Mass Assembly
Efficiencies of LAEs at z~2: stellar and halo properties
(Kusakabe+17 in prep)

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Combining stellar and halo properties is essential focusing on LAEs at z~2 whose stellar masses are derived well

- star formation mode: $M_s$ vs SFR plot
- stellar to halo mass ratio: SHMR (integrated SF efficiency)
- baryon conversion efficiency: BCE=SFR/Baryon accretion rate (differential SF efficiency)

Lilly+13 (Fig. 2)
Integrated Efficiency = \( \text{Ms/Mh} \)

- lie on the average relation (B13)?

- previous problems:
  - small sample size 250 → large statistics error
  - small area 0.3 deg\(^2\) → suffer from cosmic variance

Behroozi+13; Guaita+10, 11; Lin+12
SF mode of LAEs: burst or moderate?

- problems:
  - only bright objects are detected individually
  - shallow photometry of IRAC
  - dust attenuation curves: Calzetti? SMC(HK15)?
This study

Dark matter halo & stellar population properties of LAEs

- using ~2400 NB-selected LAEs in ~1 deg² with NB <26.4 mag (5 σ)
- dark matter halo masses: clustering analyses
- stellar properties: SED fitting
## Samples

<table>
<thead>
<tr>
<th>Field</th>
<th>Area (min^2)</th>
<th>NB mag lim (5σ, mag)</th>
<th>Number of samples(#)</th>
<th># w NBtot&lt;=25.5mag (# for SED fitting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SXDS</td>
<td>~1240</td>
<td>25.7, 2” ap</td>
<td>603</td>
<td>601(93)</td>
</tr>
<tr>
<td>COSMOS</td>
<td>~740</td>
<td>26.1, 2”ap</td>
<td>619</td>
<td>297(47)</td>
</tr>
<tr>
<td>GOODS-S</td>
<td>~580</td>
<td>26.4, 2” ap</td>
<td>269</td>
<td>51(4)</td>
</tr>
<tr>
<td>GOODS-N</td>
<td>~780</td>
<td>26.1, 3” ap</td>
<td>950</td>
<td>299 (56)</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>~1 deg^2</strong></td>
<td><strong>~2440</strong></td>
<td><strong>~1250</strong></td>
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</tr>
</tbody>
</table>

Nakajima+12, 13, Kusakabe+15, Konno+16

**five cumulative samples**

NB<=25.0, <=25.3, <=25.5, <=25.8, <=26.3
Clustering Analysis

Dark matter halo mass of cumulative sub samples

- ACF observation: Landy & Szalay+93 (error: poisson)
- ACF model: $\beta = 0.8$, fitting range=40”-1000”
- bias factor-halo mass: Tinker+10
large cosmic variance beyond statistics errors
No significant dependence on L(Lya) limit
No significant dependence on EW (NB excess)
Bias factors

- average bias = $1.24^{+0.24}_{-0.19}$ (1250 LAEs in 1 deg$^2$) vs bias=1.8±0.3 (G10; 250 LAEs in 0.3 deg$^2$)

- $M_h=4.0^{+8.6}_{-3.0} \times 10^{10}M_\odot$
Stacked SED fit

- observational data: B, V, R, I, z, J, H, K, IRAC ch1, ch2
- derived parameters: SFR, Ms, age, E(B-V)
- model: BC03 with nebular emission (lines & continuum, Ono+10) constant SFH Z=0.2Zsun (Nakajima+12), fesc(ion)=0.2 Calzetti/SMC-like attenuation curve (Kusakabe+15)
Ms vs IRX: prefer SMC

- SMC: our LAEs lie on the consensus relation also consistent with upper limit of IRX < 2.2 (3σ)

- Calzetti: four times higher IRX than those w the SMC curve Ms and SFR of our LAEs are consistent with those of previous studies

→the SMC curve is adopted
Bowens+16; HK+15; Shiva ei+16; Whitaker+14; Rodighiero+11; Daddi+07
SF mode

- our LAEs have $M_s \sim 10^9 M_{\odot}$ & SFR$\sim 3 M_{\odot}$/yr
- lie on extrapolations of SFMS: moderate SF

Shivaei+16; Whitaker+14; Rodighiero+11; Daddi+07;
Integrated SF Efficiency

- Average LAEs lie slightly above an extrapolation of B13 though the error bars marginally overlap
- SHMR~0.01-0.1 is possibly high

Behroozi+13; Guatia+10, 11; Lin+12
Differential SF Efficiency

- Baryon accretion rate (BAR) $\sim 6 \times \left(\frac{M_h}{10^{12} M_{\odot}}\right)^{1.15} (1+z)^{2.25} f_{0.15} M_{\odot}/yr$

- Baryon conversion efficiency = SFR/ BAR

- Average LAEs have BCE ~ $1.8 \pm 1.6$
  slightly higher than that of extrapolated B13 relation

Behroozi+13; Dekel+08
Physical origin of LAEs

(1) moderate SF mode + possibly high SHMR + high BCE
(2) low duty cycle: \( \sim 14\% \) in \( M_s = 10^{8.5} - 10^{9.5} M_\odot \),
\( \sim 1.6\% \) in \( M_h = 10^{10} - 10^{11} M_\odot \)
minor galaxies grow with efficient mass assembly as opposed to their low \( M_h \)

- small spin parameter of DMH and/or weak feed back
  \( \rightarrow \) increase SHMR and BCE along SFMS

- they have (had) large amount of molecular gas compared with atomic and ionized gas?
  \( \rightarrow \) the amount of HI gas is low and Lya escape easily?
Mgas is probably lower than those of galaxies with the same \( M_s \) and average SHMR

Tomczak+13; Ricciardelli+11; Dutton+10(fig.12)
future of LAEs

Our LAEs (Mh<~10^{11}@z~2) are

- progenitors of LMC-like galaxies which have Mh~0.2-3\times10^{11}M_\odot
- not that of MW-like galaxies which have Mh~1-2\times10^{12}M_\odot

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MW-like

LMC-like

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Peñarrubia+15; Wang+15;
the first estimation of cosmic variance of bias\(~(\omega_{\text{gals}}/\omega_{\text{matter}})^{0.5}\) assuming that CV comes from fluctuation of ACF of DM

consistent with the scatter of our data and G10

HSC survey is useful for further study
SSP: NB=24.5 mag(5σ) in \(6\times10^6\text{(Mpc/h)}^3\) \(\rightarrow\Delta b(\text{all})\sim0.14\) (incl. fc uncertainties\~0.14, fitting error\~0, and CV\~0)
Summary

Stellar and halo properties are derived by ~2440 LAEs at z~2 from 1deg² field

- average bias = $1.24^{+0.24}_{-0.19}$ with $M_h=4.0^{+8.6}_{-3.0} \times 10^{10} M_\odot$
  - large cosmic variance in each sub sample
  - smaller than Guaita+10 based on 0.3 deg² area

- average LAEs form star moderately lying on SFMS

- efficient mass assemble as opposed to their low $M_h$
  - moderate or possibly high SHMR
  - high BCE

- They are progenitor of LMC-like galaxies (not that of MW)

- HSC enables us to constrain $M_h$ of LAEs robustly
Appendix
Sky distribution

SXDS: $1240\text{arcmin}^2$, 0.2”/pix

COSMOS: $740\text{arcmin}^2$, 0.15”/pix
Sky distribution

GOODS-S: 580arcmin$^2$, 0.267”/pix

GOODS-N: 780arcmin$^2$, 0.3”/pix
SED fitting (fesc=0.2)
SED fitting ($f_{esc}=0.2$)
### Table 1
Results of SED fitting

<table>
<thead>
<tr>
<th>attenuation curve</th>
<th>$M_\star$ ($10^8 M_\odot$)</th>
<th>$E(B - V)<em>\star$ [$A</em>{1600}$] (mag)</th>
<th>Age (Myr)</th>
<th>SFR ($M_\odot$ yr$^{-1}$)</th>
<th>$f_{\text{esc}}^{\text{ion}}$</th>
<th>$\chi^2_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SXDS</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Calzetti</td>
<td>7.81±3.13</td>
<td>0.11±0.02 [1.1±0.2]</td>
<td>160.90±199.31</td>
<td>5.67±1.70</td>
<td>0.20±0.00</td>
<td>0.698</td>
</tr>
<tr>
<td>SMC</td>
<td>8.87±3.27</td>
<td>0.05±0.01 [0.6±0.1]</td>
<td>321.03±249.85</td>
<td>3.34±0.39</td>
<td>0.20±0.00</td>
<td>0.628</td>
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<tr>
<td>COSMOS</td>
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<td></td>
</tr>
<tr>
<td>Calzetti</td>
<td>7.89±4.89</td>
<td>0.18±0.03 [1.8±0.4]</td>
<td>71.87±130.69</td>
<td>12.31±5.41</td>
<td>0.20±0.00</td>
<td>0.667</td>
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<tr>
<td>SMC</td>
<td>13.94±3.12</td>
<td>0.07±0.02 [0.8±0.2]</td>
<td>404.16±166.73</td>
<td>4.21±1.18</td>
<td>0.20±0.00</td>
<td>0.482</td>
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<tr>
<td>GOODS-N</td>
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<tr>
<td>Calzetti</td>
<td>3.26±0.52</td>
<td>0.20±0.02 [2.0±0.2]</td>
<td>26.30±15.20</td>
<td>13.26±5.08</td>
<td>0.20±0.00</td>
<td>0.868</td>
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<tr>
<td>SMC</td>
<td>7.60±3.74</td>
<td>0.06±0.03 [0.7±0.4]</td>
<td>321.03±319.51</td>
<td>2.86±0.83</td>
<td>0.20±0.00</td>
<td>1.300</td>
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<tr>
<td>GOODS-S</td>
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</tr>
<tr>
<td>Calzetti</td>
<td>3.07±17.49</td>
<td>0.14±0.03 [1.4±1.3]</td>
<td>37.00±1397.00</td>
<td>9.00±23.39</td>
<td>0.20±0.00</td>
<td>0.101</td>
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<tr>
<td>SMC</td>
<td>10.26±10.58</td>
<td>0.02±0.07 [0.2±0.8]</td>
<td>570.89±863.12</td>
<td>2.23±24.48</td>
<td>0.20±0.00</td>
<td>0.120</td>
</tr>
</tbody>
</table>
compared with the previous work

Assuming the Calzetti curve and IRX-β relation

- Our LAEs lie similarly to the previous work

Shivaei+16; Whitaker+14; Rodighiero+11; Daddi+07; Kusakabe+15; Hagen+16; Shimakawa+16
Ms vs SFR (fesc=1)

\[ \text{fesc =1 fixed} \]
\[ \text{(no nebular lines and continuum)} \]

\[ \text{fesc =0.2 fixed} \]
\[ \text{(0.8*Nlyc translate into nebula)} \]