The Cycle of Baryons in and out of Galaxies at z<1

Nicolas Lehner
University of Notre Dame

– In collaboration with: –

Chris Howk (ND), Joseph Ribaudo (Utica), Todd Tripp (UMass), Jason Tumlinson, Andy Fox (STScI), Chris Thom (TBD), John O'Meara (St Michael), X Prochaska, Jess Werk (UCSC), Ben Oppenheimer (Leiden)

The Metallicity of the Circumgalactic Medium at z<1

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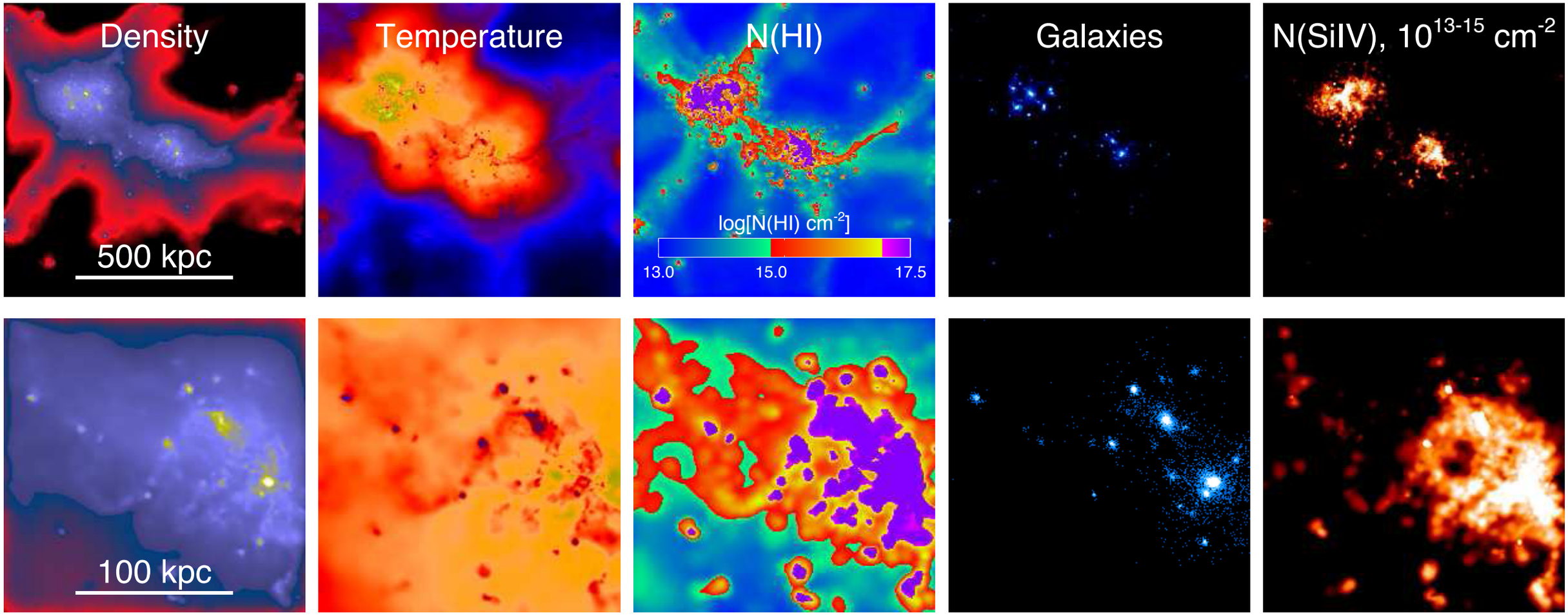
How do we study the Circumgalactic Medium (CGM)?

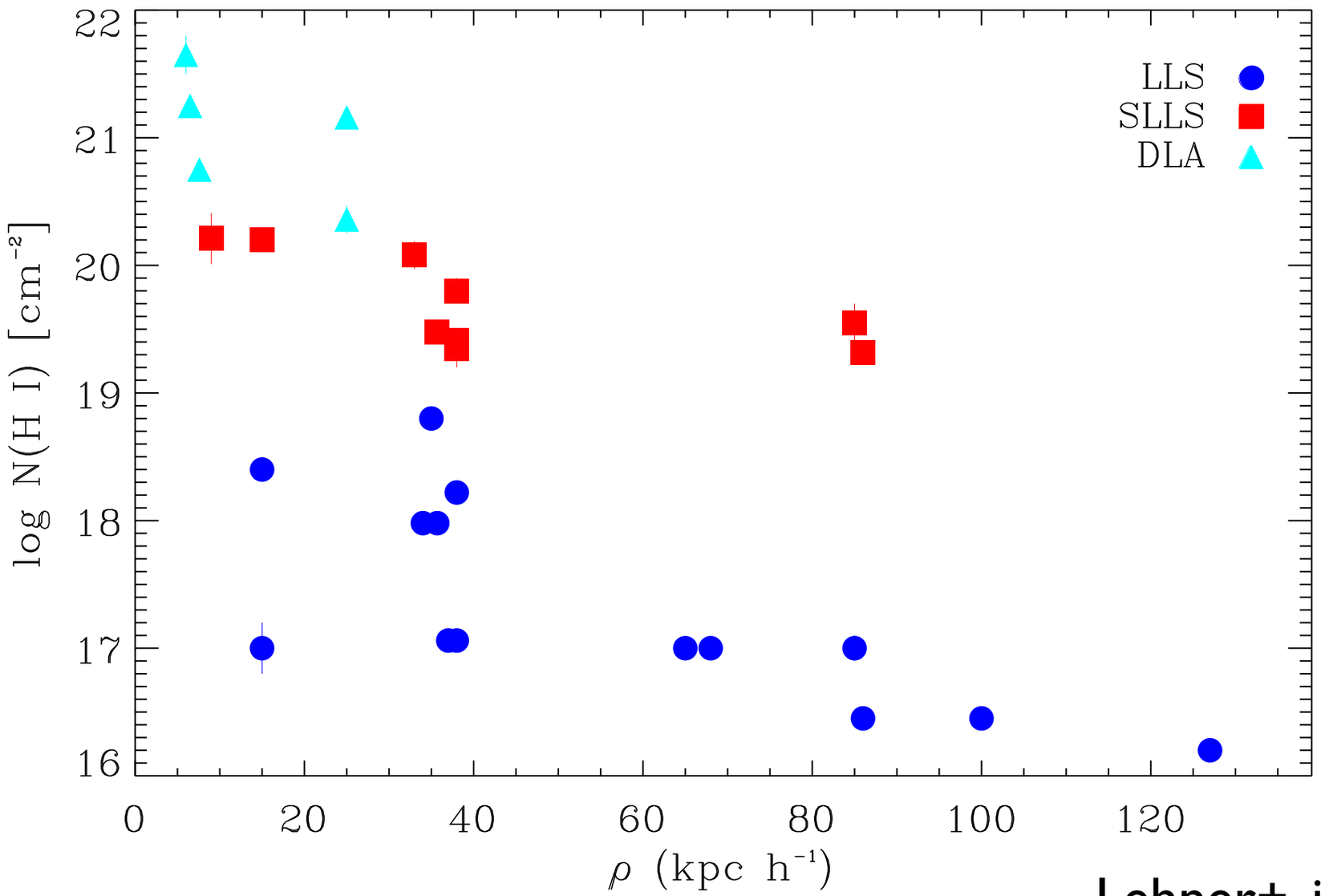


Oppenheimer+, in prep

Galaxies build up gas mass in part by the accretion of gas flowing in along filaments.
**This includes matter associated with, stripped from, or enriched by smaller galaxies.*
Galactic winds also expel metals in the CGM. Galaxies may recycle gas through their CGM.

Simulations show that H I absorbers with 10^{15-17} cm^{-2} best trace the CGM of galaxies within ~300 kpc.

Lyman limit systems and the CGM - Observations



Lehner+, in prep

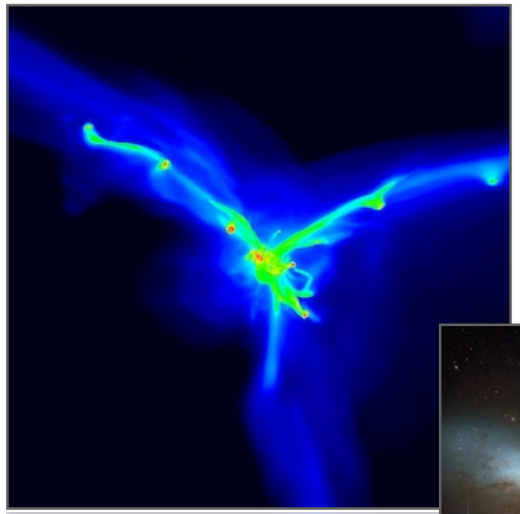
While the weak H I absorbers are very loosely connected to galaxies, significant clustering between galaxies and strong H I ($N_{HI} > 10^{15}$ cm^{-2}) absorbers points to a strong physical connection.

e.g., Lanzetta+95, Penton+02, Bowen+02, Chen+05, Morris & Jannuzi 06, Prochaska+11

Lyman limit systems: HI vs. MgII

Lyman limit systems share significant parameter space with the well-studied Mg II systems.

- LLSs tracing *infall*
- LLSs tracing *outflows*



A. Dekel

However, absorbers selected based on their H I content are not prone to a *metallicity bias.*

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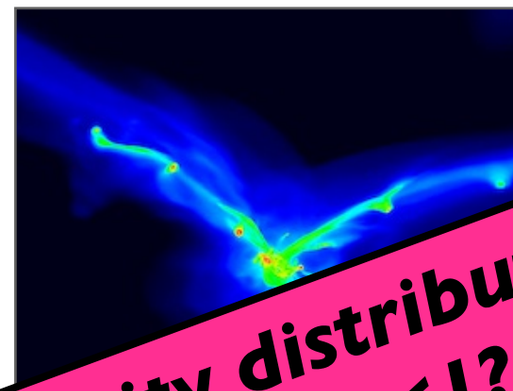
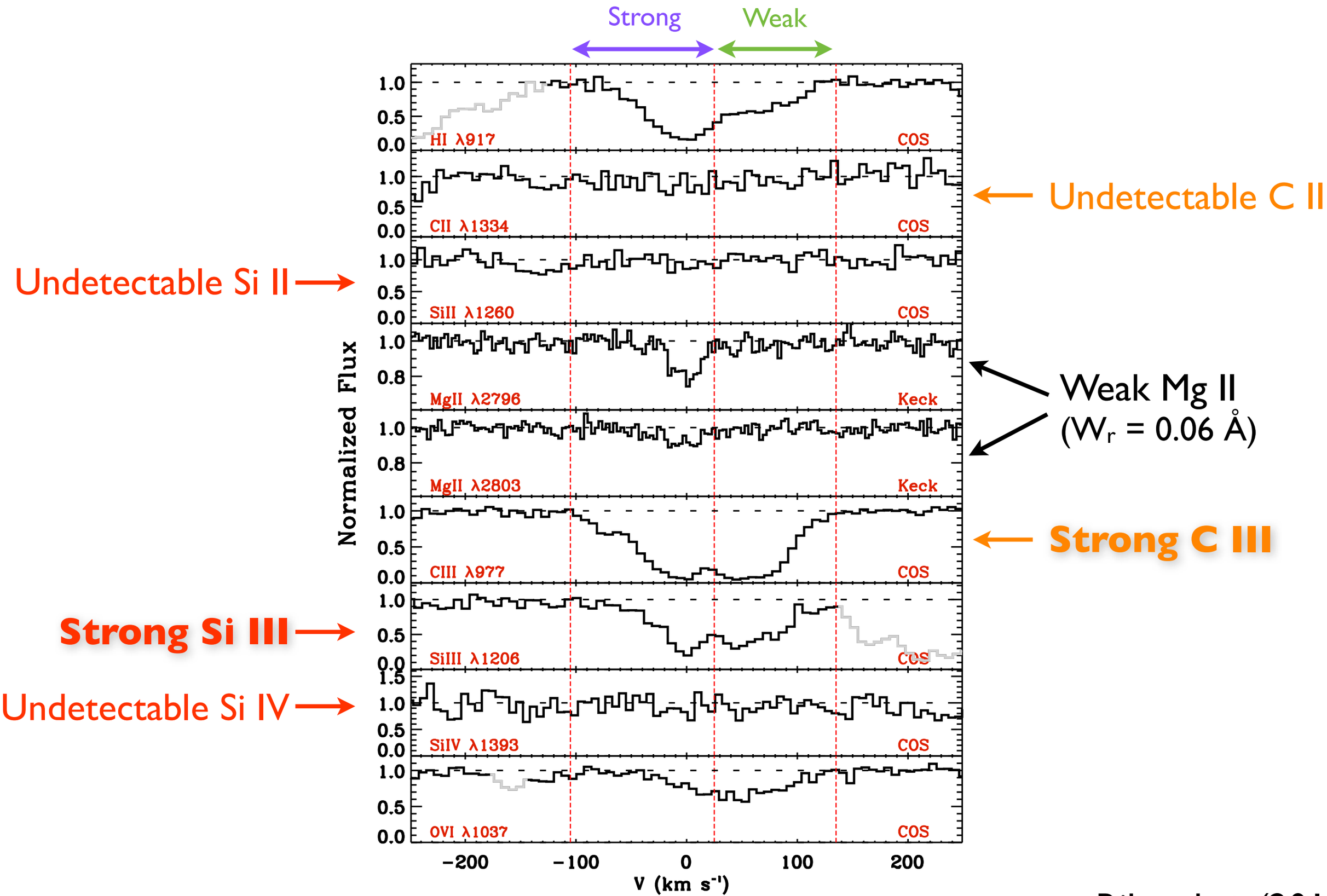


What is the metallicity distribution of the CGM/IGM at z<1?

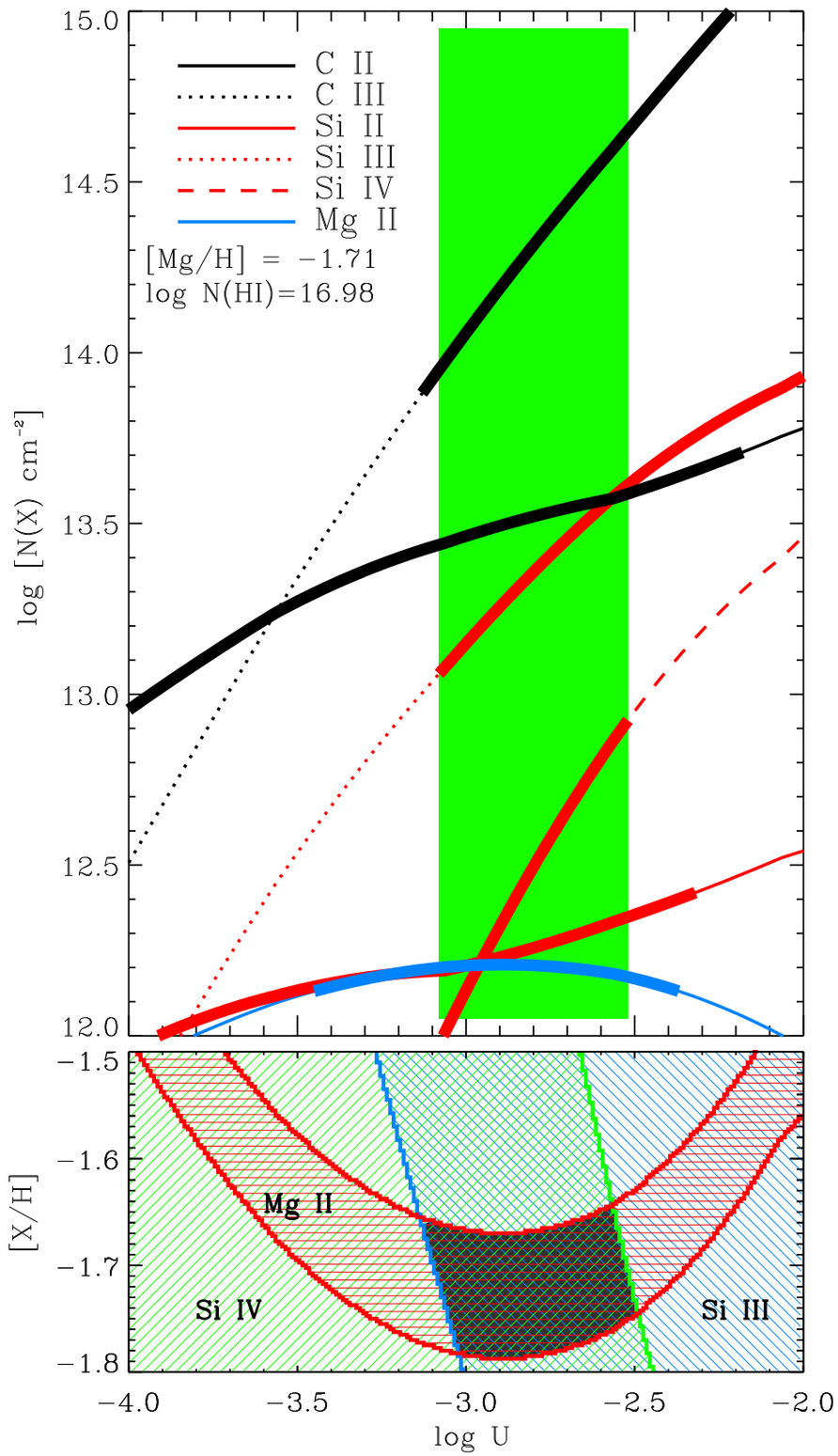
However, absorbers selected based on their H I content are not prone to a *metallicity bias.*

A seemingly pretty banal absorber at z = 0.274



Ribaudo+ (2011b)

A very low metallicity absorber at z = 0.274



LLS ionization

The ionization of the gas is well constrained by *upper limits* on:

- Si II/Si III
- Si IV/Si III
- C II/C III

Final results:

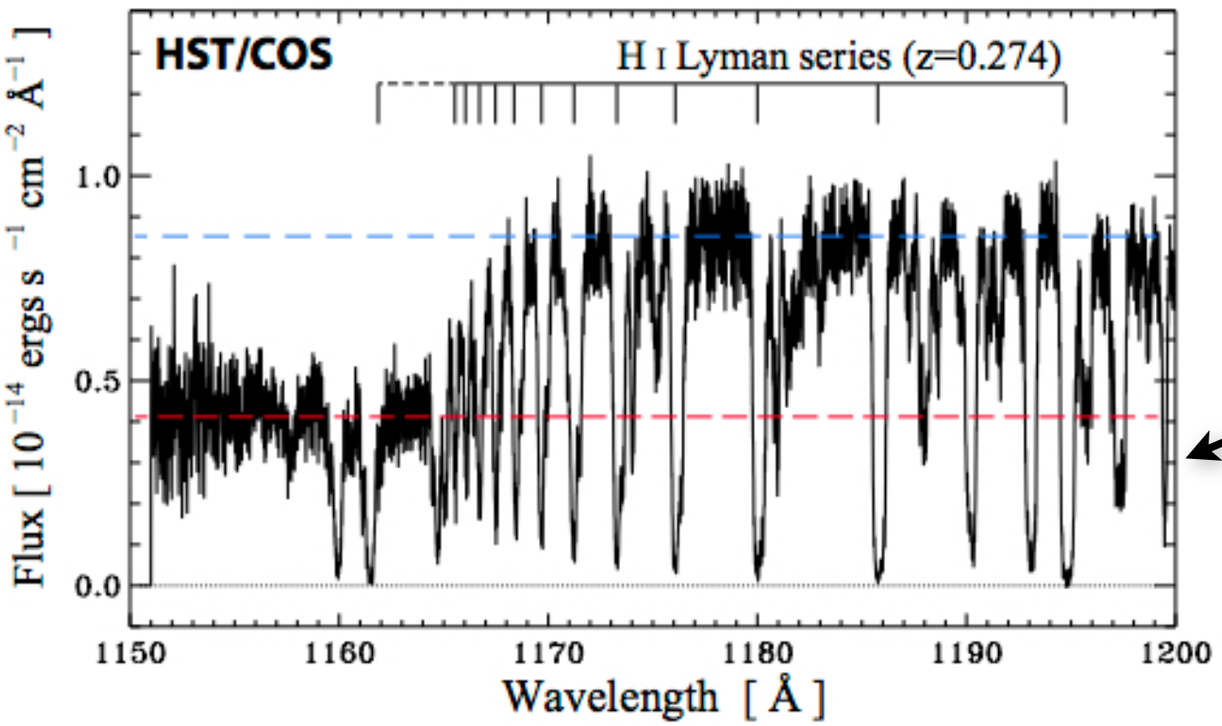
log U = -2.8 ± 0.2

[X/H] = -1.71 ± 0.06

(~2% solar)

Ribaudo+ (2011)

A probable cold accretion stream at z = 0.274



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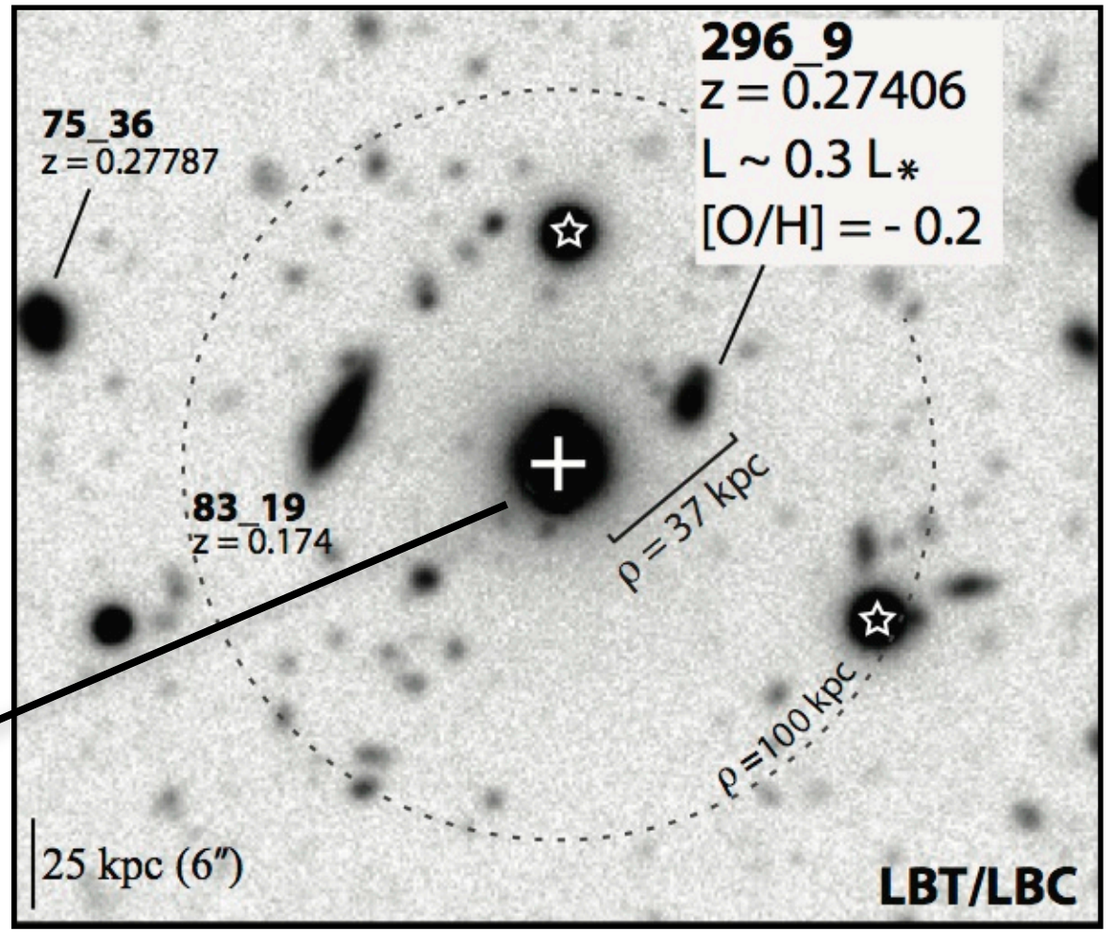


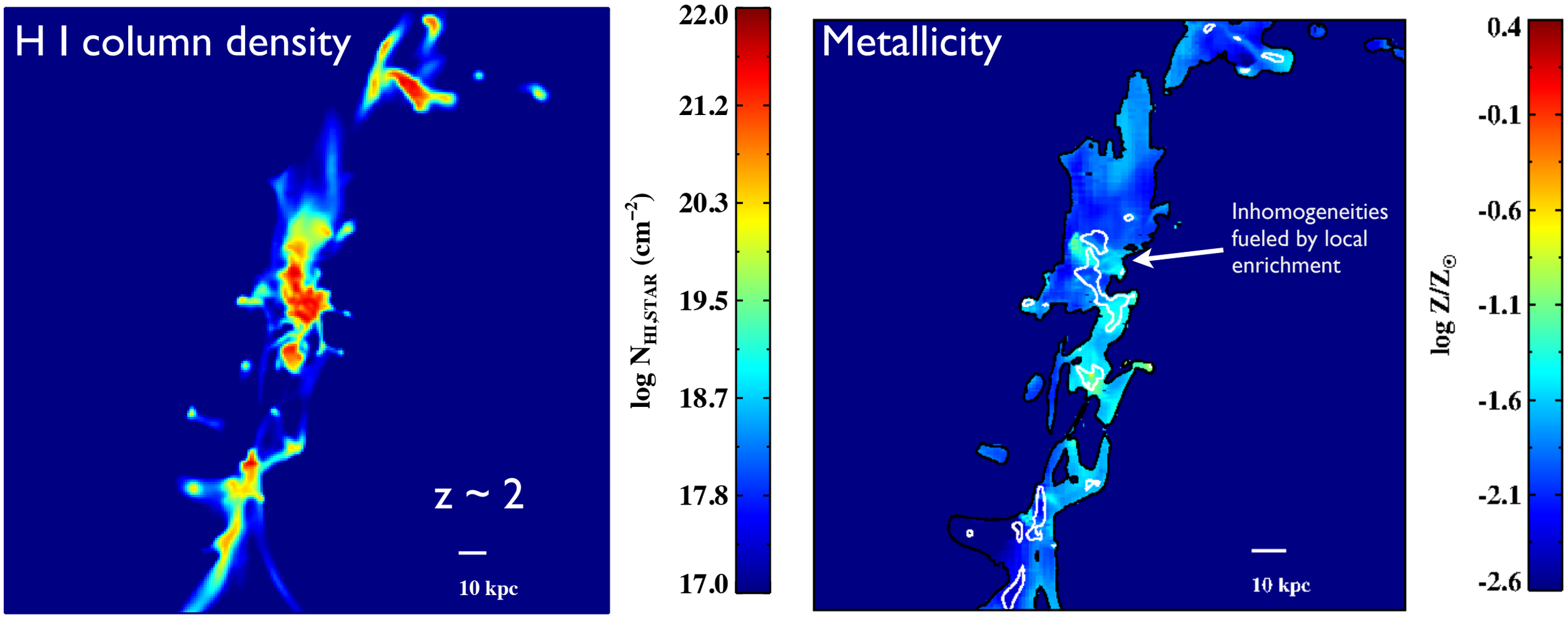
- log N(H I)$_{total}$ = 17.06±0.05
- [X/H] = -1.71 ± 0.06

The LLS and galaxy are separated by ρ = 37 kpc and Δv ~ 25 km/s.

They differ in metallicity by a factor of ~30.

Ribaudo+11

Lyman limit systems and infall



Fumagalli+ (2011)

Infall streams predicted to have:

- LLS-like column densities
- Low neutral fractions
- Covering factors ~few% within R_{vir}

  [Larger for lower N(HI), impact parameter and higher z]

- Low metallicity: $\langle Z \rangle \sim 10^{-2}\ Z_\odot$
- $\Delta v_{gal\text{-}gas} \lesssim v_{circ}$

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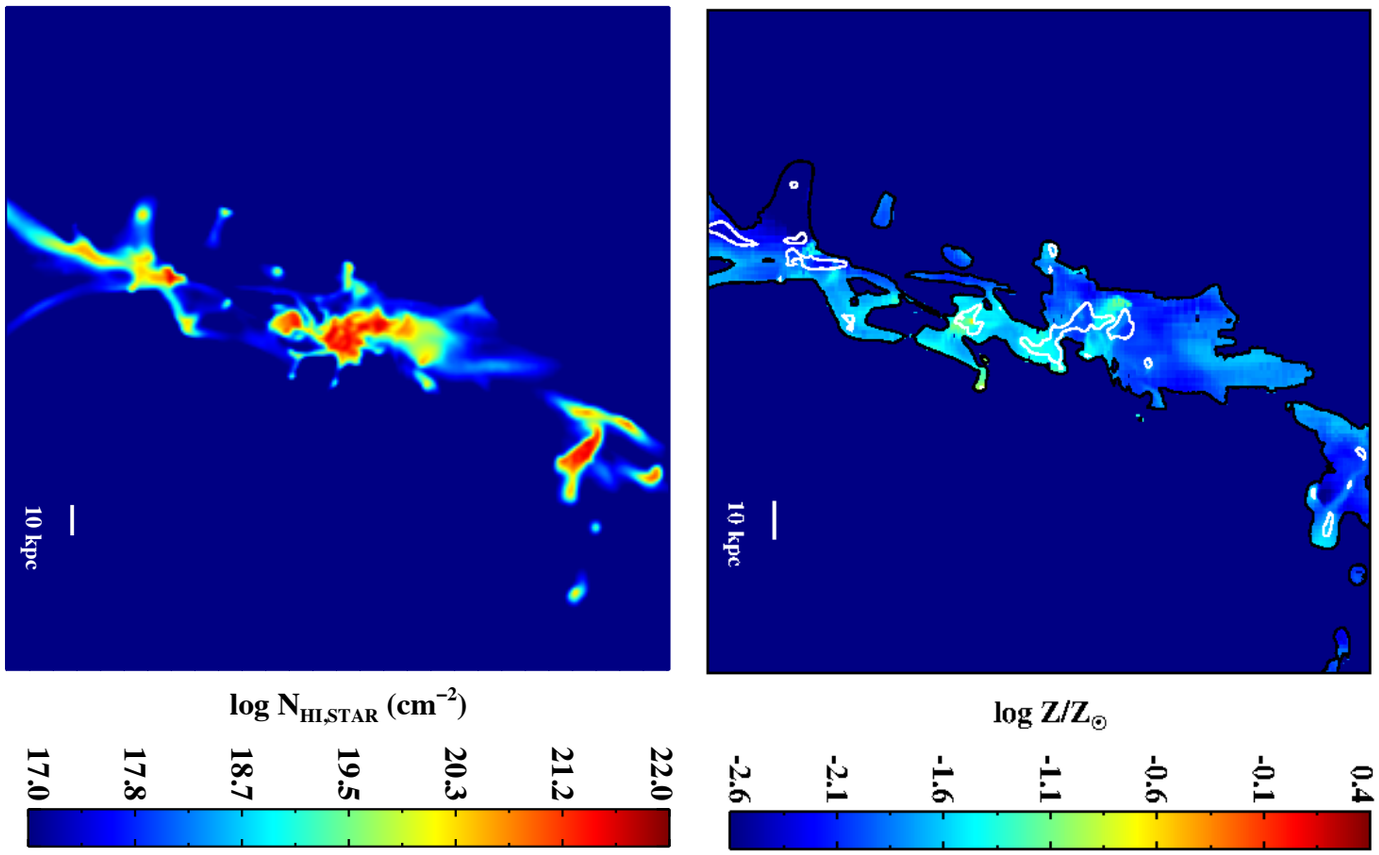

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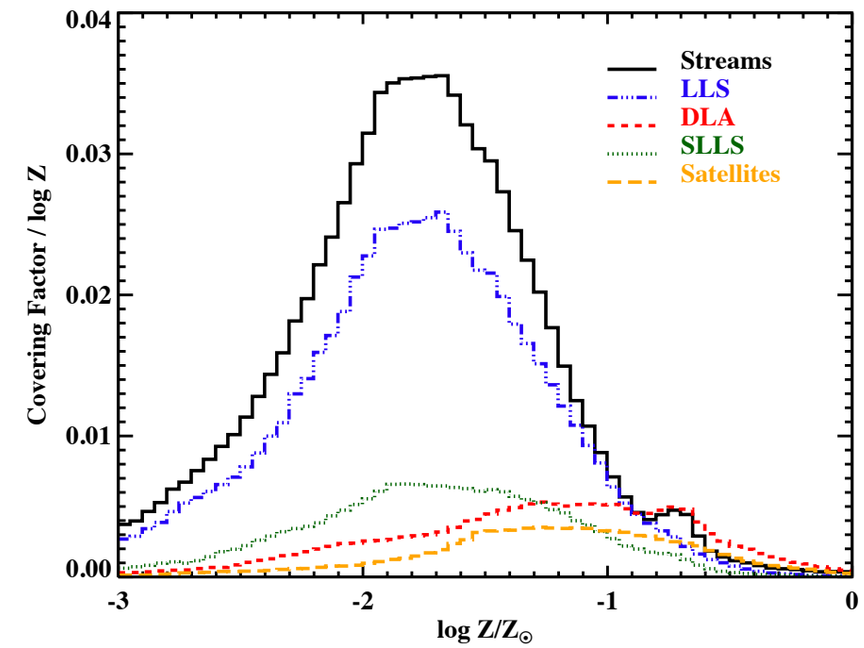


Figure 12. Distribution of metallicity, column density weighted, in the entire sample for DLAs (red dashed line), SLLSs (green dotted line) and LLSs (blue dot-dashed line). Also shown are the streams alone (black solid line) and satellites without centrals (orange long dashed line). The smooth stream component is more metal poor than the galaxies, with typical $Z \sim 0.01 Z_\odot$. However, gas in streams is not pristine, but already enriched by previous episodes of star formation.

This absorber is very similar to infalling streams seen in simulations (e.g., Birnboim & Dekel 03, Keres+05, Dekel+09, Fumagalli+11, Faucher-Giguere & Keres 11, van de Voort +12, etc.).

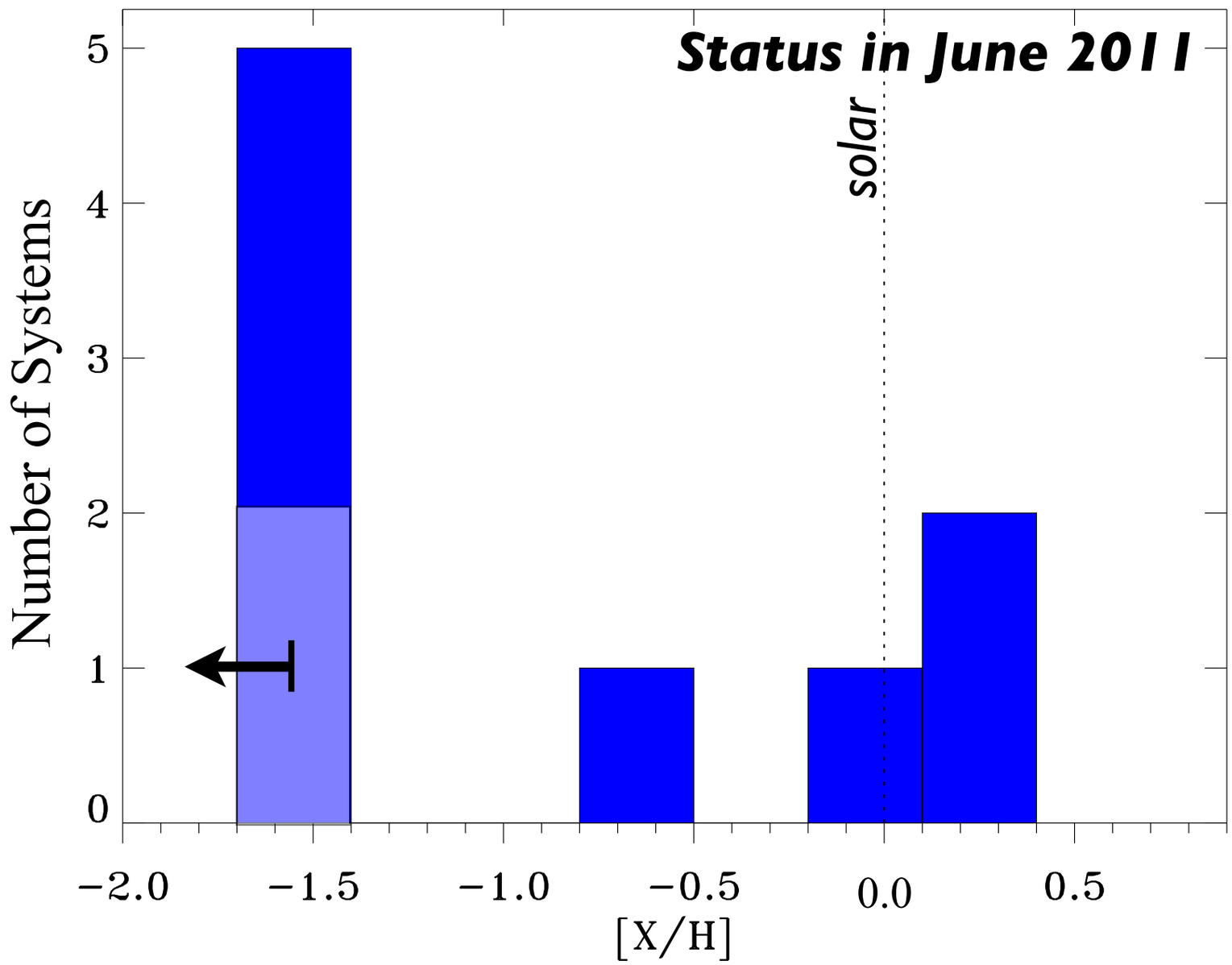
As pointed out in Ribaudo et al. (2011):

*Several such systems exist, most showing prominent **C III** and **Si III** with little other metal absorption (e.g., no Si II, Si IV, C II) [Zonak+04, Tripp+05, Cooksey+08]

Lyman limit systems as probes of infall and outflows

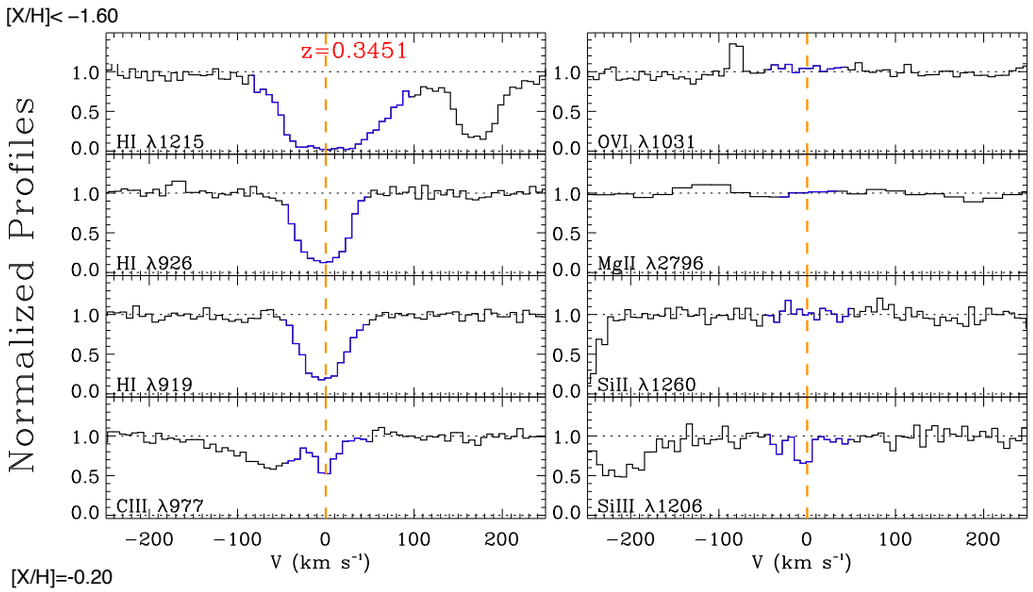
Metallicity distribution of z ≤ 1.0 Lyman limit systems

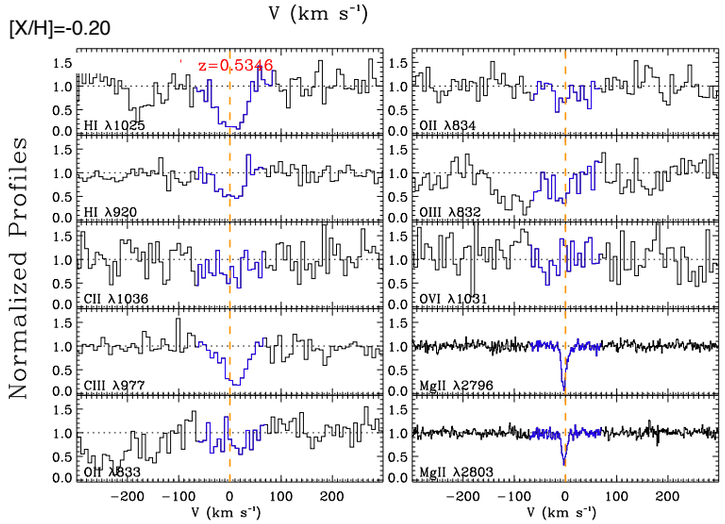
[**16.1** ≤ log N(H I) ≤ 18.5]

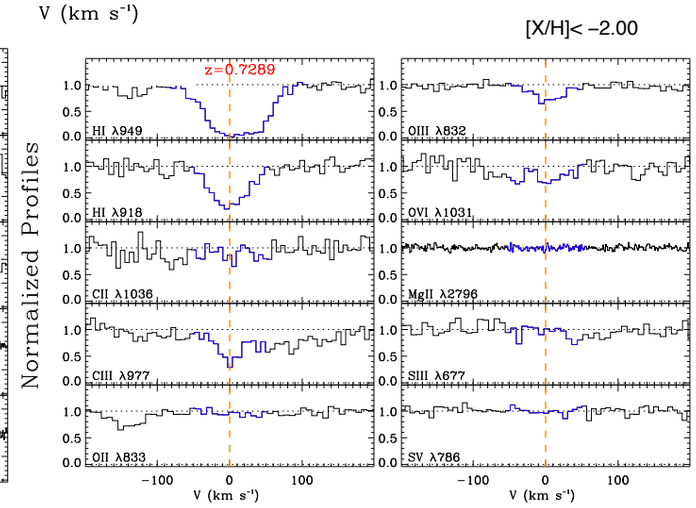


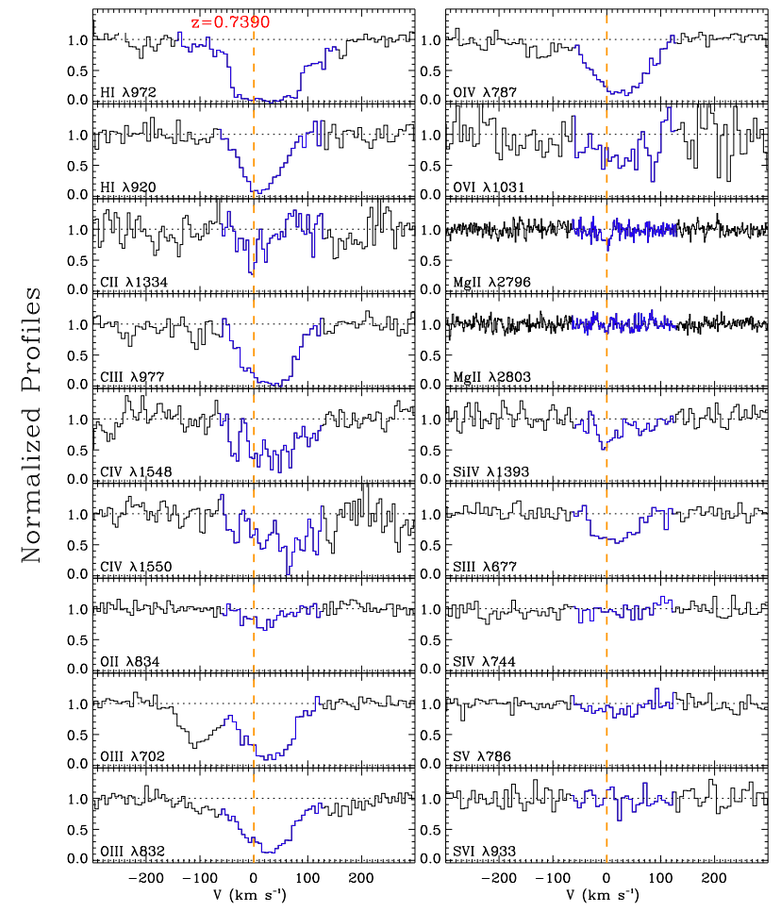
Literature and recent COS observations:

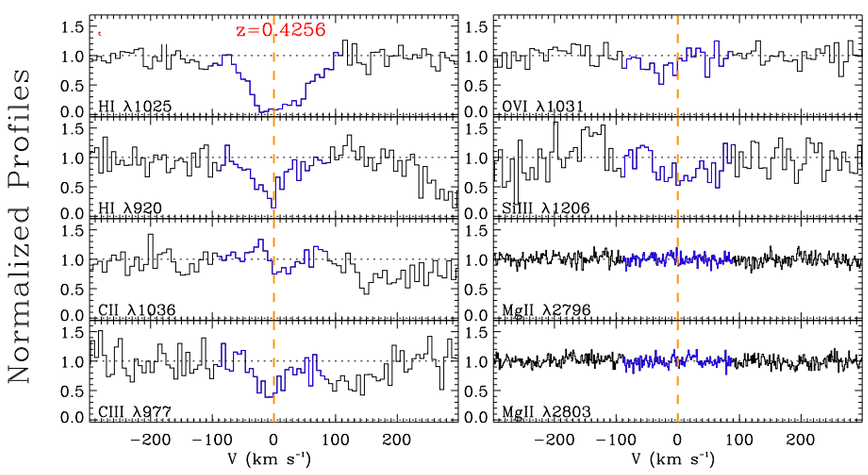
Zonak+04, Tripp+05, Jenkins+05, Cooksey+08, Lehner+ 09, Savage+11, Ribaudo+11, Tripp+11



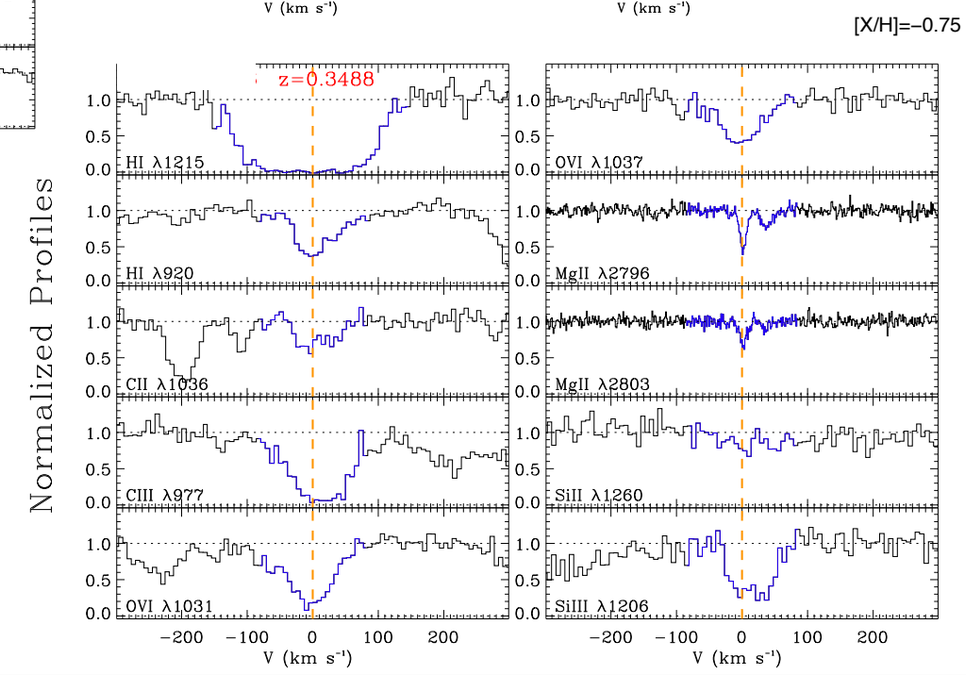








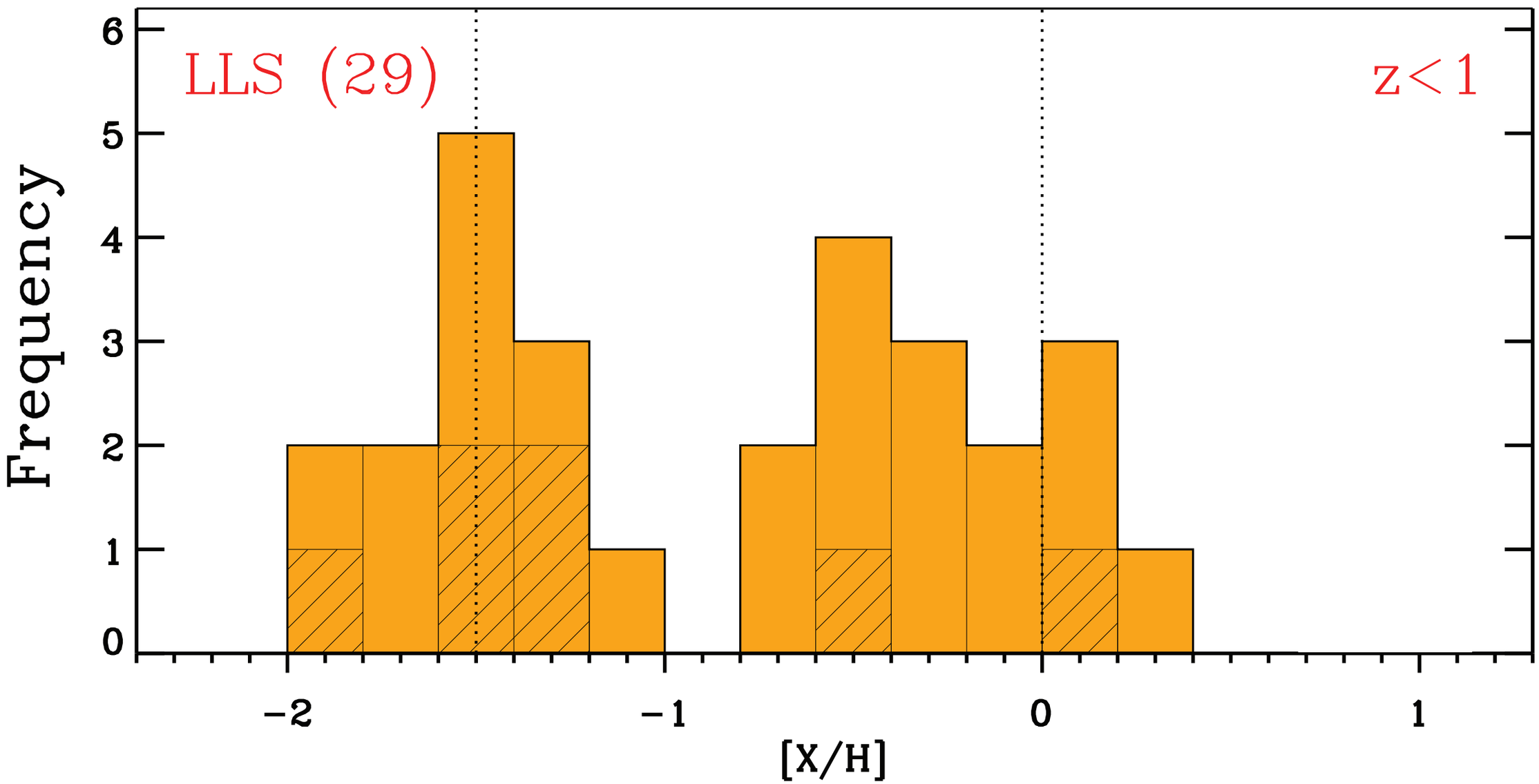
[X/H]< −1.60



SAMPLE: VARIETY OF COS AND KECK OBSERVATIONS

Lyman limit systems as probes of infall and outflows

Metallicity distribution of z ≤ 1.0 Lyman limit systems
[**16.2** ≤ log N(H I) < 19.0]



*16 new LLS measurements from COS.
*Where searches have been done, galaxies exist within ρ < 100 kpc.

Lehner+ (*in prep*)

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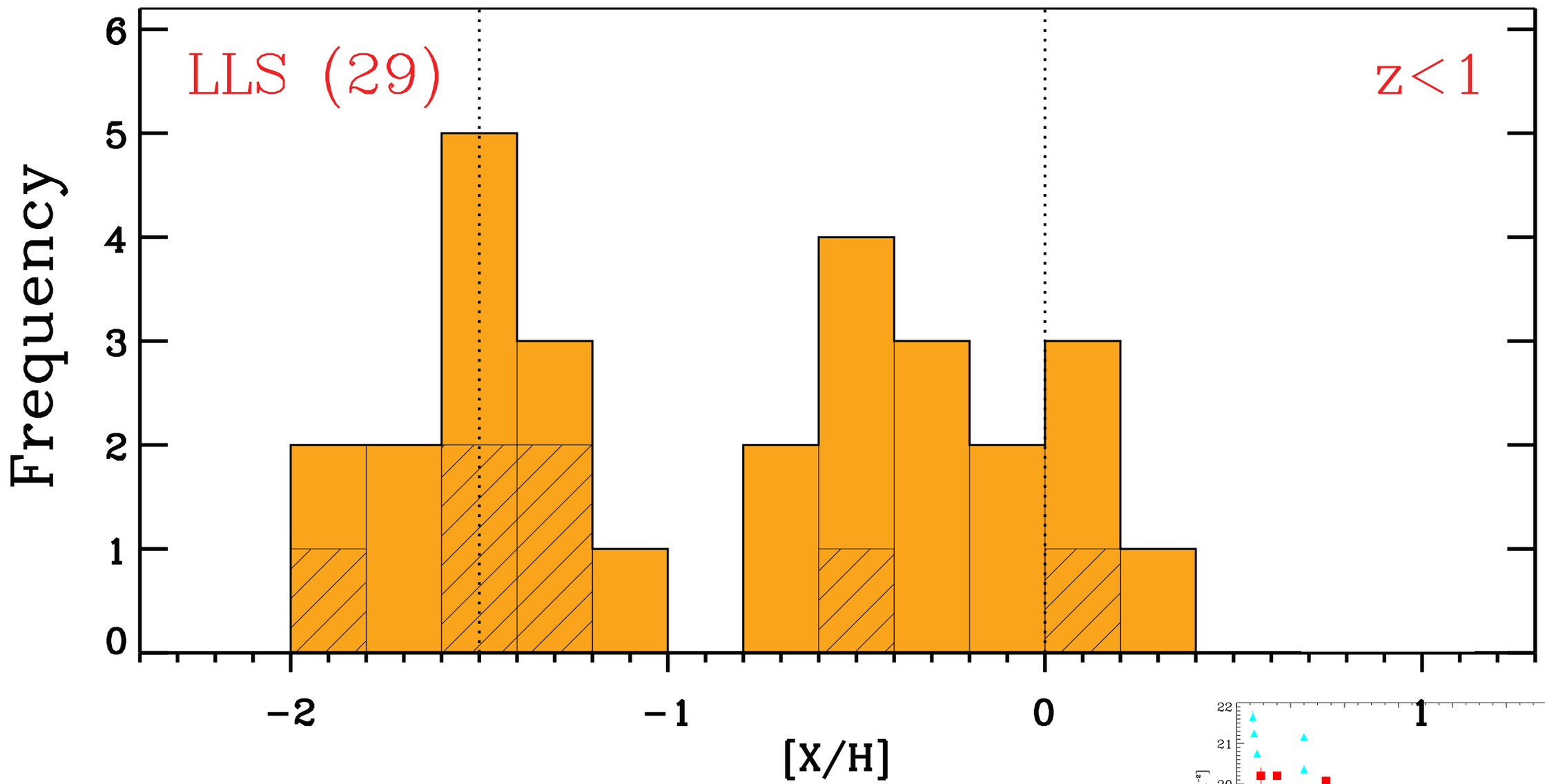

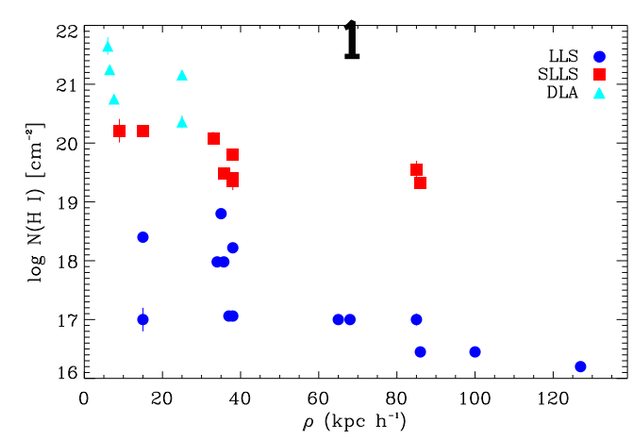

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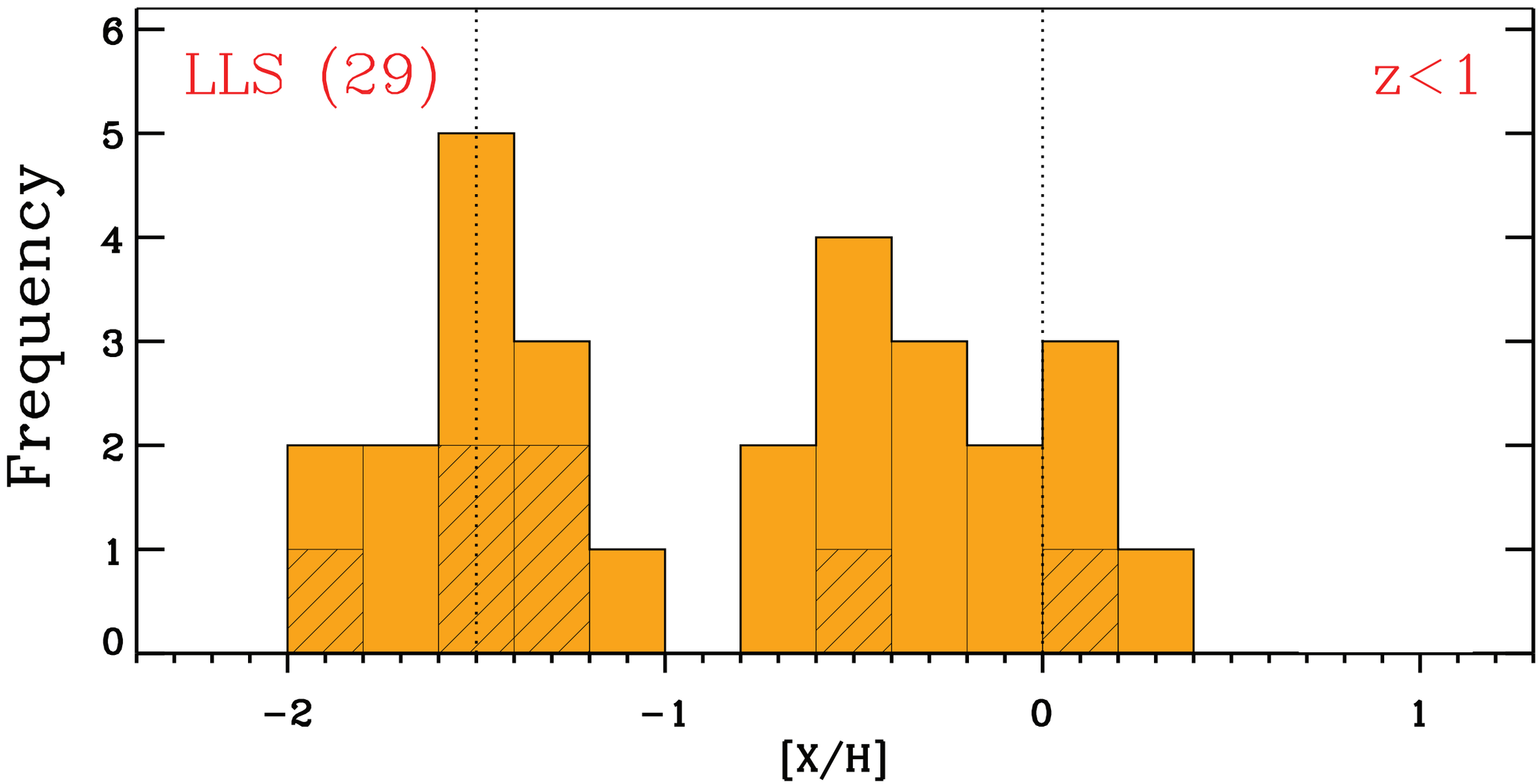

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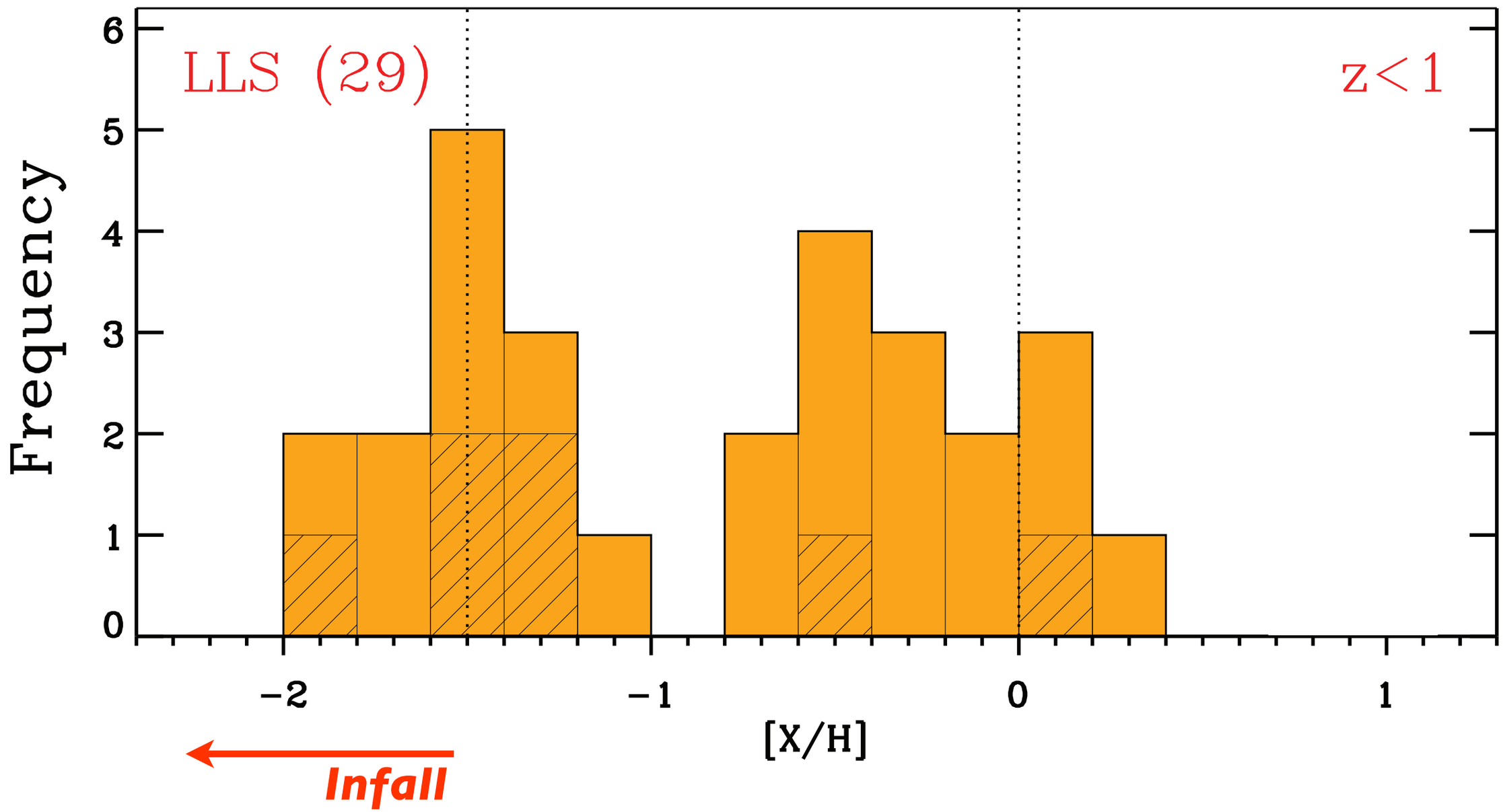

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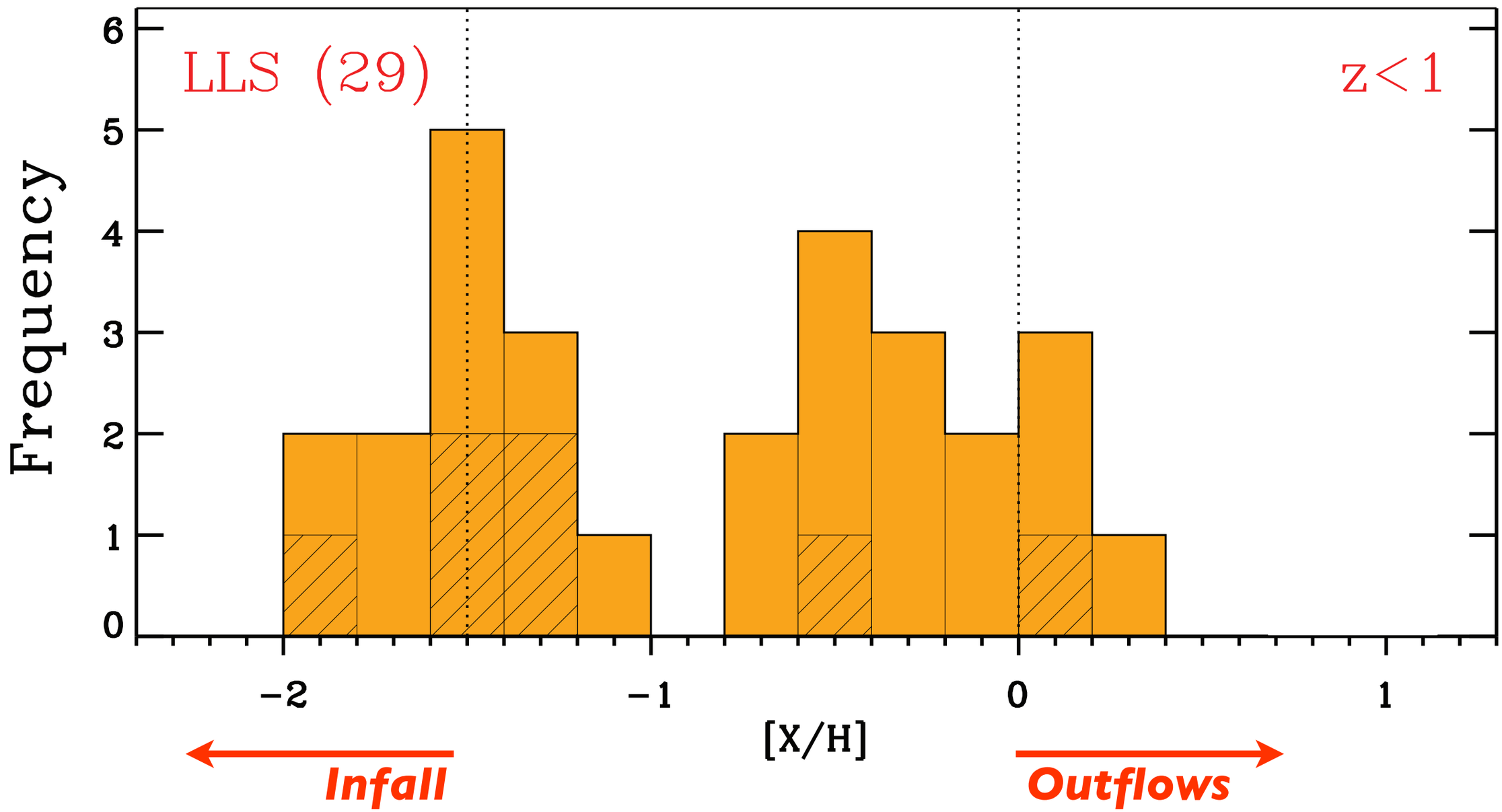

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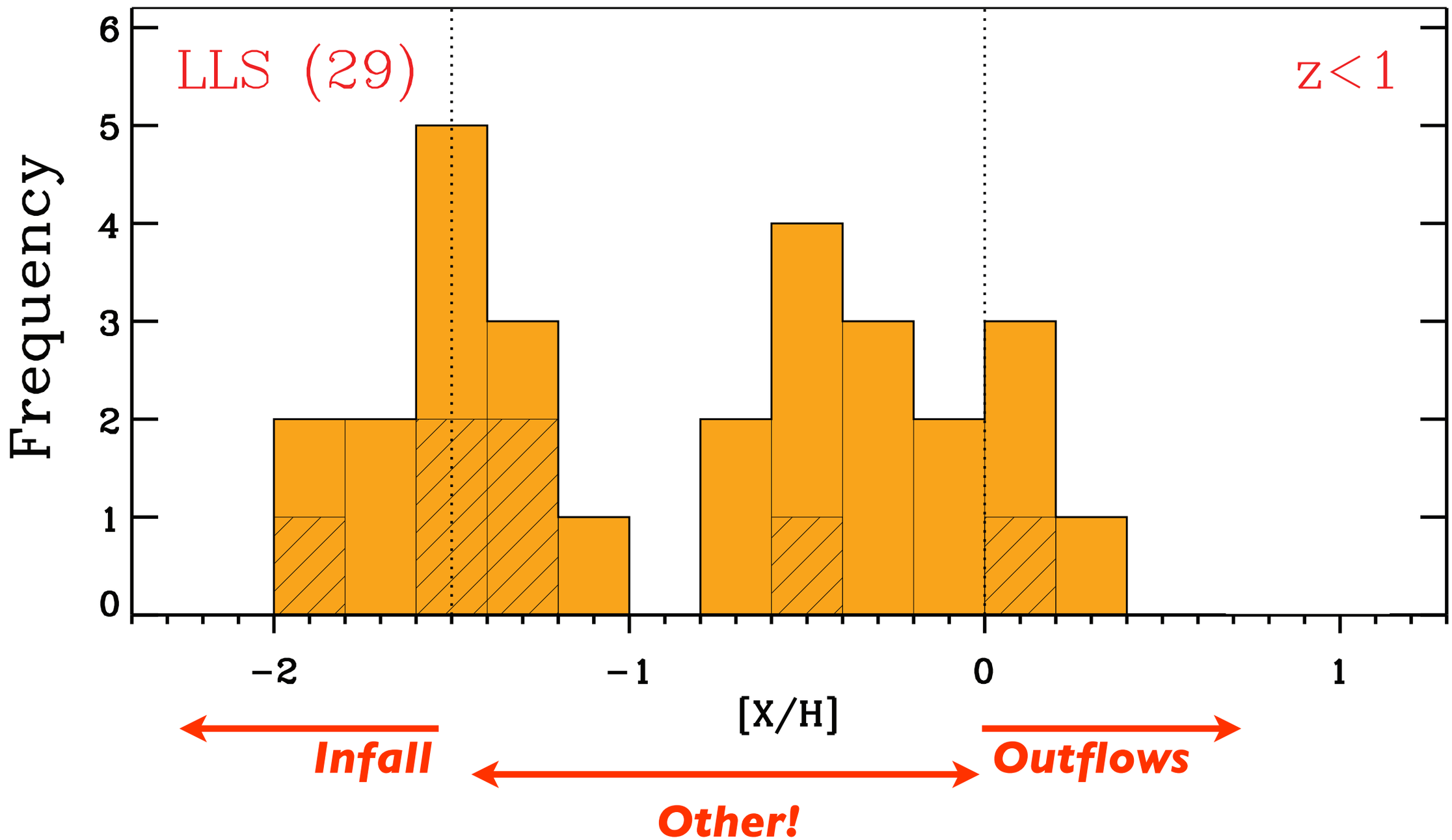

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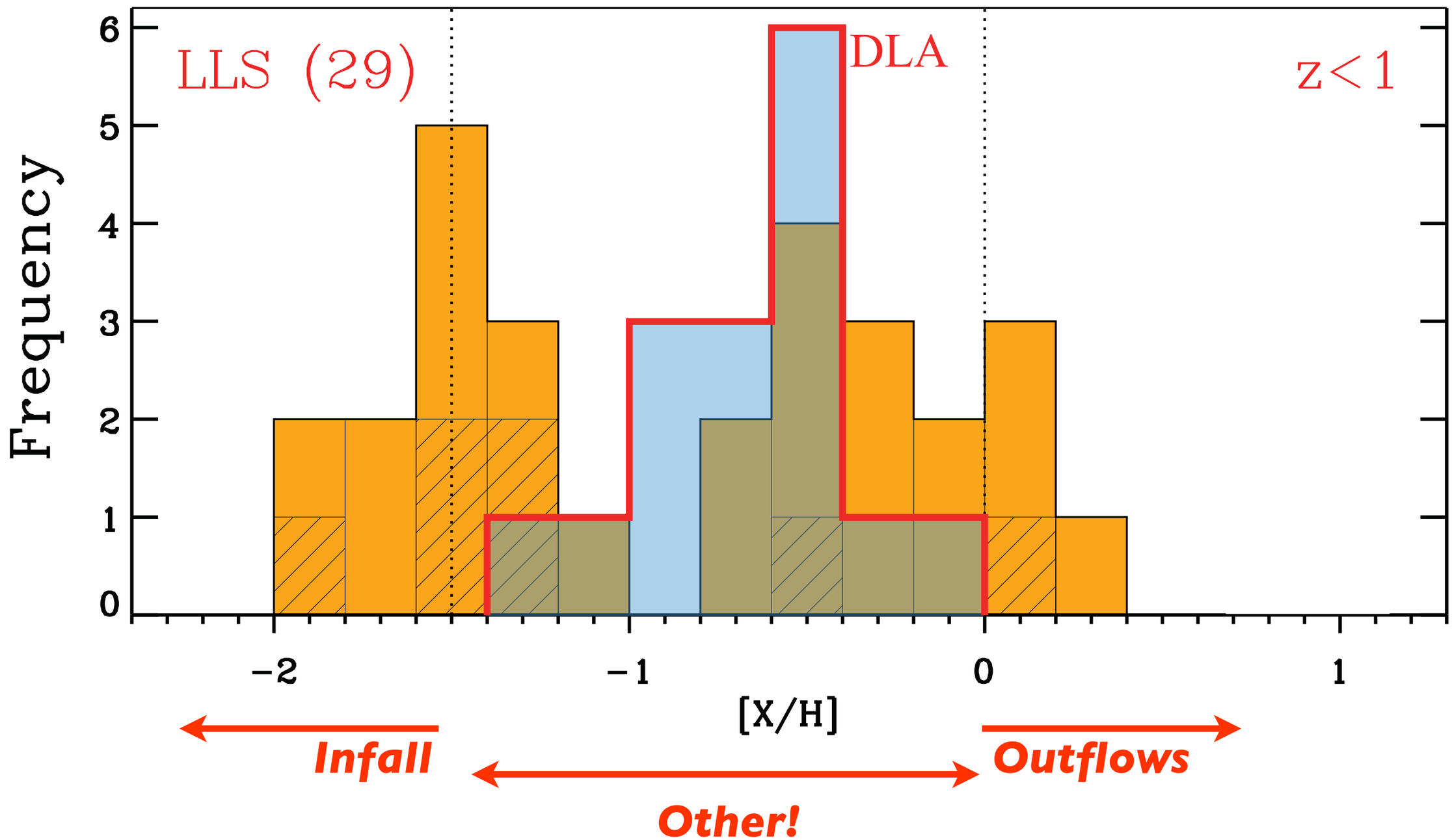
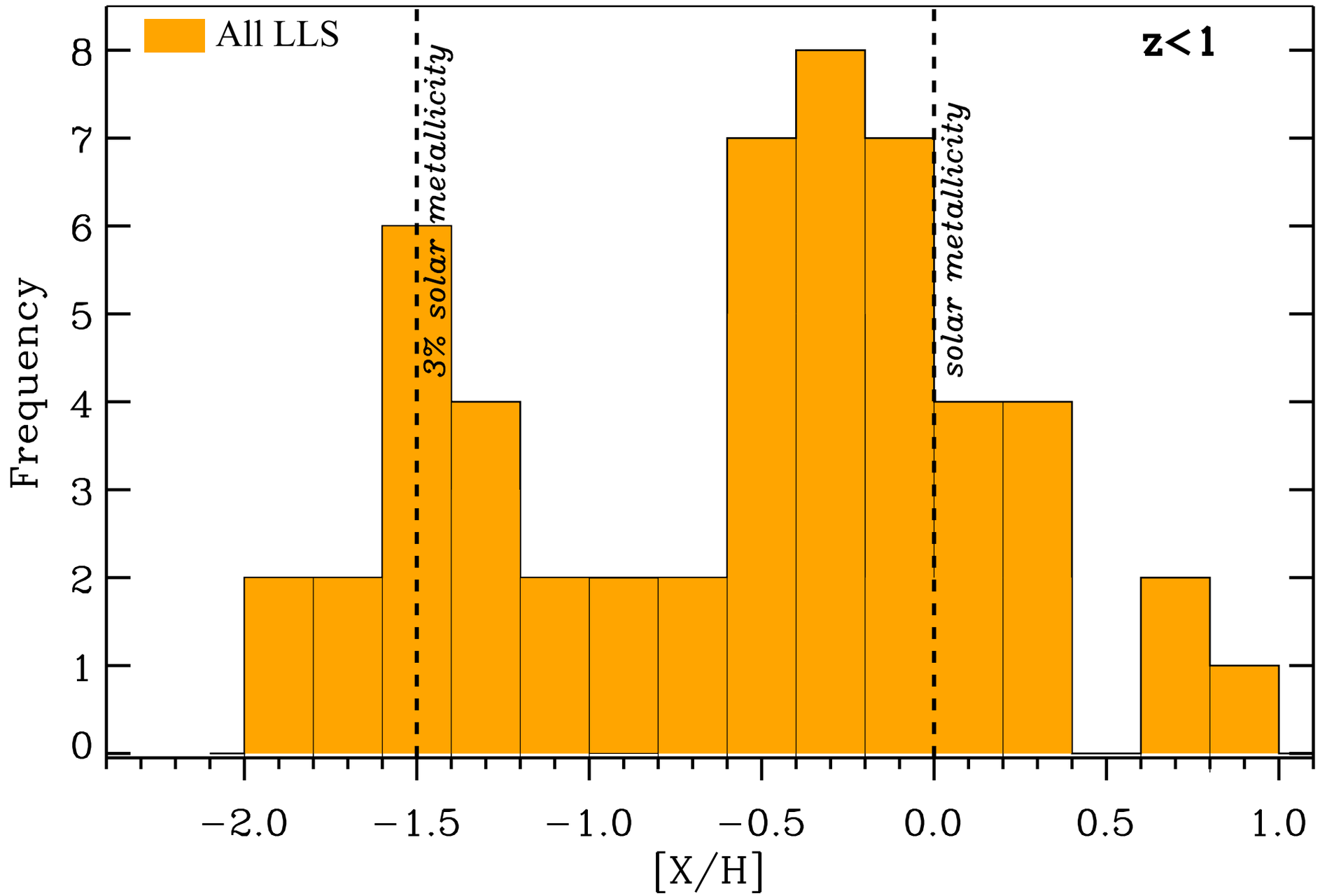


Lehner+ (*in prep*)

Battisti+, Peroux+, Pettini+, Rao+, Turnshek+, Meiring+

Lyman limit systems as probes of infall and outflows

Metallicity distribution of z ≤ 1.0 LLSs and super-LLSs
[**16.2** ≤ log N(H I) ≤ 20.3]



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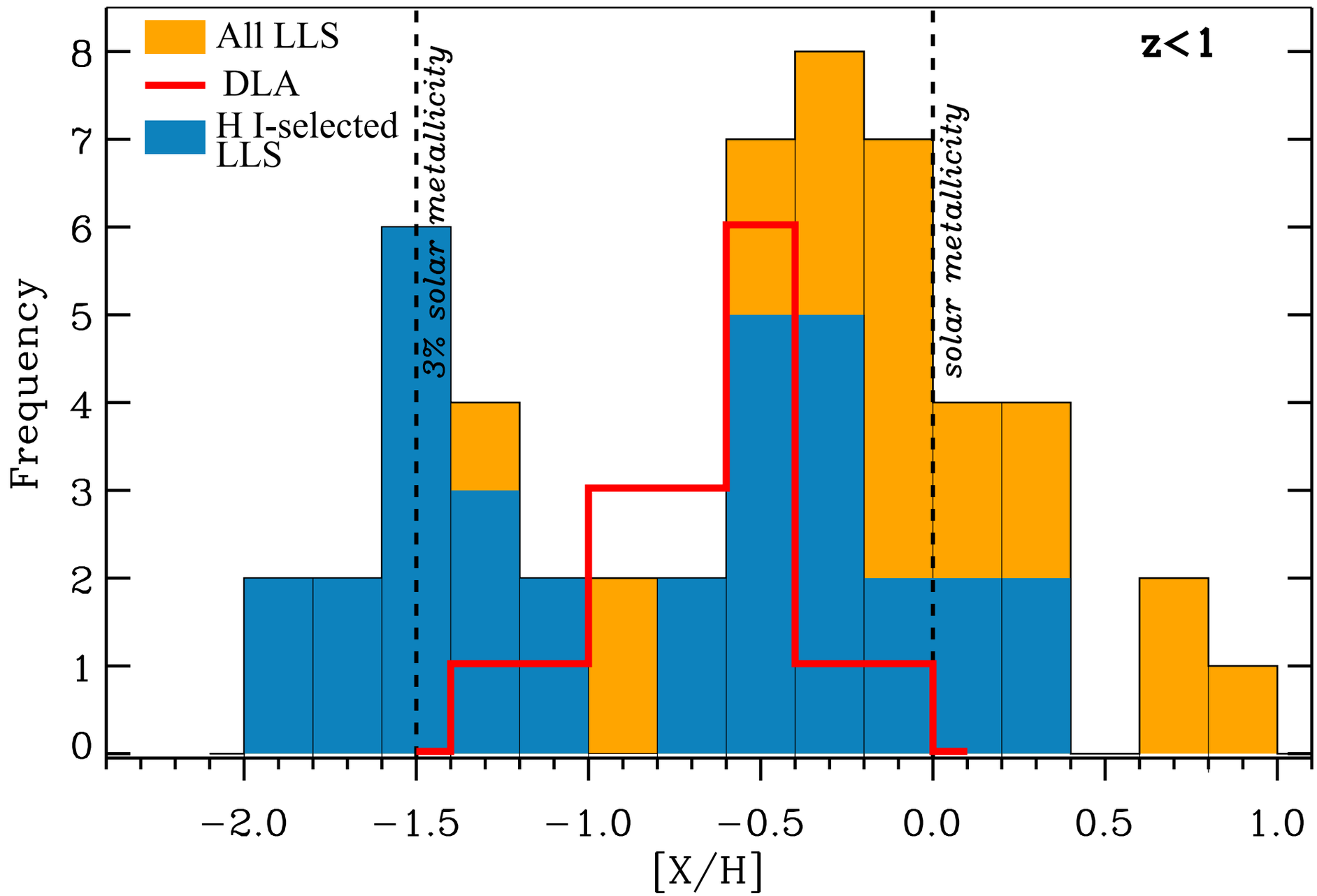
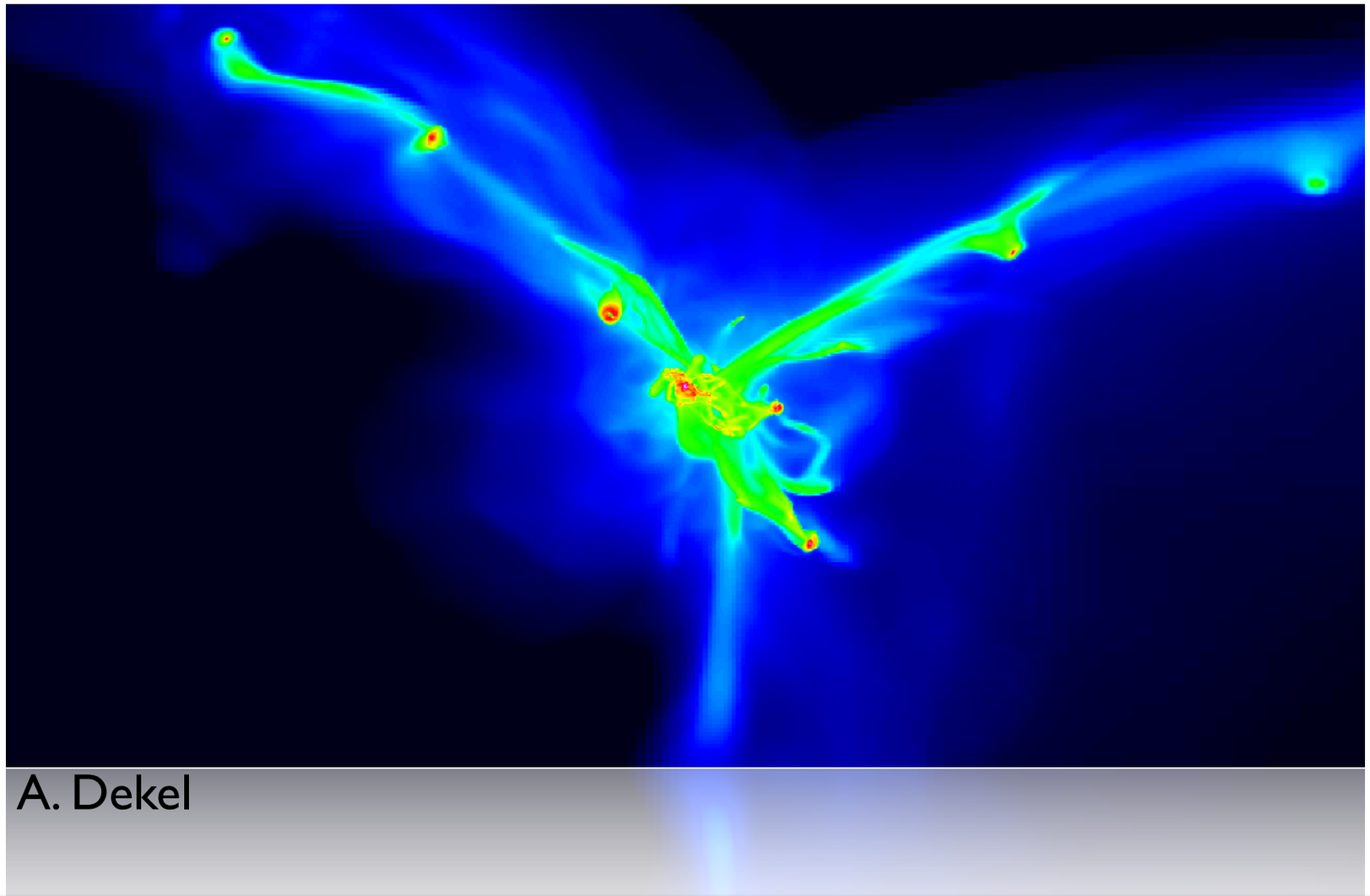


Lehner+ (*in prep*)

Have we detected cold gas accretion?



We have detected very low metallicity, ionized gas in the halos of galaxies.

The very low metallicity absorbers are not rare at z<1.

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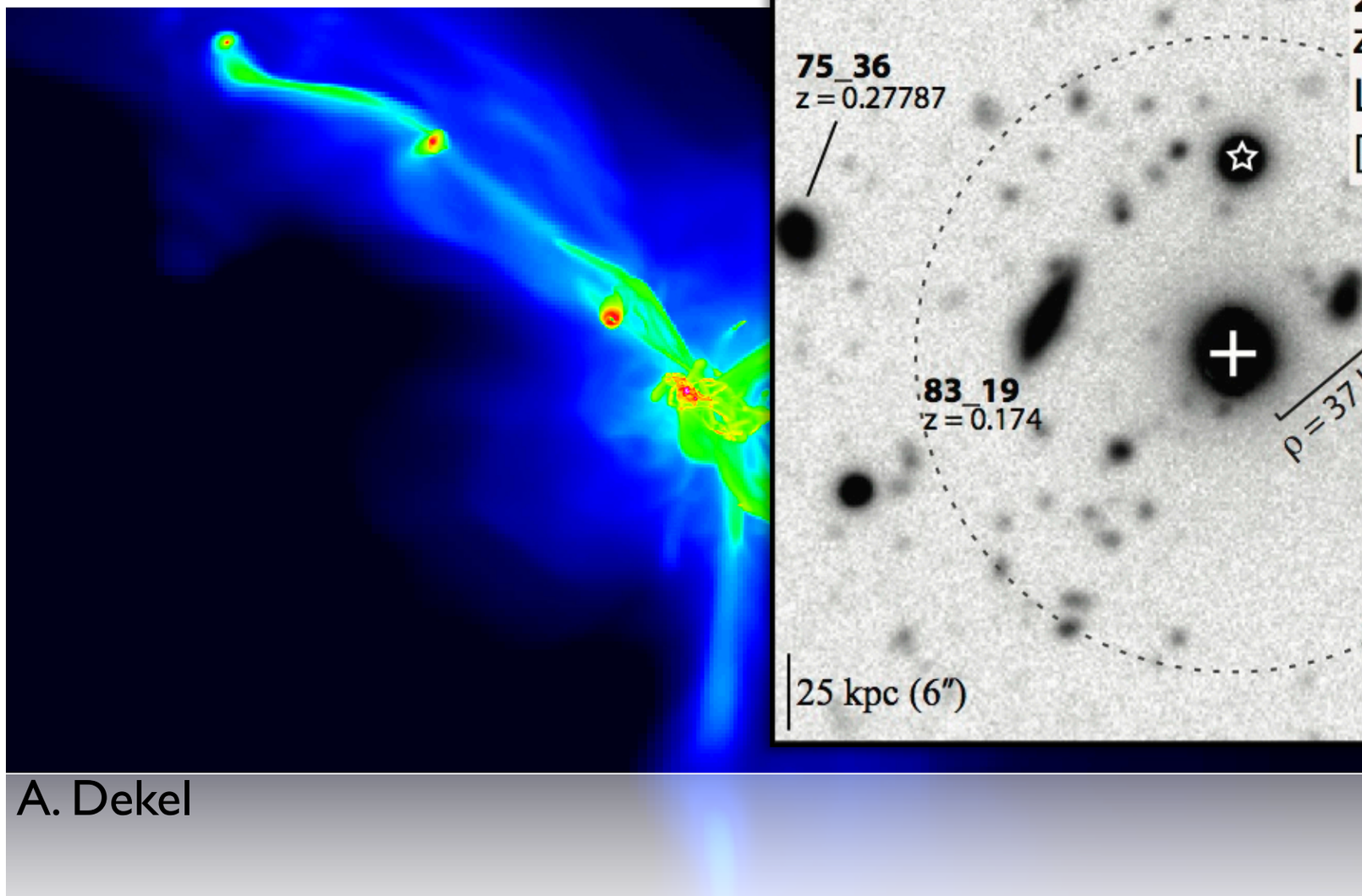

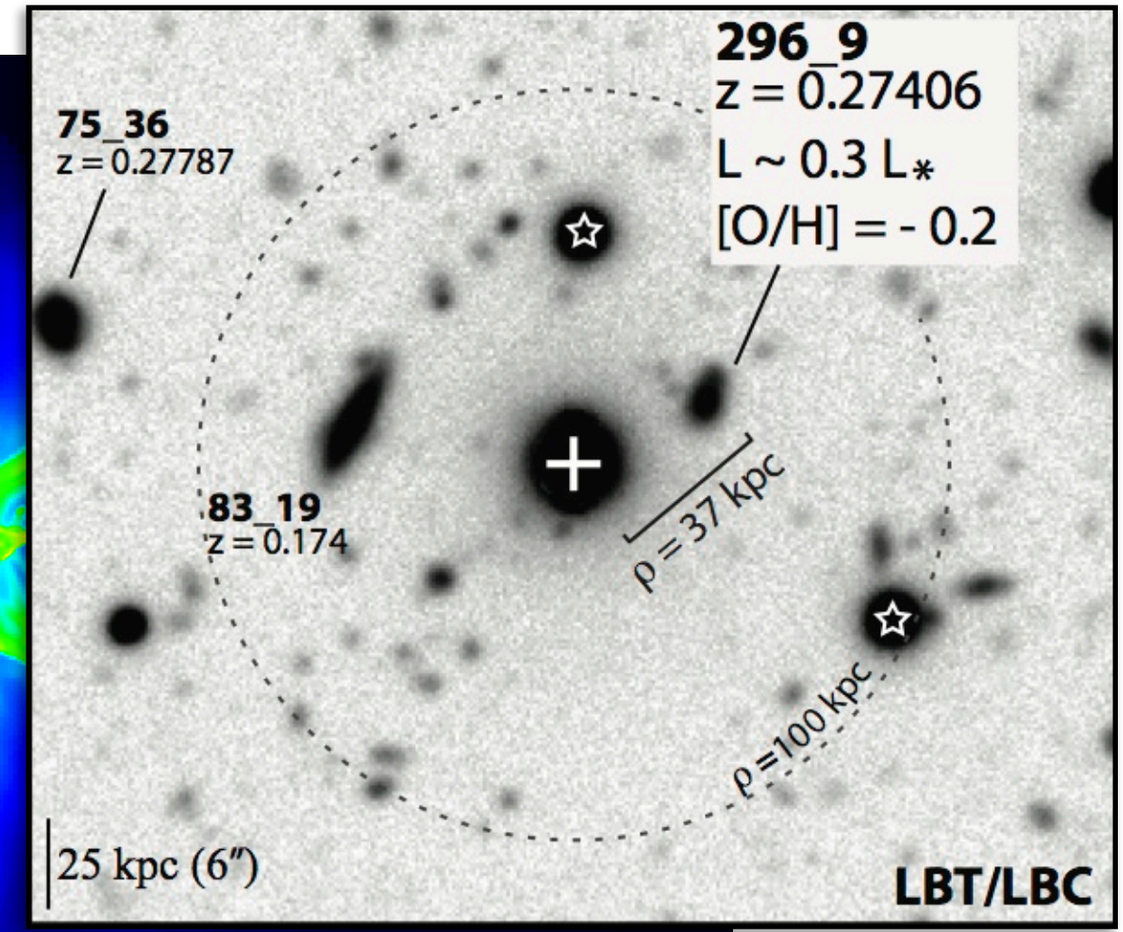

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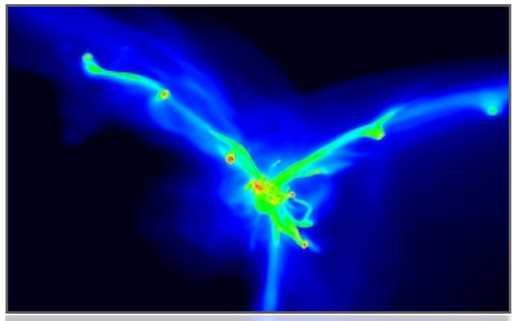
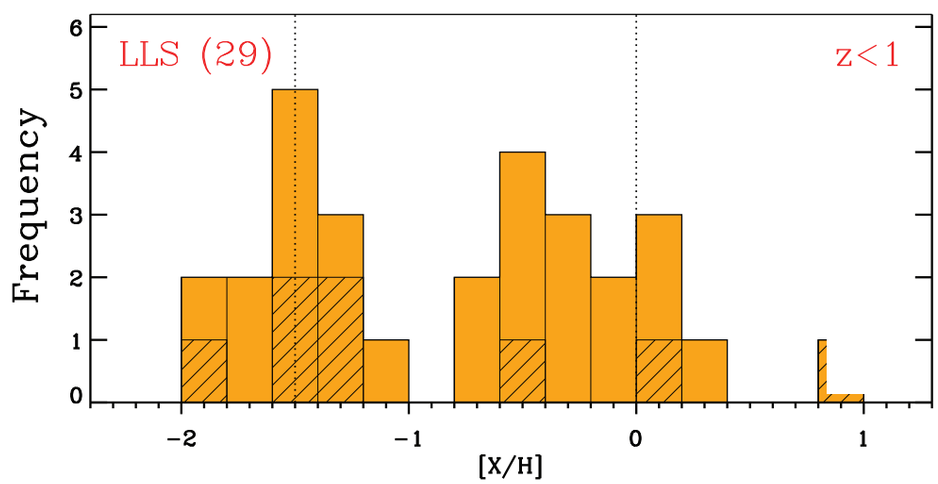
Summary

- Cleanly identifying infalling cold accretion streams in absorption is difficult at any z.



A. Dekel



- We have detected a significant number of cold, metal poor gas clouds within the virial radius of several z < 1 galaxies.
  - *There is little confusion with other metal poor phenomena at these redshifts.*

- We have determined the metallicity distribution of the CGM at z<1.
- Stay tuned, the statistics will improve dramatically soon, galaxy information...