Evolution of High-z Star–Forming Galaxies

Masami Ouchi

ICRR, Univ. of Tokyo

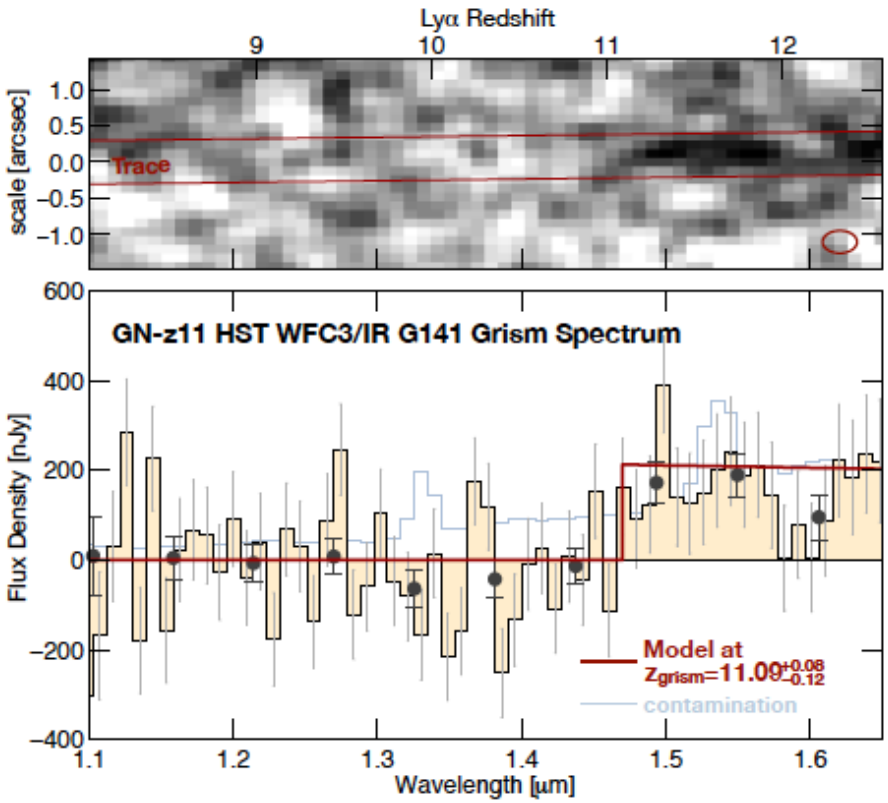
Outline

- Recent observational progresses of SF galaxies at a redshift up to z~10

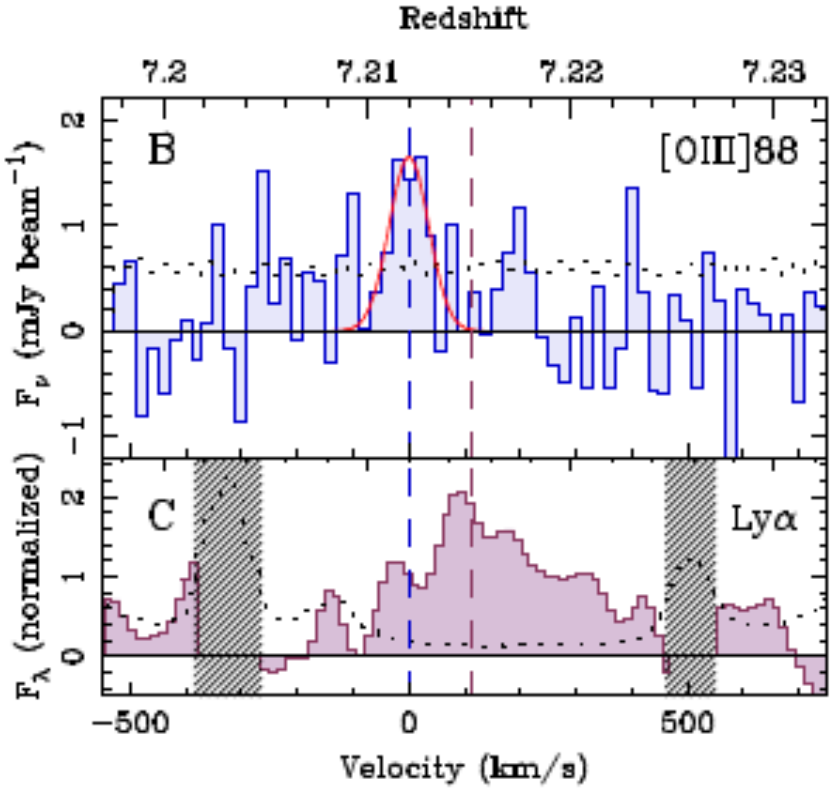
  1. Star-formation and morphology
  2. Inter-stellar medium
  3. Dark-matter halos

- Starting from HST, Keck, Subaru obs. to ALMA obs.

Recent Progresses of High-z Star-Forming Galaxy Obs.



Oesch et al. (2016)



Inoue et al. (2016)

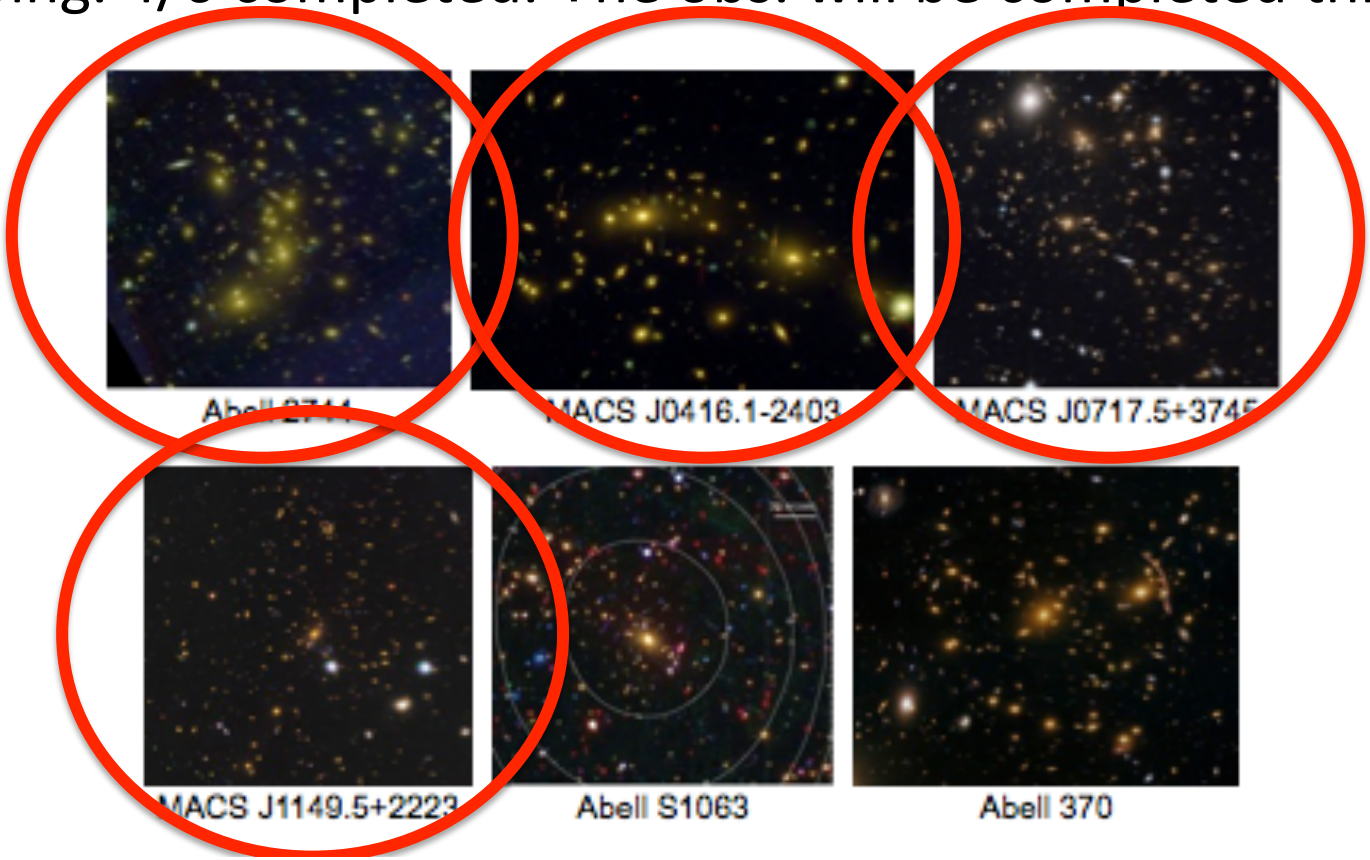
- Deep optical-NIR obs confirm galaxies up to z=8.7(Zitrin+15) and possibly z~11 (Oesch+16)?
- An [OIII]88μm detection for an optically selected gal. at z=7 with ALMA (Inoue+16)
- Optical-NIR observations and ALMA follow-up are one of major drivers of high-z gal studies.

1. STAR-FORMATION AND MORPHOLOGY

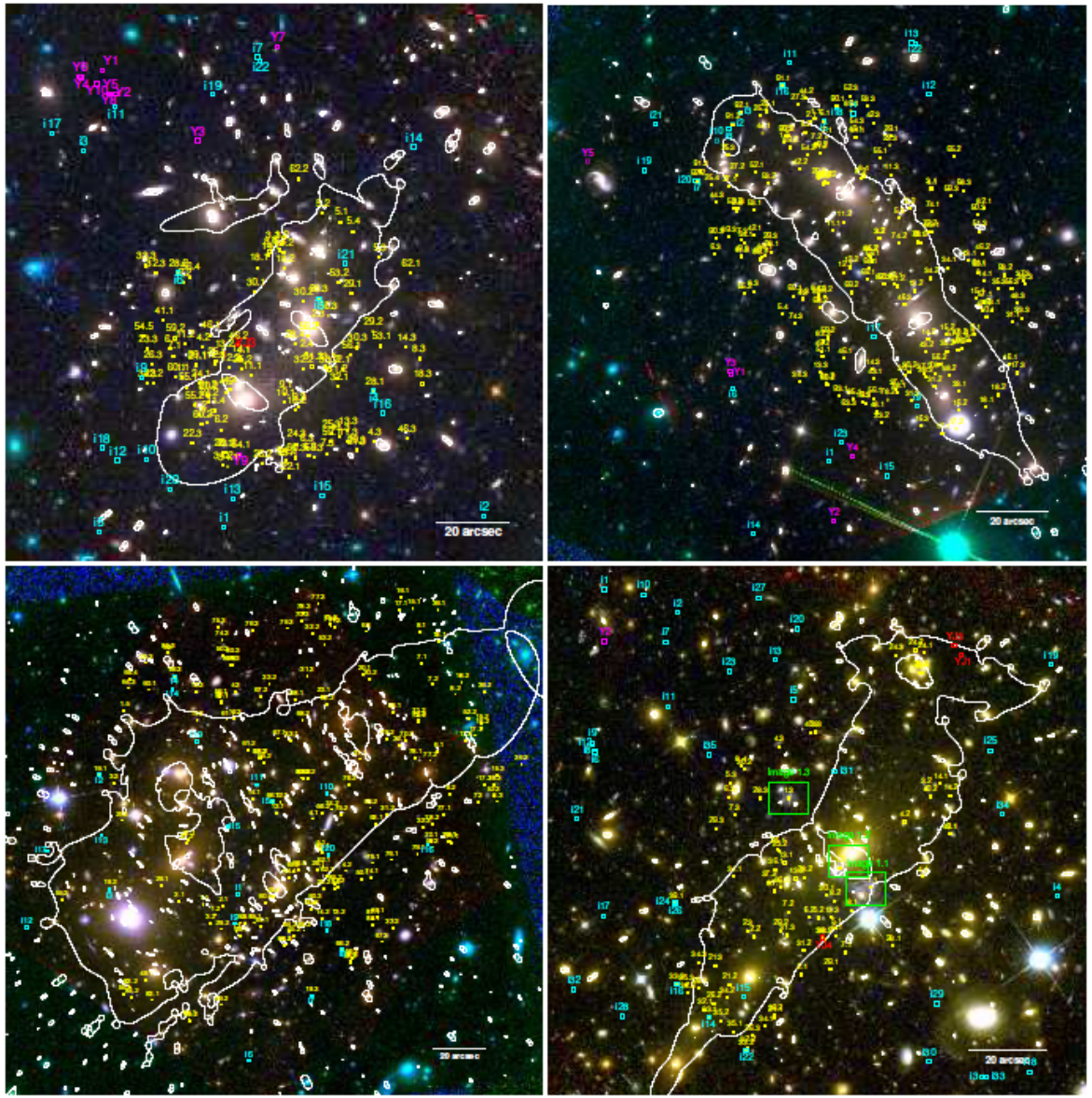
Hubble Frontier Fields (HFF)

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

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



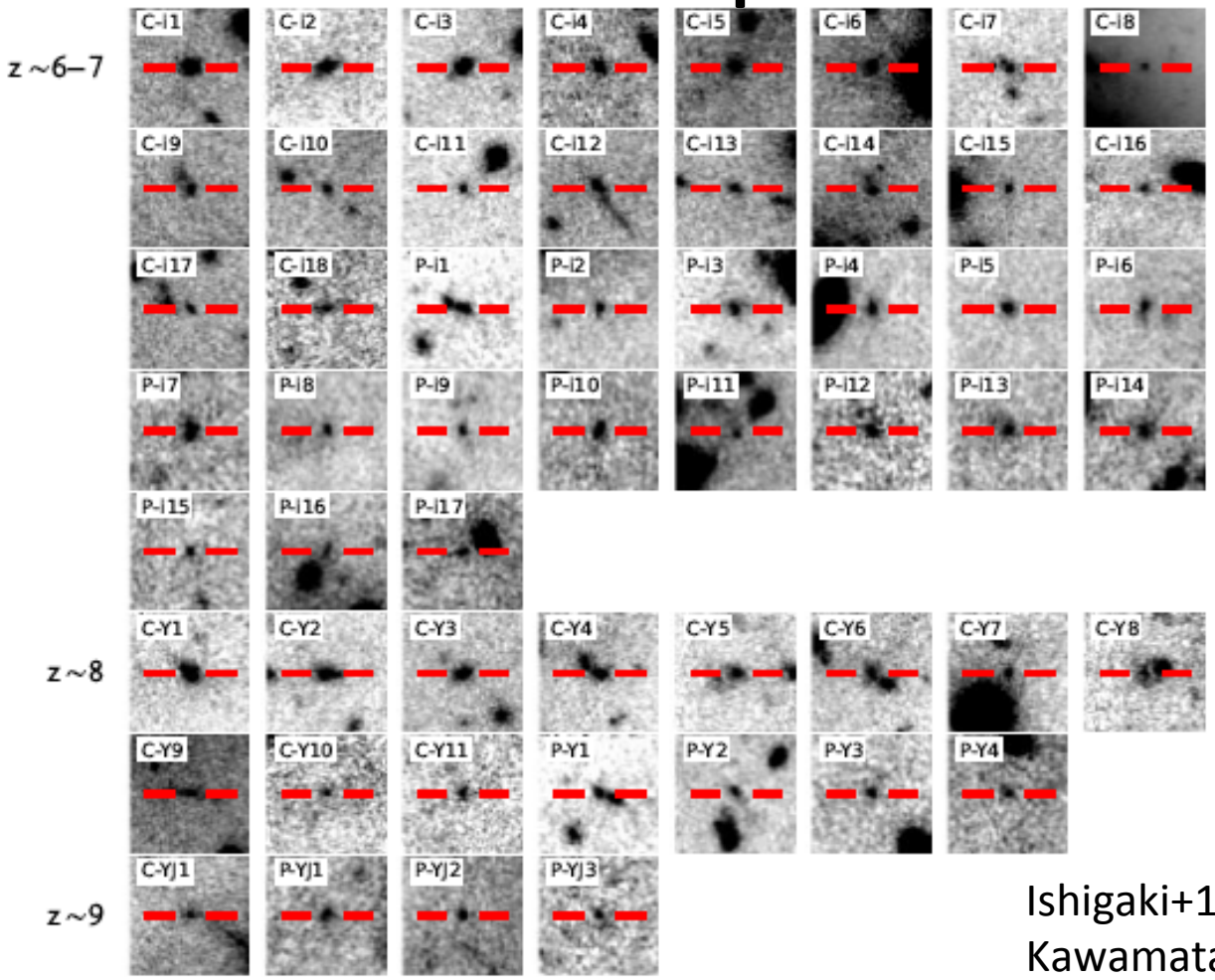
Mass Models



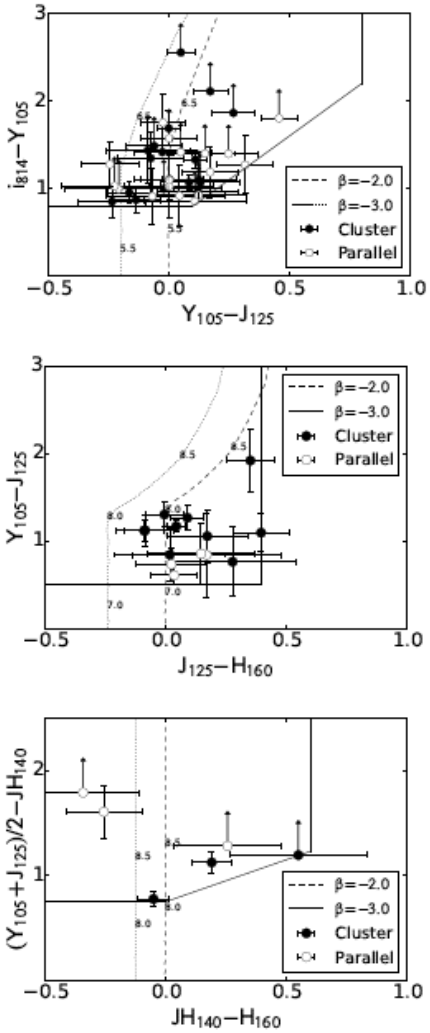
Kawamata+16

100-200 multiple images for mass modeling

HFF Dropouts at z~6-10



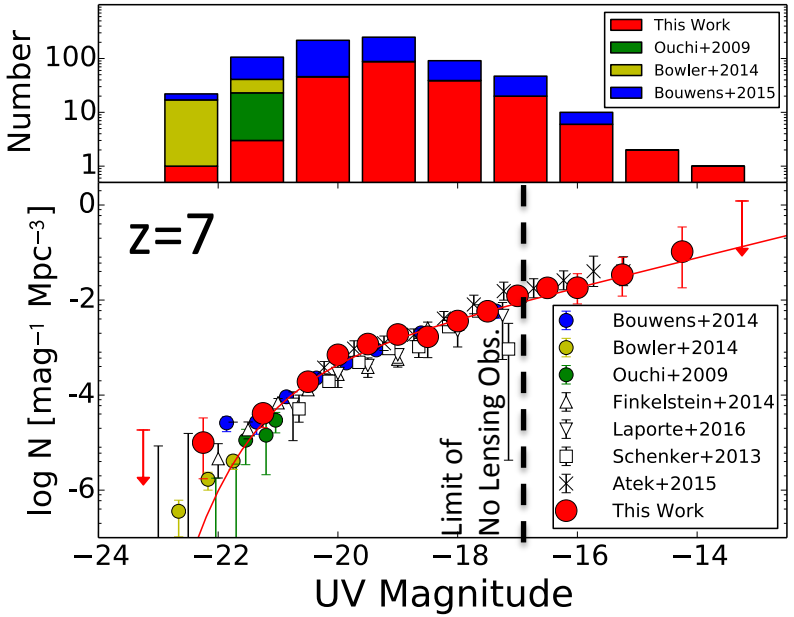
Ishigaki+15,
Kawamata+16

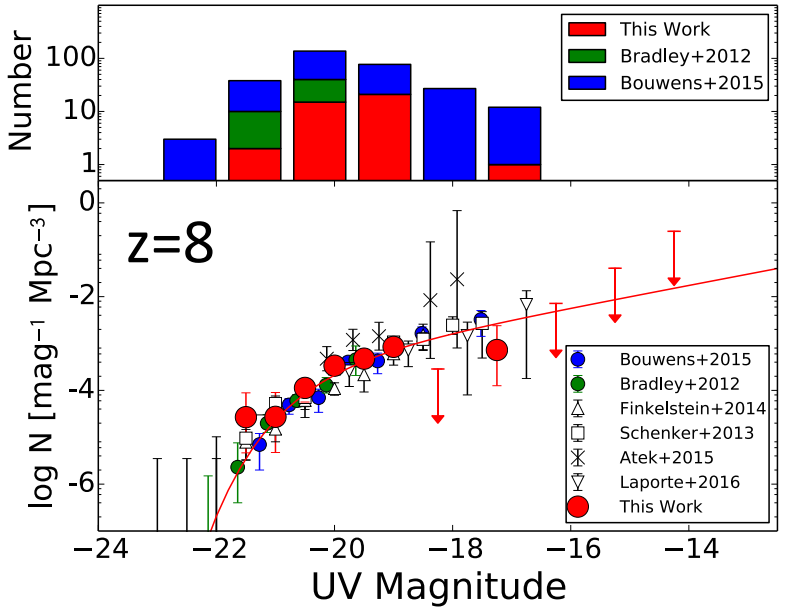


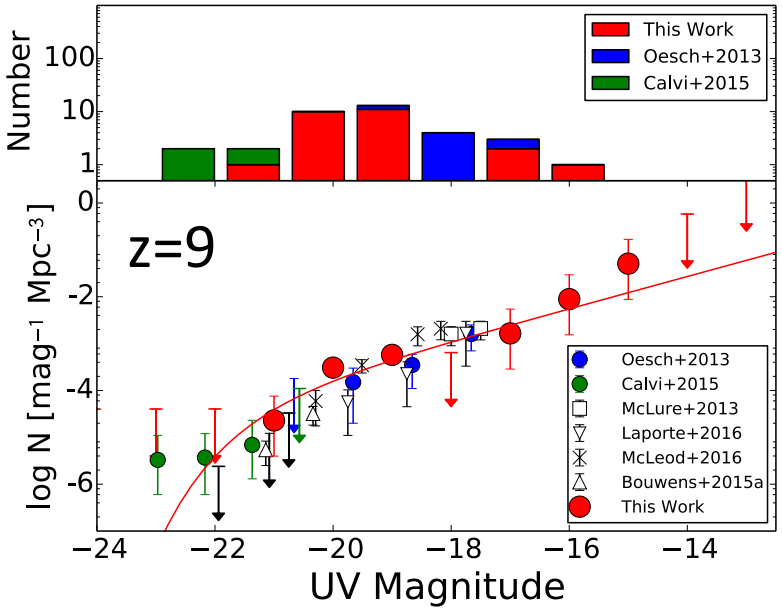
- 127 galaxies at z=6-10 identified by dropout tech, 18 out of which have μ>10 (Kawamata+16)

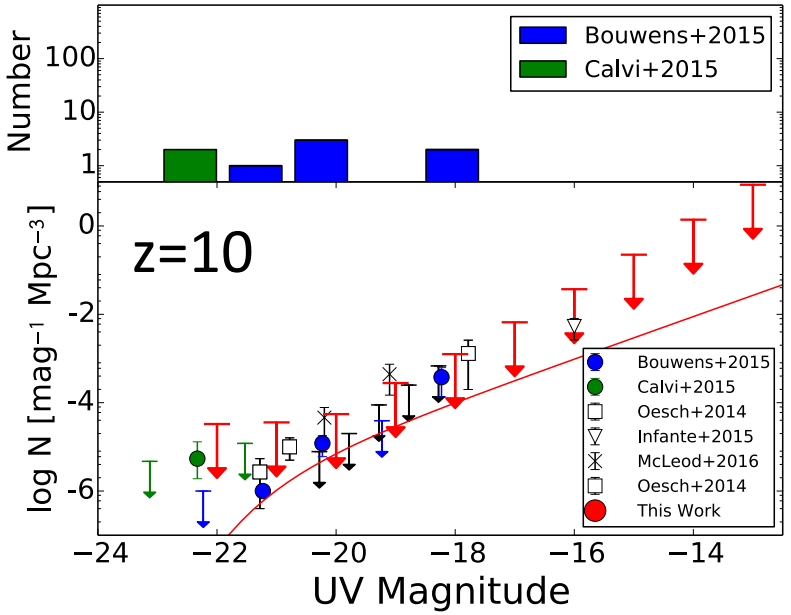
UV Luminosity Functions

Ishigaki,MO, in prep



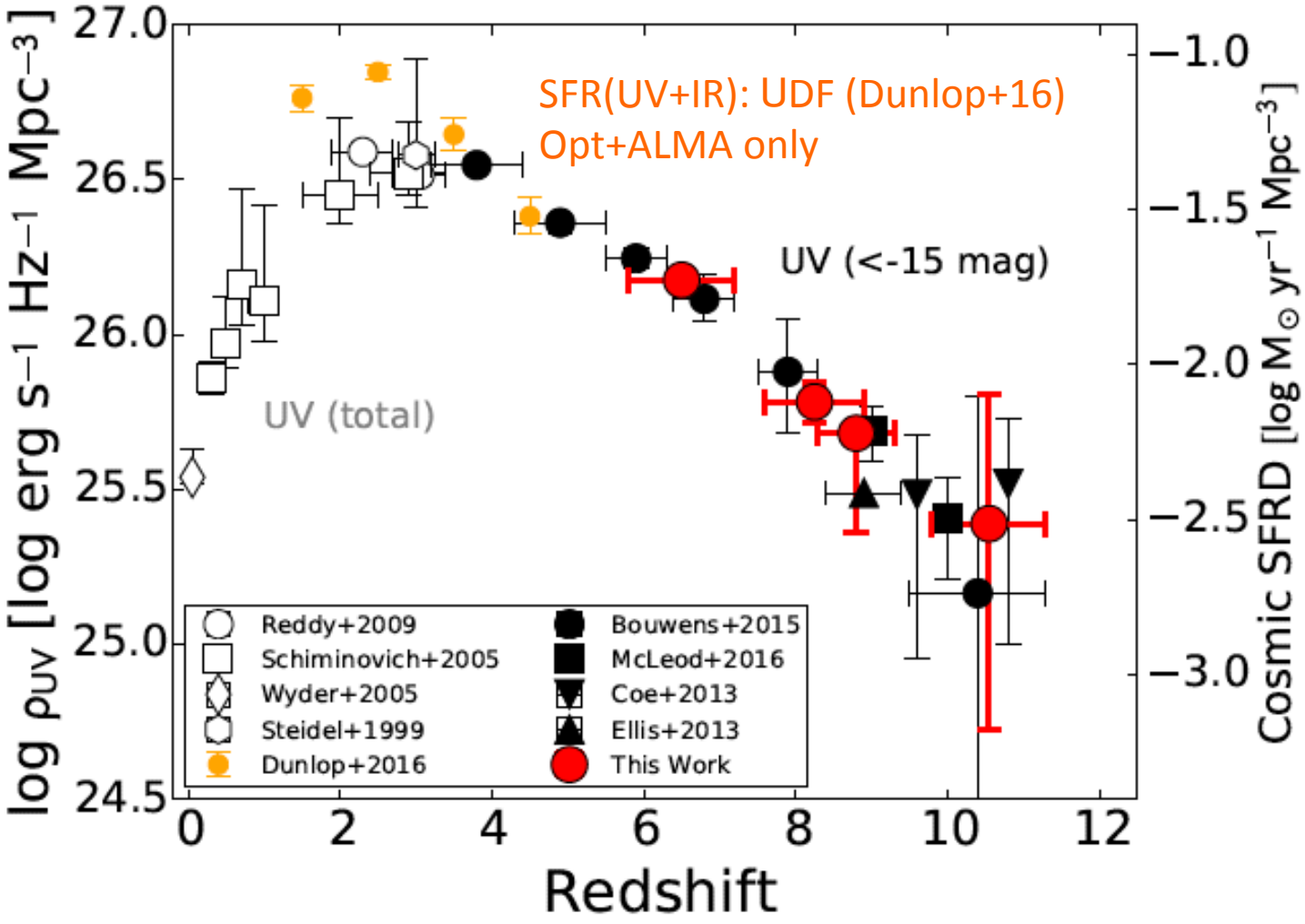






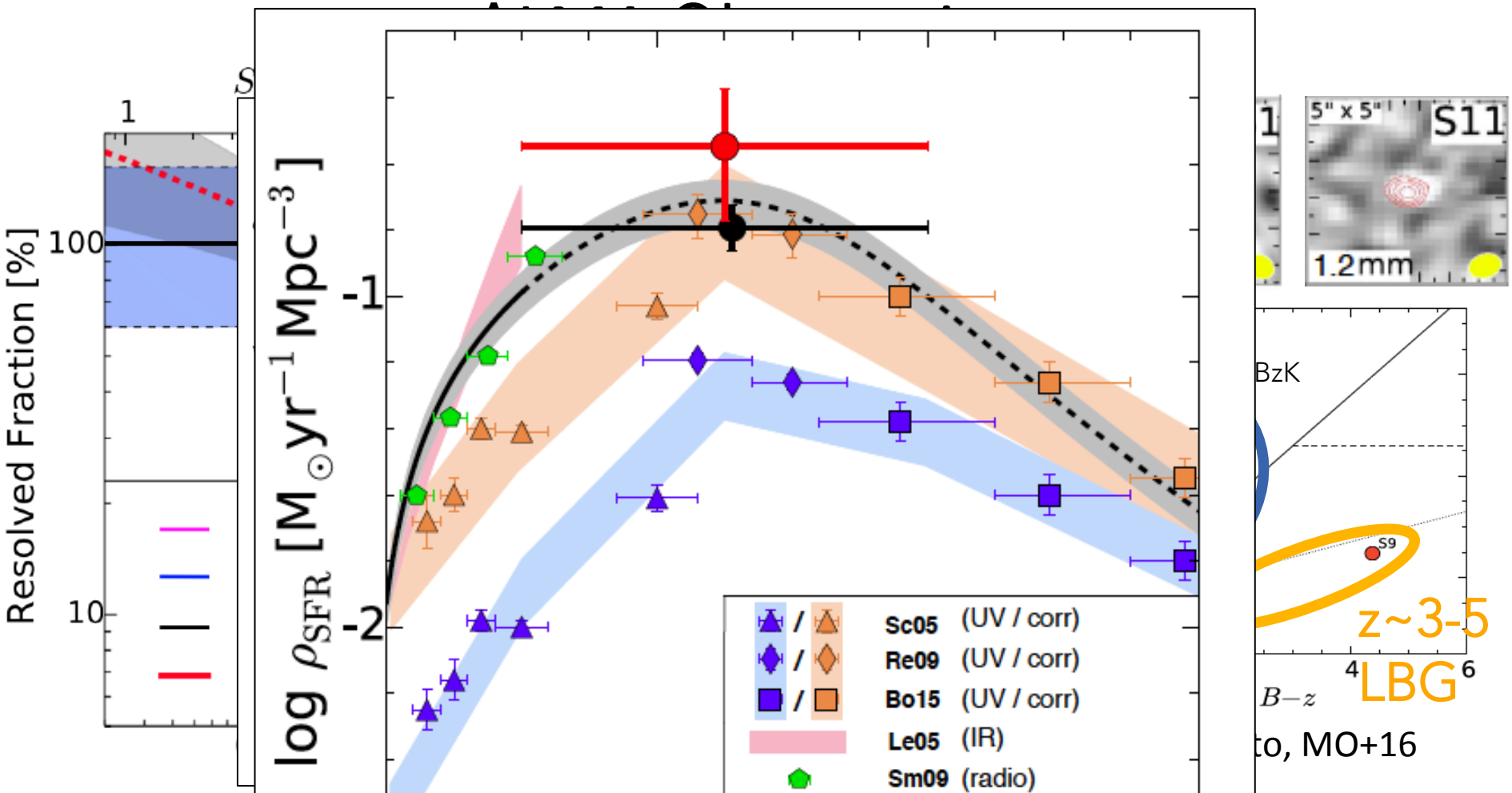
No flattening or break at the faint-end LF. No sig. of feedback effect down to ~-14 at z~7.

UV Luminosity Density Evolution



- Peaking at z~2 and decreasing from z~2 towards higher redshift
  - Rapid decrease at z>8? (e.g. Oesch+13). No rapid decrease in the large data set.

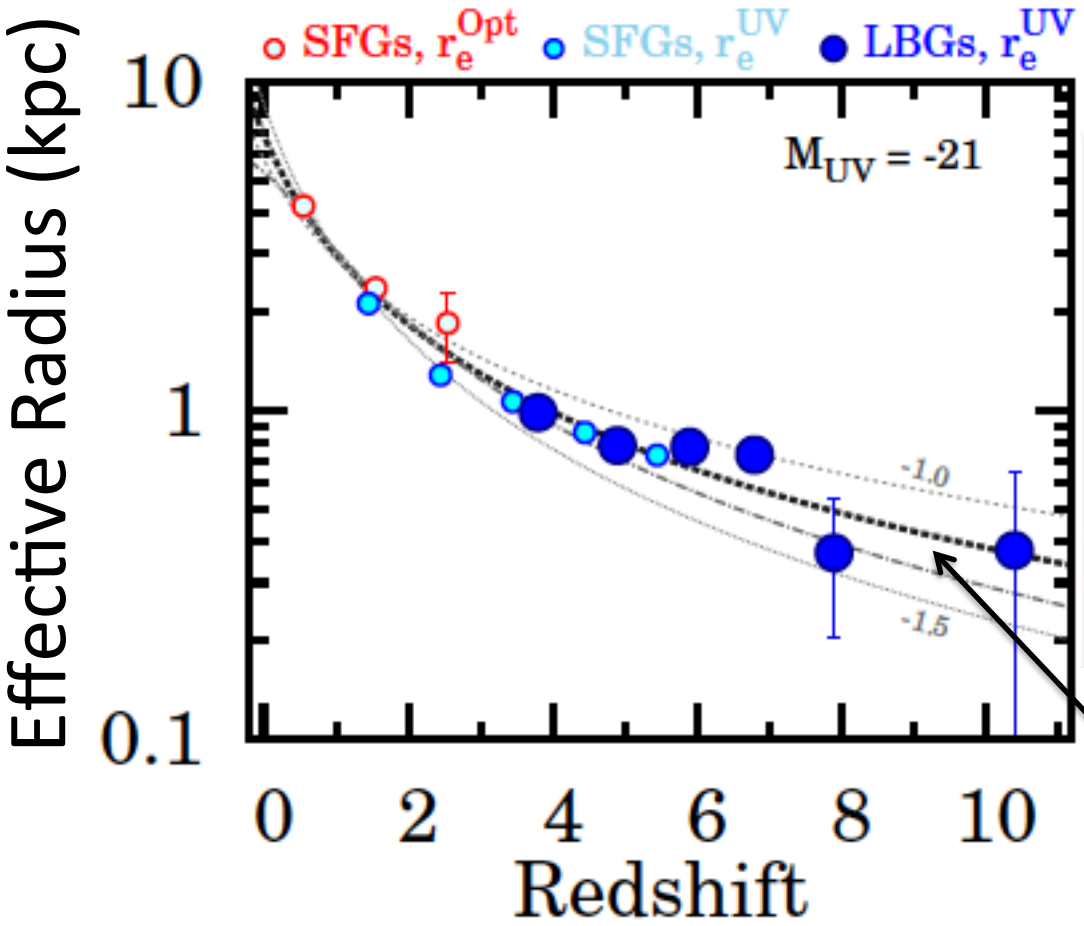
Contributions of Dusty SFGs to Cosmic SFRD?



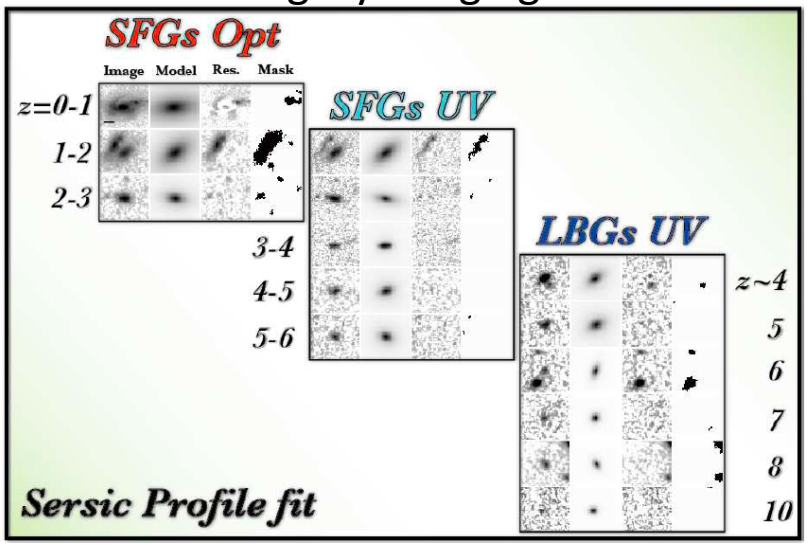
- (Sub)mm … LMA obs (Fujimoto …
- ~50% (+1… ~2
- ~40% has no clear optical-NIR counterparts (down to … 27 mag)

… to, MO+16

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

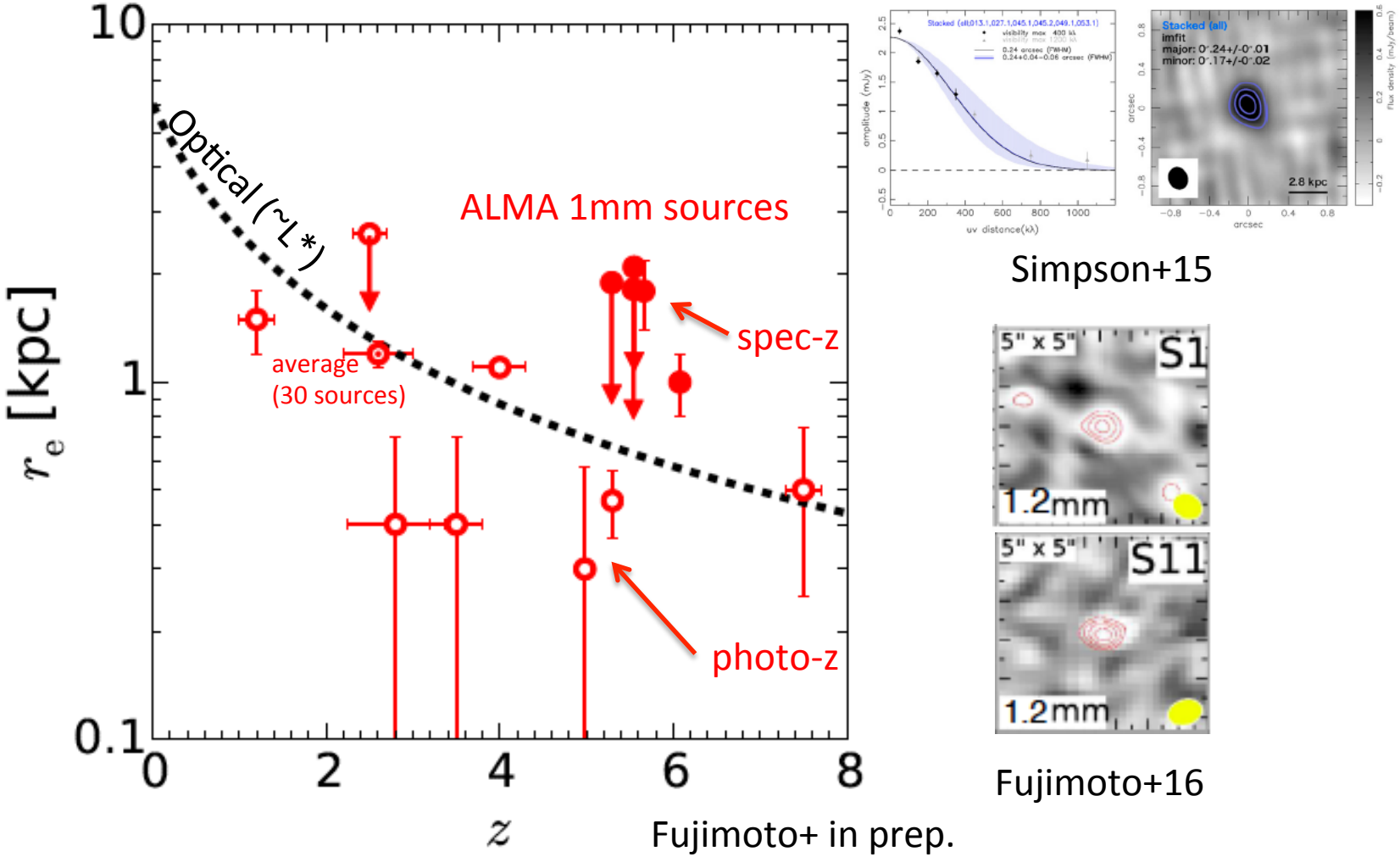
z=9
Galaxy (Average)

Ono et al. 2012

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

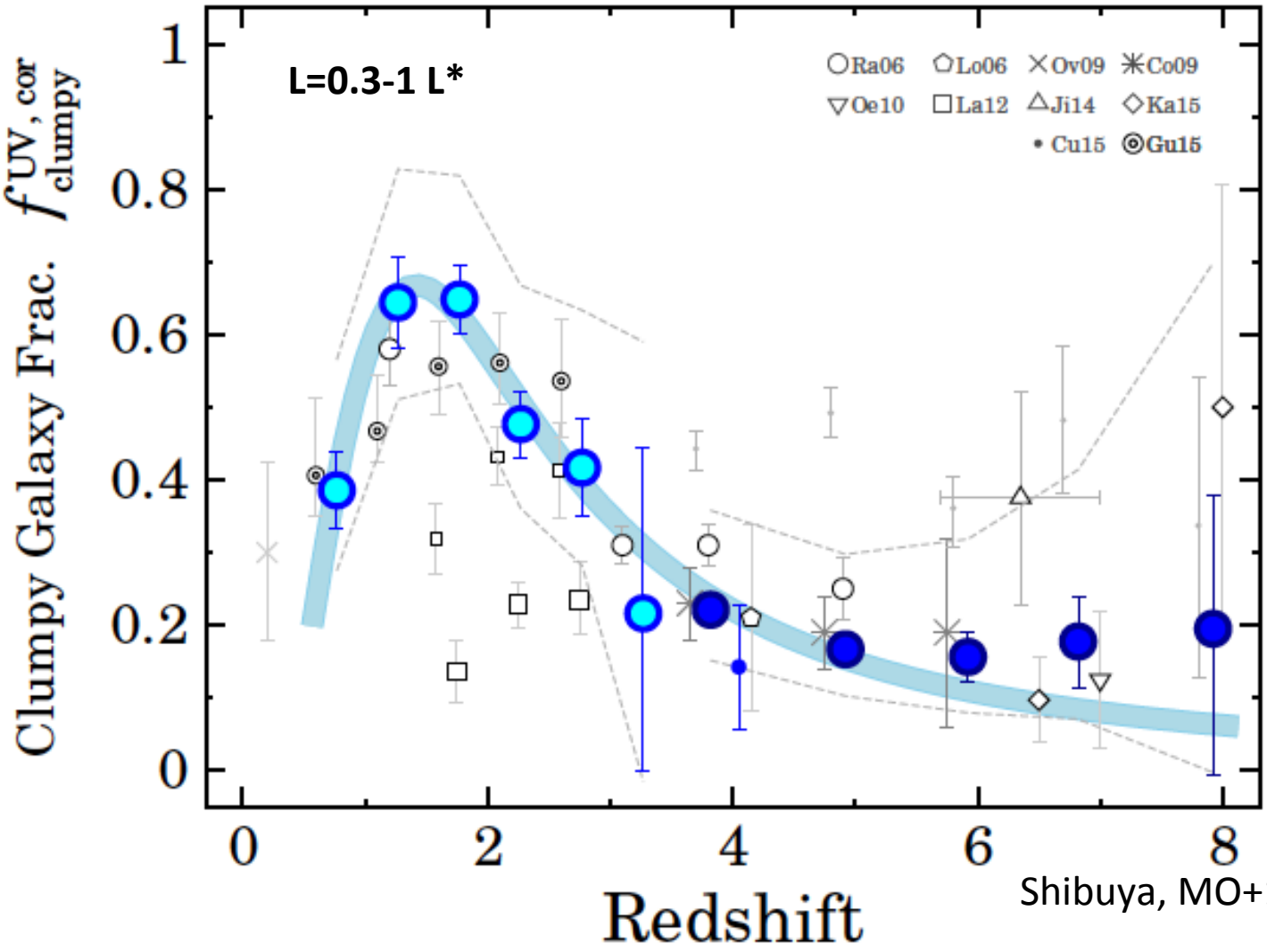
c) Shogakukan

Sizes of ALMA 1-mm Sources



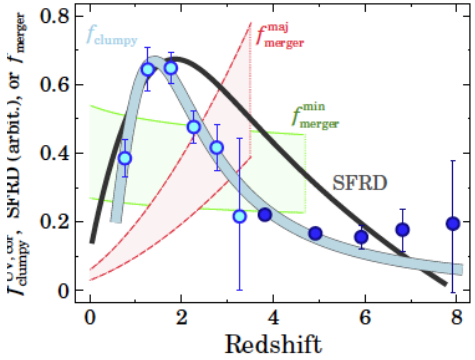
- ALMA 1 mm (dust) continuum sources
  - Compact at ~1mm: r_e <~1 kpc at z~3 (Ikarashi+15, see+ Simpson+15)
    - Compact dusty starbursts (triggered by violent mergers) ??
  - Large diversity of sizes. Inferring size-luminosity relation?

Clumpy Galaxies



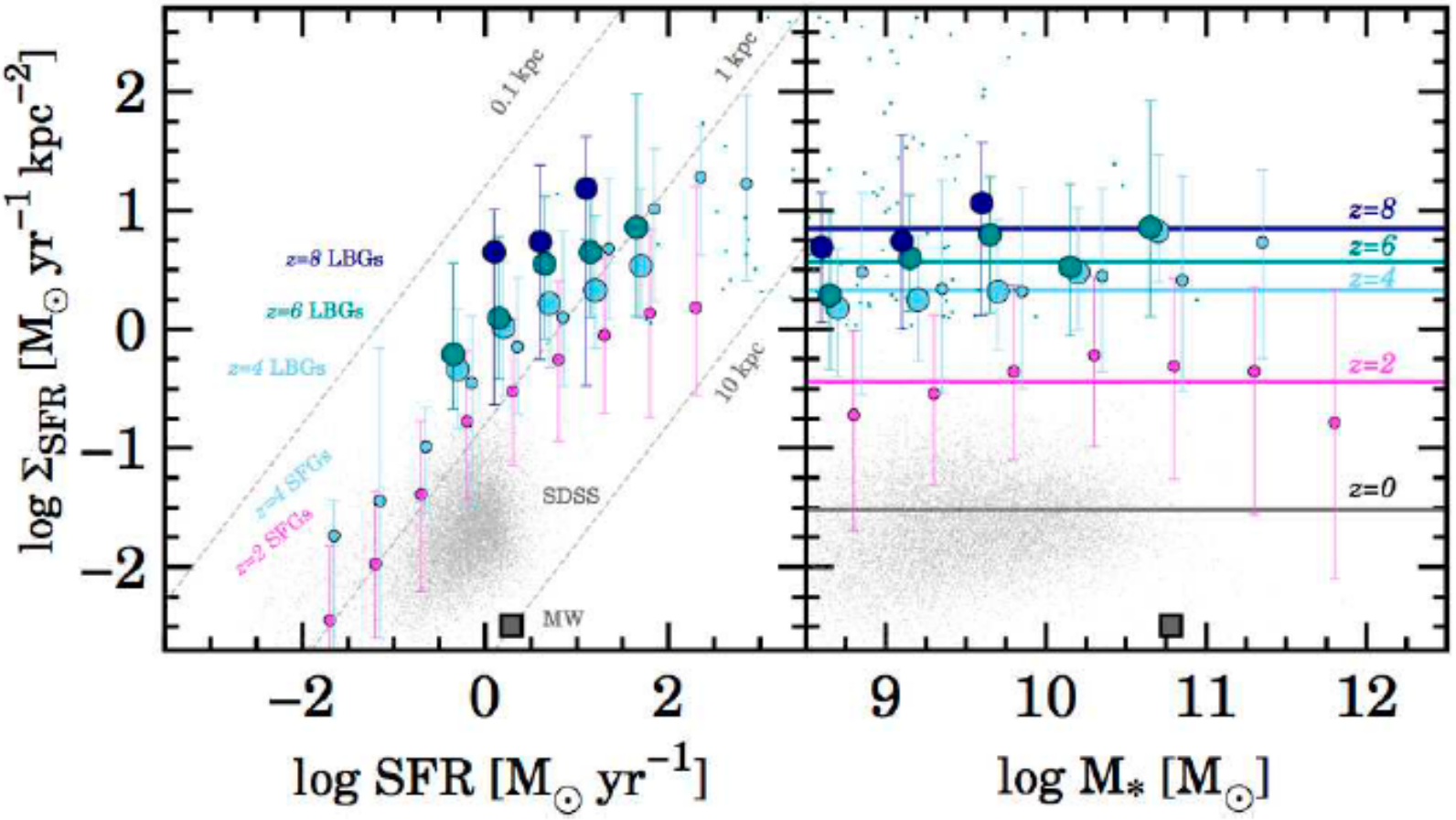
Shibuya, MO+16

cf. SFRD evolution



- $f_{clumpy} \equiv N_{clumpy}/N_{all}$: 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)?

SFR Density Evolution

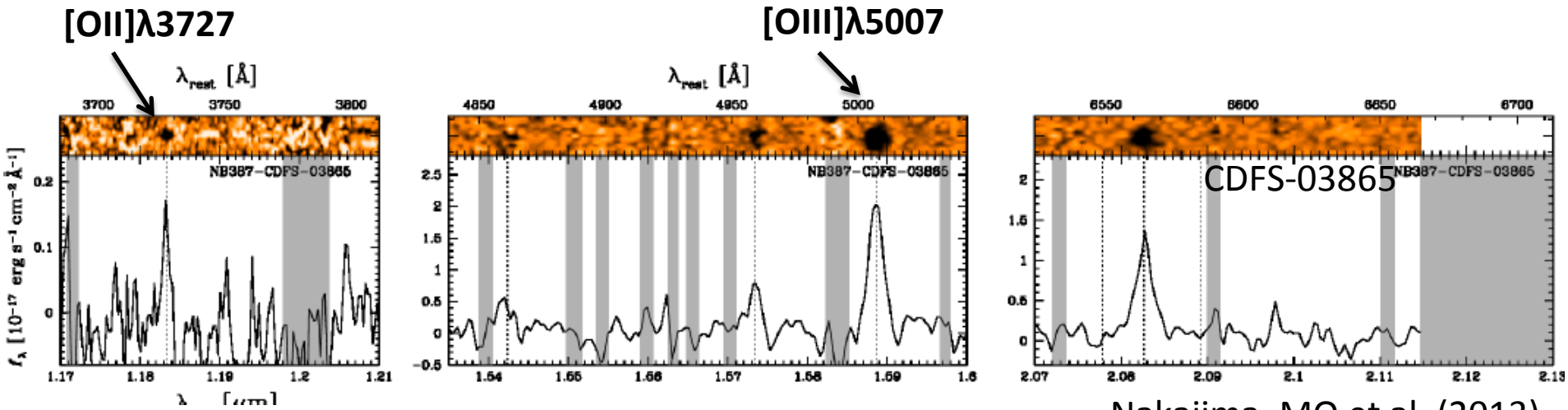


Shibuya, MO, Harikane 15

- Σ_{SFR} increases towards high-z by the size evol.
- Intensive star-formation in a small vol. Stat. ISM change?
  - e.g. [CII]158um is weak in high Σ_{SFR} galaxies (De Looze's talk).

2. INTER-STELLAR MEDIUM

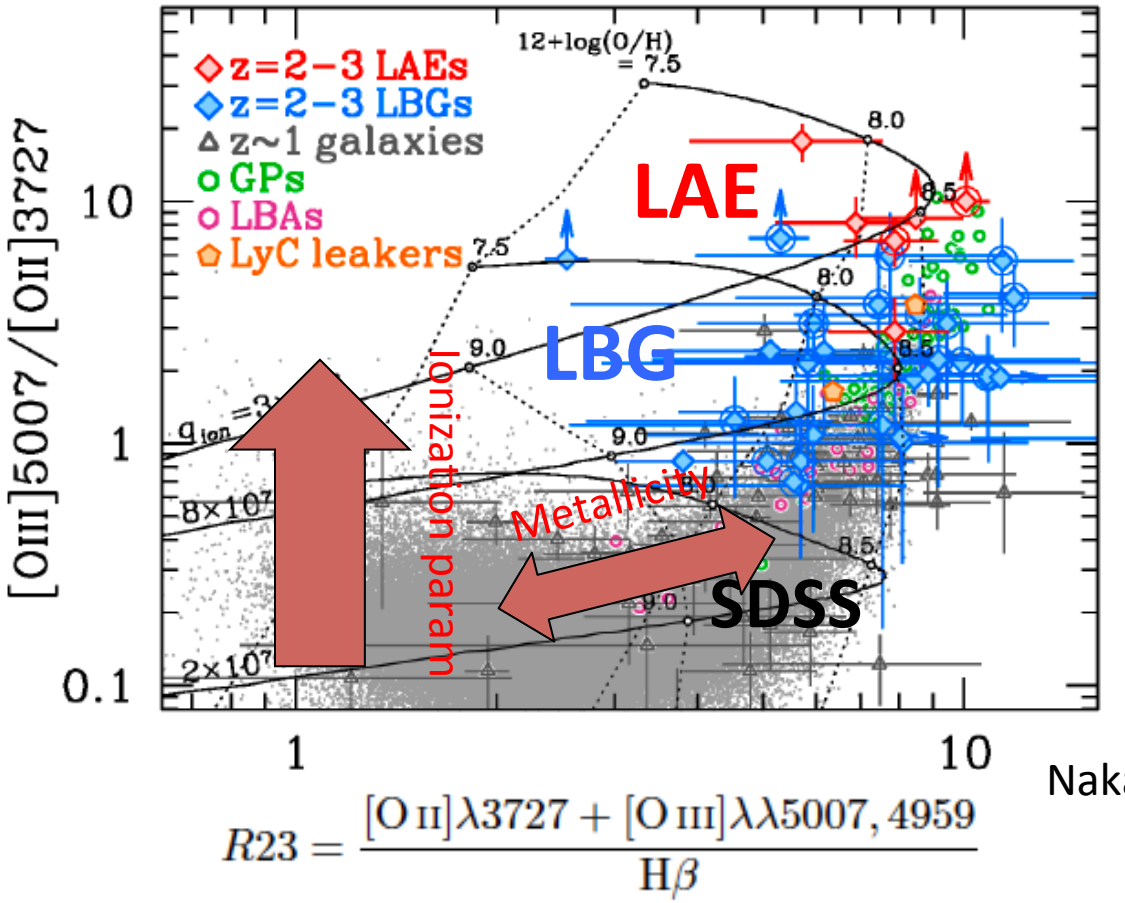
Very High f[OIII]/f[OII] ratio for High-z Galaxies?



Nakajima, MO et al. (2013)

- Deep NIR Spectra for z~2 galaxies.
  - BPT offsets (e.g. Shapley+05, Liu+08, Kewley+13, Steidel+14)
  - Very large O32=f[OIII]5007/f[OII]3727~1-10.(cf. Local galaxies <~1)
- No AGN signatures. Extinction corrected.
- Why?

High Ionization Parameter at z~2-3

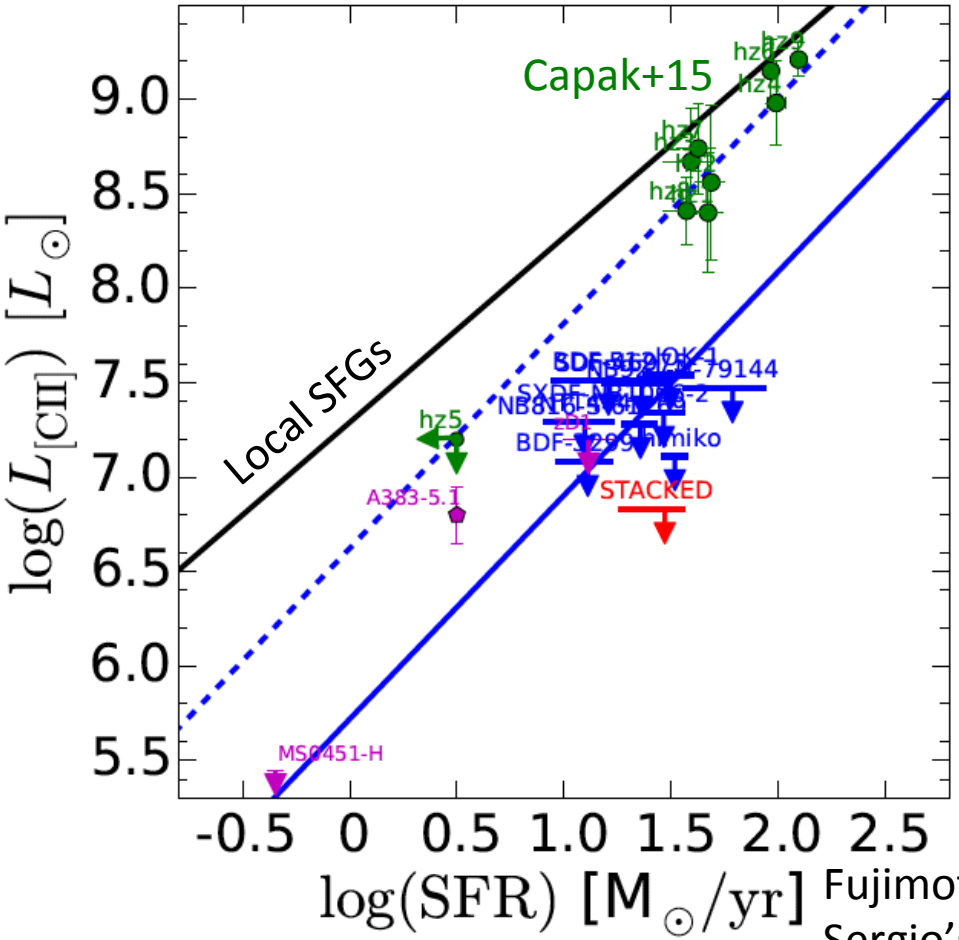


Nakajima & MO (2014)

Stark+16

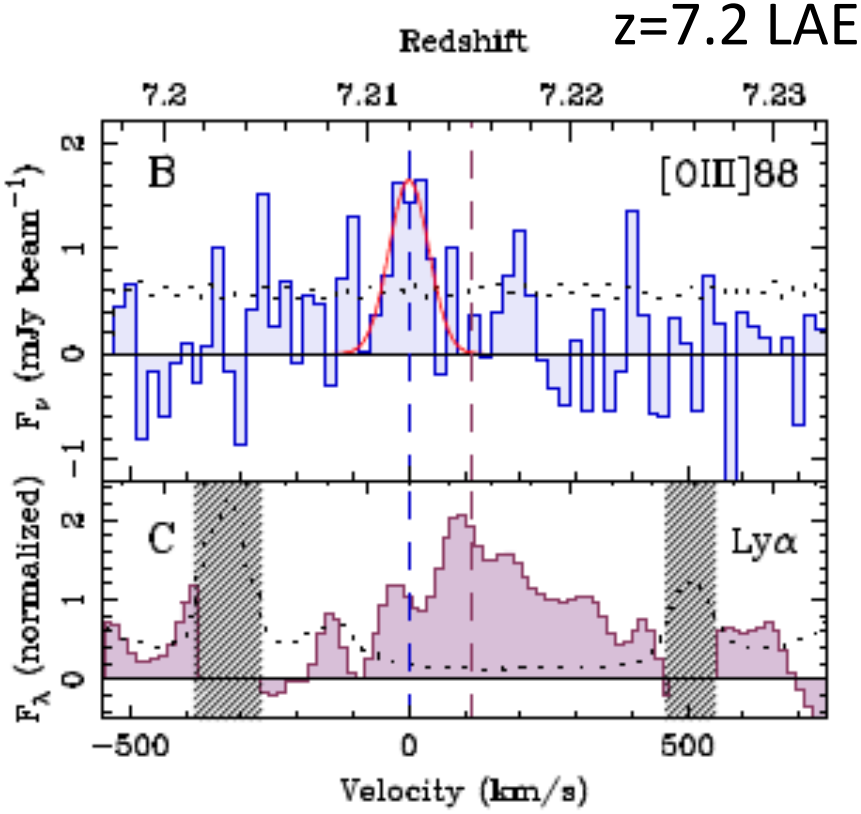
- f[OIII]/f[OII] ratios of z~2-3 LBGs/LAEs are ~x10-100 higher than SDSS gals.
  - High ionization parameter, Log(q_{ion} /cm s^{-1})~ 8-9.
  - Average ionization parameter increases towards high-z.
  - Very efficient ionizing photon production: young stellar population
    → ISM ionization state different from typical low-z galaxies
  - At z~6-8, Keck spec. identifications of CIII] and CIV (Stark+15,+16).

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



Fujimoto+ (see Sergio's poster)

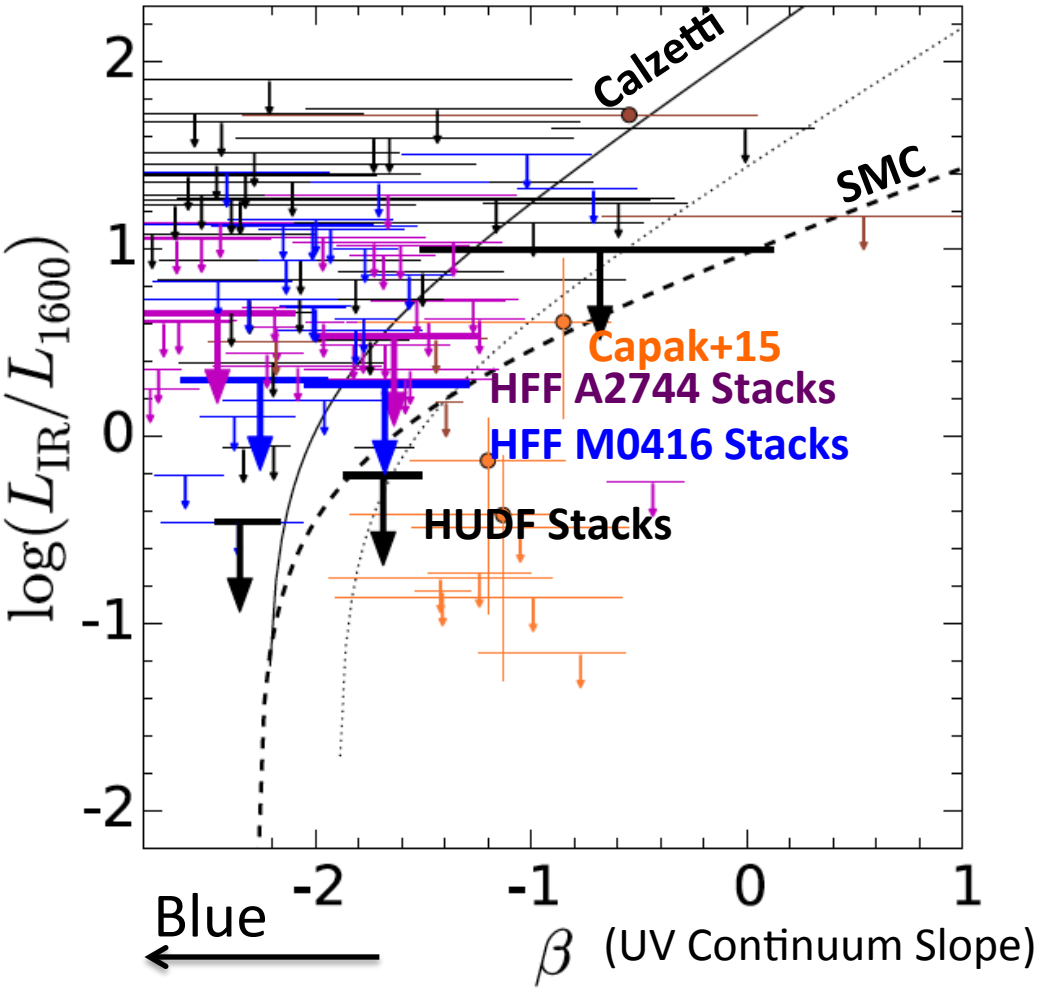
z=7.2 LAE



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 (see Gallerani's and De Looze's talks)

Very Low L_{IR}/L_{UV} for Galaxies at z~5-8

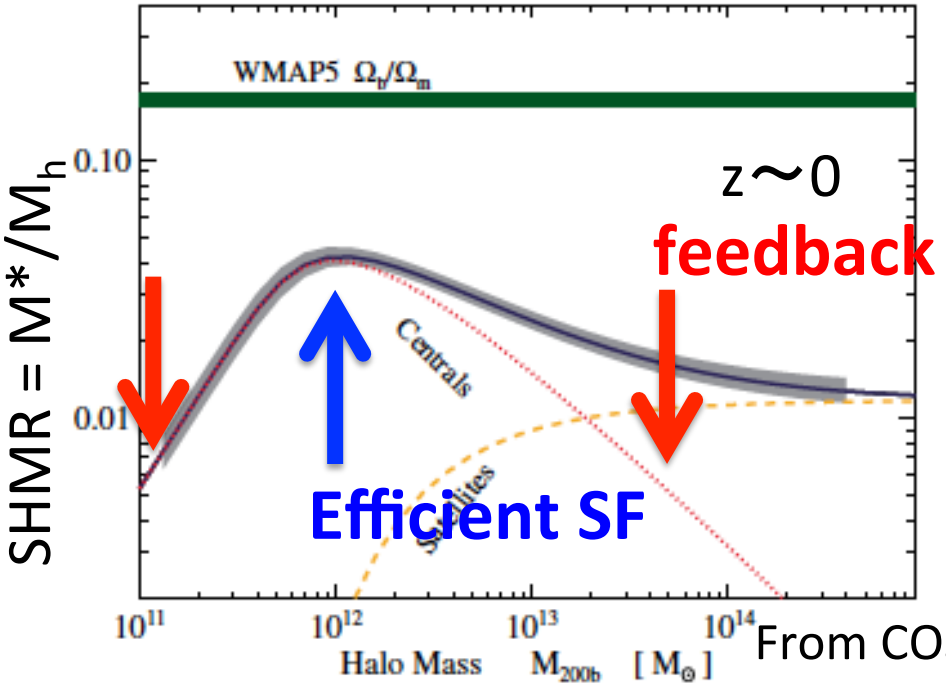


Fujimoto+in prep.
(see Bouwens+16 & Seiji's poster)

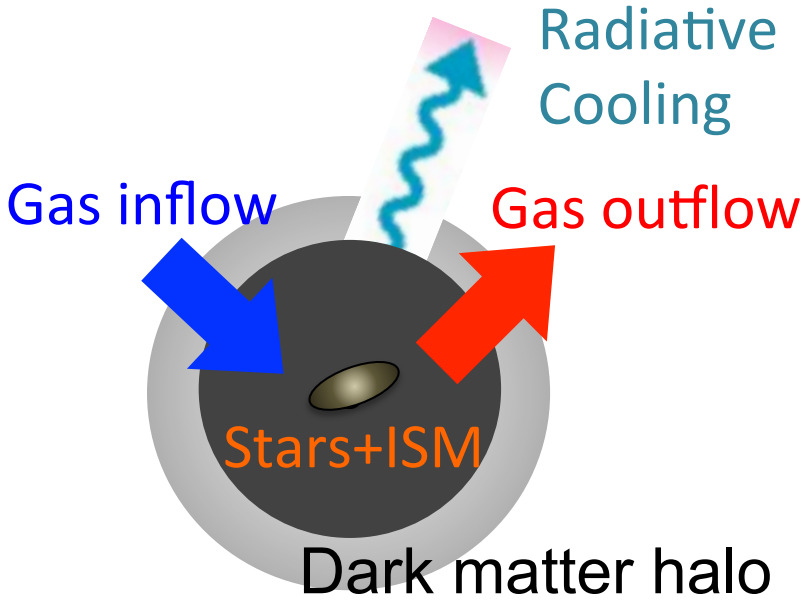
- A lot of no dust-continuum detection by ALMA obs. even w negative k-correction
- The HUDF stack falls below SMC extinction law (see also Bouwens+16)
  - Why? Dust properties (incl. dust temperature) evolve? (Ouchi+99,Bouwens+16)

3. DARK-MATTER HALO PROPERTIES

High-z Galaxy−DM Halo Connection

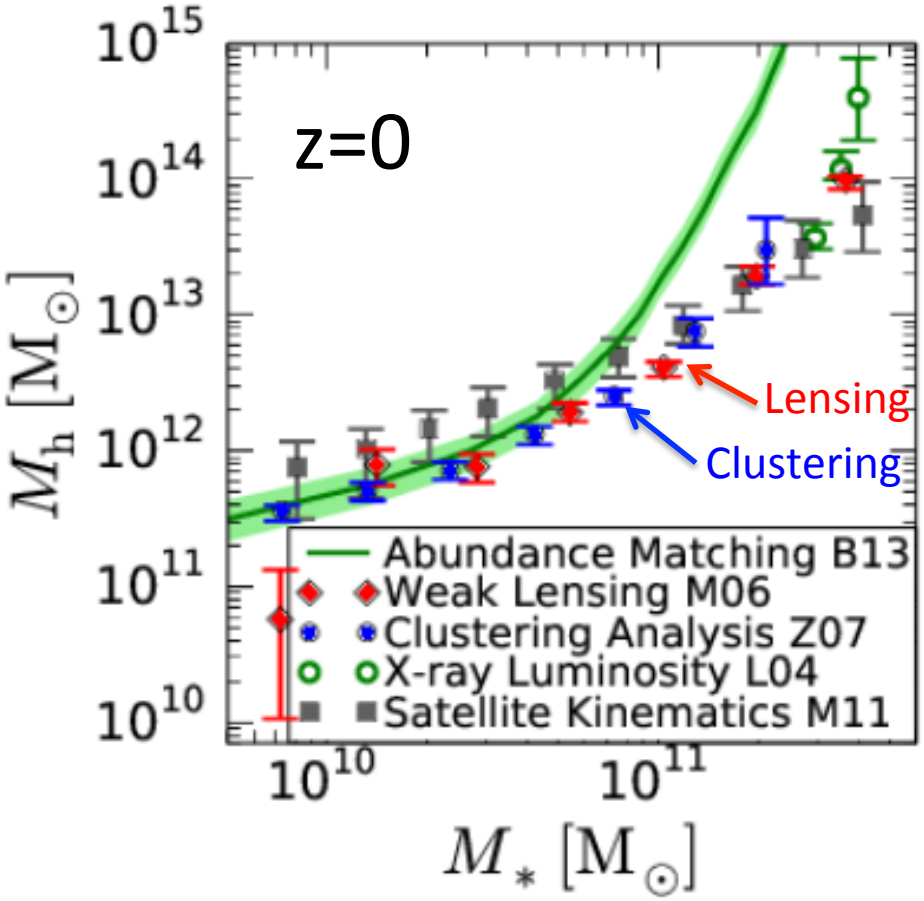


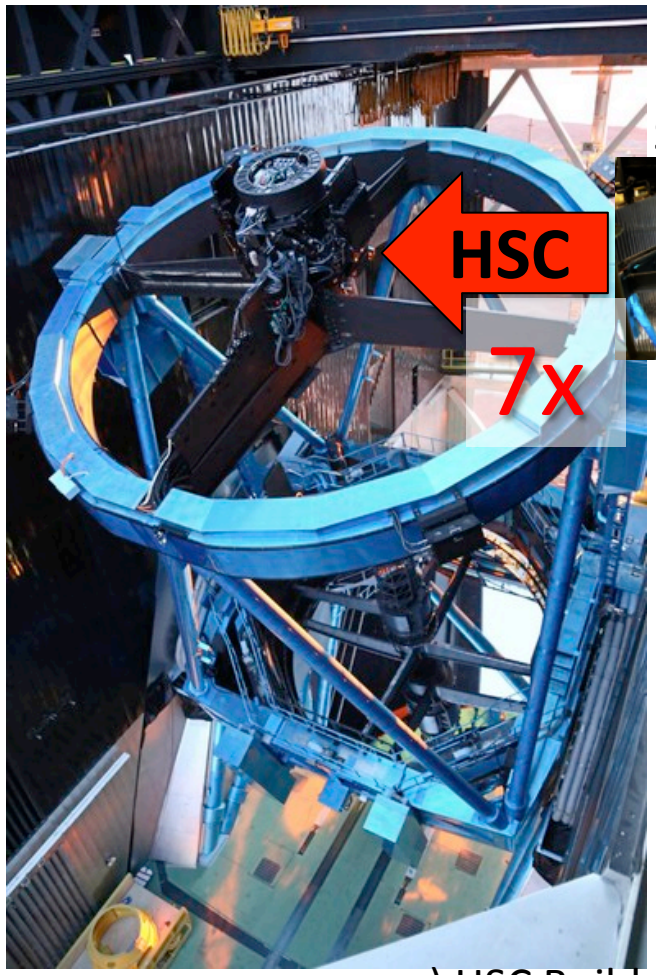
From COSMOS data
Leauthaud+12



- Stellar-to-halo mass ratio: SHMR=M_*/M_h
  - Gas cooling for SF
  - Inflow and outflow (feedback)

Clustering for DM Halo Mass Estimates



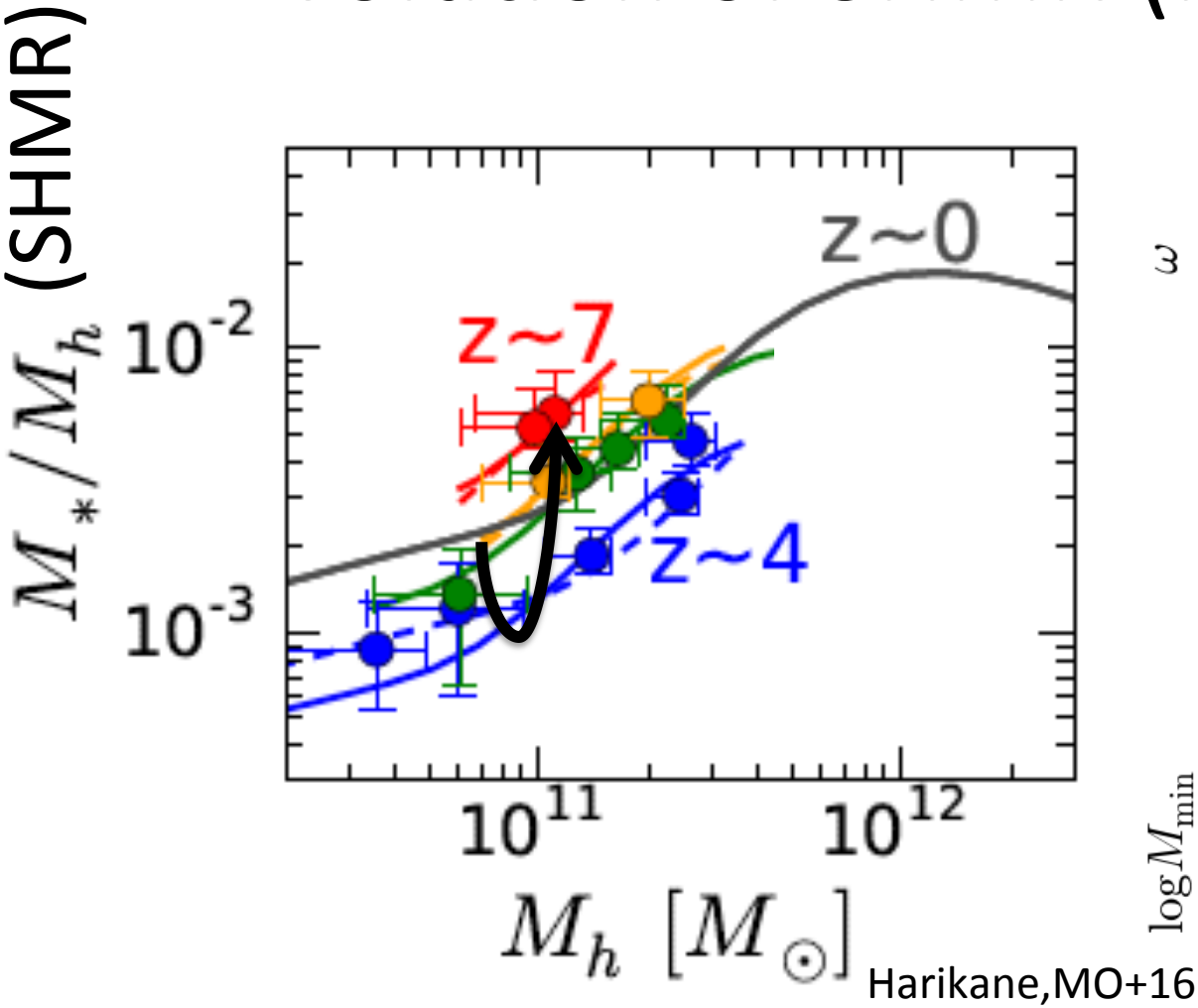


Suprime-Cam

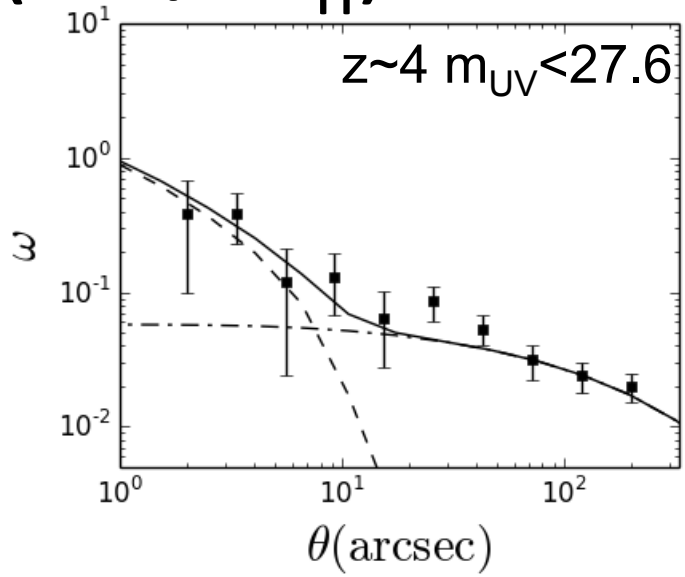
c) HSC Builder's blog

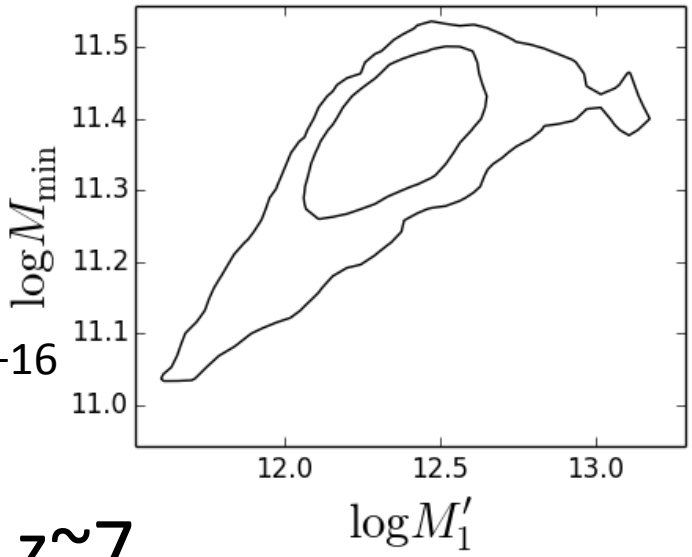
- DM halo estimates from galaxy clustering. Reliability checked at z~0.
- Large galaxy sample for galaxy clustering measurements.
- Subaru optical imager Hyper Suprime-Cam (HSC)
  - Subaru/HSC survey has started since March 24, 2014 under the collaboration of JP/US/TW.
  - ~1/3 of observations are completed.

Evolution of SHMR (M_*/M_h)



Harikane,MO+16





- SHMR at 10^{11}Mo decreases from z=0 to z~4, and increases to z~7
- Signature of feedback efficiency change??

Summary

- Recent observational progresses of galaxies at a redshift up to z~10 w data of HST, Keck, Subaru, and ALMA.
  - Star-formation and morphology (HST legacy incl. HFF)
    - No sig. of feedback eff. so far found in LF down to M_{UV}~-14mag
    - ALMA sources w no optical counterparts suggest additional SFRD ~40% at z~2
    - Optical size: $r_e \propto (1+z)^{1.1}$ at z<10, but diversity of ALMA 1mm size
    - Optical clumpy galaxy fraction peaks at z~2
    - Monotonic increase of Σ_{SFR} from z~0 to 8
  - Inter-stellar medium
    - High ionization state (high q) identified in optical nebular lines.
      → Related to the ALMA [CII]158um deficit and [OIII]88um detection?
    - Low L_{IR}/L_{UV} ratio at z>~6: dust property evolution?
  - Dark-matter halos
    - M_*/M_h ratio upturn at z>~4. Signature of feedback efficiency change?