The High-redshift Universe, Magnified

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High-redshift Galaxy Formation

- First few Gyr of cosmic history were a very exciting time!
  - Star formation grows to a peak around $z \sim 2$, then falls off
  - High density, large gas supplies, active stirring
High-redshift Galaxy Formation

- Detailed simulations now exist but physics are not completely constrained
High-redshift Galaxy Formation

- To understand galaxy formation, we want to approximate local observations
  - In FIR, we may even want to exceed local observations
- This is hard for faint emission from the cool ISM

M51 CO

M51 CII

Schinnerer et al. 2013
High-redshift Galaxy Formation

- Our view is less exciting!
  - Still true with ALMA

GN20 (z=4.05)
Hodge et al. 2015

z~6 QSOs
Carilli & Walter 2013
South Pole Telescope

R = 90 GHz, 3.2 mm
G = 150 GHz, 2.0 mm
B = 220 GHz, 1.4 mm
South Pole Telescope

SPT0547-51 (β Pic)

VLT 2.2um
SMA 1.3mm

SPT0538-50 (not β Pic!)
Gravitationally Lensed Galaxies

Vieira, DPM et al. 2013
Gravitationally Lensed Galaxies

SPT0418-47

0.15"

SPT0538-50

Vieira, DPM et al. 2013

Cycle 0 – 1min/src

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Gravitationally Lensed Galaxies

Vieira, DPM et al. 2013

SPT0418-47

0.03"

SPT013-46  SPT0125-47  SPT0125-50

SPT0300-46  SPT0319-47  SPT0345-47
[2.3:18.5] mJy  [2.3:34.3] mJy  [2.3:31.2] mJy

SPT0441-46  SPT0452-50
[2.3:45.8] mJy  [2.3:23.5] mJy

SPT0532-50  SPT0538-50  SPT2103-50  SPT2132-58
Distant Gravitationally Lensed Galaxies

Cycle 0 - 10min/src

Weiss et al. 2013

Vieira, DPM et al. 2013
Distant Gravitationally Lensed Galaxies

Cycle 4 – z=6.9

Weiss et al. 2013

Strandet et al. 2017
Marrone et al. 2018
Distant Gravitationally Lensed Galaxies

\[ z_{\text{med}} = 4.1 \quad (\sim 70 \, \text{sources}) \]

Weiss et al. 2013
Strandet et al. 2016
Interferometric Lens Modeling

SPT0346-52

Hezaveh, DPM et al. 2013

Spilker, DPM et al. 2016
Interferometric Lens Modeling

SPT0346-52

Cycle 0 Model
(Data: 2" resolution)

Cycle 2 Data
(0.15" resolution)
Advanced Lens Modeling

SDP81
Vlahakis et al. 2015
Tamura et al 2015

Reconstructed Sky Plane

Source Plane
100 pc

Hezaveh et al 2016
Advanced Lens Modeling

SDP81
Vlahakis et al. 2015
Tamura et al. 2015

Reconstructed Sky Plane

10^9 M_{\odot} Subhalo

Hezaveh et al. 2016

Vegetti et al. 2010

Source Plane
100 pc
Massive Galaxy Astrophysics: SPT0346-52

- Most intense galaxy-scale star-formation in the universe!
  - $3 \times 10^{13} \text{ L}_{\odot}$ within a 600pc half-light radius
- No evidence for AGN in X-ray
  - This is star-formation powered!

Ma et al. 2016
Massive Galaxy Astrophysics: SPT0346-52

Contours: 160um continuum
Image: 158um CII emission

Litke, DPM et al. 2018

Source-plane reconstruction

Continent

CII

Source-Plane Offset (kpc)

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Massive Galaxy Astrophysics: SPT0346-52

- A massive merger
- Two highly unstable components!
Massive Galaxy Astrophysics: Outflows

• OH 119um blue absorption against z=5.3 SMG
  • Implied mass outflow is $\sim 500M_{\odot}/yr$
    – Molecular gas depletion by SF and outflow similar
• Direct observation of quenching in massive galaxy?

Spilker et al. 2018 (submitted)
Massive Galaxy Formation: Reionization

SPT0311-58 at $z=6.900$
780 Myr after the Big Bang
IGM still 50% neutral

Marrone et al. 2018

Strandet et al. 2017
Massive Galaxy Formation: Reionization

90μm Continuum Data Model Residual Source Plane
Peak S/N = 121

CII 158μm Data Cube

-480 km/s
Peak S/N = 9

Marrone et al. 2018
Massive Galaxy Formation: Reionization

- Two galaxies!
  - Separated by 8kpc and 700 km/s
  - Very different line and continuum properties
  - Large velocity dispersions

Marrone et al. 2018
Massive Galaxy Formation: Reionization

- Total halo mass larger than any known at $z > 5$
- Only handful in whole sky

![Graph](image-url)

- DSFG
- QSO
- LBG
- HFLS3
- SPT0311-58

Age of Universe (Gyr)

$M_{\text{halo}} (M_\odot)$

Marrone et al. 2018
Massive Galaxy Formation: Reionization

NRAO/AUI/NSF; D. Berry
Massive Galaxy Formation: Reionization

160µm Continuum
(Cycle 4 – 0.25")

(Cycle 5 – 0.06")