Optically dark ALMA sources shed light on the formation of a large-scale structure at $z \sim 3.5$

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Cosmic Star Formation Density

Madau & Dickinson (2014)
Cosmic Star Formation Density

Madau & Dickinson (2014)
Cosmic Star Formation Density

Madau & Dickinson (2014)

Extremely Big Eyes on the Early Universe
**Contribution to cosmic SFD**

**optically dark galaxies = 10x equivalently massive LBGs**

Wang et al. 2019

**protocluster galaxies:**
important/dominant contributors to cosmic SFD

Chiang et al. 2017
Extremely Big Eyes on the Early Universe

Satellite

**IRAS 1985**
- 57 cm
- 41" fwhm
- 100 µm

**ISO 1995**
- 60 cm
- 100 µm

**Spitzer 2003**
- 85 cm

**Herschel 2009**
- 350 cm
- FWHM
- 100 µm = 6.7 arcsec

Ground-based

<table>
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<tr>
<th>Instrument</th>
<th>Telescope</th>
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<td>AzTEC</td>
<td>JCMT</td>
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<td>ASTE</td>
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<td>LMT (32 m)</td>
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<td>SCUBA-2</td>
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Casey et al. (2014)

Angular resolution!
Extremely Big Eyes on the Early Universe

Franco et al. 2018 (main)
Franco et al. in prep (supp)

Main catalog (19) + supplementary catalog (16) = 35 detections
> 4.8 sigma

3.5~4.8 sigma
Six optically-dark galaxies out of 35 (17%)

Main catalog:
AGS4, AGS11, AGS15, AGS17

Supplementary catalog:
AGS24, AGS25
Six optically-dark galaxies out of 35 (17%)

Main catalog: AGS4, AGS11, AGS15, AGS17

Supplementary catalog: AGS24, AGS25

Follow-up: AGS4, AGS11, AGS15, AGS17, AGS24
all detected at 2mm

AGS4 and AGS17: emission lines
Most massive galaxies: AGS4, AGS24

AGS4
$M^* = 10^{11.45} \, M_{\odot}$
$z = 4.32$

AGS24
$M^* = 10^{11.26} \, M_{\odot}$
$z = 3.5$
Most massive galaxies: **AGS4, AGS24**

Franco et al. 2018:

\[ z = 4.32 \]

\[ M^* = 10^{11.45} M_{\text{sun}} \]

(AGN, might slightly overestimated)
Most massive galaxies: **AGS4, AGS24**

Franco et al. 2018:
- $z = 4.32$
- $M^* = 10^{11.45} \, M_\odot$
  (AGN, might slightly overestimated)

- $f_{\text{obs}} = 151.44 \, \text{GHz}$
- $S/N = 8.58$

CO(7-6)
- 806.7 GHz:
- $z_{\text{spec}} = 4.326$

Extremely Big Eyes on the Early Universe
Most massive galaxies: AGS4, AGS24

Franco et al. 2018:
\[ z = 4.32 \]
\[ M^* = 10^{11.45} \, M_{\text{sun}} \]
(AGN, might slightly overestimated)

NEW
\[ f_{\text{obs}} = 151.44 \, \text{GHz} \]
\[ S/N = 8.58 \]

CO(7-6)
806.7 GHz:
\[ z_{\text{spec}} = 4.326 \]

Most massive @ \( z > 4 \)
Most massive galaxies: AGS4, AGS24

AGS24
$z = 3.5$

$M^* = 10^{11.26} \, M_{\odot}$
Most massive galaxies: AGS4, AGS24

AGS24
$z = 3.5$

$M^* = 10^{11.26} \text{ } M_{\odot}$

SFH varies:
delayed exponentially declining 11.26
exponentially declining 11.3
truncated 11.29
a second burst 11.27

Attenuation law varies:
SFH_DELAYED_FLEX + CALZETTI 11.30
SFH_DELAYED_FLEX + MAGPHYSlike 11.58
SFH_DELAYED_FLEX + CHARLOT&FALL 11.59
Most massive galaxies: AGS4, AGS24

AGS24
$z = 3.5$
$M^* = 10^{11.26} \, M_{\odot}$

$q_{\text{TIR}} (AGS24) = 2.09$

Star-forming galaxies:
radio spectral index $\alpha = -0.8$
$q_{\text{TIR}}(z=3.5) = 2.16 \pm 0.06$ (Delhaize+2017)

X-ray:
no counterpart in CDF-S 7Ms catalog
Most massive galaxies: AGS4, AGS24

AGS24
- $z = 3.5$
- $M^* = 10^{11.26} M_{\text{sun}}$
- no radio excess, no X-ray excess
- $\Rightarrow$ no AGN (contaminate $M_{\text{star}}$)
- $\Rightarrow$ Most massive non-AGN @ $z > 3$

$q_{\text{TIR}}$ (AGS24) = 2.09

Star-forming galaxies:
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Summary 1.

ALMA detects the most massive galaxies in the early Universe
optically-dark galaxies tracing an overdensity at $z \sim 3.5$

AGS11, 15, 17 within 2’ from AGS24 12 arcmin$^2$

vs.

GOODS-ALMA 69 arcmin$^2$

$\rightarrow 0.4\%$ by chance
optically-dark galaxies tracing an overdensity at $z \sim 3.5$

redshift distribution (grey):

11621 in GOODS-ALMA,
894 zs

1370 at $z = 3-4$,
94 zs (56 zs from VANDELS)

a spike at $z \sim 3.5$
optically-dark galaxies tracing an overdensity at z~3.5

projected number density at z~3.5
optically-dark galaxies tracing an overdensity at $z \sim 3.5$

AGS15
$M^* = 10^{10.66} \, M_{\text{sun}}$
$z = 3.58$

Candels 3818
$M^* = 10^{7.99} \, M_{\text{sun}}$  $10^{9.63}$
$z = 0.68 \, 3.47$
optically-dark galaxies tracing an overdensity at $z \sim 3.5$

Franco et al. 2018
optically-dark galaxies tracing an overdensity at $z \sim 3.5$

AGS24
$M^* = 10^{11.26}$ $M_{\odot}$
$z = 3.5$
optically-dark galaxies tracing an overdensity at $z \sim 3.5$

AGS24
$M^* = 10^{11.26} \, M_{\odot}$
$z = 3.5$
optically-dark galaxies tracing an overdensity at $z \sim 3.5$
Overdensity in GOODS-S:

- Straatman+16, ZFOURGE, fig.23
- Skelton+14, 3D HST, fig.24
- Franck & McGaugh 2016, CCPC-z34-002
- Forrest+17, fig.4: 6 EELGs + 20 SELGs young, less massive, less dusty reionization
Overdensity in GOODS-S:

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- Forrest+17, fig.4: 6 EELGs + 20 SELGs young, less massive, less dusty reionization
- Ginolfi+17, Candels 5001, zspec=3.473, fig.8: a massive galaxy [$\log M_{\text{star}}=10.27$] cosmic gaseous streams feeding
Summary II.

ALMA detected optically-dark galaxies trace a proto-cluster in formation at z~3.5

AGS24: candidate BCG of the proto-cluster
Summary

• Optically-dark galaxies are important contributors to the cosmic star formation density in the early Universe and tend to be associated with proto-clusters.

• Six optically-dark galaxy out of 35 detections in GOODS-ALMA
  • The most massive galaxies in GOODS-S at z≥3.5 (≈ 10^{11.3} M_{\odot})
  • Potential tracers of distant proto-clusters at z~3.5
    • AGS24: candidate BCD in the proto-cluster