The metallicity of the CGM gas over cosmic times

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– *In collaboration with:* –

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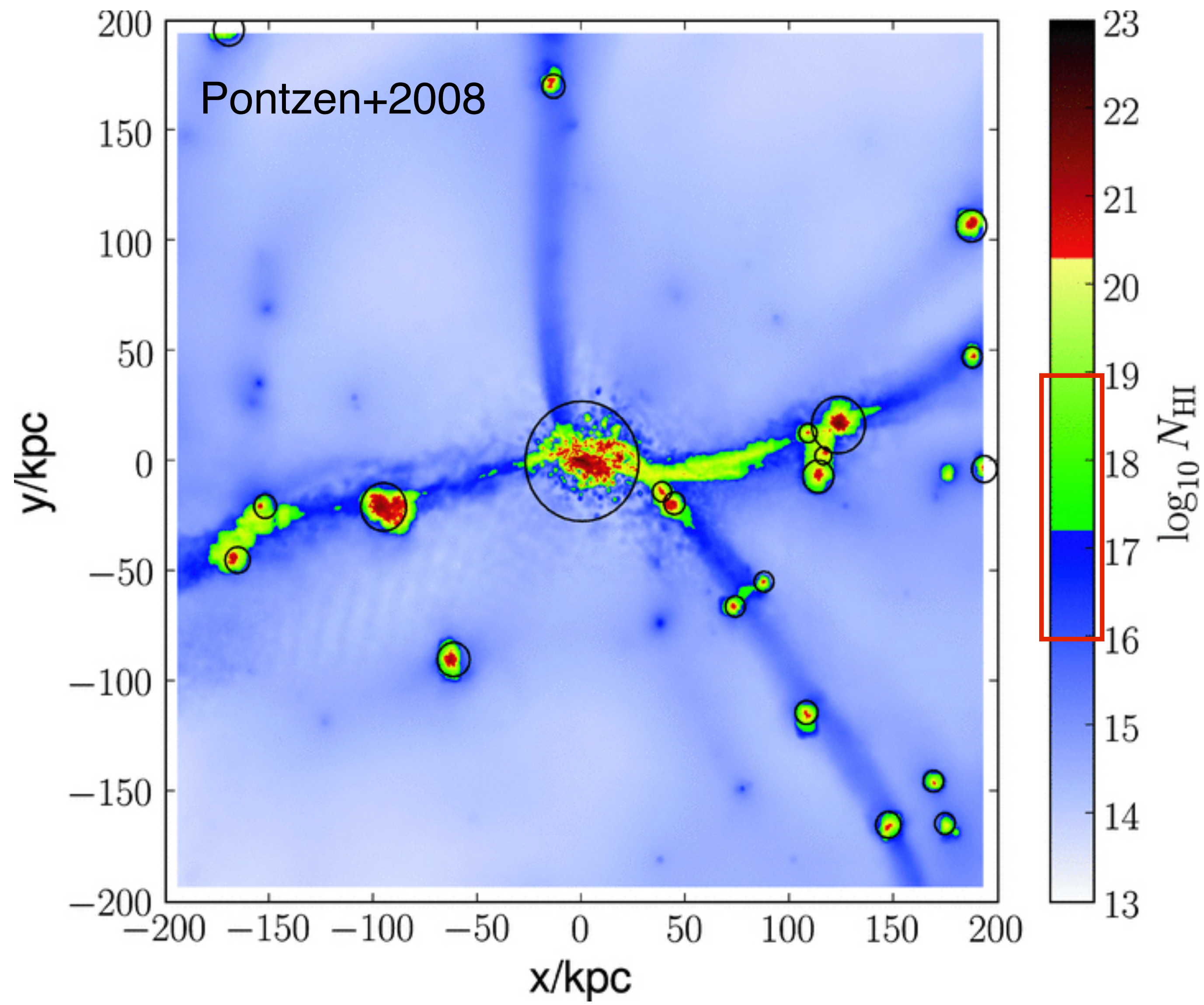
Xavier Prochaska, Jason Tumlinson, Rongmon Bordoloi, Jess Werk, Todd Tripp, Joe Ribaudo

A strategy to study the dense CGM: Lyman Limit Systems

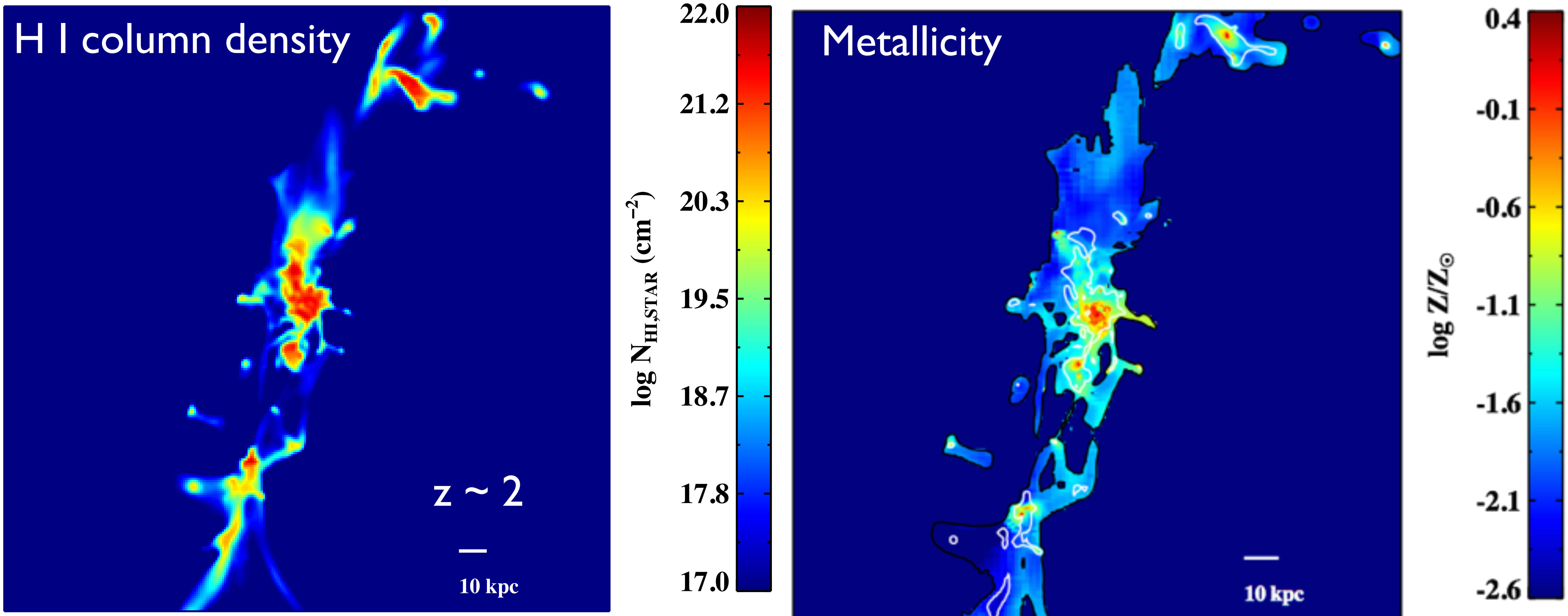


Target absorbers with H I column densities of
16.1 ≤ log N(H I) < 19

These are "Lyman limit systems" (LLSs).

These LLSs are associated with dense CGM streams empirically (Lanzetta+1995; Penton +2002; Bowen+2002; Chen+2005; Rudie+2012) and theoretically (Fumagalli+2011; Faucher-Giguère & Kereš 2011; van de Voort+2012).

HI column density/metallicity map in simulations



Fumagalli+ (2011)

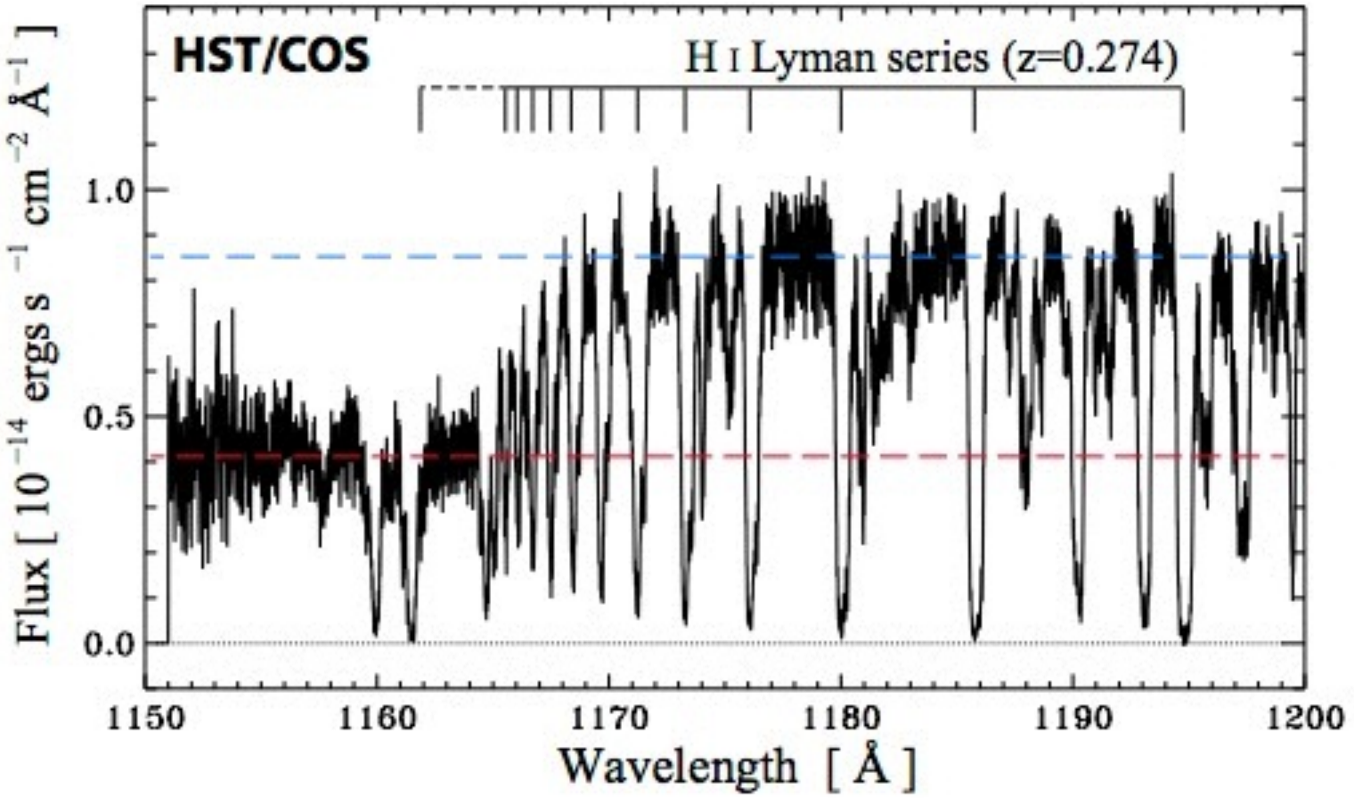
Streams in the CGM predicted to have:

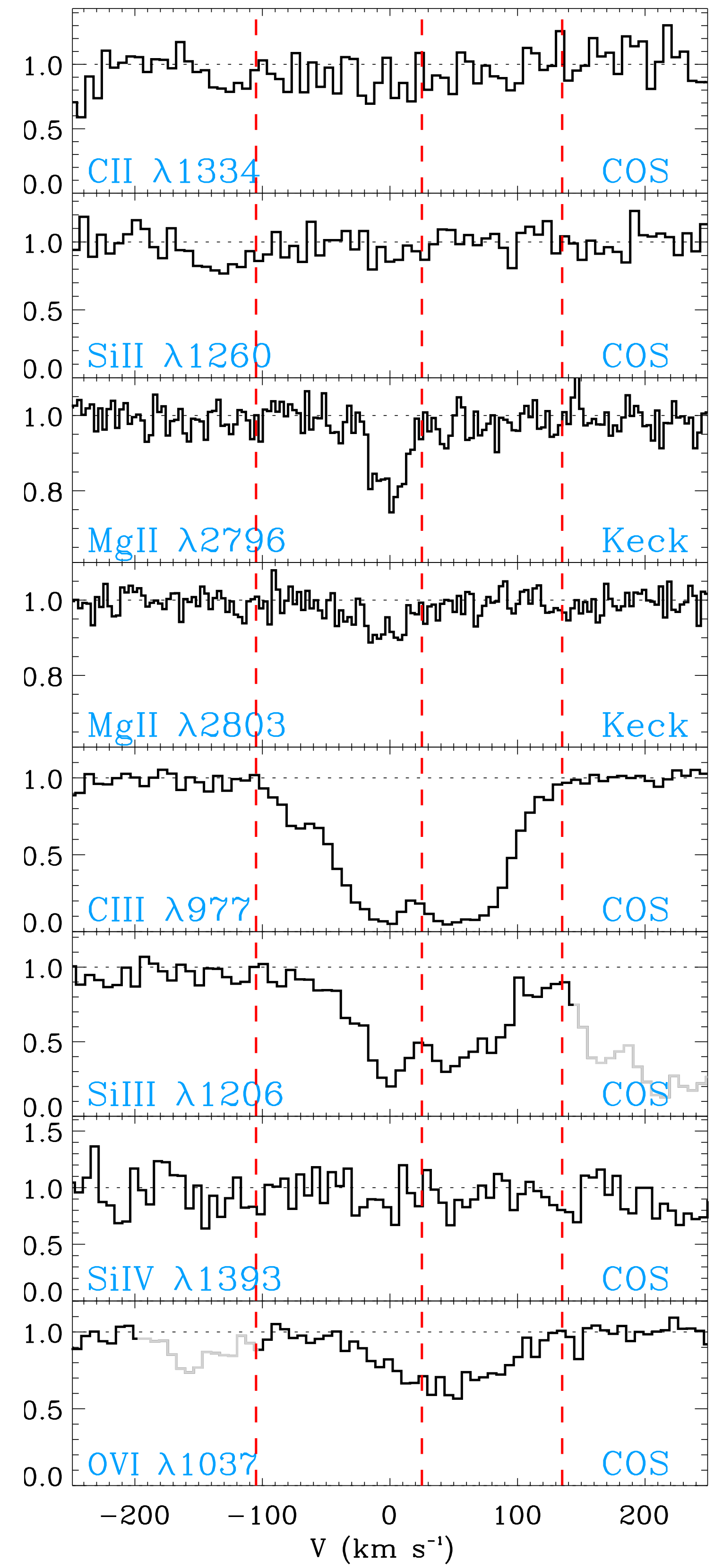
- LLS-like column densities
- Large ionization fractions
- Metallicity: $\langle Z \rangle \sim 10^{-2} Z_\odot$ to $>1 Z_\odot$

We use the metallicity of the cool gas probed LLSs as a "tracer" of the origins of the gas.

LLSs are HI-selected in order to *not bias the selection in terms of metallicities.*

HI-selection of strong HI absorbers





Ribaudo+ (2011)

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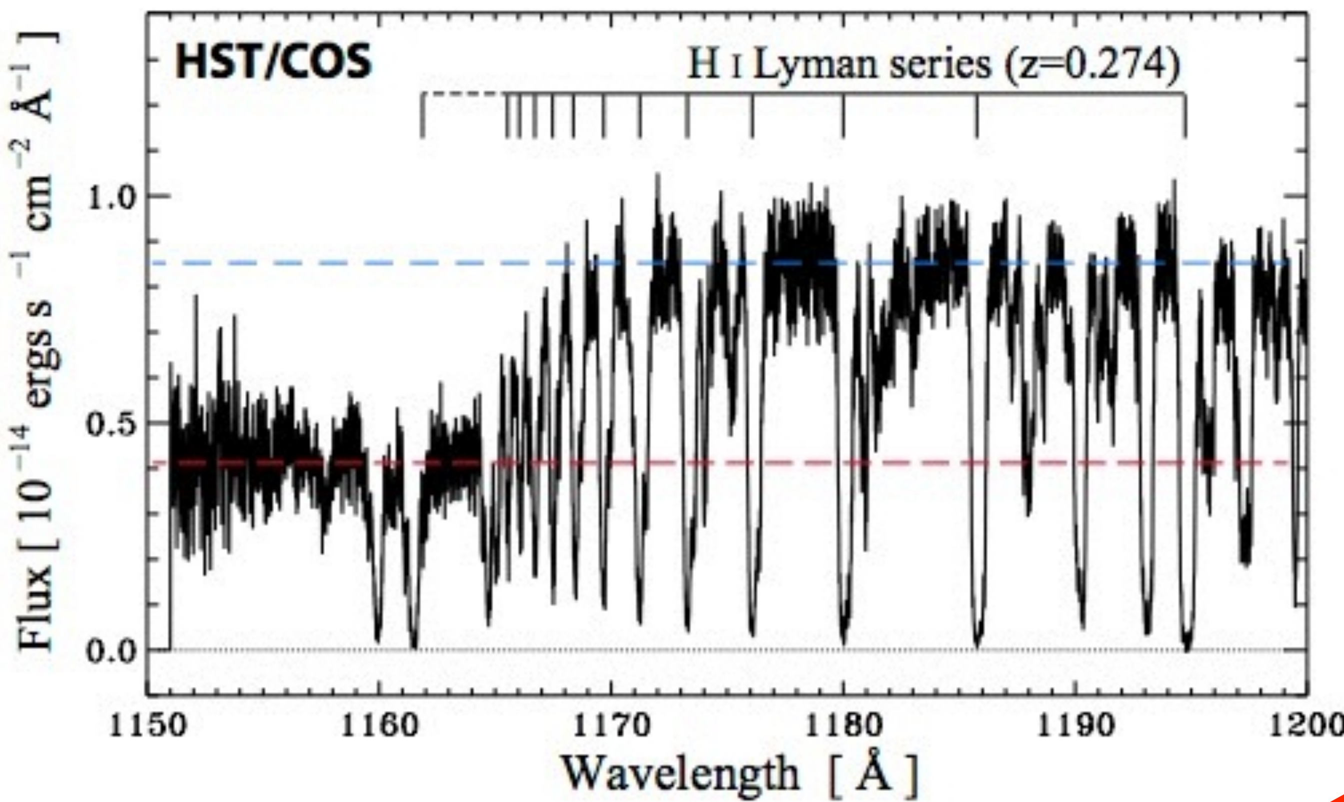
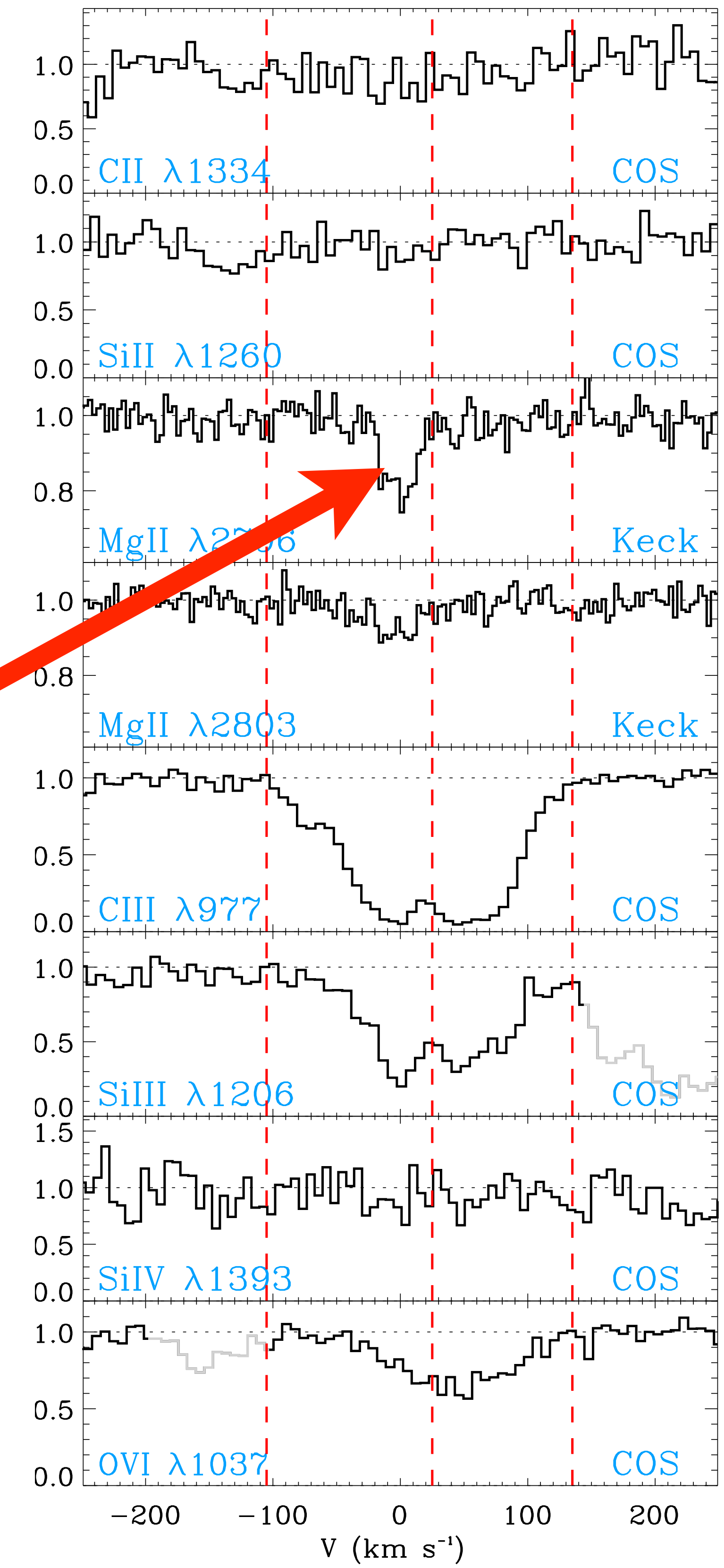
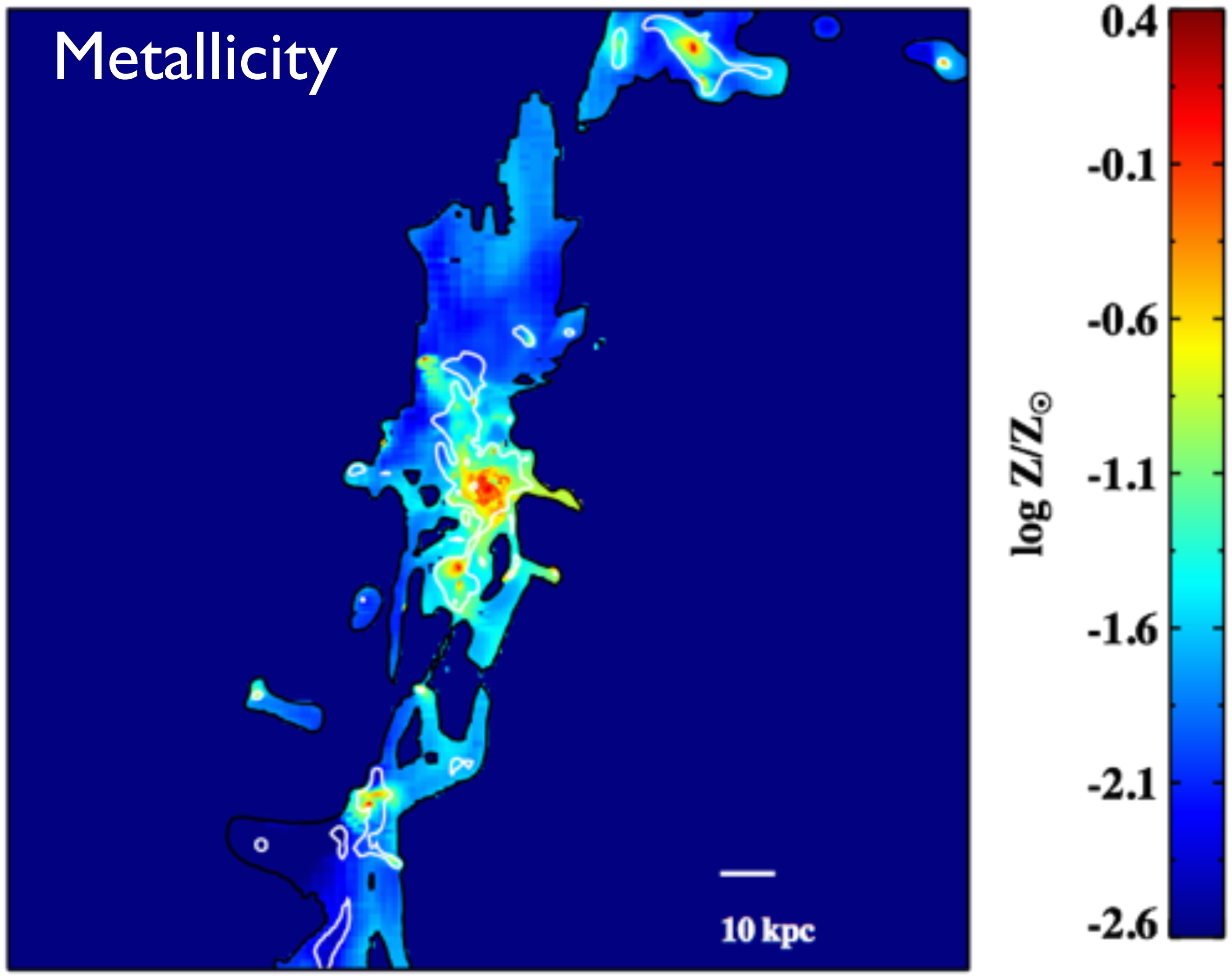




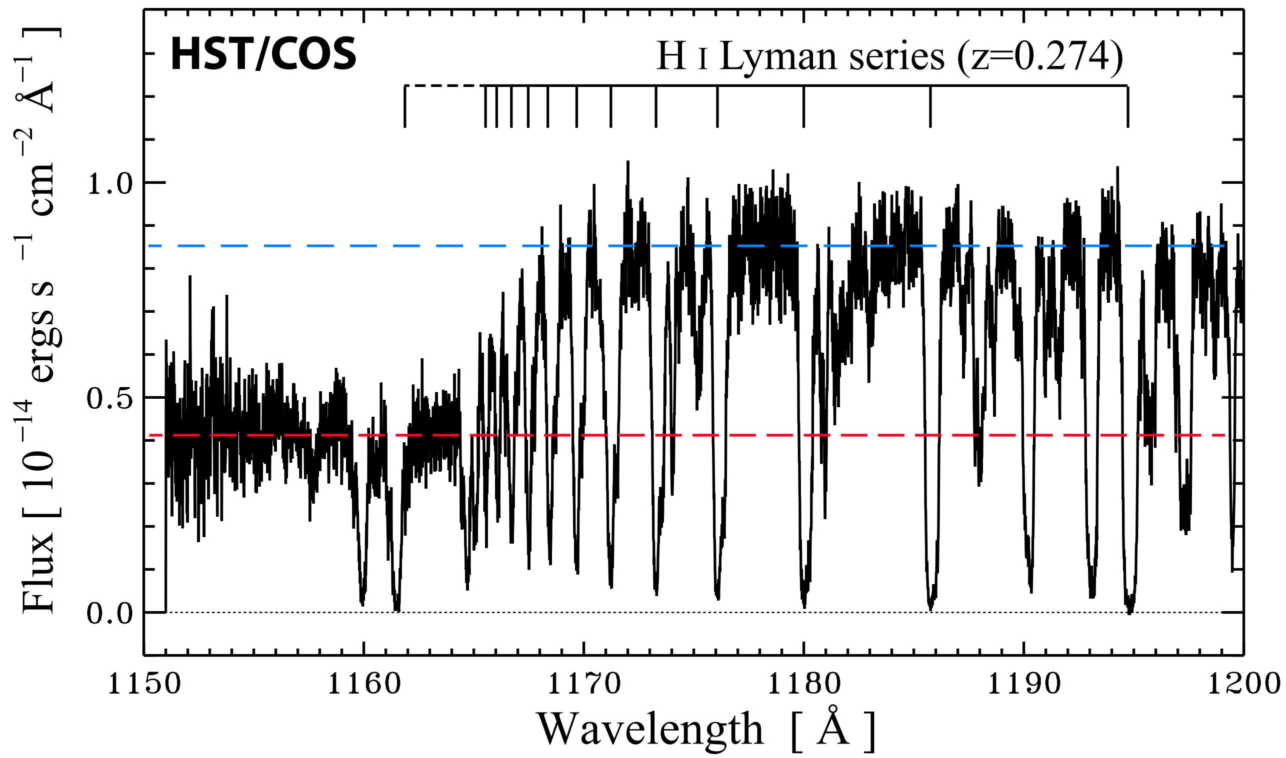
Weak Mg II!

Ribaudo+ (2011)

Key goal: Determining evolution of the CGM over 12 billion years of cosmic time



Fumagalli+ (2011)

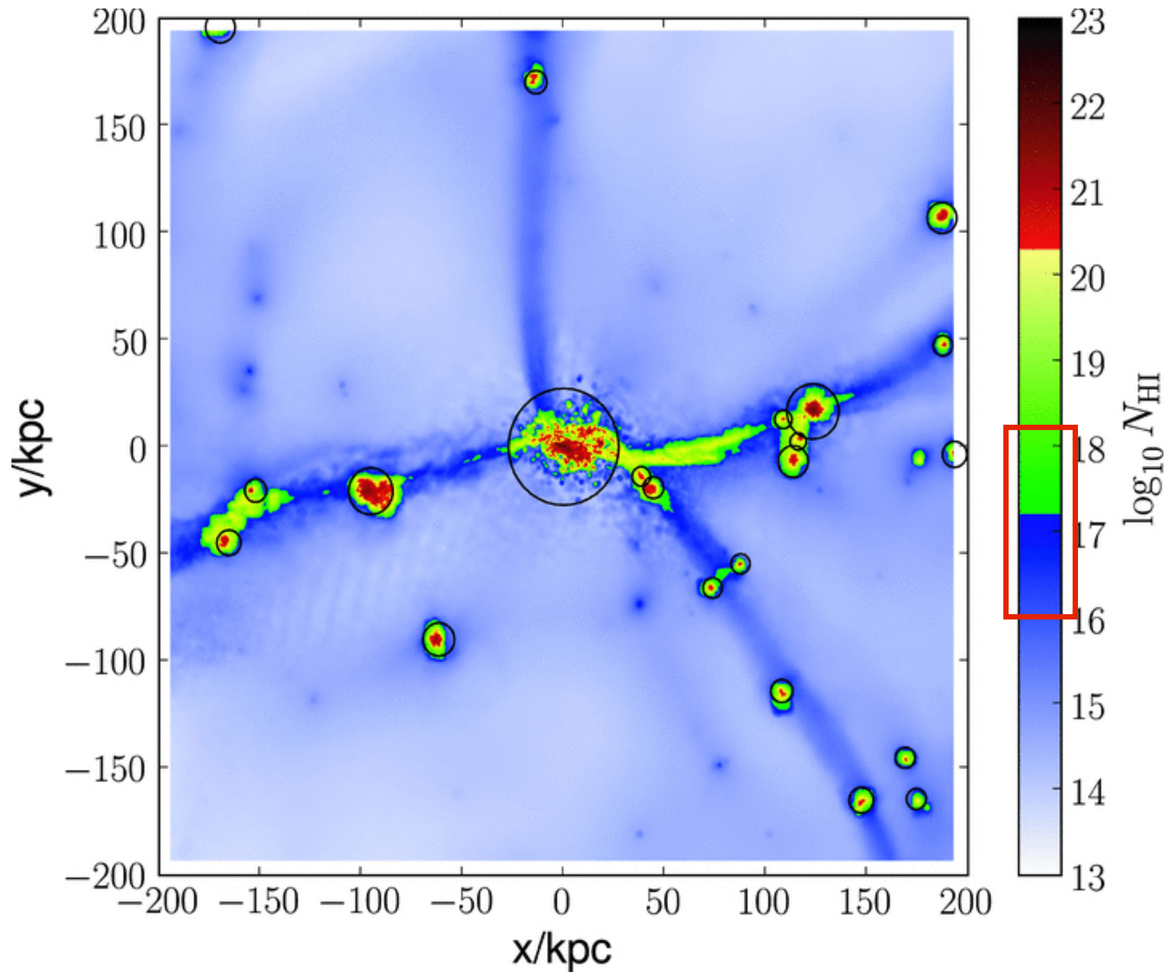


What is the metallicity distribution function (MDF) of the dense CGM?

How does the MDF change as a function of N_{HI}?

How does the MDF evolve with redshift?

The MDF of the LLSs/CGM at z<1



Sample of 28 HI selected LLSs at z<1

- Data: HST COS G130M/G160M data
- Full UV wavelength coverage
- [X/H]: X = Mg, Si, O (α-elements)
- MgII, SiII, SiIII, CII, CIII (SiIV), OI, OII, (OIII)
- Large ionization correction to derive [X/H] (uncertainty on [X/H] ~0.3-0.4 dex)
- dust depletion typically negligible.

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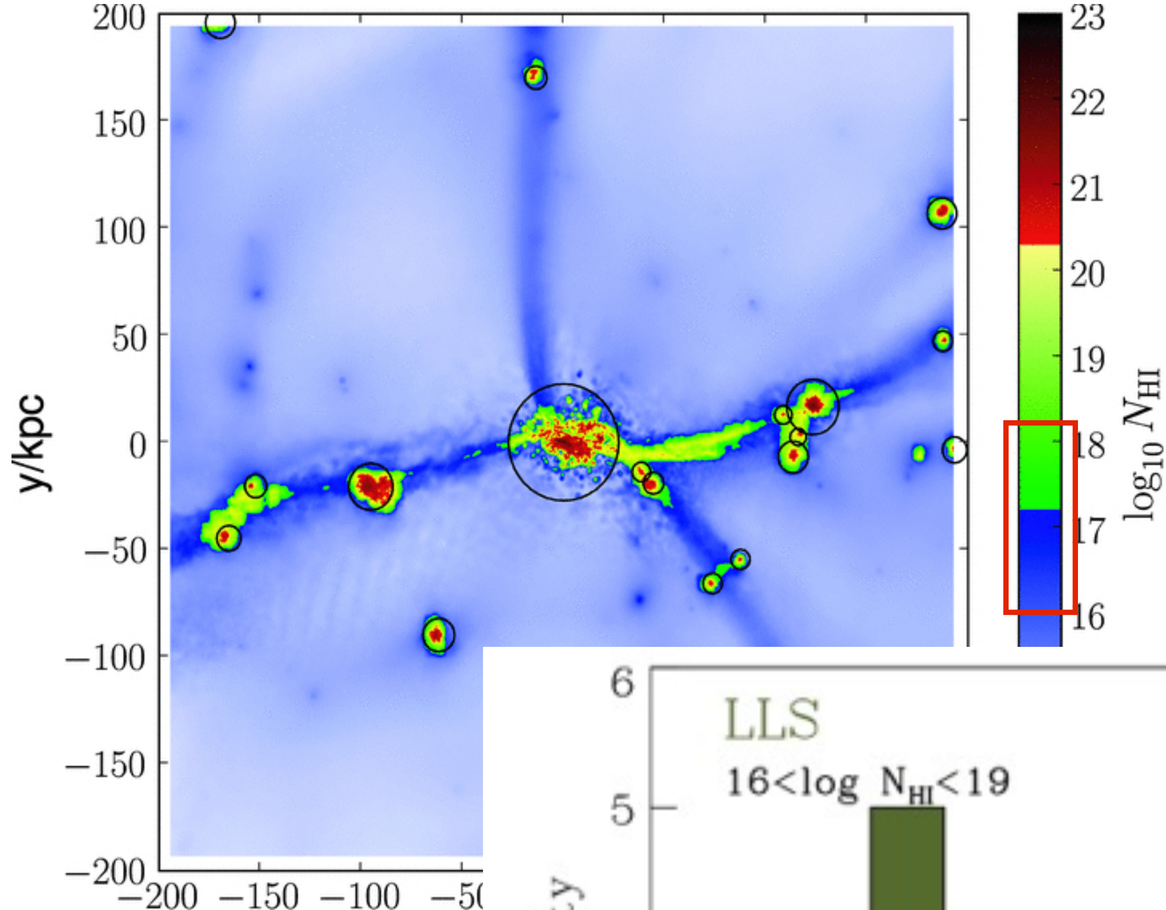

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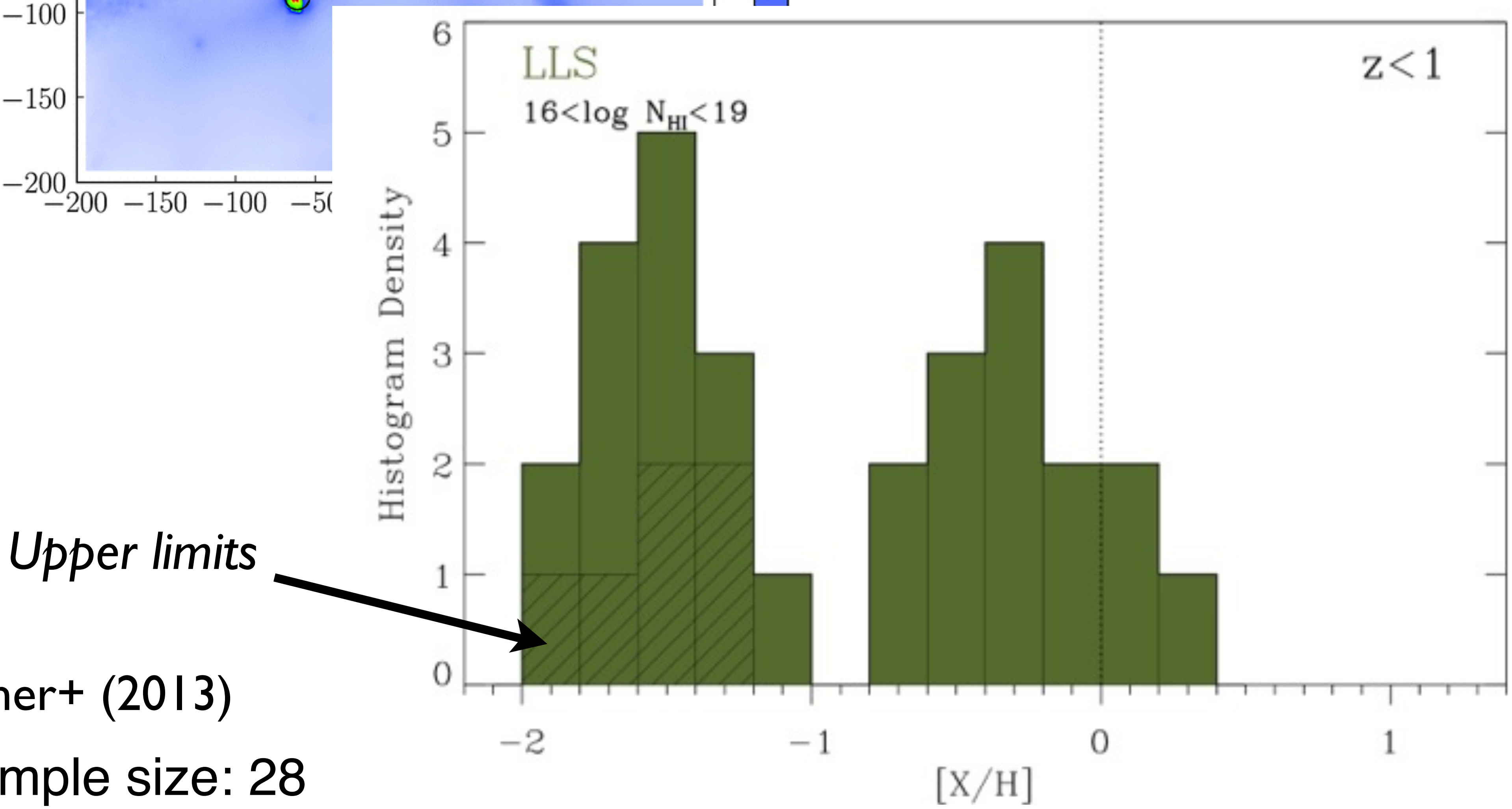
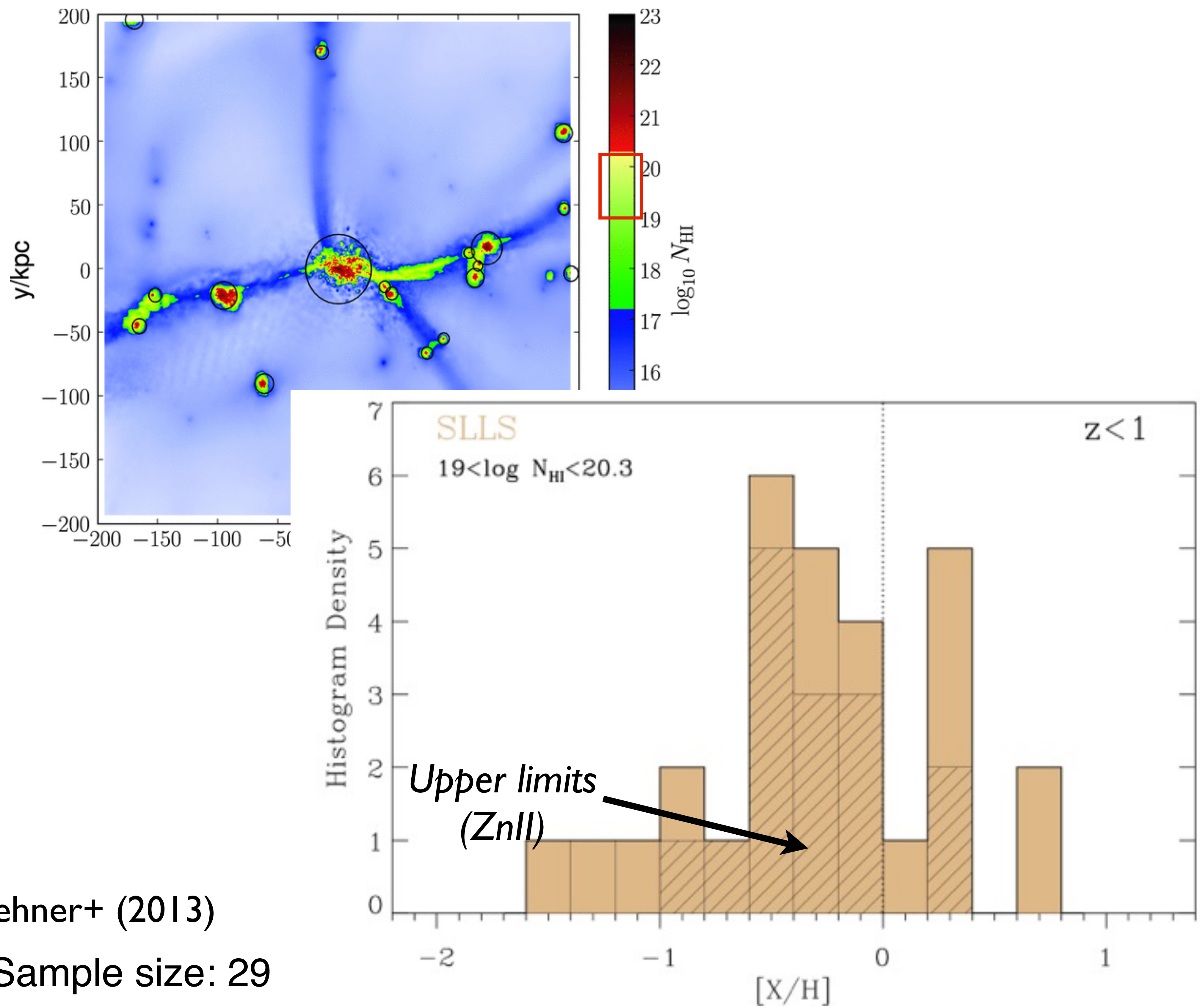


Lehner+ (2013)

Sample size: 28

Super Lyman Limits (a.k.a. sub-DLAs) at z<1



Lehner+ (2013)

Sample size: 29

Original metallicity estimates: Meiring+09, Peroux+06, Nestor+08,…

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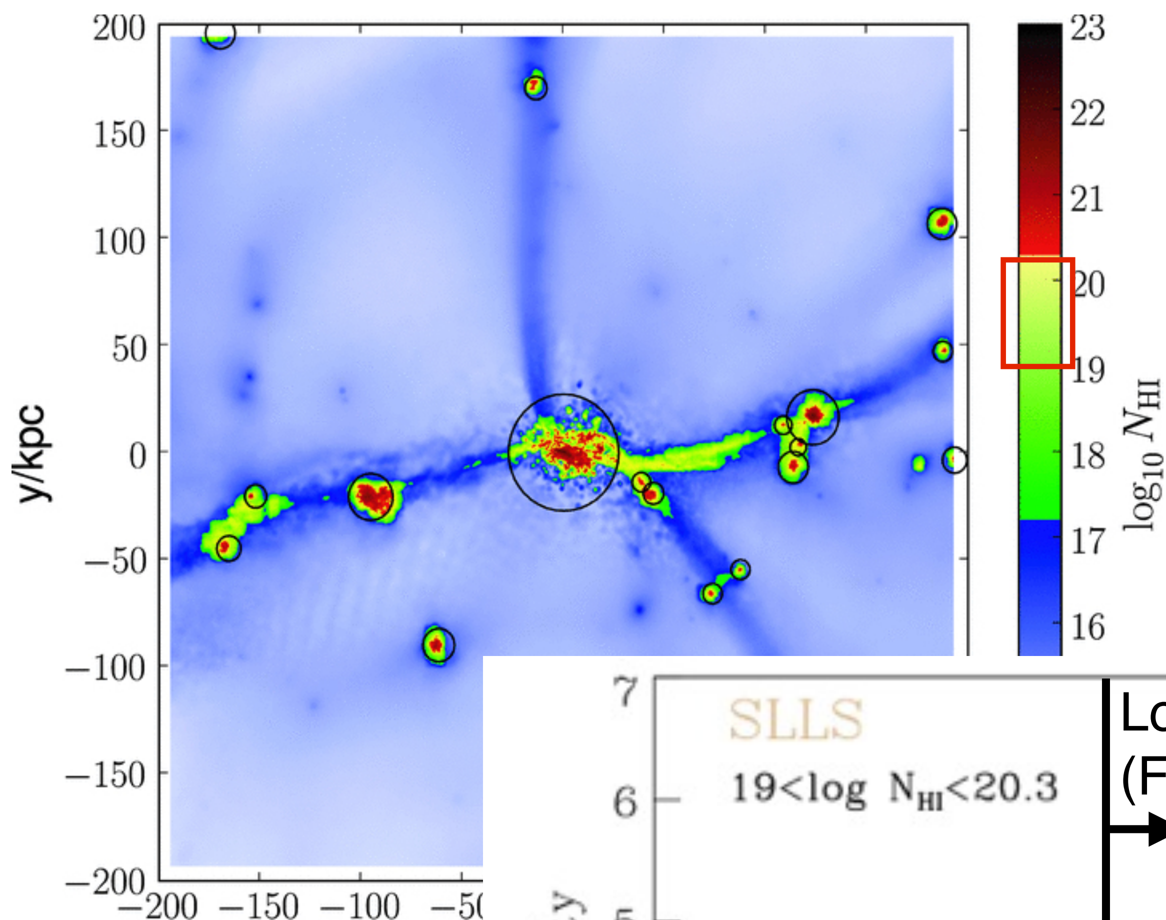

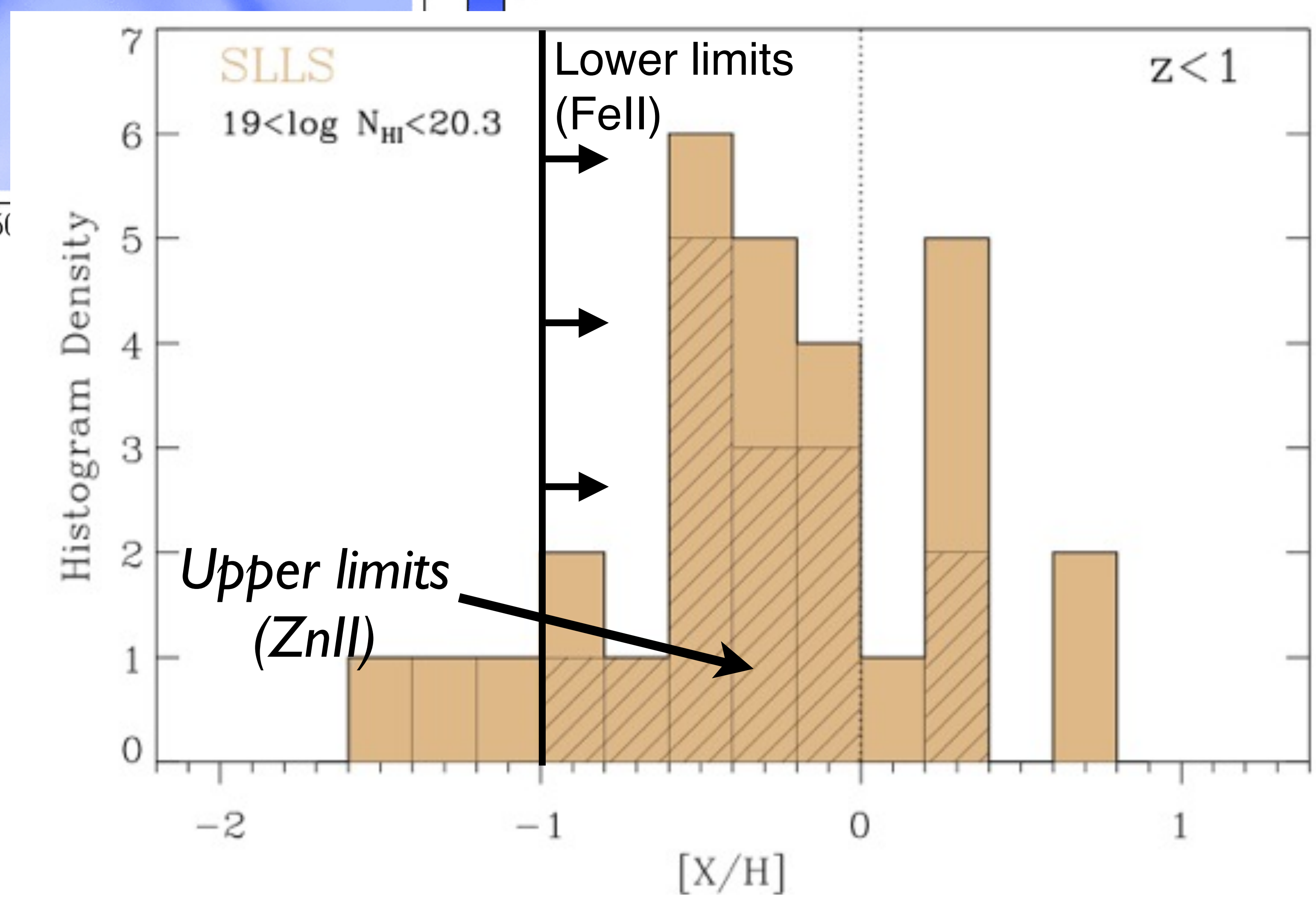

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Meiring+09, Peroux+06,
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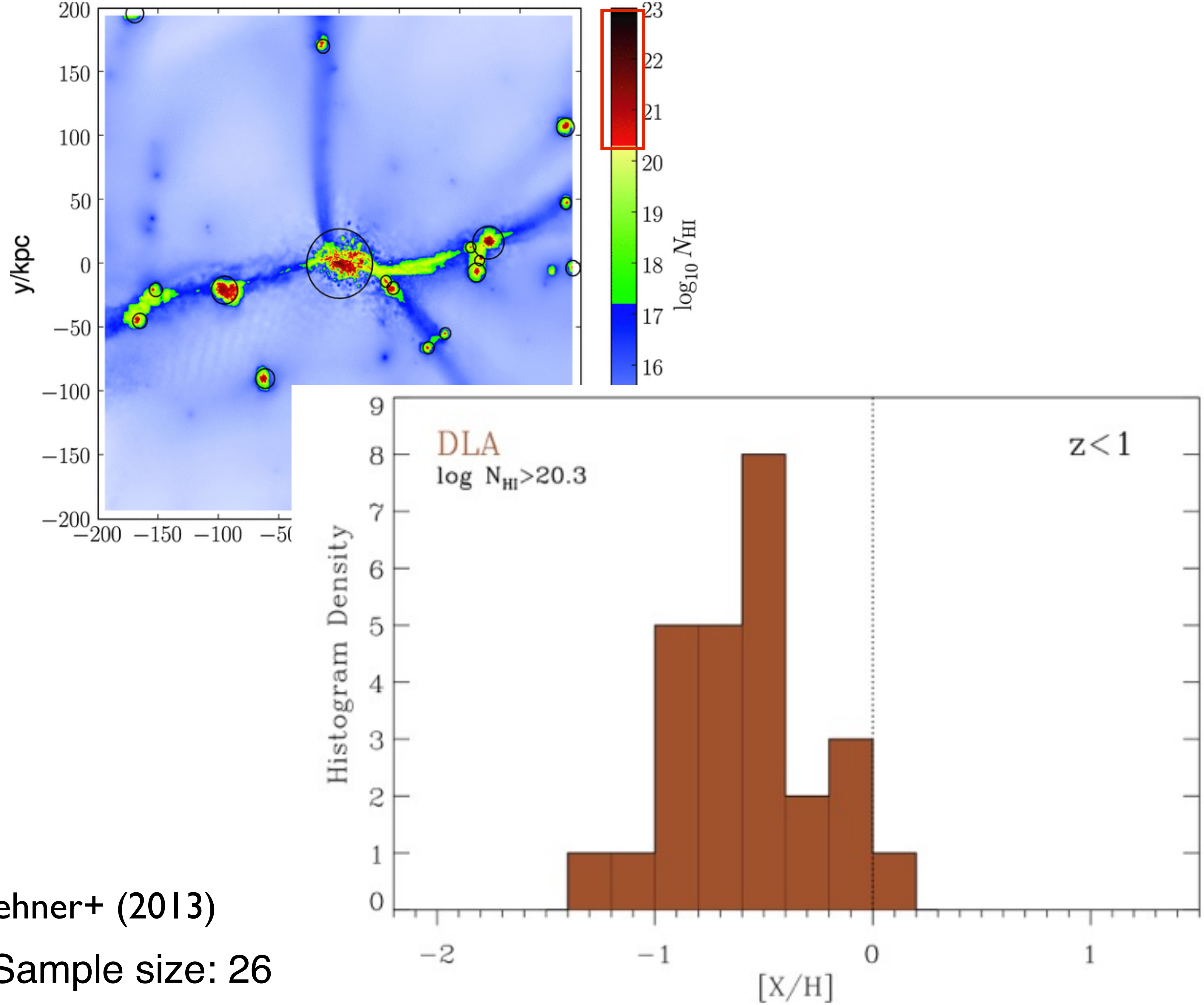
Damped Lyα absorbers at z<1



Lehner+ (2013)

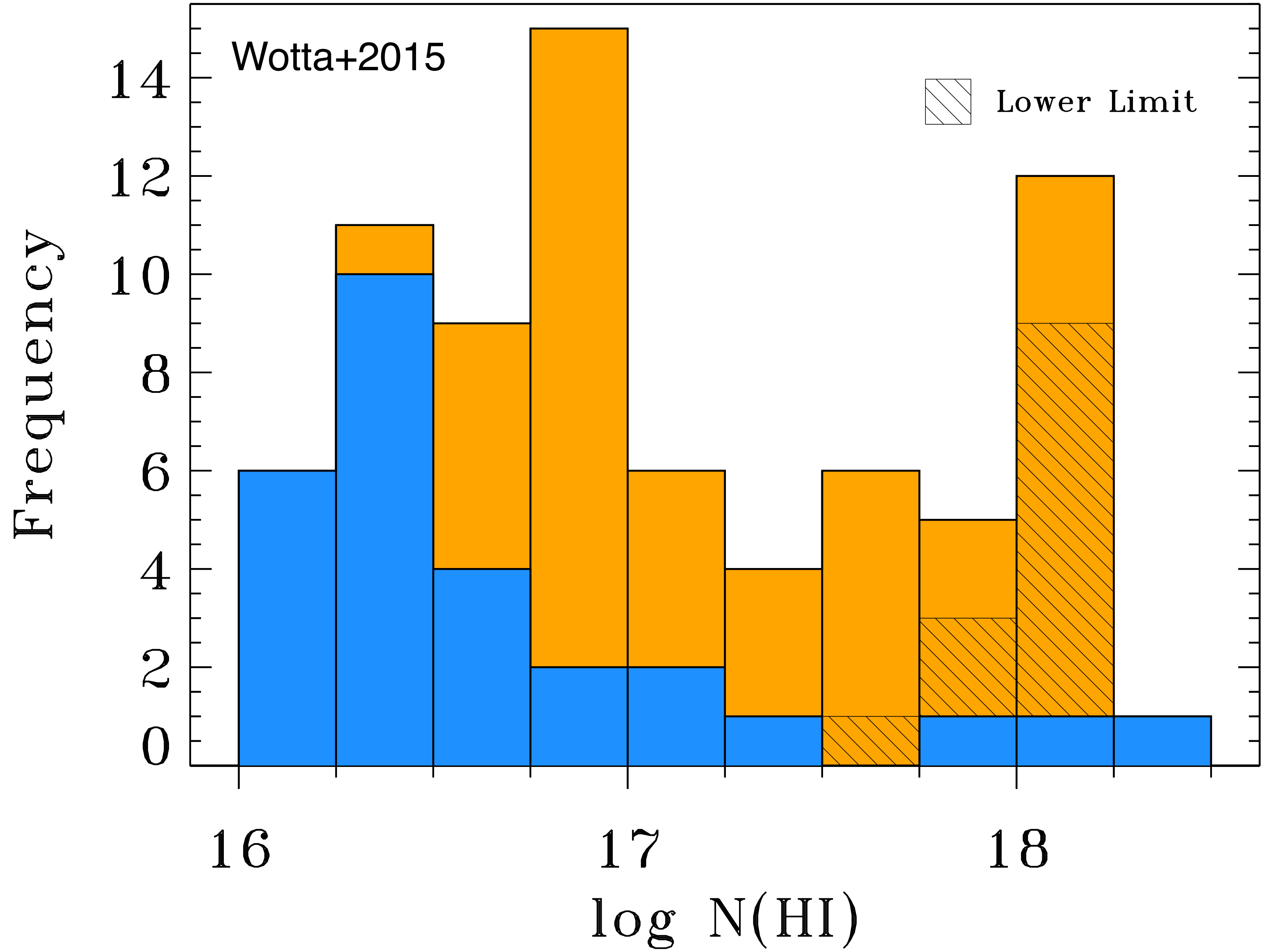
Sample size: 26

Original metallicity estimates:
Battisti+12, Peroux+06,
Nestor+08,…

X= ZnII (or SiII, OI)

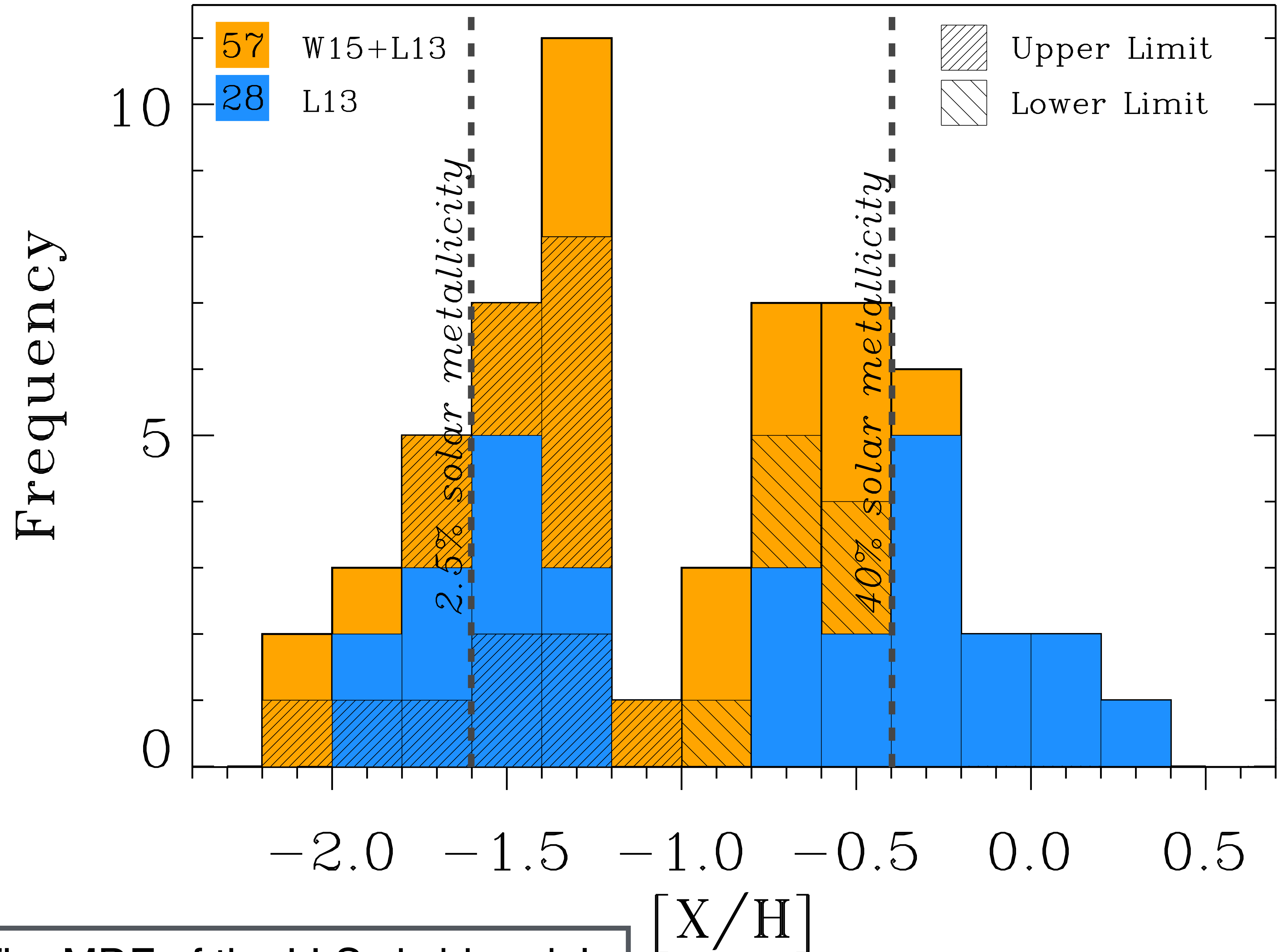
Lyman limit systems: follow-up survey

COS G140L survey of LLSs (PI: Howk)



- More uniform distribution of N(HI) in the LLS regime
- The sample size has now doubled

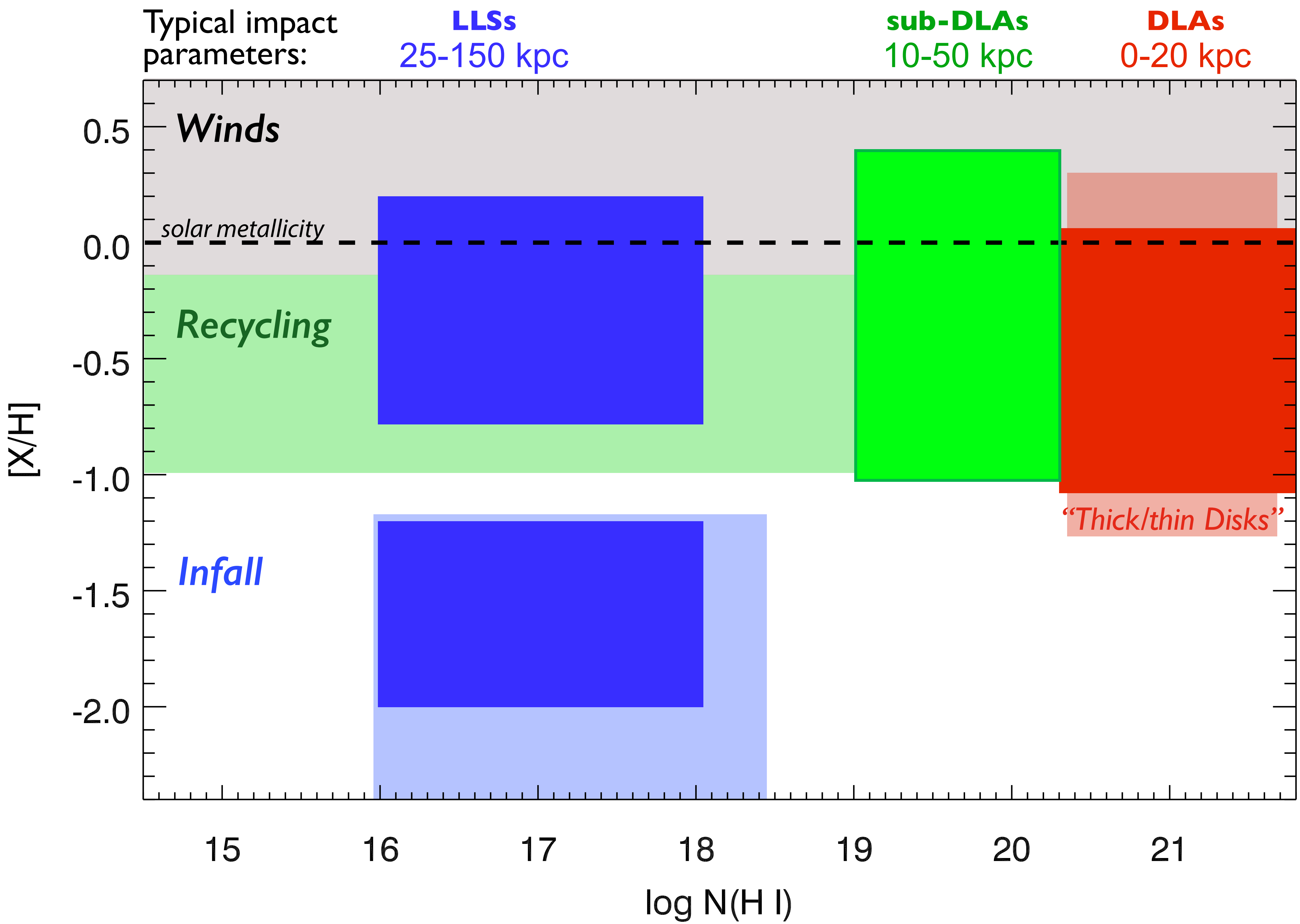
MDF of the combined sample of LLSs at z<1



The MDF of the LLSs is bimodal and unique to the LLSs.

Wotta+2015

A map of the CGM metallicities about galaxies at $z<1$



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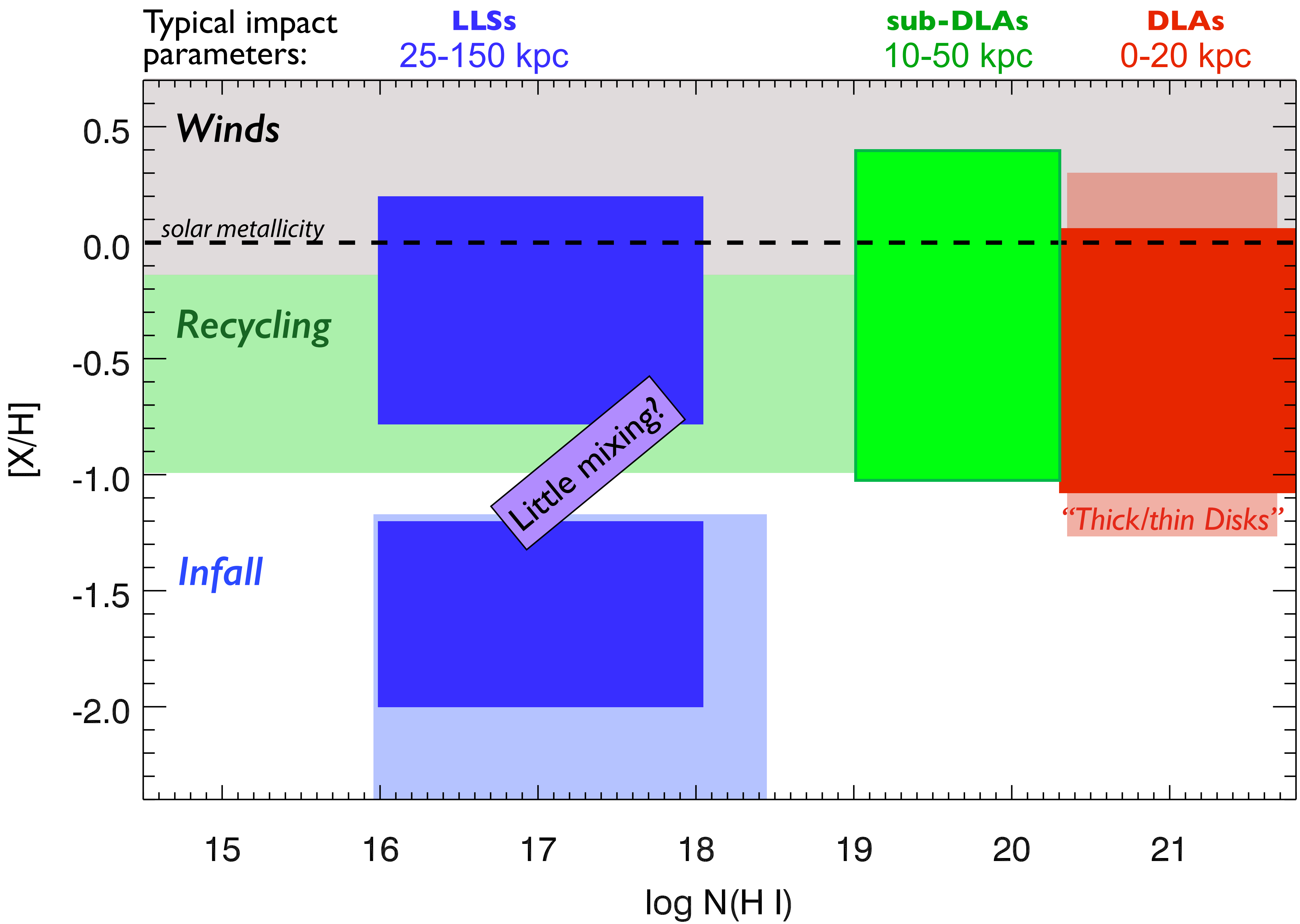

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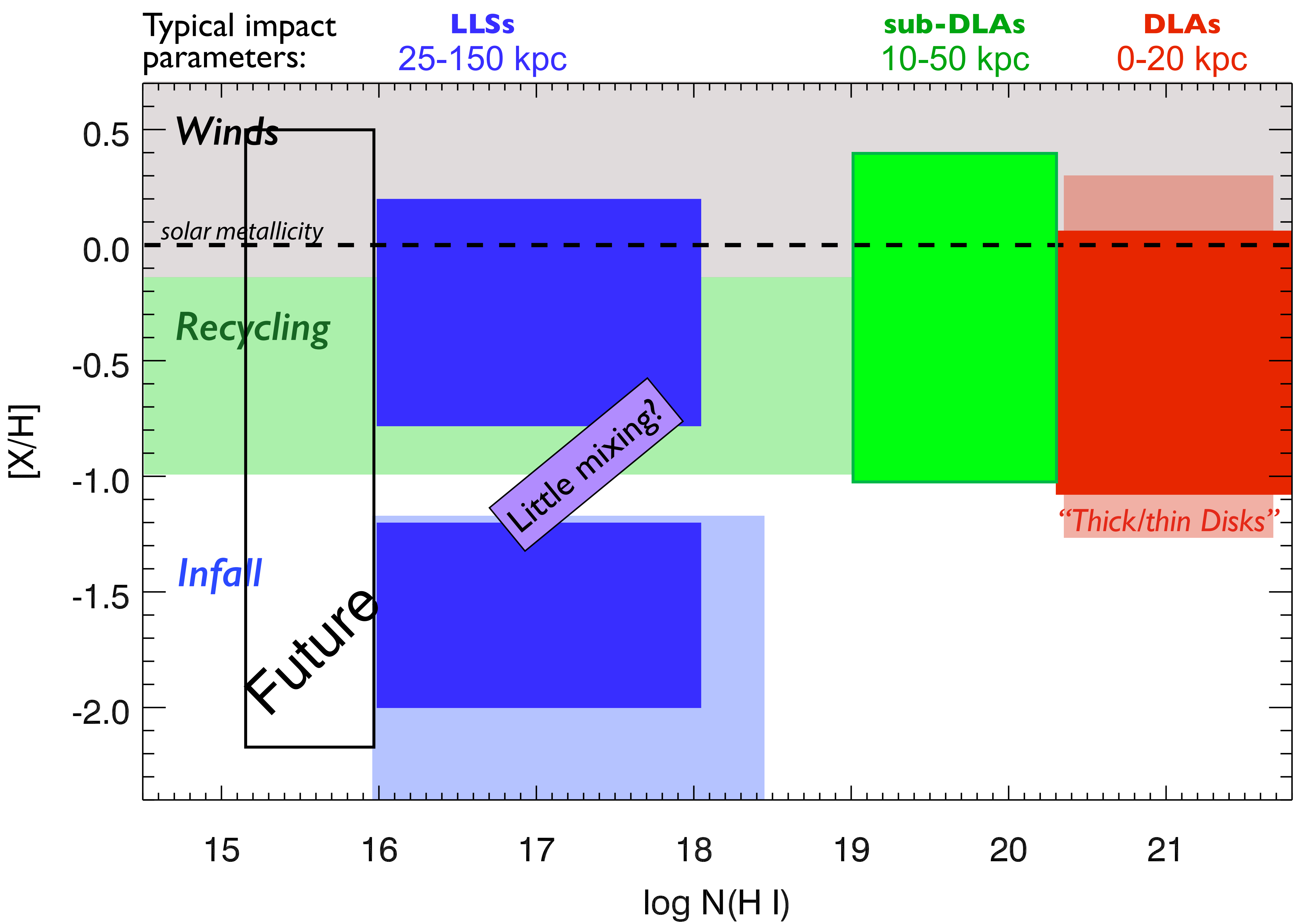
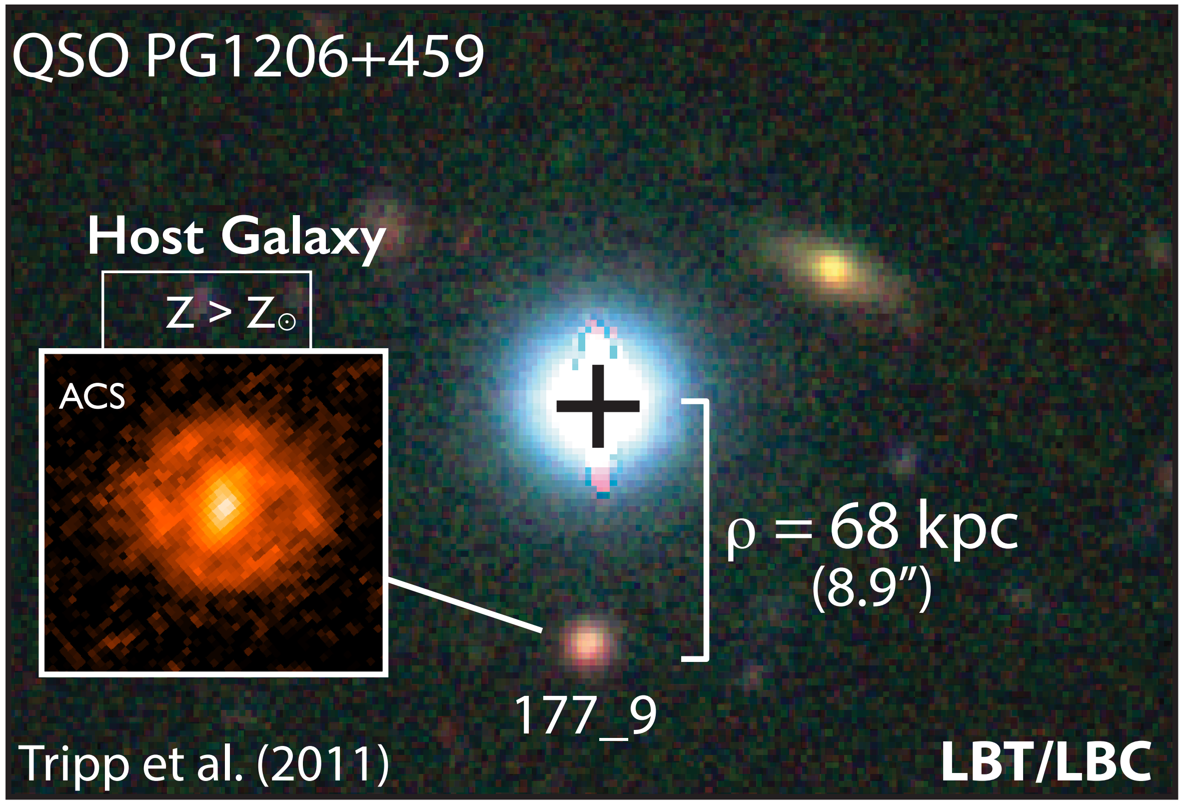
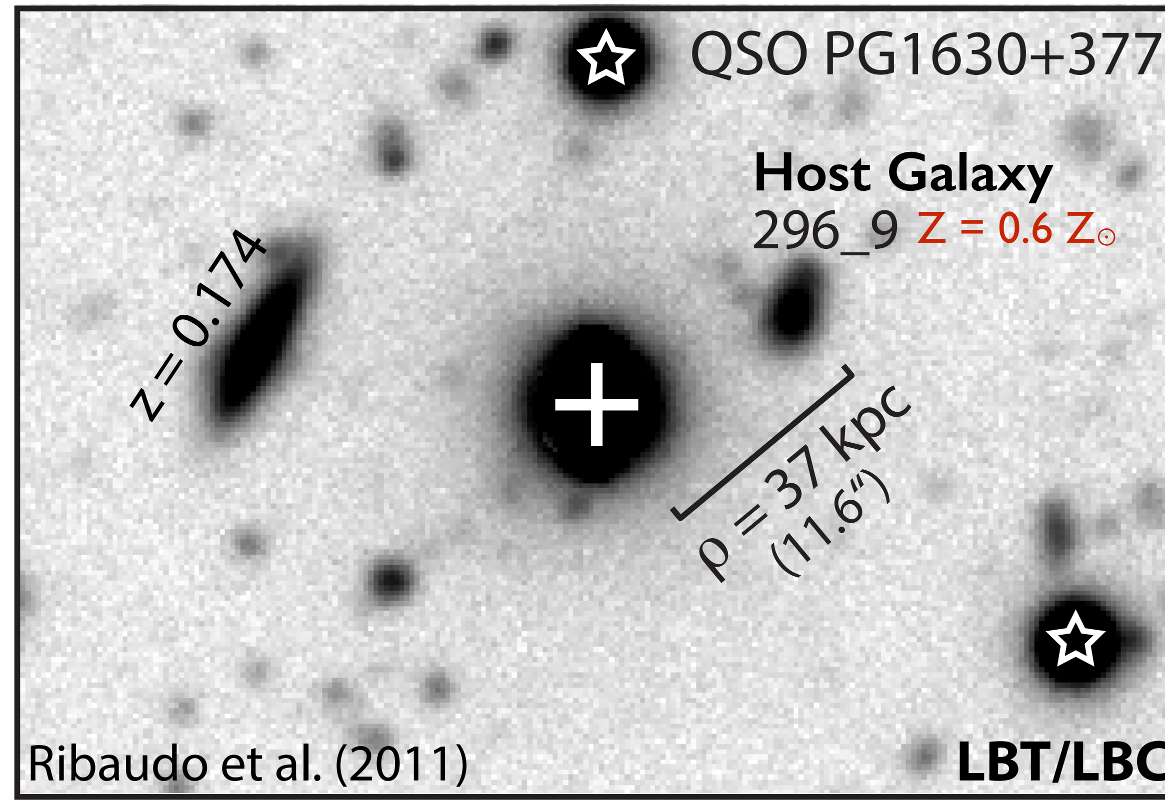


Lyman limit systems as probes of infall and outflows

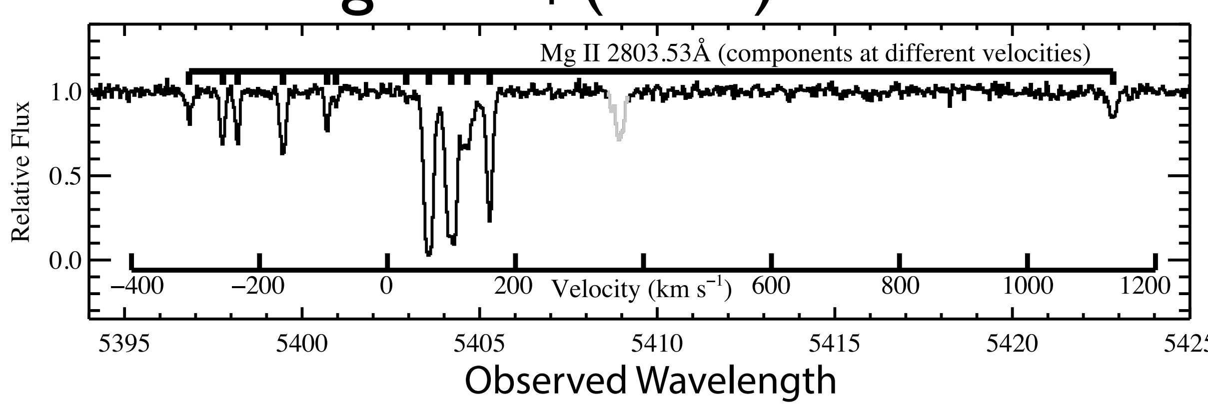
A Galactic superwind caught in the act at z = 0.92



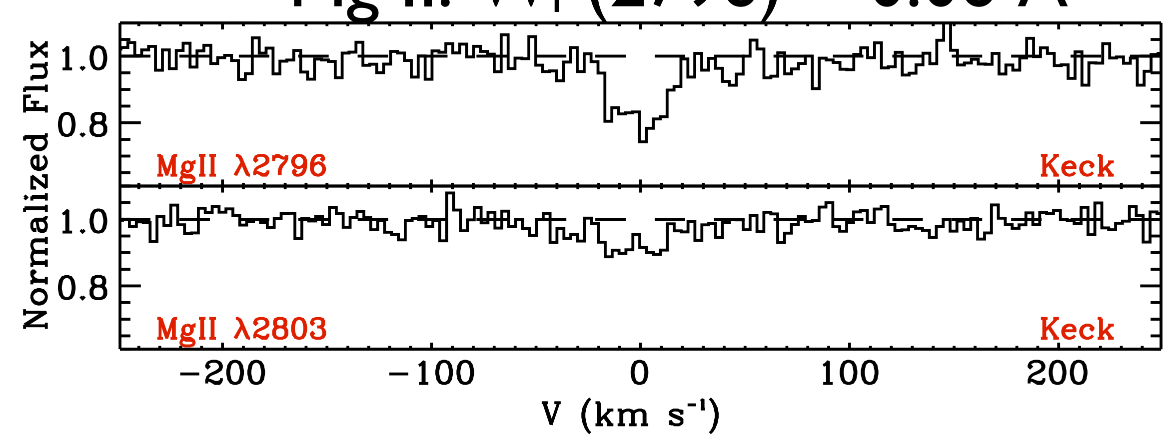
Cold accretion feeding a star-forming galaxy at z = 0.27



Mg II: W_r (2796) ~ 1 Å



Mg II: W_r (2796) ~ 0.06 Å

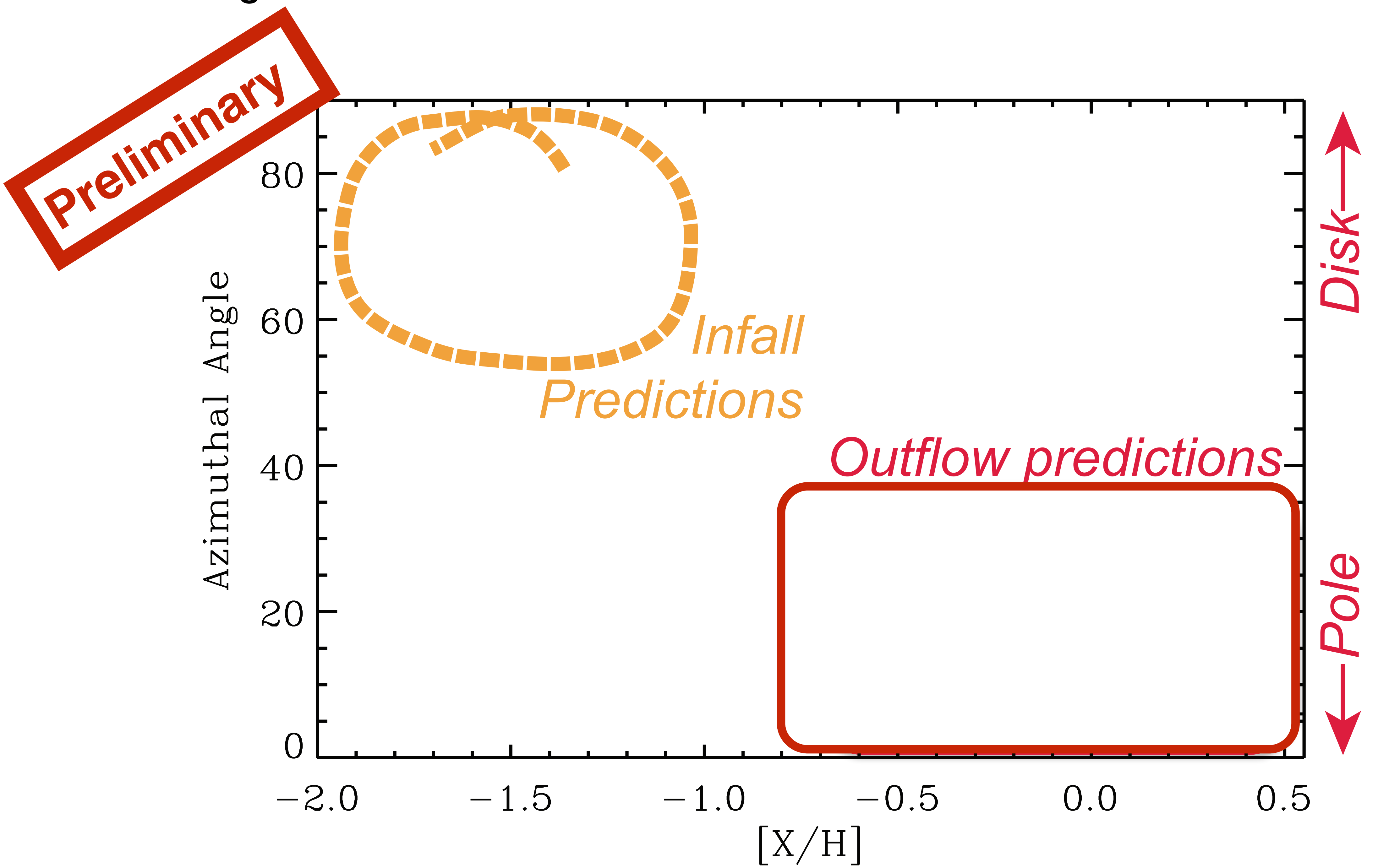


Outflow with $Z \geq Z_\odot$

Infall? with $Z \sim 0.02\ Z_\odot$

Lyman limit systems as probes of infall and outflows

Lyman limit systems with the fields imaged with HST and spectroscopically identified galaxies



See Bouche+, Bordoloi+, Kacprzack+ for that technique with MgII-selected absorbers

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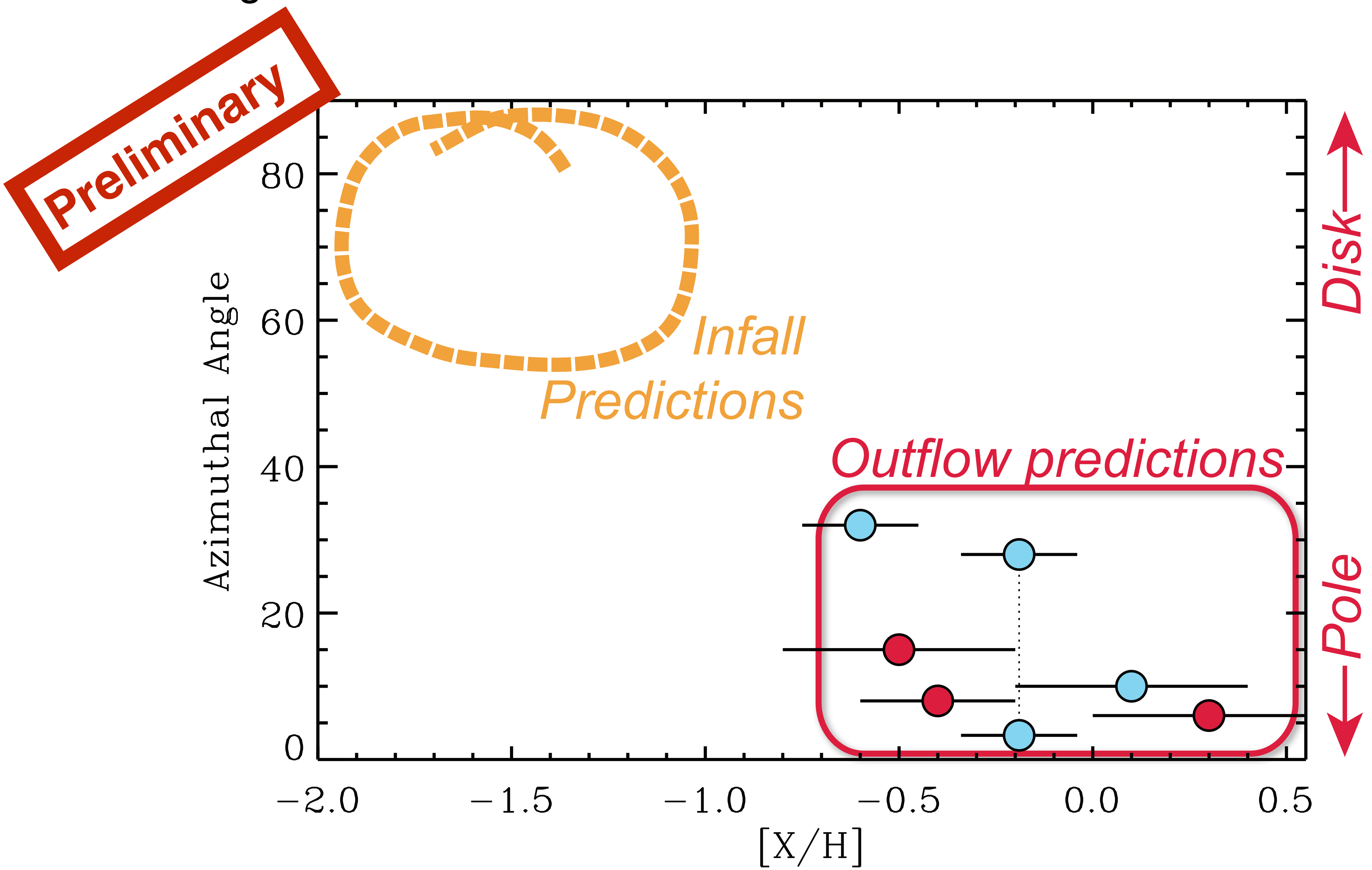

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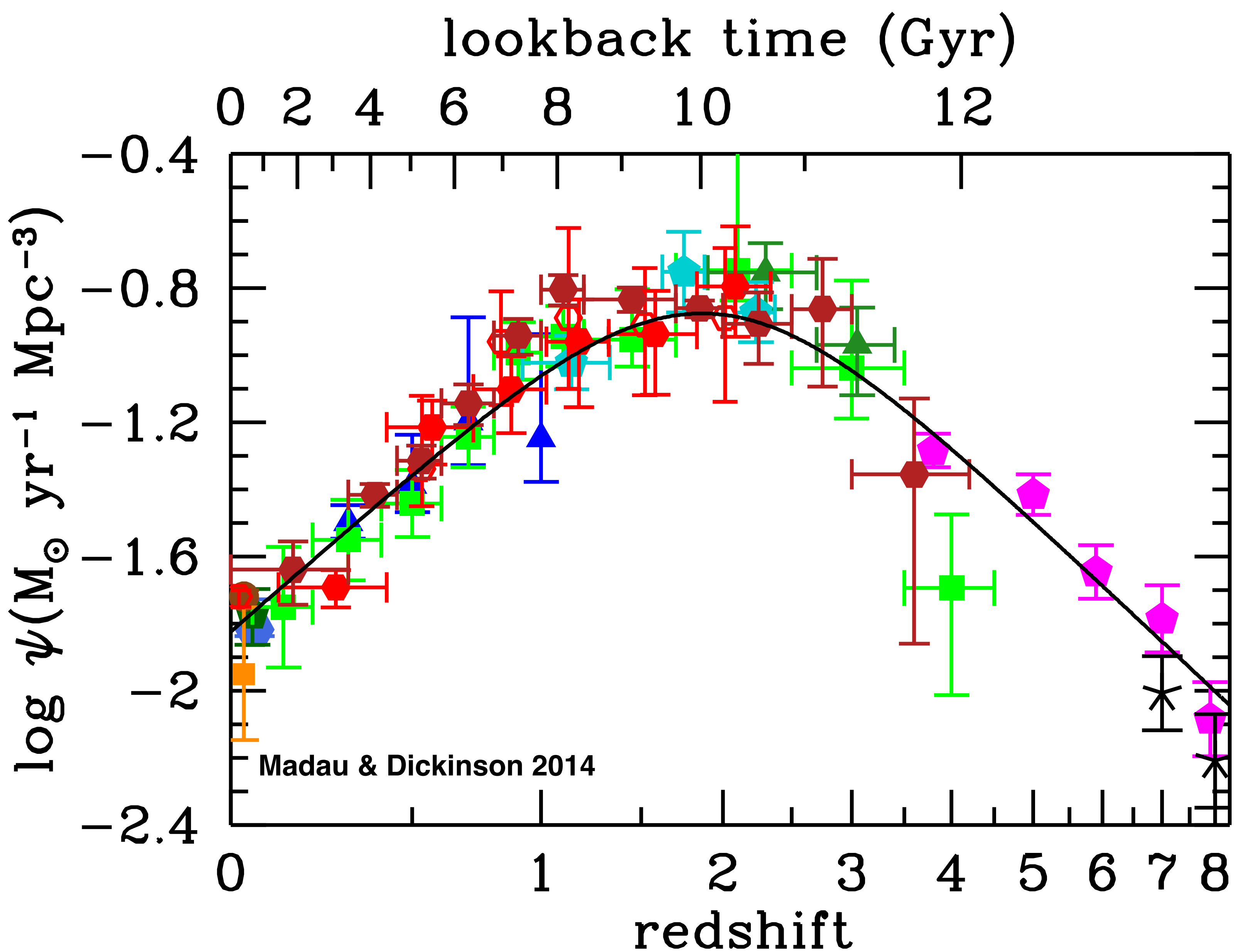
How does the MDF of the LLSs/CGM evolve with z?

Connecting the global star formation properties to those of the CGM



If the CGM and SF are intimately coupled, we should see changes in the MDF of the dense CGM, with the weighting of the infalling and expelled gas changing.

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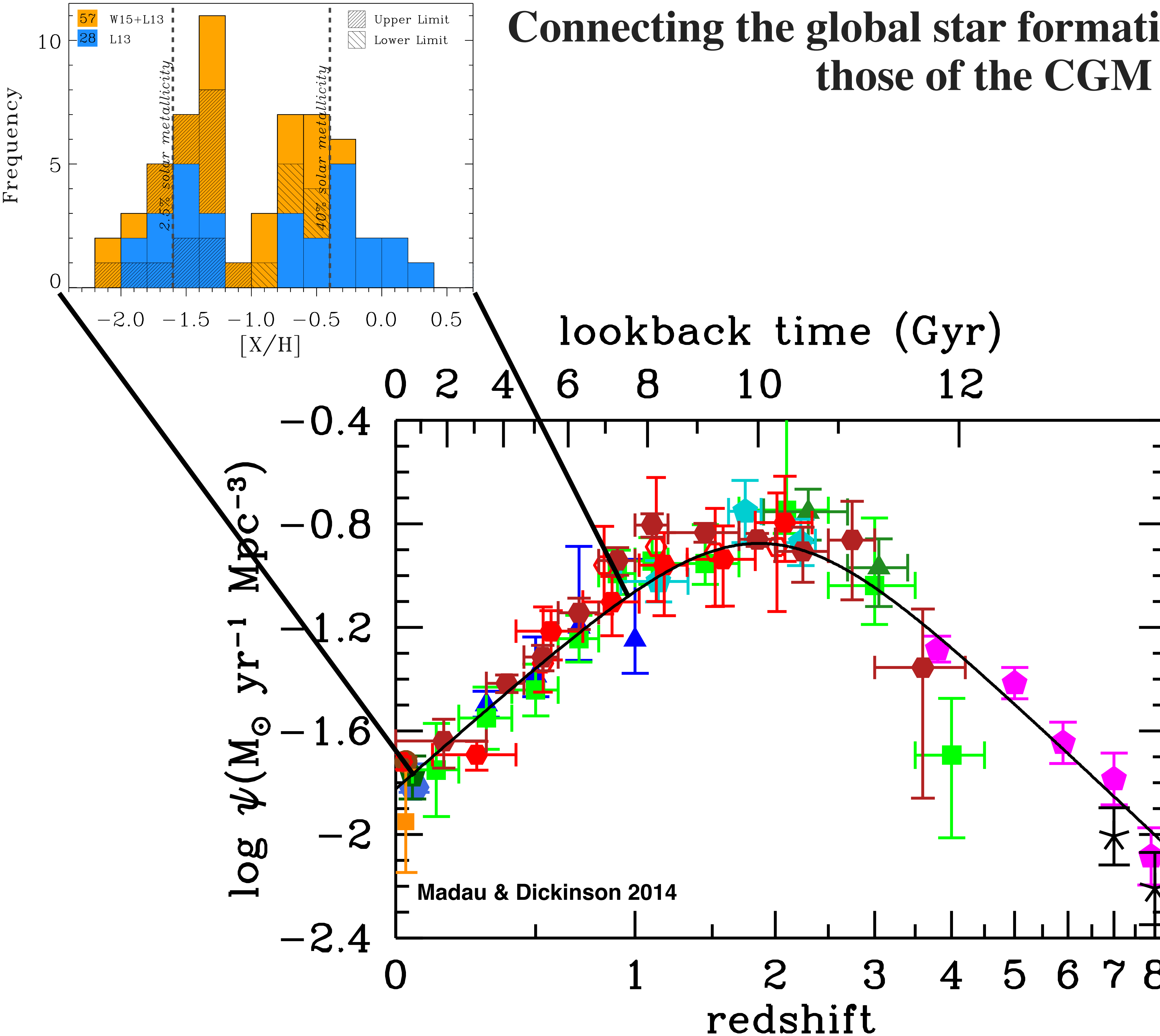

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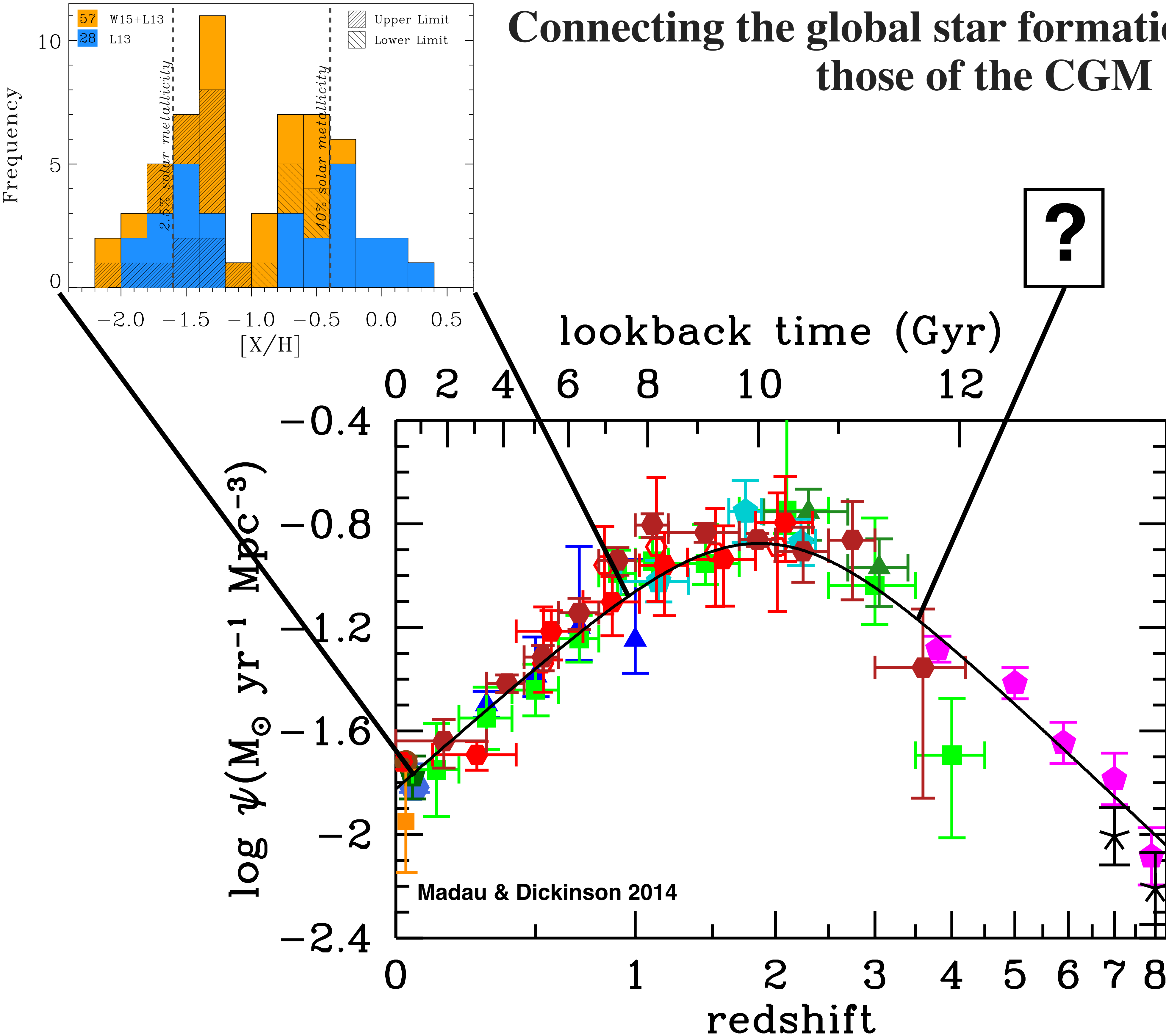

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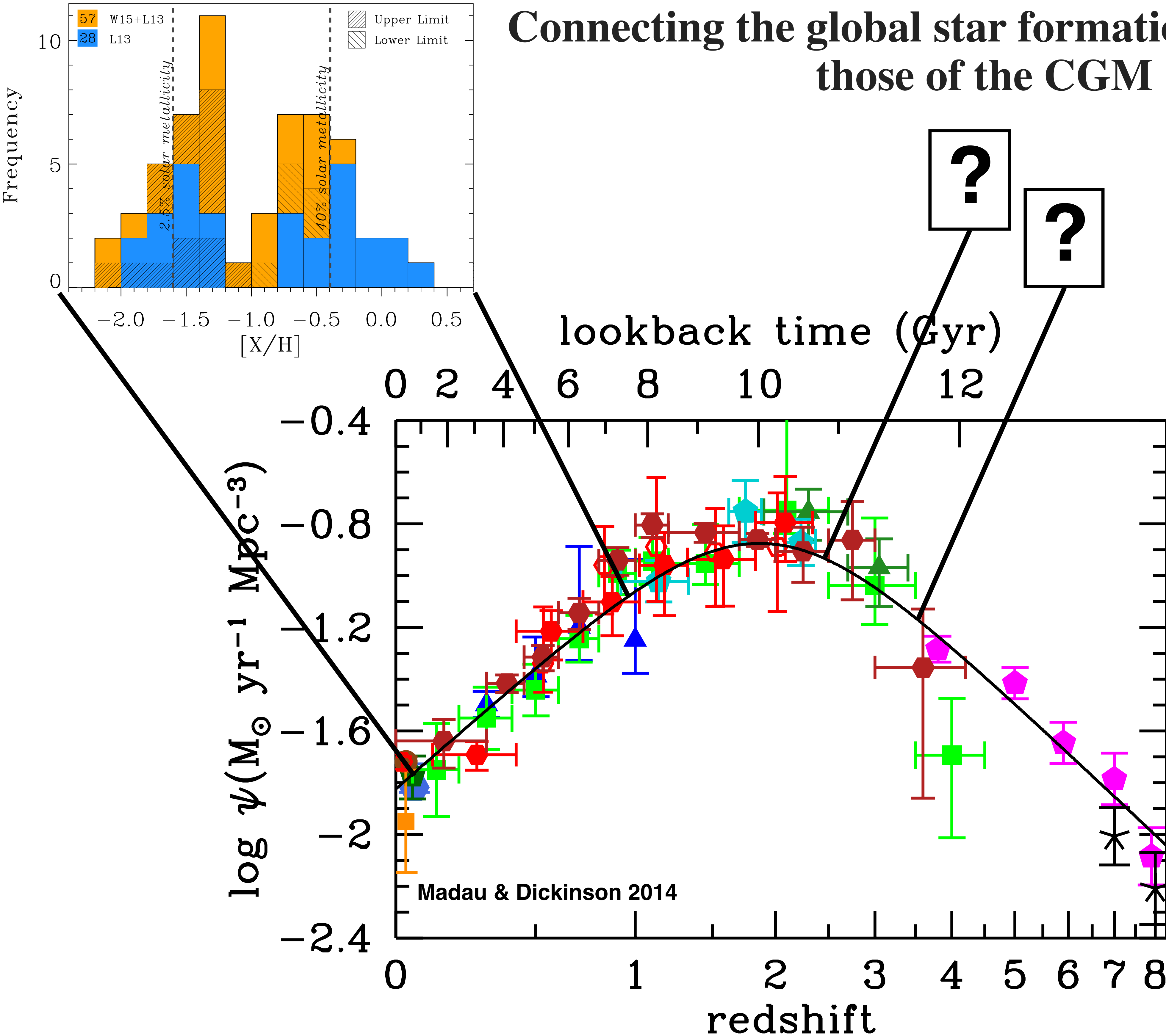

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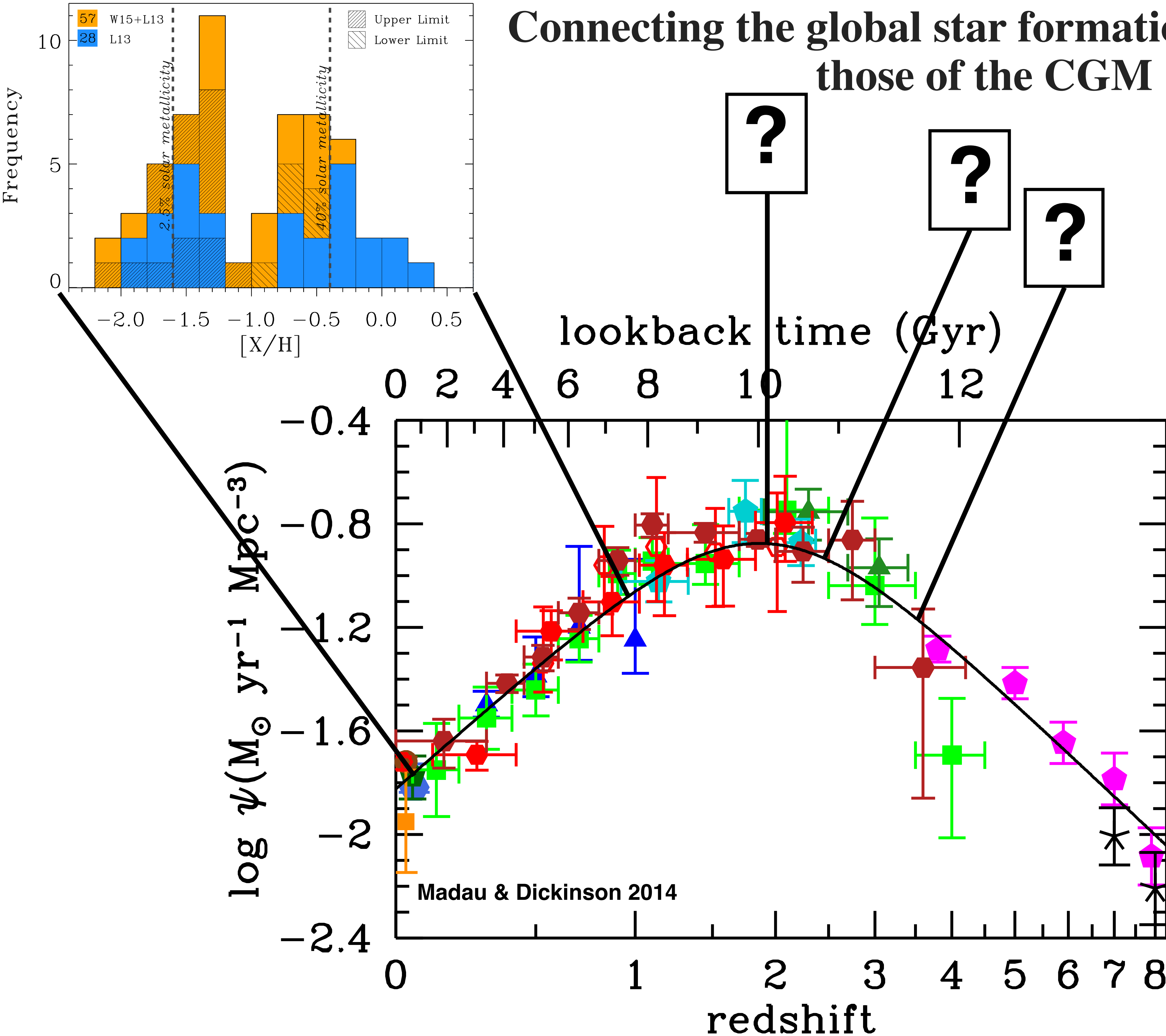

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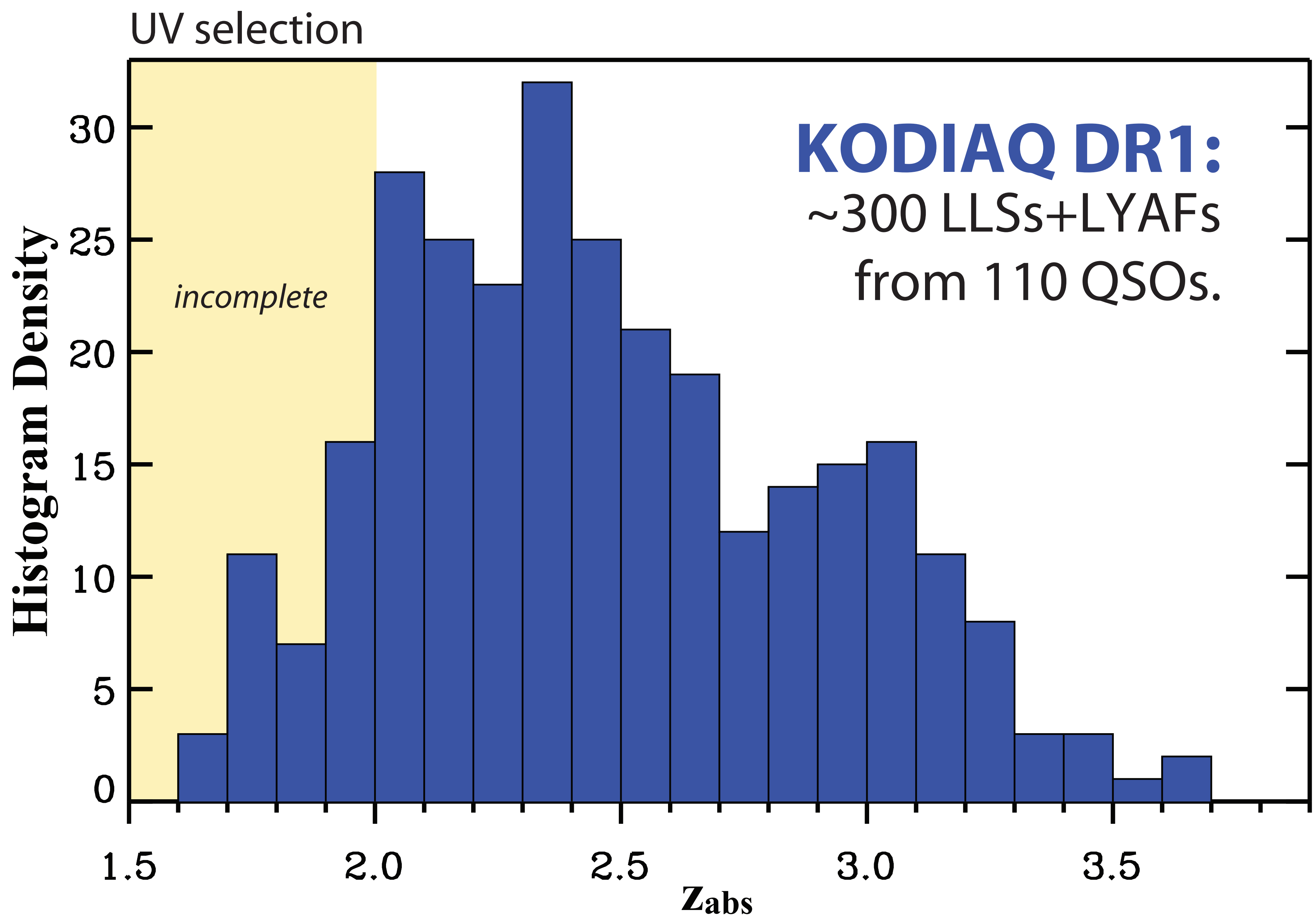
KODIAQ Z: Metallicity of the CGM at z>2

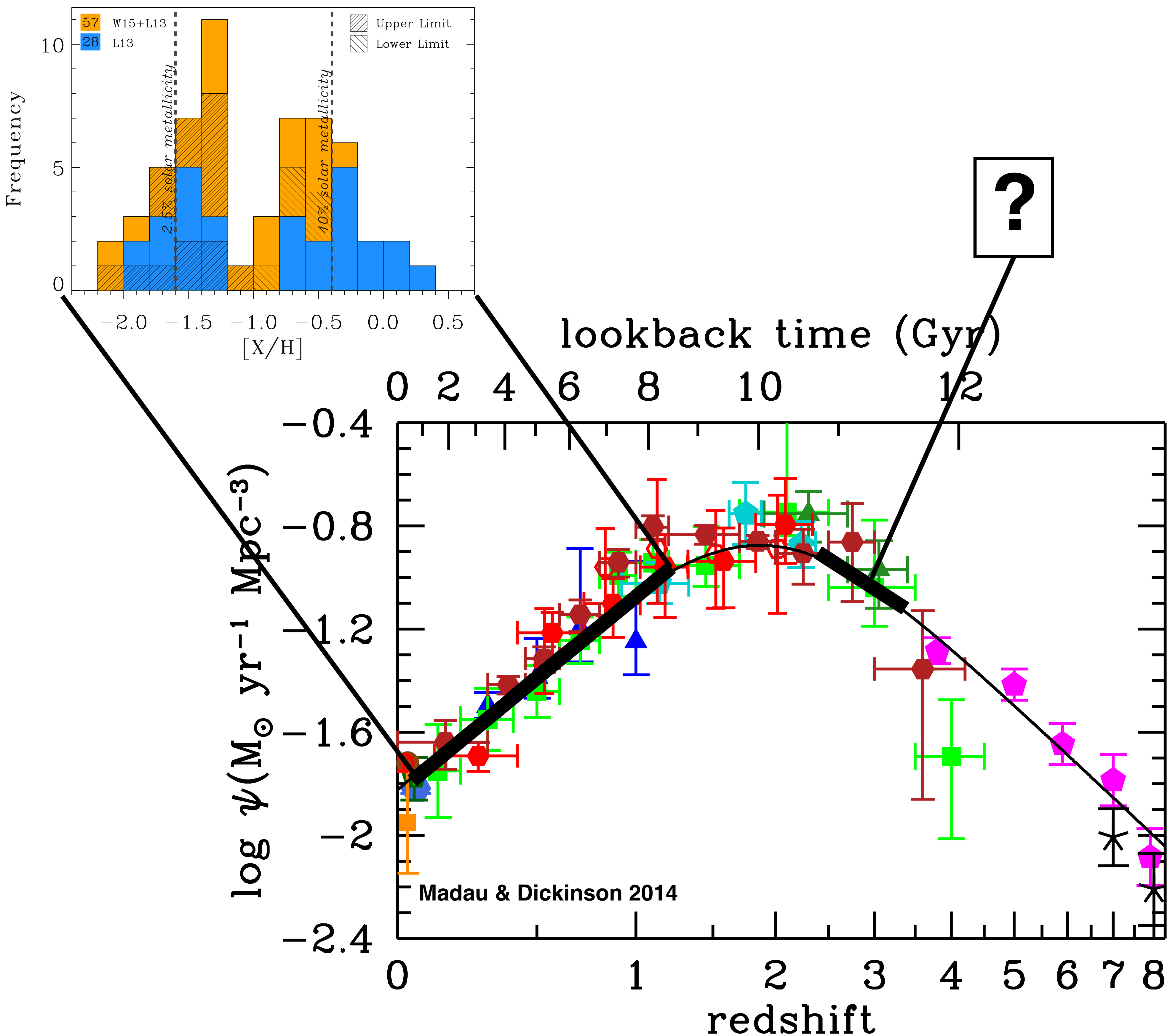


This is NOT a complete search of the entire KODIAQ database (>400 QSOs).

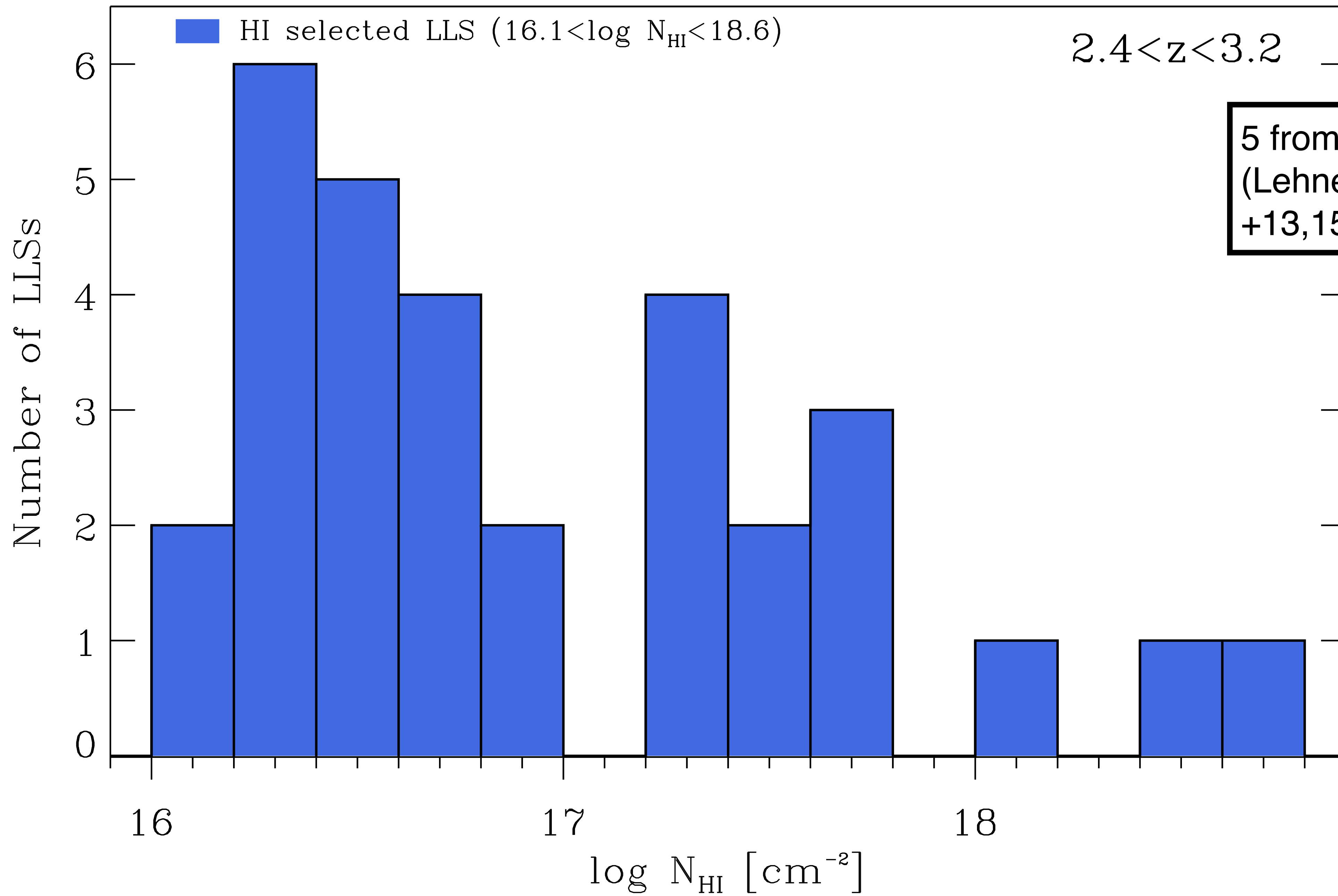
KODIAQ Z pilot study: 26 *HI-selected* LLSs (16.1<log N_{HI}<19) at 2.4<z<3.2

Lehner, O'Meara, Howk 2015

How does the MDF of the LLSs/CGM evolve with z?



KODIAQ Z pilot: MDFs of the LLSs at 2.4<z<3.2



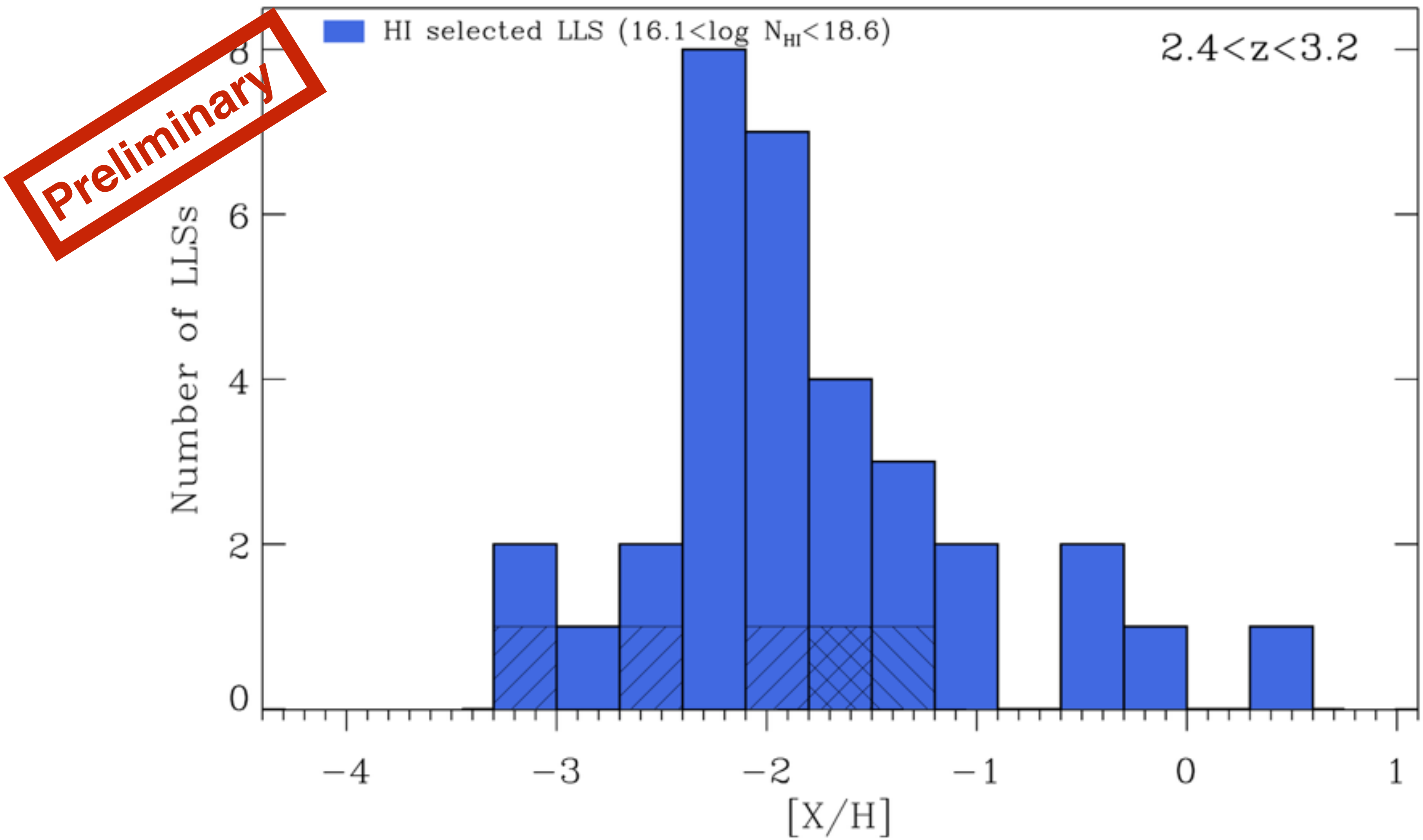
5 from the literature (Lehner+14, Crighton +13,15); 26 new LLSs.

For the ionization correction, we use same techniques, UV background, and ions (except MgII) as for the z<1 LLSs.

- [X/H]: X = Si
- SiII, SiIII, SiIV CII, CIII, CIV

Lehner+2015, in prep

KODIAQ Z pilot: MDF of the LLSs at 2.4<z<3.2



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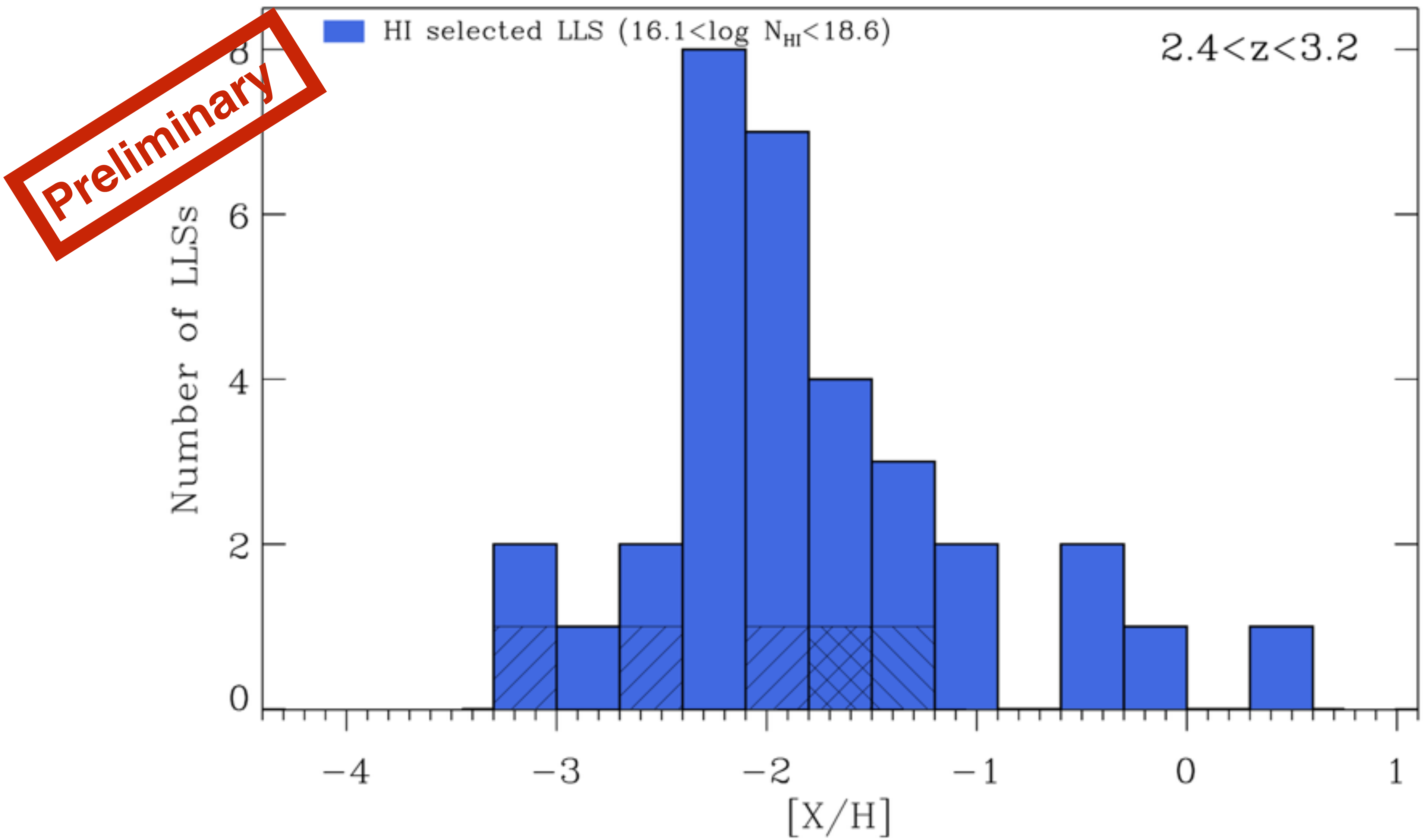
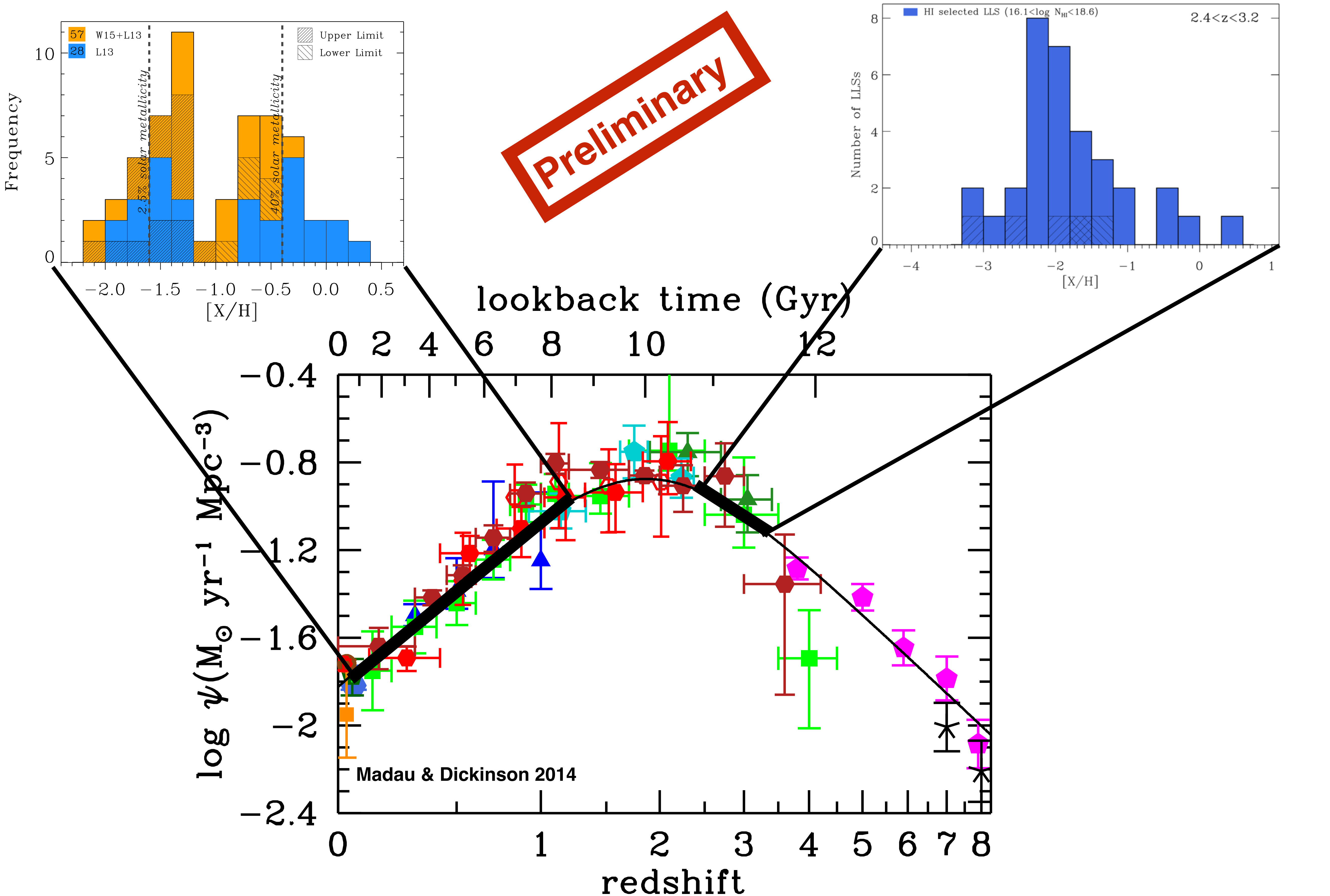


It is not bimodal anymore!

Lehner+2015, in prep

How does the MDF of the LLSs/CGM evolve with z?



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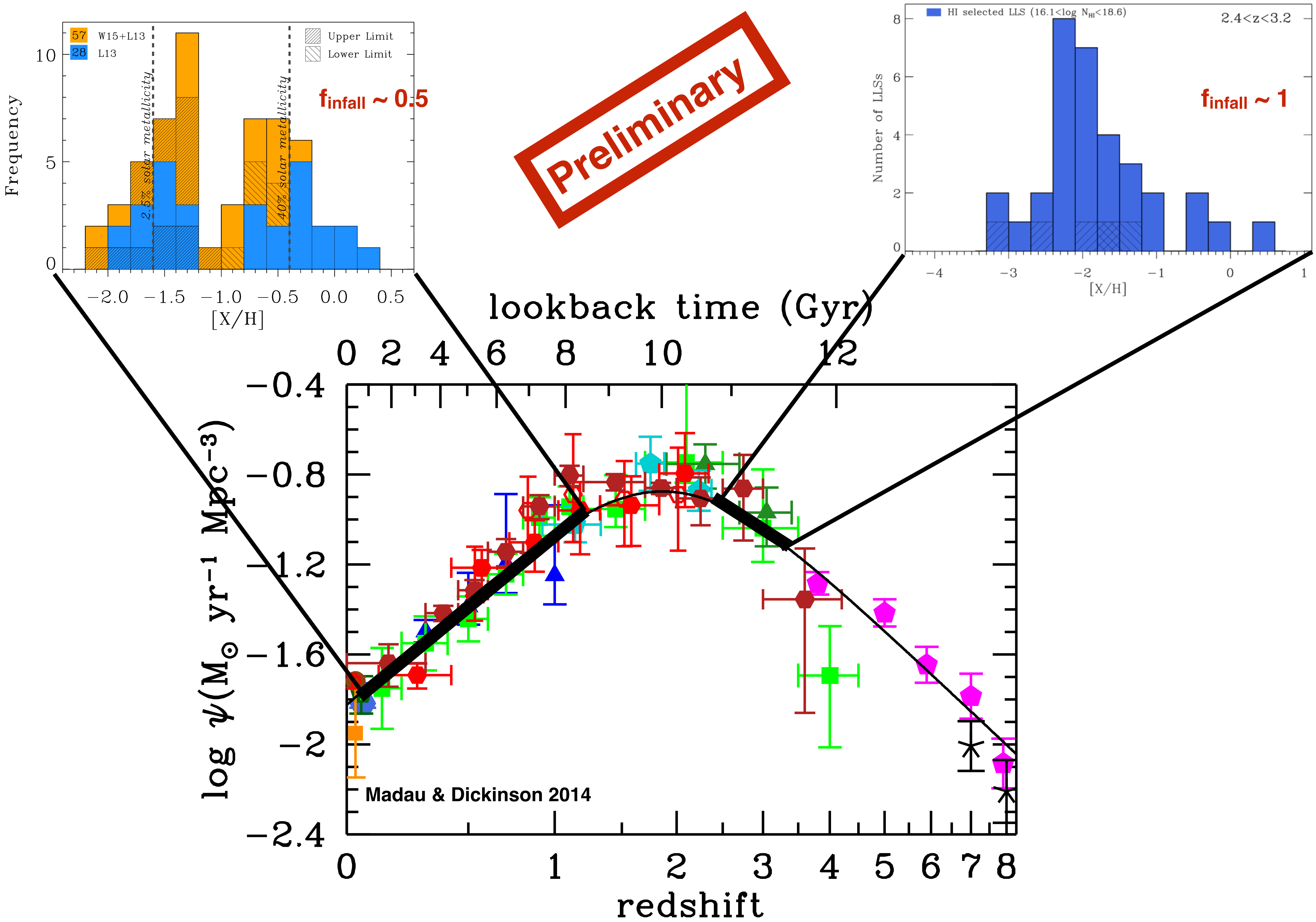

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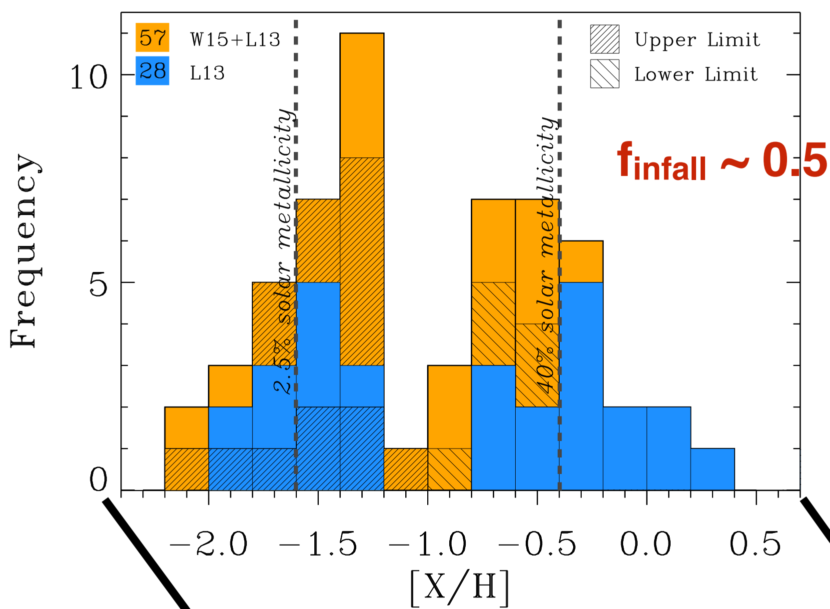
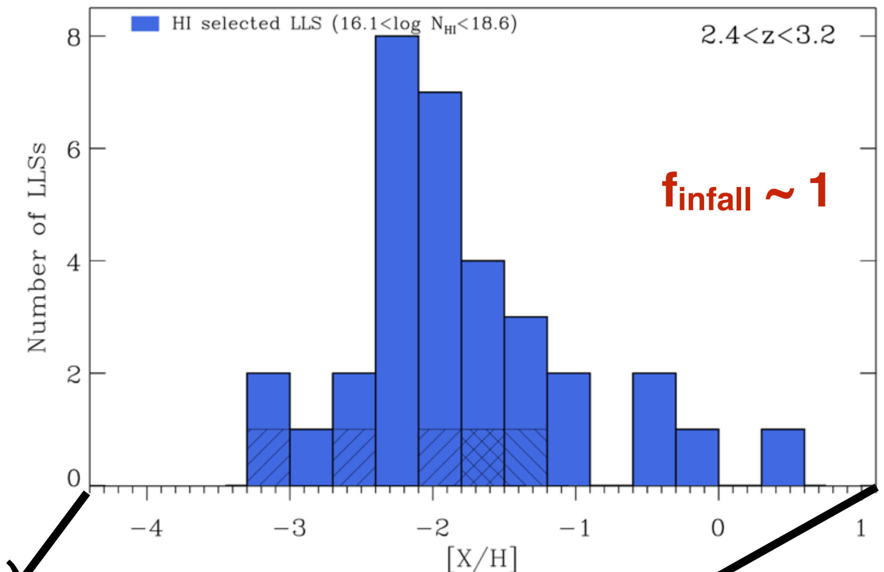
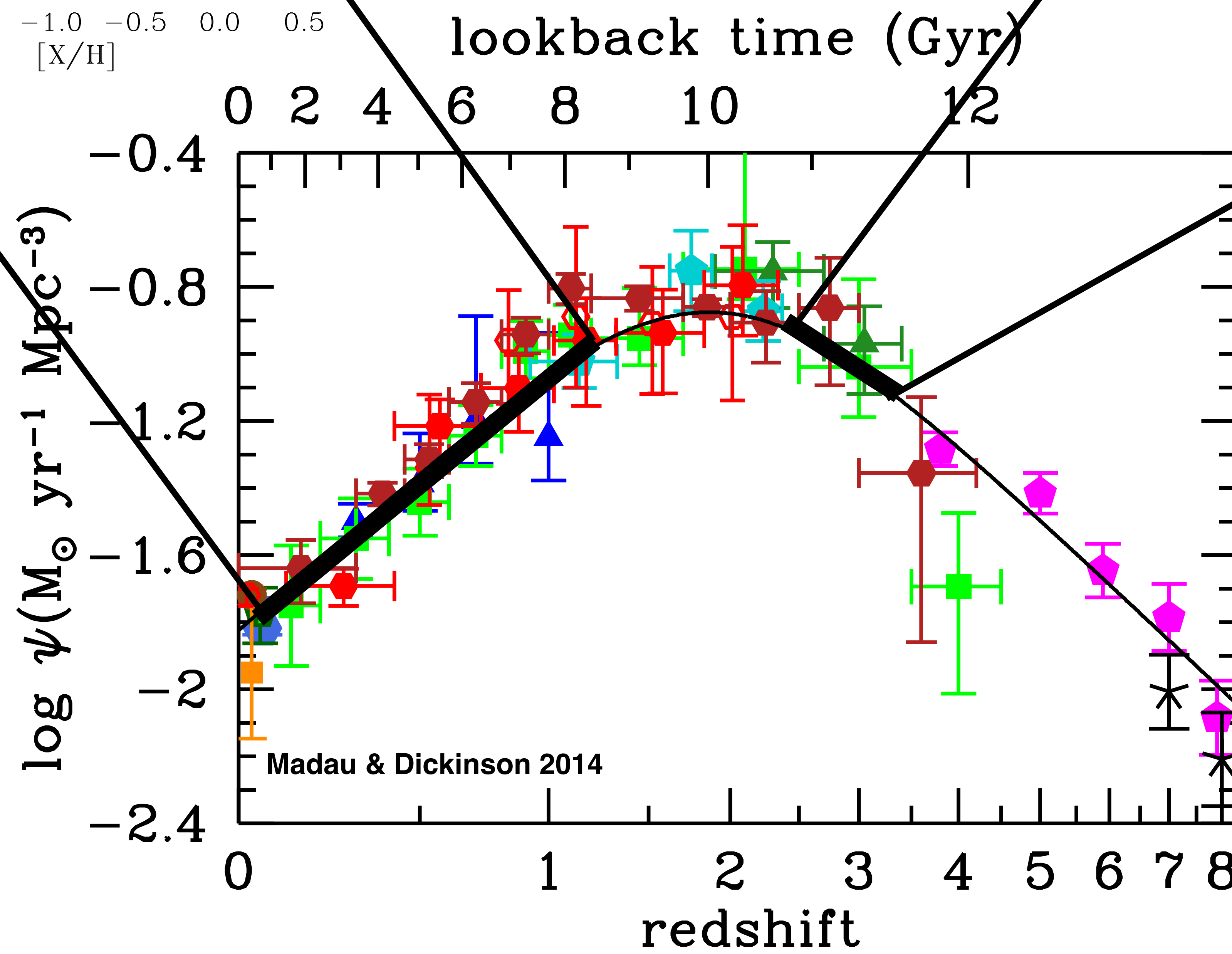


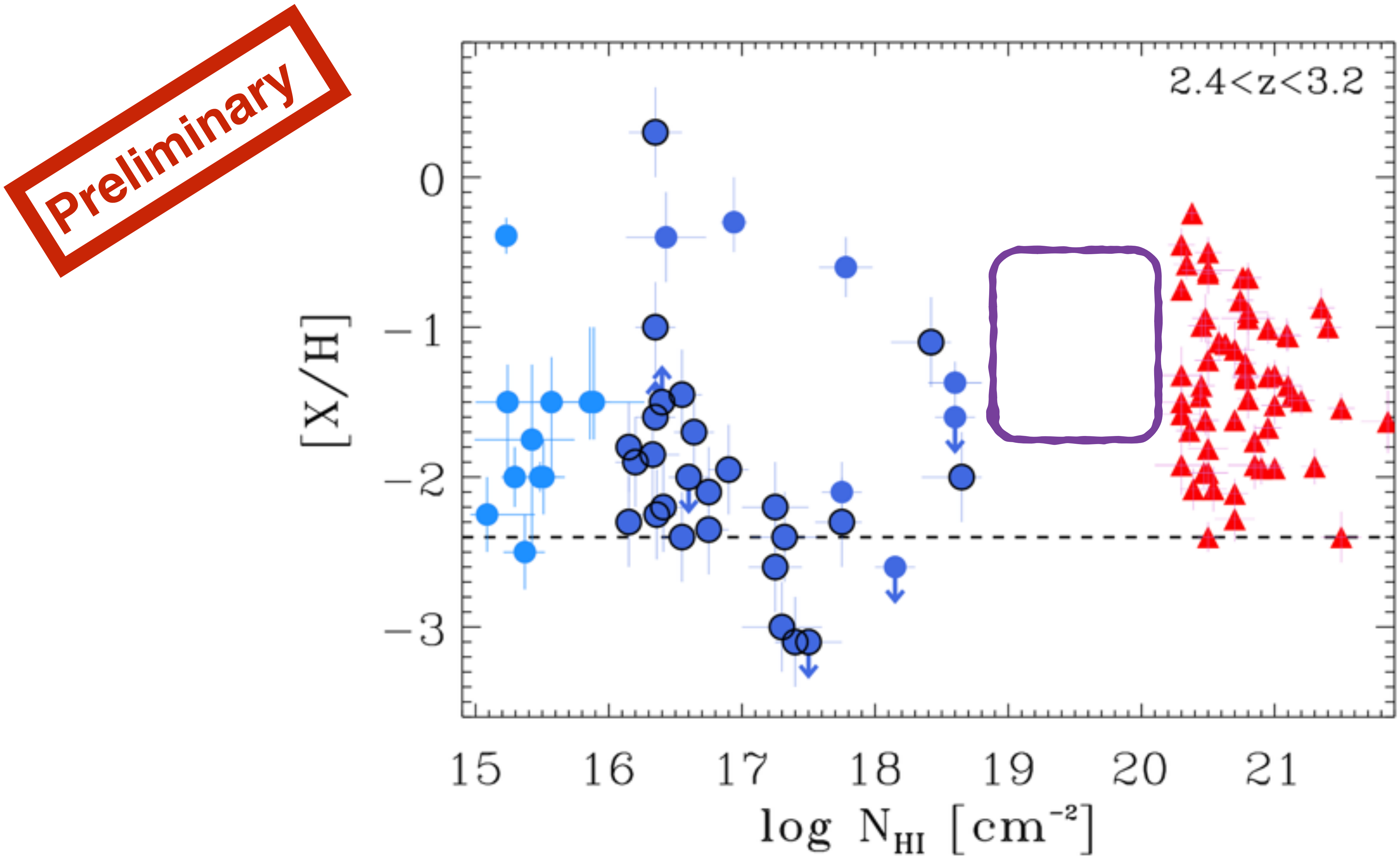
Preliminary





But remember, these same LLSs have also strong OVI absorbers (Chris Howk KODIAQ talk, Lehner+14), implying there is evidence of both strong outflows and infall in these LLSs in different gas phases.

MDF as a function of N(HI) at 2.4<z<3.2

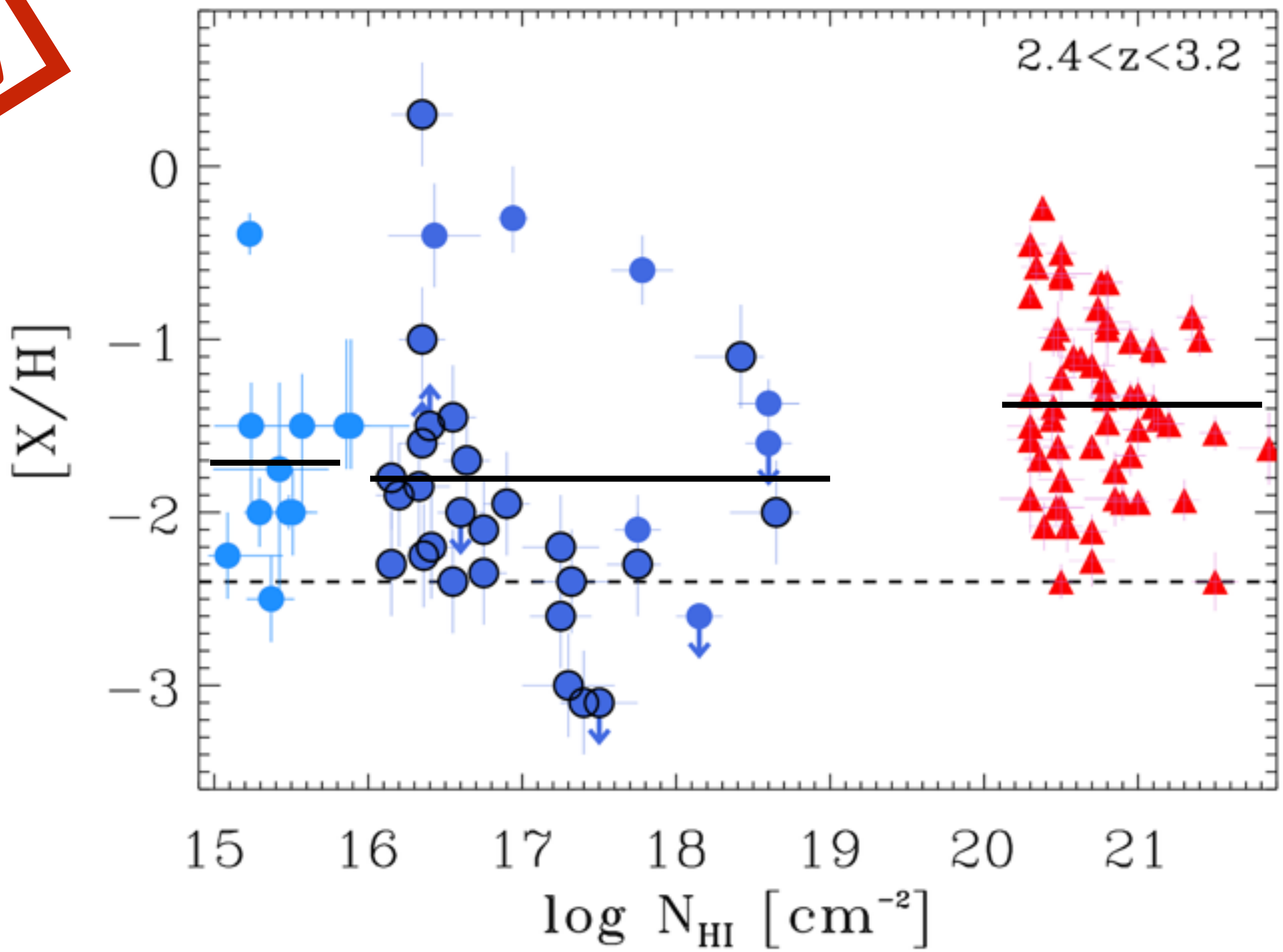


DLA: Rafelski+2012
LYAF: Simcoe+2006, Crighton+2013, 2015

Lehner+2015, in prep

MDFs of the LLSs at 2.4<z<3.2

Preliminary

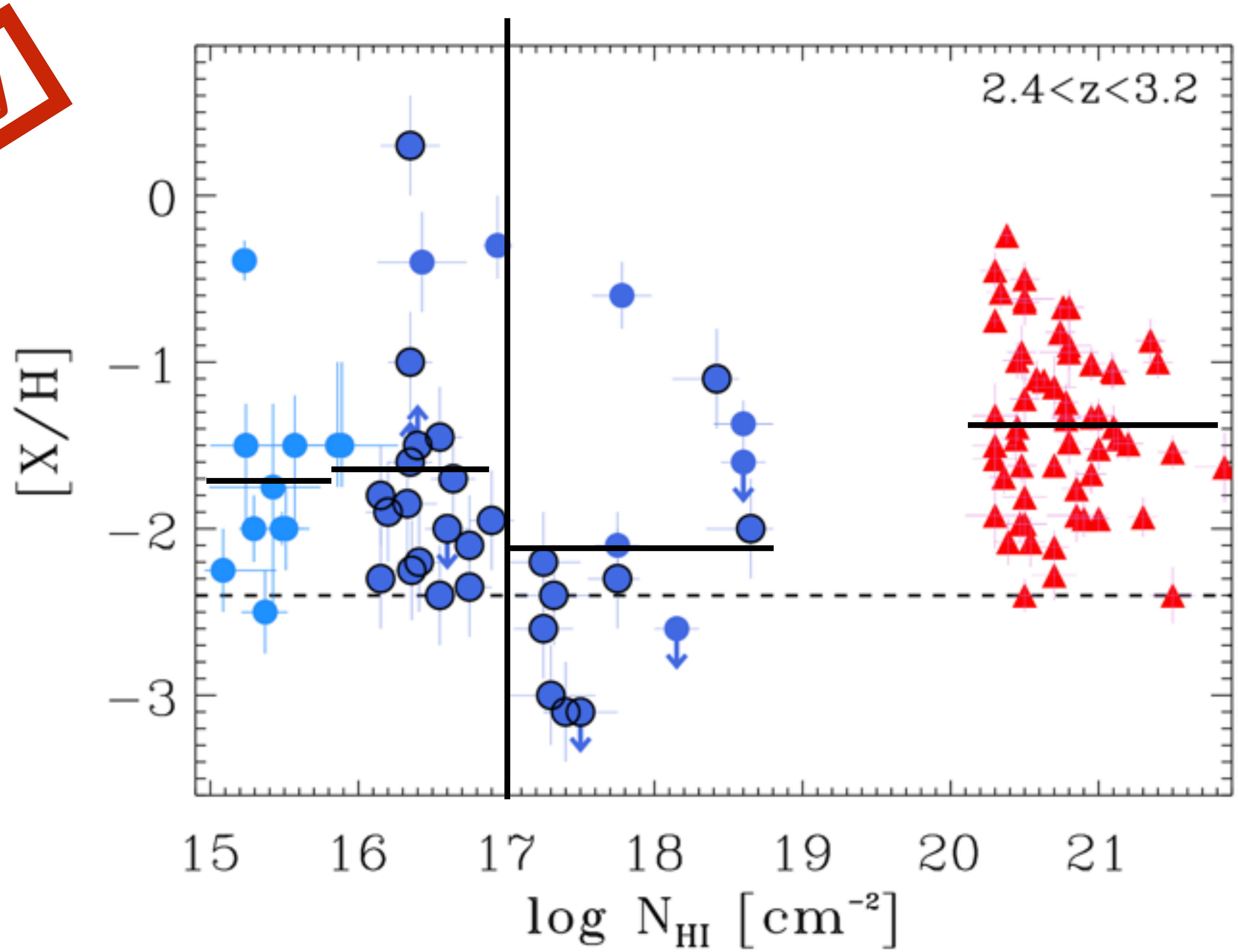


Metallicities of the LLSs are similar to LYAF but lower on average by ~0.5 dex compared to the DLAs.
There are LLSs at lower metallicities than plateau seen in the DLAS and the LYAF.

Lehner+2015, in prep

MDFs of the LLSs at $2.4<z<3.2$

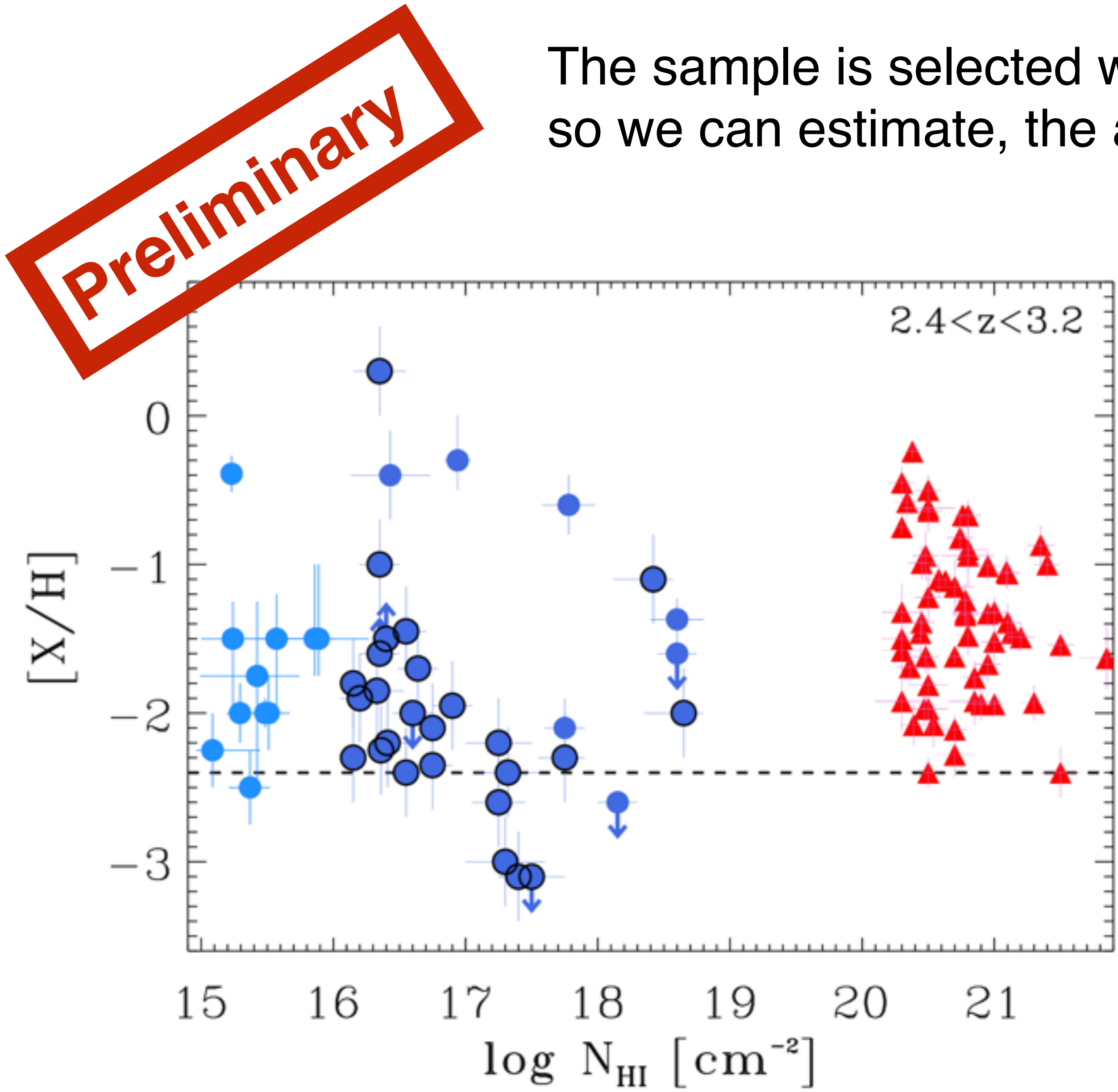
Preliminary



Lehner+2015, in prep

Fraction of pristine LLSs at 2.4<z<3.2

The sample is selected with no a priori on the metal content (low or high), so we can estimate, the amount of pristine LLSs (see Fumagalli+2011).



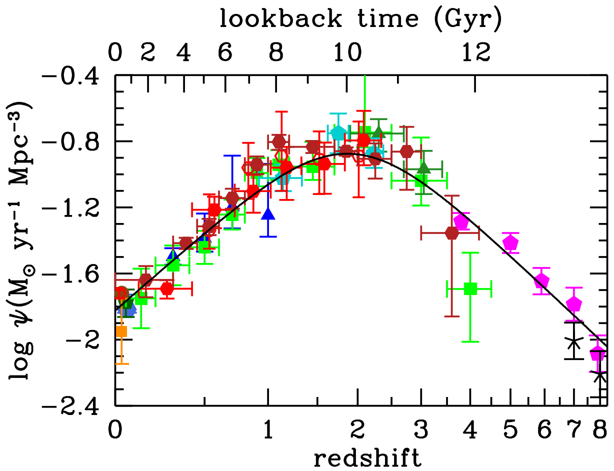
log N	[X/H]<-3	[X/H]<-4
16–19	3–24%	<16%
16–17	<25%	<25%
17–19	7–47%	<22%

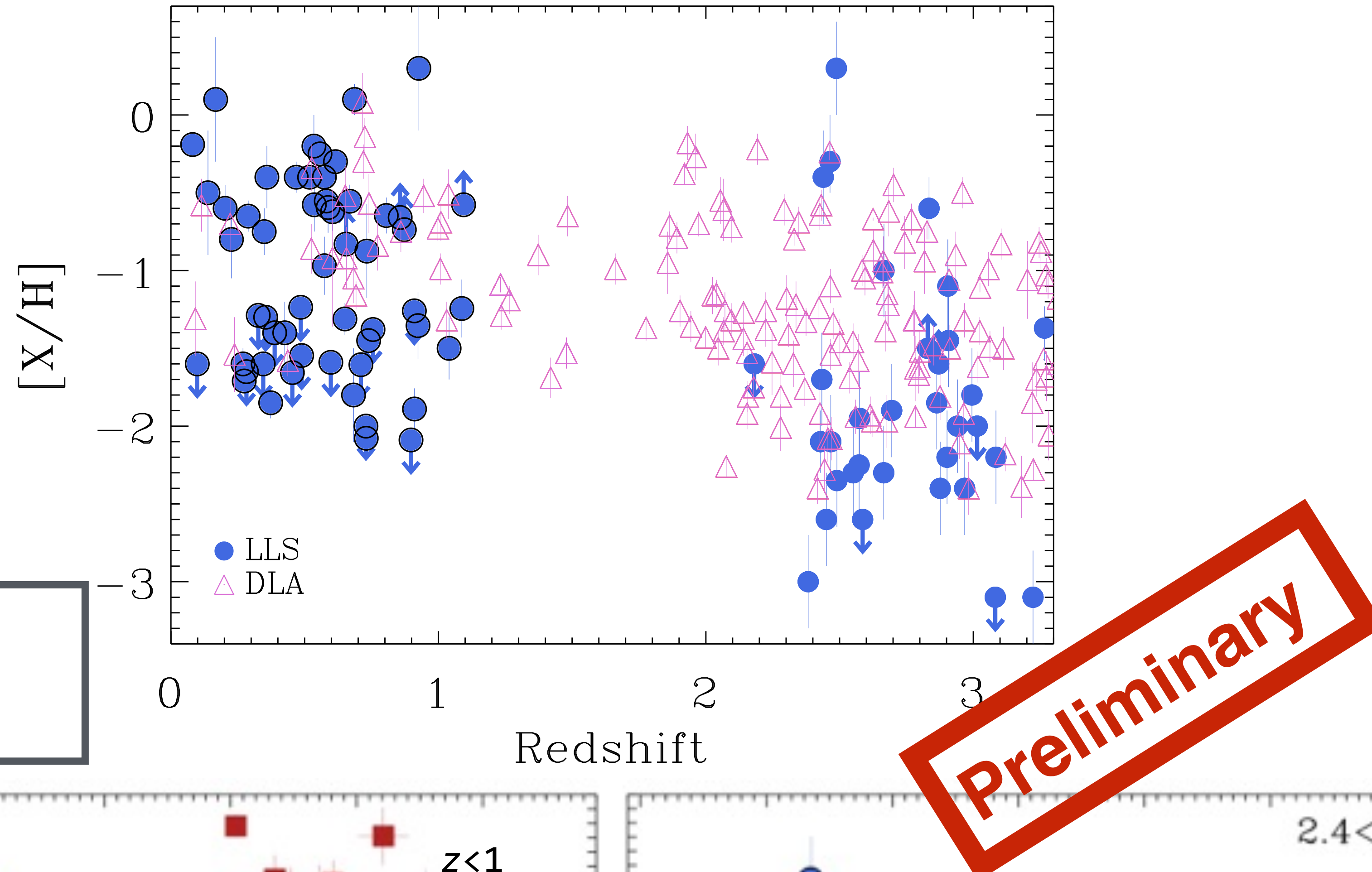
95% confidence interval

With the entire KODIAQ Z sample, we will nail down the fraction of pristine gas in the universe at z>2.

Lehner+2015, in prep

Summary





"Maps" of the CGM and galaxies over cosmic times