Near pristine DLAs: A window to the first stars

Enigmatic first stars and where to find them!

Louise Welsh

17th May 2023

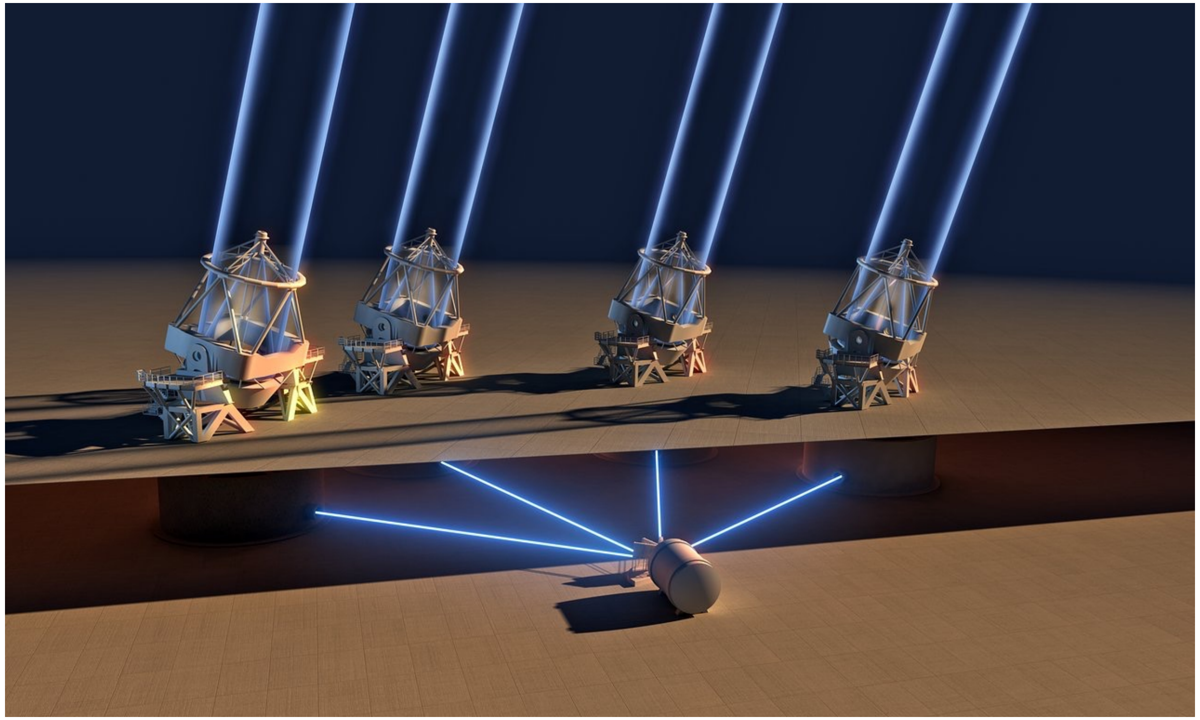

Image credit: ESO

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

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Detecting the first elements

- The chemical fingerprints of the first stars are believed to be encoded in the ***most* metal-poor** environments in the Universe.

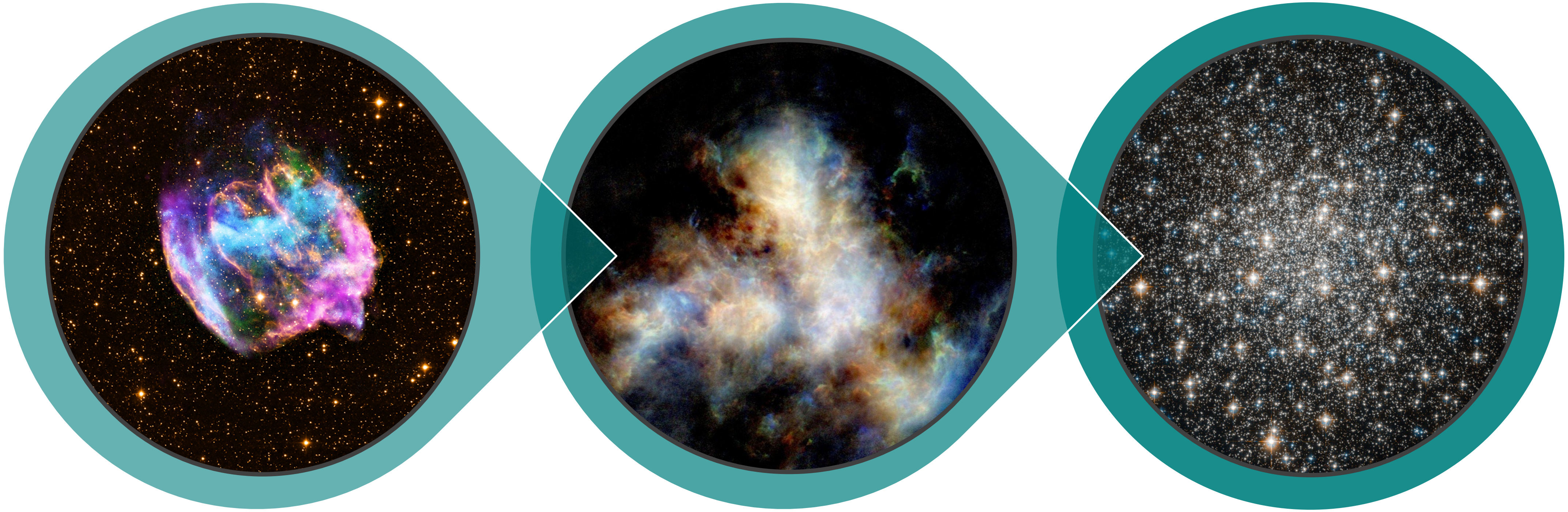
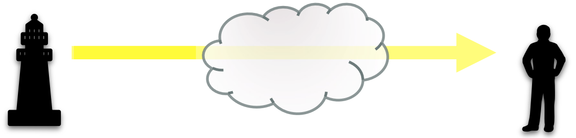


Image credit: X-ray: NASA/CXC/MIT/L.Lopez et al.; Infrared: Palomar; Radio: NSF/NRAO/VLA

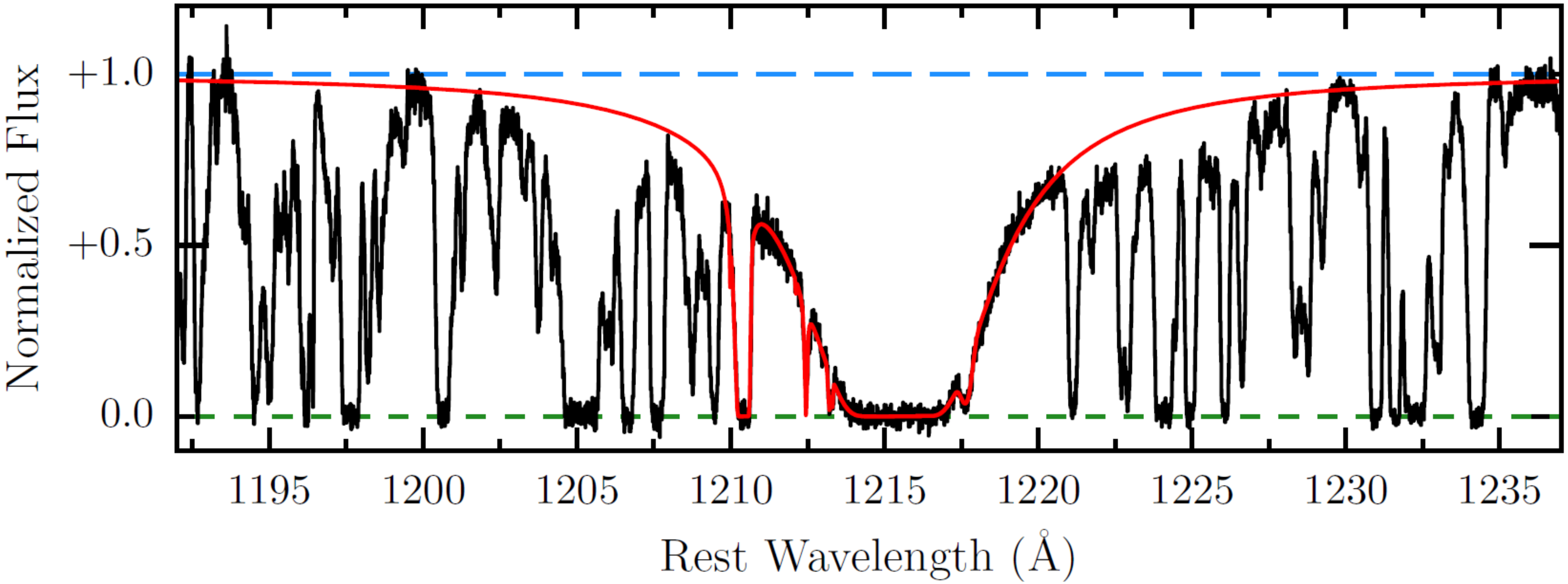
Image credit: Naomi McClure-Griffiths et al., CSIRO's ASKAP telescope

Image credit: ESA/NASA

Damped Lyman Alpha systems (DLAs)

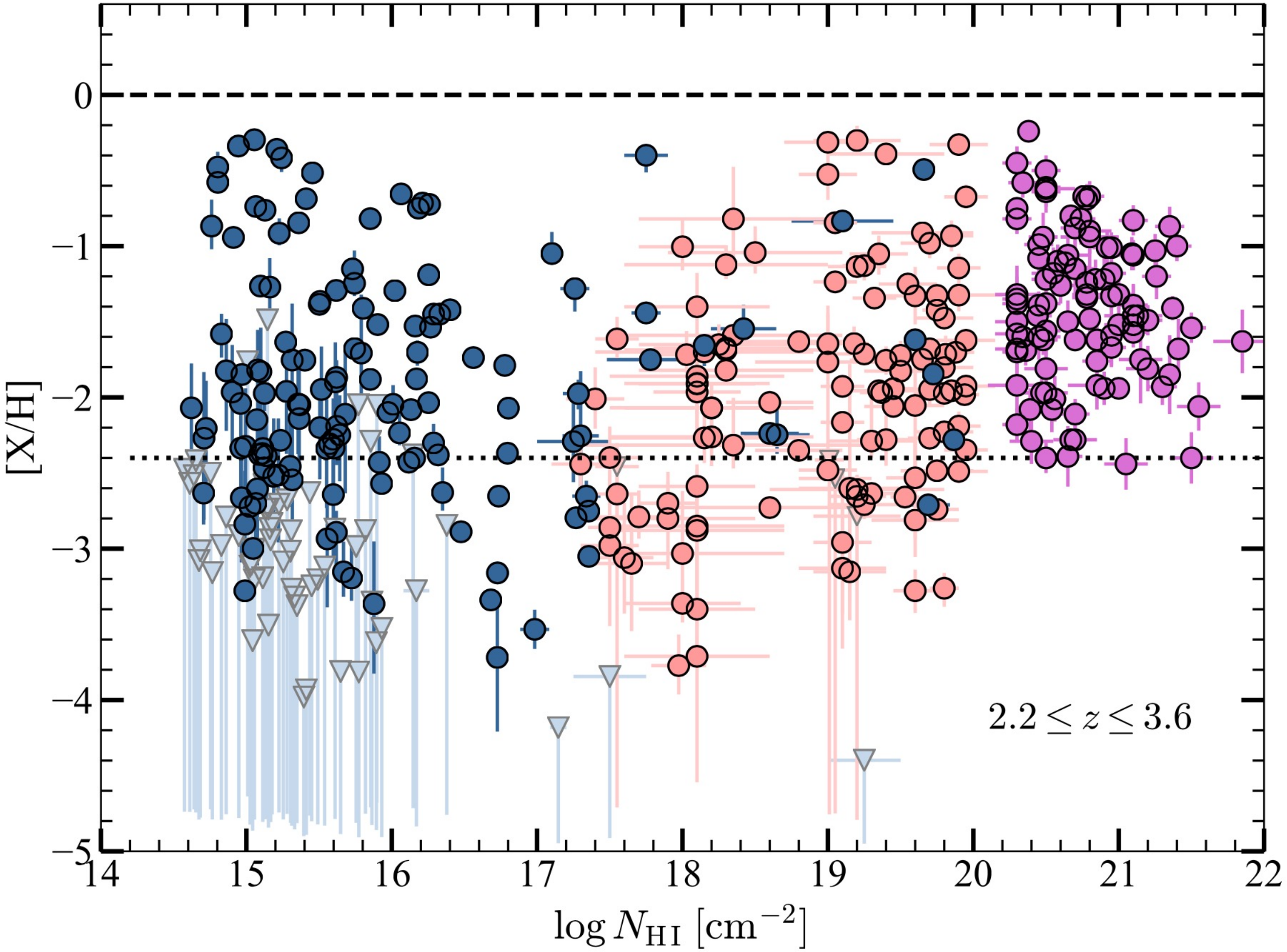


- Clouds of mostly neutral gas found along the line-of-sight towards unrelated background quasar. Characterised by $\log_{10} N(HI) / cm^{-2} > 20.3$



Metallicity at different column densities

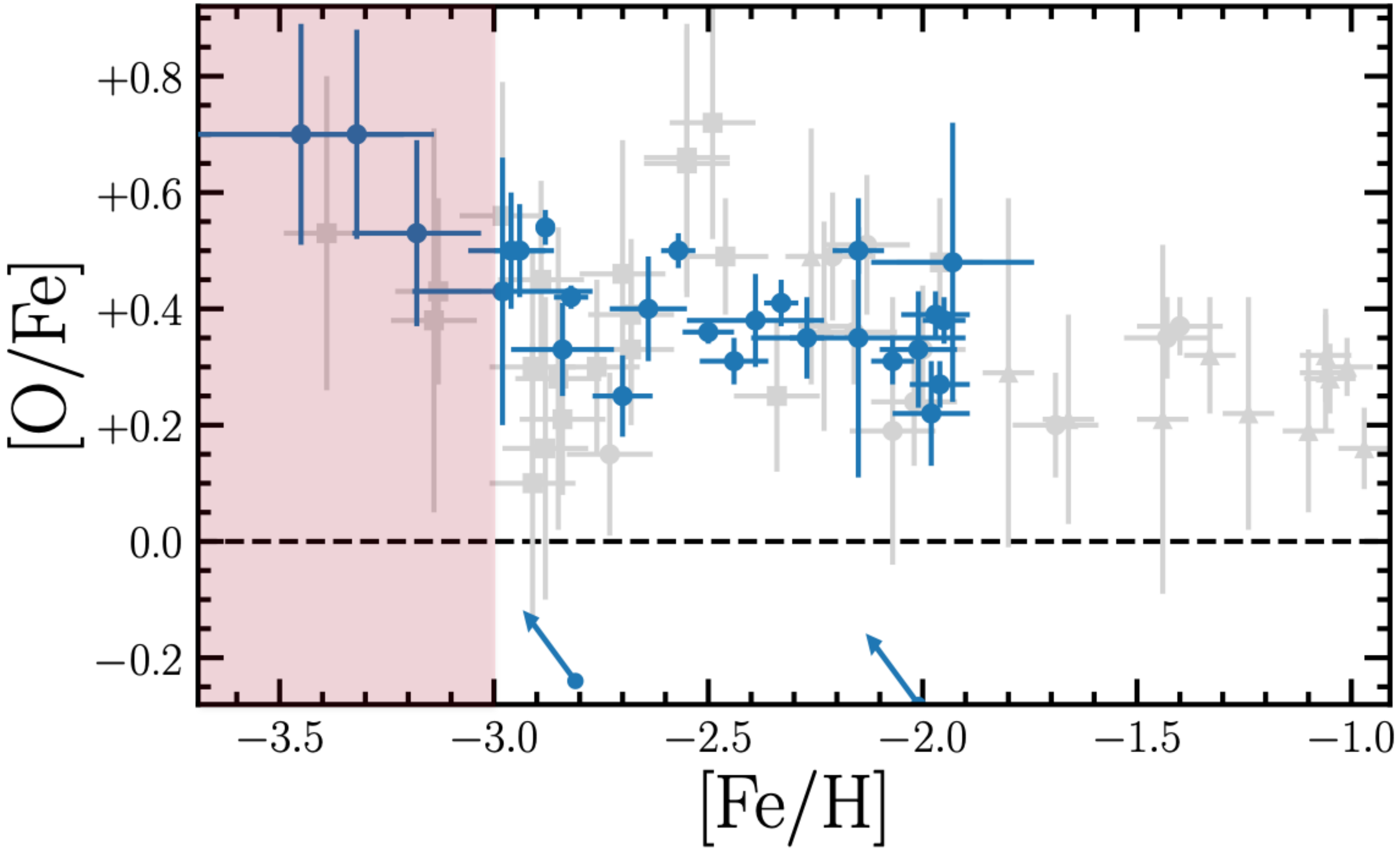
$$[X/Y] = \log(N_X/N_Y)_\star - \log(N_X/N_Y)_\odot$$



Lehner et al. (2022)
Data:
KODIAQ-Z
Fumagalli et al. (2016)
Rafelski et al. (2012)

[O/Fe] in the most metal-poor systems

fingerprint of the first stars?



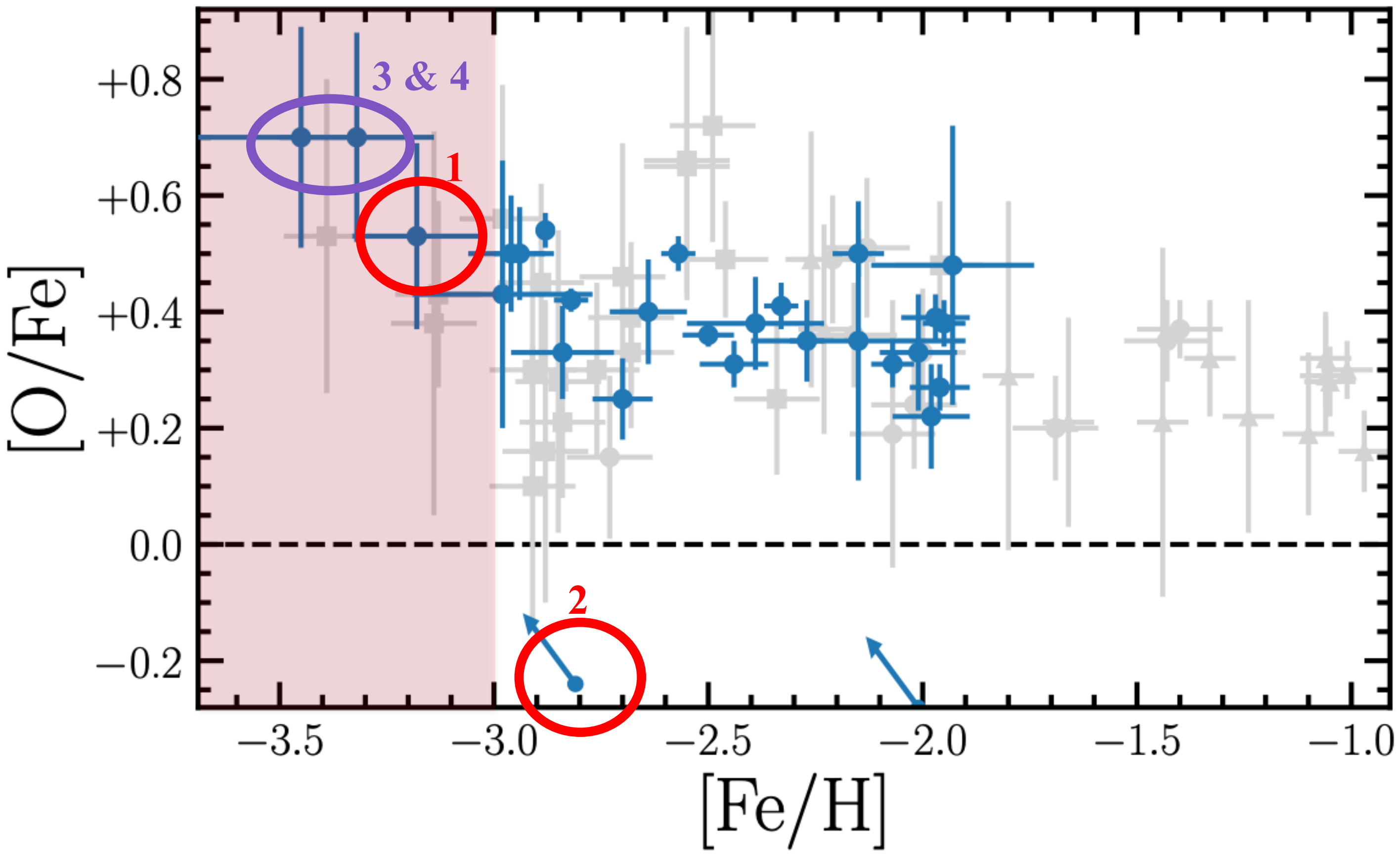
Data:

Molaro+ (2000); O'Meara+ (2001, 2006); Dessauges-Zavadsky+ (2001); Prochaska+ (2002); Dessauges-Zavadsky+ (2003); Petitjean+ (2008); Pettini+ (2008); Ellison+ (2010); Penprase+ (2010); Cooke+ (2011, 2015, 2016, 2017); Dutta+ (2014); Berg+ (2016); Morrison+ (2016); Welsh+ (2020)

Nissen+ (2002);Cayrel+ (2004); Garcia Perez+ (2006)

more pristine ⟷ more contaminated

[O/Fe] in the most metal-poor systems



Data:
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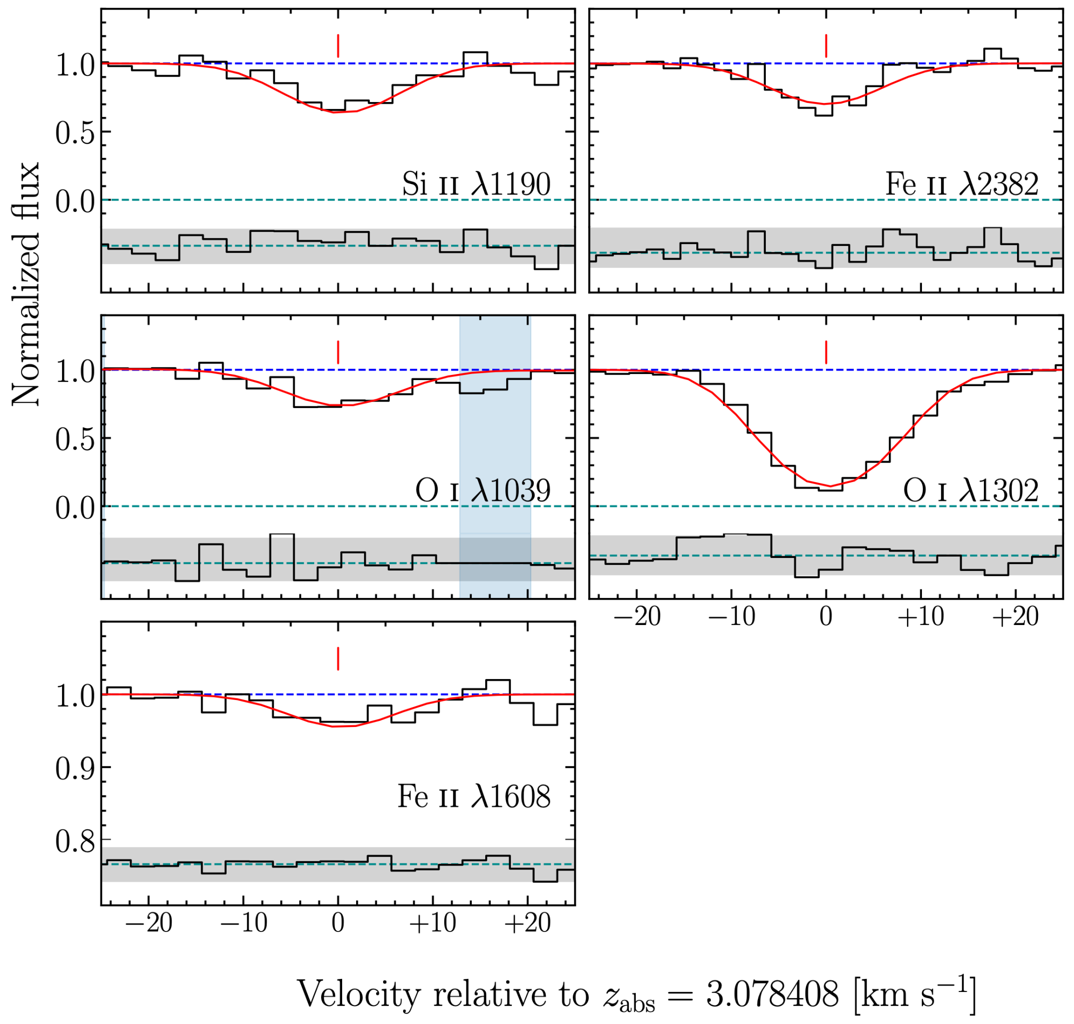
Nissen+ (2002);Cayrel+ (2004); Garcia Perez+ (2006)

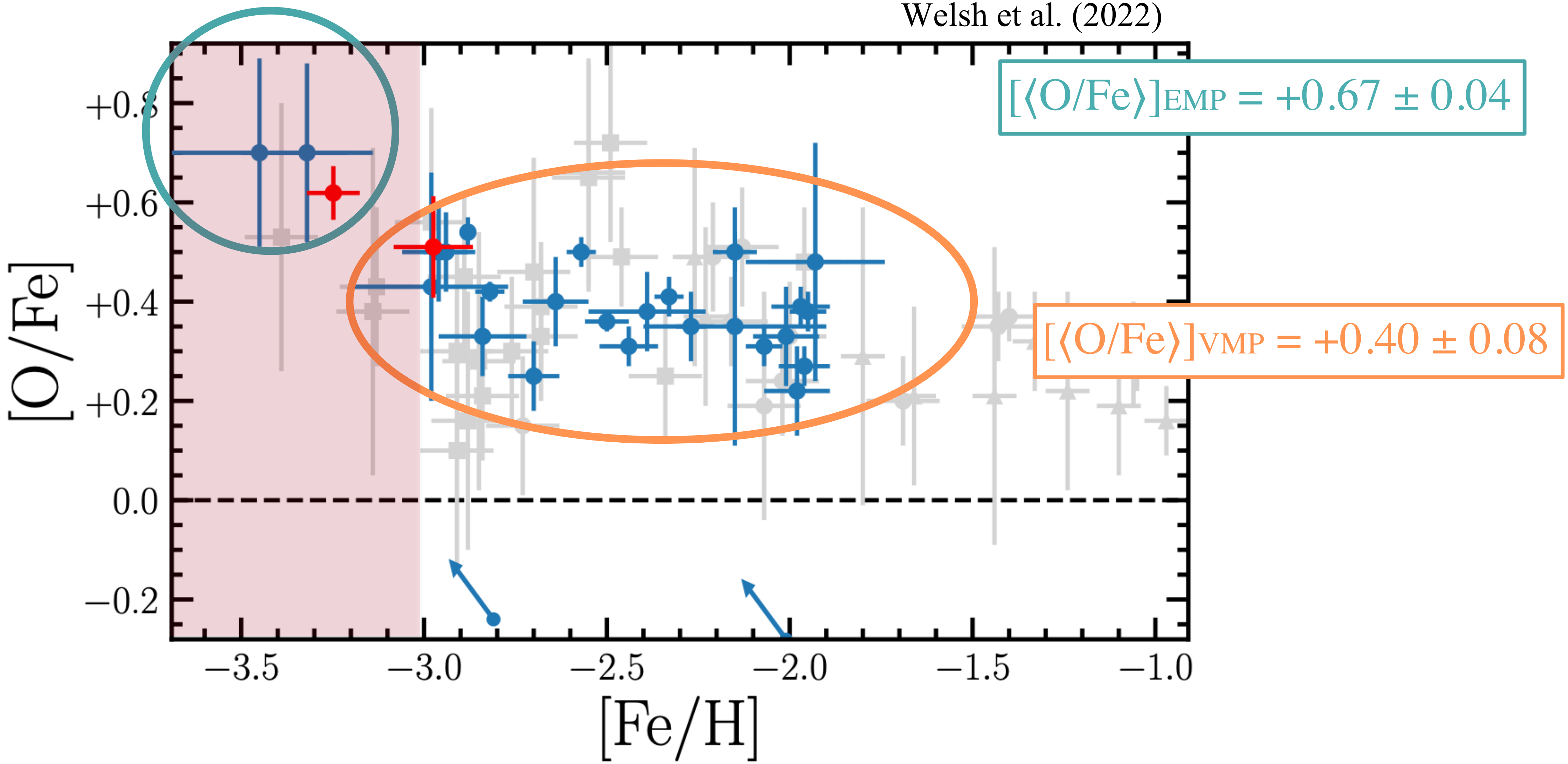
J1001+0343

- Further observations with high resolution echelle spectrograph VLT/UVES (R~40,000) of prime target at z ~ 3.
- Full complement of data confirm [Fe/H] = −3.25 ± 0.07 and [O/Fe] = +0.62 ± 0.05
- Determination of [O/Fe] improved by a factor of 3.

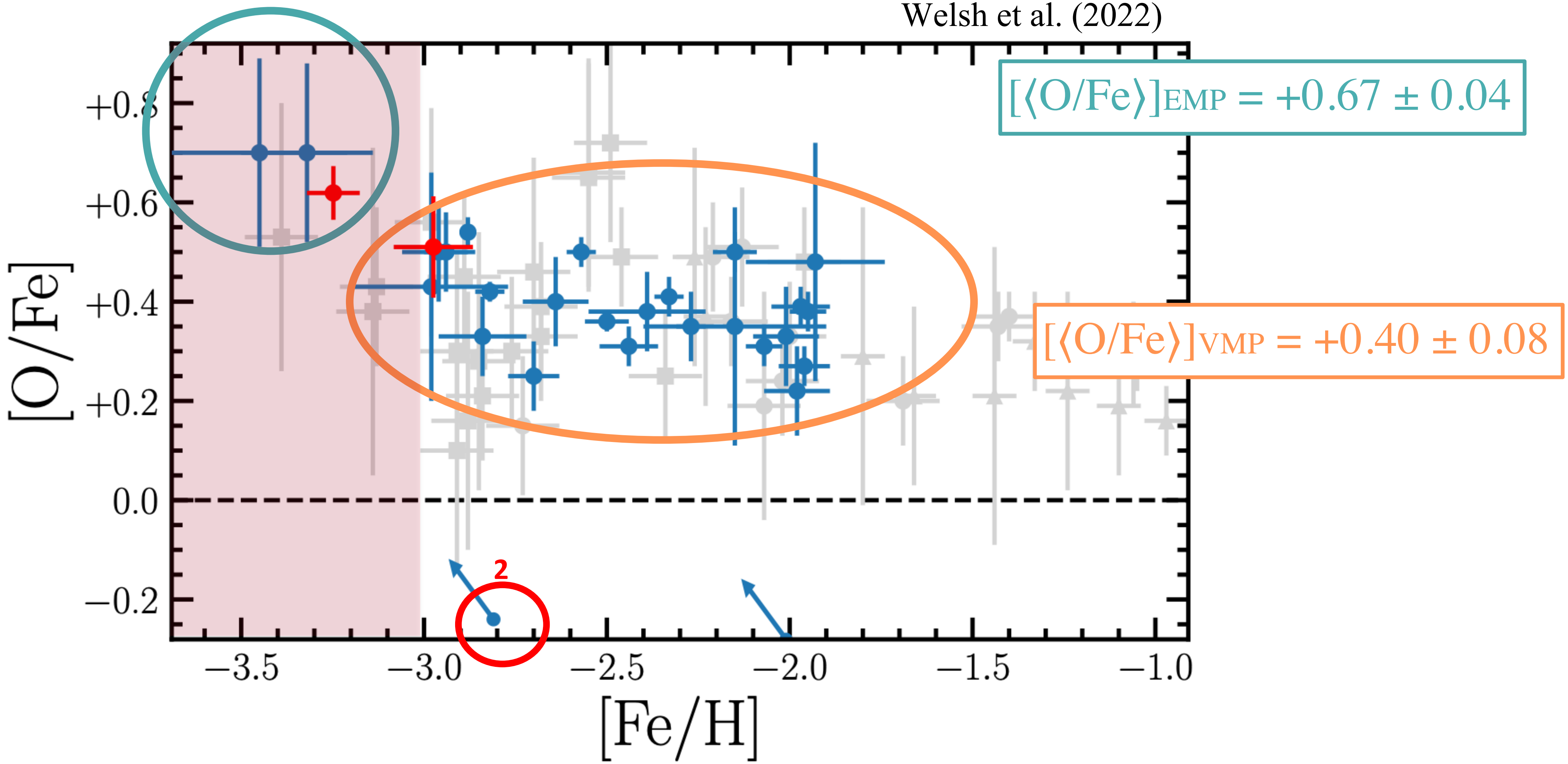


[O/Fe] in the most metal-poor systems

Welsh et al. (2022)



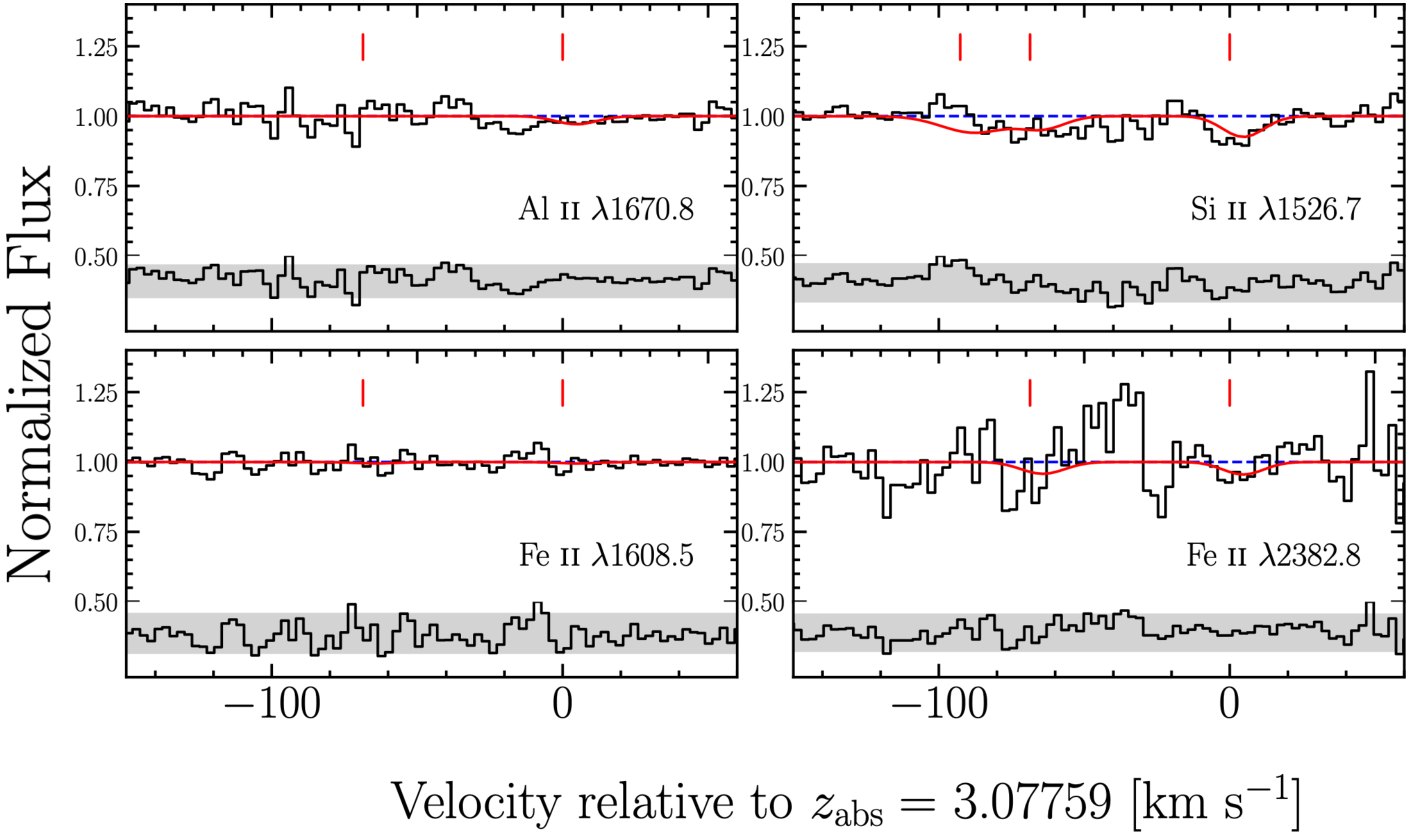
[O/Fe] in the most metal-poor systems



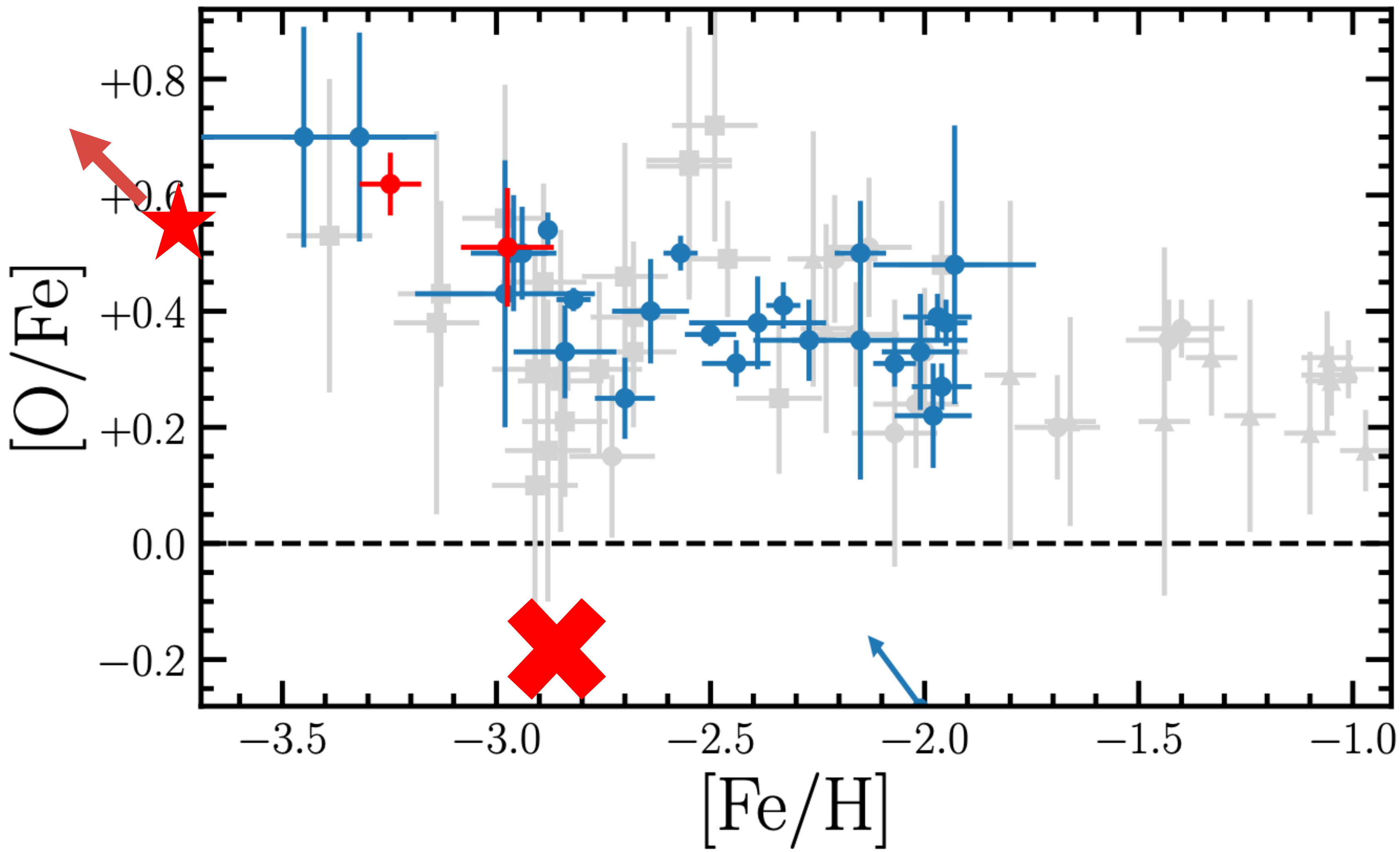
The most metal-poor DLA currently known

Ion	Total	[X/H]
H I	20.32 ± 0.05	—
C II	13.45 ± 0.08	-3.42 ± 0.07
O I	13.93 ± 0.04	-3.08 ± 0.06
Al II	$\leq 11.00^{a}$	$\leq -3.76^{a}$
Si II	12.86 ± 0.04	-3.22 ± 0.06
Fe II	$\leq 12.13^{a}$	$\leq -3.66^{a}$

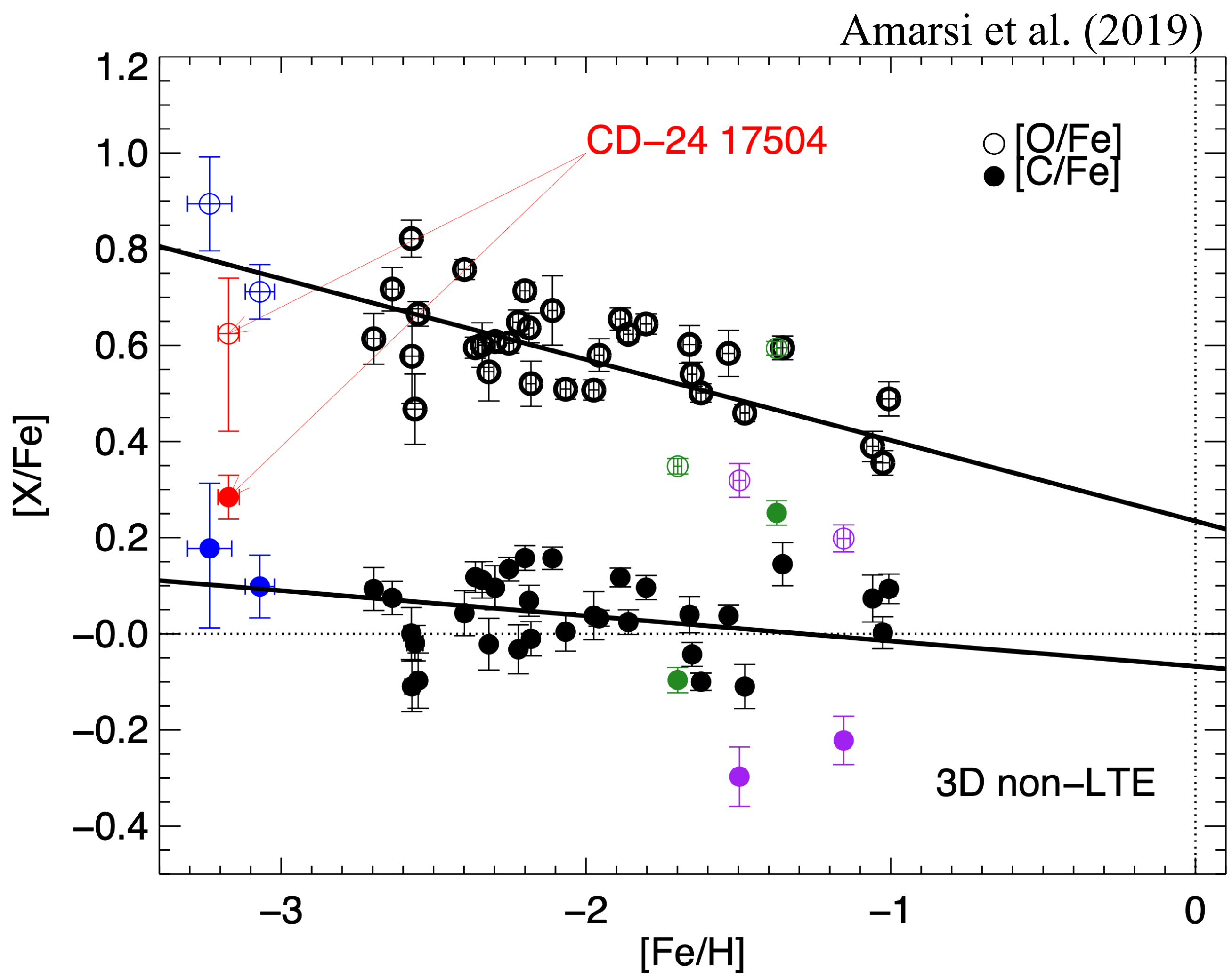
Welsh et al. (submitted)



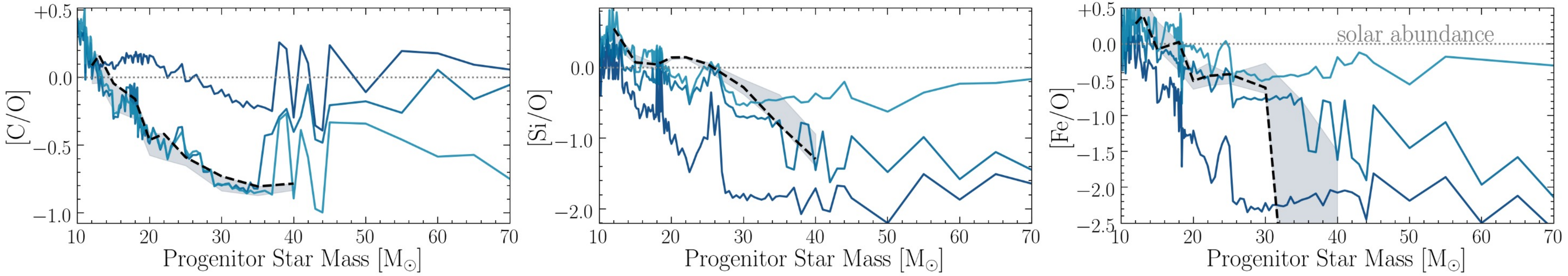
[O/Fe] in the most metal-poor systems



The same pattern is seen in stars



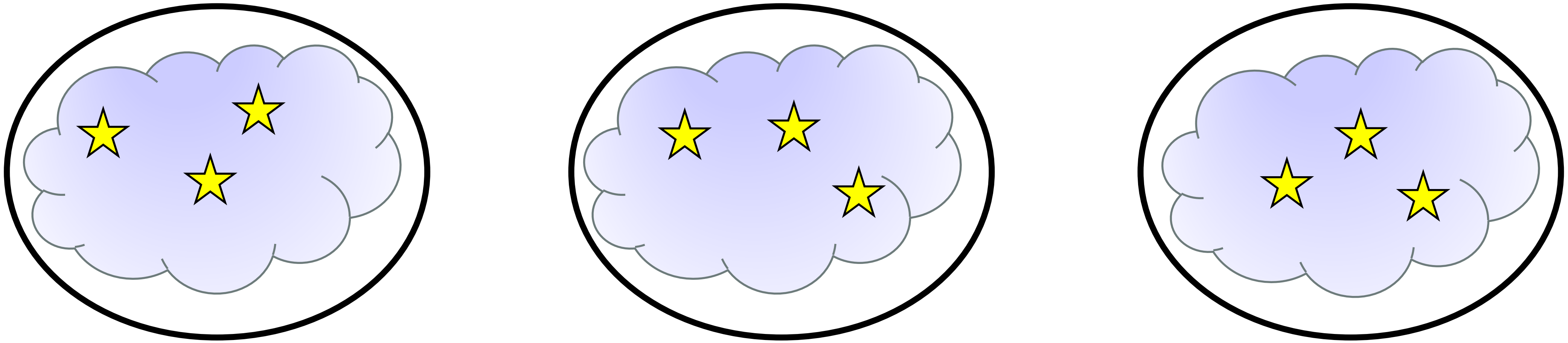
Comparison with nucleosynthetic models



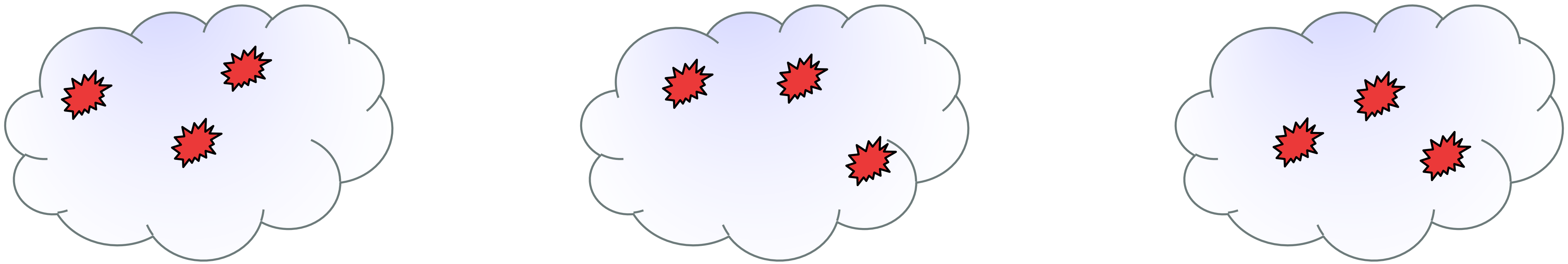
low explosion energy → high explosion energy

I use those from Woosley & Weaver (1995) Heger & Woosley (2010)

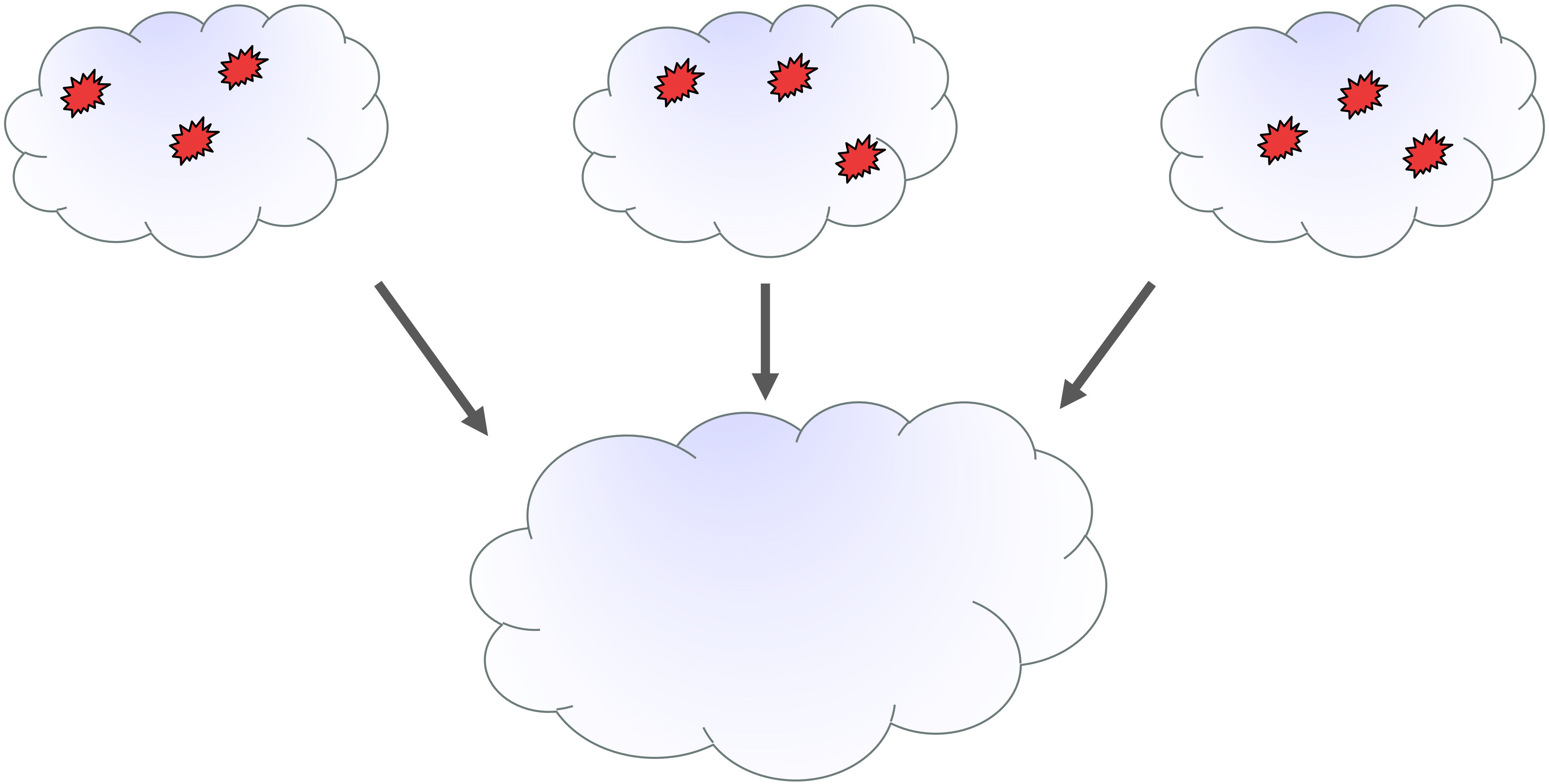
Stochastic enrichment model



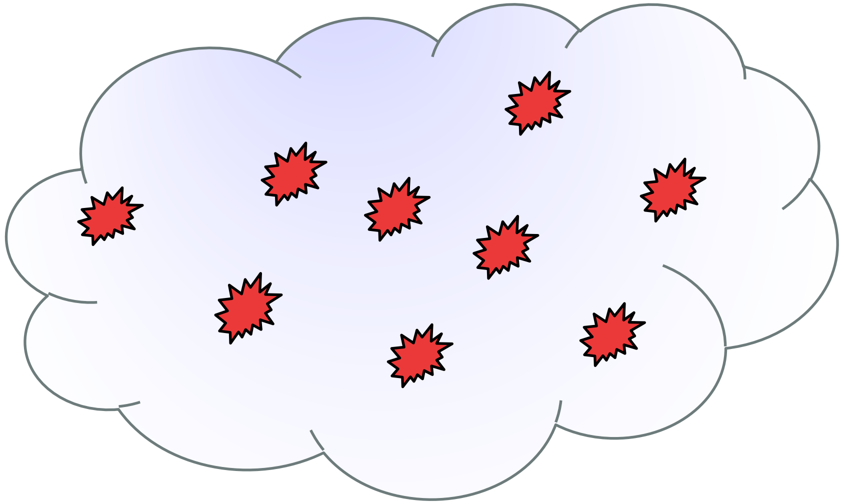
Stochastic enrichment model



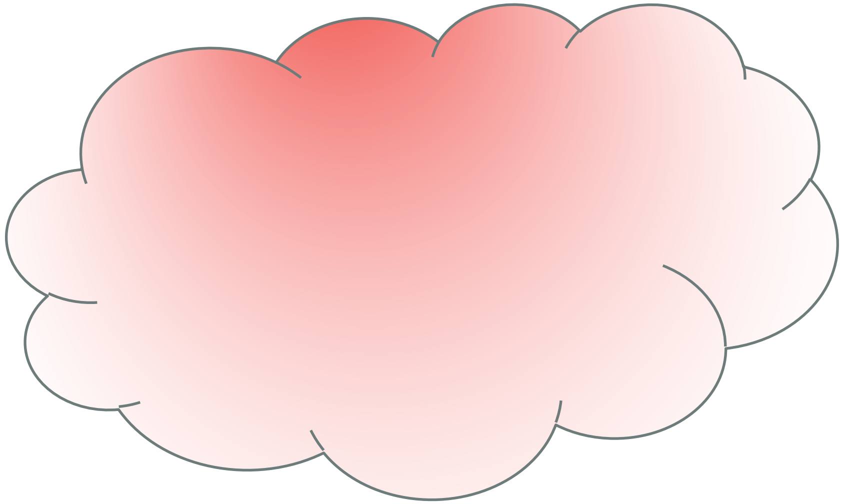
Stochastic enrichment model



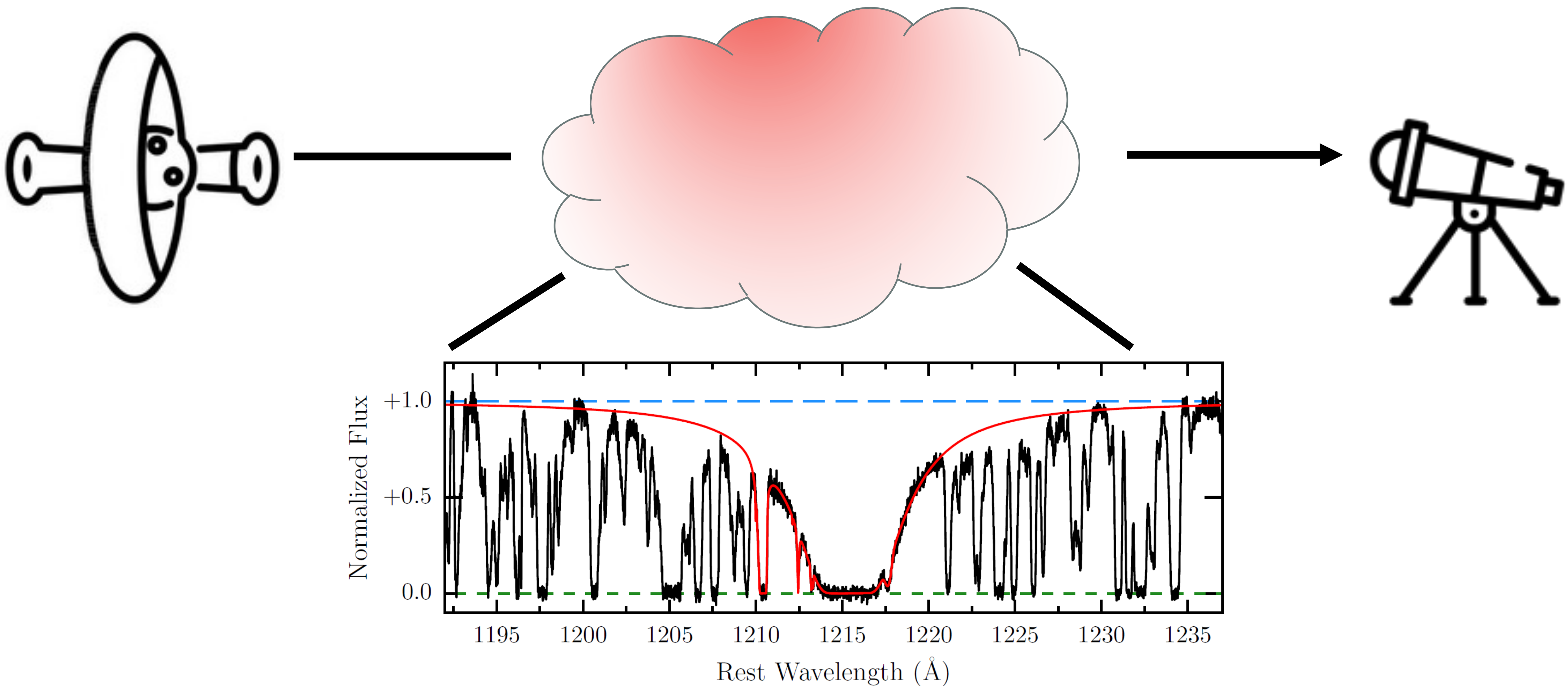
Stochastic enrichment model



Stochastic enrichment model

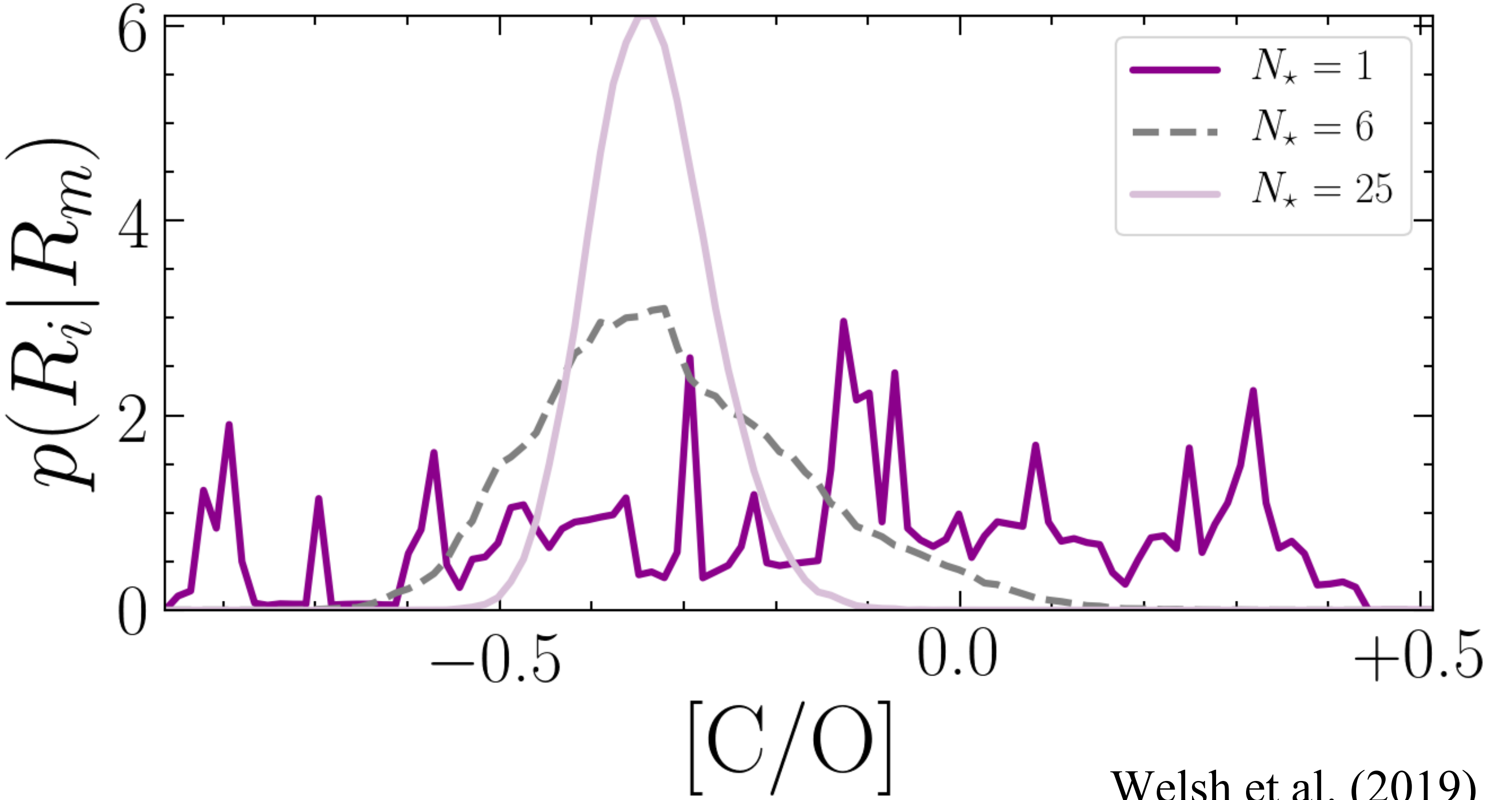


Stochastic enrichment model

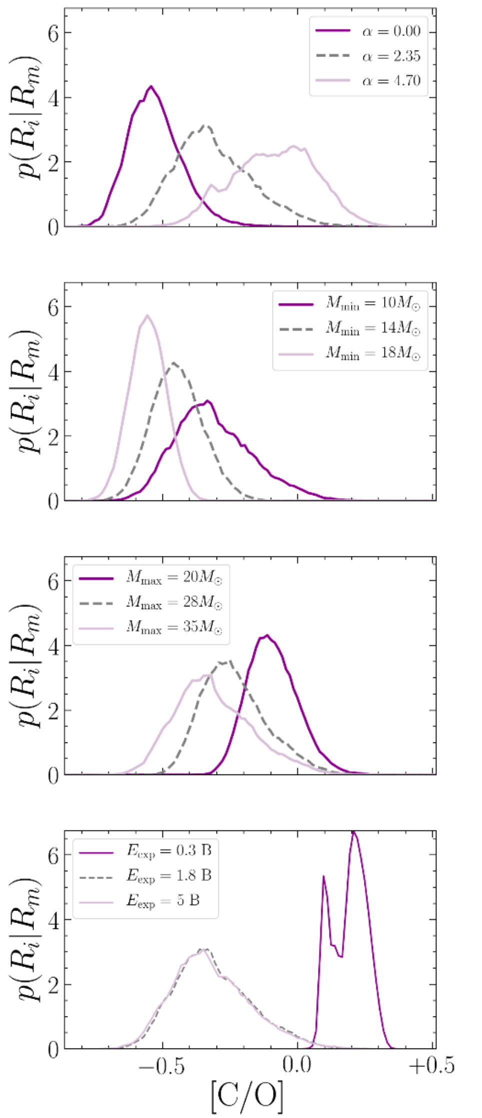


Probability of [X/Y] given an enrichment model

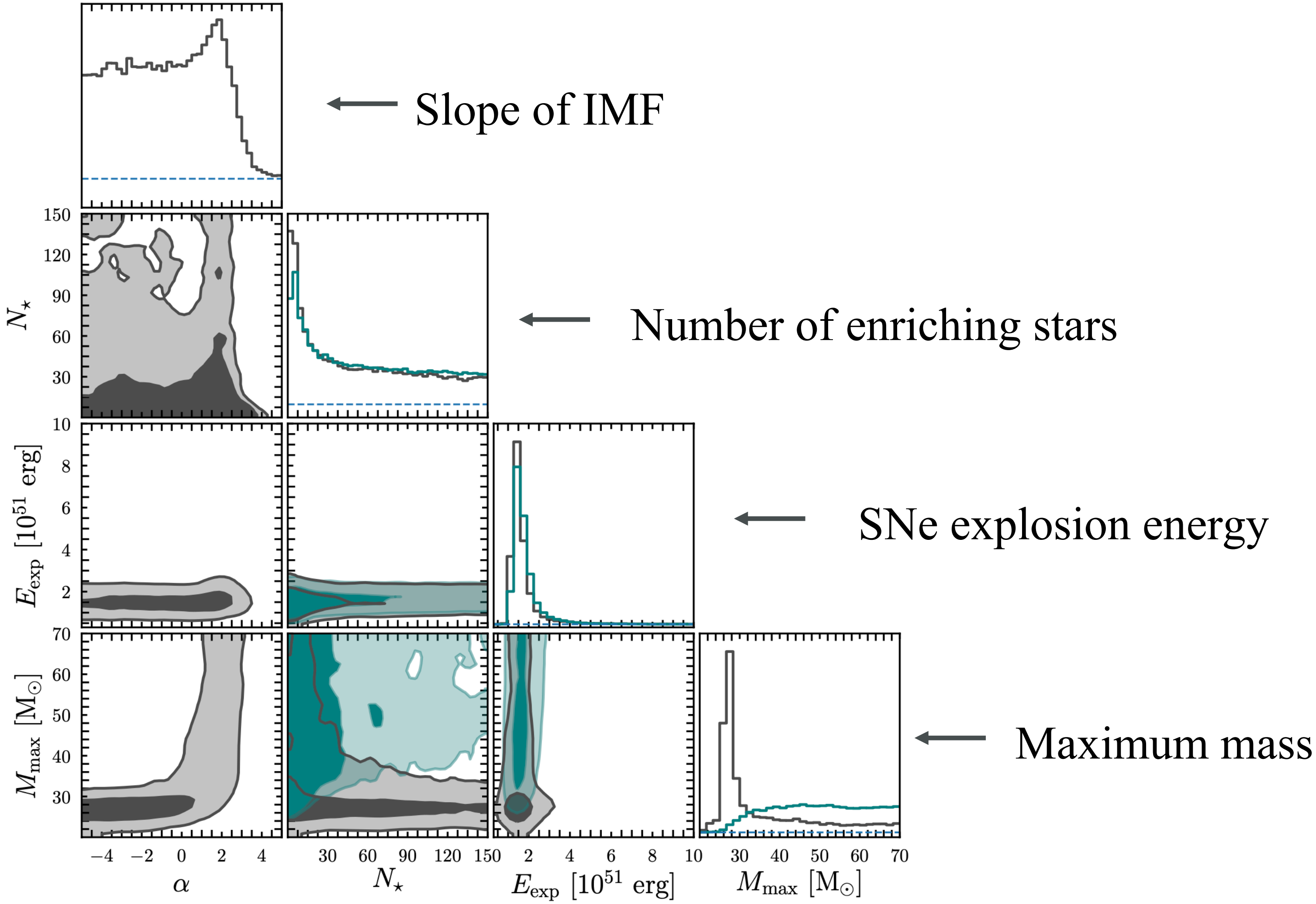
$$N_\star = \int_{M_{min}}^{M_{max}} kM^{-\alpha}dM$$



Welsh et al. (2019)

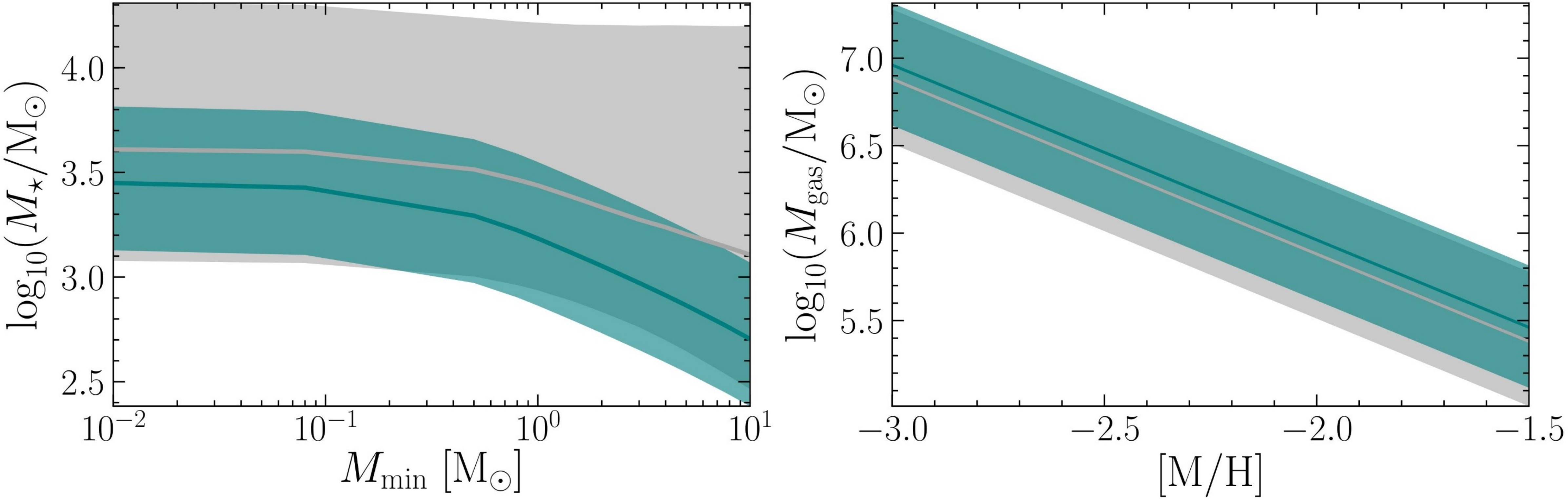


Stochastic enrichment of an EMP DLA



Inferred physical properties

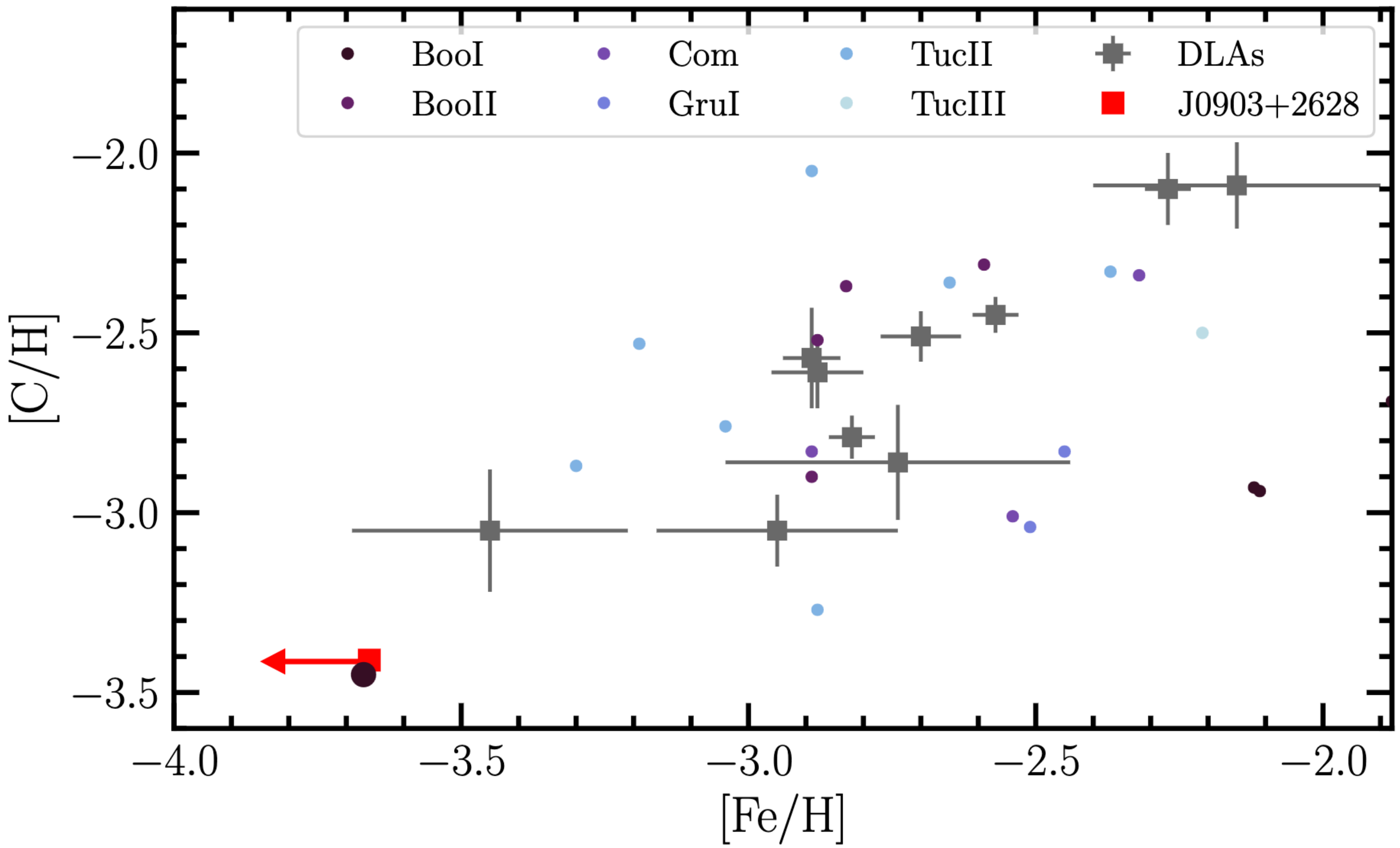
Welsh et al. (2019)



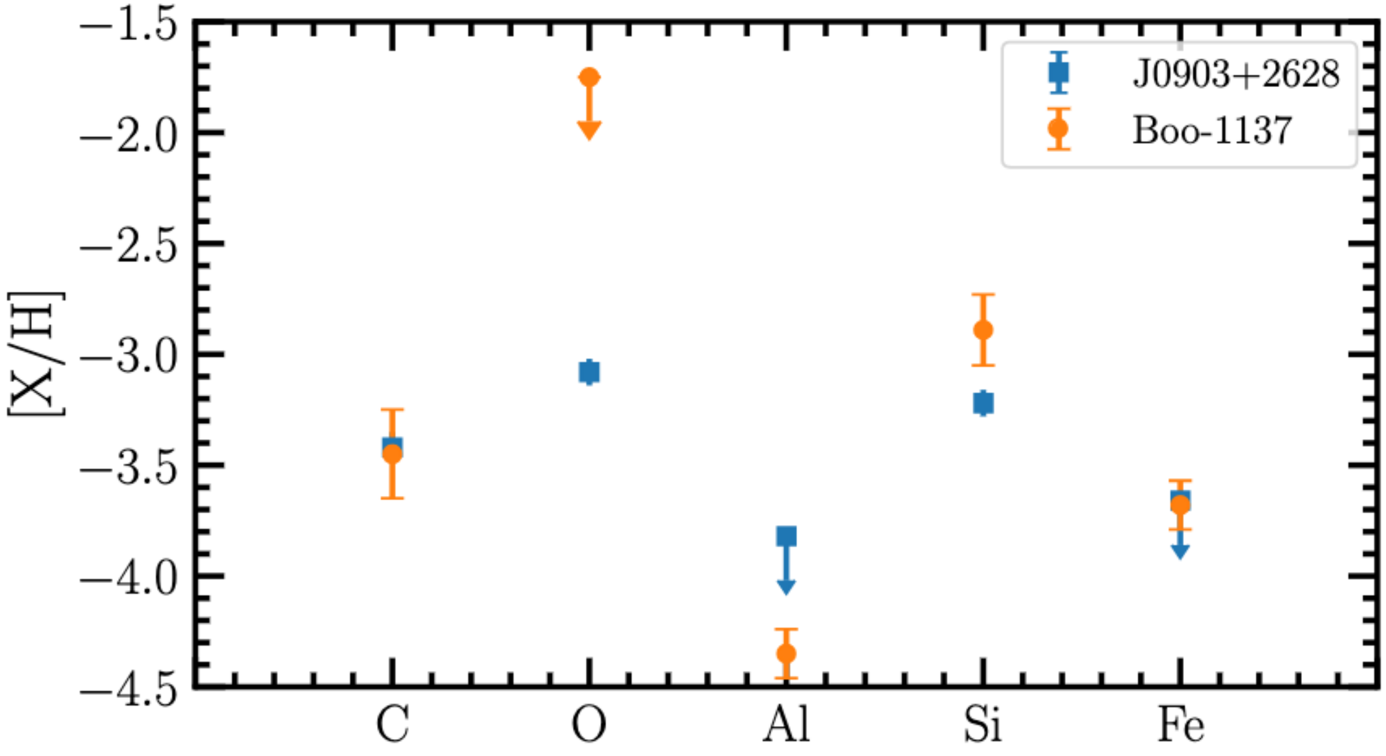
Comparable to stellar content of the faint Milky Way satellite population (Martin et al. 2008; McConnachie 2012). These typically span a mass range of $M \sim (10^2-10^5)\mathrm{M}_\odot$, and are still expected to contain gas at redshift $z\sim3$ (Wheeler et al. 2018).

Comparison with stars in UFDs

Stellar data from SAGA database (Susa et al. 2014)



A similar star Boo-1137 in Bootes I



Star from Norris et al. (2010)

El	$[X/H]_{DLA}$	$[X/H]_{\star}$
C	-3.42 ± 0.07	-3.45 ± 0.20
O	-3.08 ± 0.06	< -1.75
Al	≤ -3.82	-4.35 ± 0.11
Si	-3.22 ± 0.06	-2.89 ± 0.16^{a}
Fe	≤ -3.66	-3.68 ± 0.11

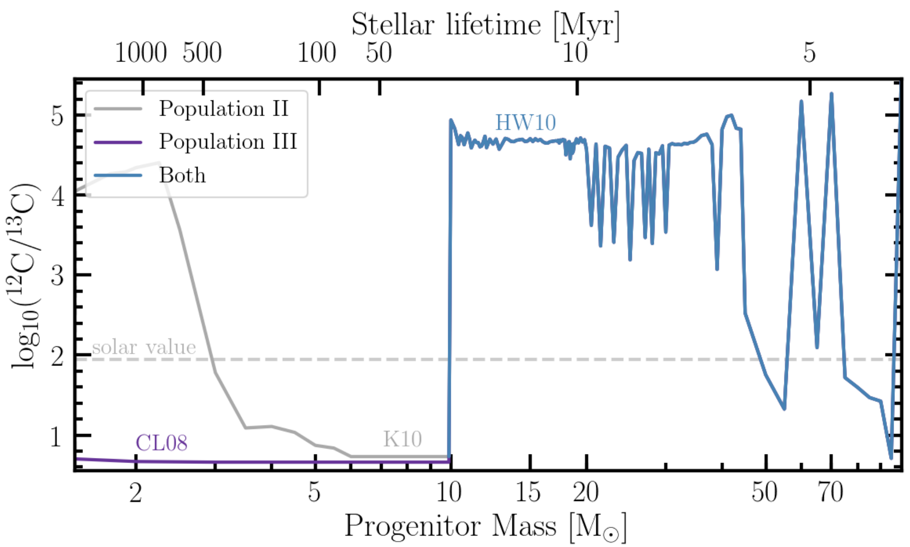
[Mg/C], [Fe/H], and A(C) abundances of Boo−1137 are indicative of enrichment via Pop III SNe (Rossi et al. 2023)

Carbon Isotope Ratio

- Simulations of stellar evolution suggest most stars predominantly produce ^{12}C,

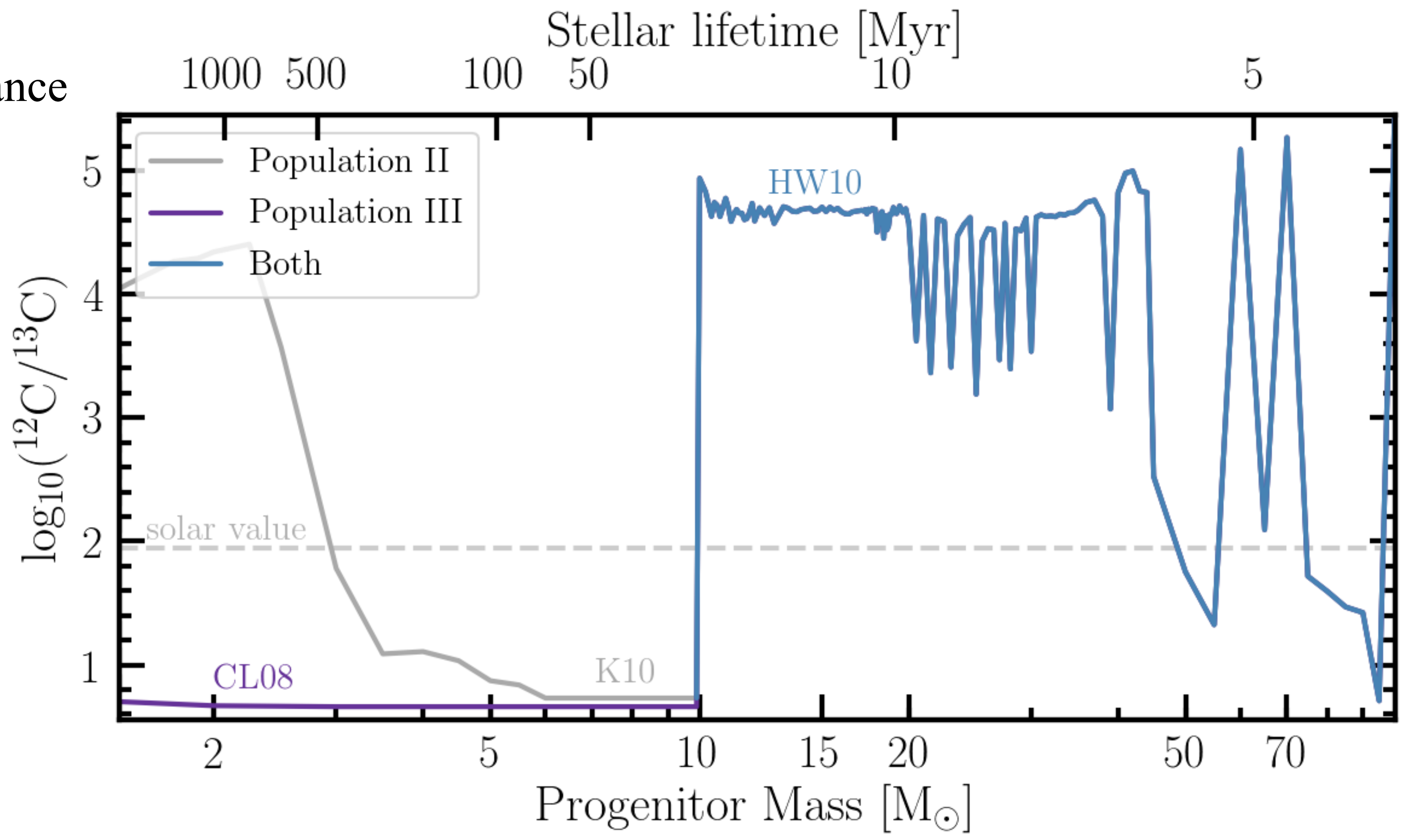
- There are two channels to produce low $^{12}C/^{13}C$ ratios in non-rotating stars:
  - → Low-mass Population III stars
  - → Intermediate-mass Population II stars

- In the future we would also like to consider yields of rapidly rotating stars (e.g. Ekström et al. 2008, Meynet et al. 2010, Limongi & Chieffi 2018)



Yields

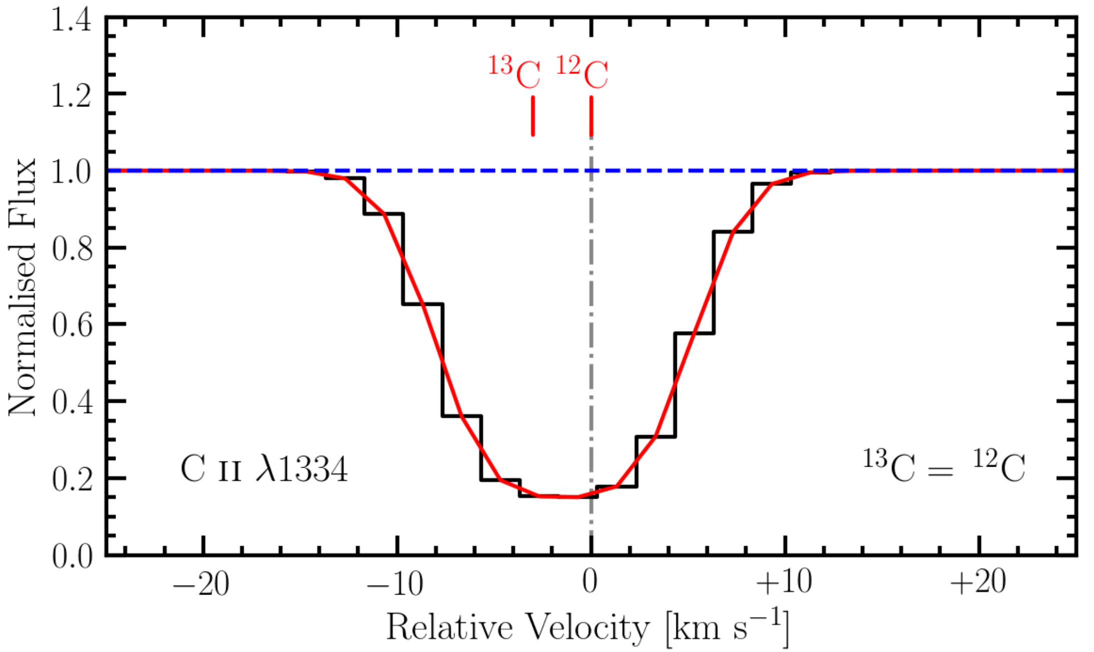
Number abundance

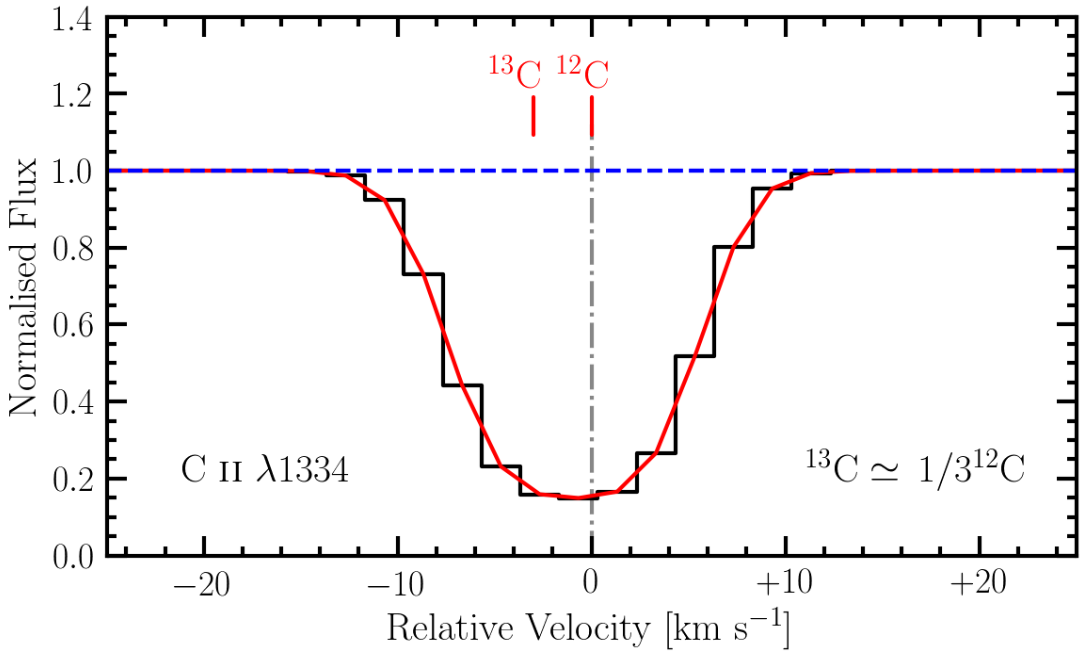


Yields:
Campbell & Lattanzio (2008)
Karakas (2010)
Heger & Woosley (2010)

C II λ1334

The presence of ^{13}C is seen as an asymmetry in C II λ1334 line



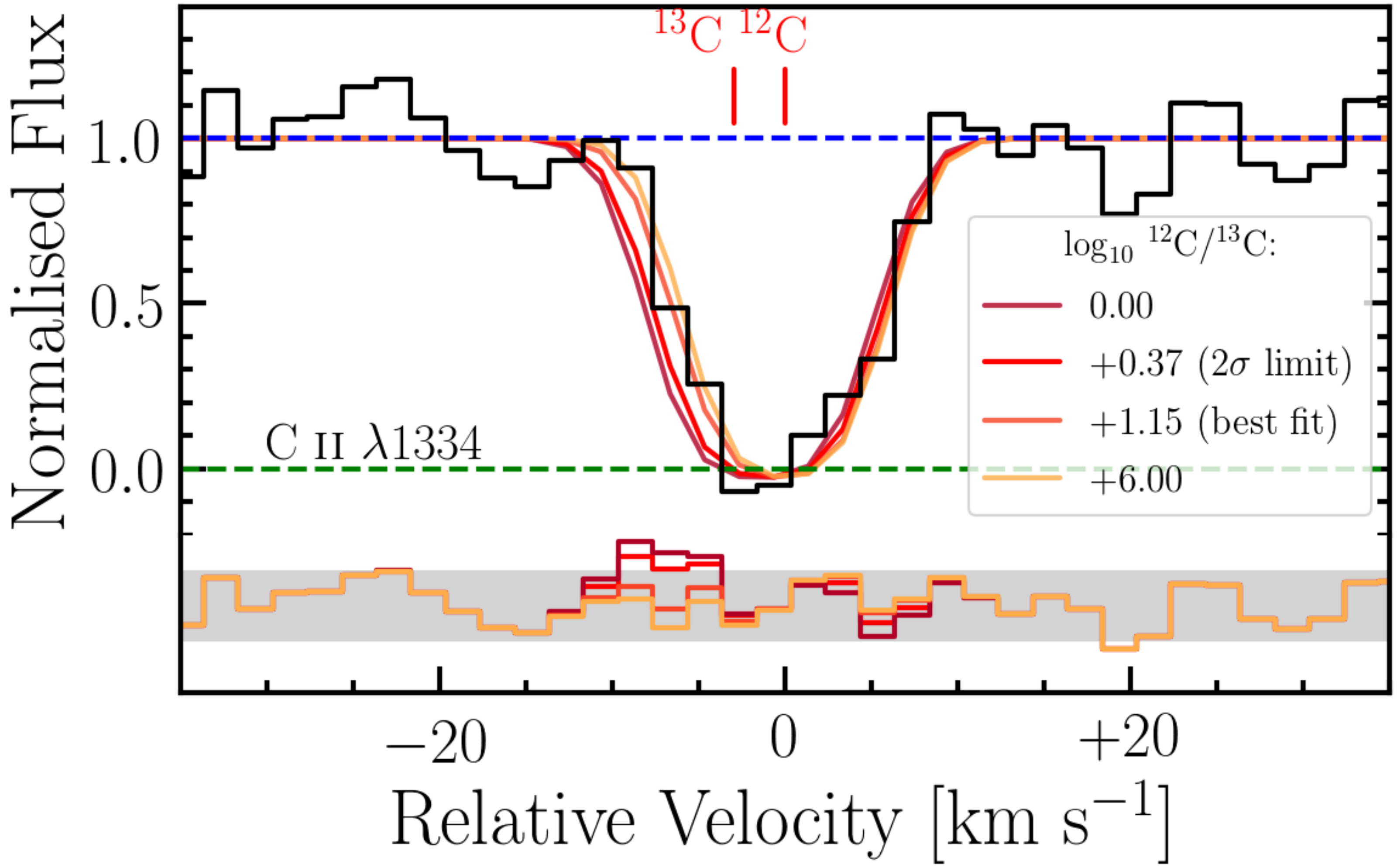


1. ESPRESSO (The Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations)

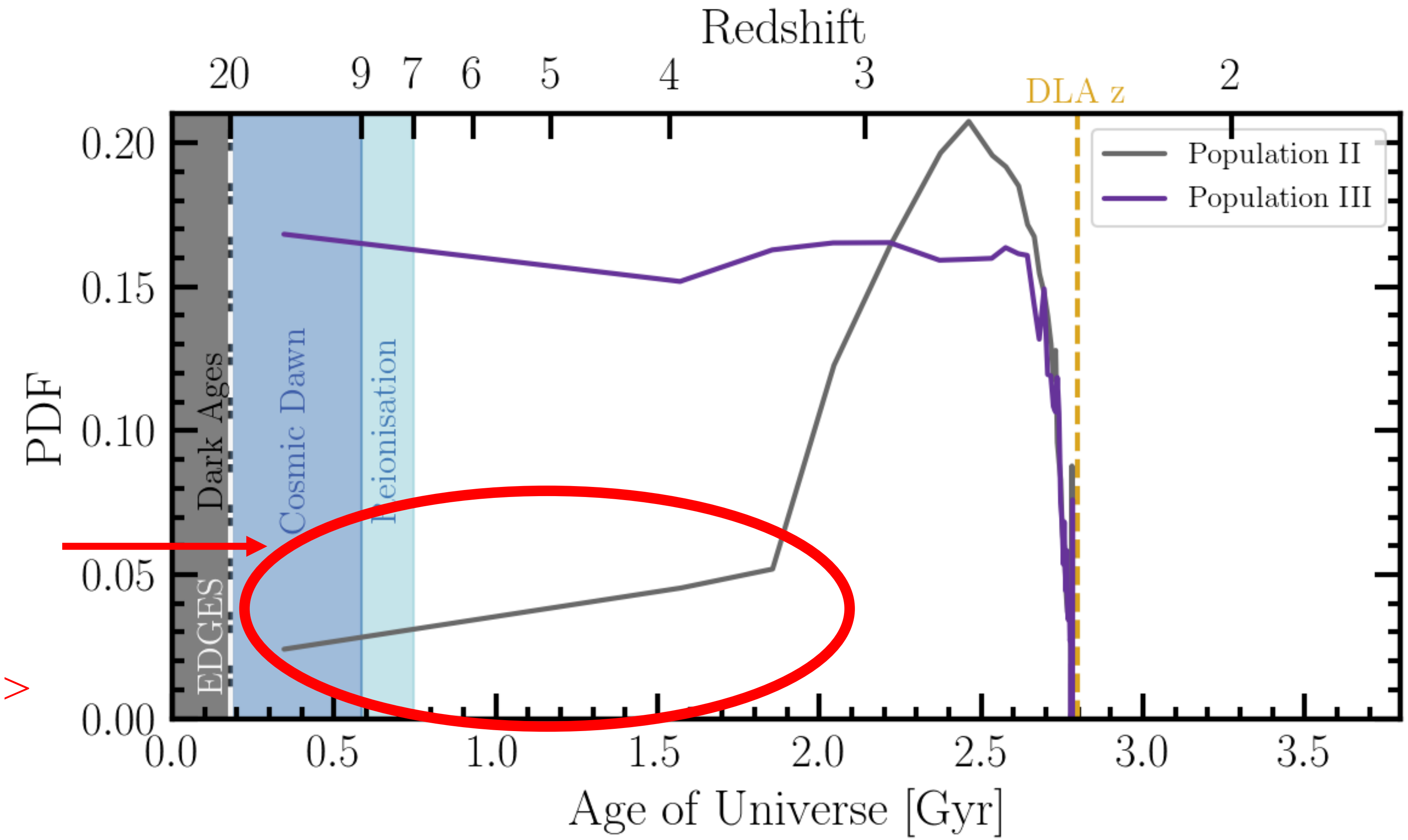
Image Credit: Miguel Claro / ESO

2. A Quiescent DLA

Welsh et al. 2020



Enrichment timescale



Following the epoch of reionisation there appears to be a lack of star formation for > 1 Gyr.

Conclusions

- Near-pristine DLAs and are an ideal tracer of chemical evolution,
- Empirical trends such as [O/Fe] vs [Fe/H] may reveal Population III enrichment,
- We can use stochastic enrichment model to draw out evolutionary relationships
- We can also search for signatures of low mass Population III stars using the carbon isotope and ESPRESSO
- The surveys and instruments in development over the next decade are ideally suited to push on this science.