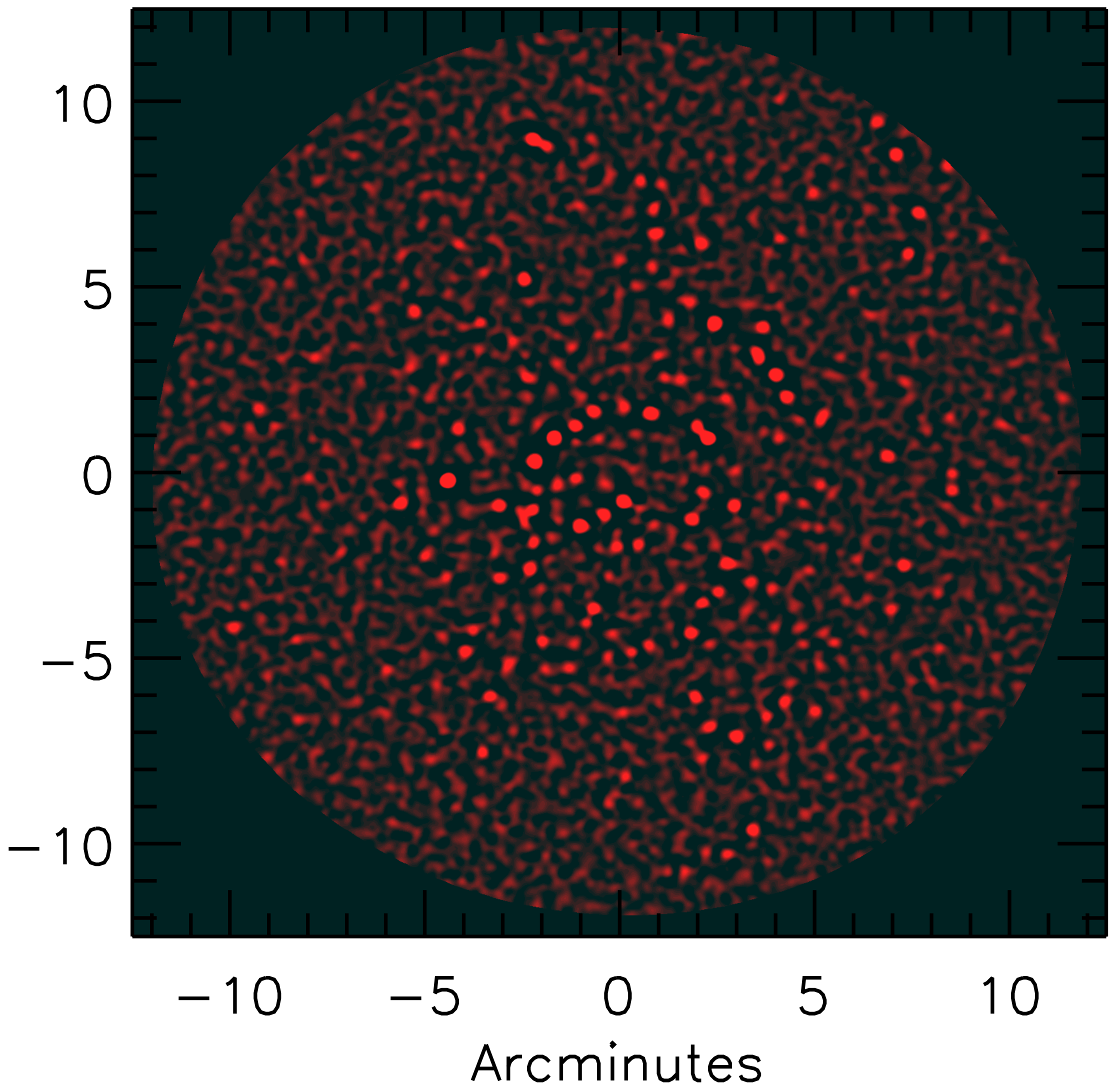
From Single-Dish to ALMA: Characterizing Dusty Galaxies

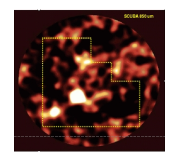
Amy Barger

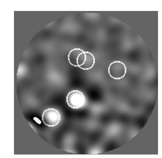
Franz Bauer, TC Chen, Len Cowie, Jorge Gonzalez-Lopez, Li-Yen Hsu, Frazer Owen, Wei-Hao Wang

Deep single-dish submm images (*Herschel* in space; JCMT, LMT, APEX, IRAM, SPT, etc, on the ground) have opened up the exploration of distant, dusty, luminous, star-forming galaxies



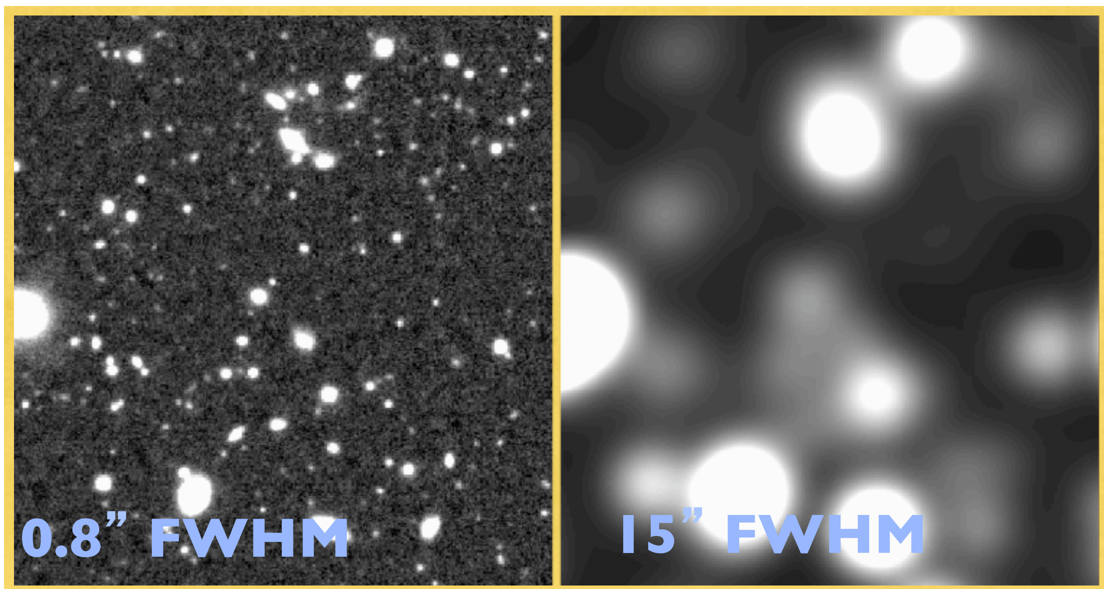
SCUBA (Hughes+1998)





SCUBA-2 (Cowie+2017)

- Advantages: cover large fields, produce uniform FIR/submm selected samples, sensitive to very high redshifts (particularly in the longer wavelength ground-based observations), not contaminated by AGN at the longer wavelengths
- Disadvantages: low resolution, blank field confusion limit



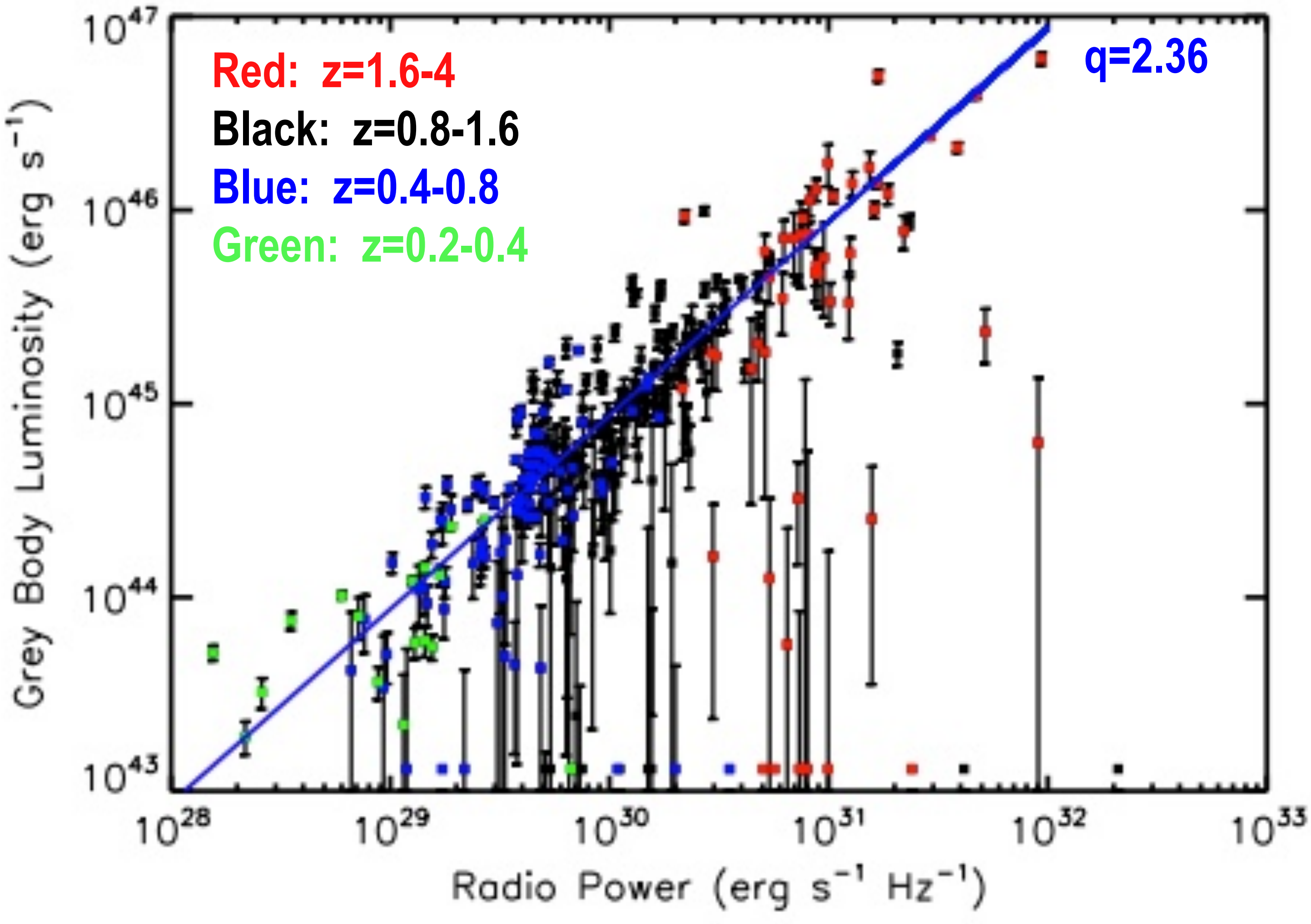
Not confusion limited. Integrating longer can detect fainter sources.

Confusion limited. Integrating longer can NOT detect fainter sources.

From Wei-Hao Wang

Since the FIR-Radio correlation seems to hold to high redshifts . . .

(Note: below excludes any sources with observed-frame 4-8 keV counterparts from CDF-N, but still substantial AGN contamination)



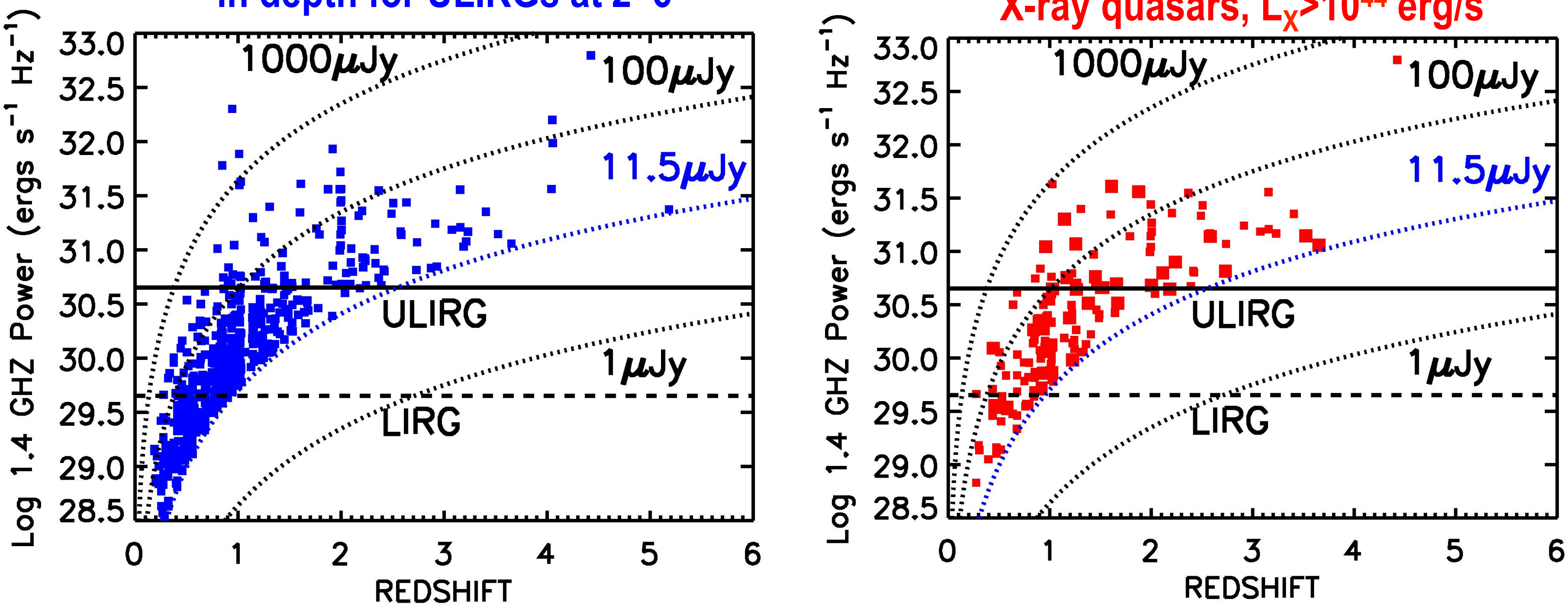
Barger+15

Large, uniform samples of high-z dusty galaxies can also be constructed from 5-20 cm imaging (e.g., VLA)

- Advantages: covers a wide field at high resolution
- Disadvantages: biased against high redshifts, highly contaminated by AGN (X-ray and red and dead)

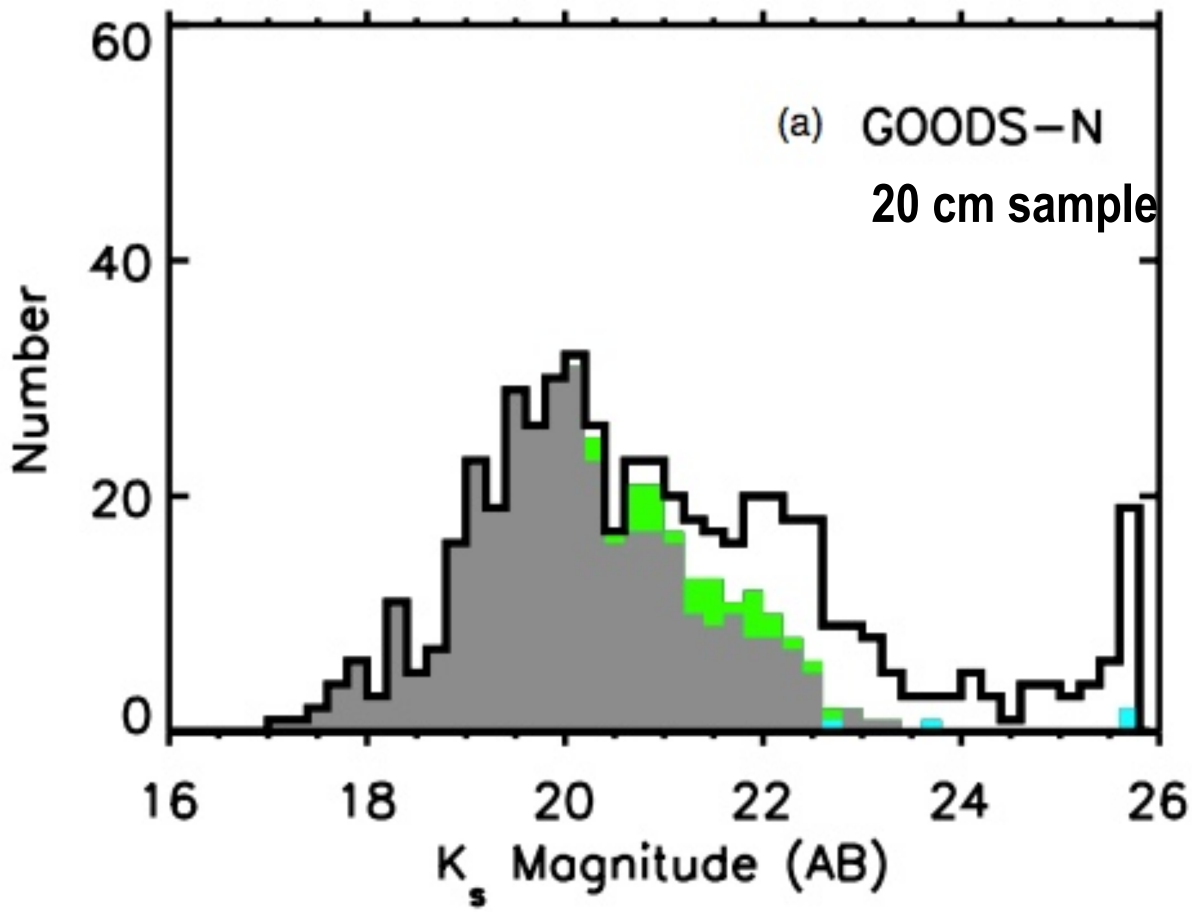
Need an order of magnitude increase in depth for ULIRGs at z=6

X-ray AGN, $L_X>10^{42}$ erg/s
X-ray quasars, $L_X>10^{44}$ erg/s



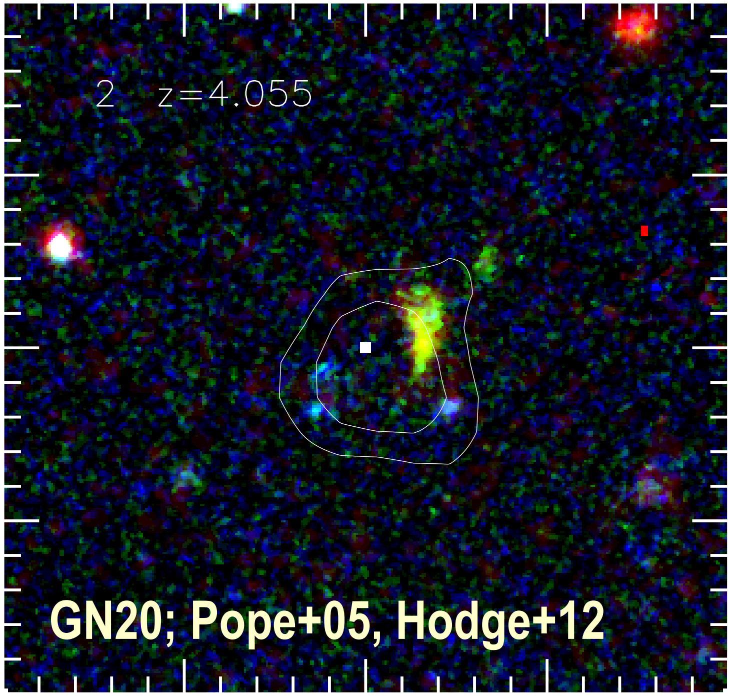
Deepest 20 cm image (5σ=11.5 μJy) by F. Owen; CDF-N X-ray image from Alexander+2003

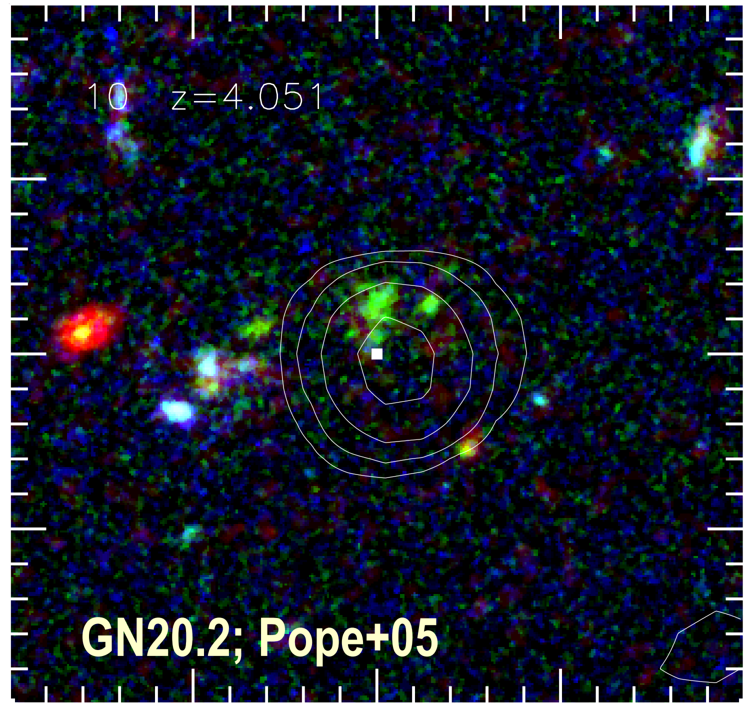
Of course, for both approaches, complete spectroscopic follow-up (and phot-zs) challenging due to the optical/NIR faint nature of many of the counterparts



Intriguingly, the limited CO (Daddi et al. 2009a,b; Walter et al. 2012) redshifts are all at z>4 and lie in an extended tail of radio sources with faint NIR counterparts (K_s>22.5)

GOODS-N





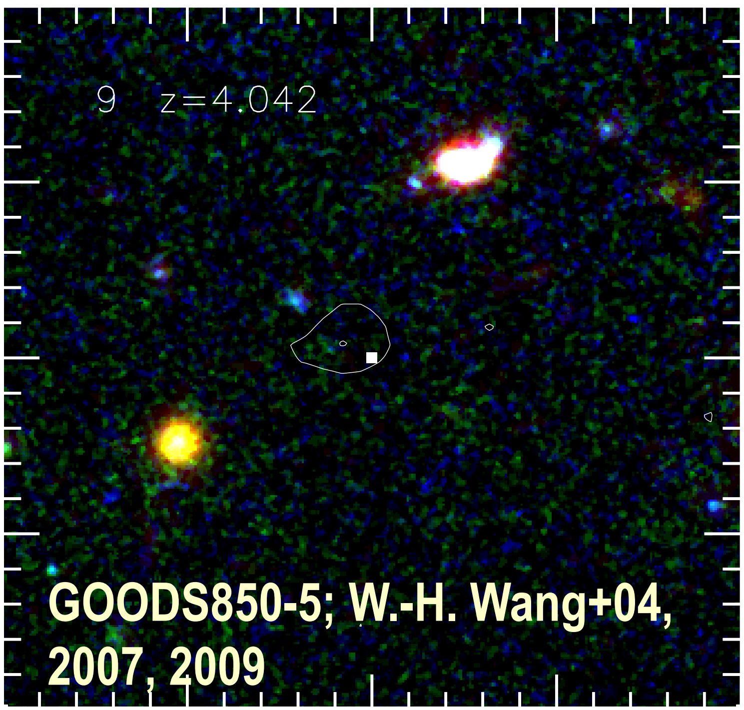
10” HST F450W, F814W, F160W

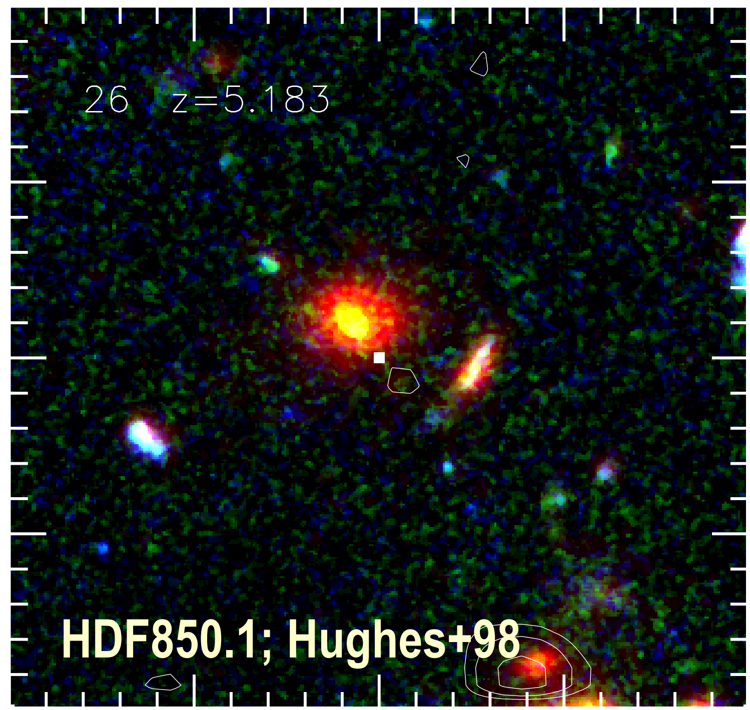
White square = centroid from SMA

White contours = VLA 20 cm

CO redshifts from Daddi+09a,b and Walter+12

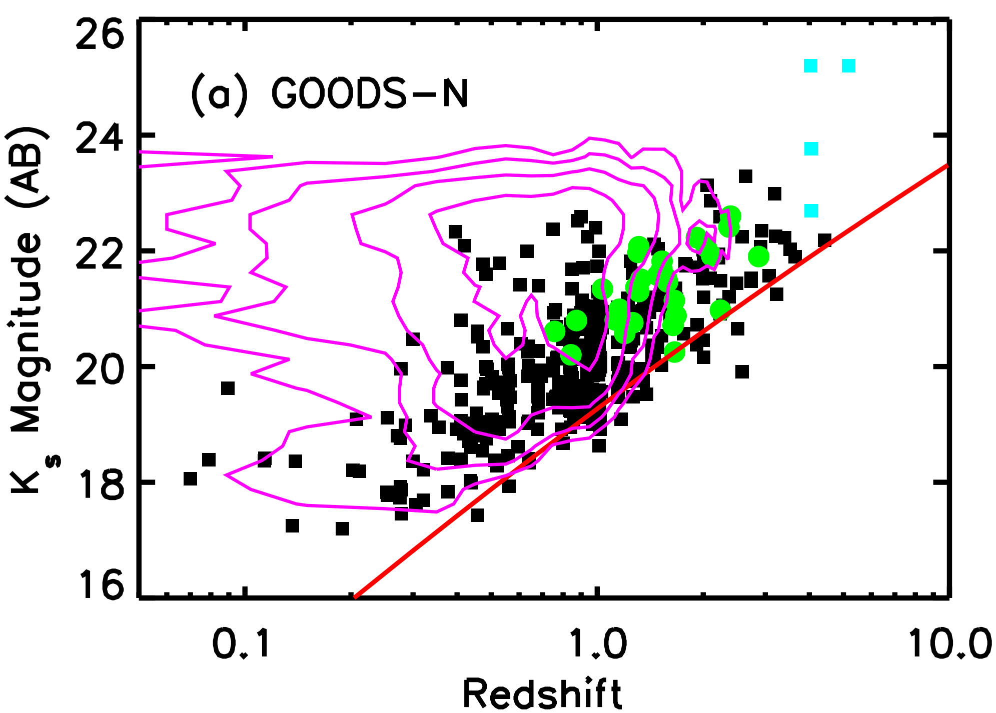
Where optical/NIR emission is observed in the higher redshift galaxies, it generally lies outside the main part of the galaxy

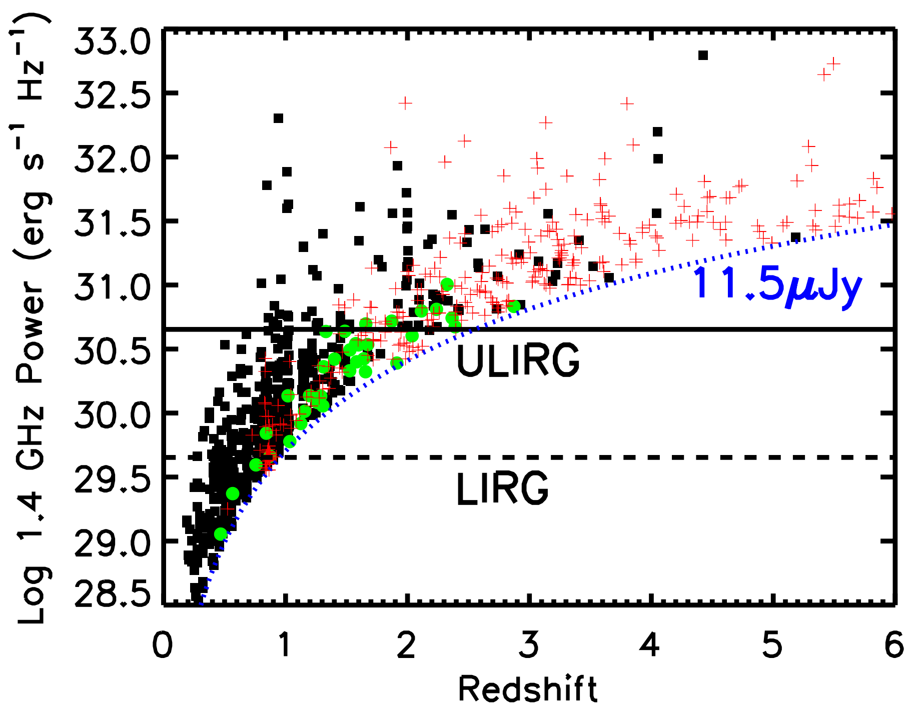




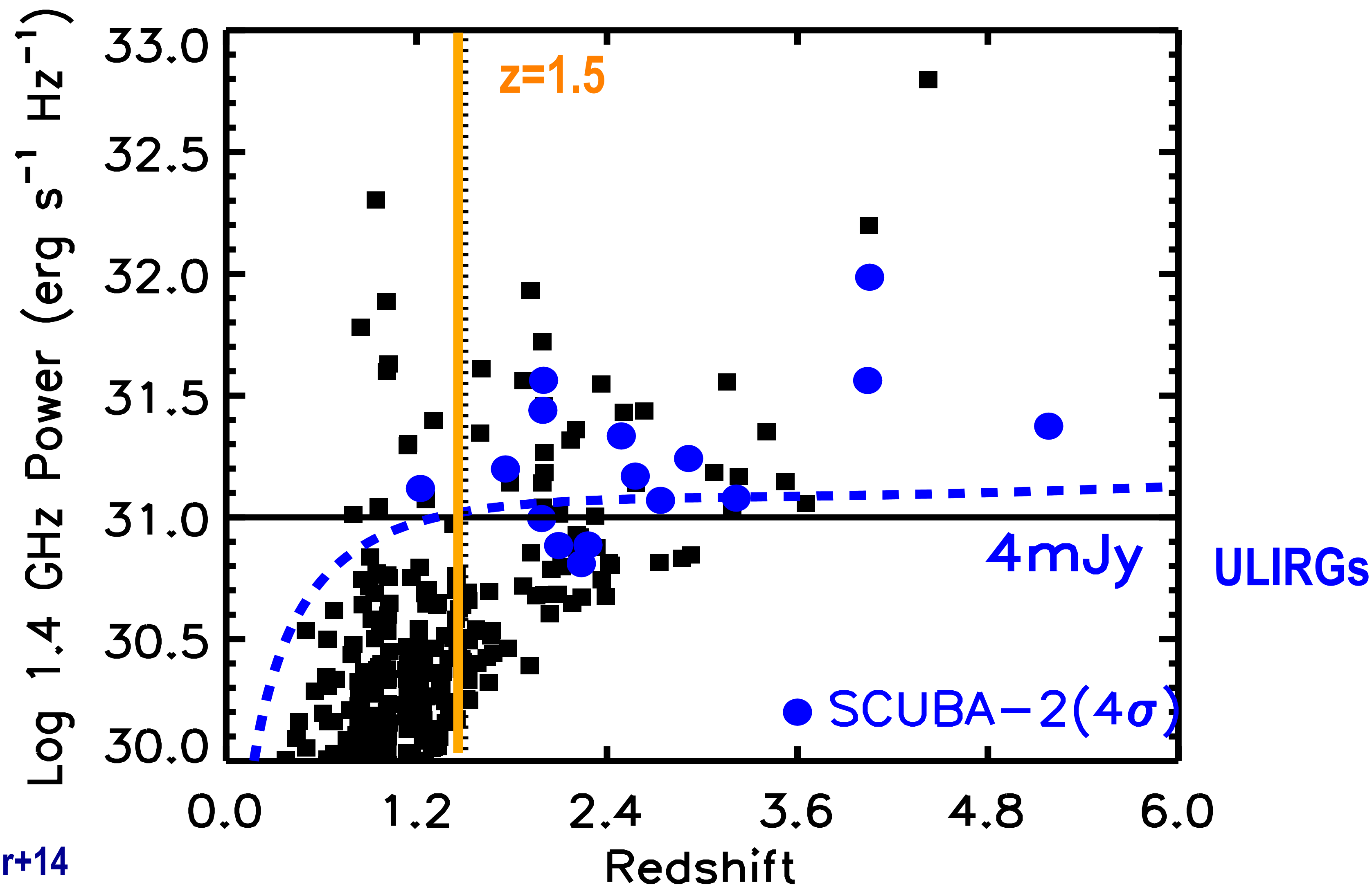
High-Redshift Radio Sources

- Most of the remaining optical/NIR faint radio sources may also lie at high redshifts
- In fact, the radio sources are nearly all located in the most *K* luminous galaxies at all redshifts, making *K* mag a crude redshift estimator [famous old *K*-z relation; Lilly & Longair 1984]



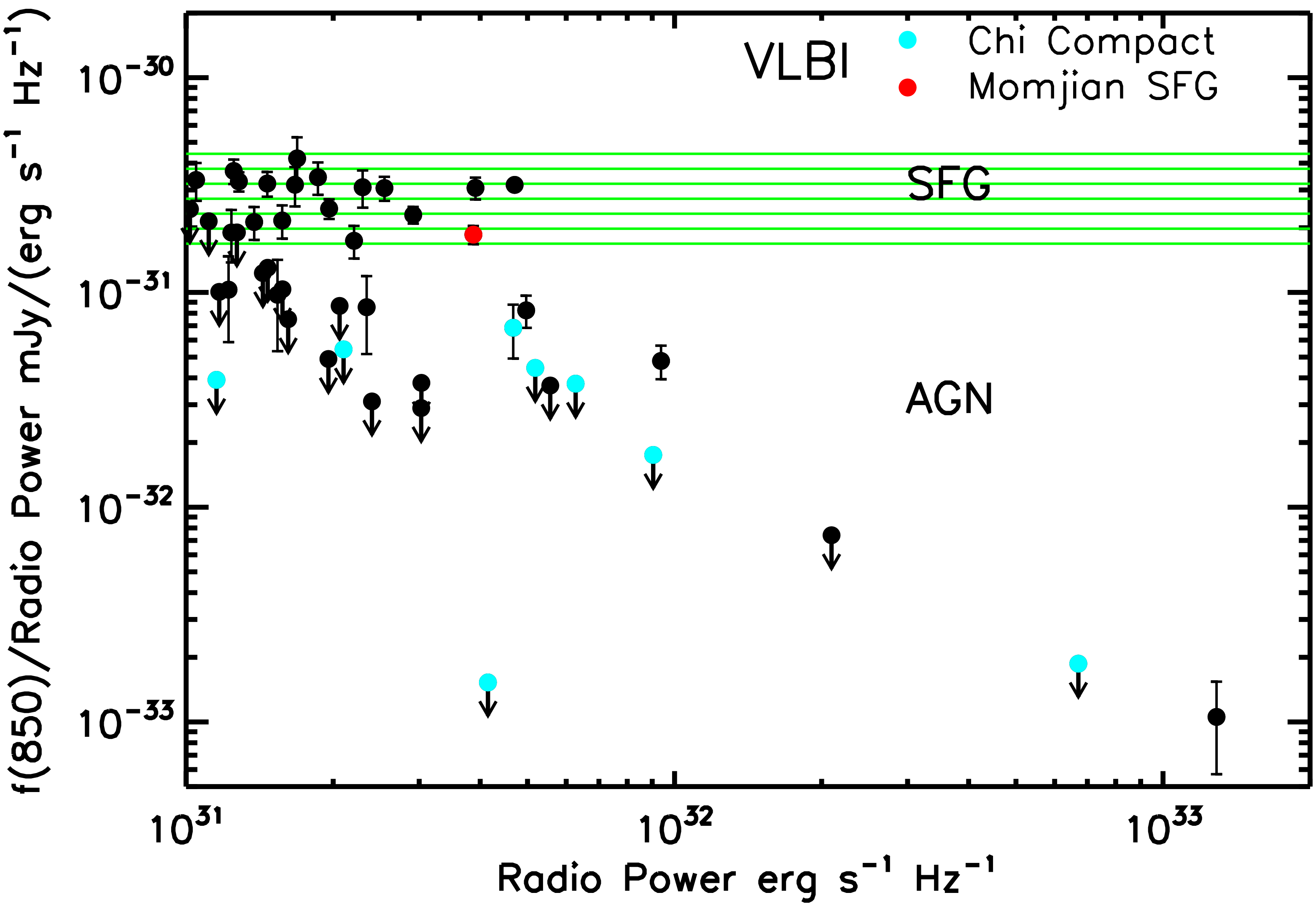


Used together, submm and radio data become much more powerful – e.g., we can pick out which sources in the high radio power sample are high-redshift star formers based on their submm detections



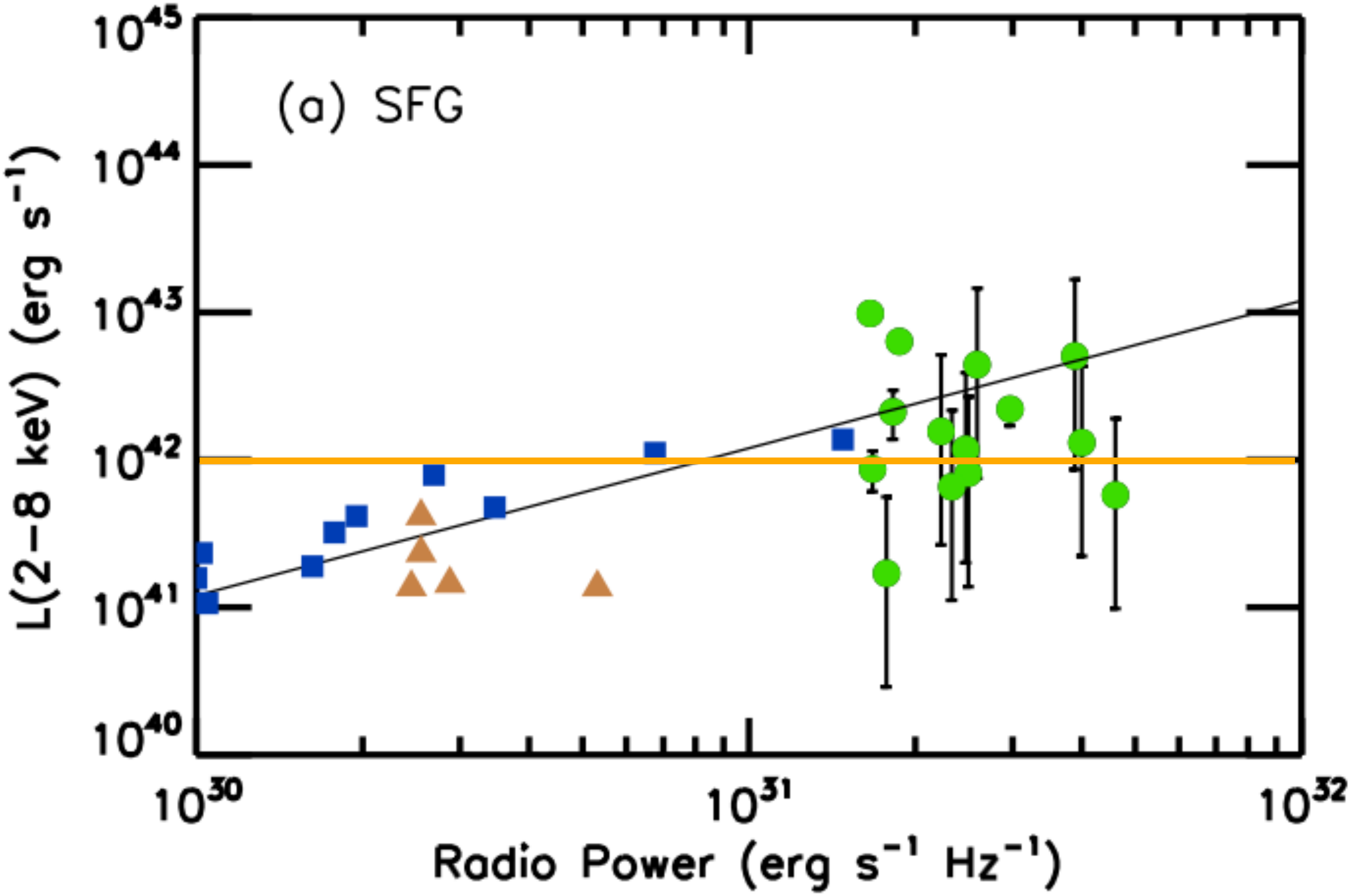
Barger+14

Encouragingly, the SFRs determined for star-forming galaxies from radio and submm agree (green). We also see hints of a maximum SFR from the radio data (see Karim+13, Barger+14 for a similar submm conclusion)



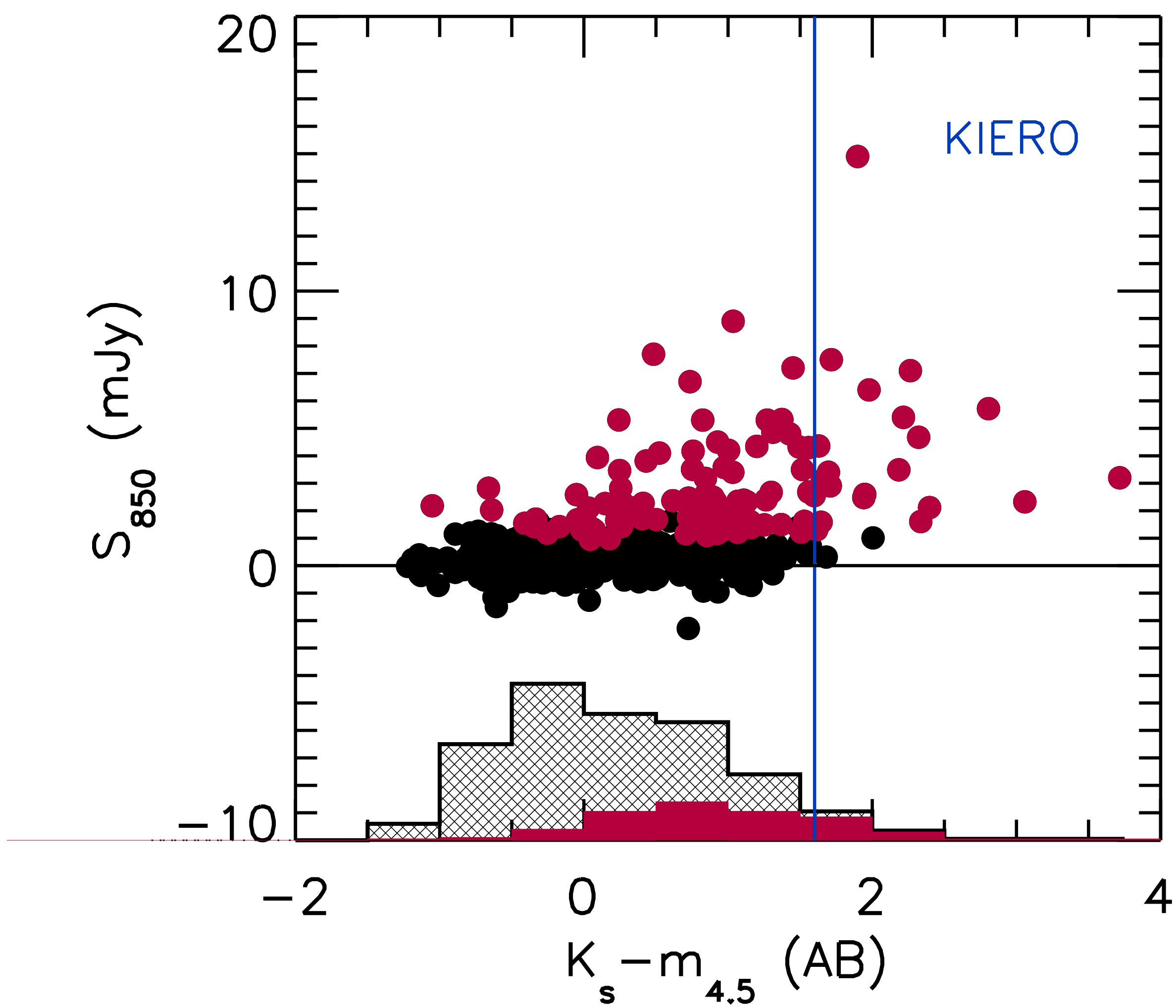
Barger+17

The X-ray luminosities of the star-forming galaxies are consistent with an extrapolation of the Mineo+14 relation to higher radio powers; caution when using $L_X>10^{42}$ erg/s to identify "clear" AGN



Using both radio and submm data, we can also examine other dusty star-forming galaxy selection methods

For example, the use of red colors, such as K – 4.5 micron > 1.6 (W.-H. Wang+12; KIEROS)

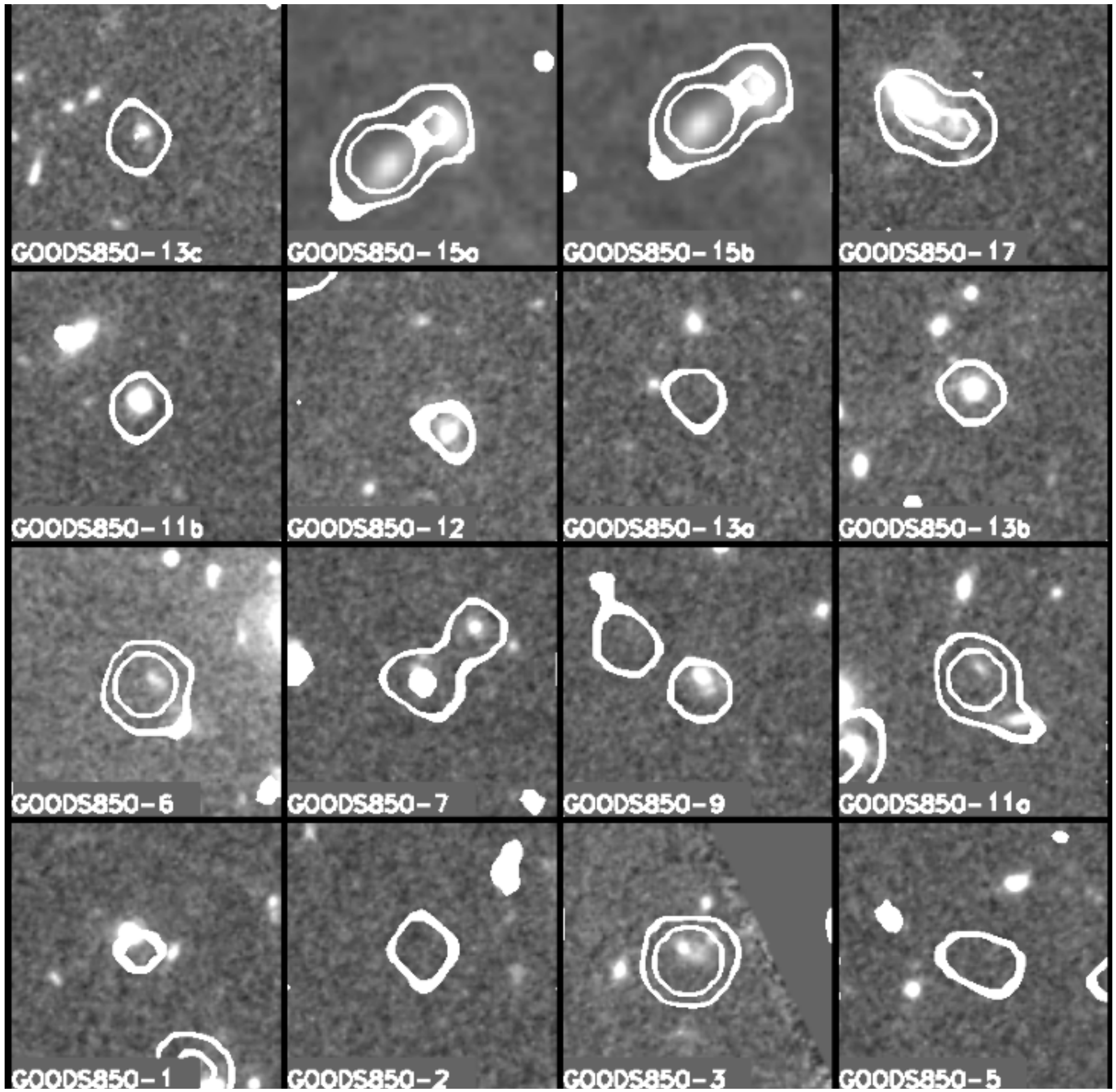


Radio sample in CDF-N

Cowie+2017

Finally, we can use the radio to locate the positions of bulk of SCUBA-2 sources (though there is ambiguity when multiple radio sources)

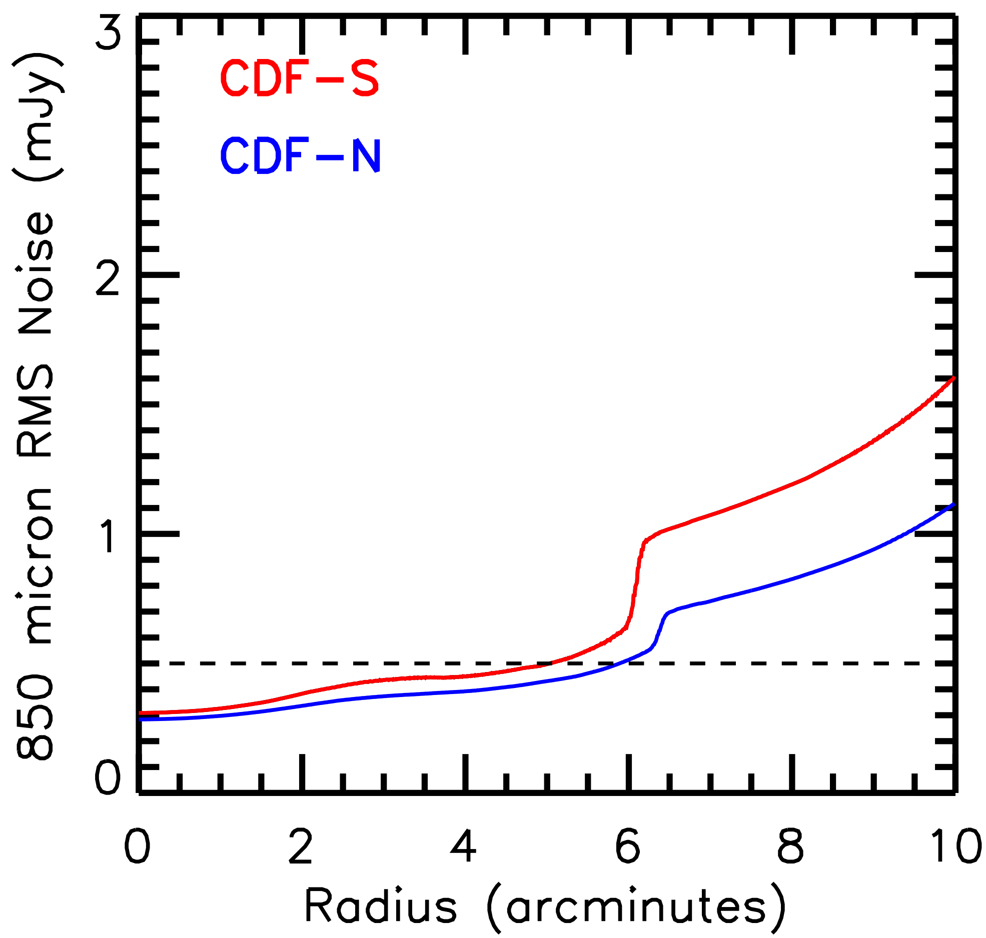
20 cm contours overlaid on HST F140W images centered on SMA positions



Barger+12

Radio data from F. Owen

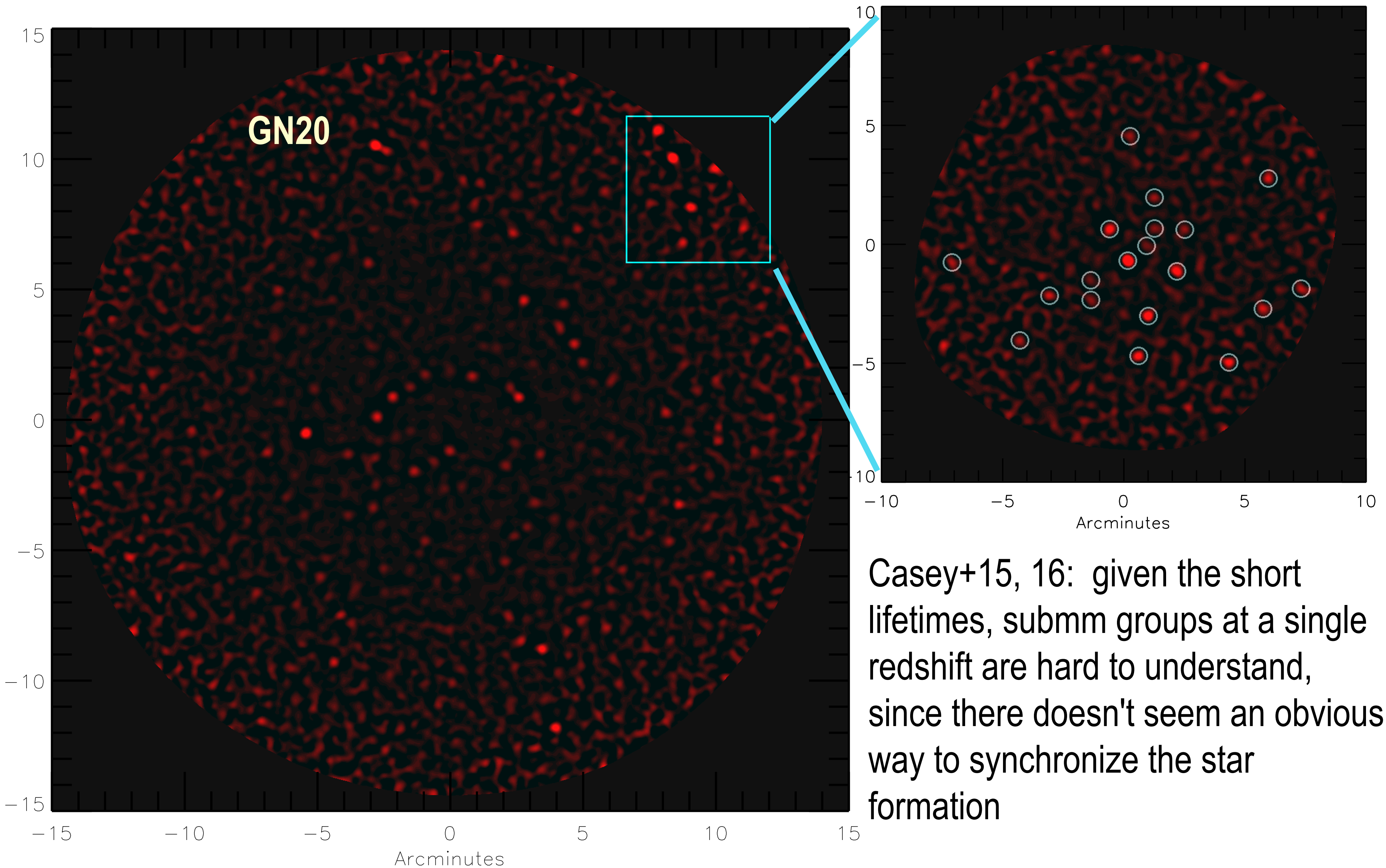
We have been carrying out deep SCUBA-2 observations (>250 hr in band 2) of both the CDF-N and CDF-S to generate >4σ samples (rms confusion noise of 0.37 mJy; flux at which confusion blending occurs is 1.6 mJy, roughly the 4σ confusion noise), and then following them up with interferometry



Are there high flux single sources?

- In the CDF-N, we have 8 SMA detections of SCUBA-2 sources with $S_{860\mu m}>10$ mJy in a 10^{th} of a square degree, *all of which are singles*

Clustering an issue: There are eight > 8 mJy sources in a single region (radio/submm flux ratio suggests z~4)

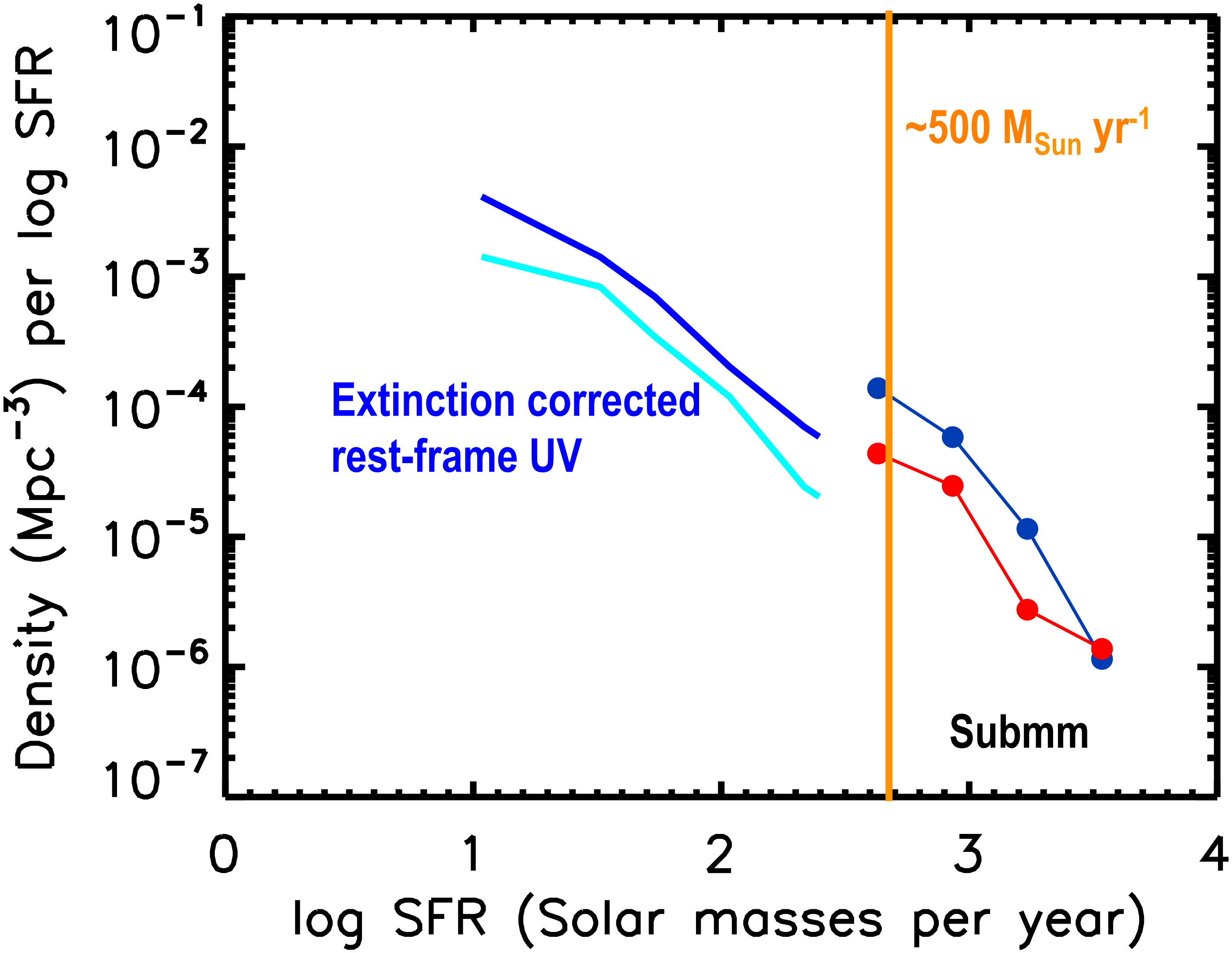


Casey+15, 16: given the short lifetimes, submm groups at a single redshift are hard to understand, since there doesn't seem an obvious way to synchronize the star formation

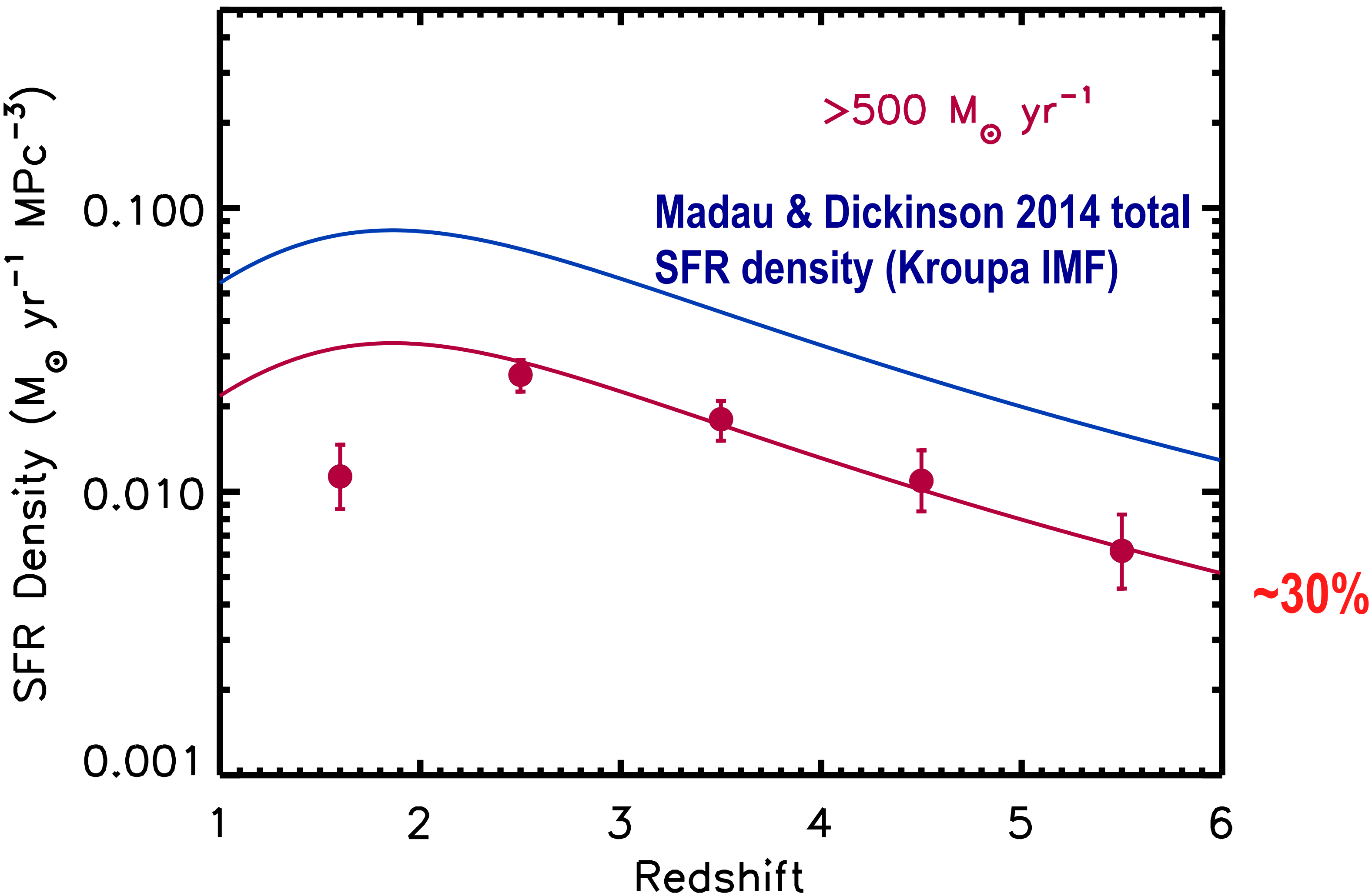
It is clear UV selections do not find the highest star-forming galaxies – the populations are completely disjoint

Curves at z=2 and z=3 from Reddy & Steidel 2009

Circles at z=2-4 and z=4-6 from SCUBA-2



Moreover, we find an impressively large and relatively invariant fraction of the overall SFR density is contained in the highest star-forming galaxies, and this is true at all redshifts to z > 5



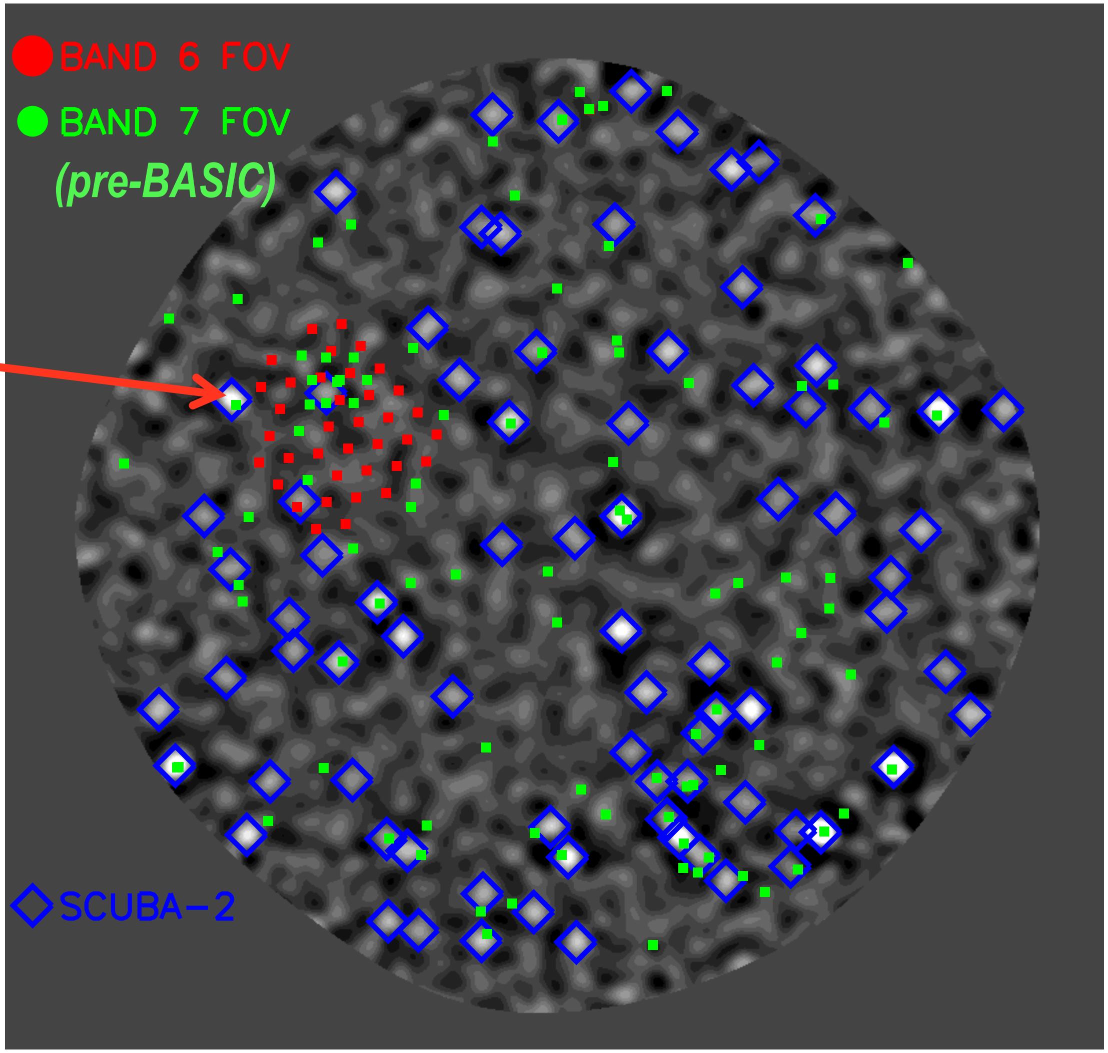
Big Question

How overlapped are the UV selected samples with the submm selected ones at fainter fluxes?

Much harder to cover directly large areas with ALMA

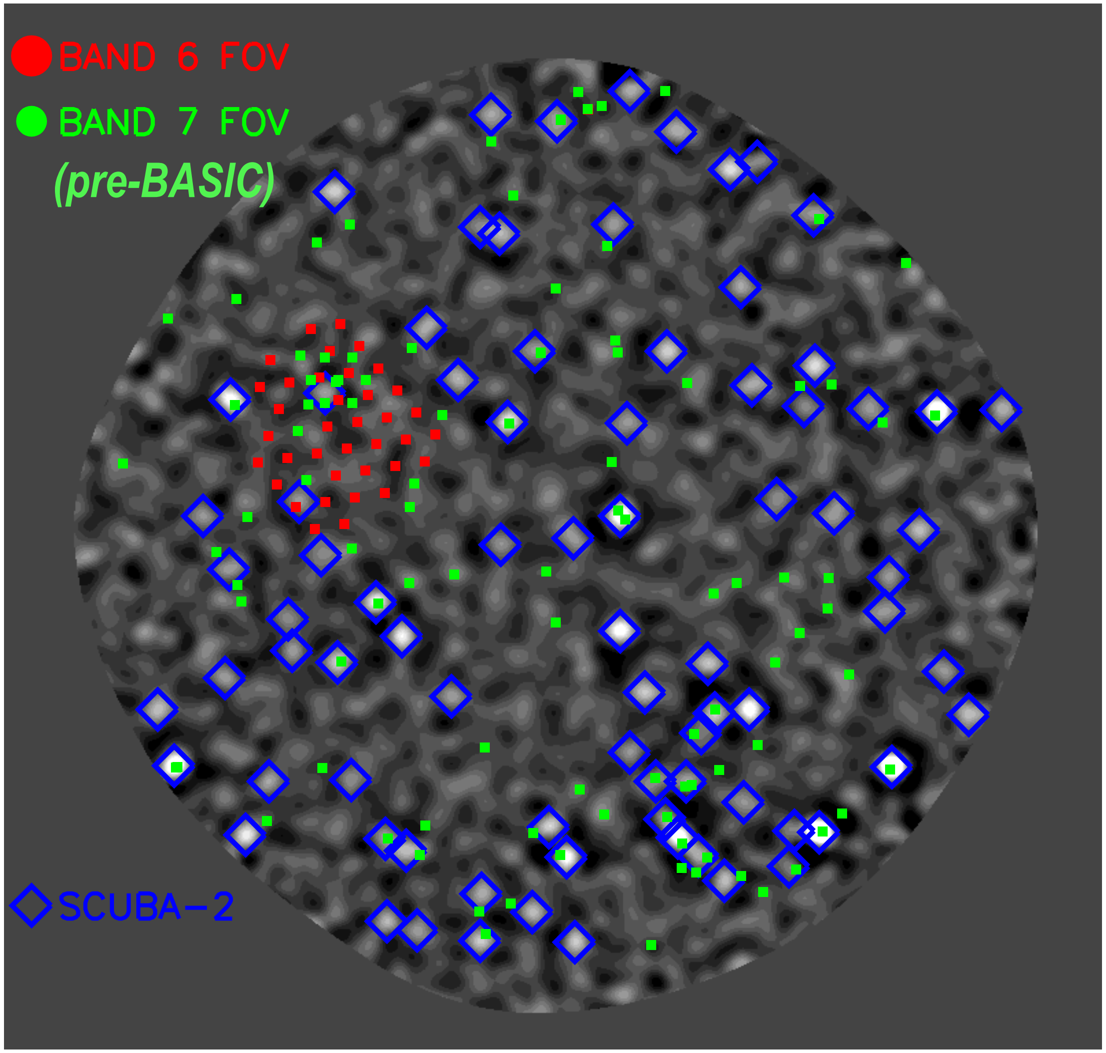
Dunlop+17 (16 sources > 120 microJy at 1.3mm [band 6]; 4.5 arcmin^2)

Walter+16 ALMA SPECtroscopic Survey (ASPECS, bands 3 and 6) contained within

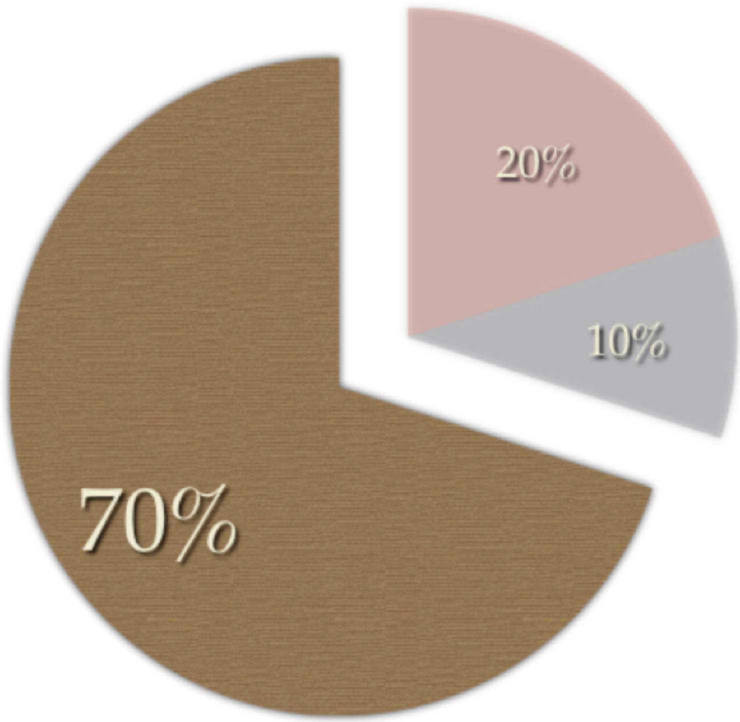


BASIC survey: our ALMA targeting of the CDF-S SCUBA-2 sources is the best way to obtain high-resolution submm images of all the >1.6 mJy sources in the field. (Below this, still need direct ALMA surveys.)

Note: only 2 BASIC sources were detected by Dunlop+17



BASIC Probes a Large Fraction of the Light (20-30%)



Other ALMA follow-up observations of blank field single-dish surveys *are shallower than BASIC and hence probe a much smaller fraction of the EBL*

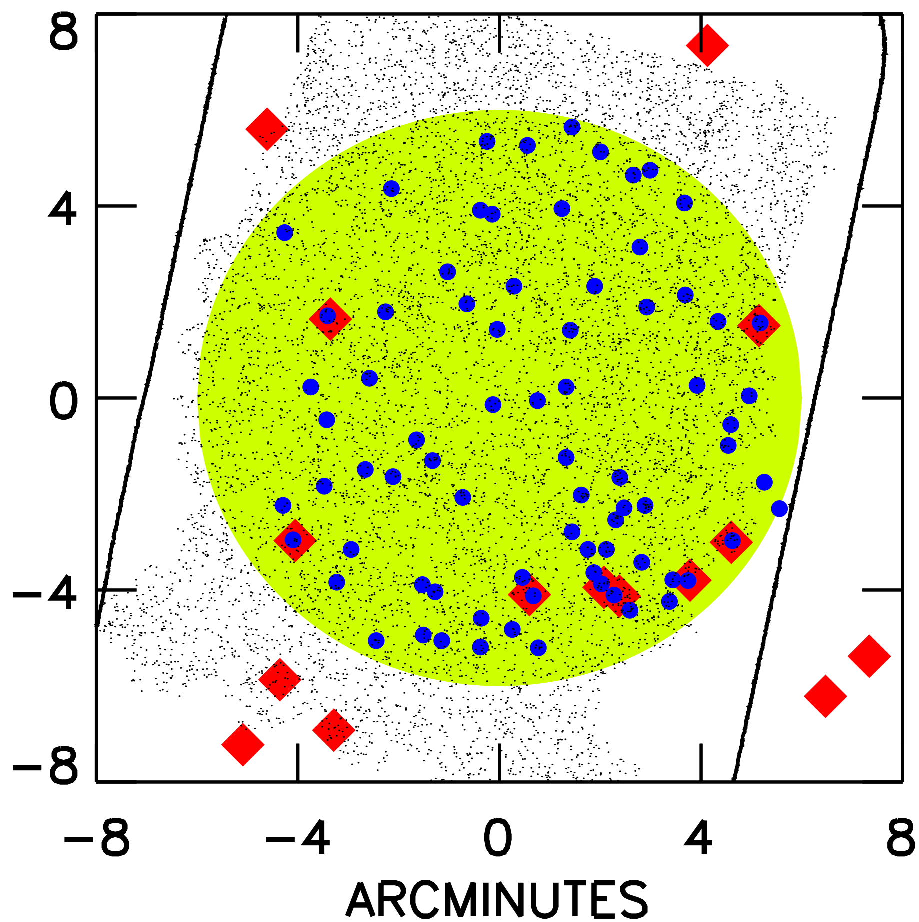
For ex, existing ALMA interferometry in the CDF-S

LABOCA (LESS; Weiss et al. 2009) surveyed the ECDF-S region, and ALESS did ALMA follow-up (e.g., Karim+13; Hodge+13)

However, (A)LESS is not deep enough to see many of the sources in the central region (which is covered by the 7 Ms X-ray image)

Red = ALESS
Blue = 4σ SCUBA-2

Deep area (<twice the central noise) in X-ray (green) for CDF-S



BASIC Survey Sources (Band 7, 870 micron)

Our goal is to detect all of the ALMA sources above a specified flux limit in the field, and we are using SCUBA-2 as an efficient way to find all of them

- **61 fields observed by us, 53 sources detected**, rms on peak fluxes ~0.13 mJy, total area ~ 5 arcmin^2, only consider sources within 8.7” radius (half-power radius of ALMA primary beam in band 7)

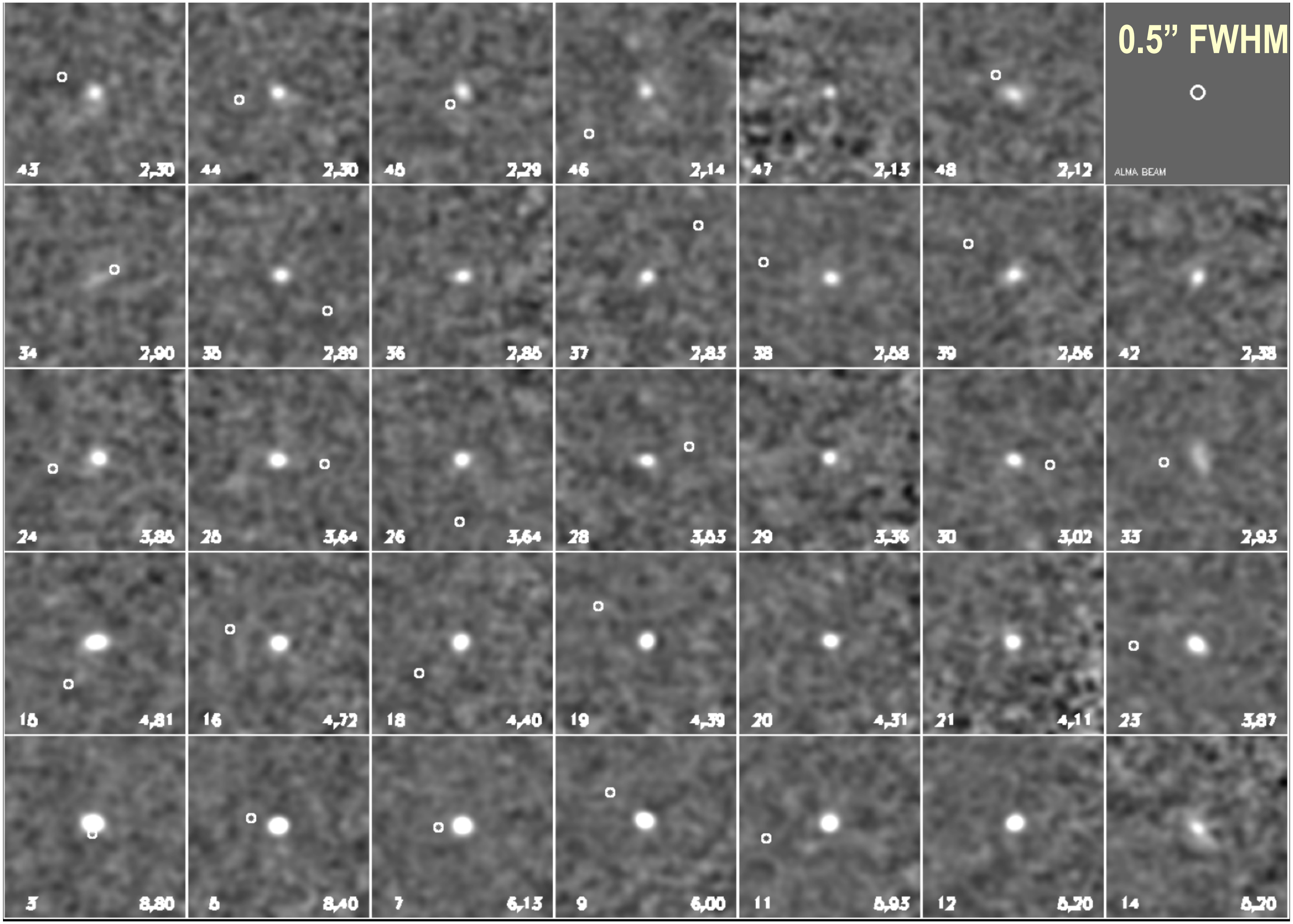
- Natural resolution 0.23”, but generally worked with 0.5” tapered images for better integrated fluxes

- Fluxes used are corrected to total using aperture corrections

- **15 additional sources taken from archive, giving a total of 68 4.5σ ALMA detections** (simulations show significant number of spurious sources at lower S/N); do not expect more than 1 contaminating source at this level

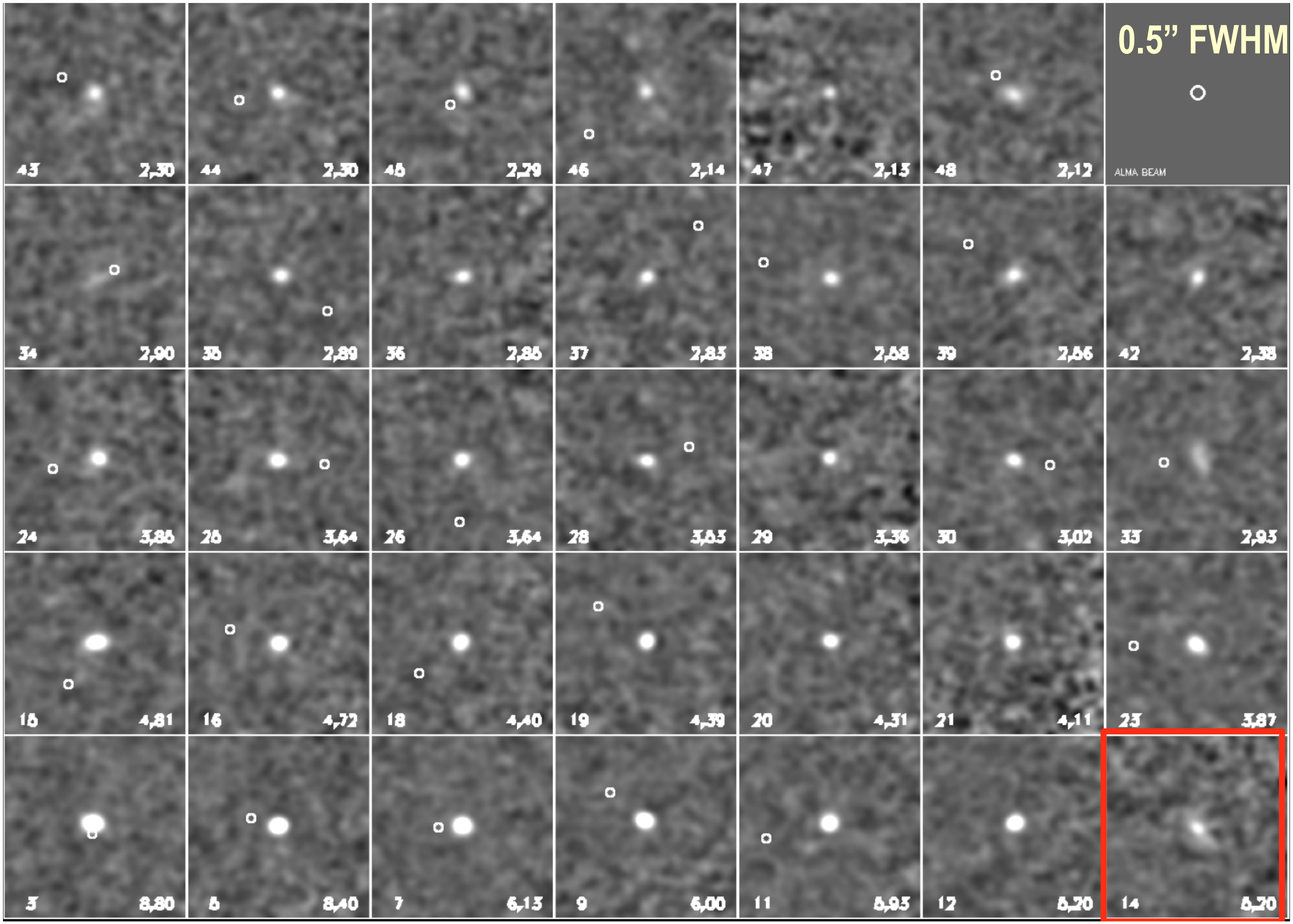
What Do the BASIC Sources Look Like?

(ordered by decreasing ALMA flux from bottom left; 8” x 8”)

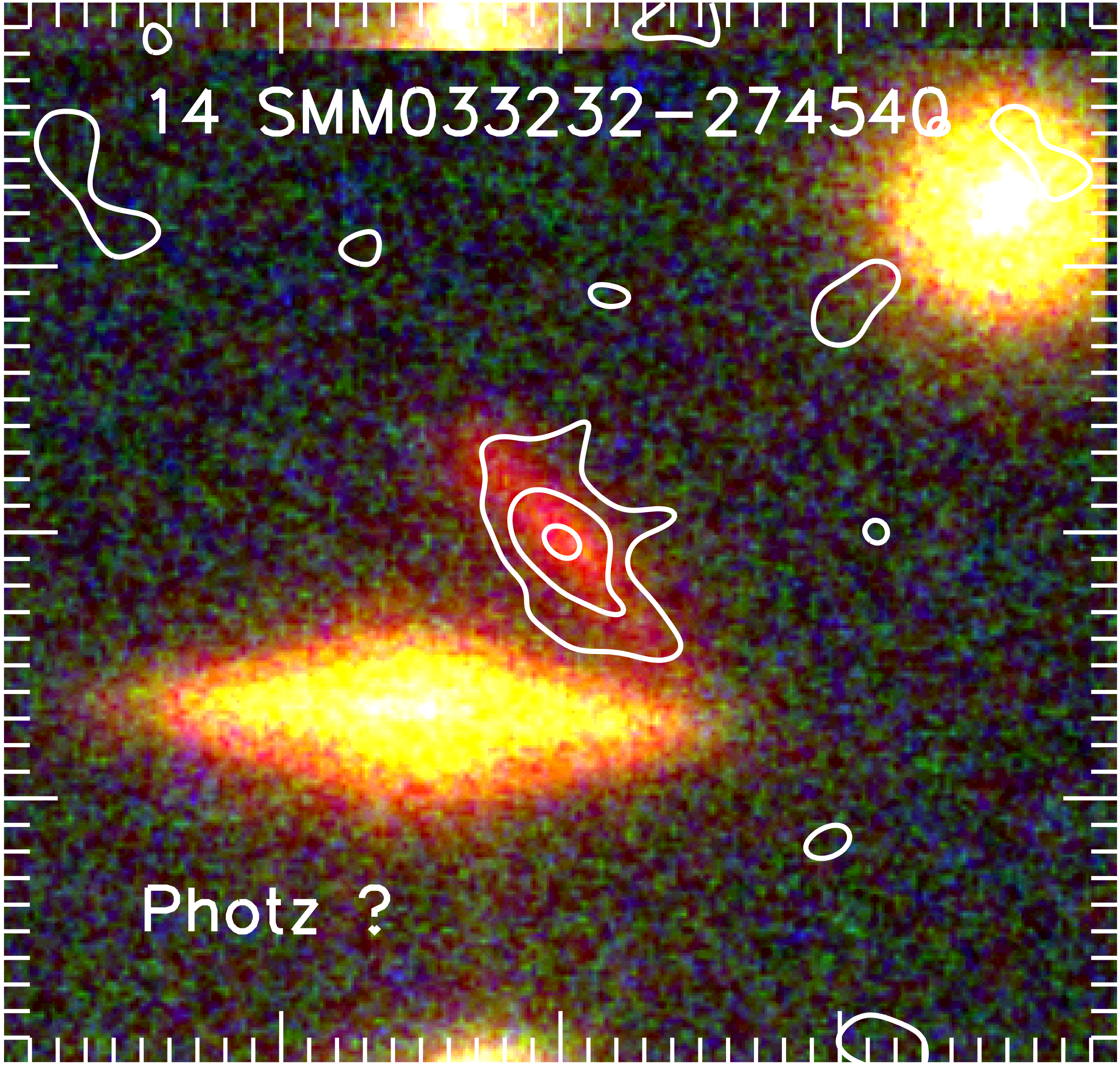


What Do the BASIC Sources Look Like?

(ordered by decreasing ALMA flux from bottom left; 8” x 8”)



HST
B,Z,H
4"x4"



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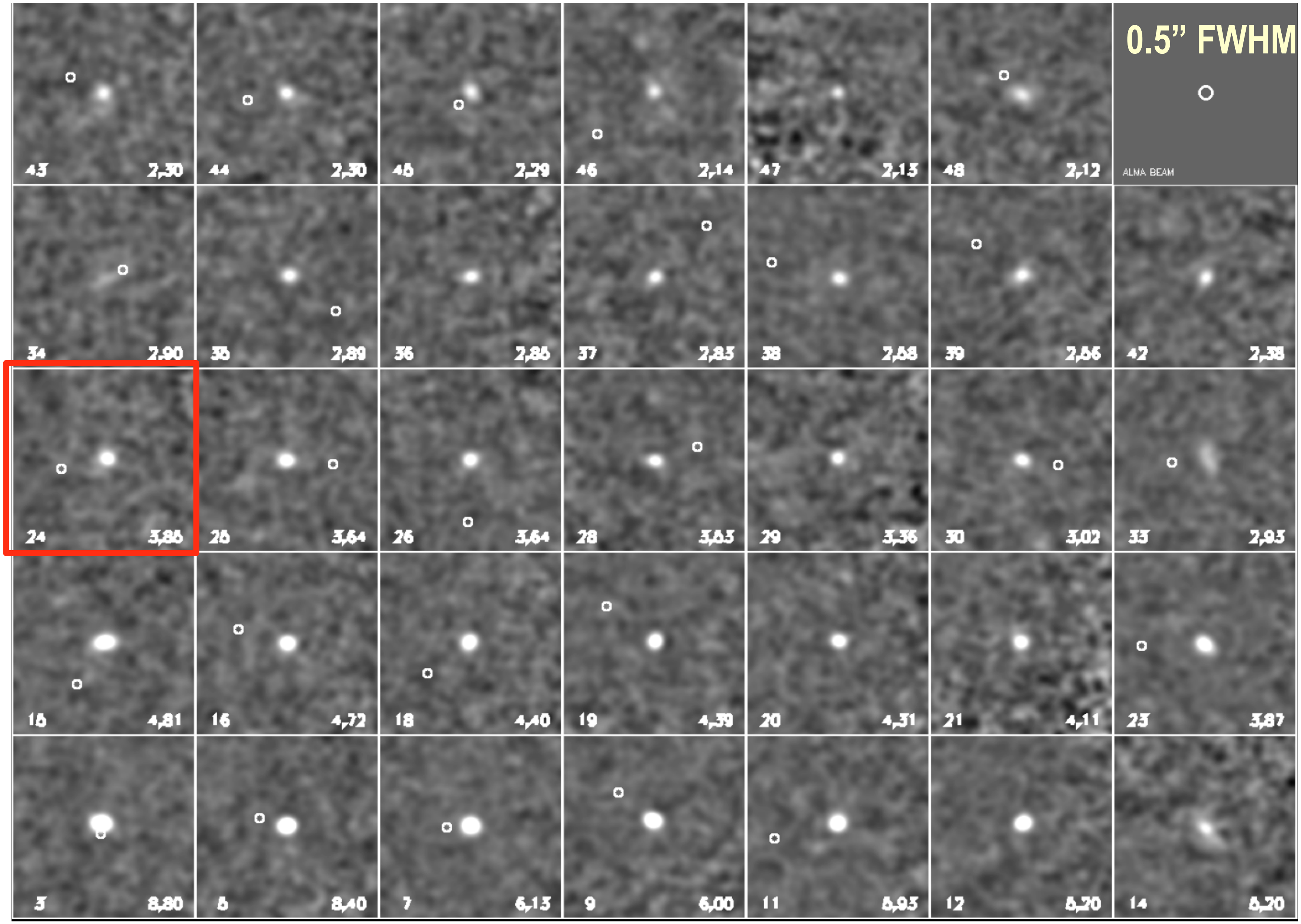
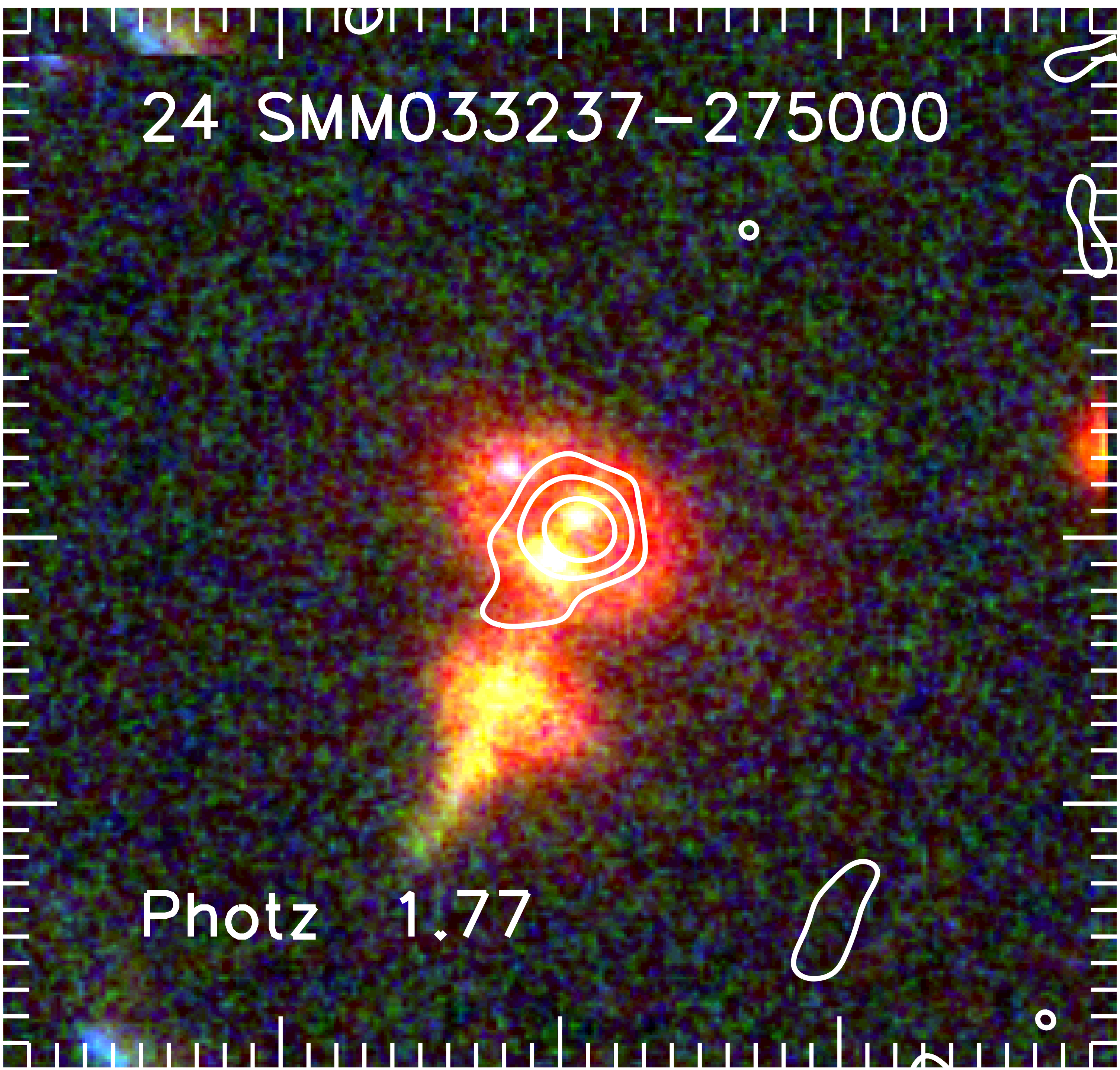
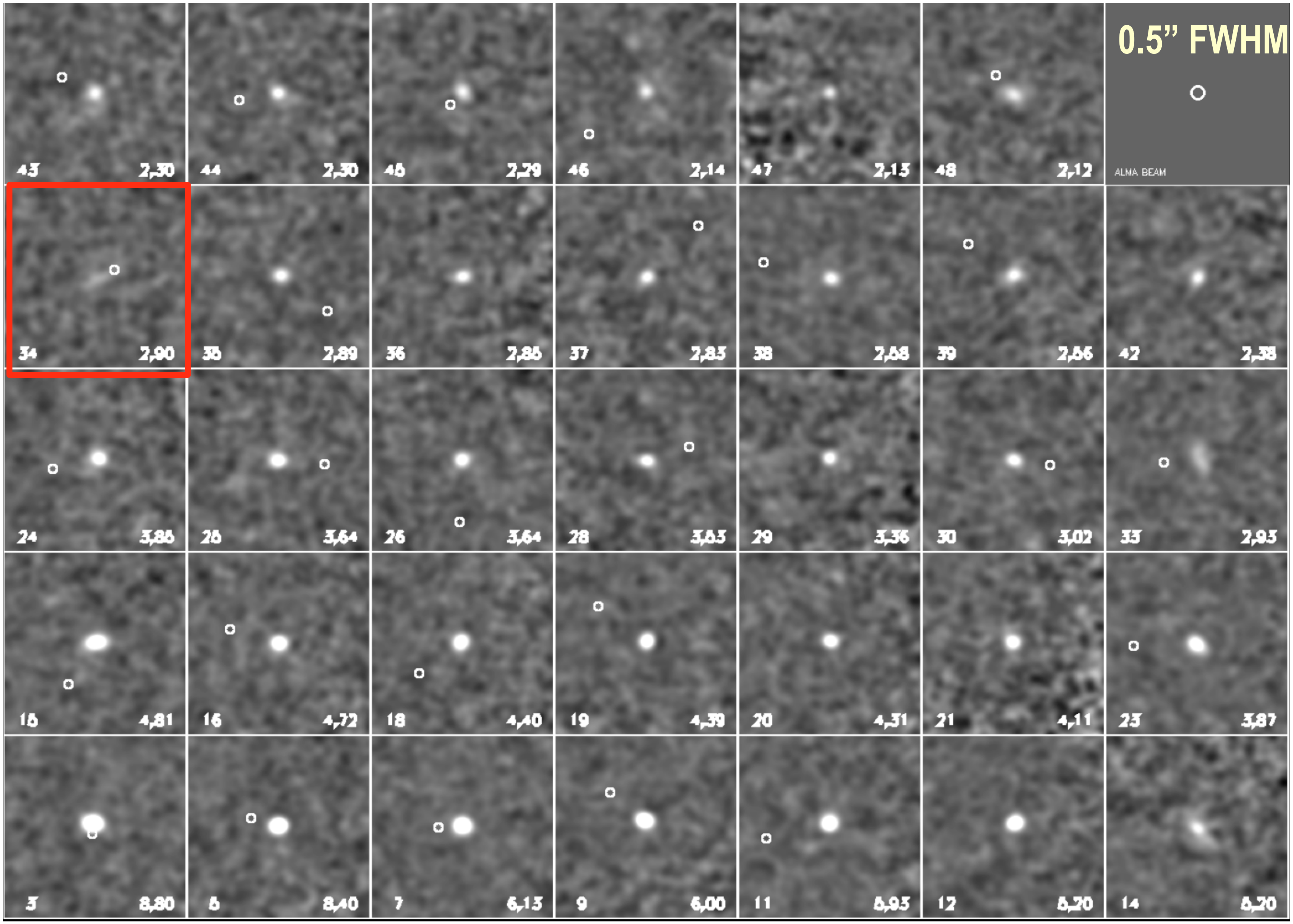
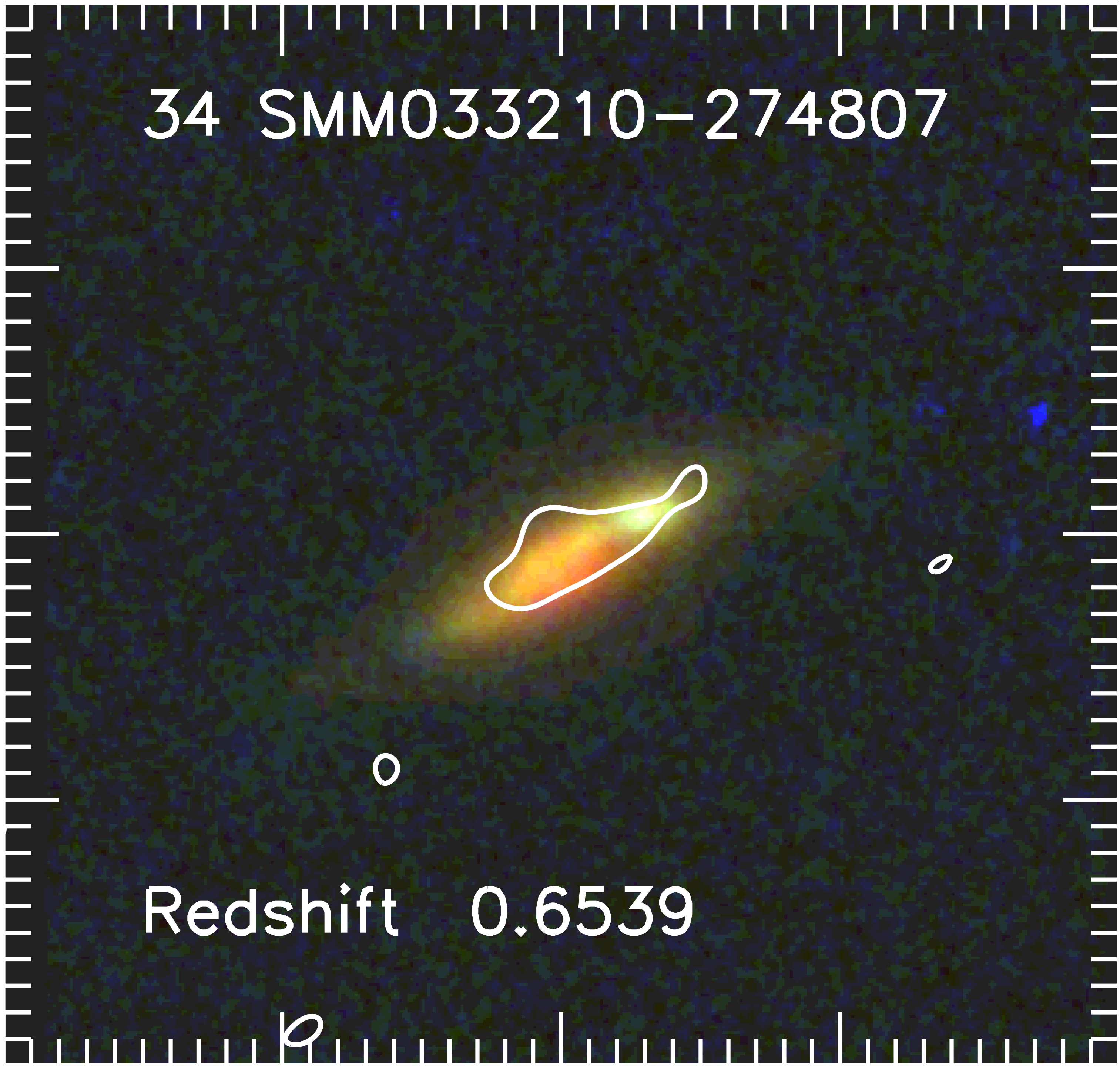



24 SMM033237-275000
Photz 1.77

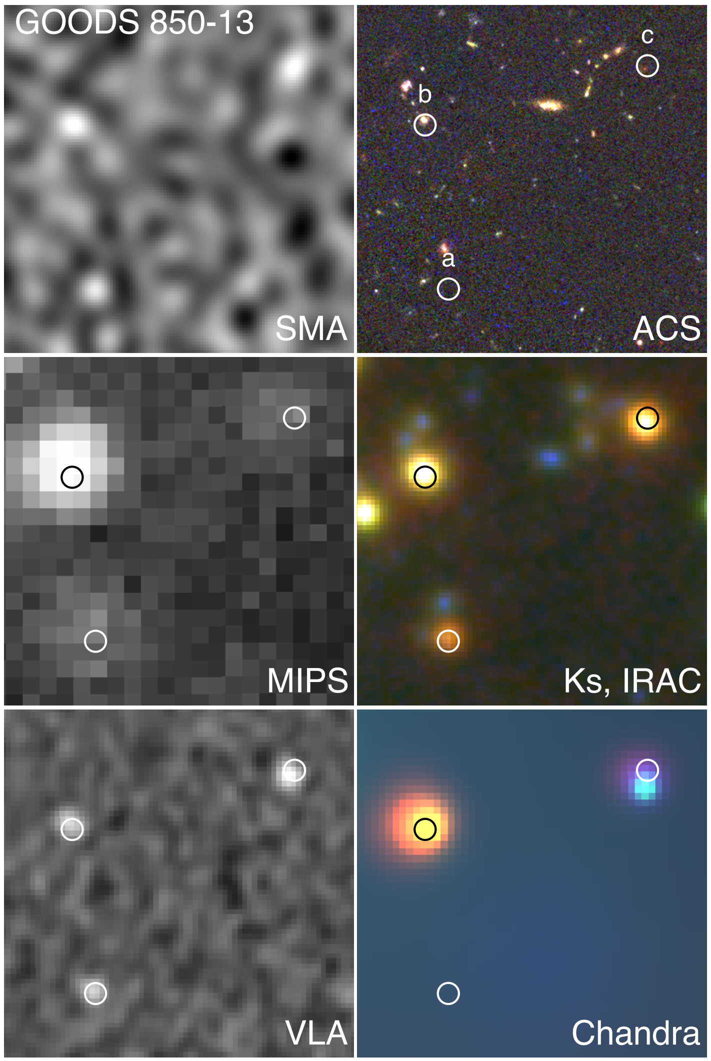
What Do the BASIC Sources Look Like?

(ordered by decreasing ALMA flux from bottom left; 8” x 8”)



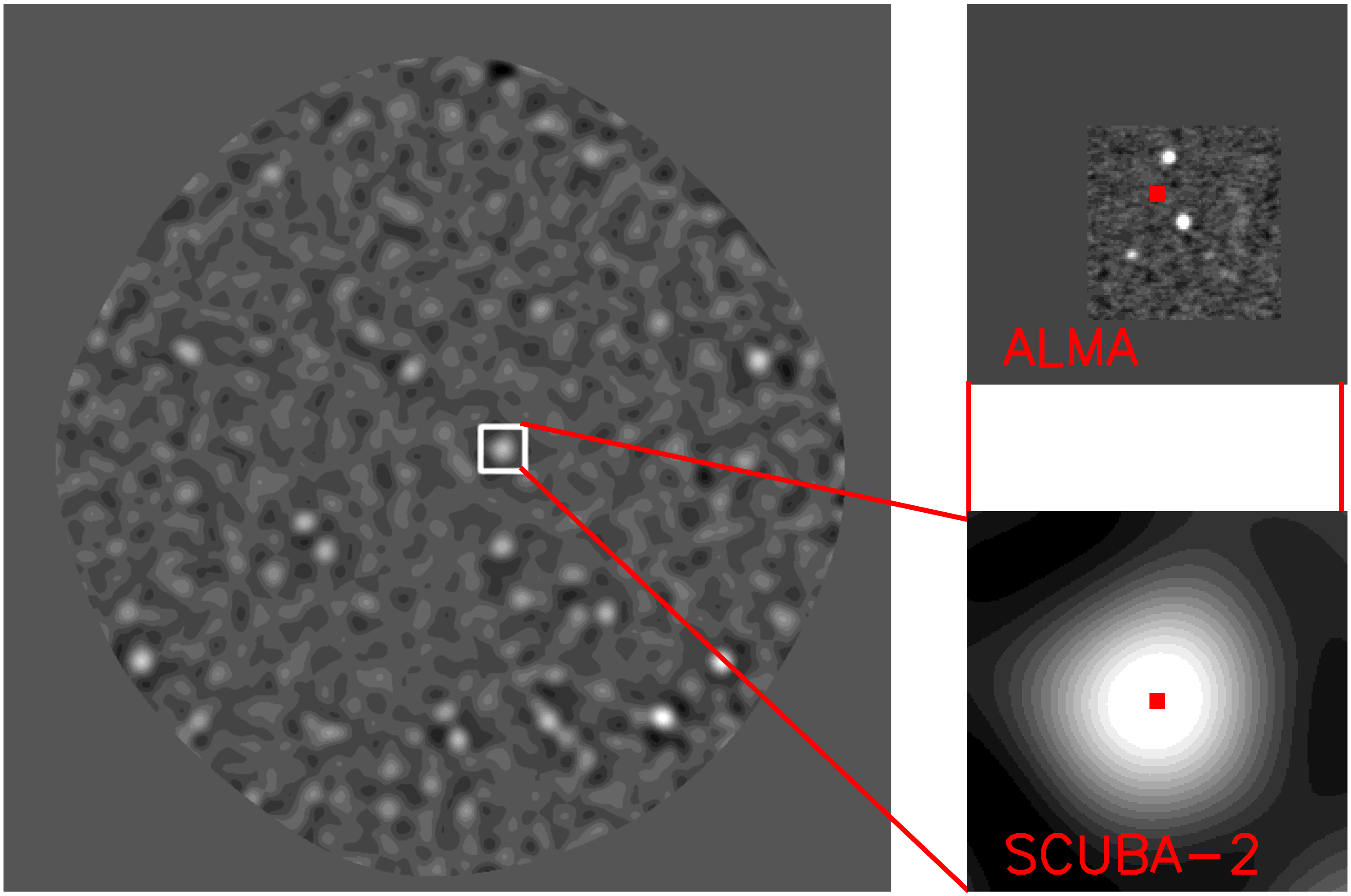

34 SMM033210-274807
Redshift 0.6539

Interferometry of Single-Dish Sources Has Revealed Some Multiplicity



Wang+11, using the SMA, was the first to discover that some bright SCUBA sources resolved into multiple, physically unrelated sources (see also Barger+12, Smolcic+12, Karim+13, Hodge+2013, etc)

Multiples found with ALMA may cause some of the SCUBA-2 sources to drop out of our flux-limited sample, *but we will still get all the ALMA sources above the SCUBA-2 flux limit (our goal)*

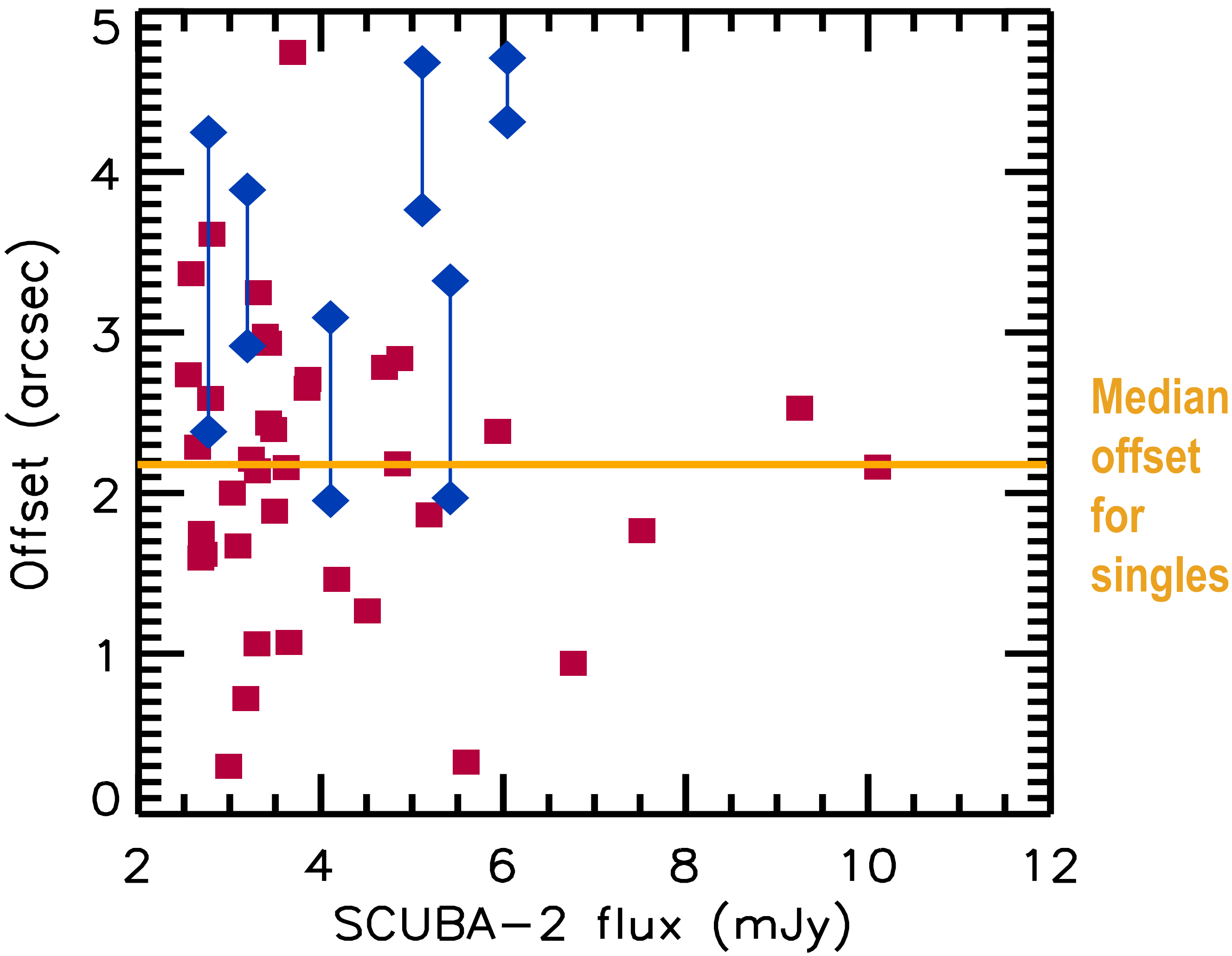


Triple from a CDF-S ALMA observation by J. Mullaney

However, in our observations, multiples turn out not to be very common

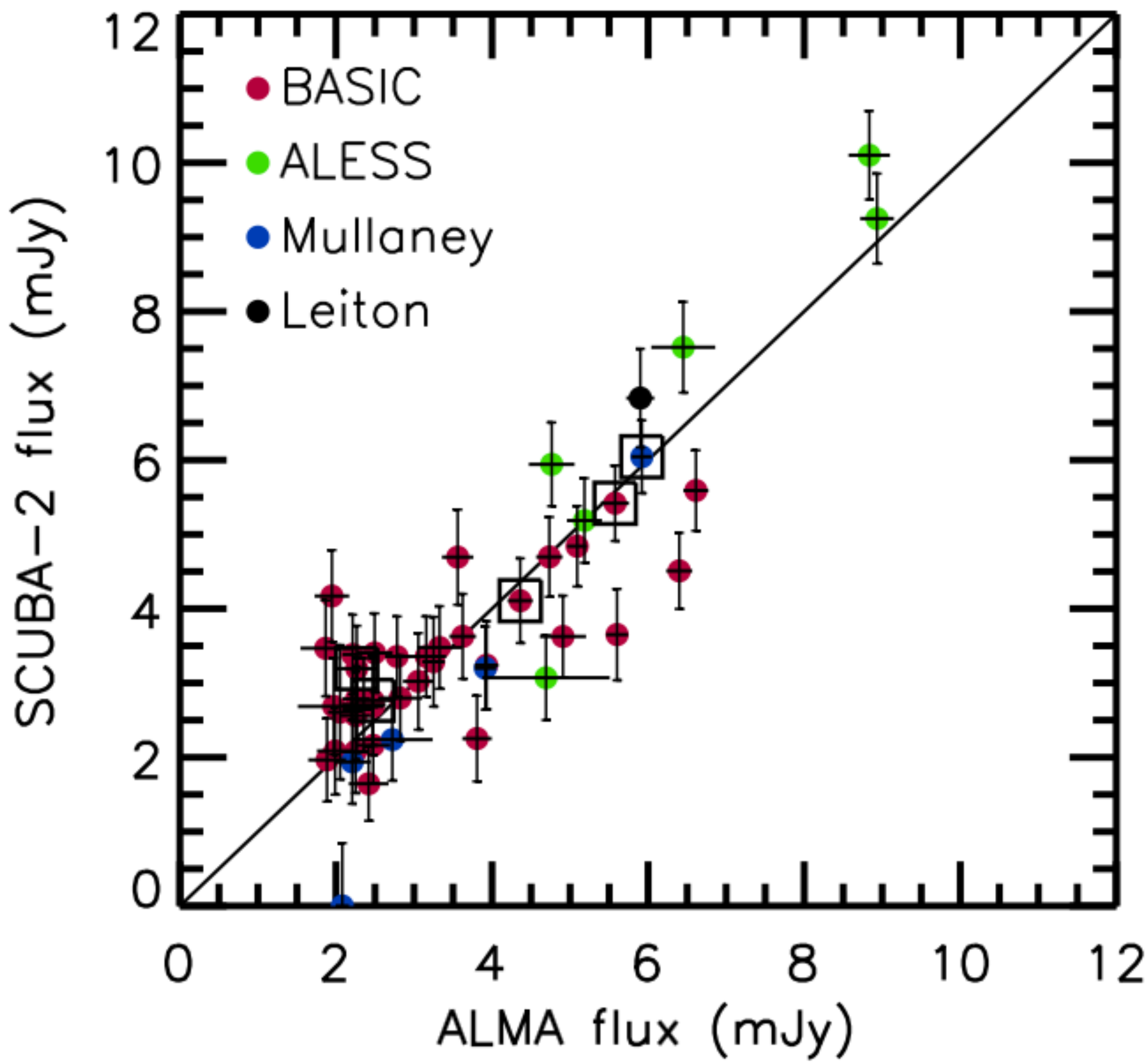
[diamonds=multiples]

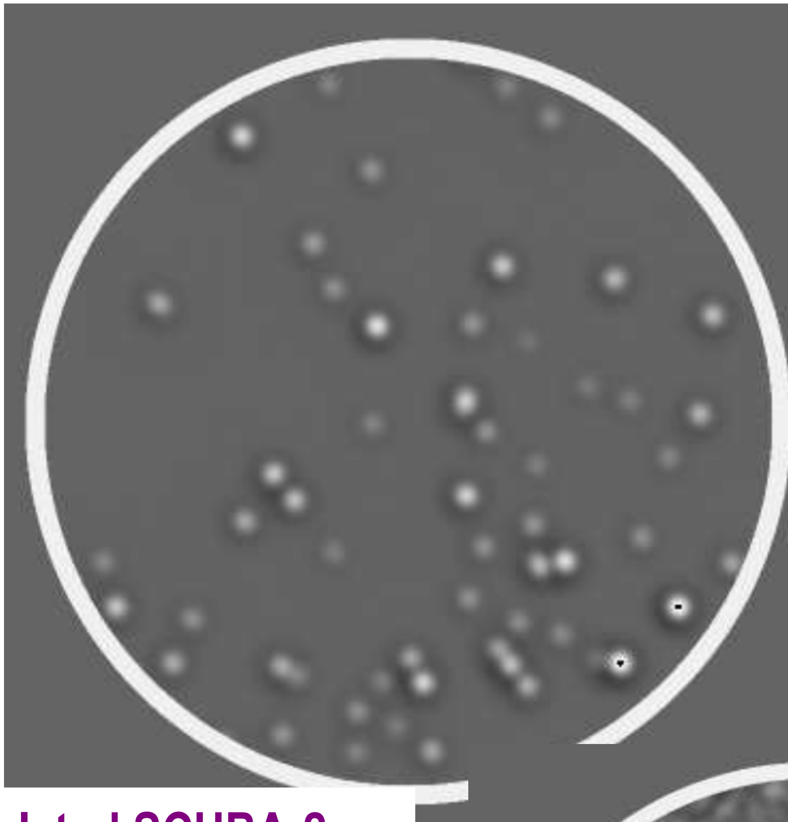
(Note: we could have detected any ALMA source contributing more than 40% of the flux at the flux limit shown here)



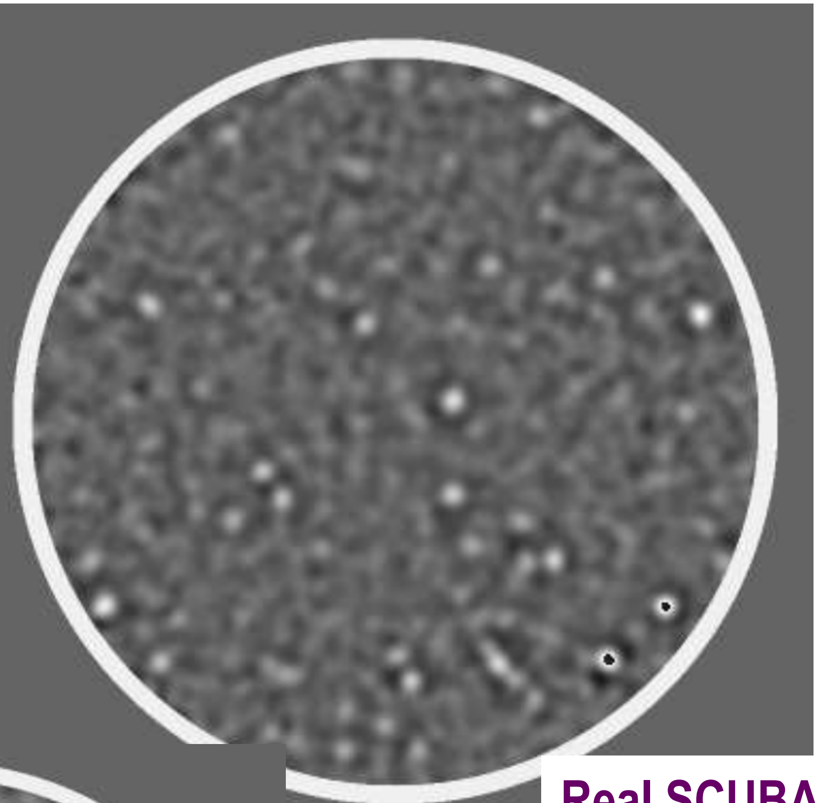
Consistency check: ALMA fluxes agree well with SCUBA-2 fluxes

[Multiples are shown as combined ALMA fluxes with square boxes]

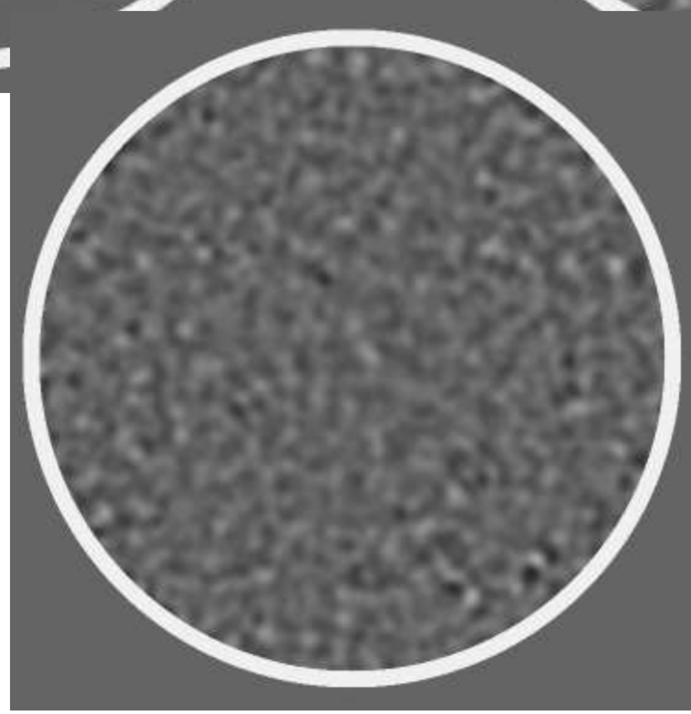




Simulated SCUBA-2 image from ALMA observations that allows for blending: Each ALMA source is convolved with the SCUBA-2 matched filter PSF and added to form a final image

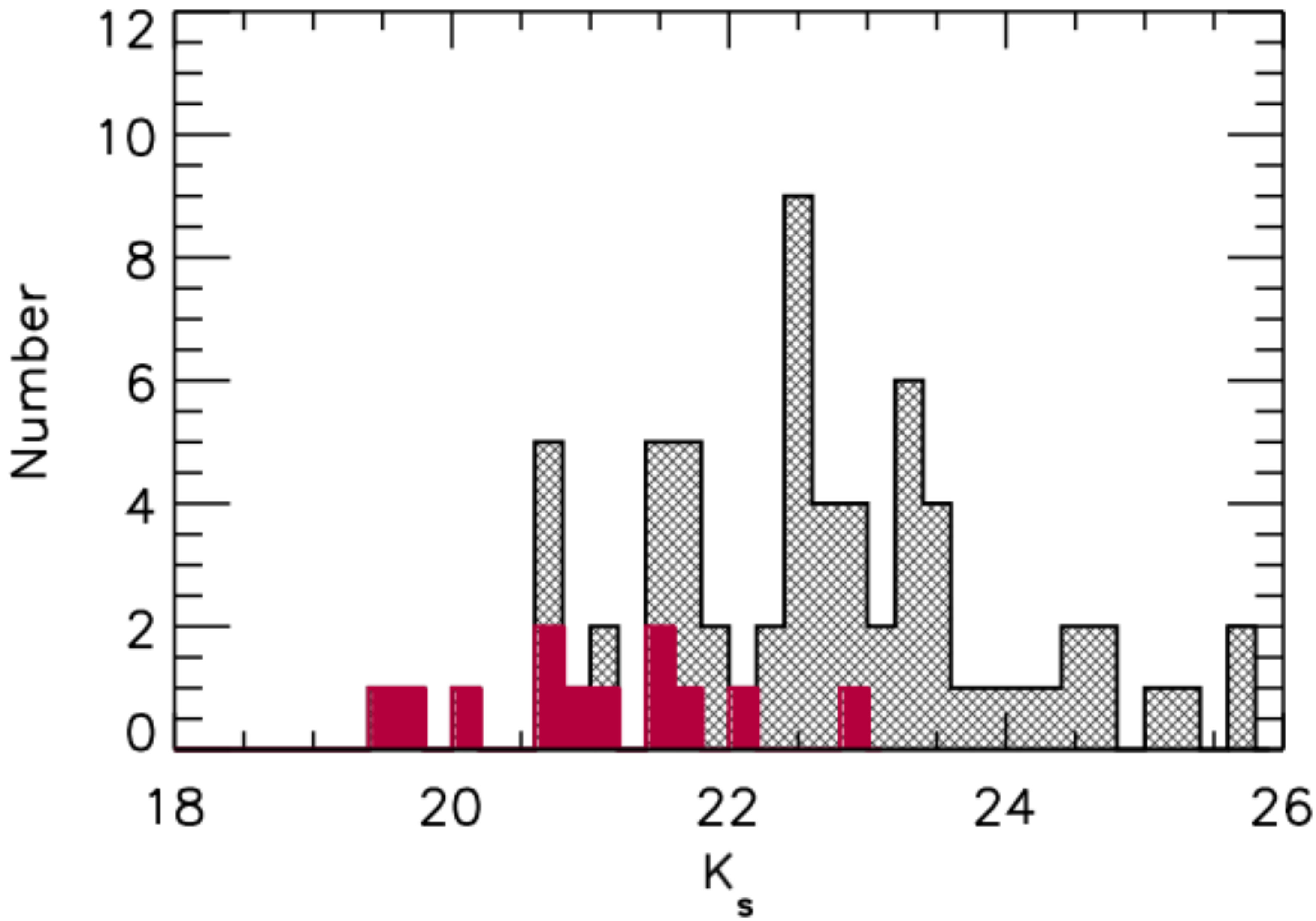


Real SCUBA-2 image



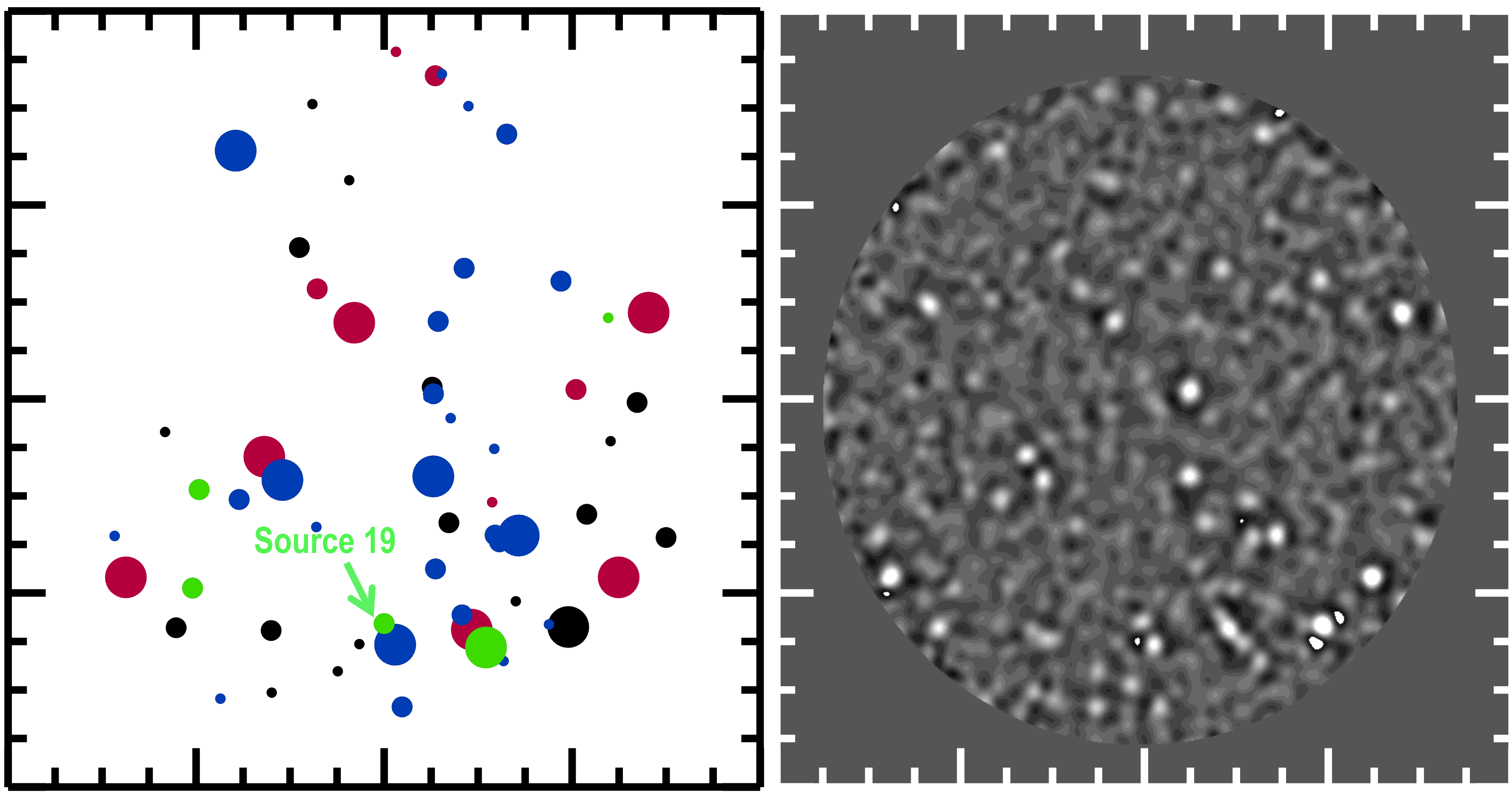
Difference image

Unsurprisingly, limited spectroscopic redshifts



Red=spectroscopic redshift
Blue-photometric redshift
Green=NIR blank
Black=other

Largest circles are >4 mJy
Medium circles are >2 mJy
Smallest circles are >1 mJy

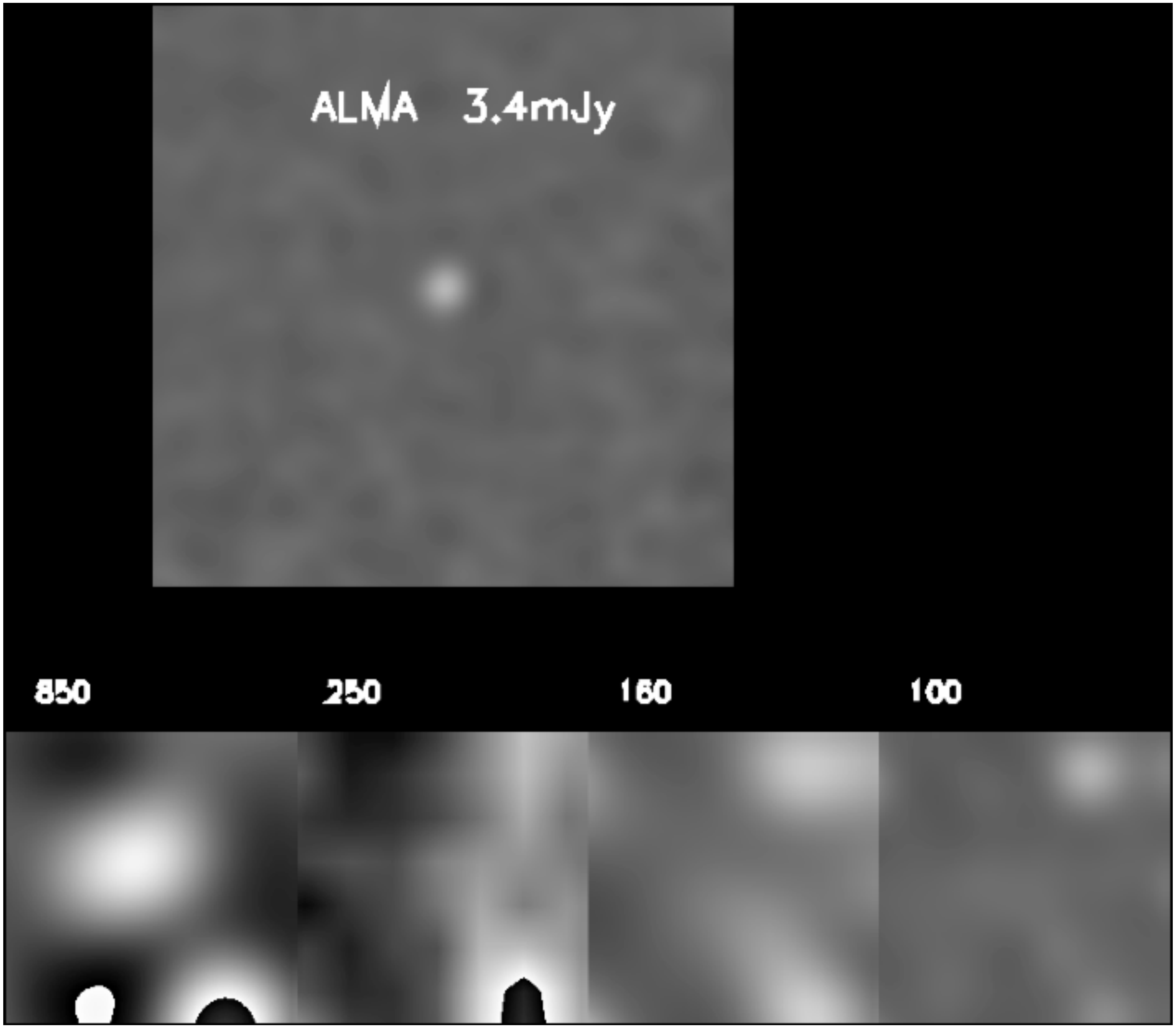


Cowie+2018

Source 19 is not even present at 250 micron, so it must be at a very high redshift

8" x 8"

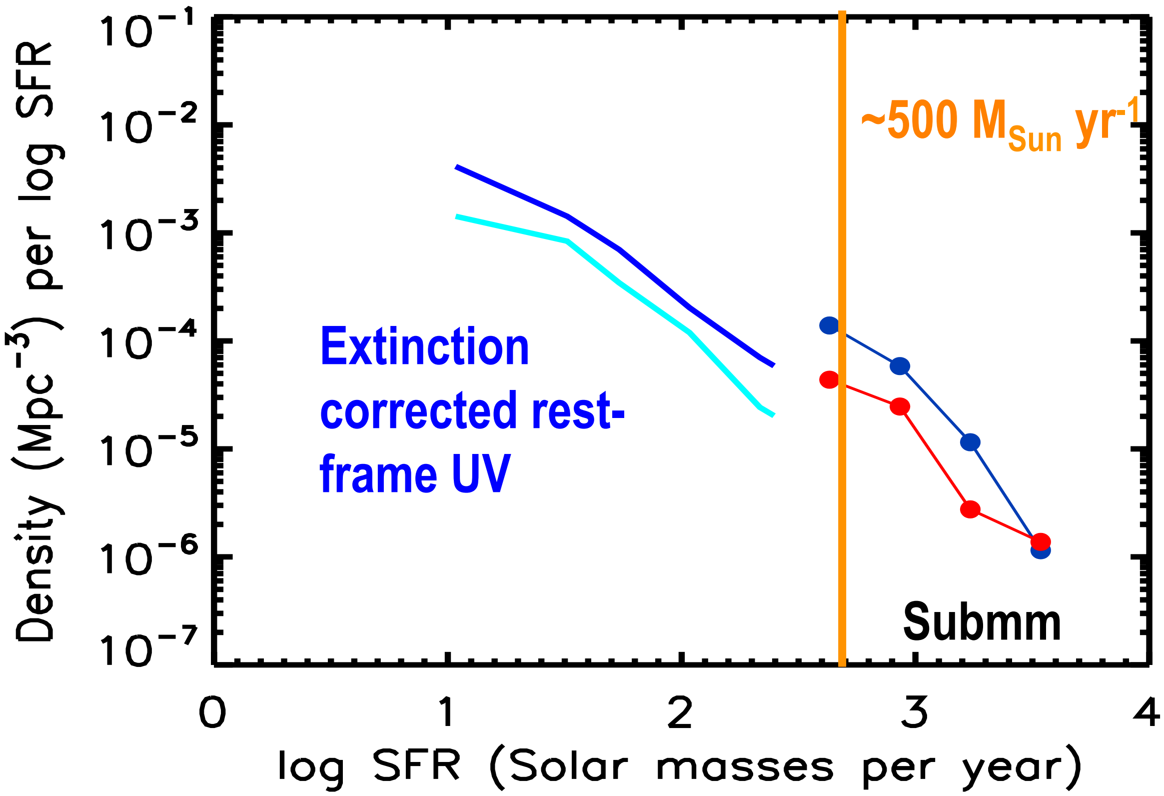
20" x 20"



Big Question

How overlapped are the UV selected samples with the submm selected ones at fainter fluxes?

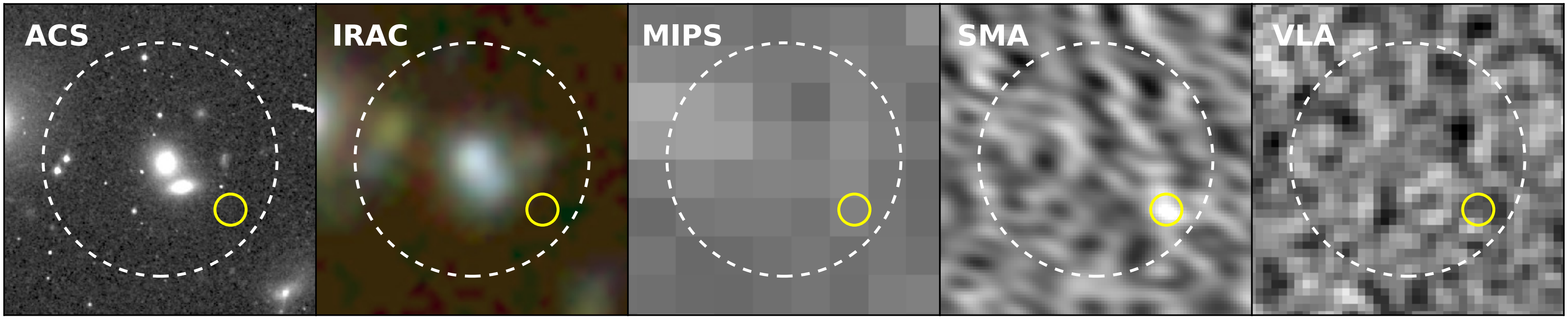
We are starting to get info from ALMA surveys of blank fields, but another approach is to exploit gravitational lensing



Lensing helps through the expansion of the source plane (reduces confusion) and through the magnification of the background sources

- TC Chen+14 used SCUBA observations of lensing cluster fields to probe the faint submm population
- All 5 SMGs that he detected with the SMA have intrinsic fluxes ~0.1-0.8 mJy (SFR~20-160 $M_{\odot}$/yr), the region of critical interest
- Expectation: at fainter submm fluxes, the sources would be less dusty, because the SEDs become more UV dominated for lower FIR luminosities (e.g., Chary & Elbaz 2001 curves)
- Hence, there should be more overlap with the UV

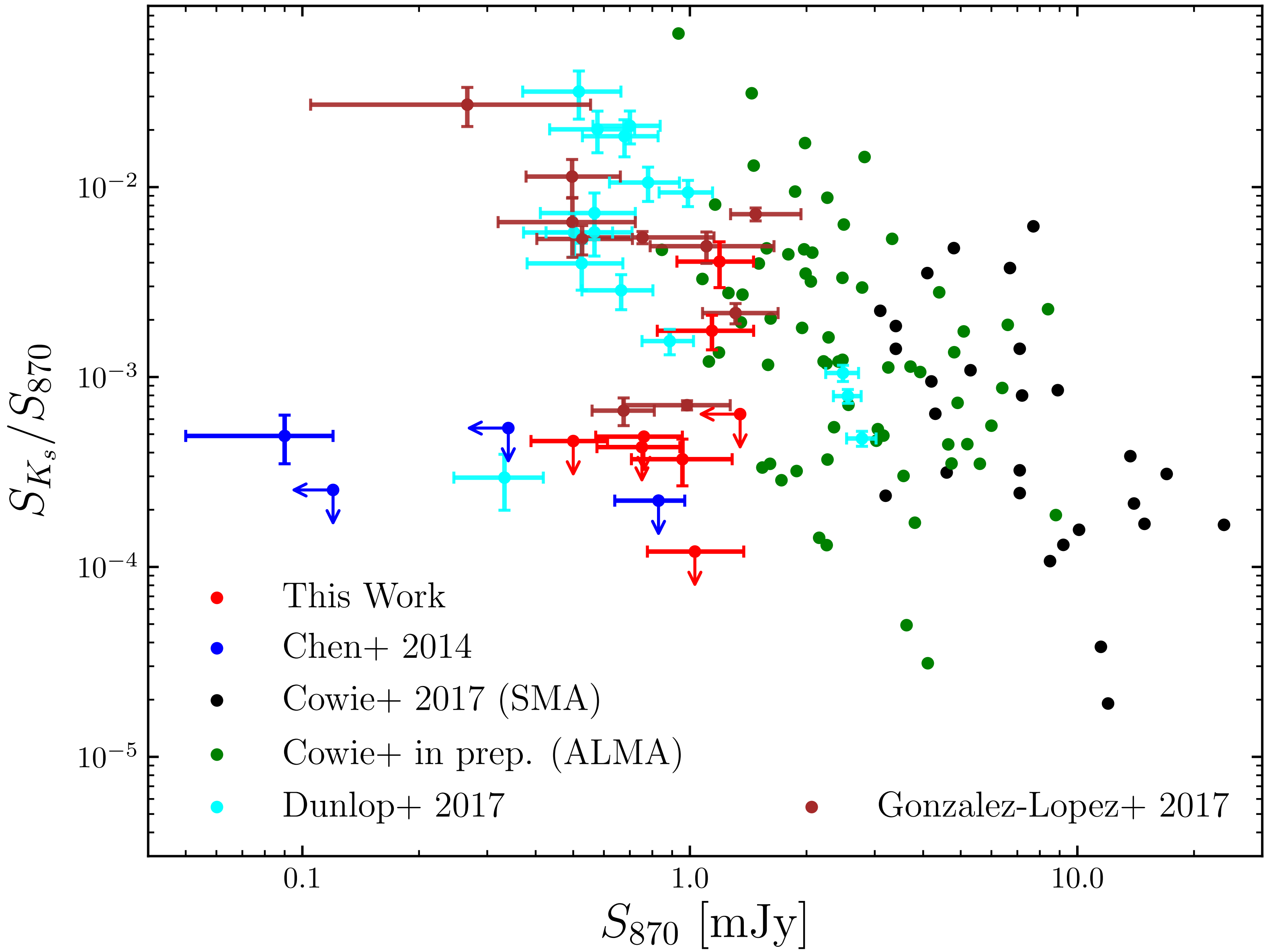
However, TC found 3/5 did not have optical/NIR counterparts!



Images: 20” x 20”
White circle: 7.5” radius SCUBA beam
Yellow circle: 1” radius SMA beam

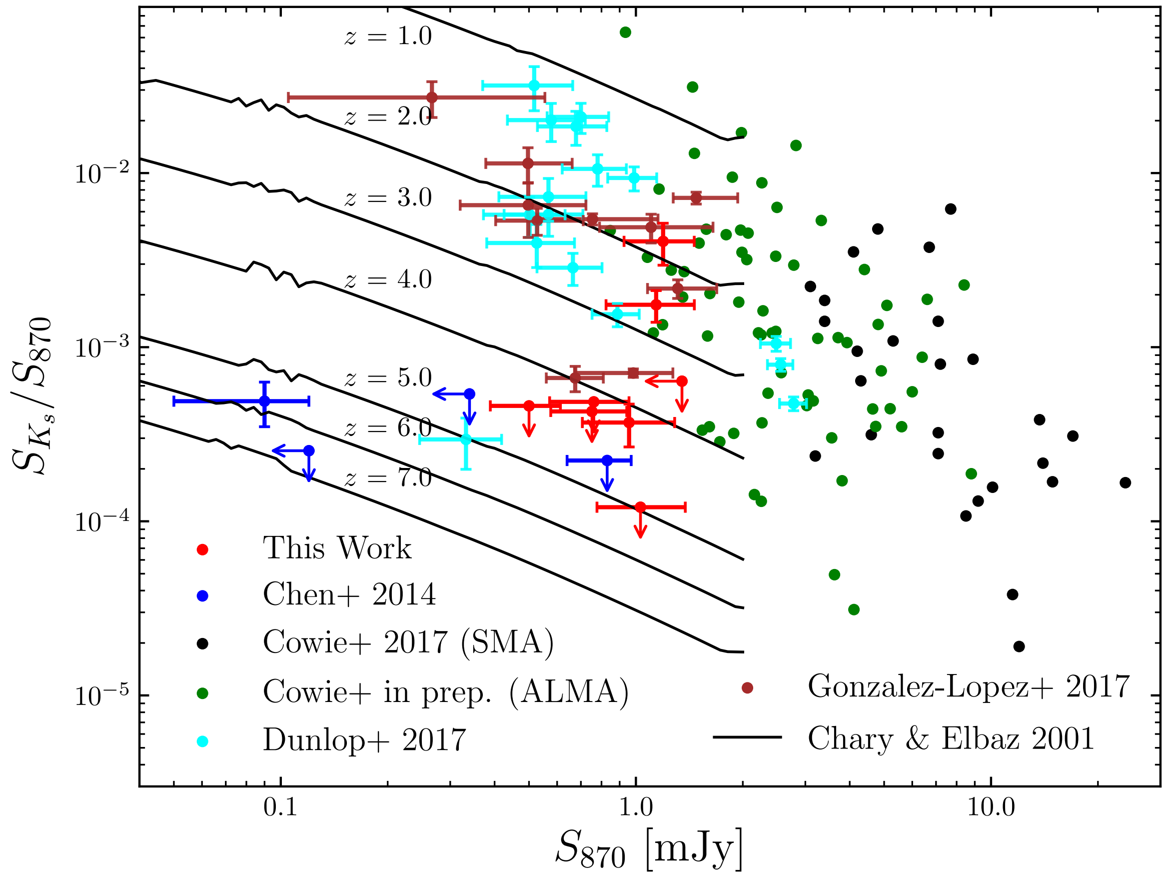
Li-Yen Hsu has continued this lensing work with SCUBA-2 and the SMA, and Gonzalez-Lopez+17 with ALMA direct imaging surveys

Evidence for bimodality at low submm fluxes?



Hsu+2017

Evidence for bimodality at low submm fluxes?



Dunlop+17 sample would be mostly consistent with being lower redshift, lower luminosity objects

However, for the sources with much lower flux ratios of K/870: if they lie at low redshifts, then they are very dusty galaxies and would not fit with the luminosity-dependent SEDs assumed in Chary & Elbaz 2001 curves. Other possibility is that they are at very high z.

Summary

- The bright submm flux end of the obscured star-forming population of galaxies is a substantial contributor to the universal star formation history, and its contribution does not change much over z=1.5-5.5

- There may be indications of bimodality in the lower submm flux end, with some being either at very high redshifts or dustier than expected for their FIR luminosity

- More work is needed to resolve the Big Question of how overlapped UV selected samples are with submm selected samples at fainter fluxes, but there may be many lower luminosity dust-obscured galaxies that are also not included in the optical star formation history