High-Redshift Predictions and Early Results from the Frontier Fields

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MACSJ0416.1-2403
Frontier Fields + SN + CLASH
deep ACS + WFC3/IR imaging
Hubble has observed galaxy evolution over 13 billion years

Hubble Sequence

Elliptical
Abell S0740
Blakeslee

Spiral
M74
Chandar

Irregular, Starburst
Antennae
Whitmore

Clump clusters, chains
in CANDELS
z = 2.05
Wuyts12
3 Gyr

Single clump?
r ~ 100 pc
in CLASH
A1689-zD1
z ~ 7.8
Bradley08
650 Myr

MACS0647-JD
z ~ 10.8
Coe13
420 Myr

All images from Hubble

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Frontier questions about galaxy evolution

- When did the first galaxies form?

  - $z \sim 10$ (465 Myr)
  - $z \sim 30$ (100 Myr)

  - $z < 13$ (325 Myr)

  - First galaxy: $\sim 10^8 M_\odot$
  - First stars: $\sim 10^6 M_\odot$
  - Second-generation stars
  - First low-mass stars?

  - Hubble: $z < 13$ (325 Myr)

  - Clark et al. (2011)

  - Greif et al. (2010)

  - Bromm & Yoshida 2011 ARA&A

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Frontier questions about galaxy evolution

• When did the first galaxies form?
• What were their properties?
• How many were there?
• Did they reionize the universe?
CLASH revealed two robust candidates in the first 500 Myr

MACS1149-JD
$z \sim 9.6$ (490 Myr)
Wei Zheng et al. (2012)
Nature 489, 406

MACS0647-JD
$z \sim 10.8$ (420 Myr)
Dan Coe et al. (2013)
ApJ 762, 32

in 2 / 5 “high-magnification” CLASH clusters

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How can we improve on the Hubble deep fields before the launch of JWST?

-Matt Mountain
STScI director

Hubble Probes the Early Universe

1990
Ground-based observatories

1995
Hubble Deep Field

2004
Hubble Ultra Deep Field

2010
Hubble Ultra Deep Field-IR

FUTURE
James Webb Space Telescope

Redshift (z):
Time after the Big Bang

1 4 5 6 7 8 10 >20
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

reionization
Dark Ages

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Coe & Zheng led white paper recommending deep WFC3/IR imaging of strong lensing galaxy clusters

submitted to the HDFI science working group chaired by James Bullock

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Dramatic build up at $z > 9$ (first 500 Myr)?

Implications for reionization / first galaxies?

Only one $z \sim 10$ candidate found where nine were expected (Bouwens11, Oesch13)

adapted from Bouwens12
see also Oesch12,13
Multiple models predict $z > 9$ drop off in star formation rate and mass densities.
But at least one model predicts smoother $z > 9$ evolution
And at least one recent analysis finds a smoother $z > 9$ evolution.
The Frontier Fields should confirm or rule out dramatic $z > 9$ evolution with high confidence.
Only a handful of $z > 9$ candidates have been discovered to date.

Lensed magnifications

(Zheng12, Coe13)
Only a handful of $z > 9$ candidates have been discovered to date.
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~14 $z > 9$ candidates

~200 $z \sim 8$ candidates (e.g., Bouwens14, Finkelstein14)
The Frontier Fields and BoRG\([z9-10]\) may make \(z \sim 9\) the new \(z \sim 8\) with \(\sim 100\) candidates.
We predict up to $\sim 70$ $z > 9$ galaxies in the Frontier Fields (6 per field) not accounting for incompleteness.
Lens model uncertainties propagate to some, but not all, observables

<table>
<thead>
<tr>
<th>Full uncertainties</th>
<th>Reduced uncertainties (integrated quantities)</th>
<th>No added uncertainties</th>
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</thead>
<tbody>
<tr>
<td>Luminosity:</td>
<td>Number counts:</td>
<td>Colors:</td>
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<tr>
<td>- Mass</td>
<td>- Luminosity function</td>
<td>- Redshift</td>
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<tr>
<td>- Star formation rate</td>
<td>- Star formation rate</td>
<td>- Age (Balmer break)</td>
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<td>Size (radius)</td>
<td>cosmic density</td>
<td>- Metallicity</td>
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<td>- Equivalent Width (EW)</td>
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<td>- UV slope $\beta$</td>
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<td></td>
<td>Specific star formation rate (SFR / stellar mass)</td>
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Did galaxies reionize the early universe?
Pre-FF submitted lens models of Abell 2744

"CATS" (PIs Kneib & Natarajan)
Richard Limousin

Sharon Johnson
Zitrin: NFW
Zitrin: LTM

Williams Sebesta
Bradac Hoag
Merten (wide field)

Abell 2744
red = magnification for a lensed galaxy at $z = 9$
green = HST
blue = mass

3 new lens models submitted based in part on Frontier Fields HST imaging

<table>
<thead>
<tr>
<th>Model</th>
<th>Abell 2744</th>
<th>MACS J0416.1-2403</th>
<th>MACS J0717.5+3745</th>
<th>MACS J1149.5+2223</th>
<th>Abell S1063</th>
<th>Abell 370</th>
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</table>

Interactive model magnification web tool

**Input**

RA, Dec, redshift of lensed galaxies

**Output**

Magnification estimates with uncertainties

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Uncertainty calculations add a few seconds response time per lensed galaxy per group.

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This web-based lens model tool is not supported or maintained by MAST. If you have any questions about its use, or about the accuracy of its results, please email Dan Coe at Dano@Yale.edu.
The lensed Frontier Fields are yielding the faintest galaxies yet observed.
Lens models yield consistent predictions for faint lensed number counts

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Large extrapolations required to estimate faint galaxy contribution to reionization

\[ M_{UV} -10 \] (smallest galaxies?)

\[ z \sim 8 \] luminosity function

field data

other uncertainties:
- escape fraction
- clumping factor
The Frontier Fields will tightly constrain high-z luminosity function faint end slopes

$z \sim 7$ LF faint end slope: 
precision $\rightarrow$ 0.05

UV luminosity density: 
2x precision $\rightarrow$ 30%

Robertson et al. (2014)
The need for multiple sightlines: cosmic variance

$\phi^* / \langle \phi^* \rangle$

Relative Normalization

Redshift

factor of 3 (+/- 50%)

Bouwens et al. 2014
arXiv:1403.4295

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Cosmic variance estimates for the Frontier Fields

Brighter galaxies are more biased tracers of mass

Bias diminishes over time as larger galaxies form
Lensing can increase cosmic variance

Lensing
decreases search volume: CV ↑
and probes fainter galaxies: CV ↓
Lensing can increase cosmic variance

Lensing decreases search volume: CV ↑
and probes fainter galaxies: CV ↓
Lensing affects cosmic variance by 
\(~10\%\) wrt blank field at \(z = 7 – 10\)

Lensing decreases search volume: \(CV \uparrow\)
and probes fainter galaxies: \(CV \downarrow\)

Brant cautions that nonlinear halo bias
(not included here)
will be more significant for the lensed fields
with their smaller volumes
High-z candidates lensed by A2744

(see papers led by Zheng; Atek; Laporte; Coe; Zitrin; Ishigaki; Oesch...)

Ishigaki et al. (2014)
SExtractor detection with CLASH parameters

Abell 2744 complete Hubble Frontier Fields imaging
More aggressive SExtractor parameters

z ~ 10 candidate (Zitrin et al.)

Abell 2744 complete Hubble Frontier Fields imaging
9 < z < 11 galaxies can look like red z ~ 2 galaxies in the FF HST filters
$z \sim 10$ galaxies can look like red $z \sim 2$ galaxies in the FF HST filters

$z = 11.0$ starburst
$z = 2.5$ elliptical
$z \sim 10$ galaxies can look like red $z \sim 2$ galaxies in the FF HST filters

$z = 11.0$ starburst
$z = 2.5$ elliptical
Hubble + Spitzer photometry can distinguish blue $z \sim 10$ galaxies from red $z \sim 2$ galaxies
Spitzer photometry adds confidence to $z \sim 10$ candidates

$z = 9.6$ starburst

JD1A photometry from Zitrin et al.
Spitzer detection limits within ~2 mag of HST flux add confidence to z ~ 10 candidates

JD1A HST photometry from Zitrin et al.

z = 3.2 elliptical

inflated Spitzer uncertainties

2.5 mag
The Frontier Fields will strongly constrain high-z galaxy evolution and reionization

I believe our biggest current obstacles (which are being overcome) are detecting faint galaxies and HST + Spitzer photometry, not lensing uncertainties nor cosmic variance.
Thank you