IGM/CGM probed by PFS

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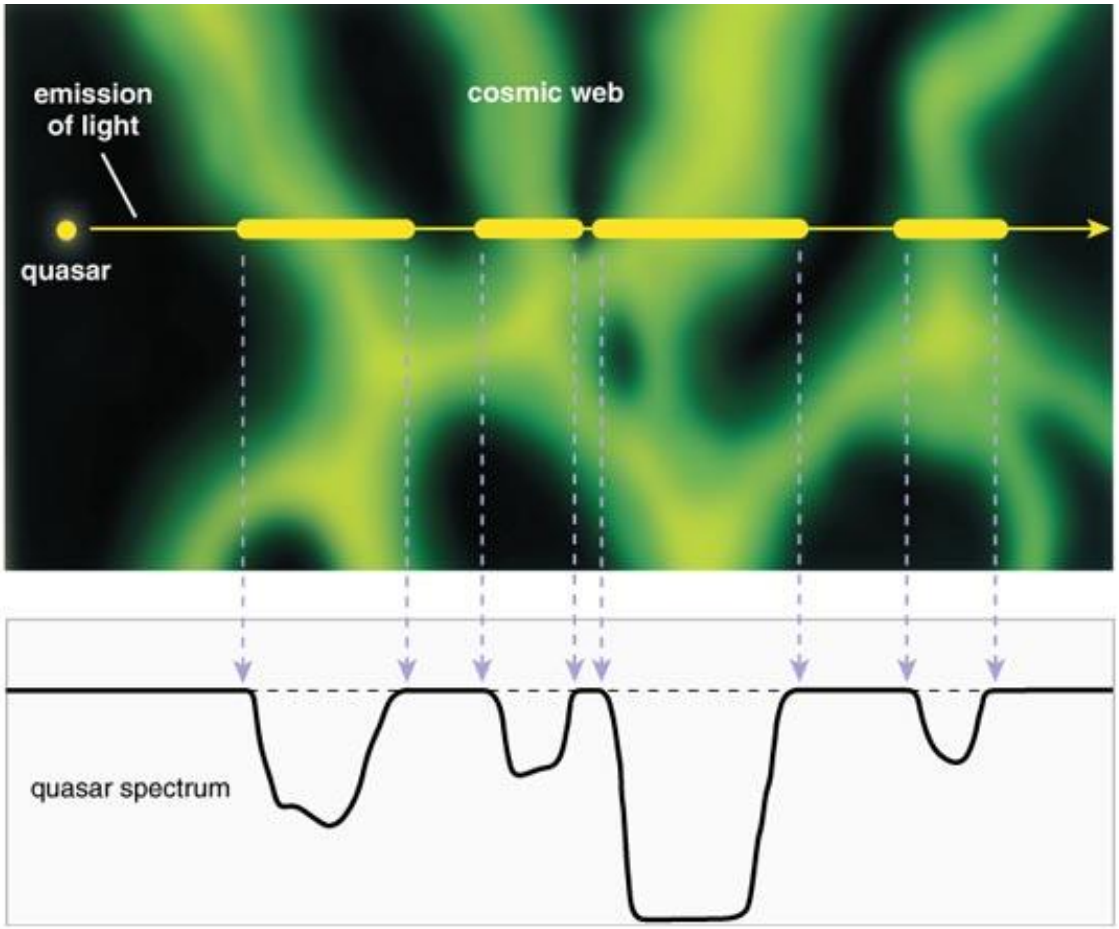
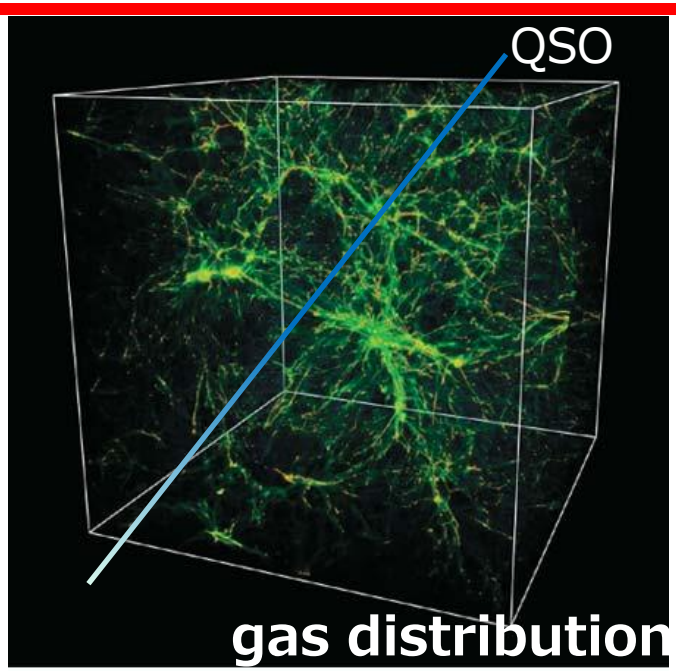
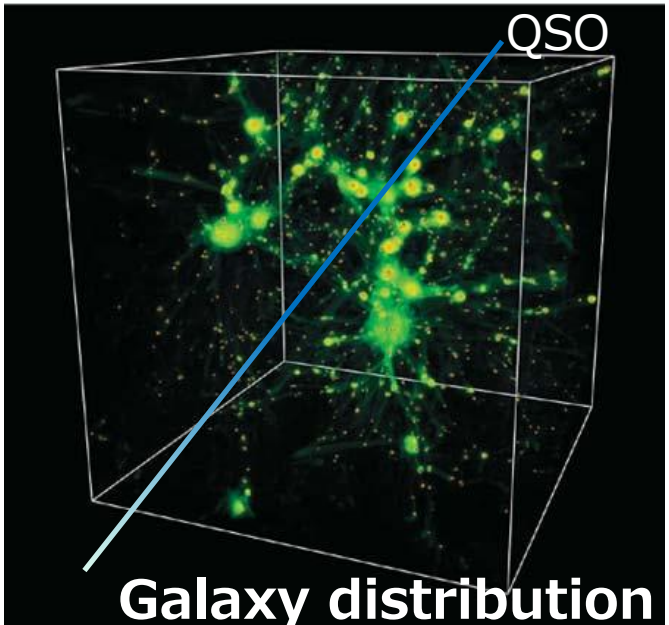
（NAOJ）

IGM and large scale structure

- High-z quasars as “beacons” to light up the foreground structure
- IGM: quasar absorption system

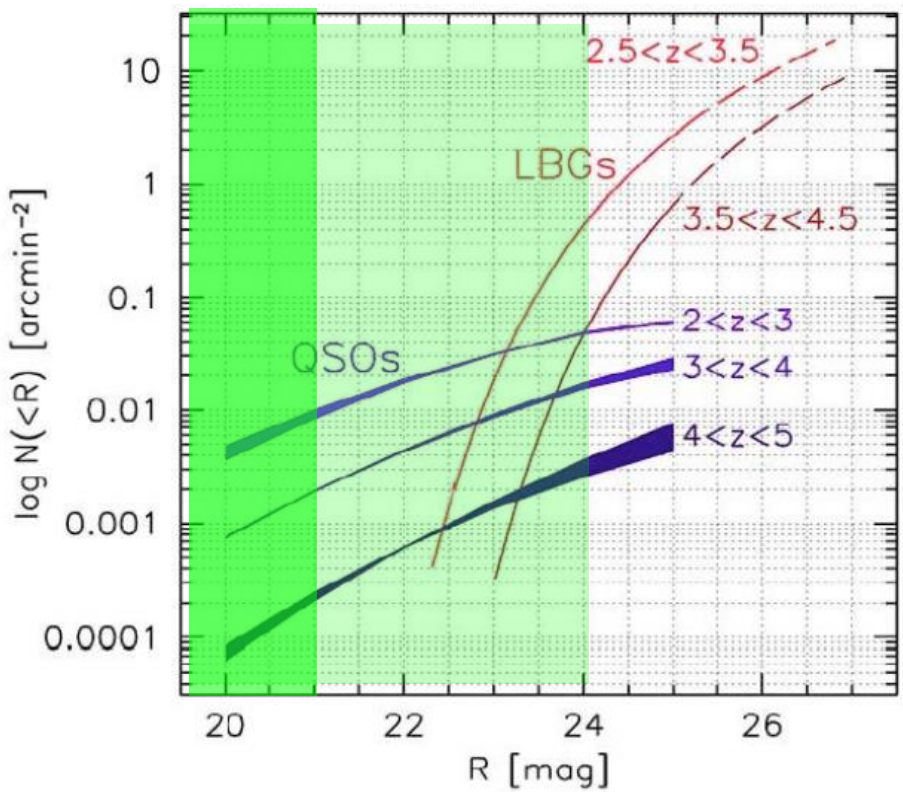


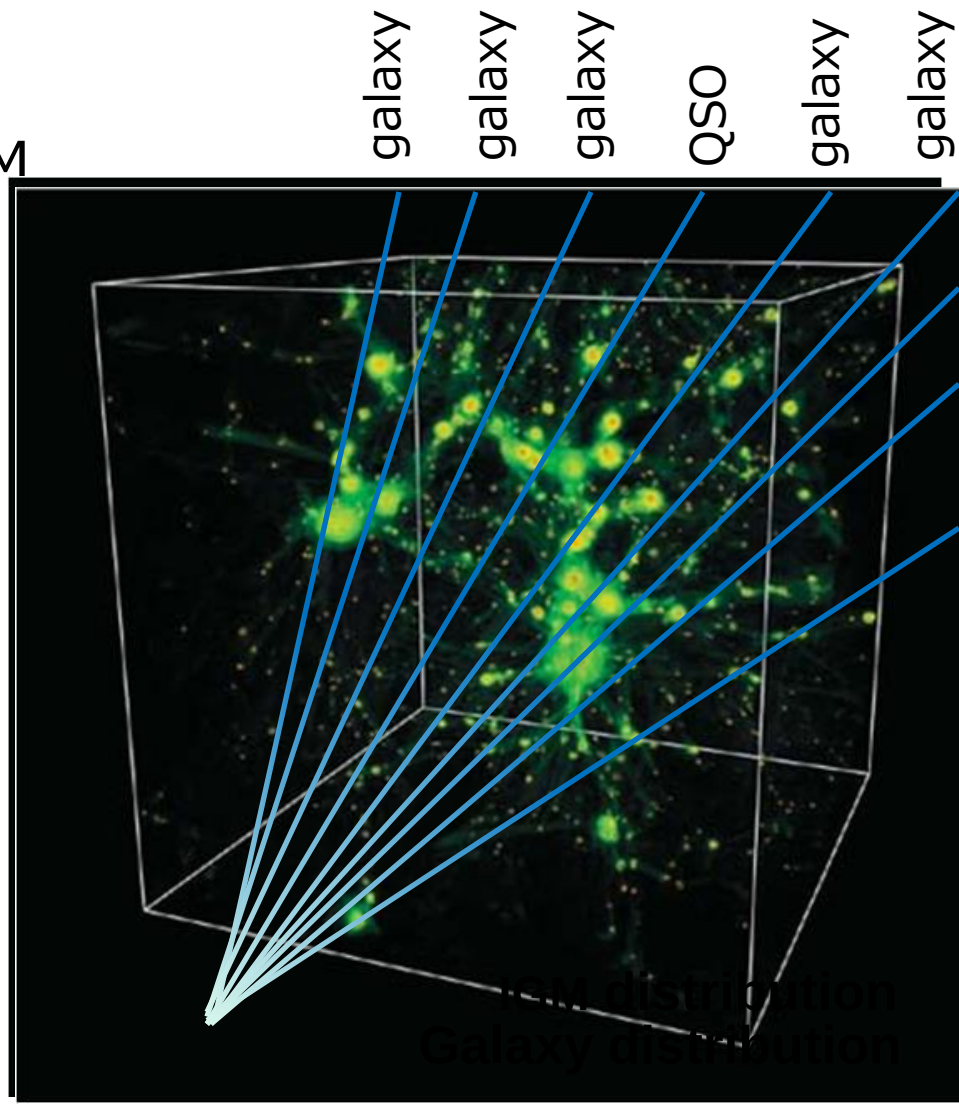




IGM tomography

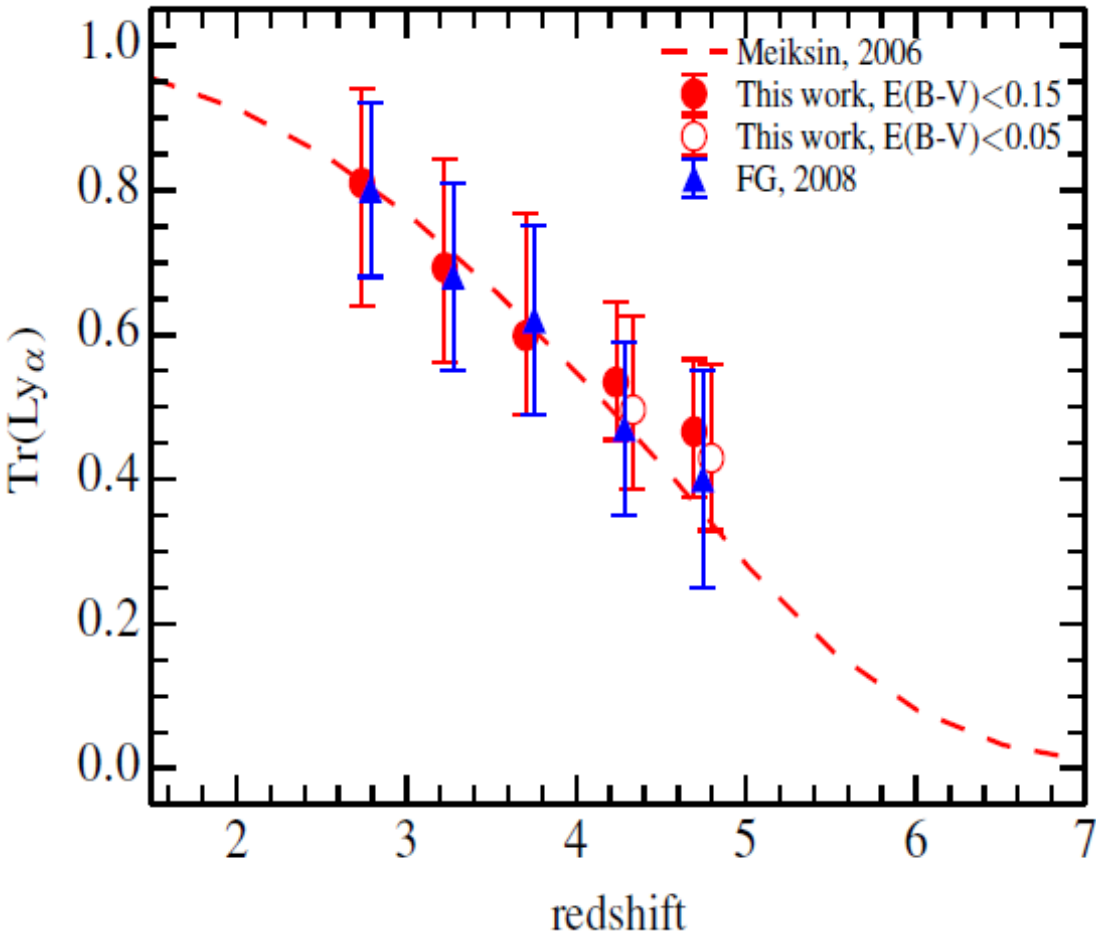
- PFS R~2300 mode: lim.mag.=24mag (12hr)
- Galaxies are dominant in number density (0.14/arcmin^2)
- Space correlation ~4Mpc scale
- Mapping the 3D cosmic web
- 3Dmap of HI・metal・star・DM

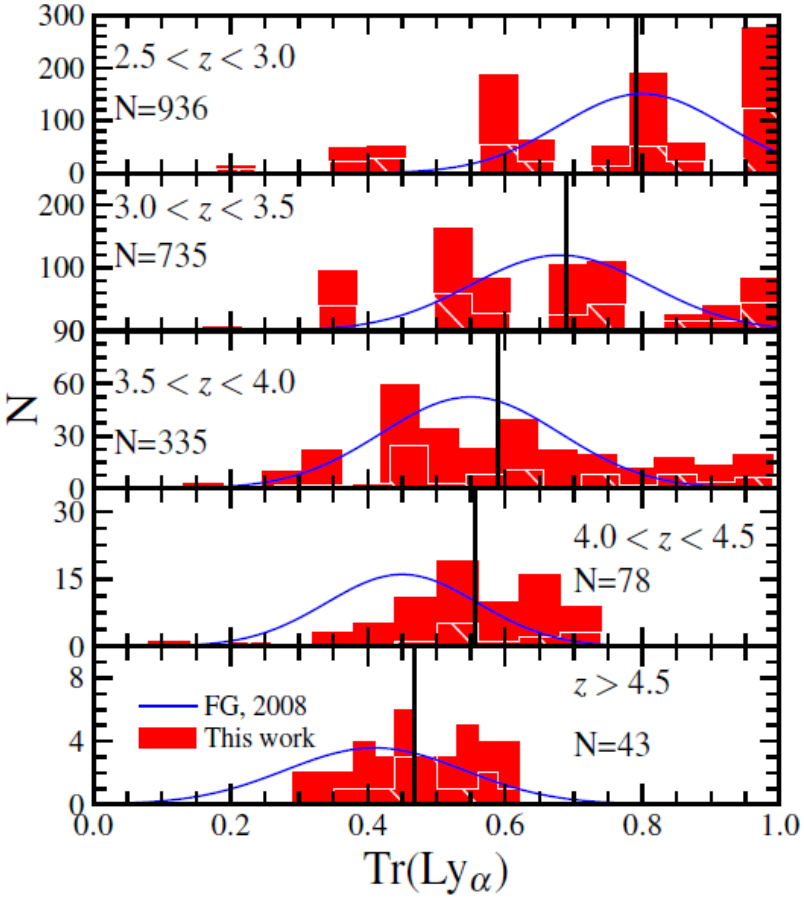




"TMT Detailed Science case: 2007"

Large variance in IGM transmission

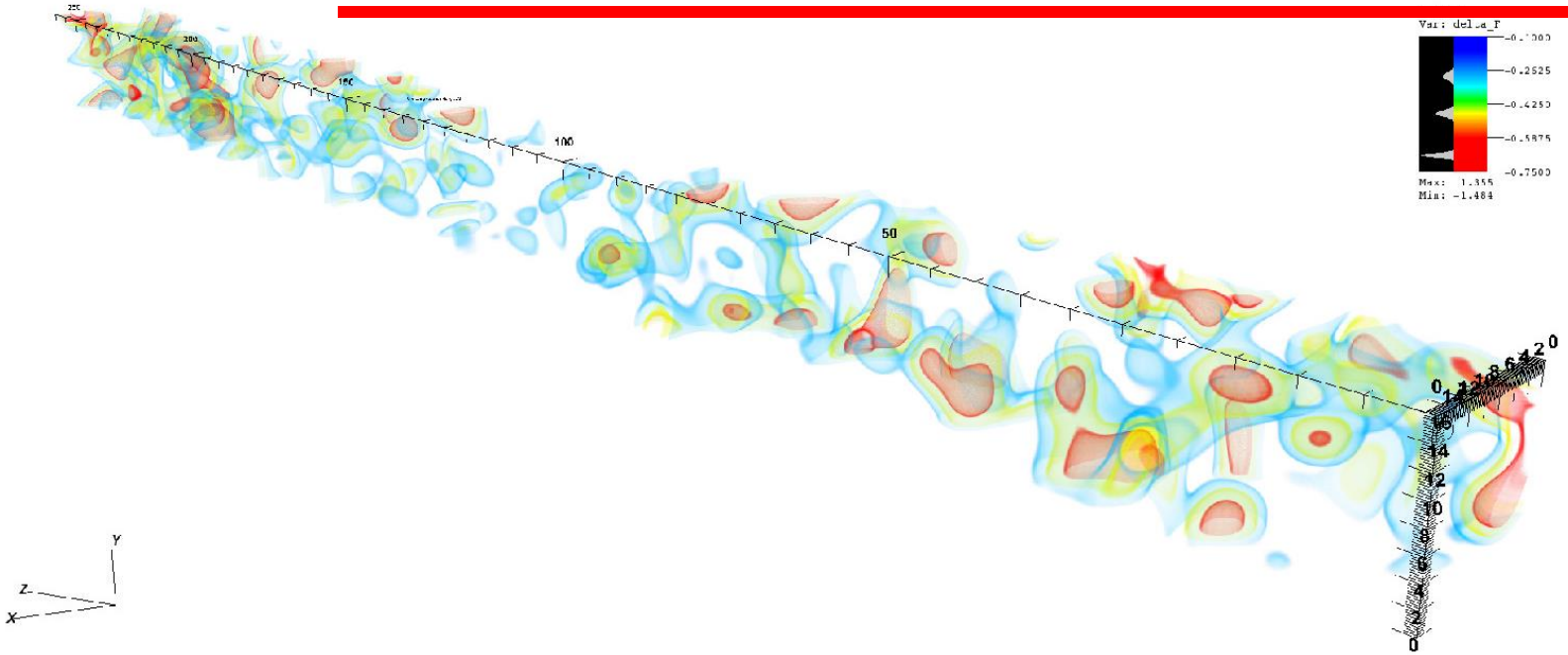




- 2127 galaxy LOS: The dispersion of IGM transmission around the mean is large, ranging from 1σ=0.15 at z=2.8 to 1σ=0.10 at z=4.8, very similar to that reported from QSOs

Thomas+ 14

First 3D Map of Cosmic Web at z > 2

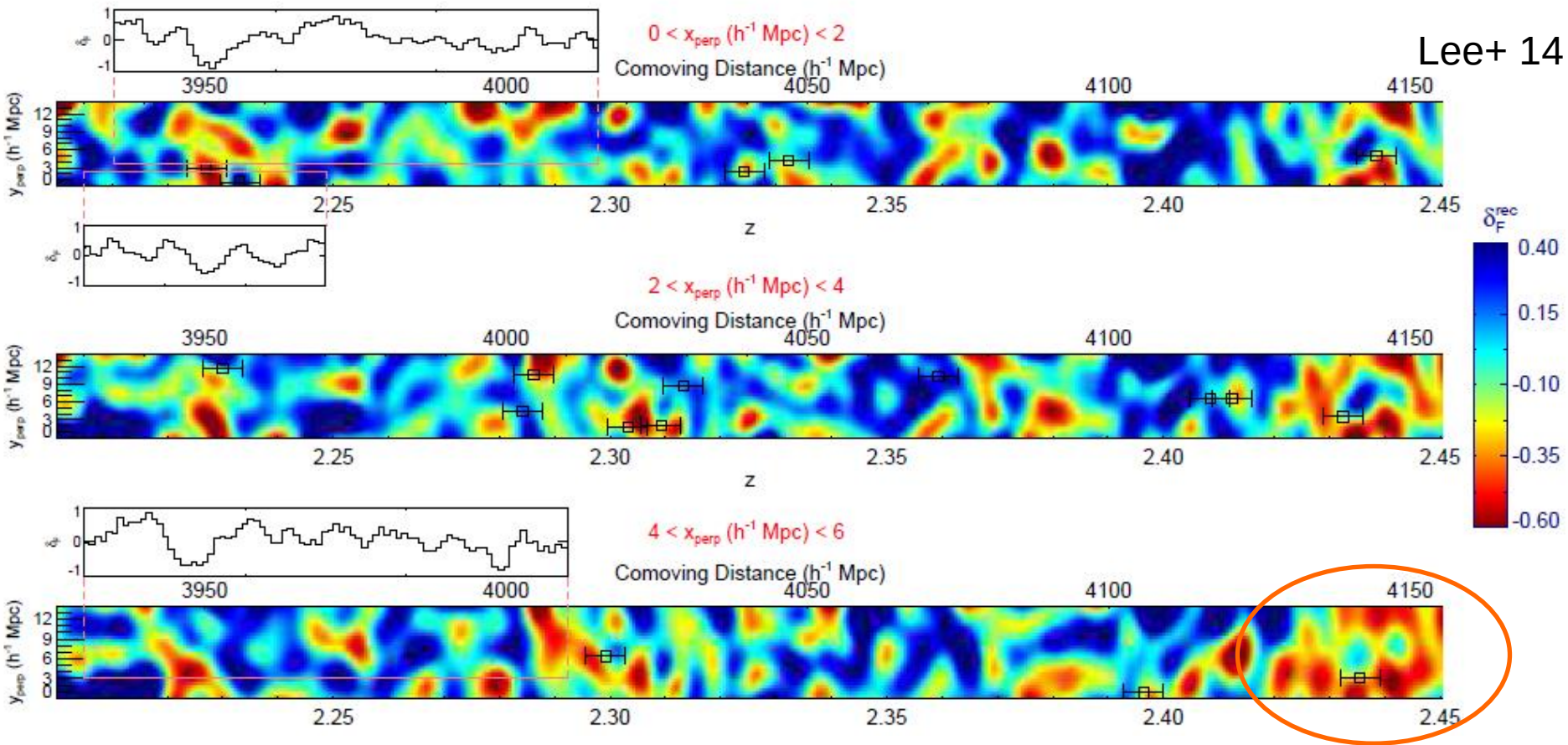


Lee+ 14, 15

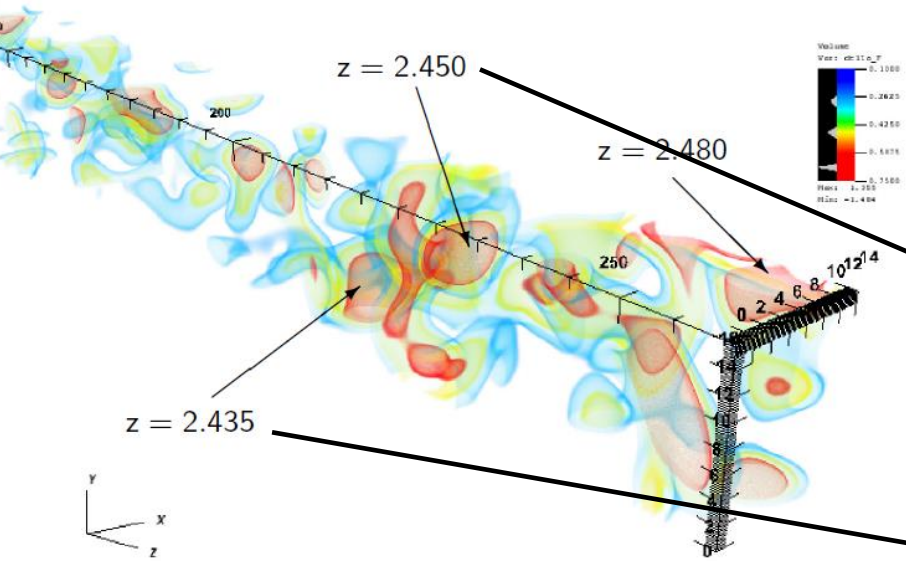
- "Collection of closely-separated sightlines enable tomographic reconstruction of 3D absorption field on scales comparable to sightline separation" (Pichon et al 2001)
- COSMOS/CANDELS/3D-HST fields
- 58 LBGs @z=2.3-3.0, 11.5'x13.5', separation=3.5pMpc
- R~1000, SNR~3-4/Å
- $V = (14\times16)h^{-2}Mpc^2\times260h^{-1}Mpc\sim 5.82\times10^4h^{-3}Mpc^3$

First 3D Map of Cosmic Web at z > 2

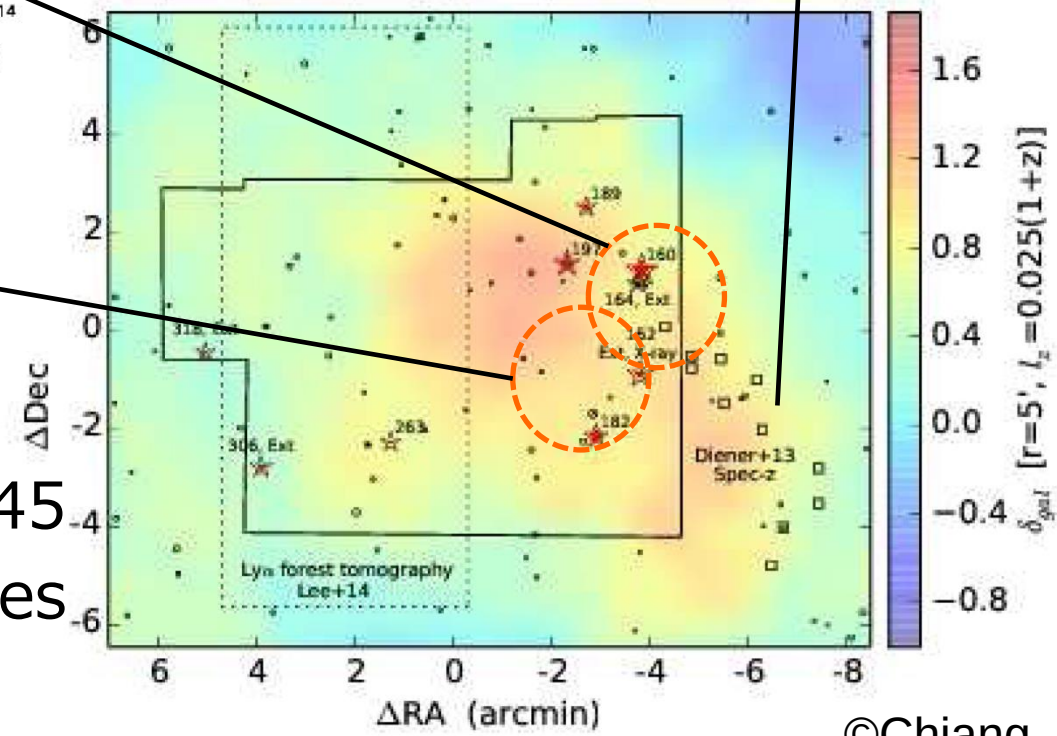
- Spec. identified galaxies at z=2.2-2.45 preferentially occupy high-density regions
- Overdensities seen in the map are typically probed by multiple independent sightlines



A Protocluster detected in tomography



Protocluster @z=2.45 11LBGs



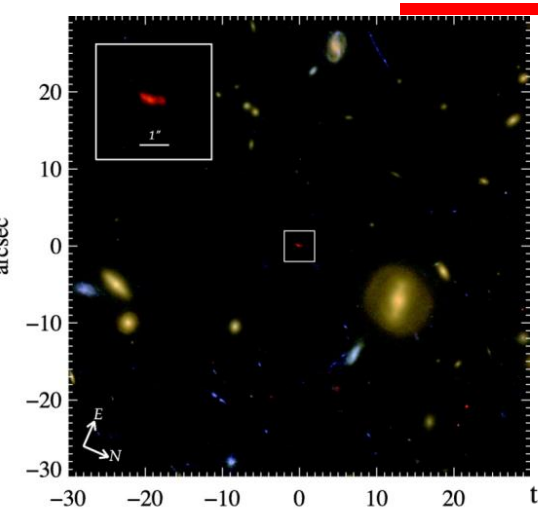
©Chiang

- IGM overdensity at z~2.45
- A protocluster that evolves into $M(z=0)\sim3\times10^{14}M_{\odot}$

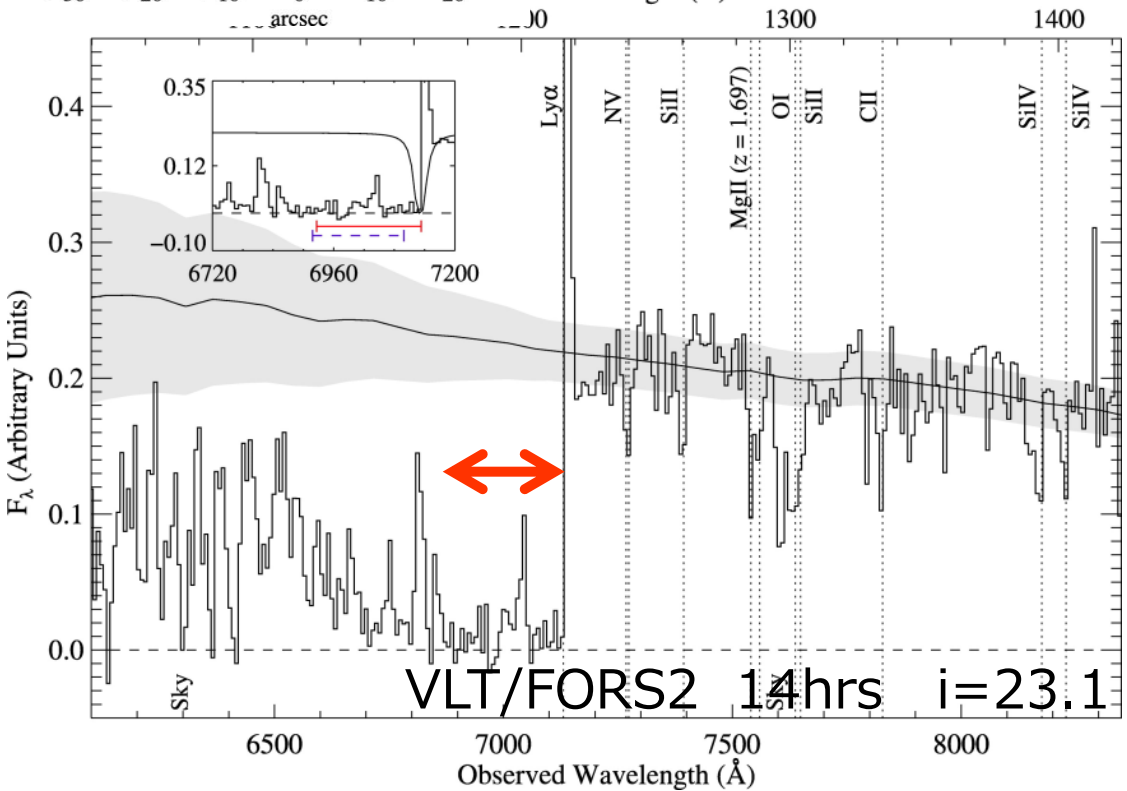
Credit: Yi-Kuan Chiang (UT Austin)

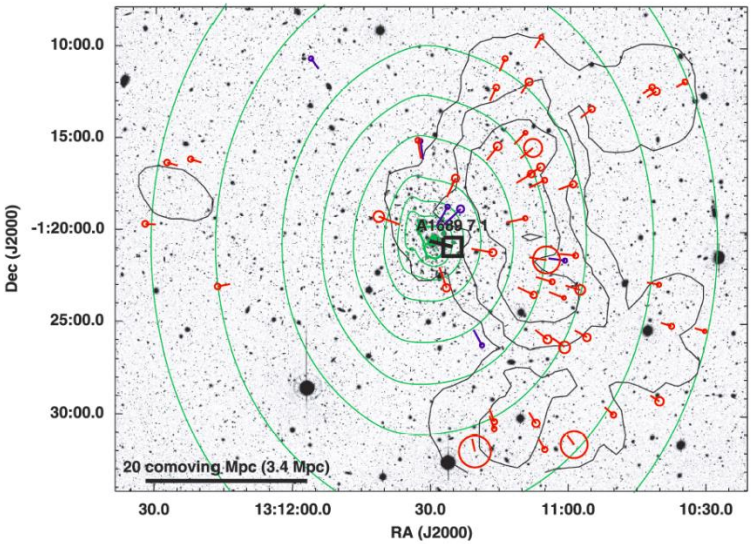
Color Scale	Overdensity of photo-z candidates
Stars	HETDEX Pilot Survey (Chiang et al, submitted)
Squares	zCOSMOS spectro-z's from Diener et al 2015

Protocluster as an IGM overdense region



- HI clouds of ~10^{17}/cm^3 (LSS) at z=4.86 extending 14pMpc along the LOS in front of the lensed galaxy
- LAE overdensity 4 x 12 pMpc at ~4σ significance

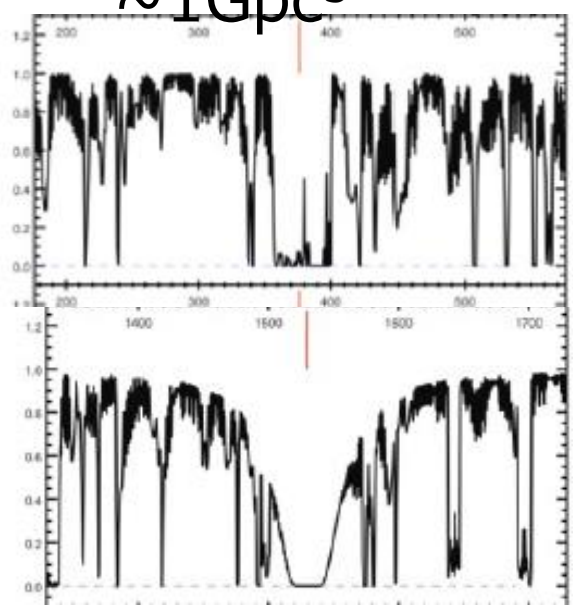




Frye+ 08, Matsuda, NK+ 10

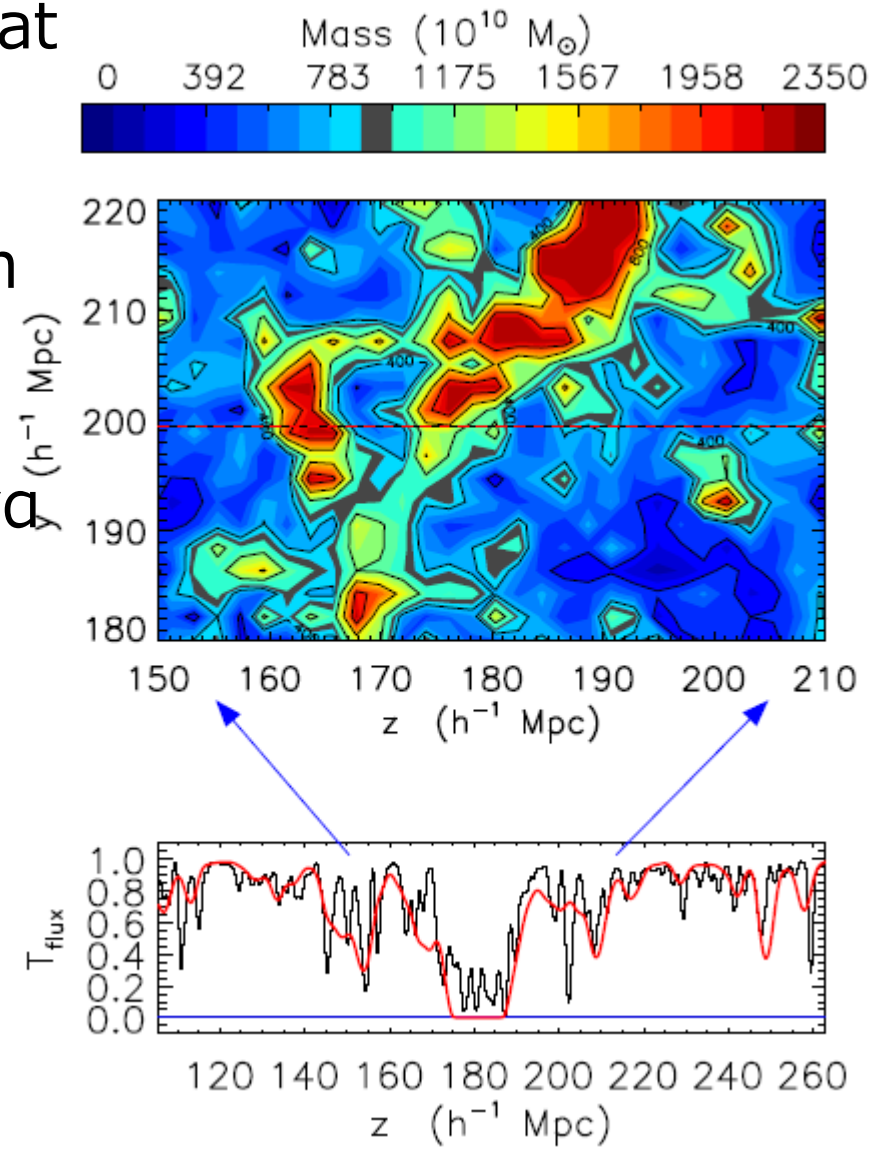
Protocluster as an IGM overdense region

- SDSS-III: ~160000 quasars at z>2.2 over 10,000 deg^2
- identify overlapped multiple Lyα lines that originated from the IGM overdensity in a protocluster
- the highest overdensity of Lyα absorbers selected from ~1Gpc^3



IGM overdensity at z~3

DLA NHI=20.4



Cai, NK et al. in prep.

PFS IGM tomography(draft)

	CLAMATO	PFS	TMT/WFOS
FOV	1sqdeg	<10sqdeg	-
spacial resolution	2.4Mpc	4Mpc	<1Mpc
N of BG sources	1000	600x10FOV	-
spec. resolution	1000	2300	5000
lim mag	24.85	24	24.5
integration time	15hrs	12hrs	5hrs
S/N	3	3	50

- Assumptions:
  - To probe z=2.3 LyA forest
  - PFS blue (380-450nm) R~2300
  - 12hr integration → lim.mag.=24mag (S/N=3)
  - 4visits(x3hr)/FOV
  - Galaxies are dominant in number density (0.14/arcmin^2)
  - ~600spectra/FOV, several FOVs from the lowest-density to highest-density

PFS IGM tomography(draft)

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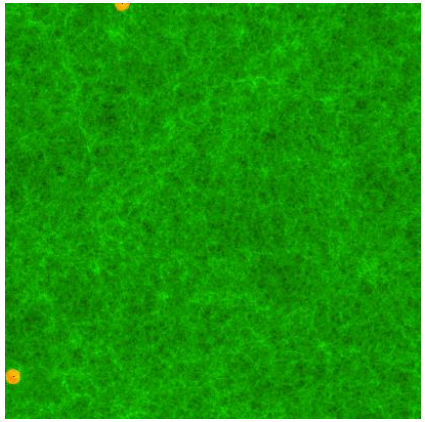
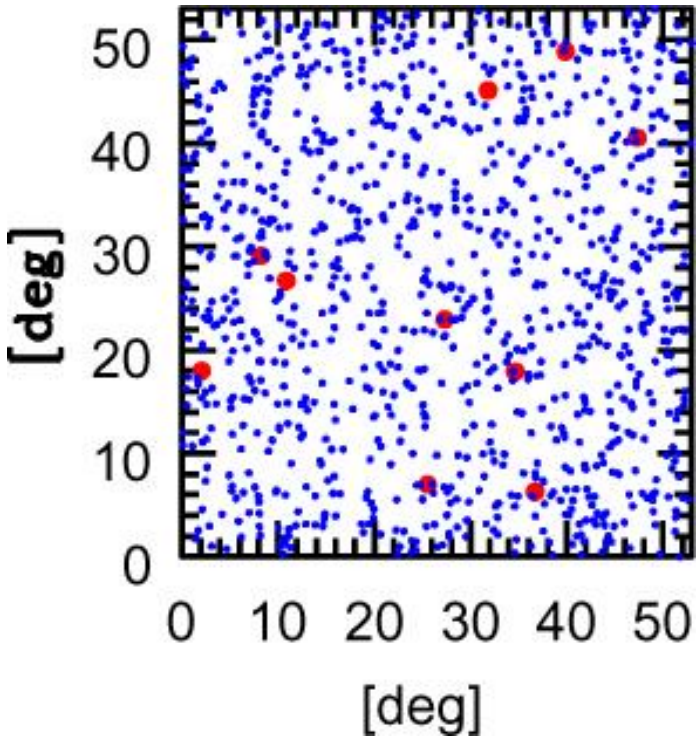
S/N	3	3	50

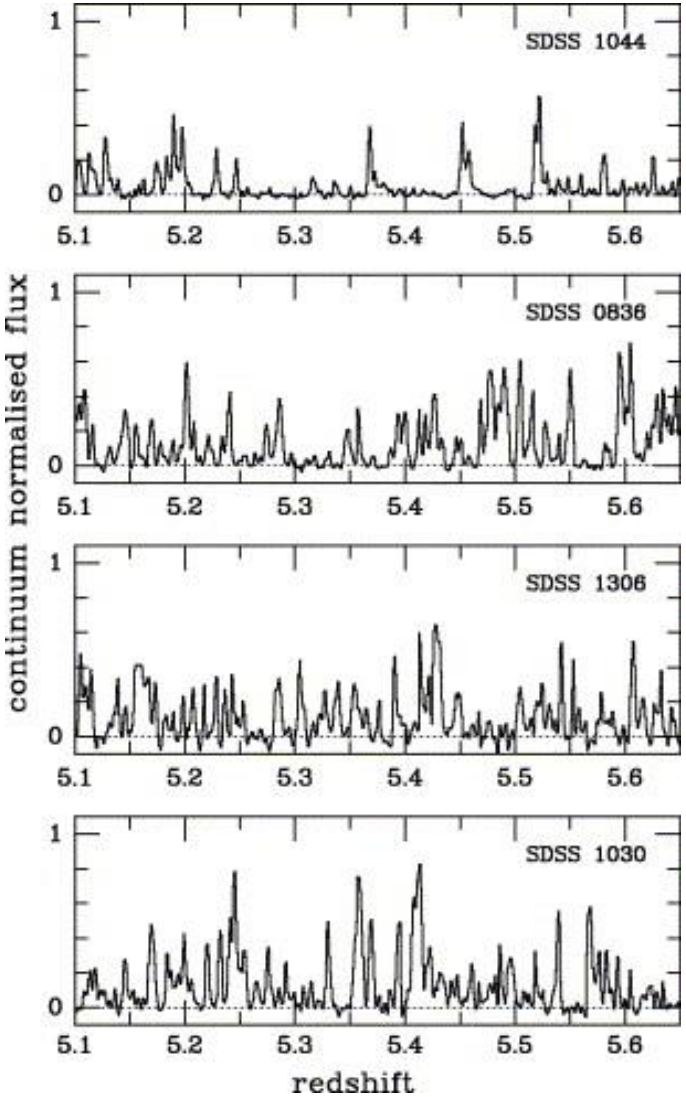
- Advantages
  - Wide survey to trace LSS in high-z
  - Strong synergy w/PFS galaxy survey at z~2
  - Long-λ: precise measurements of continuum slope
  - able to detect (thick) metal lines
  - 3Dmap of HI・metal・star・DM by a synergy w/HSC WL survey
  - Complementary to HSC protocluster survey

IGM ionization tomography

- Large spatial variance of GP trough among many different QSO-LOS at z~6
- Evidence for a patchy reionization?
- PFS: multiple line-of sights with ~35Mpc scale sampling
  ← 1/20 of SDSS
- **mapping the IGM ionization**

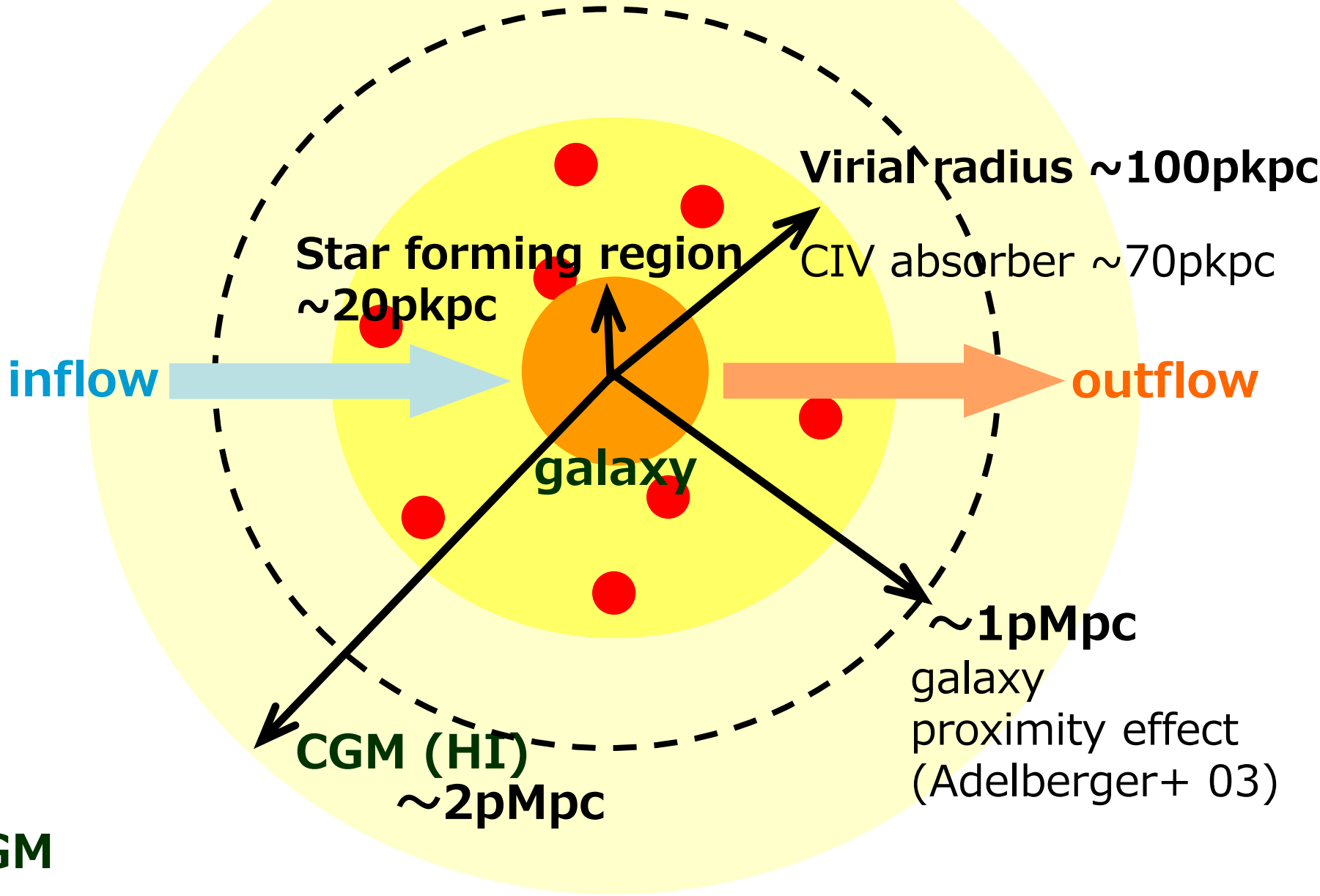






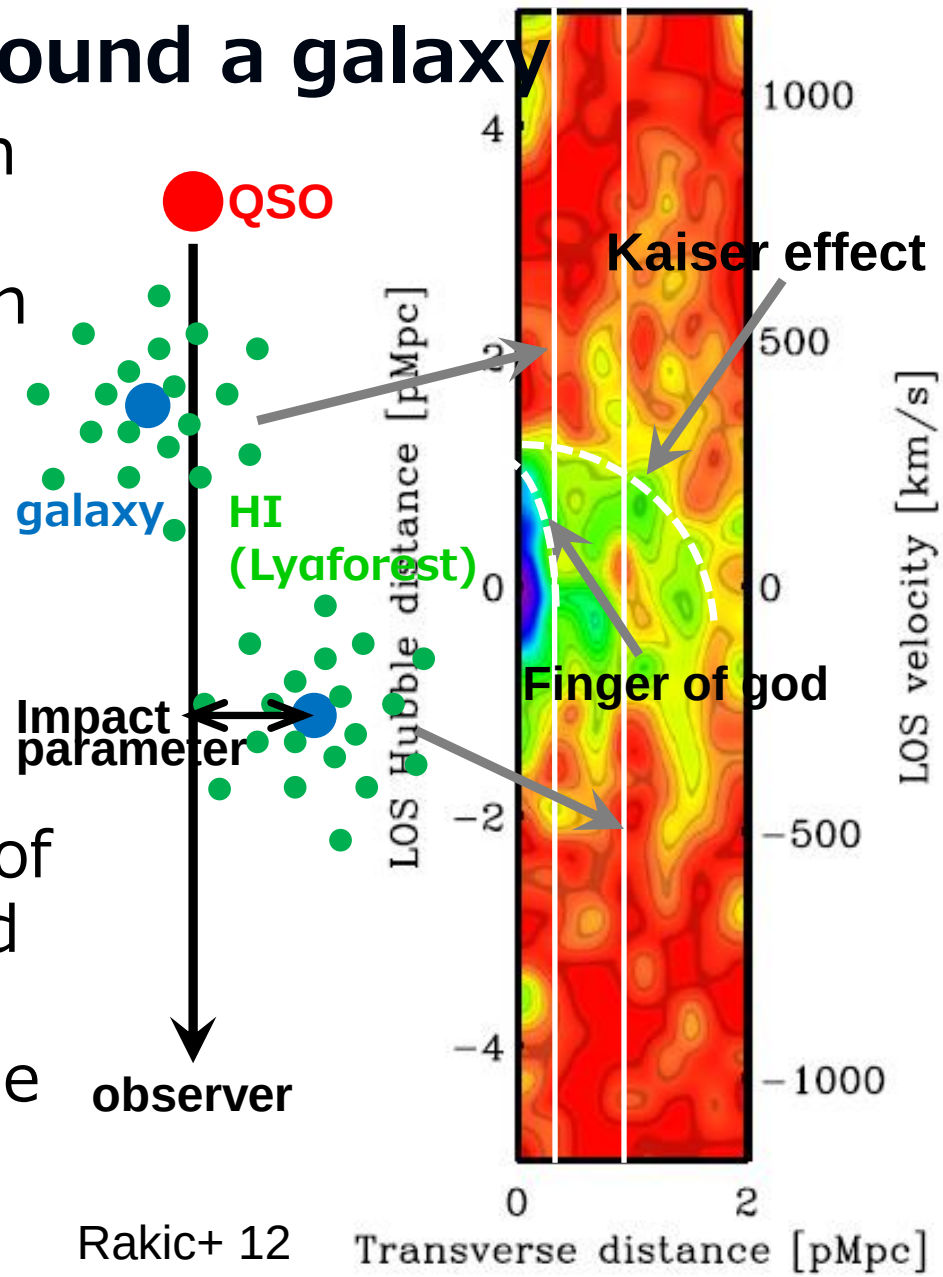
Djorgovski+ 06

CGM (Circumgalactic medium)



CGM (Circumgalactic medium)

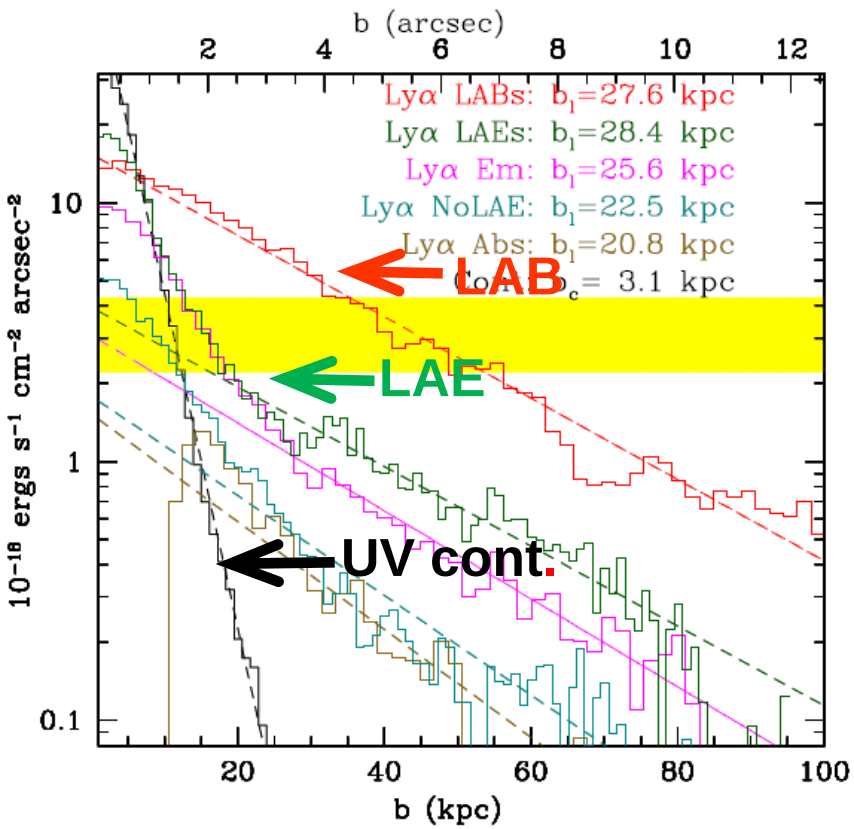
- **surrounding HI gas around a galaxy**
- 2D map of the HI absorption around galaxies by plotting the median Lyα optical depth as a function of transverse and LOS separation from galaxies.
- The median HI density remains enhanced out to ~3pMpc
- Redshift space anisotropies of "finger-of-god" (<1Mpc) and "Kaiser-effect" (~2Mpc) are found, suggesting large-scale inflow (Rakic+2012)

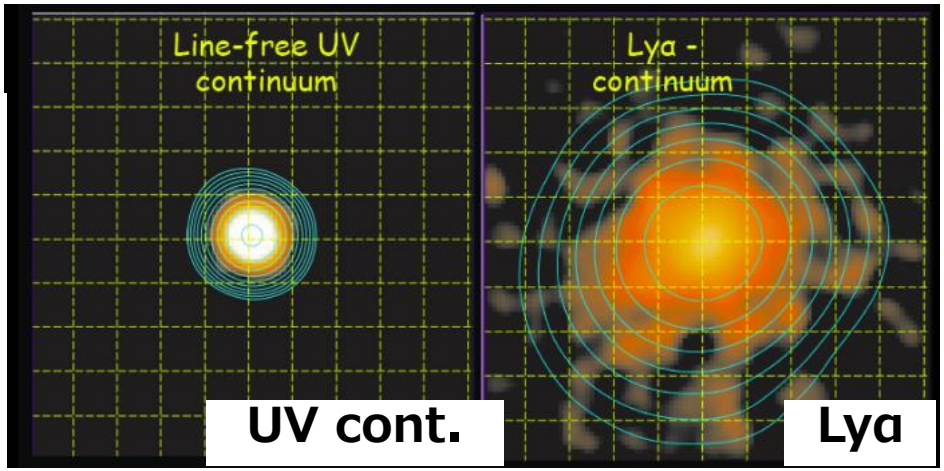


Rakic+ 12

Lyα halo

- Lyα photons are scattered by the CGM HI, which extends to 2Mpc.
- Ubiquitous Lyα halo





see also Matsuda+12, Momose+14

Steidel+ 11

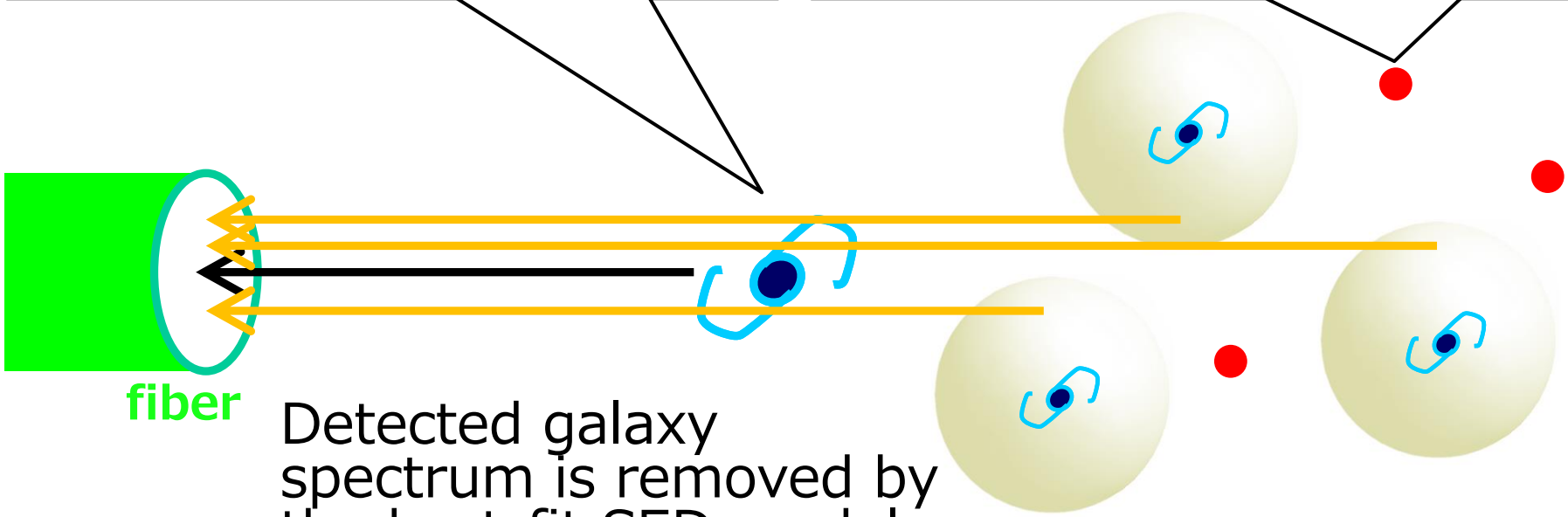
- Mass accretion from CGM → gas reservoir for star formation
- AGN, SNe, outflow → feedback from galaxy to CGM

Lyα intensity mapping to explore CGM

1,000,000 galaxy spectra at 0.15<z<0.70
3647<λ<5470A → Lyα at 2.0<z<3.5

SDSS/BOSS DR10

~130,000 quasar spectra at 2.0<z<3.5



Detected galaxy spectrum is removed by the best-fit SED model

Residuals after subtracting galaxy +sky emissions

Croft+ 15

Lyα intensity mapping to explore CGM

- cross-correlation is consistent with originated from λCDM(Ω_m=0.30$^{+0.10}_{-0.07}$) mass spectrum at z=2.55

$$\xi_{q\alpha}(r) = b_q b_\alpha f_\beta \langle \mu_\alpha \rangle \xi(r)$$

  bq: quasar bias factor

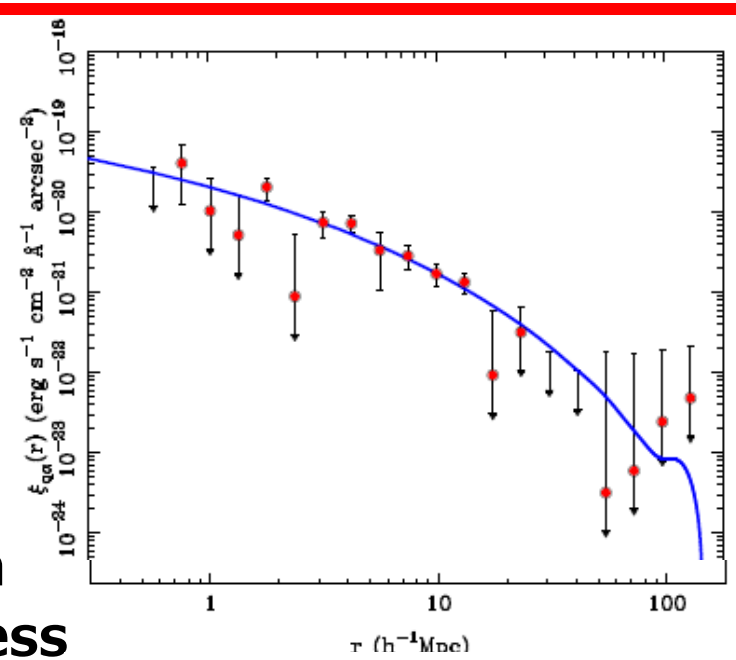
  bα: LyA bias factor

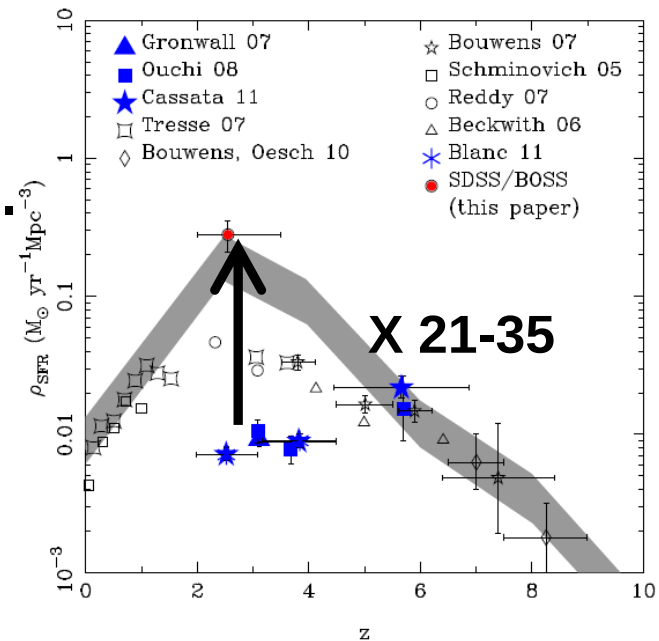
  fβ : corrections for redshift distortion

  <μα>: mean Lyα surface brightness

  ξ(r): λCDM CF

- Resultant mean Lyα surface density is consistent w/total SFRD.
- suggesting all Lyα photons produced in stars at z=2.55 escaping from their host galaxies and being detected.





PFS Lyα intensity mapping(draft)

- Advantages
  - NO specific requirements for the survey design
  - CC w/galaxies at the same redshifts → more accurate and systematic measurements will be achieved.
  - All PFS fiber spectra can be used. PFS Cosmology survey
    → ~4M targets(fibers) (+fibers for sky) x 0.8M OII emitters at 2<z<2.4
    → SNR x6 improvement over BOSS
  - CC w/different subsample w/SFR, environment, ⋯
  - Long-λ: Trace the CGM evolution

Summary

- IGM tomography will be one of the unique science cases to enhance PFS capability
- Lyα intensity mapping to explore the CGM can be done without any pain by using PFS-SSP data