Leaving Star Formation in the Dust

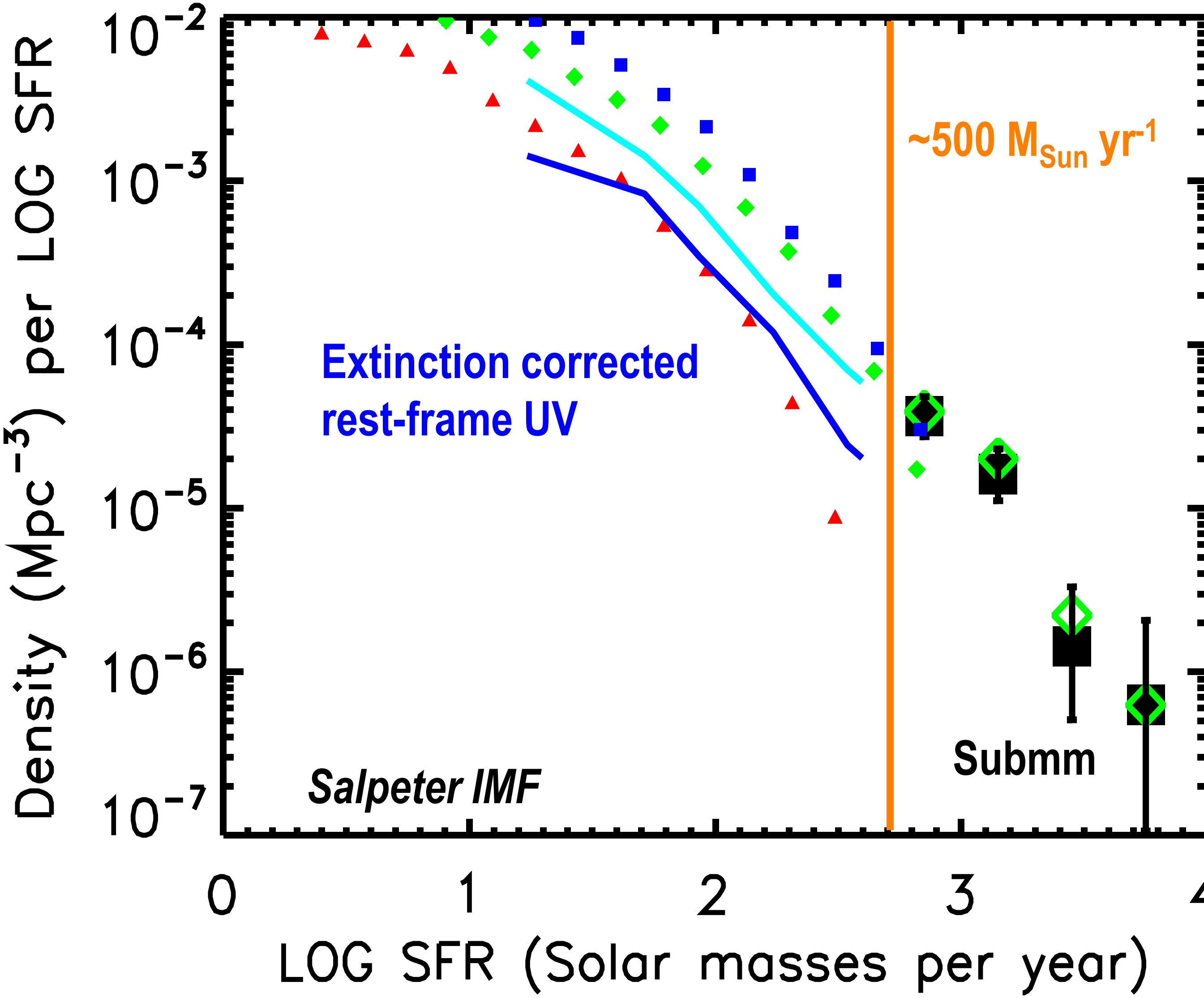
Len Cowie

Do UV Selections Find the Highest Star-forming Galaxies?
NO!

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

Black squares from Barger et al. 2014: based on 850 micron sources with fluxes > 2mJy



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

We miss galaxies using UV selection, because they are faint

And we under-estimate the bolometric luminosity corrections for the galaxies we do see in the UV

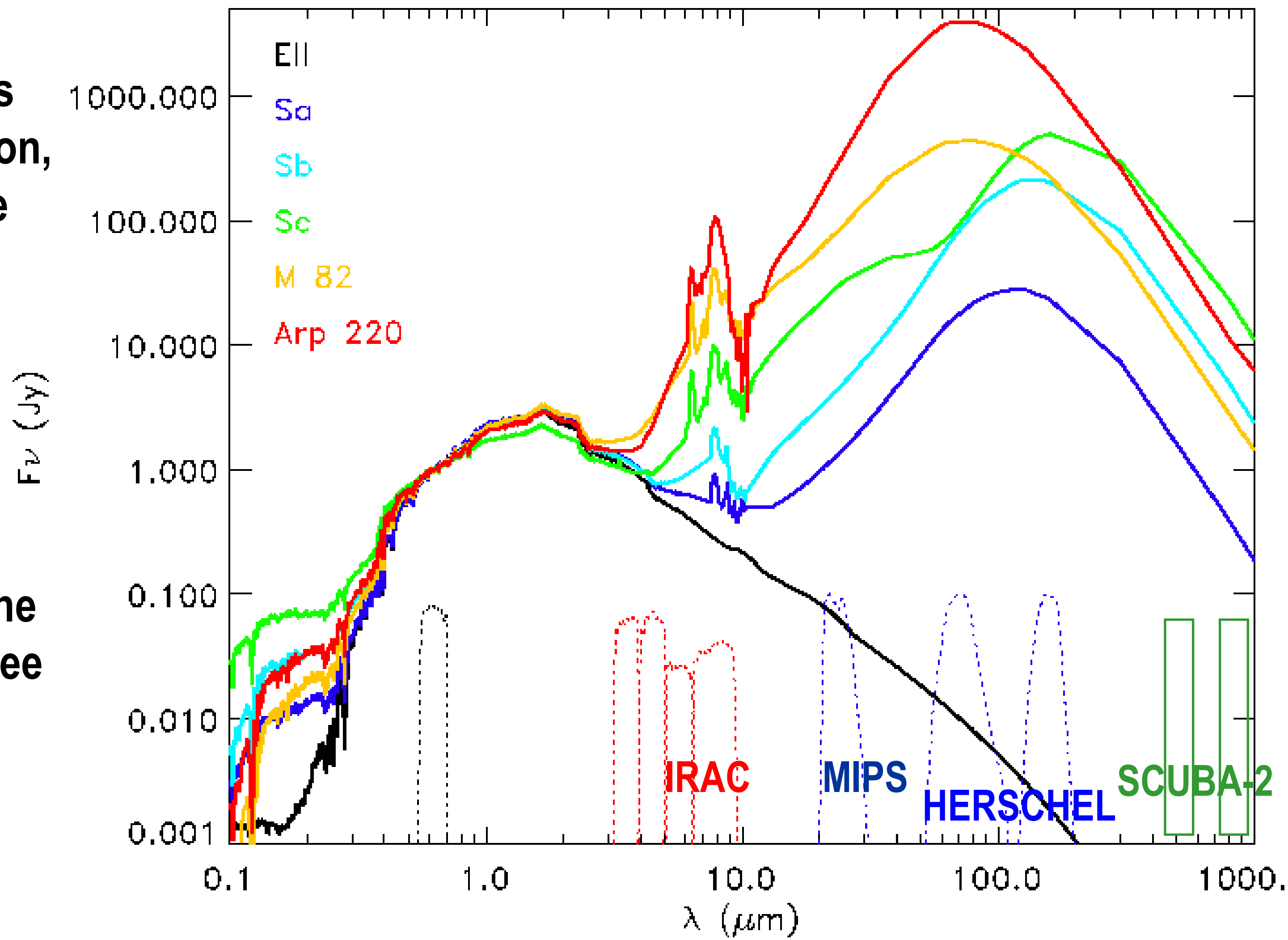
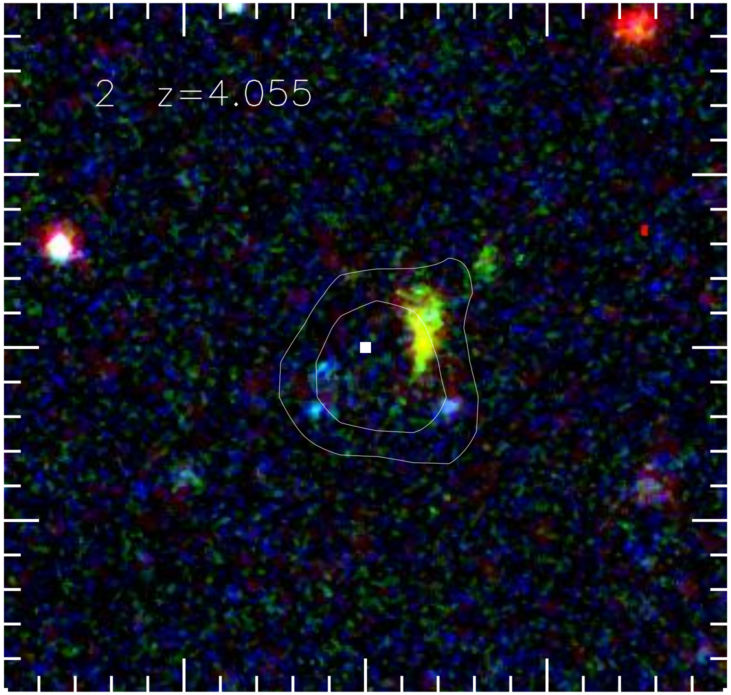


Figure from Polletta

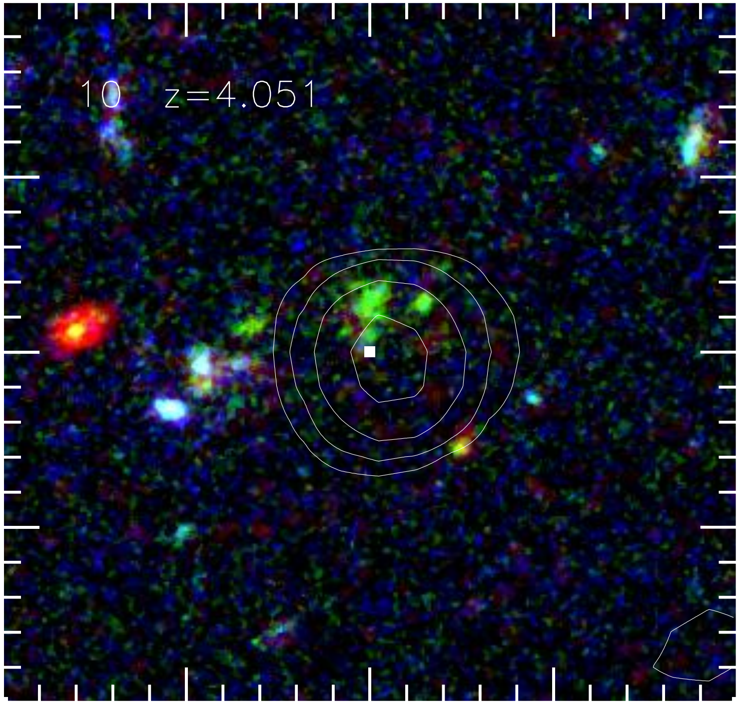


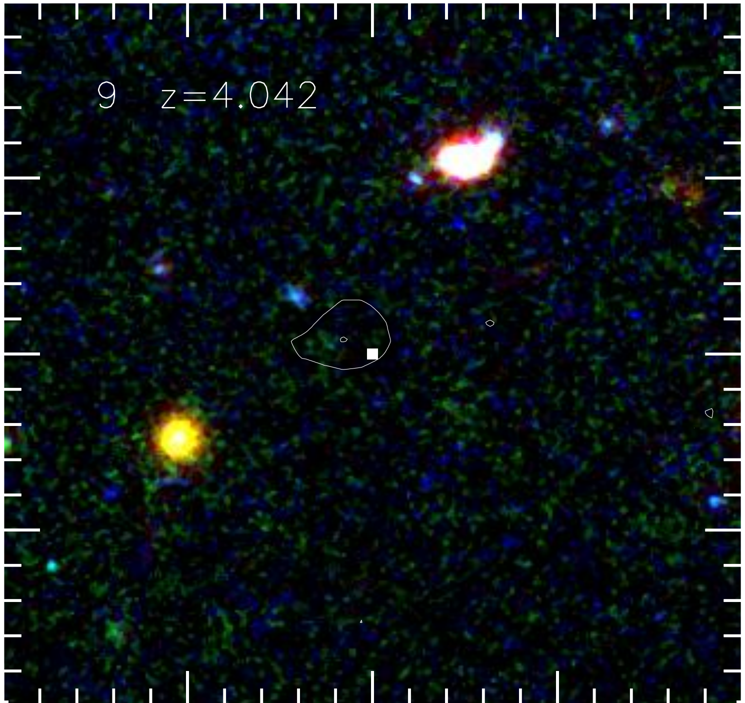
CANDELS-GOODS-N

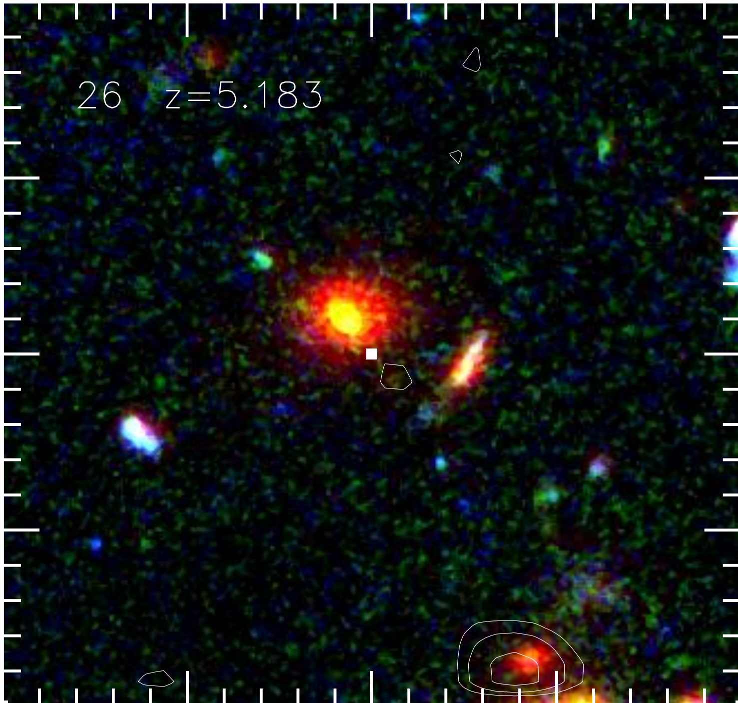
Red=F160W
Green=F814W
Blue-F450W

Contours=20cm

White square=SMA centroid







Evolution of the Most Massively Star-Forming Galaxies

- What fraction of the star formation is missed in the UV selected samples?

- How does the star formation rate density function in the most massively star-forming galaxies evolve with redshift?

- Is there a maximum star formation rate (SFR) in high-redshift galaxies?

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

- ~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

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. We don't need extreme depth…. 2mJy at 850 micron is good… so the confusion limit is not an issue

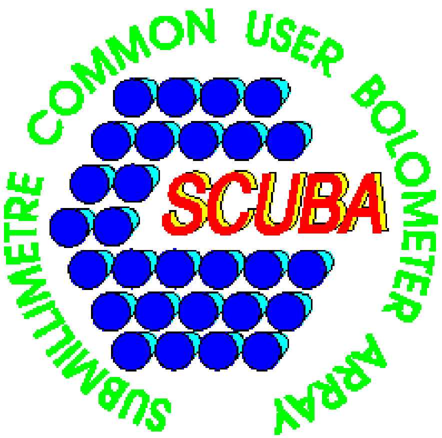
- Use the radio to obtain precise positions, sizes, and redshift estimates

- Use submm interferometry to identify interesting cases where there is no radio identification, or where there is more than one possible radio counterpart and to make sure the flux isn't from multiple galaxies

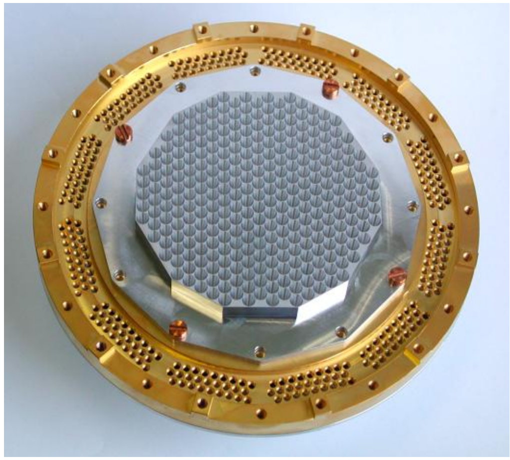
- In addition, use radio and *Chandra/XMM* to identify AGN

Single Dish Submillimeter imaging has evolved

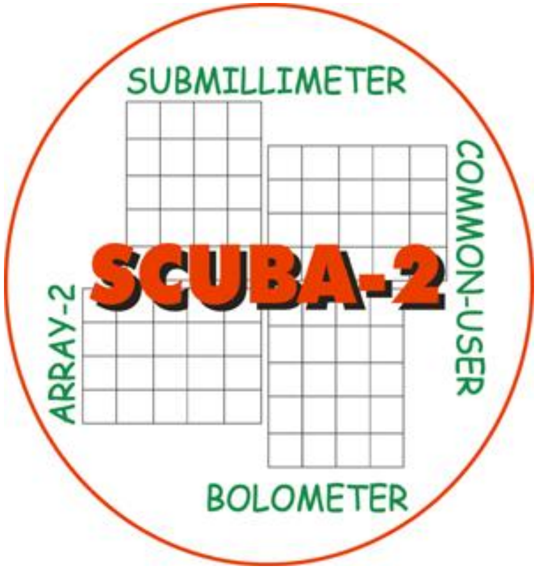
SCUBA (37)



LABOCA (295)



SCUBA-2 (5120)

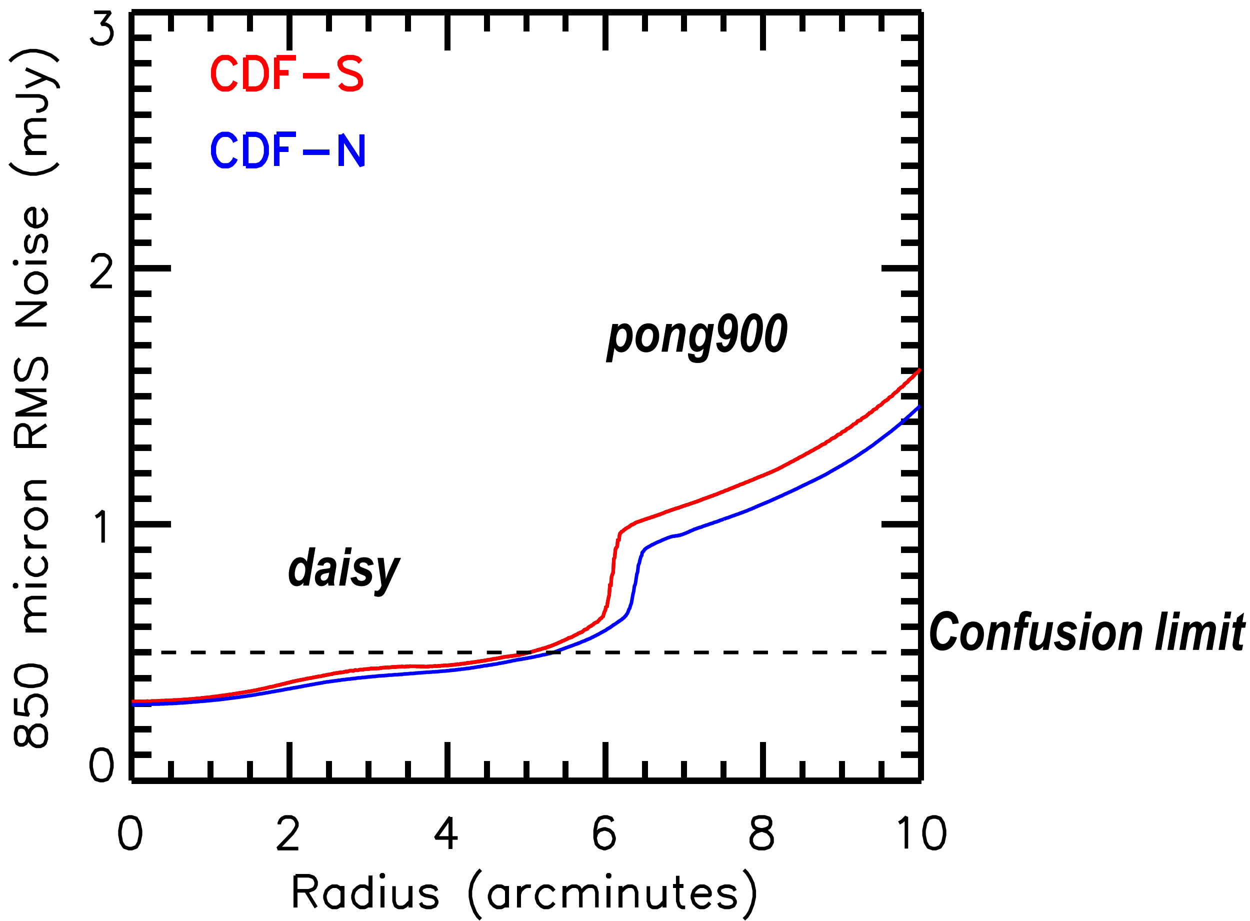


SCUBA-2 has a large 7'x7' field-of-view (5120 pixels)
Fully sampled - Nyquist at 850μm

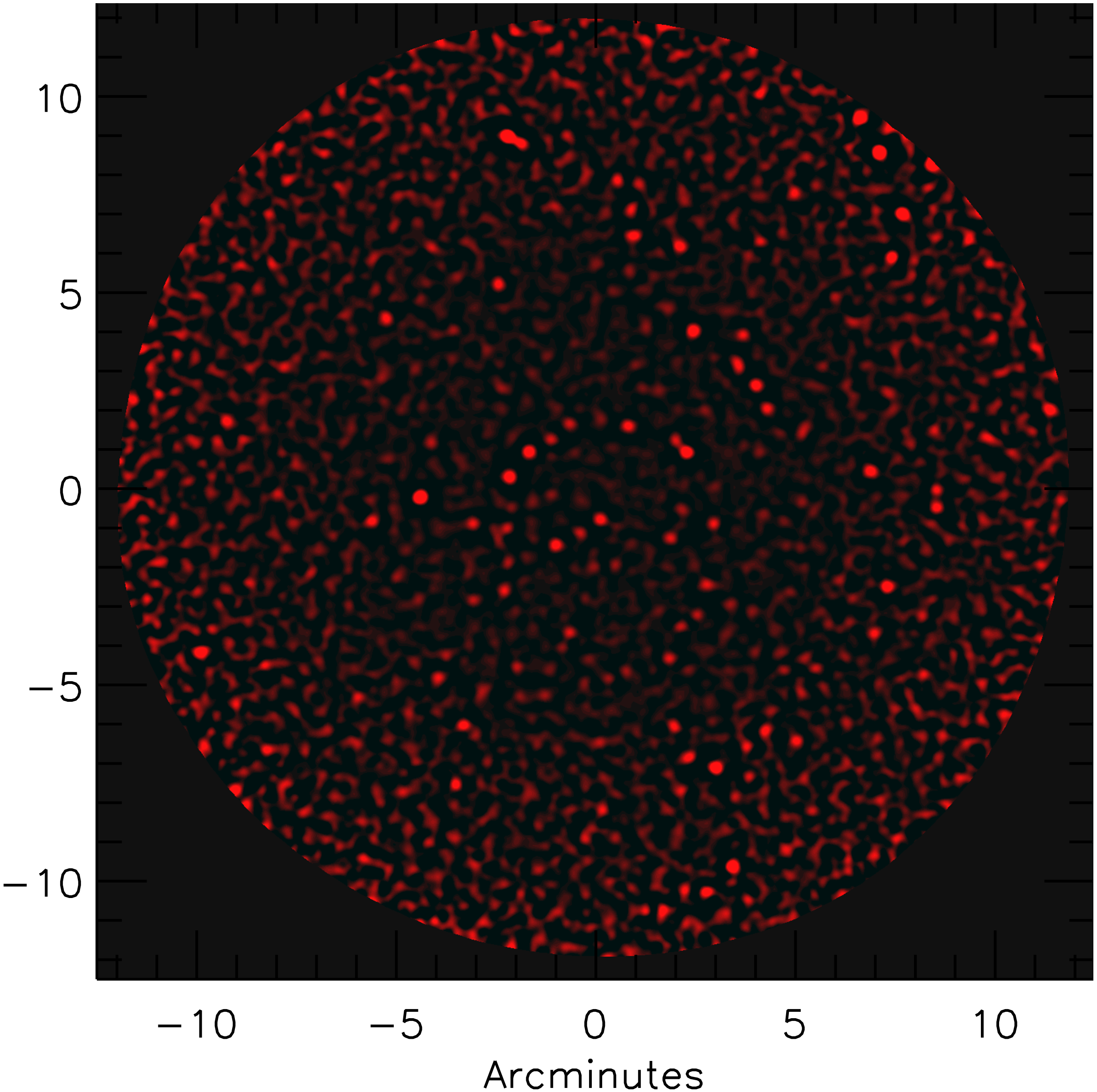
Holland et al. (2006, 2013)

Large and deep submm samples are made possible by SCUBA-2 on JCMT, but are still expensive

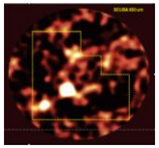
We have observed >230 hours (bands 1 and 2) on the CDF-N/GOODS-N and CDF-S/GOODS-S fields (ongoing).

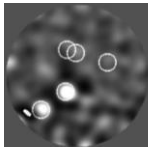


SCUBA-2 image deeper than SCUBA image of HDF-N, covers 120 arcmin^2. Homogeneous, cleanly selected, well calibrated: 185 4σ sources



SCUBA
(Hughes et al. 1998)

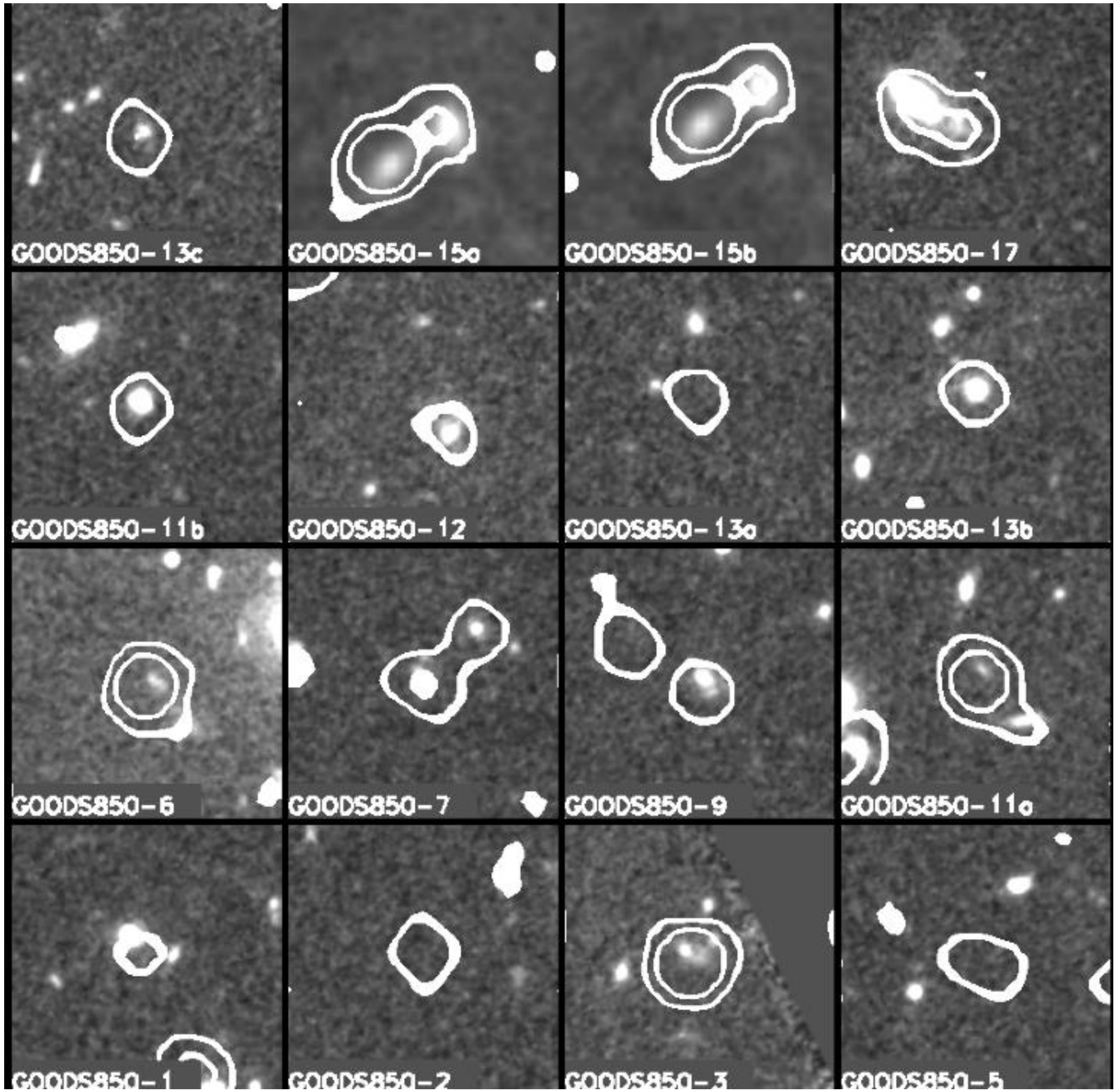




SCUBA-2
(Cowie et al. 2016)

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

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

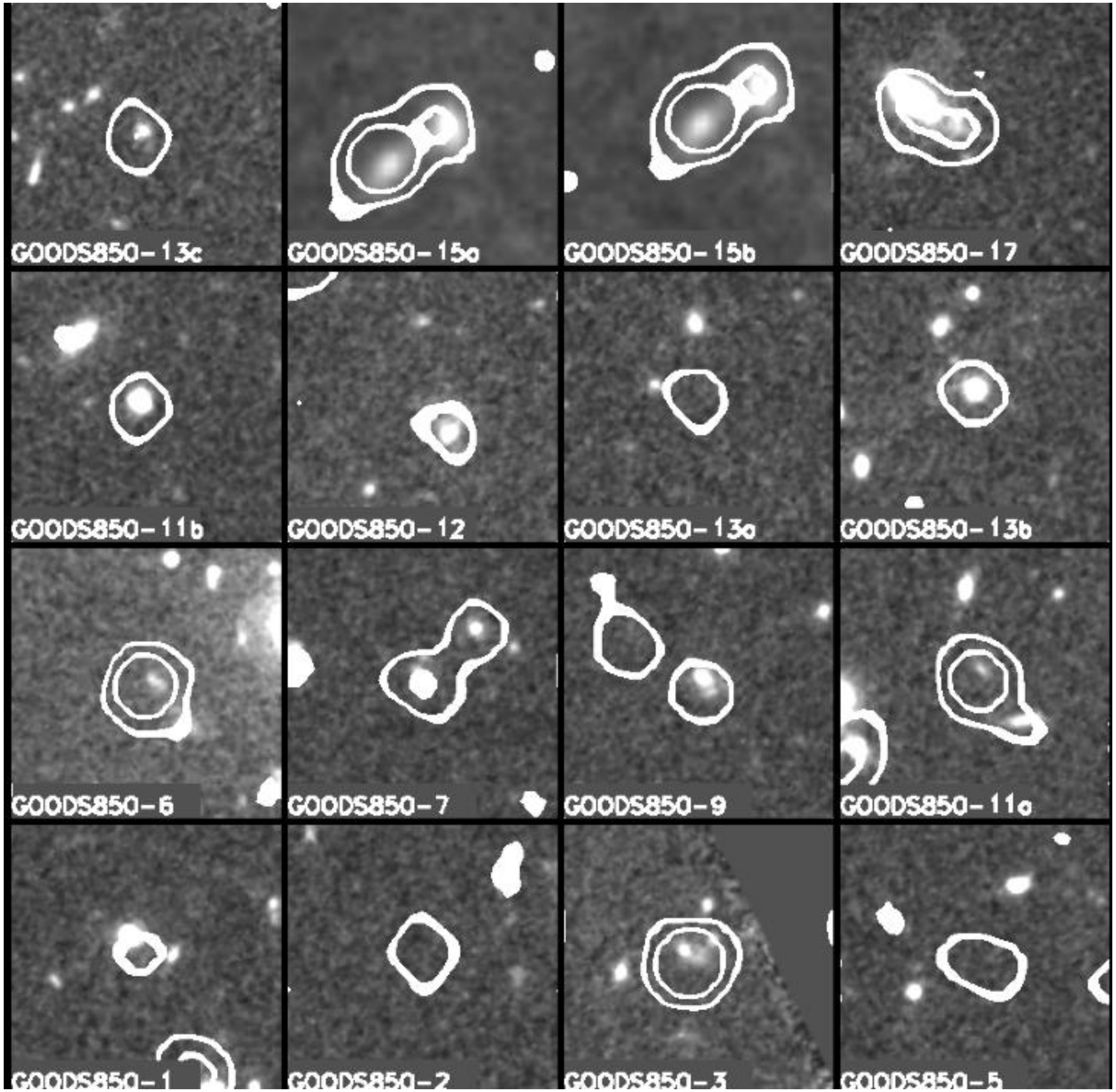


Barger et al. 2012

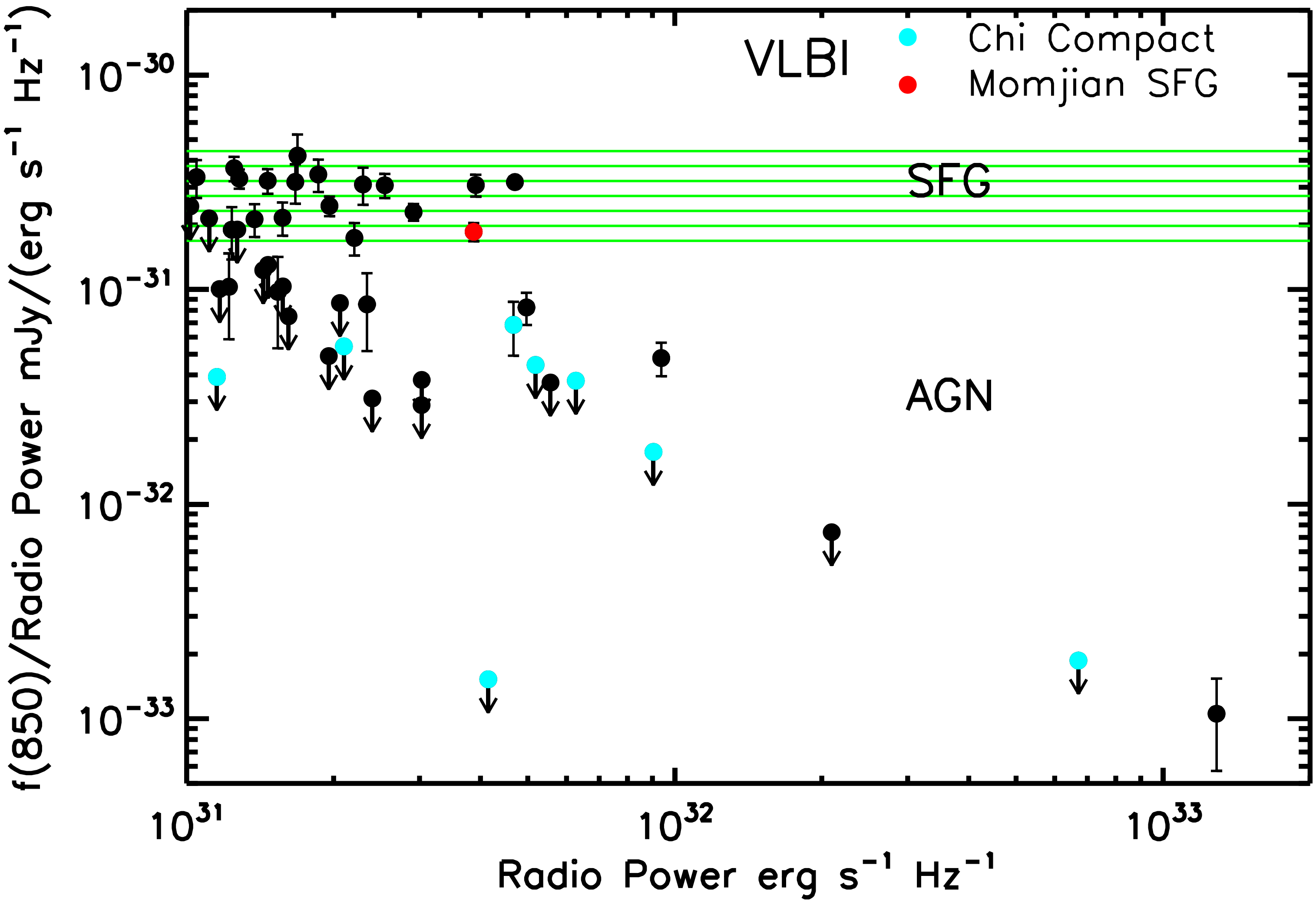
Radio data from Owen 2016

However, if relied only on radio for positions, then 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

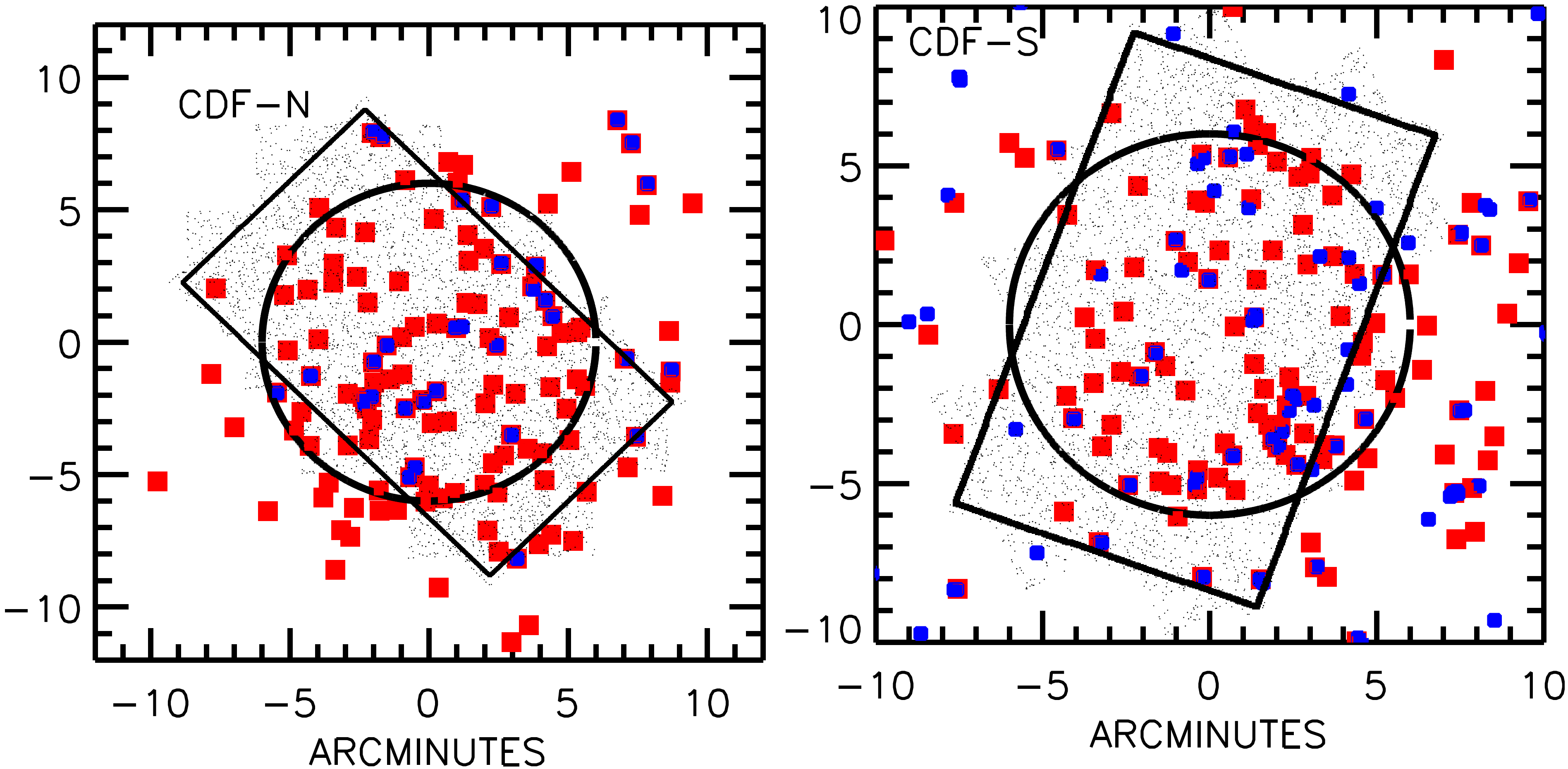


The submillimeter flux to radio power ratio seems to provide a clear separation between AGN dominated and SF dominated (confirmed by limited VLBI data) – we also see hints of a maximum SFR



Cowie et al. 2016

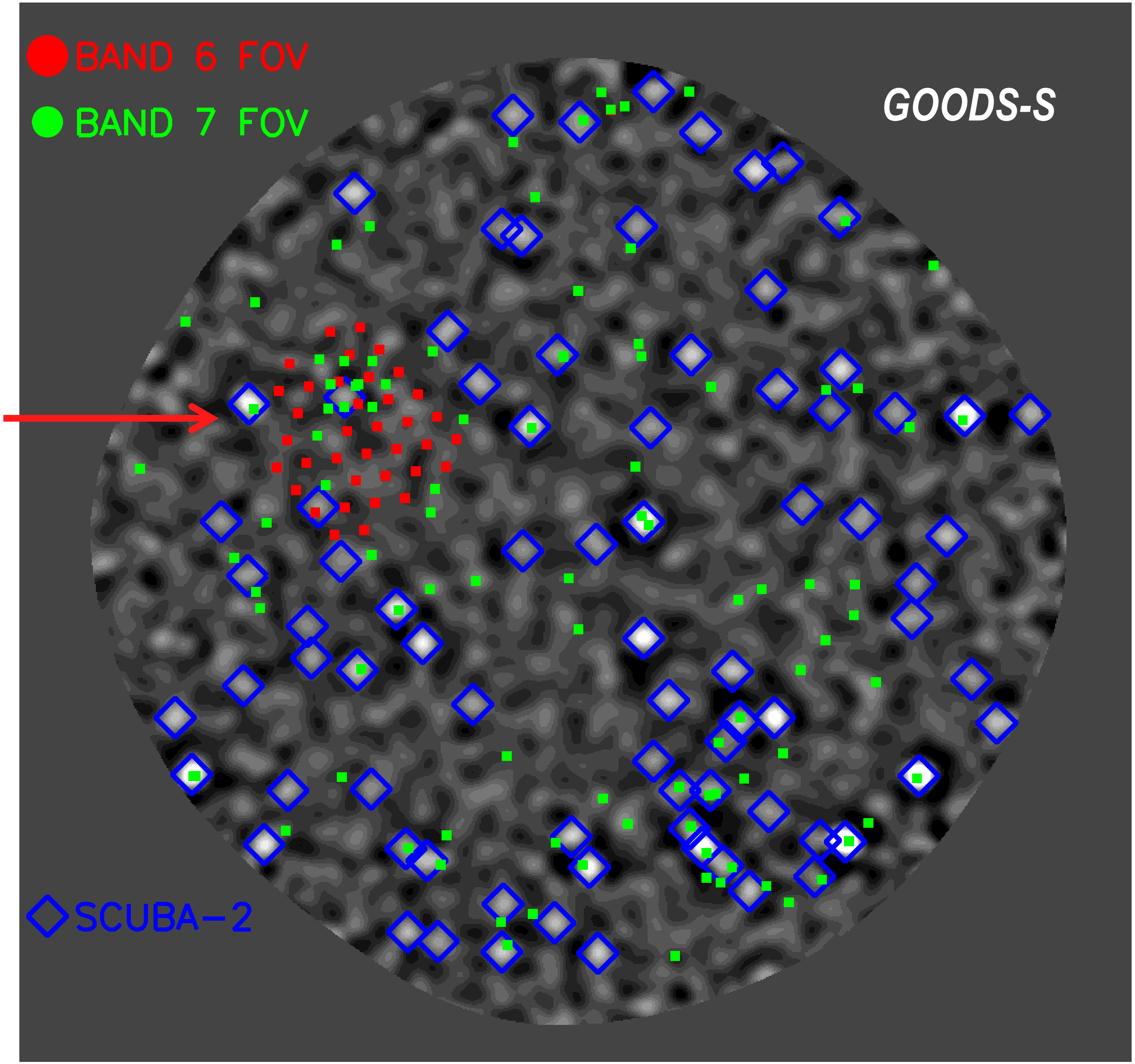
Interferometric Submillimeter Follow-up



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

Note: Blank ALMA Surveys Go Deep, but Small Areas

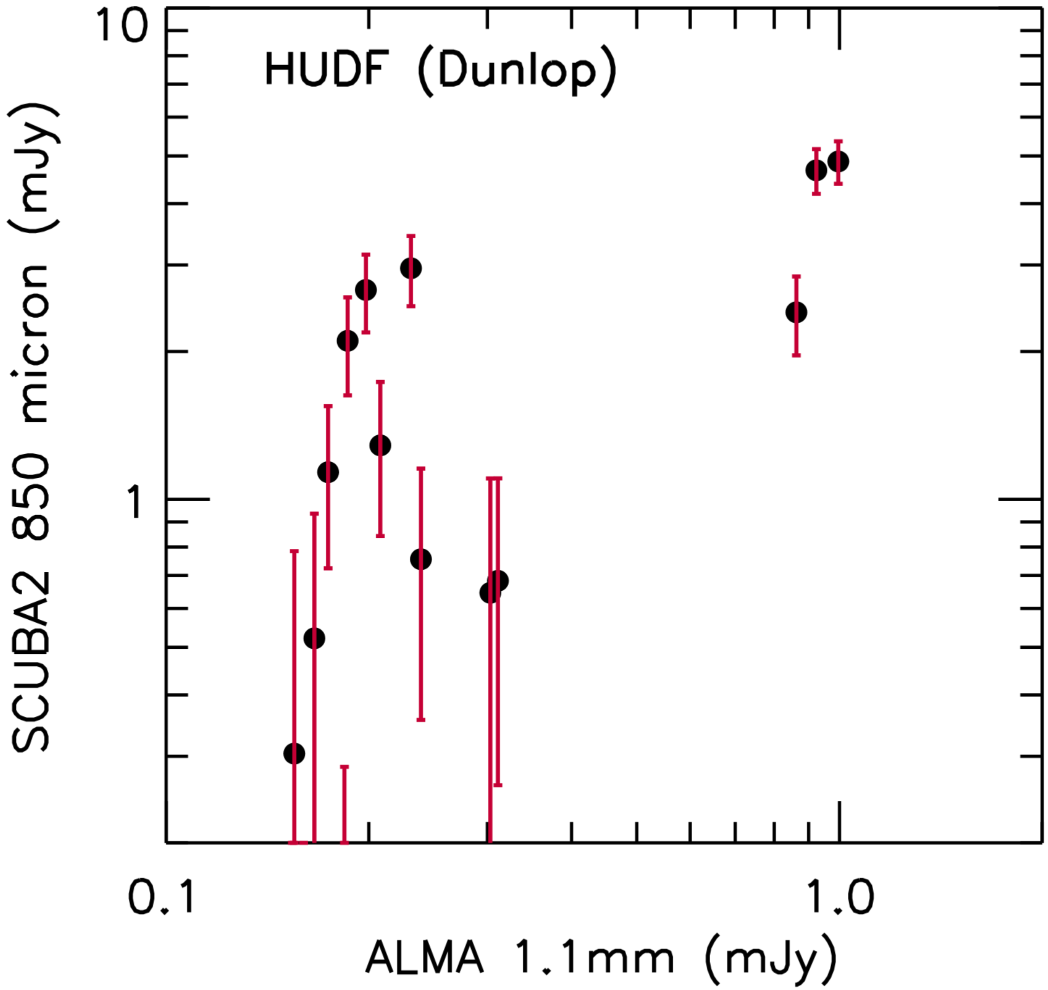
Dunlop et al. 2016; Walter et al. 2016 survey contained within (HUDF)



Note: Blank ALMA Surveys Go Deep, but Small Areas

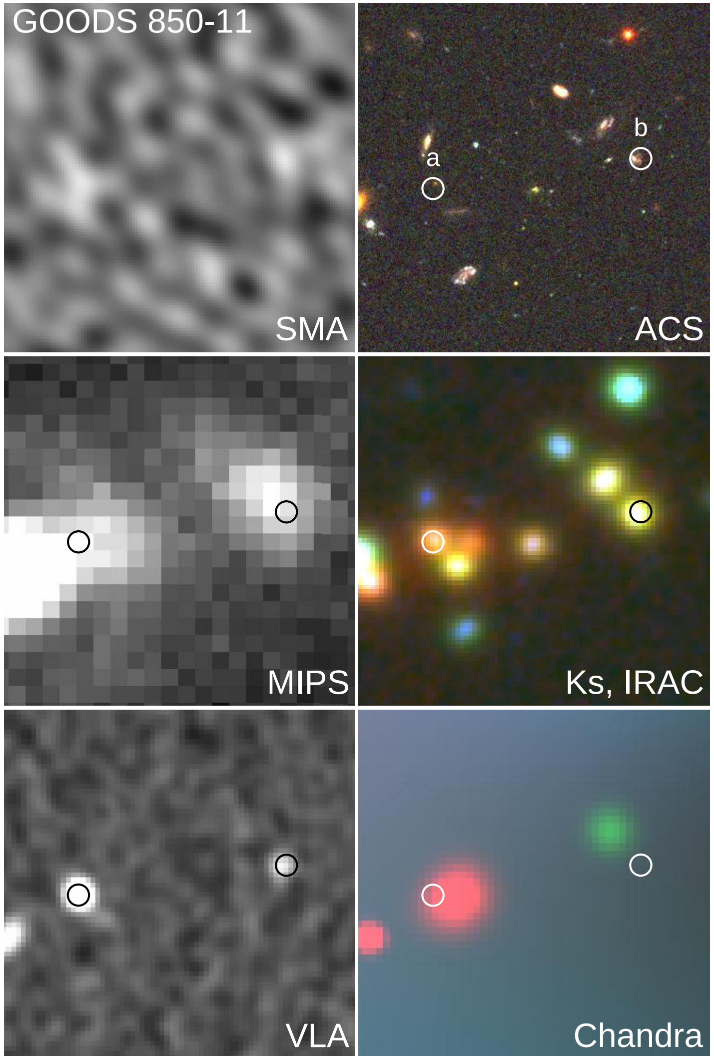
arXiv:1606.00227

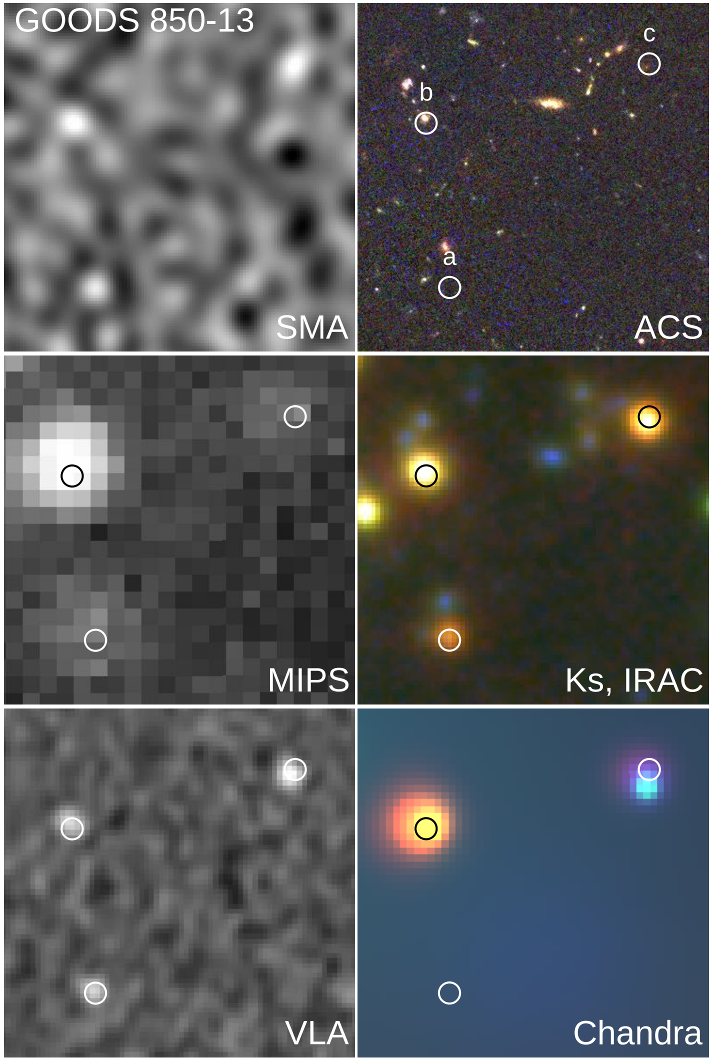
Dunlop et al. detects 16 (3.5σ) sources in the HUDF…6 are detected with SCUBA-2 including all 3 of the brighter sources



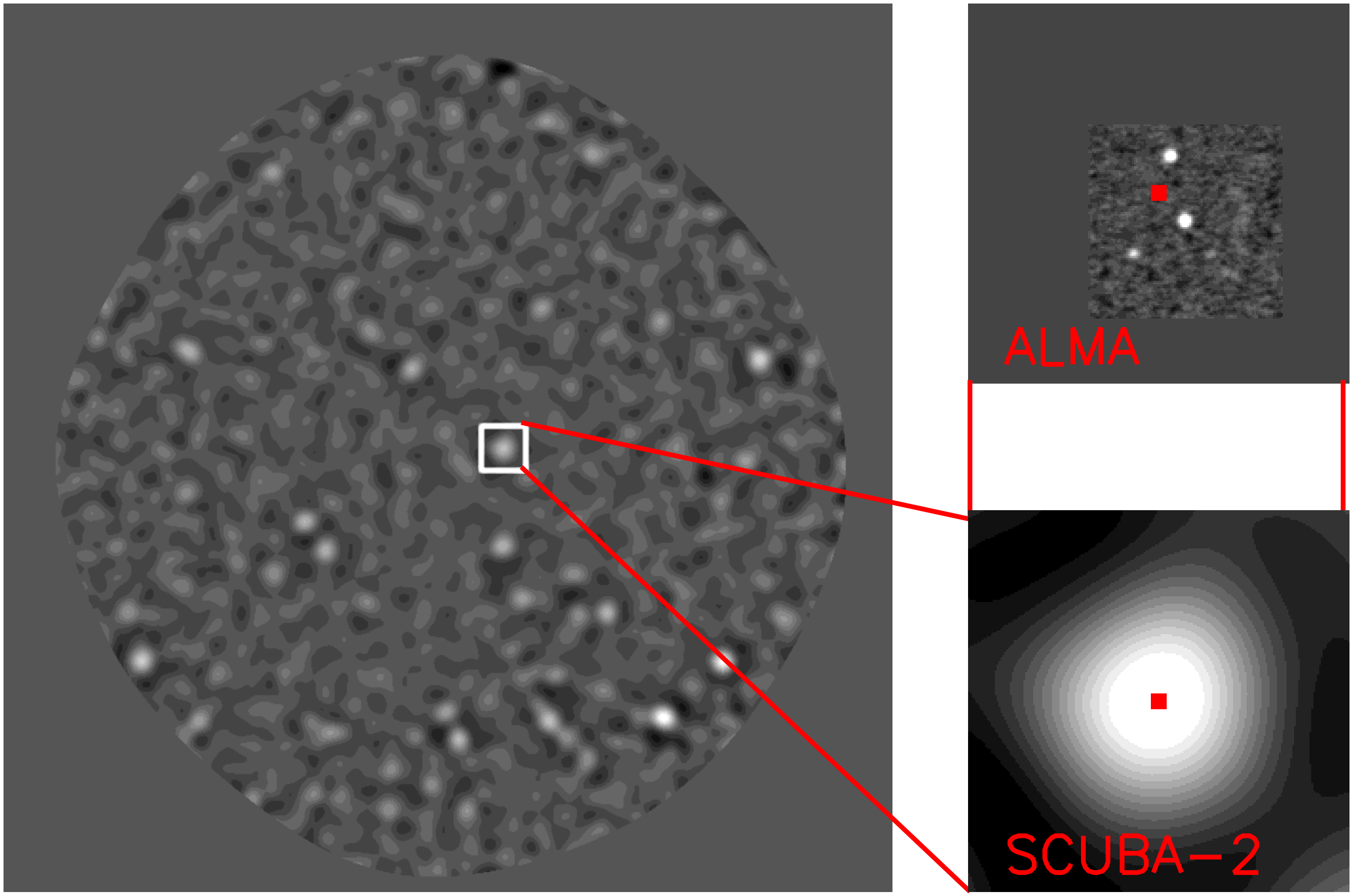
Interferometry Has Revealed Some Multiplicity

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





Triple corresponding to a submm source in GOODS-S



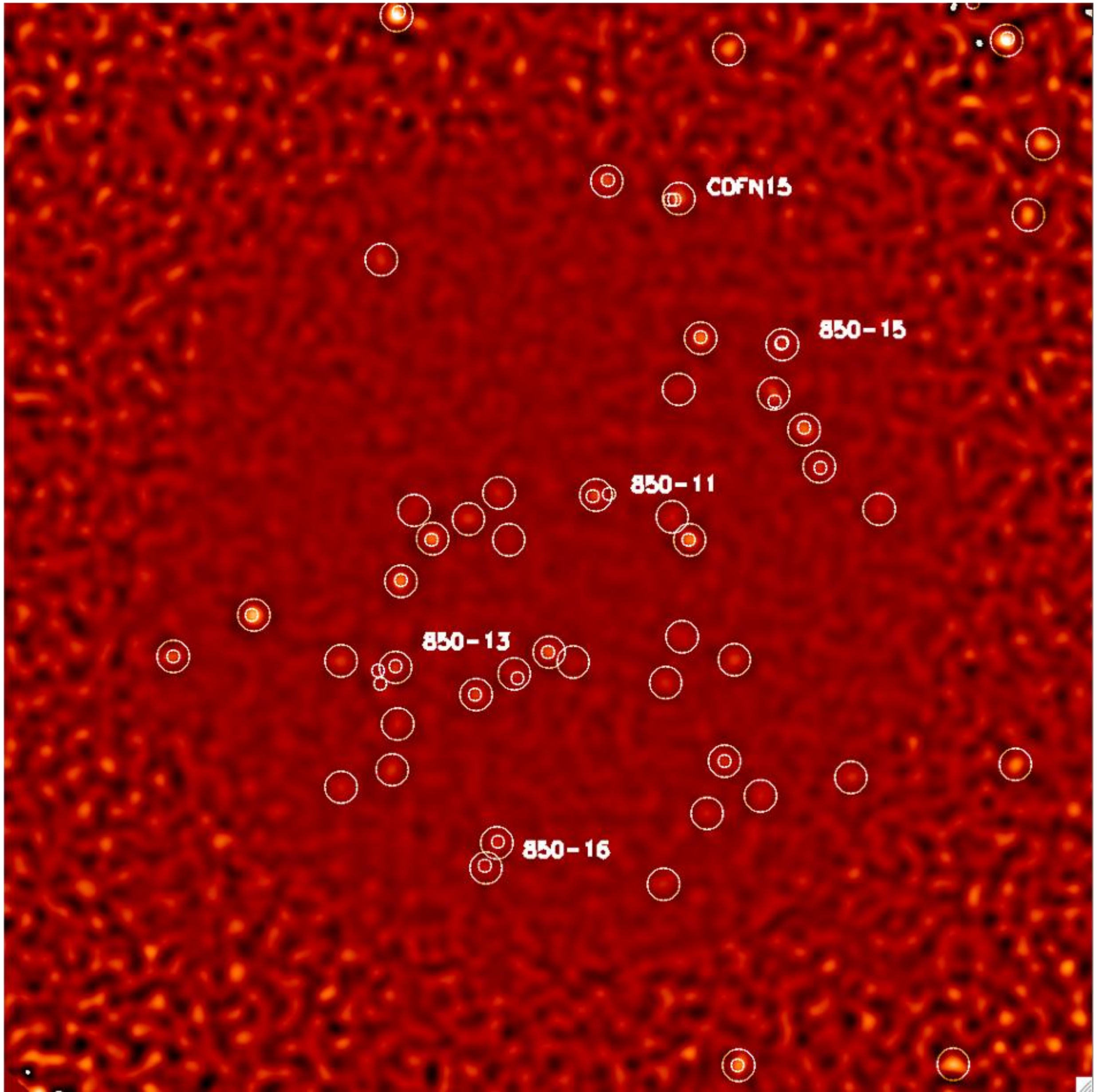
(ALMA observation from J. Mullaney)

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

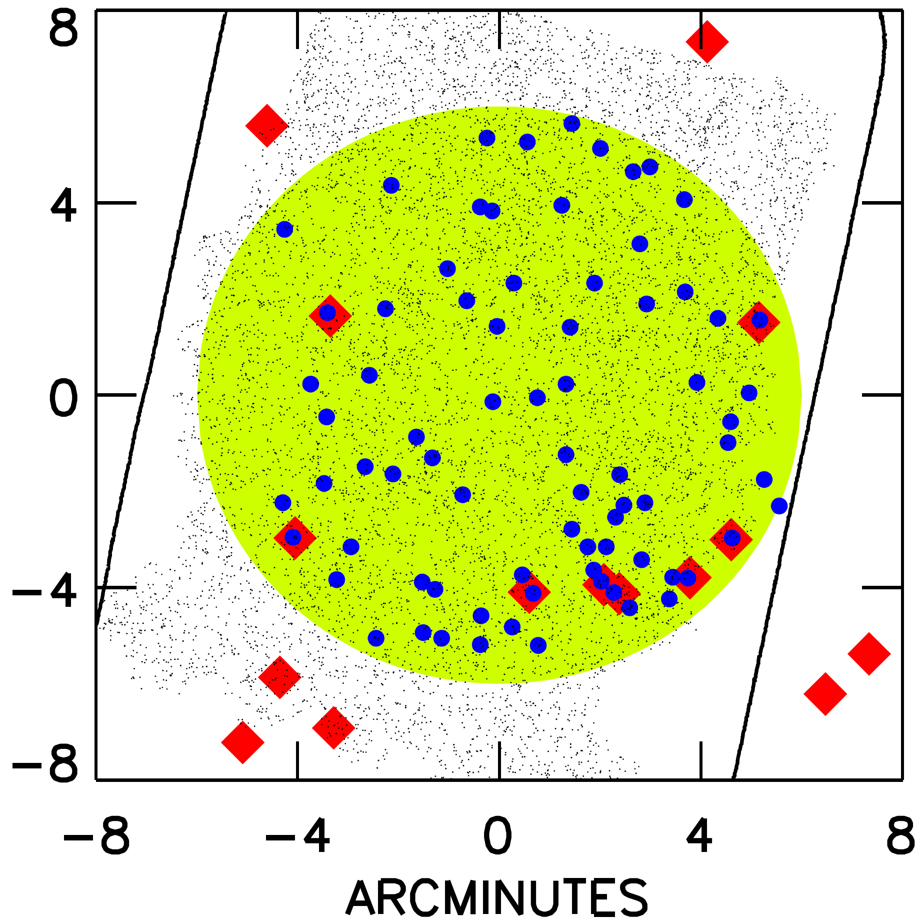
LABOCA (LESS; Weiss et al. 2009) was used to survey the CDF-S, and ALMA was used to follow-up the sources (ALESS; Hodge et al. 2013)

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

Red open = LESS; solid = ALESS

Blue = 4σ SCUBA-2

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



Is There a Maximum SFR?

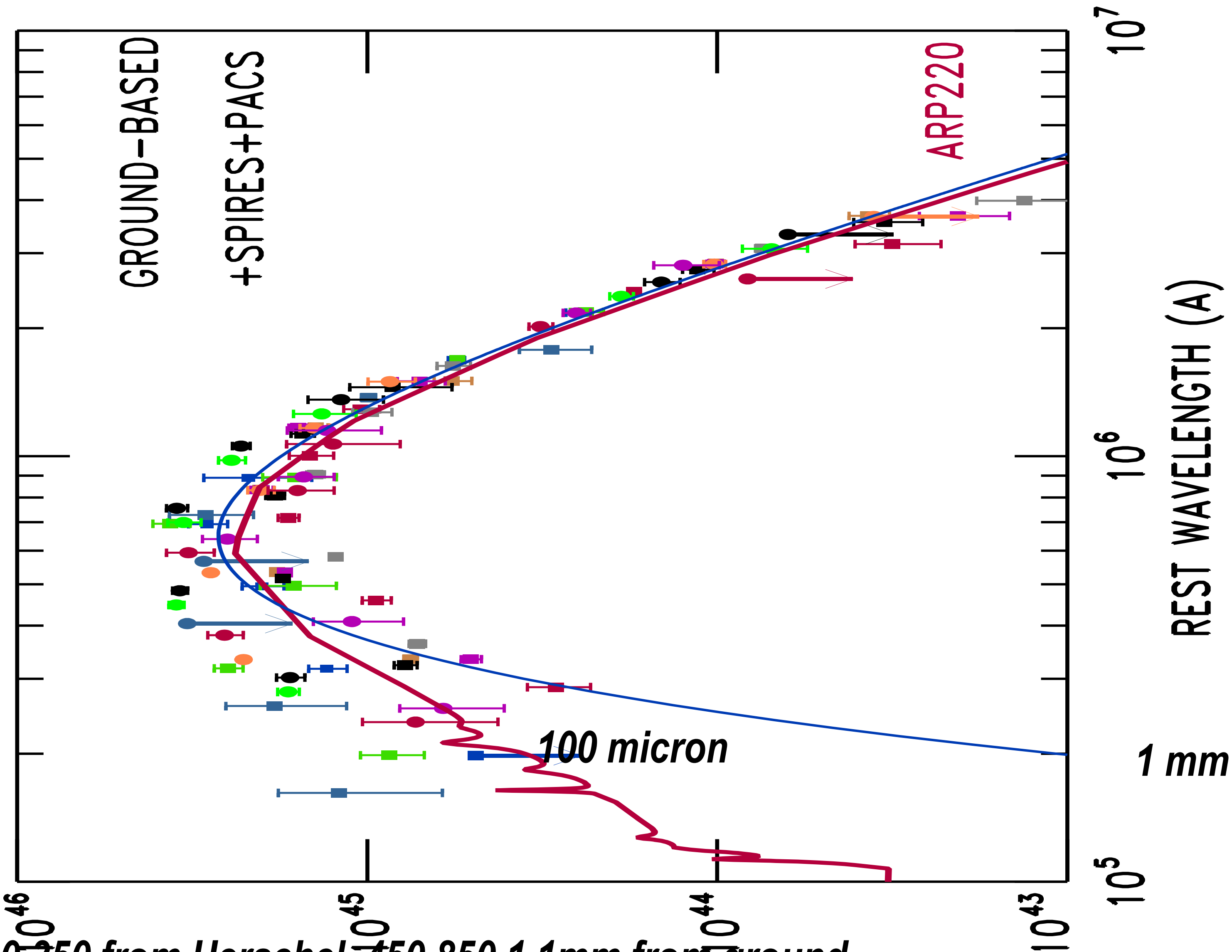
- All of the brightest ALESS sources ($S_{870\mu m}$>12 mJy) were found to be composed of emission from multiple fainter sources, each with $S_{870\mu m}$<9 mJy; no ALMA source was >9 mJy (Karim et al. 2013)

- 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*

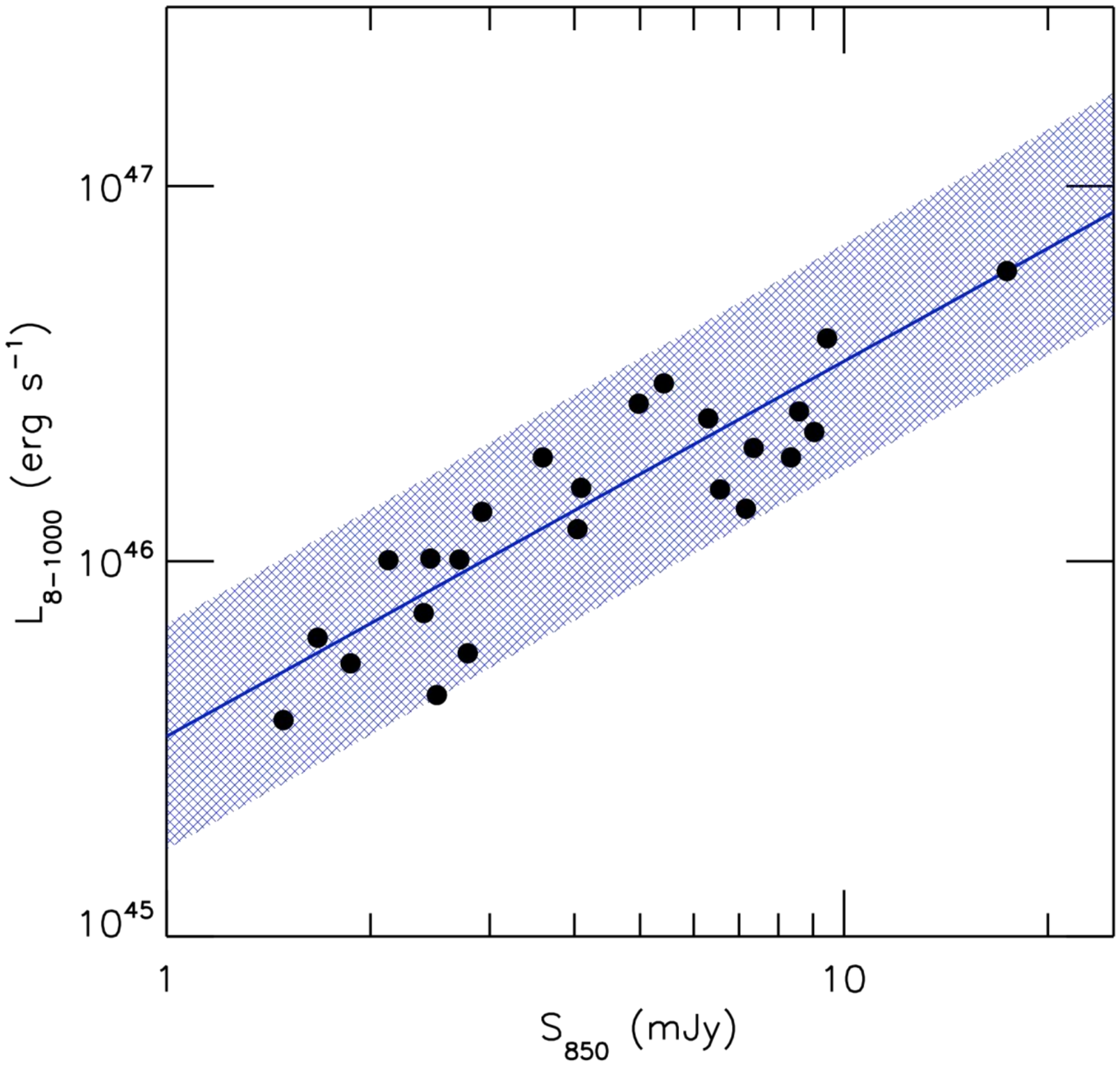
[LABOCA (19.2") has a larger beam size than SCUBA-2 (14"), so multiplicity or non-detections may be more common in LABOCA/ALMA observations than in SCUBA-2/SMA observations]

SEDs for 13 brightest SMGs in GOODS-N with spectroscopic redshifts lying in deep Herschel region:

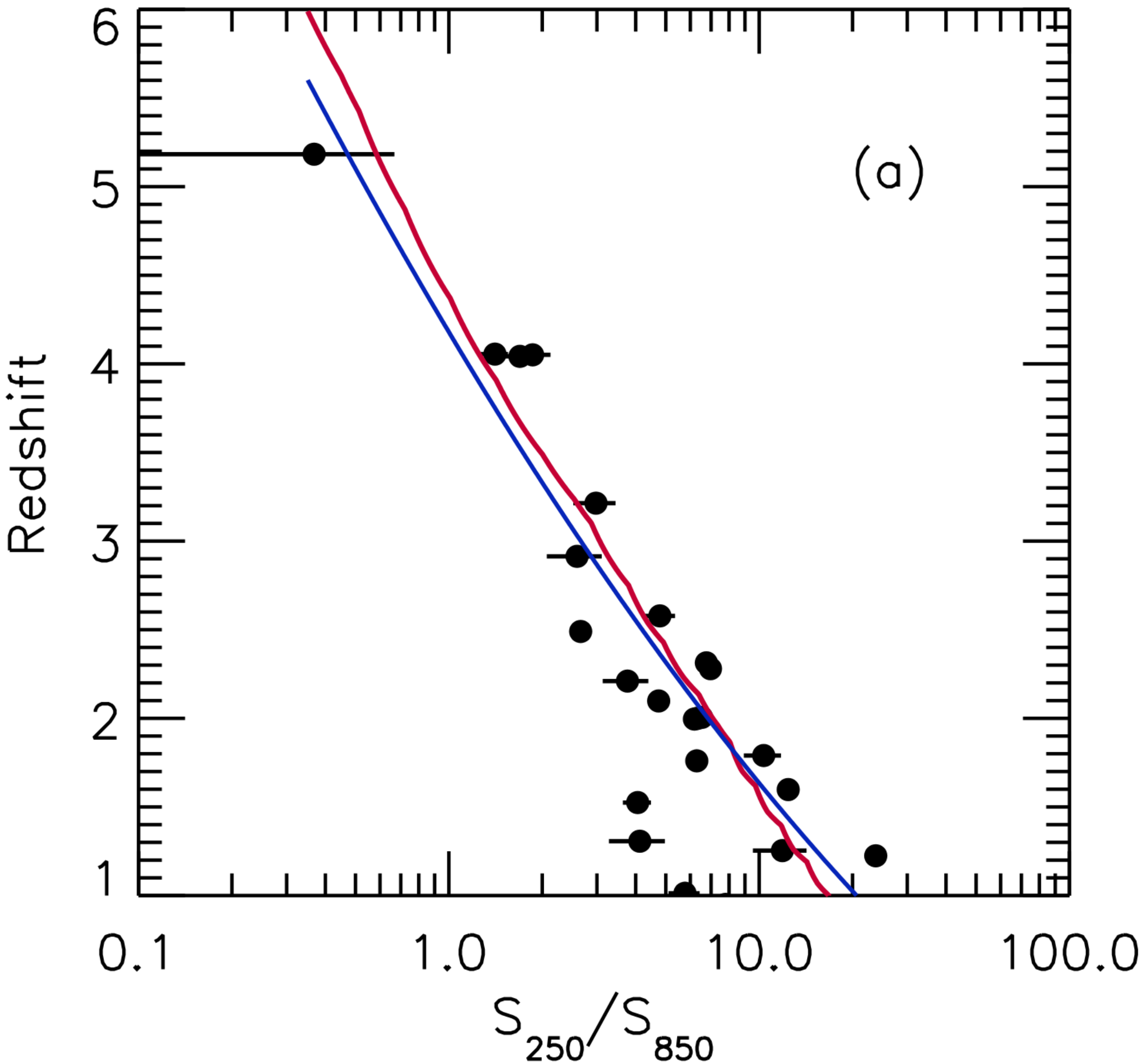


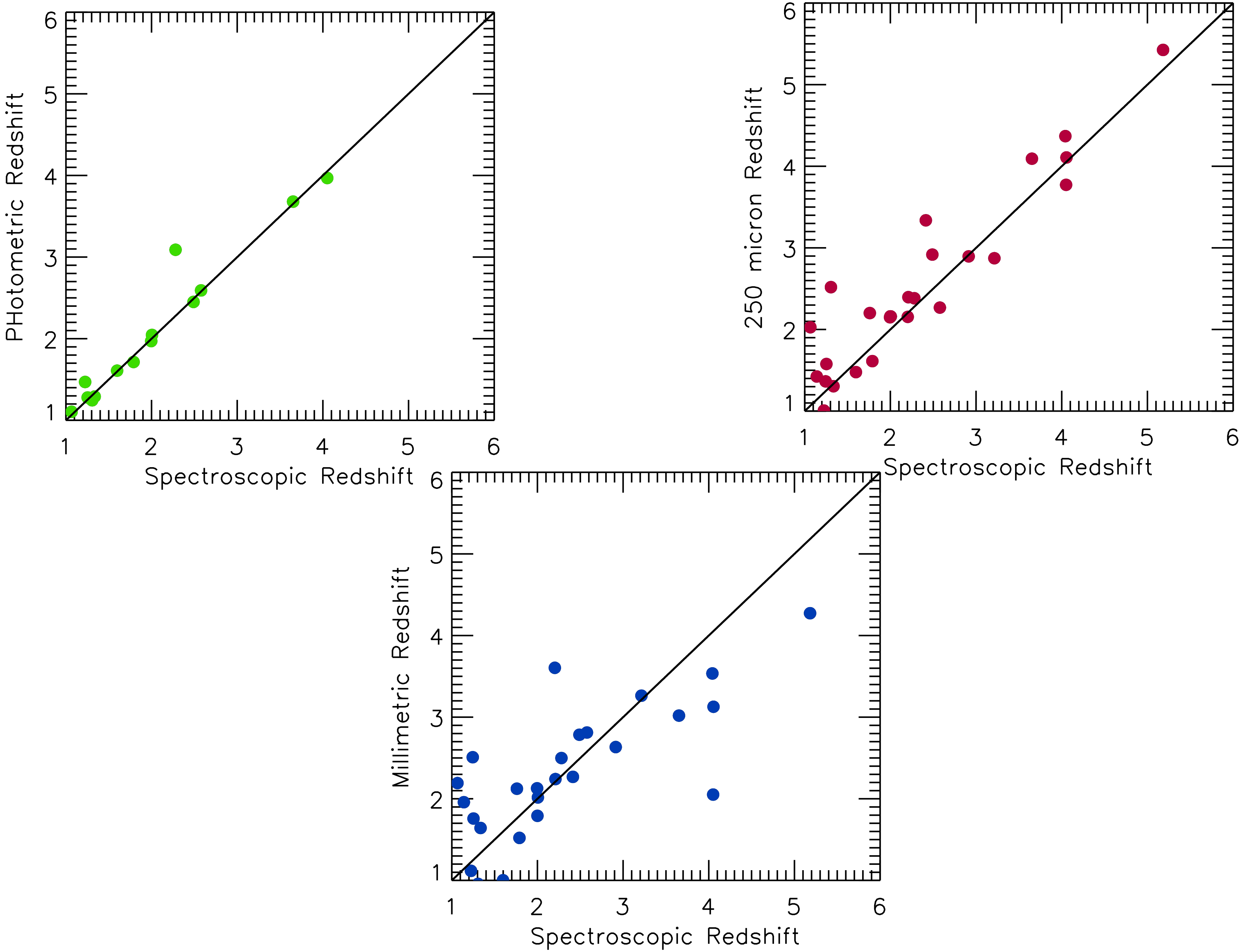
100,150,250,350 from Herschel, 450,850,1.1mm from ground

850 micron fluxes determine FIR luminosities to a factor of two



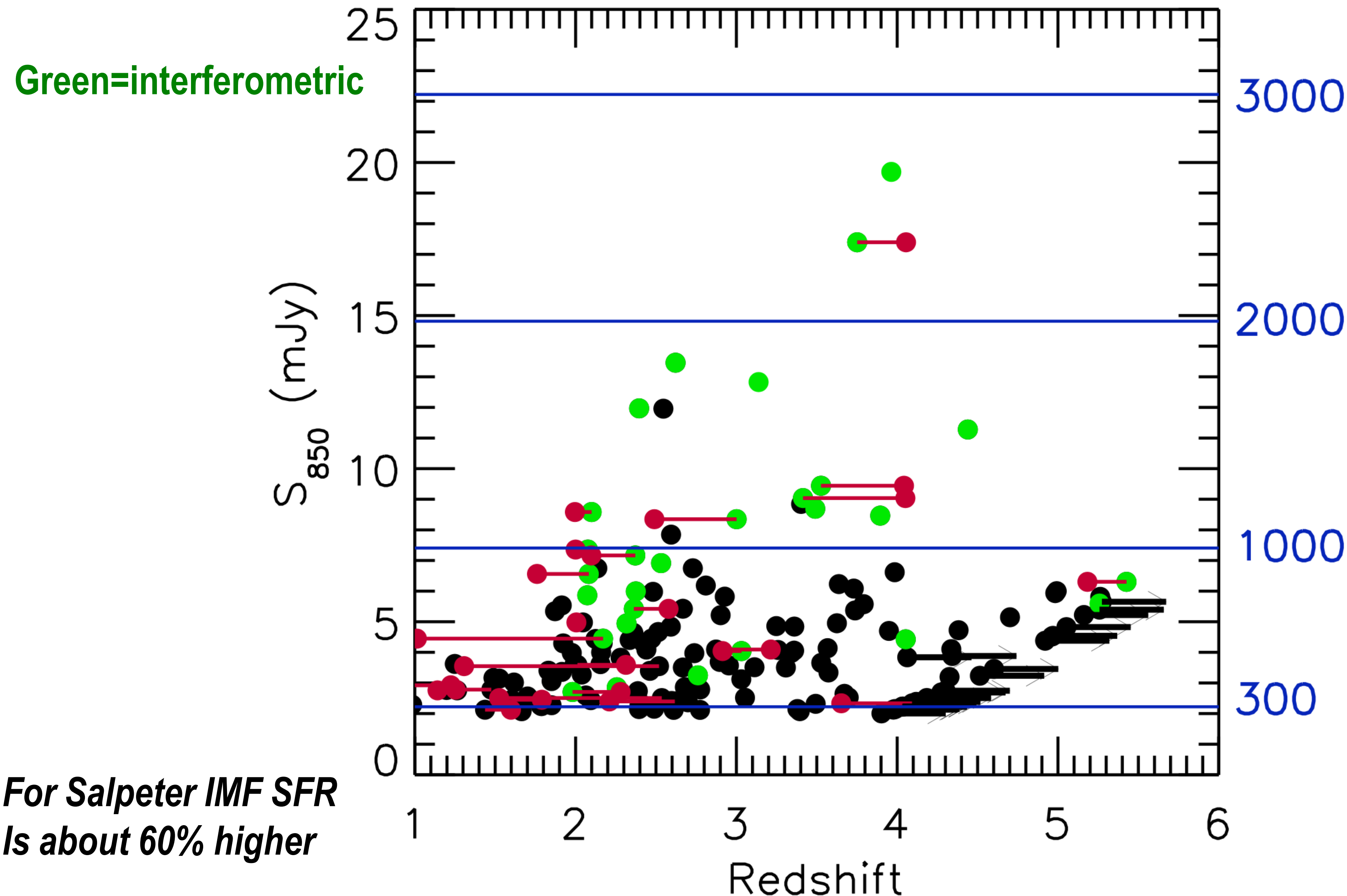
250/850 micron Ratio as Redshift Estimator



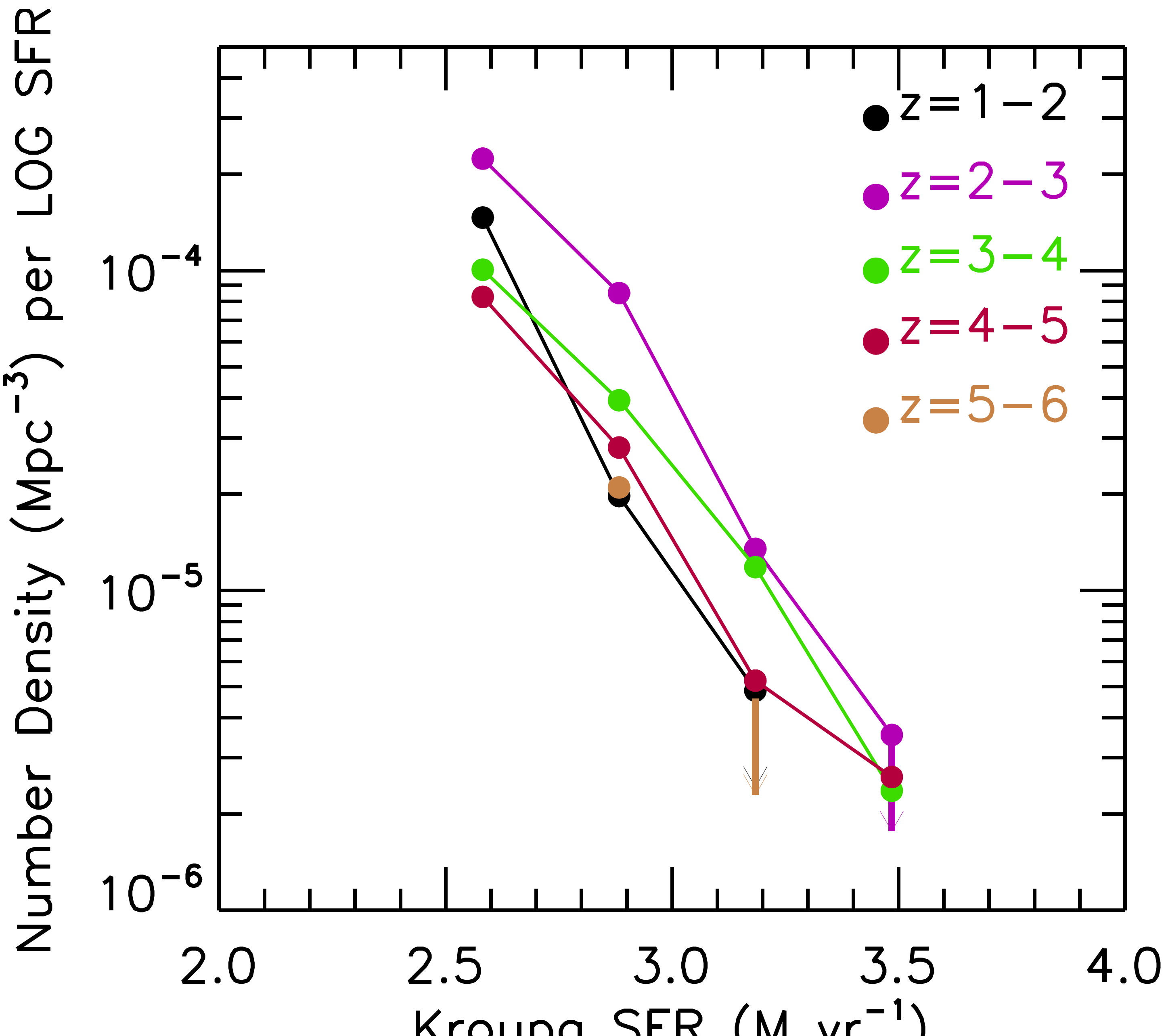


PHotometric Redshift
Spectroscopic Redshift
250 micron Redshift
Spectroscopic Redshift
Millimetric Redshift
Spectroscopic Redshift

The SFRs of the GOODS-N Submm Galaxies Range from 300 to 3000 M_{sun} /yr (Kroupa IMF)

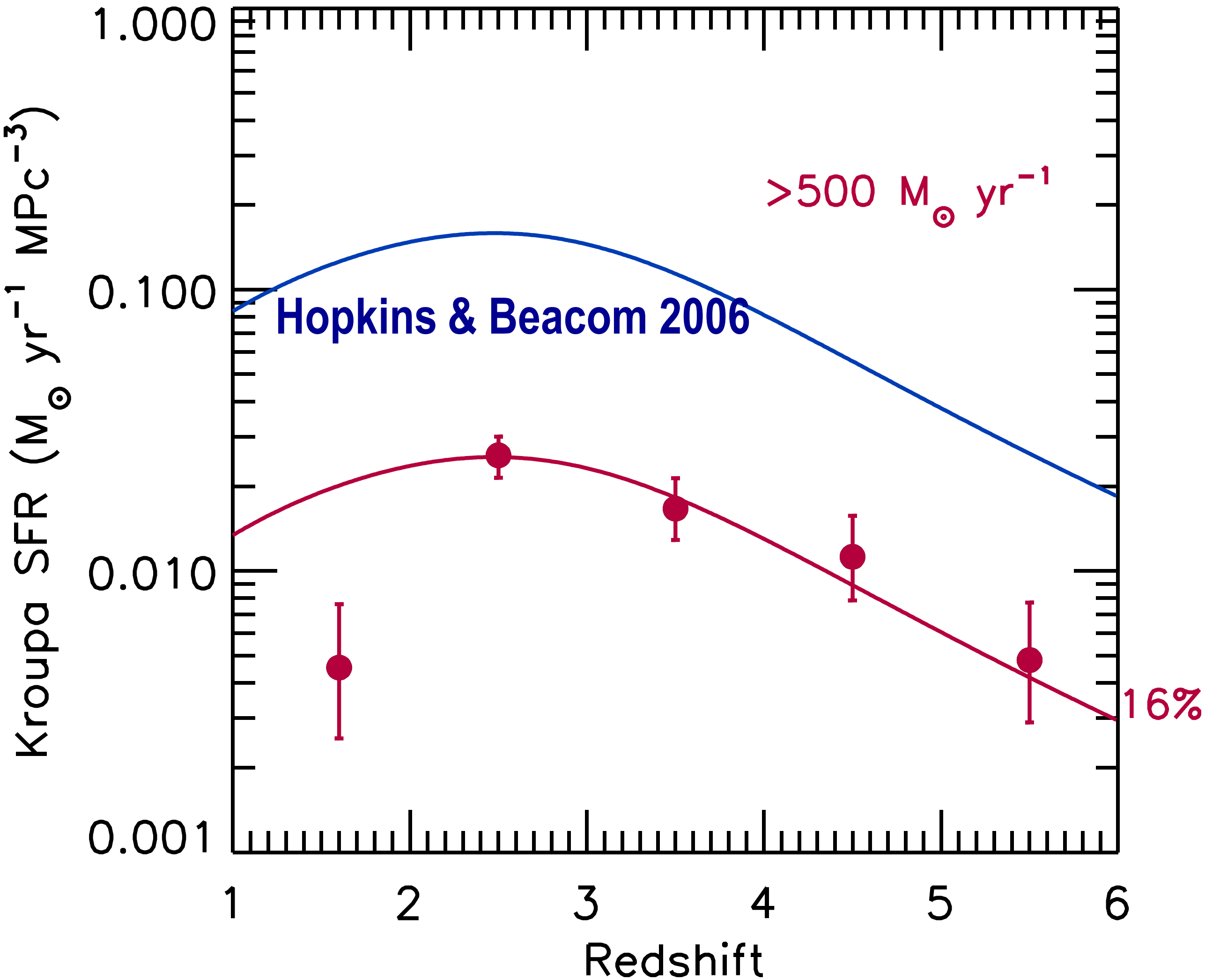


For Salpeter IMF SFR Is about 60% higher



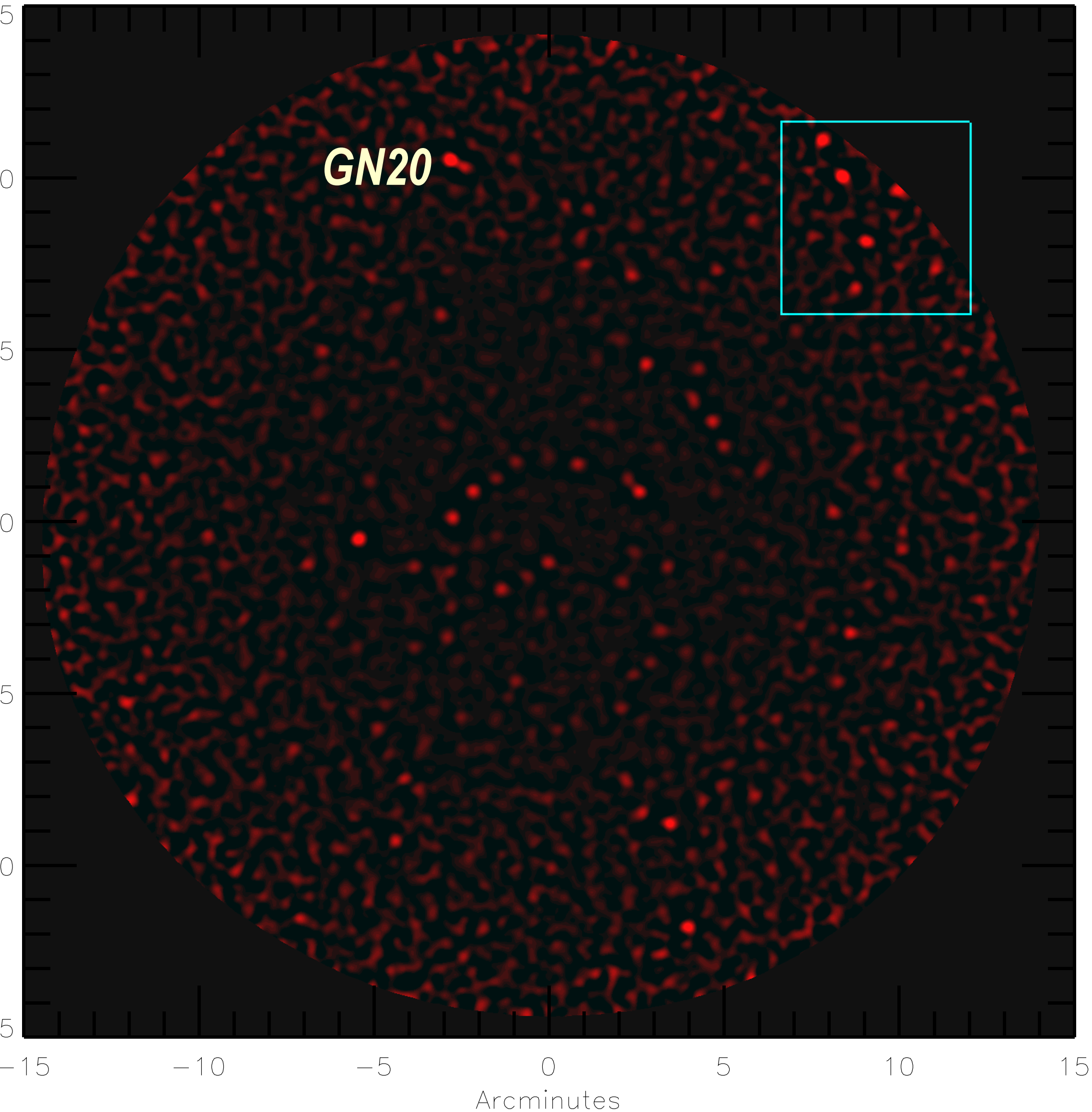
z=1−2
z=2−3
z=3−4
z=4−5
z=5−6
10^{-4}
10^{-5}
10^{-6}
2.0
2.5
3.0
3.5
4.0
Number Density (Mpc^{-3}) per LOG SFR
Kroupa SFR (M yr^{-1})

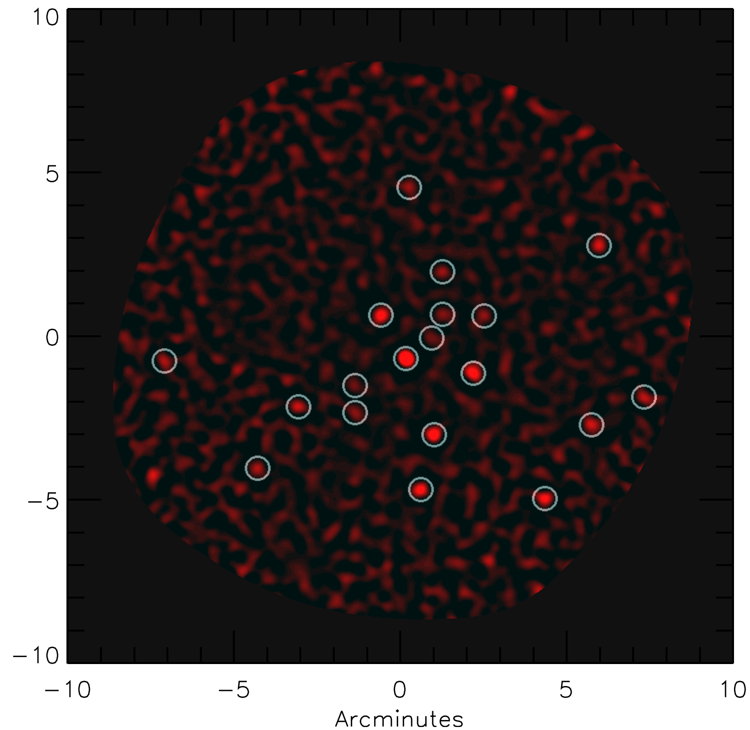
A large and relatively invariant fraction of the overall SFR density is contained in these massively star-forming galaxies, and this is true at all redshifts to beyond z=5



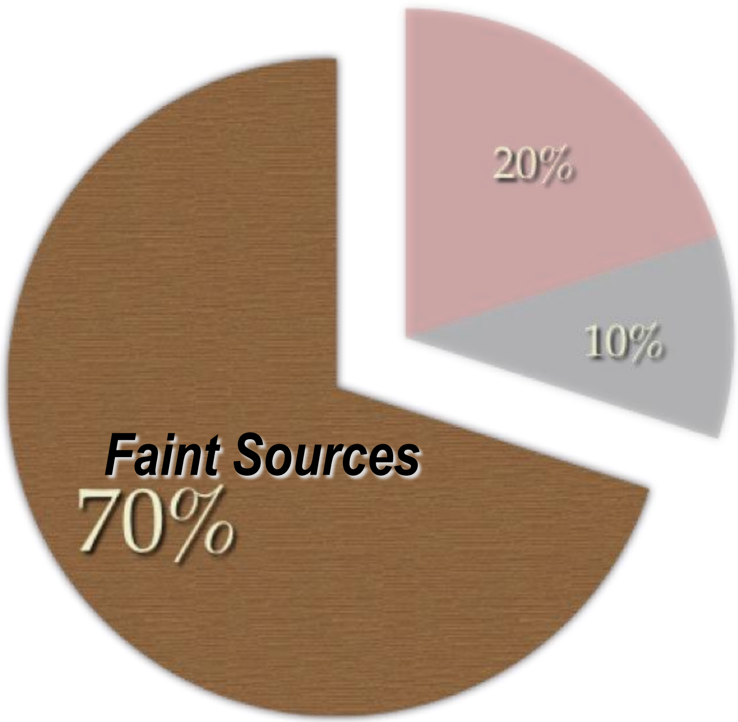
Since the samples are disjoint, the two contributions need to be added!

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



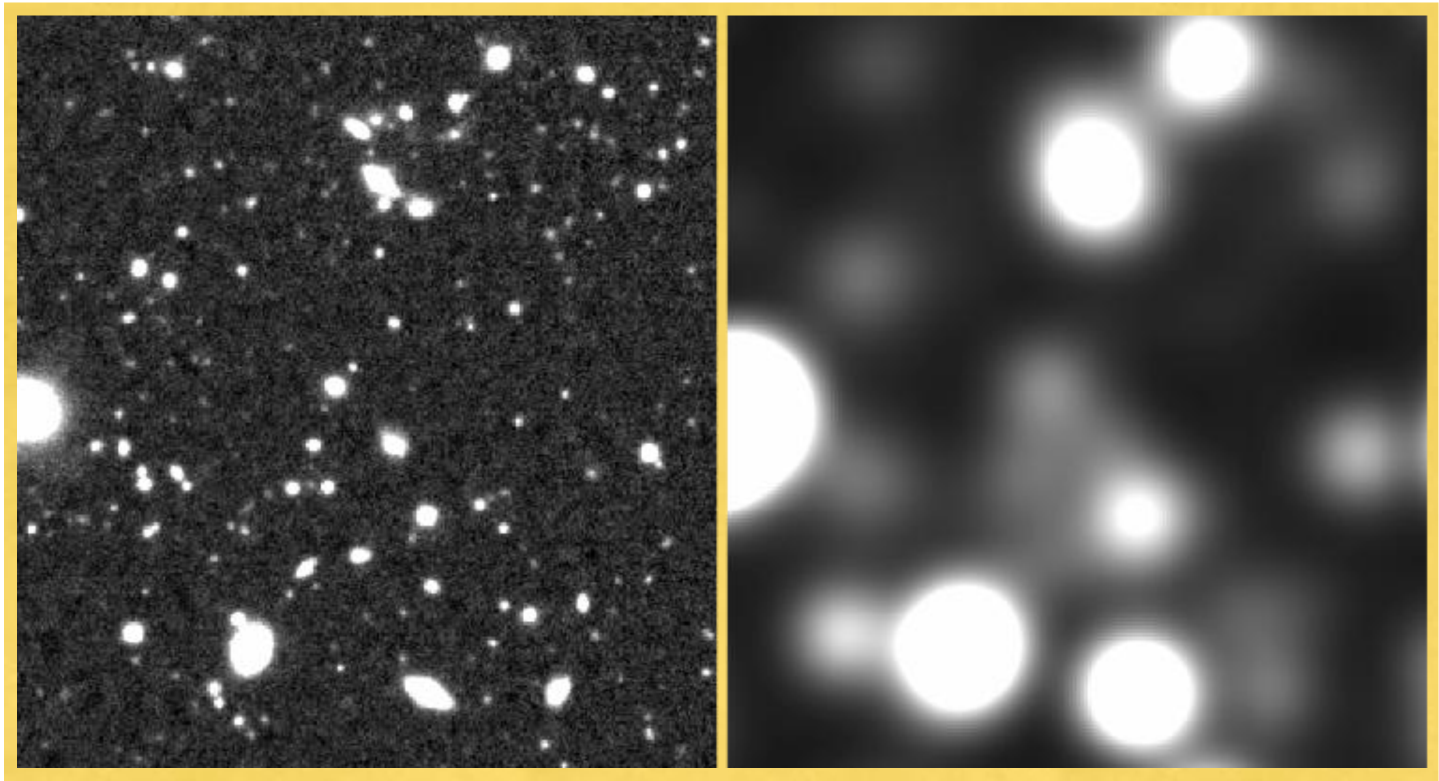


But might we be missing yet further contributions in the UV samples?



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

Not confusion limited. Integrating longer can detect fainter sources.

15" FWHM

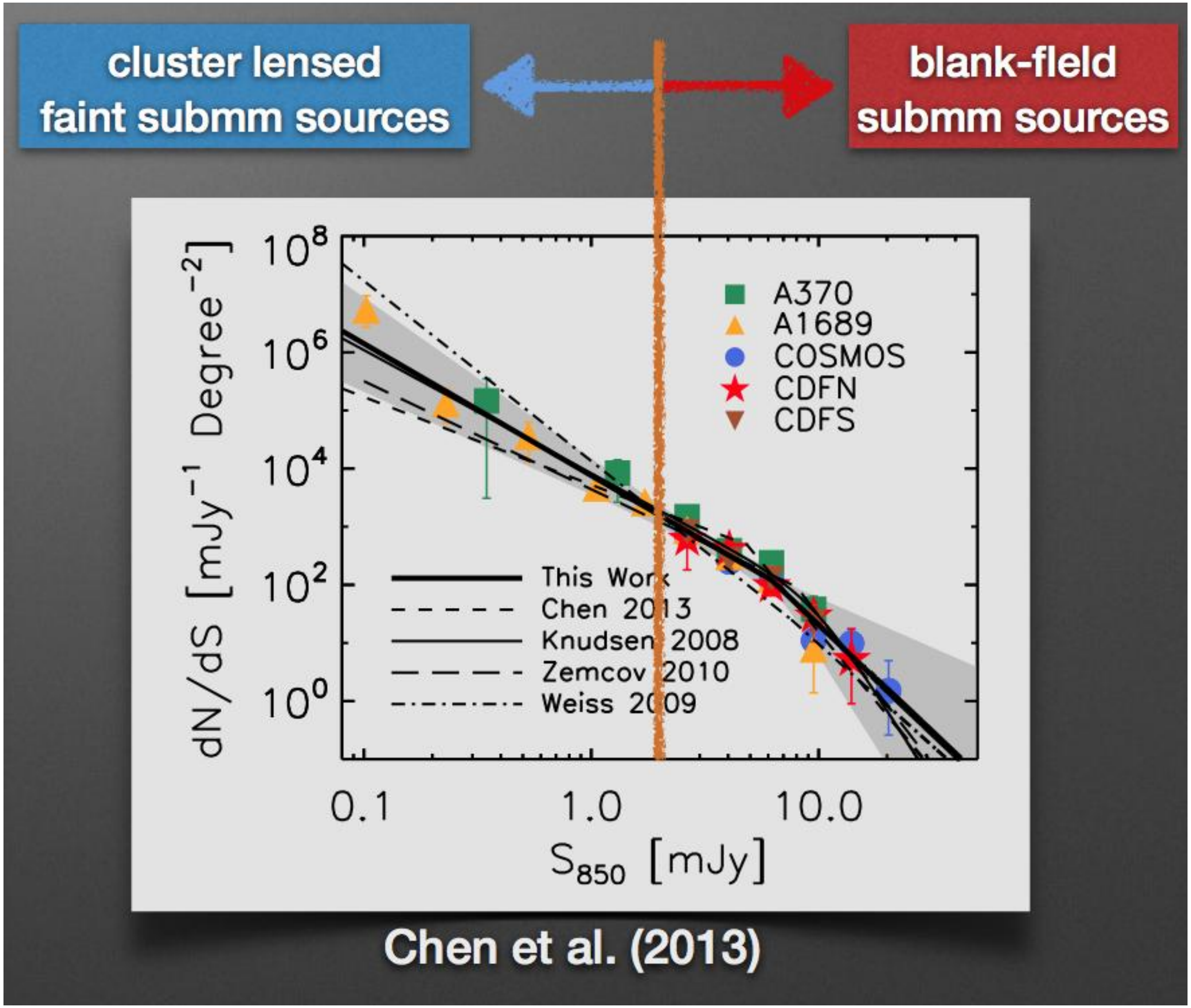
Confusion limited. Integrating longer can NOT detect fainter sources.

Breaking the Confusion Limit

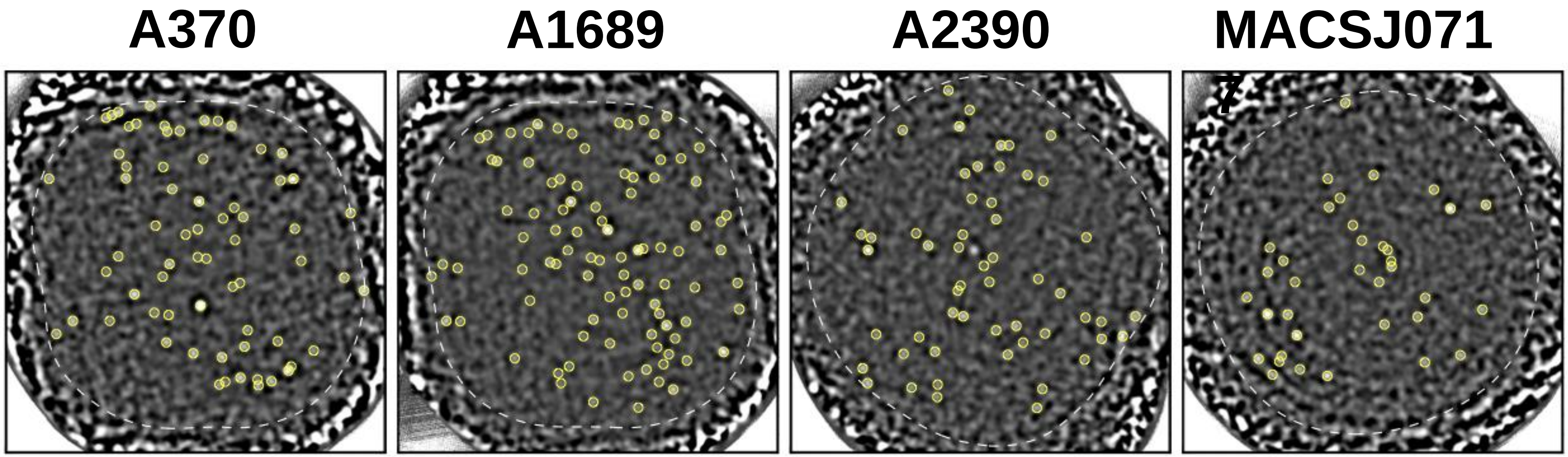
To get to these fainter submm fluxes, we need to go beyond the confusion limit

We can do this with interferometers, but again we suffer from the small field problem (Dunlops sample of 16 objects all have optical/IR counterparts… Bouwens (arXiv:1606.05280) only detected a handful of LBGs in the HUDF all at relatively low redshift z~2)

The alternative is to observe behind massive clusters of galaxies, (HST Frontier fields) where the magnification and source plane expansion allows us to detect fainter submm galaxies. This has the advantage that the optical/NIR and radio are also magnified



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

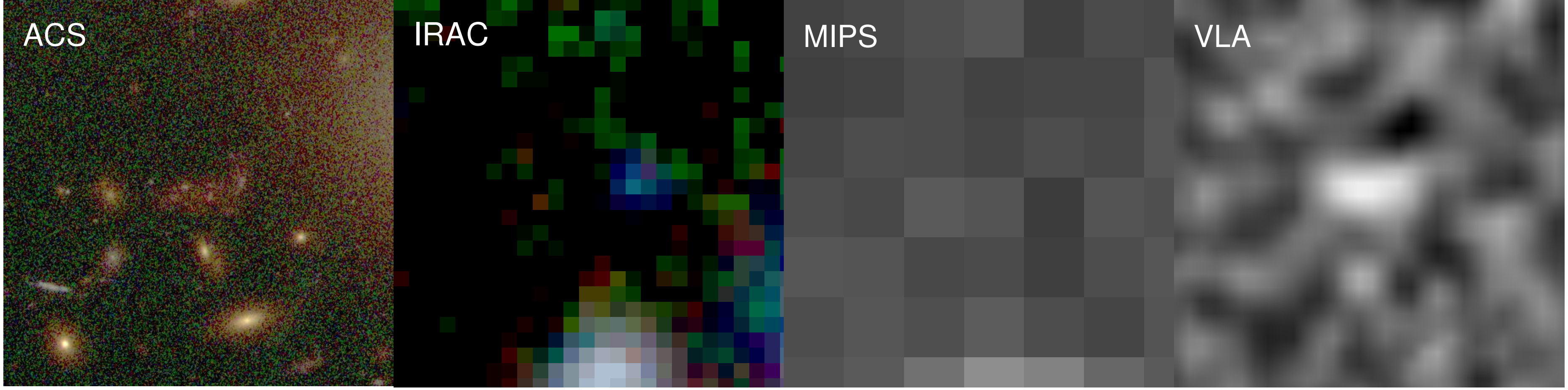


Images: 14′ x 14′ (>10 hrs; goal is 1σ of ~0.3 mJy at 850 and 2.5 mJy at 450)

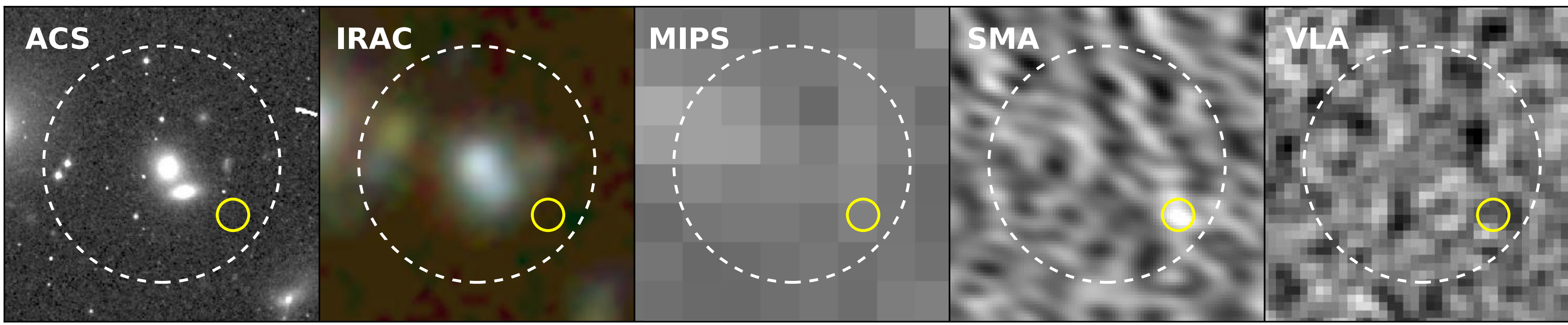
All 5 SMGs detected in Chen et al. (2014) with the SMA have intrinsic fluxes ~0.1-0.8 mJy (SFR~20-160 $M_\odot$/yr), the region of critical interest for tying together the galaxies seen in the rest-frame UV selected samples with those seen in the submm samples

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

Summary

- Submm galaxies have SFRs up to 3000 M_{Sun} yr^{-1} over z=1.5-6 (extinction corrected UV-selected galaxies only reach ~300 M_{Sun} yr^{-1})

- 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

  – But sample sizes are still small, and more observations are needed. These are coming soon (or just arriving) from both ALMA and the frontier field clusters

The End

Conclusions: Star Formation History Not Complete

- The most luminous star formers are mostly disjoint from the UV selected samples: they extend to very high SFRs … at least 3000 solar masses/yr for a Kroupa IMF

- There is emerging evidence that even at lower luminosities there are some star-forming galaxies that are missing from the UV samples

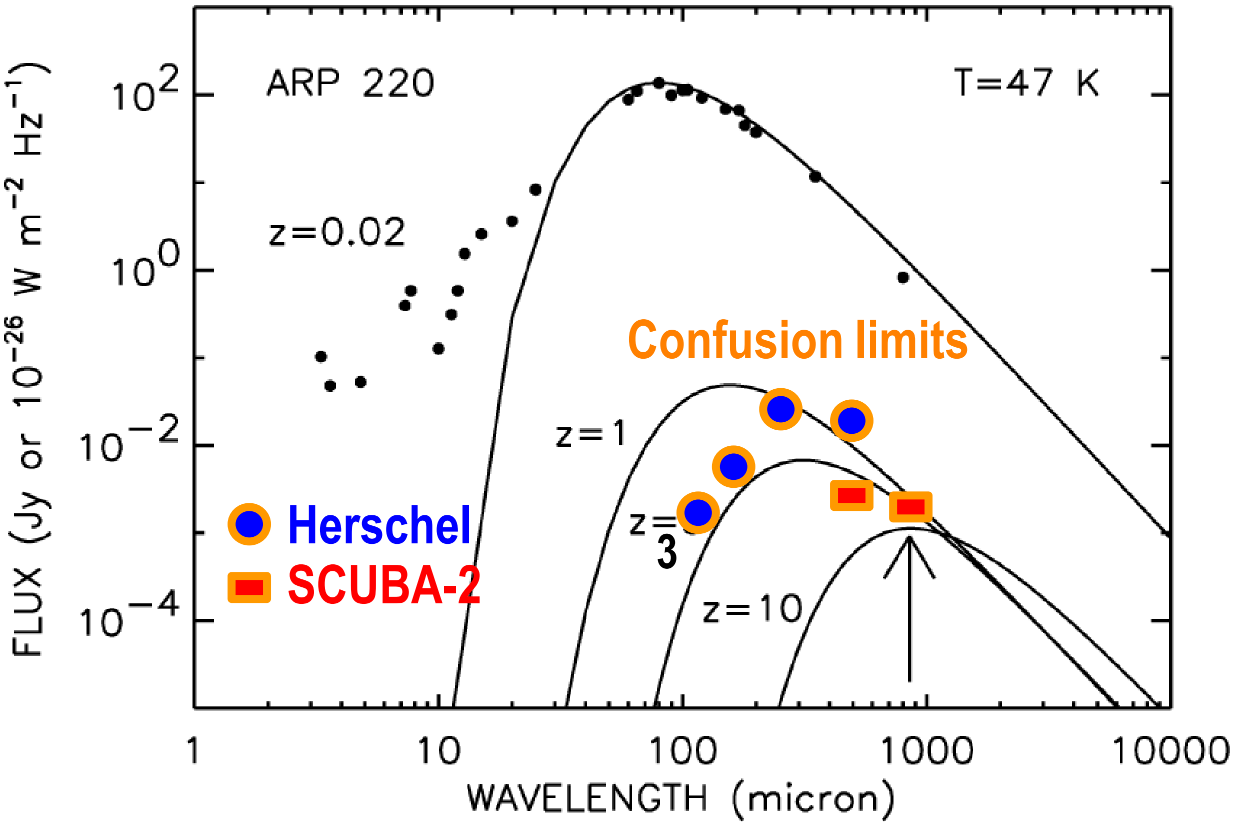
- These could be at high redshifts

- But sample sizes are still small, and more observations are needed. These are coming soon from both ALMA and the frontier field clusters

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

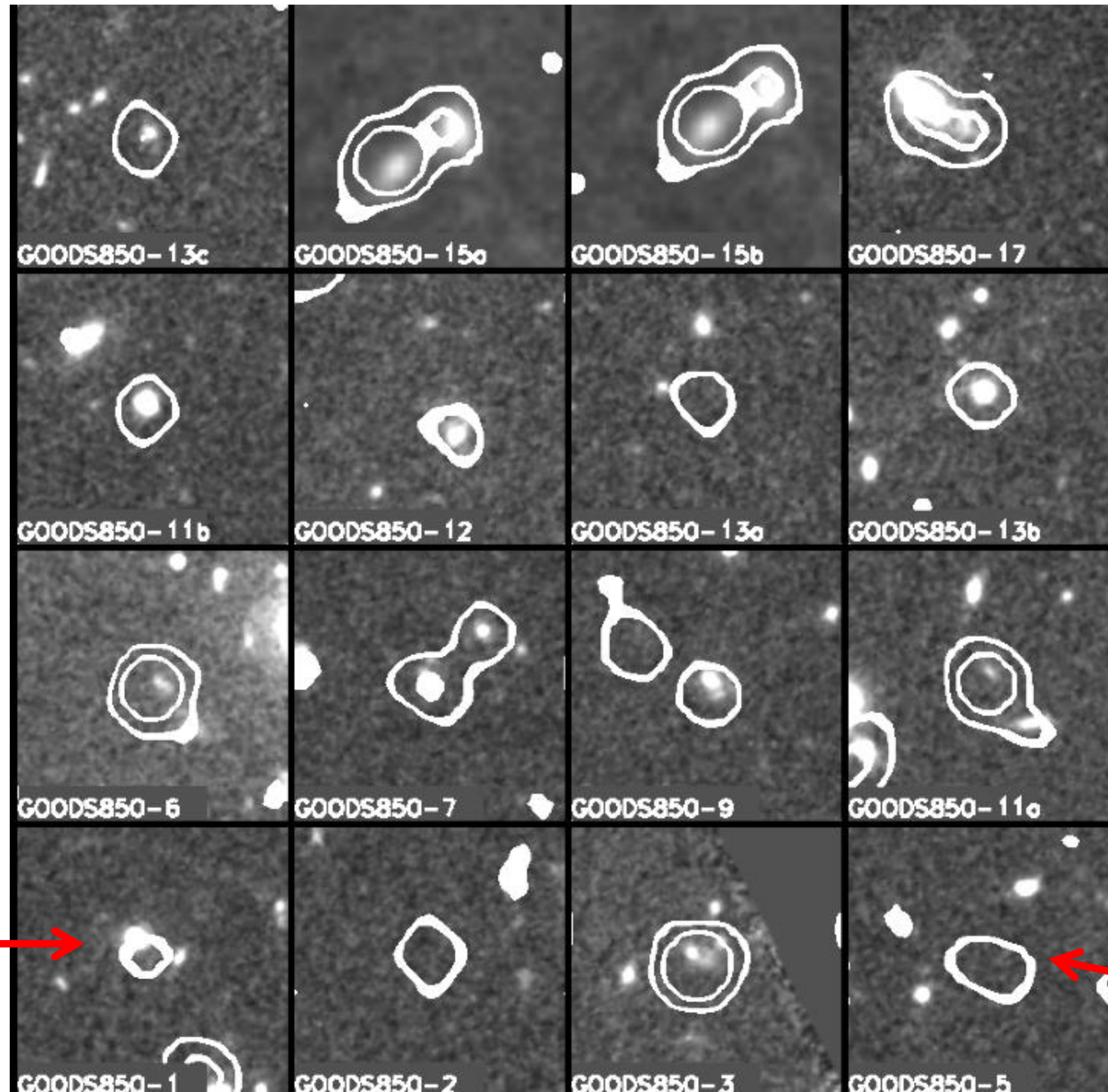
However, *Herschel* hits the confusion limit faster than ground based instruments at longer wavelengths (3.5 m telescope vs 15 m JCMT), so it is best to search for very high z dusty galaxies with ground based mm/submm observations



Confusion limits shown for 10 beams per source

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



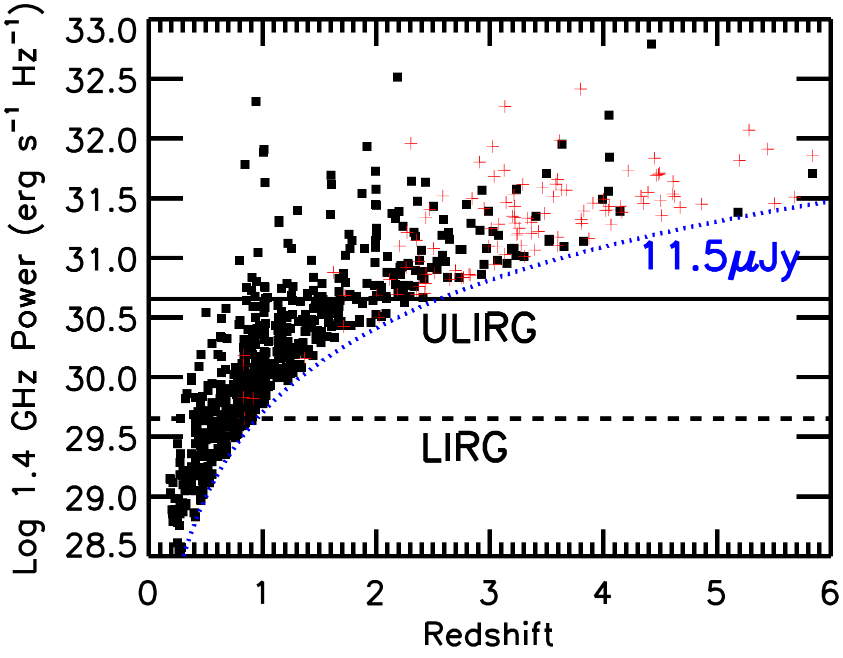
HDF850.1
z=5.183

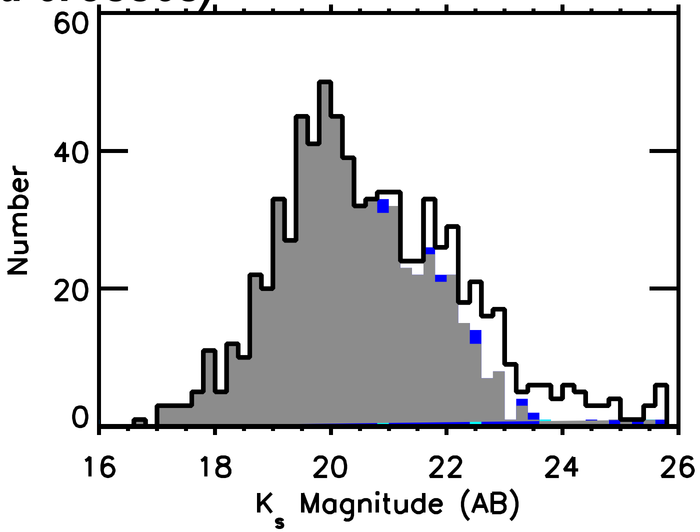
z=4.04

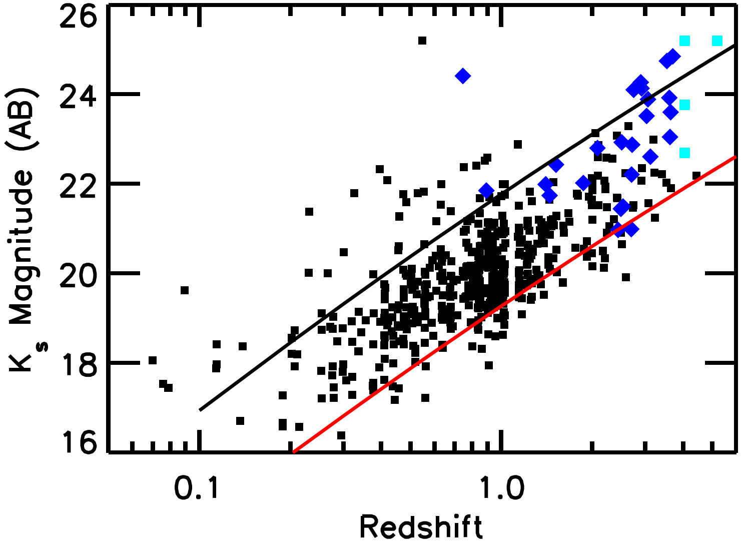
Current radio limits bias against high z

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

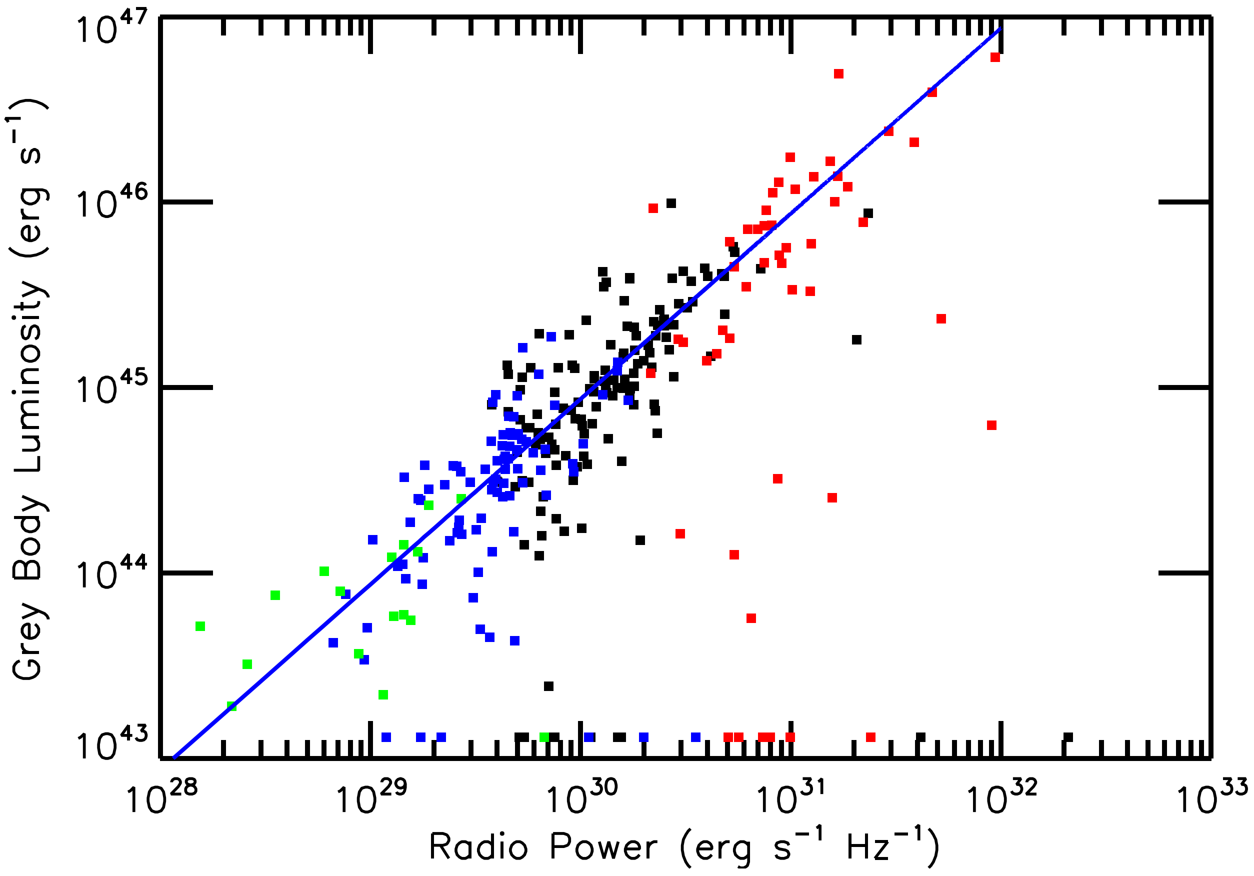
70% spectroscopic complete
85% with phot-z
Remainder K band faint
K-z relationships suggests missing objects are high z (red crosses)





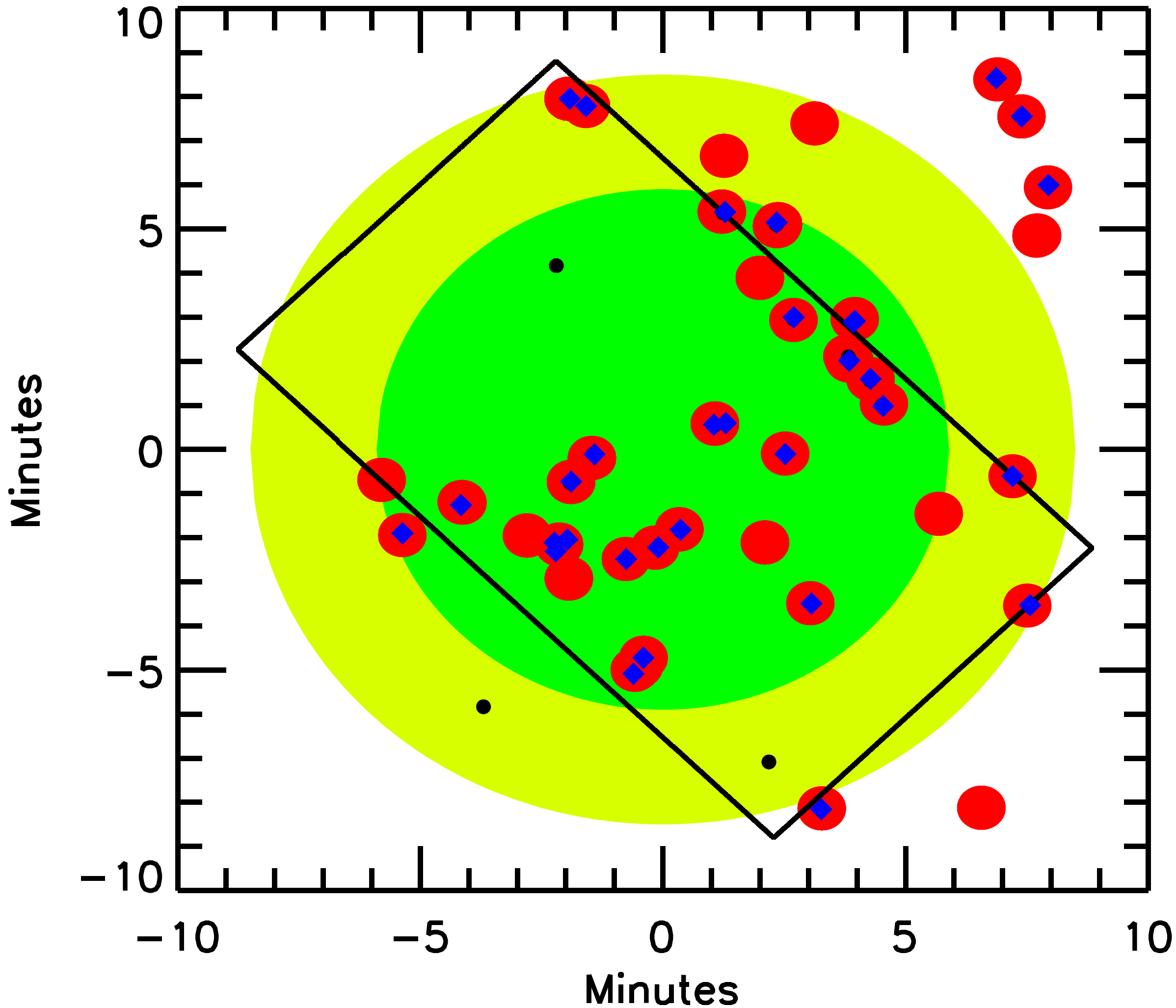


Radio-Fir correlation



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

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



SCUBA-2 5mJy

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

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

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

Red: 24" radius

Rectangle: GOODS-N HST

SFR Distribution Function

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