“The Mass Assembly and Color Evolution of the Milky way-like Galaxies at z~0.5-3.0”

○Takahiro Morishita[1,2]

(The Astrophysical Journal, 805,34, 2015)

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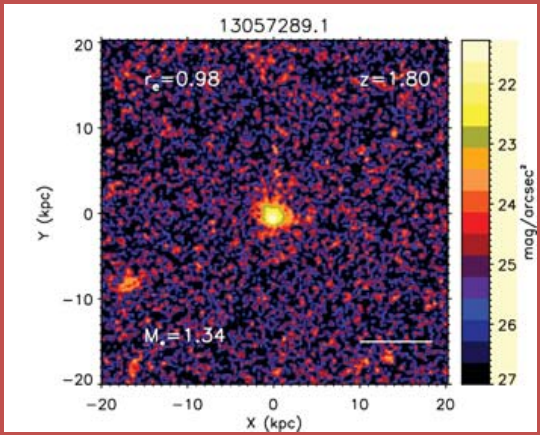
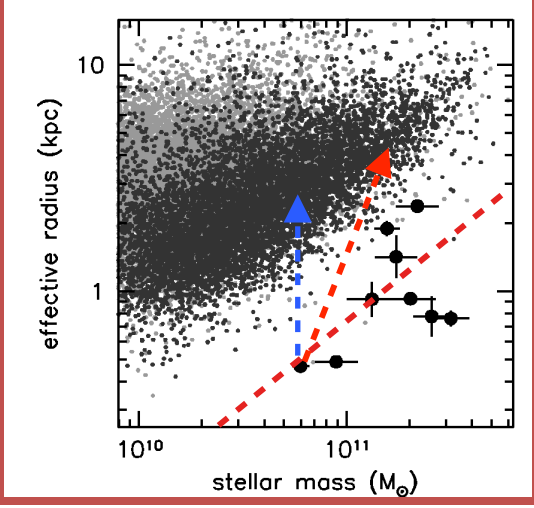
Background : Where did we live?

External - Extragalactic study at z<3-4

Red nuggets:

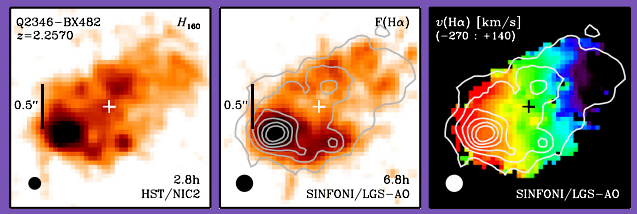
Massive (M_*~$10^{11}M_{sun}$), but small (r_e~1kpc). Dispersion dominated (σ~300-400km/s).

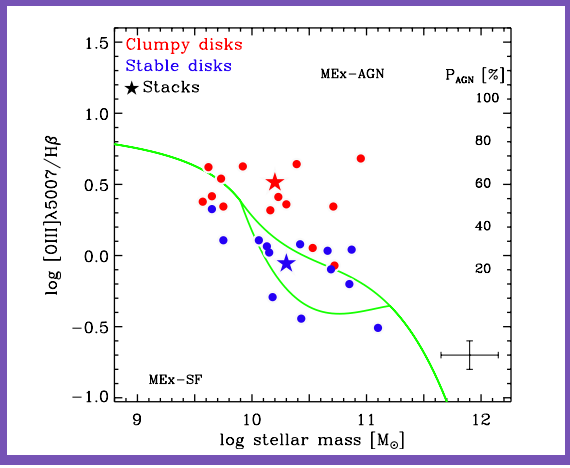




Clumpy galaxies:

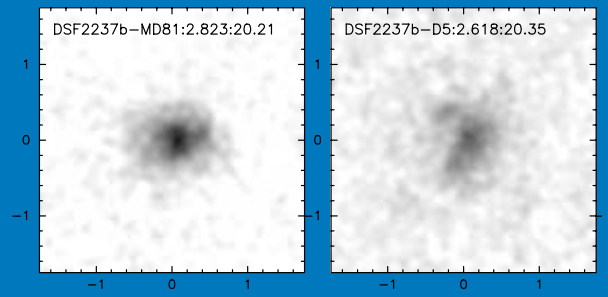
Massive (M_*~$10^{10\text{-}11}M_{sun}$).
Significant star-formation activity.
Rotation supported?





LBGs:

Less massive (M_*~$10^{9\text{-}10}M_{sun}$), not so small (~2-5kpc).
Star-formation activity. Disk feature?



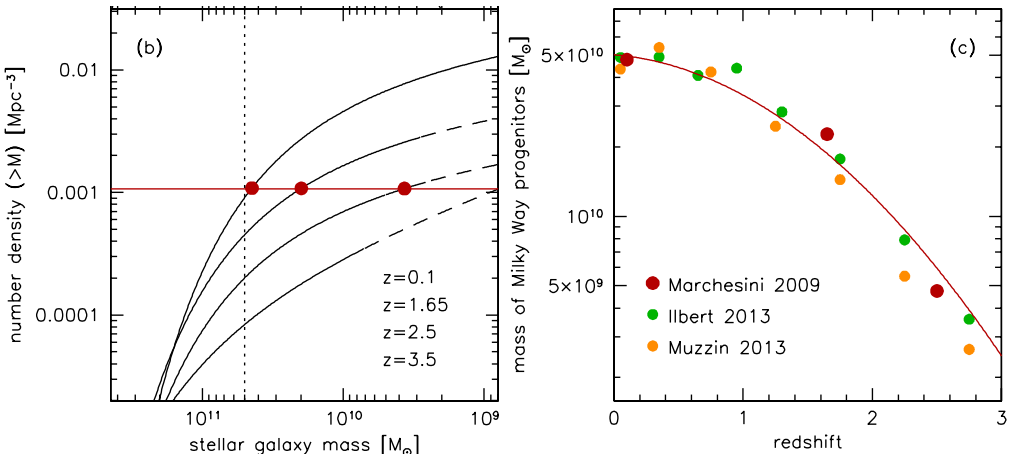
LAEs:

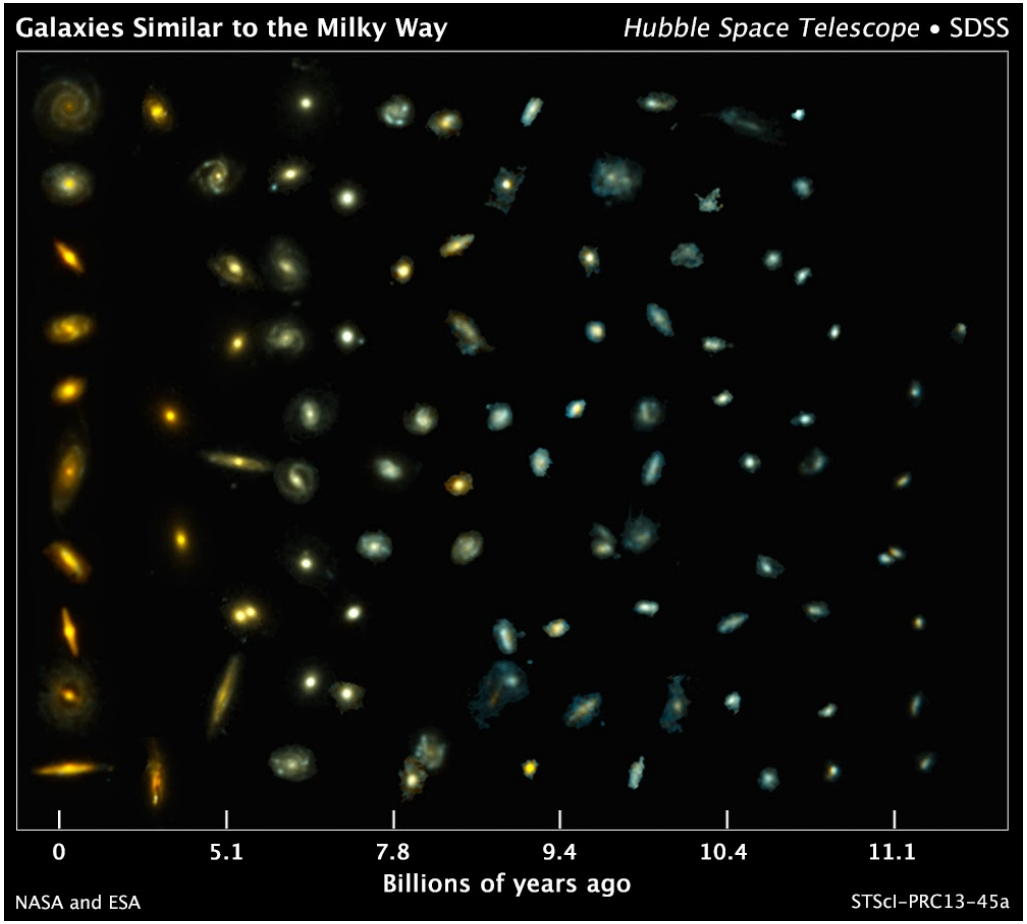
?

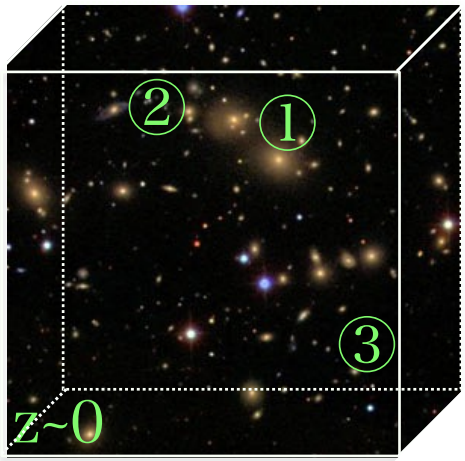
Trujillo+07,MNRAS; van Dokkum+08,ApJL; Guo+15,ApJ; Forster-Schreiber+11,ApJ; Bournaud+12,ApJ; Akiyama+08,ApJS

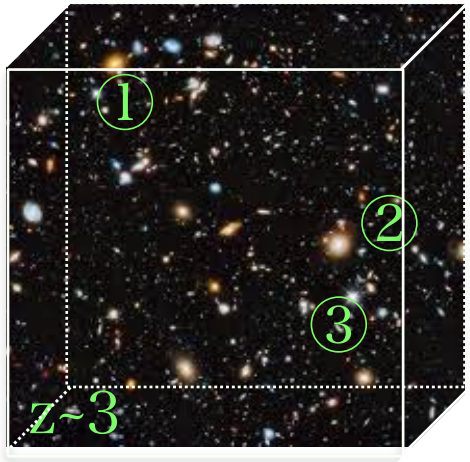
Background : Where did we live?

External - Extragalactic study of progenitors





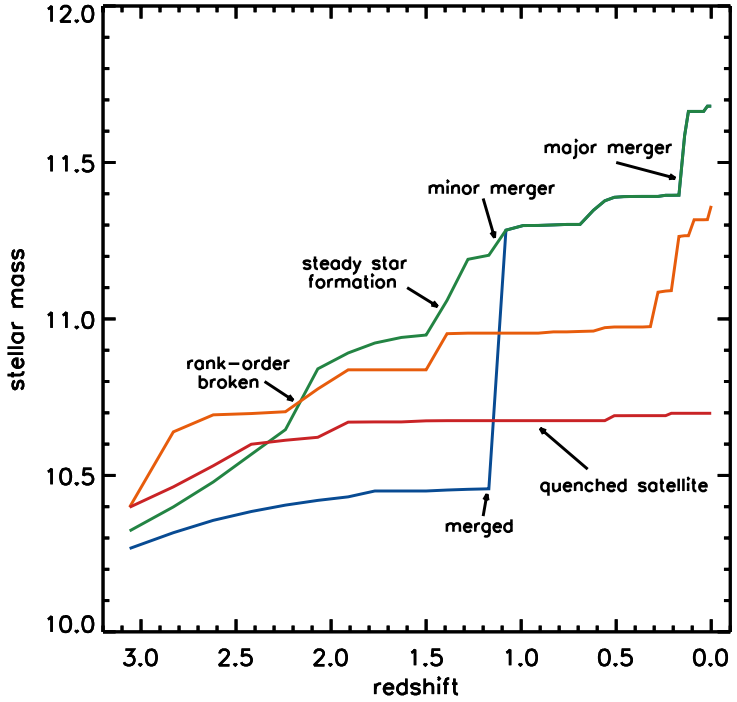


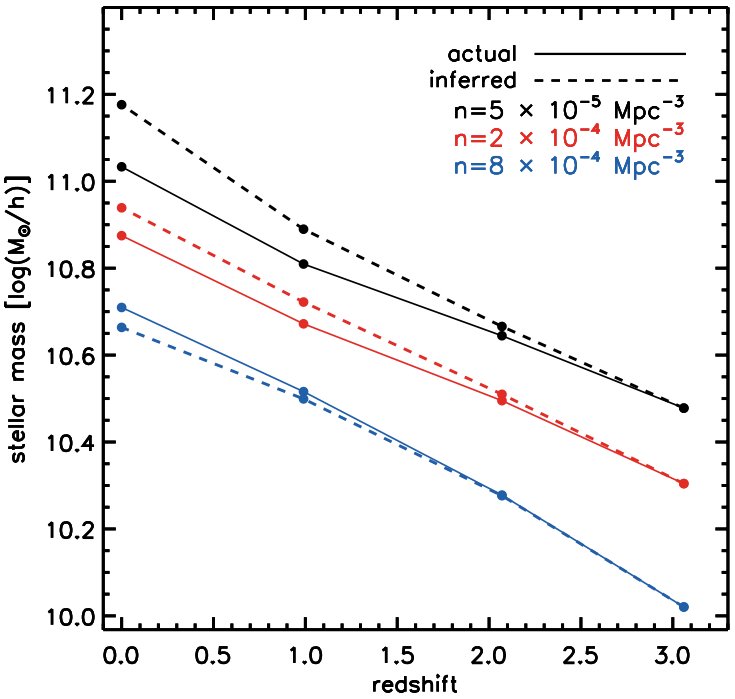


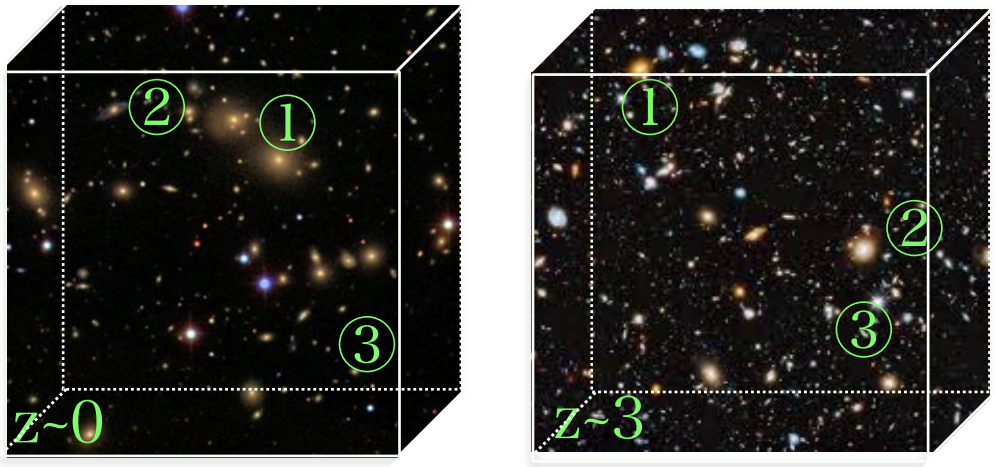
van Dokkum+10,13,ApJ; Patel+13,ApJ; Marchesini+14,ApJ; Leja+13,ApJ

Background : Where did we live?

External - Extragalactic study of progenitors





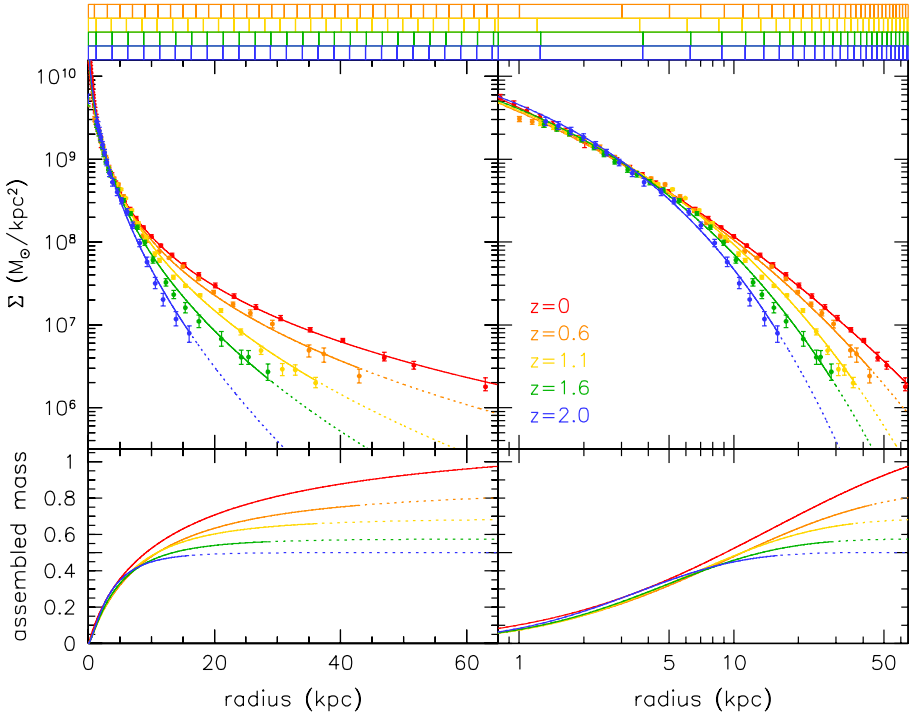


あとで話しましょう

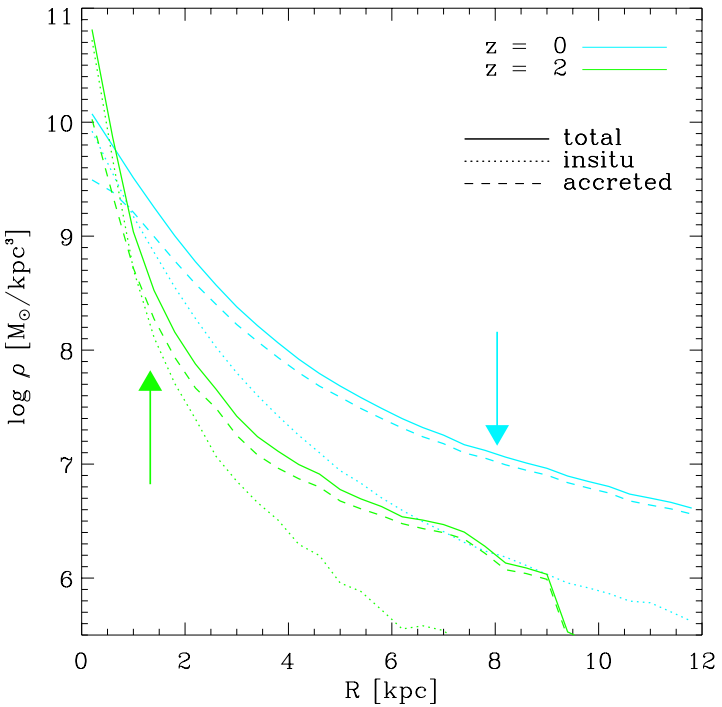
van Dokkum+10,13,ApJ; Patel+13,ApJ; Marchesini+14,ApJ; Leja+13,ApJ

Background : Where did we live?

External - Extragalactic study of progenitors



Oser+12



- Massive galaxies ($\log M_{z\sim0} \sim 11.5$)
- Inside-out growth;
  - Bulge forms rapidly,
  - and then accretion on outer part
- Two-phase evolution.

Numerous minor mergers
(collapsed at early time)
> Rare major merger

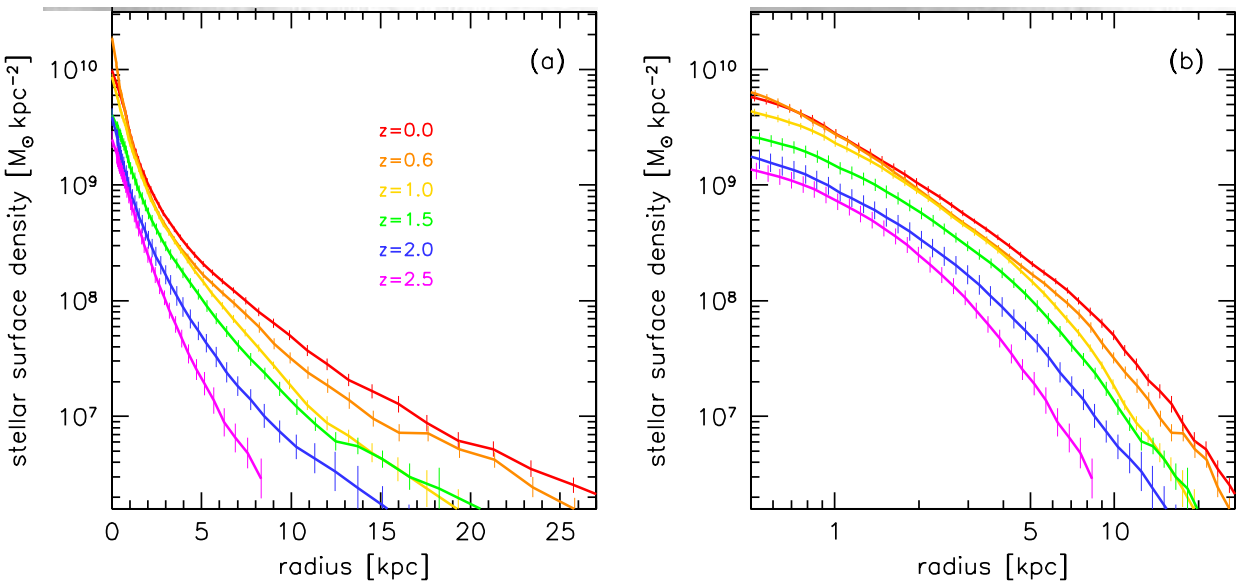
van Dokkum+10,ApJ; Oser+10,+12,ApJ; Marchesini+14,ApJ

Background : Where did we live?

External - Extragalactic study of progenitors

?

van Dokkum+13



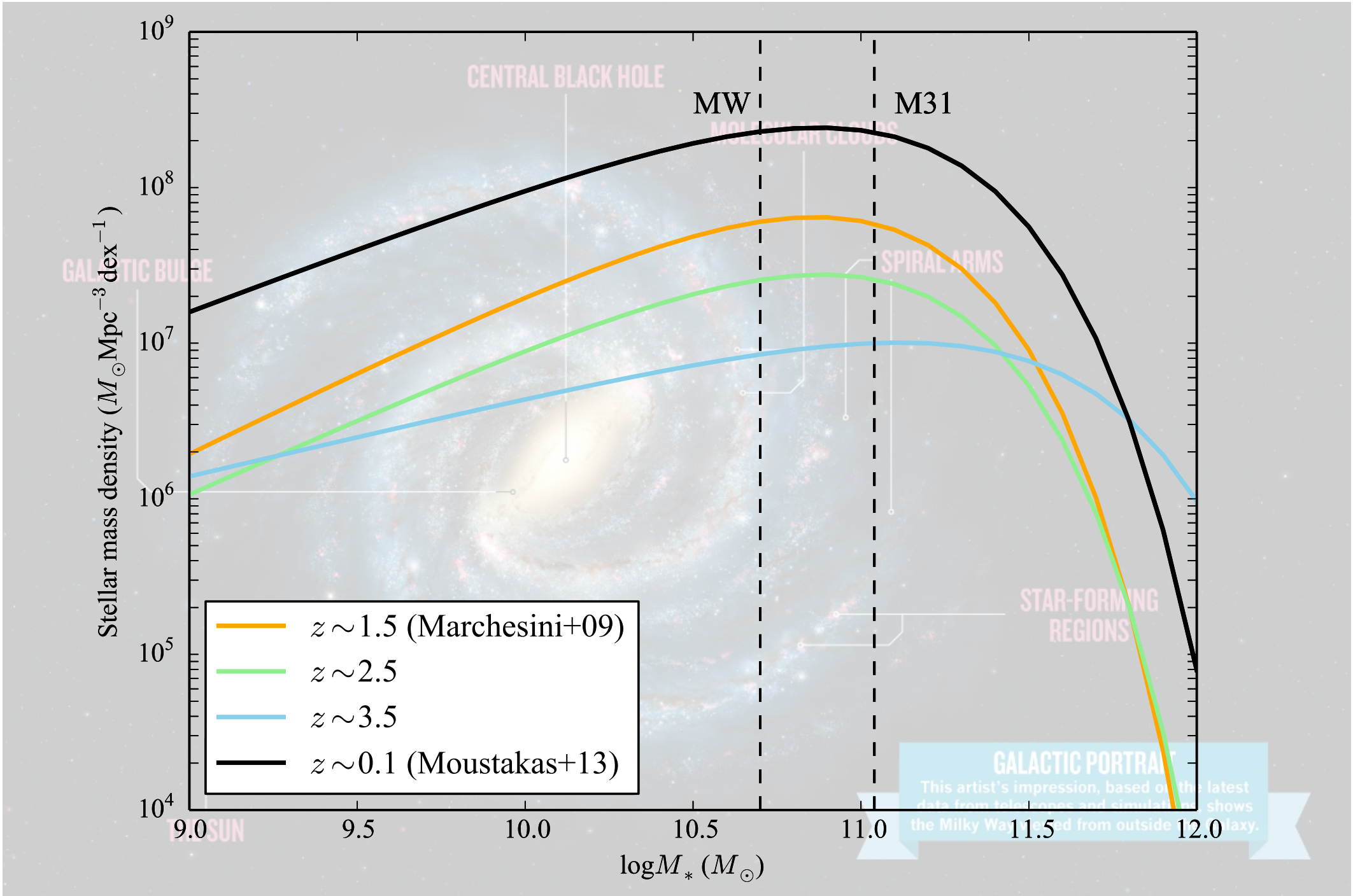
- Milky way-size galaxies ($\log M_{z\sim0} \sim 10.7$)
- Self-similar growth (z~3 to ~0.6)

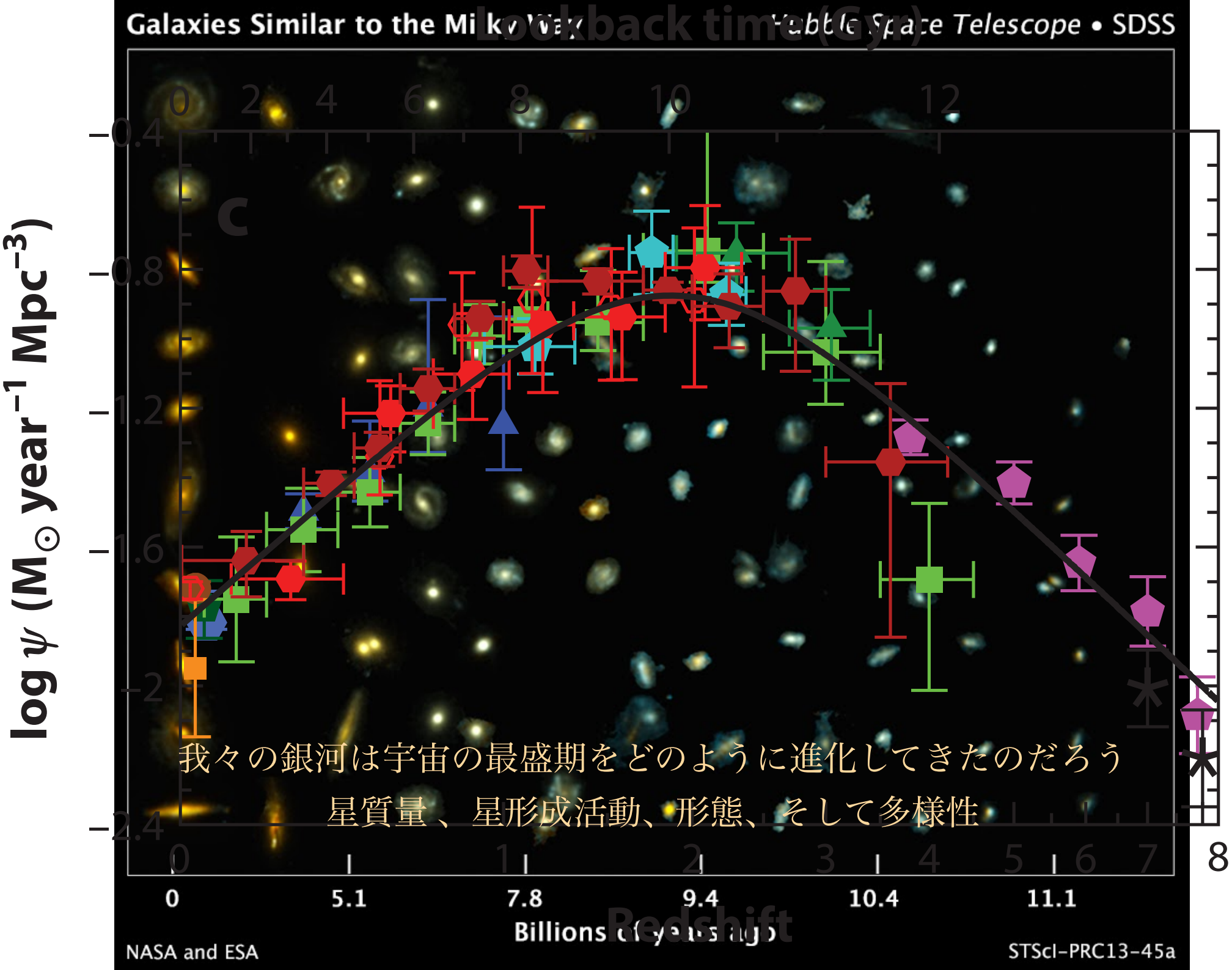
Inside-out (disk) growth?

(Larson 76; Haywood+13, and more.)

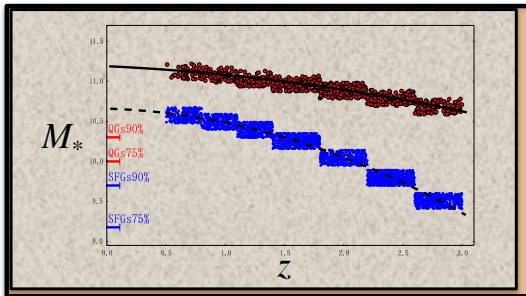
van Dokkum+13,ApJ; Patel+13,ApJ, and This work!

Background : Where do we live?



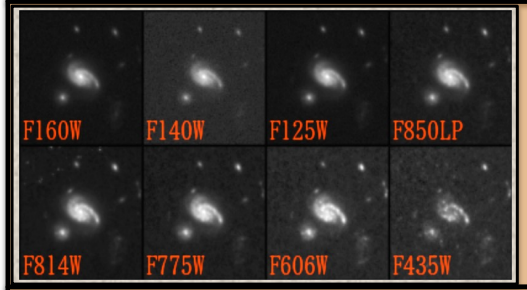

Galaxies Similar to the Milky Way
Hubble Space Telescope • SDSS
Lookback time (Gyr)
0
2
4
6
8
10
12
c
0.4
0.8
1.2
1.6
2
2.4
log ψ (M⊙ year⁻¹ Mpc⁻³)
我々の銀河は宇宙の最盛期をどのように進化してきたのだろう
星質量、星形成活動、形態、そして多様性
0
1
2
3
4
5
6
7
8
0
5.1
7.8
9.4
10.4
11.1
Redshift
Billions of years ago
NASA and ESA
STScI-PRC13-45a

Data reduction: Flowchart



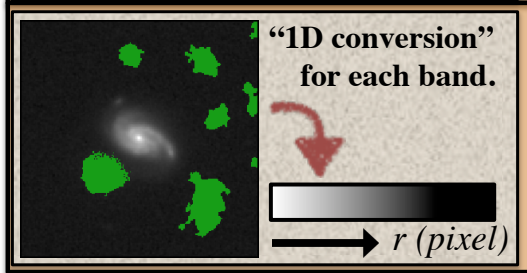
Sample extraction based on a constant number density for each population (Milky Way-like and massive galaxies).

1



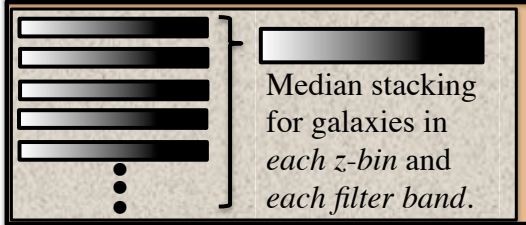
Mosaic images are convolved to the FWHM of F160W (~0.″18), and then each sample is extracted into 500×500 pixels.
(*Left*: Examples of convolved images, but in 200×200 pixel stamps here.)

2



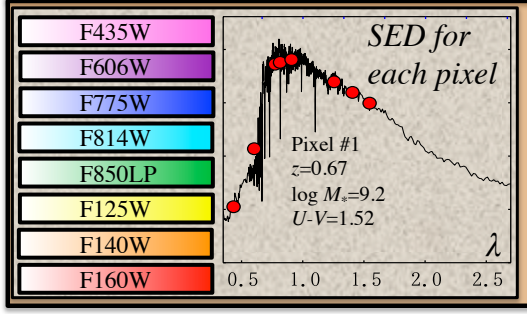
Contaminants in the postage are listed and masked (green regions in *left figure*) by SExtractor, and then the local sky is subtracted. The stamp for each filter band is converted into one dimensional (1D) image using Eq.(6).

3



Stacking the geometry-corrected 1D light profiles in each redshift bin, for each filter band.

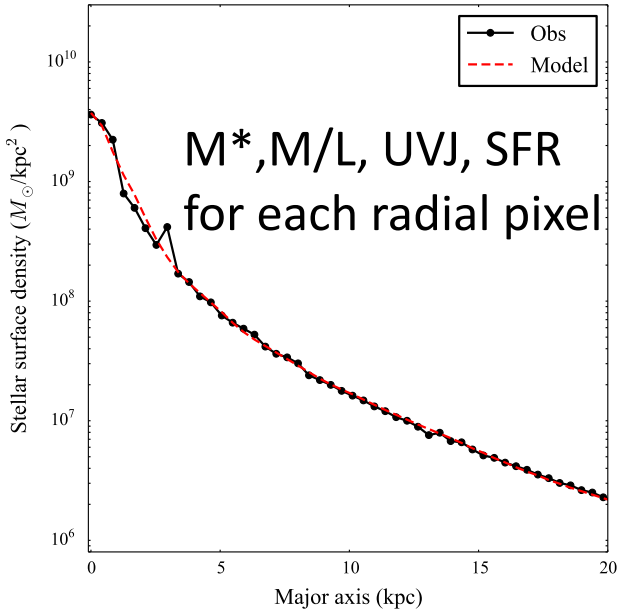
4

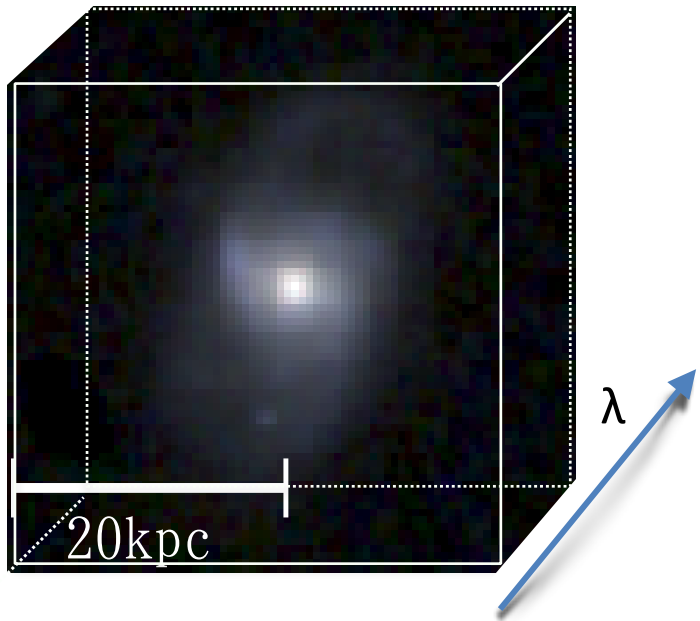


SED fitting is conducted for each pixel in the 1D image ("**Radial SED fit**"), to obtain the stellar mass and rest-frame color.

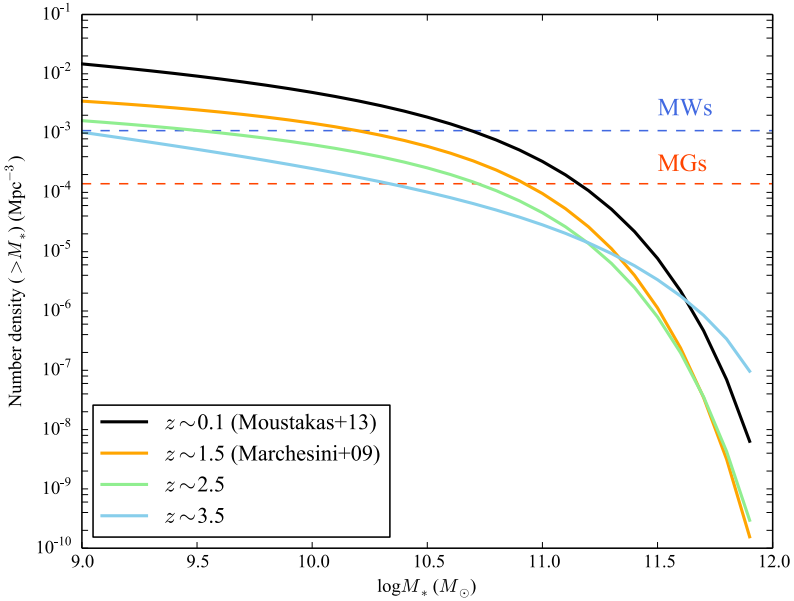
Criterion: $S/N_{F850LP}>3 \wedge S/N_{F125W}>3 \wedge S/N_{F160W}>3$.

5





Data reduction: 1.Selection of MWs and MGs



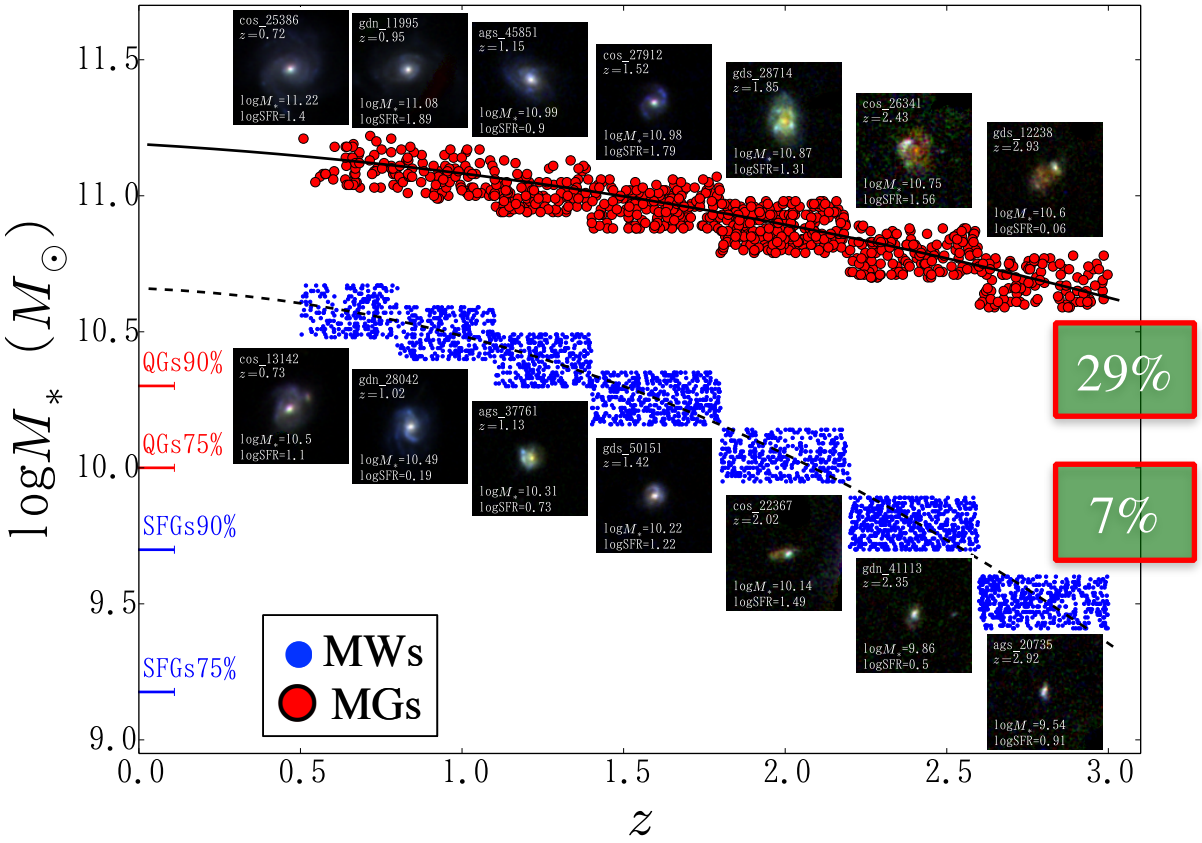
From 3D-HST catalog (Skelton+14),

Milky way progenitors (MWs):

$\log(M_*/M) = 10.66 - 0.045z - 0.13z^2$ (van Dokkum+13)

Massive galaxy progenitors (MGs):

$\log(M_*/M) = 11.19 - 0.068z - 0.04z^2$ (Patel+13)

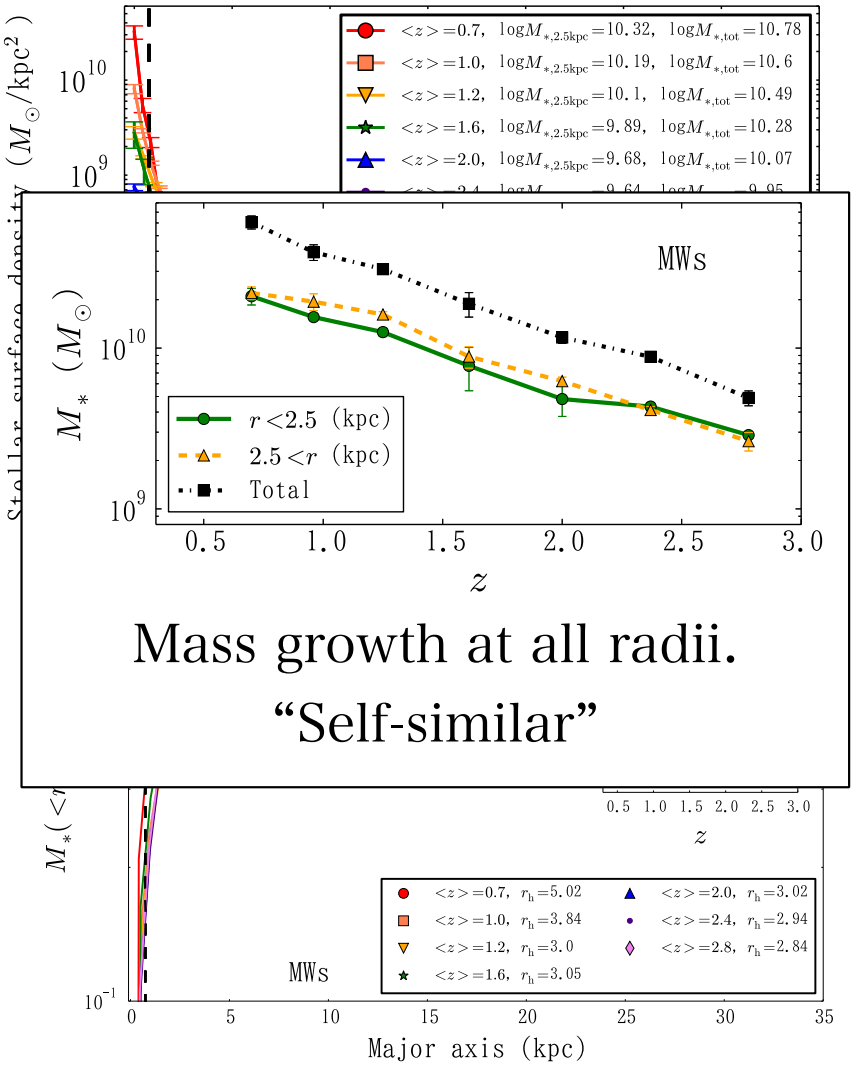


- Consistency with abundance matching.
- Impact of merger and quenching?

-> Negligible, at <u>lower mass</u> (Leja+13)
(We'll discuss later.)

Results: Stellar mass accumulation at 0.5<z<3.0

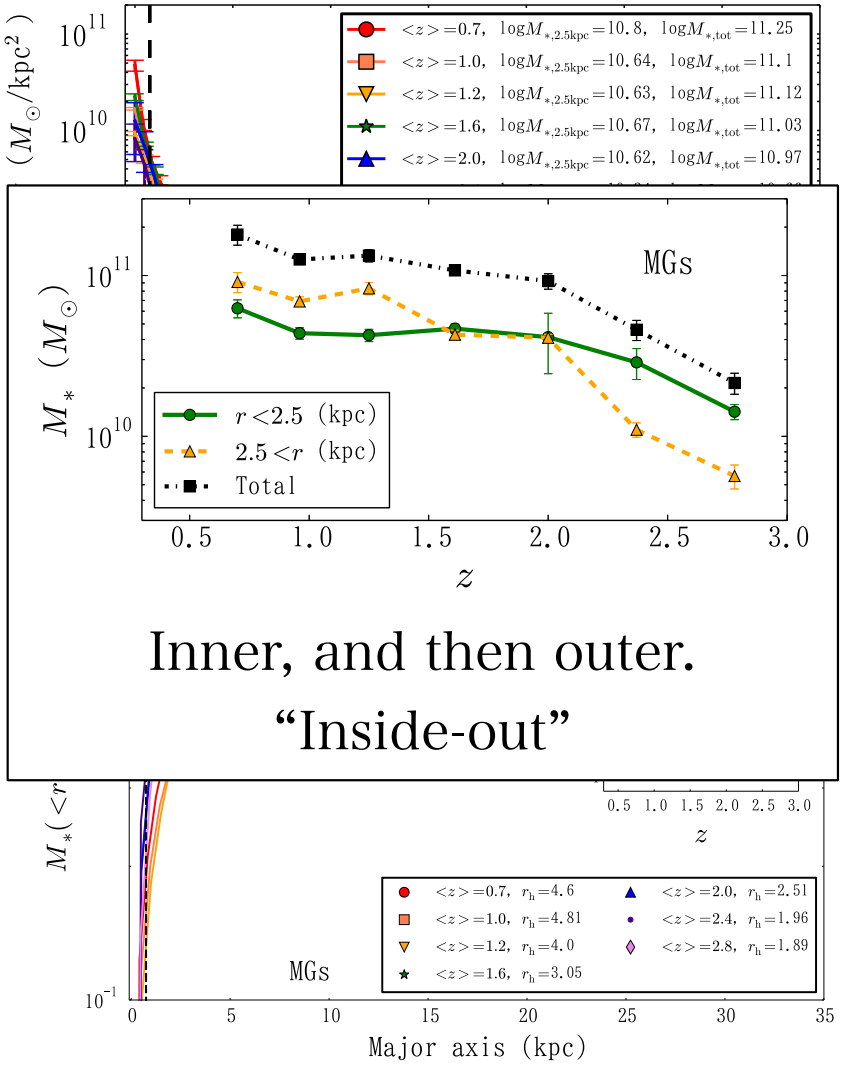
MWs



Mass growth at all radii.

"Self-similar"

MGs



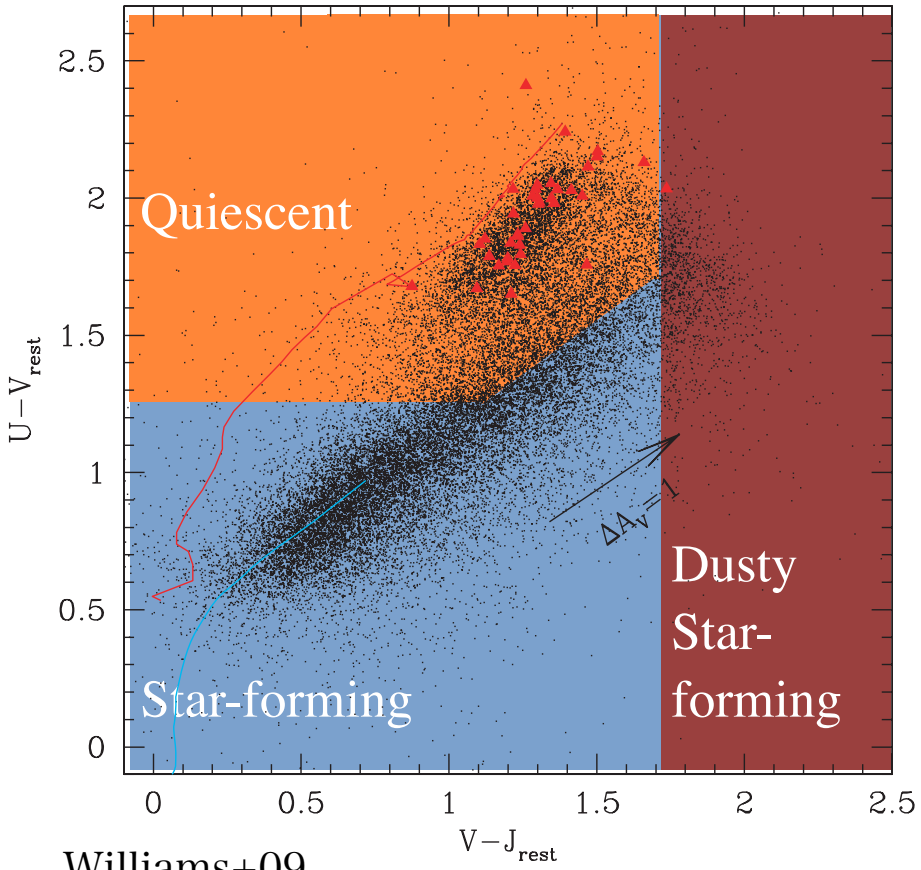
Inner, and then outer.

"Inside-out"

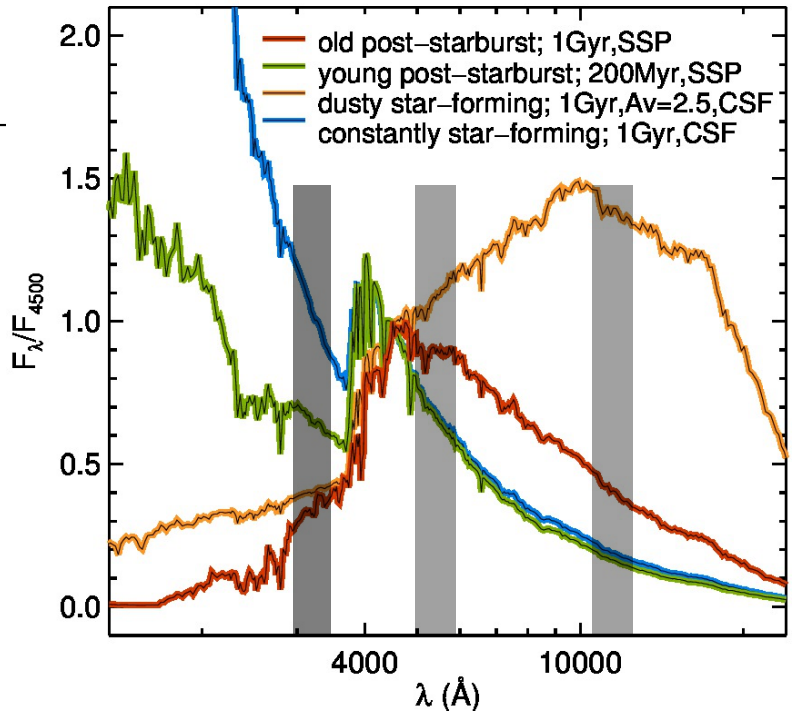
*Previous studies used light (e.g.,F160W) profiles.

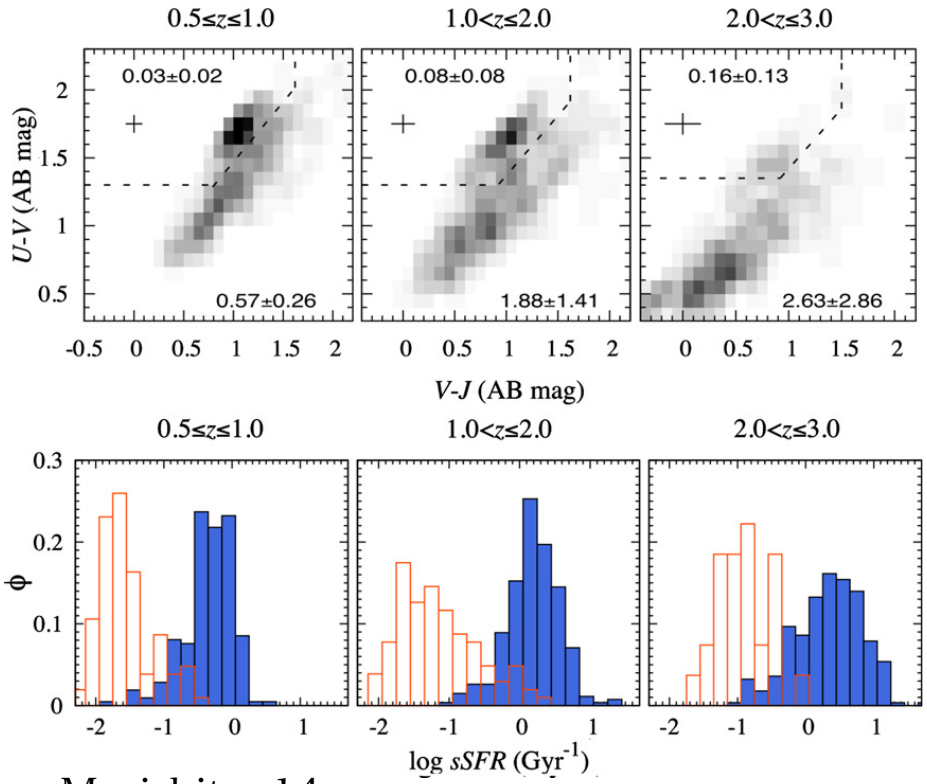
Results: Color gradient and evolution

Rest-frame *U-V*, *U-J* colors



Williams+09

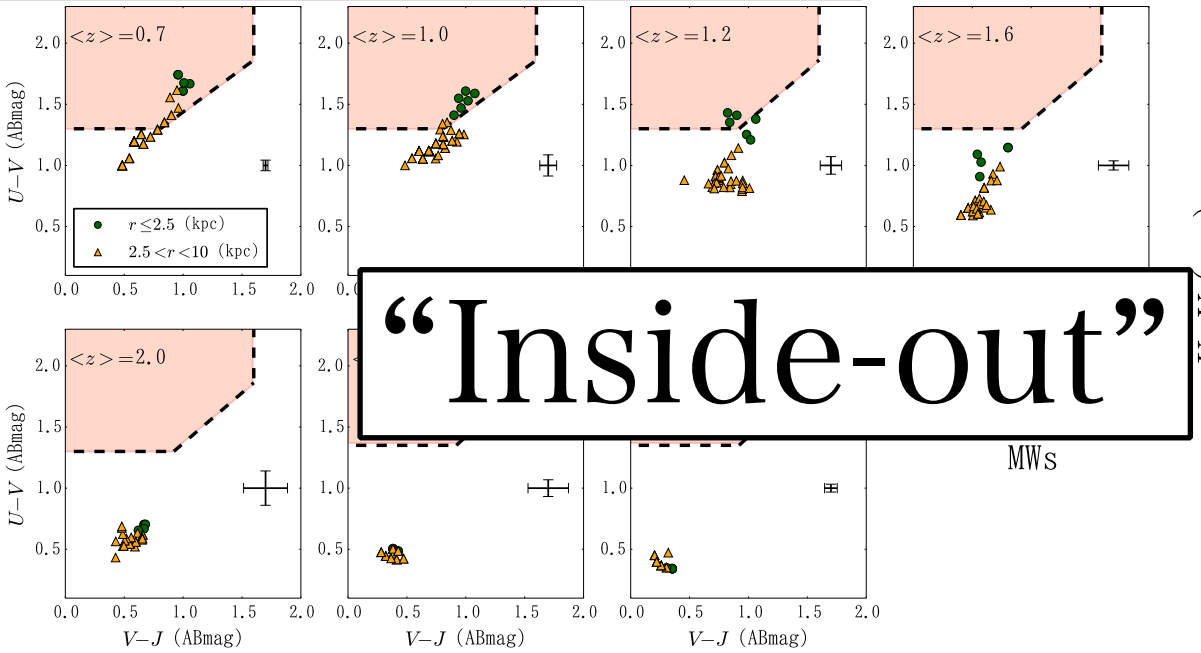




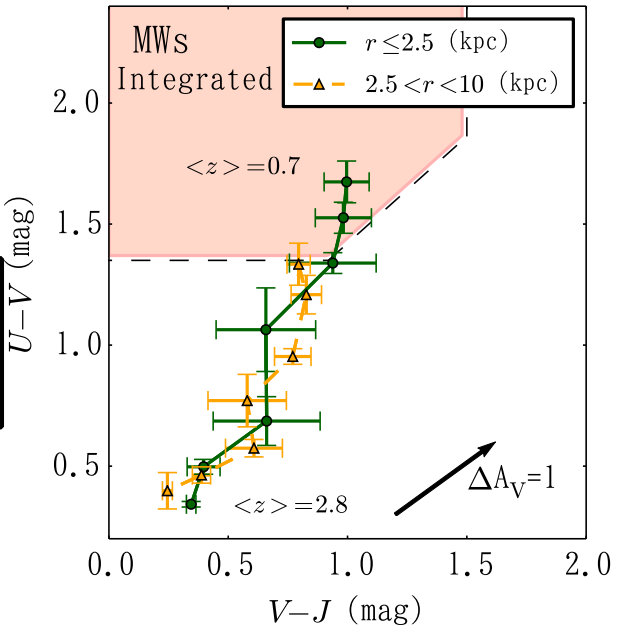
Morishita+14

Results: Color gradient and evolution

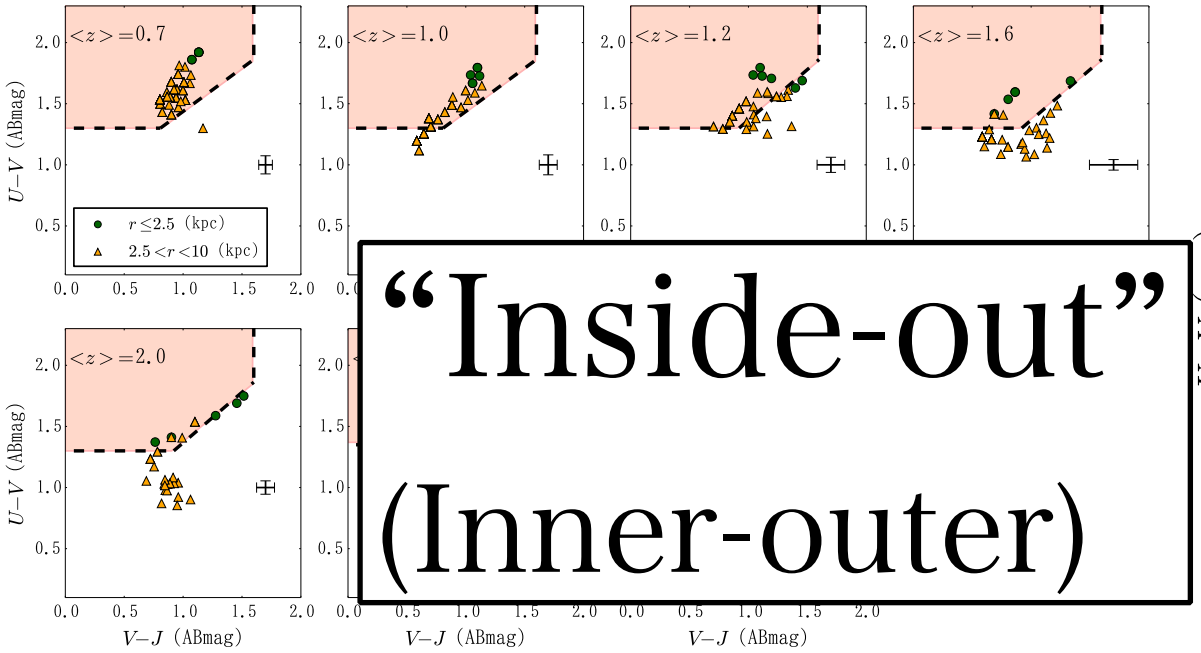
MWs



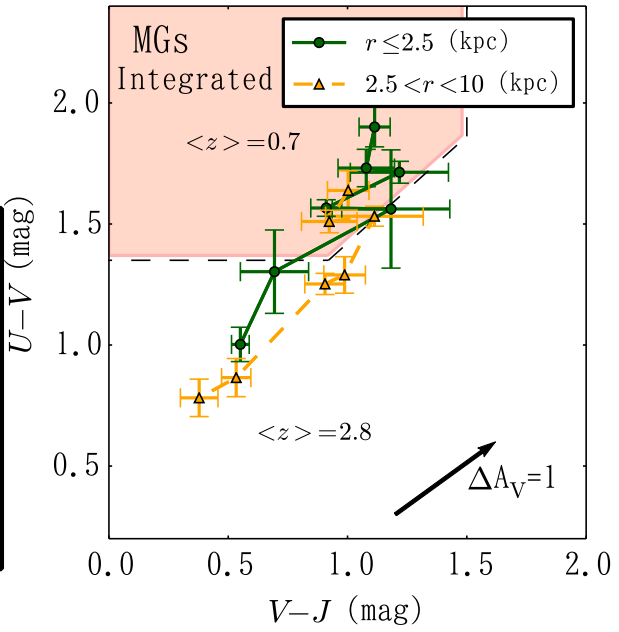
“Inside-out”



MGs



“Inside-out” (Inner-outer)



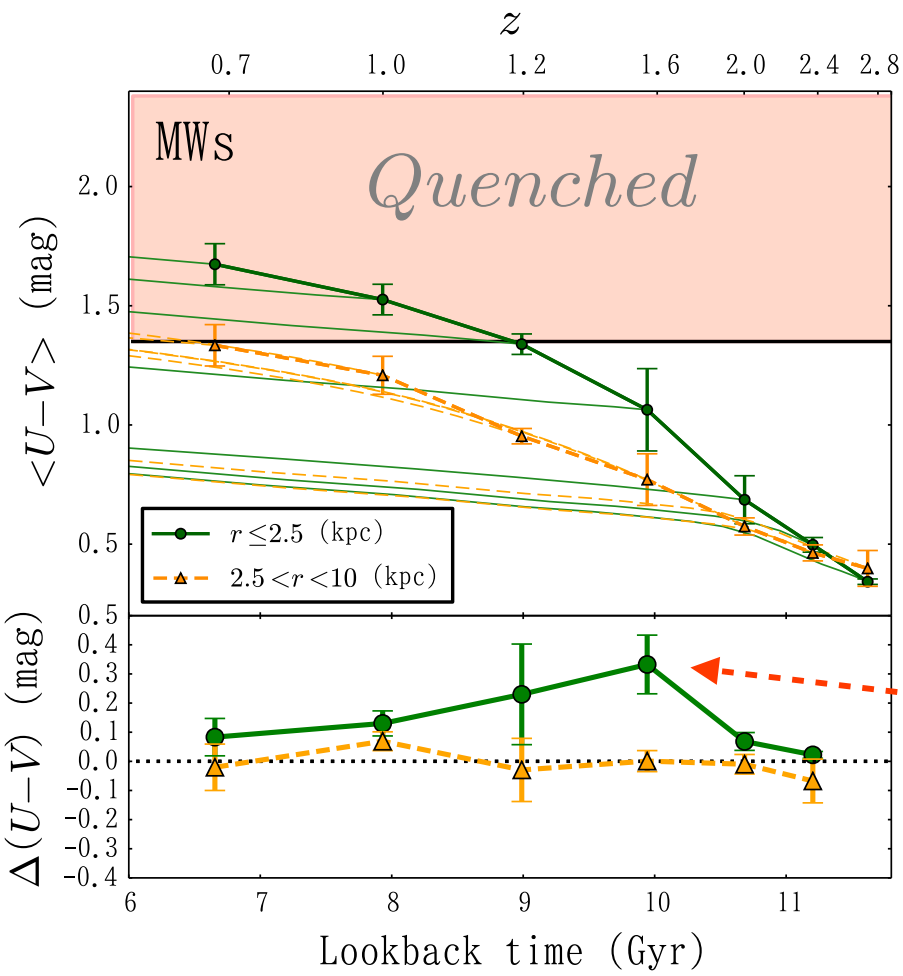
Discussion

✔ MGs evolve the stellar and colors in inside-out way.

? MWs evolve the stellar mass in self-similar way,
but the colors in inside-out way.

- What is the physical mechanism(s)?
- When did it happen?
- Where in the galaxy did it happen?

Discussion: Color gradient and evolution



- Thick lines: Observed.
- Thin lines: Stellar population model, including star formation (BC03).

The inner part of MWs suddenly reddens at z~1.2-1.6 (T~4Gyr).

- End of the bulge/thick disk formation? (e.g., Snaith+14)
- Compactness and quenching (Franx+08;Williams+10)

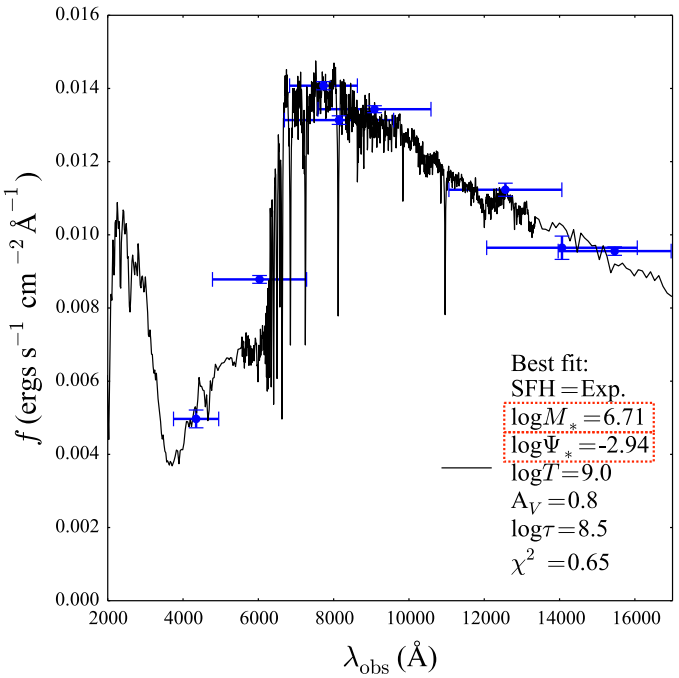
-> Bulge formation and quenching (Martig+09;Genzel+14)

-> Low-mass stars heat dust (Kajisawa,T.M.,+15; ポスターNo.10)

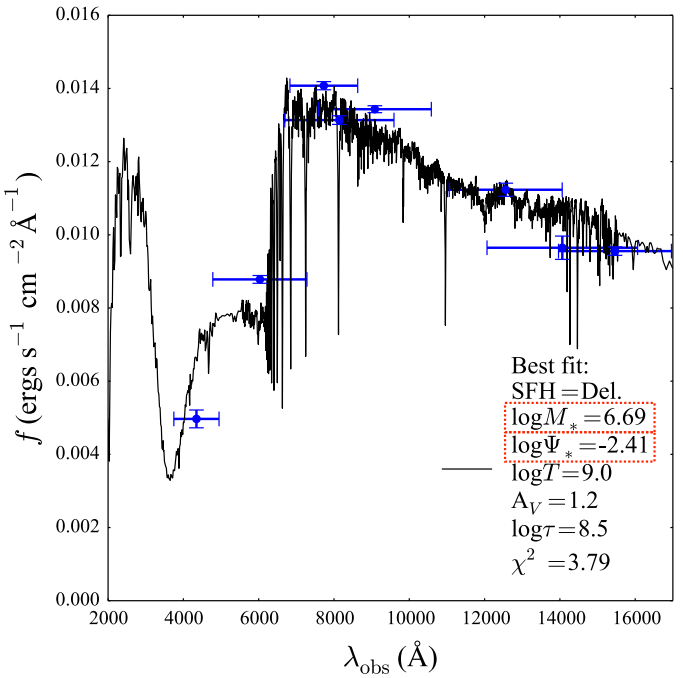
Discussion: Star formation rate (SED)

We usually assume a star formation history,
but …

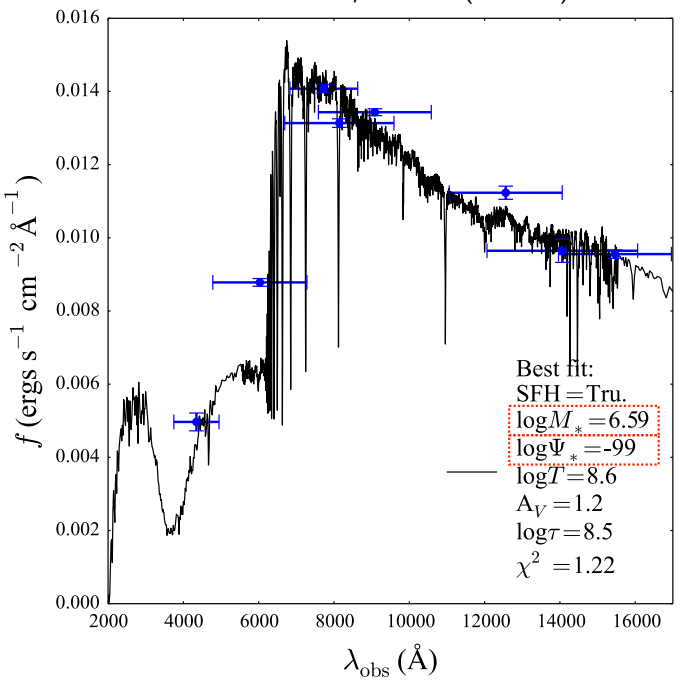
Exponential: $\psi \propto \exp(-t/\tau)$



Delayed: $\psi \propto t^{*}\exp(-t/\tau)$

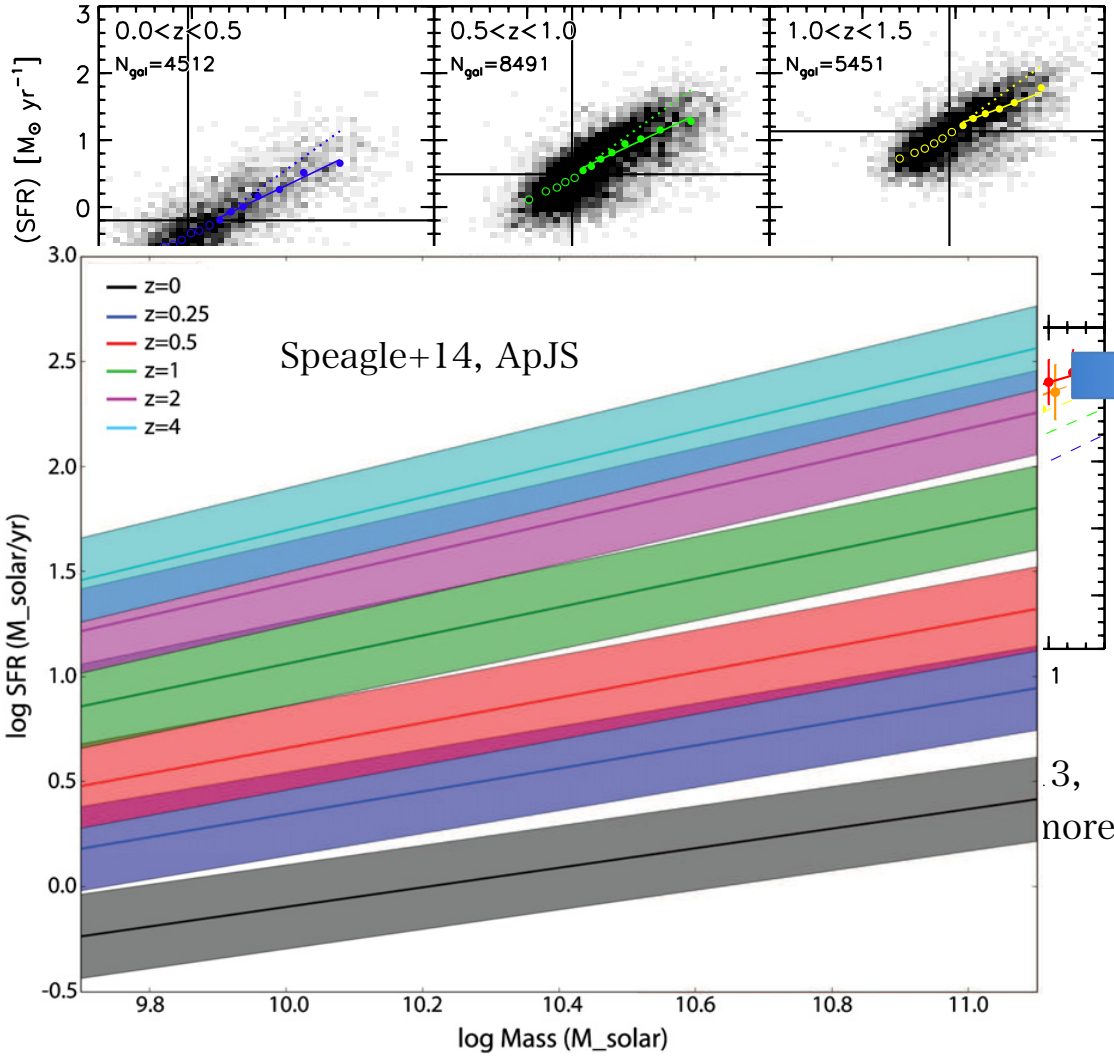


Truncated: $\psi = \text{const.}\ (t < \tau)$
$\psi = 0\ (t > \tau)$



Stellar masses are in good agreement, but the others are not.
(See also Wuyts+11)

Discussion: Star formation main sequence



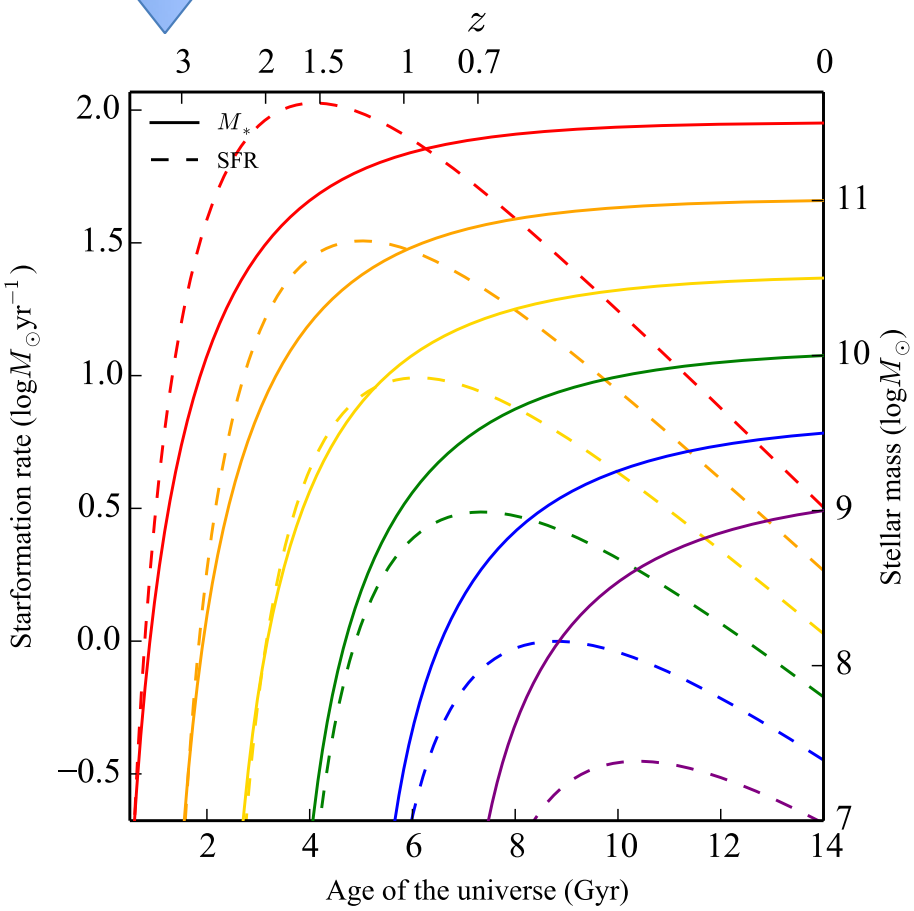
3,

nore.

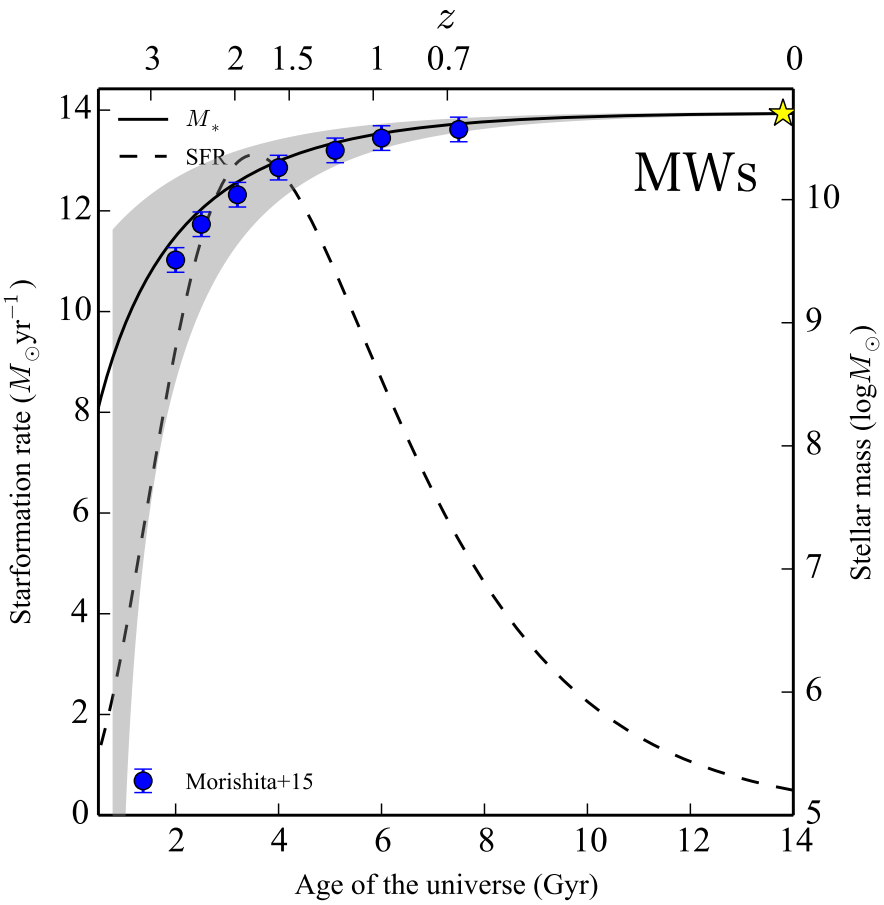
$$\log \psi(M_*, t) = (0.84 \pm 0.02 - 0.026 \pm 0.003 \times t) \log M_* - (6.51 \pm 0.24 - 0.11 \pm 0.03 \times t), \quad (28)$$

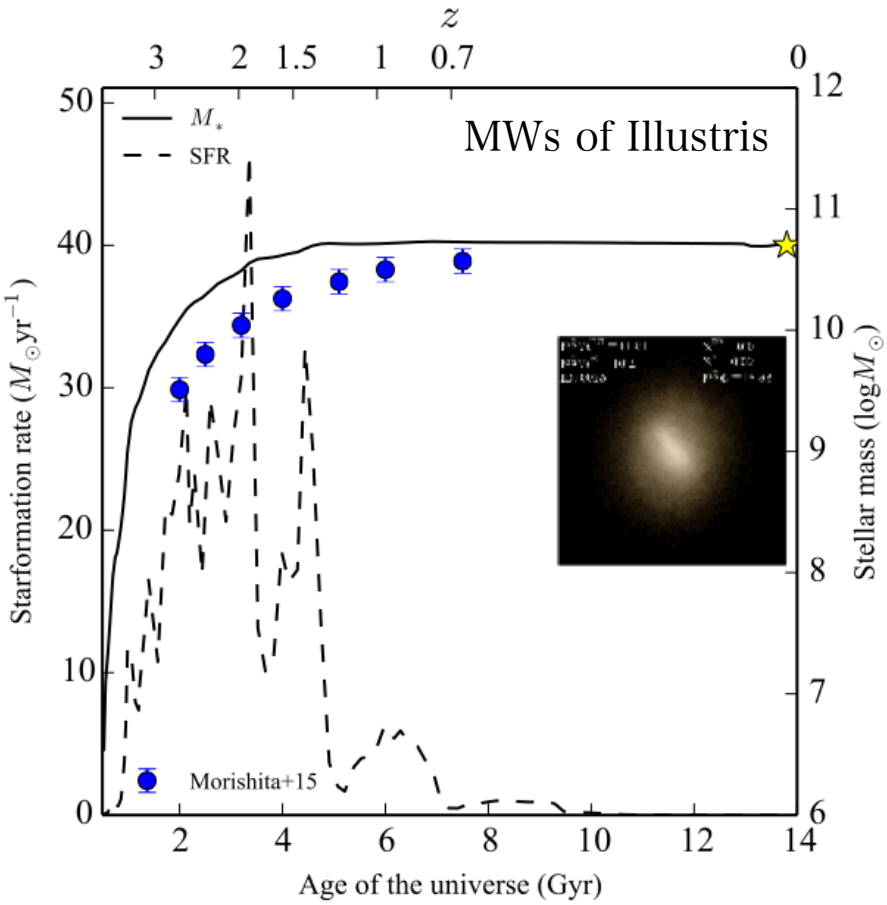
$$\Delta M(M,t) = (1\text{-}R)^*SFR(M,t)^* \Delta t$$

R: return fraction = 0.36



Discussion: Star formation main sequence





-Solid, dashed lines: SFMS, with scatter (gray)

-Points: Constant ND

MWs evolve on the main sequence.

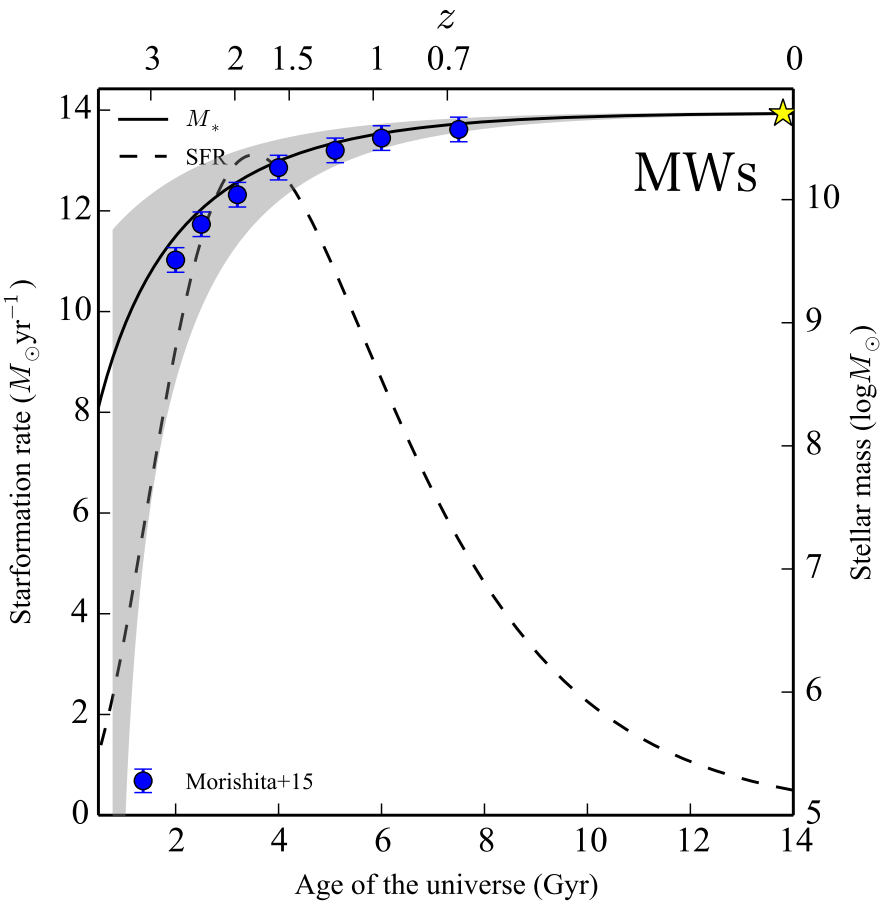
-Difference between inner and outer parts?

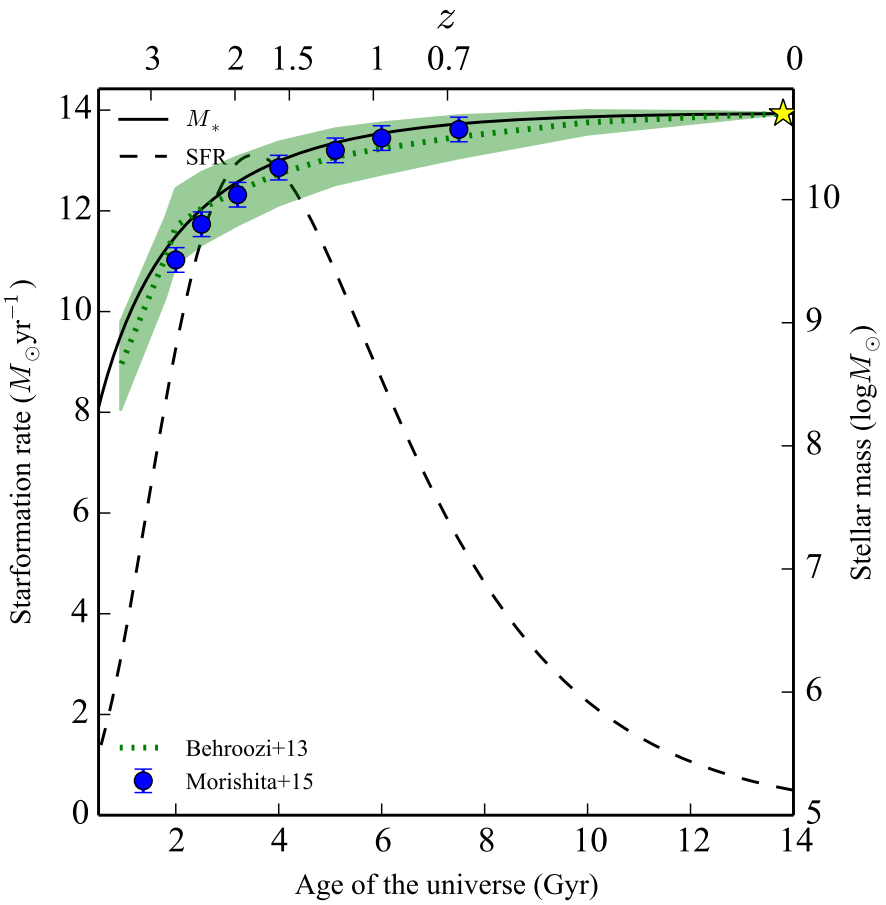
-> Resolved SFRs with IFUs+AO or HST grism?

(e.g., Wuyts+13)

-> Molecular gas mass map?

Discussion: Star formation main sequence



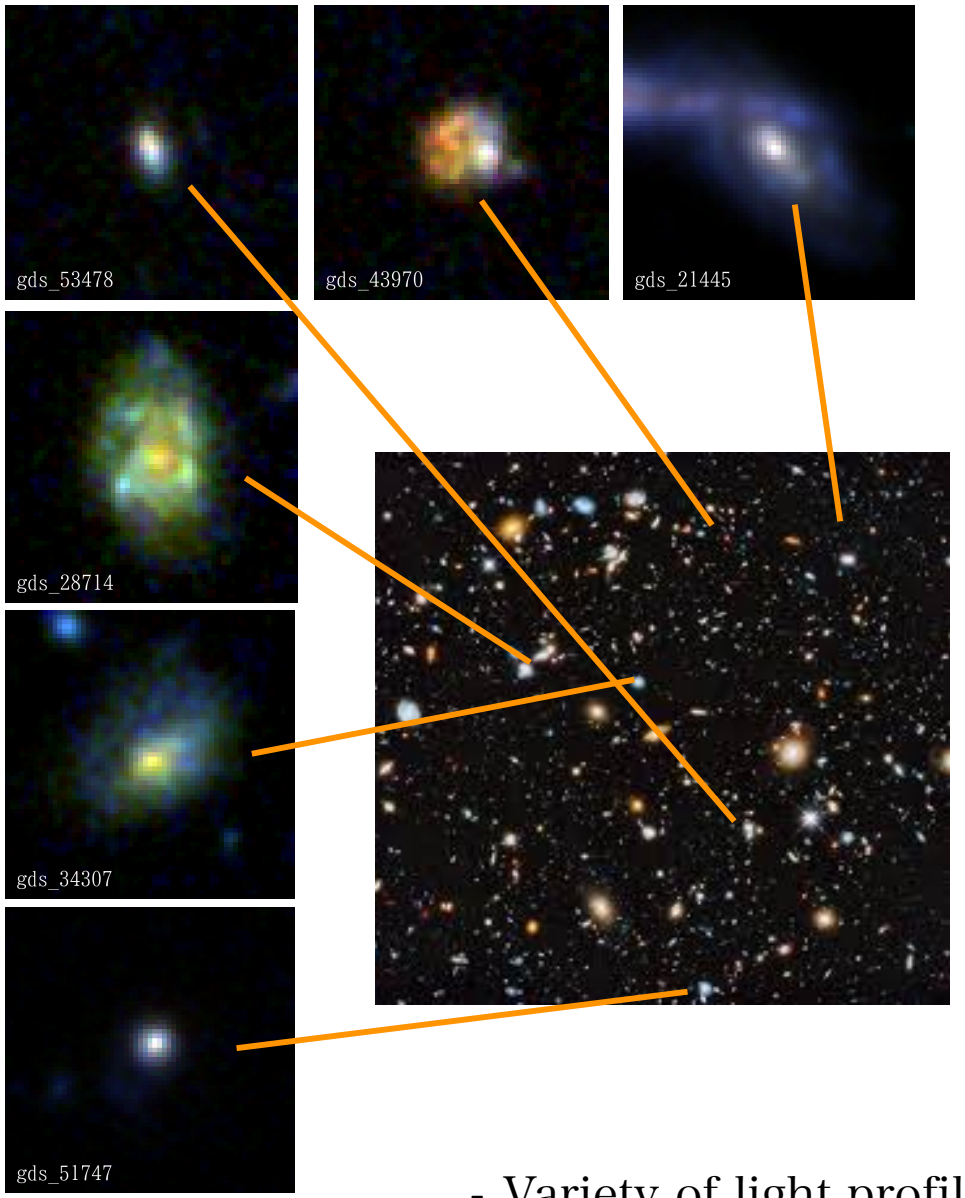


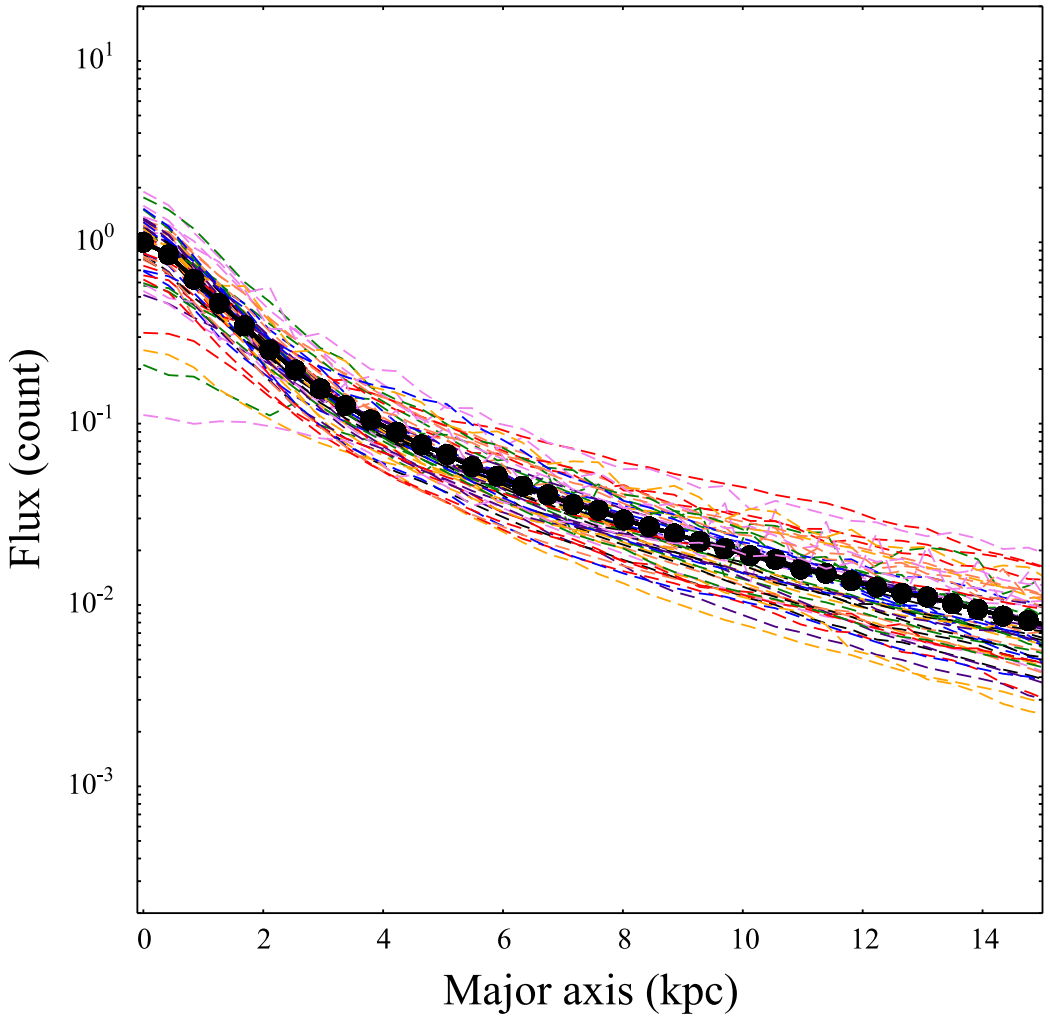
-Solid, dashed lines: SFMS, with scatter (gray)

-Points: Constant ND

-Dotted: Abundance matching (Behroozi+13), with scatter (green)

Discussion: Variety in the radial profile

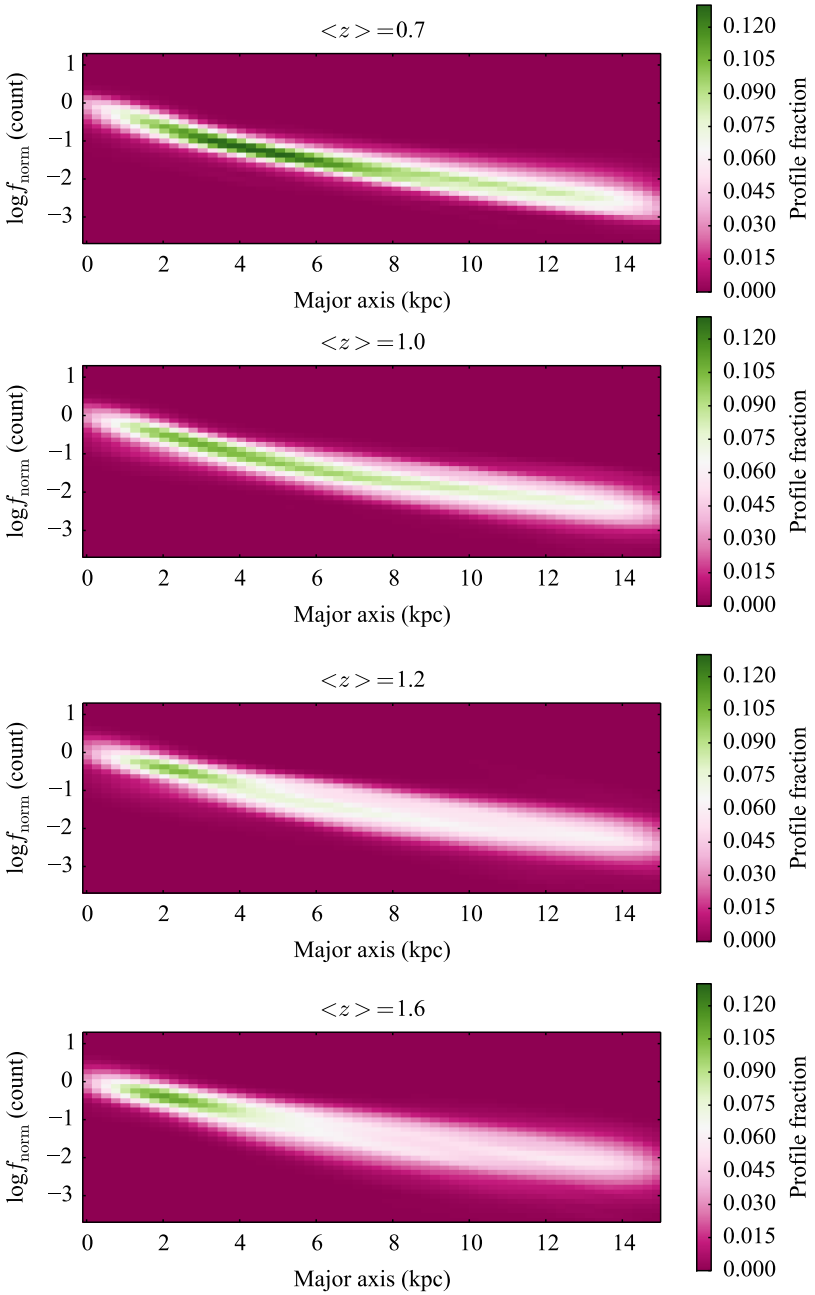


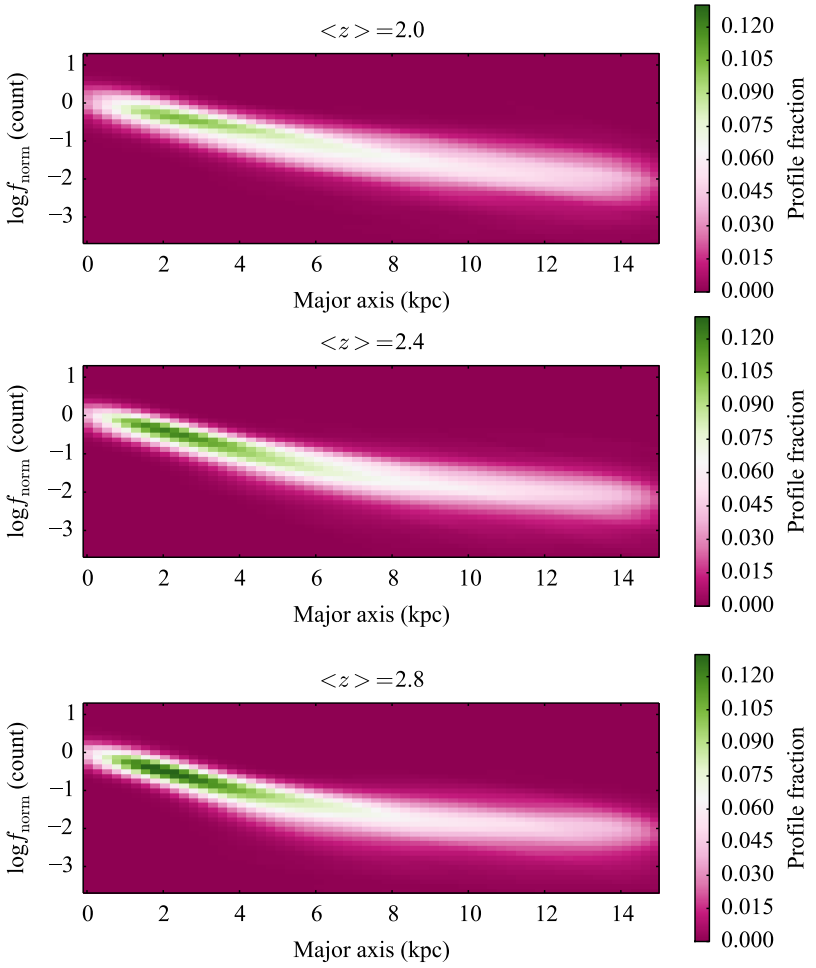


- Variety of light profile = “Morphological variety”
- Scatter around the median.

Discussion: Variety in the radial profile -MWs

z~0.7

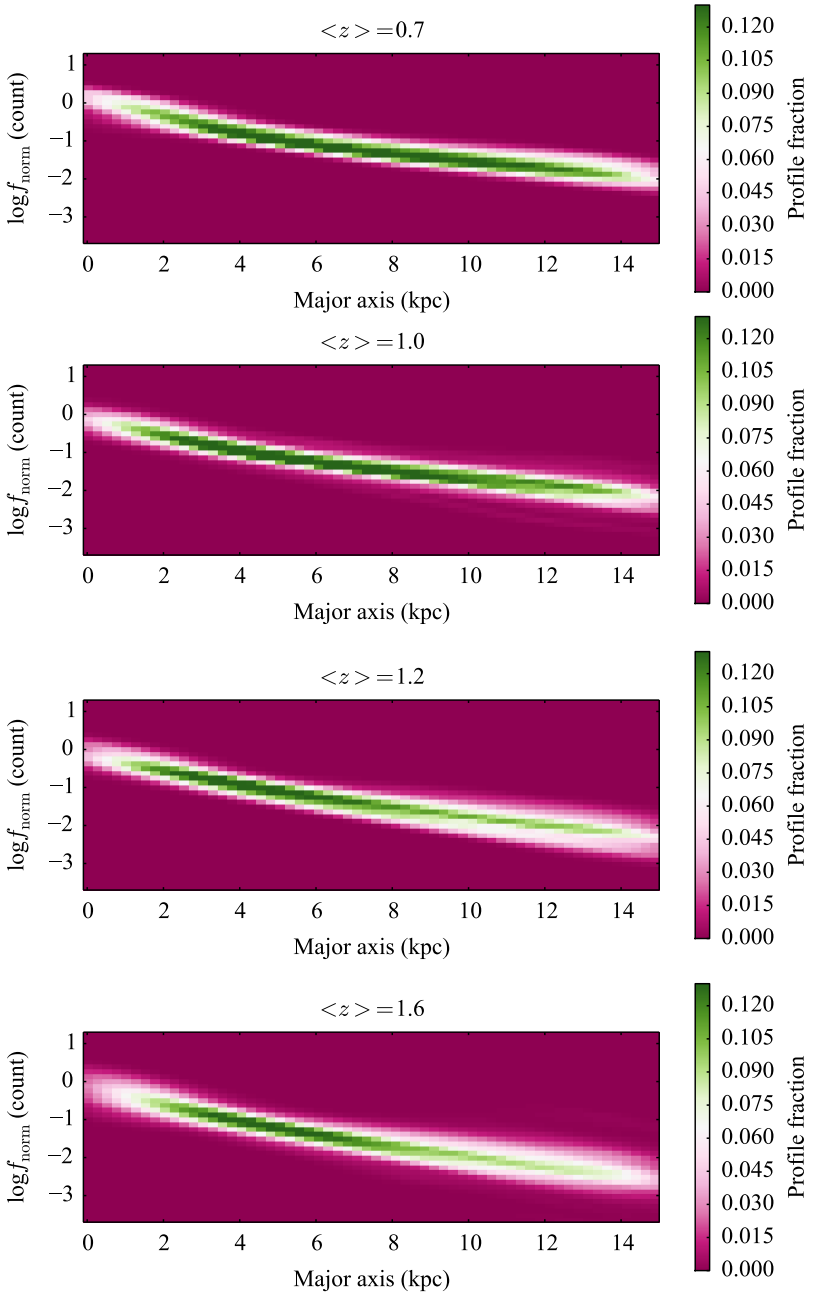


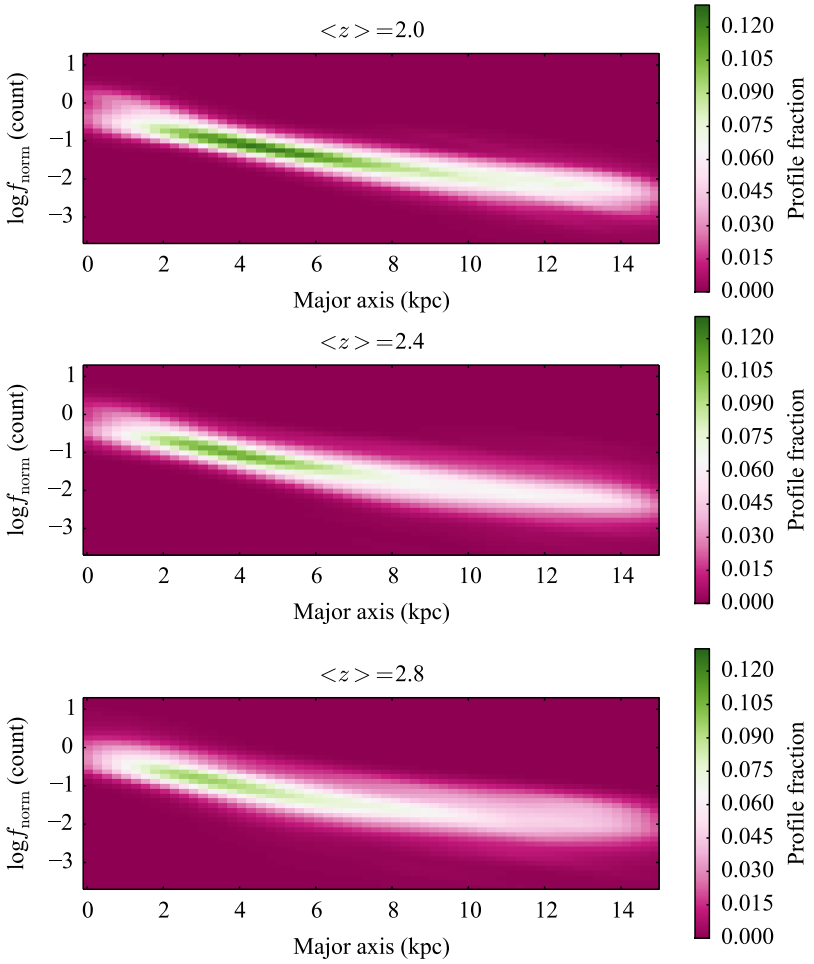


z~2.8

Discussion: Variety in the radial profile -MGs

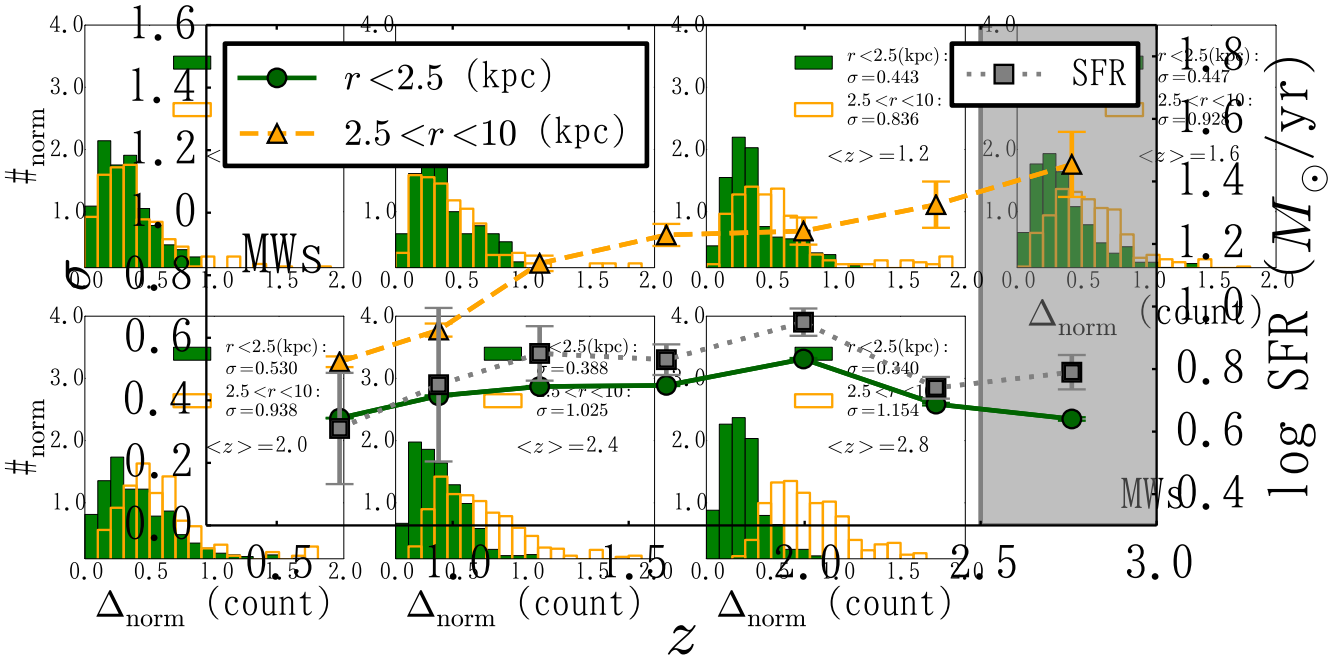
z~0.7





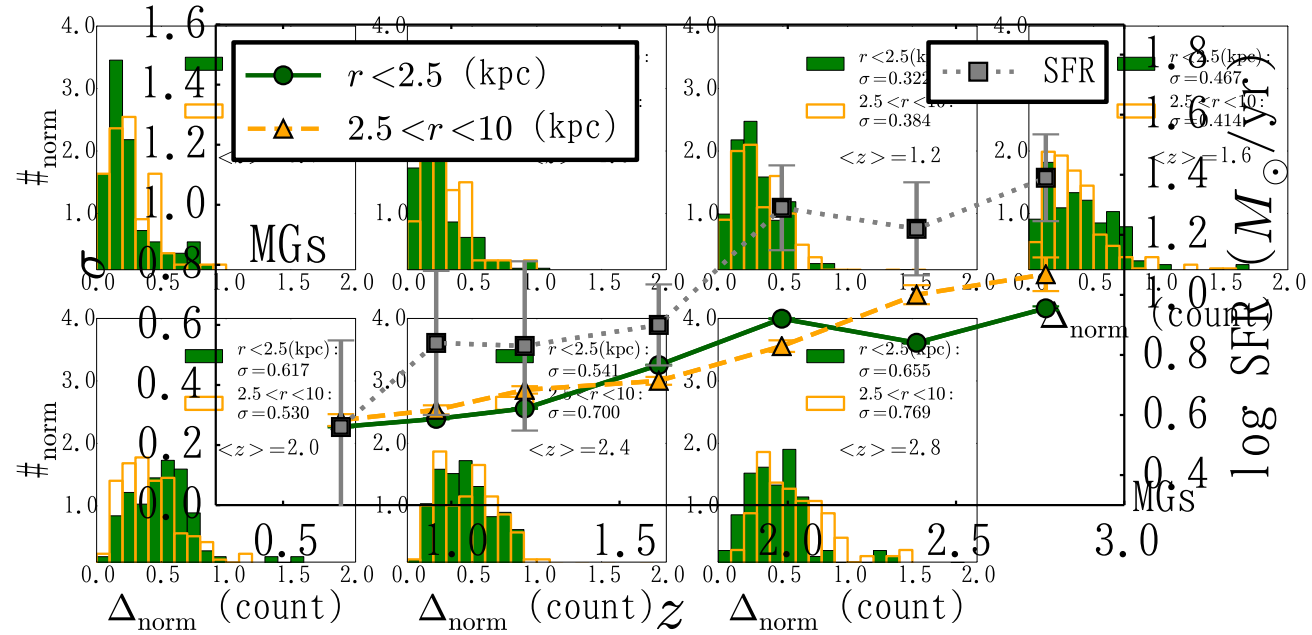
z~2.8

Discussion: Variety in the radial profile -MGs



$$\Delta_{\mathrm{norm},x} = \frac{1}{S_x}\sum_{i}^{x} \left| \frac{f_{i,\mathrm{median}} - f_{i,\mathrm{obs}}}{f_{i,\mathrm{median}}} \right|, \qquad (8)$$

- The outer parts of MWs show variety at z>1.0, and decrease at z<1.0.
- Star formation activity in the outer part and quenching?



- Both parts of MGs rapidly decrease the variety.
- We scarcely see the variety at z~0.5.

Summary:

	MWs		MGs	
Mass growth	7% of MW(z~0) at z~3	"Self-similar"	29% of MW(z~0) at z~3	"Inside-out"
Mechanism	Normal star formation?	Need accurate SFR maps.	Rapid bulge formation, and then minor merger.	
UVJ Color	Inner-to-outer.	Central part quenched at z~1.2.	Inner-to-outer.	Central part at z>2.4. (Whole at z~2.0.)
Variety	Outer parts still show various profiles.	Star formation in the outer part?	Rapidly decrease since z~2.0.	Now show "Homogeneity."

In the era of TMT, we need resolved study;

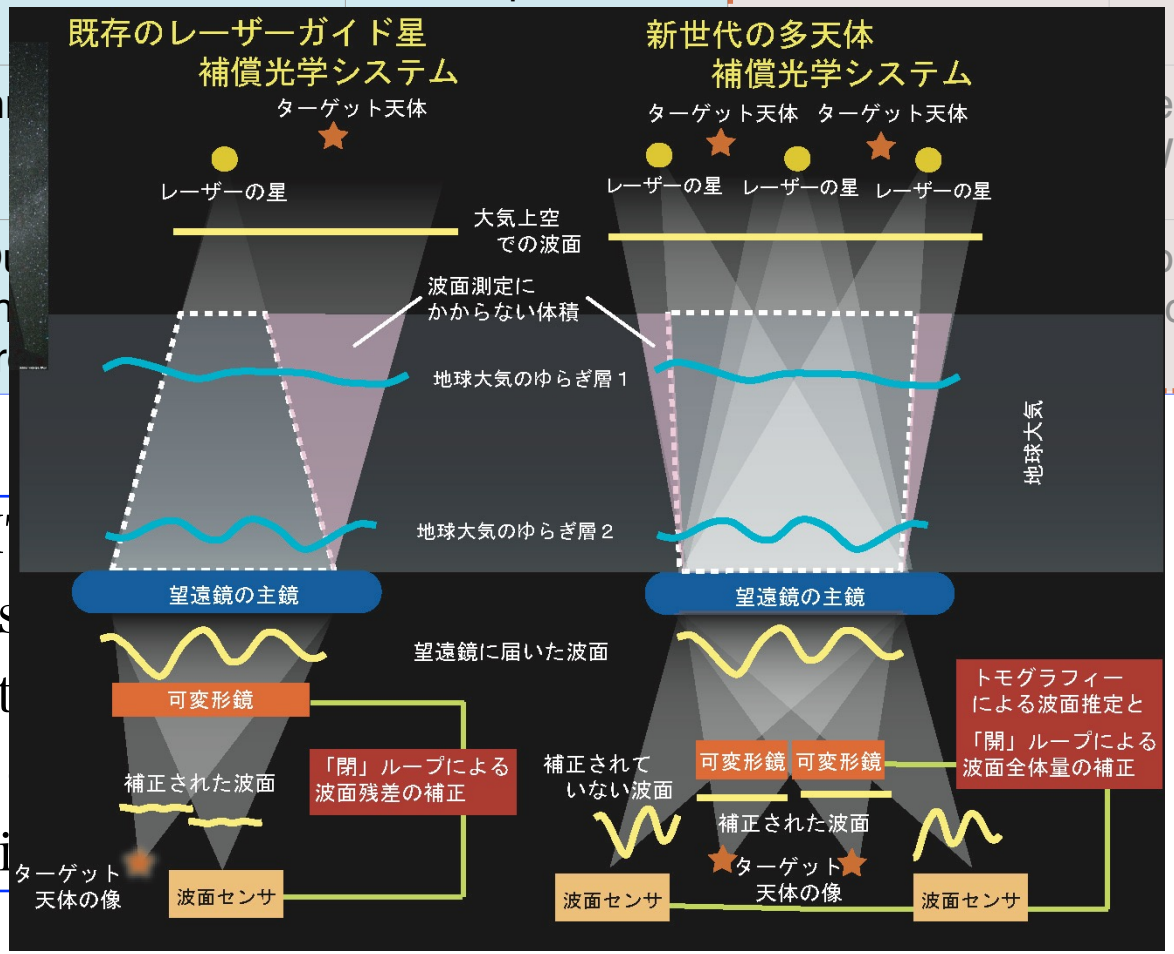
- Very accurate study of normal galaxies at z~1, when the bulge and thick/thin disk formed (=quenched).
- Star formation (including dust attenuation), stellar kinematics/metallicity.

Summary:

	MWs		MGs	
Mass growth	7% of MW(z~0) at	“Self-similar”	29% of MW(z~0) at	“Inside-out”
	formation?	SFR maps.	formation, and then	
UVJ Color	In		entral part at z>2.4. /hole at z~2.0.)	
Variety	Ou sh pr		ow show omogeneity.”	

TMT-AGE project : TMT Analyzer for Galaxies in the Early universe

PI M.Akiyama



In the era of TM
- Very accurate s
  the bulge and t
- Star formation
  stellar kinemati