Mapping High-Redshift Star Formation with the NGVLA

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Star Formation History (SFH)

The rest-frame UV light density has been mapped using HST out to beyond z=10 (e.g., many candidates in the Hubble Ultradeep Field, CLASH, and Frontier Fields)

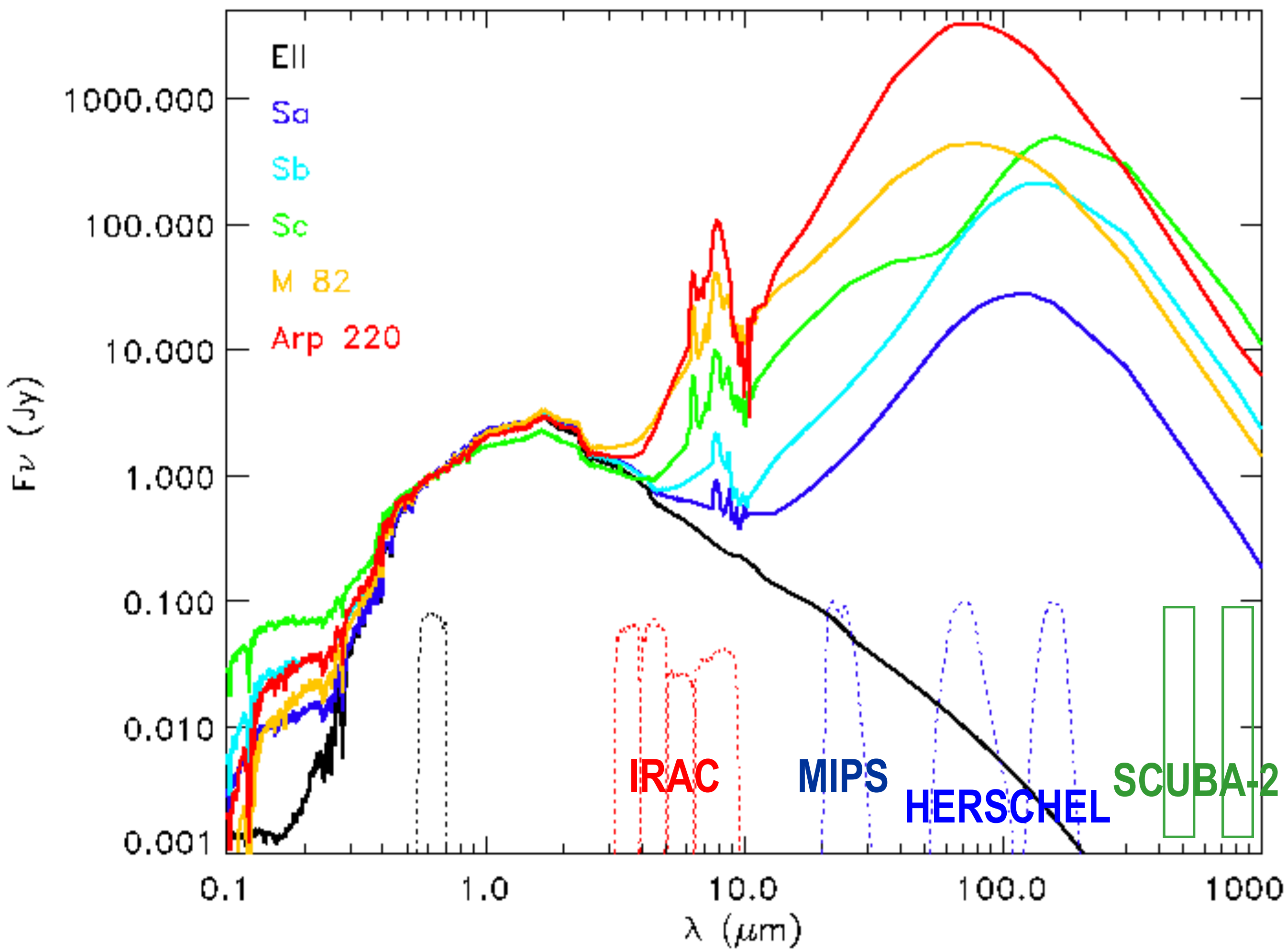
This has been very successful, so why is it necessary to do this in the radio?

WFC3/IR: 850 - 1170nm
UDF 4.7 arcmin^2
60 orbits in YJH

Very luminous galaxies emit much of their light at IR to mm wavelengths and may be very faint in the UV/optical

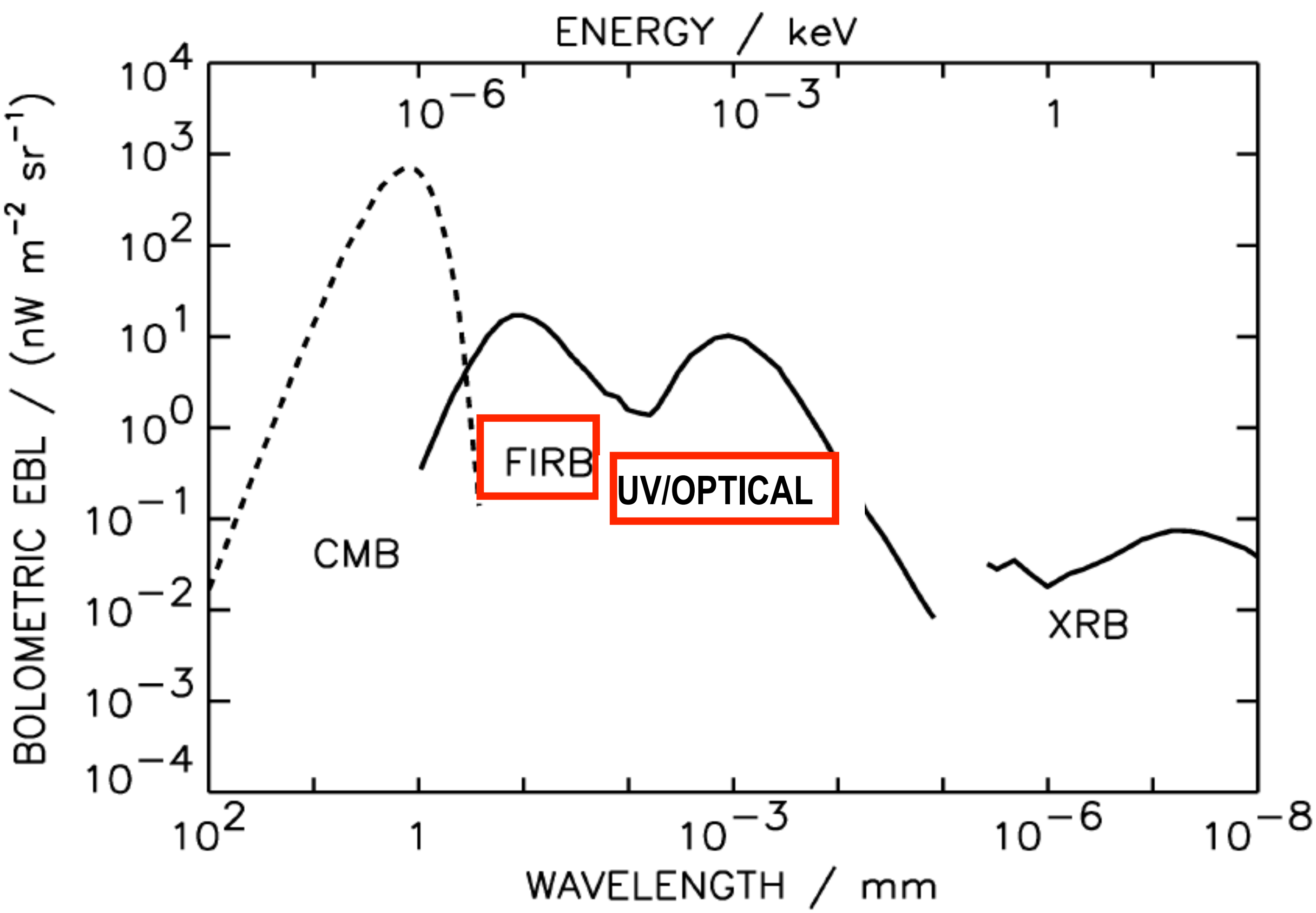
With only UV, do not know how much star formation we are missing, or how good our corrections are for the galaxies we do find

The radio does not suffer from extinction



From Polletta

In fact, since the universe produces comparable amounts of energy in the FIR and optical, we really should be developing a detailed understanding of the FIR population at all redshifts, but this requires uniformly selected samples



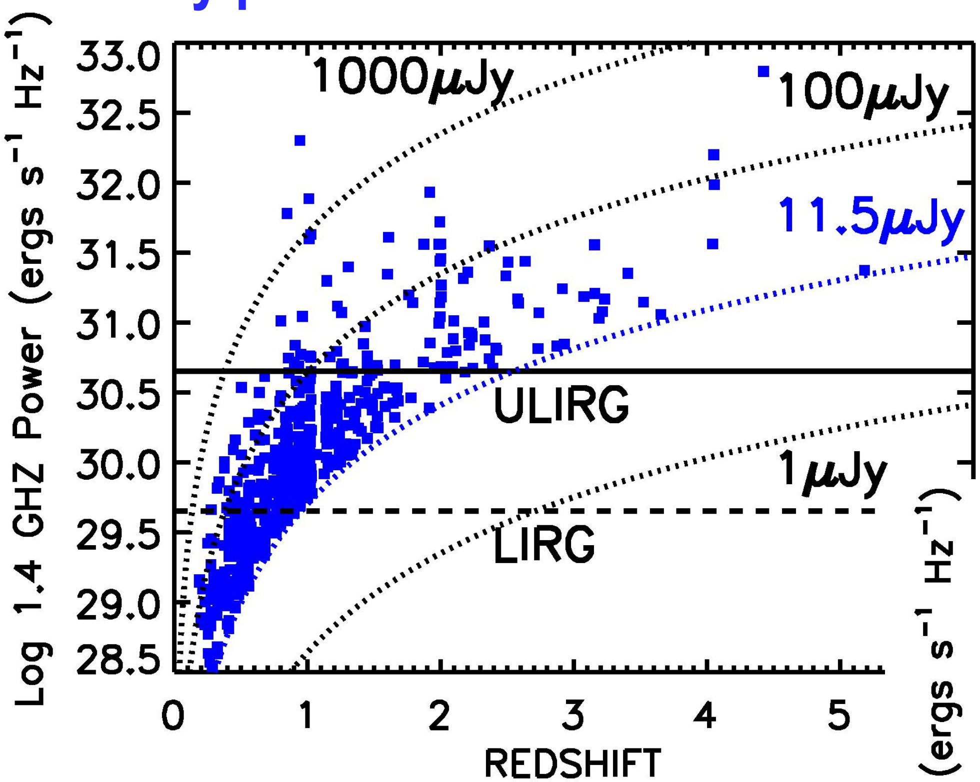
How can we construct such samples?

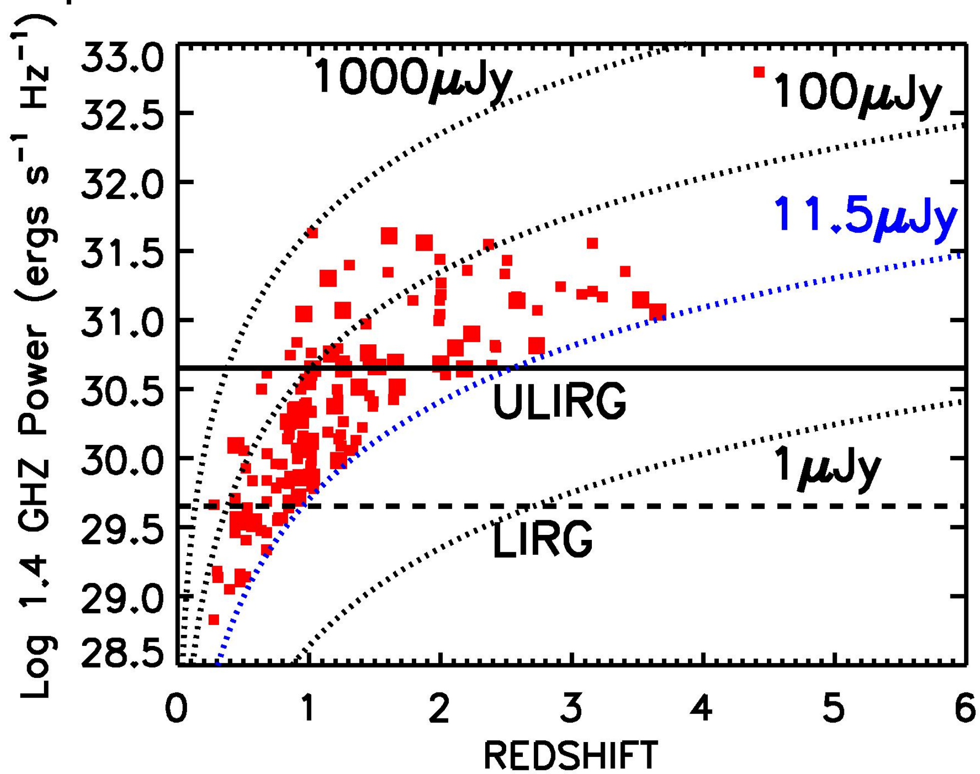
- Single dish submm imaging (*Herschel* in space; JCMT, LMT, APEX, etc on the ground)
  - Advantages: large fields, uniform FIR/submm selected samples, as sensitive to high redshifts as to low redshifts
  - Disadvantages: low resolution, confusion limit

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

- Radio continuum imaging (VLA)
  - Advantages: wide field, high resolution
  - *Current* disadvantages: limited to the most luminous objects at high redshifts, contaminated by AGN, SFR calibration uncertainties

The current deepest 1.4 GHz VLA image (5σ=11.5 μJy of CDF-N; F. Owen) only probes ULIRGs to z~3 and LIRGs to z~1; there are many AGN



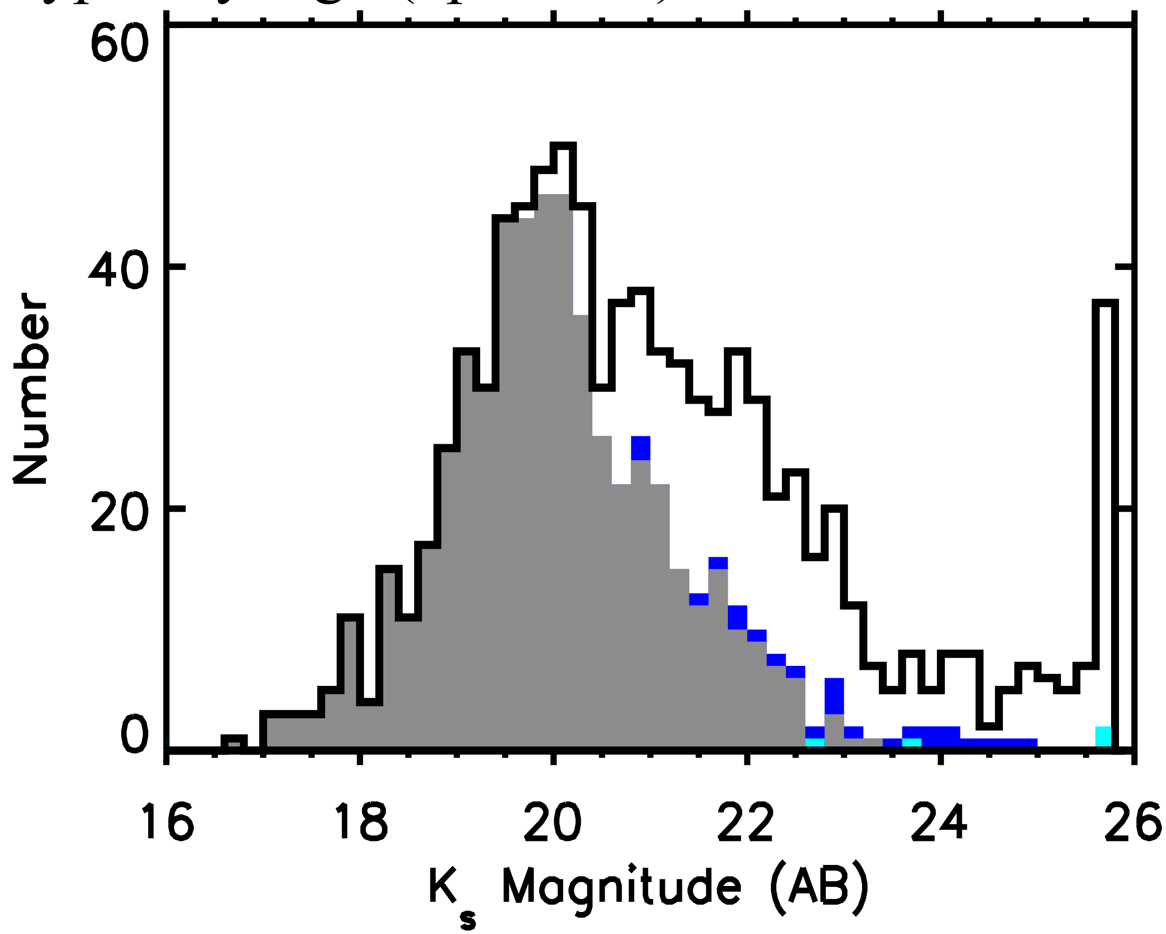


X-ray AGN with $L_X>10^{42}$ erg/s (small)

X-ray quasars with $L_X>10^{44}$ erg/s (large)

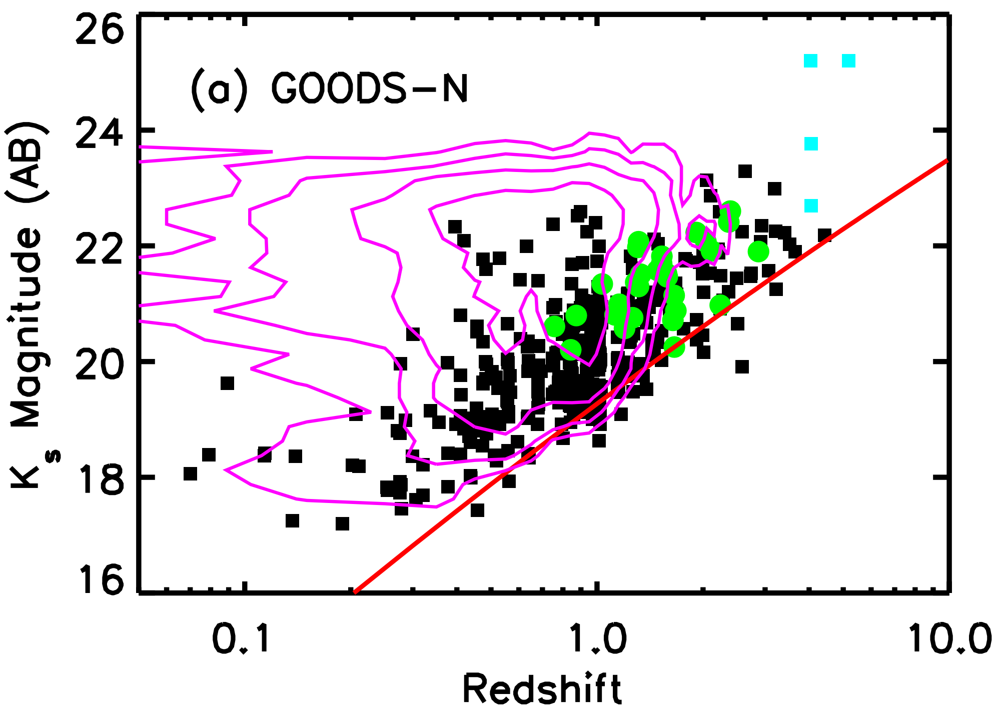
Many of the high-z radio sources are faint in the optical/NIR

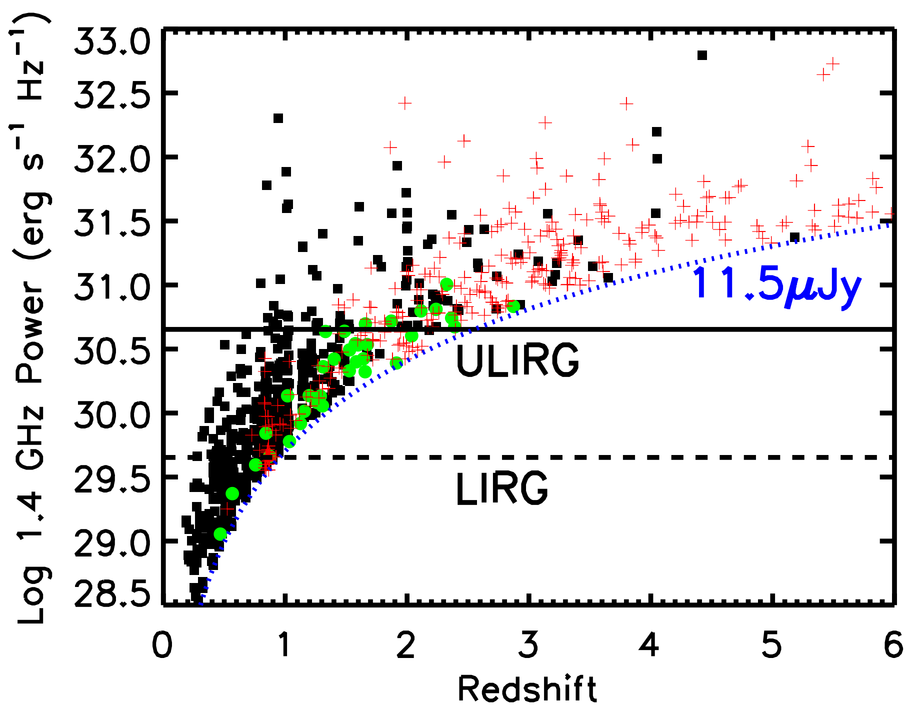
- Obtaining spectroscopic/photometric z for these is challenging
- Sources with millimetric (using submm/radio ratio) and CO redshifts mostly lie in the extended radio source tail at K_s>22.5; they are typically high (up to z~5)



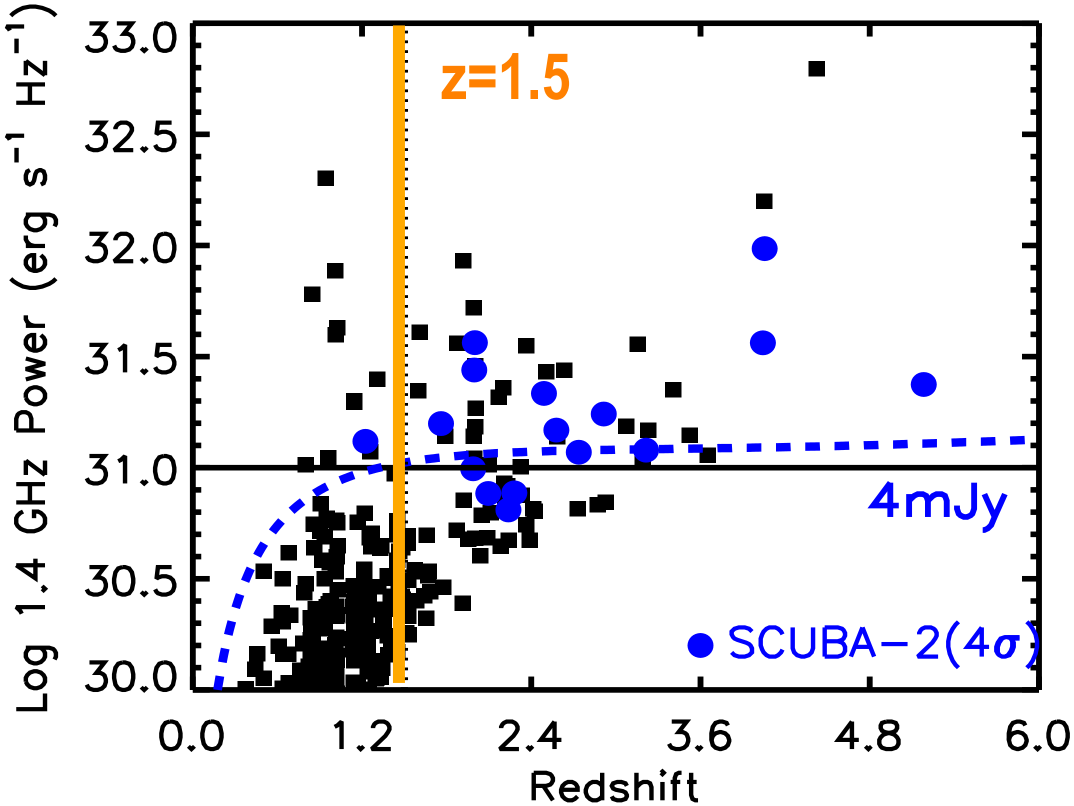
High-Redshift Radio Sources

- 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 z, making K magnitude a crude redshift estimator [famous old K-z relation]
- *What are all these radio sources: AGN or star formers?*





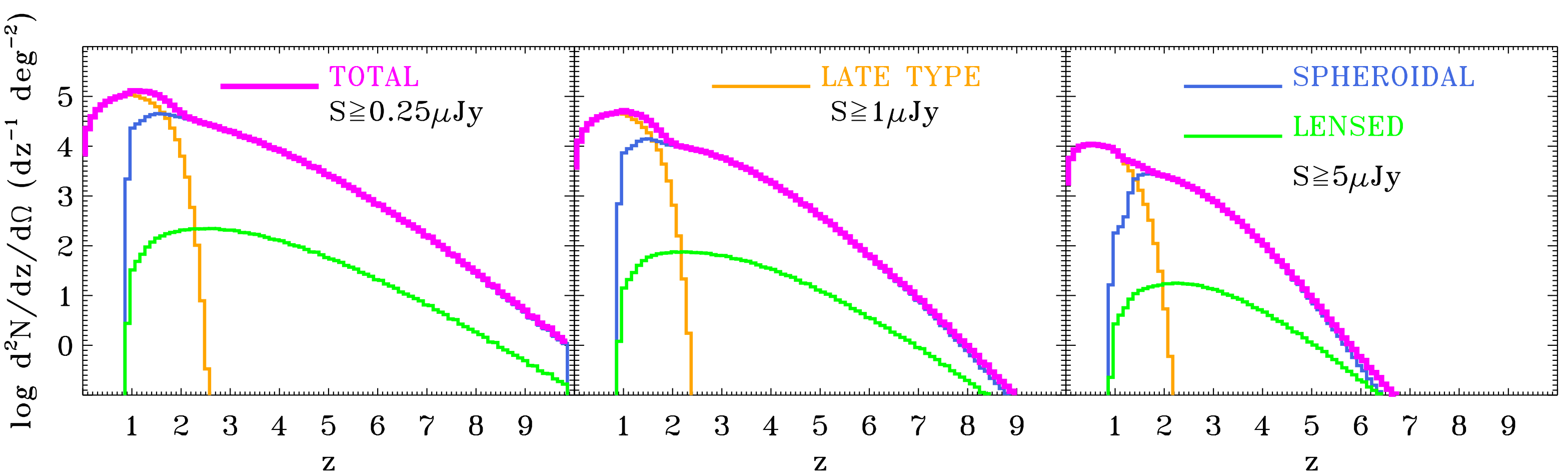
From the submm, we know that at least some high radio power sources are high-z star formers



ULIRGs

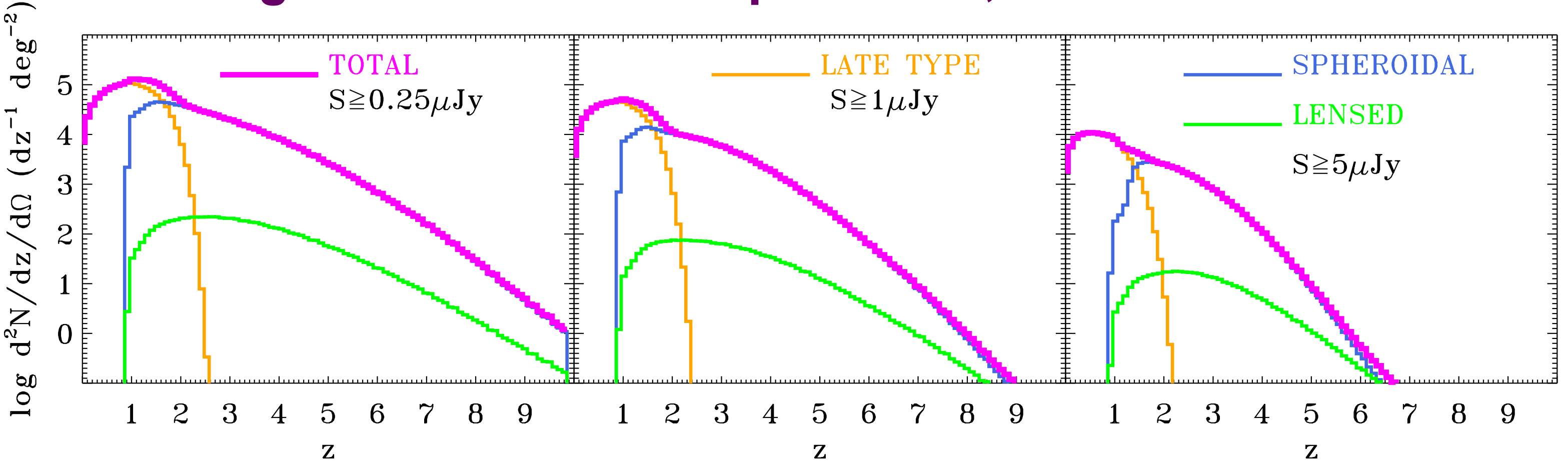
SKA 1.4 GHz models predict many high-z sources as push to 0.25 μJy

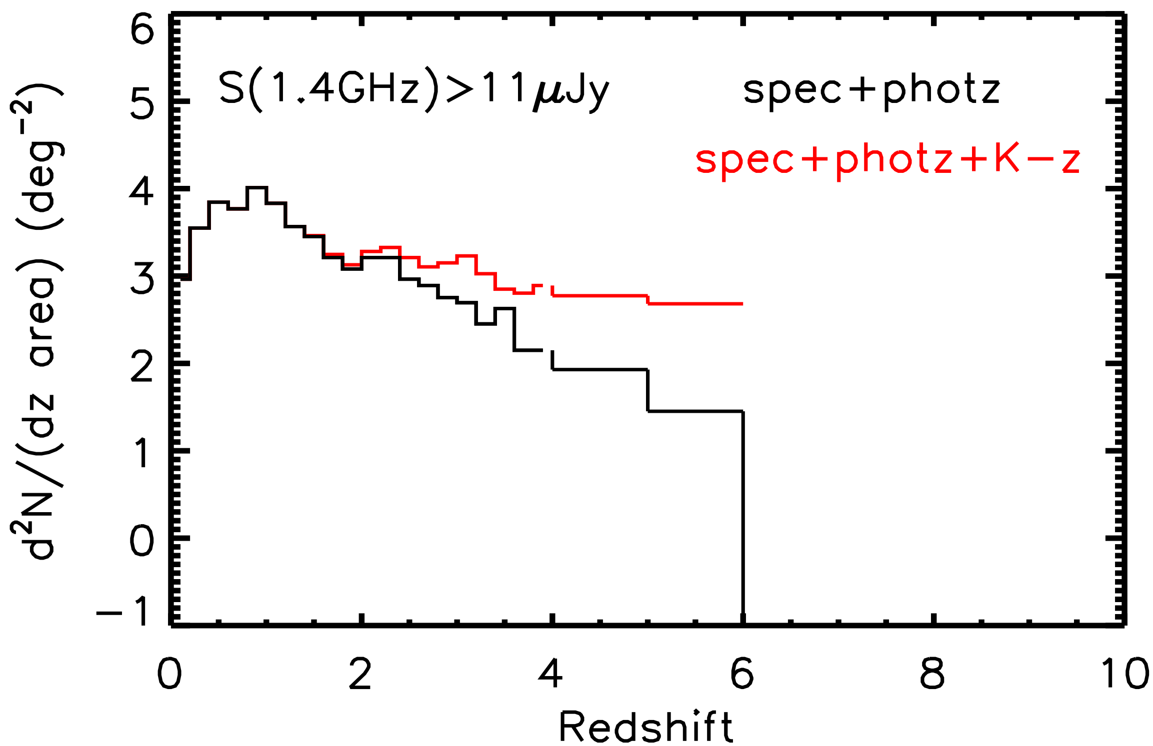
Mancuso et al. 2014 models



Data agree well with models for z<4, but already we see many more ULIRGs at higher redshifts than predicted, which bodes well

Mancuso et al. 2014 models





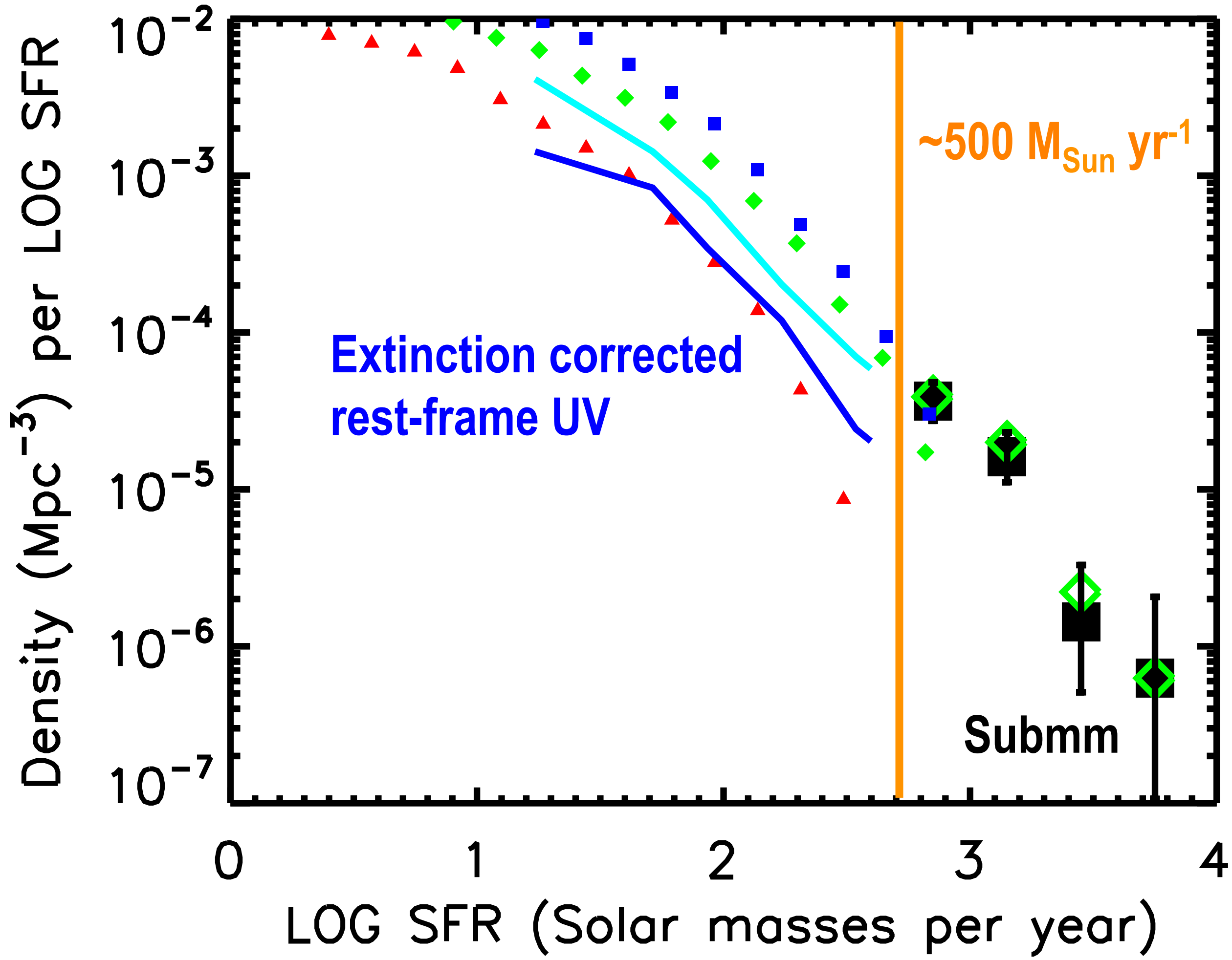
GOODS-N observed

How deep do we need to go in the radio for SFH?

UV samples max out at ~500 M_{Sun} yr^{-1}, even after extinction correction, so we at least need to be able to find all the ULIRGS to z~5-6 if we are to obtain an accurate accounting of the highest SFR galaxies in the SFH

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

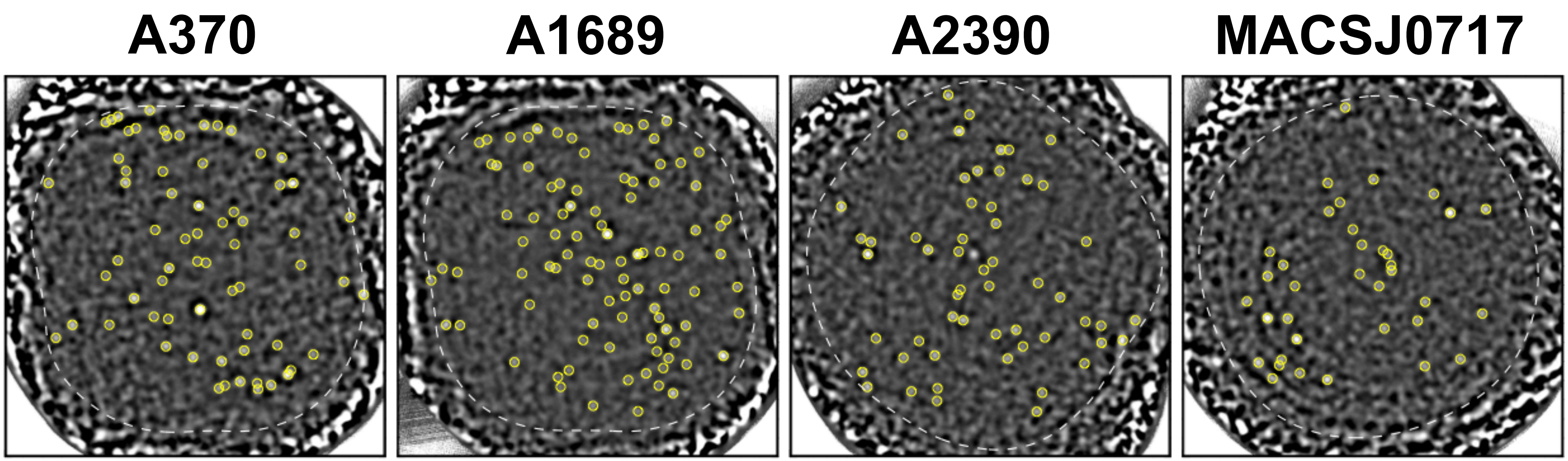


Barger et al. 2014

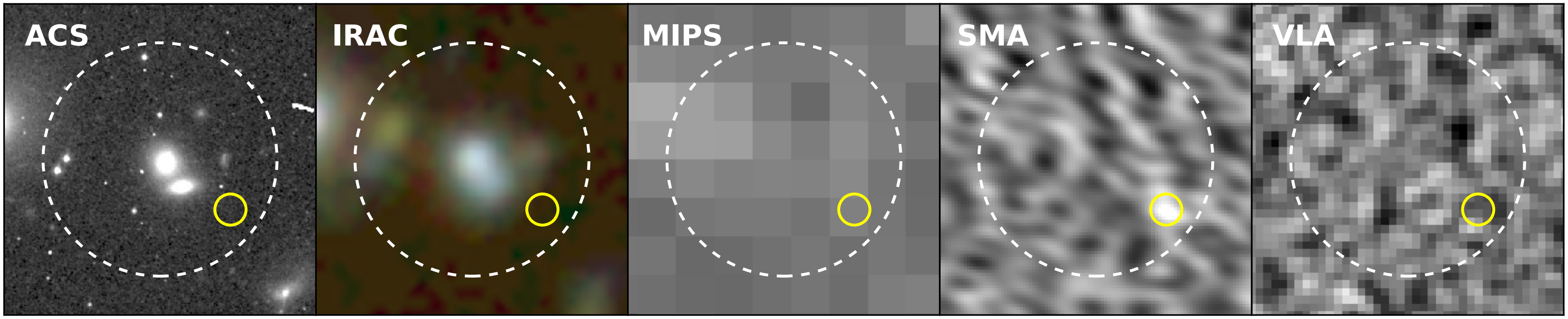
How deep do we need to go in the radio for SFH?

- What about lower SFR galaxies (LIRGs), which are not typically included in the FIR/submm samples due to the confusion? Do optical/NIR selections give a relatively complete accounting of these?

- Hints from submm observations of massive lensing cluster fields (advantages of magnification and source plane expansion) (Chen et al. 2014)



3/5 with SMA positions do not have optical/NIR counterparts



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

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

The NGVLA can help us construct a complete SFH by giving a large homogeneous sample that is insensitive to extinction over a wide range of luminosities and SFRs and out to high redshifts (i.e., ULIRGs and LIRGs to z~5-6)

NGVLA

- At 1.4 GHz, 5xVLA in 40 hrs (5σ=0.25 μJy)
- 12 m dish, field-of-view 67ʹ (smaller frequencies have the advantage of a larger field-of-view to get the numbers)
- 1000 objects at z>6, and some out to z=10!
- At z=3, measure galaxies down to near-Milky Way luminosities

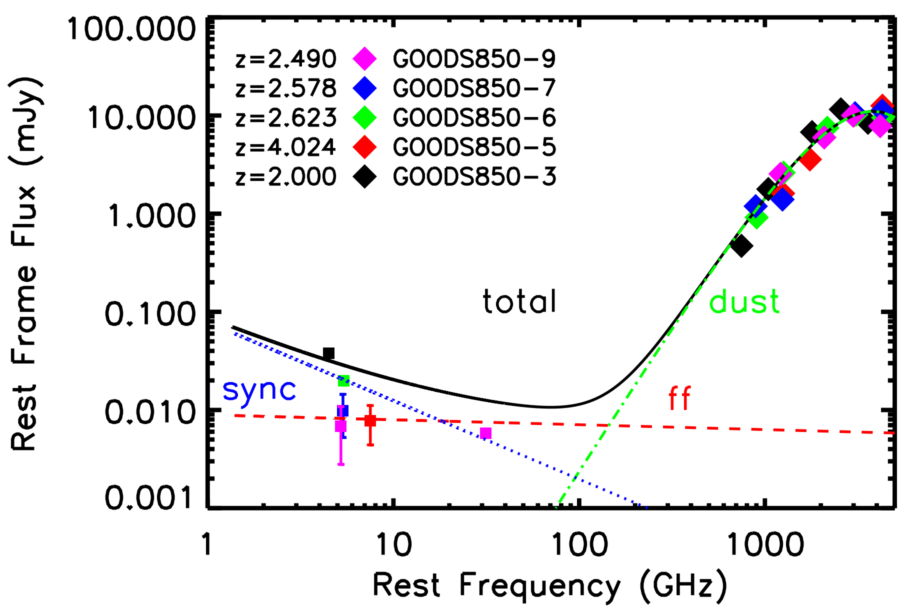
Three Major Issues for Mapping an Accurate SFH using the Radio

- What are the dominant physical mechanisms contributing to the radio emission at high redshifts?
- How well can we calibrate these mechanisms to estimate SFRs (need to understand the complexities)?
- Can we separate AGN from star-forming galaxies (SFGs)?

What frequencies should the NGVLA be operating at for this science goal?

Free-free emission is dominant at rest-frame 10s of GHz and is directly proportional to the production rate of ionizing photons by young, massive stars (though it may be biased towards bursts)

Synchrotron with constant spectral index

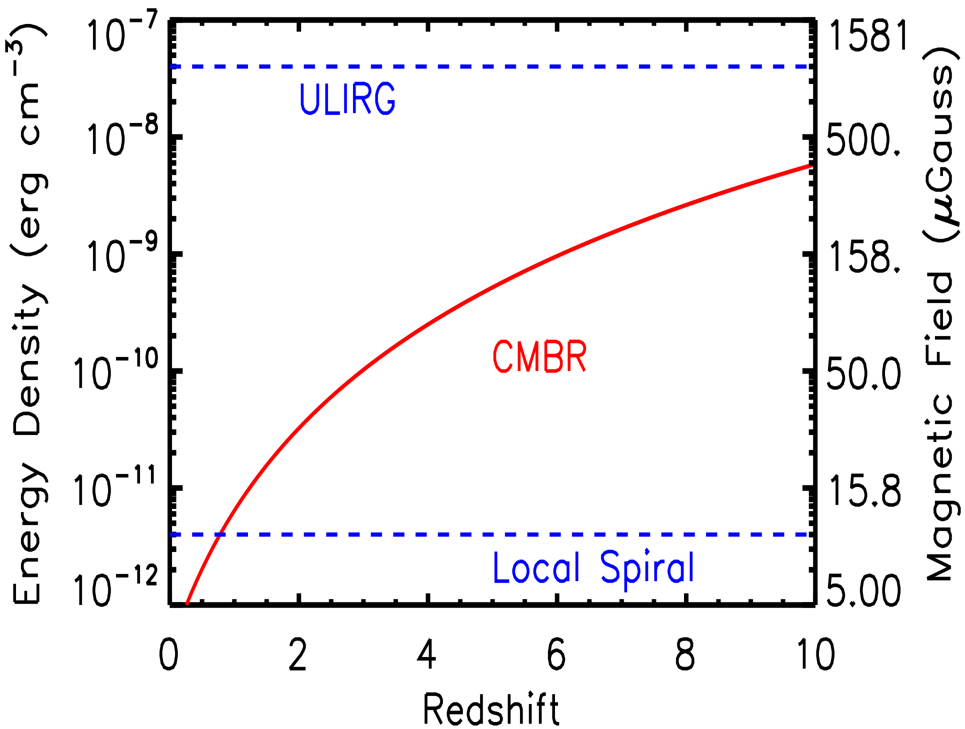


However, there can be substantial synchrotron contributions that also have to be taken into account
(e.g., Rabidoux et al. 2014 give a free-free fraction of 55% at 30 GHz for a sample of local star-forming galaxies)

With radio SEDs (i.e., multiple measurements, including in the pure synchrotron region), can get a rough estimate of the relative fractions for more accurate SFRs

Another complication: CMBR quenching of synchrotron

- Compton cooling of relativistic electrons on the CMBR dominates over the synchrotron emission when the CMBR energy density exceeds the galaxy magnetic energy density (Condon 1992)

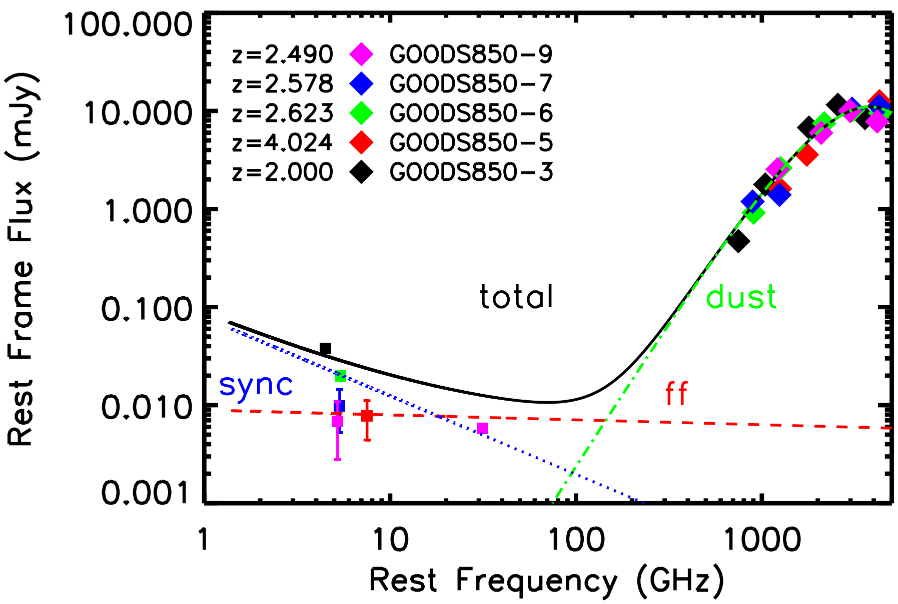


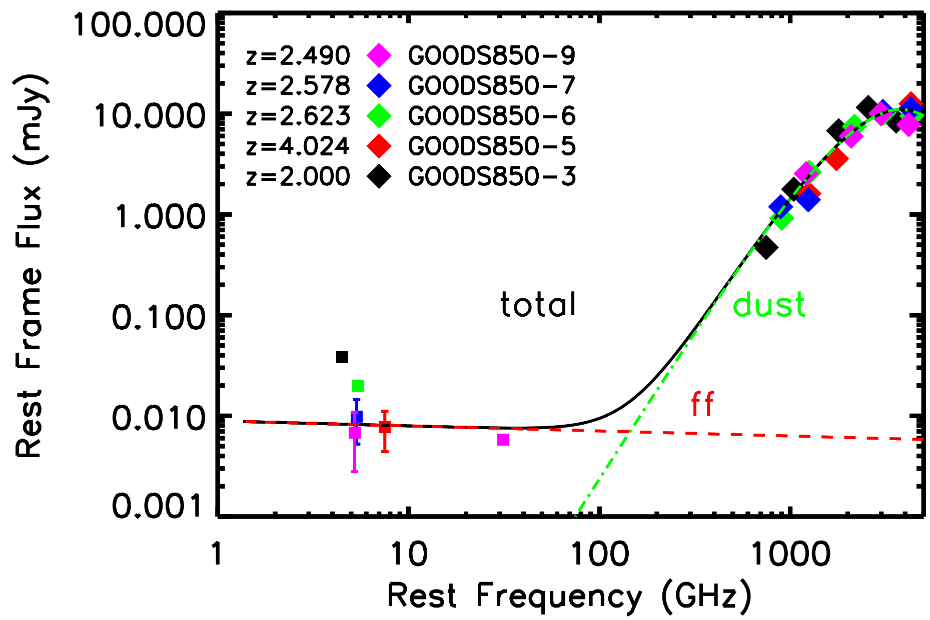
- Since the energy density of the CMBR goes as $(1+z)^4$, there is a *redshift dependence*

- Moreover, the synchrotron emission will be highly quenched in lower SFR galaxies but possibly never in ULIRGs, so there is also a *luminosity dependence*

This means that higher redshift galaxies with moderate SFRs will be totally free-free

Synchrotron with constant spectral index

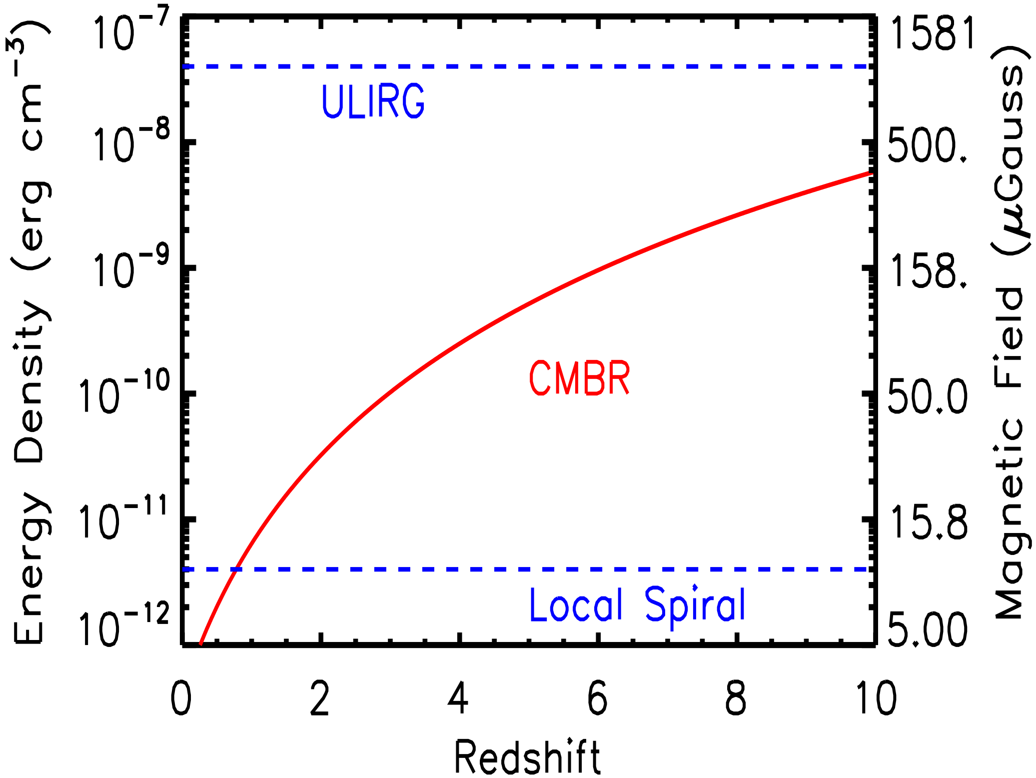




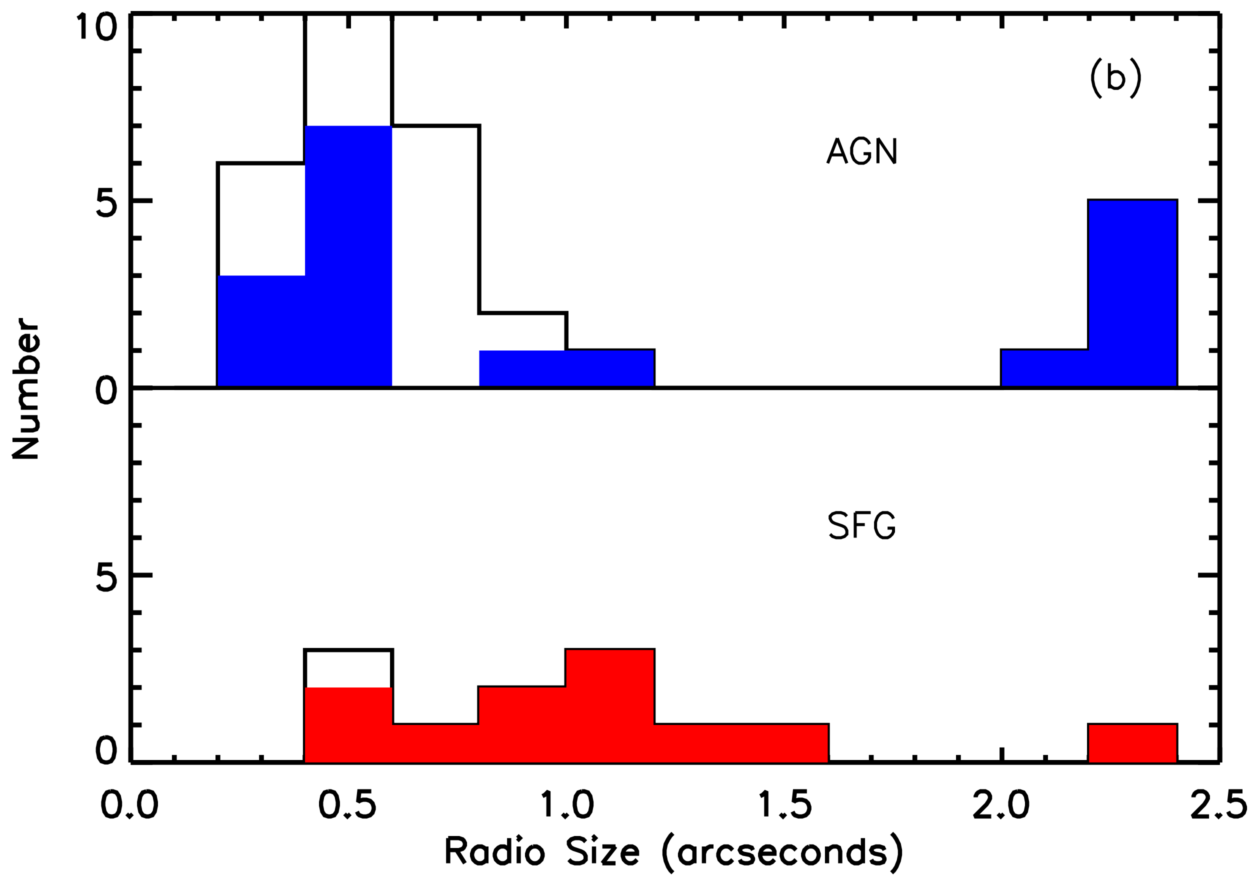
For this reason, the most secure SFRs will come from observations made at high frequencies (rest-frame 30-50 GHz) where the free-free emission significantly dominates for *all* galaxies

Interesting benefit of CMBR quenching of synchrotron

By mapping out the radio SEDs for a number of galaxies of a given luminosity with the NGVLA and seeing at what redshift the shape changes from synchrotron + free-free to free-free only, can get a rough galactic magnetic field measurement for that luminosity by equating it to the CMBR energy density



Another benefit: extended AGN are expected to be quenched by CMBR at high redshifts, leaving only compacts (e.g., Afonso et al. 2014; magnetic fields in extended radio jets small)



Typical sizes for SFGs are ~1”, larger than for compact AGN, so it should be straightforward to separate SFGs from AGN with moderately sub-arcsecond spatial resolution

Summary

- The NGVLA will uniformly map SF over a wide redshift and luminosity range (up to a z~3 Milky Way galaxy and a z~6 LIRG) while avoiding selection biases from dust extinction

- Large FoV at lower frequencies will find large numbers of z>6 galaxies

- At rest-frame 30-50 GHz, the radio emission will be significantly dominated by free-free emission (avoids issue of accurately measuring free-free and synchrotron fractions, as well as CMBR quenching of synchrotron emission in lower luminosity galaxies), giving a measure of instantaneous SFRs for SFH

- Possible to roughly estimate magnetic field strengths as a function of luminosity from SED mapping of radio sources (reveals the redshift where synchrotron suppression occurs)

- Only moderate angular resolution is needed to separate AGN from SFGs (low frequency adequate)