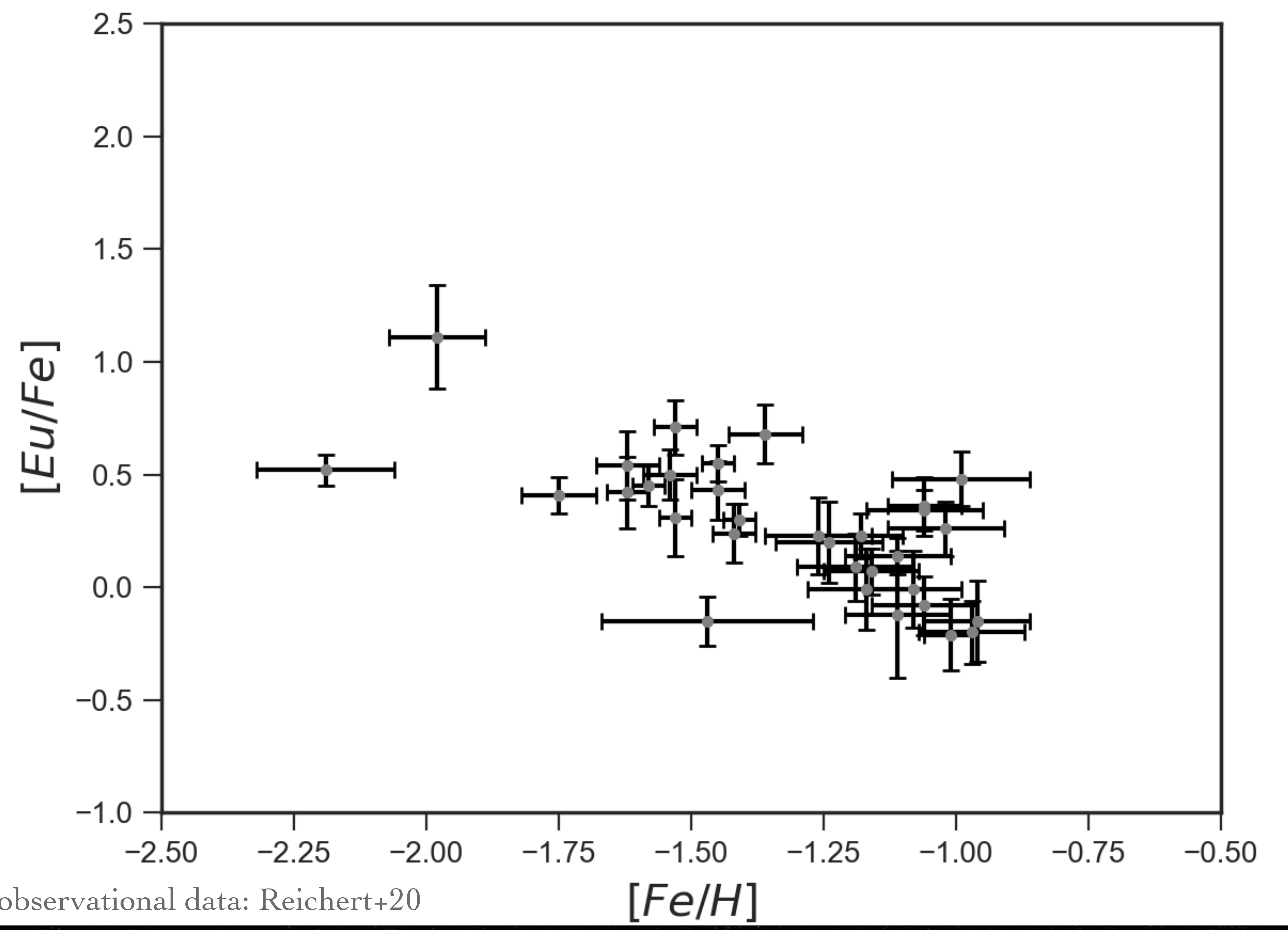
$[X/H] = log(X/H) - log(X/H)_\odot$

Sculptor dSph - the [Eu/Fe] vs [Fe/H]

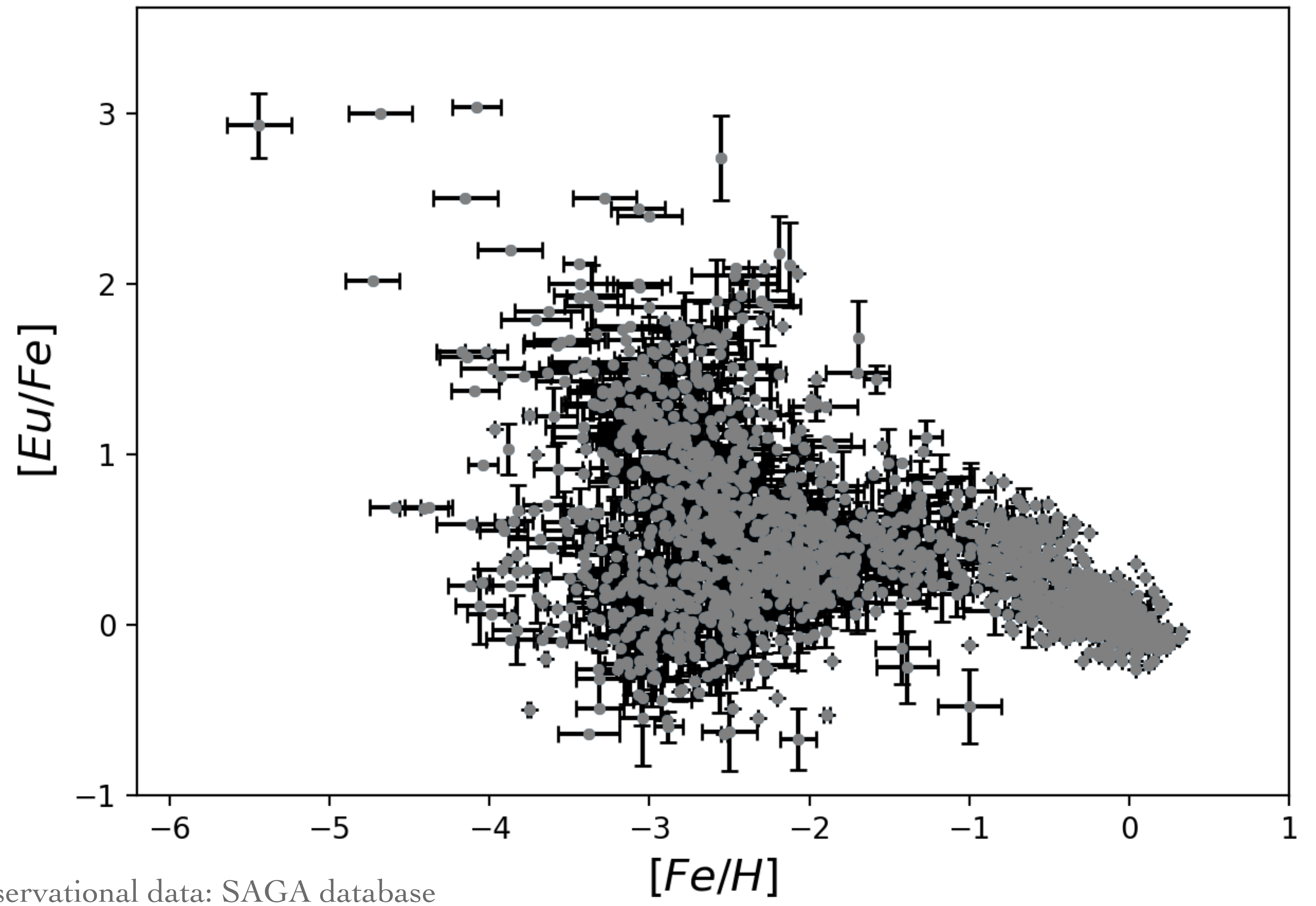


observational data: Reichert+20

Sculptor dSph - the [Eu/Fe] vs [Fe/H]



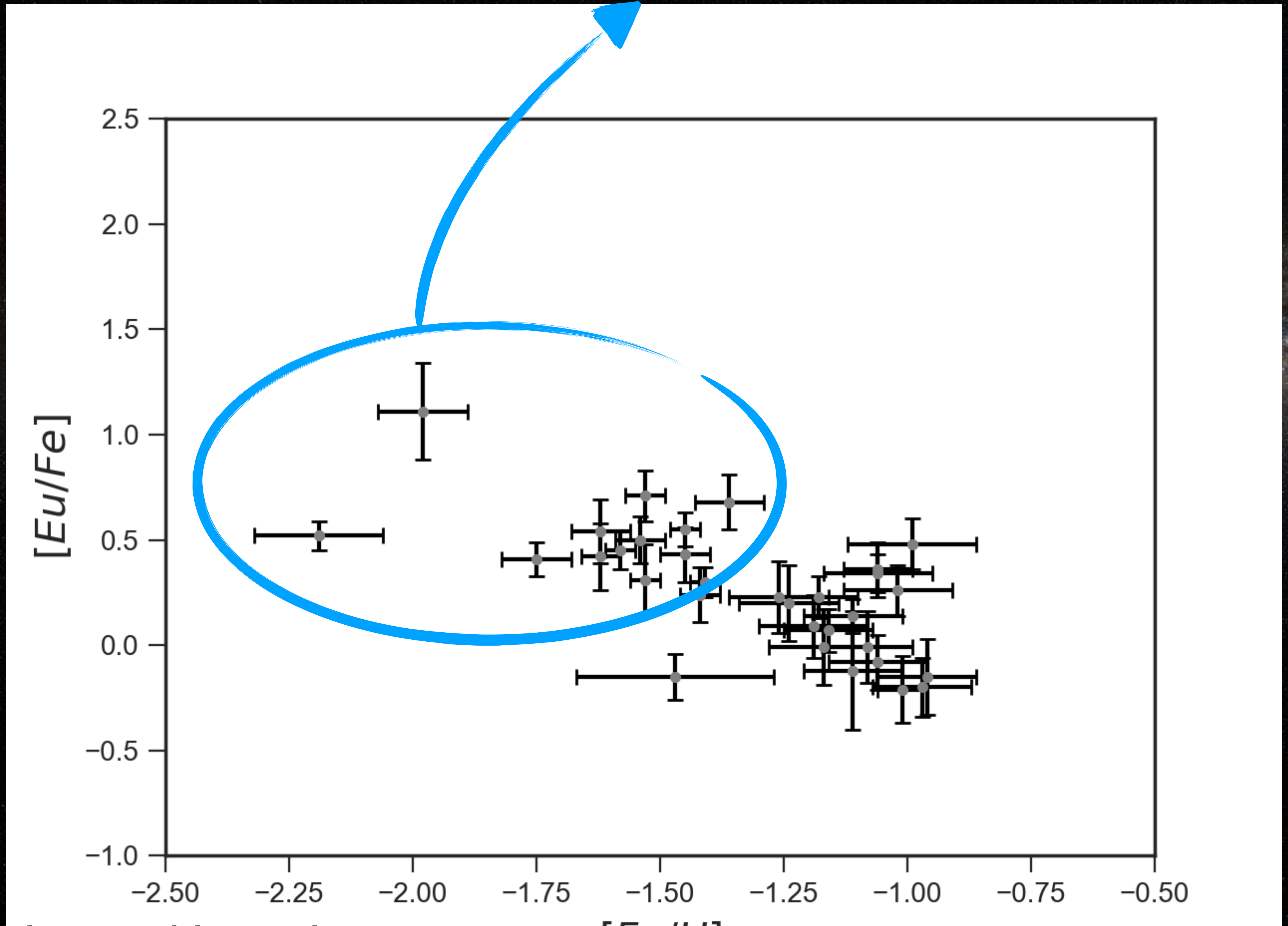
observational data: Reichert+20



observational data: SAGA database

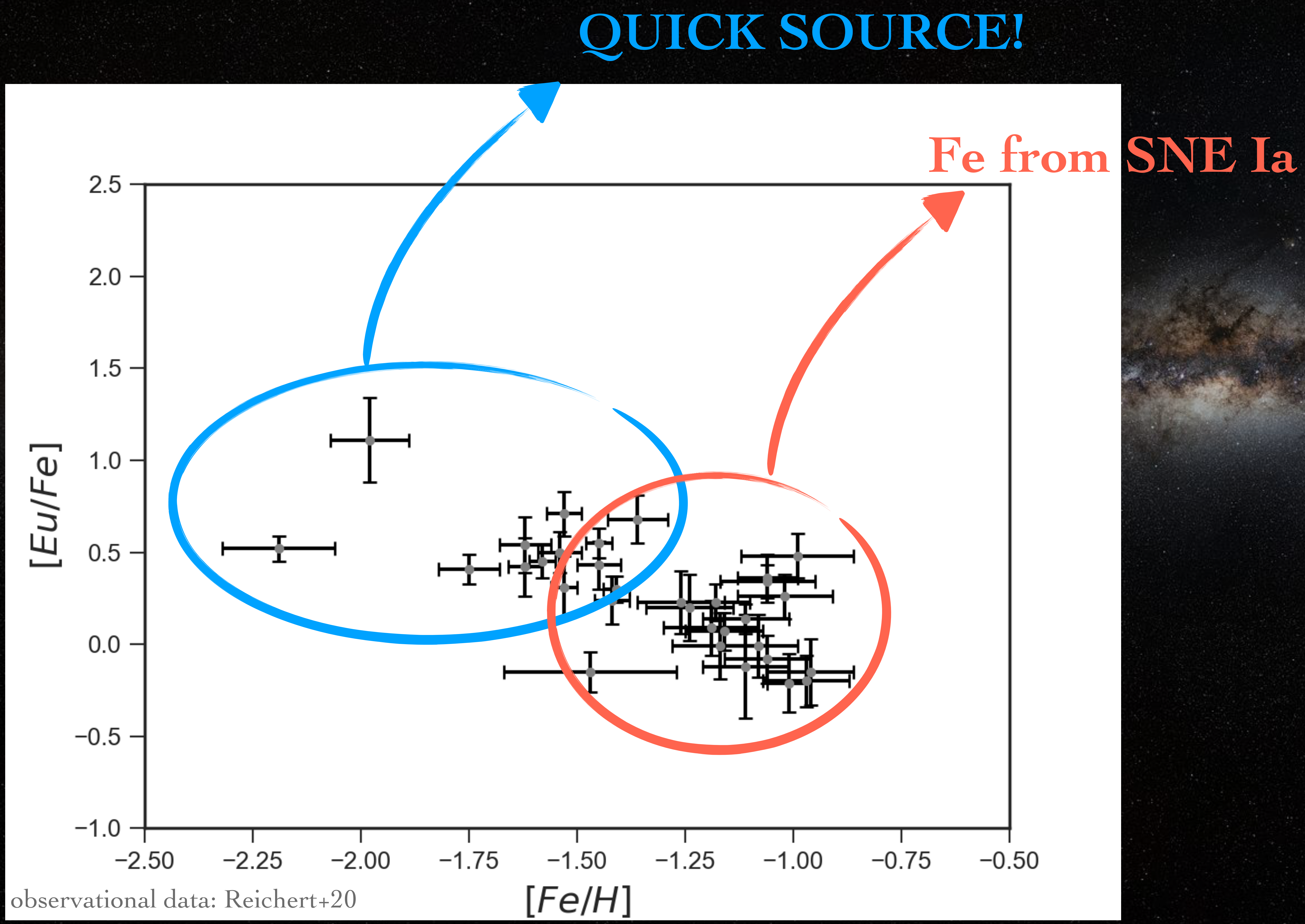
Sculptor dSph - the [Eu/Fe] vs [Fe/H]

QUICK SOURCE!

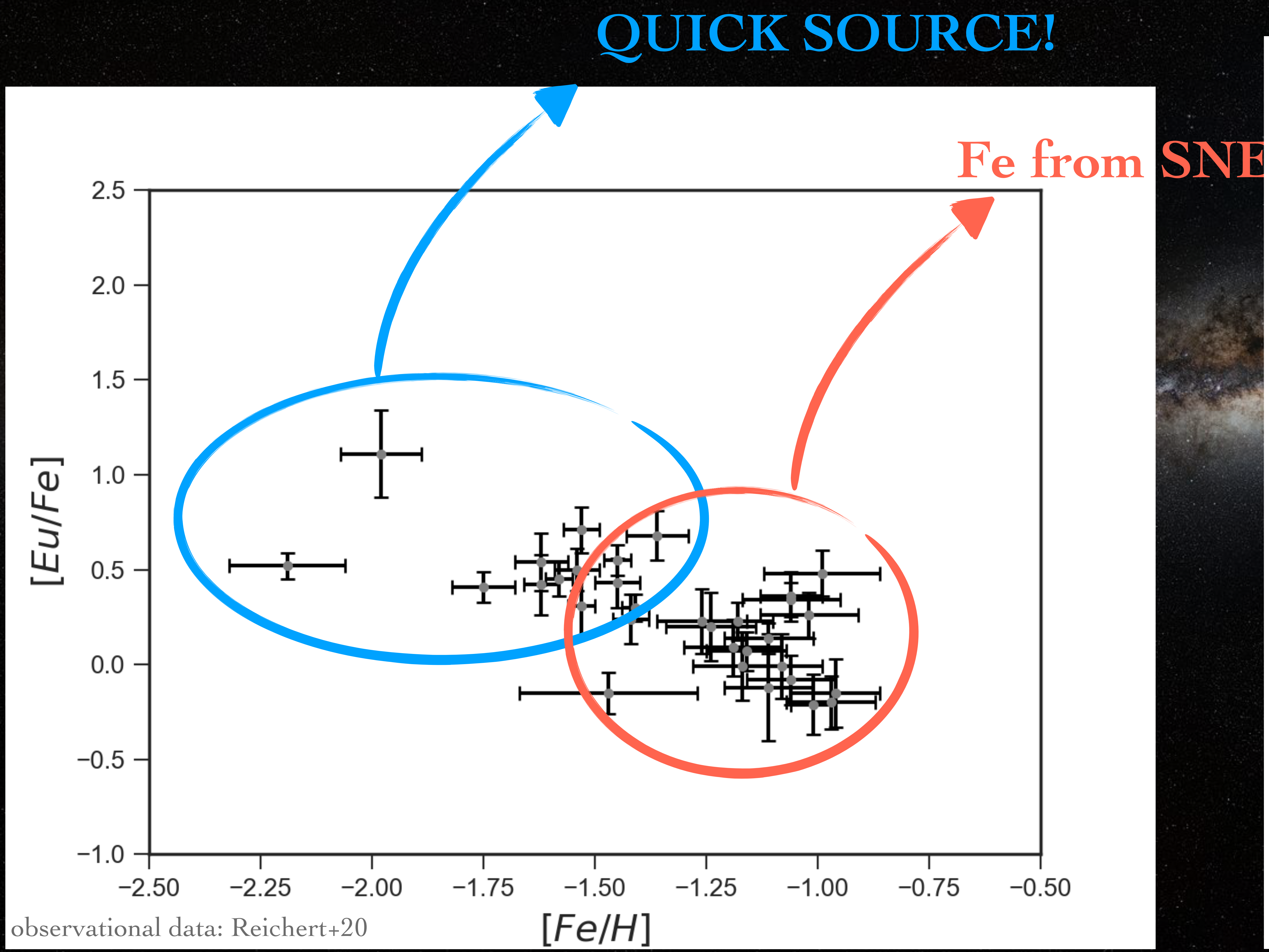


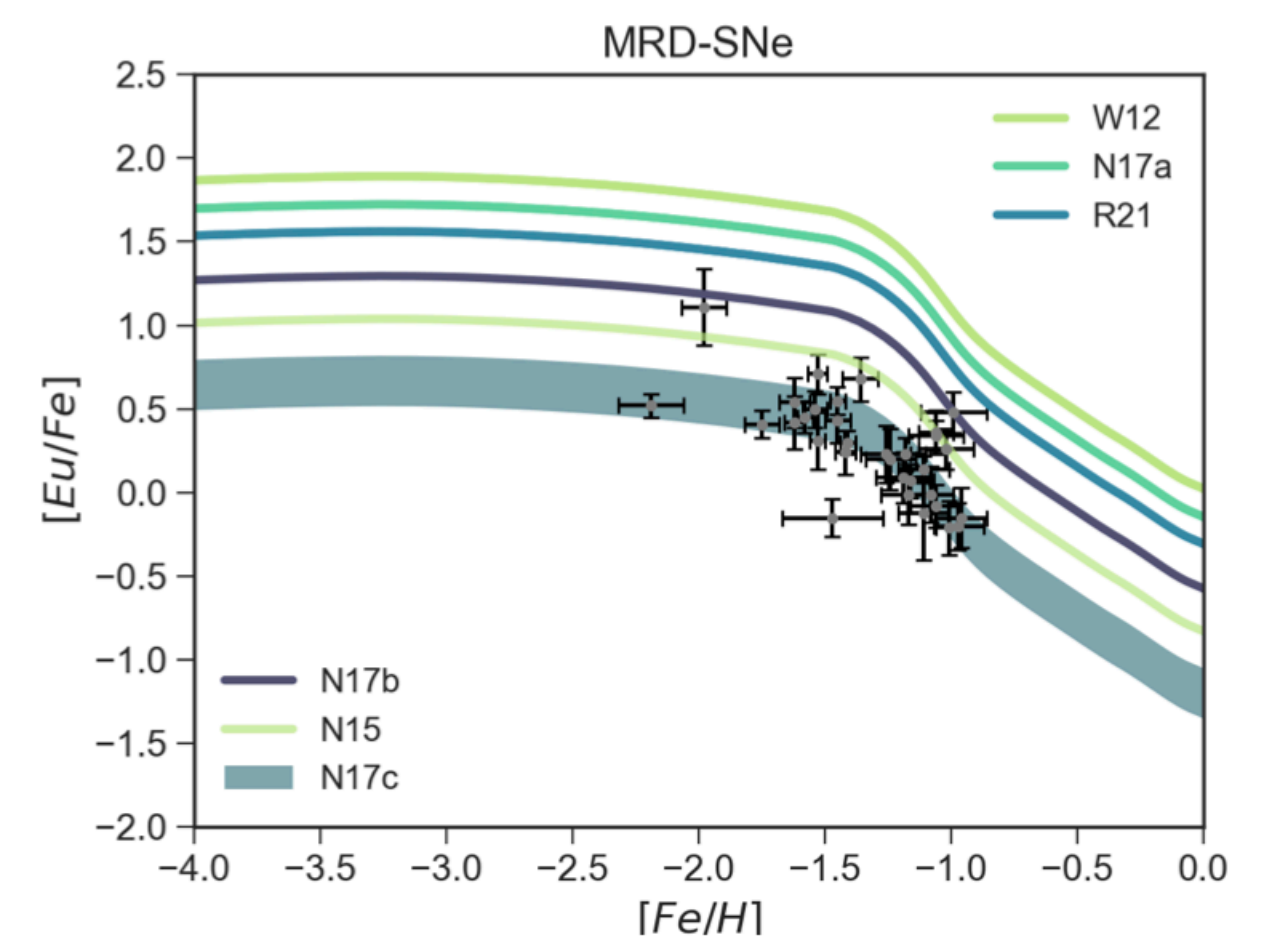
observational data: Reichert+20

Sculptor dSph - the [Eu/Fe] vs [Fe/H]

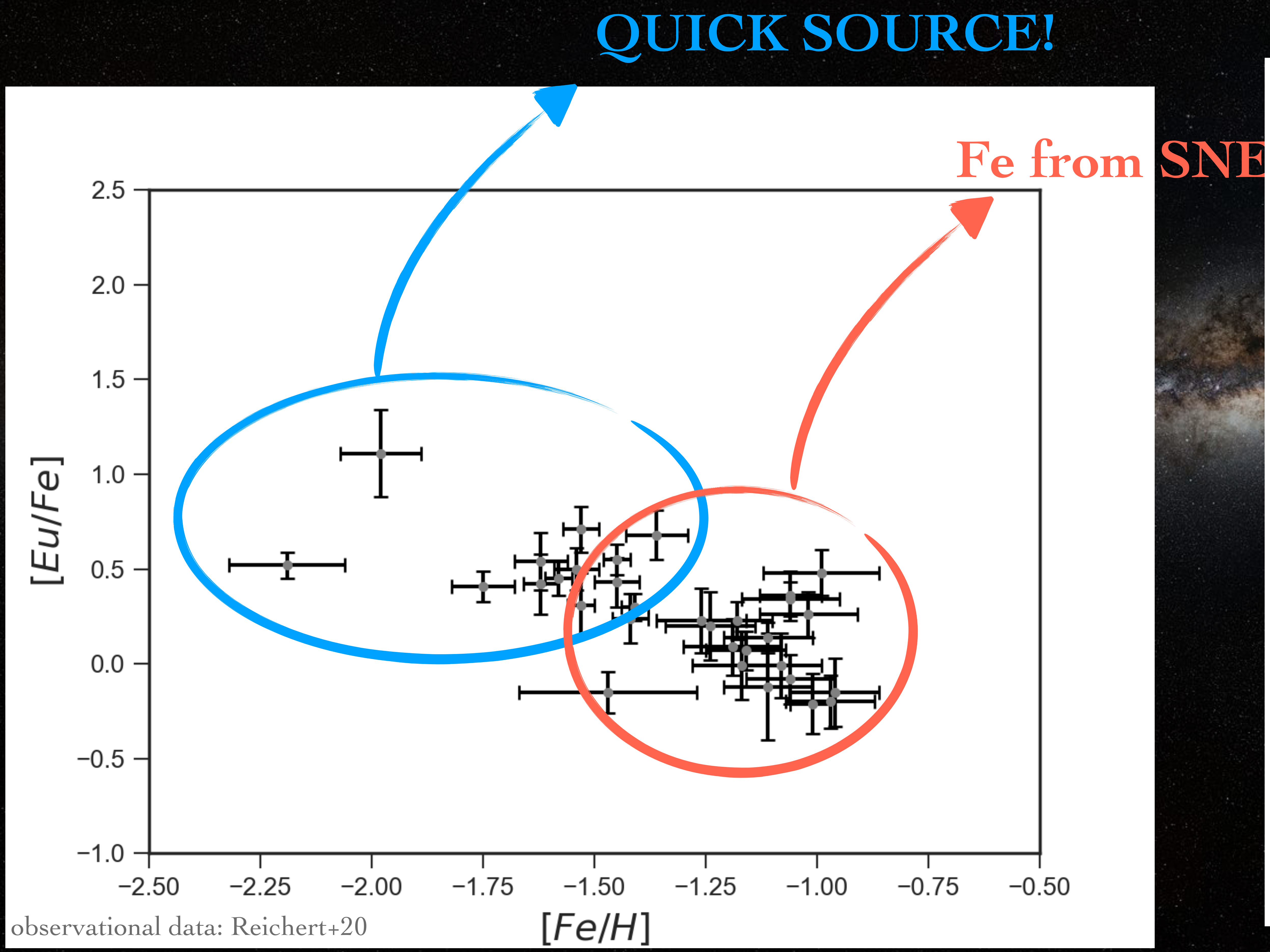


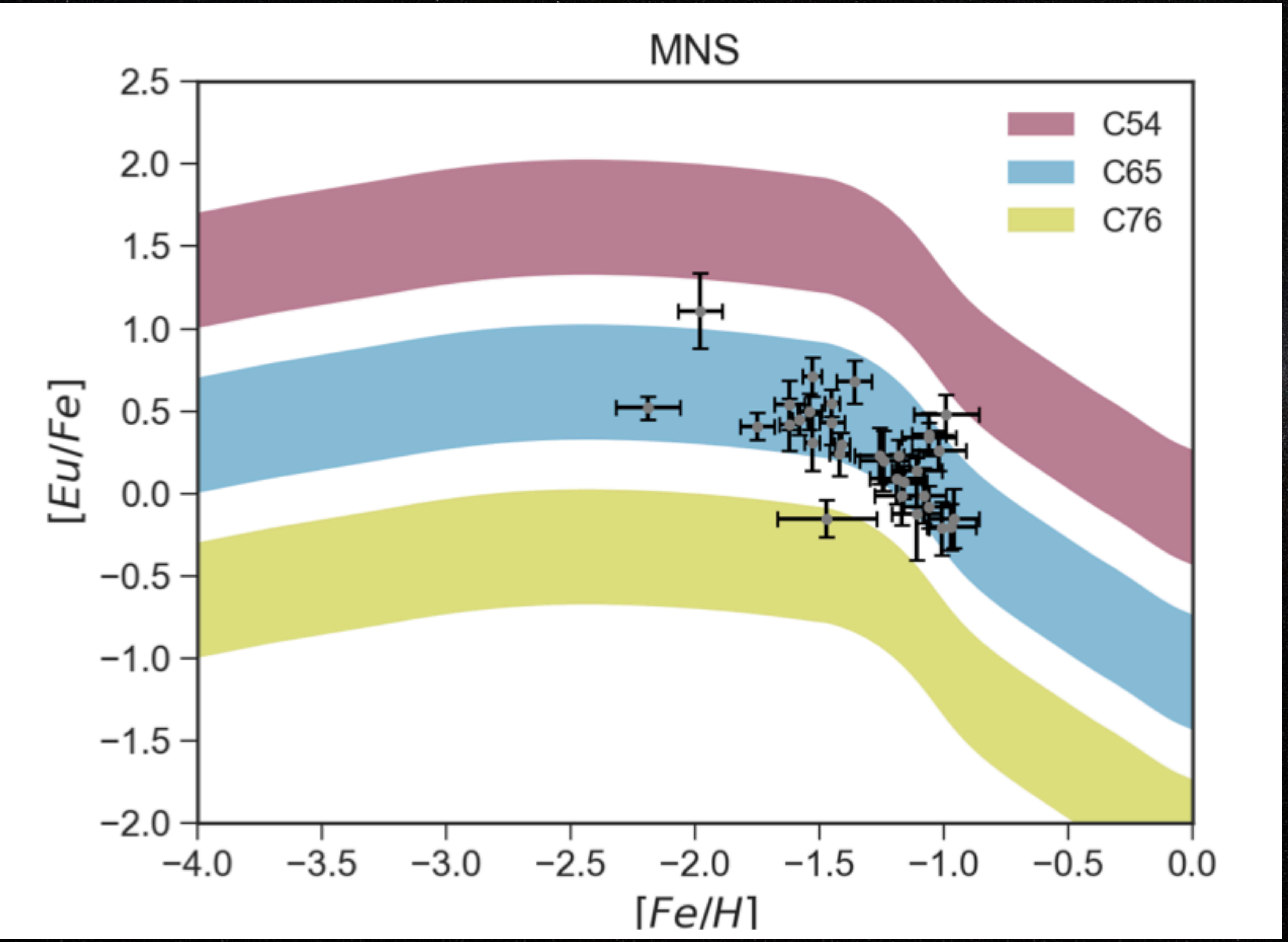
Sculptor dSph - the [Eu/Fe] vs [Fe/H]



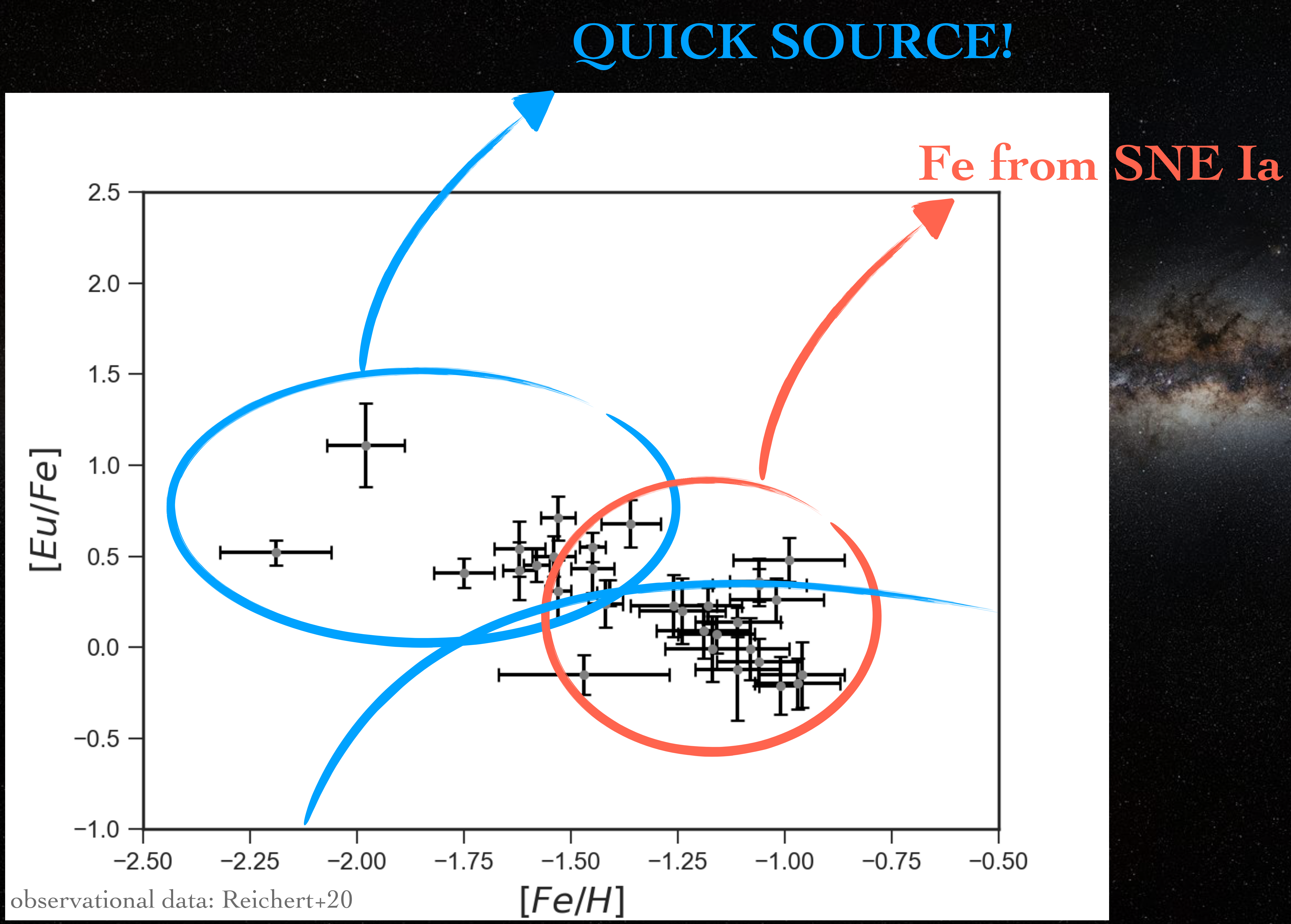


Sculptor dSph - the [Eu/Fe] vs [Fe/H]

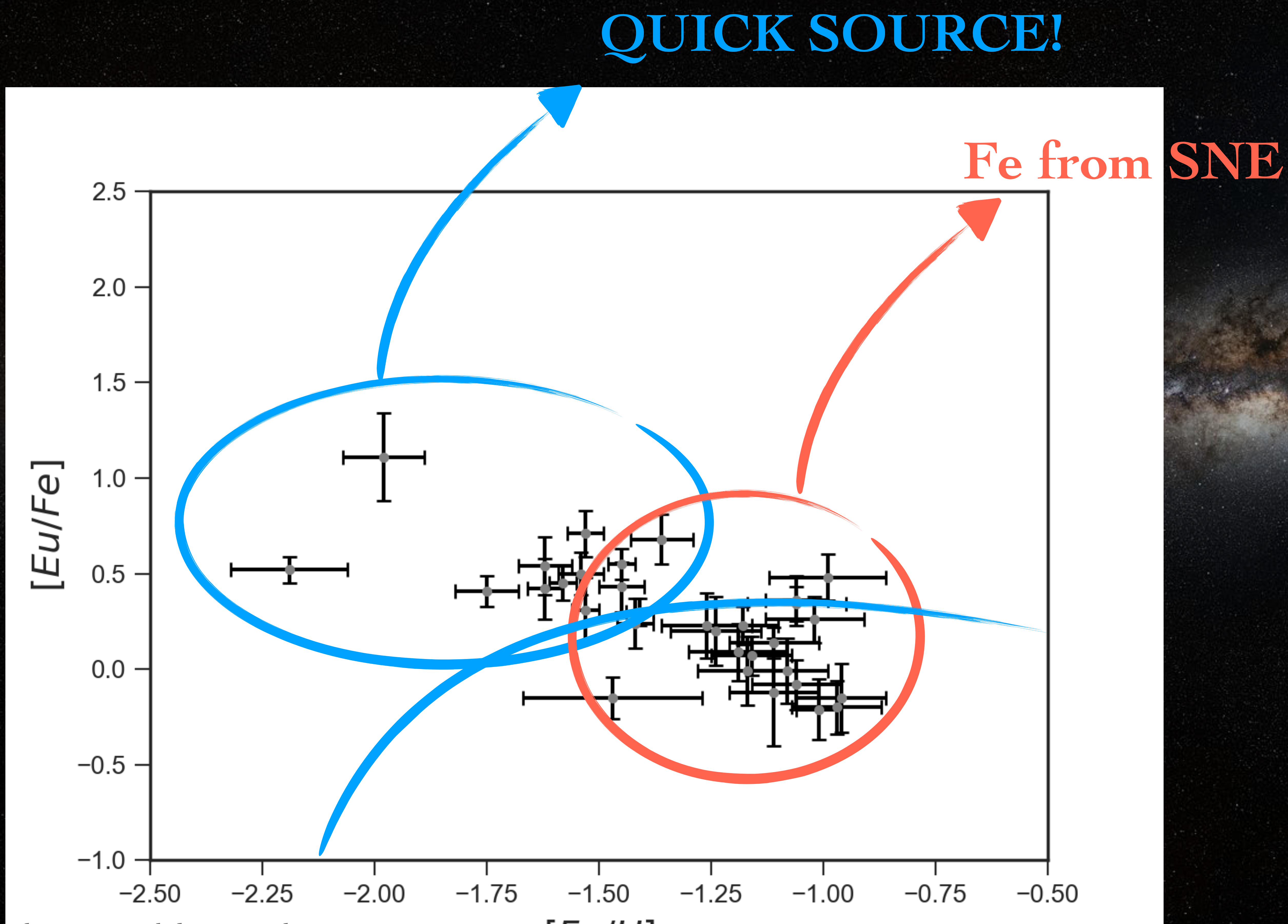




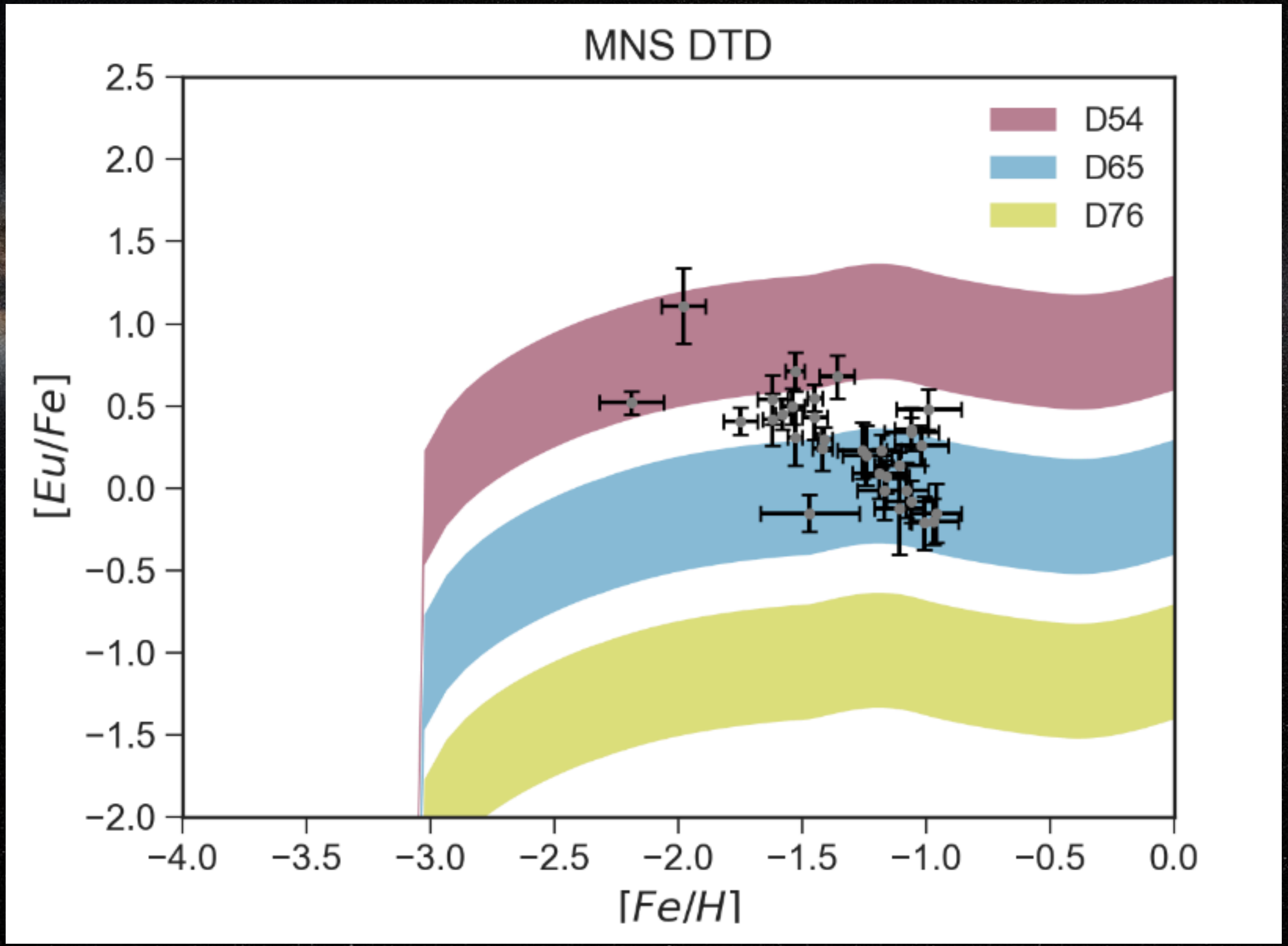
Sculptor dSph - the [Eu/Fe] vs [Fe/H]



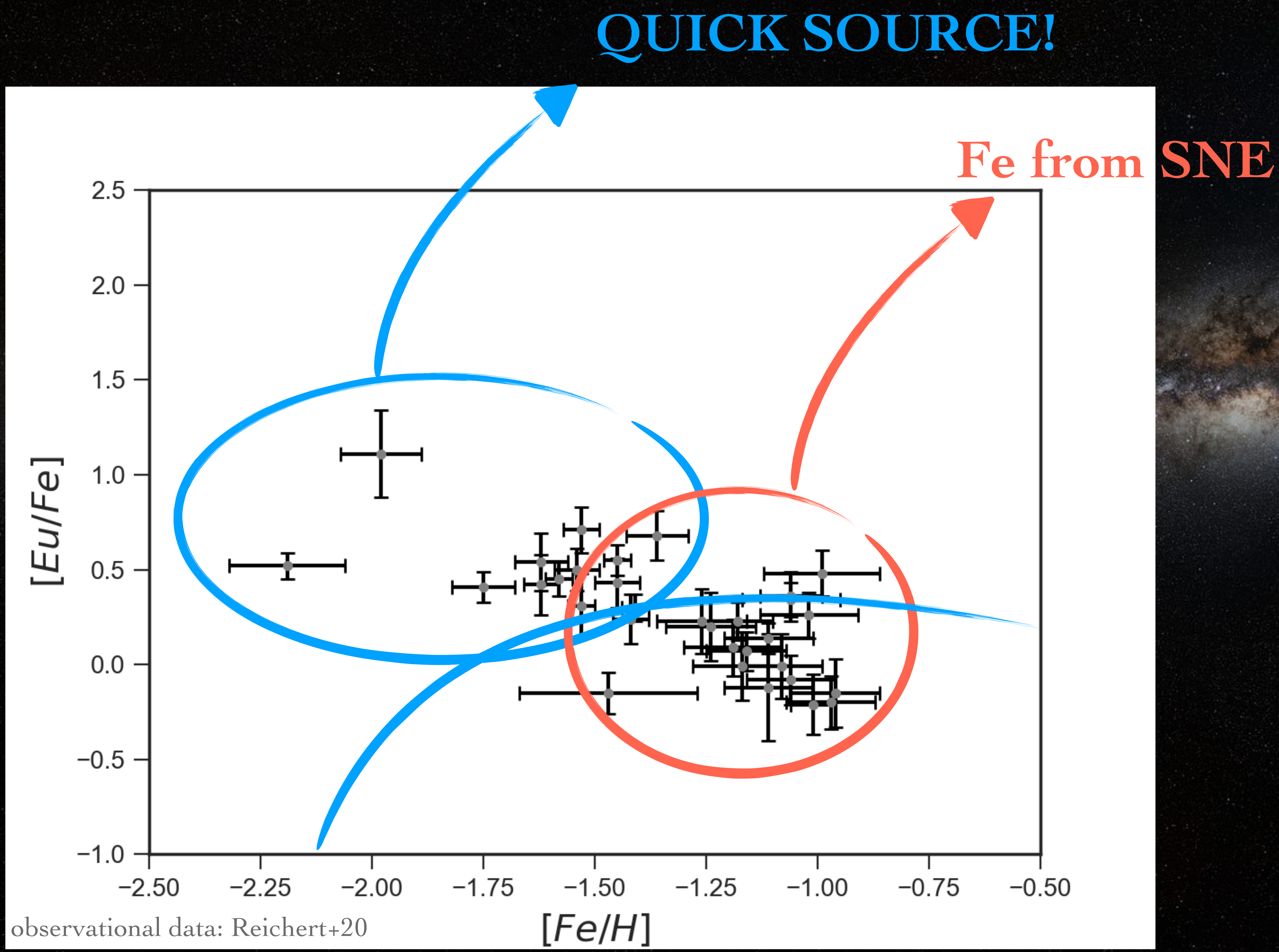
Sculptor dSph - the [Eu/Fe] vs [Fe/H]



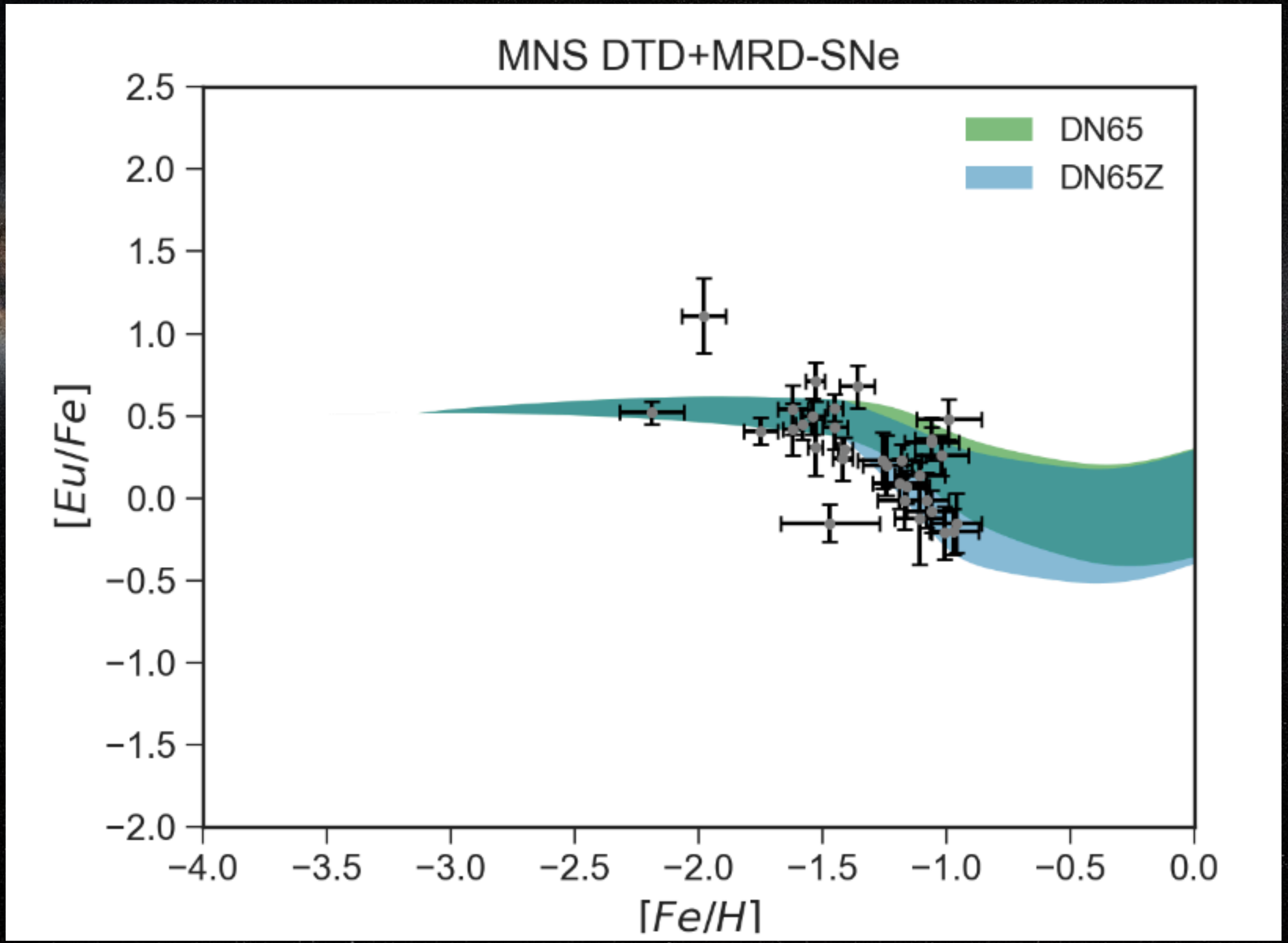
observational data: Reichert+20



Sculptor dSph - the [Eu/Fe] vs [Fe/H]



observational data: Reichert+20

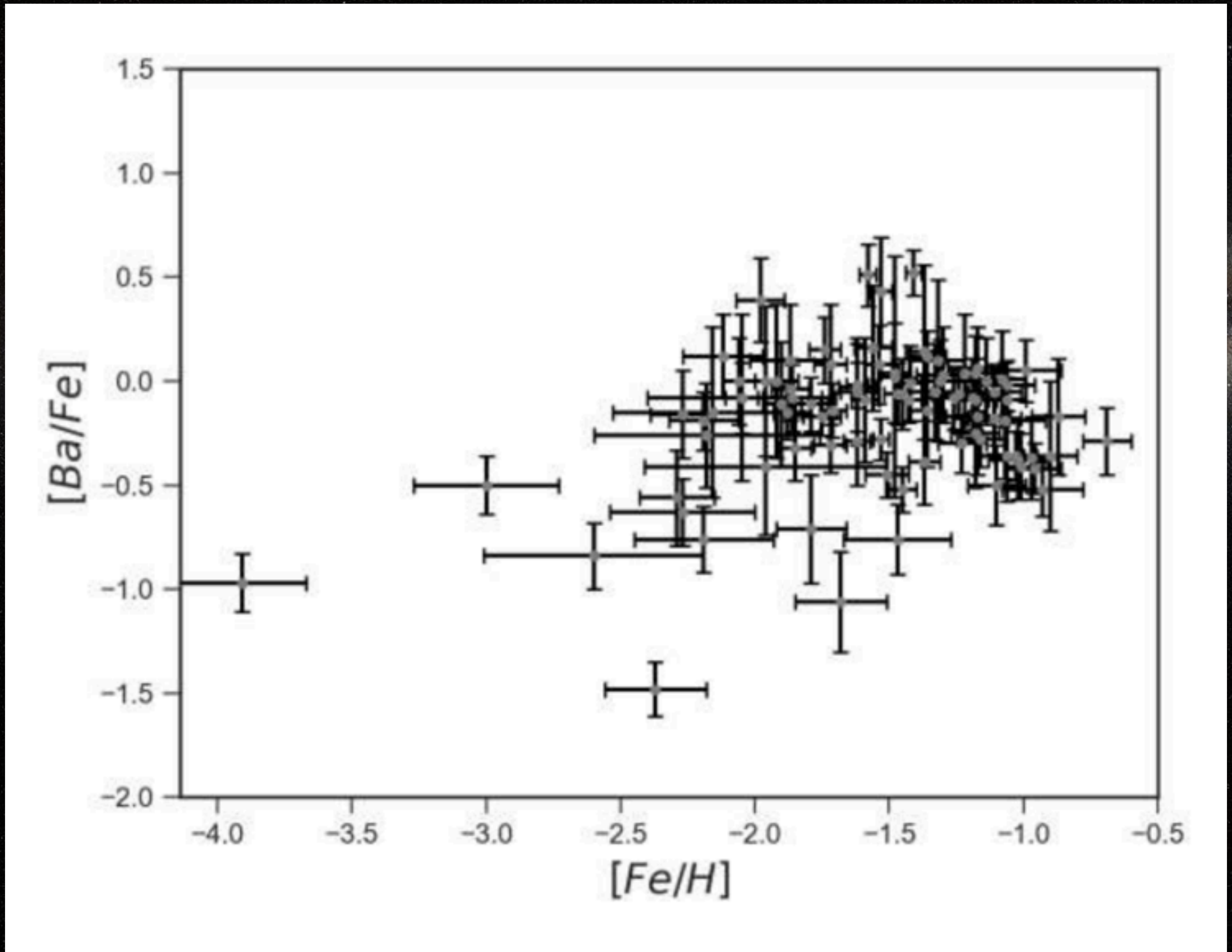


Conclusion

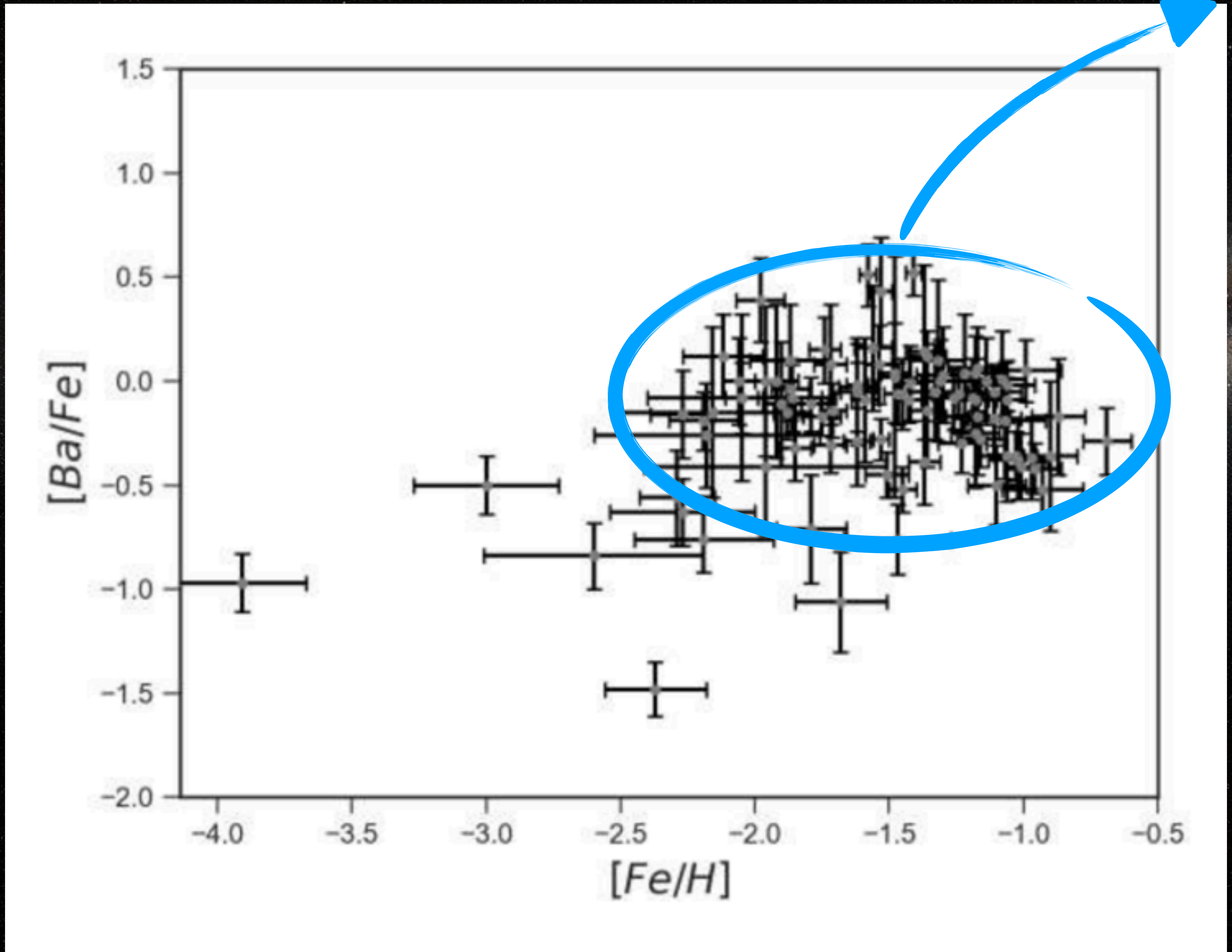
In order to reproduce the [Eu/Fe] vs [Fe/H] in dwarf galaxies we need Eu to be produced by both a quick source and a delayed one. In particular, the quick source can be represented by MRD-SNe and the delayed one can be represented by MNS with a DTD!

Matteucci et al. 2014, Simonetti et al. 2019, Cotè et al. 2019, Skùladòttir & Salvadori 2020, Molero et al. 2021, ..

Sculptor dSph - heavy elements

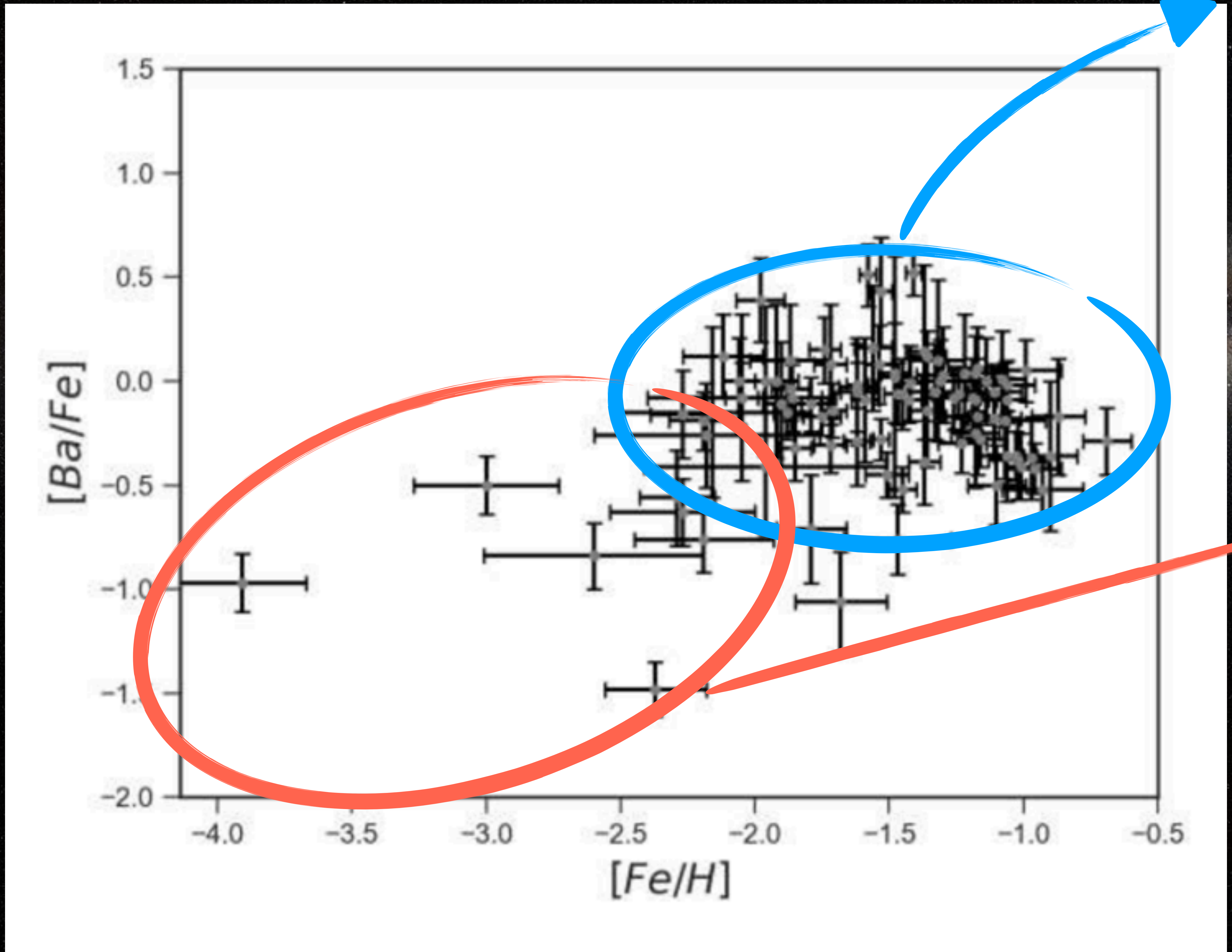


Sculptor dSph - heavy elements



LIMS: s-process component

Sculptor dSph - heavy elements

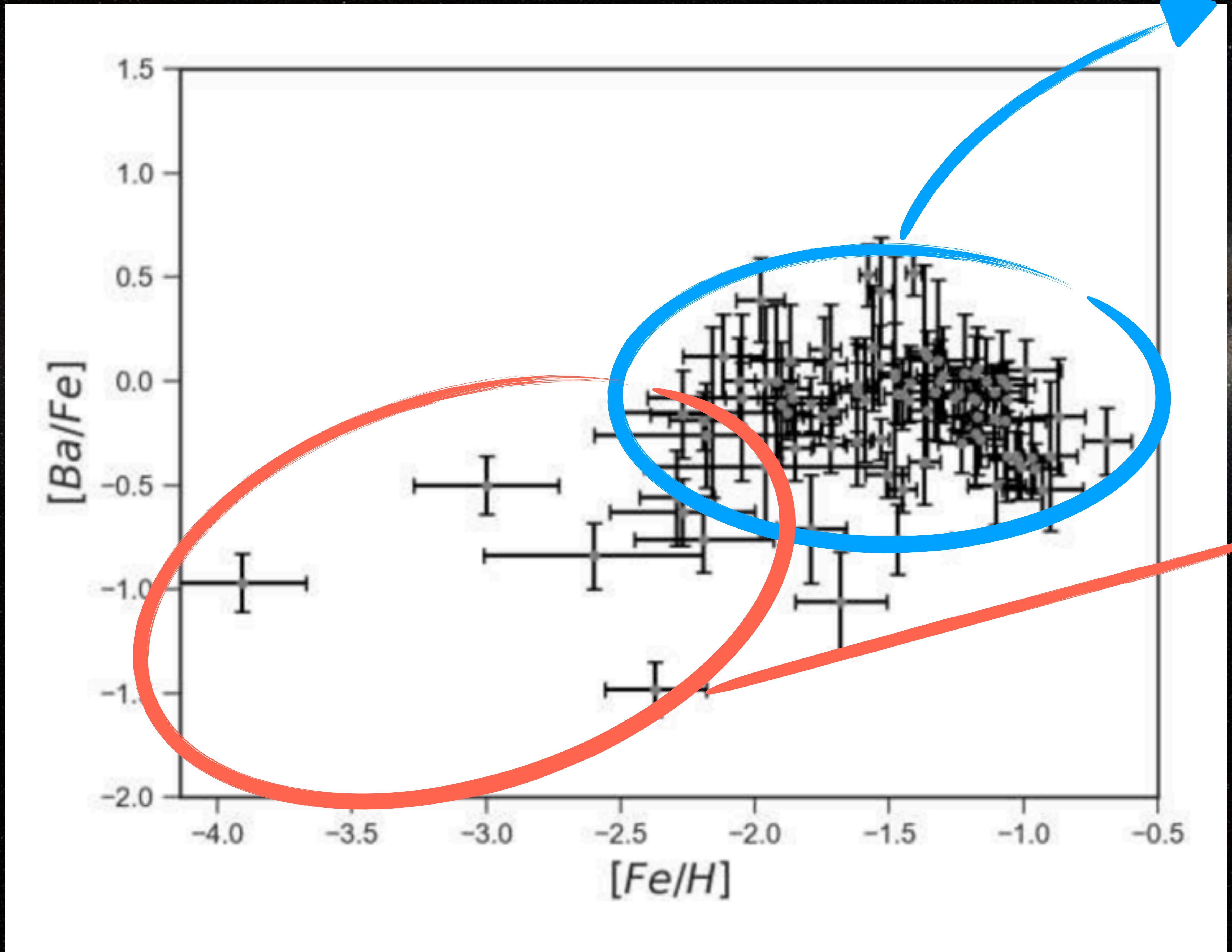


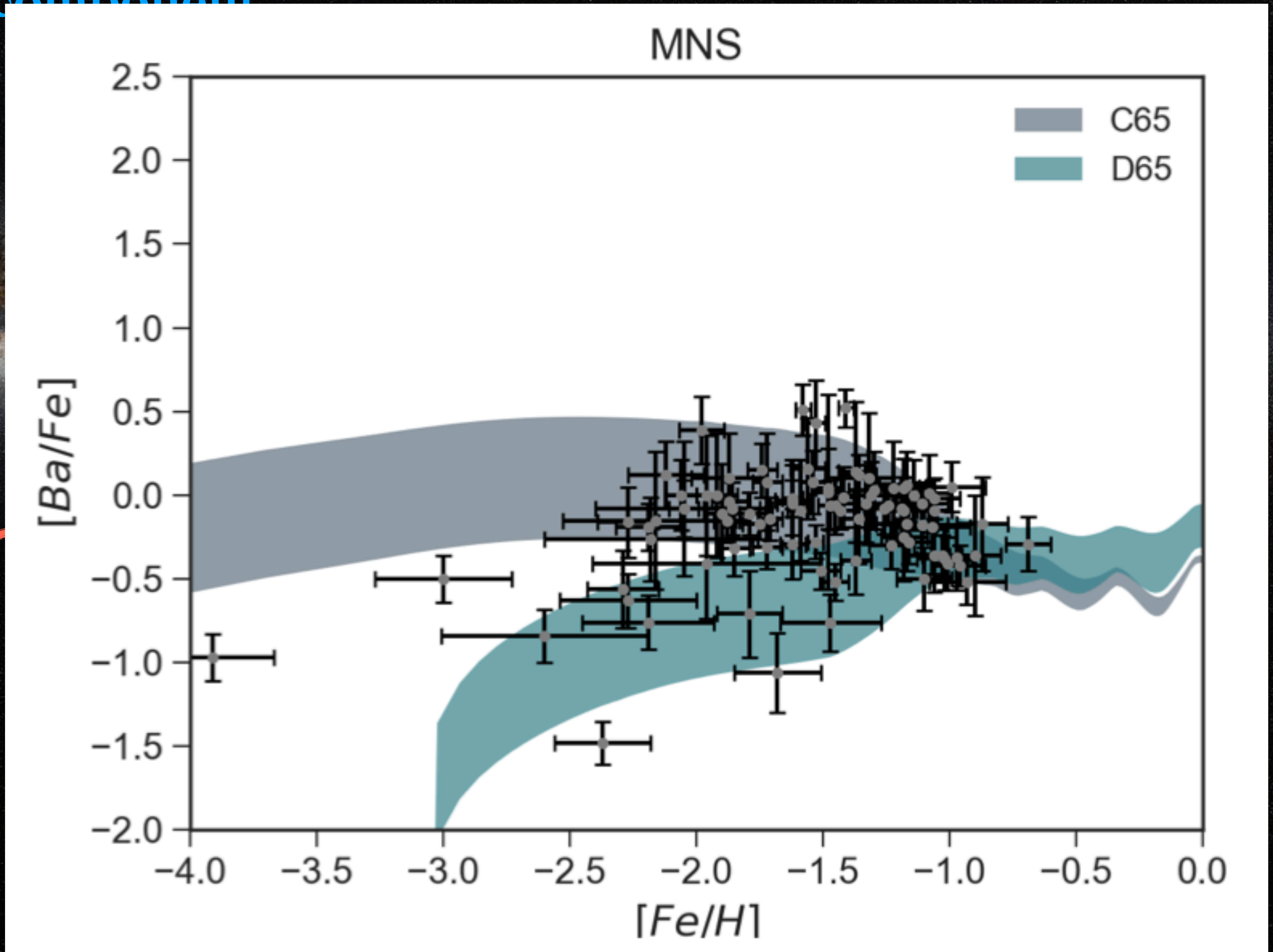
LIMS: s-process component

Delayed source: MNS with DTD?

Sculptor dSph - heavy elements

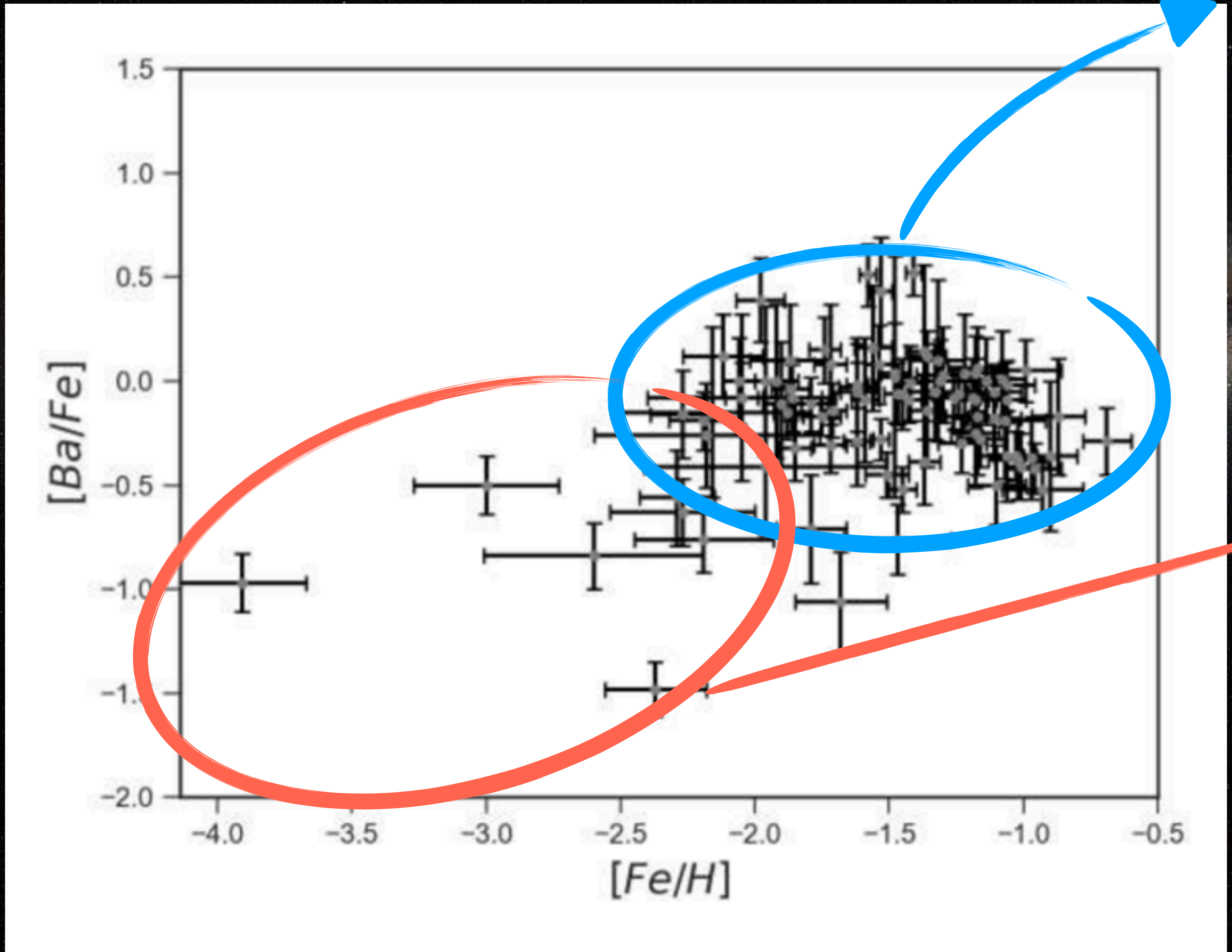
LIMS: s-process component

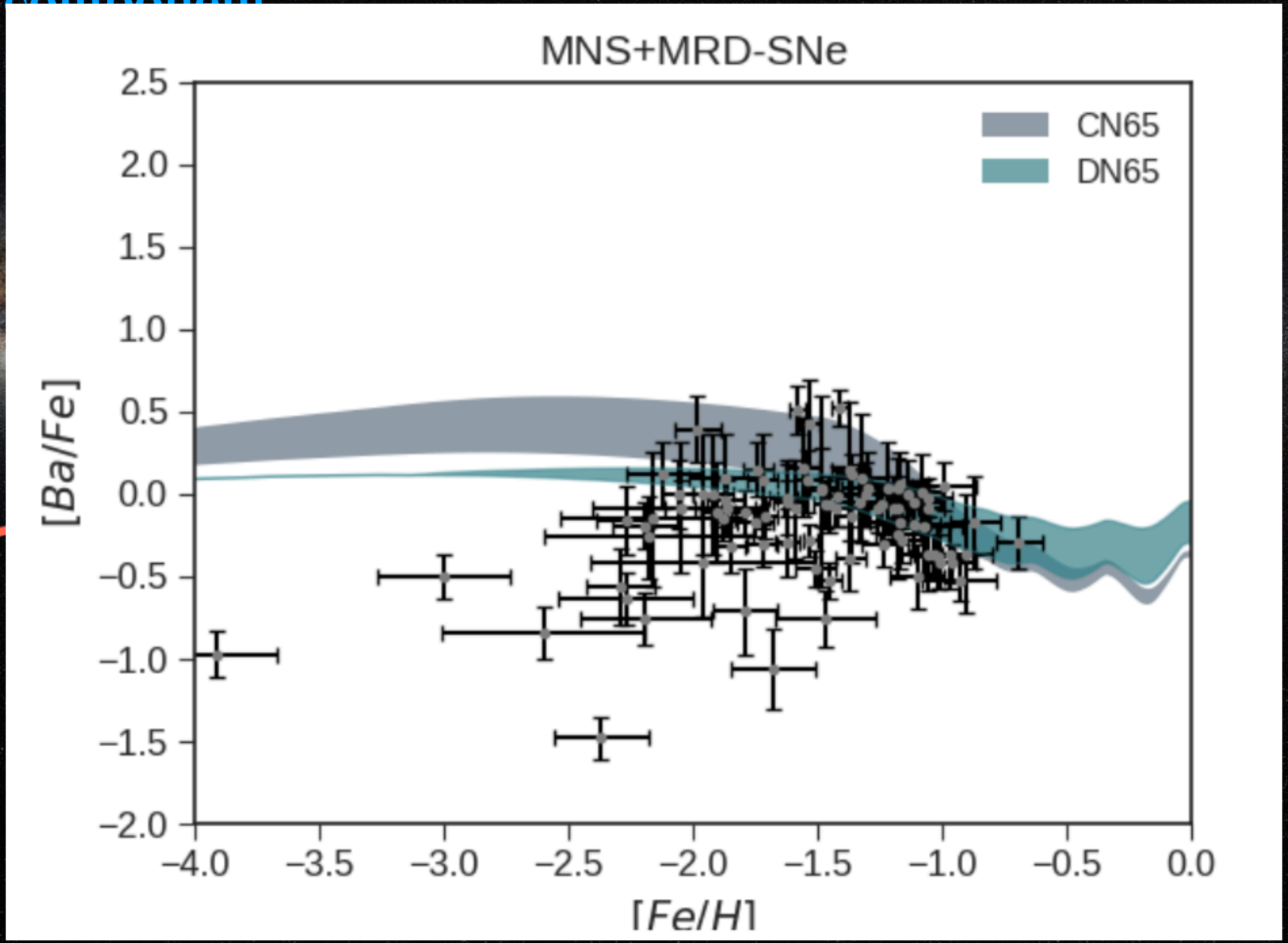




Sculptor dSph - heavy elements

LIMS: s-process component





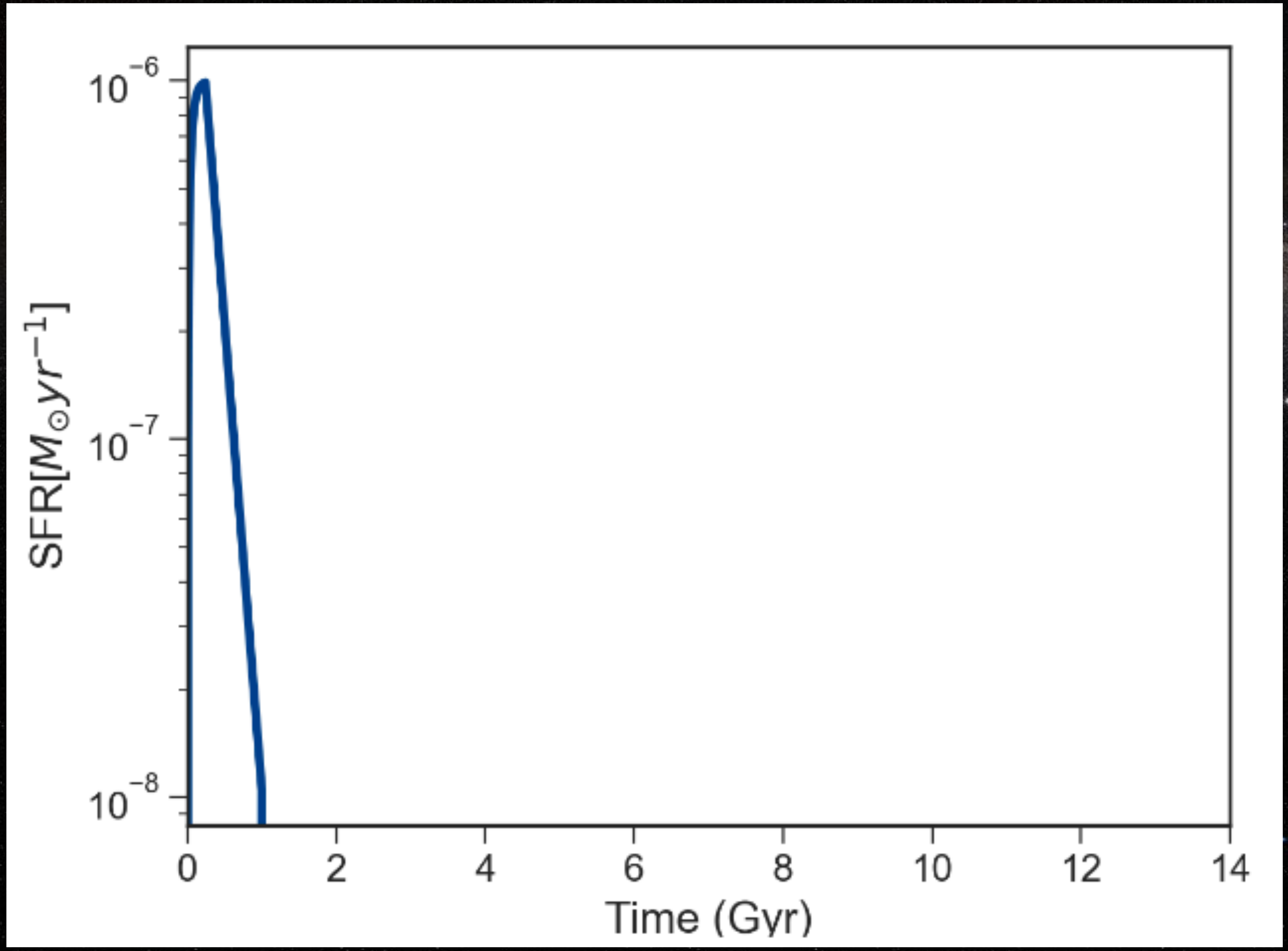
Conclusion

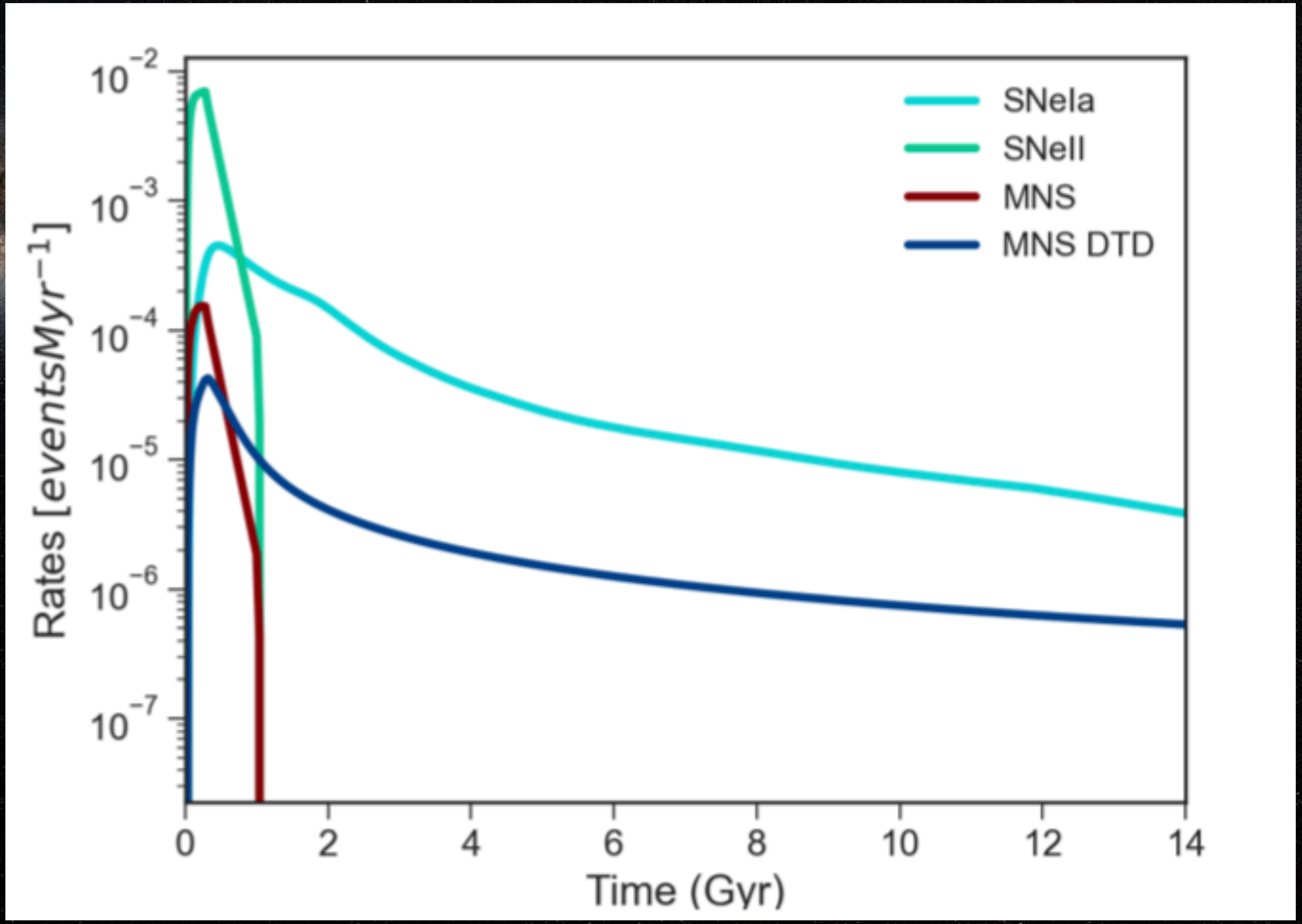
In order to reproduce the [Eu/Fe] vs [Fe/H] in dwarf galaxies we need Eu to be produced by both a quick source and a delayed one. In particular, the quick source can be represented by MRD-SNe and the delayed one can be represented by MNS with a DTD!

If both a quick source and a delayed one are adopted for the production of r-process elements, the [Eu/Fe] vs [Fe/H] is successfully reproduced. In particular, the quick source can be represented by MRD-SNe and the delayed one by MNS with a DTD. However, those model fails in reproducing the low-metallicity data of the [Ba/Fe] vs [Fe/H].

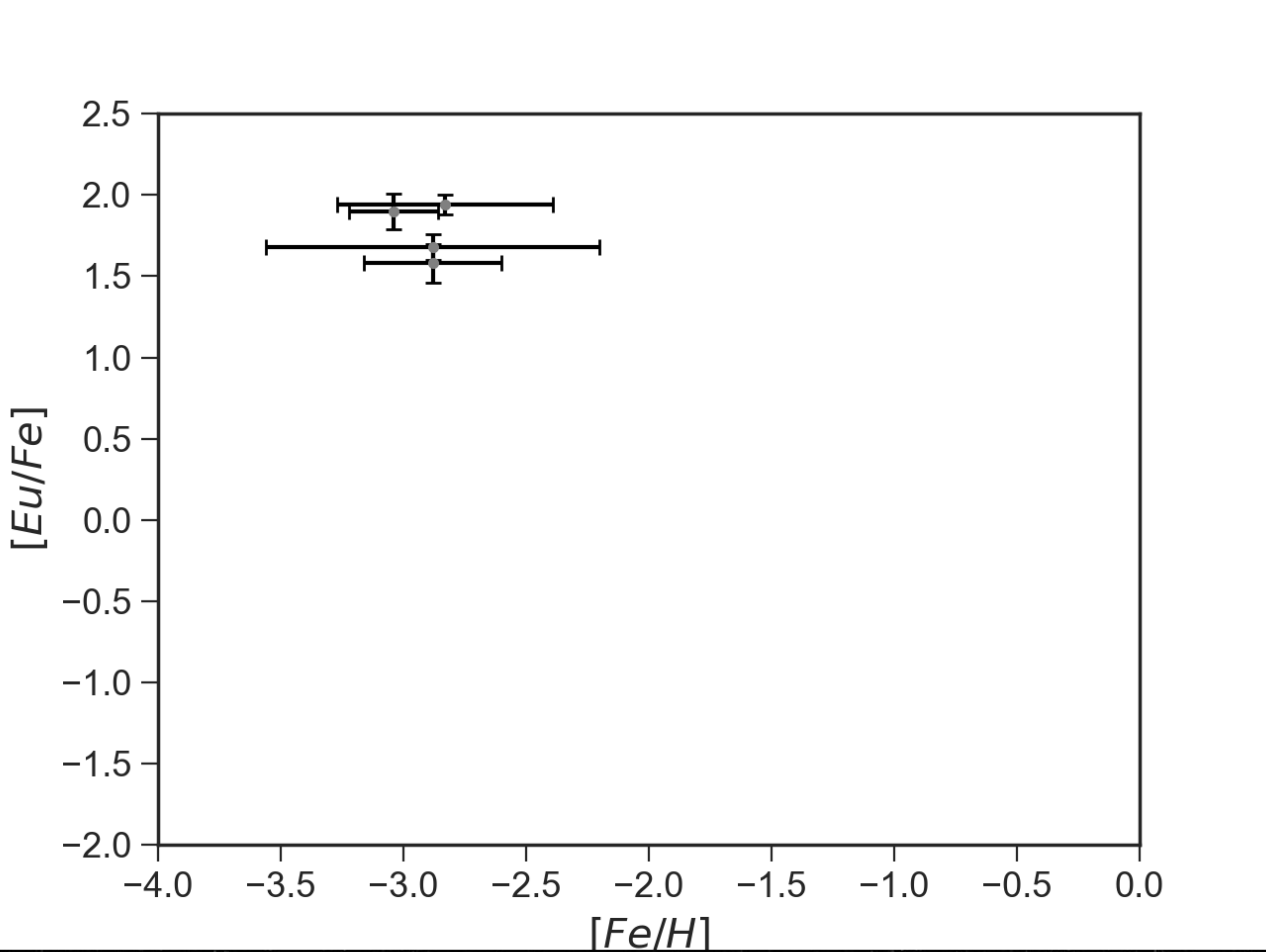
Reticulum II UFD

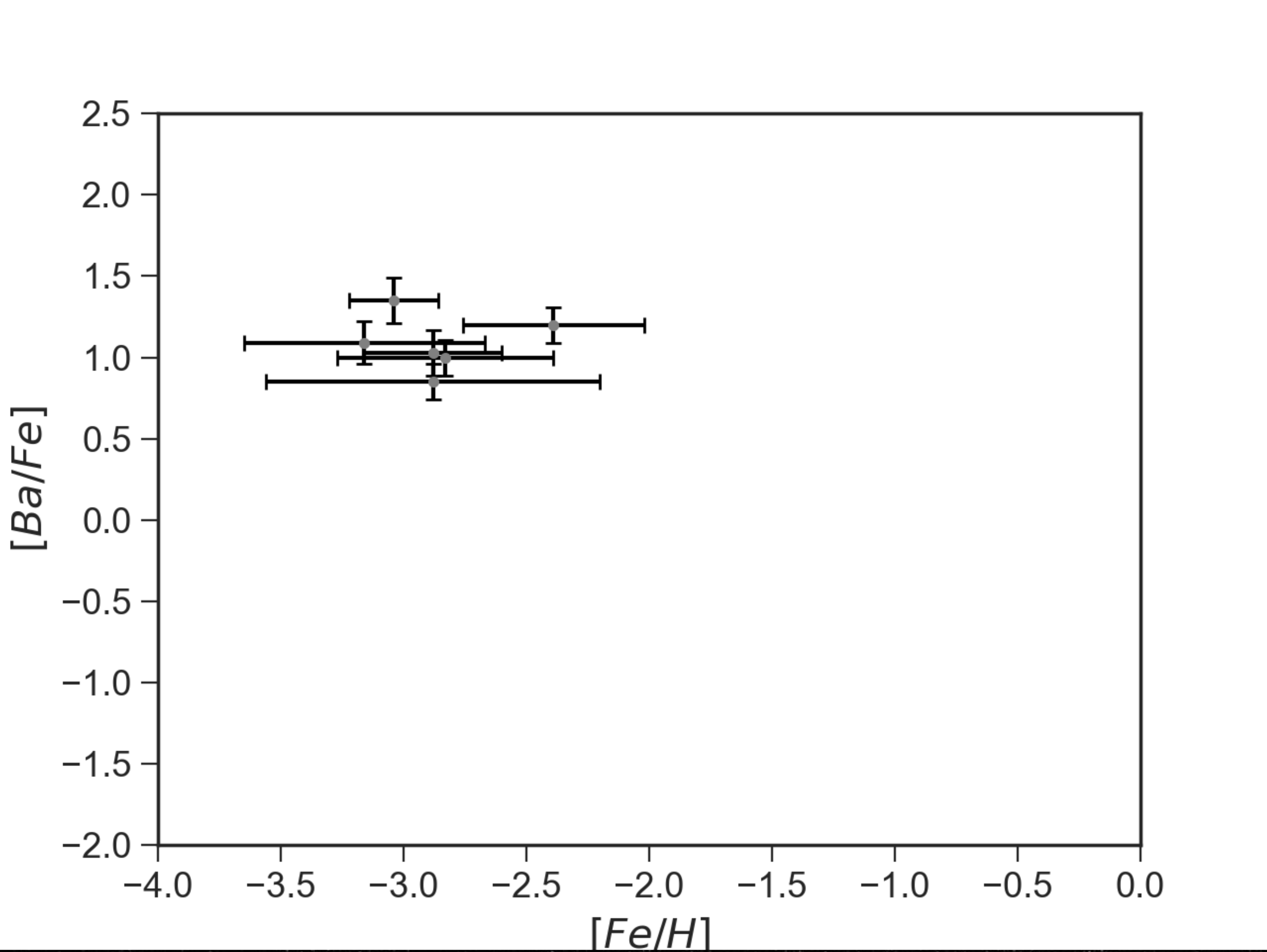
$M = 10^3\ M_\odot$





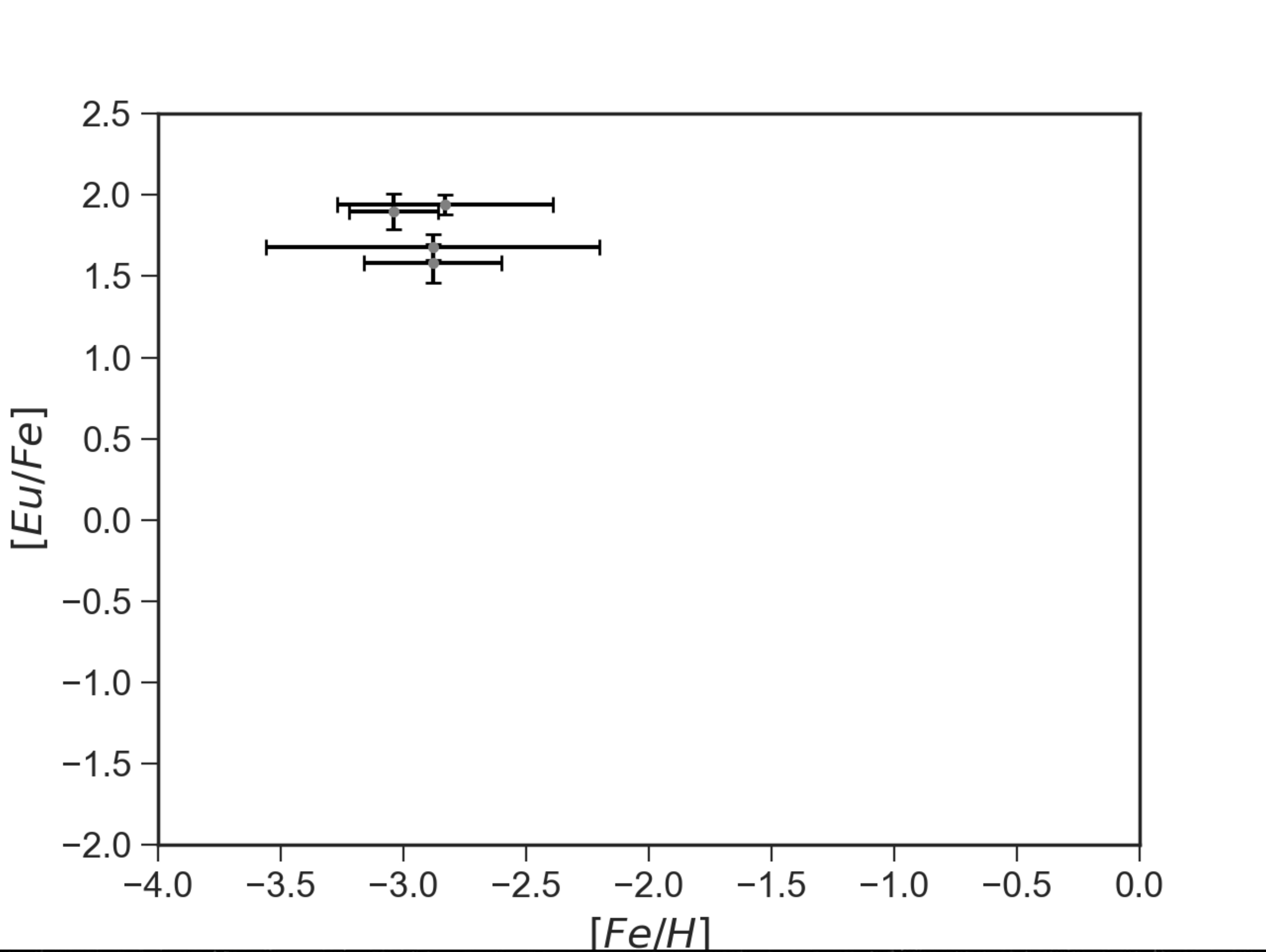
Reticulum II UFD

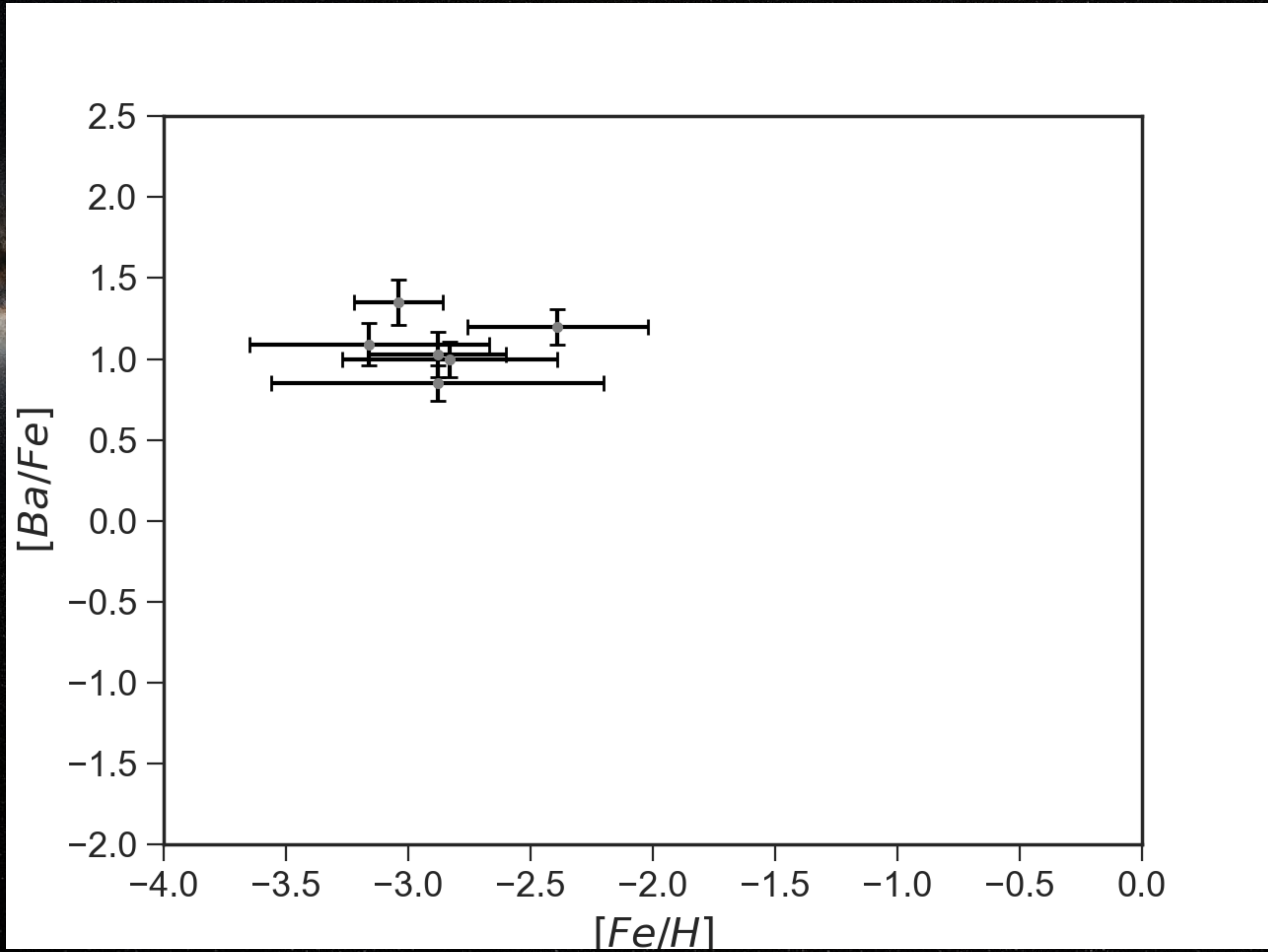




Reticulum II UFD

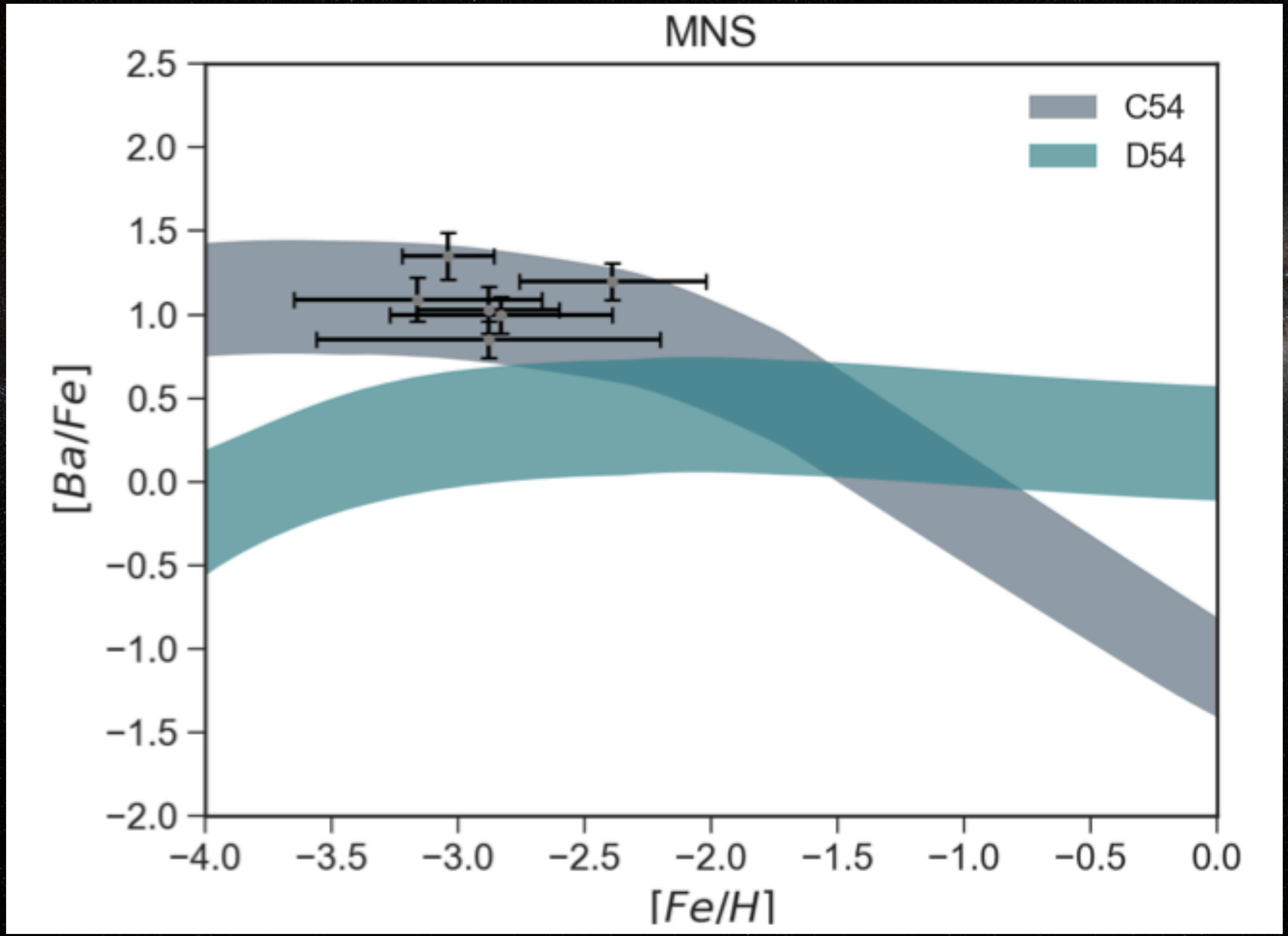
QUICK SOURCE!

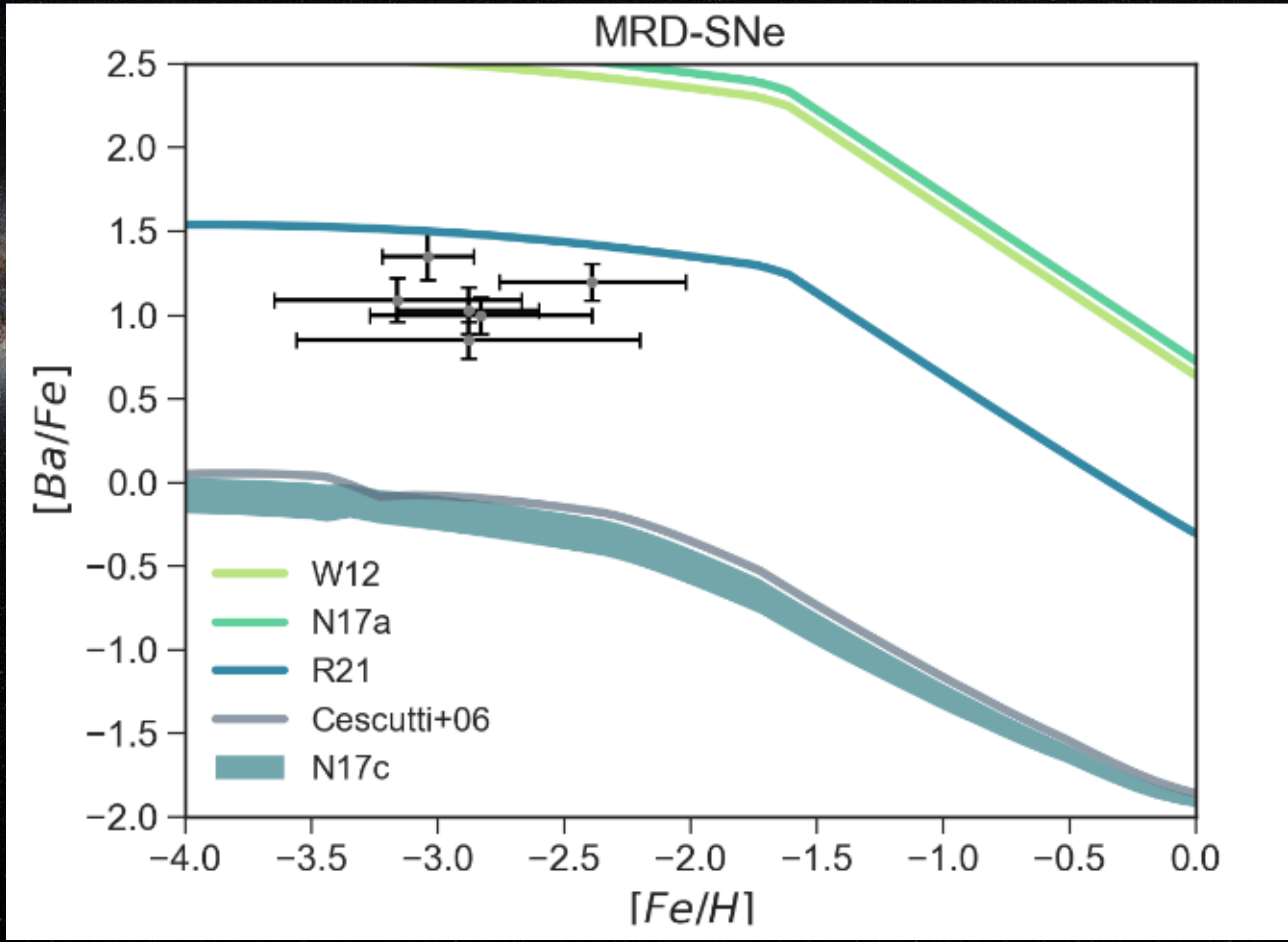




Reticulum II UFD

Reticulum II UFD





Conclusion

A quick source for the production of both Eu and r-process Ba is needed in order to reproduce both the [Eu/Fe] and the [Ba/Fe] vs [Fe/H]. This quick source can be represented either by MNS with a short and constant delay time for merging or by MRD-SNe. However, yields must be 1-2 order of magnitude higher than those estimated for the other galaxies!

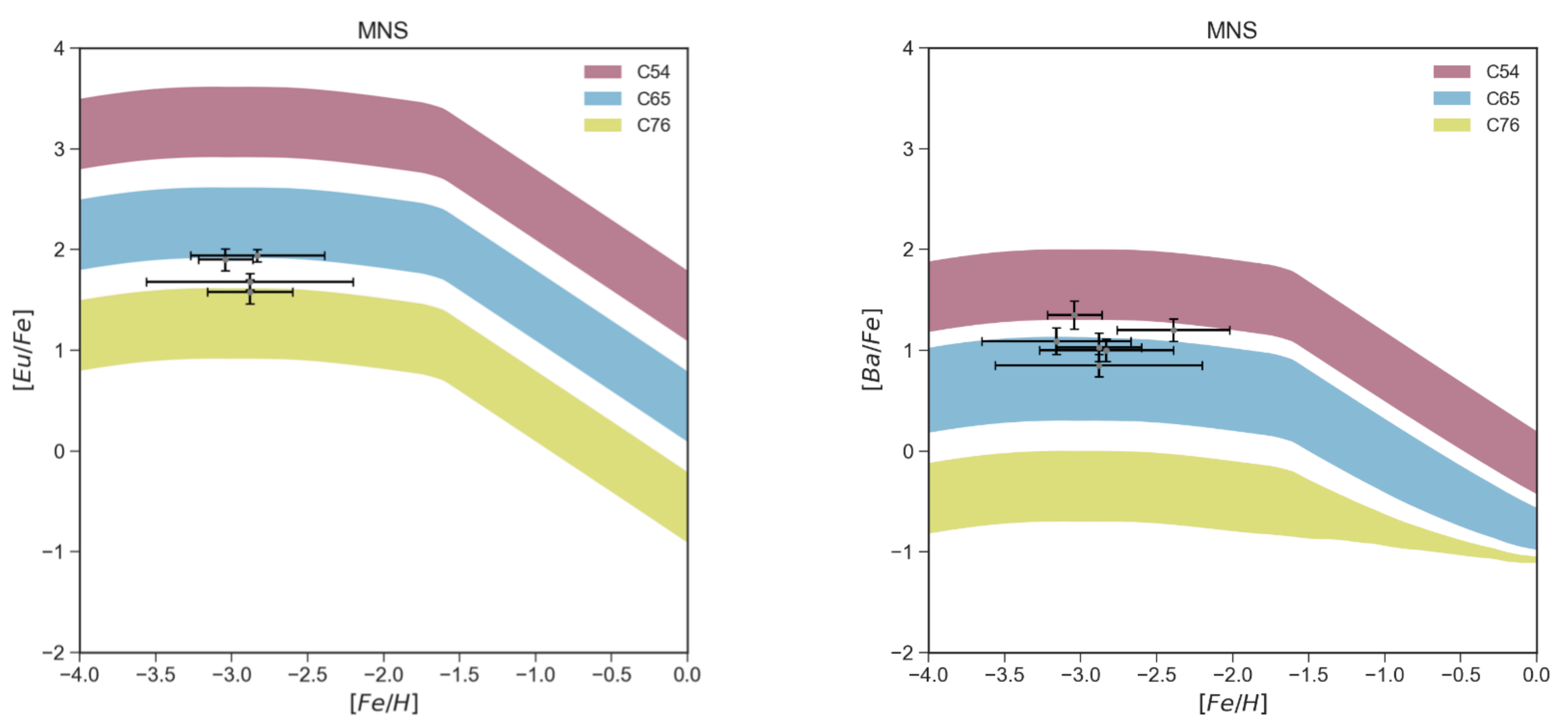
$$10^{-5} - 10^{-4}\ M_{\odot}$$

In agreement with Ji et al. 2016

But… How it is possible that the same nucleosynthetic event produces different amounts of r-process material in different environments?

But… How it is possible that the same nucleosynthetic event produces different amounts of r-process material in different environments?

If we force the rate of MNS to be equal to 1 in the first Gyr:



Conclusion

If we force the rate of MNS to be equal to 1, we can adopt much more realistic yields of Eu/Ba similar to those adopted for the other dSphs/UFDs. In order to obtain such a rate we had to set $\alpha_{MNS} = 1$, namely we had to assume a probability of 100% of having a MNS event.

Discussion

- We modelled the chemical evolution of 7 dSph and 2 UFD galaxies and adopted new nucleosynthesis prescriptions for the production of Eu and the r-process Ba produced in MNS and tested different prescriptions for MRD-SNe r-process elements
- A possible scenario is one in which NS merge with a DTD and produce Eu with MRD-SNe:

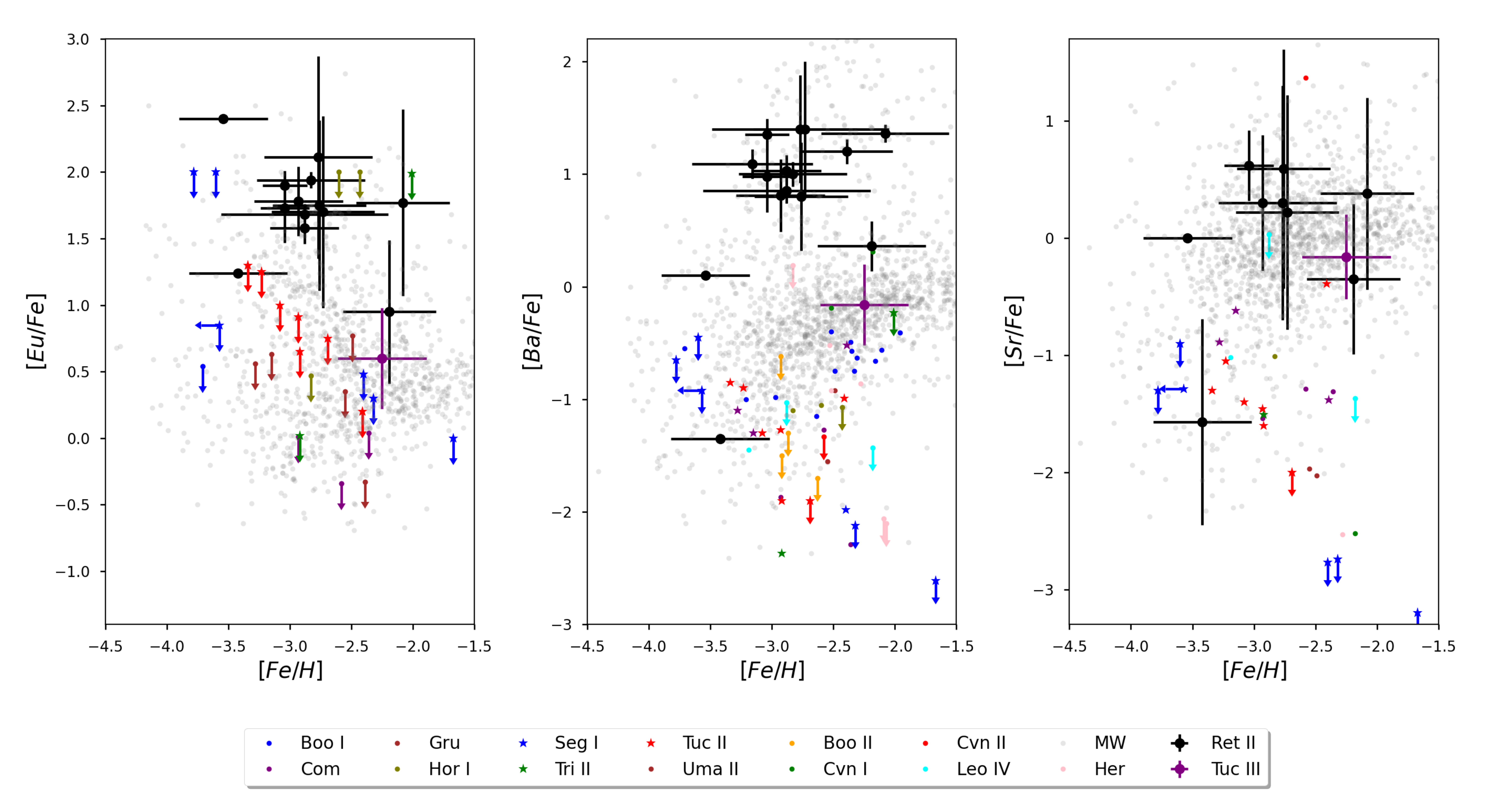
[Eu/Fe] vs. [Fe/H] ✓ [Ba/Fe] vs. [Fe/H] ✗

- [Ba/Fe] can be reproduced if only MNS with a DTD are producing the r-process fraction of Ba, if also MRD-SNe partecipate to this process the agreement is lost.
- A second source for the production of the "weak" s-process fraction could be included, such as rotating massive stars (Cescutti+13, Cescutti&Chiappini+14, Cescutti+15, Rizzuti+21).

Discussion

- Conclusions for Reticulum II are different from those for the other galaxies, because of its peculiar r-/s- process elements pattern.
- A scenario which well reproduces the Eu and Ba is the one in which a quick source pollutes the ISM really fast and with large amount of r-process elements, larger than that adopted for the other galaxies.
- The assumption that the same nucleosynthesis events produce different total amount of r-process material in different environments need further discussion.
- If we force the rate of MNS to be equal to 1 in the first Gyr of SF in Reticulum II then we can adopt a more realist r-process yield, similar to that adopted for the other systems.
- In order to do that however we have to assume a probability of 100% of having a MNS event.

More investigations..



Thank you for the attention!