A deep ALMA image of the HUDF

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Dunlop et al. 2016, arXiv:1606.00227

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+ Ross McLure, Andy Biggs, Jim Geach, Rob Ivison, Michal Michalowski, Wiphu Rujopakarn, Alison Kirkpatrick, Richard Ellis, Eelco van Kampen, John Peacock, Douglas Scott, Mark Swinbank, Tom Targett, et al.

IAP Paris

June 2016

Background: Hubble Ultra Deep Field

ACS HUDF + UDF09 + HUDF12 program = deepest optical-infrared image

Final UDF12 depths
(AB mag)

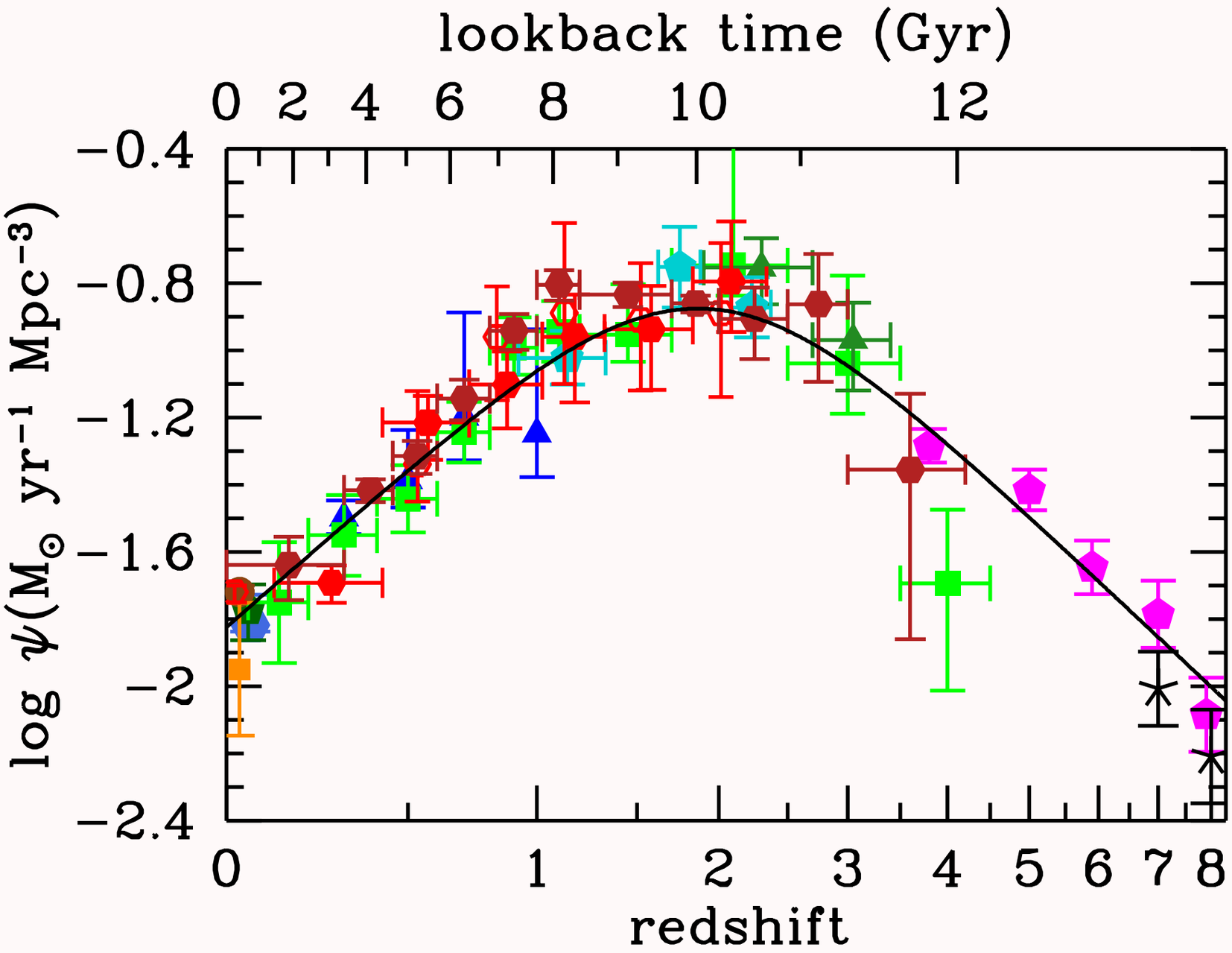
Y_{105} = 30.0

J_{125} = 29.5

J_{140} = 29.5

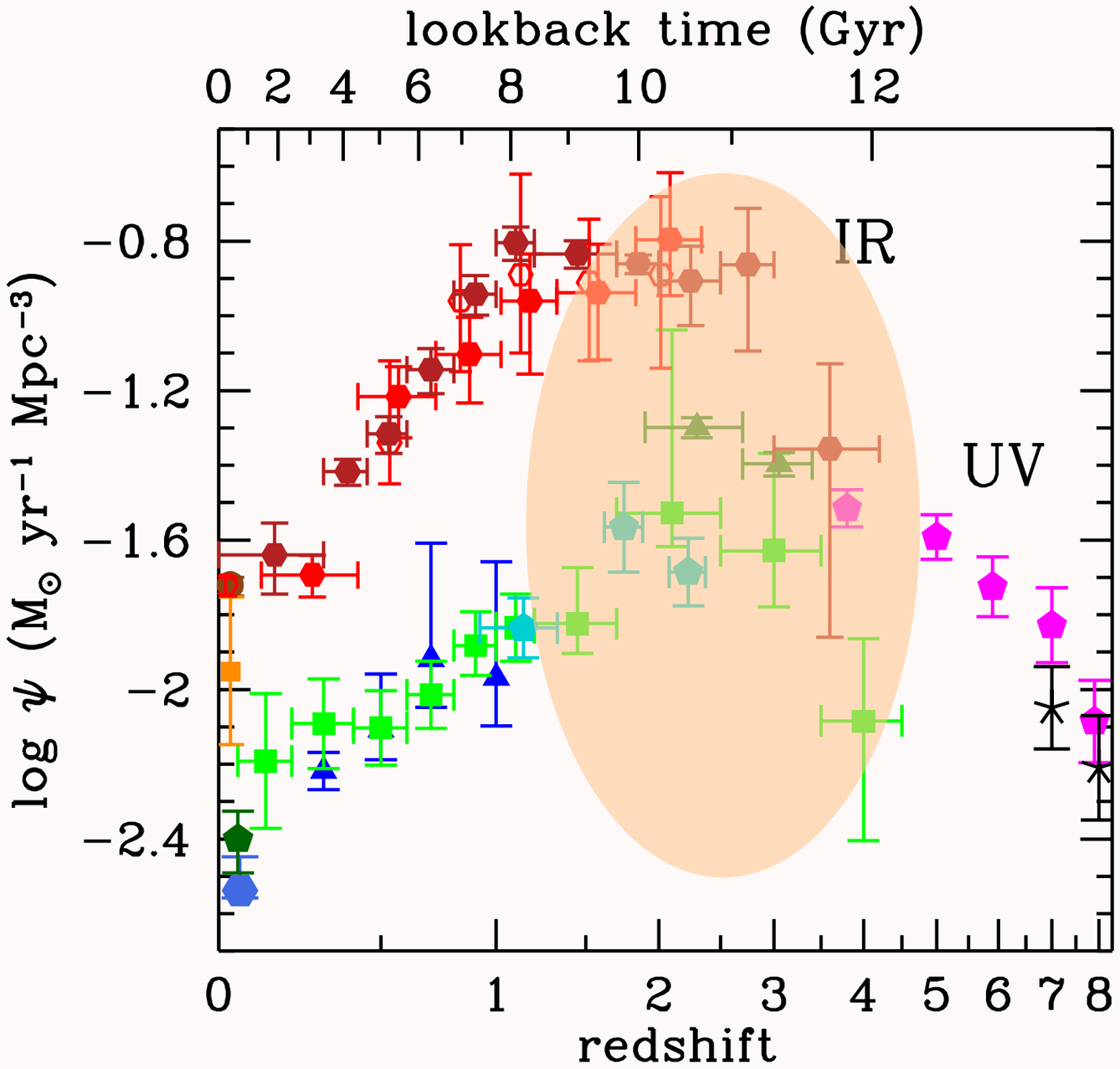
H_{160} = 29.5

Background: Cosmic SF history



Madau & Dickinson 2014, ARAA, 52, 415

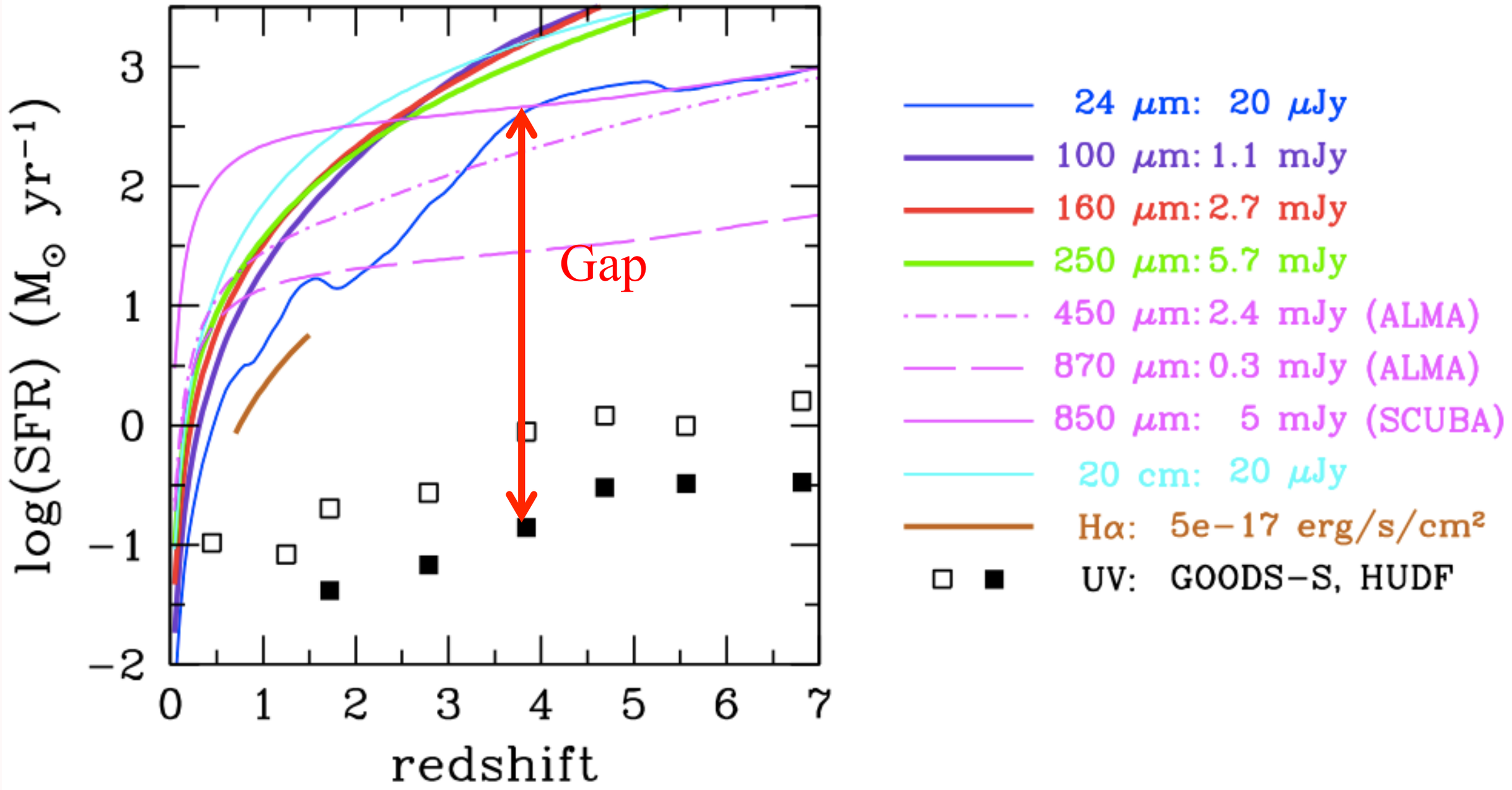
Background: Cosmic SF history



Madau & Dickinson 2014, ARAA, 52, 415

Background: star-formation rate indicators

Relative sensitivities of multi-wavelength probes

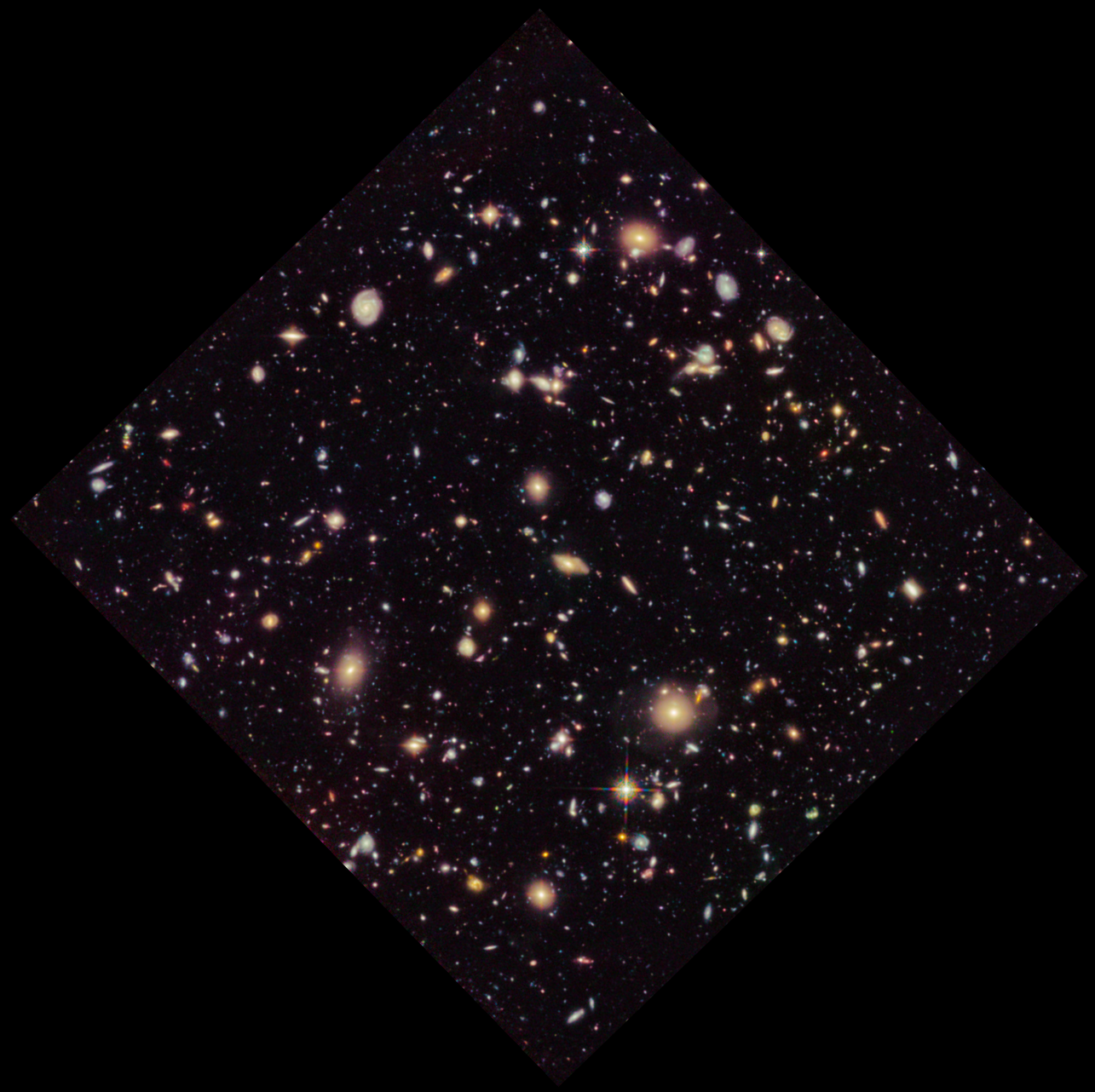


Madau & Dickinson 2014

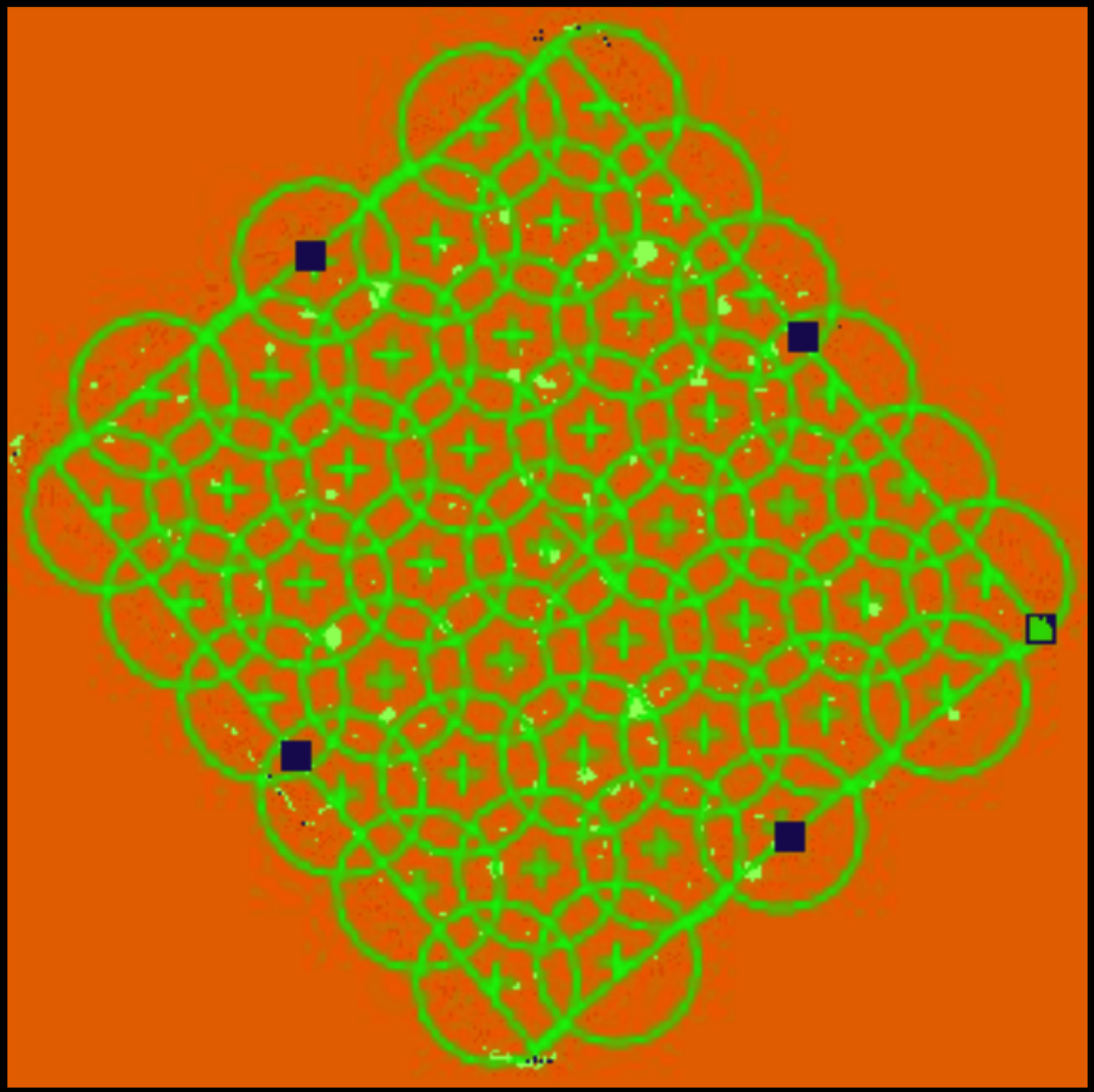
ALMA 1.3-mm image of the HUDF

- Planned to try to bridge this gap, with deep ALMA imaging of HUDF
- Chose 1.3mm because of sensitivity to high-redshift
- Also practical – only 45 pointings, and didn't require best weather
- Asked for FWHM ~0.7 arcsec to avoid resolving out emission
- Awarded 20 hours (13 hr of exposure) in Cycle 1 – by far largest proposal
- Rolled into Cycle 2, and completed in summer 2015
- Native resolution ~0.4 arcsec, tapered to produce ~0.7 arcsec image
- Requested rms per beam 30 micro-Jy, got 35 micro-Jy

ALMA 1.3-mm image of the HUDF

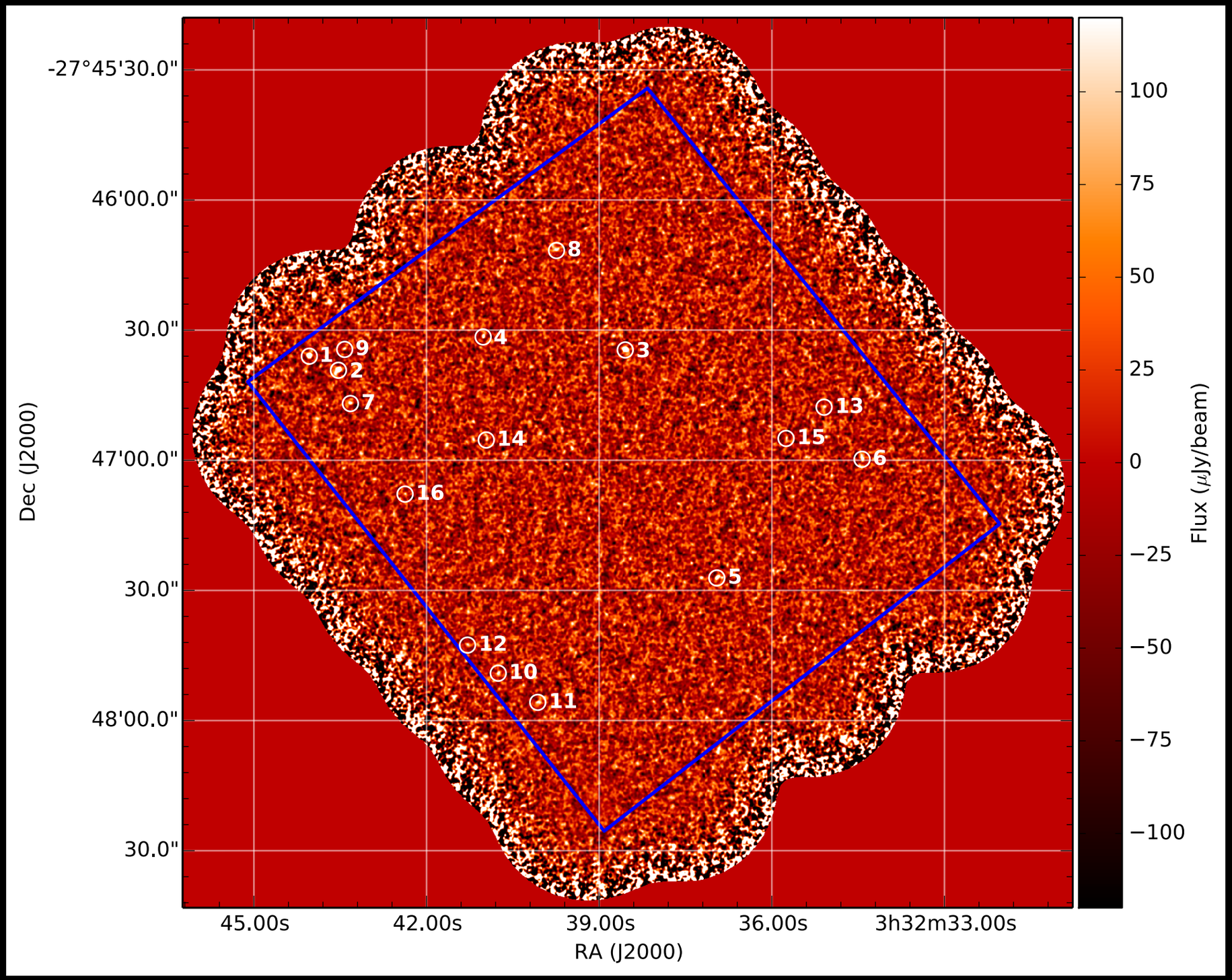


ALMA 1.3-mm image of the HUDF



ALMA 1.3-mm image of the HUDF

20 hours from summer 2014, and summer 2015



1.3 mm

rms 35 μJy

0.7 arcsec

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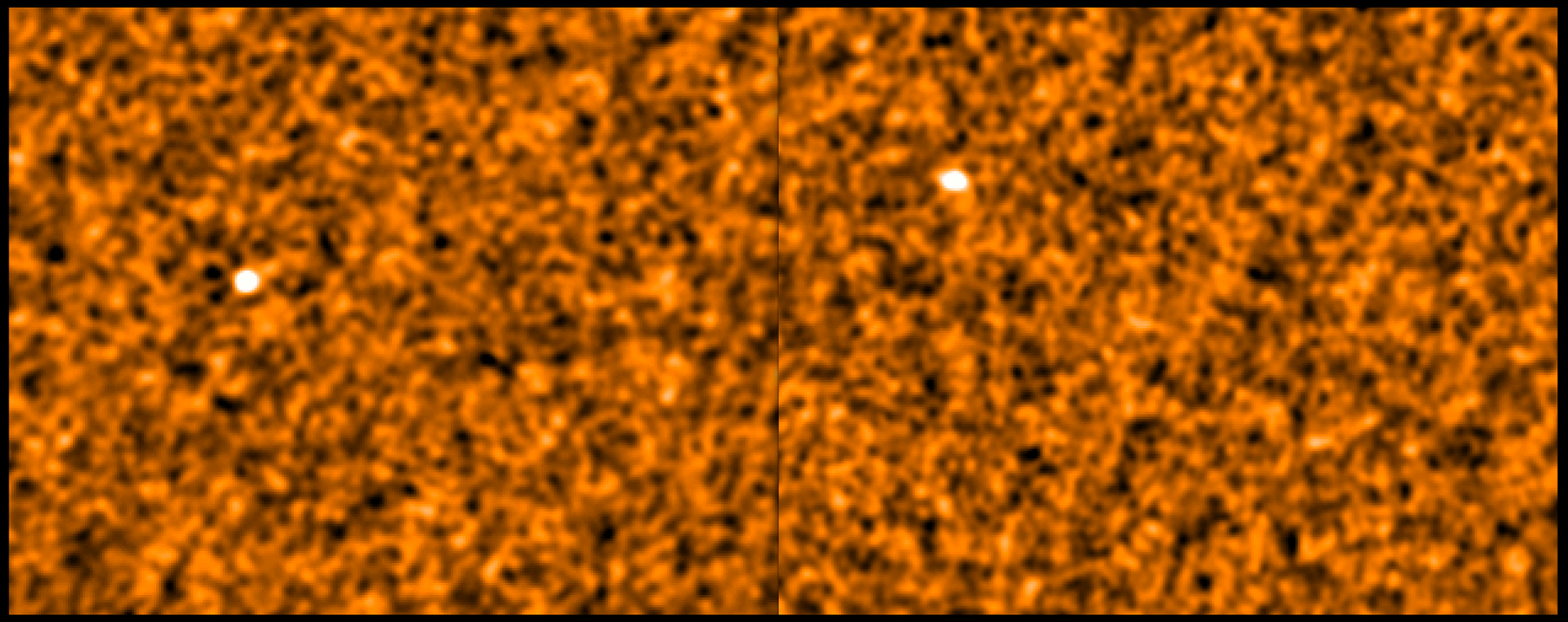
ALMA 1.3-mm image of the HUDF

Search for sources yielded ~50 > 3.5 σ peaks

But ~30 > 3.5 σ peaks in negative image

Naively expect only ~ 10 spurious sources given number of beams

But detailed simulation of Gaussian beam filtered white noise shows number of spurious peaks as expected

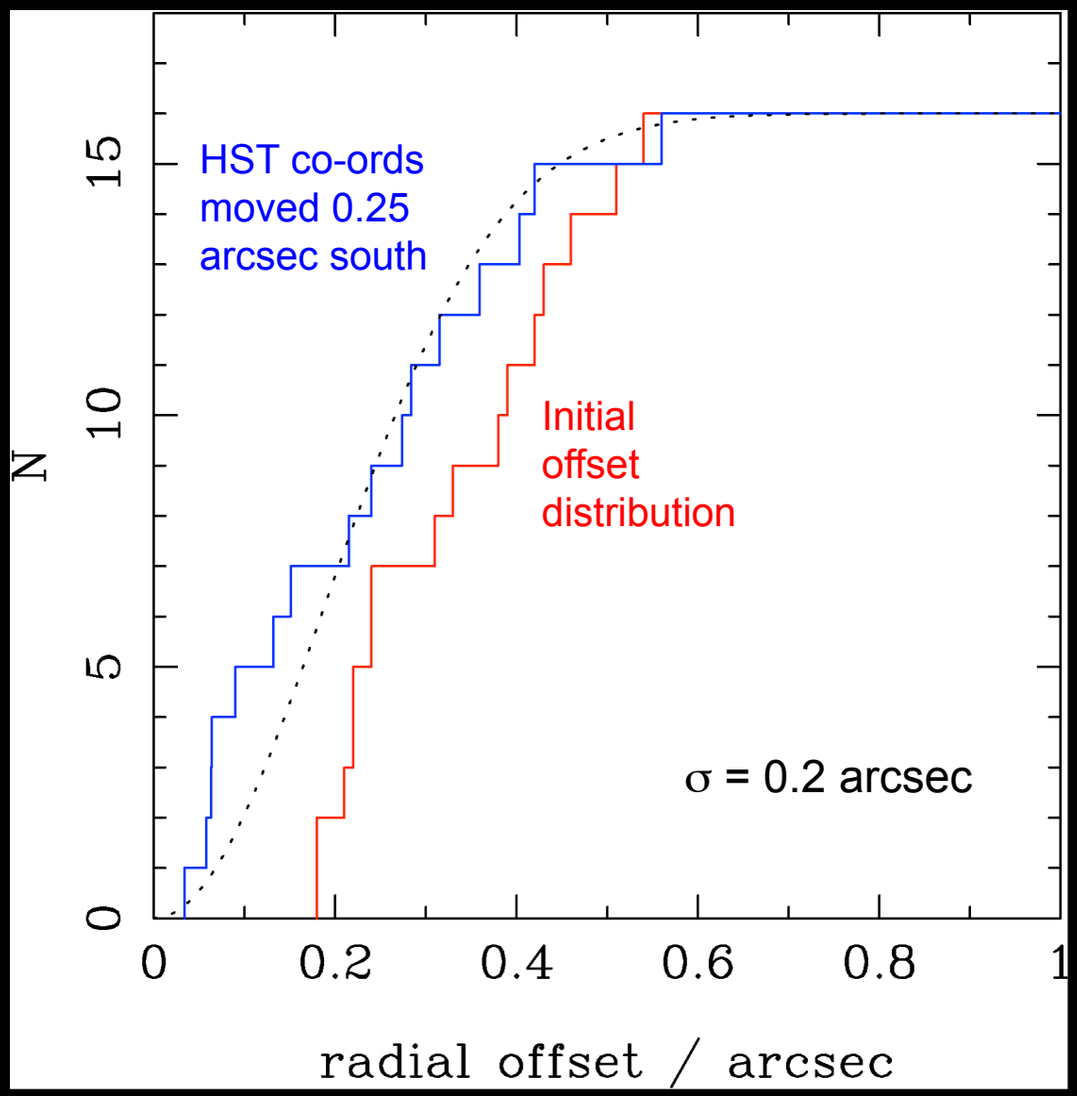


Peacock et al. in prep

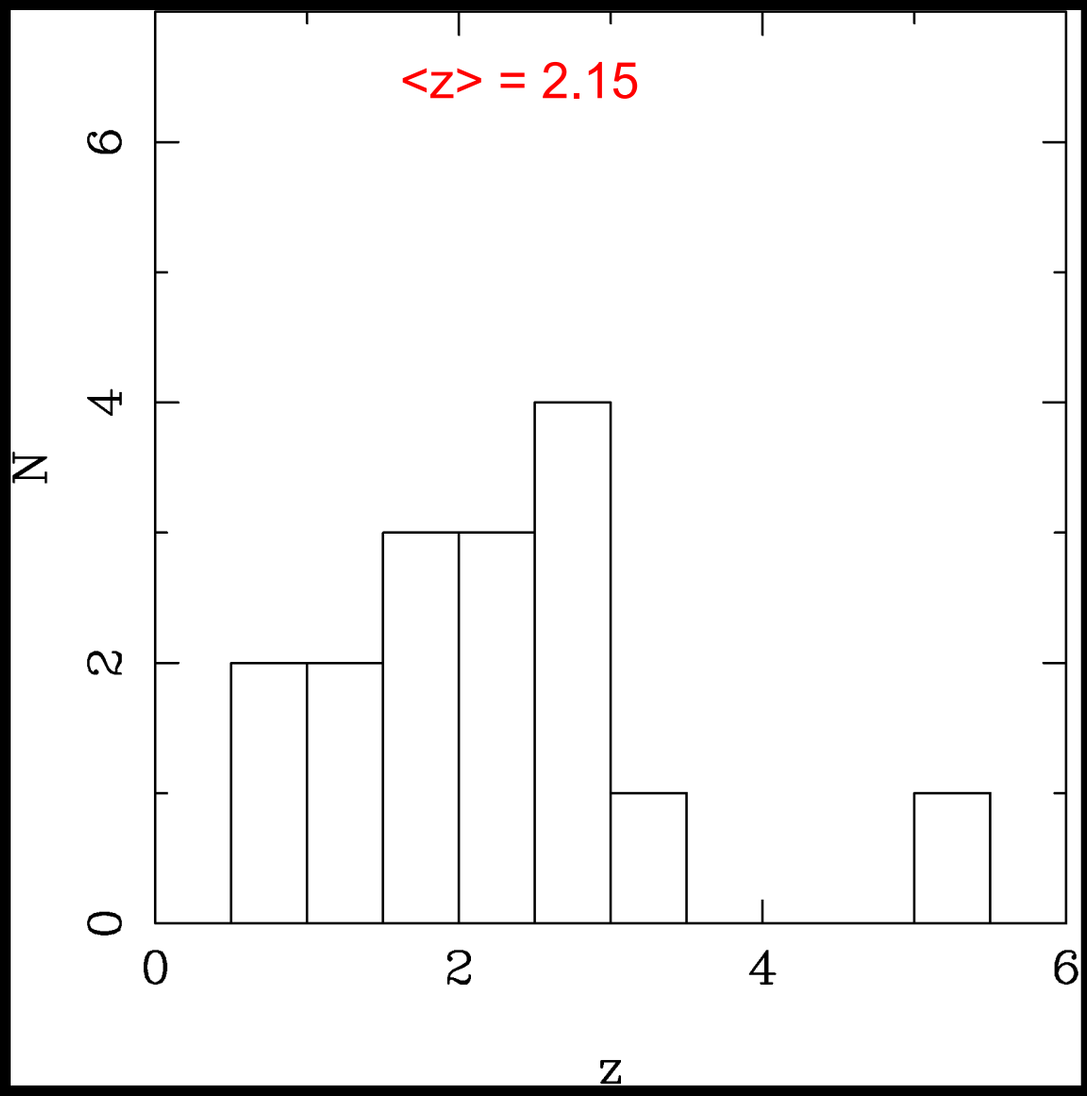
Therefore expect only 15-20 sources to be real …… how to find them ?

The galaxies: locating real sources via HST counterparts

Searched for HST counterparts within ~0.5 arcsec
Found 16, all brighter than H_{160}=27 mag, despite data reaching to 30 mag



ALMA-HST offsets



Redshift distribution

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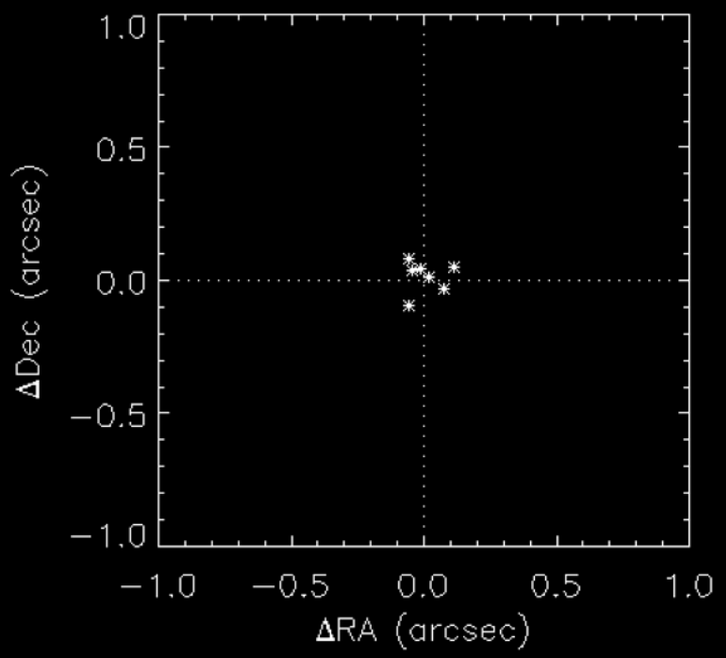
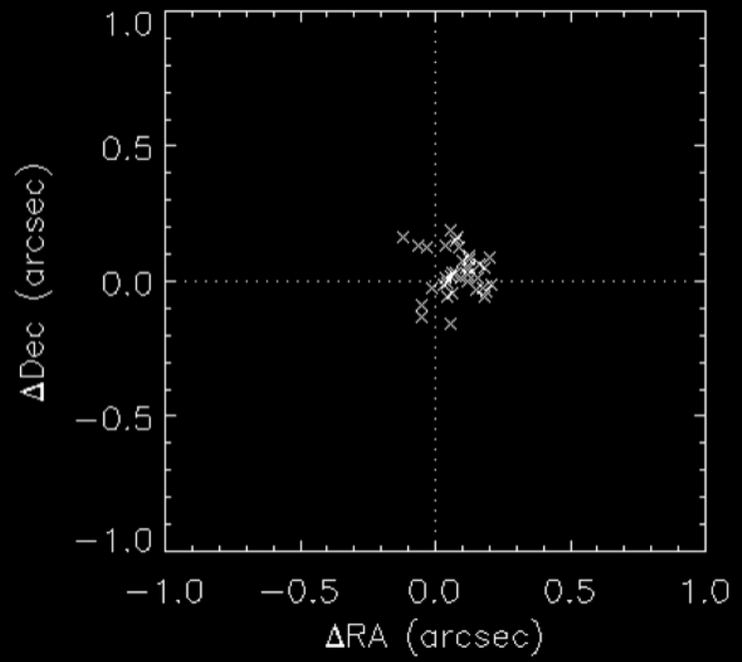
The galaxies - radio imaging centred on HUDF

- 12 / 16 sources also detected in new deep 6 GHz JVLA imaging

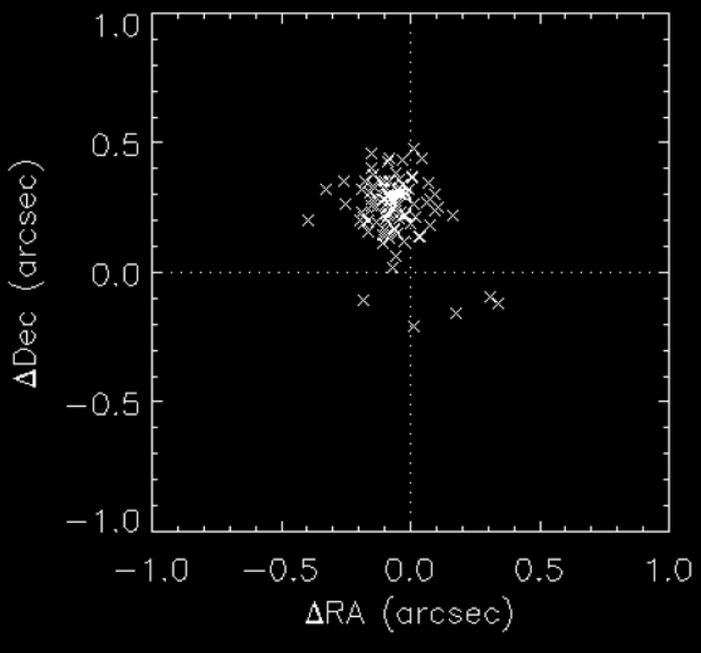
ALMA - JVLA



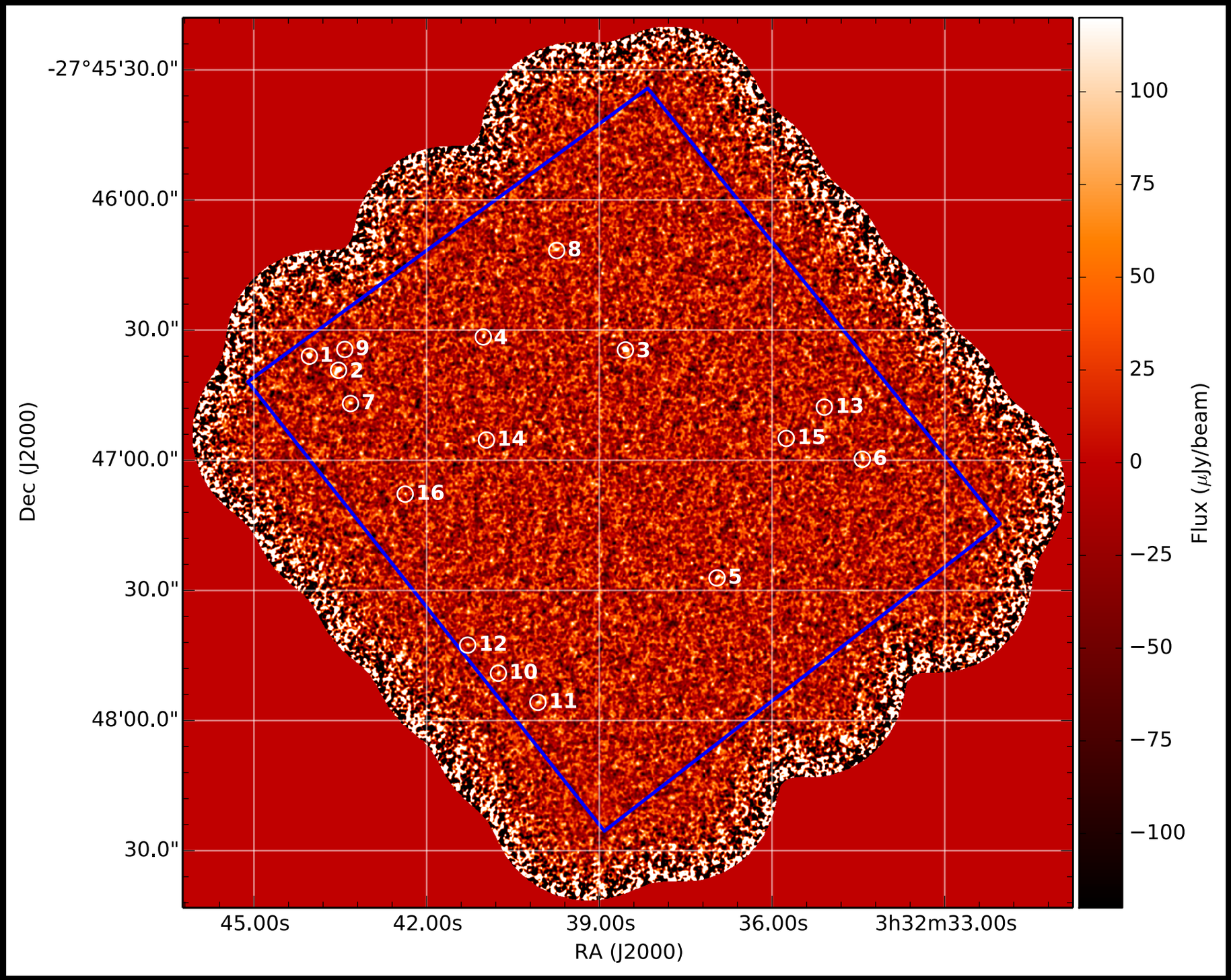
JVLA - VLA



F160W - JVLA



The galaxies: 16 ALMA-detected sources



16 sources

$S_{1.3} > 120\mu Jy$

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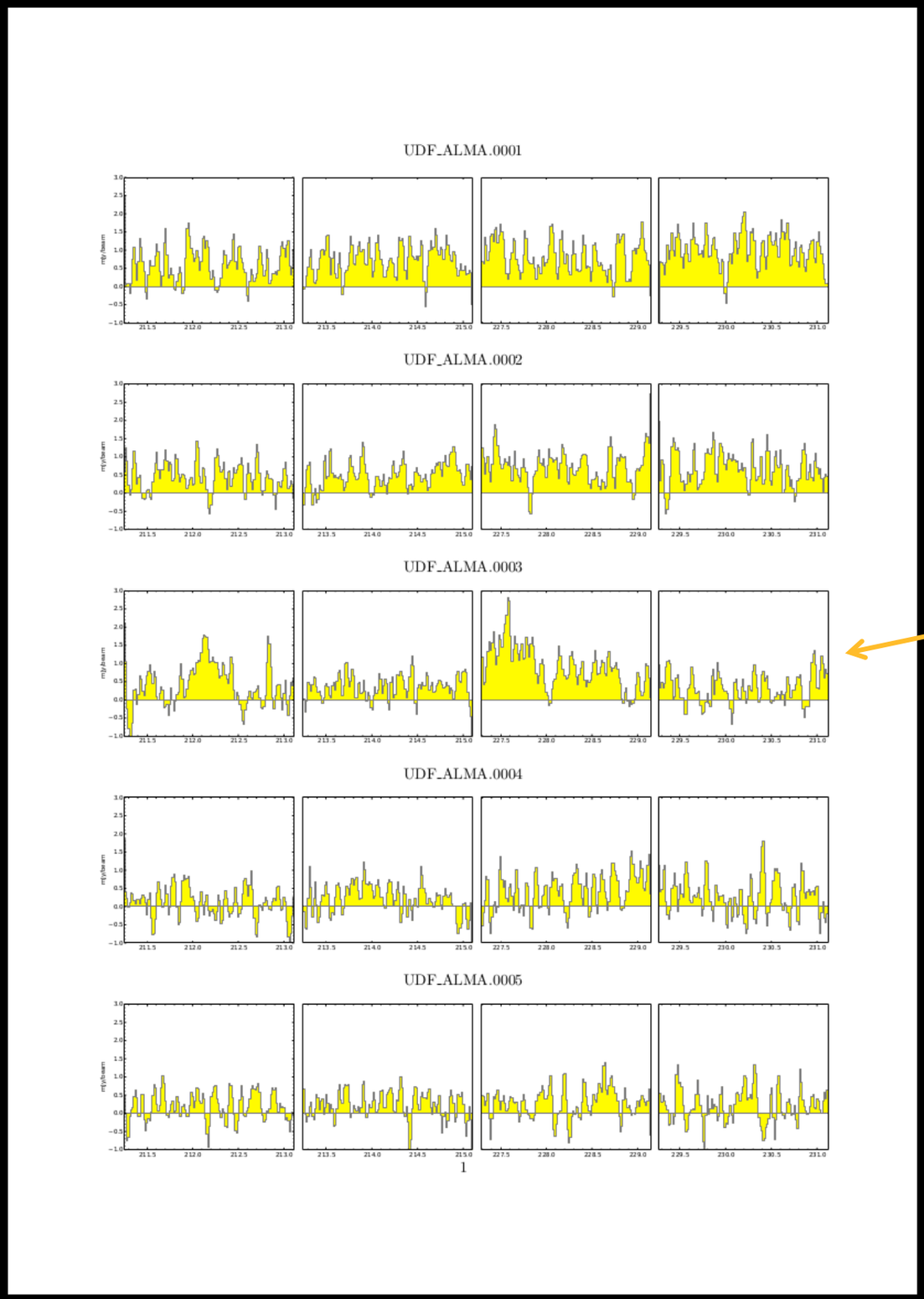
The galaxies: ALMA properties



Primarily continuum

3 sources with lines

Most prominent is
UDF3, z = 2.541
CO, H_2O, CI

(see Ivison, Biggs et al., in prep)

The galaxies

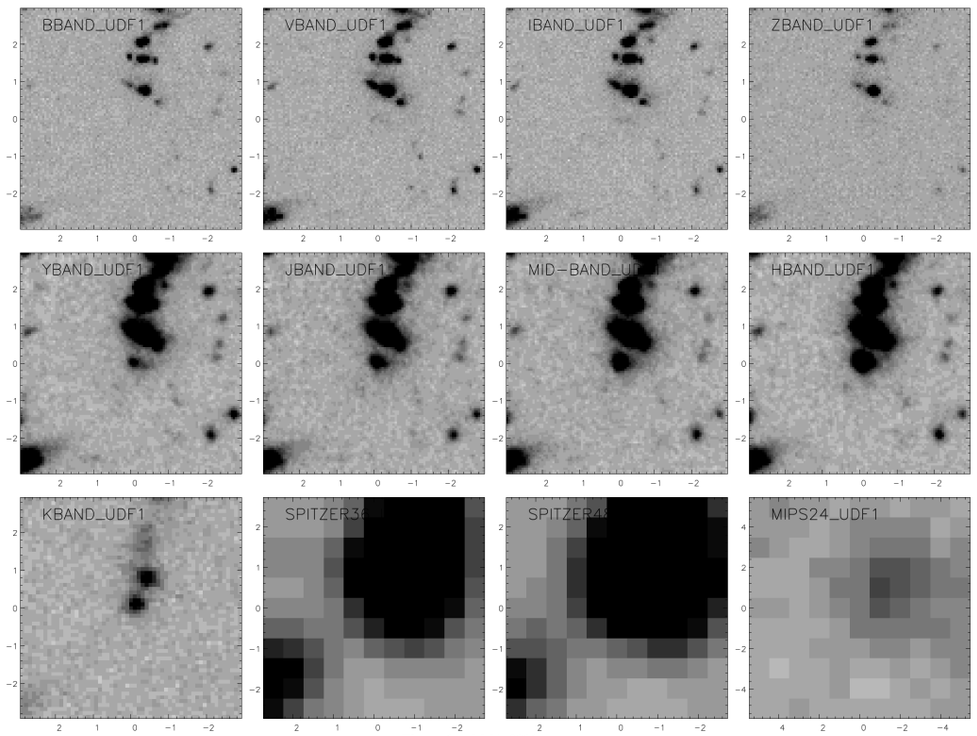
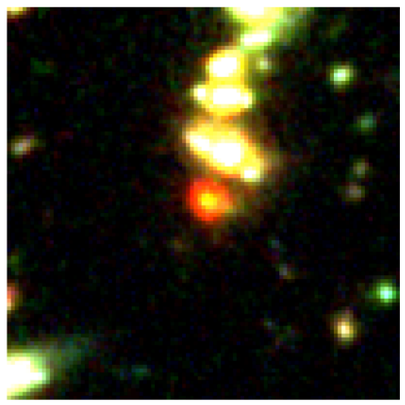
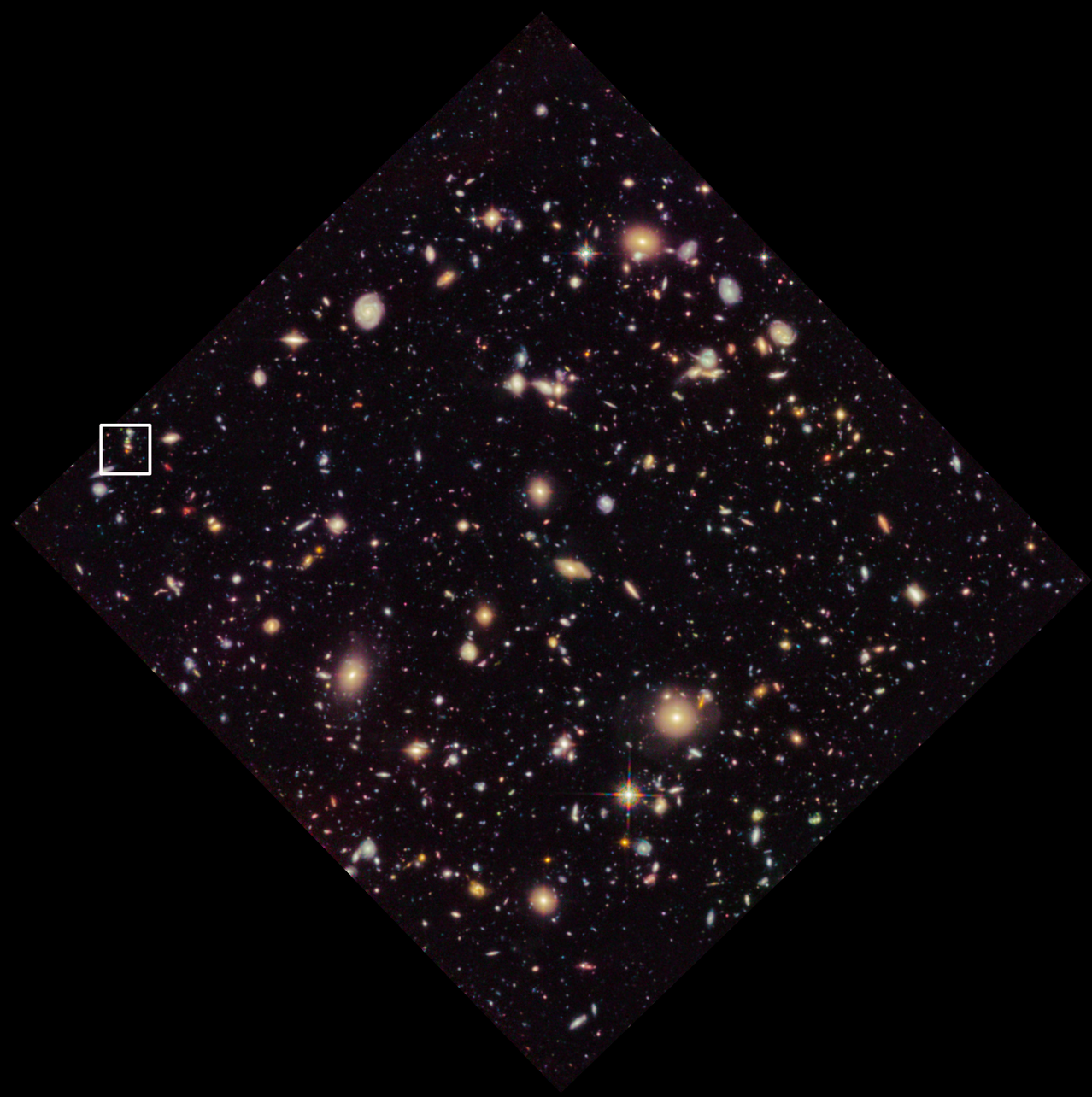


Figure 1. ALMA-0001





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The galaxies

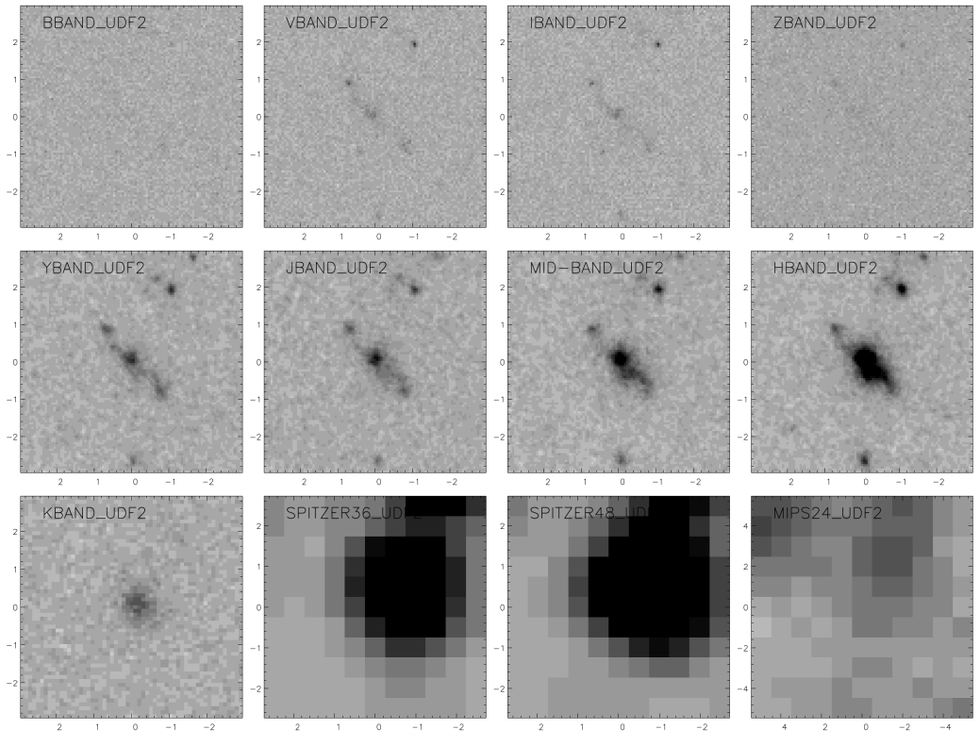
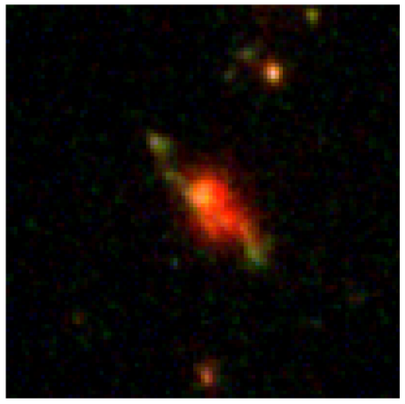
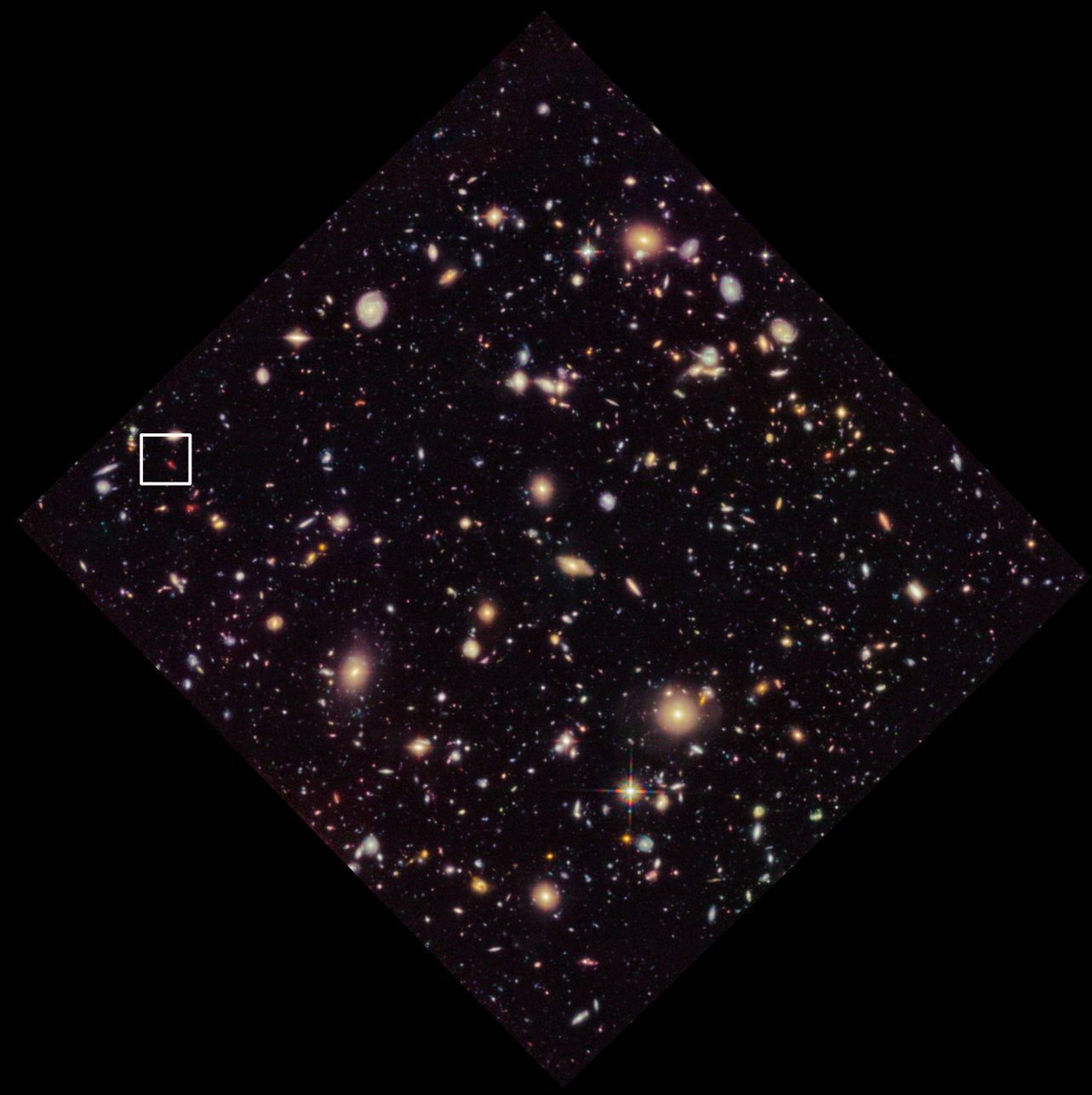


Figure 2. ALMA-0002





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The galaxies

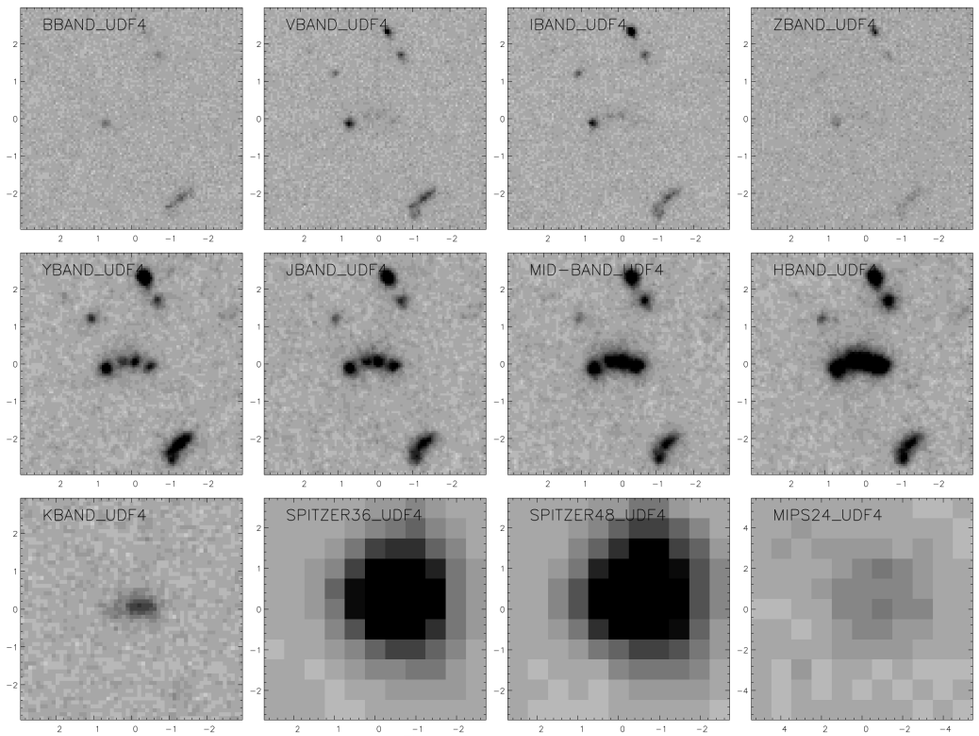
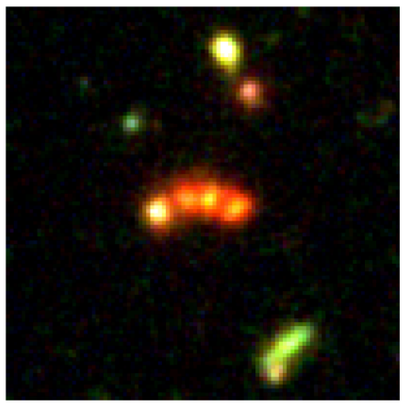
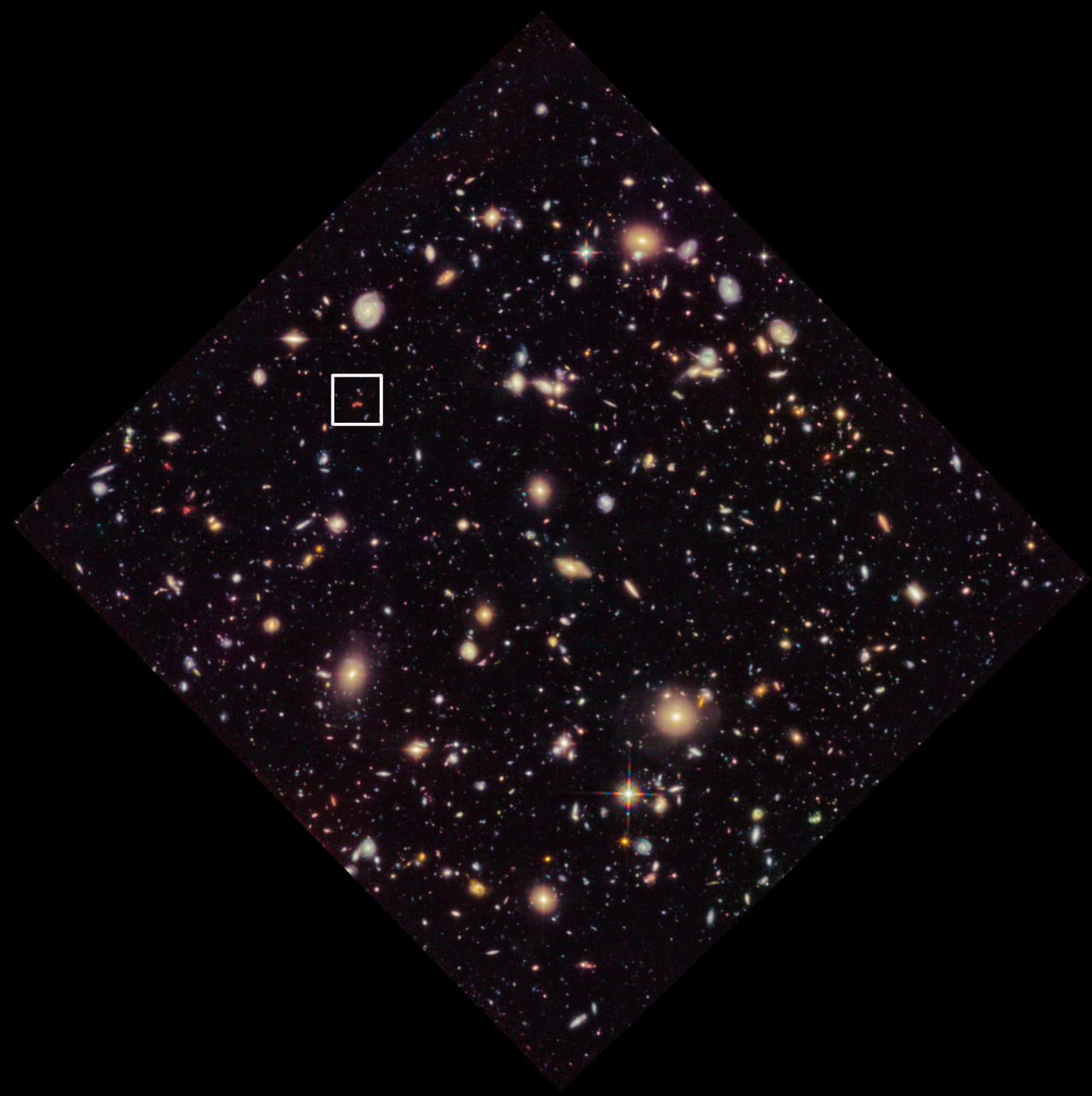


Figure 4. ALMA-0004





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The galaxies

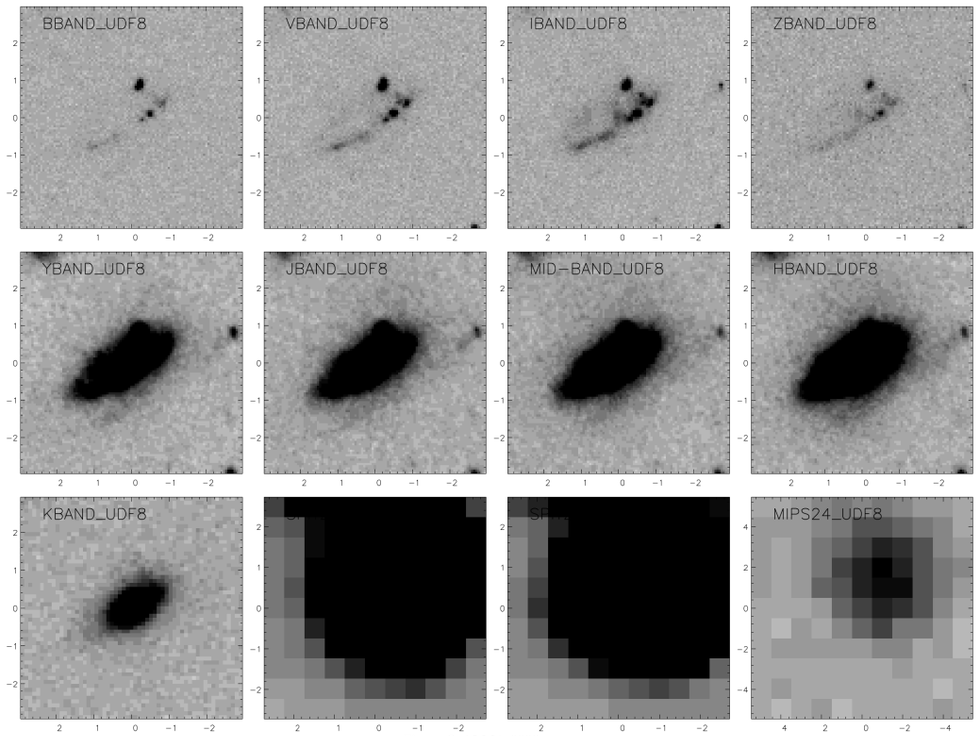
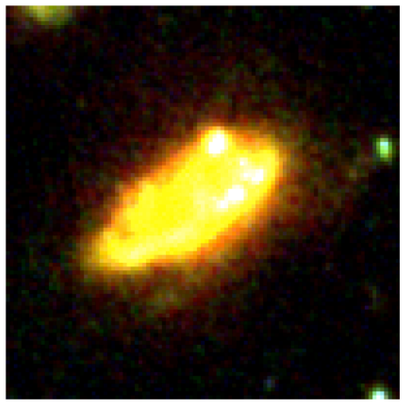
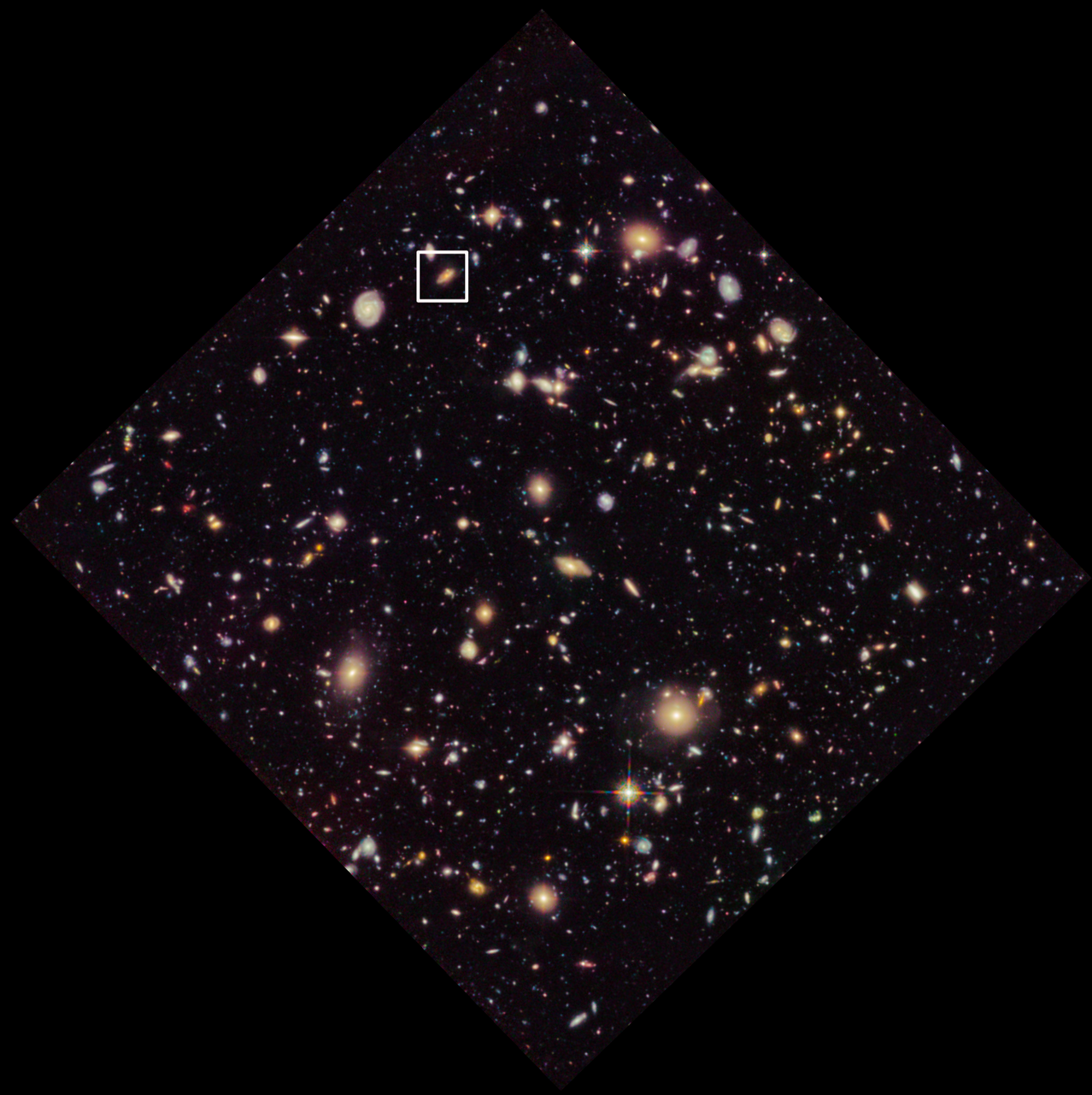


Figure 8. ALMA-0008





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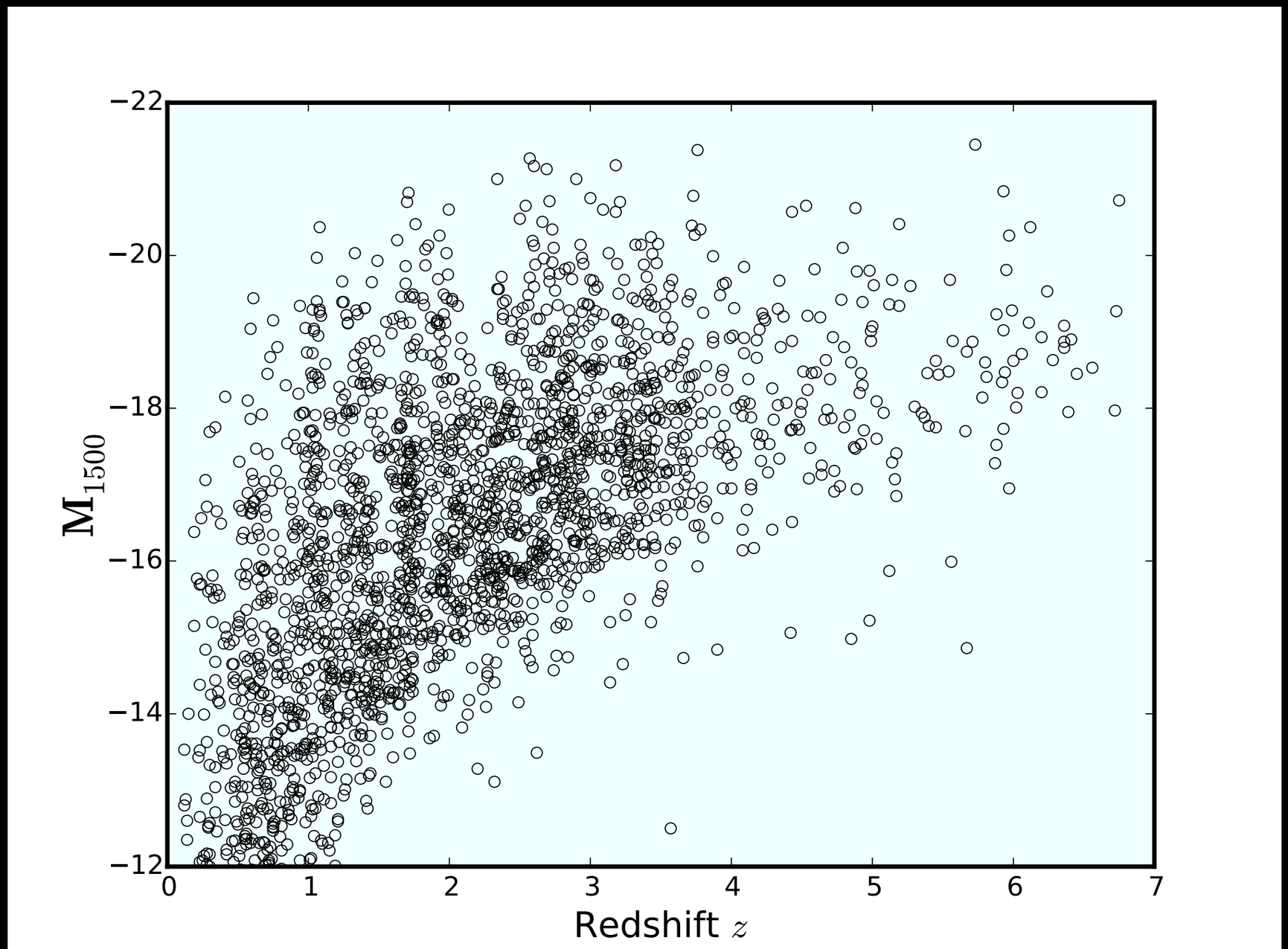
The galaxies

The M_{UV} - redshift plane



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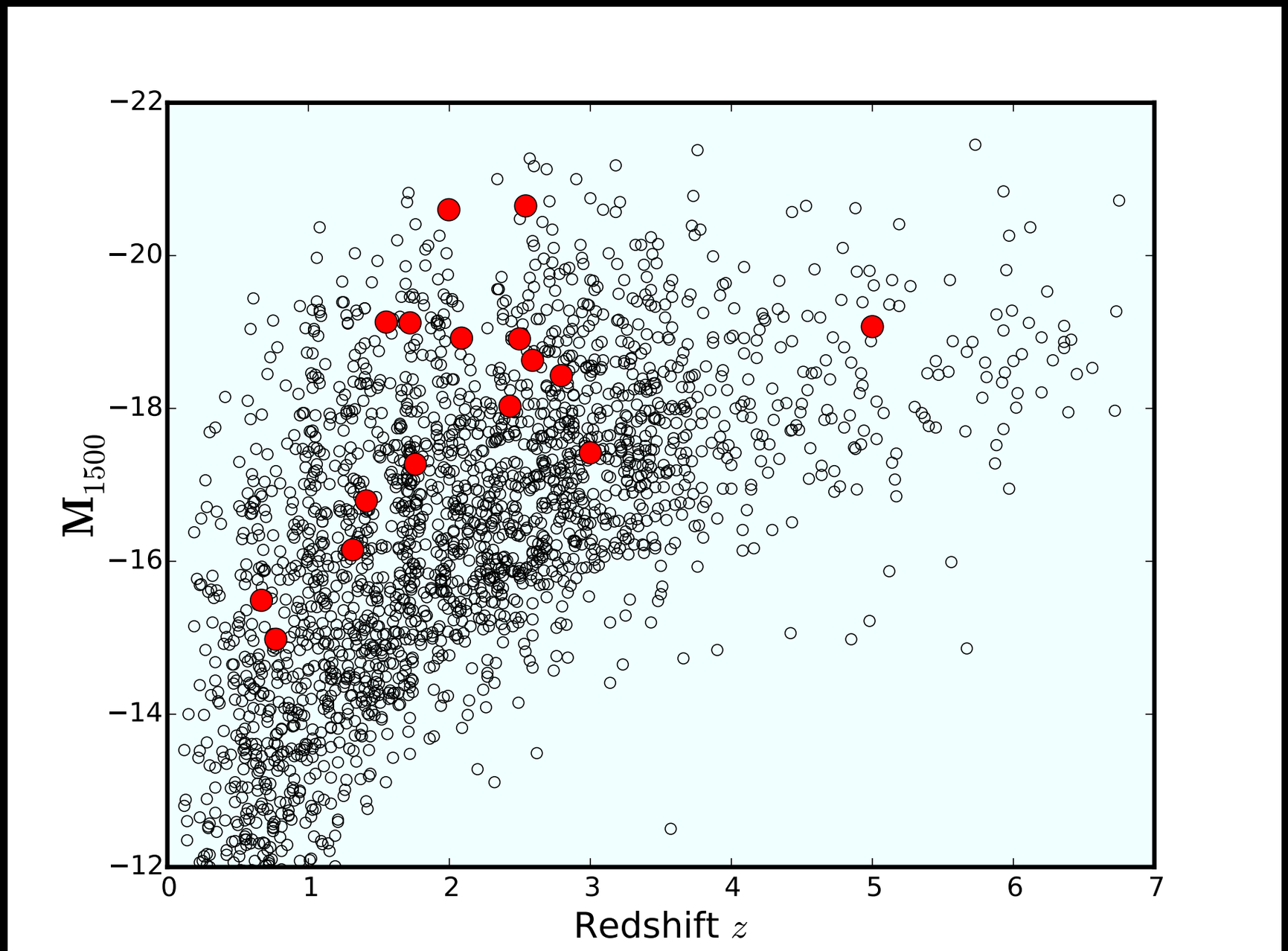
The galaxies

The M_{UV} - redshift plane



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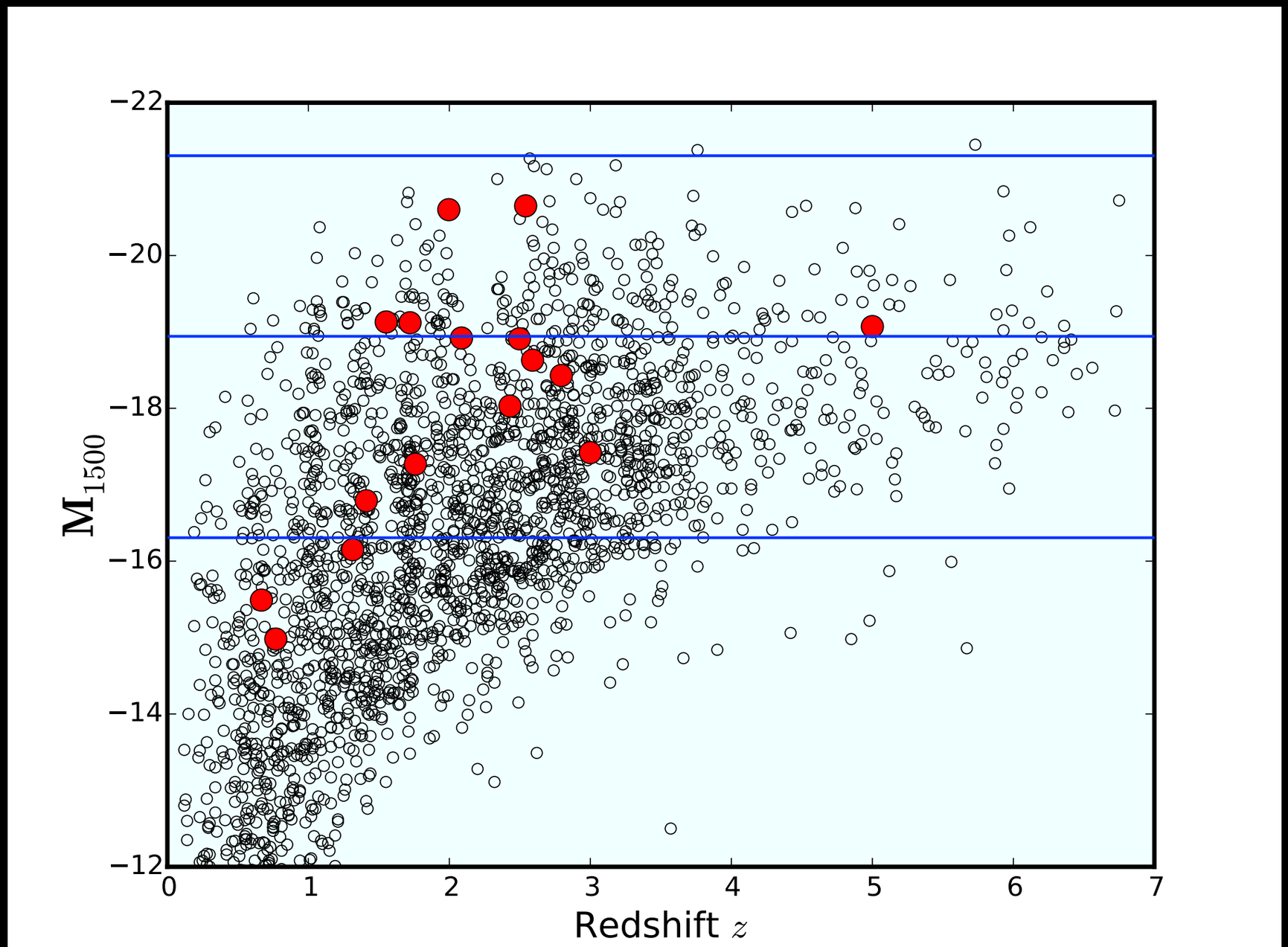
The galaxies

The M_{UV} - redshift plane



10 M_{sun} yr^{-1}

1 M_{sun} yr^{-1}

0.1 M_{sun} yr^{-1}

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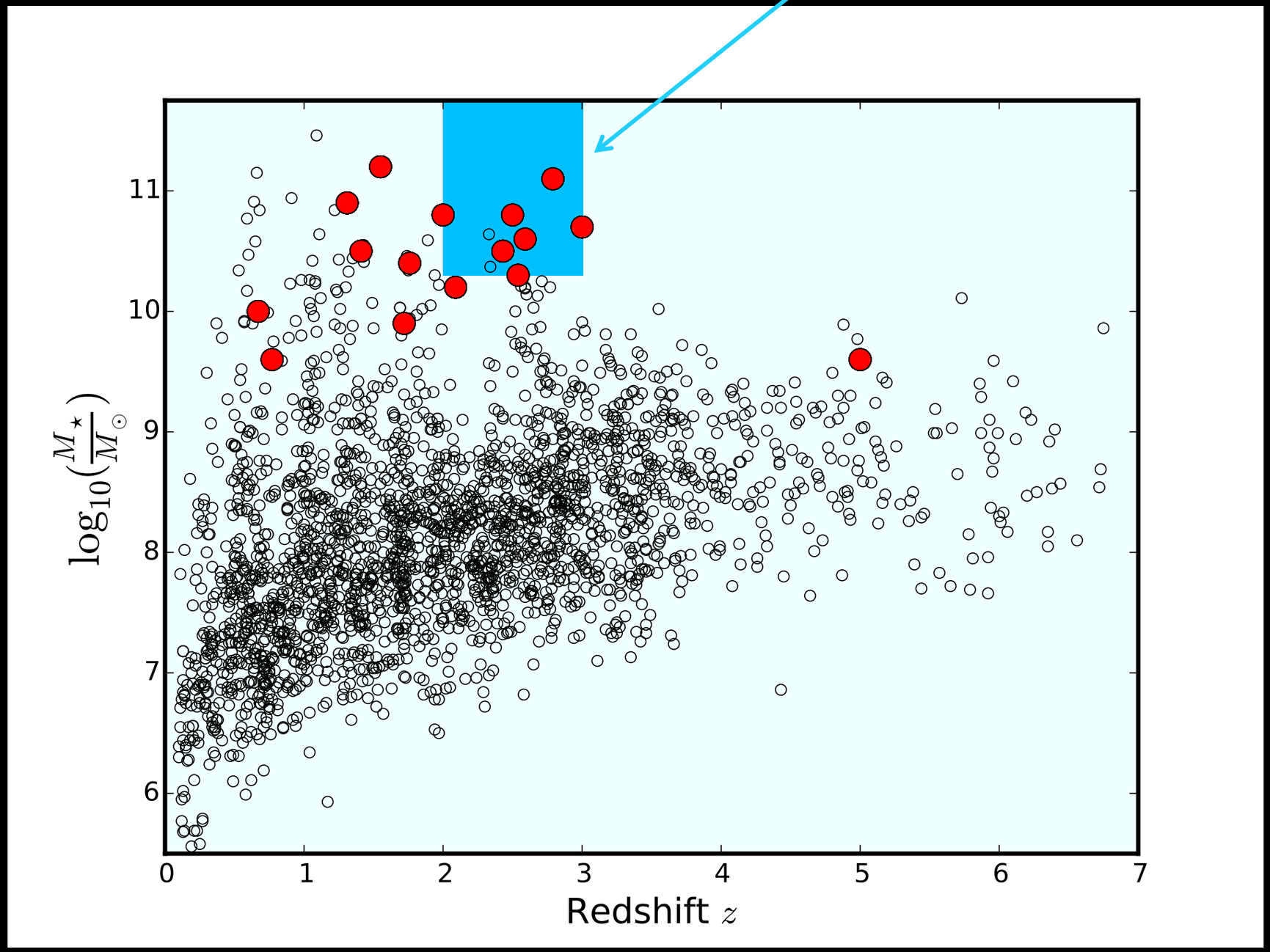
The galaxies

The mass - redshift plane

7/9 galaxies with $M^* > 2 \times 10^{10} M_{sun}$ and $2 < z < 3$ detected with ALMA



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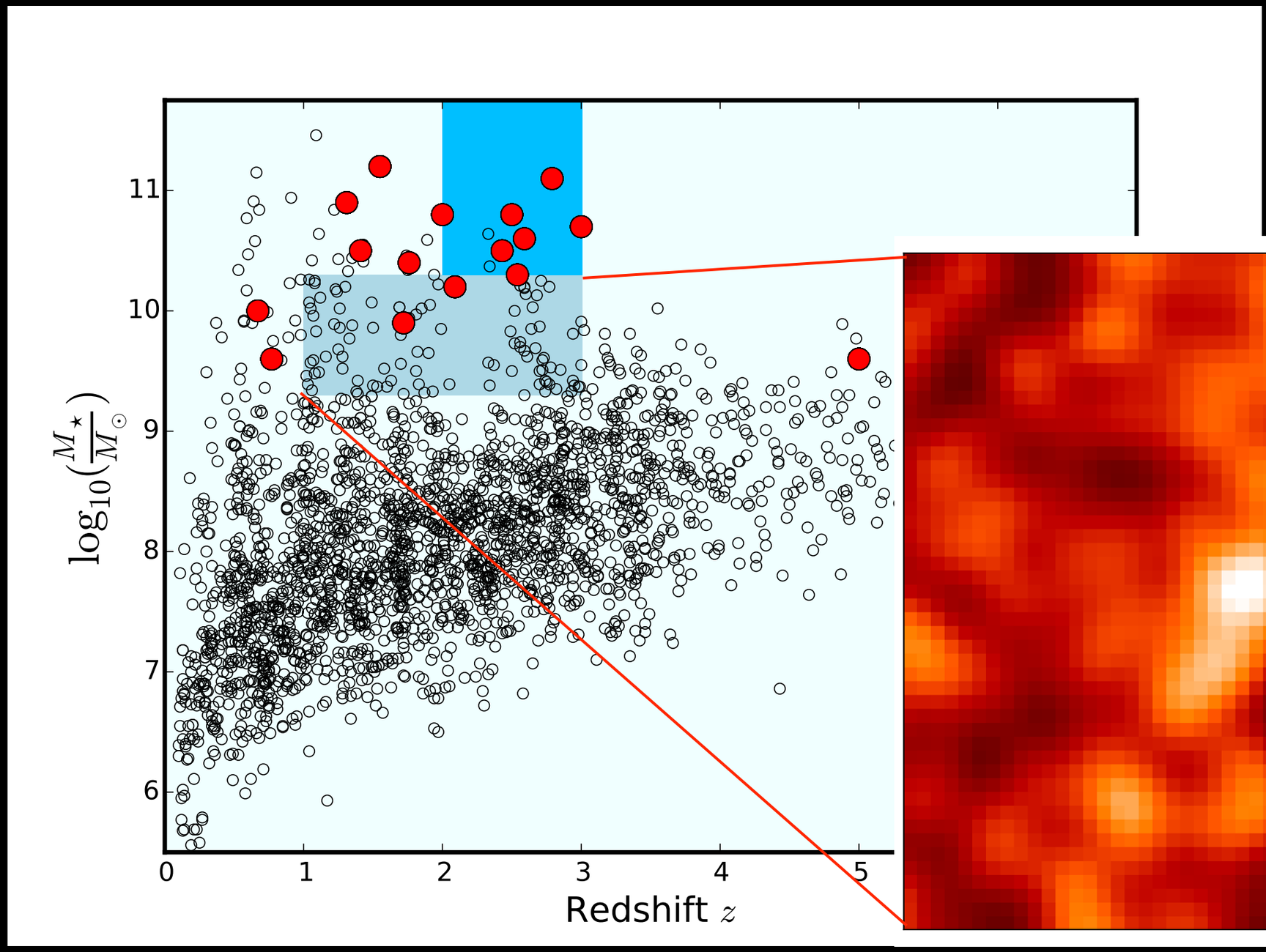
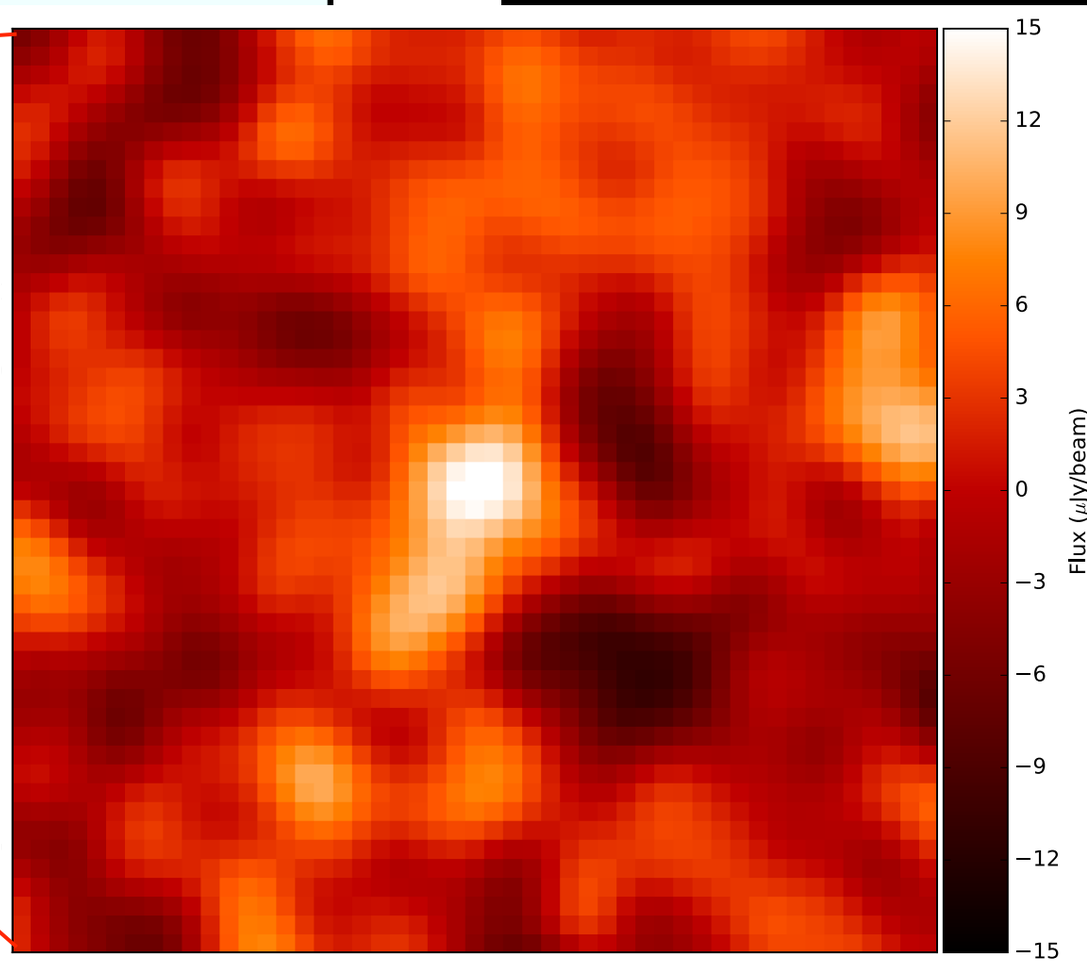
Stacks and the mm background

Push deeper, with stacking…..



89 galaxies



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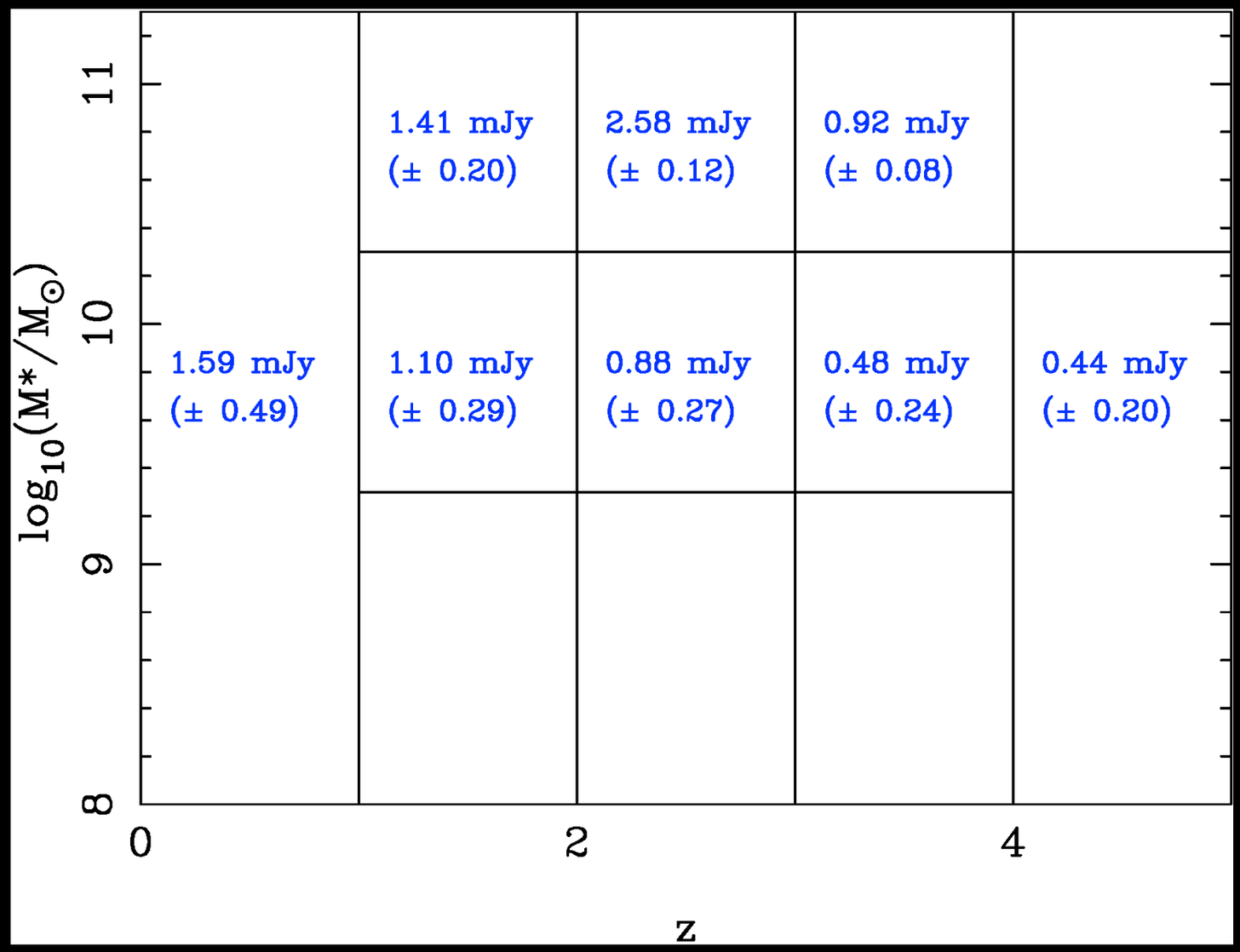
Stacks and the mm background

Push deeper, with stacking…..



Flux density distribution on mass – z plane

Sources + stacks

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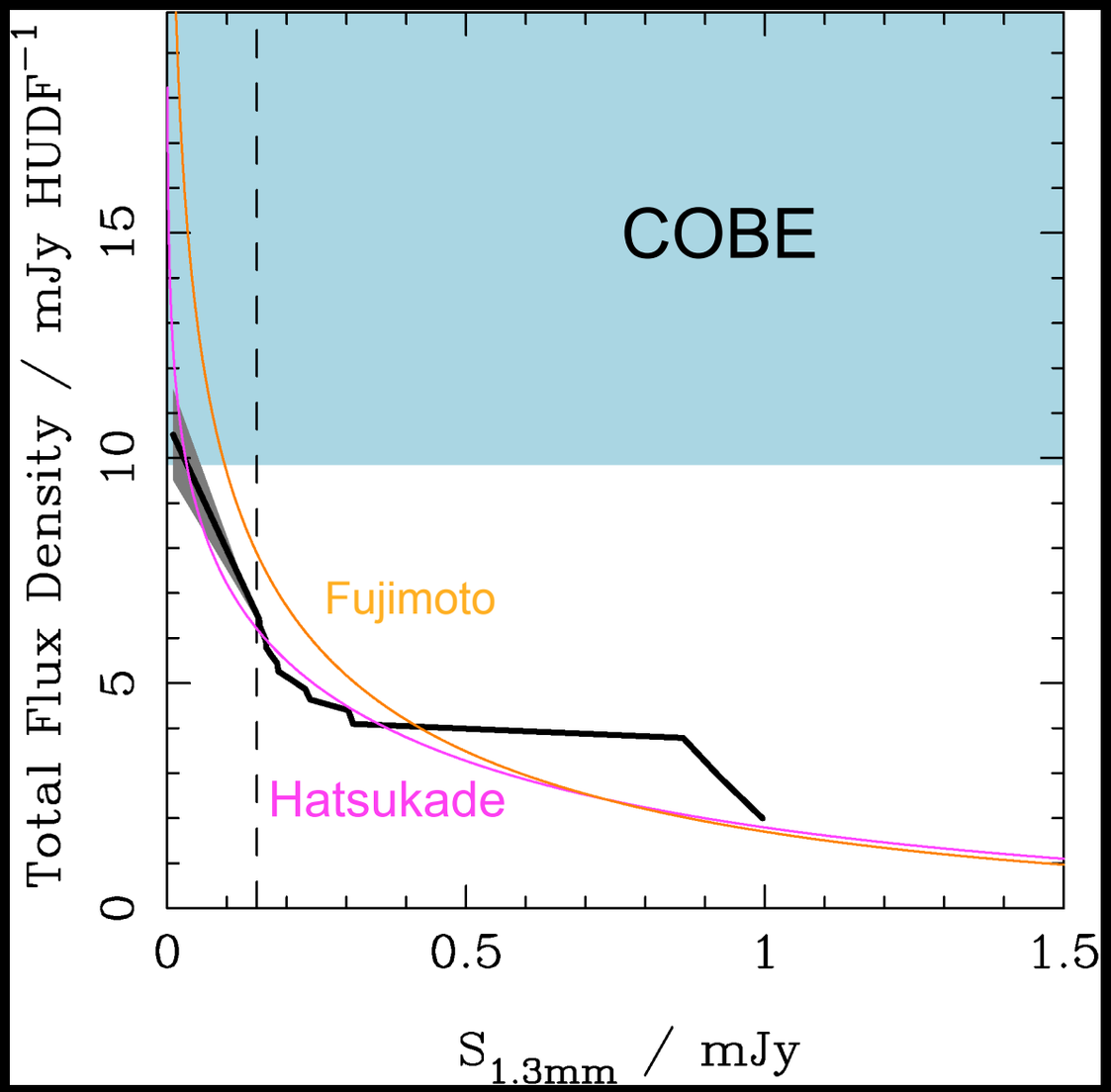
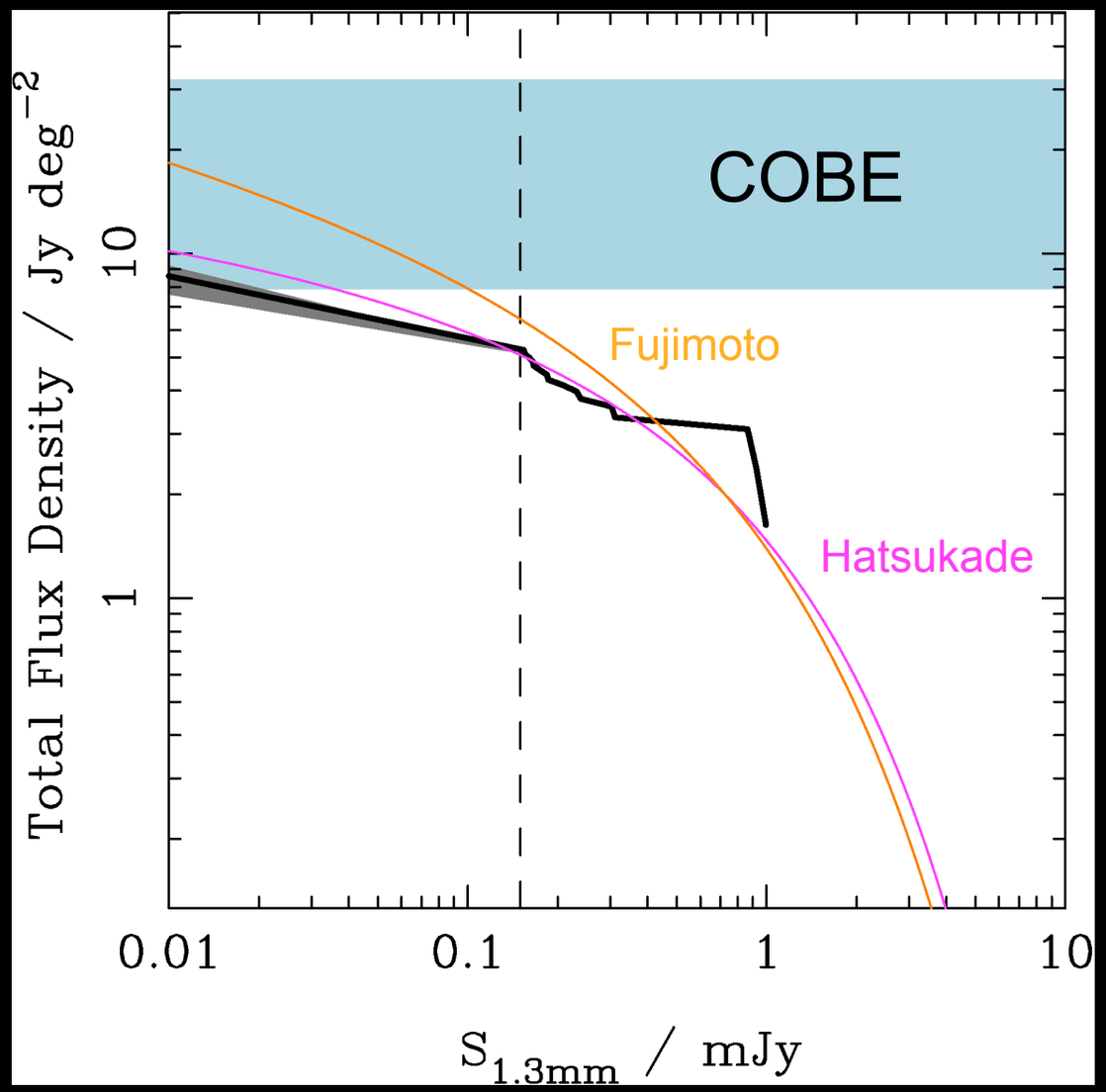
4. Stacks and the mm background

Total flux density





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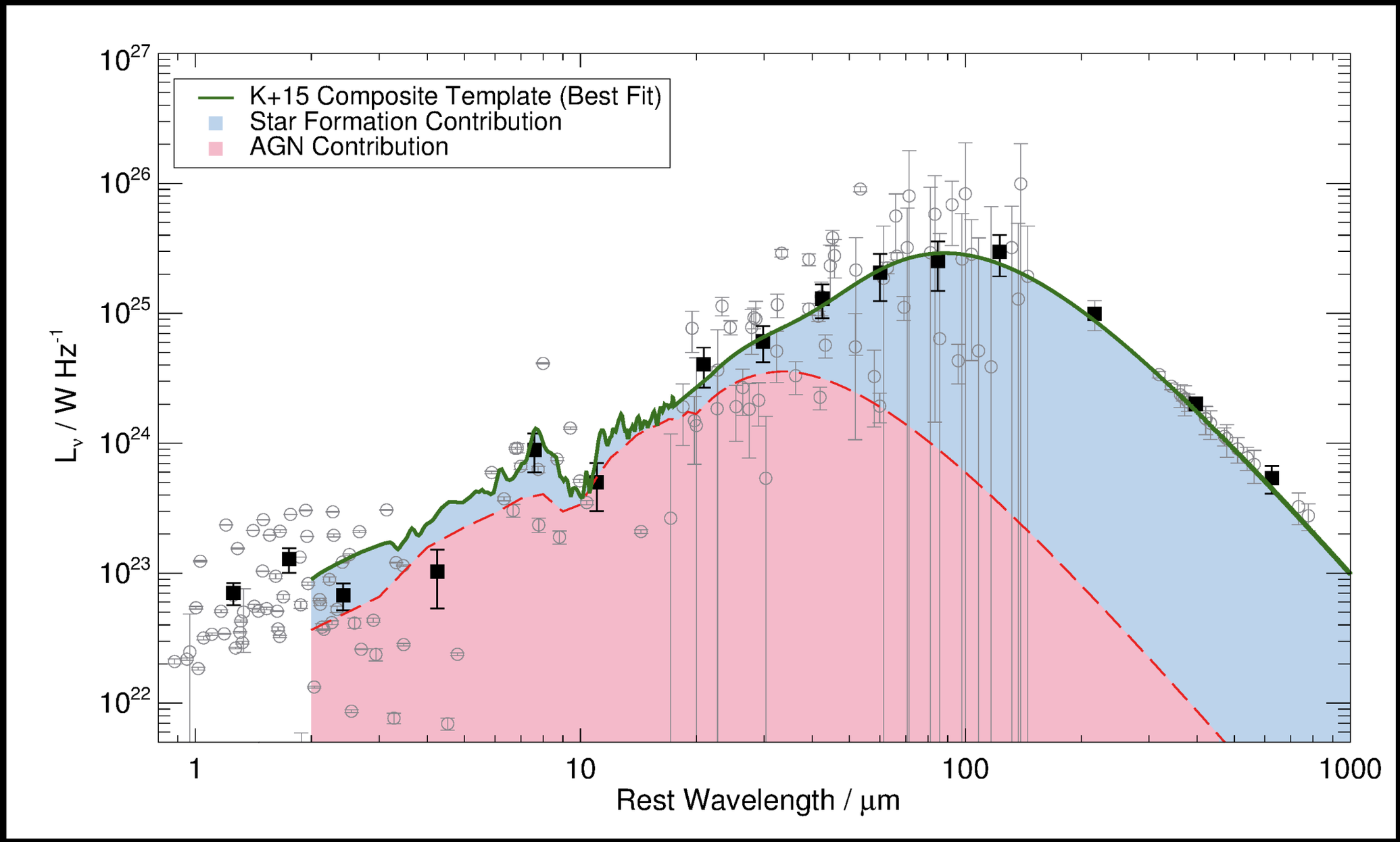
Star formation and obscuration

Establishing the appropriate long-wavelength template



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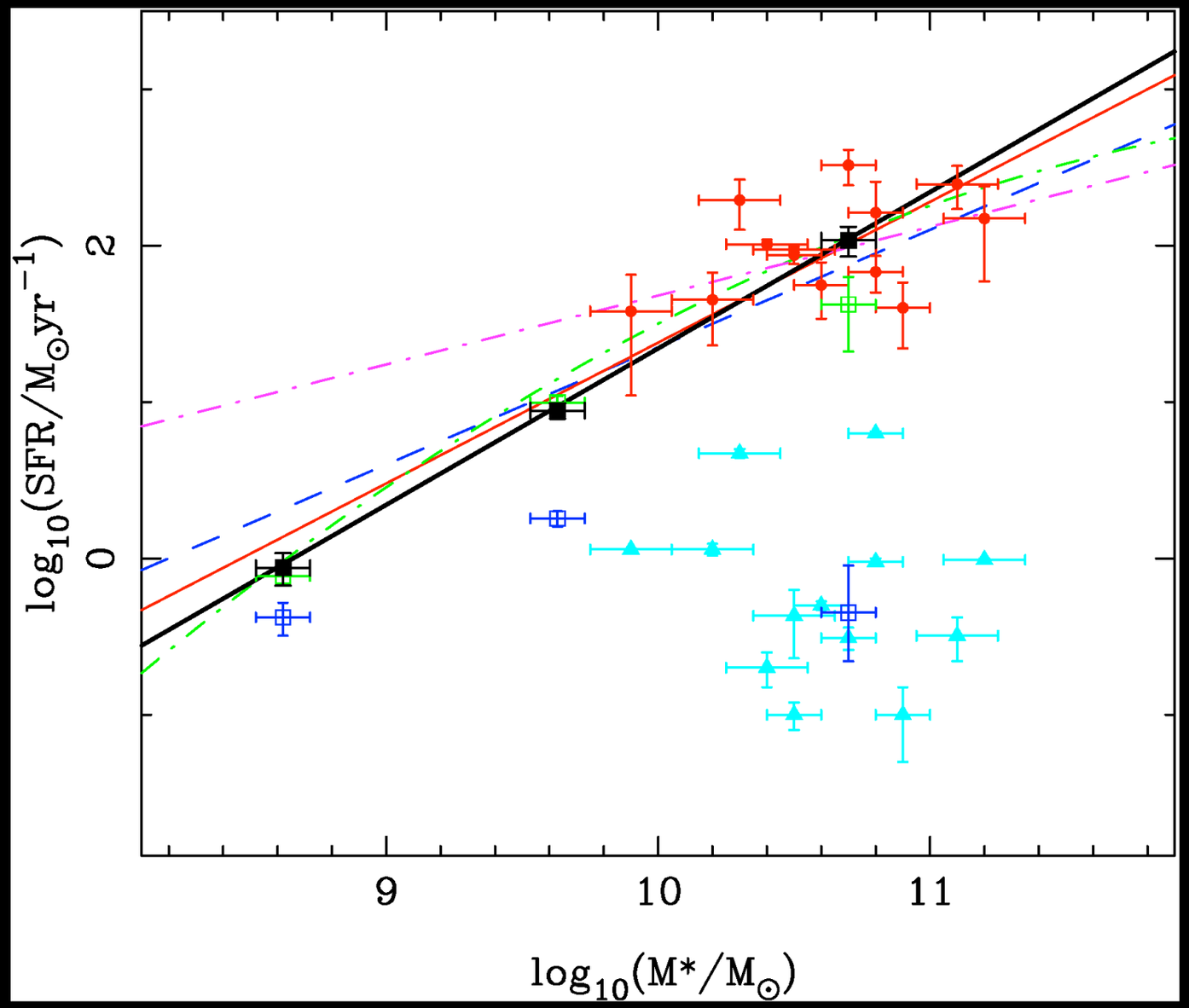
Star formation and obscuration

The star-forming "main sequence"

Obscured and visible star-formation rates



ALMA-detected galaxies on the main sequence at z ~ 2

SFR α M*

sSFR = 2.2 Gyr^{-1}

No evidence for flattening at high mass

Optical/near-IR SED fitting works well at lower masses, but falls short by factor ~2 at $M^* > 10^{10} M_{sun}$

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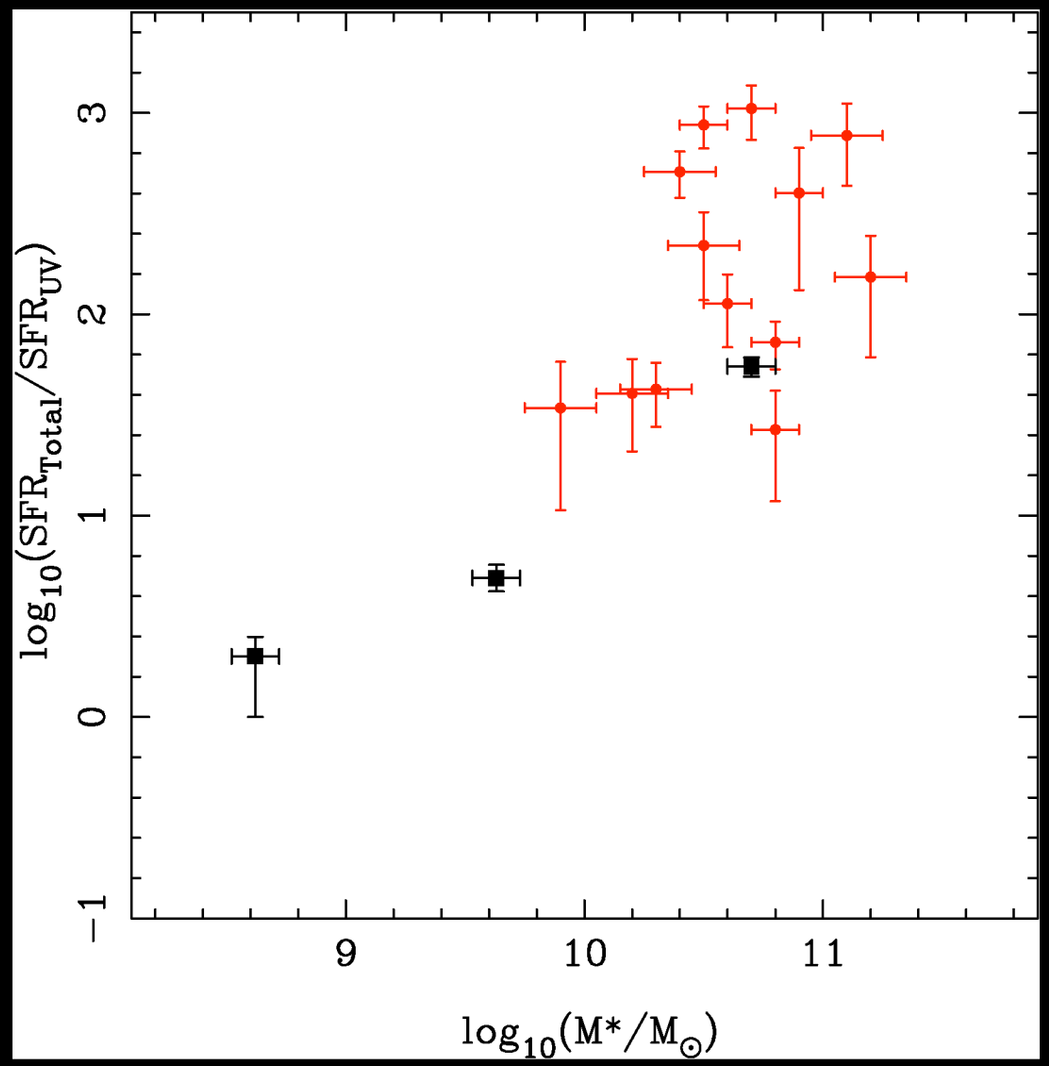
Star formation and obscuration

Obscuration as a function of stellar mass



Median SFR_{tot}/SFR_{vis}~200
for detected sources

Stacks=volume averages show
SFR_{tot}/SFR_{vis} = 50 at $\log_{10}M^*$ = 10.7
SFR_{tot}/SFR_{vis} = 5 at $\log_{10}M^*$ = 9.7

Double whammy !

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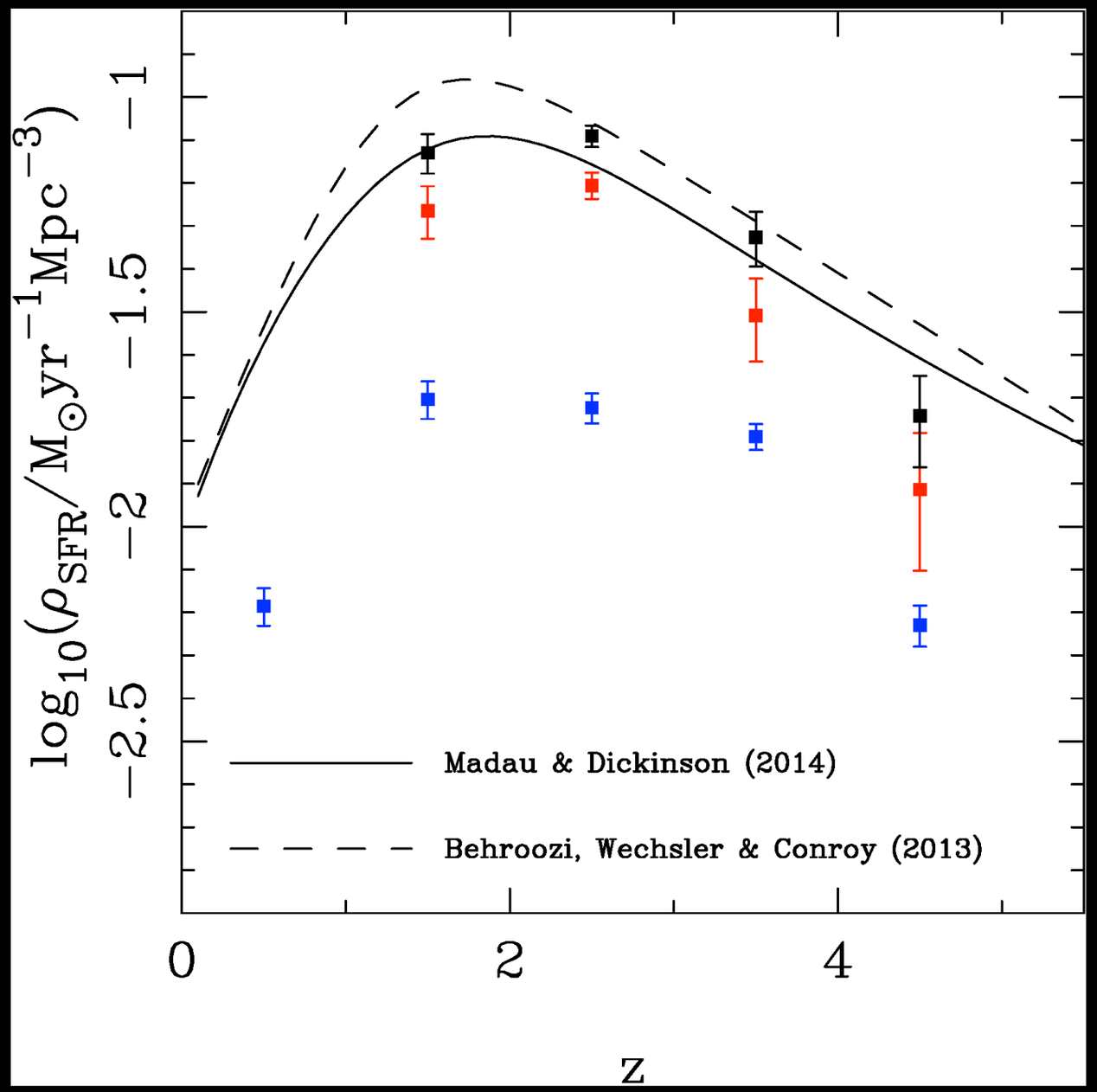
Cosmic star-formation history

Obscured and visible comoving star-formation rate density



Simply summing ALMA FIR and HST UV star formation within the HUDF in each redshift bin

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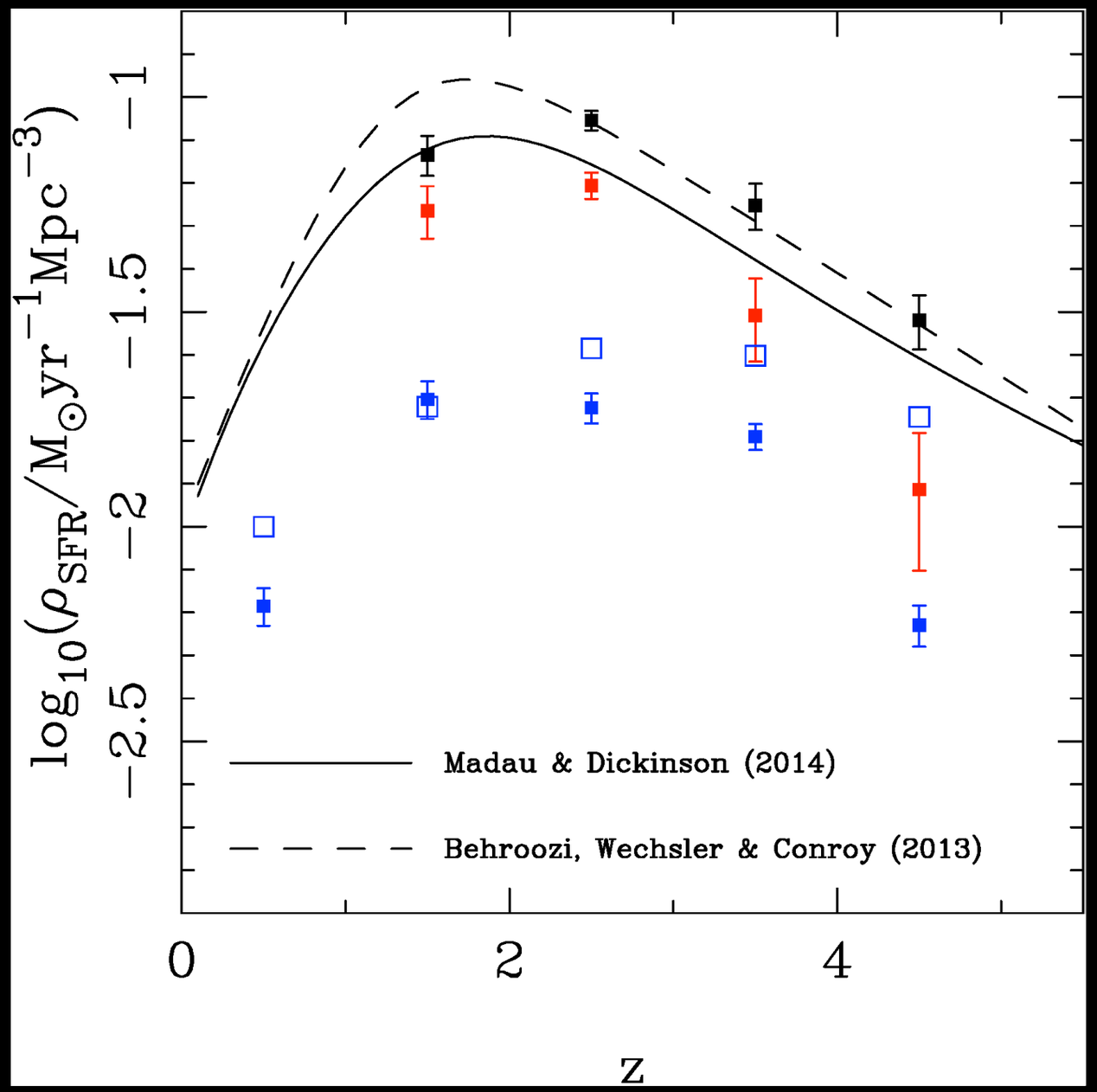
Cosmic star-formation history

Obscured and visible comoving star-formation rate density



Integrate UV LF to M_{UV} = -15 mag

Peak at z ~ 2.5

z ~ 4 marks transition between unobscured and dust-obscured star-forming Universe

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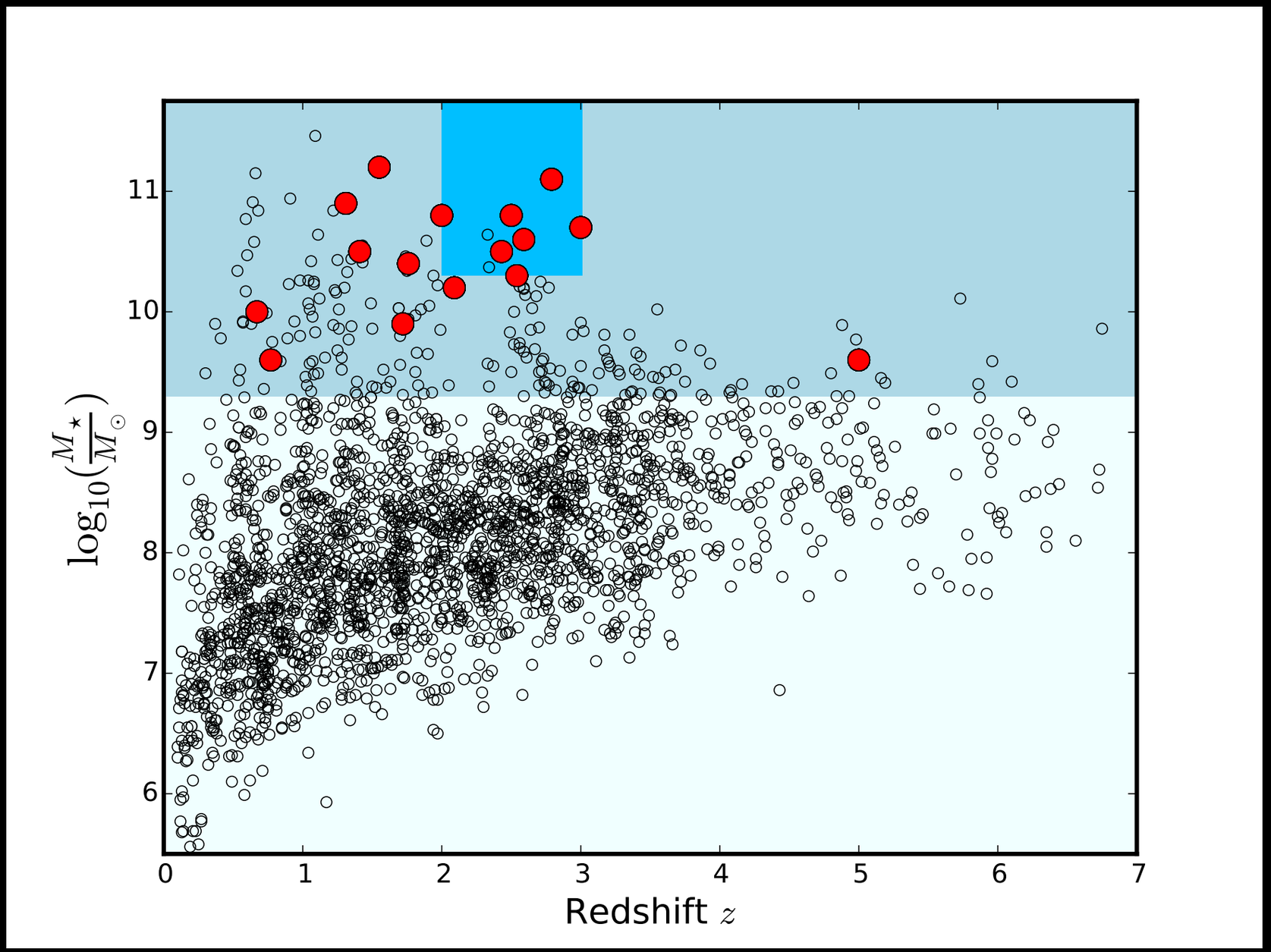
Future prospects

- Clear motivation for pushing deeper
- Cycle 4 Large Proposal – requesting ~120 hours at 850 μm



Reaching ~4 - 5 times deeper in SFR sensitivity

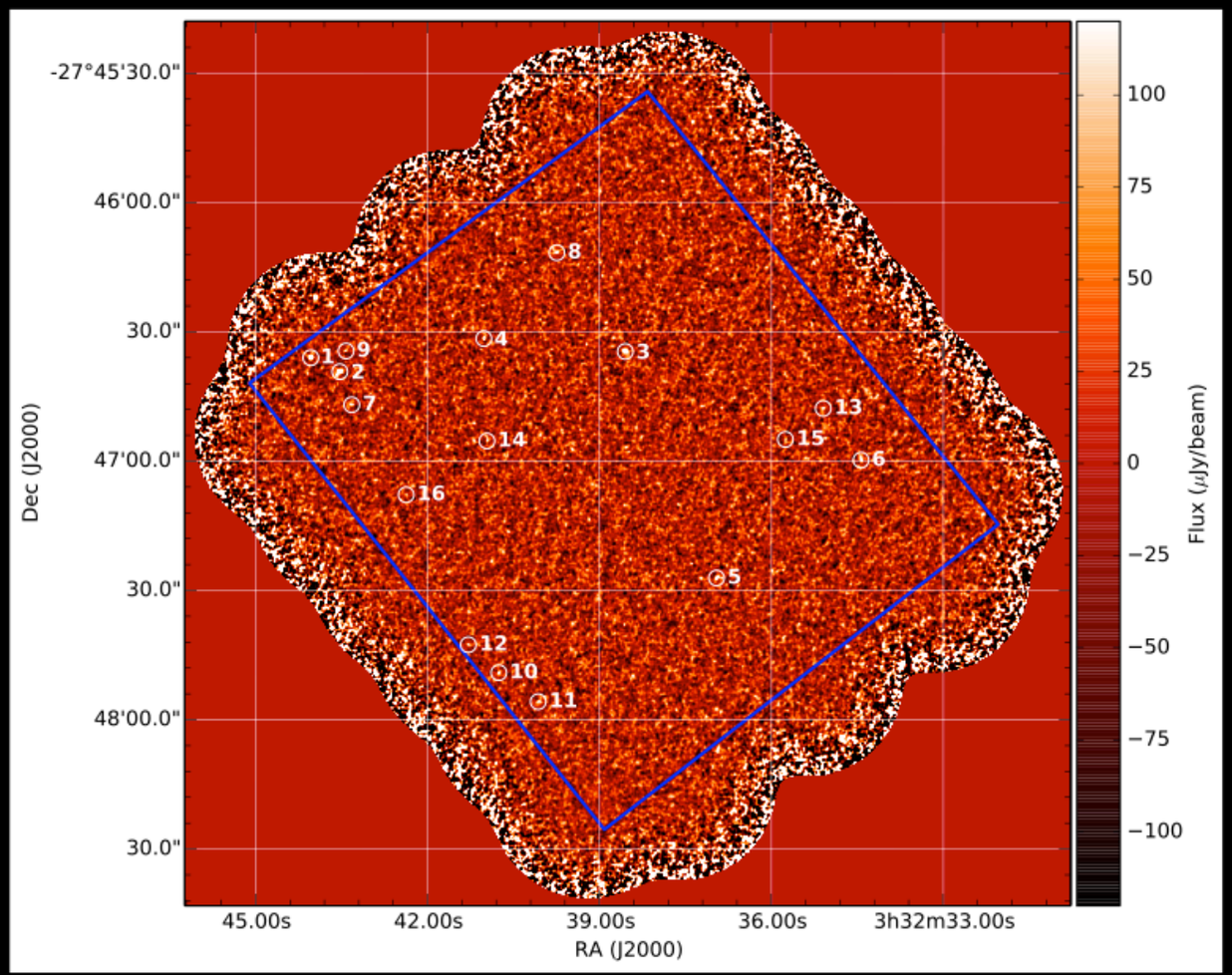
Expect to detect ~50 –100 sources out to z ~ 6

…..or prove genuine evolution of dust content

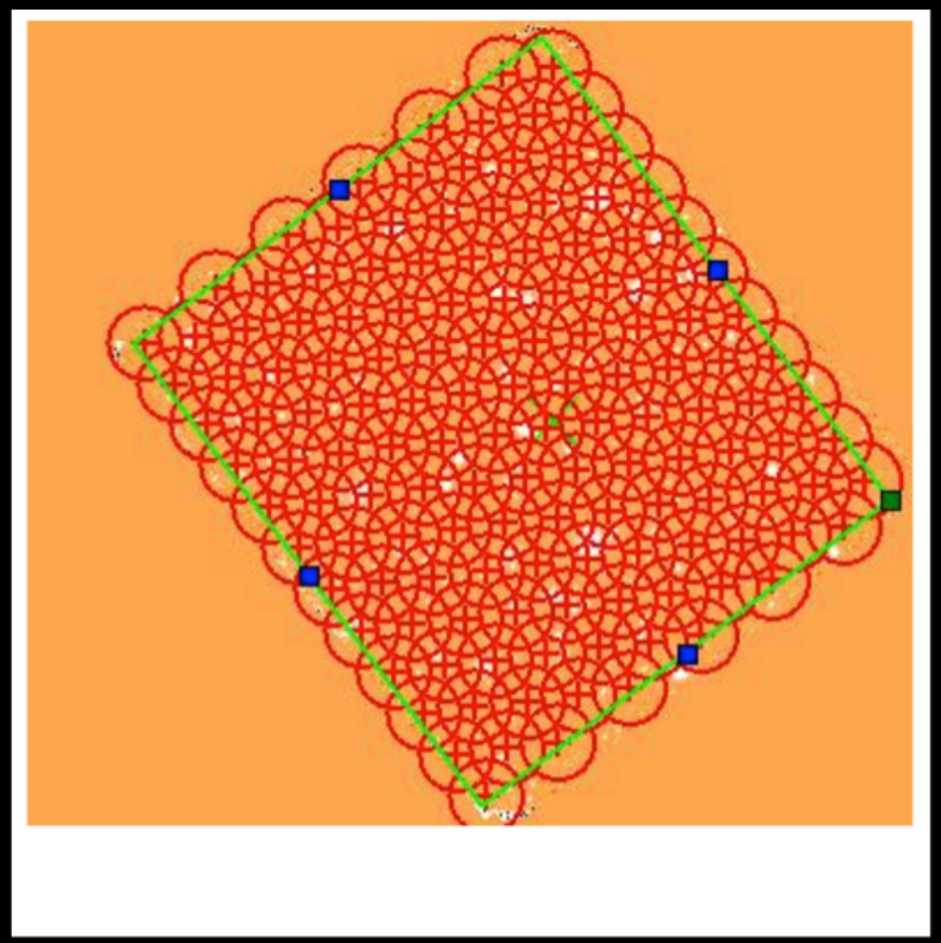
Future prospects

Proposed 138 pointing mosaic, reaching σ_{850} = 35 μJy

Expect to detect ~50 –100 sources out to z ~ 6



Observed 1.3 mm



Planned 850 μm

Summary

- Completed first deep ALMA image of HUDF
- Achieved $\sigma_{1.3}$ = 35 μJy, at 0.7 arcsec FWHM, over 4.5 arcmin^2
- 16 sources, mean z = 2.15 (13 spec z, 3 photometric z)
- Confirm stellar mass best predictor of SFR at high z
- Stacks in mass/redshift reveal most (all?) of 1.3mm background
- Steep main sequence, sSFR = 2.2 Gyr $^{-1}$ at z ~ 2
- Steep mass dependence of dust obscuration
- Universe transits from primarily unobscured to obscured at z ~ 4