Dark Matter Halo and Stellar Properties of Extremely Low-Mass Galaxies at $z \sim 2$
(Kusakabe+16 in prep)

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Stellar masses & SFRs at z \sim 2

![Graph showing the relationship between stellar mass and SFR at z \sim 2 with data points and fitting lines.](image-url)
Stellar masses & SFRs at z~2

emission lines (e.g., Lyα) & Gravitational lensing survey

- problems
  - individual: only bright gals, poor IRAC S/N
  - stacked: only average properties

- Ms<10^8M_☉: less than 30 galaxies have stellar population estimates with large uncertainties

Shivaei+16; Popping+15; Whitaker+14; Rodighiero+11; Daddi+07; Kusakabe+15; Vargas+14; Hagen+14; Stark+14; Atek+14
Dark matter halos at z~2

- problems (Guaita+10):
  - small sample size (250) → large statistics error
  - small survey area (0.3 deg$^2$) → suffer from cosmic variance

- No study for galaxies with $M_\star < 10^8 M_\odot$
This study

Dark matter halo & stellar population properties of
- low mass (Ms~10^8 M☉)
- extremely low-mass (Ms<10^8 M☉)
galaxies at z~2

- ~2400 NB LAEs in ~1 deg^2
  NB <26.4 mag (5σ)

- sub samples based on NB excess & magnitude
- 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 (5 σ, mag)</th>
<th>Number of samples</th>
<th>Clustering analyses</th>
<th>SED fitting</th>
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<tbody>
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<td>26.1, 3” ap</td>
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<td><strong>TOTAL</strong></td>
<td>~1 deg^2</td>
<td>~2440</td>
<td></td>
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</table>

(Nakajima+12, 13, Kusakabe+15, Konno+16)
Sub-sample criteria

- Divided into three sub-samples based on NB excess implying
  \[\text{EW}(\text{Ly}\alpha) = 9-17\text{Å}, 17-35\text{Å}, >35\text{Å}\]
Sub-sample criteria

- Divided into four sub-samples based on **NB magnitude**: 26.15-25.9 mag, 25.9-25.5 mag, 25.5-25.0 mag, <25.0 mag
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
Dark Matter Halo masses

- **large cosmic variance** beyond statistics errors
- No significant dependence on L(Lya) limit
- No significant dependence on EW (NB excess)
Dark Matter Halo masses

- average bias = $1.32 \pm 0.19$ (2440 LAEs in 1 deg$^2$) 
  $< \text{bias}=1.8 \pm 0.3$ (G10; 250 LAEs in 0.3 deg$^2$)
Stacked SED fit

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

- Ms are distributed widely: $\sim 10^7 - 10^9 M_\odot$
- average LAEs: $\sim 10^9 M_\odot$
Mh vs Ms

- Average LAEs lie on B13 extrapolation
- Ms: 2 dex range
- Mh: maybe wide distribution
- HSC survey is useful for further study
Ms vs SFR

- LAEs with larger EW have smaller stellar masses
- 2/3 LAEs: lie on the extrapolation of the SFMS
- 1/3 LAEs: SB galaxies with stellar mass of $\sim 10^7 M_\odot$
  - ~200 candidates of extremely low-Ms galaxies
  - >> less than 30 galaxies in the previous work
Extremely Low-Mass LAEs: physical properties

- $\text{EW}(\text{Lya}) \sim 80\text{Å}$
  $L(\text{Ly}a) = 1.7 \times 10^{42} \text{ erg/s}$,
  $\beta \sim -2$
  $M_{UV} \sim -18.5\text{mag}$

- $M_* \sim 2.6 \times 10^7 \text{M}_\odot$
  sSFR $\sim 160 \text{ /Gyr}$
  Age $\sim 7 \text{ Myr}$
  fesc of LyC $\sim 30\%$
  $L(\text{Ha}) \sim 6 \times 10^{41} \text{ erg/s}$

- $M_h \sim 10^{10}-10^{11}\text{M}_\odot$
  Baryon Conversion Efficiency
  $= \text{SFR}/\text{baryon accretion rate} \sim 0.1-1$
  $\gtrsim$ typical value 0.1 from B13’s relation
Extremely Low-Mass Galaxies: number density

- $n \approx 6 \times 10^{-4} / \text{Mpc}^3 / \text{dex}$
- Approximately 200 objects in $3.5 \times 10^5 \text{Mpc}^3$
- Assumed MS range $10^7 - 8 \text{M}_\odot$

- ~10-100 times smaller than extrapolation of SMF
- Large number of Extremely Low-Mass Galaxies with undetectably low SFRs
Extremely Low-Mass Galaxies: universality of the strong starburst

- Galaxies form stars along SFMS at $M_* = 10^7 - 10^8 M_\odot$
  - Staying time between $M_* = 10^7$ and $10^8 M_\odot \sim 300$ Myr

- Age/staying time $\sim 10/300 \sim 1/30$
  - $n(M_* = 10^7 - 10^8 M_\odot) = 6 \times 10^{-4} \times 30 \sim 2 \times 10^{-2} / \text{Mpc}^3 / \text{dex}$
  - Comparable to extrapolation of observed SMF at $z \sim 2$
Extremely Low-Mass Galaxies: universality of the strong starburst

- galaxies form stars along SFMS at $M_s = 10^7 - 10^8 M_\odot$
  → staying time between $M_s = 10^7$ and $10^8 M_\odot \sim 300$ Myr

- age/staying time $\sim 10/300 \sim 1/30$
  $n(M_s = 10^7-10^8 M_\odot) = 6 \times 10^{-4} \times 30 \sim 2 \times 10^{-2} /\text{Mpc}^3/\text{dex}$
  → comparable to extrapolation of observed SMF at $z \sim 2$

- majority of $M_s \sim 10^7-10^8 M_\odot$ galaxies
  may experience the strong SB and
  may acquire significant fraction of mass from a strong SB

- more robust discussion will be obtained by HSC survey!
Extremely Low-Mass Galaxies: mechanism of short time burst

- Short time scale of the strong SB:
  - young age \(< 10\) Myr
  - small number density

a) **SN FB terminates the strong SB shortly** → SB phase before onset of SN FB?

b) **no sufficient gas supply?**
   not inconsistent with
   a relatively high BCE
   (=SFR/baryon accretion rate)

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![FIRE simulation (Muratov+15)]
Summary

~2440 LAEs at z~2 from 1deg² field

- average bias parameter = 1.32 ± 0.19 Mh \( \sim 10^{10}-10^{11} \)M\(_{\odot}\)
  - large cosmic variance
  - smaller than Guaita+10 based on 0.3 deg² area

- stellar masses are distributed over \( \sim 10^7-10^9 \)M\(_{\odot}\)
  - large EW(Lya) objects have smaller stellar masses

- ~2/3 form star moderately lying on SFMS
  - ~1/3 have extremely low stellar mass (Ms~\(10^7-10^8\)M\(_{\odot}\))
    - with strong star burst

- Extremely low-mass LAEs:
  - ~200 objects! \( \gg \) 30 (previous work)
  - high sSFR, young age, high BCE → short burst time scale

- HSC enables us to study Mh variation of LAEs
  and physical properties of extremely low-mass galaxies