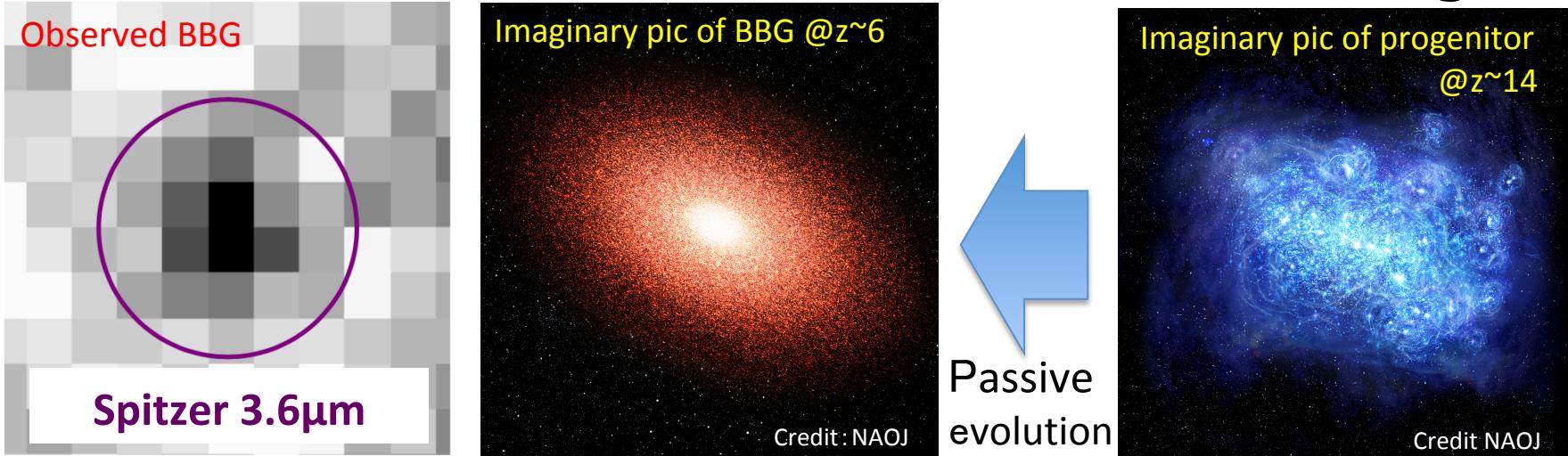


Balmer Break Galaxy candidates in the Reionization Epoch: Hint on Star-Formation Activity

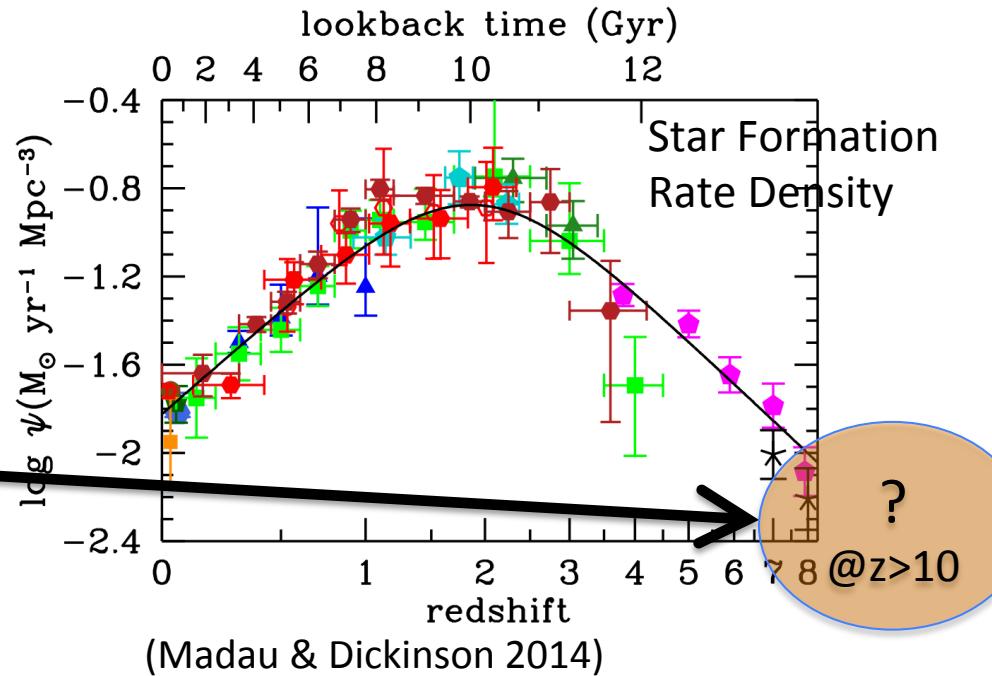
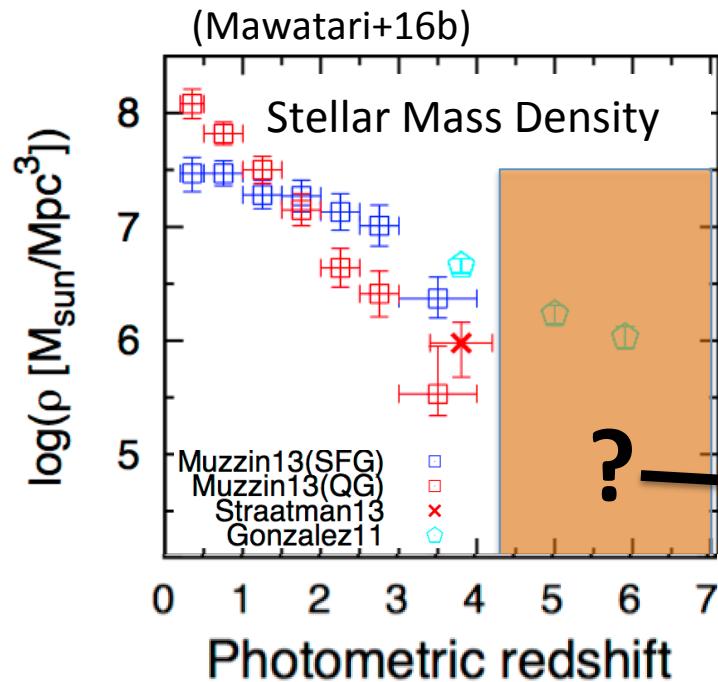


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Potential power of passive galaxy for highest-z



Motivation

(1) Search for passive galaxies at $z > 5$ (2) To constrain SFRD at $z > 10$

"Passive galaxy" in this work:

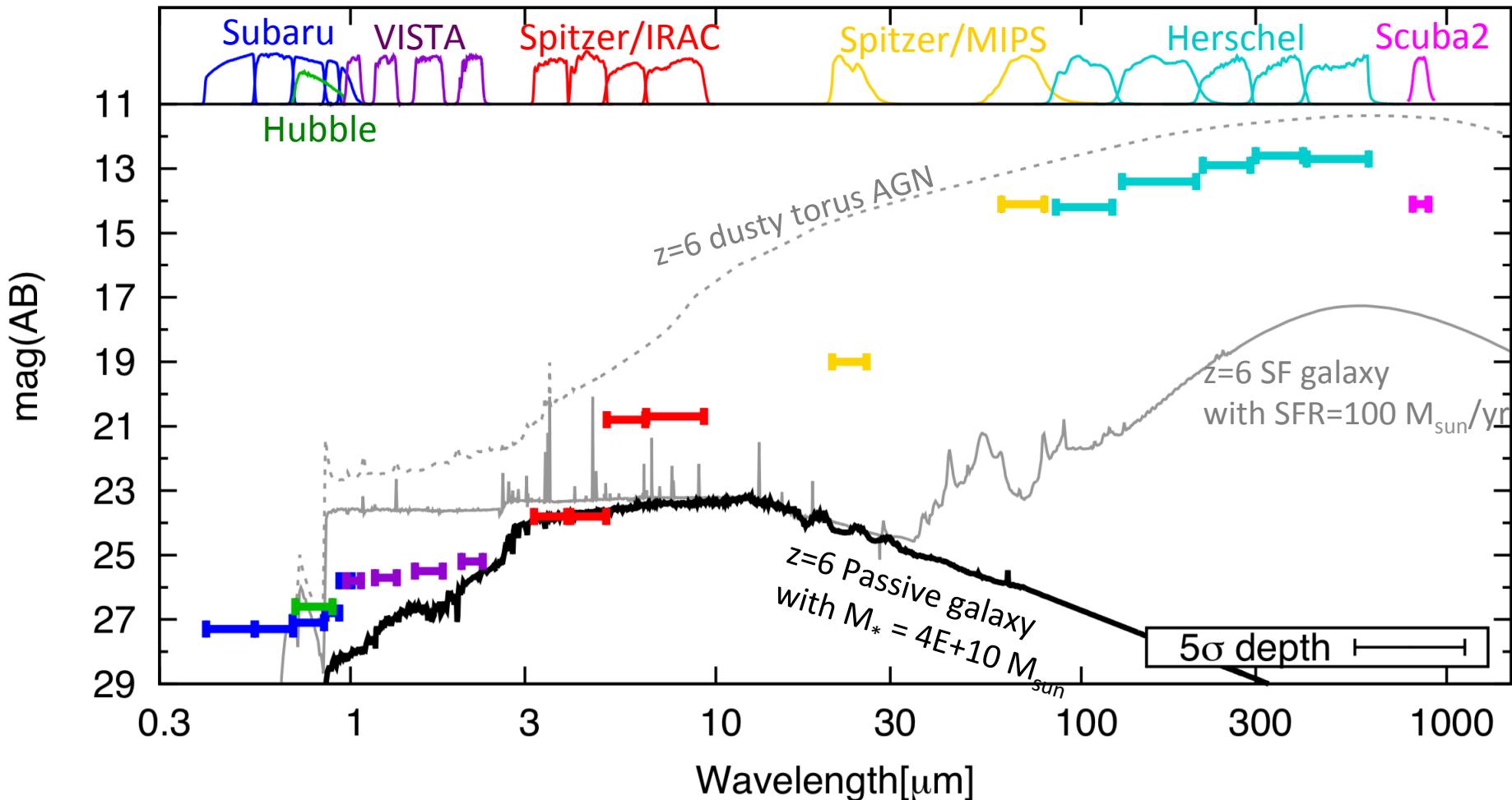
Galaxy with strong Balmer-break (Balmer-break galaxy; BBG)
experiencing > 200 Myr after stopping star-formation

Data

Imaging data available in COSMOS

UVISTA UD stripes 1~3 (Area = 0.5deg²)

K~25 & [3.6]~24 depth
↔ z~6 passive galaxy down to
 $M_* \sim 4 \times 10^{10} \text{ Msun.}$



Basic idea of color selection

Red K-[3.6]
Blue [3.6] – [4.5]

Faint in FIR

$z \sim 6$ BBG selection

● Balmer Break Galaxy (BBG) selection

- We focus on isolated objects in the K and 3.6um image

$N \sim 37,000$

- The NIR Color selection

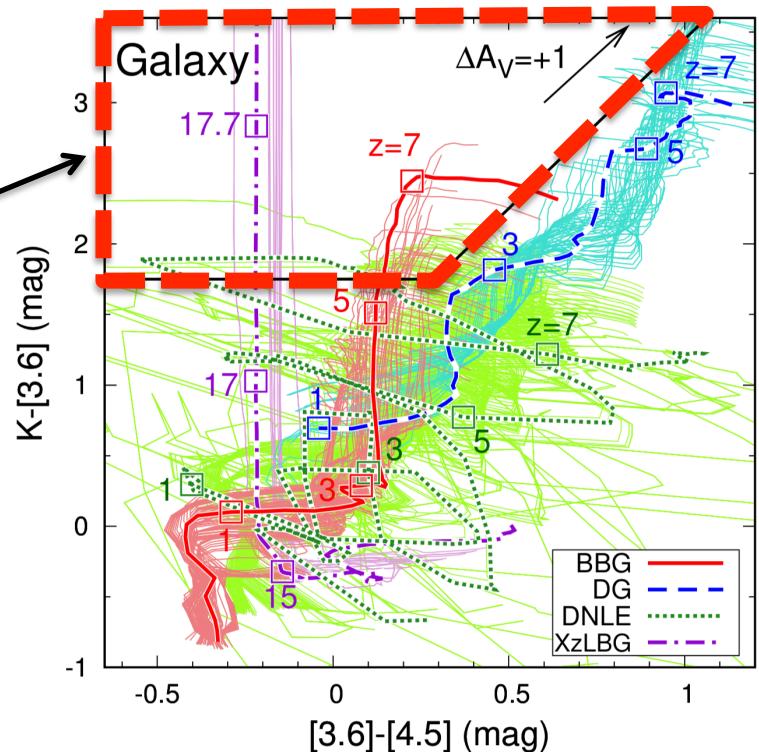
$$K - [3.6] > 1.75$$

$$K - [3.6] > 2.4([3.6] - [4.5]) + 1.05$$

(c.f. Mawatari+16b)

$N = 23$

- Non-detection in optical, MIR($\lambda > 10\text{um}$), FIR, radio, and X-ray to remove strong line emitters, extremely dusty galaxies, and AGNs.



$N = 6$

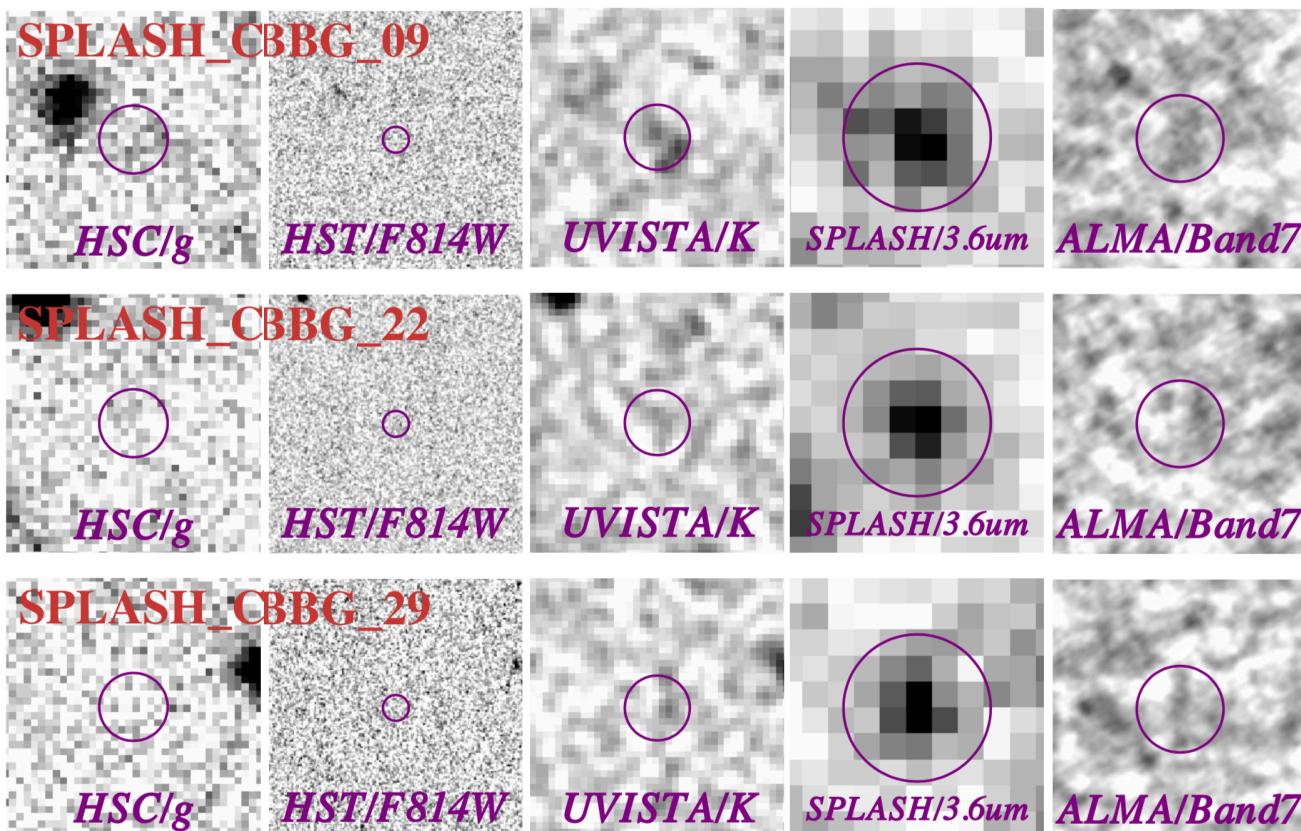
z~6 BBG selection with ALMA

- Very deep ALMA Band7 observations

- Cycle5 #2017.1.01259.S (P.I.: K. Mawatari)
- 40min on-source integration for each object
- 1sigma RMS $\sim 30\mu\text{Jy}$ / beam with beam size $\sim 0.48'' \times 0.42''$)

x ~100 deeper than
Herschel/Scuba2

3 are not detected \Leftrightarrow most likely BBGs at z~6



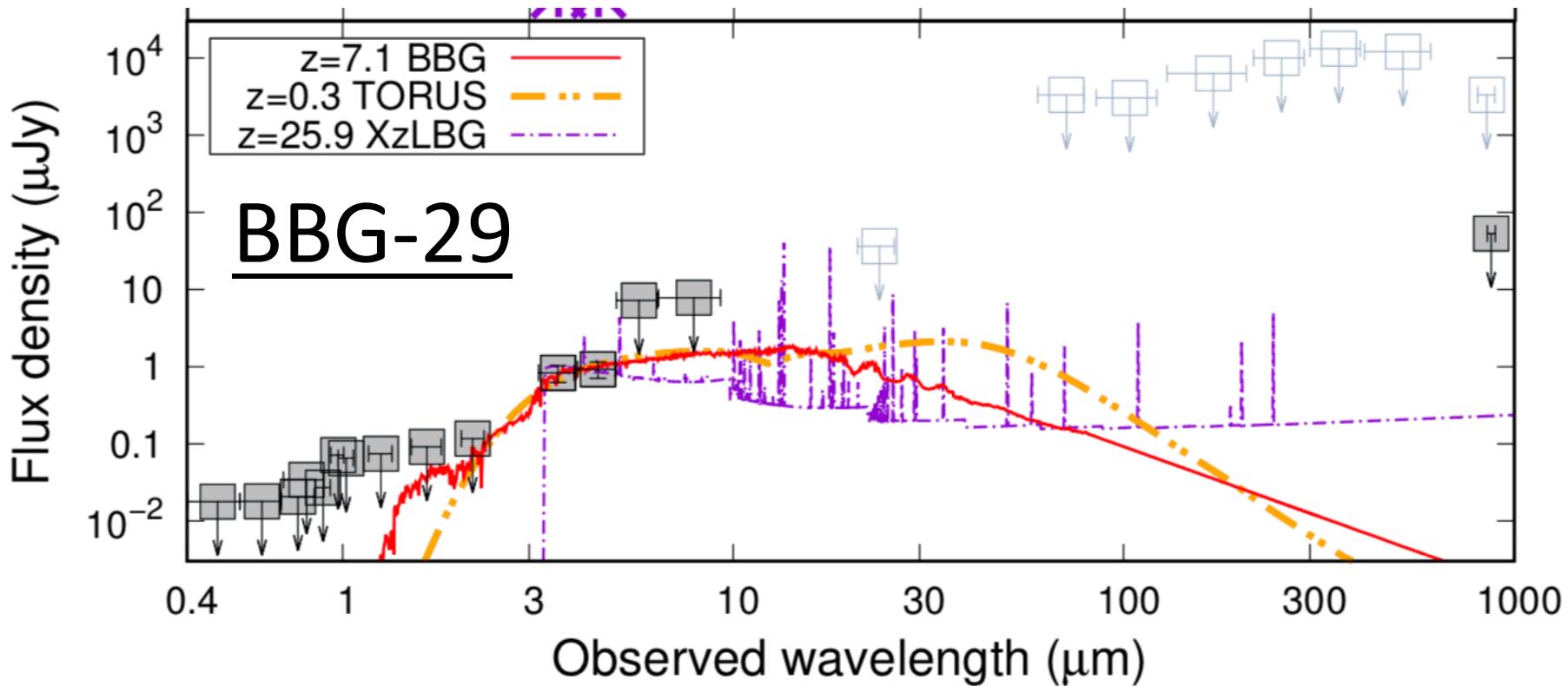
SED fitting setting

- Original SED tool, [PANHIT](#), is used with very wide variety of the templates.
(Mawatari+, IAU #341 proc; Hashimoto+18a; Tamura+19)

Group name	Galaxy	AGN	
Template type ^a	SND : Star + Nebular + Dust	SWIRE AGN	TORUS
SFH	Exp-declining/rising $(\tau_{\text{SFH}} = \pm 0.03, \pm 0.06, \pm 0.1, \pm 0.3, \pm 0.6, \pm 1, \text{ and } \pm 10 \text{ Gyr})$, Constant-SFR	— Empirical (Polletta+07)	— Theoretical, no host gal (Fritz+06)
Metallicity (Z)	0.0001, 0.004, and 0.02	—	—
Age (T_{age}) [Gyr]	0.001 – age of the Universe	—	—
Redshift ^b	0.1 - 30	0.1 – 8	0.1 – 8
Dust A_V^c [mag]	0 – 10	–2 – +2	0

IMF: Chabrier (2003)

SED fitting result (1)SED



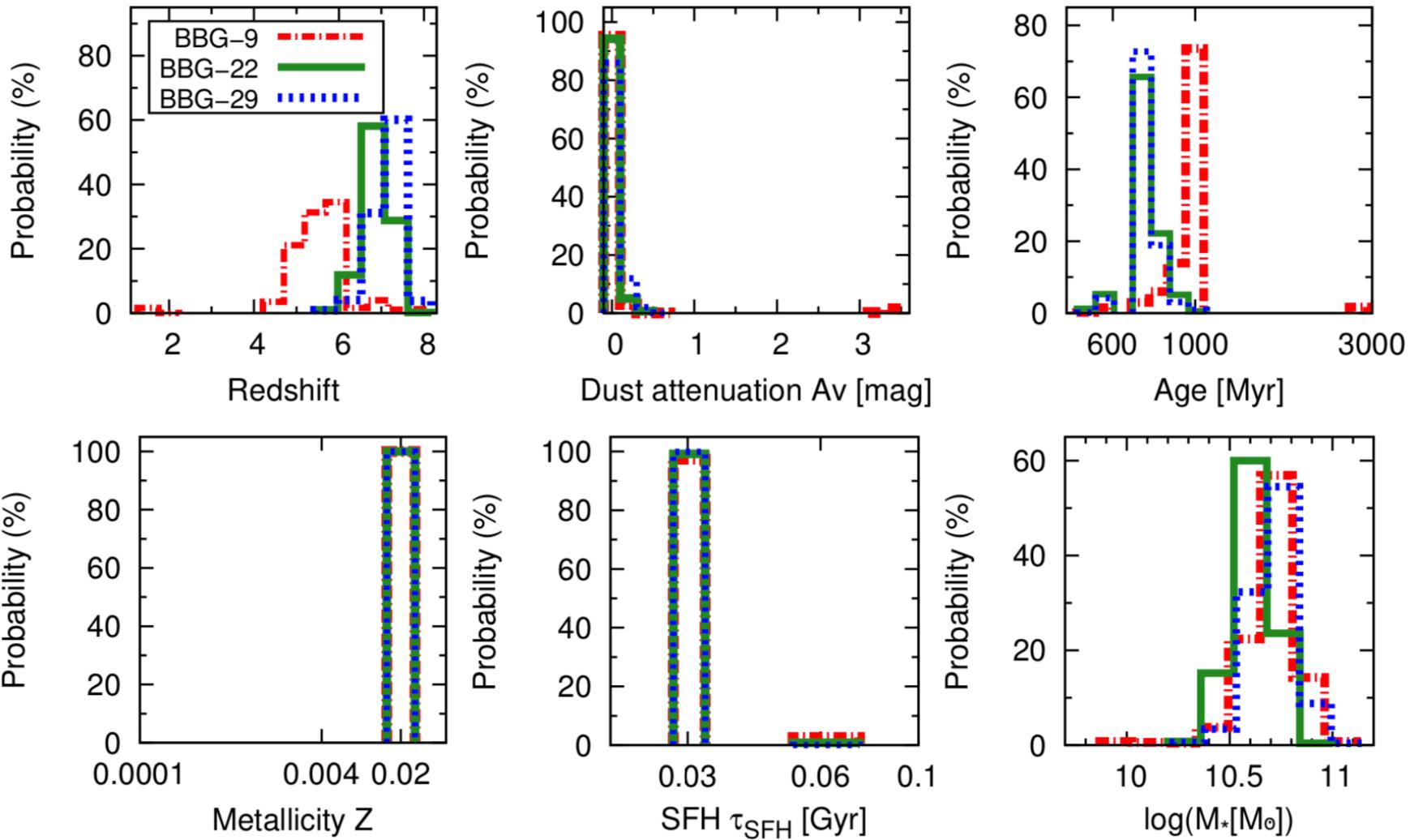
- BBG at $z = 7.1$ with $M_* = 5\text{E}+10 \text{ M}_{\odot}$ and age = 0.7Gyr

- TORUS at $z \sim 0$ with $M_{\text{BH}} = 200 \sim 2\text{E}+6 \text{ M}_{\odot}$, $M_{\text{host},*} < 2\text{E}+6 \text{ M}_{\odot}$

Less Likely

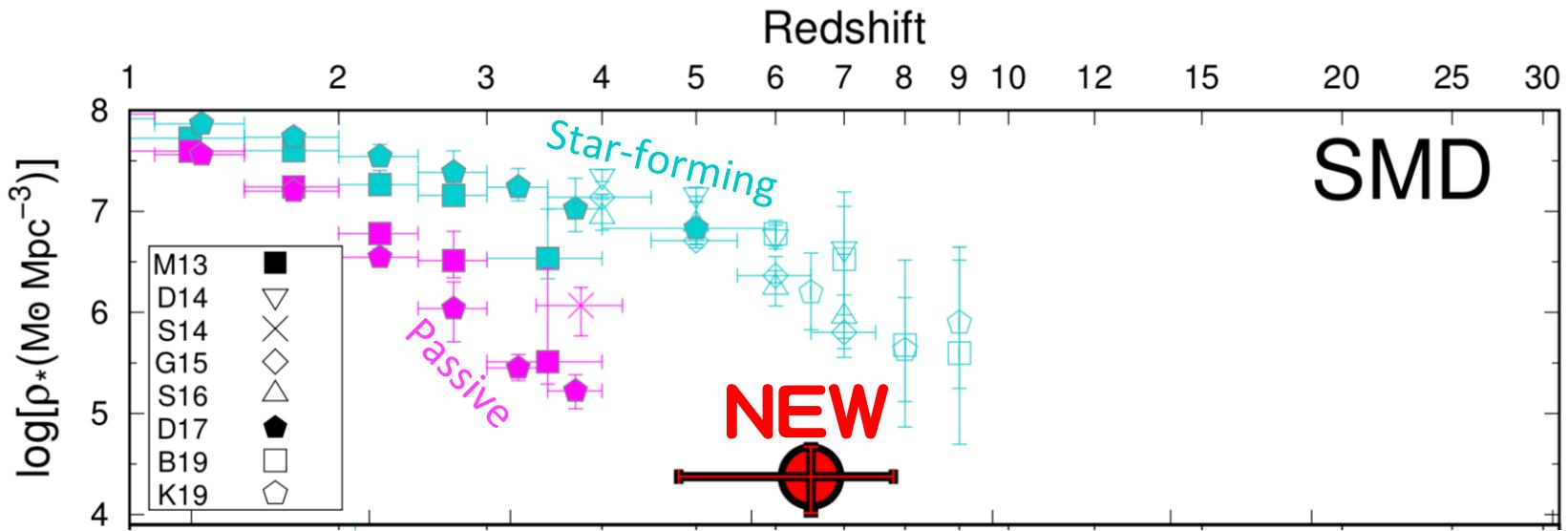
- LBG at $z = 25.9$ with $M_{\text{UV}} \sim -24$

SED fitting result (2)PDF of properties



SFR < 10Msun/yr (from 3 σ in ALMA / Y-band)

Stellar Mass Density of z~6 BBGs



SMD of the BBGs at $z \sim 6$ is consistent with the measurements for lower- z passive galaxies.

star-forming (cyan symbols) and passive (magenta symbols) galaxies at lower redshifts from the literature (M13: Muzzin et al. 2013, D14: Duncan et al. 2014, S14: Straatman et al. 2014, G15: Grazian et al. 2015, S16: Song et al. 2016, D17: Davidzon et al. 2017, B19: Bhatawdekar et al. 2019, and K19: Kikuchi et al. 2019). The vertical error-bar associated with our BBG

Progenitors of z~6 BBGs

● Def. of the progenitor

: age = τ_{SFH}

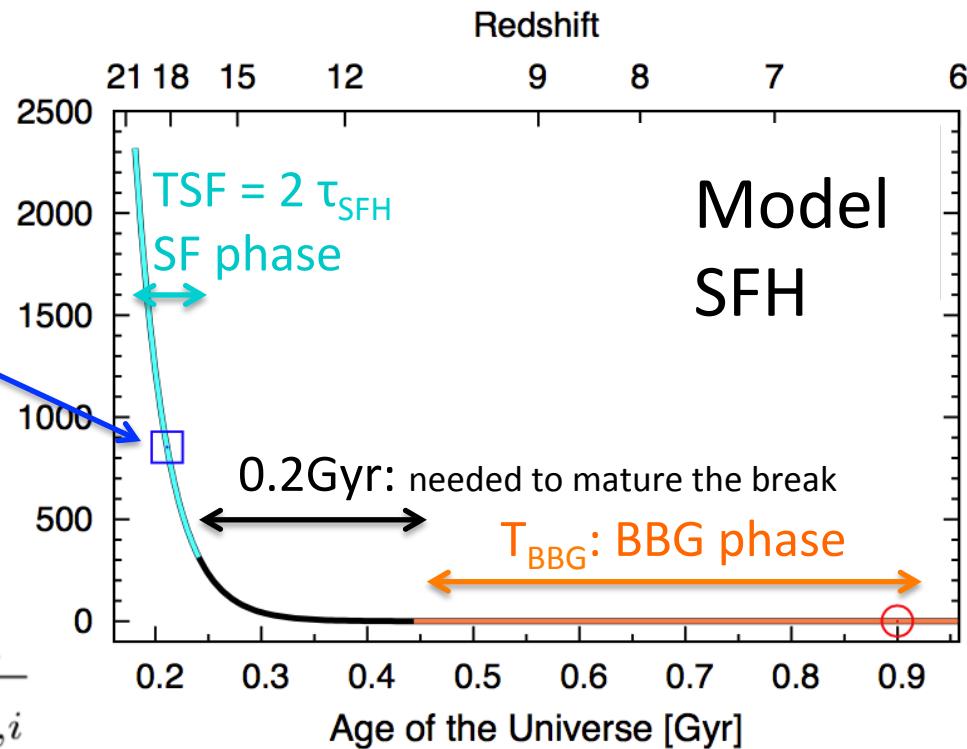
 Progenitors' z and SFR
are sensitive to SFH shape...

● SFRD of the progenitors

$$\rho_{\text{SFR}} \approx \sum_{i=1}^3 \frac{M_{*,i}^{\text{BBG}}}{T_{\text{SF},i}} \times \frac{1}{V_{\text{eff}}} \times \frac{T_{\text{SF},i}}{T_{\text{BBG},i}}$$

$$\approx \frac{\rho_*^{\text{BBG}}}{\langle T_{\text{BBG}} \rangle}$$

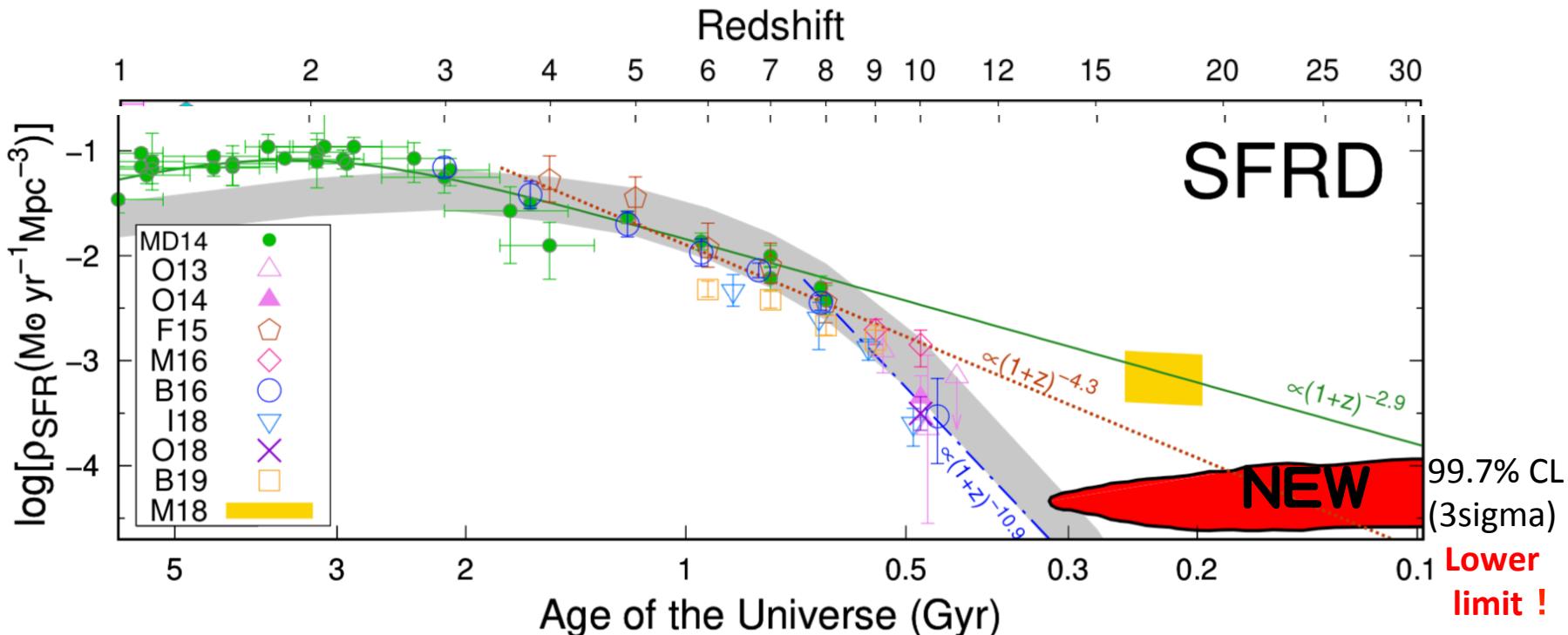
 Fraction of observable timescale



 Progenitors' SFRD
is less sensitive to SFH assumption!

Star Formation Rate Density at $z \sim 20$

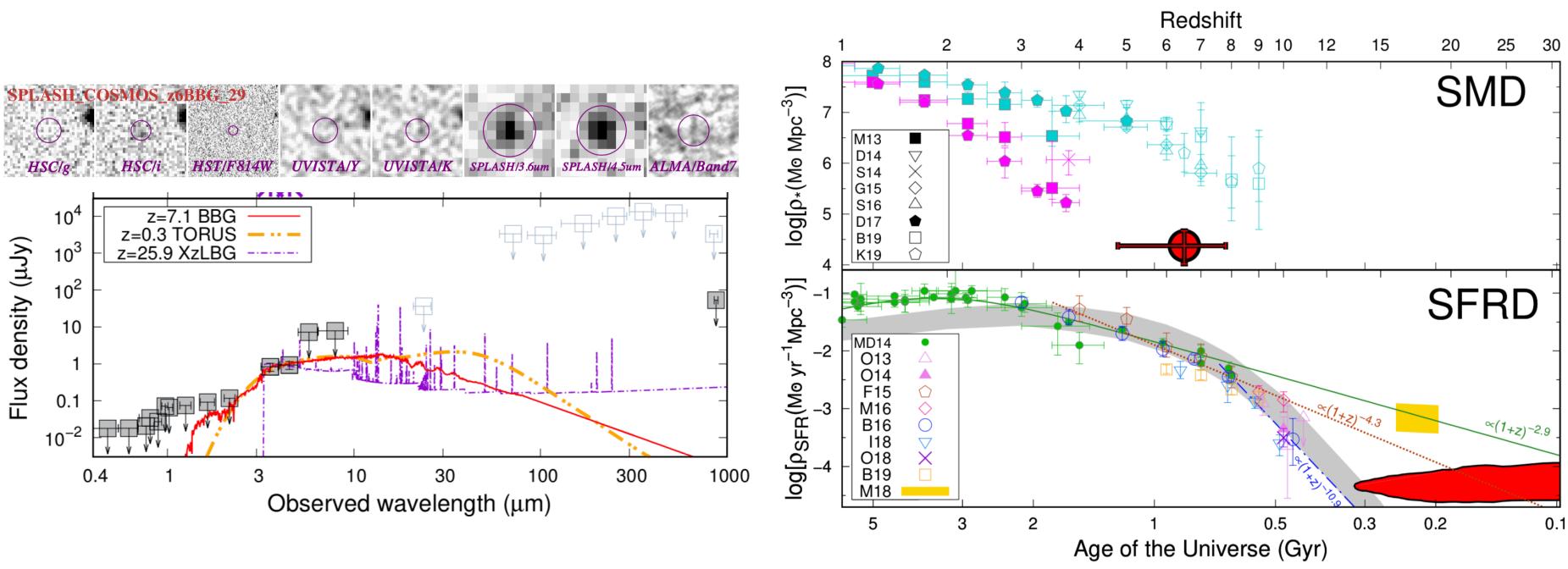
- ✓ $2.4\text{E-}5 < \text{SFRD}/(\text{Msun/yr/Mpc}^3) < 1.2\text{E-}4$ at $z > 14$ (99.7% confidence level)
- ✓ Our result supports smooth evolution (Finkelstein+15, Kikuchi+19) rather than rapidly declining evolution (Oesch+14,18, Harikane+18).
- ✓ Relatively high SFRD indicates higher SF efficiency at $z > 10$.



confidence level (3σ). The SFRD measurements at $z \lesssim 10$ are collected from the literature (MD14: Madau & Dickinson 2014, O13: Oesch et al. 2013, O14: Oesch et al. 2014, F15: Finkelstein et al. 2015a, M16: McLeod et al. 2016, B16: Bouwens et al. 2016, I18: Ishigaki et al. 2018, O18: Oesch et al. 2018, and B19: Bhatawdekar et al. 2019). All of them at $4 \lesssim z \lesssim 10$ are

Summary

- Photometric selection of 3 passive galaxies at $z \sim 6$
- Their SEDs are well fit by the old galaxy model **at $z \sim 6$ with ~ 0.7 Gyr passive (non-star-forming) phase.**
- Their expected **star-formation epoch is $z > 14$!**
- Spectroscopic confirmation is very important. (\Rightarrow JWST)



- Open question
: How did they produce stars as massive as $\sim 5 \times 10^{10} \text{ Msun}$ by $z \sim 14$??