The rest-frame optical sizes of massive galaxies with suppressed star formation at z~4

soon submitted…

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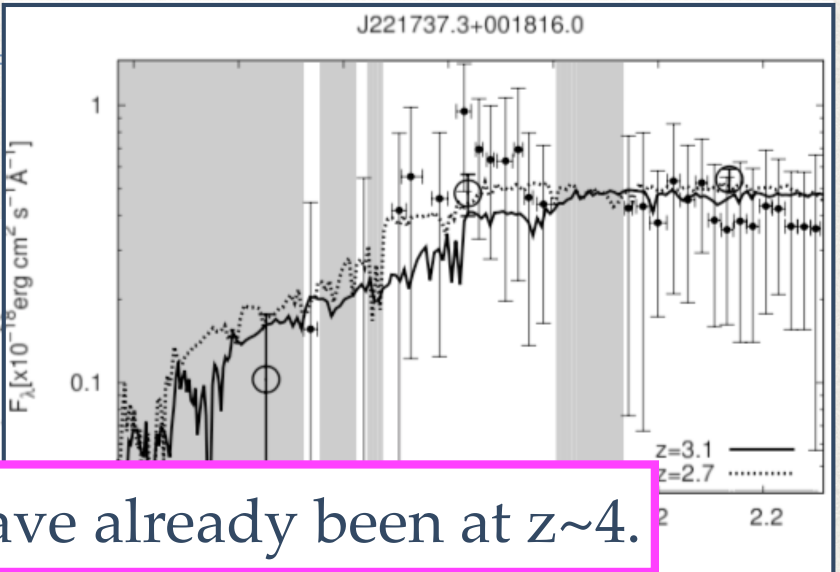
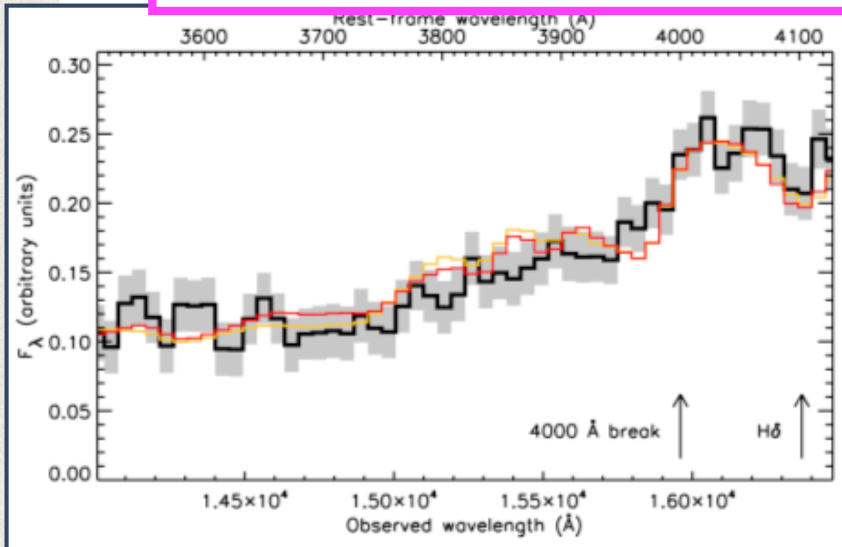
1. Introduction: Massive quiescent galaxies at high redshift

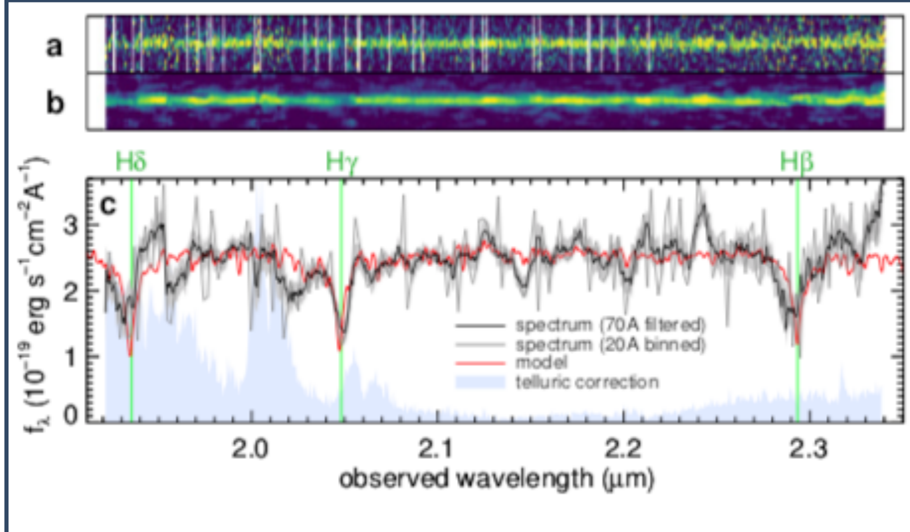


Quiescent galaxies (early-type like) have already been at z~4.

Passive galaxy at zsp=3.0-3.1(Kubo+2015)



Passive galaxy at zsp=2.993(Gobat+2012)

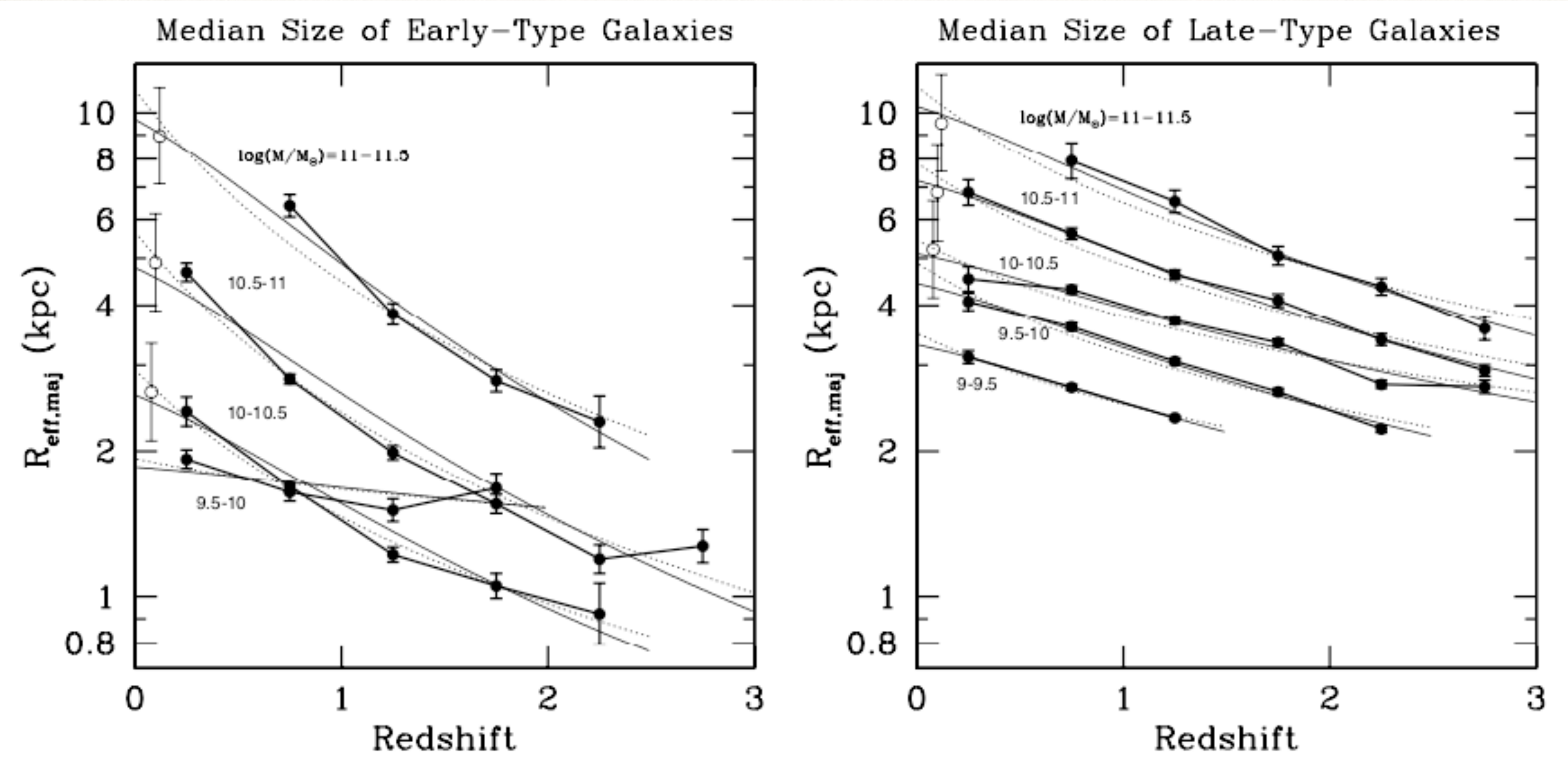


zsp=3.717 quiescent? galaxy(Glazebrook+2017)

...rmation
...oto-z, and
...cific SFRs

rest-frame UVJ diagram in va...

1. Introduction: Size growth of galaxies

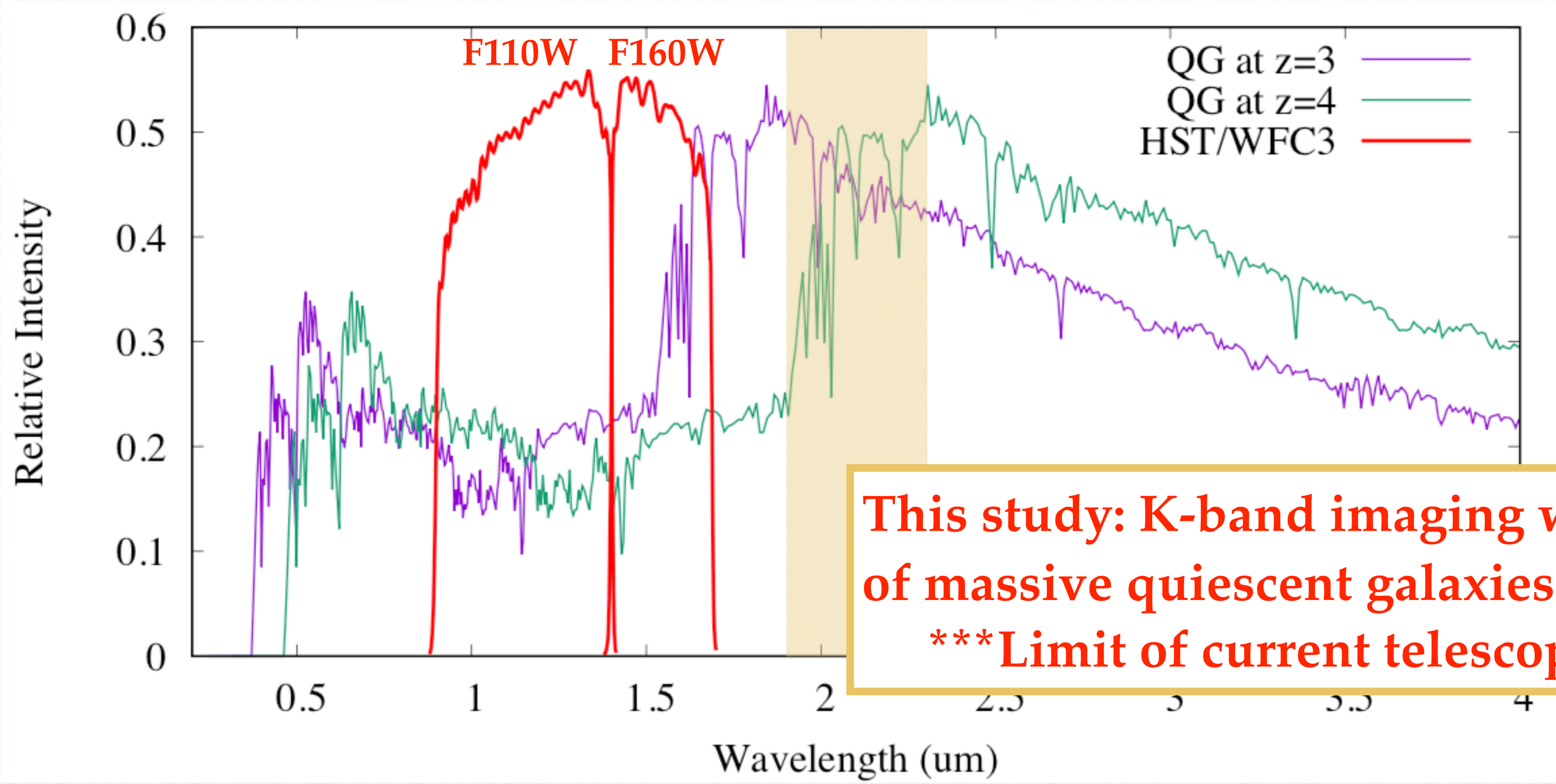


van der Wel+2014

at z>3?

- Typical size of galaxies becomes compact with redshift
- Large size growth of early-type galaxies
- What is the driver of this strong size growth? minor mergers? adiabatic expantion? change of typical mass of quenched galaxies?

1. Introduction: Size growth at z>3?



This study: K-band imaging with AO of massive quiescent galaxies at z=4
*****Limit of current telescopes*****

- To compare the size correctly, deep and high resolution imaging at rest-frame optical is needed.
- But the bandpass of HST is shorter than 1.7um...

2. Target: Massive quiescent galaxies at z=4 from SXDS survey

- Massive quiescent galaxies at z~4 are selected from SXDS field
- uBVRizJHK, IRAC photometric catalog for 10^5 objects in ~0.7 deg^2
- Estimating photometric redshift from a custom code (Tanaka et al. 2015) where $\sigma(\Delta z/(1+z))=0.029$
- Selecting galaxies with suppressed star formation at 3.5<z_phot<4.5

2. Target: Massive quiescent galaxies at z=4 from SXDS survey

Selecting galaxies with specific SFR of $<10^{-9.5}\mathrm{yr}^{-1}$

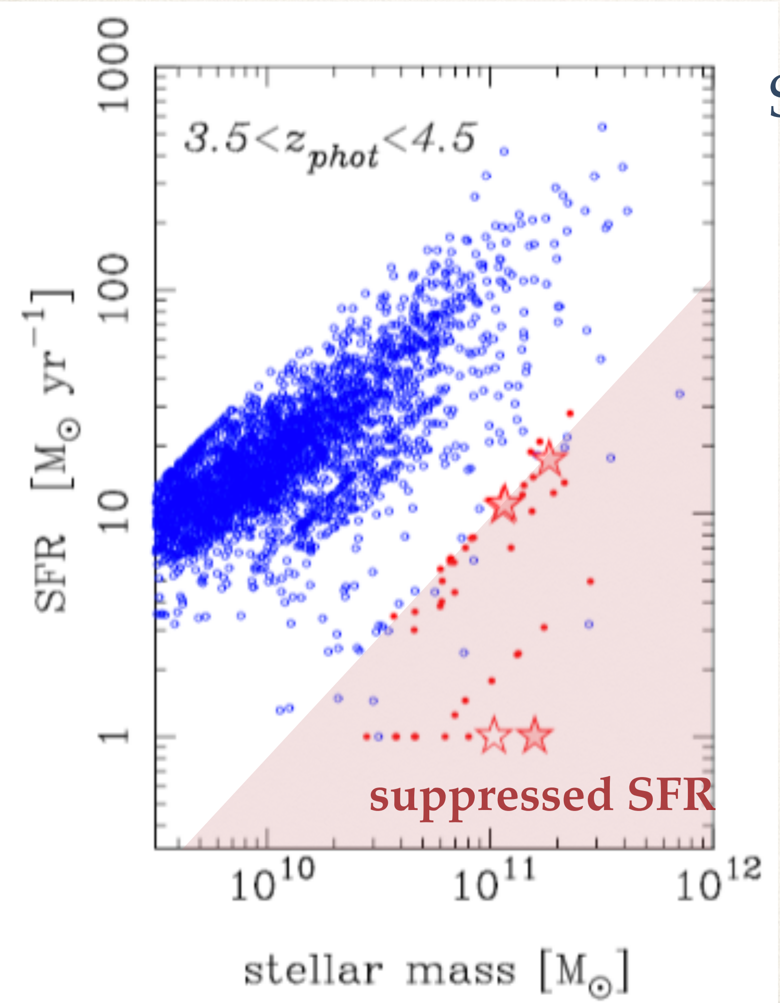


Fig.1 M* v.s. SFR

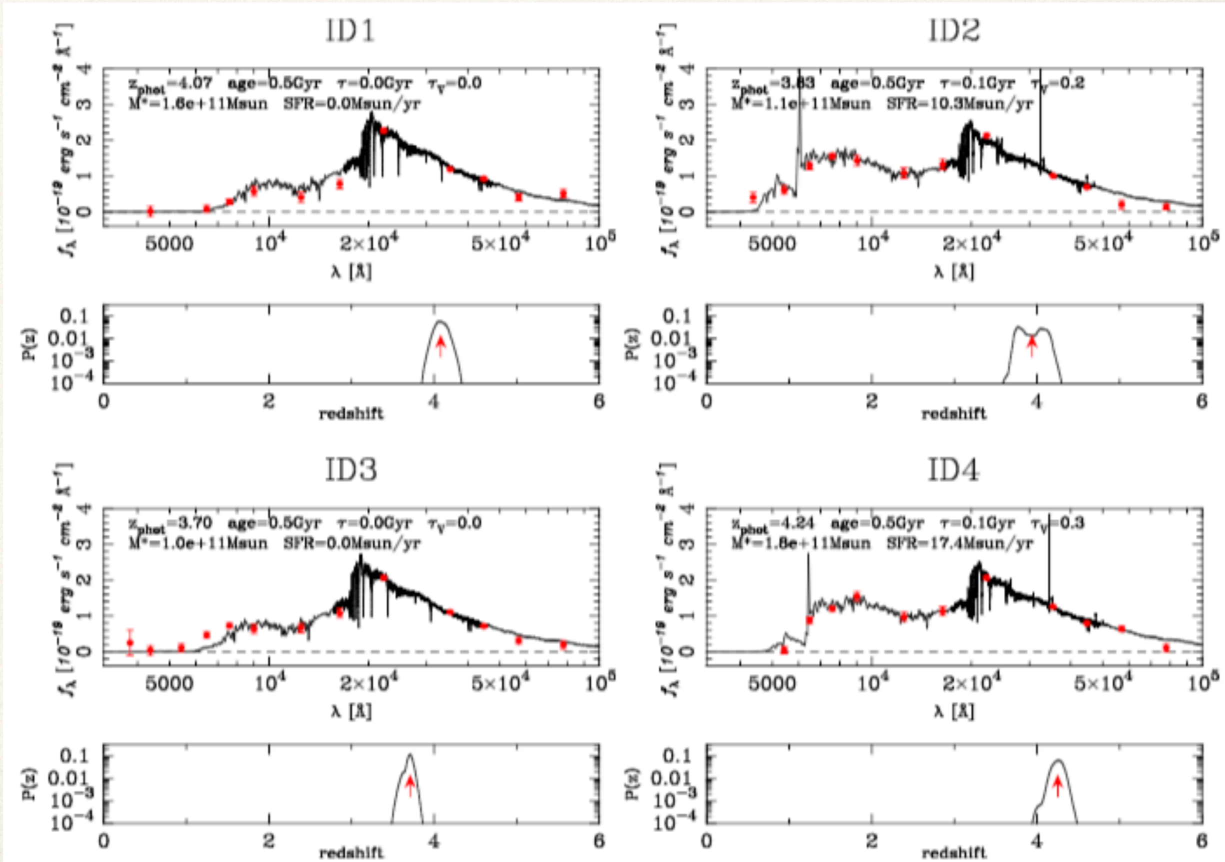


Fig.2 SEDs of quisecent galaxies

3. Observation: IRCS-AO K-band imaging

- We conduct the K′-band imaging of the brightest five (KAB=22.5-23) quiescent galaxies at z~4 with Subaru IRCS-AO188 on Sep. 2016 (PI: M. Tanaka).
- LGS or NGS are used in stable condition. Data is reduced with standard manner for IRCS.
- 0.3~1 h total exposures for each target. FWHM PSF =0″.15~0″.23.

Table 2. Summary of observations

ID	R.A. (h:m:s)	Dec (d:m:s)	EXPTIME (min)	ZEROPOINT (mag)	depth[a] (mag)	separation[b] (arcsec)	FWHM PSF[c] (arcsec)
1	02:19:01.511	-05:18:29.07	33	25.43	24.7	72(33)	0.17
2	02:17:59.073	-05:09:39.89	18	25.43	24.6	53(34)	0.21
3	02:17:22.781	-05:17:33.34	35	25.41	24.9	48(16)	0.15
4	02:17:19.833	-04:43:34.75	43	25.43	25.0	41(38)	0.23
5	02:16:58.232	-05:08:35.21	54	25.41	25.0	37(13)	0.19

4. Size measurements
4.1 Flux completeness

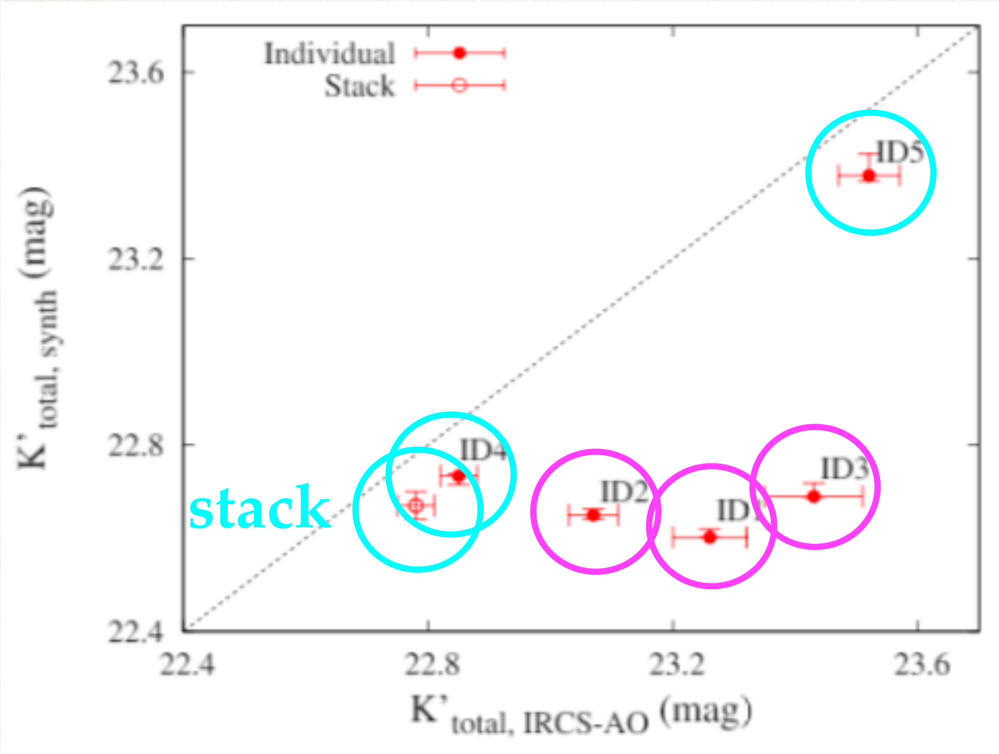


Fig.3 Total magnitudes in IRCS-AO K′
v.s. K′ (WFCAM K corrected by SED fitting)

- Flux completeness of our targets on our IRCS-AO K′-band compared with deeper K-band image with WFCAM.
- Total fluxes of ID1~ID3 measured on our K′-band is not complete compared with those measured on deep K-band image of WFCAM
- Flux incompleteness is small for ID4, ID5 and stack.

4. Size measurements
4.2 GALFIT fitting and errors

- The images of galaxies are fitted to Sersic models using GALFIT (Peng 2010).
- Since the PSF is marginally nonuniform (ΔFWHM ~ 0″.03) and our targets are very small (re~1kpc), Sersic indices cannot be constrained well (σ(n)~2.3)
- χ2 of Sersic model fits are only marginally better than those of PSF model fits… Not well resolved. The measured sizes can be upper limit value.

4. Size measurements
4.2 GALFIT fitting and errors

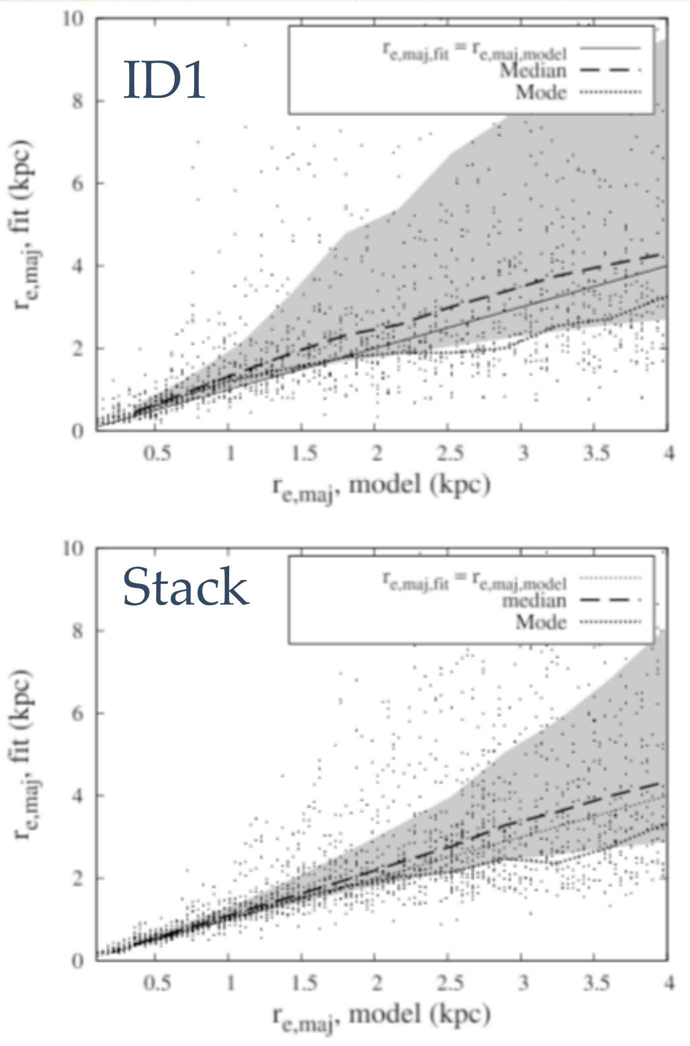


Fig.4 Simulated size errors

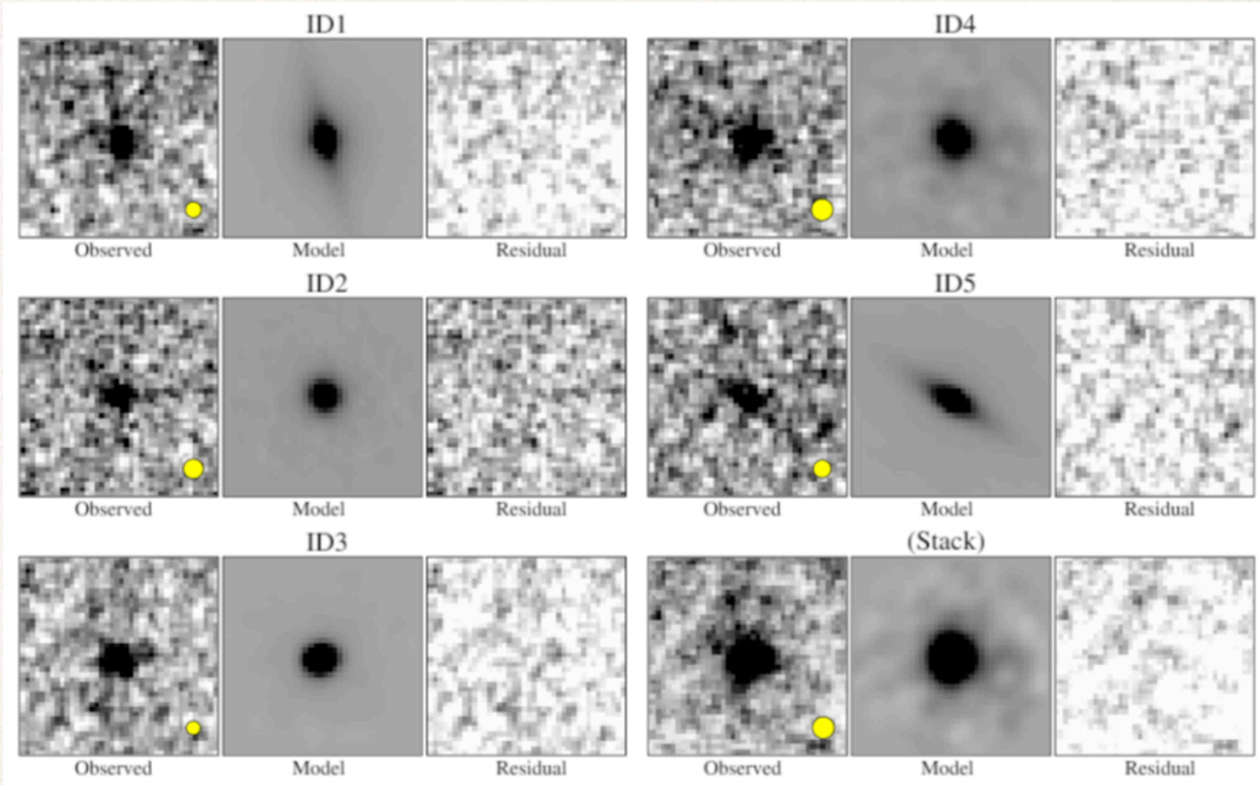


Fig.5 Observed, model and residual images

Stack: Δre±0.2 kpc for re~1kpc in typical

4. Size measurements
4.3 Results

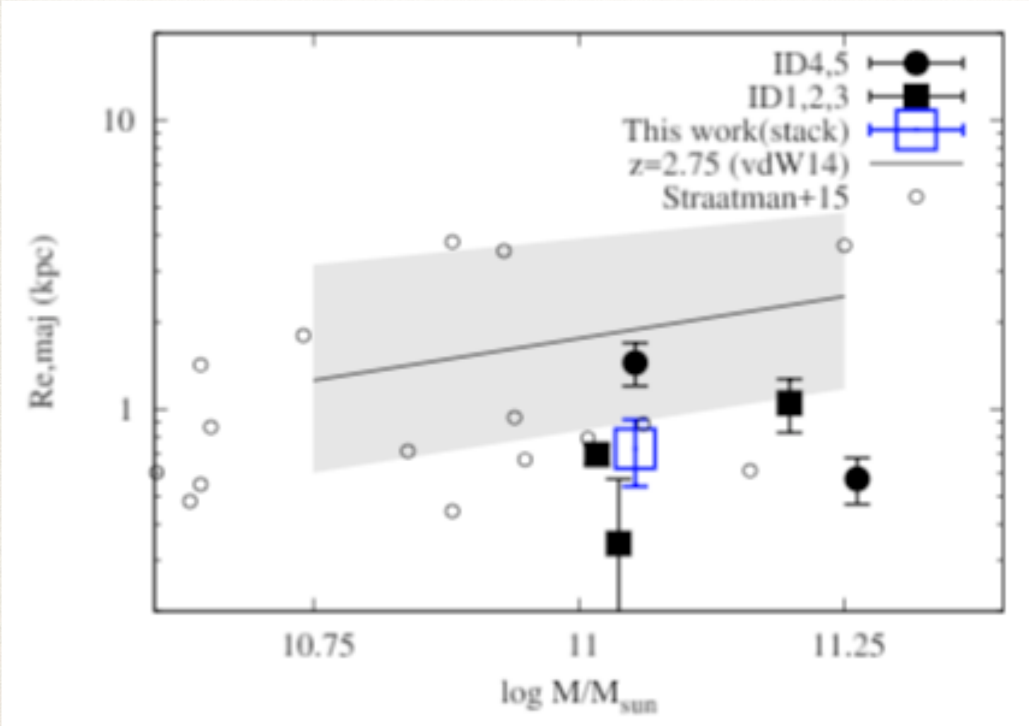


Fig.6 Mass-size relation at z=4

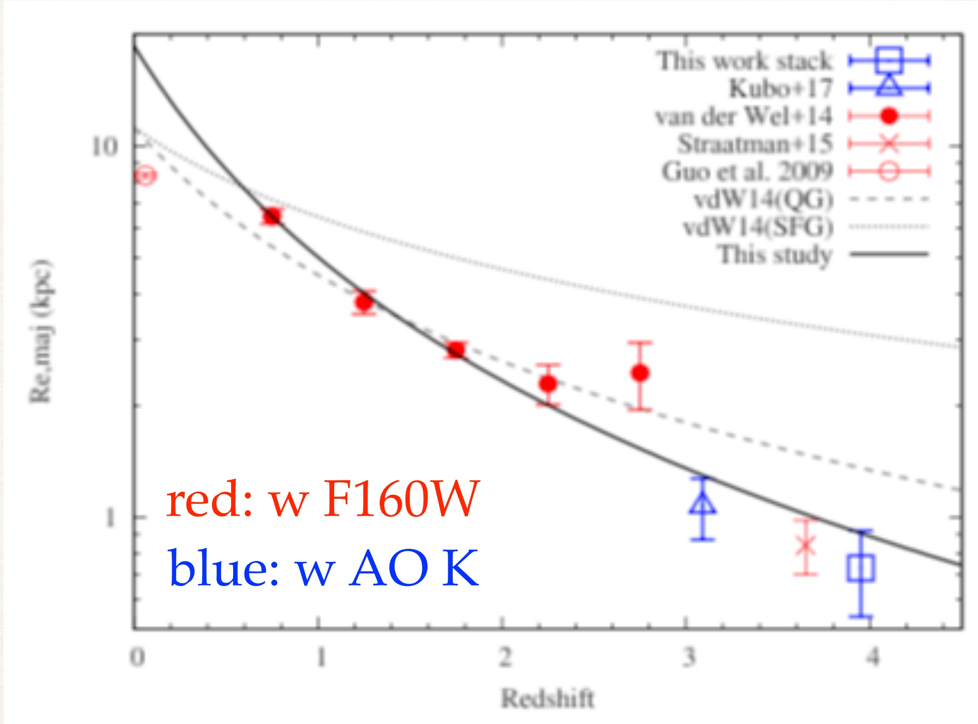


Fig.7 Size-redshift relation for $M^{*}=10^{11} \sim 10^{11.5}$ Msun

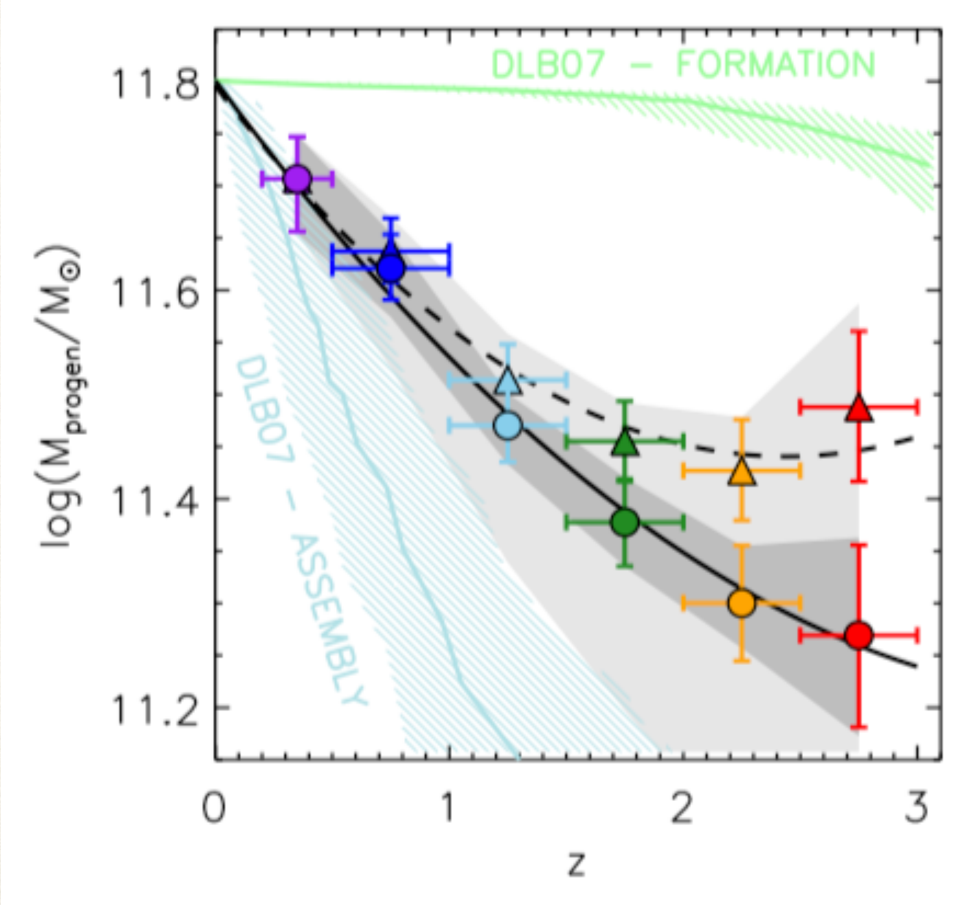
- Size evolution of massive quiescent galaxies continues at z>3.
- Adding the results at z>3, steeper size growth is favored.
- Note that our result at z=4 can be just an upper limit…

5. Discussion

- Size evolution at constant mass = typical size of galaxies at each redshift.
- ≠ evolution history of individual galaxies.
- In this section, we interpret our results into the size-stellar mass growth history of massive-end galaxies today.

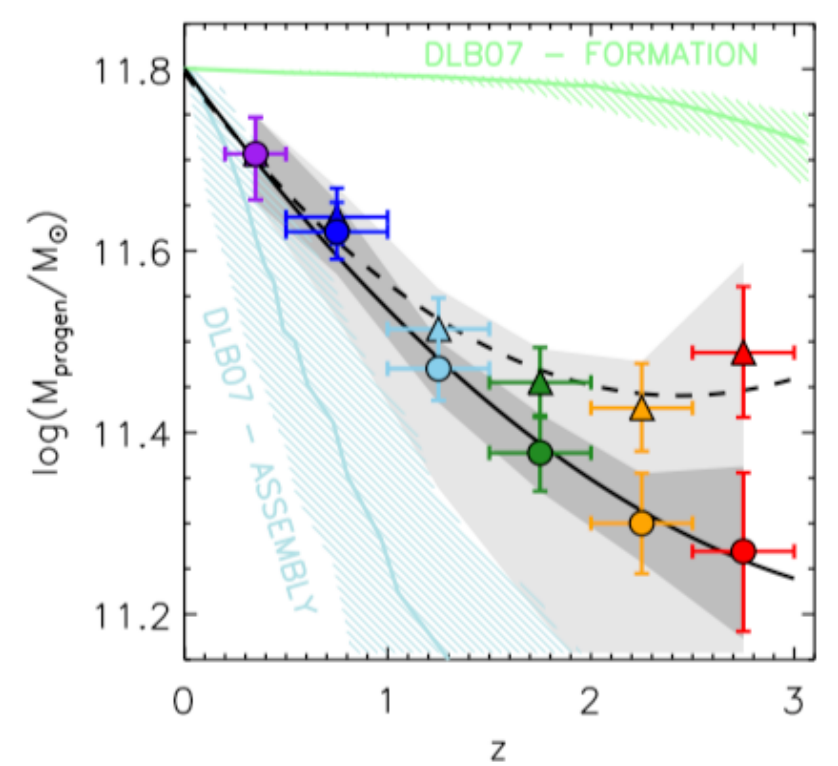
5. Discussion

- Marchesini et al. (2014)… draw the stellar mass evolution of ultra-massive galaxies (UMGs) today with abundance matching technique.
- Our targets are roughly on their M*-redshift relation.
- We can draw the size growth history of UMGs from z=0 to 4 by combining the stellar mass-redshift relation (Marchesini+14) and size-stellar mass relation at each redshift (van del Wel +2014)



Stellar mass evolution of UMGs(Marchesini+14)

Stellar mass of UMG progenitors

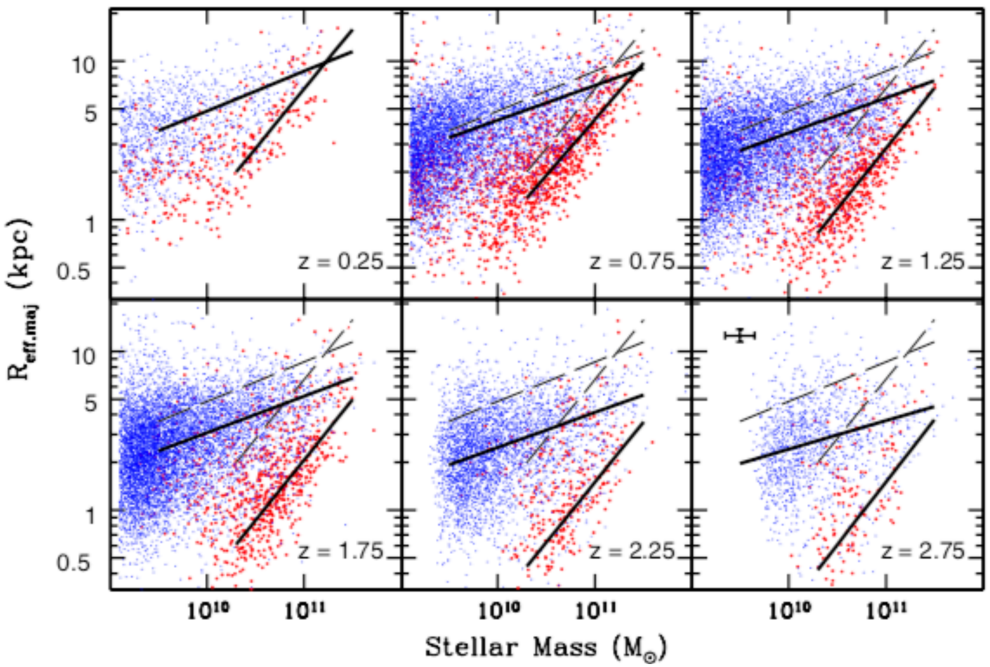


Stellar mass of the progenitors of UMG at each redshift from Marchesini+14 (Note that the relation at z>3 is just an extension of that at z<3)

Stellar mass → size

z=0: the size of UMGs ($M^* \sim 10^{11.8}$) Msun in SDSS (Guo et al. 2010)

0.25<z<2.75



Use the size-M* relation of van der Wel+14

z>3

Since the stellar mass of the progenitors from Marchesini+14 is similar to our sample, we just use observed sizes.

Size-stellar mass growth history of UMGs

5. Discussion

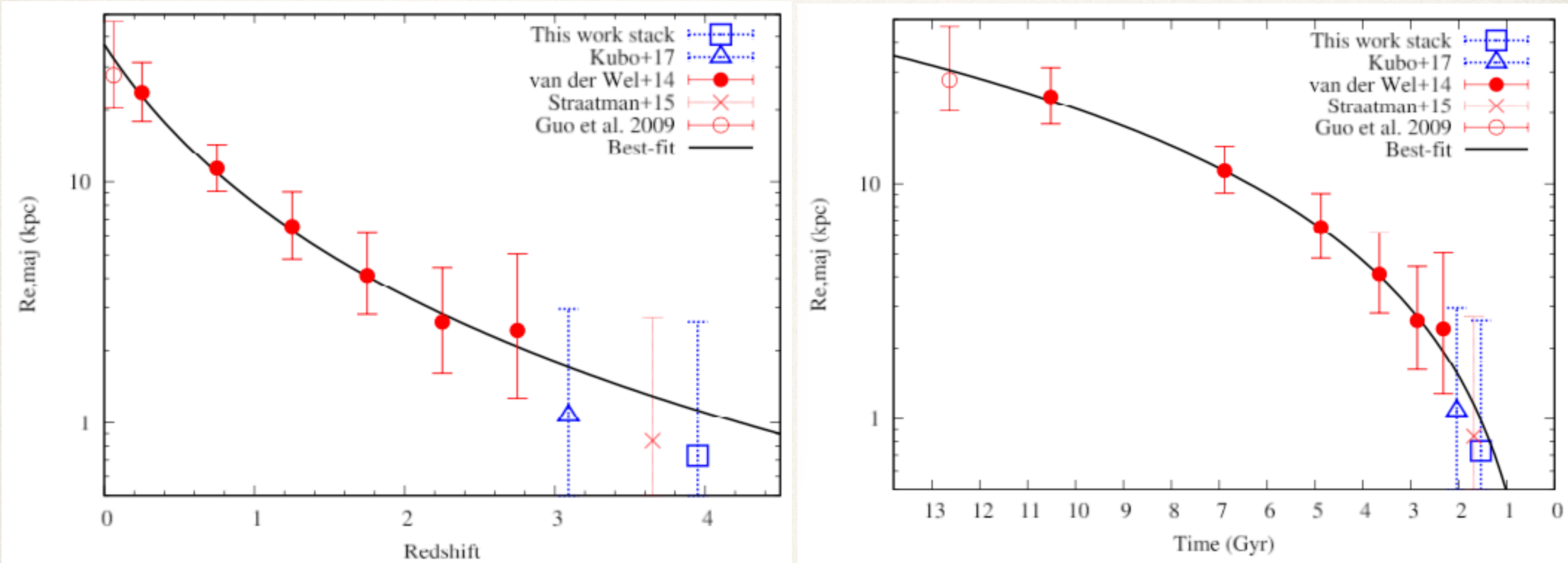


Fig.8 Size-redshift(*left*) and Size-Cosmic time(*right*) relations of UMGs

- Rapid growth at early time.
- Size-redshift: re/kpc = $A\times(1+z)^{B}$ where A = 37.1±2.3 and B = −2.2 ± 0.1
- Size-Cosmic time: log(re/kpc) = A + B log(t/Gyr) where A = −0.31±0.04 and B = 1.63±0.05

5. Discussion

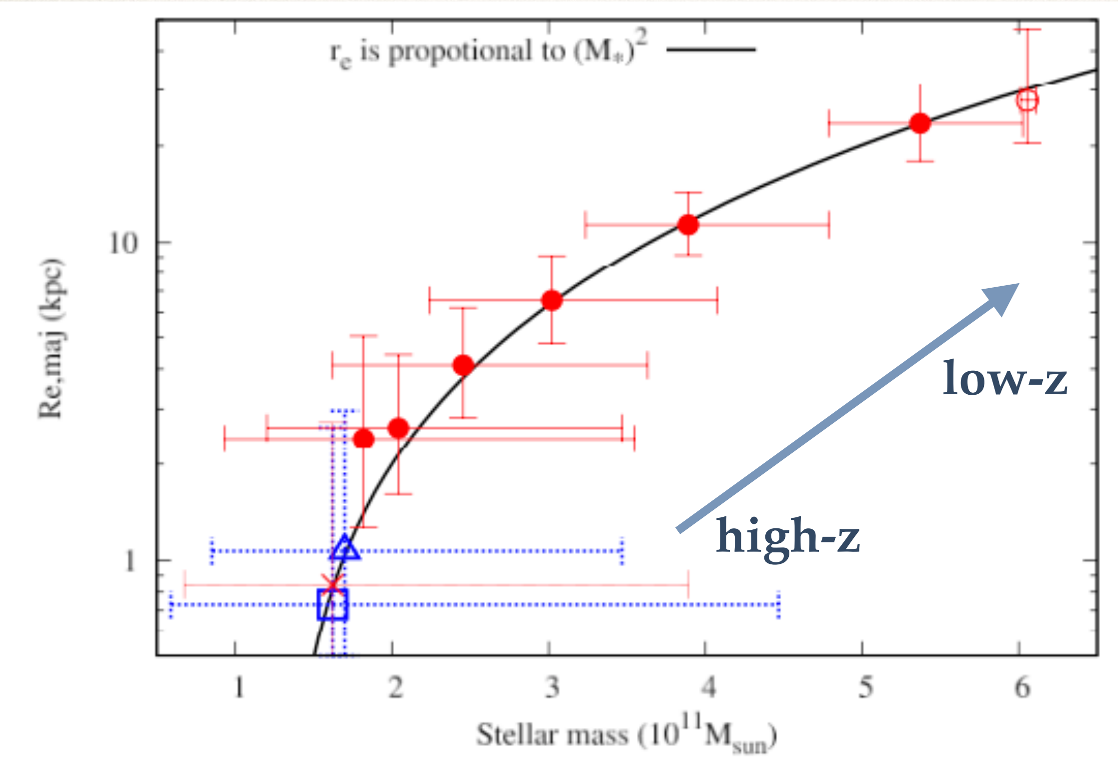


Fig.9 size-stellar mass growth of UMGs

- UMGs grow as Re ∝ M*^2 … size evolution driven by minor dry mergers (Naab et al. 2009; van Dokkum et al. 2010)
- Similar size growth history for massive-end galaxies was predicted in IllustrisTNG simulation (Genel et al. 2018).

6. Conclusion

- We select massive galaxies suppressed star formation at z=4 from ~0.7 deg^2 of SXDS field.
- Then we conducted the K-band imaging of the brightest five of them by using IRCS-AO on Subaru Telescope to evaluate their sizes.
- We draw the size evolution of massive quiescent galaxies in rest-frame optical at up to z=4 for the first time. The typical size of massive quiescent galaxies continues to become small up to z=4.
- We interpret our results into the size evolution of UMGs today and found that their size-stellar mass growth history is similar to that driven by minor dry mergers.

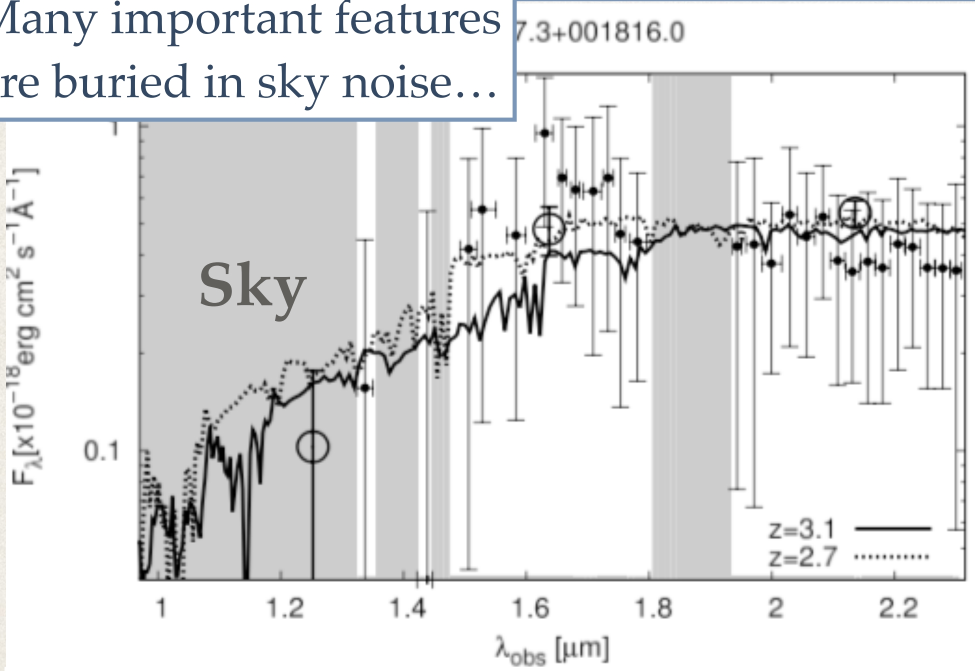
7. Requirement (of LUVOIR and ELTs)

- We found,
  - Size evolution continues at z=4 at least.
  - <0″.1 resolution is needed to obtain non-upper limit size of galaxies at z≧4 (even at massive-end). PSF uniformity of <<0″.01 is also needed.
  - 10-m class AO K-band imaging of galaxies at z>3 is very hard…
- Further questions:
  - Size evolution at z>4?
  - Size evolution of lower mass ($M^*<10^{11}M_{sun}$) descendant?
  - Rest-frame optical (not affected by dust) morphologies of dusty starburst galaxies at z>3; plausible adjacent progenitors?
  - Sersic indices?
  - Kinematic evolution? How fundamental plane built?
  - Radial gradient of stellar population?

Hardly achieved with HST and 10m class ground based telescopes+AO (and JWST?)

7. Requirement (of LUVOIR and ELTs)

Many important features are buried in sky noise…



NIR specrtoscopy of QG at z=3 with Subaru(Kubo+2015)

JWST Spatial resolution

Filter	Wavelength (μm)	PSF FWHM (arcsec)	PSF FWHM (pixel)
F200W	1.989	0.066	2.141
F356W	3.568	0.115	1.830
F444W	4.408	0.145	2.302

- To confirm redshift and study kinematics of quiescent galaxies at z>3, we need to see from space.
- However, to study morphologies, JWST may not be enough: we need deep (>>27 mag) imaging at ≧ 2μm with small and stable PSF(FWHM <<0".1 & ΔFWHM <<0".01).

LUVOIR and ELTs are necessary!