A deep ALMA image of the Hubble Ultra Deep Field

J.S. Dunlop et al. submitted to MNRAS

Presented by H. Umehata

Abstract

ABSTRACT

We present the results of the first, deep ALMA imaging covering the full $\simeq 4.5\,\mathrm{arcmin}^2$ of the Hubble Ultra Deep Field (HUDF) as previously imaged with WFC3/IR on the *HST*. Using a mosaic of 45 ALMA pointings, we have obtained a homogeneous image of the HUDF at $\lambda = 1.3\,\mathrm{mm}$, achieving an rms sensitivity $\sigma_{1.3} \simeq 35\,\mu\mathrm{Jy}$, at a resolution of $\simeq 0.7\,\mathrm{arcsec}$. From an initial list of $\simeq 50 > 3.5\sigma$ peaks, a rigorous analysis confirms 16 sources with flux densities $S_{1.3} > 120\,\mu\mathrm{Jy}$. All of these have secure galaxy counterparts with robust redshifts ($\langle z \rangle = 2.15$), and 12 are also detected at 6 GHz in new ultra-deep JVLA imaging. Due to the wealth of supporting data in this unique field, the physical properties of the ALMA sources are well constrained, including, crucially, their stellar masses (M_*) and UV+FIR star-formation rates (SFR). Our results show that stellar mass is the best predictor of SFR in the high-redshift Universe; indeed at $z \geq 2$ our ALMA sample contains 7 of the 9 galaxies in the HUDF with $M_* \geq 2 \times 10^{10}\,\mathrm{M}_\odot$, and we detect only one galaxy at $z > 3.5$, reflecting the rapid drop-off of high-mass galaxies with increasing redshift. The detected sources, coupled with stacking, allow us to probe the redshift/mass distribution of the 1.3-mm background down to $S_{1.3} \simeq 10\,\mu\mathrm{Jy}$. We find strong evidence for a steep 'main sequence' for star-forming galaxies at $z \simeq 2$, with $\mathrm{SFR} \propto M_*$ and a mean specific $\mathrm{SFR} \simeq 2.2\,\mathrm{Gyr}^{-1}$. Moreover, we find that $\simeq 85\%$ of total star formation at $z \simeq 2$ is enshrouded in dust, with $\simeq 65\%$ of all star formation at this epoch occurring in high-mass galaxies ($M_* > 2 \times 10^{10}\,\mathrm{M}_\odot$), for which the average obscured:unobscured SF ratio is $\simeq 200$. Finally, we combine our new ALMA results with the existing *HST* data to revisit the cosmic evolution of star-formation rate density (ρ_{SFR}); we find that ρ_{SFR} peaks at $z \simeq 2.5$, and that the star-forming Universe transits from primarily unobscured to primarily obscured thereafter at $z \simeq 4$.

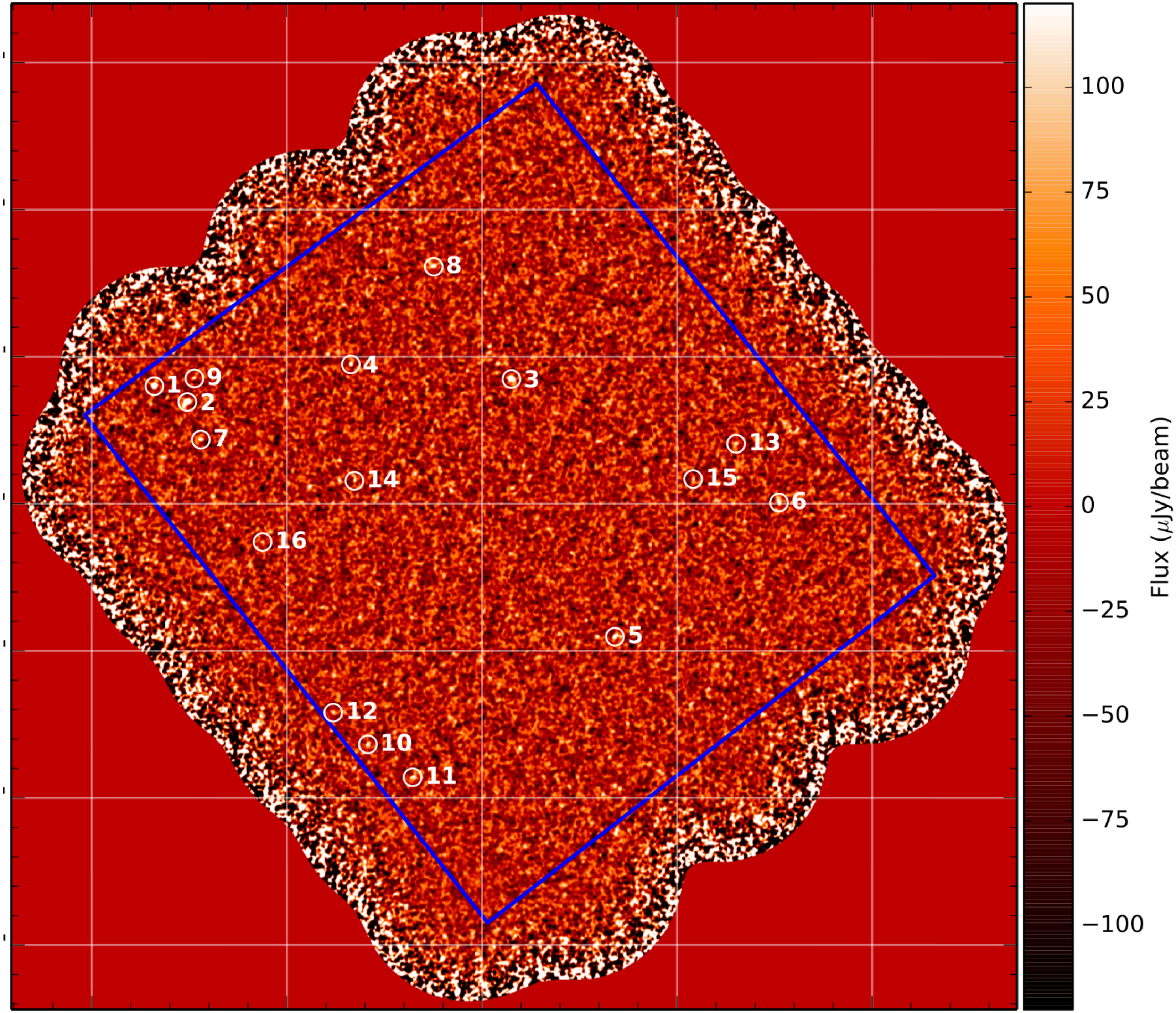
ALMA Observations

§ Observations

- 13 days in 2014-2015
- Max baseline: 550-1250 m
- 45-pointing mosaic (separated by x0.8 antenna beam)
  - one SB terminated after 20 pointing -> included.

§ Reduction and Imaging

- standard procedures using CASA
- CLEAN with natural weighting:
  -> synthesized beam: 589 x 503 mas^2
- A 220 x 180 kλ taper:
  -> ~requested beam: 707x672 mas^2
- final mosaic sensitivity at center: 34 uJy/beam
- no deconvolution.



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
100
75
50
25
0
−25
−50
−75
−100
Flux (μJy/beam)

Other wavelength data

§ Optical/NIR 5σ depth

- ACS: B,V,I,z -> 29.7,30.2, 29.9, 29.8
- WFC3: Y,J125,J140,H160 -> 29.7, 29.2, 29.2, 29.2
- HAWK-I: Ks -> 26.5

§ Other data

- Spitzer / Herschel

  -> ‘we fitted the Herschel maps with appropriate beams at the ALMA source positions’

- Radio: rms 0.32 uJy/beam at 6 GHz

  -> 27 radio sources with >5sigma

- MUSE: 3x3 mosaic of 18.2 ksec (+ 65 ksec in the centre)

  -> detected line(s) for 6/16 ALMA sources

  -> 4/6 are new.

ALMA Source Extraction

§ Method

- create 'noise' map

  -> evaluated the standard deviation for each pixel.
- then make 'SNR' map
- Search and Destroy. (AIPS/SAD-like?)

§ Survey area

- 4.4 arcmin^2 with σ<40 uJy (Cf. 34 uJy at centre)
- positive: 47 sources with >=3.5σ

  negative: 29 sources with >=3.5σ

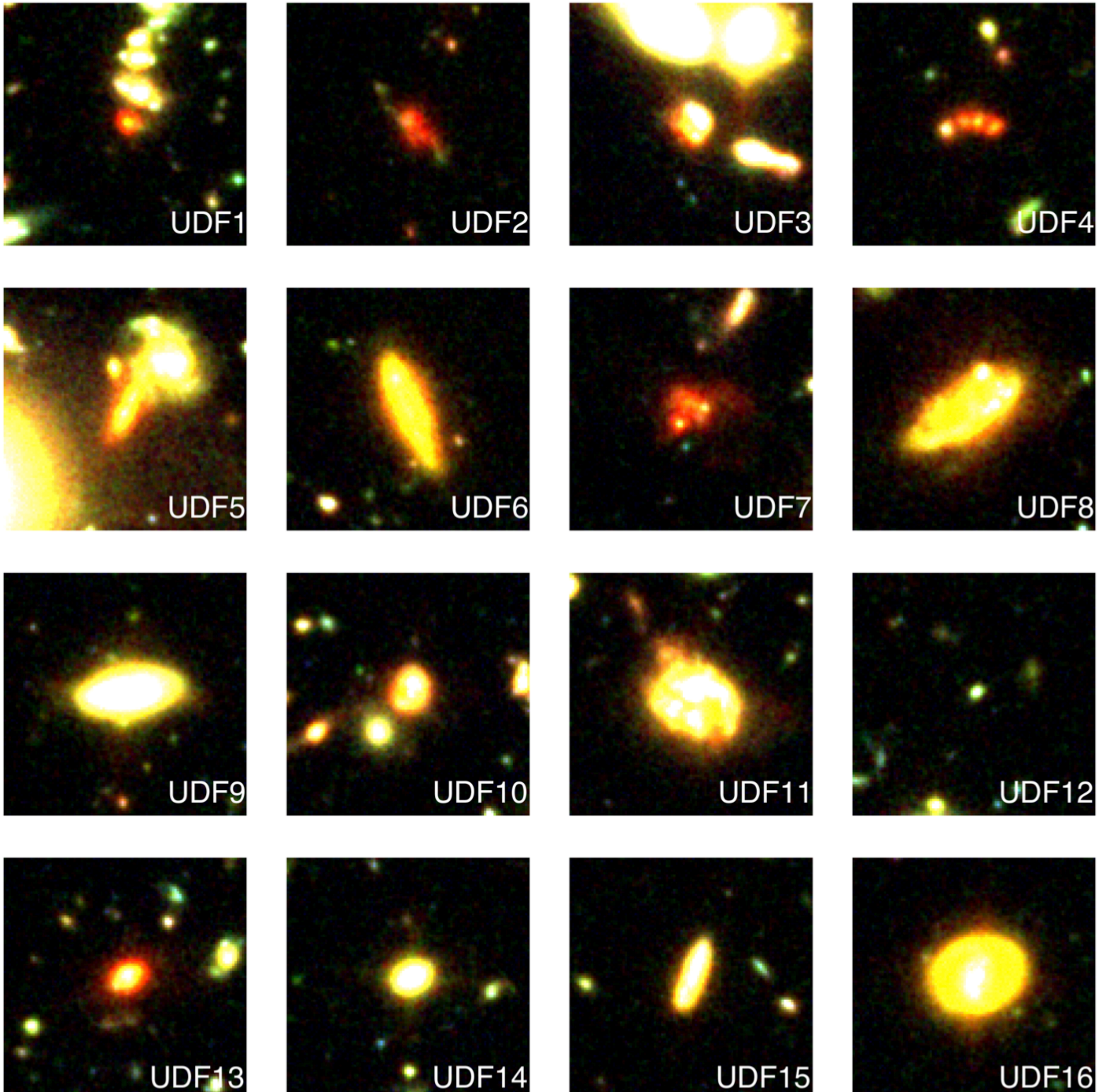
  => 15-20 sources would be real.

(…counts as a function of SNR?)

- 5 sources with 6σ are 'secure'
- 7 'negative' sources with 4σ

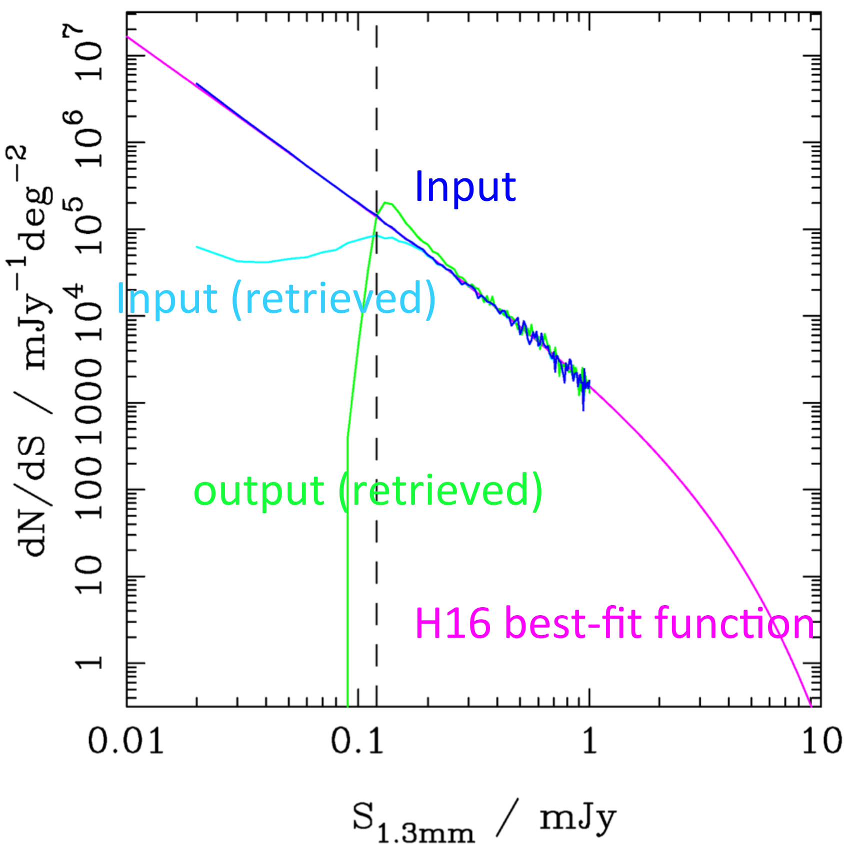
ALMA Source Catalog

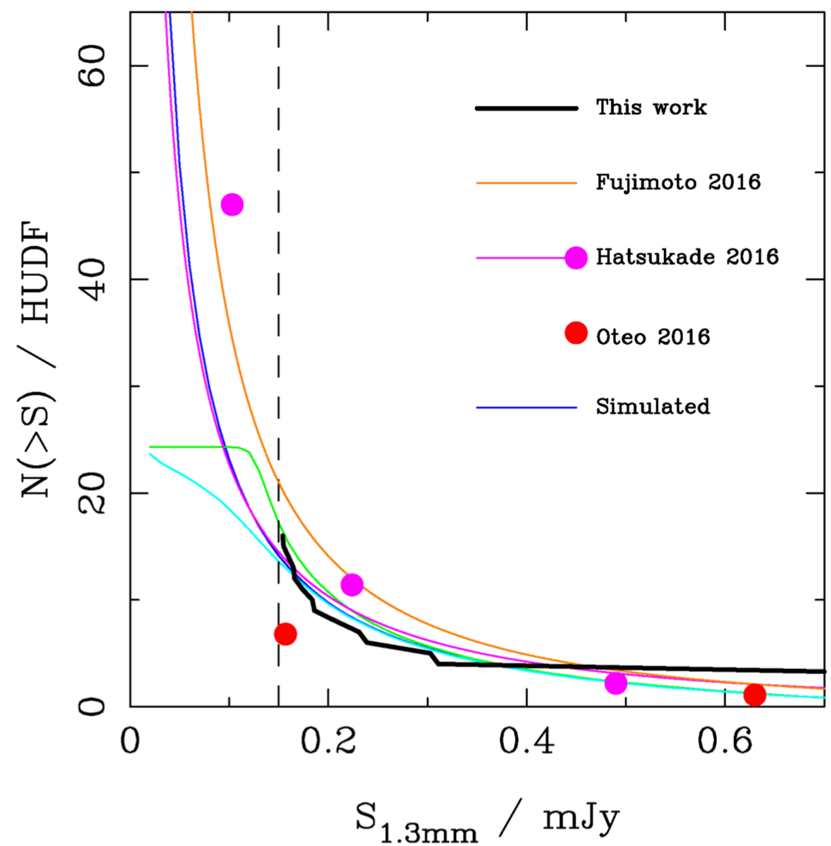
ID	RA (ALMA) /deg	Dec (ALMA) /deg	$S_{1.3mm}$ /μJy	S/N 1.3mm	RA (*HST*) /deg	Dec (*HST*) /deg	Δ_1 /arcsec	Δ_2 /arcsec	H_{160} /ABmag	z	Ref
UDF1	53.18348	−27.77667	924 ± 76	18.37	53.18345	−27.77658	0.33	0.13	24.75	3.00	
UDF2	53.18137	−27.77757	996 ± 87	16.82	53.18140	−27.77746	0.38	0.15	24.70	2.794	1
UDF3	53.16062	−27.77627	863 ± 84	13.99	53.16060	−27.77613	0.51	0.27	23.41	2.541	2
UDF4	53.17090	−27.77544	303 ± 46	6.63	53.17090	−27.77539	0.18	0.06	24.85	2.43	
UDF5	53.15398	−27.79087	311 ± 49	6.33	53.15405	−27.79091	0.24	0.42	23.30	1.759	3
UDF6	53.14347	−27.78327	239 ± 49	4.93	53.14347	−27.78321	0.22	0.03	22.27	1.411	2
UDF7	53.18051	−27.77970	231 ± 48	4.92	53.18052	−27.77965	0.21	0.06	24.17	2.59	
UDF8	53.16559	−27.76990	208 ± 46	4.50	53.16555	−27.76979	0.43	0.22	21.75	1.552	4
UDF9	53.18092	−27.77624	198 ± 39	4.26	53.18105	−27.77617	0.46	0.40	21.41	0.667	2
UDF10	53.16981	−27.79697	184 ± 46	4.02	53.16969	−27.79702	0.42	0.56	23.32	2.086	3
UDF11	53.16695	−27.79884	186 ± 46	4.02	53.16690	−27.79869	0.54	0.31	21.62	1.996	2, 4
UDF12	53.17203	−27.79517	154 ± 40	3.86	53.17212	−27.79509	0.39	0.28	27.00	5.000	5
UDF13	53.14622	−27.77994	174 ± 45	3.85	53.14615	−27.77988	0.31	0.24	23.27	2.497	3
UDF14	53.17067	−27.78204	160 ± 44	3.67	53.17069	−27.78197	0.24	0.06	22.76	0.769	2
UDF15	53.14897	−27.78194	166 ± 46	3.56	53.14902	−27.78196	0.18	0.36	23.37	1.721	3
UDF16	53.17655	−27.78550	155 ± 44	3.51	53.17658	−27.78545	0.22	0.09	21.42	1.314	2, 6


UDF1
UDF2
UDF3
UDF4
UDF5
UDF6
UDF7
UDF8
UDF9
UDF10
UDF11
UDF12
UDF13
UDF14
UDF15
UDF16

i+Y+H
6”x6”

Number Counts





- 'in very good agreement with integration of the Schechter function of H16'.
- significant work still needs to be done to clarify the faint-end.

Properties

↓ SED Fit
Chabrier IMF

↓ SED Fit ↓

↓ Multiple Templates

ID	$\log_{10}(M_*/\mathrm{M}_\odot)$	$\mathrm{SFR_{UV}}$ $/\mathrm{M_\odot yr^{-1}}$	A_V /mag	$\mathrm{SFR_{SED}}$ $/\mathrm{M_\odot yr^{-1}}$	$\mathrm{SFR_{FIR1}}$ $/\mathrm{M_\odot yr^{-1}}$	$\mathrm{SFR_{FIR2}}$ $/\mathrm{M_\odot yr^{-1}}$	$\mathrm{SFR_{Rad}}$ $/\mathrm{M_\odot yr^{-1}}$	$\mathrm{SFR_{obs}}/$ $\mathrm{SFR_{UV}}$	sSFR $/\mathrm{Gyr^{-1}}$
UDF1	10.7±0.10	0.31±0.05	3.1	399.4	326±83	364±82	439±28	1052±317	6.50±2.24
UDF2	11.1±0.15	0.32±0.10	2.2	50.2	247±76	194±64	242±22	772±339	1.96±0.92
UDF3†	10.3±0.15	4.70±0.30	0.9	42.0	195±69	173±1	400±17	41± 15	9.77±4.88
UDF4	10.5±0.15	0.43±0.20	1.6	20.0	94± 4	58± 5	89±17	219±102	2.97±1.05
UDF5	10.4±0.15	0.20±0.05	2.4	36.1	102± 7	67±25	86± 6	510±132	4.06±1.46
UDF6	10.5±0.10	0.10±0.02	2.8	78.0	87±11	66± 5	68± 5	870±205	2.75±0.73
UDF7	10.6±0.10	0.50±0.03	1.5	16.5	56±22	77±42	617±20	112± 45	1.41±0.64
UDF8	11.2±0.15	0.98±0.02	1.6	35.8	149±90	94±37	73± 5	152± 92	0.94±0.66
UDF9	10.0±0.10	0.06±0.01	0.9	0.5	23±25	5± 2	5± 1	383±421	2.30±2.56
UDF10	10.2±0.15	1.14±0.10	1.5	37.0	45±22	34± 7	<35	39± 20	2.84±1.71
UDF11	10.8±0.10	6.29±0.20	1.4	162.8	162±94	232±10	172±14	26± 15	2.57±1.60
UDF12	9.6±0.15	1.55±0.10	0.2	2.6	37±14	21± 7	<100	24± 10	9.29±4.80
UDF13	10.8±0.10	0.95±0.05	1.3	18.0	68±18	60±19	142±17	72± 19	1.08±0.38
UDF14	9.7±0.10	0.05±0.01	1.3	1.0	44±17	3± 2	<4	880±383	8.78±3.96
UDF15	9.9±0.15	1.14±0.02	1.1	15.5	38±27	25± 8	<20	33± 24	4.78±3.79
UDF16	10.9±0.10	0.10±0.05	0.6	0.5	40±18	25± 4	38± 3	400±269	0.50±0.26

↑ rest frame UV
(1500A)

↑ HUDF Template= 'Best'

↑ 6GHz

Redshifts

- 13 spec-z + 3 photo-z

- The distribution is in very good agreement with classical SMGs.

  -> <z>=2.15

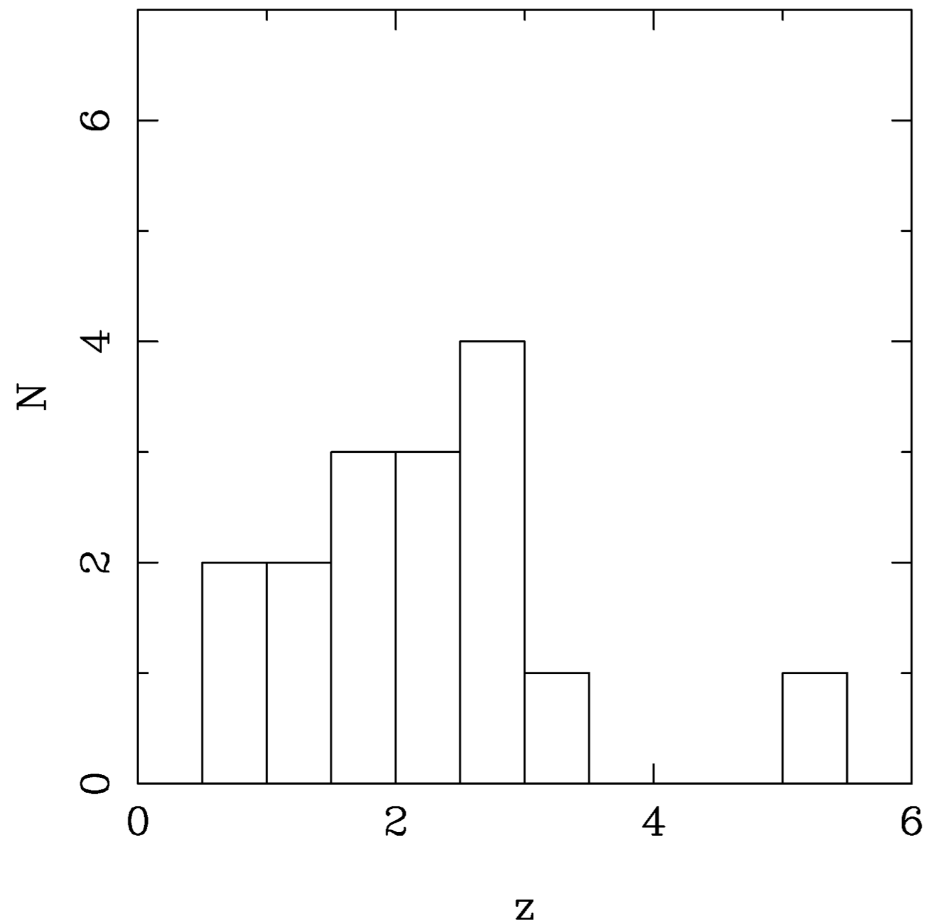
  13/16 are at z=1.5-3.

- only one detection beyond z=3.1

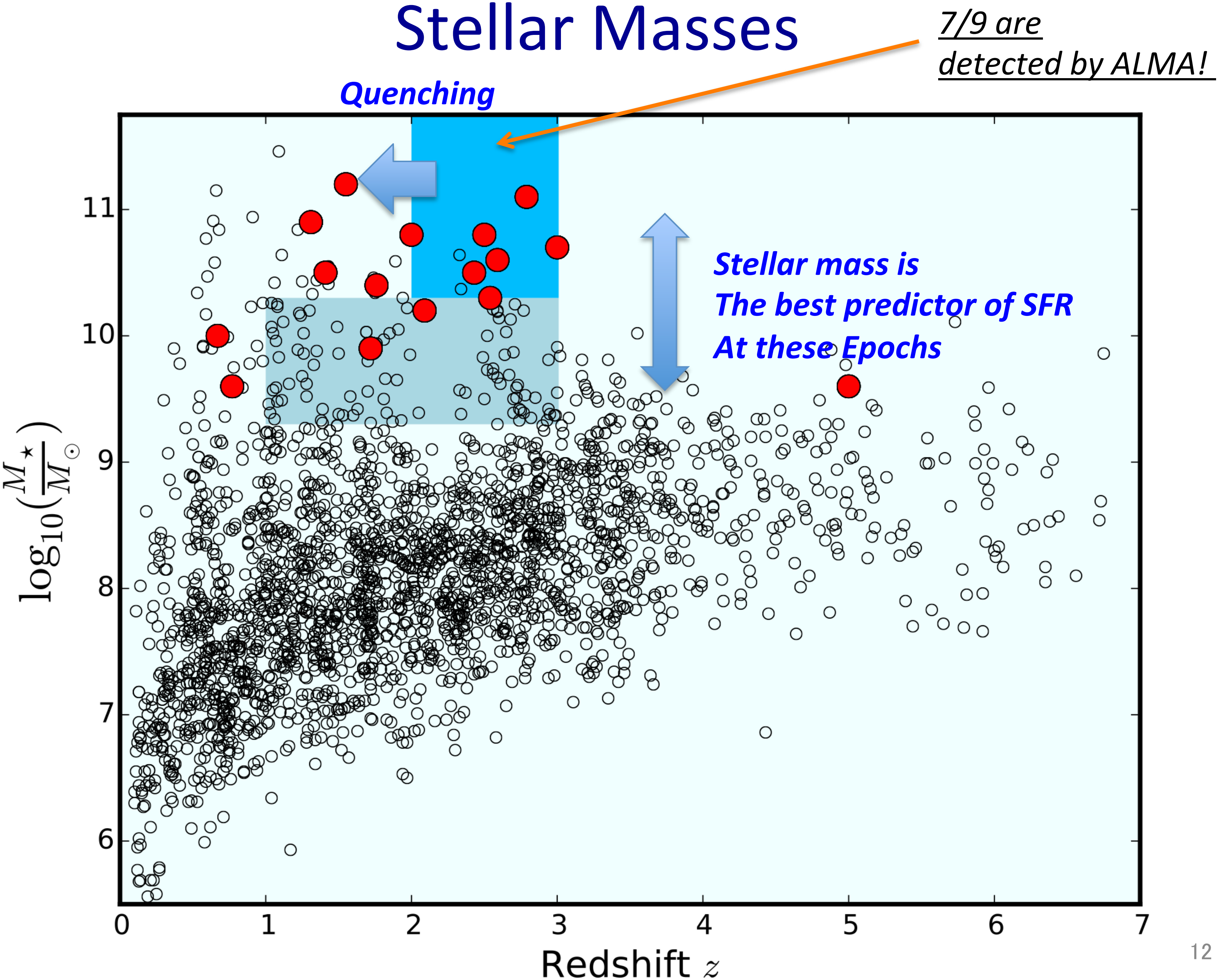
  => the absence of high-mass galaxies at these redshifts.

- the decline at z<1.5

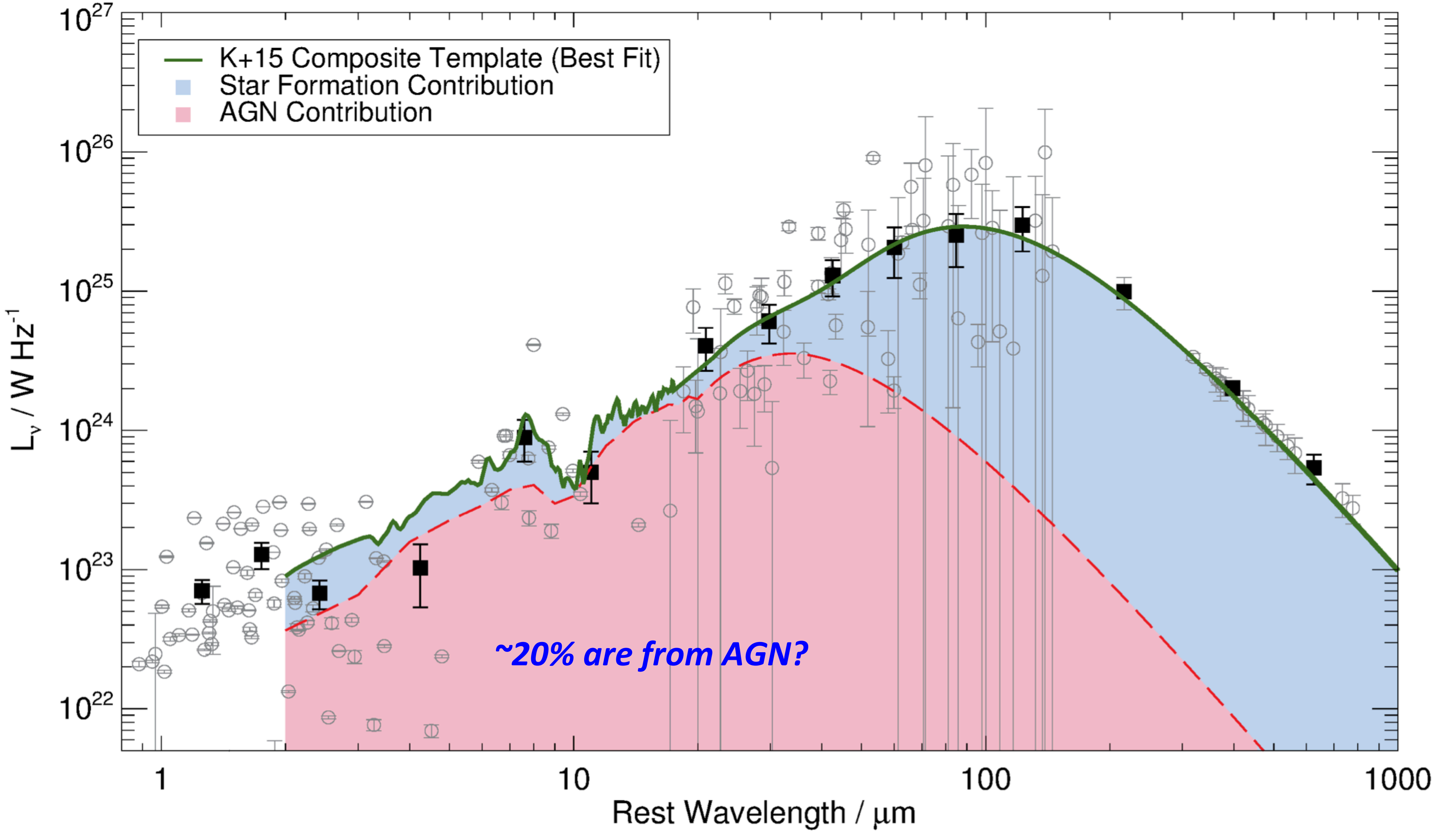
  => quenching of SF activity in high-mass galaxies.



Stellar Masses

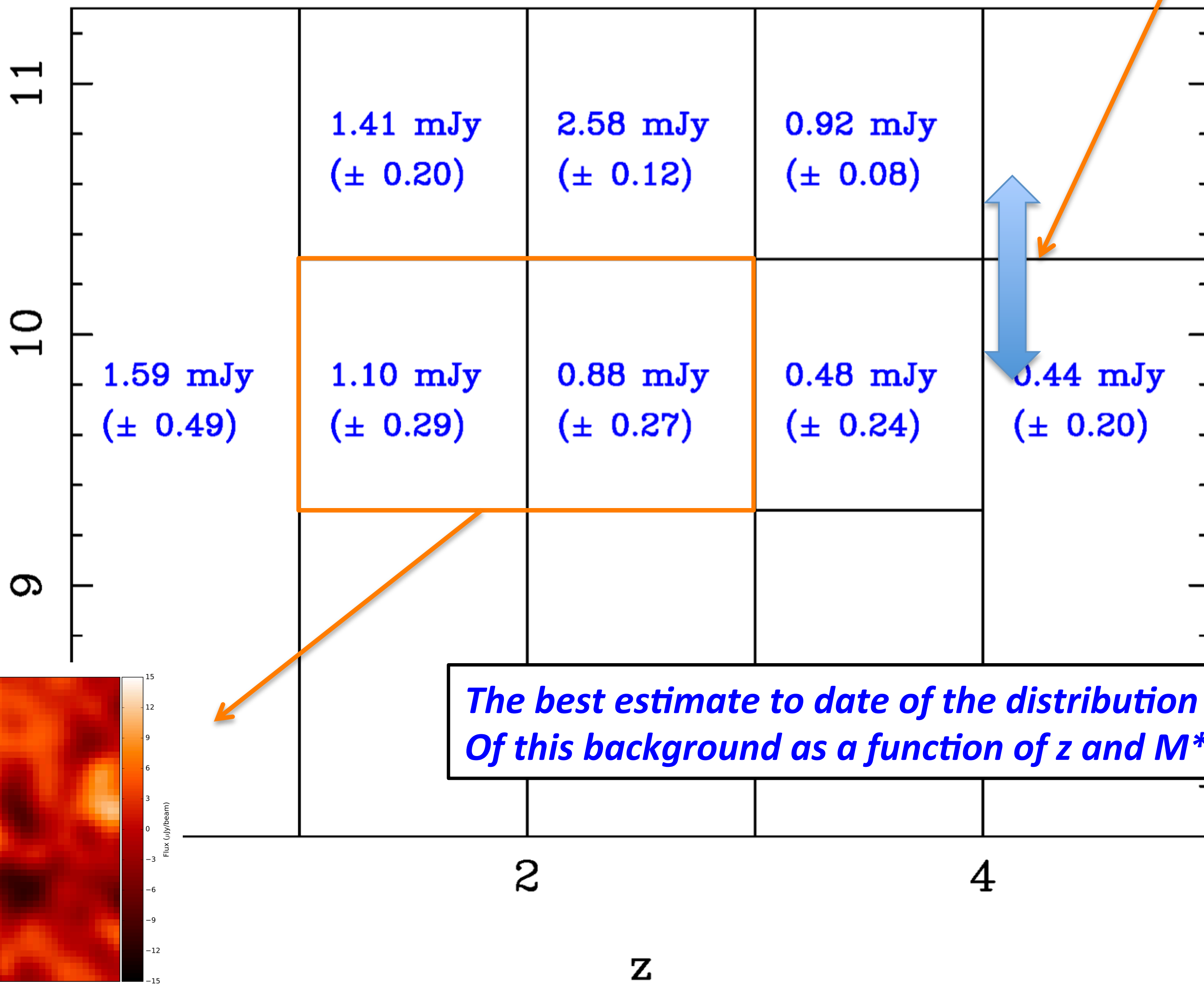


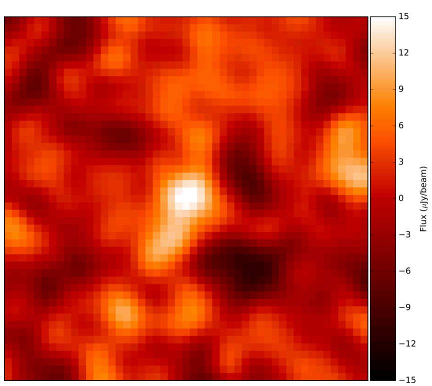
Combined Templates



Stacking Analysis

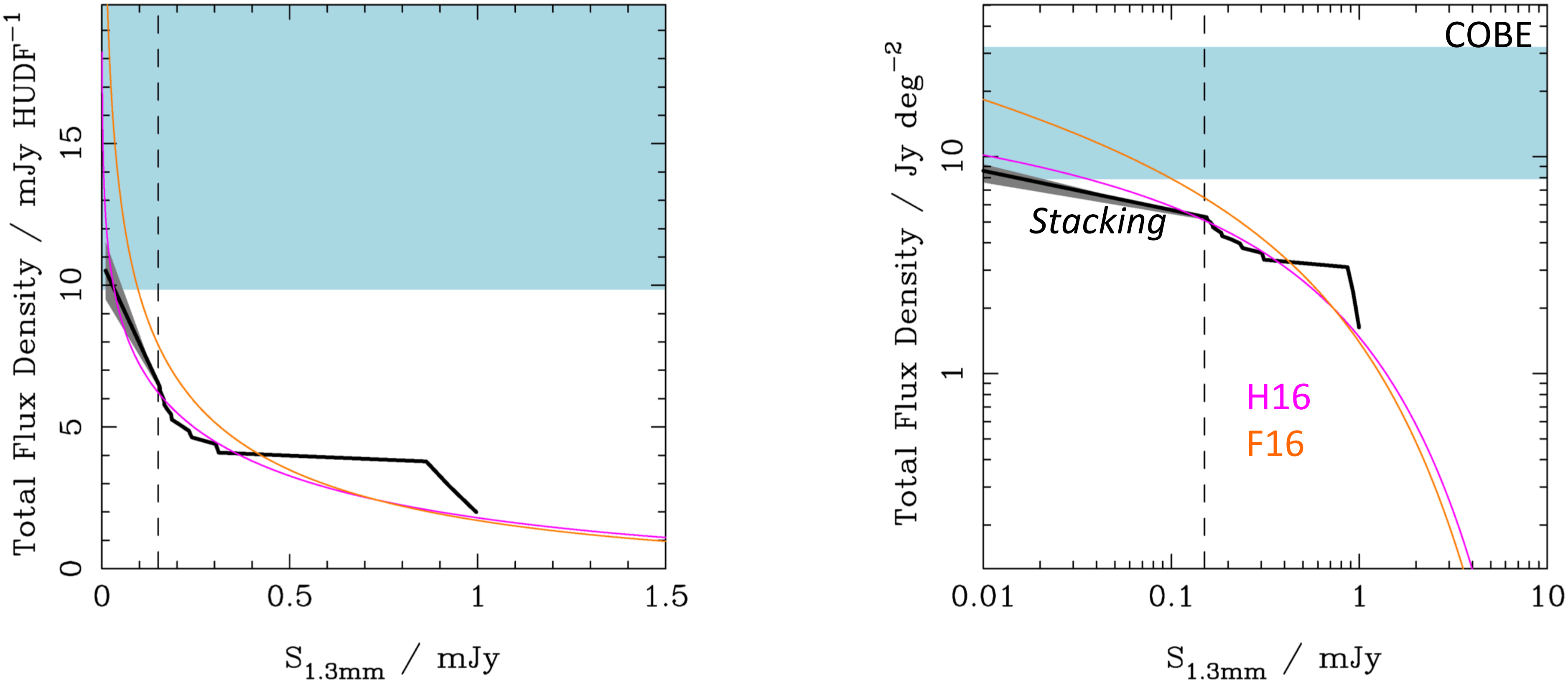
The steep dependence of Dust-obscured SF on M*





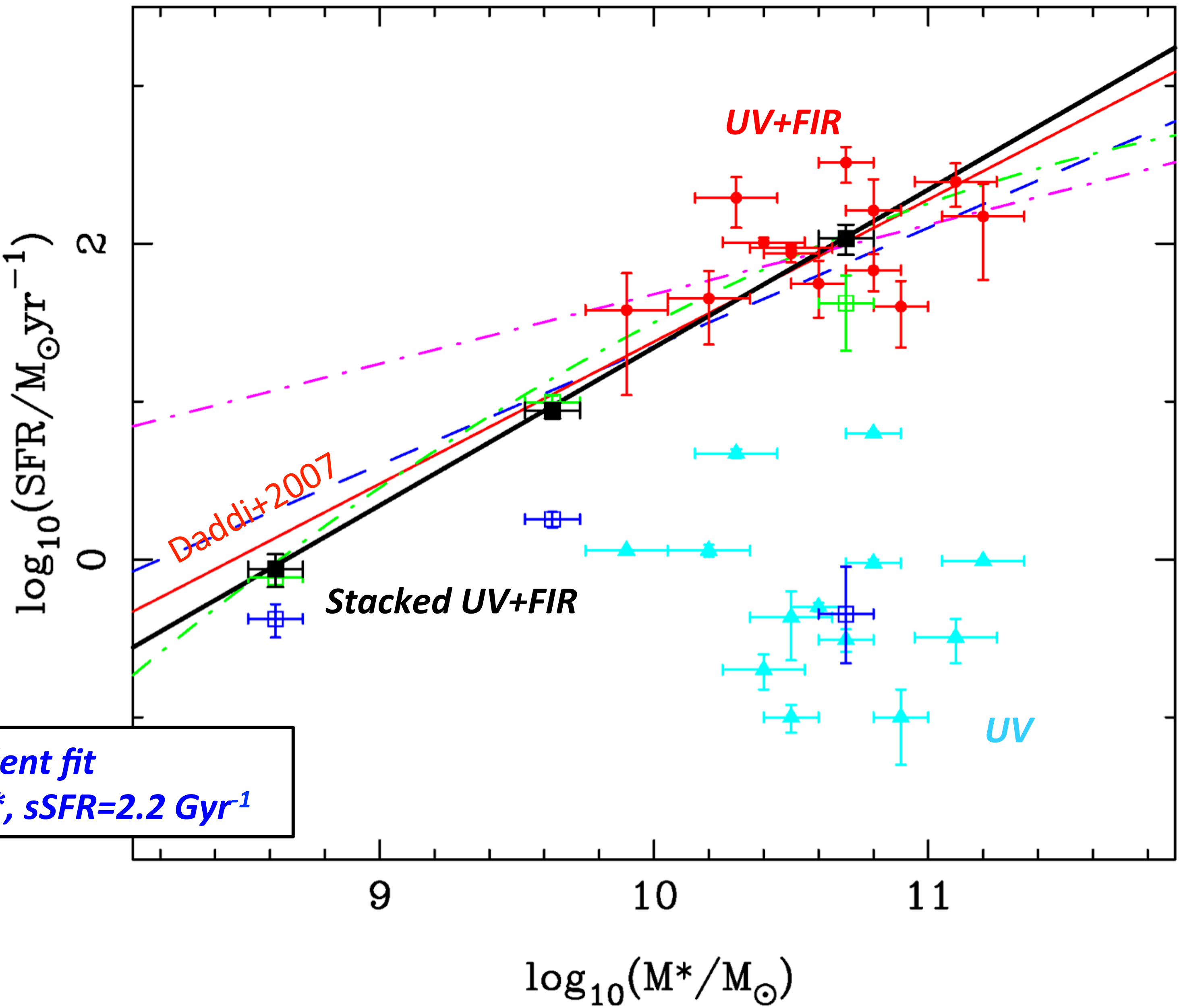
The best estimate to date of the distribution Of this background as a function of z and M*

EBL



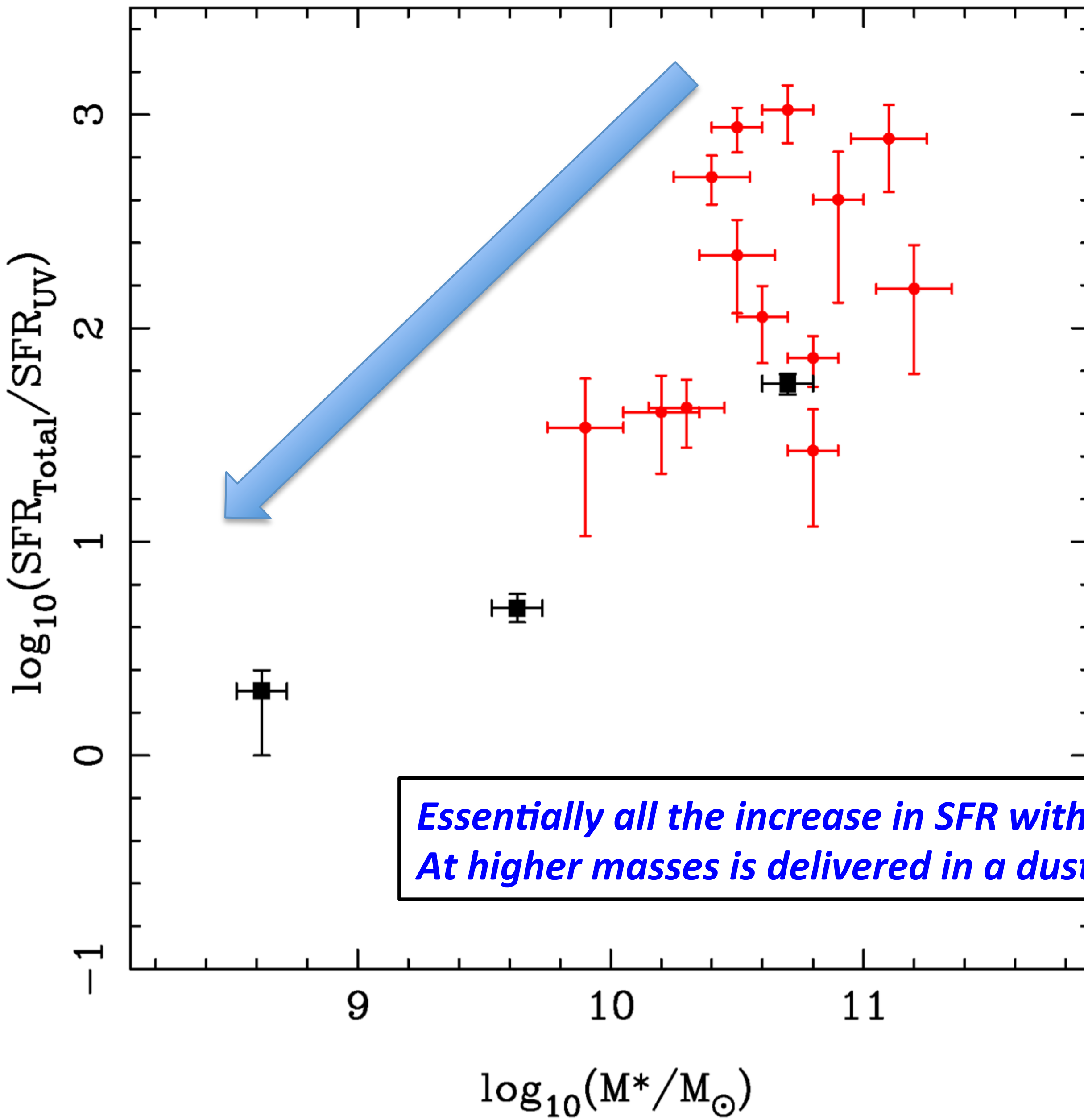
- consistent with the 1-σ lower bound on the COBE estimate
- 'we would require to approximately double the flux density in HUDF'

The star-forming MS



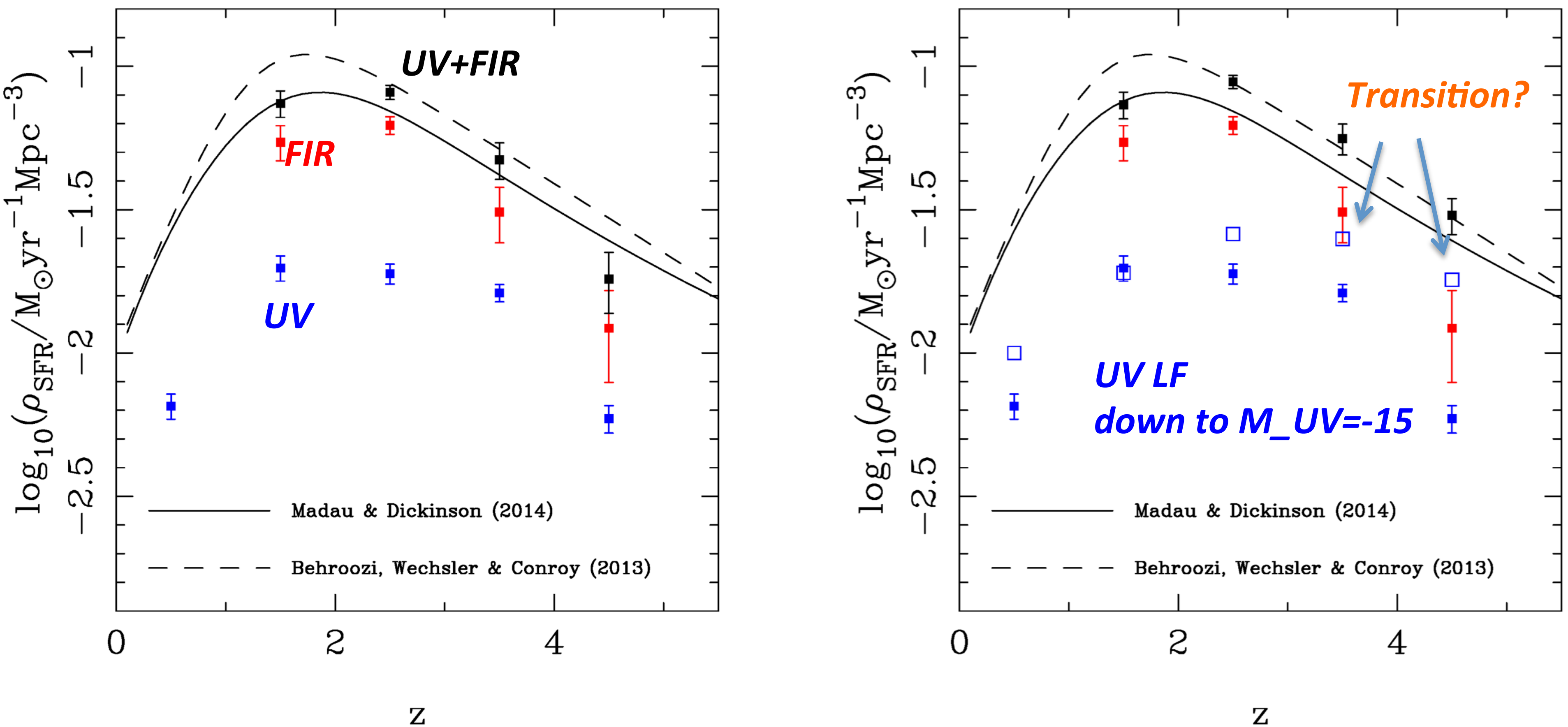
An excellent fit
SFR ∝ M*, sSFR=2.2 Gyr⁻¹

Obscured vs unobscured



Essentially all the increase in SFR with M* on the MS At higher masses is delivered in a dust-obscured form.

Cosmic star-formation history



- 'This is the first time a direct census of ρ_SFR(obscured) has been performed at these redshift.'
- At z>4, most of the SF in the Universe is unobscured.

Abstract

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We present the results of the first, deep ALMA imaging covering the full $\simeq 4.5\,\mathrm{arcmin}^2$ of the Hubble Ultra Deep Field (HUDF) as previously imaged with WFC3/IR on the *HST*. Using a mosaic of 45 ALMA pointings, we have obtained a homogeneous image of the HUDF at $\lambda = 1.3\,\mathrm{mm}$, achieving an rms sensitivity $\sigma_{1.3} \simeq 35\,\mu\mathrm{Jy}$, at a resolution of $\simeq 0.7\,\mathrm{arcsec}$. From an initial list of $\simeq 50 > 3.5\sigma$ peaks, a rigorous analysis confirms 16 sources with flux densities $S_{1.3} > 120\,\mu\mathrm{Jy}$. All of these have secure galaxy counterparts with robust redshifts ($\langle z \rangle = 2.15$), and 12 are also detected at 6 GHz in new ultra-deep JVLA imaging. Due to the wealth of supporting data in this unique field, the physical properties of the ALMA sources are well constrained, including, crucially, their stellar masses (M_*) and UV+FIR star-formation rates (SFR). Our results show that stellar mass is the best predictor of SFR in the high-redshift Universe; indeed at $z \geq 2$ our ALMA sample contains 7 of the 9 galaxies in the HUDF with $M_* \geq 2 \times 10^{10}\,\mathrm{M}_\odot$, and we detect only one galaxy at $z > 3.5$, reflecting the rapid drop-off of high-mass galaxies with increasing redshift. The detected sources, coupled with stacking, allow us to probe the redshift/mass distribution of the 1.3-mm background down to $S_{1.3} \simeq 10\,\mu\mathrm{Jy}$. We find strong evidence for a steep 'main sequence' for star-forming galaxies at $z \simeq 2$, with $\mathrm{SFR} \propto M_*$ and a mean specific SFR $\simeq 2.2\,\mathrm{Gyr}^{-1}$. Moreover, we find that $\simeq 85\%$ of total star formation at $z \simeq 2$ is enshrouded in dust, with $\simeq 65\%$ of all star formation at this epoch occurring in high-mass galaxies ($M_* > 2 \times 10^{10}\,\mathrm{M}_\odot$), for which the average obscured:unobscured SF ratio is $\simeq 200$. Finally, we combine our new ALMA results with the existing *HST* data to revisit the cosmic evolution of star-formation rate density (ρ_{SFR}); we find that ρ_{SFR} peaks at $z \simeq 2.5$, and that the star-forming Universe transits from primarily unobscured to primarily obscured thereafter at $z \simeq 4$.