A new method to constrain the UVB via fluorescent Lyman-α emission

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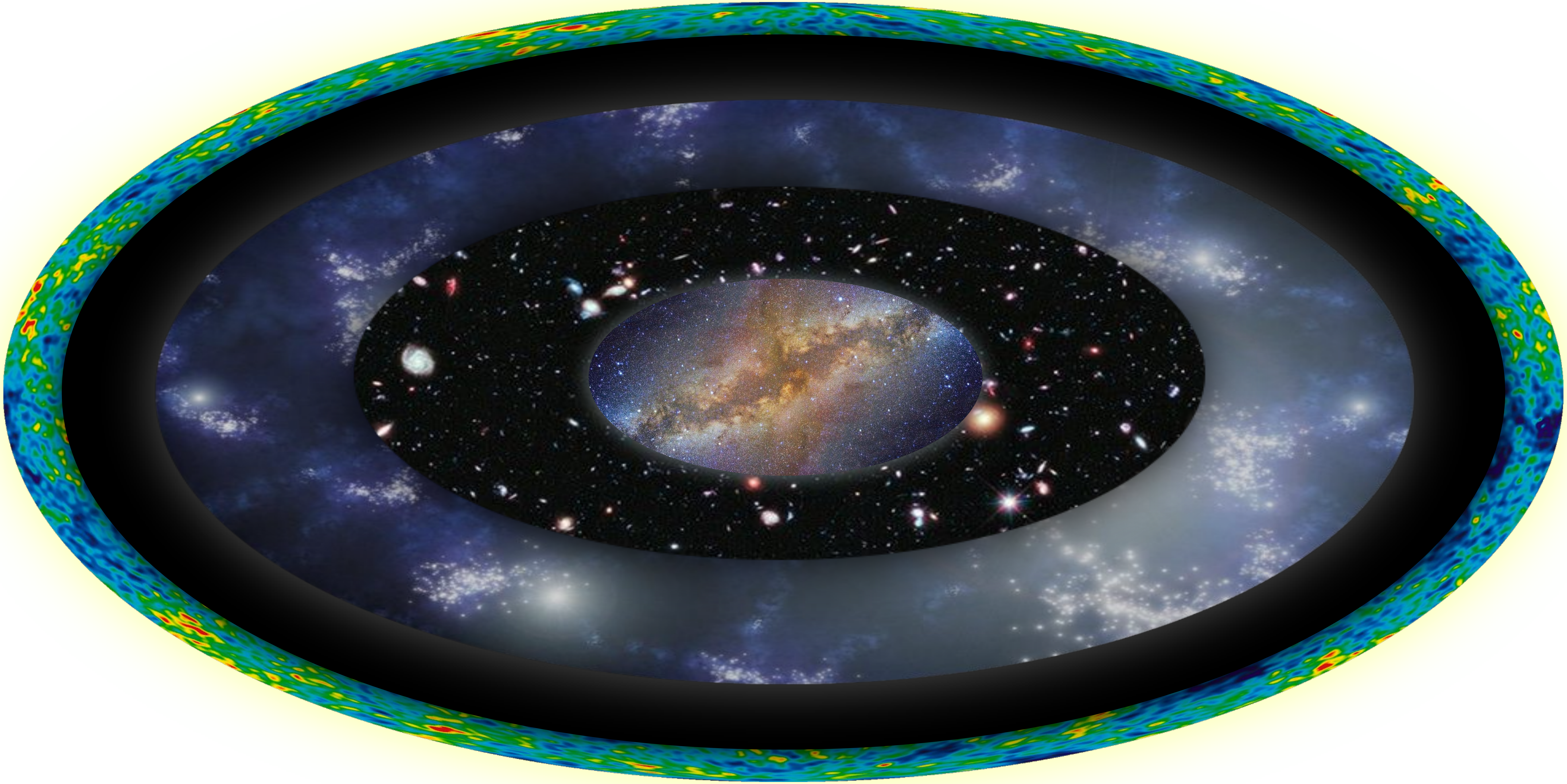
muse
multi unit spectroscopic explorer

The Observable Universe



The Cosmic UV Background

Why do we care?

- Responsible for the Reionization the Intergalactic Medium (IGM) & for sustaining its high ionization state up to our current time
- Regulates temperature of the IGM
- Regulates gas accretion from the IGM to galaxies, therefore relevant to early galaxy evolution

The Cosmic UV Background

How to detect it?

Angle-average monochromatic intensity

Photoionization rate of neutral hydrogen

Hydrogen photoionization cross section

$$\Gamma_{\rm HI} = 4\pi \int_{\nu_0}^{\infty} \frac{\mathrm{J}_\nu \, \sigma_\nu \, \mathrm{d}\nu}{\mathrm{h}\nu}$$

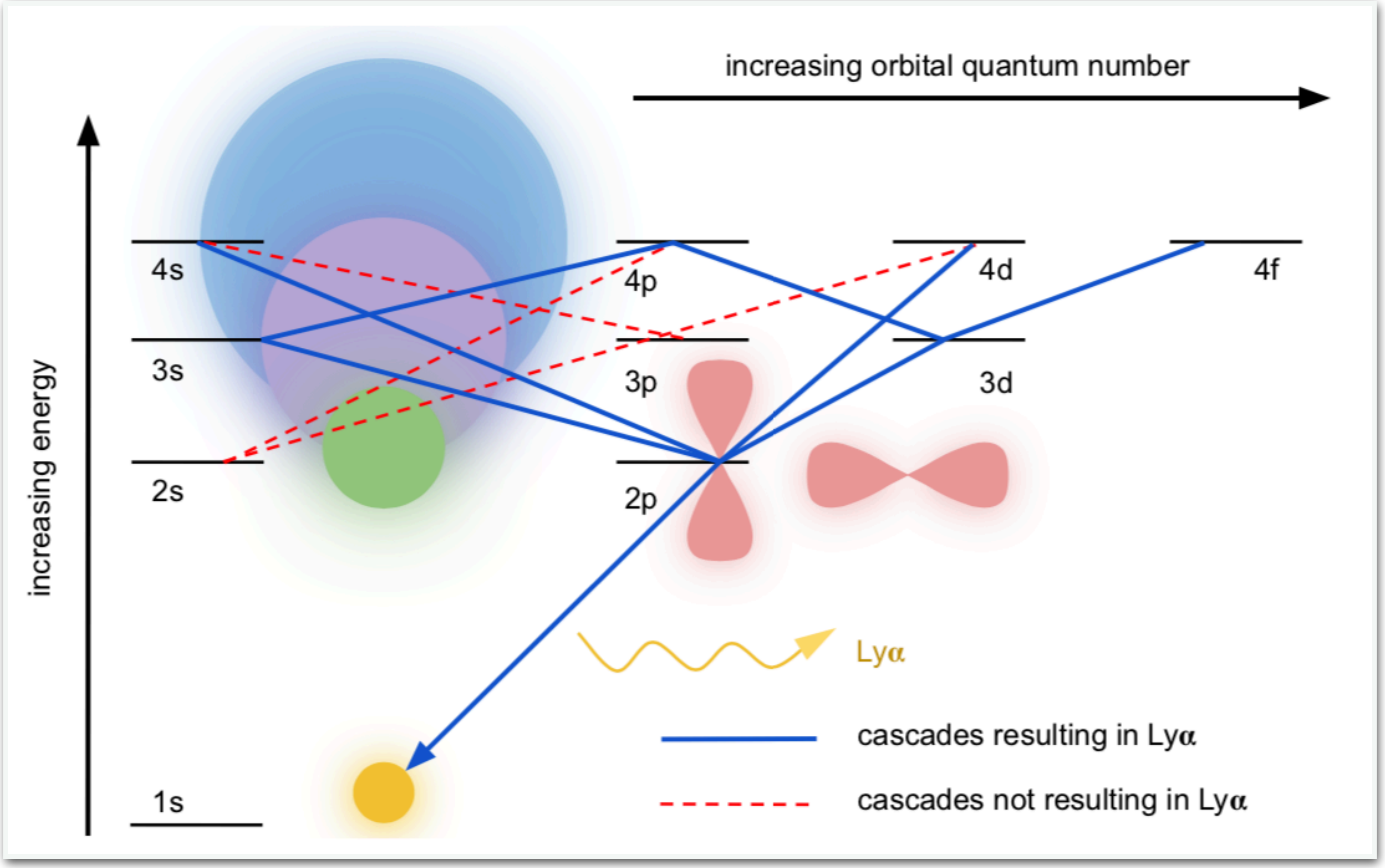
The Cosmic UV Background

How to detect it?

$$\Gamma_{\rm HI} = 4\pi \int_{\nu_0}^{\infty} \frac{\mathrm{J}_\nu \, \sigma_\nu \, \mathrm{d}\nu}{\mathrm{h}\nu}$$

How to detect the UVB?

Lyα emission

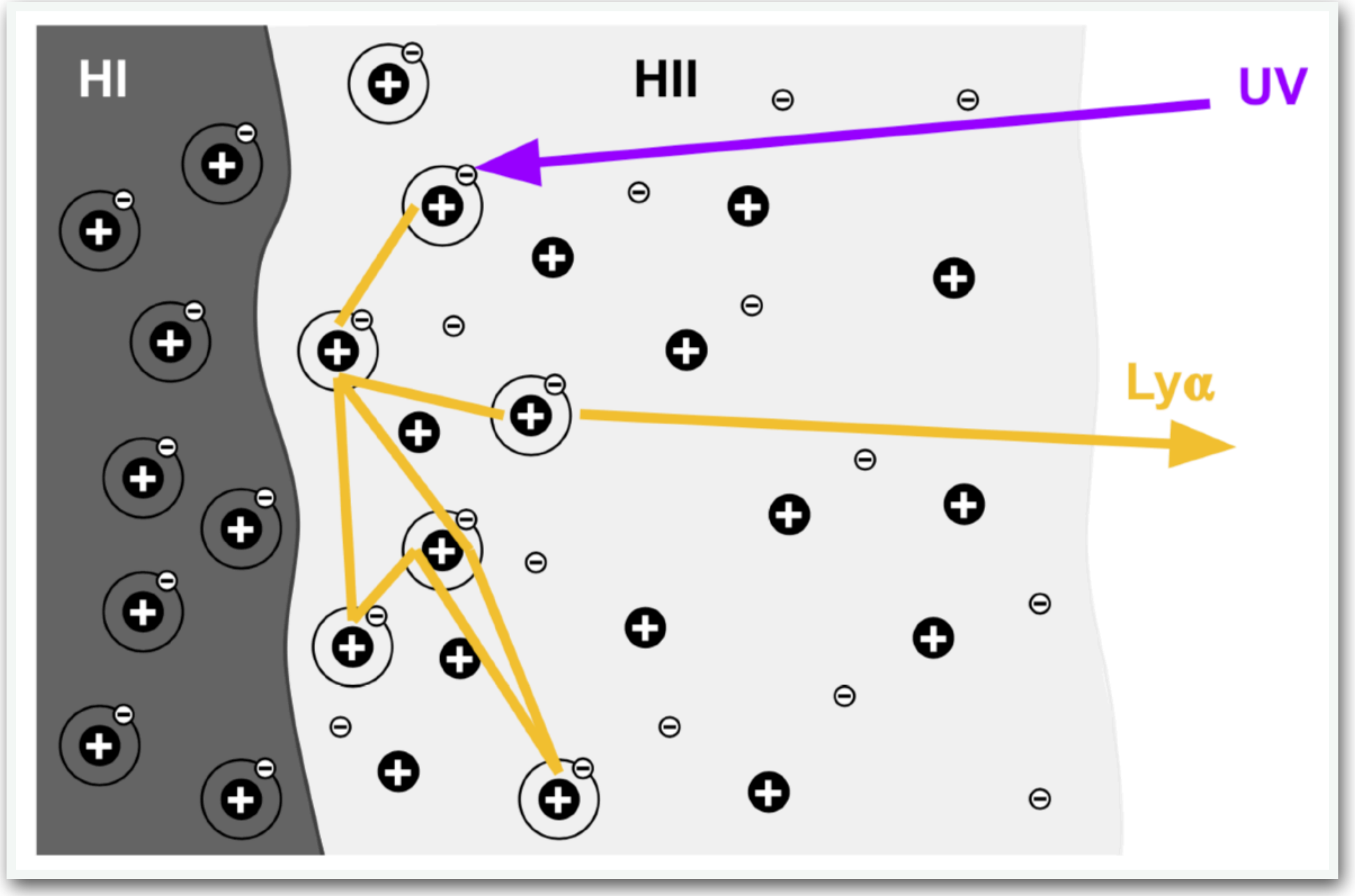


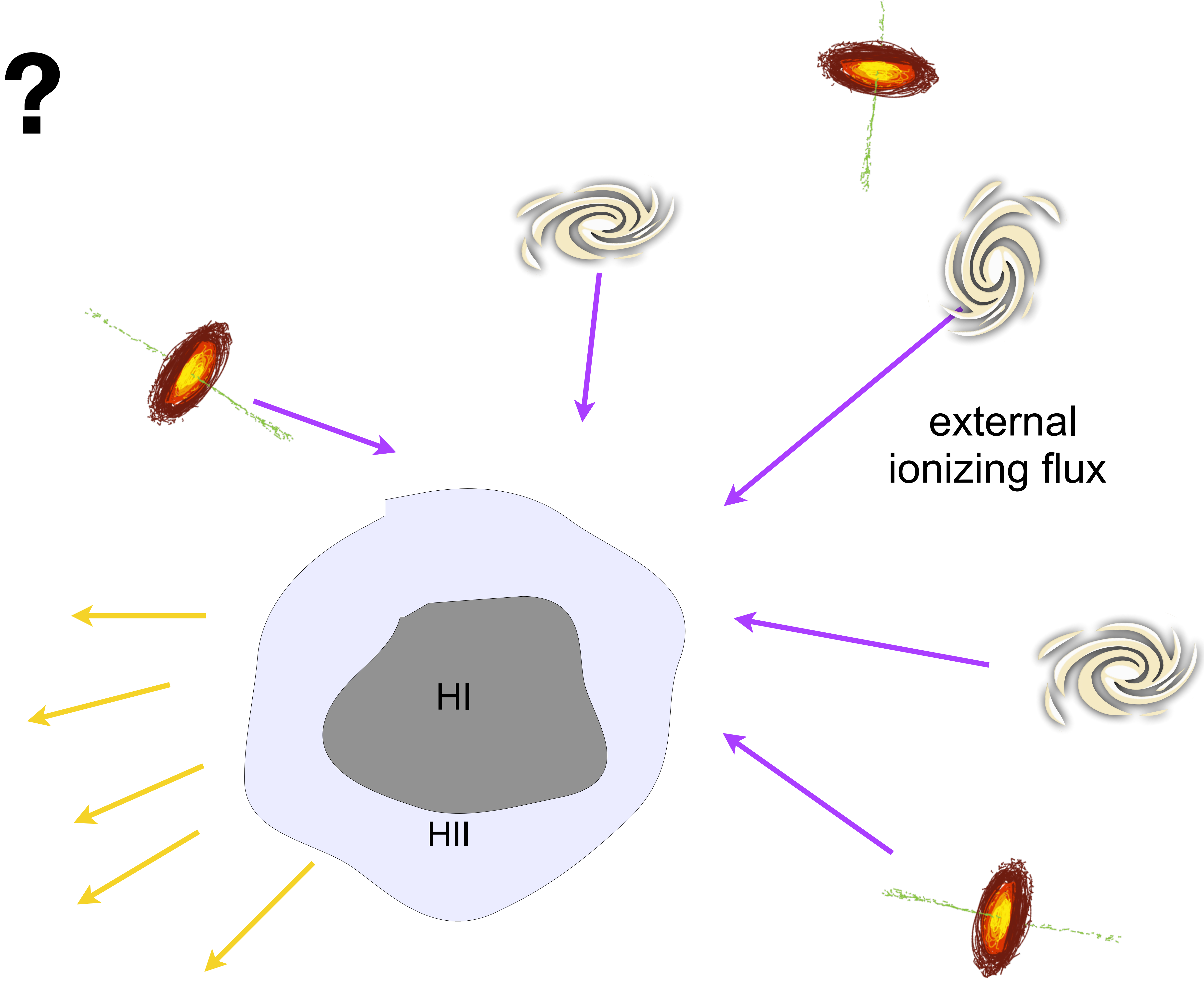
How to detect the UVB?

Fluorescent Lyα emission

Lyman-Limit System (LLS):

$$N_{HI} > 10^{17.2}\,\mathrm{cm}^{-2}\ (\tau_{LL} > 1)$$





$$\mathrm{R}_{\mathrm{Ly}\alpha} = \epsilon_{\mathrm{thick}} \int_{\nu_0}^{4\nu_0} \frac{J_\nu \, d\nu}{h\nu}$$

$\epsilon_{\mathrm{thick}}$ ~68% for T = 10^4 K

How to detect the UVB?

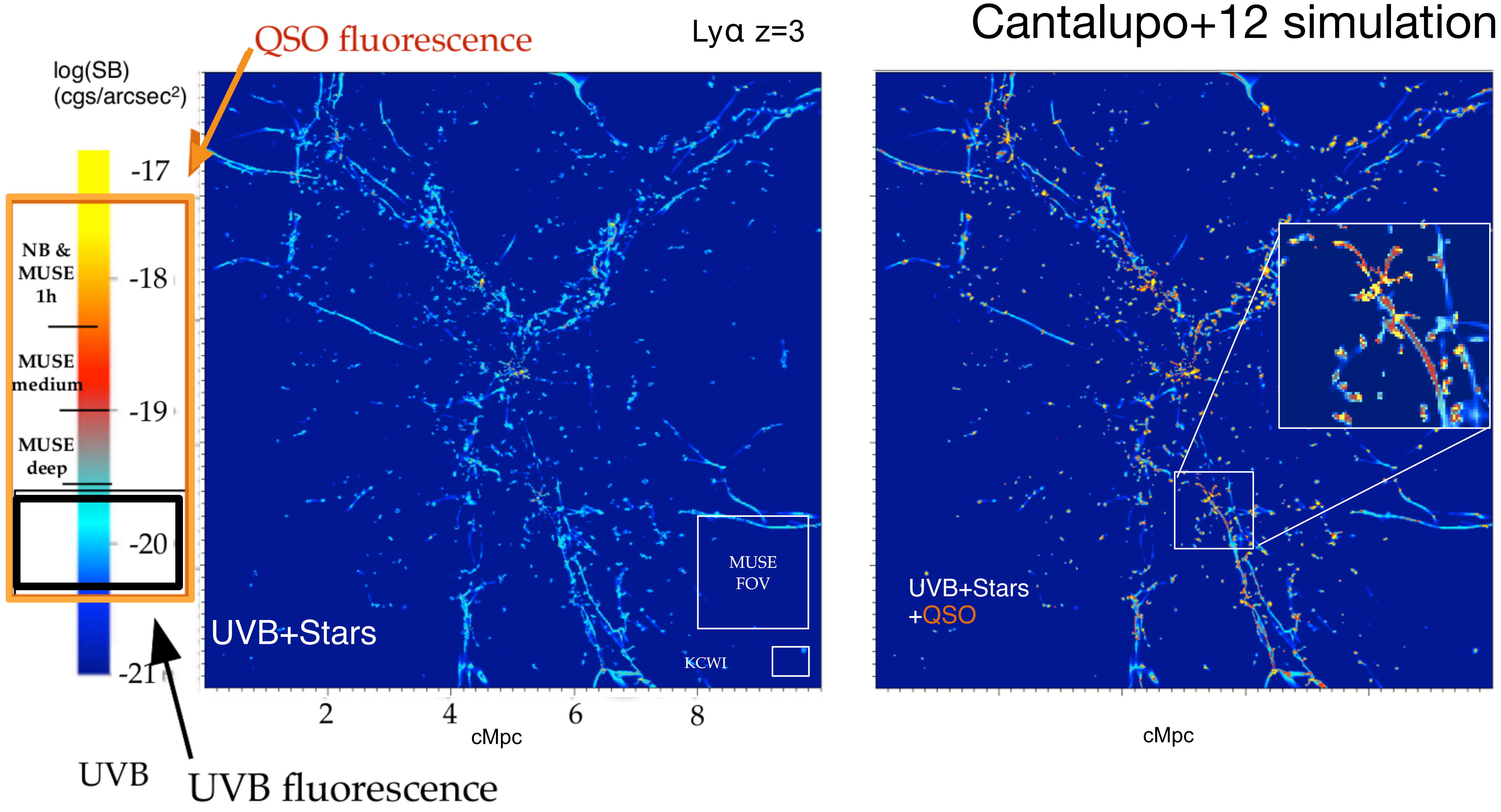
Fluorescent Lyα emission

$$\Gamma_{\rm HI} = 4\pi \int_{\nu_0}^{\infty} \frac{J_\nu\, \sigma_\nu\, d\nu}{h\nu}$$

$$\mathrm{R}_{\rm Ly\alpha} = \epsilon_{\rm thick} \int_{\nu_0}^{4\nu_0} \frac{J_\nu\, d\nu}{h\nu}$$

$$\mathrm{SB}_{\rm Ly\alpha} \simeq 1.84 \times 10^{-17} \mathrm{erg\,s^{-1}\,cm^{-2}\,arcsec^{-2}} \left(\frac{\Gamma_{\rm HI}}{10^{-12}\mathrm{s}^{-1}}\right)\left(\frac{\bar{\sigma}_{\nu_{\rm HI}}}{10^{-18}\mathrm{cm}^2}\right)^{-1}(1+z)^{-4}.$$

Cantalupo+12 simulation



Expected Lyα surface brightness (SB) for UVB fluorescence $\sim 10^{-20}$ erg/s/cm²/arcsec² (z=3.5)

Stacking is currently required

How to detect the UVB via Lyα emission?

Valid only for a single LLS

$$\mathrm{SB_{Ly\alpha}} \simeq 1.84 \times 10^{-17} \mathrm{erg\,s^{-1}\,cm^{-2}\,arcsec^{-2}} \left(\frac{\Gamma_{\mathrm{HI}}}{10^{-12}\mathrm{s}^{-1}}\right)\left(\frac{\bar{\sigma}_{\nu_{\mathrm{HI}}}}{10^{-18}\mathrm{cm}^2}\right)^{-1}(1+z)^{-4}.$$

The covering fraction of Lyman limit systems

$\times$ $\mathrm{f_{LLS}}$

$$\mathrm{f_{LLS}} \times \Gamma_{\mathrm{HI}} = \mathrm{SB_{Ly\alpha,obs}} \times \frac{\Gamma_{\mathrm{HI,model}}}{\mathrm{SB_{Ly\alpha,model}}}.$$

Chosen model
Haardt & Madau 2012
(HM12)

New method to constrain the UVB

- Based on fluorescent Lyα emission
- Independent of previous methods
- Depends weakly on the UVB spectral shape
- Stacking around “normal” galaxies on deep observations
- Requires knowing the distribution of LLS around galaxies

Observations

MUSE Integral Field Spectrograph

$\mathrm{Ly}\alpha$ redshift range:

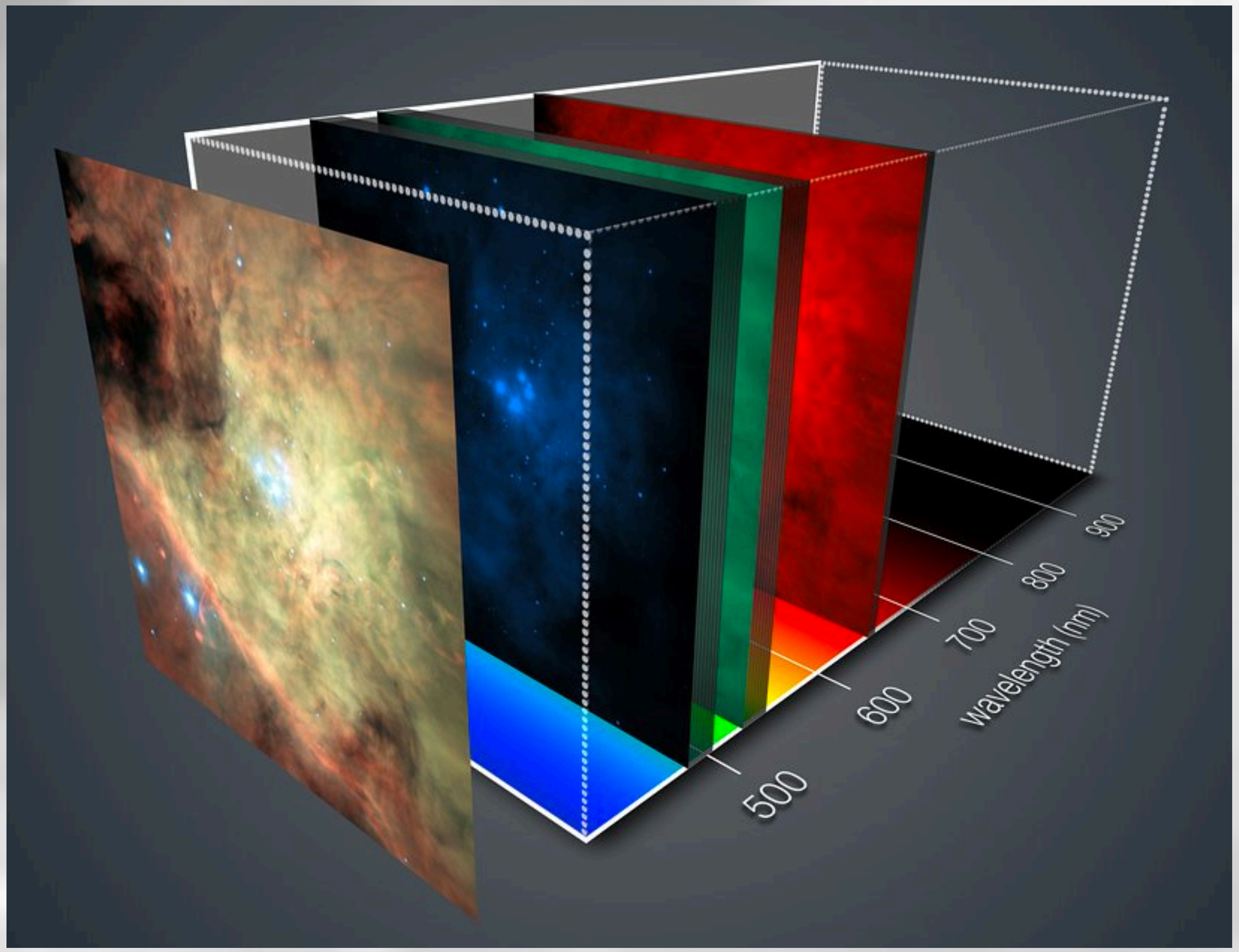
$2.9 < z < 6.6$

Voxel size:

0.2” x 0.2” x 1.25 Å

At $z=3.5$,

~1.5 kpc x 1.5 kpc x 120 kpc (60 km/s)



Field of View:

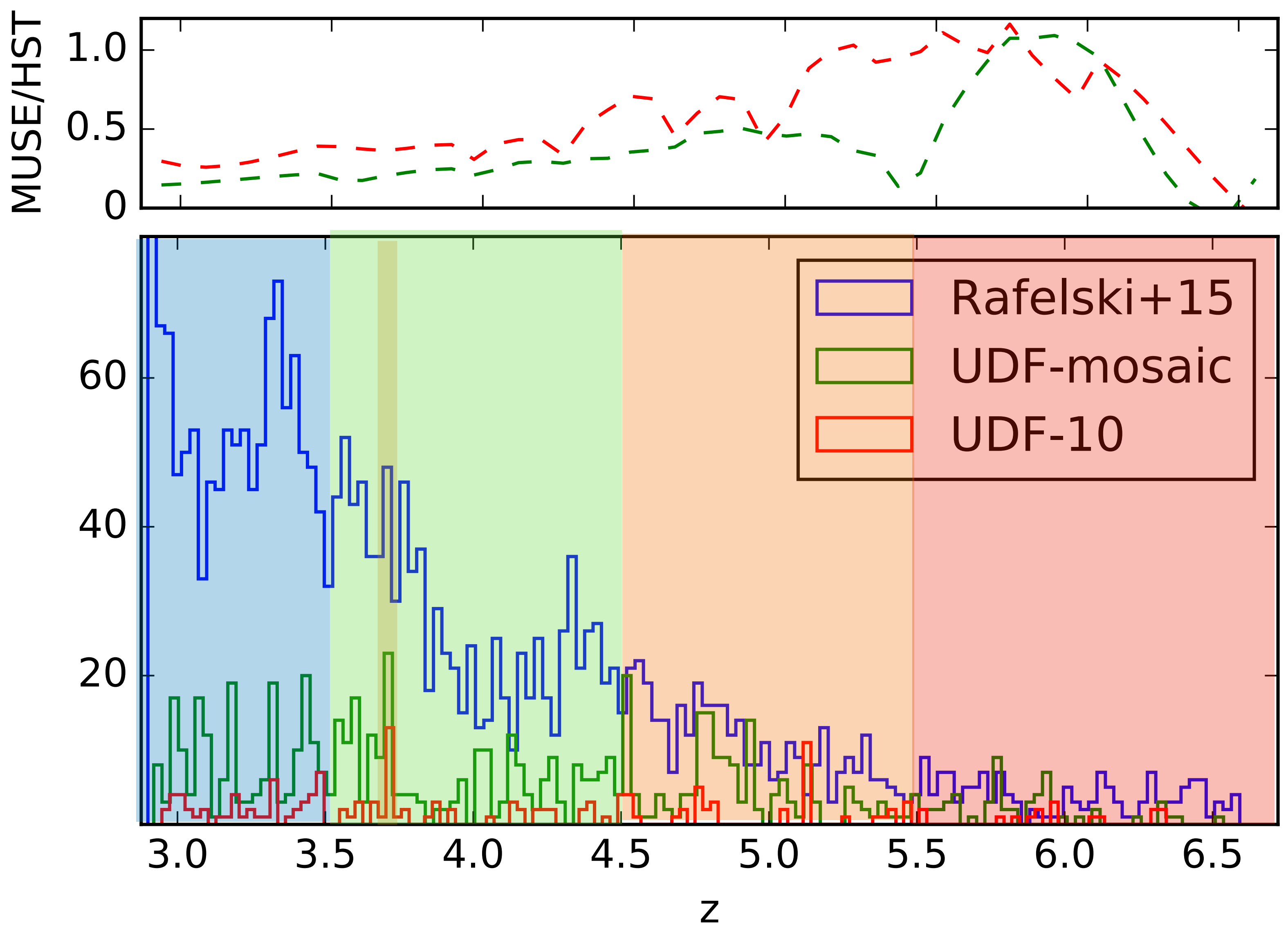
1x1 arcmin^2

VLT @ Paranal

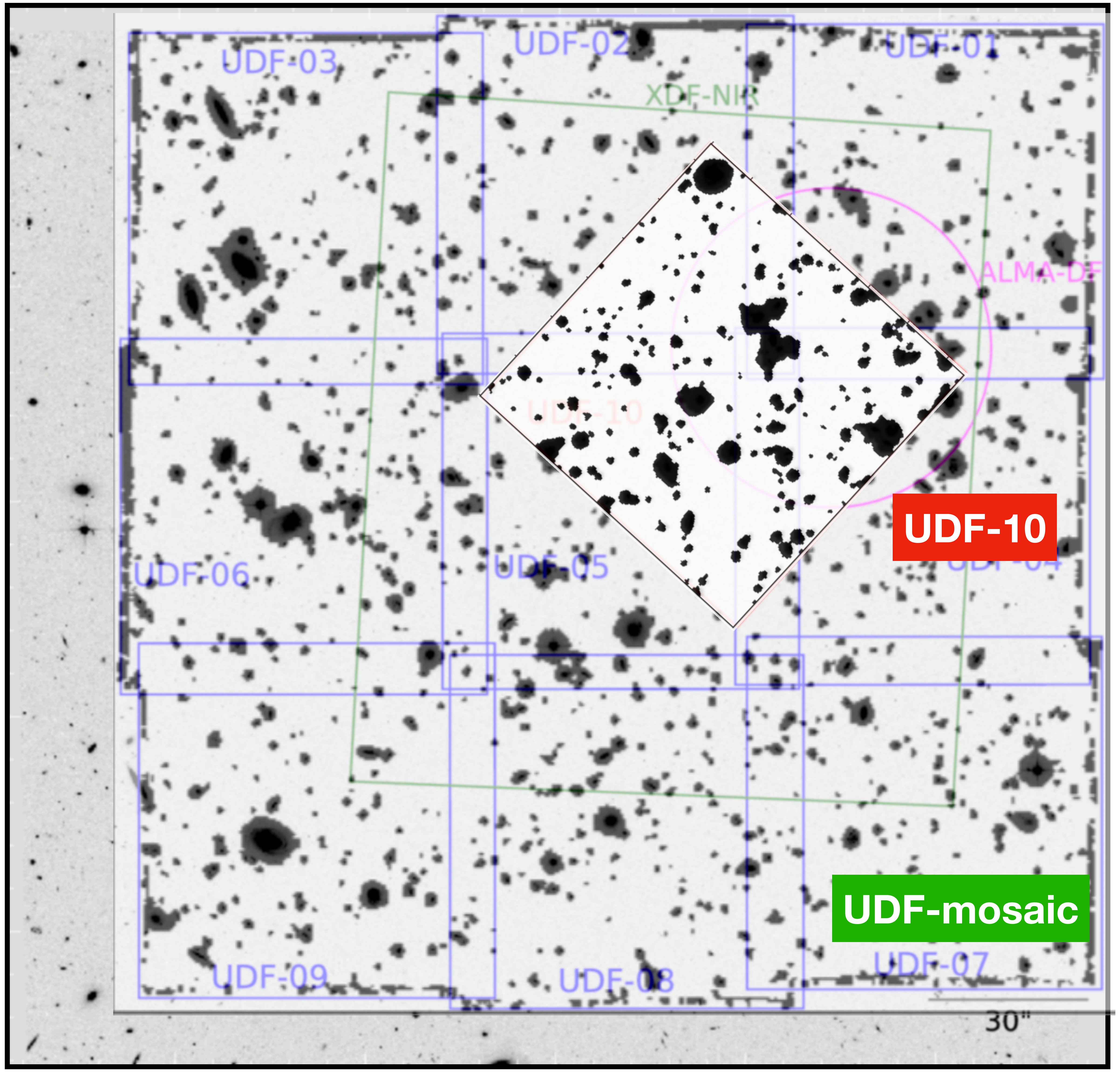
Observations

MUSE Ultra Deep Field

LAE redshift distribution



4 redshift bins to avoid evolution of the UVB and fLLS but maintain a sufficiently high SNR



$$\mathrm{SB}_{5500\text{Å}} \sim 10^{-19} \mathrm{erg\,s^{-1}cm^{-2}arcsec^{-2}}$$

30 h field

1 arcmin^2

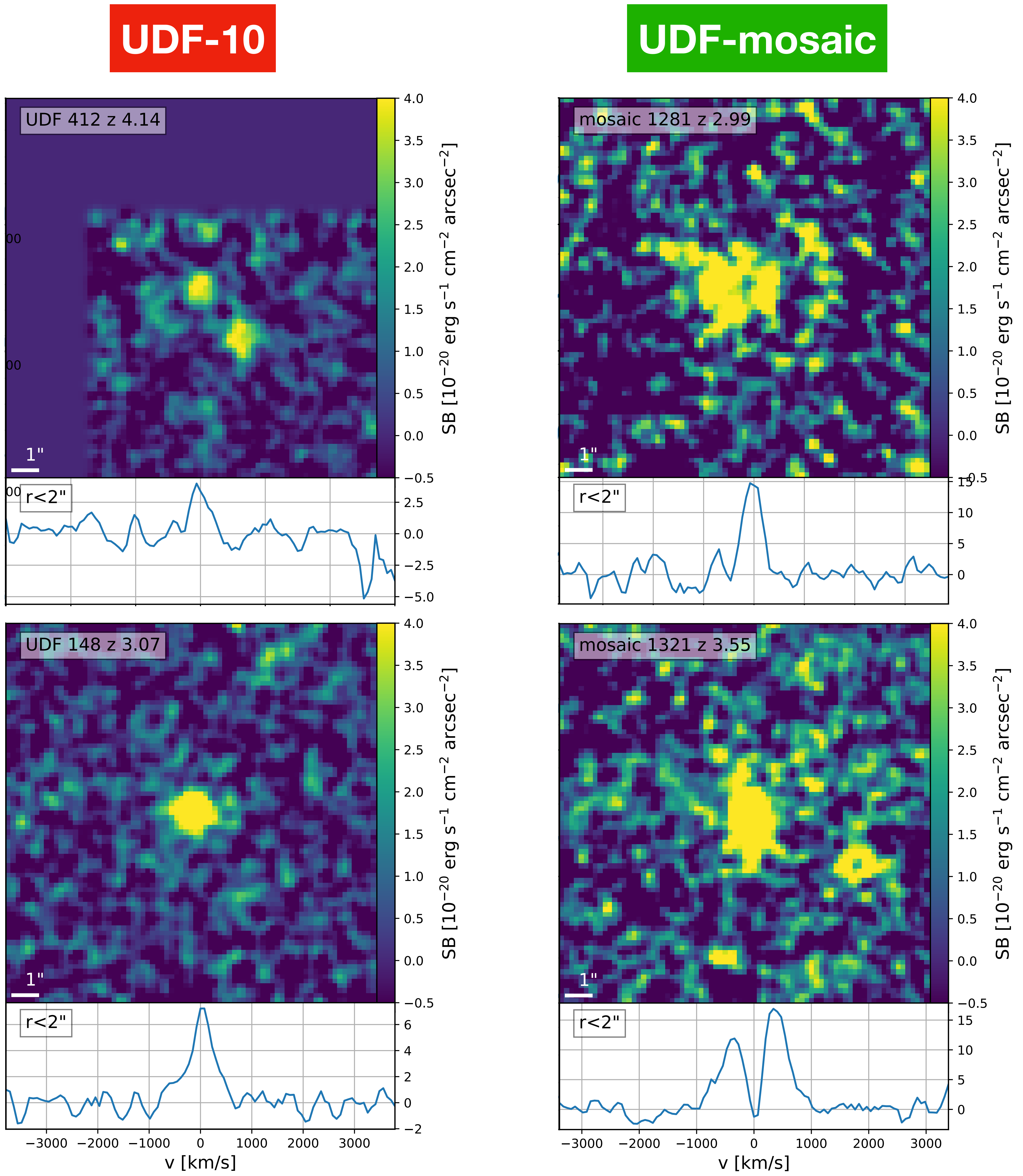
10 h per field

3x3 arcmin^2

Observations

Subcube extraction & stacking

- Subcubes of $40'' \times 40'' \times 125\,\text{Å}$
- Centered on the 3D peak of the Lyα emission
- Background truncated after $20''$ and $12.5\,\text{Å}$ from the center for each subcube
- Stacking using average 3σ clipping algorithm for each voxel



Simulations

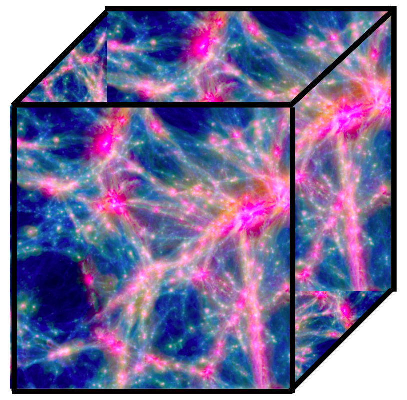
Why are they necessary?

- Lack of observational constraints on f_{LLS} at $z>3$
- Some cosmological simulations can produce a gas density distribution within the IGM and around realistic galaxies
- Mock cubes similar to real data can be produced and compared with other observational results

Simulations

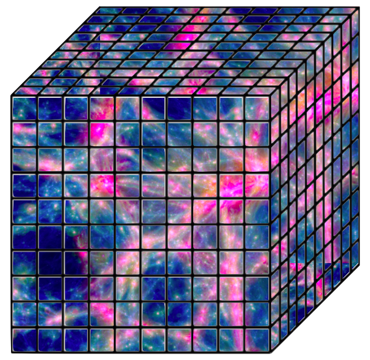
Mock cube generation

select simulation



EAGLE
Recal-L0025N0752
25 cMpc^3

particle to grid



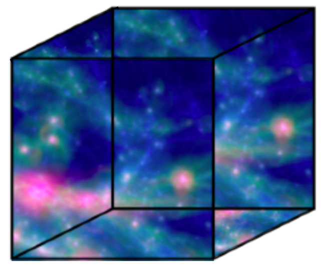
n_H, T

Line of sight (LoS)
1.25Å

n_{HI}

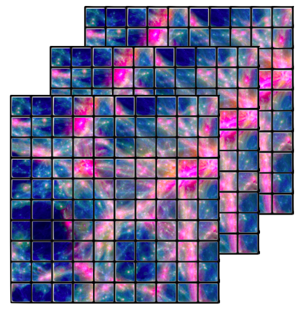
caculate H neutral density for equilibrium:

$$n_{\mathrm{H\,I}}\,\Gamma_{\mathrm{TOT}} = \alpha_{\mathrm{A}}\; n_{\mathrm{e}}\; n_{\mathrm{H\,II}},$$
$$\Gamma_{\mathrm{TOT}} = \Gamma_{\mathrm{Phot}} + \Gamma_{\mathrm{Col}},$$

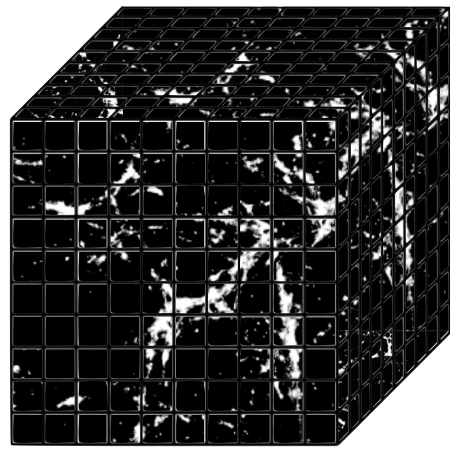


N_{HI}

colapse one direction to obtain a column density



f_{LLS}

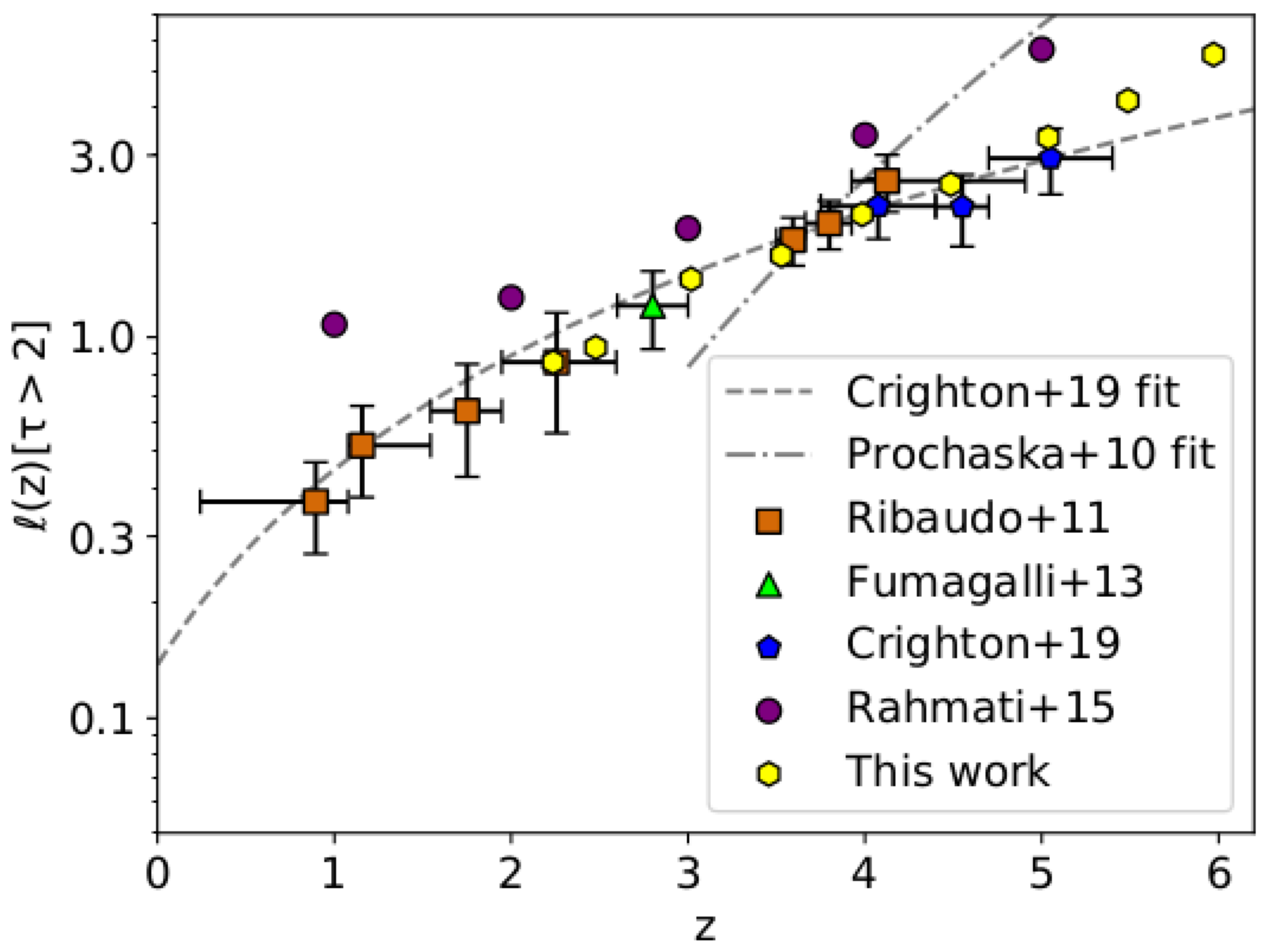


Convert to LLS covering fraction:
$N_{HI} > 10^{17.5}$ = 1
(τ_{LL}>2)
otherwise 0

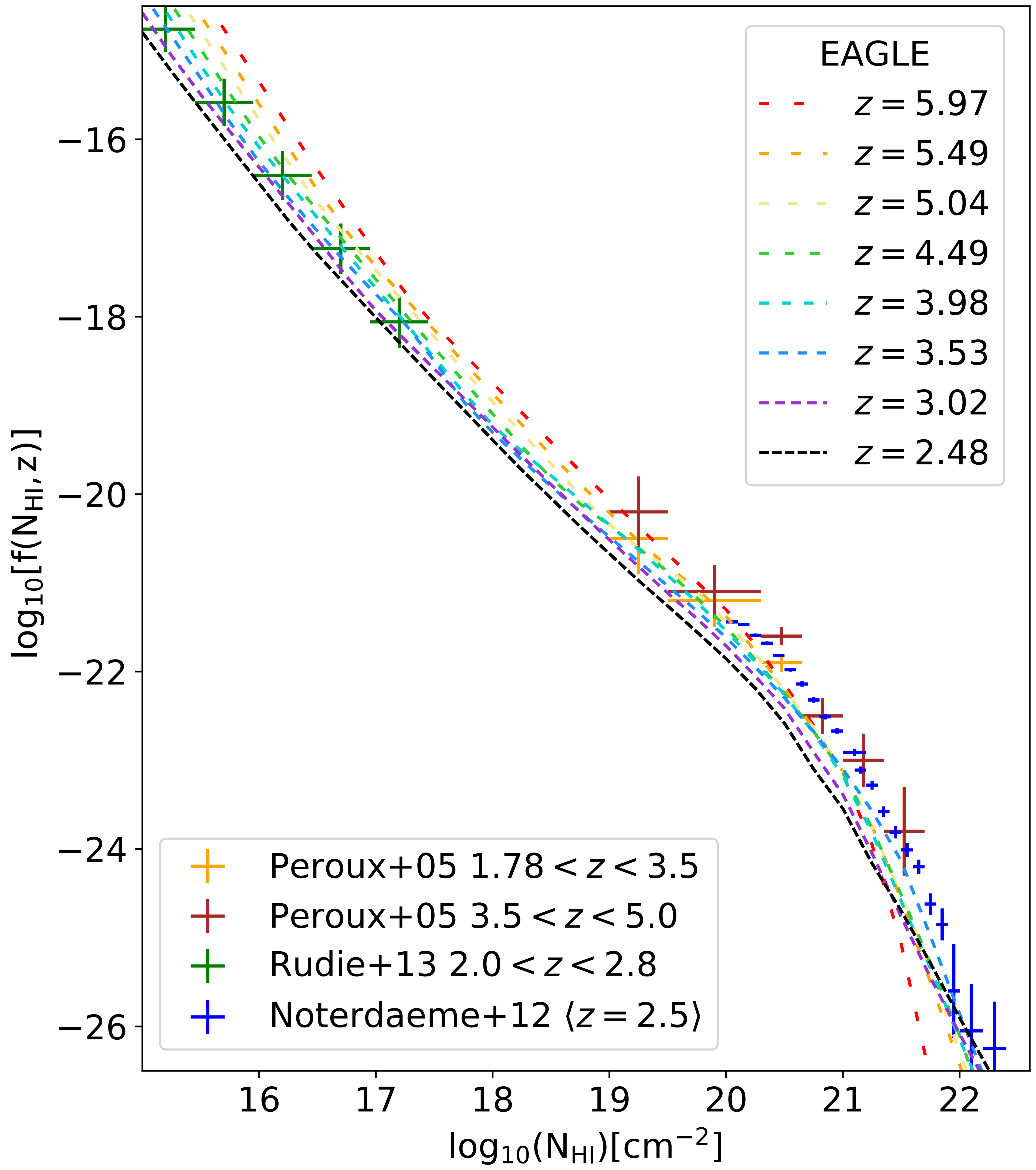
Simulations

Constraining f_{LLS}

Number of LLSs per unit redshift



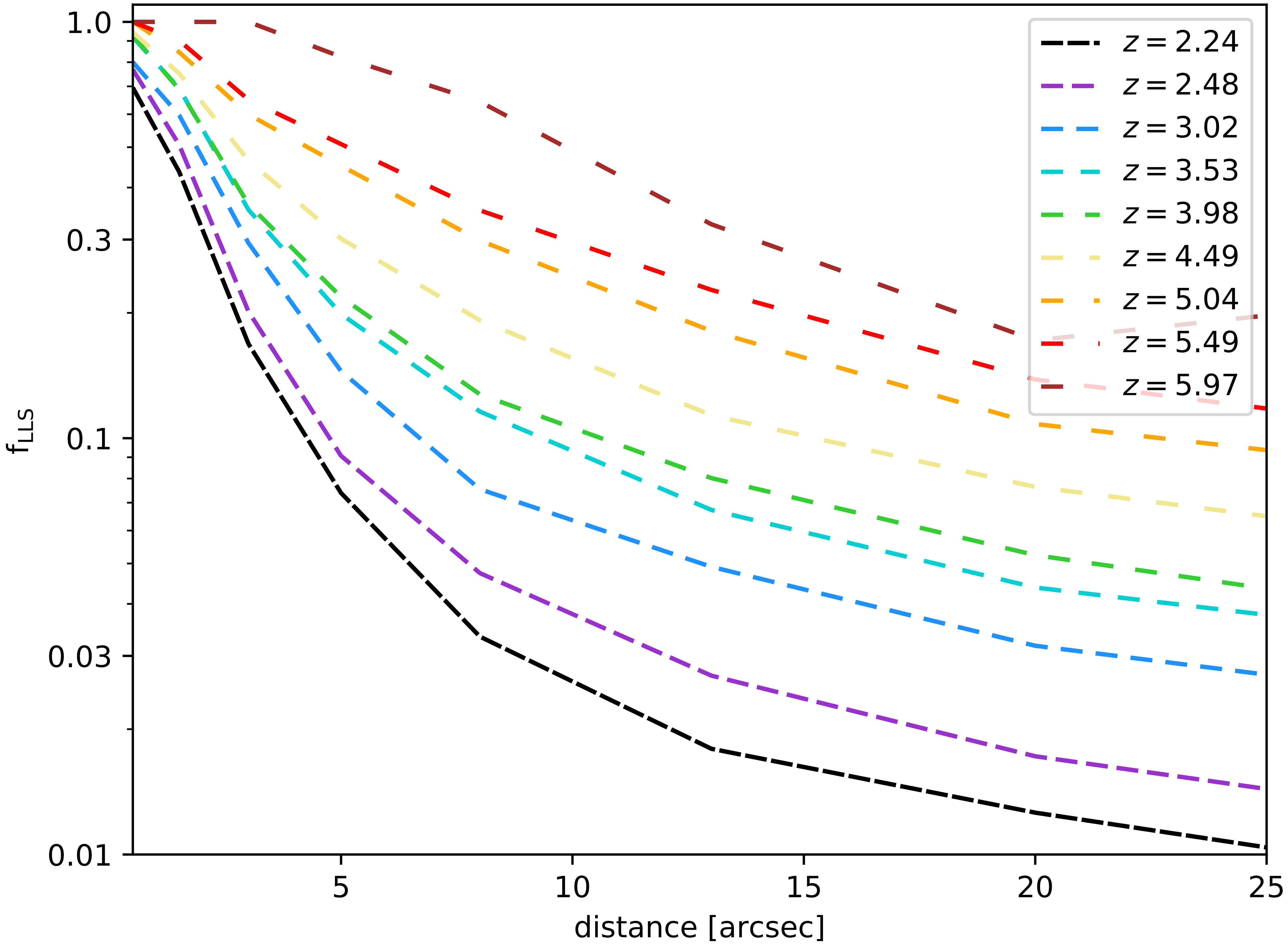
Column density distribution



Gallego+2021

Simulations

Stacked f_{LLS} radial profiles around star-forming galaxies



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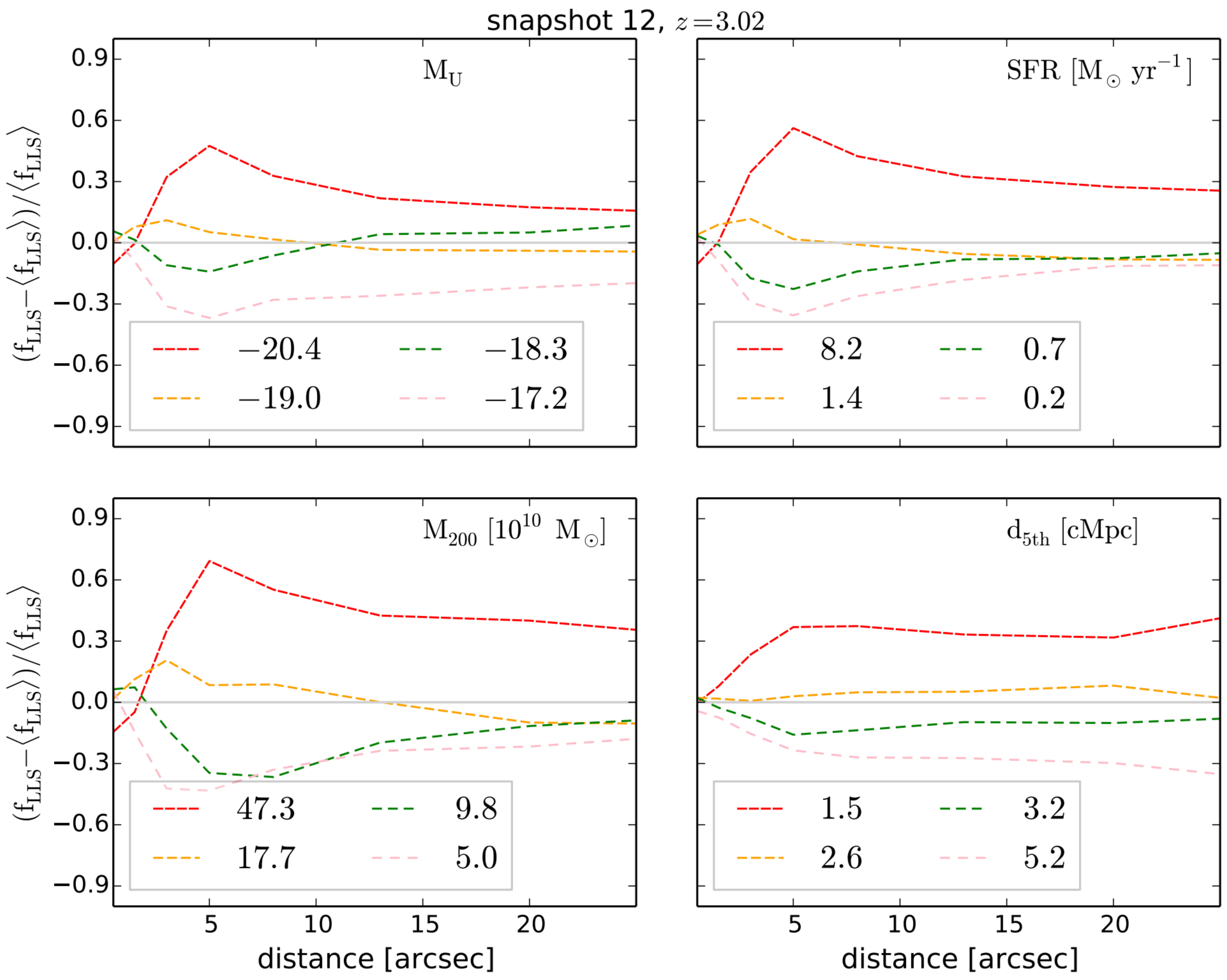
Simulations

LLS covering fraction radial profiles



d_{5th}: distance to the 5th closest neighbour

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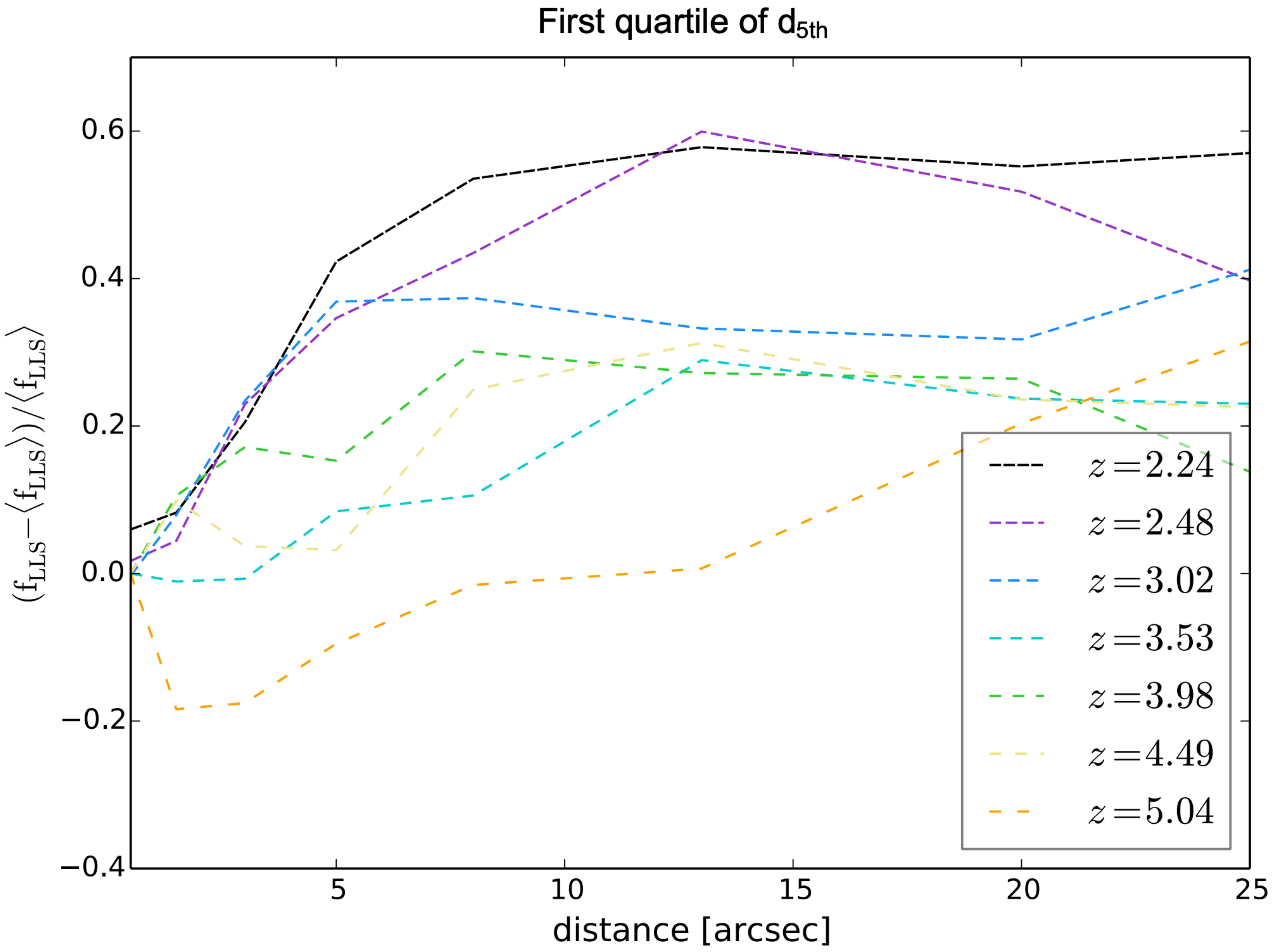
Simulations

LLS covering fraction radial profiles



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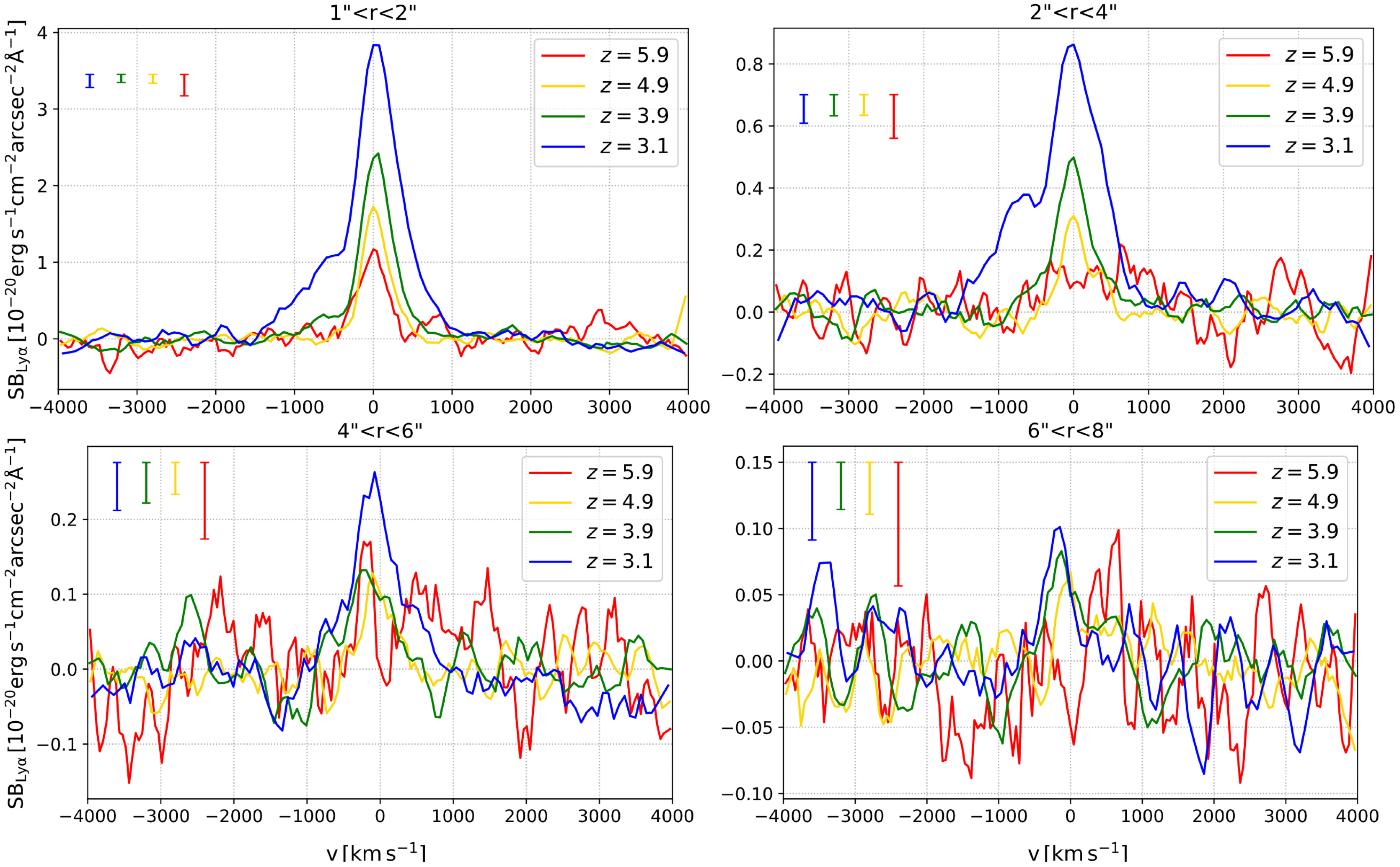
Results

Stacked spectra



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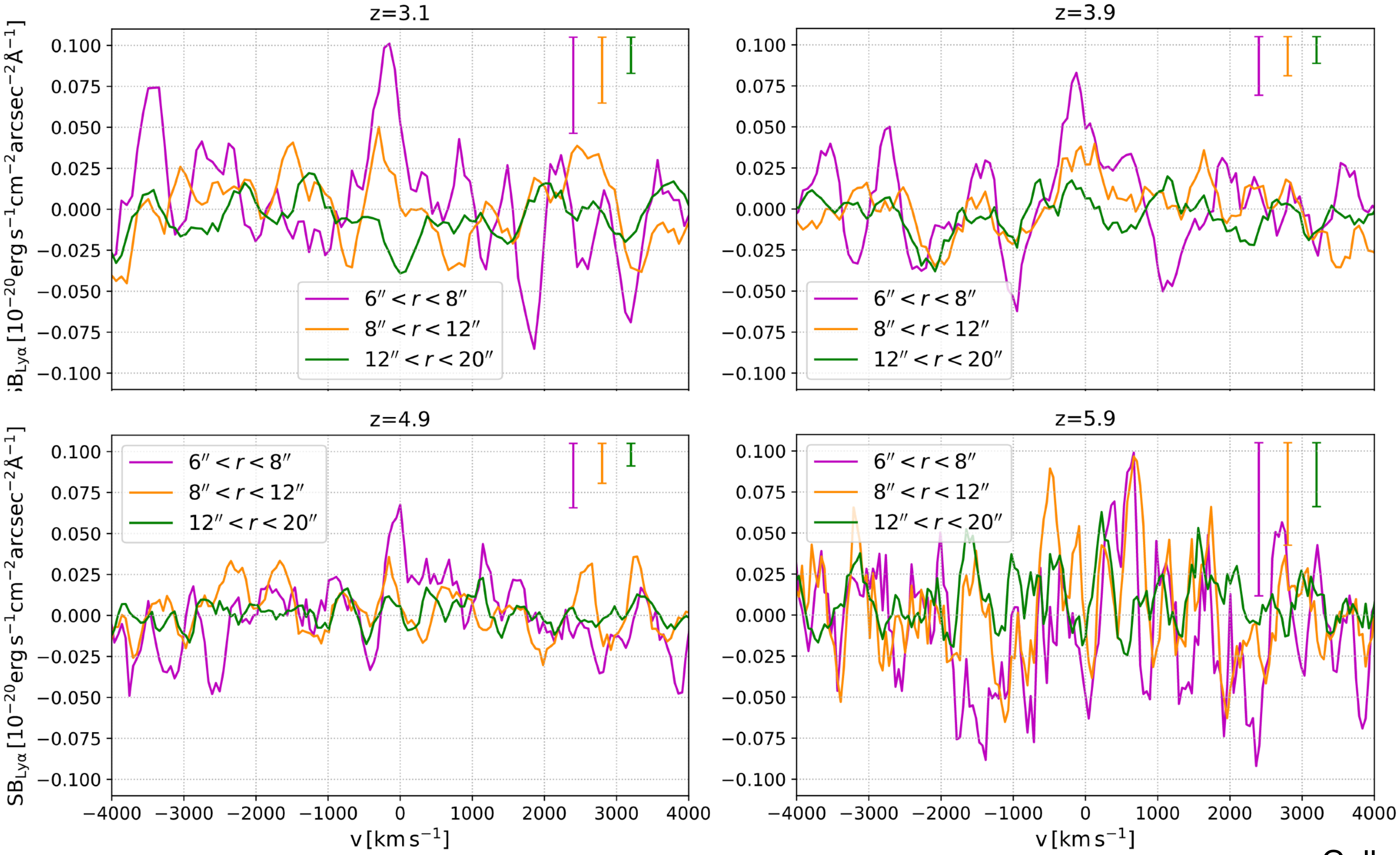
Results

Stacked spectra



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Results

Observational summary

$$\boxed{\mathrm{f_{LLS}} \times \Gamma_{\mathrm{HI}} = \mathrm{SB}_{\mathrm{Ly}\alpha,\mathrm{obs}} \times \frac{\Gamma_{\mathrm{HI,model}}}{\mathrm{SB}_{\mathrm{Ly}\alpha,\mathrm{model}}}.}$$

SB $[10^{-20}\,\mathrm{erg\,s^{-2}cm^{-2}arcsec^{-2}}]$ between 8” and 20” away from LAEs

z range	z mean	Number of LAEs (UDF-10, -mosaic)	Expected HM12 $\mathrm{SB_{Ly\alpha}}$	Measured $\mathrm{SB_{Ly\alpha}}$	Predicted $\Gamma_{\mathrm{HI}} \times \mathrm{f_{LLS}}$	Predicted $\mathrm{f_{LLS}}$ for HM12	Predicted $\mathrm{f_{LLS}}$ for HM01
2.9 - 3.4	3.1	33, 140	2.0	< 0.18	< 0.07	$< 9\%$	$< 6\%$
3.4 - 4.5	3.9	46, 242	0.79	0.19 ± 0.07	0.11 ± 0.05	$24\% \pm 9\%$	$15\% \pm 5\%$
4.5 - 5.5	4.9	43, 162	0.28	< 0.14	< 0.22	$< 50\%$	$< 35\%$
5.5 - 6.5	5.9	16, 54	0.1	< 0.36	< 1.0	$< 100\%$	$< 100\%$

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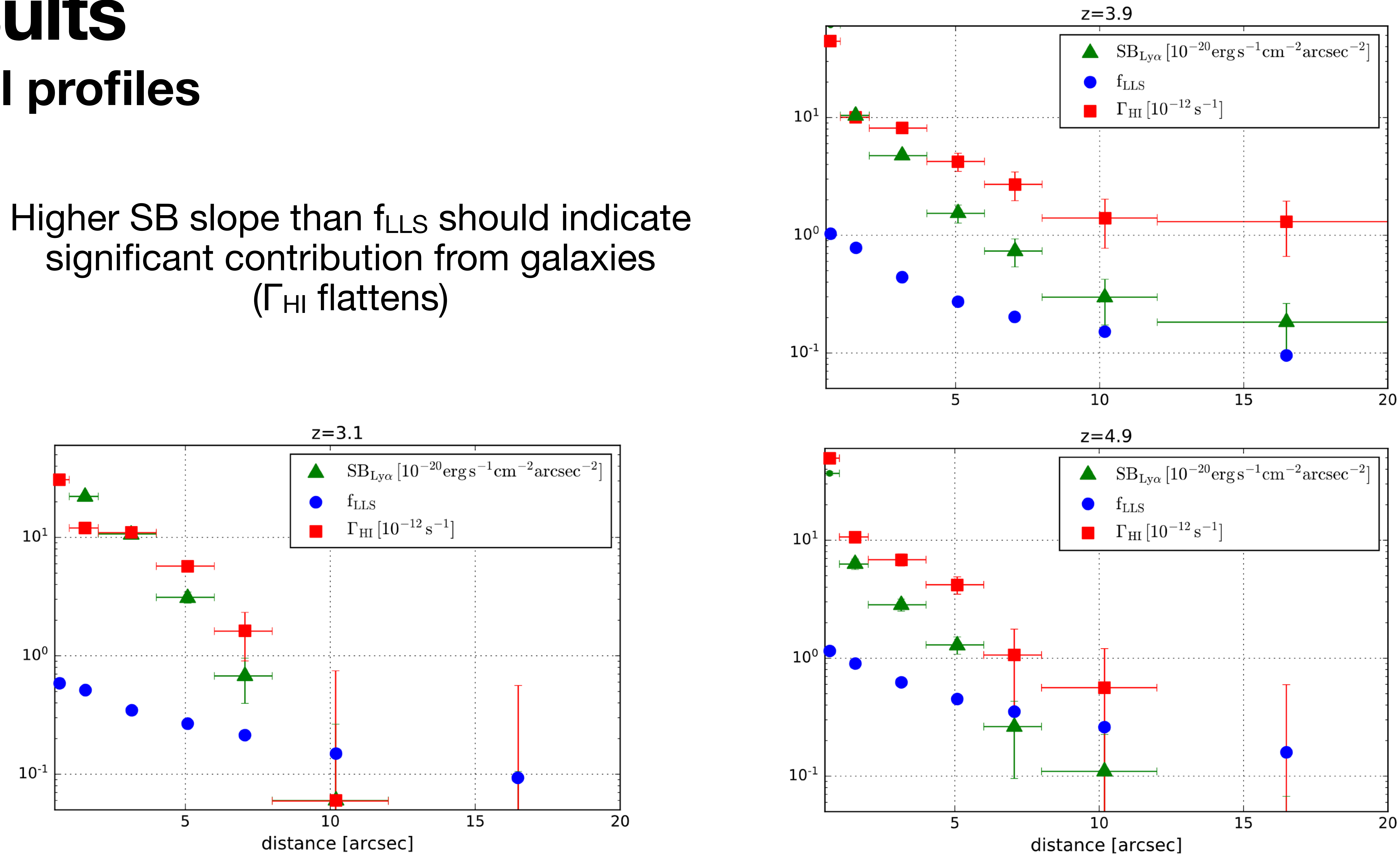
Results

Radial profiles

Higher SB slope than f_{LLS} should indicate significant contribution from galaxies (Γ_{HI} flattens)

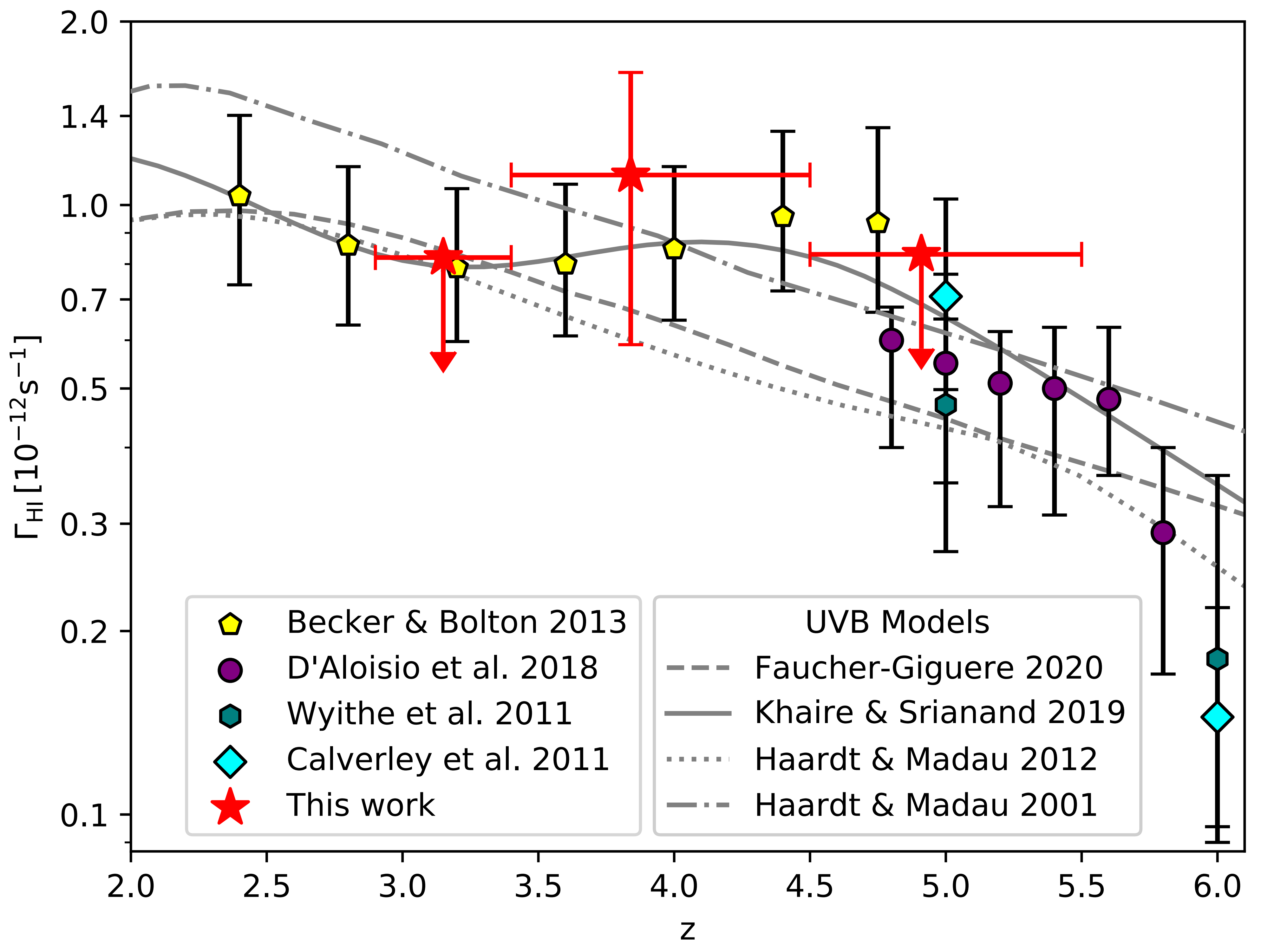


UVB Constraints

Summary

$$\mathrm{f_{LLS}} \times \Gamma_{\mathrm{HI}} = \mathrm{SB}_{\mathrm{Ly}\alpha,\mathrm{obs}} \times \frac{\Gamma_{\mathrm{HI,model}}}{\mathrm{SB}_{\mathrm{Ly}\alpha,\mathrm{model}}}.$$

z mean	Measured $\mathrm{SB}_{\mathrm{Ly}\alpha}$	$\mathrm{f_{LLS}}$ EAGLE	Predicted Γ_{HI}
3.1	< 0.18	$8.3 \pm 0.2\%$	< 0.82
3.9	0.19 ± 0.07	$10.6 \pm 0.4\%$	1.12 ± 0.53
4.9	< 0.14	$20.2 \pm 0.7\%$	< 0.85



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Other Mechanisms Affecting the Observed Lyα

Basic assumption

Fluorescence by the UVB is the only mechanism producing Lyα emission.

Other potential mechanisms

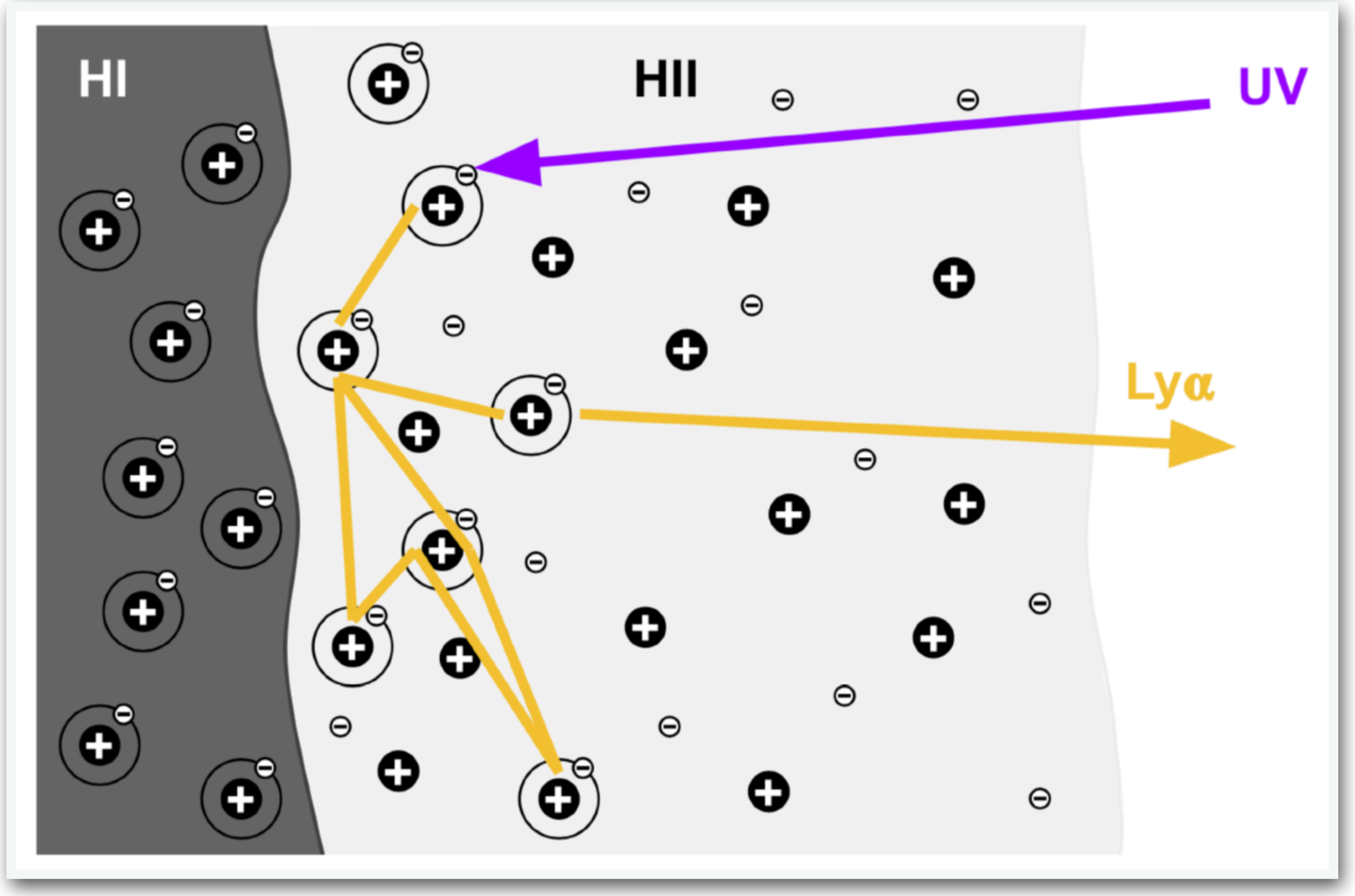
- Scattering
- Collisional excitation
- Ionizing radiation from central galaxies
- Local sources of ionizing or Lyα photons
- Absorption by dust
- Close AGN

Except for dust, they should enhance the expected emission.

Other Mechanisms Affecting the Observed Lyα

Scattering

- Lyα photons escaping from HII regions within galaxies and scattering to the IGM
- Requires a medium with optical depth $\tau \sim 1$



Collisional excitation

- Extremely sensitive to temperature
- Requires partially ionized medium
- Some CE could occur in the transition between the ionized exterior and the neutral interior of the clouds but it's very difficult to model
- There could be redshift dependence

Other Mechanisms Affecting the Observed Lyα

Ionizing radiation from central galaxies

- Ionzing photons escaping from the central galaxies
- Expected to decay with radius at least by the inverse-squared law
- As with the UVB, their contribution should be proportional to the ionizing radiation intensity
- Depends on the ionizing escape fraction and the production rate of ionizing photons
- Current UVB models assume dominant UVB radiation from galaxies at $z>3$ and a monotonic increase of the escape fraction. This does not match our results if this contribution is relevant.

Other Mechanisms Affecting the Observed Lyα

Local sources of ionizing and Lyα photons

- Many uncertainties in the low end of the UV and Lyα luminosity functions
- Undetected galaxies could contribute to the UV and Lyα photons
- Some theoretical models suggest a higher UV escape fraction for faint galaxies
- Those galaxies may be considered part of the total UVB budget

Absorption by dust

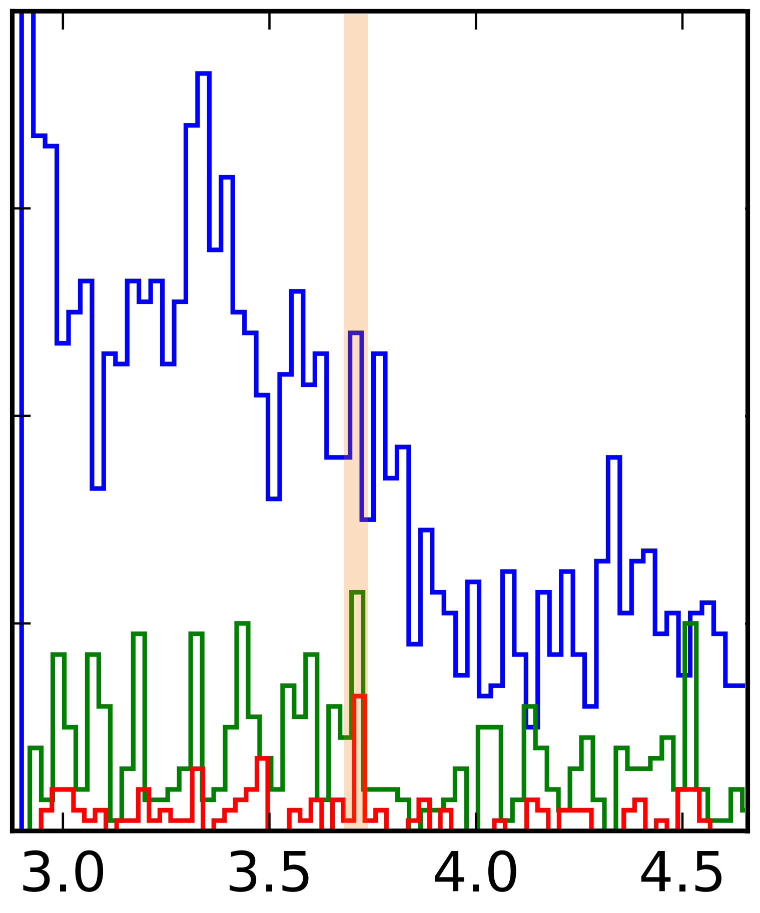
- Bias in the opposite direction of the other mechanisms
- Assuming Lyα photons are intergalactic, numerical simulations suggest little to no dust

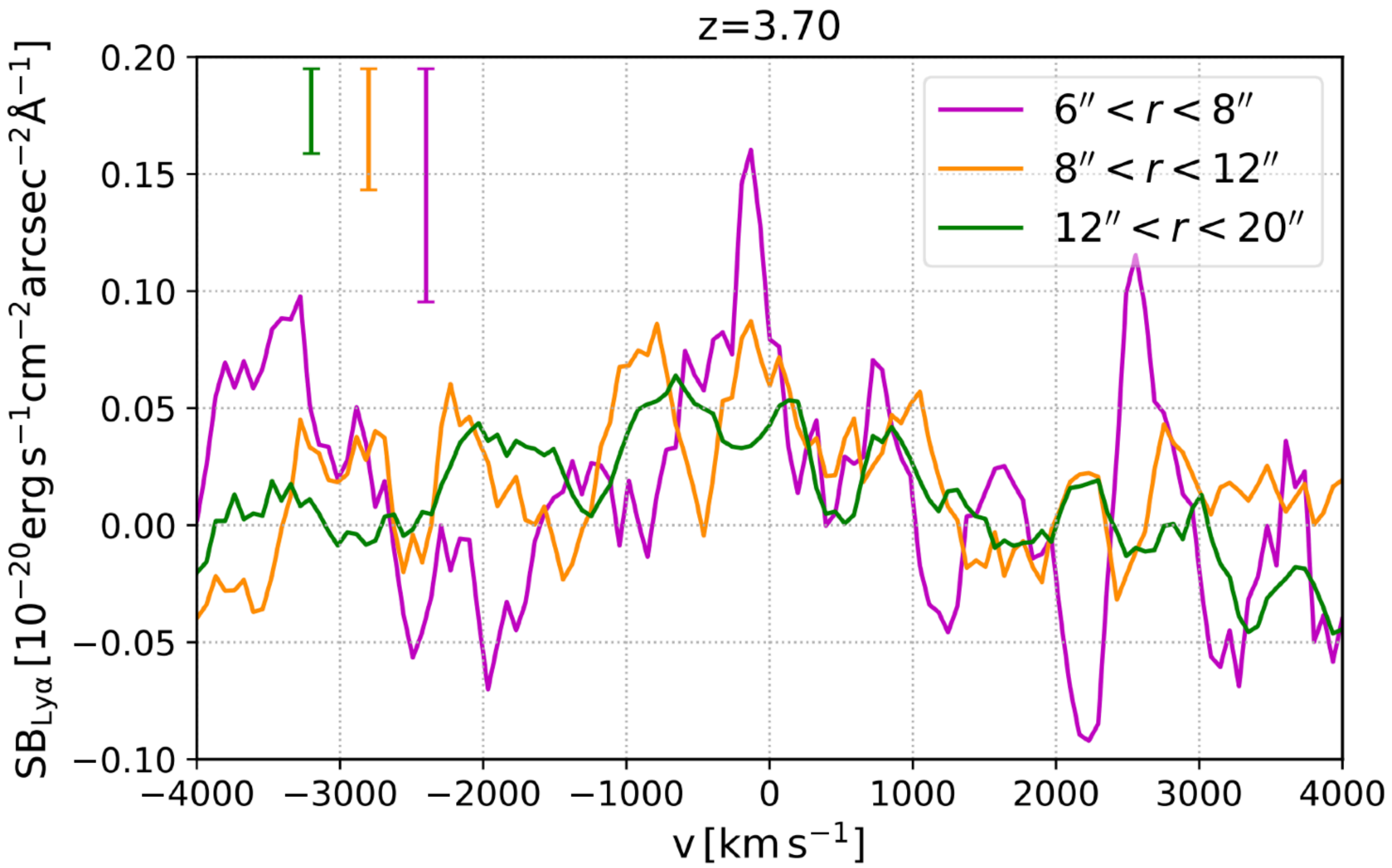
Other Mechanisms Affecting the Observed Lyα

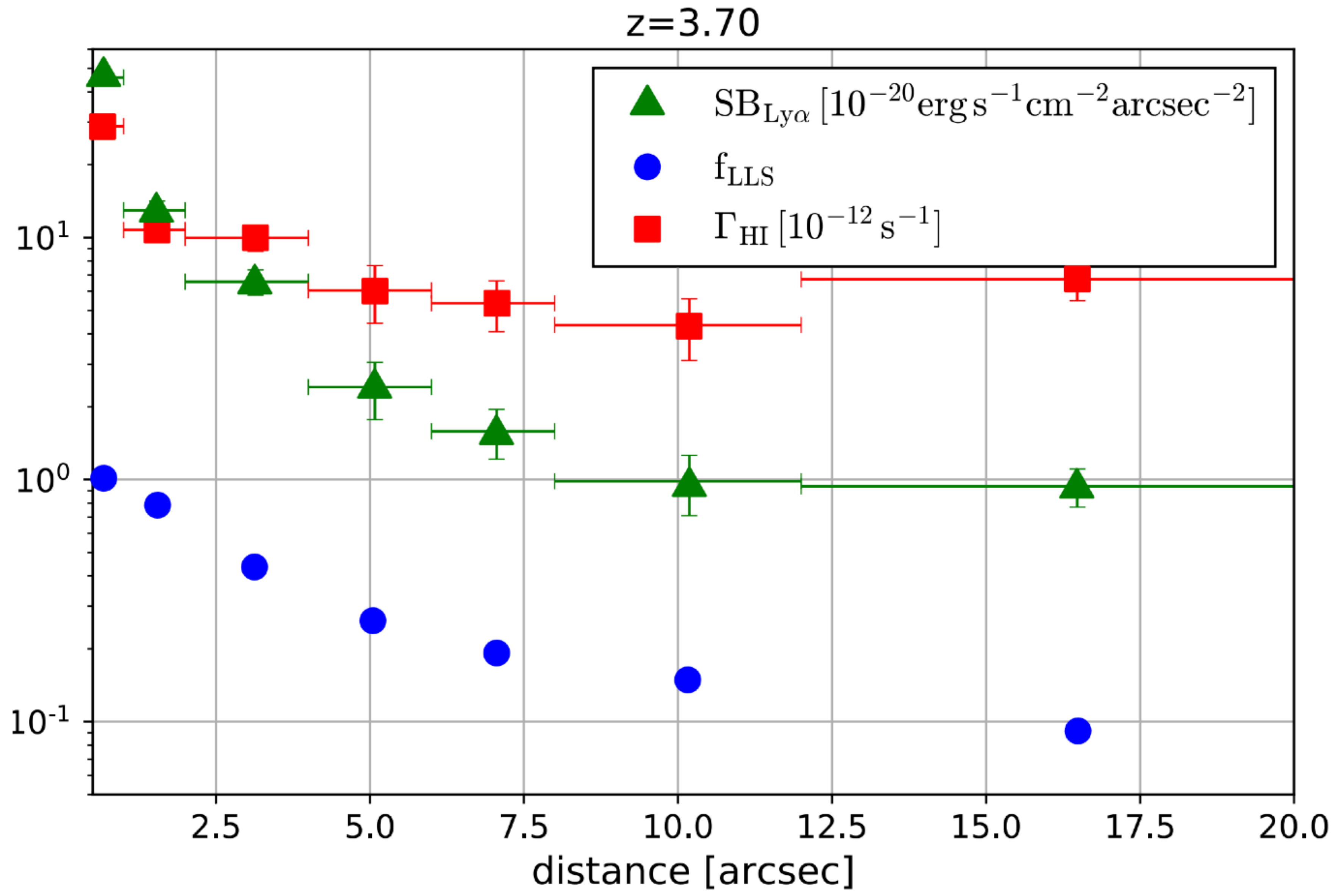
AGN contribution

- The majority of AGNs close to the MUSE field lie within $3.6 < z < 3.8$ which was excluded from our analysis
- Current catalogs suffer from severe incompleteness due to LoS obscuration
- AGNs are highly variable
- With simplified calculations we obtain about 4 AGN proximity regions within our detection at $3.4 < z < 4.5$ and about 4% of our selected galaxies could be affected

Γ_{HI} around galaxy and AGN overdensities



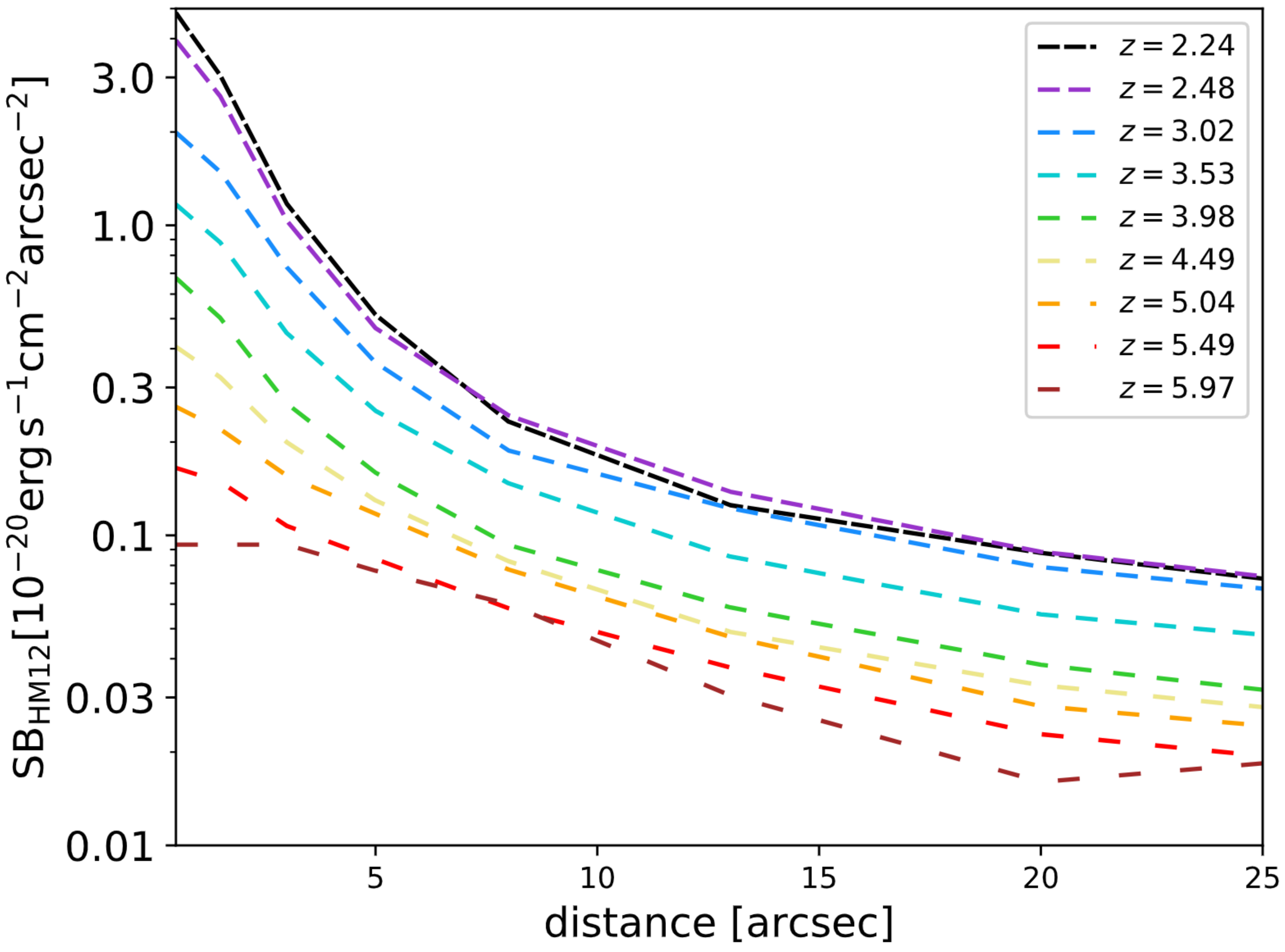


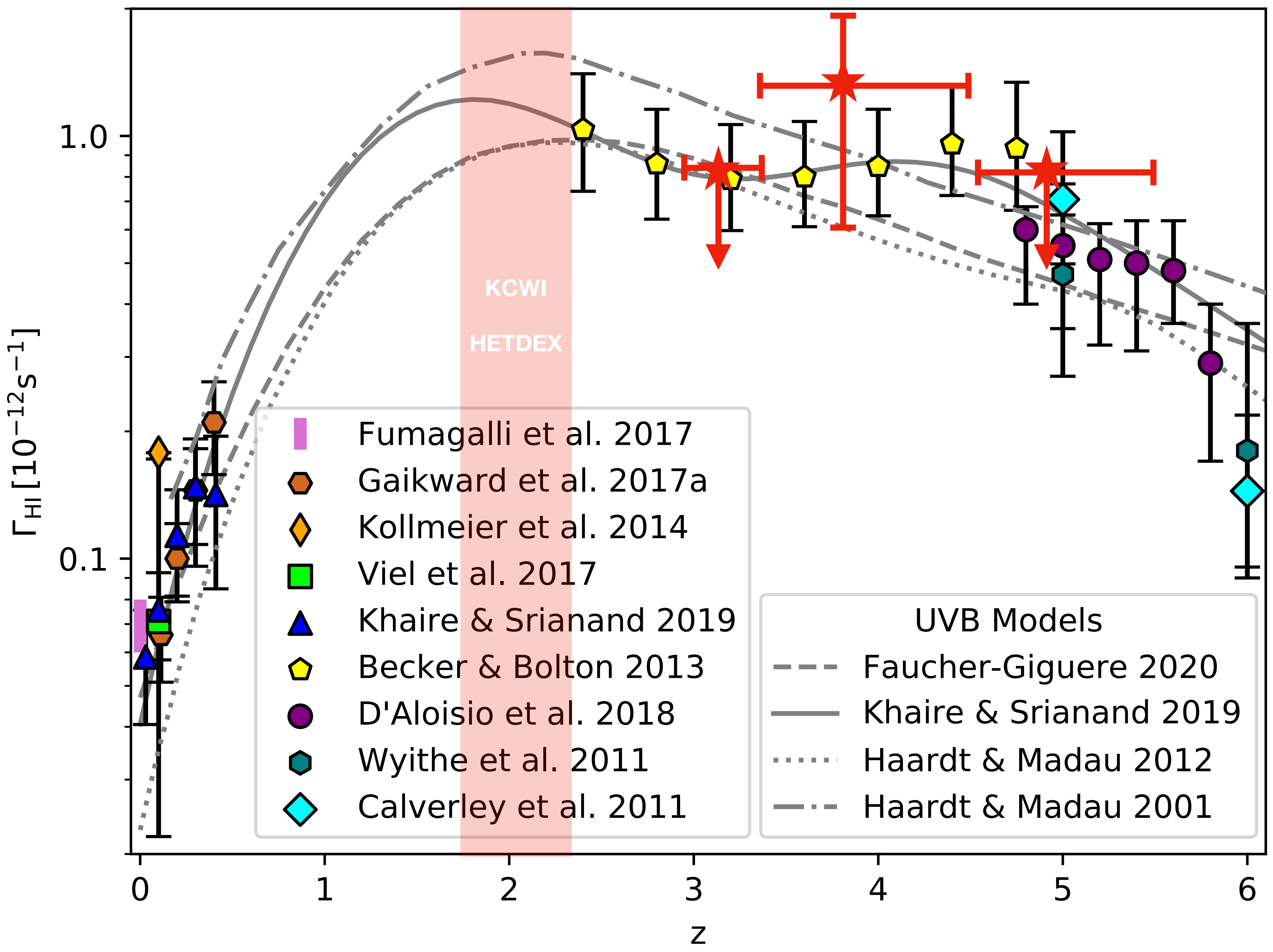


- We derived $\Gamma_{HI} \approx 6 \times 10^{-12}\,s^{-1}$, 10 times higher than HM12, for the overdose region between 3.65 < z < 3.75
- Could be due to the UV contribution from an AGN overdensity, consistent with previous expectations
- It is also possible an increased LLS covering fraction. We expect about 20% enhanced f_{LLS} from simulations, resulting in a Γ_{HI} still above the UVB

Prospects for the Future

EAGLE Mock Cubes SB prediction





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Summary

- The UVB shapes the ionization state and thermal evolution of the IGM
- We developed a new method to constrain the UVB, based on the detection of fluorescent Lya emission around galaxies
- This method is independent of previous studies with several parameters difficult to estimate
- We apply this method to MUSE deep observations combined with simulation constraints and obtain 2 upper limits for the UVB at 3.1 and 4.9, and a detection at 3.9
- Our results are consistent with previous studies and suggest a non-monotonic decrease of the UVB with increasing redshift between $3<z<5$, as suggested by some other indirect measurements
- These results also suggest the covering fraction of LLS at $3 < z < 4.5$ to be less than 25% within 150 kpc from LAEs

Thanks!

Sakura time in Zurich