Our Current View of Galaxy Build-up at Cosmic Dawn

6th Subaru Conference Hiroshima

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The history of astronomy is a history of receding horizons.

E. P. Hubble
Identifying Galaxies at High Redshifts

**Lyα Emitters**

<table>
<thead>
<tr>
<th>B</th>
<th>V</th>
<th>R</th>
<th>i′</th>
<th>z′</th>
<th>NB</th>
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<tr>
<td><img src="image1.png" alt="Image of Lyα Emitters" /></td>
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**Lyman Break Galaxies**

- Typical intrinsic spectrum of massive star
- Received on earth, after passing through ISM

![Image of Lyman Break Galaxies](image2.png)
LBGs with HST: efficient detection out to z~10-12
LBGs with HST: efficient detection out to $z \sim 10-12$
Multi-Tiered Dataset for High-z Studies

All these HST fields combined: $<0.5 \text{ deg}^2$

credit color images: I Momcheva+3DHST
Unprecedented Galaxy Samples at $z \geq 4$
(from HST’s blank fields only)

Almost 1000 galaxies in the epoch of reionization at $z > 6$
Current frontier: $z \sim 9-10$
Source identification

UV Light / SFRs

ISM Properties
Dust Reemission

Rest-frame Optical
Stellar Masses

Spectroscopic Confirmation
K-band imaging

AGN?
Our Multi-Wavelength Census of Early Galaxies

HST:
- rest-frame UV un-obscured SFR

\[ z = 8 \]
\[ \text{SFR} \sim 5 M_\odot/\text{yr} \]

ALMA/NOEMA:
cold gas
dust re-emission closes energy balance

Spitzer:
- rest-frame optical imaging
- stellar masses
- (rest-frame optical emission lines!)

Observed Wavelength [\( \mu \text{m} \)]
Flux \( f_v \) [\( \mu \text{Jy} \)]

Dust emission:
- reprocessed UV photons

Atomic + molecular gas

HST:
- rest-frame UV un-obscured SFR

Spitzer:
- rest-frame optical imaging
- stellar masses
- (rest-frame optical emission lines!)

ALMA/NOEMA:
cold gas
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Matched Deep IRAC Data: Stellar Masses
What can we learn about these early galaxy populations?

→ Some Science Highlights
The Evolution of the UV Luminosity Function to $z \sim 8$

See also: e.g. Oesch+10a/11, Bouwens+10a,11,12; Bunker+10, Finkelstein+10/14, Wilkins+10/11, McLure+10/13, Yan+12, Bradley+12, ...
New Frontier: Faint-End Cutoff/Turnover?

Hubble Frontier Fields: can probe possible turnover in LF at faint luminosities thanks to lensing

Some debate in the literature, due to uncertainties associated with lensing and size distribution of faint galaxies

**clear**: LF continues steep at least to $M_{uv} \sim -14$

See also: e.g., Alavi+14, Atek+15, Ishigaki+15, Laporte+16
Did Galaxies Reionize the Universe?

New Planck polarization results find: $\tau_e = 0.058\pm0.012$, i.e. $z_{\text{reion}} = 8.2\pm1.1$

Consistent with estimates from ultra-faint galaxy population.
Escape of Ionizing Photons?

Escape fraction of ionizing photons is the most uncertain parameter for reionization studies. Recent progress: some sources at high redshift certainly have high enough fesc.
High-Redshift Galaxies Resolved with HST

Sizes of LBGs in first 2 Gyr of cosmic time evolve as: \( r_{1/2} \sim (1+z)^{-1} \)
Consistent with constant L at fixed halo mass.
Evidence for extremely small sizes of faint galaxies at \( z \sim 6-8 \) (e.g. Bouwens+16, Kawamata+15)

\[ M_{\text{UV}} \]

\[ r_e / \text{kpc} \]

\( z=6-8 \)
\( z=4 \)
\( z=5 \)
\( z=6 \)
\( z=7 \)
\( z=8 \)
\( z=9 \)
\( z=10 \)

See also: Ferguson+04, Bouwens+04, Ono+12, Holwerda+14, Curtis-Lake+14
Large Samples → Clustering

Fundamental quantity to measure: stellar-mass to halo-mass relation

First estimates based on $M_{UV}$ selected samples through clustering
Rest-Frame UV Colors of Galaxies at z>4

\[ f_\lambda \sim \lambda^\beta \]

\( \beta = \text{UV continuum slope} \)

UV continuum slopes have so far been used for dust corrections at z>3 based on local relations!

See also: Wilkins+11, Dunlop+12/13, Castellano+11, Bouwens+09/10, Finkelstein+10/12, Rogers+13/14
Cosmic SFR Density

Use UV continuum slope measurements to correct for dust extinction:

\[ \rightarrow \text{cosmic SFR density} \]

Remarkably smooth build-up of cosmic SFRD at z~8 to z~2-3
Below z~4, dust-obscured SFR dominates

see also e.g. Bouwens+07; Oesch+10d; Bouwens+11,15; Bunker+10, McLure+11,13, Finkelstein+12,14, Schenker+13, ...
First ALMA Constraints on LBG Dust Reemission

Much less emission than expected!
Less dust than we thought from UV slopes?

![Image of ALMA telescope array with data points and diagrams]

- Meurer et al. (1999) (Calzetti like dust)
- Pettini et al. (1998) (SMC like dust)
- This work, detections
- This work, upper limits
- This work, mean of undetected

Typically assumed dust law

- z~4-10
- z~4-10
- z~4-10

- log M<9.75
- (2σ limits)

- log_{10}M/M_⊙<9.75
- 95% confidence

Bouwens+16
see also Dunlop+16

Capak+15

UV Slope (β)

log_{10}IRX

z~5

Log-log plot showing constraints on IRX versus UV slope for different redshift bins.
Probing the Frontier of Galaxies

*HST can detect galaxies out to z~10-12*
Sample of 4 Bright z~9-10 Galaxy Candidates

H=26.8

H=26.6

H=26.0

H=26.8

NASA and ESA

GOODS-N
HST ACS/WFC WFC3/IR

ACS/WFC F435W + F606W
ACS/WFC F814W + F850LP
WFC3/IR F125W + F160W

STScI-PRC14-05a

P. Oesch, Observatoire UniGE

Subaru Conference, Nov 2016
Triply Imaged z~10 Candidate in First FF Cluster

Zitrin+14 (see also Oesch et al. 2015)

H = 29.9 mag (de-magnified)
zphot = 9.8+-0.4
magnification: 10-11x

strong geometric support of high redshift solution of photo-z

HST

OBSERVATIONS

Franx et al.

Bouwens et al.

Zheng et al.

Next, we run

A detailed description of our data reduction and pho-

Franx et al.

Zheng et al.

Bouwens et al.

Richard et al.

Calibrated Data (cBCD) images using standard meth-

SExtractor

Peng et al.

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SFRD Evolution at $z>8$

Full analysis of first 4 HFFs confirms: SFRD evolves very rapidly beyond $z \sim 8$

but see McLeod+16

see also: Zheng+12, Coe+13, Bouwens+13/15, Ellis+13, McLure+13, Ishigaki+14

$\log \text{SFR Density} \left[ M_\odot \text{yr}^{-1}/\text{Mpc}^3 \right] > 0.7 M_\odot/\text{yr}$

$\alpha (1+z)^{-3.6}$

HFF 4 Clusters
GOODS−N/S + HUDF09/XDF
CLASH
The UV Luminosity Function at the Cosmic Frontier

Including HFF galaxy candidates, now have a quite good estimate of the UV LF at $z\sim10$.

It lies a factor $\sim12x$ below the $z\sim8$ UV LF measurement at all luminosities.

Confirms fast evolution from $z\sim8$ to $z\sim10$. 

Oesch+17, in prep.
Stellar Mass Build-up

Making use of HST+Spitzer imaging over CANDELS (and accounting for rest-frame optical emission lines):

estimates of the stellar MF out to z~8

“main sequence” of star-formation at z~4-6

see also: Grazian+15, Caputi+15, Duncan+14, Ilbert+13, Muzzin+13, Gonzalez+11, Lee+12
Sample of 4 Bright $z \approx 9-10$ Galaxy Candidates

Powerful combination of HST and Spitzer to explore most distant galaxies
Stellar Mass Density Evolution to $z \sim 10$

Stellar mass density estimates at $z > 4$ nicely match up with mass limited studies at $z < 4$. Are witnessing the assembly of the first $0.1\%$ of local stellar mass density. The first two Gyr are a very active epoch of galaxy assembly.
very bright z~10 sample from Oesch+14 is within reach of the WFC3/IR grism
Lyman Break Detection at $z=11$

- 12 orbits of HST grism spectra with WFC3/IR
- Detect UV continuum (at $5.5\sigma$) and a break at $\lambda > 1.47 \mu m$
- Rule out potential lower redshift solutions (quiescent galaxy at $z \sim 2$ or strong emission line source)
- Best-fit redshift: $z=11.09\pm0.10$

$GN-z10-1 \rightarrow GN-z11$

Most distant source ever seen
Build-up of massive galaxies well underway at 400 Myr after Big Bang
Physical Properties of GN-z11 in Line with Models

The derived physical properties (SFR, mass, and age) of GN-z11 are in very good agreement with expectations from large-volume simulations.
GN-z11 is off the Charts

- Detection of GN-z11 in existing data is quite unexpected, given current models.
- Expected to require 10-100x larger areas to find one such bright z~11 galaxy as GN-z11.
- Difficult to draw conclusions based on one source. **Need larger survey!**
Changing Physics at Highest Redshifts?

Massive galaxies found in current surveys at high redshift are still compatible with “standard” picture of galaxy formation.
The Current Spectroscopic Frontier

With surprising discovery of GN-z11, HST+Spitzer have already reached into JWST territory.
Moving Forward with JWST NIRSPEC

However, JWST spectroscopy will completely revolutionize this field!

JWST can in principle get spectroscopic redshifts for every single source currently known with HST.
JWST/NIRSpec: Unprecedented Spectra

Simulation based on \( z=7.73 \) source from Oesch+15

- JWST will be extremely efficient in spectroscopic characterization of \( z>7 \) galaxies
- For brightest targets, like the recently confirmed target EGS-zs8-1 at \( z=7.73 \), we will even be able to measure absorption lines

What is the ionization state of gas in early galaxies?
What is their dynamical state?
How fast did they build up their metals?

Wide area surveys like HSC are critical to find bright targets that will provide unique information with JWST spectra
Summary

- Deep imaging with HST enabled the detection of an unprecedented sample of galaxies at z>3 (11’000), and extended our frontier into the heart of the cosmic reionization epoch (~1000 galaxies at z~7-10). Cosmic Frontier: z=11.1

- The UV LF is extremely steep during the reionization epoch (faint end slopes as steep as $\alpha = -2$) → ultra-faint galaxies likely main drivers for reionization

- Combination of very deep HST and IRAC data allow us to measure rest-frame optical colors and stellar mass build-up from z~10 to z~3-4. We now explored 97% of cosmic history in build-up of star-formation and mass

- Discovery of GN-z11 in current search area is surprising according to models: Need larger area surveys to confirm the number densities of bright galaxies at z>10. Needs to be done now with HST, likely won’t be done with JWST!

- Finding bright galaxies at high redshift (e.g. with HSC) is crucial for JWST: these sources will give access to unique information with spectroscopy