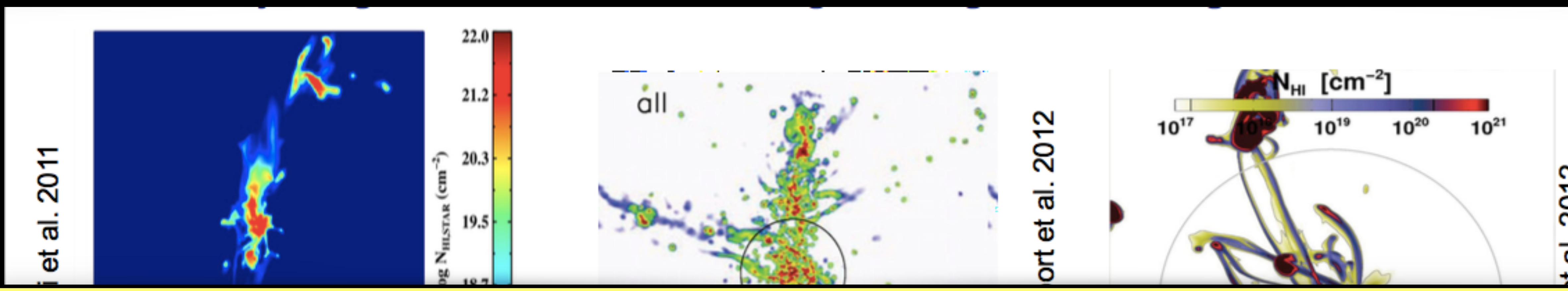
# The COS CGM Compendium: A Survey of HI-Selected absorbers at z<1

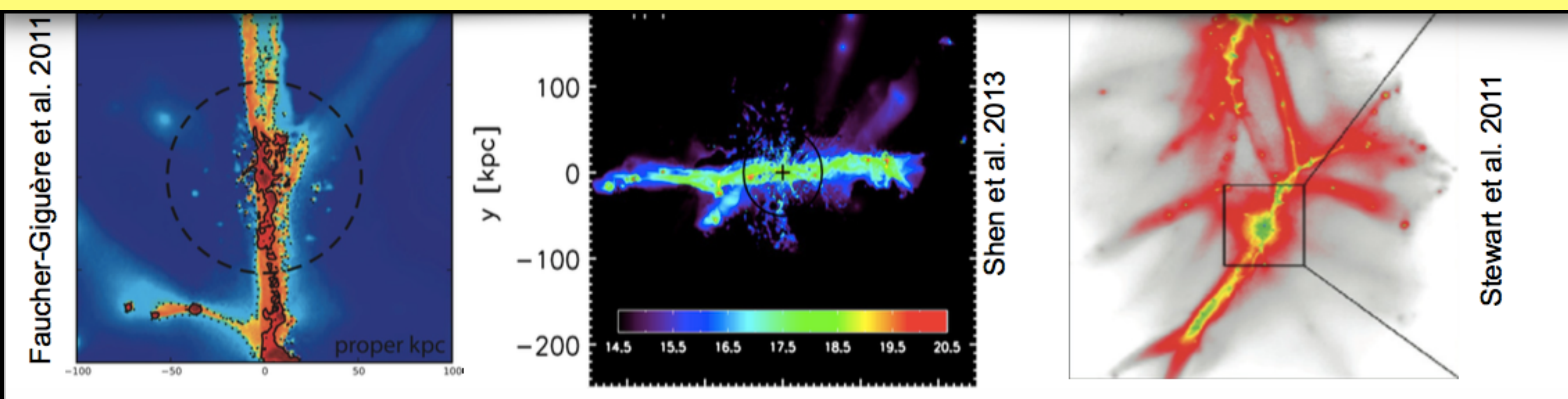
**Team: Nicolas Lehner, Chris Howk, Chris Wotta, John O'Meara, Ben Oppenheimer, Kathy Cooksey**

# The CGM of galaxies: next frontier for models

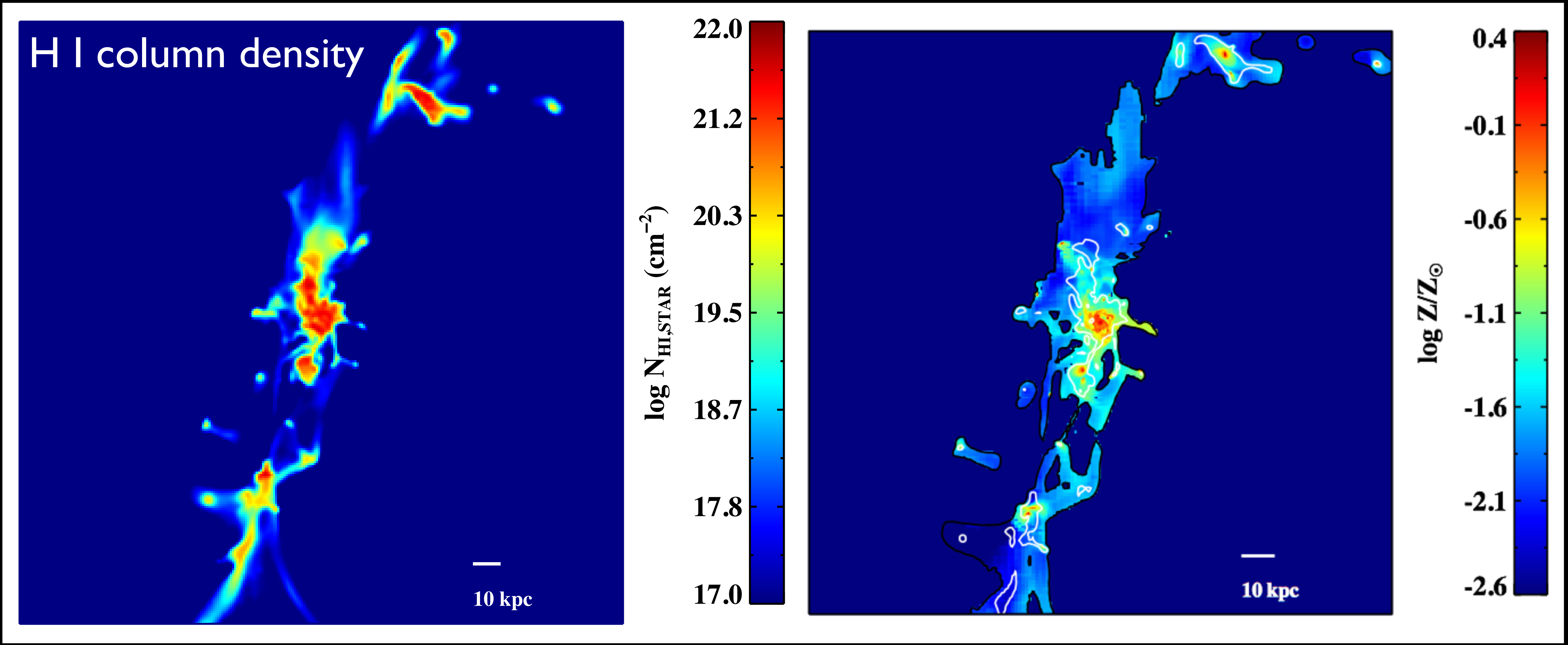
Simulations consistently predict the presence of strong HI absorption in the surroundings of galaxies




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).



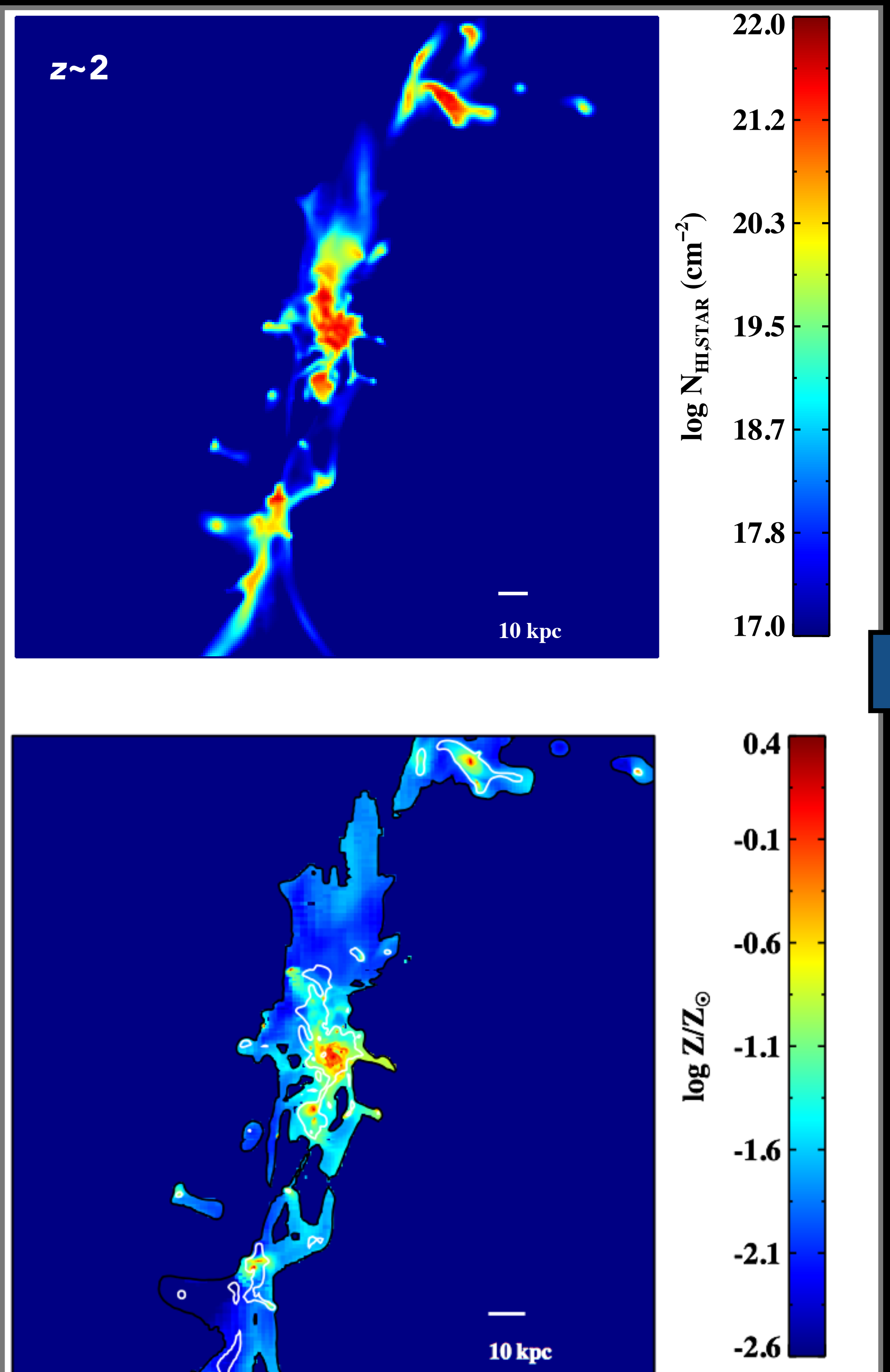
# Metallicity is a *key* property of the CGM gas



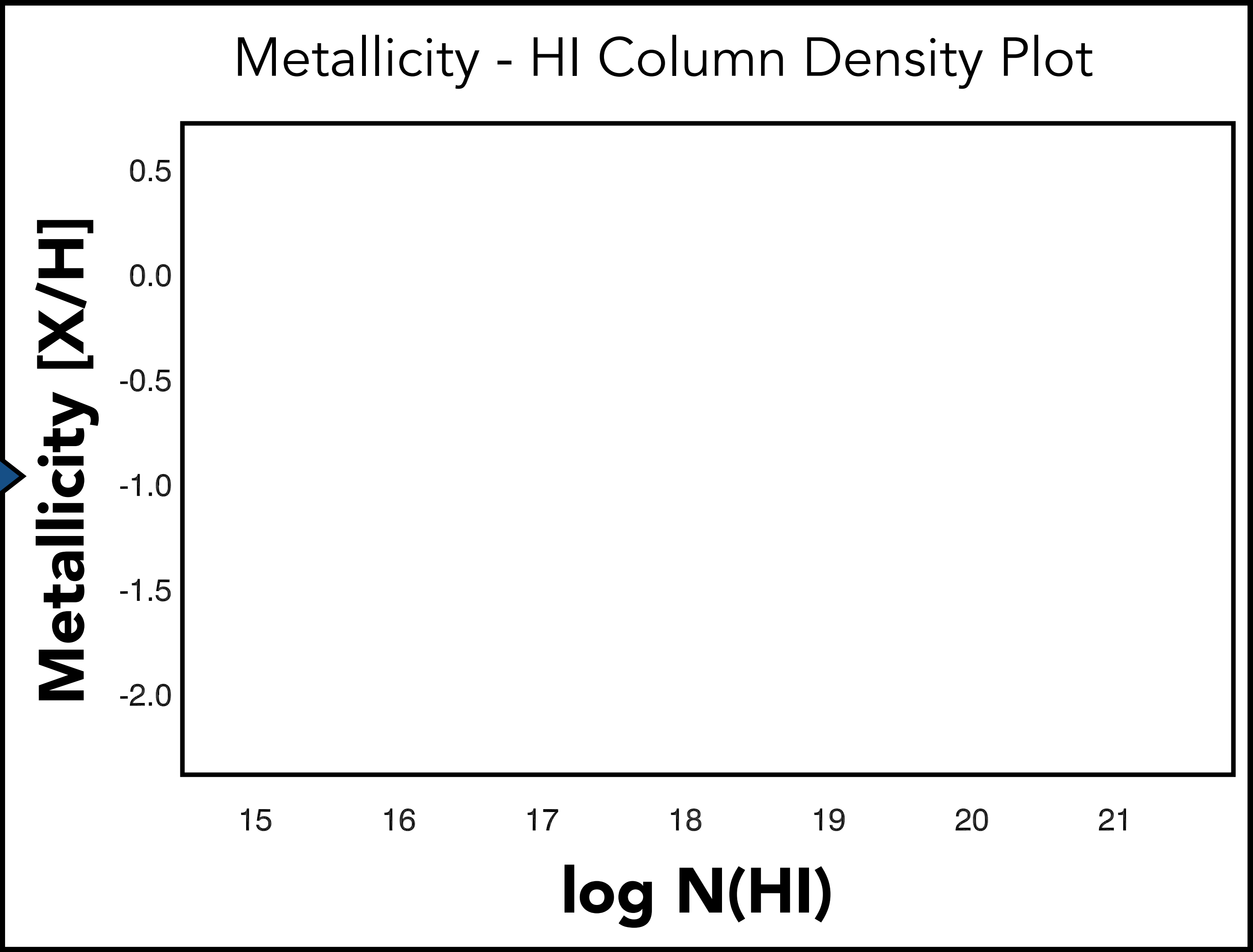

Fumagalli+ (2011)

- 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.
- We can directly test simulations using [X/H] vs $N_{HI}$ plots at different redshifts.

# 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 $N_{HI}$

Metallicity is a key property:
- How metal-enriched is the CGM gas?
- Is there pristine CGM gas at z<1?
- Critical if you want to estimate the baryon budget

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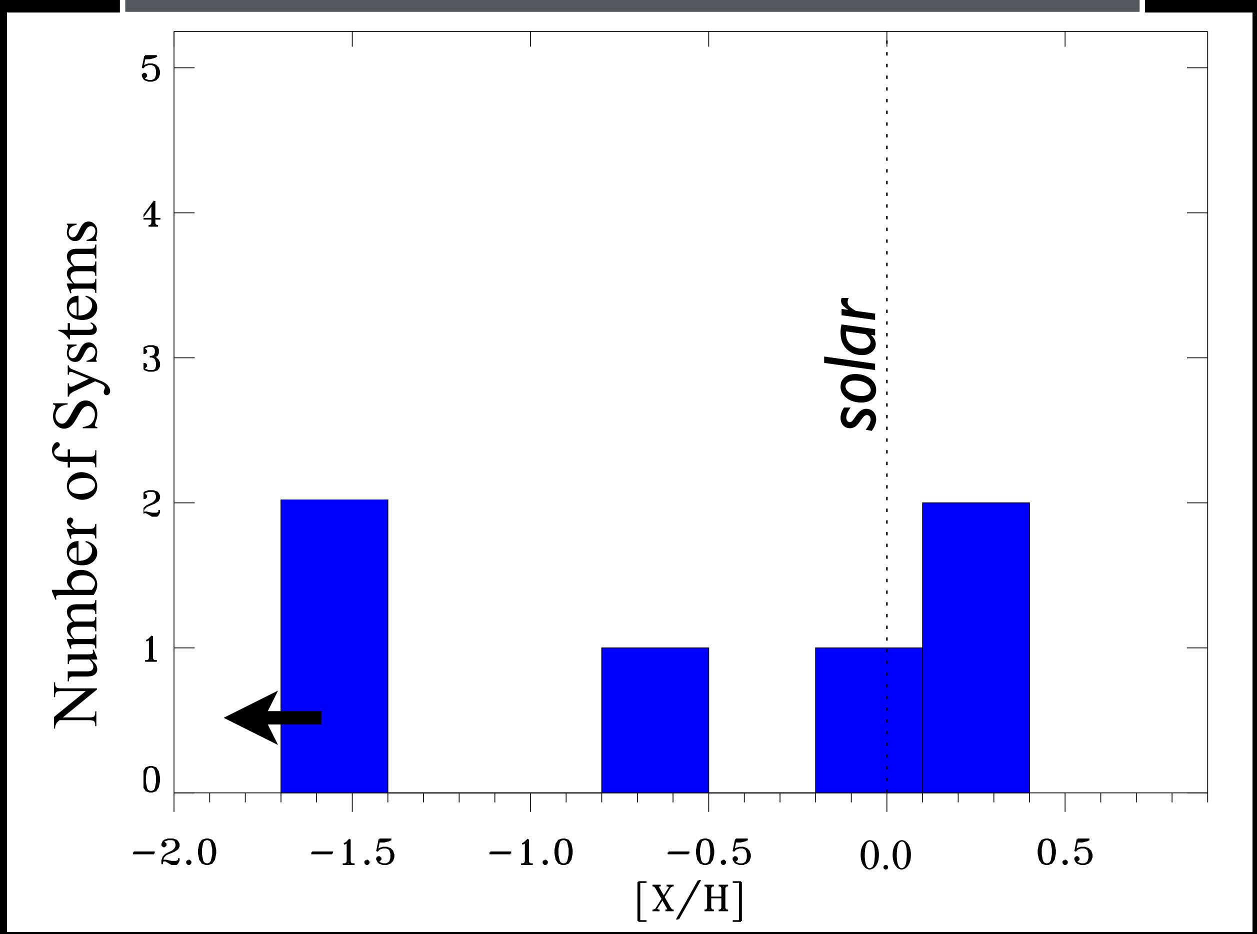
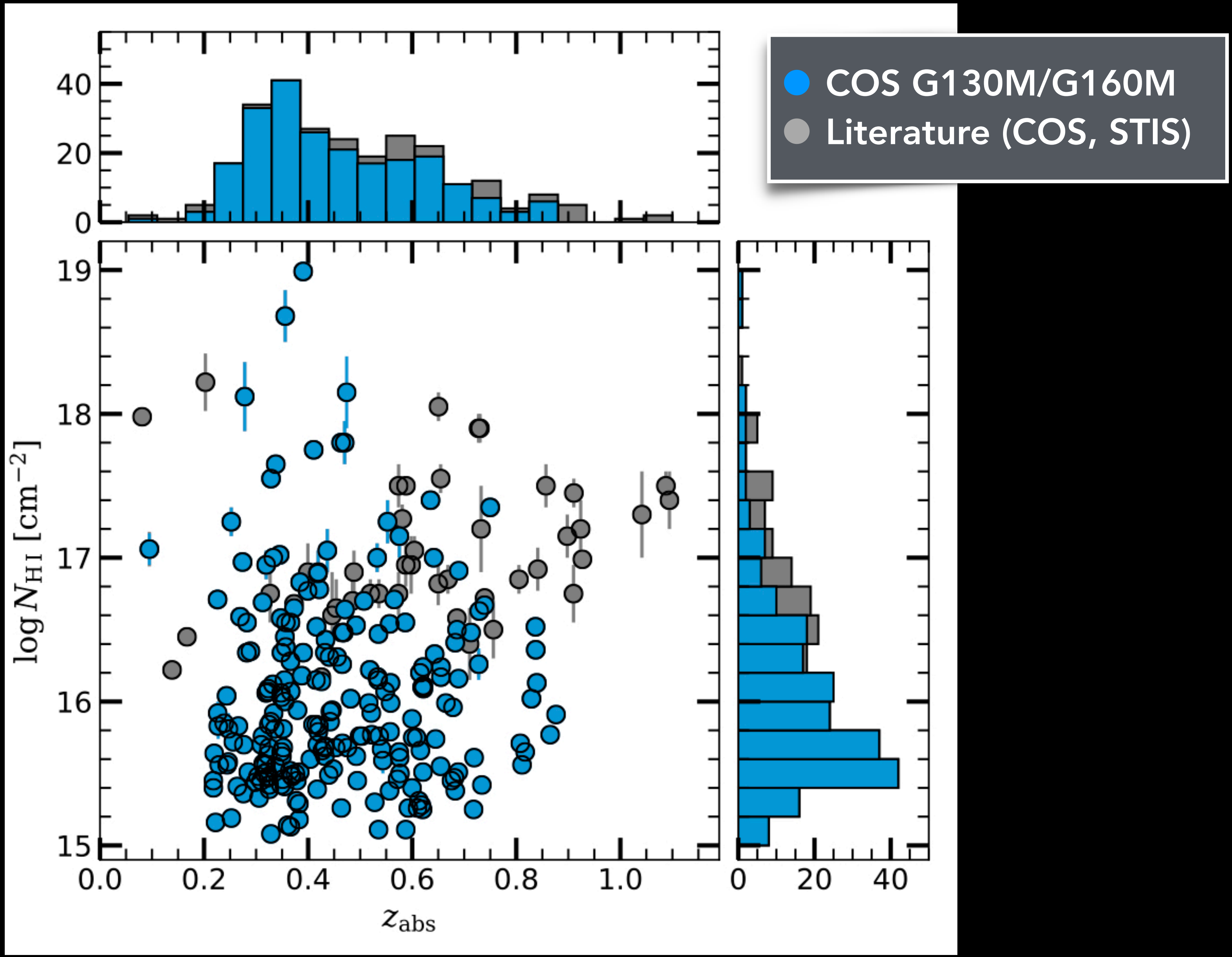
Metallicity distribution in the pre-COS era




*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

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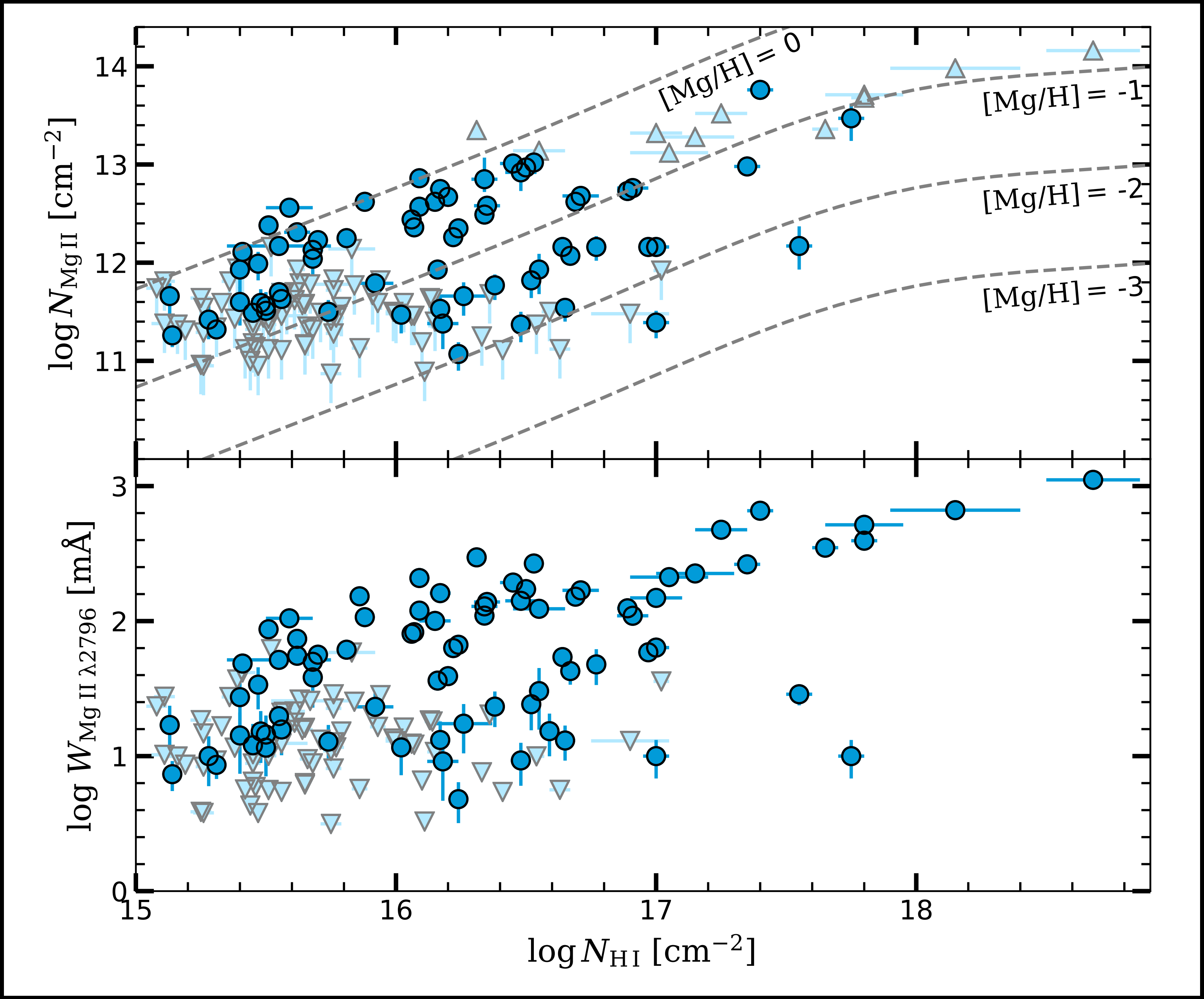
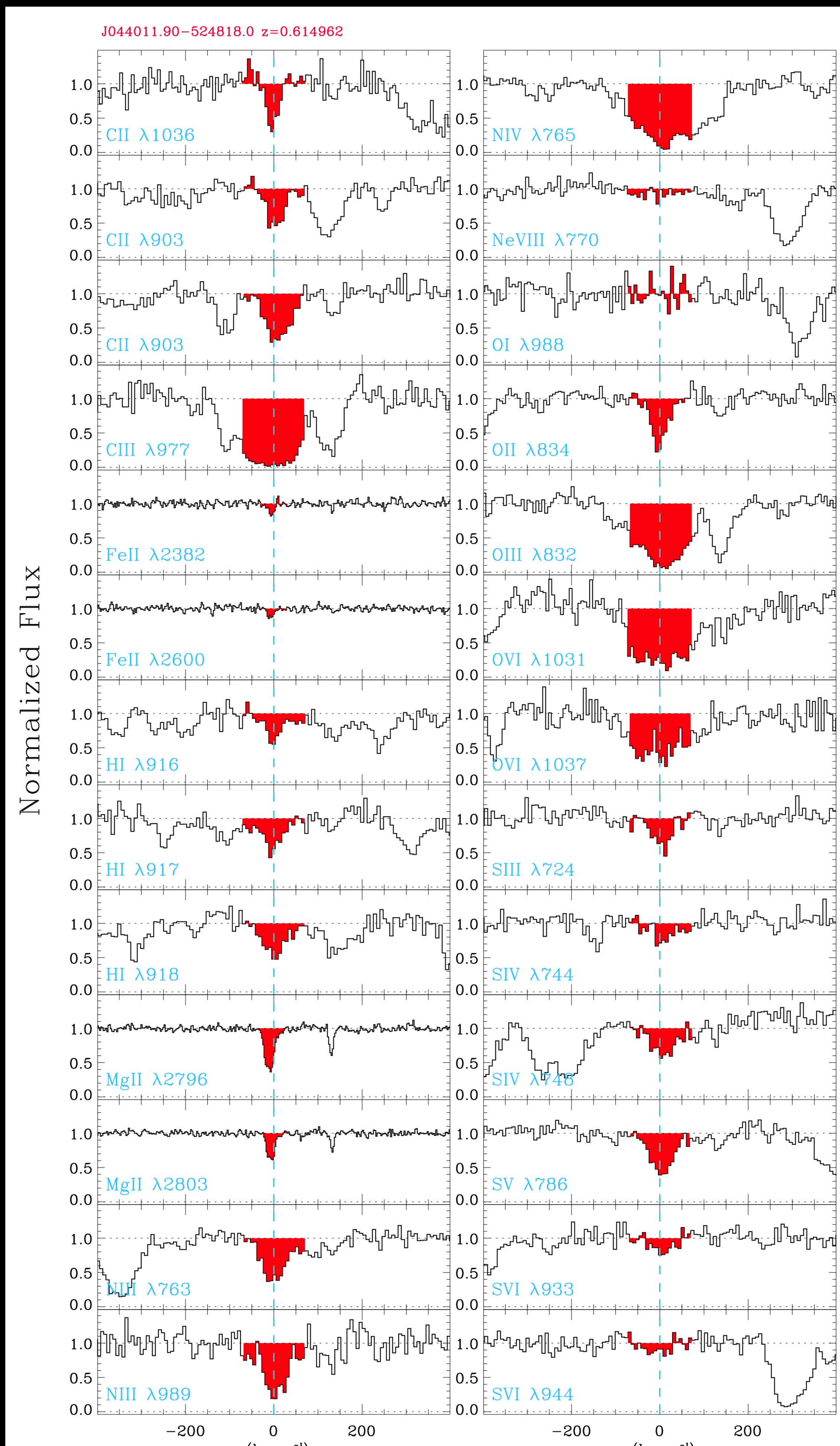
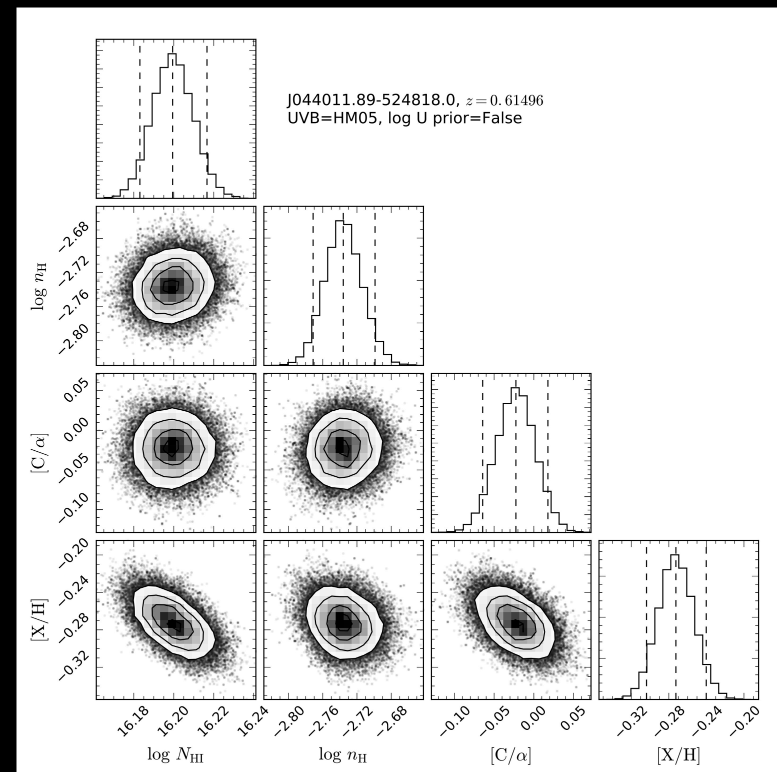
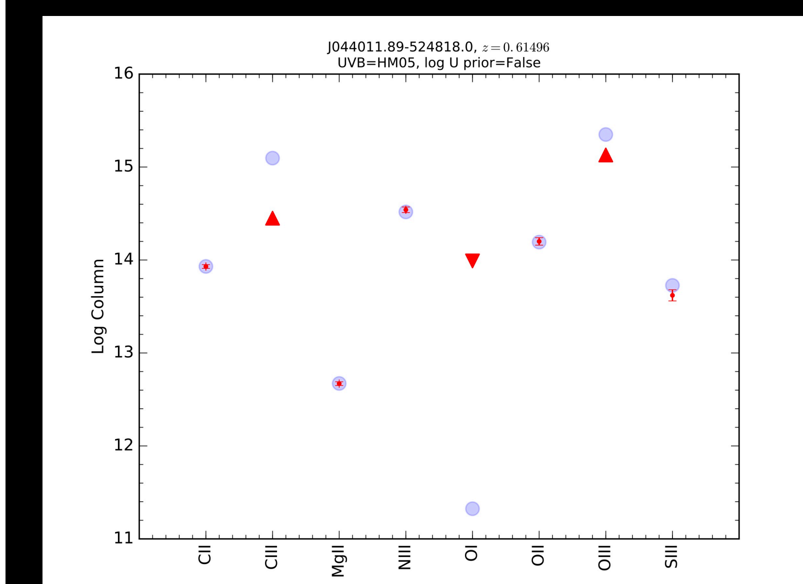



Lehner+18a, submitted

# An example: from data to a metallicity PDF



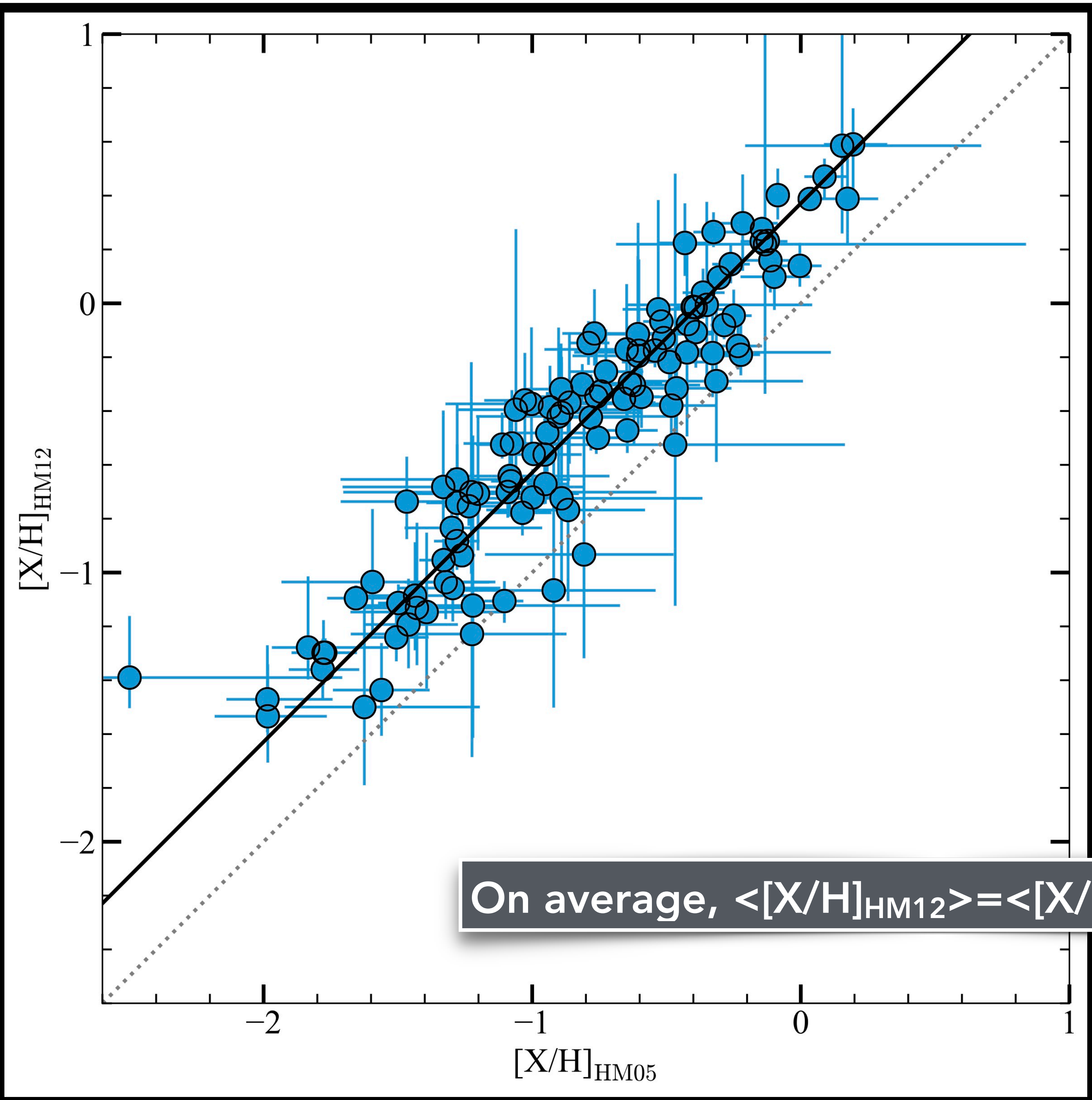




- SLFSs, pLLSs, and LLSs are all strongly ionized and therefore an ionization correction is needed to determine the metallicity.
- Use only low (CII, SiII, MgII) and intermediate ions (e.g., CIII, OII) to model the photoionization.
- C/α is allowed to vary.
- Adopt EUVB HM05 Galaxies+QSOs (HM12)
- Use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

Wotta+18, in prep

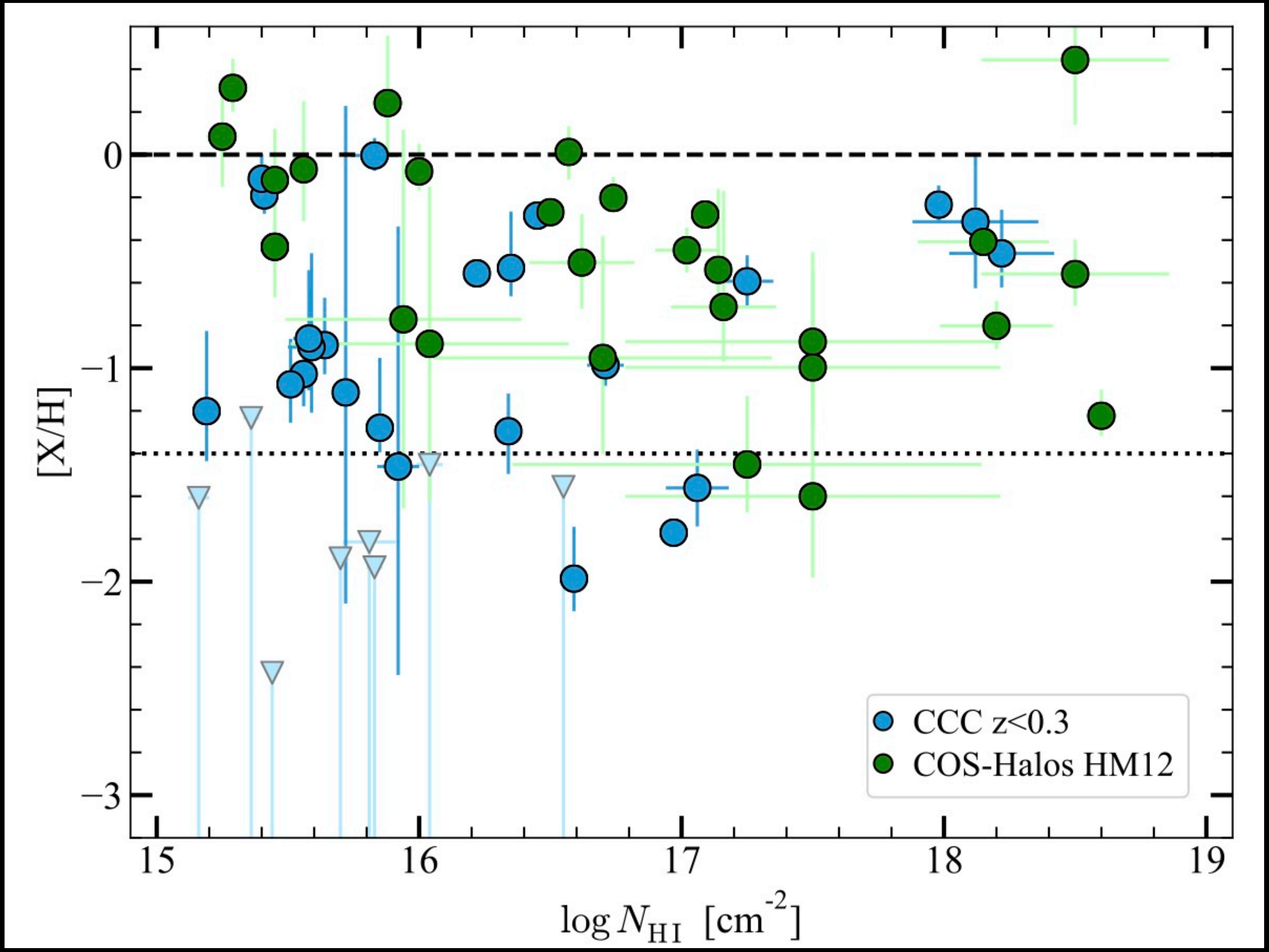
# Effects of the EUVB on the metallicity




On average, <[X/H]HM12>=<[X/H]HM05>+0.37

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

# Effect of the EUVB: CCC vs. COS-Halos

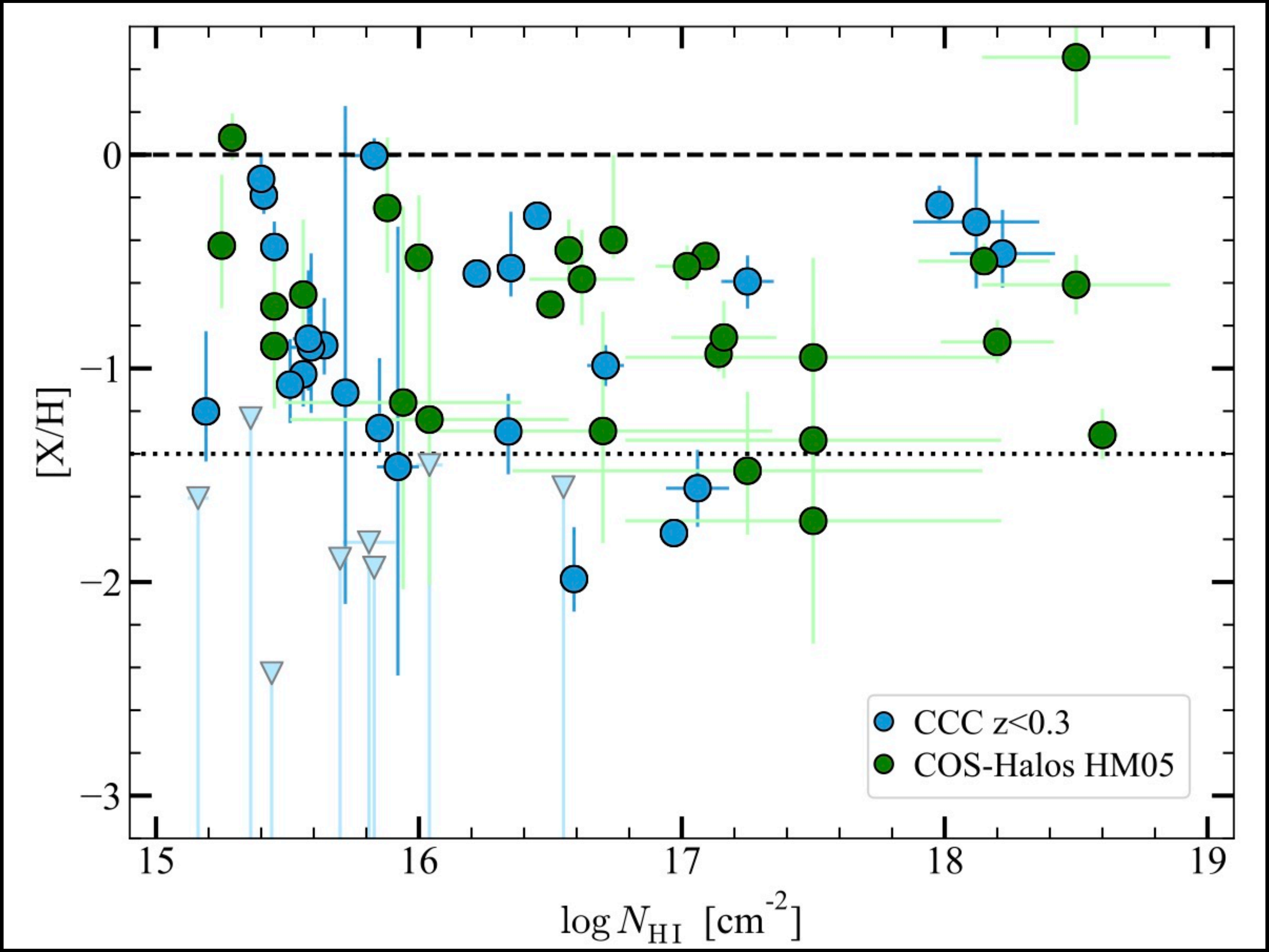



Note: COS-Halos redshifts often outside our search range.

Lehner+18b, in prep

COS-Halos: Remodeled from Prochaska+17

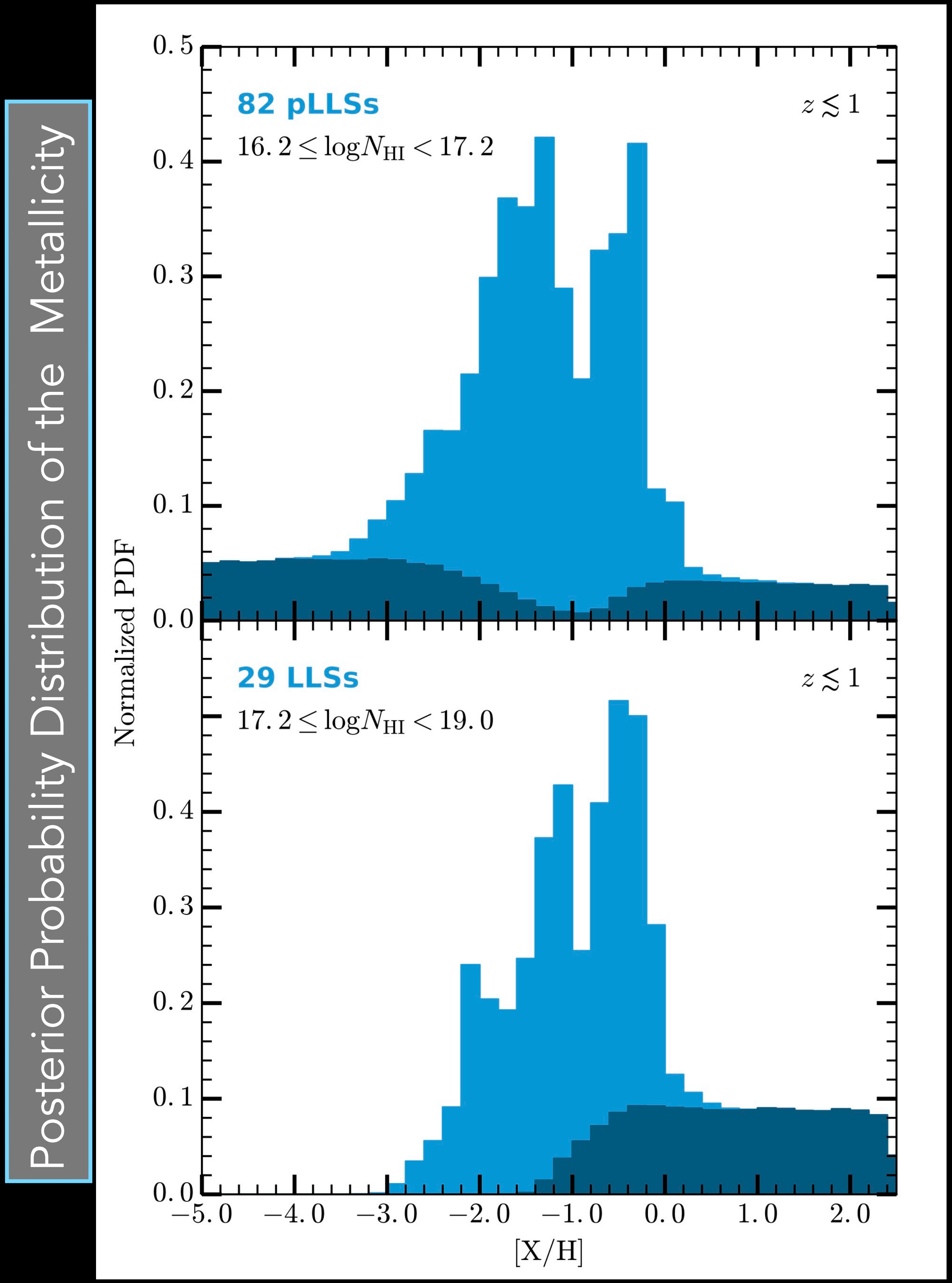
# Effect of the EUVB: CCC vs. COS-Halos




Lehner+18b, in prep

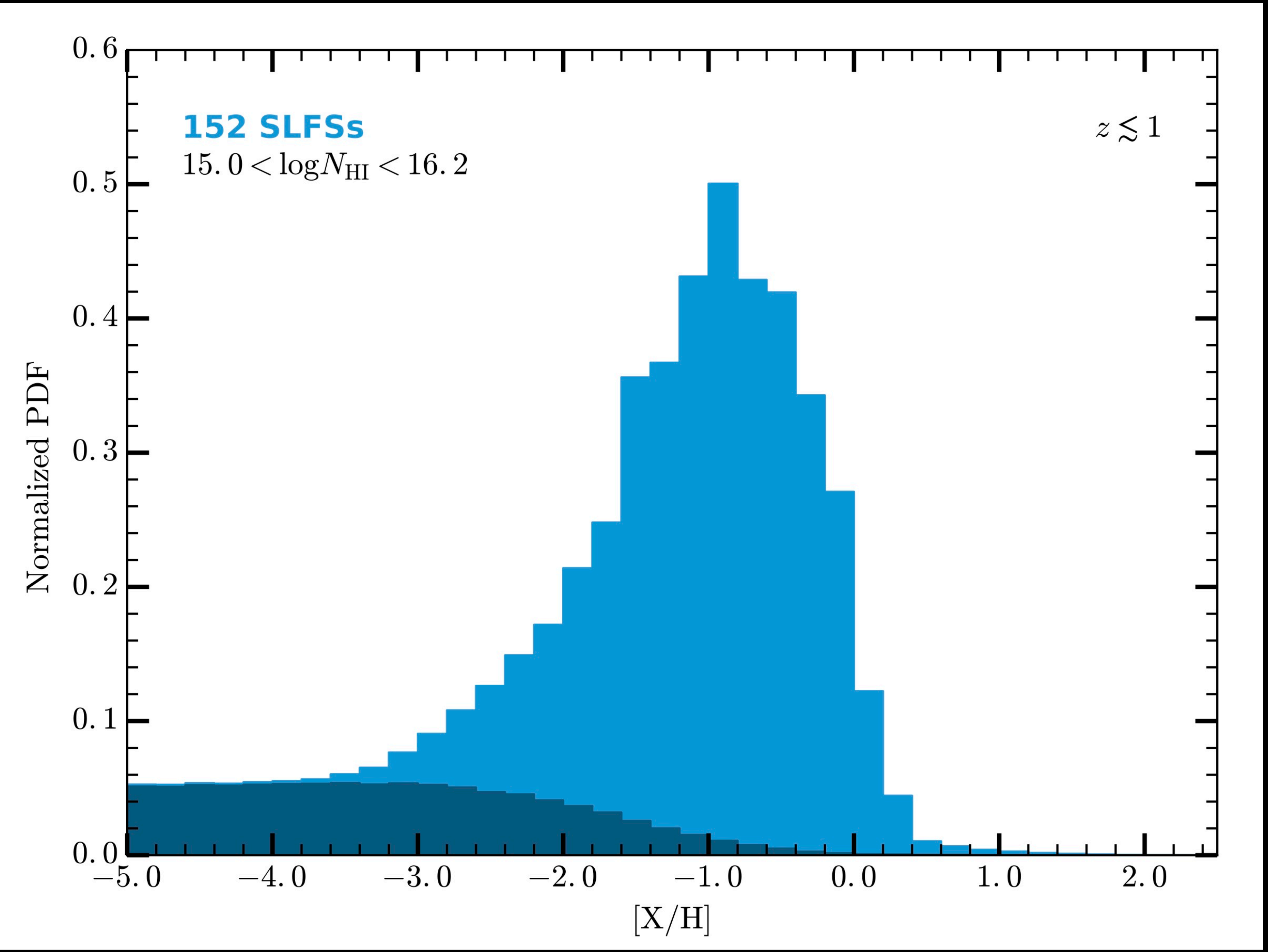
# Some of the key science results from CCC

# Results: Metallicity PDFs of the pLLSs and LLSs at z<1



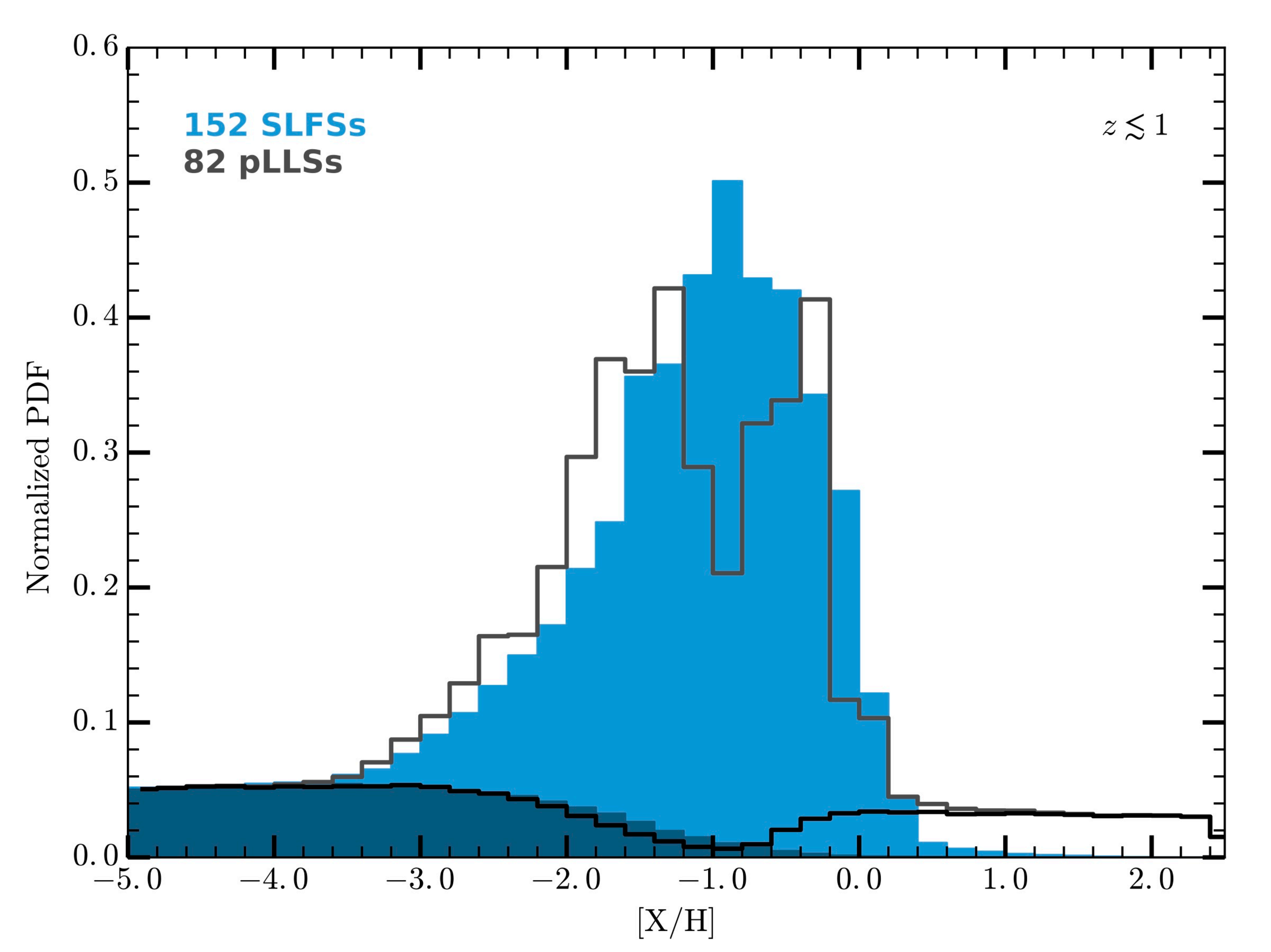

Wotta+18

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



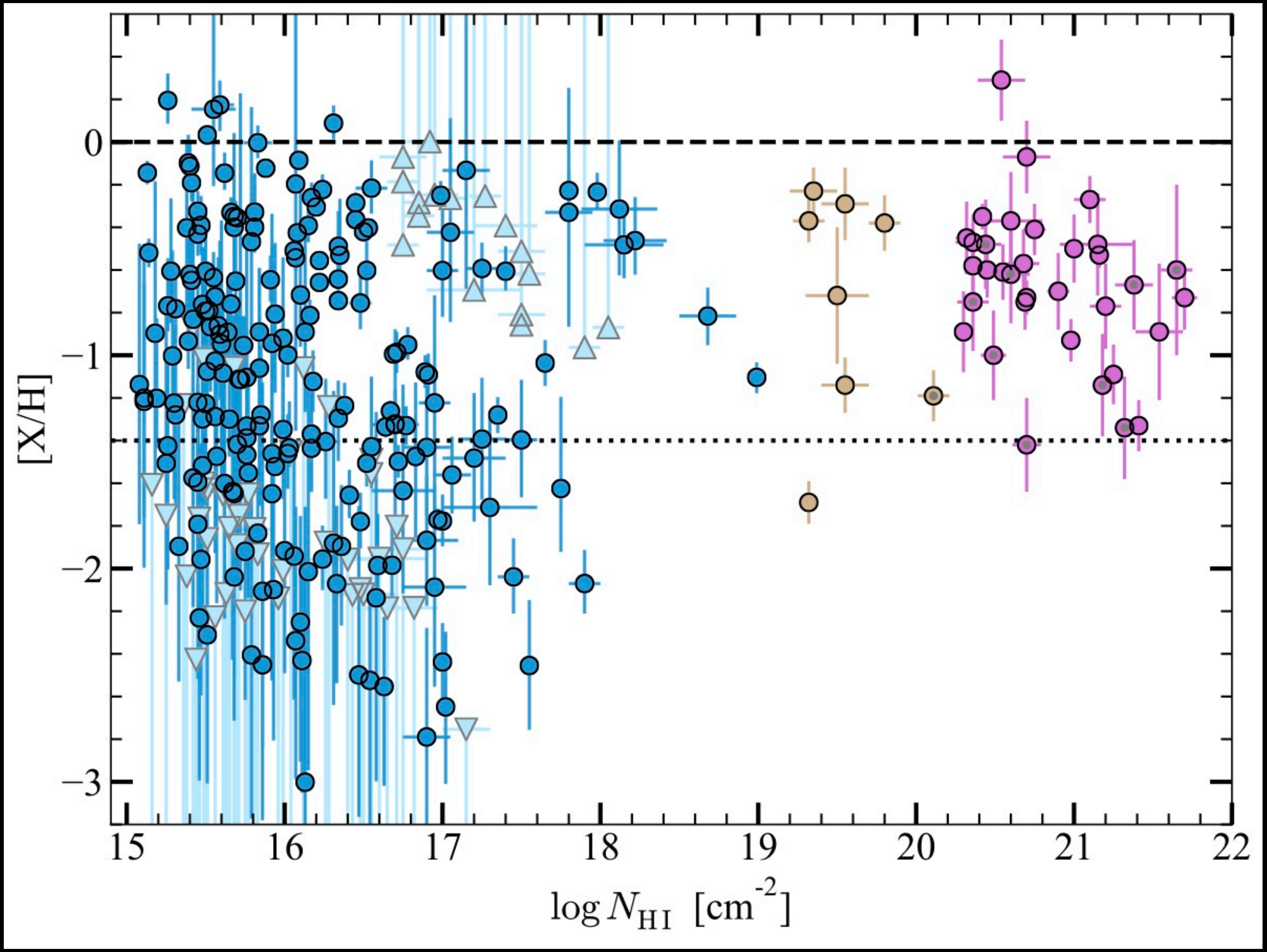

Wotta+18, Lehner+18b, in prep

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




Wotta+18, Lehner+18b, in prep

# Result: Evolution of the metallicity with $N_{HI}$

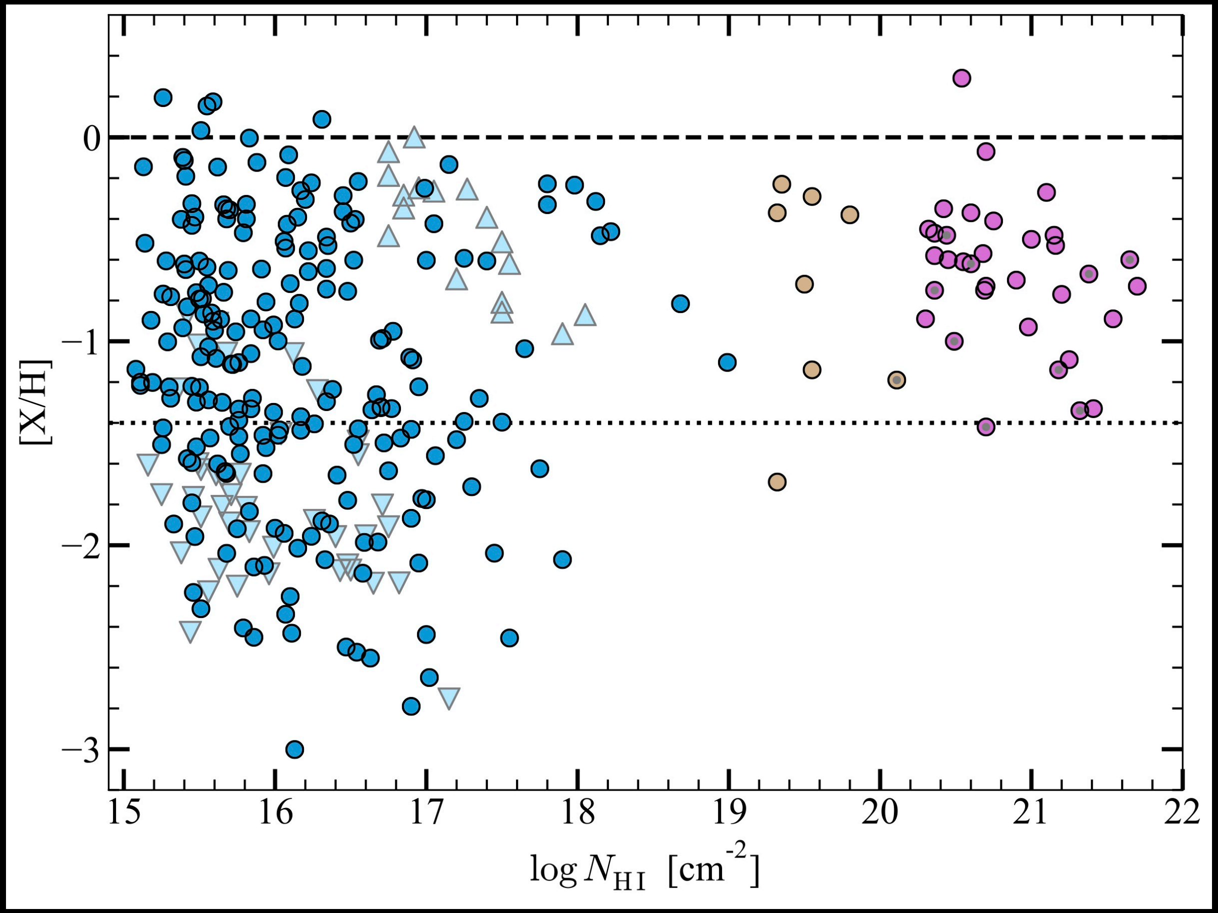


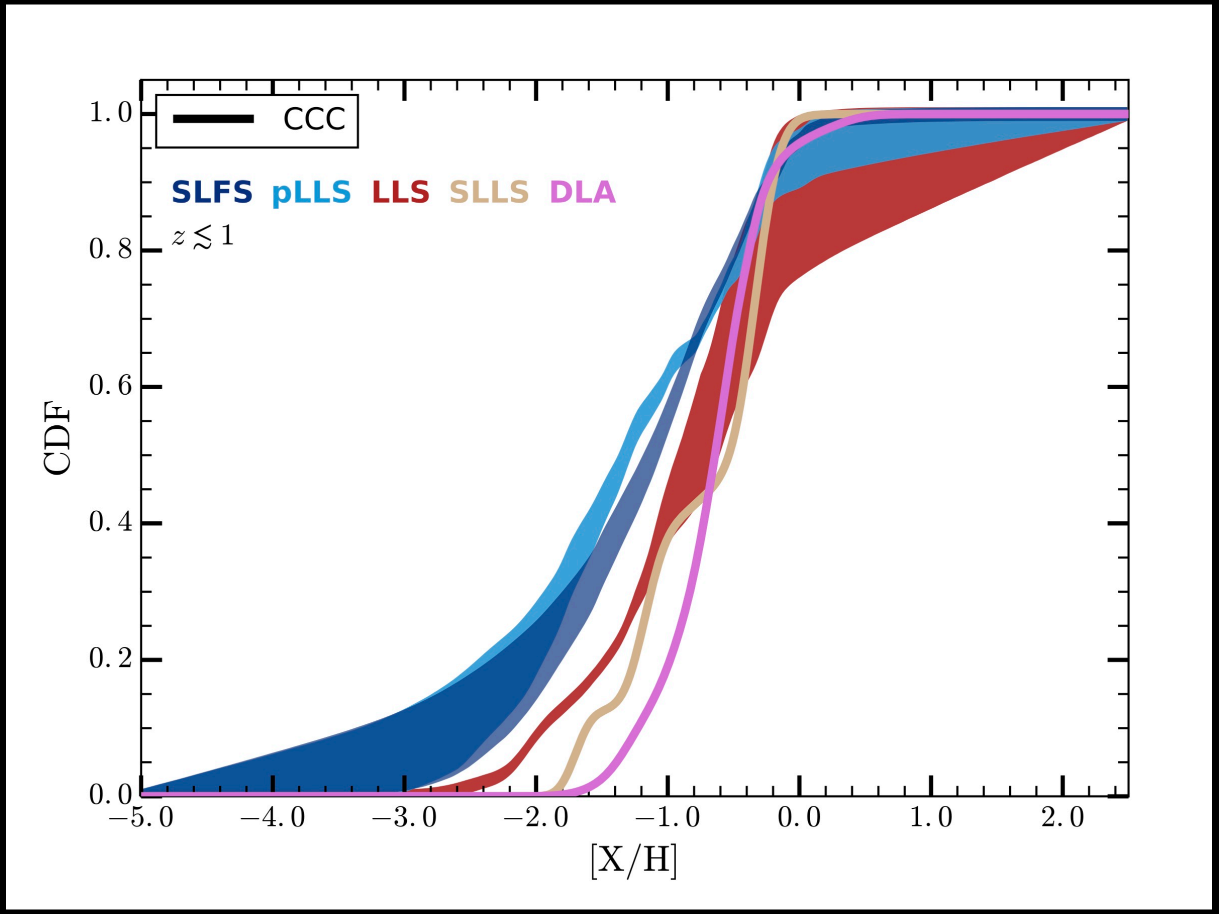

DLAs: new compilation from 3 papers: Rafelski+12, Lehner+13, Quiret+16

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 an evolution of the metallicity with $N_{HI}$.
- 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).
- Some redshift dependence for the metallicities.

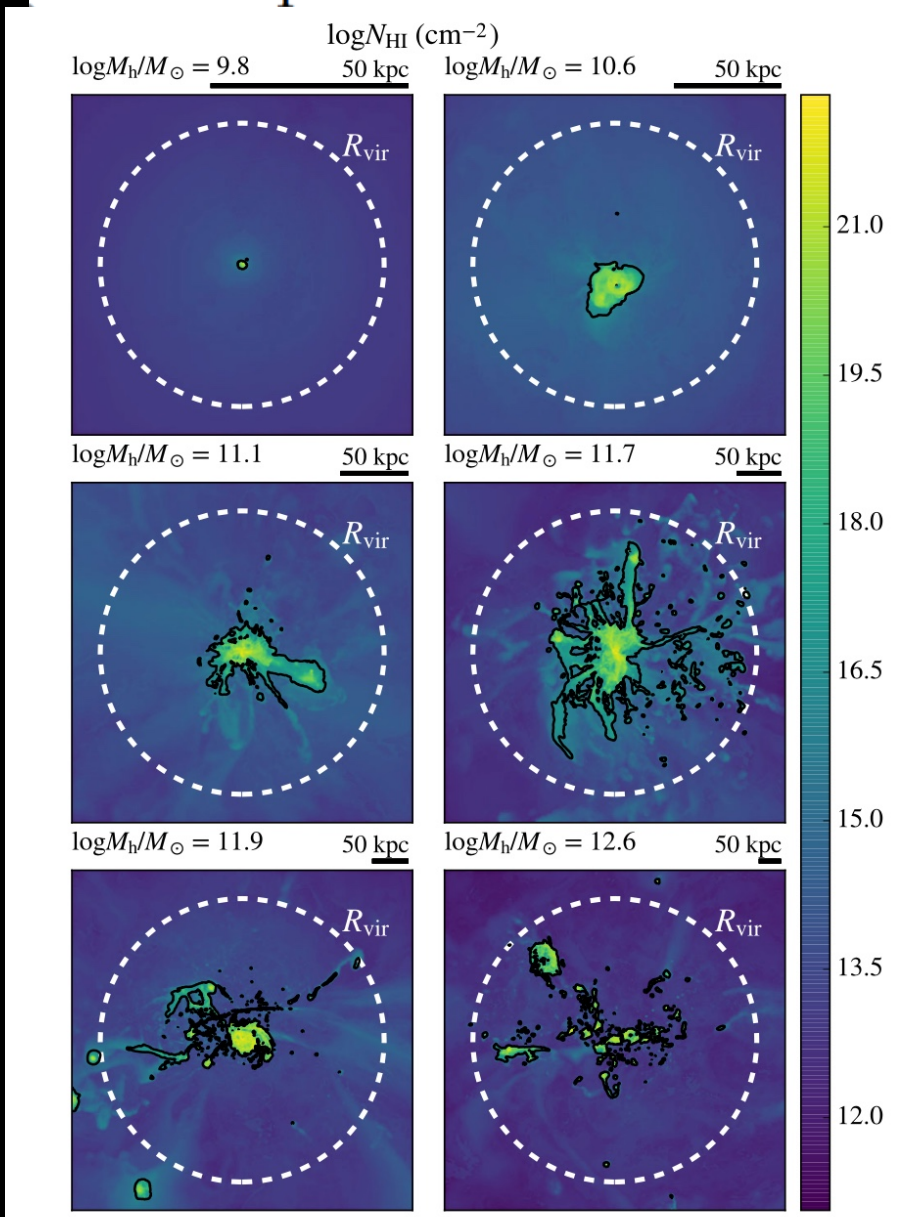
# Observations meet with simulations

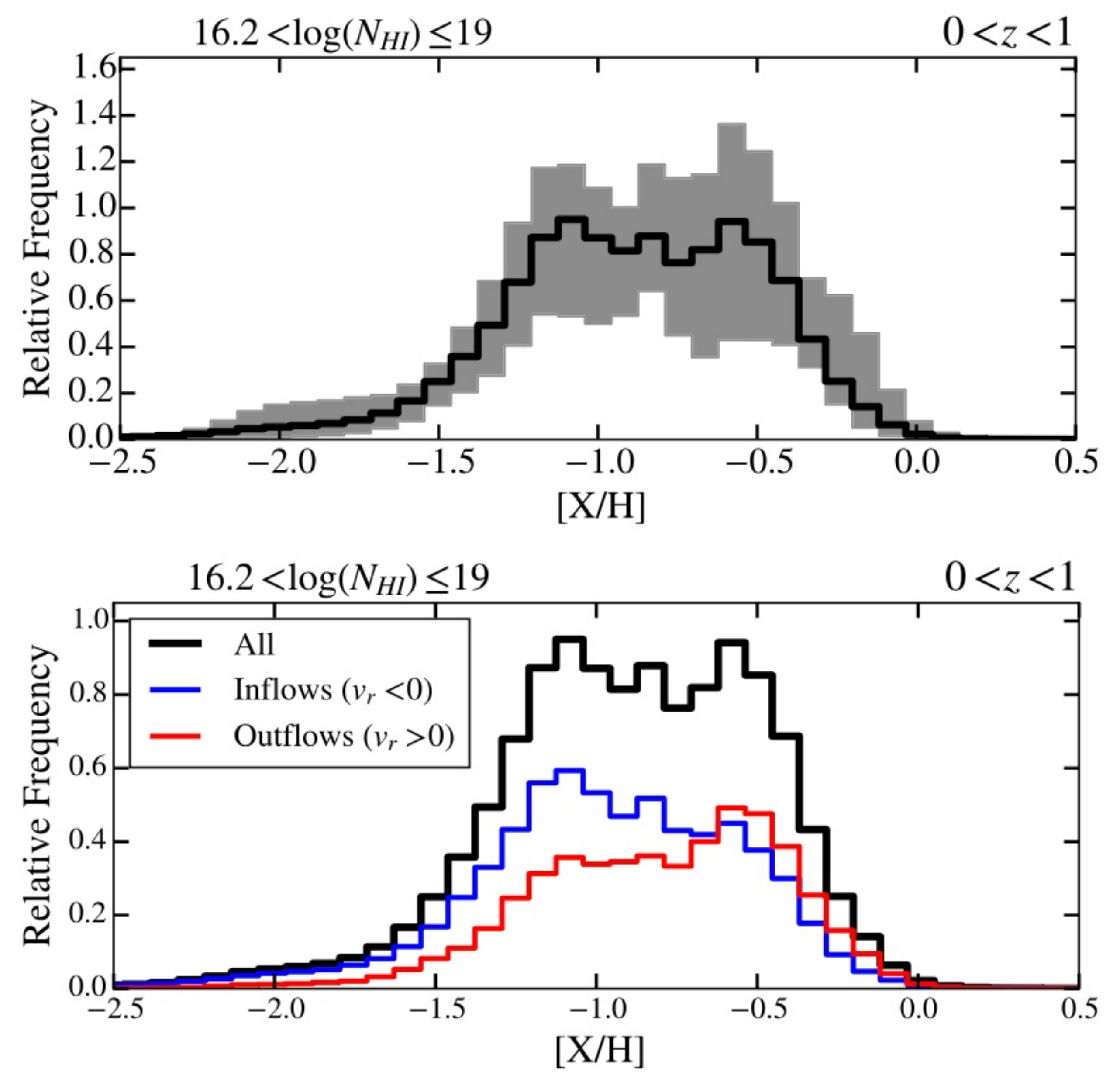
# FIRE Simulations vs. CCC

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

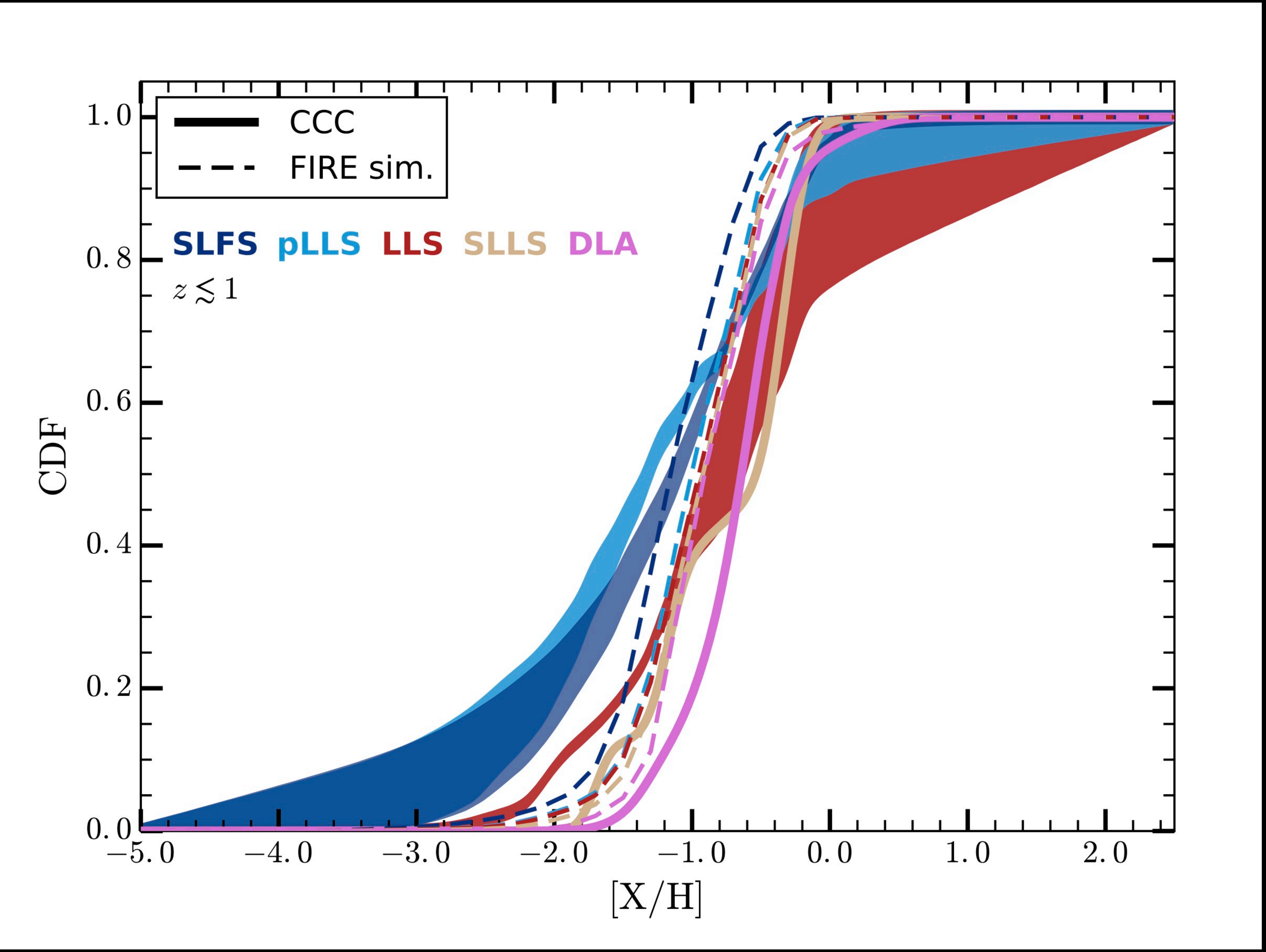
MNRAS, 2017

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]



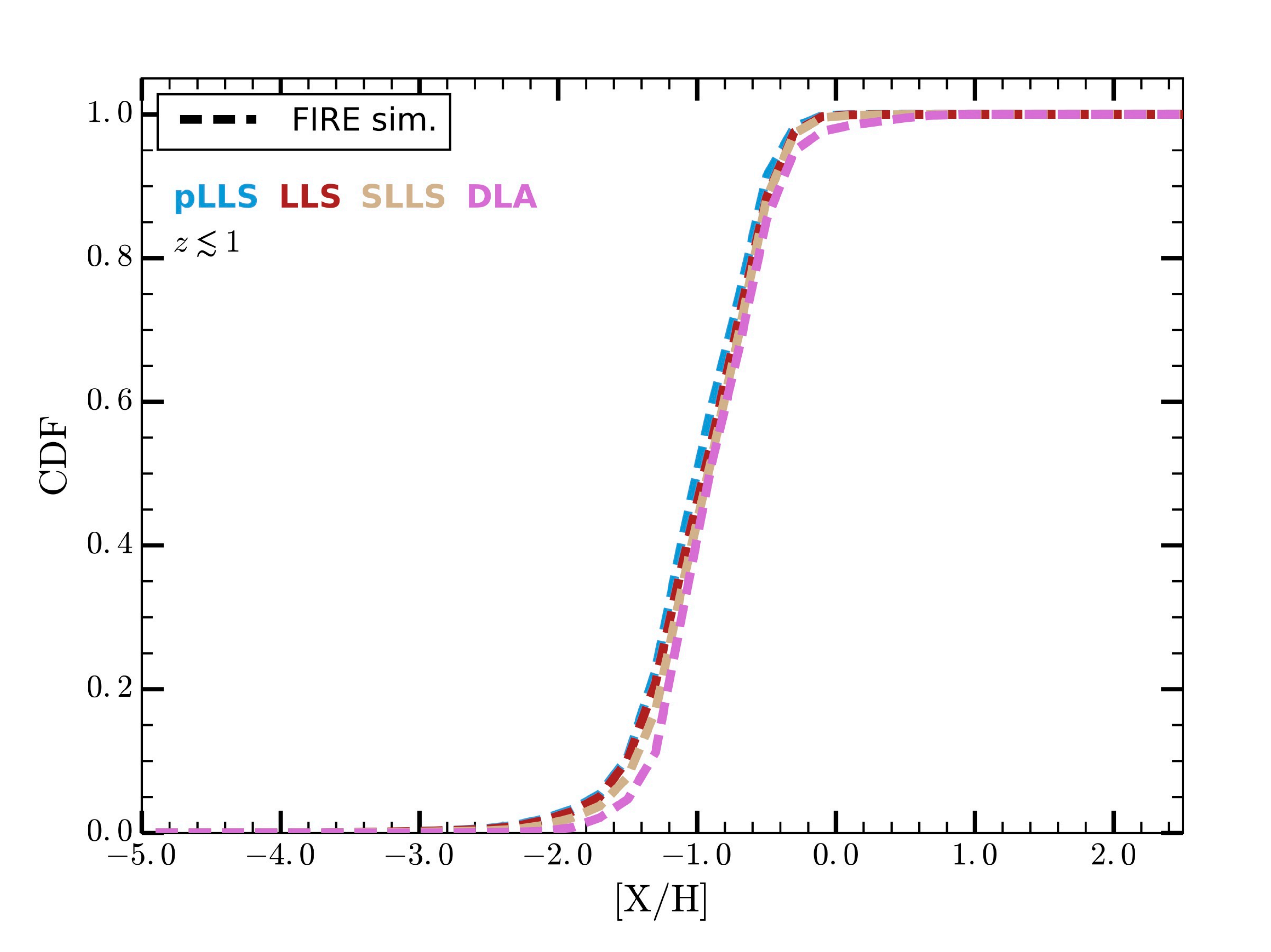



# FIRE Simulations vs. CCC




Lehner+18b, Wotta+18 in prep

# FIRE Simulations vs. CCC




Lehner+18b, Wotta+18 in prep

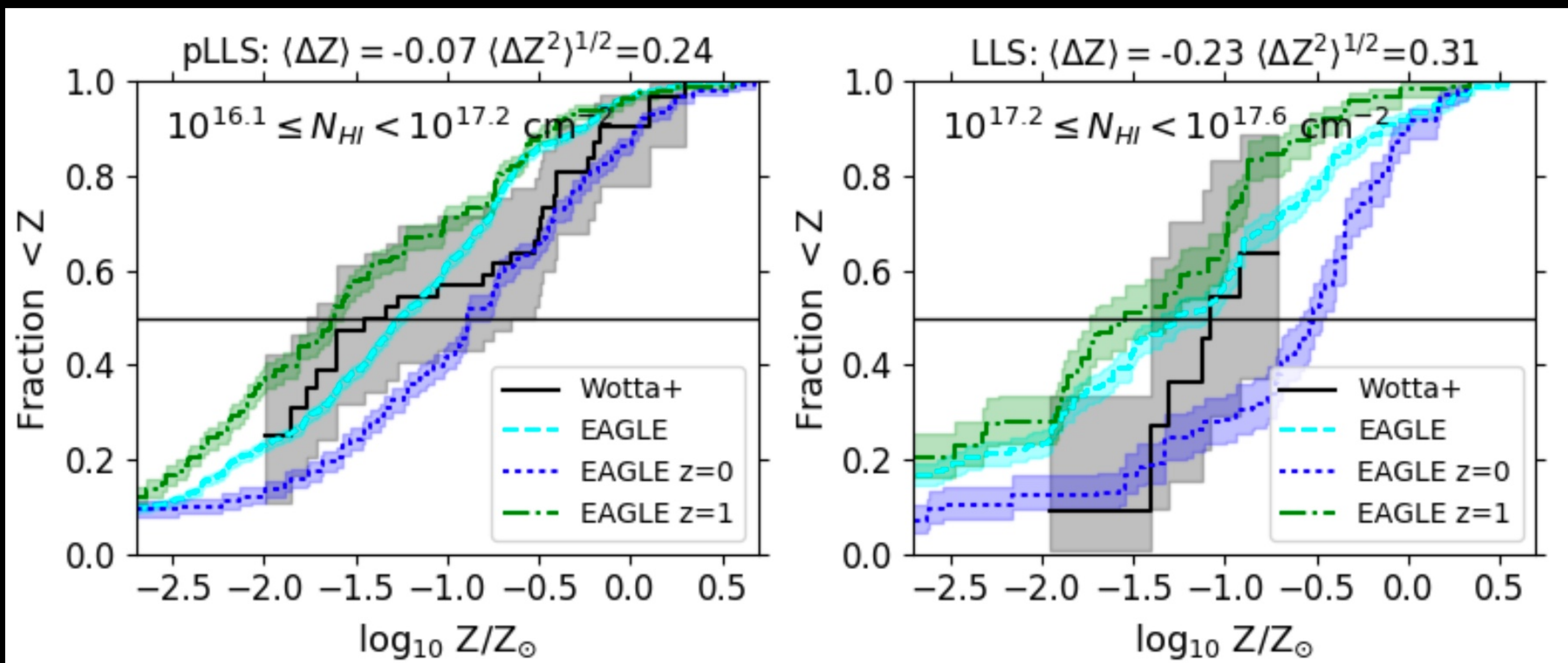
# EAGLE Simulations vs. CCC

**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*



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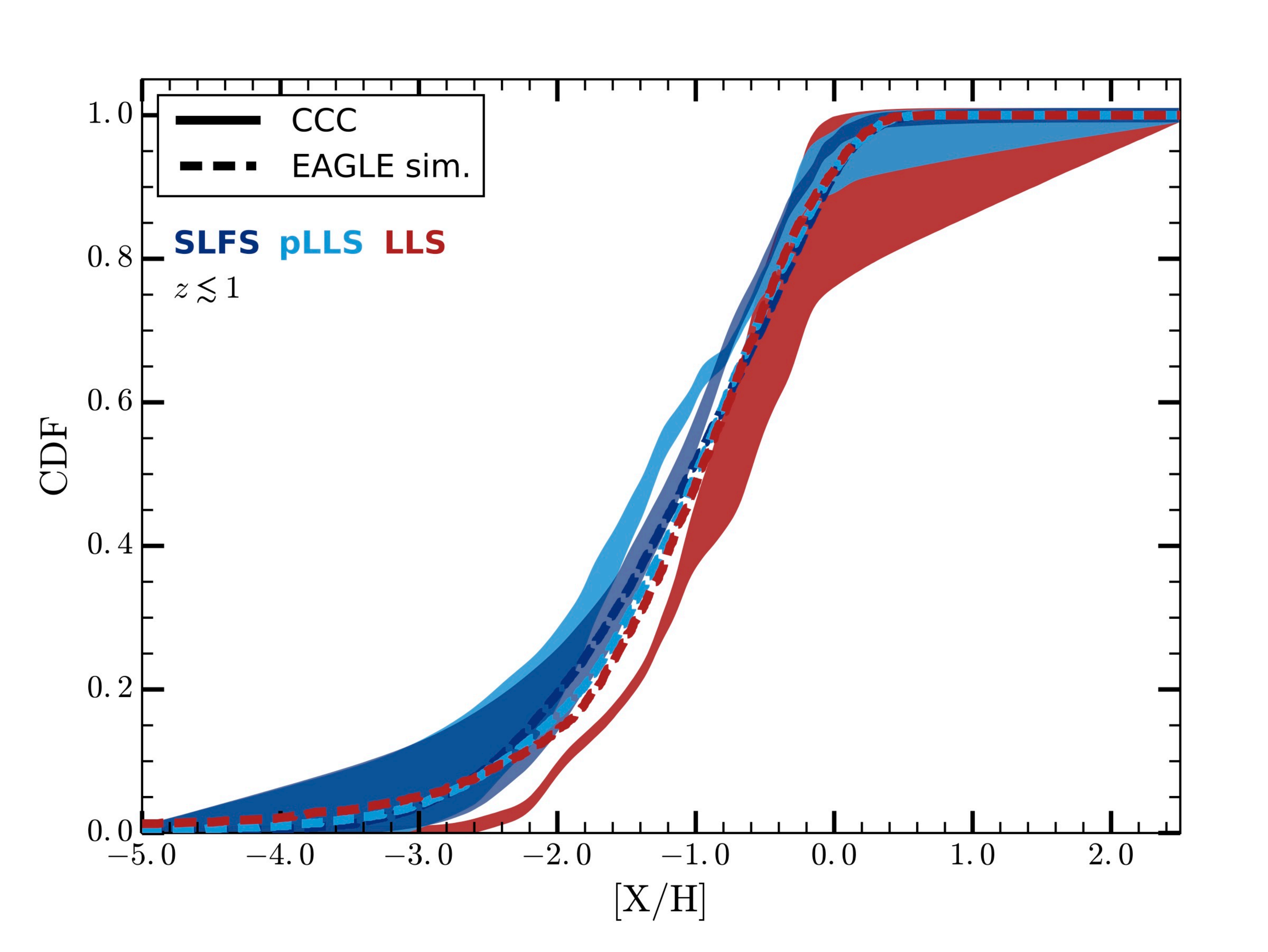
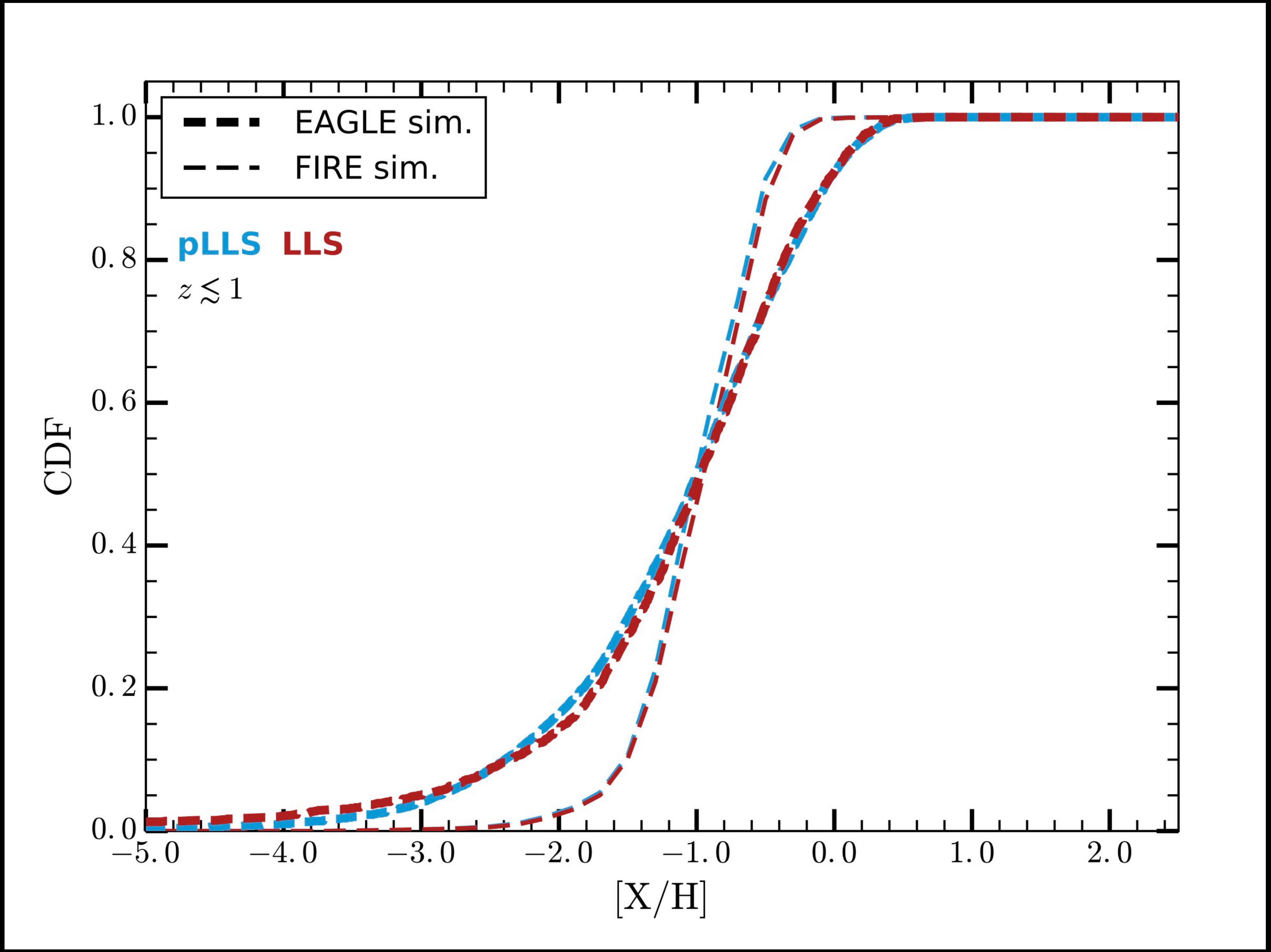
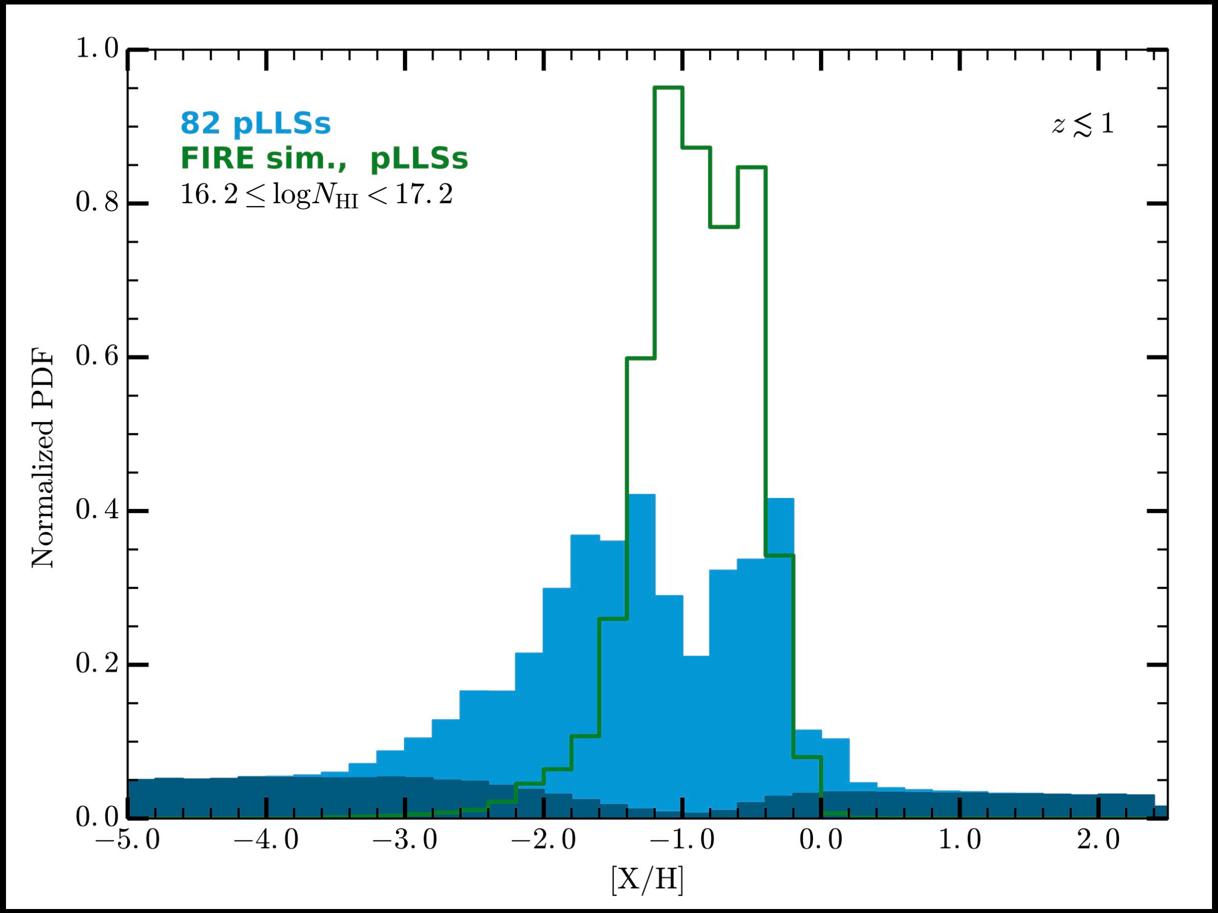
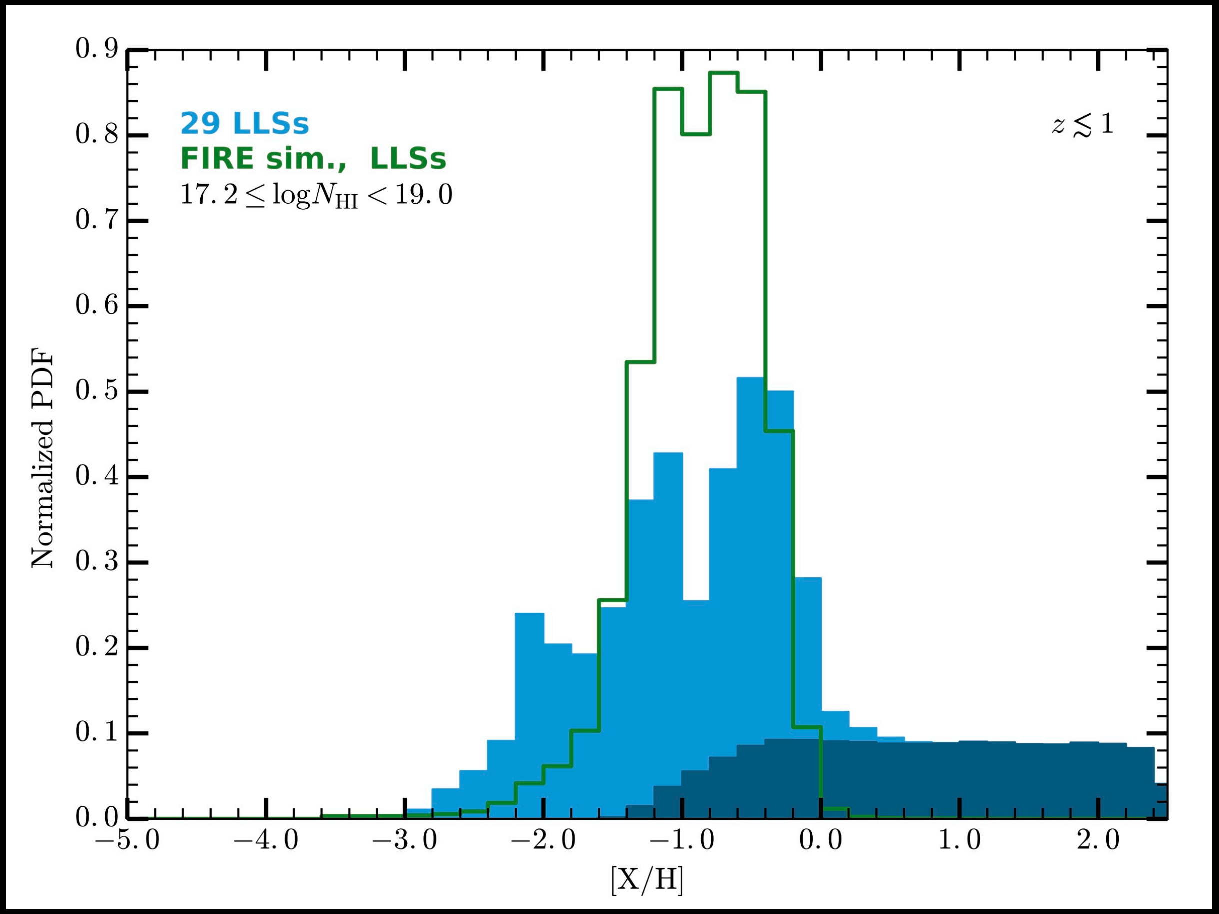


# EAGLE vs. FIRE



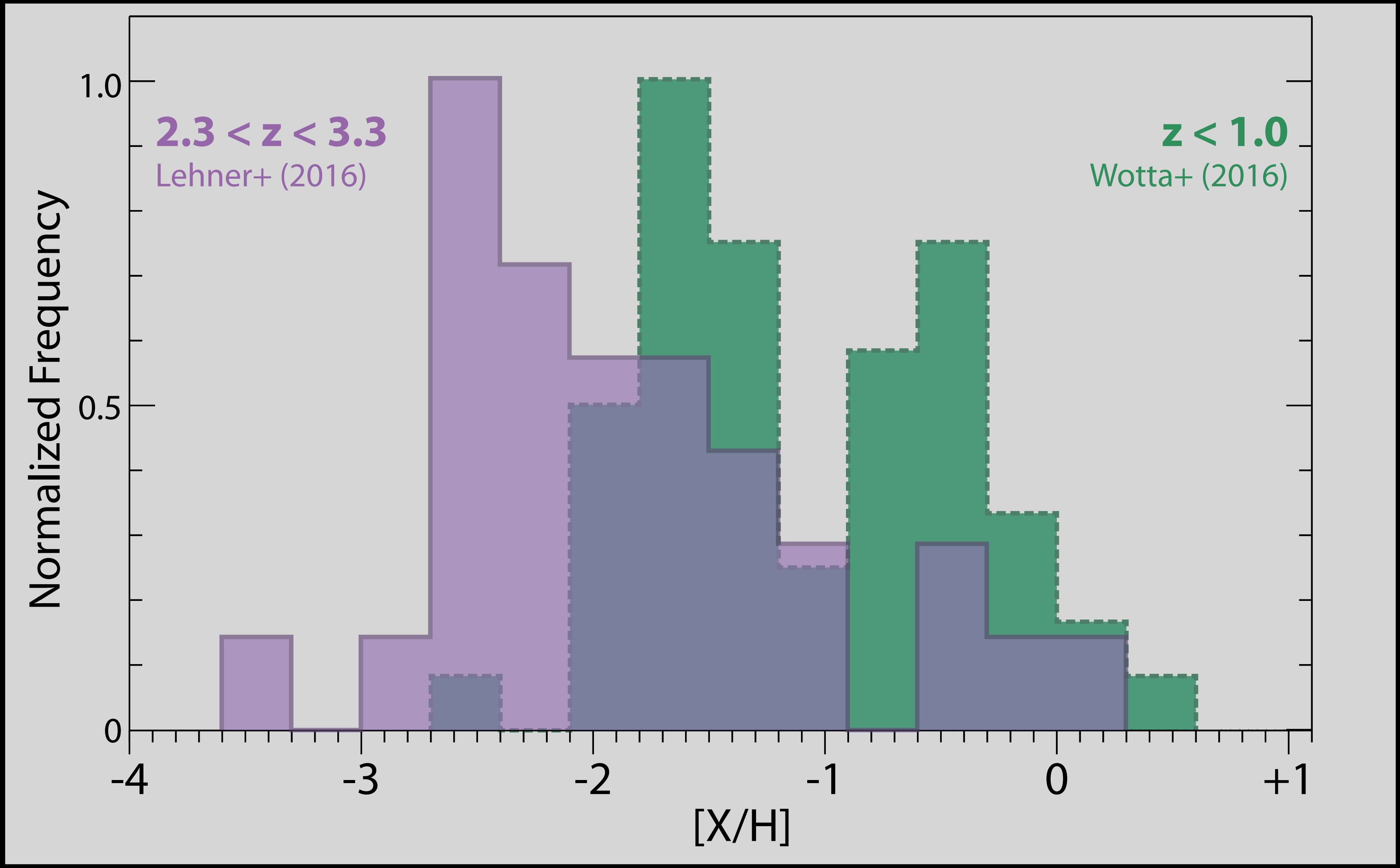
# Summary II



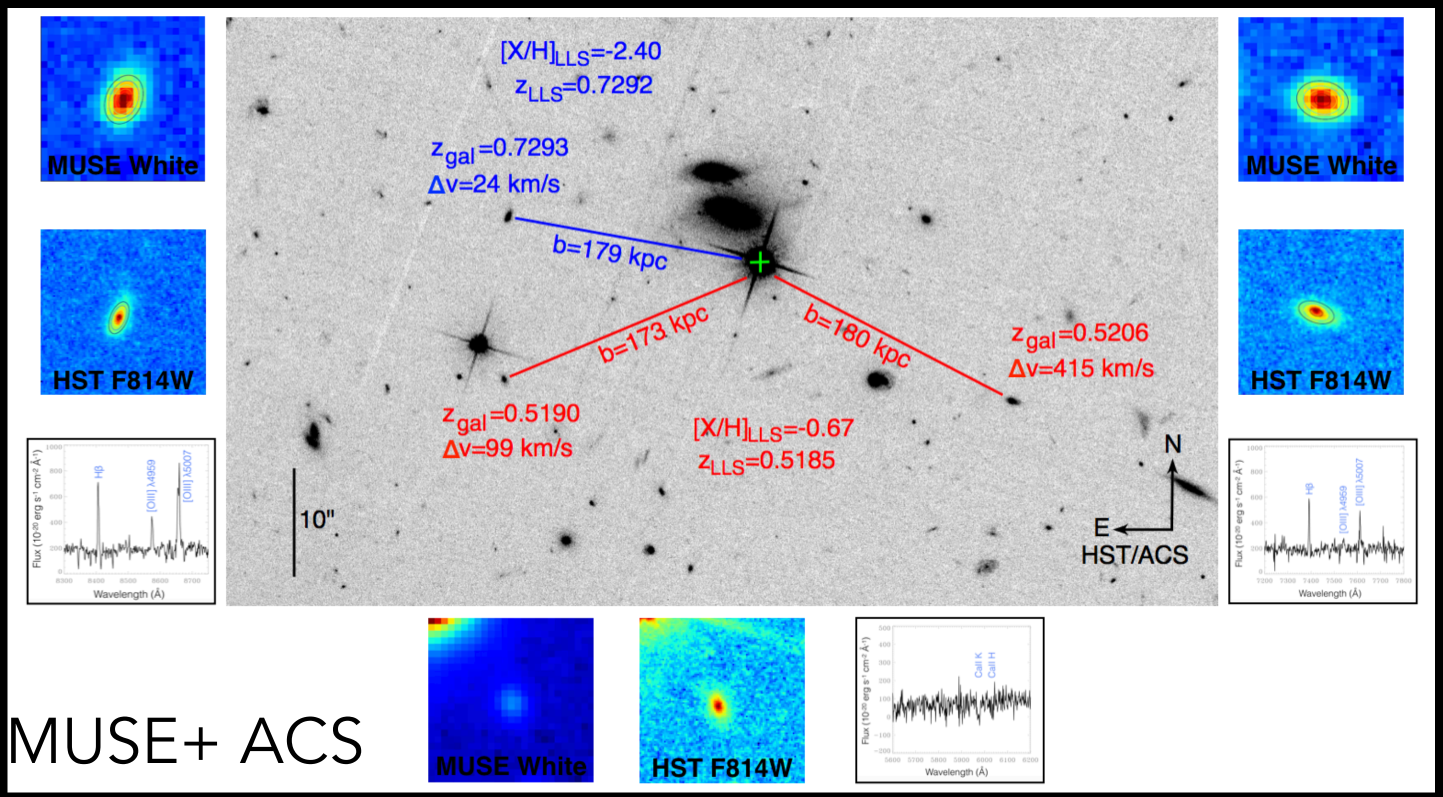

- The FIRE simulations under-predict the amount of low-metallicity gas probed by the 15<log $N_{HI}$<19 absorbers.
- The EAGLE simulations produce a similar fraction of low-metallicity SLFSs, pLLSs, and LLSs. This is driven by a strong evolution of the metallicities of these absorbers between z~0 and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

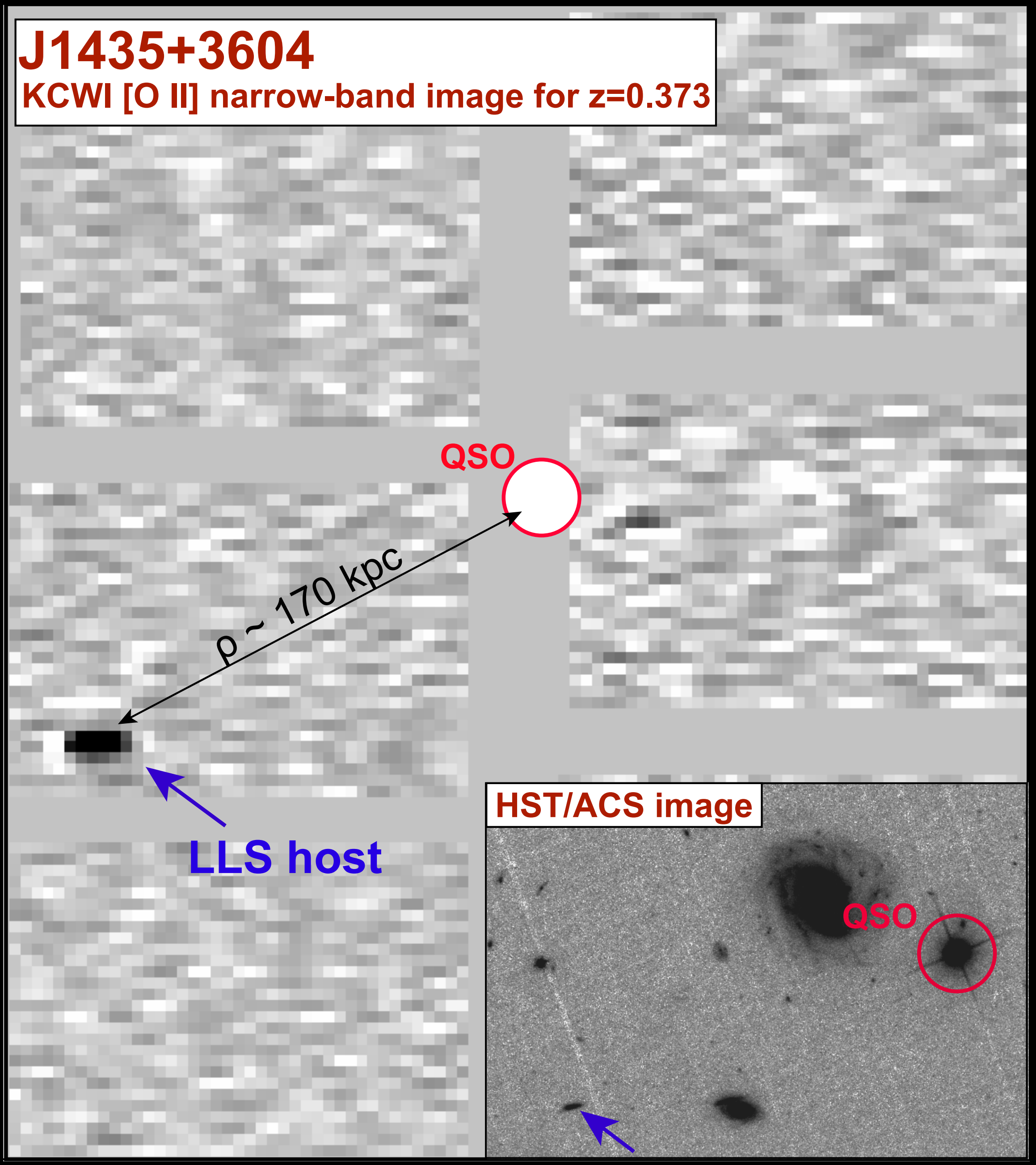
# Evolution of the metallicity with redshift




- Our Large KODIAQ survey is underway.
- 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!*** Thanks to COS, we went from samples that had less than handful of LLSs to samples of 30–60 at $z<1$. We have now a sample of nearly 300 absorbers at $z<1$ and will reach similar size sample $z>2$ in the near future with our KODIAQ database.

- With large surveys of CGM absorbers combined with MUSE & KCWI observations of their environments, we will have the 2nd CGM revolution.