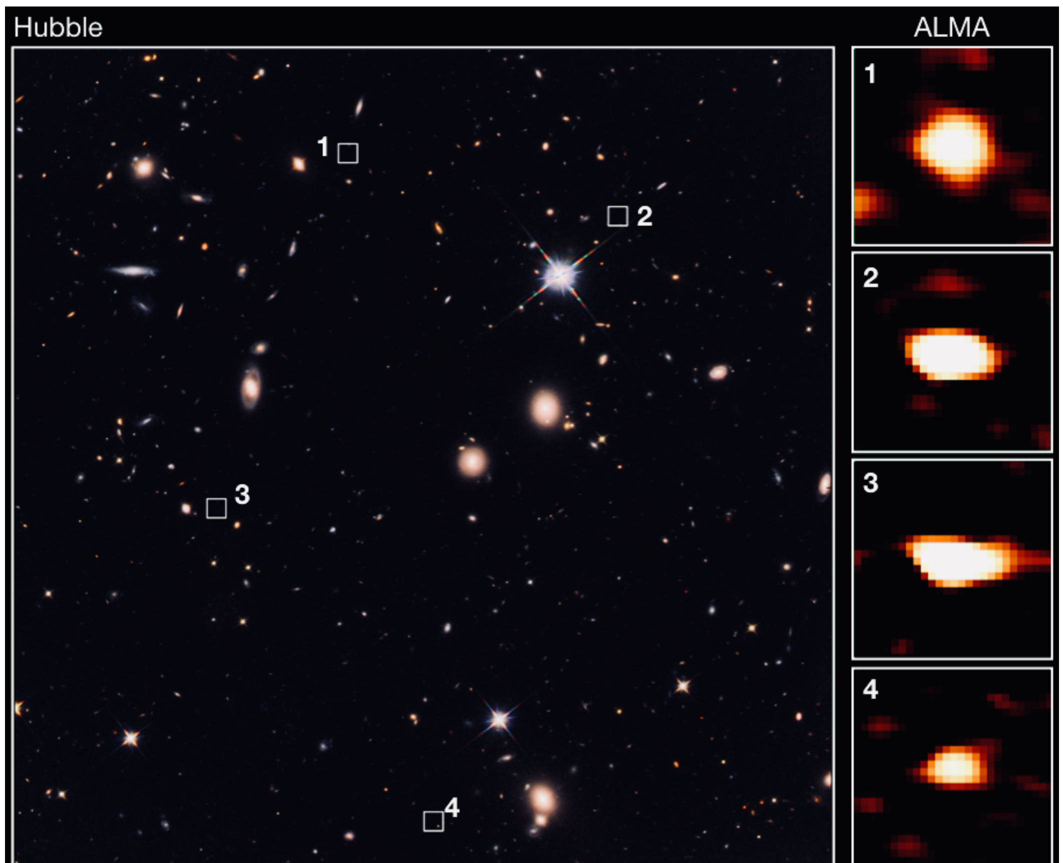
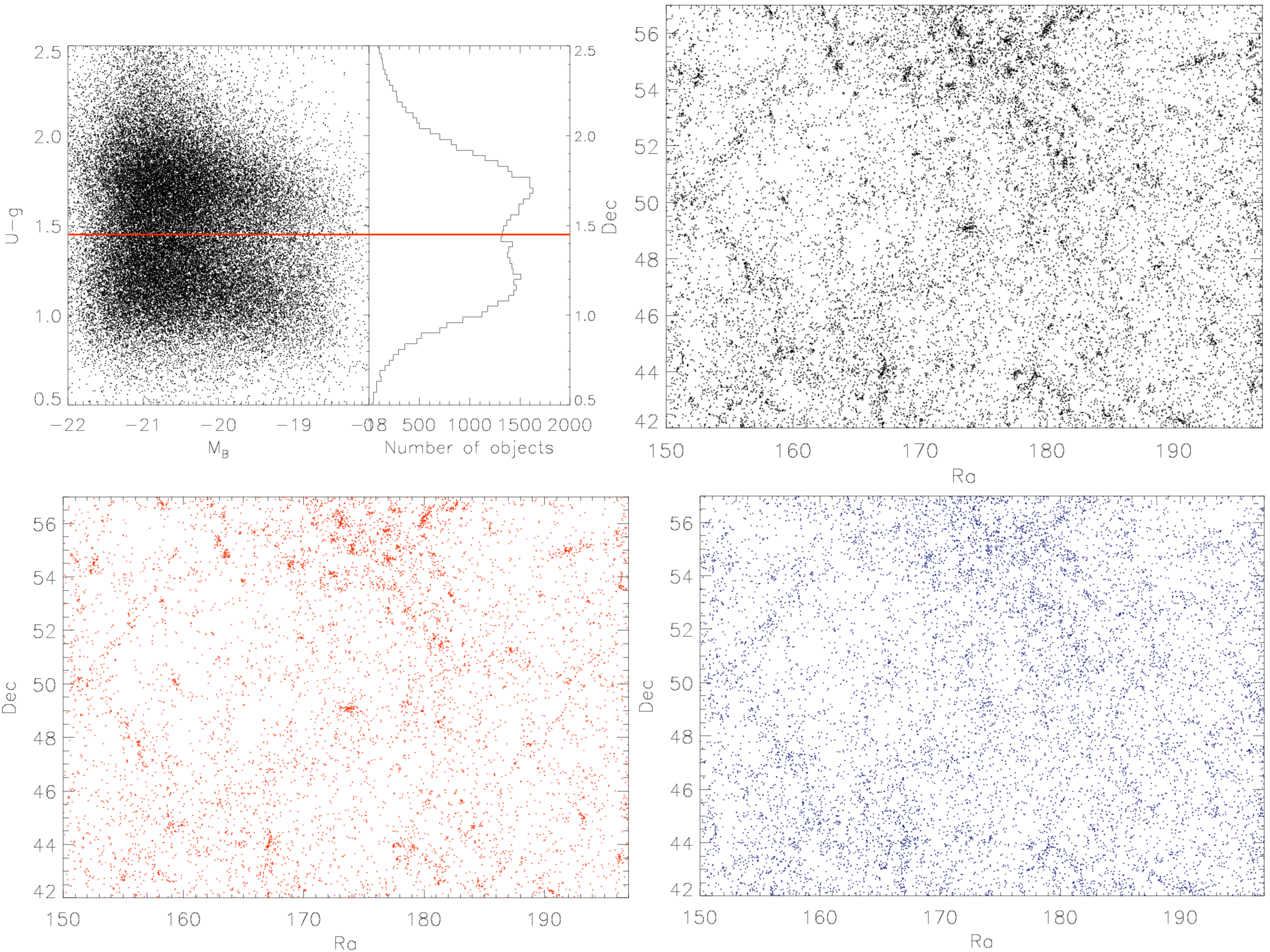
LETTER

https://doi.org/10.1038/s41586-019-1452-4

A dominant population of optically invisible massive galaxies in the early Universe

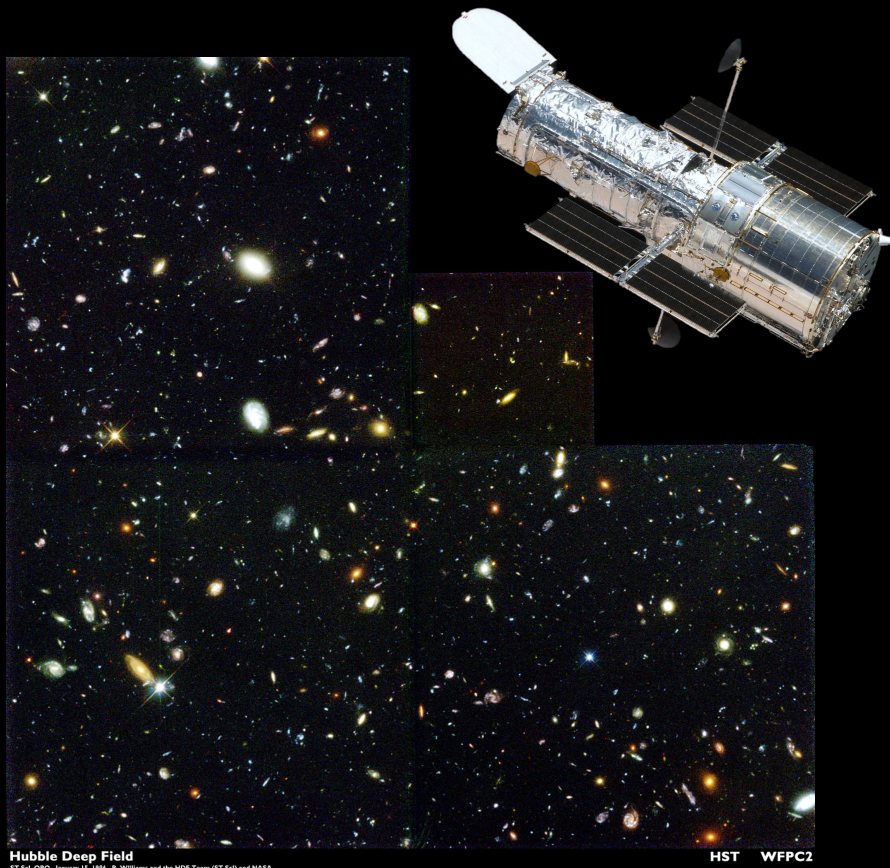
T. Wang[1,2,3]*, C. Schreiber[2,4,5], D. Elbaz[2], Y. Yoshimura[1], K. Kohno[1,6], X. Shu[7], Y. Yamaguchi[1], M. Pannella[8], M. Franco[2], J. Huang[9], C.-F. Lim[10,11] & W.-H. Wang[10]

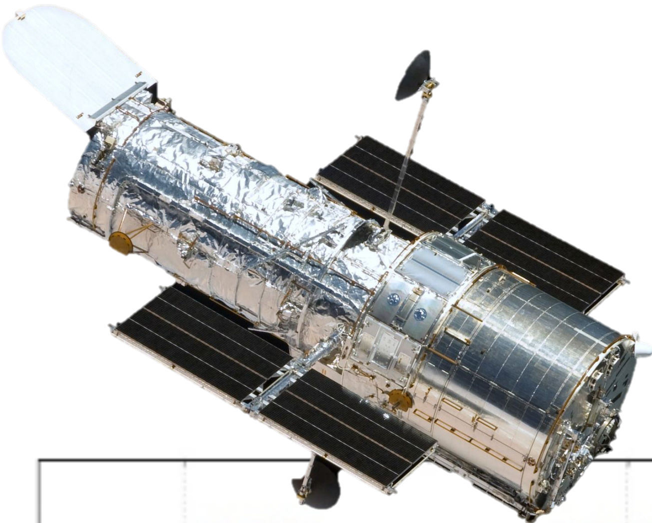


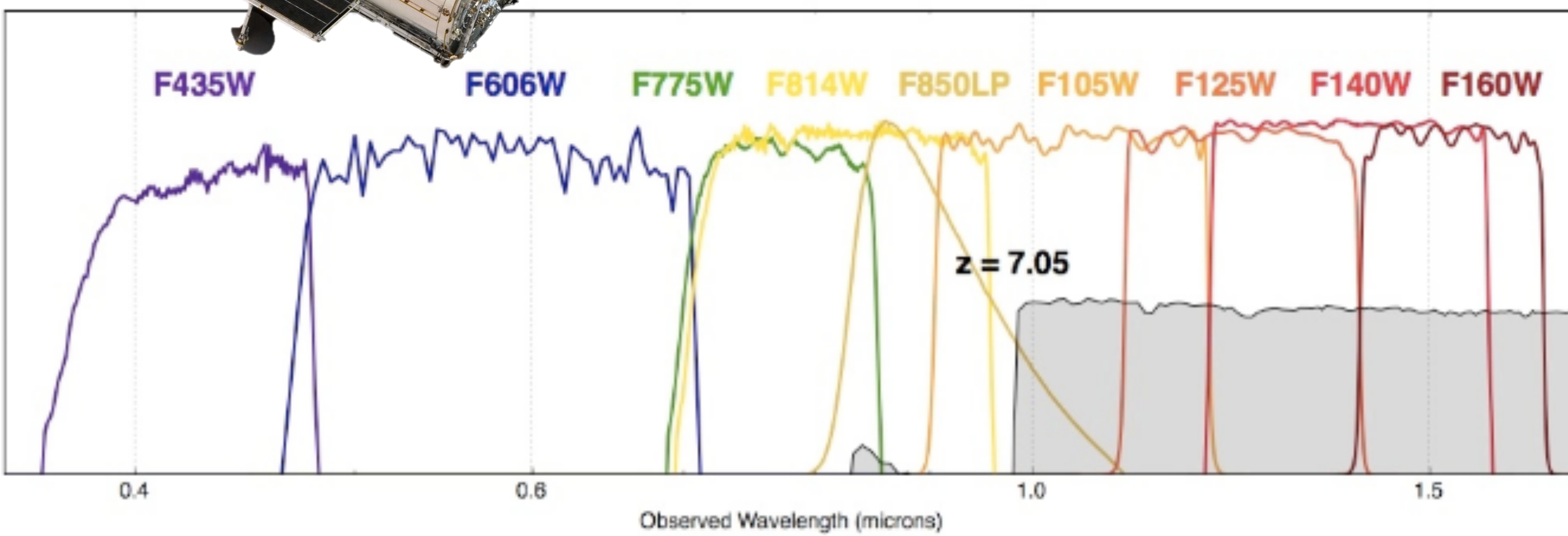


U−g
M_B
Number of objects
Dec
Ra

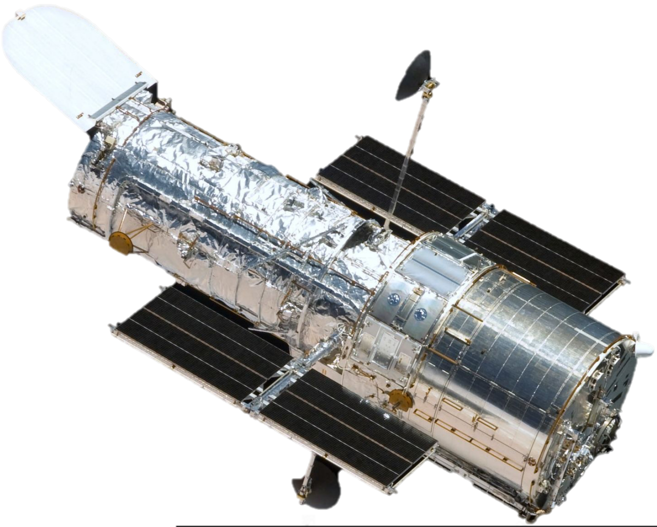
160 arcsec

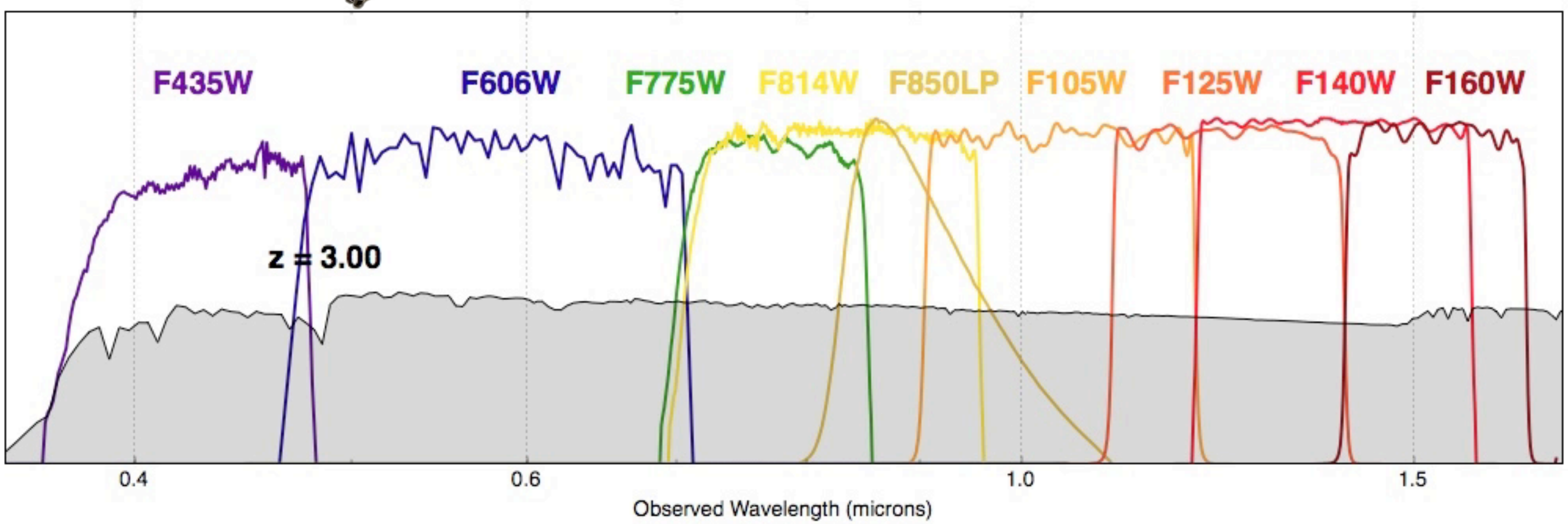

Hubble Deep Field
ST ScI OPO January 15, 1996 R. Williams and the HDF Team (ST ScI) and NASA
HST
WFPC2

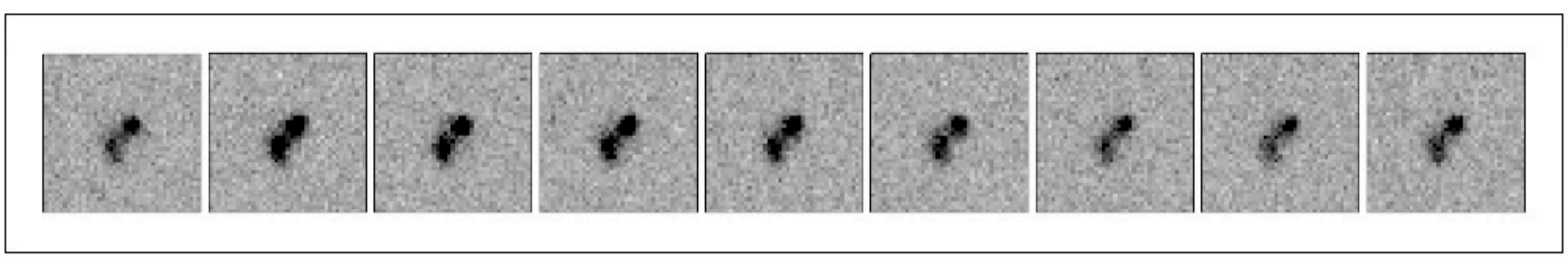




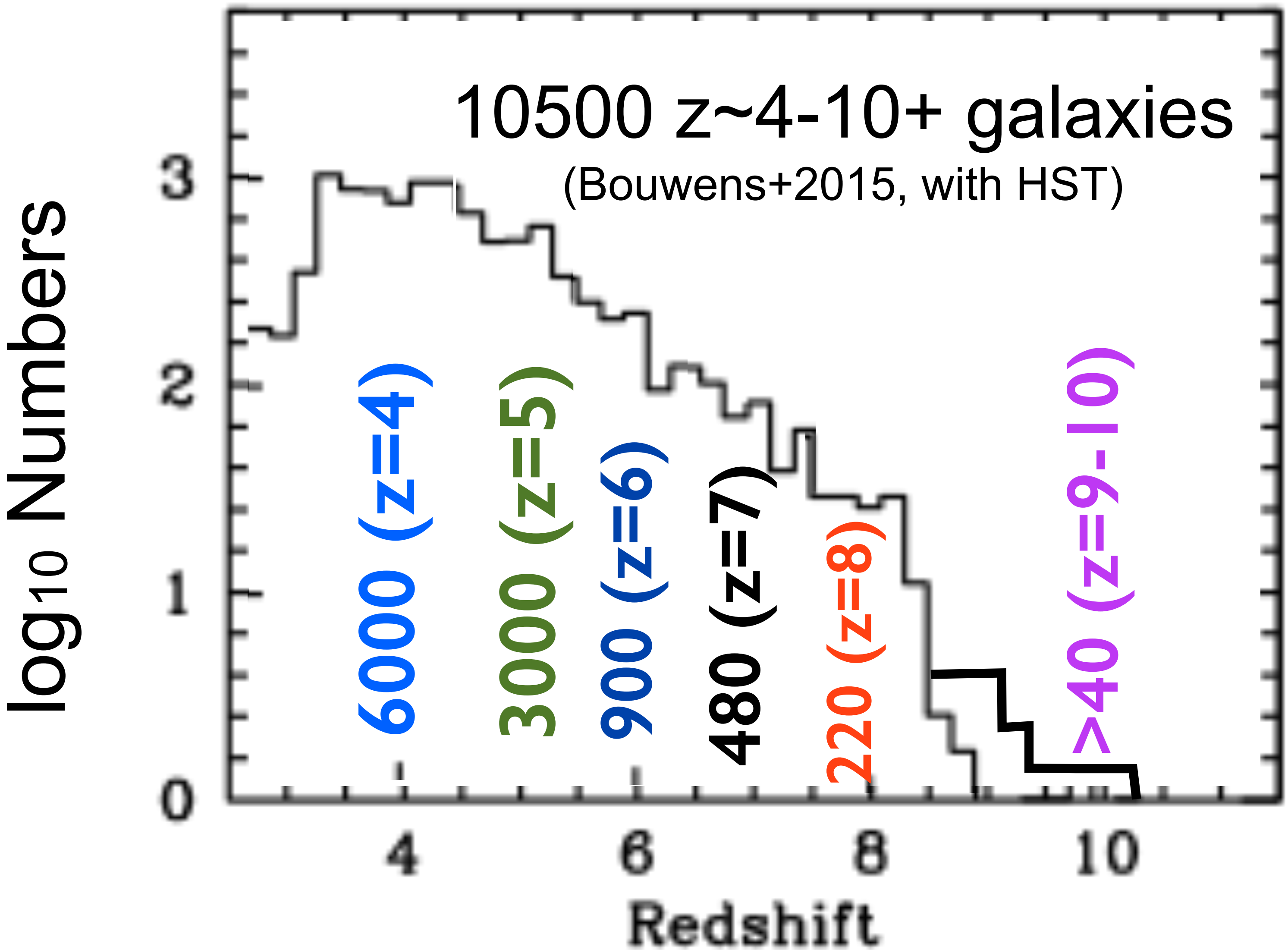
F435W F606W F775W F814W F850LP F105W F125W F140W F160W

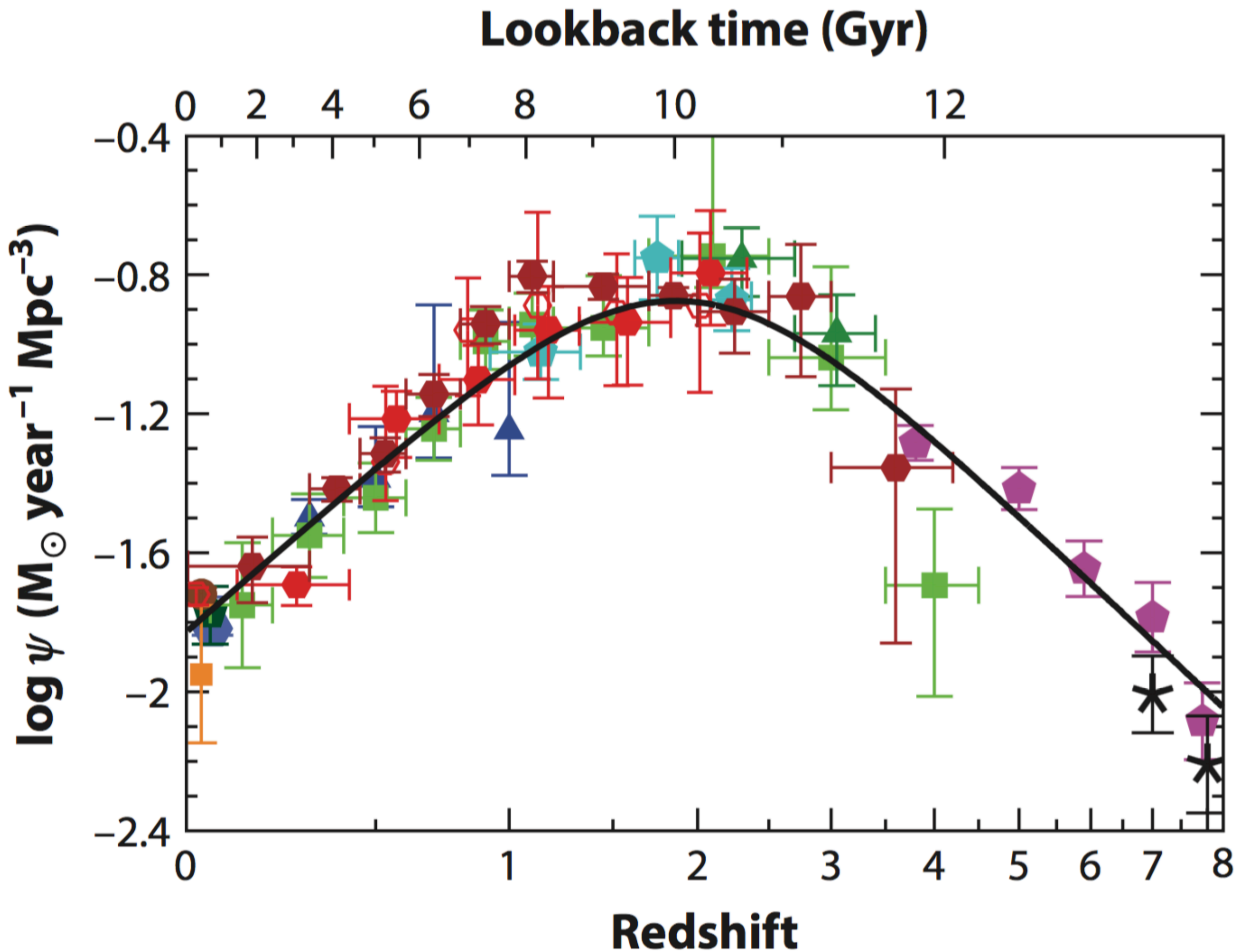



F435W
F606W
F775W
F814W
F850LP
F105W
F125W
F140W
F160W
z = 3.00
0.4
0.6
1.0
1.5
Observed Wavelength (microns)

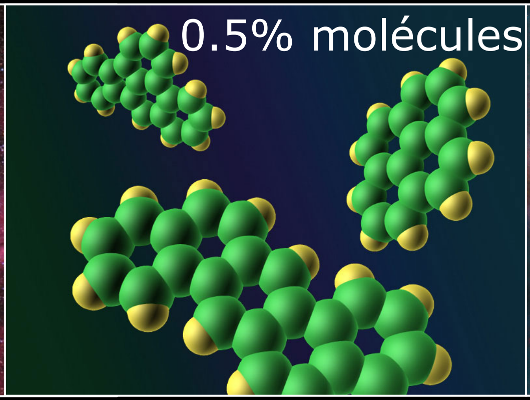


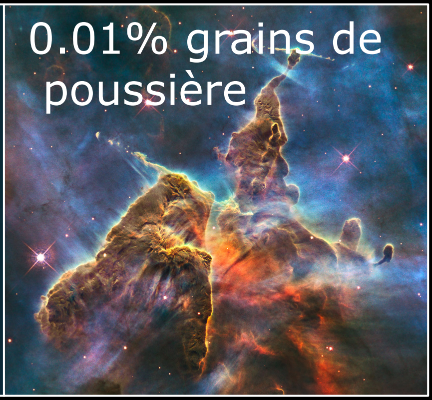
How many galaxies can we find at high redshifts?



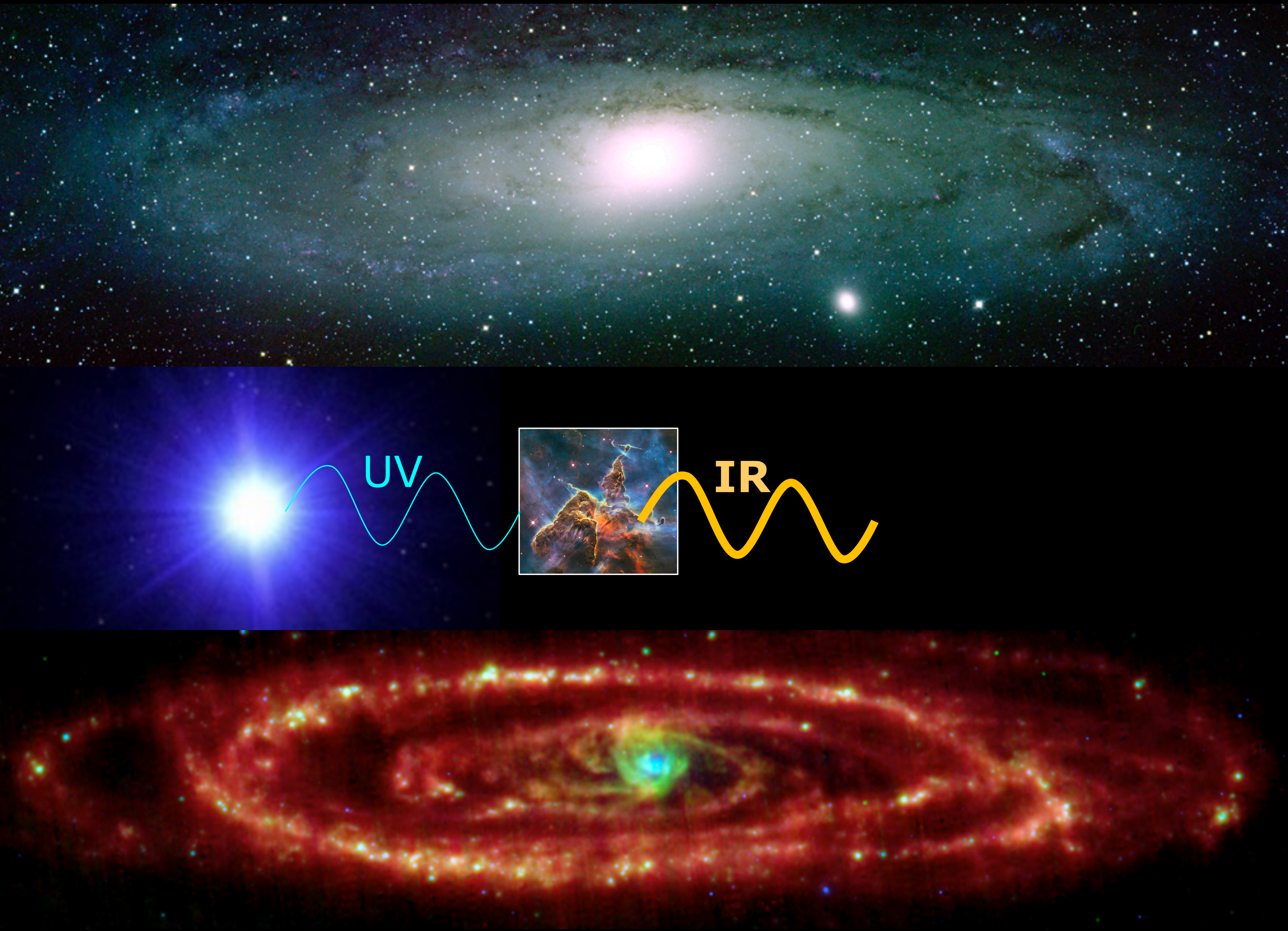


Madau & Dickinson 2014, ARAA

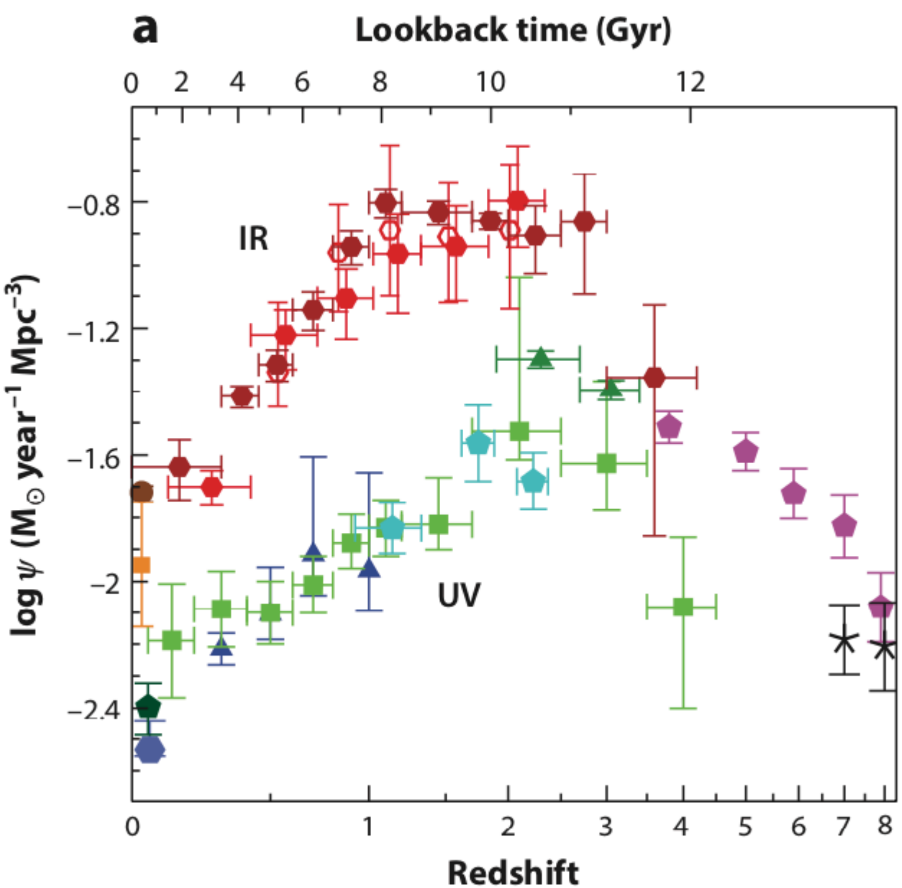


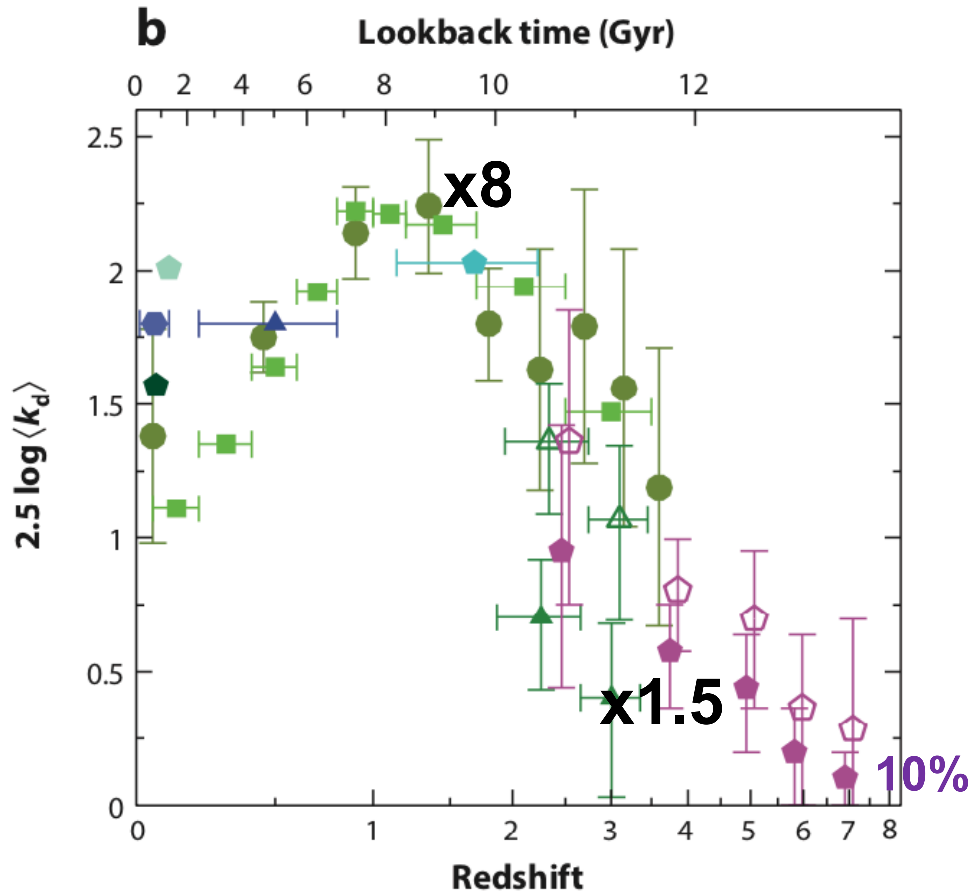


90% matière noire


UV
IR

$$\langle k_d \rangle = \rho_{IR} / \rho_{FUV} + 1$$





$2.5\log(k_d)=\ \ 1 \Rightarrow SFR_{tot}=2.5 \times SFR_{UV}$

$2.5\log(k_d)=0.5 \Rightarrow SFR_{tot}=1.6 \times SFR_{UV}$

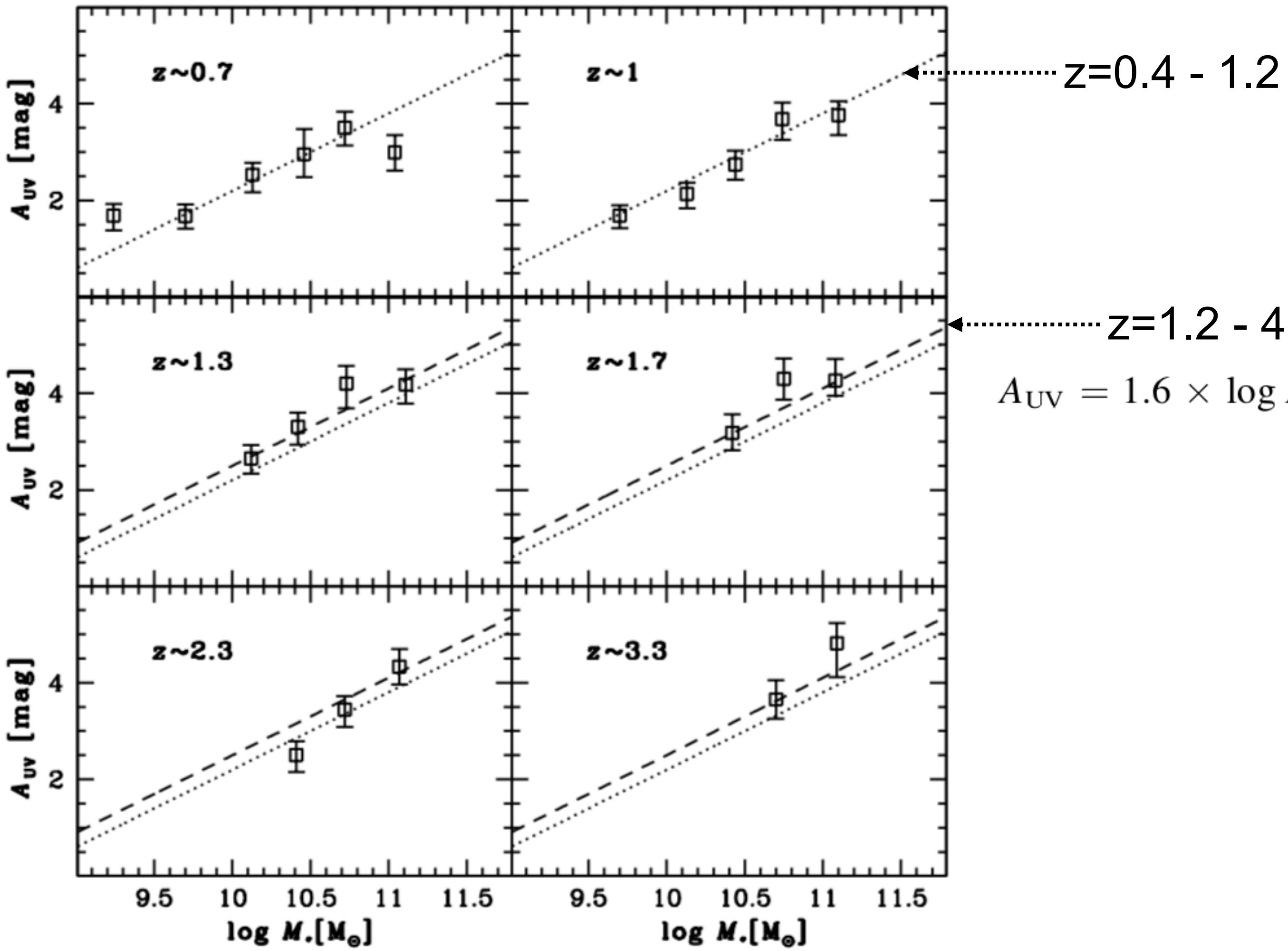
$2.5\log(k_d)=0.1 \Rightarrow SFR_{tot}=1.1 \times SFR_{UV}$

Madau & Dickinson 2014, ARAA

THE ASTROPHYSICAL JOURNAL, 807:141 (20pp), 2015 July 10 doi:10.1088/0004-637X/807/2/141

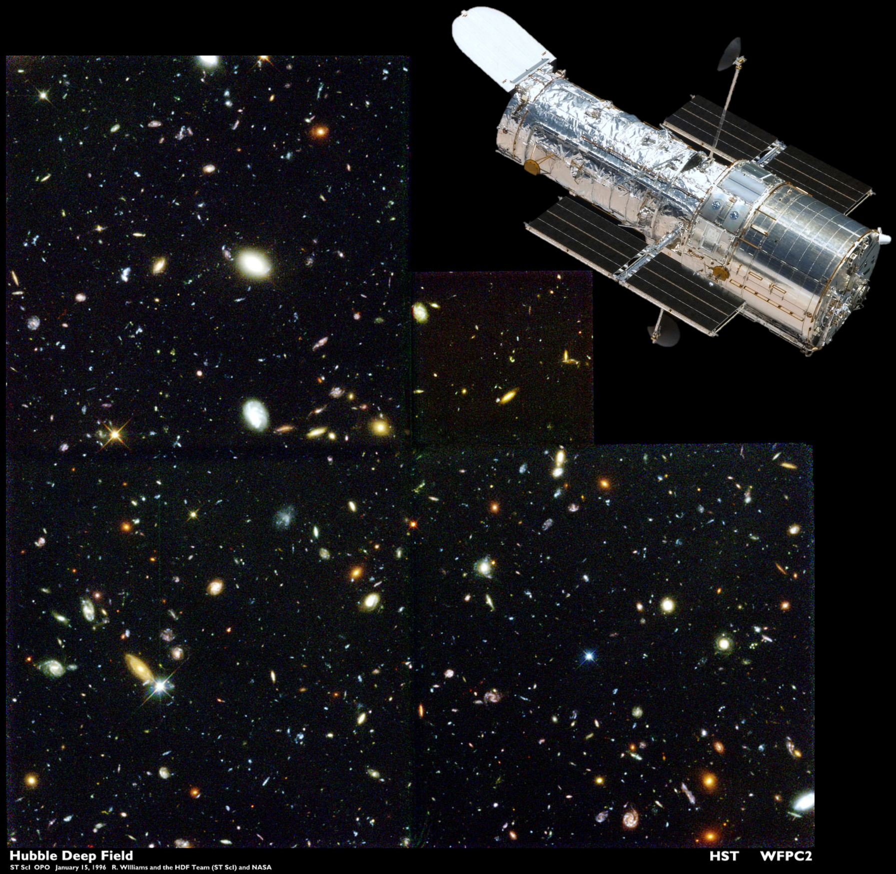
GOODS-*HERSCHEL*: STAR FORMATION, DUST ATTENUATION, AND THE FIR–RADIO CORRELATION ON THE MAIN SEQUENCE OF STAR-FORMING GALAXIES UP TO $z \simeq 4$*

M. PANNELLA[1,2,25], D. ELBAZ[1], E. DADDI[1], M. DICKINSON[3], H. S. HWANG[1,4], C. SCHREIBER[1], V. STRAZZULLO[1,5], H. AUSSEL[1], M. BETHERMIN[1,6], V. BUAT[7], V. CHARMANDARIS[8,9], A. CIBINEL[1,10], S. JUNEAU[1], R. J. IVISON[6,11], D. LE BORGNE[2,12], E. LE FLOC'H[1], R. LEITON[1,13], L. LIN[14], G. MAGDIS[8,15], G. E. MORRISON[16,17], J. MULLANEY[1,18], M. ONODERA[19], A. RENZINI[20], S. SALIM[21], M. T. SARGENT[1,10], D. SCOTT[22], X. SHU[1,23], AND T. WANG[1,24]



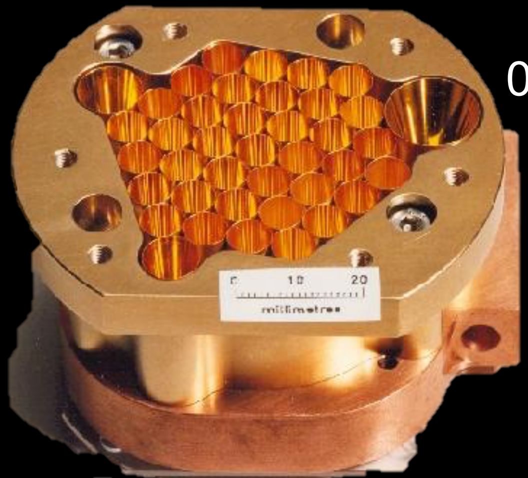
$$A_{UV} = 1.6 \times \log M_* - 13.5 \text{ mag} \quad \text{for } z = 1.2\text{–}4$$

160 arcsec

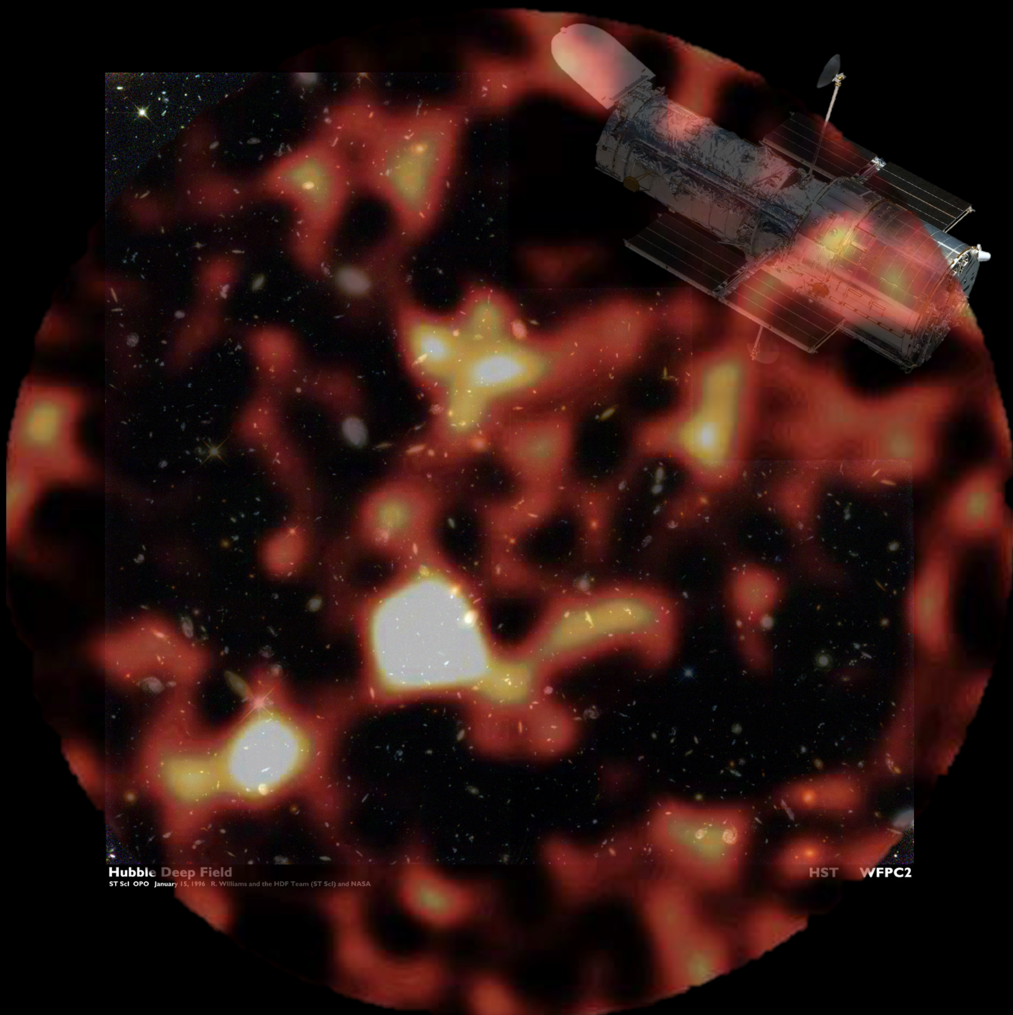


Submillimetre Common-User Bolometer Array (37 pixels)

SCUBA
0.45 &
0.85mm

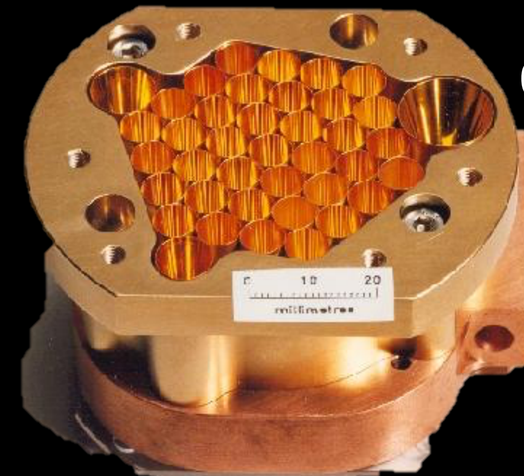


JCMT Hawaii (15m)



Submillimetre Common-User Bolometer Array (37 pixels)

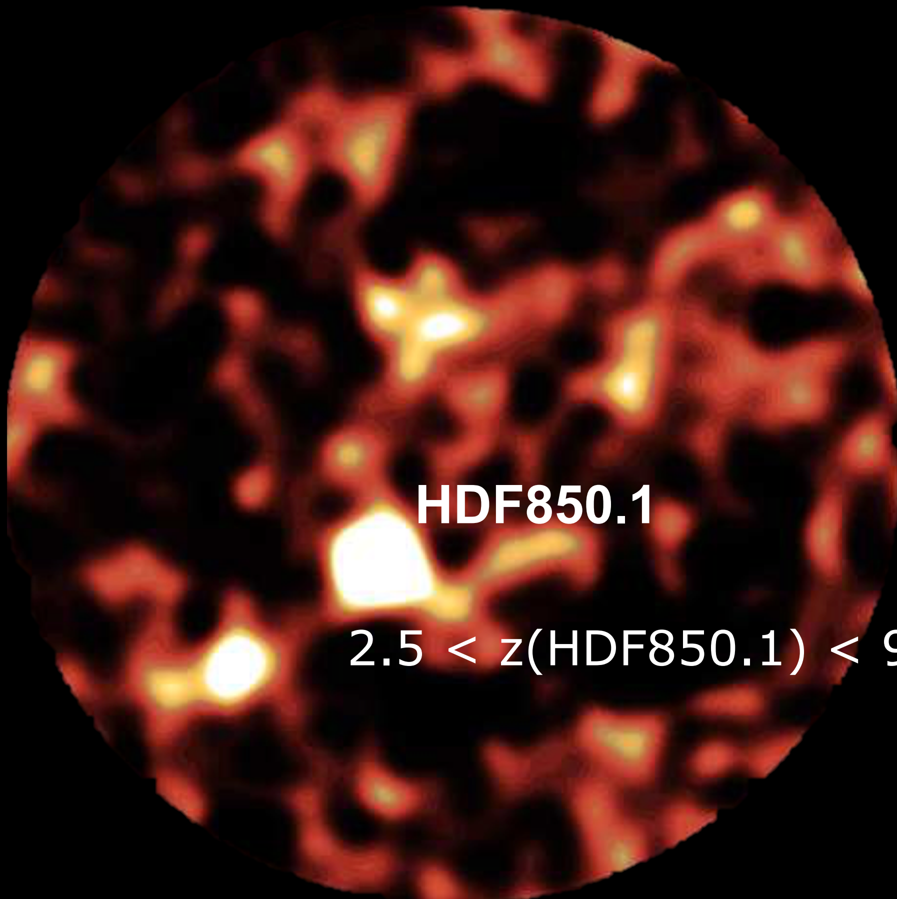
SCUBA
0.45 &
0.85mm



JCMT Hawaii (15m)

200 arcsec

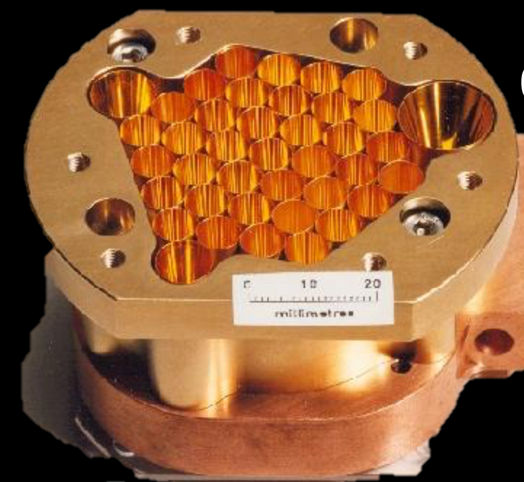
Carte à 0.85mm



Tâche de diffraction = 14.7 arcsec
bruit = 0.45 mJy , HDF850.1: 7 mJy (S/N=15)
Hughes et al. (1998)

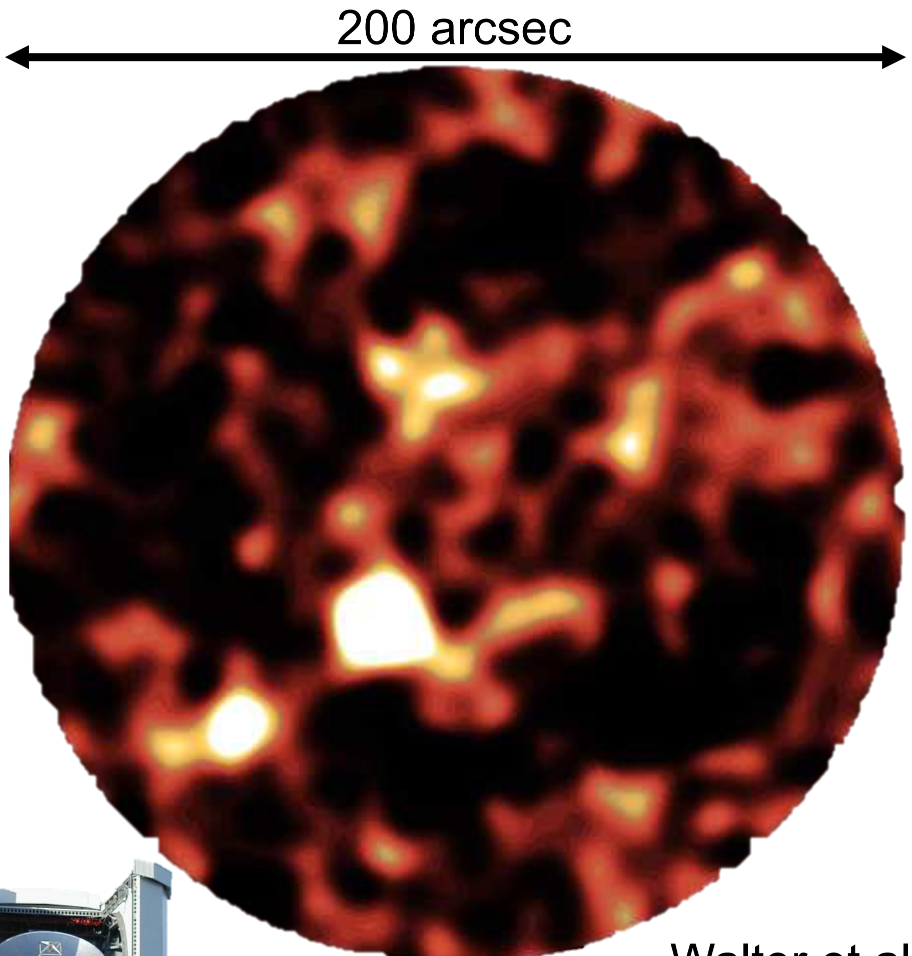
Submillimetre Common-User Bolometer Array (37 pixels)

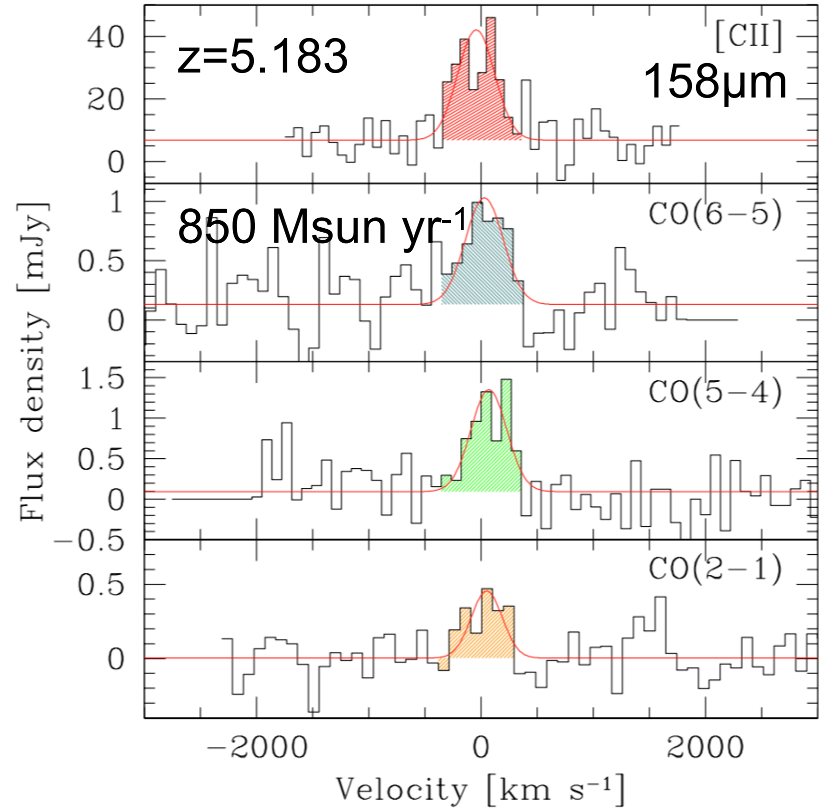
SCUBA
0.45 &
0.85mm



JCMT Hawaii (15m)

HDF850.1 at the IRAM Plateau de Bure Interferometer





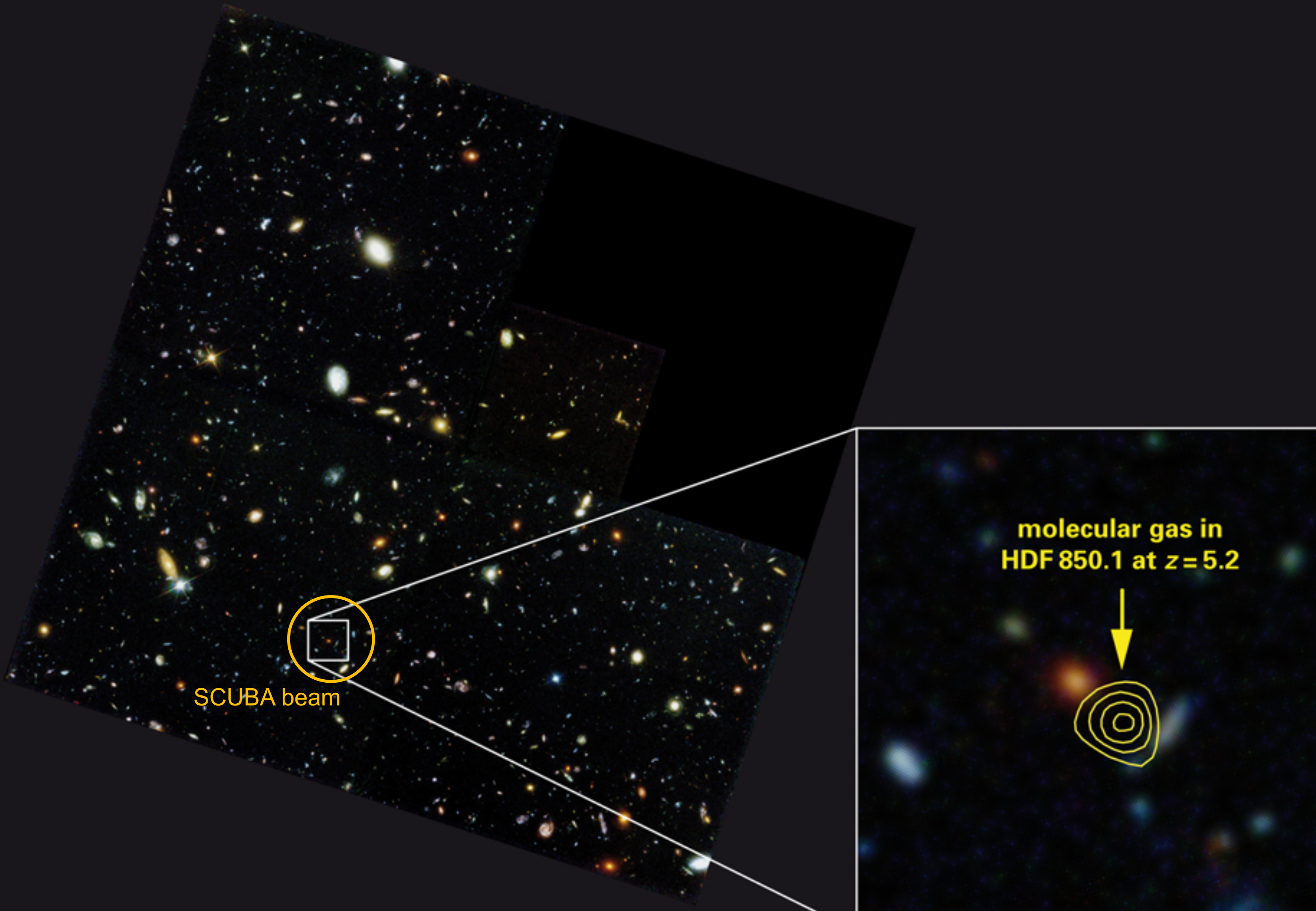
CO resolution = 2.3 arcsec
[CII] resolution = 1.2''x0.8''

Walter et al. (2012)

Tâche de diffraction = 14.7 arcsec
bruit = 0.45 mJy , HDF850.1: 7 mJy (S/N=15)
Hughes et al. (1998)

Interféromètre Plateau de Bure
IRAM – 7 antennes de 15m

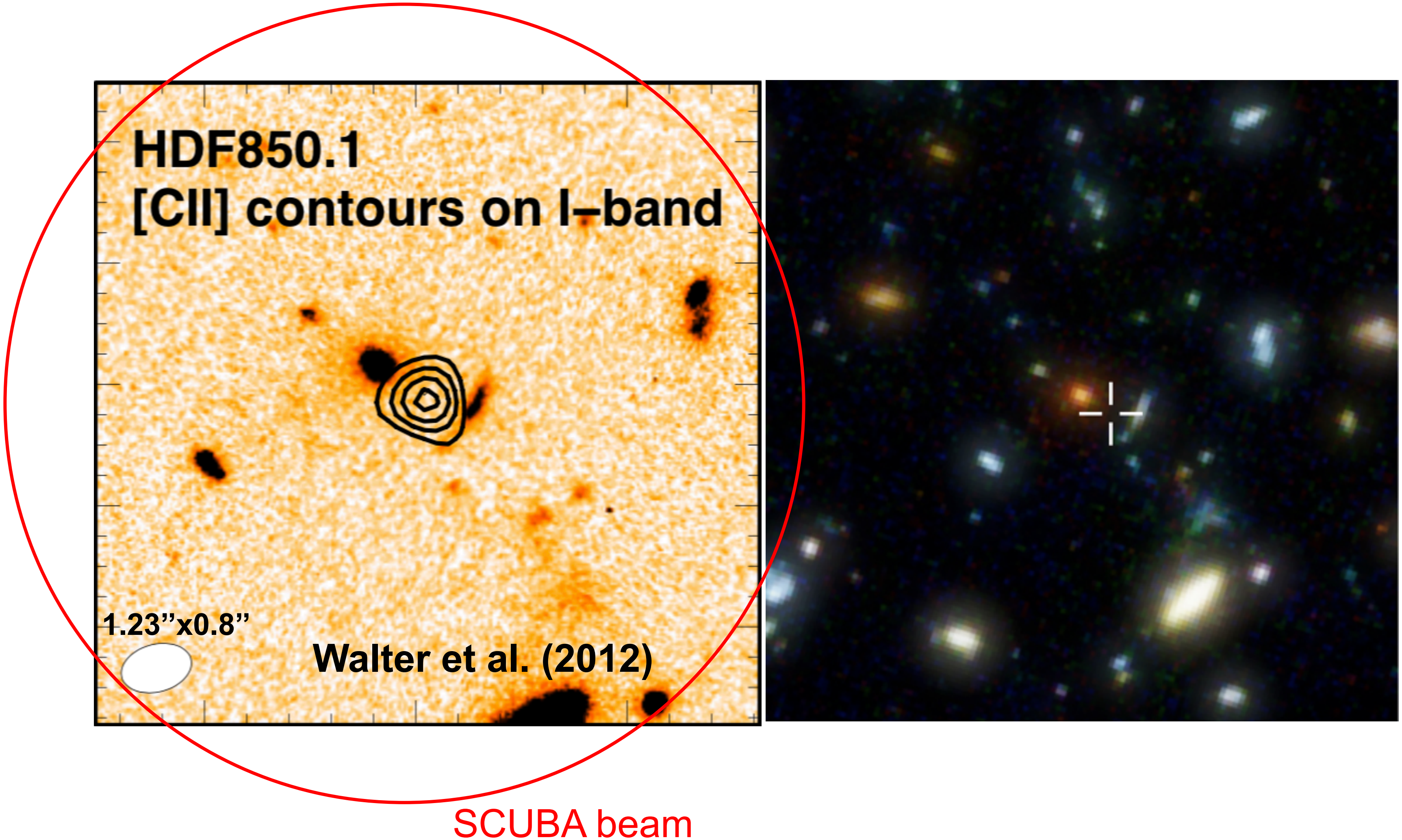
The Intense Starburst HDF 850.1 in a Galaxy Overdensity at $z = 5.2$ in the Hubble Deep Field



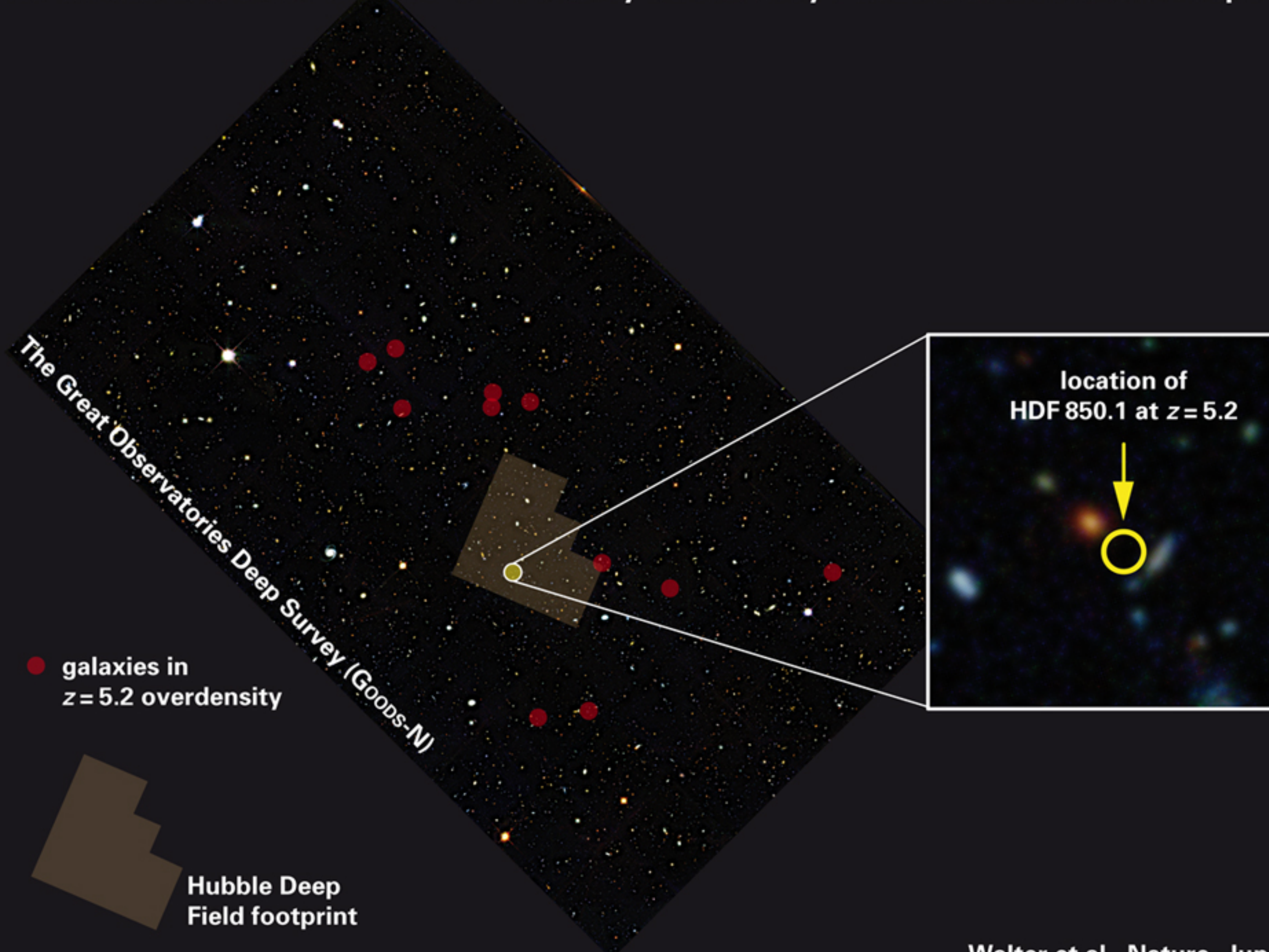
Hubble Deep Field: Image credit STScI and NASA

Walter et al., Nature, June 2012

HDF850.1 at the IRAM Plateau de Bure Interferometer



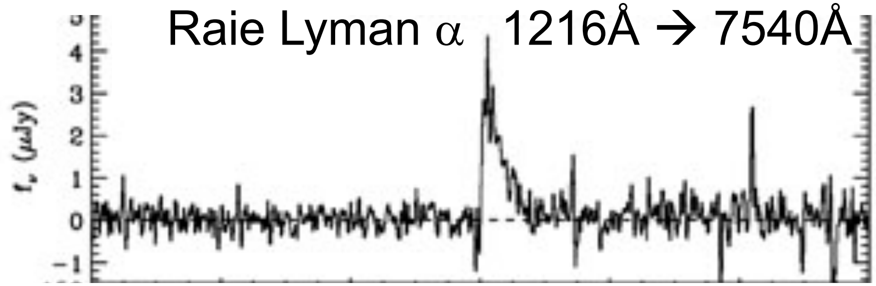
The Intense Starburst HDF 850.1 in a Galaxy Overdensity at $z = 5.2$ in the Hubble Deep Field

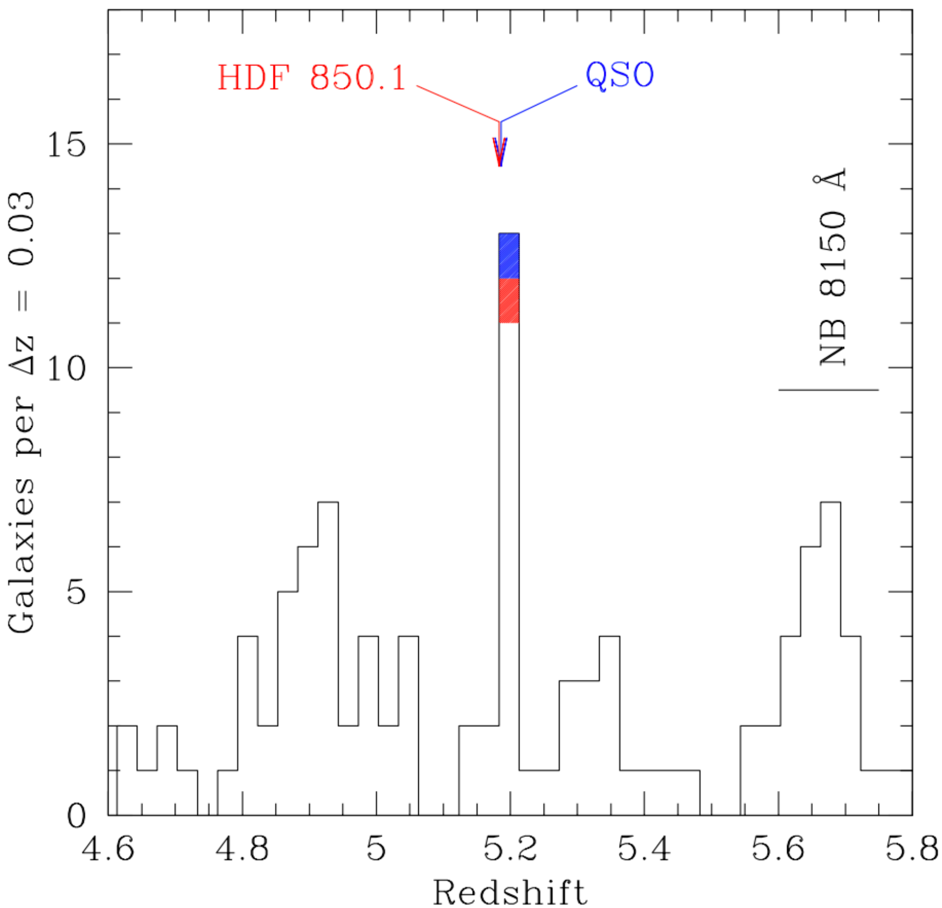


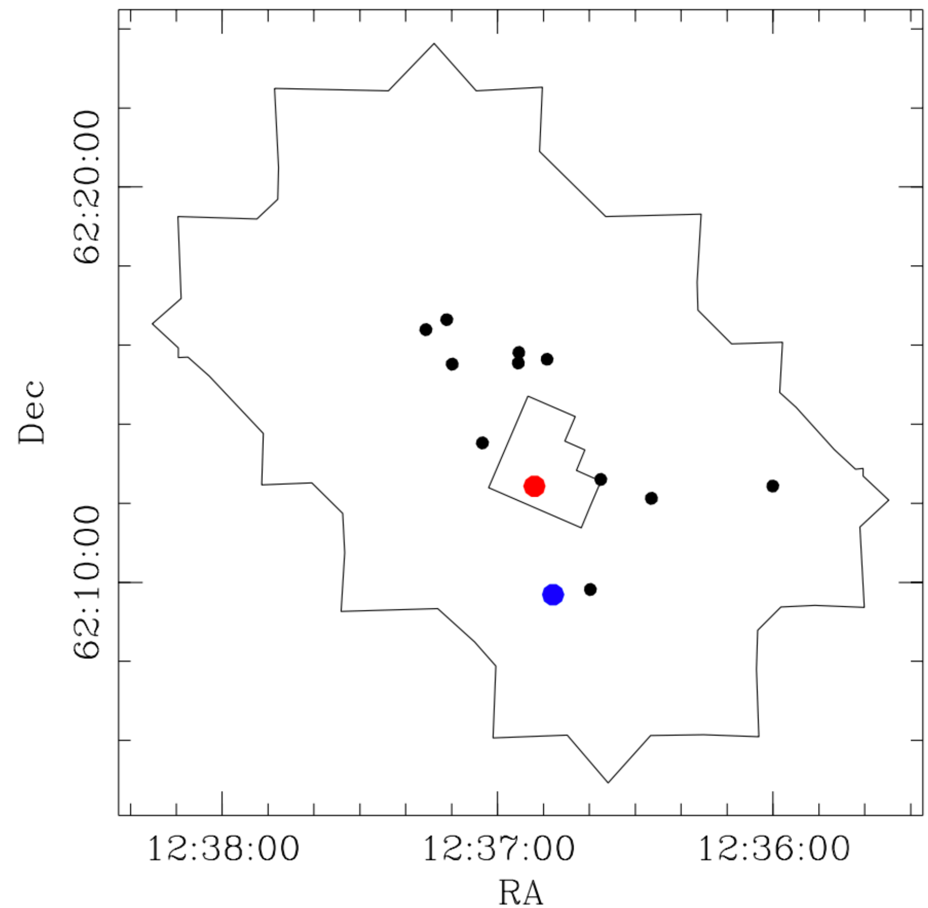
Walter et al., Nature, June 2012

HDF850.1 et son environnement

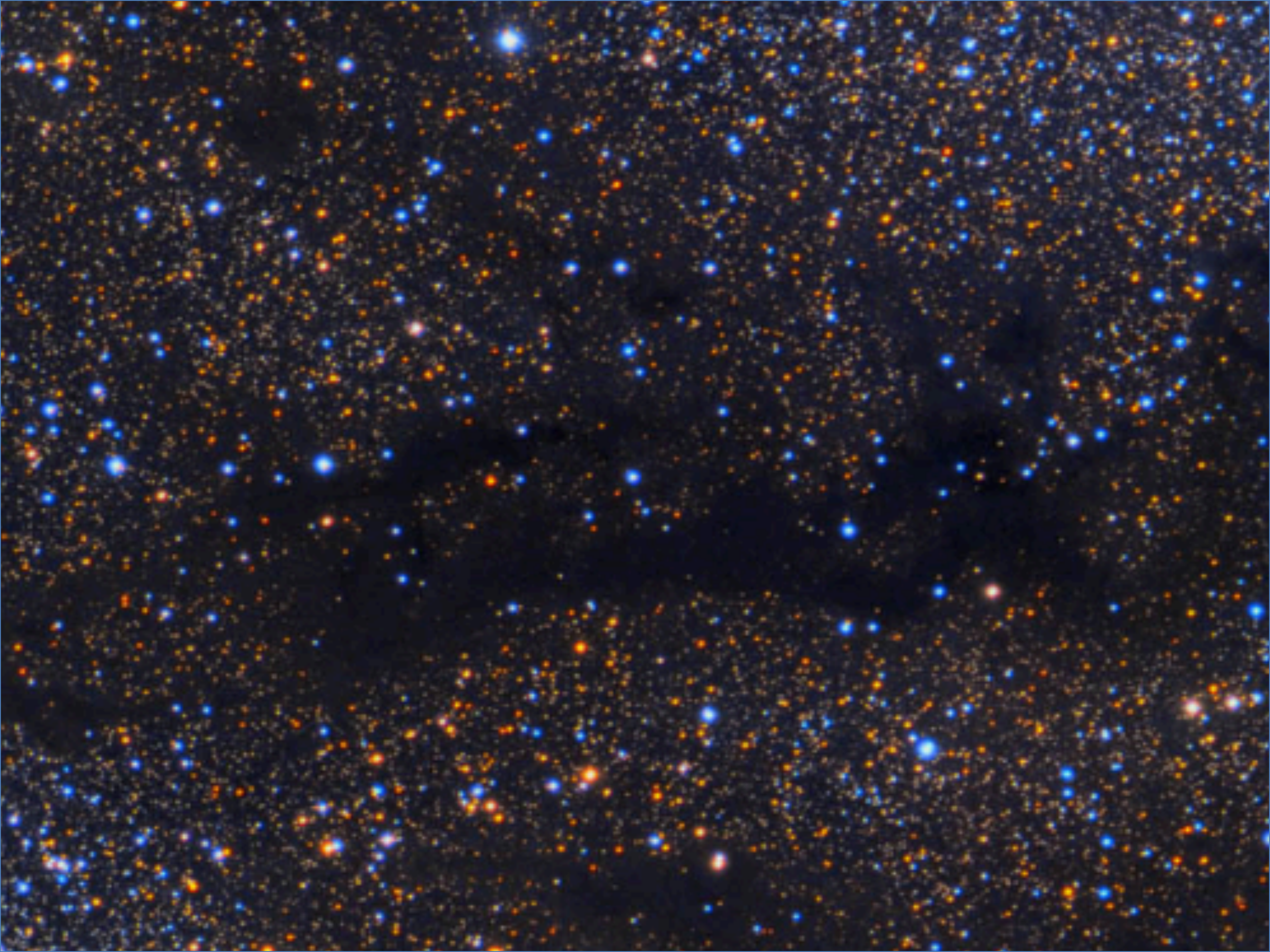
Une galaxie de la masse de la Voie lactée
1 milliard d'années après le Big Bang...
née dans une grande structure



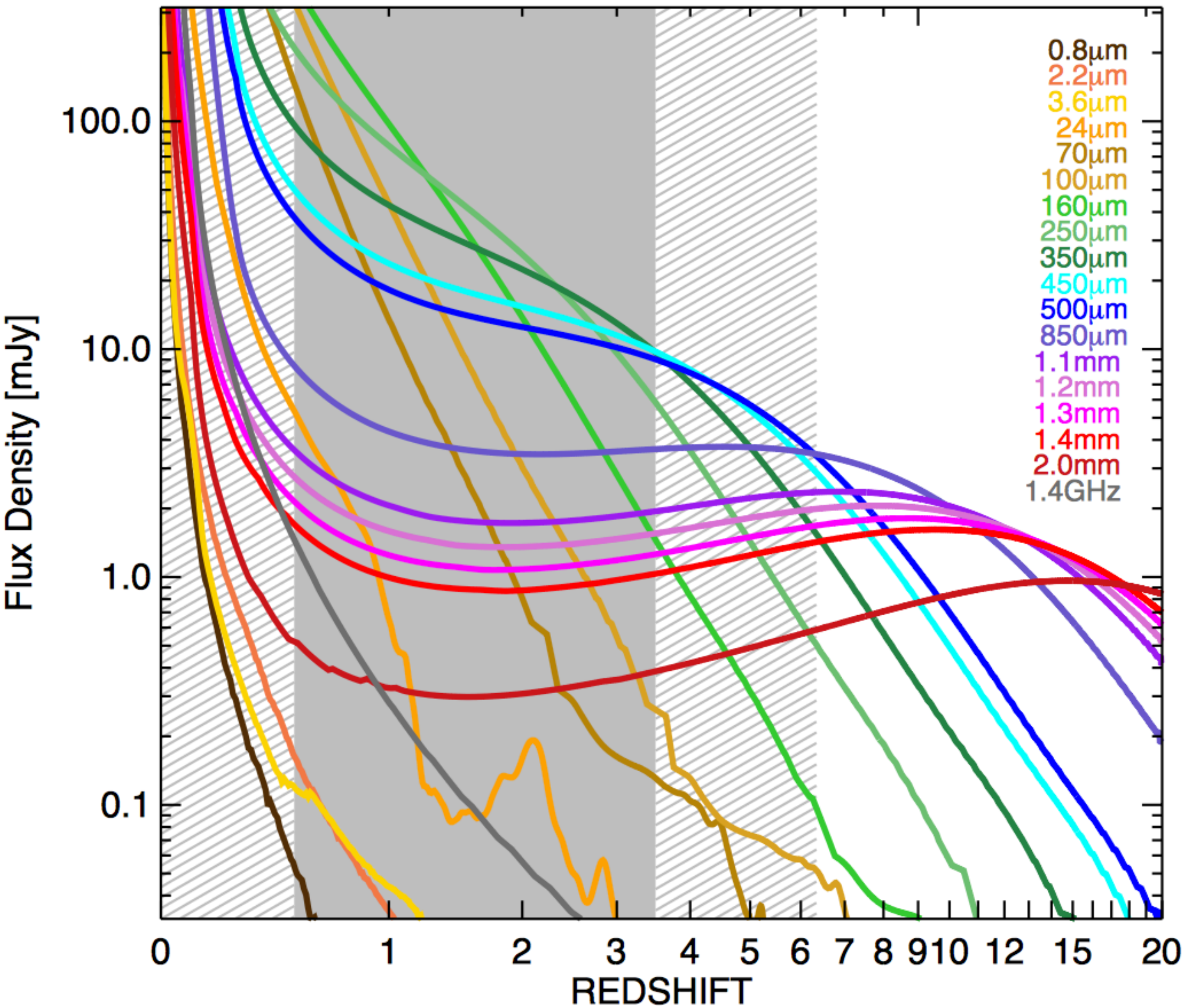




Walter et al. (2012)



K-correction



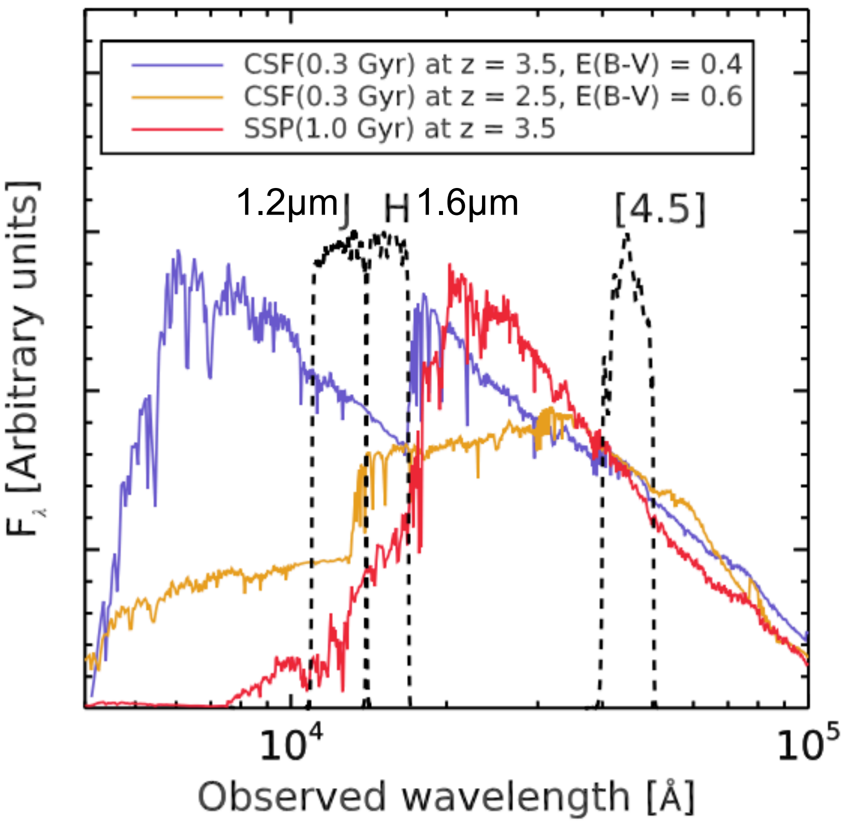
Casey et al. 2014

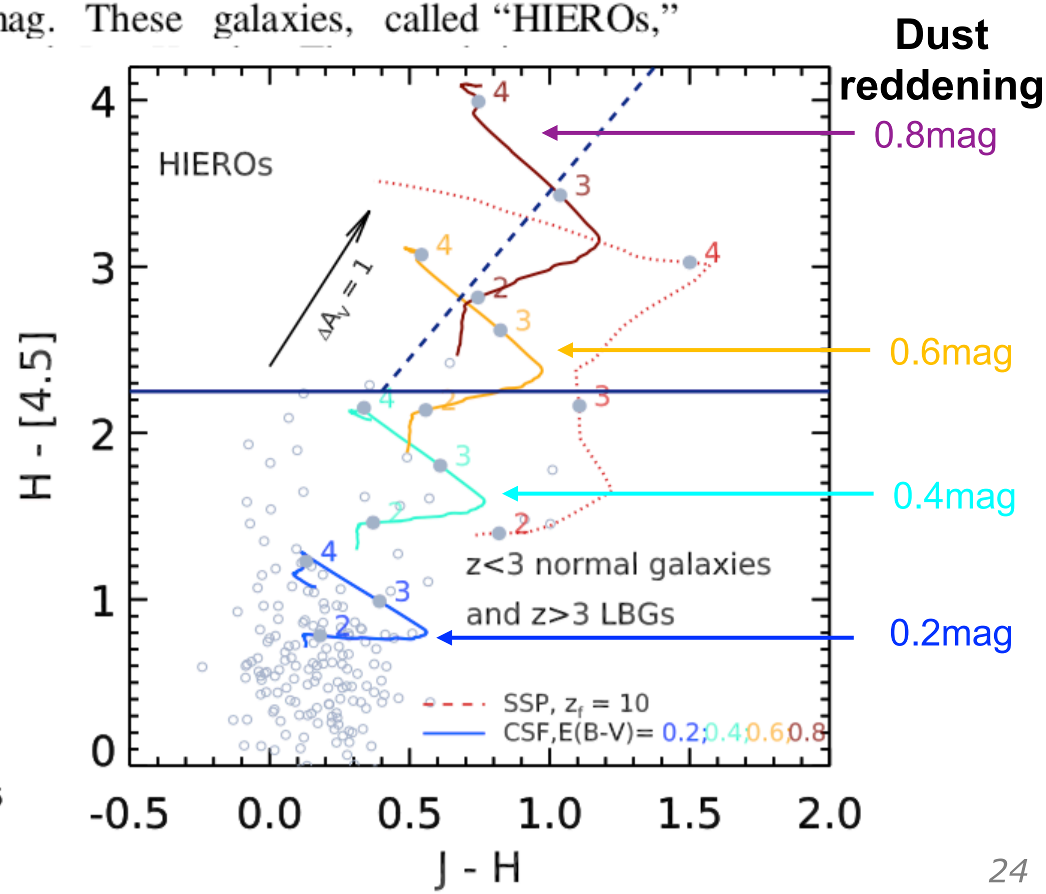
THE ASTROPHYSICAL JOURNAL, 816:84 (17pp), 2016 January 10 doi:10.3847/0004-637X/816/2/84

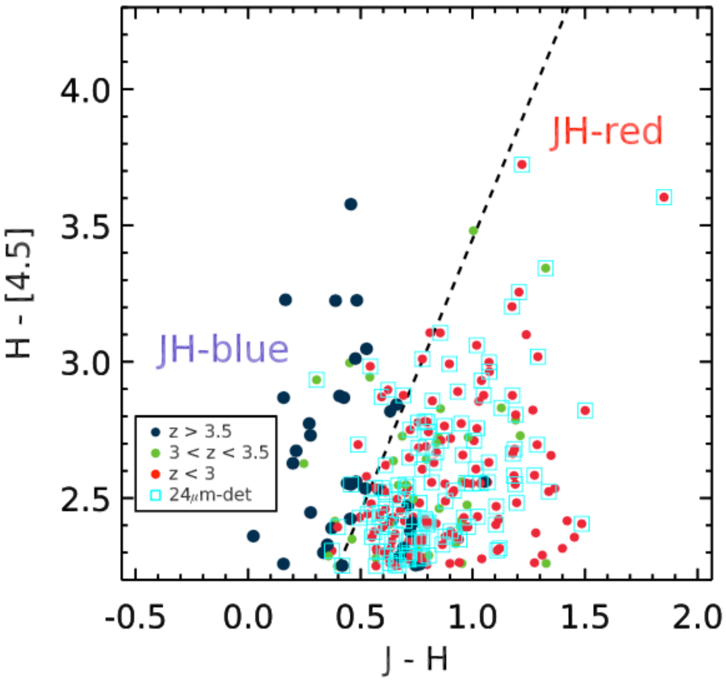
INFRARED COLOR SELECTION OF MASSIVE GALAXIES AT $z > 3$

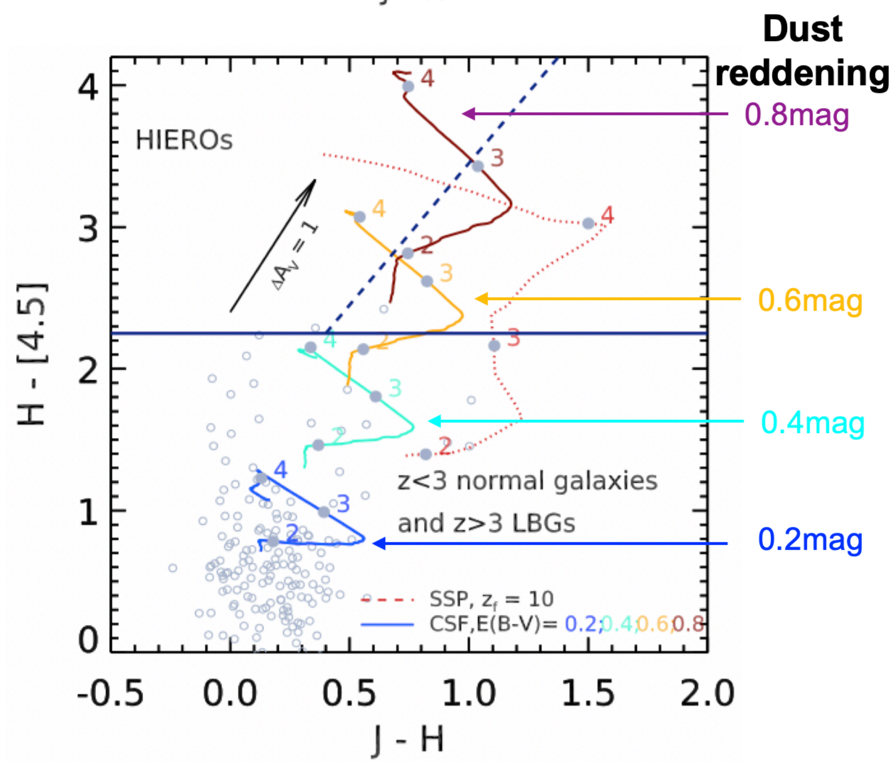
T. WANG (王涛)[1], D. ELBAZ[1], C. SCHREIBER[1], M. PANNELLA[1], X. SHU[2], S. P. WILLNER[3], M. L. N. ASHBY[3], J.-S. HUANG[3,4,5], A. FONTANA[6], A. DEKEL[7], E. DADDI[1], H. C. FERGUSON[8], J. DUNLOP[9], L. CIESLA[1], A. M. KOEKEMOER[8], M. GIAVALISCO[10], K. BOUTSIA[6], S. FINKELSTEIN[11], S. JUNEAU[1], G. BARRO[12], D. C. KOO[12], M. J. MICHAŁOWSKI[9], G. ORELLANA[13], Y. LU[14], M. CASTELLANO[6], N. BOURNE[9], F. BUITRAGO[9], P. SANTINI[6], S. M. FABER[12], N. HATHI[15], R. A. LUCAS[8], AND P. G. PÉREZ-GONZÁLEZ[16]

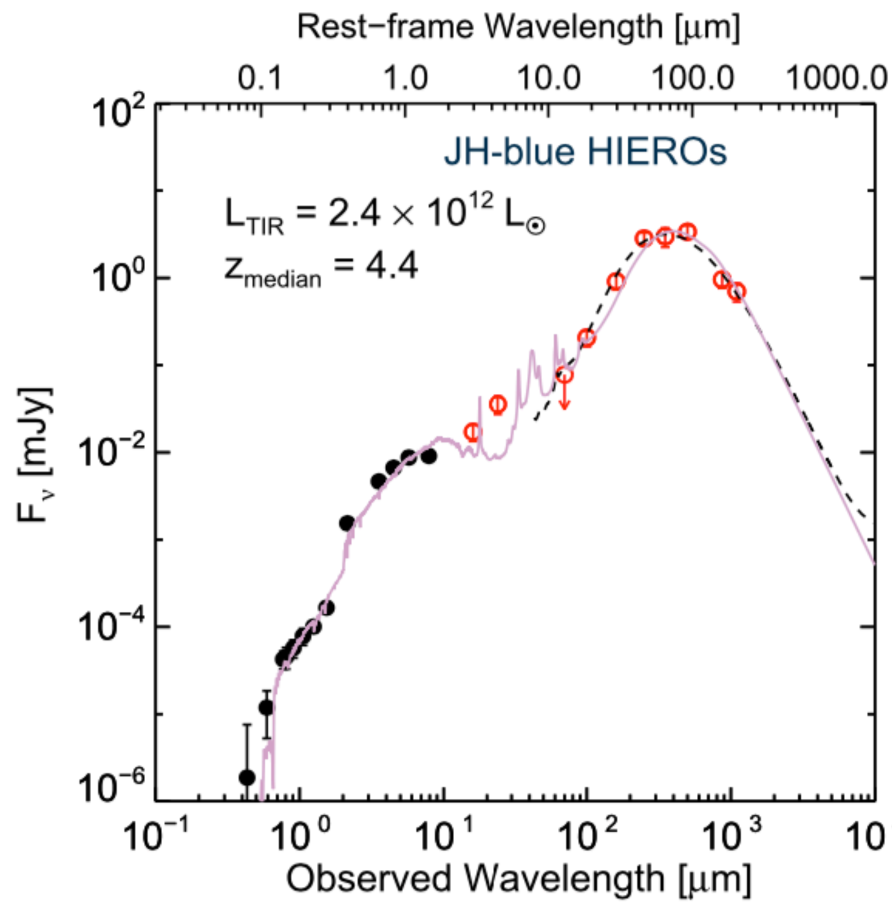
We introduce a new color selection technique to identify high-redshift, massive galaxies that are systematically missed by Lyman-break selection. The new selection is based on the H_{160} (H) and Infrared Array Camera (IRAC) 4.5 μm bands, specifically $H - [4.5] > 2.25$ mag. These galaxies, called "HIEROs,"

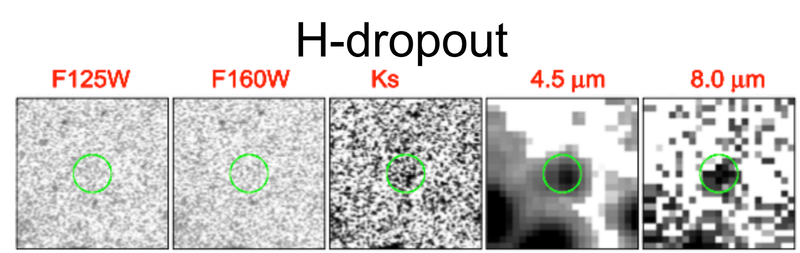





JH-red
JH-blue
z > 3.5
3 < z < 3.5
z < 3
24μm-det
H - [4.5]
J - H


Dust reddening
0.8mag
0.6mag
0.4mag
0.2mag
HIEROs
ΔA_V = 1
z<3 normal galaxies
and z>3 LBGs
SSP, z_f = 10
CSF,E(B-V)= 0.2,0.4,0.6,0.8
H - [4.5]
J - H


Rest−frame Wavelength [μm]
JH-blue HIEROs
L_TIR = 2.4 × 10^12 L_⊙
z_median = 4.4
F_ν [mJy]
Observed Wavelength [μm]

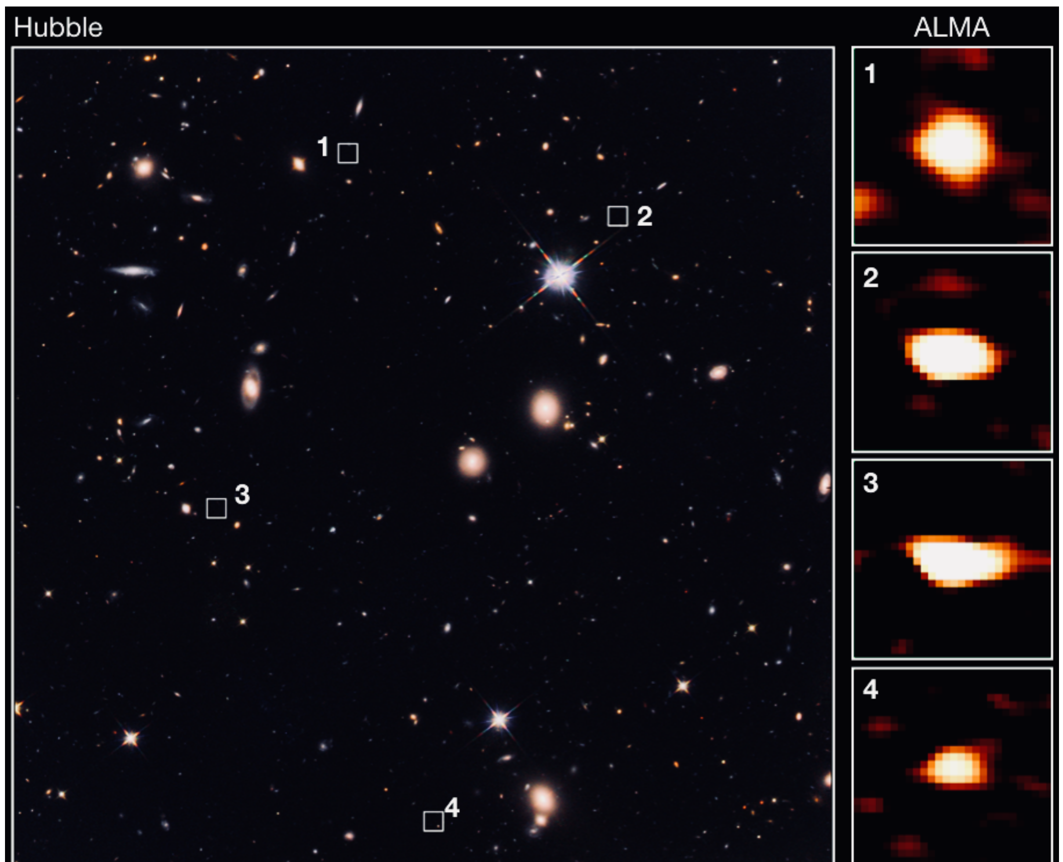

H-dropout
F125W
F160W
Ks
4.5 μm
8.0 μm

LETTER

https://doi.org/10.1038/s41586-019-1452-4

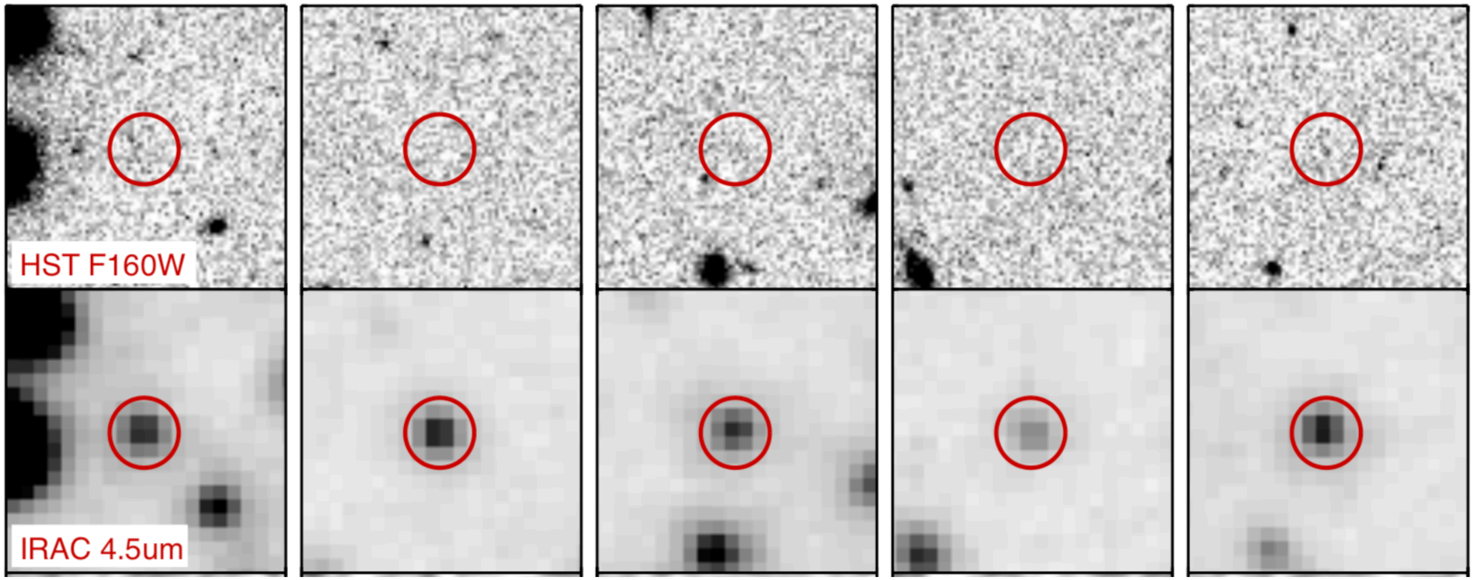
A dominant population of optically invisible massive galaxies in the early Universe

T. Wang[1,2,3]*, C. Schreiber[2,4,5], D. Elbaz[2], Y. Yoshimura[1], K. Kohno[1,6], X. Shu[7], Y. Yamaguchi[1], M. Pannella[8], M. Franco[2], J. Huang[9], C.-F. Lim[10,11] & W.-H. Wang[10]



ALMA targets: 4.5μm sources undetected by HST in GOODS-S, UDS and CANDELS-COSMOS

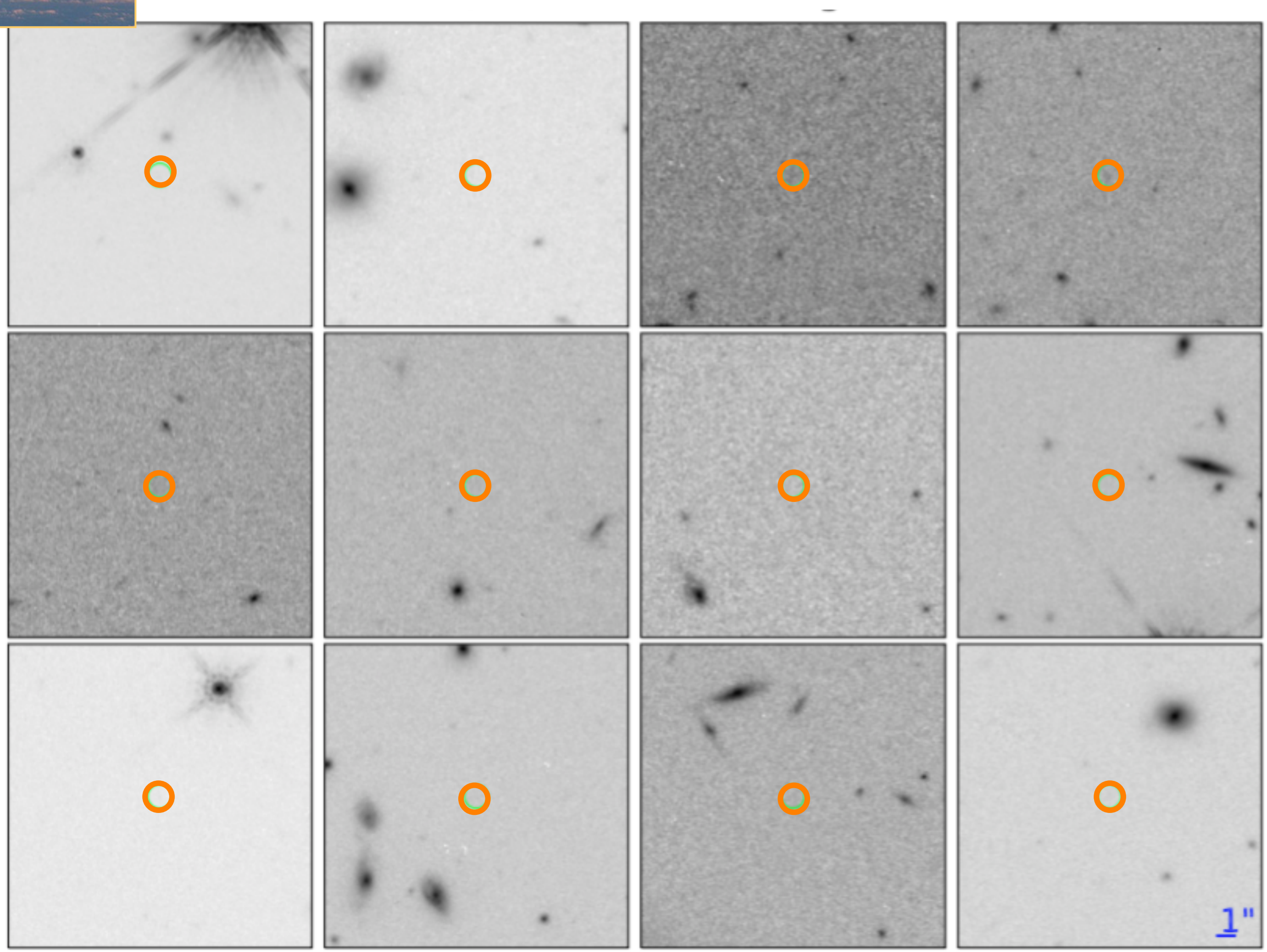
H-dropouts

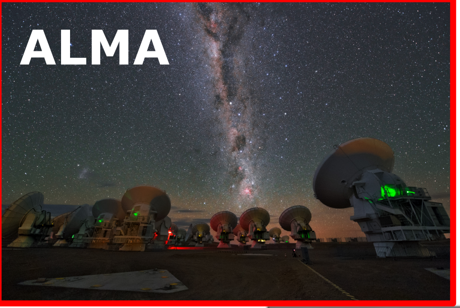


[4.5] brighter than 24
→ $M_\star > 10^{10.1\text{-}10.4}\ M_\odot$ at $z \sim 3 - 6$

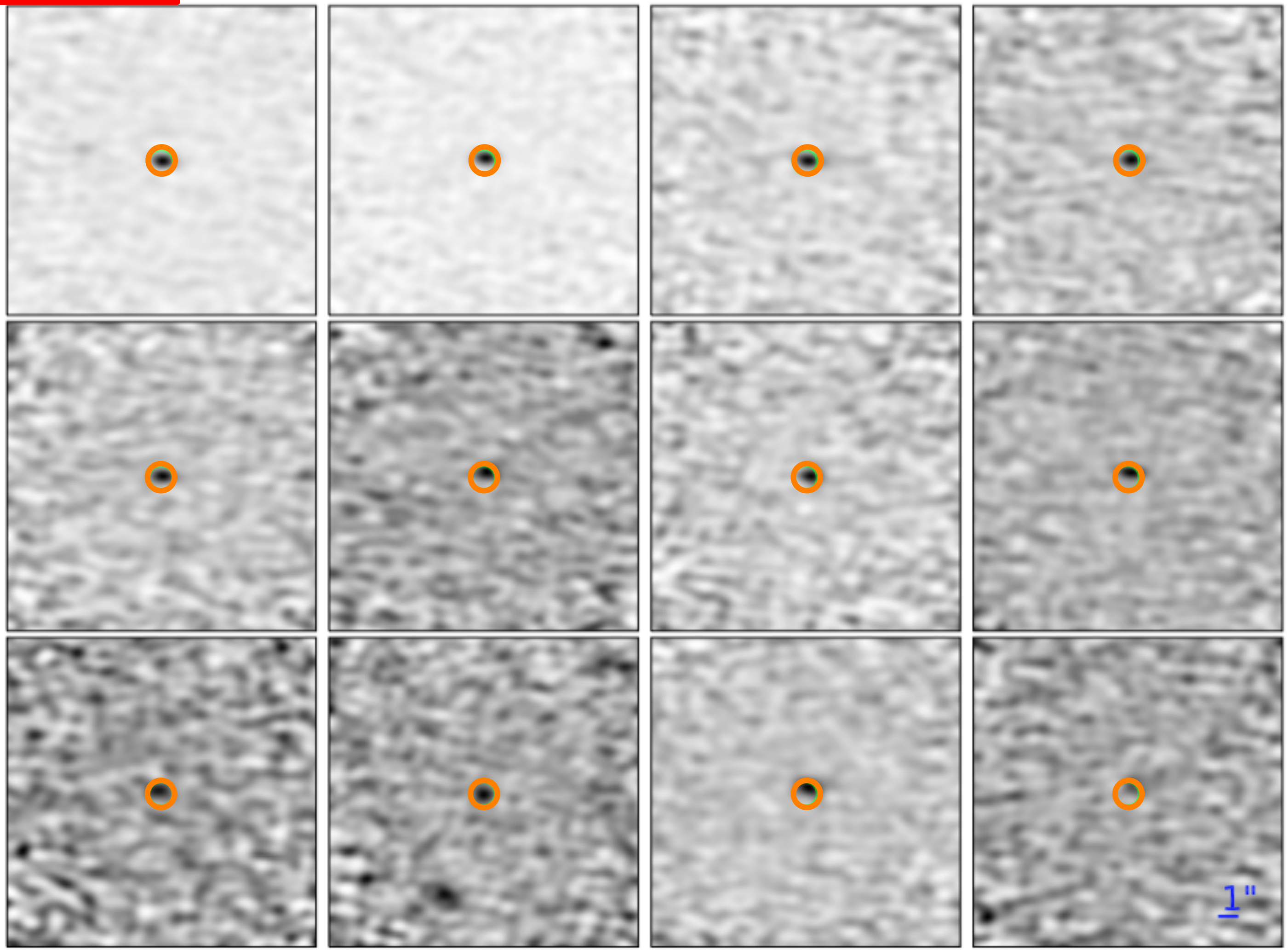
HST H-band fainter than 27 (AB)
(Wang, Elbaz +16)

HST/WFC3 1.6μm ~2 hours



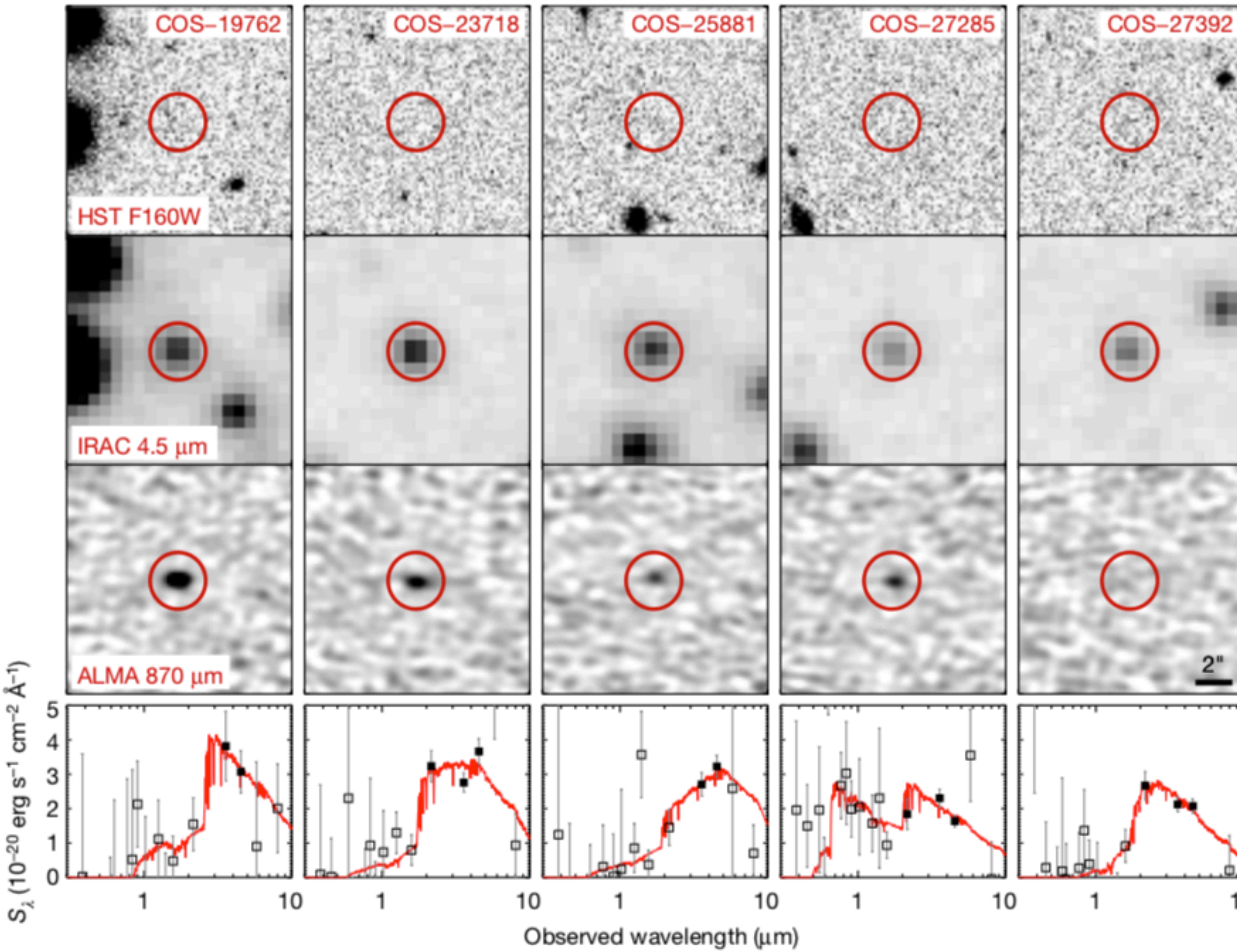


ALMA 870μm 1.8 min/galaxy

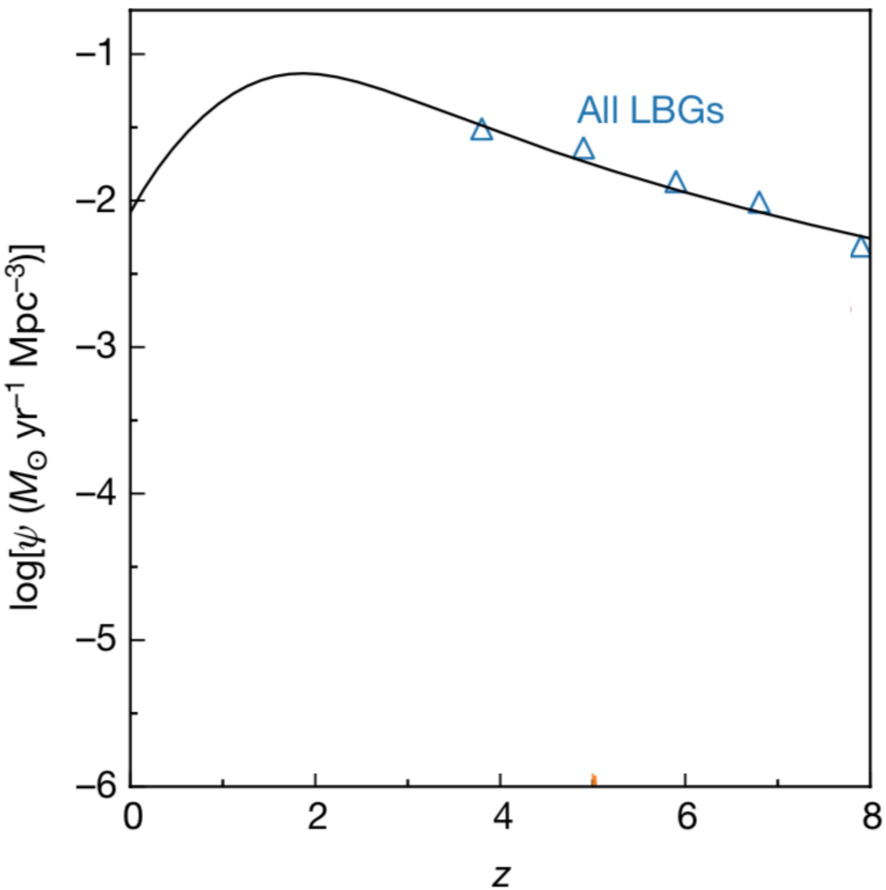


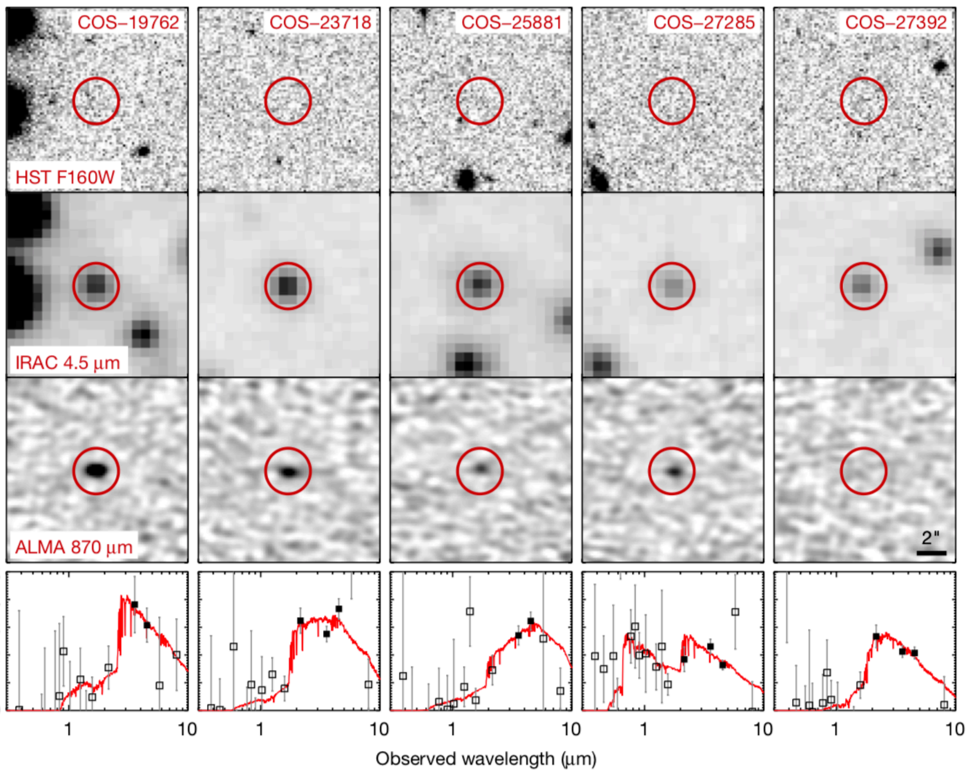
ALMA detects 39 out of 63 H-dropouts in 1.8’ at 870μm

[4.5] < 24 mag → $M_\star > 10^{10.1\text{-}10.4}\ M_\odot$ at z ~ 3 – 6 (Wang, Elbaz +16)



The most massive galaxies in the early universe are optically dark

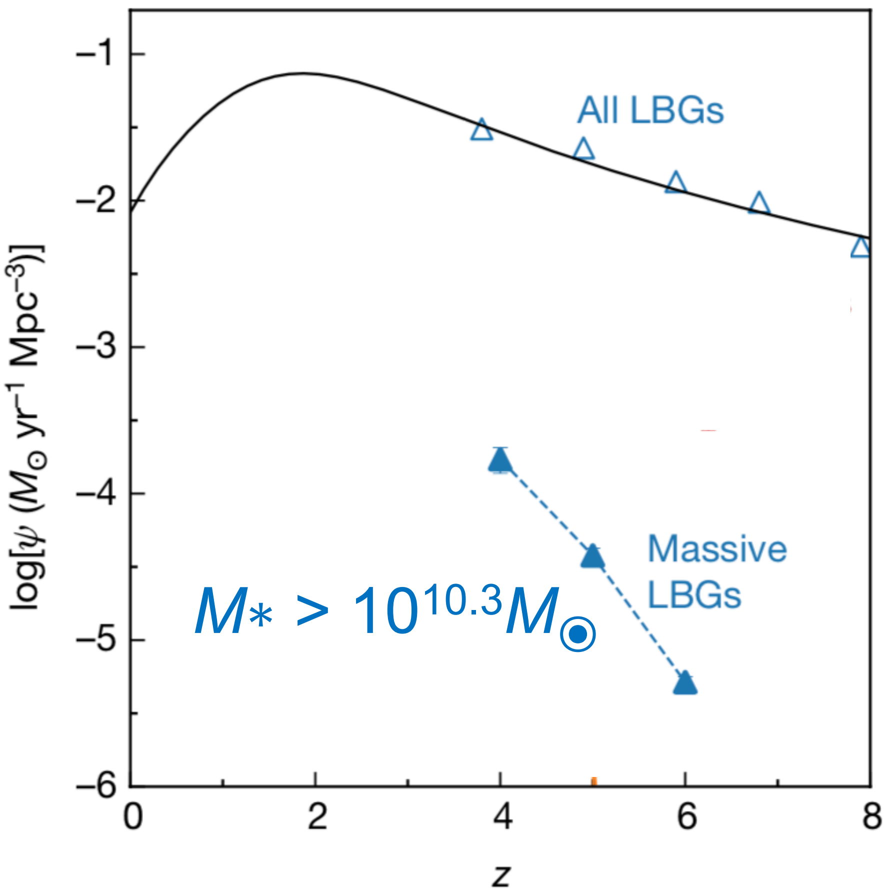


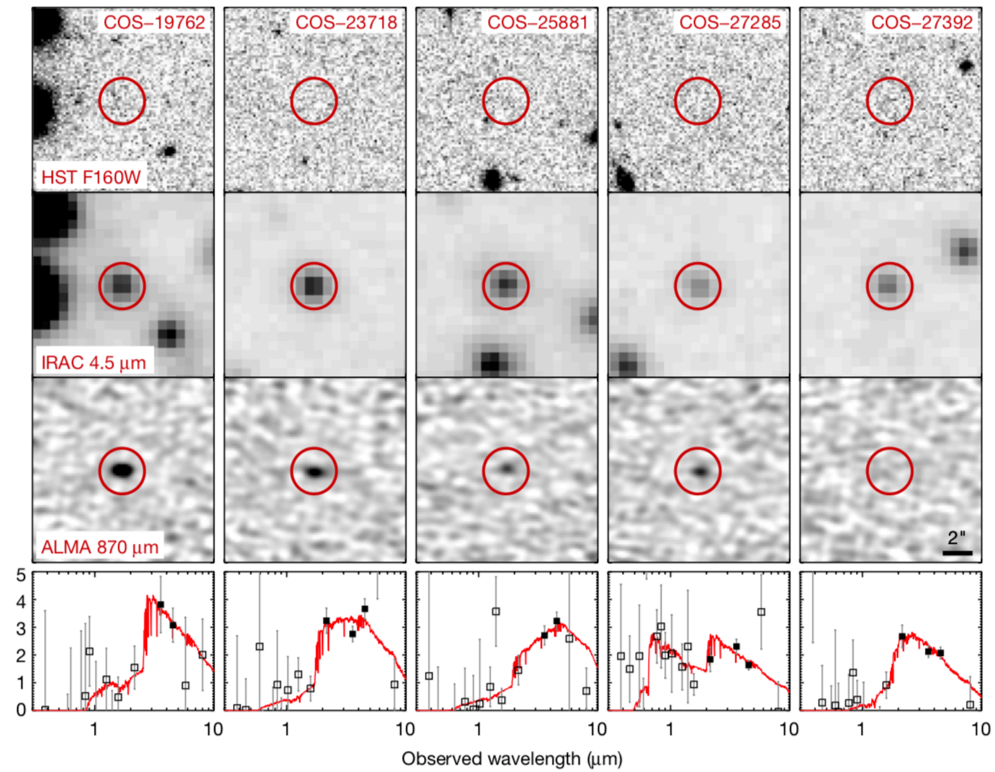


space density: n ~ 10^{-5} Mpc^{-3} , SFR ~ 200 $M_{\odot} yr^{-1}$

Wang, Schreiber, Elbaz +19, Nature

The most massive galaxies in the early universe are optically dark





space density: $n \sim 10^{-5}$ Mpc^{-3} , SFR $\sim 200\ M_\odot \mathrm{yr}^{-1}$

Wang, Schreiber, Elbaz +19, Nature

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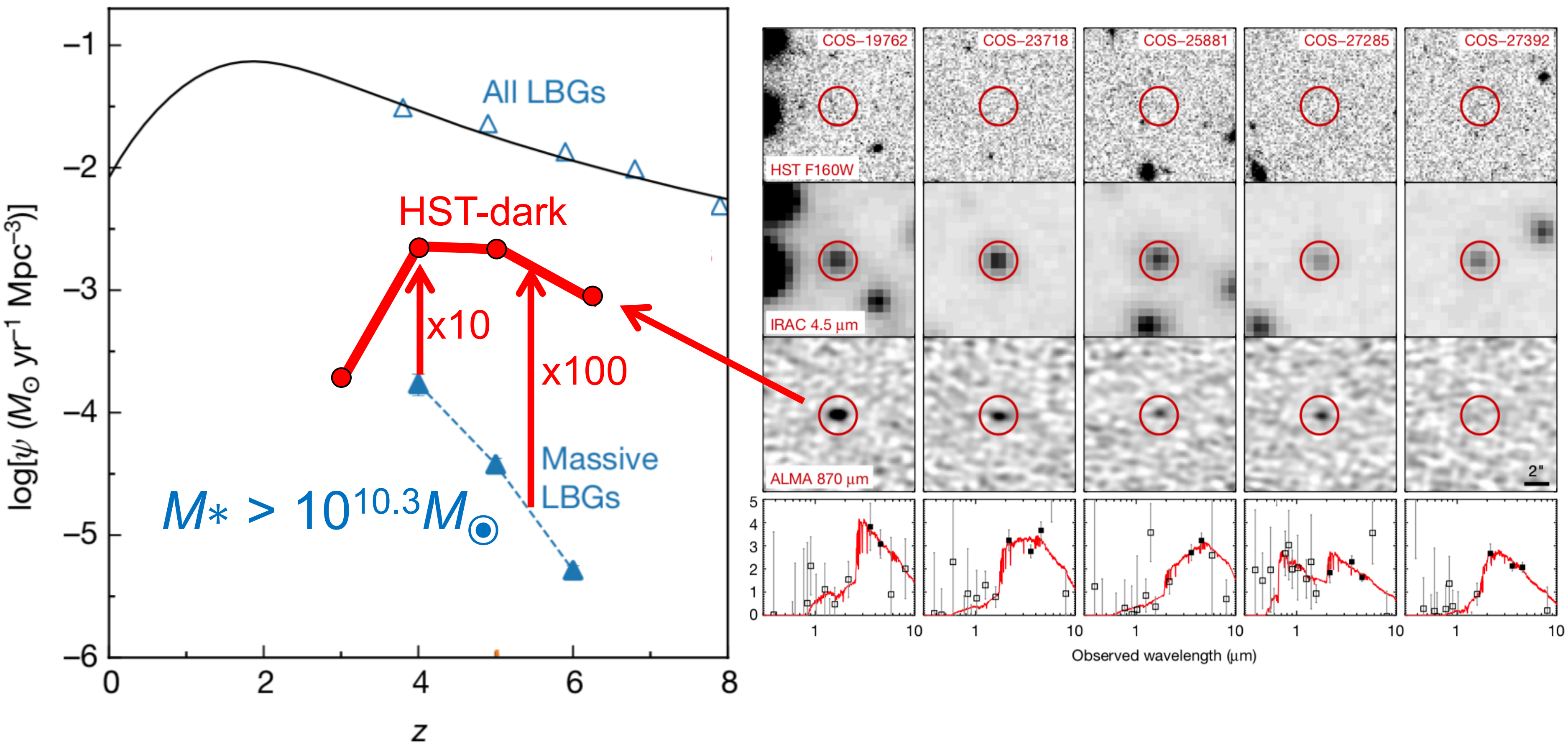

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Wang, Schreiber, Elbaz +19, Nature

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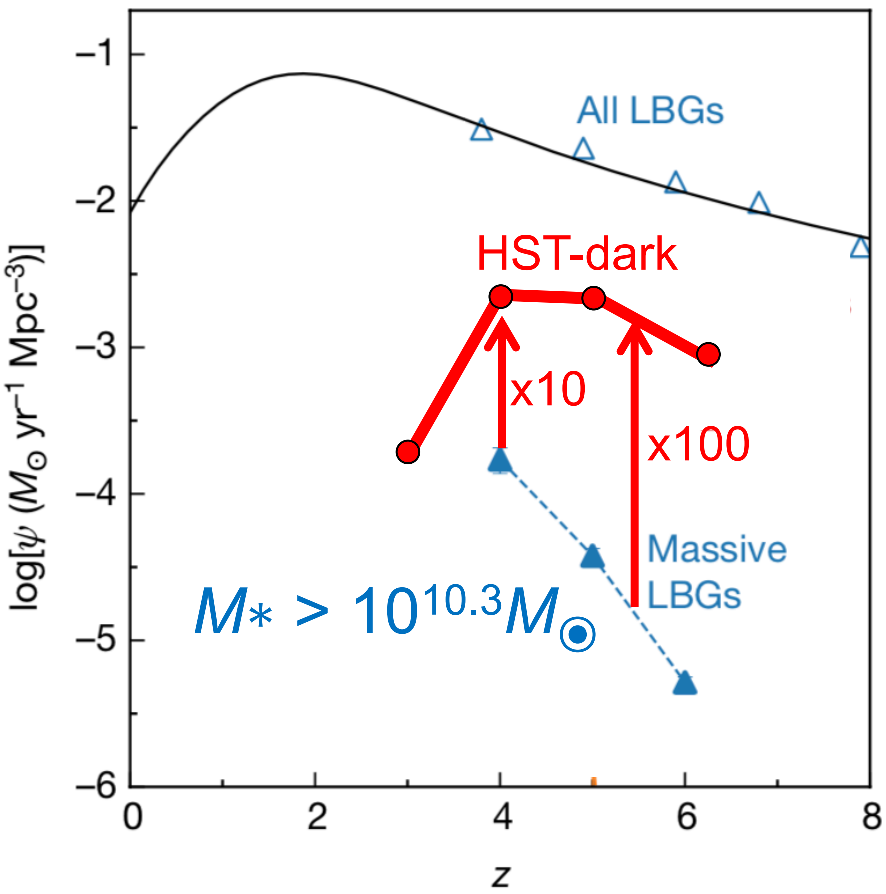

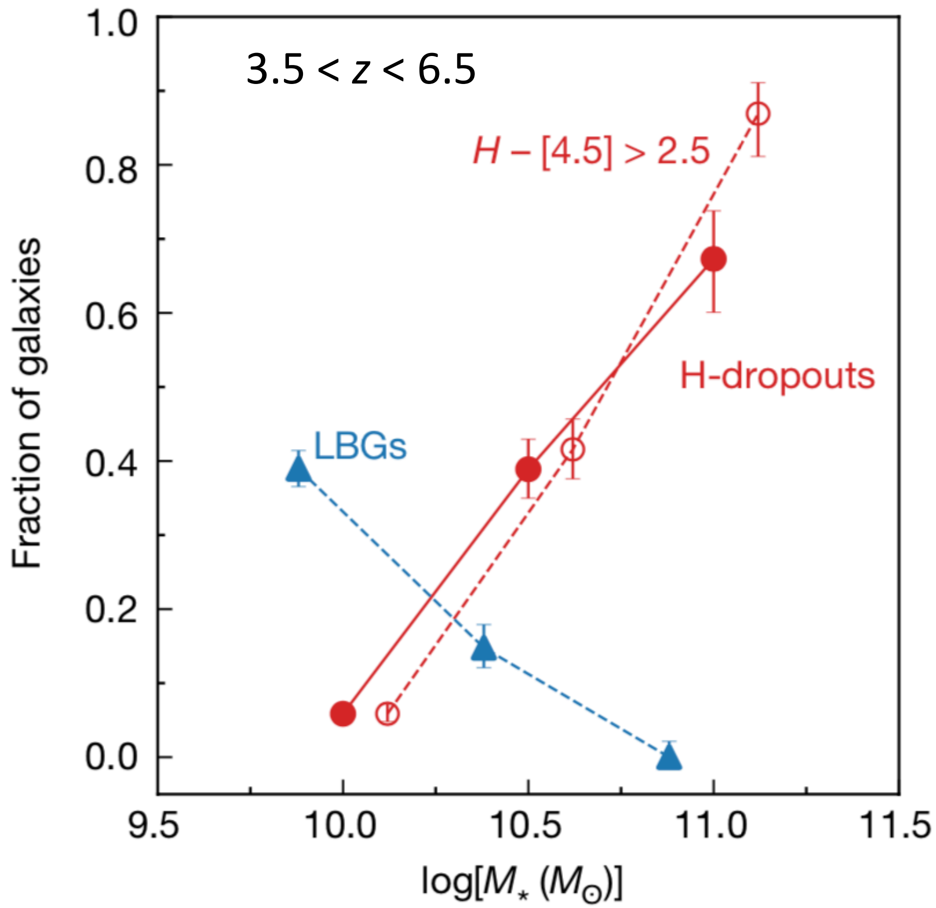

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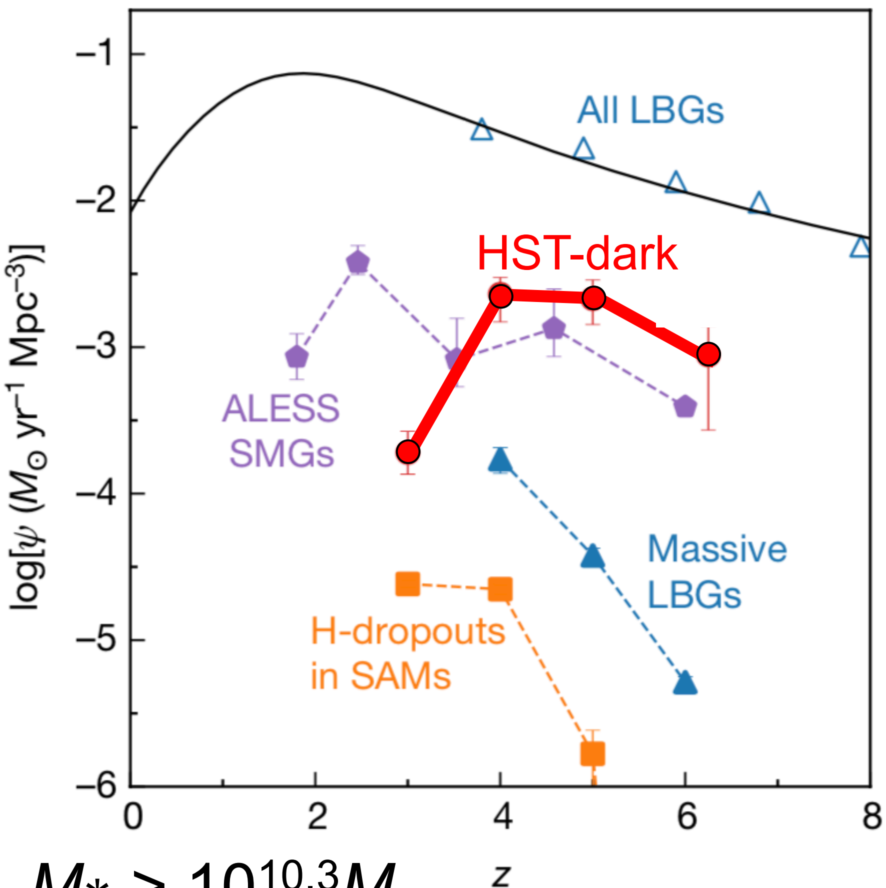
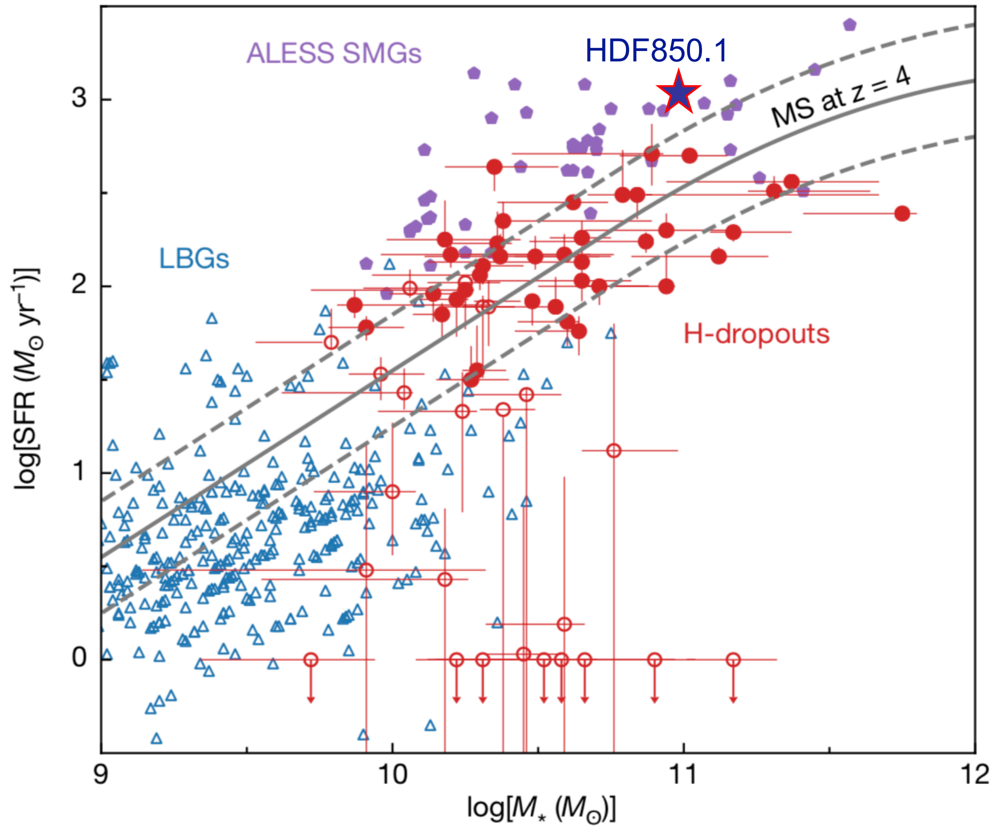
Wang, Schreiber, Elbaz +19, Nature

The most massive galaxies in the early universe are optically dark



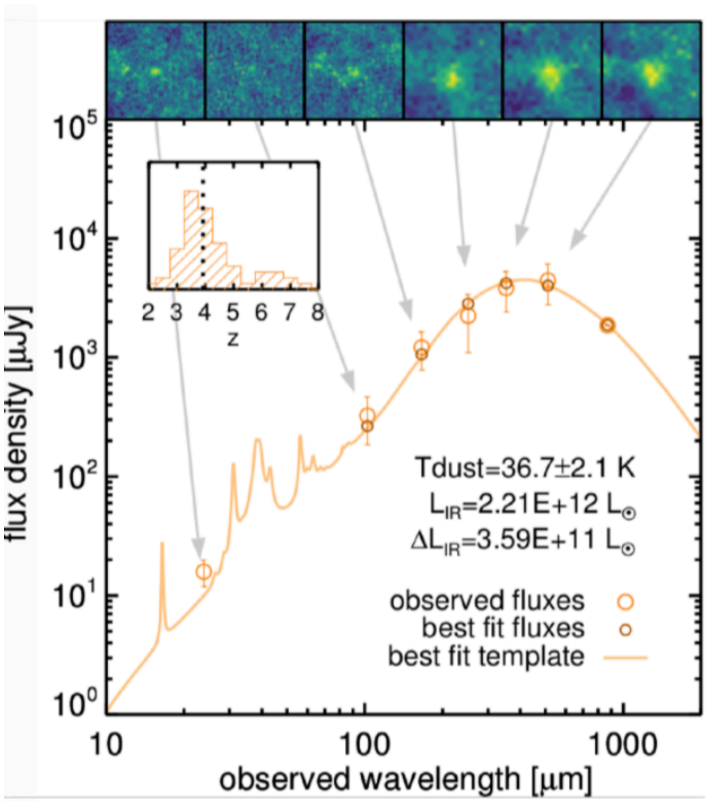


$M_* > 10^{10.3} M_\odot$

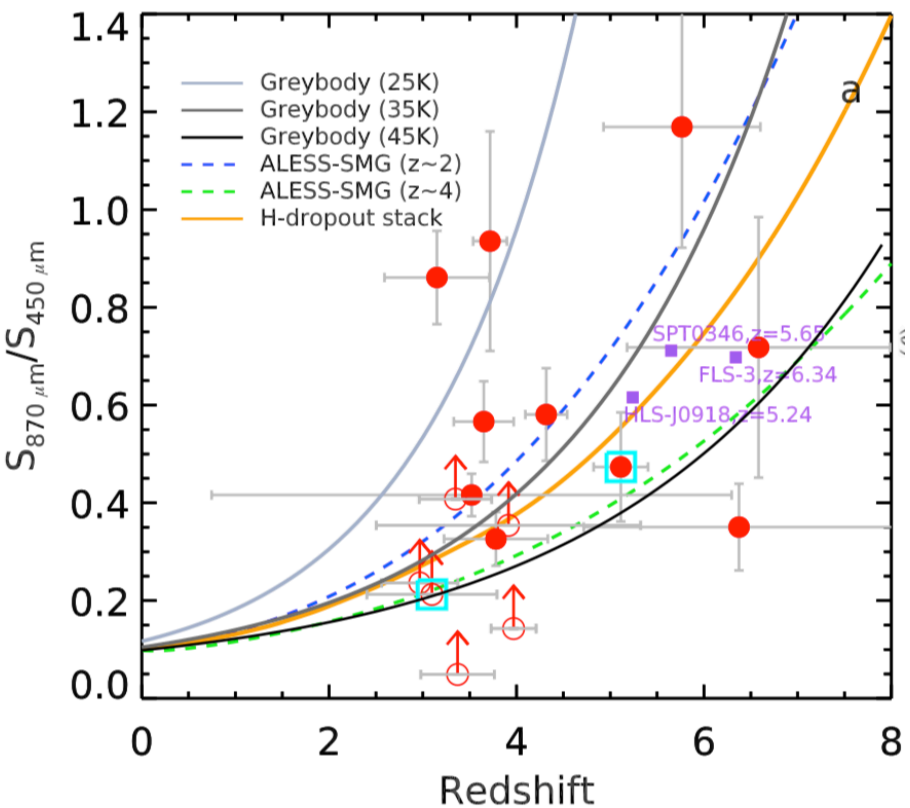
space density: n ~ 10^{-5} Mpc^{-3} , SFR ~ 200 $M_\odot yr^{-1}$

Wang, Schreiber, Elbaz +19, Nature

Confirming the redshifts of the HST-dark galaxies

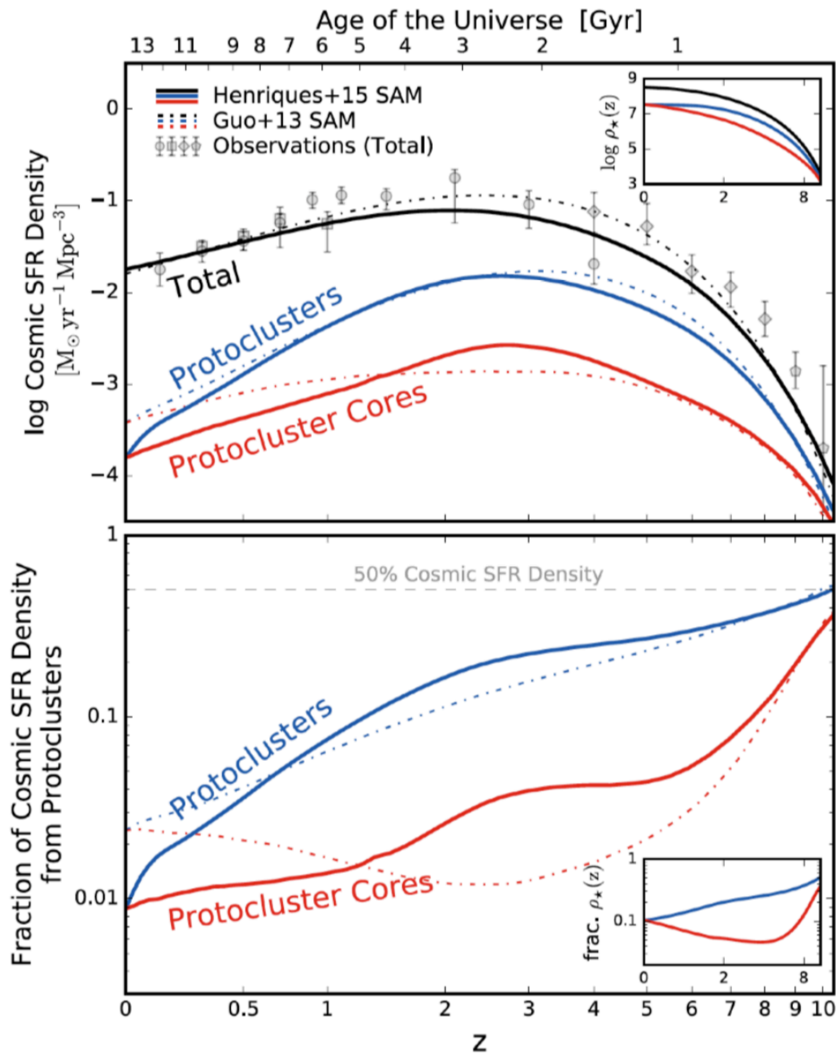


Stacked far-infrared SED peaking at ~400um



Extremely red 870um/450um colors: half of the sample are likely at z>4

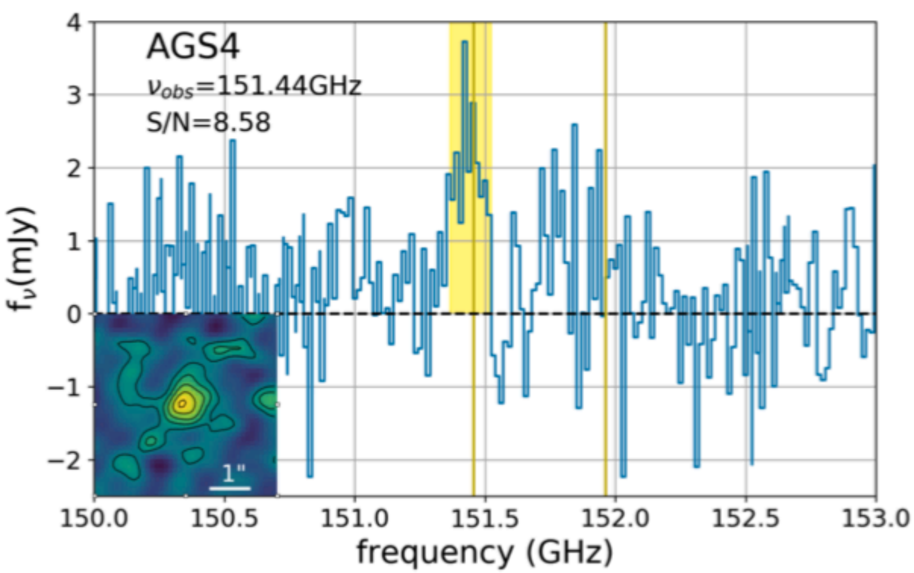
A higher contribution from protoclusters to the cosmic SFR density at higher redshifts

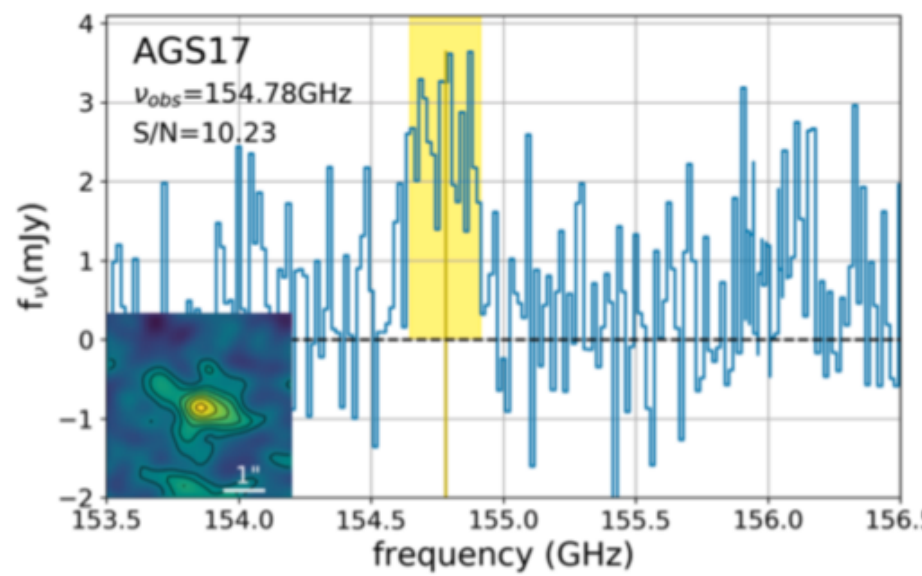


Chiang+2015

GOODS-ALMA: optically-dark ALMA galaxies shed light on a cluster in formation at $z = 3.5$

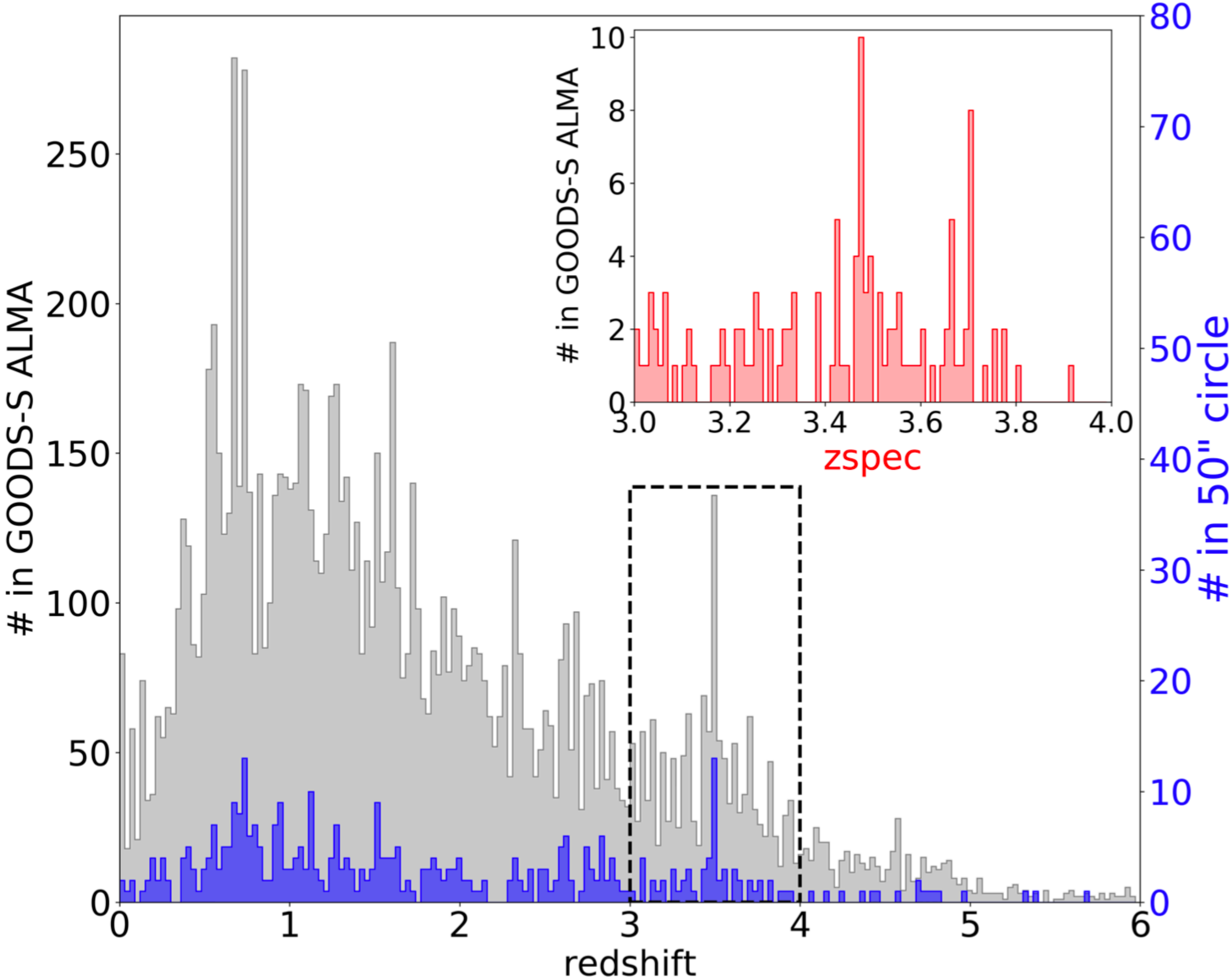
L. Zhou[1,2,3★], D. Elbaz[2], M. Franco[2,4], B. Magnelli[5], C. Schreiber[6], T. Wang[2,7], L. Ciesla[2,8], E. Daddi[2], M. Dickinson[9], N. Nagar[10], G. Magdis[11,12,13,14], D. M. Alexander[15], M. Béthermin[8], R. Demarco[10], J. Mullaney[16], F. Bournaud[2], H. Ferguson[17], S. L. Finkelstein[18], M. Giavalisco[19], H. Inami[20], D. Iono[21,22], S. Juneau[2,9], G. Lagache[8], H. Messias[23,24], K. Motohara[25], K. Okumura[2], M. Pannella[26], C. Papovich[27,28], A. Pope[19], W. Rujopakarn[29,30,31], Y. Shi[1,3], X. Shu[32], and J. Silverman[33]



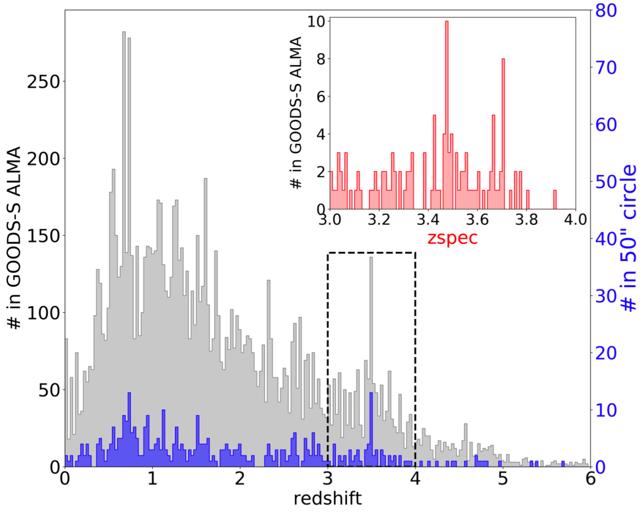


z=3.556

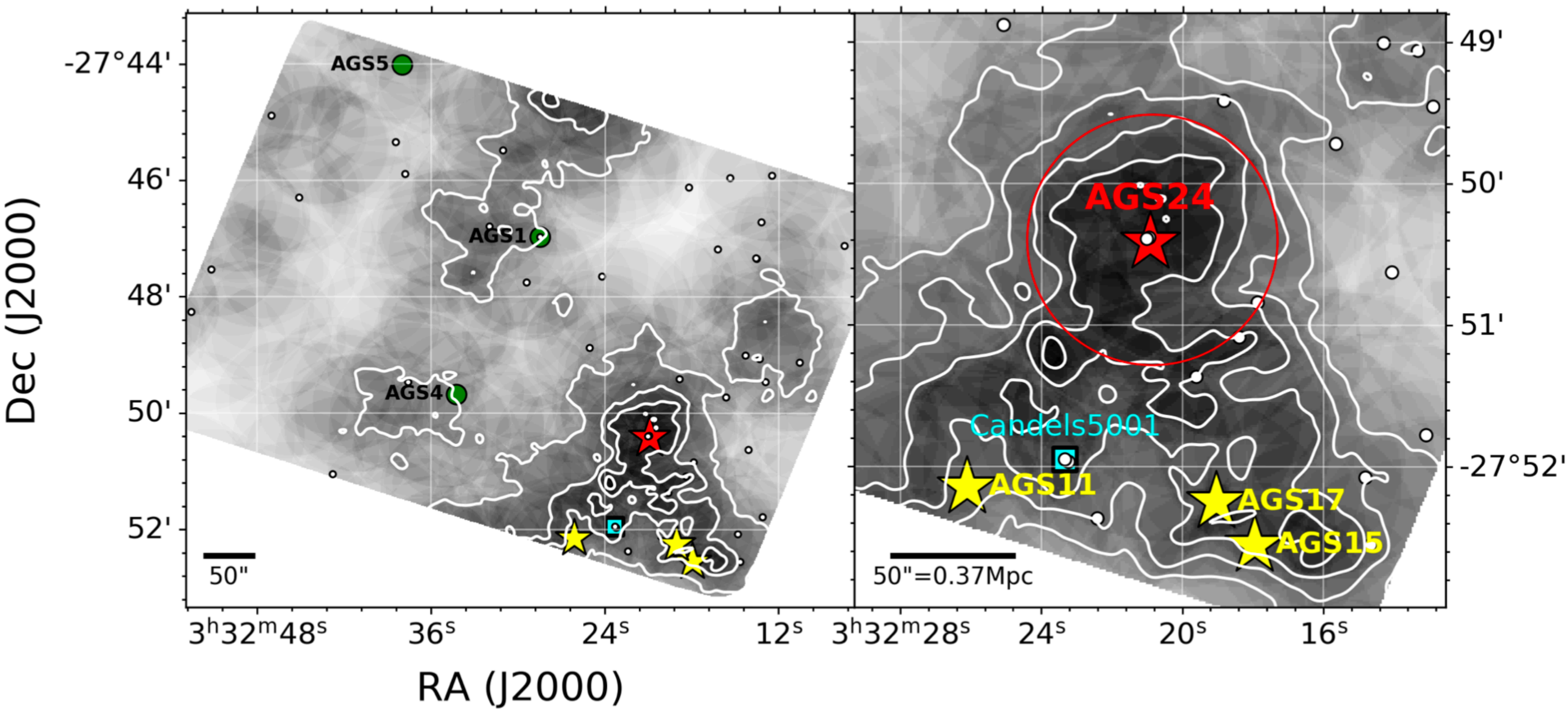
z=3.467



in GOODS-S ALMA
250
200
150
100
50
0
0
1
2
3
4
5
6
redshift
80
70
60
50
40
30
20
10
0
in 50" circle
10
8
6
4
2
0
3.0
3.2
3.4
3.6
3.8
4.0
zspec



in GOODS-S ALMA
in 50" circle
redshift
zspec



AGS5
AGS1
AGS4
AGS24
Candels5001
AGS11
AGS17
AGS15
50"
50"=0.37Mpc
Dec (J2000)
RA (J2000)