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

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ÉCOLE DOCTORALE Astronomie et Astrophysique d'île-de-France

université PARIS-SACLAY

Extremely Big Eyes on the Early Universe

cea énergie atomique • énergies alternatives

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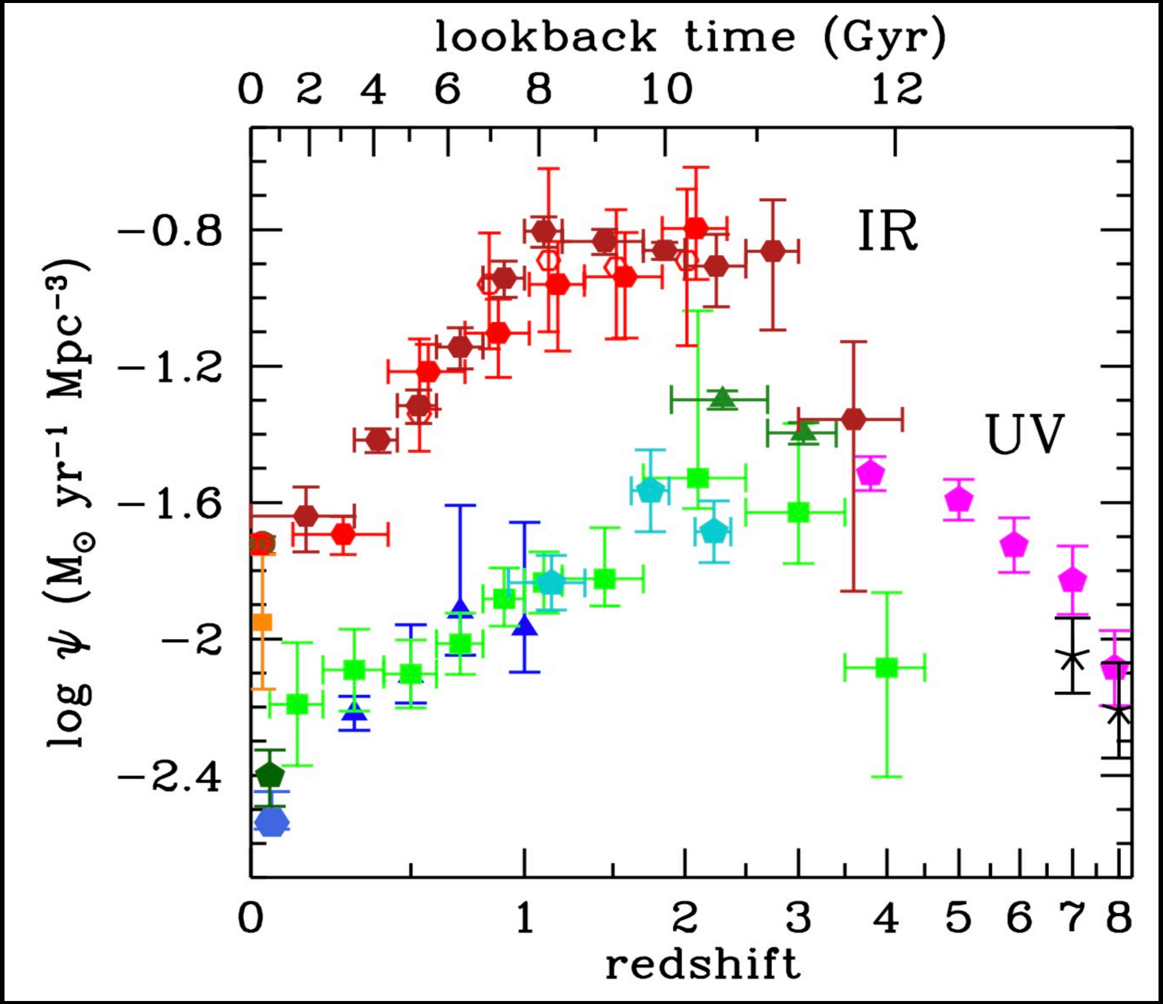
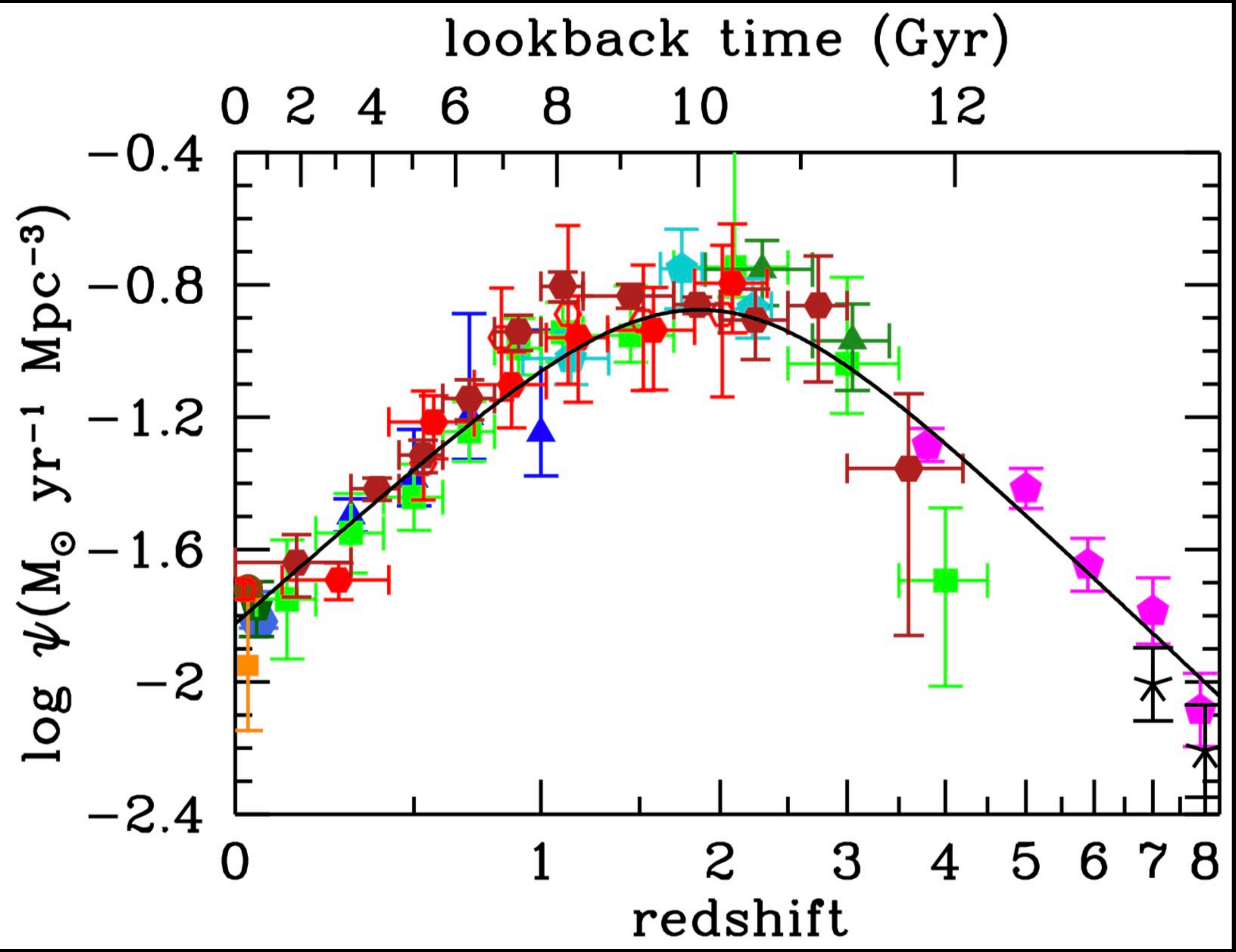
Cosmic Star Formation Density



Madau & Dickinson (2014)

Cosmic Star Formation Density



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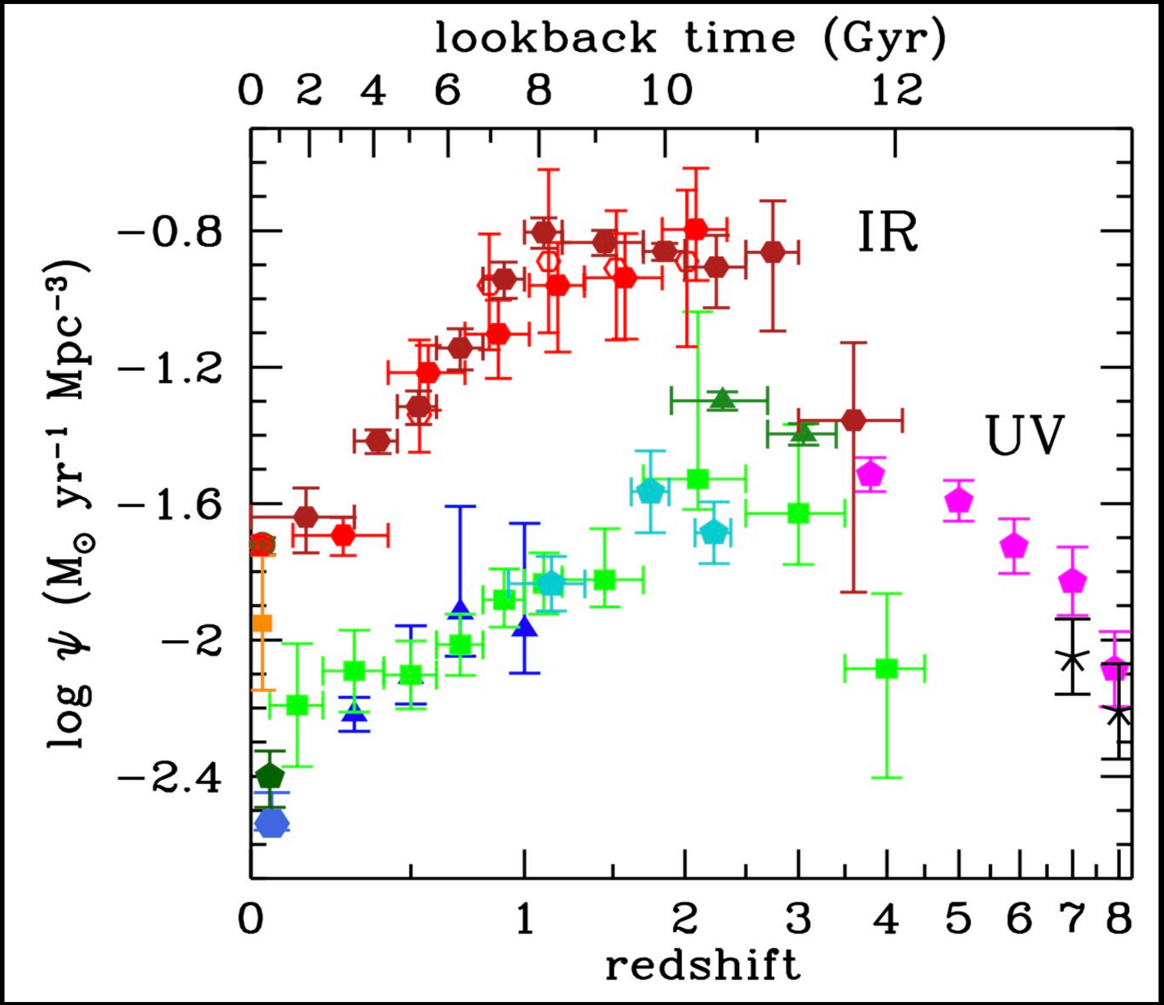
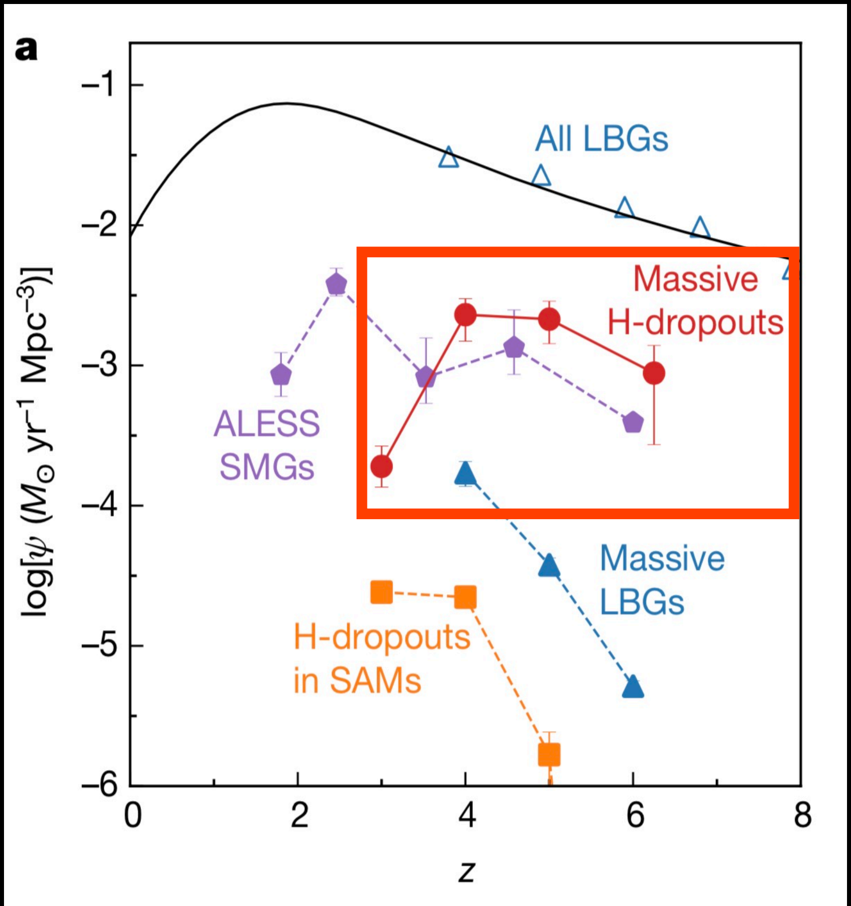
Cosmic Star Formation Density



Madau & Dickinson (2014)

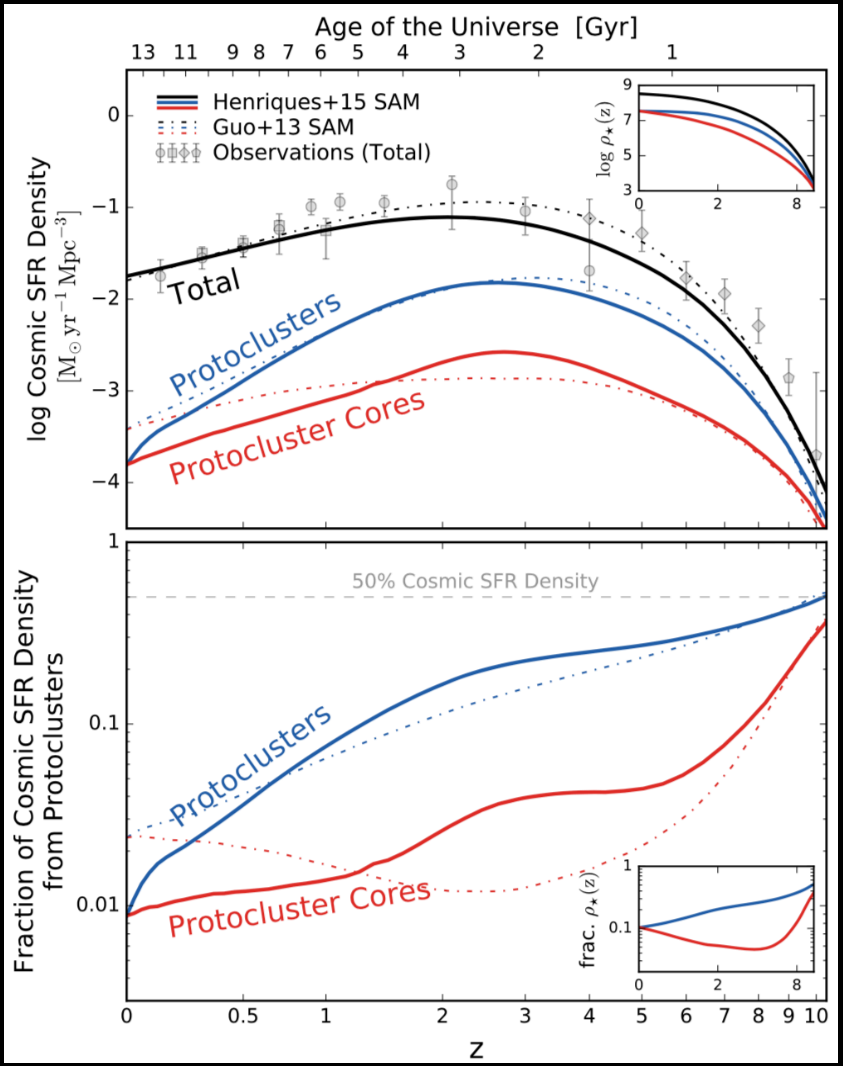
Contribution to cosmic SFD

optically dark galaxies =
10x equivalently massive LBGs



Wang et al. 2019

protocluster galaxies:
important/dominant contributors to cosmic SFD



Chiang et al. 2017

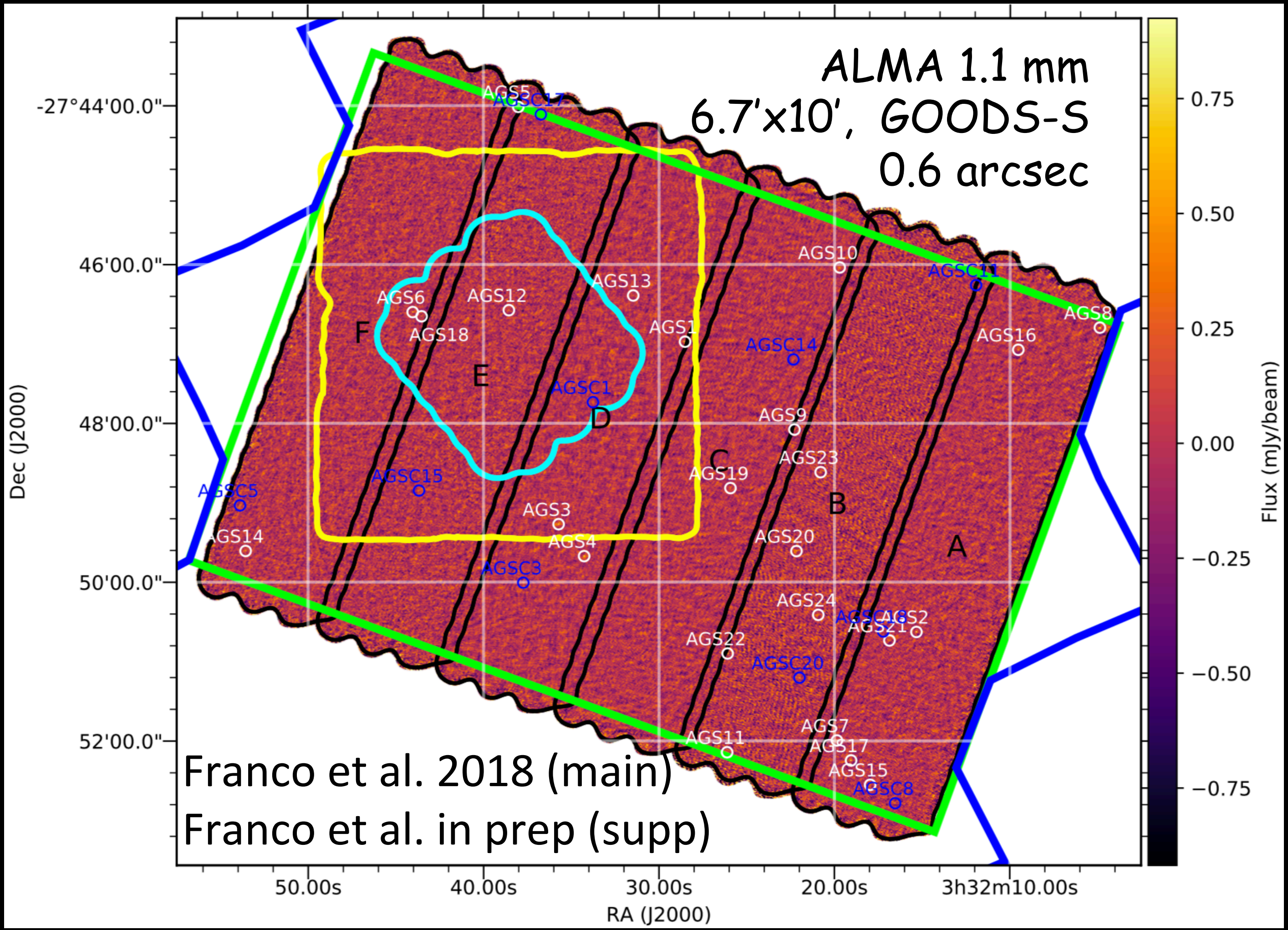
Satellite

Ground-based

AzTEC	JCMT	19″
	ASTE	29″
	LMT (32 m)	9″
	LMT (50 m)	6″
Laboca	APEX	19″
ACT	ACT	54″
		69″
		98″
SPT	SPT	69″
		63″
Saboca	APEX	8″
GISMO	IRAM 30m	24″
Scuba-2	JCMT	15″
		7″

Casey et al. (2014)

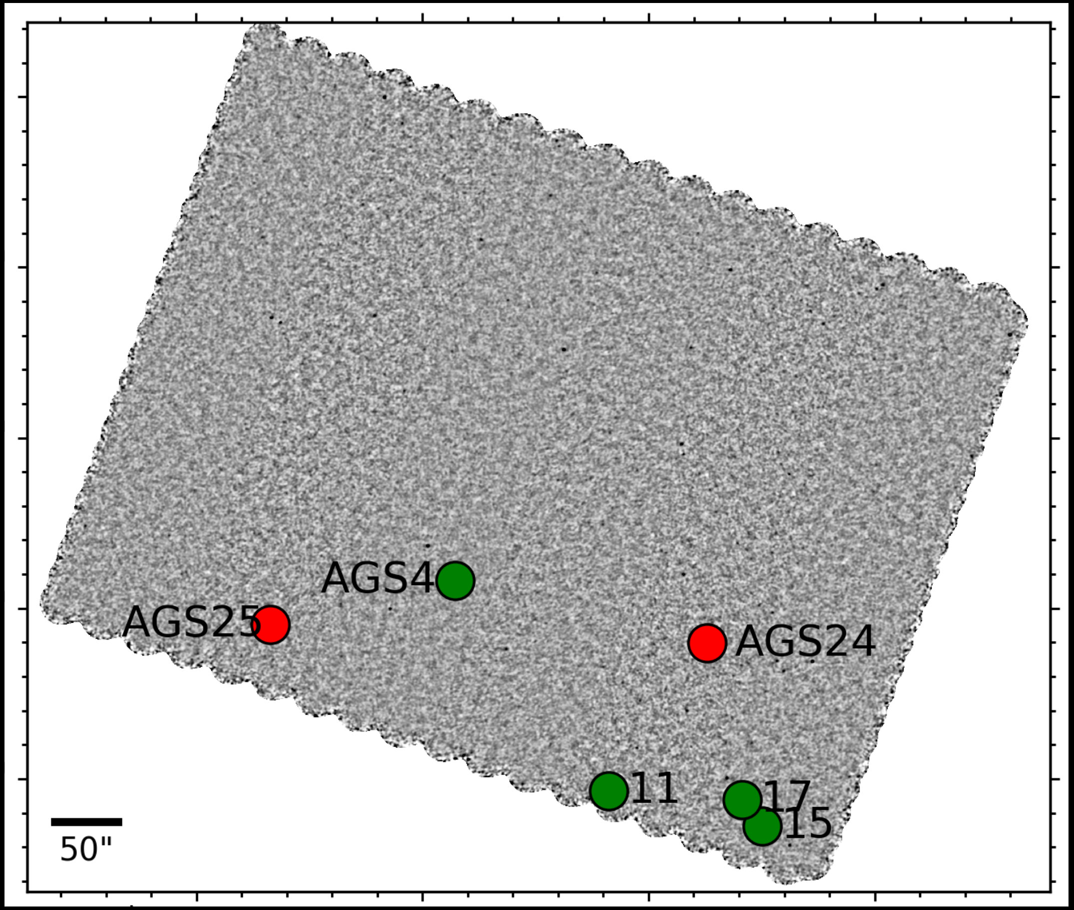
Angular resolution !



Main catalog (19) + supplementary catalog (16) = 35 detections

> 4.8 sigma 3.5~4.8 sigma

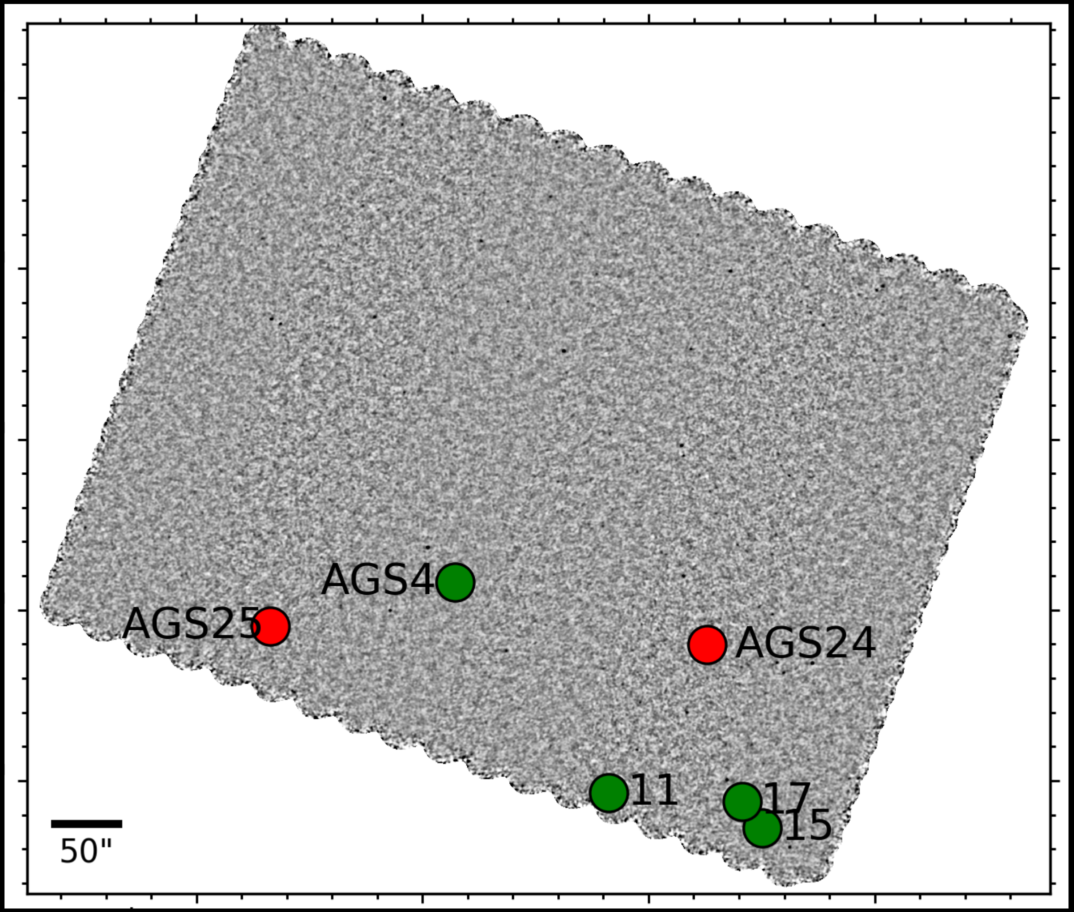
Six optically-dark galaxies out of 35 (17%)



Main catalog:
AGS4, AGS11, AGS15, AGS17

Supplementary catalog:
AGS24, AGS25

Six optically-dark galaxies out of 35 (17%)



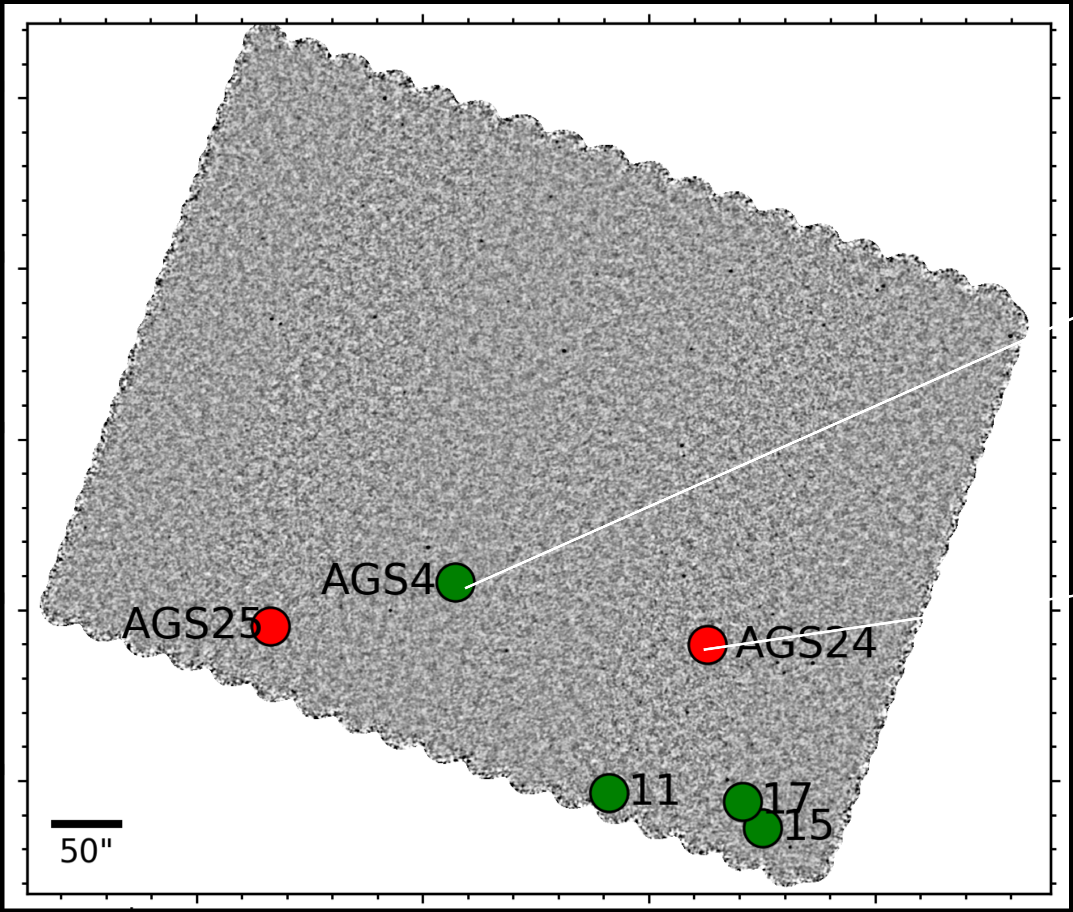
Main catalog:
AGS4, AGS11, AGS15, AGS17

Supplementary catalog:
AGS24, AGS25

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

AGS4 and AGS17: emission lines

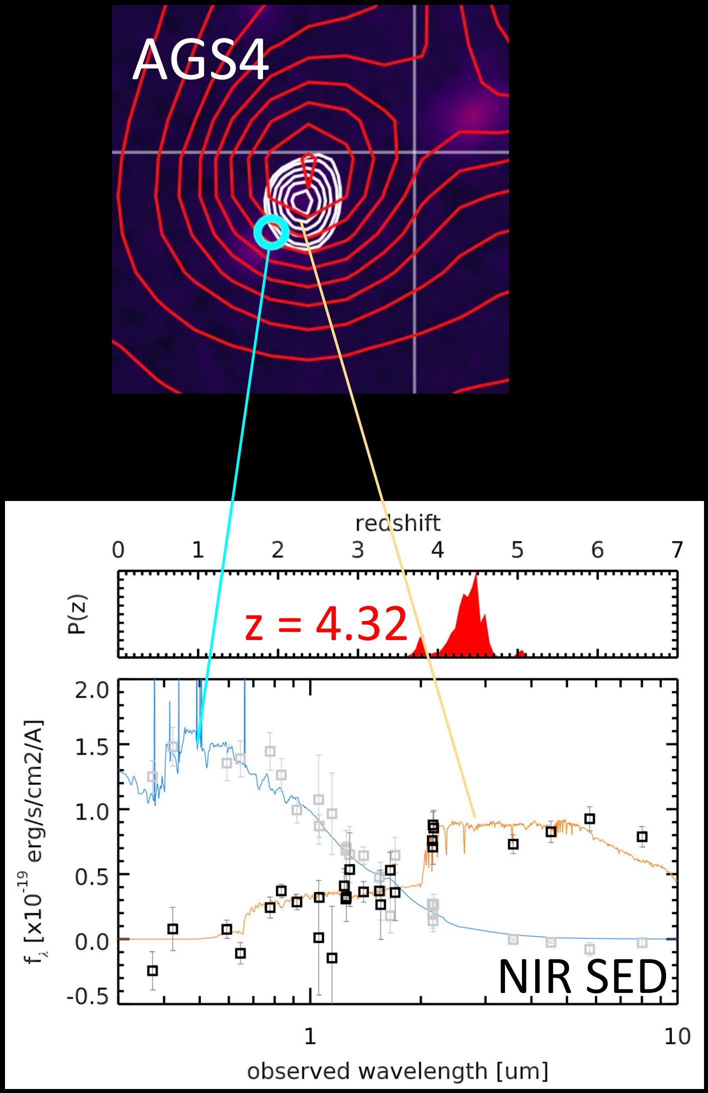
Most massive galaxies: AGS4, AGS24



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

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

Most massive galaxies: AGS4, AGS24

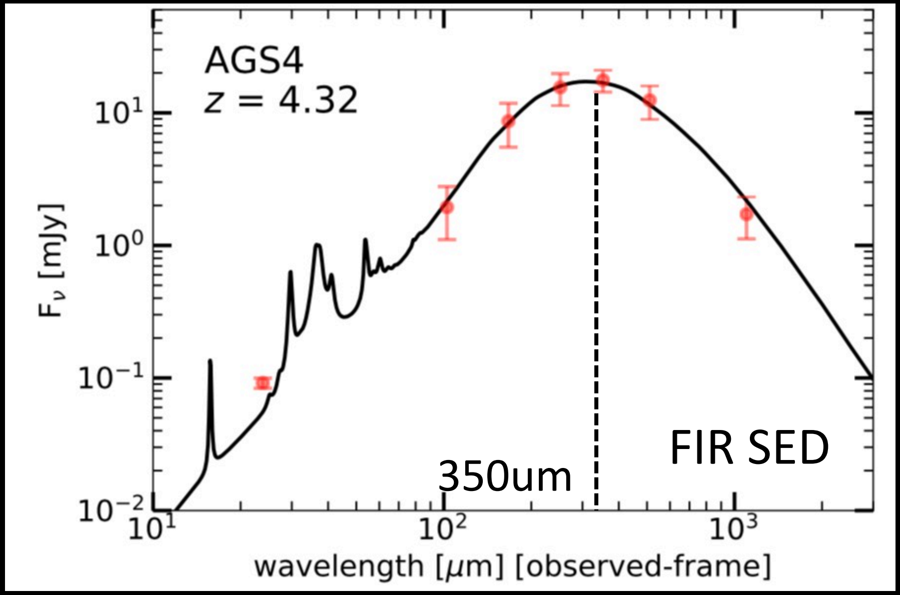


Franco et al. 2018:

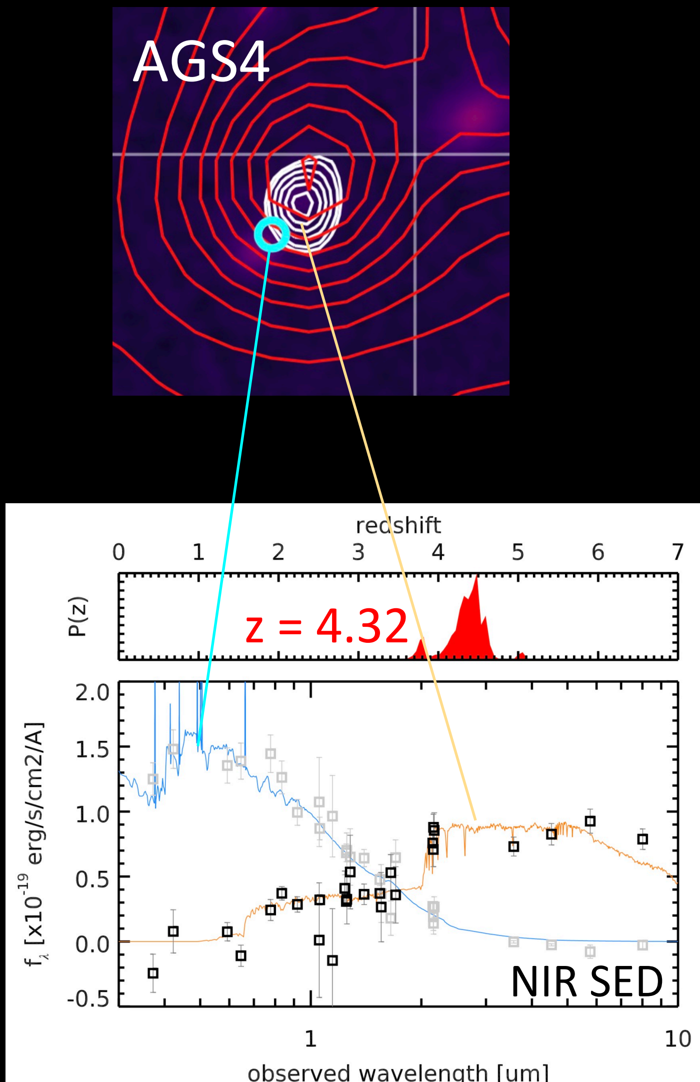
$z = 4.32$

$M^* = 10^{11.45}\ M_{sun}$

(AGN, might slightly overestimated)



Most massive galaxies: AGS4, AGS24



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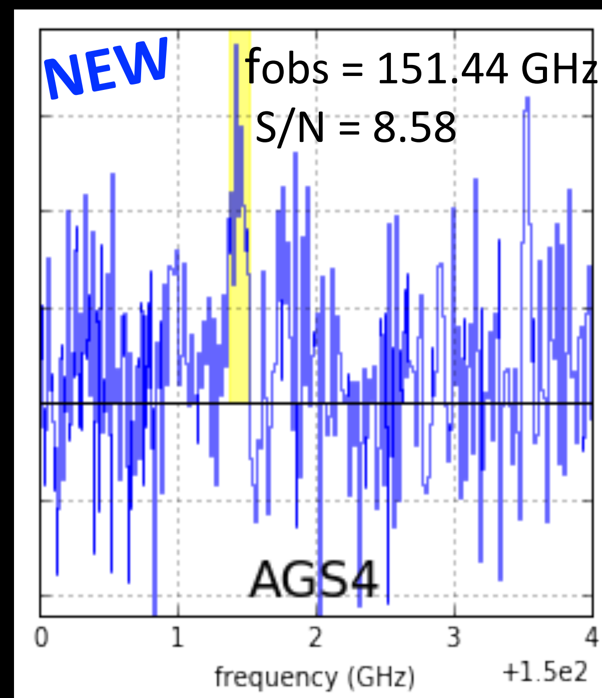
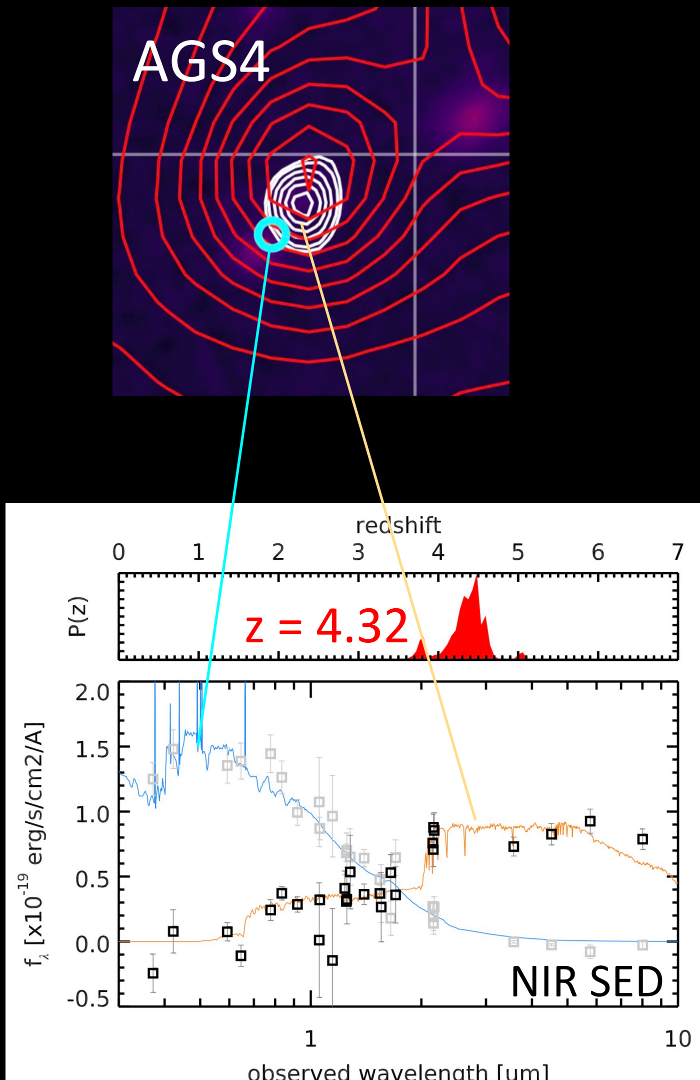


CO(7-6)

806.7 GHz:

z_spec = 4.326

Most massive galaxies: AGS4, AGS24



Franco et al. 2018:

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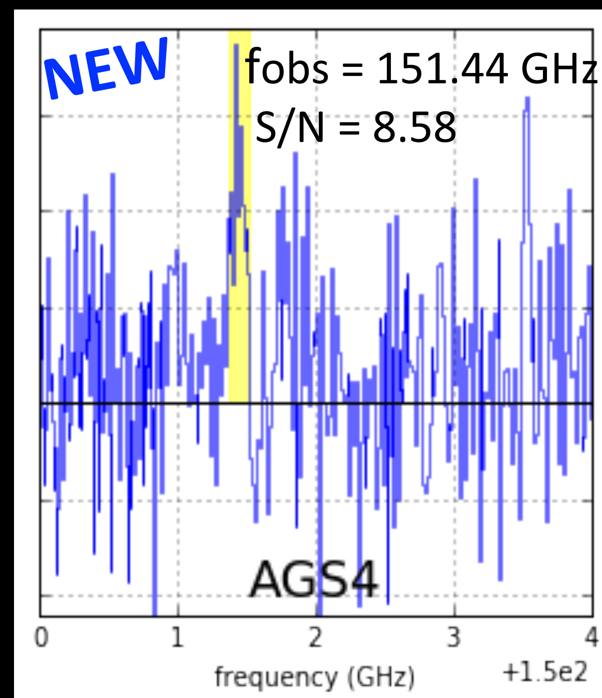
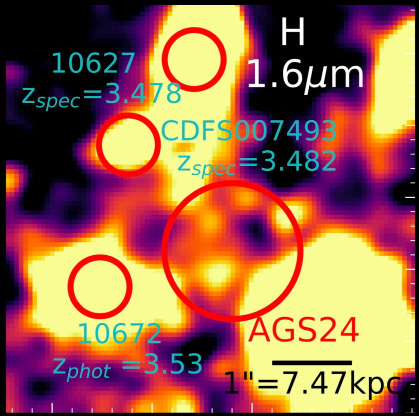


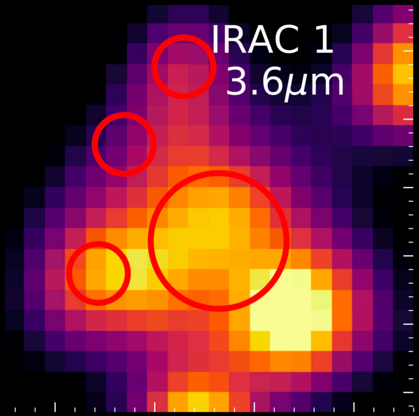
CO(7-6) 806.7 GHz:

z_spec = 4.326

Most massive @z>4

Most massive galaxies: AGS4, AGS24

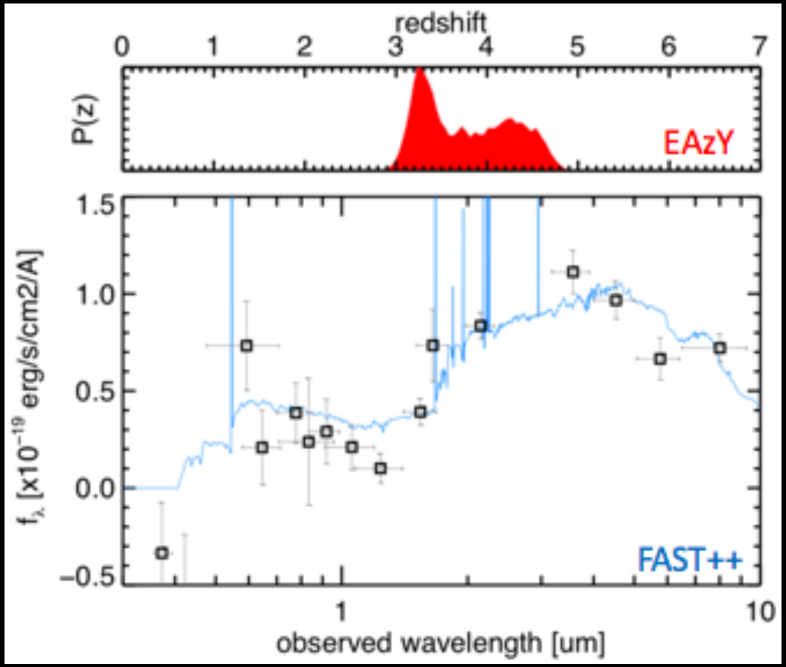




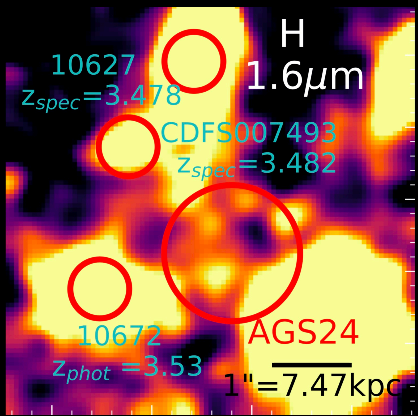
AGS24

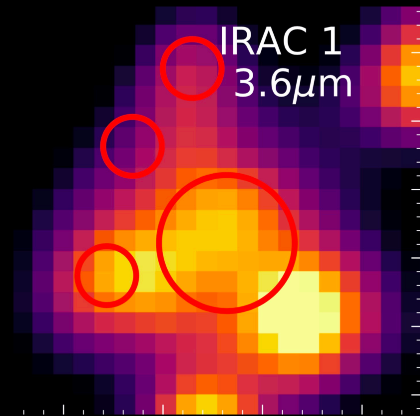
z = 3.5

$M^* = 10^{11.26}\ M_{sun}$



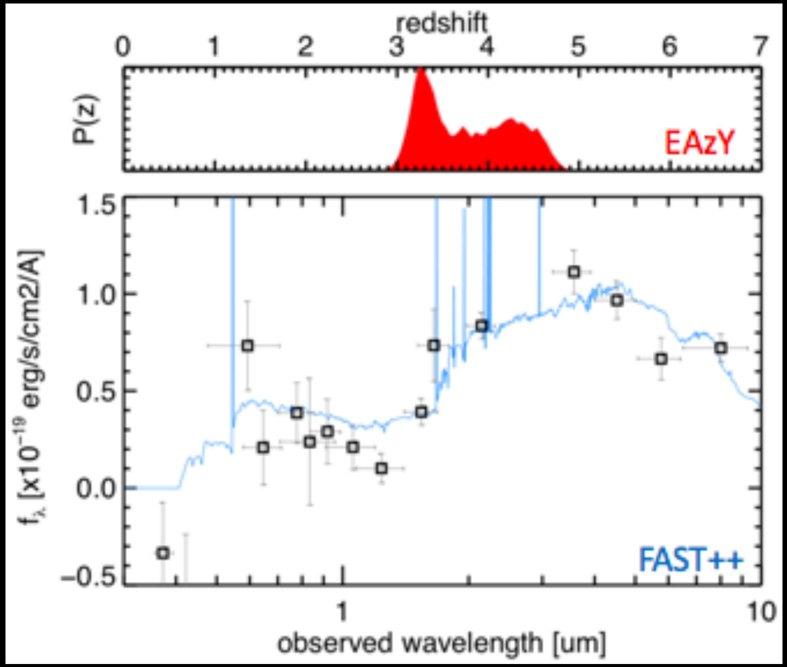
Most massive galaxies: AGS4, AGS24





AGS24
z = 3.5

$M^* = 10^{11.26}\ M_{sun}$



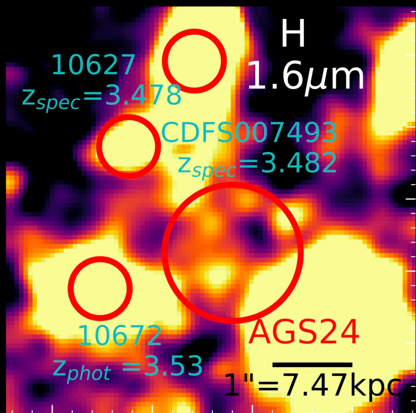
SFH varies:

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_{sun}

q_{TIR} (AGS24) = 2.09

$$q_{\rm TIR} = \log\left(\frac{L_{\rm TIR}}{3.75\times 10^{12}\ {\rm Hz}}\right) - \log\left(\frac{L_{\rm 1.4\ GHz}}{{\rm W\ m^{-2}\ Hz^{-1}}}\right).$$

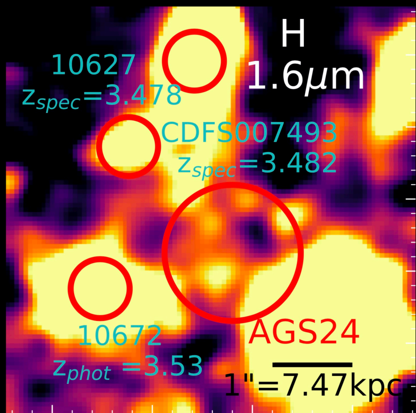
where $L_{\rm TIR}$ is total infrared Luminosity (8-1000 μm), and

$$L_{\rm 1.4\ GHz}\,({\rm W\ Hz^{-1}}) = \frac{4\pi D_L^2}{(1+z)^{\alpha+1}}\left(\frac{1.4}{\nu}\right)^{\alpha} S_{\nu}.$$

Star-forming galaxies:
radio spectral index α= -0.8
qTIR(z=3.5) = 2.16 +- 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_{sun}

no radio excess, no X-ray excess
$\Rightarrow$ no AGN (contaminate M_{star})
$\Rightarrow$ Most massive non-AGN @z>3

q_{TIR} (AGS24) = 2.09

$$q_{\mathrm{TIR}} = \log\left(\frac{L_{\mathrm{TIR}}}{3.75\times 10^{12}\ \mathrm{Hz}}\right) - \log\left(\frac{L_{1.4\ \mathrm{GHz}}}{\mathrm{W\ m^{-2}\ Hz^{-1}}}\right).$$

where L_{TIR} is total infrared Luminosity (8-1000 μm), and

$$L_{1.4\ \mathrm{GHz}}\,(\mathrm{W\ Hz^{-1}}) = \frac{4\pi D_L^2}{(1+z)^{\alpha+1}}\left(\frac{1.4}{\nu}\right)^{\alpha} S_\nu.$$

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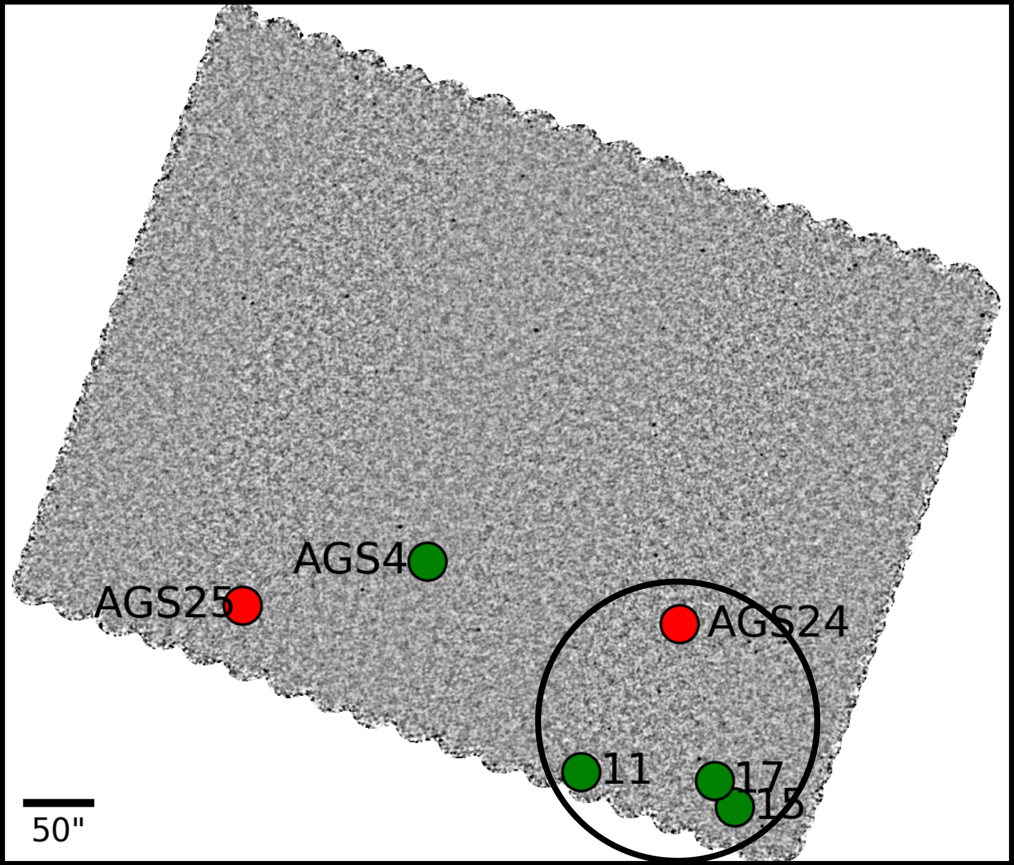
qTIR(z=3.5) = 2.16 +- 0.06 (Delhaize+2017)

X-ray:
no counterpart in CDF-S 7Ms catalog

Summary I.

ALMA detects the most massive galaxies in the early Universe

optically-dark galaxies tracing an overdensity at z~3.5



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

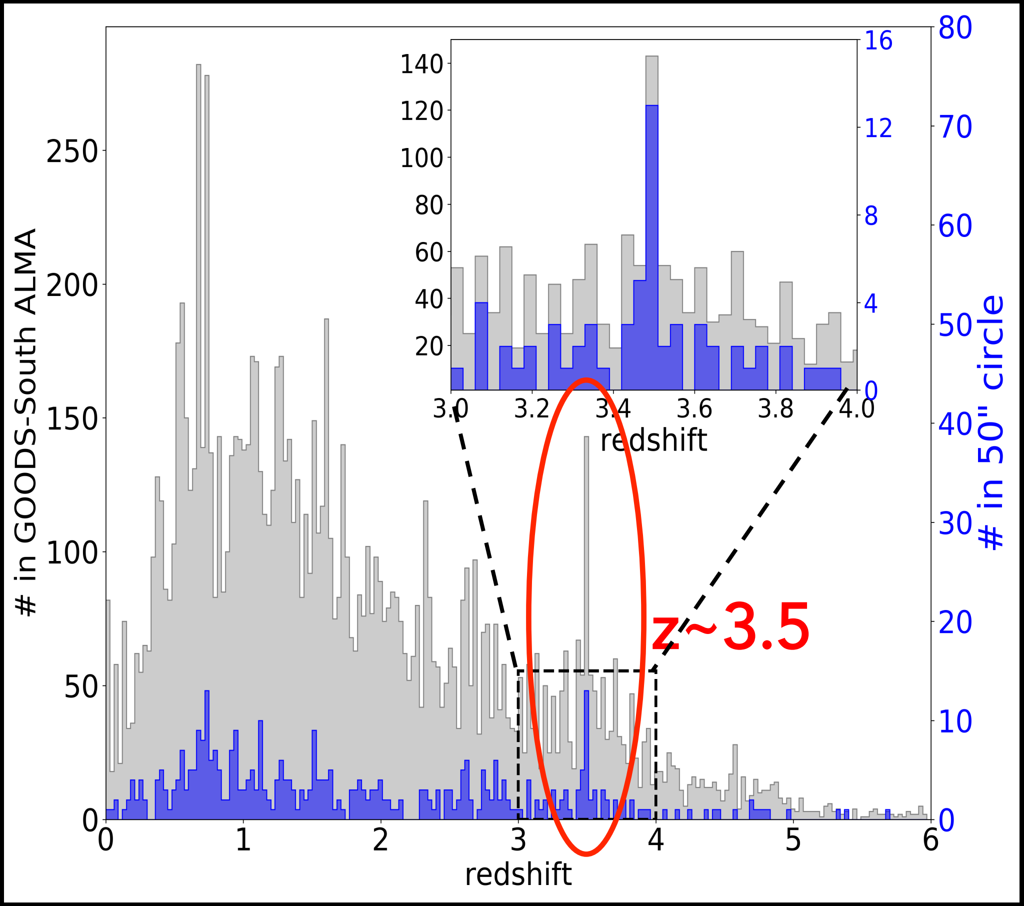
vs.

GOODS-ALMA 69 $arcmin^2$

-> 0.4% by chance

optically-dark galaxies tracing an overdensity at z~3.5

#



redshift

redshift distribution (grey):

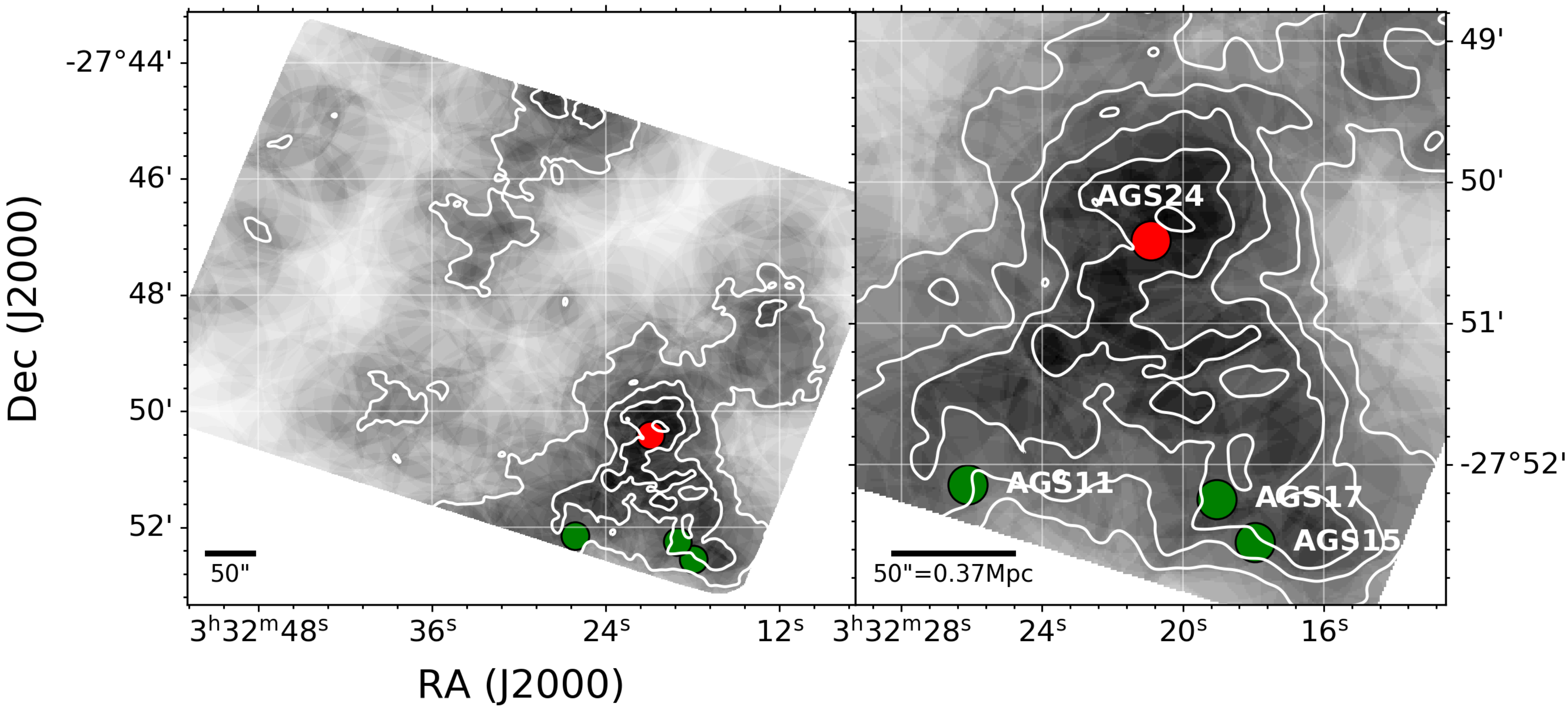
11621 in GOODS-ALMA,
894 zspec

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

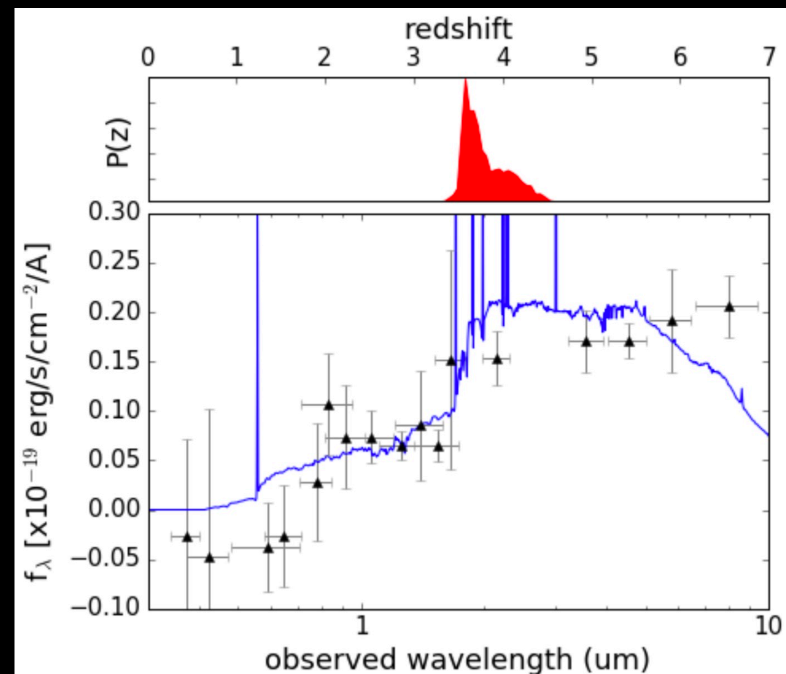
a spike at z~3.5

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~3.5



AGS15

$M^* = 10^{10.66}\ M_{sun}$

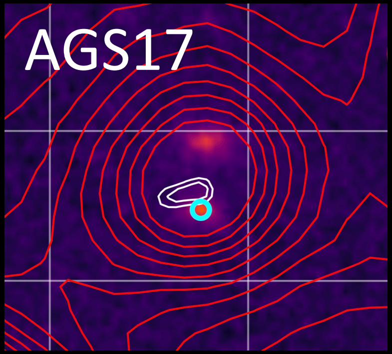
$z = 3.58$

Candels 3818

$M^* = 10^{7.99}\ M_{sun}$ $\cancel{10^{9.63}}$

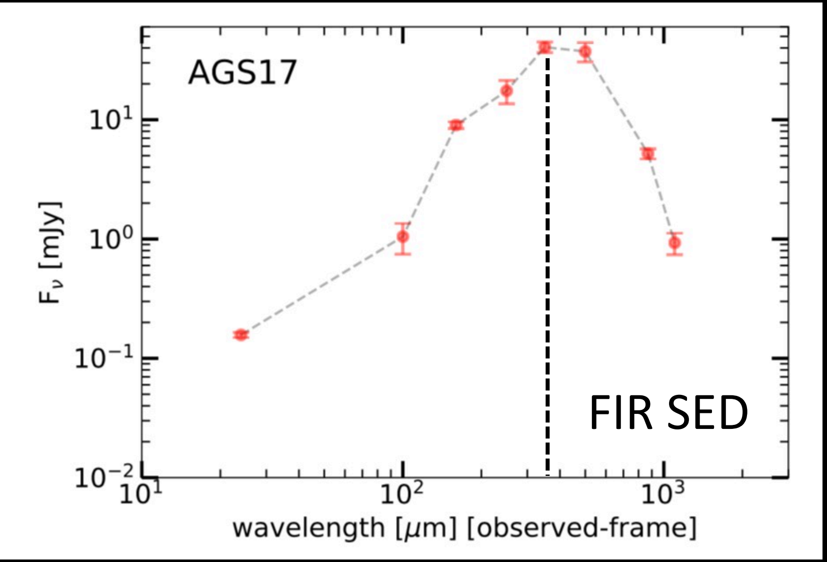
$z = 0.68$ $\cancel{3.47}$

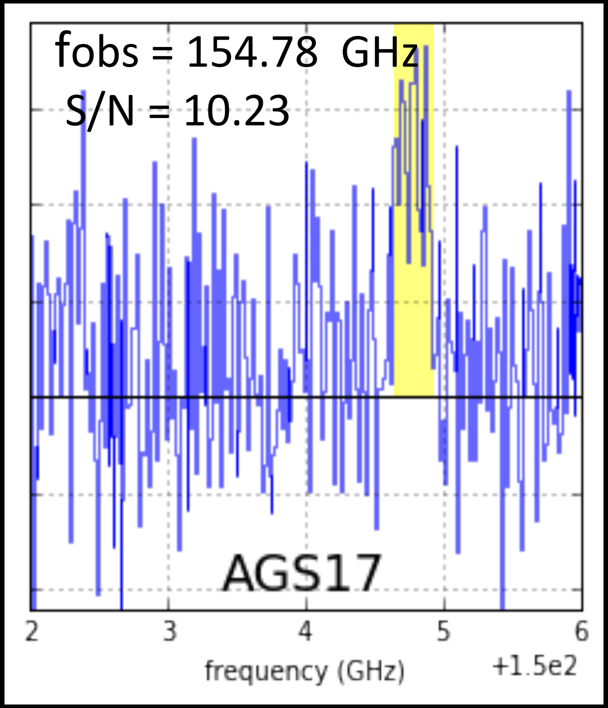
optically-dark galaxies tracing an overdensity at z~3.5



Candels 4414
z =1.85

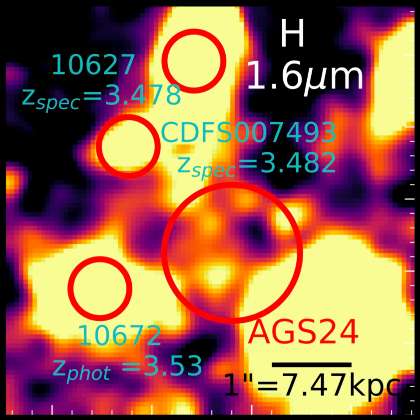
CO(6-5) 691.4 GHz:
z_spec = 3.467

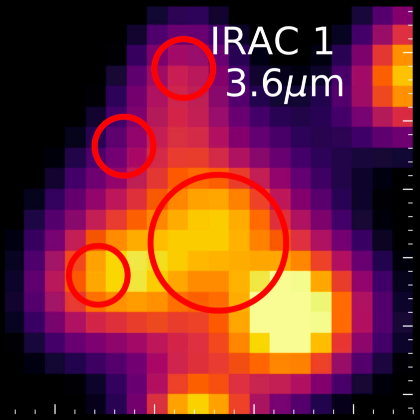


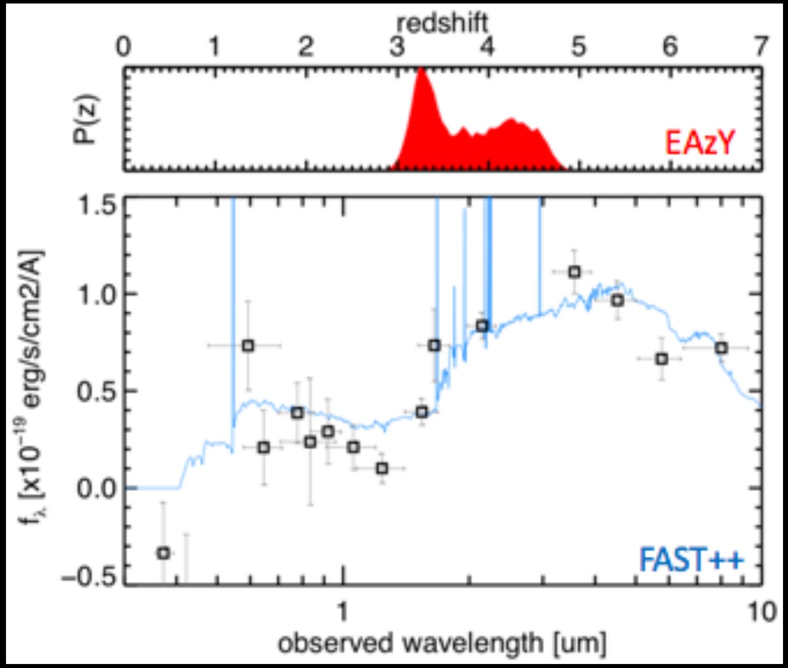


Franco et al. 2018

optically-dark galaxies tracing an overdensity at z~3.5







AGS24
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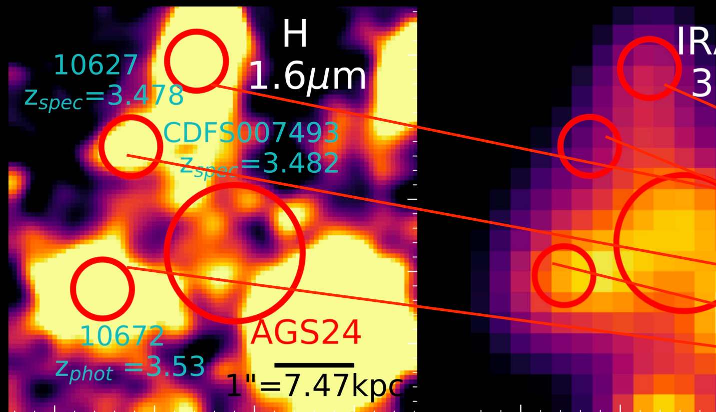
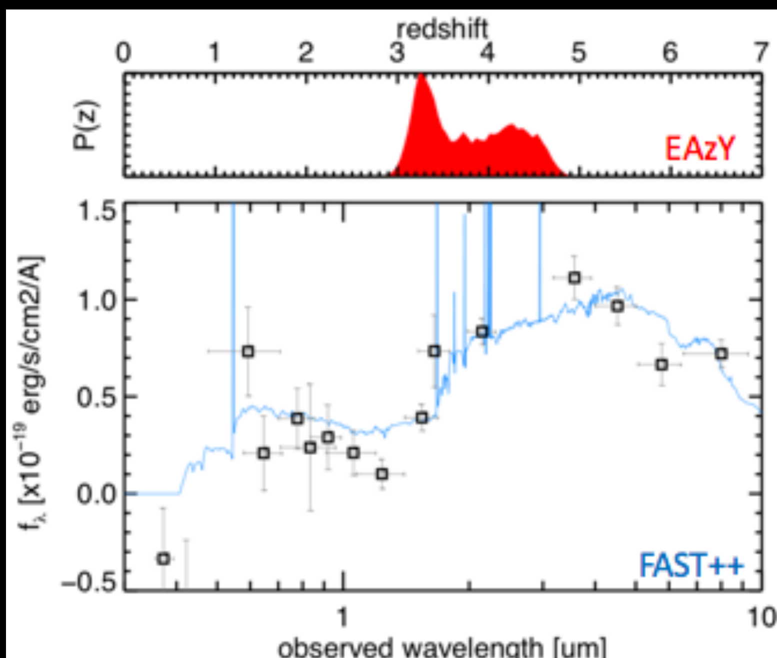
$z = 3.5$

optically-dark galaxies tracing an overdensity at z~3.5



ID	z_{spec}	z_{phot}	$M_\star$ (10^{10} $M_\odot$)	SFR ($M_\odot$ yr^{-1})
ZFOURGE10672	–	3.53	5.88	30.2
ZFOURGE10627	3.478	3.48	2.63	14.8
CDFS007493	3.482	–	0.41	–



AGS24
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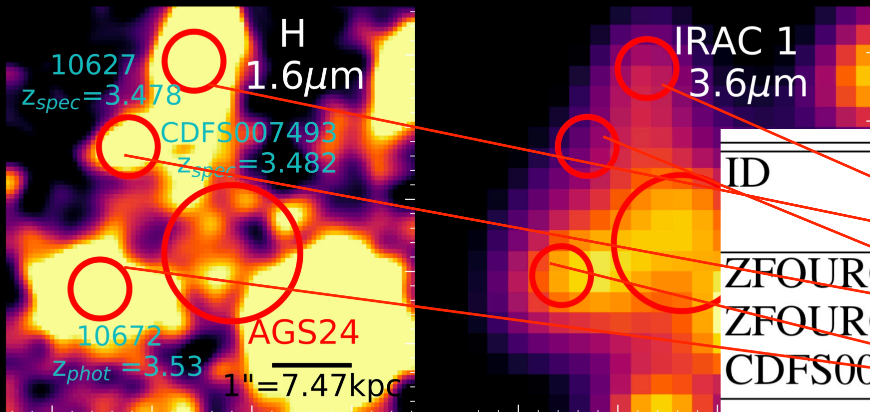
optically-dark galaxies tracing an overdensity at z~3.5



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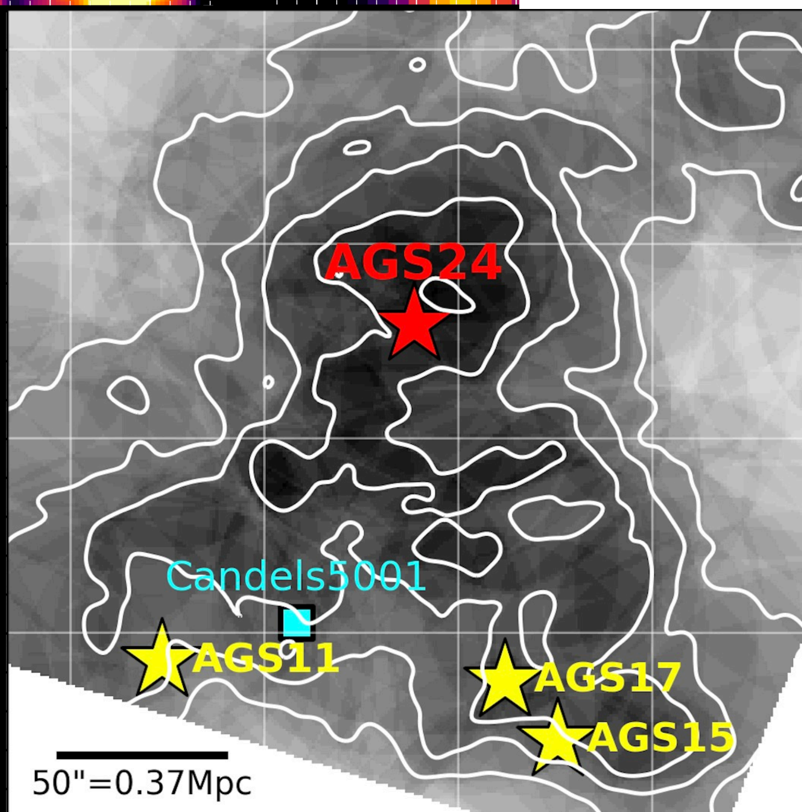

AGS24

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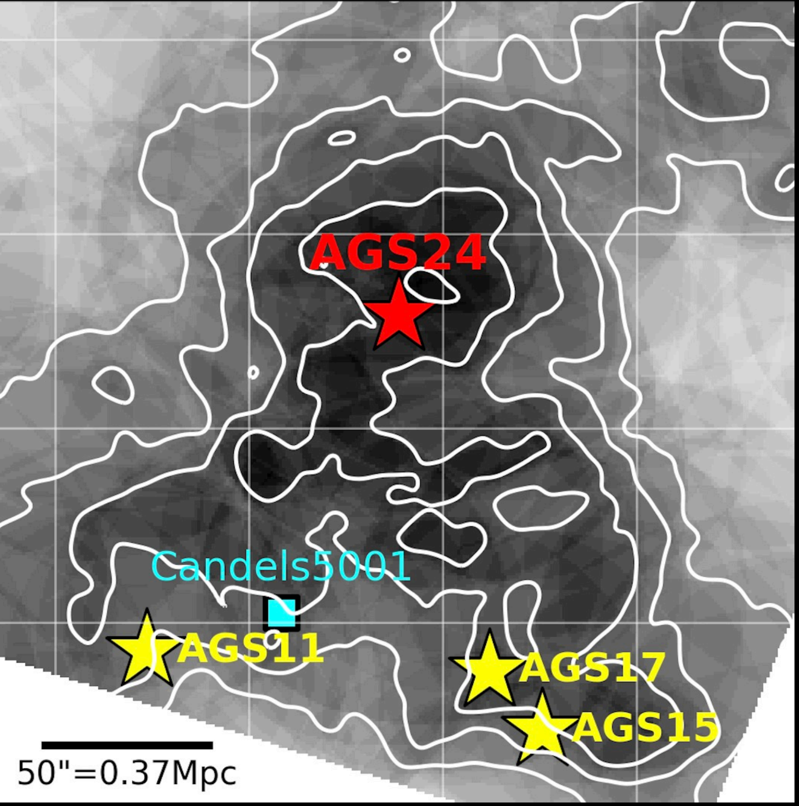
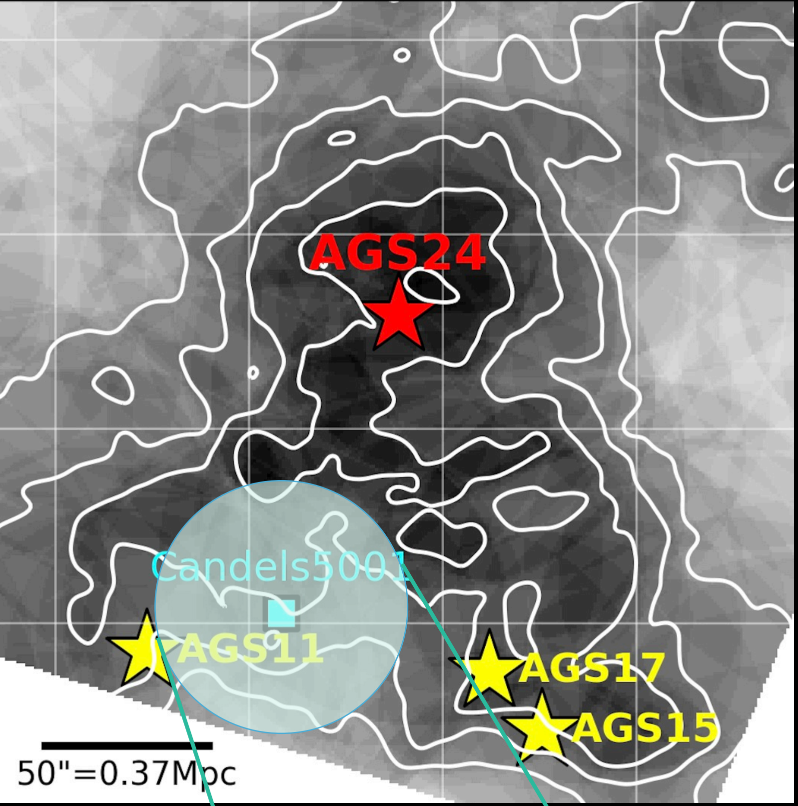


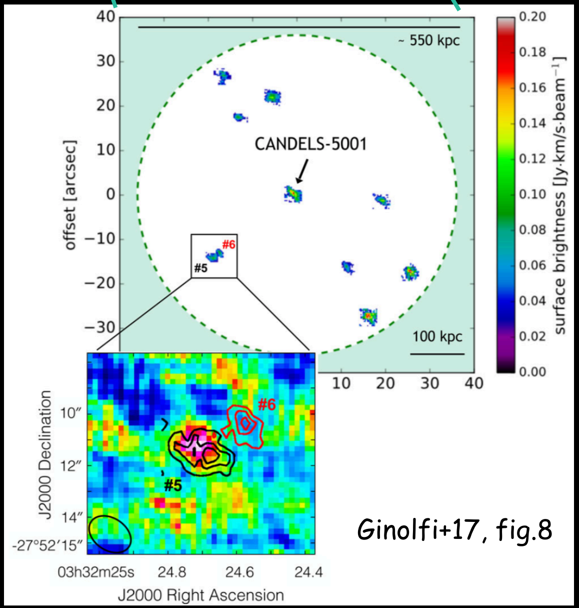
Overdensity in GOODS-S:

- 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





Ginolfi+17, fig.8

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

- Ginolfi+17,
  Candels 5001, zspec= 3.473, fig.8:
  a massive galaxy [log M_{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 $z \geq 3.5$ ($\sim 10^{11.3} M_{sun}$)
  - Potential tracers of distant proto-clusters at $z \sim 3.5$
    - AGS24: candidate BCD in the proto-cluster