Massively Star-Forming Dusty Galaxies

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JCMT Users Meeting

The luminous dusty star-formation history: We are using SCUBA-2 to address three questions

- What fraction of the SF is in luminous dusty galaxies?
- Is there a maximum star formation rate (SFR) in high-redshift galaxies? (Amy Barger)
- Are the SF contributions measured from the rest-frame UV selected population distinct from the SF contributions from the submm/FIR selected galaxy population? (TC Chen, Li-Yen Hsu)

Very luminous galaxies emit much of their light at IR to mm wavelengths

With only UV/mid-IR, we do not know how many galaxies we are simply missing, or how good our bolometric luminosity corrections are for the galaxies we do find. Some will have catastrophic errors.

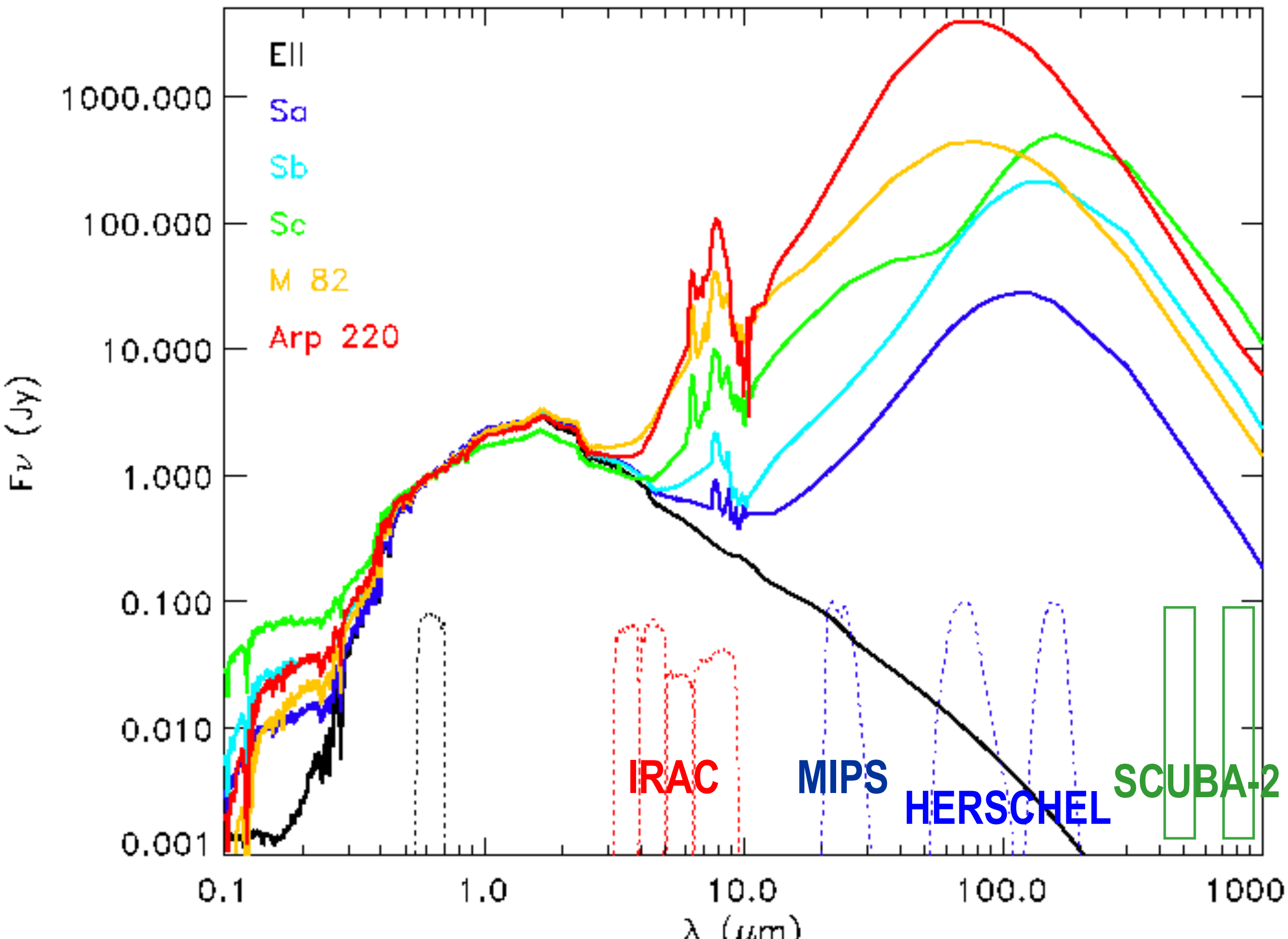
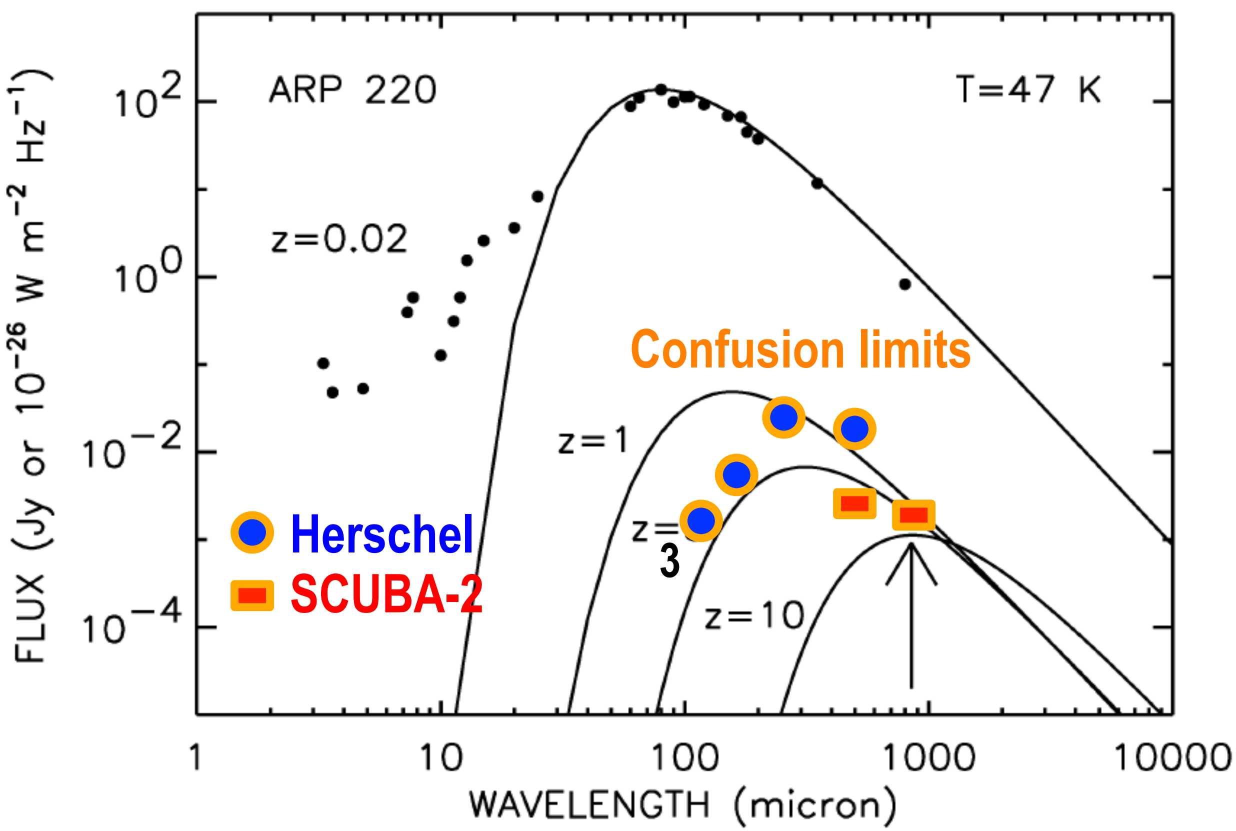


Figure from Polletta

Submillimeter selected galaxies are sensitive to very high redshift galaxies because of their steep negative K correction

At lower redshifts (z<2) Herschel observations are best for studying the dusty star formers

However, *Herschel* hits the confusion limit faster than ground based instruments at longer wavelengths (3.5 m telescope vs 15 m JCMT), so it is best to search for very high z dusty galaxies with ground based mm/ submm observations.



Confusion limits shown for 10 beams per source

How can we construct large, uniform samples of high-redshift luminous, dusty galaxies to study?

- ~10 cm imaging (VLA, etc)
  - Advantages: wide field, high resolution
  - Disadvantages: biased against high redshifts, contaminated by AGN, calibration of SF conversion

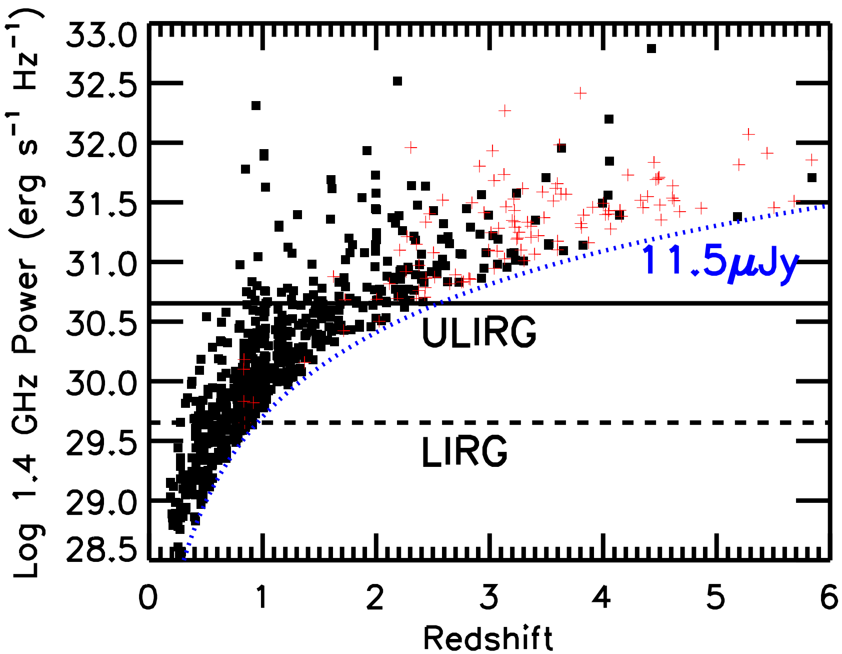
- Single dish submm/mm imaging (*Herschel* in space; JCMT, LMT, APEX, IRAM, SPT, etc on the ground)
  - Advantages: large fields, uniform FIR/submm selected samples, sensitive to very high redshifts particularly in the longer wavelength ground based observations.
  - Disadvantages: low resolution, confusion limit

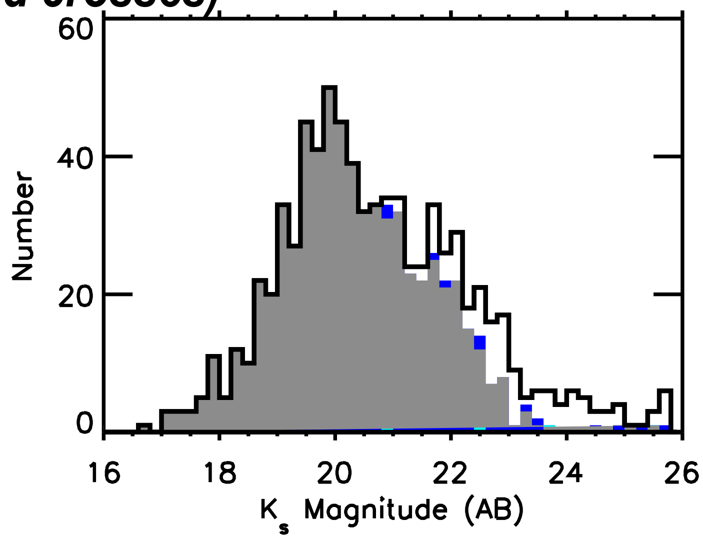
- Interferometric submm/mm imaging (ALMA, IRAM PdB, SMA)
  - Advantages: high spatial resolution and sensitivity
  - Disadvantages: very small field-of-view

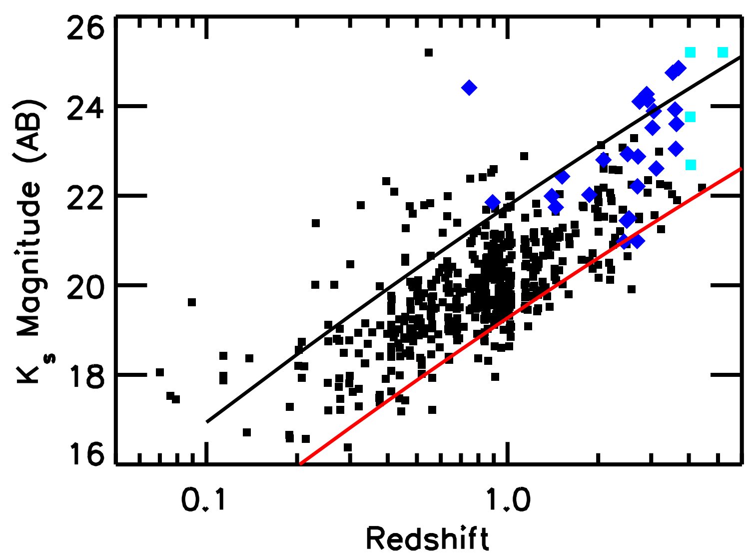
Current radio limits bias against high z

GOODS-N
Barger et al 2014
(Based on radio data from Owen 2015)

70% spectroscopic complete
85% with phot-z
Remainder K band faint
K-z relationships suggests missing objects are high z (red crosses)







Best to Exploit Strengths of Each Type of Observation

•Use single-dish far-infrared-submm imaging to construct large samples of far-infrared selected samples.

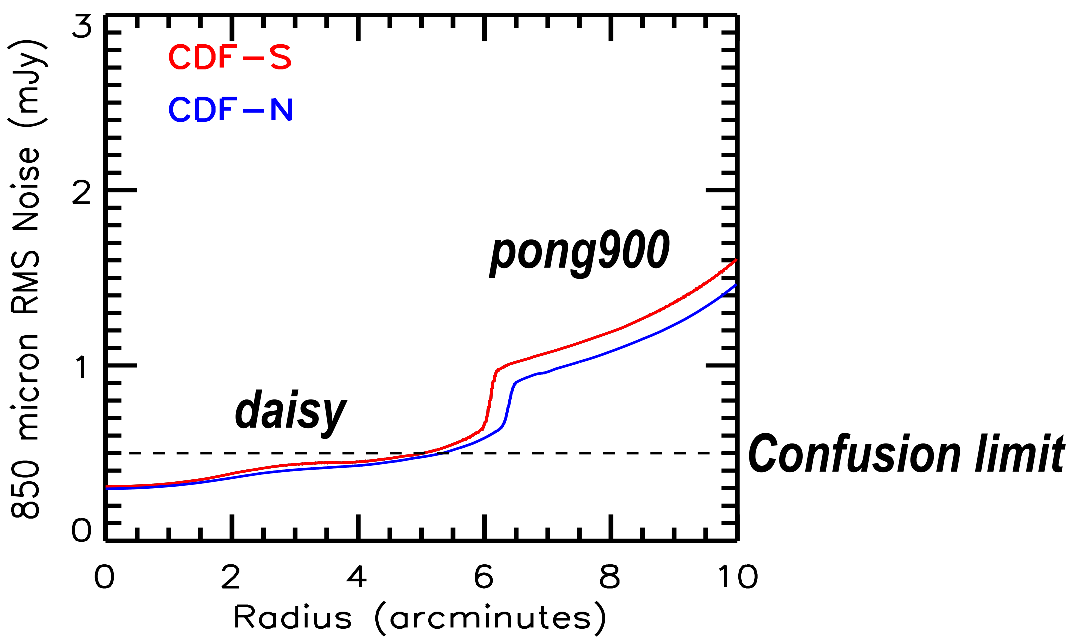
•Use the radio to obtain precise positions, sizes, and redshift estimates

•Use submm interferometry to identify interesting cases where there is no radio identification, or where there is more than one possible radio counterpart

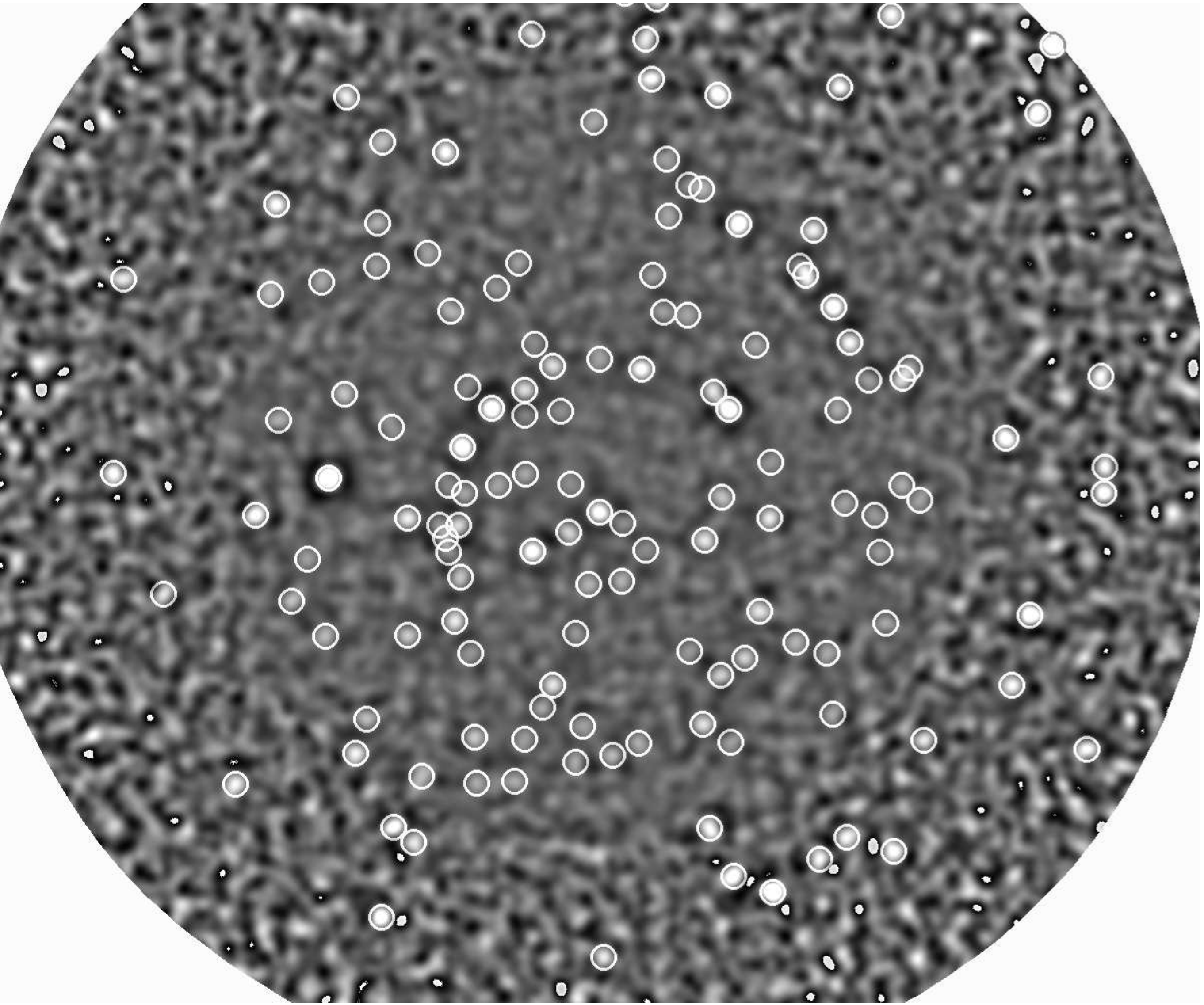
•In addition, use *Chandra/XMM* to identify X-ray AGNs

Large and deep submillimeter samples are made possible by SCUBA-2 but are still expensive

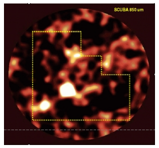
- >230 band 2 hours on the CDF-N/GOODS-N and CDF-S/GOODS-S fields
- >150 band 1 hours on 7 cluster lensing fields including 4 of the frontier field clusters



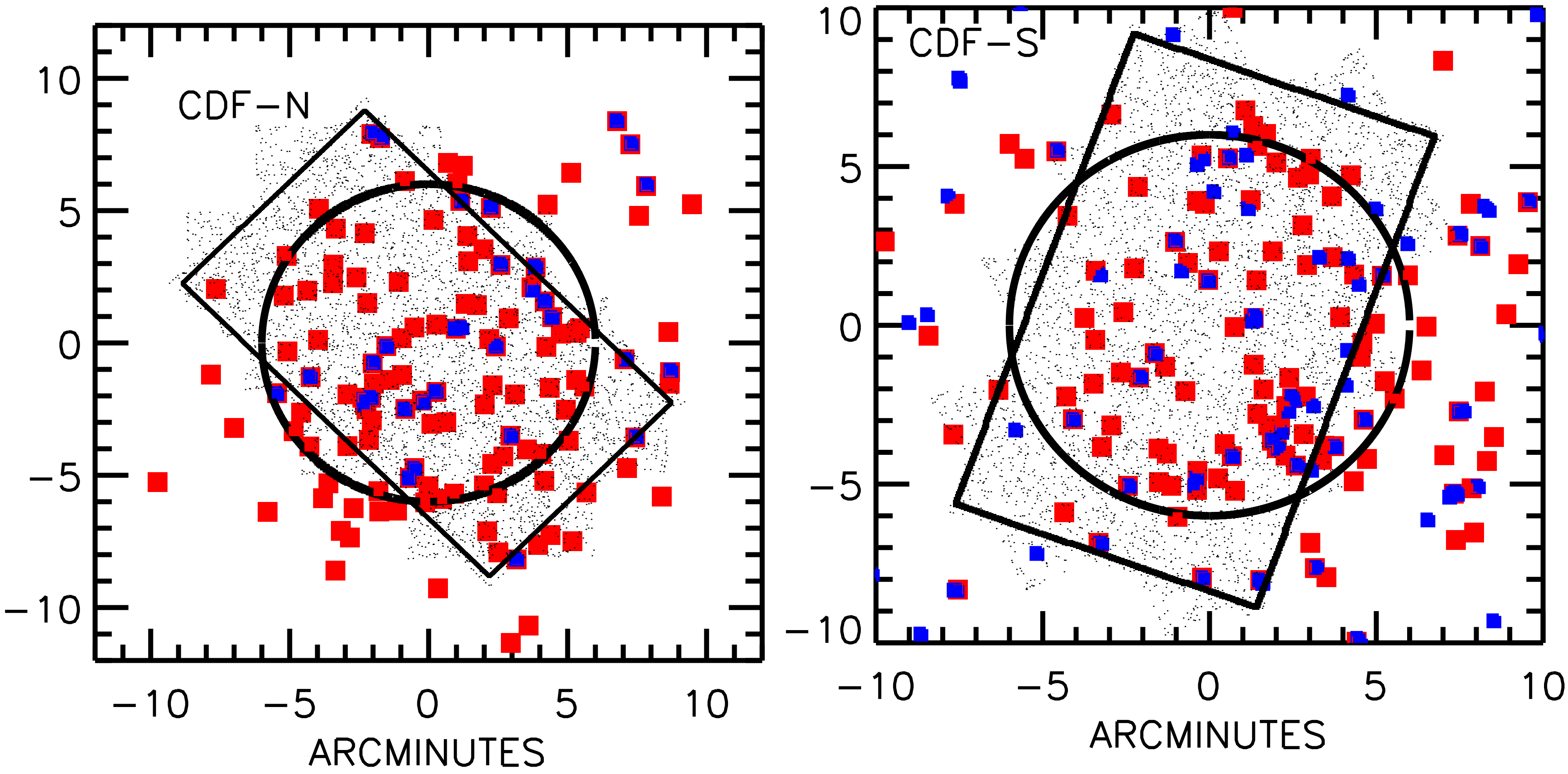
SCUBA-2 image deeper than SCUBA image of HDF-N over 120 arcmin^2. Homogeneous, cleanly selected, and well calibrated : 145 4 sigma sources



SCUBA
(Hughes et al. 1998)



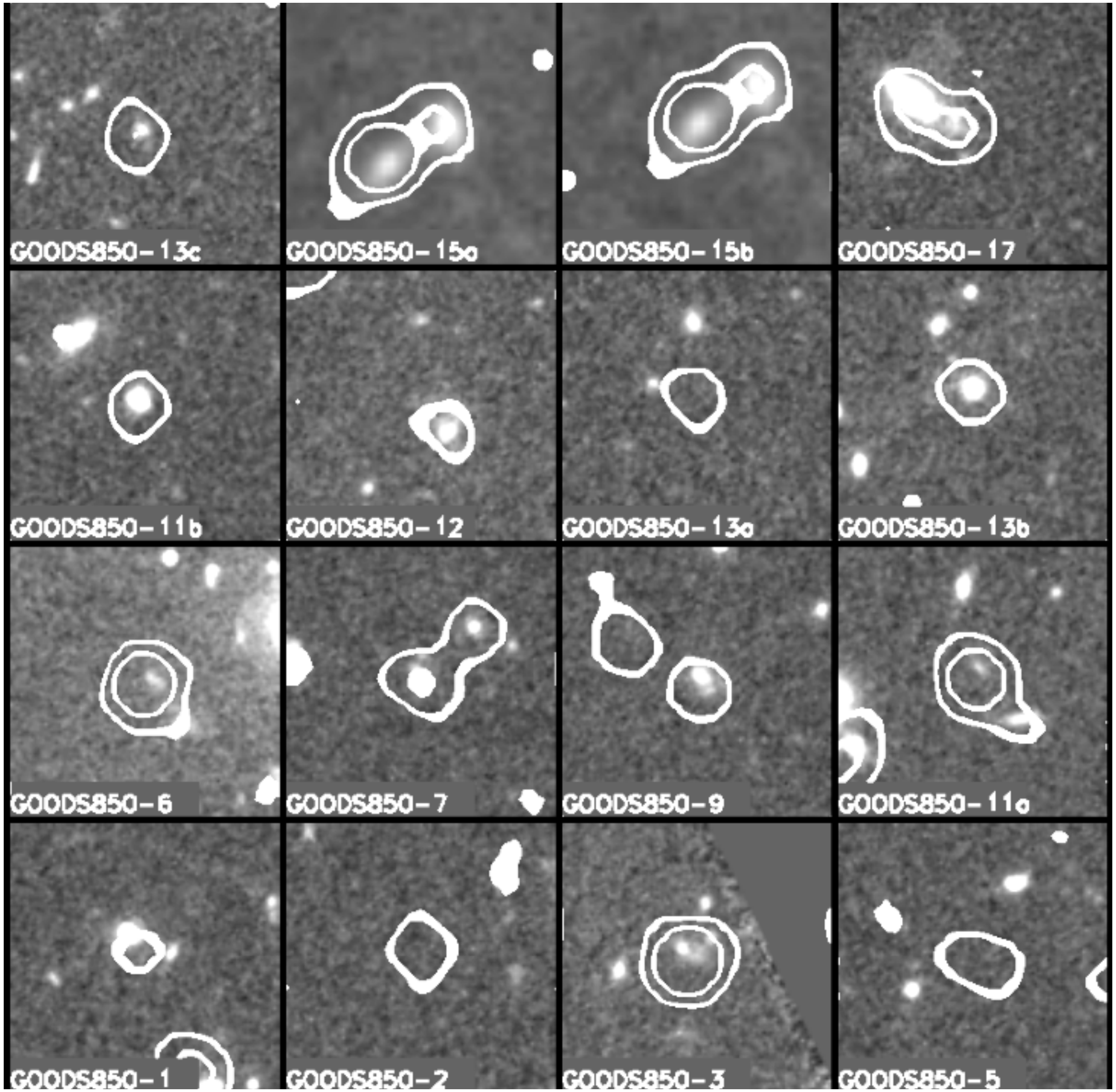
Submillimeter sources in the GOODS/Chandra fields



Red = SCUBA-2 290 sources **Blue = SMA (CDF-N) 32 or ALMA (CDF-S) 48)**

Nearly all the CDF-N SCUBA-2 sources have radio counterparts in a 2.4microJy rms 20cm image

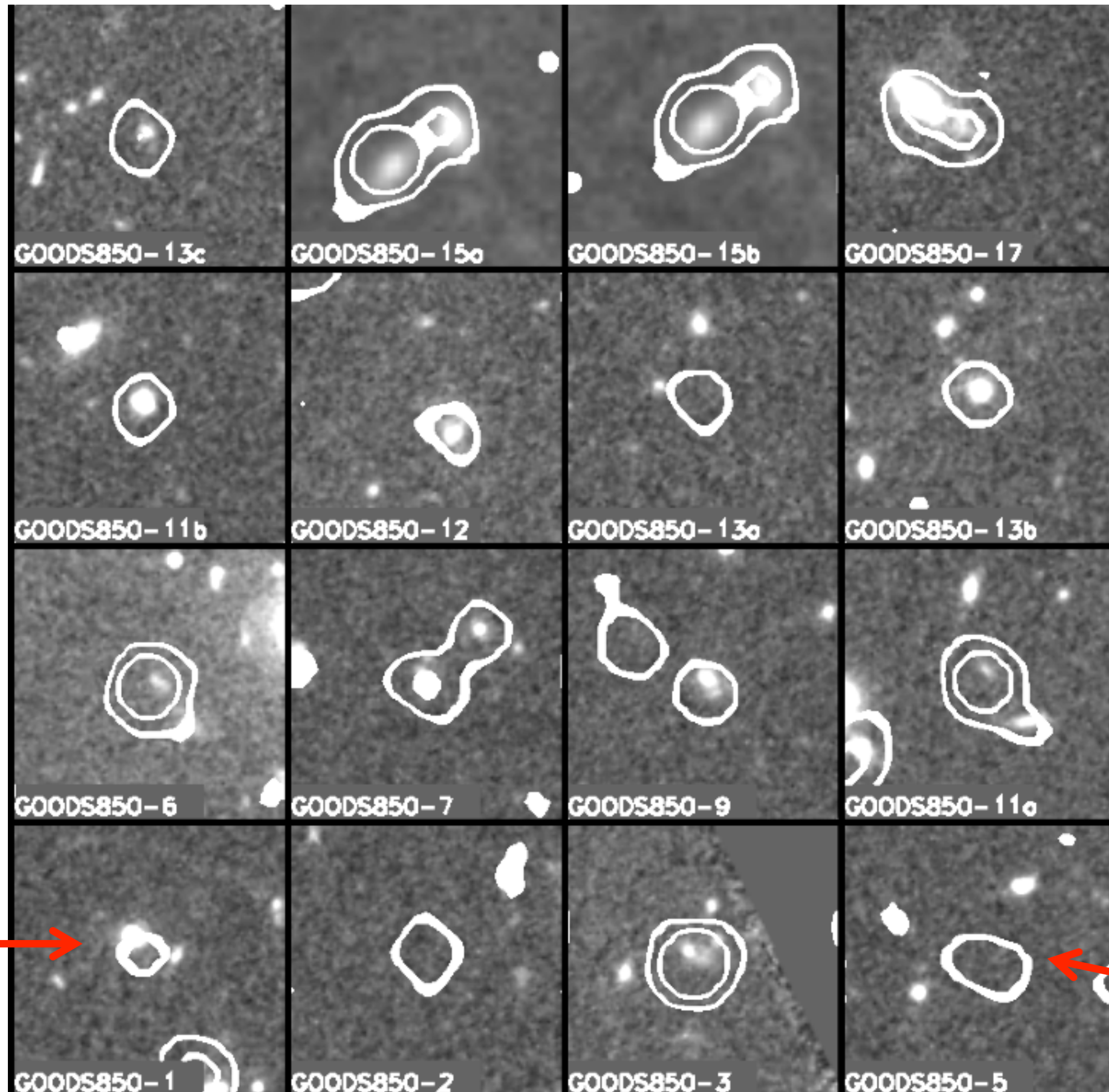
20 cm contours overlaid on HST F140W images centered on SMA positions.



Barger et al. 2012
Radio data Owen 2015

Though note that a number of the sources do not have NIR counterparts in the HST data

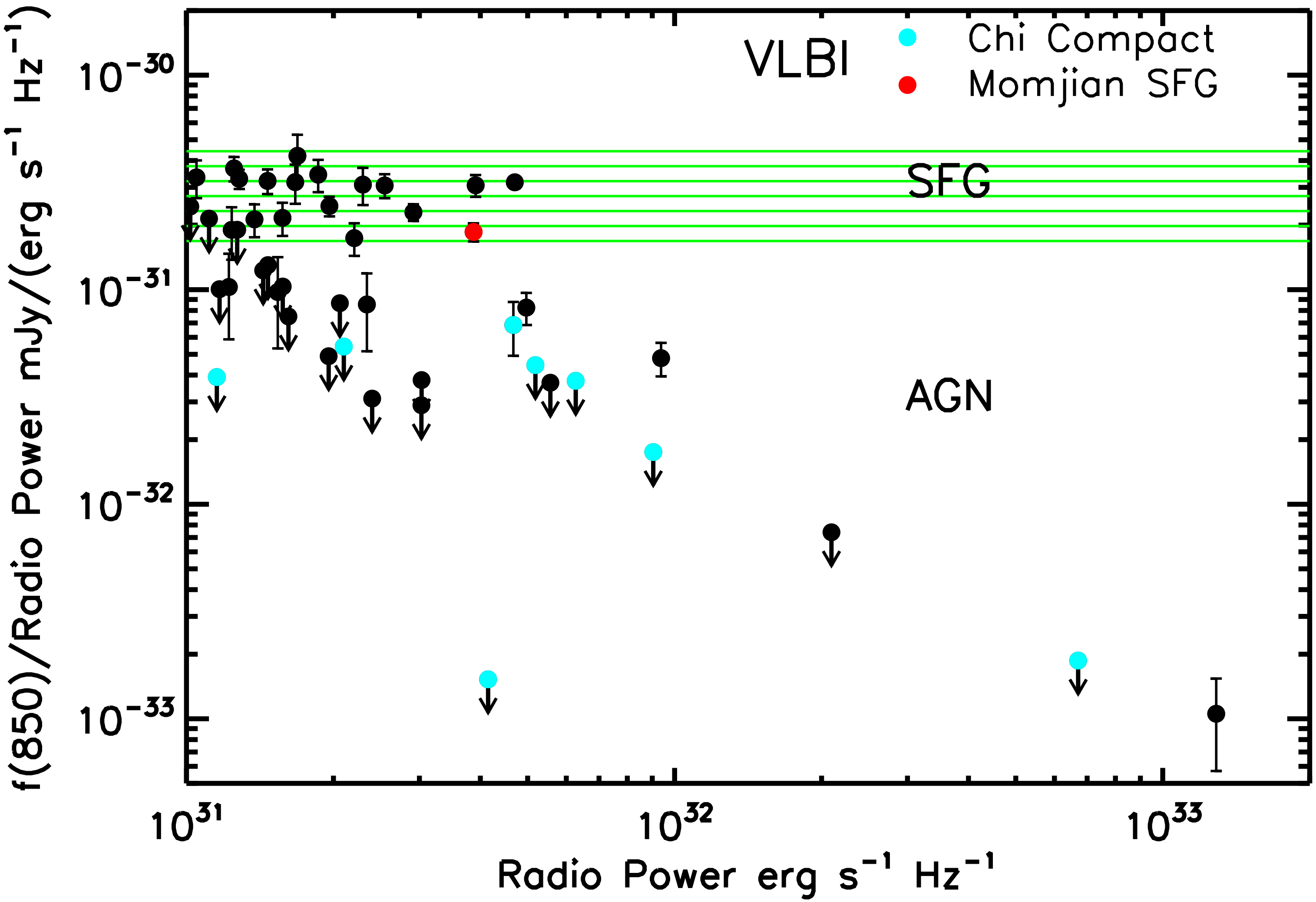
20 cm contours overlaid on the HST F140W images centered on the SMA positions of the SMA sample



HDF850.1
z=5.183

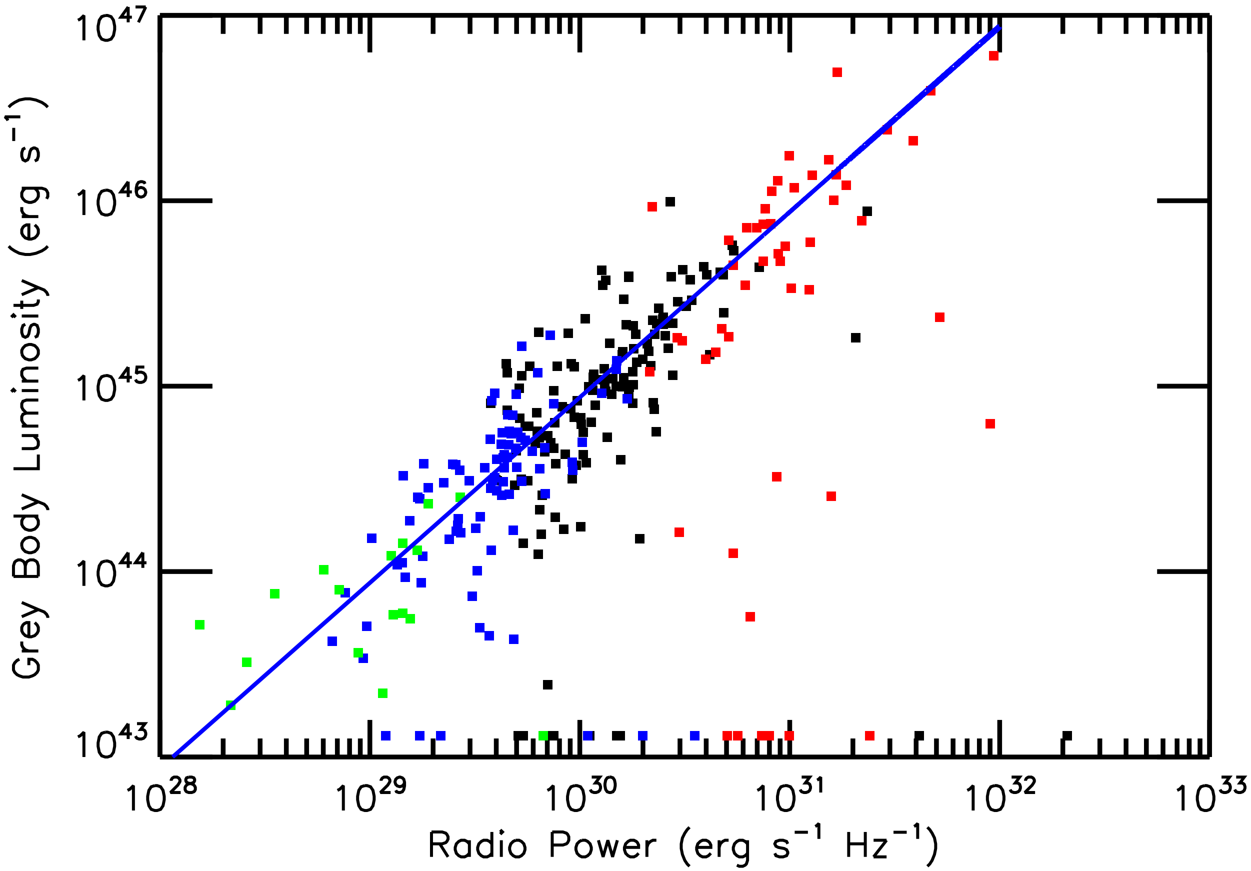
z=4.04

The submillimeter flux to radio power ratio seems to provide a clear separation between AGN dominated and SF dominated (confirmed by limited VLBI data) – we also see hints of a maximum SFR



Cowie et al. 2015

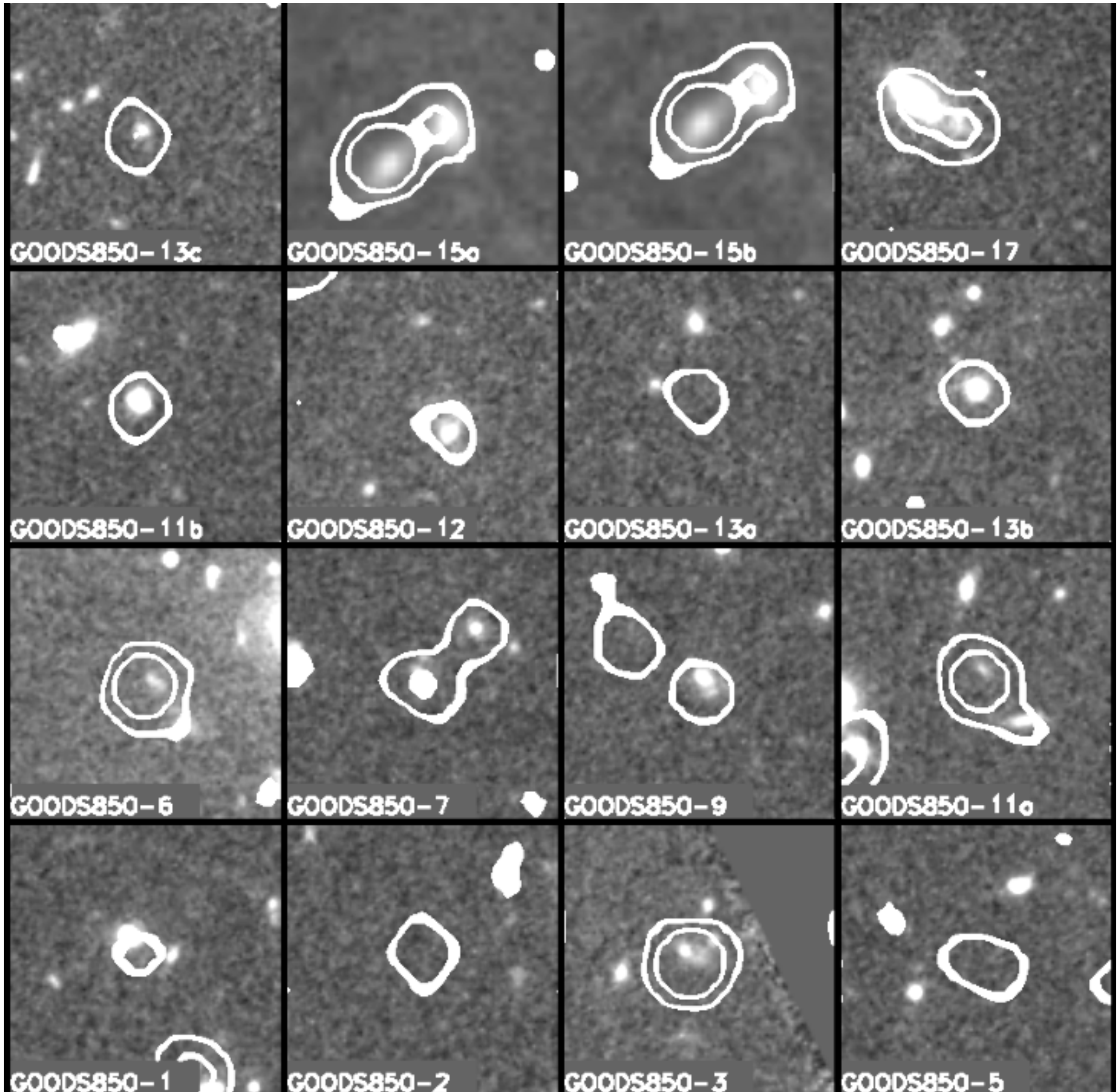
Radio-Fir correlation



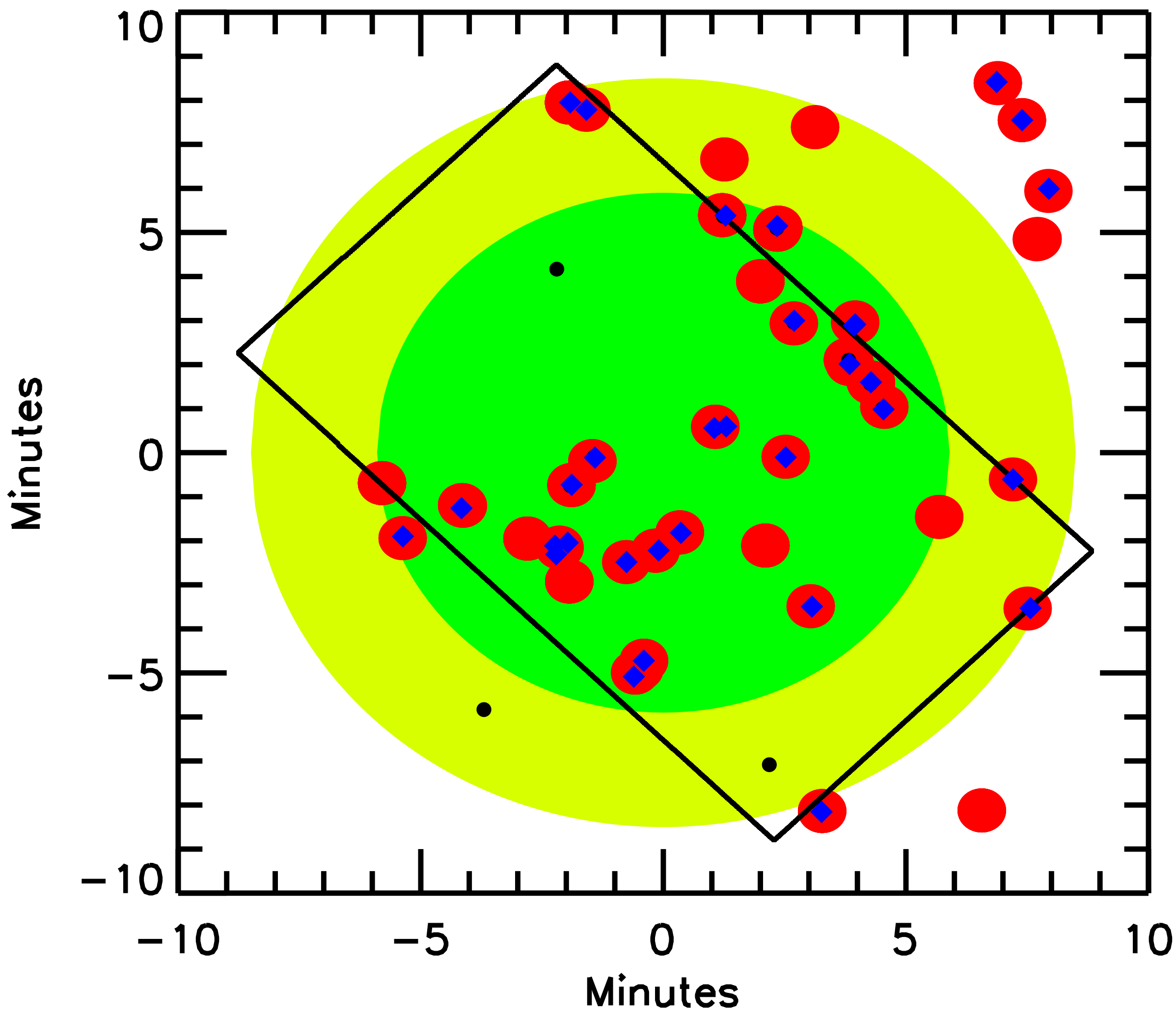
Red z=1.6-4
Black z=0.8-16
Blue z=0.4-0.8
Green z=0.2-0,4

If we relied only on the radio for positions, then there would still be ambiguity when multiple radio sources

20 cm contours overlaid on the HST F140W images centered on the SMA positions of the SMA sample



SMA follow-up in the CDF-N for accurate positions
Note the small field-of-view (ALMA's is even smaller)



(Darkest green: 850 μm rms noise less than 0.55 mJy)

Red: 24" radius

Rectangle: GOODS-N HST

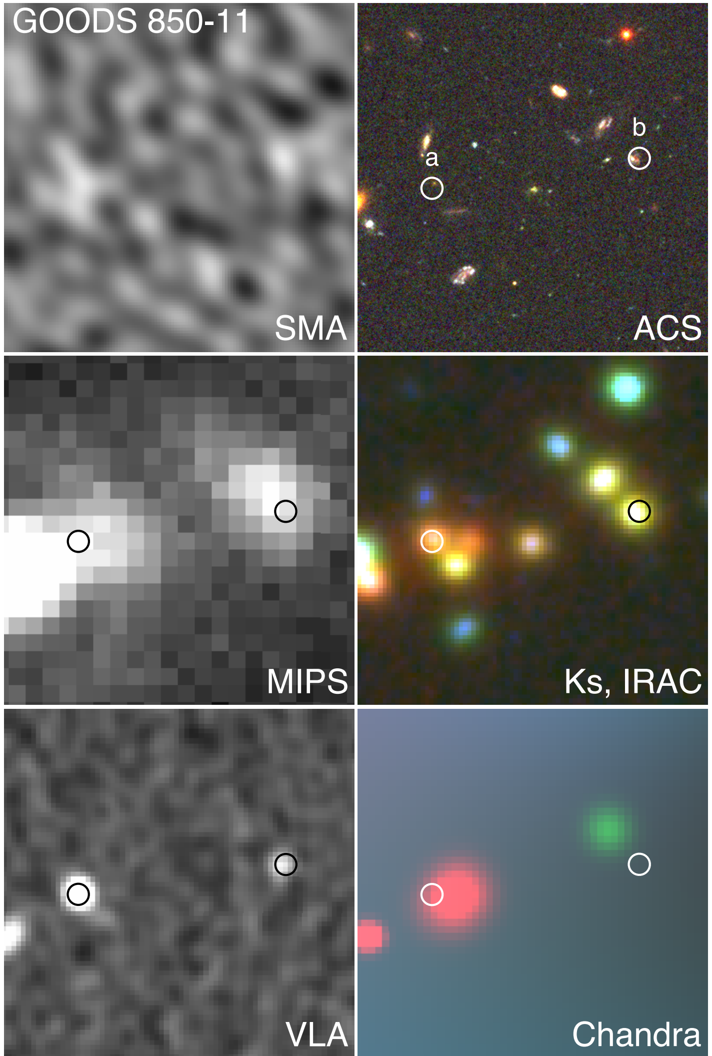
SCUBA-2 5mJy

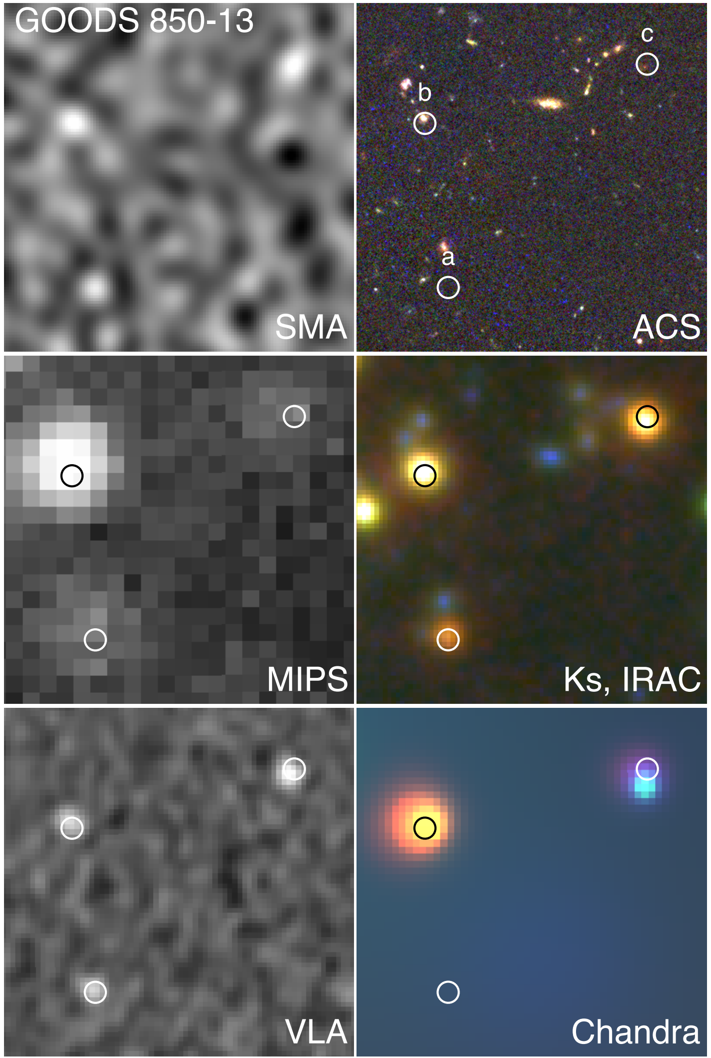
All SMA observed areas, including non-SCUBA-2 targets

32 SMA detections (includes nearly all >5 mJy SCUBA-2 sources)

Interferometry Has Revealed Some Multiplicity

Wang et al. (2011) using the SMA first discovered that some bright SCUBA sources resolved into multiple, physically unrelated sources



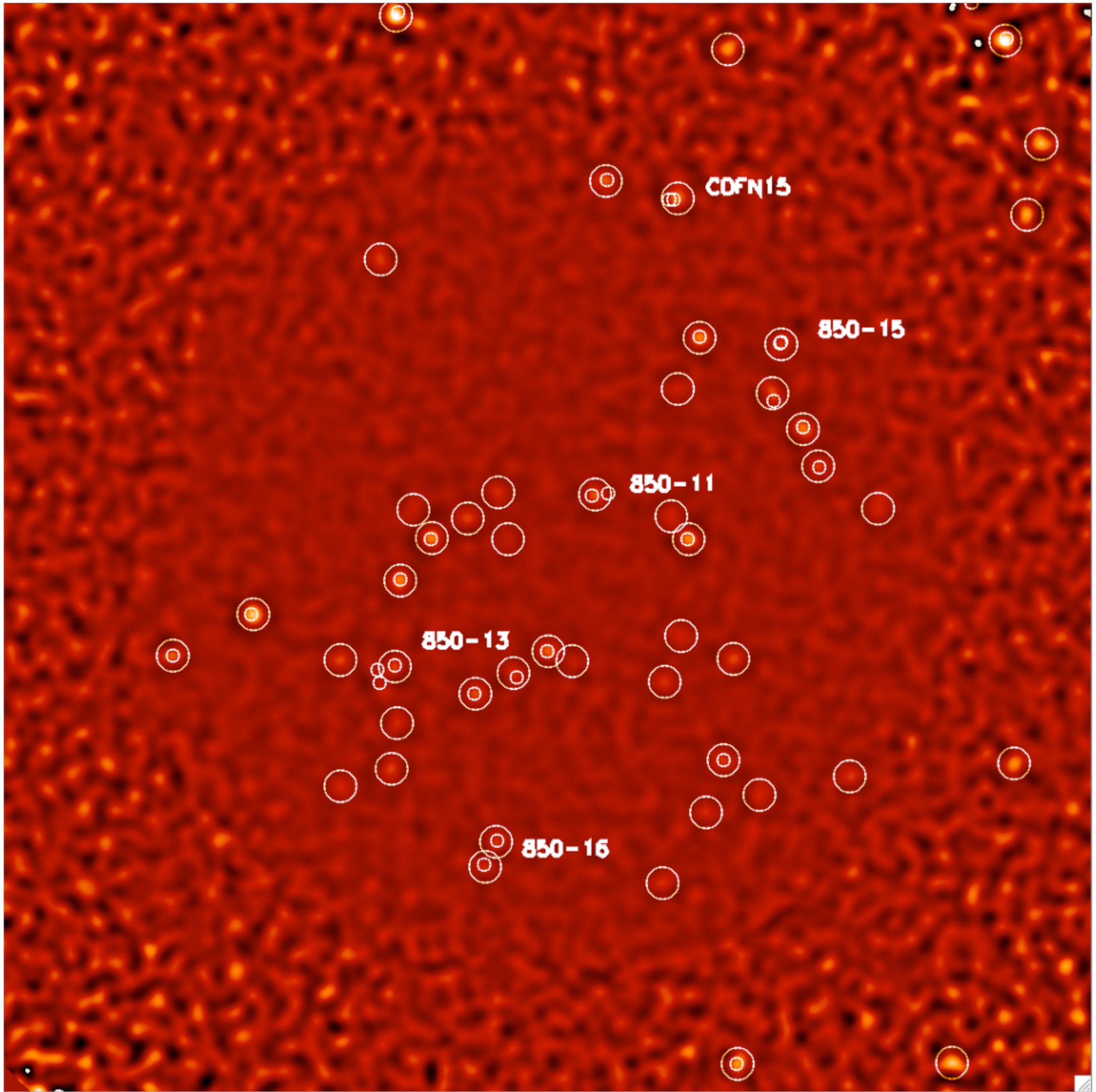


But most bright SCUBA-2 sources are singles

SCUBA-2 12' radius field

SCUBA-2 positions (larger circles)

SMA sources (small circles)

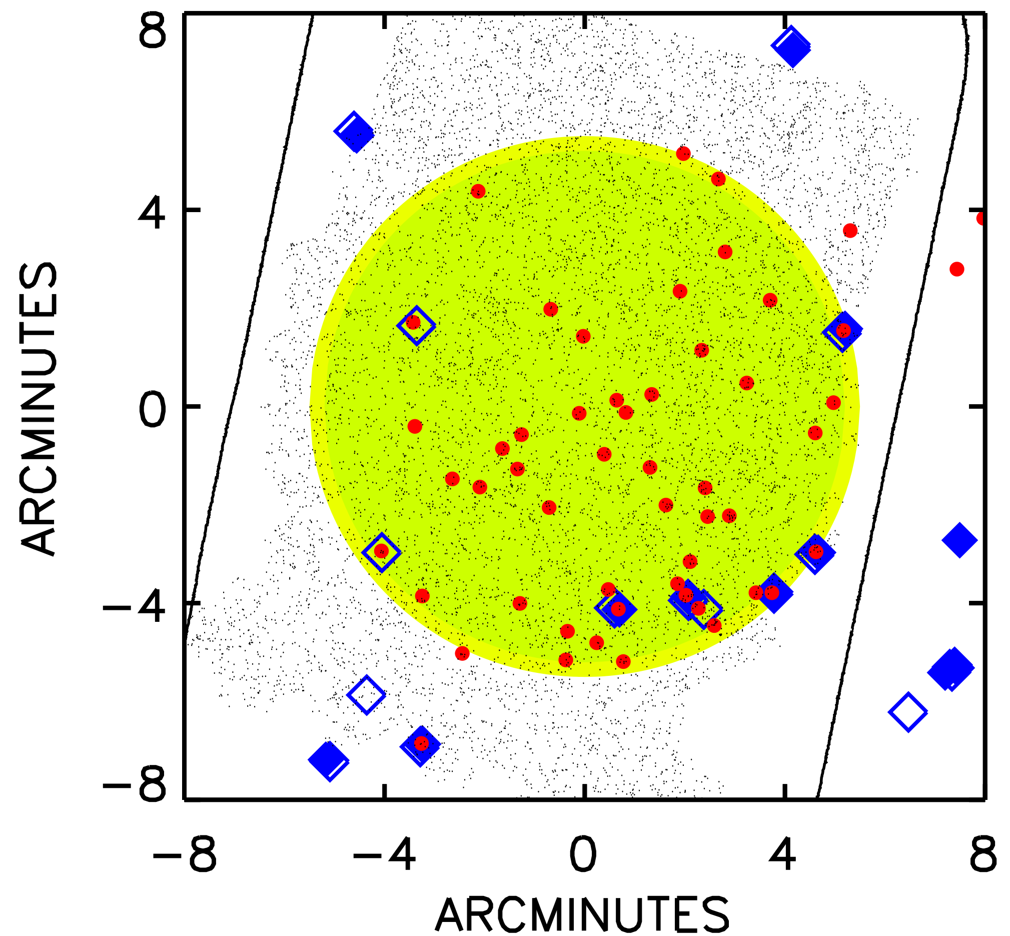


ALMA ALESS Survey in CDF-S

LABOCA (LESS; Weiss et al. 2009) was used to survey the CDF-S, and ALMA was used to follow-up the sources (ALESS; Hodge et al. 2013)

Our SCUBA-2 images are much deeper and find many more sources in the central region covered by the 4 Ms X-ray image

Deep areas (<twice the central noise) in X-ray (green) and SCUBA-2 (yellow) for CDF-S



Blue open = LESS; solid = ALESS

Red = 4σ SCUBA-2

Is There a Maximum SFR?

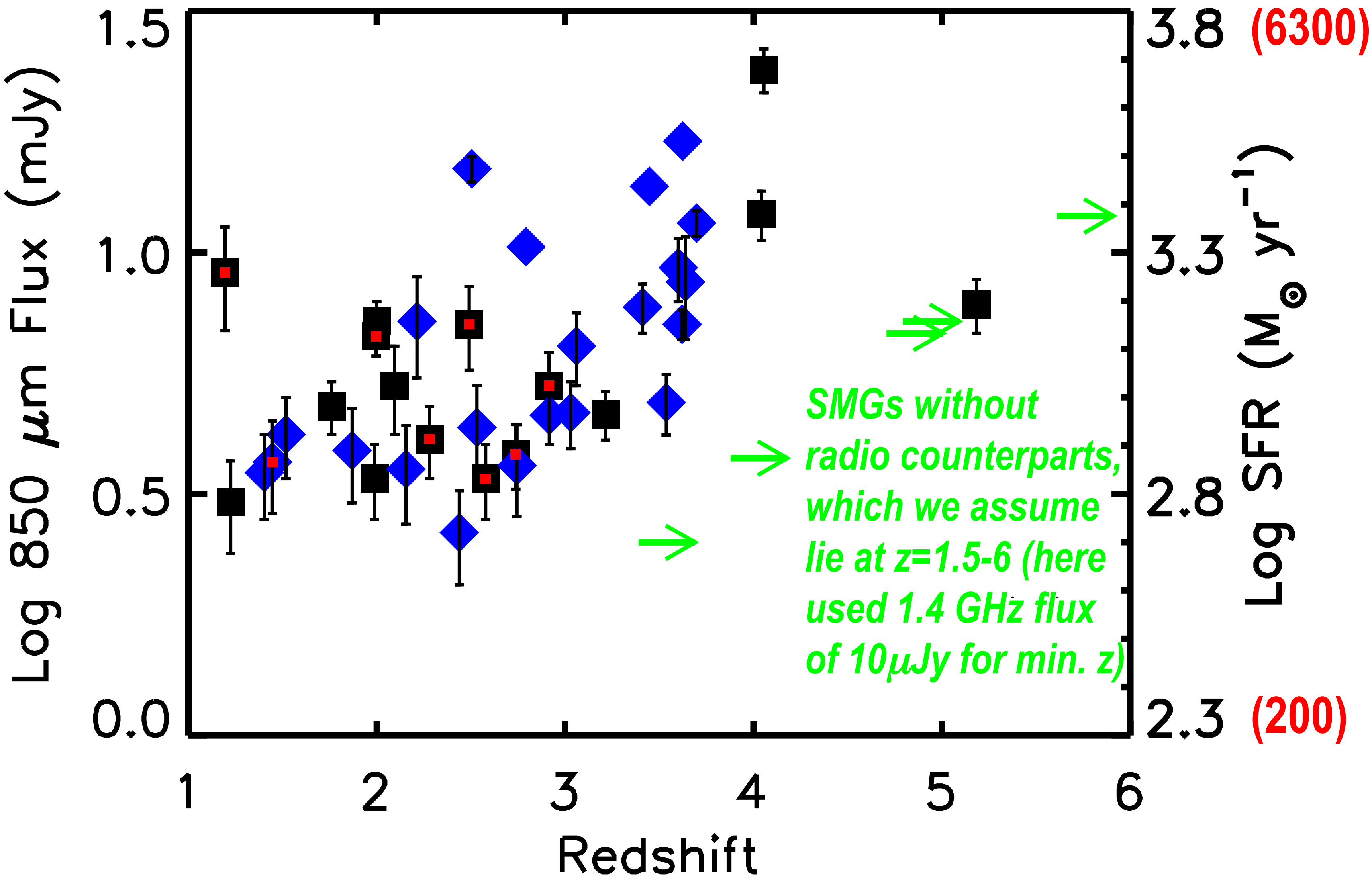
- All of the brightest ALESS sources ($S_{870\mu m}$>12 mJy) were found to be composed of emission from multiple fainter sources, each with $S_{870\mu m}$<9 mJy; no ALMA source was >9 mJy (Karim et al. 2013)

- Thus, Karim et al. proposed a natural limit of <1000 $M_{Sun}\ yr^{-1}$ on the SFRs

- In the CDF-N, we have 6 SMA detections of SCUBA-2 sources with $S_{860\mu m}$>11 mJy (brightest 23.9 mJy), *all of which are singles*

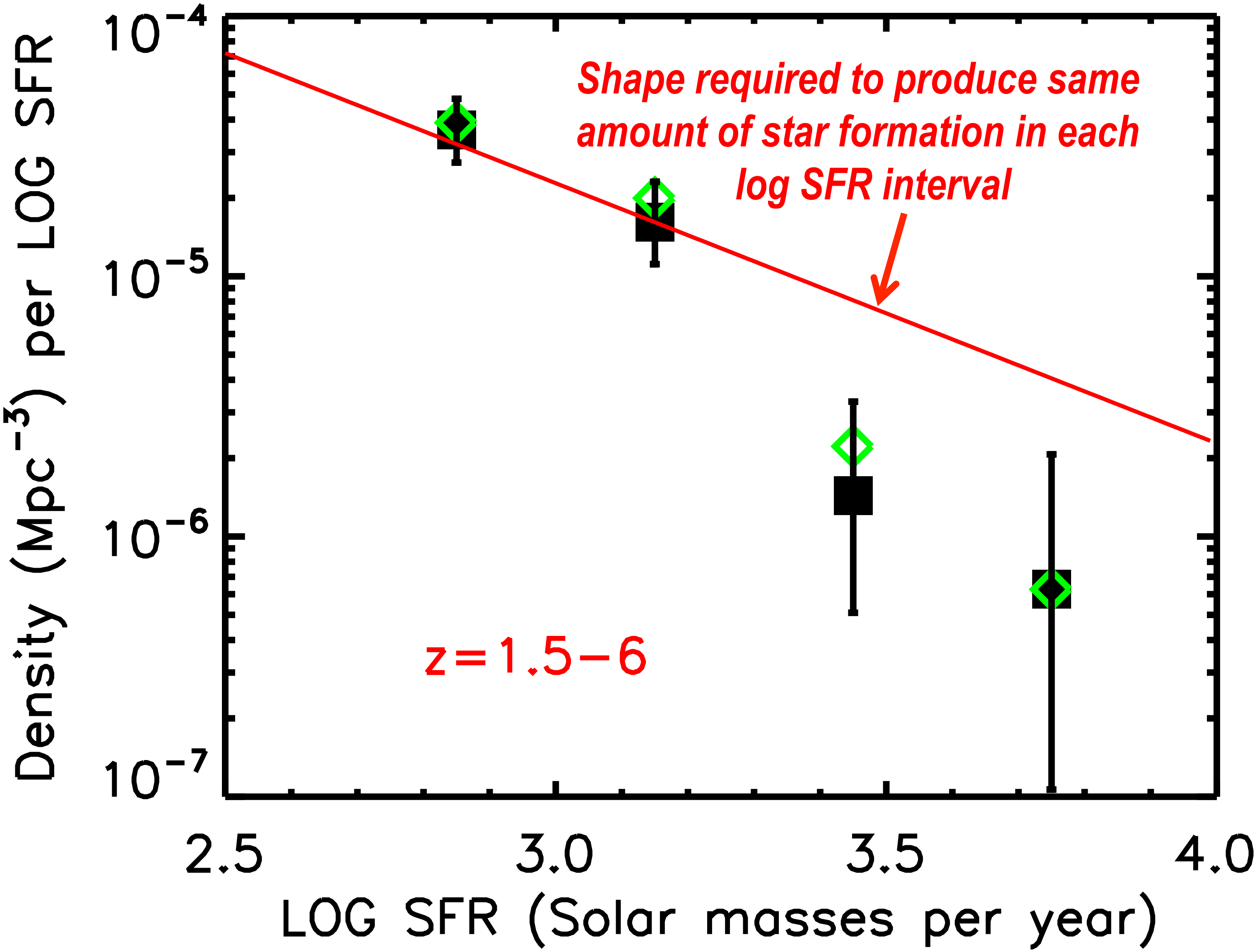
[LABOCA (19.2") has a larger beam size than SCUBA-2 (14"), so multiplicity or non-detections may be more common in LABOCA/ALMA observations than in SCUBA-2/SMA observations]

The SFRs of our submm galaxies range from 400 to 6000 M_{Sun} yr^{-1} (SALPETER IMF)

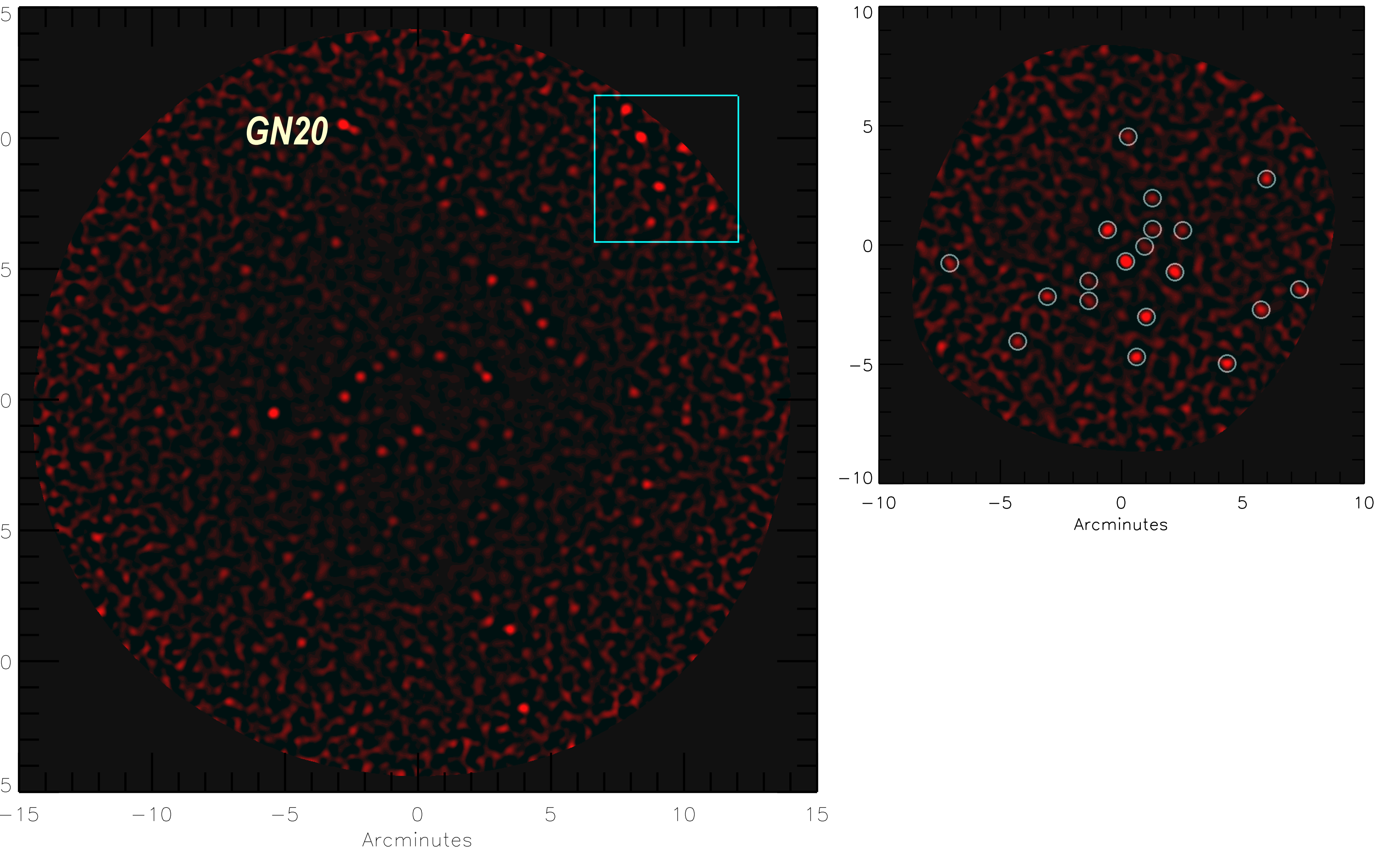


SFR Distribution Function

contributions to the SFR density begin to drop above 2000 M_{Sun} yr^{-1}



Clustering is an issue however: many of the bright CDF-N sources lie in a single region (z=4 protocluster?)



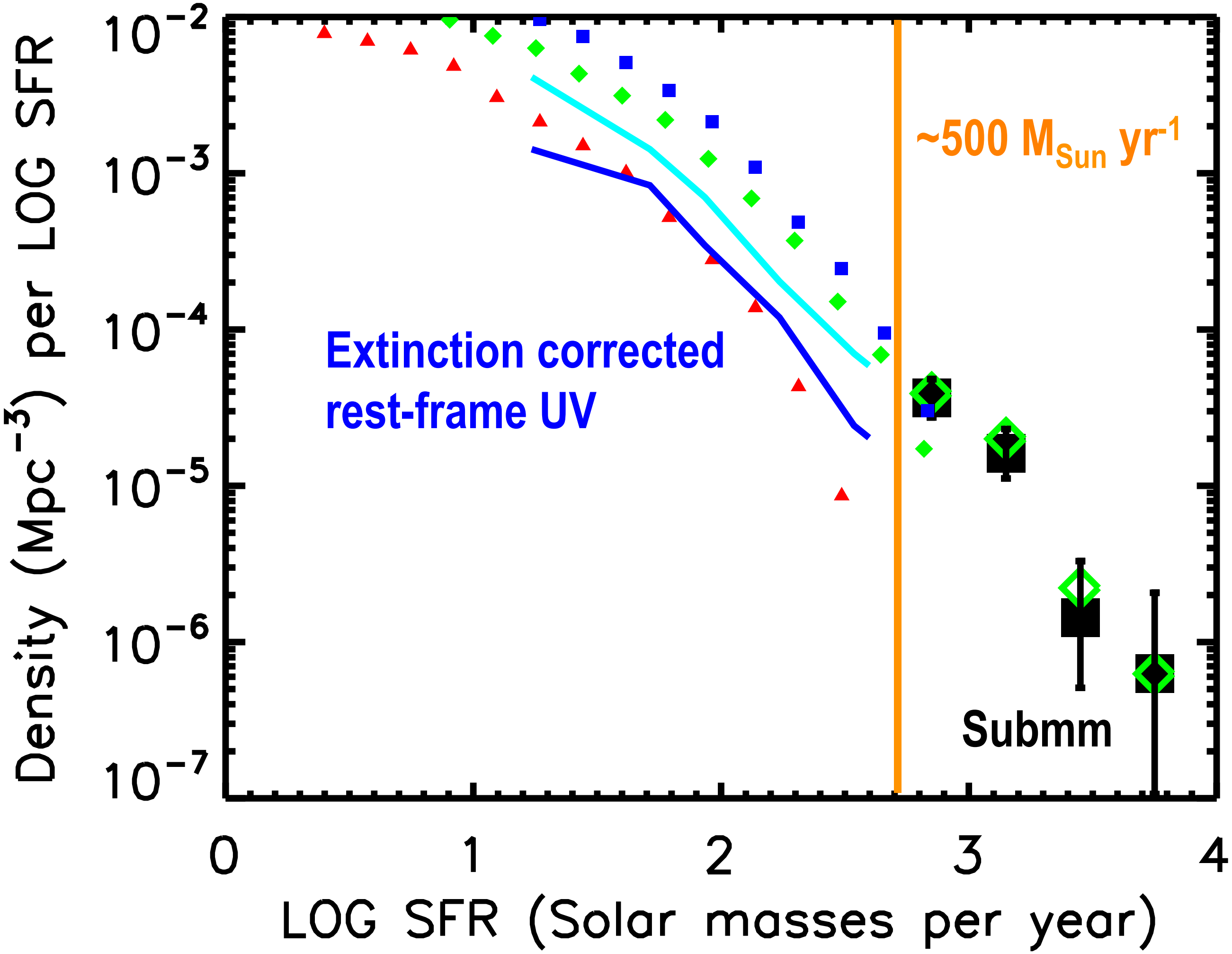
Big Question

Are the SF contributions measured from the rest-frame UV selected population distinct from the SF contributions from the submm/FIR selected galaxy population?

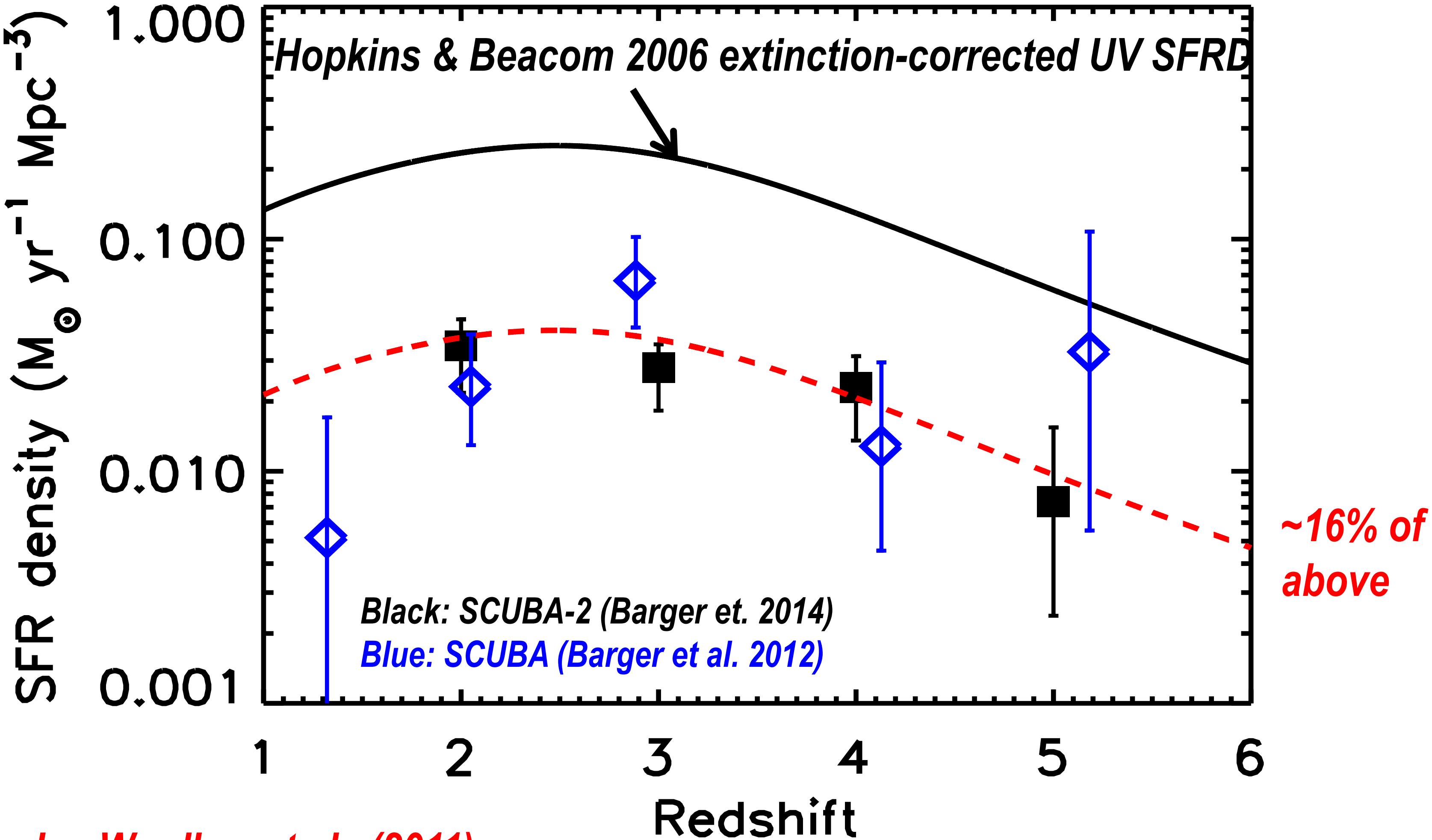
Yes! The submm is a unique probe of the highest SFR galaxies --- the rest-frame UV selected samples max out at ~500 M_{Sun} yr^{-1}, even after extinction correction

Symbols at z=4.8, 3.8, and 3.1 from van der Burg et al. 2010

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



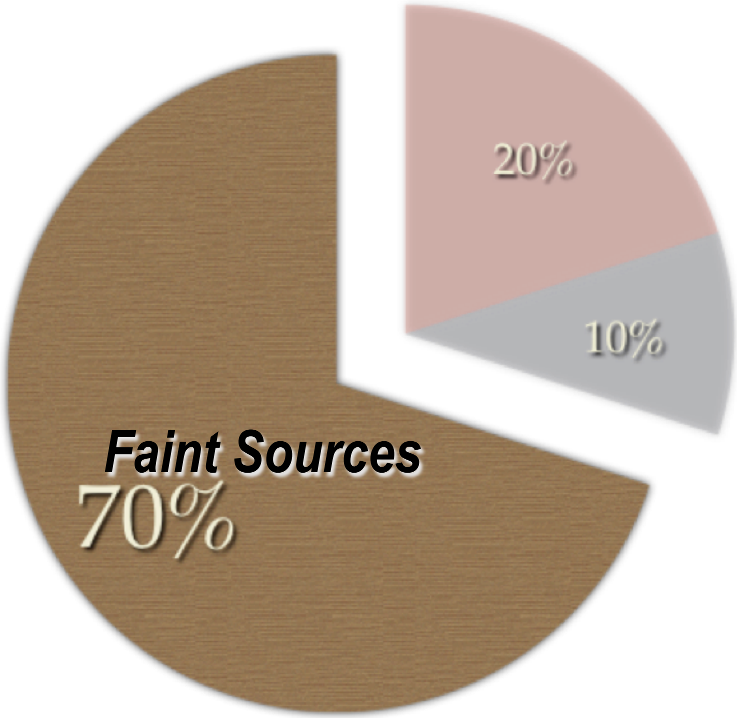
Moreover, a large and relatively invariant fraction of the overall SFR density is contained in these massively star-forming galaxies, and this is true at all redshifts to beyond z=5 (Question1).



See also Wardlow et al . (2011)

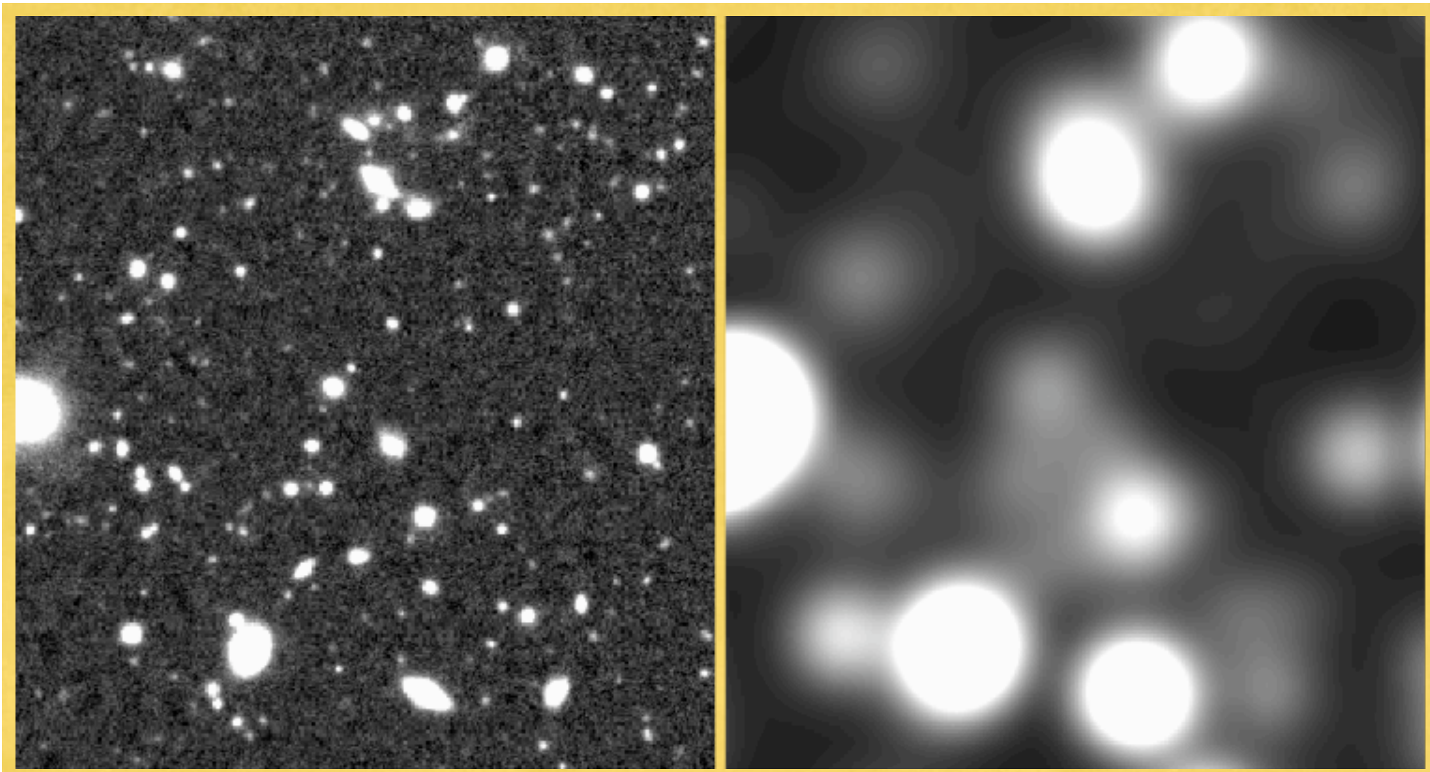
Since the samples are disjoint, the two contributions need to be added!

But might we be missing yet further contributions in the UV samples?



Only 20-30% of the submm extragalactic background light is contained in bright submm galaxies

Unfortunately, single dish observations limited by confusion when we want to probe fainter (<2 mJy at 850 microns)



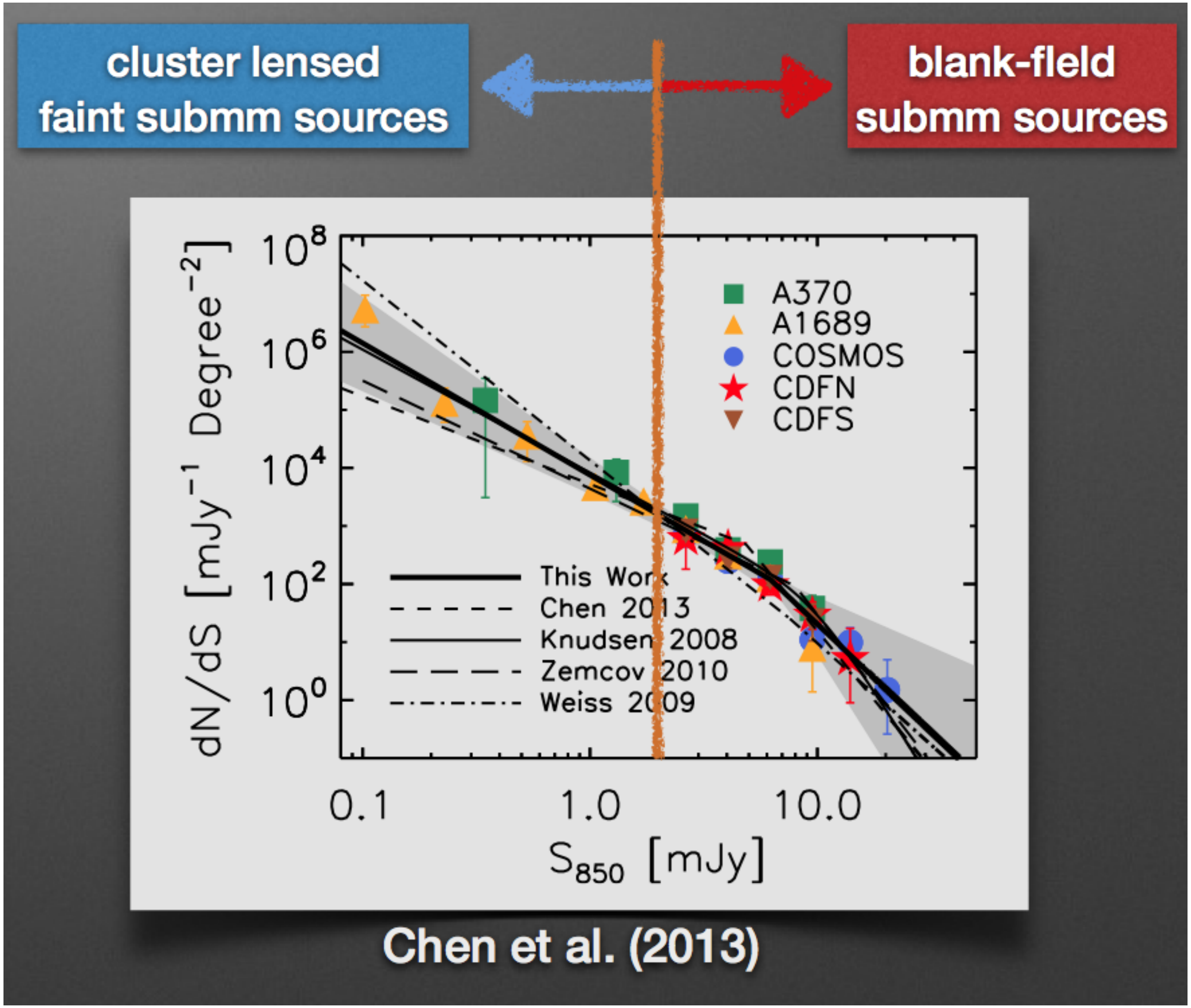
0.8" FWHM	15" FWHM
Not confusion limited. Integrating longer can detect fainter sources.	**Confusion limited. Integrating longer can NOT detect fainter sources.**

Breaking the Confusion Limit

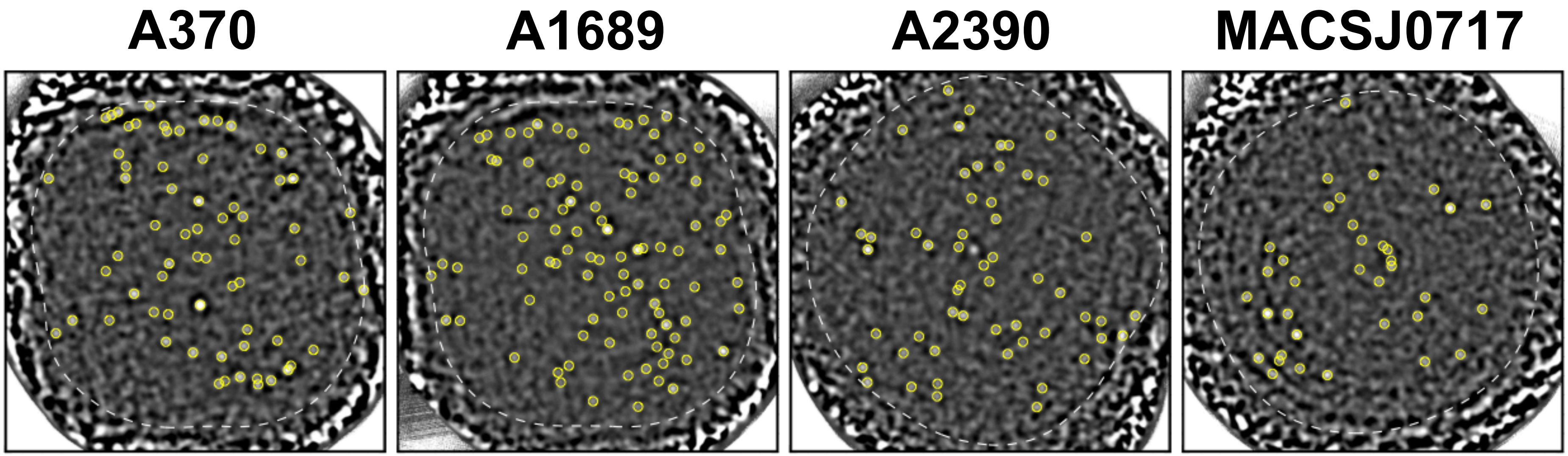
To get to these fainter submm fluxes, we need to go beyond the confusion limit

We can do this with interferometers, but again we suffer from the small field problem

The alternative is to observe behind massive clusters of galaxies, where the magnification and source plane expansion allows us to detect fainter submm galaxies



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

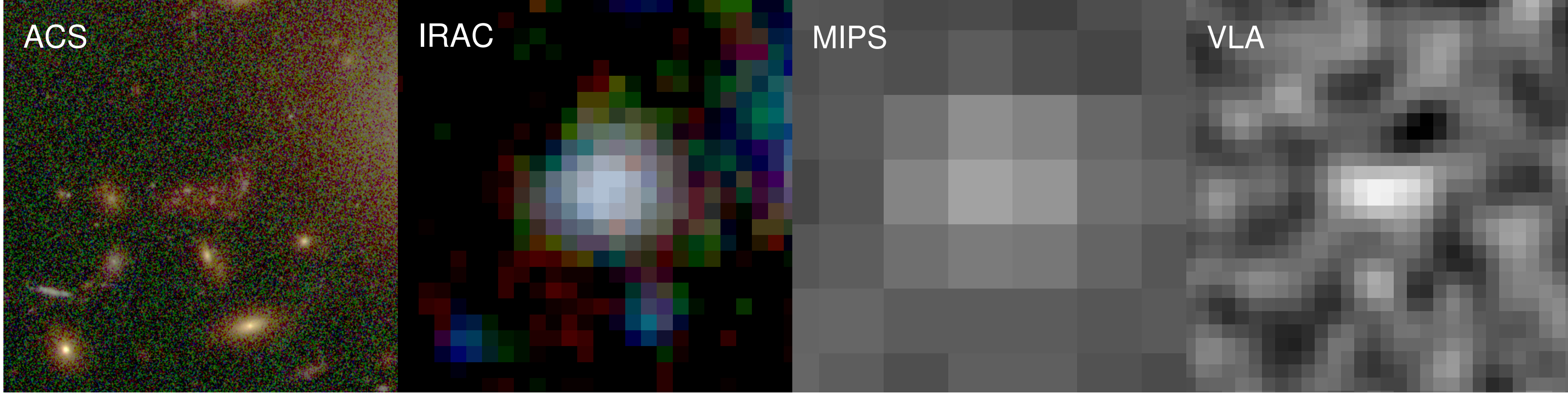


Images: 14’ x 14’ (>10 hrs; goal is 1σ of ~0.3 mJy at 850 and 2.5 mJy at 450)

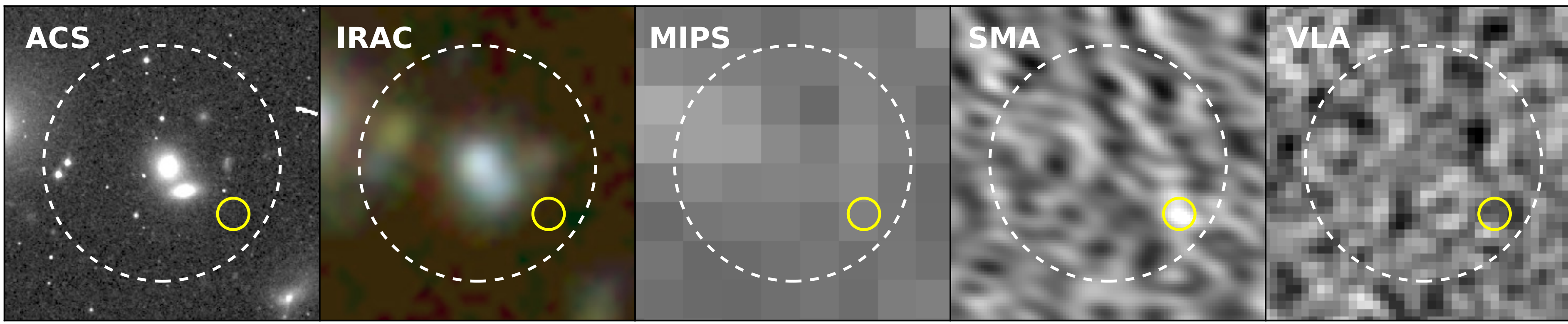
All 5 SMGs detected in Chen et al. (2014) with the SMA have intrinsic fluxes ~0.1-0.8 mJy (SFR~20-160 $M_{\odot}$/yr), the region of critical interest for tying together the galaxies seen in the rest-frame UV selected samples with those seen in the submm samples

Key question: how overlapped are the two populations?

Look for optical/NIR counterparts to the faint SMGs



However, 3/5 do not have optical/NIR counterparts



Images: 20" x 20"
White circle: 7.5" radius SCUBA-2 beam
Yellow circle: 1" radius SMA beam

Thus, many low-luminosity, obscured star-forming galaxies may also not be included in the measured optical star formation history!

Star Formation History Not Complete

- The most luminous star formers are mostly disjoint from the UV selected samples
- There is emerging evidence that even at lower luminosities there are star-forming galaxies that are missing from the UV samples
- These could be at high redshifts
- But sample sizes are still small, and more observations are needed

Summary

- Submm galaxies have SFRs up to 6000 M_{Sun} yr^{-1} over z=1.5-6 (extinction corrected UV-selected galaxies only reach ~500 M_{Sun} yr^{-1}), but there is a turn-down at > 2000 M_{Sun} yr^{-1} in the SFR distribution function

- The UV based SF history is not complete:
  - Bright submm galaxies contribute an additional ~16% of the optical SF history at all z>1 (to be added to the UV contribution)
  - Additional contributions to the SF history may come from faint submm galaxies, which do not appear to be fully overlapped with UV-selected galaxies

The End