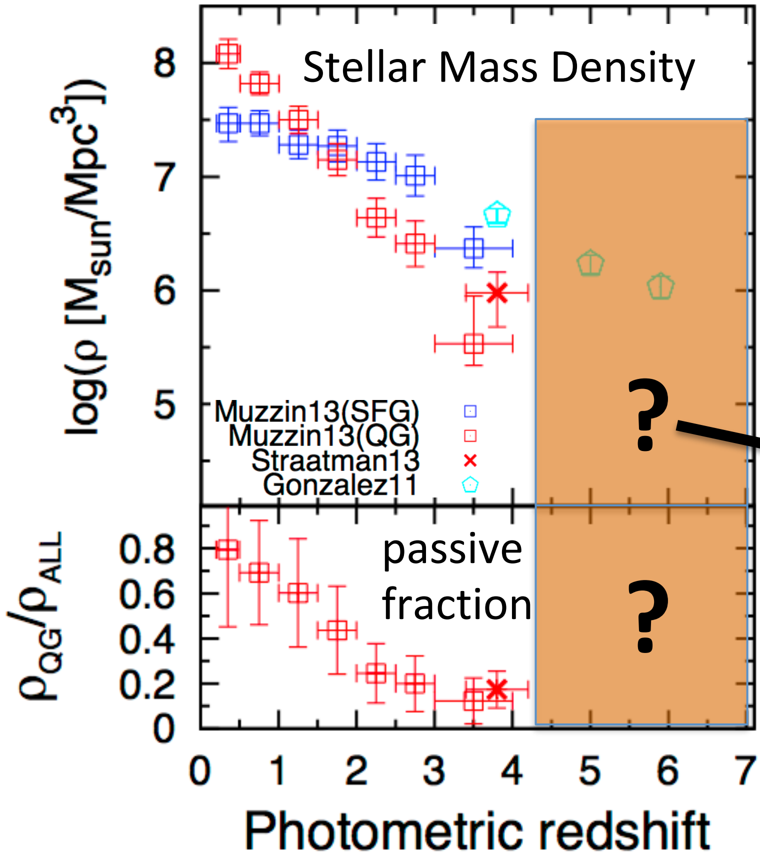
Challenge to the Most Distant Evolved Galaxies: Hint on Star-formation Activity during the First 500 Million Years of the Cosmic History

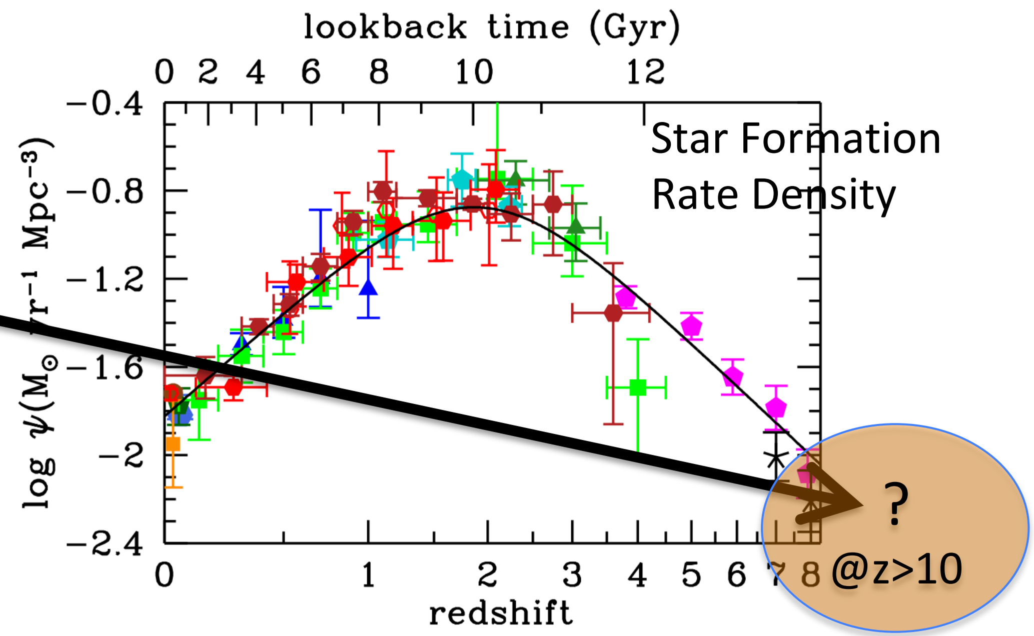
Ken Mawatari (ICRR Fellow)

Background

"Passive galaxy" in this work:
galaxy experiencing > 200Myr after stopping star-formation



Stars of z~6 passive galaxies should have been formed at much higher redshift (z>10!)



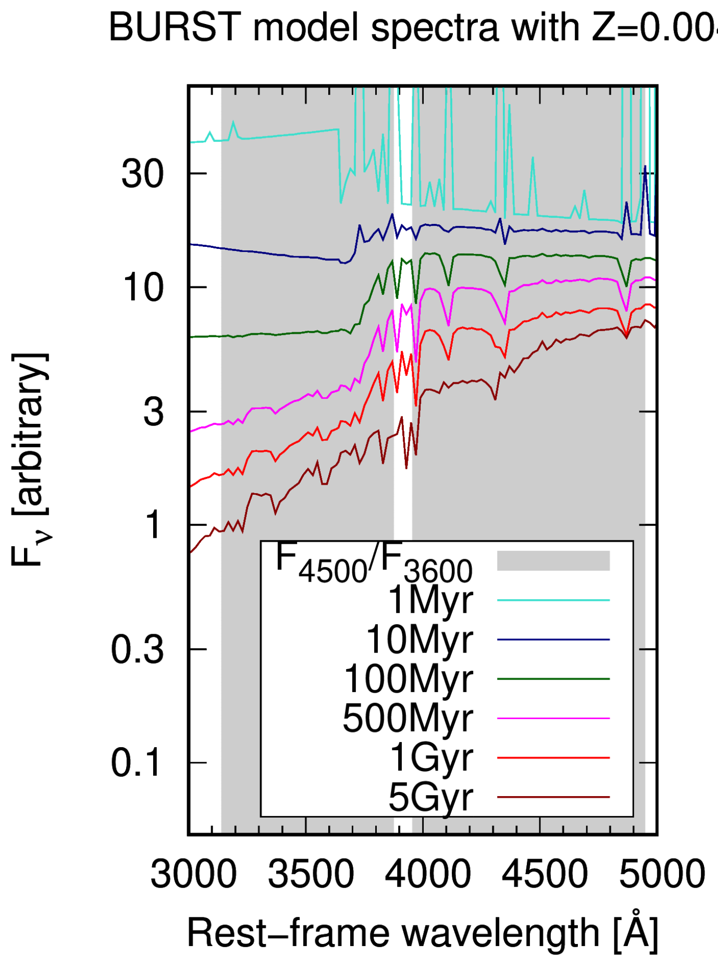
(Madau & Dickinson 2014)

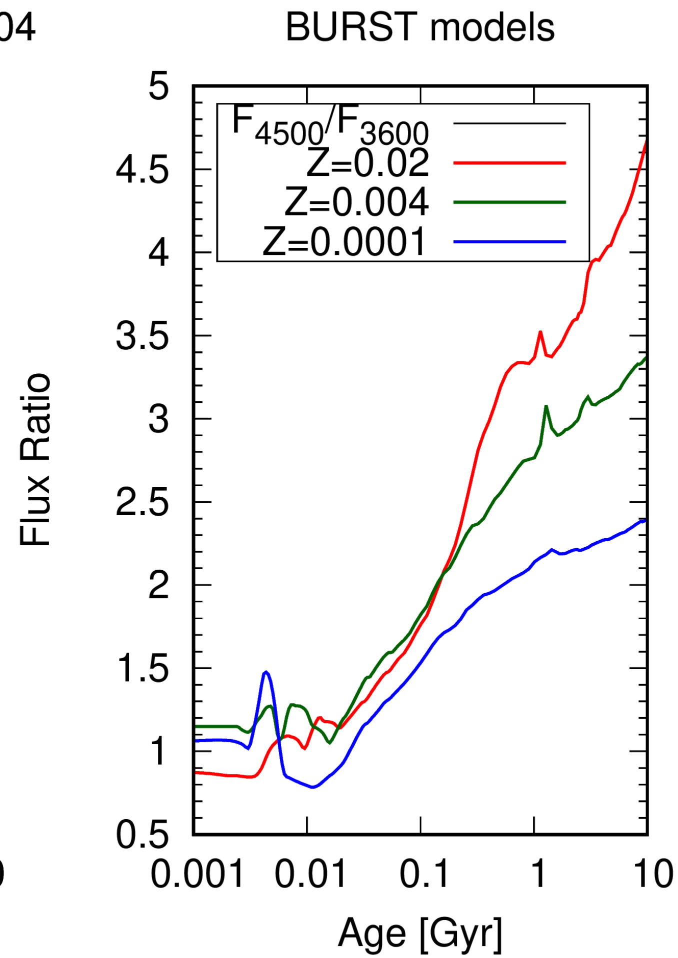
Motivation

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

Balmer/4000A break

Key spectral feature of passive galaxies





Balmer Break becomes stronger with older age or higher metallicity.

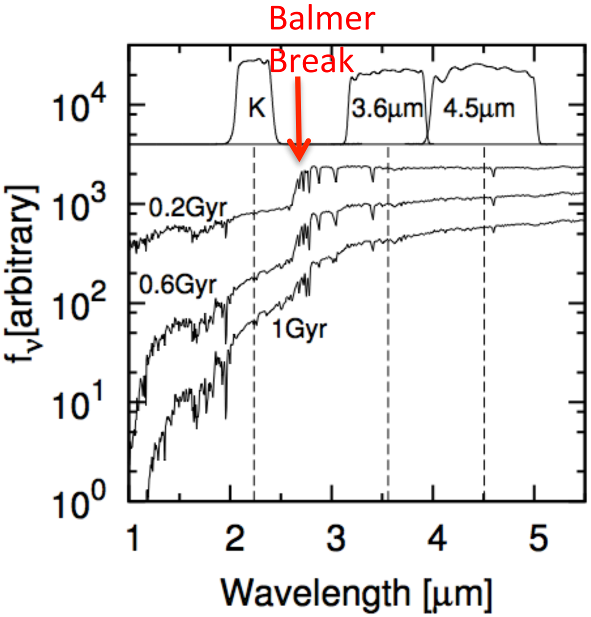
Balmer Break Galaxy (BBG) = Passive galaxy

Color selection of passive galaxies

Observed near-infrared (2 – 5um) colors of model galaxies (Bruzual & Charlot 2003)

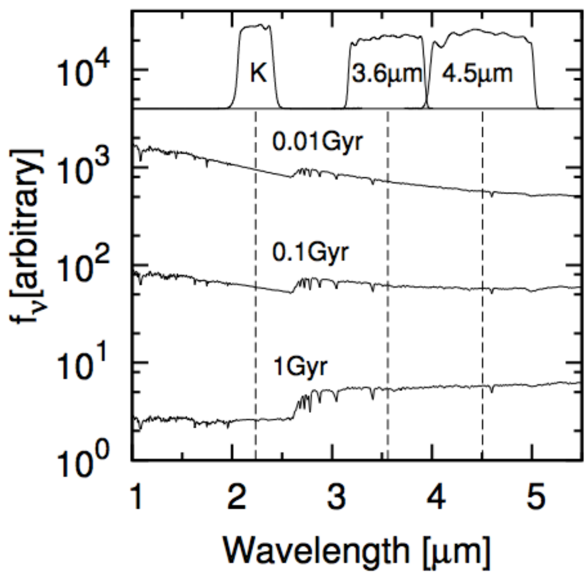
K, Spitzer-3.6um, and 4.5um bands

（1）Passive model@z~6



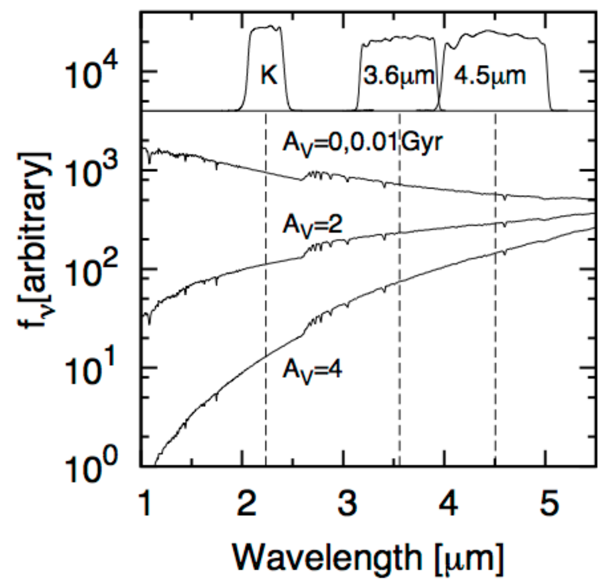
Red around Balmer Break
Blue at longer wavelength

（2）Star-forming



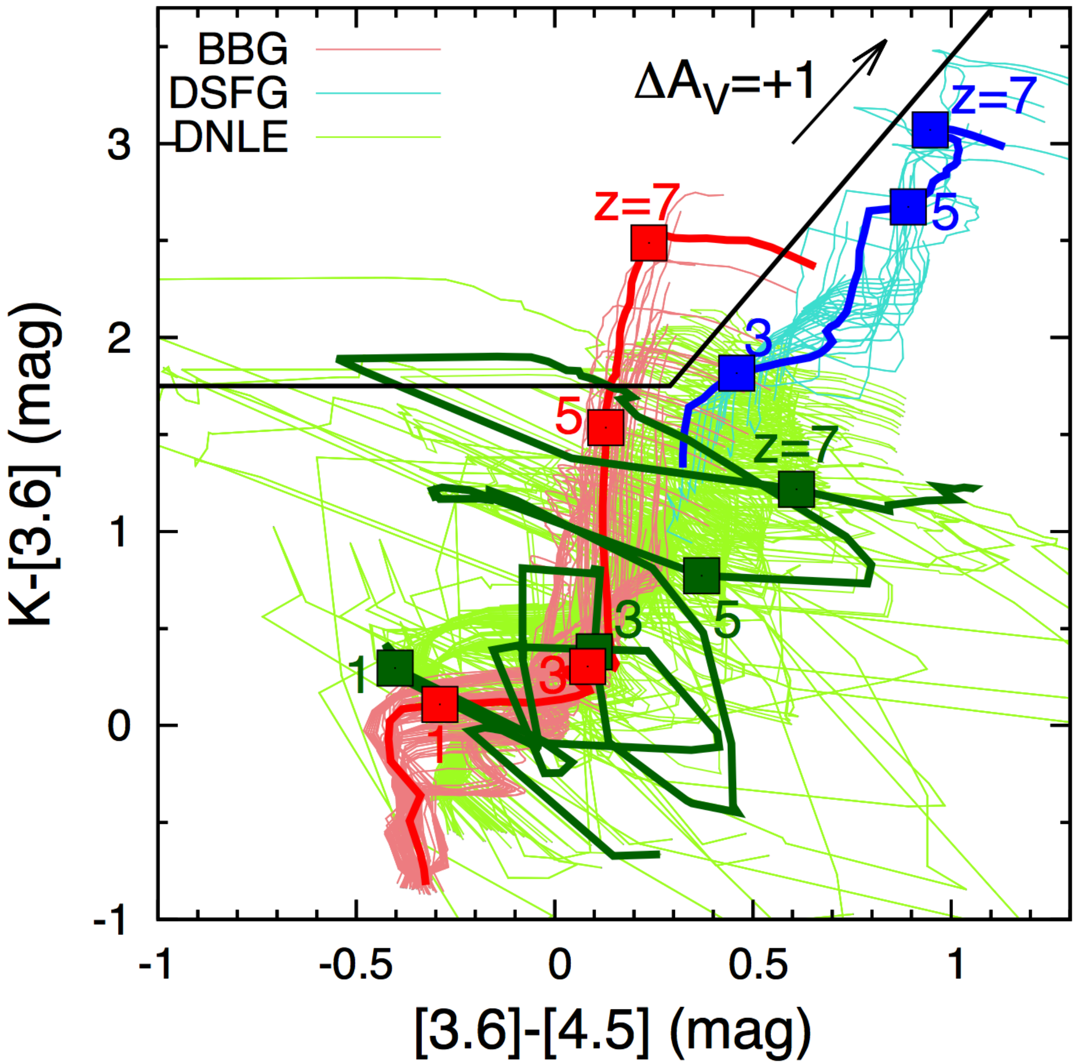
Blue around Balmer Break
Blue at longer wavelength

（3）Star-forming＋Dust



Red around Balmer Break
Red at longer wavelength

Color selection of passive galaxies



Models are composite of stellar continuum (Bruzual&Charlot03), Nebular emissions (Inoue+11)

Three types of galaxies with red K-[3.6] color.

(1) Balmer Break Galaxy (BBG)
age >200Myr

(2) Dusty Star-forming galaxy (DSFG)

(3) Dusty Nebular-line emitter (DNLE)
Extremely young star-forming galaxy has very strong emission lines

Criteria for BBG at 5<z<8
$K - [3.6] > 1.75$
$K - [3.6] > 2.4([3.6]-[4.5])+1.05$

c.f. Mawatari+16b

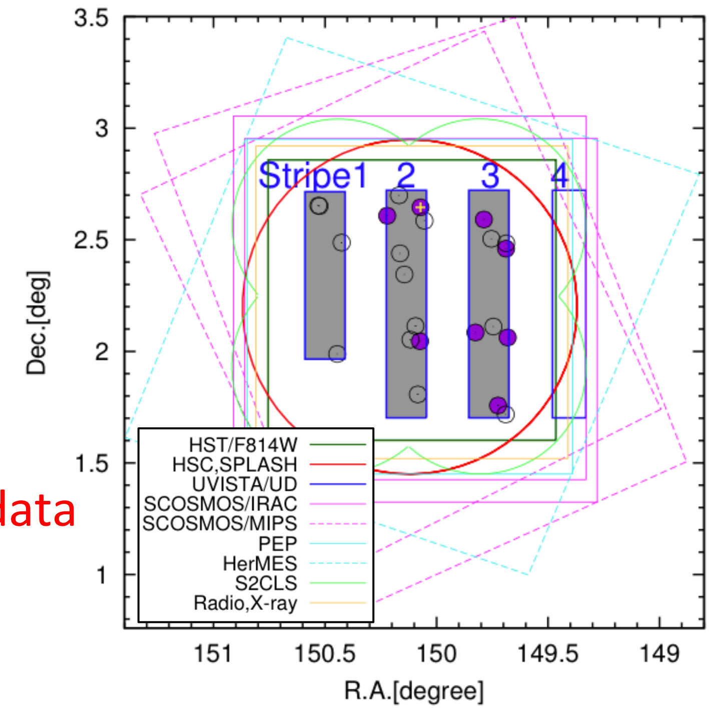
Data

All the imaging data available in the UVISTA UD stripes 1～3.

Instrument	Filter	FWHM* (arcsec)	Limiting flux† (5σ)	Survey
HST/ACS	*F814W*	0.10	27.5(26.6§) mag	COSMOS
Subaru/HSC	g	0.75	26.9 mag	SSP/UD S16A
Subaru/HSC	r	0.54	27.0 mag	SSP/UD S16A
Subaru/HSC	i	0.61	26.5 mag	SSP/UD S16A
Subaru/HSC	z	0.56	26.2 mag	SSP/UD S16A
Subaru/HSC	y	0.70	25.2 mag	SSP/UD S16A
VISTA/VIRCAM	Y	0.8	25.8 mag	UltraVISTA/UD DR3
VISTA/VIRCAM	J	0.77	25.7 mag	UltraVISTA/UD DR3
VISTA/VIRCAM	H	0.75	25.5 mag	UltaraVISTA/UD DR3
VISTA/VIRCAM	K_s	0.75	25.2 mag	UltraVISTA/UD DR3
Spitzer/IRAC	3.6μm	1.7	23.8 mag	SPLASH
Spitzer/IRAC	4.5μm	1.6	23.8 mag	SPLASH
Spitzer/IRAC	5.8μm	1.8	20.7 mag	S-COSMOS
Spitzer/IRAC	8.0μm	2.1	20.7 mag	S-COSMOS
Spitzer/MIPS	24μm	5.9	19.0 mag	S-COSMOS
Spitzer/MIPS	70μm	18.6	14.1 mag	S-COSMOS
Herschel/PACS	100μm	7.2	14.2 mag	PEP DR1
Herschel/PACS	160μm	12.0	13.4 mag	PEP DR1
Herschel/SPIRE	250μm	18.15	14.1 mag	HerMES DR4
Herschel/SPIRE	350μm	25.15	14.4 mag	HerMES DR4
Herschel/SPIRE	500μm	36.3	14.0 mag	HerMES DR4
JCMT/SCUBA2	850μm	8.0	14.1 mag	S2CLS
VLA	1.4 GHz	–	75 μJy	VLA-COSMOS/Large
XMM – Newton	0.5-2 keV	–	5×10^{-16} erg cm^{-2} s^{-1}	XMM-COSMOS
XMM – Newton	2-10 keV	–	3×10^{-15} erg cm^{-2} s^{-1}	XMM-COSMOS
XMM – Newton	5-10 keV	–	7×10^{-15} erg cm^{-2} s^{-1}	XMM-COSMOS
Chandra	0.5-2 keV	–	2.2×10^{-16} erg cm^{-2} s^{-1}	Chandra COSMOS Legacy
Chandra	2-10 keV	–	1.5×10^{-15} erg cm^{-2} s^{-1}	Chandra COSMOS Legacy
Chandra	0.5-10 keV	–	8.9×10^{-16} erg cm^{-2} s^{-1}	Chandra COSMOS Legacy

Key data

Used area



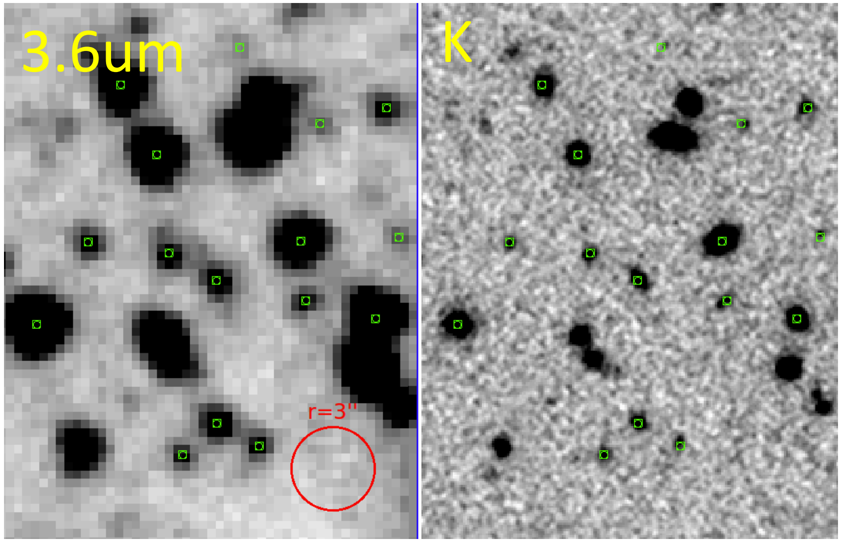
Depth of K～25 & [3.6]～24 mag enable us to detect passive galaxies down to $M_* \sim 3\times10^{10}$ Msun.

z～6 BBG selection

● Balmer Break Galaxy (BBG) selection

・We focus on only
isolated objects in the K and 3.6um image
for photometric accuracy.

N～37000



・The Color selection

$K - [3.6] > 1.75$

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

N = 23

・Non-detection in
optical, MIR(λ >10um), FIR, radio, and X-ray
to remove
strong line emitters, extremely dusty galaxies,
and AGNs.

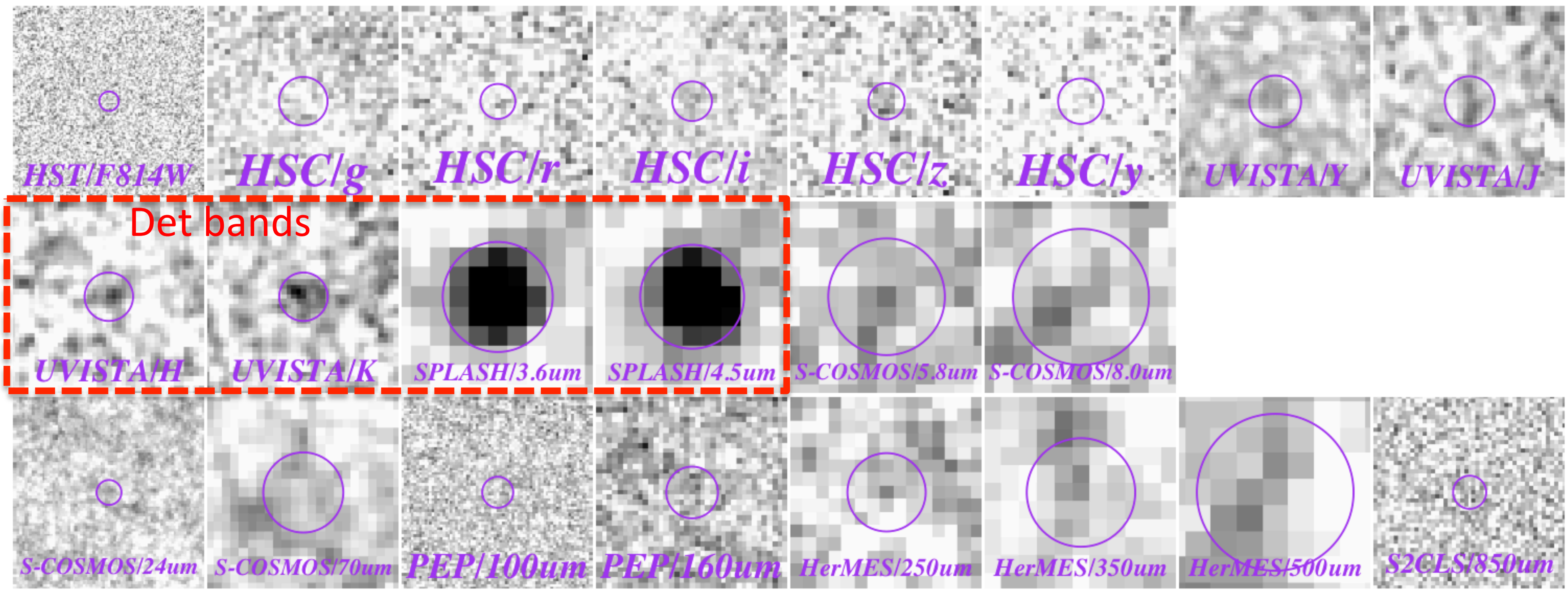
⇒ **8 BBG candidates at z～6**

Stacking

● **Stacking of the 8 BBG candidates**

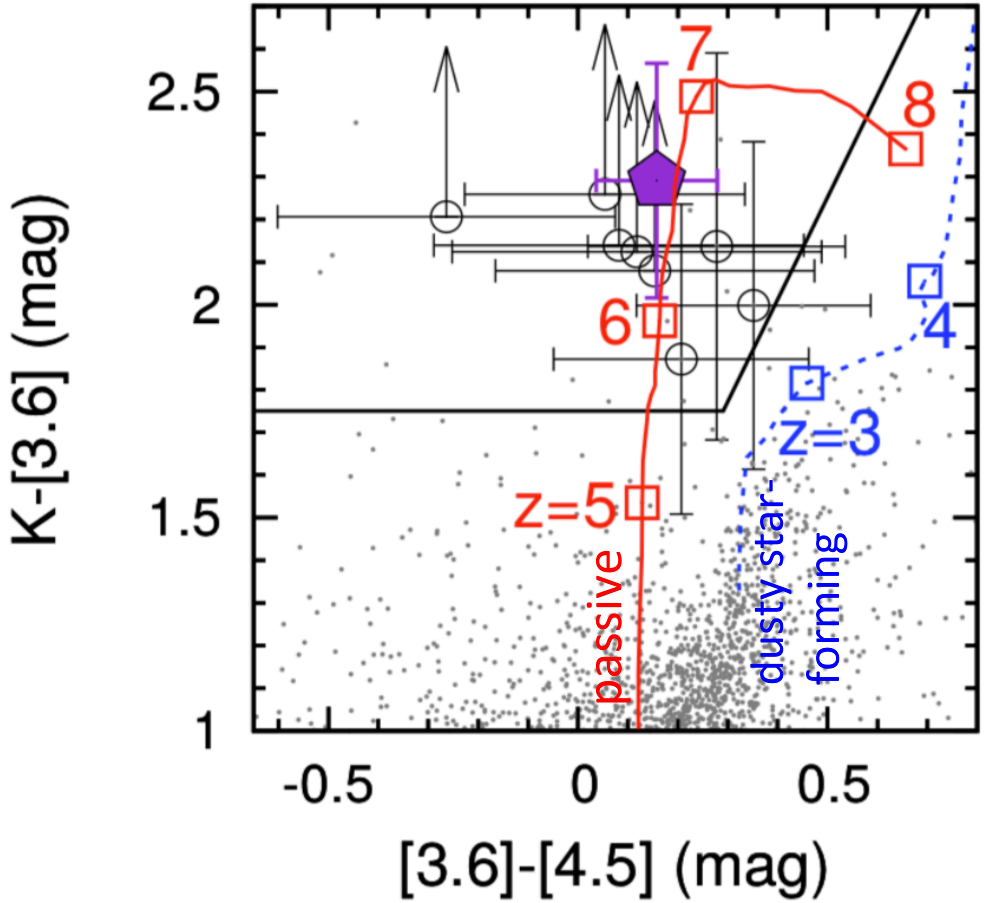
Detections in the H, K, 3.6um, 4.5um, and very deep constraints in other bands.

x ~sqrt(8) improvement in photometry



z~6 BBGs' color

- Photometric selection of 8 passive galaxies with the strong Balmer break at z ~ 6



Open circles: the 8 BBG candidates
Filled violet pentagon: stacked BBG

SED fitting

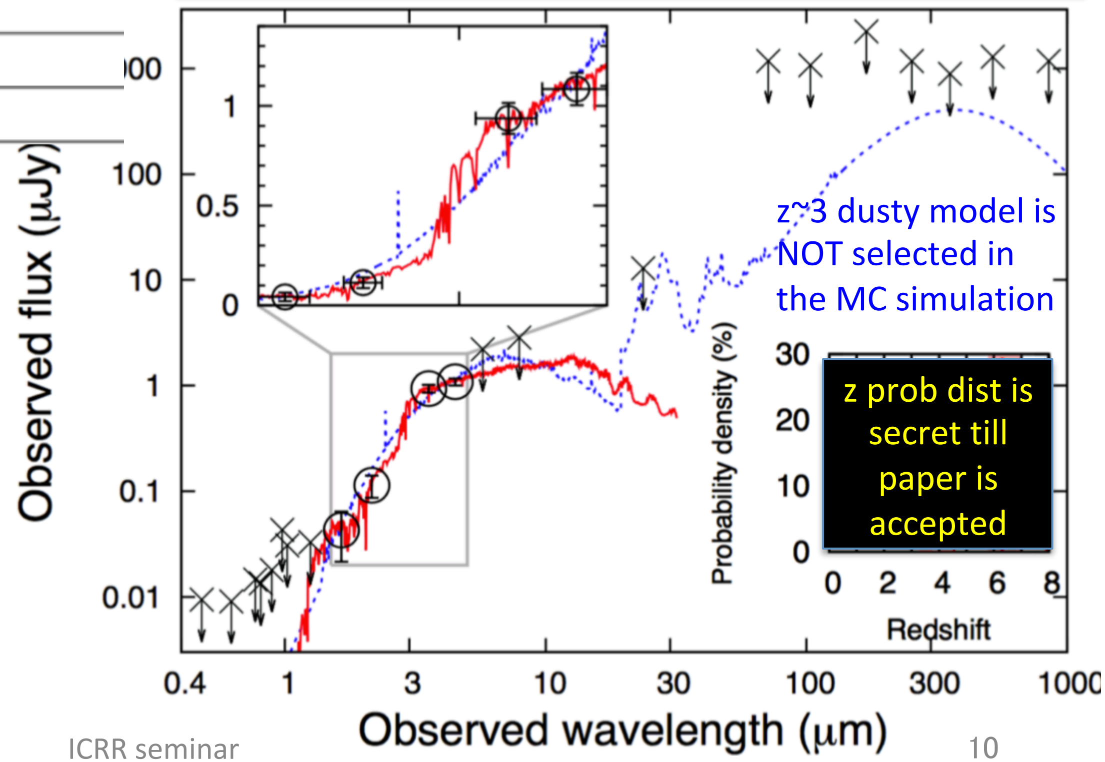
- Model template fitting for the stacked Spectral Energy Distribution (SED) results in the best-fit by an old galaxy model at z ∼ 6 with 0.7 Gyr passive phase.

Supplementary Table 2: **Model parameter range on SED fitting**

Templates	BC03+line+Dust
SFH	Exp-decline/rising, constant-SF (τ = 0.03, 0.06, 0.1, 0.3, 0.6, 1, and 10 Gyr)
Metallicity	0.0001, 0.004, and 0.02
Age [Gyr]	0.001 – age of the Universe
Redshift	0 – 8
Dust A_V	0 – 10 ※

※ We forbidden extremely dusty passive parameter space where the Kennicutt-Schdmit law is completely broken:
$A_v > 4 \times SFR^{0.3}$

Sorry, but the best-fit parameter values are secret till paper is accepted

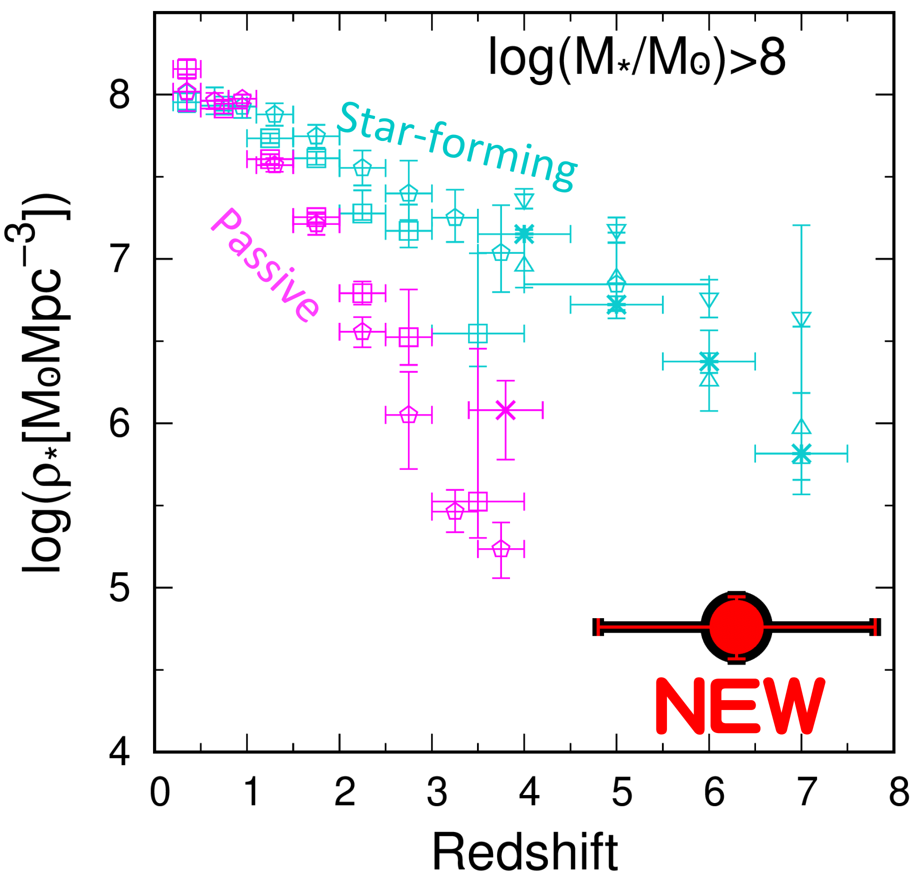


Stellar Mass Density of z~6 BBGs

Assumption
: The 8 candidates are all BBGs at $z = 5 - 8$, with $M_* = 4 \times 10^{10} M_{sun}$

After correcting the detection incompleteness, stellar mass density (SMD) of z~6 BBGs is

Sorry, but the SMD value is secret till paper is accepted



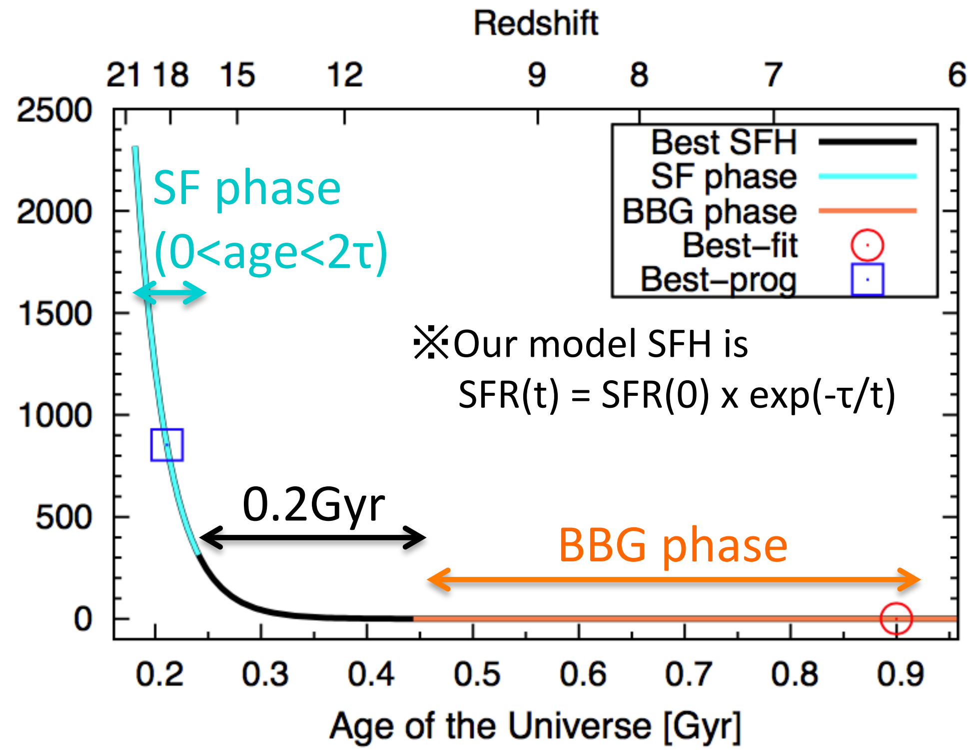
- consistent with the trend at z = 0 - 4
- passive fraction～3%

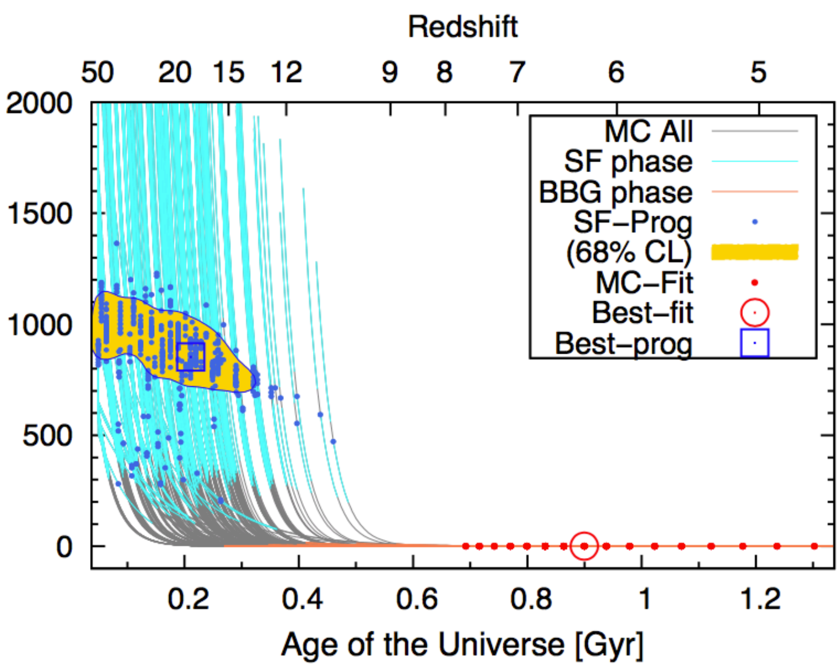
Formation and quenching of first massive galaxies in the universe was proceeded by z = 6 !

Progenitors of z~6 BBGs

● Star–forming progenitors

- Best-fit model suggests the star-forming progenitor (age=τ) at z ～18 with SFR ～ 900M_{sun}/yr





- We also investigated SFHs of all best-fit models in the MC runs.

Star Formation Rate Density at z～20

SFRD of the BBG progenitors is estimated via

$$SFRD_{prog} = SFR(t=\tau) \times n_{prog} \times f_{obs}$$

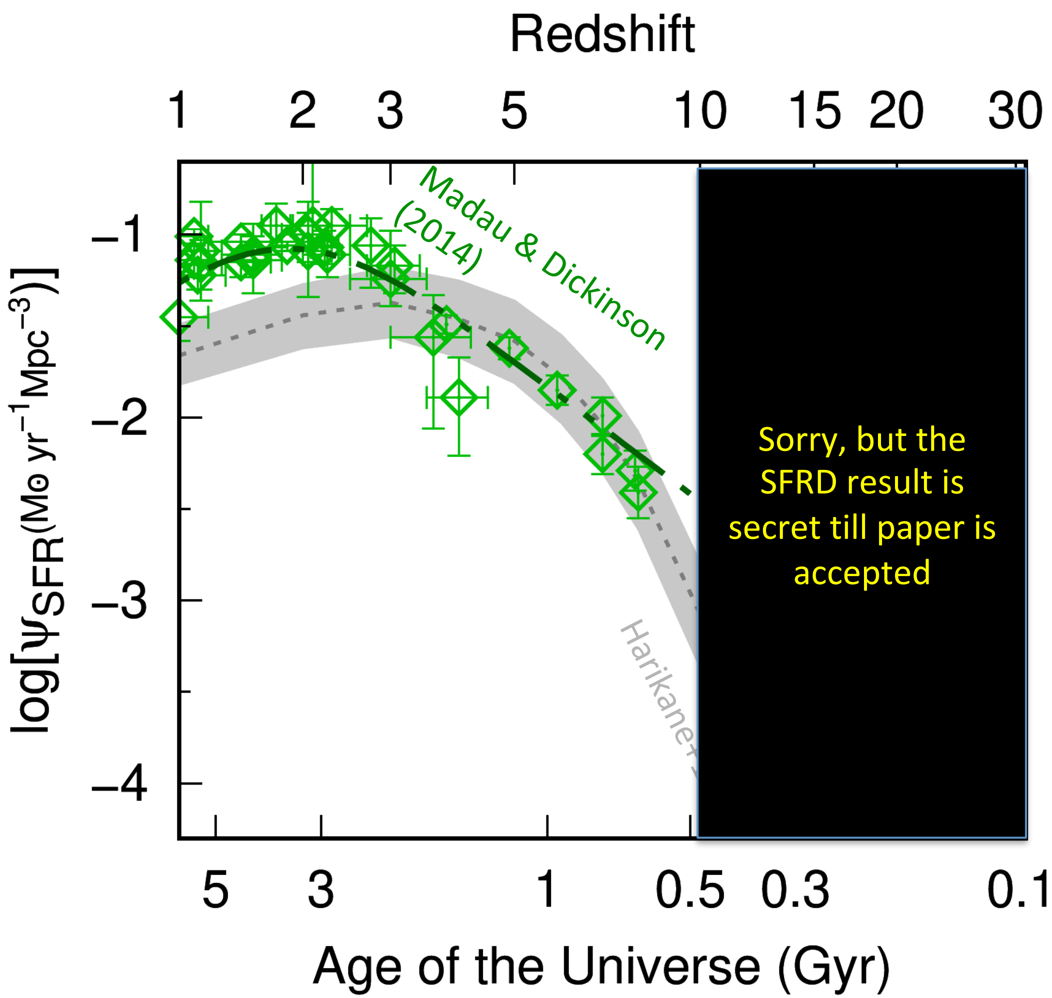
Number density of the BBG progenitors
= that of the BBGs at z~6

Typical SFR of the BBG progenitors

$$f_{obs} = \frac{T_{SF}}{T_{BBG}} = \frac{2 \times \tau}{age_{BBG} - 2 \times \tau - 0.2Gyr}$$

: Fraction of observable timescale

Star Formation Rate Density at z～20



SFRD of the BBG progenitors is regarded as a lower-limit of the cosmic SFRD.

We constrain the SFRD at z>10 for the first time.

Summary

- Photometric selection of 8 passive galaxies with the strong Balmer break at z ~ 6
- Their SEDs are well fit by old galaxy model at z ∼ 6 with > 0.5 Gyr passive (non-star-forming) phase.
- Their expected star-formation epoch is z > 15!
- Follow-up observation by ALMA is proceeding now.
- Spectroscopic confirmation is very important. (=> JWST)