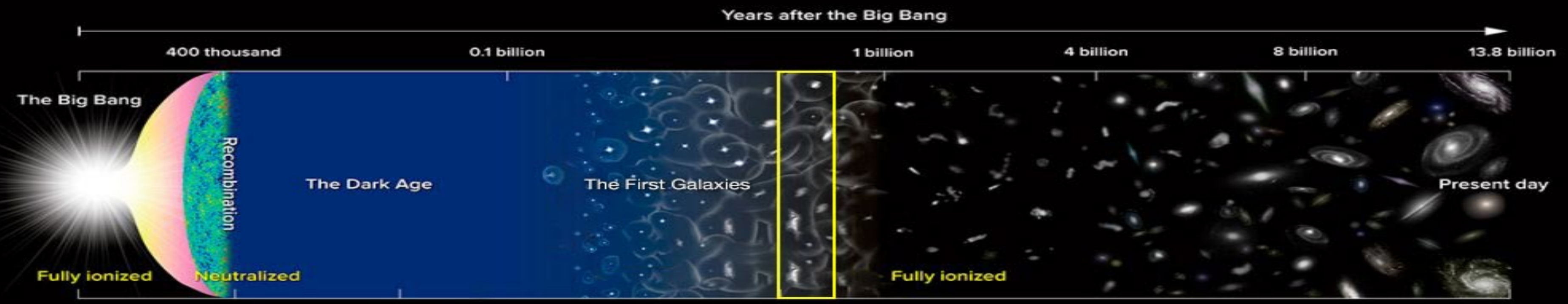


LAGER: Lyman Alpha Galaxies in the Epoch of Reionization

Probing Reionization at z~7 with the First Narrowband Filter on DECam

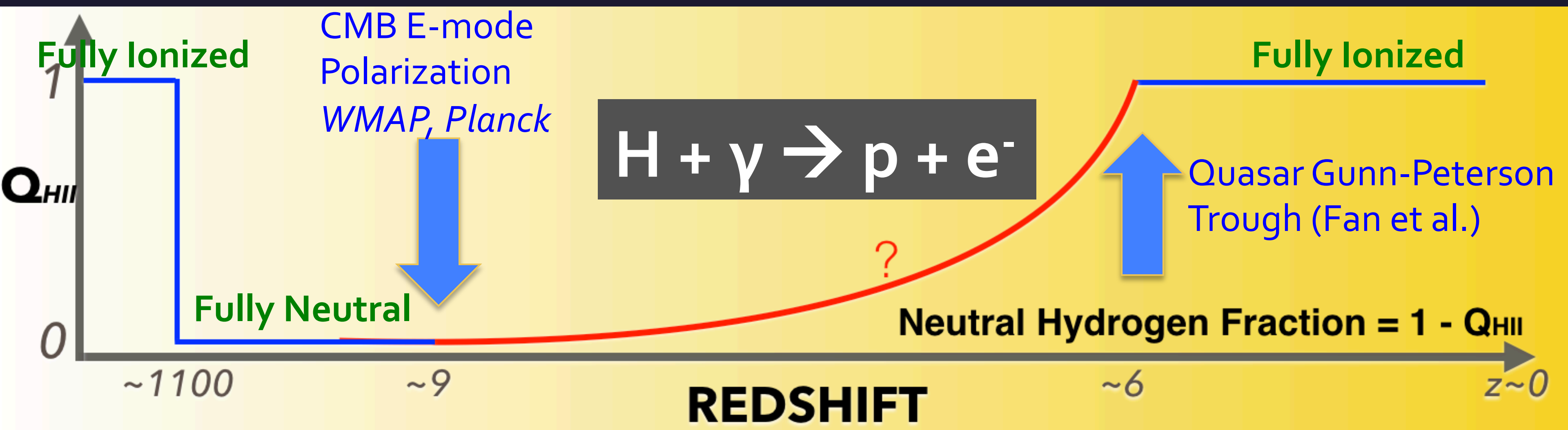
Zhenya Zheng (SHAO)

on behalf of the LAGER Team

Outline

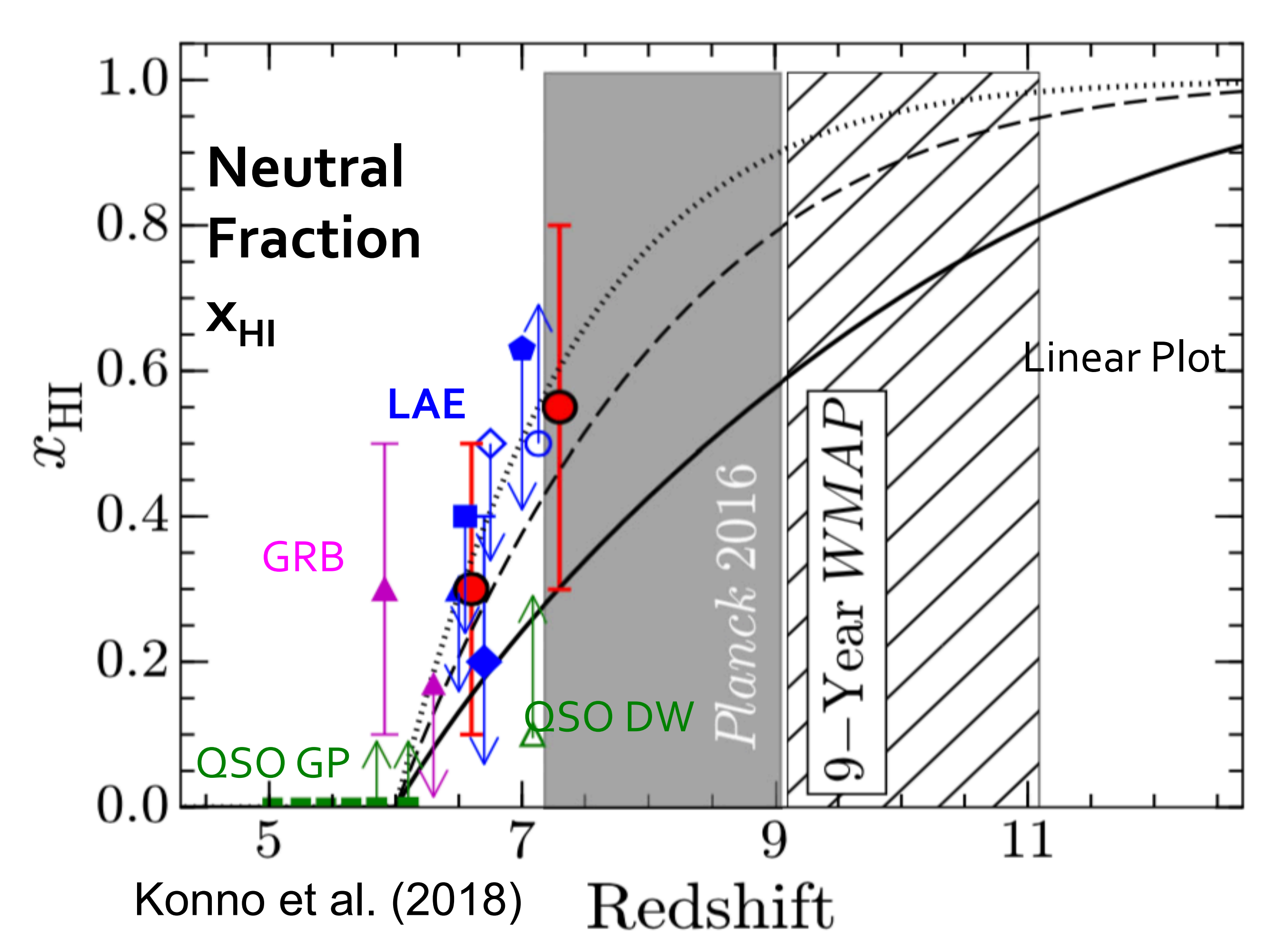
- Introduction of LAGER Survey
    - Survey Background
    - LAGER Project (2015 Dec. -2018 Mar.)
- LAGER's First Results
    - z~7 LFs of Lyα galaxies
    - z~7 Bubbles (See Sangeeta's talk)
- Recent Updates with LAGER
    - Data & Science
- Comparison with HSC-NB: DECam-NB is Unique
- Conclusion

Origin of CMB
Dark Ages
Epoch of Reionization: First Stars & First Galaxies
Modern Universe
Big Bang
1. Last Phase Change of the Whole Universe (H + γ → p + e-)
2. First Generation Stars, BHs, and Galaxies
Today
400 kyr
500 Myr
1 Gyr
5 Gyr
13 Gyr
Time



Fully Ionized
CMB E-mode Polarization
WMAP, Planck
H + γ → p + e-
Fully Ionized
1
QHII
0
Quasar Gunn-Peterson Trough (Fan et al.)
?
Fully Neutral
Neutral Hydrogen Fraction = 1 - QHII
~1100
~9
REDSHIFT
~6
z~0

Global History of Reionization



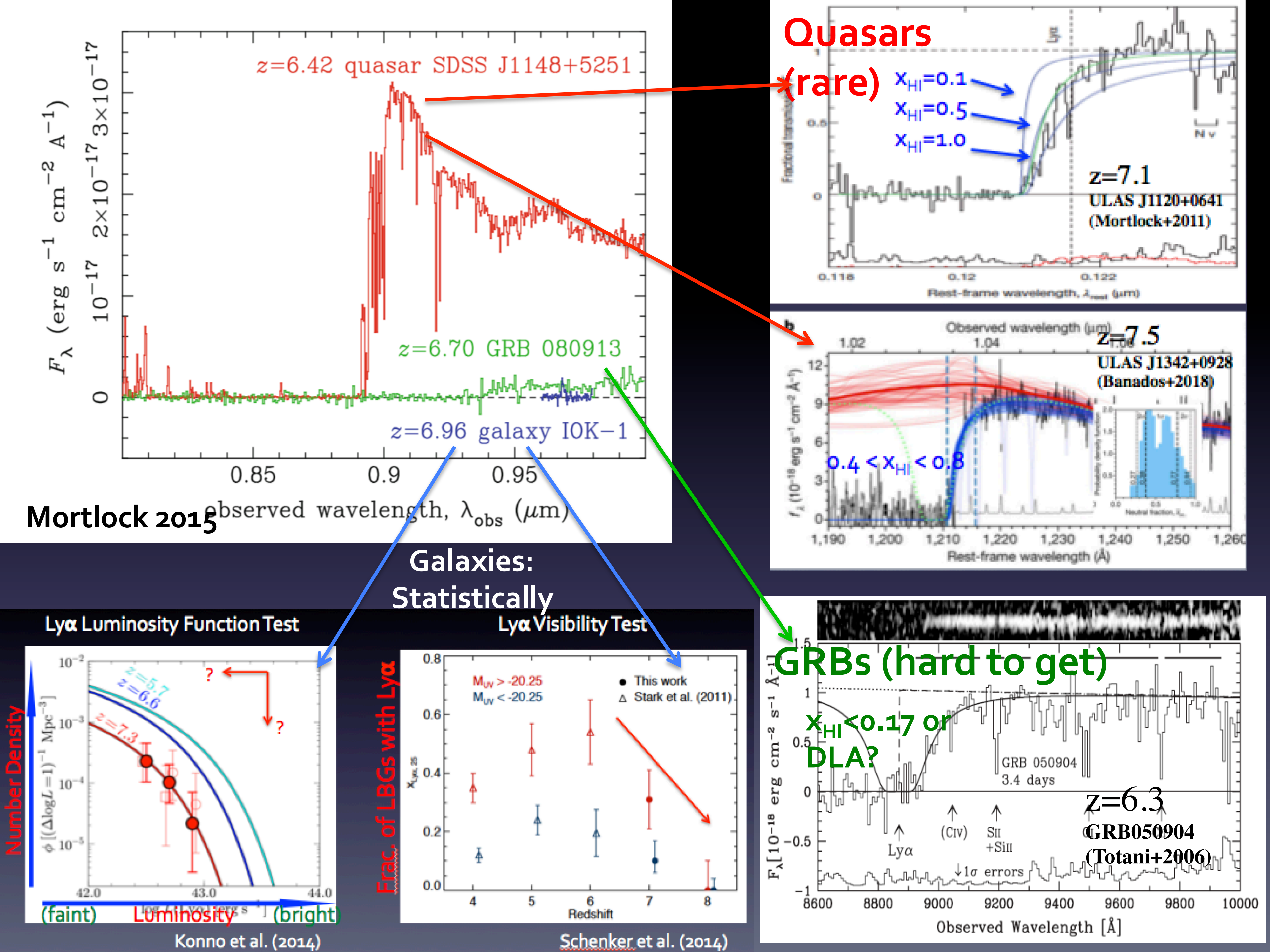
- Quasar Gunn-Peterson
- Quasar Damping Wing
- GRB Damping Wing

EoR Probes with Lya Galaxies:

1. Lya LF of Lya Galaxies in EoR
2. Lya Visibility
3. Clustering of Lya Galaxies
4. Ionizing Volume

See also: Sharma+16, Robertson+15, Mitra+15, Bouwens+15, Kakiichi+16, Greig & Mesinger17 …

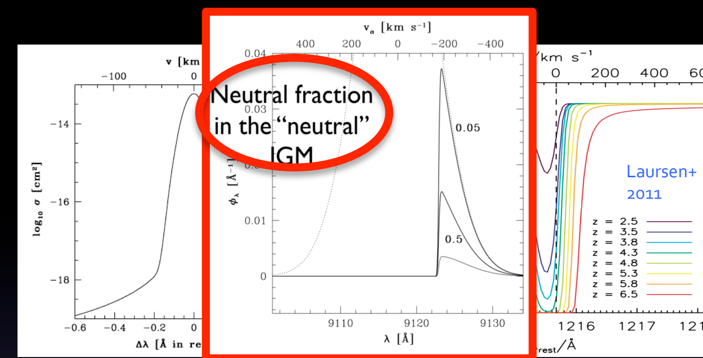
- X_{HI} increases from z~6
- Large dispersion at z>~7 → Reason: Limited galaxy sample at z >~ 7



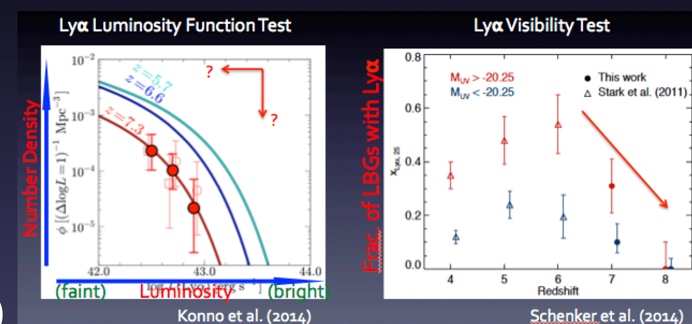
z=6.42 quasar SDSS J1148+5251
z=6.70 GRB 080913
z=6.96 galaxy IOK−1
F_λ (erg s^{-1} cm^{-2} Å^{-1})
0.85
0.9
0.95
observed wavelength, λ_{obs} (μm)
Mortlock 2015
Quasars (rare)
x_{HI}=0.1
x_{HI}=0.5
x_{HI}=1.0
z=7.1
ULAS J1120+0641
(Mortlock+2011)
Rest-frame wavelength, λ_{rest} (μm)
Observed wavelength (μm)
z=7.5
ULAS J1342+0928
(Banados+2018)
0.4 < x_{HI} < 0.8
Rest-frame wavelength (Å)
Galaxies: Statistically
Lyα Luminosity Function Test
Number Density
(faint)
Luminosity
(bright)
Konno et al. (2014)
Lyα Visibility Test
Frac. of LBGs with Lyα
M_{UV} > -20.25
M_{UV} < -20.25
This work
Stark et al. (2011)
Redshift
Schenker et al. (2014)
GRBs (hard to get)
x_{HI}<0.17 or DLA?
GRB 050904
3.4 days
Lyα
(CIV)
SII +SiII
↓1σ errors
z=6.3
GRB050904
(Totani+2006)
Observed Wavelength [Å]

– Probing Reionization with Lyα Galaxies (**EoR History & Topology**):

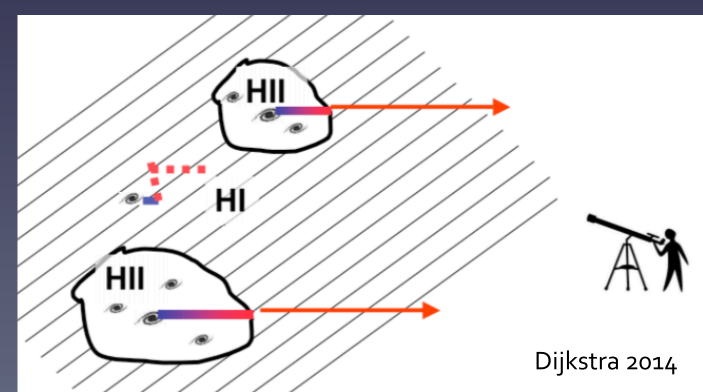
Reason: Damping Wing Absorption of Lyα Photons by (partially) Neutral IGM



Probing EoR History: Comparing the Statistical Properties of Lyα Galaxies in EoR and Post-Rionization Epoch (Lyα LF Test, Lyα Visibility Test,…)



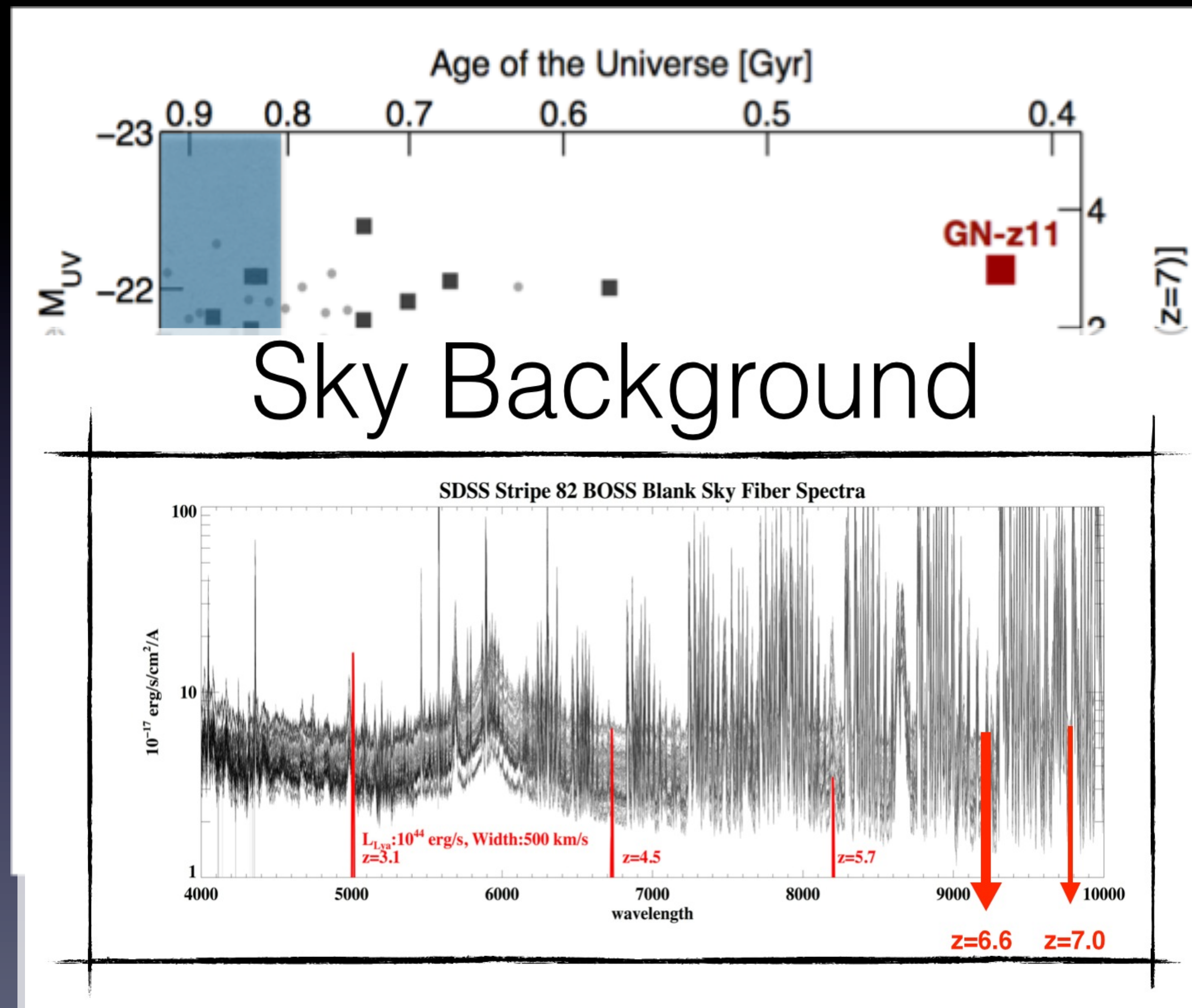
Mapping EoR Topology: IGM Environment on the Appeared Distribution of Lyα Galaxies (Clustering Analysis, Ionizing Volume, Lya & 21cm CCF)



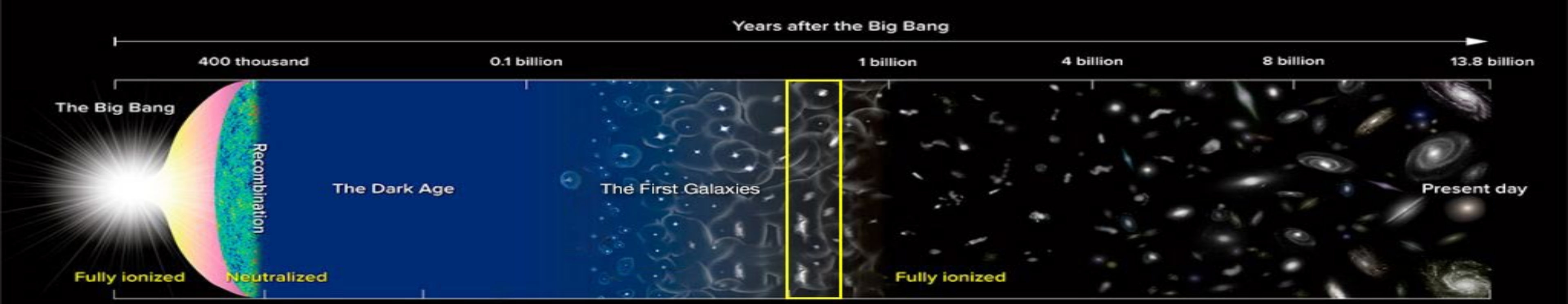
Observational Challenges at z >~ 7

- **Most of these z >~ 7 candidate galaxies are selected from space:** Hundreds of LBGs from HST vs. ~20+ LAEs with ground NB before 2016;

- **12 galaxies (3 LAEs) with spec. conformation at z >~ 7 (2006-2016):** 2 with HST grism, 1 with 6.5m Magellan, and others with 8-10m telescopes. Most of these are confirmed via their Lyα lines.



Need to increase the LAE sample at z>~7



Lyman Alpha Galaxies in the Epoch of Reionization (LAGER)

CHINA

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Francisco Valdes (NOAO)
Alicia Gonzalez (ASU),
Vithal Tilvi (ASU) ,
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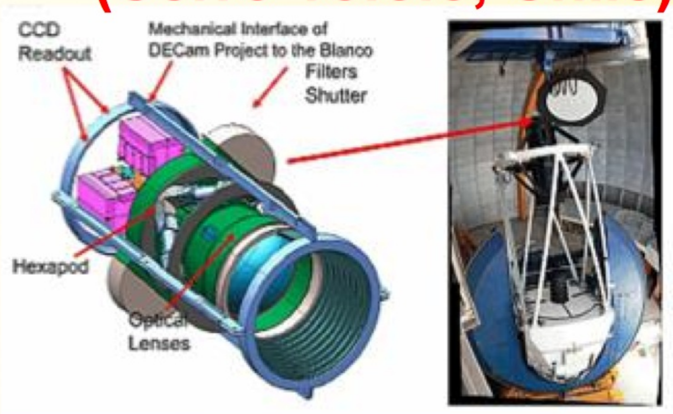
Felipe Barrientos (PUC),
Huan Yang (LCO),
Pascale Hibon (ESO),
Gaspar Galaz (PUC),
Franz Bauer (PUC), …

The LAGER Project

CTIO 4m Blanco Telescope
(Cerro Tololo, Chile)



+

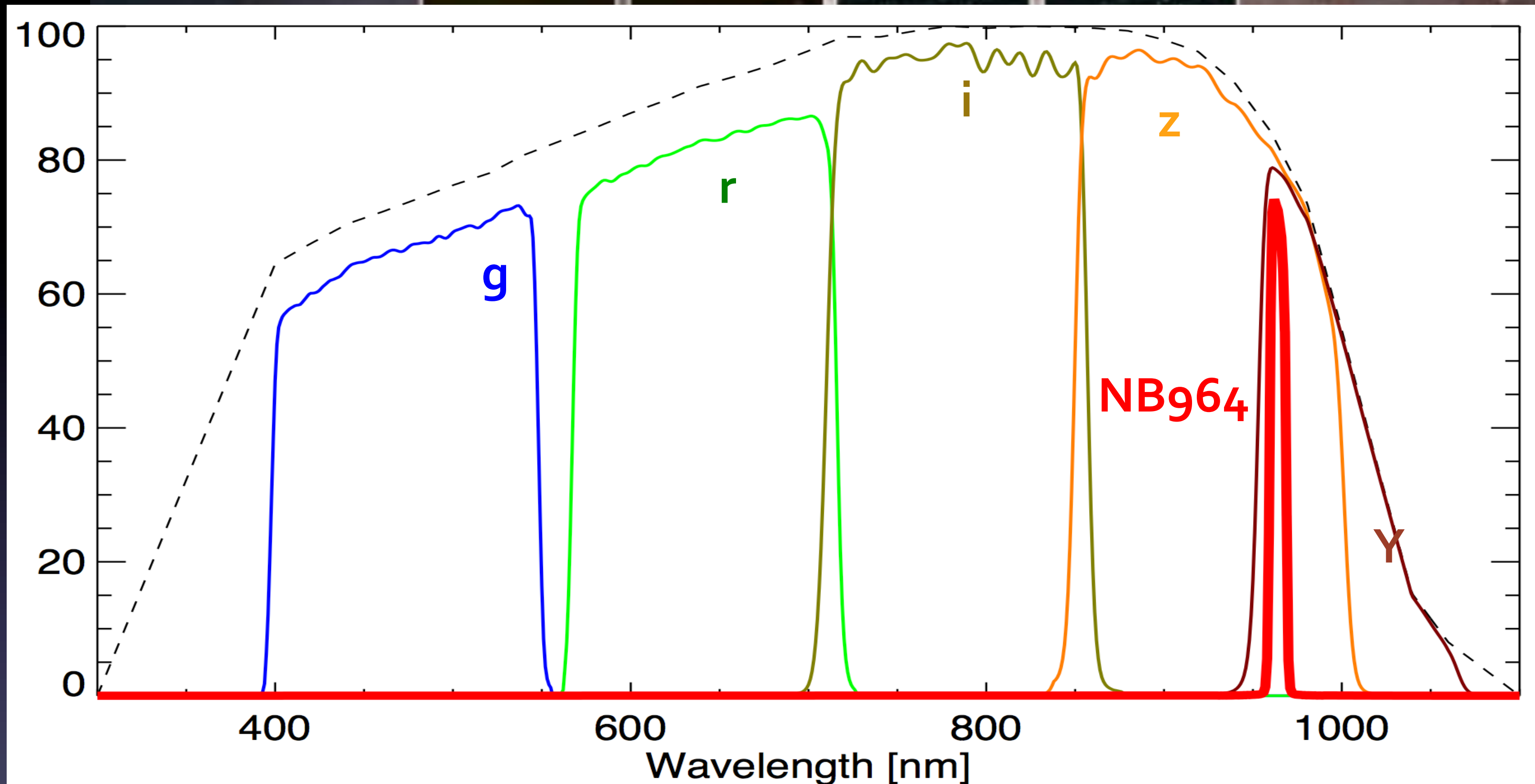
Dark Energy Camera
(FOV = 3 sq-deg)

Lyman
Alpha
Galaxies in the
Epoch of
Reionization

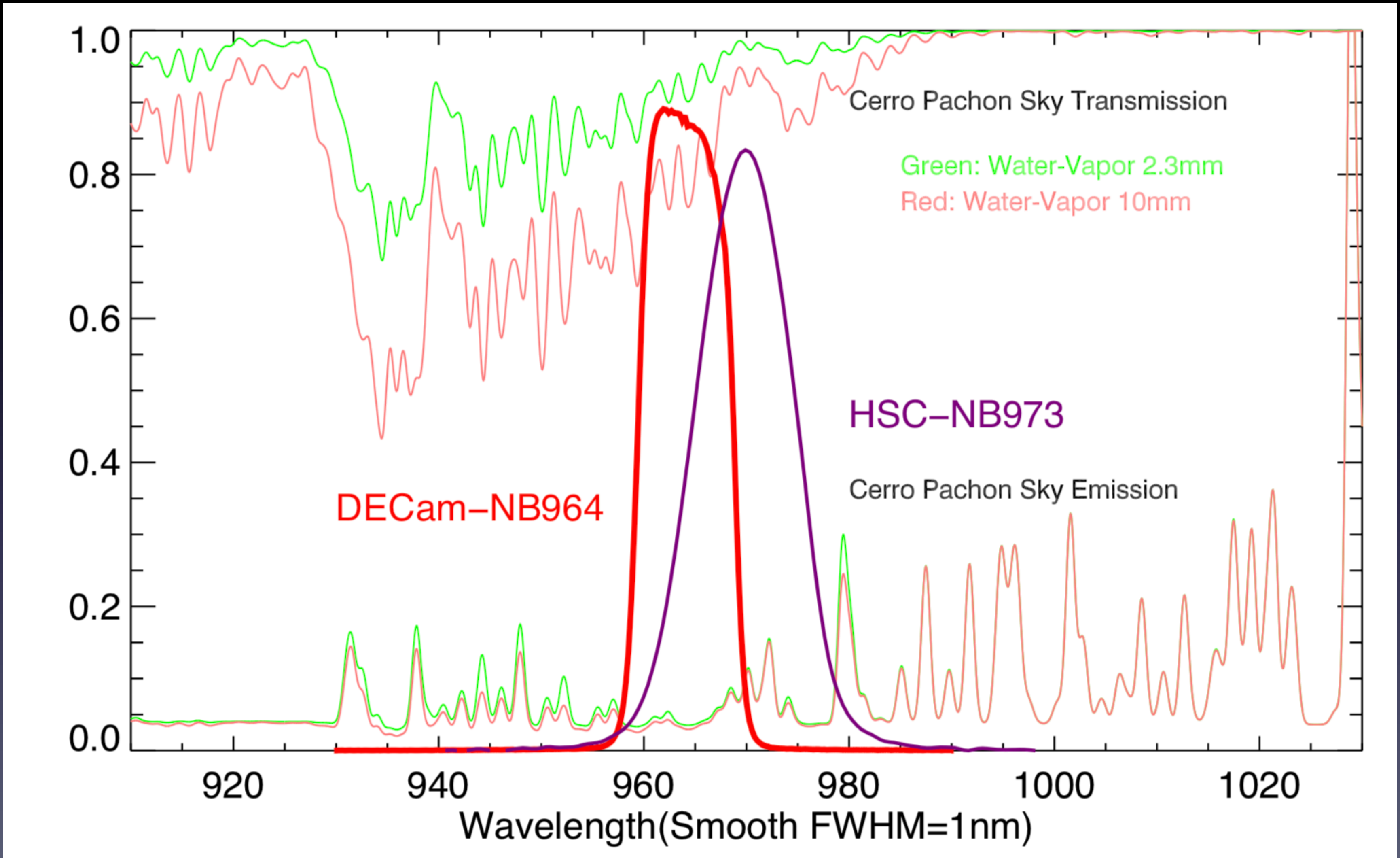
NB964 Narrowband Filter

Wc = 9642 Å & FWHM = 92 Å
→ z(Lyα) = 6.93+/-0.04

Why DECam?



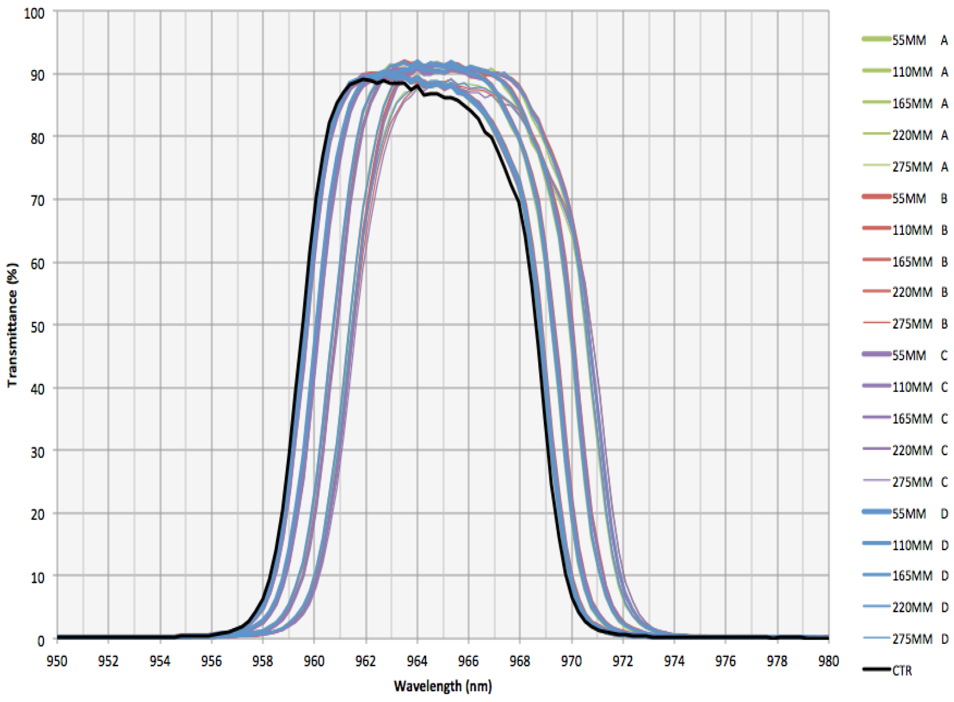
NB964 Filter Profile vs. Sky Lines



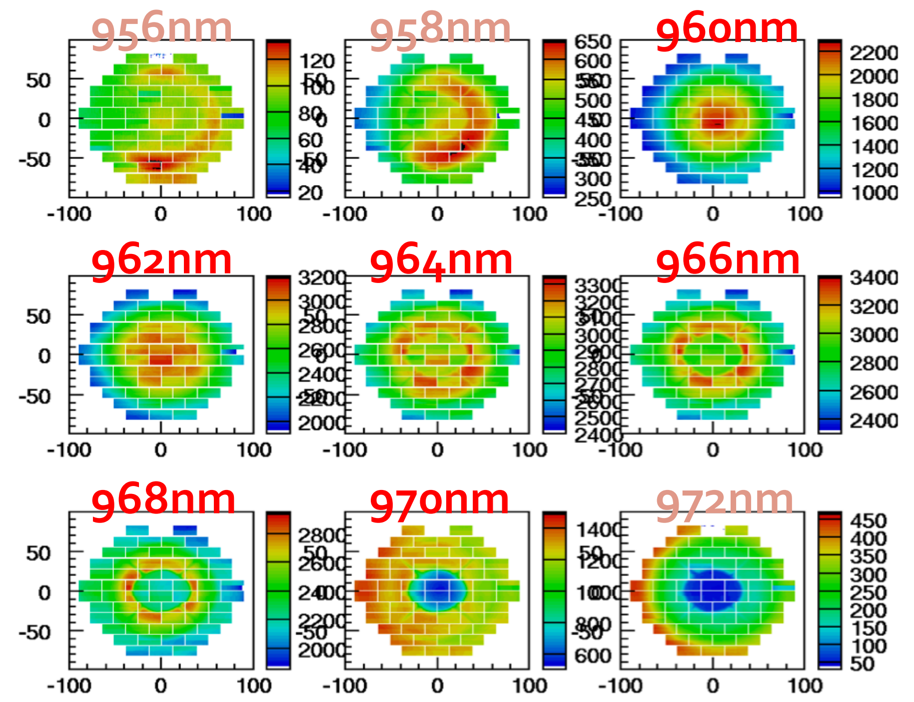
NB964 Filter Design: Zheng, Rhoads et al. in Prep. 2018

NB964 Filter Performance

1. NB filter lab-test
(Multi-curves for different Radii)



2. NB filter on-site test
(Spatial dist. as a function of λ)

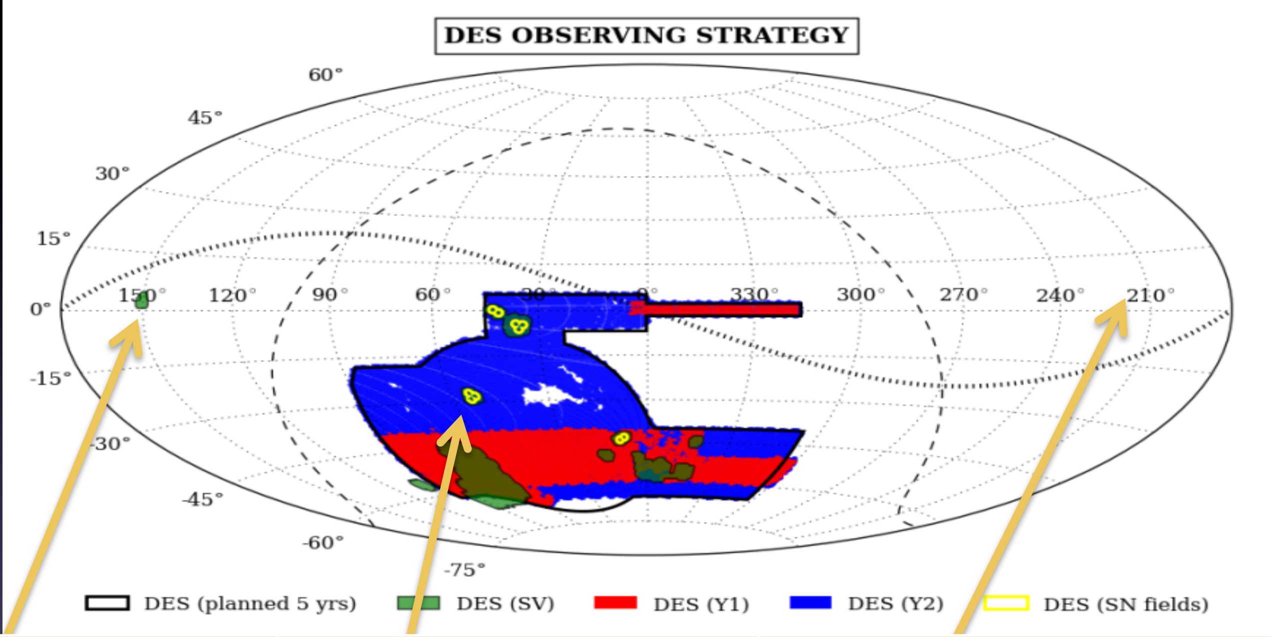


LAGER Runs

Summary (2015 Dec. – 2018 Mar.):

- **21 nights** awarded & Observed with DECam & NB964, but 5 with bad weather.

- **4 fields** with NB964 T_exp **~ 20-40 hrs each**.



Fields	COSMOS	CDF-S	GAMA15a,b
NB Exp. Time	**44 hrs**	**35 hrs**	**20 hrs x 2**
Date Obs.	Dec. 7 15; Feb. 4-9 16; Mar. 9-12 16; Dec. 24-27 17	Dec. 7 15; Mar. 9-12 16; Nov. 25-26 16	May 24-29 17 (w. bad weather); Mar. 5-10 18

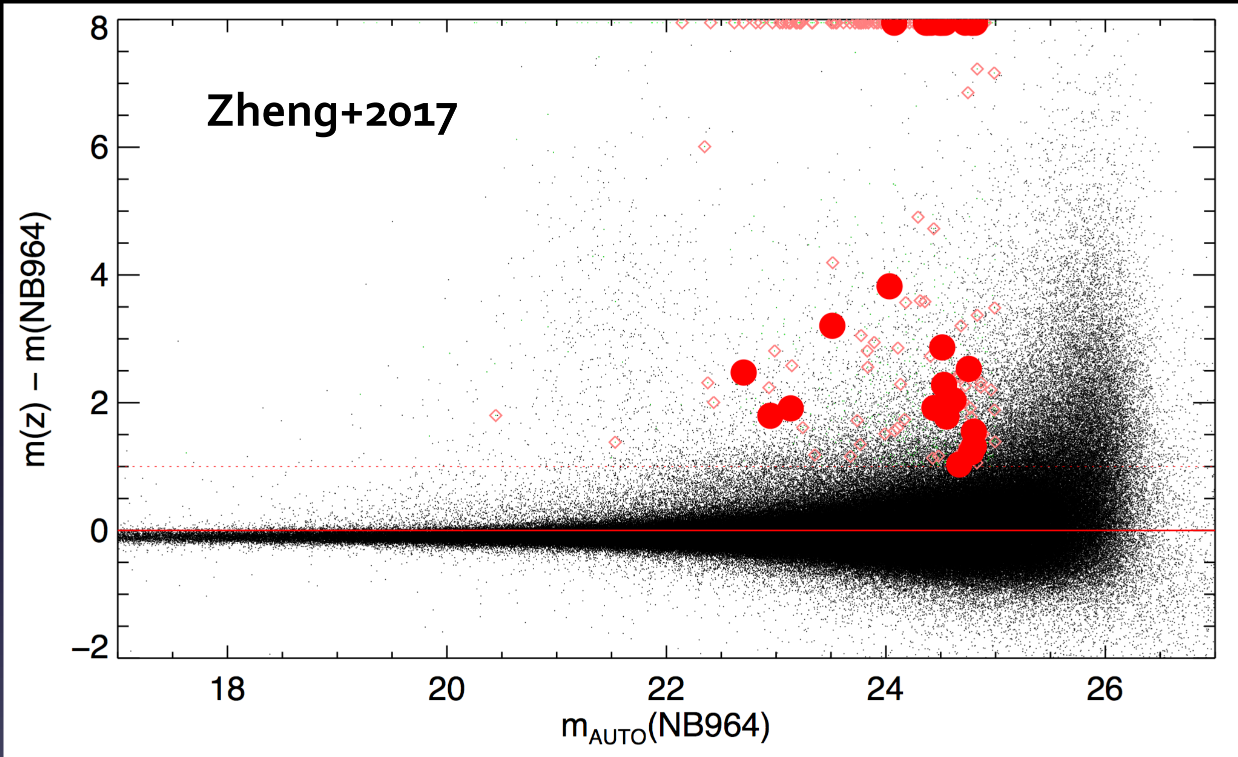
Candidate LAEs at z~7

Selection Criteria:

- Non-Detection in Blue Bands:
  DECam-ugri < 3 σ & Subaru-BVgri < 3 σ & Subaru-NB711, NB816,NB921 < 3 σ
- NB Significant:
  NB964(>5 σ) < 25
- Line Significant:

DECam-z – NB964 >= 1

& EW_r(Lyα) > 10 Å



We find 23 (22 new) candidate LAEs at z~7 in the COSMOS field.

Survey Volume = 1.26×10^6 cMpc³ (>4 V_other_z7)

First Results from LAGER:

LAGER-COSMOS in 34 hrs NB964

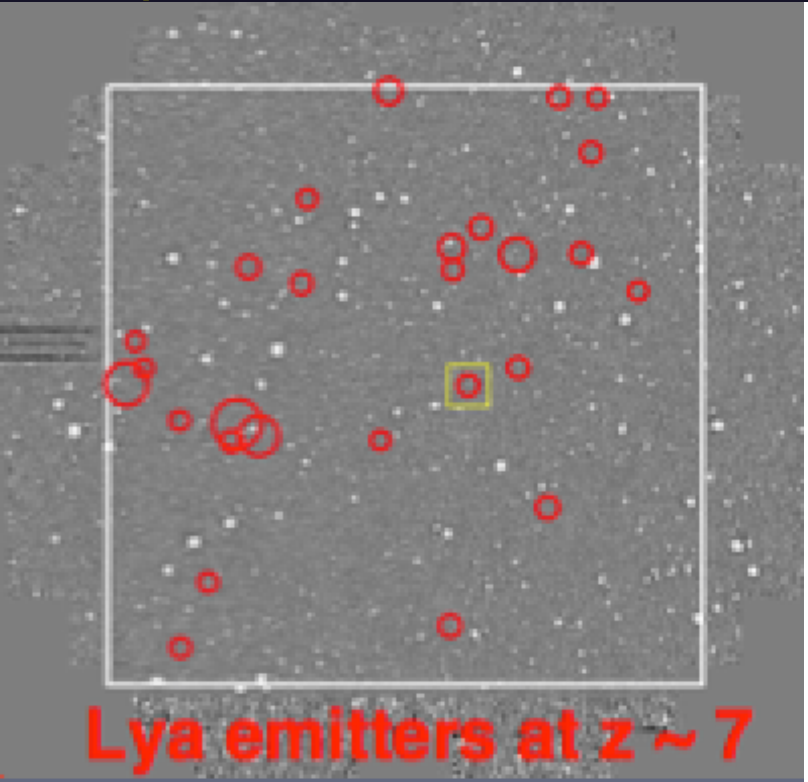
Inhomogeneous Distribution of 23 z~7 LAEs (largest to date) in LAGER-COSMOS:

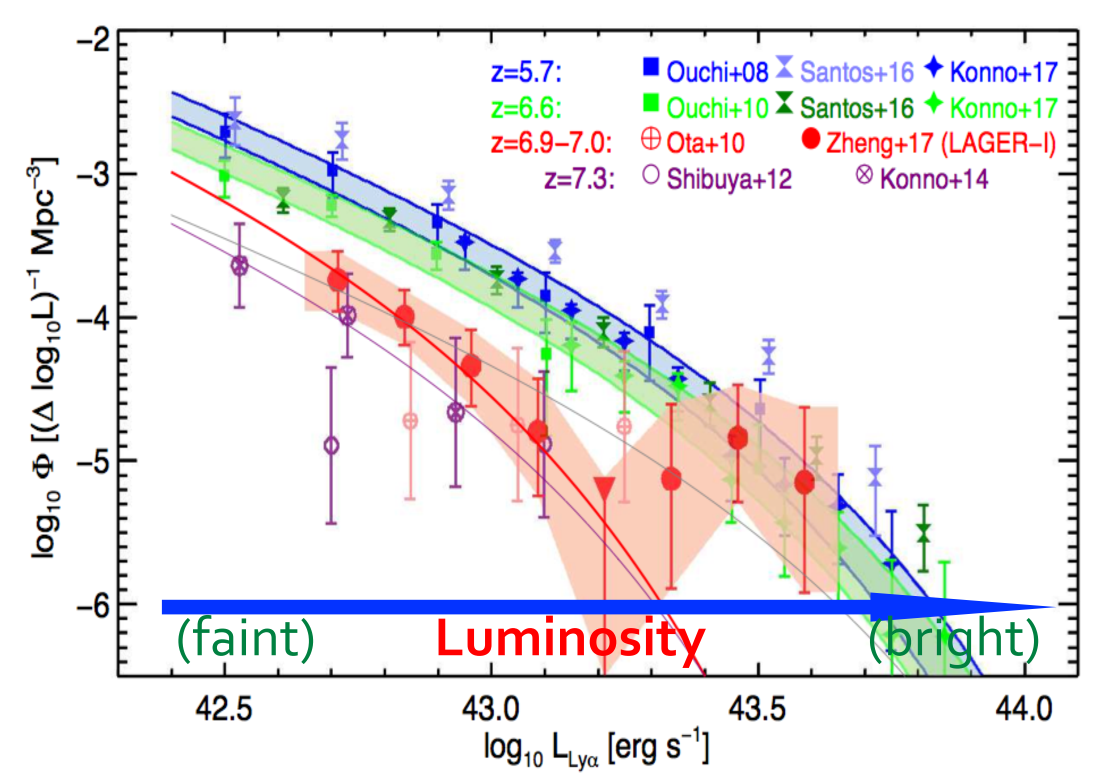
Patchy Reionization?

- **Little Evolution of Lyα LF at z ~ 3-6**:
(Ouchi+08, Faisst+2014, Zheng+2016, ..)

At z~7 (Zheng+2017) :

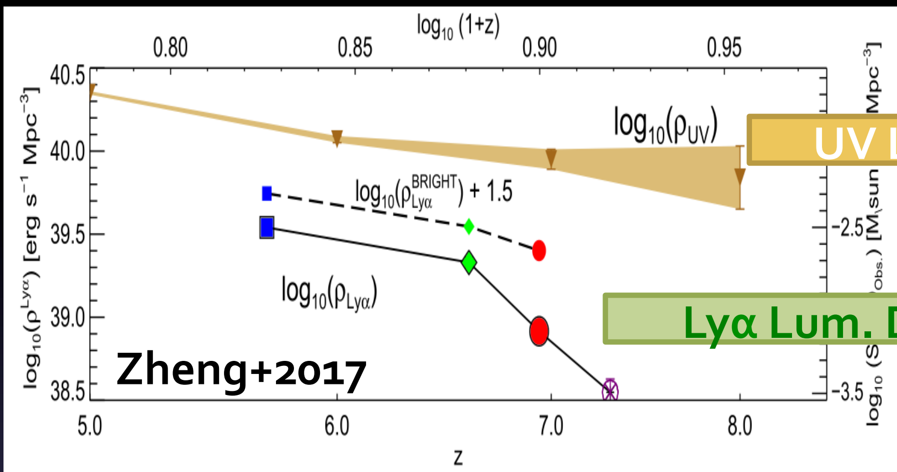
1. **Different Evolution at Bright & Faint Ends**
2. **Bright-End Excess**





Lyman-α Luminosity Function (LF) Test

Probing IGM Neutral Fraction at z~7 with LAGER

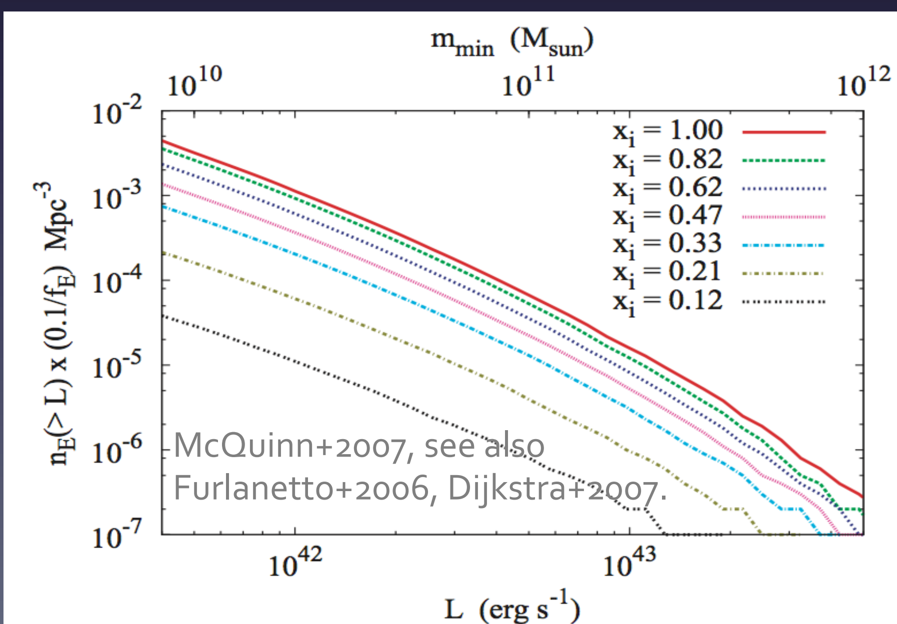


UV Lum. D.

UV LD Represents the Galaxy Evolution

Lyα Lum. Density

Lyα LD Represents the Joint Effect of
1) Galaxy Evolution &
2) Resonant Scattering by Neutral IGM



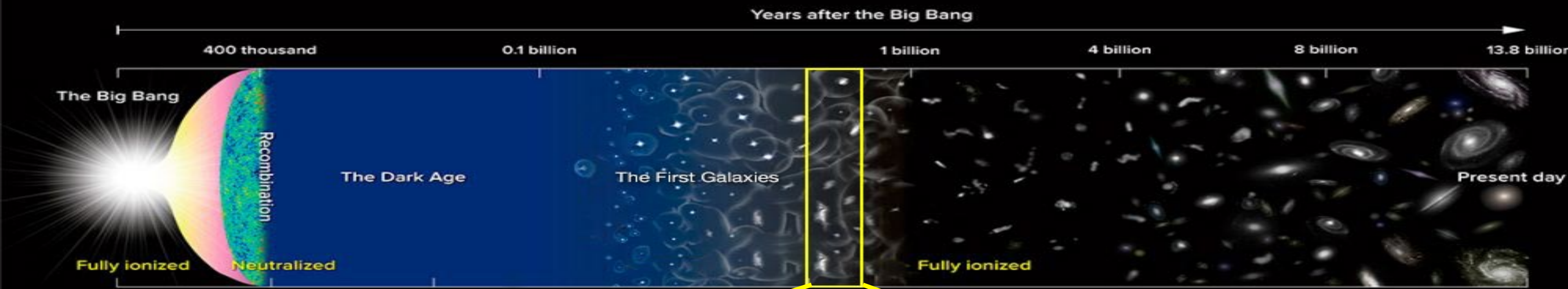
IGM Transmission Factor T':

(UV from Finkelstein+15)

$$T'_{z=6.9} = \frac{T^{\rm IGM}_{Ly\alpha,z=6.9}}{T^{\rm IGM}_{Ly\alpha,z=5.7}} = \frac{\rho^{Ly\alpha,tot}_{z=6.9}/\rho^{Ly\alpha,tot}_{z=5.7}}{\rho^{\rm UV}_{z=6.9}/\rho^{\rm UV}_{z=5.7}}.$$

T' = 0.37 ➔

x_HI ~ 0.4-0.6 at z~7



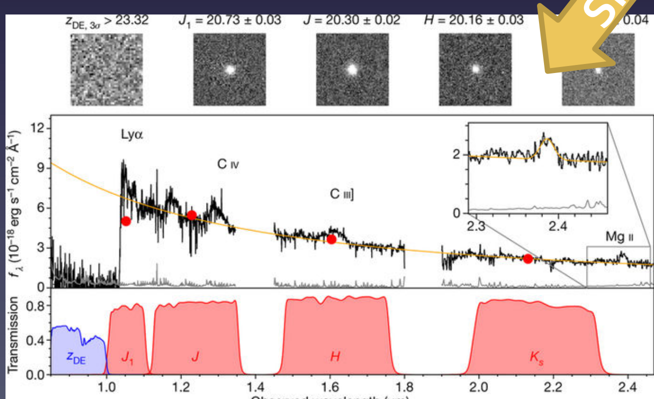
1. EoR Contributors
2. EoR History
3. EoR Topology

Epoch of Reionization

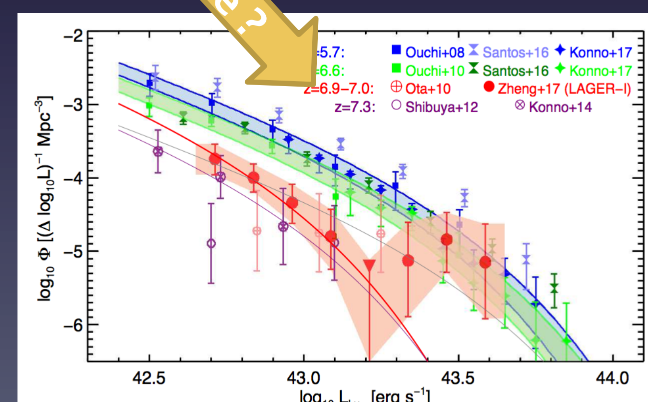
SMBH

Bubble ?

Banados+2017,
J1342+0928, z=7.54



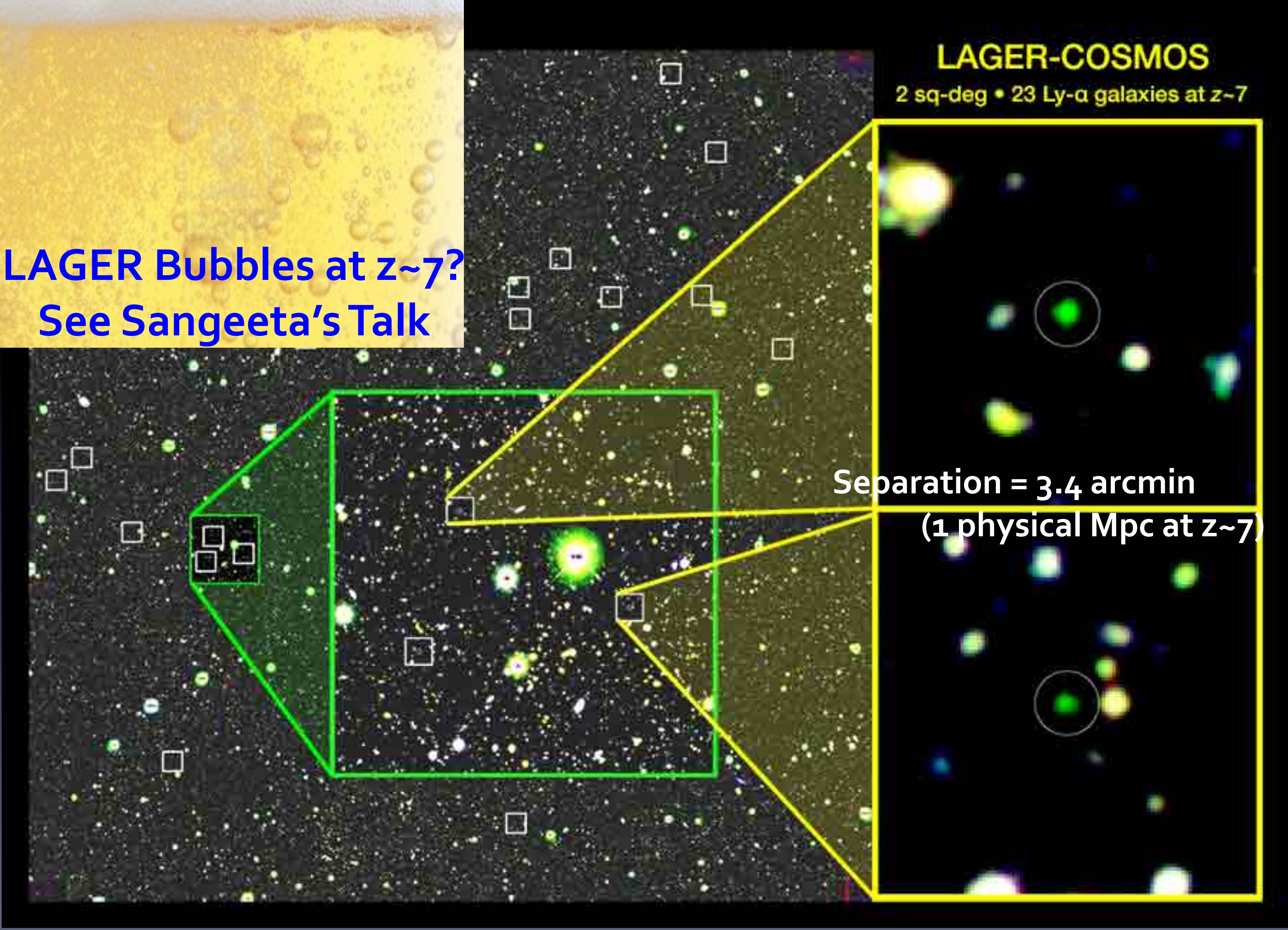
Zheng+2017, z=6.94
Bright-end Excess
LAGER-COSMOS



Zhenya Zheng @ SHAO

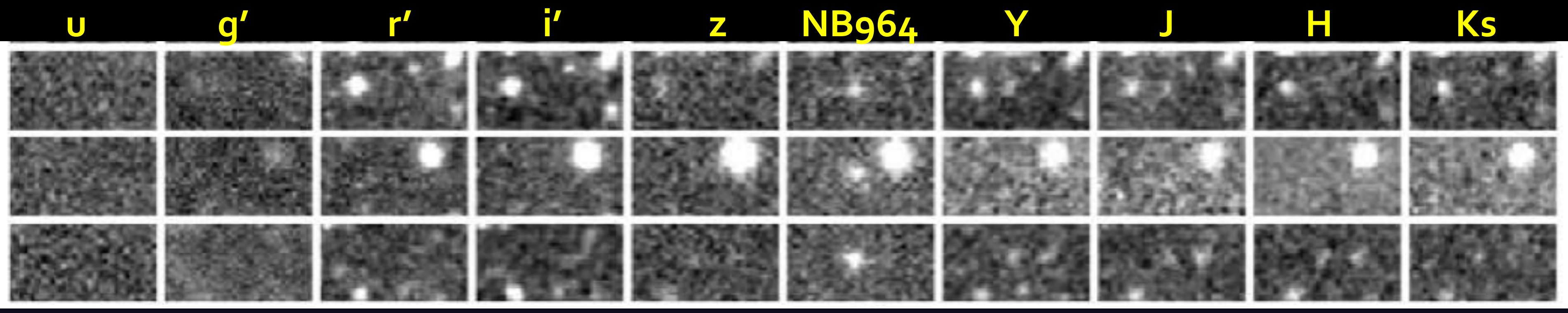
Image credit: Top: NAOJ;
Middle: Robin Dienel & Carnegie Obs.

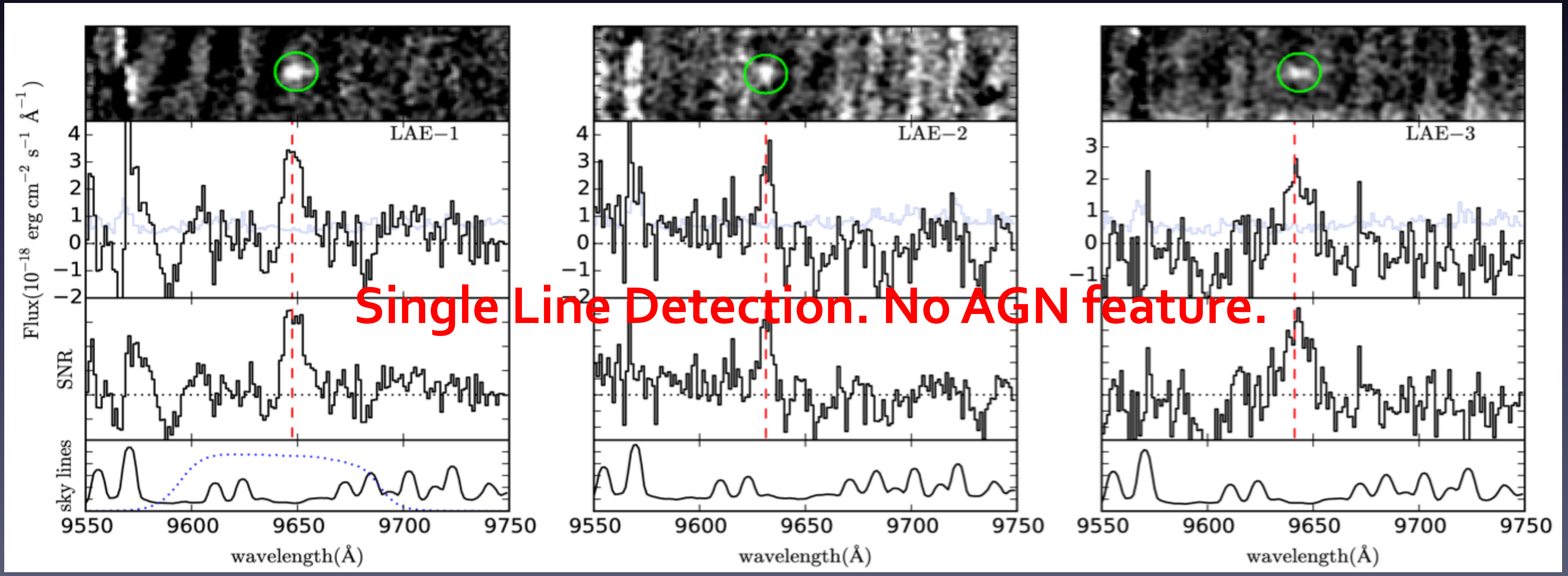
LAGER Bubbles at z~7?
See Sangeeta's Talk



Separation = 3.4 arcmin
(1 physical Mpc at z~7)

Spec. Confirmation of the 3 Brightest LAEs



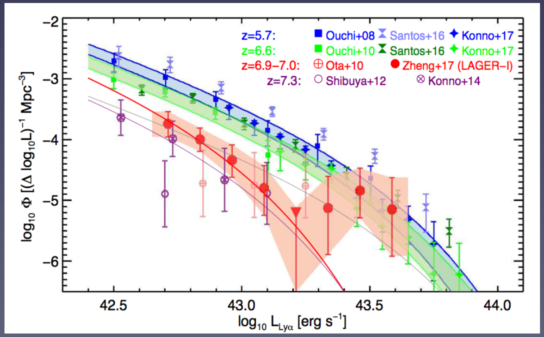


6 hrs Magellan/IMACS obs. on Feb 6-8, 2017 (**FWHM~200-300 km/s**)

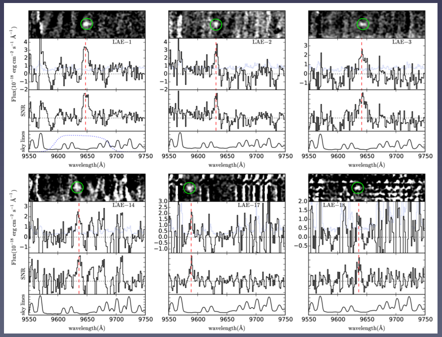
Hu et al., 2017, ApJL, 845, L16 (arXiv:1706.03586).

Summary of First LAGER Results

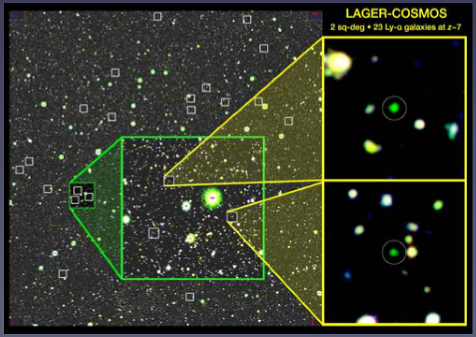
- LAGER is the largest narrowband survey for LAEs at z~7 so far.
- The new Lyα LF from LAGER LAEs shows different evolution at the faint-end and at the bright-end → $x\_HI \sim 0.4$–0.6 at $z \sim 7$.
- LAGER helps us to find and confirm 3 most luminous LAEs at z~7 , of which 2 are likely to reside in an ionizing bubble.



Zheng, Wang, Rhoads et al. 2017



Hu, Wang, Zheng et al. 2017



NOAO Press Release 1703

LAGER Status Updates
(2018-)

Data:

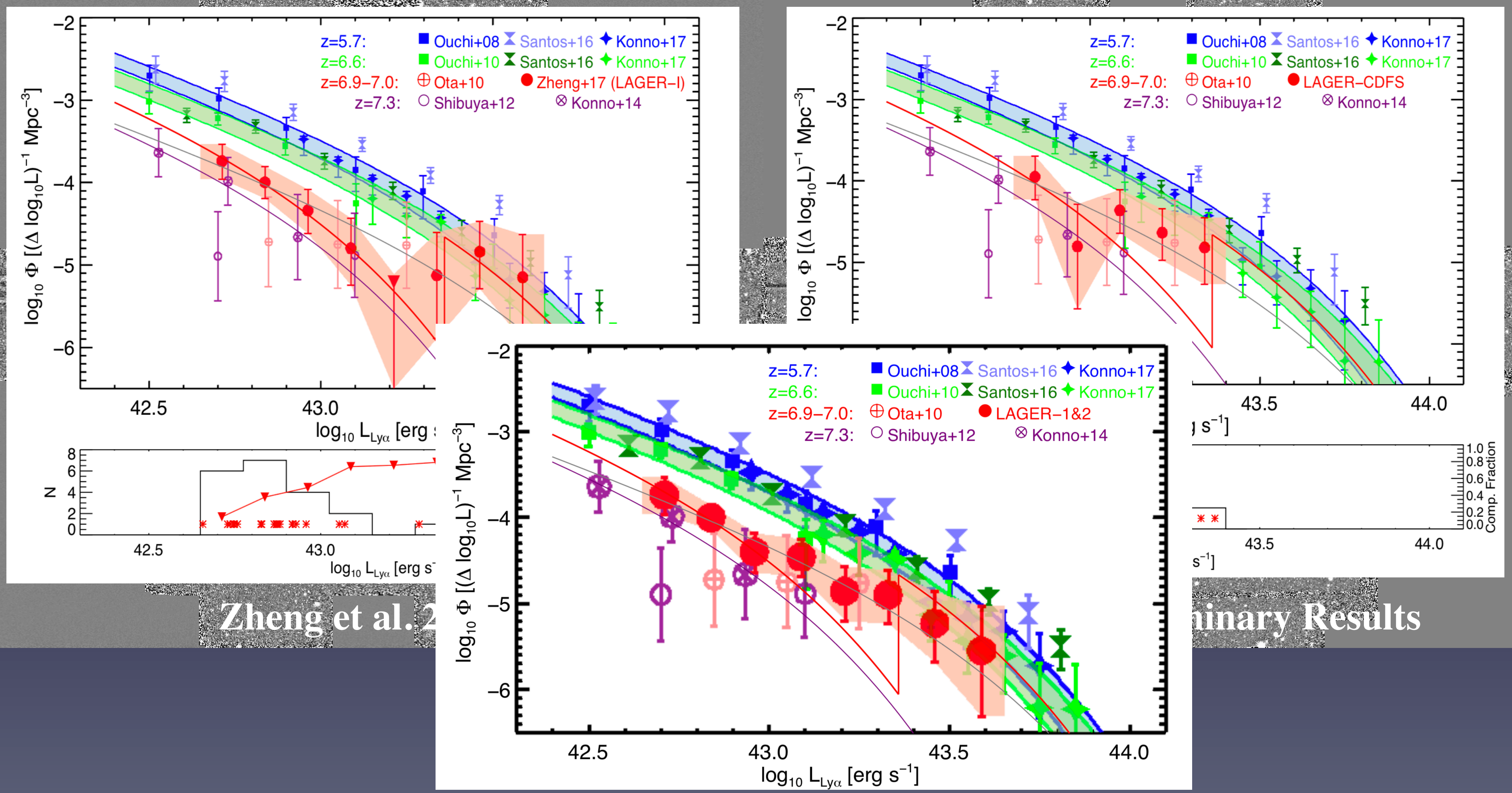
1. More NB964 imaging data;
2. Improved image stacking methods

   (Sigma-clipping weighted coadding with Swarp; LSST pipeline coadding);
3. Better & deeper broadband images (HSC & DES)

Science:

1. Opt. & IR spectroscopic followup (Magellan, VLT, Keck, Gemini, HET)
2. Lya LFs in other fields
3. Clustering Analysis
4. 21cm & Lya CCF
5. Low-z

COSMOS vs. CDFS



Improve the Lyα LF at z~7 to give better constraints on x_{HI}

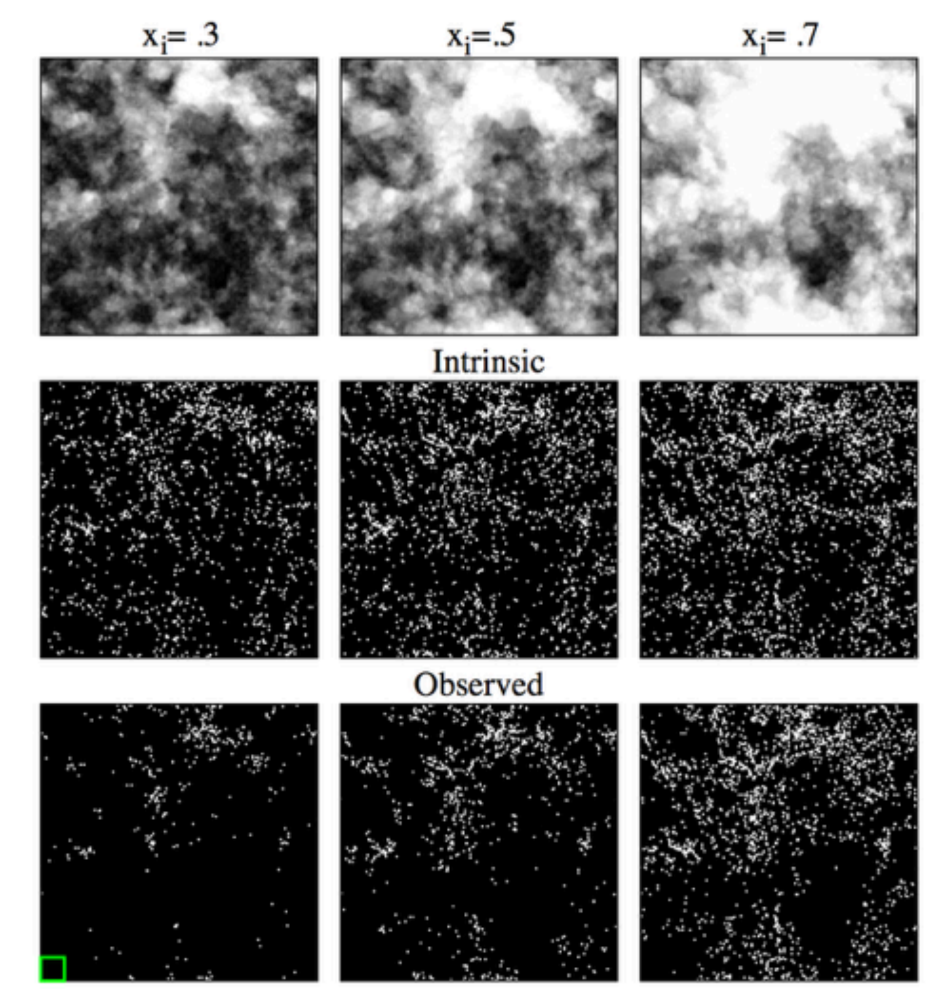
Clustering Test of Lyα Galaxies

Average ionization fraction

Distribution of ionized gas

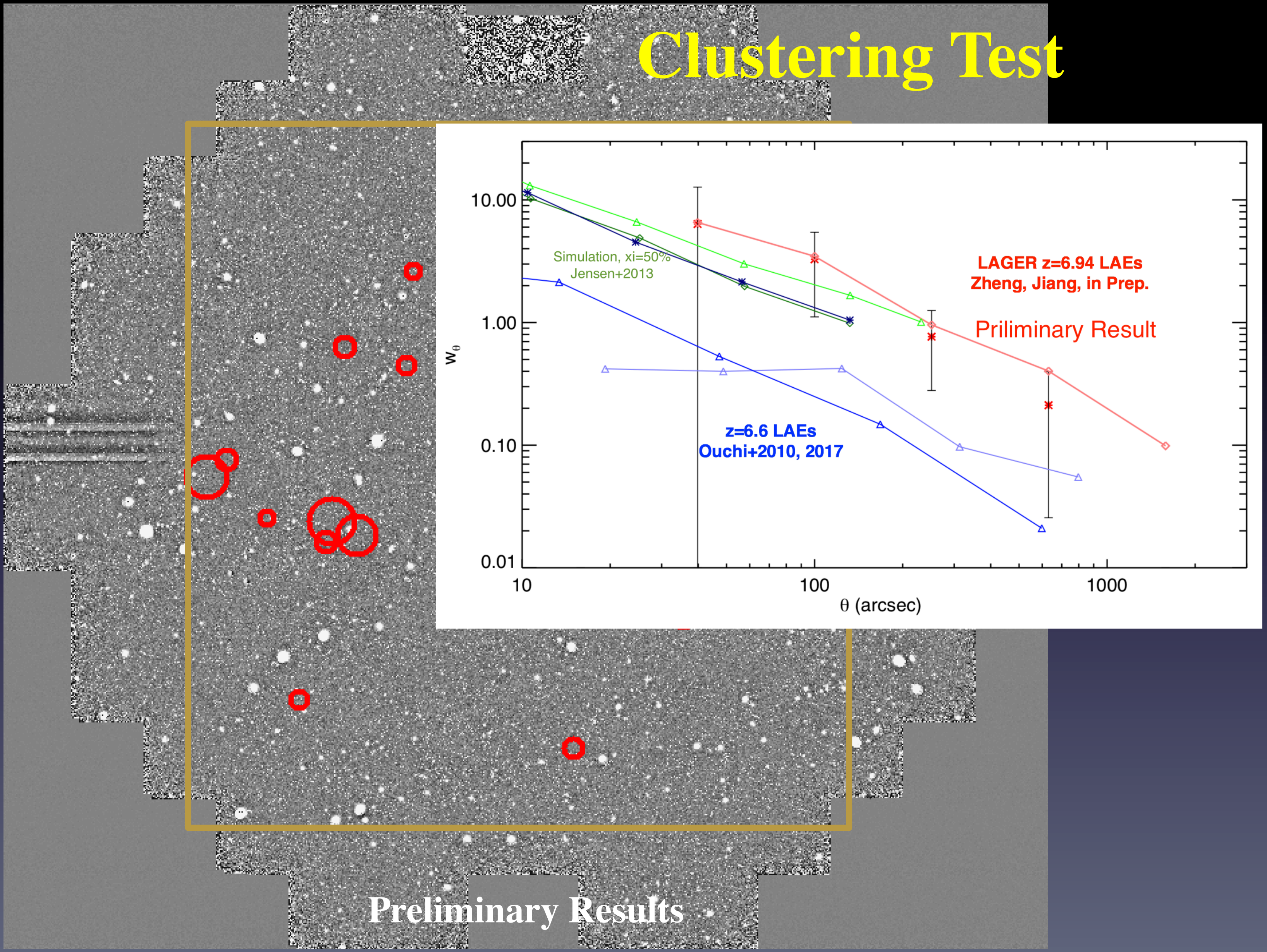
Intrinsic distribution of galaxies

Apparent distribution of galaxies



McQuinn 2007

Improved COSMOS Sample



Lyα & 21 cm Cross Correlation Test

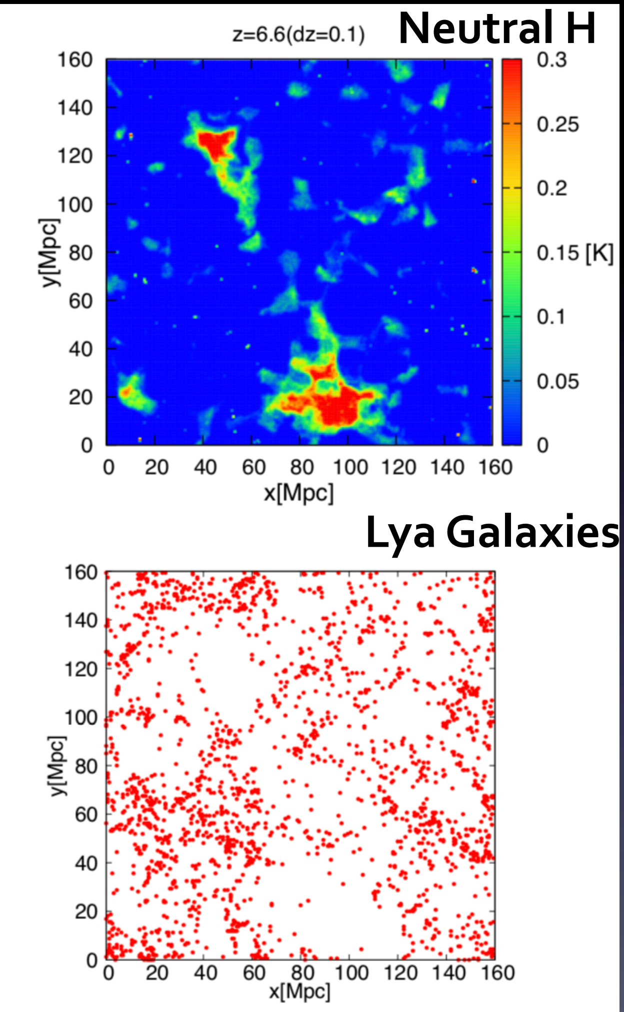
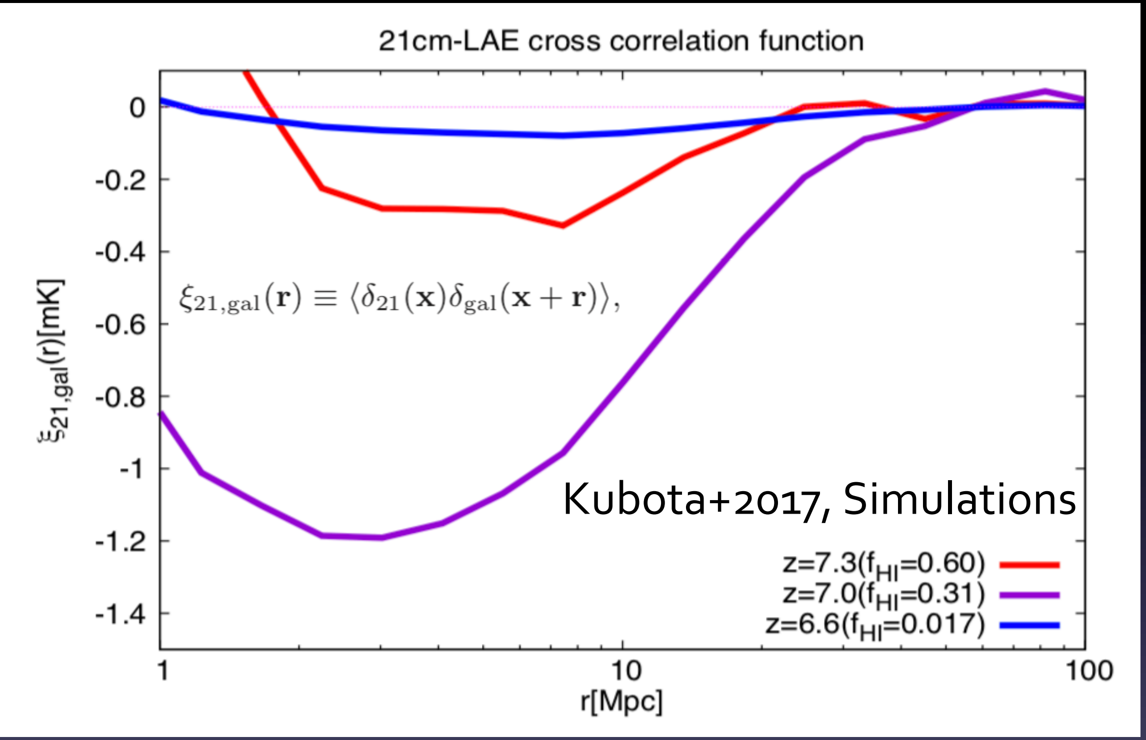


Figure 2. Top: the 21cm brightness temperature in mid model at redshift $z = 6.6$. In fully ionized region $\delta T_b \sim 0$mK. **Bottom**: the associated LAE distribution. The panels are maps integrated within $\Delta z = 0.1 \sim 40$Mpc.



$$\delta T_b(z) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{m}}) \left(\frac{1+z}{10}\frac{0.15}{\Omega_{\mathrm{m}} h^2}\right)^{\frac{1}{2}} \left(\frac{\Omega_{\mathrm{b}} h^2}{0.023}\right) \ [\mathrm{mK}],$$

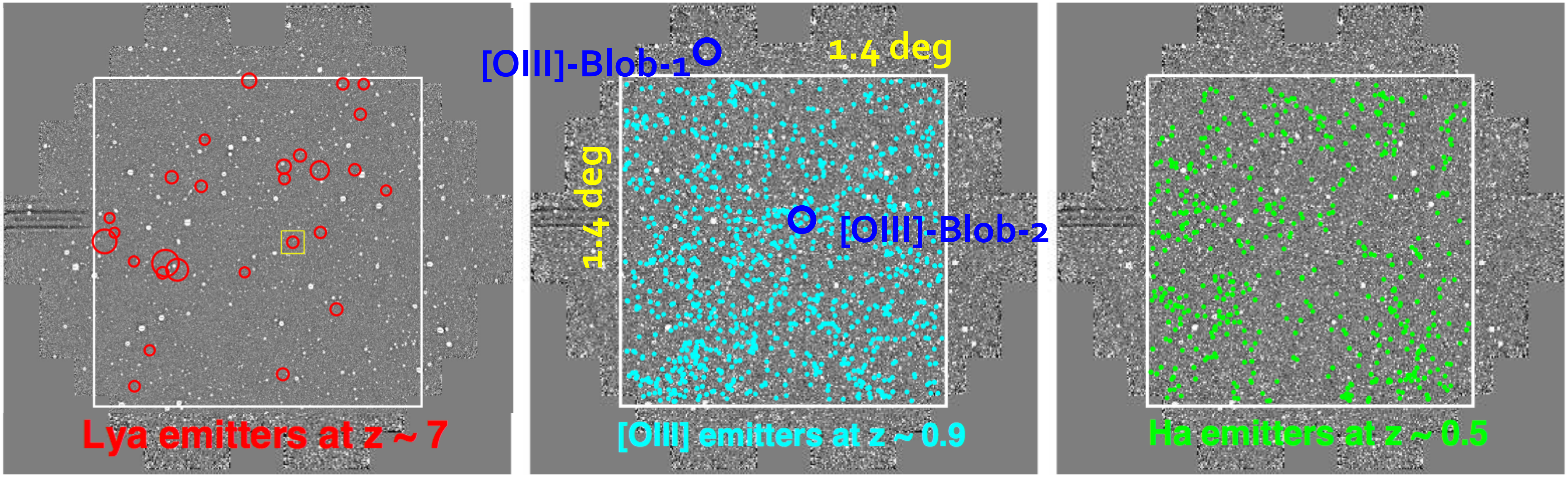
$$\delta_{21}(\mathbf{x}, z) \equiv \frac{\delta T_b(\mathbf{x}, z) - \overline{\delta T_b}(z)}{\overline{\delta T_b}(z)}, \qquad \delta_{\mathrm{gal}}(\mathbf{x}, z) \equiv \frac{n_{\mathrm{gal}}(\mathbf{x}, z) - \bar{n}_{\mathrm{gal}}(z)}{\bar{n}_{\mathrm{gal}}(z)},$$

Available & Future 21cm arrays:

- PAPER (South Africa & WV)
- MWA (Australia) [we are preparing MWA proposal now]
- **SKA (Australia & South Africa)**

Low-z ELGs & Blobs from LAGER Survey

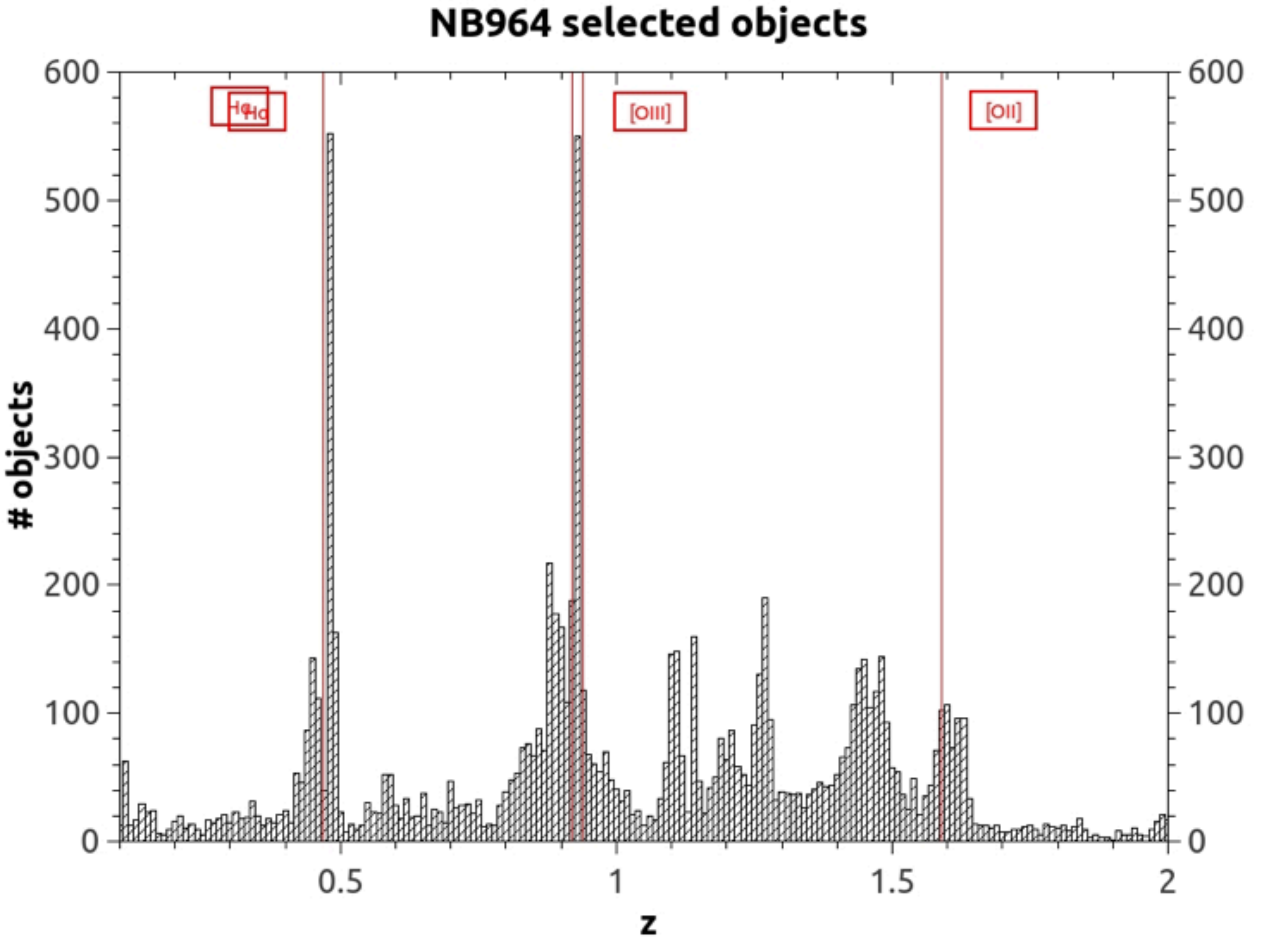
Giant Nebulae; Luminosity Functions;
Star-Formation History; Galaxy-BH Coevolution; …



There are ~1300 OIII emitters at z~0.9, and ~700 Ha emitters at z~0.5 selected with NB964 in the COSMOS field.

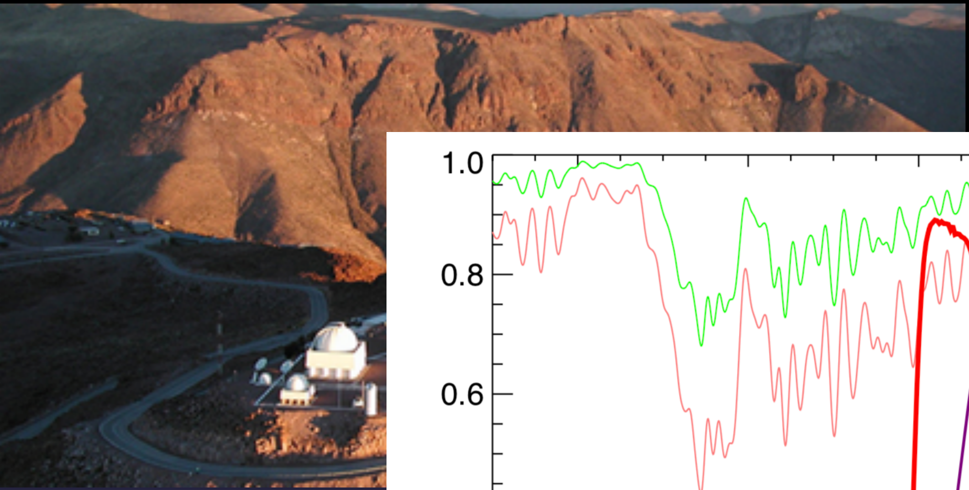
Most of the [OIII] emitters are similar to the Green Pea Galaxies (e.g., Yang+2016).

We also find two [OIII] Blobs, which are similar to the Green Bean Galaxies (e.g., Schirmer+2013).

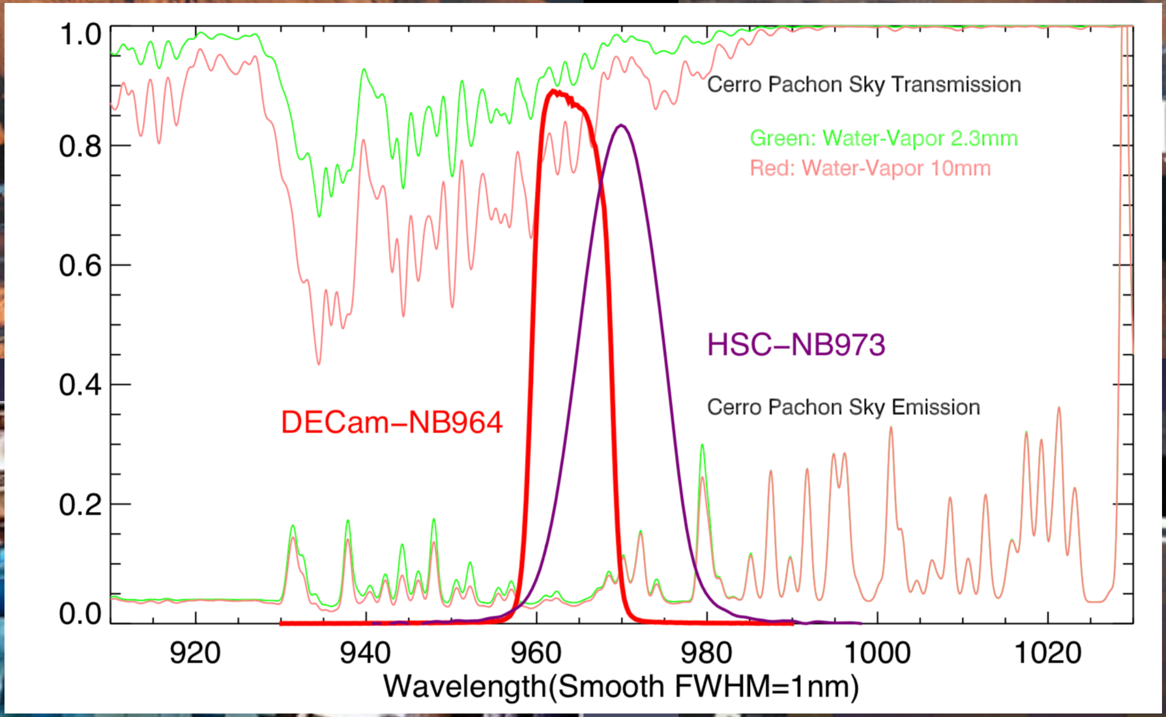

NB964 selected objects
Hα
Hα
[OIII]
[OII]
objects
z
0
100
200
300
400
500
600
0.5
1
1.5
2

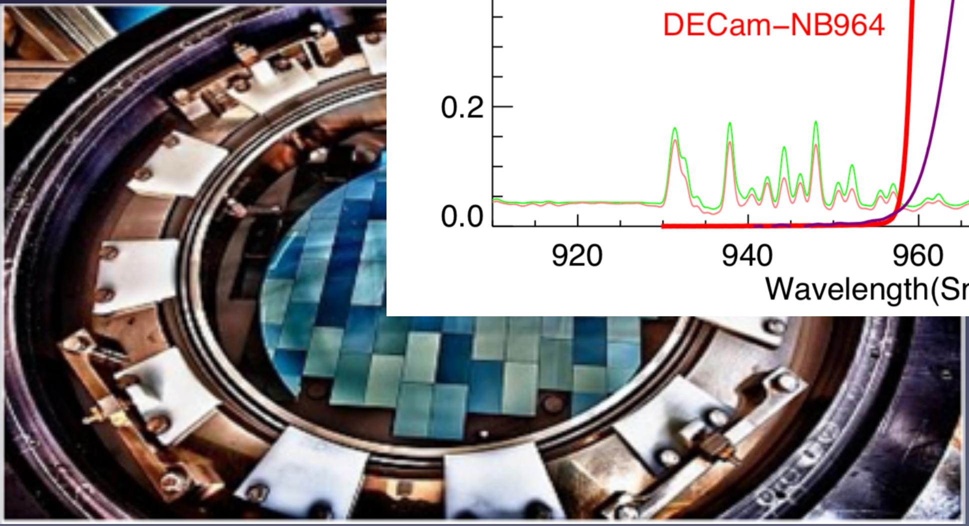
Comparison Between
DECam NB964 & HSC NB973

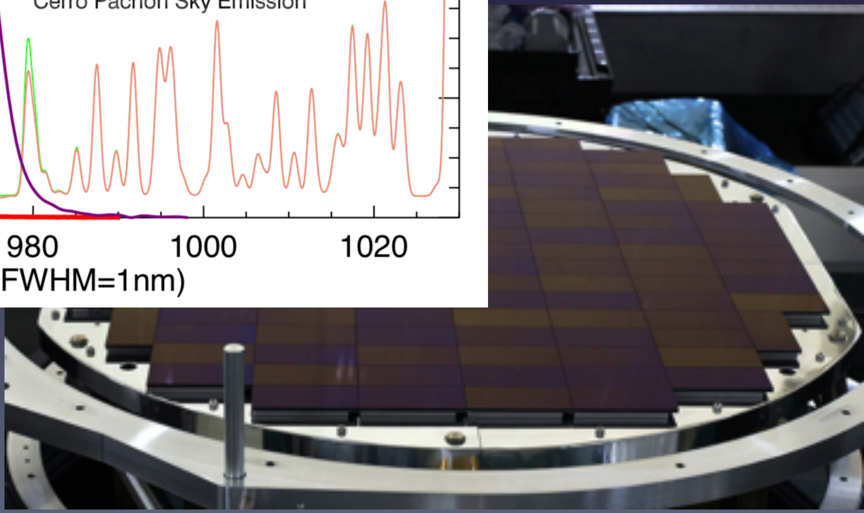
Chile **Blanco (4m)**



Hawaii **Subaru (8m)**







DECam (3 sq-deg, f-ratio: 2.9)

HSC (1.7 sq-deg, f-ratio: 2.2)

Conclusion

- LAGER is the largest narrowband survey for LAEs at z~7 so far.
- The Lyα LF from LAGER LAEs shows different evolution at the faint-end and at the bright-end → x_HI ∼ 0.4–0.6 at z ∼ 7.
- LAGER has helped us to find and confirm 3 most luminous LAEs at z~7 , of which 2 are likely to reside in an ionizing bubble.
- More data have been collected through LAGER, based on which a series of work are on-going: new LFs, clustering analysis, Lya-21 CCF, low-z ELGs ...
- DECam/NB964 is better than HSC/NB973 at catching luminous z~7 LAEs


Thanks!
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