Galaxy Formation and Cosmic Reionization over the History of the Universe

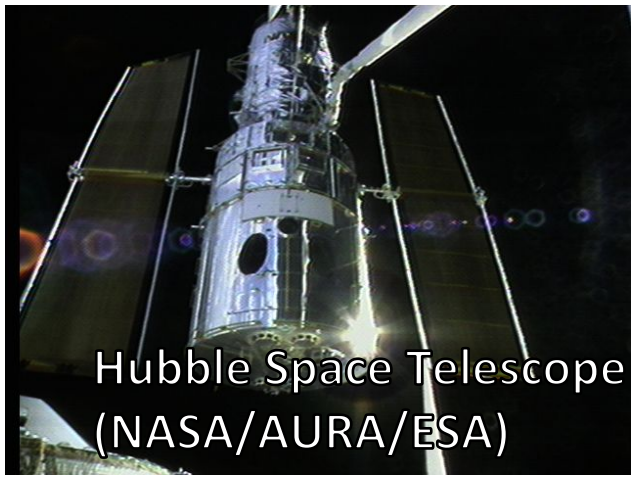
MACSJ0717.5+3745
Credit:NASA, ESA and the HST Frontier Fields team (STScI)

Masami Ouchi

U. Tokyo, ICRR

Galaxy Formation Studied with Large Telescopes


10m Keck Telescopes(Calf Assoc.)


Hubble Space Telescope (NASA/AURA/ESA)

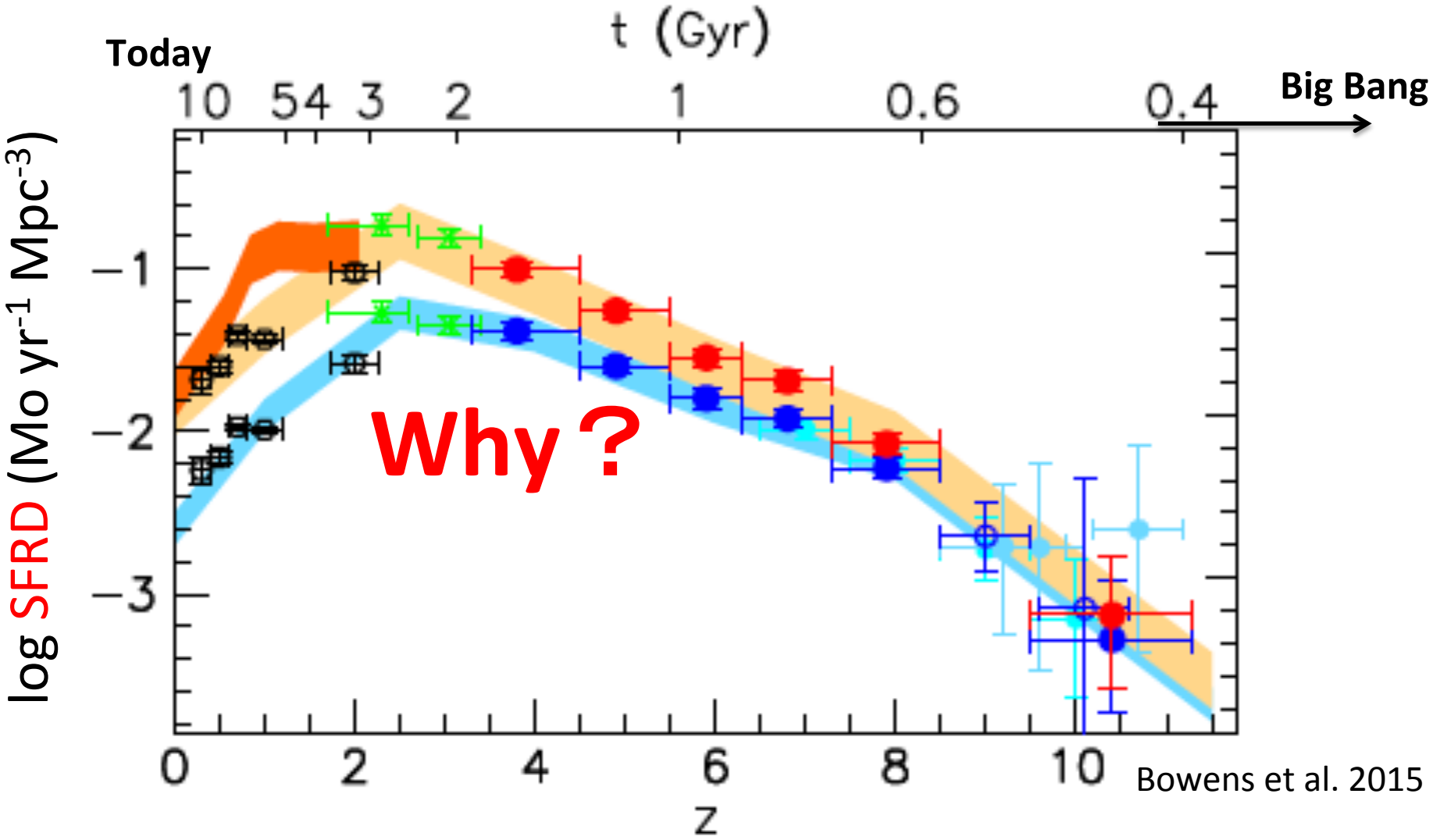

8.2m Subaru Telescope (NAOJ)


Chandra X-ray Observatory (NASA/SAO/CXC)


Spitzer Space Telescope (NASA/JPL/Caltech)


ALMA(ESO/NRAO/NAOJ..)

Galaxies in the Cosmic Evolution

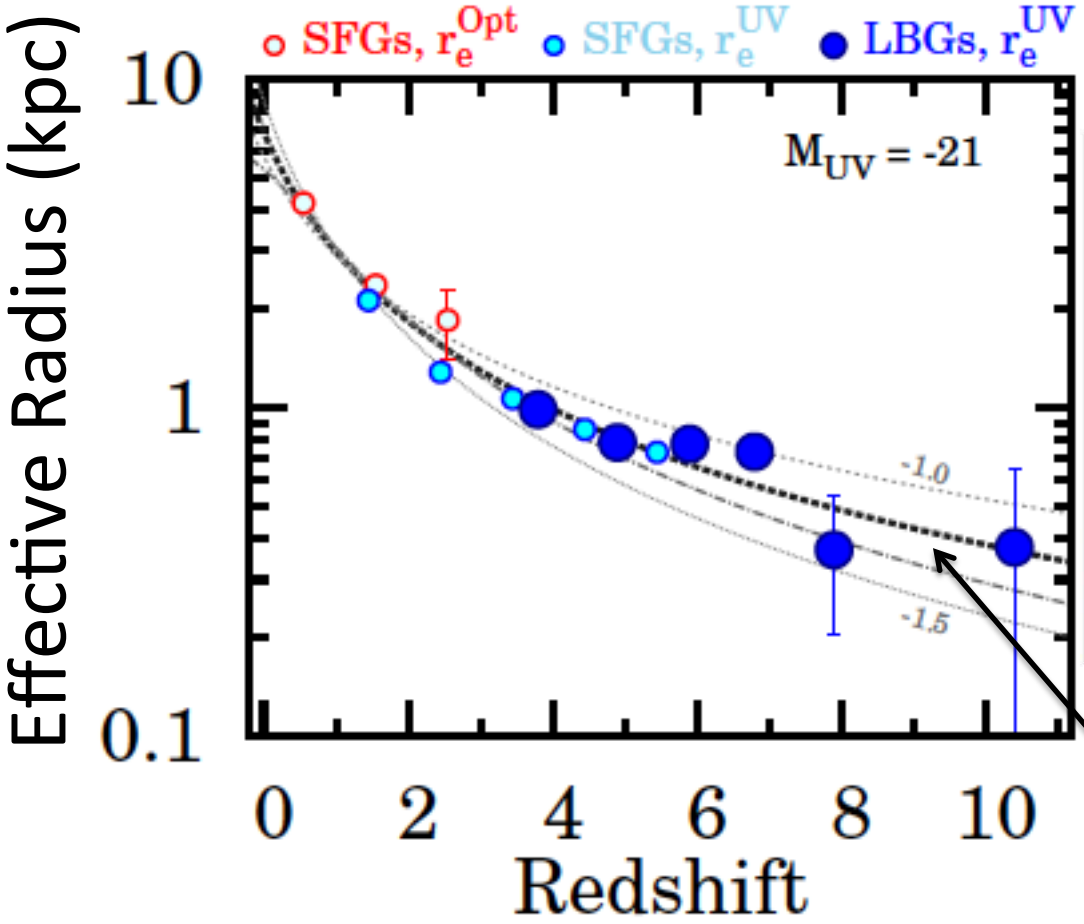


Bowens et al. 2015

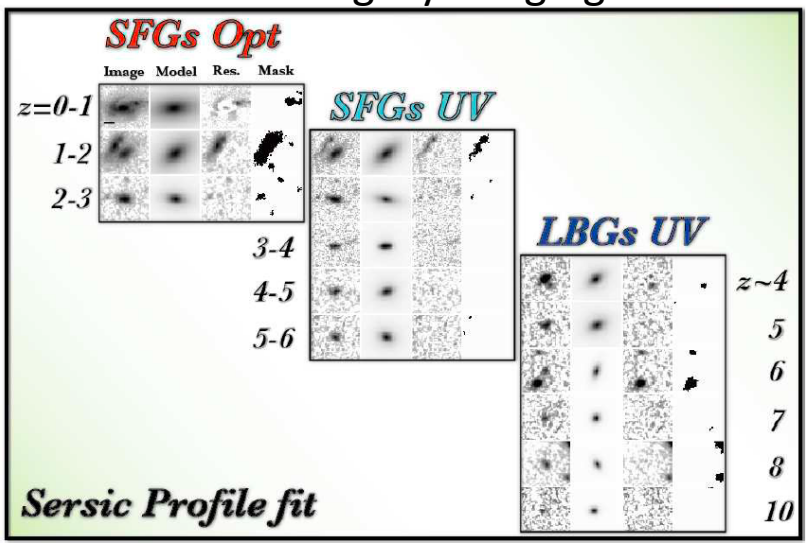
UV/IR luminosities (short-lifetime massive stars) of galaxies → star-formation rate

- Cosmic star-formation rate density (SFRD) evolution
  - Peaking at z~2 (a.k.a cosmic noon)
  - Decreasing from z~2 towards high-z

Galaxy Morphology Evolution: 1) Size



Hubble Legacy Imaging Data



Shibuya, MO, Harikane+15

see also Holwerda+15, Curtis-Lake+15

Only r_e=300-400pc
Size of MW GMA

- Average Sersic index -> n=1.5 (disk-ish profile)

  Corrected for cosmological SB dimming effects by fitting

z=0

Milky Way

M82

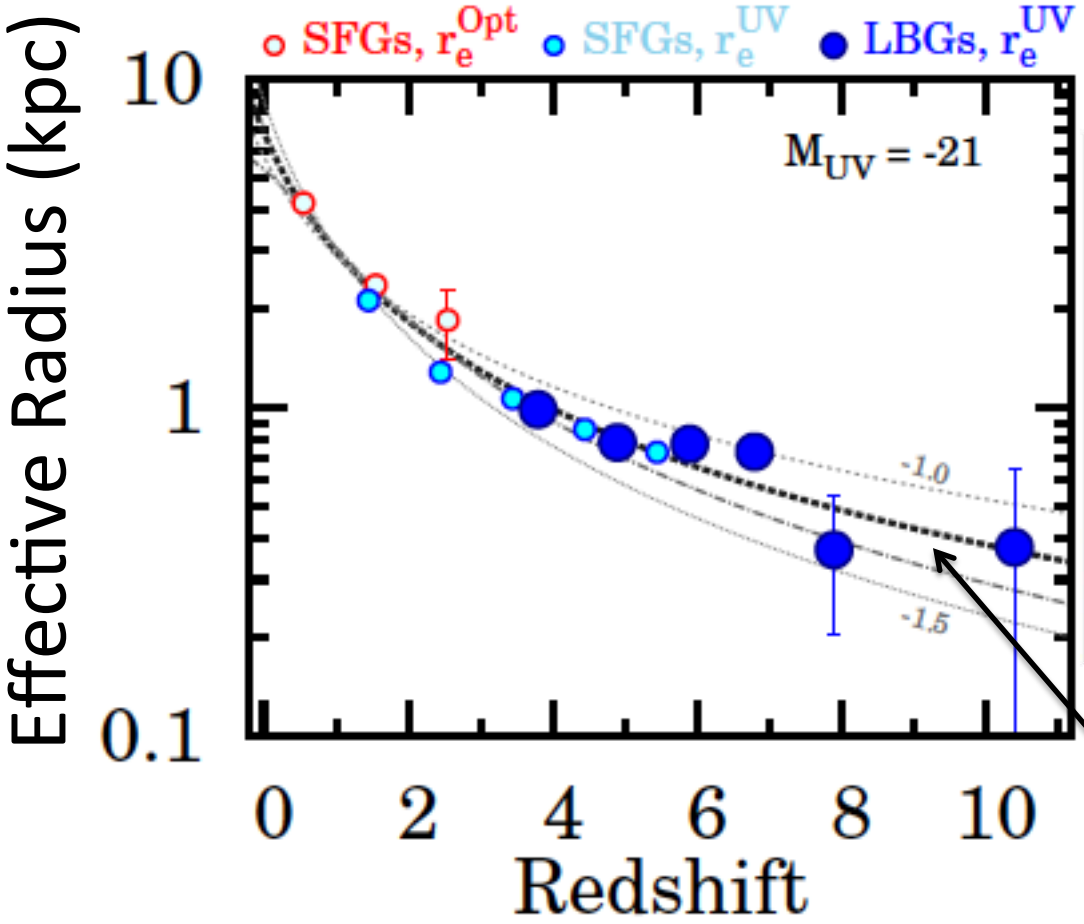
z∼10
Galaxy (Average)

Ono et al. 2012

NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Illustration
(Shogakukan)

Galaxy Morphology Evolution: 1) Size



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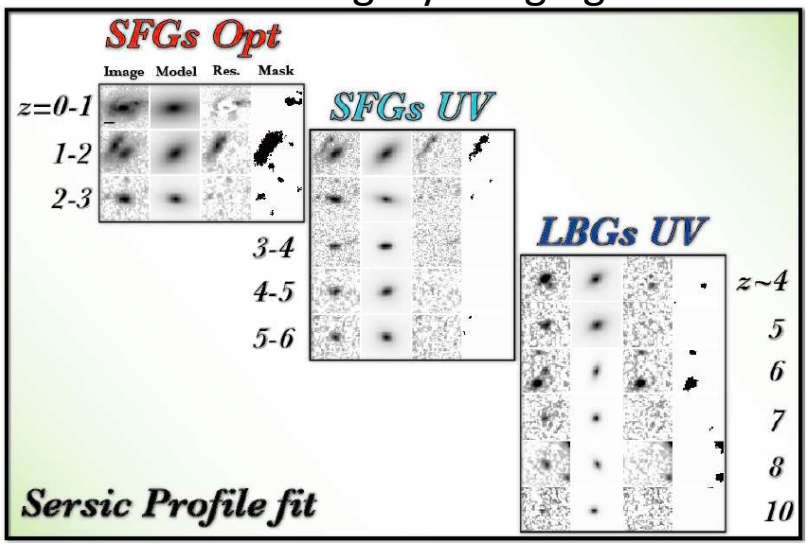

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Size of MW GMA

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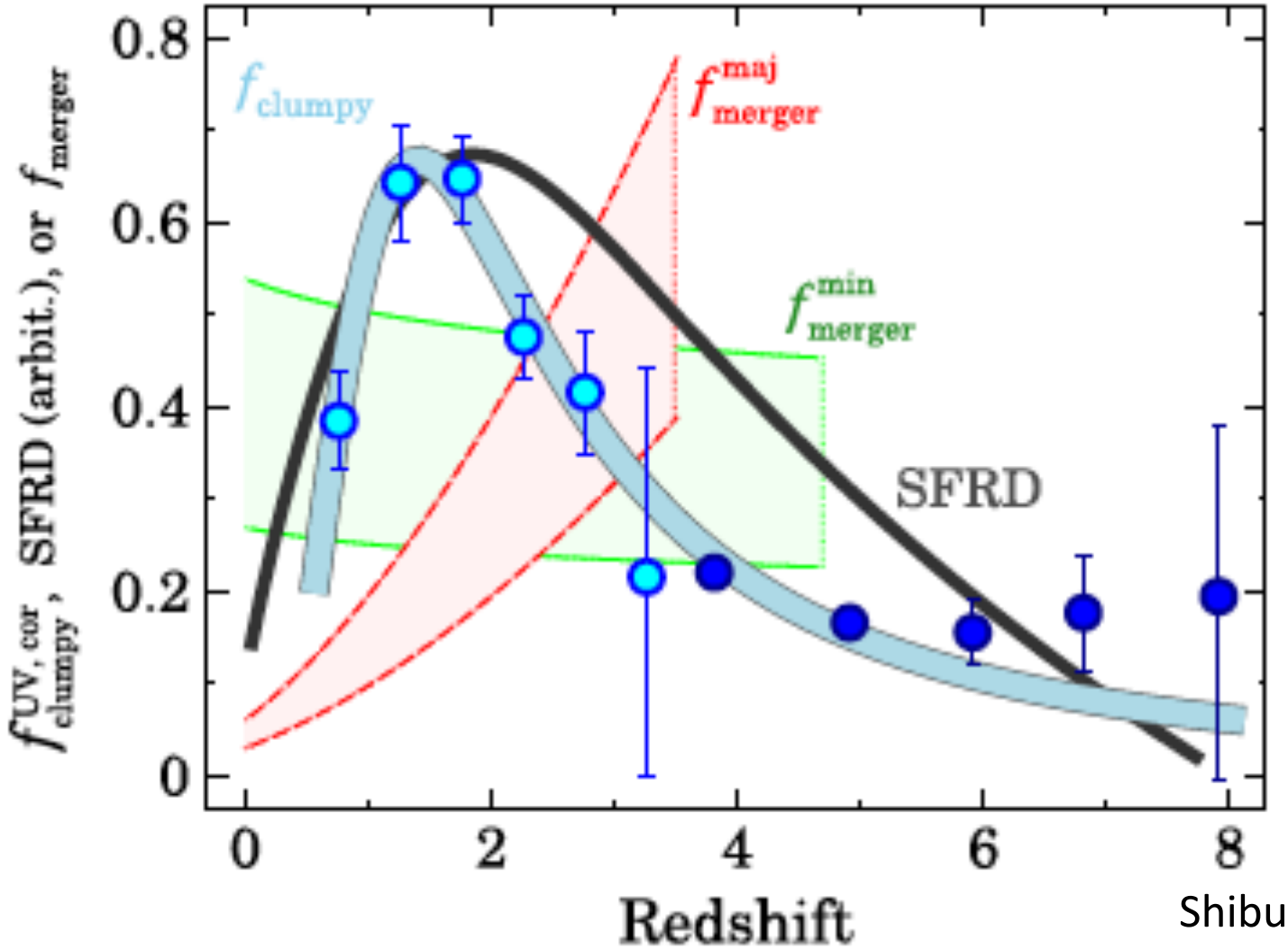
$$r_e \propto (1+z)^{-1.12\pm0.06}$$

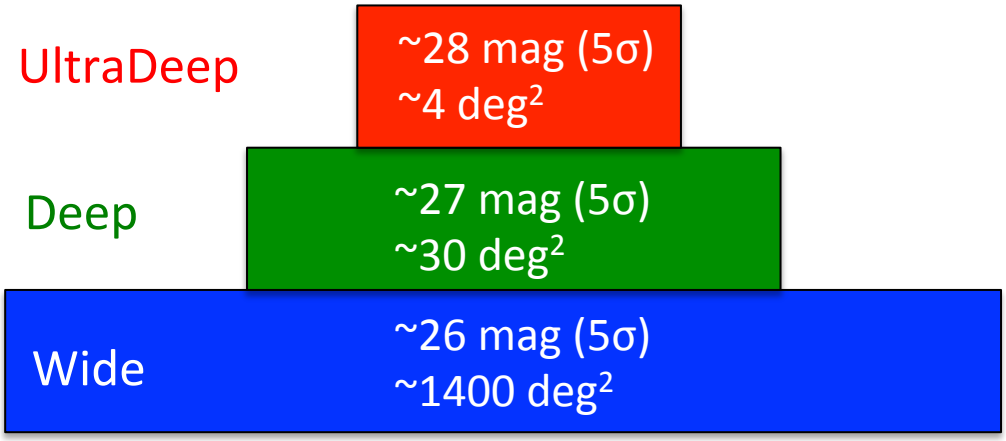
Galaxy Morphology Evolution: 2) Clumps

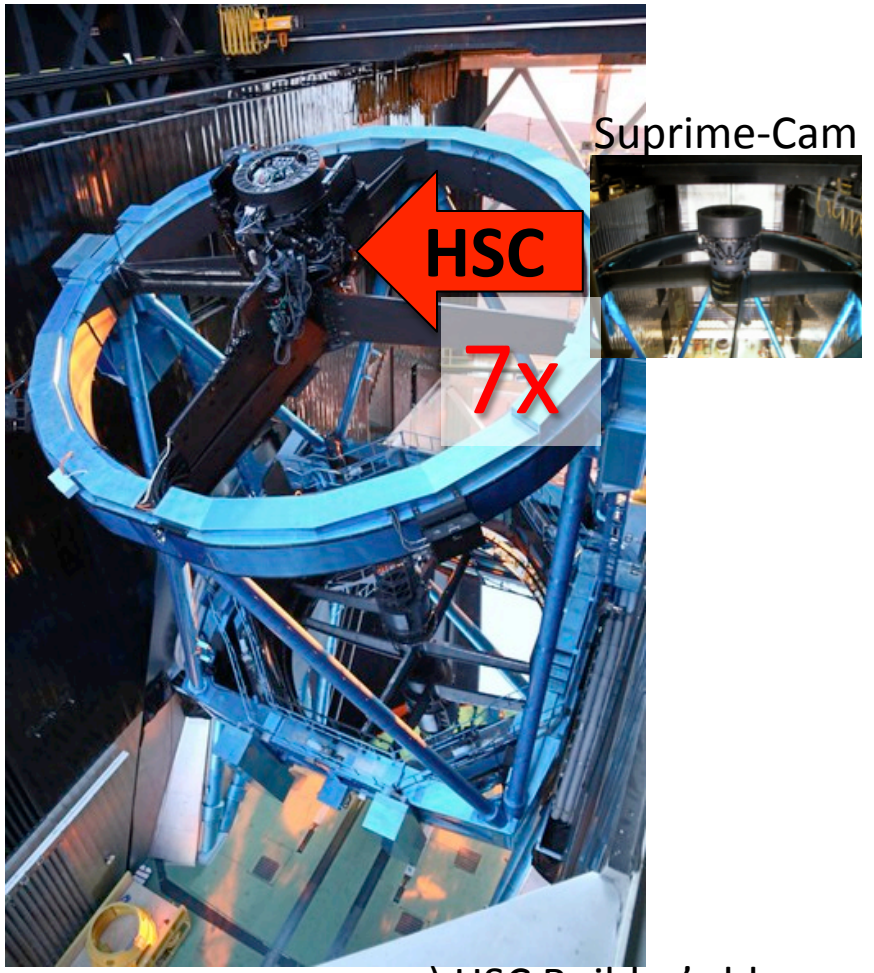


Shibuya, MO, Harikane+16

- Evolution of clumpy galaxy frac. (N_{clump}/N_{all}) → following SFRD evolution
- Merger?? But merger rate evolves by $(1+z)^{2\text{-}3}$ (Millenium/Illustris simu.)
- Why? Adding another question to galaxy formation problems.

Subaru Hyper Suprime-Cam (HSC) Survey

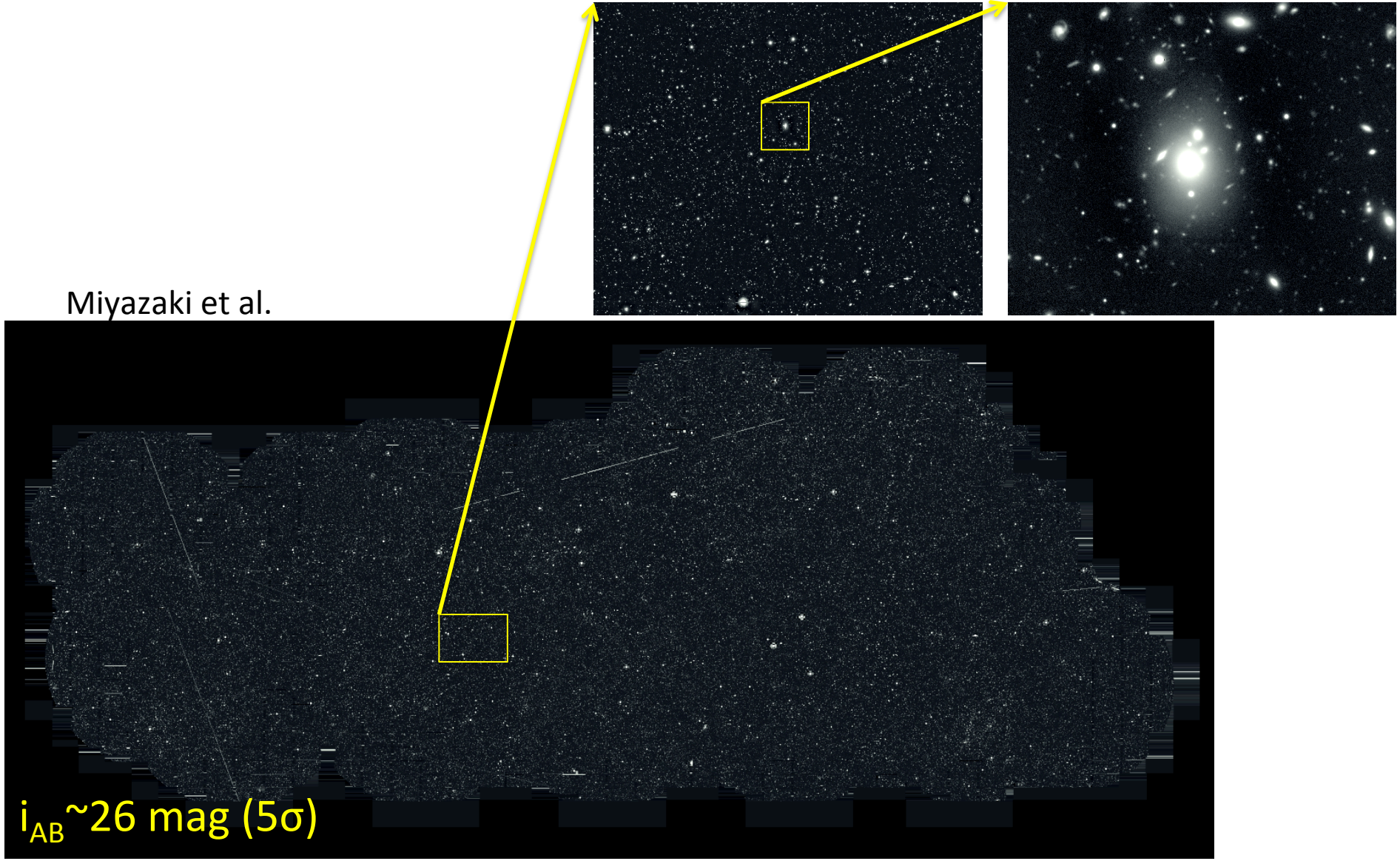




c) HSC Builder's blog

- Subaru HSC: very wide-field optical imager w FoV 1.8 deg²
  - HSC survey (PI: Miyazaki) has started since 2014 under the collaboration of Japan, Princeton, and Taiwan.

HSC Survey Data



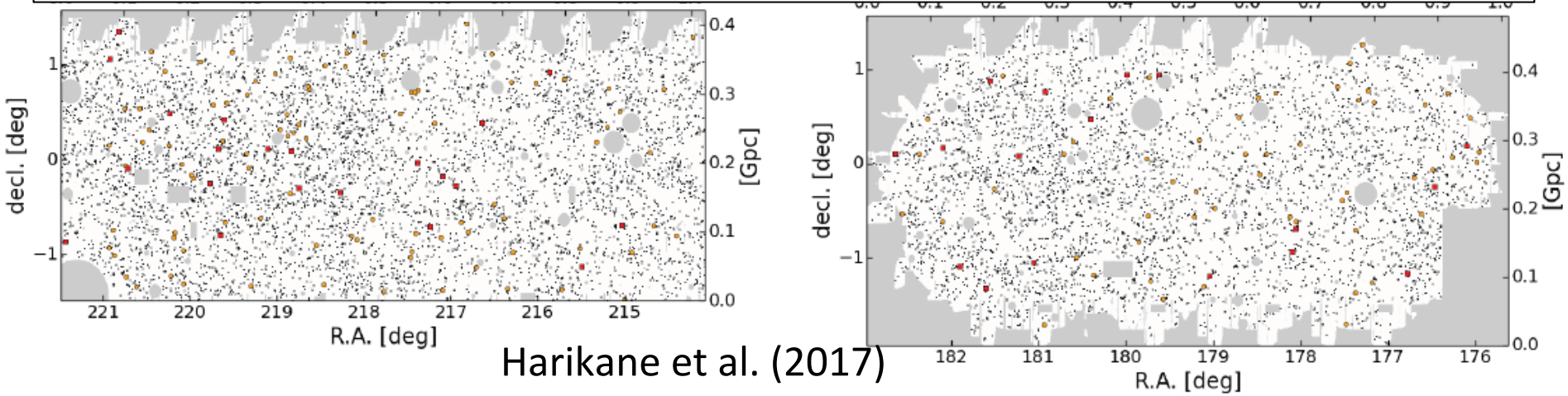
- GAMA field (~20 deg^2)
- It took effectively 0.3 nights! Seeing: 0.4-0.6 arcsec (FWHM).

Largest Sample of High-z Galaxies at z=4-7

Examples

Ono et al. (2017)

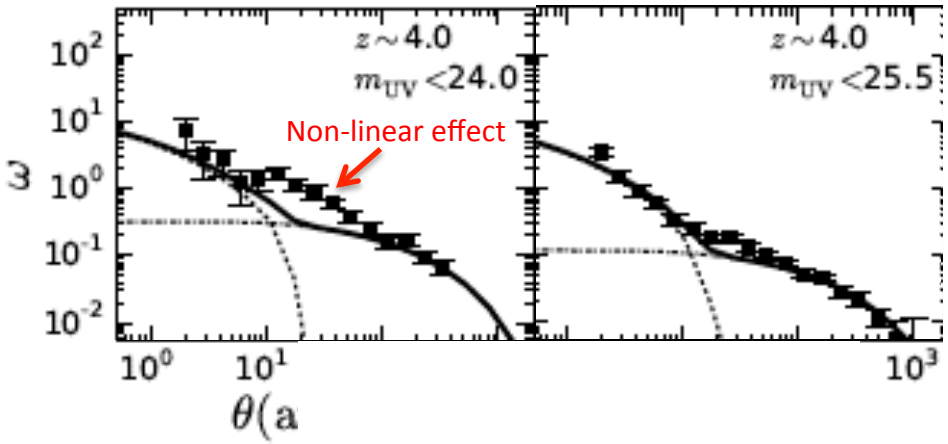
～100 times larger than prev. samples
First cosmological probe of z≳4 galaxies

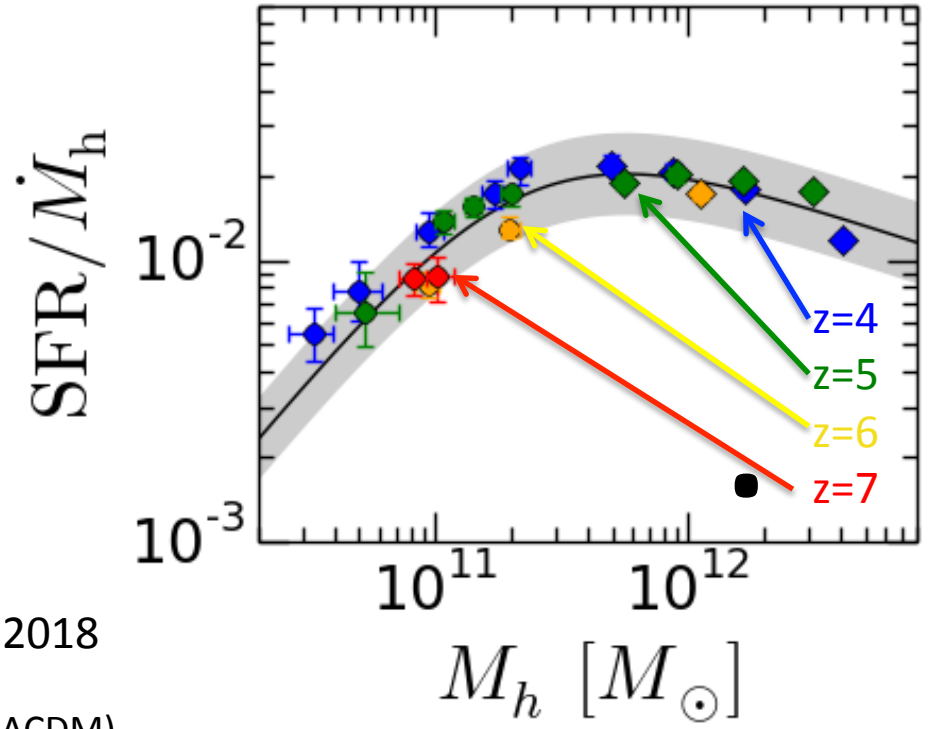


Harikane et al. (2017)

- **579,555 galaxies** (by dropout technique)
  over 100 deg^2 → 1.4 Gpc^3 (cosmology scale)

Clustering and Fundamental Relation





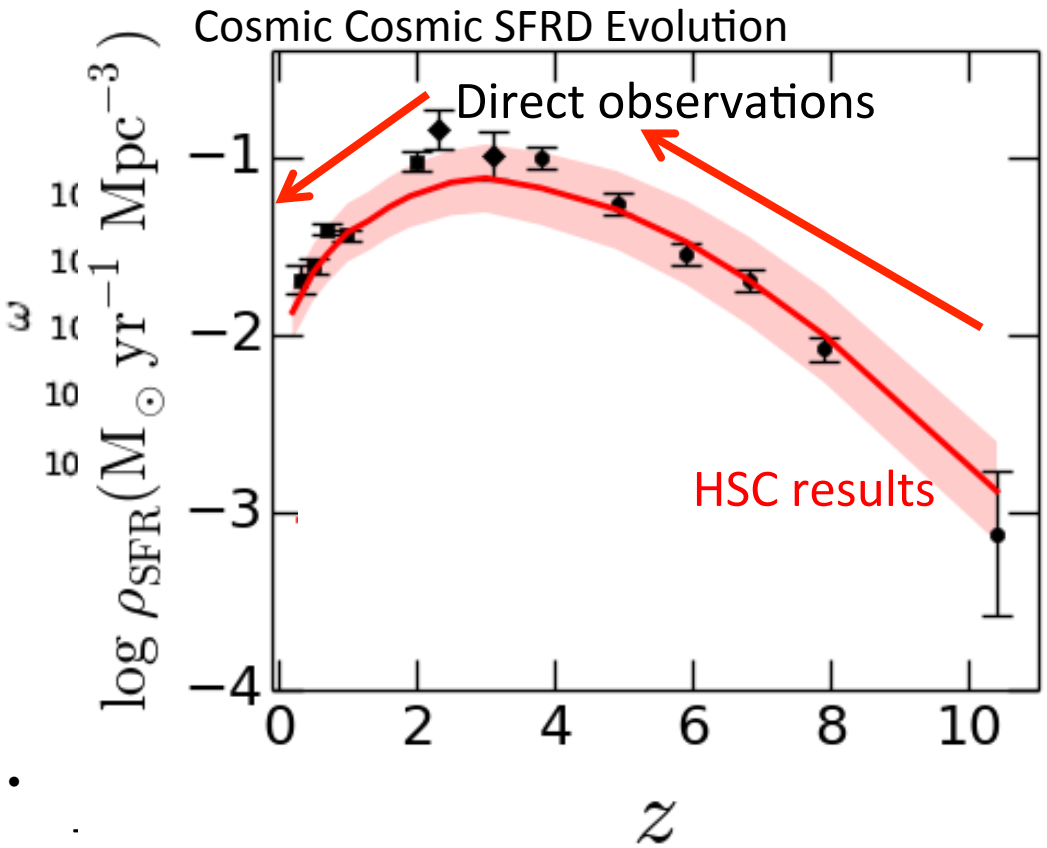
Harikane et al. 2016, 2018

- Precision angular correlation functions (cf. HOD model, ΛCDM)
  → Definitive identification of non-linear effect

- HOD model fitting -> Halo mass (+mass accretion rate)
  → We find the fundamental relation of SFR/$\dot{M}_{\rm h}$ vs. $M_{\rm h}$
  → SF regulated by mass accretion (i.e. gas accretion from LSS

SFRD evolution = Structure Form. x Cosmic Ex.

Clustering and Fundamental Relation



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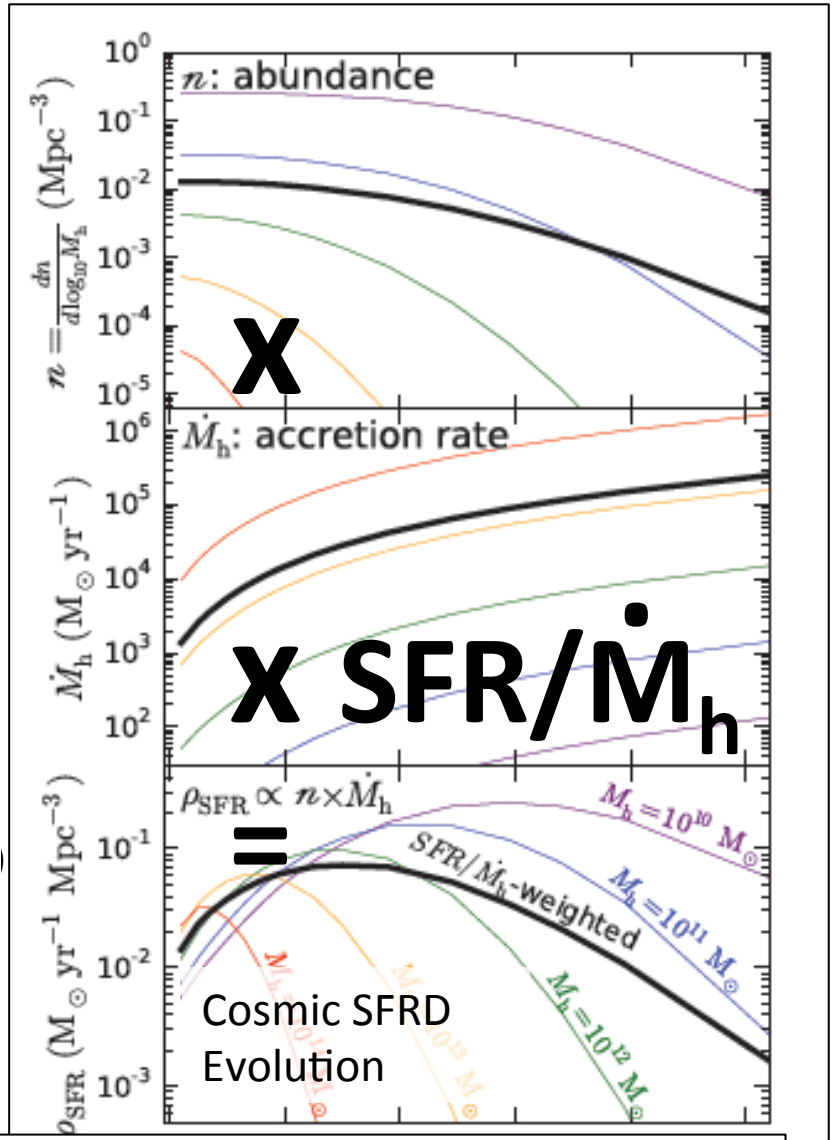
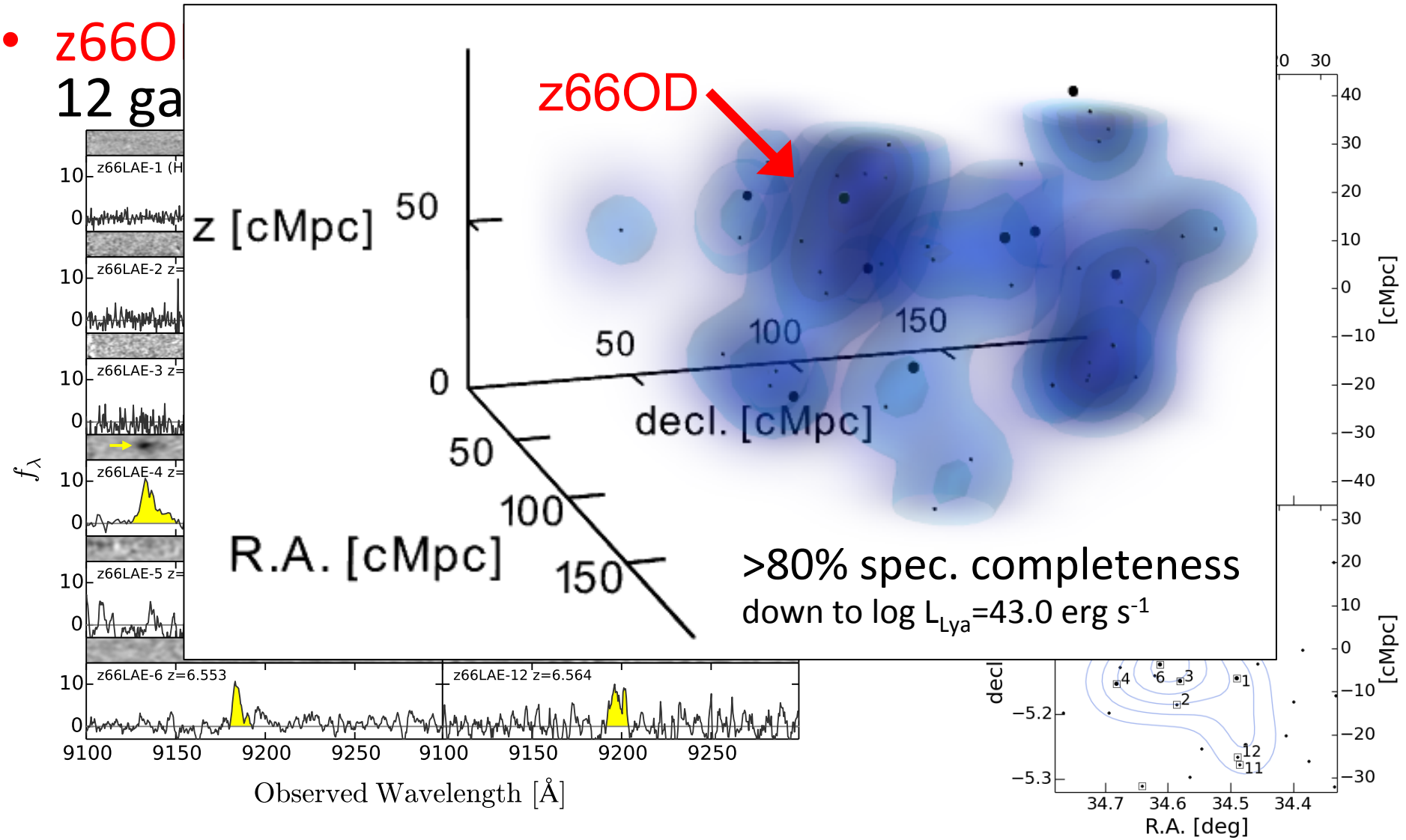


SFRD evolution = Structure Form. x Cosmic Ex.

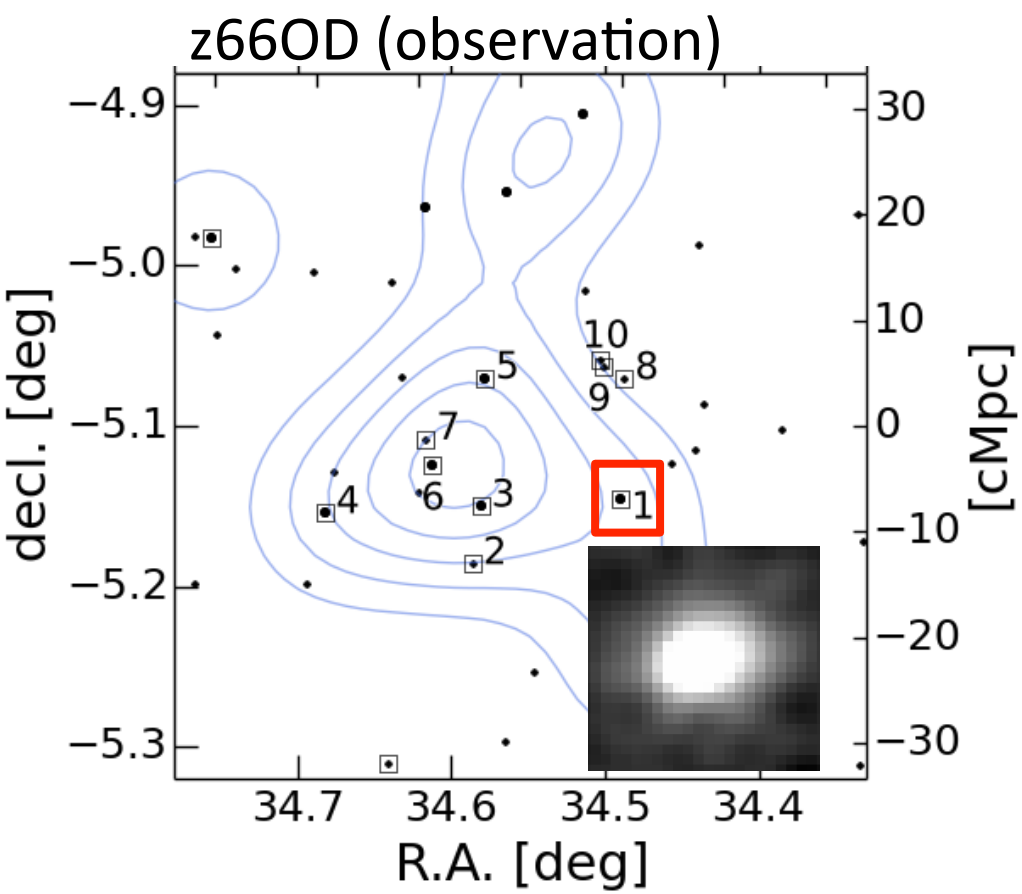
3D Large Scale Structure & Protocluster at z~7

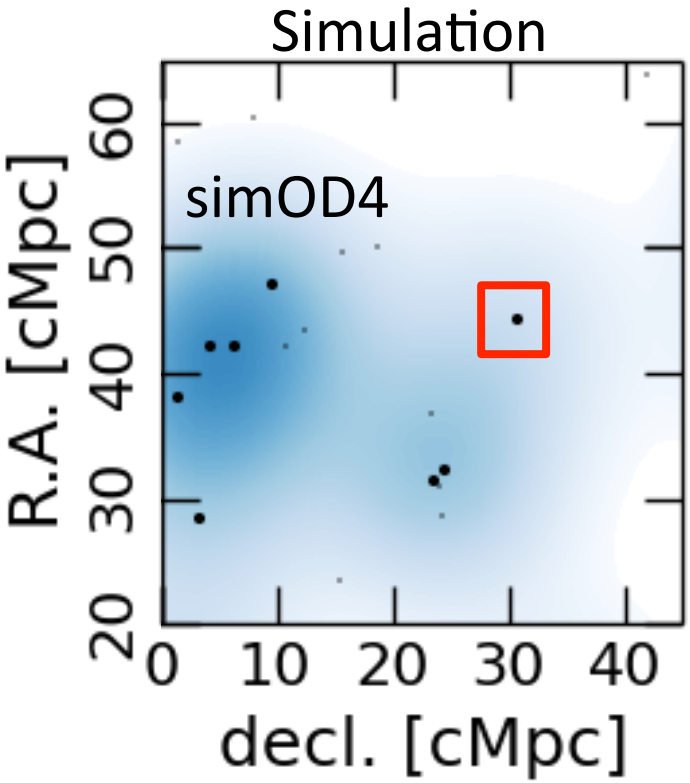
- z66O
  12 ga



Galaxy Distribution in z66OD

Most massive galaxy located at the edge of z66OD

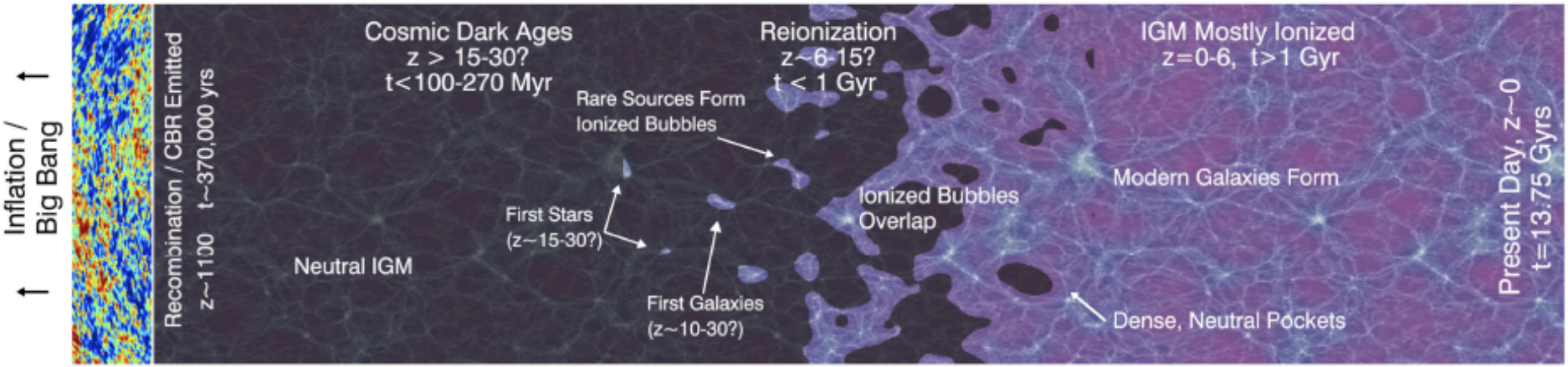




→Need detailed comparisons with the simulations

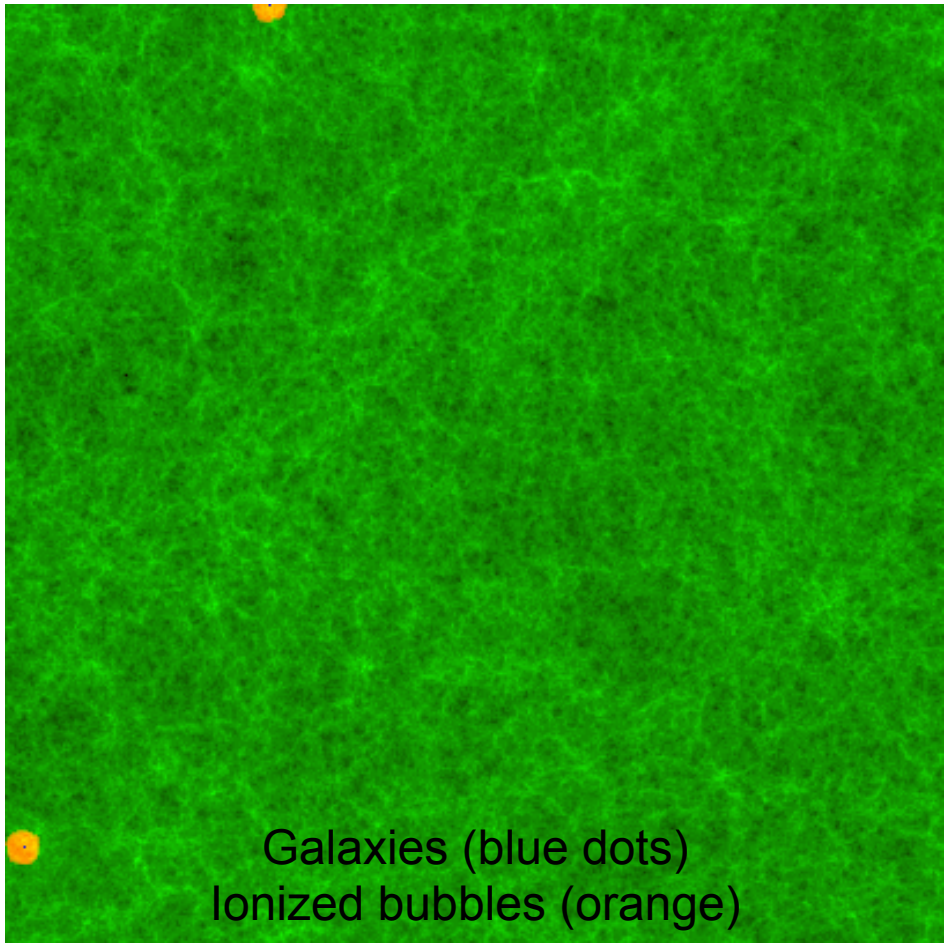
COSMIC REIONIZATION

H+γ→p+e- (Hydrogen ionization) at z>6



Robertson et al. (2010)

Predictions and Questions



N-body+RT simulation
Iliev et al. (2006)

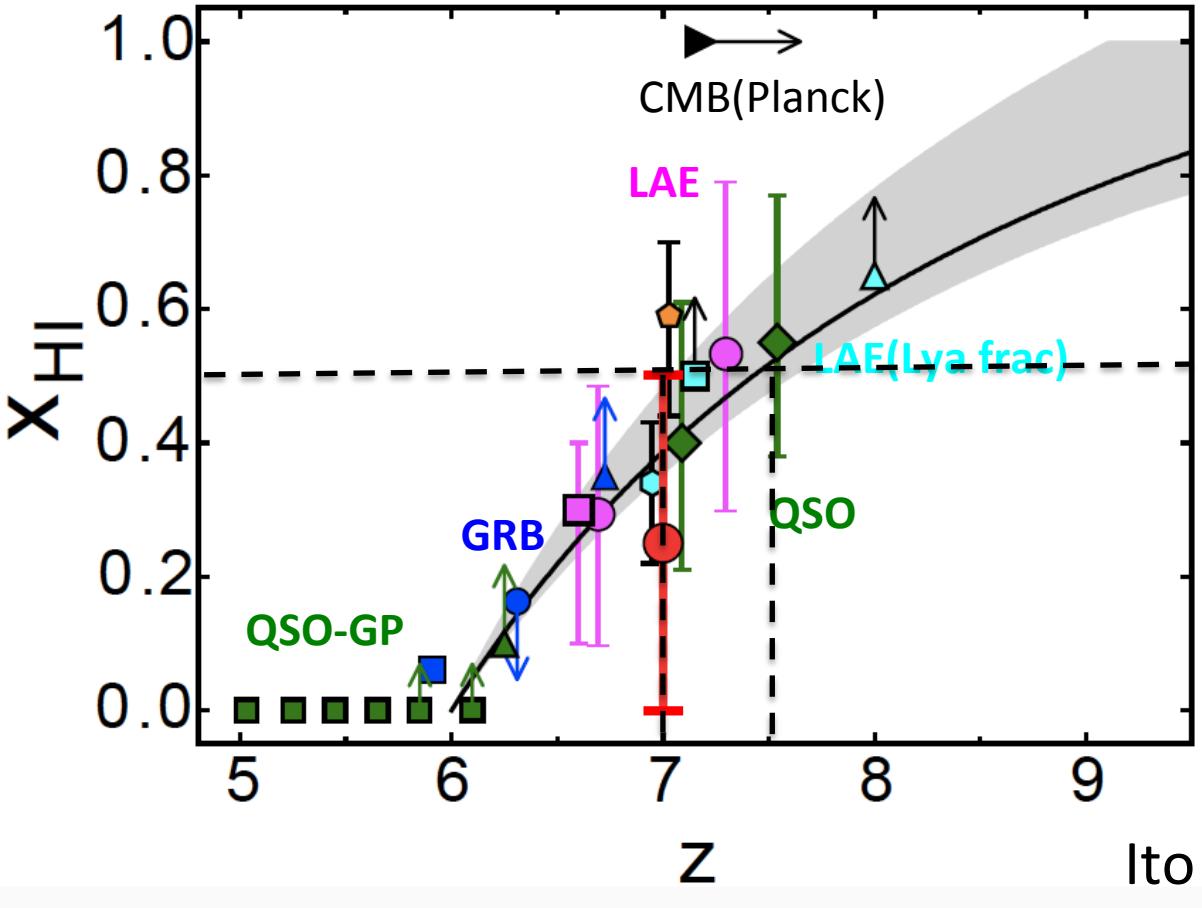
Questions

1) Cosmic Reionization History: Neutral hydrogen fraction $x_{HI}(z) = N_{HI}/N_H$

2) Major reionization sources: Galaxies, AGN, or anything else?

3) Physical Properties of Reionization: Ionized bubbles? Inside-out?

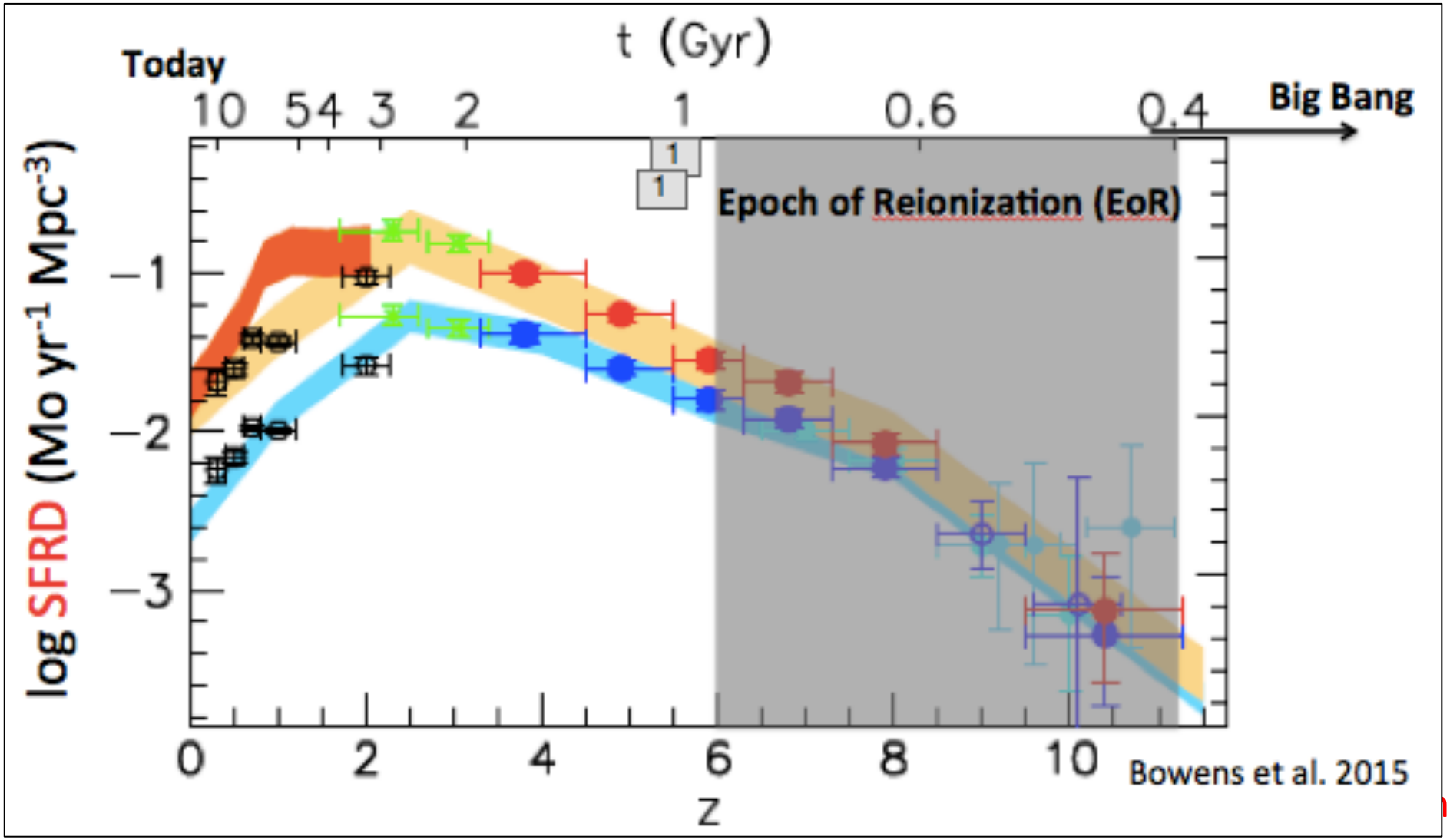
1) Cosmic Reionization History



Ito et al. 2018

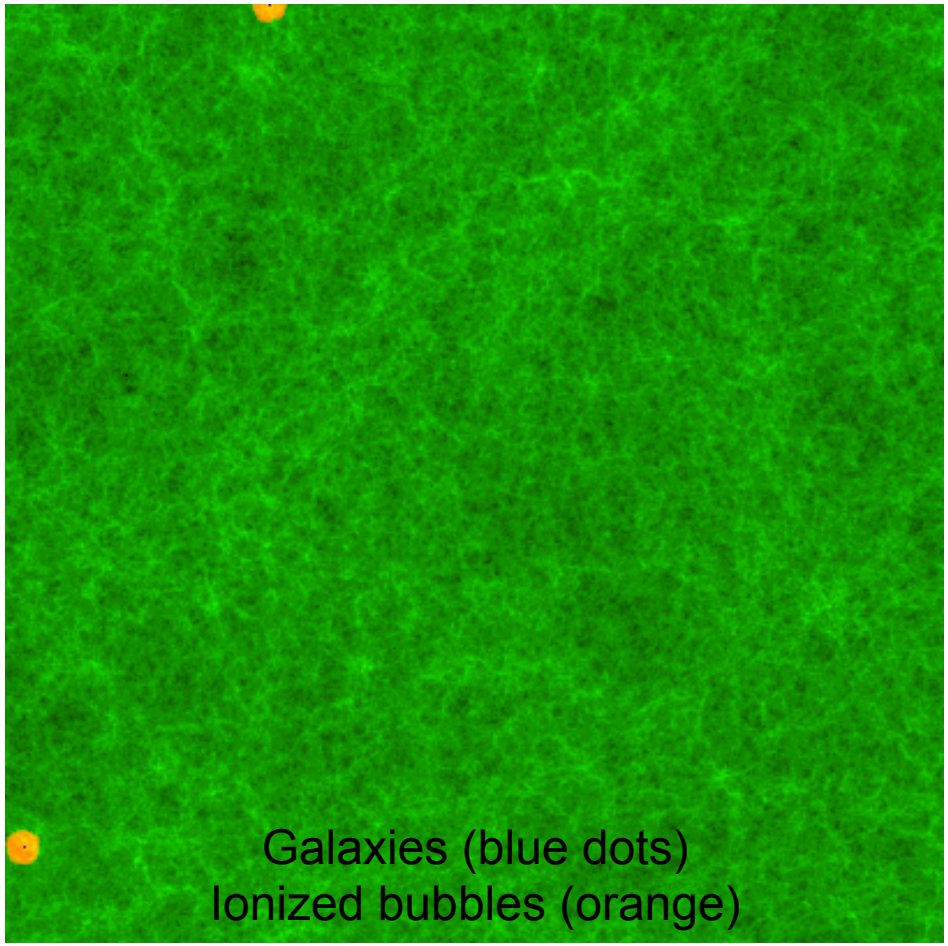
- x_{HI}=50% at z =~ 7.0-7.5
- Suggesting the late reionization

2) Sources of Reionization



- $\Delta z=3$ (-1/+2) [for Q_{HII}=10%-99%] Consistent w kSZ measurements of Planck2016

Predictions and Questions



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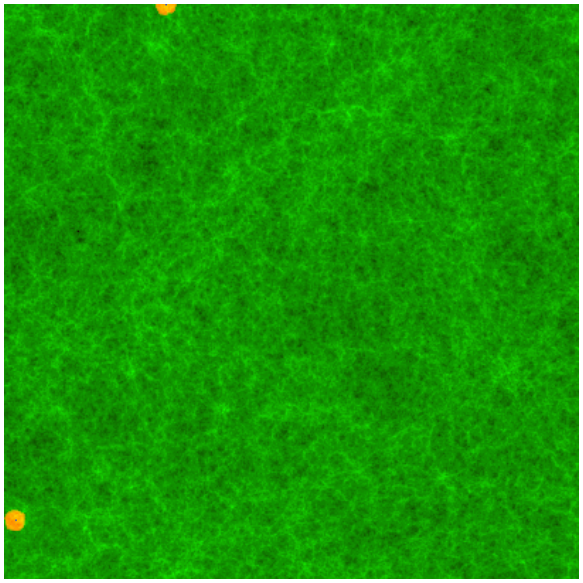
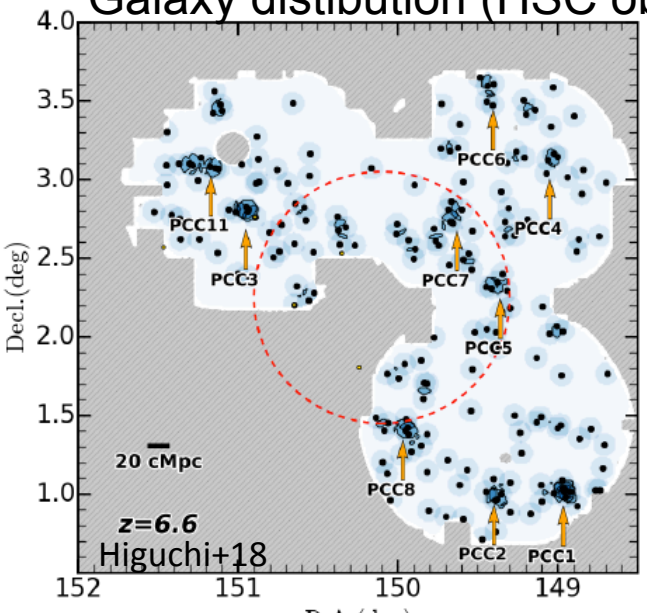
Early Cosmic Structure: Reionization

RT simulations

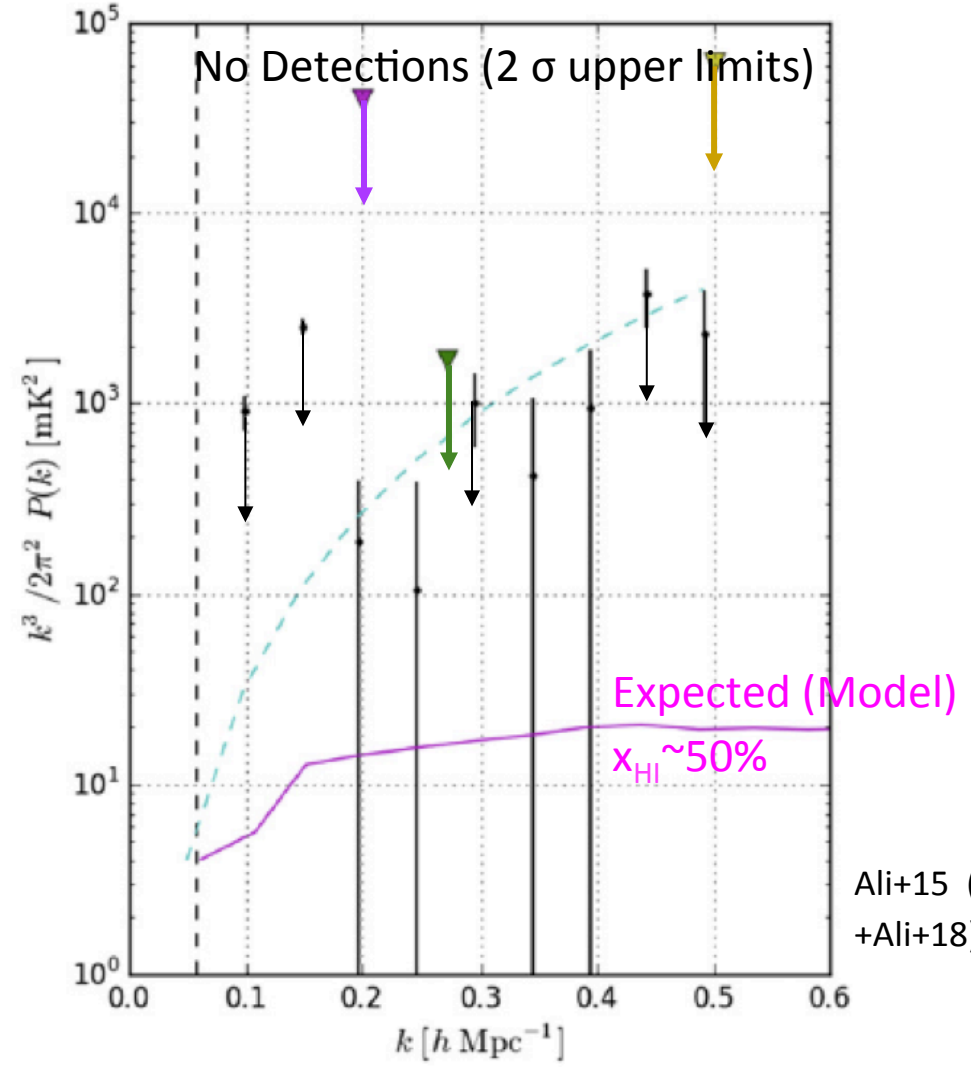


Galaxies (blue dots),ionized bubbles (orange) (Iliev+06)

Galaxy distibution (HSC obs)



Epoch of Reionization (EoR) HI 21cm Auto Power Spectrum

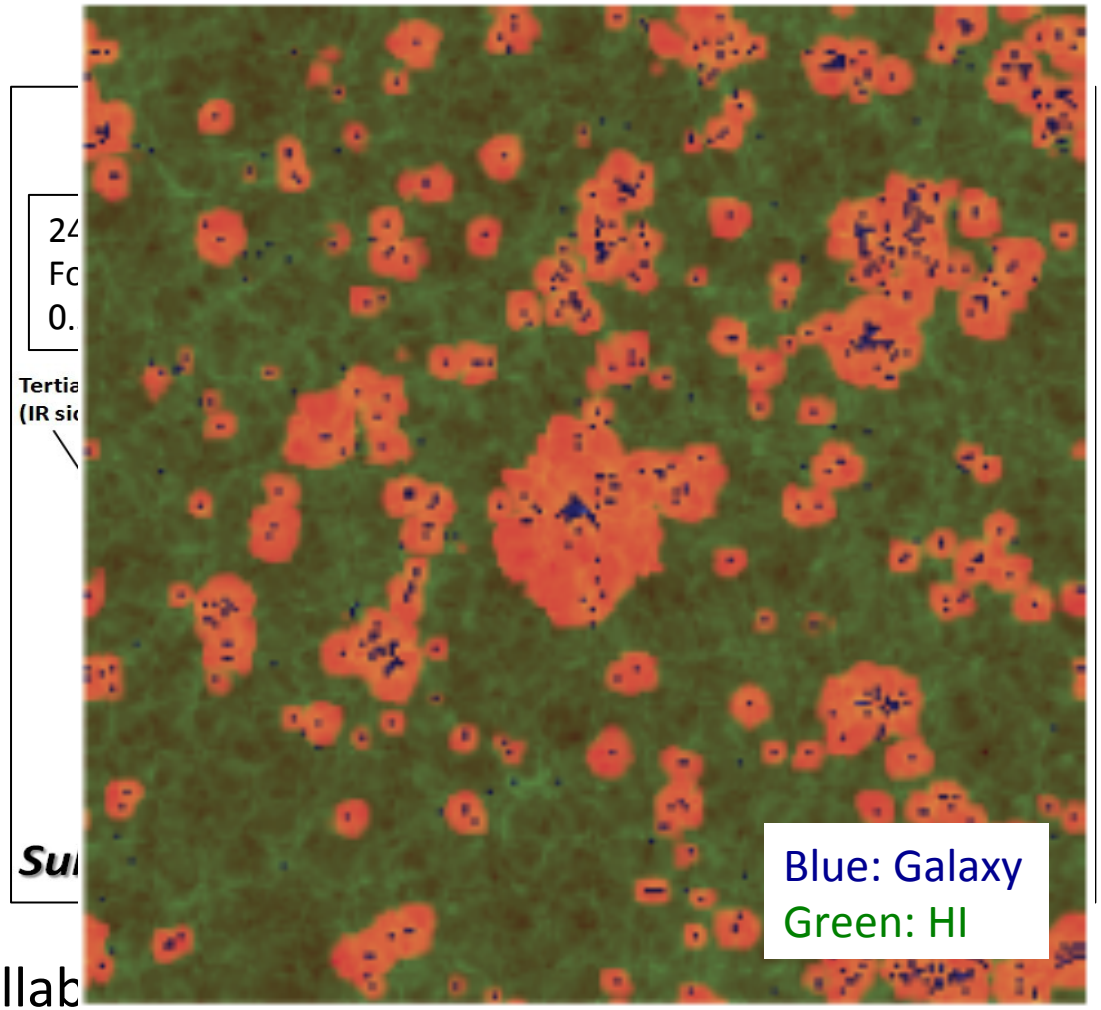


Ali+15 (see +Ali+18)

No detections of 21cm EoR signals, due to foreground sys.

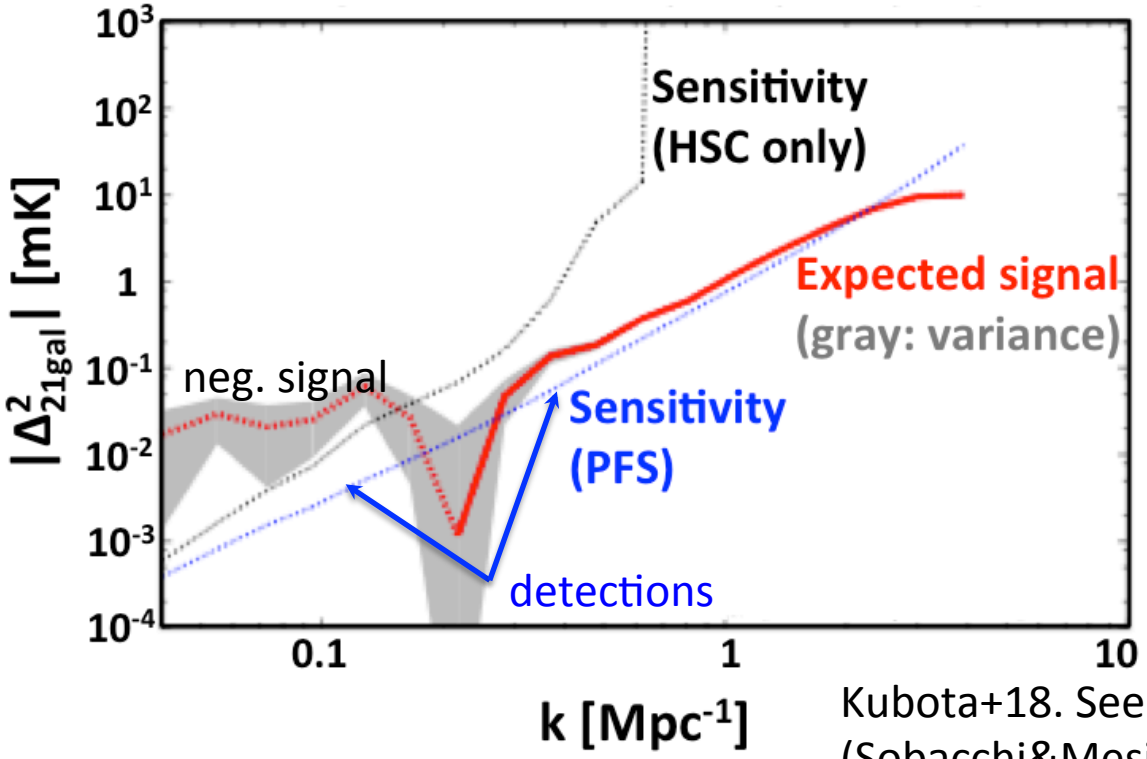
- Cross Correlation with real signal of galaxies at EoR

Subaru Prime Focus Spectrograph (PFS)



- Under the collab nned FL 2021)
- Spectroscopy for ~10,000 galaxies at the EoR (z=6-7) over 15 deg^2 area

First Detection of EoR HI 21cm Signal by Galaxy-21cm Cross Correlation



21cm: MWA,SKA

Kubota+18. See similar predictions (Sobacchi&Mesinger+16, Hutter+18)

- Goal-1: Detection of the cross-correlation signals -> Evidence of early cosmic HI struc.
  - Positive cross-correlation at k~0.4 Mpc^{-1} at ~5 sigma
  - Negative cross-correlation at k~0.1 Mpc^{-1} at ~3 sigma

- Goal-2: Determination of the transition scale at z=6.6 with Δk=~0.1 Mpc^{-1} accuracy
  - First definitive evidence of cosmic ionized bubbles

PFS survey will start in 2022

Summary

Reviewing galaxy formation and cosmic reionization

- Cosmic SFRD evolution (+galaxy morphology evol.)

- Subaru HSC survey (579,555 gals at z=4-7 in 100 deg^2)
  - Fundamental relation at z=4-7 (SFR/$\dot{M}_h$ vs M_h). Mass accretion regulates the star-formation

    → SFRD evolution (=abundance increase x accretion decrease)
  - 3D galaxy map at z=6.6 → proto-cluster at z=6.585

- Cosmic reionization
  - 3 major questions and study progresses. Physical process?
  - PFS survey → Detecting ionized bubbles