Constraining the chemistry of the first stars from the most metal-poor sub-damped Lyman alpha systems

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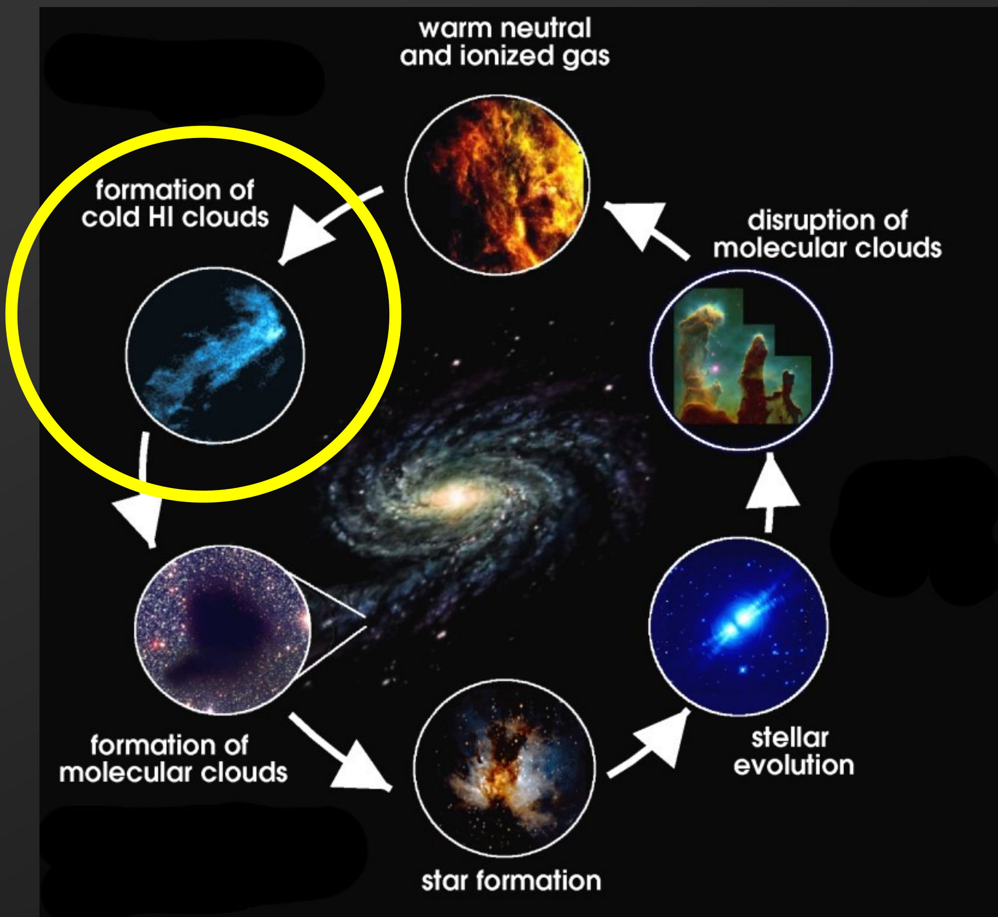
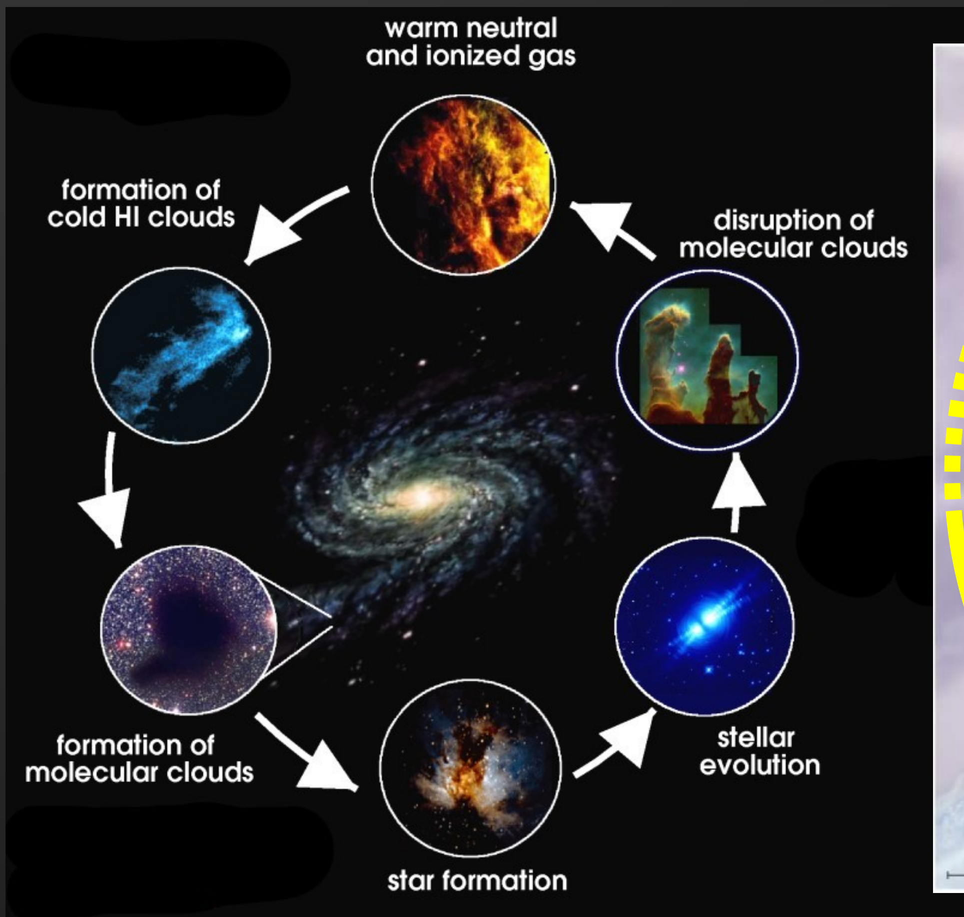
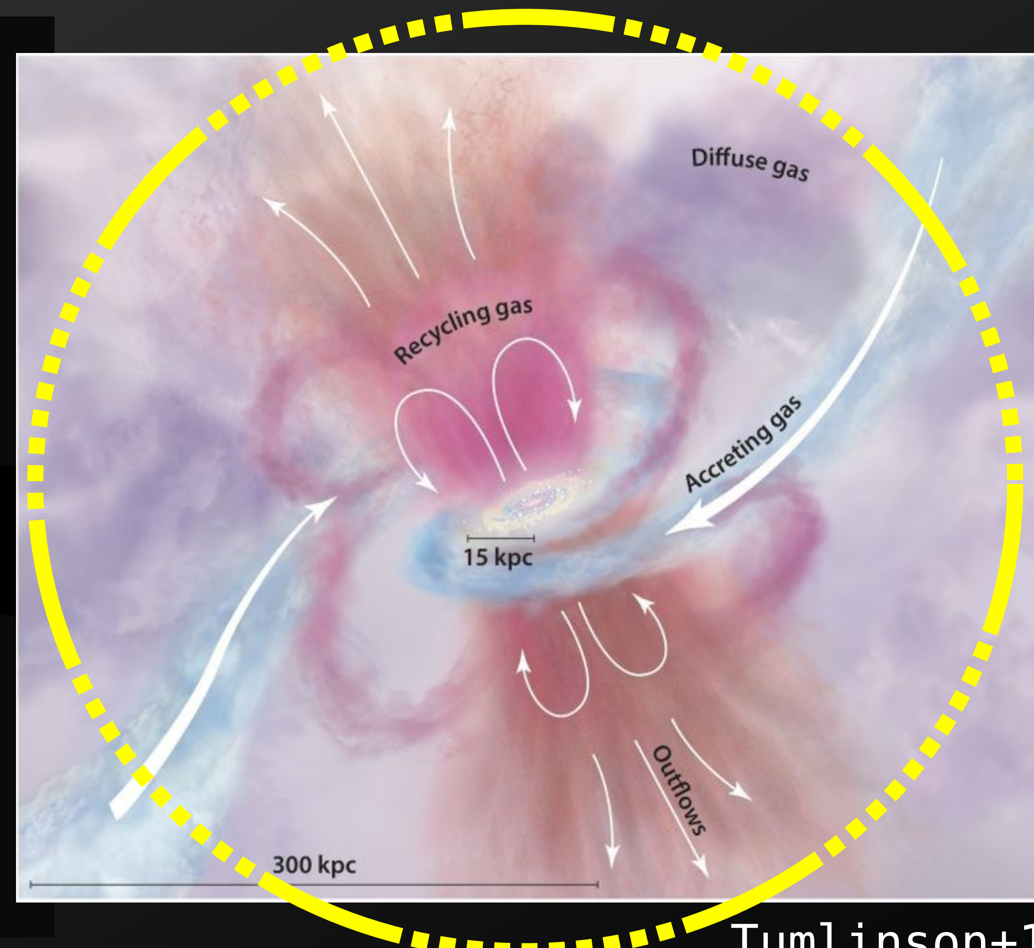
Baryon cycling in galaxies



Interstellar medium (ISM)

Baryon cycling in galaxies



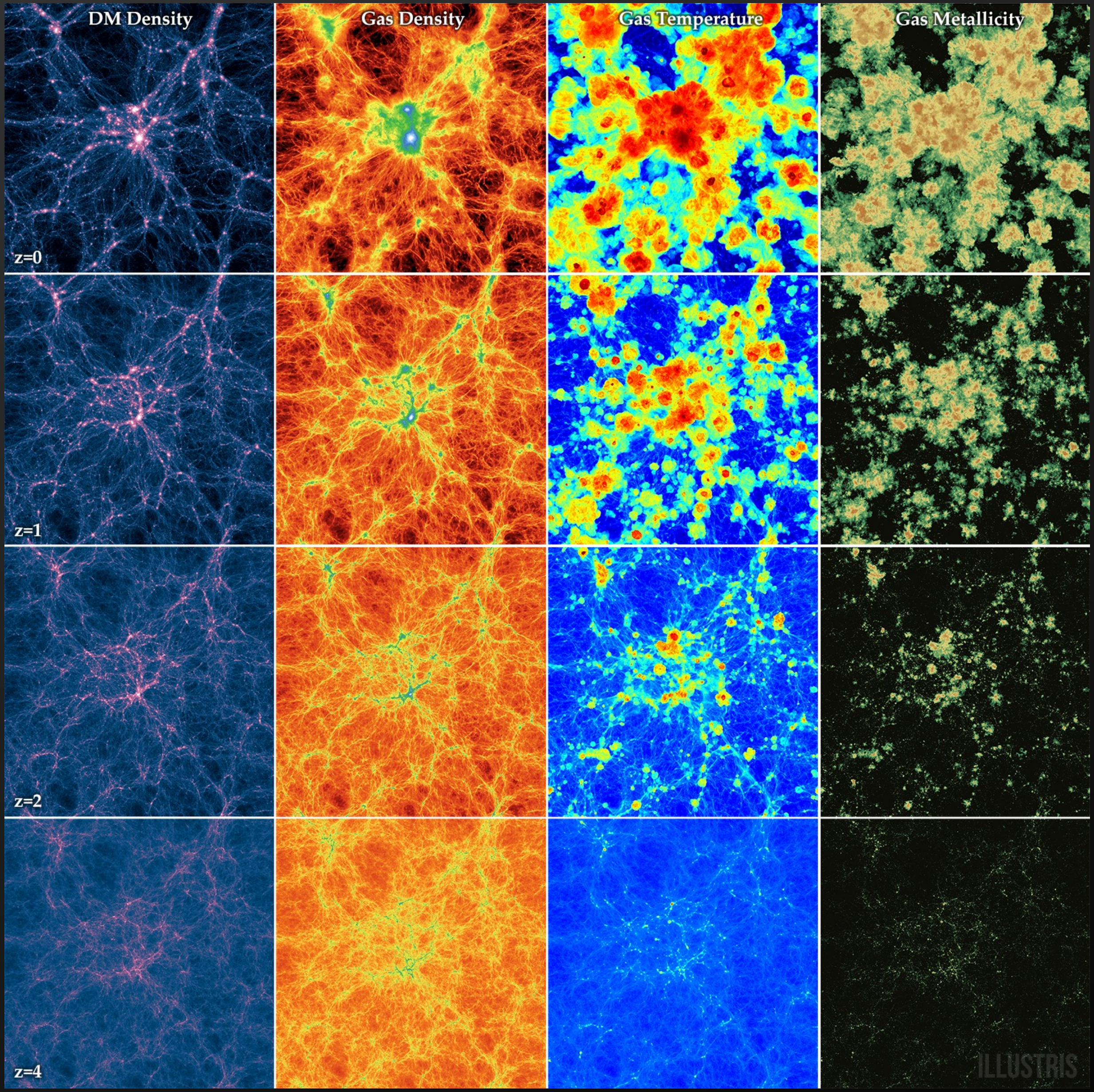


Tumlinson+17

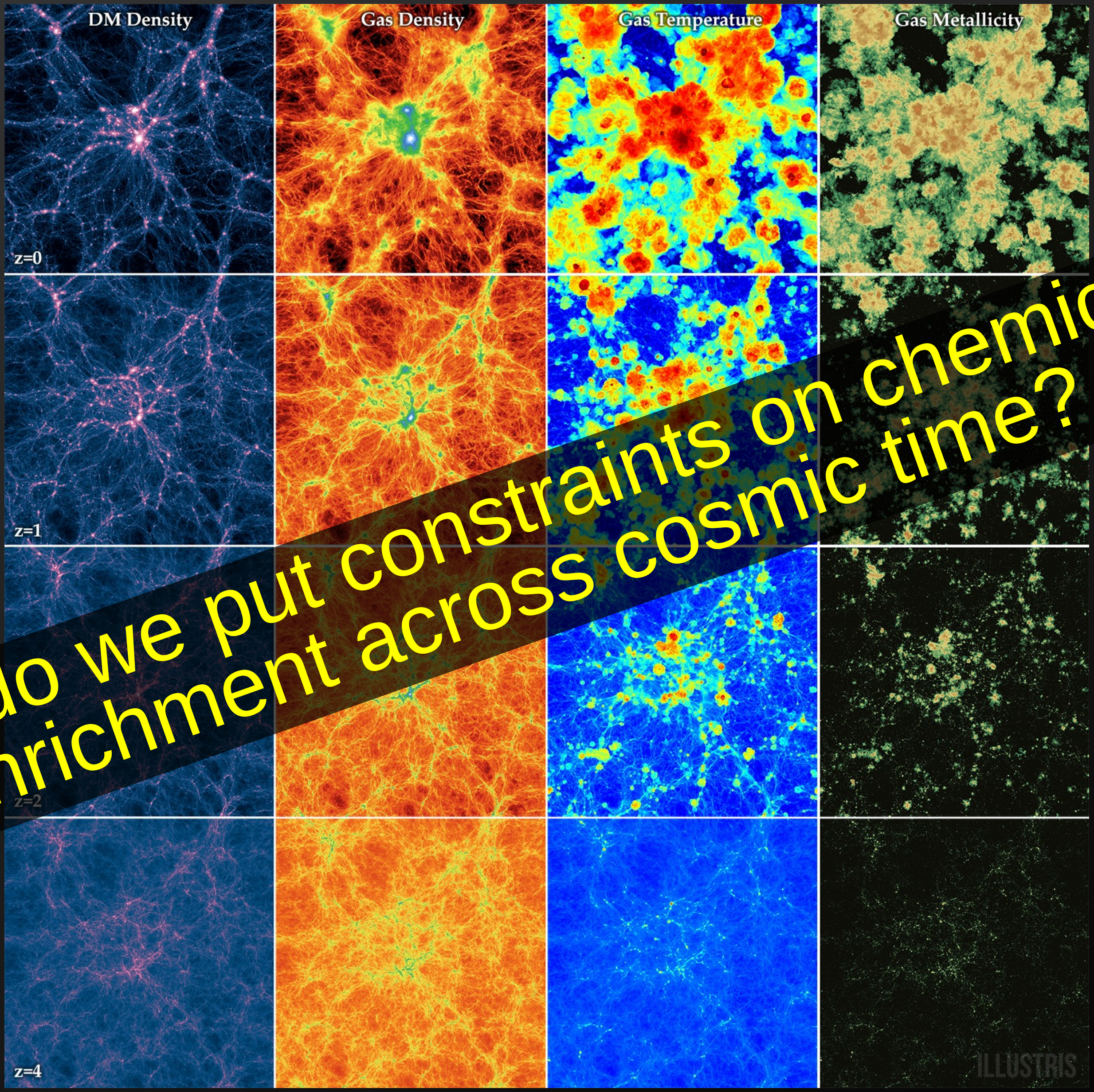
Interstellar medium (ISM)

Circumgalactic medium (CGM)

Baryon cycling in galaxies

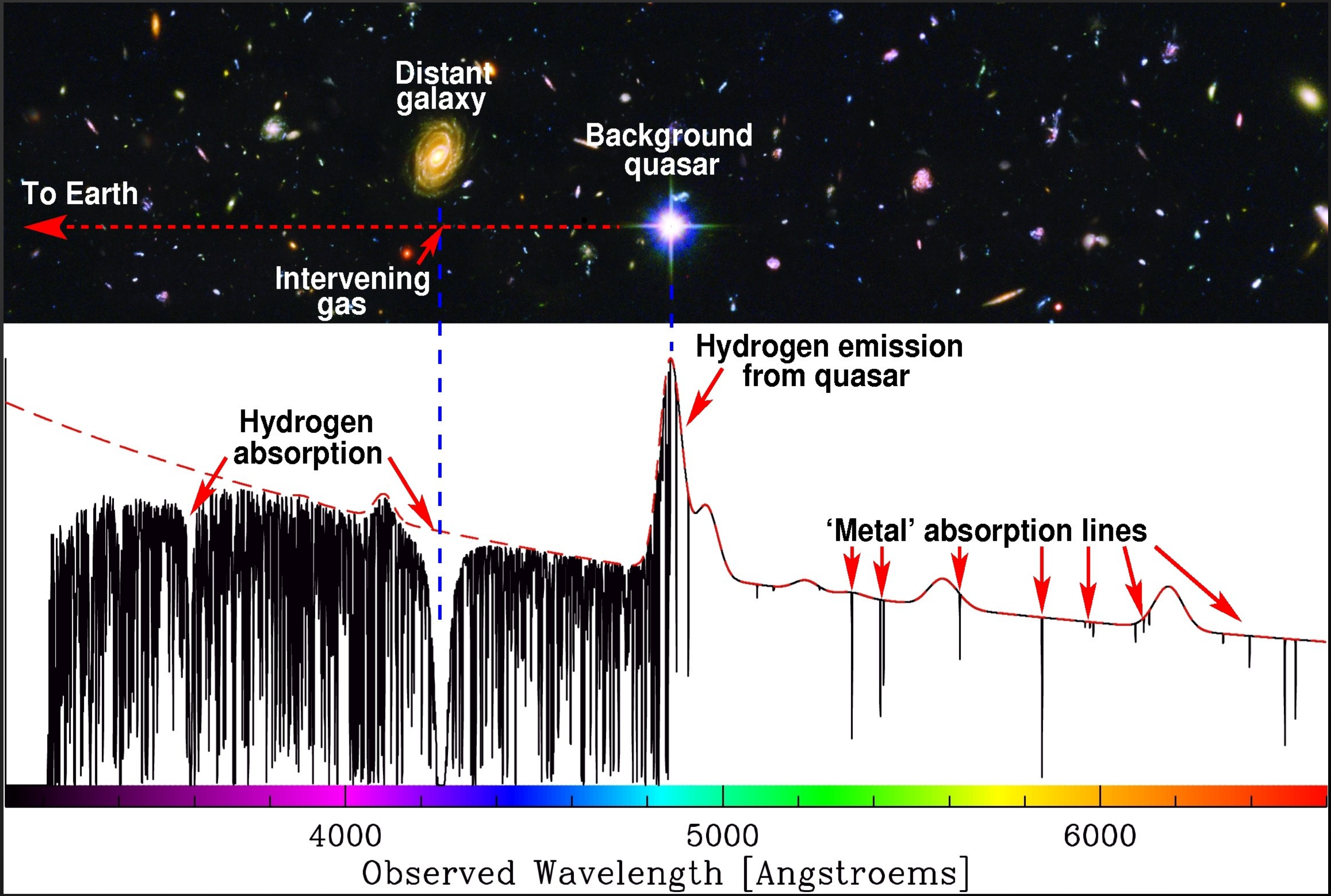


Baryon cycling in galaxies



How do we put constraints on chemical enrichment across cosmic time?

Quasar absorption lines in a nutshell

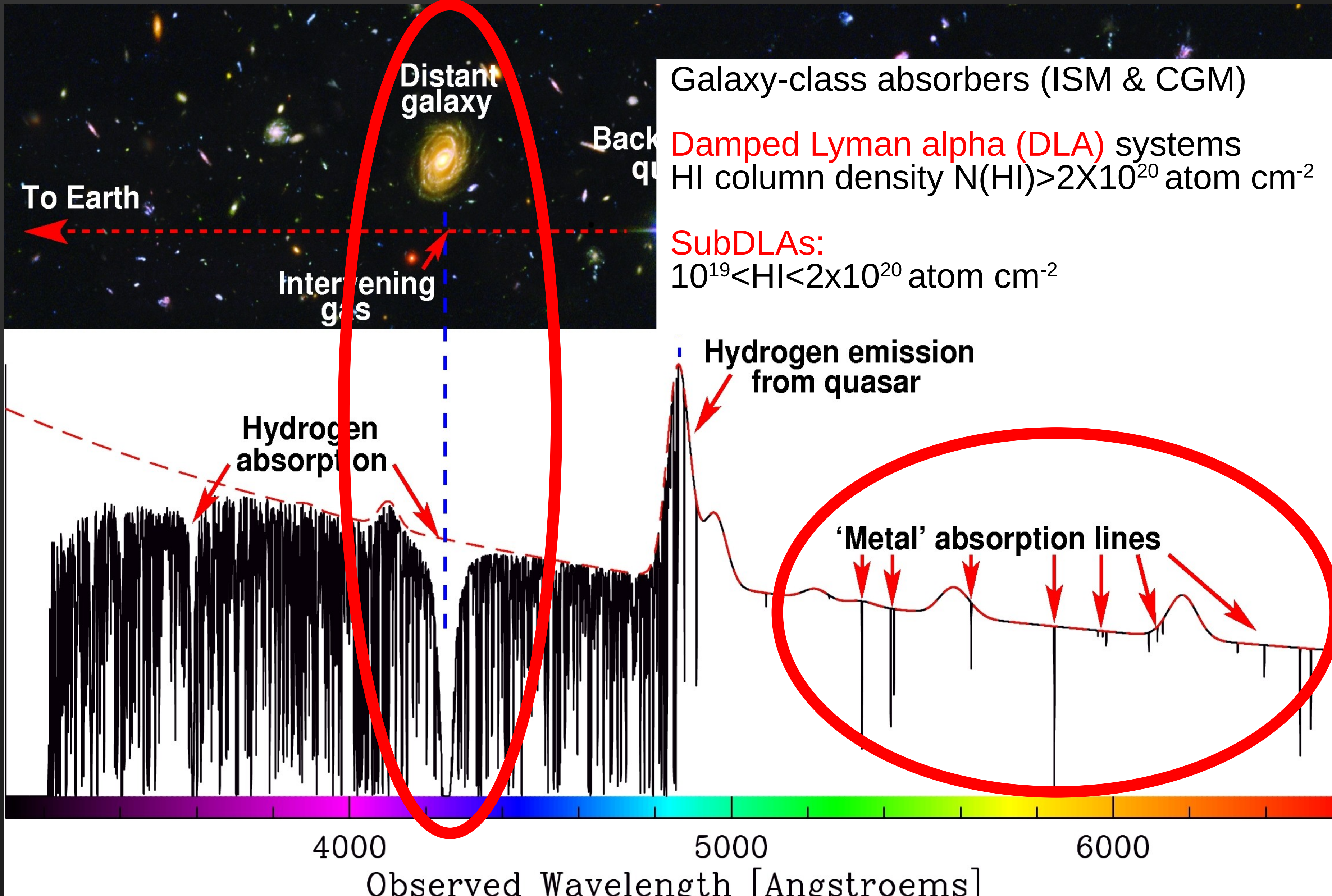


Quasar absorption lines in a nutshell

Galaxy-class absorbers (ISM & CGM)

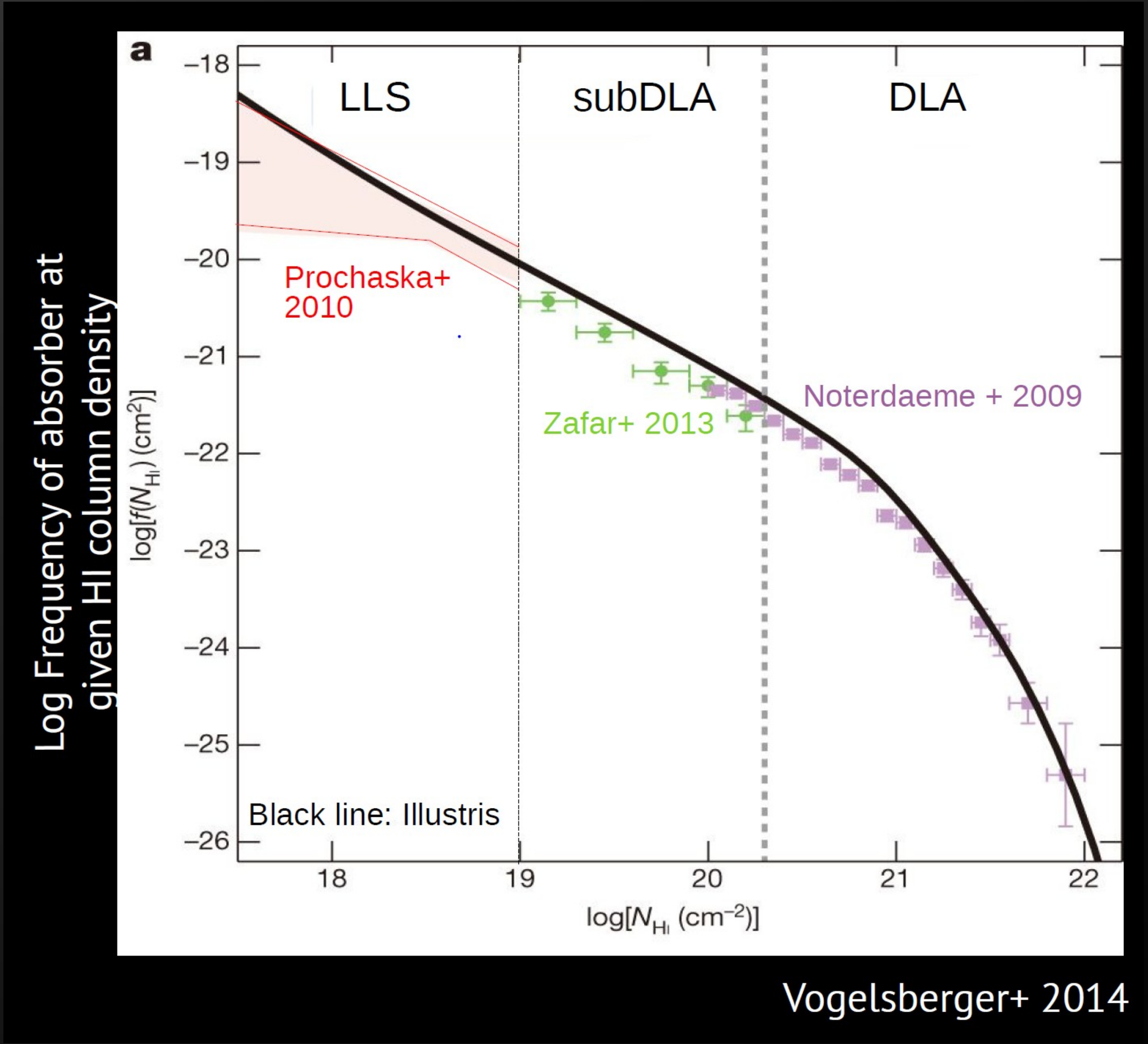
Damped Lyman alpha (DLA) systems
HI column density $N(HI) > 2X10^{20}$ atom cm^{-2}

SubDLAs:
$10^{19} < HI < 2x10^{20}$ atom cm^{-2}



The role of (sub)DLAs in the Universe

- Trace the majority of HI gas reservoirs in the Universe
  - The gas that fuels future star formation



Vogelsberger+ 2014

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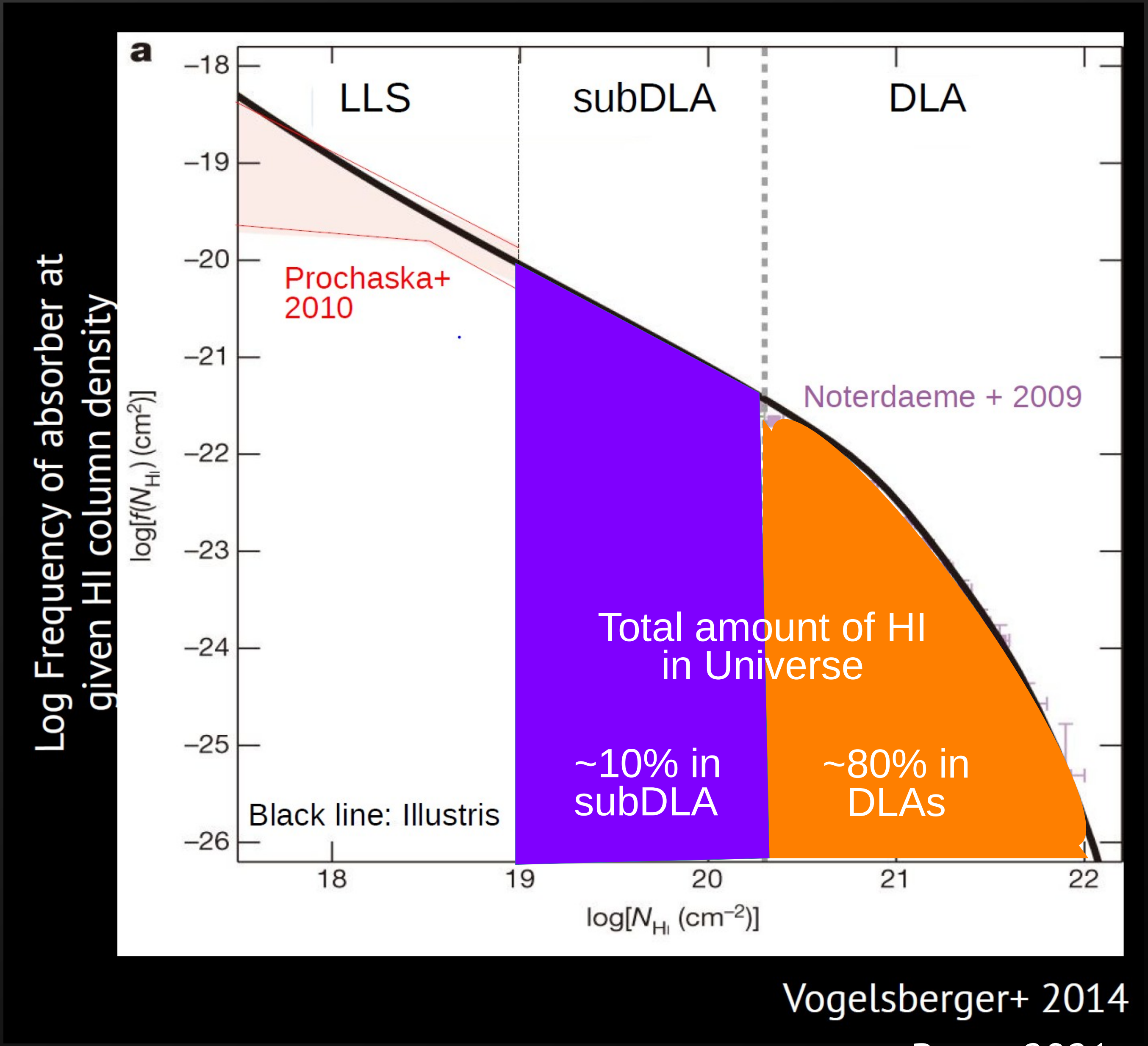
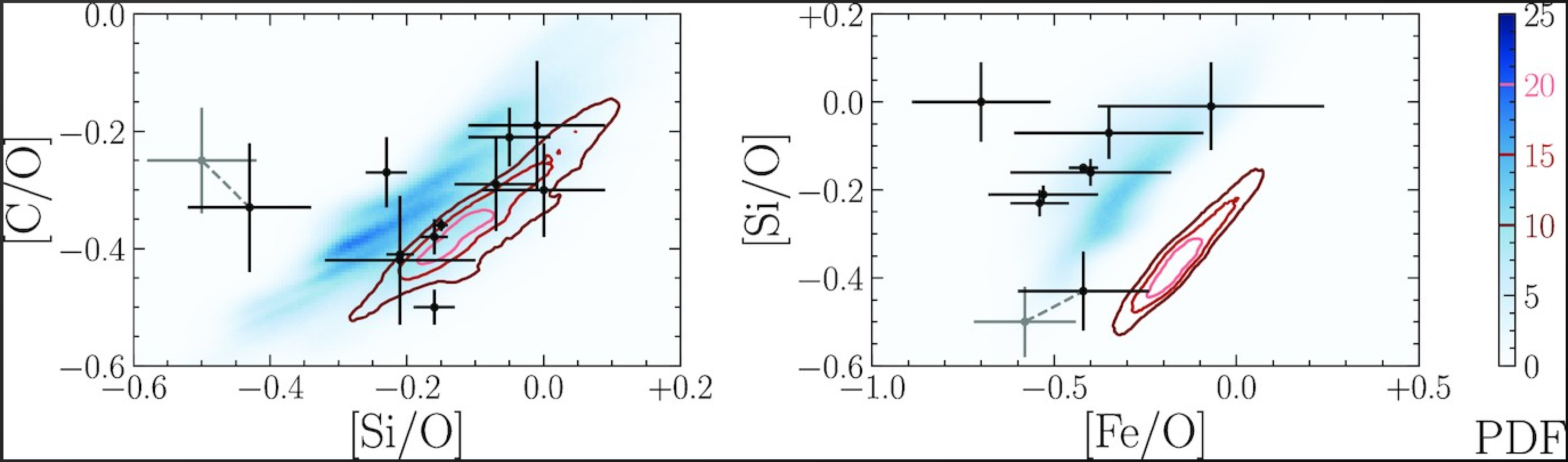


Vogelsberger+ 2014

Berg+ 2021

The role of (sub)DLAs in the Universe

- Seen out to the highest redshift QSOs => chemical evolution across the Universe



Welsh+ 2019

Low explosion energy (2.5E51 ergs)
High explosion energy (5E51 ergs)

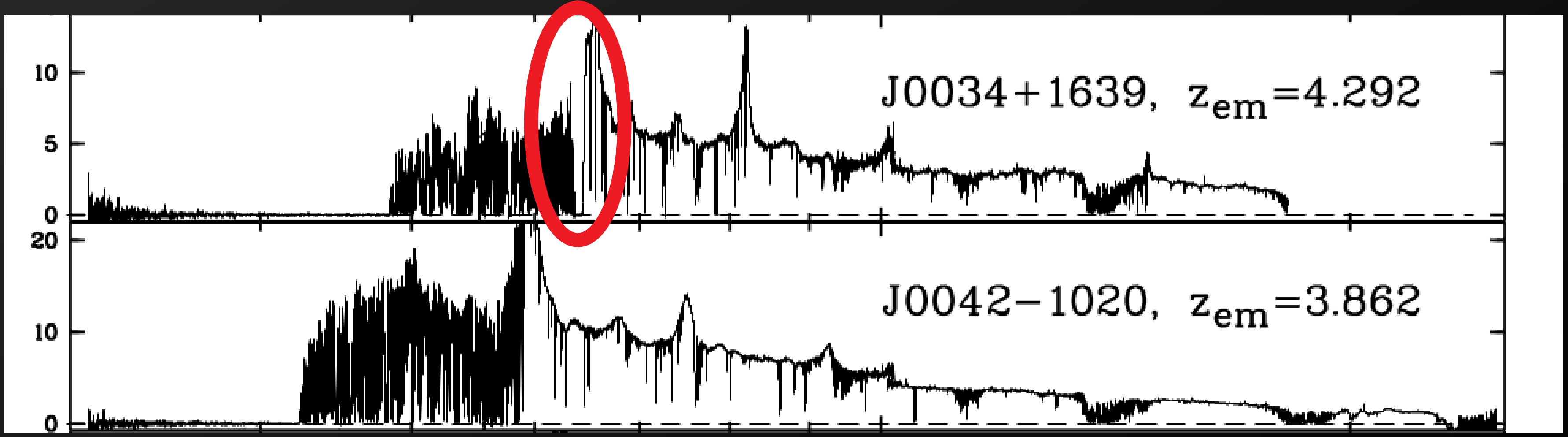
Pop. II vs III enrichment
and SNe properties

The role of (sub)DLAs in the Universe

- Trace the majority of HI gas reservoirs in the Universe
- Seen out to the highest redshift QSOs => chemical evolution across the Universe
- How can we use subDLAs to constrain the first stars?

XQ-100
A legacy survey of “high”-z quasars

- 100 quasars @ redshifts 3.5<z<4.5 observed with X-Shooter (PI: S. Lopez)
- 235 subDLA and DLA absorbers identified based on Ly-series absorption
- Resolution + λ-coverage ideal for chemical evolution

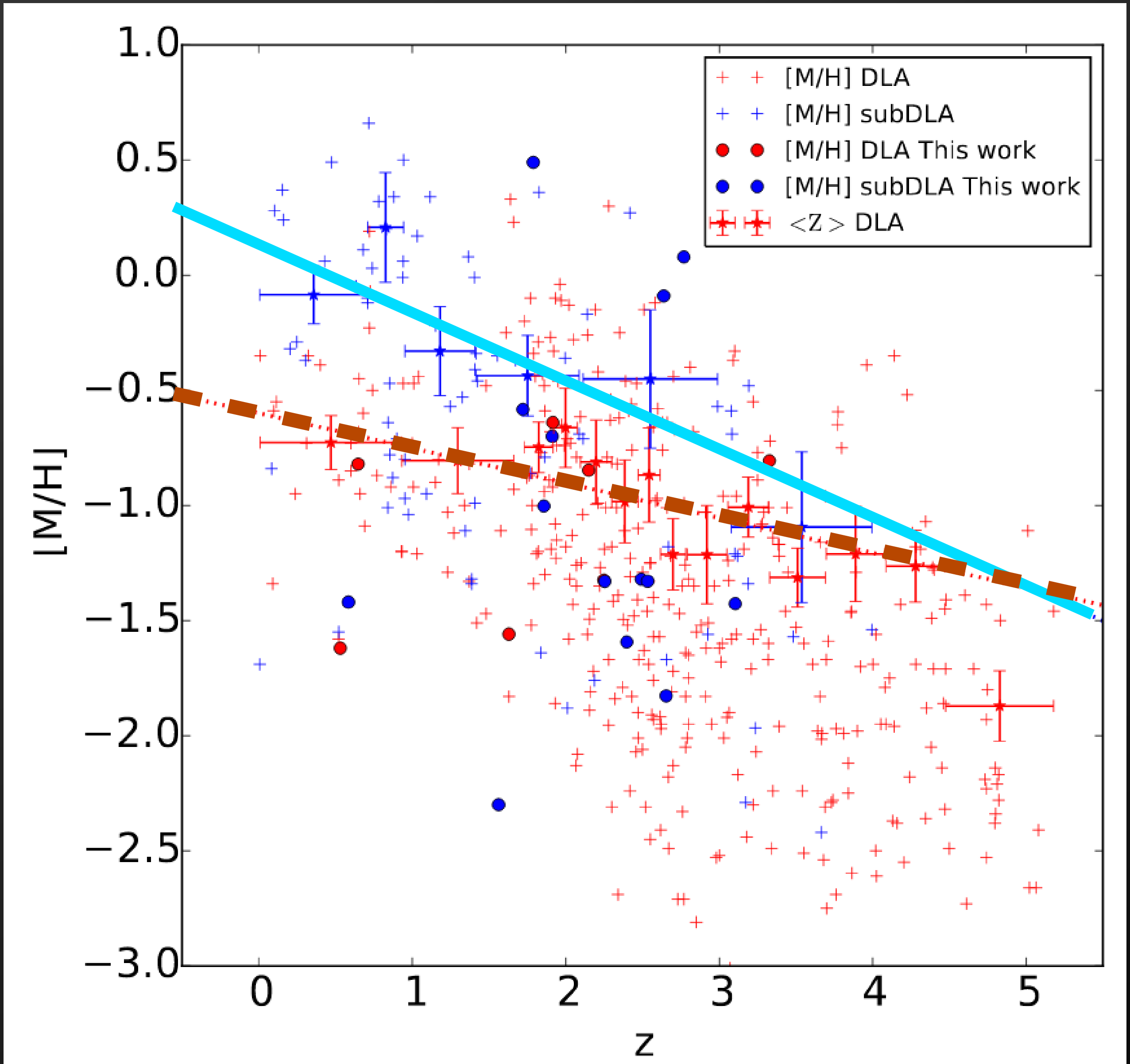


XQ-100
A legacy survey of “high”-z quasars

- 100 quasars @ redshifts 3.5<z<4.5 observed with X-Shooter (PI: S. Lopez)
- Several science topics including:
  - LyA forest power spectrum → Constraining dark matter properties (Irsic+ 2017a, 2017b)
  - Measuring the metallicity of the integalactic medium (D’Odorico+ 2022)
  - Studying proximity effect of QSOs (Perrotta+ 2016, 2018)
  - Intervening strong LyA absorbers (Sanchez-Ramirez+ 2016; Christensen+ 2017; Berg+ 2016,2017,2019, 2021; Saccardi+ 2023)

Cosmic metallicity evolution of (sub)DLAs

Cosmic metallicity evolution of (sub)DLAs



SubDLAs appear to be more metal-rich than DLAs

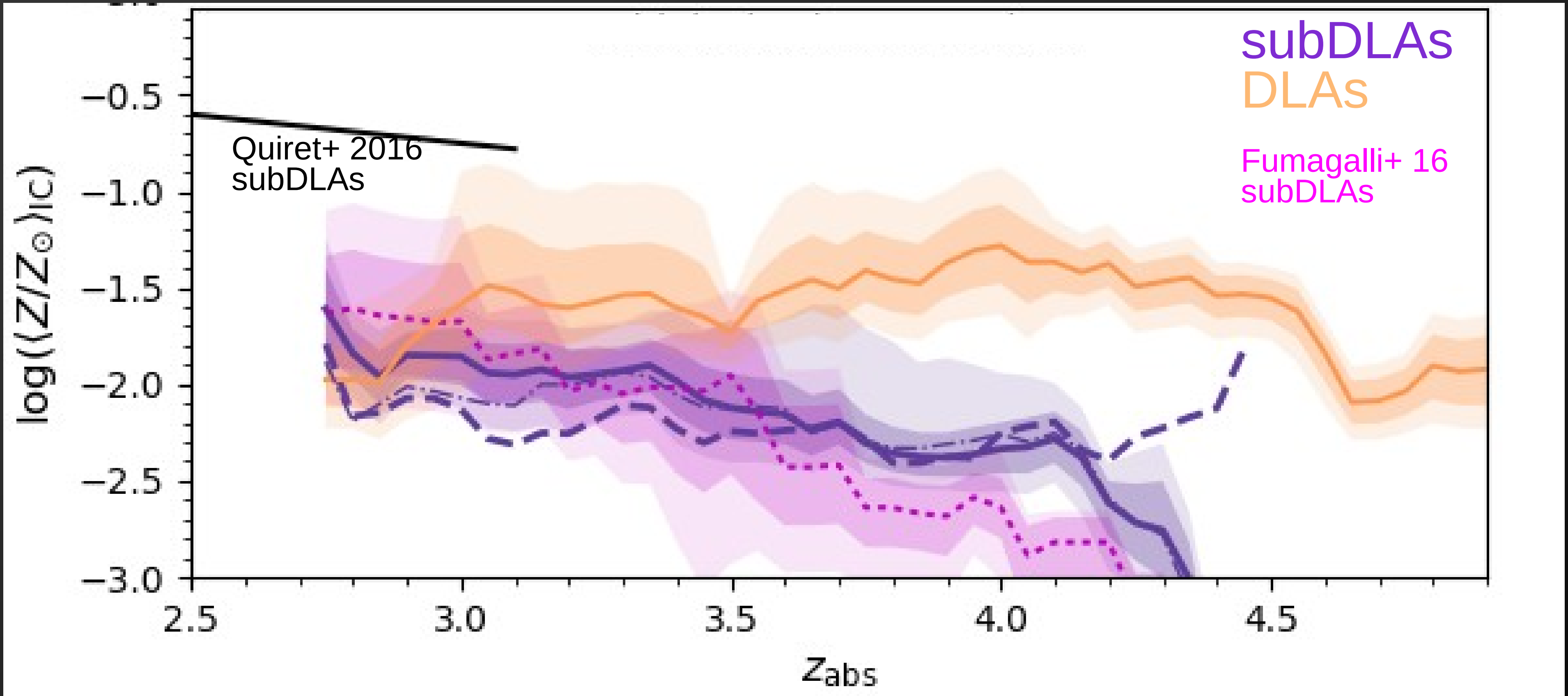
- SubDLAs are gas associated with more massive galaxies?
- Biases in subDLA selection at z<2?

Why is less dense gas more metal rich?

Quiret+ 2016

Metallicity evolution of (sub)DLAs

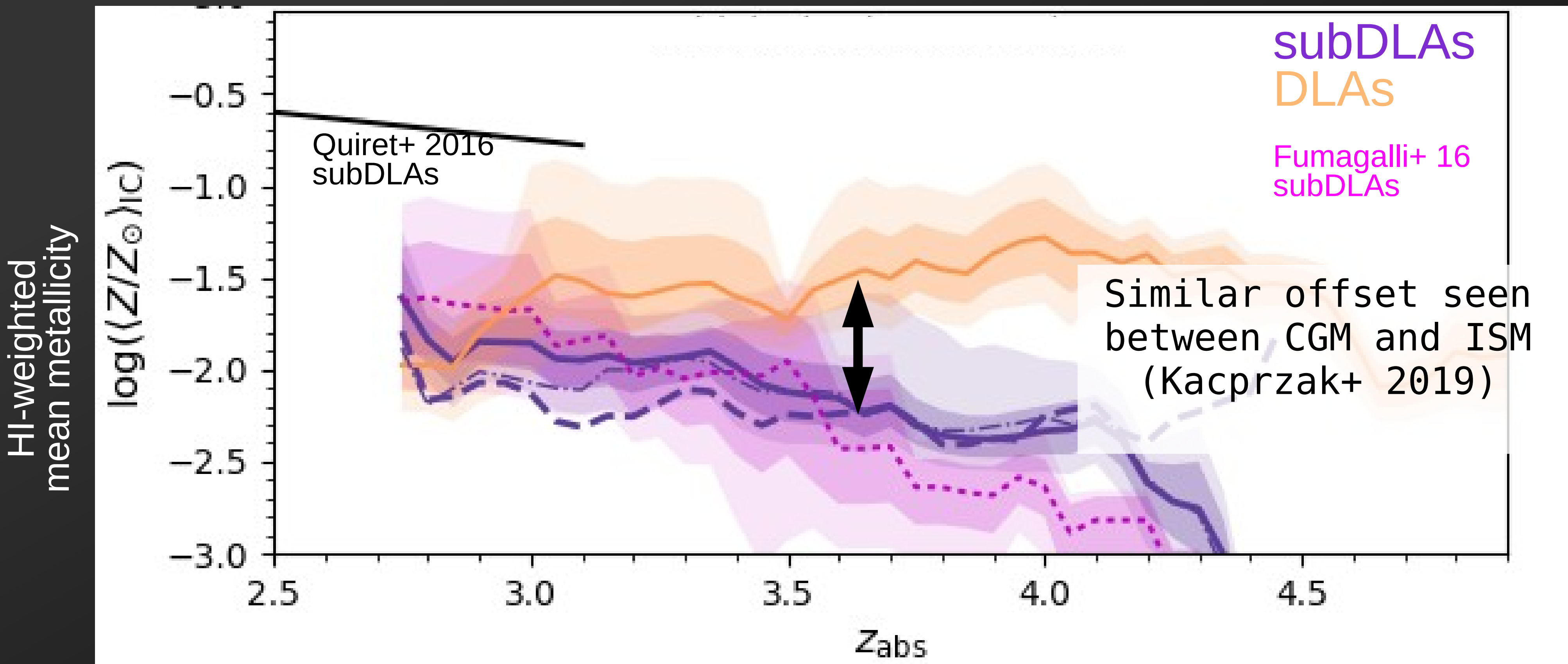
HI-weighted
mean metallicity



Berg+ 2021

With ionization corrections
(Fumagalli+ 2017)

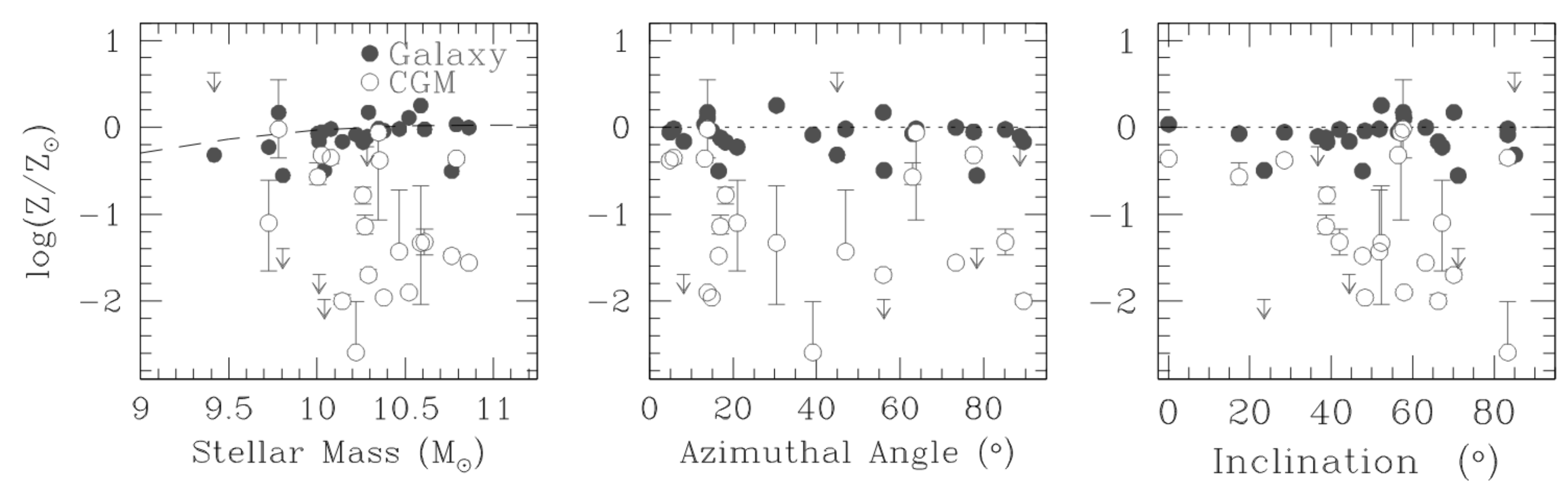
Metallicity evolution of (sub)DLAs



Berg+ 2021

For 2.5<z<4.5, subDLAs are more metal-poor than DLAs - subDLAs trace CGM?

Comparing the metallicty of CGM and ISM

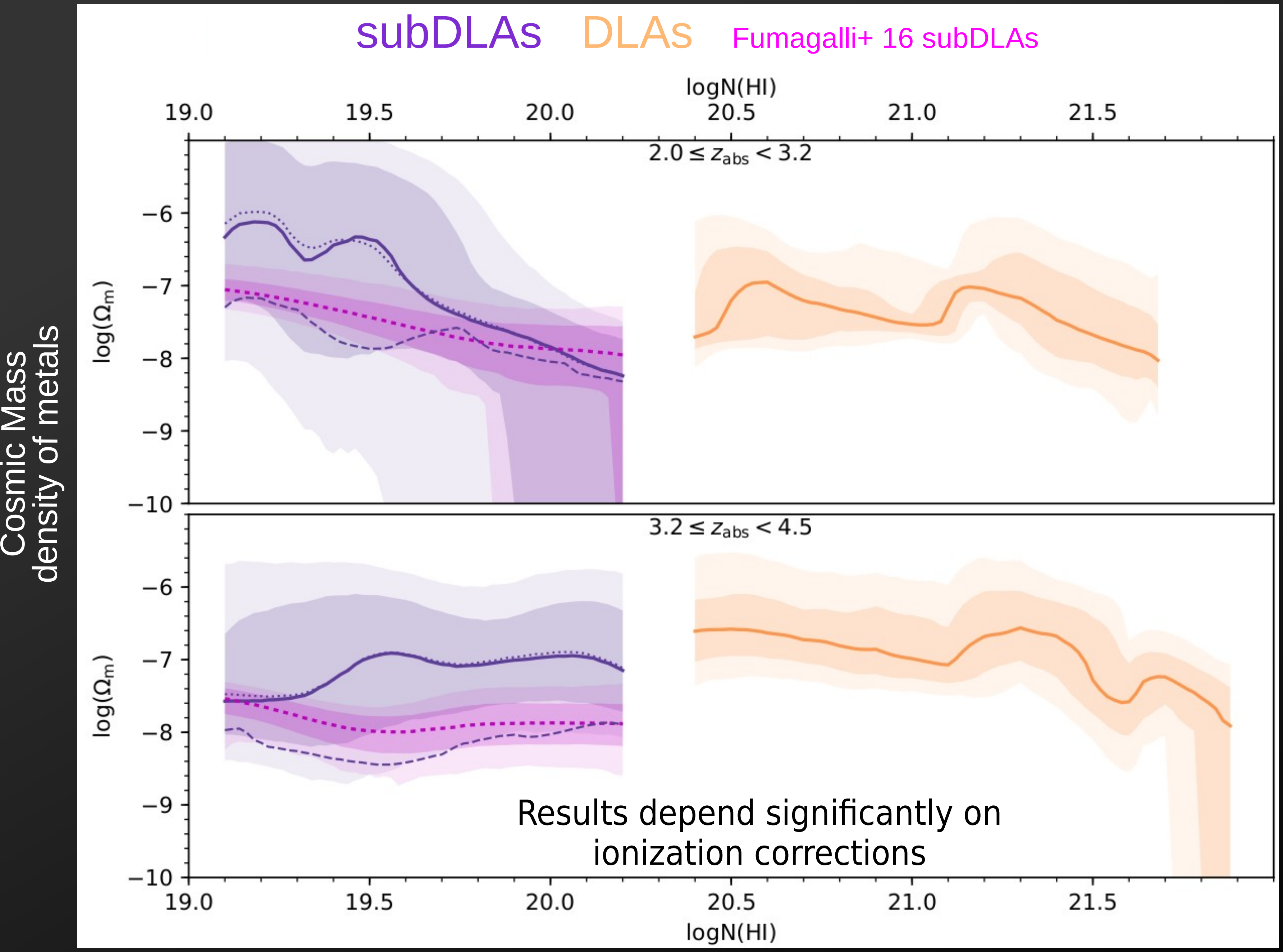


Kacprzak+ 2019

The CGM is more metal-poor than the ISM (at $z<0.5$)

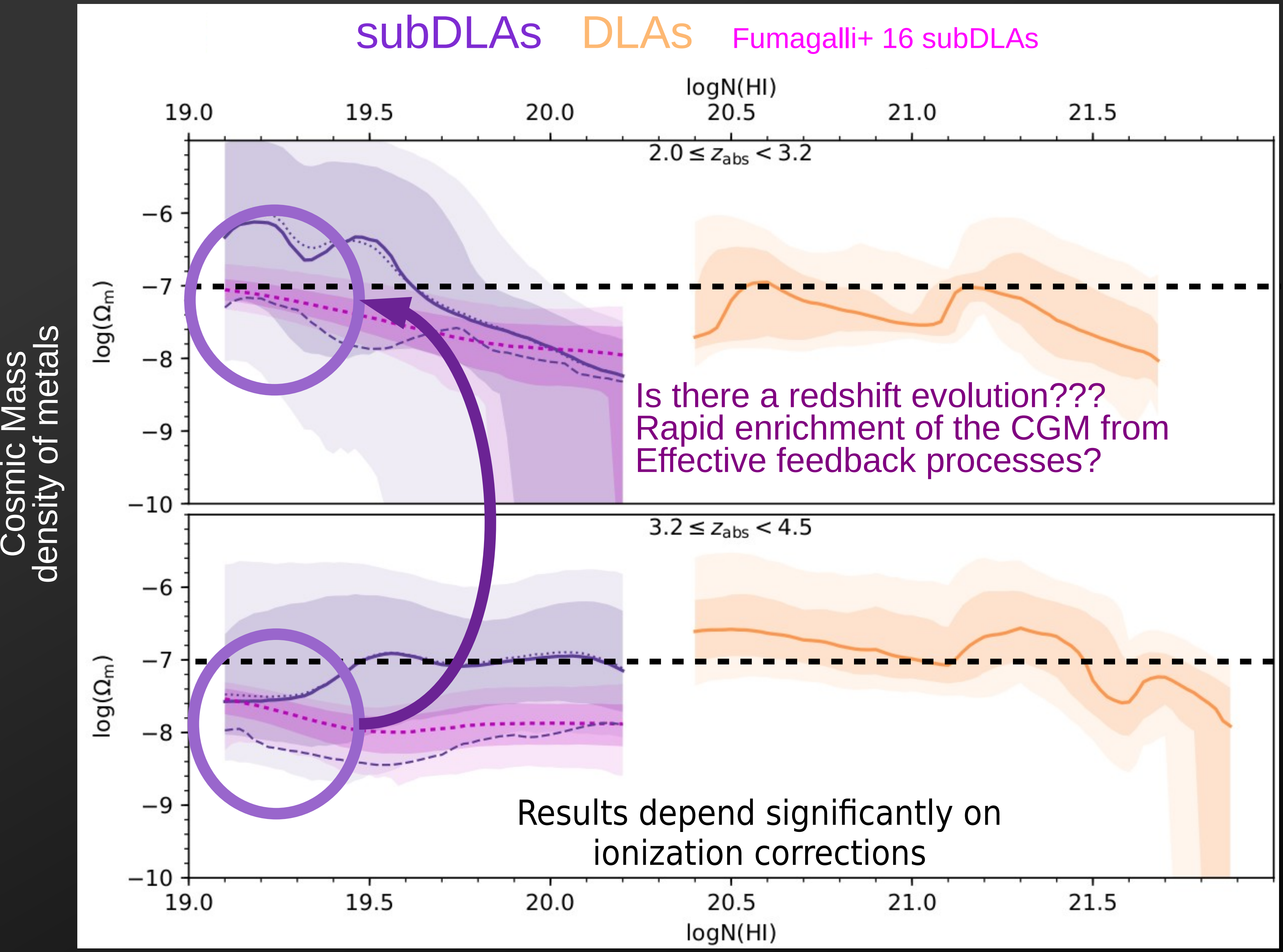
Delay in metal-enrichment? Dilution from IGM accretion?

How much metal mass is in (sub)DLAs?



Berg+ 2021

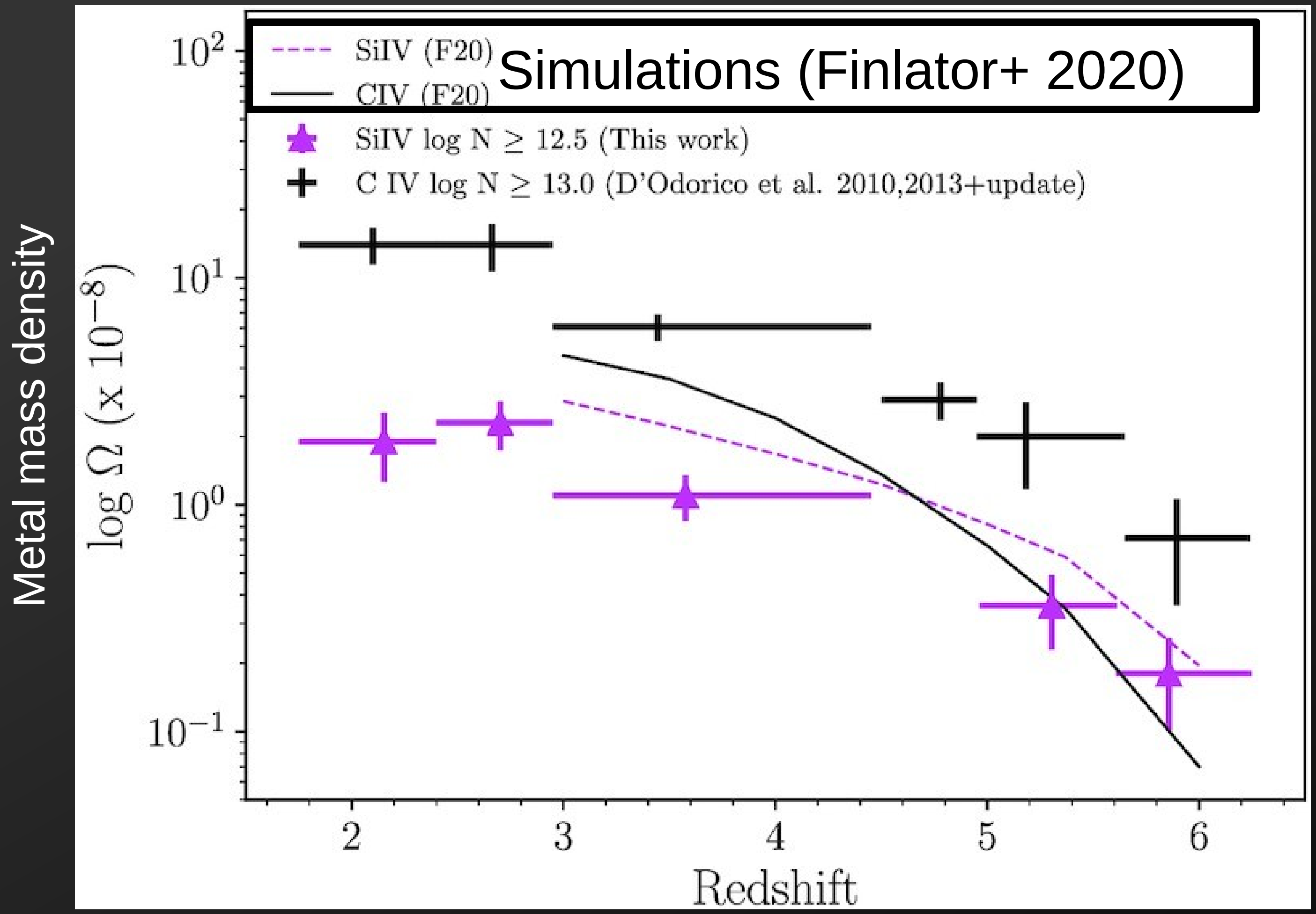
How much metal mass is in (sub)DLAs?



See also
D'Odorico+22
for C IV
& Si IV

Berg+ 2021

Metal enrichment in highly-ionized gas



D'Odorico+ 2022

Simulations struggle to reproduce simultaneously both CIV and SiIV statistics

=> Constraints on feedback and ionization implementation in simulations

Cosmic metallicity evolution of (sub)DLAs

- SubDLAs, on average, more metal-poor than DLAs at 2<z<4
  - More frequent than subDLAs – good place to measure detailed chemical abundances of the first stars?
  - These low HI column densities, likely tracing CGM, are sensitive to feedback – enrich rapidly?

Chemical abundance ratios of (sub)DLAs

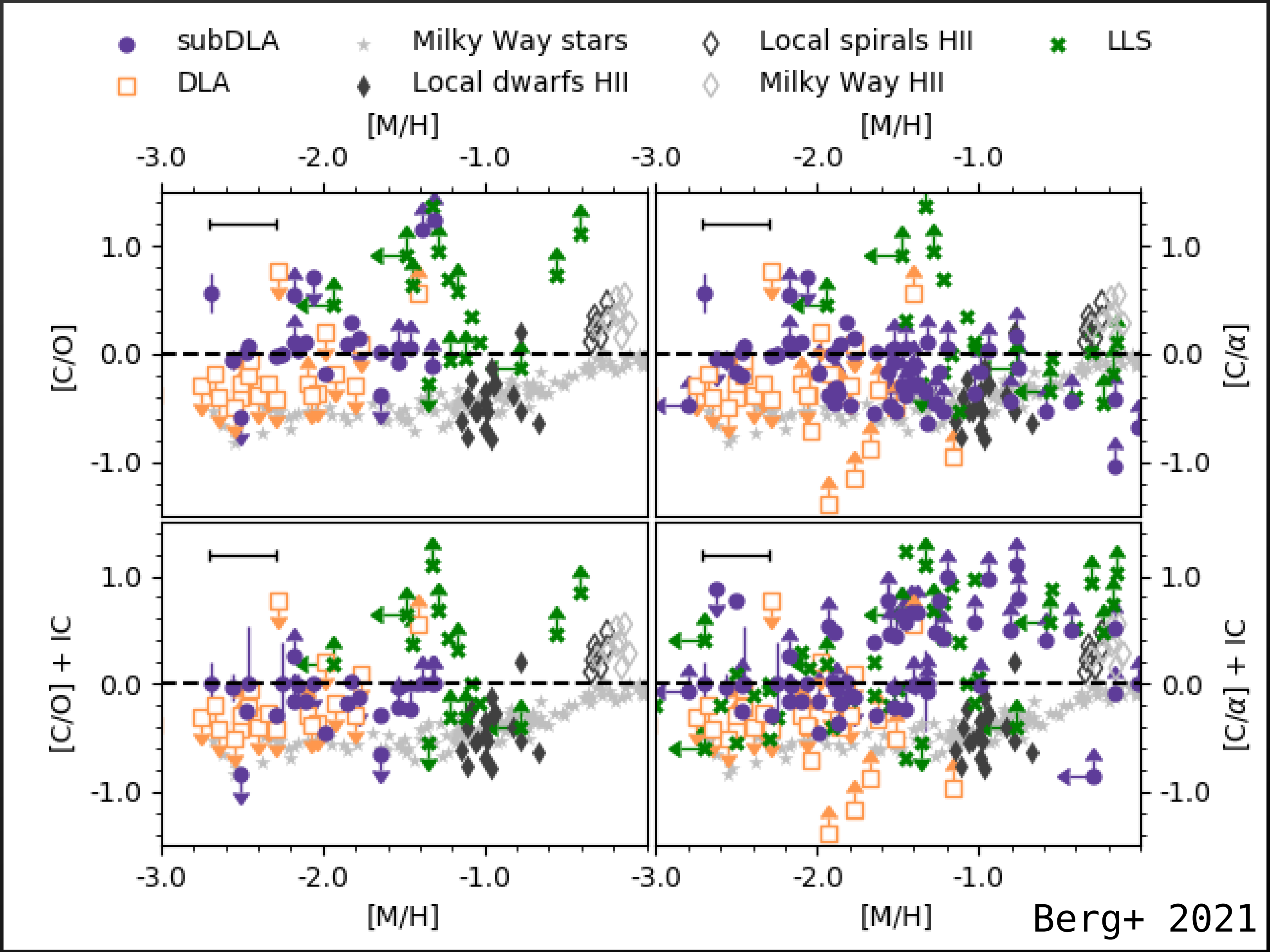
How do chemical abundances in metal-poor subDLAs compare to other metal-poor probes?

Detailed abundances: [C/O]

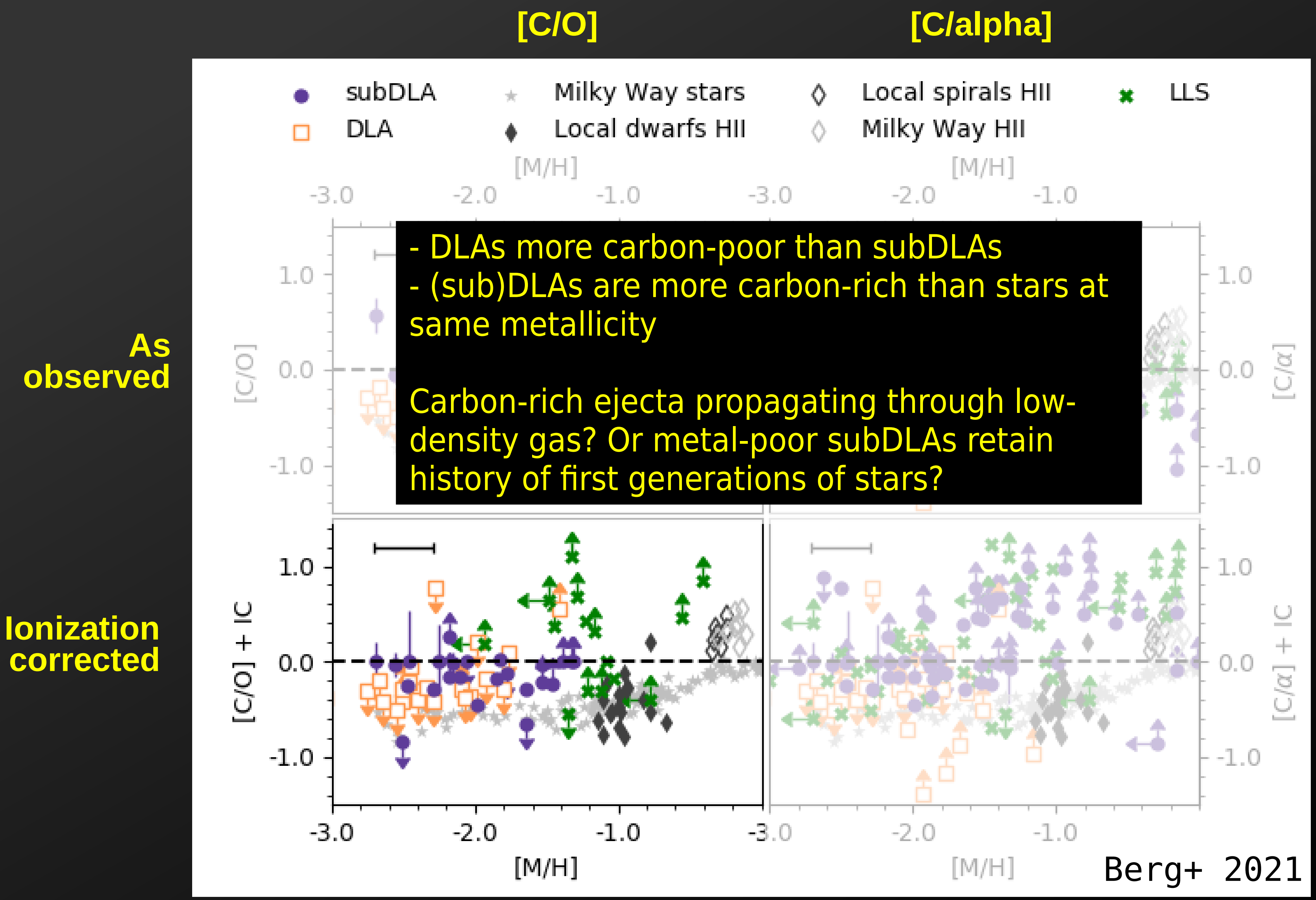
[C/O] **[C/alpha]**

As observed

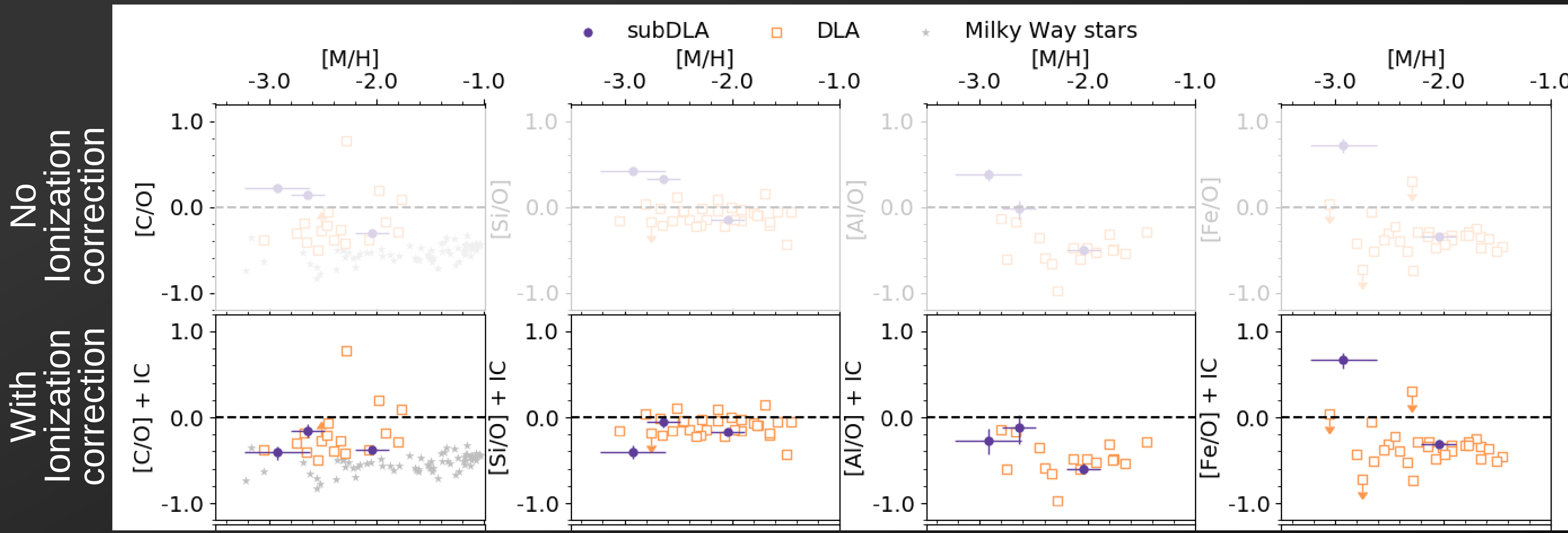
Ionization corrected



Detailed abundances: [C/O]



A closer look with UVES



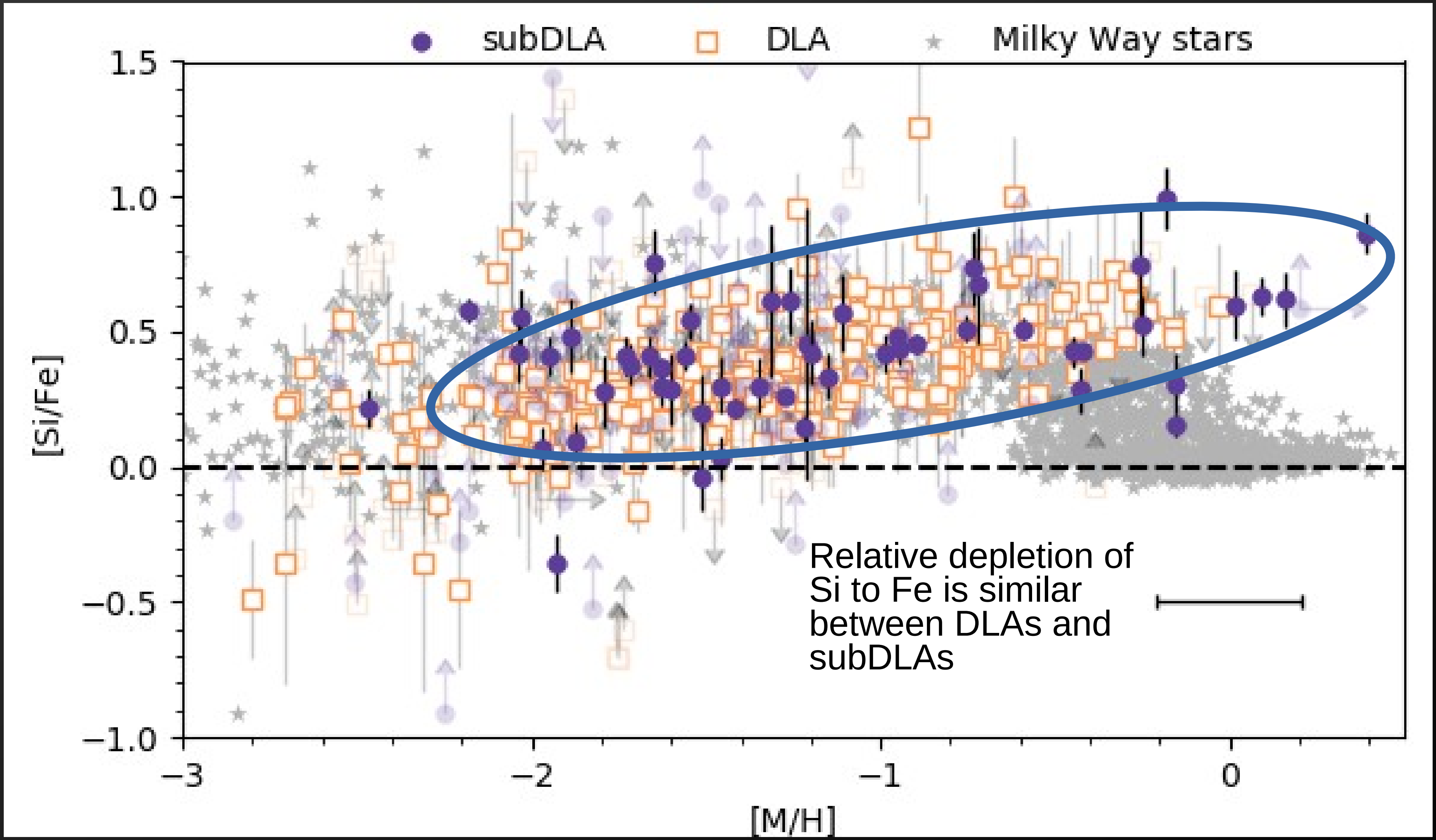
Berg+ (in prep)

Metal-poor subDLAs and DLAs seem to be roughly consistent with eachother:

[C/O] relatively high compared to stars

[Al/O] decreases with metallicity?

[Si/Fe] – a quick comment on dust

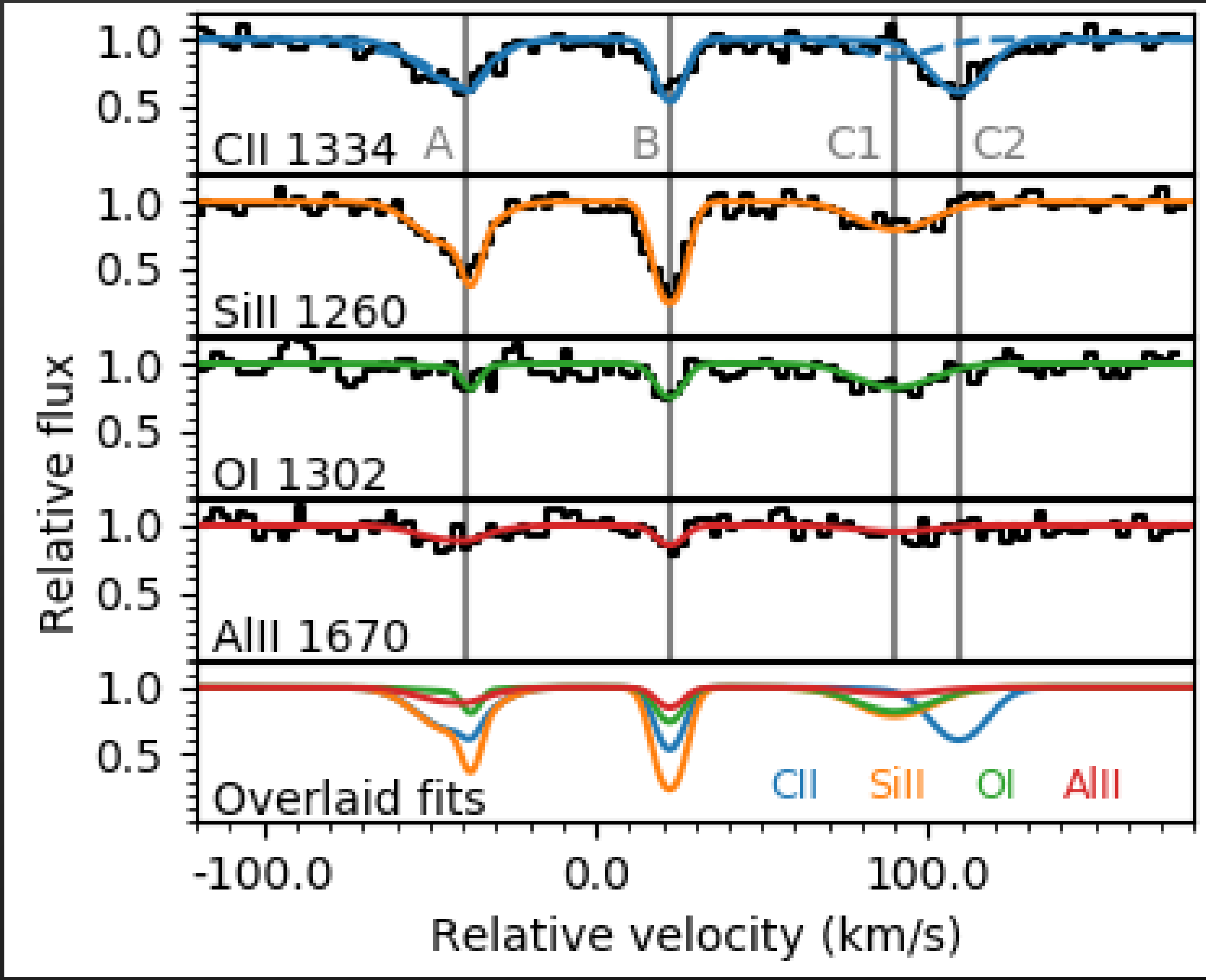


Berg+2021

Chemical homogeneity – multiplicity in Pop. III environments

- DLAs typically show the same chemical abundance ratio for each component
- Metal-poor subDLAs don't…?
  - Ionization effect or multiplicity in nucleosynthesis?

Chemical homogeneity – multiplicity in Pop. III environments



SubDLA with inhomogenous abundance ratio?

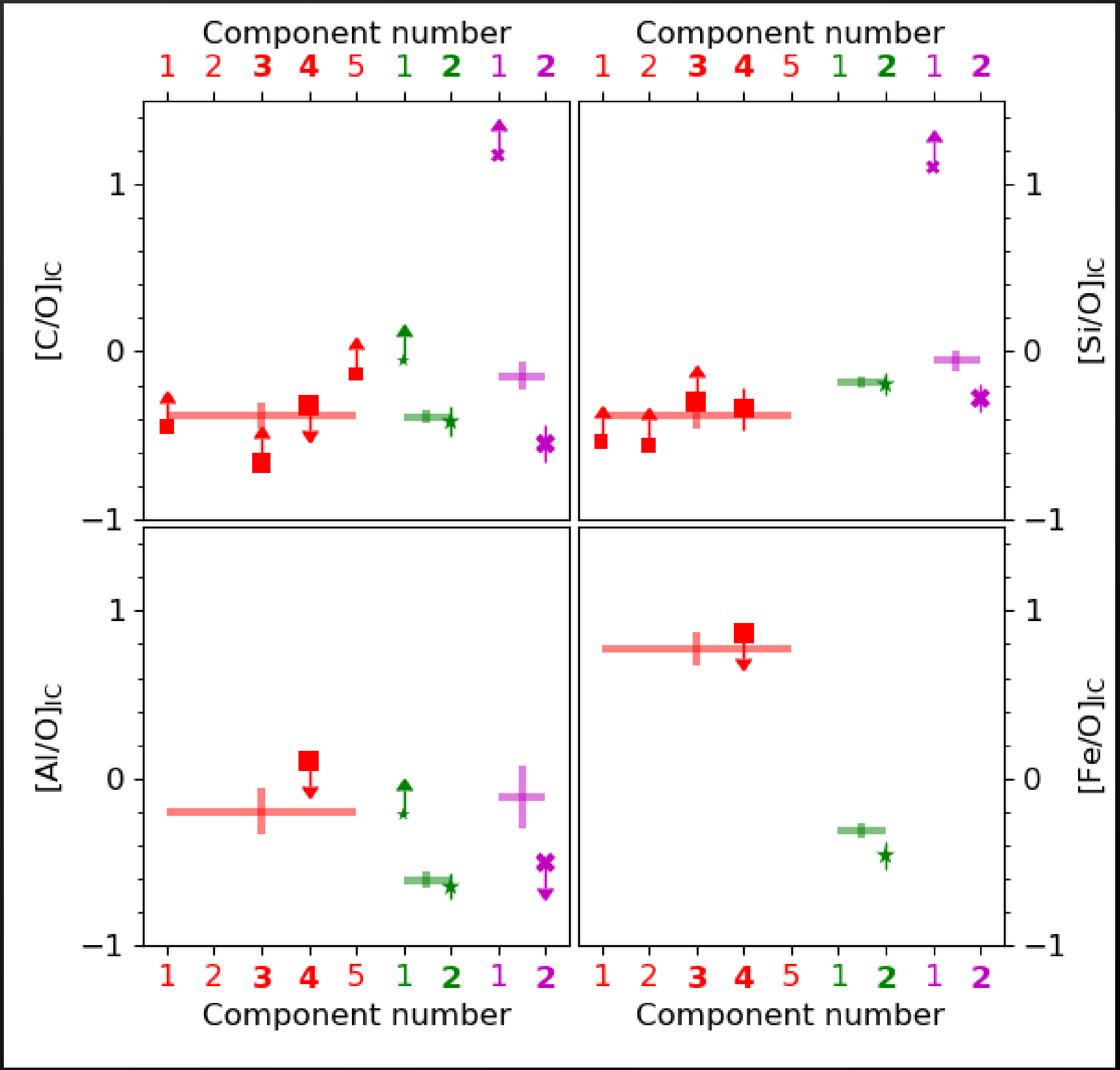
E.g. Si/O in Component c1 similar but OI much weaker in A/B

Al/O is relatively stronger in component A than all others.

Chemical homogeneity – multiplicity in Pop. III environments

Chemical abundances per component in 3 systems (different colours)

Solid lines – average value of absorber
Points – component value



Berg+ (in prep)

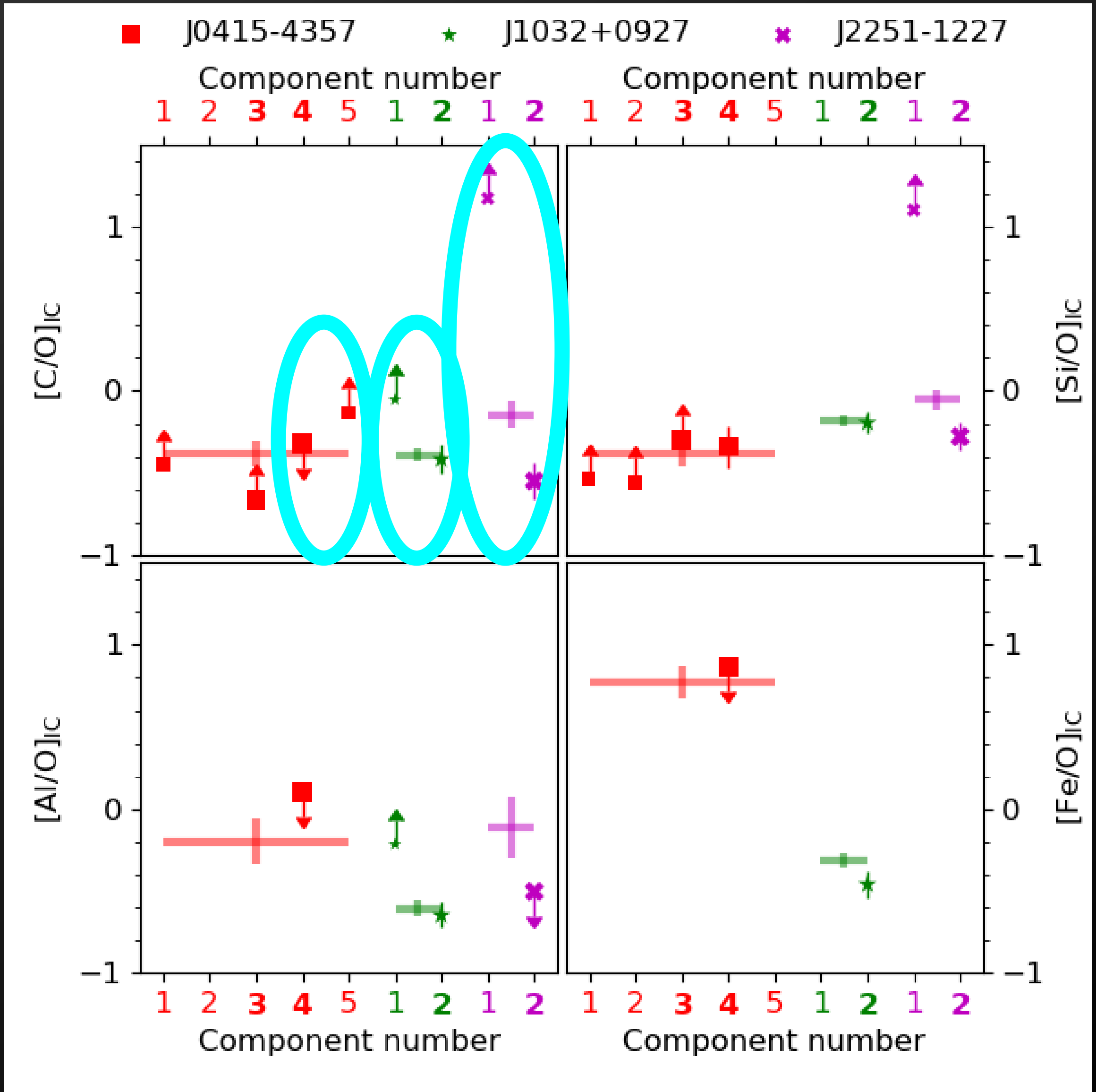
Chemical homogeneity – multiplicity in Pop. III environments

Chemical abundances per component in 3 systems

Solid lines – average value of absorber
Points – component value

[C/O] in at least one system shows discrepancies between components

Need better S/N to really hammer down these limits!



Berg+ (in prep)

Take away summary

- SubDLAs show similar metallicty evolution as DLAs; but on average metal-poor

- (sub)DLAs great place to constrain chemical enrichment at high redshifts
  - SubDLAs ~5x more frequent – build larger samples!
  - Metal-poor systems may be showing inhomogeneous material; stay tuned!

Ionization corrections

Question for YOU! – What intrinsic abundance pattern should be assumed for ionization corrections?

Typically solar abundance pattern assumed; results do not change much for [M/H] ~ -2 (Fumagalli+ 17)

Can we assume a constant [Si/O] rather than a pattern?