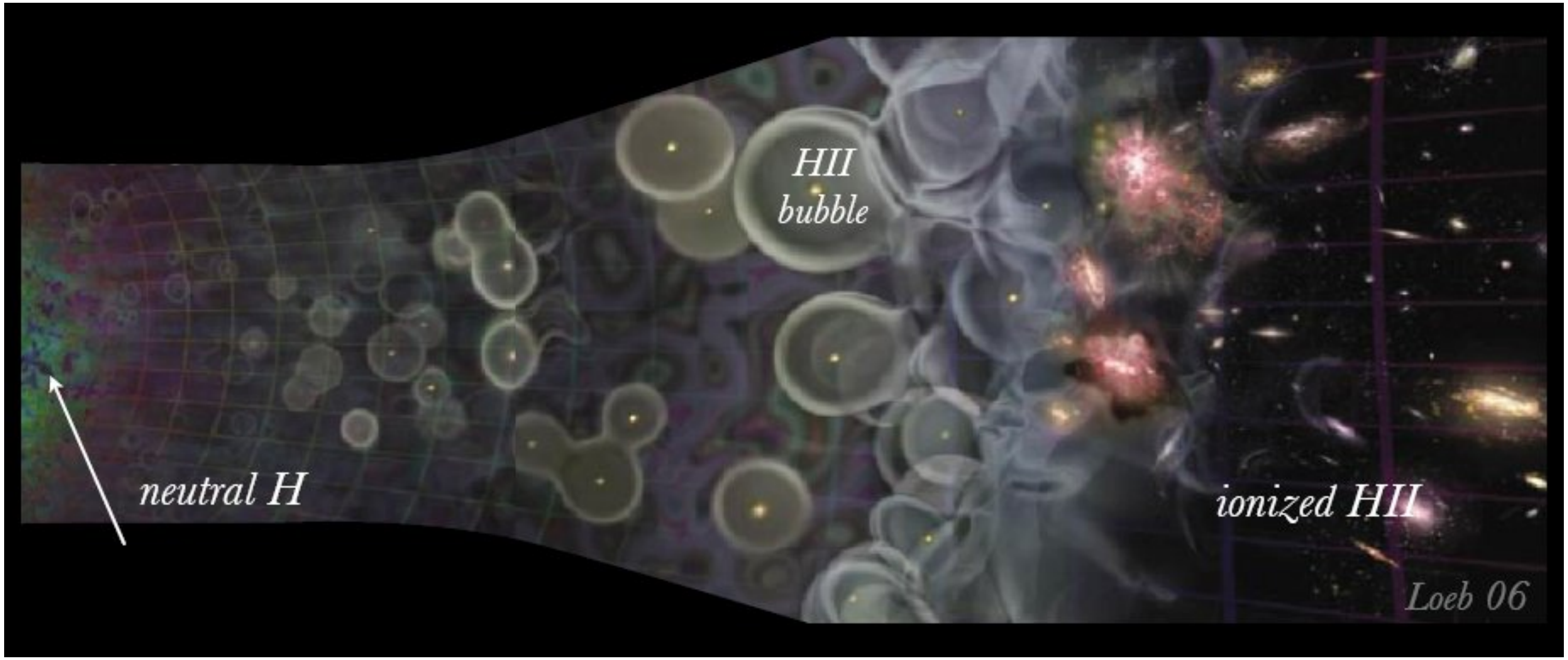
銀河形成と宇宙再電離が織りなす
初期の宇宙進化



大内 正己

(東京大学 宇宙線研究所)

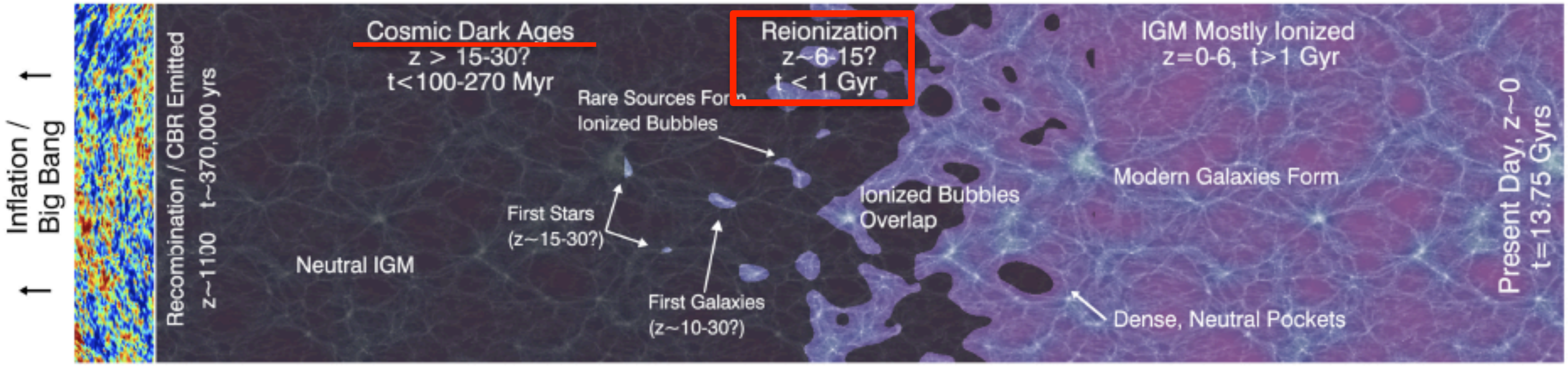
Outline

- What is ‘cosmic reionization’?
  a) Reionization history
  b) Physical reasons of reionization, known to date.

  → Open questions (unknowns)

- Future Projects

Cosmic Reionization



Robertson et al. (2010)

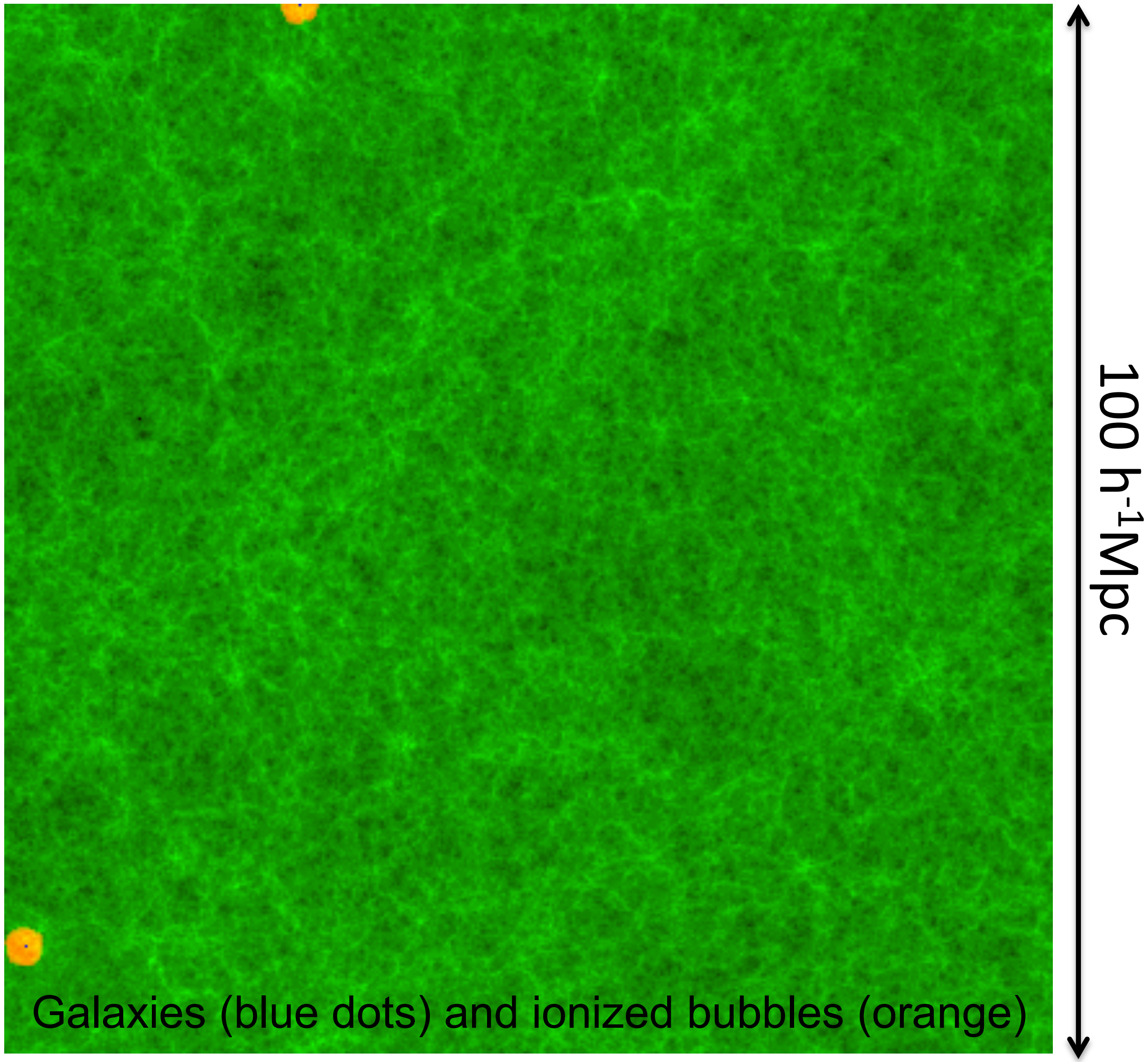
Cosmic Reionization:

Universe filled with neutral hydrogen

→ Ionized hydrogen at z>6

H+γ→p+e-   (Hydrogen ionization)

Cosmic Reionization

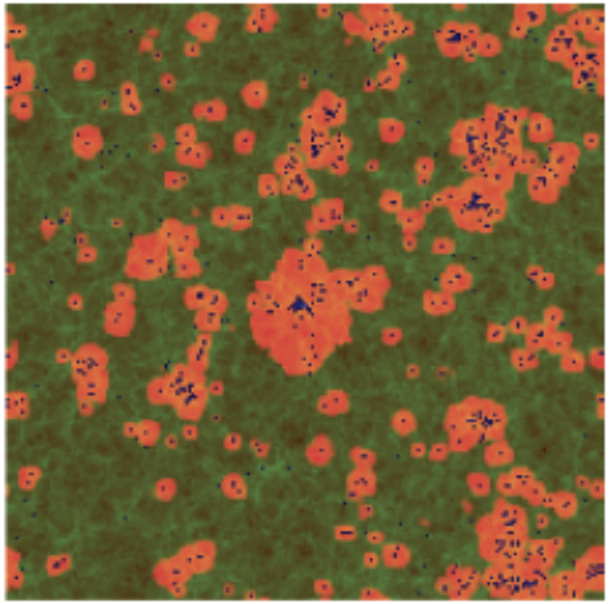


RT simulations (Iliev et al. 2006)

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

Tight Relation between
Cosmic Reionization & Galaxy Formation

Reionization

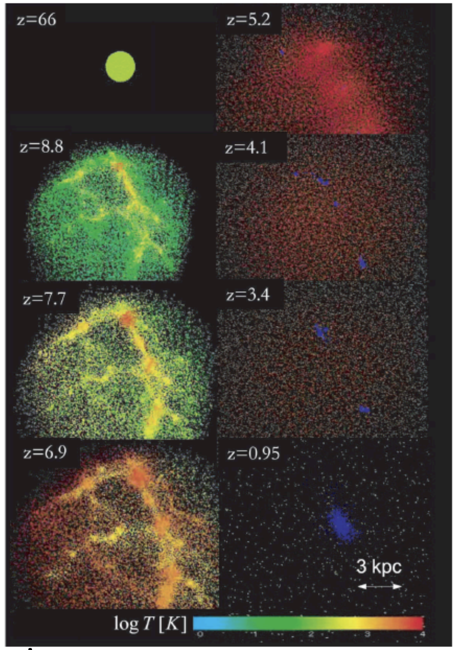


Ionized IGM(orange), neutral IGM(green), and Galaxies (blue)

Ionizing photons
to ionize the universe

Intense UV background
to suppress dwarf-galaxy formation

Galaxy/star formation

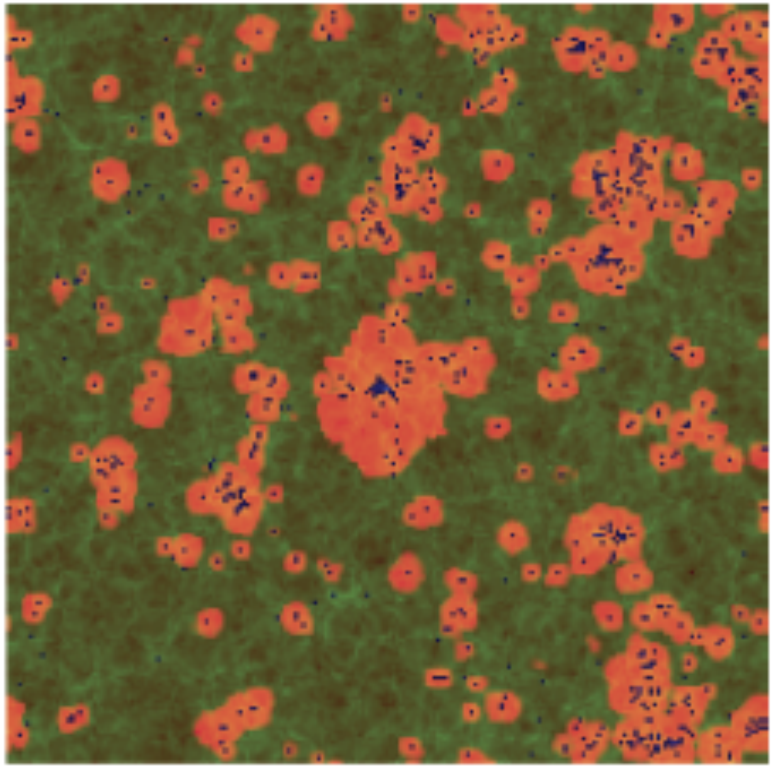


M(halo)=6e7 Mo
z_c=1.7

Susa & Umemura+04

COSMIC REIONIZATION HISTORY KNOWN TO DATE

How Do You Probe Cosmic Reionization?

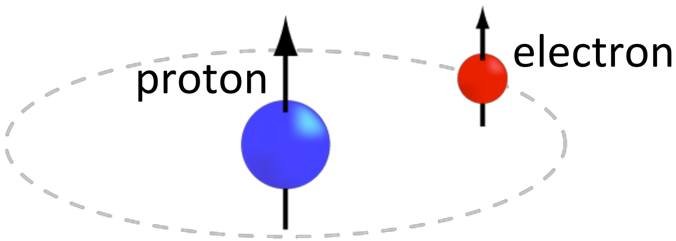


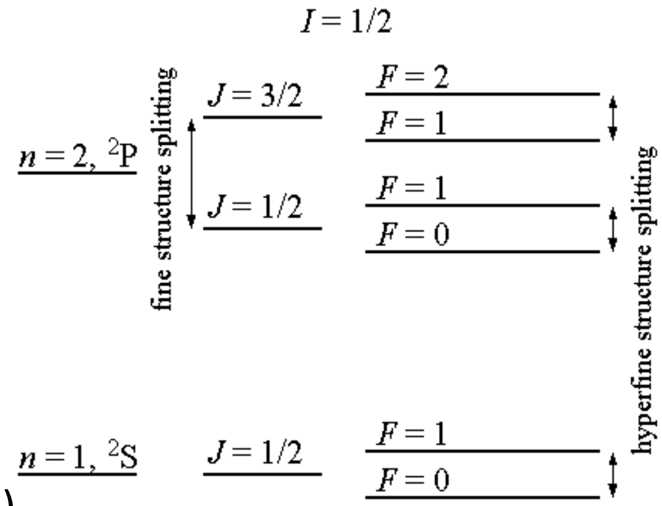
Galaxy (blue)、Neutral H（green）、H^+ (orange)

- 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)

21cm Emission from Neutral Hydrogen

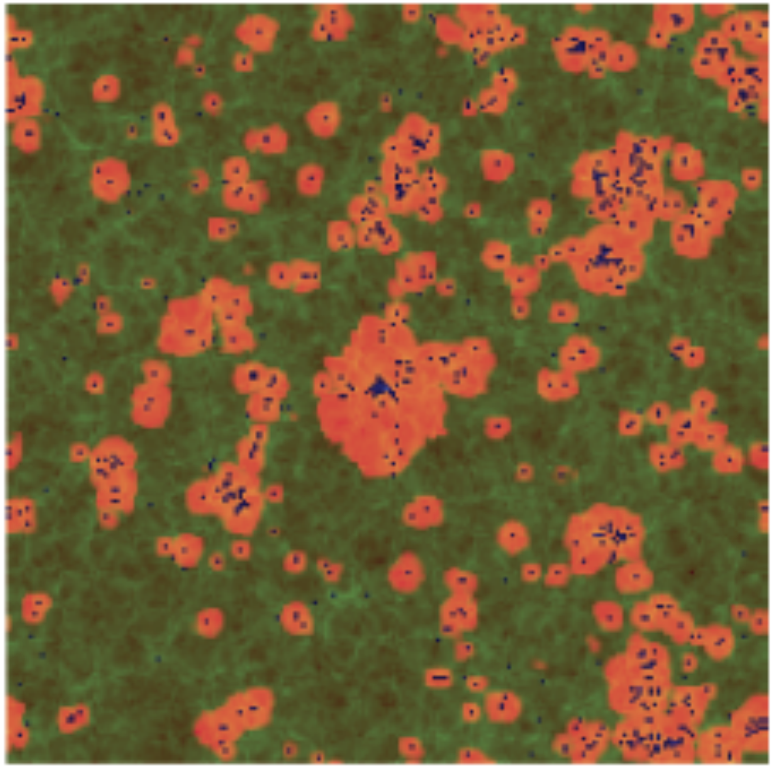
Neutral hydrogen epoch (incl. cosmic dark age):
A hyperfine structure line of hydrogen (21 cm radio emission)





Hydrogen atom (ground ^{2}S state)
parallel spins→ anti-parallel spins
cf. Fine structure line cased by the spin-orbit interaction (**S**･**L**).

How Do You Probe Cosmic Reionization?



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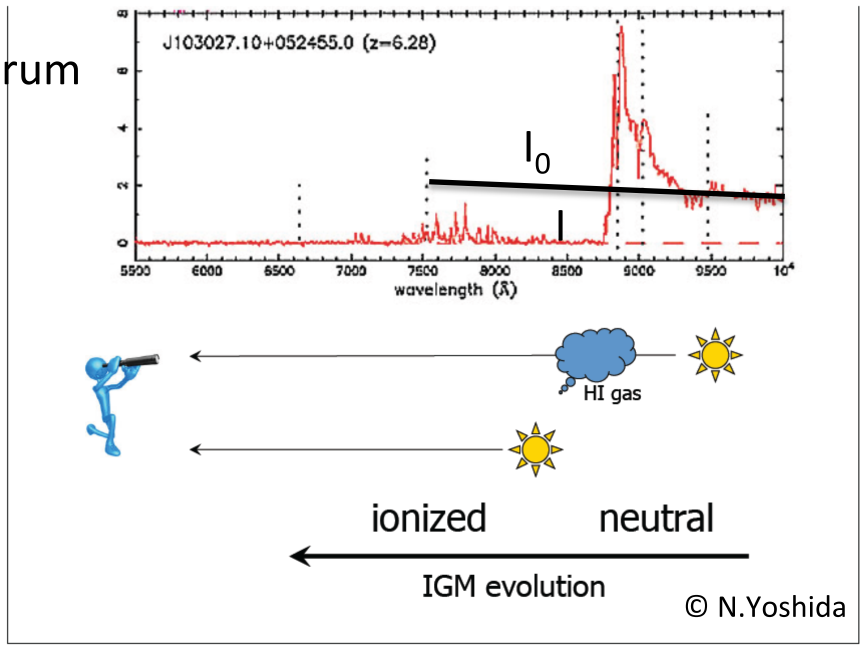
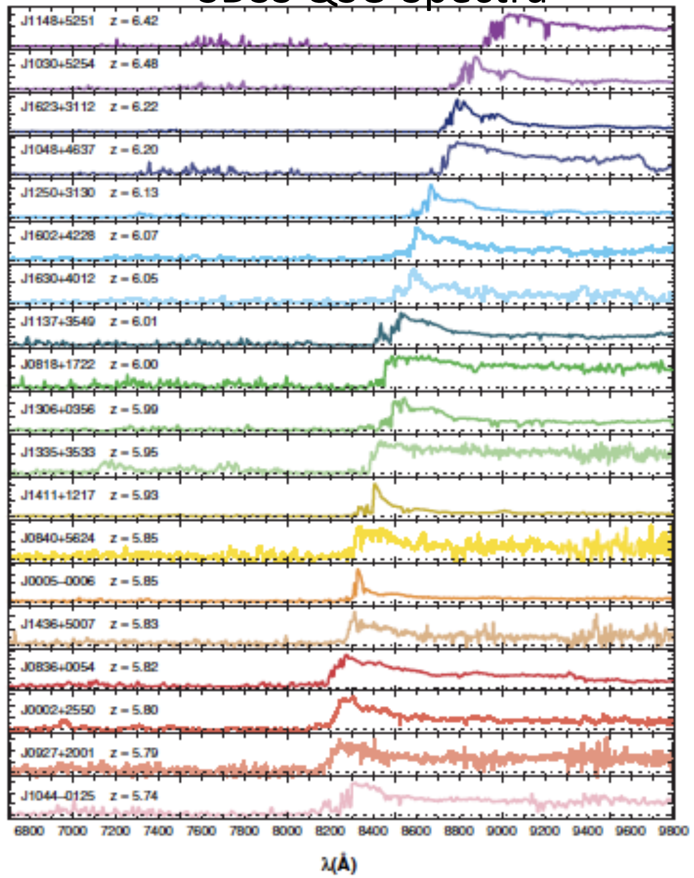
Quiz: How can you measure the ionization states of the universe?

Probing Reionization History (1)
Gunn Peterson τ

QSO Spectrum



SDSS QSO Spectra



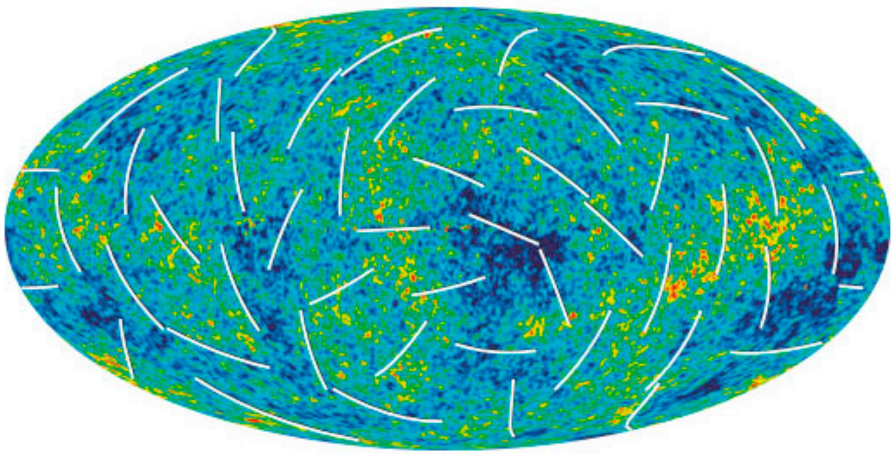
$$\tau_{GP}(z) = 4.9\times10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{HI}}{n_H}\right)$$

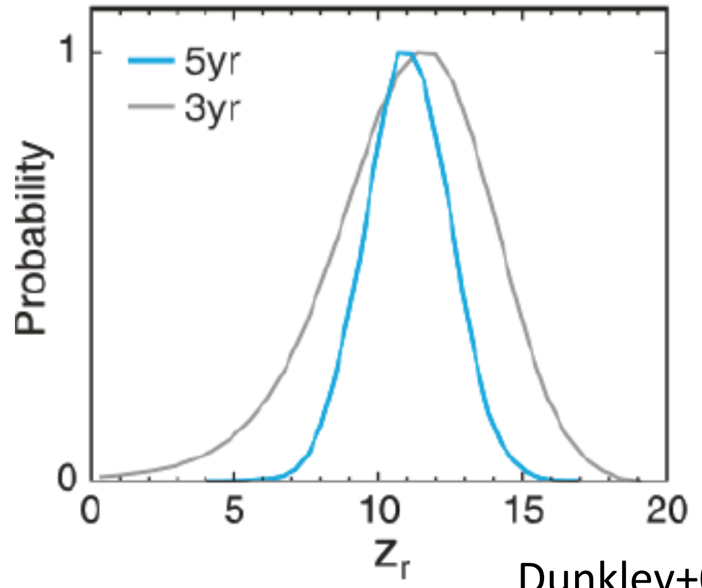
Gunn-Peterson optical depth ($\rightarrow I/I_0=e^{-\tau_{GP}}$): GP test

For (n_{HI}/n_H)>~0.01% at z~6, large τ_{GP} ! (due to large σ_{Lya})

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

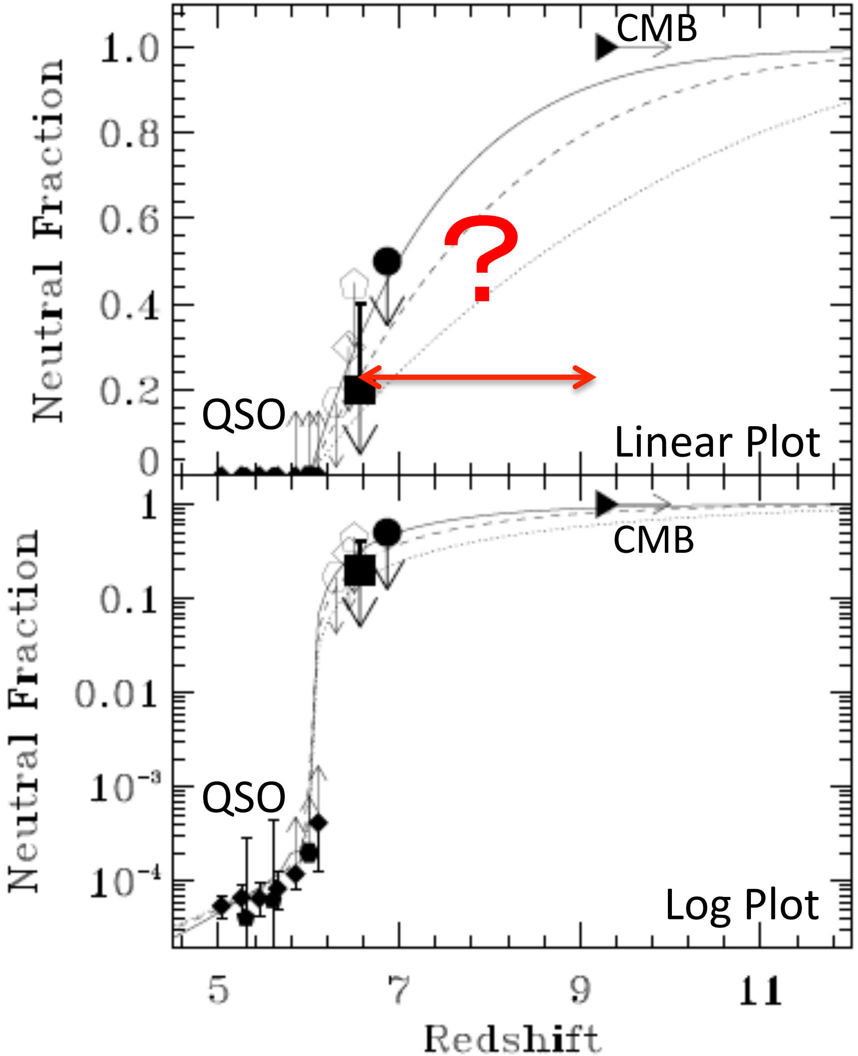
$$\tau(z) = \sigma_{\rm T} \int_0^z n_{\rm e}(z') \frac{{\rm d}l(z')}{{\rm d}z'} {\rm d}z',$$

→ Instantenous reionization at z_r

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

- τ = 0.089±0.032 (Plank2013), 0.084 ± 0.013 (WMAP9; Hinshaw+12)
- →z_r~10-11 (instantaneous reionization)
- Problem: No time resolution

Reionization History
from GP test and CMB Polarization



Ouchi et al. (2010)

- Neutral hydrogen fraction, x_{HI}, $=n_{HI}/n_H$, is increasing beyond z~6.
- No constraints at z~6-10 (GP test, $x_{HI}<10^{-4}$; CMB no time res.).
- Many competing models. Sharp/extended reionization?

Probing Reionization History (3)
Lyα Damping Wing Absorption

Absorption cross section (→voigt profile)

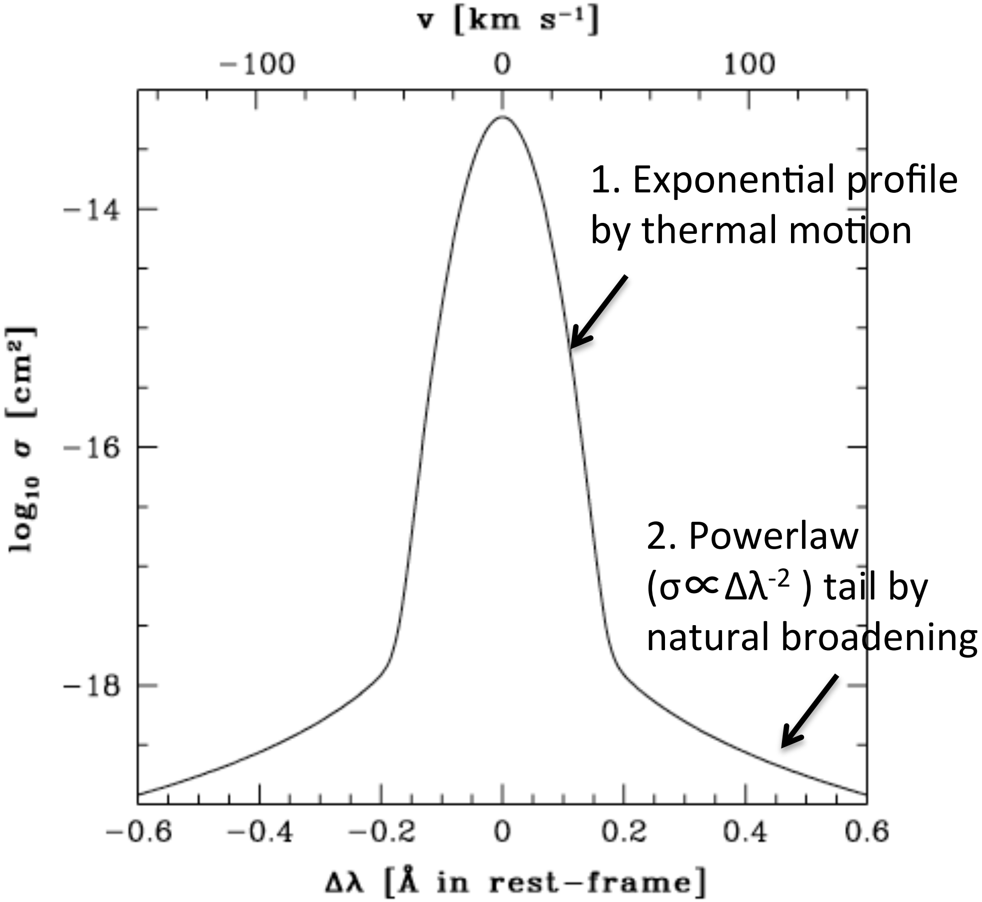
$$\sigma_V(\nu) = \int_{-\infty}^{\infty} M(v)\sigma_N(\nu - \nu_\alpha v/c)\,dv,$$

Maxwellian velocity distribution

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

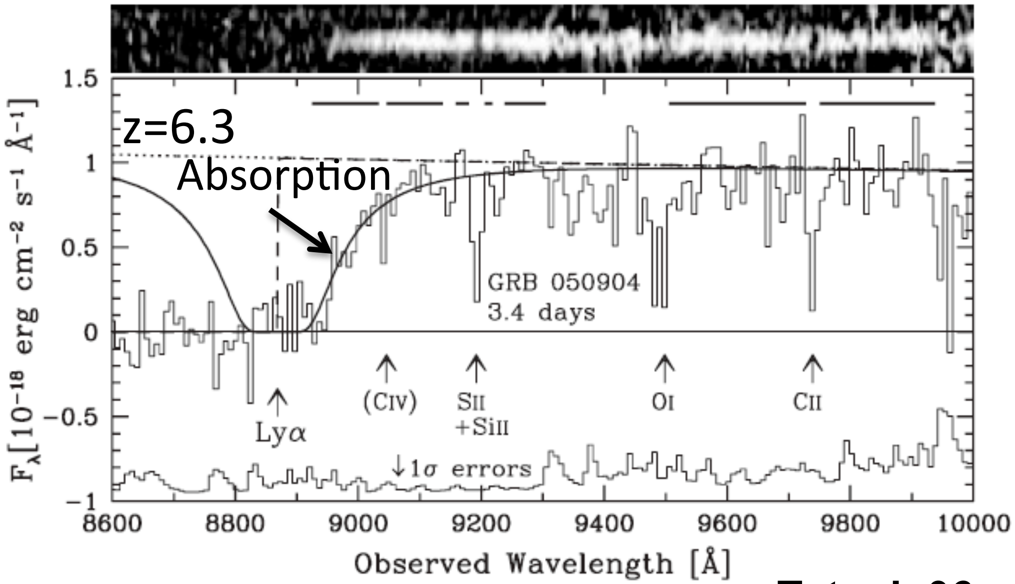
Natural absorption cross section

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

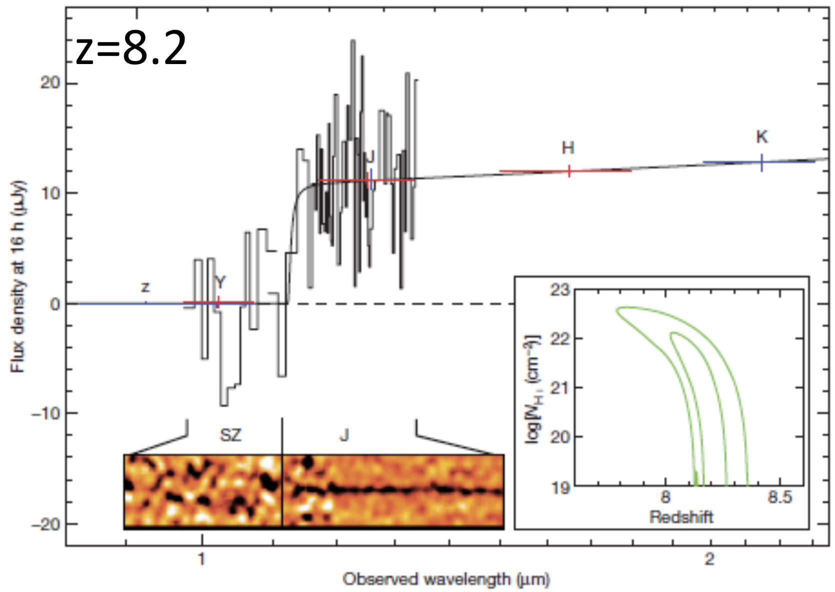


- Damping wing absorption of inter-galactic medium (IGM) just in front of a very bright object (GRB, QSO, and galaxy) at z>~7
-

Damping Wing Absorption
(a) GRBs?



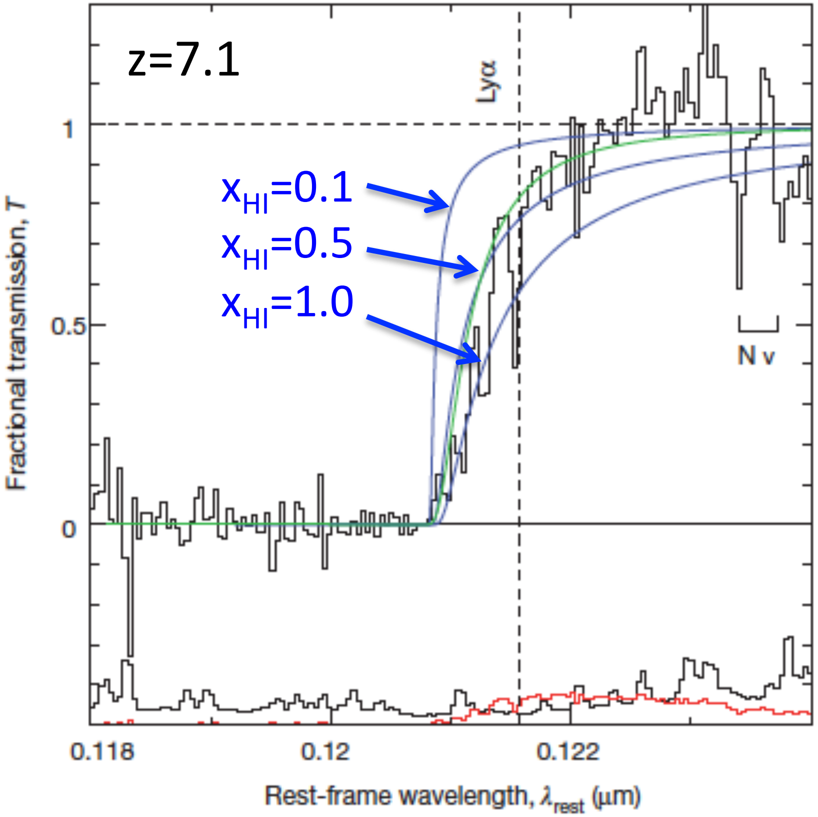
Totani+06



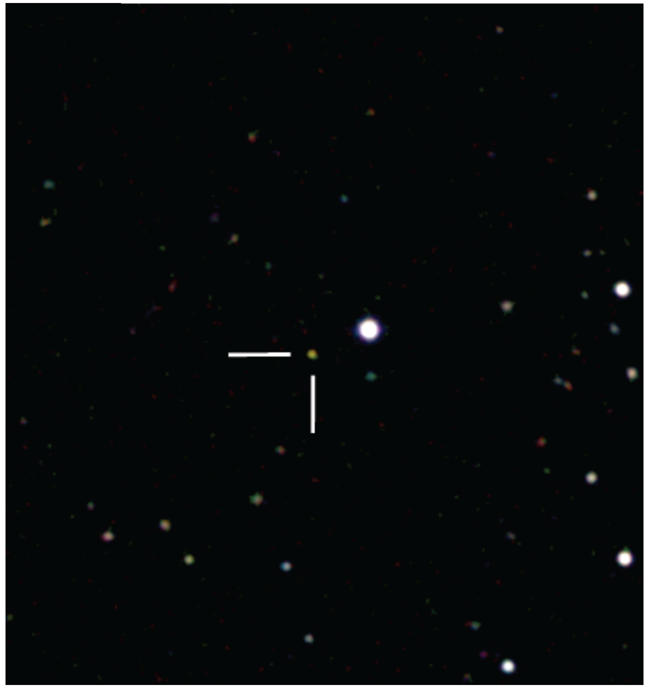
Tanvir+09

- 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



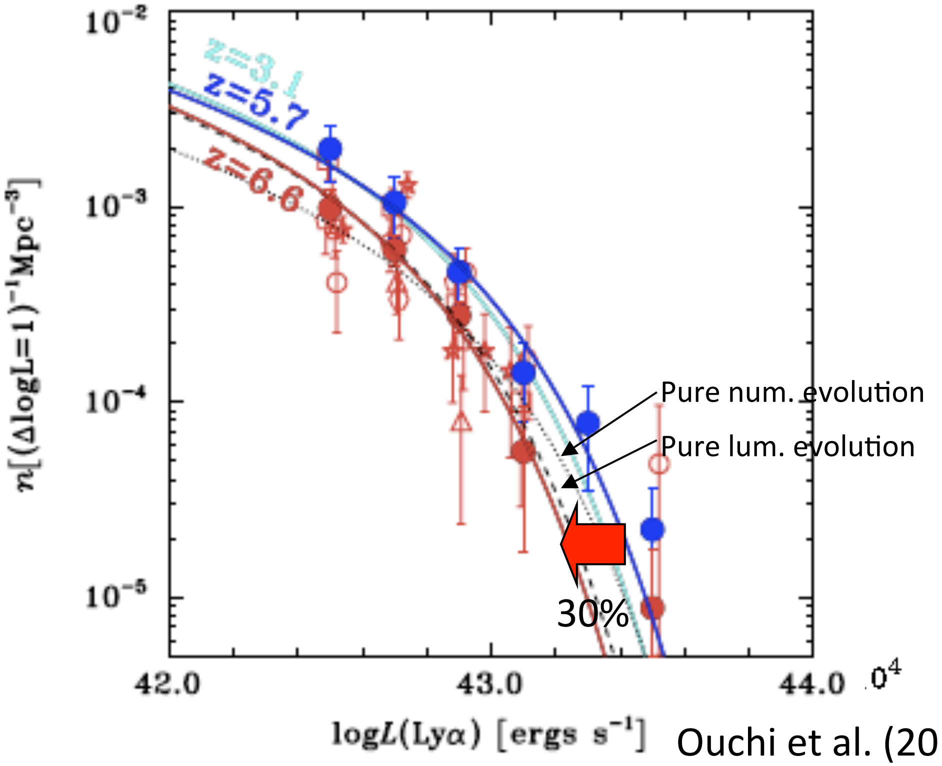
Mortlock et al. (2011)

- 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

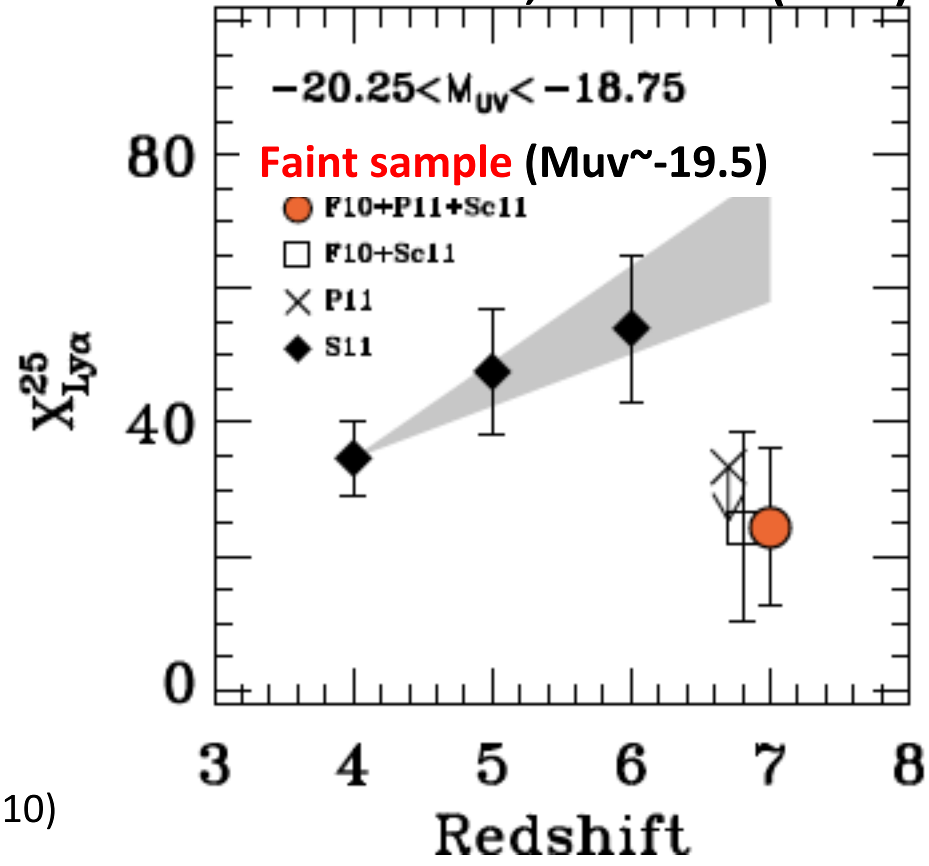
Damping Wing Absorption
(c) Galaxies

Lya Luminosity Function (Lya LF)



Ouchi et al. (2010)

Ono, MO et al. (2011)



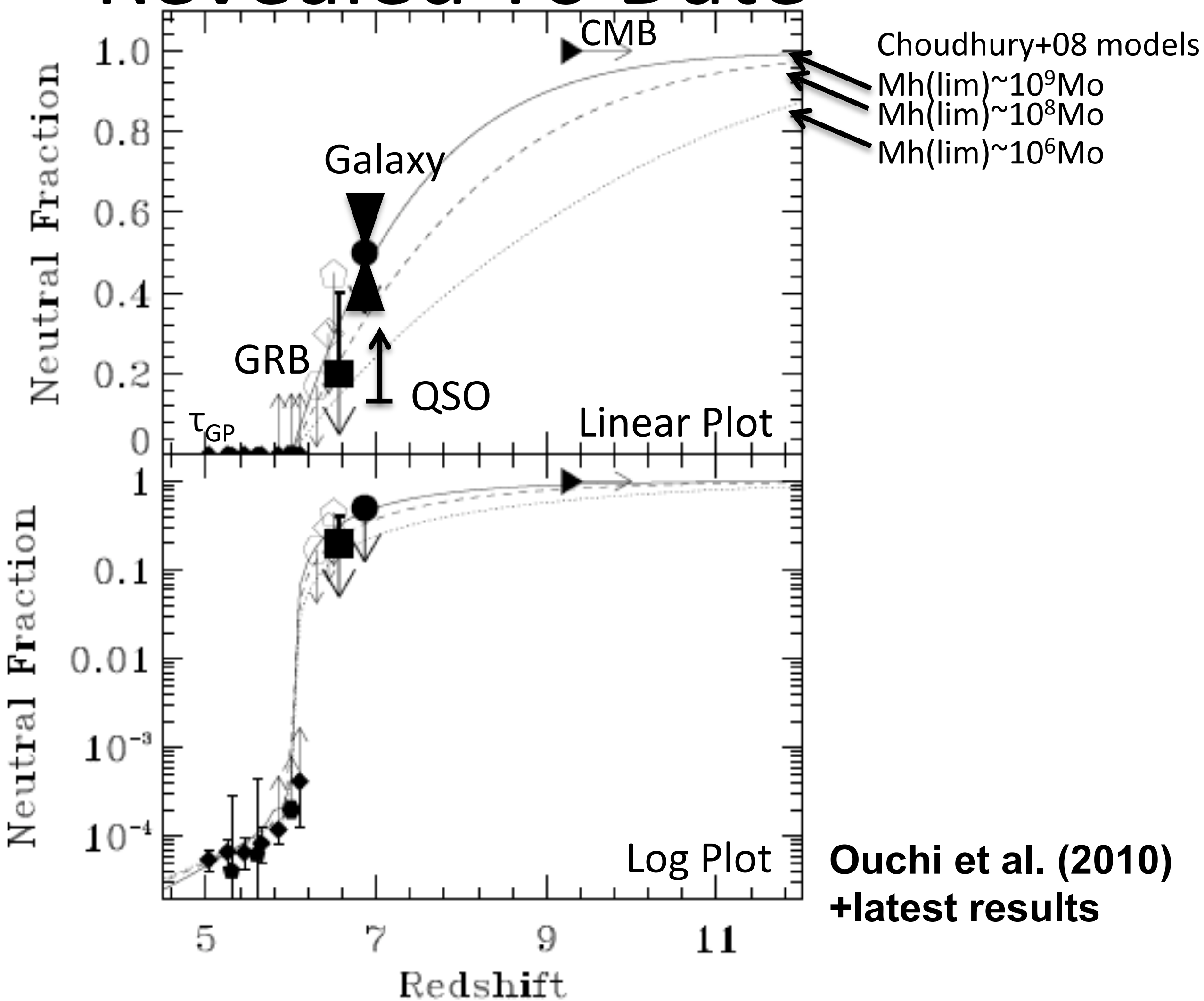
- Lya emission line from galaxies are also absorbed by damping wing absorption.

→ 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 Revealed To Date



Ouchi et al. (2010) +latest results

- Neutral hydrogen fraction, x_{HI}, is increasing beyond z~6.
- Although x_{HI}<1 at z~7 is known. Large uncertainties for z>6 constraints. Not clear about sharp/extended reionization? →Next generation surveys.

Probes of Cosmic Reionization Hisoty

1. Gunn Peterson test for Lya absorption w QSOs
   Problem: Limited to z<~6

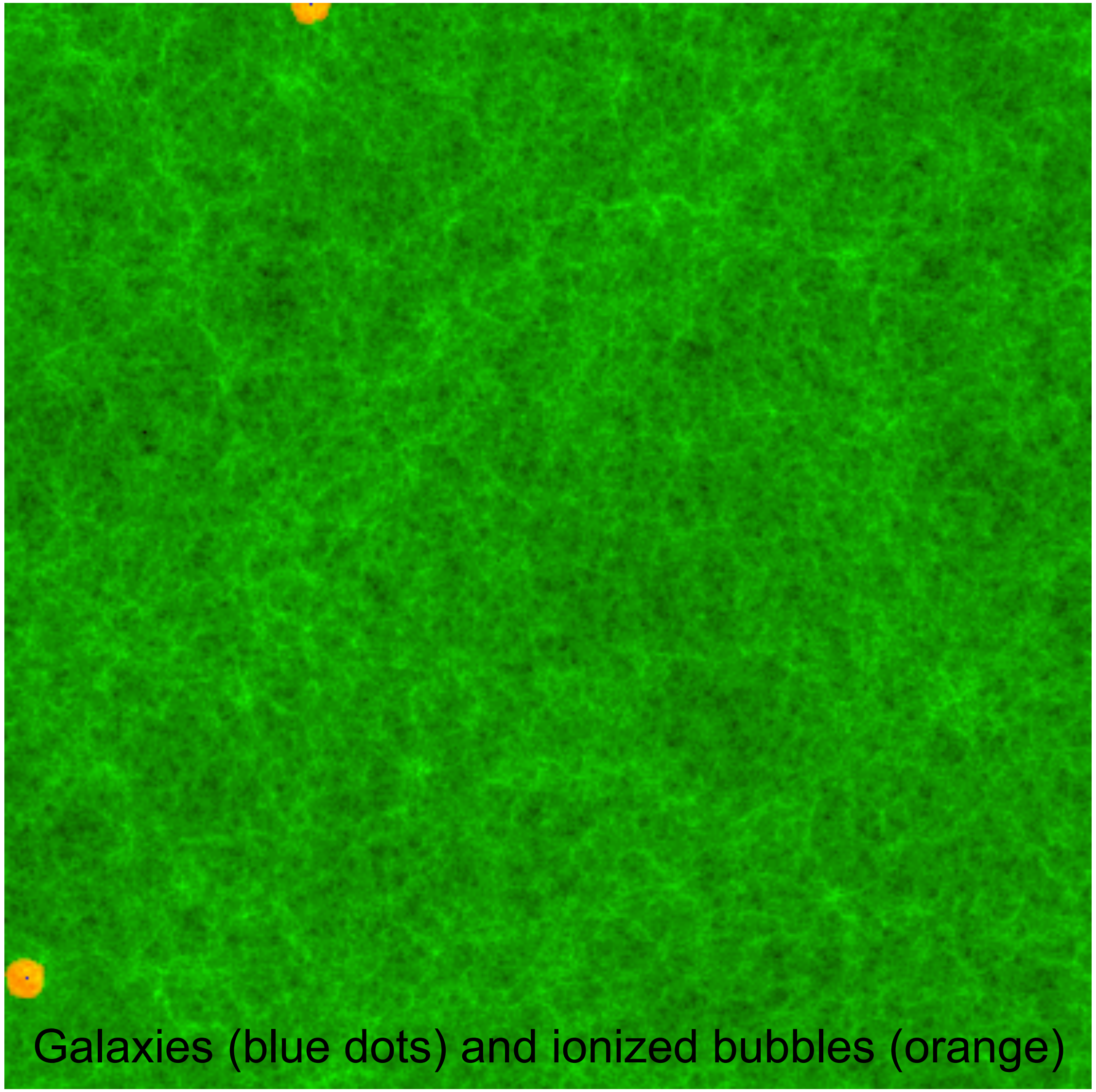
2. CMB polarization (τ_e only)
   Problem: Difficult to obtain time resolution

3. Lya dumping wing absorption
   a) GRBs, b) QSOs, c) Lya emitting galaxies
   Problem: One needs great sensitivities for Lya galaxies or identification of rare GRBs and QSOs.

Although the reionization epoch z~6-10 is known. Not clear about sharp/extended reionization?

PHYSICAL REASON OF COSMIC REIONIZATION

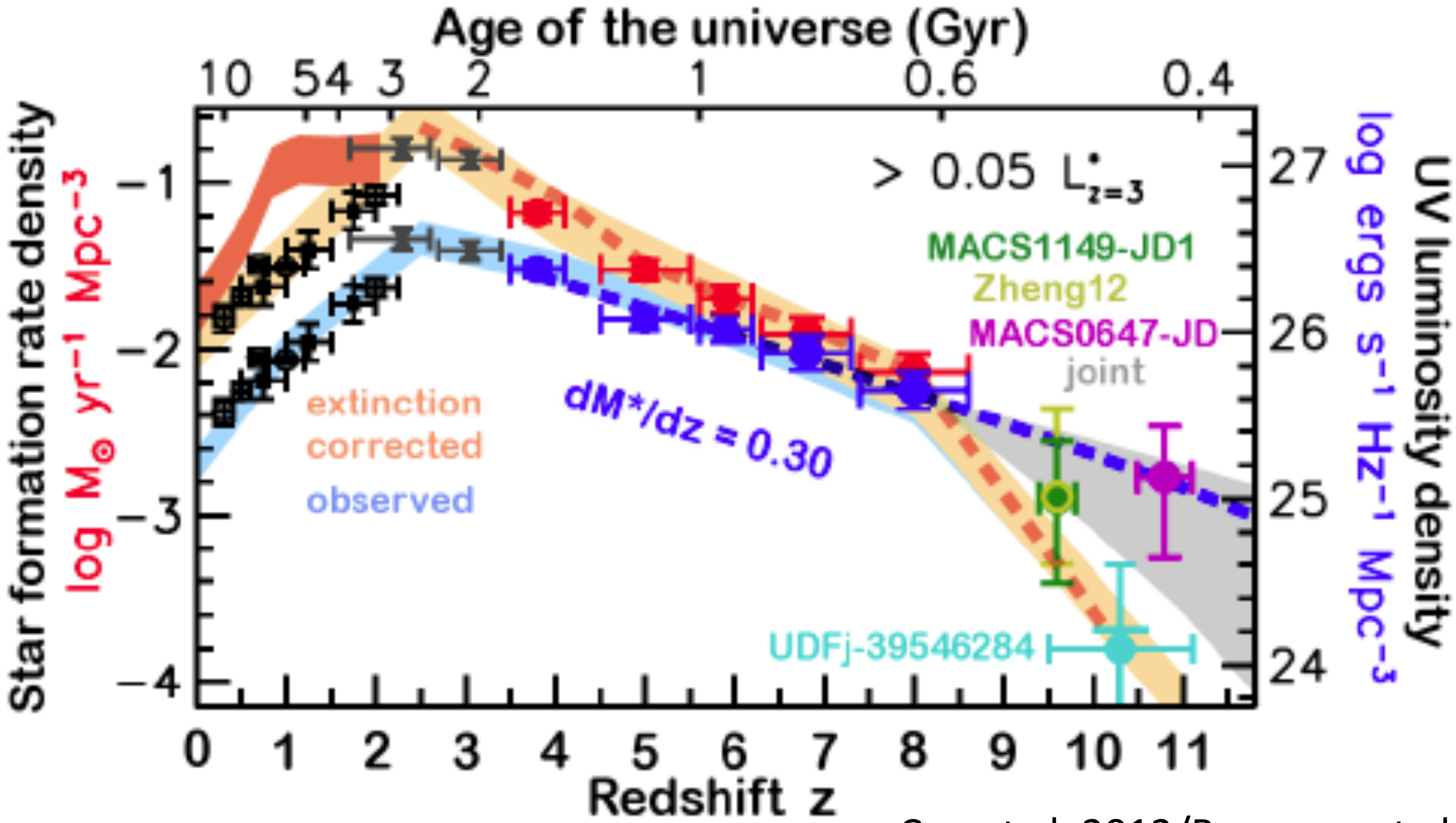
Recall: Cosmic reionization



RT simulations (Iliev et al. 2006)

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

Star-Formation History Known To Date



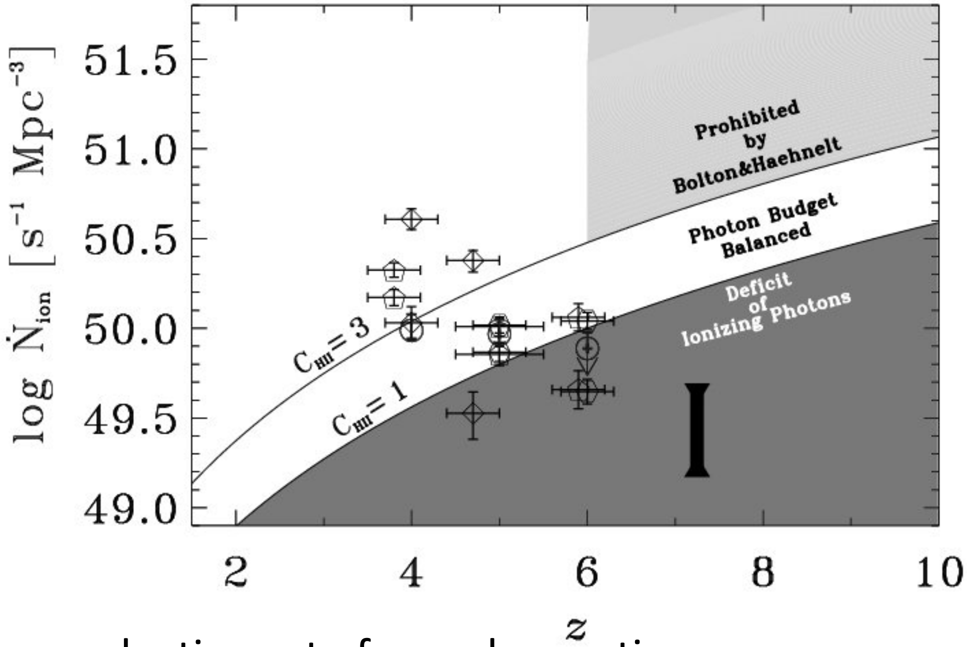
Coe et al. 2012/Bouwens et al. 2012

- Hubble Ultradeep field(HUDF)+CLASH
  - Peaking at z~2-3.
  - z~7 SFRD comparable today.
  - Rapid buildup in SFRD at z~8-10 and beyond??

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 observations

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

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

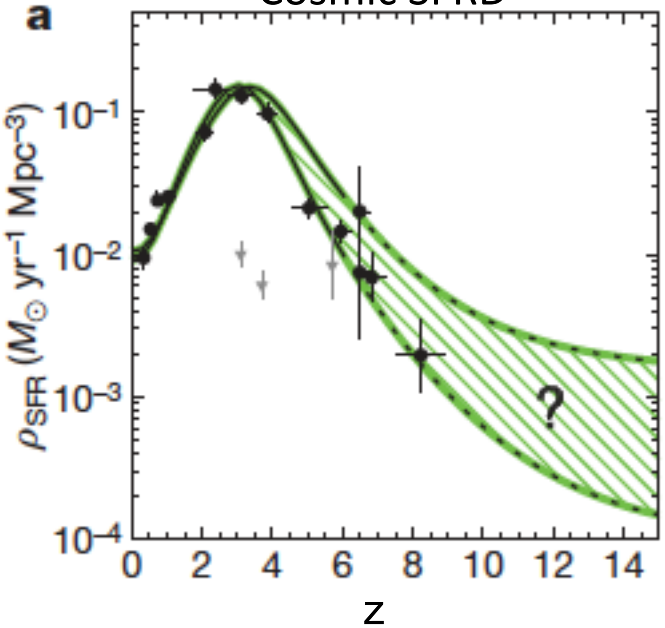
- Ionizing photons required for ionized Universe are given by

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

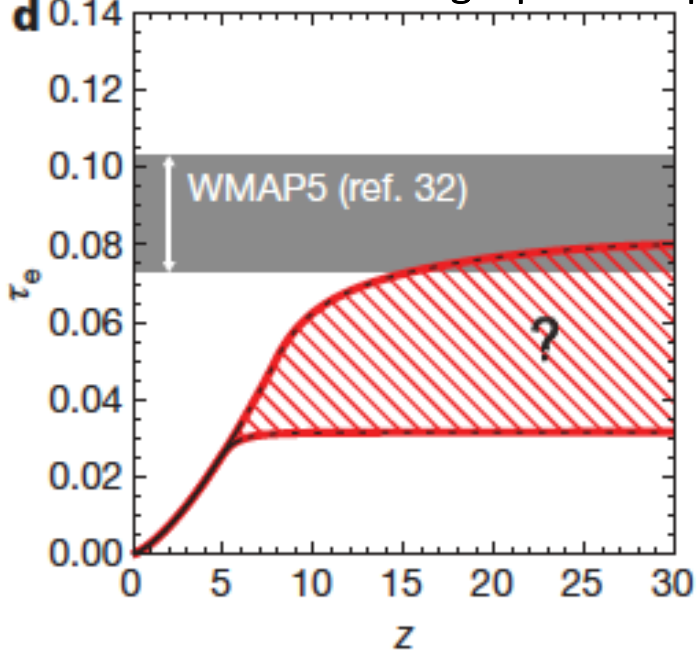
C_{HII} is a clumping factor, $C_{HII}=\langle n_{HII}^2\rangle/\langle n_{HII}\rangle^2$; $C_{HII}=1$ is for uniform universe.

Missing Ionizing Photon Problem?

Cosmic SFRD



Thomson Scattering Optical Depth



Robertson+10

Estimating ionizing photon budget.

– SF history ($\propto \rho_{uv}$)→ 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?

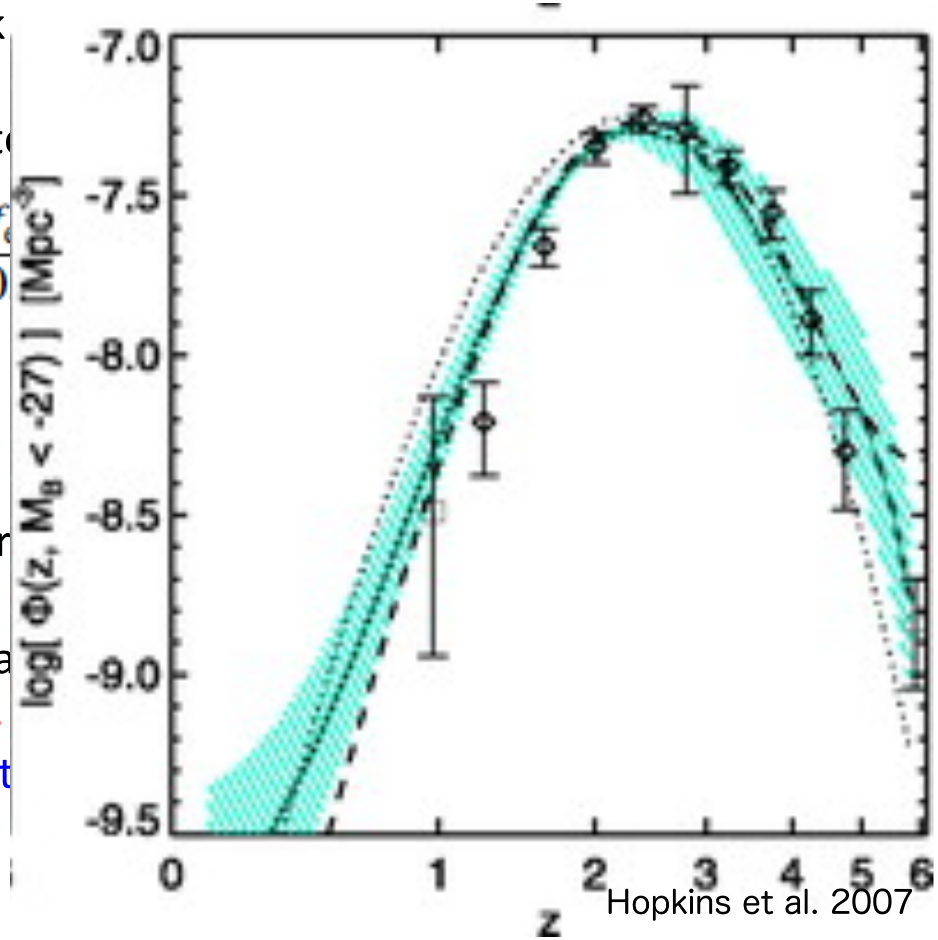
Missing Ionizing Photons (from Galaxies)?

- The other sources of reionization?
  - Quasars? But only a few % of ionizing photons at z~6 (e.g. Srbinovsky & Wyithe+07)
  - What else? Primordial blackholes?? Dark
- Uncertainties of ionizing photon emission rat

$$\dot{N}_{\rm ion}({\rm s}^{-1}\ {\rm Mpc}^{-3}) = 10^{49.7}\left(\frac{\epsilon^{\rm g}}{10^{25}}\right)\left(\frac{\alpha_{\rm s}}{3}\right)^{-1}\left(\frac{f_{\rm e}}{0}\right.$$

  - ϵ^{g}:UV luminosity density from galaxies
  - α_s:spectral index
  - f_{esc} :Escape fraction of ionizing photons fr

→ Changing properties of star-forming gala
Unexpectedly large pop. of faint galaxies
Efficient massive star formation(IMF/met
Increase of fesc (fesc>0.2; Ouchi+09b)?



Hopkins et al. 2007

Open Questions

1. Cosmic reionization history. Sharp/Extended reionization hisotry?

2. What are reionizing sources? Missing ionizing photon problem?

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

FUTURE OBSERVATIONS

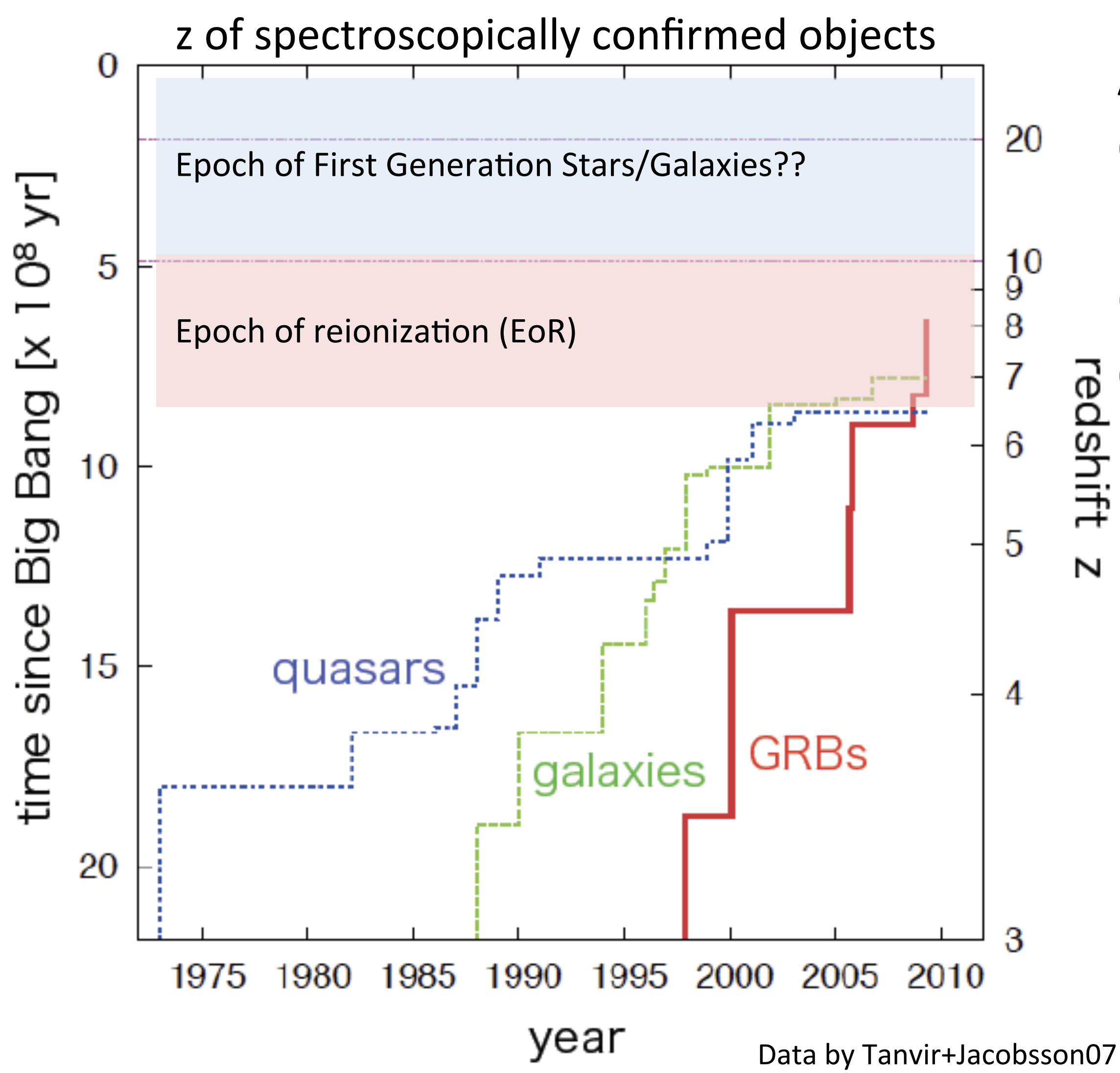
Open Questions

1. Cosmic reionization history. Sharp/Extended reionization hisotry?

2. What are reionizing sources? Missing ionizing photon problem?

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

How Distant/Old Epoch do the Latest Observations Reach?

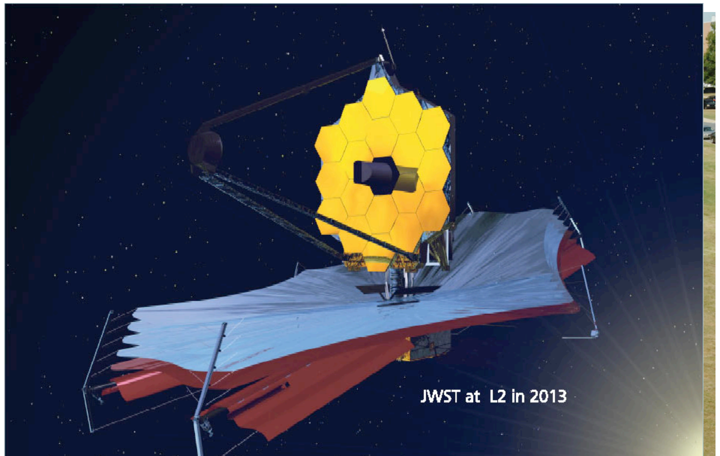


As of 2012
Galaxy: z=7.2
(cand: z~12)
QSO: z=7.1
GRB: z=8.2

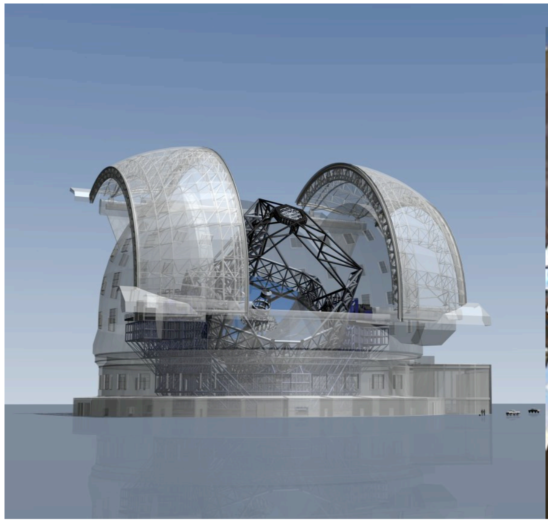
Data by Tanvir+Jacobsson07
updated by Yamazaki

Probing the Heart of the Reionization Epoch z~7-11 and Beyond

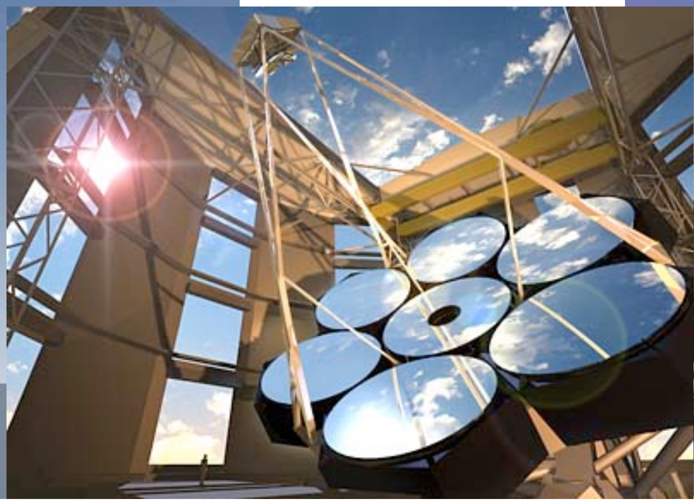
- Large space telescope (6.5m)
- Extremely large ground-based telescope (~30m)



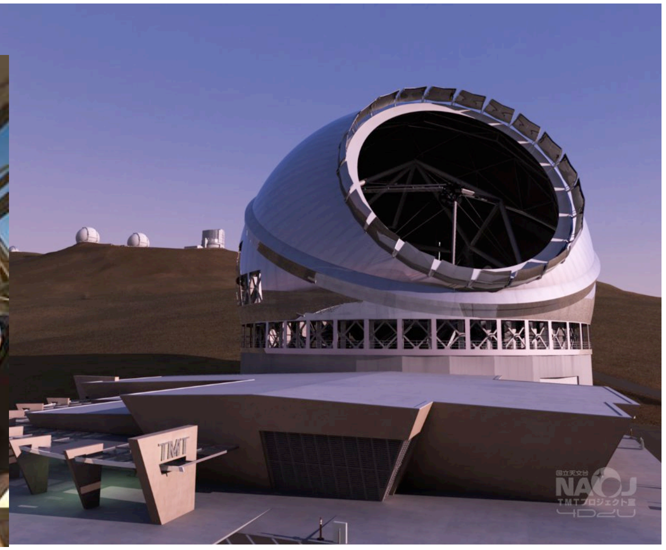
James Webb Space Telescope (JWST; >2018)



European Extremely Large Telescope (E-ELT; >2021)



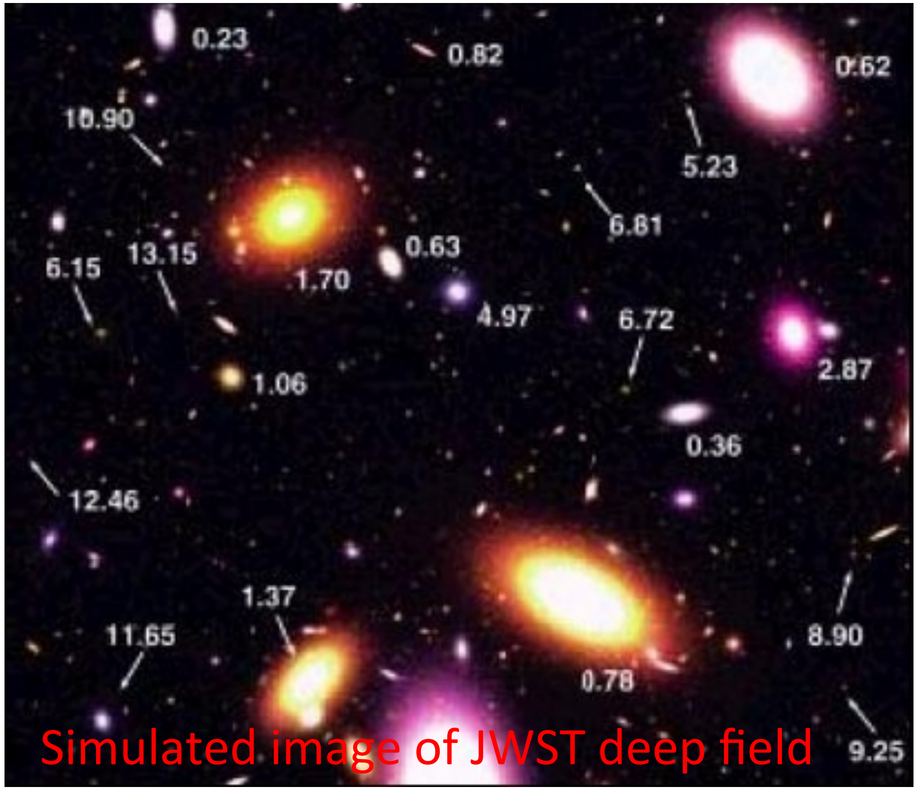
Giant Magellan Telescope (GMT; >2022)

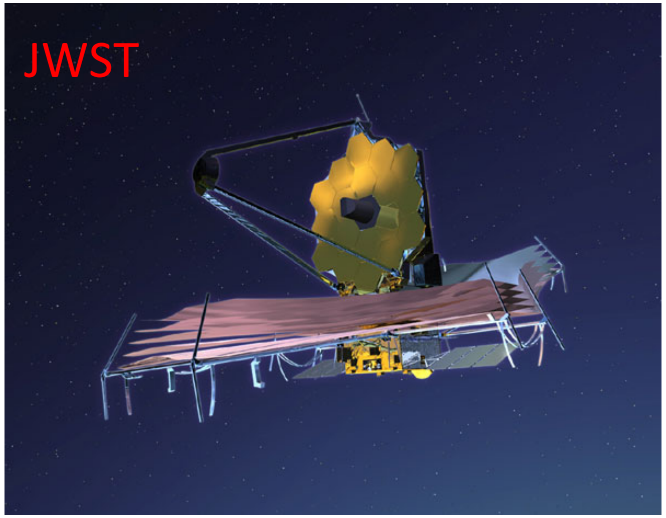


Thirty Meter Telescope (TMT; > 2022) incl. Japan

[redacted]

TMT (and JWST)





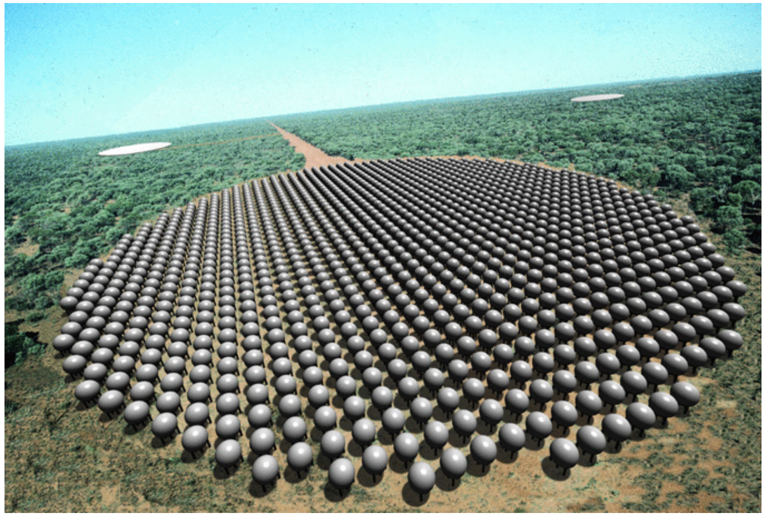
- The sensitivity is about 100 times better. (Subaru K band 25mag-> JWST >30 mag). A lot of breakthroughs are expected.

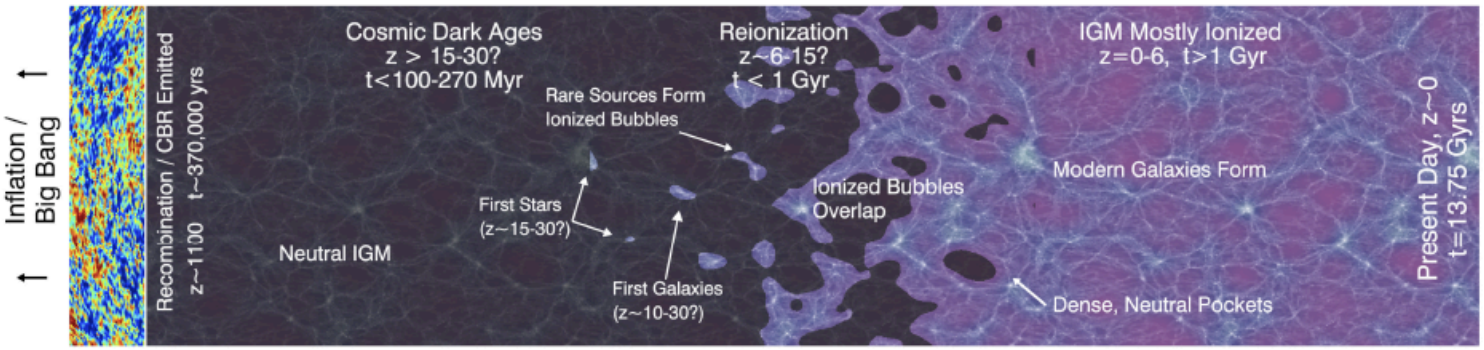
HI 21cm Observations

- HI neutral hydrogen→ 21cm emission (spin flip of hydrogen atom)

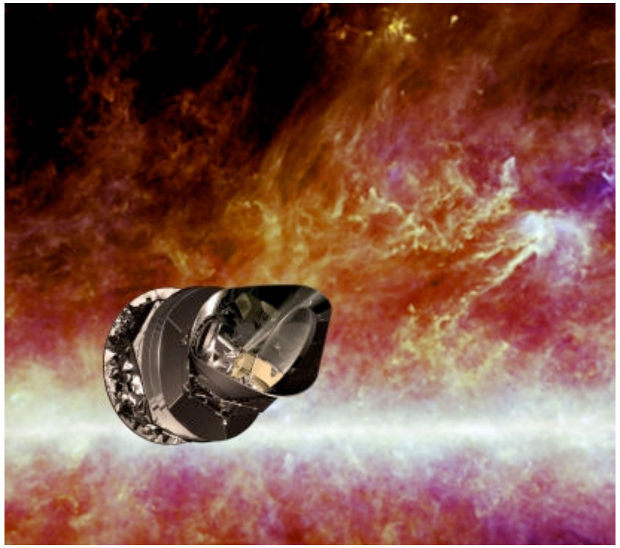
- LOFAR and NWA: Observing
- Square Kilometer Array (SKA; >2020) → reionization (z~6-12 IGM hydrogen)

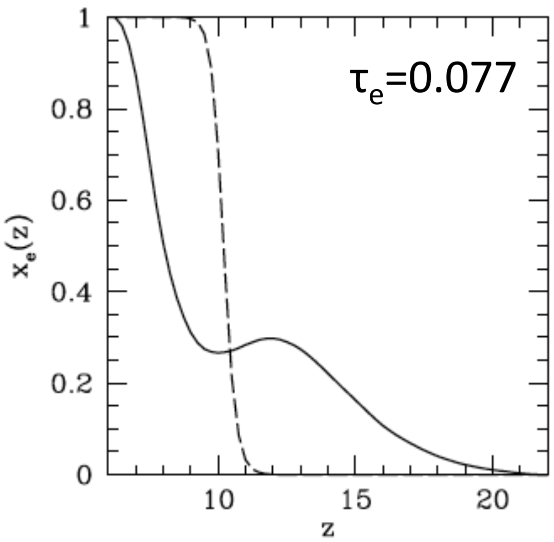
Square Kilometer Array

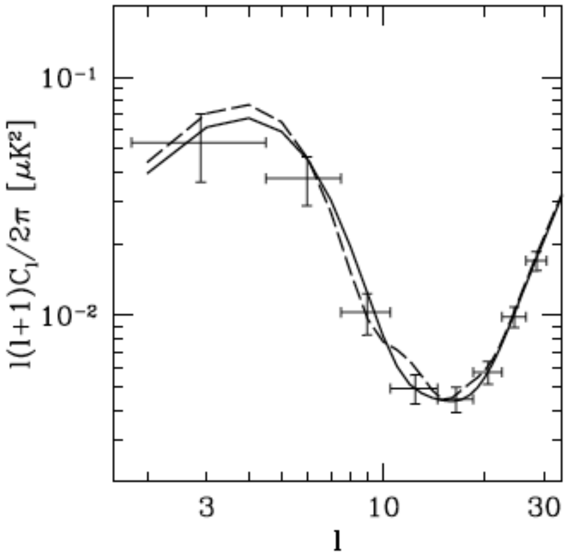




CMBPol







Zaldarriaga et al. 2008

- Power spectrum of E-mode polarization. Spatial distribution of polarized light → distinguishing the different reionization hisotory.

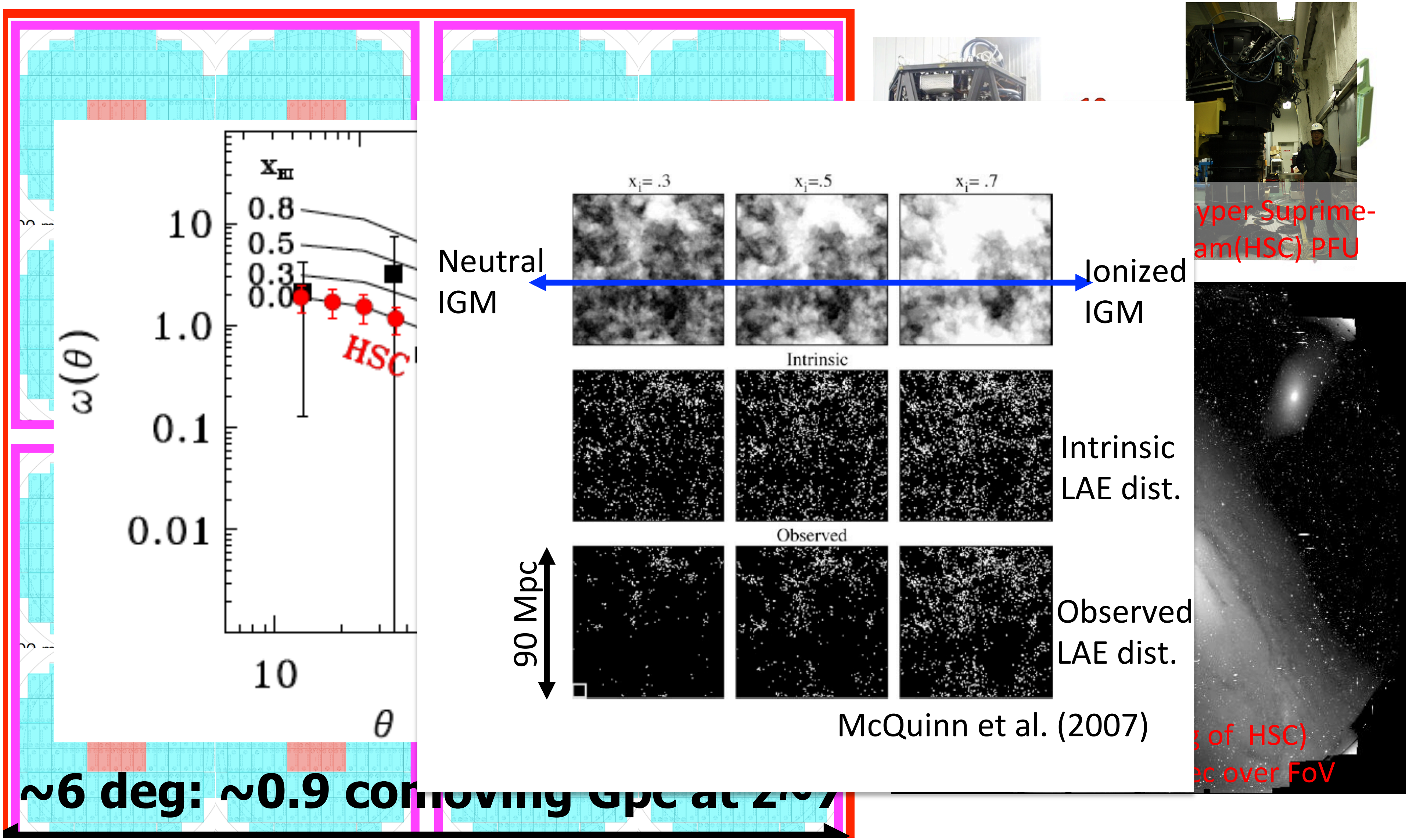
Open Questions

1. Cosmic reionization history. Sharp/Extended reionization hisotry?

2. What are reionizing sources? Missing ionizing photon problem?

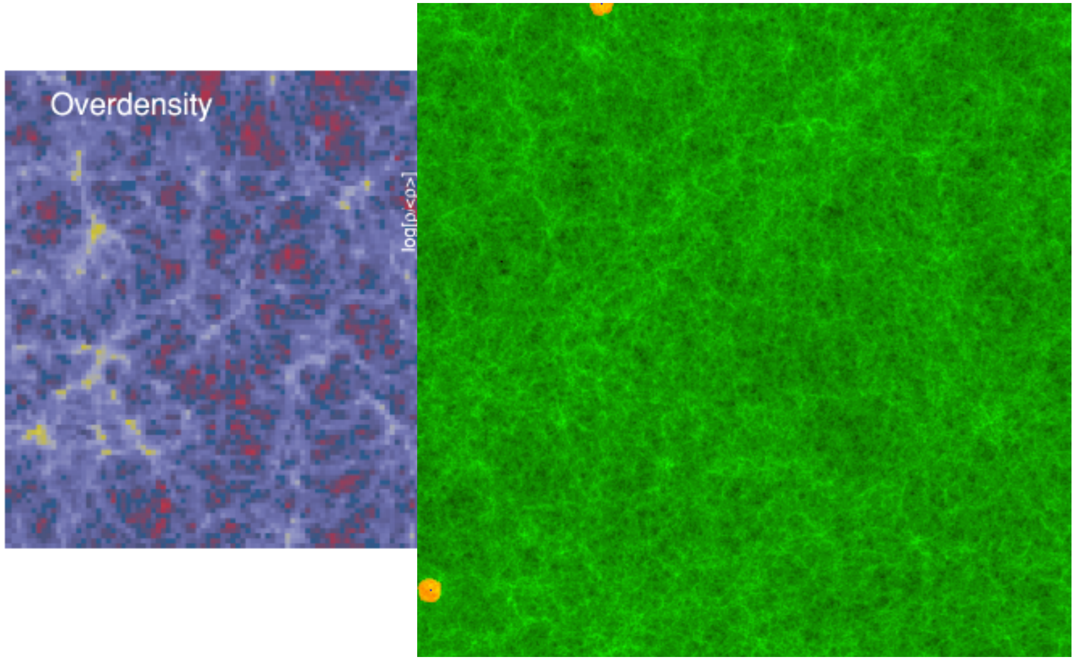
3. Physical process (inside-out, outside-in, filament-last?)

Hyper Suprime-Cam (HSC) Survey

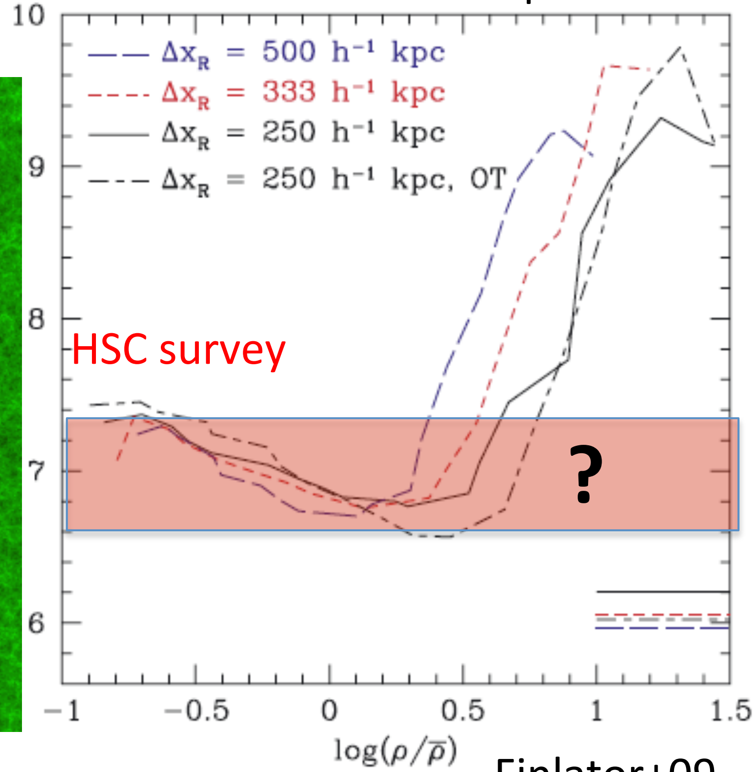


- Reducing the errors of IGM x_{HI} down to ~10% (model variance limit) w 10,000 LAEs at z~6-7
- Clustering→Investigating reionization process that cannot be addressed by the previous studies (topology of ionized bubbles etc.). HSC 300-night survey is starting next year.

Reionization Processes from Bubble Topology



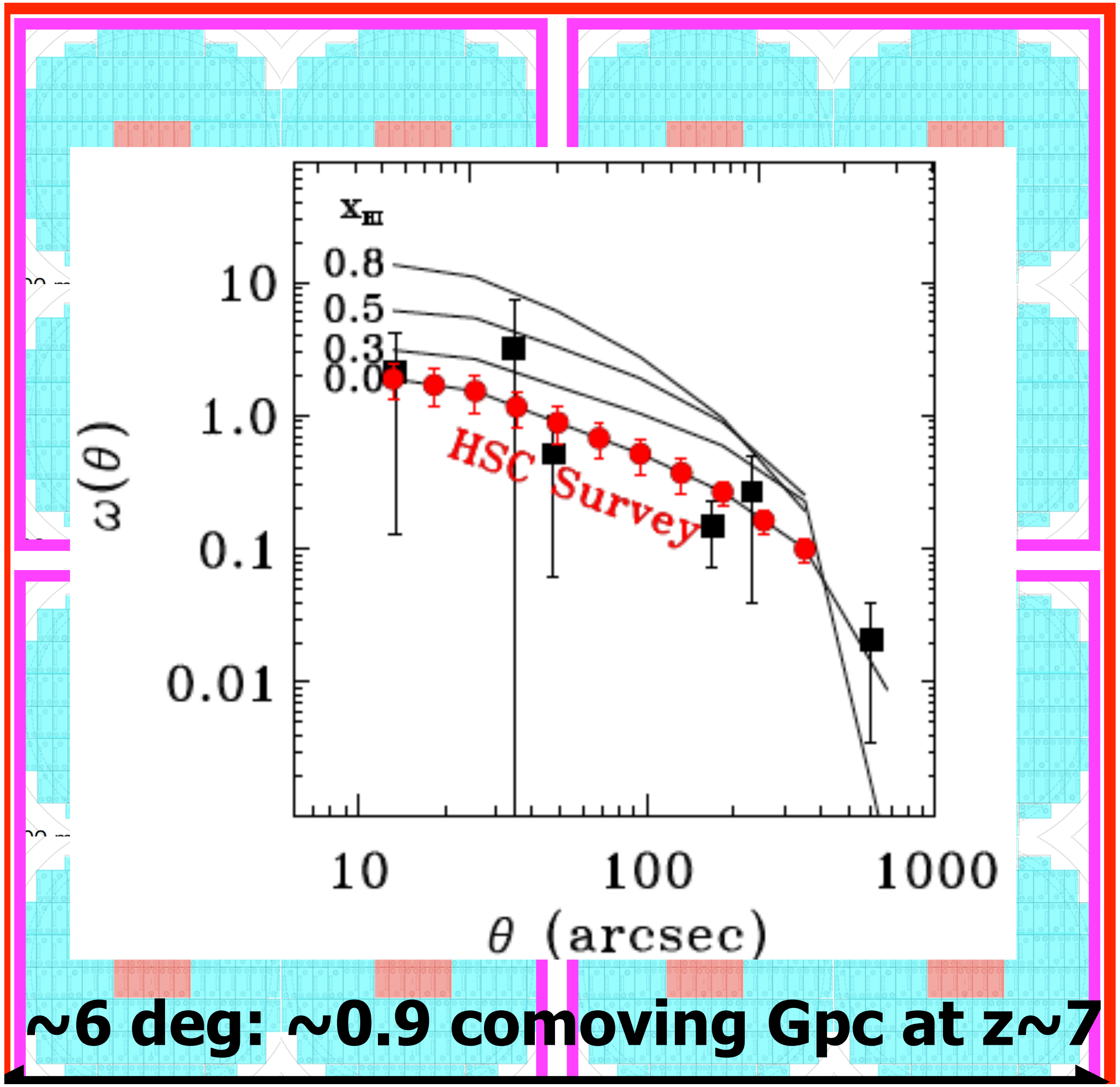
Predicted ionized epoch

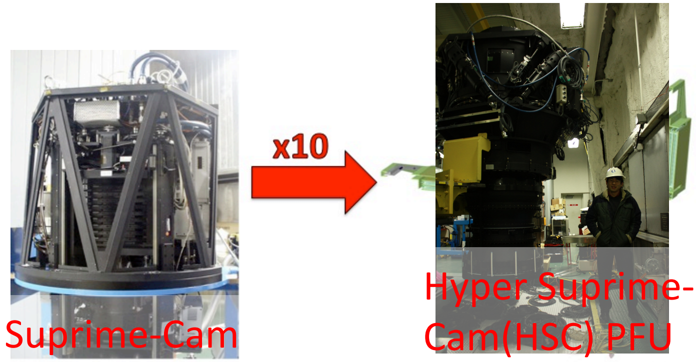


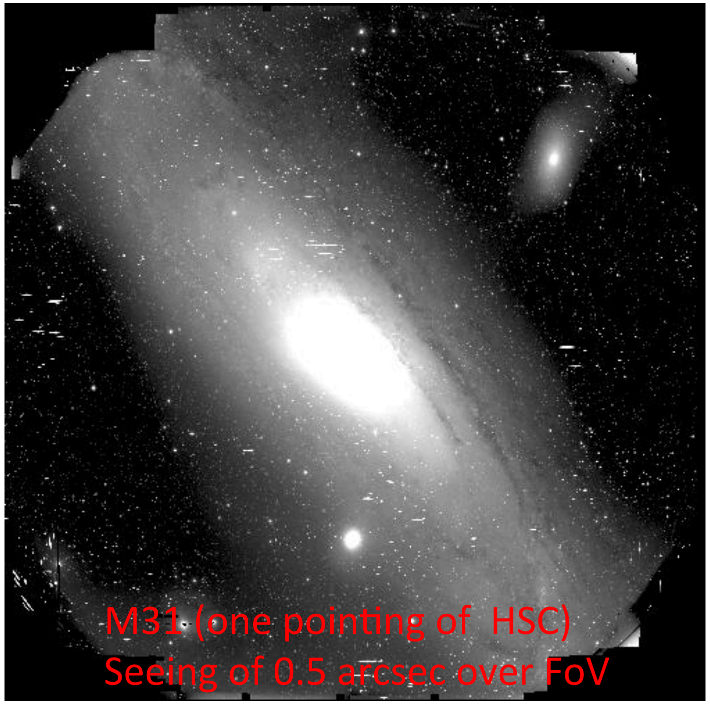
Finlator+09

– 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



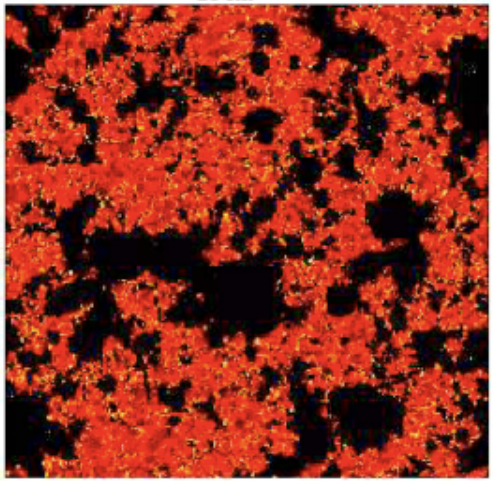




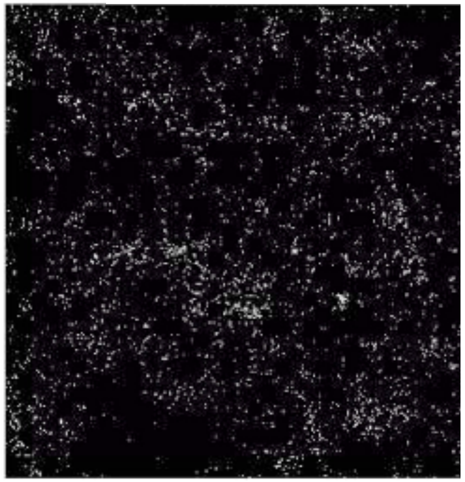
- Reducing the errors of IGM x_{HI} down to ~10% (model variance limit) w 10,000 LAEs at z~6-7
- Clustering→Investigating reionization process that cannot be addressed by the previous studies (topology of ionized bubbles etc.). HSC 300-night survey is starting next year.

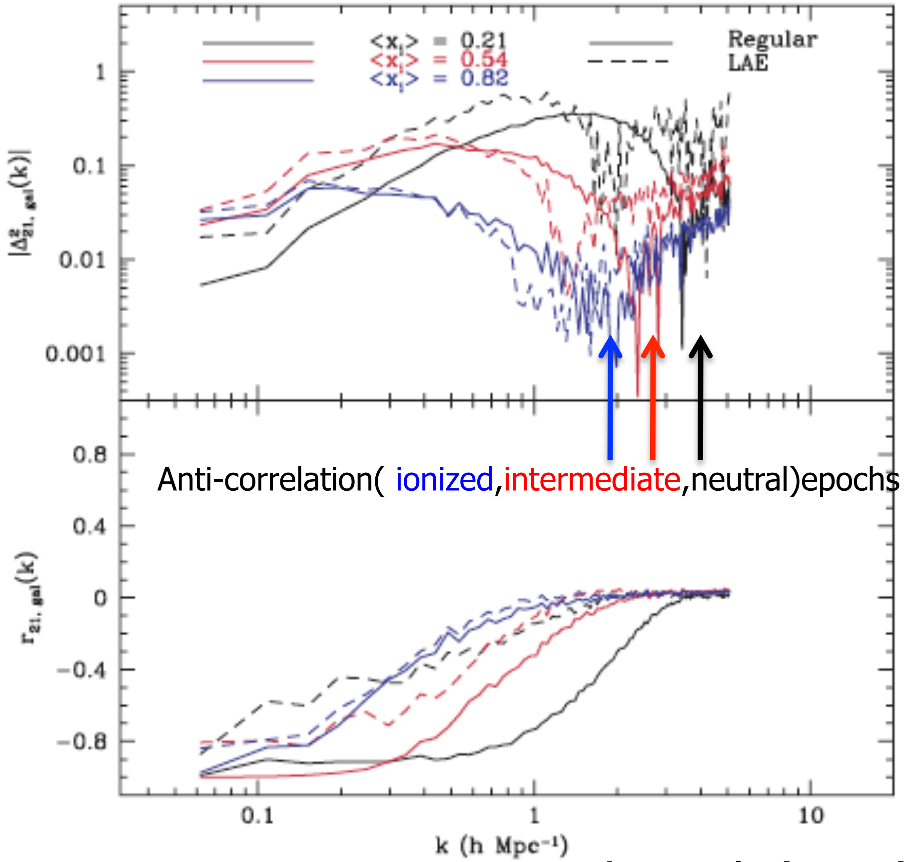
Physical Process of Reionization

21cm



Galaxies





Lidz et al. (2009)

- HI distributions (from 21cm) and galaxies (from optical) anti-correlate.
- Distance scales of anti-correlation→ 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+), HSC(Sugiyama, Yoshida, Ouchi)

Very Large+Detailed Cosmological Simulations

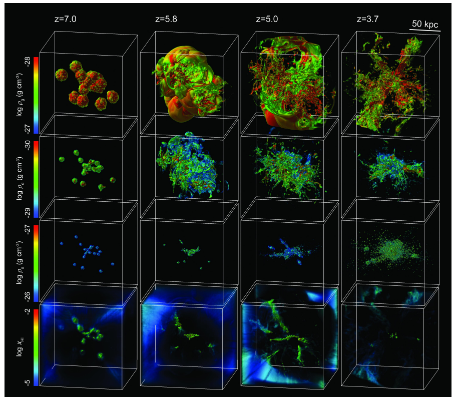
- N-body, SPH, radiative transfer (RT) simulations for the size of HSC survey (~1Gpc; Umemura, Mori [Tsukuba], Inoue [OsakaSangyo], et al.)

T2K-Tsukuba

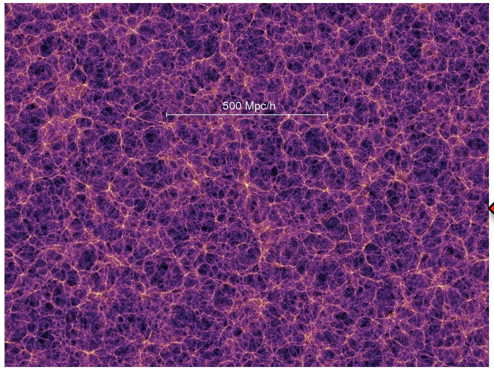
- Two step simulations
  - For detailed galaxy formation and ionizing photon emission processes (fesc evolution, faint galaxies+suppression etc; ~100kpc; Hasegawa+12)
  - ~1Gpc size N-body and RT simulations (~resolution: 100kpc)

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

K computer



SPH simulations with RT(Yajima+09)



N-body simulations (Springel+05)

Hyper Suprime-Cam Results

Summary

- What is ‘cosmic reionization’?
  a) Reionization history
  - Gunn Peterson test (QSO)
  - Cosmic Microwave Background Polarization
  - Lyα Damping Wing
    →z~6-10 reionization epoch

  b) Physical reasons of reionization, known to date.
  Can galaxies reionize the universe??

- Open questions (unknowns)
  1. Cosmic reionization history. Sharp/Extended reionization hisotry?
  2. What are reionizing sources? Missing ionizing photon problem?
  3. Physical process (inside-out, outside-in, filament-last?)

- Future Projects (optical/NIR-radio):
  - For 1 and 2: TMT, JWST, LOFAR/SKA, CMB pol satellites, Subaru/HSC
  - For 3: Subaru/HSC x LOFAR/SKA