Probing Early Galaxies with the Hubble, Subaru, and ALMA Legacy Data

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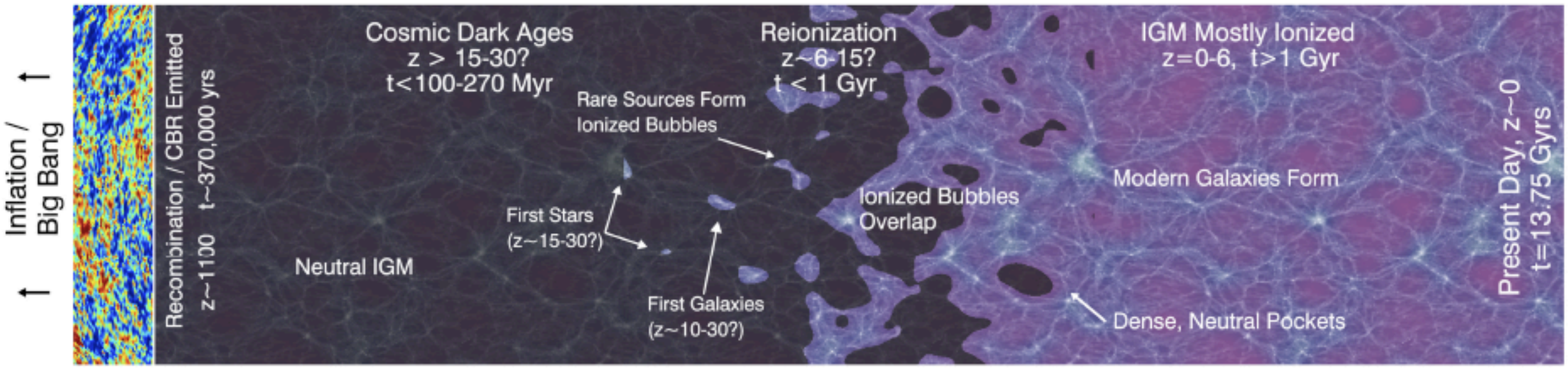
Outline

- Recent observational progresses for early galaxies and reionization at a redshift up to z~10.
  - Hubble+Subaru+Planck2016 const. on $Q_{HII}(z)$, f_{esc} & M_{truc}
  - Hubble and ALMA measurements of morphology & ISM
  - On-going Subaru surveys



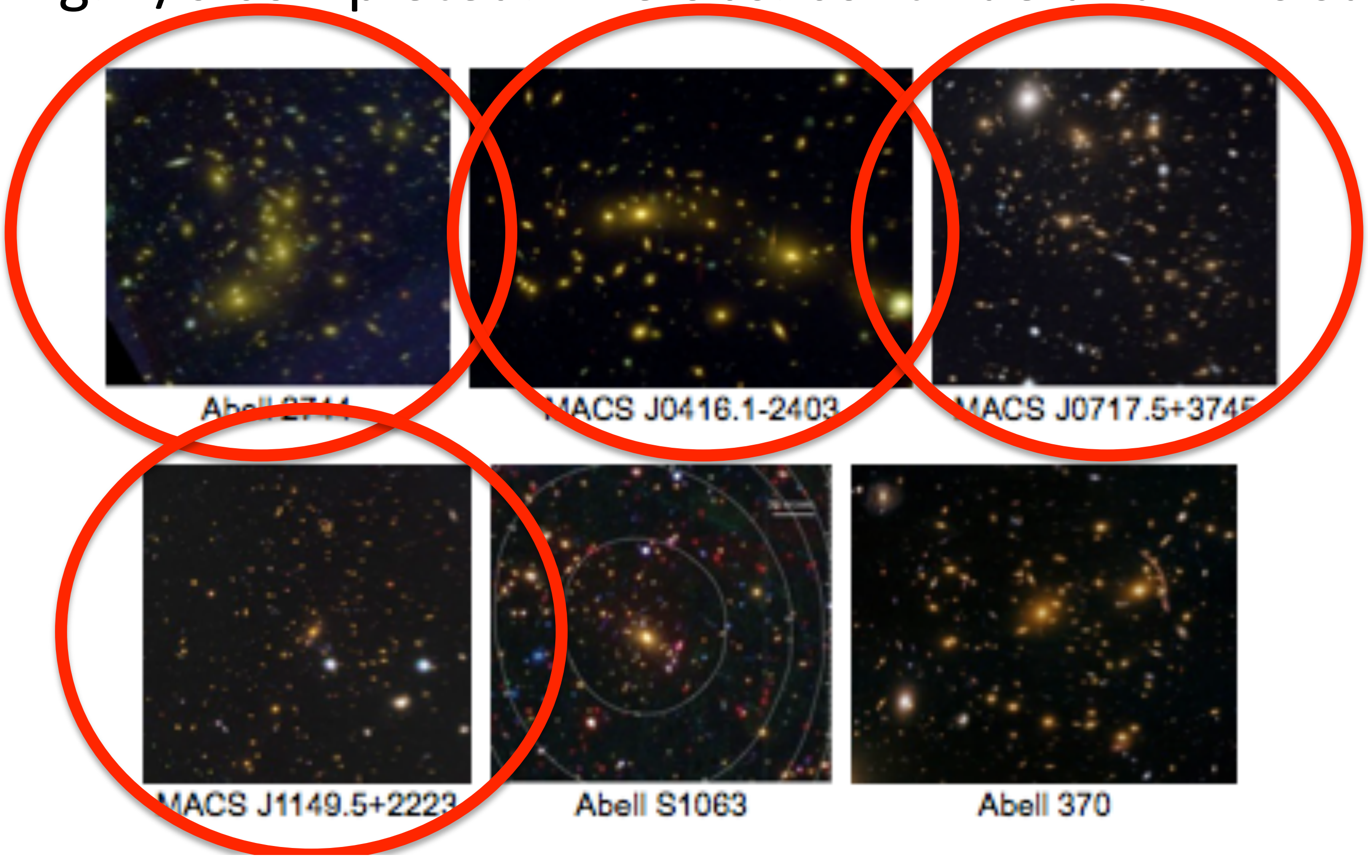
Robertson et al. (2010)

EARLY GALAXIES AND REIONIZATION

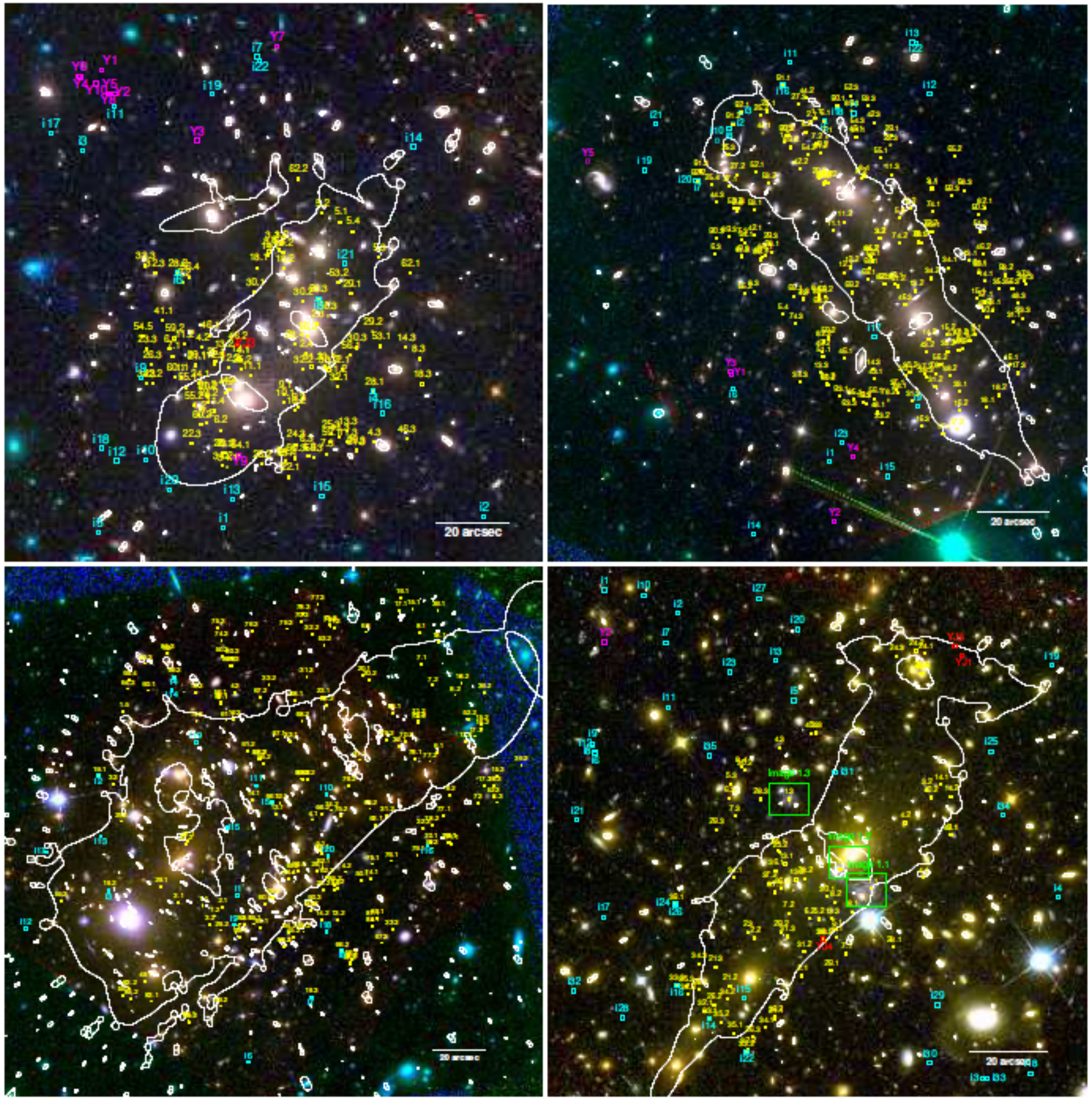
Hubble Frontier Fields (HFF)

- 6 clusters by deep Hubble ACS and WFC3-IR imaging (Lotz+16)
- Lensing magnifications for faint galaxies behind the clusters.

- 3 year program spending 840 orbits. Started from fall 2013.
  (Atek+14,15, Ishigaki+15, Oesch+15,McLeod+15,+16, Livermore+16…)
- On-going. 4/6 completed. The obs. continue until this summer.



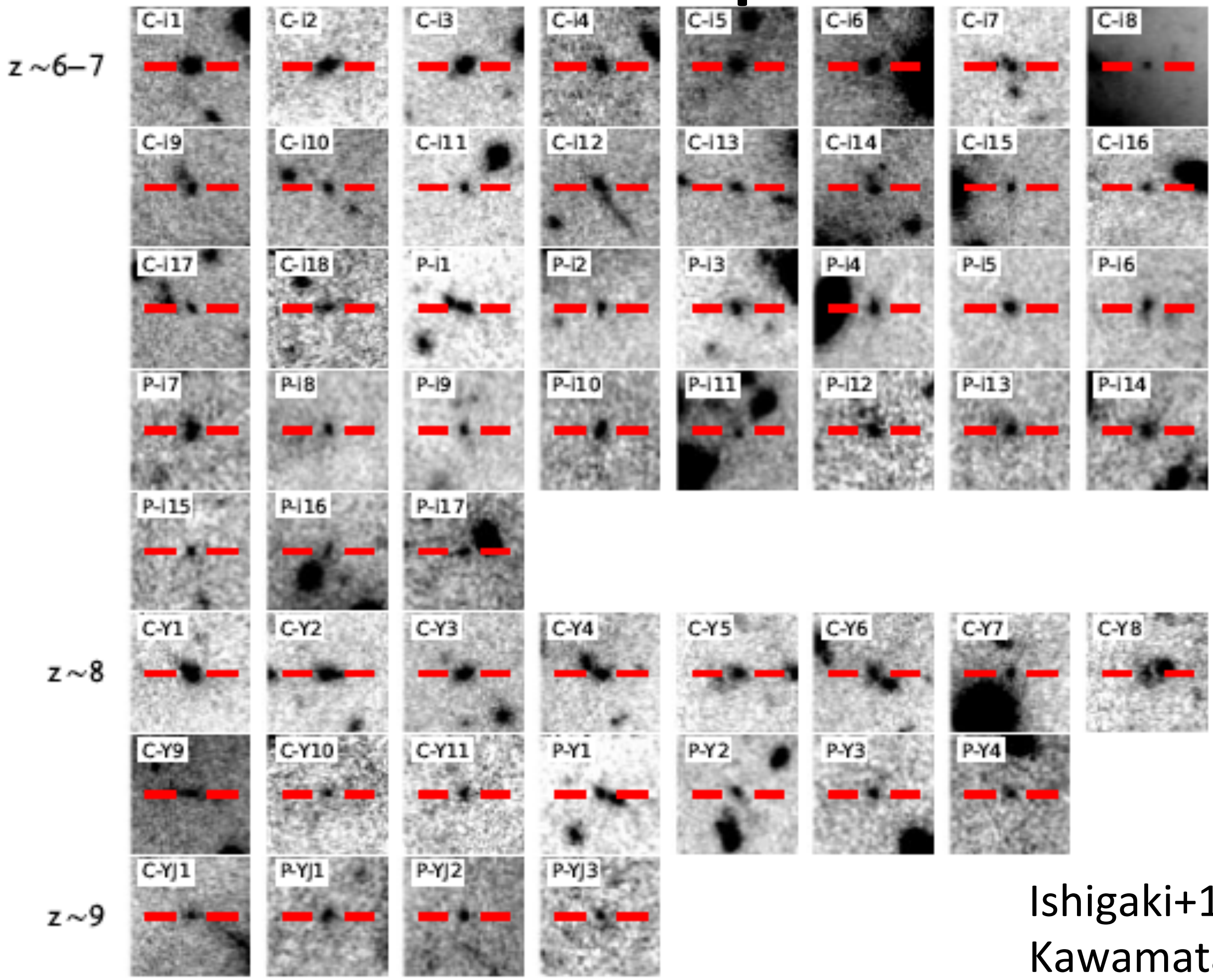
Mass Models

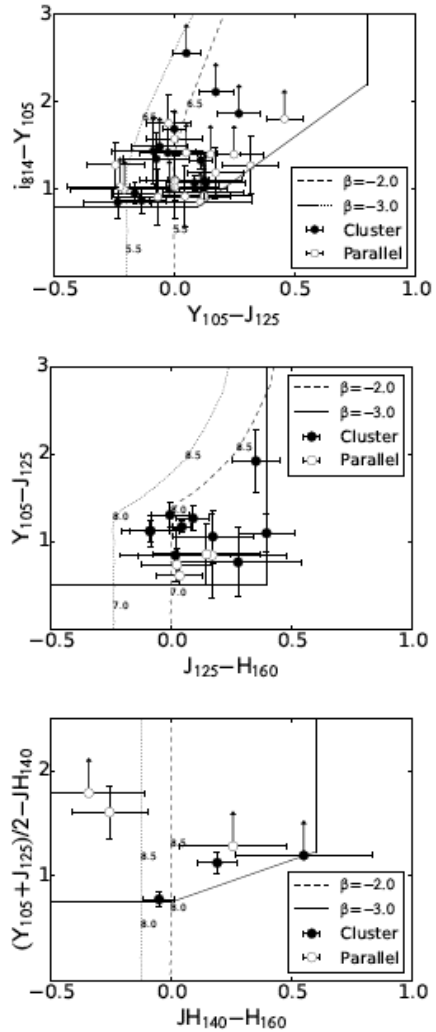


Kawamata+16

100-200 multiple images for modeling w parametric lensing package (glafic; Oguri+10)

HFF Dropouts at z~6-10



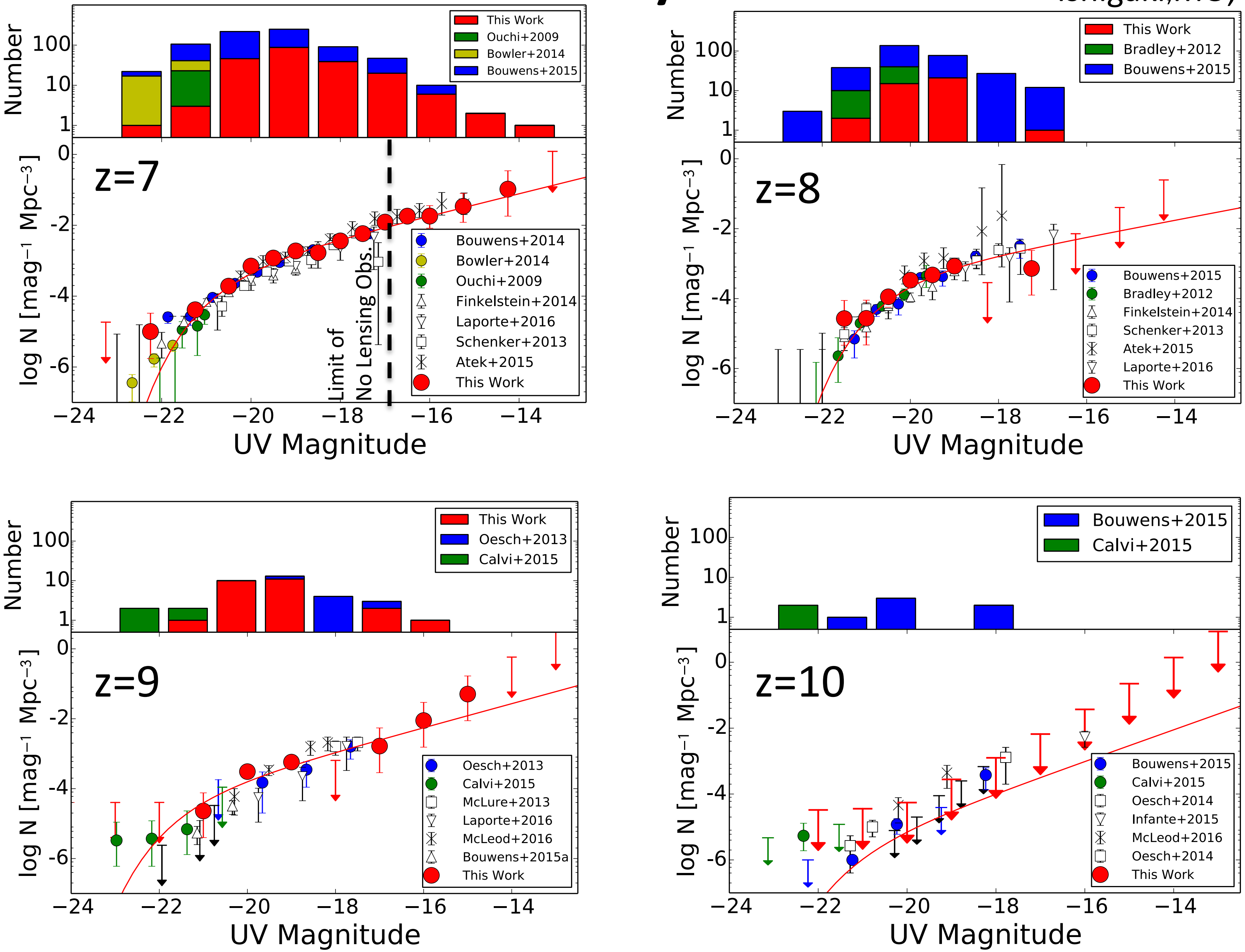


Ishigaki+15,
Kawamata+16

- 127 galaxies at z=6-10 identified by dropout technique, 18 out of which have μ>10 (Kawamata +16)

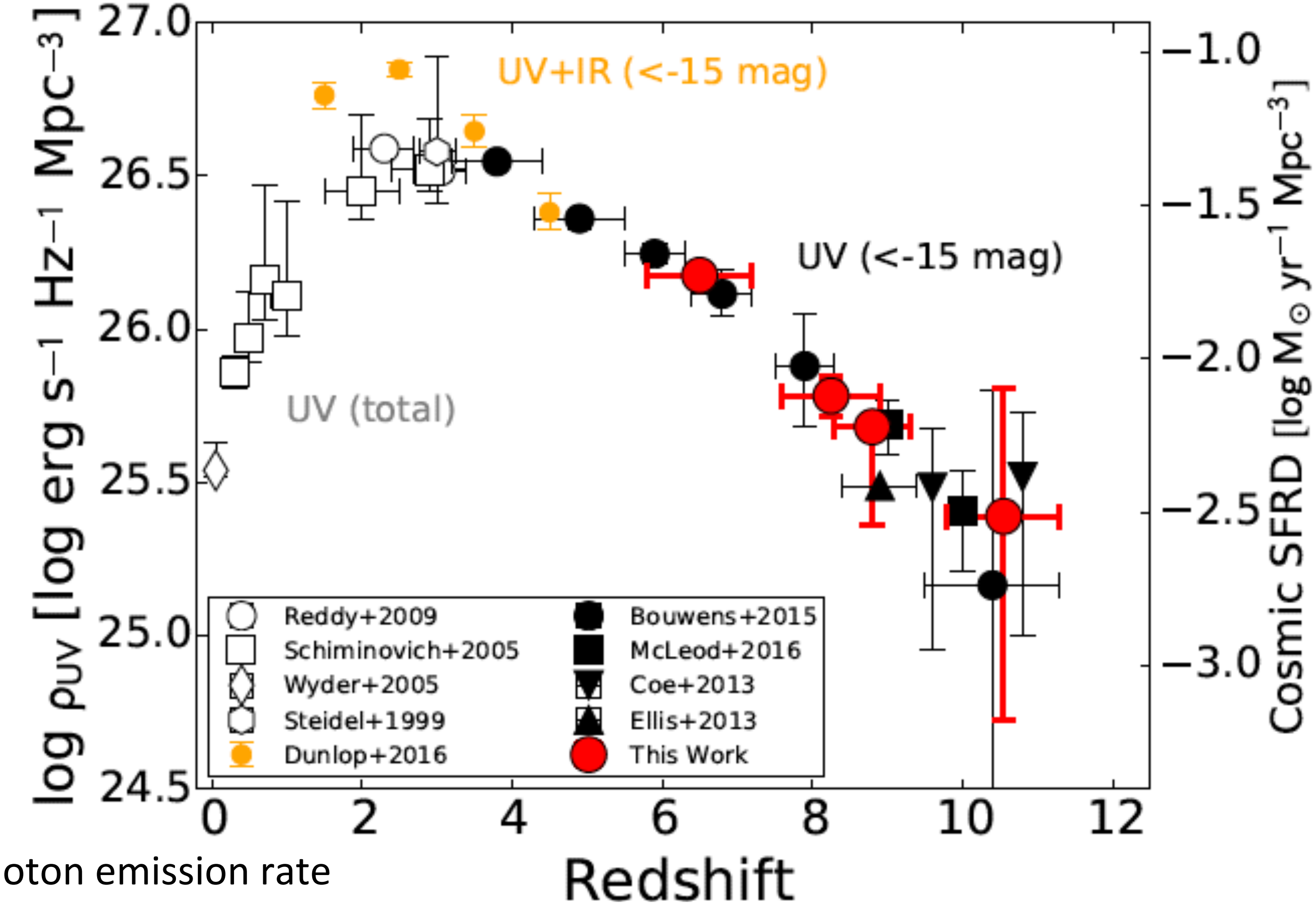
UV Luminosity Functions

Ishigaki,MO, in prep



No flattening or break at the faint-end LF. No sig. of feedback effect down to ~-14mag at z~7.

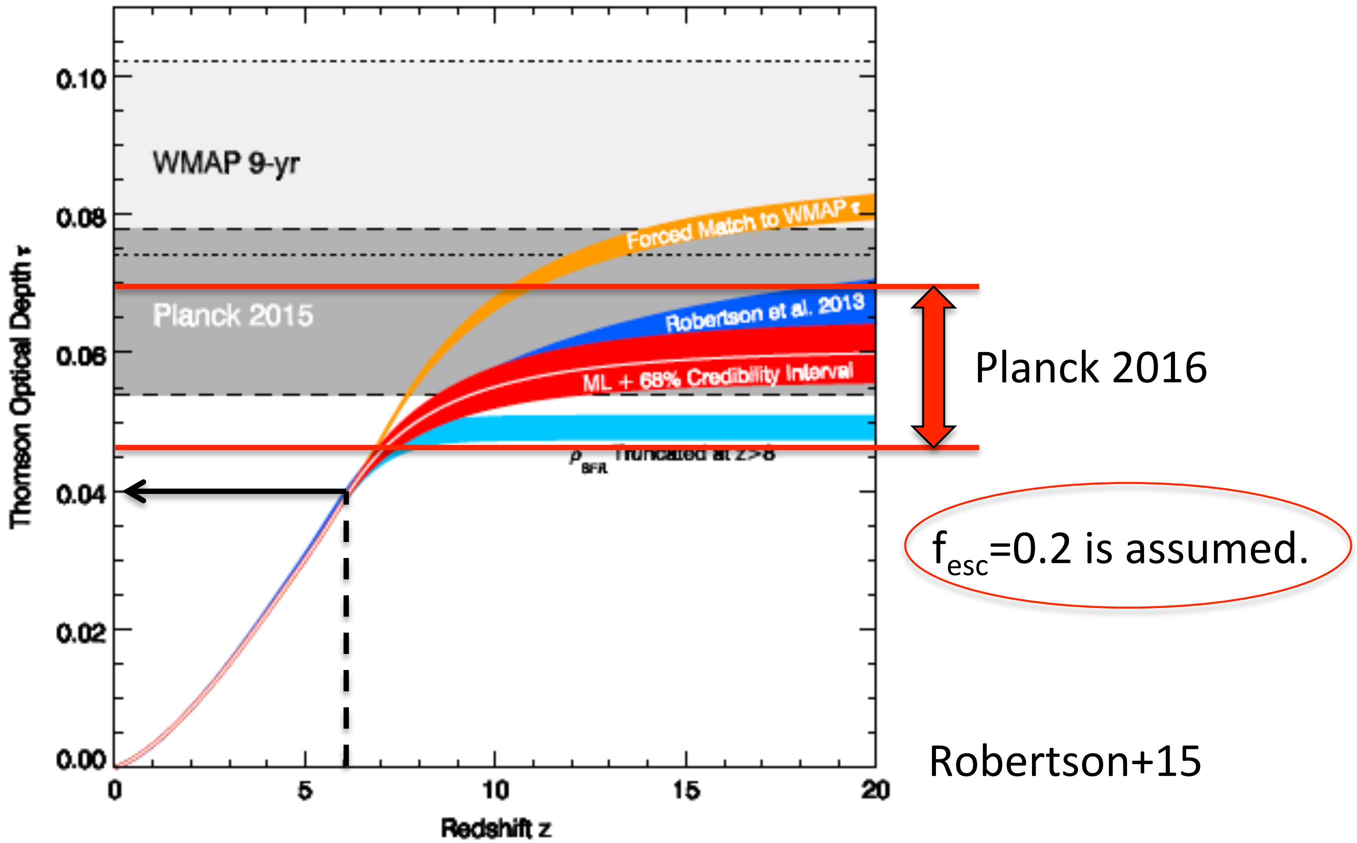
Evolution of UV Luminosity Density



Ionizing photon emission rate

$$\dot{n}_{\rm ion} = \int_{-\infty}^{M_{\rm trunc}} f_{\rm esc}(M_{\rm UV})\xi_{\rm ion}(M_{\rm UV})\underbrace{\Phi(M_{\rm UV})L(M_{\rm UV})dM_{\rm UV}}_{\rho_{\rm UV}}$$

Background: Ionizing Photon Shortage Not Serious?



- ρ_{UV} is decreasing to z~10, while large WMAP/Planck2013 τ_e suggests more ion. photons??

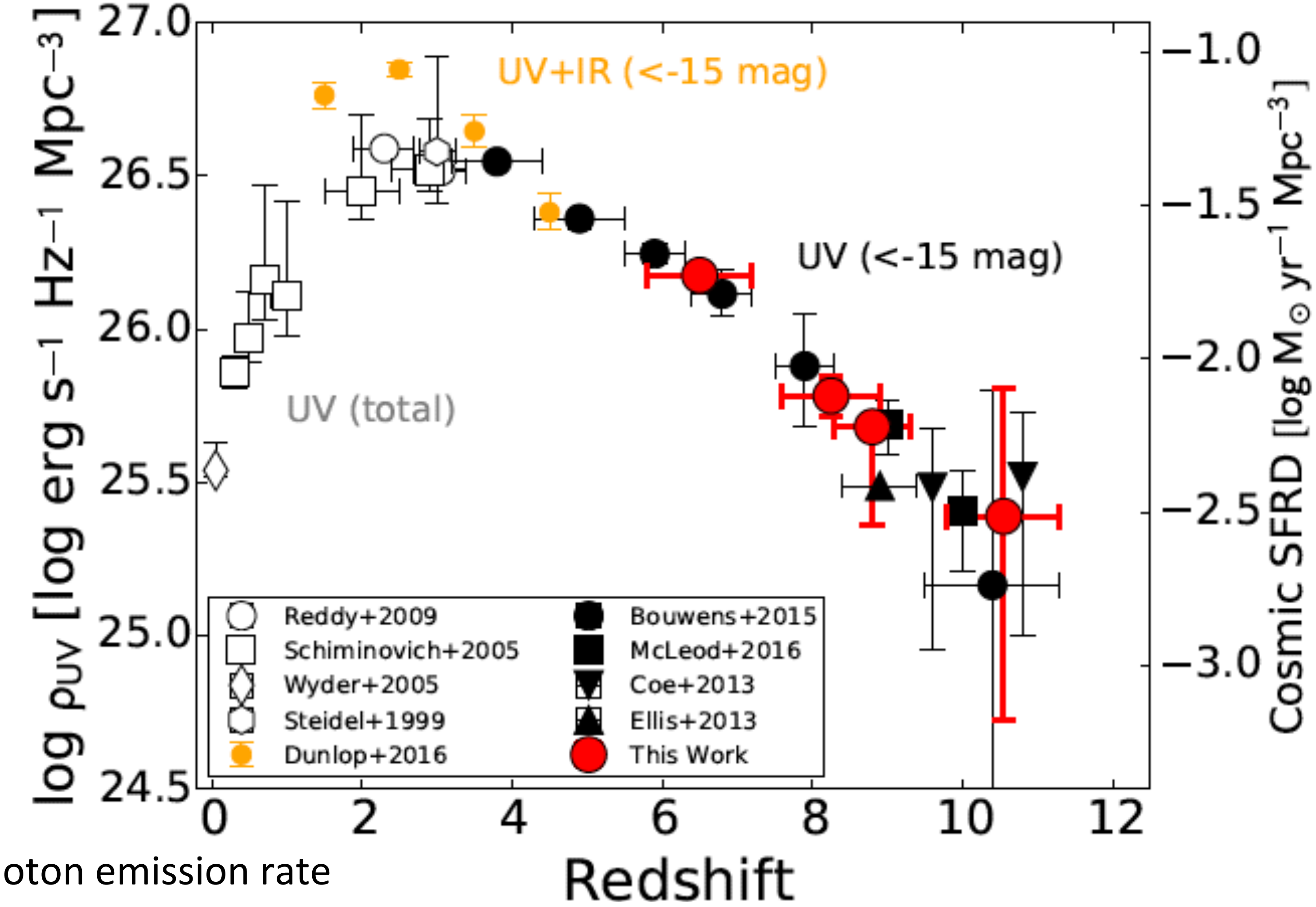
→ Problem of the ionizing photon shortage

- CMB estimate τ_e decreases from ~0.09 to ~0.07 (Planck2015),to τ_e=0.058±0.012(Planck2016)
  - $\Delta\tau_e$=0.04 at z=0-6 in ionized univ.→Only the remaining $\Delta\tau_e$ ~0.01-0.02 at z>6 (Ishigaki15)

→ Ionizing photon shortage is no more serious problems. Worrying too many ionizing photons.

- Strong physical constraints with Planck2016 and the HST res. Including an upper limit of f_{esc}.

Evolution of UV Luminosity Density



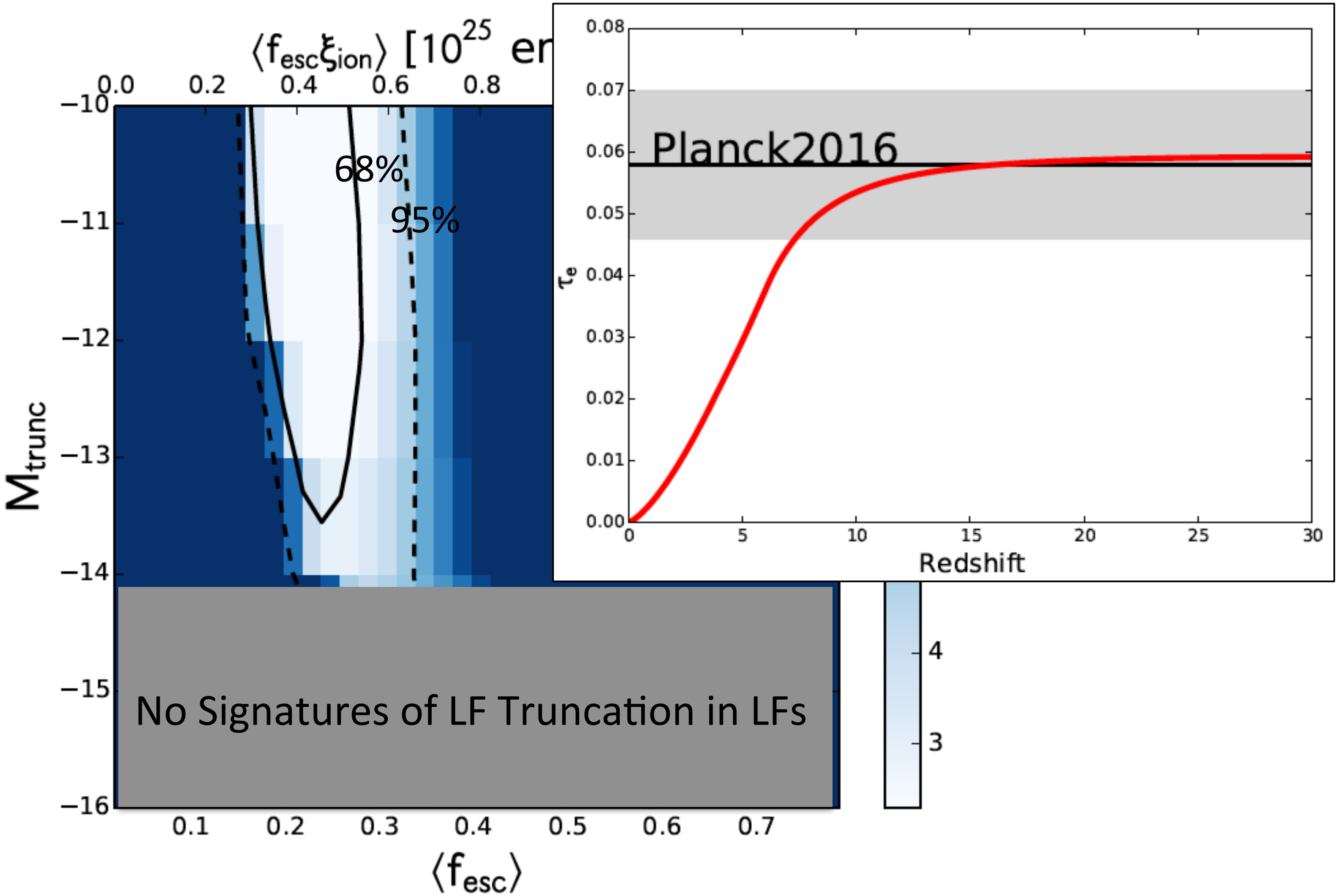
Ionizing photon emission rate

$$\dot{n}_{\rm ion} = \int_{-\infty}^{M_{\rm trunc}} f_{\rm esc}(M_{\rm UV})\xi_{\rm ion}(M_{\rm UV})\Phi(M_{\rm UV})L(M_{\rm UV})dM_{\rm UV}$$

3 free parameters

$\rho_{\rm UV}$

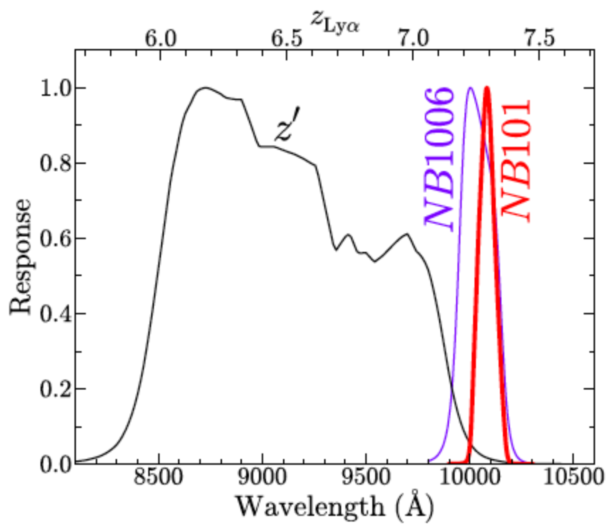
Constraints on f_{esc} and M_{trunc}

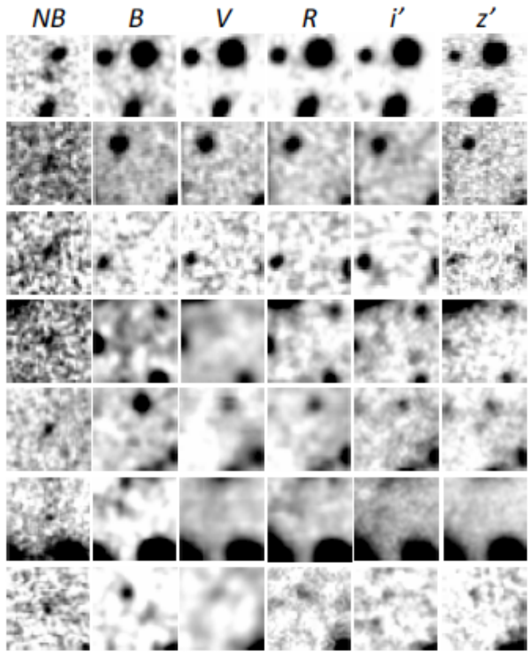


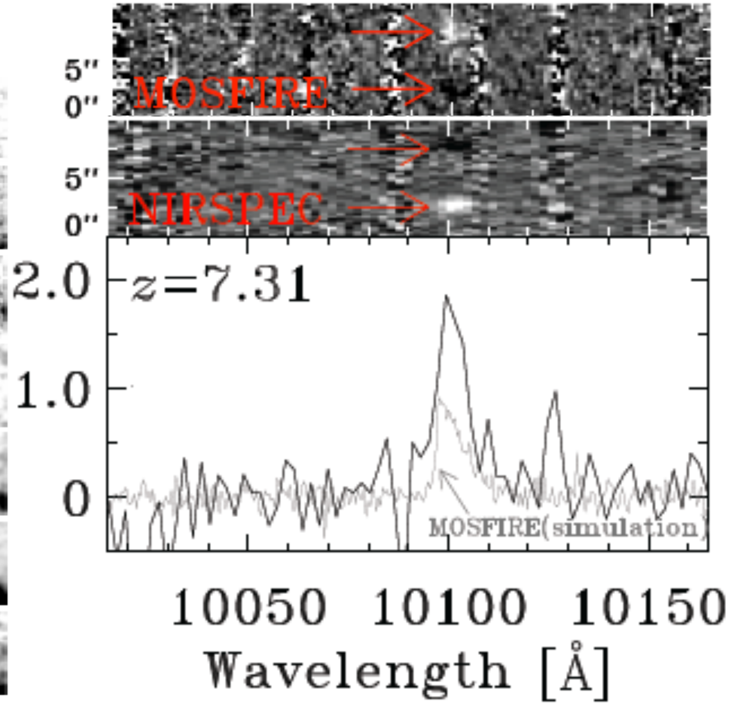
- $<f_{esc}>$~0.15-0.3 (for log $<\xi_{ion}>$=25.2). Note the upper limit of f_{esc}<0.3
- M_{trunc} >~ -13

If the other ionizing sources (excpt. Galaxies) give negligible contributions to ion phot. prod.

Ultra-Deep Subaru NB Imaging
Keck Spectroscopy for z=7.3 LAEs





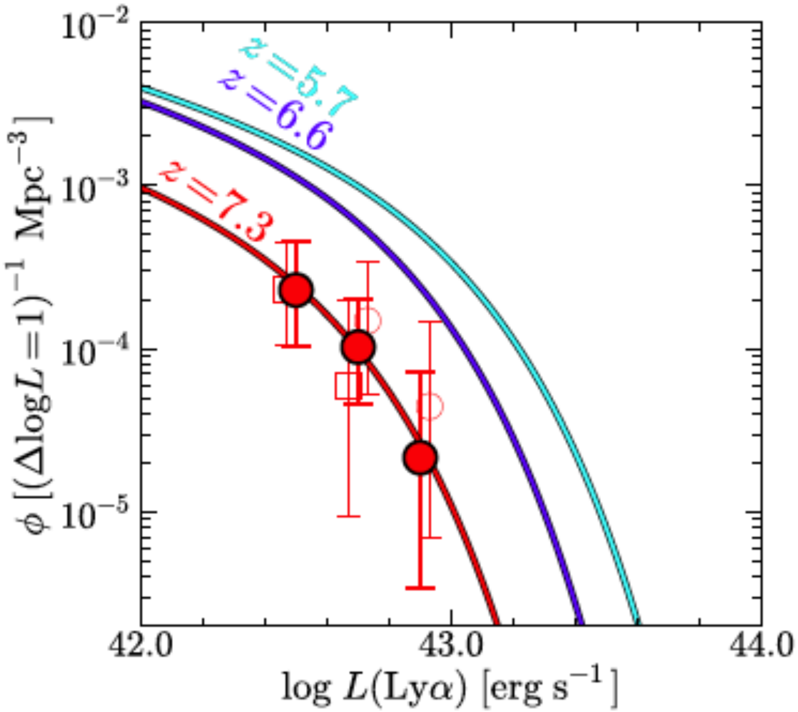


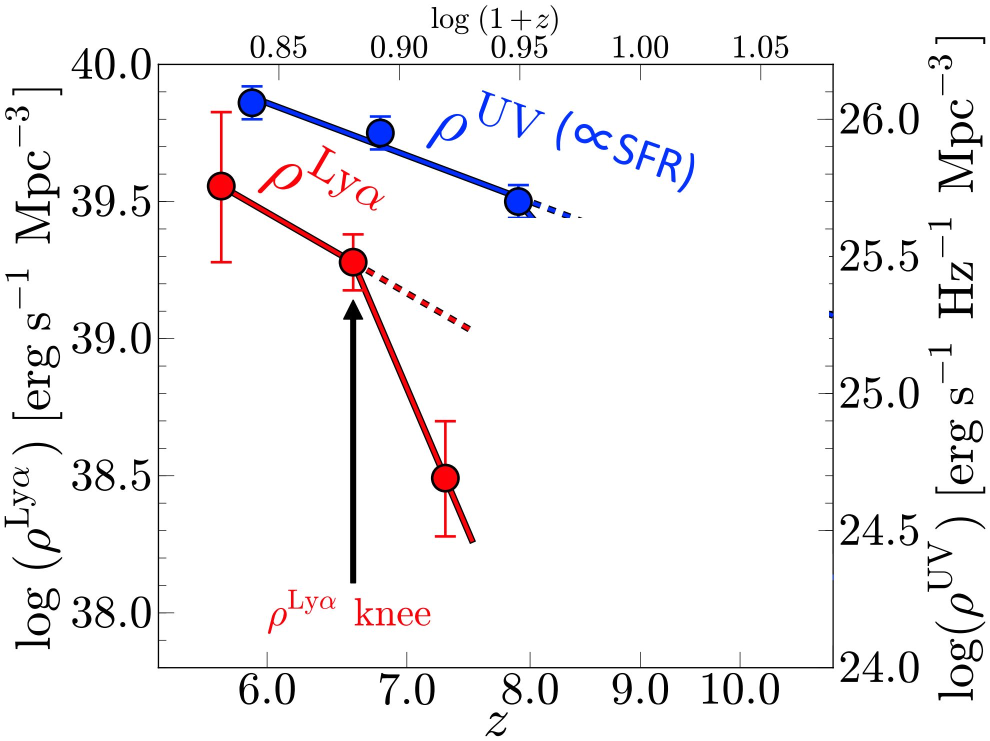
Konno, MO et al. (2014)

- Lya emitter (LAE) sensitive to neutral IGM: Subaru deep (106 hour integ.) large area survey
- At z=7.3, a comparable Lya lum. depth as previous lower-z (z=3-6) survey (Konno+14).
- However, only 7 sources… ~1/10 of the expected number if no evolution from z=6.6.

Accelerated Evolution of Lya Luminosity at z>~7

Lya Luminosity Function (Lya LF)



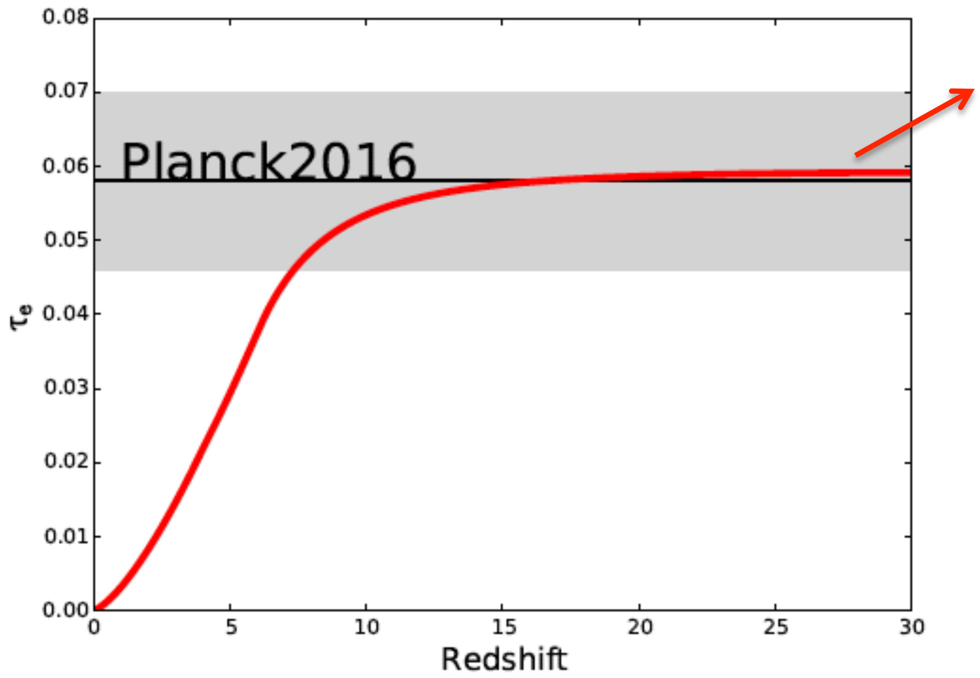


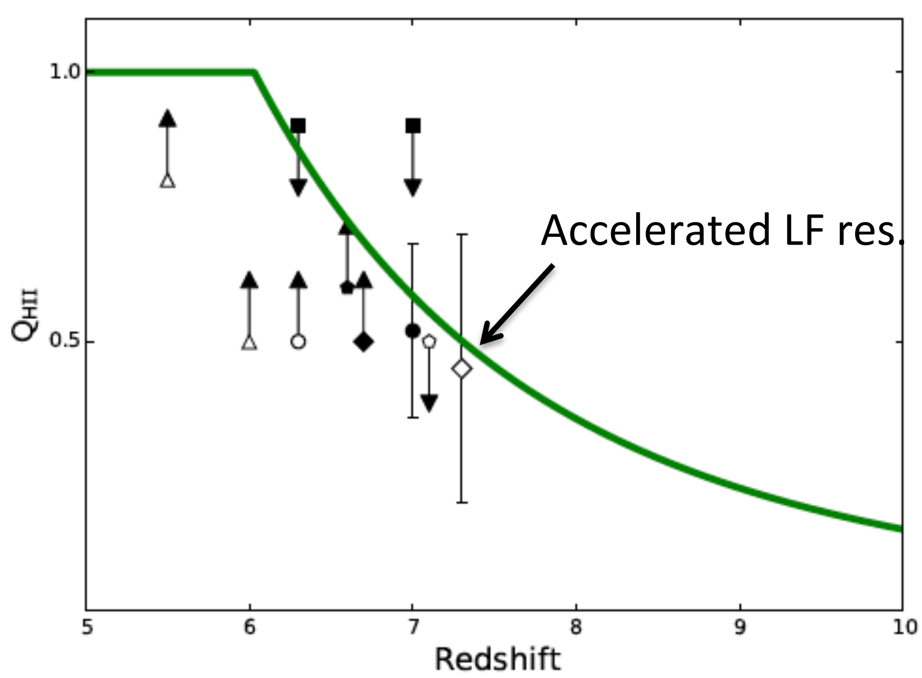
Konno, MO et al. (2014)

- Decreasing Lya LFs (and ρ_{Lya}) from z=6.6 even to 7.3. Moreover, the Lya LF (and ρ_{Lya}) is accelerated at z>~7.
- No accelerated evol. of UV LFs(ρ_{UV}) at z~7
  - Likely by IGM scattering of Lya (cosmic reionization),

  →the evolution of Q_{HII} is rapid at z~7

Reionization History and CMB τ_e



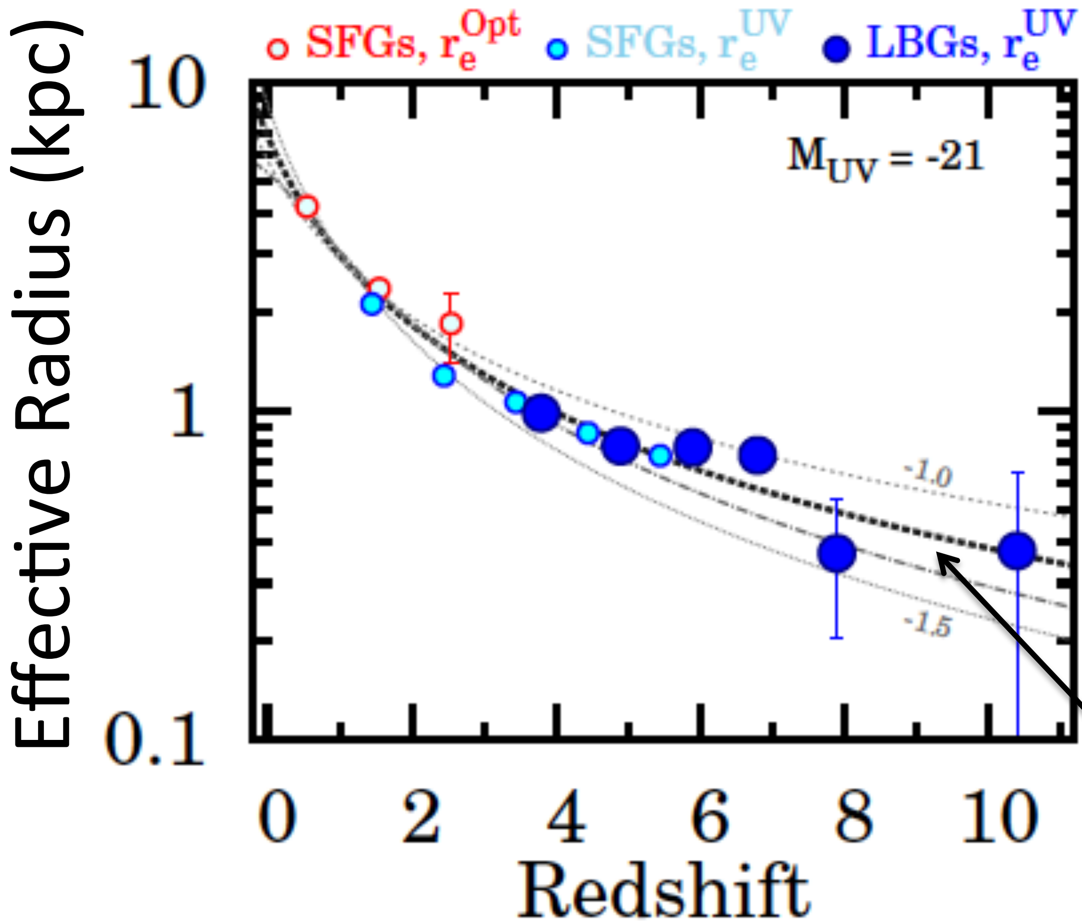


- Q_{HII} estimates from the accelerated Lya evolution.
  - Prefer moderately low Q_{HII} at z~7. Late reionization.

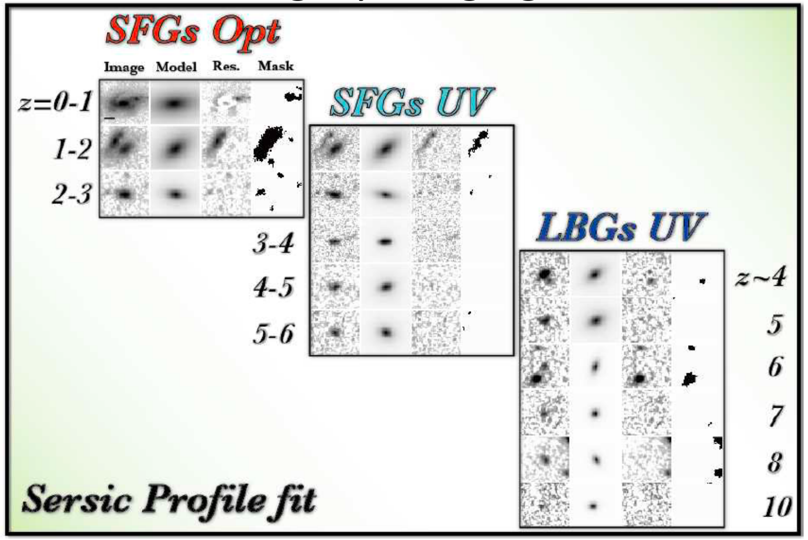
Consistent Results of
$Q_{HII}(z)$ and Ionizing Sources, τ_e, f_{esc}, M_{trunc}

MORPHOLOGY AND ISM

Galaxy Morphologies in the HST optical-NIR data



HST Legacy Imaging Data



Shibuya, MO, Harikane+15

see+ Ferguson+04,....Holwerda+15, Curtis-Lake+15

Only r_e=a few 100pc at z>~4

- Average Sersic index for ~190,000 SF gals-> n=~1.5 (disk-ish)

Corrected for SB dimming effects by fitting

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

z=0

Milky Way

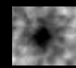
M82

c) Shogakukan

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

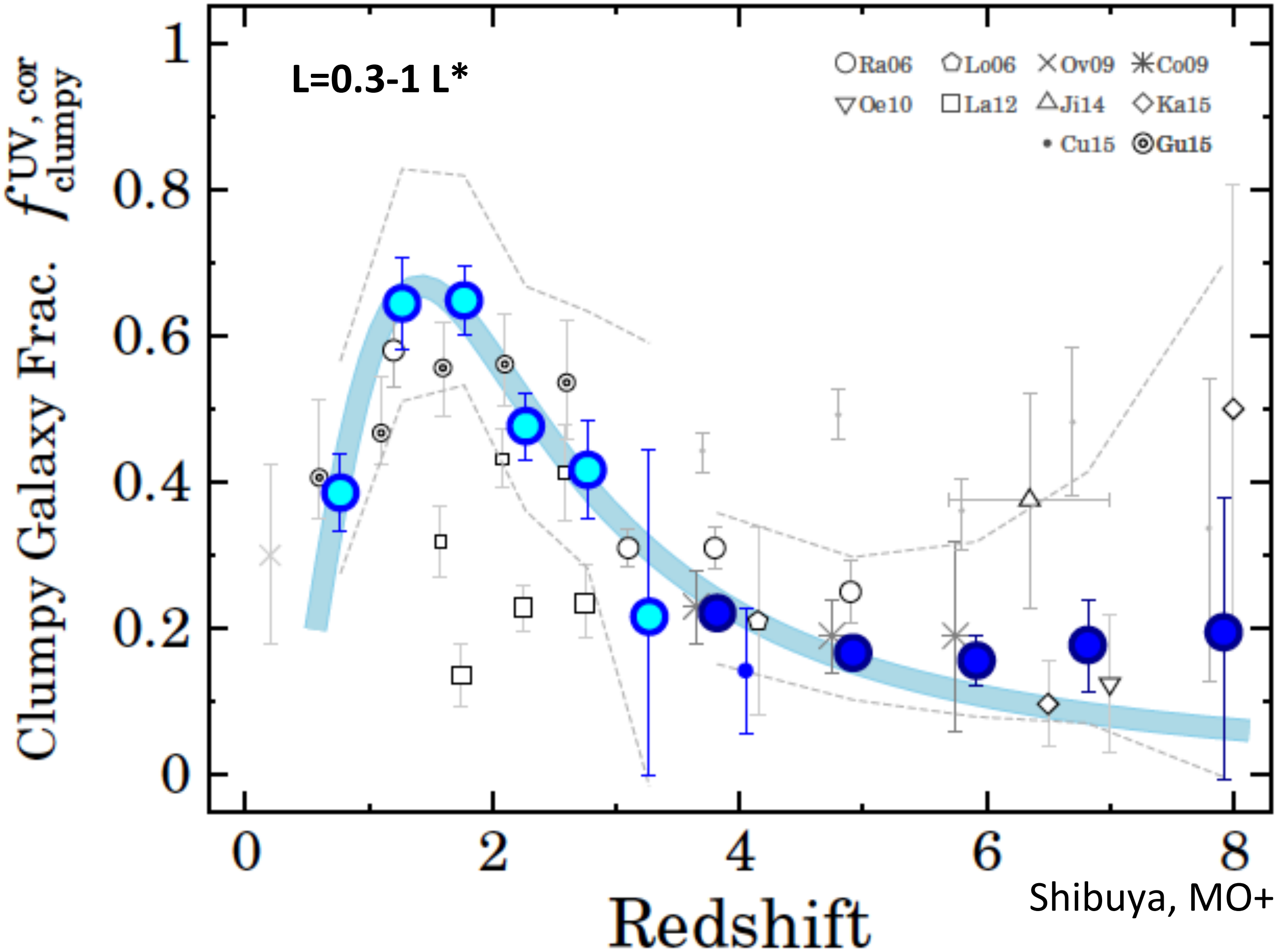
z=9

Galaxy (Average)

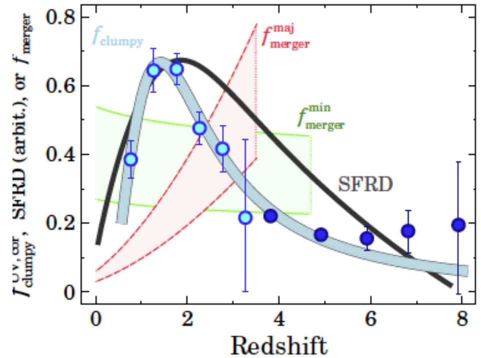


Ono et al. 2012

Clumpy Galaxies



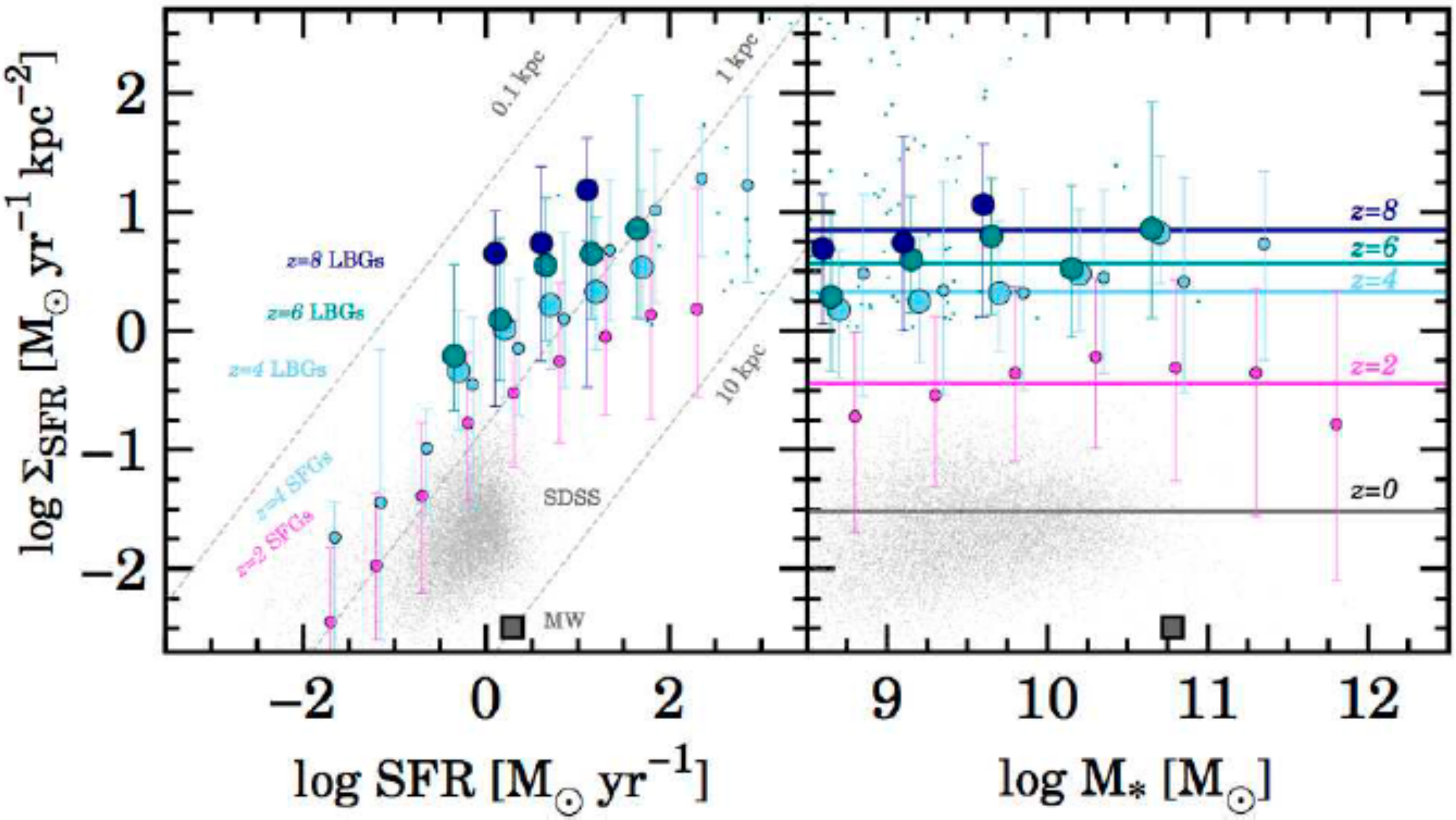
cf. SFRD evolution



Shibuya, MO+16

- $f_{clumpy} \equiv N_{clumpy}/N_{all}$: Majority of ~L* galaxies at z~2 have clumps (see+Guo+14)
- Evolution of f_{clumpy} follows the trend of the SFRD evolution
- Consistent with violent disk instability (VDI) scenario (Keres+05,+09)?

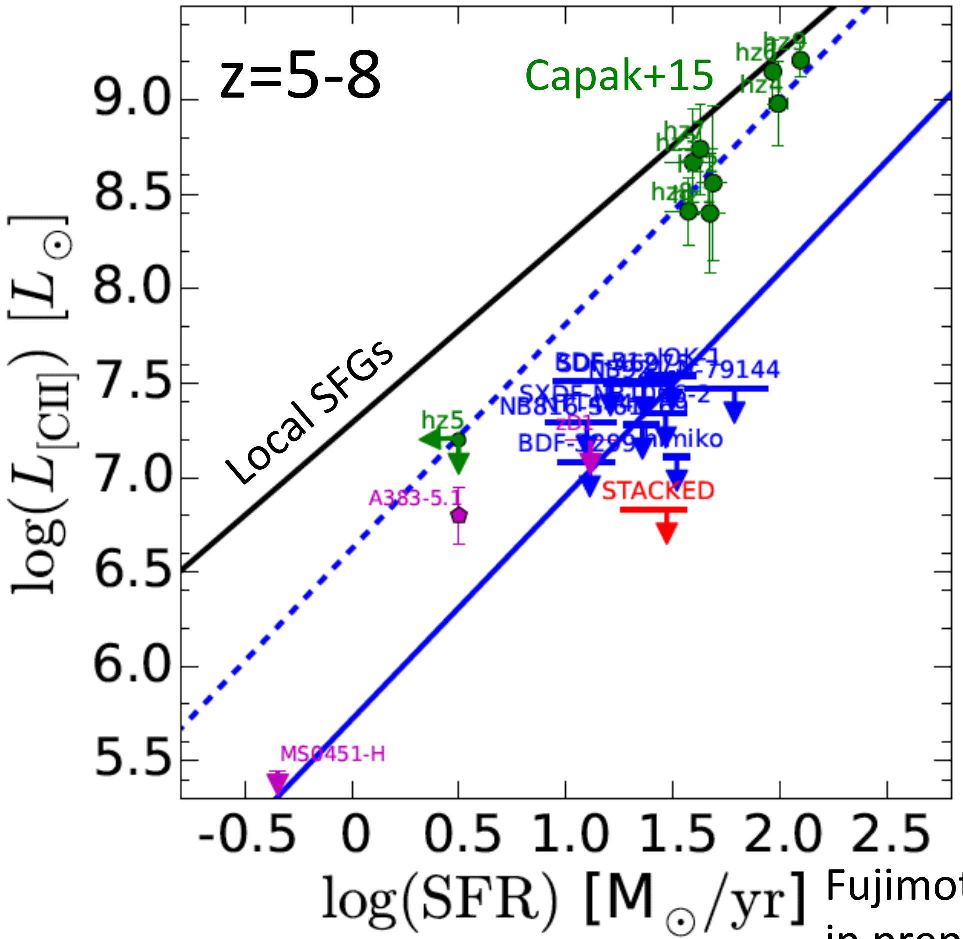
SFG Size Evolution



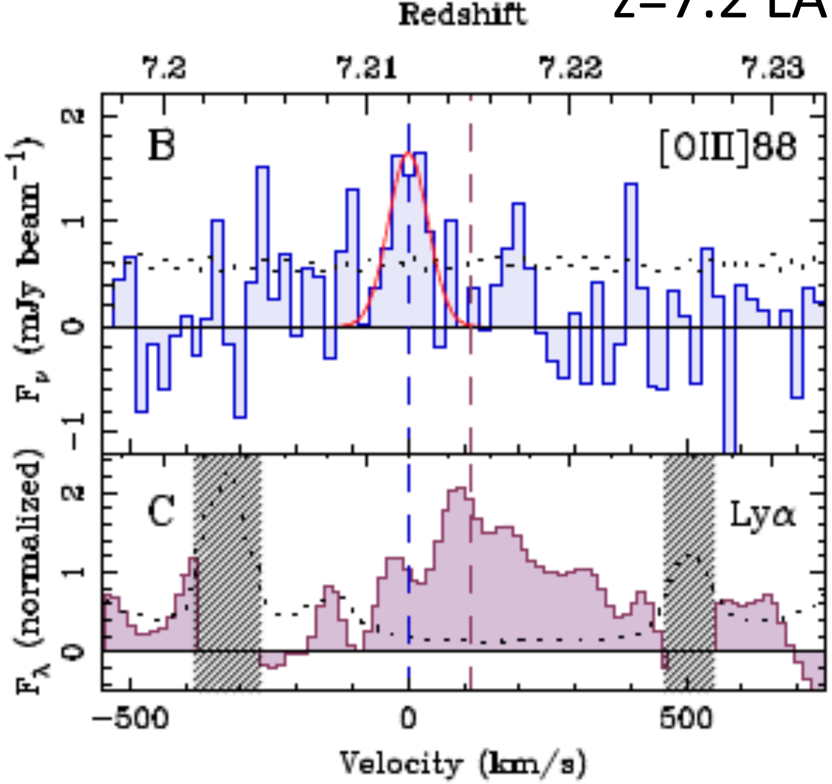
Shibuya, MO, Harikane+15

- Σ_{SFR} increases towards high-z by the size evol.
- Intensive star-formation in a small vol. ISM change?

High Ionization ISM for a Large Frac. of Gal. Suggested by ALMA Obs.



Fujimoto, MO+ in prep.



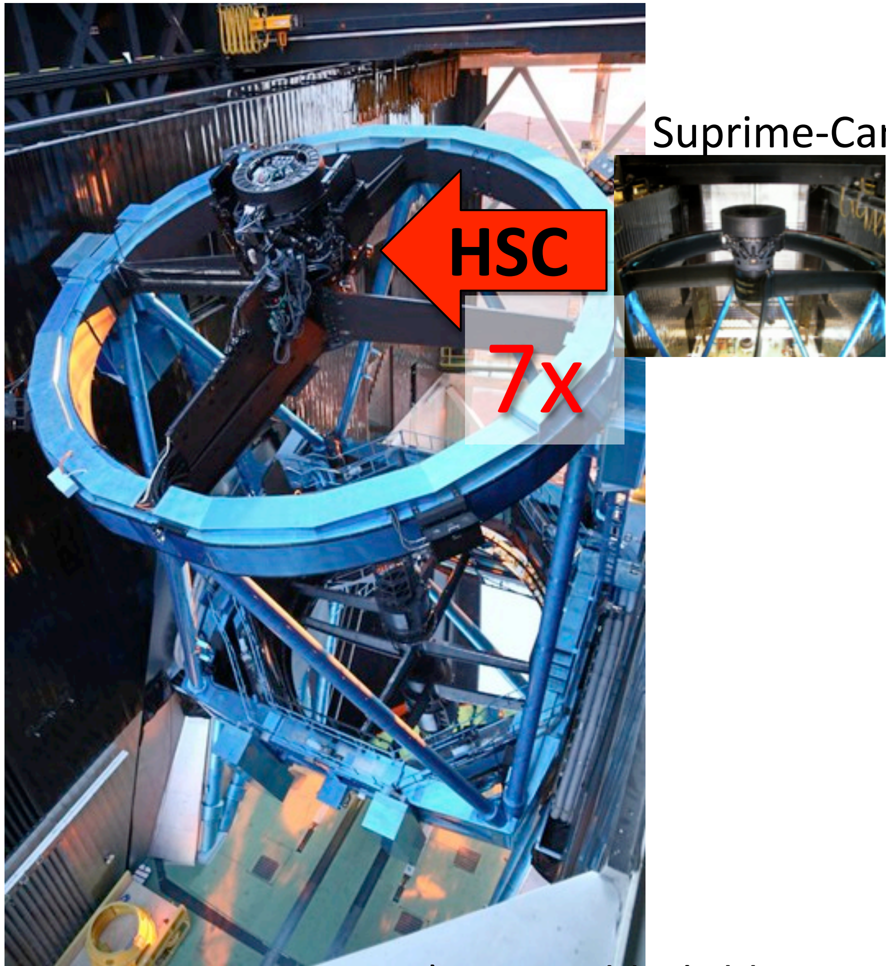
Inoue et al. (2016)

- Deficit of [CII]158um emission (Ouchi+13,Ota+14,Knudsen+16; cf. Capak+15)
- Detection of [OIII]88um, but no [CII]158m (Inoue+16).

→High ionization state of ISM (consistent w CIII]+CIV det.:Stark+15,+16; Maseda's talk)

ON GOING SUBARU SURVEYS

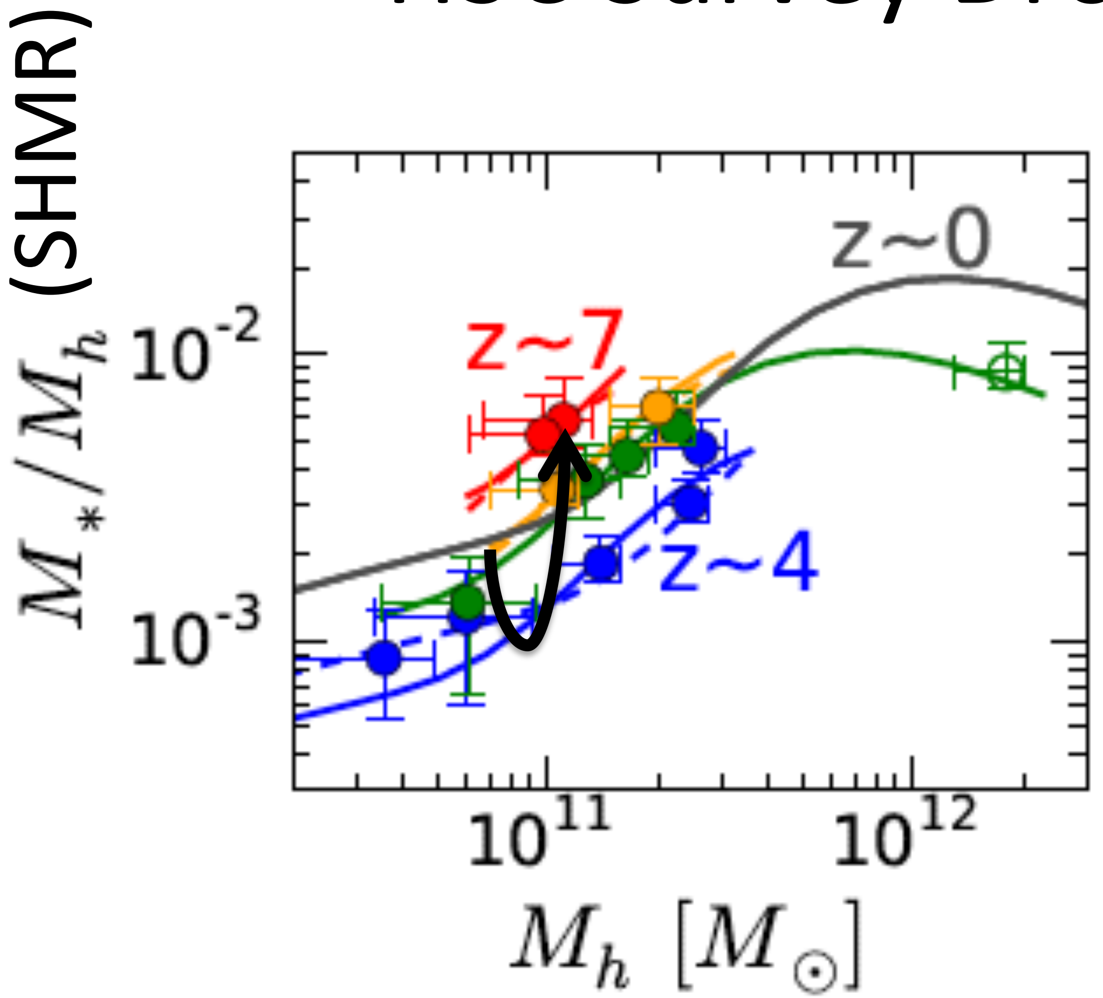
Subaru Hyper Suprime-Cam (HSC) Surevey

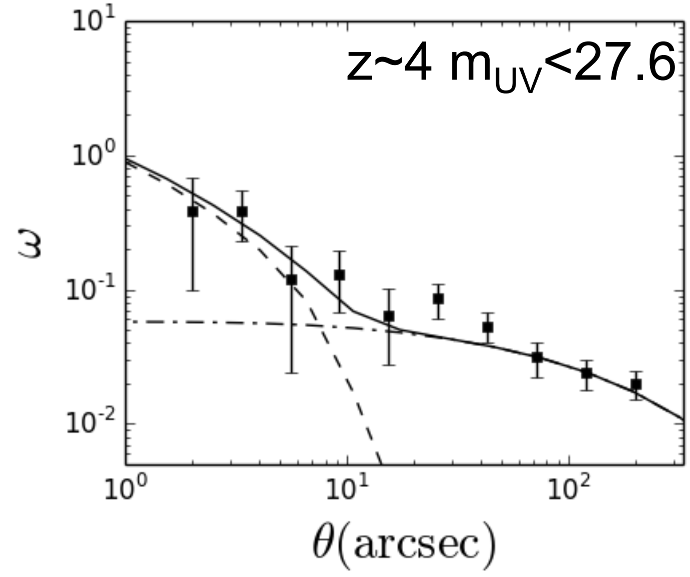


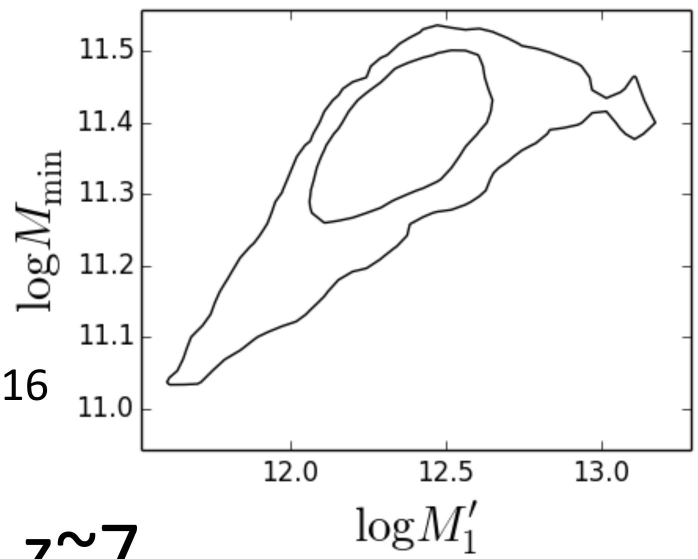
c) HSC Builder's blog

- Subaru optical imager Hyper Suprime-Cam (HSC)
  - Subaru/HSC survey has started since March 24, 2014 under the collaboration of JP/US/TW.
  - ~1/3 of observations are completed.

HSC Survey Dropouts







Harikane,MO+ ApJ, 2016

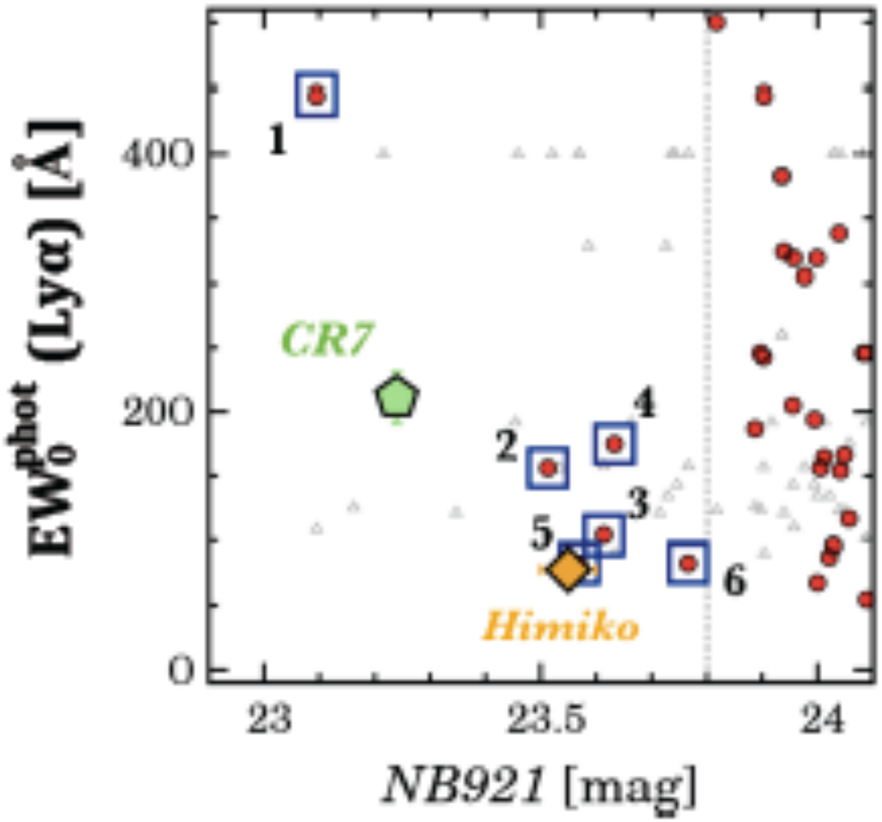
- SHMR at 10^{11}Mo decreases

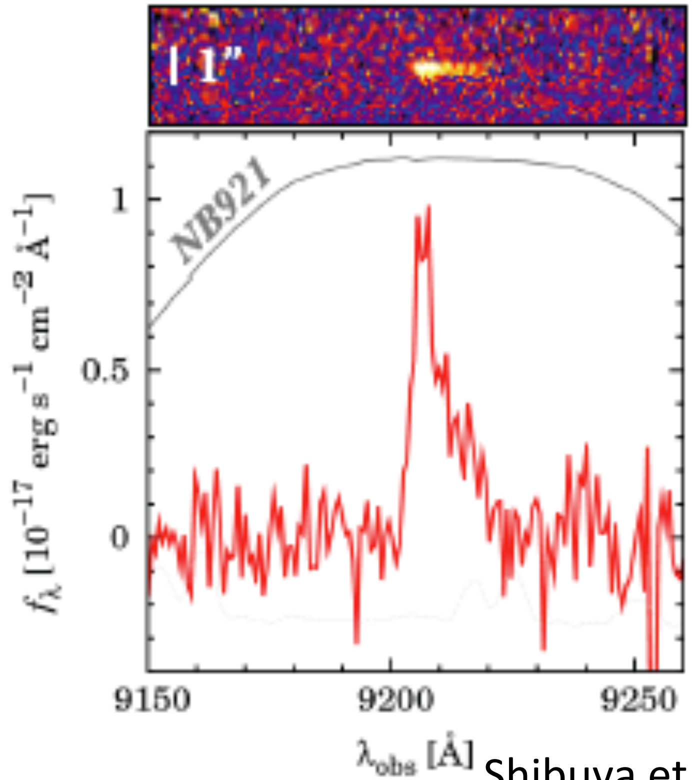
from z=0 to z~4, and increases to z~7

- Signature of feedback efficiency change??

HSC Survey z~6-7 LAEs (On-Going)

z=6.6 LAE Candidates





Shibuya et al. in prep.

- Goals: LAEs at z=5.7, and 6.6 in 30 deg^2 (and z=7.3 in 3 deg^2).
  - Expecting ~20,000 LAEs (hundreds of Lya blobs) down to L(Lyα)~3x10^{42}erg/s

- Now:
  - Shallow data only (~20 deg^2 data for z=6.6 LAEs and ~5 deg^2 data for z=5.7 LAEs)
  - Several rare bright LAEs, like Himiko, CR7, and COLA1 are identified (w spec. conf.).
  - Faint AGN and galaxy contribution?

Summary

- The HST, Subaru, and ALMA study results of Early galaxies and reionization up to z~10.
  - Hubble+Subaru+Planck2016 const. on f_{esc} M_{truc} & $Q_{HII}(z)$
    - $\langle f_{esc} \rangle \sim 0.15$-$0.3$
    - No truncation found in LFs. The statics also infers $M_{trunc} > -13$
    - $Q_{HII}(z)$ of Subaru LAE suggests moderately high HI frac at z~7-8

    → Self-consistent picture of reion history and ionizing photons.
  - Hubble and ALMA constraints on morphology and ISM
    - More compact galaxies towards high-z: $r_e \propto (1+z)^{-1.1}$
    - Clumpy galaxy fraction peaks at z~2, and decreases towards z~8
    - High Σ_{SFR}. ALMA [CII]158um deficit and [OIII]88um detections Suggestive of high ionization state.
  - On-going Subaru surveys
    - M_*/M_h ratio upturn(z>~4) Signature of feedback efficiency change?
    - Large area HSC LAE survey identifying high EW(Lya) objects