

Direct-Detection Survey Spectroscopy with CCAT

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with

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July 18, 2007

Topics

- Scientific motivation for terrestrial submillimeter spectroscopy.
- Sensitivities of CCAT for spectroscopy, context with ALMA & pending flight opportunities.
- C+ Science and high-z survey outline:
 - areal and redshift density of sources accessible to CCAT.
- Optimal spectrometer choices, relationships to present-day instruments.

Introduction: IR astronomy is far-IR astronomy

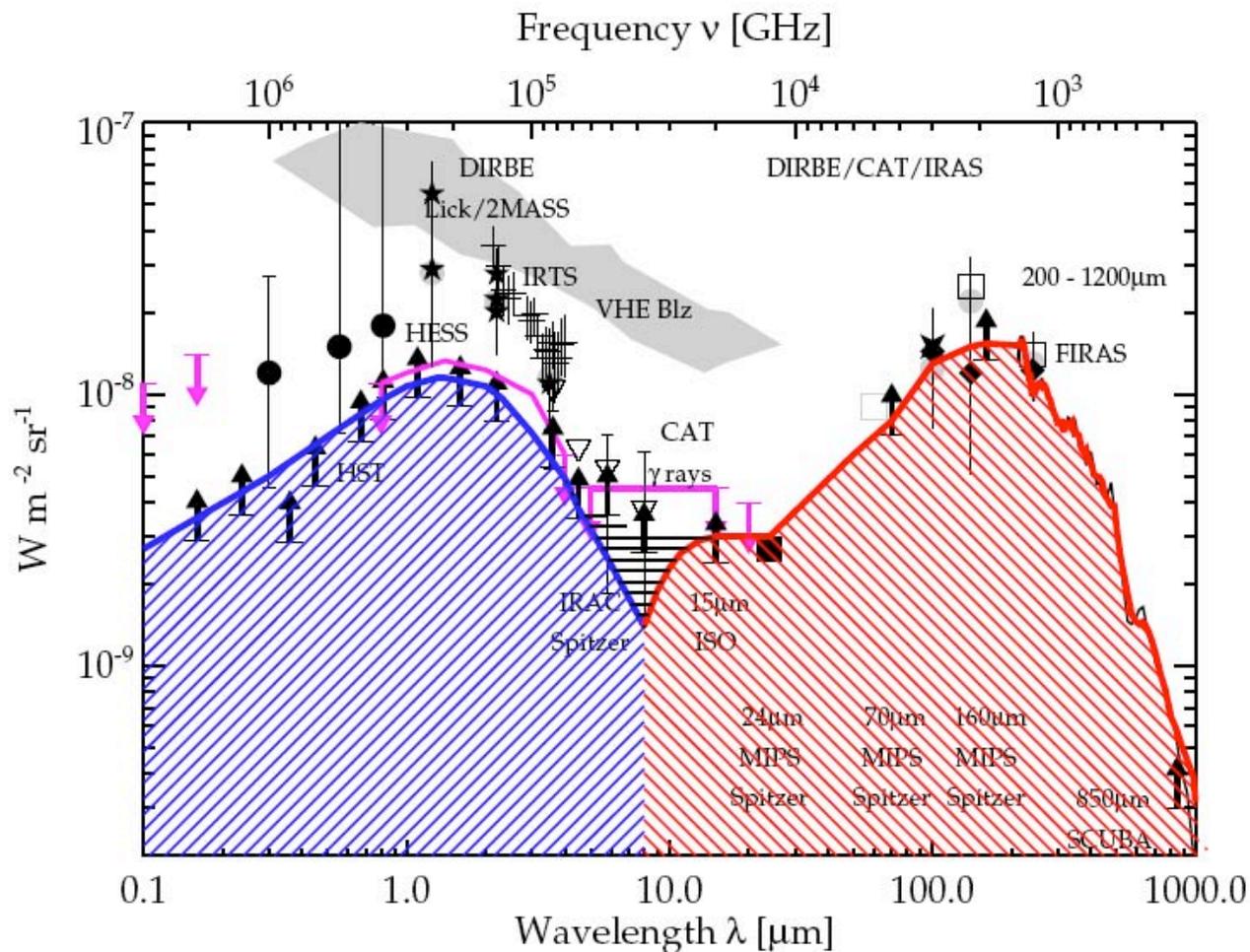


Fig. 13. Our best Cosmic Optical Background (blue-shaded, left) and Cosmic Infrared Background (red-shaded, right) estimates. The gray-shaded area represents the region of overlap. See Fig. 9 for the other symbols.

Cosmic Backgrounds
Galaxy counts +
COBE + Spitzer
(Dole et al. 2005)

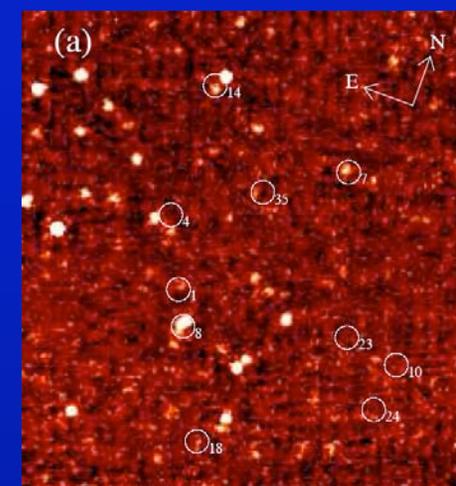
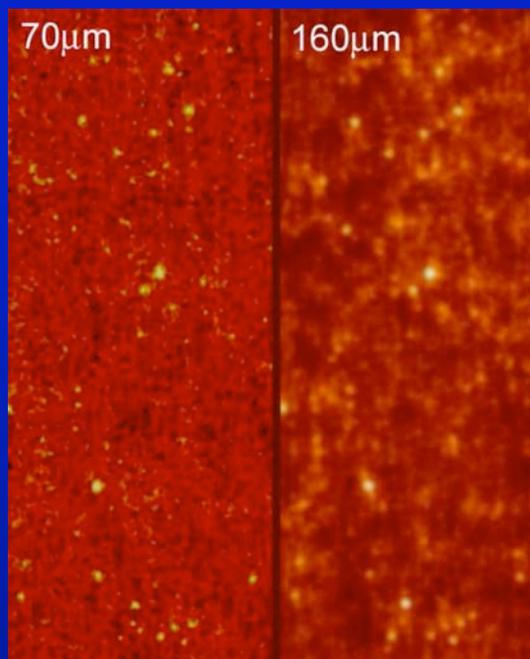
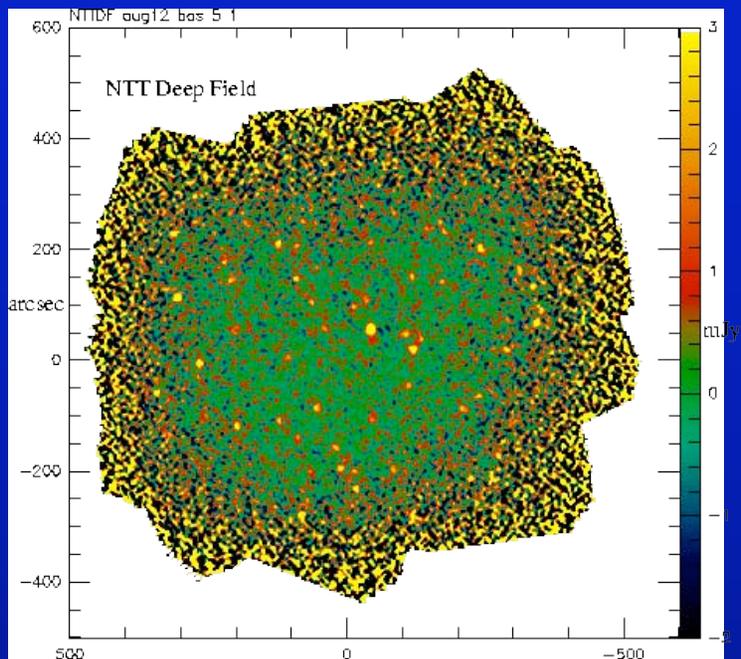
- History of stars and galaxies written at both optical / NIR and far-IR wavelengths.

Questions:

What have we learned about the production of the CFIRB?

What is the relationship between the populations producing the CFIRB and the COB?

Far-IR background is being resolved into galaxies



Spitzer MIPS 24 μm
Lockman Hole
Egami et al. (2004)

MAMBO / IRAM 30 m
1.3 mm 60 hours, 40 sources
10% of BG

Bertoldi et al. (2000);
Carilli et al. (2001c, 2002b);
Dannerbauer et al. (2002);
Voss (2002);
Eales et al. (2002)
Greve et al (2005)

Spitzer MIPS
Chandra Deep Field South
70 (23%) 160 (7%)

Dole et al. (2004)

Dole et al. (2004)

CCAT at 350 μm: Similar to SAFIR at 160 μm

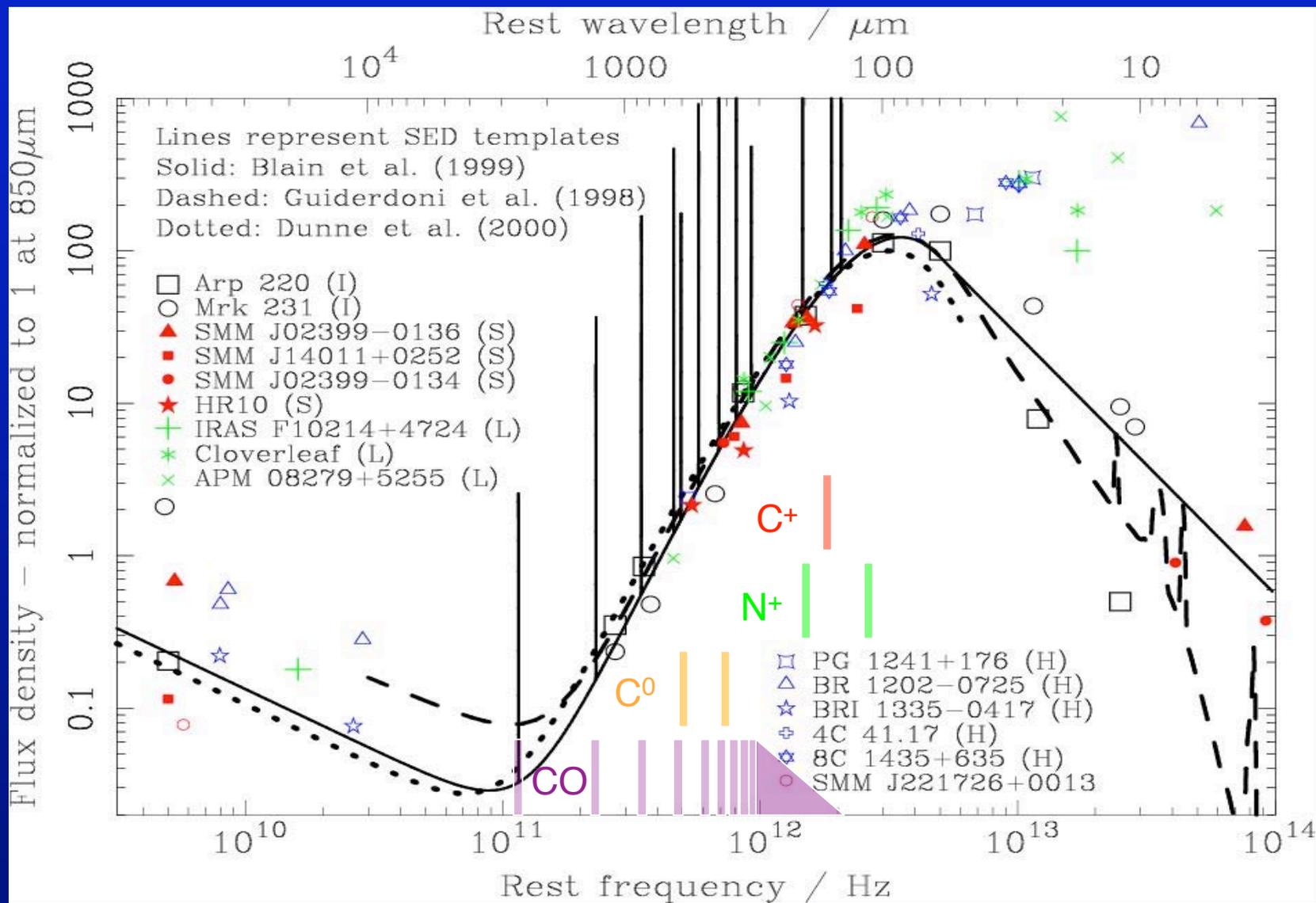
Future observatories will resolve the bulk of the background into individual sources, but How to do meaningful follow up of these sources?

TABLE 3
POTENTIAL RESOLUTION OF THE COSMIC INFRARED BACKGROUND

	24 μm ^a	70 μm ^a	160 μm ^a
<i>Spitzer</i>	74%	59%	18%
<i>Herschel</i> ^b / <i>SPICA</i>	98%	93%	58%
<i>JWST</i> ^b	99%	—	—
<i>SAFIR</i>	100%	99%	94%

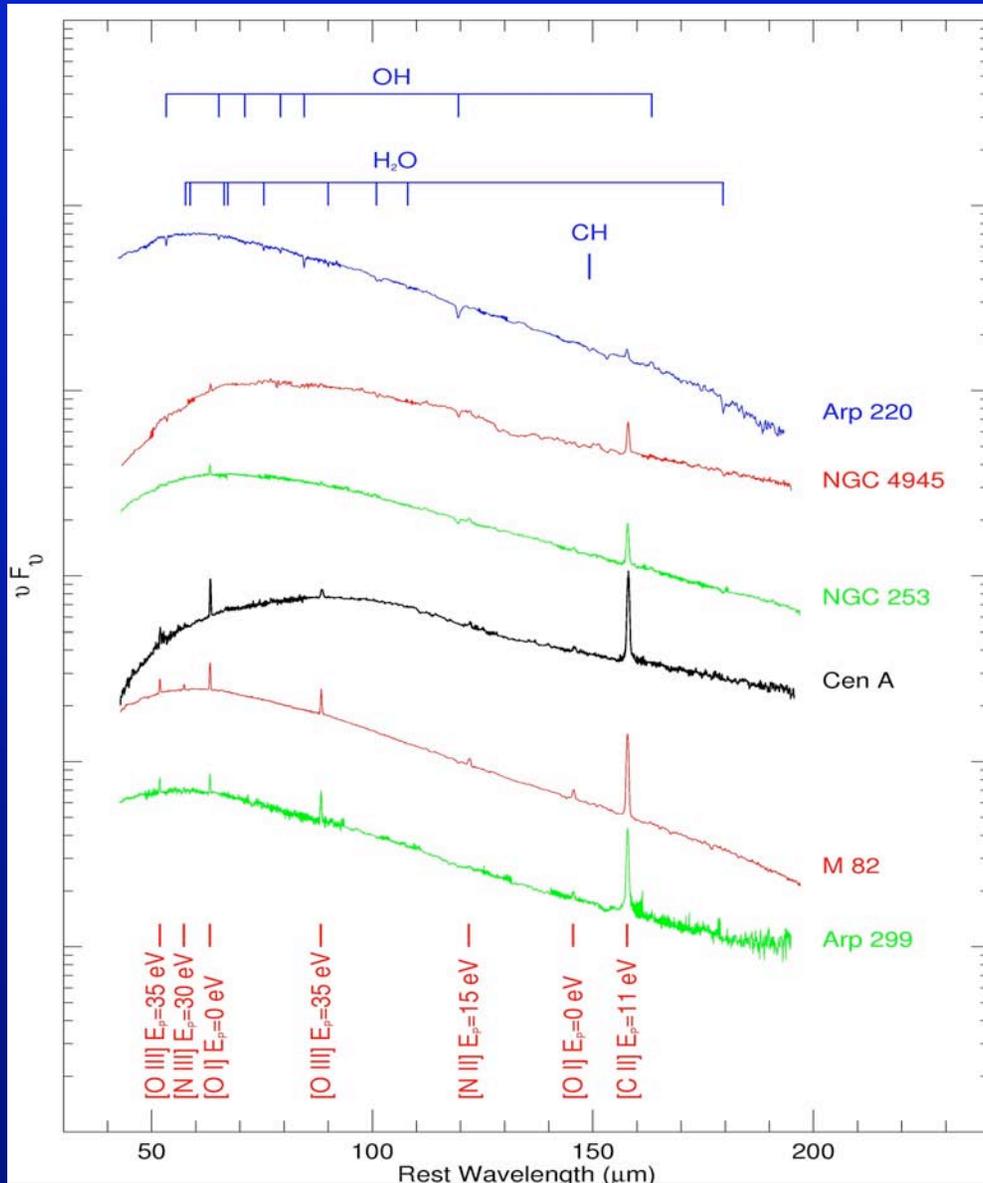
NOTE. — (a) Using the CIB value from Lagache et al. (2004) and using the limiting flux using the SDC limit and assuming confusion-limited surveys. (b) This hypothesis might not be valid for *Herschel* and *JWST*.

Extragalactic spectroscopy beyond 100 microns



SED courtesy A. Blain

CCAT -- redshifted fine structure lines



Fine structure lines probe ionized and neutral atomic gas.

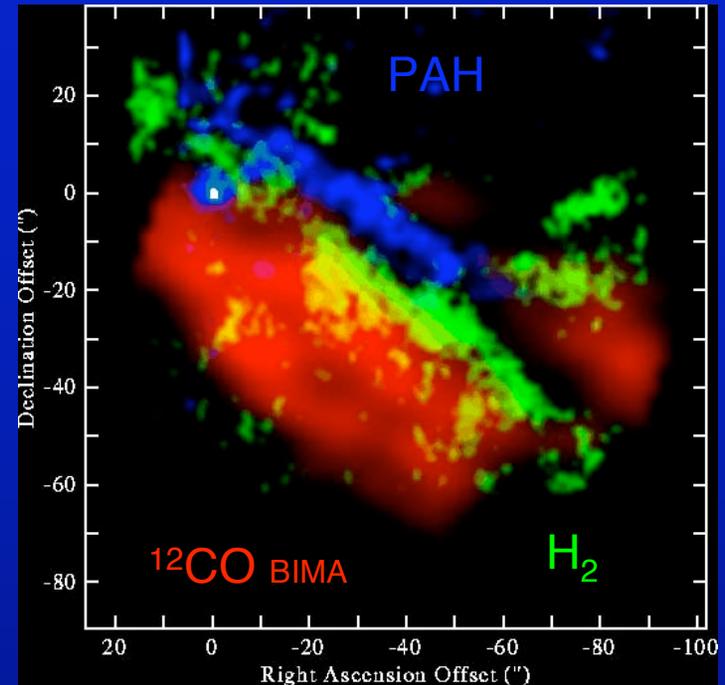
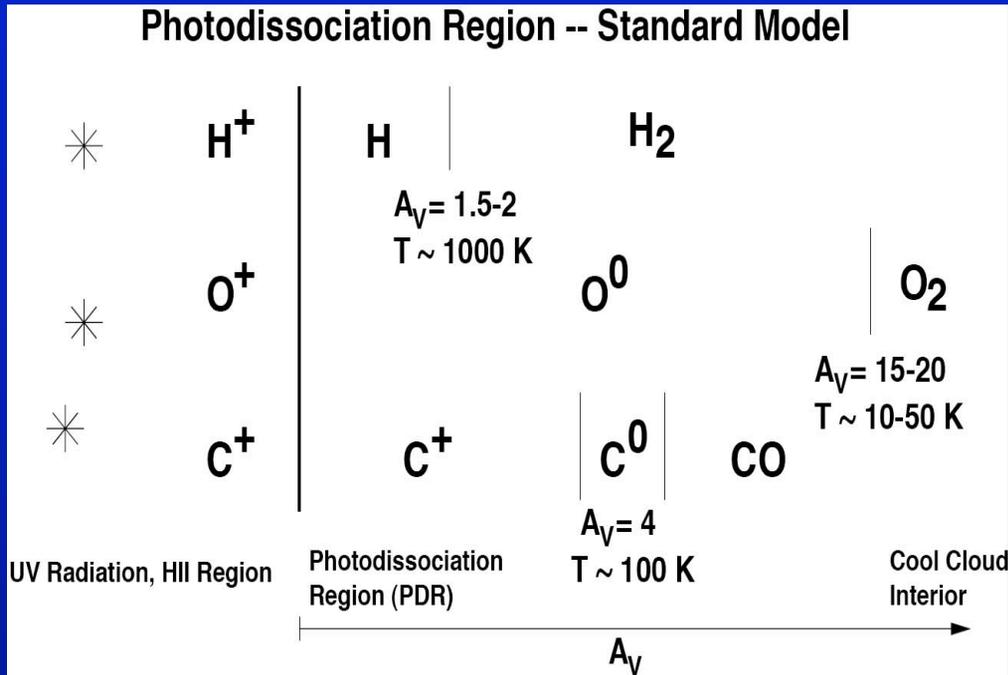
- HII region densities
- Atomic gas pressures
- UV field strength and hardness
- Starburst / AGN discriminator
- Stellar mass function

• Suite of lines is redshifted into CCAT atmospheric windows -- provides redshift template independent of optical follow-up.

-> Also provides unique, extinction-free astrophysical probes:
UV field strength, hardness
-> stellar mass function.

J. Fischer et al. 1999

The Physics of the [CII] Line



- The [CII] line arises from photodissociation regions (PDRs) on the surfaces of far-UV exposed molecular clouds
- The gas in these PDRs is heated by electrons ejected by far-UV photons: photoelectric heating
- About 1% of the far-UV photon energy goes into heating the gas. The rest goes into heating the dust which re-radiates in the far-IR continuum.
- The gas is cooled primarily by the [CII] line (important contributions from [OI] and [SII] as well for warm, dense PDRs).

The Physics of the [CII] Line

The [CII] to far-IR continuum luminosity ratio, R is a sensitive indicator of the strength of the ambient ISRF, G

- In high UV fields (young starbursts, ULIRGs, AGNs), R is depressed
 - Reduced efficiency of photoelectric effect
 - Increased cooling in [OI] 63 μm line
- More diffuse fields (like M82 and the Milky Way) result in *larger* [CII]/far-IR ratio

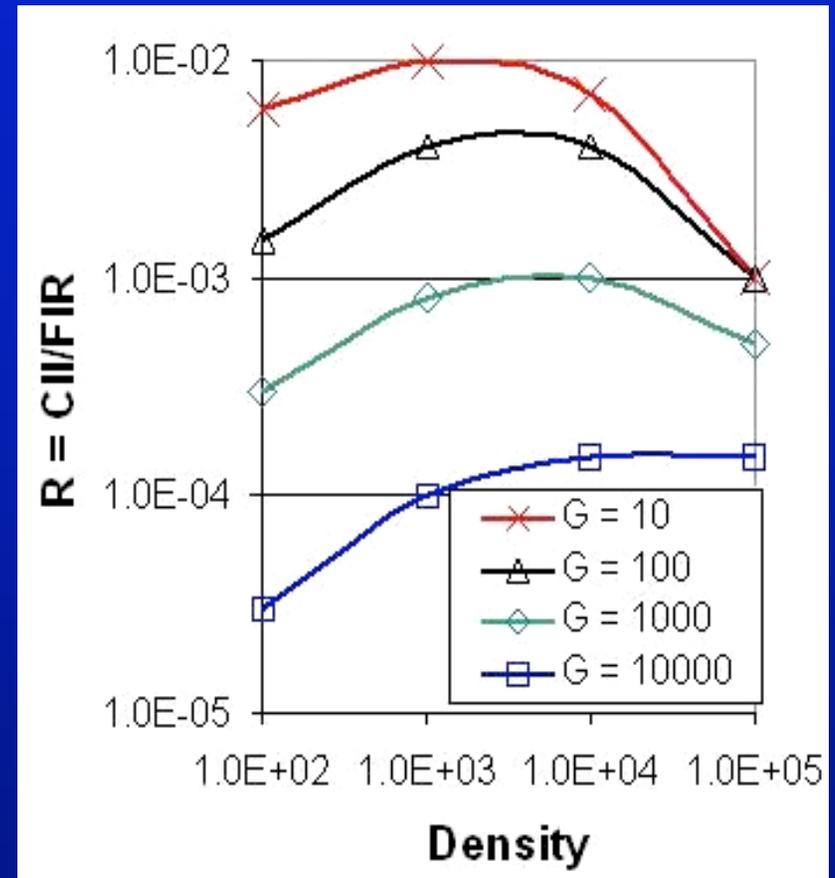
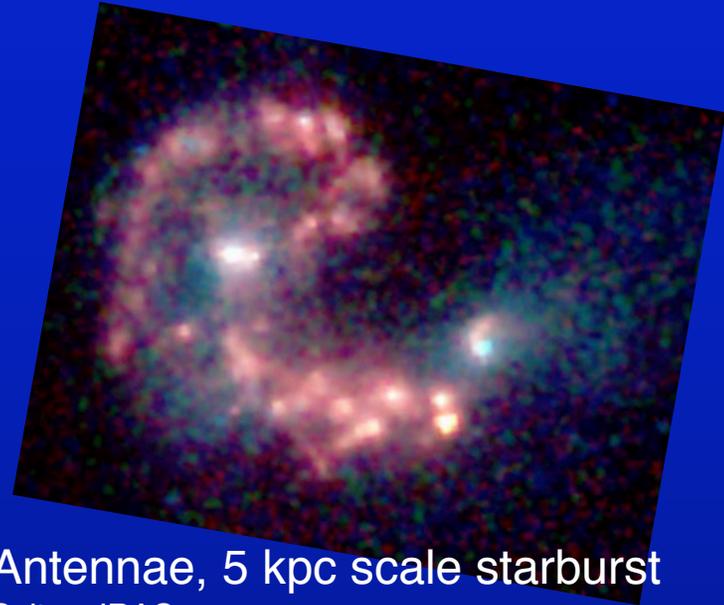


Fig. 2 [CII]/far-IR continuum luminosity ratio vs. density for various G (from Kaufman et al.).

The Physics of Redshifted [CII]

- For sources with unit beam filling factor, G and $I_{\text{far-IR}}$ are equal
- Therefore the ratio of the observed quantity, $I_{\text{far-IR}}$, to the derived quantity, G , is equal to the source beam filling factor, or *physical extent of the starburst*.
- *Notice that it is extremely useful that we can detect the underlying continuum simultaneously with the line – a strong advantage for using a broadband direct-detection system.*

Are starbursts extremely localized (and vigorous) in SMGs, or are they extended?

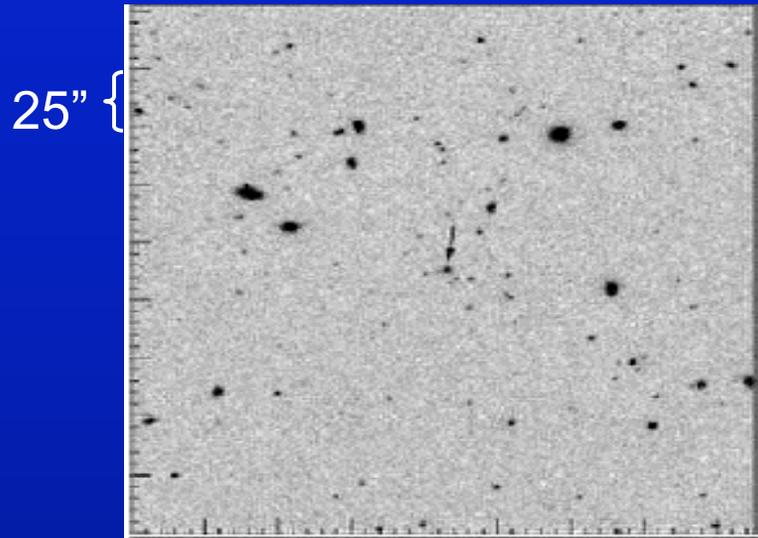


Antennae, 5 kpc scale starburst
Spitzer IRAC

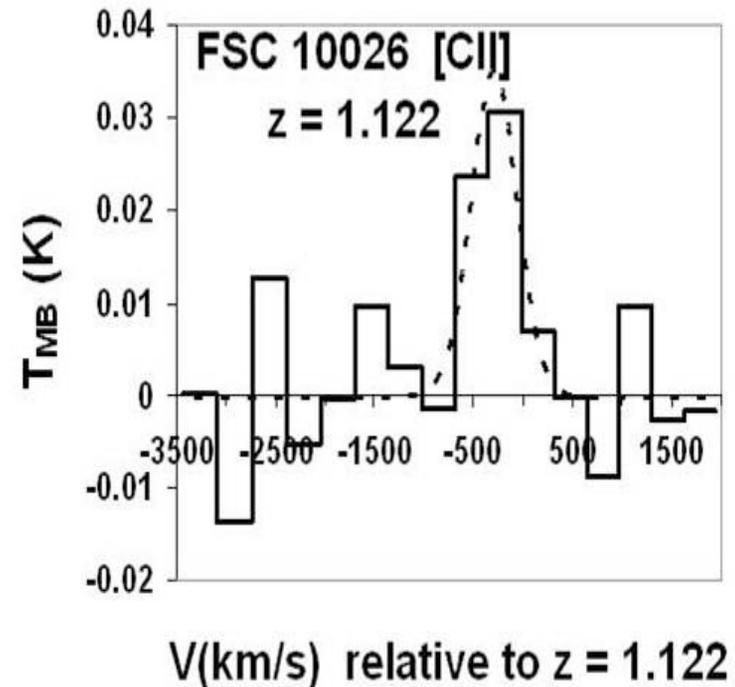


Arp220, Activity concentrated
in central kpc. ISO CAM

C+ in an IRAS Galaxy at $z = 1.12$



K_s band image of
FSC10026+4949
(Farrah et al. 2004)



ZEUS/CSO
(Hailey-Dunsheath et al. 2007)

- Detected [CII] line (S/N = 6.4) FSC10026+4949 using ZEUS on the CSO ($t_{\text{int}} \sim 1$ hour, $t_{\text{l.o.s.}} \sim 20\%$)
- $L_{\text{far-IR}} \sim 6.5 \times 10^{13} L_{\odot}$ (Duncan et al. 2004) and $L_{[\text{CII}]} \sim 4.5 \times 10^{10} L_{\odot}$
 $\Rightarrow R \sim 7 \times 10^{-4}$

Gordon Stacey

Bright C+ at high-z: Implications

- $R \sim 7 \times 10^{-4} \Rightarrow G \sim 2000$

- Beam $\sim 11''$

- $\Rightarrow \chi_{\text{Far-IR}} \sim 55$

- $\Rightarrow \phi \sim \chi/2 \div G \sim 1.4\%$

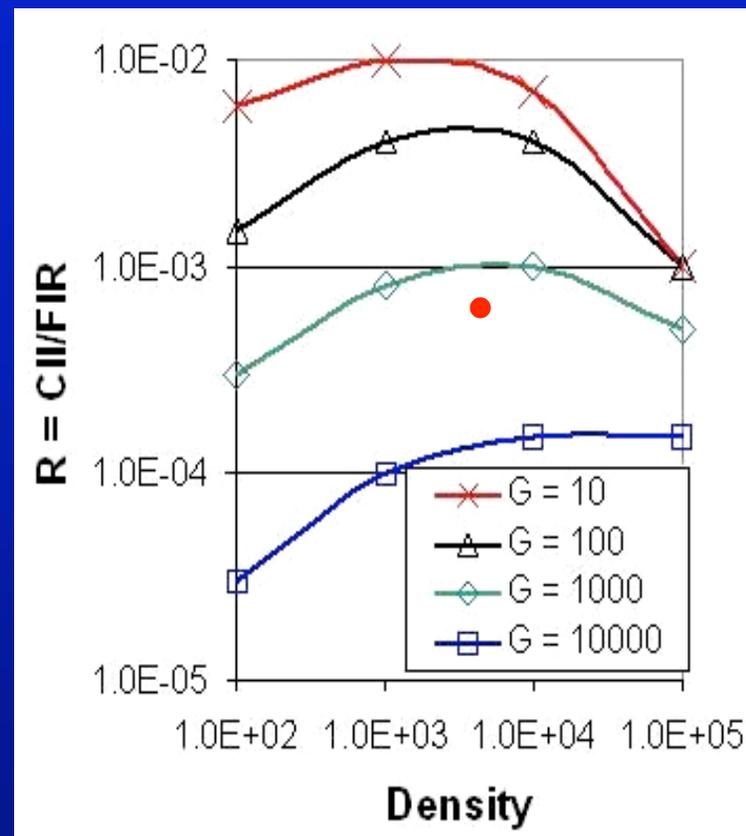
- $\Rightarrow d_{\text{source}} \sim 10 \text{ kpc}$

Starformation is extended on kpc scales

- Agreement with Chapman (2004) et al. results:

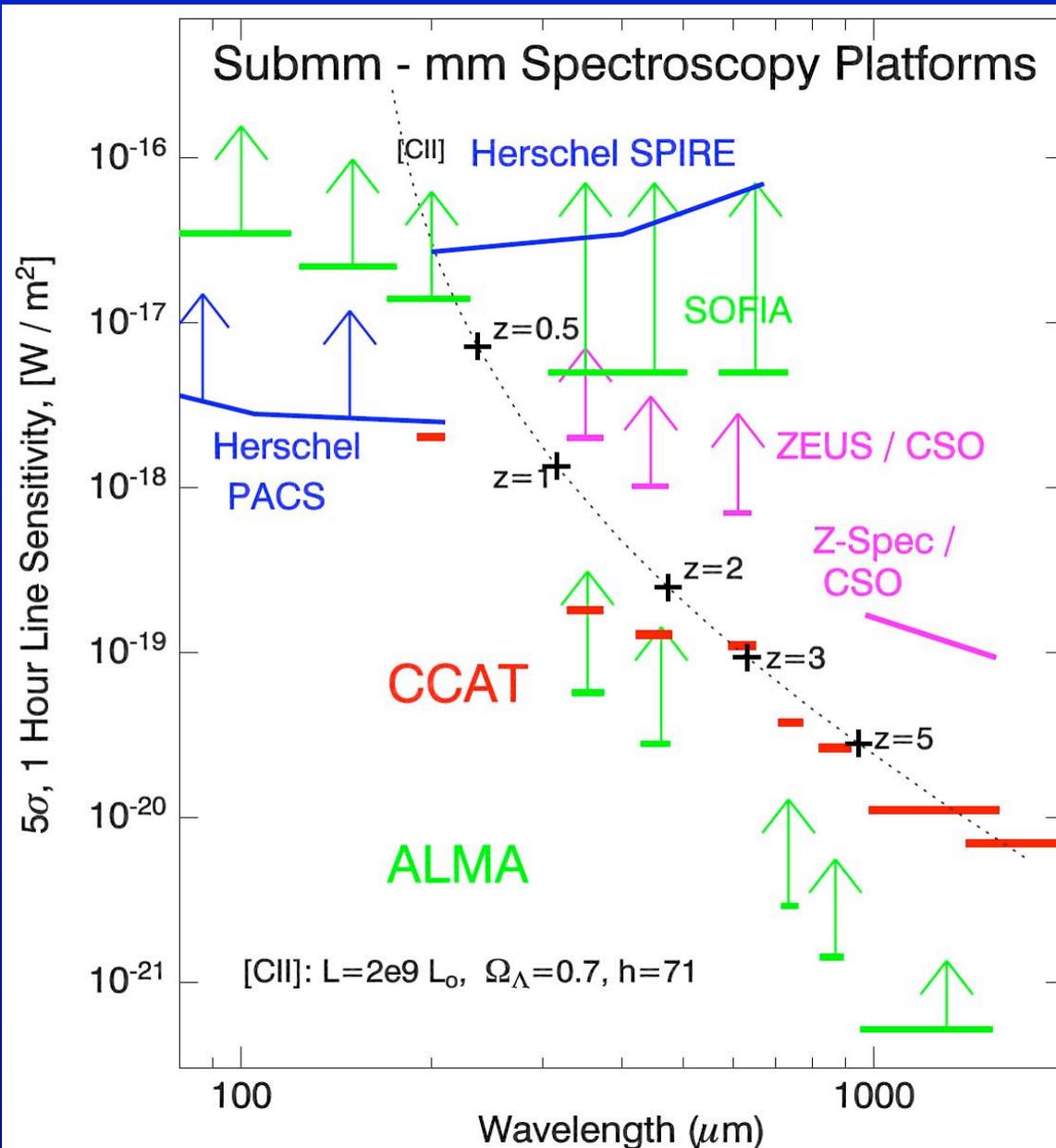
 - unlike local ULIRGs, starformation in 8/12 SMGs is galaxy-wide
 - Scales $\sim 45 \text{ kpc}^2$
 - Rates $\sim 45 M_{\odot}/\text{yr}/\text{kpc}^2$

- Far-UV radiation field high, but not unlike local starbursters



[CII]/far-IR continuum luminosity ratio vs. density for various G (from Kaufman et al).

CCAT Spectroscopic Sensitivities

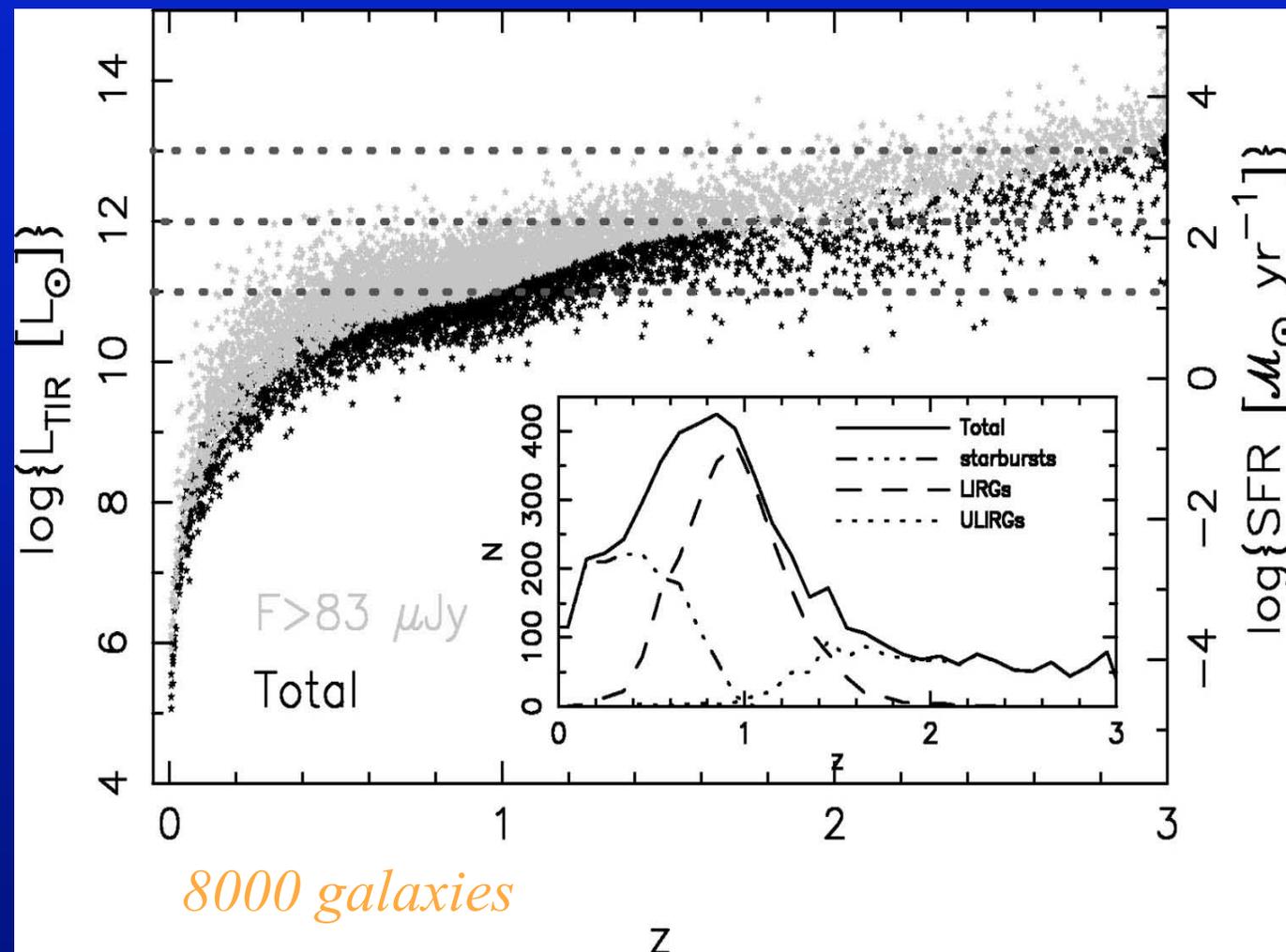


Herschel, SOFIA -- small collecting area, no substantial advantage since warm apertures.

CCAT less sensitive than ALMA, but with full window bandwidth, CCAT can carry out spectroscopic surveys on galaxies with comparable speed.

Can be even faster if coupling many galaxies at once.

MIPS 24 μ m sensitivity, redshift selection



8000 galaxies

Perez-Gonzalez et al. (2006)

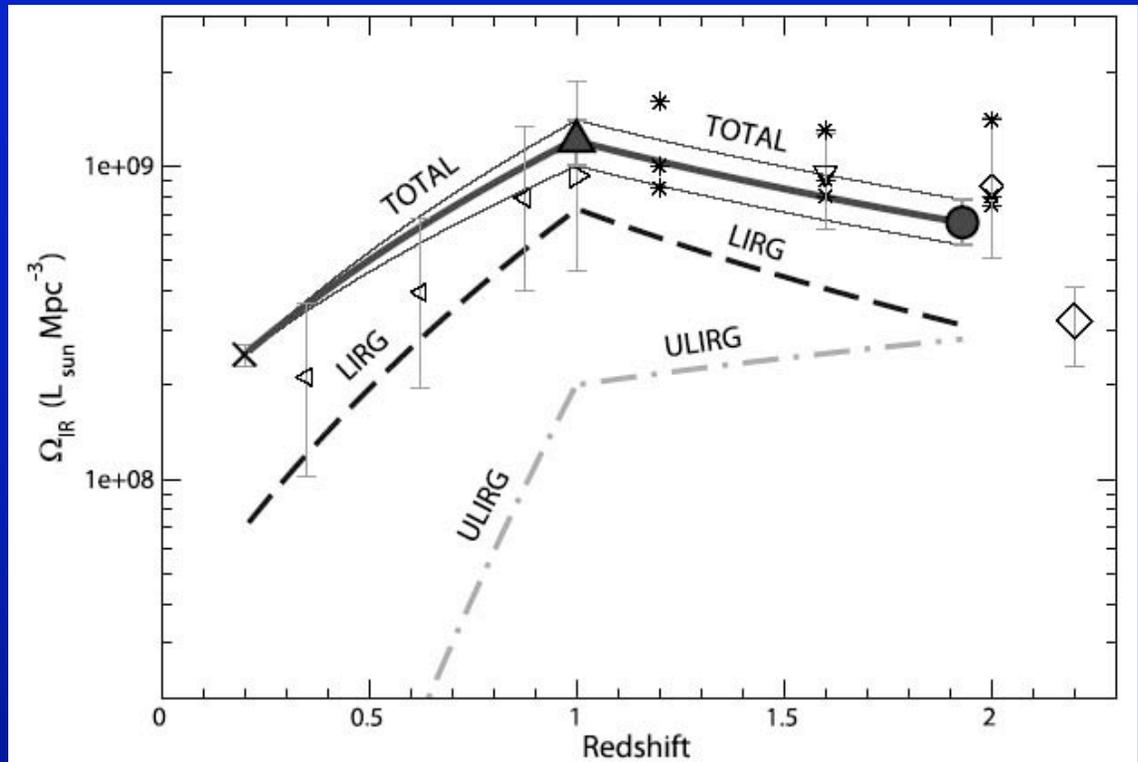
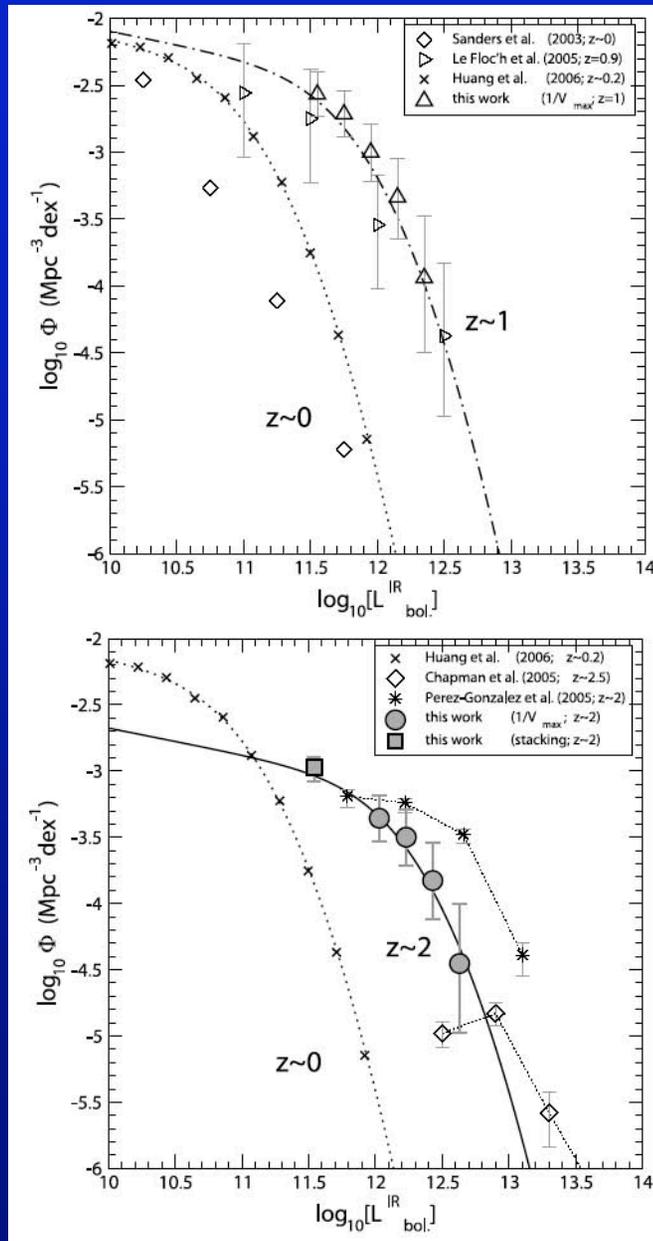
24 micron surveys (MIPS GTO team):

Spectroscopic and photometric redshifts

Use SED models to estimate luminosities from 24 micron fluxes

LIRGs to $z \sim 1$,
ULIRGs to $z \sim 2$

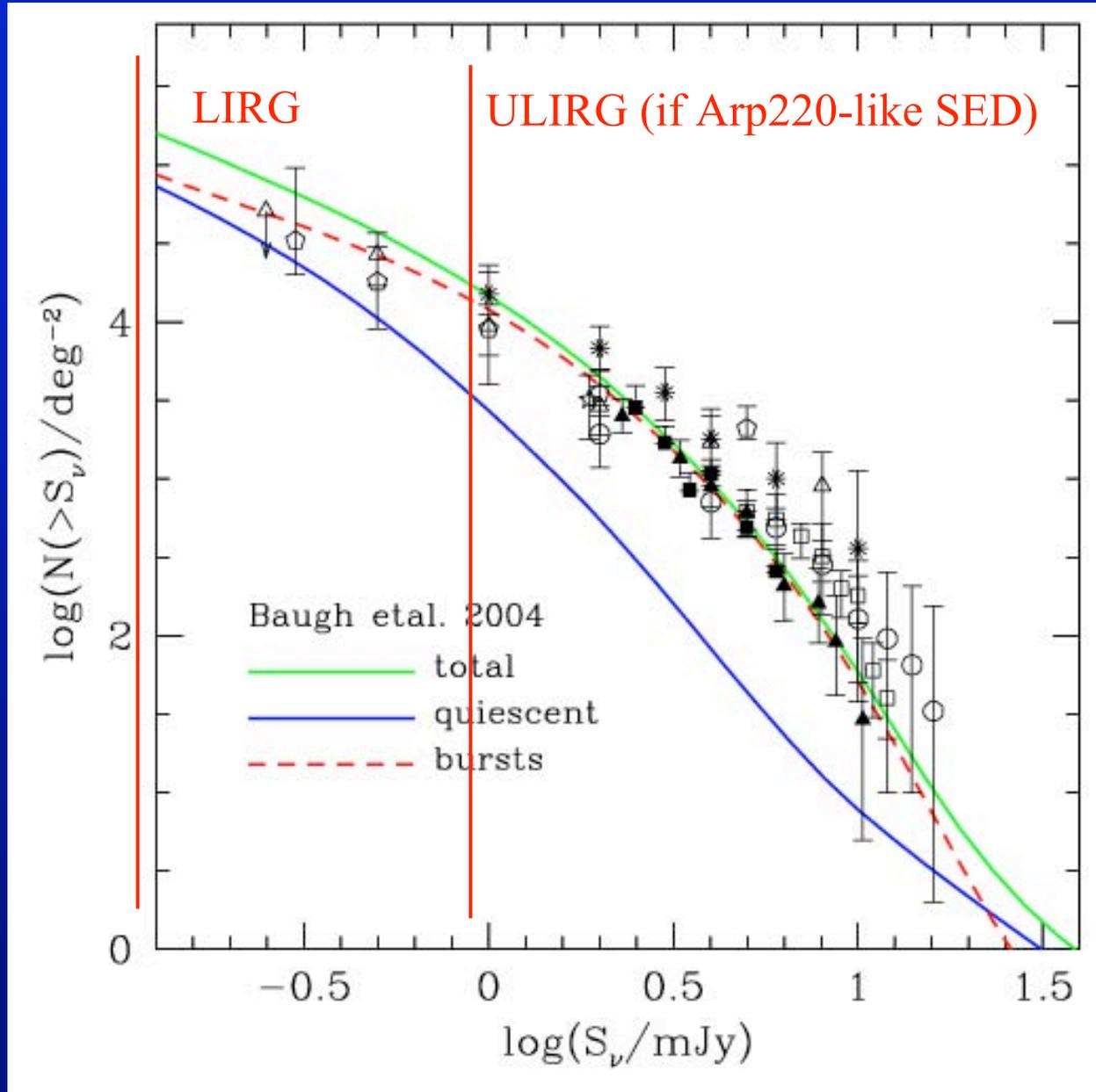
MIPS 24 μ m; IR Luminosity Evolution



8-micron luminosity functions converted to total IR luminosity functions -> comoving luminosity density

MIPS team Caputi et al. 2007, ApJ 660:97-116

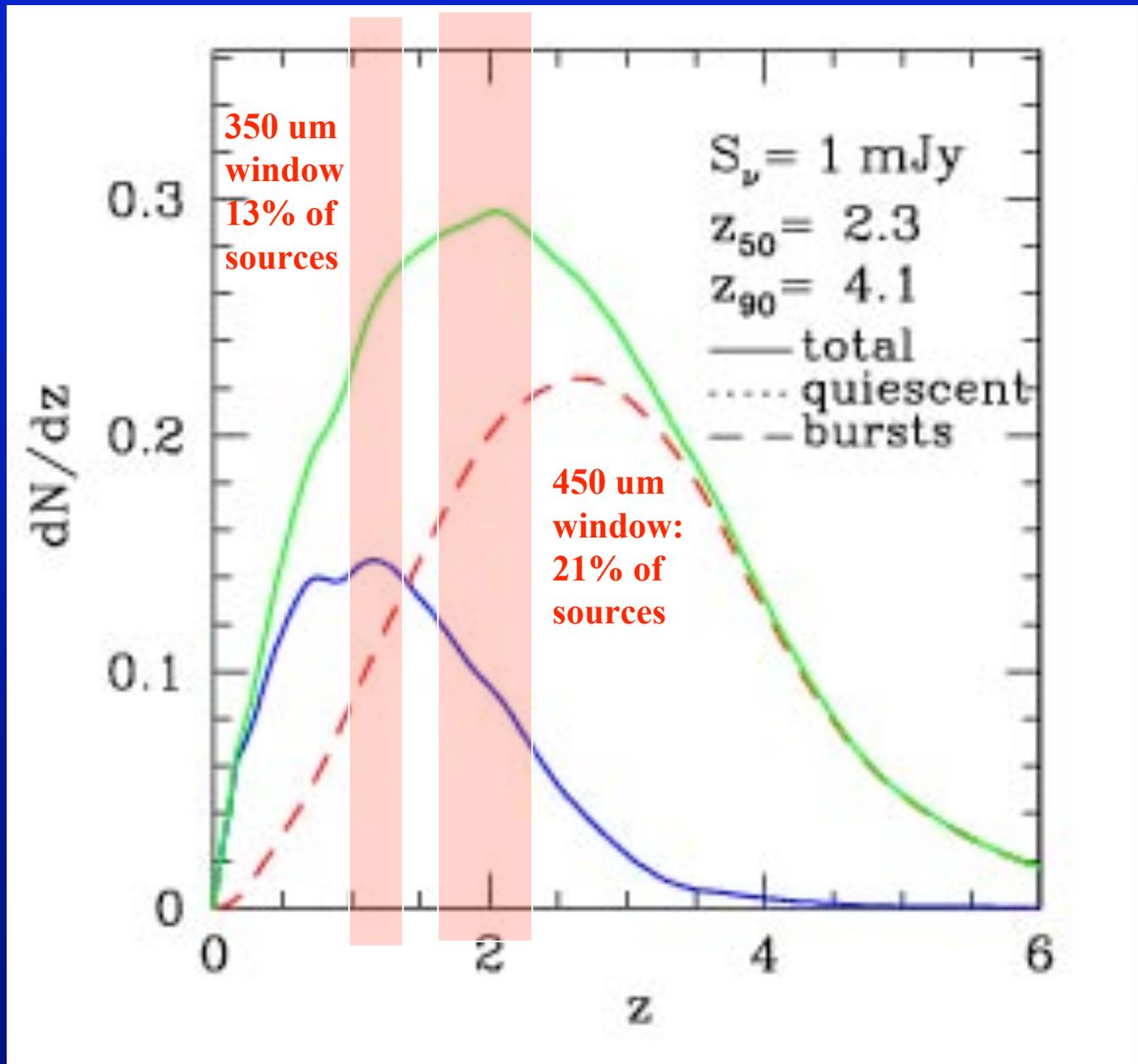
850 micron N(S) is to first order a luminosity function



Models from
A. Benson et
al. (Galform
group)

modified IMF
and star
formation
timescale
included to
reproduce
850 micron
counts

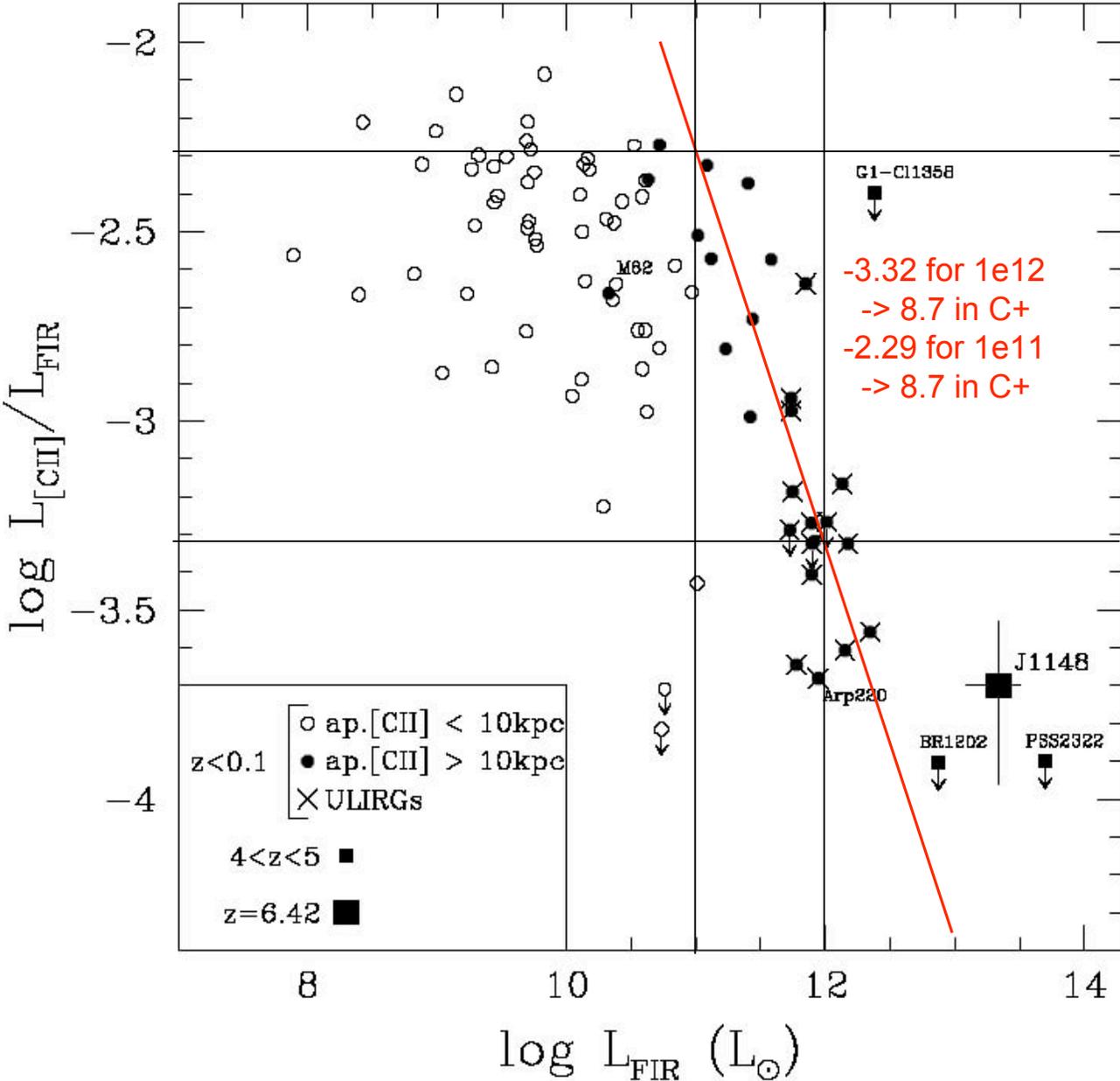
Models provide approach to CCAT population z distribution: Apply to C+



350 & 450 microns window are likely to access 31% of the 850 micron population in C+

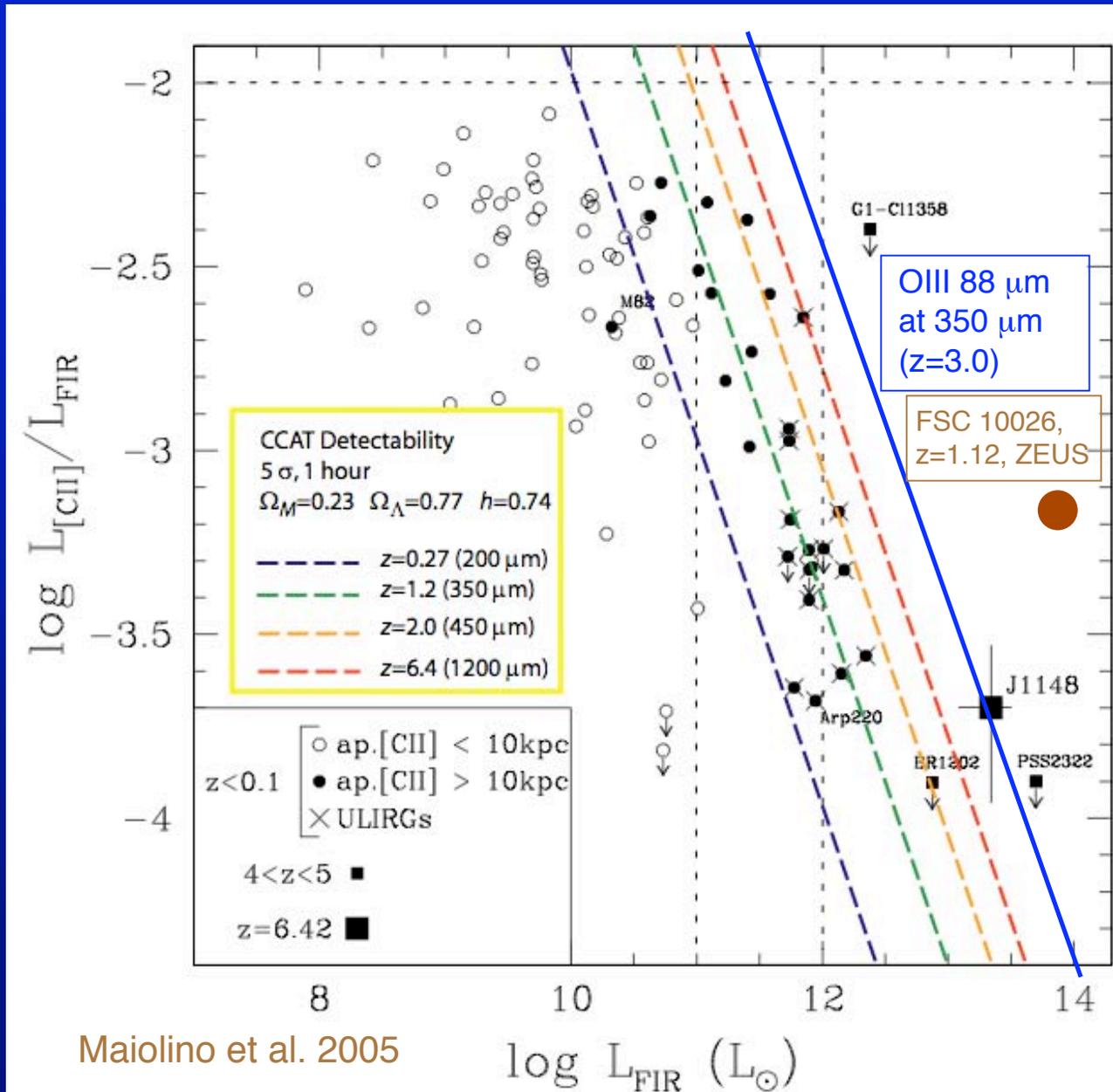
Redshift Distribution from GALFORM model -- similar to Chapman

C+ Line luminosity fraction -> from Maiolano 05



Local-universe LIRGs and ULIRGs have similar C+ intensities -> Saturation of C+

Redshifted C+ Detectability with CCAT

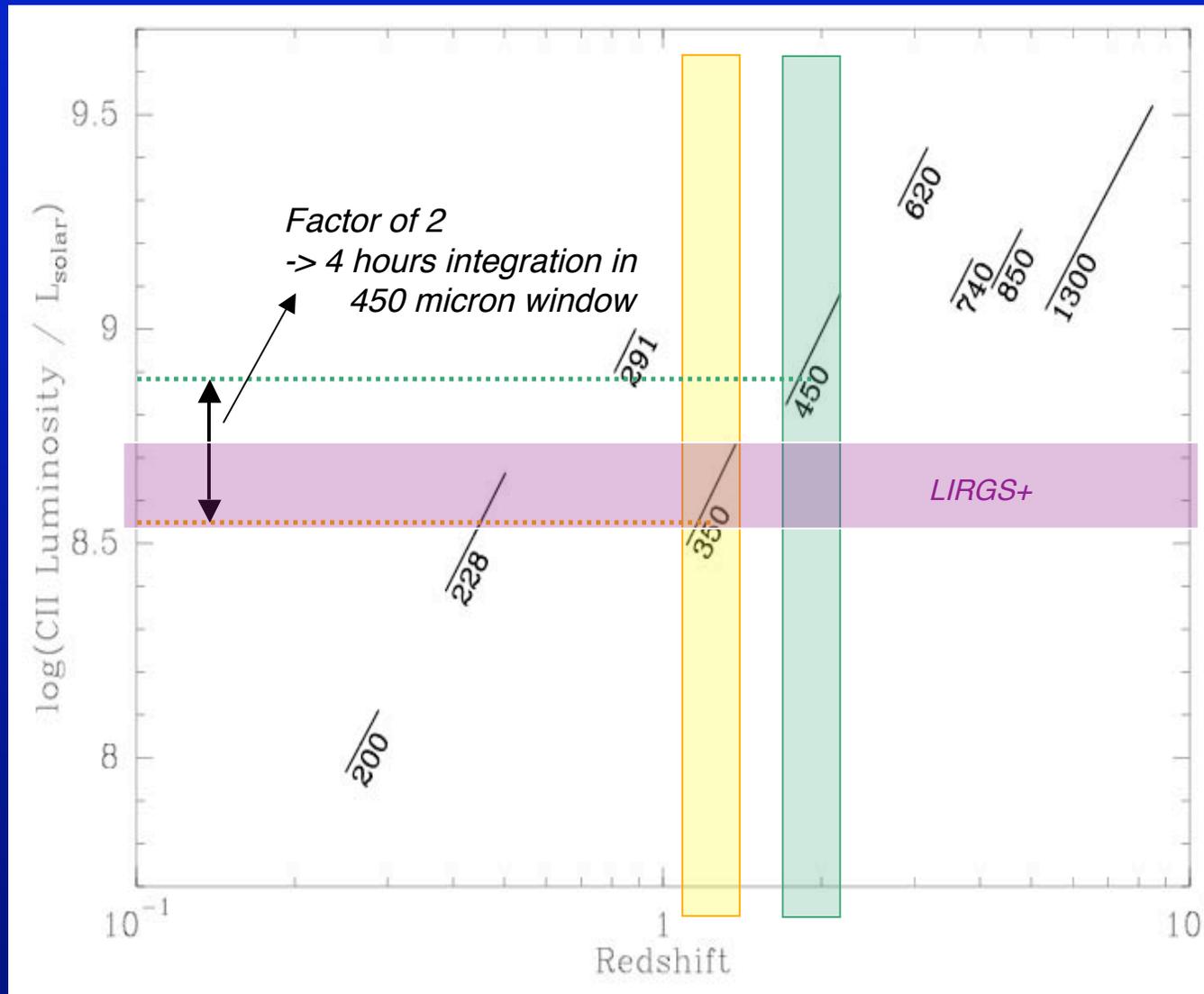


- *Constant C+ luminosity* ($\log L_{\text{C}^+} \sim 8.7$) for LIRGS to ULIRGS

-> CCAT 350 μm sensitivities well-matched to these sources at redshift 1-1.4

- 88 μm [OIII] detectable for ULIRGS at $z=3$ if $f_{\text{line}} > 0.003$

Redshifted C+ Detectability with CCAT



- Constant C+ luminosity ($\log L_{C+} \sim 8.7$) for LIRGS+

- > CCAT 350 μm 1-hour sensitivity well-matched to these sources at redshift 1-1.4

- 4 hours @ 450 μm ($z \sim 1.8-2.2$) for the same sources.

How many such sources are there per area per redshift?

Source populations for CCAT C+ spectroscopy

MIPS 24 micron surveys:

biased toward low- z ($z \sim 1$), but deep in L -- approaching knee at $z \sim 1$ LIRG

Use SED model and photometric redshifts to derive luminosity function at various redshifts (Papovich, Perez-Gonzalez, LeFloc'h, Egami, et al.)

MIPS 24 reaches out to $z \sim 1$ for LIRGS, $z \sim 2$ with ULIRGS

Egami, LeFloc'h et al measure ~ 1440 galaxies per square degree with $\log L > 11.25$ at $1.0 < z < 1.2$

850 micron counts:

span the redshift range with almost uniform selection, but shallow in L

- ***shows redshift range, extrapolate to lower- L***

According to a reasonable 850 micron redshift distribution based on e.g. Chapman et al. measurements (w/ recent $z \sim 1$ additions) or Benson model, the 1.0--1.2 redshift range should account for 5% of the total 850 micron sources at any given flux density.

This implies $3e4$ total galaxies per sq deg with $\log L > 11.25$ per sq deg -> ***matched by 850 micron counts.***

So we have a $z \sim 1$ population measured at both 24 and 850.

Source densities for C+ spectroscopy with CCAT

350 micron window

Redshift range 1-1.2 (low-z half of the window):

Density of $\text{Log } L > 1e11$ sources = $7.1 \text{ e}4 \times 0.2 \times 0.24 = 3.4 \text{ e}3$
= **36 galaxies per square degree per 300 km/s spectral bin.**
= 1 source per 40,000 CCAT beams per spectral bin.

450 micron window (extrapolated)

Redshift range 1.8-2.0 (low-z half of the window) using a Chapman or Benson redshift distribution.

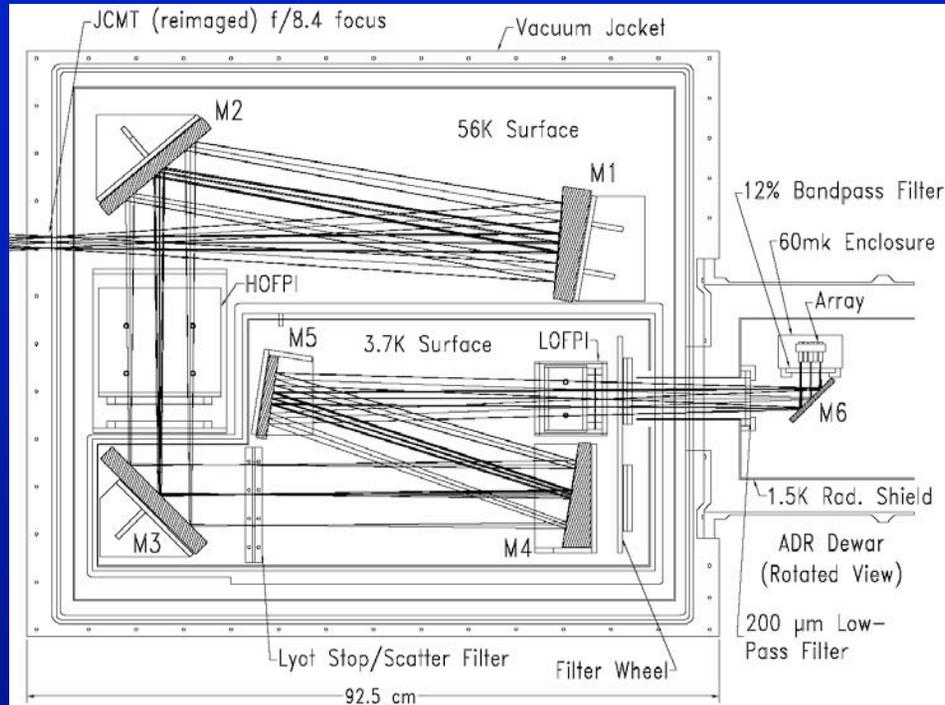
Density of $\text{Log } L > 1e11$ sources = $7.1e4 \times 0.2 \times 0.29 = 4.3 \text{ e}3$
= **62 galaxies per square degree per spectral bin**
= 1 source per 14,000 CCAT beams per spectral bin

Options for CCAT spectrometers

- **Grating spectrometer is the best choice for point sources.**
 - 1st order → octave of instantaneous bandwidth
 - Potential for 350, 450 micron windows simultaneously
 - Good efficiency
 - Only moderate resolution
 - Potential for multi-object capability further multiplies efficiency
- **Fabry-Perot naturally accommodates spectral mapping at discrete (known) frequencies.**
 - Offers potential for high-resolution ($R \sim 10,000$) over modest fields
 - But scanning time results in sensitivity penalty, esp for searching
- **Fourier transform spectrometer (FTS) couples the full band to a single detector.**
 - Sensitivity penalty
- **Heterodyne receivers provide the highest spectral resolution.**
 - But suffer from quantum noise
 - $NEP_{QN} \sim h\nu [\delta\nu]^{1/2}$ vs. $NEP_{BG} \sim h\nu [n(n+1)\delta\nu]^{1/2}$
 - Also offer limited bandwidth:
 - 10 GHz IF bandwidth at 1 THz gives $\nu / \Delta\nu \sim 100$

CCAT Imaging Fabry-Perot Interferometer

SPIFI demonstrates concept at JCMT & the South Pole



5x5 spatial array, two scanning FPs provide R up to 10,000 at 200-500 microns

60 mK ADR-cooled focal plane

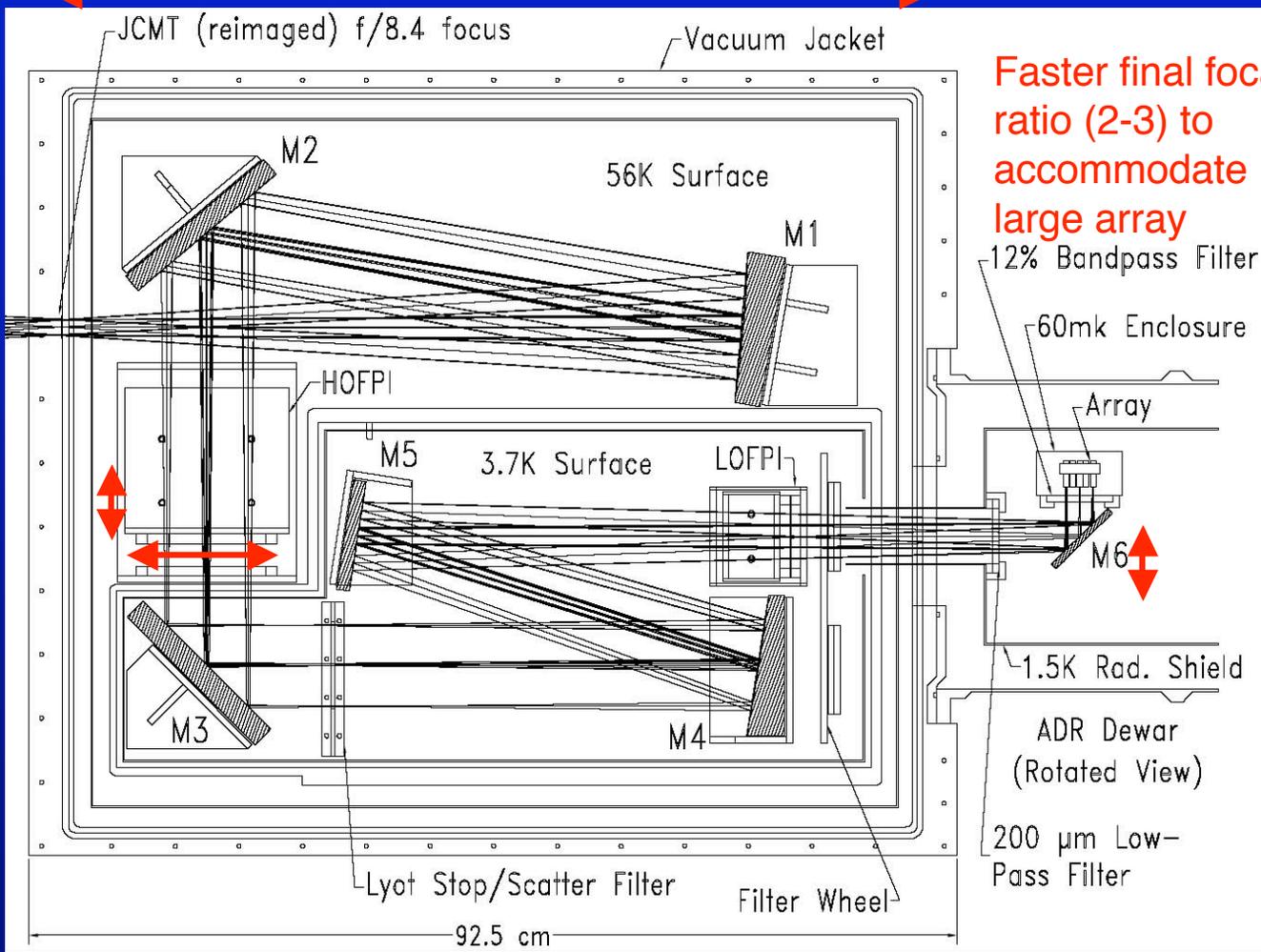
CCAT IFPI will be much larger than SPIFI due to the huge throughput

8 x 20 cm = 160 cm collimator focus

Full field at f/8:
20 cm window!

Etalon spacing is modest: few cm even for 650 μm

Collimated beam + overheads: 25 cm dia (and etalon must be near pupil)

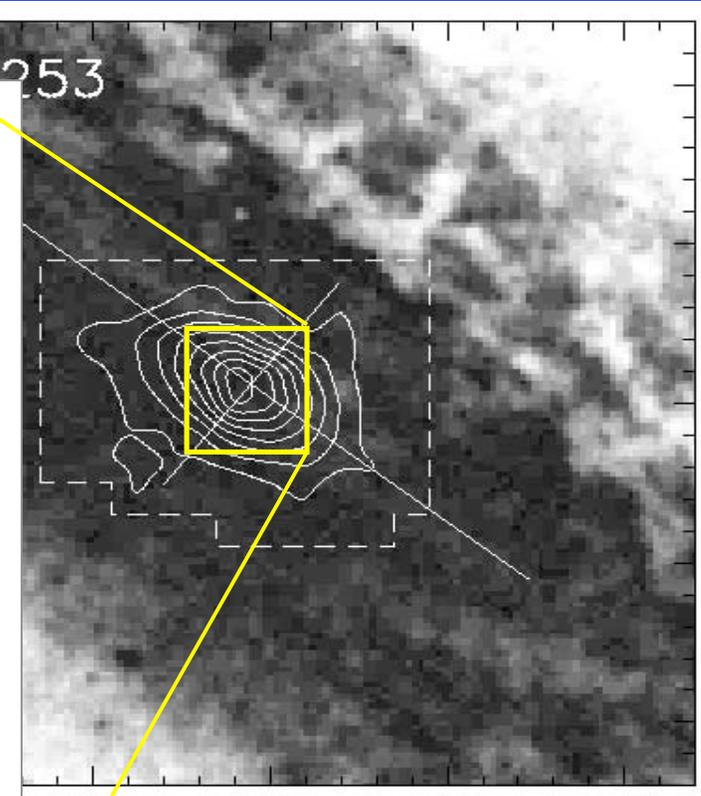
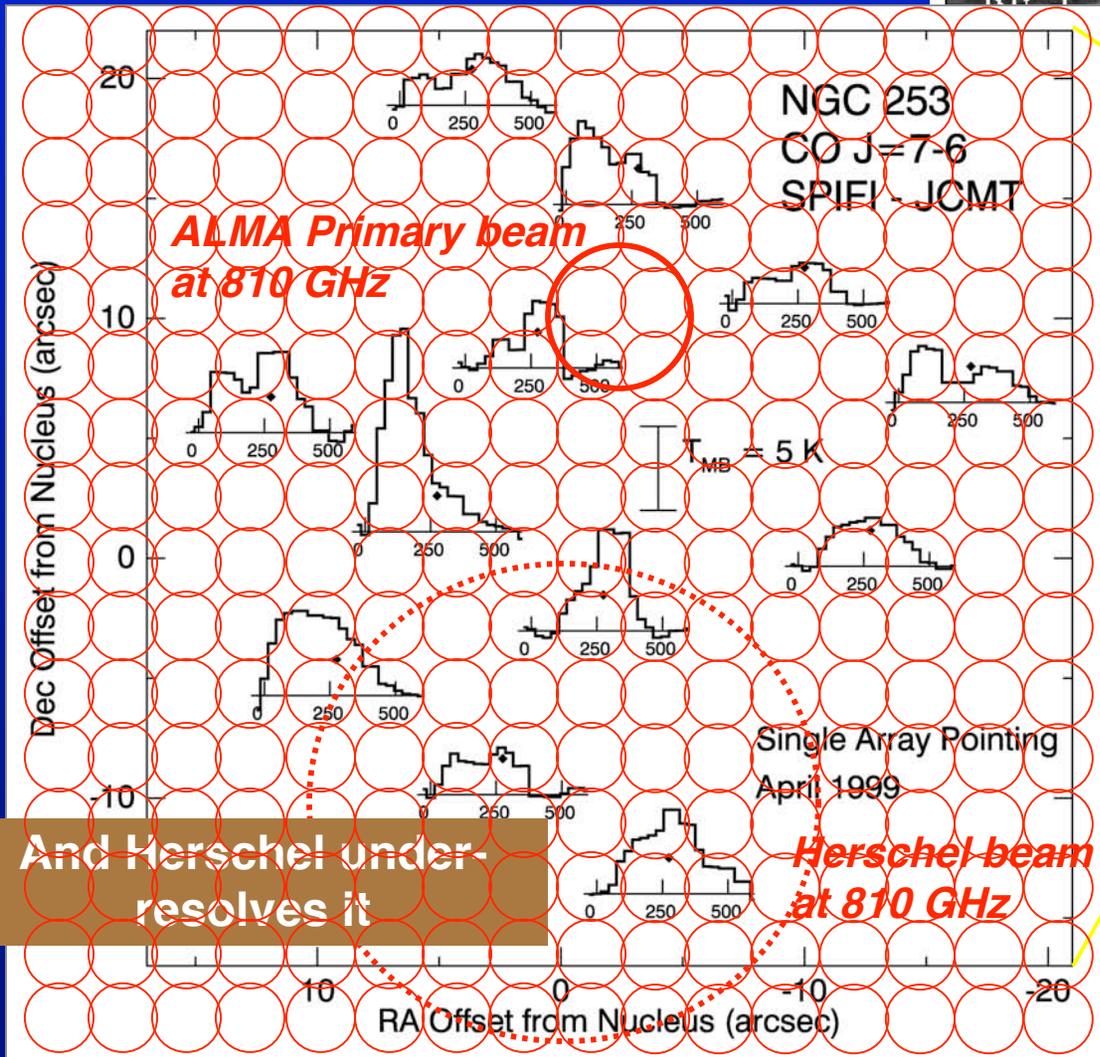


Faster final focal ratio (2-3) to accommodate large array

Array is as large as 10 cm

Factor of two in all dimensions of the optical train

ALMA will resolve out extended emission in nearby galaxies



CO 3-2
M. Dumke et al. 2001,

16x16 array on CCAT

CO 7-6
Bradford et al. 2003,

CCAT can reach comfortably to redshift 0.1 for LIRGS in the CO 7-6, 6-5 and CI transitions

C+ Detection Rate: Comparison Between F-P & Grating

Fabry-Perot

Source detection rate =

$$dN / dz \times \Omega$$

$dN / dz = 36 \text{ -- } 62$ per square deg, per res el.
 $= 1.7e-2$ sq deg

Rate = 0.6-0.7

Grating

Source detection rate =

$$z_fraction \times N_mos$$

$z_fraction = 0.3$ (including 350 & 450)

$N_mos = ?$ (10-100)

Rate = 0.3 x 10-100

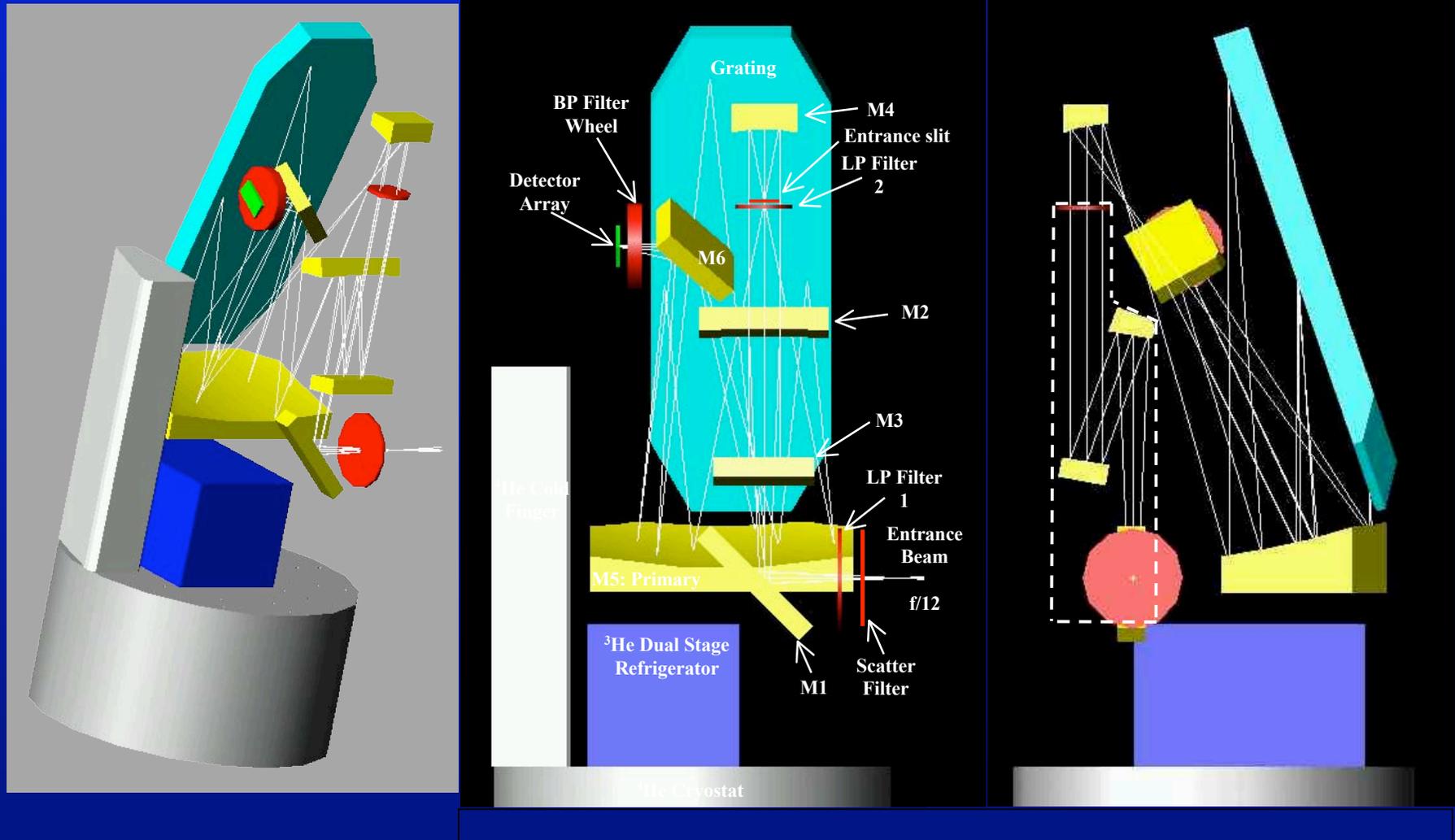
~FEW SOURCES PER HOUR

*Could a Fabry-Perot serve to select sources at specific redshift from a field ?
Yes, but source densities are low enough that detection rate in the field will be low.
Broadband grating is faster if you can couple even a couple sources*

Most optimistic $R=1000$ FP at 350 microns: $200 \times 200 = 4e4$ beams or $1.7e-2$ sq deg
Take 10 resolution element scan: Gives $1.7e-2 \times 36 \times 10 = 6$ LIRG+ sources
In 10 hours observation. Doesn't look good, not enough volume due to finite z

**NOTE ALMA: 3 times more sensitive -> 10 times faster per tuning
BUT MUST TUNE ~20 tunings to cover the full 350 / 450 bands**

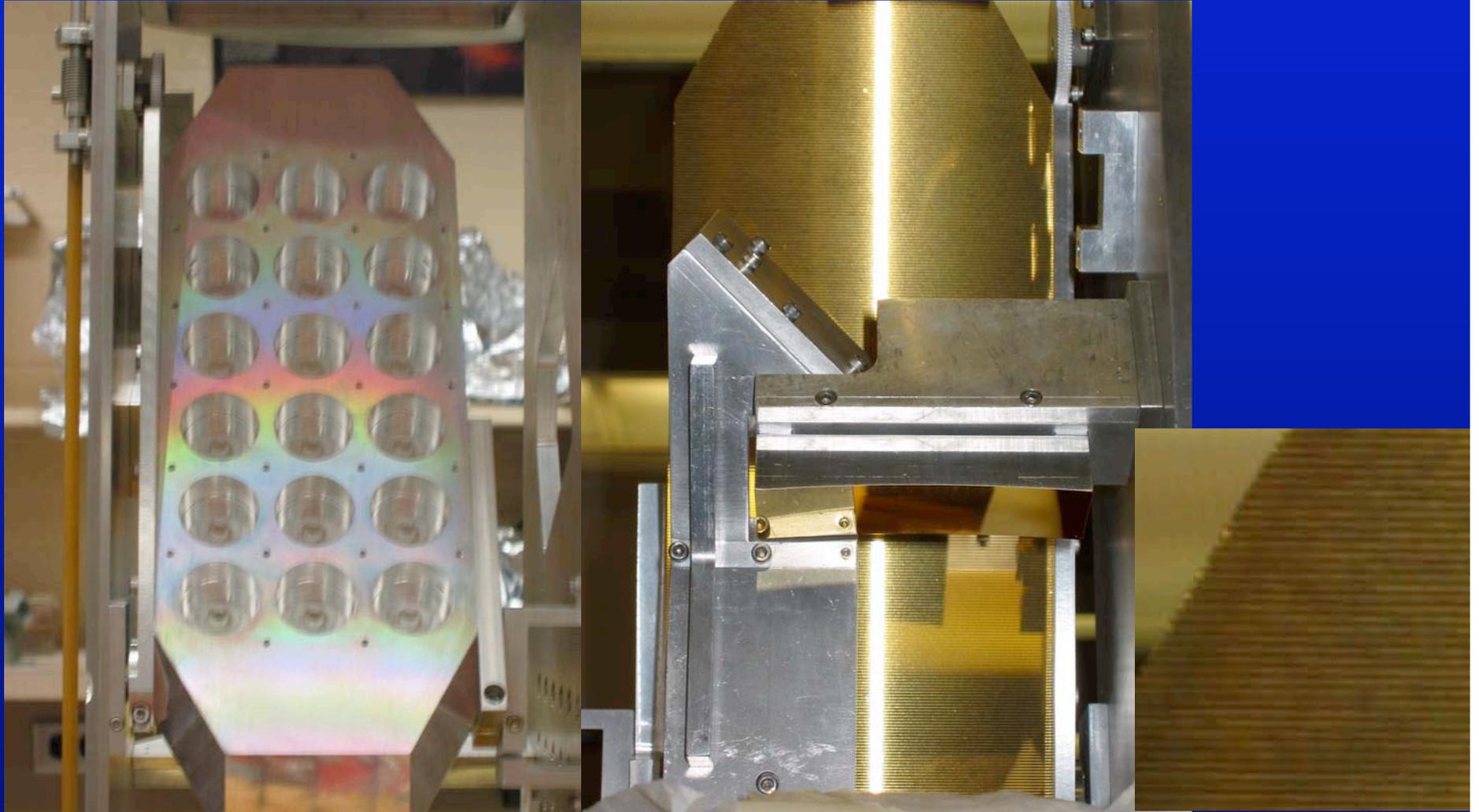
Examples of submillimeter-wave echelle grating: ZEUS for the JCMT / APEX



Cornell -- Stacey, [Haley-Dunsheath](#), Nikola

350, 450 μm windows w/ $R \sim 1000-1500$

ZEUS Grating



- *Manufactured by Zumtobel Staff GmbH (Austria).*

ZEUS on the CSO

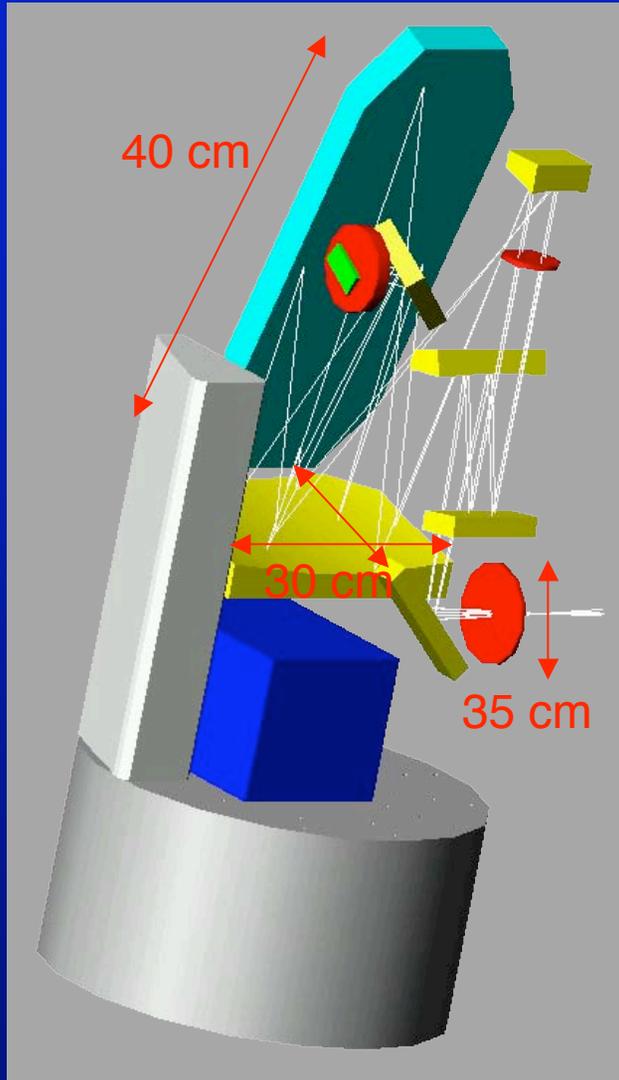


Spectroscopic Surveys with CCAT -- Waterloo, ON -- July 18, 2007



Matt Bradford

CCAT echelle will be large



So grating and collimator are a large fraction of 1 meter in all dimensions -- 1.5-2 times larger than ZEUS

Reimaging optics size will depend on the size of the slit, but also grows relative to ZEUS:

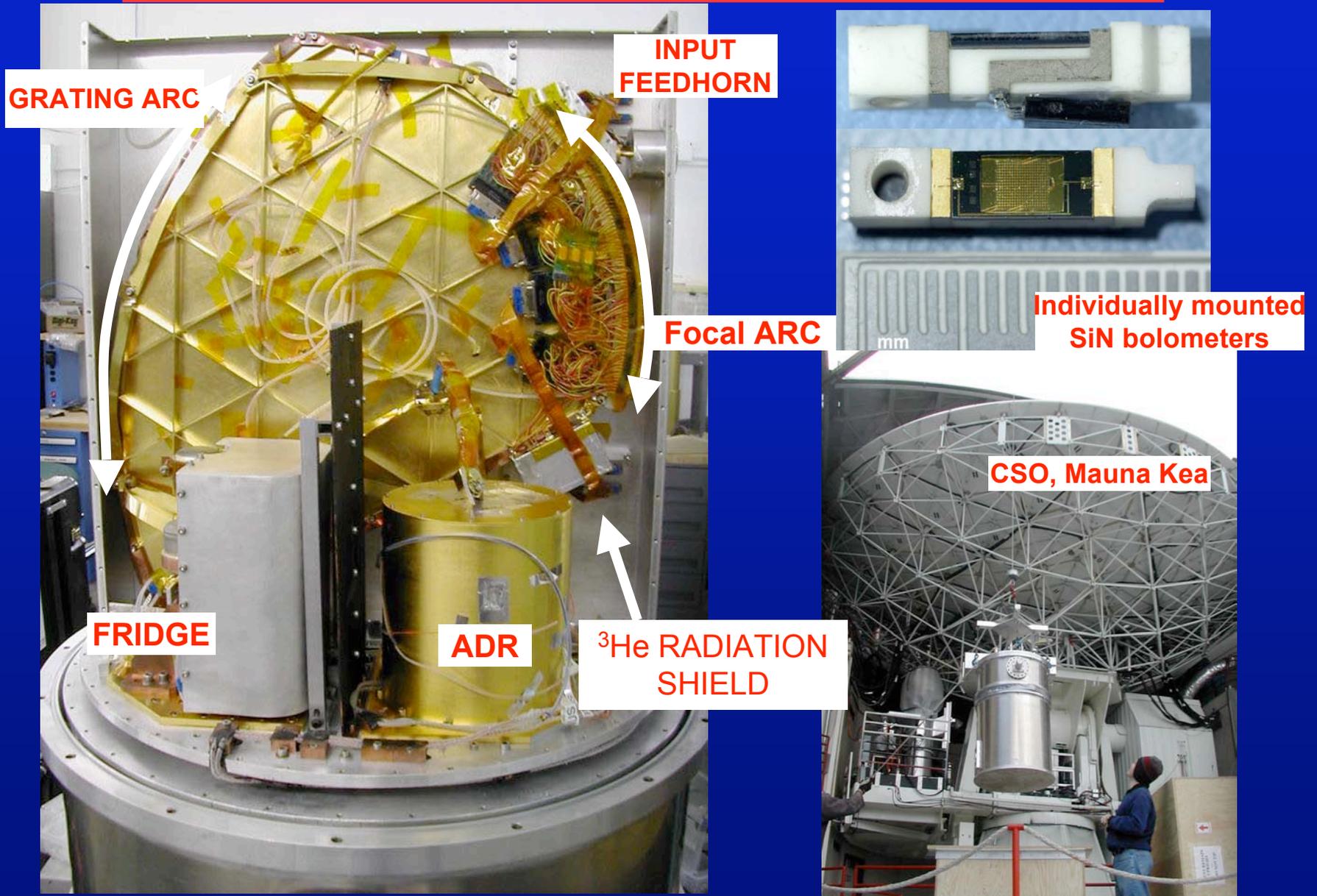
--scales as telescope $f\#$ x #of beams: Relative to ZEUS, CCAT echelle will have $8/12 \times 128/32 = 2.7$ times larger reimaging optics.

- **Requires 35 cm (+ overhead) window if reimaged from telescope focus inside cryostat (but can be shaped like a slit)**

Optics envelope inside cryostat approaching 1 meter in all dimensions.

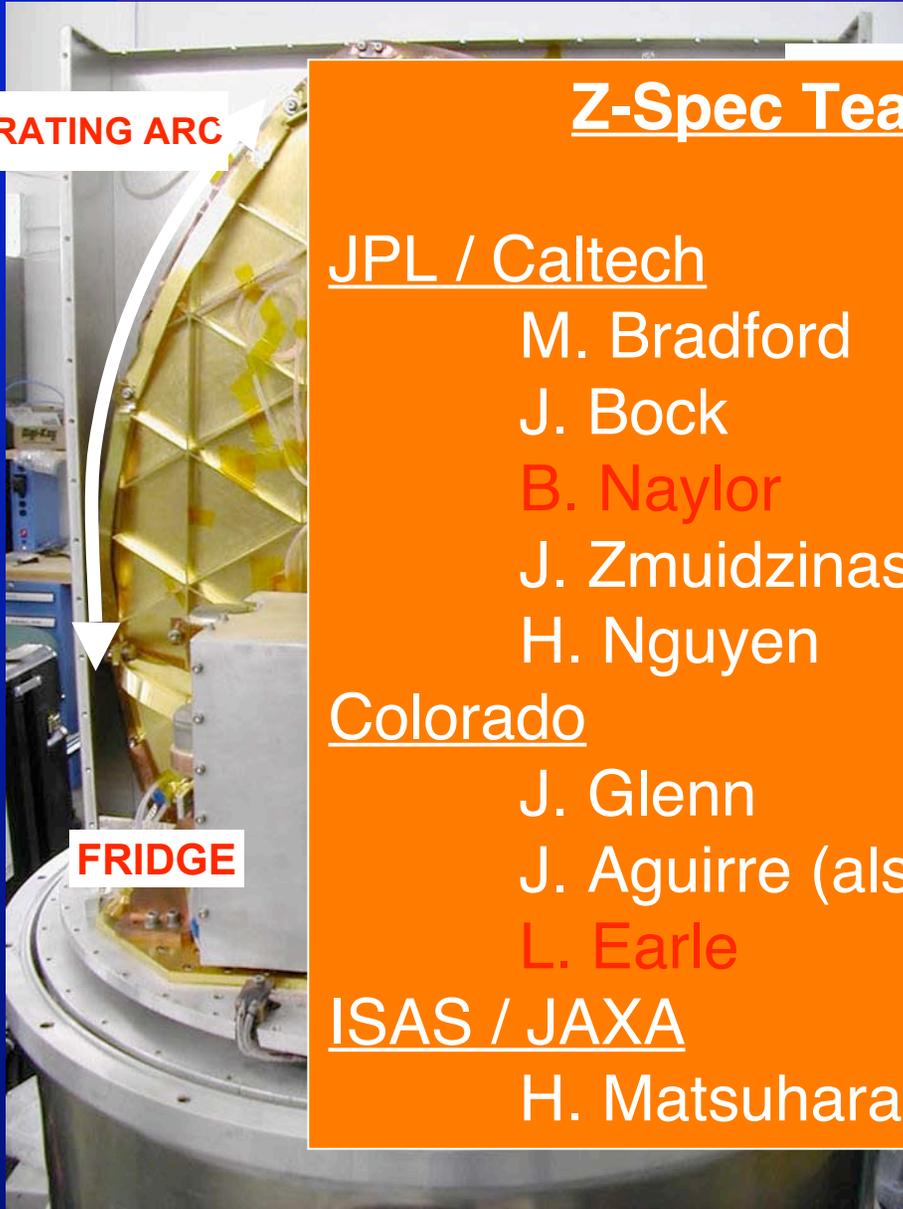
Large but doable.

True broadband spectroscopy in the submillimeter: Z-Spec, a 1st order grating covering 190-305 GHz.



True Broadband Spectroscopy in the Submillimeter: Z-Spec, a 1st order grating covering 190-305 GHz

GRATING ARC



FRIDGE

Z-Spec Team

JPL / Caltech

M. Bradford

J. Bock

B. Naylor

J. Zmuidzinas

H. Nguyen

Colorado

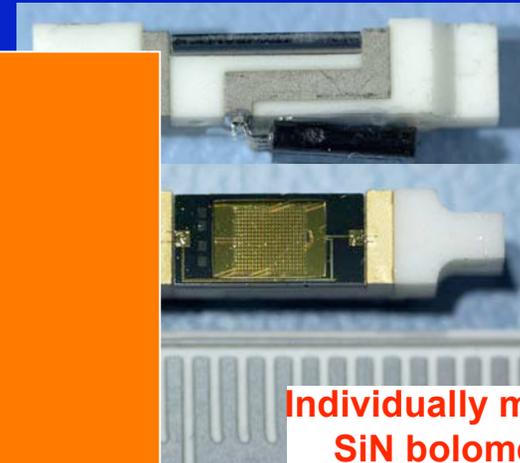
J. Glenn

J. Aguirre (also NRAO)

L. Earle

ISAS / JAXA

H. Matsuhara



**Individually mounted
SiN bolometers**



CSO, Mauna Kea

Z-Spec labor force

Bret Naylor
Caltech Ph.D. student
(finishing August)

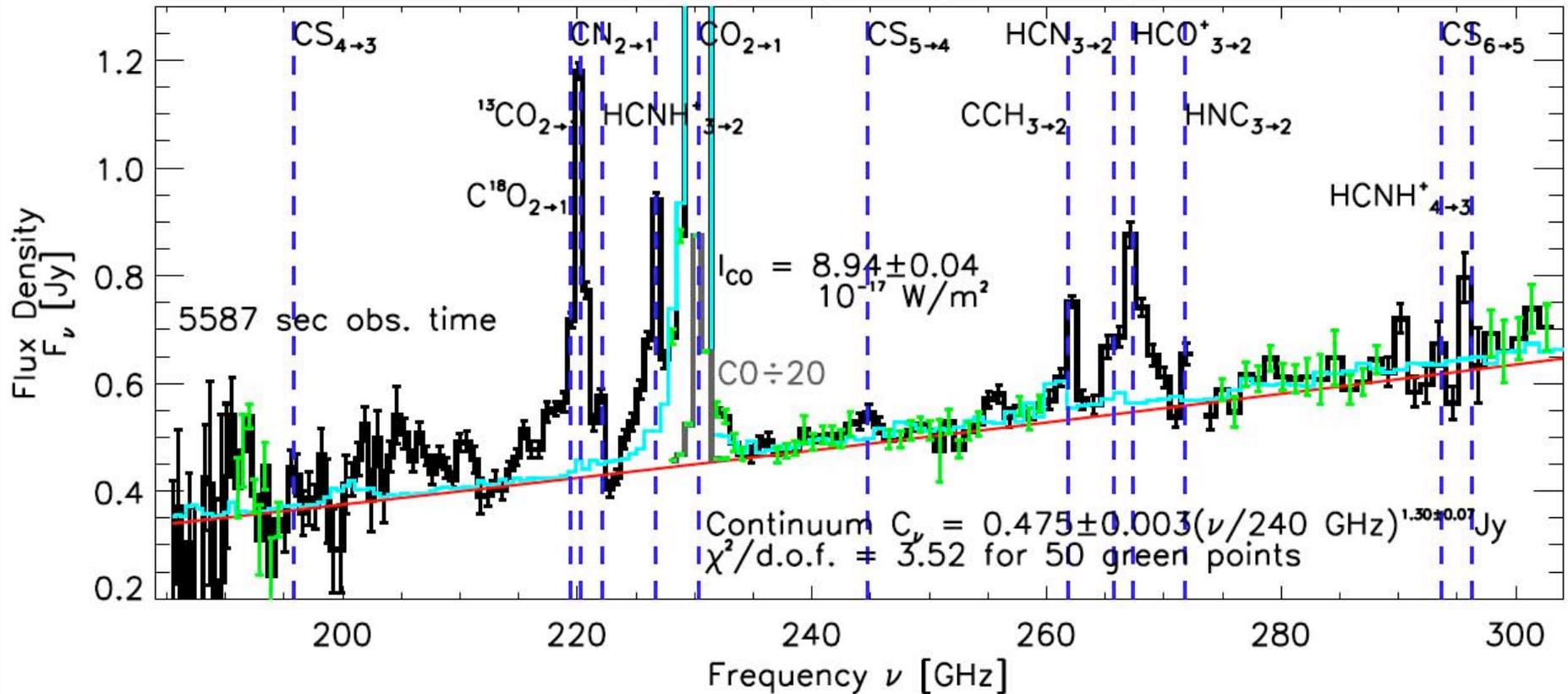
James Aguirre
Jansky Fellow
Colorado, NRAO

Lieko Earle
Colorado Ph.D. student
(finishing Dec)



Z-Spec first results

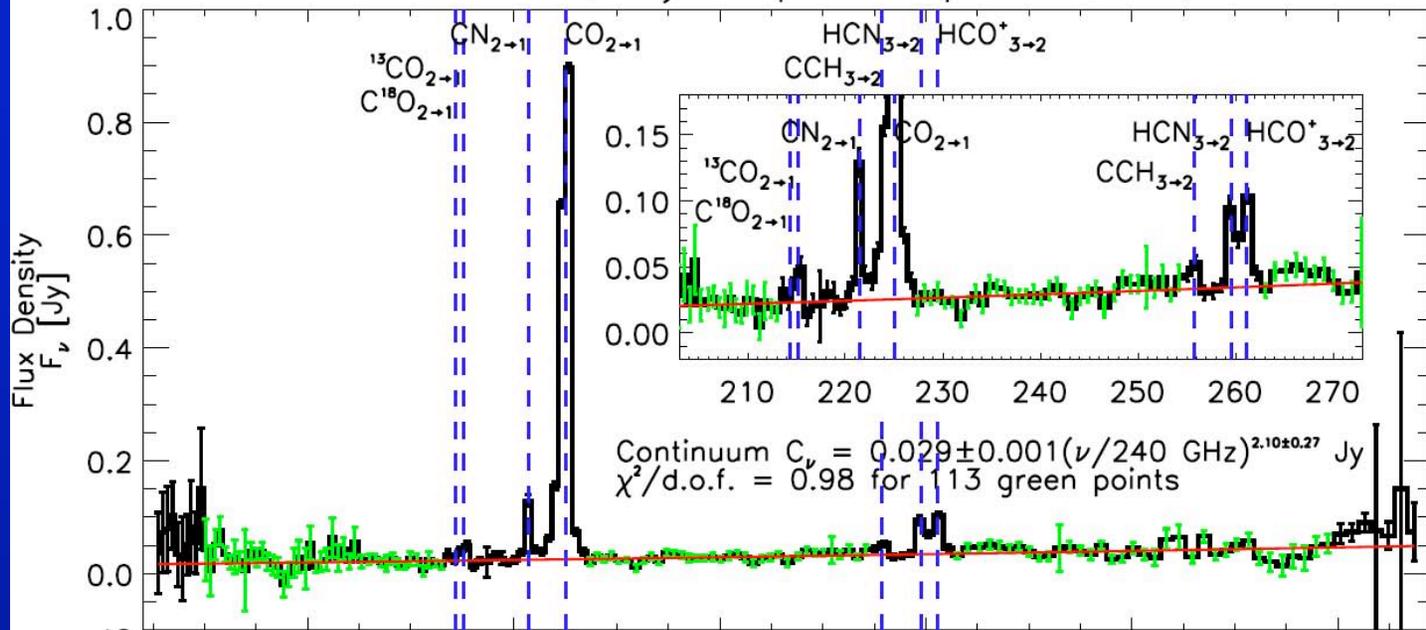
M82 Nucleus Observed by Z-Spec on April 14, 2006



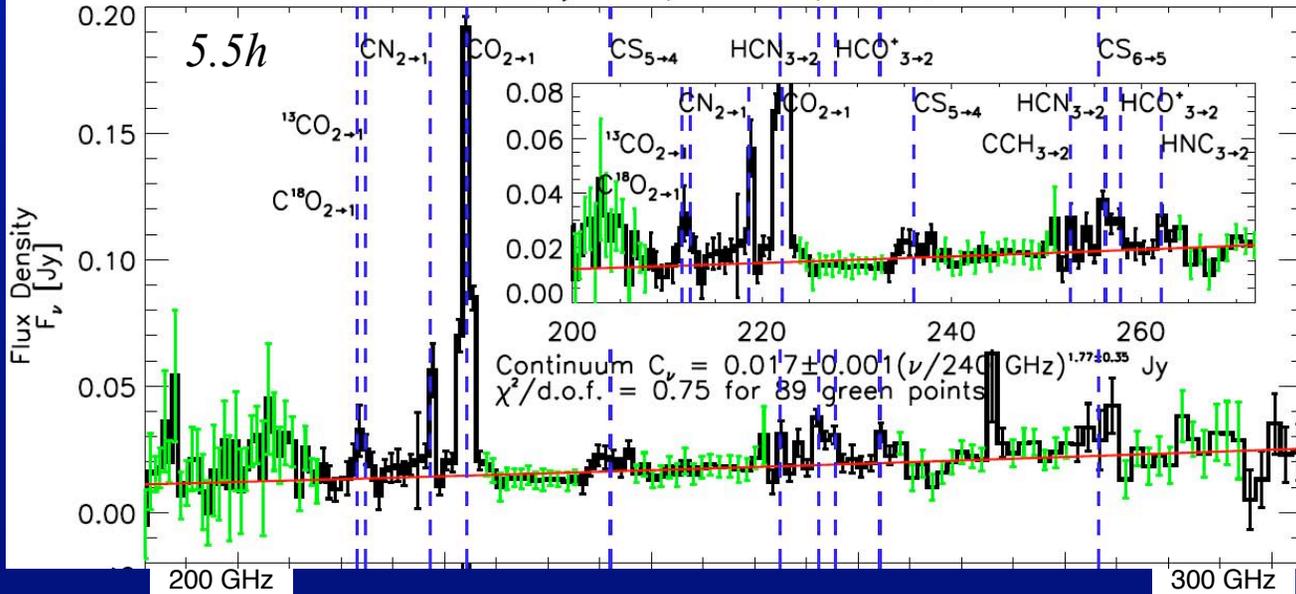
- At least 8 spectral features
 - Excellent line-free continuum
- Bret Naylor et al. in prep (Caltech Ph.D. Dissertation)*

Z-Spec approaching its photon-noise limits at the CSO

NGC6240 Observed by Z-Spec on April 16 & 17, 2006



Mrk273 Observed by Z-Spec on April 19, 27 & 28, 2006



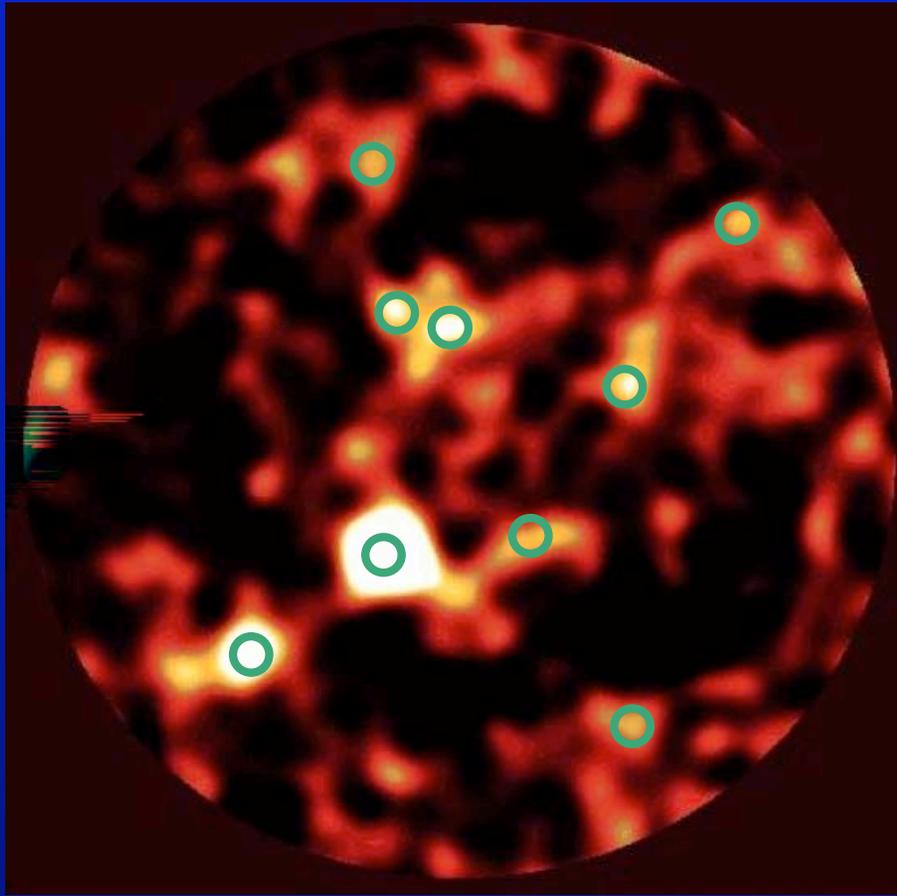
ULIRG spectroscopy for CO, isotopes, density tracers.

Lieko Earle Ph.D. dissertation

High-redshift observations coming.

Sensitivities 0.5-0.8 Jy sqrt sec for each channel in the band center

Both waveguide and free-space echelle grating spectrometers could accommodate a multi-object front end.



Hughes et al. SCUBA HDF North

- Remember CCAT continuum surveys at 350, 450 will go much deeper
- Will be ~110 LIRG+ galaxies in this 5.6 sq arcmin field.

*Source density of LIRG+ galaxies:
71,000 per square degree
= 1 every 180 sq arcsec
= 1 every 10 CCAT 350 / 450 mm
beams.*

*With slit of 1 x 30 beams:
Could position slit to get at least 2,
perhaps 3 sources with no additional
effort except field rotation.*

Ideal system:

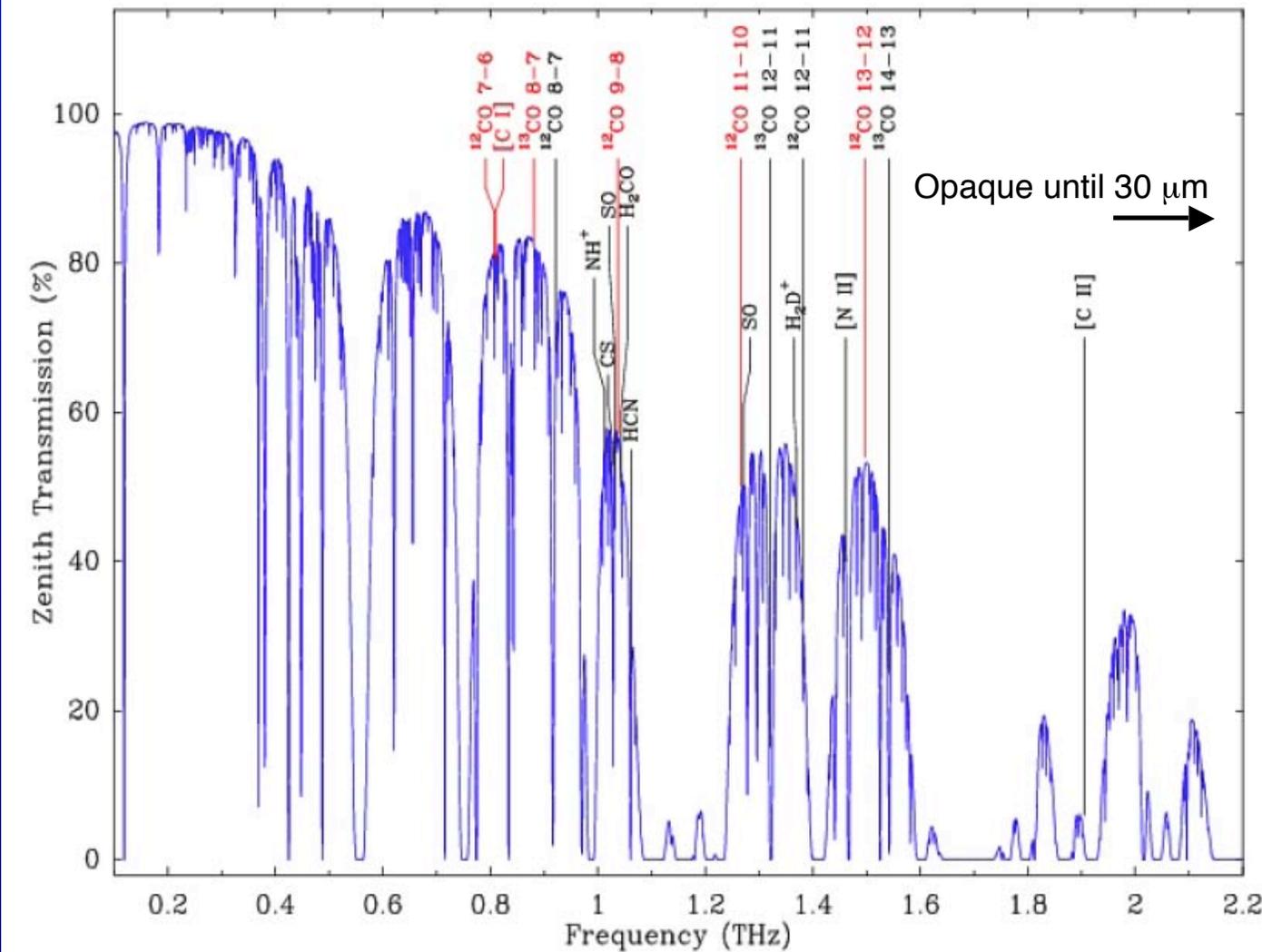
- 10-50 feeds patrolling 4 sq arcmin field.
- 8 x 8 cm in the native f/8 telescope focus.
- feeding slit of echelle or multiple Z-Spec-like devices
- **Mirror arms or flexible waveguide**

Conclusions

- Tens of thousands to millions of galaxies will be discovered in far-IR to millimeter continuum surveys in the next 15 years.
- Spectroscopic follow-up will be the bottleneck.
- CCAT can be competitive with ALMA for spectral surveying in the short submillimeter.
 - a multi-object broadband grating can exceed ALMA for spectral-survey follow-up of LIRG+ galaxies.
- Galaxies w/ $L > 10^{11}$ have \sim constant C+ flux and are detectable with CCAT spectrograph.
 - \sim 1 hour in the 350 micron band
 - \sim 4 hours in the 450 micron band
 - together these bands will capture \sim 30% of all the 850 μm -selected sources
- Existing spectrographs with modest upgrades can reach close to the fundamental photon-noise limits of CCAT.
- Ideal CCAT spectrometer is a multi-object low-order grating.
 - We CAN get redshifts: few to couple tens per hour.

extras

This interesting half of the luminosity has been difficult to observe



Atmosphere is opaque and warm

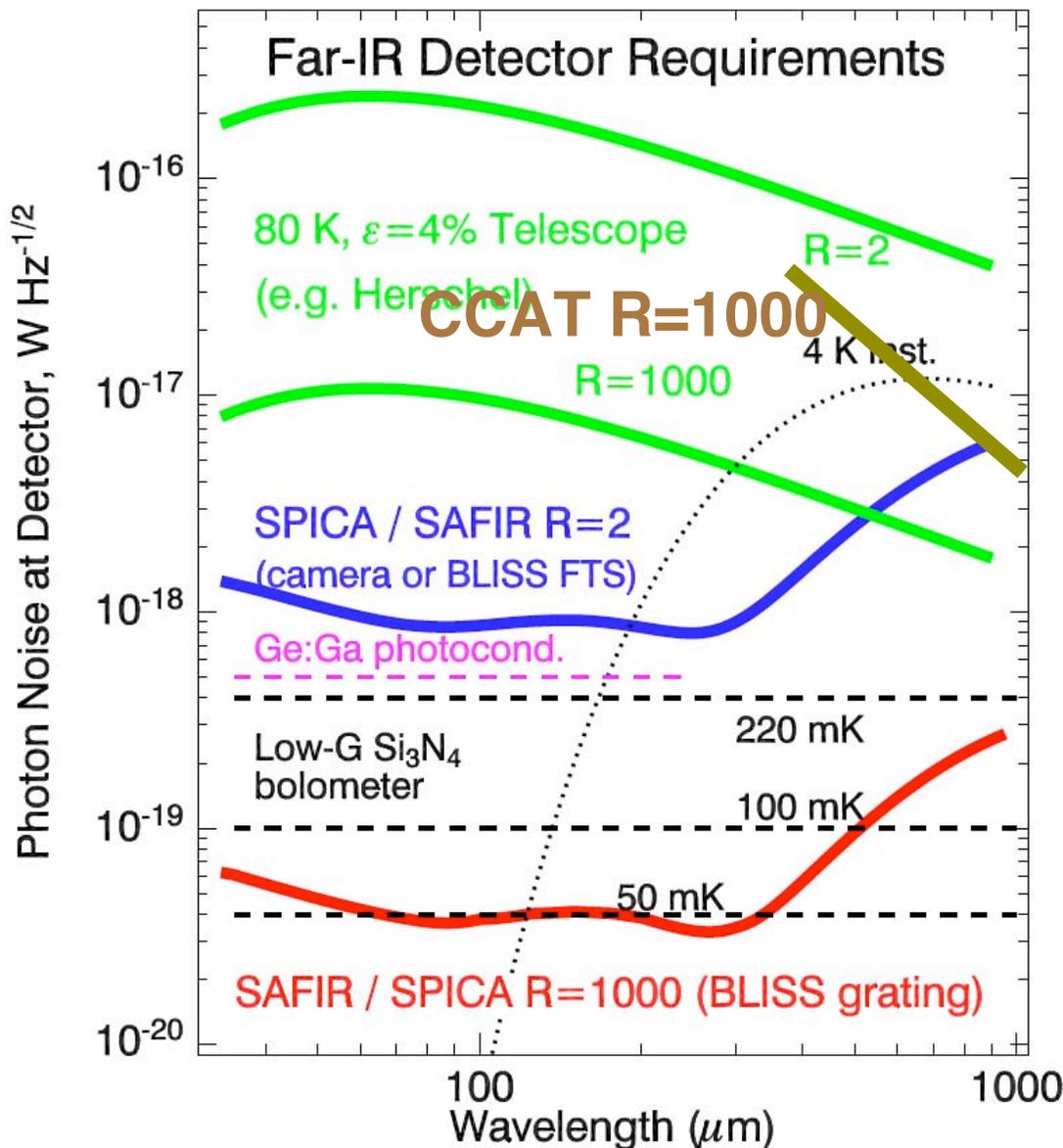
- Reduces transmission
- Introduces loading

-> CCAT to be at the best terrestrial site

- Far-IR /submm detector technology also behind optical / near-IR,

-> But rapidly coming of age with multi k-pix arrays

Detectors for CCAT spectroscopy -- TES or MKID technology being developed for flight



Want ~ 30 kpixel array for CCAT spectrometers.

Sensitive detectors are under development for low-background flight experiments.

Requirements for $R=1000$ at $\lambda < 1$ mm with the CCAT are of order $10^{-17} W Hz^{-1/2}$.

Achievable with existing devices.

TES MUX can work equally well at these NEPs -- development is similar to that of SW CAM, SCUBA-2.

$R \sim 10,000$ at the long wavelengths starts to become a relevant testbed for SAFIR / SPICA detectors.

4 K instrument: $A\Omega = 3 \text{ mm}^2$, $\Delta\lambda/\lambda = 50 \%$, $\epsilon = 10 \%$

CCAT Spectrometer Telescope Requirements

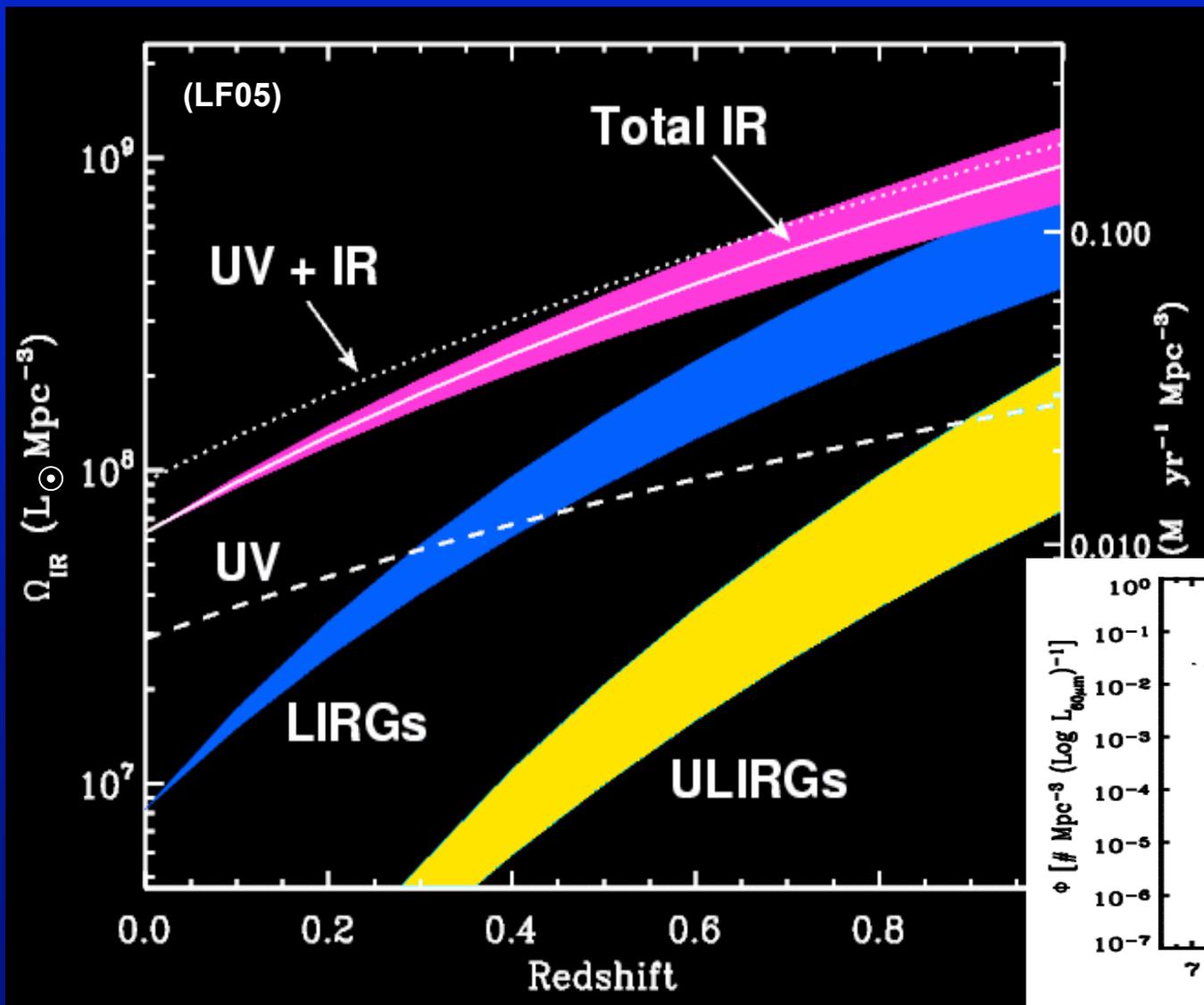
- **Very similar to cameras:**
 - 1-2 tons of cryostat + electronics
 - 5-10 kW of electrical power
 - More modest field sizes -- few square arcmin
 - Similar data rates.
- **BUT GRATING SPECTROMETER WOULD LIKE A CHOPPING SECONDARY**
- **Slit spectrometer needs field or instrument rotation capability**
 - MOSSCCAT may be able to track sources (but not chop!)

CCAT Spectrometer Budget

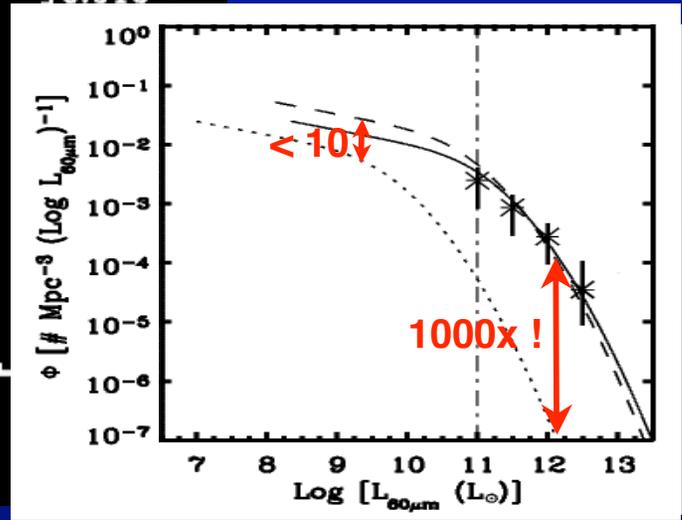
- **Option 1: Use modestly-upgraded Z-Spec and ZEUS**
 - Labor: 10 FTE = \$1.5 M,
 - Dual Z-Spec grating + detectors + electronics (NTD): \$0.5 M
 - ADR + array for for ZEUS: \$0.5 M
 - Total: \$2.5 M for upgraded Z-Spec & ZEUS.
- **Option 2: Dedicated Multi-Object CCAT Spectrometer**
 - 30 kpix TES array + MUX + electronics: \$6.7 M (NIST -- estimate from SW CAM camera)
 - Labor: 27 FTE: \$4 M, includes spectrometer optics fabrication
 - Cryostat, pulse tube, ADR or dilution fridge: \$0.5 M
 - Multi-object front end development + fabrication: \$2.0 M
 - Total: \$13.2 M

ULIRG evolution with redshift

From E. LeFloc'h
 SPICA workshop Nov 06



- * ULIRGs are rare objects at $z \sim 0$
- * They underwent a strong evolution with lookback time
- * They produce $\sim 10\%$ of the IR energy budget at $z \sim 1$



Scope of CCAT Imaging Fabry-Perot

CCAT -IFPI will be much larger than SPIFI due to the large throughput
 Limitation is beam divergence in the high-res FP.

$$D_{\text{col}} \sim 1.5 \lambda (R \times n_{\text{beams}})^{1/2} \quad \text{so } \Omega \sim D_{\text{col}}^4 / (1.5 \lambda R)^2$$

wavelength	R=1000			R=10000		
	array	col. Bm.	sq deg	array	spacing	d local
220.0	256	15.2	1.31E-02	44	18.33	2.23
330.0	196	20.0	1.73E-02	20	27.50	2.26
370.0	156	20.0	1.37E-02	16	30.83	2.27
430.0	116	20.1	1.03E-02	12	35.83	2.28
490.0	90	20.1	8.02E-03	8	40.83	2.12
650.0	51	20.1	4.53E-03	5	54.17	2.23
850.0	30	20.2	2.68E-03	3	70.83	2.25
1200.0	15	20.1	1.34E-03	1.5	100.00	2.25

11' x 11' field

Will require
detailed optical
design

Field size driven
by 20 cm beam,
assumes no
spatial
oversampling

1-D field
size for
20 cm
beam

High-
order FP
spacing
(mm) w/
F=60

Order-sorter also
requires
collimated 2.2cm
(or slow) beam

A new $R \sim 1000$ echelle spectrometer for CCAT

Design: Grating 816 micron pitch

Tilt	λ min	λ max	BW	R	slit	# pix on slit
3rd order						
58 deg	439	485	9.7%	800		
54 deg	418	462	9.3%	822	5.8	2.08
62 deg	456	504	11.0%	903		
4th order						
57 deg	330	356	7.1%	1100	4.3	1.44
63 deg	350	377	8.2%	1245		
6th order						
56.5 deg	221.3	232.7	5.0%	1646	2.7	0.96
7th order						
60.5 deg	198.7	207.4	4.3%	1920	2.7	0.96

Assuming 128 spectral element array

-- e.g. 0.86 mm pixels -- f/2.5 spectrometer, slightly oversampled

Angular deviation off the grating 18 deg total.

collimator must be oversized by 12 cm !

--> 30 cm diameter collimator

--> grating 30 cm by 40 cm, to accommodate spatial throughput

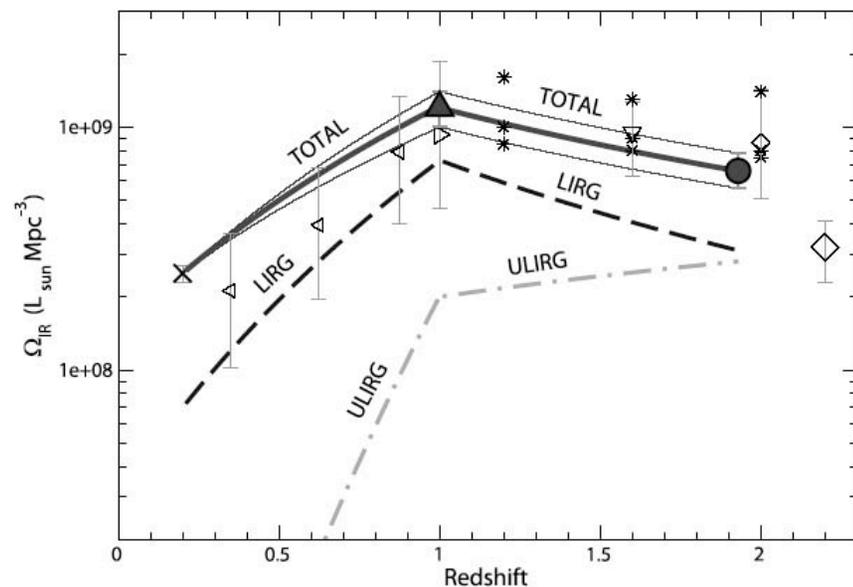


FIG. 15.—Evolution of the comoving bolometric IR luminosity density with redshift. The filled upward-pointing triangle and circle at redshifts $z = 1$ and 1.93 indicate the estimations of the respective bolometric IR luminosity density obtained in this work: $\Omega_{\text{IR}} = (1.2 \pm 0.2) \times 10^9$ and $(6.6^{+1.2}_{-1.0}) \times 10^8 L_{\odot} \text{Mpc}^{-3}$. The density at $z = 0.2$ has been obtained from the bolometric IR LF derived from the $8 \mu\text{m}$ LF by Huang et al. (2006). The thick solid line corresponds to an interpolation between these redshifts, assuming a $[(1 + z_2)/(1 + z_1)]^x$ evolution. The thin solid lines indicate error bars on this evolution. Dashed and dot-dashed lines show the contributions of LIRGs and ULIRGs, respectively, at different redshifts. Other symbols refer to IR luminosity densities taken from the literature and based on different data sets: *ISO* mid-IR (Flores et al. 1999; left-pointing triangles), *Spitzer* mid-IR (Le Floc'h et al. 2005; Pérez-González et al. 2005; right-pointing triangle and asterisks, respectively), submillimeter (Barger et al. 2000; Chapman et al. 2005; small and large diamonds, respectively), and radio (Haarsma et al. 2000; downward-pointing triangle). Some of these IR luminosity densities have been obtained from the star formation rate densities compiled by Hopkins (2004) and converted with the Kennicutt (1998) formula $\text{SFR} = 1.72 \times 10^{-10} L_{\text{IR}}$. [See the electronic edition of the *Journal* for a color version of this figure.]