A review of observational studies of the CGM and IGM

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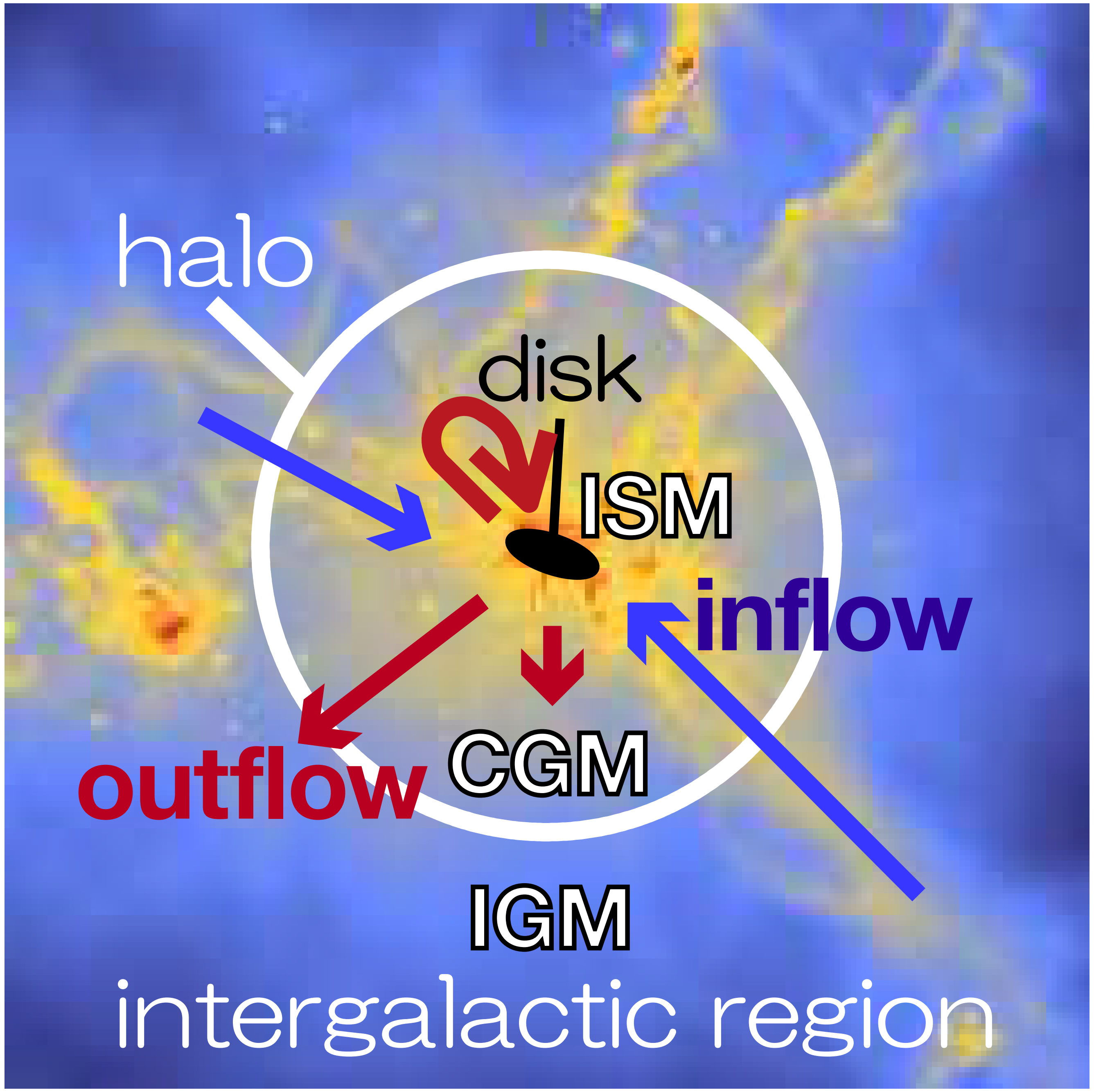
Galaxy and IGM Workshop 2020, August 3, 2020

CGM and IGM are crucial to trace an evolution of galaxies



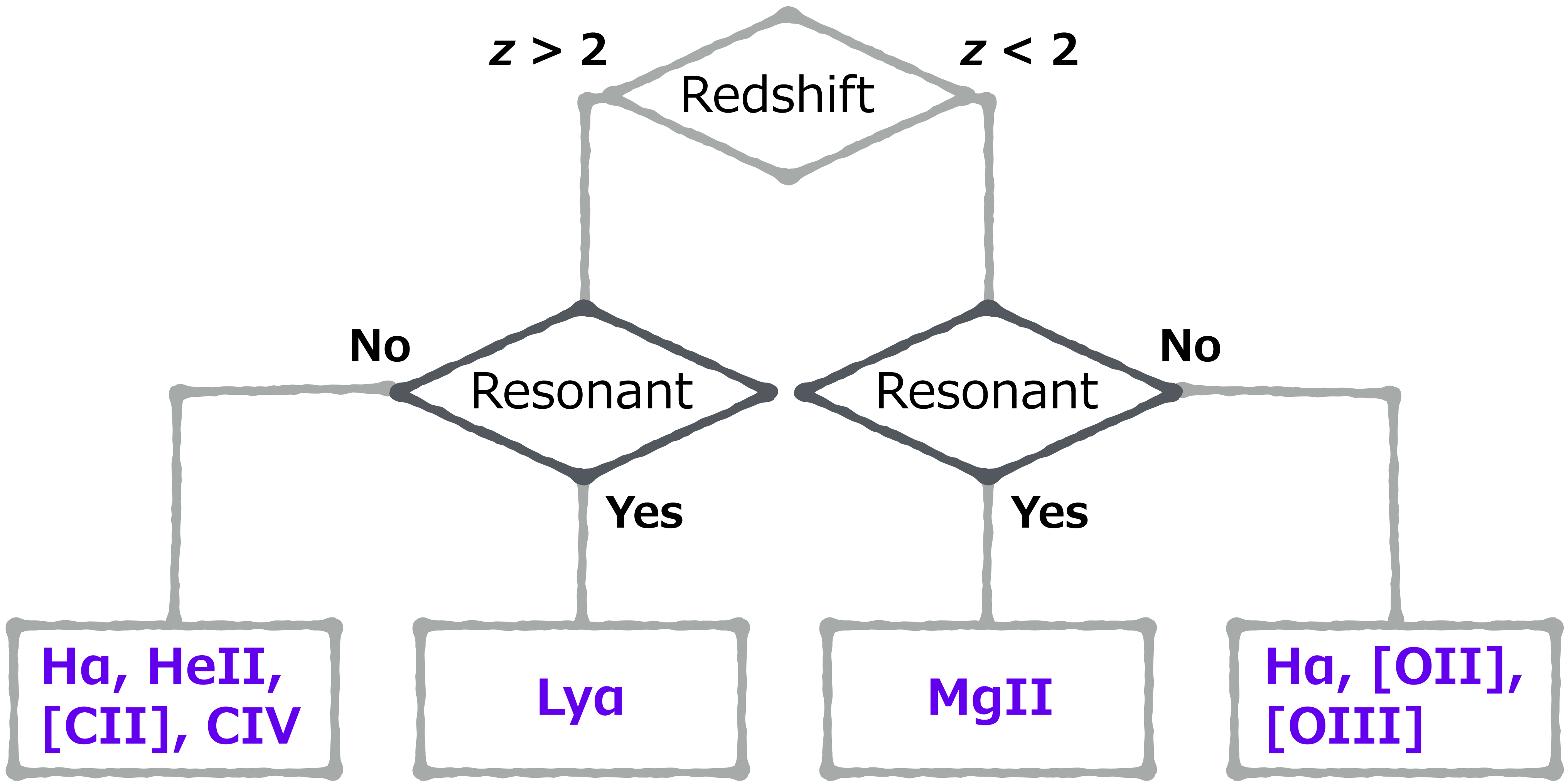
Diagnostics

	Absorption	Emission
Preference	Column density	Preferentially from high density
Physical Quantity	Gas phase, Abundances, Kinematics	Sizes, Morphology, Velocity fields,
Advantage	Wide dynamic range of column density	No privileged LoS
Dis-advantage	Limitation of one and random LoS	Too faint signal

※ LoS = line of sight

Van de Voort+16

Diagnostics to identify the CGM and IGM by line emission

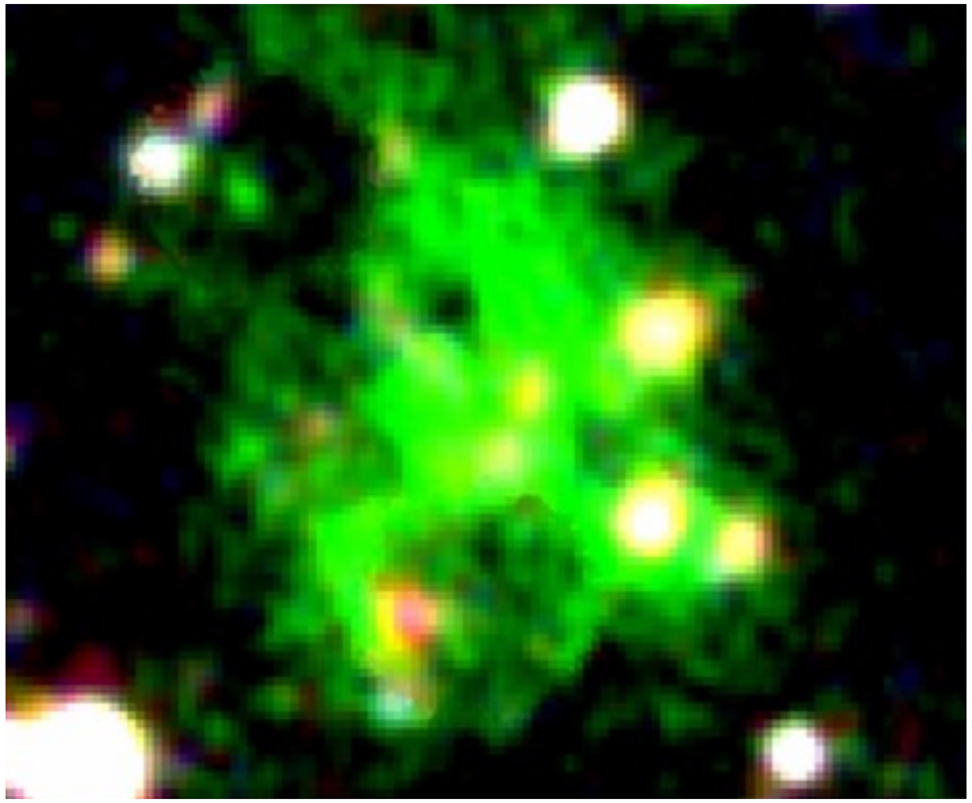


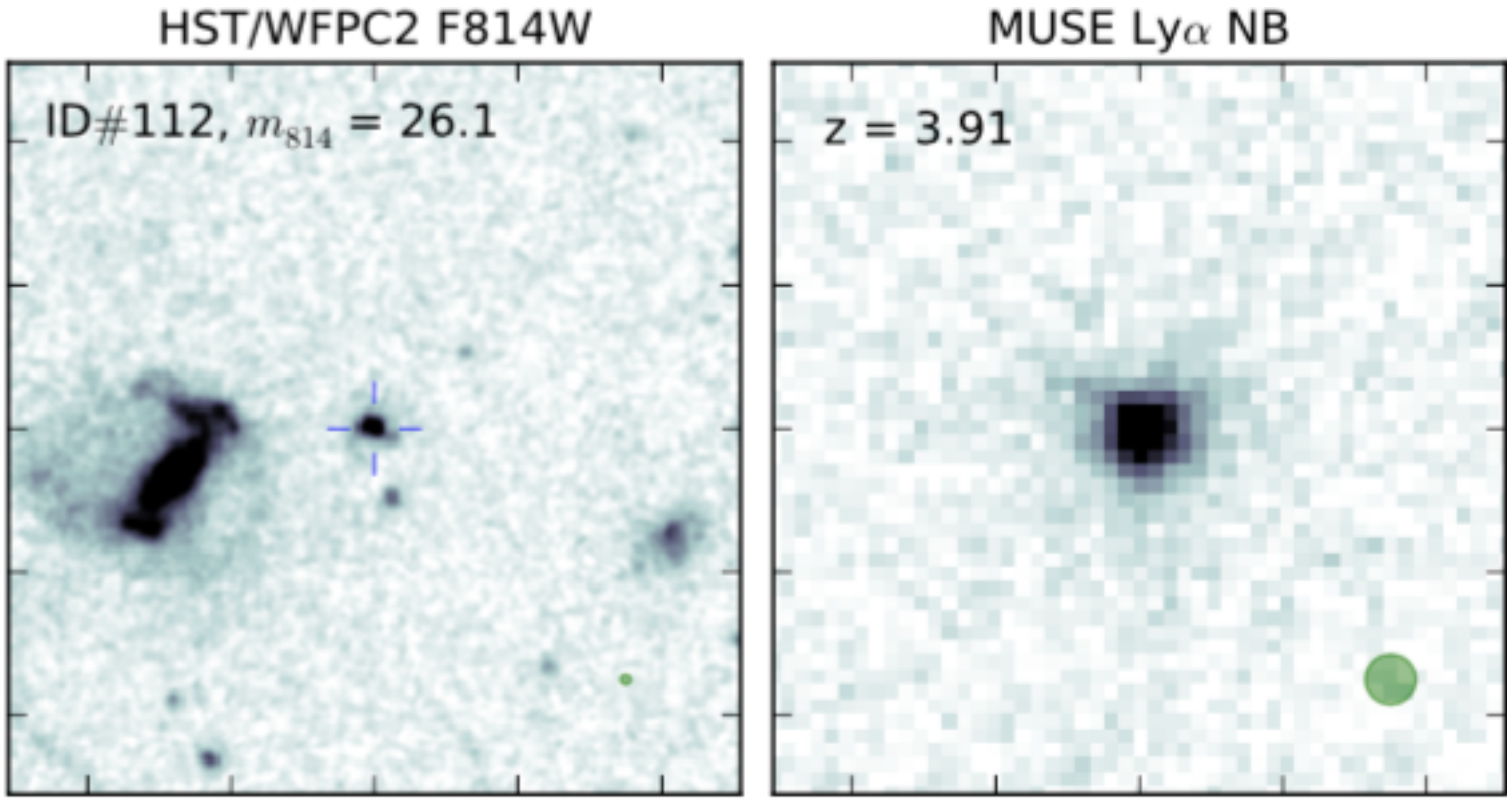
Contents of this review

- ✦ **Lyα line as a tracer of the CGM and IGM**
- ✦ **Metal and nebular lines to identify the CGM**
- ✦ **Studies with the IGM tomography for future PFS survey**

Lyα emission as the most commonly used tracer

For the CGM scale …





Lyα blobs

- Intrinsically very bright and extended Lyα feature
- There tends to be several star-forming galaxies and/or AGNs

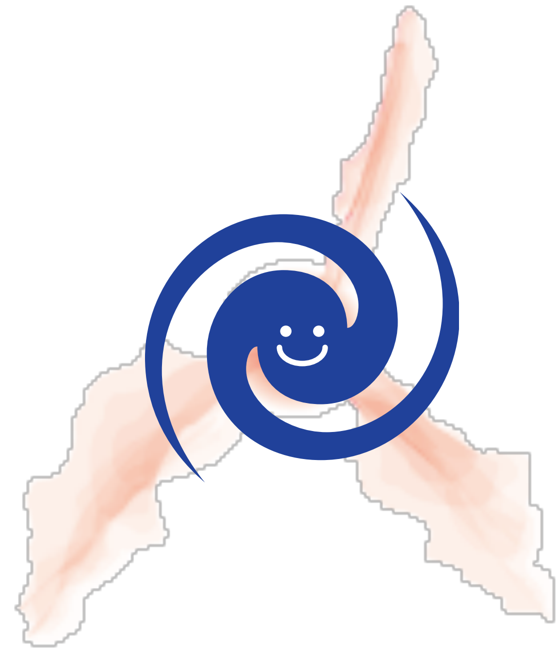
Lyα halos/nebular

- Faint and extended Lyα feature around UV disk
- Found mostly around QSOs or LAEs
  - LAEs : Stacking —> Individual detection
  - QSOs : Individual detection

Q : Origin, Connection between the halo and galaxies, Redshift evolution?

Matsuda+06; Wisotzki+16

What is the origin of Lyα emission in the CGM?



= Fluorescent =
Recombination of HI gas in the CGM by ionizing photons from central galaxies

= Scattering =
Resonant scattering of Lyα photons from central galaxies by HI gas in the CGM

= Cold flow =
Shock heating by the cold gas from the IGM (~10^4 K) can radiate Lyα

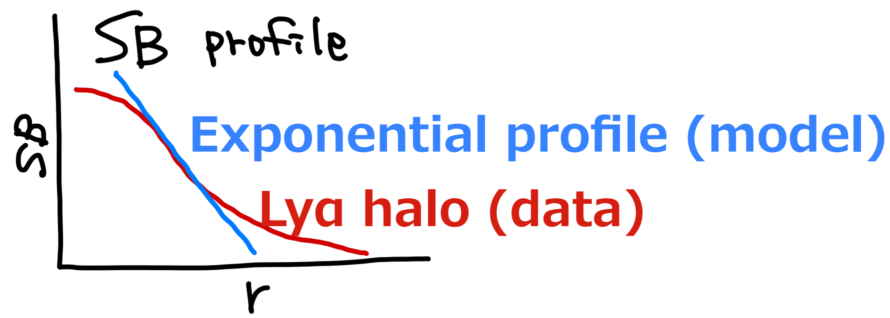
= Satellite galaxies =
Lyα emission by star formation in satellite galaxies (for stacking)

Likely Matsuda+12 Leclercq+17, 20 Kusakabe+19 **Unlikely**	Matsuda+12 MR+16 Wisotzki+16 Xue+17 Leclercq+17, 20 Claeyssens+19 Kusakabe+19 Wu+20	Matsuda+12 Leclercq+17 MR+16 Xue+17 Kusakabe+19 Leclercq+20	Matsuda+12 Momose+16 Xue+17 Leclercq+17, 20 Kusakabe+19 Wu+20

※ Based on measured quantities (e.g. $EW_{\mathrm{Ly\alpha}}$, r_s, spatial offset of Lyα emission, radial profile)

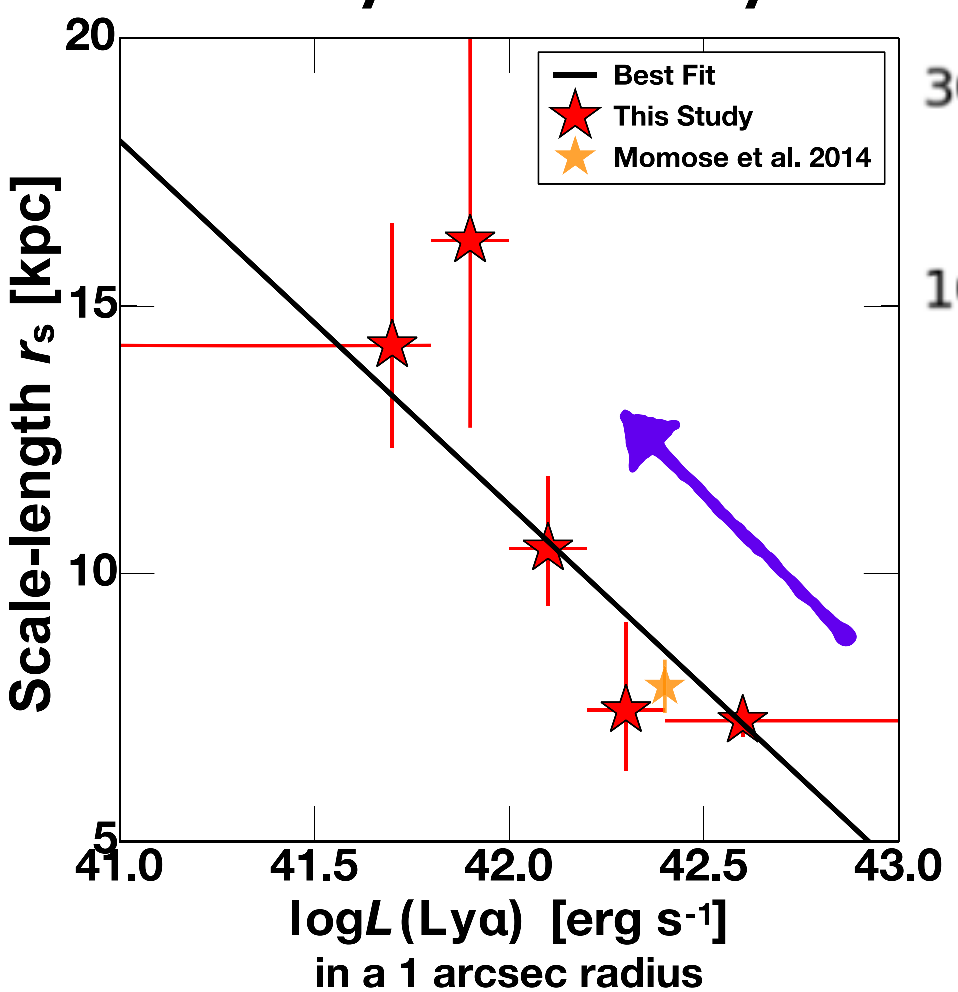
MR+16; Kusakabe's slide

Connection between Lyα halos and galaxies | LAEs - I

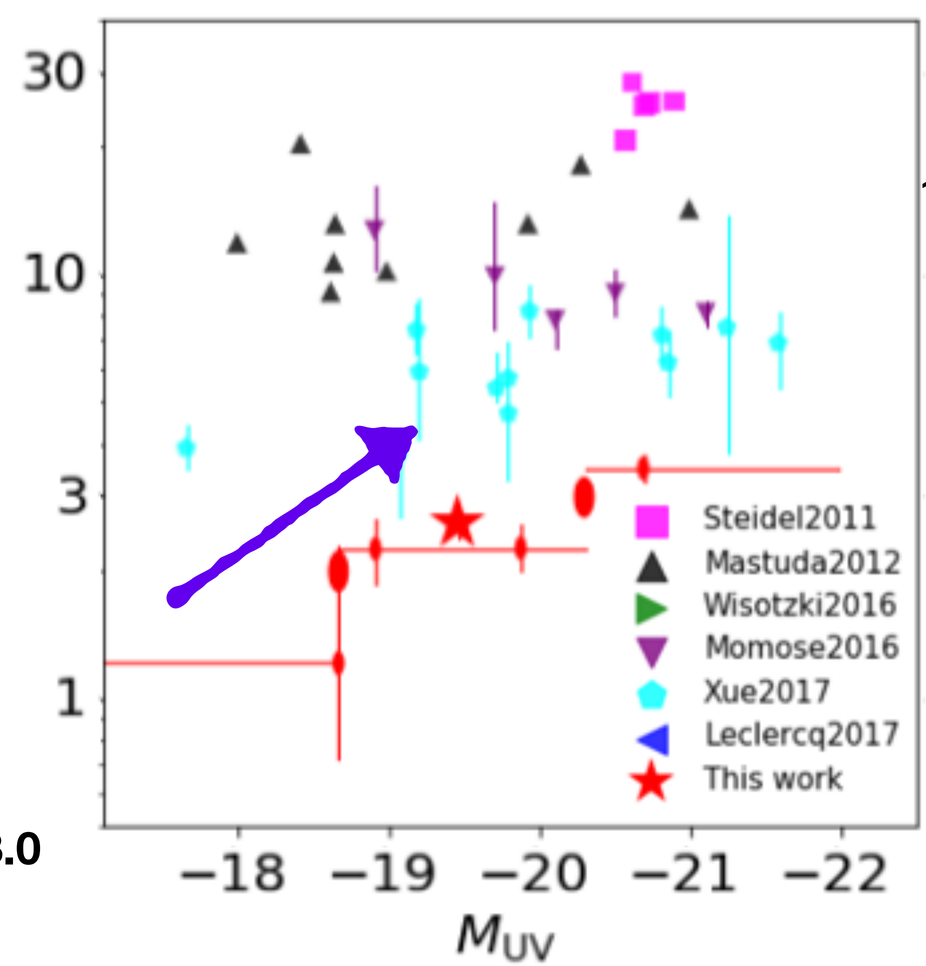


scale-length (r_s)
$S(r) = S_0 \exp(-r/r_s)$

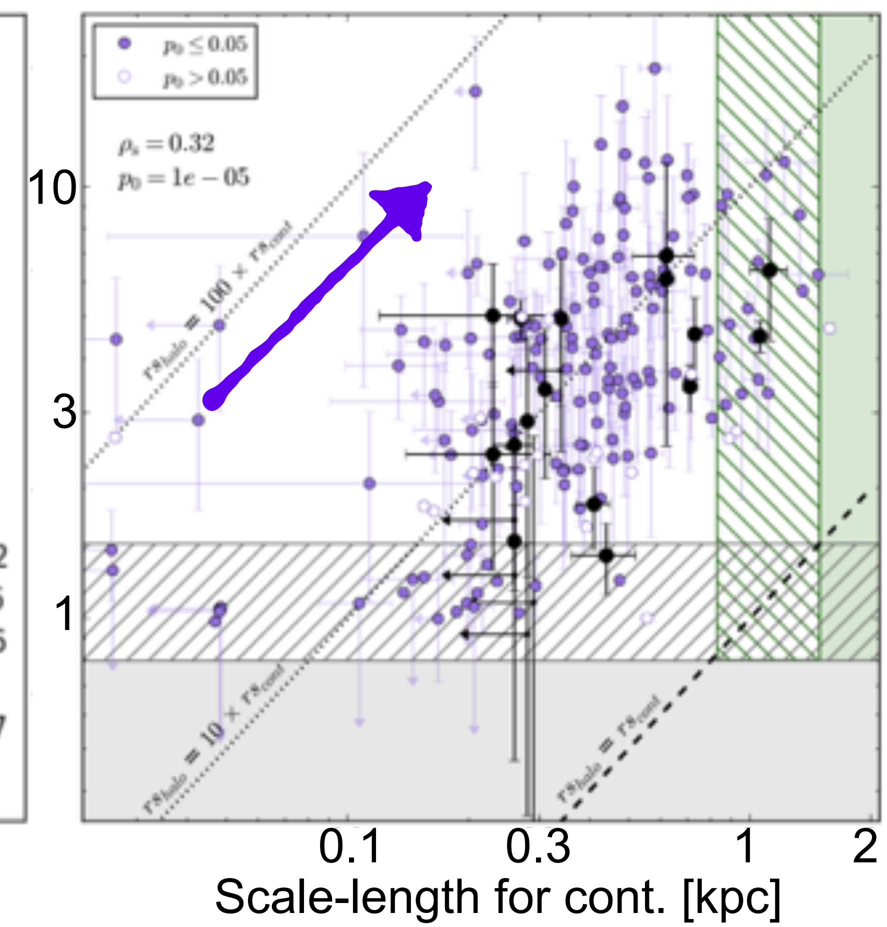
vs Lyα luminosity



vs UV luminosity



vs UV continuum size

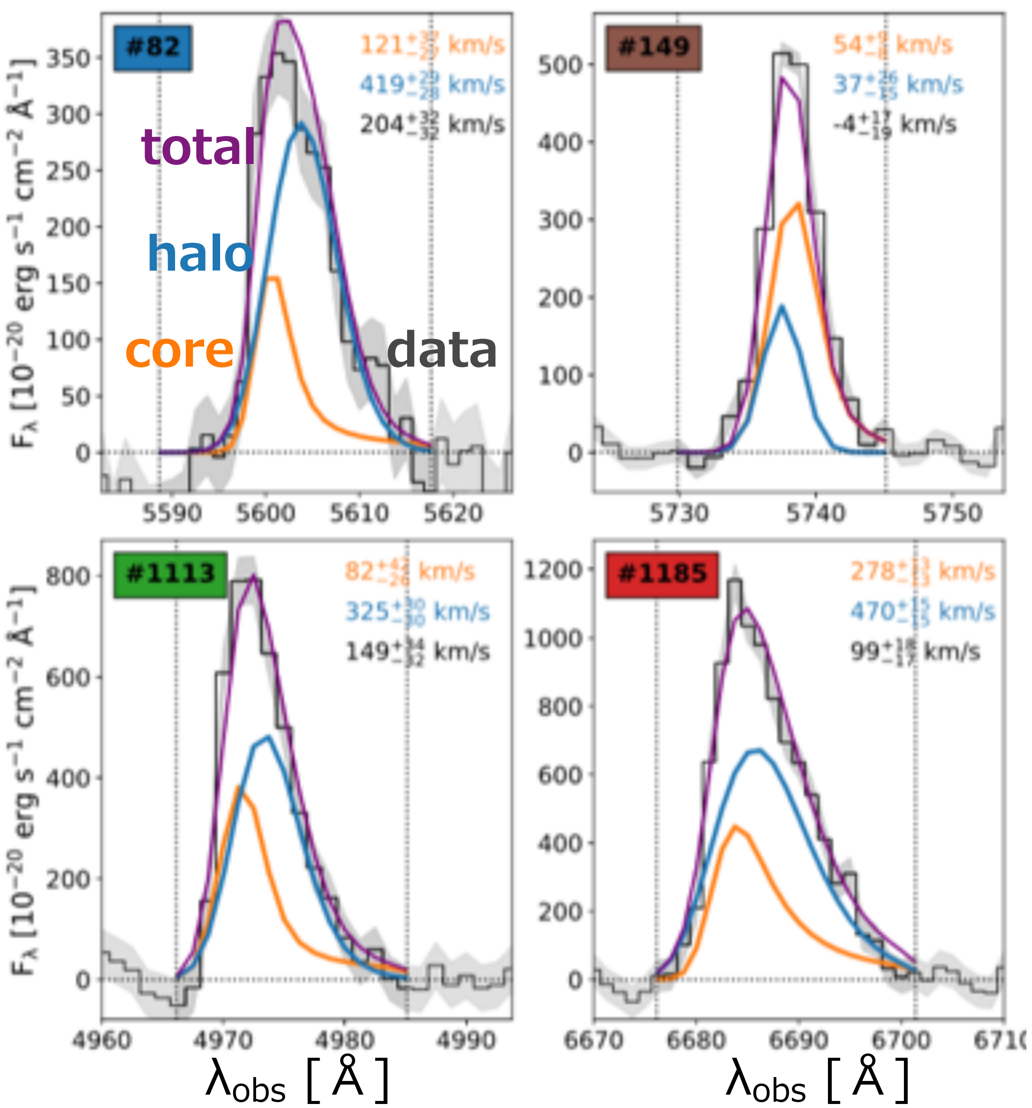


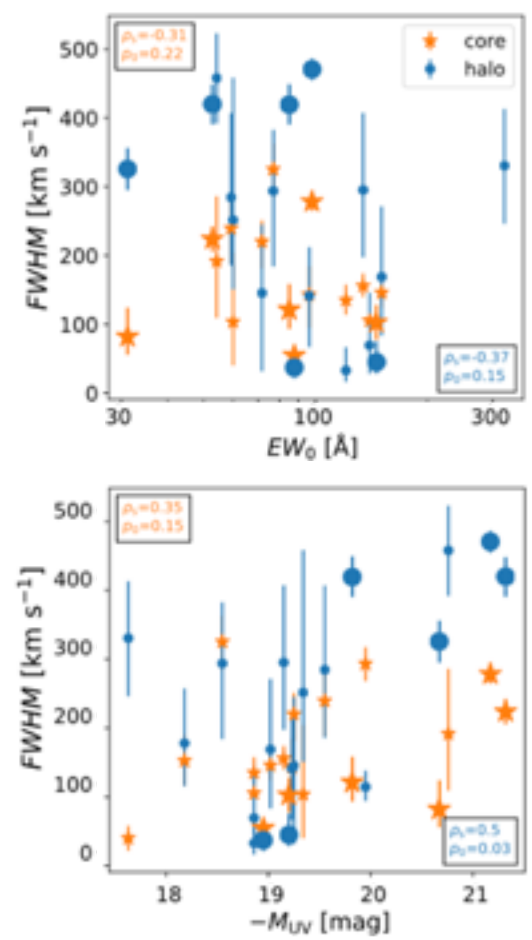
No common sense so far …

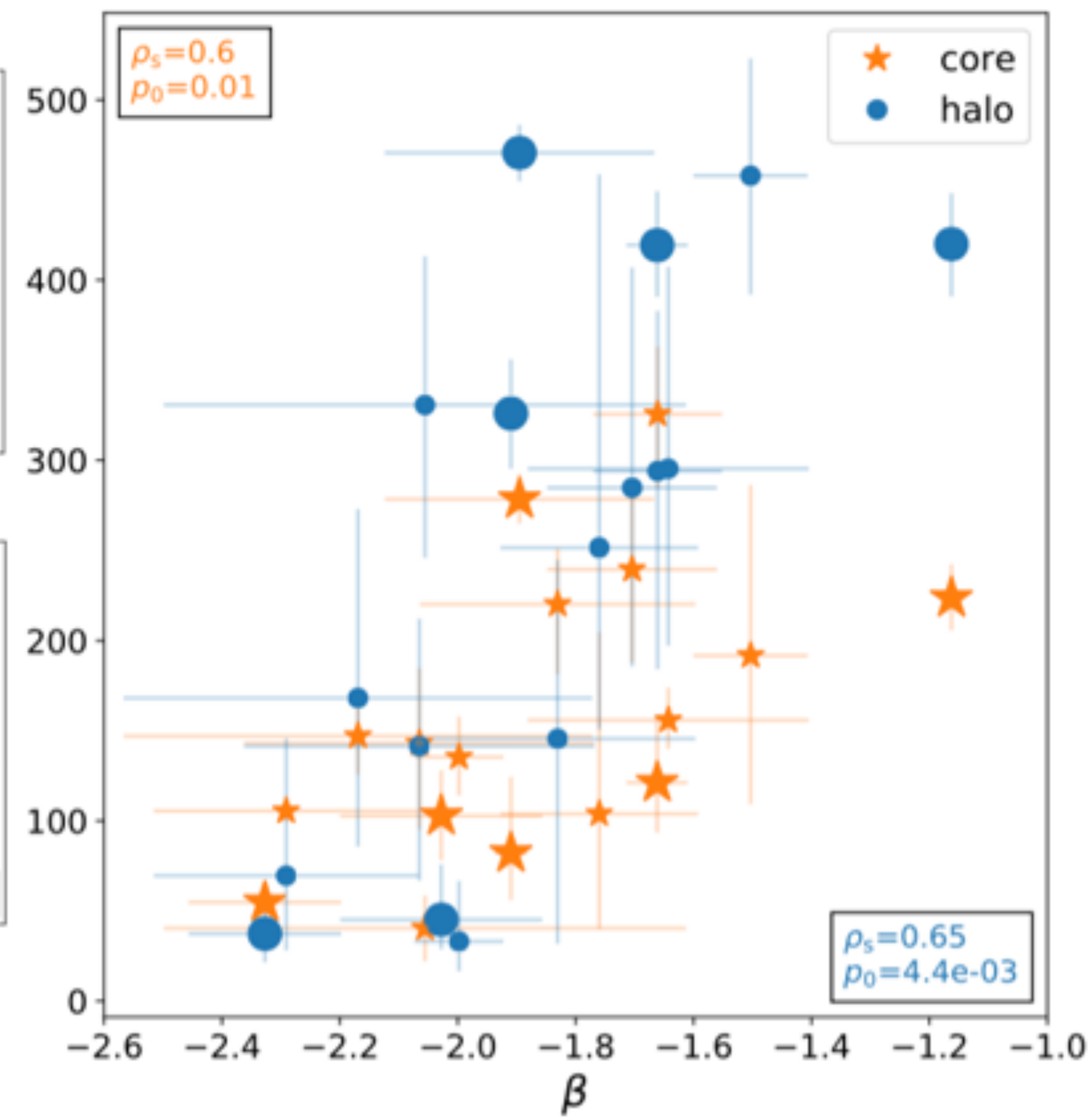
- Presence and direction of correlations are different in each study
- Necessity of further investigations and theoretical models

MR+16; Leclercq+17; Wu+20

Detail investigation of Lyα spectra of halos owing to IFU







Large diversity of spectra

- Amplitude, Peak wavelength, asymmetric parameter, FHWM

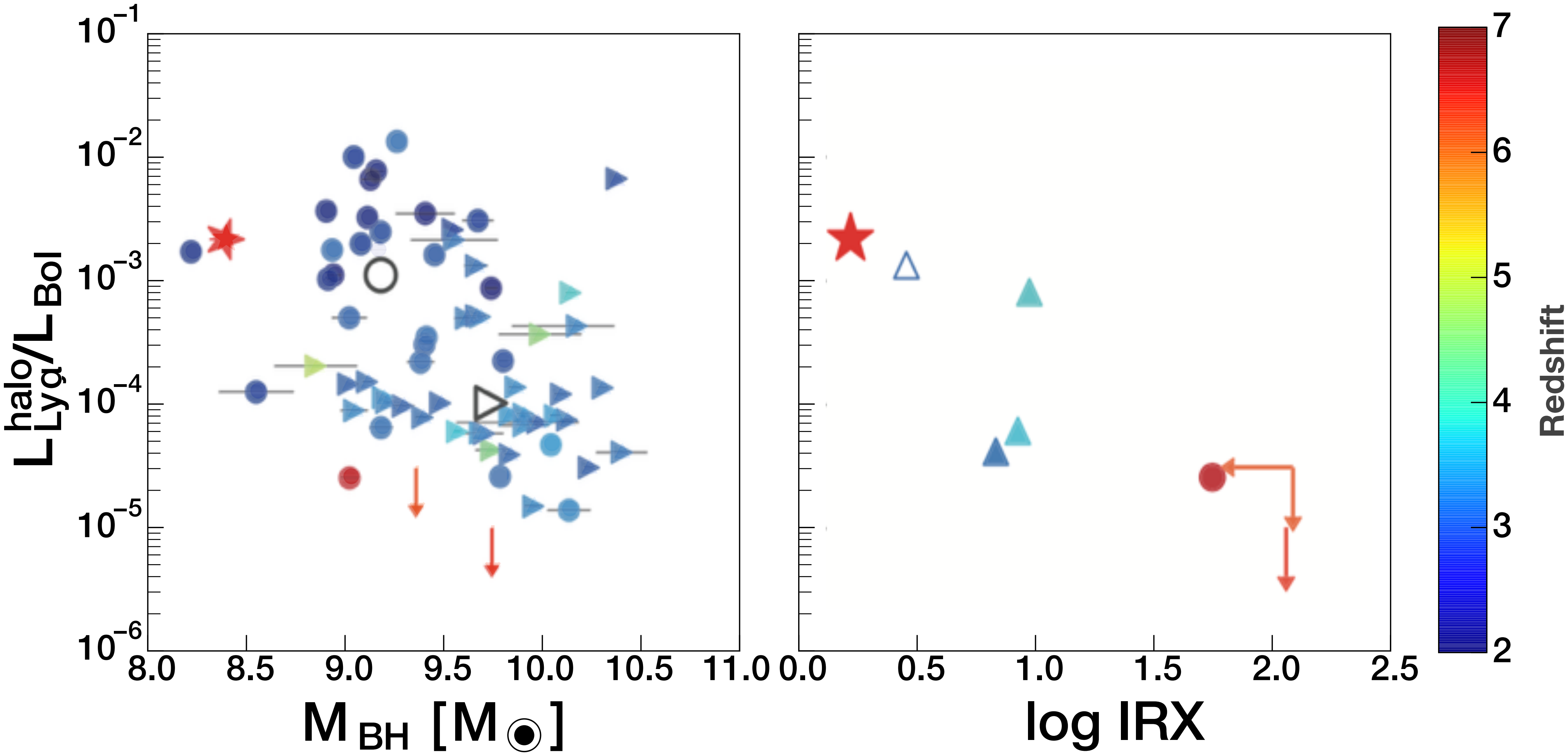
The lack of strong correlations between any parameters of LAEs and Lyα spectra

- But there is one between FWHM of Lyα line and UV-slope β

Need for realistic spatially resolved models of Lyα halos

Leclercq+20

Connection between Lyα halos and galaxies | QSOs



Possible anti-correlations between Lyα luminosity in a halo and

- black hole mass
- IRX (= IR luminosity / UV luminosity)

Hypotheses : younger QSOs tend to have luminous halos

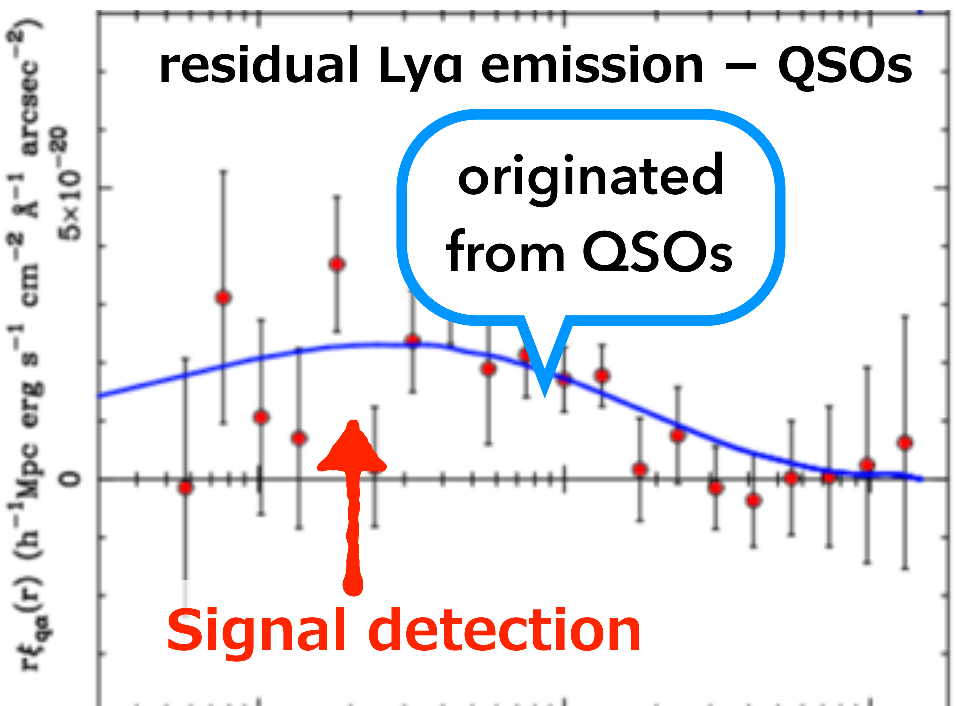
- Necessity of more investigations with further QSO sample

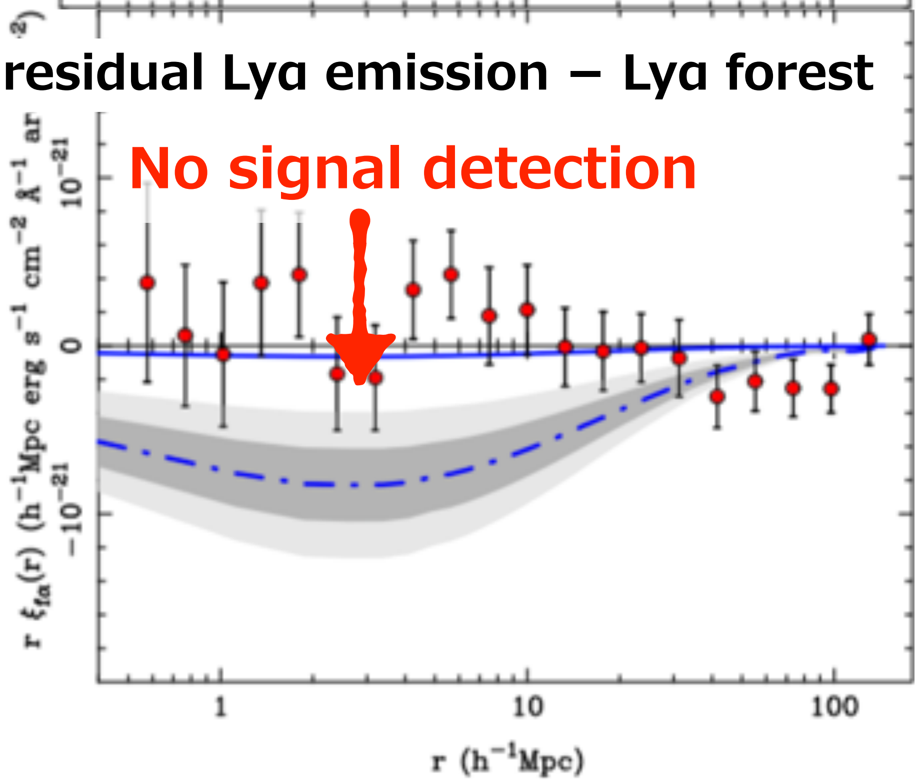
MR+19 and references therein

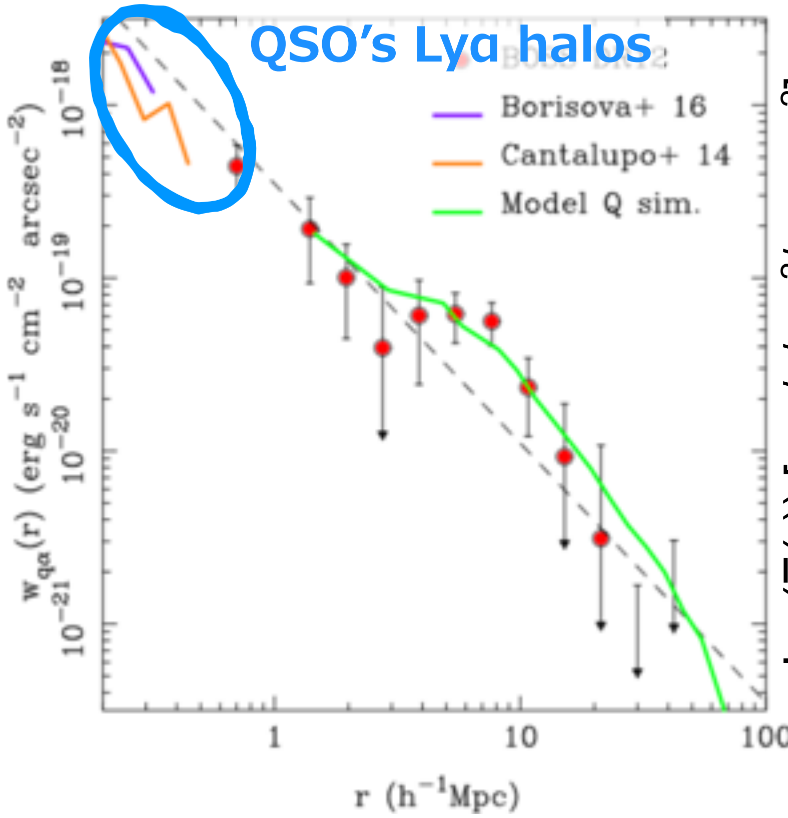
Indirect detection of Lyα emission from the IGM

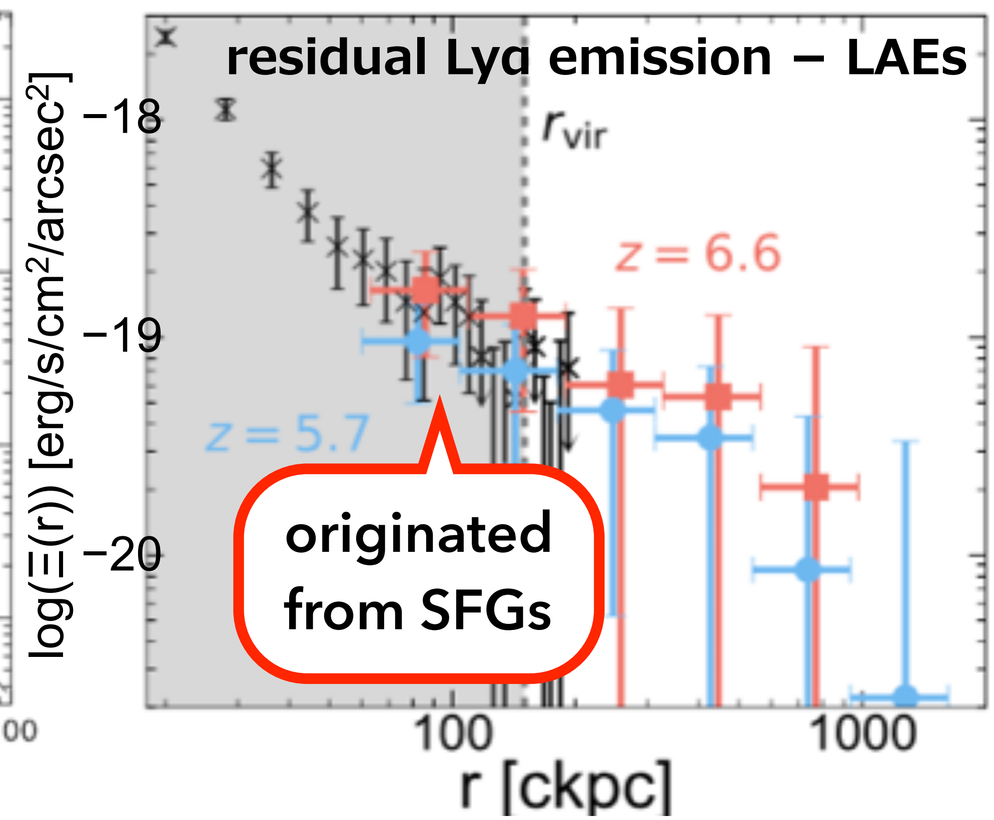
For the IGM scale …

Indirect detection of large-scale Lyα emission by cross-correlation analysis







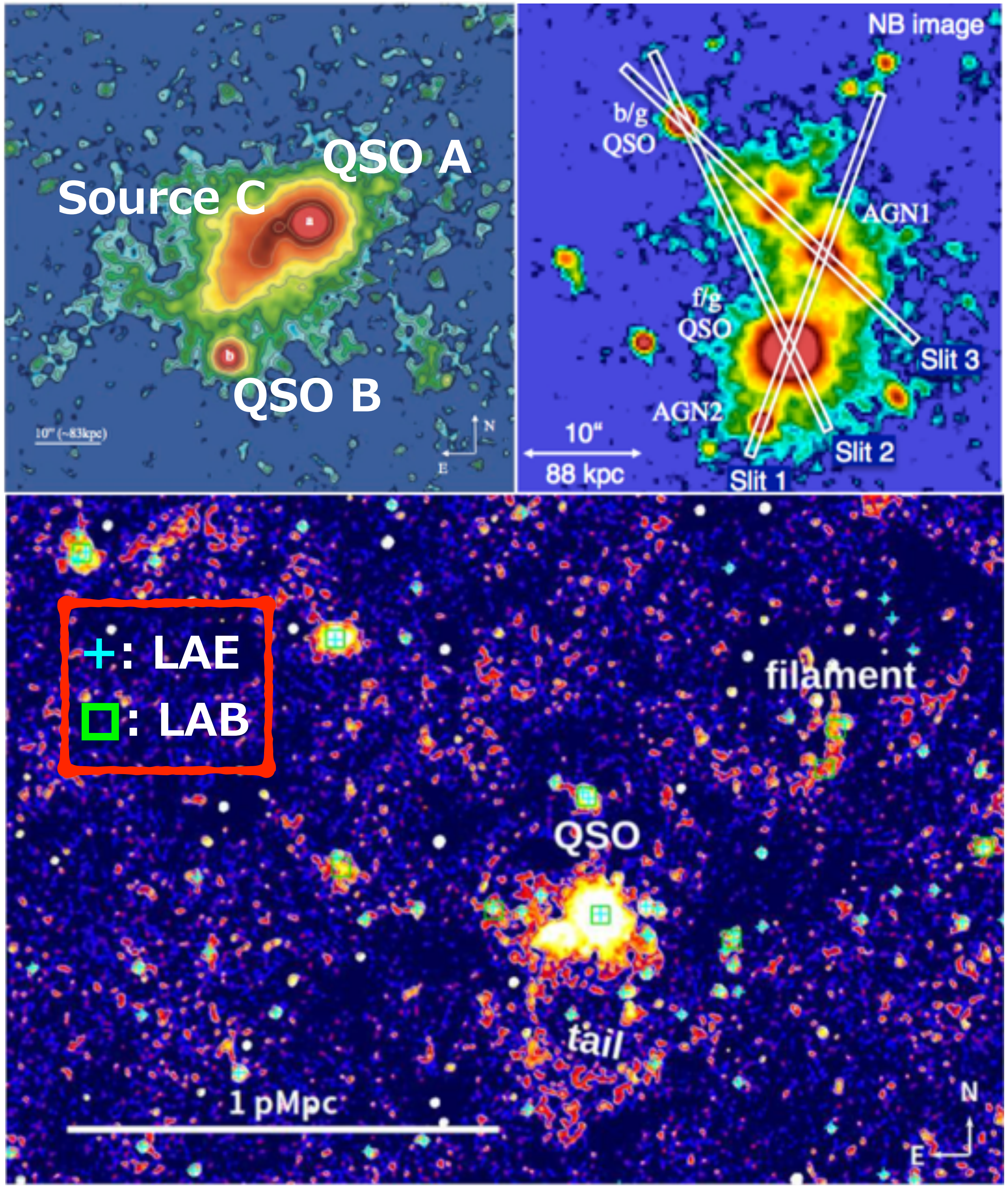


Cause of diffuse Lyα emission in the IGM

- QSOs : recombination by hard ionizing photons from QSOs
- SFGs : scattering of Lyα photons from central galaxies

※ SFGs = star-forming galaxies

Croft+16, 18; Kakuma+19; see also Kikuchihara's talk

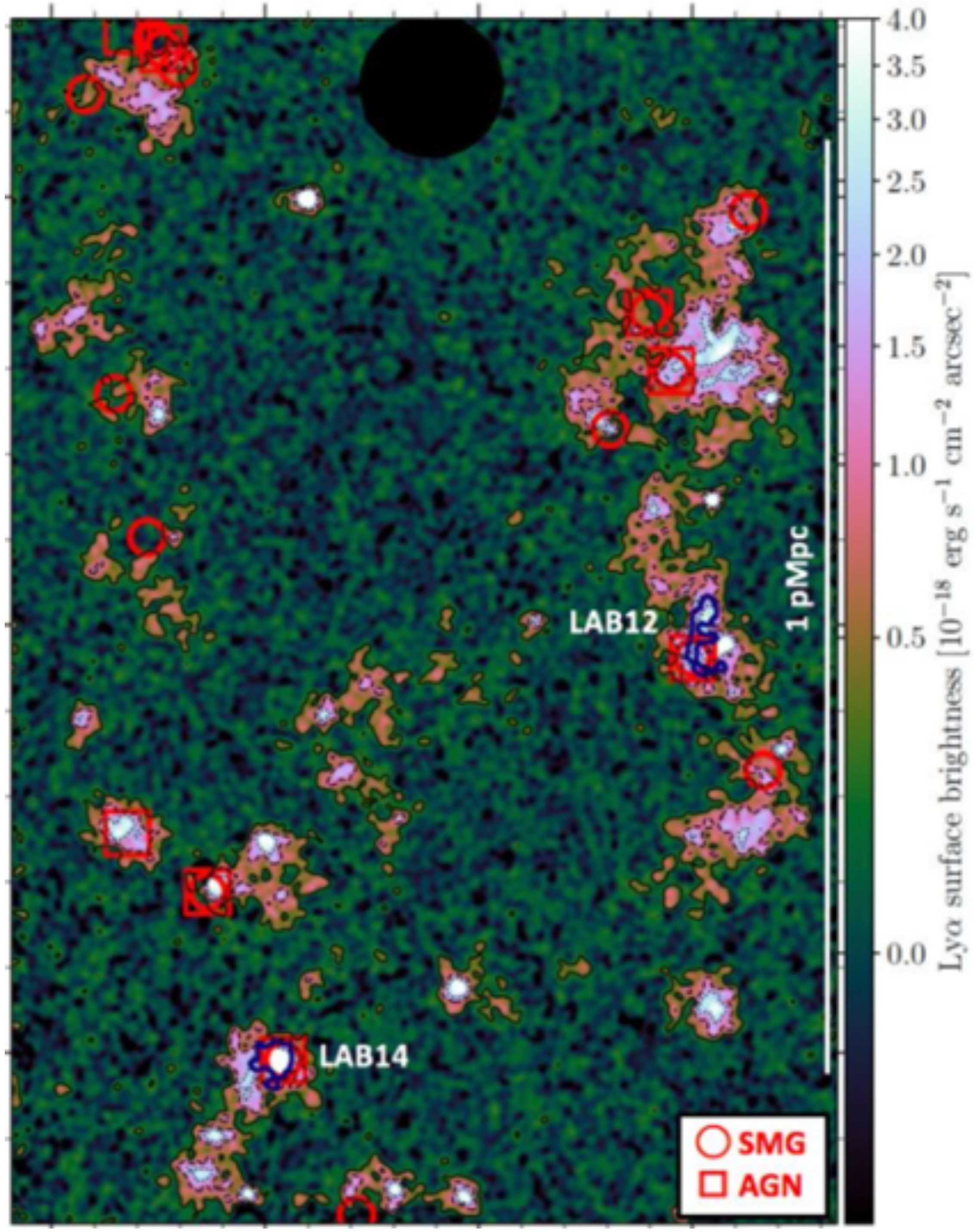


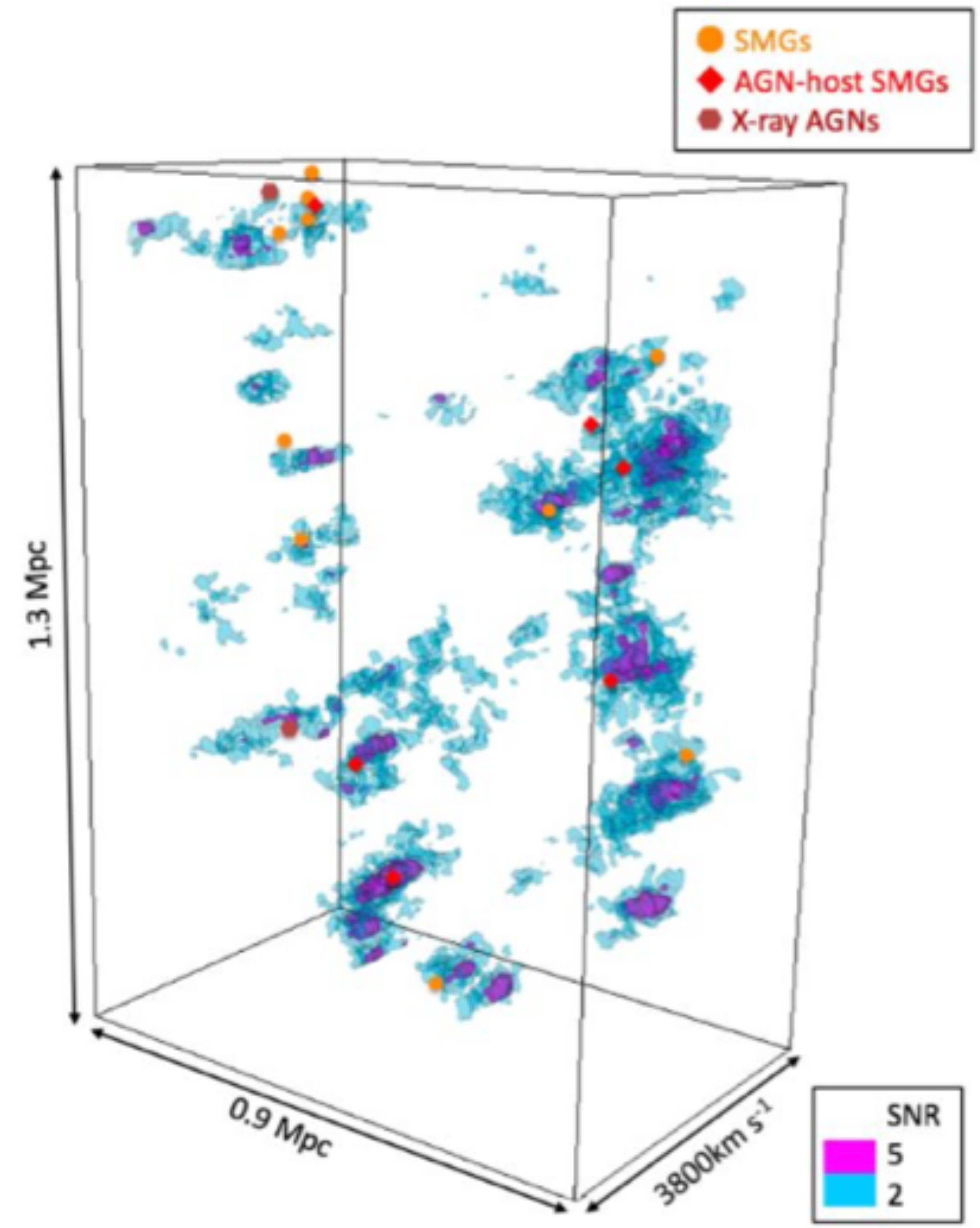
Large-scale Lyα emission around luminous QSOs

- Sometimes called ELANe (Enormous Lyα nebulae)
- Overall extents are beyond r_{vir}
- Powered by more than one QSOs/AGNs and/or several bright star-forming galaxies

Cantalupo+14; Hennawi+15; Kikuta+19

Direct detection of Lyα emission from the IGM





Filamentary structure of Lyα emission in a galaxy overdensity

- Extending more than 1 pMpc
- Ionizing photons from intense star formation and SMBHs likely produce those Lyα filaments

Umehata+19

Summary of Lyα

CGM scale

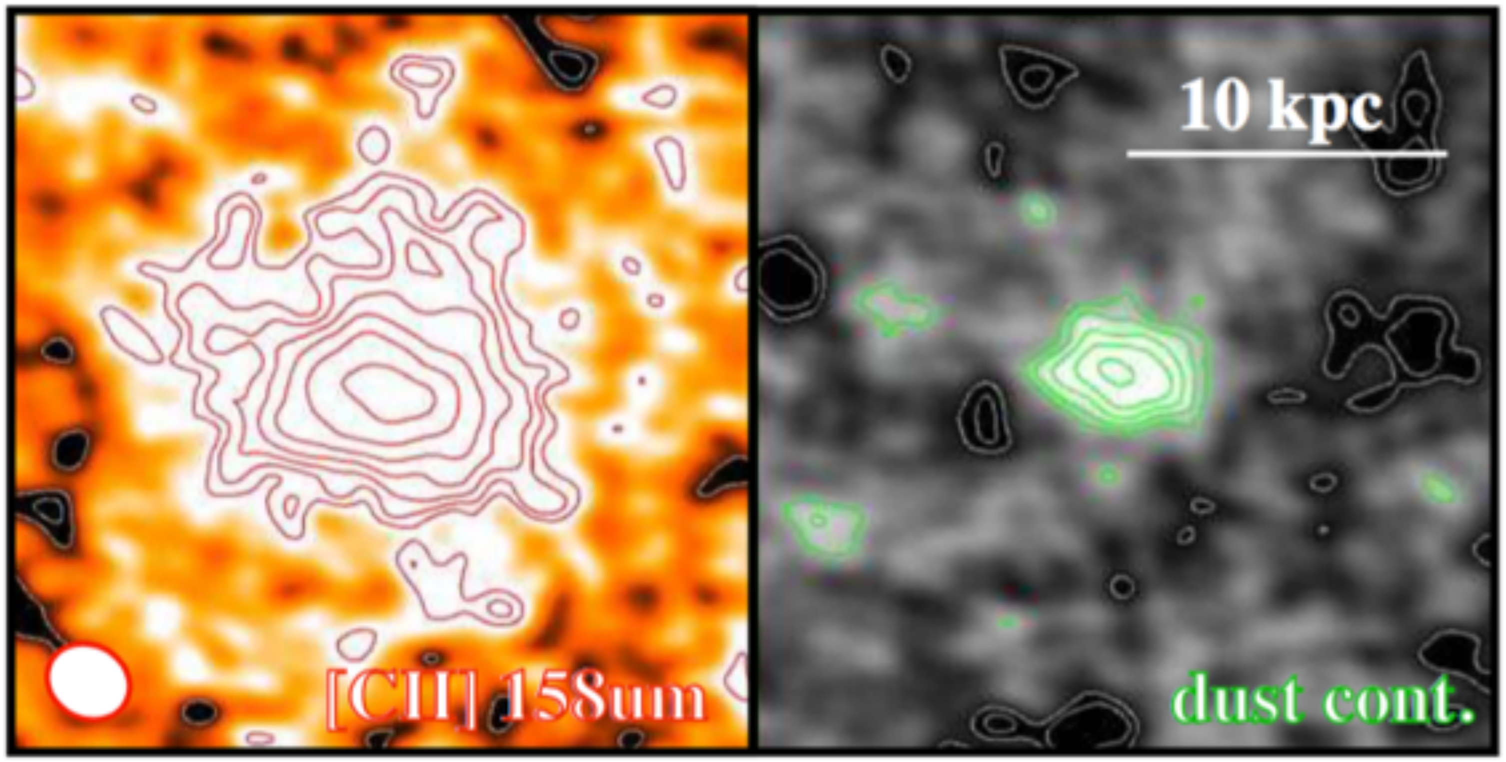
- Well studied around LAEs and QSOs
- Ubiquitously present around LAEs
- The current issues are to unveil the origin, connection between the halo and galaxies and redshift evolution
- Detail investigation of Lyα spectra becomes feasible

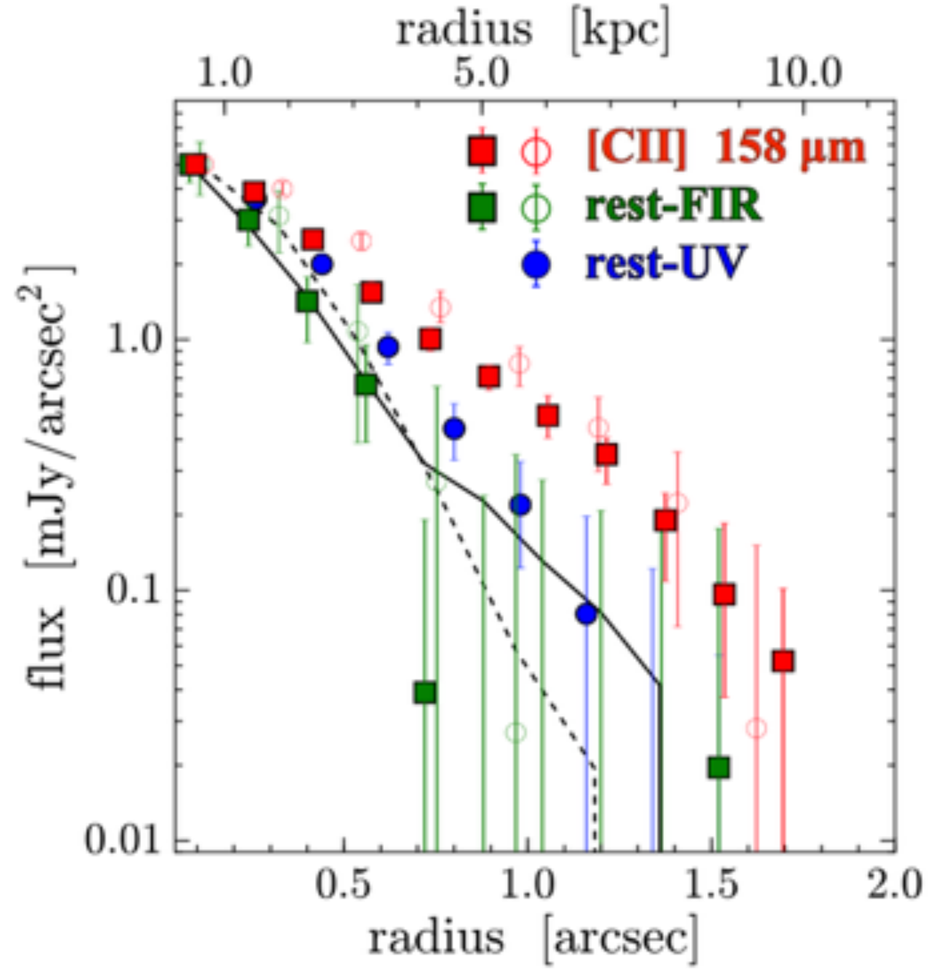
IGM scale

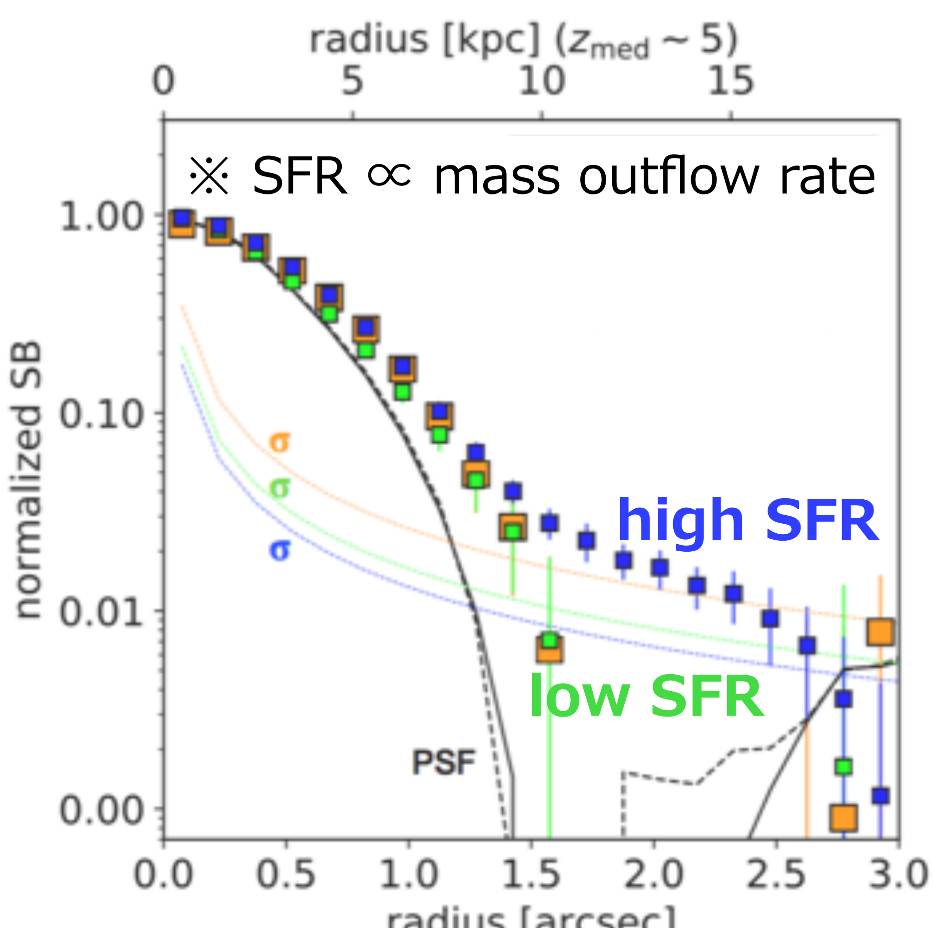
- Indirect detections by cross-correlation analysis
- Direct identifications around luminous QSOs and galaxy overdensity

Further investigations are needed for the both CGM and IGM scale

Metal line halos | [CII] halos







Extended [CII] 158 μm halo

- Stacking 18 SFGs at z > 5
- 5 times extent than UV continuum
- 10 kpc extent
- Comparable the SB profile of Lyα
- Origin is not identified yet, but outflow is always required to enrich the CGM with carbon

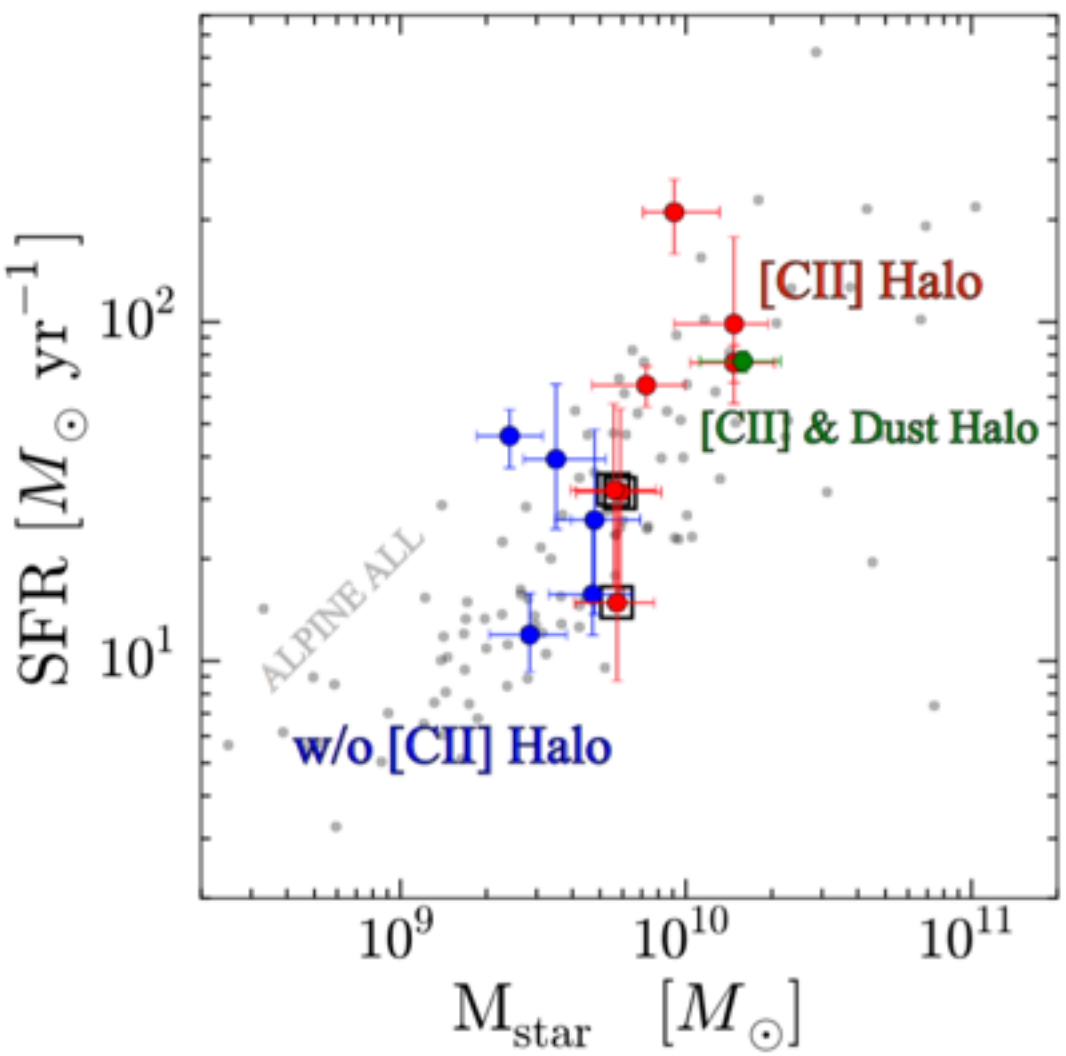
※ SB = surface brightness

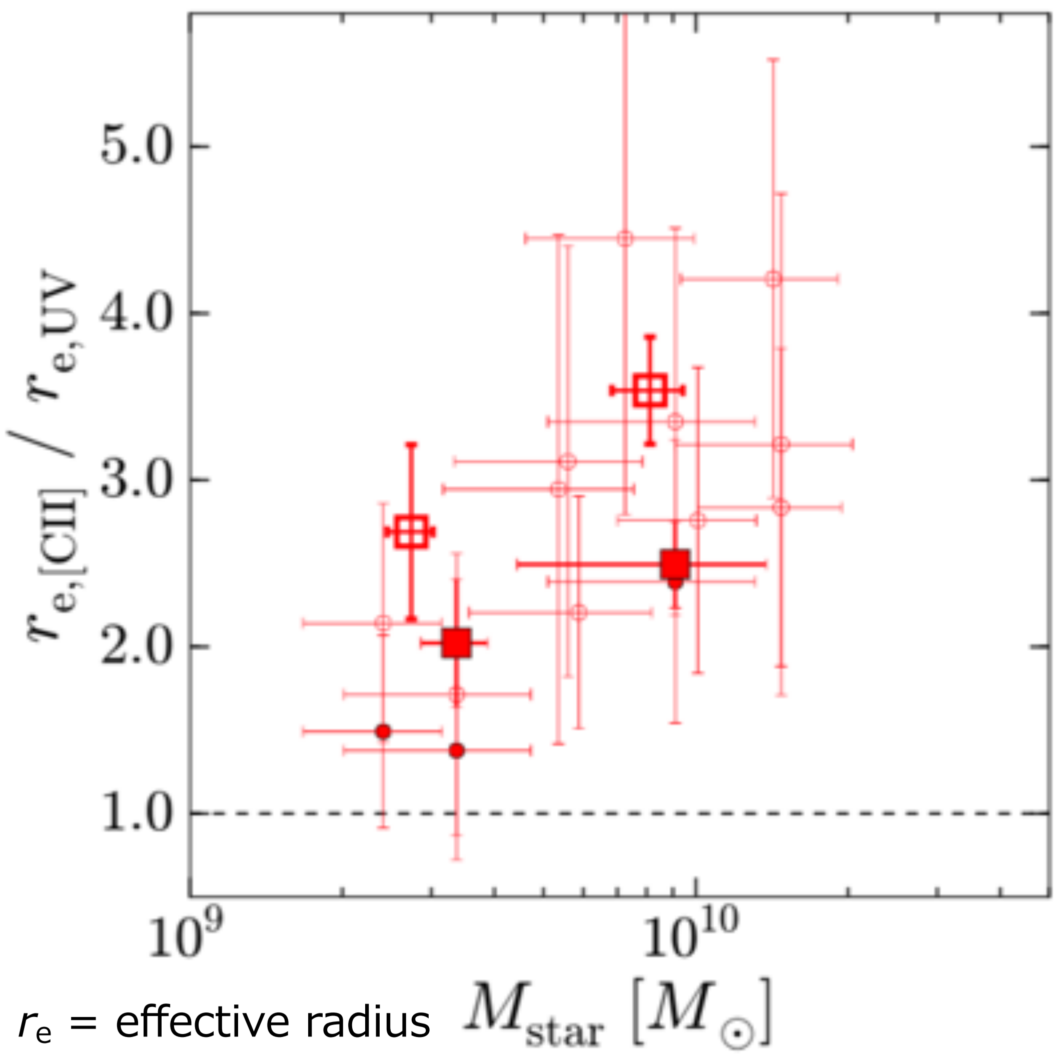
Fujimoto+19; Ginolfi+19

Metal line halos | [CII] halos around individual SFGs

ALPINE−ALMA [CII] survey

- Identified [CII] halos around 30% of ALPINE sources





※ r_e = effective radius

Conditions of w/ [CII] halos

- Higher SFR, higher stellar mass, smaller $EW_{Ly\alpha}$
- More blue- (red-)shifted metal absorption (Lyα line)

Correlations to galactic properties

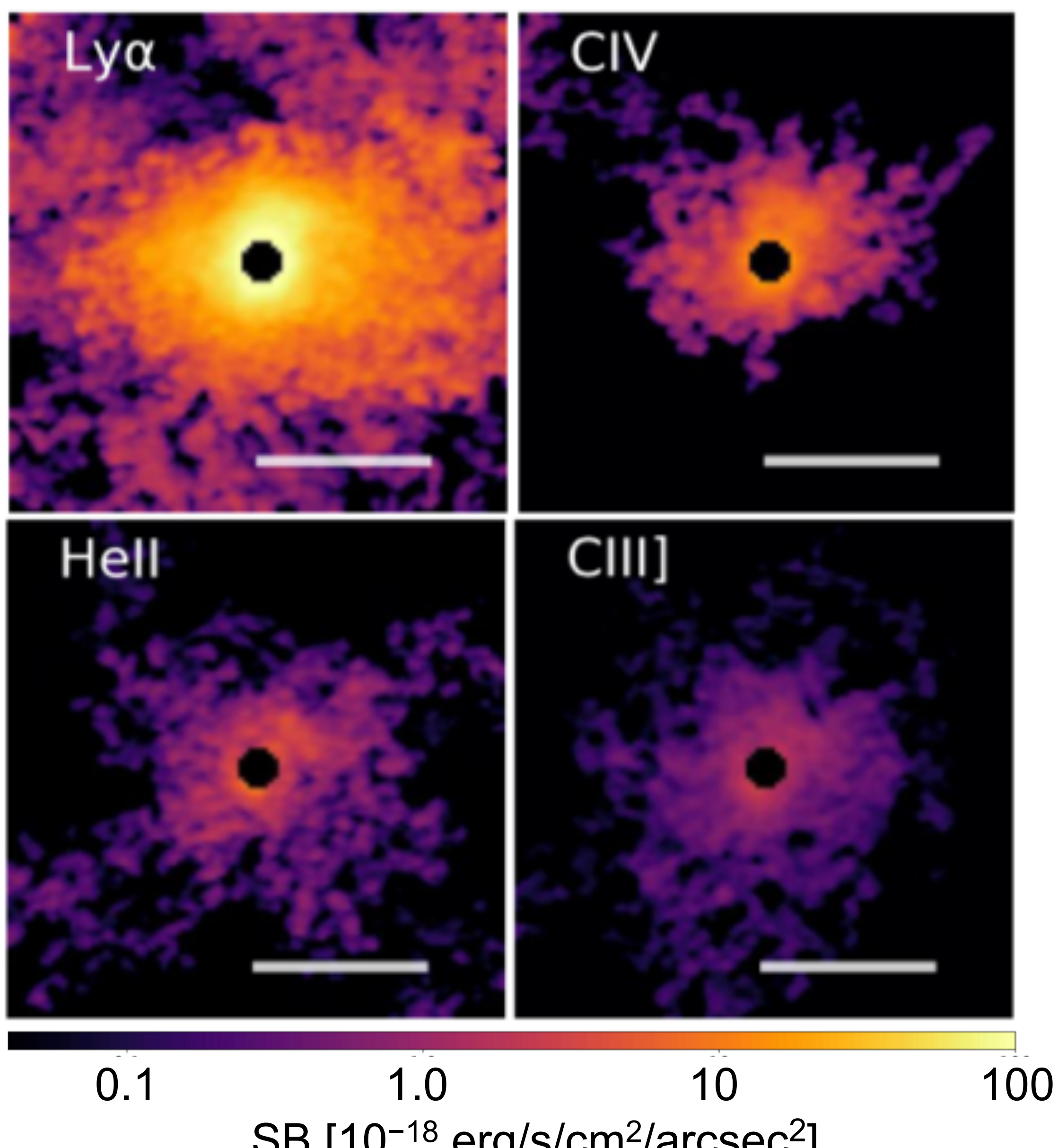
- $r_{e,[CII]}$ exceeds $r_{e,UV}$ by a factor of 2-3
- The ratio ($r_{e,[CII]}/r_{e,UV}$) correlates with stellar mass

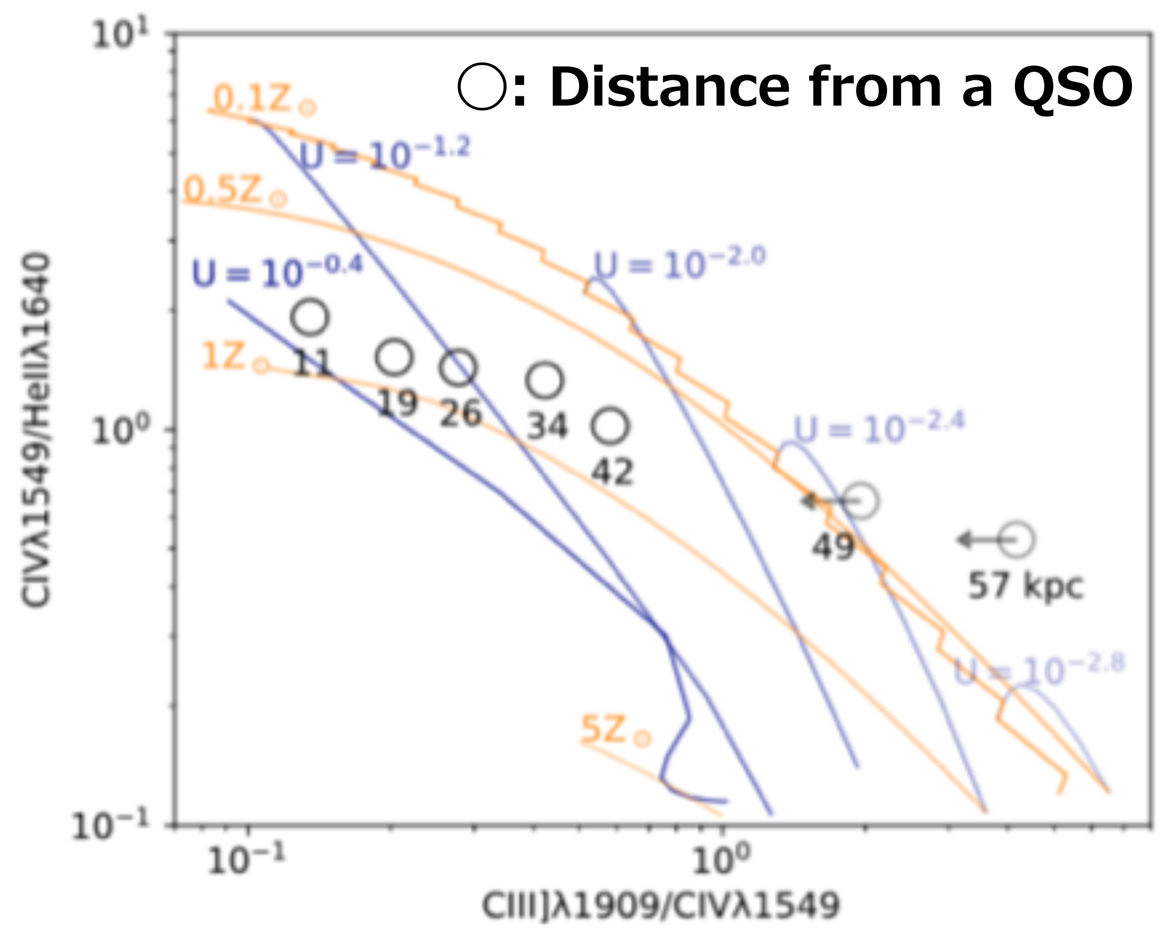
Fujimoto+20b

CIII] λ1909 and CIV λ1549

- The brightest UV lines from gas photoionized by QSOs after Lyα
- Their line ratios are used to constrain metallicity, ionization parameter and gas density even in the CGM

Stacking of 80 QSOs



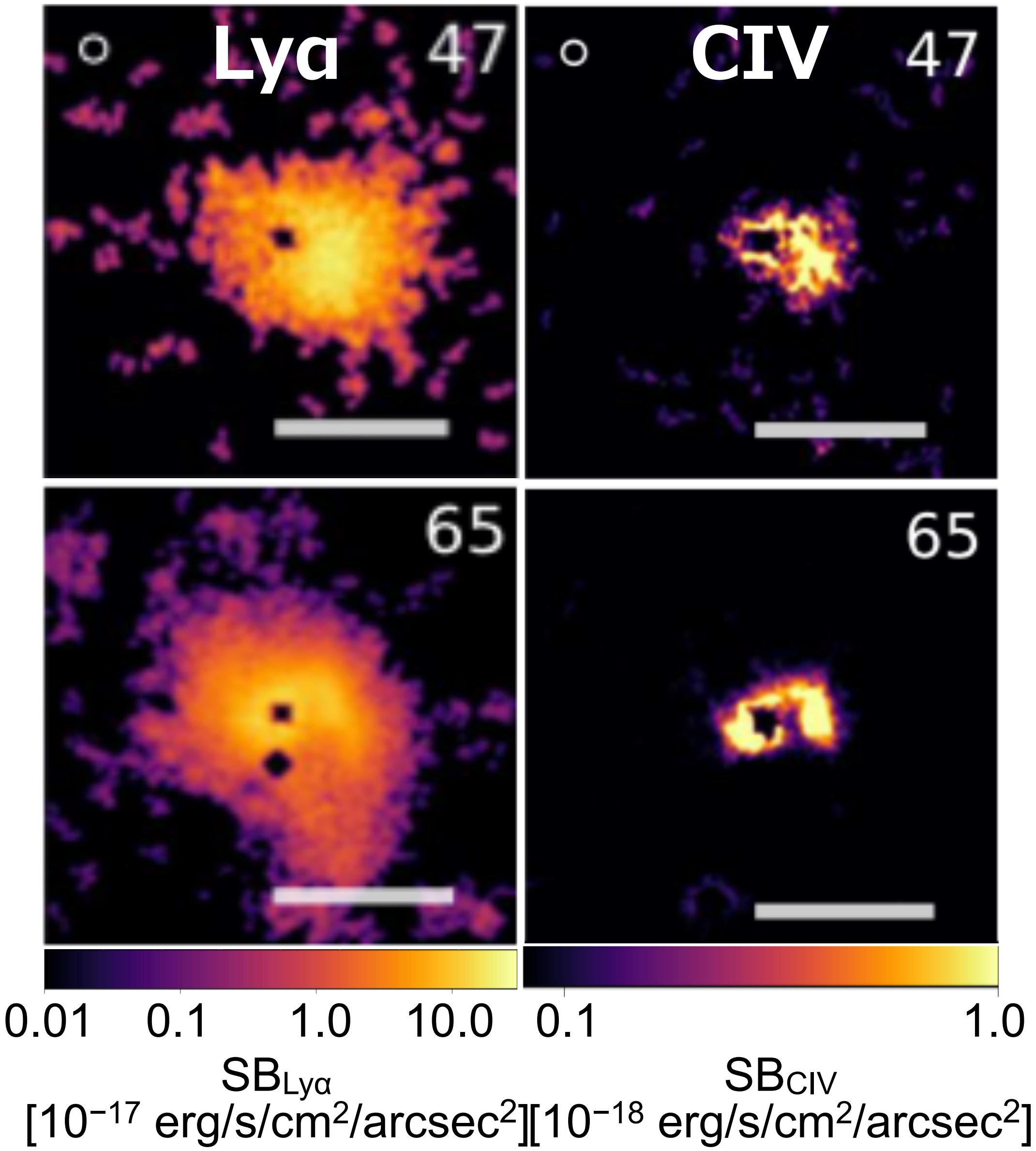


Radial variation of metallicity and ionization parameters

- Metallicity : Staying between $0.5 < Z/Z_\odot < 1$ up to 42 kpc
- Ionization parameter: Decreasing with the distance

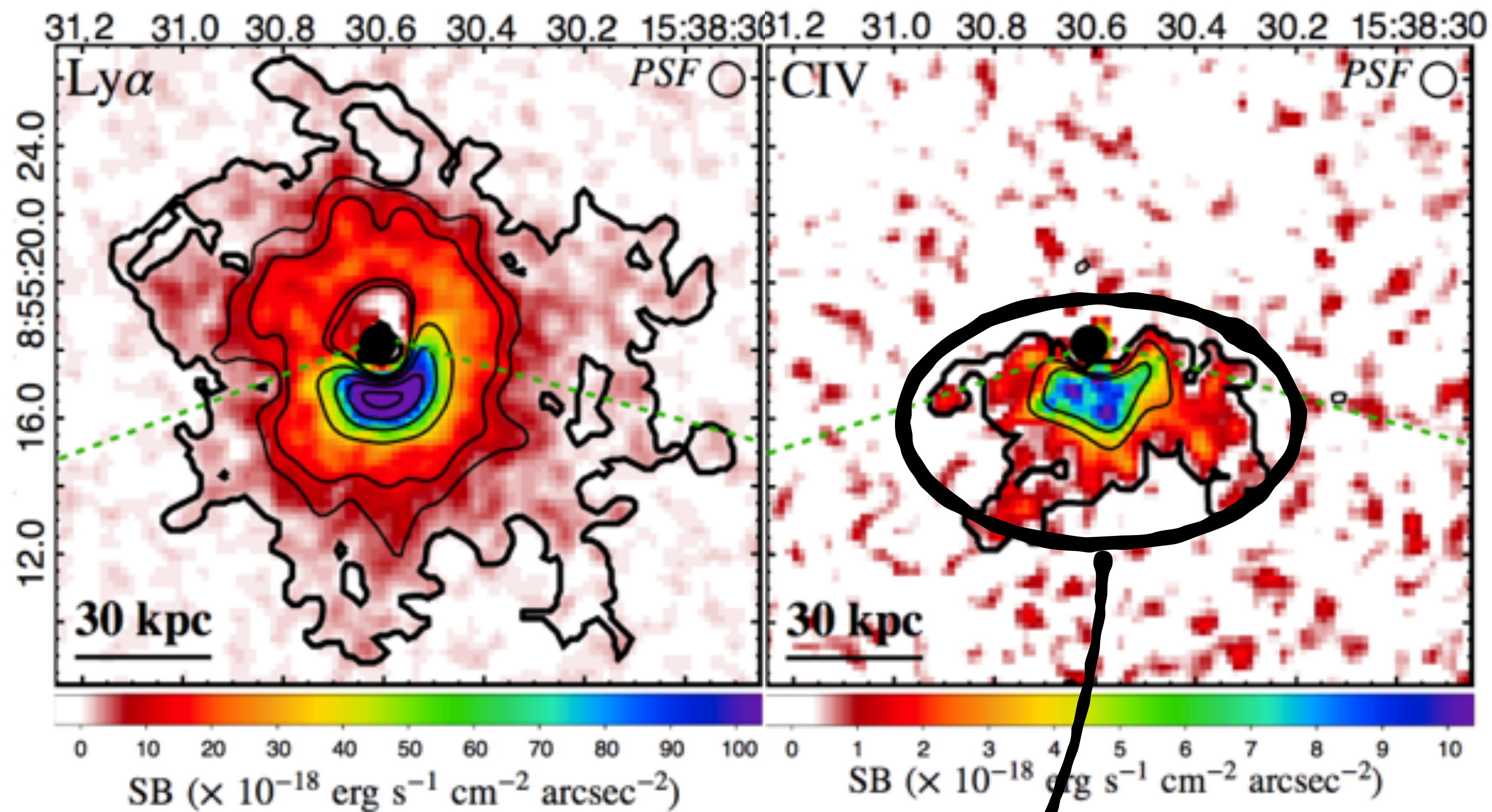
Guo+20

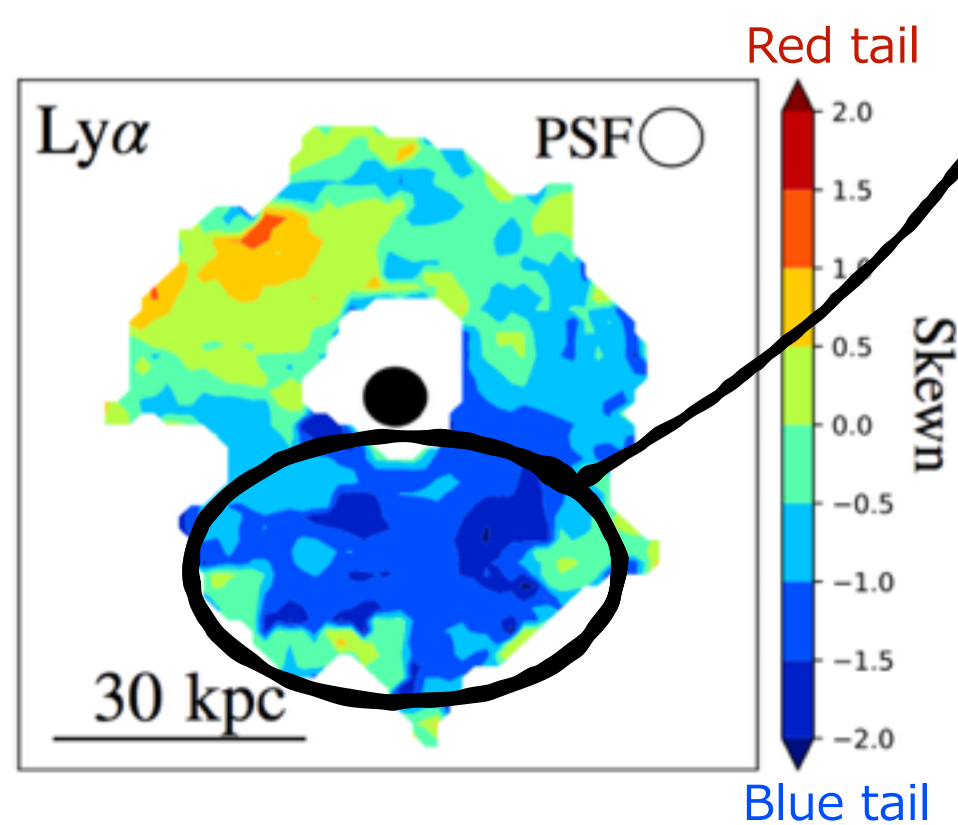
Metal line halos | CIV



CIV halo around individual QSOs

- Generally faint
- Metal distributions in the CGM traced by CIV halos seem to be inhomogeneous

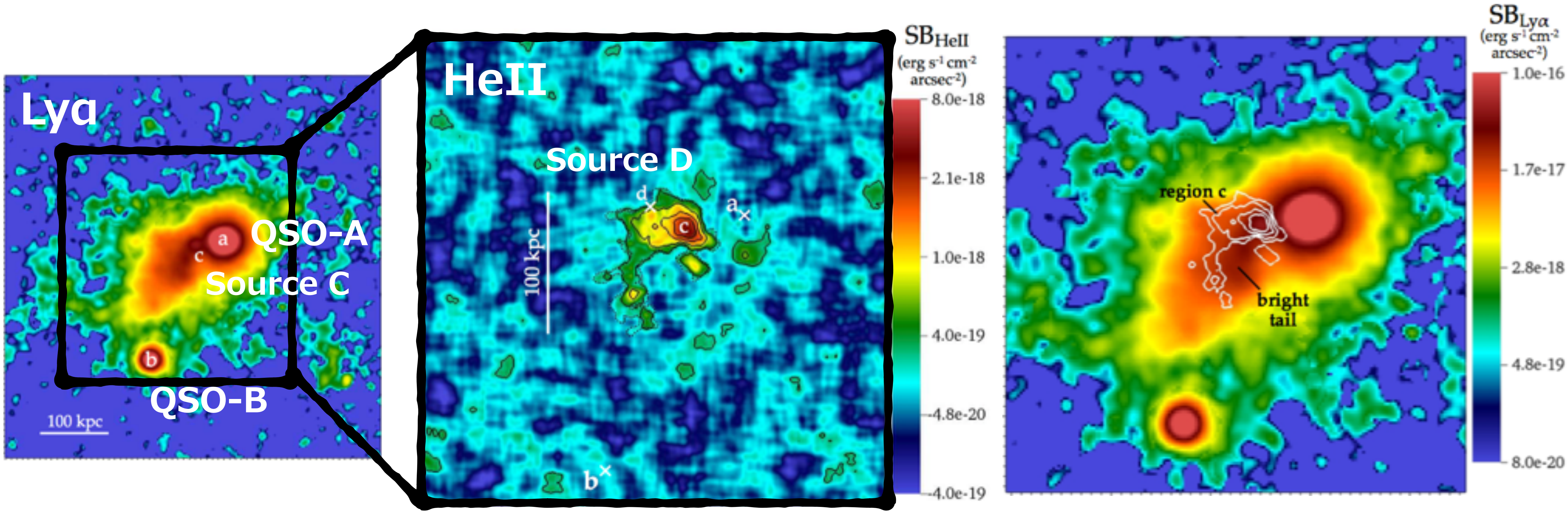


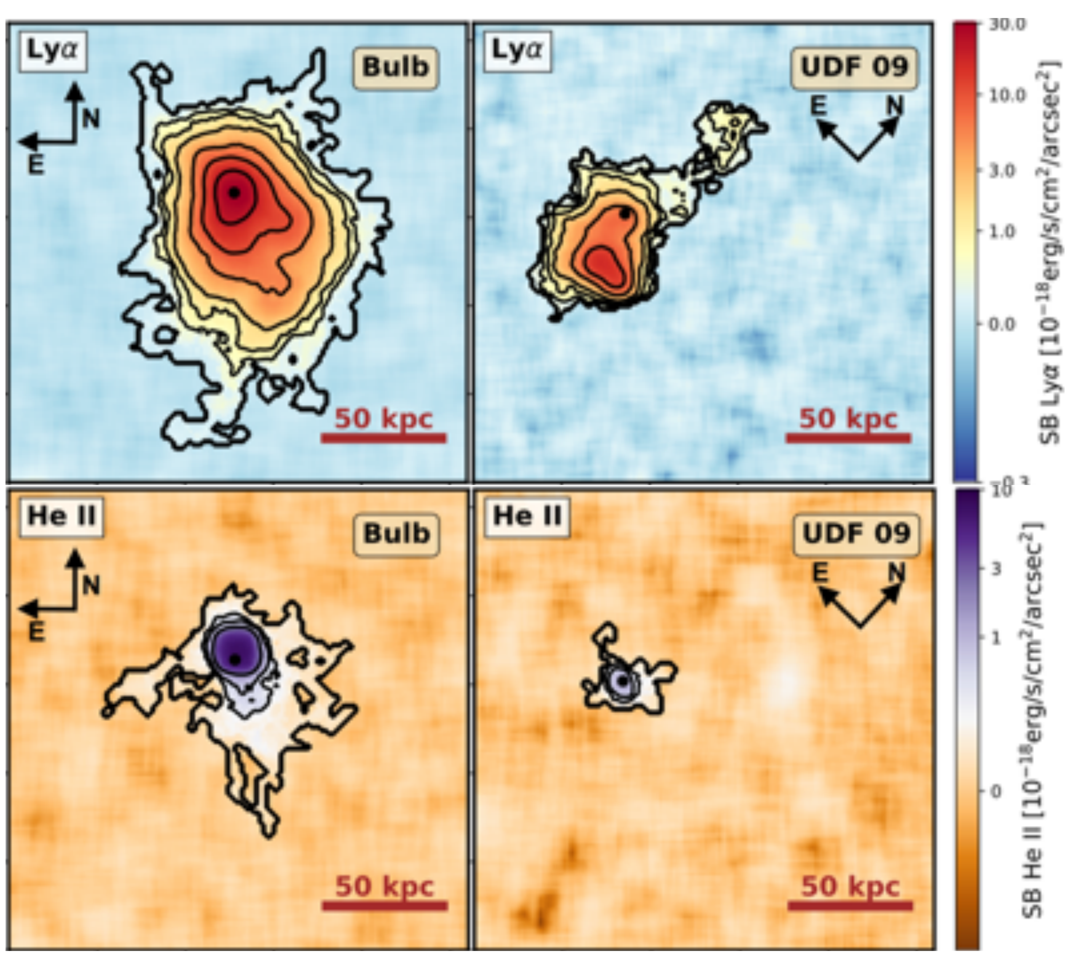


Outflow?

Guo+20; Travascio+20

Ionized gas tracer | HeII



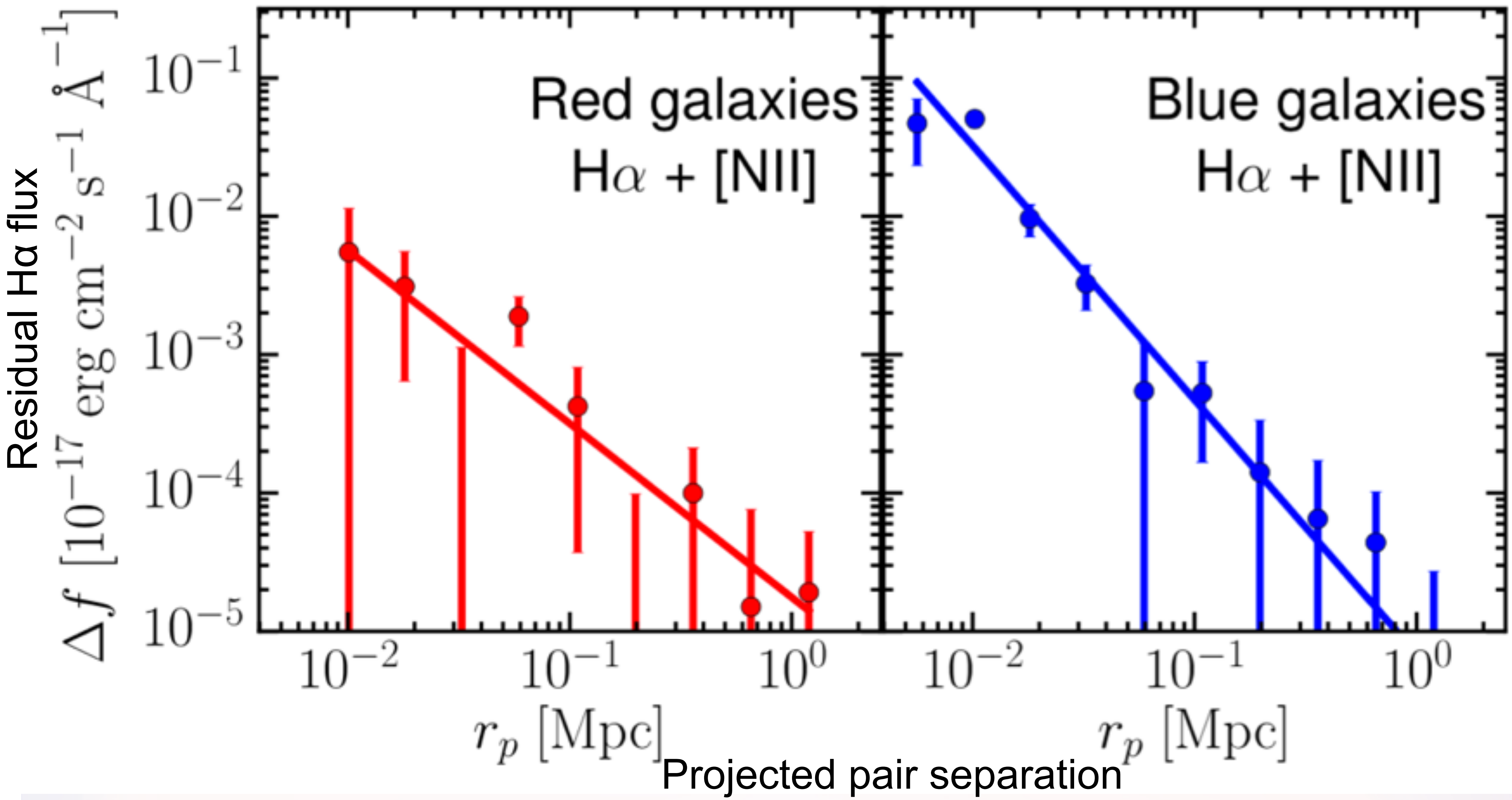


HeII λ1640

- By hard ionizing photons from AGNs/SMBHs and/or PopIII stars
- Mostly around QSOs and AGNs at higher-z
- Spatial distributions of HeII halos are not coincident with those of Lyα halos
- Flux ratio can be used to constrain the density with some assumptions

Cantalupo+19; den Brok+20

Ionized gas tracer | Hα



Hα halo

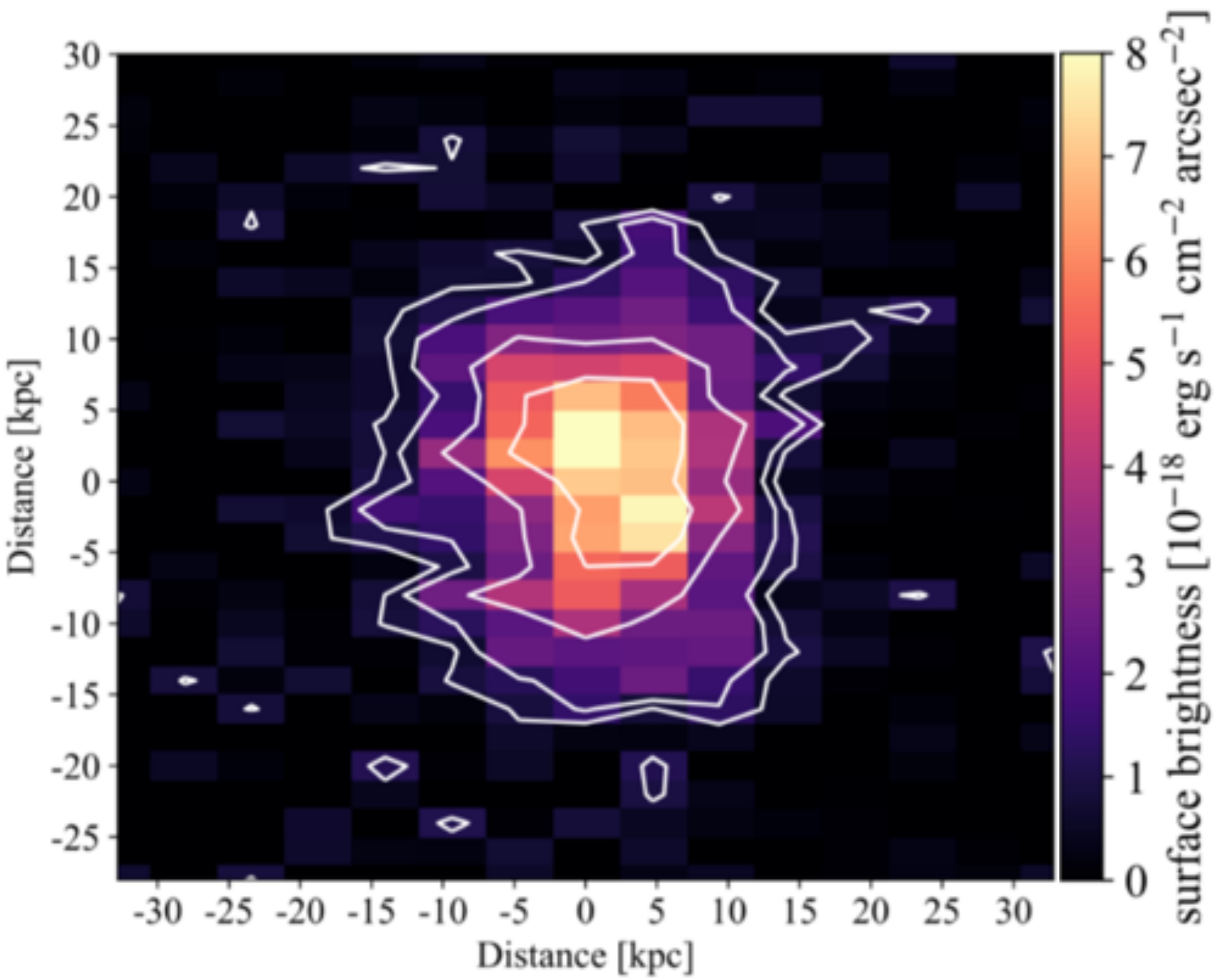
- Trace the ionized gas
- Identify Hα emission up to a few 100 kpc
- Universally confirmed around red/blue, interacting/isolated and high/low stellar mass galaxies

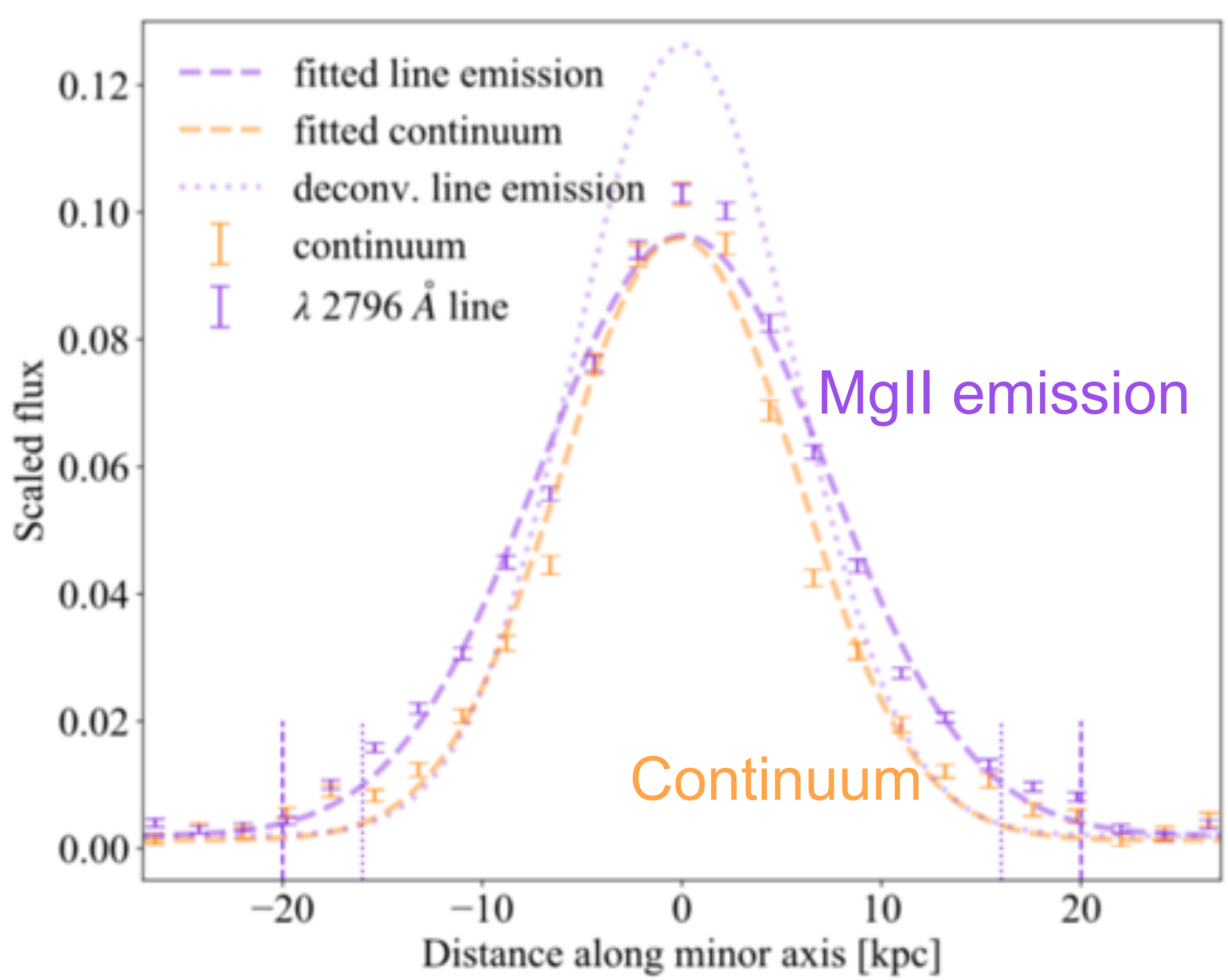
Zhang+16,18a,b,19,20

Another resonant line but Lyα, MgII

MgII λλ2798/2803 doublet

- Among the most abundant metal ions in the universe
- Strong line
- Could show very similar scattering as Lyα
- Increasing attentions (several papers will be submitted)





Burchett+20

Summary of another emissions but Lyα

Metal lines

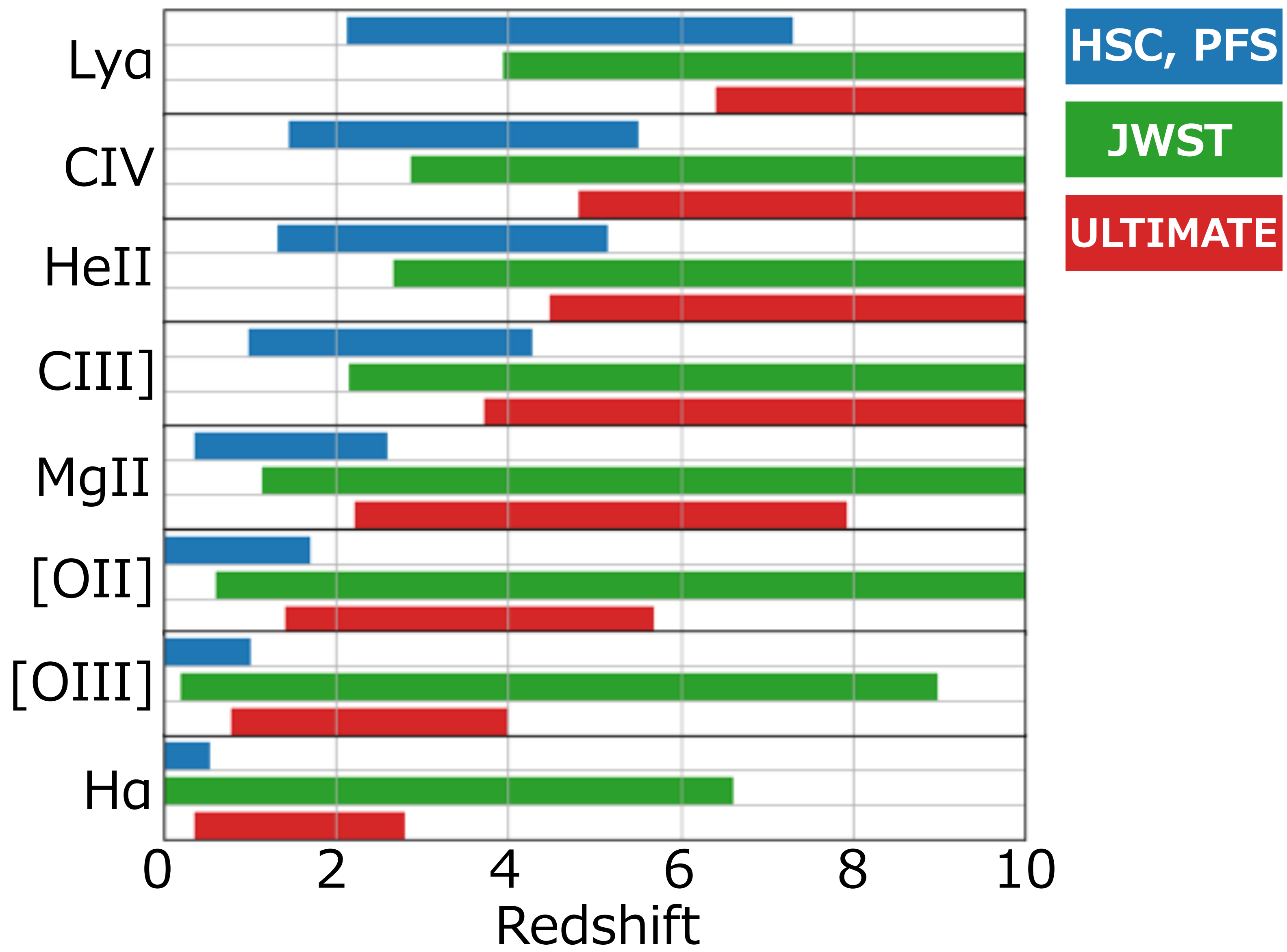
- Carbon: [CII], CIII], CIV

Tracer of ionized gas

- Hα and HeII

Resonant line

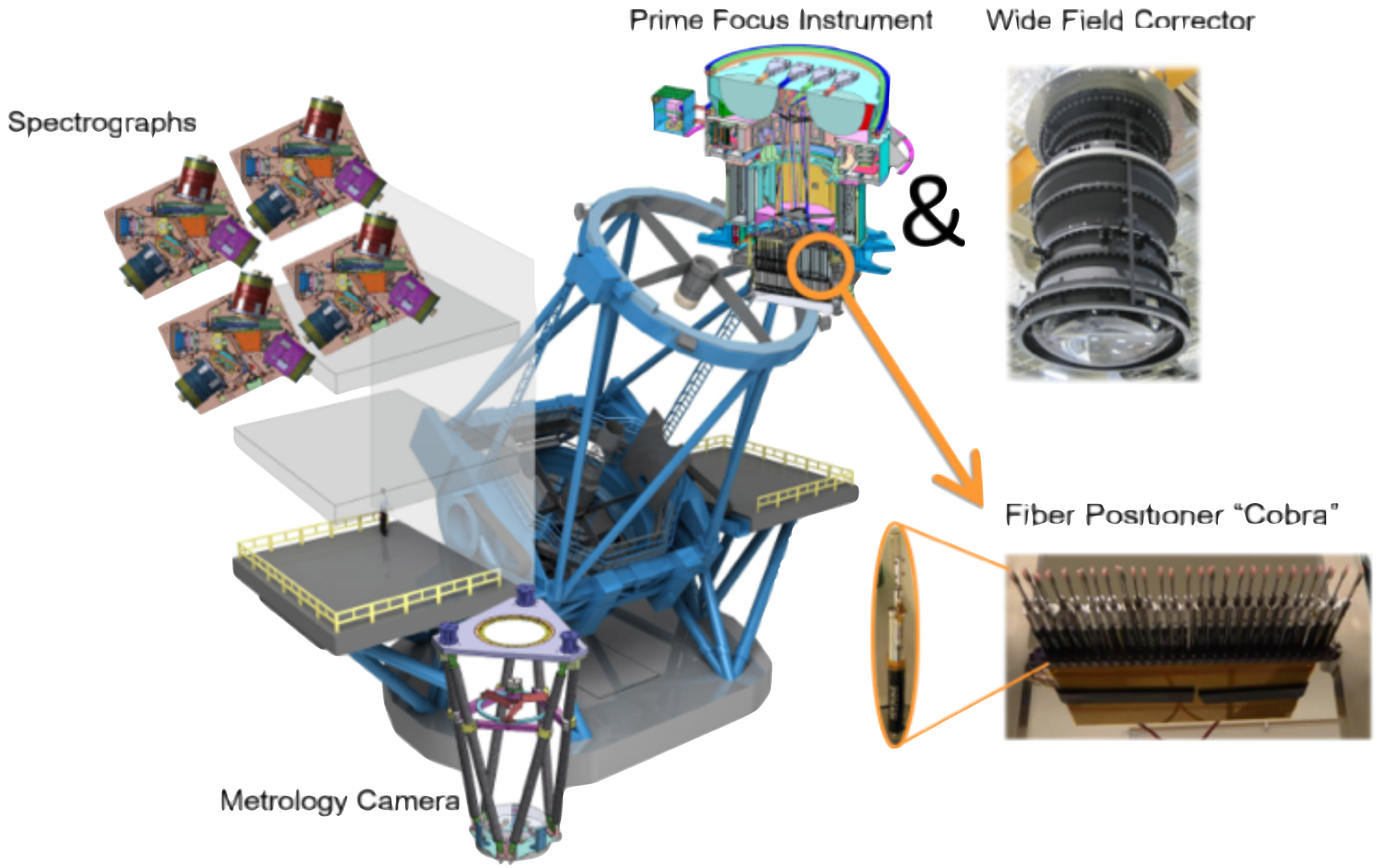
- MgII (for galaxies at $z < 2$)



Both resonant and non-resonant emissions are crucial

The upcoming telescope and instruments will provide new capabilities

For future PFS survey

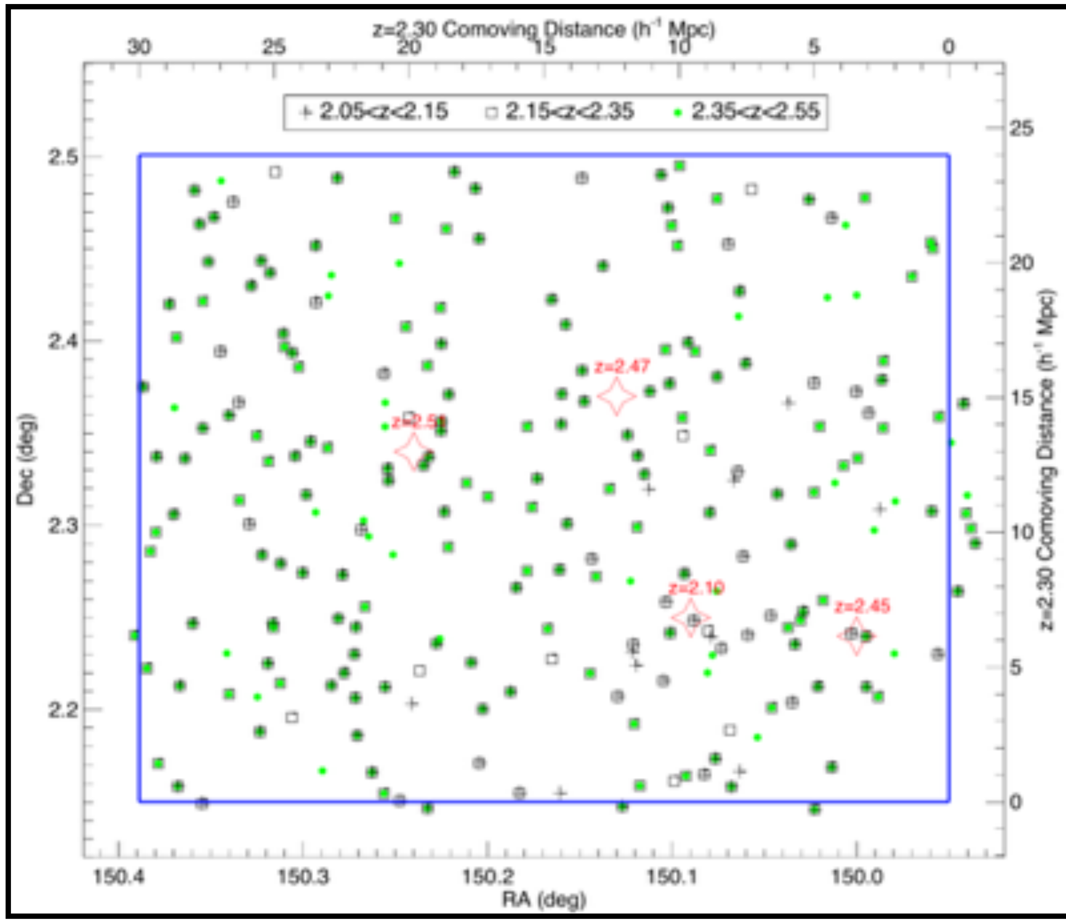


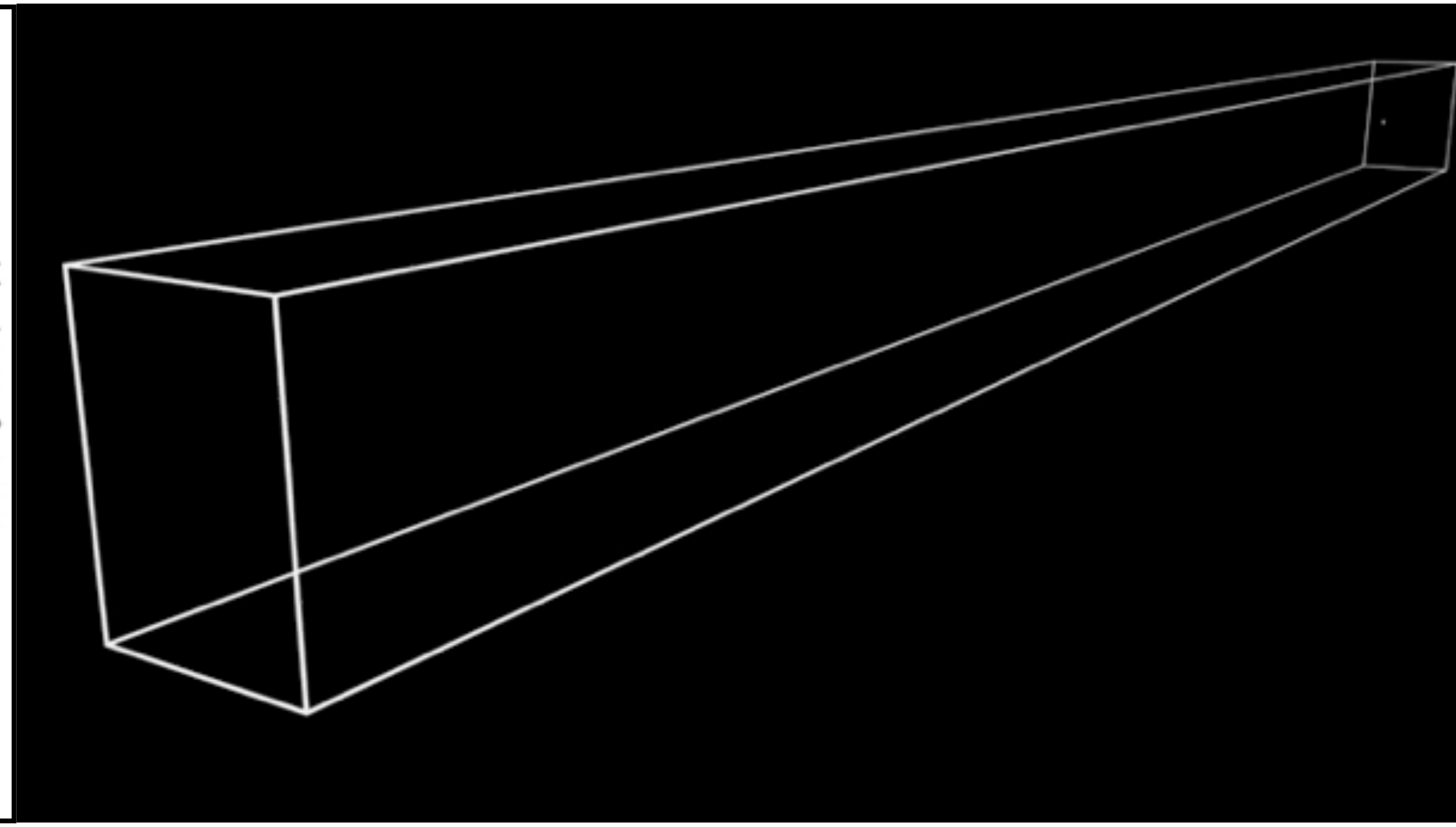
Planning the Subaru strategic program with ~300 nights in 2023−2027

One of the major goals is to generate a 3D tomographic map of HI in the IGM

- z = 2.1−2.6
- About 100 times larger volume than CLAMATO

3D tomographic map of HI in the IGM





Reconstruction of HI in the IGM from Lyα forest absorptions

- Hundreds of bright galaxies' and QSOs' spectra as background lights
- Resolution corresponds to the mean separation of background galaxies
- Pixel value is the transmission flux excess δ_F

$$\delta_{\mathrm{F}} \equiv \frac{F(x)}{\langle F_z(x)\rangle} - 1$$

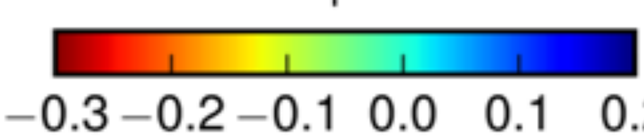
Lyα forest transmission

cosmic mean
Lyα forest transmission

Strong
HI abs.

$\delta_{\mathrm{F}}^{\mathrm{rec}}$

Weak
HI abs.



Pichon+01; Lee+16b, 18

3D IGM HI tomographic map | large survey

CLAMATO (complete)

Volume : 3.15×10^5 $(h^{-1}$ Mpc$)^3$

Redshift : 2.05−2.55

Resolution: 2.5 h^{-1} Mpc

Telescope : Keck-I

LATIS (on-going)

Volume : 4×10^6 $(h^{-1}$ Mpc$)^3$

Redshift : 2.2−2.8

Resolution: 2.5 h^{-1} Mpc

Telescope : Magellan

SDSS stripe 82 (complete)

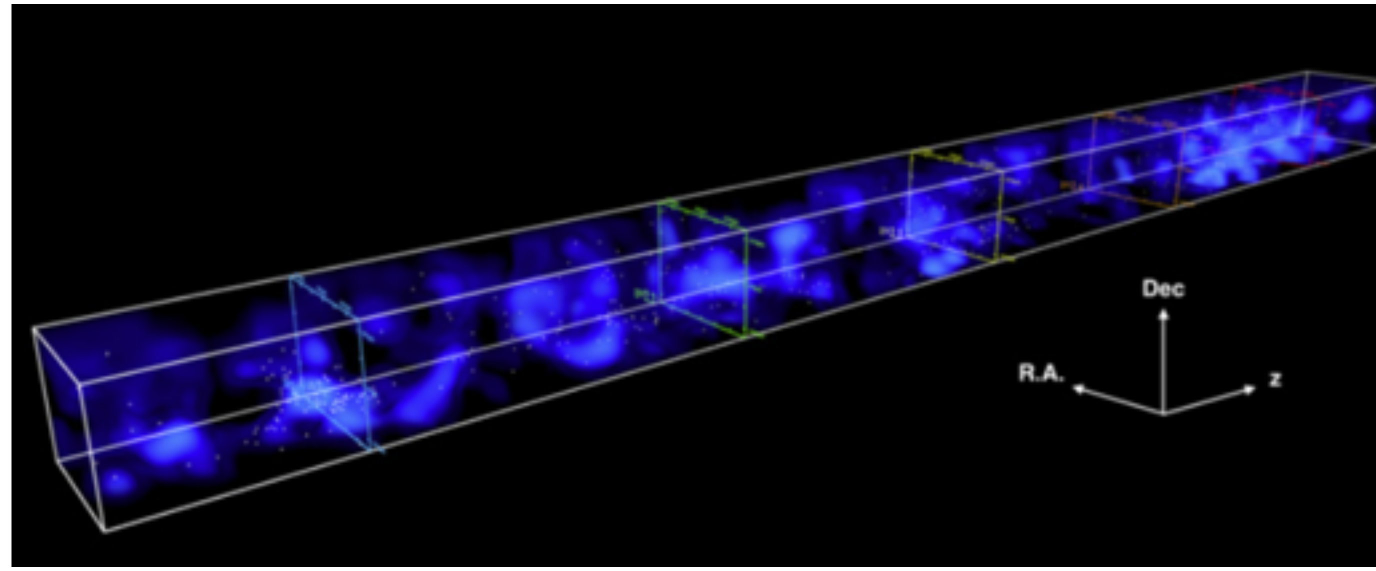
Volume : 9.4×10^8 $(h^{-1}$ Mpc$)^3$

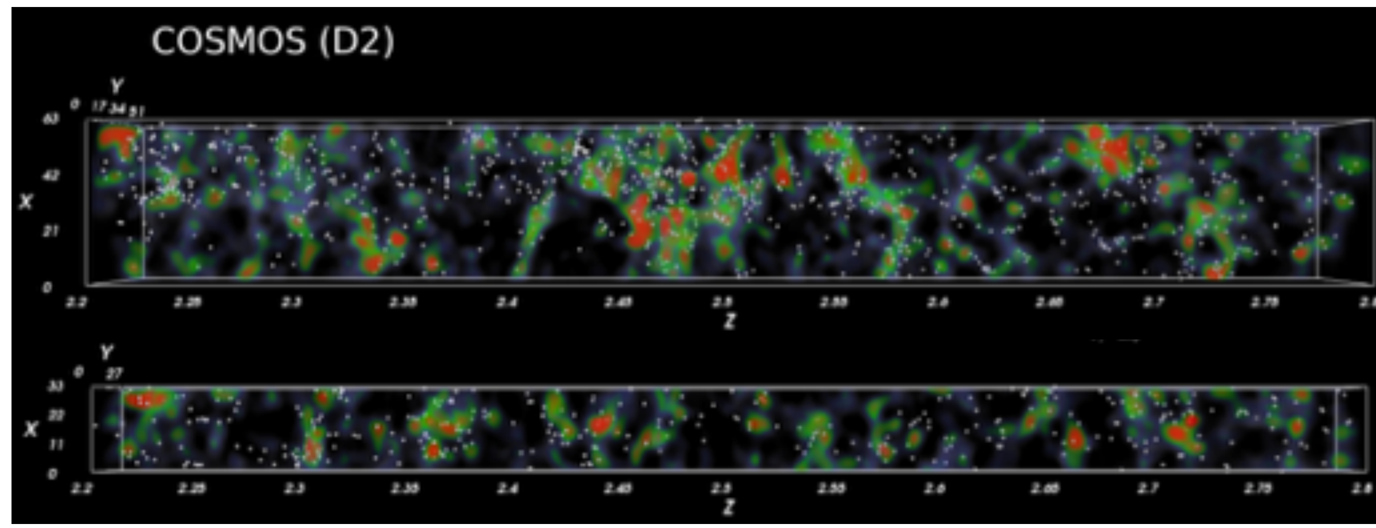
Redshift : 2.1−3.2

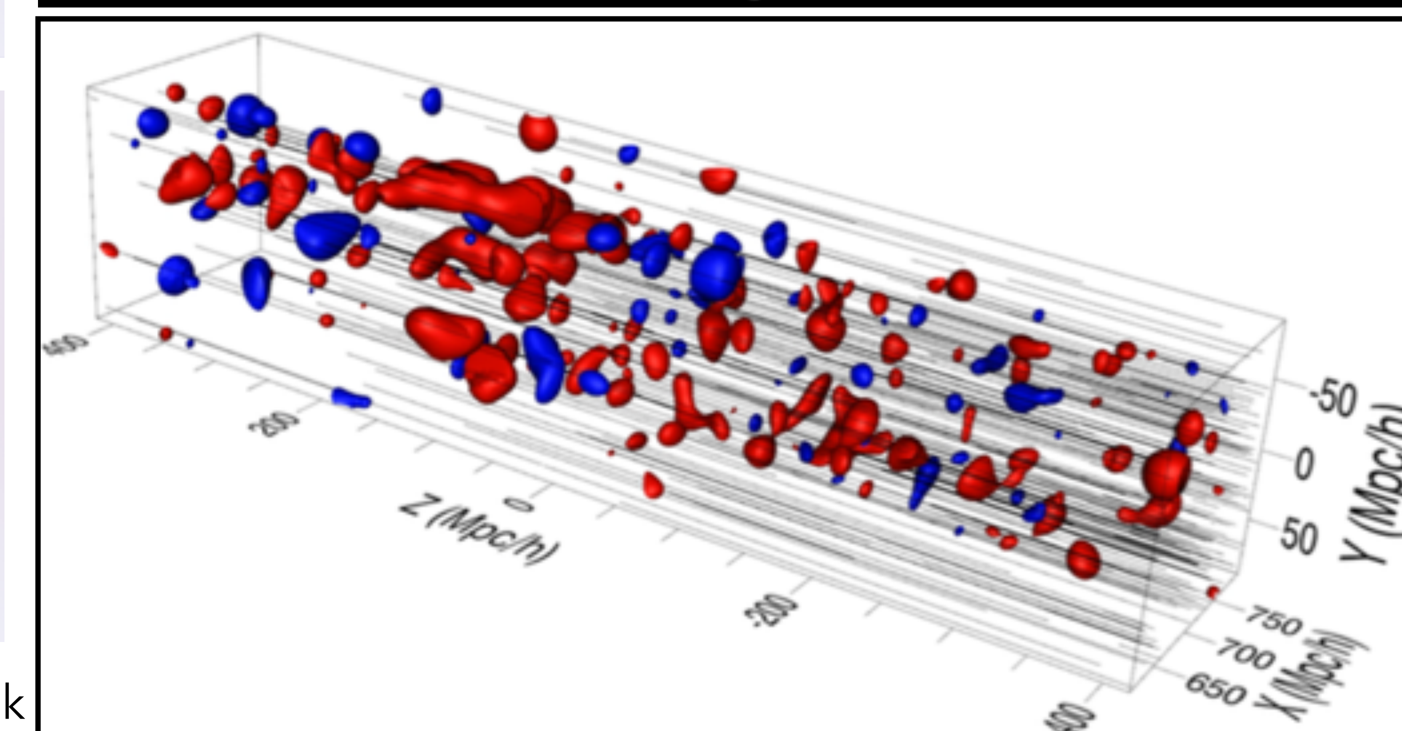
Resolution: 13 h^{-1} Mpc

Telescope : SDSS

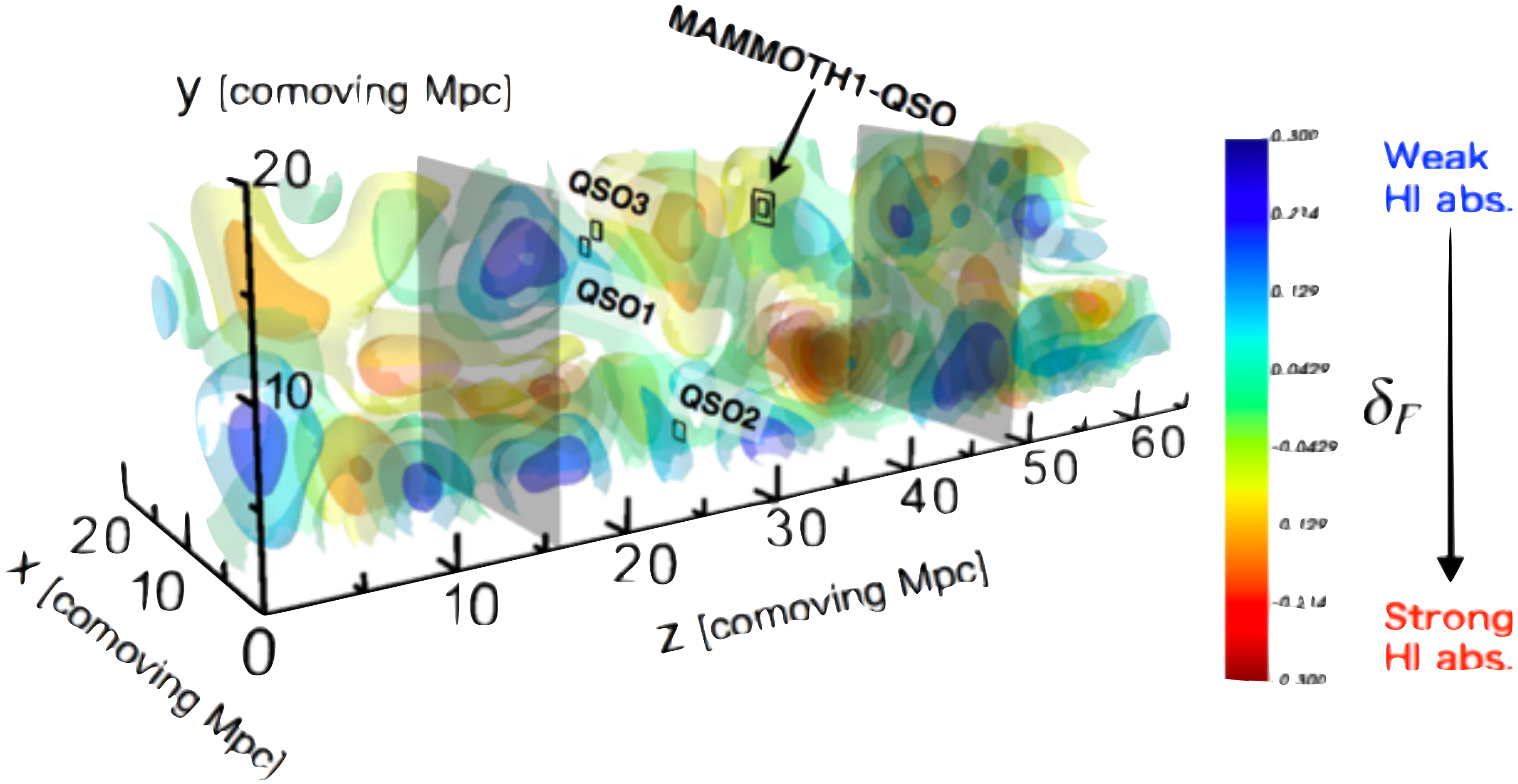
Lee+16b,18; Newman+20; Ravoux+20; see also Sun's talk



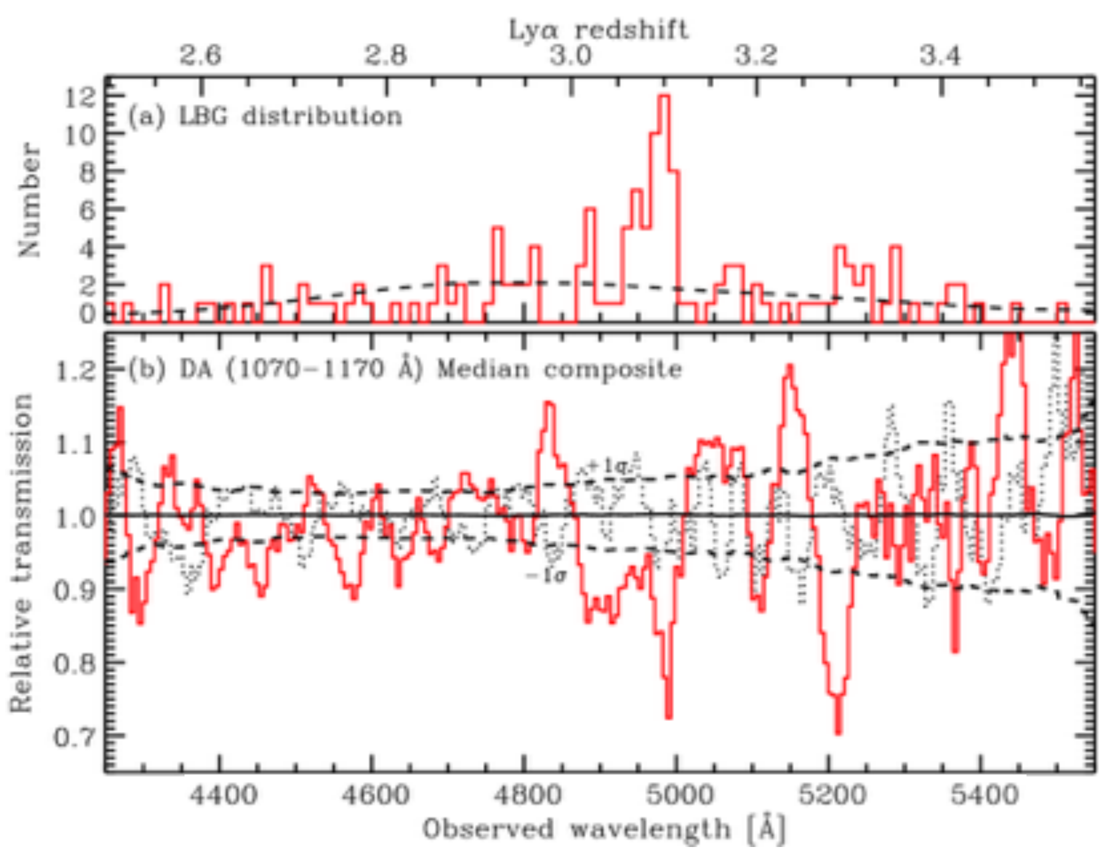




3D IGM HI tomographic map | specific fields



MAMMOTH1
Redshift : 2.25−2.40
Resolution: 2.6 h^{-1} Mpc
$N_{\mathrm{background}}$: 16



SSA22 (but no tomography map)
Redshift : 2.5−3.6
$N_{\mathrm{background}}$: 77

Hayashino+19; Mukae+20

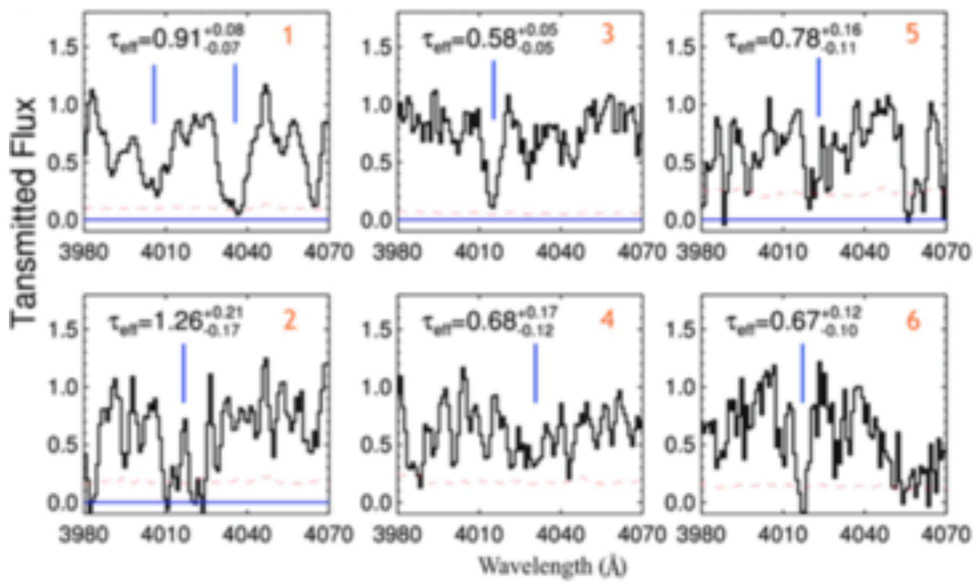
Finding overdensities

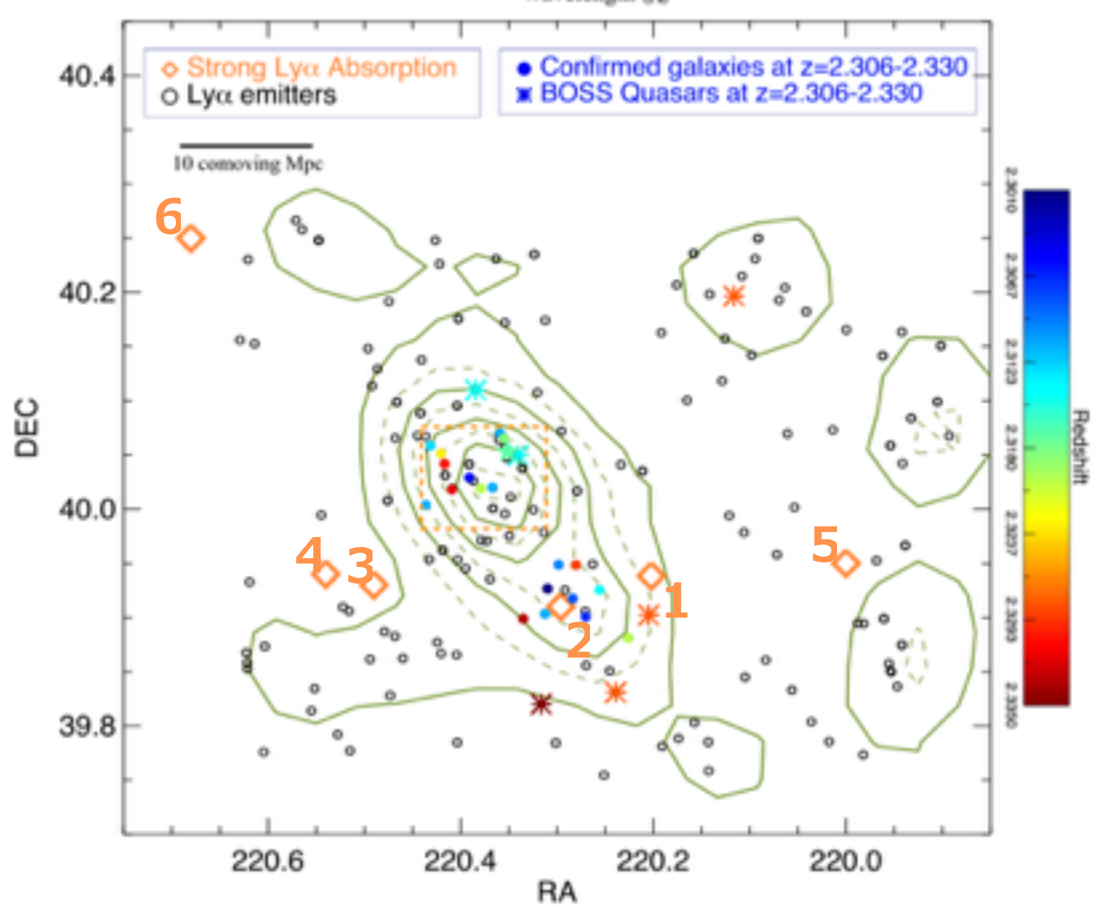
New mean to find galaxy overdensity with strong Lyα forest absorption

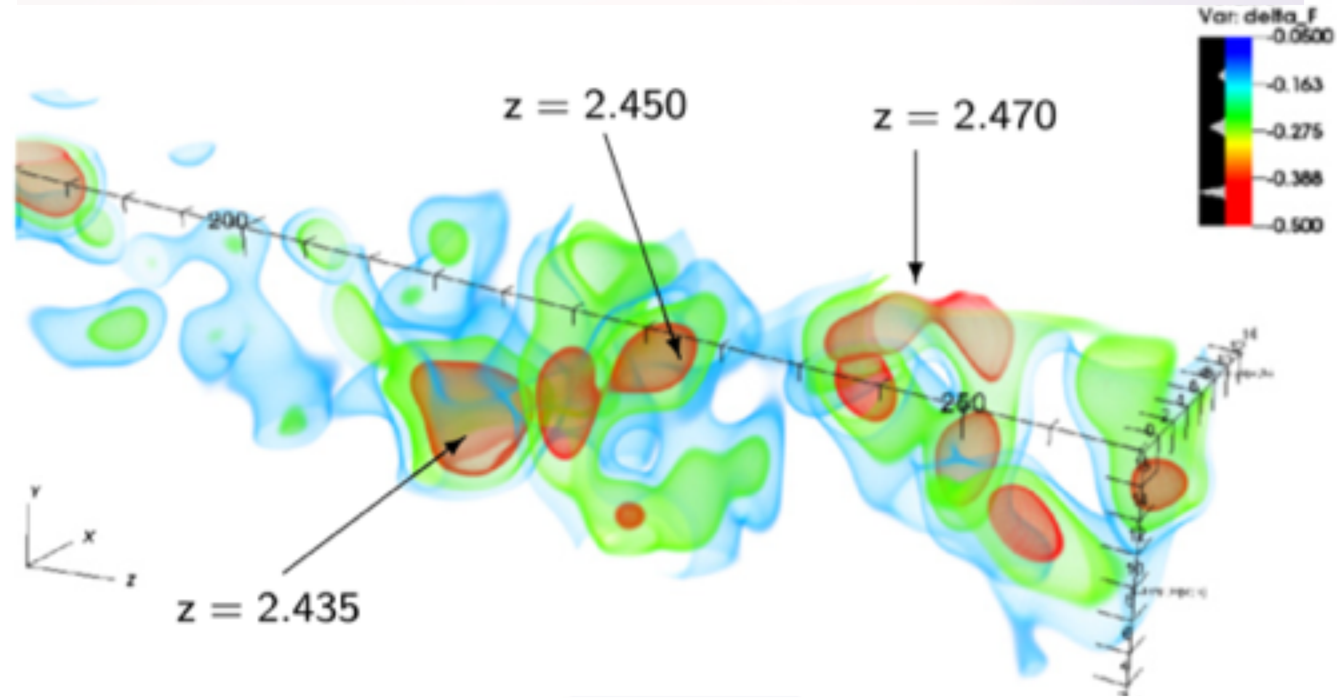
- Unbiased galaxy overdensity

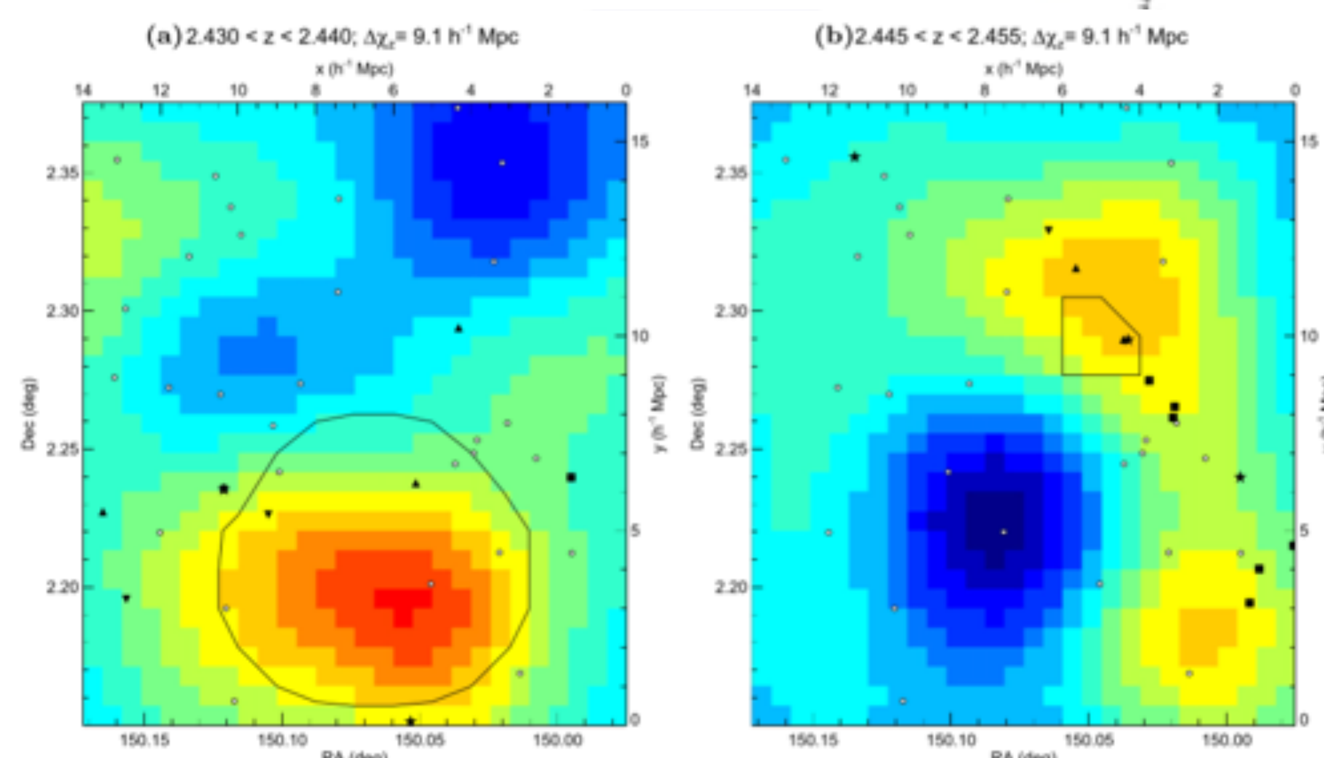
Coincidence of locations

- Overdensities of the IGM and galaxy (i.e. known proto-cluster)



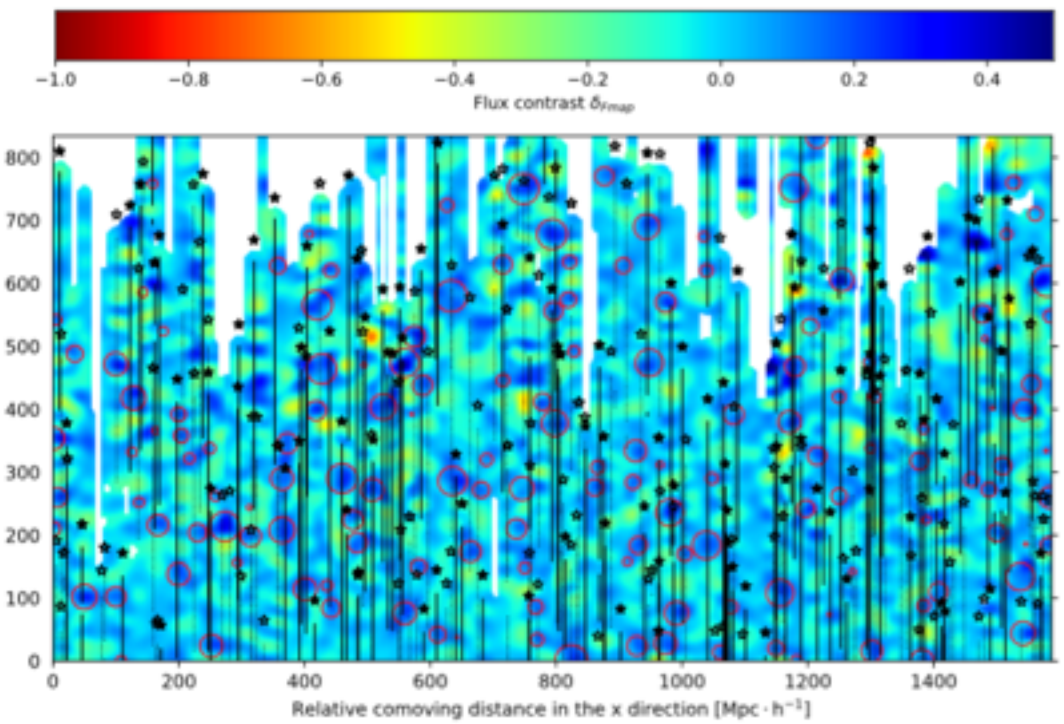


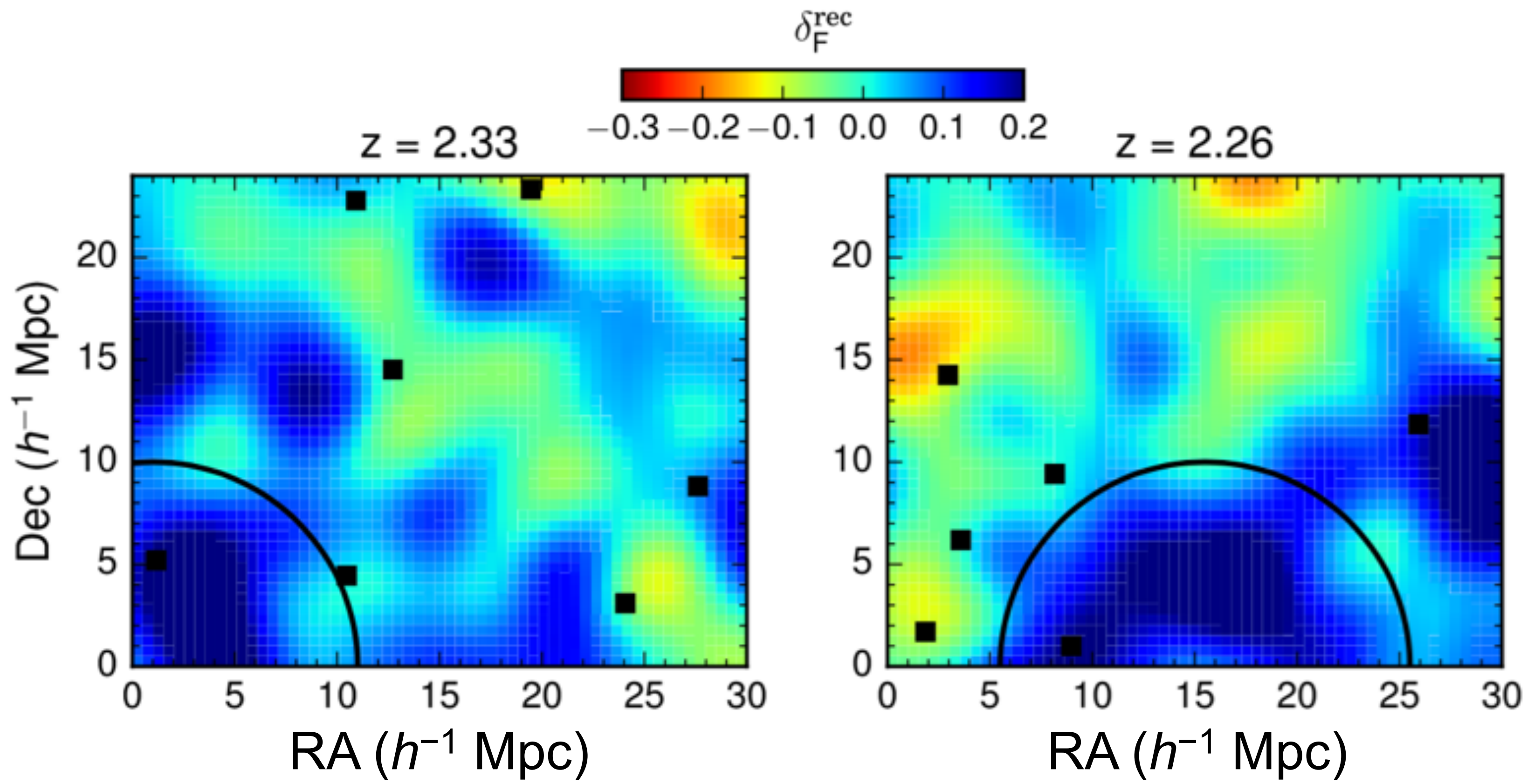


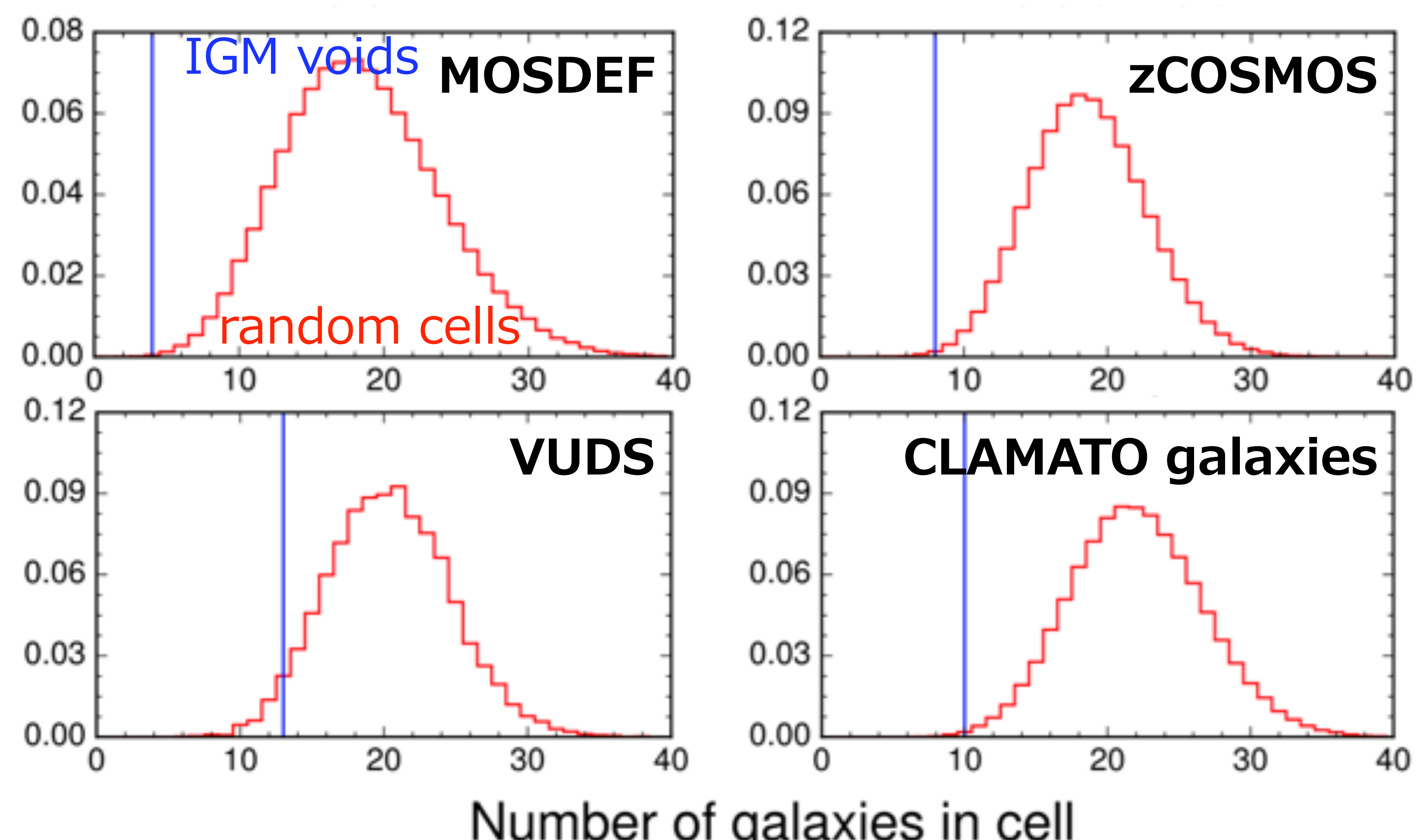


Lee+16a; Cai+16, 17

Finding voids





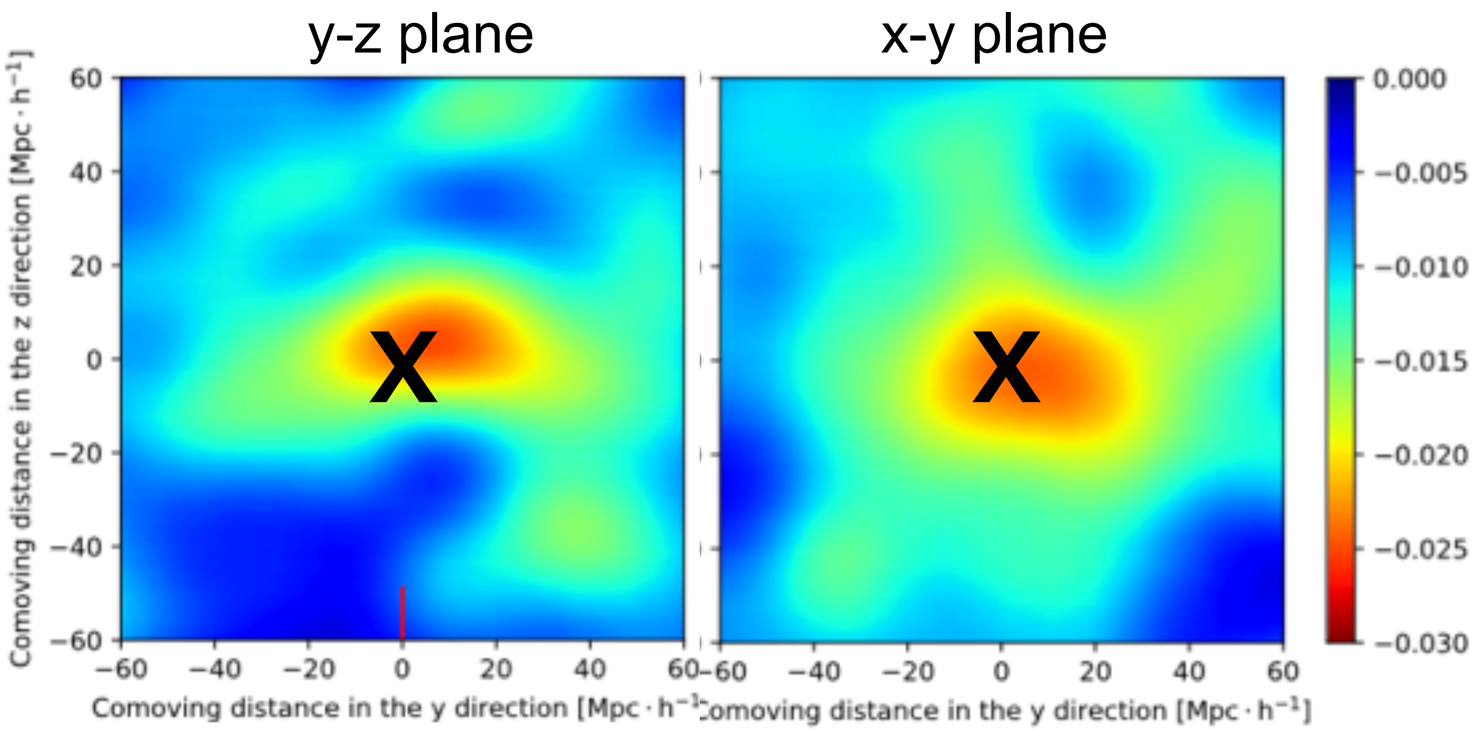


Voids of the IGM

- Corresponding to voids of matter density
- 18–20% in the CLAMATO
- Underdense in galaxies by 5.95σ
- Geometry is not isotropic

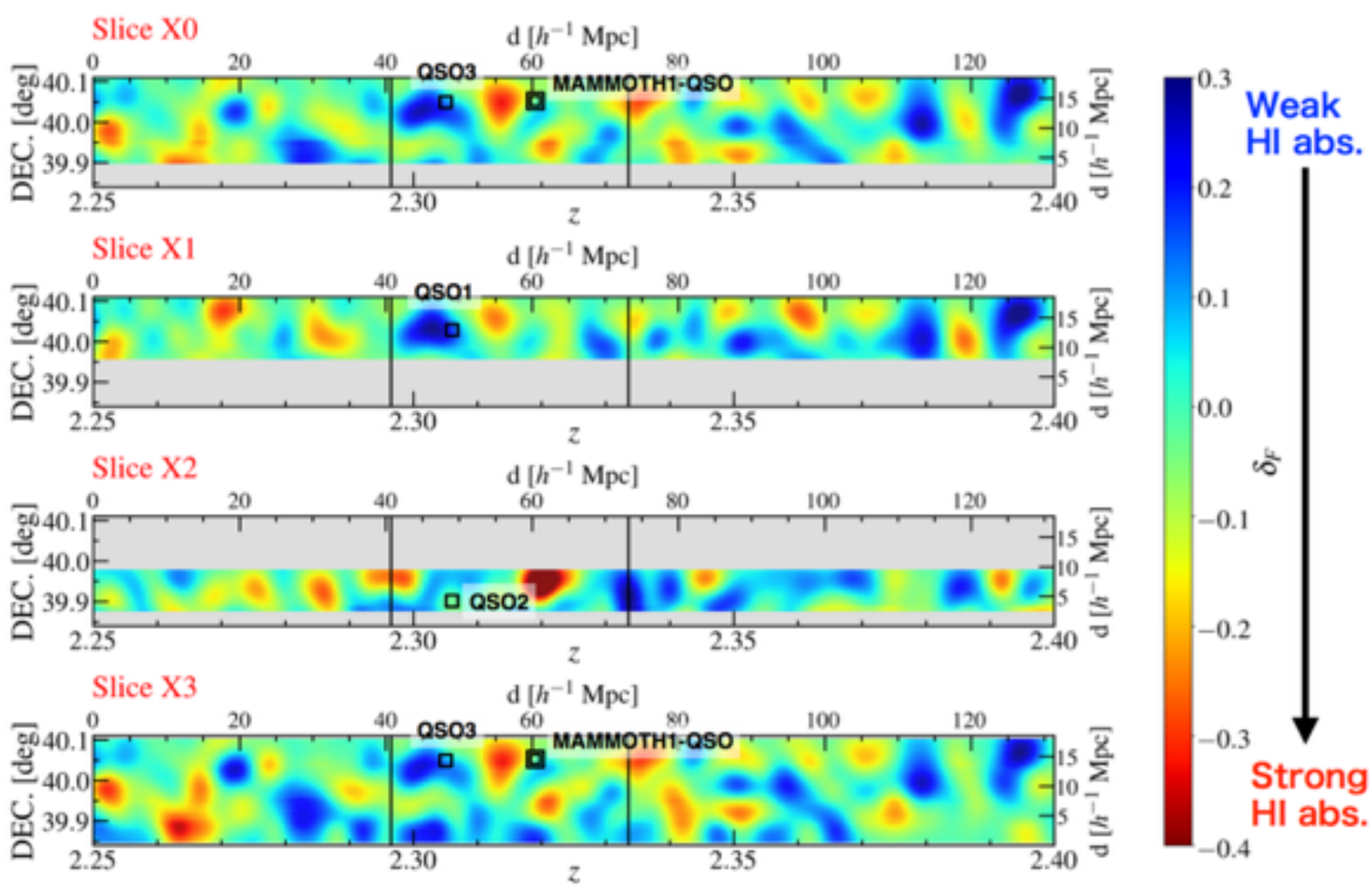
Krolewski+18; Ravoux+20; see also Sun's talk

Characterizing the IGM by 2D map



Stacking around QSOs

- 5.2σ excess of HI absorption with respect to a random
- Cannot identify the proximity effect due to the larger resolution (13 h^{-1} Mpc)

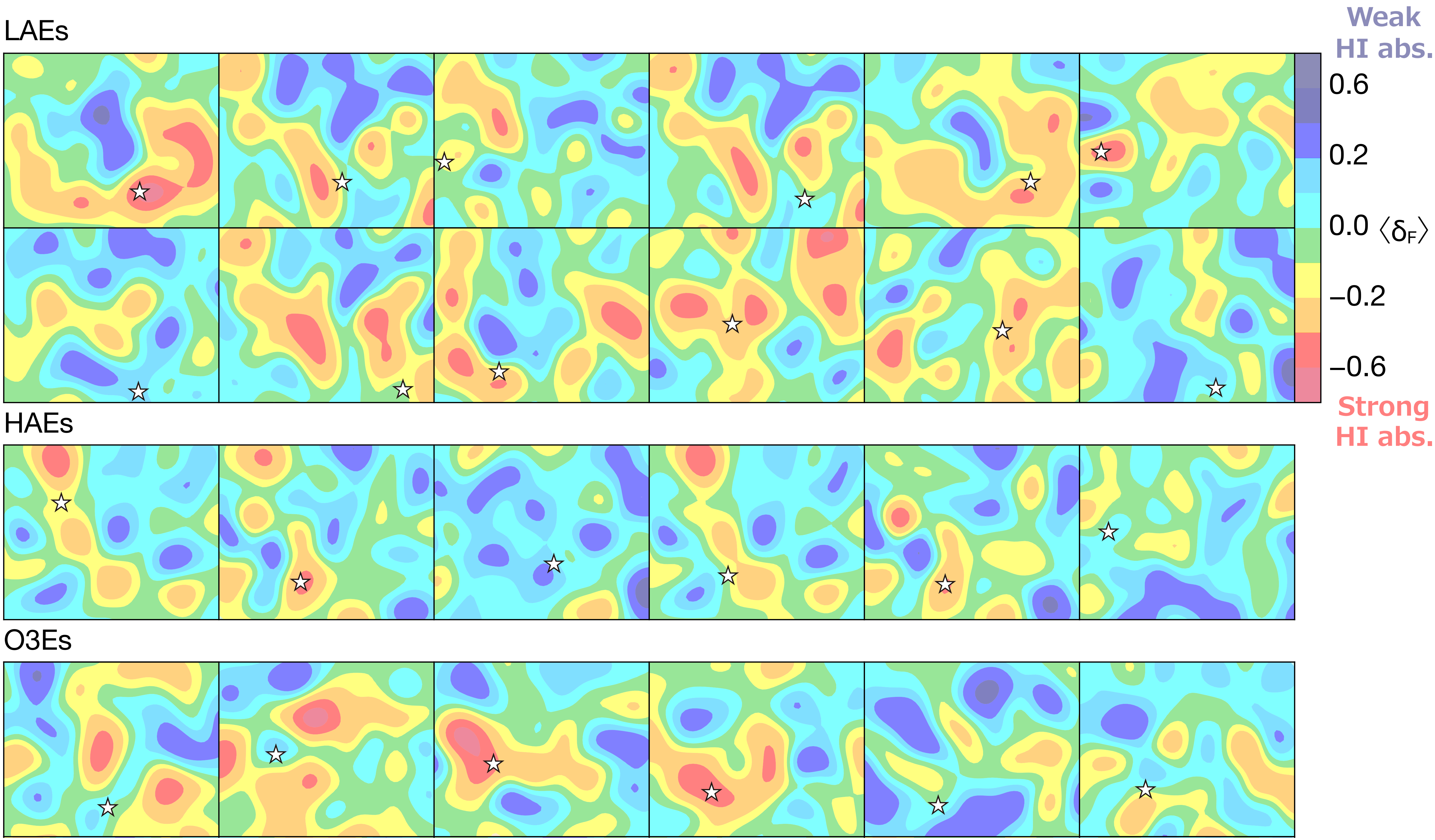


Individual QSOs

- Variety among individual QSOs
- Weak HI absorption is probably due to the proximity effect

Mukae+20; Ravoux+20

Characterizing the IGM by 2D map



A variety of the IGM environments among individual star-forming galaxies

MR+20b

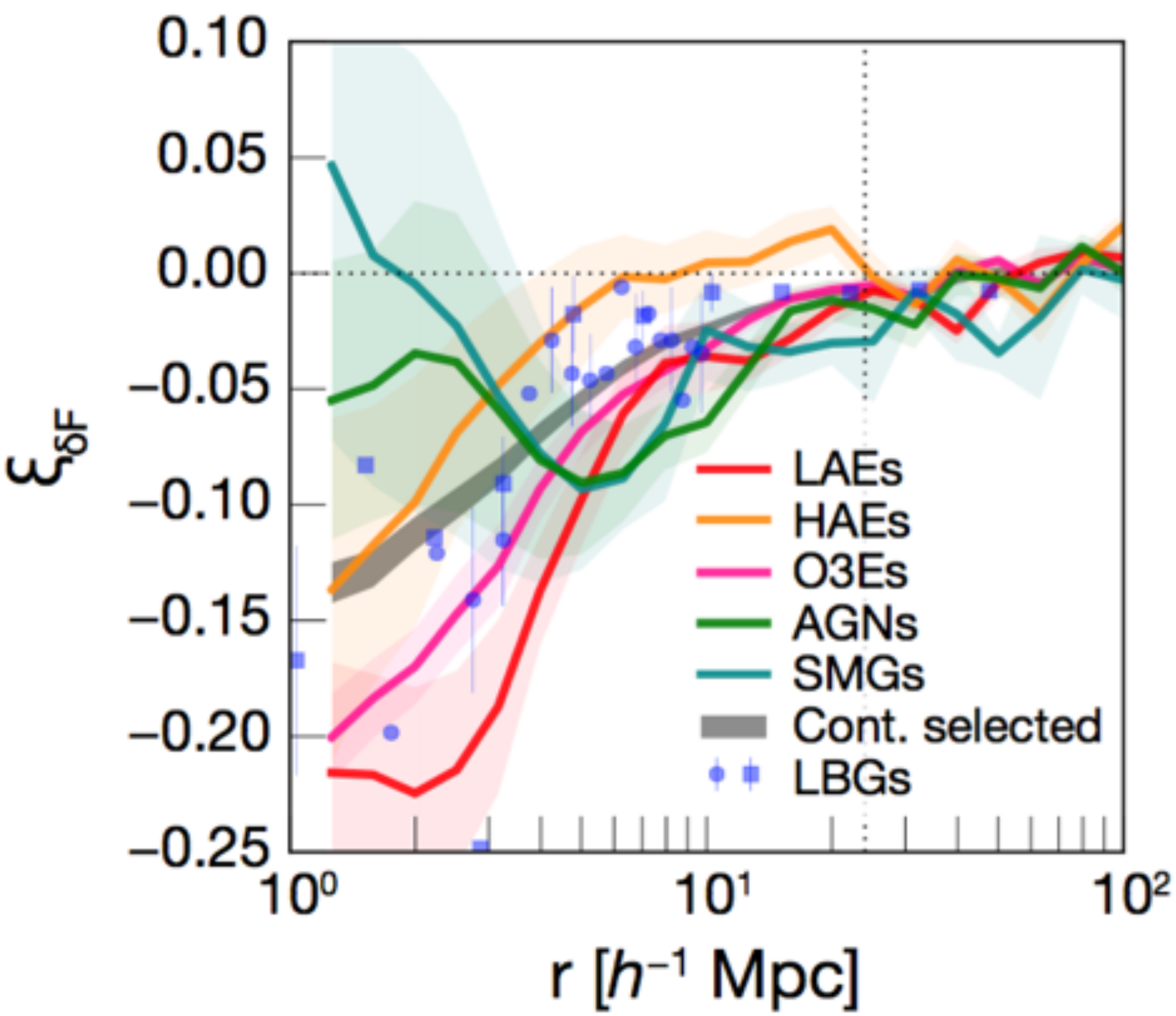
Characterizing the IGM by δ_F distribution around galaxies

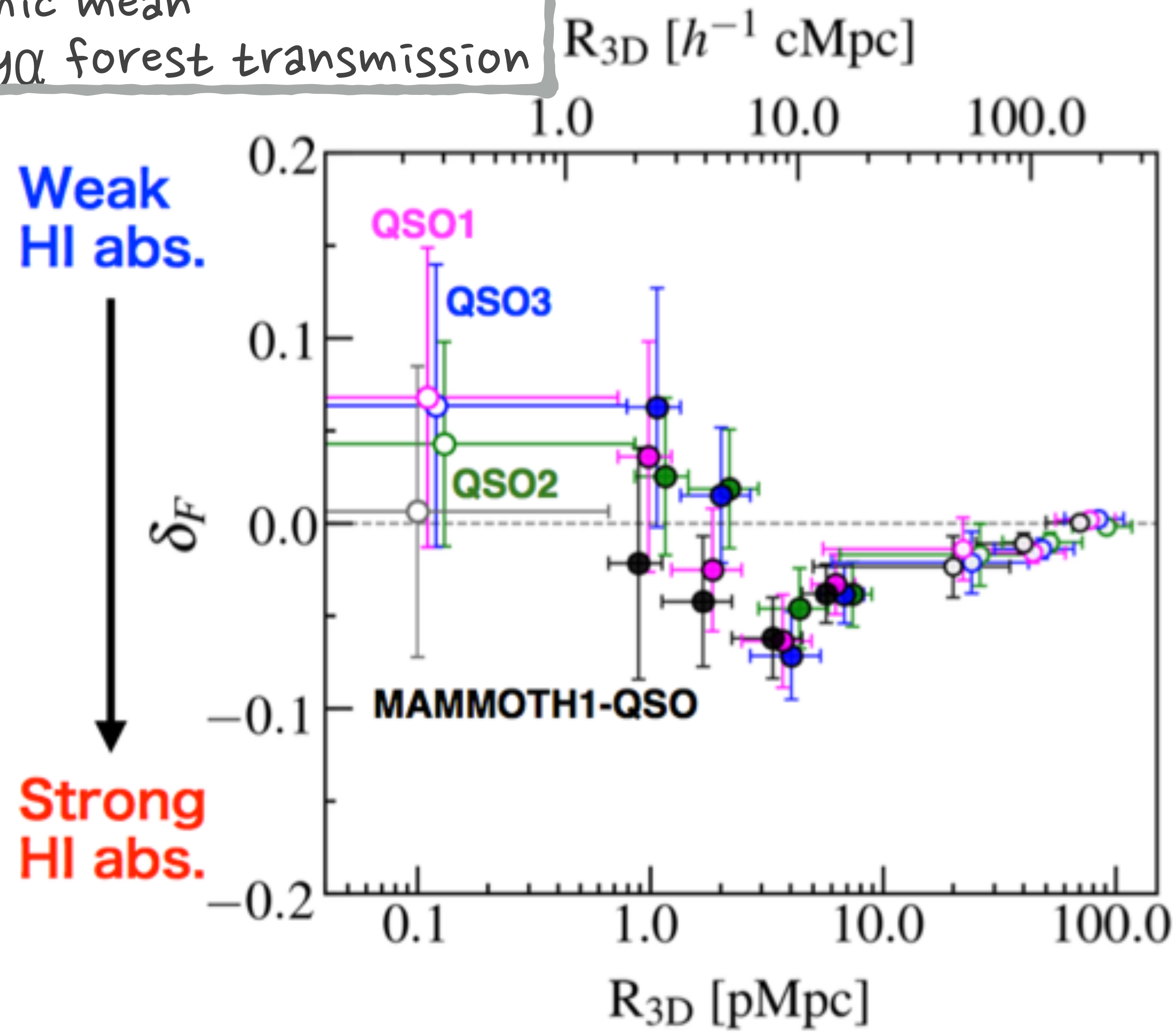
the excess

$$\delta_F \equiv \frac{F(x)}{\langle F_z(x) \rangle} - 1$$

Lyα forest transmission

cosmic mean Lyα forest transmission





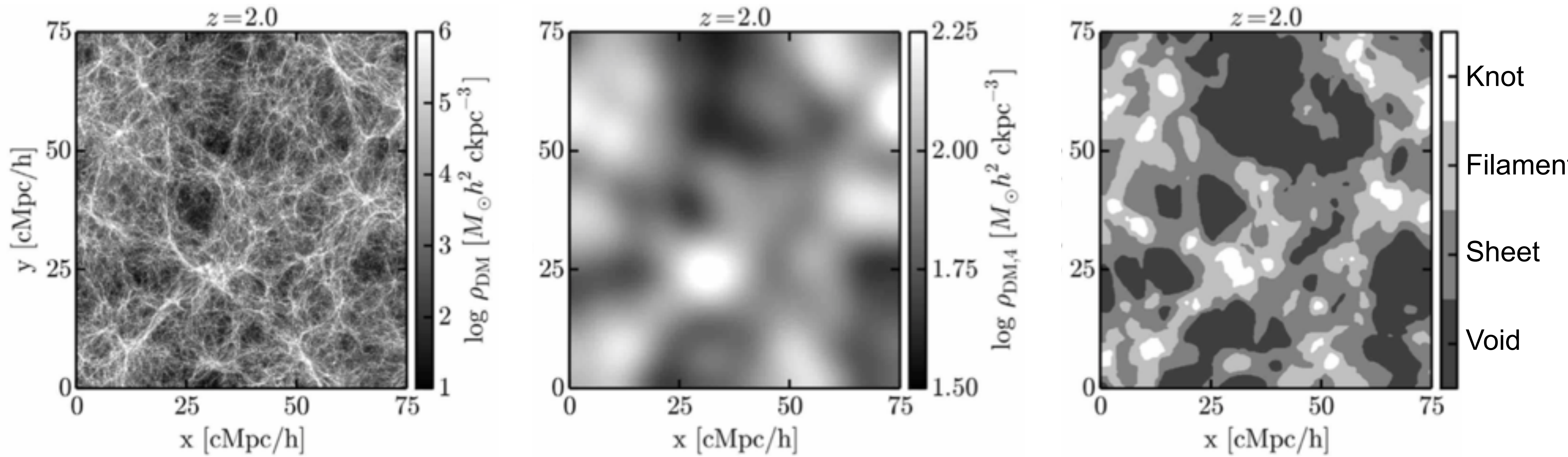
Calculate cross-correlation functions

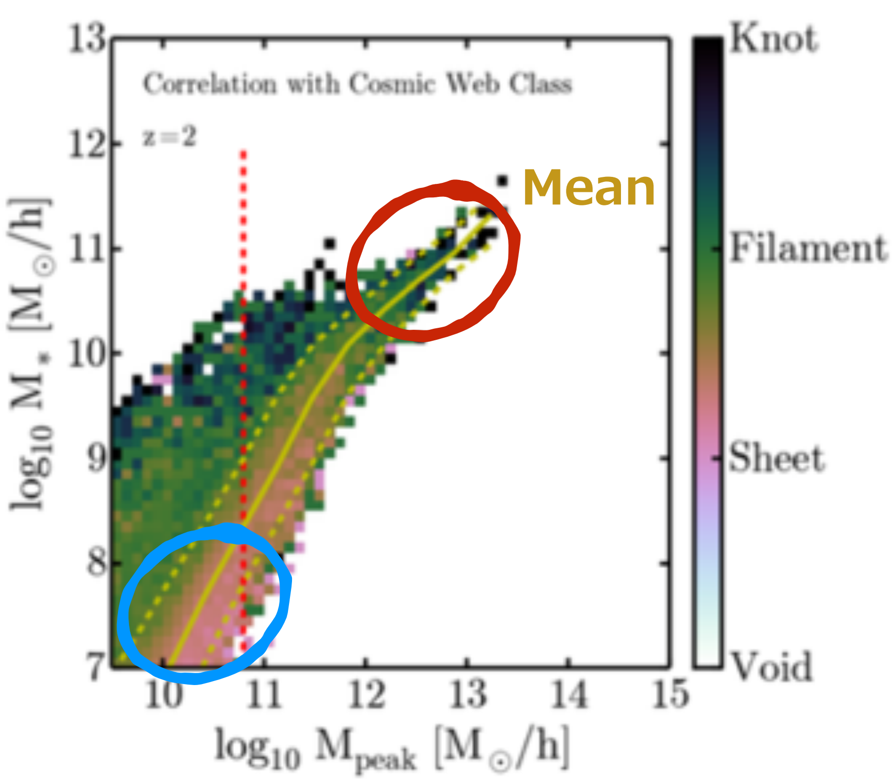
- A variety of CCFs depending on galaxy populations
- Generally signal strengths correlate with a halo mass (but at r > 5 cMpc)

Measure the mean δ_F

- Common turnover at r ~ 3 pMpc
- Comparable to proximity zone of QSOs at z = 2 (a few pMpc)

Mukae+20; MR+20b; see also Liang's talk





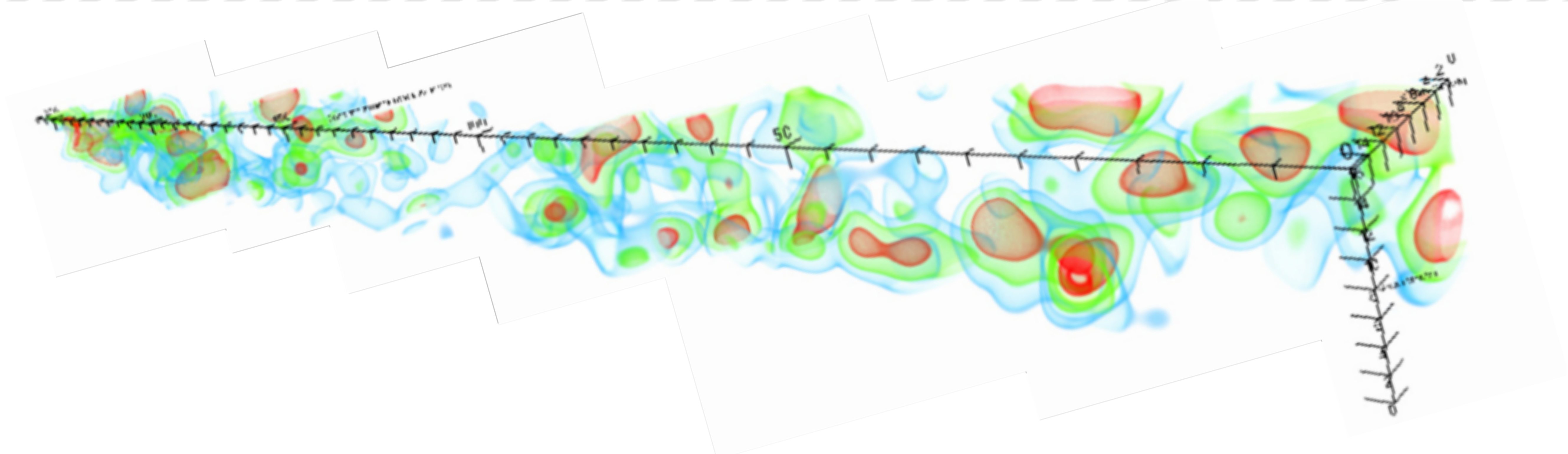
Identify morphology

- Knot, filament, sheet, void
- There are several ways

Examine the IGM morphology and galactic properties

- Massive : knots and filaments
- Lower mass: sheets and voids

Martizzi+19, 20



Producing 3D IGM tomography is one of the goal of PFS survey

What we can examine with 3D tomography map

- Finding overdensities and voids
- Characterizing the IGM by 2D maps, δF distribution, and morphology to unveil the IGM—galaxy connection

This field is not matured, but will be active for next decade!

Lee+16

A task of IGM observations

Propose an observational study of the CGM and/or IGM utilizing Subaru telescope's strength

Number of published papers studying the CGM and IGM by emission