

Physical Properties of UDF 12 Galaxies in Cosmological simulations

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参考文献

Shimizu et al. 2014, arXiv:1310.0114

Inoue, IS et al. 2014, ApJ, 780, 18

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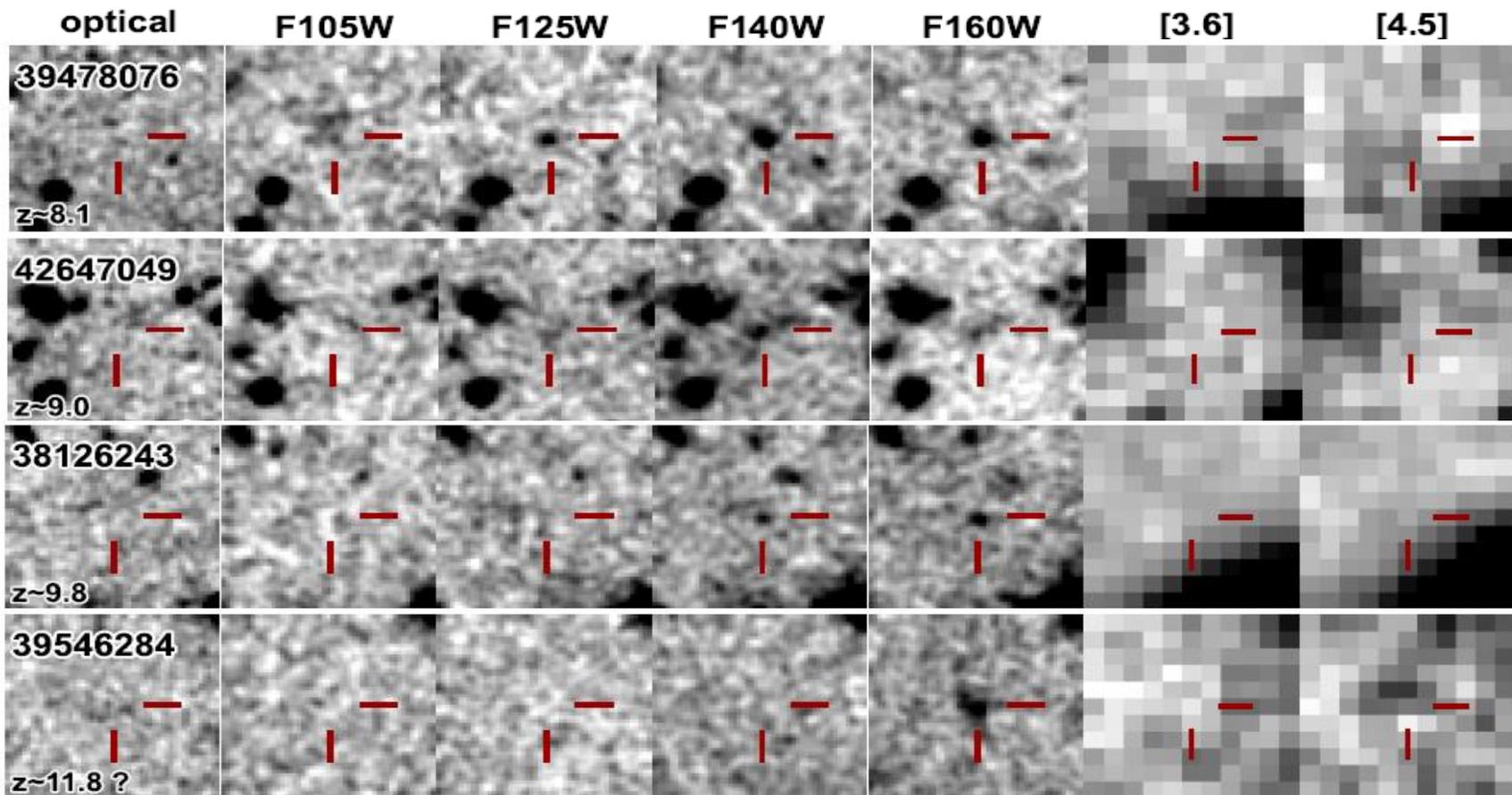
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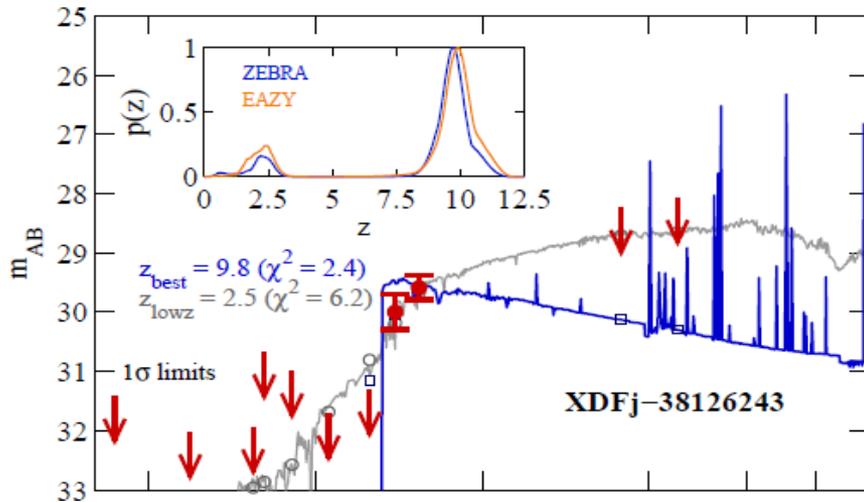
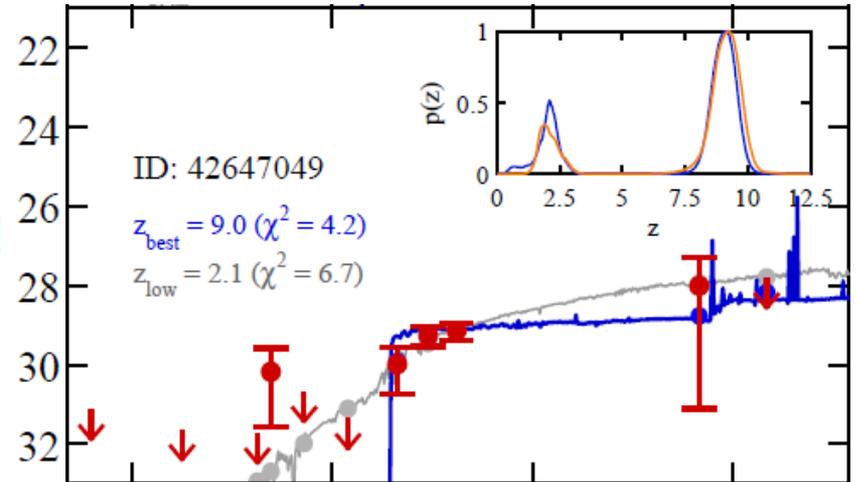
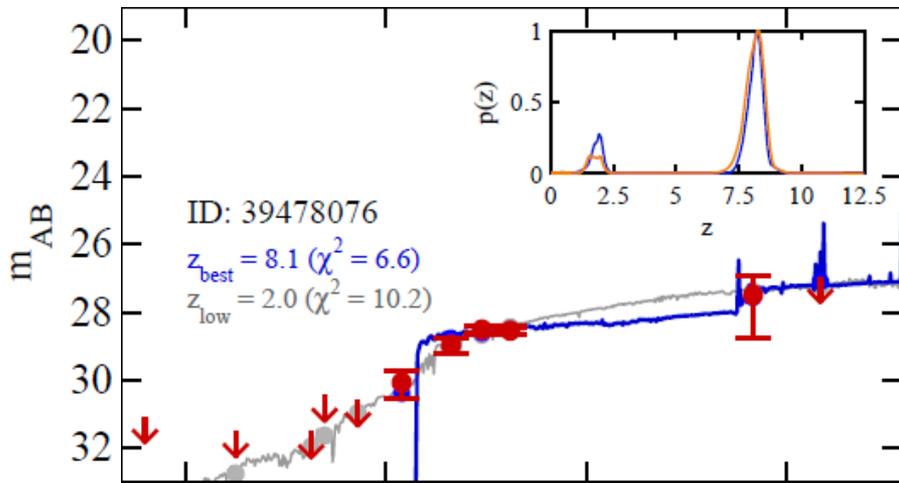
Introduction

UDF12 Galaxies

ハッブル望遠鏡に新たに搭載された WFC3/IR (Y, J, H) カメラを用いたディープな (~ 30 mag) 観測 (e.g., すばる望遠鏡 J band ~ 25 mag)
⇒ 多くの赤方偏移 $z=7$ を超える銀河候補を発見!



UDF12 Galaxies



Spritzer 宇宙望遠鏡等による静止系可視域の十分に深いデータの欠如



Photo-z (SED fitting) による銀河の物理量 (星質量、星形成率) の見積もりの不定性が大

宇宙論的流体計算を用いて、UDF12 galaxy の物理量を推定する

Simulation

Simulation Details

- **Cosmology : Λ CDM**

$$(\Omega_m, \Omega_b, \Omega_\Lambda, h, \sigma_8) = (0.27, 0.046, 0.73, 0.7, 0.81)$$

- **Simulation code : Gadget-3**

*radiative cooling/heating, star formation, SN & galactic wind feedback
sub-particle multiphase ISM model (based on Okamoto et al.2008,2009)*

- **SED calculation**

\Rightarrow Stellar mass function

PEGASE.2

- **Dust attenuation**

metallicity dependence, Calzetti low

\Rightarrow UV luminosity function

- **IGM transmission**

Madau 1994

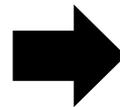
- **Simulation parameter sets**

Boxsize : 50Mpc/h

Number of particles : 2×640^3

$M_{dm} :$ $3.0 \times 10^7 M_{sun}$

$M_{gas} :$ $6.0 \times 10^6 M_{sun}$

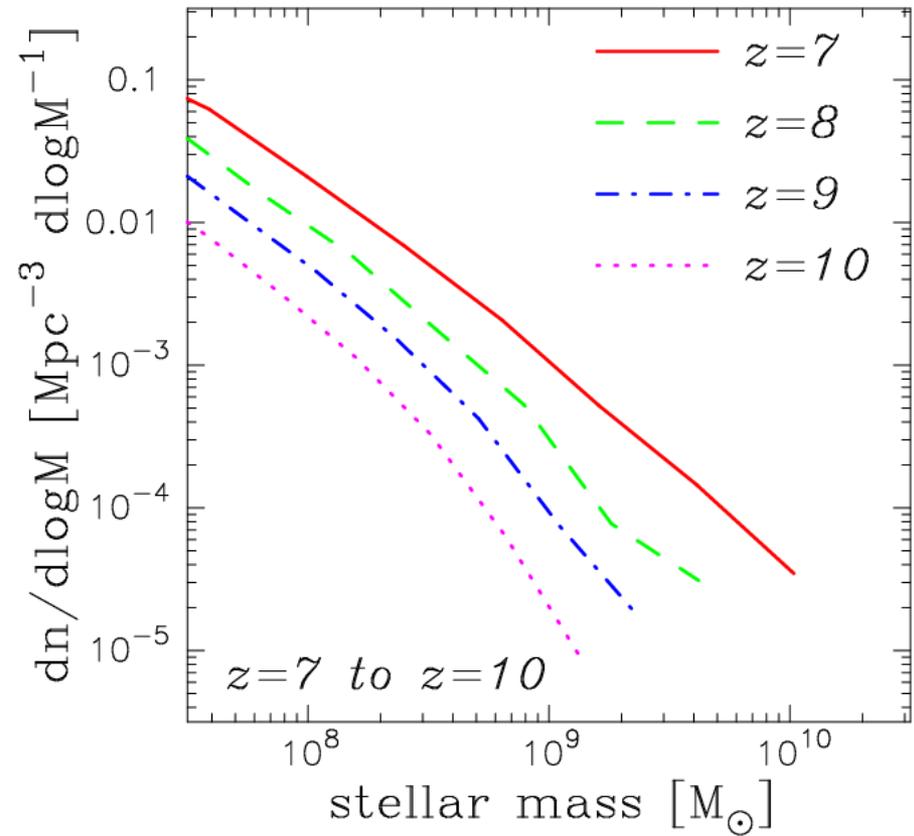
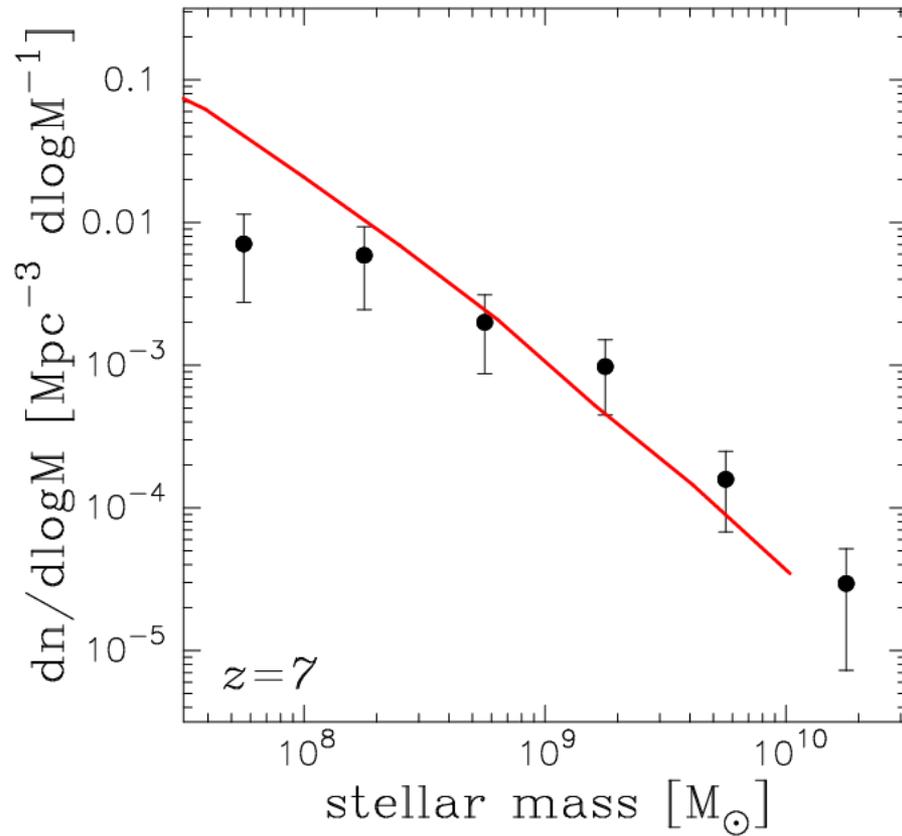


Minimum halo mass: $\sim 10^9 M_{sun}$

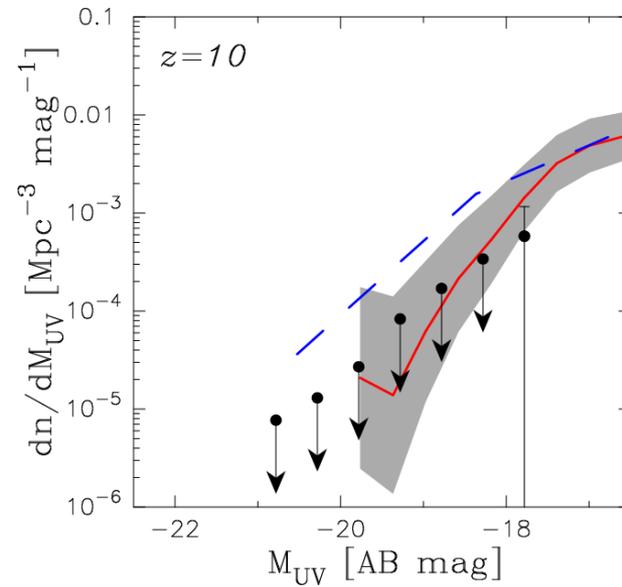
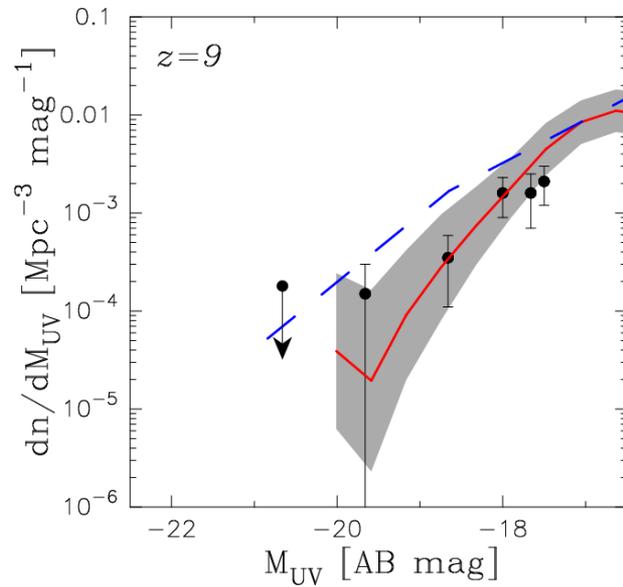
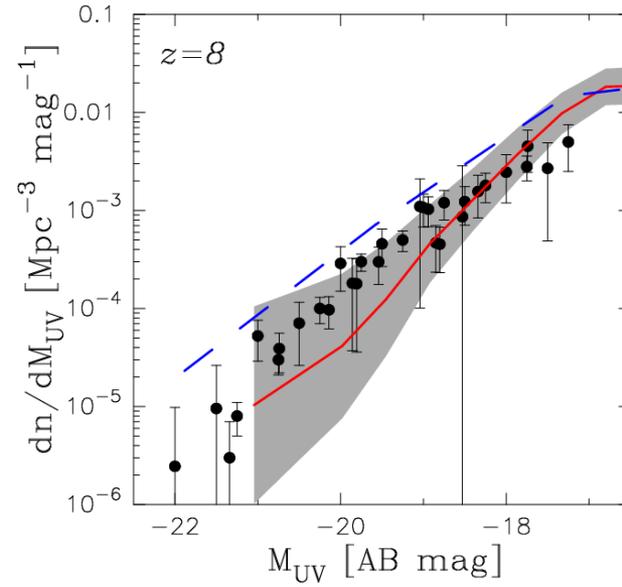
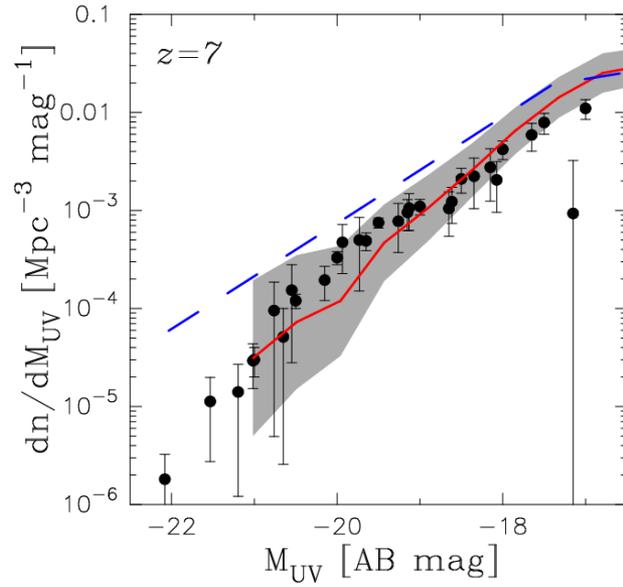
Minimum stellar mass: $\sim 10^7 M_{sun}$

Stellar Mass Function

IMF : Salpeter IMF

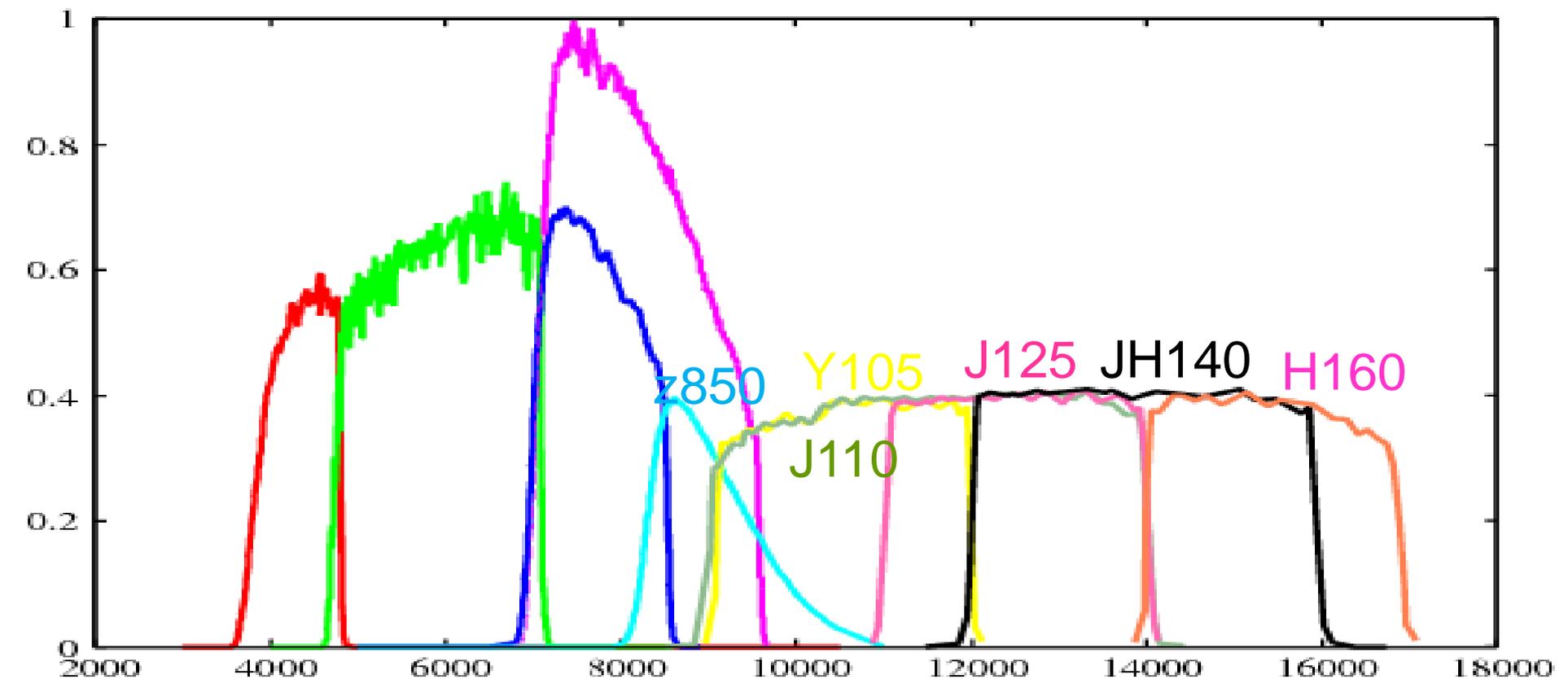
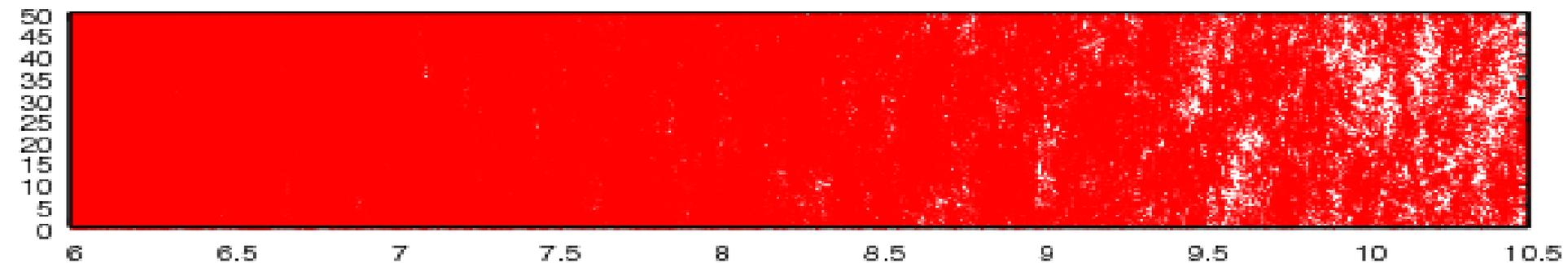


UV Luminosity Function

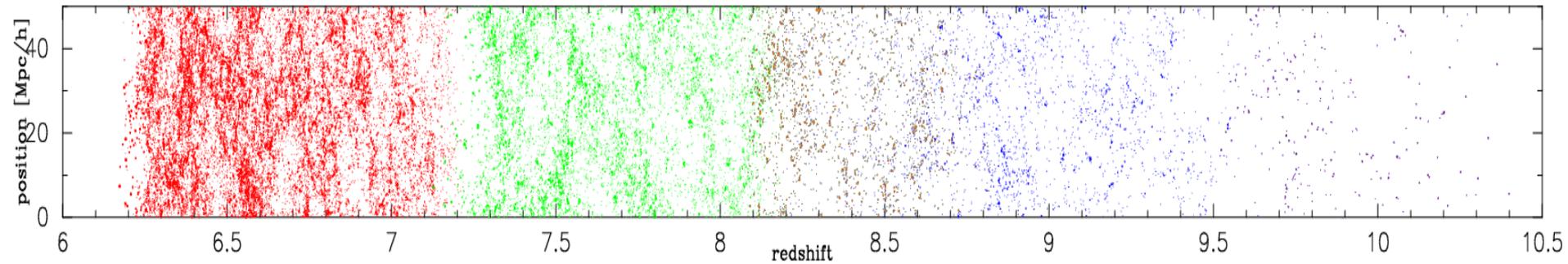


Virtual Observation

Color Selections of our Simulations



Color Selections of our Simulations



$z \sim 7$ selection conditions

$$z_{850} - Y_{105} > 0.7$$

$$Y_{105} - J_{125} < 0.4$$

$$+ Y_{105} < 30, J_{125} < 30$$

$z \sim 8$ selection conditions

$$Y_{105} - J_{125} > 0.5$$

$$J_{125} - H_{160} < 0.4$$

$$+ J_{125} < 30, H_{160} < 30$$

Schenker et al. 2013

$z \sim 9$ selection conditions

$$(Y_{105} - J_{125})/2 - JH_{140} > 0.75$$

$$(Y_{105} - J_{125})/2 - JH_{140} > 0.75 + 1.3(JH_{140} - H_{160})$$

$$+ JH_{140} < 30, H_{160} < 30$$

$z \sim 10$ selection conditions

$$J_{125} - H_{160} > 1.2$$

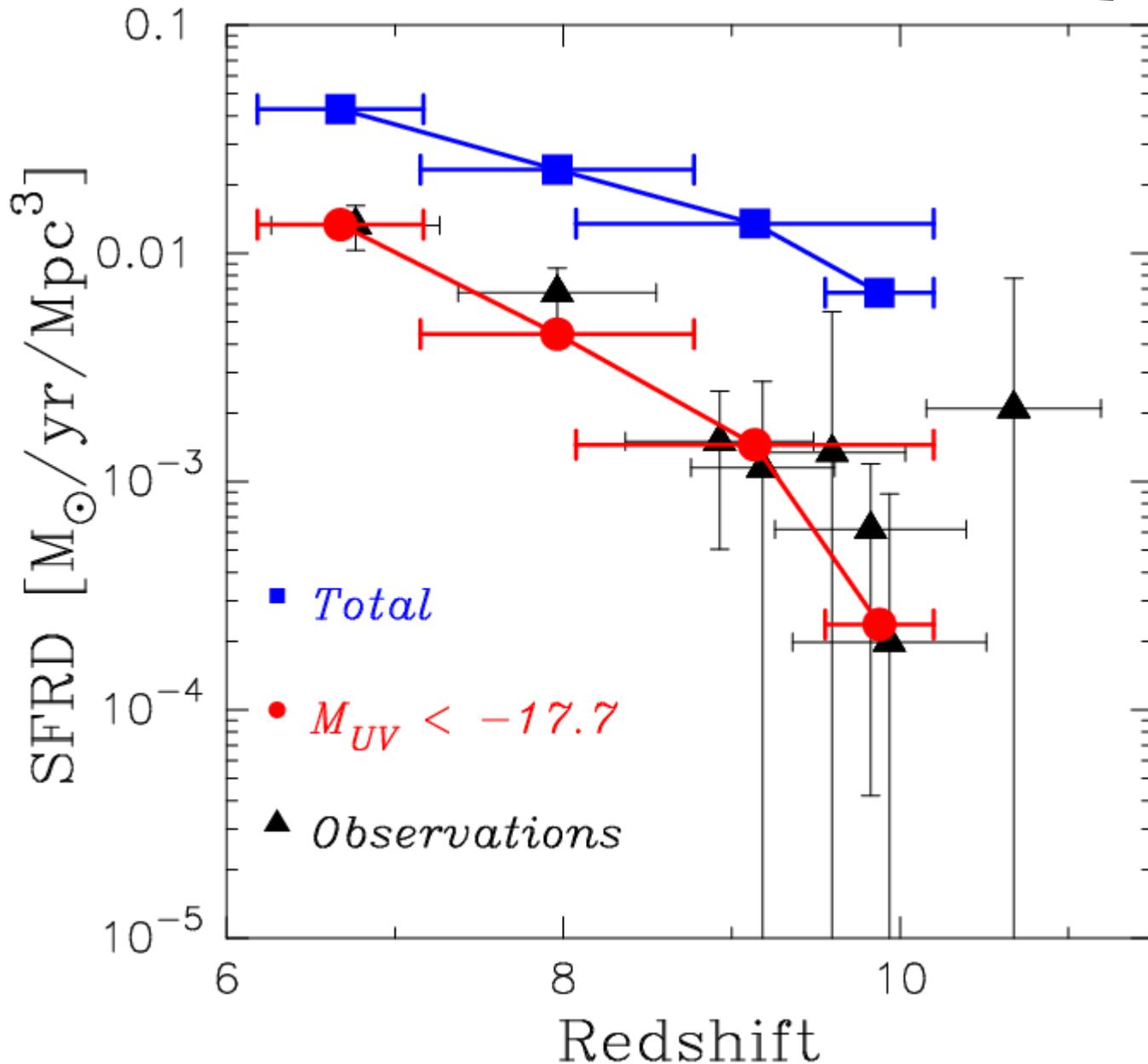
$$JH_{140} - H_{160} < 1.0$$

$$+ JH_{140} < 30, H_{160} < 30$$

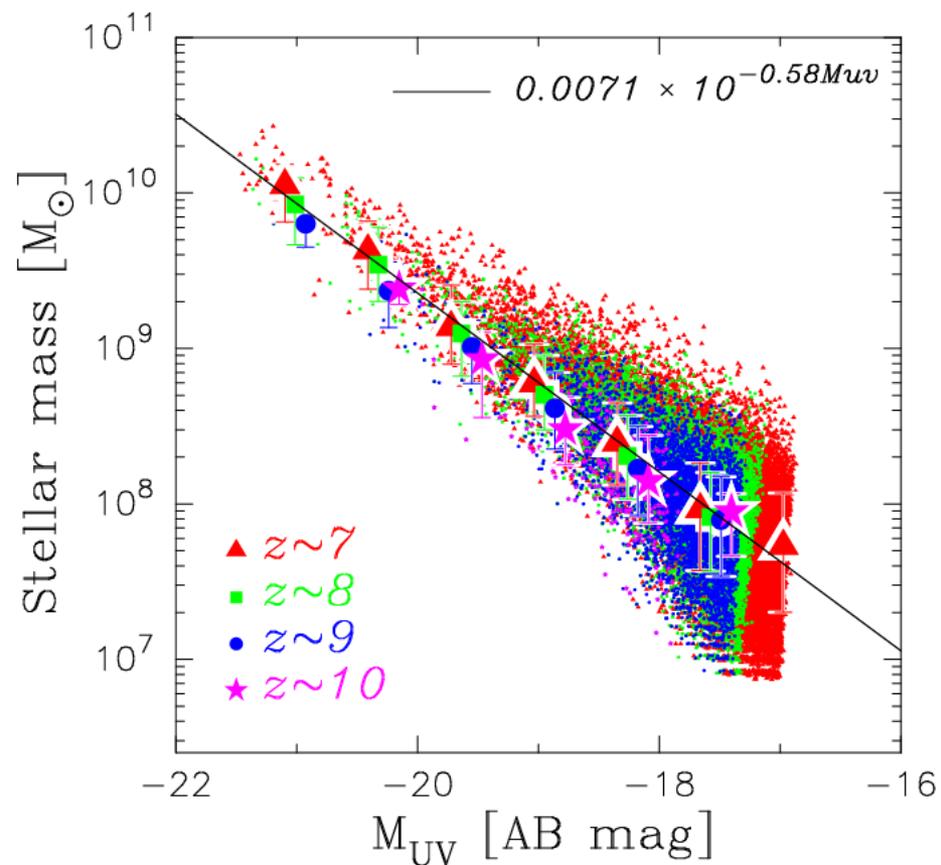
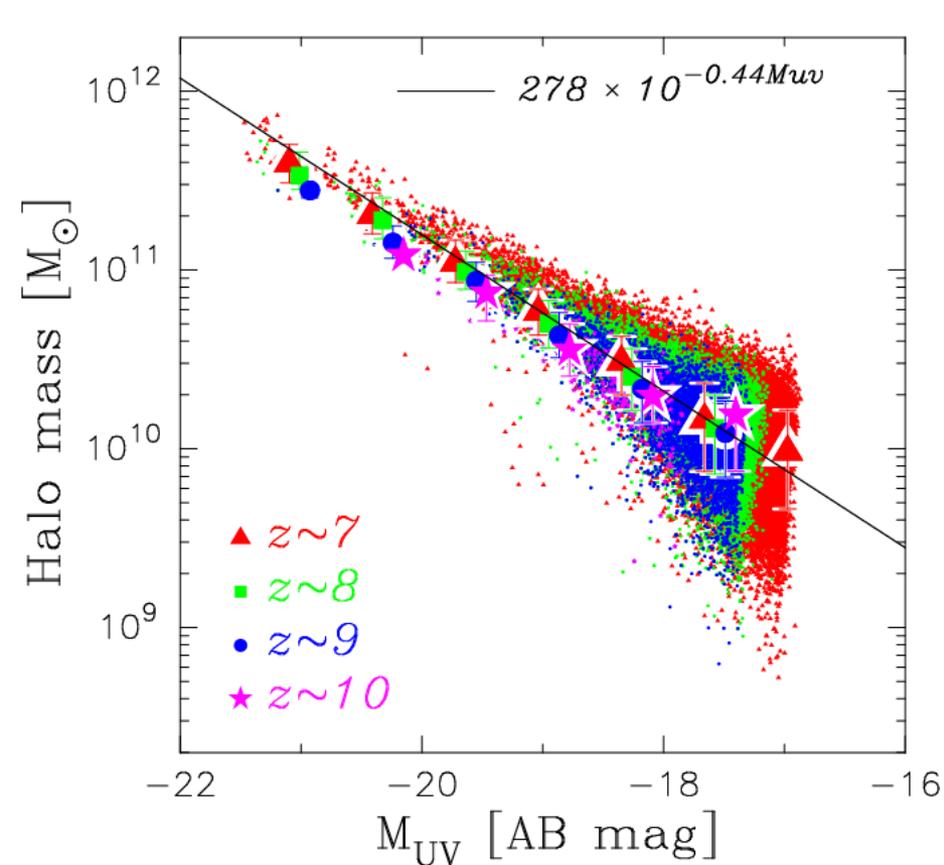
Oesch et al. 2013

Results

Star Formation History

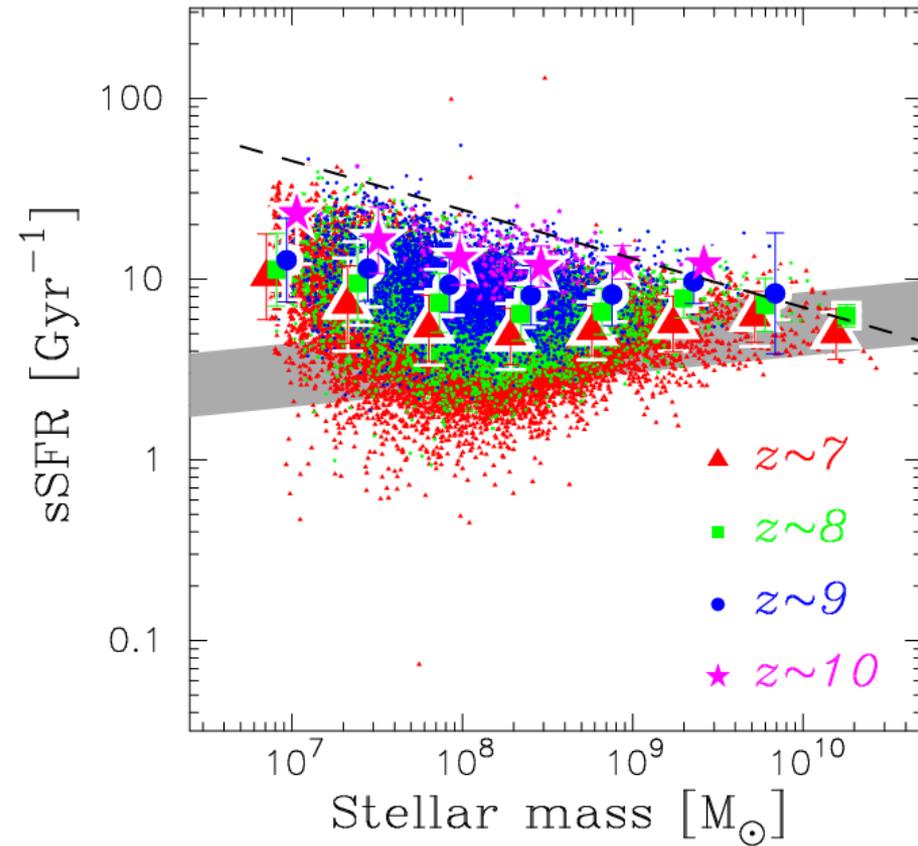
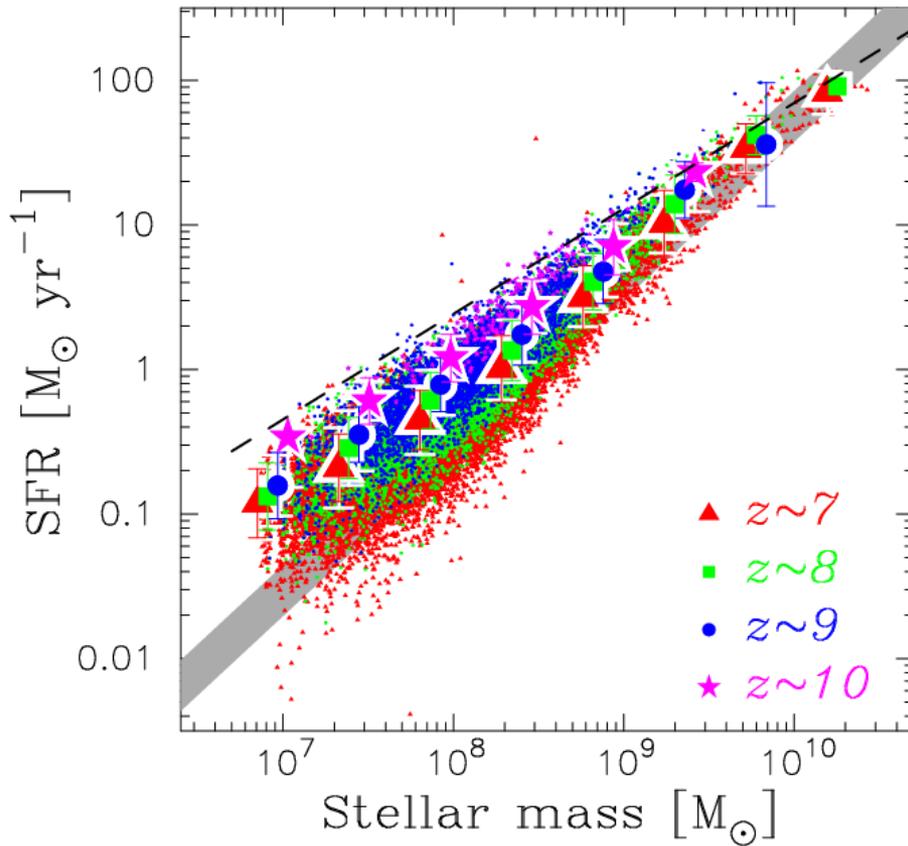


Halo Mass & Stellar Mass



- UV 光度とハロー質量 (星質量) との関係は赤方偏移にほとんど依存しない
- UV 光度はハロー質量 (星質量) と相関する
- UV 光度は星質量とより強く相関する

SFR & sSFR



- Main sequence のような分布
- quiescent phase というよりは、starburst phase
- この関係は基本的には、ダークマターの降着率と強く関係している
- シミュレーション結果と簡単な見積もりのずれは、バリオン物理が重要であることを示唆

What mechanism makes main sequence like distribution?

可能性として、SFR は dark matter の halo への降着率で決まると仮定

$$SFR = f_* \left(\frac{\Omega_b}{\Omega_m} \right) \frac{dM_{halo}}{dt}$$

Dark matter の降着率は (McBride et al.2009, Ishiyama et al.2013),

$$\frac{dM_{halo}}{dt} = 1.79 \times 10^{-14} f(z) \left(\frac{M_{halo}}{M_\odot} \right)^{1.094}$$

$$f(z) = (1 + 1.75z) \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}$$

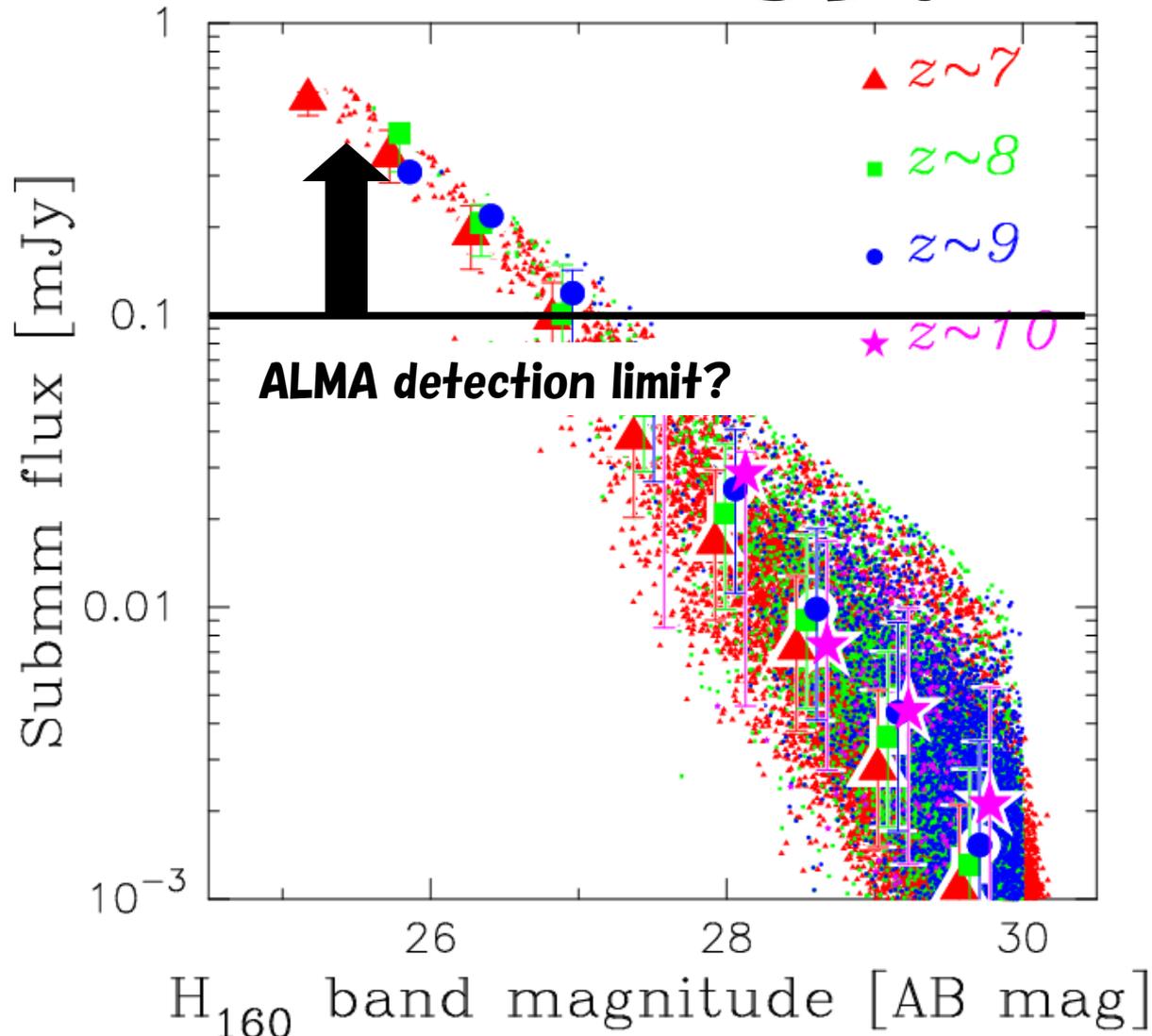
Halo mass と stellar mass の比 $f_* \Omega_b / \Omega_m \sim 0.01$ とすると、

$$SFR \sim (4.3_{z \sim 7}, 9.7_{z \sim 10}) \times 10^{-10} \left(\frac{M_*}{M_\odot} \right)^{1.094} M_\odot \text{ yr}^{-1}$$

$$sSFR \sim (0.43_{z \sim 7}, 0.97_{z \sim 10}) \left(\frac{M_*}{M_\odot} \right)^{0.094} \text{ Gyr}^{-1}$$

Discussion

Submm Flux at 350 GHz



●赤方偏移の依存性は弱い

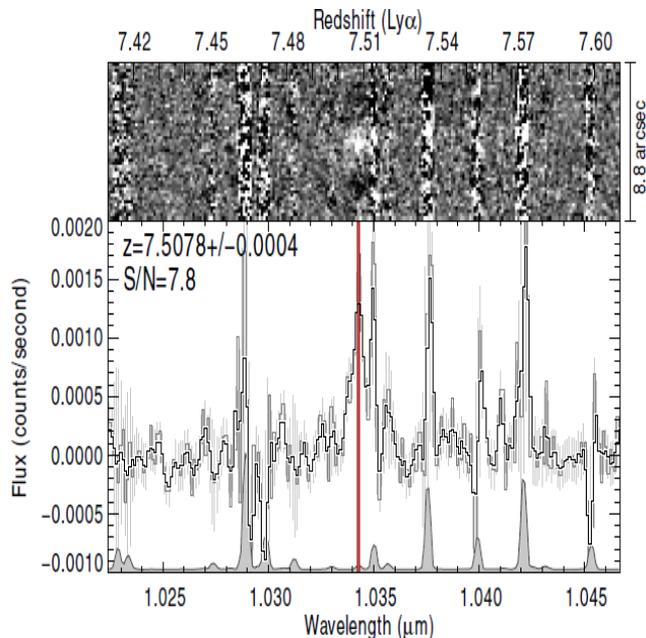
● $H_{160} < 27$ の銀河はサブミリフラックス > 0.1 mJy を期待できる

Spectroscopy using [OIII] Line

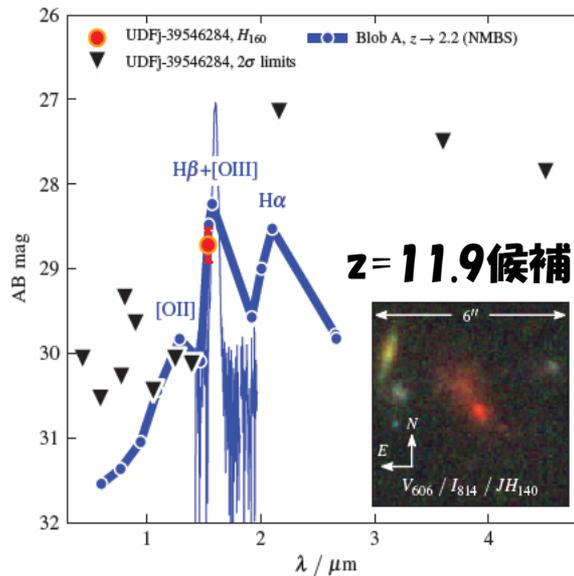
Spectroscopy of High- z Galaxies ($z > 8$)

$z = 8$ を超える銀河の分光観測 ($\text{Ly}\alpha$) は
いまだに成功例なし！！

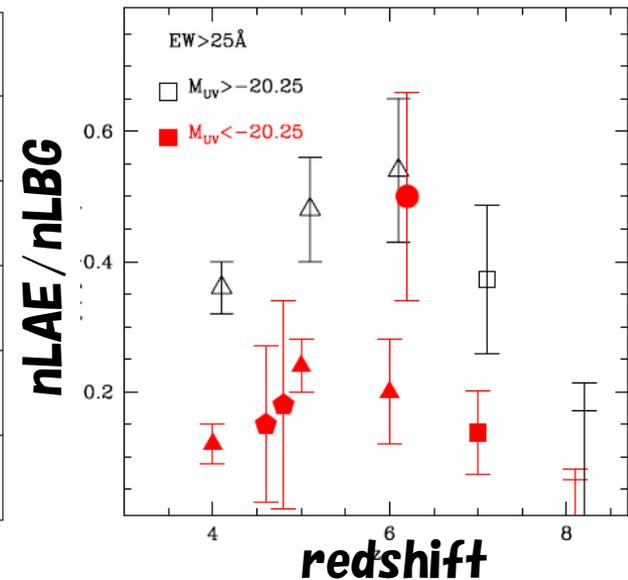
- ✓ Brammer et al., Bunker et al., Capak et al., Treu et al.
- ✓ $\text{Ly}\alpha$ 輝線がIGMによって強く吸収されている？



Finkelstein et al. 2013



Brammer et al. 2013



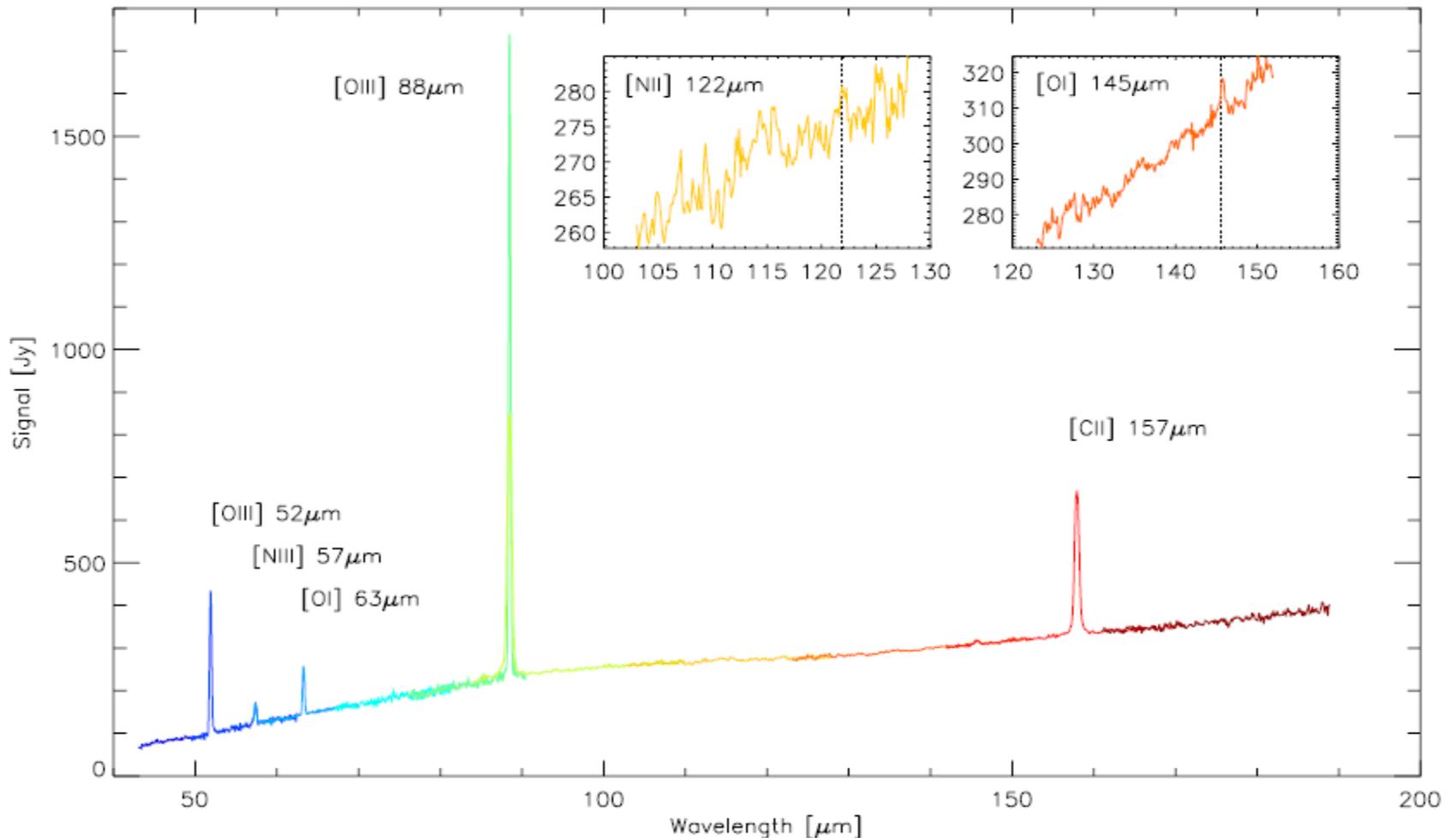
Treu et al. 2013

Alternative Nebular Emission Line

- $\text{Ly}\alpha$ 輝線が受からない \Rightarrow ほかの輝線の可能性
- ALMA observation ([CII] $157\ \mu\text{m}$)
 - ✓ Band 6: $211\sim 275\ \text{GHz}$ @ $z=5.9\sim 8.0$
 - ✓ Band 5: $163\sim 211\ \text{GHz}$ @ $z=8.0\sim 10.7$
 - ✓ 多くの high- z LAEs で [CII] 輝線が受かっていない
- [OIII] ($88\ \mu\text{m}$) line
 - ✓ Band 7: $275\sim 373\ \text{GHz}$ \rightarrow [OIII] ($88\ \mu\text{m}$) @ $z=8.0\sim 11.2!$
- Simple emitting mechanism of [OIII] ($88\ \mu\text{m}$) line
 - ✓ 大部分の [OIII] ($88\ \mu\text{m}$) は HII region から放出されている
 - ✓ [CII] ($157\ \mu\text{m}$) は HII region だけでなく PDR からも出ている
 - \Rightarrow [CII] ($157\ \mu\text{m}$) 輝線はより複雑な放射機構を考える必要がある

[OIII] (88 μm) emission line

HII region in LMC by Lebouteiller et al. 2012 using Hershel



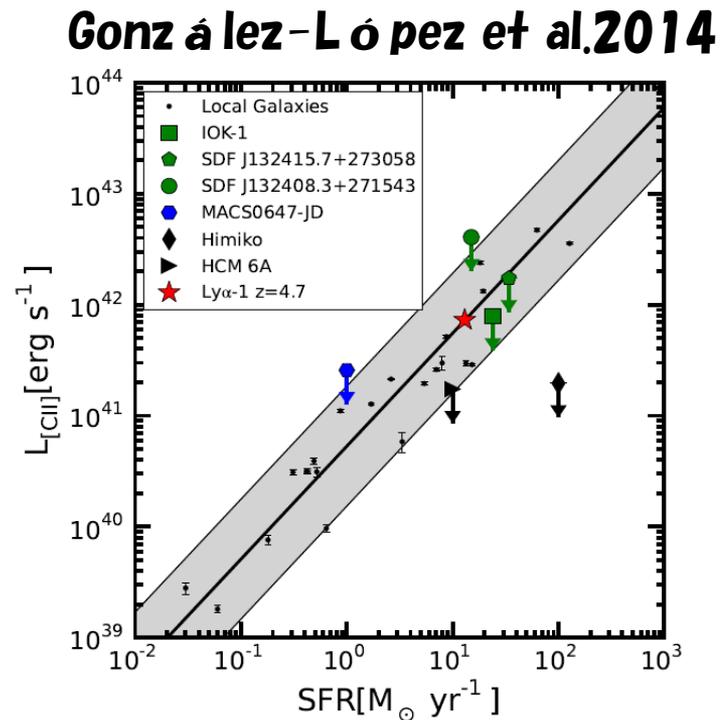
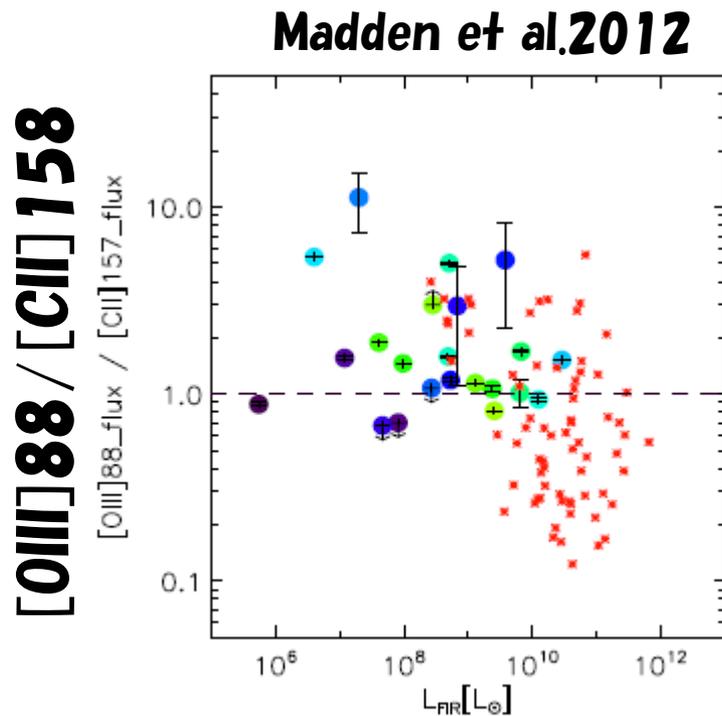
[OIII] Line in Low Metallicity Environment

● Herschel observation

✓ $[OIII]88 / [CII]158 = 1 \sim 10$ in low metallicity dwarf galaxies at local Universe

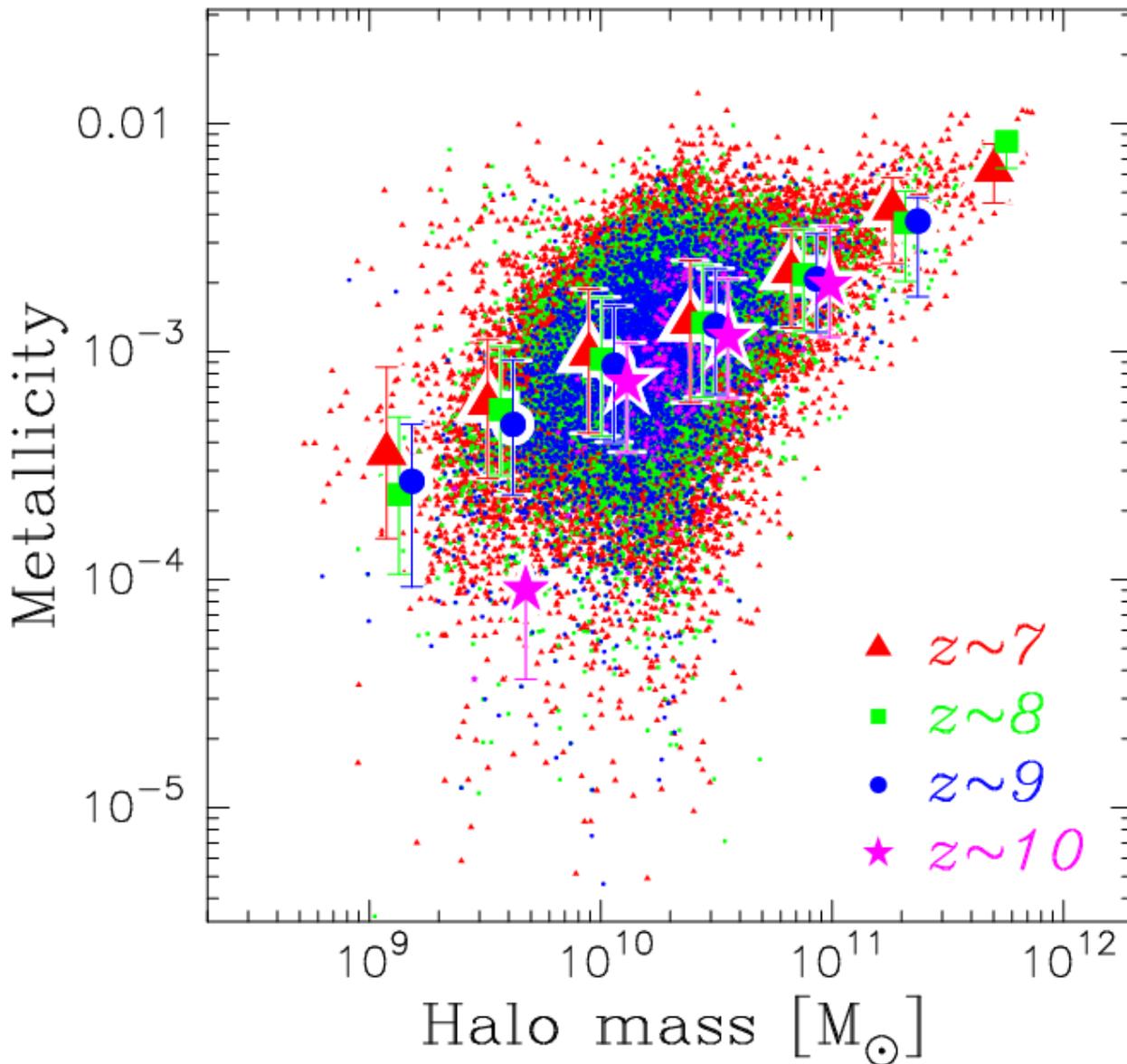
● ALMA observation

✓ Non-detection of [CII] ($158 \mu m$) line of many high-z LAEs



Nebular Metallicity

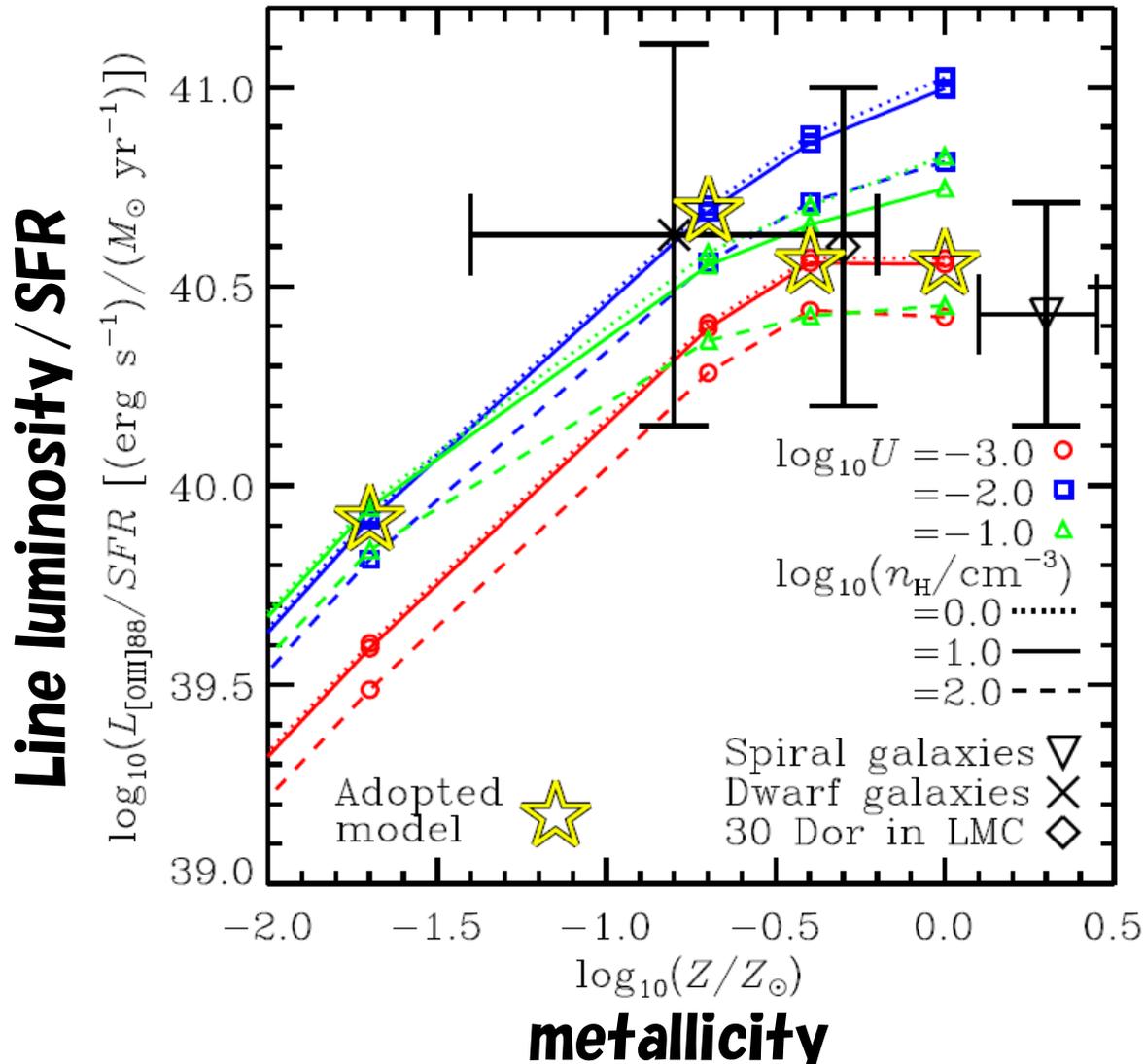
● **New definition for the metallicity of simulated galaxies**



$$Z_{\text{neb}} = \frac{\sum_i Z_i L_i^{\text{LyC}}}{\sum_i L_i^{\text{LyC}}}$$

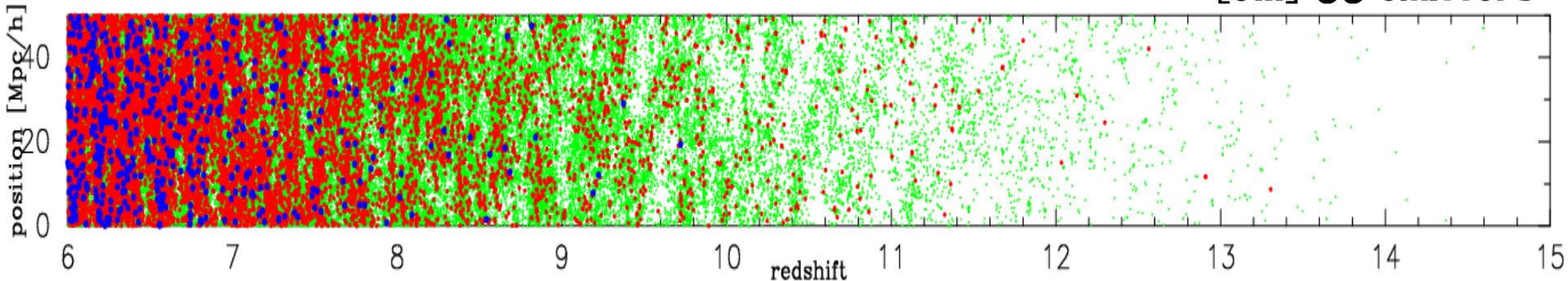
[OIII] Emission Line Model

Cloudy c13.00 (Ferland et al.2013)

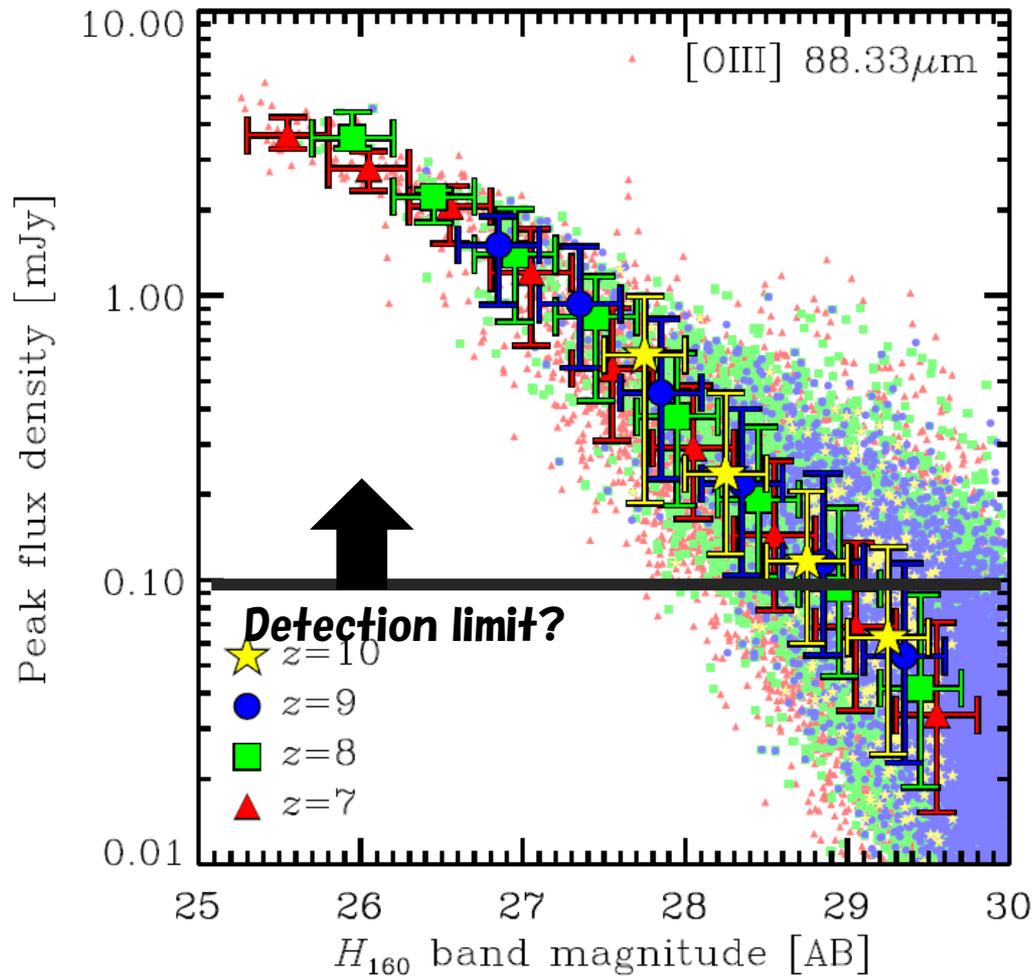


[OIII] (88 μ m) Emitting Galaxies in Light-Cone

● 0.01 mJy ~ 0.1 mJy ● 0.1 mJy ~ 1 mJy ● 1 mJy ~ 10 mJy [OIII] 88 emitters



OIII (88 μ m) flux density $z > 7$



- WISH は [OIII] emitter @ $z > 8$ を探し出すには非常に有用
- 期待値 : 1850 / deg² ($z \sim 8$), 495 / deg² ($z \sim 9$), 35 / deg² ($z \sim 10$)
- CLASH survey (重力レンズ) もねらい目s

Summary

UDF12 galaxy の物理的特徴

- ✓ ハロー質量 (星質量) : $10^9 \sim 10^{12}$ ($10^7 \sim 10^{10}$) M_{sun}
- ✓ UV 光度はハロー質量 (星質量) とほぼ比例関係
- ✓ UV 光度の質量依存性は $z \sim 10$ から $z \sim 7$ までほぼ無進化
- ✓ $z \sim 10$ においても $Z \sim 0.1 Z_{\text{sun}}$ 程度の物がある
⇒ 重元素汚染の進化は早い
- ✓ SFR と sSFR はほぼダークマターの降着率で説明できる
(シミュレーションと簡単な見積もりのずれはバリオン物理の重要性も示唆)
- ✓ $H_{160} < 27$ でサブミリワックス > 0.1 mJy
- ✓ [OIII] (88 μm) 輝線は、ALMA を用いた $z = 8$ を超えるような銀河の分光観測に有用 $\leftarrow H_{160} < 27$ で $f_{[\text{OIII}]} > 1$ mJy

Appendix

Dust Attenuation

- **Optical depth at 1500 Å**

$$\tau_d = \frac{3\Sigma_d}{4a_d s}$$

a_d : typical size of dust grains
 s : material density of dust grains

- **Dust surface mass density**

$$\Sigma_d = \frac{M_d}{\pi r_d^2}$$

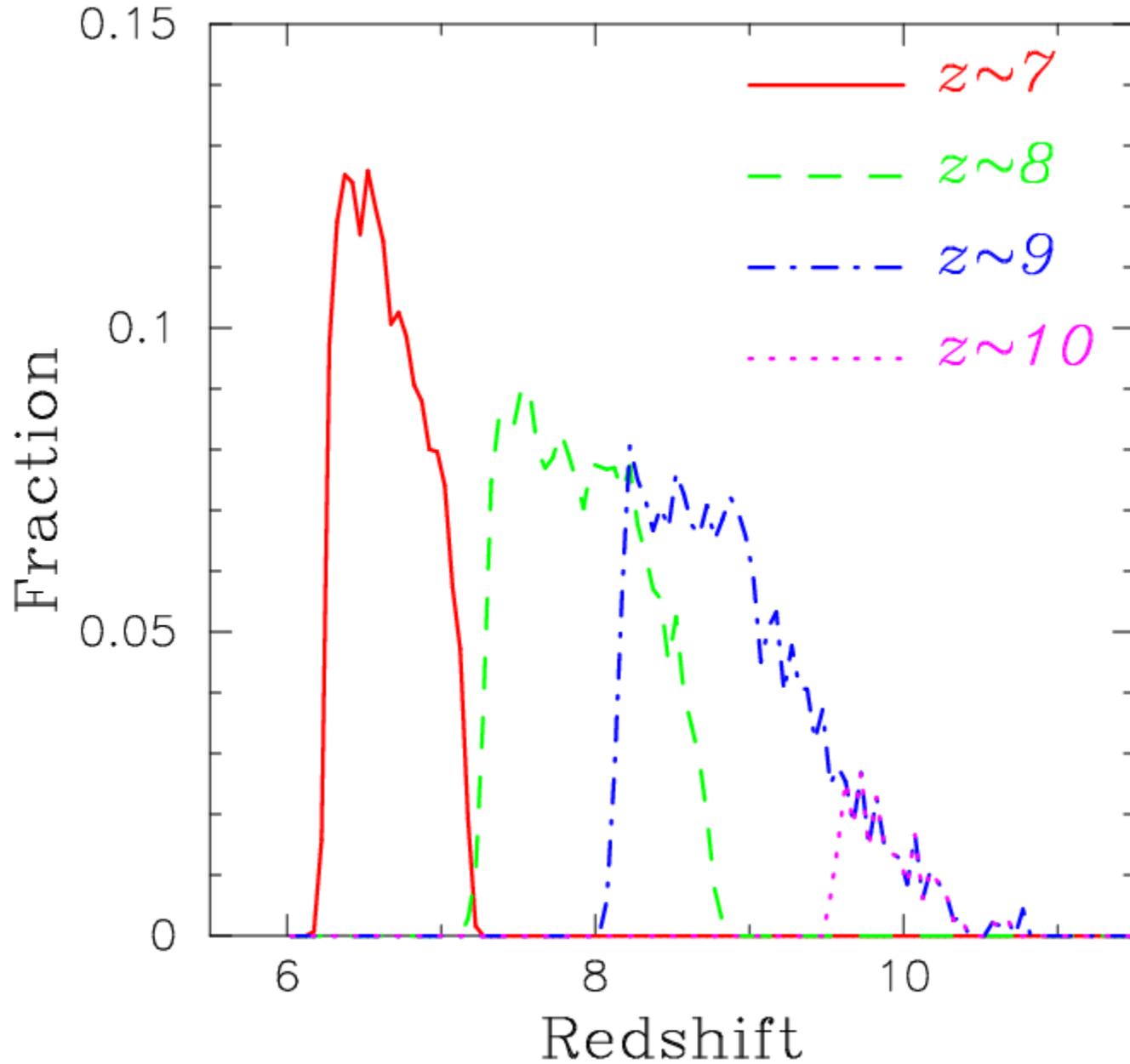
M_d : dust mass
 r_d : effective radius of the dust

- **Escape probability of UV photons at 1500 Å**

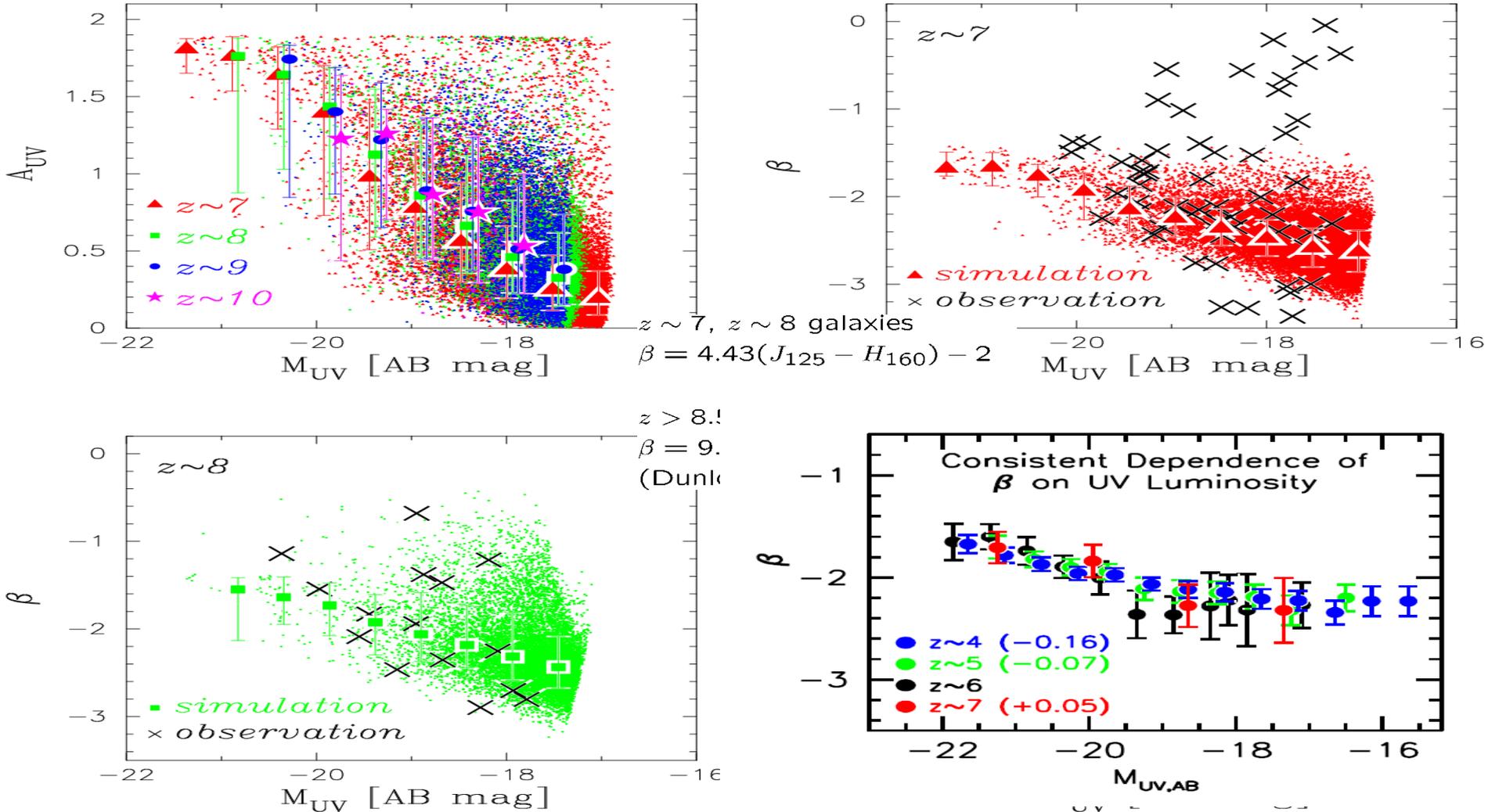
$$f_{UV} = \frac{1-\delta}{2}(1 + e^{-\tau_d}) + \frac{\delta}{\tau_d}(1 - e^{-\tau_d})$$

サンドウィッチモデル ($\delta = 1$ スラブモデル)

Color Selection Efficiency

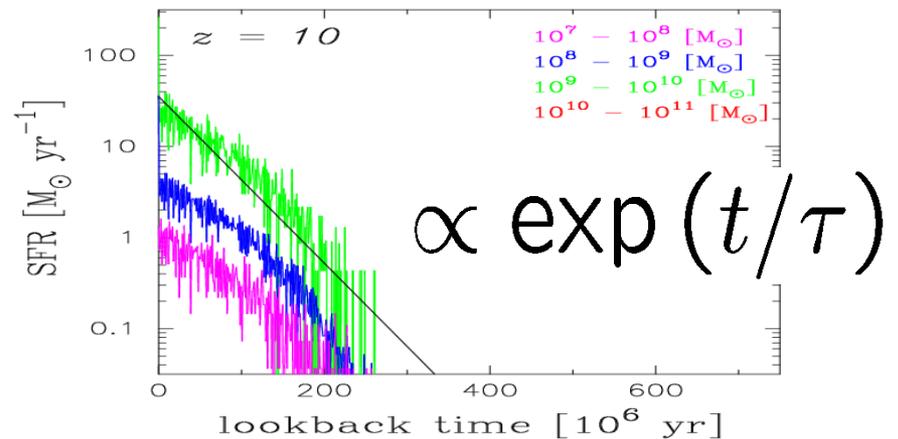
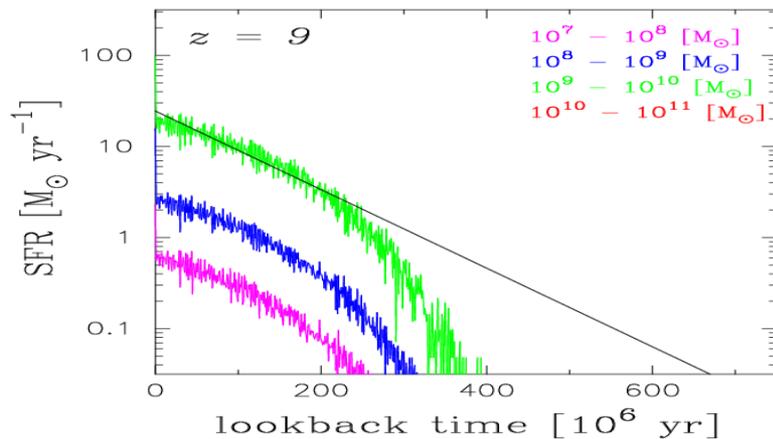
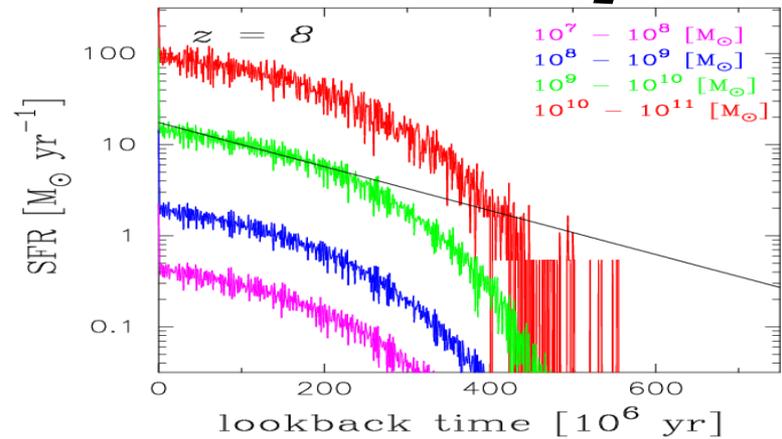
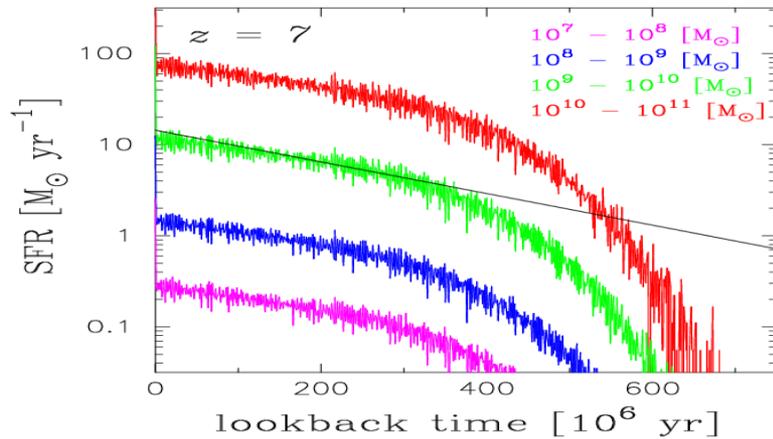


Dust Attenuation



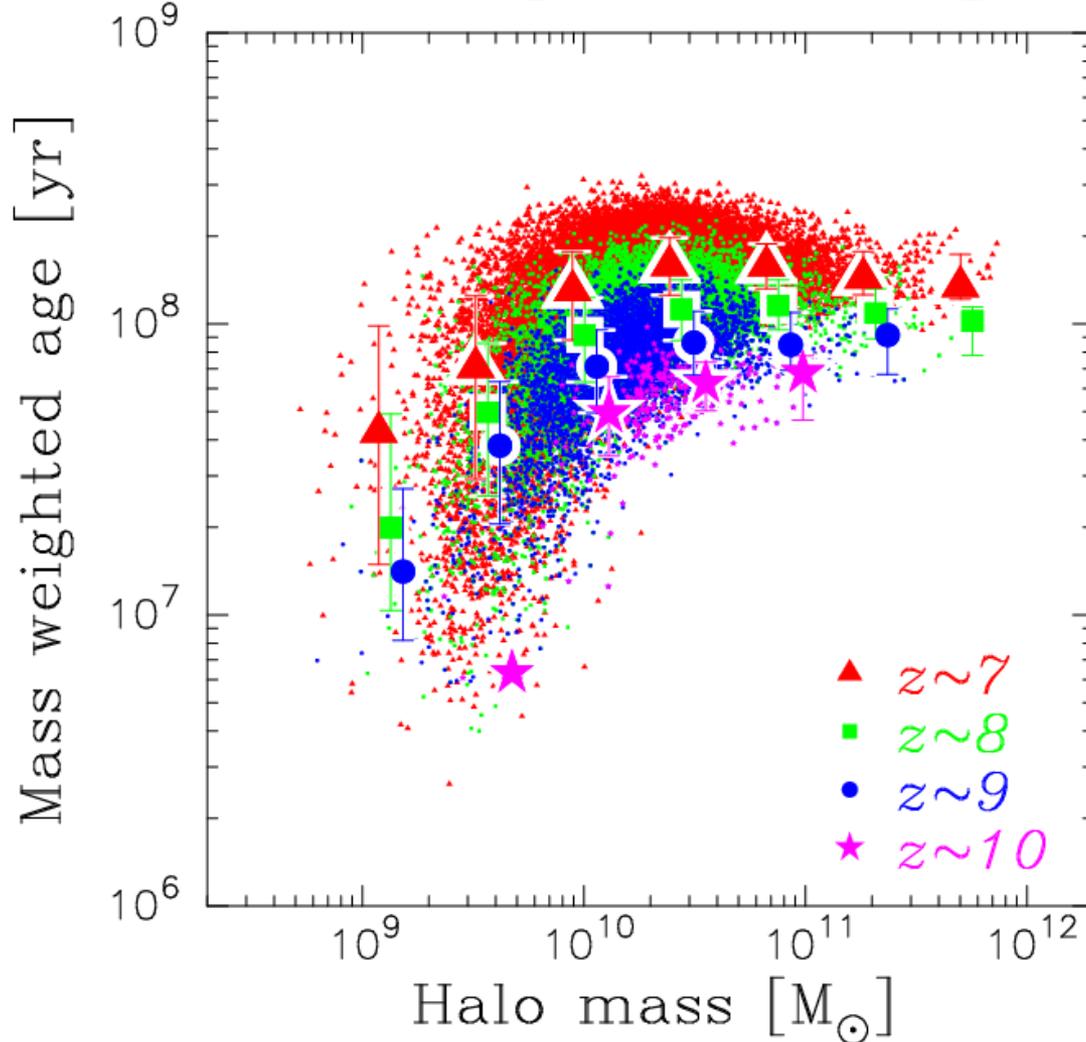
- Dust attenuation (A_{UV}) is proportional to the UV luminosity.
- UV slope β also is proportional to the UV luminosity.
- UV slope of simulated galaxies is similar to observations.

Star Formation History



- The SFR clearly increases with time.
- It is strongly preferable to choose increasing SFR with the time (e.g., exponentially increasing) for the SED fitting method.
- Typical star formation time scales are **250 Myr** ($z \sim 7$), **180 Myr** ($z \sim 8$), **100 Myr** ($z \sim 9$) and **50 Myr** ($z \sim 10$).

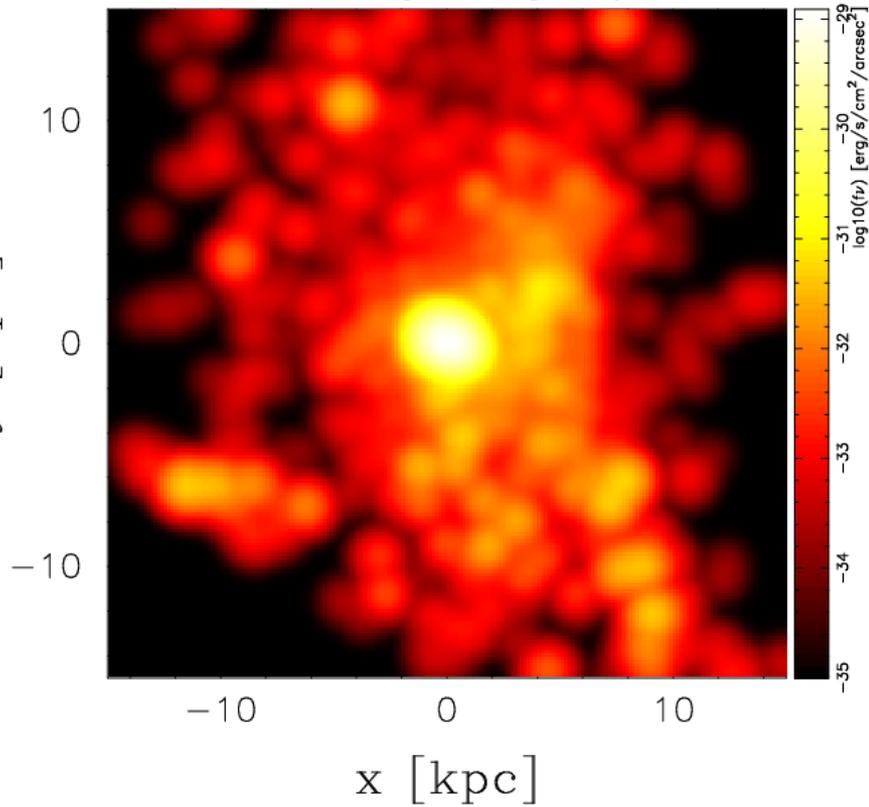
Mass Weighted Age



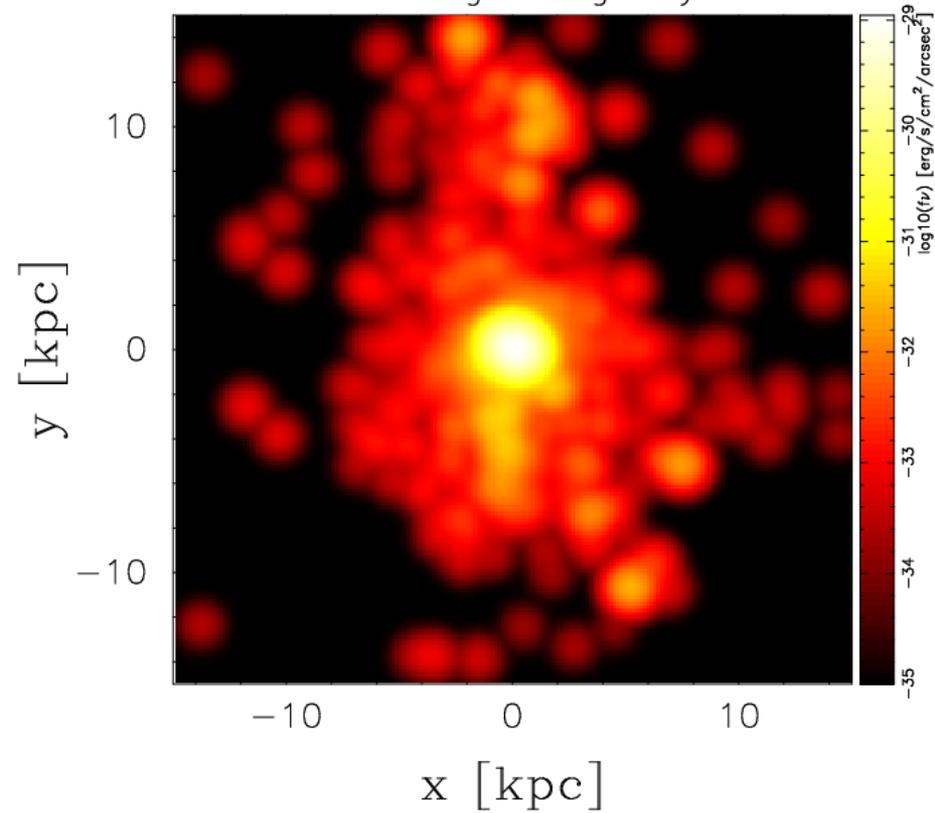
- Typical ages are **200 Myr** ($z \sim 7$), **130 Myr** ($z \sim 8$), **80 Myr** ($z \sim 9$) and **50 Myr** ($z \sim 10$).
- The values are similar to the typical star formation time scale.

Luminosity map of *brightest galaxy*

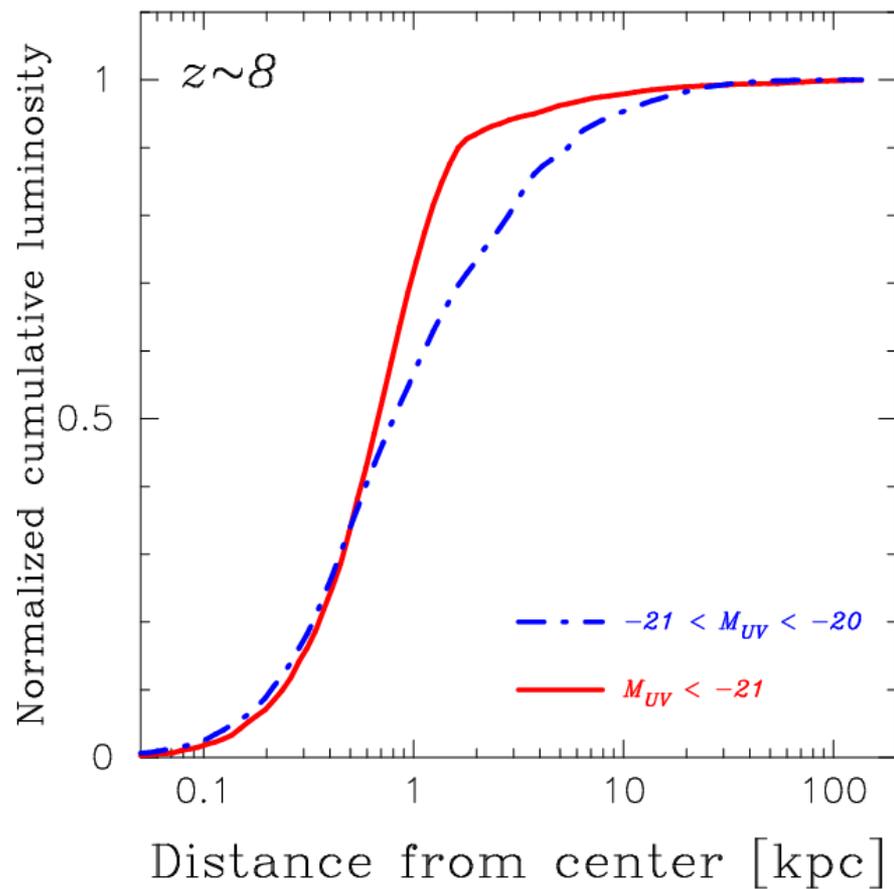
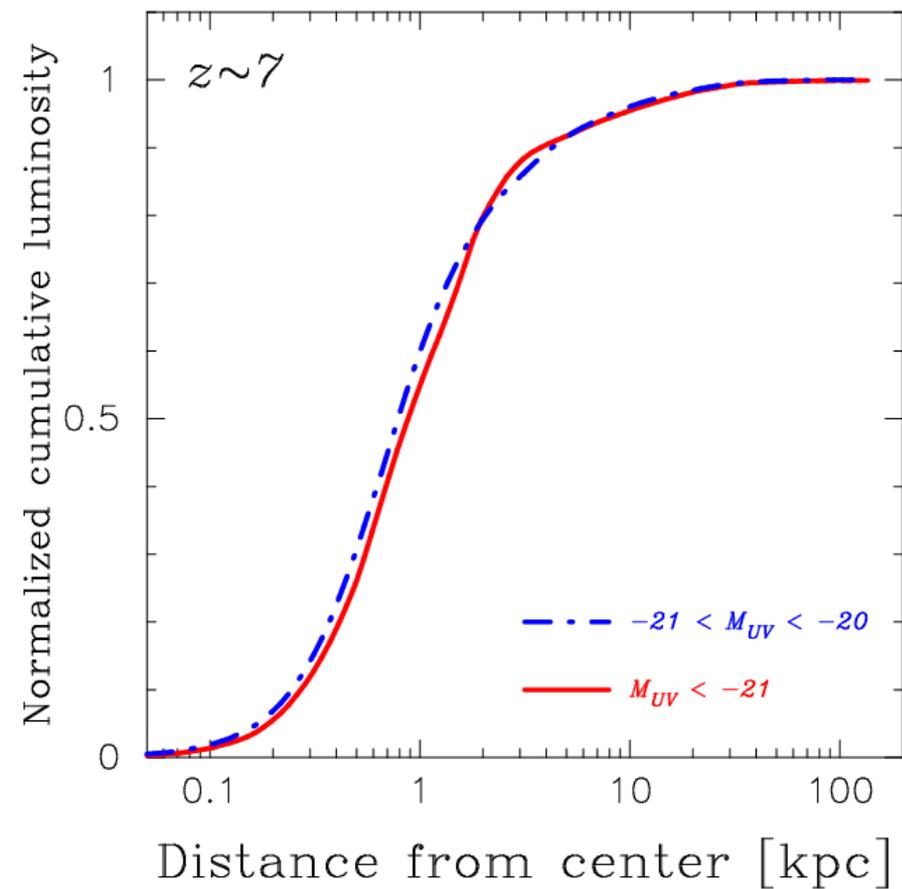
$z \sim 7$ brightest galaxy



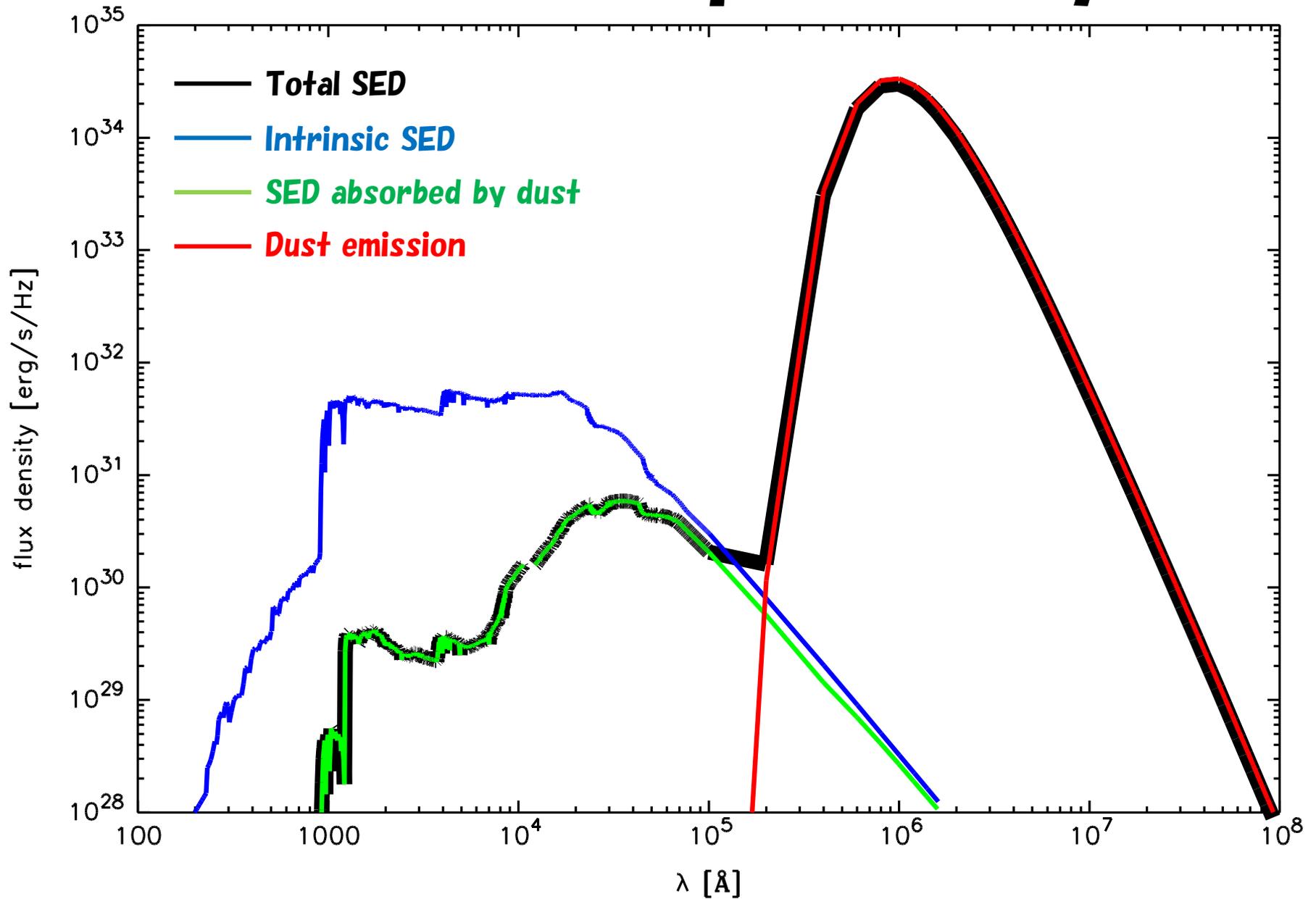
$z \sim 8$ brightest galaxy



Luminosity profiles (stacked image)



SEDs of Sample Galaxy



Calculation Submm flux

● Assumption

- All photons absorbed by dust re-emit as FIR photons.
- Photons source of SMGs is only SF activity.
- 50% metal mass convert to dust mass

● FIR flux

$$L_{\nu} = 4\pi M_{\text{dust}} \kappa_{\nu} B_{\nu}(T_{\text{dust}})$$

● Dust temperature

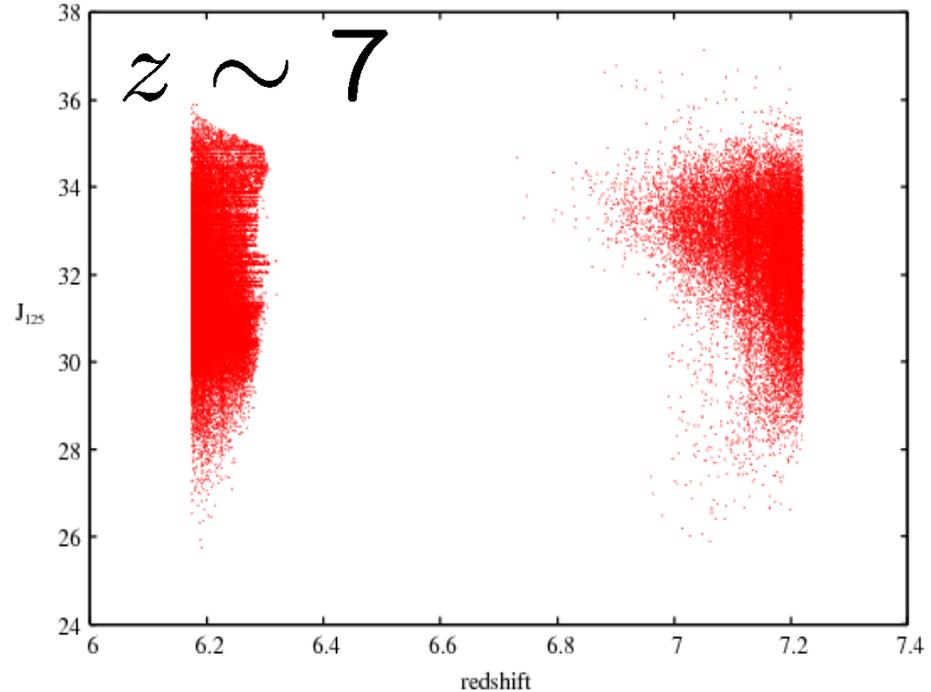
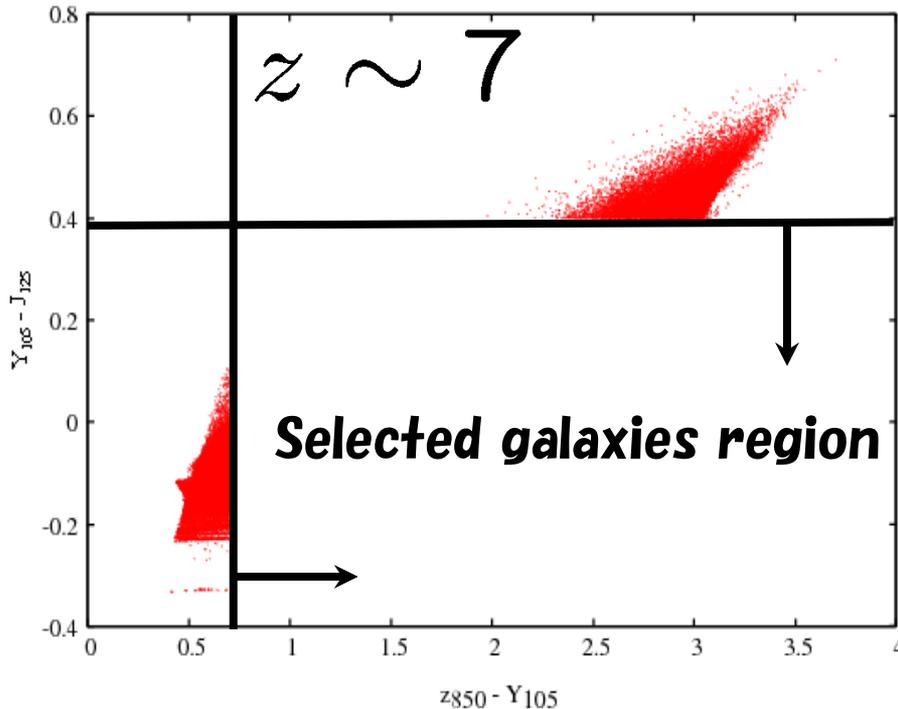
$$T_{\text{dust}} = \alpha \left(\frac{L_{\text{FIR}}/L_{\odot}}{M_{\text{dust}}/M_{\odot}} \right)^{1/(4+\beta)}$$

● Observed flux

$$f_{\nu} = \frac{(1+z)L_{\nu}(1+z)}{4\pi d_L^2}$$

Selected and Unselected galaxies

What kind of galaxies does not satisfy the color selection conditions?



- All the galaxies reside around the redshift boundaries defined by the color selection.
- There are no galaxies around middle of the redshift ranges.
- The deviation from color selection criteria of the simulated galaxies is less than 0.4 mag.
- There is no galaxy with a very red UV color.

Selected and Unselected galaxies

本研究では、4つの銀河の可能性がある。

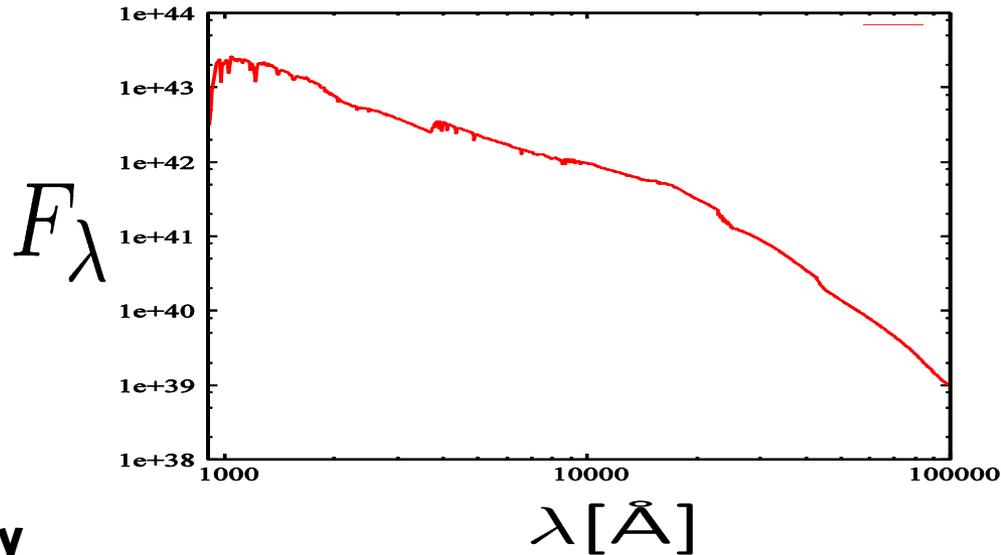
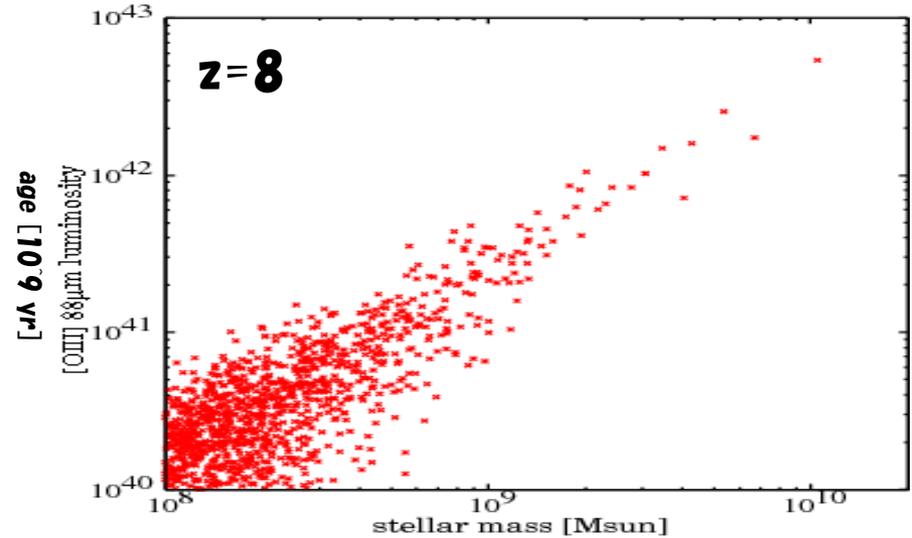
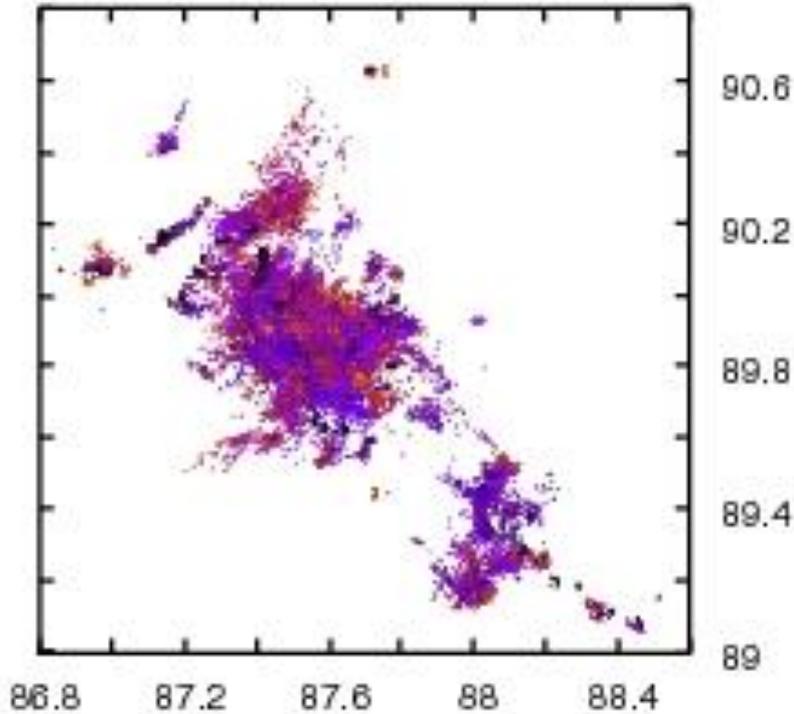
- (1) Color selection criteria を満たす + 観測しうるぐらい十分に明るい
- (2) Color selection criteria を満たす + 暗くて観測できない
- (3) Color selection criteria を満たさない + 観測しうるぐらい十分に明るい
- (4) Color selection criteria を満たさない + 暗くて観測できない

それぞれの銀河の star formation density (SFRD) への寄与は？

fraction	redshift	case (1)	case (2)	case (3)	case (4)
P_{SFRD}	$z \sim 7$	0.517 (0.774)	0.347 (0.089)	0.086 (0.122)	0.051 (0.015)
	$z \sim 8$	0.388 (0.749)	0.460 (0.098)	0.071 (0.138)	0.081 (0.015)
	$z \sim 9$	0.295 (0.793)	0.646 (0.149)	0.019 (0.055)	0.039 (0.003)
	$z \sim 10$	0.122 (0.723)	0.825 (0.224)	0.008 (0.047)	0.045 (0.006)

- Color criteria を満たす銀河 (cases [1]+[2]) の寄与は、84~95%
- 多くの銀河は、暗すぎて現在の観測機器では観測できていない

Calculation of OIII line



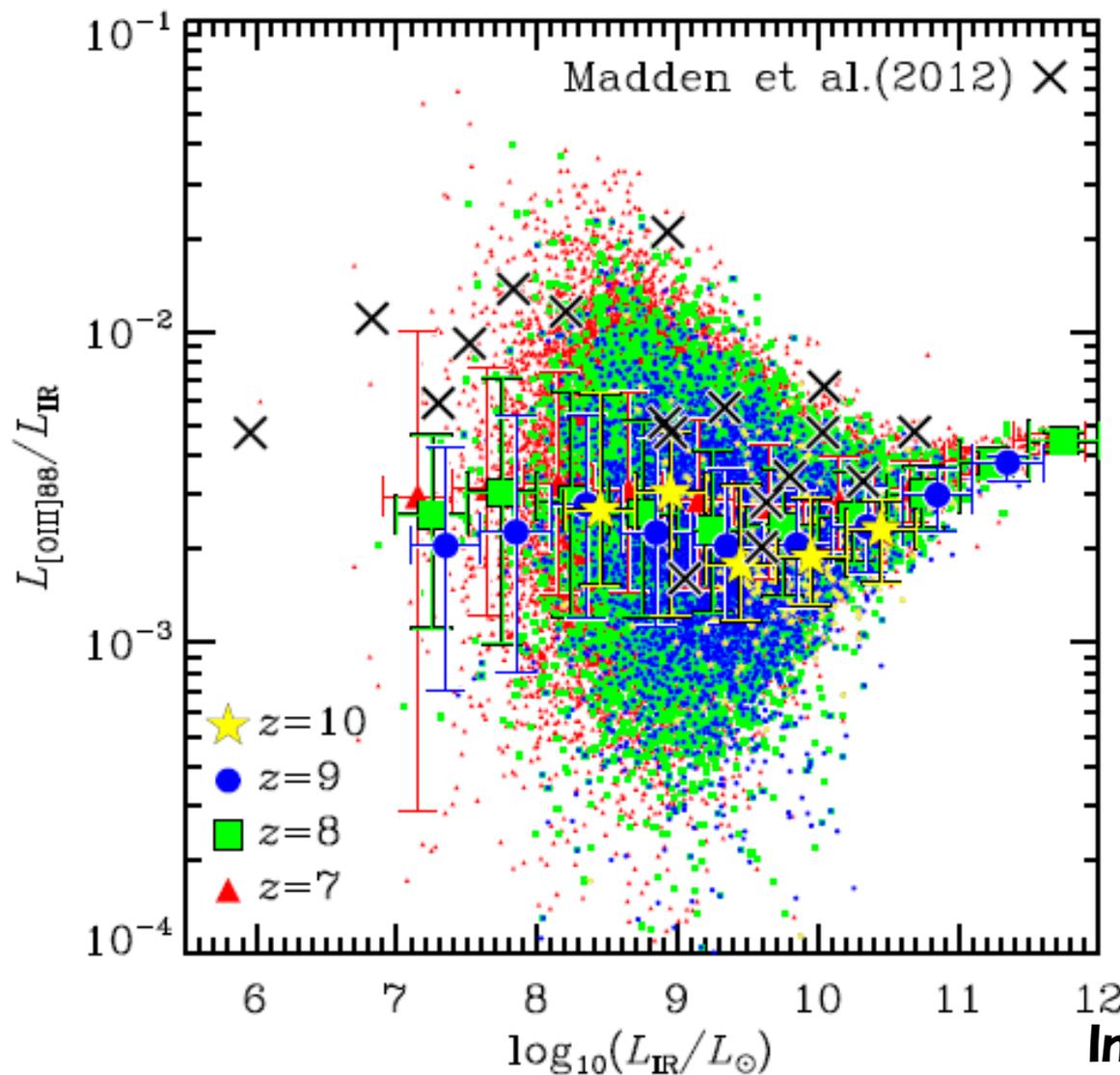
Each star particle has,,

- Formation time (age)
- Metallicity
- Mass

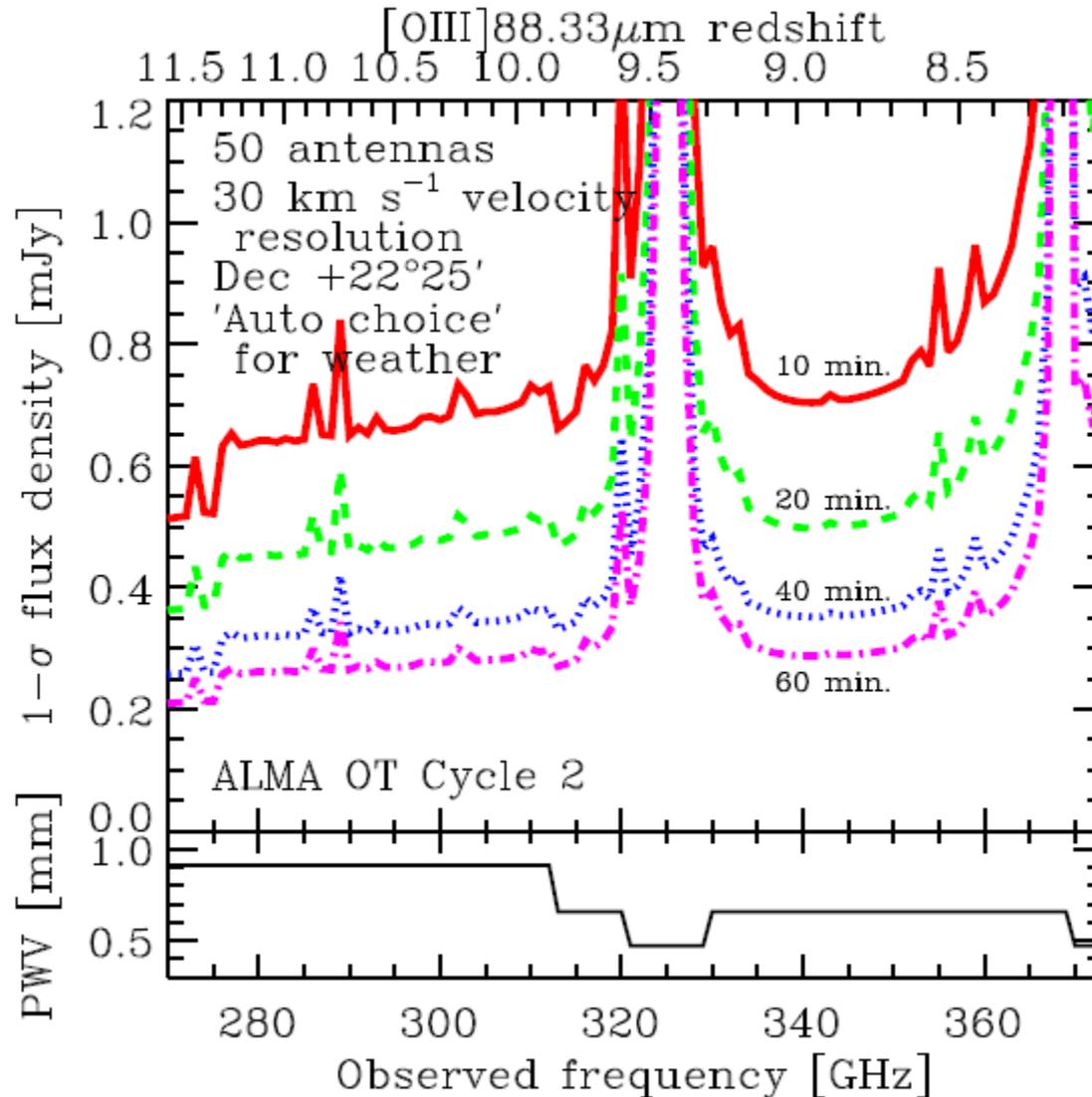
SED (continuum + line) of a galaxy

= summation each star particle (each particle has different age).

Ratio between [OIII] Luminosity and Far-Infrared Luminosity



MACS1149-JD予想[OIII]強度



Line emissivities per unit star formation rate

Z/Z_{\odot}	$\log_{10} U$	[S IV]	[Ne II]	[Ne III]	[S III]	[S III]	[Ne III]	[O III]	[N III]	[O III]	[N II]	[N II]
		10.51	12.81	15.55	18.67	33.47	36.01	51.80	57.21	88.33	121.7	205.4
1.0	-3.0	38.87	40.01	40.00	40.32	40.72	38.95	40.32	40.14	40.56	39.81	39.82
0.4	-3.0	39.09	39.50	40.07	40.10	40.46	39.02	40.33	39.70	40.56	39.04	39.07
0.2	-2.0	40.12	38.38	40.02	39.86	40.20	38.97	40.46	39.52	40.69	37.67	37.72
0.02	-2.0	39.39	37.43	39.25	39.05	39.36	38.20	39.69	38.74	39.91	36.79	36.85
5×10^{-4}	-2.0	38.07	35.58	37.75	37.42	37.73	36.71	38.18	37.14	38.41	35.25	35.31
5×10^{-6}	-2.0	36.22	33.60	35.85	35.47	35.78	34.81	36.29	35.19	36.52	33.36	33.42