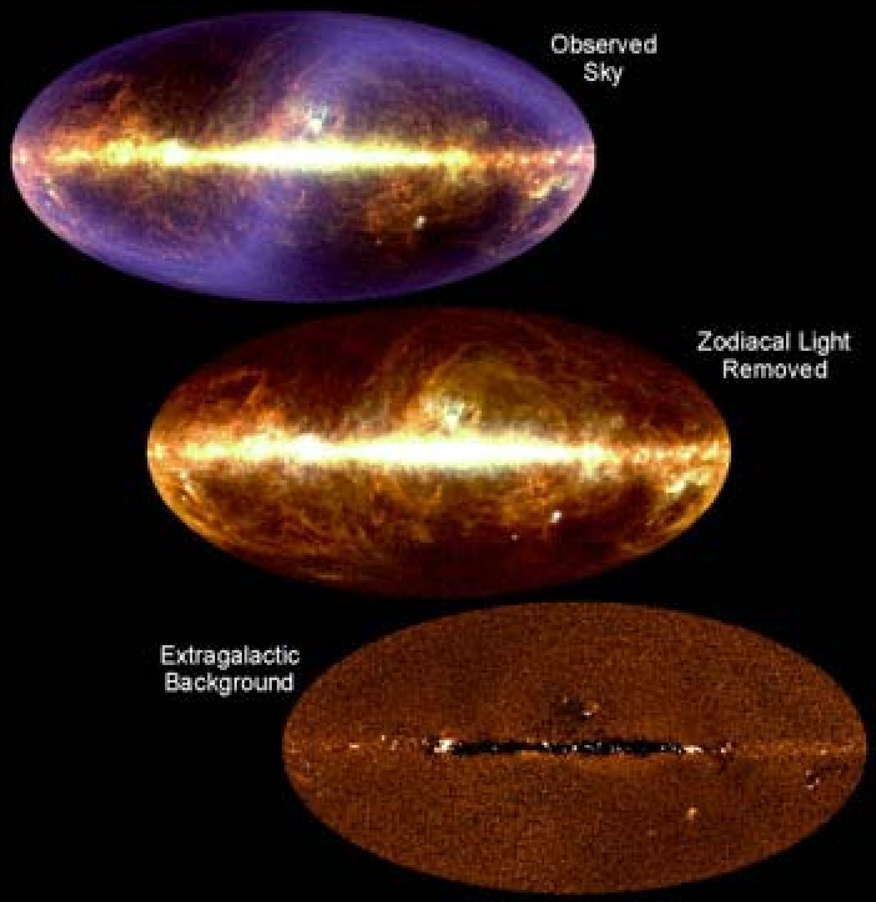
Do High Redshift galaxy studies have a dark future?

or... do submillimeter galaxies dominate the star formation in the z>>3 universe?

(Thanks to Wei-Hao Wang and Amy Barger for much of the material in the presentation...)

Submm/Far-IR EBL

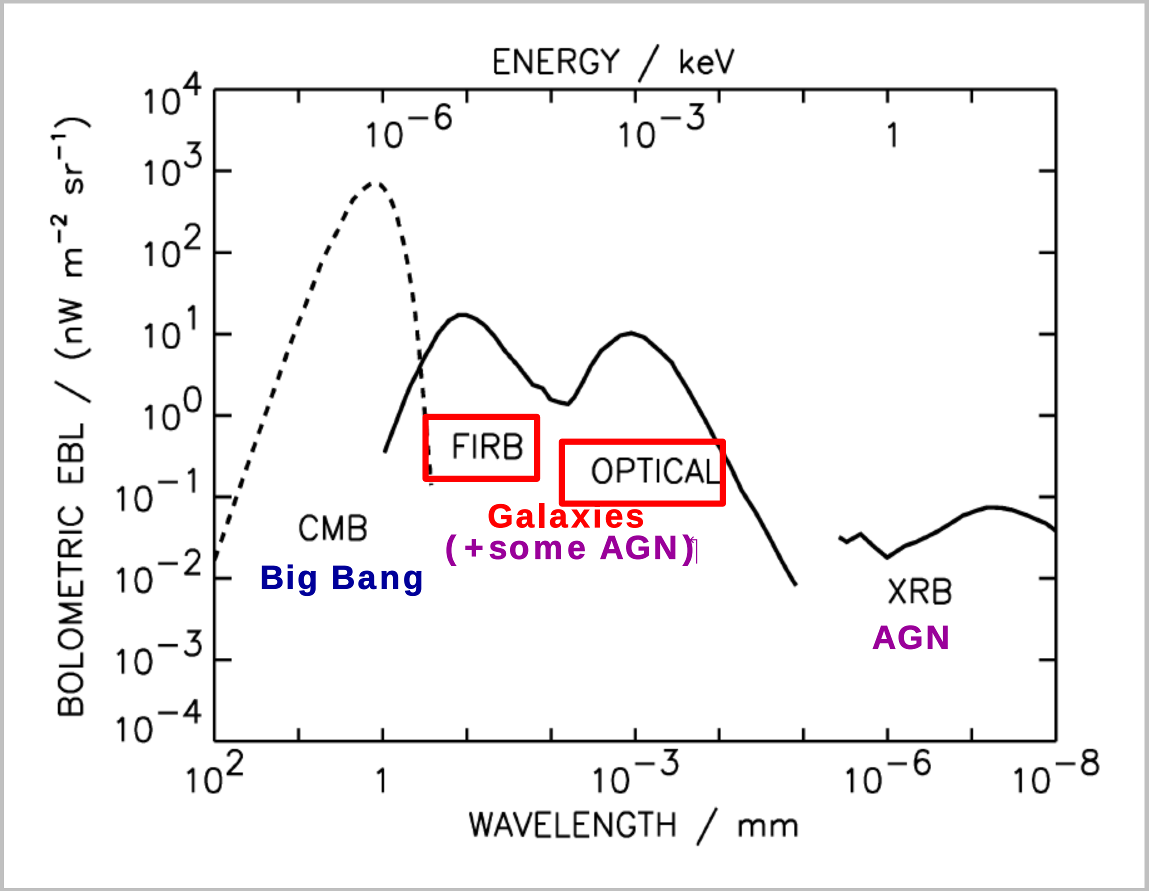
COBE/DIRBE



The submm EBL at 850 μm:
31 Jy/deg^2 (Puget et al. 1996)
44 Jy/deg^2 (Fixsen et al. 1998)

Uncertainties come from foreground subtraction.

Most of the galaxy/AGN energy produced in the universe emerges in the FIR and optical

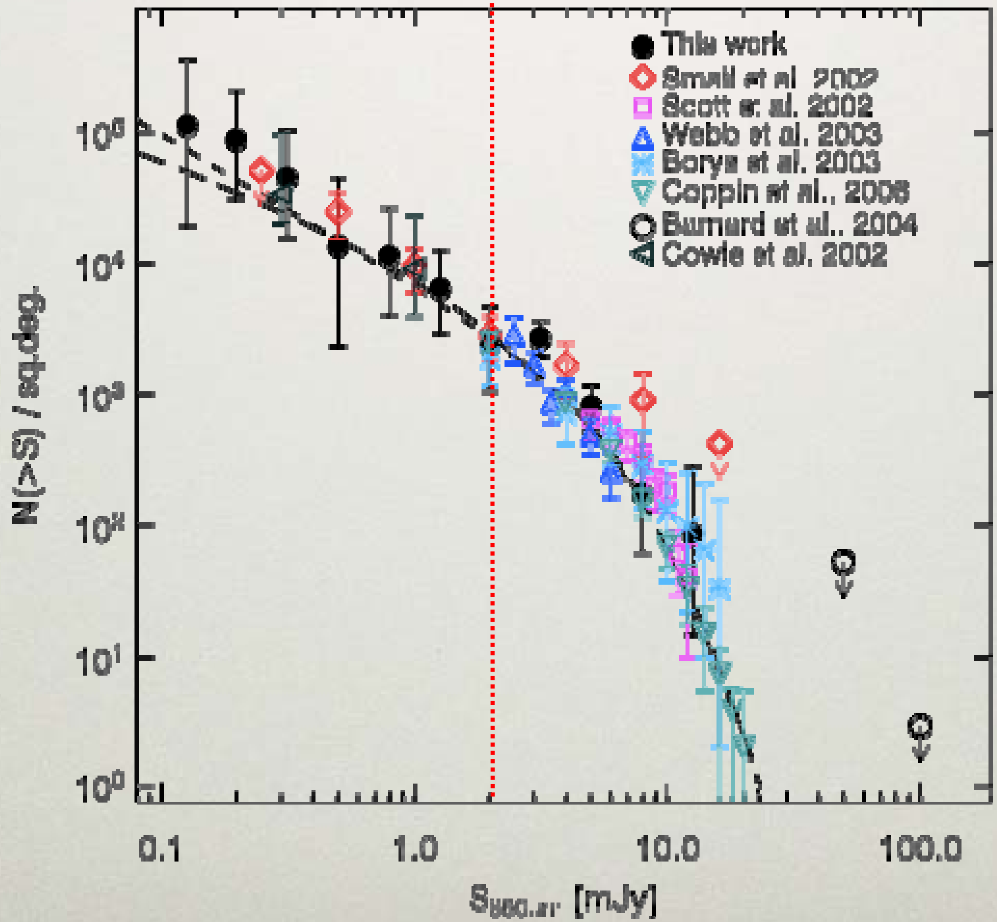


Comparable amounts of light in the FIR and optical backgrounds mean comparable amounts of star formation seen directly and obscured by dust, if the two backgrounds are formed at the same redshifts (note that if FIR were formed earlier, would have to have more star formation to make it because of the larger 1+z suppression)

Submm Number Counts: roughly resolve the EBL

Lensing cluster surveys. Probe fainter than 2 mJy.

Blank field surveys. Confusion limited at 2 mJy.



Knudsen et al. (2008)

Fundamental Challenges

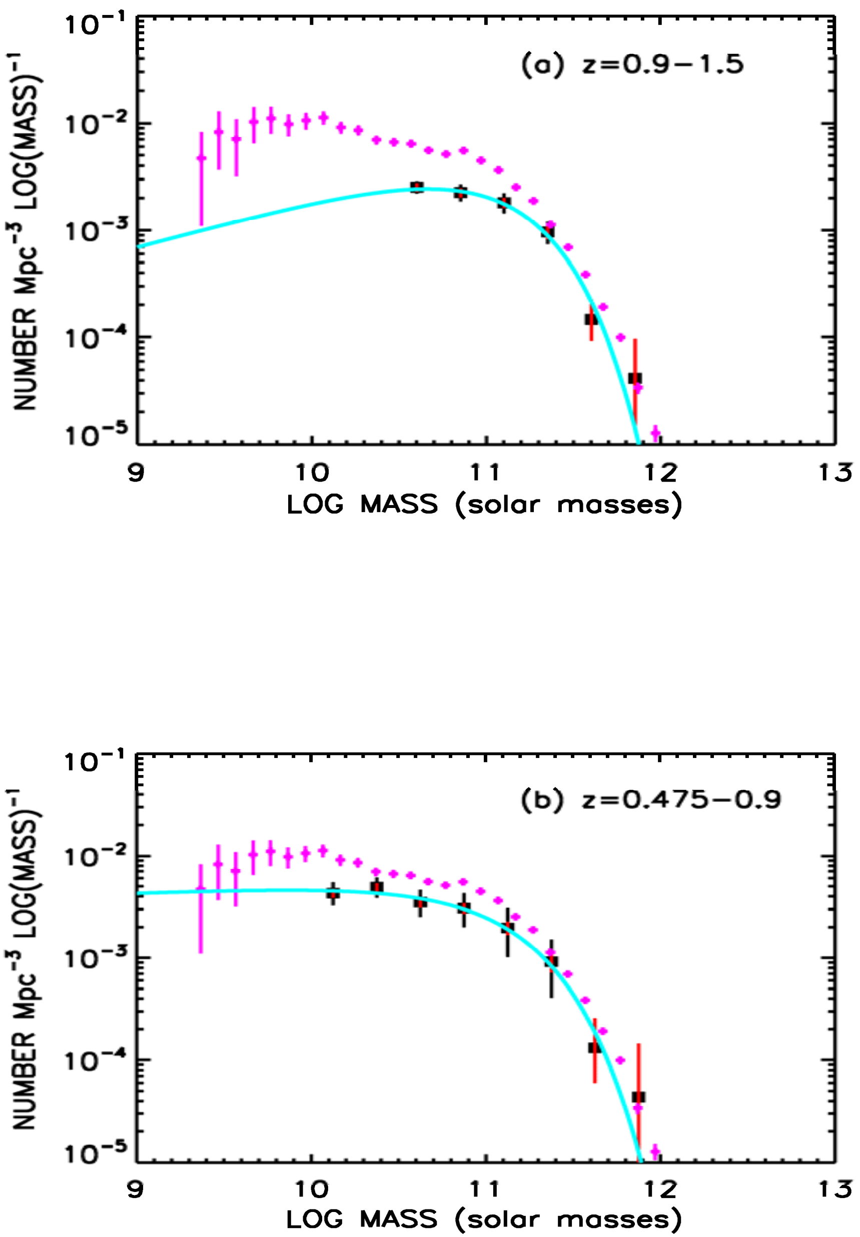
- Submmm telescopes have been very inefficient. SCUBA could discover ~1–2 submm sources in a full night of observation (cf. 10^{3-4} galaxies in an hour on Subaru). SCUBA-2 will be considerably faster.
- Resolution of single-dish submm telescopes are very poor (e.g., 15” FWHM for SCUBA at 850 μm). Identification of the true counterparts to the submm sources is extremely difficult.

○ Understanding the true nature of submm sources has been a painfully slow process.

But why might they be interesting for the very high redshift universe?

Mass functions

Purple crosses local (Cole et al. 2001)

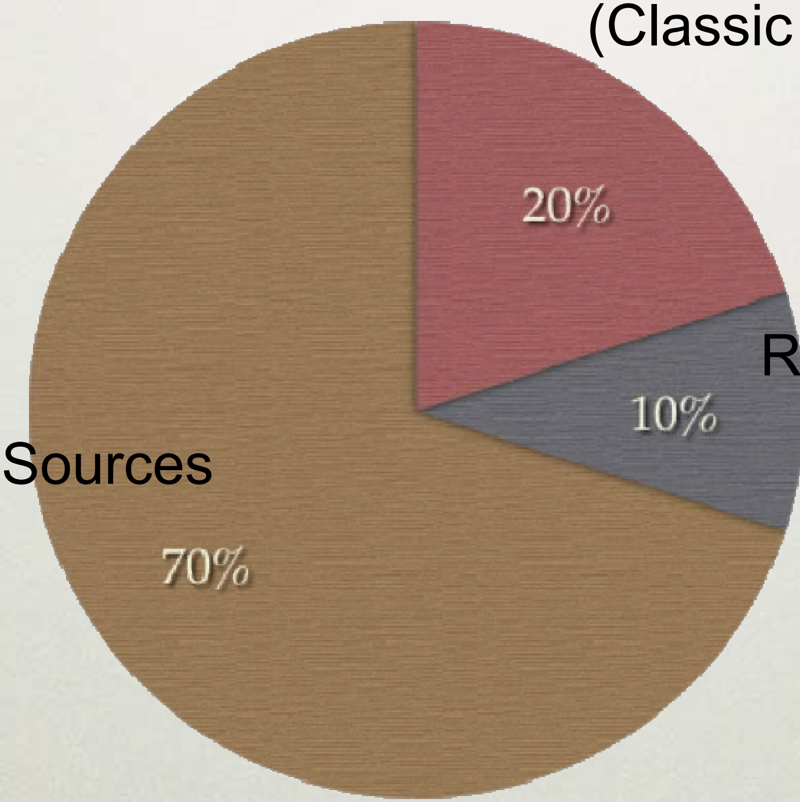


Evolved massive galaxies are already in place at early times.

Cowie and Barger 2008

Submm EBL Summary and Ourstanding Questions

Radio Identified Submm Sources
(Classic SMGs, z ~ 2-3)



Radio-Faint, Submm-Bright Sources

?

Undetected Faint Sources

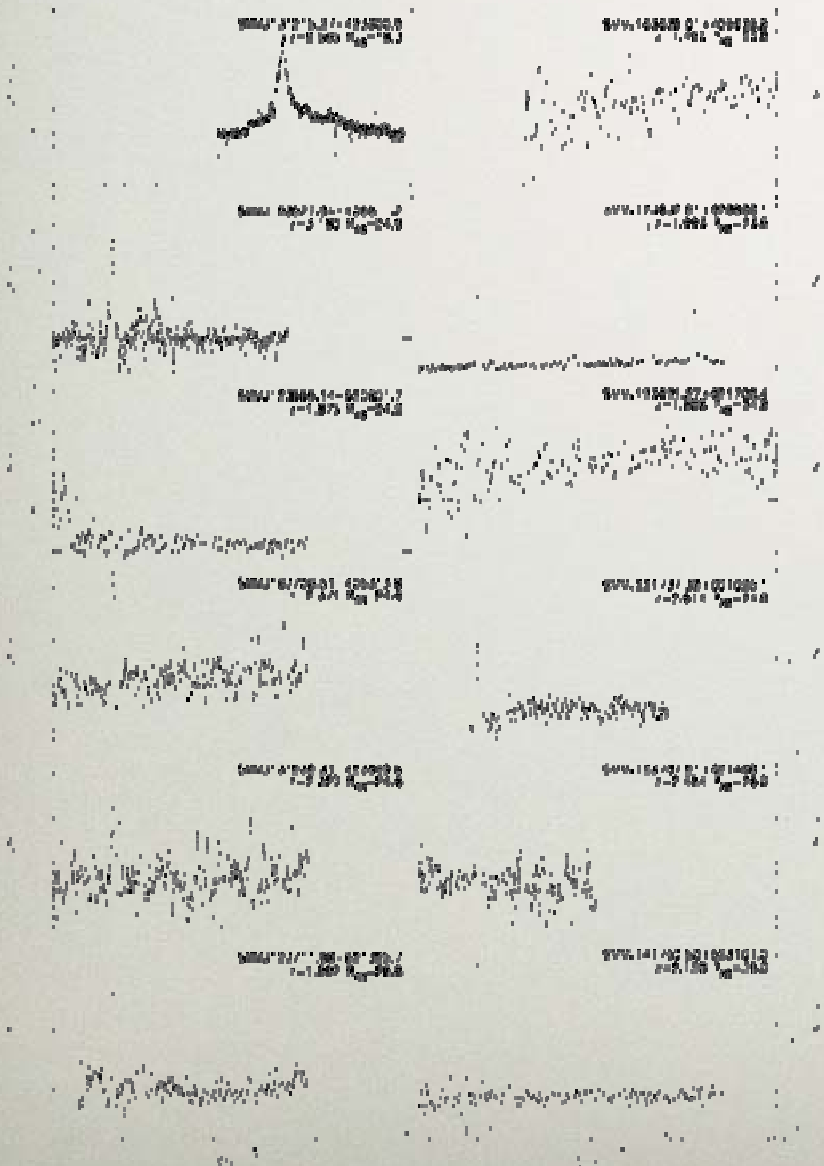
?

Total Submm EBL

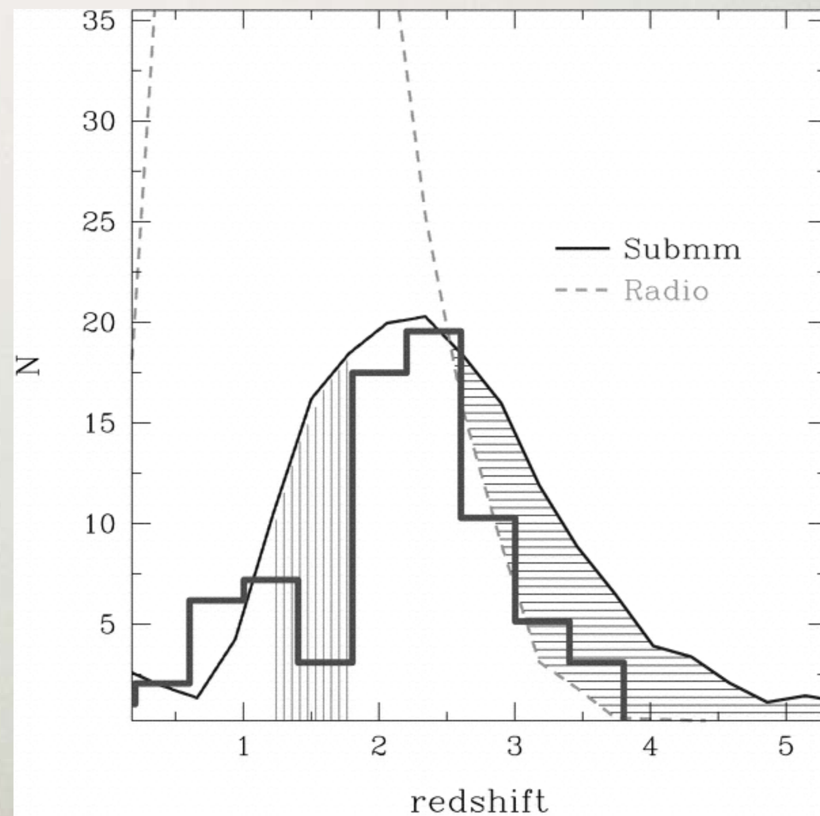
First Breakthrough: Radio Identifications

- If the well known Radio–Far-IR correlation also exist on submm galaxies, they should also emit in the radio.
- Radio interferometers (e.g., VLA) have much higher resolution and can pinpoint the location of the submm galaxies.
- Barger, Cowie and Richards (1999) showed that roughly 60%–70% of bright blank-field SCUBA sources have radio counterparts.
- Once the submm galaxies are identified, they can be followed up with large optical telescopes.
- This was first systematically done by Chapman et al. (2003, 2005).

Radio Identified Submm Sources (Classic SMGs)



- Keck spectroscopy of classic SMGs.
- Median z = 2.2, max = 3.6 (Chapman et al. 2005)



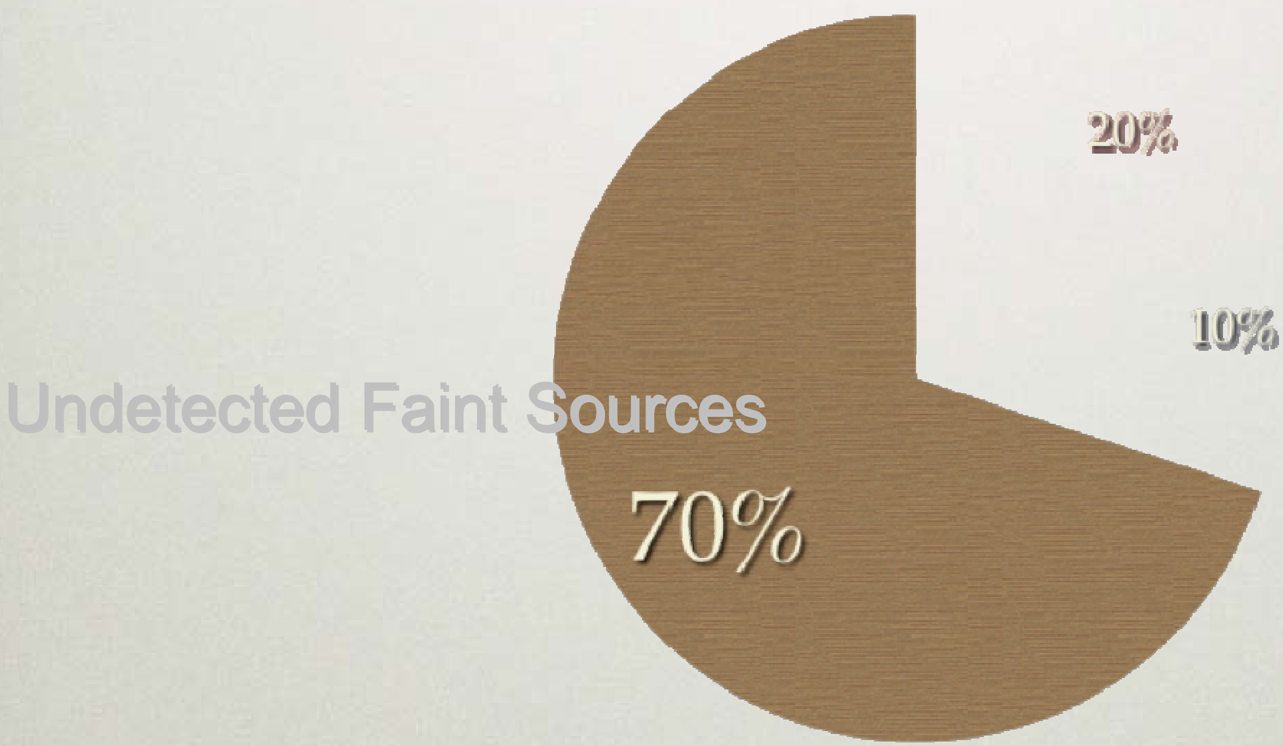
Classic SMG (1)

- Definition: radio identified SMG
- Much of the observational effort to date
- Submm flux: 5-20 mJy at 850 μm.
- Mostly starbursting galaxies. A fraction (~10%) show AGN signatures.
- Typical luminosity 10^{12}–10^{14} $L_{\odot}$ (ultraluminous and hyper-luminous), corresponding to star formation rates of 10^{2}–10^{4} $M_{\odot}$/yr (assuming Salpeter IMF).
- Redshift distribution: 1.5–3.5, peaking at ~2.5.

Classic SMG (2)

- Many show merger signatures.
- With the high SFR, can easily form a $10^{11}\ M_{\odot}$ giant elliptical galaxy given the cosmic time at z=2–3.
- Number density also comparable with giant elliptical galaxies in the present-day universe.
- Seem to be clustered or residing in dense environments (signatures of massive galaxies).
- SCUBA Half-Degree Extragalactic Survey (SHADES), the latest systematic SCUBA surveys before SCUBA died. Also see results from AzTEC.

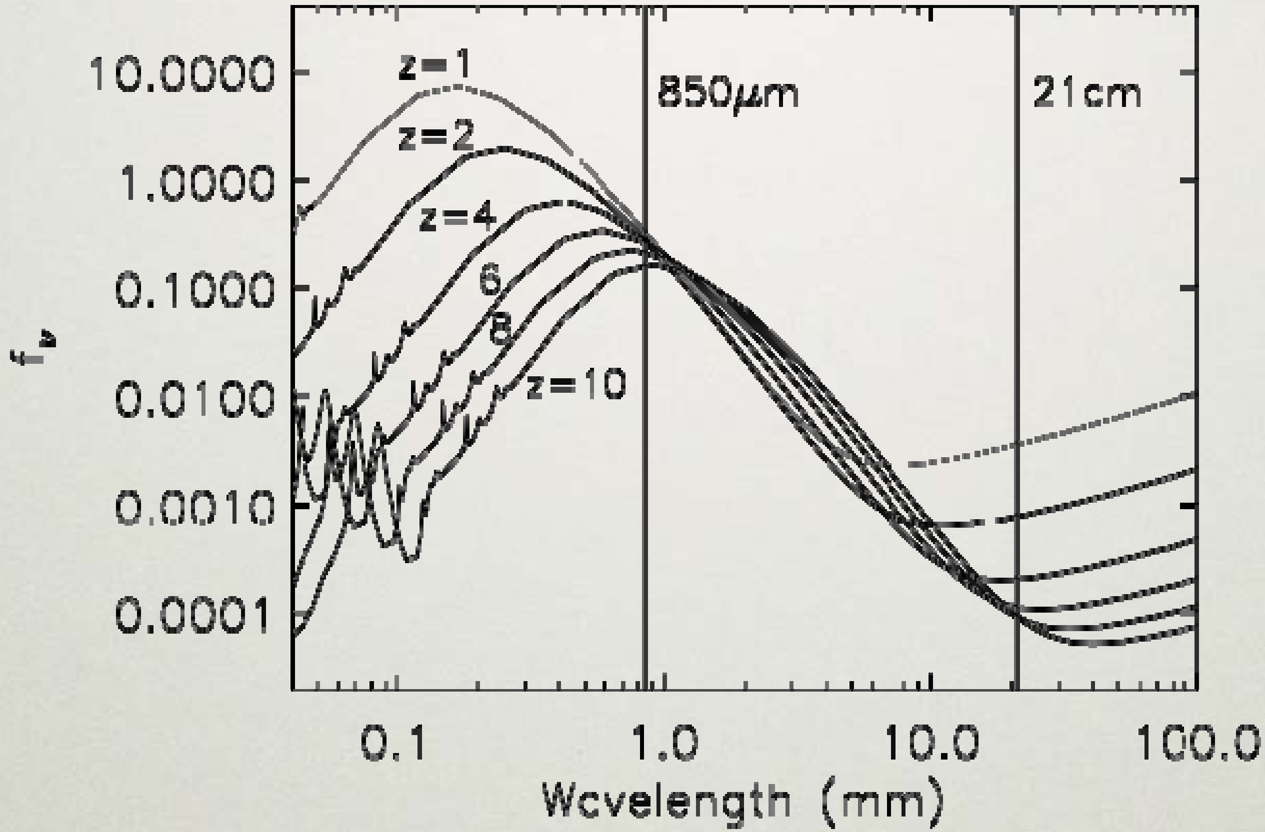
Faint Submm Sources



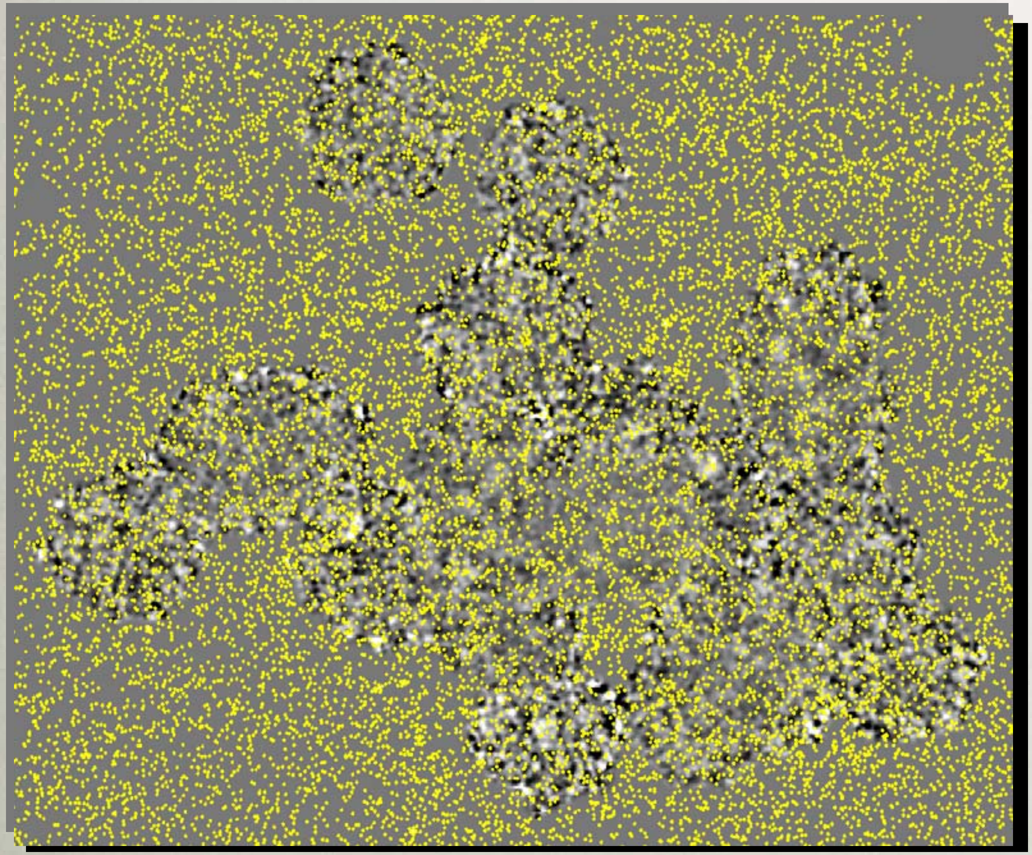
Detailed Look into the Faint Submm EBL

- About 2/3 of the submm EBL is not detected as bright submm sources.
- It comes from submm sources fainter than the detection limit (~2 mJy) of current single-dish submm telescopes.
- These faint sources are the typical sources in the submm population.
- What are they? Are they the fainter tail of the classic SMGs (also at $z = 2$–3)? Or an entirely different population?

Submillimeter sources have an odd redshift dependence because of the negative K-correction



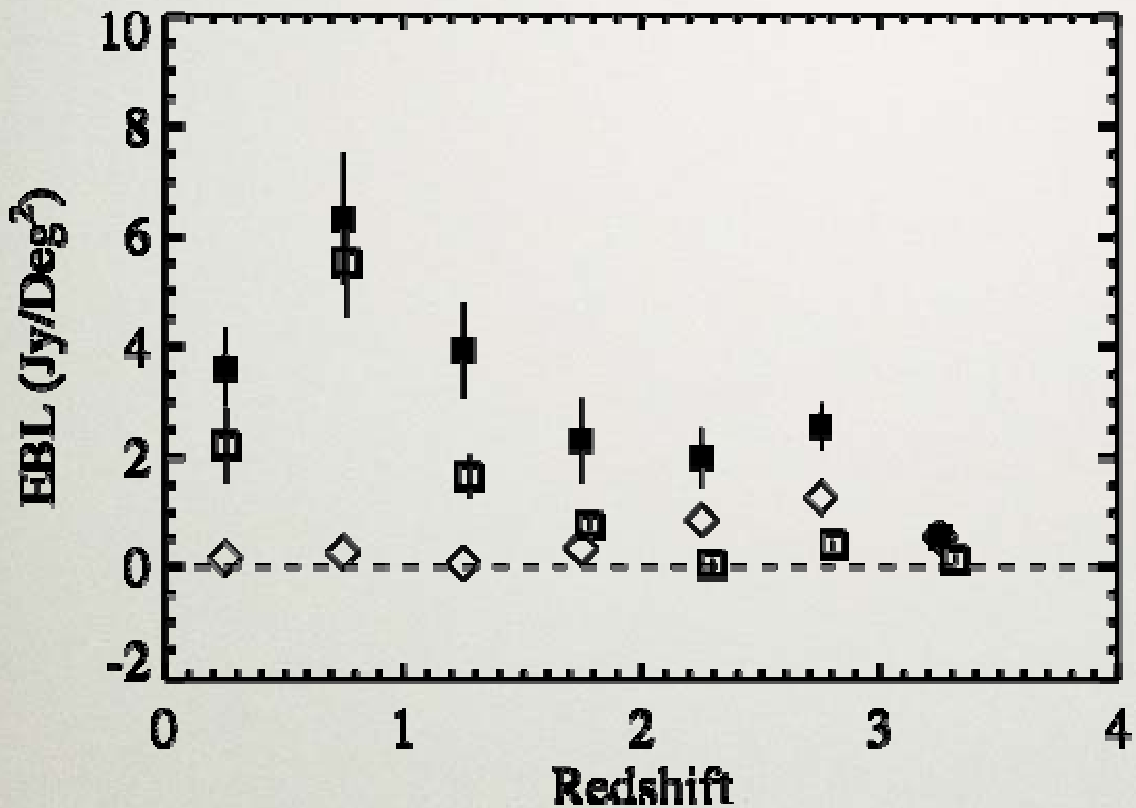
Submm Stacking Analyses

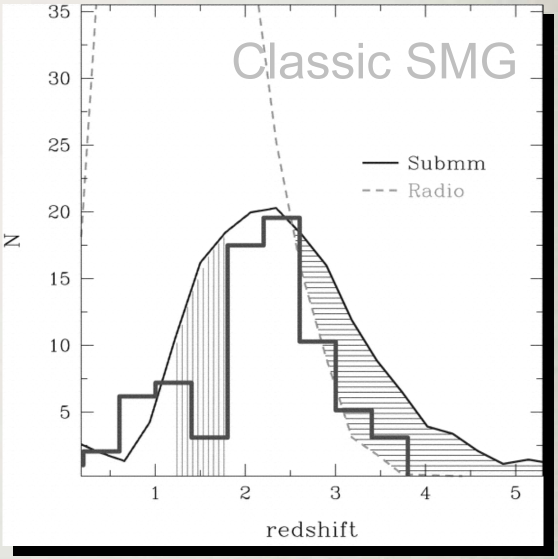


- Measure 850 μm fluxes at the locations of near-IR selected galaxies, and calculate the mean.
- With ~2000 near-IR galaxies, we detect 24 ± 2 Jy/deg2 of the 850 μm EBL.
- ~80% of the COBE EBL is detected.

Wang, Cowie, & Barger (2006)

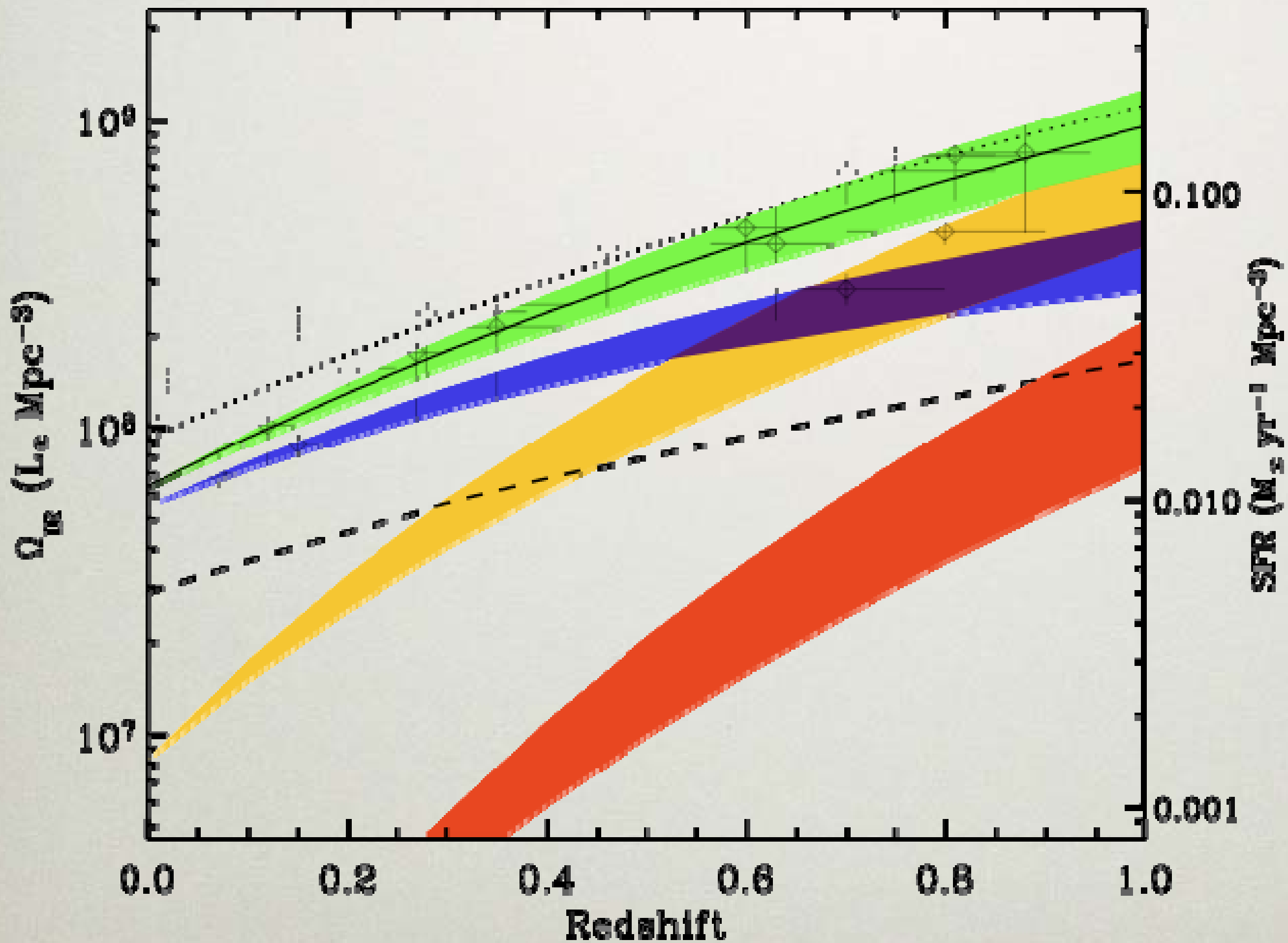
Redshift Distribution of the Submm EBL





- First measured in the GOODS-N by Wang, Cowie, & Barger (2006)
- Confirmed by SHADES in the SXDF by Serjeant et al. (2008, arXiv:0803.0475)

Mid-IR Downsizing (z<1)



total

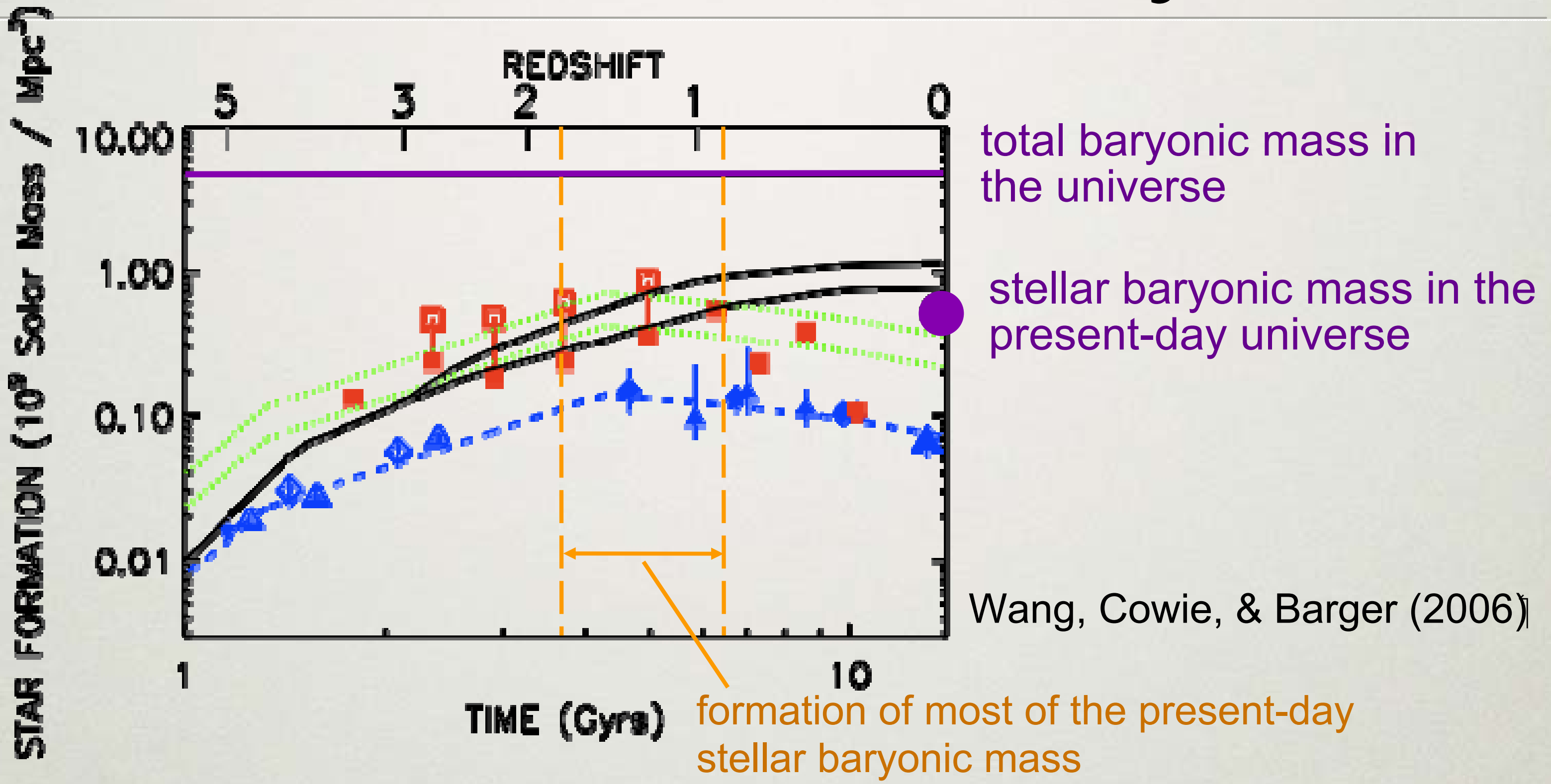
< 10^{11} $L_\odot$

> 10^{11} $L_\odot$

> 10^{12} $L_\odot$

Le Floc'h et al. (2005)

Chronodensity star formation history



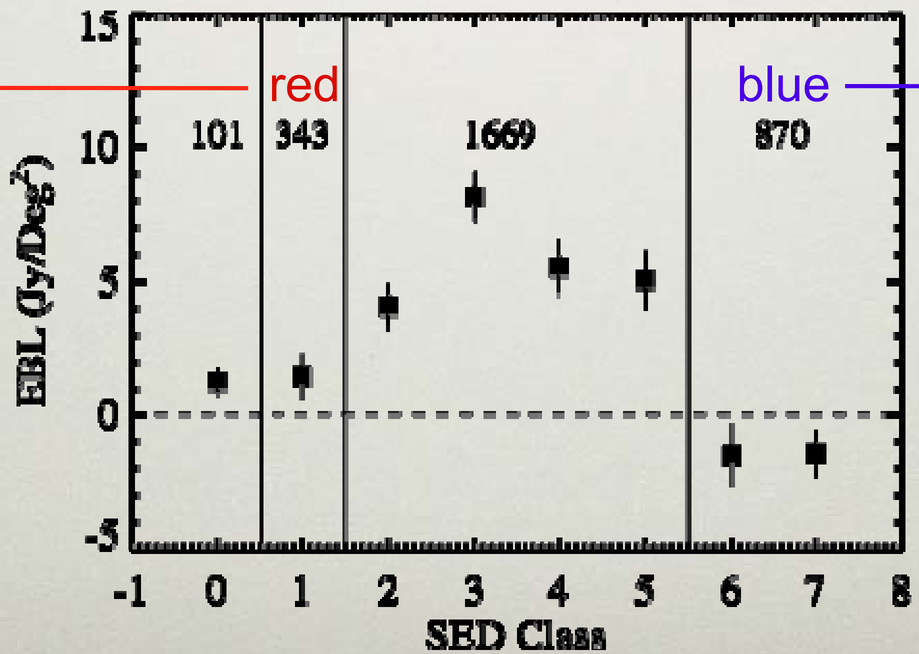
- radio/submm measurements
- integrated radio/submm star formation from z > 5
- rest-frame UV measurements without extinction correction
- rest-frame UV measurements multiplied by 3x and 5x.

Note that the submm and UV selected populations do not fully overlap.

Submm Sources and Optically Selected Galaxies

- It is well known that Lyman-break galaxies (rest-frame UV selected) are usually not submm sources.
- Most of the dusty star formation is in galaxies with the SEDs of intermediate spiral types.

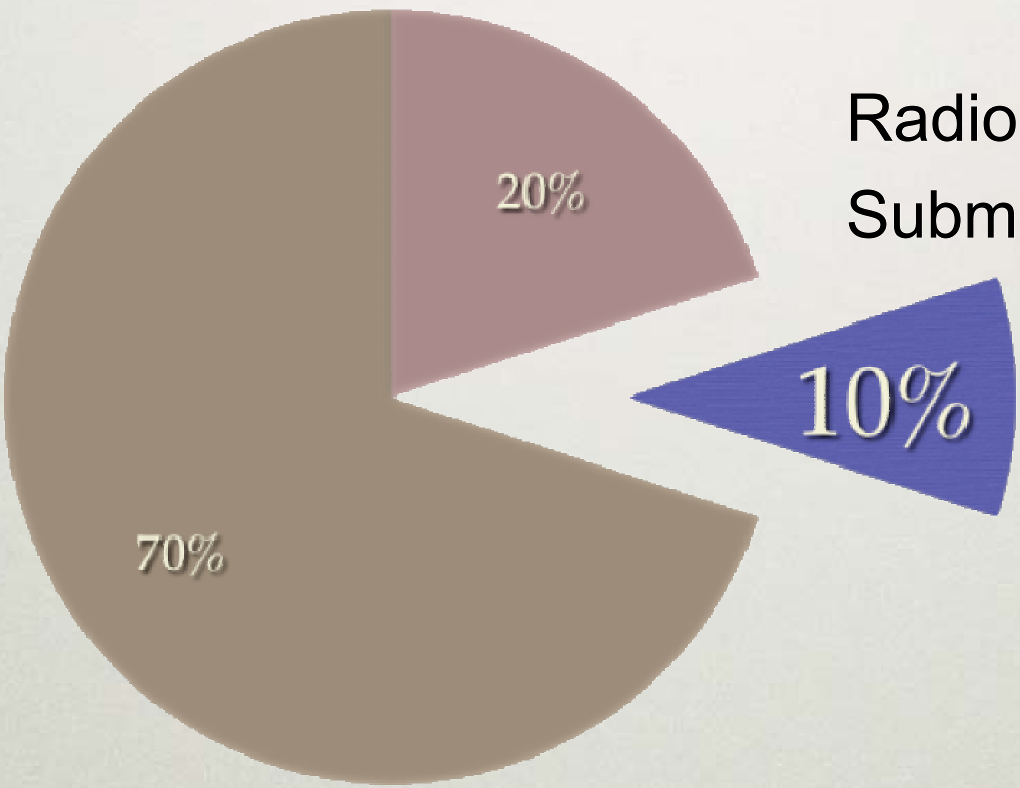
Passively evolving galaxies.



Lyman-break galaxies are a sub-class here.

Wang, Cowie, & Barger (2006)

Submmm Sources at High Redshift

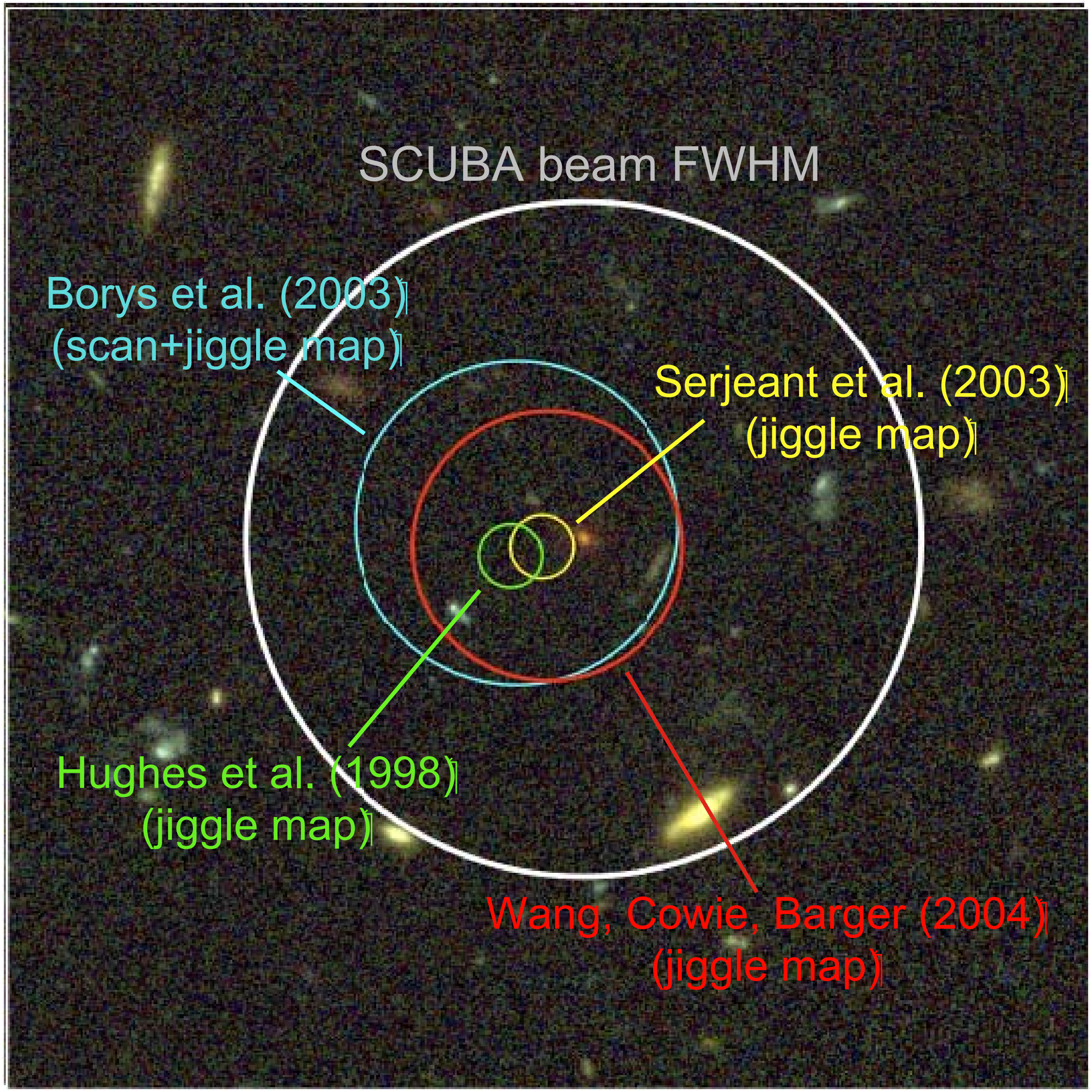


Radio-Faint,
Submm-Bright Sources

The remaining EBL

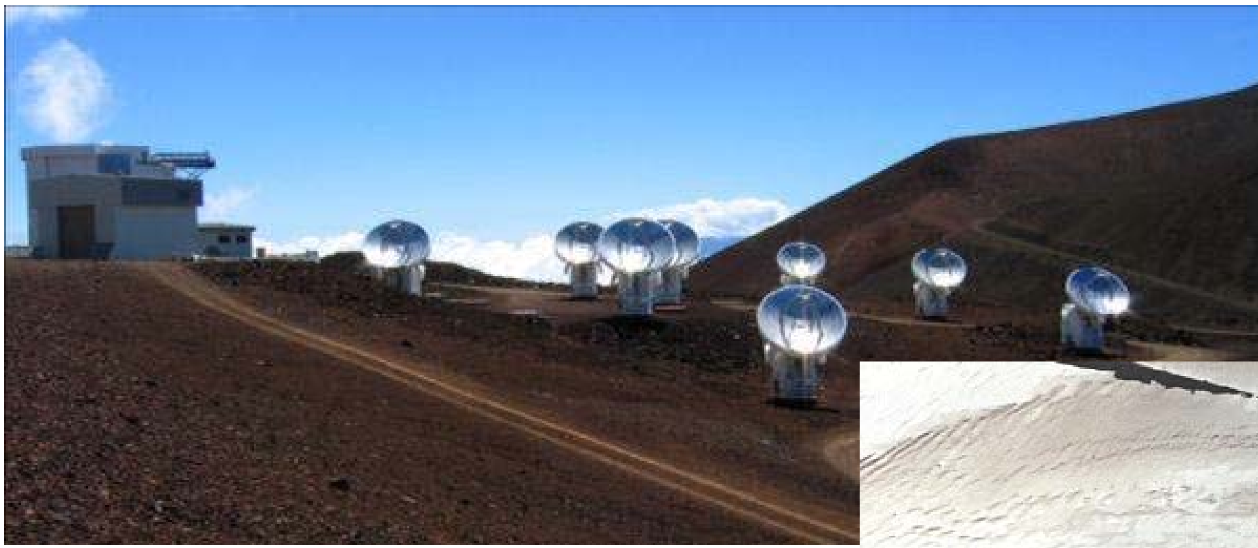
- About 1/3 of the bright submm sources do not have radio counterparts.
- These submm-bright but radio-faint sources contribute 10% to the total EBL.
- Are they the high-redshift tail of the classic SMGs?

HDF850.1: the brightest submillimeter source in the HDF proper
and a poster child for the radio faint SMGs



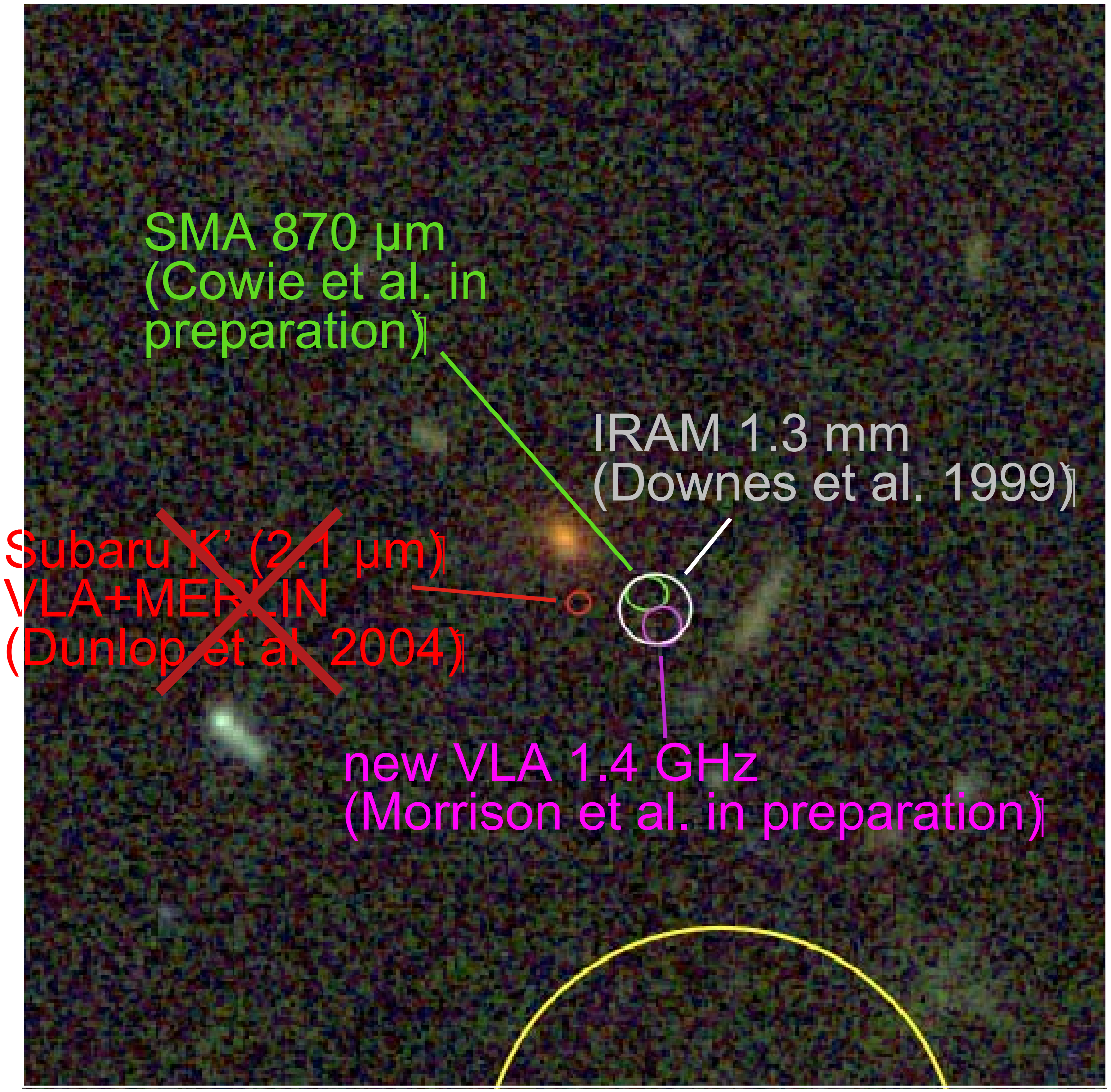
HST ACS b,v,i,z

Submillimeter Array



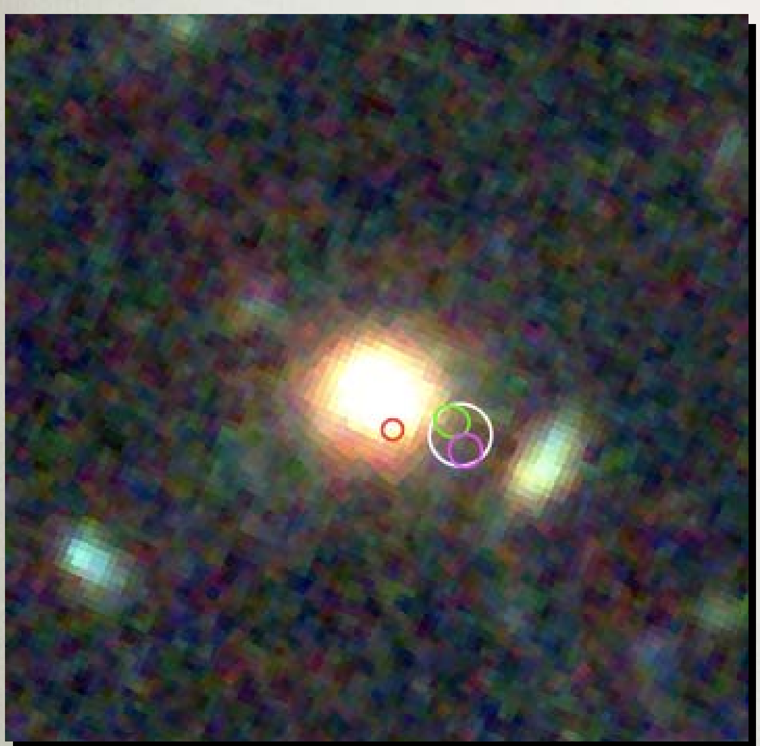
8 6-m dishes on the summit of Mauna Kea.

rms ~ 1.2 mJy at 850 µm per good night.


SMA 870 μm
(Cowie et al. in preparation)
IRAM 1.3 mm
(Downes et al. 1999)
Subaru K' (2.1 μm)
VLA+MERLIN
(Dunlop et al. 2004)
new VLA 1.4 GHz
(Morrison et al. in preparation)

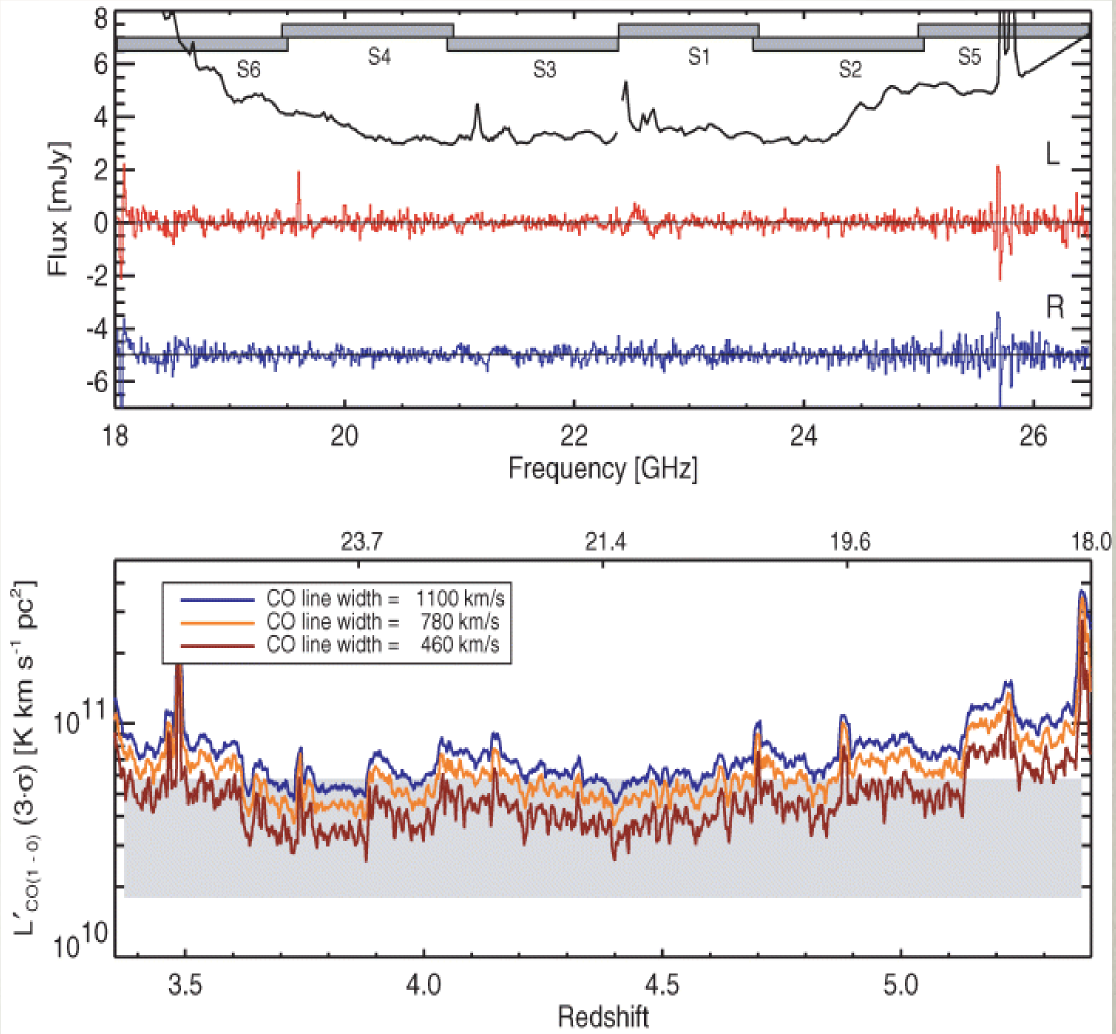
HST ACS b,v,i,z

What is HDF850.1? Radio - SMM estimate of z=4.5



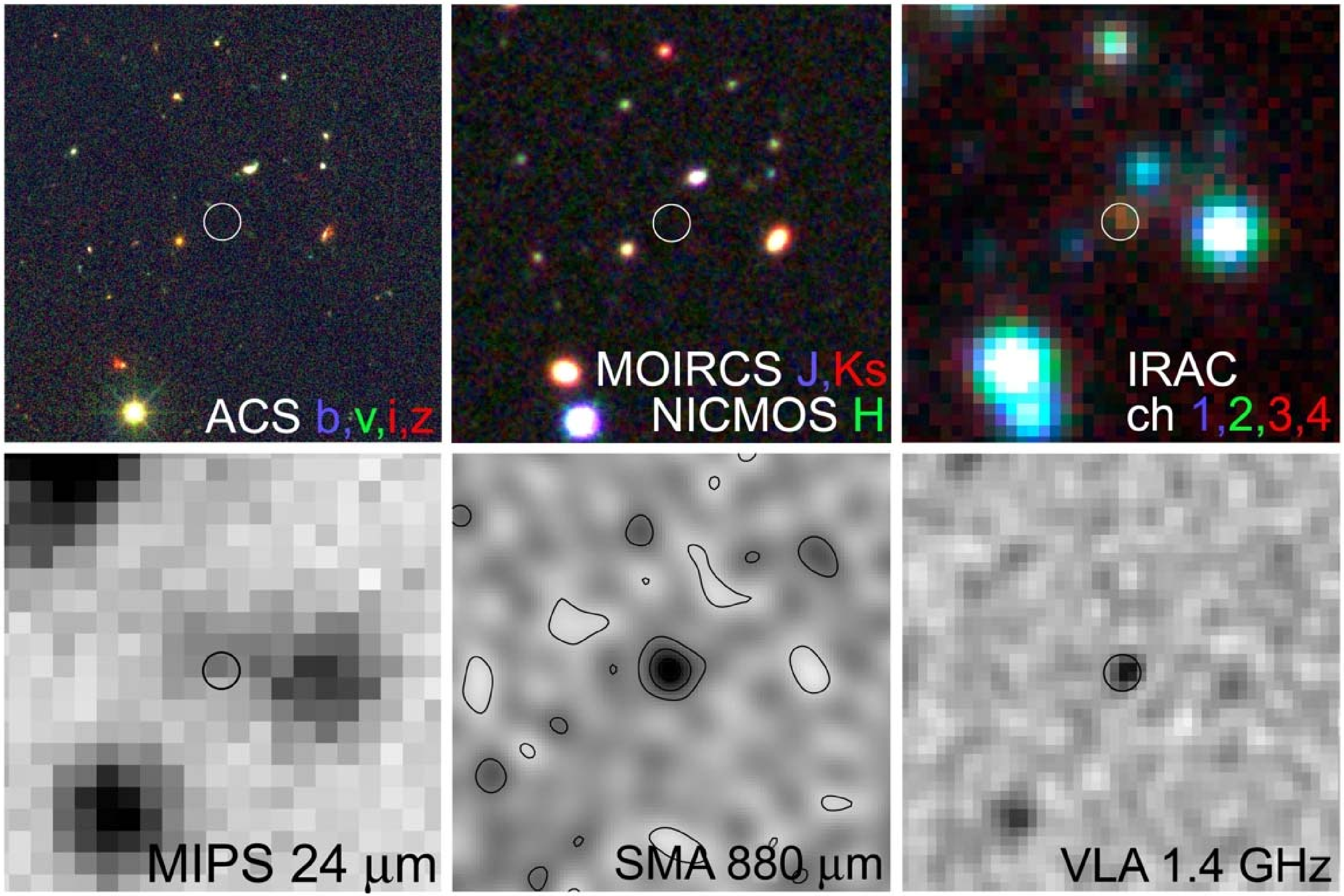
NICMOS F110W, F160W, Subaru Ks

- Nothing obvious in the optical and near-IR.
- No CO emission found by GBT between z=3.3 and 5.4.



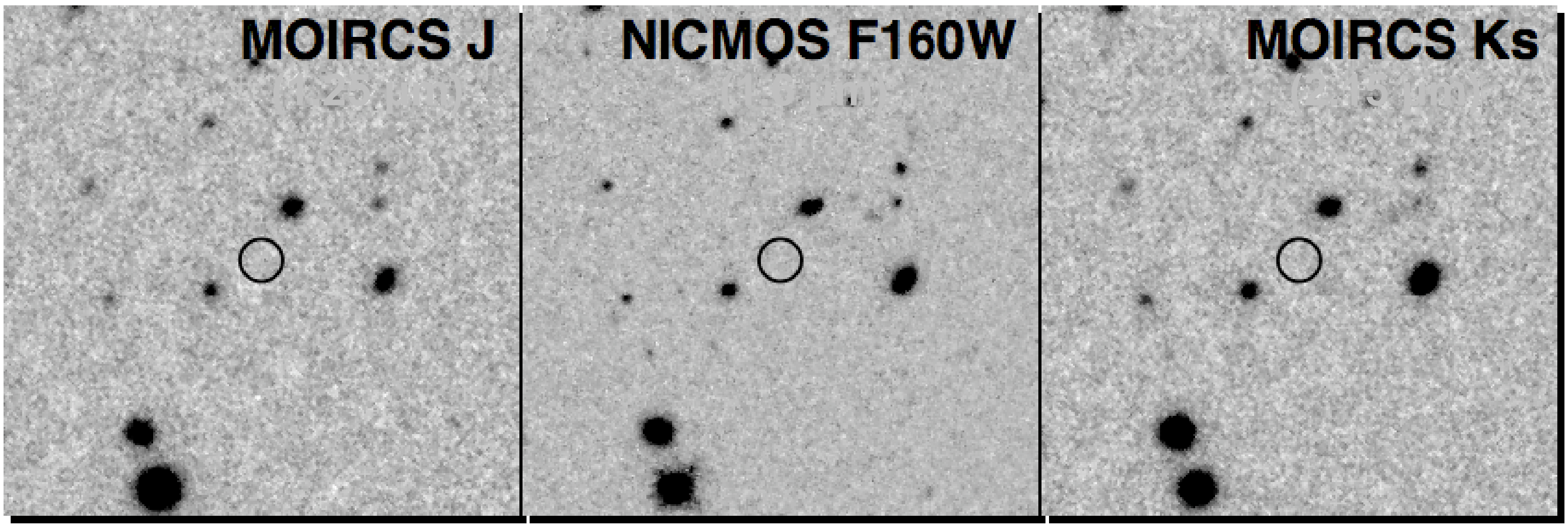
Wagg et al. (2007)

GOODS 850-5



Wang et al. (2007, 2008)

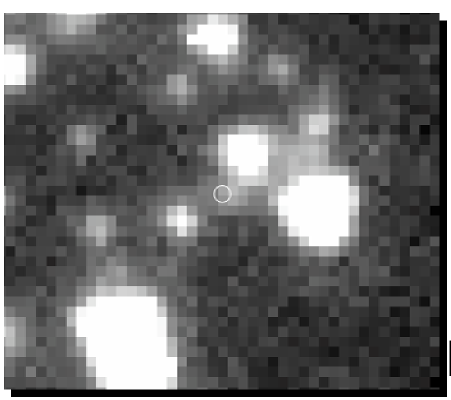
No Detections in the Near-IR



13 hr integration on Subaru
rms = 14 nJy

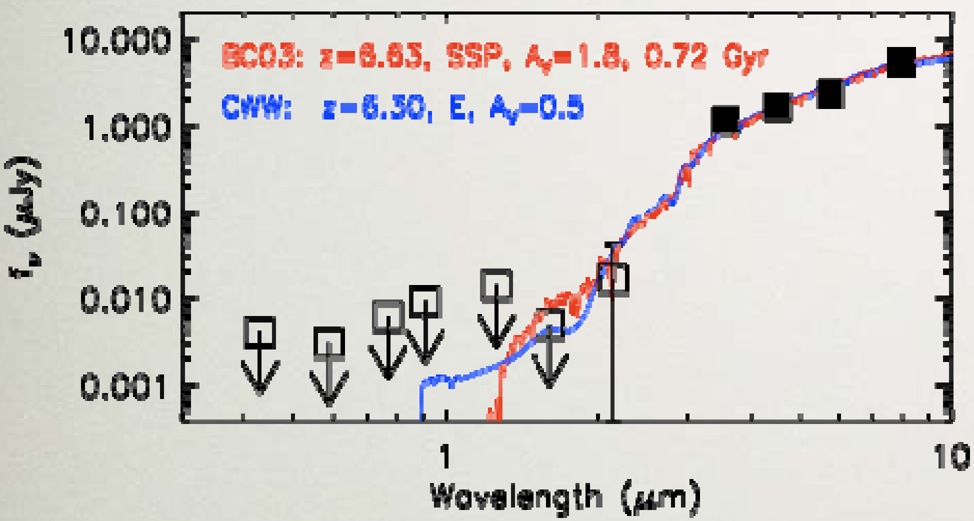
16 HST orbits
rms = 4.9 nJy

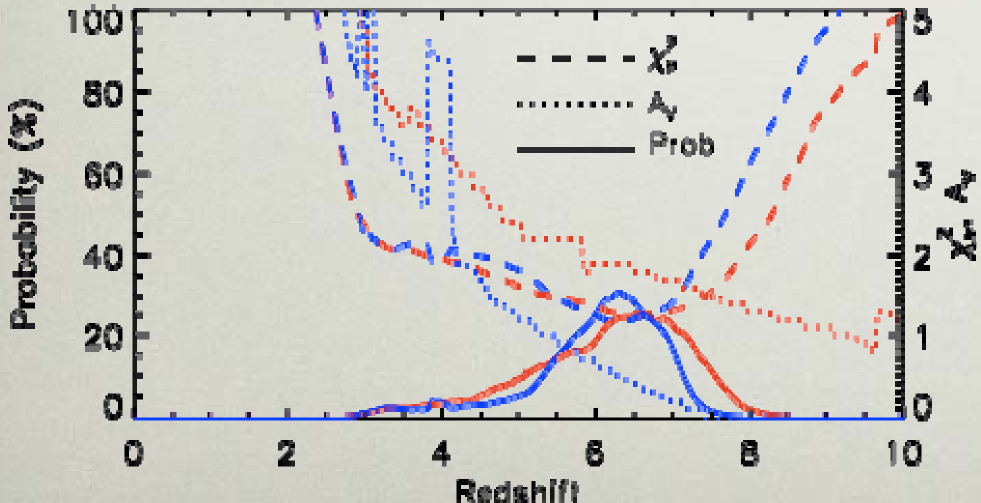
24 hr integration on Subaru
rms = 14 nJy



Detected by Spitzer @3.6–8 μm

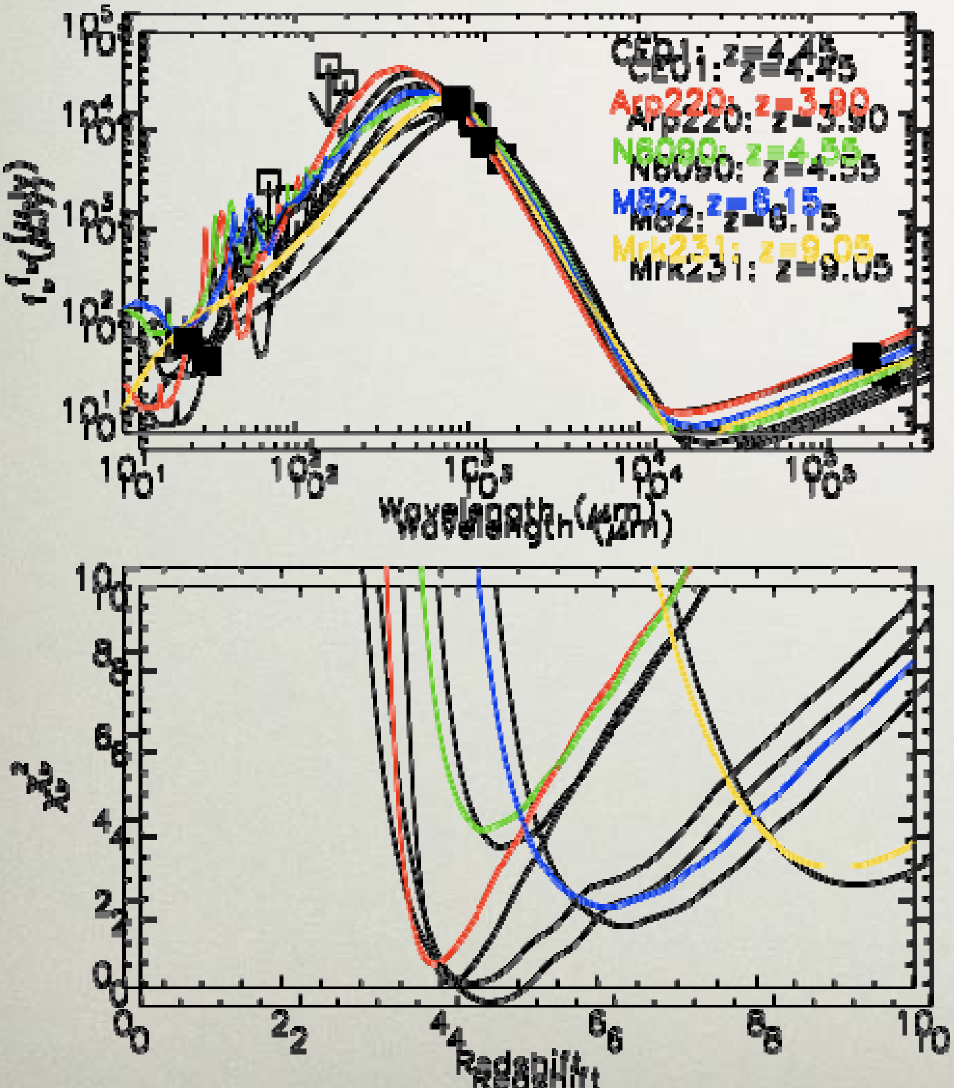
Near-IR Photometric Redshift: z ~ 6





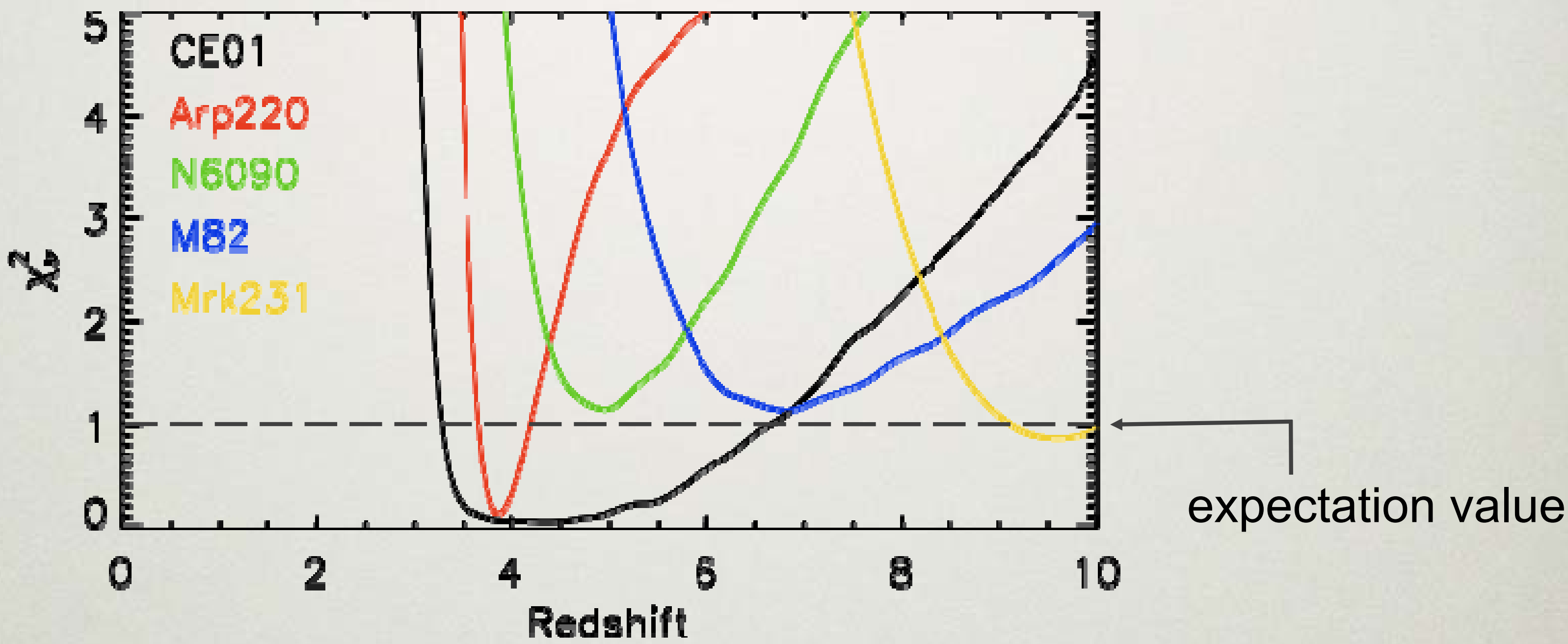
- z < 3 is ruled out.
- 1 σ range: z = 6.0–7.2.
- Best fit at z = 6.6, 0.7 Gyr old, Av=1.8. (Bruzual & Charlot 2003 templates)
- z~4 is still possible, but less likely compared to z>6.
- Wang et al. (2008)

Radio–Far-IR Photometric Redshift



- z < 3 is ruled out (consistent with optical/near-IR photo-z)
- Best fit: Arp 220 at z~4.
- Second best fit: M82 at z~6. Not as good as the Arp 220 fit, but still OK.
- Compton-thick AGN? z~9 (Mrk231)

What is Radio–FIR Correlation @z>4?



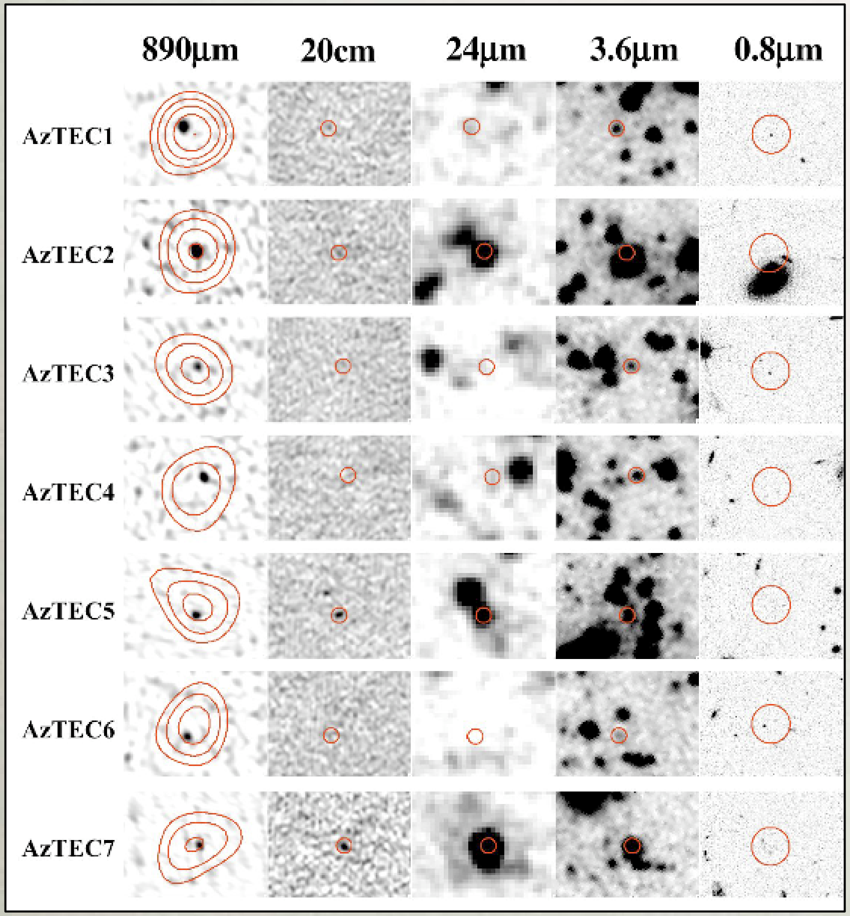
Summary on Redshift

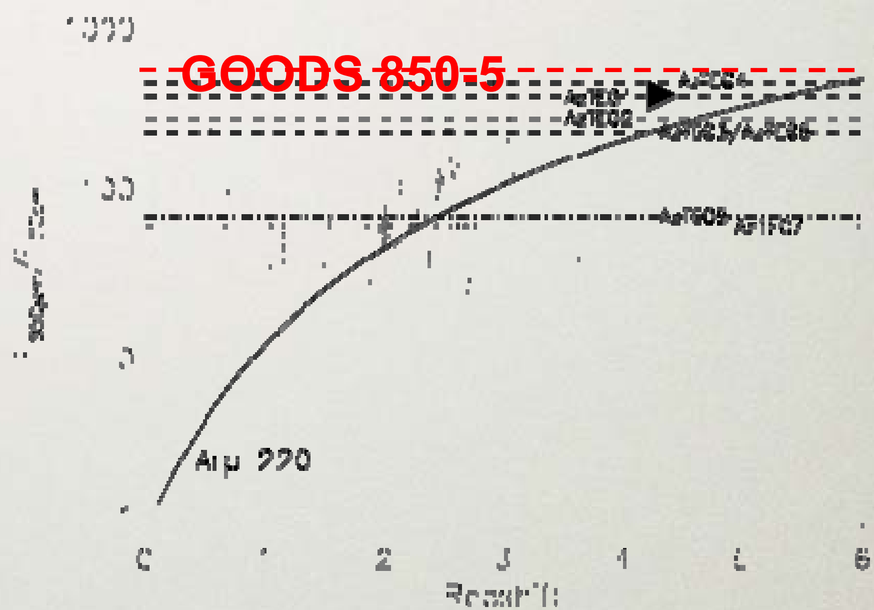
- $z < 3$ is rule out by both optical/near-IR and radio/far-IR data.
- $z = 6$–7 is preferred by the optical/near-IR photometric redshift. $z \sim 4$ is still possible but less likely.
- $z \sim 4$ is preferred by the radio–FIR correlation although $z \sim 6$ also gives an adequate fit.

Properties of GOODS 850-5

- $L_{IR} = 2 \times 10^{13}\ L_{\square}$, corresponding to SFR ~ 4000 $M_{\square}$/yr
- Old and massive stellar population of > 0.5 Gyr and ~$10^{11.5}\ M_{\square}$ is required to explain the observed near-IR SED.
- Not too surprising for z~4, but would be very unusual if it's at z > 6 for current ΛCDM galaxy formation.

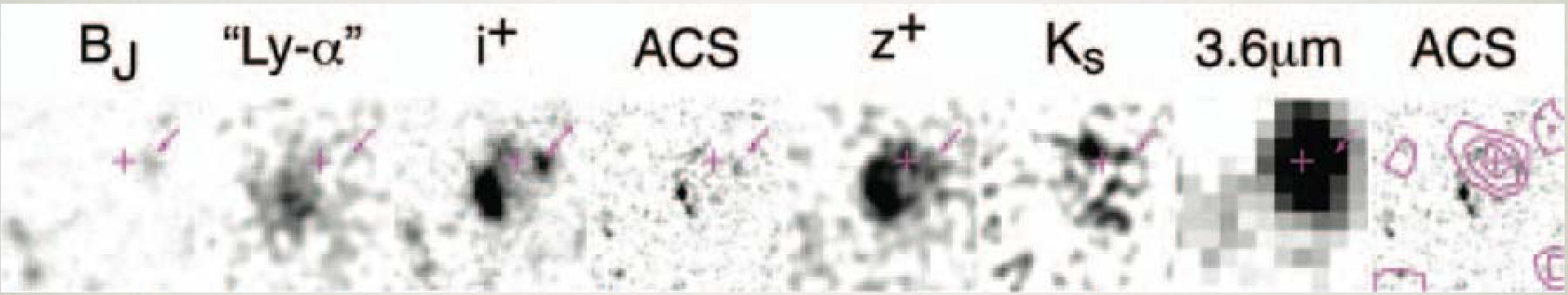
Other High-z SMGs

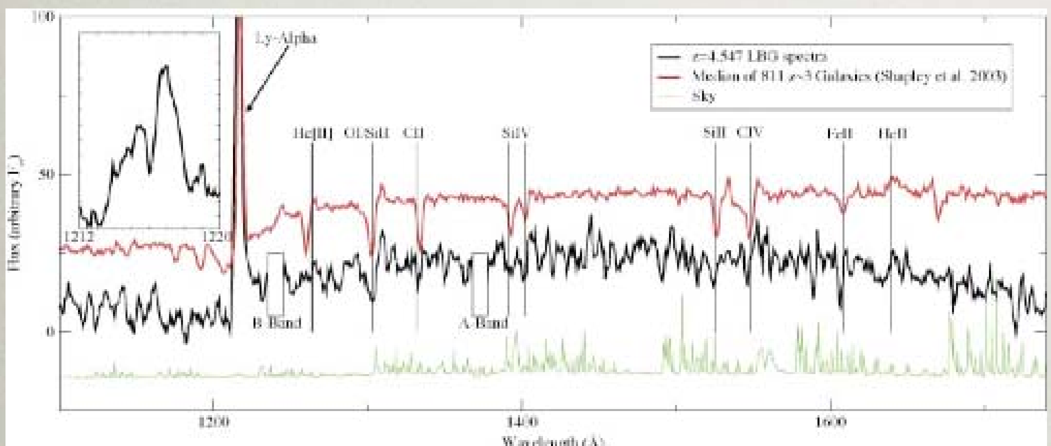


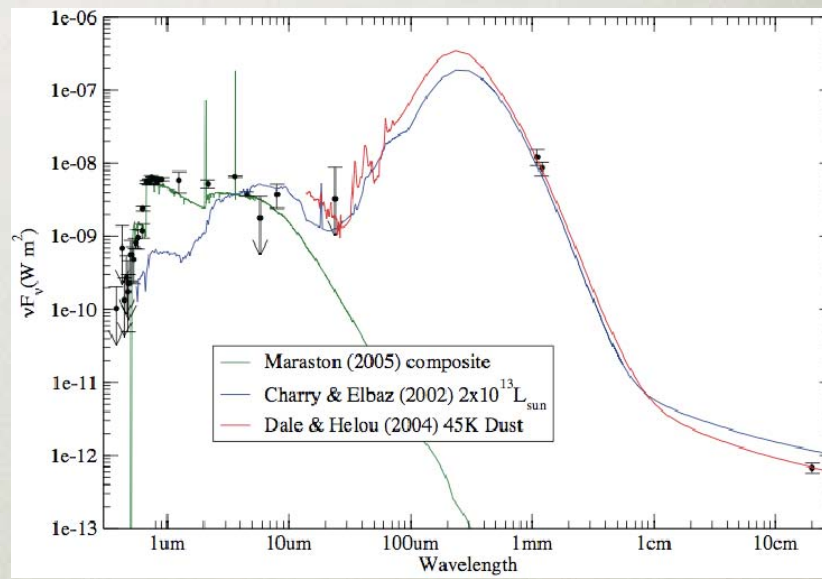


SMA identification of AzTEC 1.1 mm sources in the COSMOS field (Younger et al. 2007).

A Cosmos SMG at z=4.547

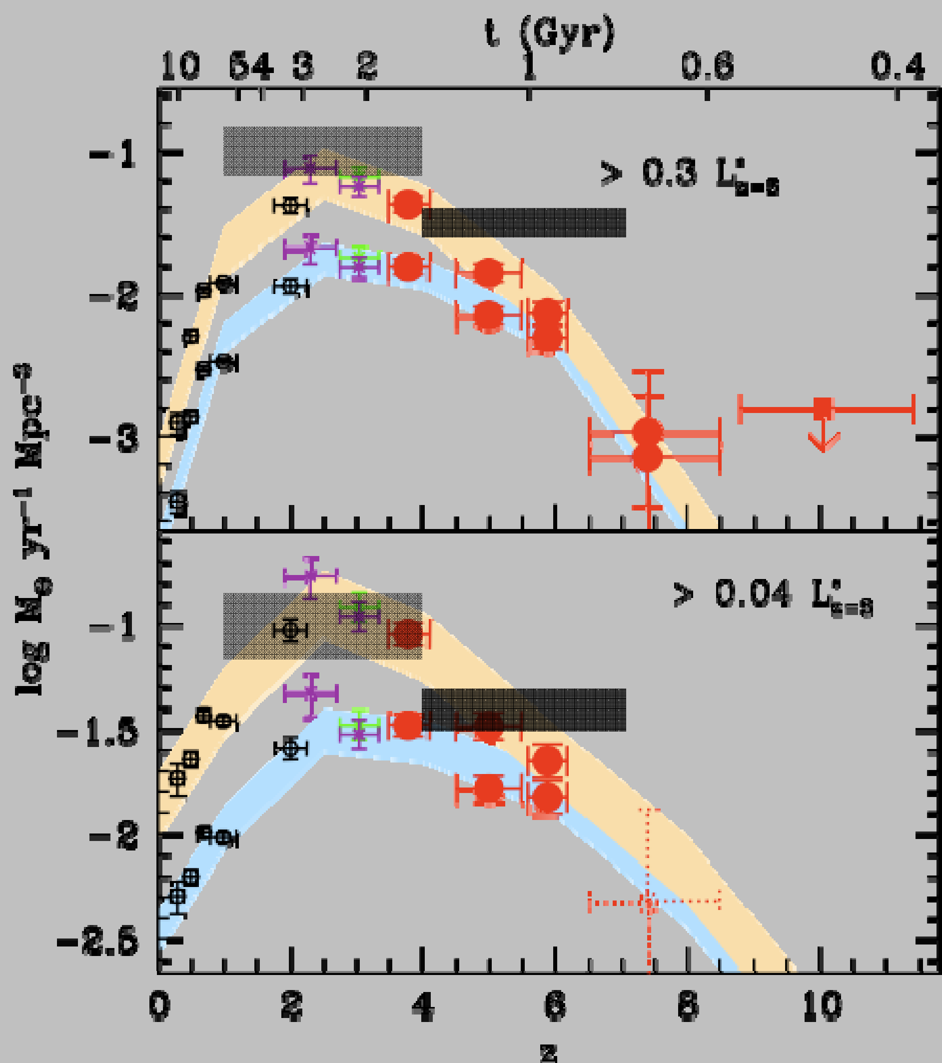






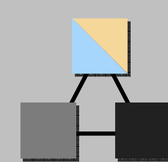
- Capak et al. (2008, ApJL, in press)

Cosmic Star Formation History



Bouwens et al. (2007)

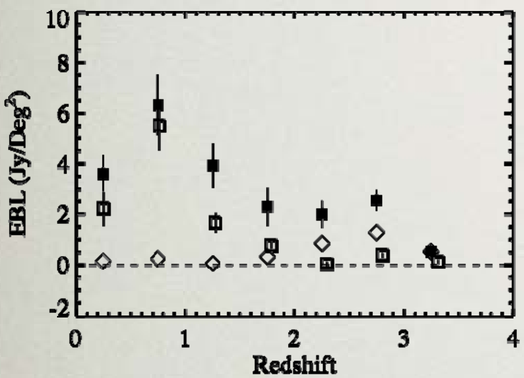
- faint submm sources detected with stacking analyses
- radio-faint, submm-bright sources
- rest-frame UV measurements with extinction correction
- rest-frame UV measurements without extinction correction

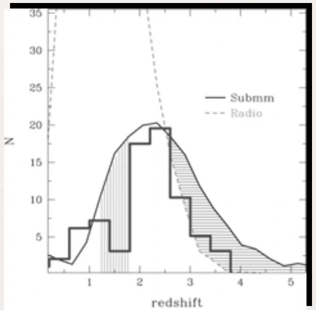


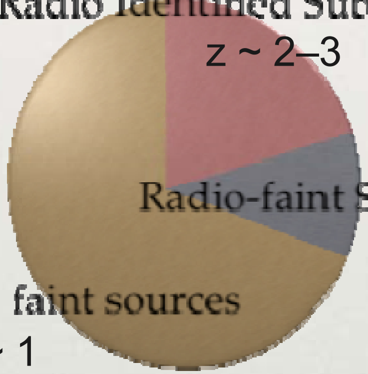
Caution: the amount of overlap between the three populations is still unclear.

Current Understanding of the Submm EBL

e







Radio Identified Submm Sources

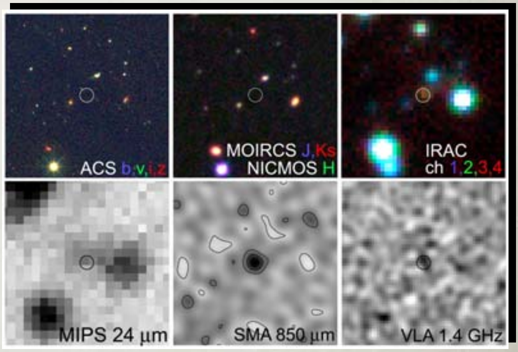
z ~ 2–3

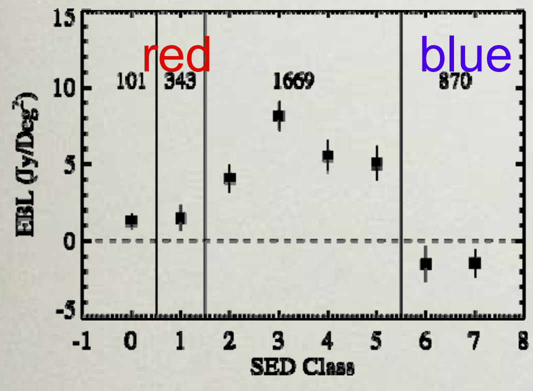
Radio-faint Submm Sources

z > 4

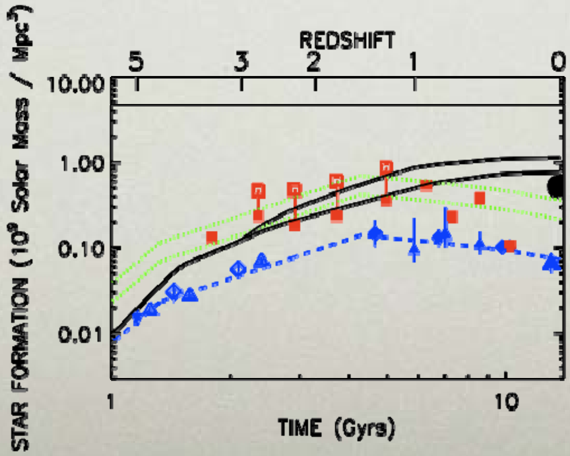
Unresolved faint sources

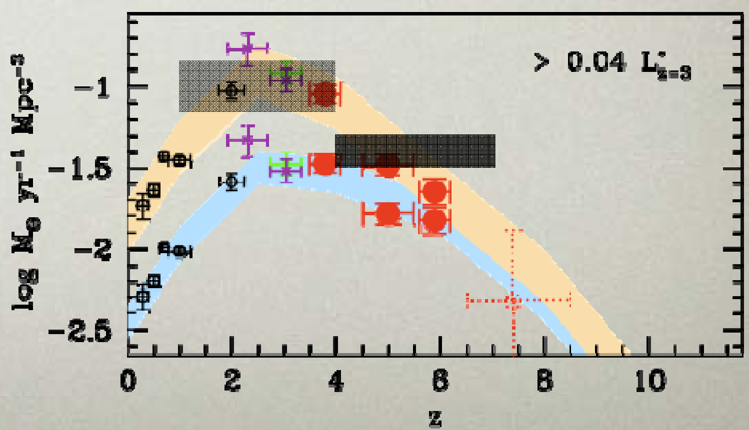
z ~ 1





DOWNSIZING
VS
HIERARCHICAL?





On to ALMA........

(and Herschel, SCUBA-2, EVLA, Zspectrometer, etc.)