

High Z Star Formation

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HIGH-Z GALAXIES: OPTICAL SUCCESS WITH LYMAN BREAK TECHNIQUE

- Simple photometric technique
 - Prominent spectral feature: Lyman break from intergalactic & interstellar neutral H absorption

$$\lambda_{\text{obs}} = \lambda_{\text{emitted}}(1 + z)$$

- Passage of Lyman break through broad-band filters allows efficient selection of high-z candidates ($z = 2.5 - 4.5$; e.g. Steidel et al. 1996)
- Substantial population of compact star-forming galaxies spectroscopically confirmed
- SFRs $3 - 15 h_{65}^{-2} M_{\odot} \text{ yr}^{-1}$ (for $q_0 = 0.5$) measured directly from far-UV continua

**MASSIVE GALAXY FORMATION WELL UNDERWAY
AT EARLY EPOCHS**

MAPPING THE STAR FORMATION HISTORY

Observe galaxies at increasing lookback times to directly reconstruct history of stellar birthrate (e.g. Madau 1997)

Major uncertainties:

- Extinction by dust can substantially modify SFR determinations — extinction estimates in UV differ by factors of 3–15! (e.g. Pettini et al. 1997; Meurer et al. 1997)
- Could we be missing an entire population of dust obscured sources? (YES!)

COBE DETECTION OF EXTRAGALACTIC FIR BACKGROUND

- **Dust absorbs AGN/stellar light, reradiates in FIR**
- **EBL is cumulative emission from all objects lying beyond our Galaxy**
- **FIRAS/DIRBE experiments on COBE (e.g. Puget et al. 1996; Fixsen et al. 1998)**
- **Total reradiated emission COMPARABLE to unobscured optical emission**
- **Thus, global SF history of Universe from optical observations very incomplete**

REST-FRAME FIR OBSERVATIONS NEEDED TO IDENTIFY HIGH-Z DUSTY GALAXIES

EXTREME DUSTY CASE: ULTRALUMINOUS INFRARED GALAXIES

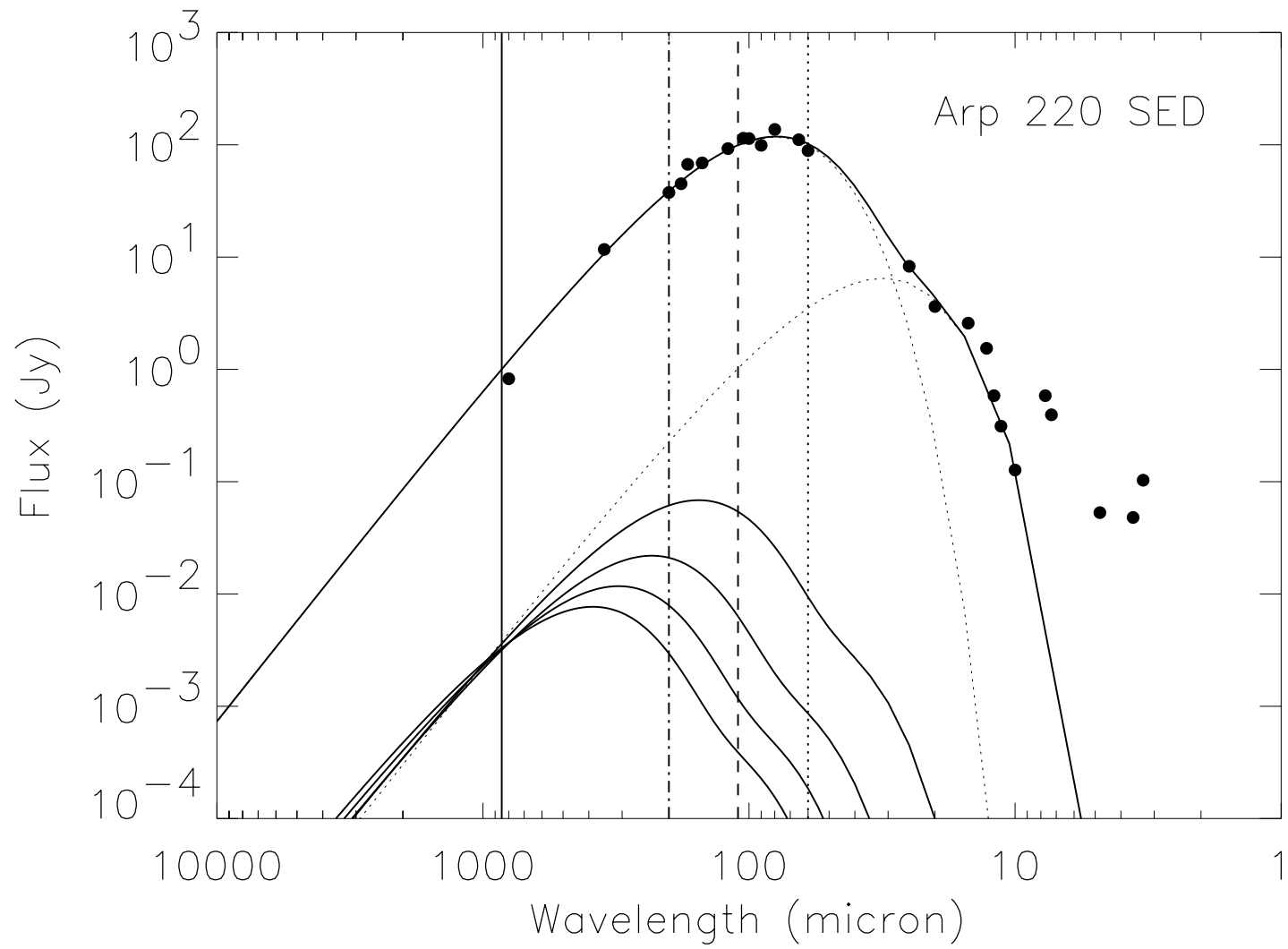
- Most luminous systems locally; $L_{FIR} > 10^{12} L_{\odot}$
- Emit large fraction of total L in FIR
- $\sim 95\%$ have merger morphology
- Powered by (a) massive starbursts induced by galaxy-galaxy collisions or (b) AGN activity
- 70–80% of small, local ULIG sample dominantly star formation (Genzel et al. 1998)
- Prototypical ULIG: Arp 220 ($z = 0.02$), modified bb with emissivity λ^{-1} , $T_{\text{dust}} = 47$ K (Klaas et al. 1997)
- Radio sources

UPCOMING: DISTANT SUBMM SOURCES SIMILAR TO ULIGs

WHY IS THE SUBMM EXCITING FOR COSMOLOGY?

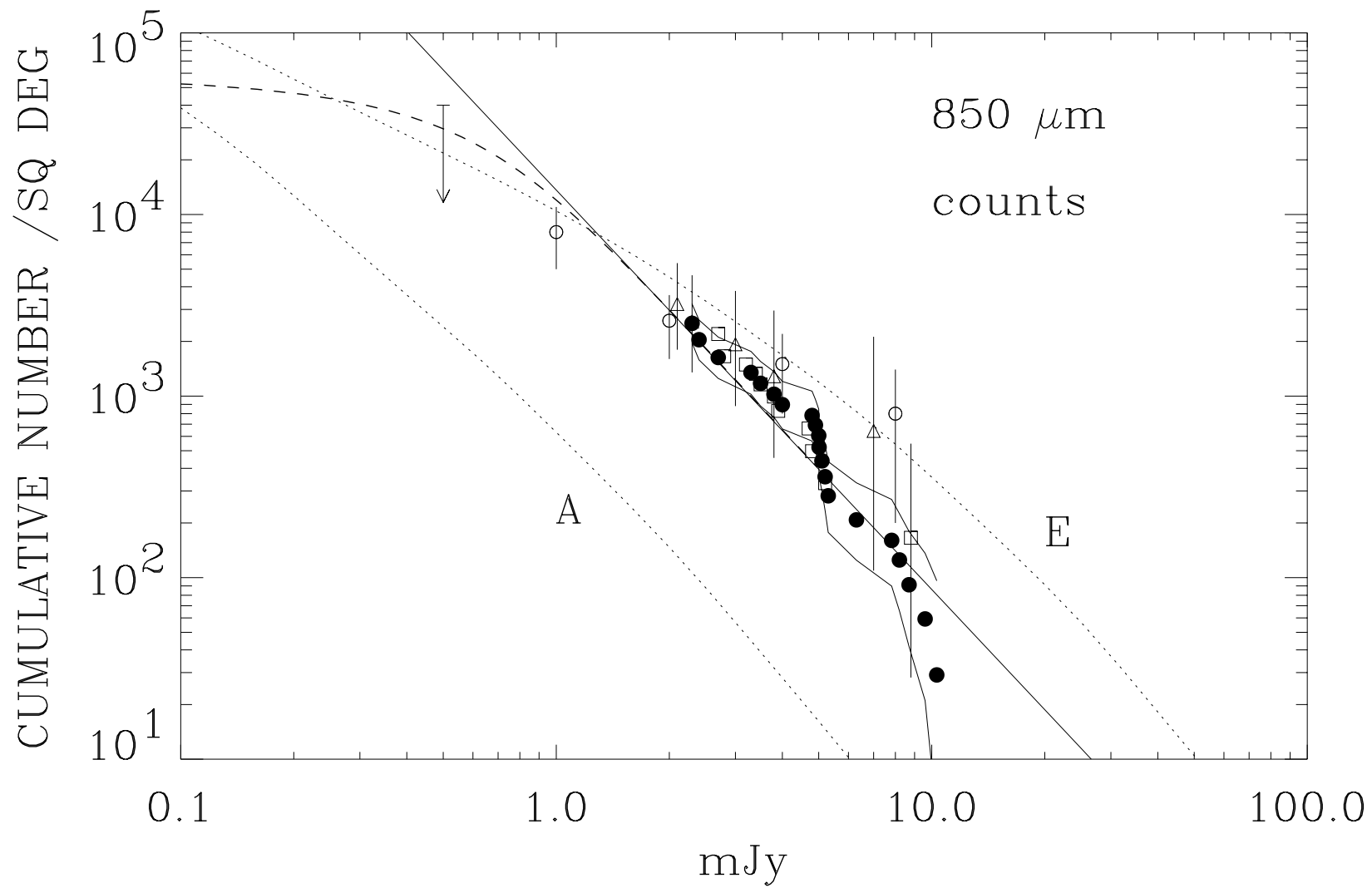
- Long suspected that much of high redshift star formation takes place inside shrouds of dust
- Dust absorbed/reradiated stellar/AGN light from high- z galaxies is observable in submm ($350\mu\text{m}$ - $2000\mu\text{m}$)
- Redshifting of dust spectrum nearly compensates for inverse square law dimming beyond $z \simeq 1$, so high- z galaxies as easy to detect

HOWEVER, HAWC NEEDED TO MAP FORM OF SED



RESOLVING THE SOURCES IN THE FIR/SUBMM EBL WITH SCUBA

- SCUBA (the Submillimeter Common User Bolometer Array; Holland et al. 1999) has needed sensitivity & area coverage
- GOAL: long integrations on well-studied fields to determine
 - Number of sources at each flux level
 - Typical properties & redshifts
- Targeted surveys
 - Gravitationally-lensed cluster fields (Smail et al. 1997, 1998; Blain et al. 1999)
 - Hawaii Survey Fields & Lockman Hole (Barger et al. 1998, 1999)
 - Hubble Deep Field (Hughes et al. 1998)
 - Canada France Redshift Survey Fields (Eales et al. 1999, Lilly et al. 1999)



SUBMM COUNTS

Rules out models without ULIGs (e.g. Guiderdoni et al. 1998)

EBL contribution = 9.3×10^3 mJy deg⁻²

20 – 30% of total EBL at 850 μ m

[4.4×10^4 , Fixsen et al. 1998]

[3.1×10^4 , Puget et al. 1996]

Parameterization of the differential counts (with S in mJy)

$$n(S) = N_o / (a + S^\alpha)$$

$\alpha = 3.2$ (2.6 – 3.9 at 95% CL)

$N_o = 3.0 \times 10^4$ deg⁻² mJy⁻¹

$a = 0.4 - 1.0$ (to fit total EBL)

Bulk of submm emission must reside in ~ 1 mJy sources

SUBMM SOURCES

Small numbers

Submm: 10^4 deg^{-2} in 1 – 10 mJy range

Optical: 10^6 deg^{-2}

BUT large submm source luminosities/SFRs inferred (assuming an Arp 220-like spectrum & $z=1-3$)

$$\text{SFR} \sim 1.5 \times 10^{-10} (L_{\text{FIR}}/L_{\odot}) M_{\odot} \text{ yr}^{-1}$$

(Scoville & Young 1983; Thronson & Telesco 1986)

- 5 mJy source has $L \sim 2.5 \times 10^{12} h_{65}^{-2} L_{\odot}$ ($q_0 = 0.5$)

$$\implies \text{SFR} \sim 350 h_{65}^{-2} M_{\odot} \text{ yr}^{-1}$$

- 1 mJy source has $L \sim 4.5 \times 10^{11} h_{65}^{-2} L_{\odot}$ ($q_0 = 0.5$)

$$\implies \text{SFR} \sim 70 h_{65}^{-2} M_{\odot} \text{ yr}^{-1}$$

High $L_{\text{FIR}}/\text{SFR} \implies$ proto-spheroids?

HAVE WE FOUND E PROGENITORS?

- Disk, spheroidal populations have comparable metal densities at present time, so expect comparable light from disk, spheroidal formation \implies explains observed approximate equality of optical, submm backgrounds
- Submm space density ($5 \times 10^{-3} h^3_{65} \text{ Mpc}^{-3}$; $q_0 = 0.5$) comparable to that of present-day Es (10^{-3})
- From CO data (Frayser et al. 1998, 1999), submm sources each have enough molecular gas to form an L^* galaxy
- Some submm sources have merger morphologies, as expected for Es forming from spirals

WHERE DO SUBMM SOURCES FIT INTO SF HISTORY OF UNIVERSE?

- Need redshifts, AGN fraction of submm population
- BUT poor SCUBA resolution causes problems in searches for optical counterparts
- We targeted a sample of gravitationally-lensed submm sources detected by Smail et al. (1998)
 - Keck LRIS observations of all possible VISIBLE counterparts (Barger et al. 1999)
 - Eases spectroscopic follow-up since brighter in optical due to lensing

REDSHIFT IDENTIFICATIONS VIA OPTICAL COUNTERPARTS

FIRM ids include

- Starburst pair at $z=2.55$ and AGN+companion at $z=2.80$, detected in CO (Fruyer et al. 1998, 1999)
- 2 central cD galaxies (Edge et al. 1999)

RELIABLE ids include

- 2 AGN (i.e. broad or high ionization emission lines) at $z=1.06$ and $z=1.15$

(Note: $< 1\%$ of general field population show AGN signatures)

POSSIBLE ids

- In range $z \sim 0.18 - 2.11$
- BUT no remarkable spectral features

RADIO EMISSION AS STAR FORMATION TRACER

- Radio emission at 1.4 GHz from star forming galaxies mainly synchrotron from relativistic e^-
- SNe remnants accelerate most of the relativistic e^-
 - Progenitors live $< 3 \times 10^7$ yr
 - Relativistic e^- have lifetimes $< 10^8$ yr
 - Radio thus probes very recent star formation
- Radio luminosity unsusceptible to dust
- Radio maps can have subarcsec position accuracy and resolution
- Remarkably tight and ubiquitous local correlation between global FIR and radio luminosities

IF SUBMM-RADIO CORRELATION HOLDS AT HIGH-Z, WE CAN PINPOINT SUBMM SOURCES

RADIO SAMPLE

- VLA observations of HDF/HFFs at 1.4 GHz to 5σ completeness limit of $40 \mu\text{Jy}$ (Richards 1999)
- Selected region (80 square arcmin) with optical/NIR imaging
- Also observed with MERLIN at 1.4 GHz to rms noise level of $3.3 \mu\text{Jy}$ giving $0.2''$ resolution images
- Richards et al. (1999) found that of the μJy radio sources
 - 60% could be identified with $I < 22$ disk galaxies
 - 20% with low luminosity AGN (weak FR Is, Seyferts, and Es)
 - BUT 20% could not be identified to $I \sim 25$

Richards (1999) showed that majority of μJy radio sources are associated with star forming galaxies:

COULD A SUBSET OF THIS POPULATION BE OPTICALLY OBSCURED?

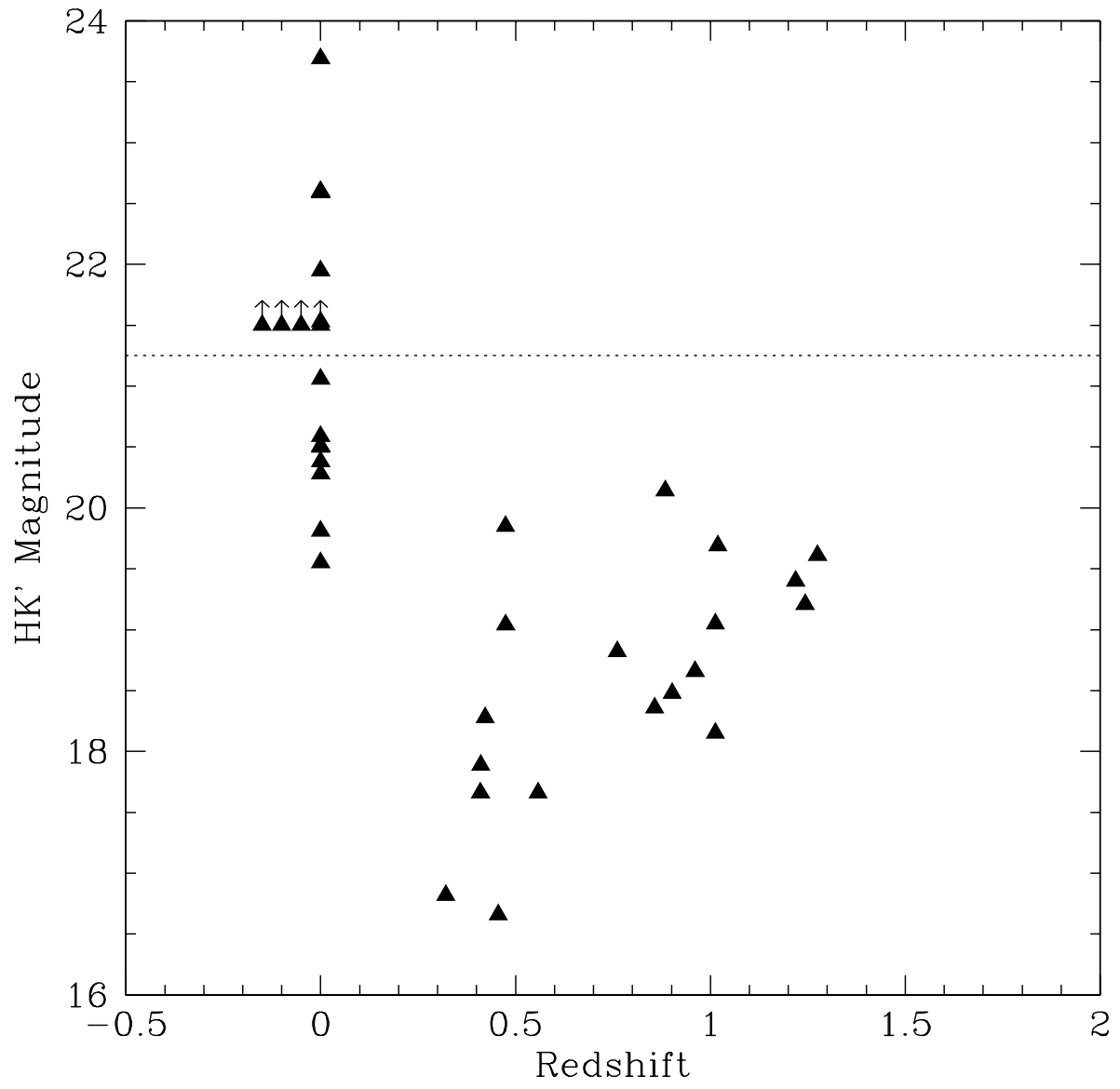
OUR OBSERVATIONAL PROGRAM

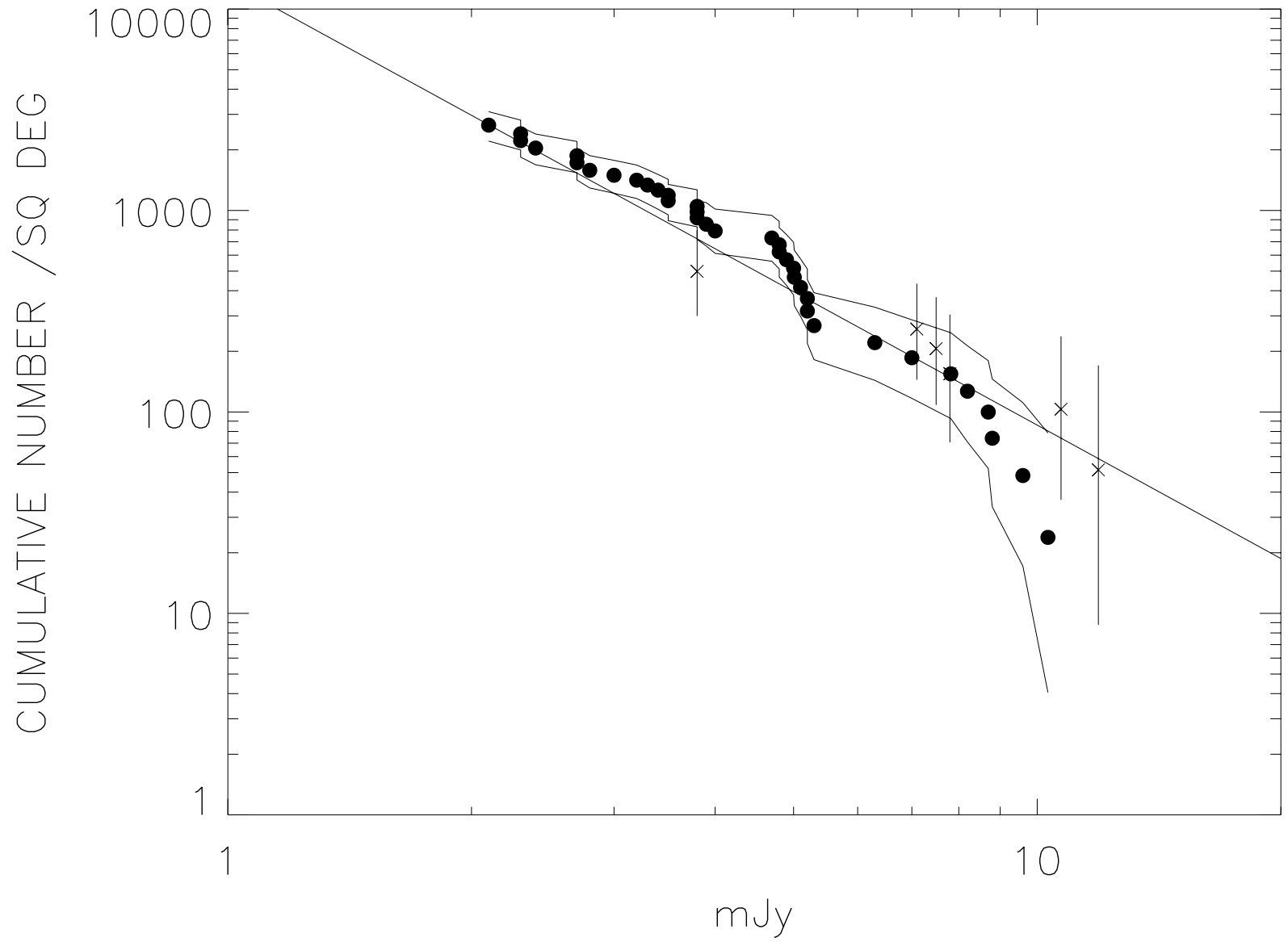
- PHASE I

- Subsample of HFF radio sources observed with LRIS on Keck II
- Spectroscopic redshifts relatively straightforward for $HK' < 21.25$ ($K < 21$) sources (all measured redshifts have $z < 1.3$)
- Adopt $HK' = 21.25$ as bright magnitude bound to optical/NIR-faint radio population

- PHASE II

- Targeted 14/16 optical/NIR-faint radio sources with SCUBA
- Used jiggle map mode to simultaneously observe 35/54 optical/NIR-bright radio sources
- Relatively shallow observations (3σ of 6 mJy)
- Detected 5/14 optical/NIR-faint sources
- Did not detect any of optical/NIR-bright sources
- Two additional > 6 mJy sources detected that are not radio sources + HDF850.1 which is seen only at 8.4 GHz





**ASSUME SEDS OF DISTANT ULIGS
SAME AS LOCAL ULIGS**

Radio flux

$$S_r = (0.148 \text{ Jy})(1+z)^{1+\alpha_r} \left(\frac{\nu}{8.4 \text{ GHz}} \right)^{\alpha_r} \left[\frac{d_L(z_{Arp})}{d_L(z)} \right]^2$$

Use standard $\alpha_r = -0.8$ to avoid synchrotron self-absorption

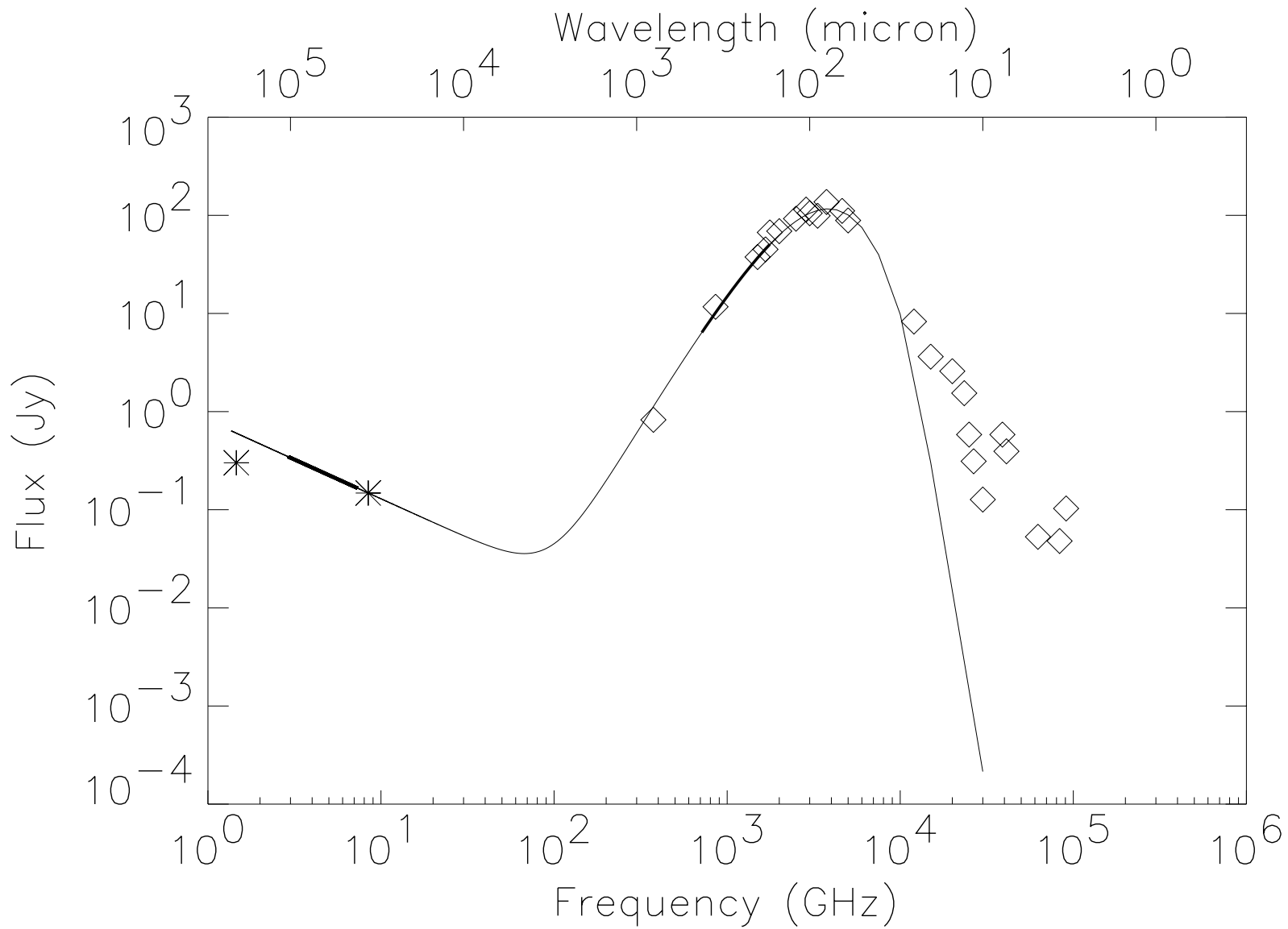
Submm flux

$$S_s = 0.57\pi B(\nu(1+z), T_d)\nu^\beta(1+z)^{1+\beta} \left[\frac{d_L(z_{Arp})}{d_L(z)} \right]^2$$

S_s/S_r is cosmology independent and can be used as a redshift estimator (Carilli & Yun 1999)

In long-wavelength limit (valid $z \leq 3$), the Arp 220 ratio is

$$\frac{S_{353 \text{ GHz}}}{S_{1.4 \text{ GHz}}} = 1.1 \times (1+z)^{3.8}$$



IS IT REASONABLE TO USE THE ARP 220 SED?

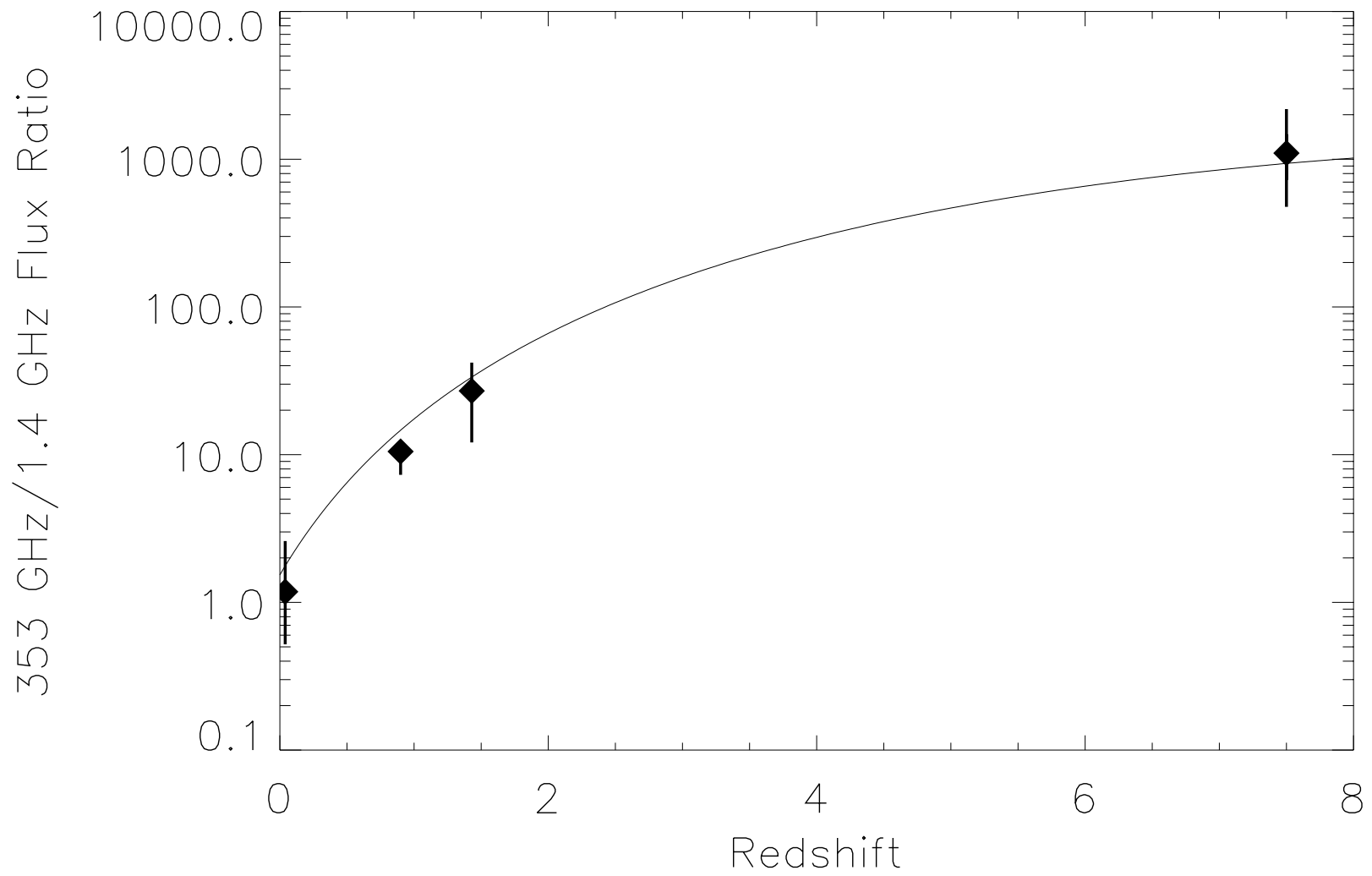
- Unevolved local ULIGs (Condon et al. 1991; Rigopoulou et al. 1996) match Arp 220 $850\mu\text{m}/20\text{cm}$ flux ratio versus z with spread less than multiplicative factor of 2

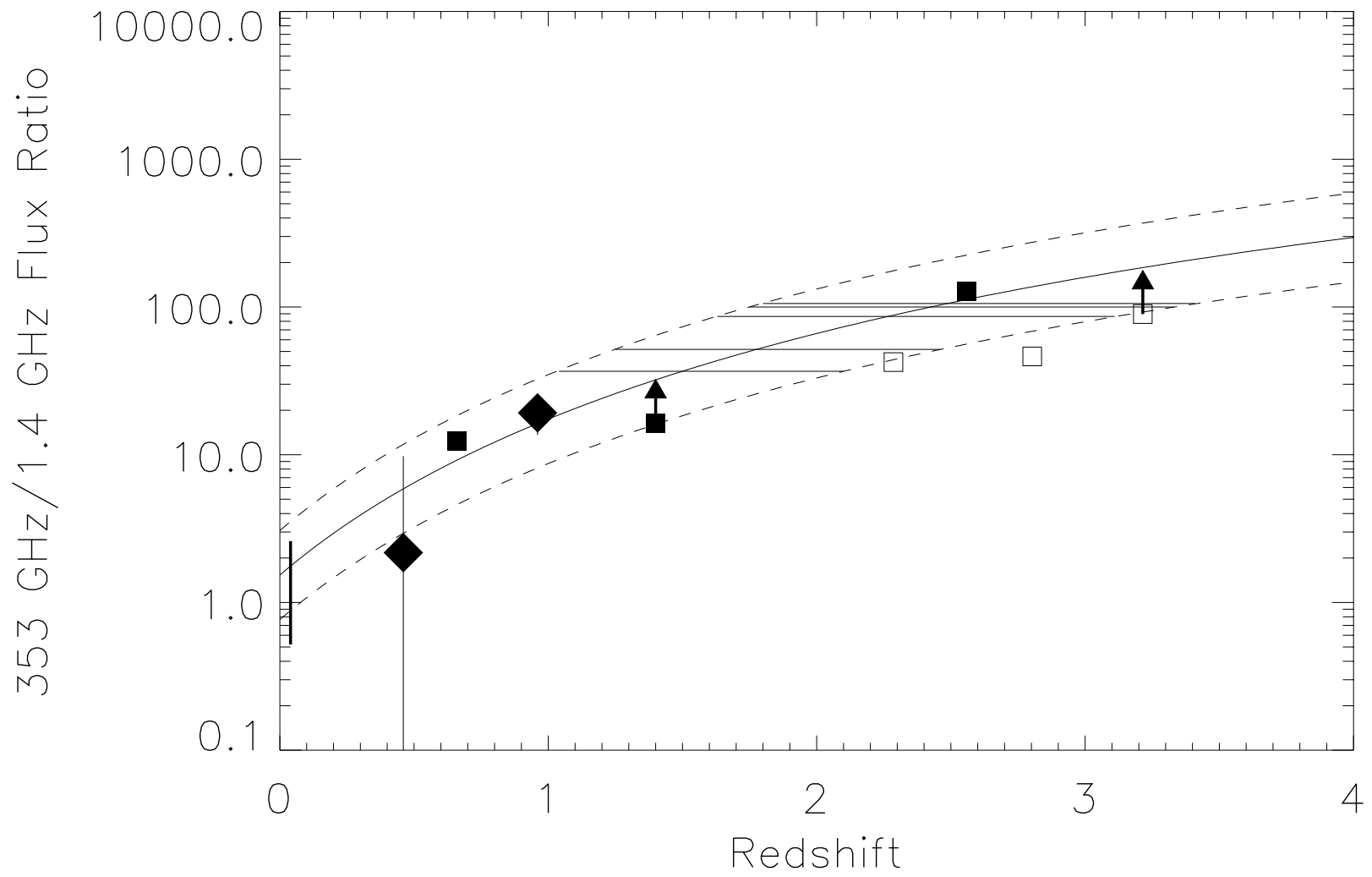
λ (μm)	z	# galaxies
100	7.5	25
350	1.44	2
450	0.9	4
800	0.06	7

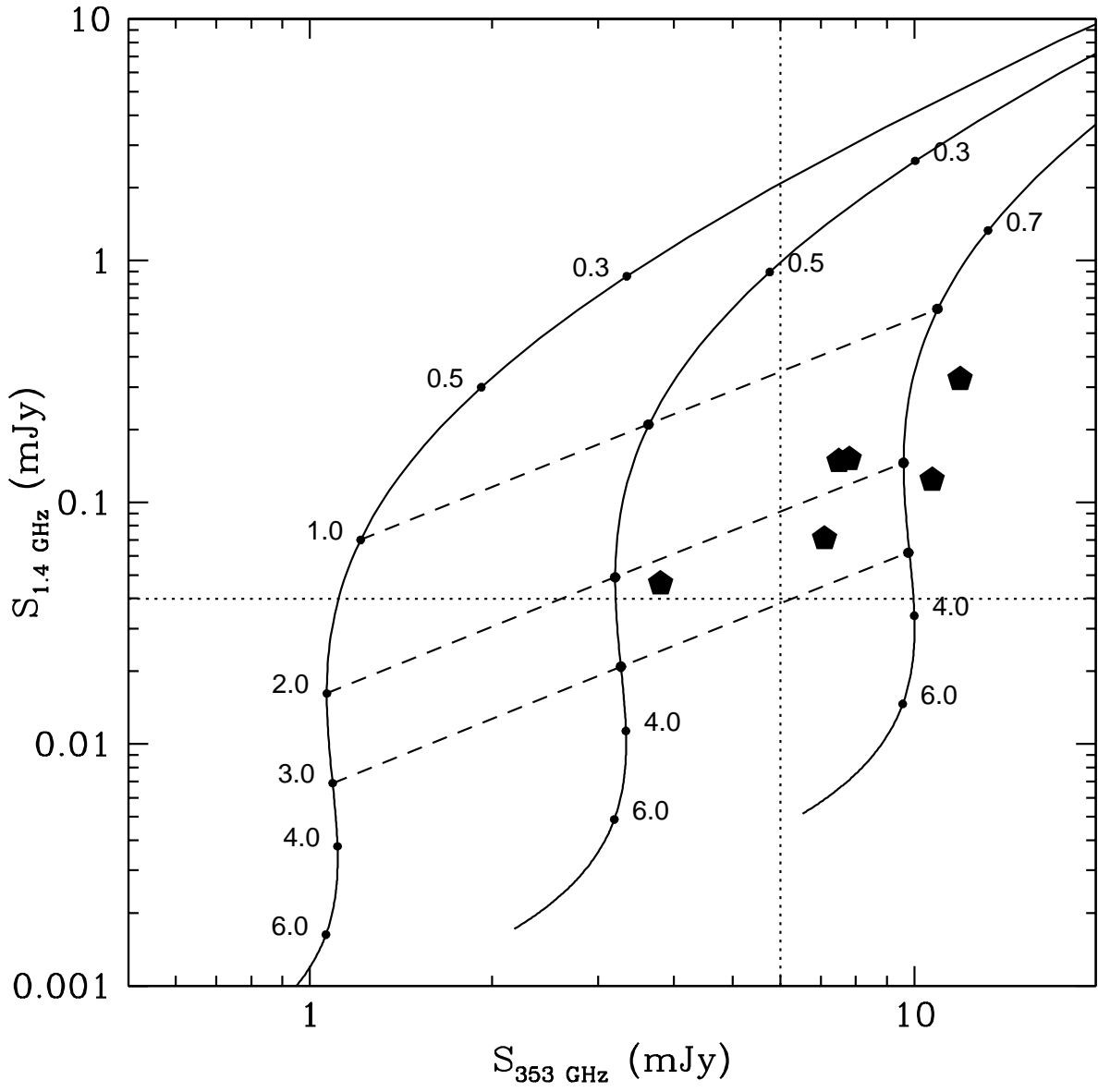
$$[1 + z = 850\mu\text{m}/\lambda]$$

- Objects with observed redshifts and both $850\mu\text{m}$ and 20cm detections also fit well on curve

**CAN ESTIMATE Z FOR ANY OBJECT HAVING BOTH
850 MICRON AND 20 CM DATA**







SUMMARY

- Distant population of dusty galaxies similar to ULIGs in local Universe
- Energy from submm sources comparable to entire optical Universe
- Bulk of submm emission must reside in ~ 1 mJy sources (to match EBL)
- Spectroscopic ids only reliable for bright starbursts and AGN (\approx one-quarter of lensed submm sample)
- Optically-faint micro-Jy radio sources pinpoint submm sources
- Submm-radio correlation predicts $z \sim 1 - 3$ for these star-forming objects
- HAWC observations will map SEDs — determine emissivities and effective temperatures, $T_d/(1+z)$, of high-redshift ULIGs
- HAWC is the only new survey instrument that will have sufficient angular resolution to resolve a significant fraction of the EBL at $60 - 200\mu\text{m}$