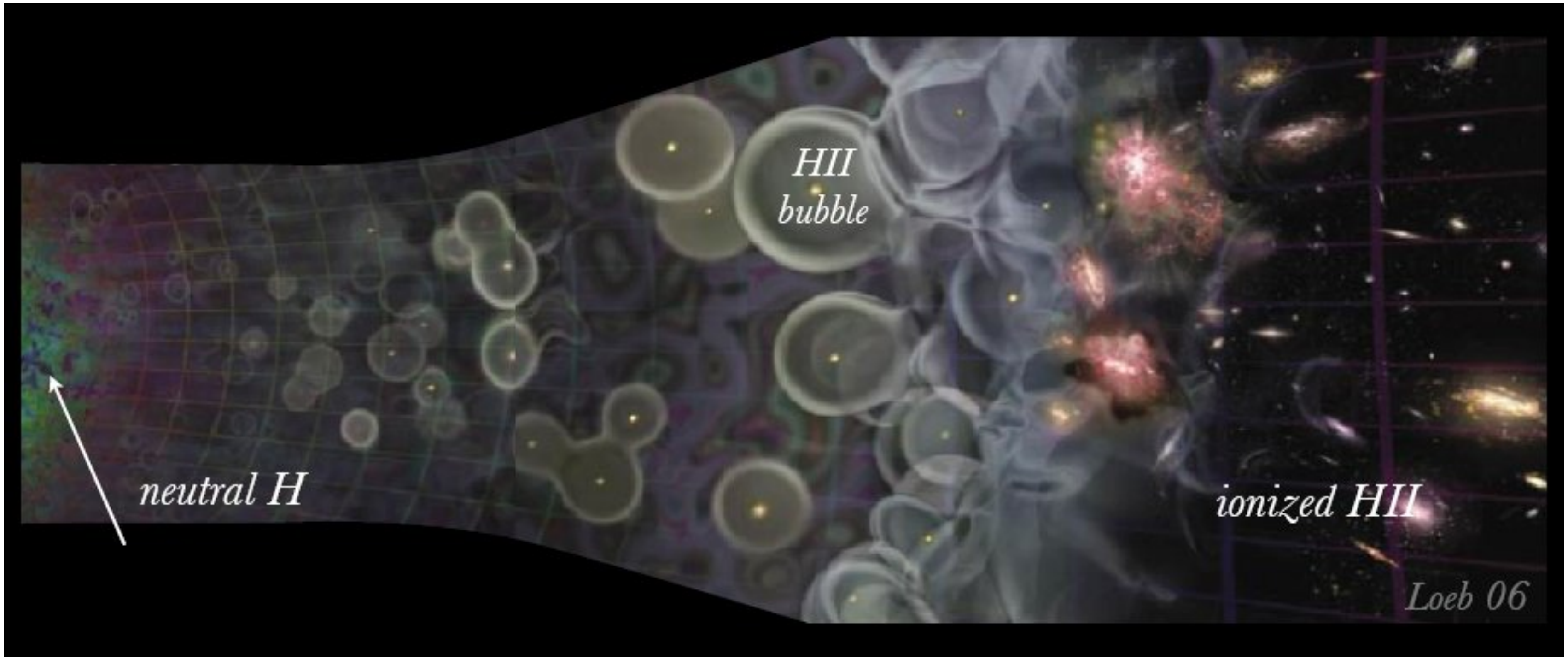
宇宙再電離の観測研究
---現状と課題---



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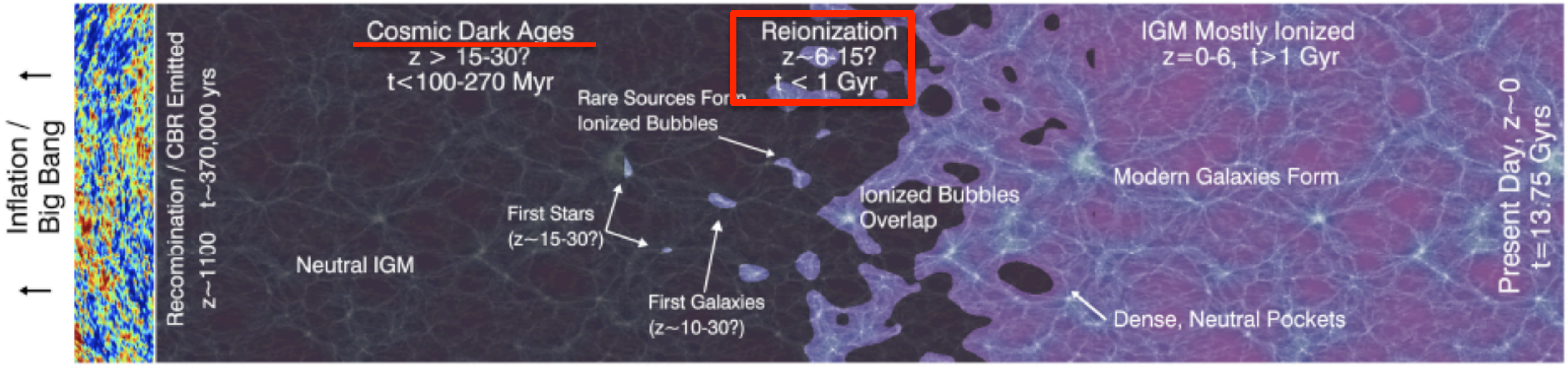
Outline

- Introduction (reionizaiton tightly connected with galaxy formation)

- Three open questions (unknowns)
  1. Cosmic reionization history.
  2. Reionization sources
  3. Physical process

Cosmic Reionization

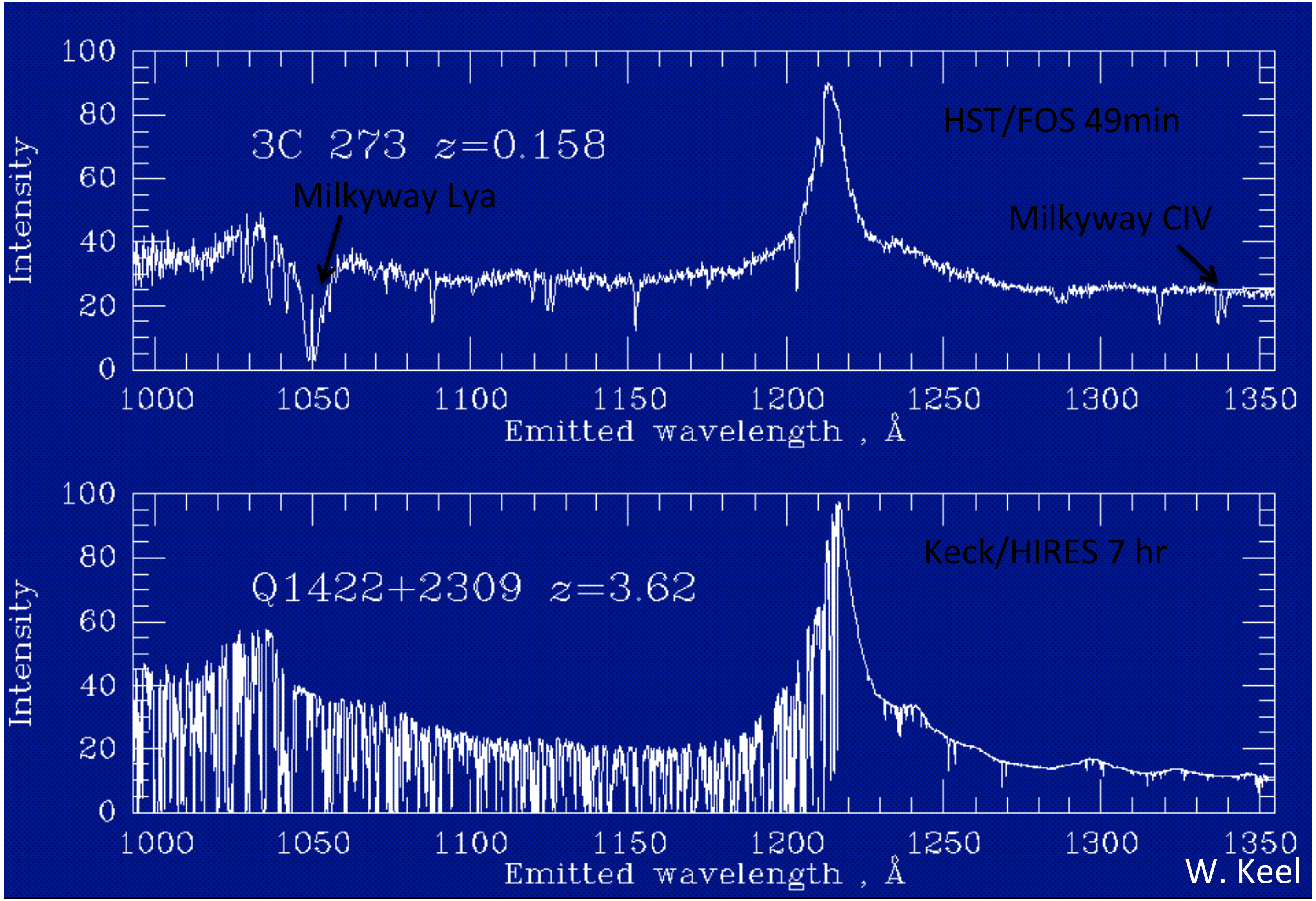


Robertson et al. (2010)

Cosmic Reionization:
Universe filled with neutral hydrogen
→ Ionized hydrogen at z>6

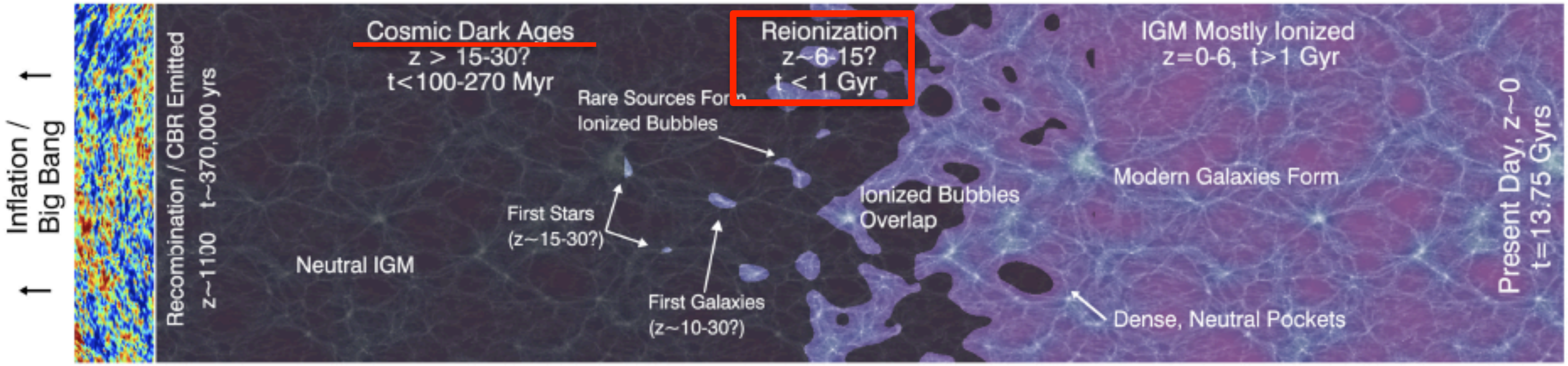
H+γ→p+e-   (Hydrogen ionization)

QSO Spectra



- Almost no neutral hydrogen (Lya) absorption at z~0→ Local IGM is ionized.

Cosmic Reionization



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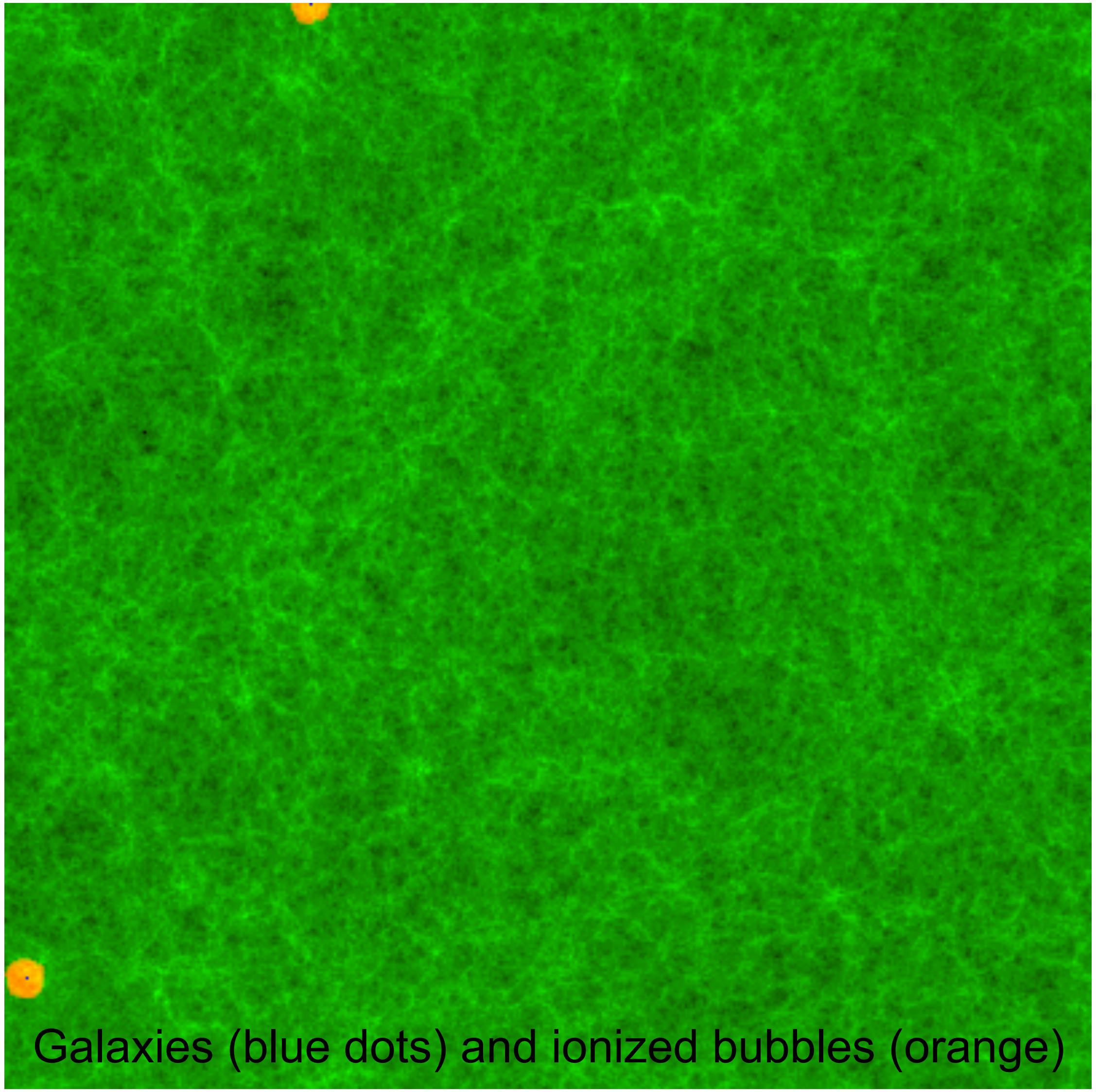
Cosmic reionization

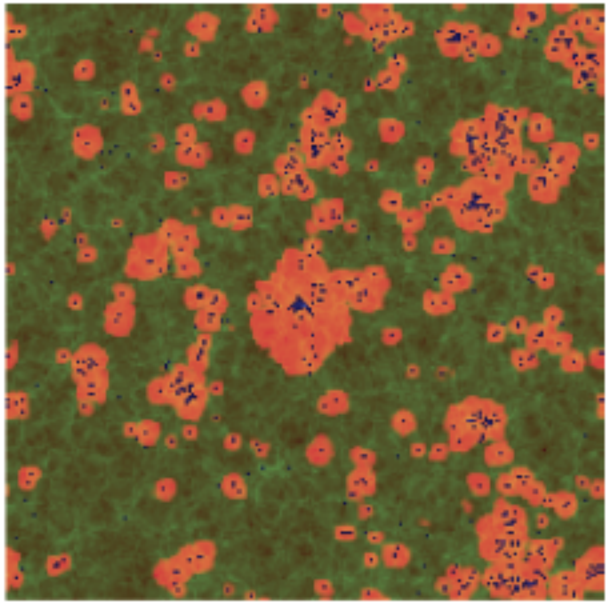


RT simulations (Iliev et al. 2006)

- Basic picture: Ionizing photons from star-forming galaxies make ionized bubbles that fill the universe-> reionization.

Tight Relation between Cosmic Reionization & Galaxy Formation

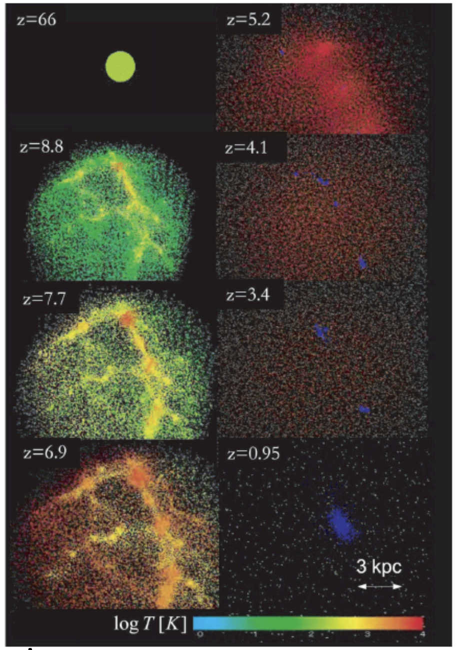
Reionization



Ionizing photons
to ionize the universe

Intense UV background
to suppress dwarf-galaxy formation

Galaxy/star formation



Ionized IGM(orange), neutral IGM(green), and Galaxies (blue)

M(halo)=6e7 Mo
z_c=1.7

Susa & Umemura+04

Open Questions

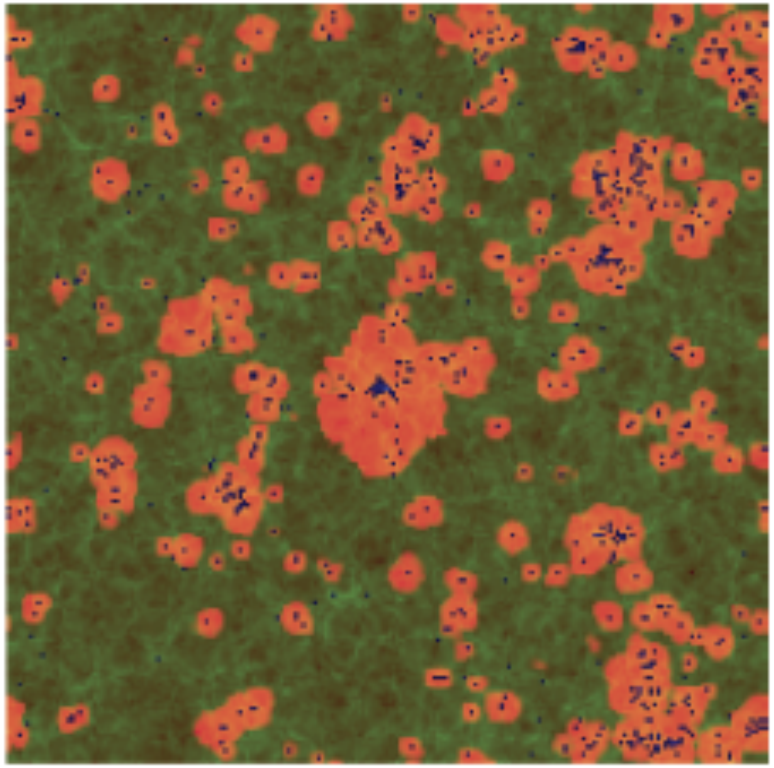
1. Cosmic reionization history. Optical vs. CMB observations.

2. What are reionization sources? Ionizing photon budget balanced?

3. Physical process (inside-out, outside-in, filament-last?)

COSMIC REIONIZATION HISTORY

How Do You Probe Cosmic Reionization?



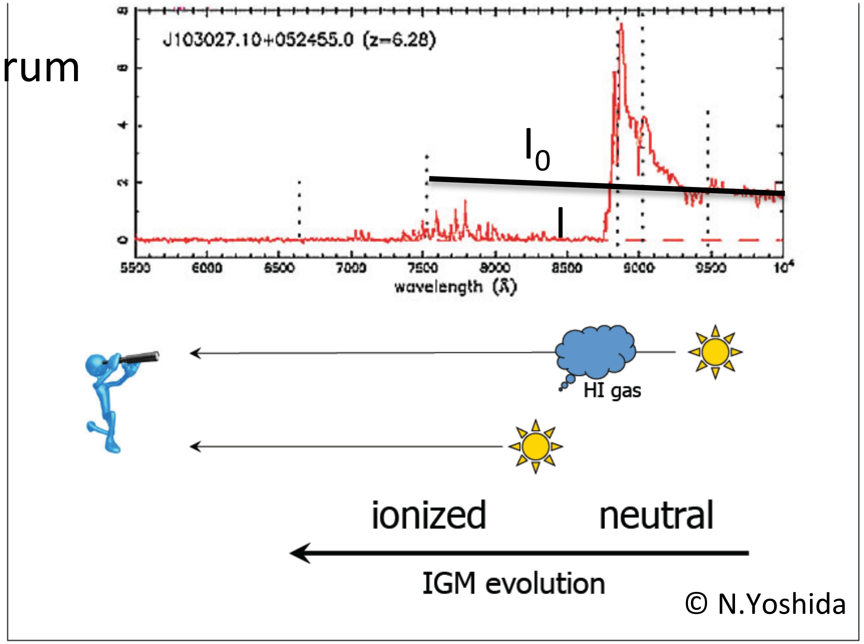
Galaxy (blue)、Neutral H（green）、H^+ (orange)

- Evolution of ionization states(neutral/ionized) → Cosmic reionization history
  - Neutral hydrogen fraction: $x_{HI} = (n_{HI}/n_H)$. Estimating $x_{HI}(z)$

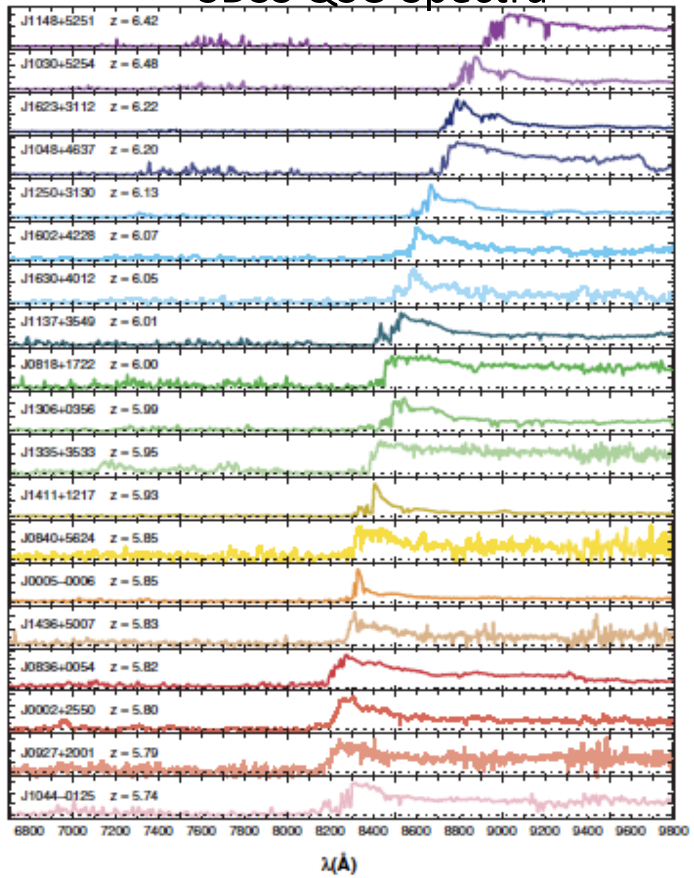
  - Emission from ionized gas (e.g Lya lines)
    - The density of ionized gas is extremely small, 5×10^{-6} times smaller than that of Galactic gas. →Extremely faint/area. Very difficult to detect.
  - Emission from neutral gas (21cm line)
    - Again, too faint. No detections (PAPER, GMRT)

Probing Reionization History (1)
Gunn Peterson τ

QSO Spectrum



SDSS QSO Spectra



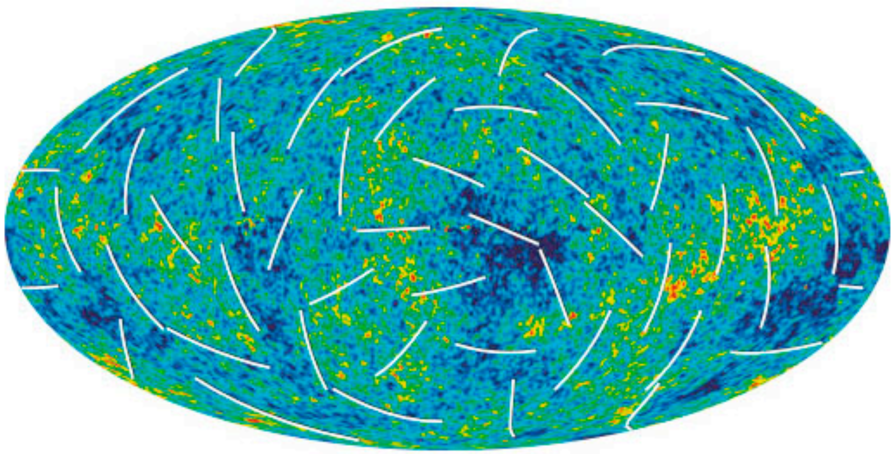
$$\tau_{GP}(z) = 4.9\times10^5\left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2}\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{1+z}{7}\right)^{3/2}\left(\frac{n_{HI}}{n_H}\right)$$

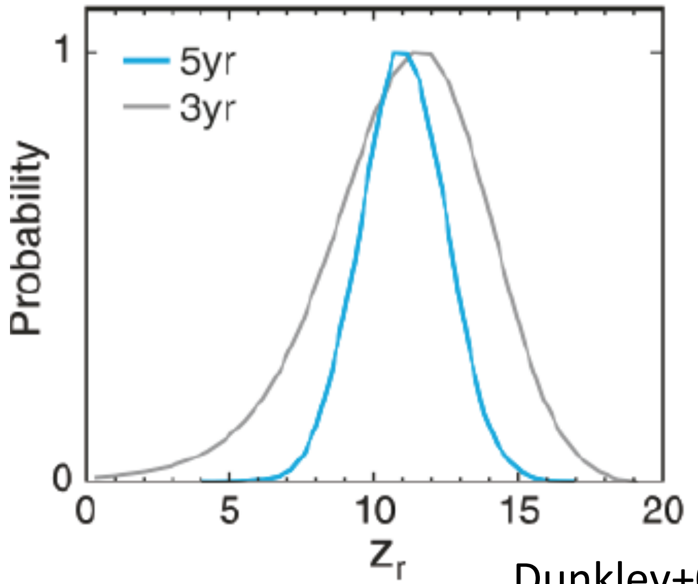
Gunn-Peterson optical depth ($\rightarrow I/I_0=e^{-\tau_{GP}}$): GP test

For (n_{HI}/n_H)>~0.01% at z~6, large τ_{GP} ! (due to large $\sigma_{Ly\alpha}$)

Problem: no x_{HI} estimates beyond z~6 with Gunn-Peterson optical depth

Probing Reionization History (2) CMB Polarization





Dunkley+09

- Cosmic microwave background (400 photons/cm^3)
- CMB photons interact with free electrons in the ionized (+partly ionized) universe via Thomson scattering → Polarization (incl. temp. fluctuation suppression)
- Optical depth of Thomson scattering

$$\tau(z) = \sigma_T \int_0^z n_e(z') \frac{dl(z')}{dz'} dz',$$

→ Instantenous reionization at z_r

$$\tau(z_{ri}) \approx 0.07 \left(\frac{h}{0.7}\right) \left(\frac{\Omega_{b,0}}{0.04}\right) \left(\frac{\Omega_{m,0}}{0.3}\right)^{-1/2} \left(\frac{1+z_{ri}}{10}\right)^{3/2}.$$

- τ = 0.089±0.032 (Plank2013), 0.084 ± 0.013 (WMAP9; Hinshaw+12)
- →z_r~10-11 (instantaneous reionization; cf. Δz=4.4; Zhan et al. 2011)
- *Problem: No time resolution*

Probing Reionization History (3)
Lyα Damping Wing Absorption

Absorption cross section (→voigt profile)

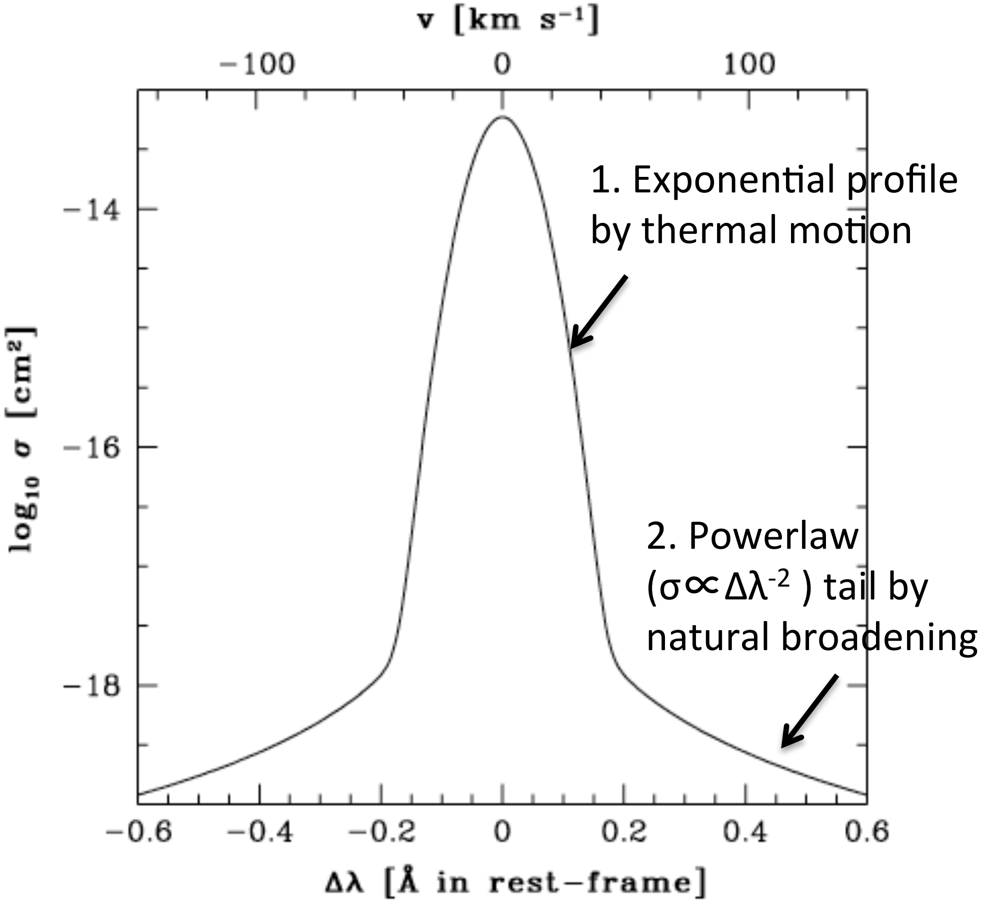
$$\sigma_V(\nu) = \int_{-\infty}^{\infty} M(v)\sigma_N(\nu - \nu_\alpha v/c)\, dv,$$

Maxwellian velocity distribution

$$M(v) = \left(\frac{m_H}{2\pi kT}\right)^{1/2} \exp\left(-\frac{m_H v^2}{2kT}\right),$$

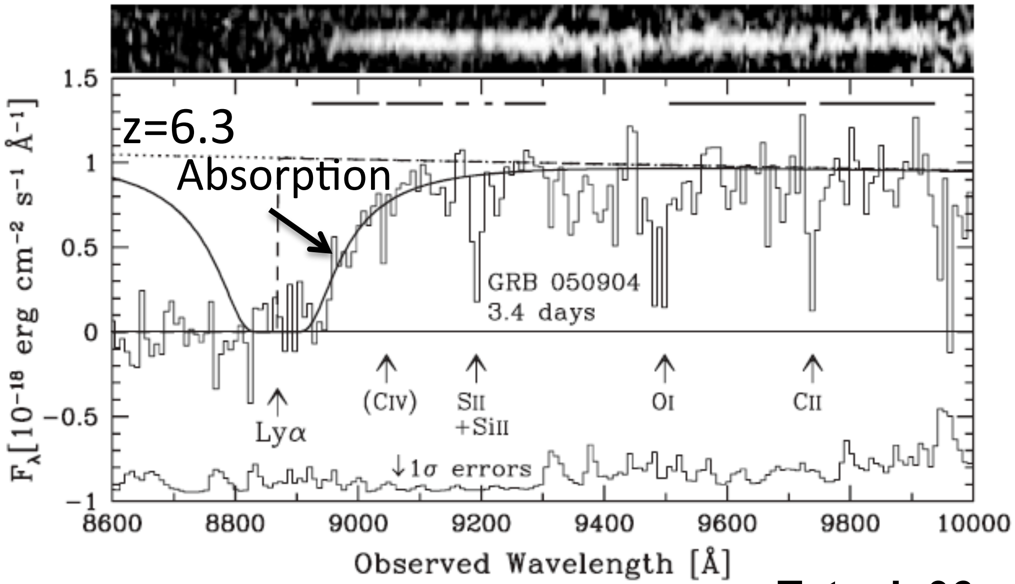
Natural absorption cross section

$$\sigma_N(\nu) = \frac{3\lambda_\alpha^2 A_{21}^2}{8\pi} \frac{(\nu/\nu_\alpha)^4}{4\pi^2(\nu-\nu_\alpha)^2 + \left(A_{21}^2/4\right)(\nu/\nu_\alpha)^6},$$

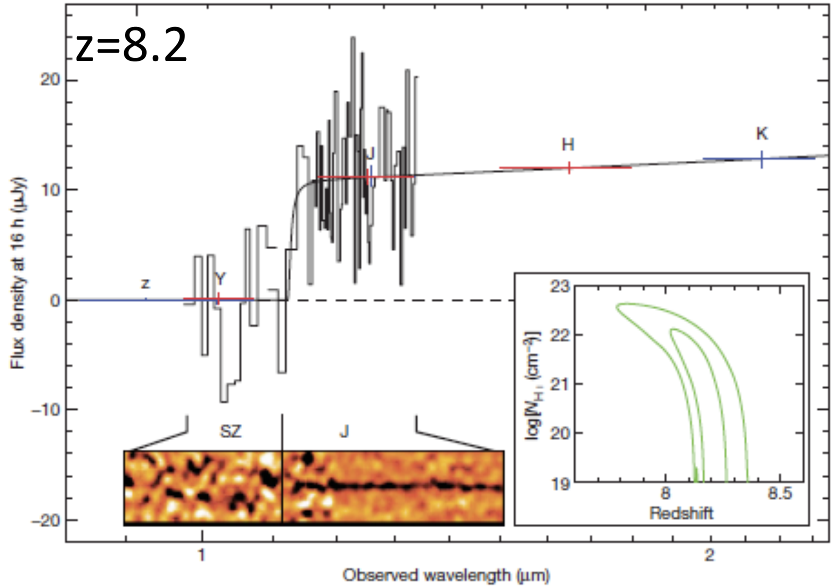


- Damping wing absorption of inter-galactic medium (IGM) just in front of a very bright object (GRB, QSO, and galaxy) at z>~7
-

Damping Wing Absorption
(a) GRBs?



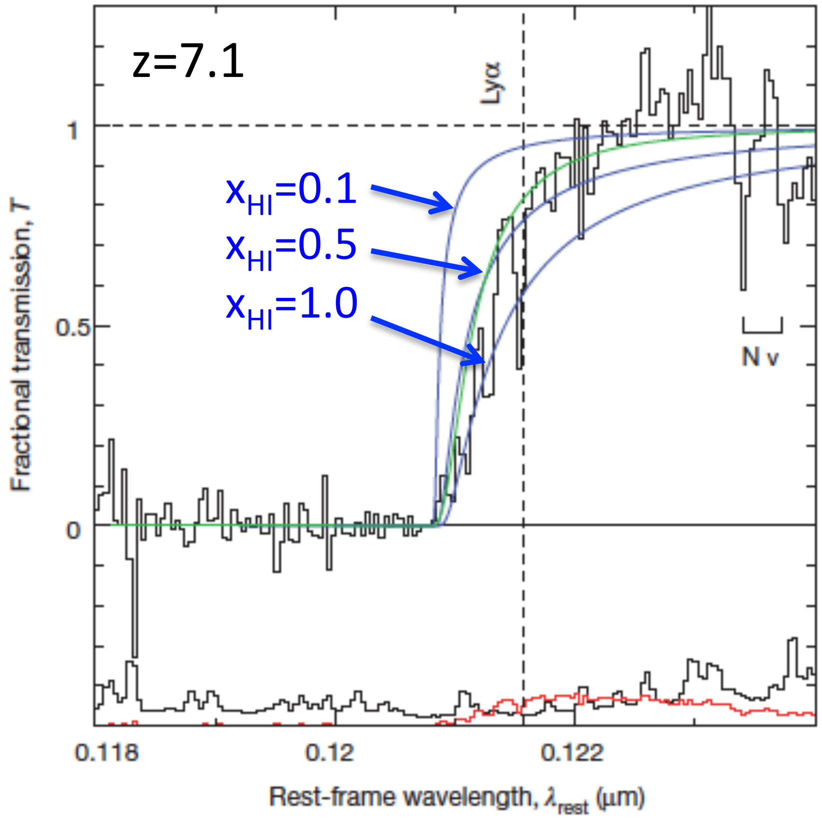
Totani+06



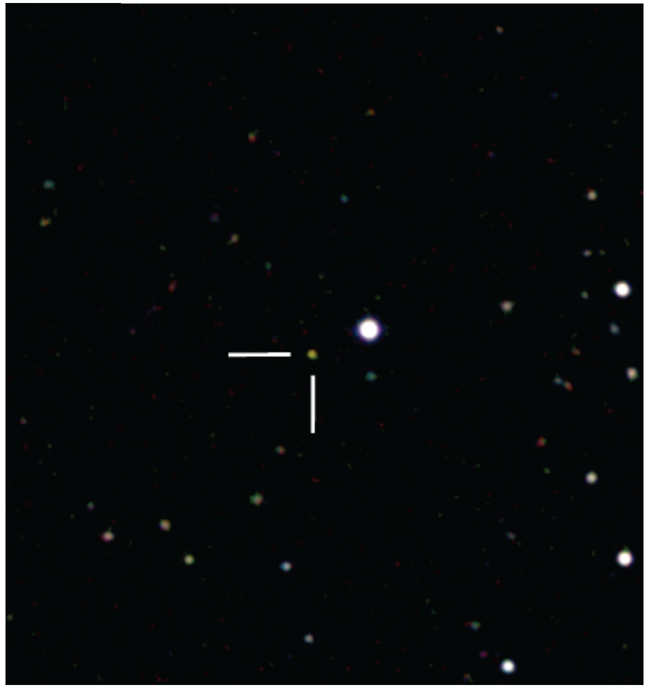
Tanvir+09

- The absorption found in the GRB at z=6.3 (GRB050904). Damping wing absorption or the gas associated with the host galaxy (DLA)? Upper limit of x_{HI}<0.17
- The highest redshift GRB at z=8.2 (GRB090423) → too faint to identify the absorption.

Damping Wing Absorption
(b) Quasars



ULAS J1120+0641



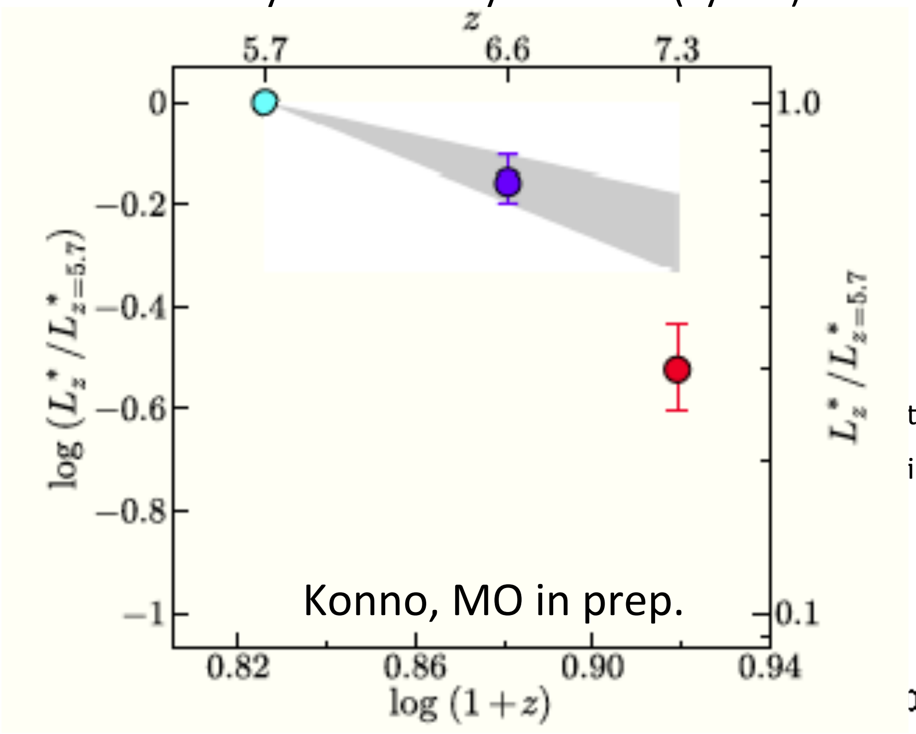
Mortlock et al. (2011)

- z=7.1 Quasar. Most distant, so far.
- Assuming the damping wing absorption of neutral IGM

→x_{HI}=0.1-0.5 is preferred. Considering the gas associated with the host galaxy, x_{HI}=1 is rejected. Mortlock et al. concluded x_{HI}>0.1

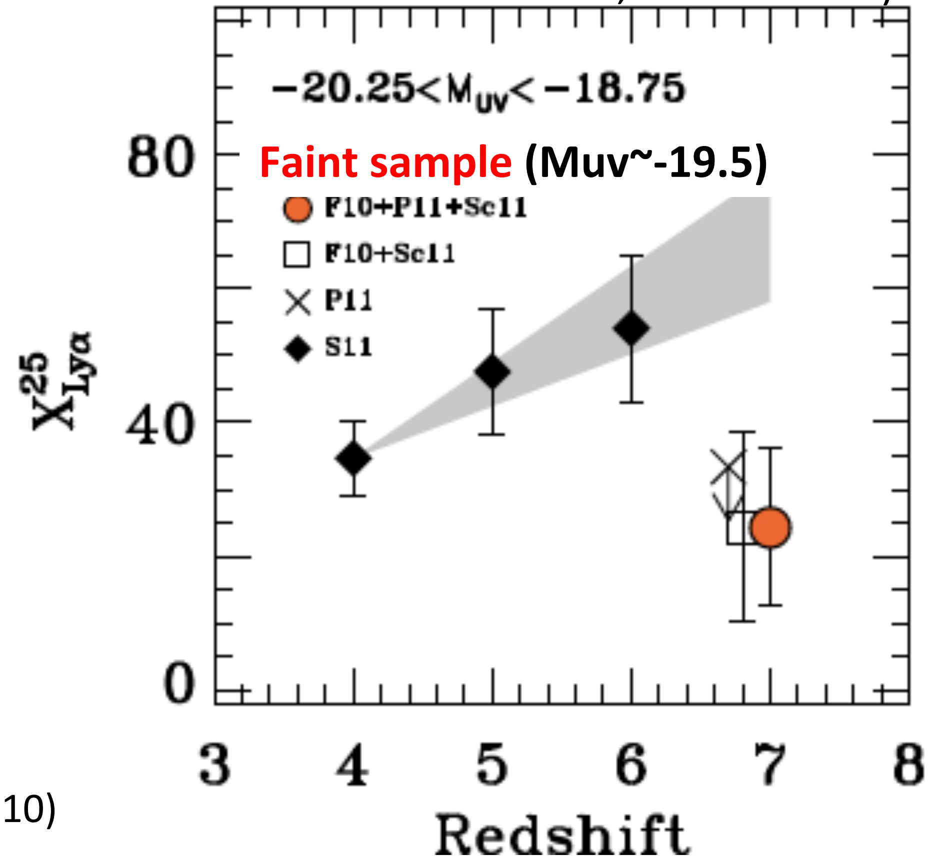
Damping Wing Absorption (c) Galaxies

Lya Luminosity Function (Lya LF)



Ouchi et al. (2010)

Ono, MO+12 (see also Pentericci+11,Schenker+12)



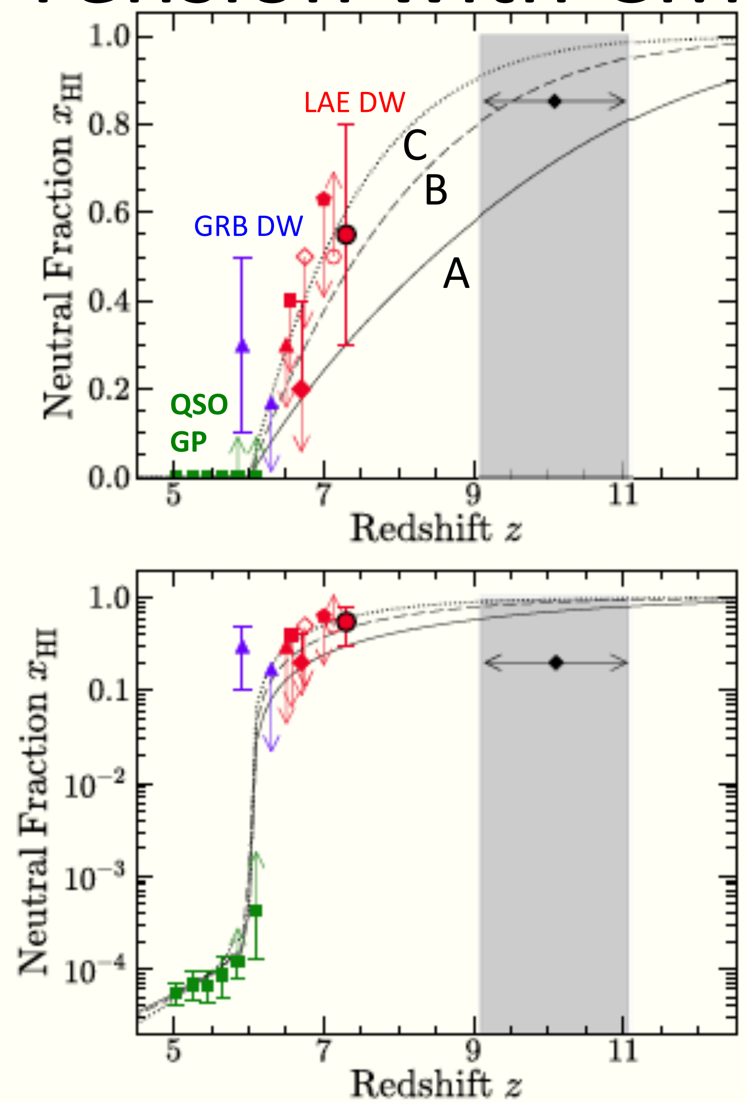
- Lya emission line from galaxies are also absorbed by damping wing absorption.

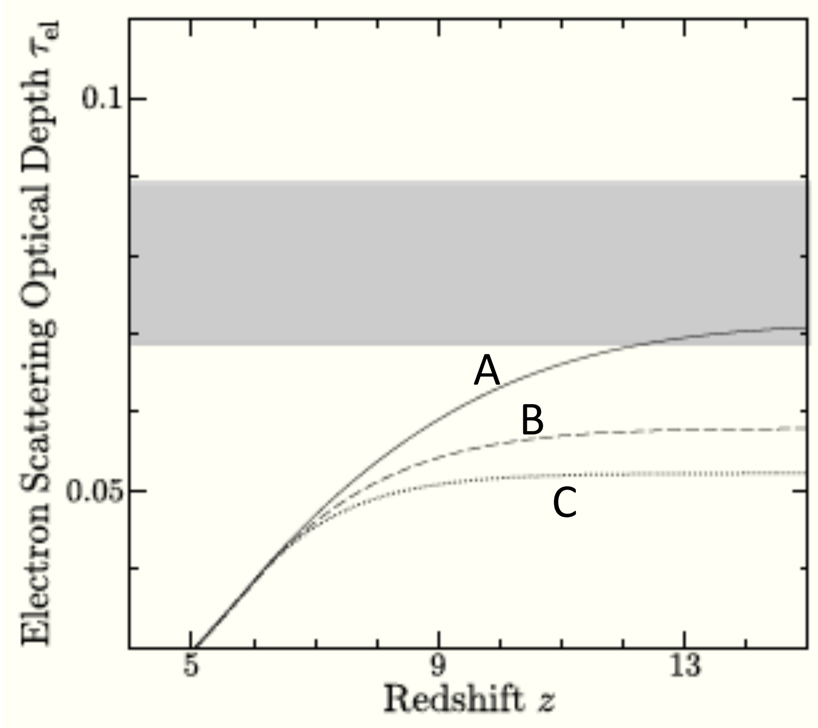
→ Towards the more neutral universe, one expects less galaxies with a strong Lya emission line.

- Fraction of Lya emitting galaxy to all galaxies, X_{Lya}. Significant drop of X_{Lya} at z~7.

→ Explaining it with damping wing absorption, x_{HI}~0.5

Reionization History
---Tension with CMB Measurements---





Konno, MO et al. in prep.

- x_{HI} estimates are too high at z~7 to explain τ?
- Or too high τ value??

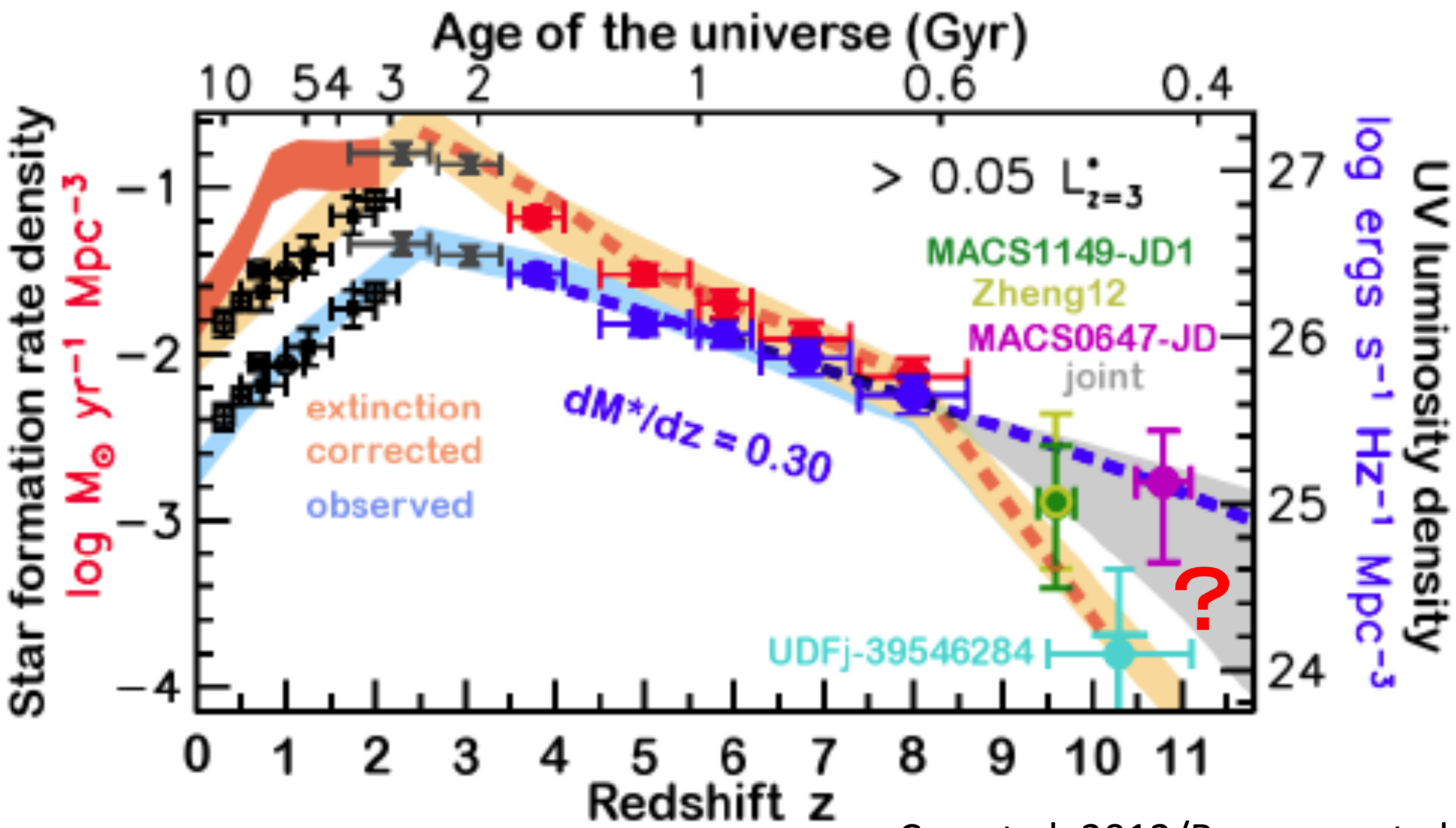
Why is there a tension between optical and CMB results?

Three possibilities so far claimed

- The existence of clumpy HI clouds within the ionized bubbles that absorb Ly selectively (Bolton & Haenelt 2013)
- Long extended cosmic reionization where the early star-formation at z > 10 are efficiently emitting ionizing photons to make intermediate HI fraction at z > 10 (Dunkley et al. 2009).
- Ionizing photon escape fraction is high, and that Ly photons are not efficiently produced in galaxies at z > 7 (Dijkstra et al. 2014).

REIONIZATION SOURCES

Star-Formation History Known To Date



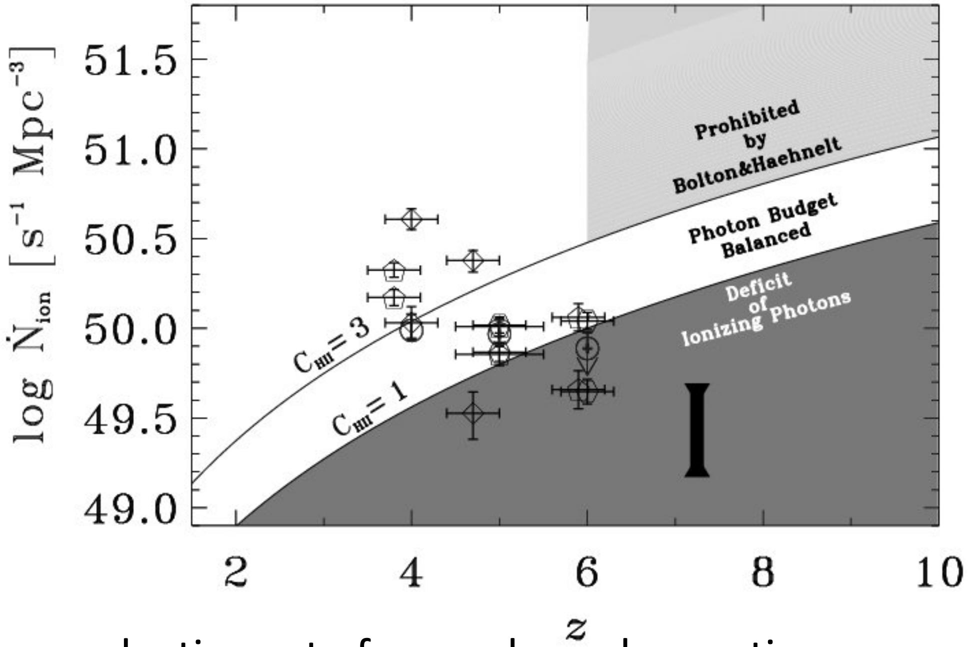
Coe et al. 2012/Bouwens et al. 2012

- Hubble Ultradeep field(HUDF)+CLASH
  - Peaking at z~2-3.
  - z~7 SFRD comparable today.
  - Rapid buildup in SFRD at z>~8-10 or not?? (Oesch+13 vs. Ellis+13)

Dropping Star Formation Rate

--lower ionizing photon production rate towards high-z--

Evolution of Ionizing photon emission density



Ouchi+09b

- Ionizing photon production rate from galaxy observations

$$\dot{N}_{ion}(s^{-1}\ Mpc^{-3}) = 10^{49.7}\left(\frac{\epsilon^g}{10^{25}}\right)\left(\frac{\alpha_s}{3}\right)^{-1}\left(\frac{f_{esc}}{0.1}\right),$$

Ionizing emission density at ~900A, ε^g~ρ/6=2e25 for z~7, spectral index, α_s~3, and escape fraction, f_{esc}~0.04
→log dN_{ion}/dt = 49.6 s^{-1} Mpc^{-3}

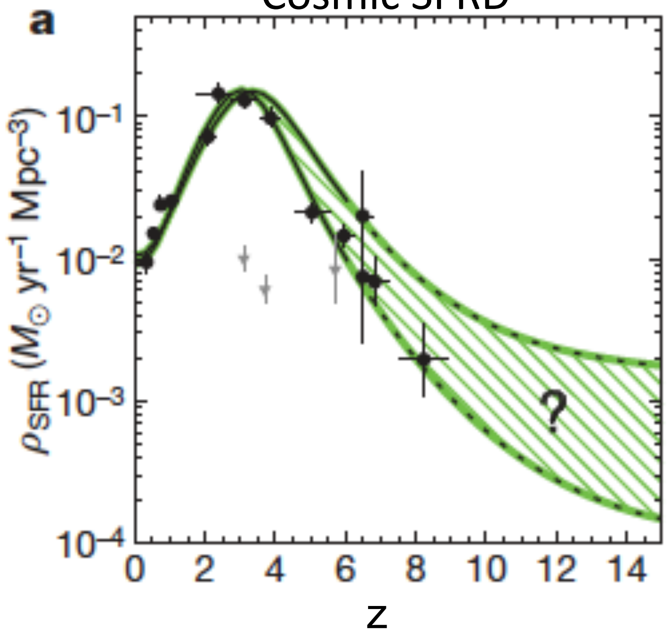
- Ionizing photons required for ionized Universe are given by

$$\dot{N}_{ion}(s^{-1}\ Mpc^{-3}) = 10^{47.4} C_{H\,II}(1+z)^3$$

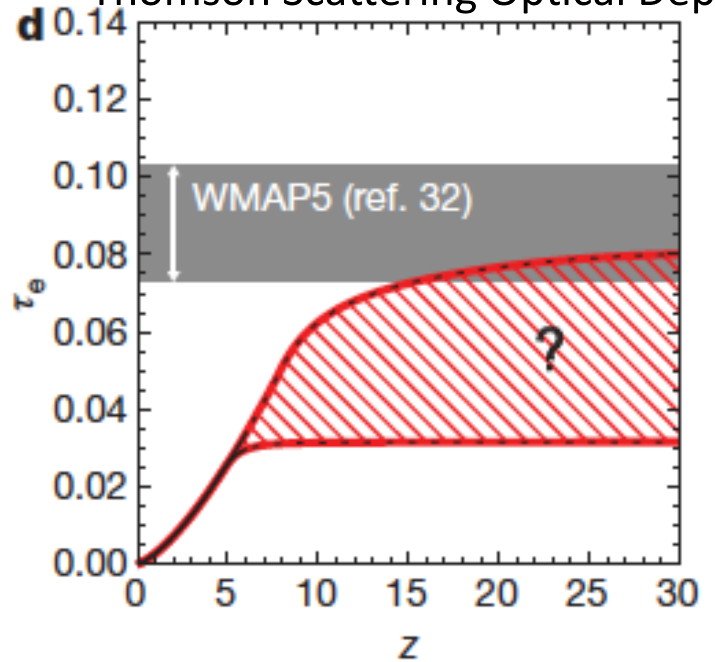
C_{HII} is a clumping factor, $C_{HII}=\langle n_{HII}^2\rangle/\langle n_{HII}\rangle^2$; C_{HII}=1 is for uniform universe.

Missing Ionizing Photon Problem?

Cosmic SFRD



Thomson Scattering Optical Depth

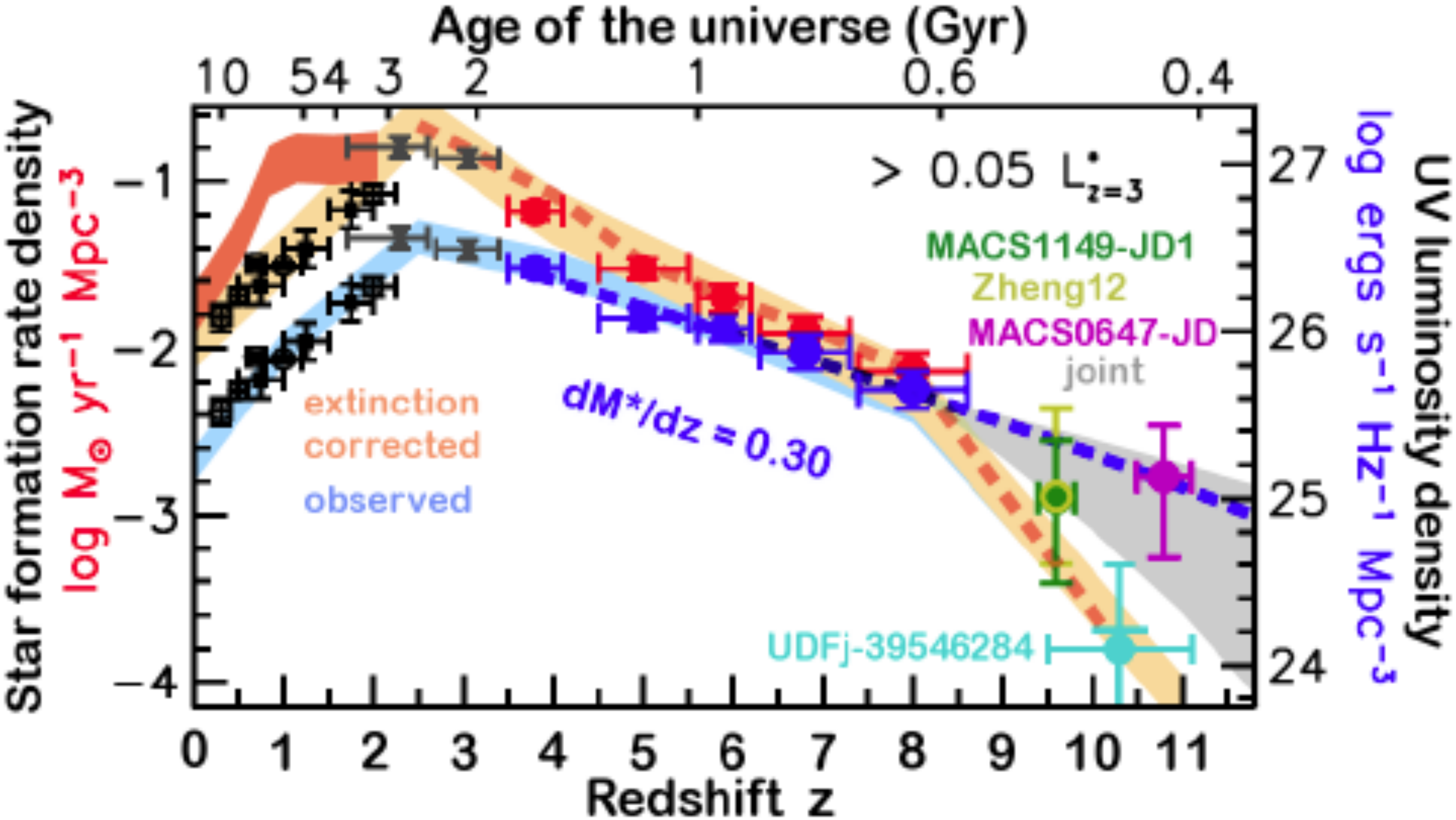


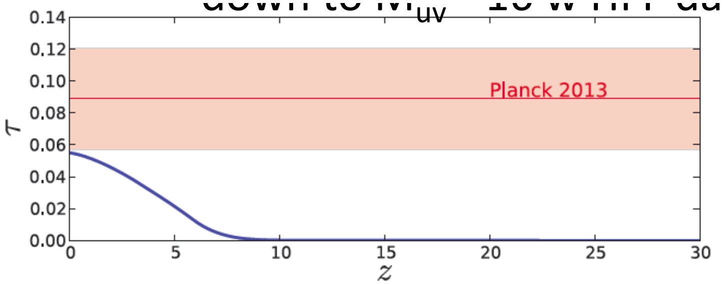
Robertson+10

Estimating ionizing photon budget.

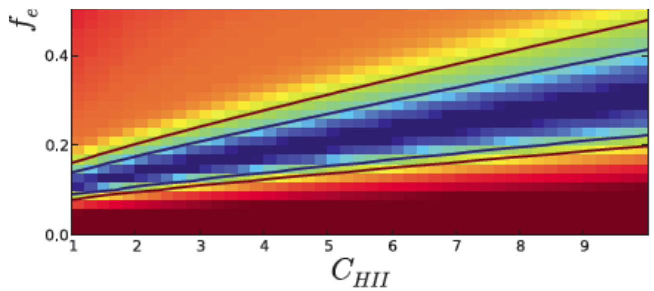
- SF history ($\propto \varepsilon$)→ ionizing photon rate (dN_{ion}/dt)
- Electron density, $n_e(z)$→ Thomson scattering τ_e
- τ_e from galaxies is smaller than τ_e from CMB measurement
  - →Shortage of ionizing photons. Are ionizing photons missing?

But, galaxies can be major reionization sources, in case of high fesc>0.2, flatter spectrum (α), and/or faint galaxy (m>-18) contribution to ε (e.g. Robertson+12)





Ishigaki+
in prep.



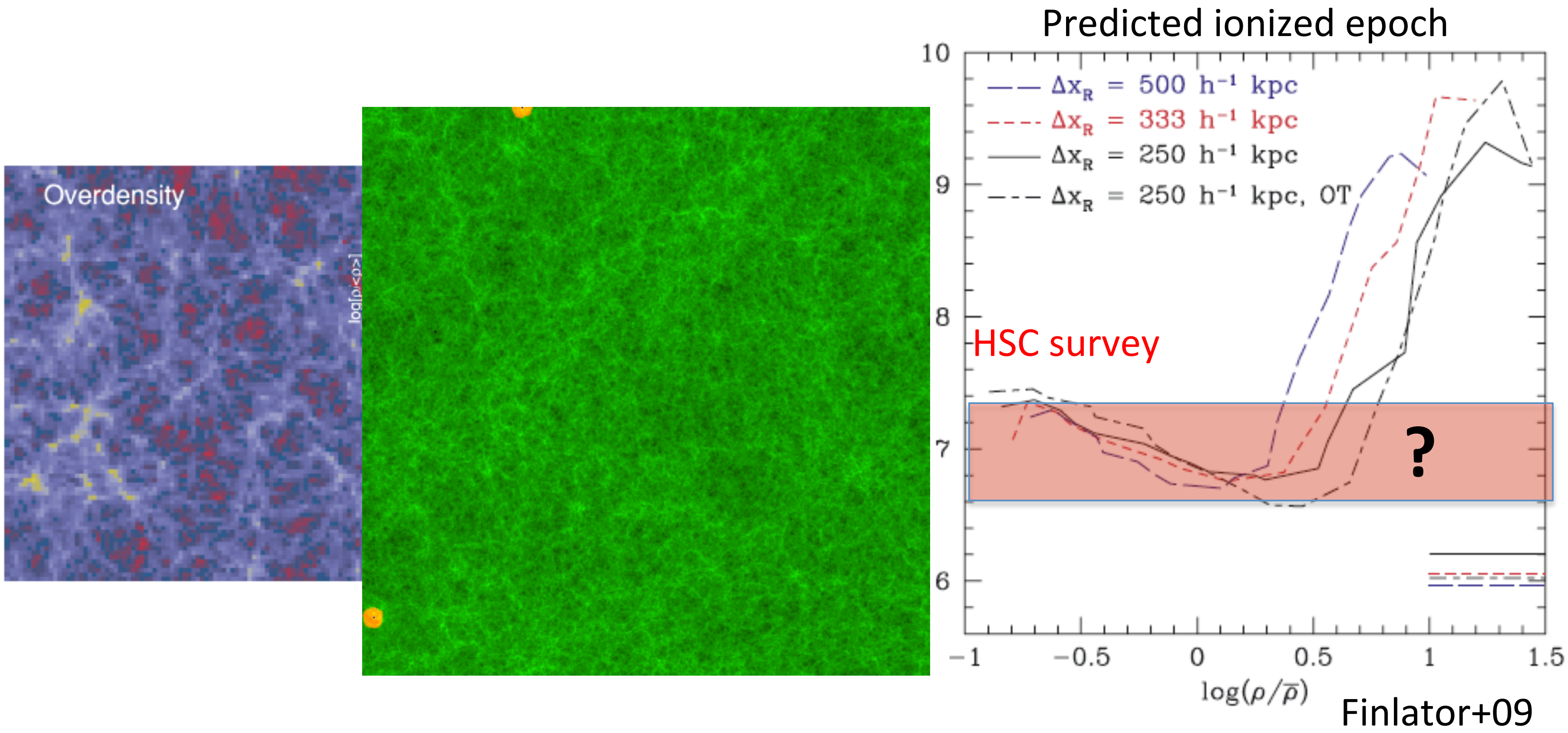
- $\epsilon(z)$ and τ from observations. Unknown par: f_{esc}, C_{HII}, and M_{trunc}

HFF's 1/6 data set→ f_{esc}>0.1 at the >2 sigma level

Extended SFR (reionization) history is preferred.

PHYSICAL PROCESS OF REIONIZATION

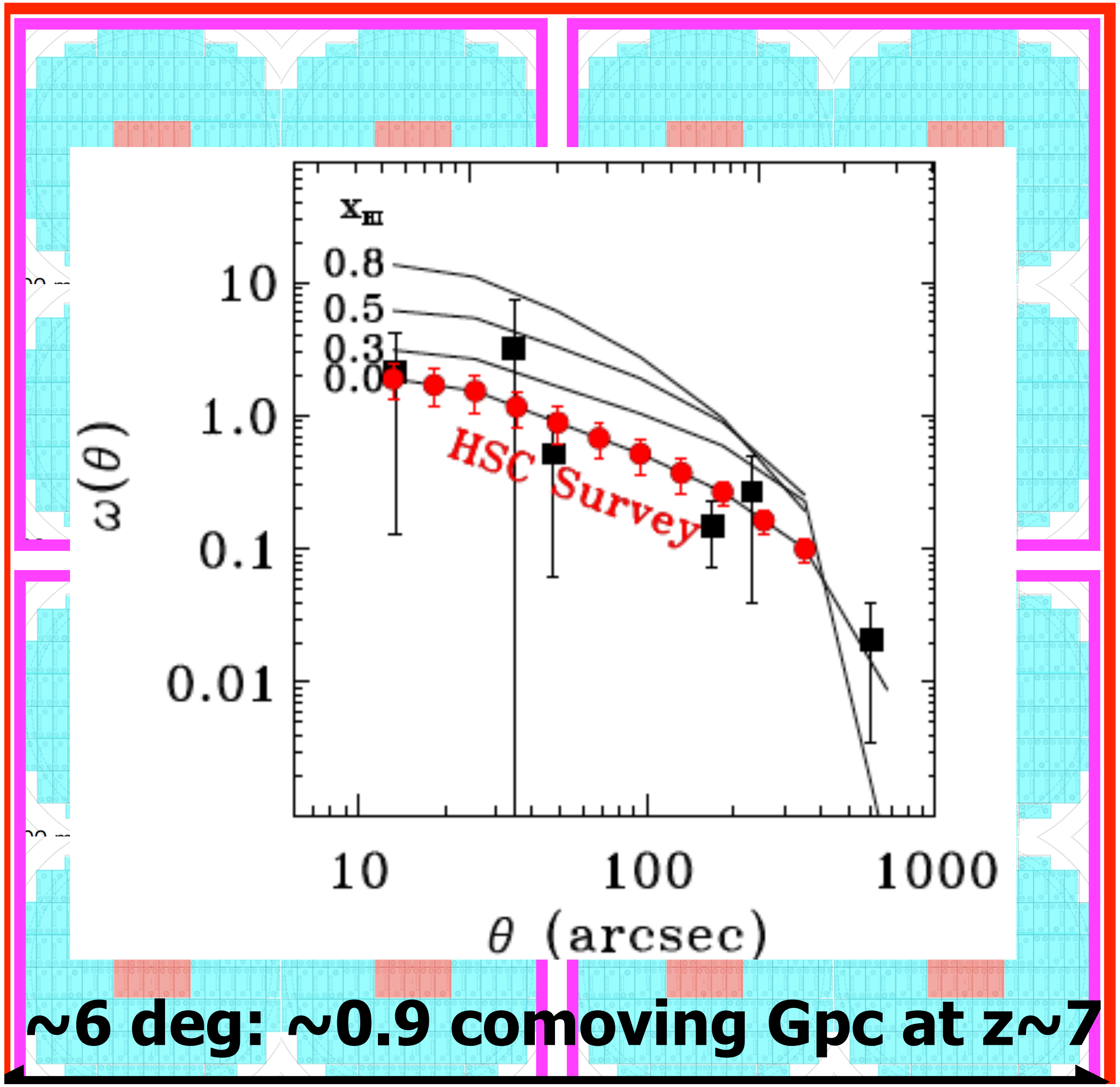
Reionization Processes from Bubble Topology

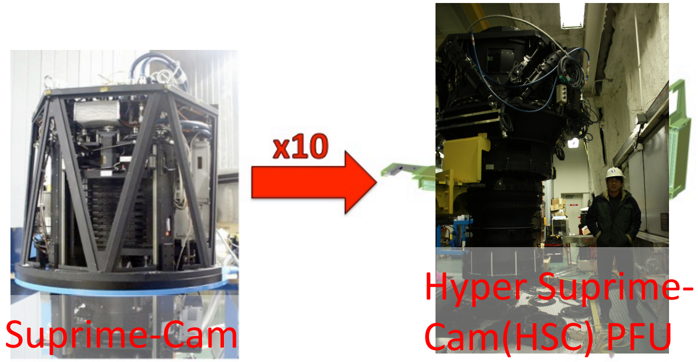


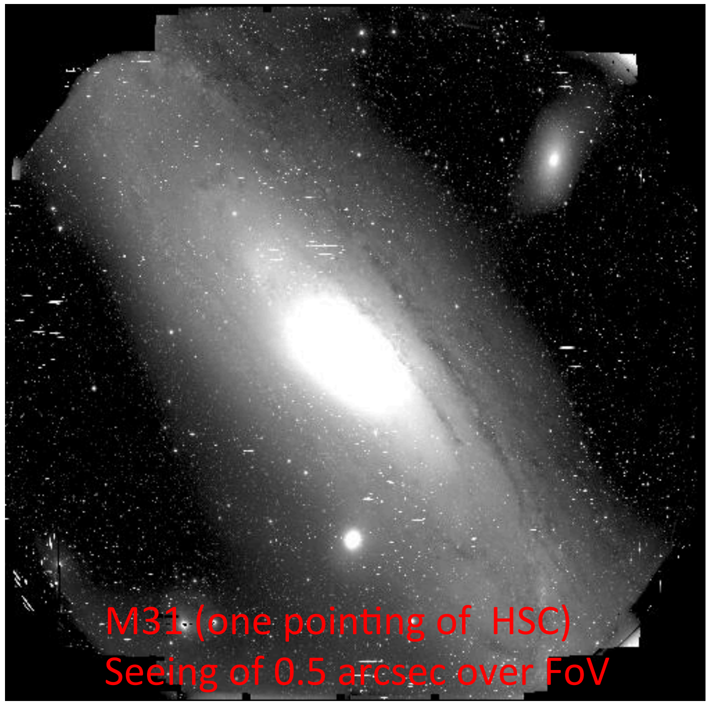
– Physical processes (inside-out, outside-in, filament-last?)

– Clustering of Lya emitters: imprints of neutral fraction and ionized bubble topology（McQuinn et al. 2007, Jensen et al. 2013)

Hyper Suprime-Cam (HSC) Survey



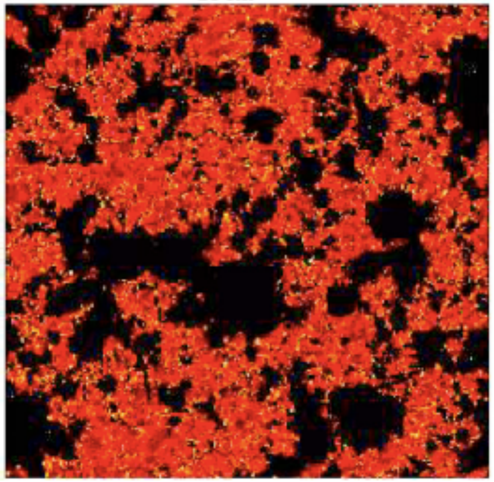




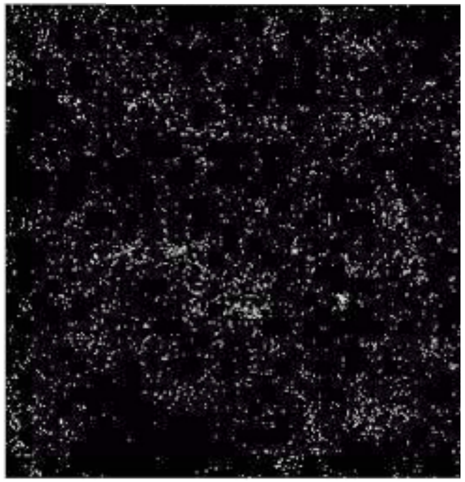
- Reducing the errors of IGM x_{HI} down to ~10% (model variance limit) w 10,000 LAEs at z~6-7
- Clustering→Investigating reionization process that cannot be addressed by the previous studies (topology of ionized bubbles etc.). HSC 300-night survey is starting today.

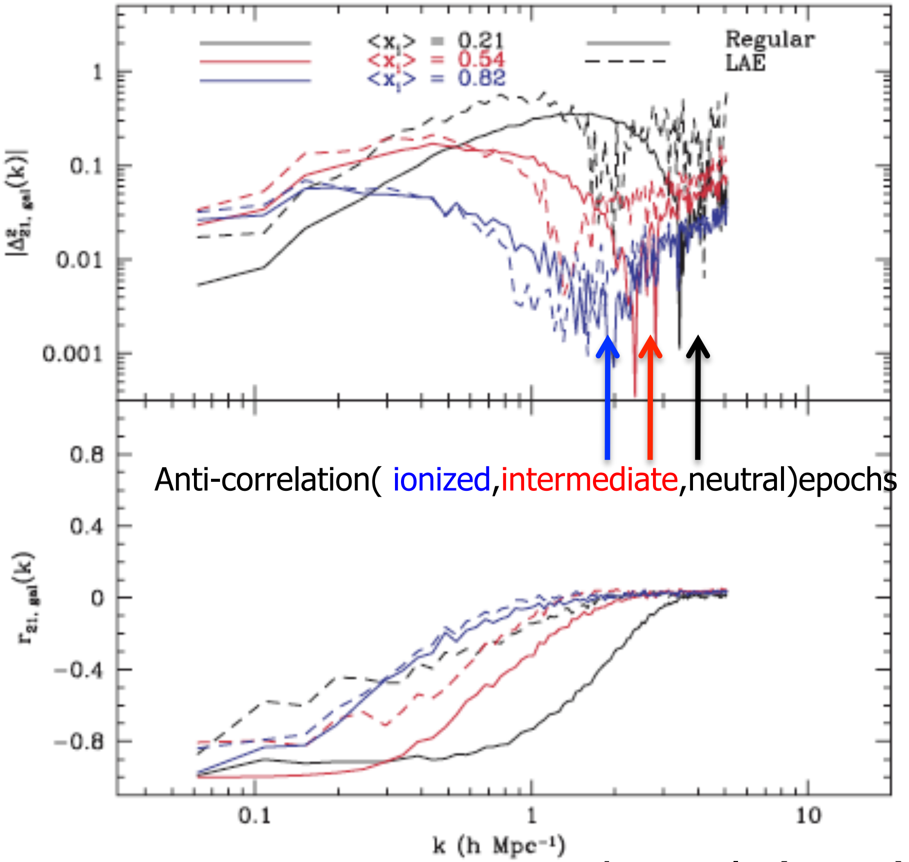
Physical Process of Reionization

21cm



Galaxies





Lidz et al. (2009)

- HI distributions (from 21cm) and galaxies (from optical) anti-correlate.
- Distance scales of anti-correlation→ ~Inside-out (typical sizes of ionized bubbles at the epoch)
- 21cm-galaxy corss-power spectrum. LOFAR 21cm+ Subaru/HSC(+PFS) survey in ELAIS-N1→~3σ detection of signal (Lidz+09).
  - LOFAR(Zaroubi+)

Summary

- Reionization studied by observations
- Three open questions
  - Cosmic reionization history. Sharp/Extended reionization hisotry?
  - What are reionization sources? Ionizing photon budget balanced?
  - Physical process (inside-out, outside-in, filament-last?)

On-going observations addressing these issues.
The major questions may be changed in the SKA era.

The role of SKA→

Reliable confirmation,
Addressing unresolved issues, and
Synergistic data (HI vs. ionizing sources).