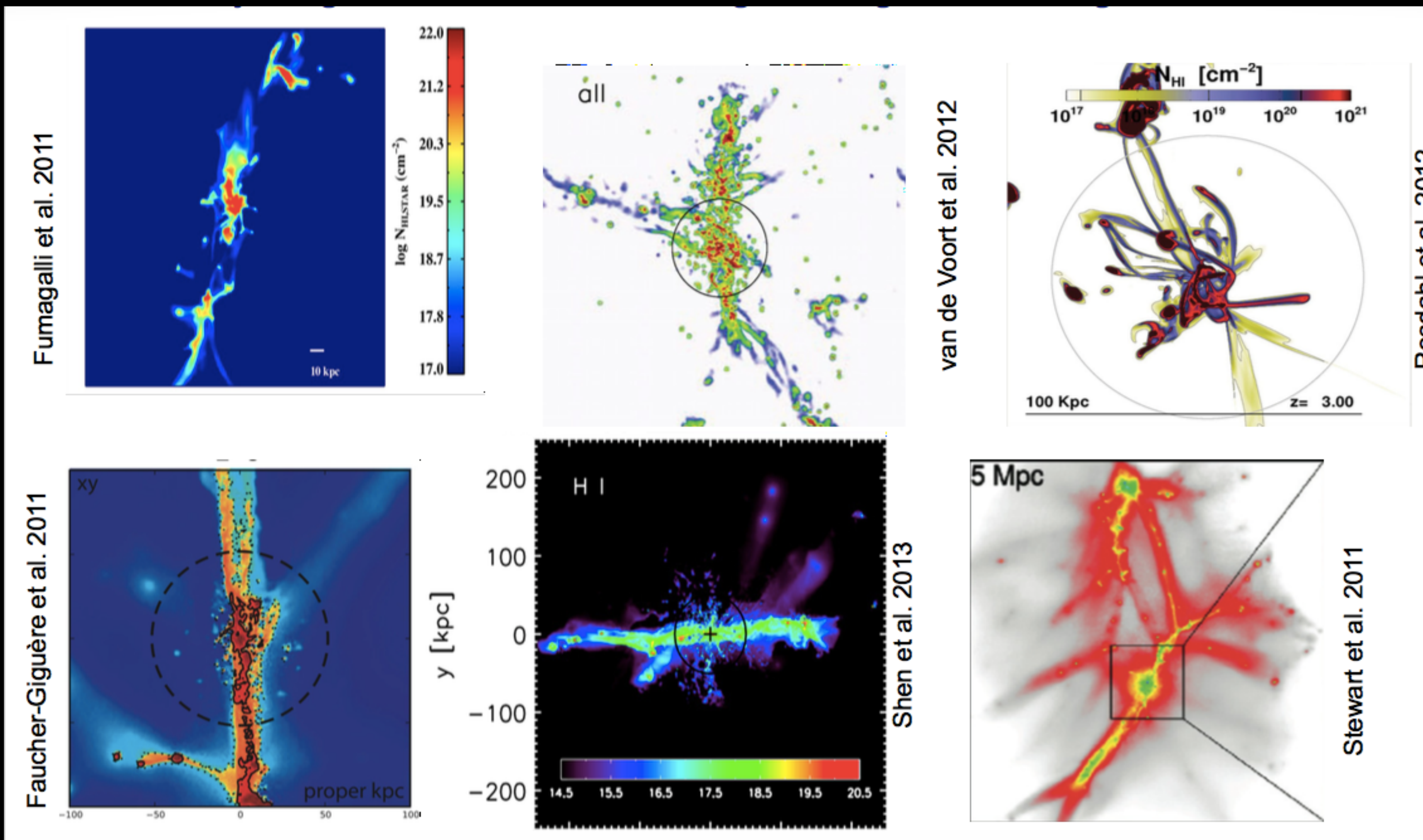
The COS CGM Compendium:
A Survey of HI-Selected absorbers at z<1

Team: Nicolas Lehner, Chris Howk, Chris Wotta, John O'Meara, Ben Oppenheimer, Kathy Cooksey

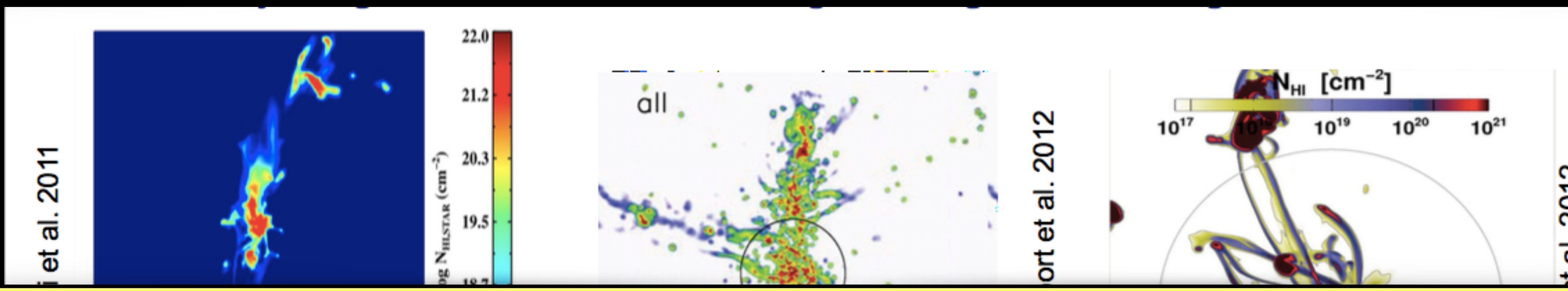
The CGM of galaxies: next frontier for models

Simulations consistently predict the presence of strong HI absorption in the surroundings of galaxies

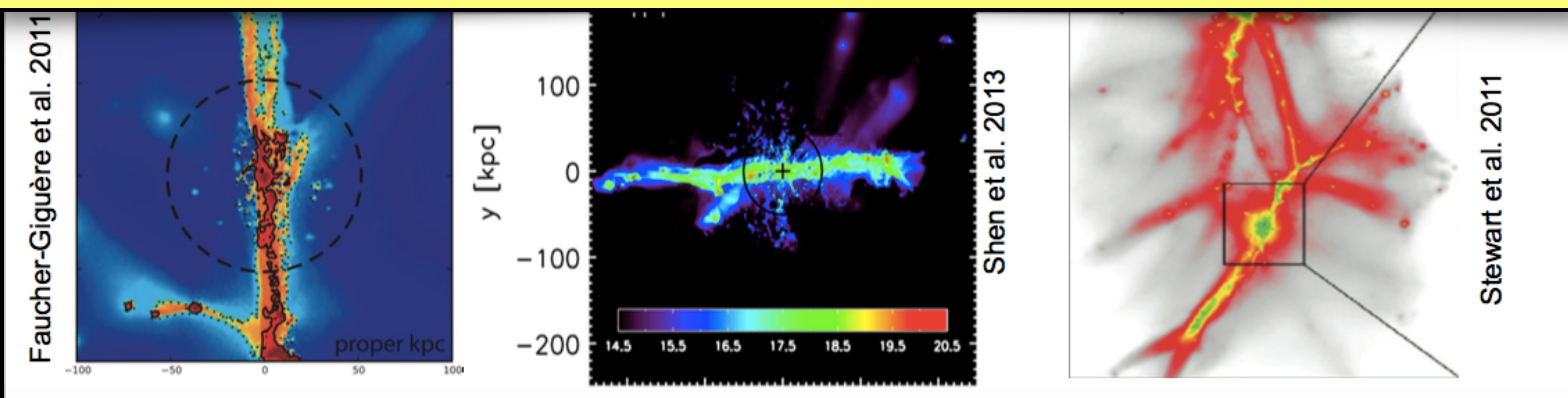


The CGM of galaxies: next frontier for models

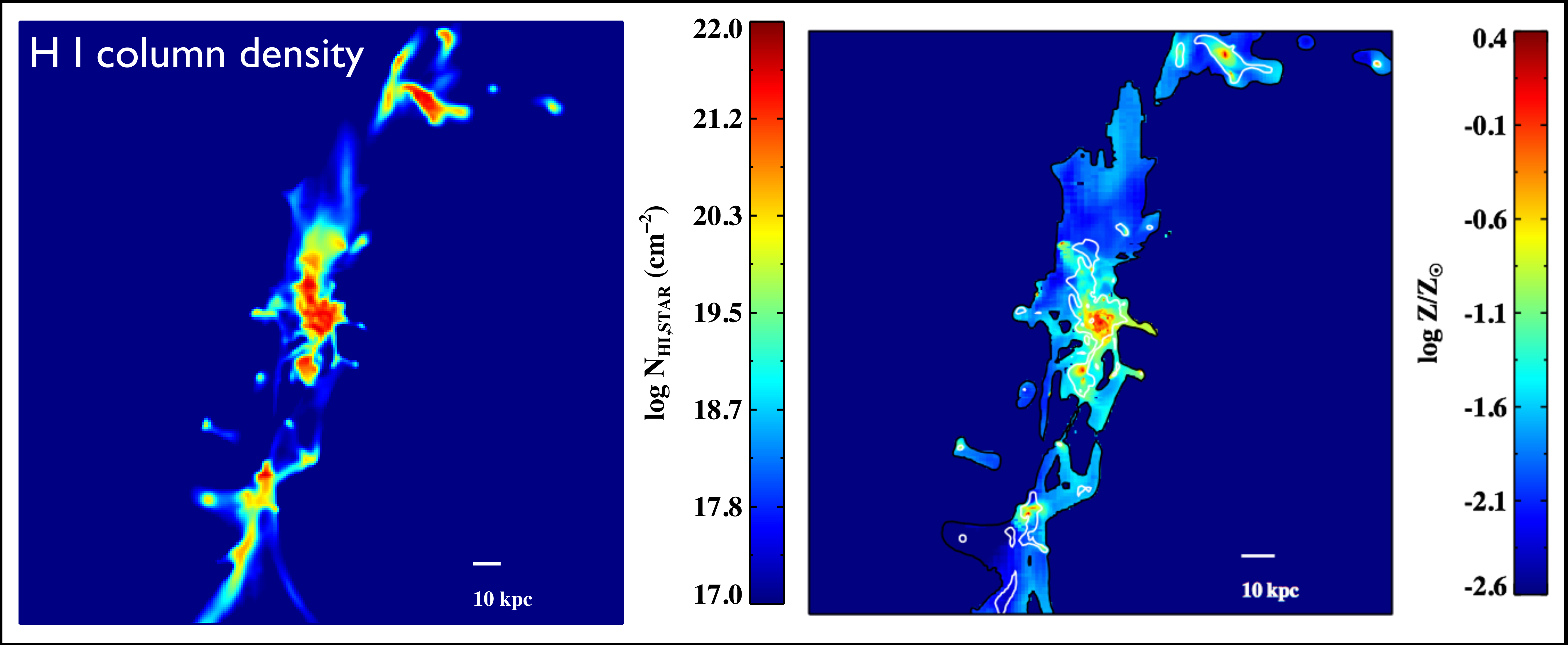
Simulations consistently predict the presence of strong HI absorption in the surroundings of galaxies



Observations at low redshift also show that absorbers with log N_{HI}>15 are typically found in the CGM of galaxies, while lower N(HI) absorbers are not (at least at low redshift).



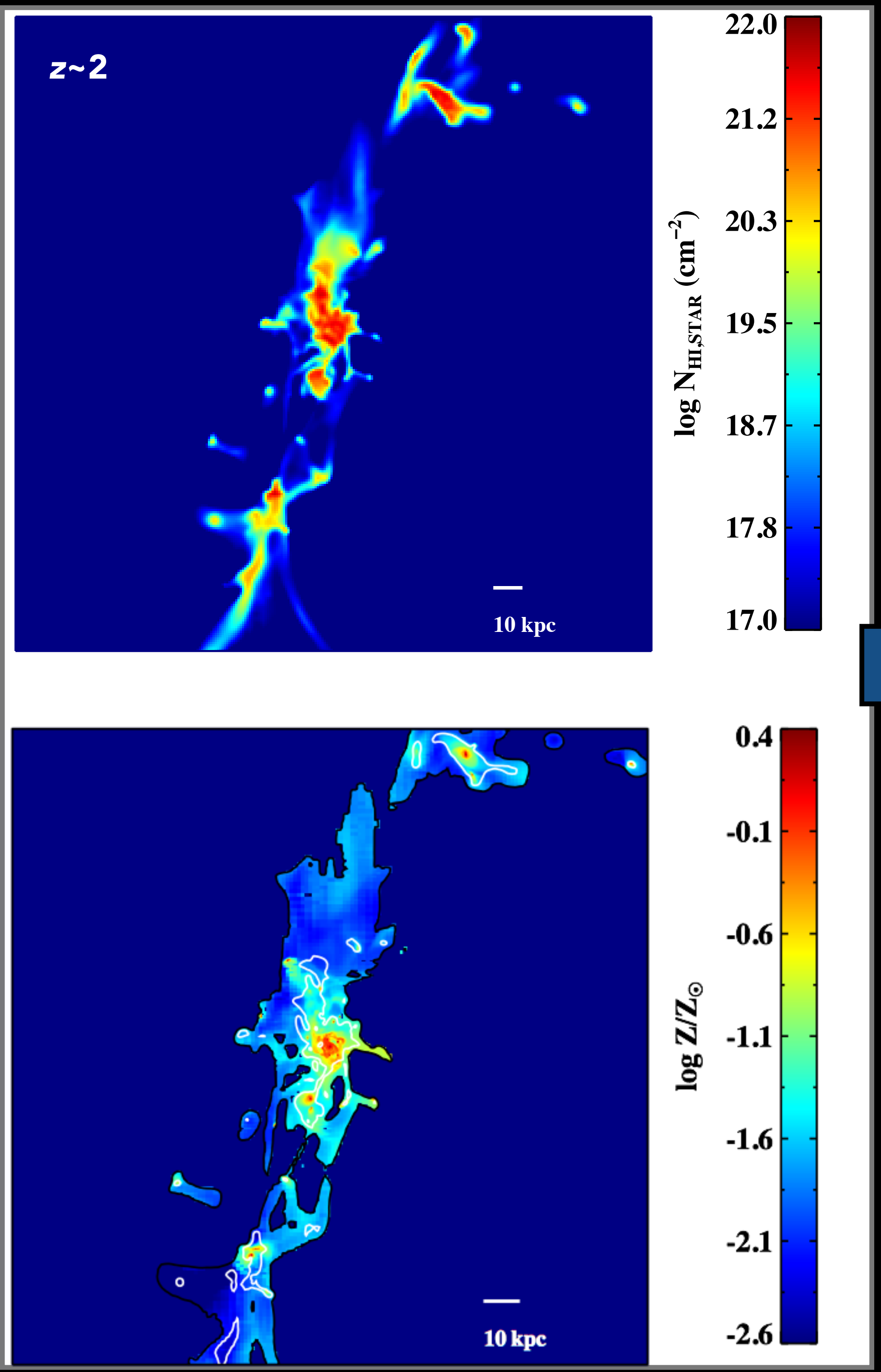
Metallicity is a *key* property of the CGM gas



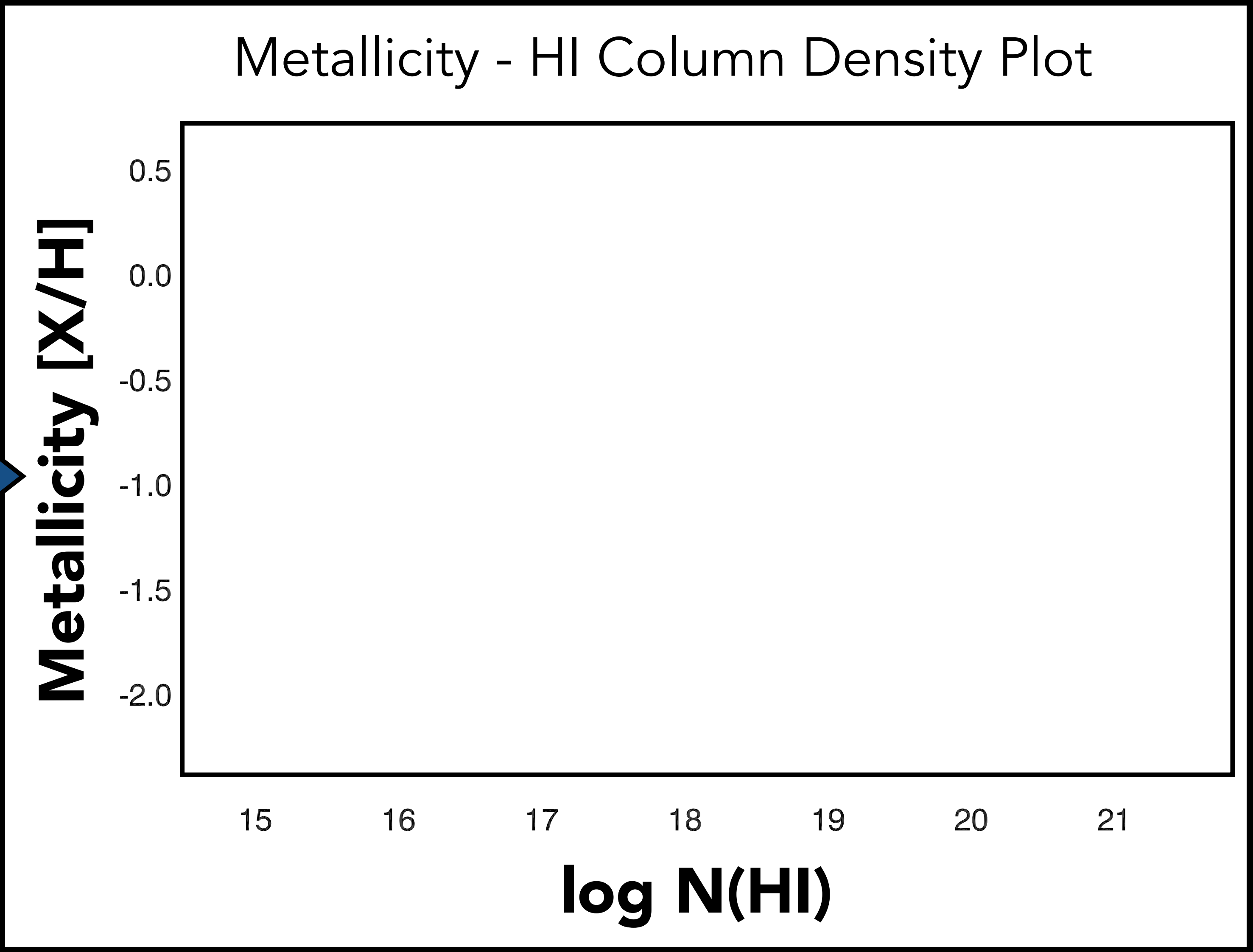
Fumagalli+ (2011)

- ✦ We can use the metallicity of the cool gas probed by LLSs as a "tracer" of the origins of the gas.
- ✦ We can use the strength of the HI absorption as a direct probe of the galaxies and their environment.

A map of the gas-metallicity of the universe



Fumagalli+ (2011)



The COS CGM Compendium

Goal: Determining the metallicity of HI-selected absorbers with 15<log N_{HI}<19 at z<1

A shot in the dark using absorbers known to probe the denser regions of the universe at the IGM/galaxy interface (i.e., the CGM).

COS G130M and G160M survey complemented with Keck HIRES (KODIAQ and new) and VLT UVES (archival + new) observations (MgII, FeII).

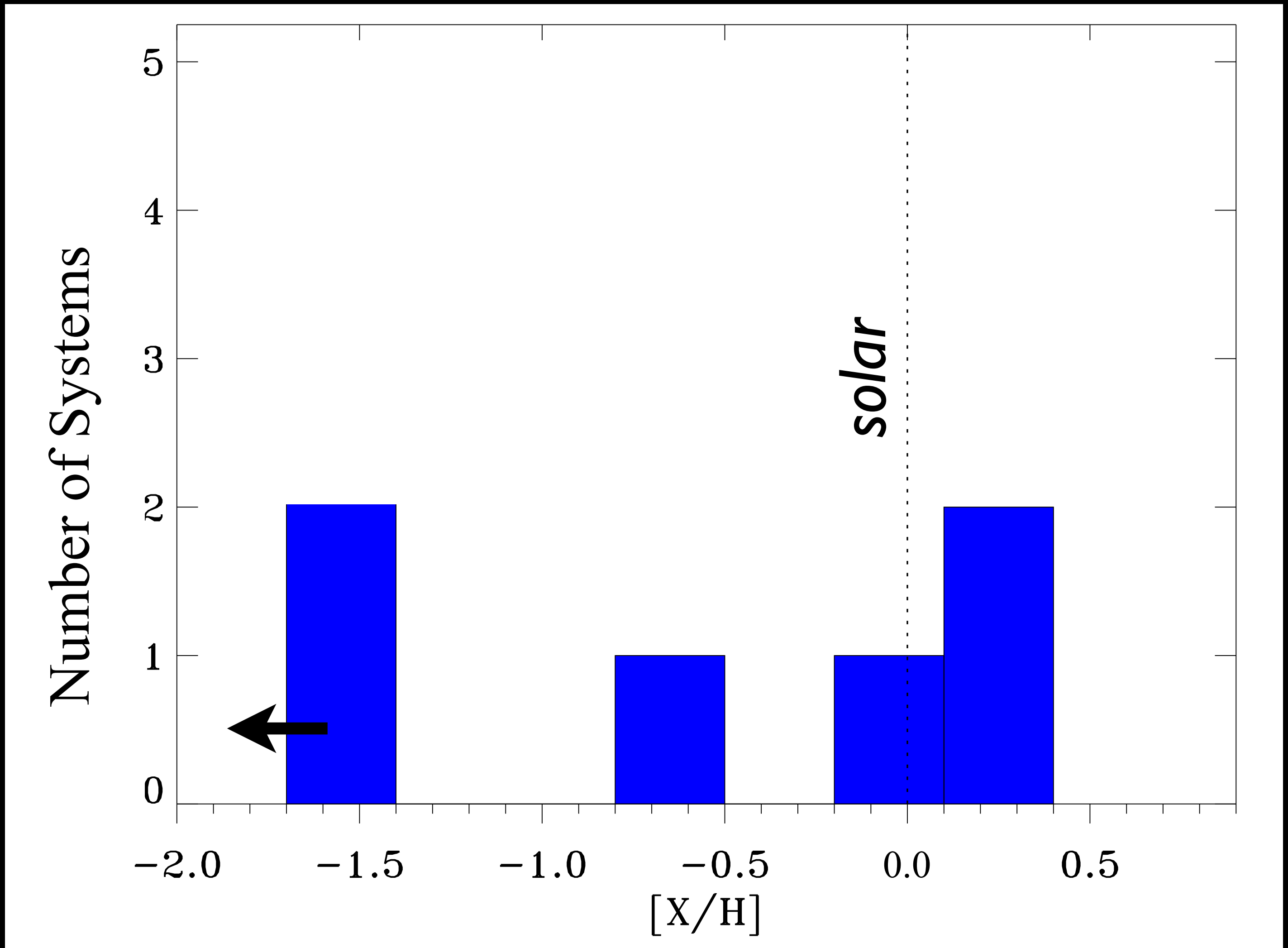
- **SLFSs:15 < log N_{HI} <16.2**
- **pLLSs:16.2 < log N_{HI} <17.2**
- **LLSs: 17.2 ≤ log N_{HI} <19**
- SLLSs: 19 ≤ log N_{HI} < 20.3
- DLAs: 20.3 ≤ log N_{HI}

- How metal-enriched is the CGM gas?
- Is there pristine CGM gas at z<1?
- How does the metallicity evolve with N_{HI} and z?

The COS CGM Compendium

Goal: Determining the metallicity of *HI-selected* absorbers with 15<log N_{HI}<19 at z<1

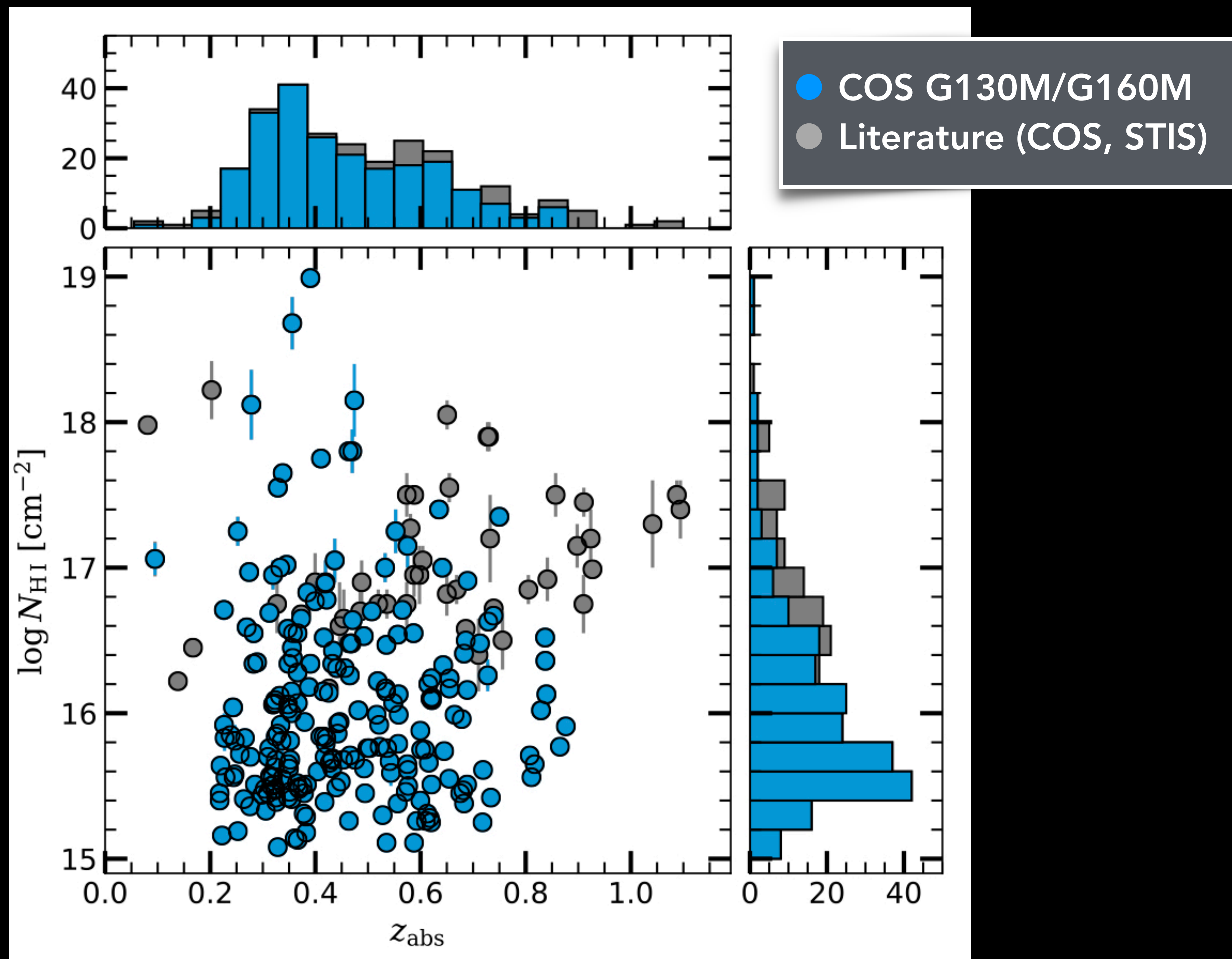
Metallicity distribution in the pre-COS era



6 pLLS/LLS metallicities determined in pre-COS era
Zonak+04, Jenkins+05, Prochaska+04,05, Cooksey+08, Lehner+09

The CCC sample: **263 absorbers**

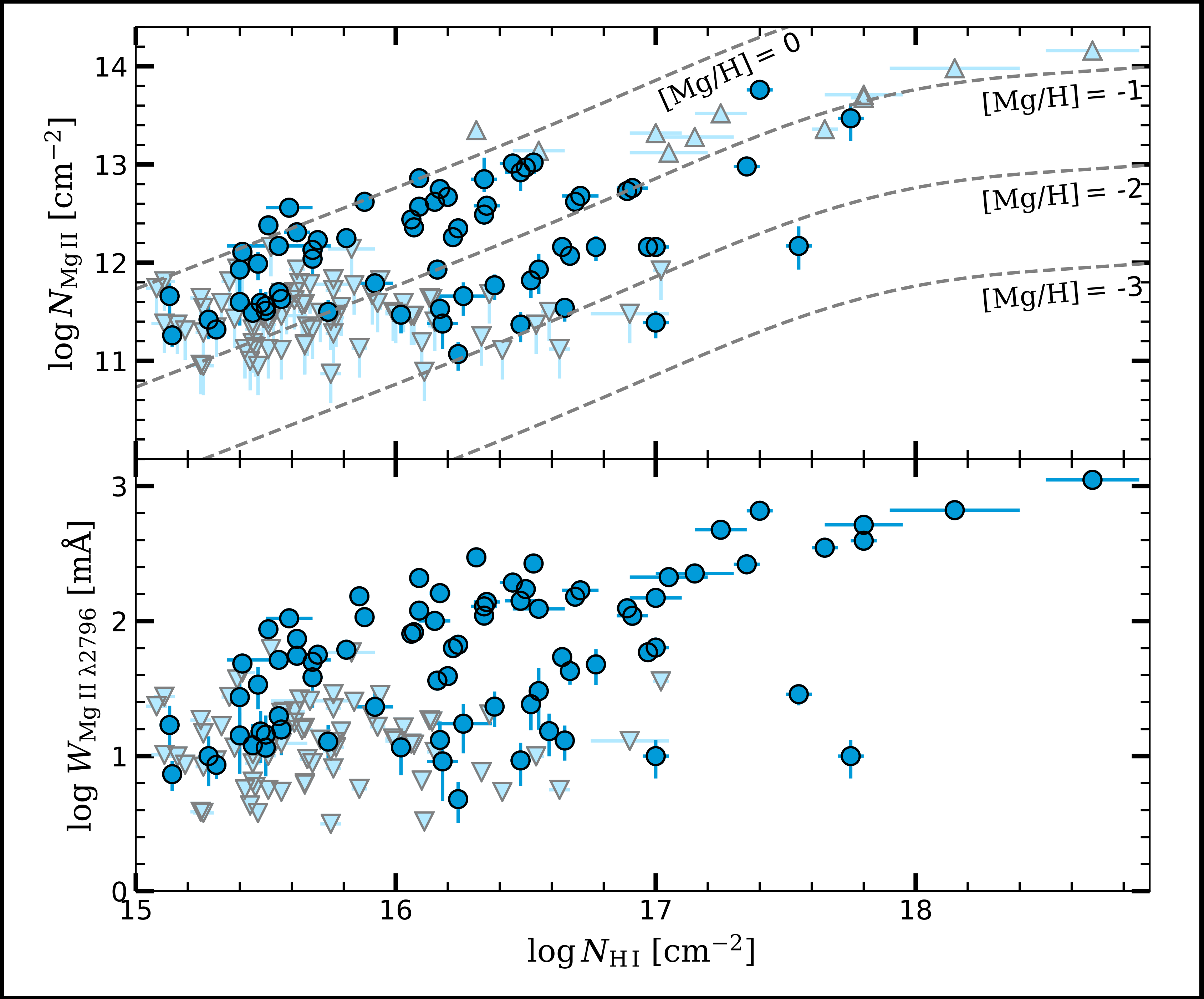
- SLFSs:15 < log N_{HI} <16.2: 152
- pLLSs:16.2 < log N_{HI} <17.2: 82
- LLSs: 17.2 ≤ log N_{HI} <19: 29



Lehner+18a, submitted

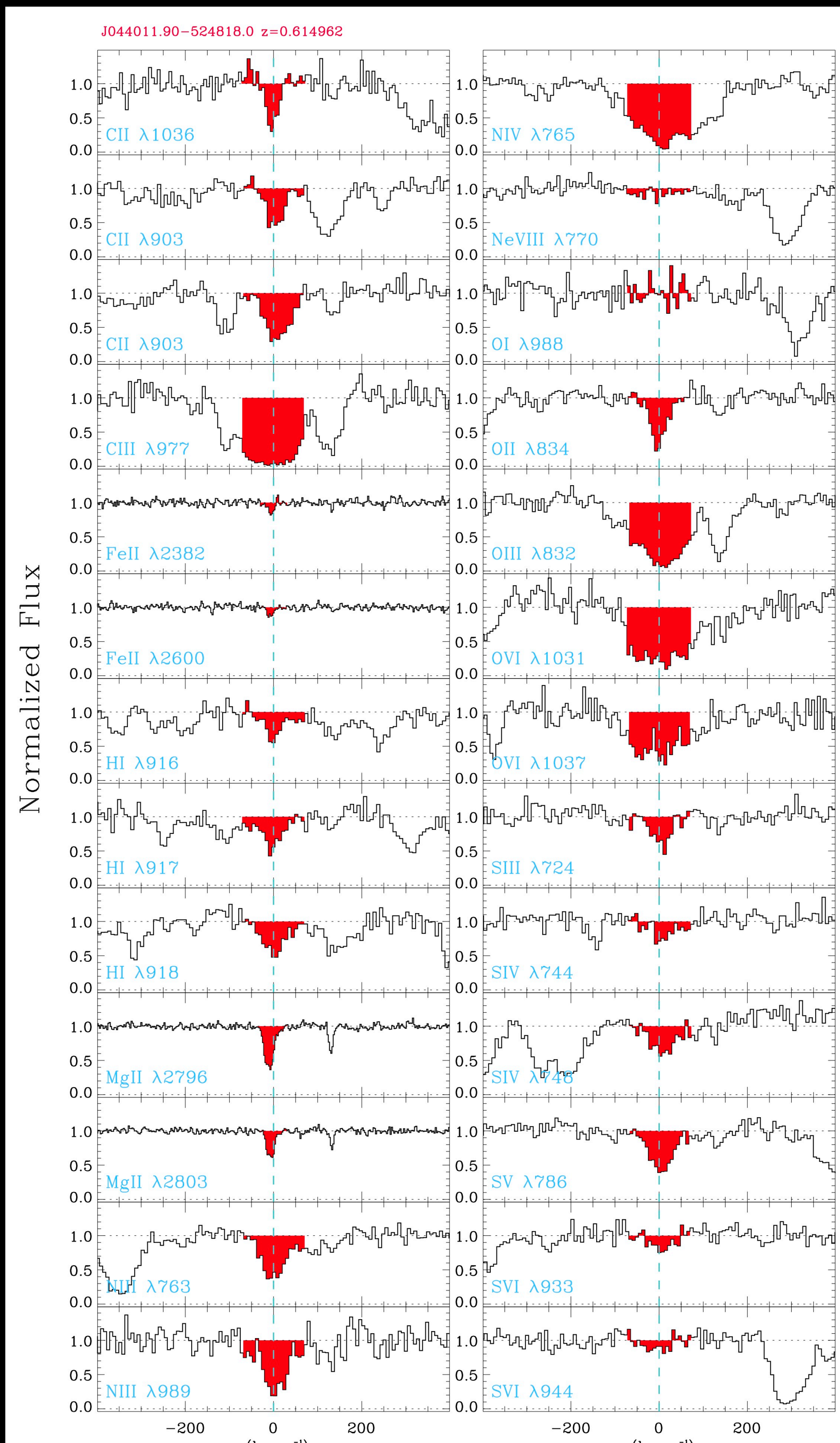
CCC empirical results: MgII vs. HI

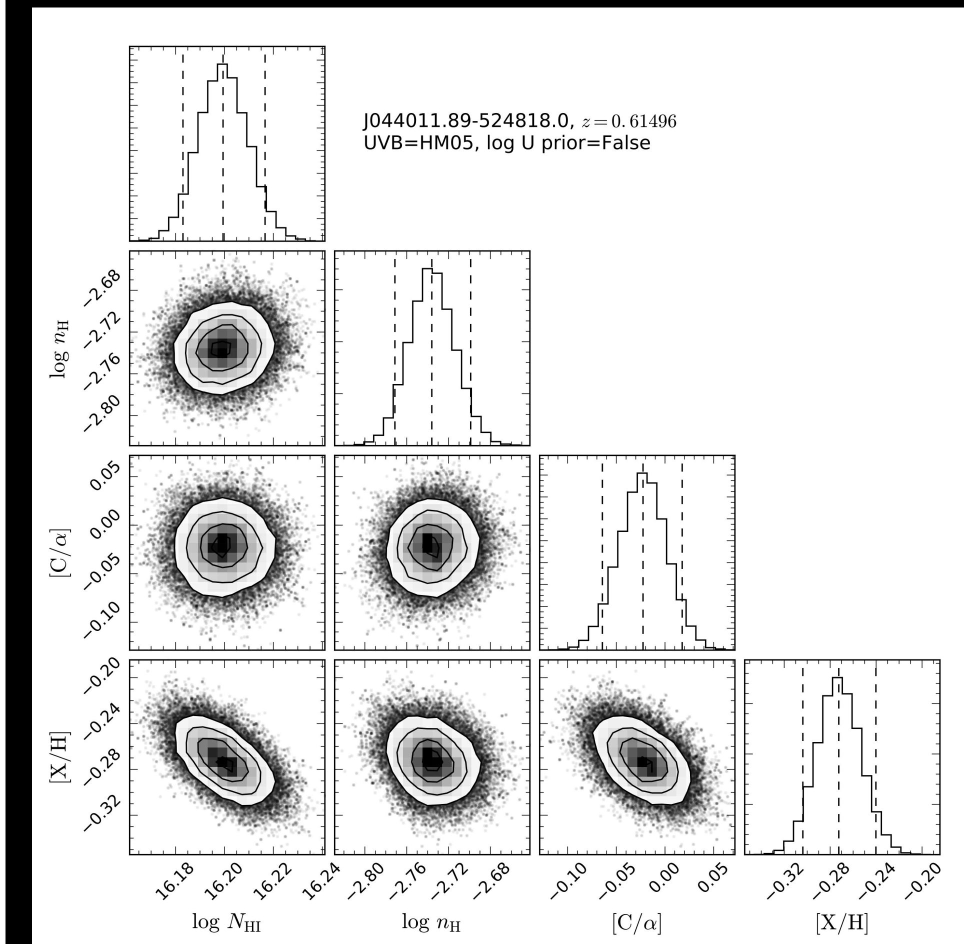
- SLFSs:15 < log N_{HI} <16.2: 152
- pLLSs:16.2 < log N_{HI} <17.2: 82
- LLSs: 17.2 ≤ log N_{HI} <19: 29

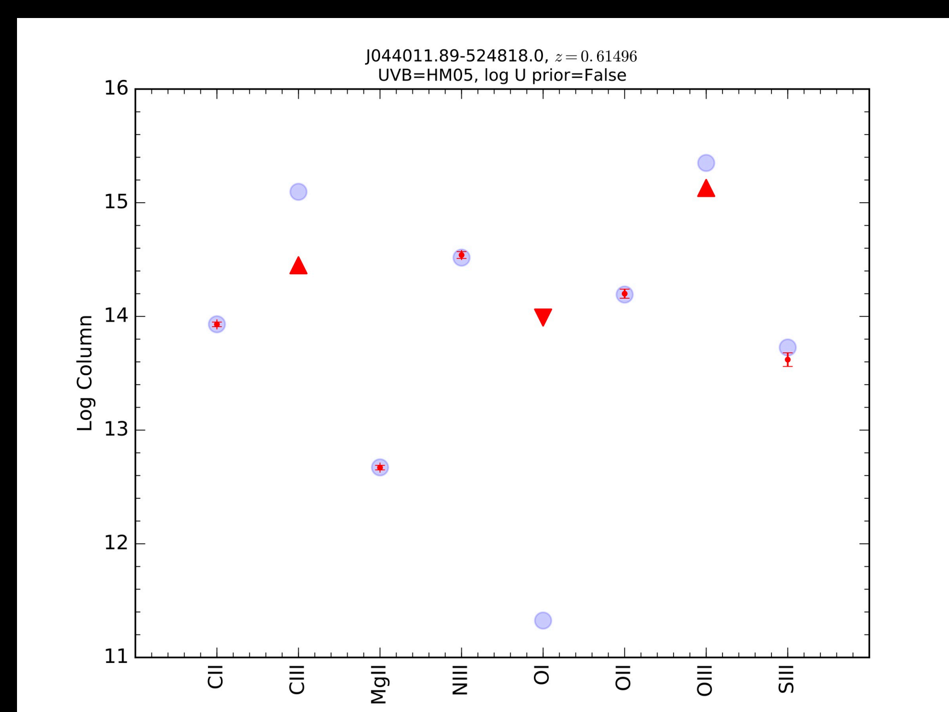


Lehner+18a, submitted

CCC Methodology: from data to a metallicity PDF



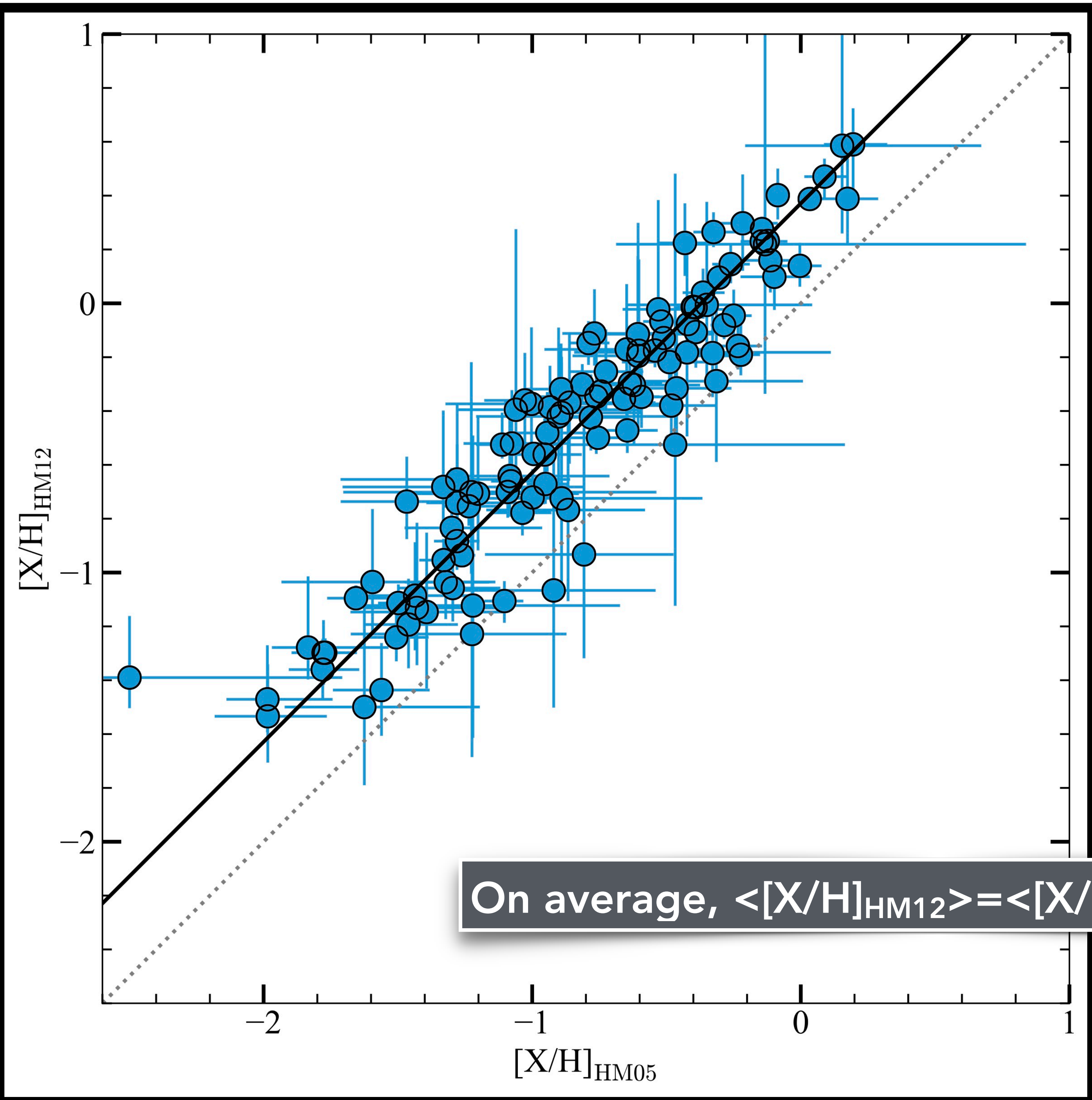




- SLFSs, pLLSs, and LLSs are all strongly ionized and therefore an ionization correction is needed to determine the metallicity.
- Use only low (CII, SiII, MgII) and intermediate ions (e.g., CIII, OII) to model the photoionization.
- C/α is allowed to vary.
- Adopt EUVB HM05 Galaxies+QSOs (HM12)
- Use Bayesian MCMC formalism (from Fumagalli+16) to model the ionization.
- Output: posterior PDFs.

Wotta+18, in prep

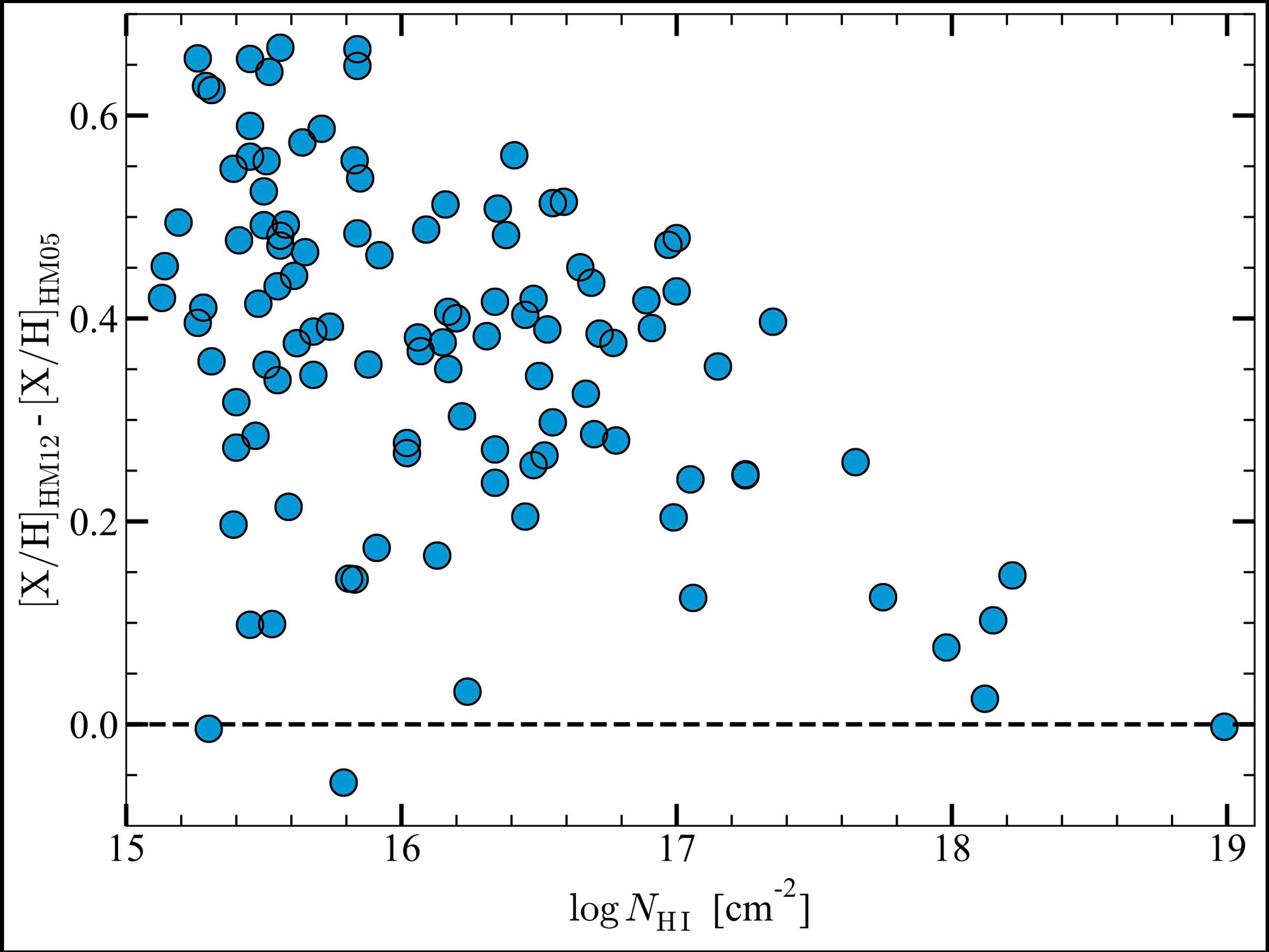
Effects of the EUVB on the metallicity



On average, <$[X/H]_{HM12}$>=<$[X/H]_{HM05}$>+0.37

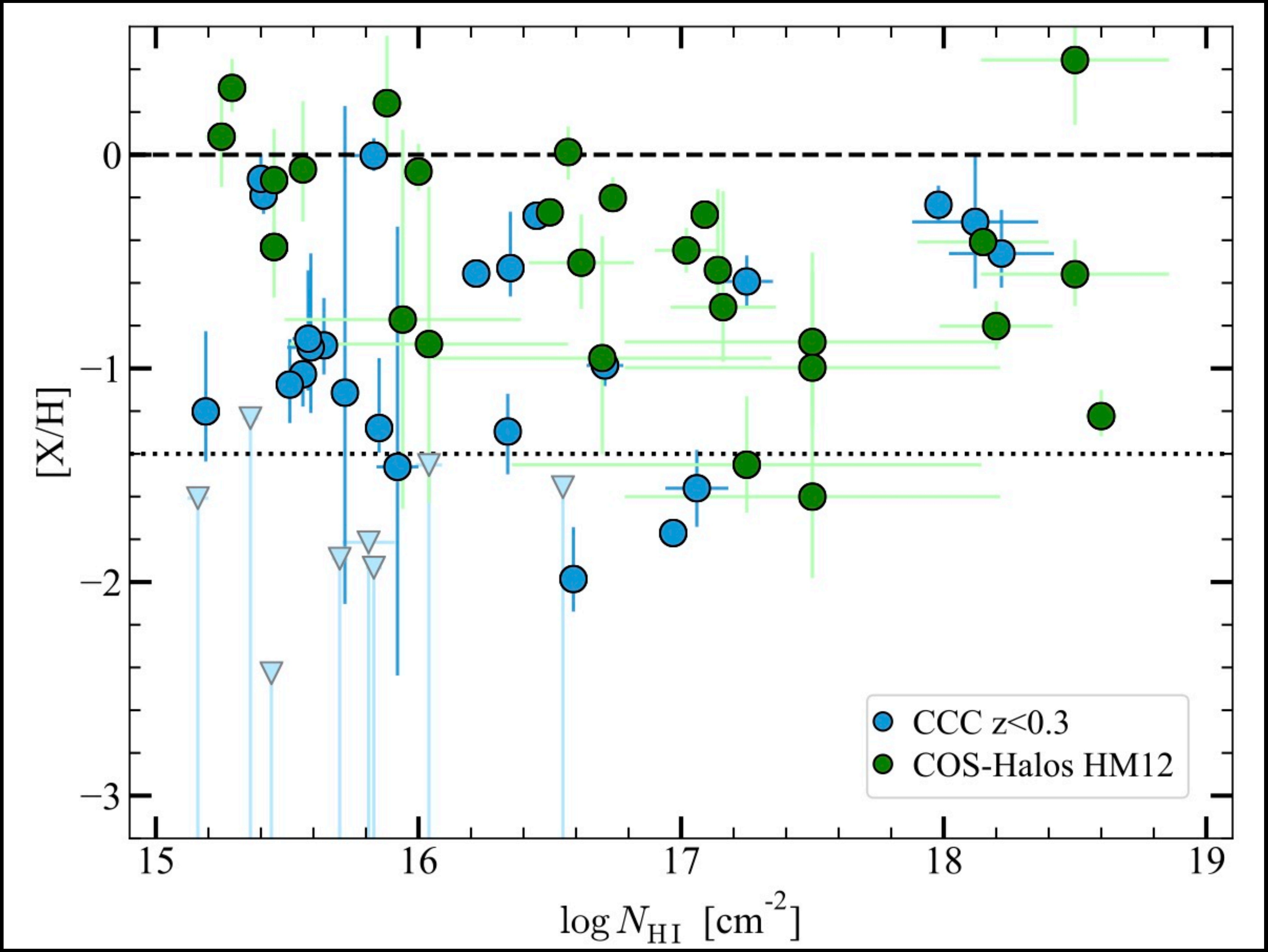
Wotta+18, in prep (see also Wotta+16)

Effects of the EUVB on the metallicity



Wotta+18, in prep (see also Wotta+16)

Effect of the EUVB: CCC vs. COS-Halos

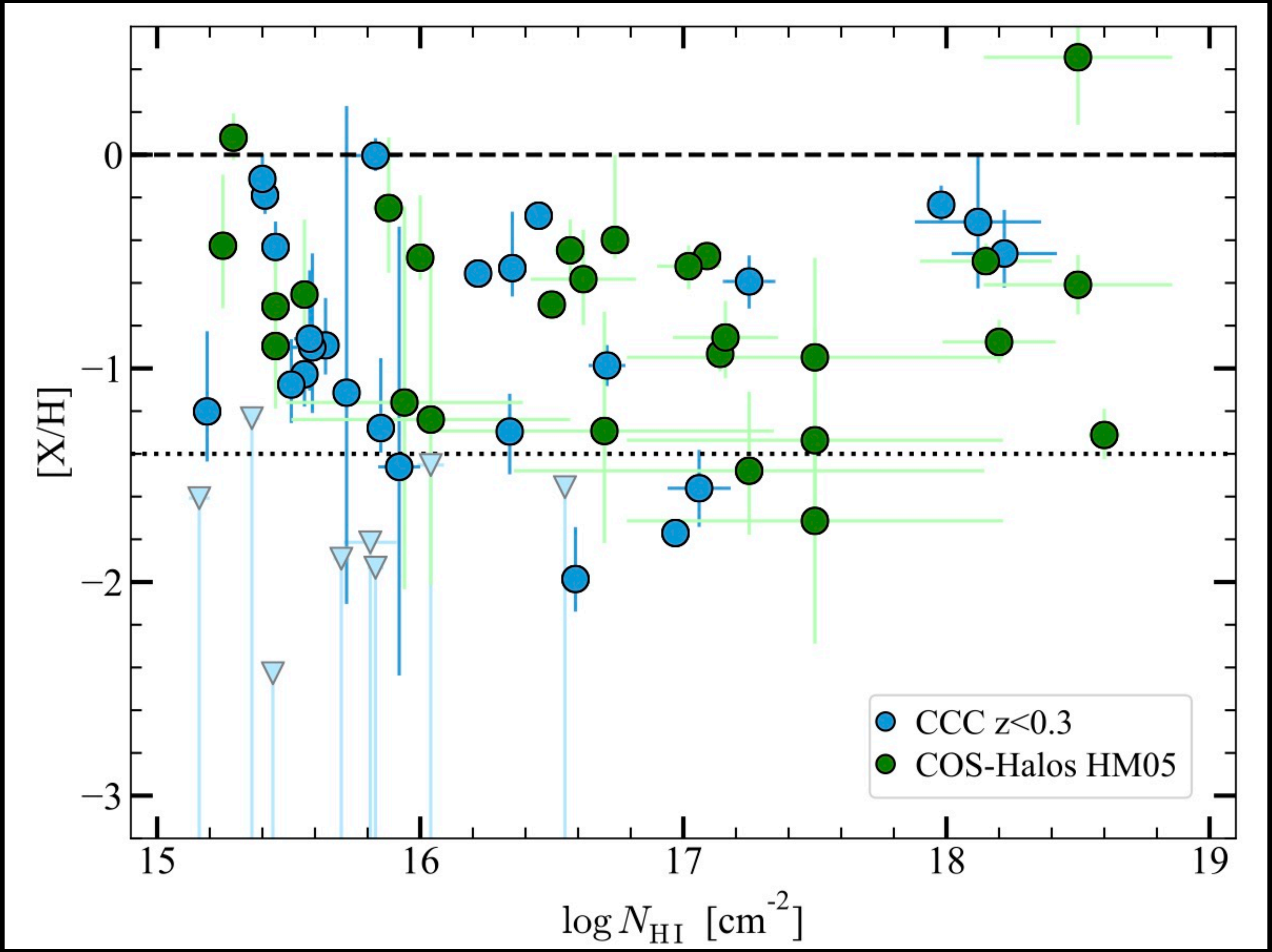


Note: COS-Halos redshifts often outside our search range.

Lehner+18b, in prep

COS-Halos: Remodeled from Prochaska+17

Effect of the EUVB: CCC vs. COS-Halos

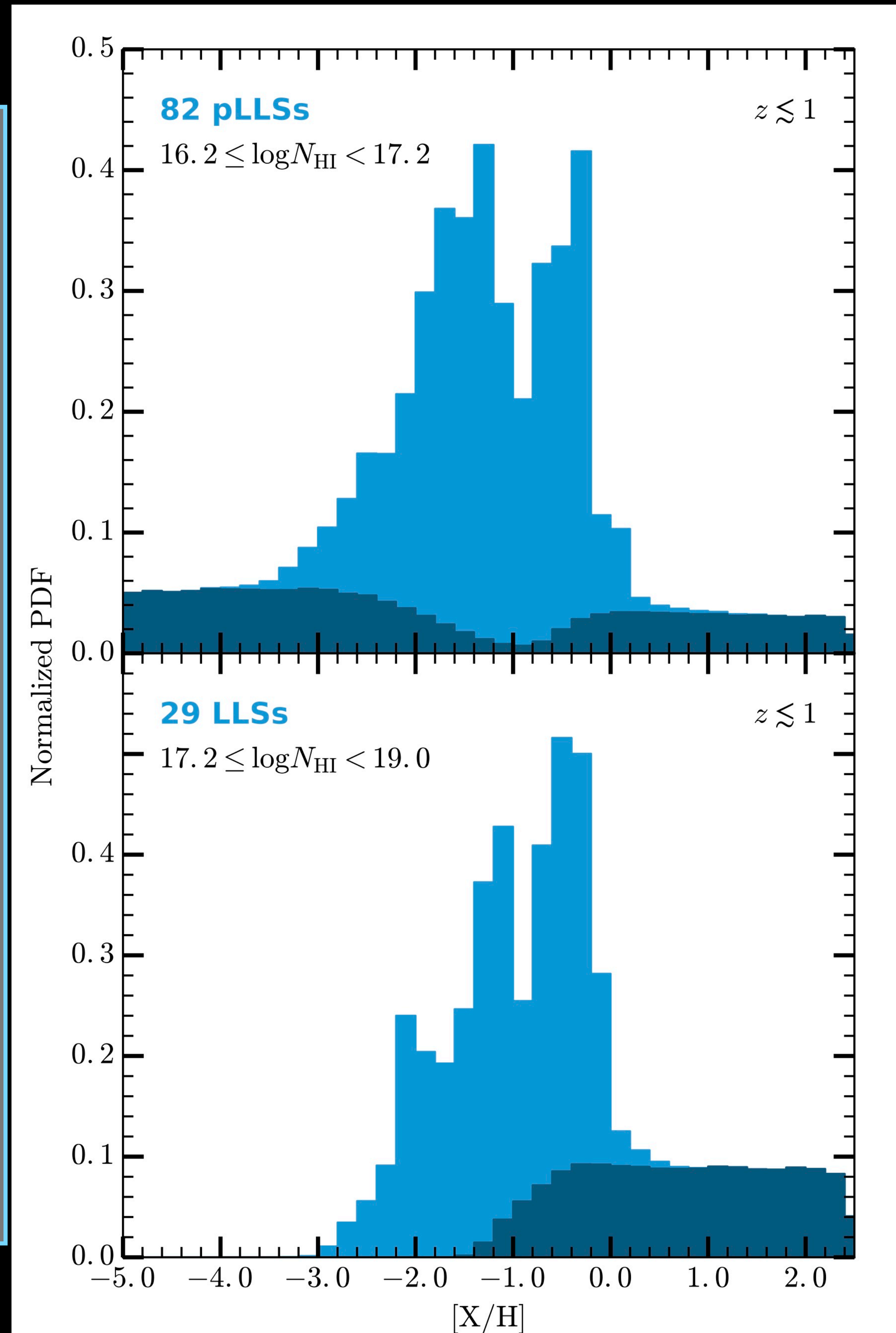


Lehner+18b, in prep

Some of the key science results from CCC

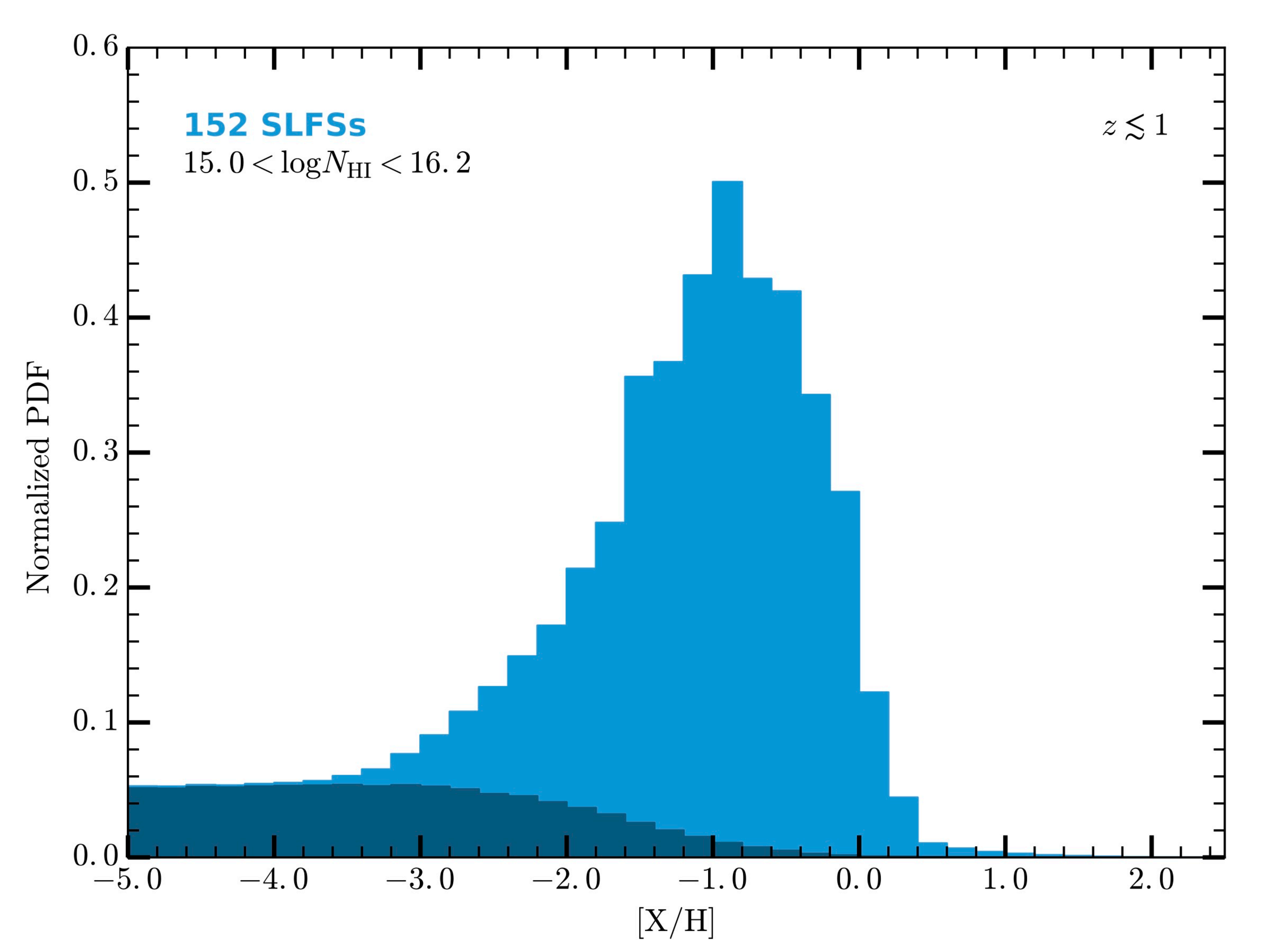
Results I & II: Metallicity PDFs of pLLSs and LLSs at z<1

Posterior Probability Distribution of the Metallicity



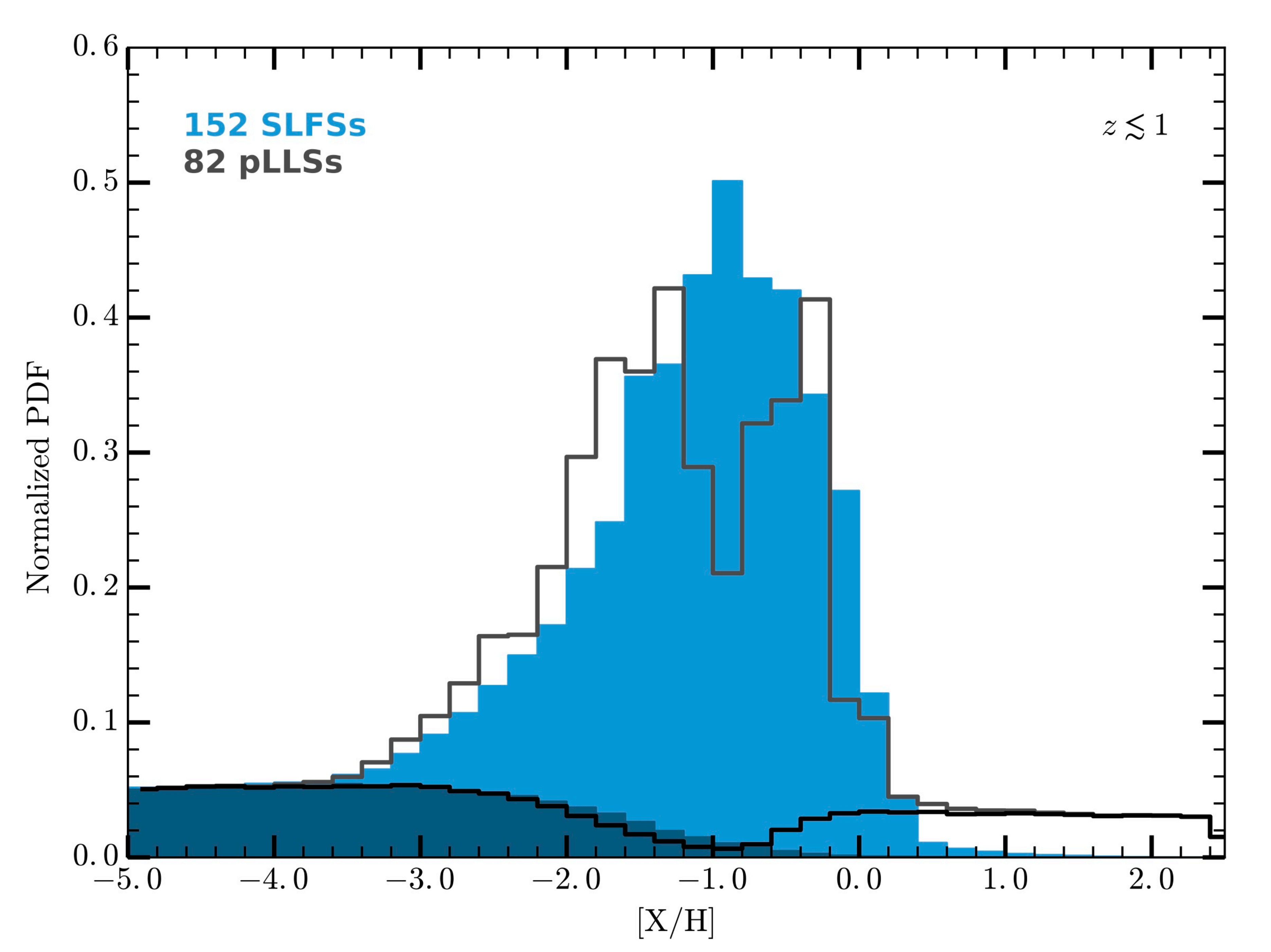
Wotta+18

Result III: Metallicity PDFs of the SLFSs at z<1



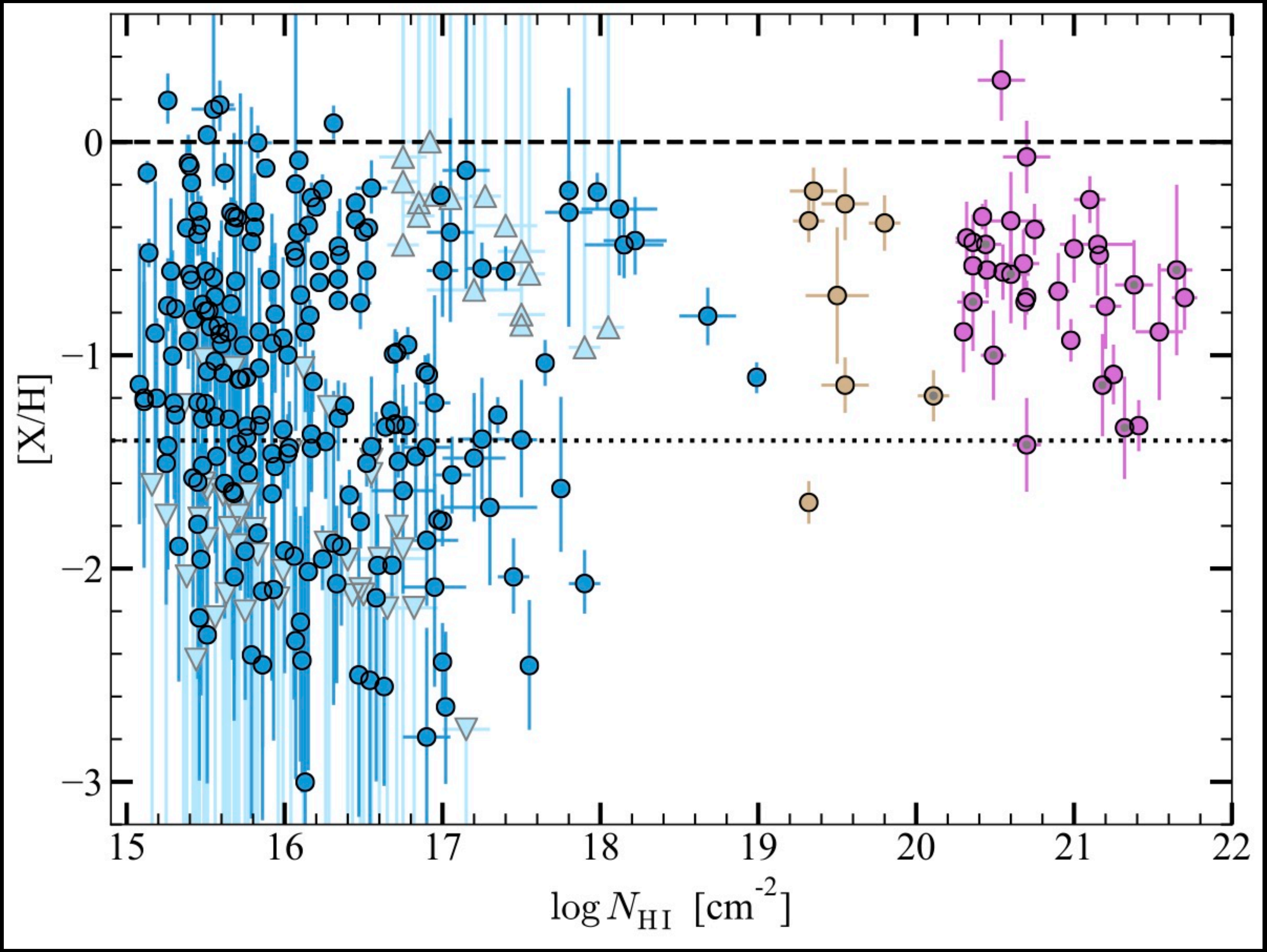
Wotta+18, Lehner+18b, in prep

Result: Metallicity PDFs of the SLFSs and pLLSs at z<1



Wotta+18, Lehner+18b, in prep

Result IV: Evolution of the metallicity with $N_{\rm HI}$

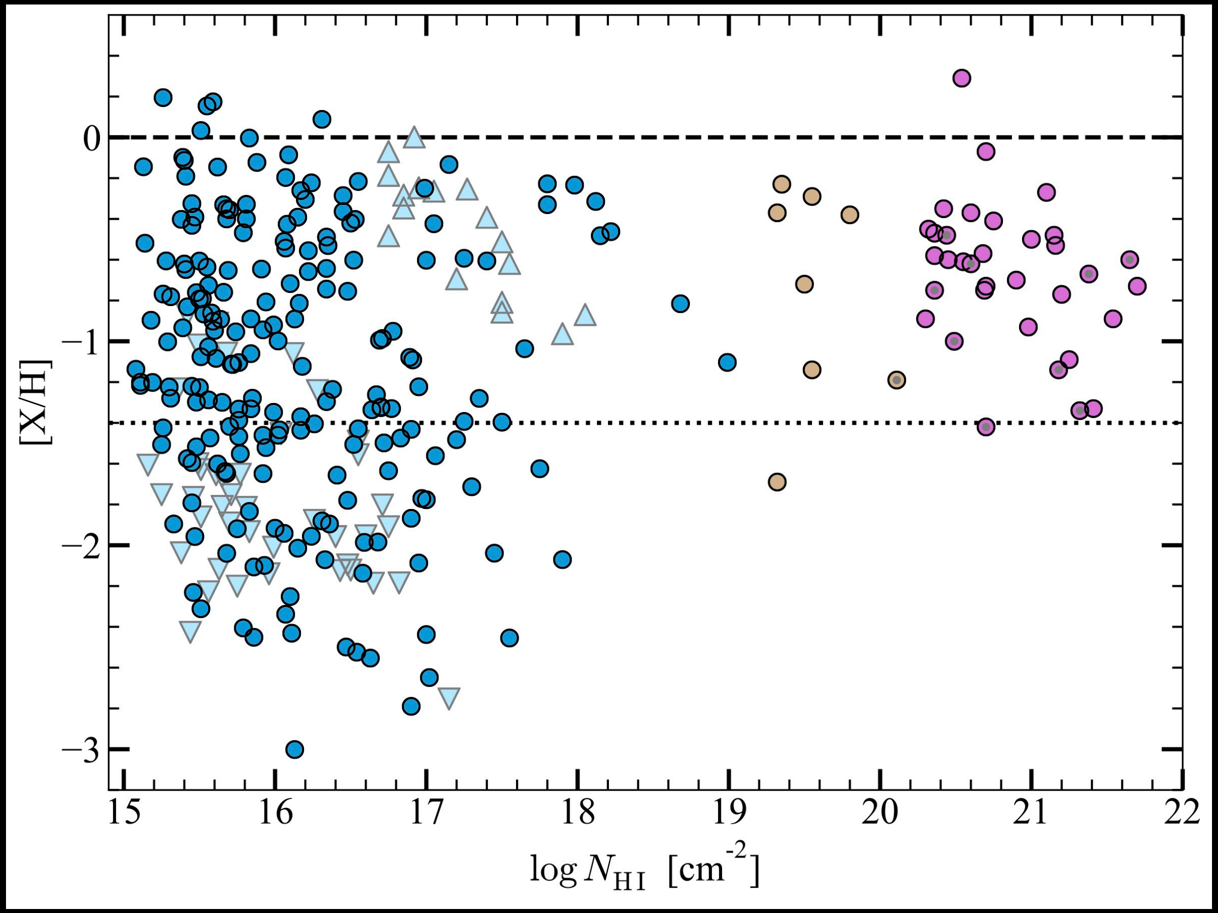


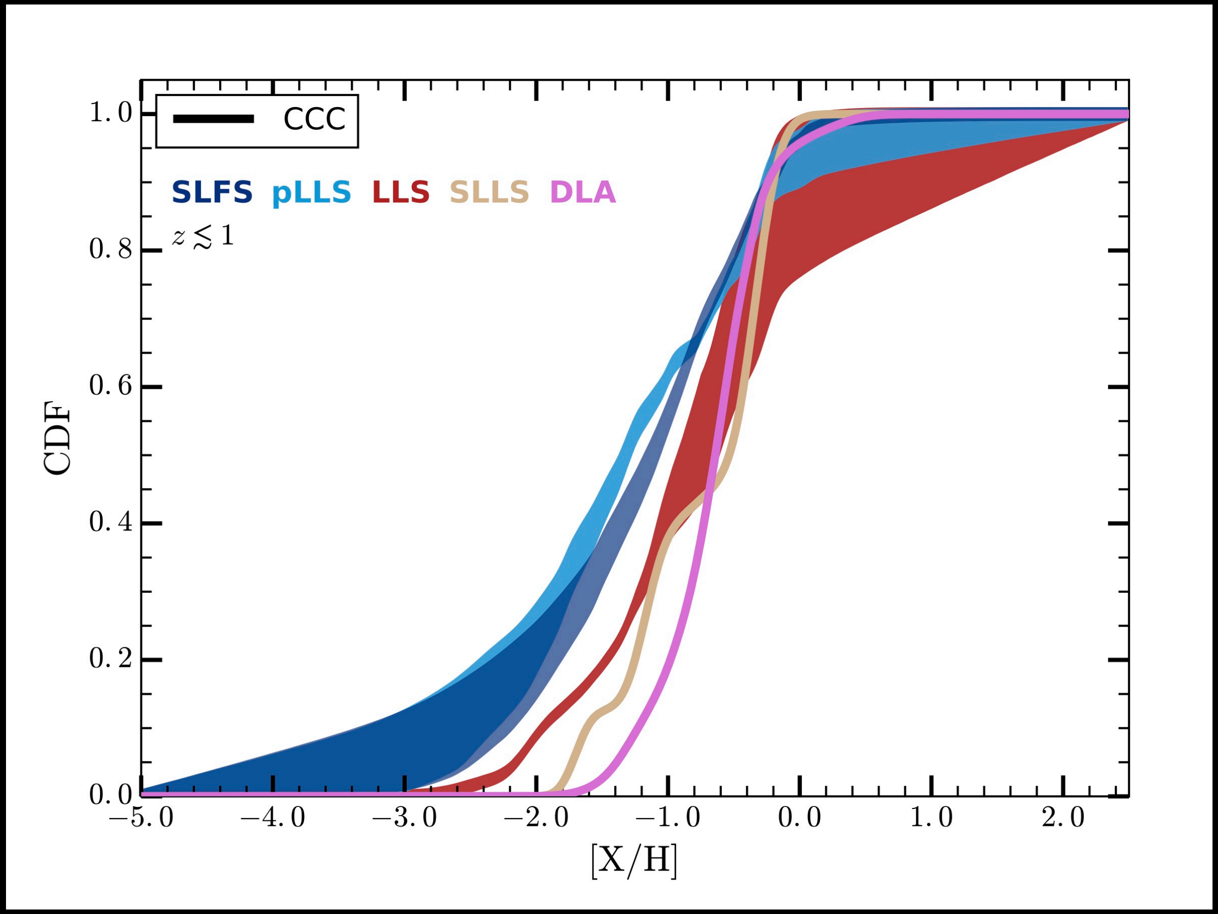
DLAs: new compilation from 3 papers: Rafelski+12, Lehner+13, Quiret+16

SLLSs: only *HI-selected* SLLSs from literature (Tripp+05; Battisti+12; Crighton+13; Quiret+16)

Wotta+18a, Lehner+18, in prep

Summary I





- There is a strong evolution of the metallicity with $N_{\rm HI}$. Enriched metal gas seen at any z; metal-poor gas ([X/H]<-1.4) mostly only observed at log $N_{\rm HI}$<18.
- There is a large reservoir of ***metal-poor cool gas*** in the dense ionized medium of the universe probed by SLFSs, pLLSs, and LLSs.
- No strong evidence of pristine gas at z<1, but some gas hasn't been enriched much since z~2-3 (see Lehner+16, Fumagalli+16, Simcoe+04).
- Interpretations: gas inflows, outflows, recycled gas.

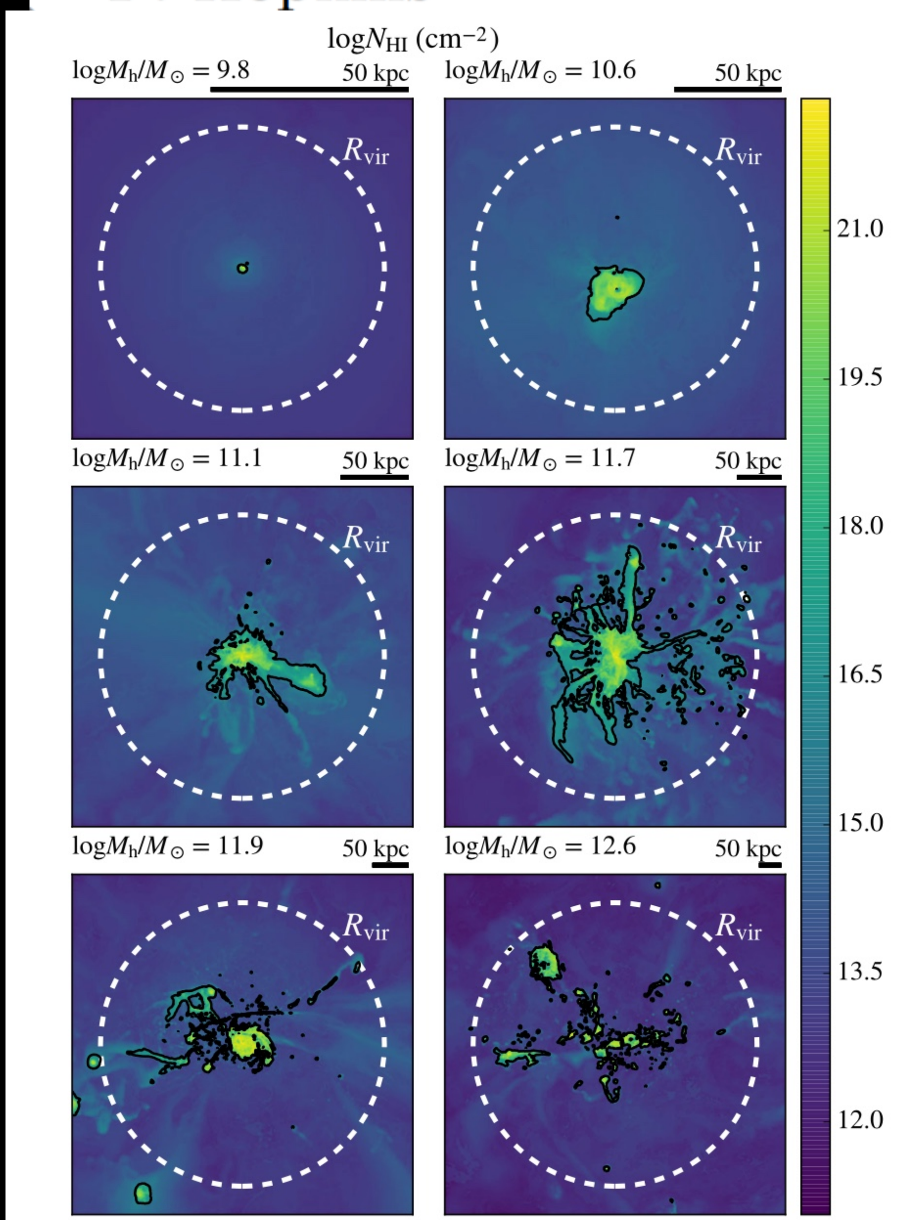
Simulations vs. observations

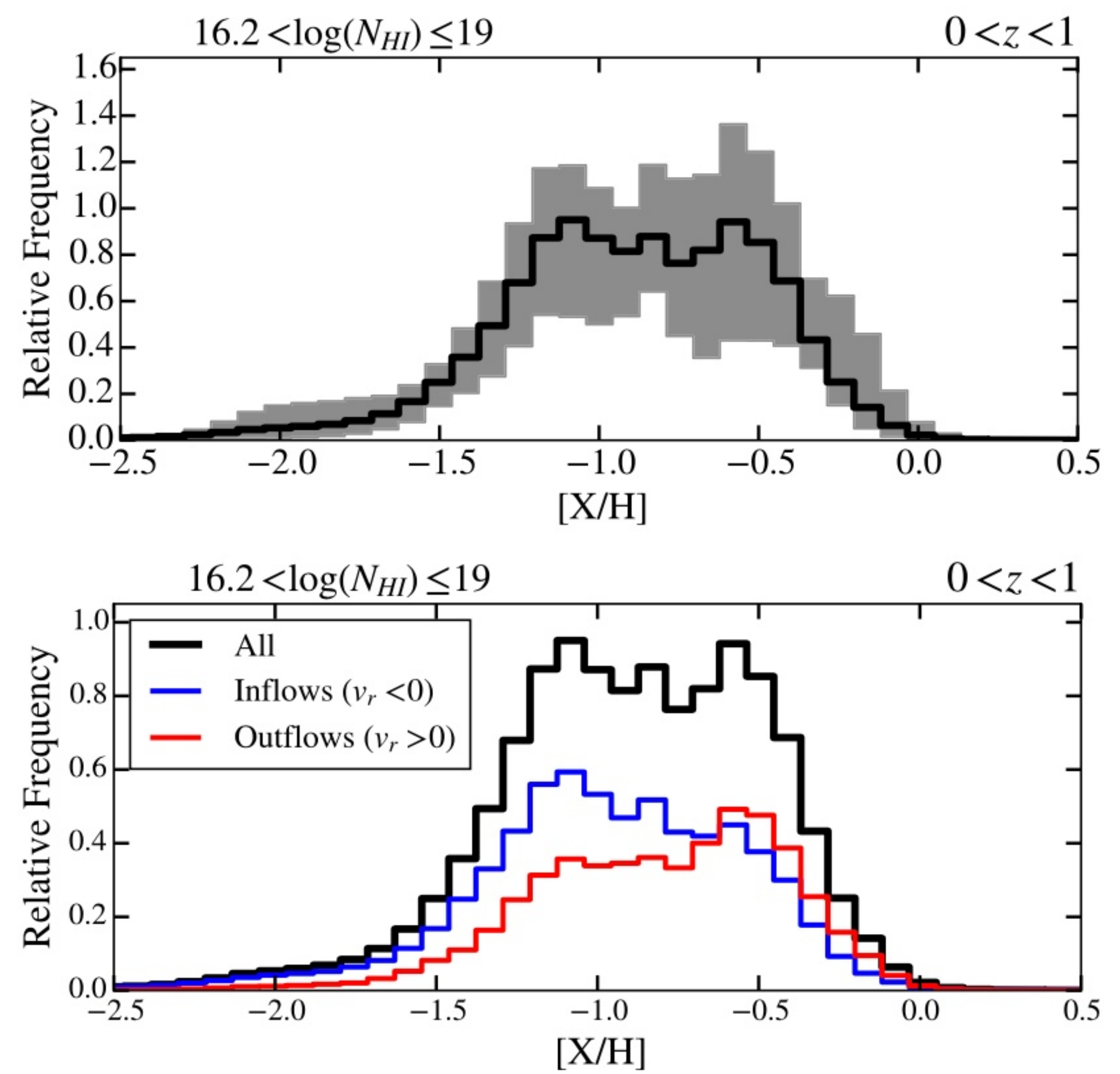
FIRE Simulations vs. CCC

Low-Redshift Lyman Limit Systems as Diagnostics of Cosmological Inflows and Outflows

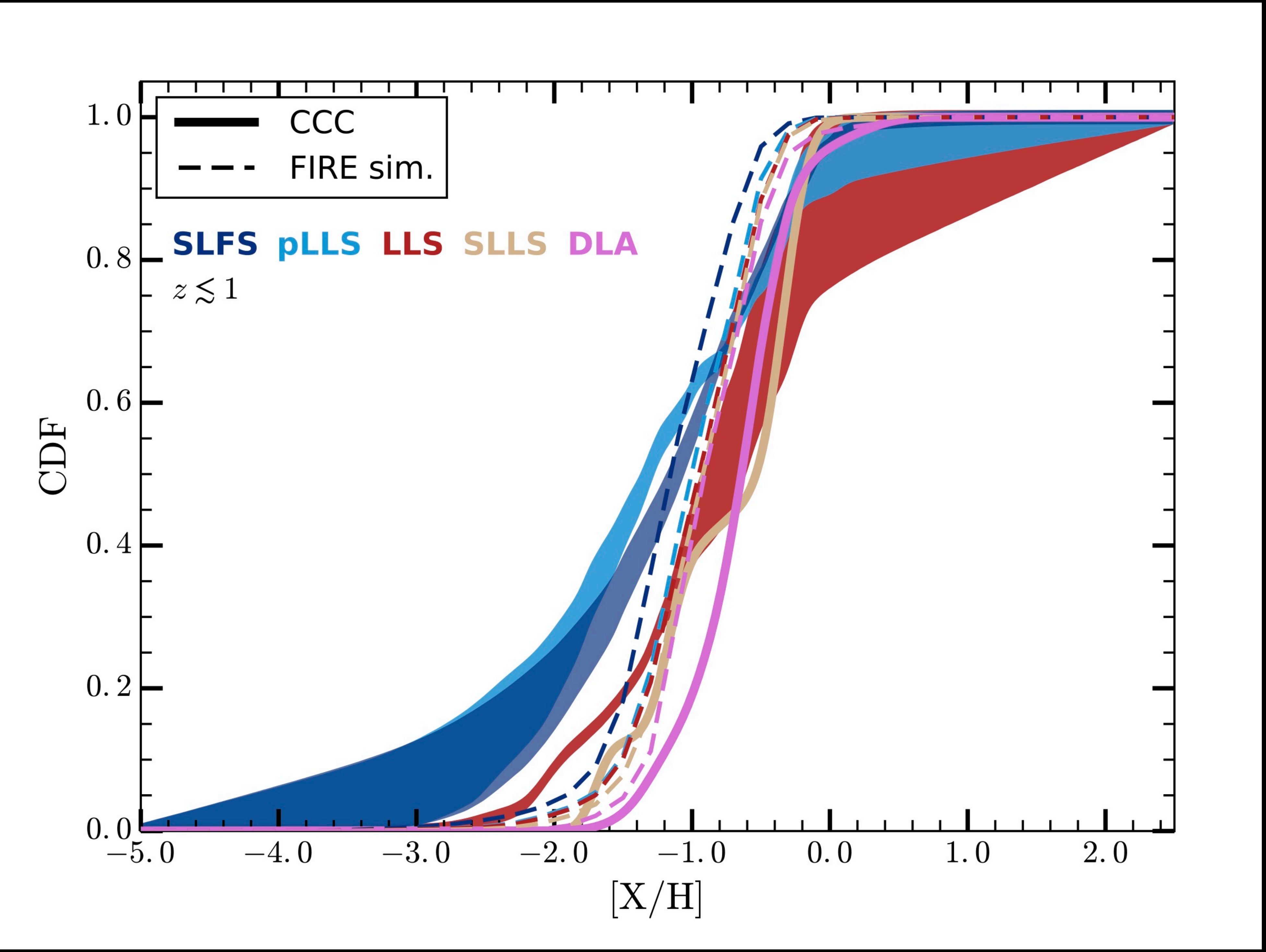
MNRAS, 2017

Zachary Hafen,[1]* Claude-André Faucher-Giguère,[1] Daniel Anglés-Alcázar,[1] Dušan Kereš,[2] Robert Feldmann,[3] T. K. Chan,[2] Eliot Quataert,[3] Norman Murray,[4] Philip F. Hopkins[5]



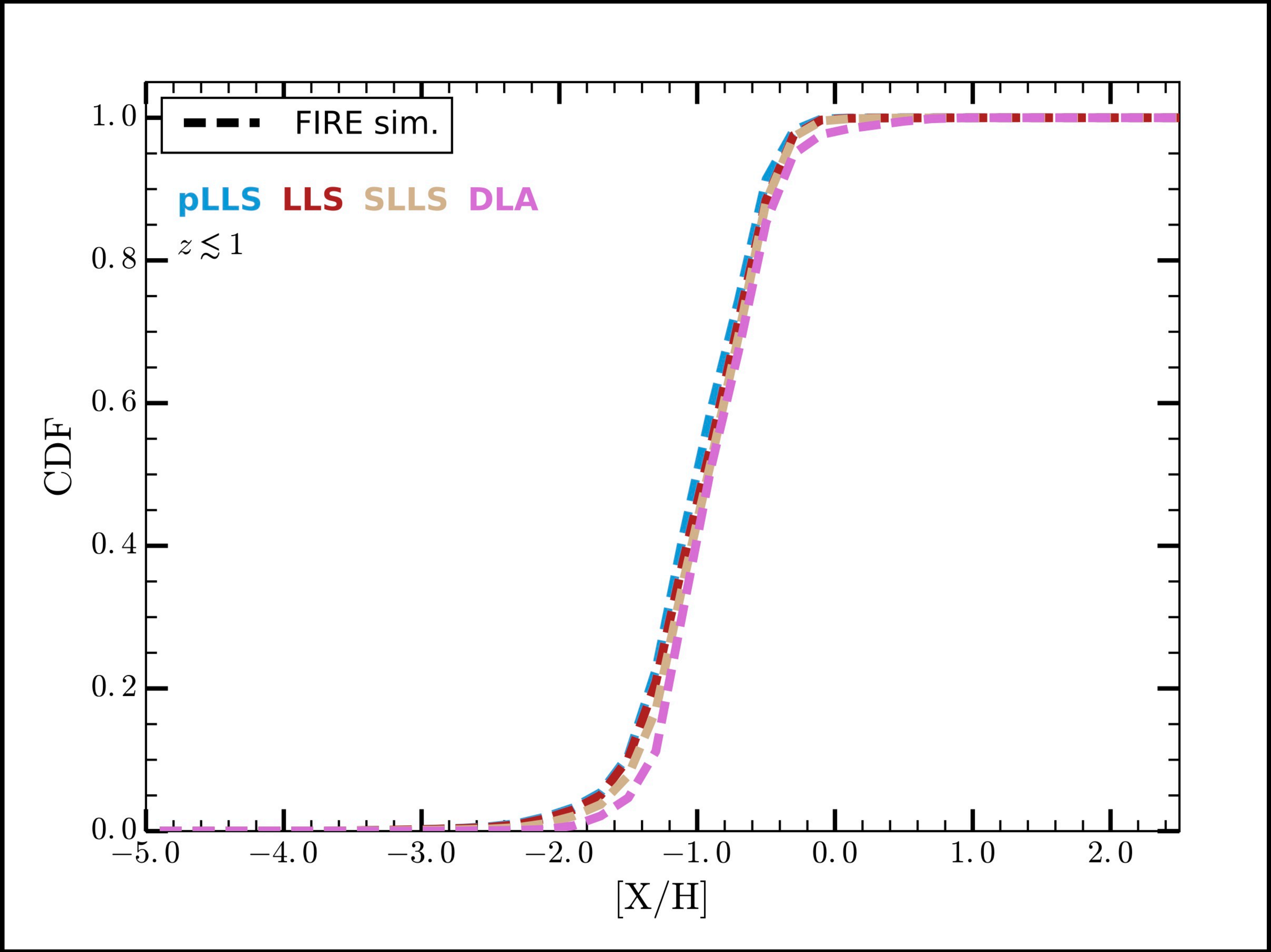


FIRE Simulations vs. CCC



Lehner+18b, Wotta+18 in prep

FIRE Simulations vs. CCC



Lehner+18b, Wotta+18 in prep

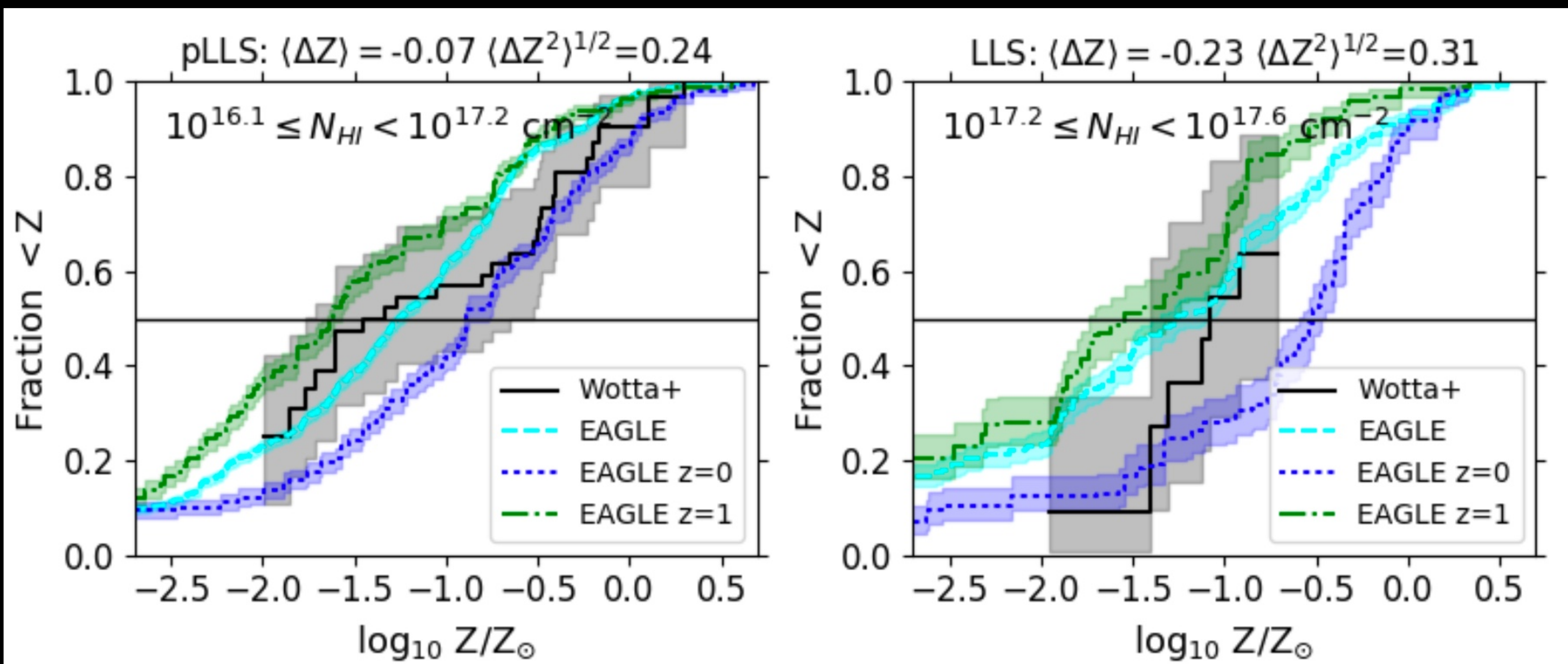
EAGLE Simulations vs. CCC

The metallicity distribution of HI systems in the EAGLE cosmological simulation

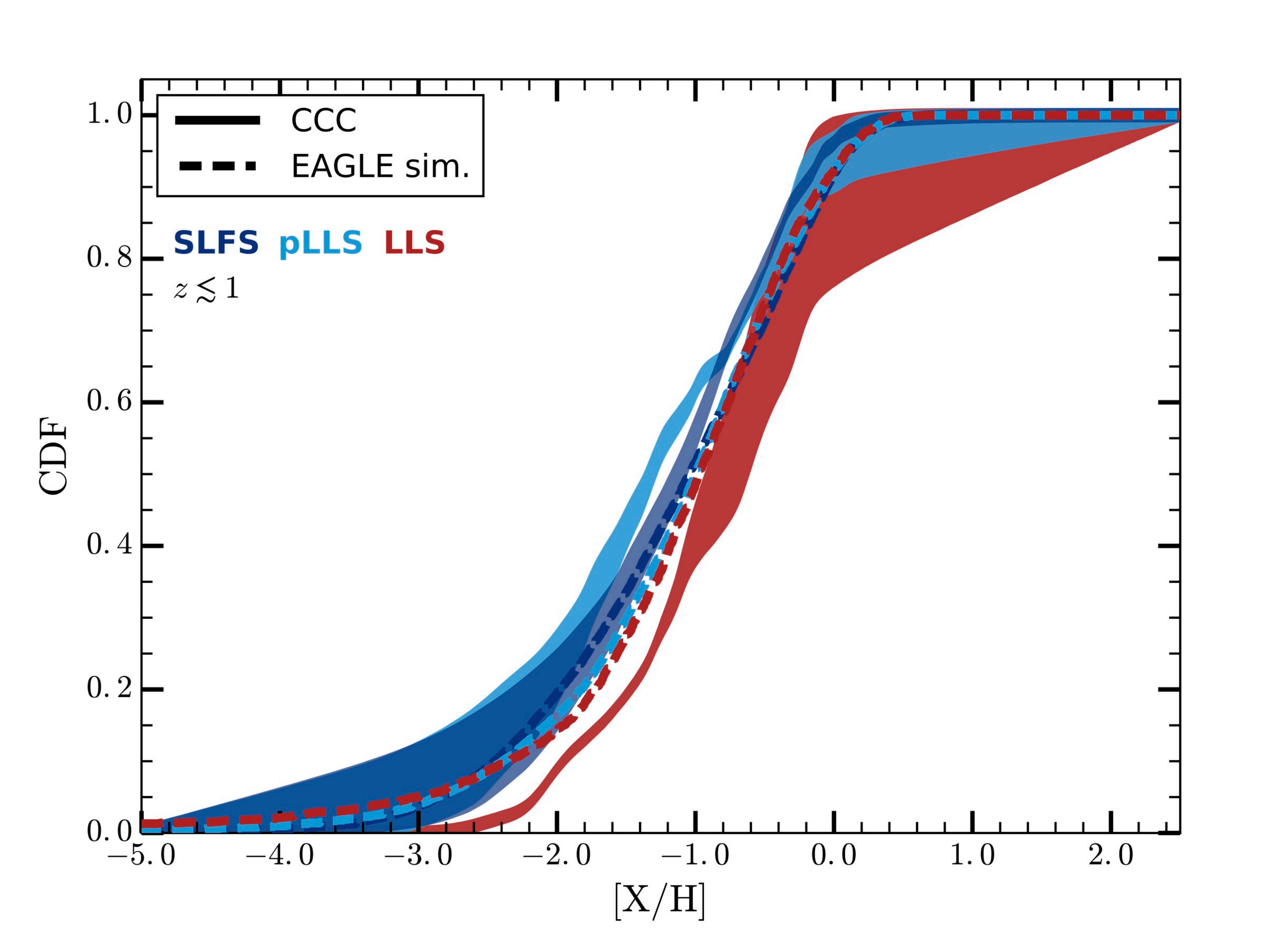
MNRAS, 2018

Alireza Rahmati[1], Benjamin D. Oppenheimer[2⋆]

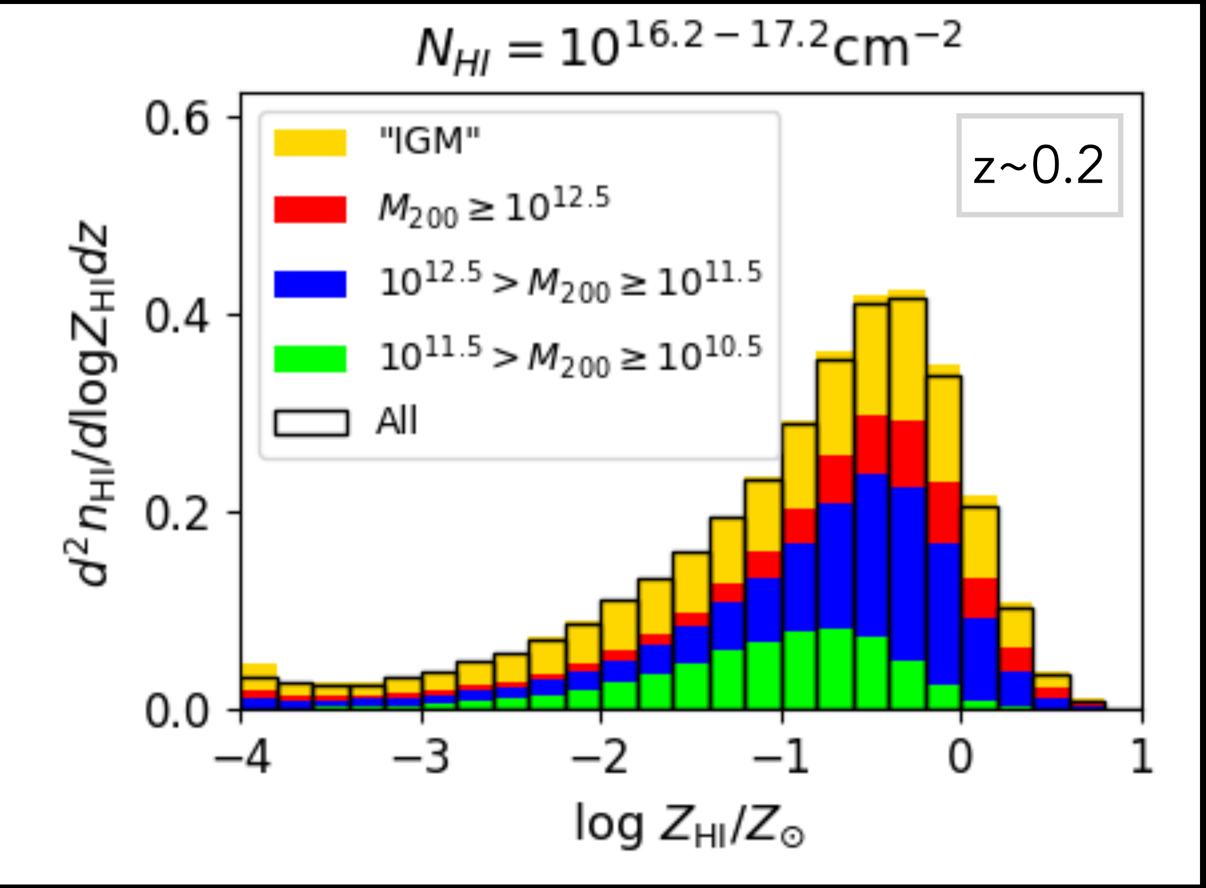
[1] *Institute for Computational Science, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*
[2] *CASA, Department of Astrophysical and Planetary Sciences, University of Colorado, 389 UCB, Boulder, CO 80309, USA*

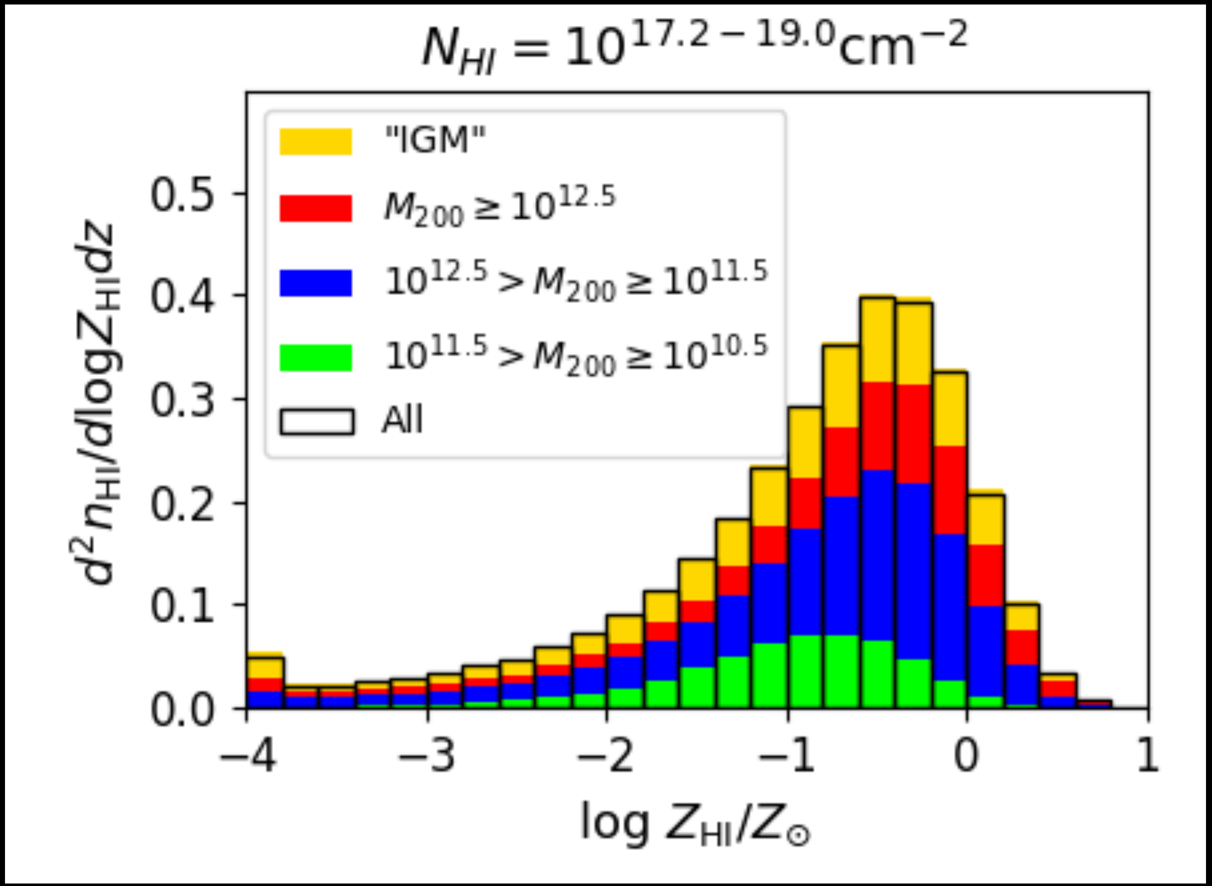


EAGLE Simulations vs. CCC

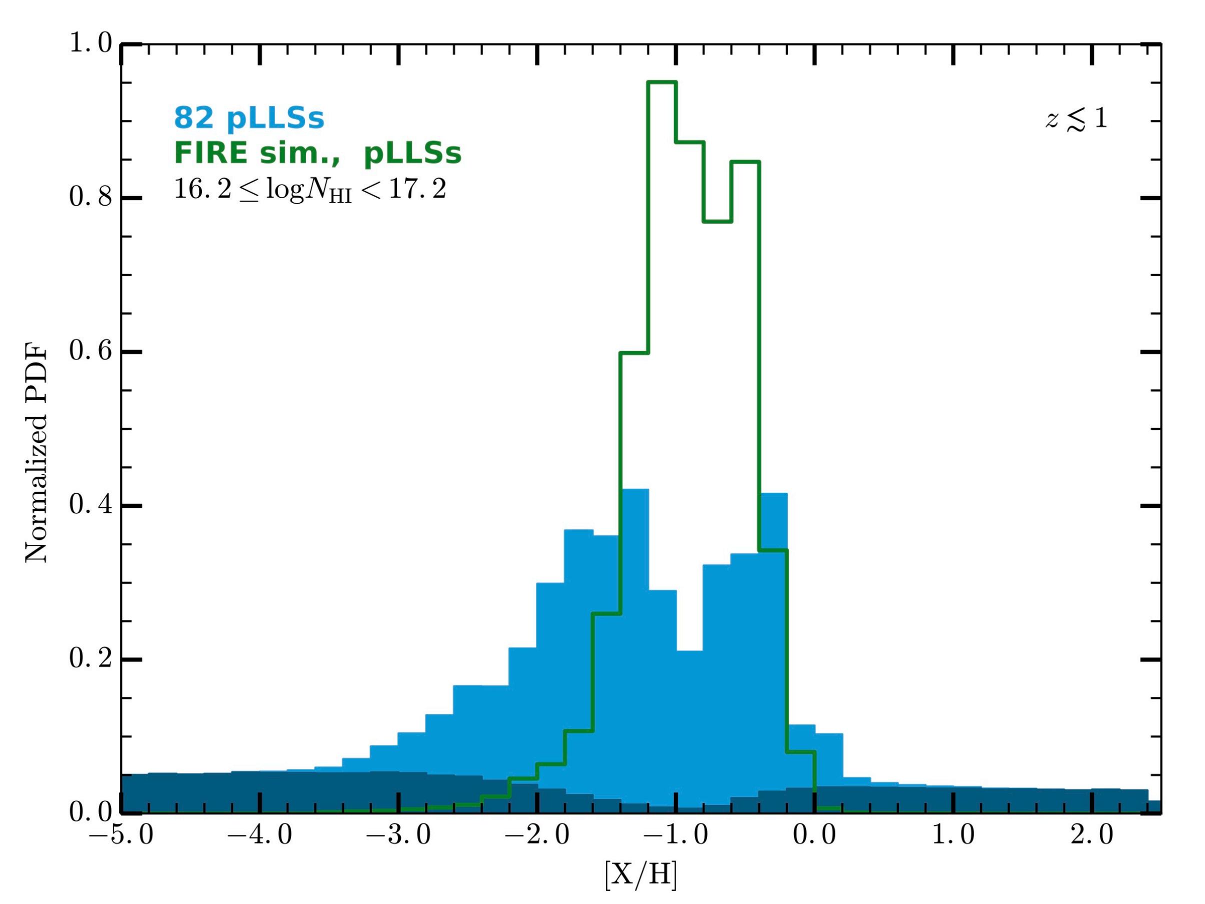


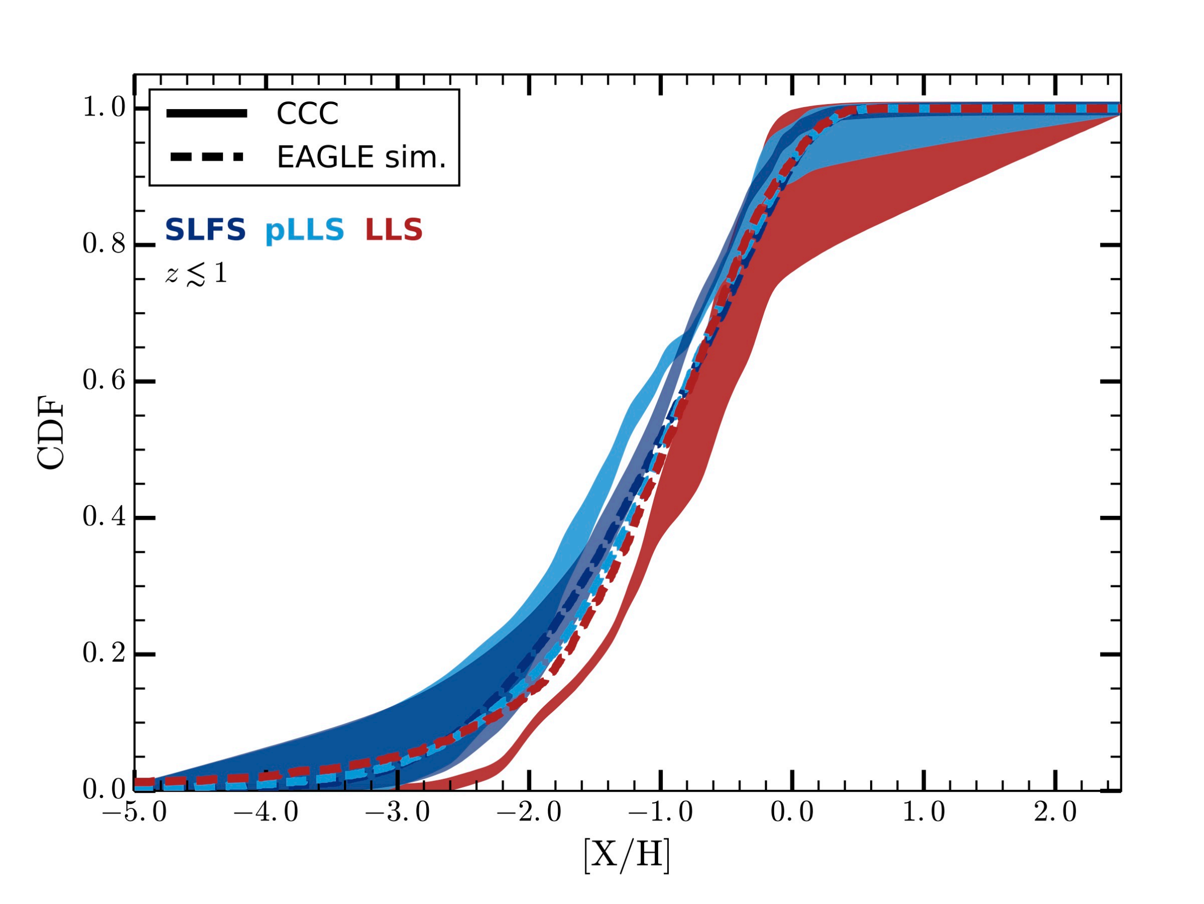
EAGLE: Galaxies Masses and CGM Metallicities





Summary II

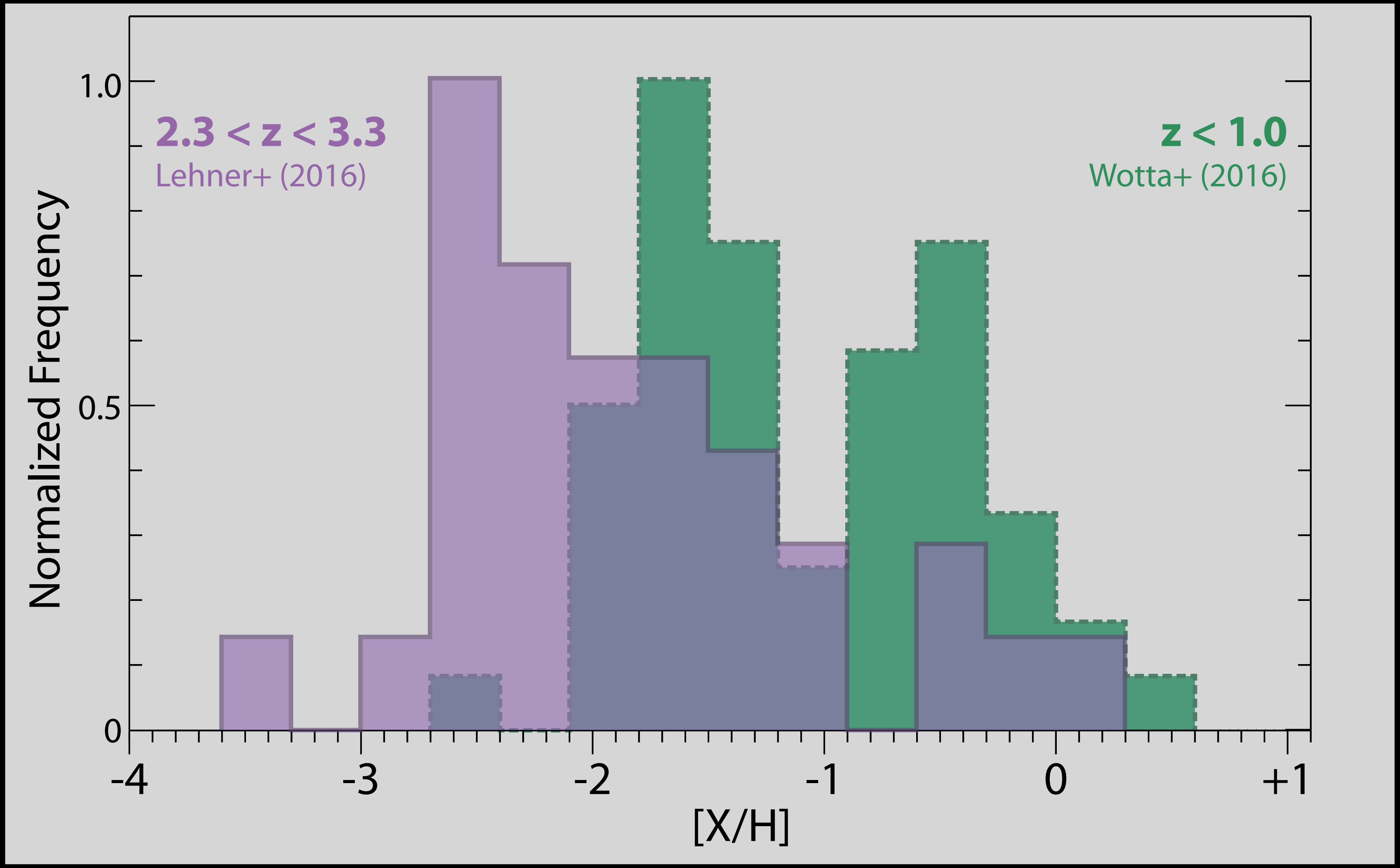




- The FIRE simulations under-predict the amount of low-metallicity gas probed by the 15<log $N_{\rm HI}$<19 absorbers.
- The EAGLE simulations produce a similar fraction of low-metallicity SLFSs, pLLSs, and LLSs. This is driven by a strong evolution of the metallicities of these absorbers between z~0 and 1, which is not observed in the CCC survey.
- The metallicity PDFs of the 15<log $N_{\rm HI}$<22 absorbers are nearly identical in the FIRE and EAGLE simulations.

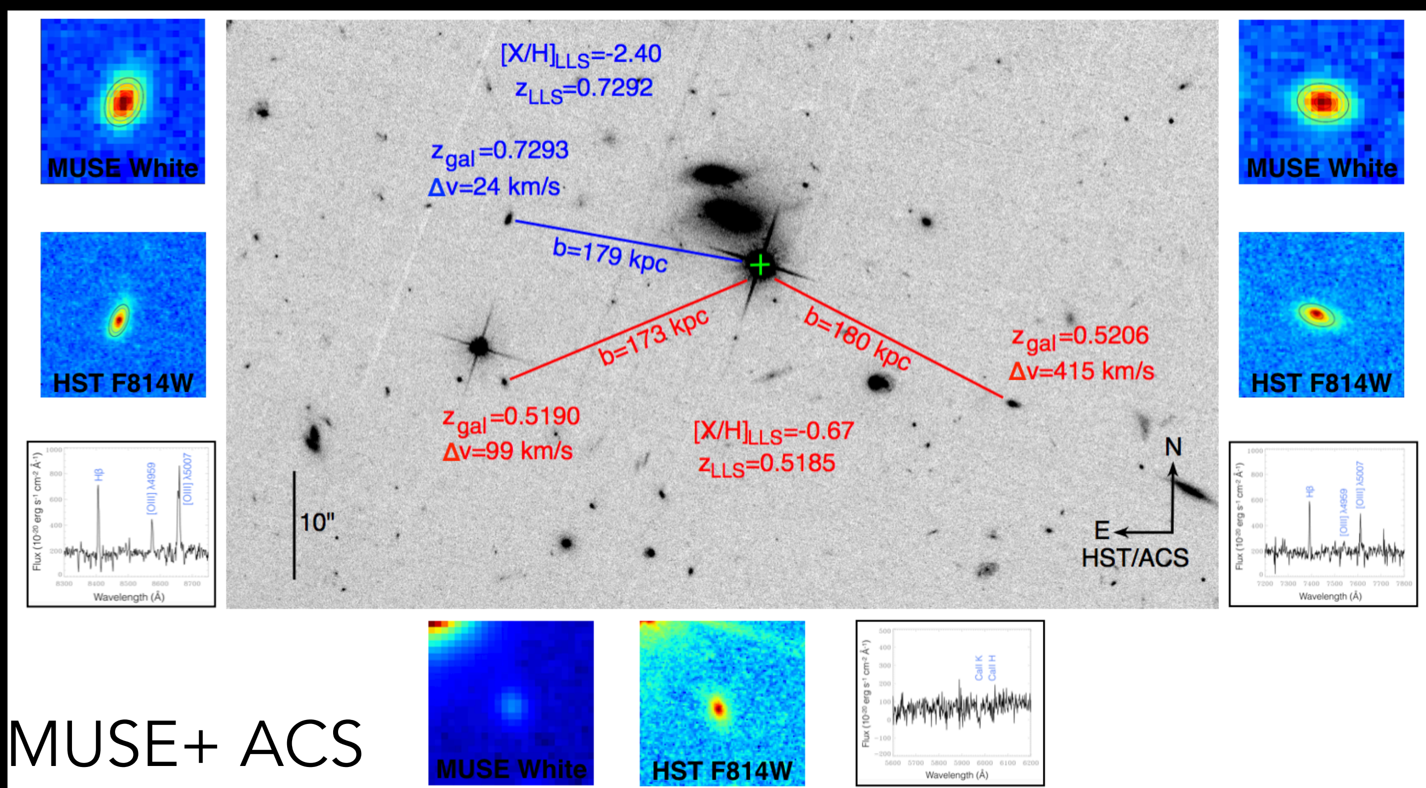
Ongoing and Future Projects

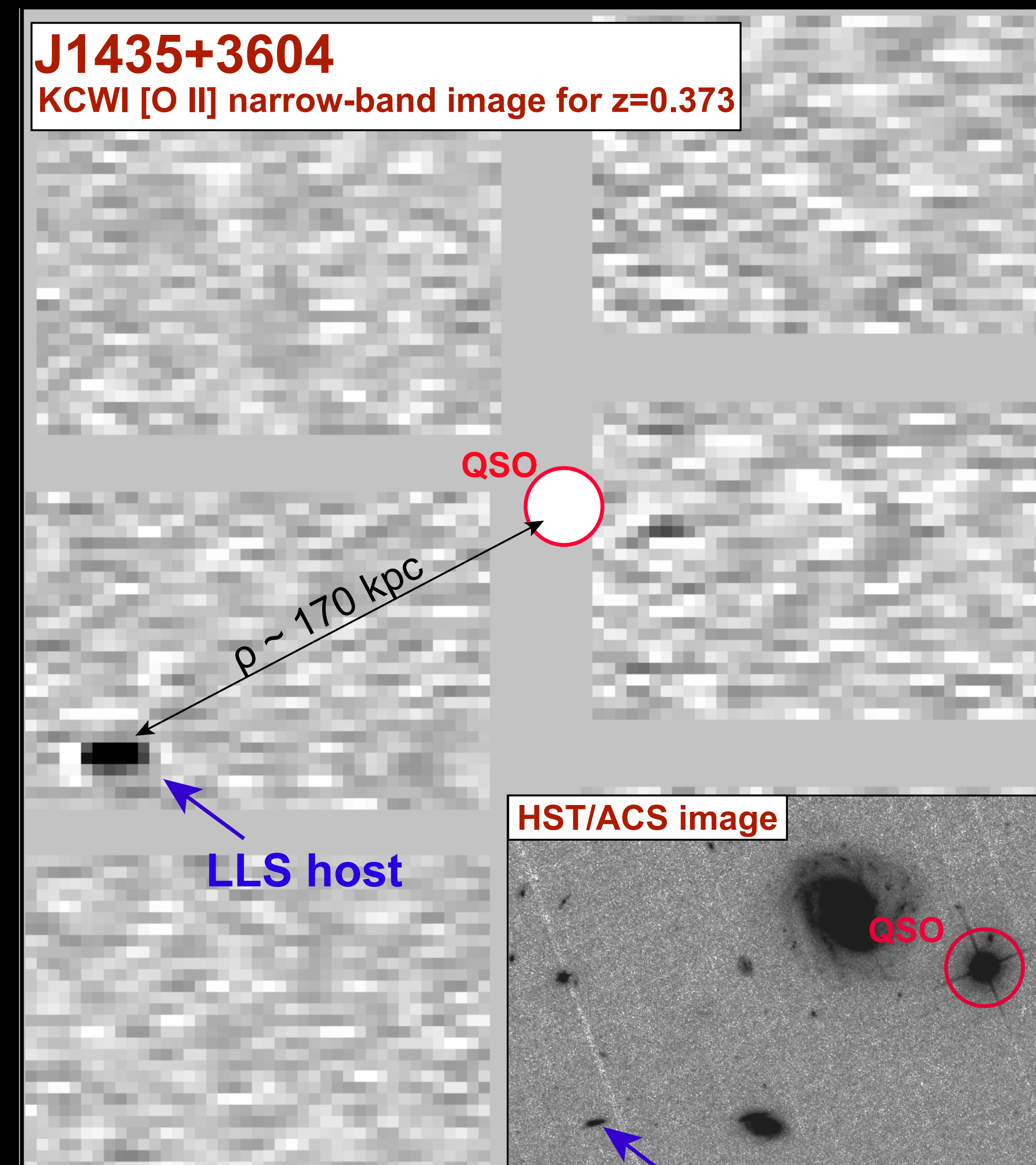
Evolution of the metallicity with redshift



- Our Large KODIAQ survey is underway (Lehner+16).
- We will study the evolution of the metallicity of the absorbers with 15<log NHI<19 over cosmic time.

Coming soon: Galaxies!





- How do the properties (metallicity, but also N(OVI), etc.) of the LLSs correlate with properties of the galaxies?

Summary

- Metal-enriched inflows and outflows are quite common at low redshift.
- There is a large reservoir of ***metal-poor cool gas*** in the dense ionized medium of the universe probed by pLLSs and LLSs ***at all z*** that may eventually accrete onto galaxies.
- ***Strength in numbers: large archives are changing the game!***
- With large surveys of CGM absorbers combined with MUSE & KCWI (and other instruments in the making) observations of their environments as well as new simulations, we will have the 2nd CGM revolution.