Linking Galaxy Formation with Cosmic Reionization
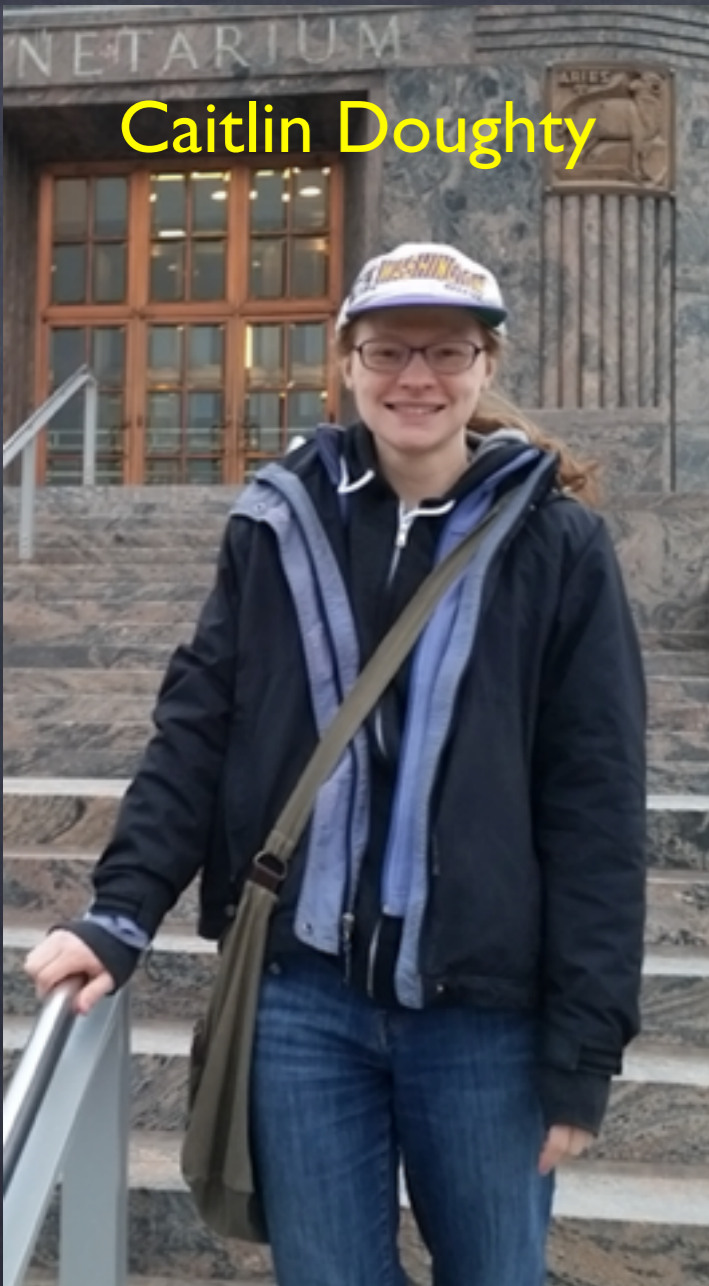
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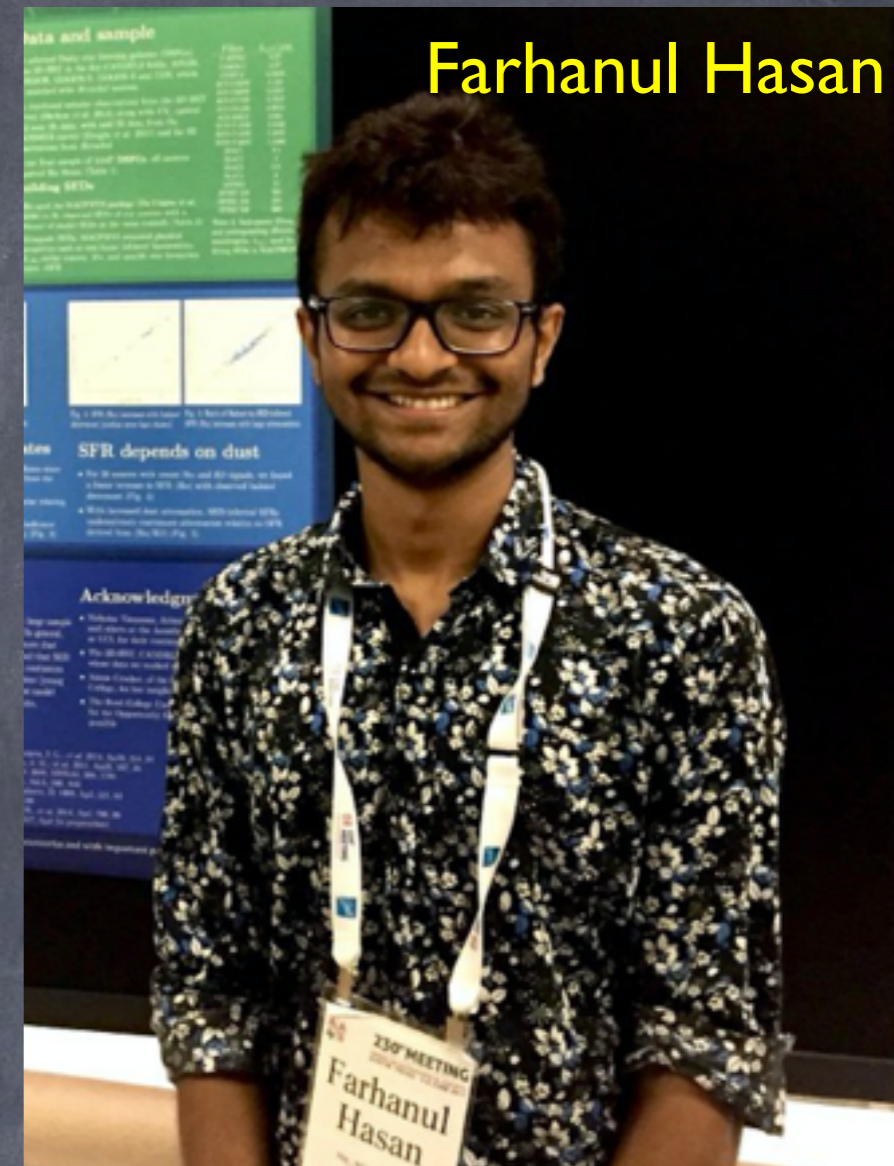
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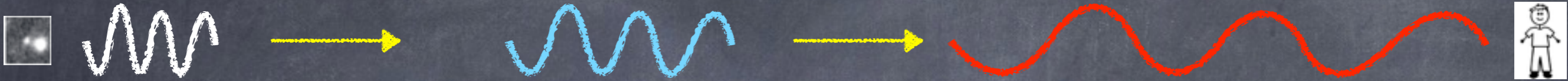
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Background: Cosmological Redshift and Time

Redshift (z): As the Universe expands, the wavelength of light that traverses it expands at the same rate. When cosmologists measure the factor by which a source's light has expanded in wavelength, then they are *also* measuring how much the Universe has expanded since the light was emitted. If we know how rapidly the Universe was expanding at different times, then we can compute how old the Universe was when the light was emitted. High redshift = early times.
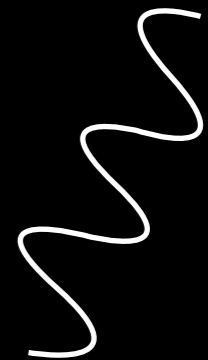
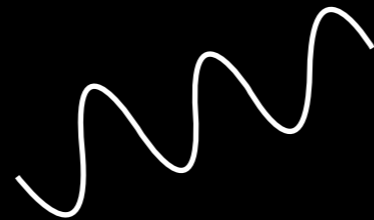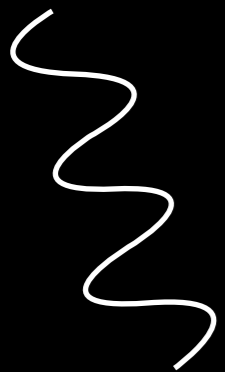$$1 + z \equiv \frac{\lambda(observed)}{\lambda(emitted)}$$

z	t/Gyr	
10	0.47	reionization starts
5.5	1.0	reionization ends
3	2.1	
2	3.2	cosmic Noon
0.4	9.4	Sun forms
0	13.8	today

CDM: 300 kyr < t < 50 Myr (z > 50)
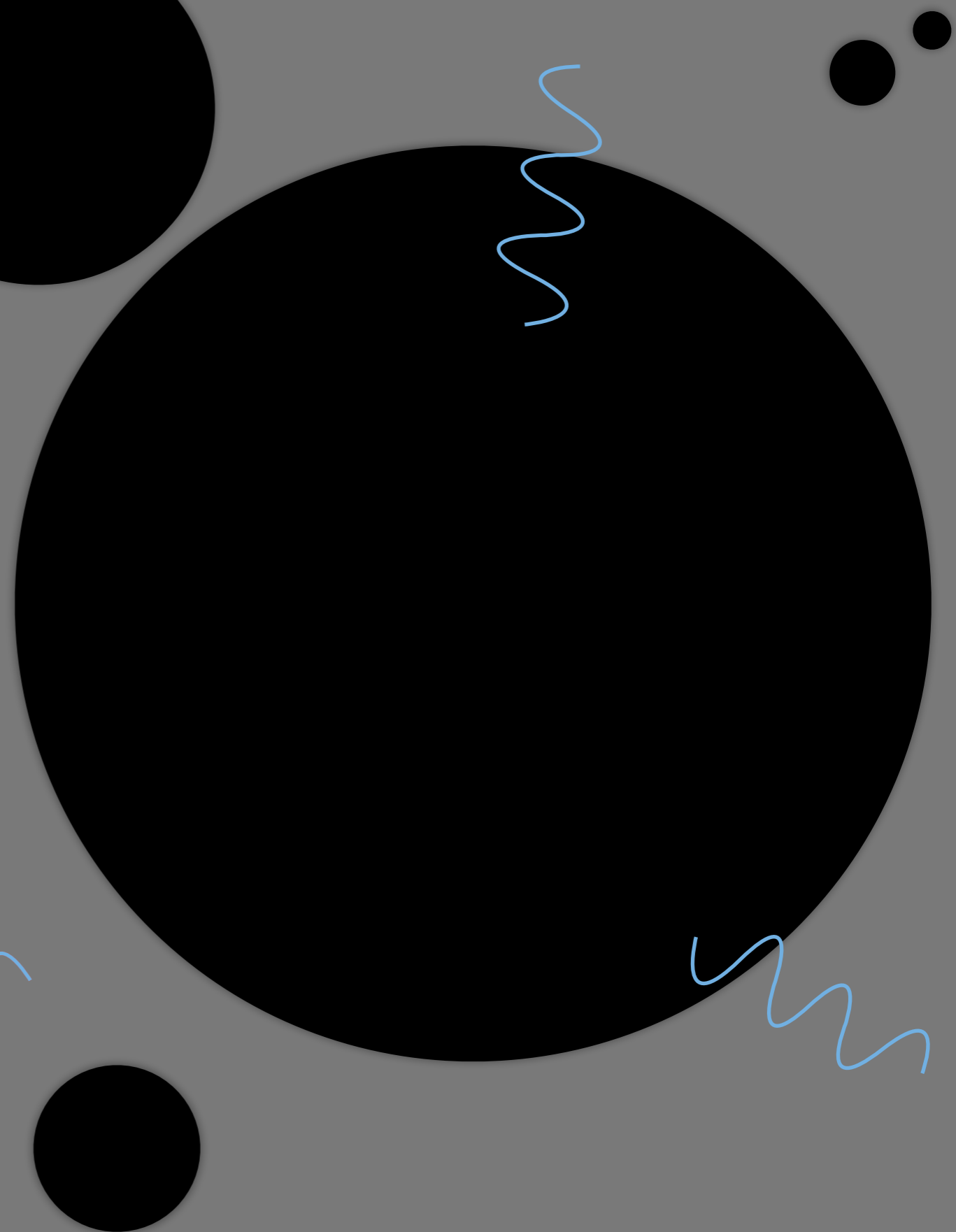
Uniform (to 10^{-5}) mixture of dark matter, neutral "baryons" (non-dark matter), and cosmic background radiation

Dark matter "curdles" under gravity into energetically bound dark matter halos of many sizes. Small halos merge to form bigger halos. Universe's still-neutral matter becomes increasingly inhomogeneous.

The gas within large dark matter halos cools and collapses to form galaxies. Their stars emit UV light that ionizes and heats the Universe. "This is the last time that the average hydrogen atom did anything interesting." (J. Rhoads) Universe is now a plasma. (This phase includes the epoch probed by EDGES; Bowman+2018)
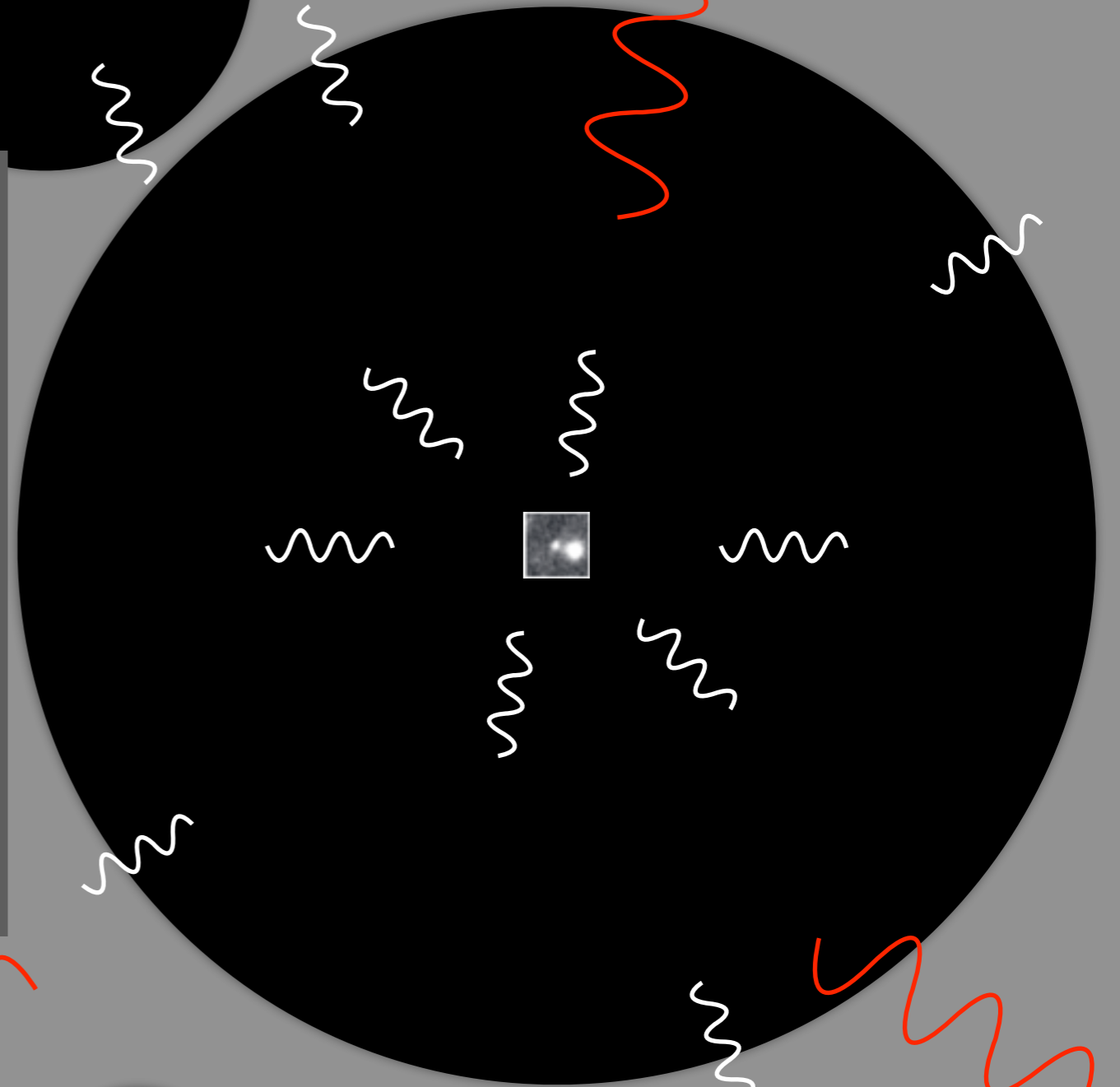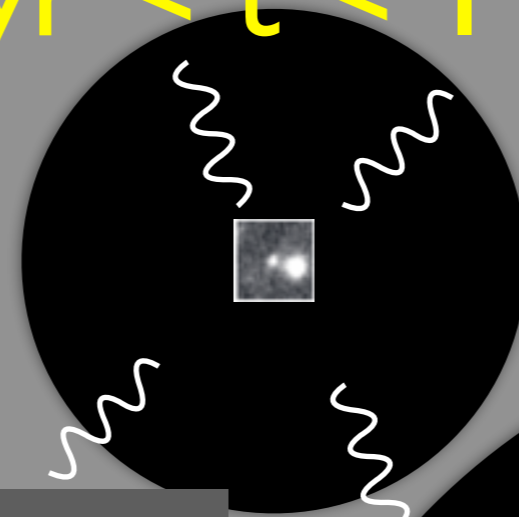
CDM: 300 Myr < *t* < 1 Gyr (25 > z > 5)

IGM

IGM

IGM

CGM

IGM

ISM
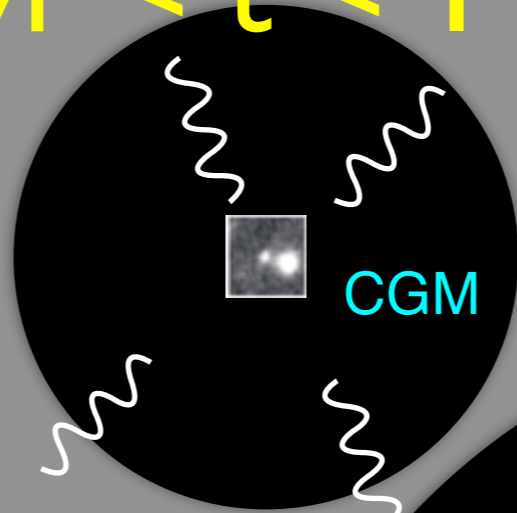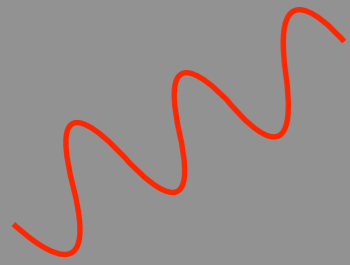
CGM

There are now three phases for baryonic matter and two sources of light:
• matter: ISM, CGM, IGM
• light: CMB, UVB
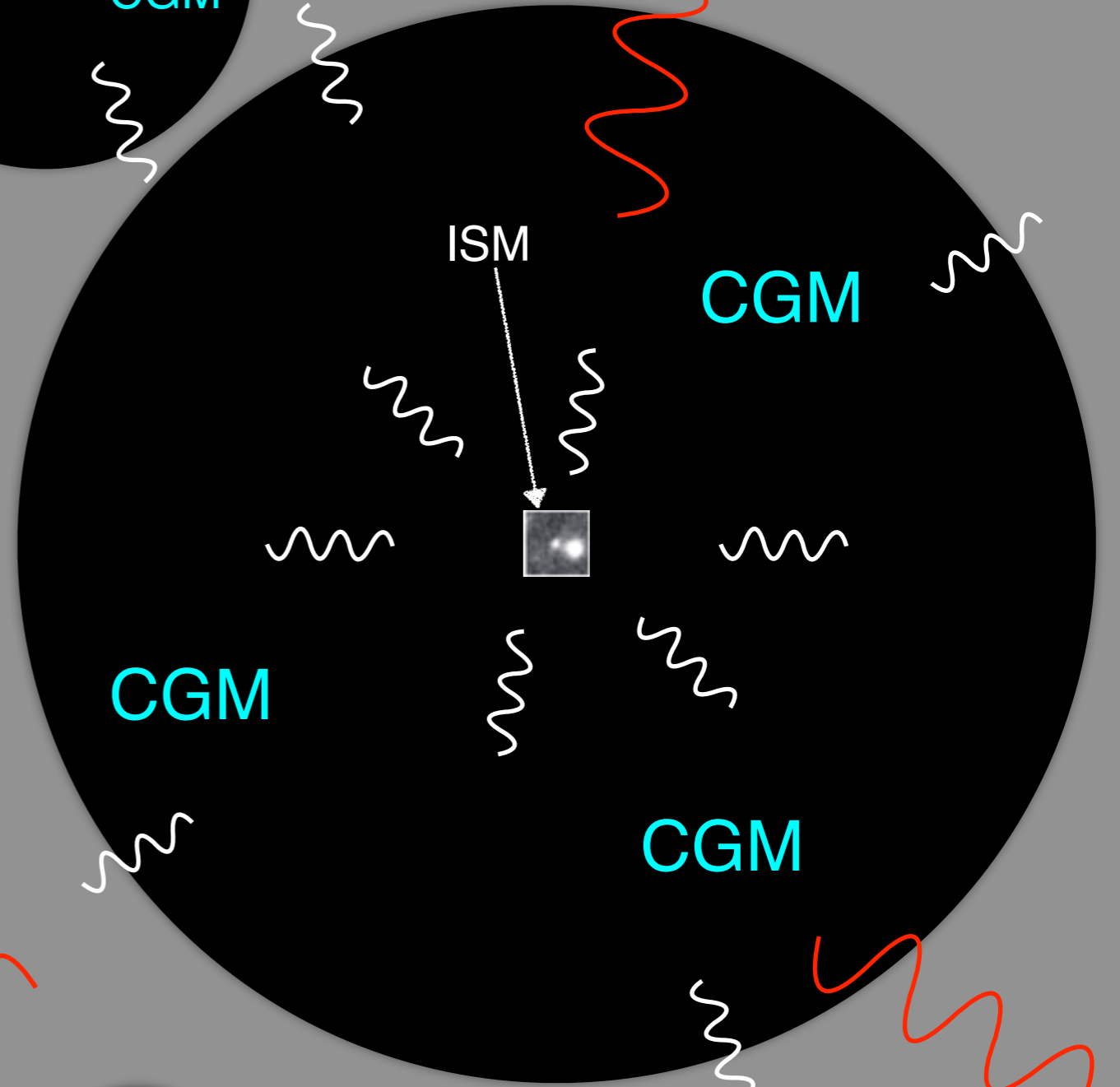
CGM

CGM

IGM
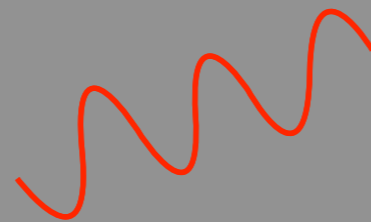
IGM
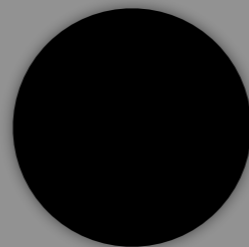
IGM

Magnitudes and Parsecs

Apparent Magnitude

- Lower # = brighter object
- introduced by Hipparchus to classify stars by brightness.
- Vega = 0
- Jupiter & Mars = -3
- faintest thing an 8-meter ground-based telescope can see = 27

Absolute Magnitude

- what an object's apparent magnitude *would be* if it were a point-source 10 parsecs away
- Milky Way: -21
- HST limit @ z=6: -17
- JWST limit @ z=6: -15

Parsec

- "parallax-second"
- distance of a star that appears to wobble annually by 1 3600th of a degree on the sky owing to Earth's orbital motion
- 1 pc $\simeq$ 3.18 light-years
- distance btw neighboring stars in galaxies ~ a few pc
- distance btw neighboring bright galaxies ~ a few Mpc

IGM

IGM

Vocabulary List
redshift (z)
dark matter halo
interstellar medium (ISM)
circumgalactic medium (CGM)
intergalactic medium (IGM)
HI, HII: atoms and protons
AGN = QSO = quasar
reionization
magnitude
pc (also kpc, Mpc, Gpc)
CMB
metal = !(H || He || Li)
UVB = UV background from stars + QSOs;
it is what drives reionization

ISM

CGM

M

CGM
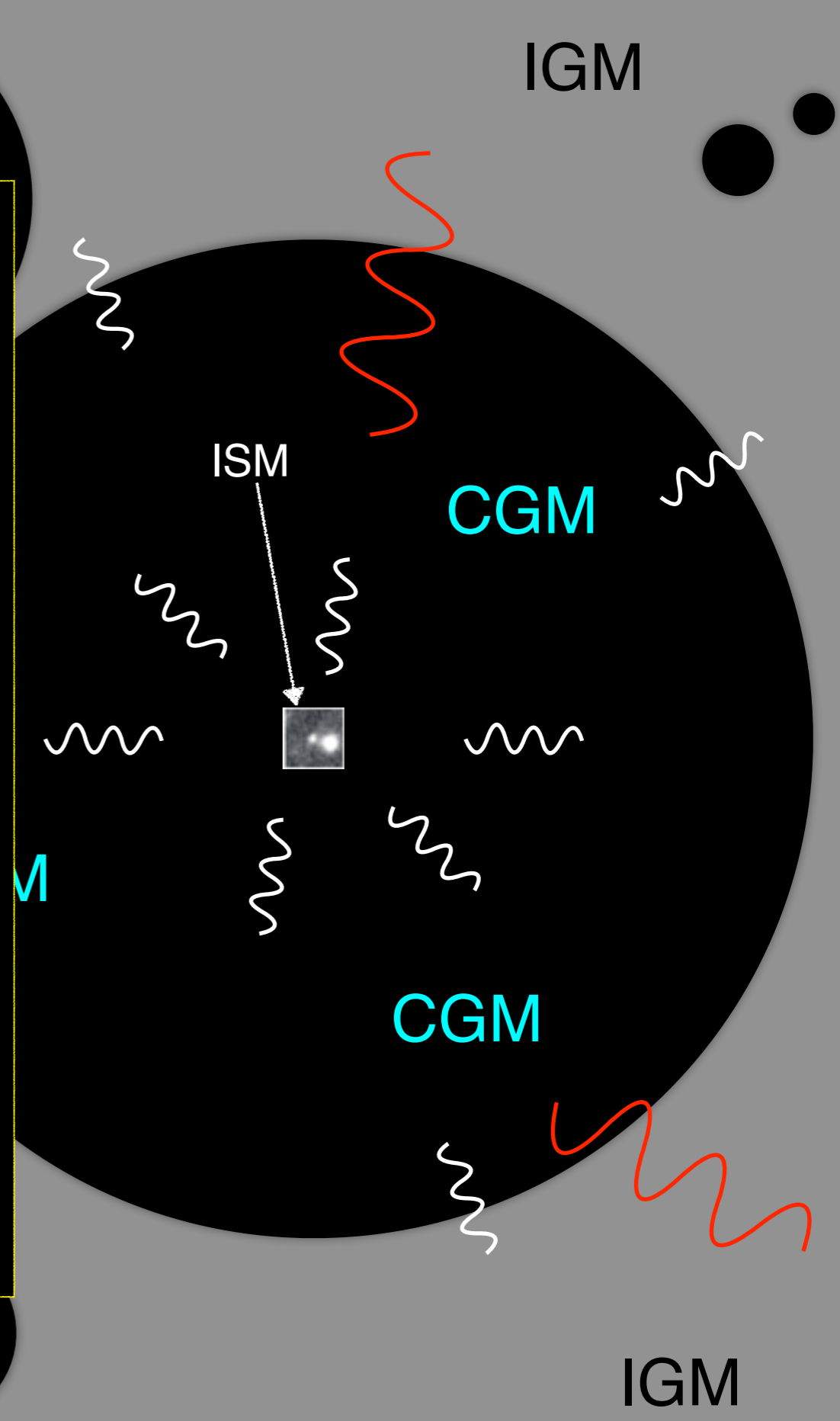
IGM

IGM

My Tool: Cosmological Simulations

Model structure formation and reionization numerically, then compare predictions versus observations.

Strengths:
• accounts realistically for many processes on scales > 100 pc
• enables many complementary observational tests
• pretty movies

Weaknesses:
• computationally expensive
• dynamic range limitations:
  • miss large, rare things
  • miss small-scale processes (like what E. Scannapieco works on)

$z = 12.0$

$\log_{10}(N_{HI})$ [cm^{-2}]

19

17

15

HI column density

$\log_{10}(T)$ [K]

5.0

4.5

4.0

Temperature

18 comoving Mpc
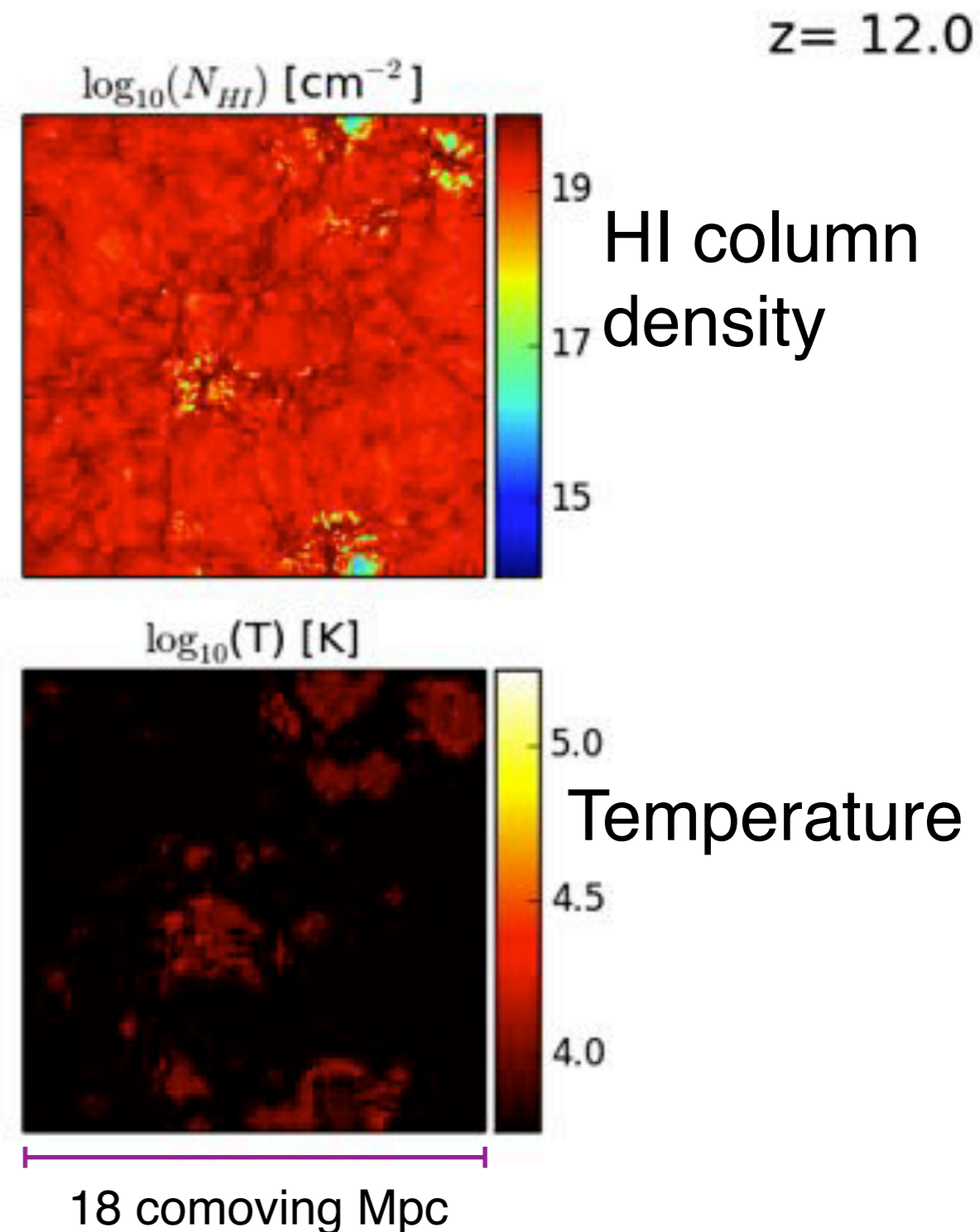
Broad Questions

(1) How did galaxies form stars during the first billion years?
(2) How did early galaxies enrich and irradiate their environments?
(3) How does the circumgalactic medium (CGM) respond to reionization?

Broad Question 1: How did galaxies form stars during the first billion years?

Narrower Question: What was the minimum mass of dark matter halo in which galaxy formation proceeded efficiently?

?

?

?

(1) Minimum Halo Mass for Galaxies
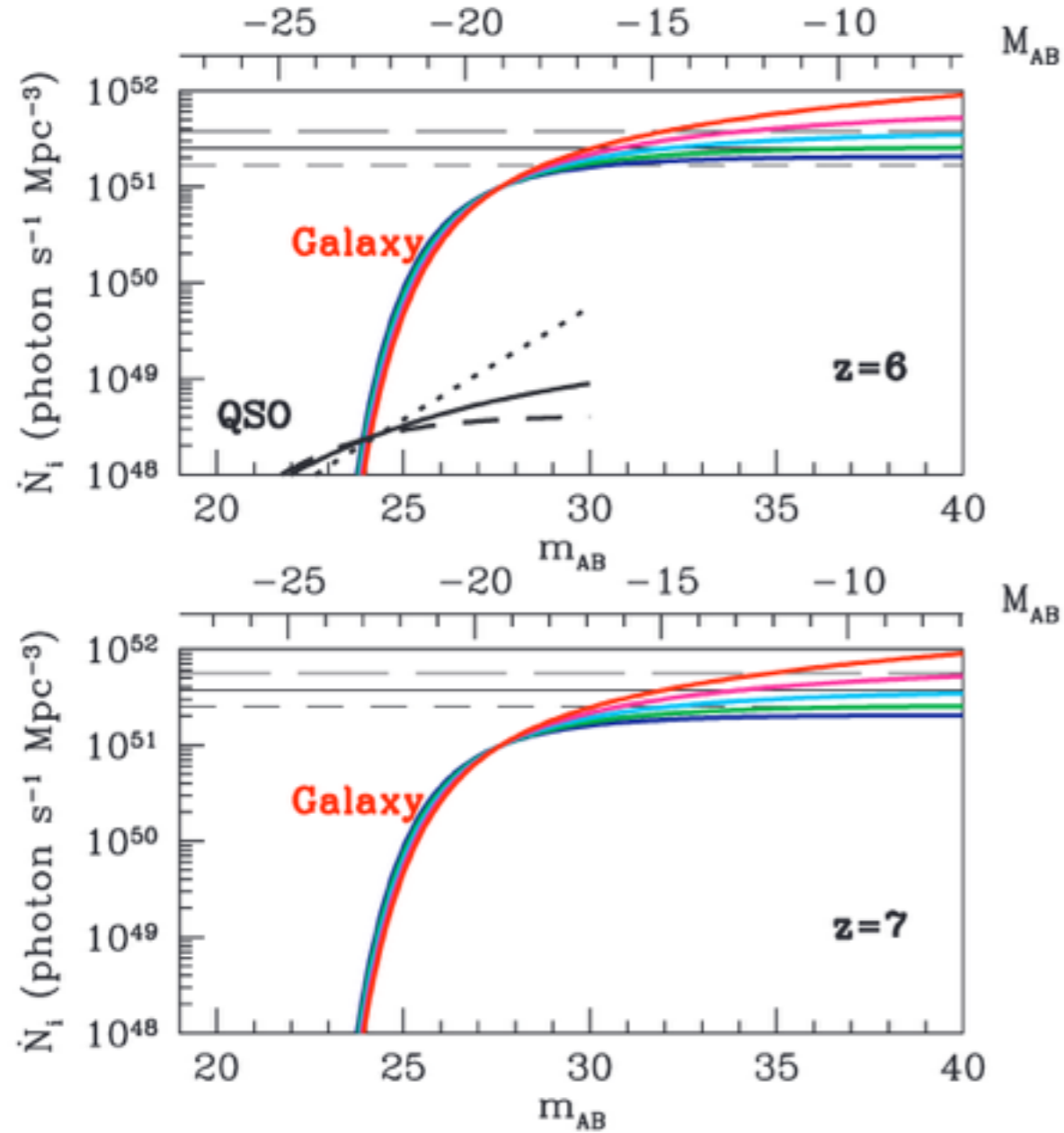
Observational motivation: in order for galaxies to drive HI reionization, there must be many faint ones. To have many faint galaxies, low-mass halos must have been efficient at forming stars.

(1) Minimum Halo Mass for Galaxies

Theoretical Motivation:

Models for galaxy formation were being proposed in which galaxy formation was suppressed in halo masses below an *assumed* minimum:

- 10^9 M_0: Iliev+2007; Mesinger+2008; Alvarez+2012
- 10^{10} M_0: Krumholz & Dekel 2012; Kuhlen+2012
- 10^{11} M_0: Bouché+2010
- *variable*: Finkelstein+2019

Do observations constrain this minimum?

(1) Minimum Halo Mass for Galaxies

KF, MKM Prescott, et al. 2016 (data: Livermore+2016)
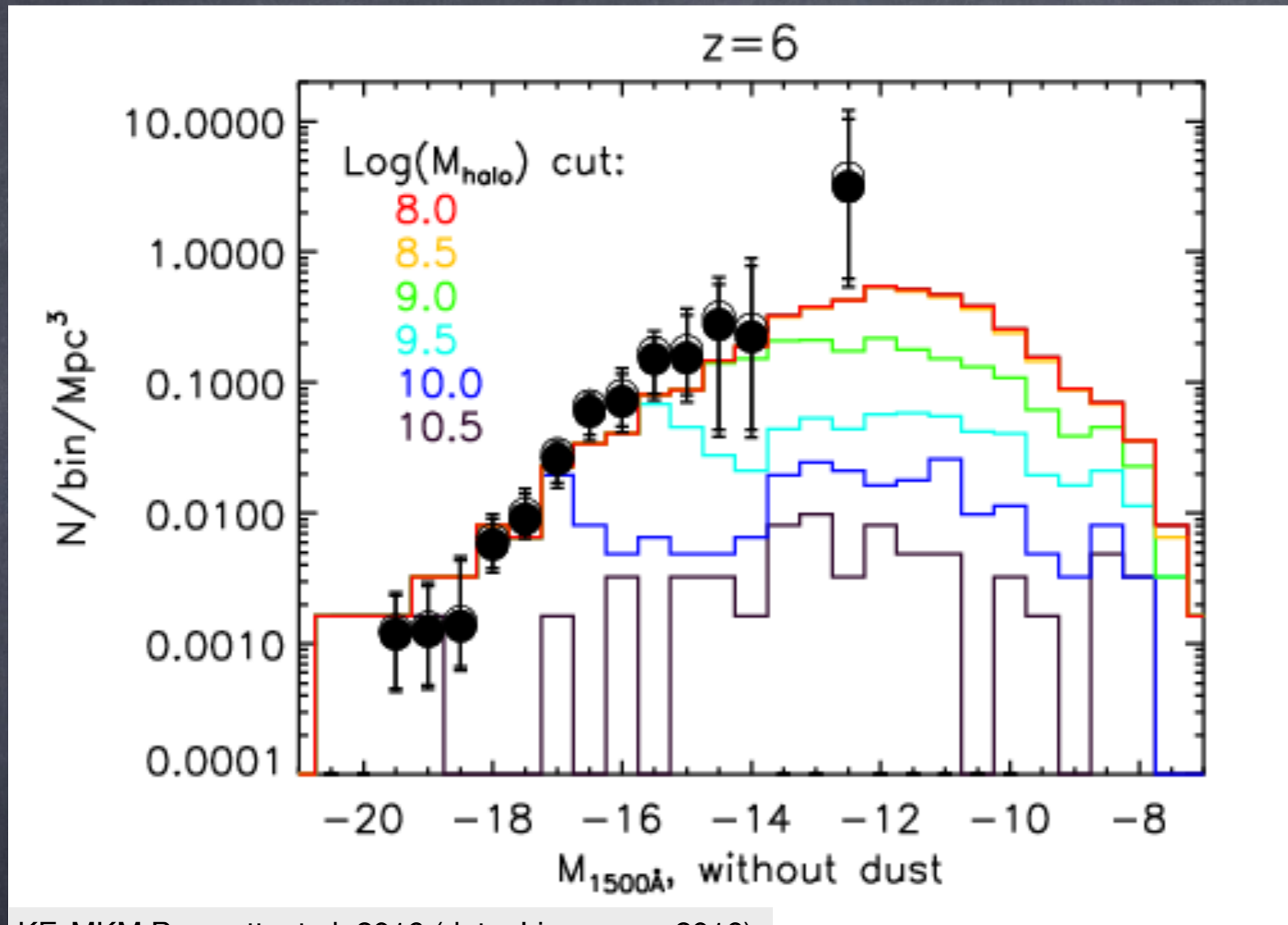
By throwing out galaxies in successively larger halos, we introduce successively larger conflict with observations. At what halo mass is the conflict significant?

(I) Minimum Halo Mass for Galaxies
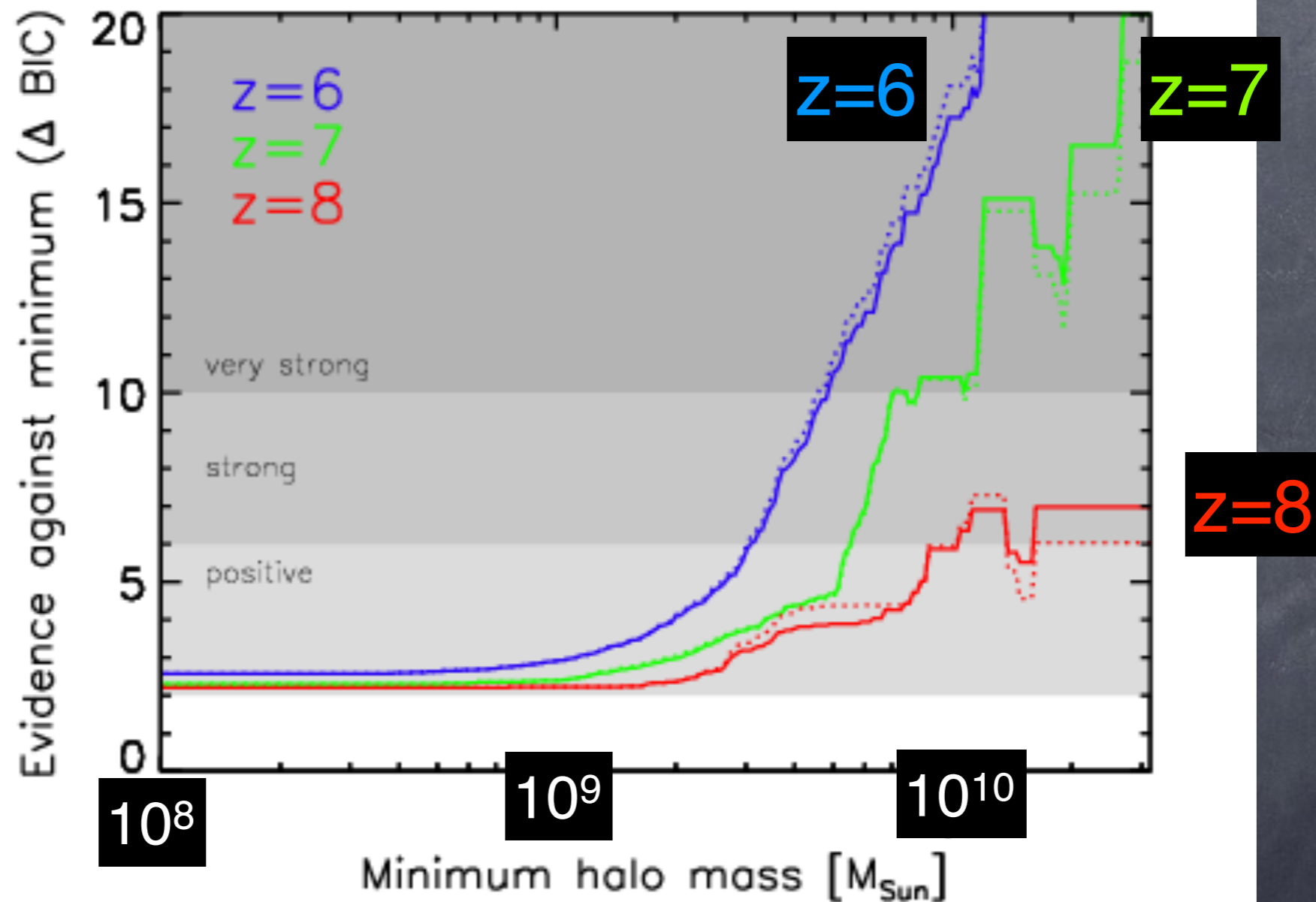
KF, MKM Prescott, et al. 2016 (data: Livermore+2016)

Models in which the minimum halo mass for galaxy formation is $> 2 \times 10^9$ M$_0$ are ruled out at $z = 6$.

Broad Question 11: How did early galaxies enrich their environments with metals?

Narrower Question: How does the observed line incidence of CIV absorbers constrain feedback models?

KF+2015

(2) Incidence of CIV absorbers

A1689-zD1; Watson+2015
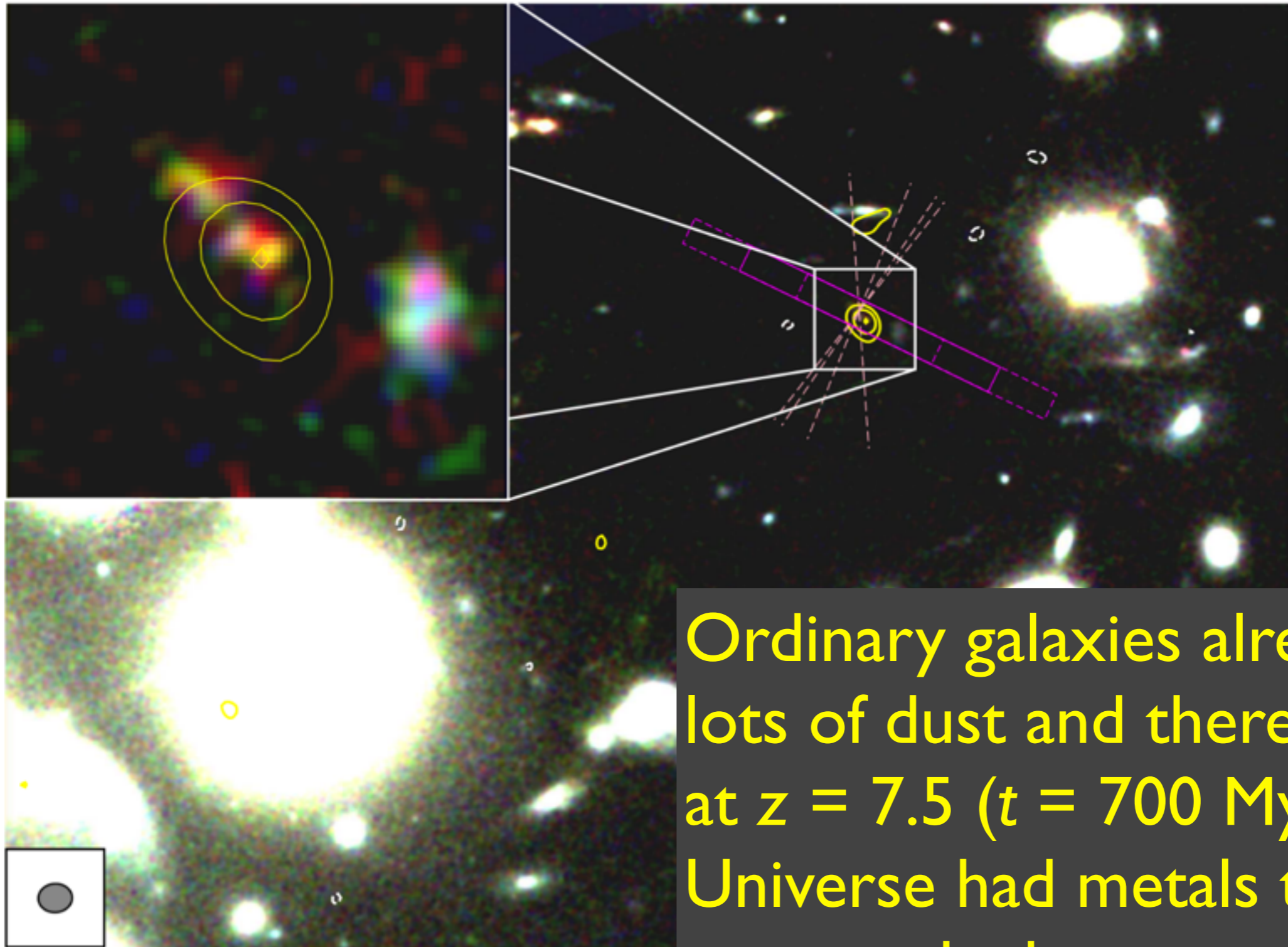
Ordinary galaxies already had lots of dust and therefore metals at $z = 7.5$ ($t = 700$ Myr). So the Universe had metals then. How many and where were they?

(2) Incidence of CIV absorbers

KF+2015
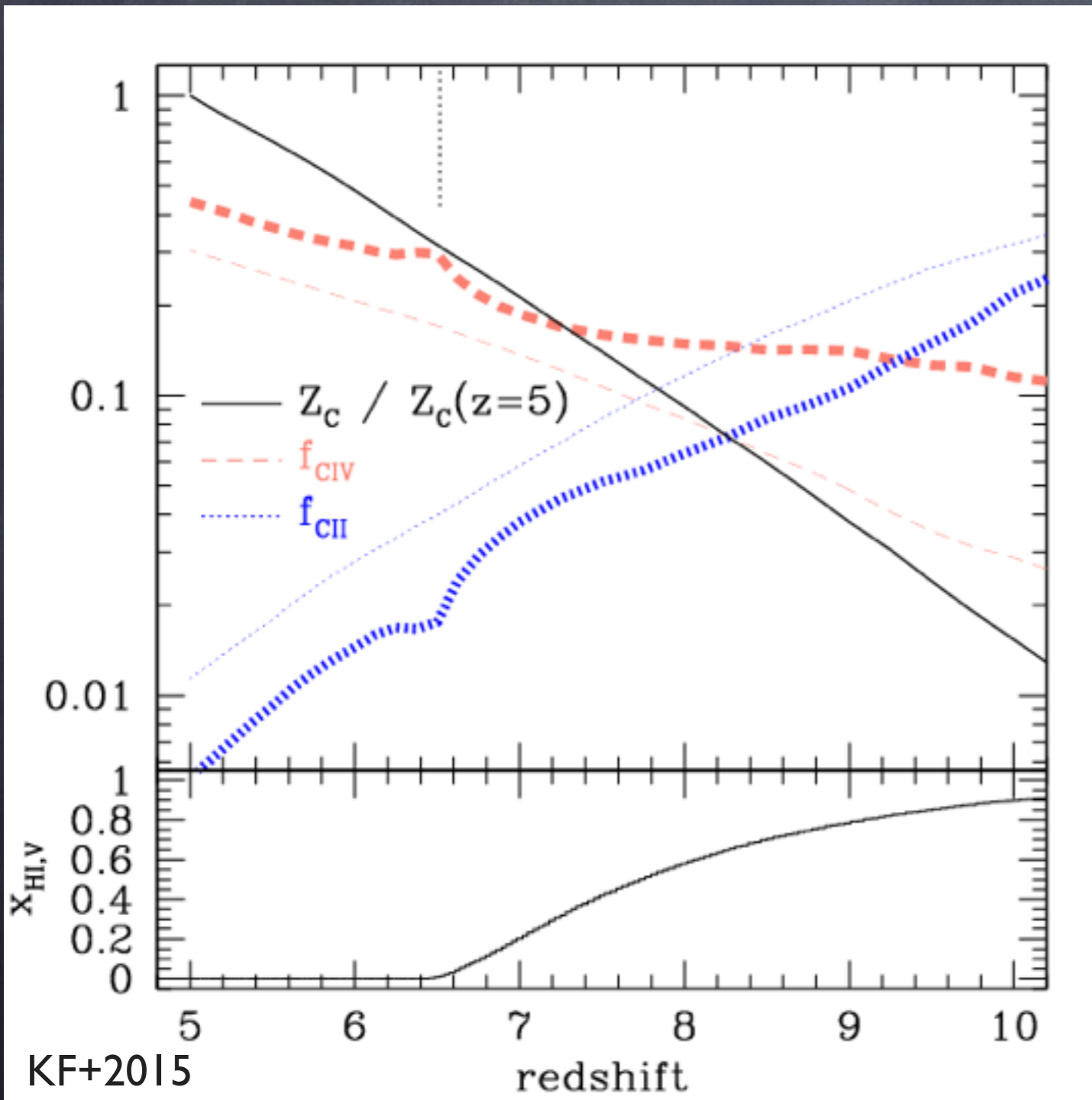
time

The black curve shows that the carbon mass fraction in the IGM is predicted to grow steadily as new stars eject new metals out of galaxies.

How can we test this?

Metal Absorber: traces overdense gas associated with galaxies where metallicity, density, and the UVB all fluctuate strongly on small scales.

Lyman-α Forest: traces filamentary gas that is far from galaxies; its properties fluctuate gently.

CIV ("carbon 4"): carbon atoms that are missing three of their electrons. Very easy to see in absorption.

(Lyman-α forest)

CIV

B
weak absorber

A
strong absorber

B

A

Lyman−α

(unabsorbed continuum)

1
0.8
0.6
0.4
0.2
0

1
0.8
0.6
0.4
0.2
0

−500   0   500

velocity [km s⁻¹]
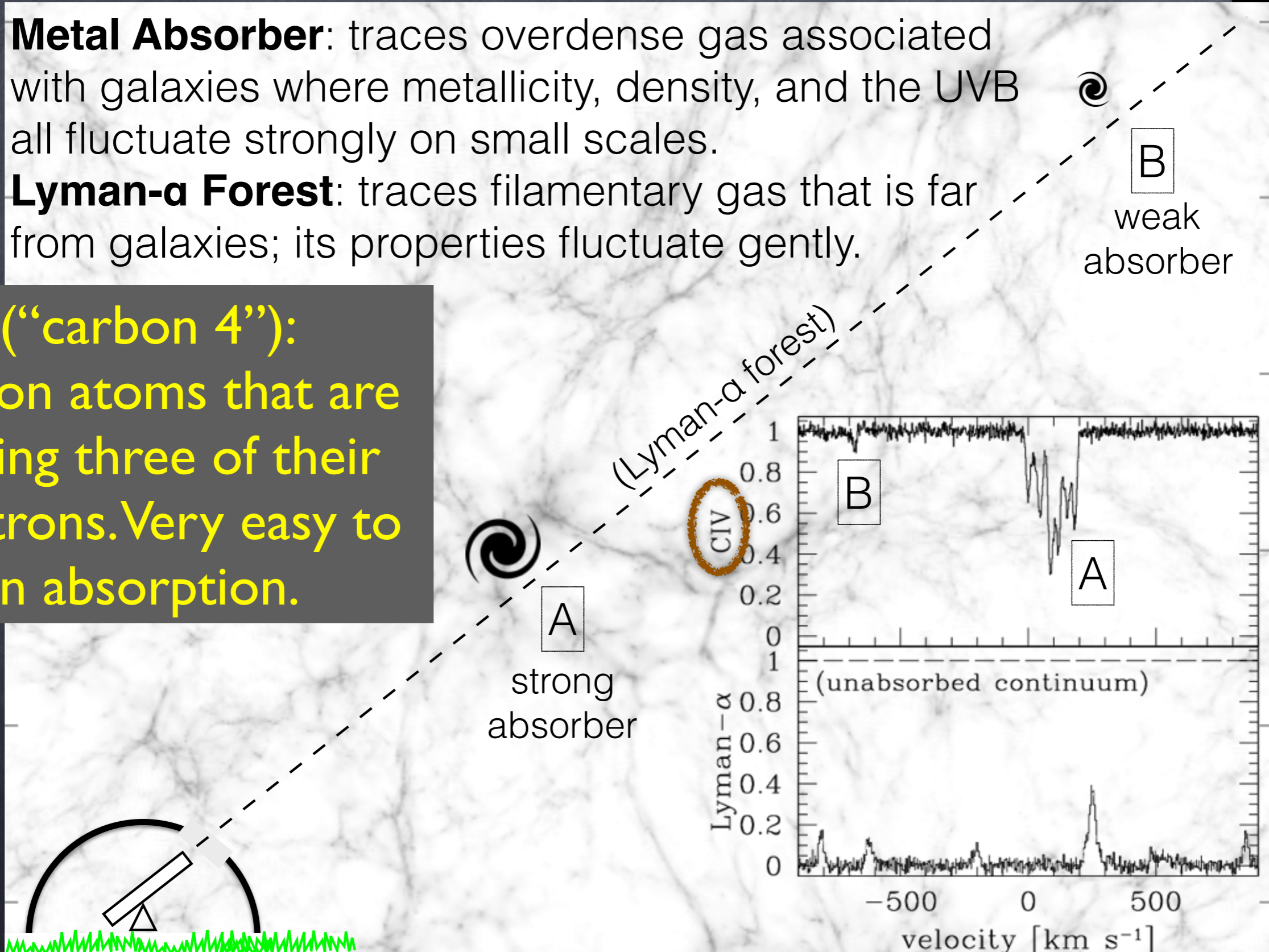
Simulated Sightlines (Theuns+1998)

- extract local Z, T, v, ρ, *and* J_ν
- compute ion abundance ratios using a custom ionization solver
- add noise, instrumental response
- synthetic absorbers are then detected & measured realistically

Simulated Sightlines (Theuns+1998)

KF+2016
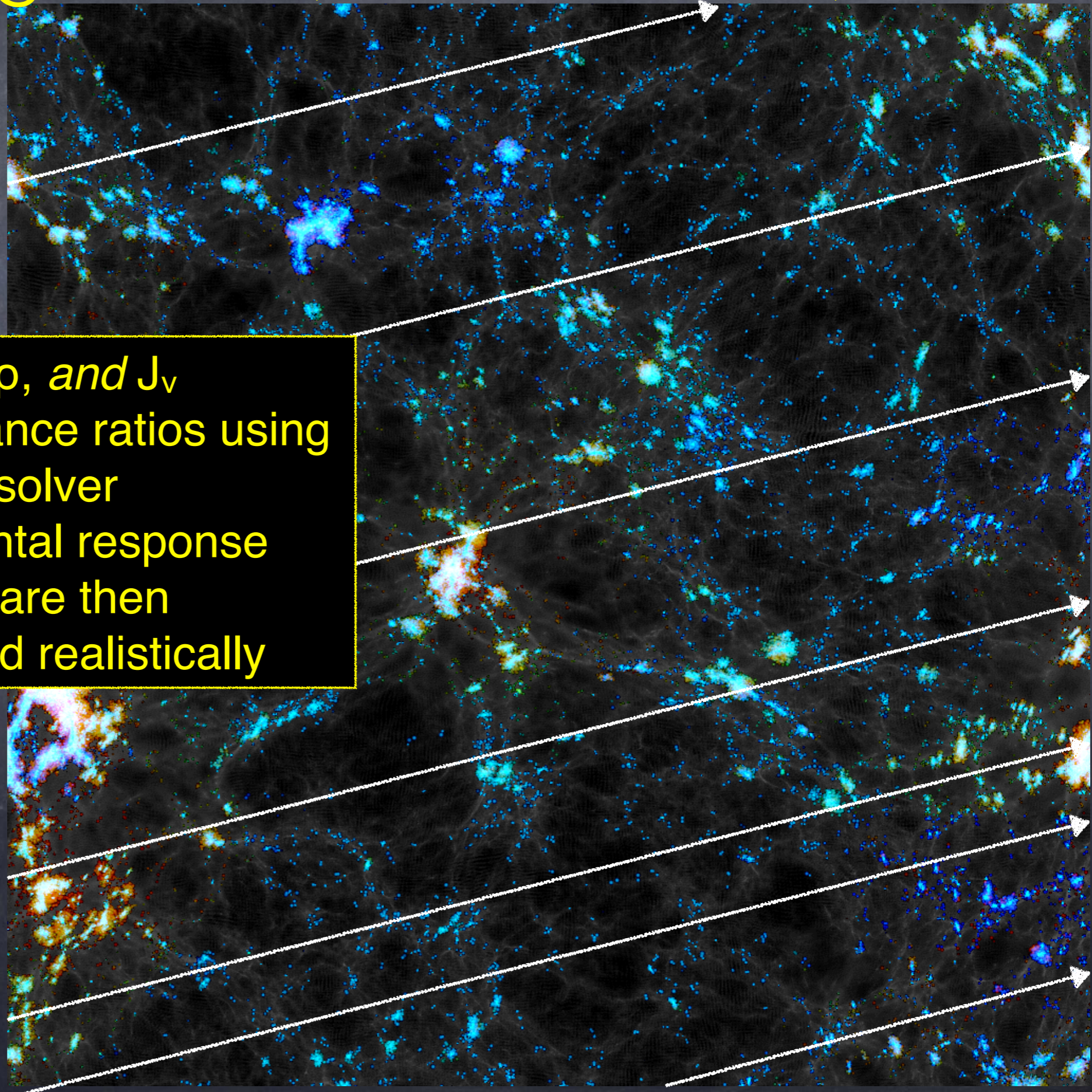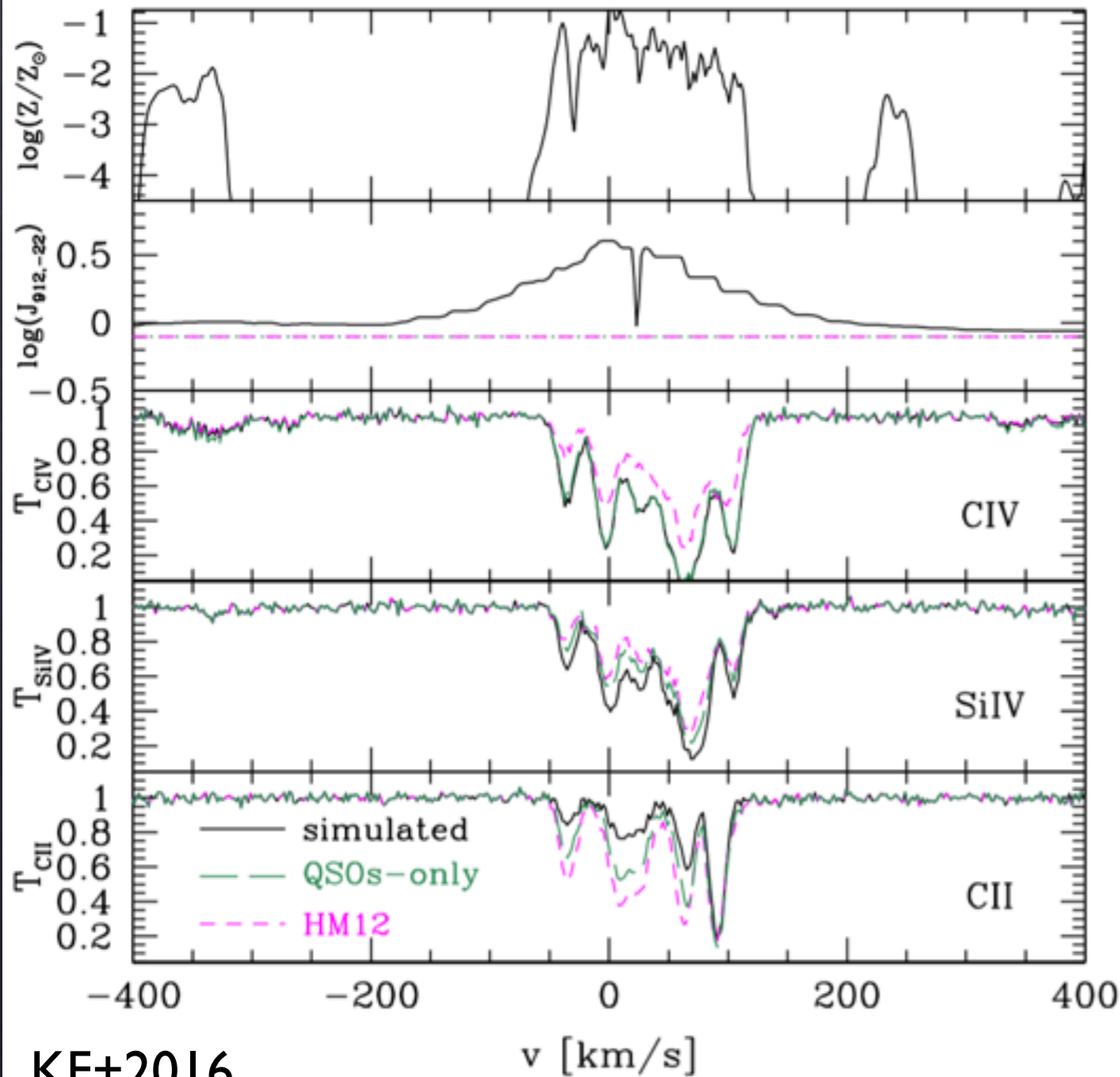
Characterizing absorption lines

Equivalent Width (EW): measures the geometric area of an absorption feature in a spectrum.
Unit: Å or km/s.
Easy to measure, difficult to predict.

Column density: number of ions per unit area along the sightline that are required to produce that level of absorption.
Unit: ions/cm^{-2}
Difficult to measure, easy to predict.

(2) Incidence of CIV absorbers

KF+2015

weak systems   strong systems
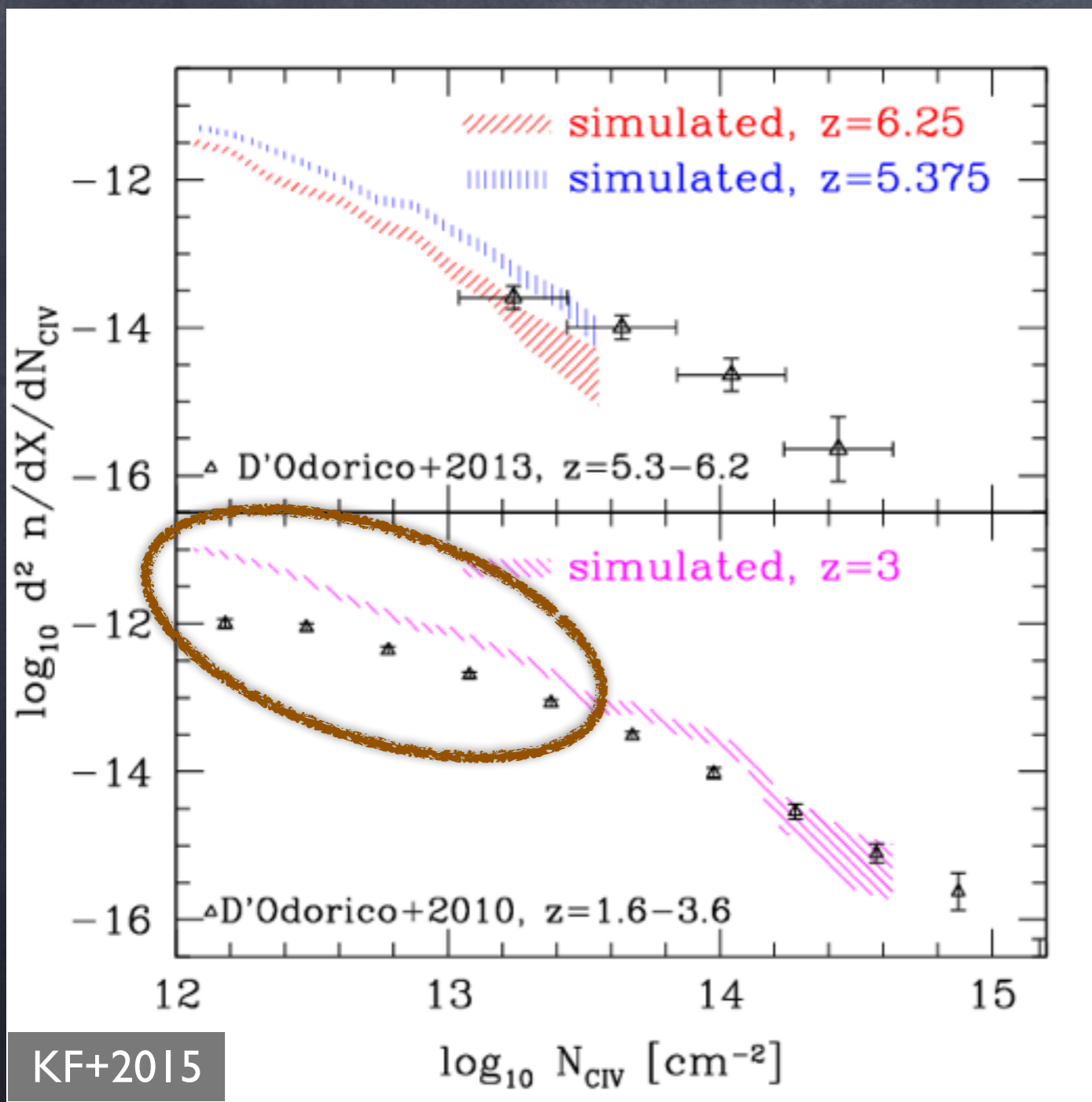
A preliminary comparison at z=3 suggested that the simulation <u>ejected too much carbon</u>.

Weaknesses of this study:
- formed too many stars
- UVB too strong
- small simulation volume
- column densities hard to measure consistently.

Better models, more data!

(2) Incidence of CIV absorbers

Hasan,…,KF+2020
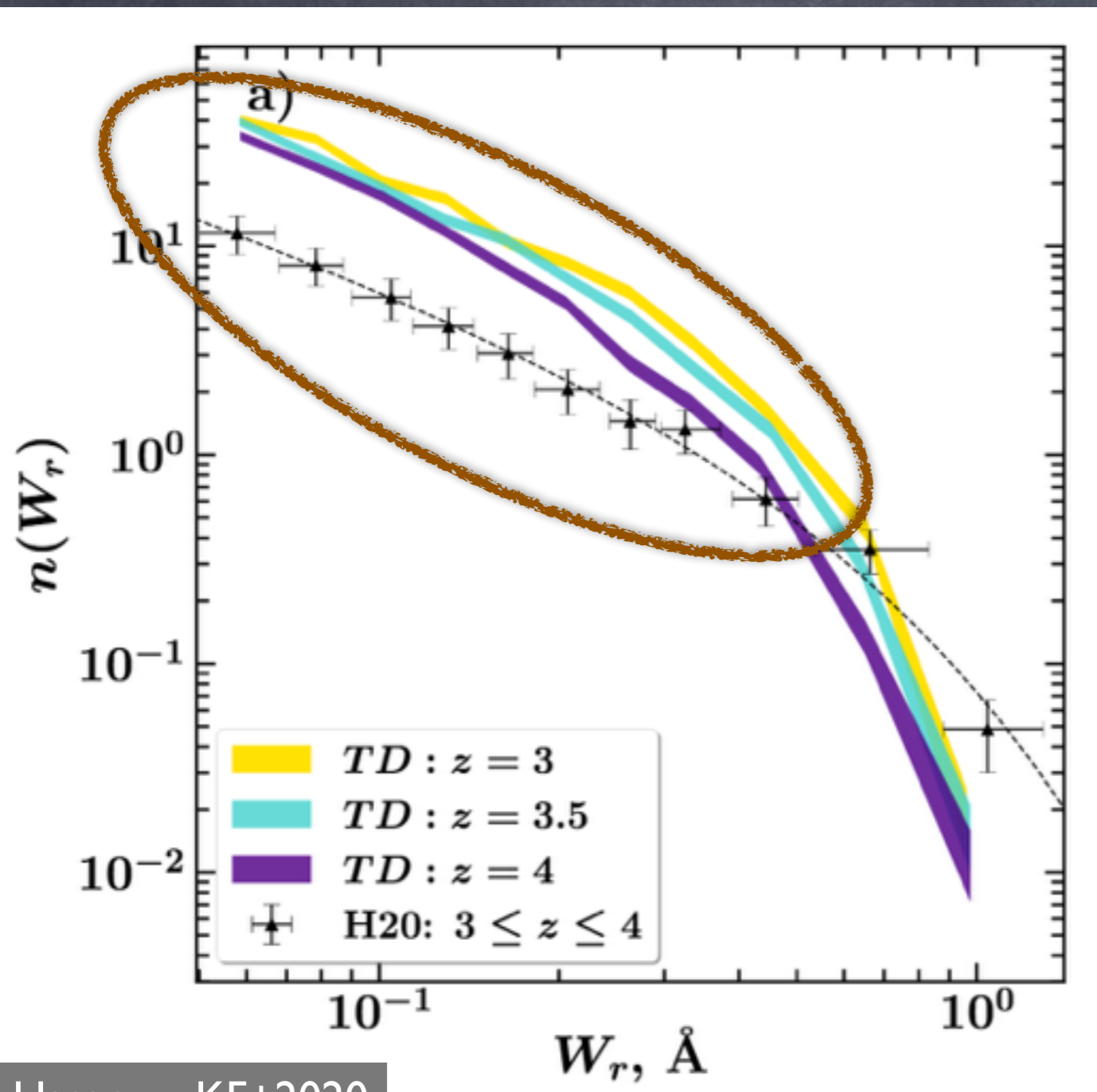
weak systems

strong systems

New model with:
- correct number of stars
- correct UVB amplitude
- 15x the cosmological volume

Also, absorbers characterized in a more consistent way via EWs.

…same result.

Broad Question 11: How did early galaxies enrich their environments with metals?

Narrower Question: How does the observed line incidence of CIV absorbers constrain feedback models?

Takeaway: By cosmic noon, the model robustly overproduces weak CIV absorbers. Possible explanations:
- forming or ejecting too much C
- enriched gas is too diffuse (not clumpy enough)
- dust depletion important
- UVB is too strong around low-mass galaxies

Broad Question III: How did early galaxies irradiate their environments?

Narrower Question: How do the statistics of metal absorbers reflect the *intensity* and *spectral hardness* of the ionizing background in the CGM?

Definitions
intensity: the overall amount of ionizing light
spectral hardness: the ratio of high-energy to low-energy ionizing light. For example, the spectral slope from 91.2—912 Å.

Concept
ionization equilibrium: the condition that ionizations out of and recombinations into each ionization state are in equilibrium.
Higher ionization states are favored in *diffuse* media with an *intense* and/or *hard* UVB.

CIV and SiIV are (relatively) high-ionization ions.

3. Absorber Abundance Reflects UVB Hardness

KF+2020
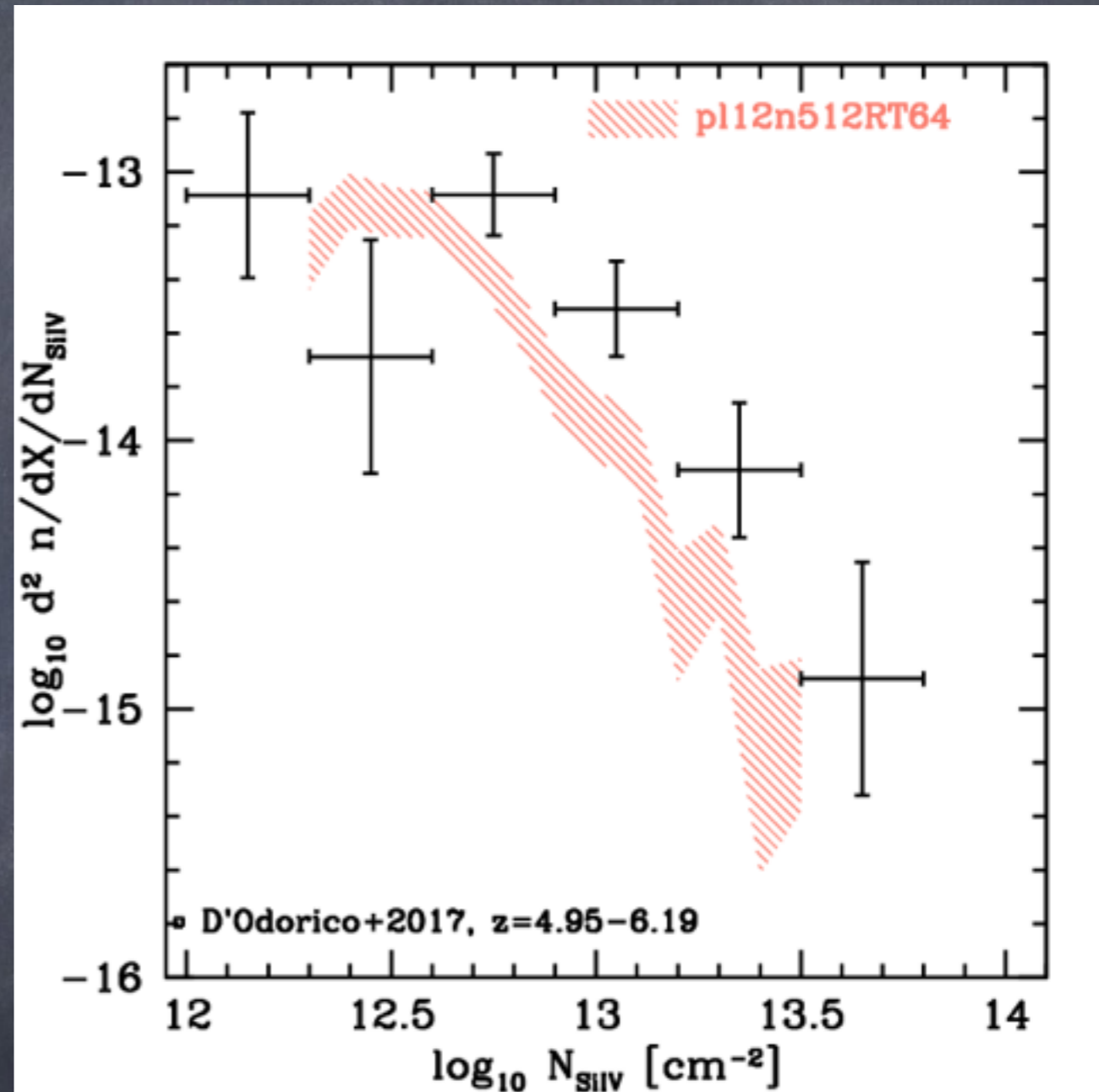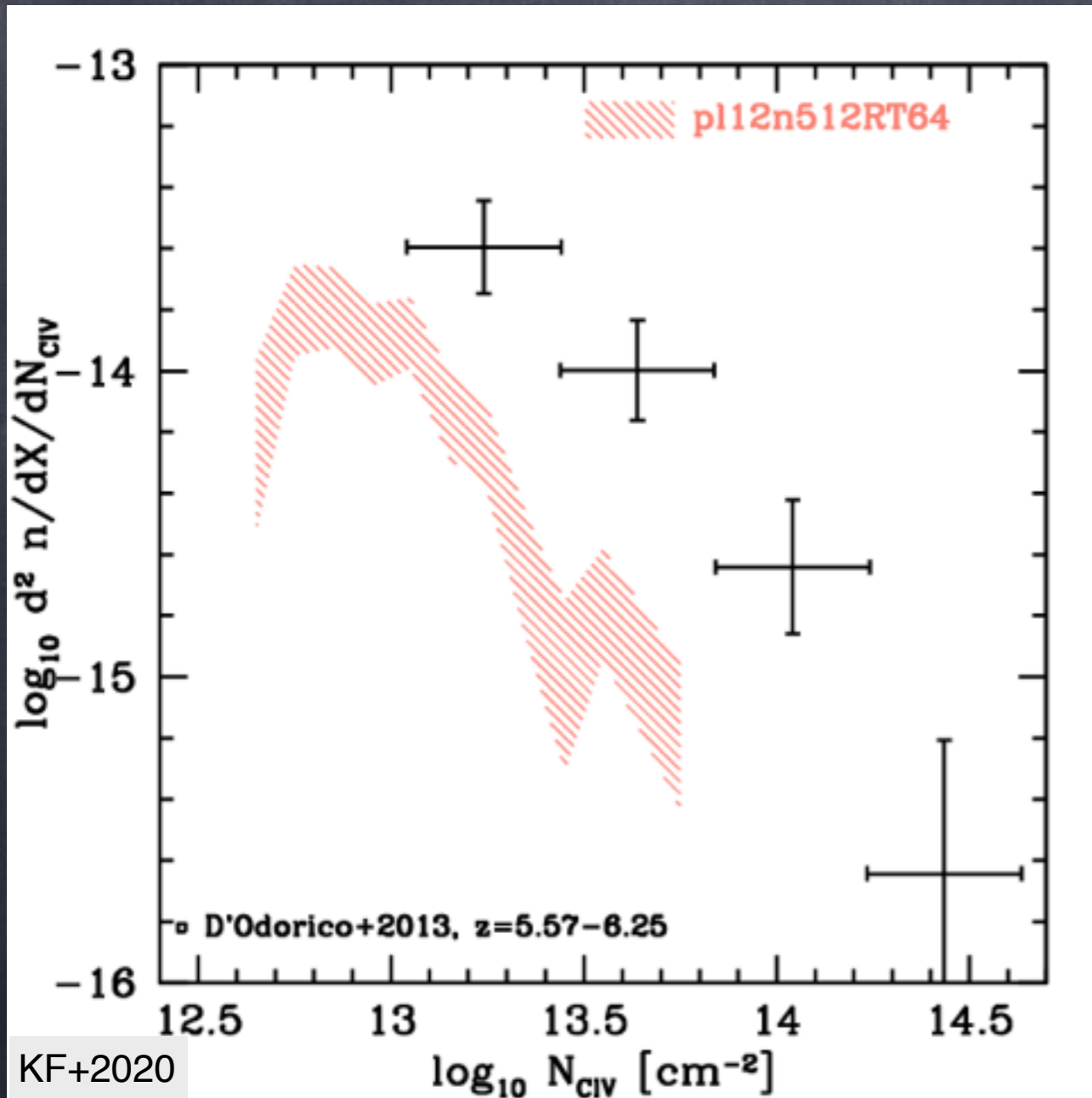
In 2016, a model that produces too few stars and a UVB that is too weak (though reionization completes at z=6): *underproduces* both CIV and SiIV at z~6

3. Absorber Abundance Reflects UVB Hardness
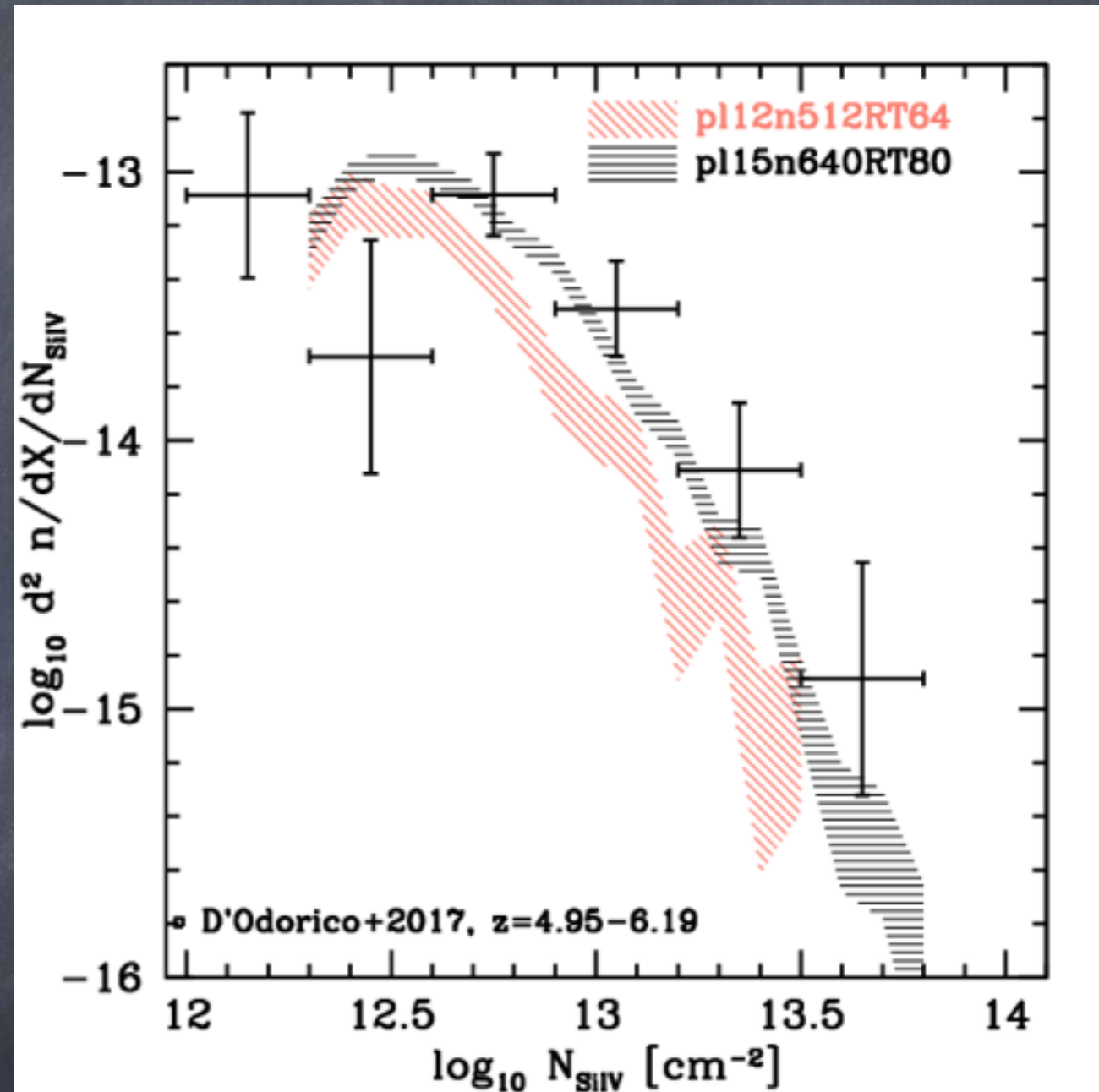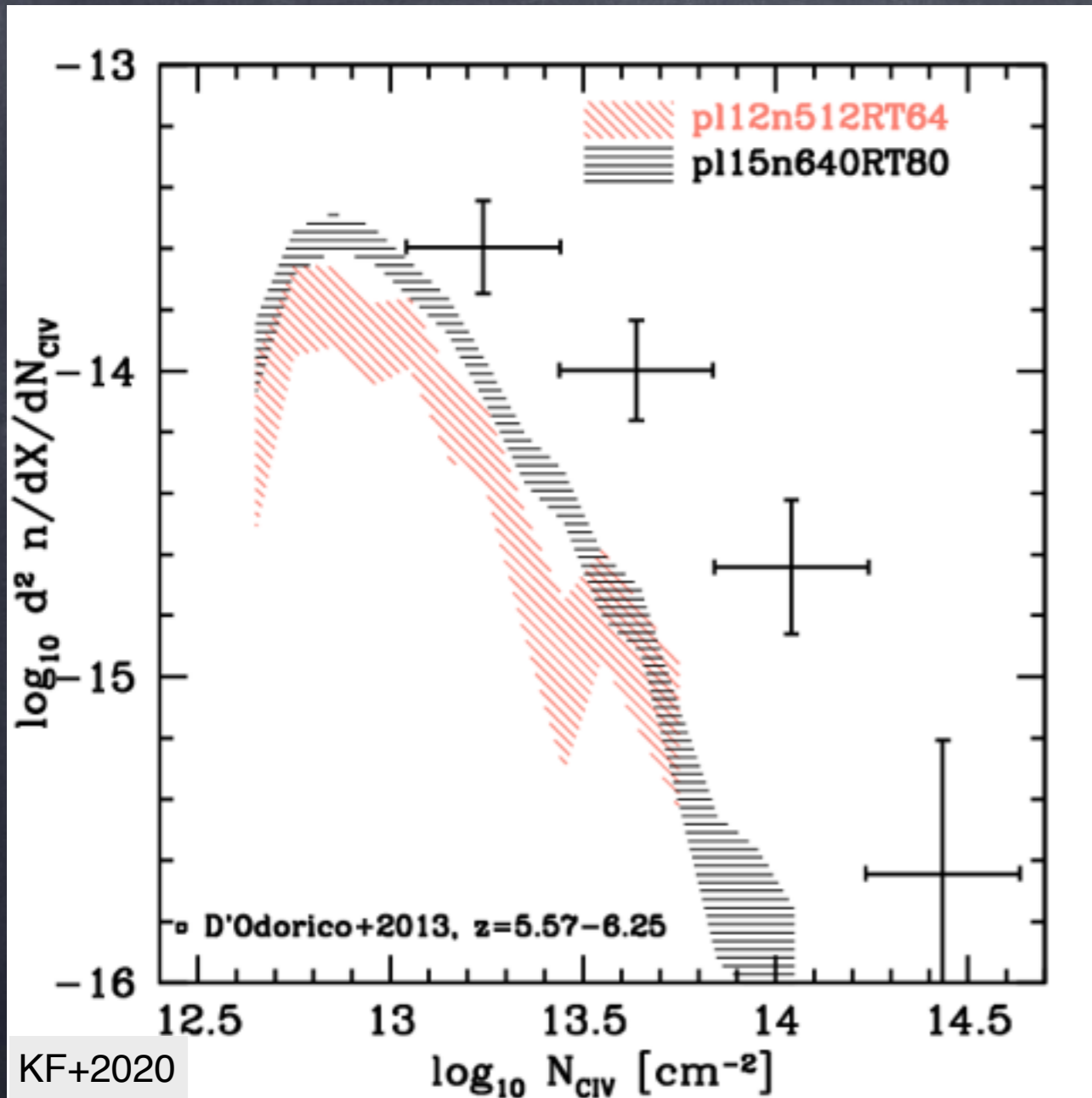
KF+2020

In 2018, a model that produces enough stars, a realistic UVB, and the same reionization history: *underproduces* CIV but *matches* SiIV (again, at z~6). *What gives?*

The Escape Scenario can Changes the UVB's Spectral Slope

Zackrisson+2013

(a) Direct star light with LyC
HI
HII
Star light and nebular emission, but no LyC
Ionization-bounded nebula with holes

(b) Strömgren radius
HII
Star light with LyC and nebular emission
Density-bounded nebula
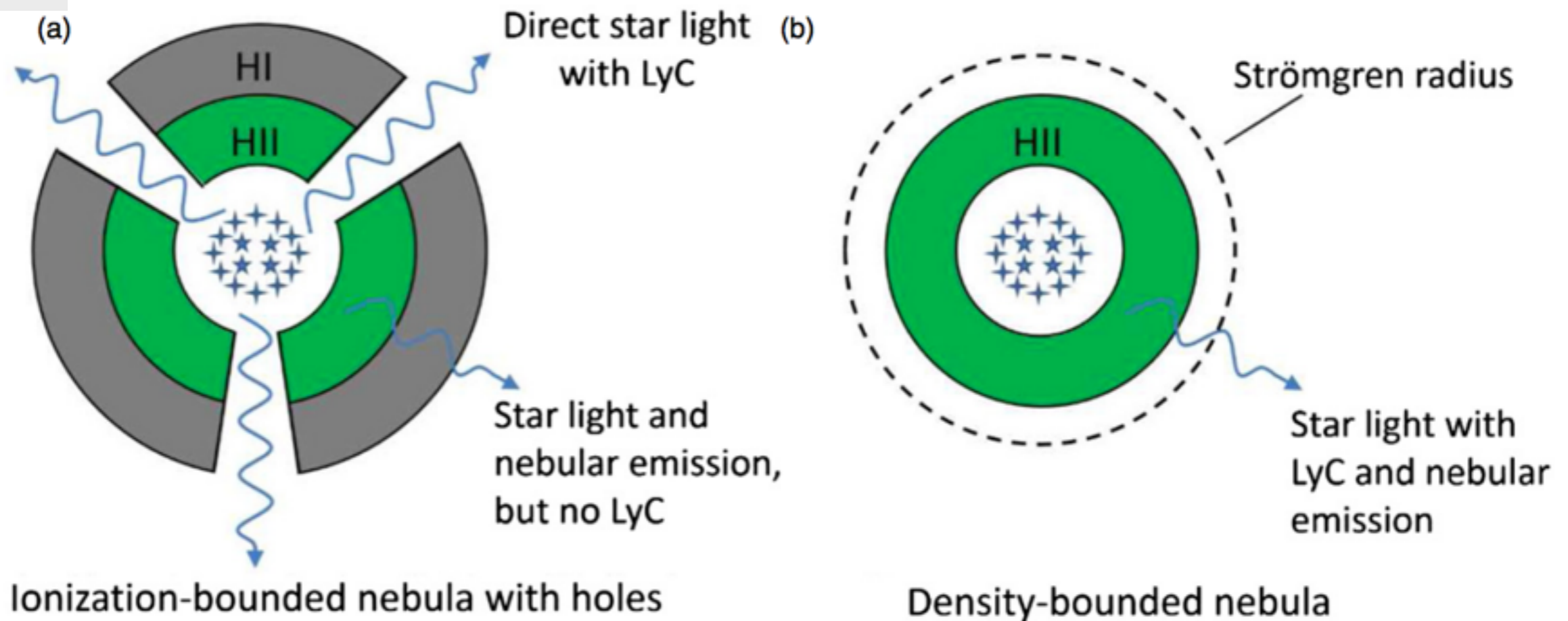
scalar f_{esc}

f_{esc} is a function of energy →expect spectral filtering

3.Absorber Abundance Reflects UVB Hardness
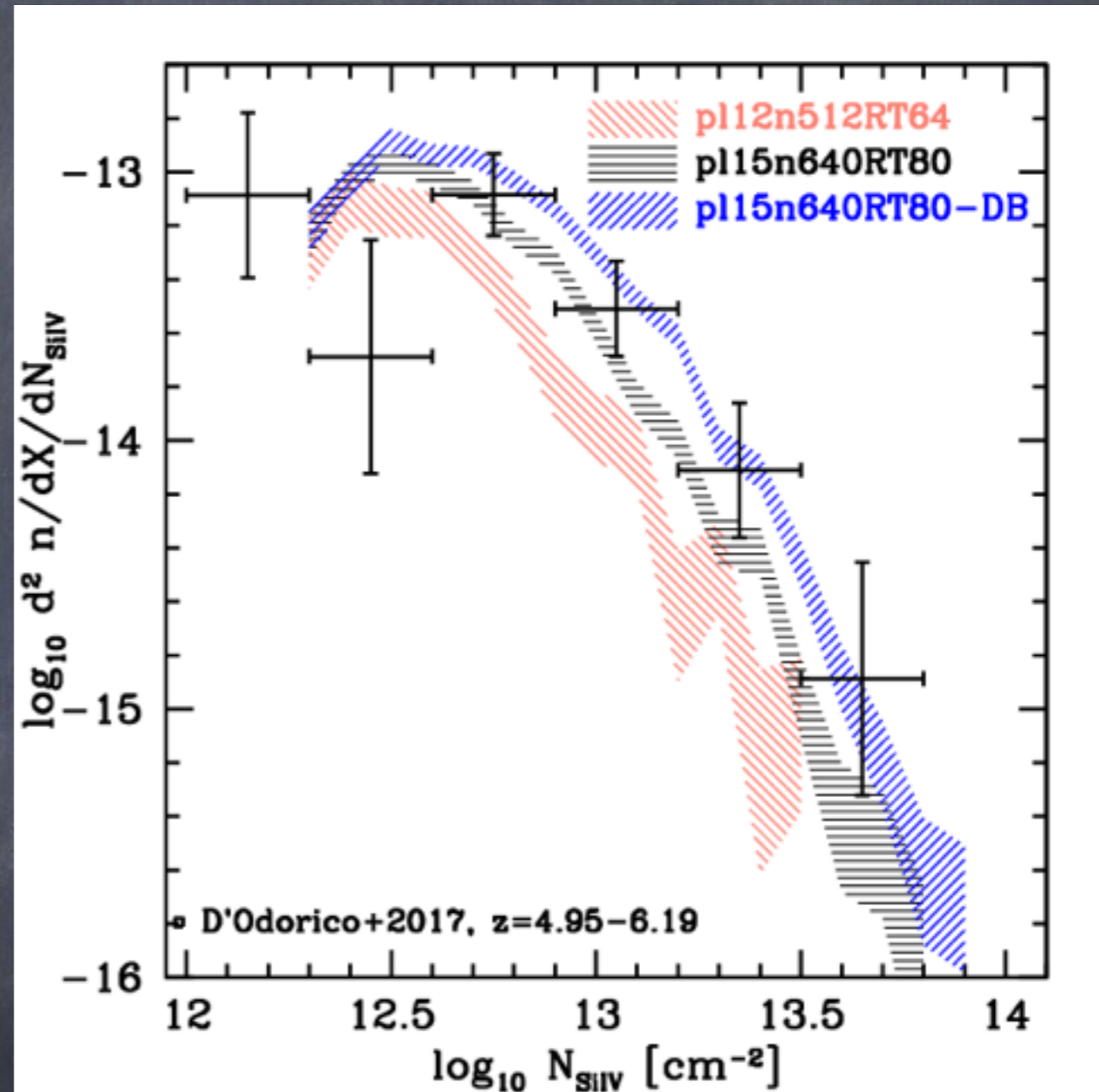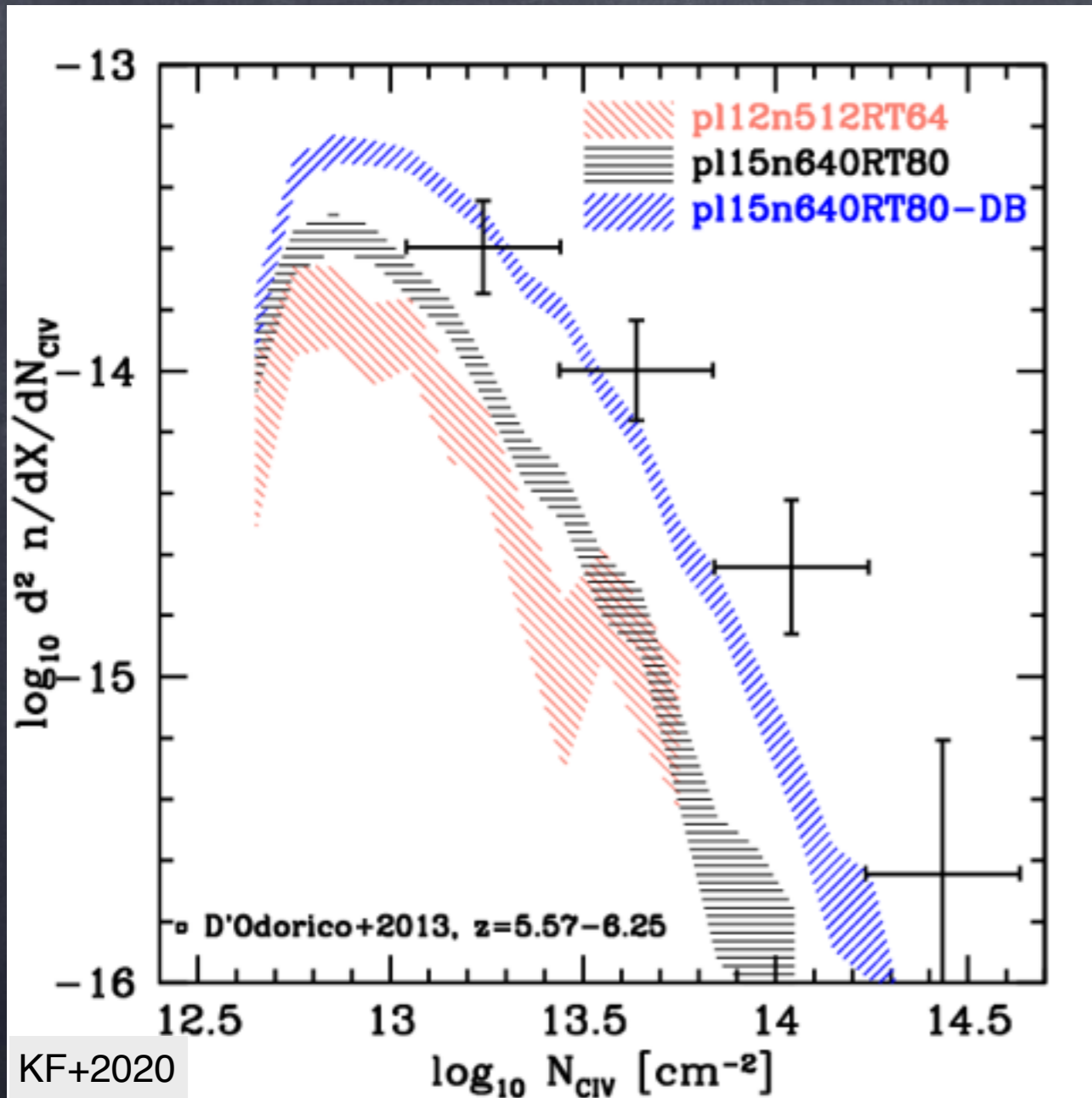
KF+2020

If I assume that the way in which light escapes galaxies favors hard UV (*density-bounded escape*) then CIV is nearly reproduced.

Measuring UVB Hardness by Counting Galaxies

HST orbits/5σ detection: 118   19   1

Legend:
- DB, $N_{CIV} > 10^{14}$ cm^{-2}
- IB, $N_{CIV} > 10^{14}$ cm^{-2}
- DB, $N_{CIV} > 5 \times 10^{13}$ cm^{-2}
- IB, $N_{CIV} > 5 \times 10^{13}$ cm^{-2}

JWST limit

Cai+2017   Diaz+2011   Diaz+2014

field

$N (<M_{UV}, <250$ pkpc$)$

$\Delta(>M_{UV})$

M_{UV}
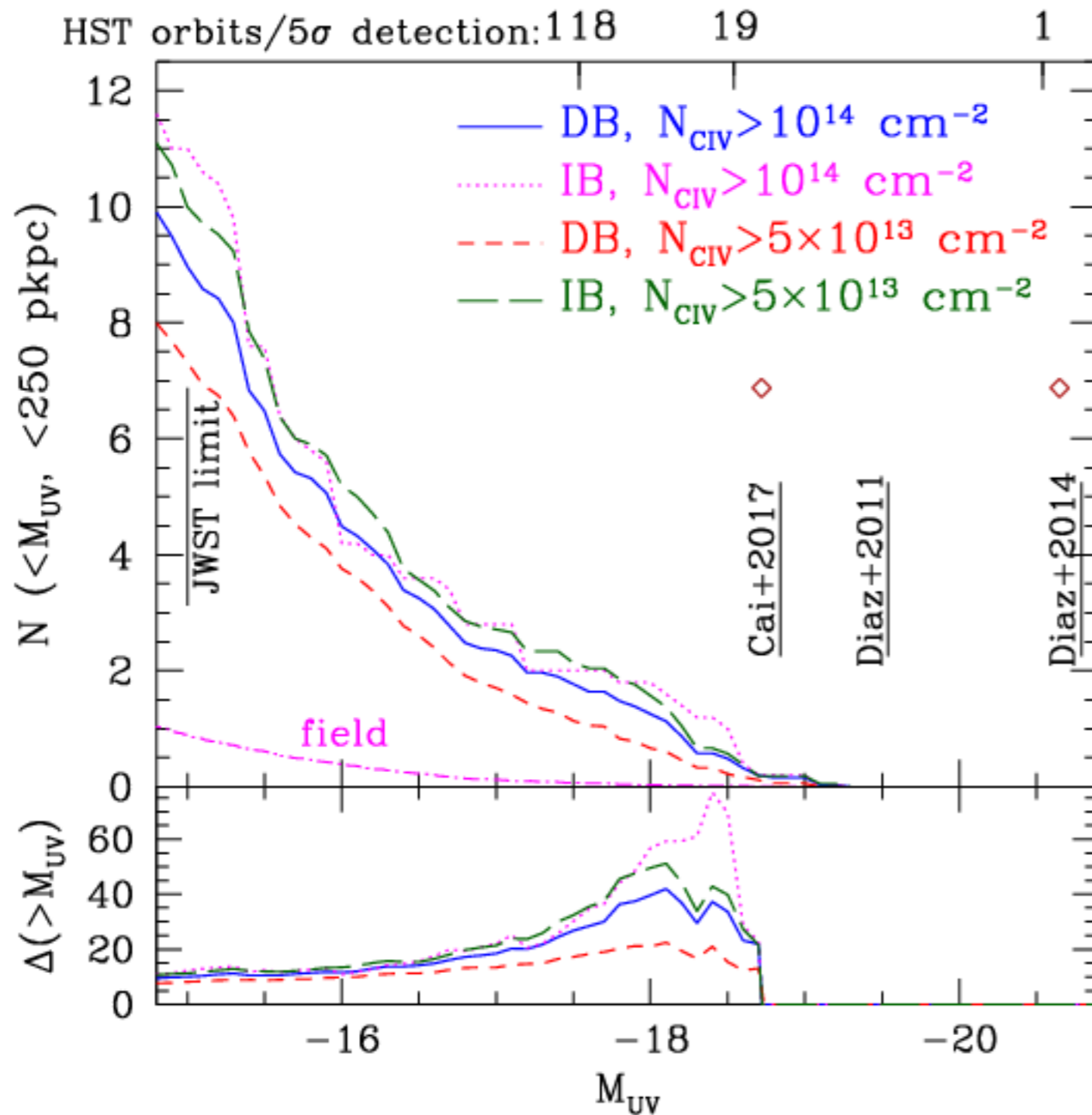
z=5.75; KF+2020

If galaxies emit a harder ionizing background, then they produce CIV more efficiently.

→fewer neighboring galaxies are expected per strong CIV absorber.

Measurable w/ JWST.

3. Aligned Absorber Statistics Reflect UVB

UVB + spatial fluctuations   uniform UVB   QSO-driven reionization

D'Odorico et al. 2013

simulated   HM12   QSOs

Doughty, KF+2018

The QSO-driven model fares best, confirming that a harder UVB is required than the one predicted out-of-the box. (This does not have to come from QSOs though.)

UVB + spatial fluctuations | uniform UVB | QSO-driven reionization

Doughty, KF+2018

The QSO-driven model fare...
confirming that a harder UV...
required than the one predi...
out-of-the box. (This does n...
have to come from QSOs th...

Table 1. Normalized probabilities for all aligned pairs. The lower and upper confidence levels are given at the 16 and 84 percentiles and calculated using bootstrapping with 10^4 iterations.

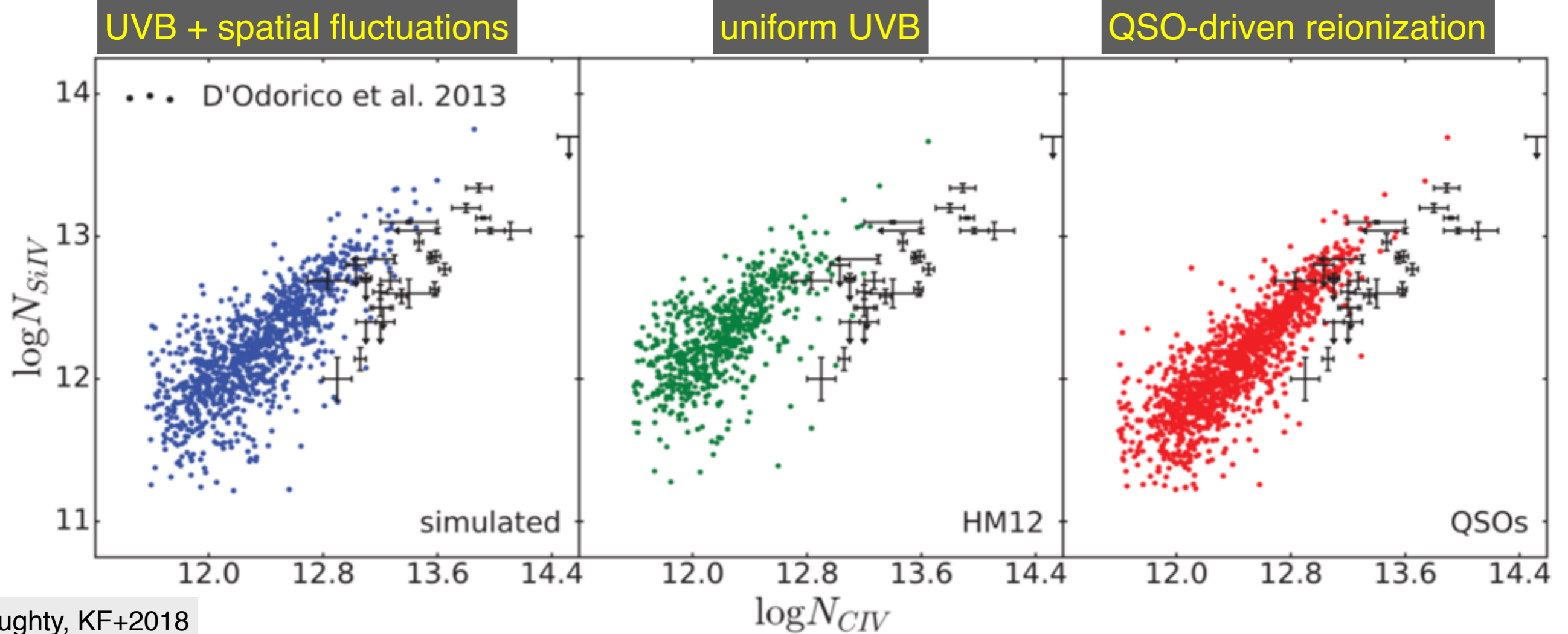|	C IV/Si IV	C II/C IV	Si II/Si IV	O I/C IV
Simulated	$0.32^{0.51}_{0.14}$	$0.33^{0.33}_{0.33}$	$0.21^{0.58}_{0.21}$	$0.33^{1.00}_{0.33}$
HM12	$0.16^{0.32}_{0.03}$	$0.33^{0.33}_{0.33}$	$0.58^{0.58}_{0.58}$	$0.33^{1.00}_{0.33}$
QSO-only	$0.52^{0.58}_{0.31}$	$0.33^{0.33}_{0.33}$	$0.21^{0.58}_{0.21}$	$0.33^{0.33}_{0.33}$

[1]The column density cut-off values used are as follows: $\log N_{C IV, min} = 13.25$, $\log N_{C II, min} = 12.49$, $\log N_{Si II, min} = 12.12$, and $\log N_{O I, min} = 13.49$.

Broad Question III: How did early galaxies irradiate their environments?

Narrower Question: How do the statistics of metal absorbers reflect the *intensity* and *spectral hardness* of the ionizing background in the CGM?

Takeaway: The incidences of CIV and SiIV absorbers and the statistics of aligned absorbers are sensitive to the history of star formation and to the slope of the escaping ionizing continuum. Data favor relatively hard UVBs as expected in density-bounded escape scenarios, but do not require QSO-driven reionization.

Broad Question III: How did early galaxies enrich their environments with metals?

Narrower Question: How do the statistics of metal absorbers reflect the *intensity* and *spectral hardness* of the ionizing background in the CGM?

On QSO-driven HI reionization: it
- is impossible (Shapiro & Giroux 1987, Yan & Windhorst 2004; Parsa+2018);
- overheats the IGM (D'Aloisio+2017);
- underproduces the CMB optical depth to Thomson scattering or overproduces observed ionizing emissivity at z=5 (Hassan+2018)

Broad Question IV: How does the circumgalactic medium (CGM) respond to reionization?

Narrower Question: Does the line incidence of neutral oxygen (OI) absorbers respond to the progress of HI reionization?

OI Absorbers Notice HI Reionization

Background: Prior to HI reionization, H and He were neutral and metals were in low-ionization states. OI, SiII, CII, and MgII should be in regions where the Universe has not yet been reionized. Can we use them like "clocks" to time reionization?

Theory: Oh 2002; Furlanetto & Loeb 2003; KF+2013,2015; Keating+2014; Doughty, KF+2019; Hennawi+2020

Observations: Becker+2011,2019; Codoreanu+2018

OI Absorbers Notice HI Reionization

Despite ongoing metal enrichment, the number density of OI absorbers is flat or declines in time.

It drops when HI reionization completes. This *may have been observed* by Becker +2019.

obs: Becker+2019; use EW > 0.05 Å

Doughty, KF+2019
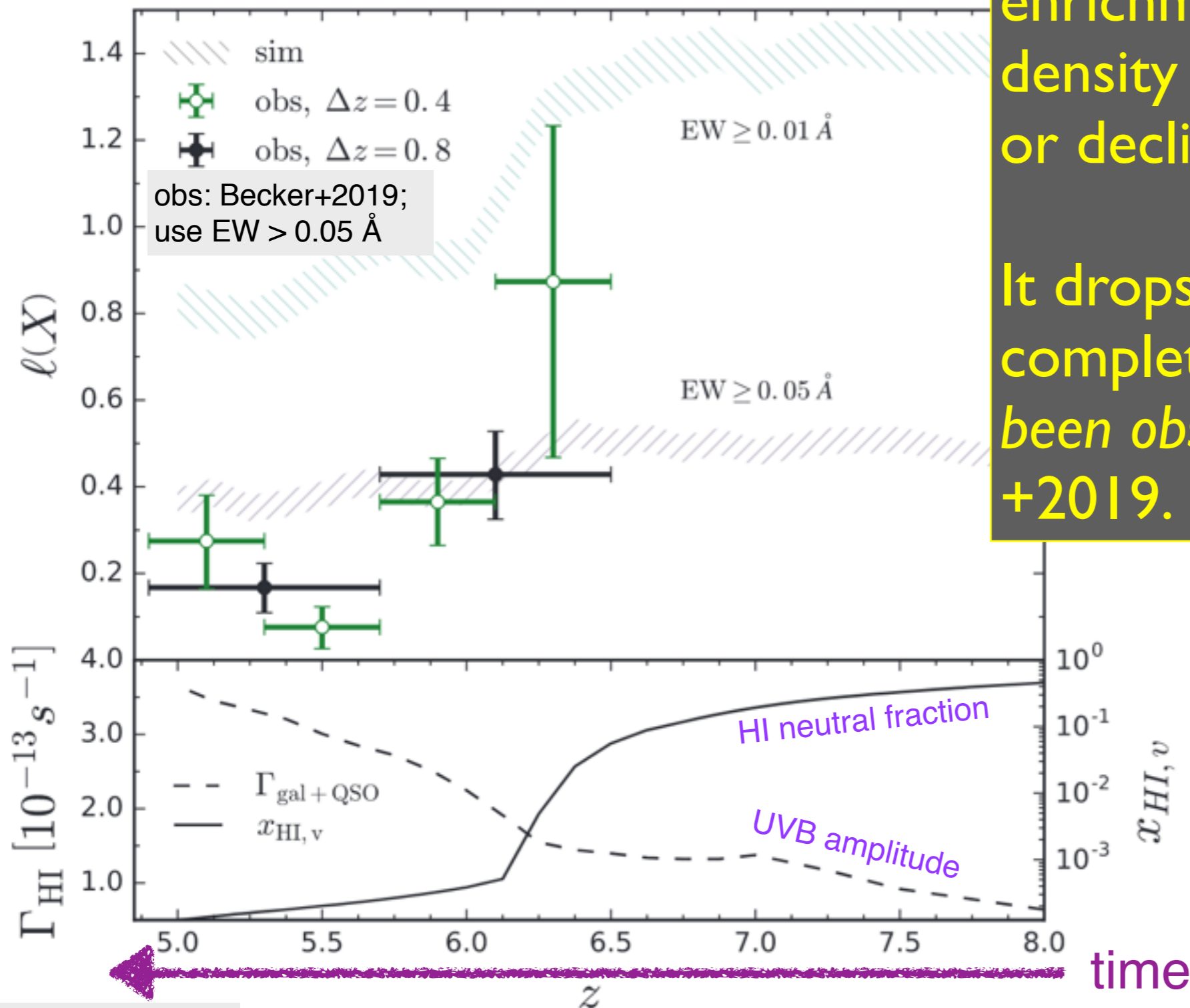
Broad Question IV: How does the circumgalactic medium (CGM) reflect the progress of reionization?

Narrower Question: Does the line incidence of neutral oxygen (OI) absorbers respond to the progress of HI reionization?

Takeaway: Yes! Recent measurements indicate qualitative agreement with predictions in two ways:
• OI incidence does not grow the way CIV does;
• It shows a feature around z=5–6 consistent with the completion of HI reionization.

What have we learned

- halos more massive than 2×10^9 M_0 grow galaxies
- models overproduce weak CIV absorbers at $z = 3$ and underproduce all of them at $z = 6$
- density-bounded escape can eliminate the latter gap (testable w/ JWST)
- OI absorbers should (and do) "notice" HI reionization in that their line incidence is flat or declining and drops around $z = 5$–6

Things that we sure would love to know

- ionizing emissivity from massive, low-metallicity stars
- the wavelength-dependence of the ionizing escape fraction (well…the mass- and redshift-dependences too)
- the small-scale structure of the CGM (computation!)
- the galaxy mass-metallicity relation at $z \geq 5$