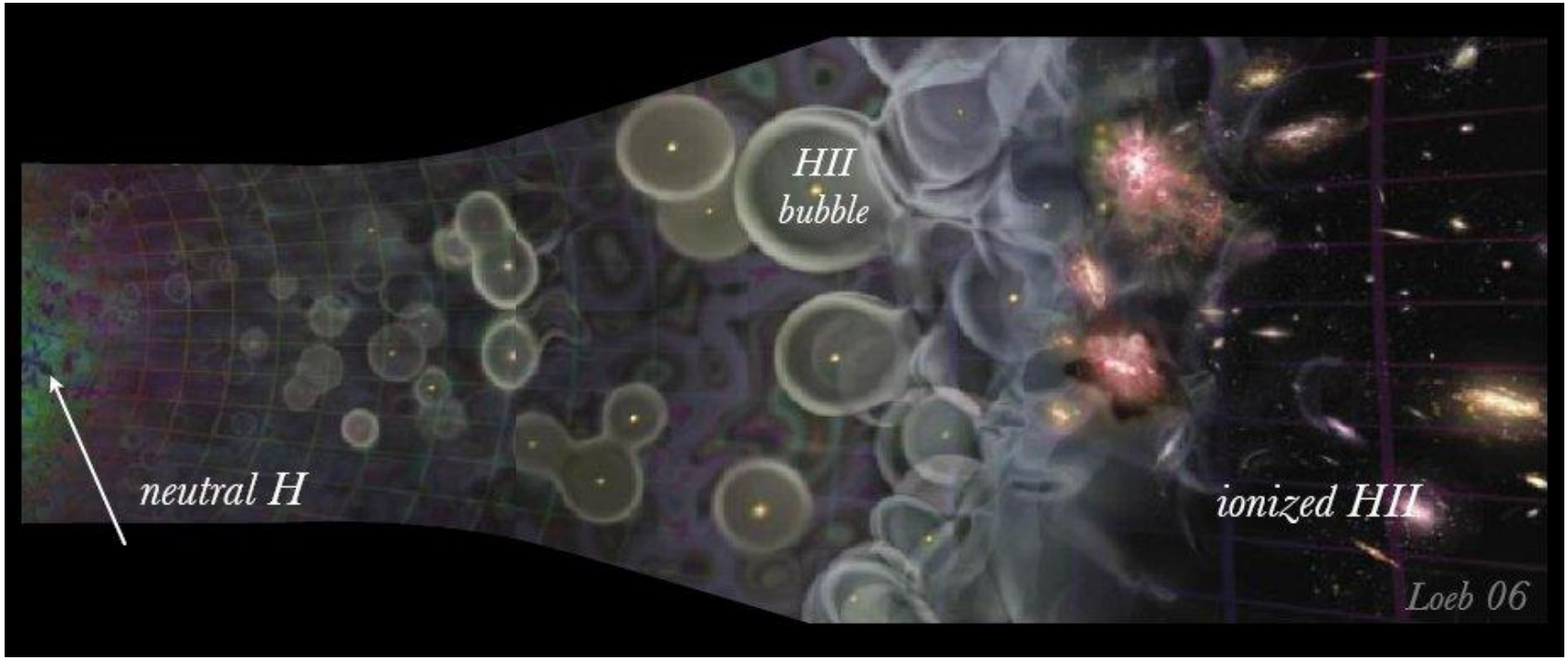
Probing the Epoch of Reionization



Masami Ouchi

(U. Tokyo, ICRR/IPMU)

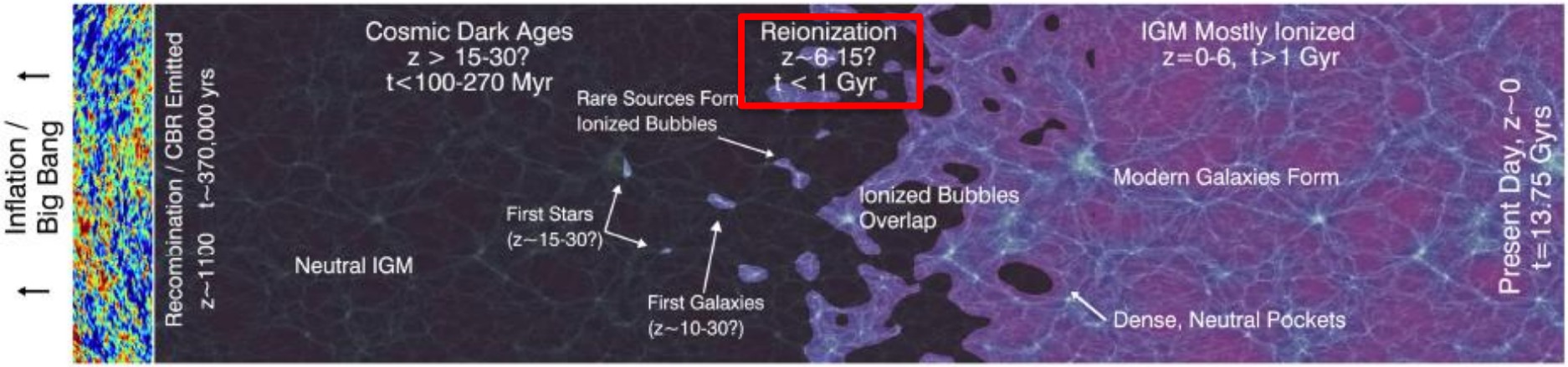
Outline

- Introduction
  - Our understanding and open questions about cosmic reionization

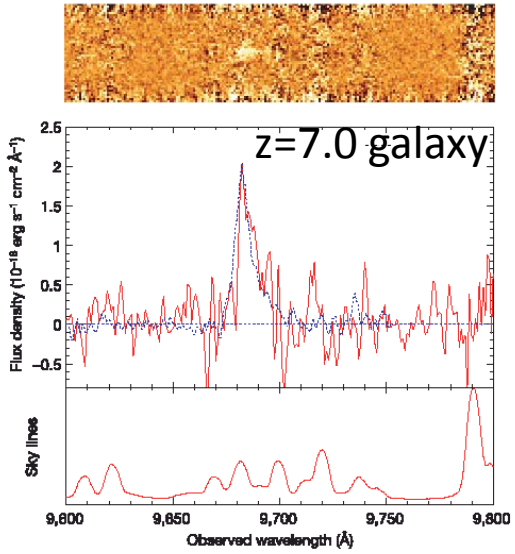
- Subaru+Keck optical-NIR deep surveys
  - Evolution of neutral hydrogen fraction probed with high-z galaxies
    1. Lya emitters (LAEs)
    2. Dropout galaxies
       - Discovery of the most distant galaxy at z>7.
       - Comparison of 3 similar z~7 galaxy papers that appear this months.

- Next generation survey and simulations

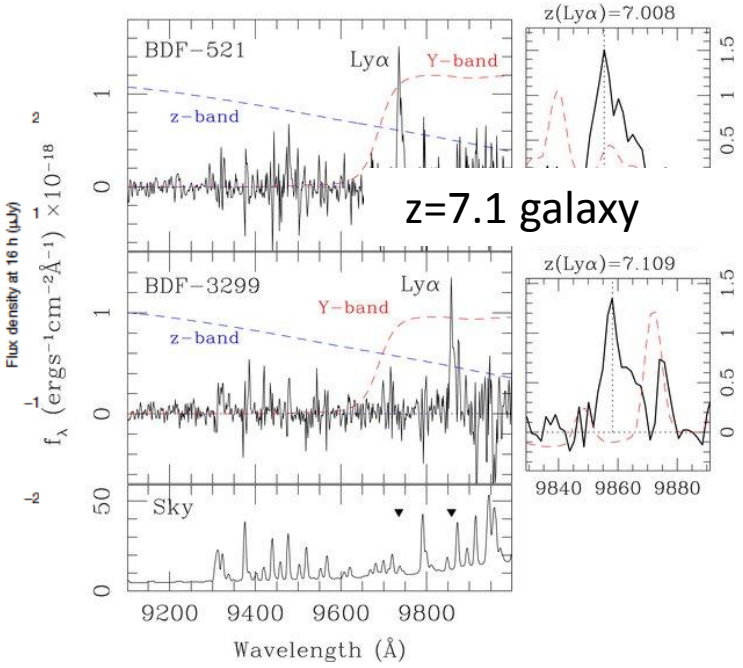
The Epoch of Reionization (EoR)



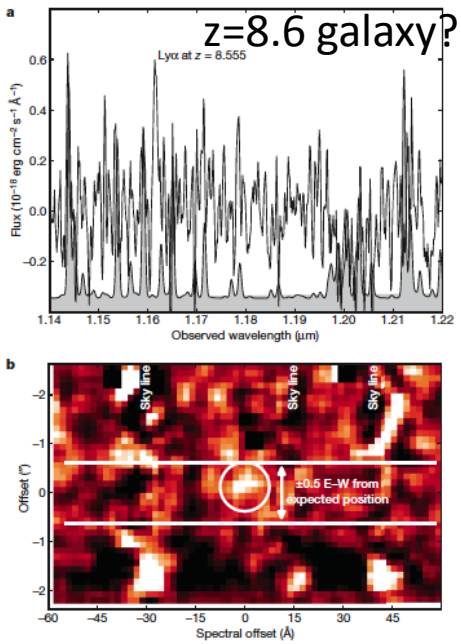
Robertson et al. (2010)



Iye et al. (2006)

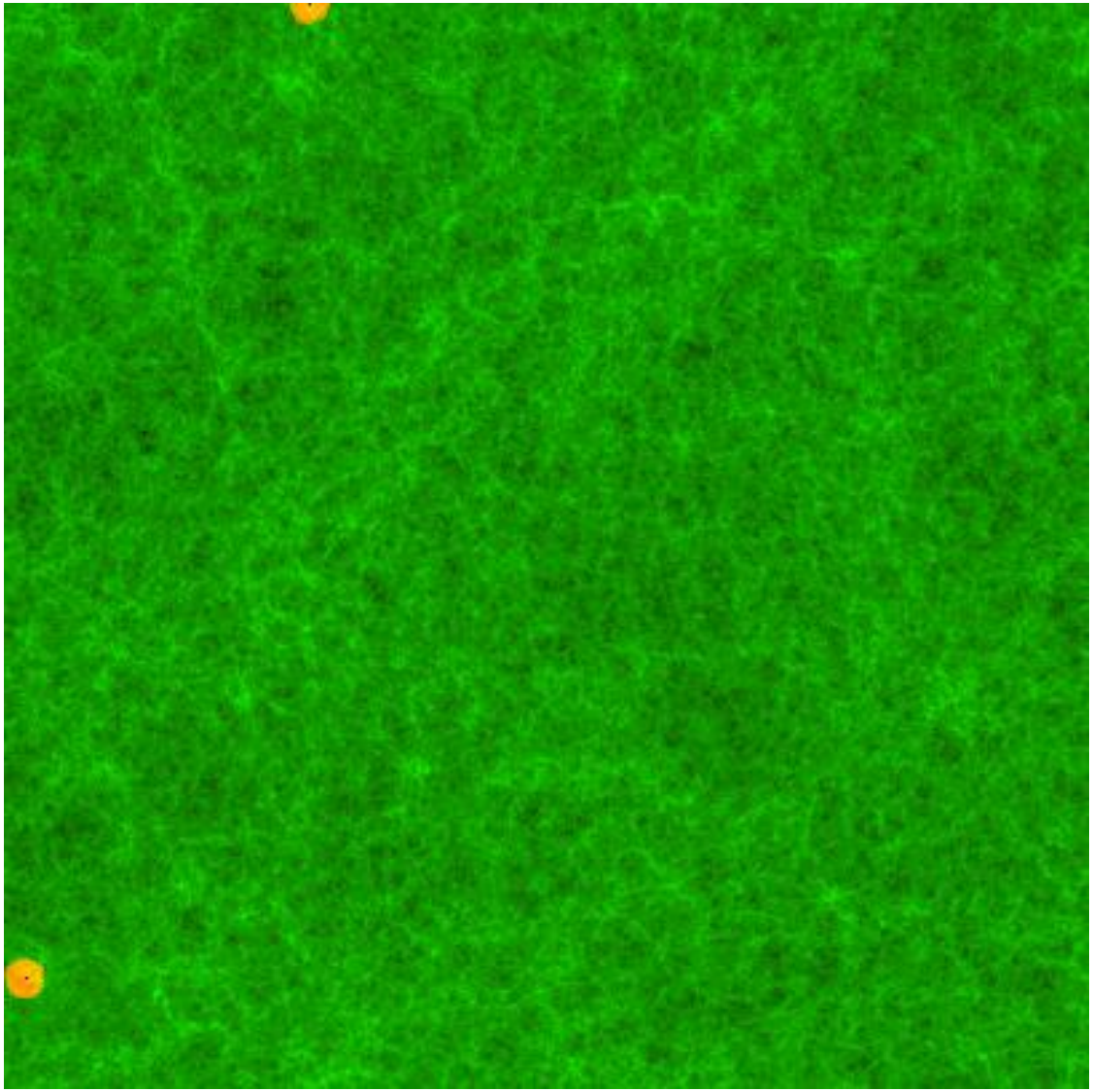


Vanzella et al. (2010)



Lehnert et al. (2010)

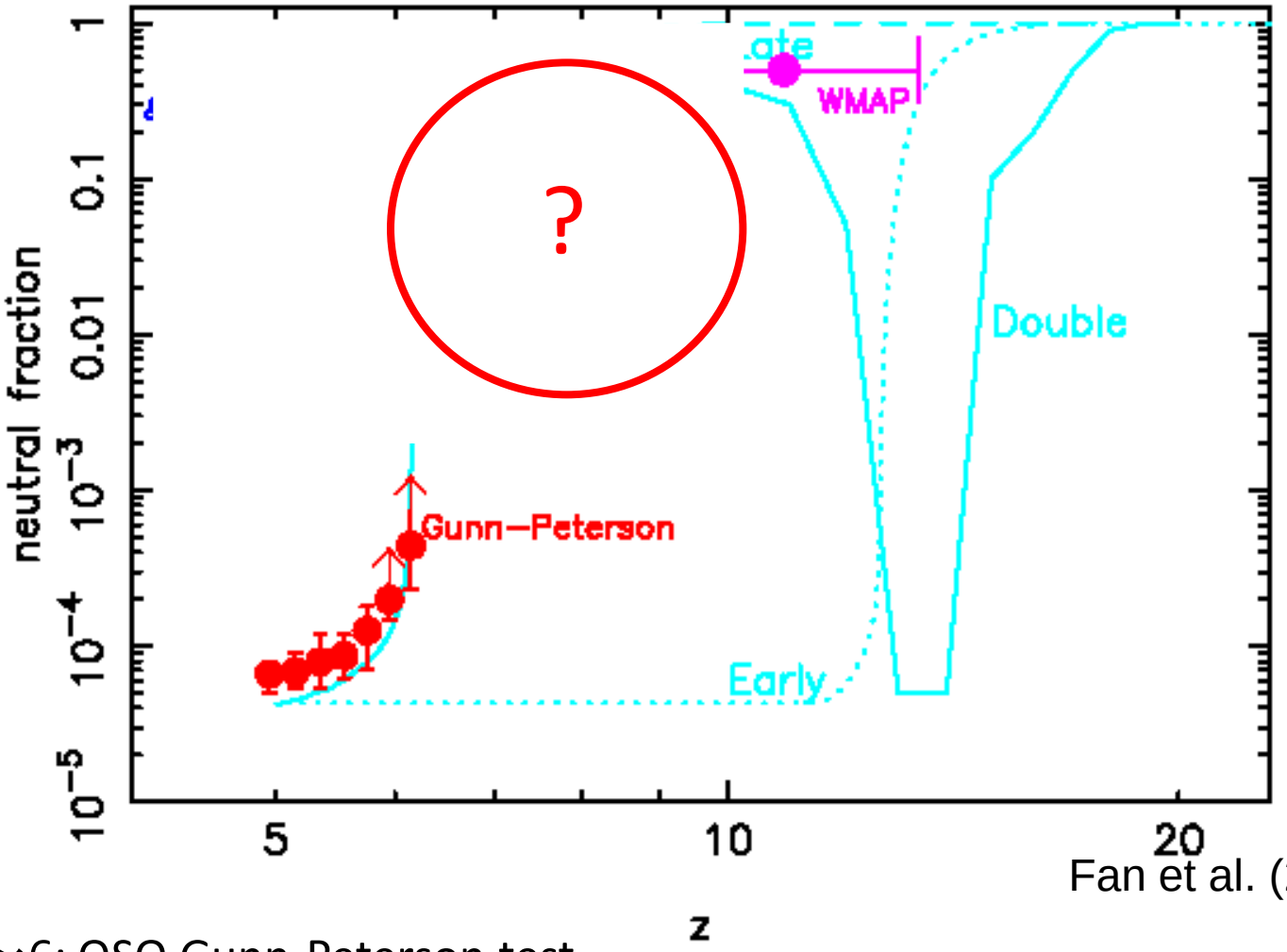
Cosmic reionization



the radiative transfer model
(Iliev et al. 2006)

Galaxies (blue dots) and ionized bubbles (orange)

Open Questions (1)
Evolution of Neutral Hydrogen Fraction



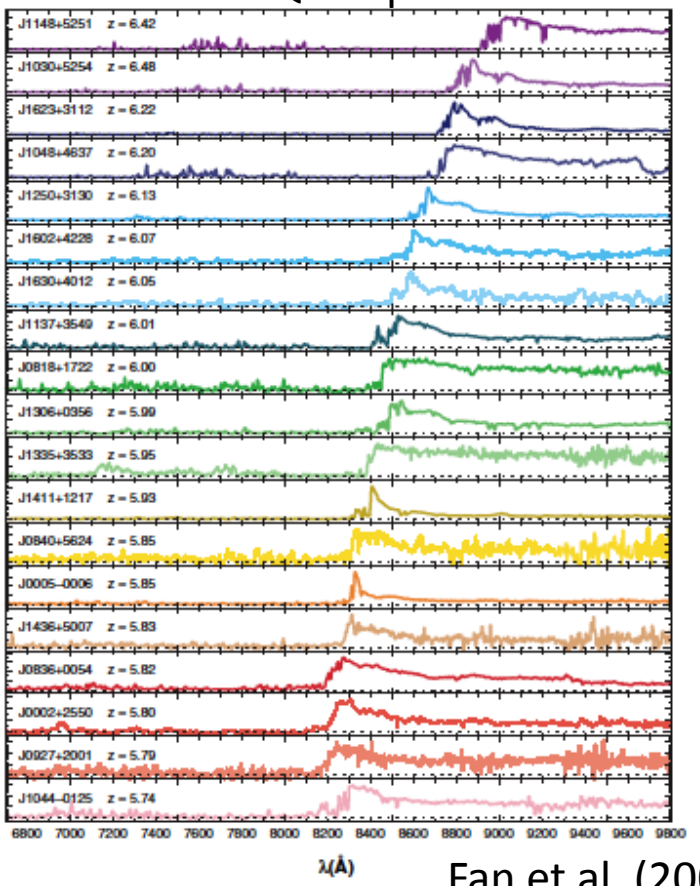
Fan et al. (2006)

- z～6: QSO Gunn-Peterson test
- z～11: CMB Thomson scattering optical depth

  sharp reionization or extended reionization (Dunkley+09)?

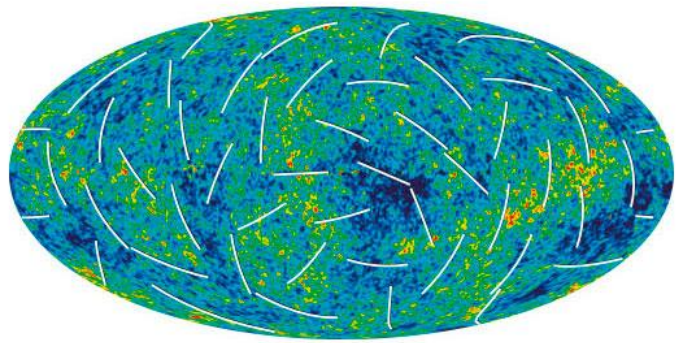
Two Limits on Reionization History

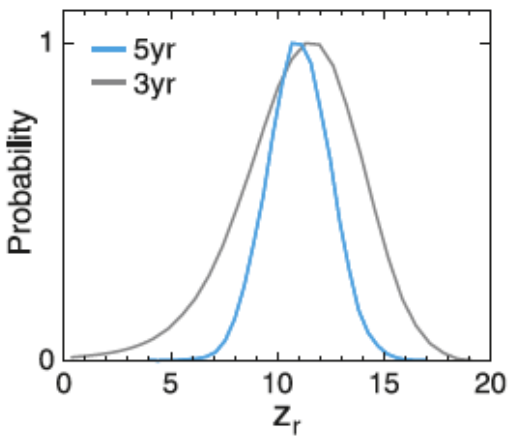
SDSS QSO Spectra

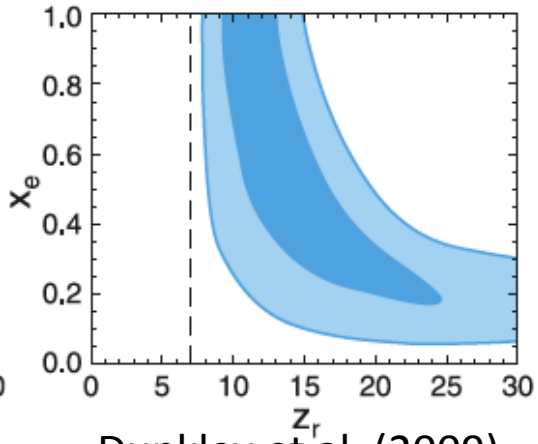


Fan et al. (2006)

CMB







Dunkley et al. (2009)

Gunn-Peterson test:

$x_{HI}>10^{-4}$ (>0.01%) at z>~5.7

Problem: no x_{HI} estimates beyond z~6...(cf. near-zone transmission of LyaDW; Mortlock+11)

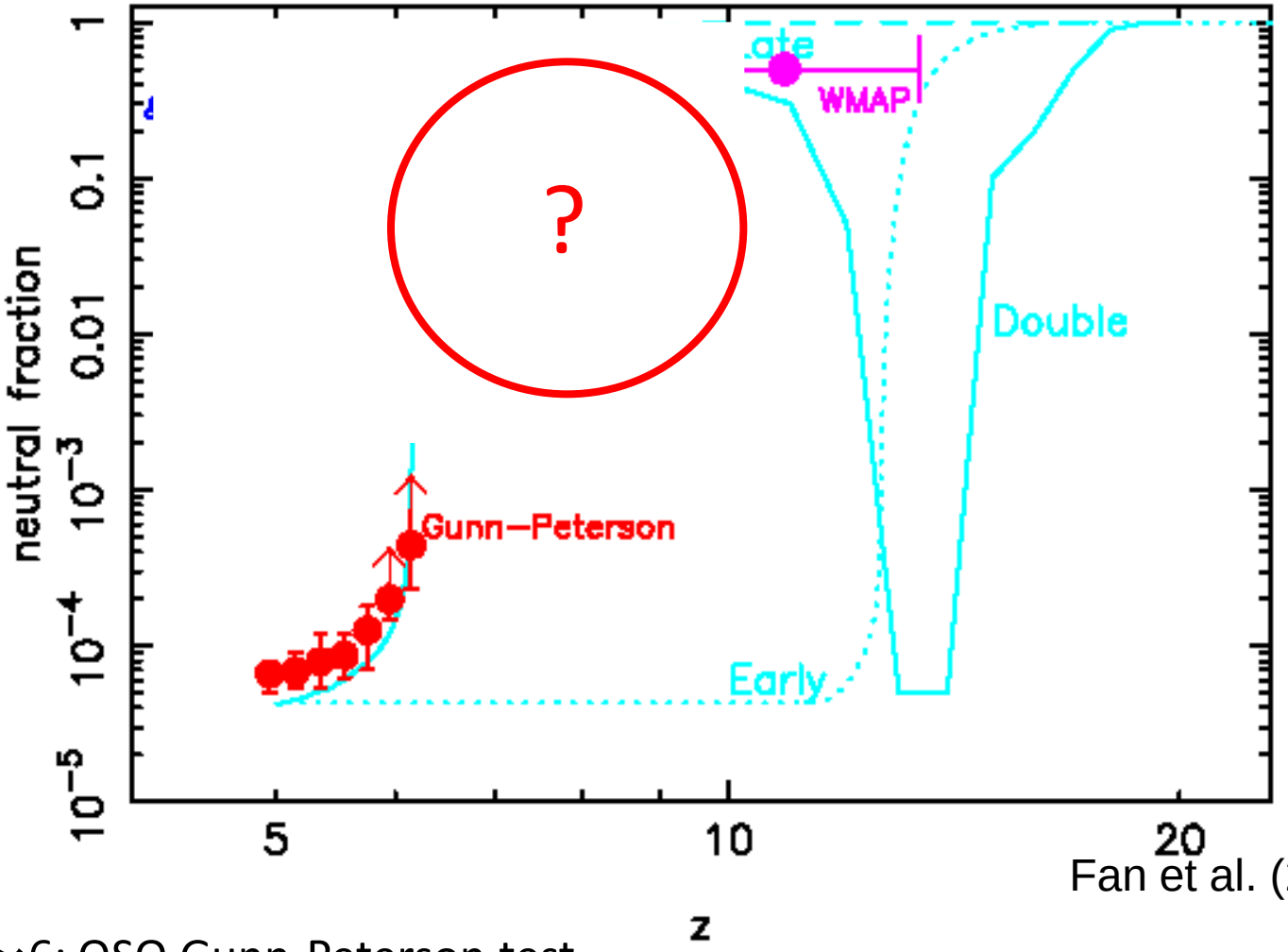
Thomson scattering optical depth:

z_{ion}=10.5+/-1.2 (Dunkley+09, Komatsu+09, Larson+10),

if reionization is instantaneous

Problem: no time resolution…

Open Questions (1)
Evolution of Neutral Hydrogen Fraction



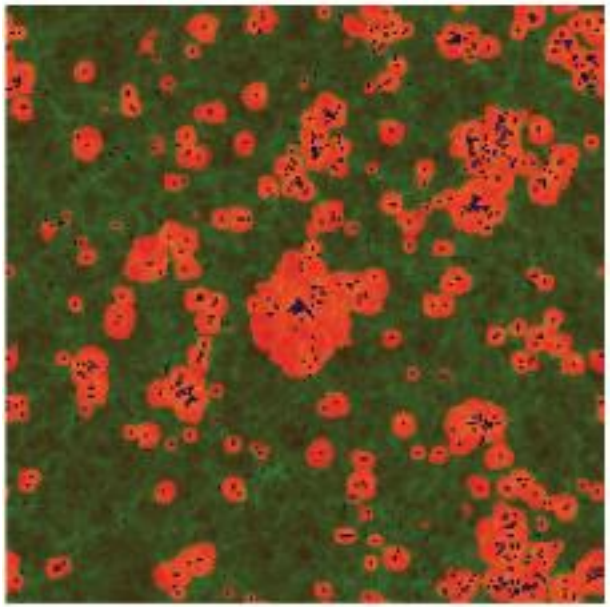
Fan et al. (2006)

- z～6: QSO Gunn-Peterson test
- z～11: CMB Thomson scattering optical depth

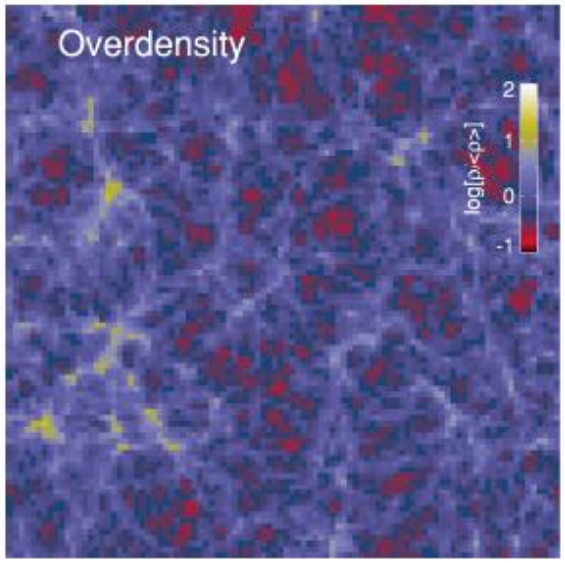
  sharp reionization (e.g. Fukugita+94) or extended reionization (Dunkley+09)?

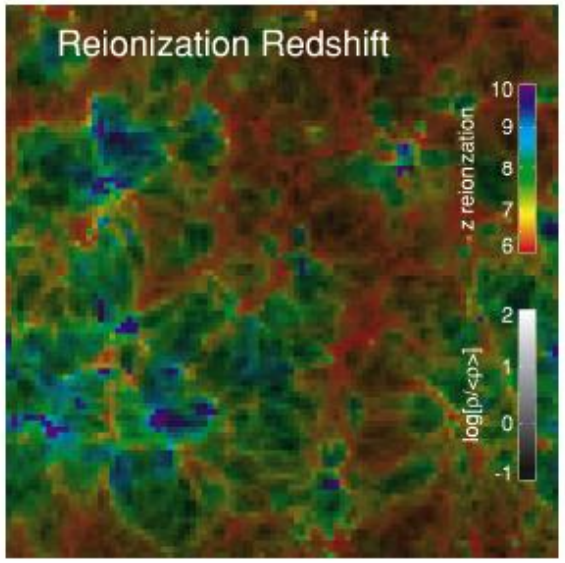
Open Questions (2)
Ionization process

Inside-out? Outside-in?



Or filament-last?





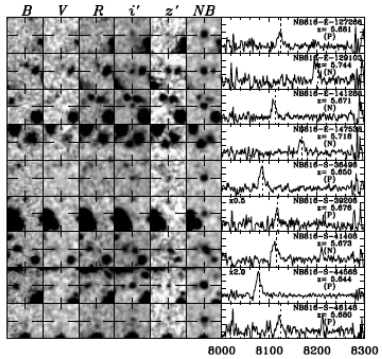
Finlator+09

- The ionization process: How did the ionized regions extend?
  - Depending on distribution of ionizing sources and IGM density
  - Inside-out (e.g. Furlanetto et al. 2004), outside-in (e.g. Miralda-Escude et al. 2000), or filament-last (Finlator et al. 2009).

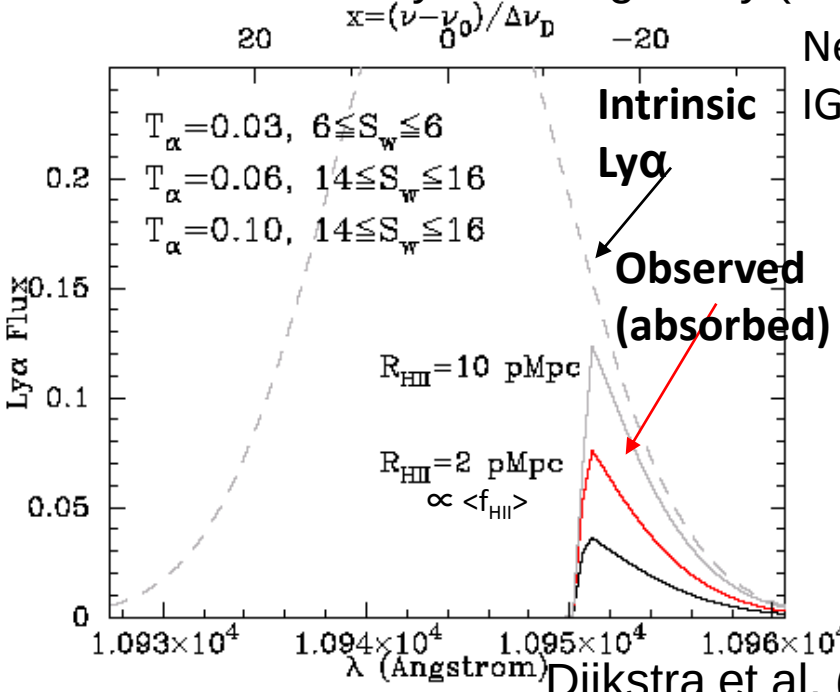
Not enough S/N with the present 21cm-obs facilities such as LOFAR

LAE as a Probe of Cosmic Reionization

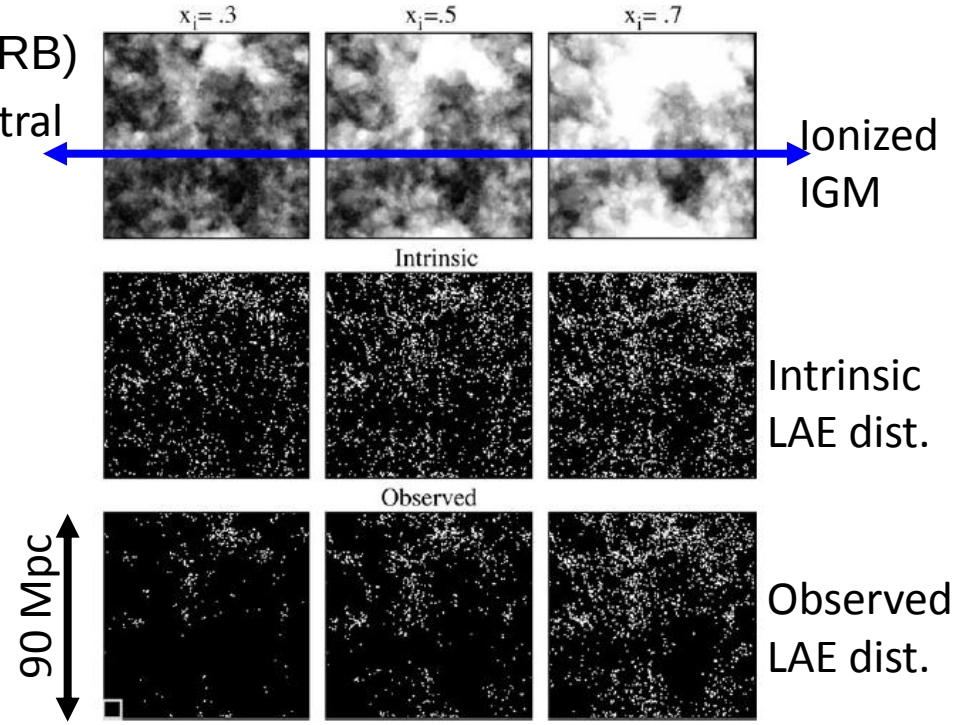
- Lya emitters (LAEs): high-z SF galaxies
  - Lya emitters+models can constrain hydrogen neutral fraction at ~10-100% level (corresponding to z~6-10) from Lya damping absorption of IGM
  - It provides hints for the reionization process from LAE distribution.
  - Less biased by inhomogeneity (cf GRB)



LAE at z=6 (Ouchi et al. 2008)



Dijkstra et al. (2007)



McQuinn et al. (2007)

Lya damping wing absorption→

i) Less abundant observed LAEs in more neutral univ

ii) Broader line width (by ~10% level)

LAEs in ionized bubbles can be observed→

iii) Clustering of observed LAEs is boosted.

1. SUBARU+KECK SURVEYS

Subaru Surveys for LAEs at z~7

Subaru/XMM-Newton Deep Survey field (SXDS ; 1 deg^2;i=27.0) [2^{h}18^{m}00^s ,-5^{o}00'00"]

Previous survey in SDF(0.2 deg^2;i=27.4) [13^{h}24^{m}39^s ,+27^{o}29'26"]

The largest-area galaxy survey beyond redshift 6

At z~7
~200 Mpc (comoving)

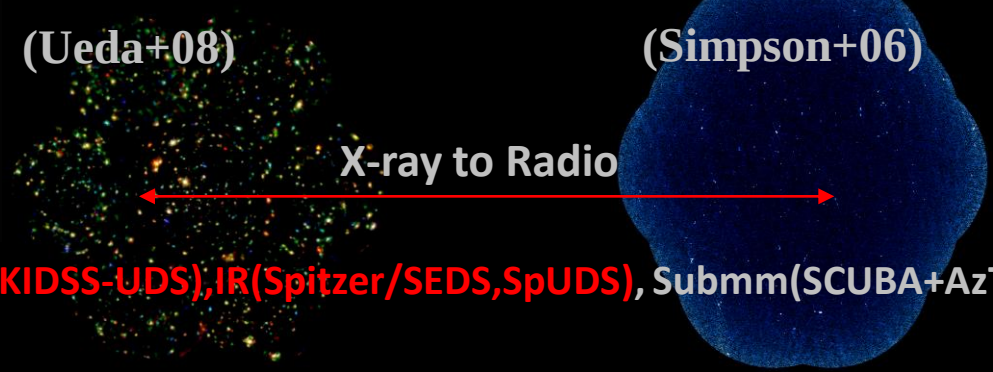
(Furusawa+08)

(Kashikawa+06)

Sizes of HUDF and ERS for HST/WFC3 galaxies at z>6

XMM-Newton 0.5-2 (Ueda+08)

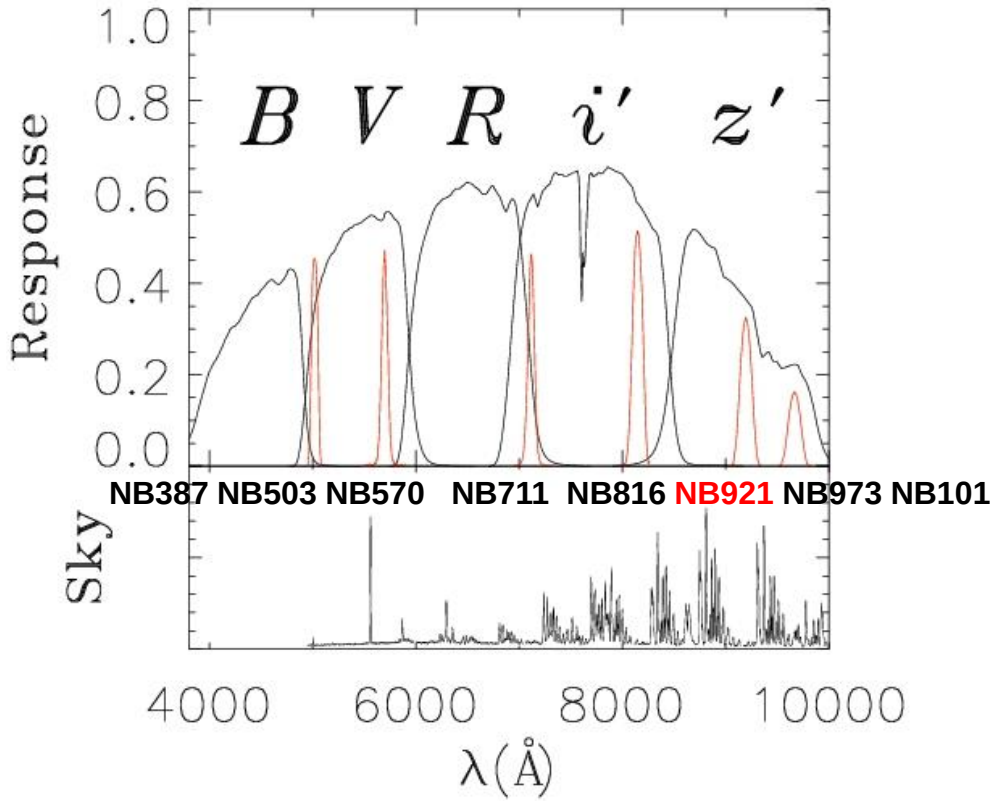
VLA 1.4 GHz (Simpson+06)



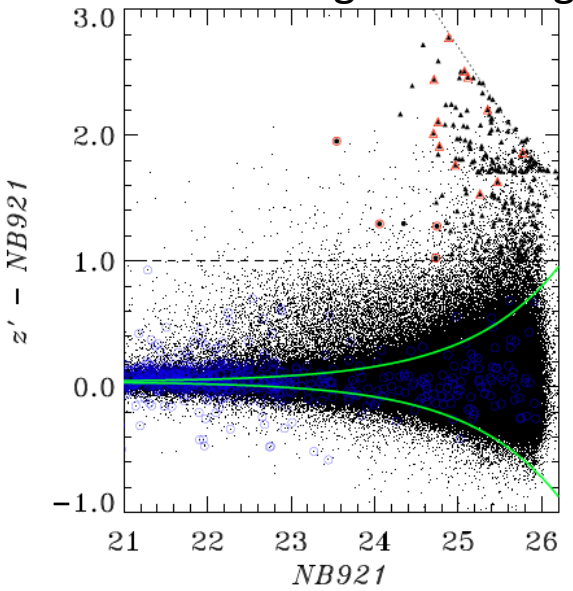
X-ray to Radio

+Available deep X-ray(XMM), UV(GALEX), NIR(UKIDSS-UDS),IR(Spitzer/SEDS,SpUDS), Submm(SCUBA+Az
Radio(VLA,GMRT)

207 Lyα Emitters at z=6.6

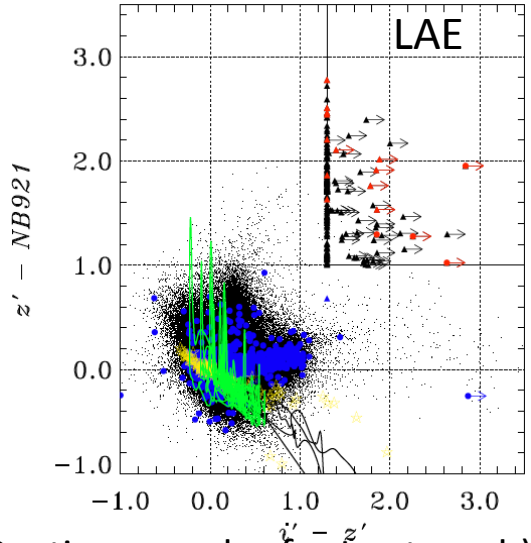


Color magnitude diagram



(Narrow-band excess color for emission)

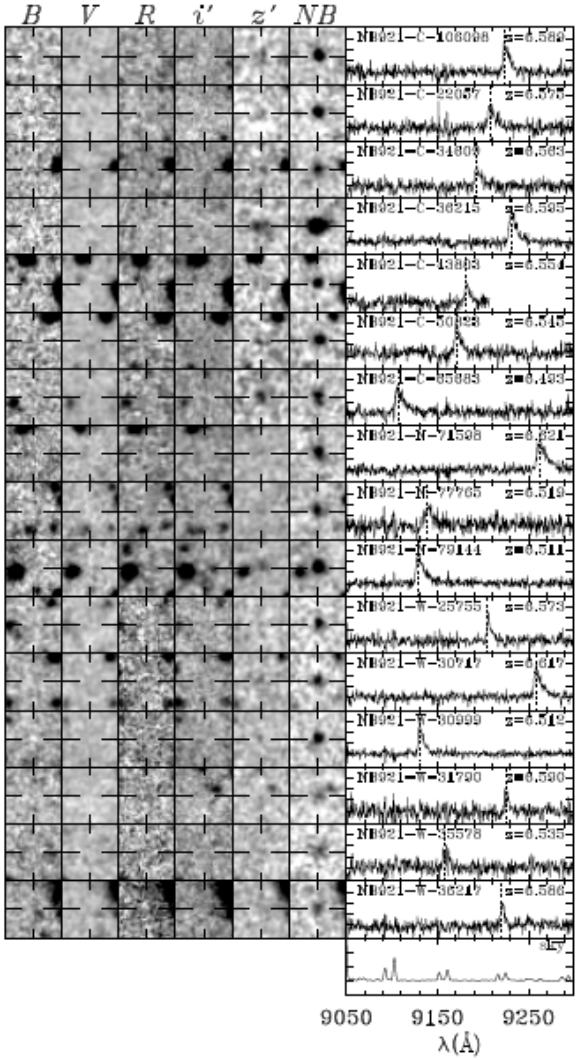
Two color diagram

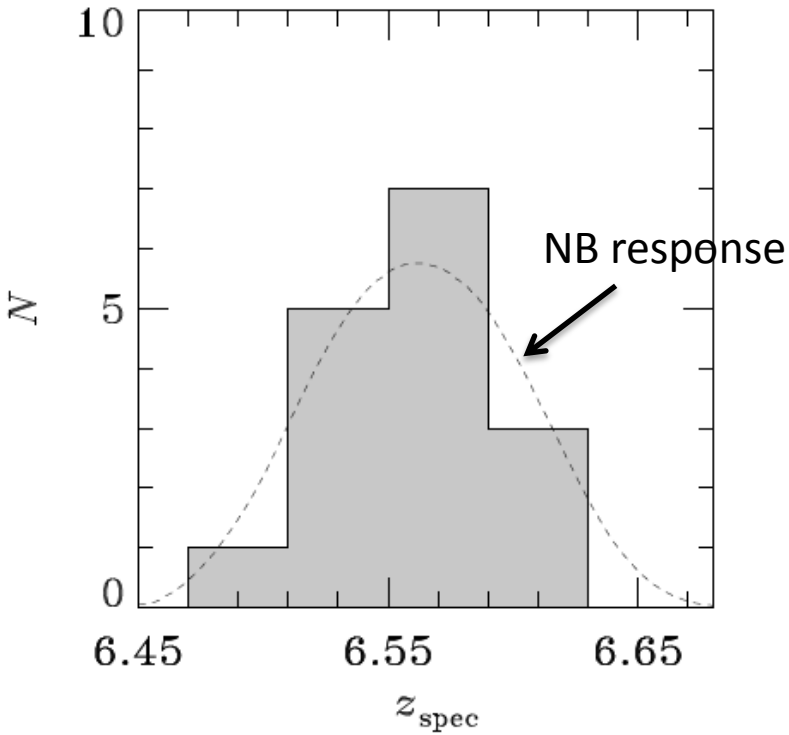


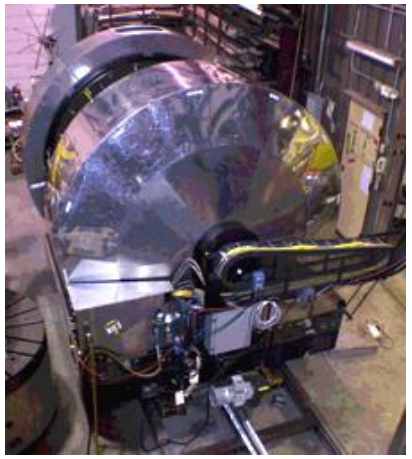
(Continuum color for Lya trough)

10 Subaru nights in 2005-2007 for NB921
(+40 nights for broad band data in SXDS project).
207 Lyα Emitters (LAEs) with L>~2.5e42 erg/s, EW_0>~14A (Ouchi et al. 2009)
(In my talk, we compare the results of the previous large-area LAE

Spectroscopic Confirmation







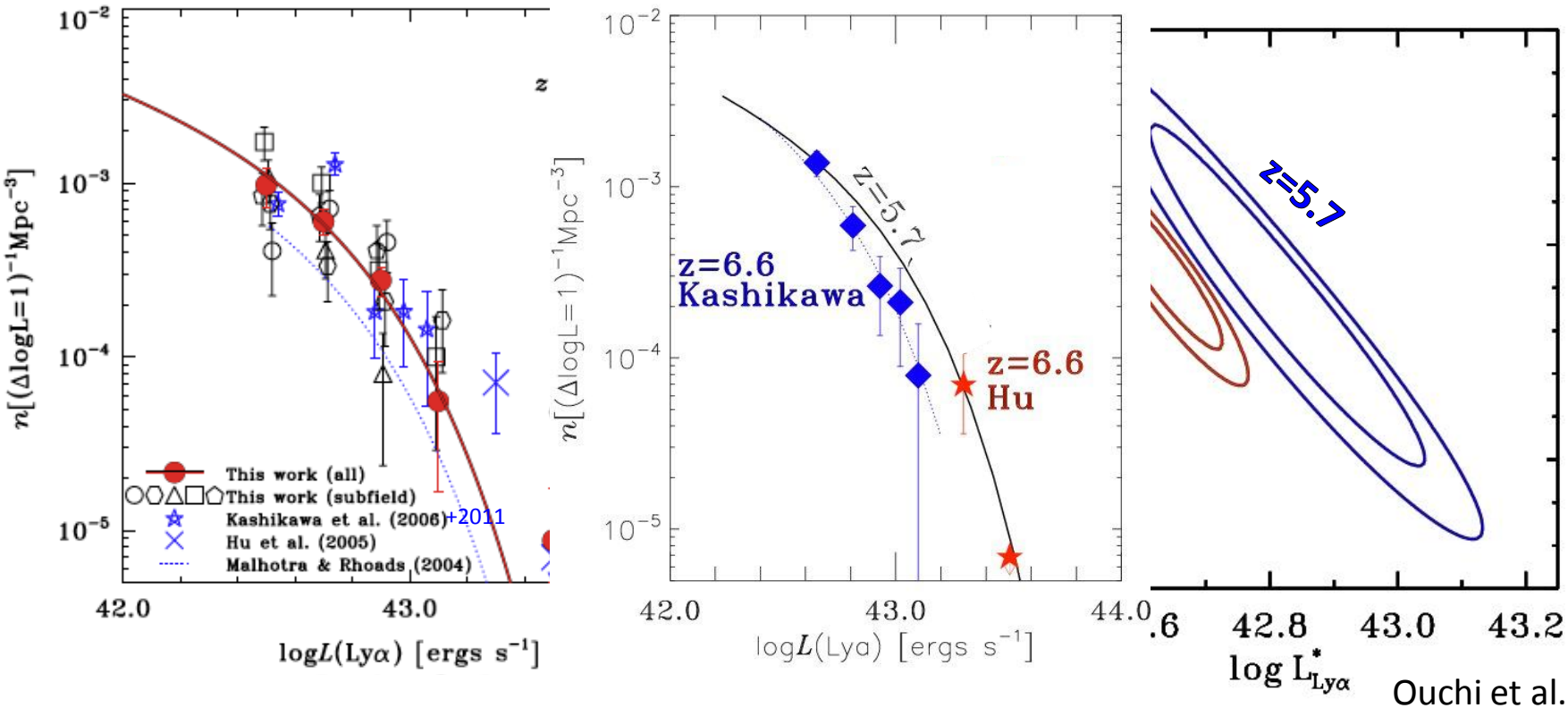
Keck/DEIMOS

- Spec. confirmation with 10m-Keck/DEIMOS (2007-2008) and 6.5m-Magellan/IMACS(2007-2010)
  28 LAEs (16 of 28 by Keck/DEIMOS)
  - No foreground contaminants in our follow-up spectra + 3233 SXDS spec. catalog.
  - Fraction of contamination (foreground interloper) is quite low (0-30%).

2. EVOLUTION OF LYA LUMINOSITY FUNCTION

Lya LF Evolution from z=5.7 to z=6.6: Signature of Galaxy Evolution and/or Reionization

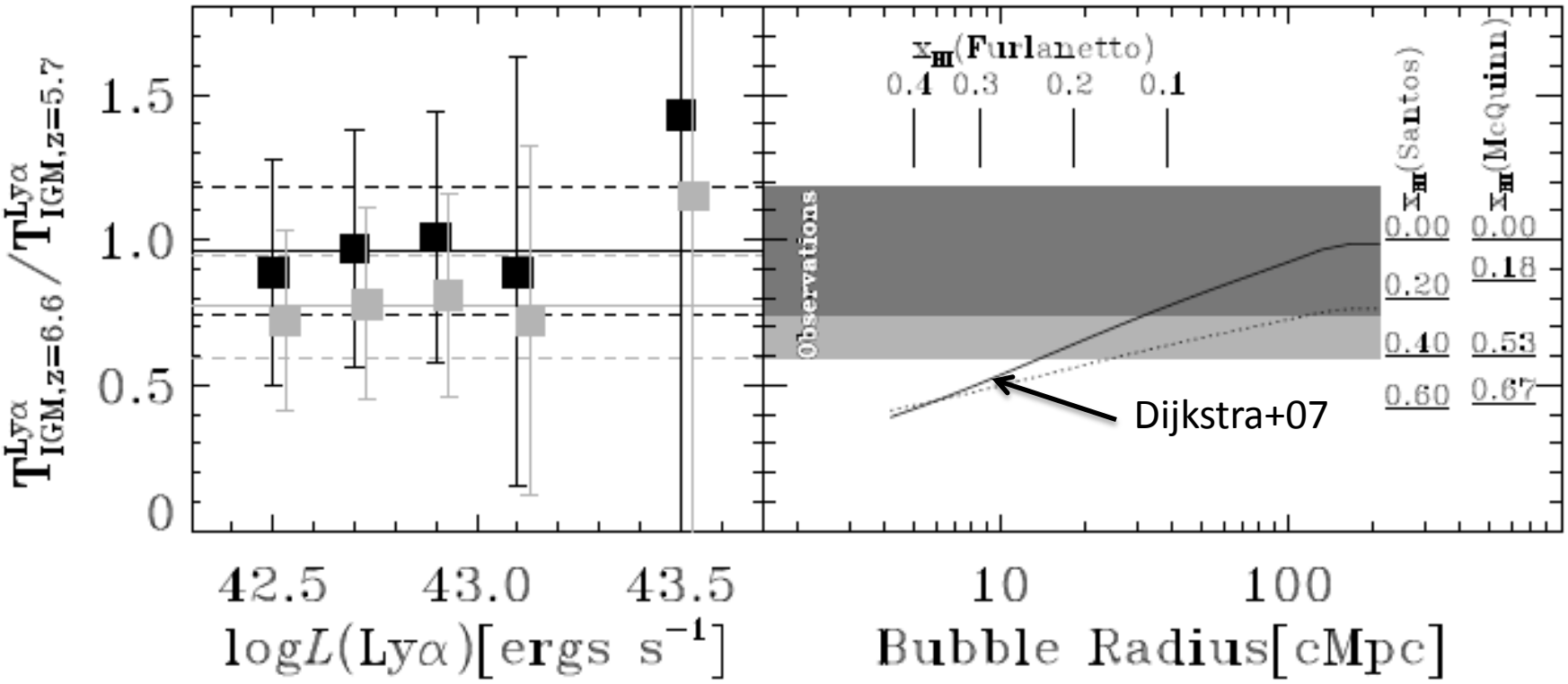
Lya Luminosity Function (Lya LF)



Ouchi et al. (2010)

- Different claims of LF evolution. No evolution vs. decrease (Malhotra+04, Hu+05/06, Kashikawa+06).
- The new large Subaru data in independent cosmic volumes show the decrease of LF from z=5.7-6.6 at >90% CL. Statistically, pure lum.(L*) dimming by 30% is more preferable.
- Signature of reionization and/or galaxy formation? Galaxy formation effect (SFR density decrease; e.g. Bouwens+08, Ouchi+09, Oesch+10). Any contributions from cosmic reionization??

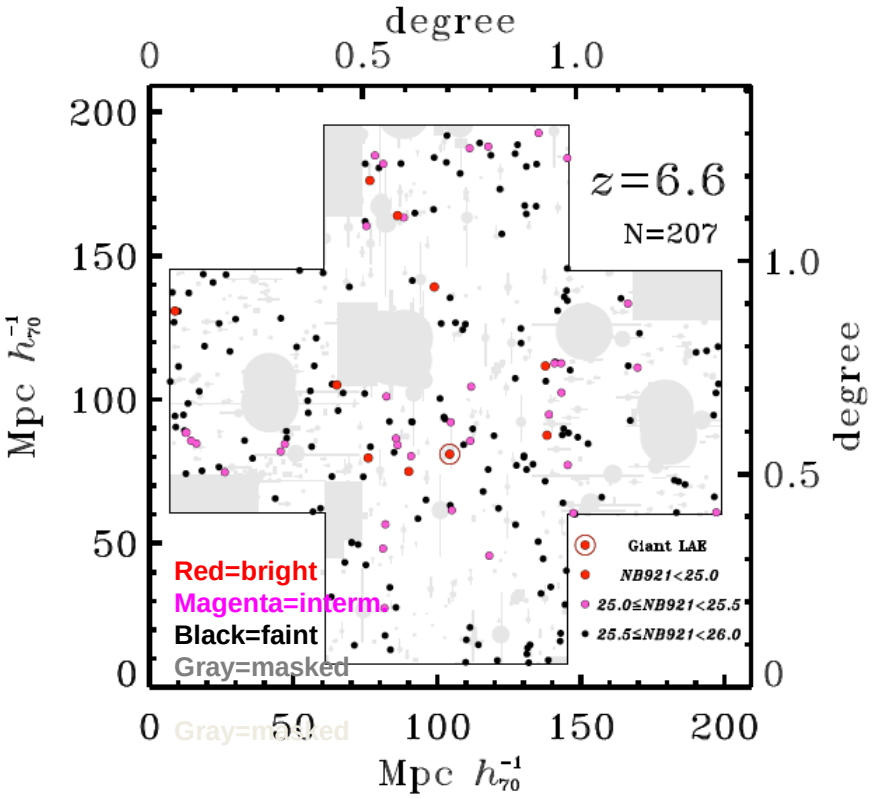
Transmission of Lya (through IGM): Contribution from Cosmic Reionization

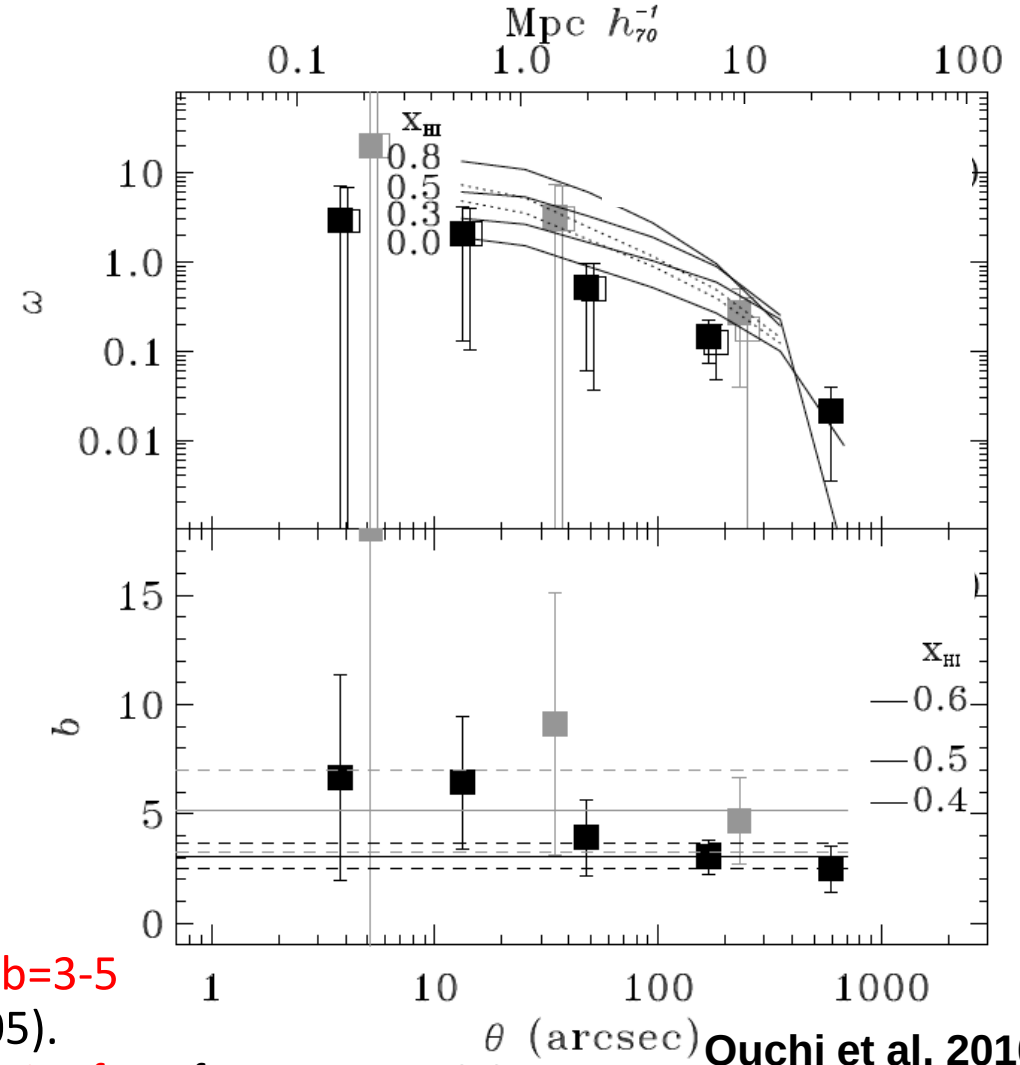


- Three scenarios
  - $T^{Lya}(z=6.6)/T^{Lya}(z=5.7)=0.7$ (No galaxy evolution and no f^{Lya} evolution)
  - $T^{Lya}(z=6.6)/T^{Lya}(z=5.7)=1.0$ (w/ galaxy evolution)
  - $T^{Lya}(z=6.6)/T^{Lya}(z=5.7)=0.8$ (w/ galaxy evolution and f^{Lya} evolution)
- In either case, $T^{Lya}(z=6.6)/T^{Lya}(z=5.7)$ is near unity, 0.8 ± 0.2. There would exist the evolution owing to reionization, but a contribution from reionization is mild.
- Comparing our result of $T^{Lya}(z=6.6)/T^{Lya}(z=5.7)=0.8$, all models indicate $x_{HI}<\sim0.2+/-0.2$.

2. EVOLUTION OF CLUSTERING

Clustering of LAEs at z~7



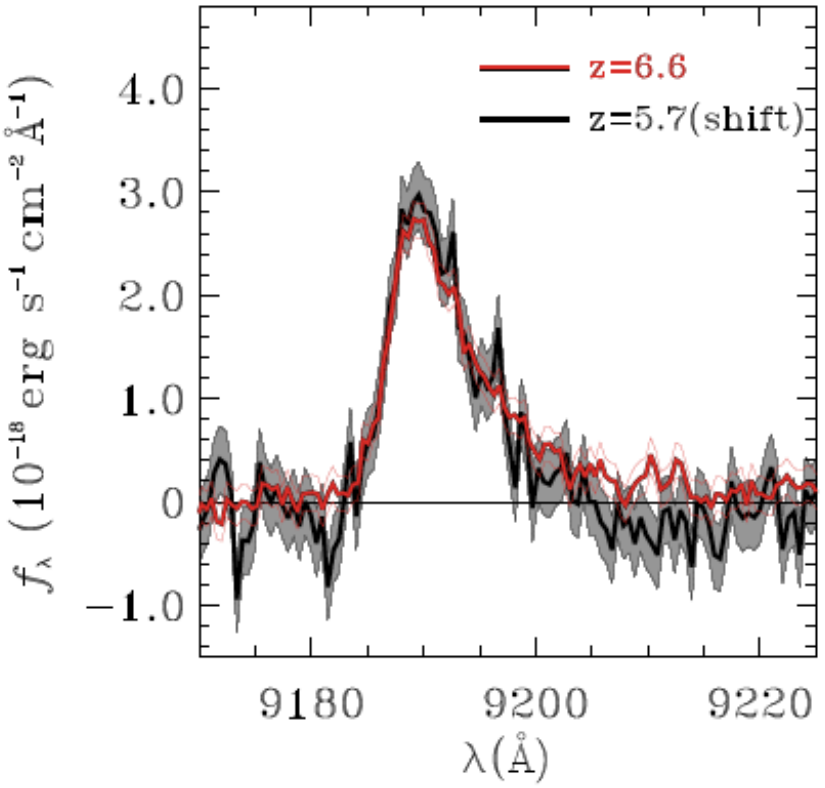


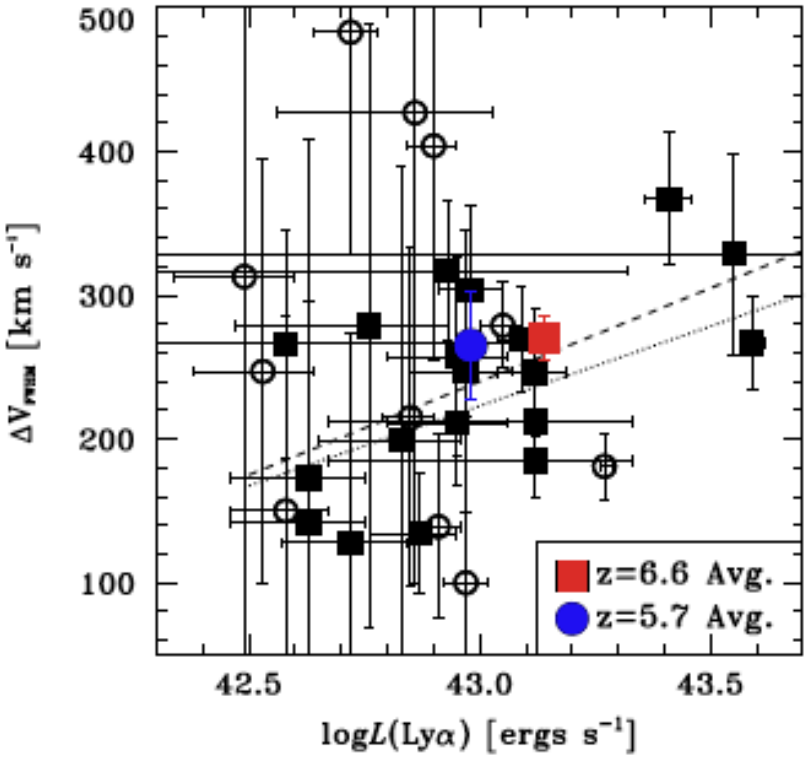
Ouchi et al. 2010

- Detection of clustering signal at z=6.6: b=3-5
- For LAEs at z=5.7: b=3.4±1.8 (Ouchi+05).
  - We see no significant increase of clustering from from z=5.7 to 6.6
    → Negligible enhancement of clustering amplitude by reionization at z=6.6.
  - Upper limits: $x_{HI} \lesssim 0.5$ (McQuinn+07); $x_{HI} \lesssim 0.5$ (Furlanetto+06)→ Constraints from clustering: $x_{HI} \lesssim 0.5$

3. EVOLUTION OF LYA LINE PROFILE

Lyα Line Width

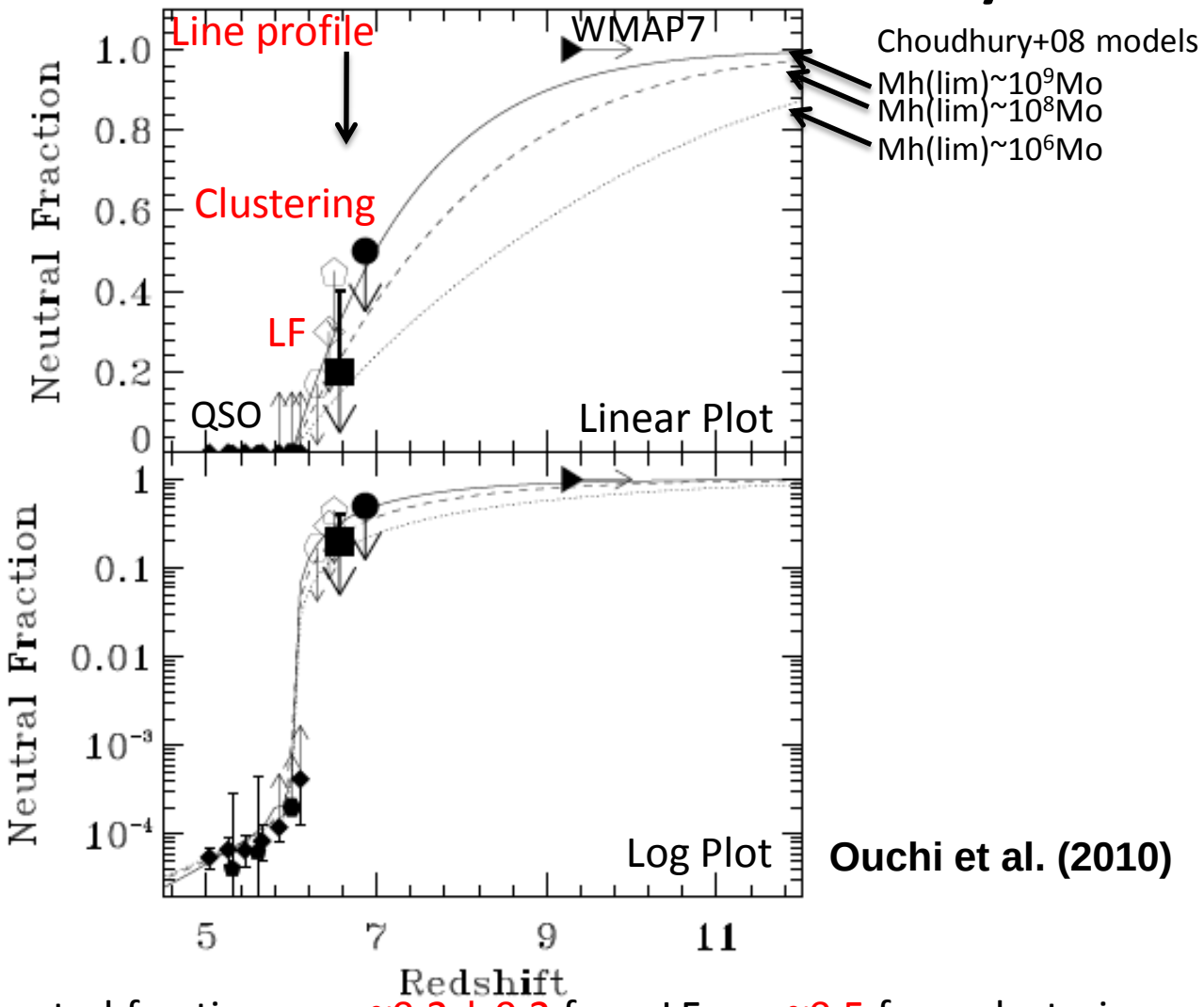




Ouchi et al. (2010)

- No significant Lya line broadening at the level of >14%
- No signature of anti-correlation in Lya Velocity-luminosity relation
  → No signature of x_{HI}~1 (cf. Haiman & Cen 2005)

Cosmic Reionization History



Ouchi et al. (2010)

- Our constraints on neutral fraction: x_{HI}<~0.2±0.2 from LF, x_{HI}<~0.5 from clustering, x_{HI}<~1 from Lya line profile at z=6.6

Three independent estimates provide consistent results. Taking the strongest constraint (x_{HI}<~0.2±0.2),

The relatively early reionization is favorable.

4. REIONIZATION PROBED WITH DROPOUT GALAXIES

Three Similar arXiv papers appear in ~a week

15 Jul 2011

SPECTROSCOPIC CONFIRMATION OF THREE z-DROPOUT GALAXIES AT $z = 6.844 - 7.213$: LYMAN ALPHA DEMOGRAPHY OF $z \sim 7$ GALAXIES‡

Yoshiaki Ono [1], Masami Ouchi [2,3], Bahram Mobasher [4], Mark Dickinson [5], Kyle Penner [6], Kazuhiro Shimasaku [1,7], Benjamin J. Weiner [8], Jeyhan S. Kartaltepe [5], Kimihiko Nakajima [1], Hooshang Nayyeri [4], Daniel Stern [9], Nobunari Kashikawa [10], and Hyron Spinrad [11]

submitted to ApJ

ABSTRACT

We present the results of our ultra-deep Keck/DEIMOS spectroscopy of z-dropout galaxies in the SDF and GOODS-N. For 3 out of 11 objects, we detect an emission line at $\sim 1\mu$m with a signal-to-noise ratio of ~ 10. The lines show asymmetric profiles with high weighted skewness values, consistent with being Lyα, yielding redshifts of $z = 7.213$, 6.965, and 6.844. Specifically, we confirm the $z = 7.213$ object in two independent DEIMOS runs with different spectroscopic configurations. The $z = 6.965$ object is a known Lyα emitter, IOK-1, for which our improved spectrum at a higher resolution yields a robust skewness measurement. The three z-dropouts have Lyα fluxes of 3×10^{-17} erg s^{-1} cm^{-2} and rest-frame equivalent widths $EW_0^{Ly\alpha} = 33 - 43$Å. Based on the largest spectroscopy sample of 43

Our team
(Ono, MO et al. 2011)

7 Jul 2011

SPECTROSCOPIC CONFIRMATION OF Z~ 7 LBGS: PROBING THE EARLIEST GALAXIES AND THE EPOCH OF REIONIZATION

L.Pentericci[1] A. Fontana [1] E. Vanzella[2] M. Castellano [1] A. Grazian [1] M. Dijkstra [3] K. Boutsia [1] S. Cristiani [2] M. Dickinson[4] E. Giallongo [1] M. Giavalisco [5] R. Maiolino [1] A. Moorwood[6*] P. Santini [1]
[1] INAF Osservatorio Astronomico di Roma, Via Frascati 33,00040 Monteporzio (RM), Italy
[2] INAF Osservatorio Astronomico di Trieste, Via G.B.Tiepolo 11, 34131 Trieste, Italy
[3] Max-Planck-Instit fr Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
[4] National Optical Astronomy Observatory, PO Box 26732, Tucson, AZ 85726, USA
[5] Department of Astronomy, University of Massachusetts, 710 North Pleasant Street, Amherst, MA 01003 and
[6] European Southern Observatory, Karl-Schwarzschild Strasse, 85748 Garching bei Munchen, German

Draft version July 8, 2011

ABSTRACT

We present the final results from our ultra-deep spectroscopic campaign with FORS2 at the ESO/VLT for the confirmation of $z \simeq 7$ "z–band dropout" candidates selected from our VLT/Hawk-I imaging survey over three independent fields. In particular we report on two newly discovered galaxies at redshift ~ 6.7 in the NTT deep field: both galaxies show a Lyα emission line with rest-frame EWs

European team
(Pentericci et al. 2011)

6 Jul 2011

KECK SPECTROSCOPY OF FAINT $3 < Z < 8$ LYMAN BREAK GALAXIES:- EVIDENCE FOR A DECLINING FRACTION OF EMISSION LINE SOURCES IN THE REDSHIFT RANGE $6 < Z < 8$

Matthew A. Schenker[1], Daniel P. Stark[2], Richard S. Ellis[1], Brant E. Robertson[1], James S. Dunlop[3], Ross J. McLure[3], Jean-Paul Kneib[4] & Johan Richard[5]

Draft version July 8, 2011

ABSTRACT

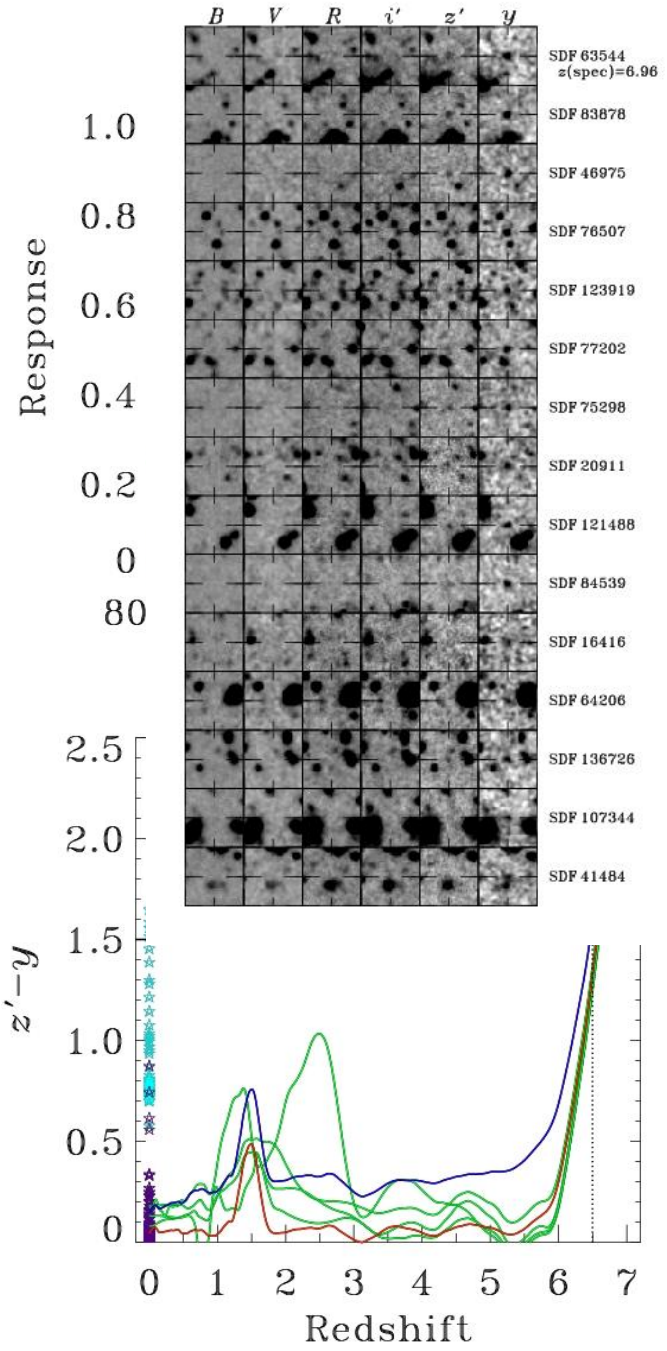
Using deep Keck spectroscopy of Lyman break galaxies selected from infrared imaging data taken with the Wide Field Camera 3 onboard the Hubble Space Telescope, we present new evidence for a reversal in the redshift-dependent fraction of star forming galaxies with detectable Lyman alpha (Lyα) emission in the redshift range $6.3 < z < 8.8$. Our earlier surveys with the DEIMOS spectrograph demonstrated a significant increase with redshift in the fraction of line emitting galaxies over the interval $4 < z < 6$, particularly for intrinsically faint systems which dominate the luminosity density. Using the longer wavelength sensitivities of LRIS and NIRSPEC, we have targeted 19 Lyman break galaxies selected using recent WFC3/IR data whose photometric redshifts are in the range $6.3 < z < 8.8$ and which span a wide range of intrinsic luminosities. Our spectroscopic exposures typically reach

US+UK team
(Schenker et al. 2011)

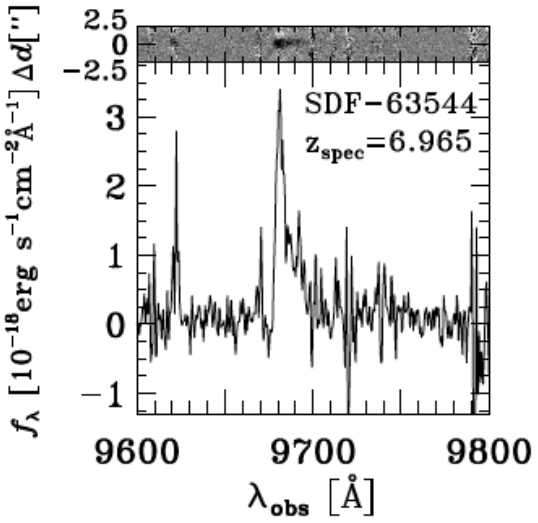
- Very active (+competitive) field!!

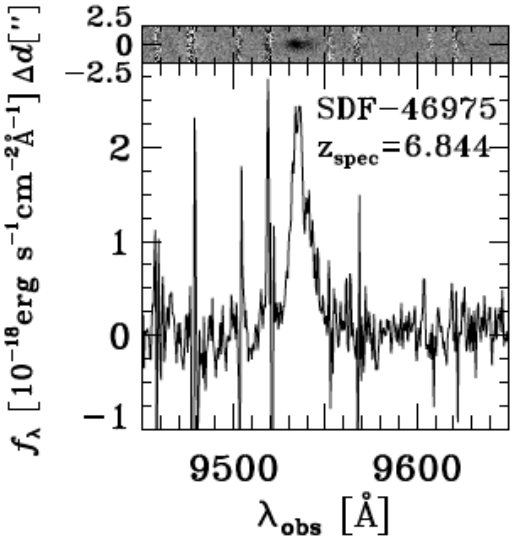
Subaru z-dropout samples

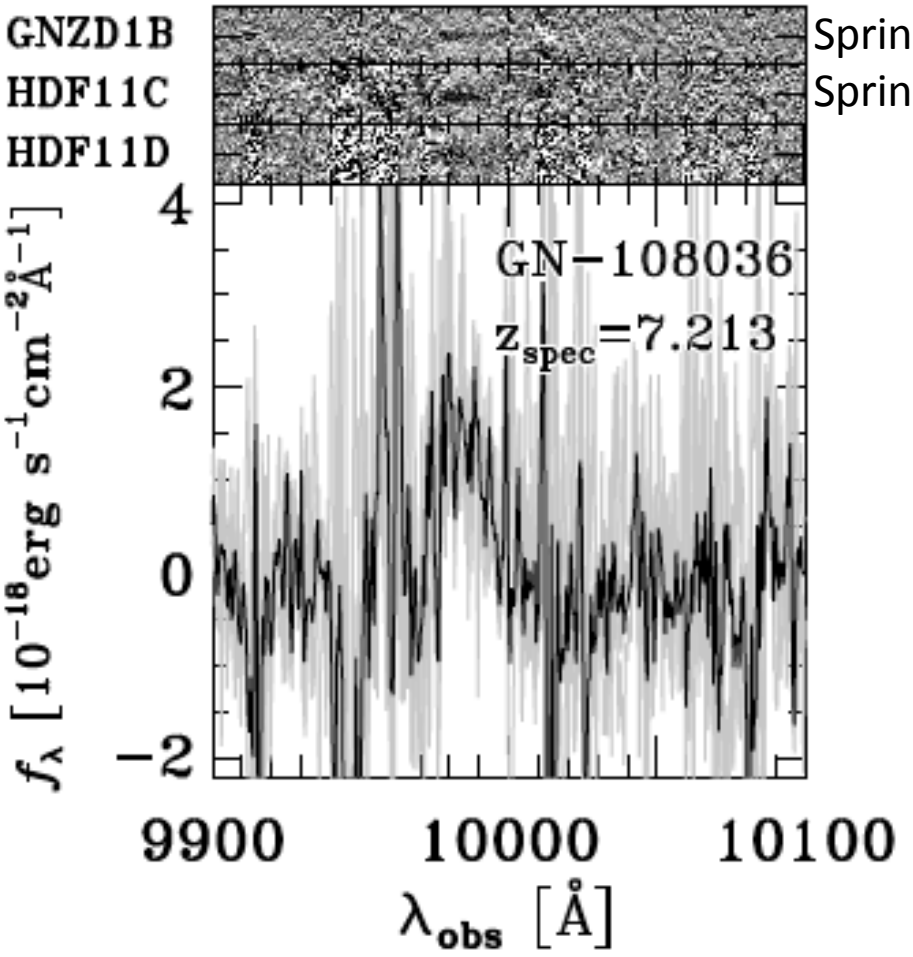
- Samples of z-dropouts in SDF+GOODS (observations in 2007-2009)
  - 1568 arcmin^2 with y=26.1 (2-3 mag shallower, but ~100 times larger area than HST/WFC3; e.g. Bouwens et al. 2010)
  - z-dropouts(z-y>1.5&lacking blue flux)
    - 22 z~7 dropout candidates



Spectroscopic Identification of Galaxies at z=6.844-7.213



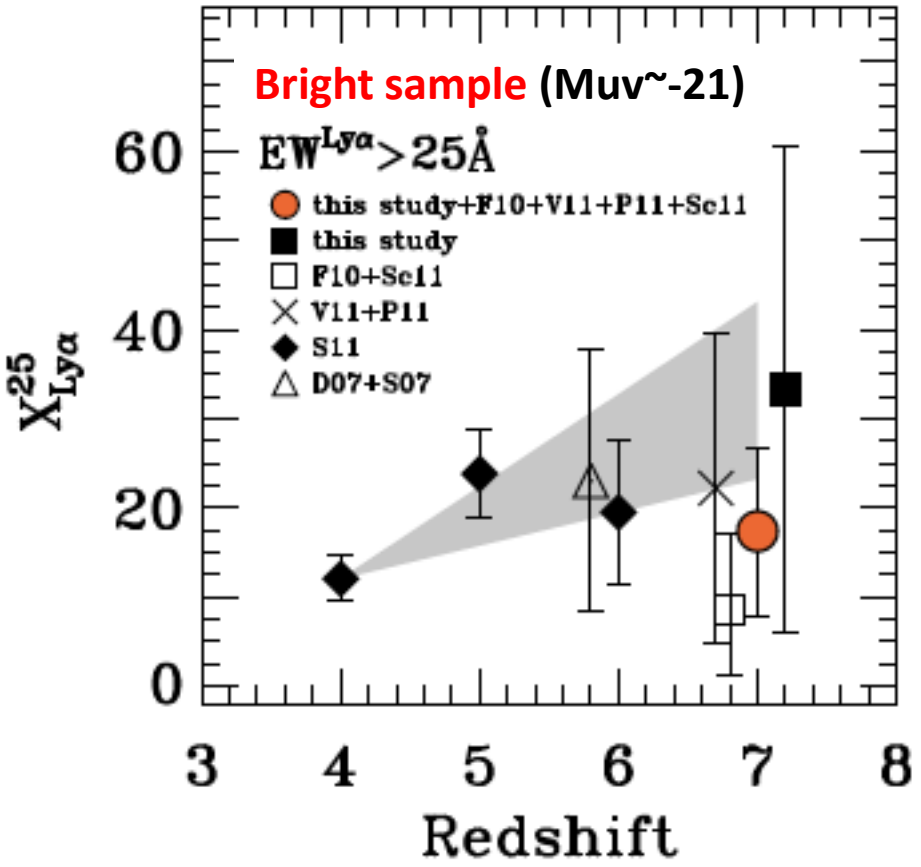


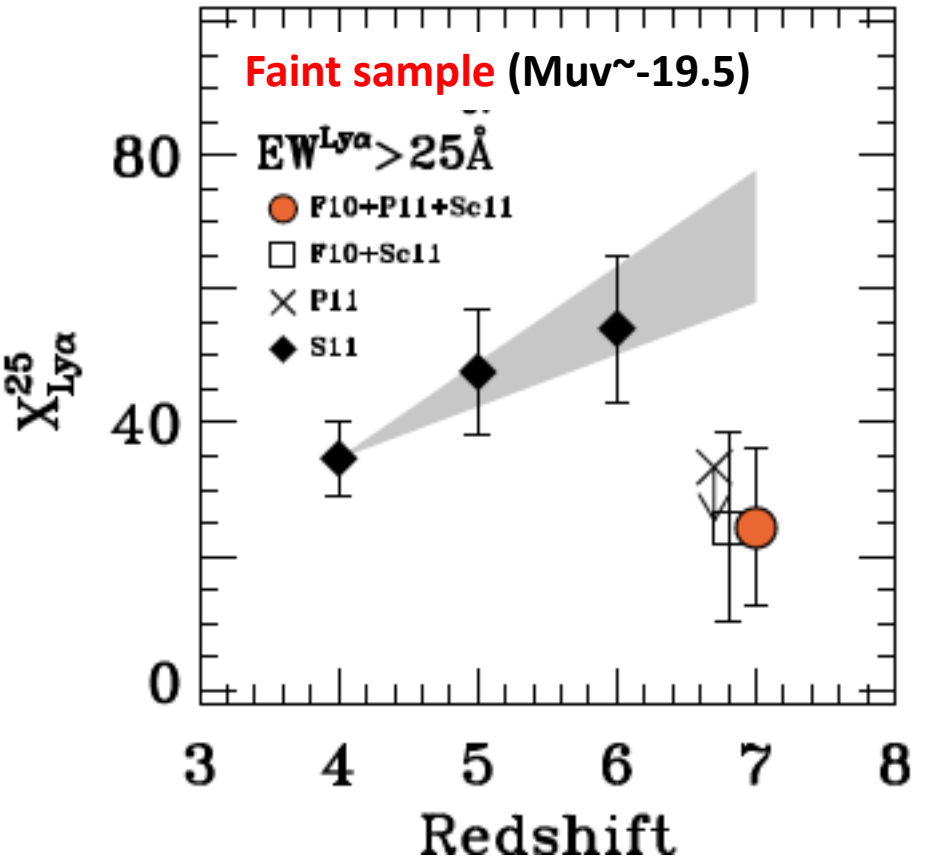


Ono, MO et al. (2011)

- z=7.213 galaxy: Most distant galaxy confirmed to date!? (cf. Lehnert et al. 2010 and Vanzella et al. 2010)

Lya Emitting Galaxy Fraction (Summary of the 3 papers: 43 galaxies)

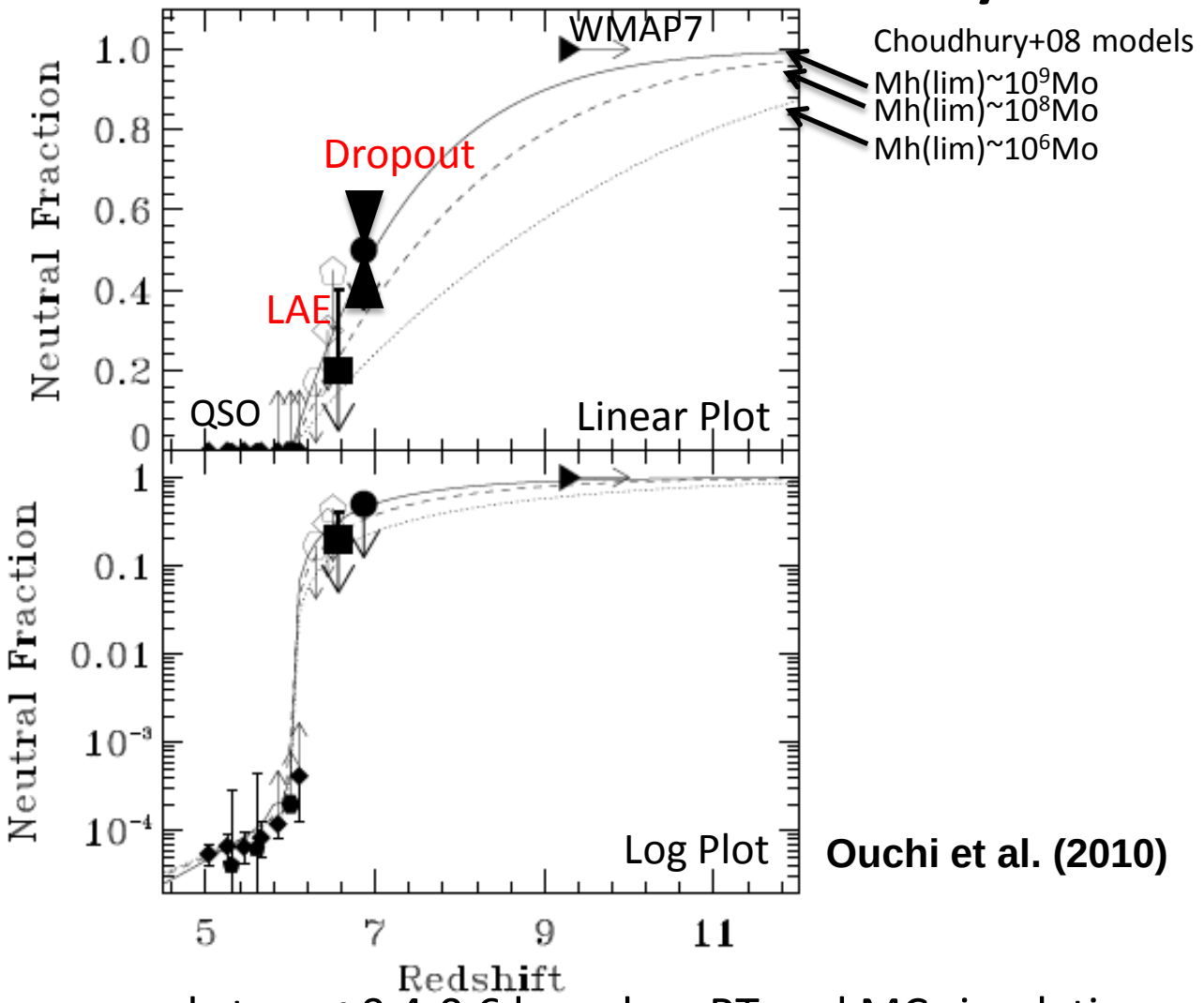




Ono, MO et al. (2011)

- The fraction of Lya emitting galaxies is low, ~20%.→ Signature of reionization?
- The amplitude of drop is larger in faint galaxies than in bright galaxies →suggestive of inside-out reionization.

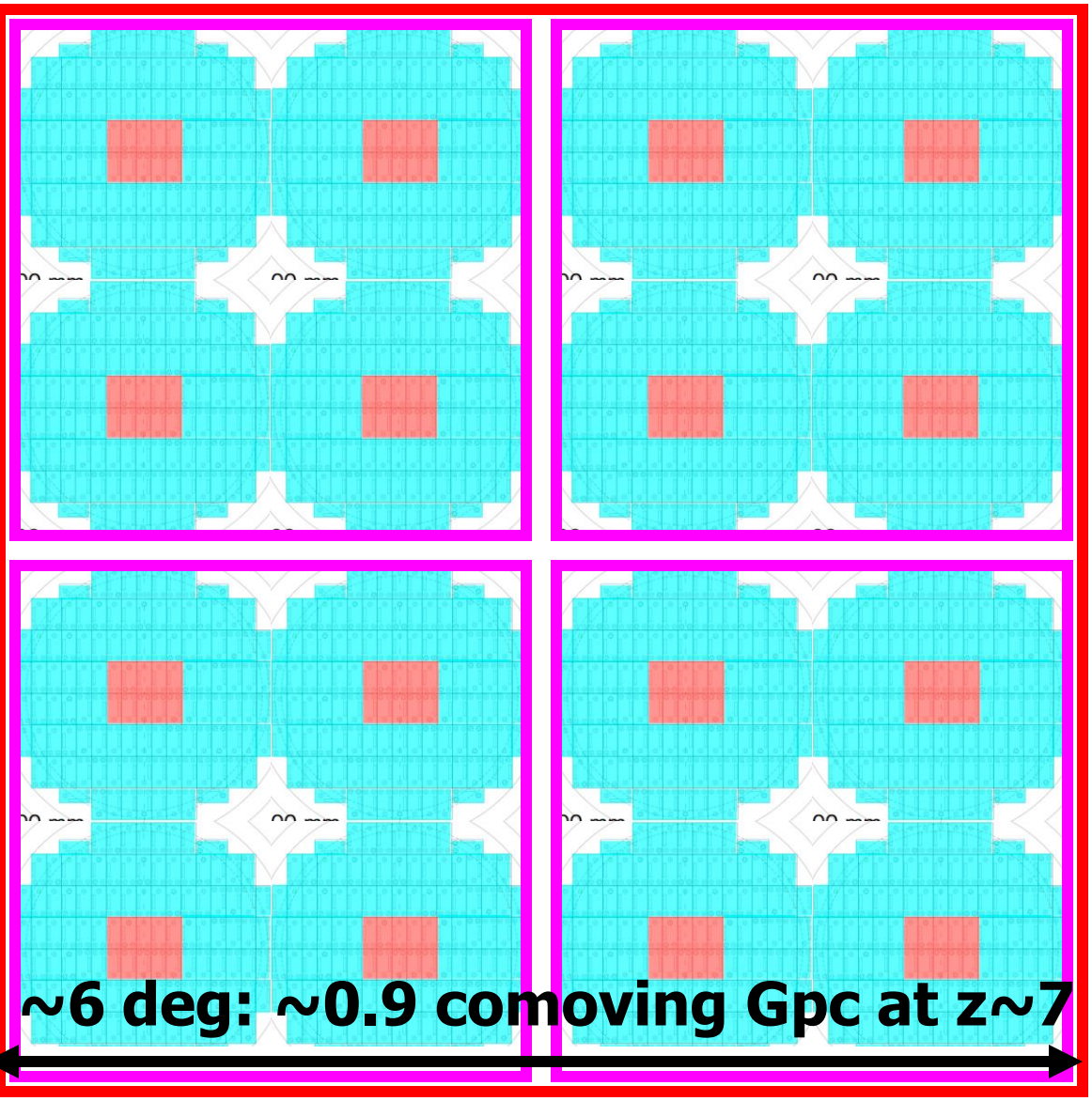
Cosmic Reionization History



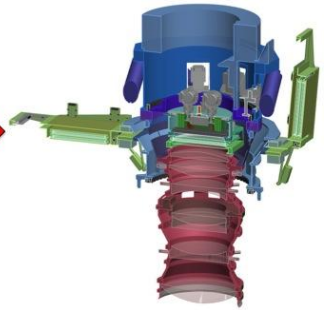
Ouchi et al. (2010)

- This drop of X_{Lya} corresponds to x_{HI}~0.4-0.6 based on RT and MC simulations (Schenker+11,Pentericci+11).
- It is consistent within the 1-2 sigma error of the LAE test, but largely scattered.
- Large uncertainties that cannot distinguish sharp and extended reionization.

Next Generation Survey with Hyper Suprime-Cam and PFS

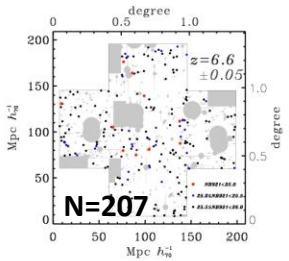


x10

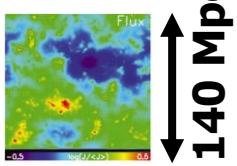


Suprime-Cam

Hyper Suprime-Cam(HSC; 2011-)



Present largest obs. (Ouchi+10) 1/30



Current model (Mesinger+09)

- Reducing the errors of IGM ionized fraction down to ~10% (model variance limit)
- Concluding reionization process (inside-out, outside-in, or filament-last)

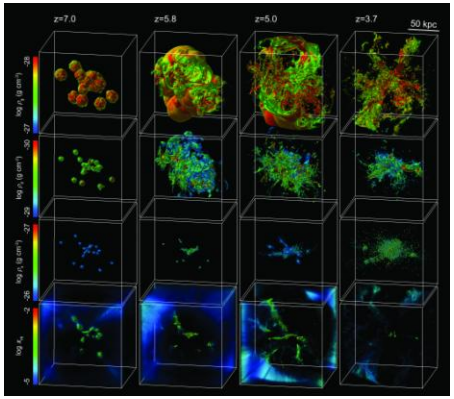
Very Large+Detailed Cosmological Simulations

- N-body, SPH, radiative transfer (RT) simulations for the size of HSC survey (~1Gpc; Umemura, Mori [Tsukuba], Inoue [OsakaSangyo], et al.)
- Two step simulations
  - For detailed galaxy formation and ionizing photon emission processes (fesc evolution, faint galaxies+suppression etc; ~100kpc)
  - ~1Gpc size N-body and RT simulations (~resolution: 100kpc)

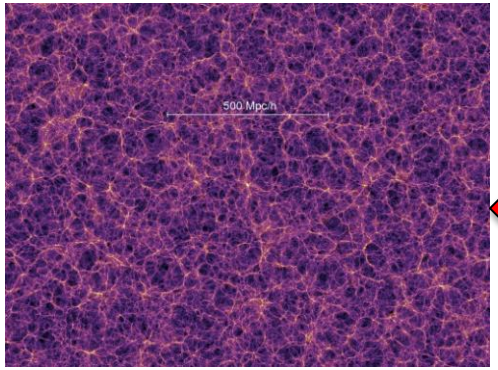
  → comparing it with HSC obs. results (addressing fesc evolution, faint galaxies, and ionization process).

T2K-Tsukuba

K computer (京)



SPH simulations with RT(Yajima+09)



N-body simulations (Springel+05)

HSC+PFS results

Summary

- Subaru+Keck survey for reionization and galaxy formation. Based on the sample of 207 LAEs at z=6.6 (+22 z-dropouts at z~7) from Subaru/Suprime-Cam and Keck/DEIMOS observations, we obtain/perform

- Evolution of neutral hydrogen fraction with LAEs
  - Lya LF decrease (but only 30% in L*) from z=5.7 to 6.6. →x_{HI}<~0.2.
  - First Identification of clustering(z>6).No significant rise of clustering amplitude→x_{HI}<~0.5
  - No Lya line broadening and anti-correlation of Lya luminosity-width relation→ x_{HI}<~1.0

  All of three tests are consistent. : x_{HI}<~0.2±0.2 at z~6.6

- Lya demography of z-dropouts
  - Discovery of z=7.213 galaxy. Most distant galaxy found to date?
  - Lya emitting galaxy fraction decreases from z~6 to 7. Signature of neutral IGM increase? x_{HI}<~0.4-0.6 at z~7?
  - The Lya emiting fraction of faint galaxies have a larger drop than that of bright galaxies→suggesting inside-out model.

- Results of LAE and dropout tests are consistent within the 1-2 sigma errors, but large errors dominated by statistics.

- Planned HSC and PFS survey and very large-scale simulations
  - Resolving the problem of large uncertainties, and Unveiling reionization history+proc.