CCAT Instrumentation

Gordon Stacey representing the efforts of many people involved in CCAT instrumentation studies

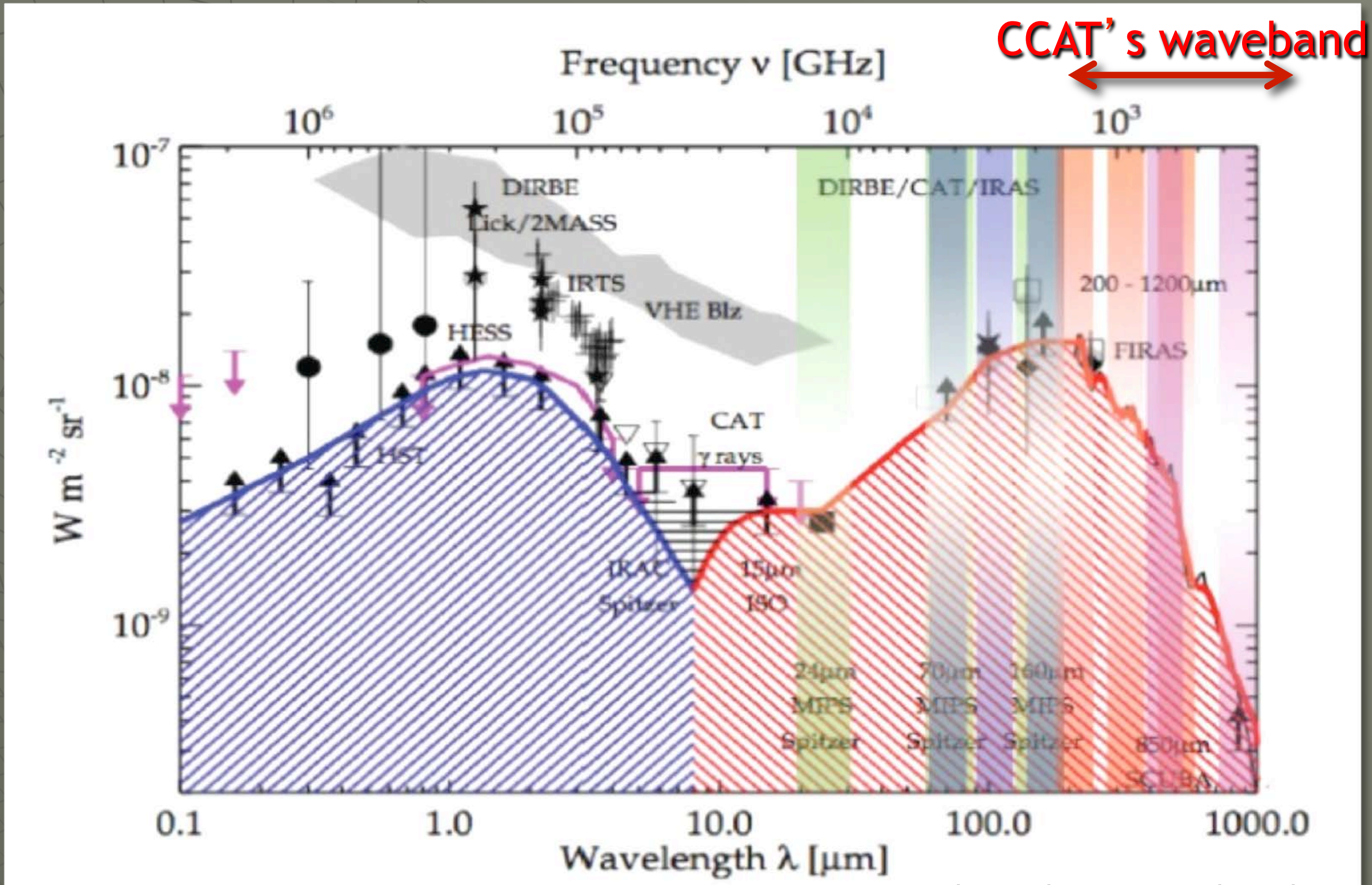
What is CCAT?

- A 25 m submm telescope that will operate at wavelengths as short as 200 um
  - Why 25 m?
    - Matches ALMA continuum sensitivity in short submm
    - Significantly breaks confusion limit of smaller apertures
    - High altitude, smooth surface, large aperture ⇒ > 10 times more sensitive than current single dish facilities
- Located in the Atacama desert in northern Chile at very high elevation - 5600 m
  - ⇒ much of the time has PWV < 0.5 mm
- Its location enables maximal synergy with ALMA
  - Locates sources for ALMA follow-up
- Takes advantage of rapid growth in submm detector technology to map large regions at high angular resolution

What will we see?

- Primary science
  - Exploration of the Kuiper Belt
  - Star and planetary system formation
  - Sunyaev-Zeldovich Effect
  - Surveys of star forming galaxies in the early Universe
- These science topics emphasize wide-field imaging – hence our first light instruments will include cameras
- Studies of primordial galaxies requires redshifts – we also include direct detection spectrometers

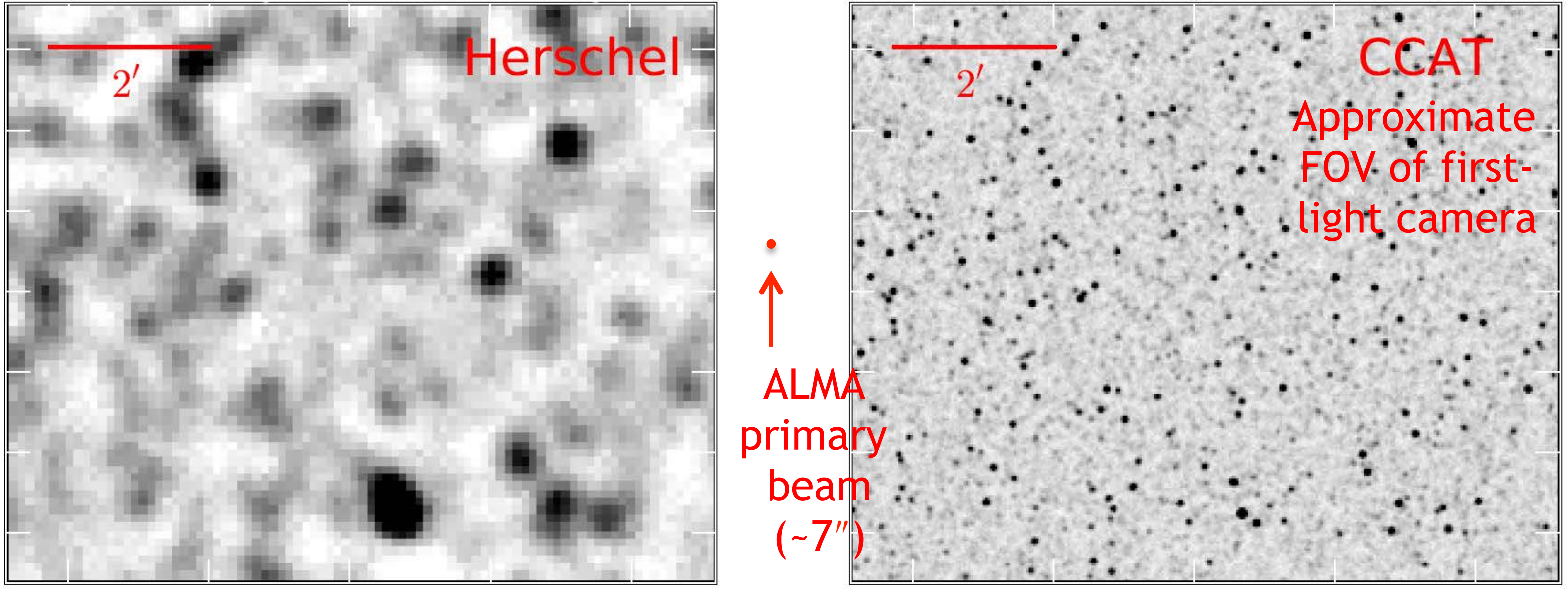
Resolving the Origins of the Cosmic Far-infrared Background



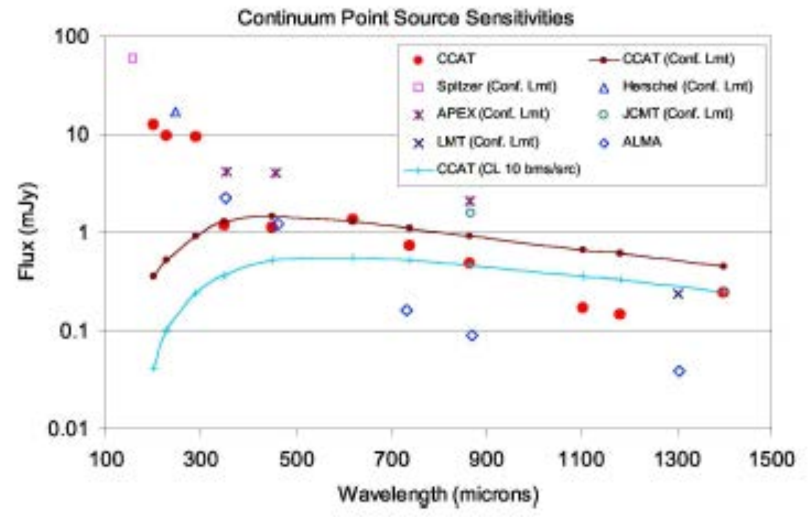
Dole et al. (2006) and S. Oliver

1. 50% of the extragalactic background radiation is in the FIR/submm
2. Only a fraction the CFIRB has been accounted for with galaxies
3. The FIR/submm luminosity function must evolve strongly for z > 0.

CCAT, Hershel and ALMA


350 μm

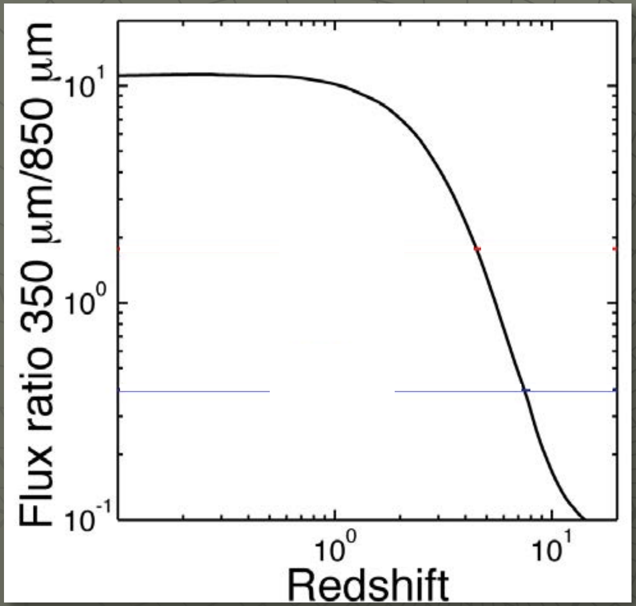
Simulated maps of the same patch of sky based on *Herschel* number counts

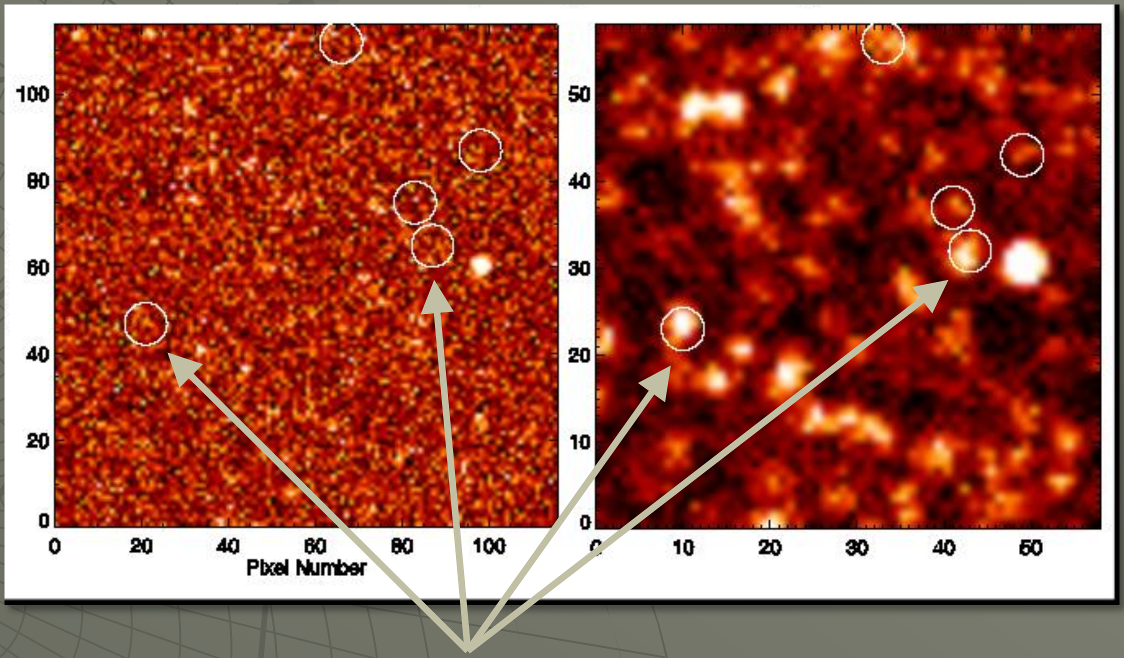


At 450 μm, CCAT and ALMA will have approximately the same mapping speed *per beam*.

With the 5′ FOV first-light camera and *~8,500 beams*, CCAT's mapping speed will be ~8,500x higher.

Identifying the Highest Redshift Sources





>5σ 850 μm detection, 350 μm nondetections

Baseline CCAT Instrumentation

- Three Primary Science Instruments
  - Submillimeter wave camera
  - Near millimeter wave camera
  - Multi-object direct detection spectrometer
    - Z-spec
    - ZEUS/ZEUS-2
  - Transferred, and future instrumentation
    - Full FoV cameras
    - Heterodyne spectrometers/arrays

Submm Camera: Summary

- We envision a > 50,000 pixel submm camera at first light
- Primary band is 350 μm ~ 40,000 pixels ⇔ 5’ FoV
  - Filter wheel to access 450, 620, (200) μm
- Dichroic splits off a long wavelength 850 μm band
  - Or perhaps more likely we will have an (independent) mm wave camera for 740 μm and longer wavelengths
  - At least 10,000 pixels at longer wavelengths
- Advanced Technology Array Camera

ATACamera

Submm Camera Decision Tree – Field of View

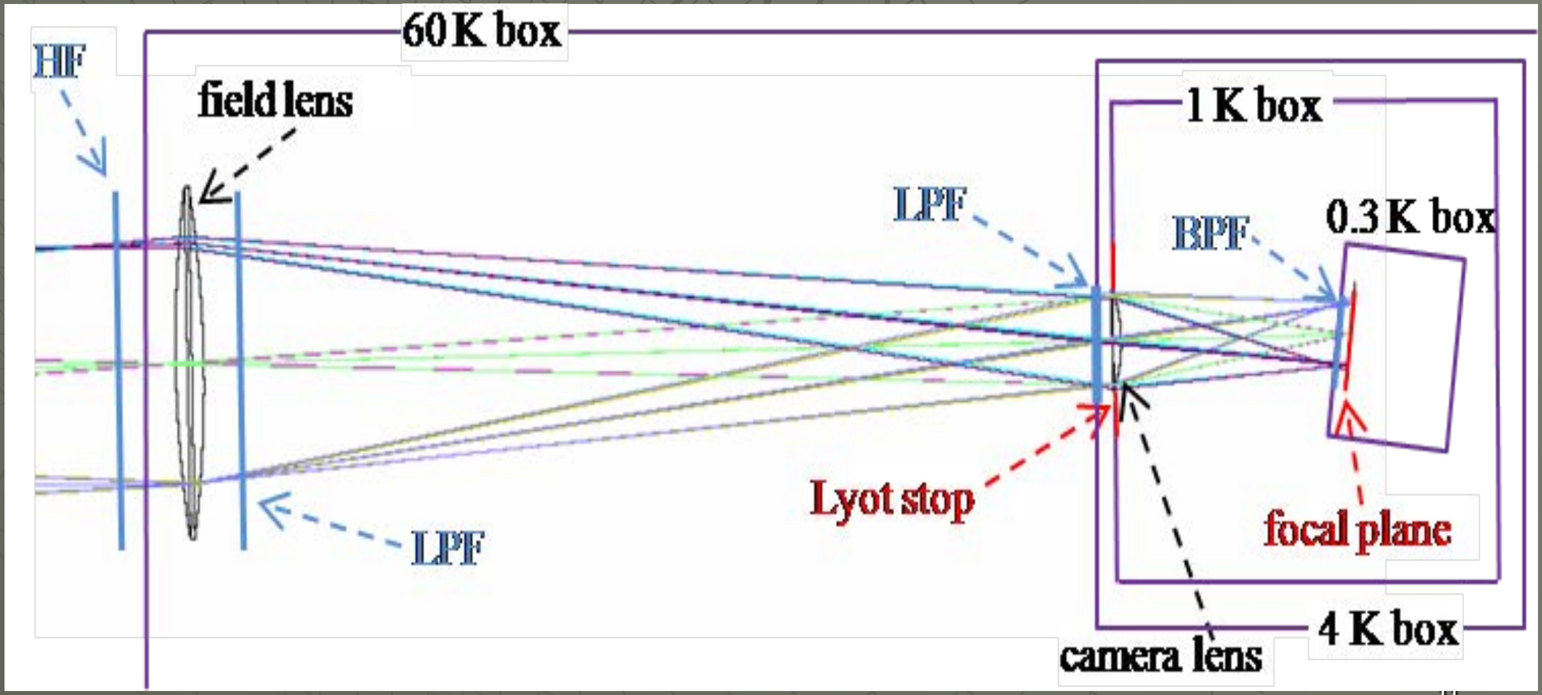
- The telescope delivers up to 1º FOV – why are we designing to a 5’ FOV?
  - Science: Initial science deliverable with 5’ FOV cameras
  - Image Scale: One can not couple the entire 1° FoV into a background limited camera ⇒ smaller sub-systems
  - Technology: Current technology suggests 40,000 pixels is a reasonable goal – this delivers Nyquist sampled images over a 5’ × 5’ FOV at 350 μm
    - tiling a 30’ FOV requires ***one million pixels*** at 350 um, -- extremely expensive using today’s technologies
    - Future developments will greatly reduce the costs – therefore mega pixel cameras are postponed

Two Designs Considered

- All reflective design
  - Maximizes throughput
  - Minimizes emissivity
  - Off-axis approach leads to BIG (3-4 m class) optics – but 5’ FoV design not too bad…
- Transmissive design with field lens
  - System is remarkably more compact
  - Throughput and emissivity quite good
- Direct imaging
  - Would be fine at 200 um, over-sampled at longer wavelengths
  - Problems with stray light…

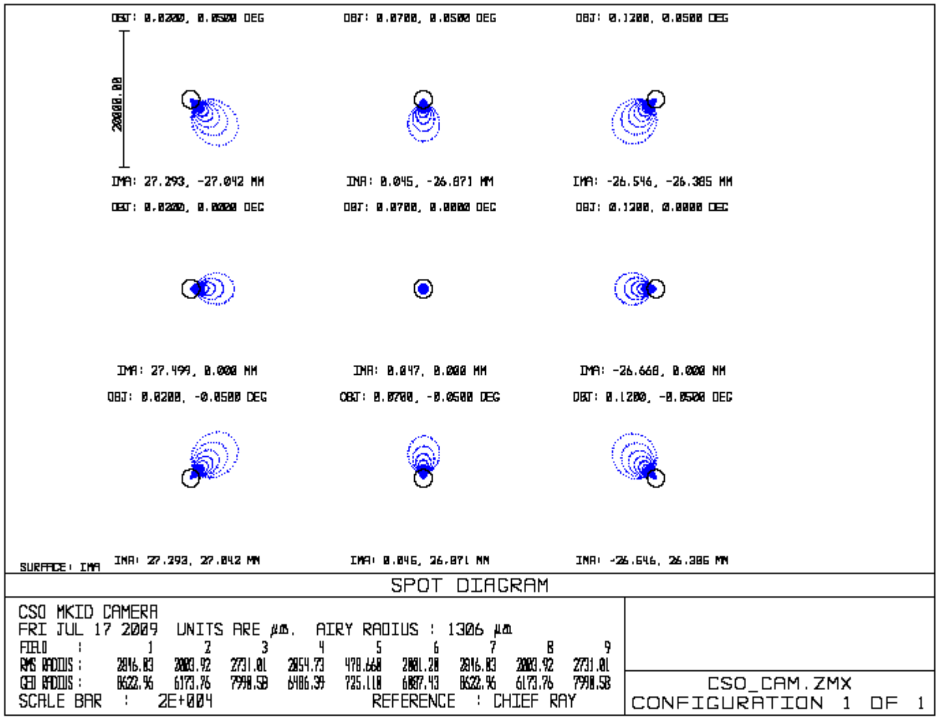
ATACamera

- Cornell – Caltech – Colorado collaboration
- First light camera composed of sub-cameras
- Dichroic 5’ field of view on CCAT
  - 40,000 pixel at 350 μm and 10,000 pixels at 850 μm
- FoV broken into 3 – 3’ “sub” fields (128×128): minimizing both aberrations and window size



Ray-trace

- Spot sizes quite good – circles are Airy disk
- Sub-cameras have Strehl ratios > 90% over nearly entire FoV (centered at angle of 0.07°)



SPOT DIAGRAM

```
CSO MKID CAMERA
FRI JUL 17 2009  UNITS ARE µm.   AIRY RADIUS : 1306 µm
FIELD      :        1        2        3        4        5        6        7        8        9
RMS RADIUS :  2016.83  2003.92  2731.01  2054.73  478.668  2001.28  2016.83  2003.92  2731.01
GEO RADIUS :  8622.96  6173.76  7998.58  6486.39  725.118  6087.43  8622.96  6173.76  7998.58
SCALE BAR  :   2E+004                 REFERENCE  : CHIEF RAY
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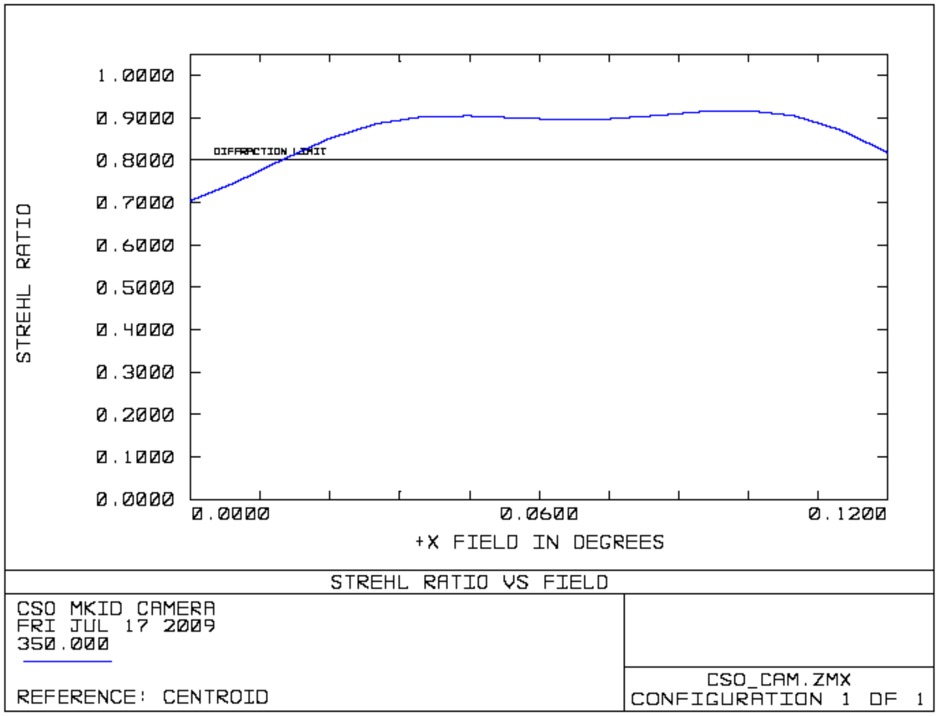
CSO_CAM.ZMX
CONFIGURATION 1 OF 1



STREHL RATIO VS FIELD

CSO MKID CAMERA
FRI JUL 17 2009
350.000

REFERENCE: CENTROID

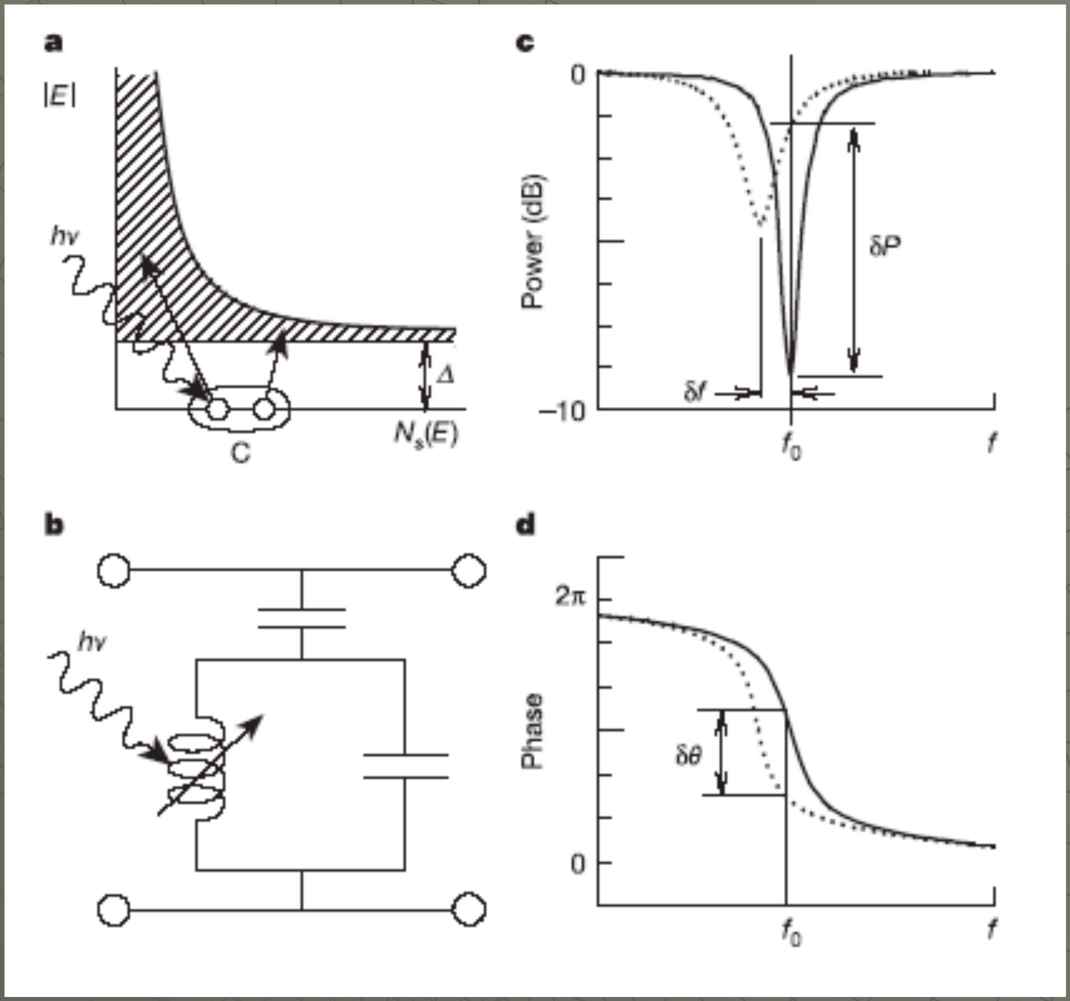
CSO_CAM.ZMX
CONFIGURATION 1 OF 1

Detectors

- Our preliminary design base-lined TES sensed SQUID multiplexed arrays as in SCUBA-2
- Workable, within budgets for 40,000 pixel camera
- Submm MKID devices are now the preferred option
  - Considerably less complex architecture that is more readily scalable to large arrays
  - Considerably less complex read-out electronics as well.

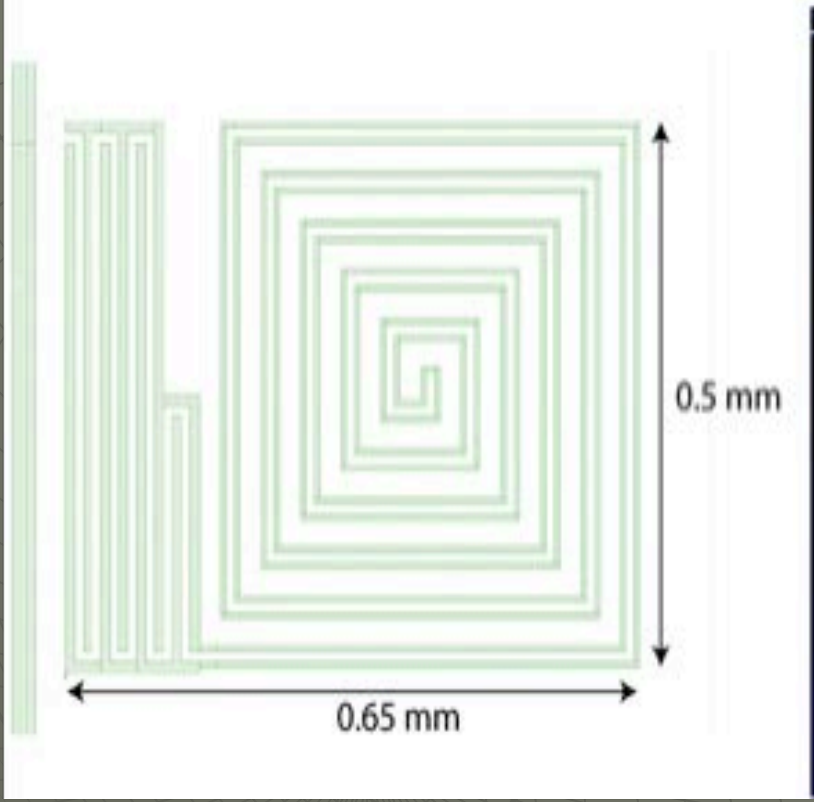
⇒ Considerably less cost

MKID Principles

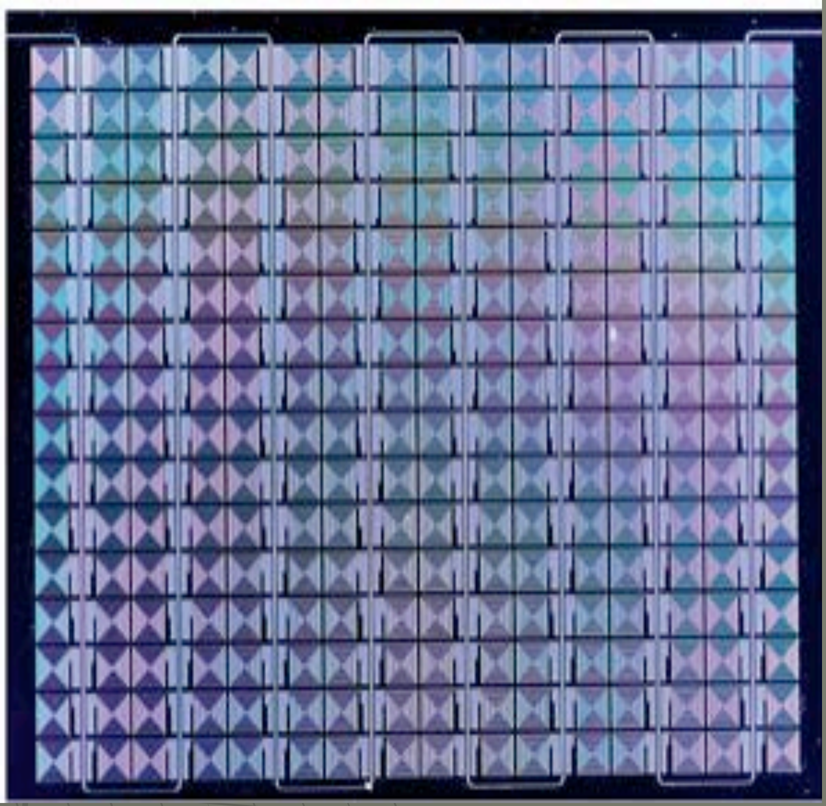


- Photon detector is incorporated into a superconducting resonator circuit
- Photon absorption causes the frequency and line-width of the resonator to change
- Frequency domain multiplexing achieved by designing resonators with slightly different resonant frequencies and using a broadband low noise microwave amplifier to read out the array

Array Development at JPL

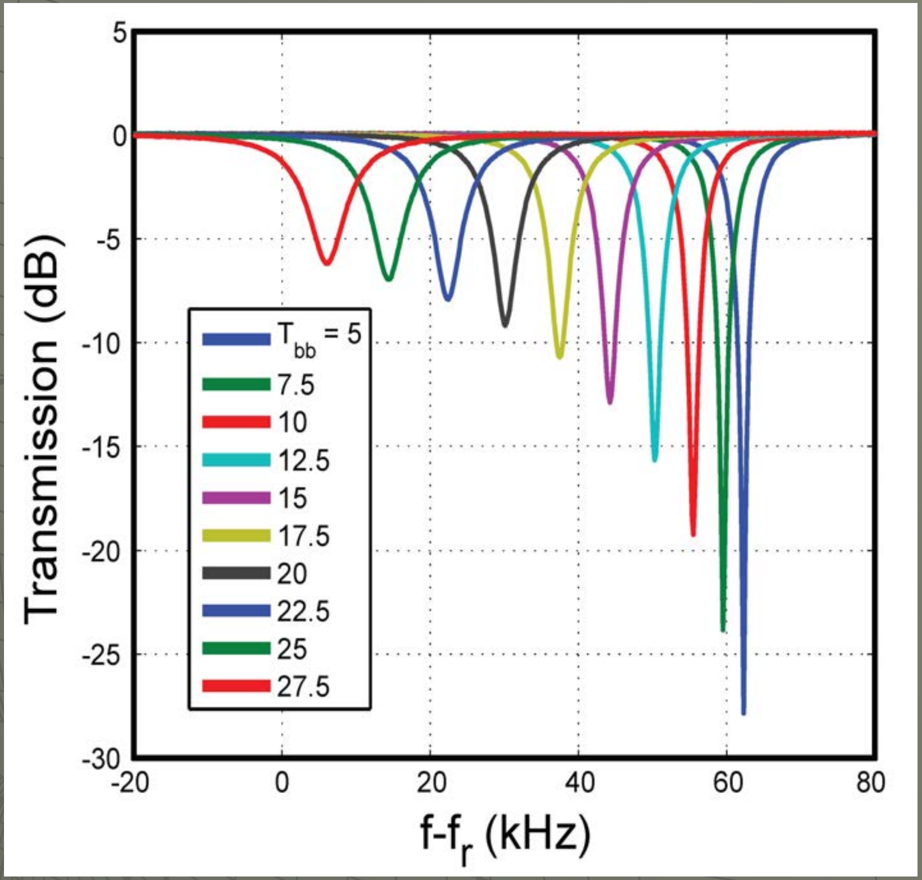


Lumped-element 350 µm direct absorption MKID pixel spiral inductor/ absorber and an inter-digitated capacitor



16×16 array of TiN spiral lumped-element pixels 256 pixels coupled to one feedline visible at the top and bottom

200 μm MKID Device



Demonstration of TiN far-IR MKID device at 200 μm illustrating the inductive (frequency shift) and dissipative (resonance width) response to temperature (Peter Day et al.)

Predicted Sensitivity

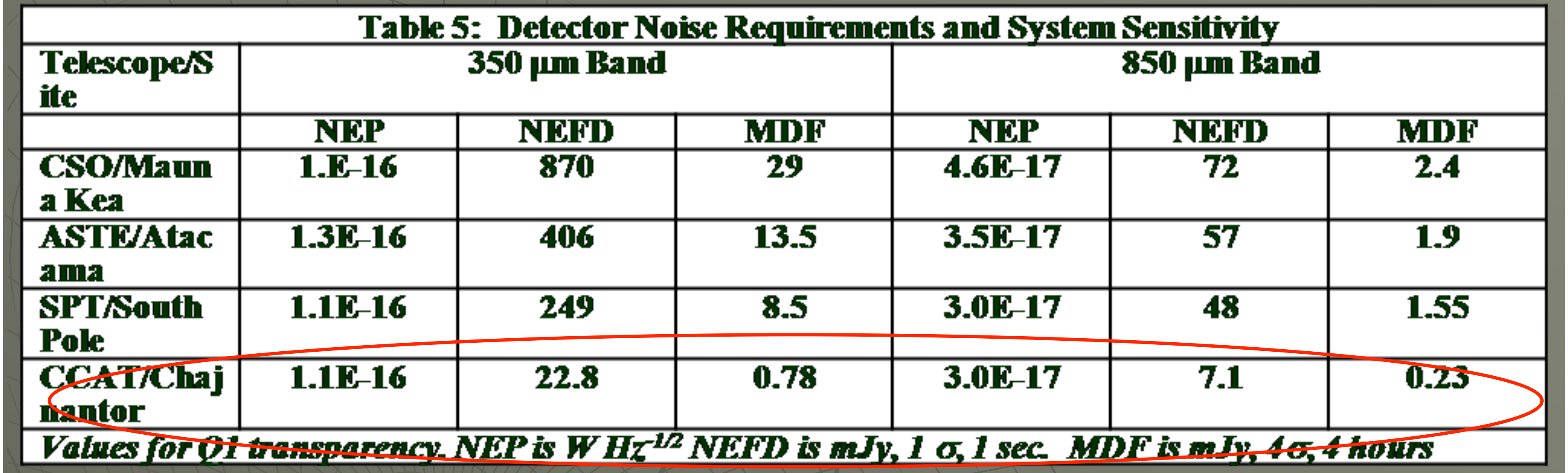


Table 5: Detector Noise Requirements and System Sensitivity

Telescope/Site	350 µm Band			850 µm Band		
	NEP	NEFD	MDF	NEP	NEFD	MDF
CSO/Mauna Kea	1.E-16	870	29	4.6E-17	72	2.4
ASTE/Atacama	1.3E-16	406	13.5	3.5E-17	57	1.9
SPT/South Pole	1.1E-16	249	8.5	3.0E-17	48	1.55
CCAT/Chajnantor	1.1E-16	22.8	0.78	3.0E-17	7.1	0.23

Values for Q1 transparency. NEP is W $Hz^{-1/2}$ NEFD is mJy, 1 σ, 1 sec. MDF is mJy, 4σ, 4 hours

Can detect Milky Way at z ~ 1 to 2!

How Many Sources

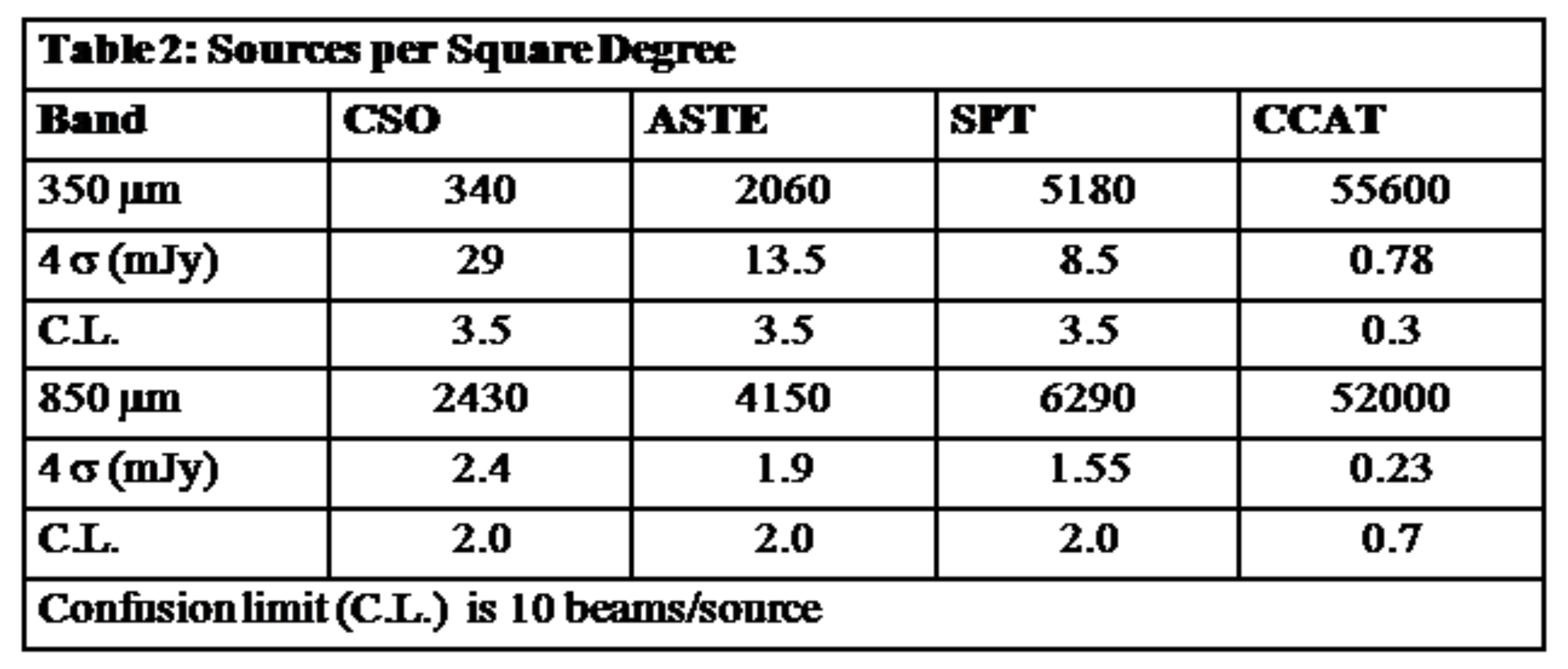


Table 2: Sources per Square Degree

Band	**CSO**	**ASTE**	**SPT**	**CCAT**
350 µm	340	2060	5180	55600
4 σ (mJy)	29	13.5	8.5	0.78
C.L.	3.5	3.5	3.5	0.3
850 µm	2430	4150	6290	52000
4 σ (mJy)	2.4	1.9	1.55	0.23
C.L.	2.0	2.0	2.0	0.7

Confusion limit (C.L.) is 10 beams/source

- 4 hours/pixel, 2000 hour survey – 14° survey in 2 years

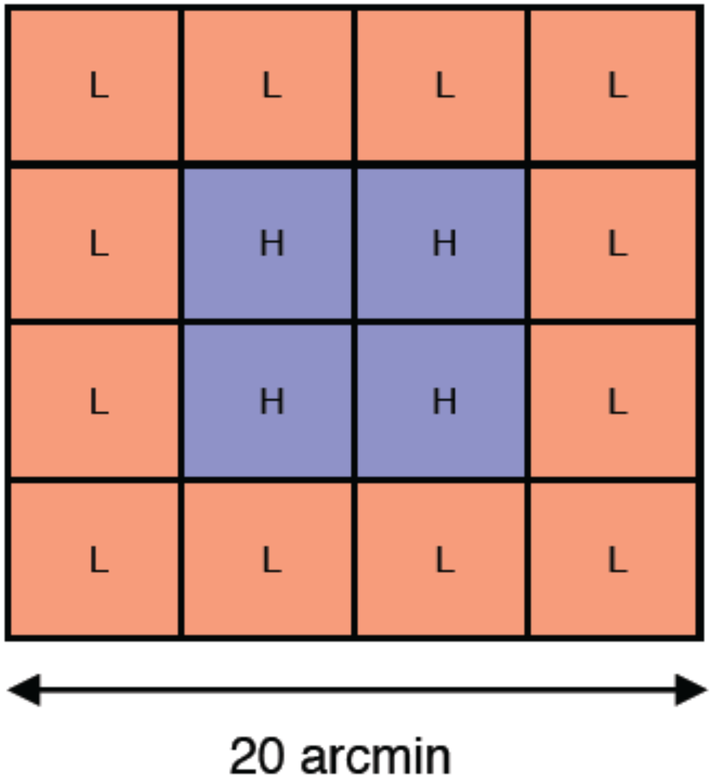
  Approaches half a million sources/year

Transmillimeter Wave Camera –Sunil Golwala

- Low wavelength Camera for CCAT
- Antenna-coupled arrays of bolometers
  - Can’t do 50,000 feed-horns
  - Single polarization antenna coupled design leads to a simple way to cover multiple bands with varying pixel sizes
  - Nb slot antenna and microstrip limits shortest λ to > 740 um (405 GHz)
- Beam definition achieved with phased array antenna
- Signal detection with either MKIDS or TES devices

Pixel Numerology

- Design driven by desire to keep detector counts reasonable, yet gain substantially in mapping speed over SCUBA-2/MUSIC generation.
- Could increase 740 μm, 870 μm pixel counts by ~x4 more if readouts capable



L = low-resolution tile
H = high-resolution tile

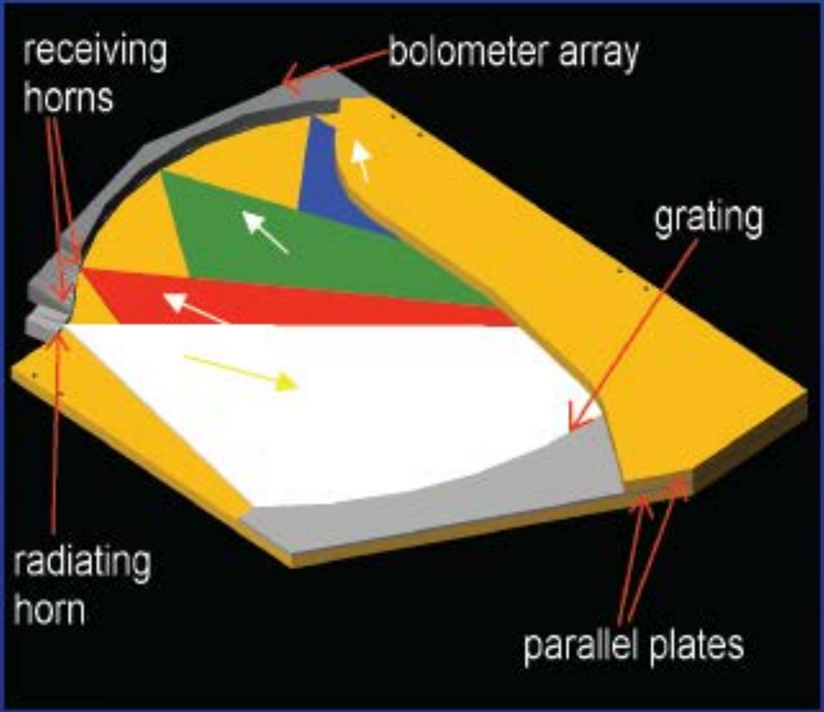
Band GHz (μm)	Δν (GHz)	Pixel Size f·λ	Number of Spatial Pixels
150 (2000)	30	1.15	16 tiles × 256 = 4096
220 (1400)	40	1.6	16 tiles × 256 = 4096
275 (1100)	50	2.1	16 tiles × 256 = 4096
350 (870)	40	0.7 2.8	4 tiles × 4096 = 16384 12 tiles × 256 = 3072
405 (740)	30	0.8 3.2	4 tiles × 4096 = 16384 12 tiles × 256 = 3072
Total			51,200 detectors

At f/2, 1 tile is approximately 74 mm across, a good fit for 4" wafer processing. Focal plane is 30 cm across, a "reasonable" size.

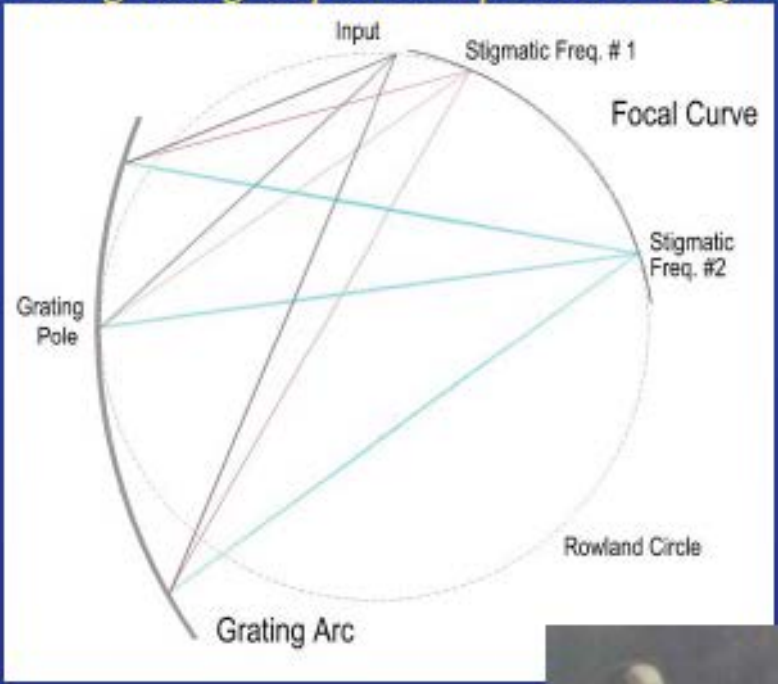
Direct Detection Spectrometers

- For broad-band spectroscopy of broad, faint lines, direct detection spectrometers are the instruments of choice.
  - Detectors are not subject to the quantum noise limit and are now sufficiently sensitive to ensure background limited performance at high resolving powers
  - Very large bandwidths $\Delta\nu \sim \nu$ are possible
- Need to consider 3 types of direct detection spectrometers
  - Fourier Transform spectrometers: naturally broad band
  - Fabry-Perot interferometers: high sensitivity, but must scan
  - Grating spectrometers: spectral multiplexing monochrometer
    - Free space spectrometers
    - Waveguide spectrometers
  - Niche for all systems: here we focus on grating spectrometers since we are interested in maximizing point source sensitivity

Ultra-compact approach: WaFIRS spectrometer



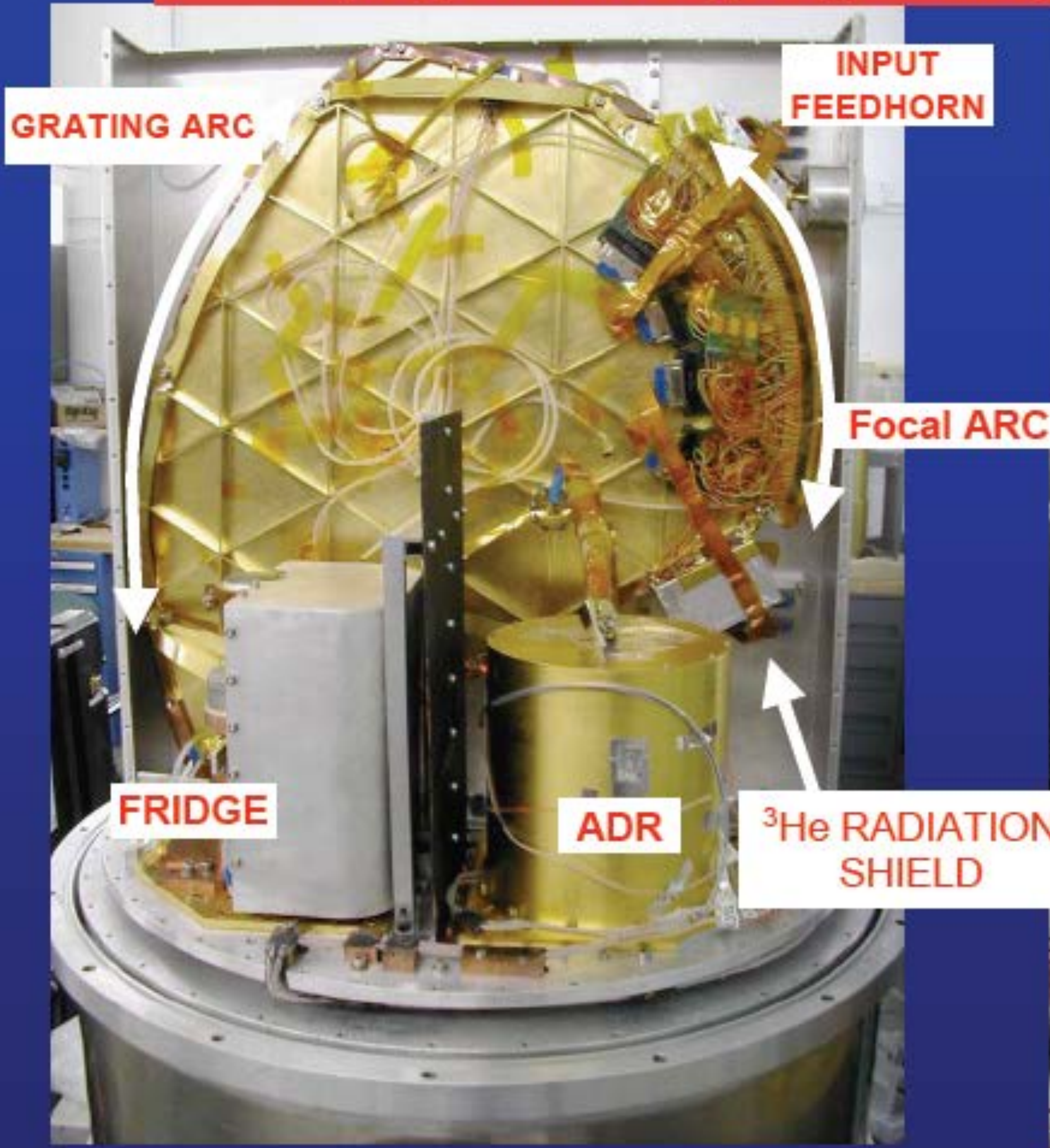
curved grating in parallel plate waveguide

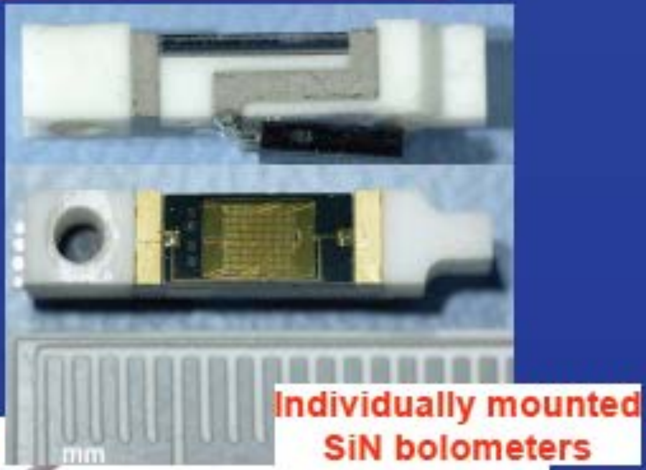


- Propagation confined in parallel-plate waveguide
  - 2-D Geometry
  - Stray light eliminated
- Curved grating diffracts and focuses
  - Efficient use of space
  - No additional optical elements
- Custom "stigmatic" grating design possible at long wavelengths

H.A. Rowland, 1883, Phil. Mag 16
K.A. McGreer, 1996, IEEE Phot. Tech. 8

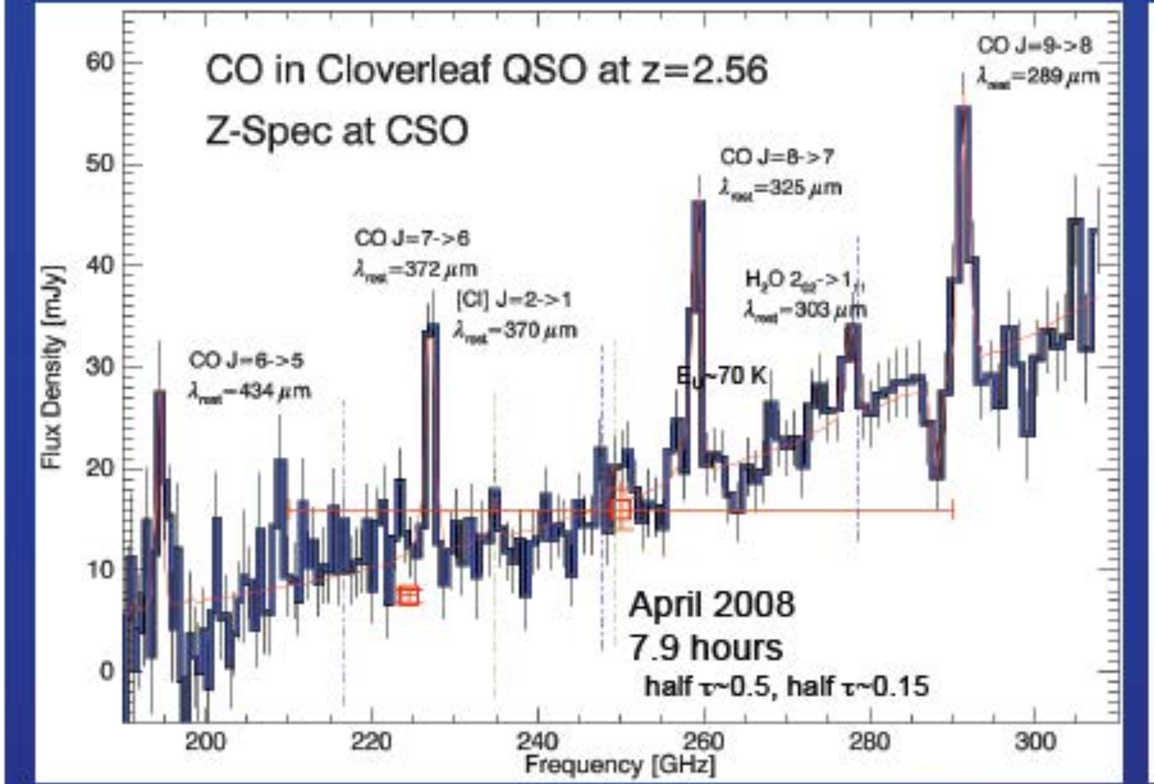
True broadband spectroscopy in the submillimeter: Z-Spec, a 1st order grating covering 190-305 GHz.

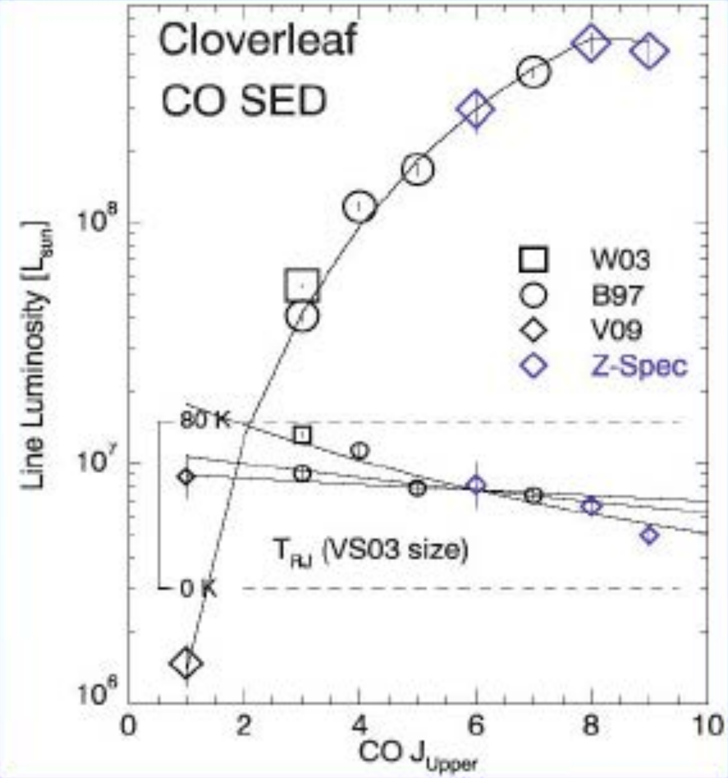


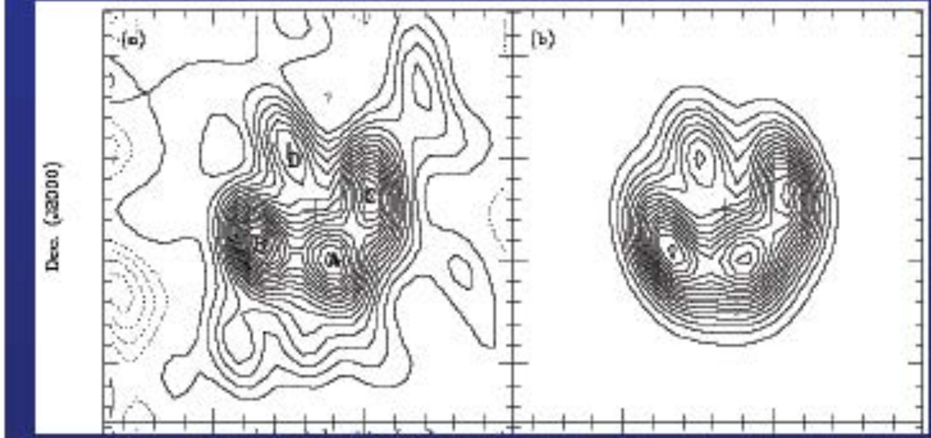


Z-Spec Team

Bradford, Bock, Nguyen, Naylor, Zmuidzinas (*JPL & Caltech*)
Glenn, L. Earle, P. Maloney (*CASA, University of Colorado*)
Aguirre, Scott, Lupu (*U.. Penn*)
Matsuhara (*ISAS / JAXA*)







Venturini and Solomon, 2003, using PdB data
Intrinsic source is 650 by 560 pc disk, m=11

- Source size breaks T / n degeneracy, requires T>50 K
- CO cooling / far-IR exceeds local starbursts & ULIRGS by 2-5.
- X-rays may be heating the gas.
- Plenty of energy, easy to get high gas line / dust luminosity with X-rays (e.g. Maloney et al.)
- Bulk heating like X-rays (or cosmic rays) increases minimum temp to which gas cools, thus increases the stellar IMF.

Z-Spec as a Redshift Engine

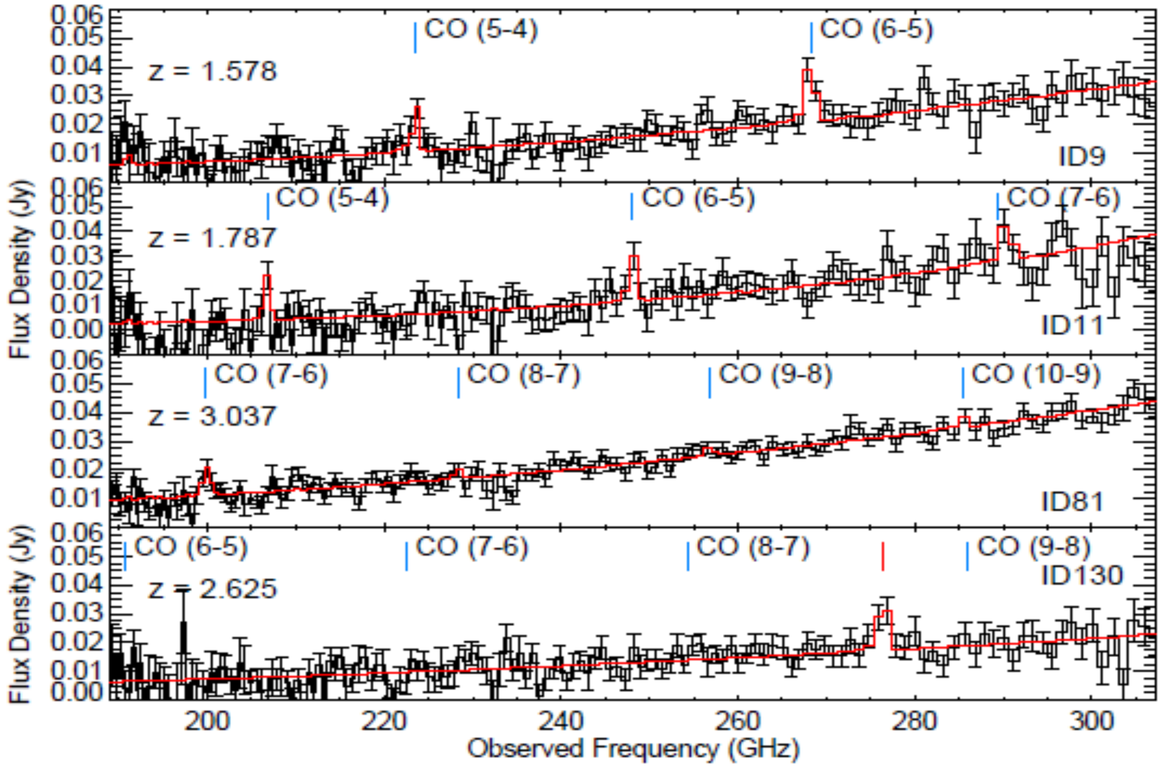


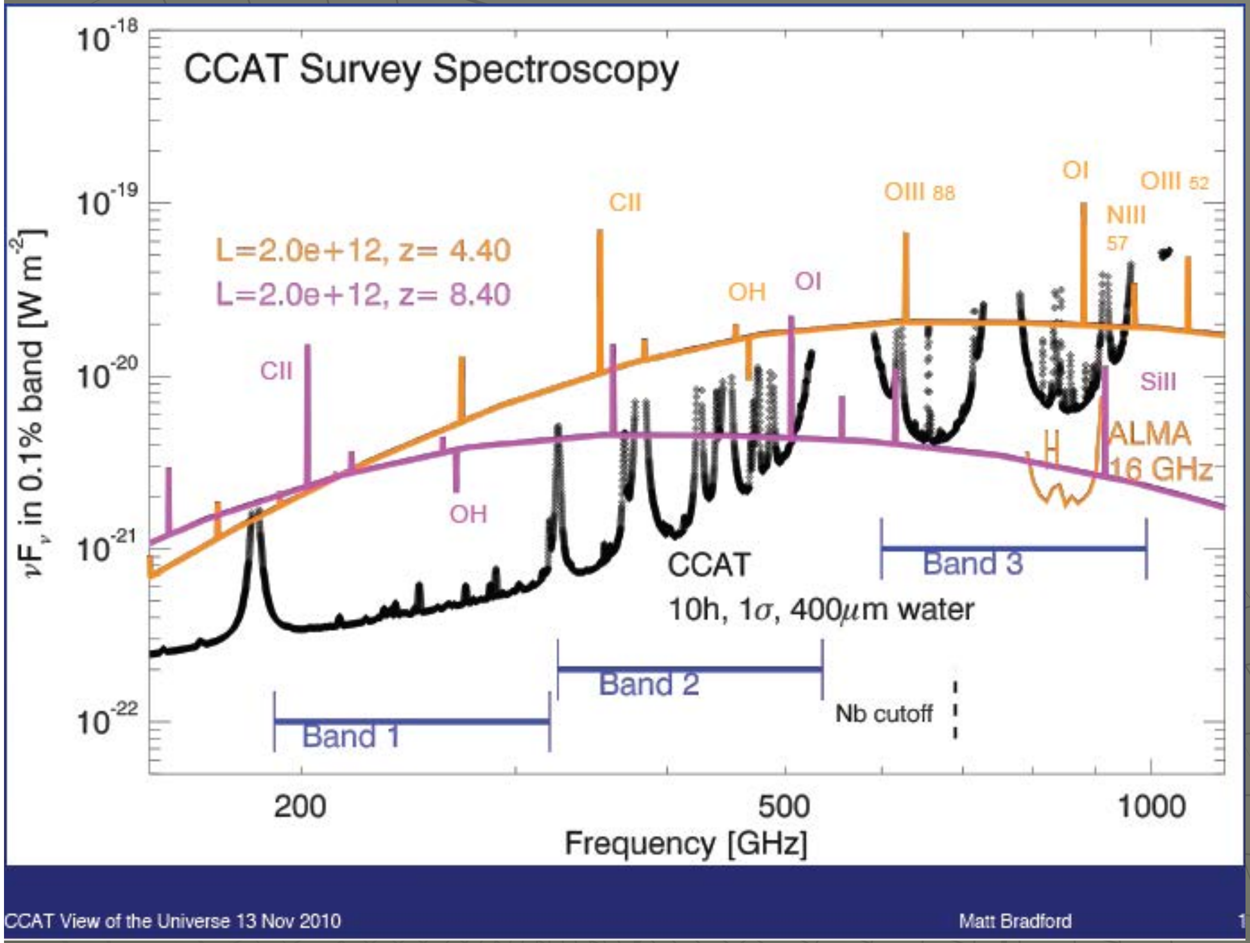
Fig. 1.— The Z-Spec spectra of four submillimeter bright H-ATLAS galaxies. The fit to the continuum and CO lines at the measured redshift is overplotted in red, and the positions of the strongest lines falling in the Z-Spec bandpass are indicated by the vertical blue lines. The line indicated in red in the spectrum of SDP.130 is unidentified.

- Broad bandwidth is very useful for determining redshifts of submm galaxies
- Observed (redshifted) spacing between CO rotational lines given by:

$\Delta\nu$ = 115 GHz/(1+z)

Lupu et al. 2010

Beyond CO



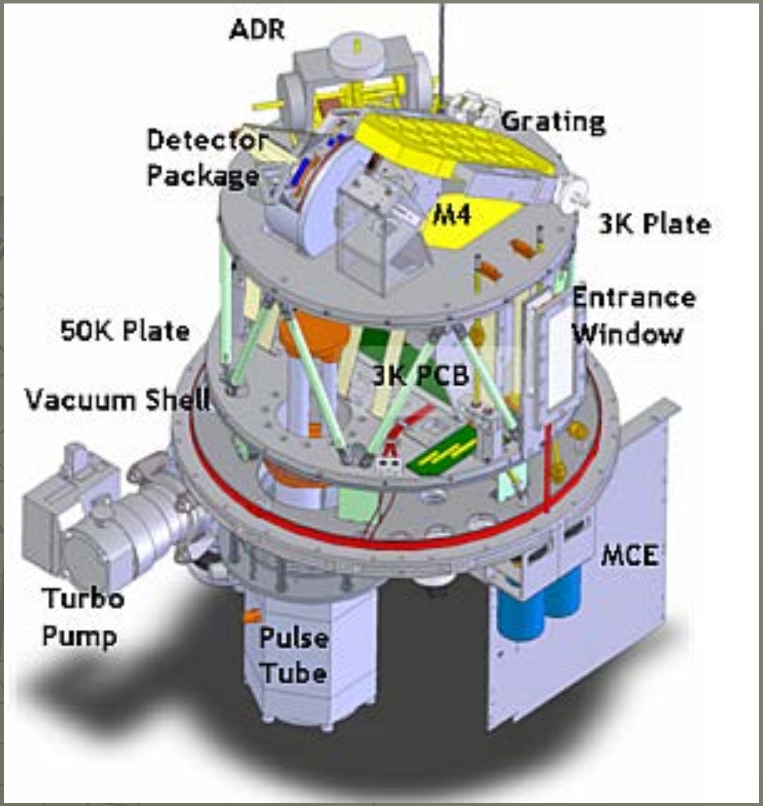
- Far-IR FS lines much more luminous than CO
- Redshift engine
- Diagnostics of physical conditions of gas and radiation fields
- Could cover submm – mm windows with 3 Z-spec like devices
- Simultaneous with dichroic optics

The Redshift (z) and Early Universe Spectrometer: ZEUS

S. Hailey-Dunsheath
Cornell PhD 2009

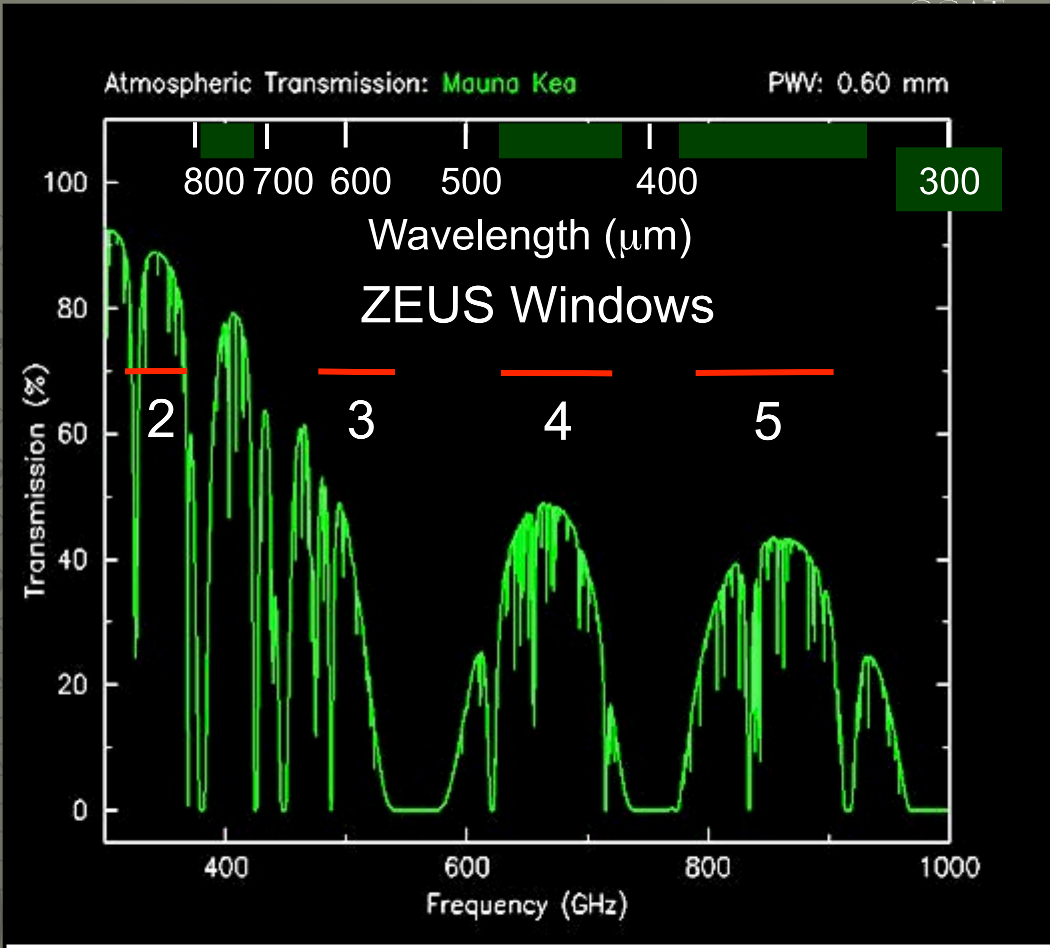
- "Free-Space" submm (650 and 850 GHz) grating spectrometer
  ◊R ≡ $\lambda/\Delta\lambda$ ~ 1000 ◊ BW ~ 20 GHz ◊ T_{rec}(SSB) < 40 K
- ZEUS on CSO for several years – single beam on the sky
- Upgrade to ZEUS-2 a
  - 5 color (200, 230, 350, 450, 610 μm bands);
  - ◊ 40 GHz Bandwidth ◊ 10, 9, & 5 beam system

ZEUS-2


ADR
Grating
Detector Package
M4
3K Plate
Entrance Window
50K Plate
3K PCB
Vacuum Shell
MCE
Turbo Pump
Pulse Tube

Design Choices

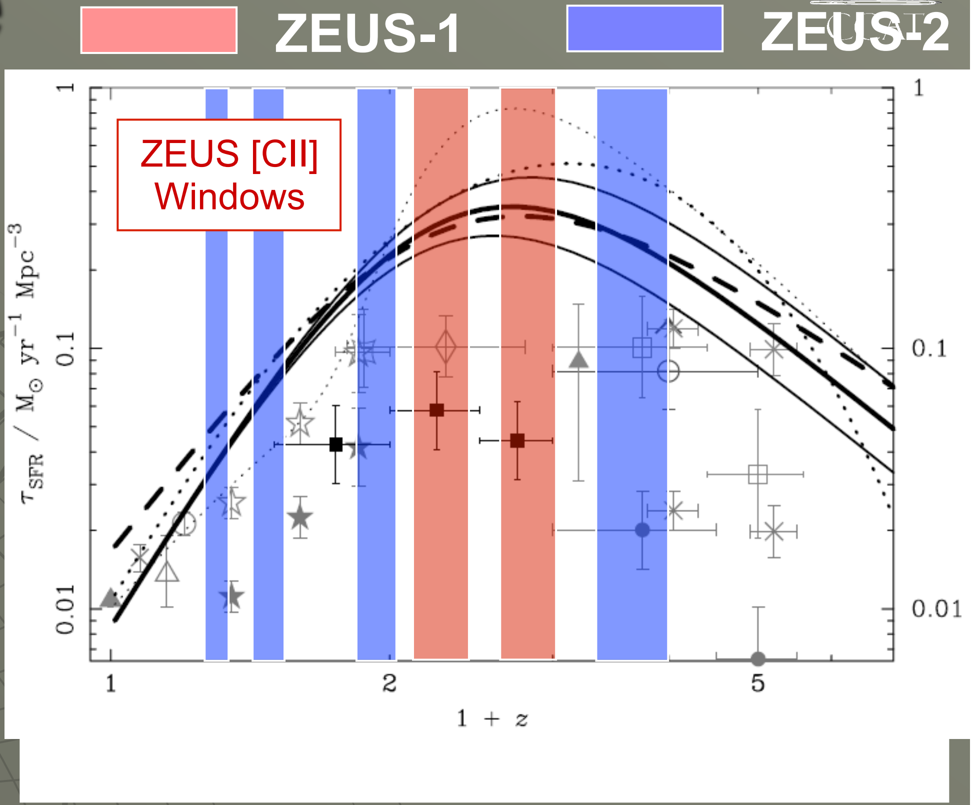
- Choose R ≡ λ/Δλ ~ 1000 optimized for detection of extragalactic lines
- Near diffraction limit:
  - Maximizes sensitivity to point sources
  - Minimizes grating size for a given R
- Long slit in ZEUS-2
  - Spatial multiplexing
  - Correlated noise removal for point sources
- Choose to operate in n = 2, 3, 4, 5, 9 orders which covers the 890, 610, 450, 350 and 200 μm windows respectively



ZEUS spectral coverage superposed on Mauna Kea windows on an excellent night

ZEUS-2 Traces [CII] Cooling Line

- 158 um [CII] line is dominant coolant of neutral ISM
- ZEUS can detect [CII] at z ~ 1 to 2 characterizing star formation in galaxies at the historic peak of star formation in the Universe
- ZEUS provides a unique opportunity to explore this epoch through the [CII] line
- Approximately 40% of the submm galaxy population has redshifts such that the [CII] line falls in the 350 (z ~ 1) or 450 (z~2) µm windows

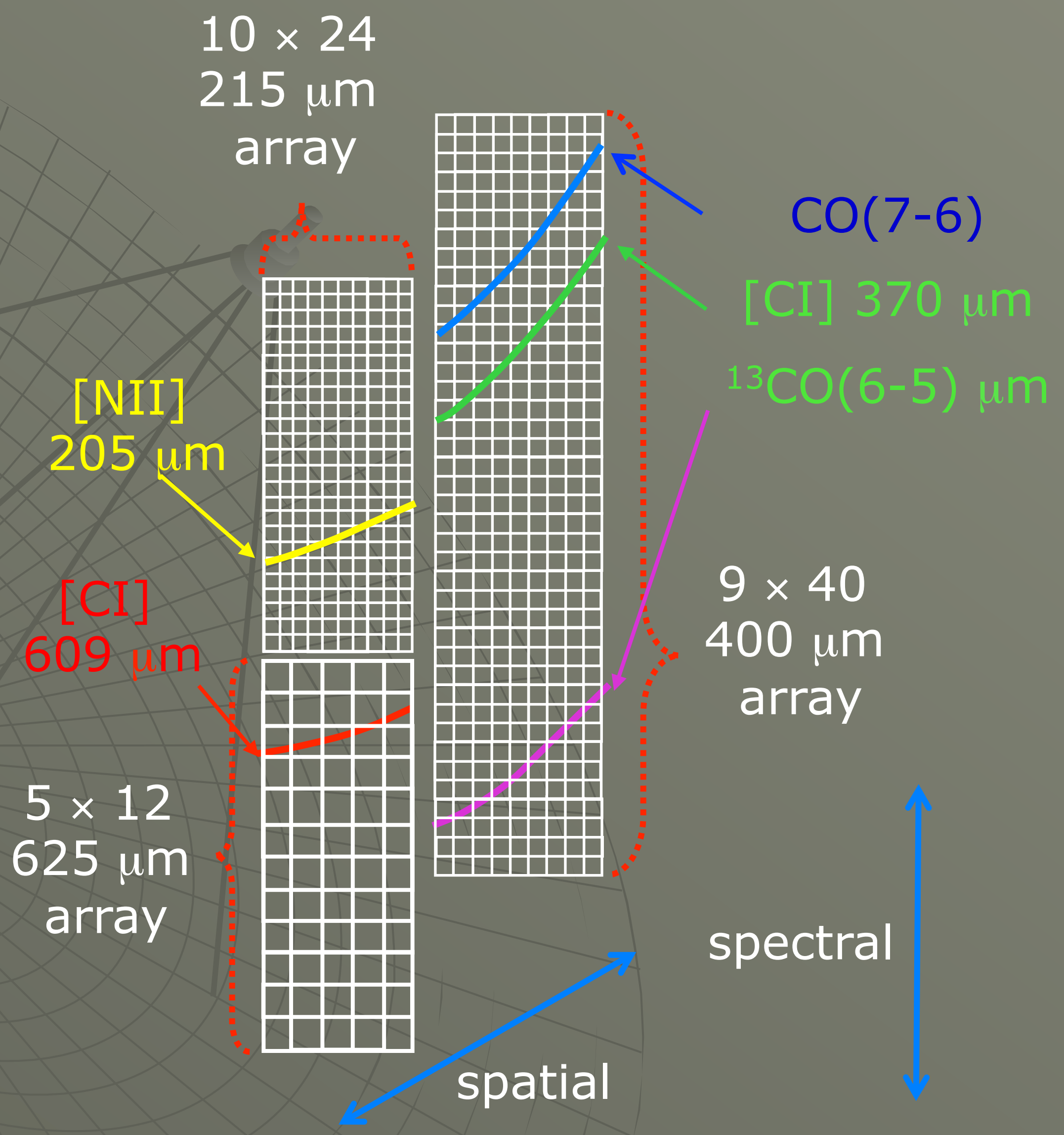


With ZEUS-2 on CSO and APEX we can extend these studies from z >4 to 0.25 -- tracing the history of star formation from 12 Gyr ago, through its peak 10 Gyr ago to the present epoch

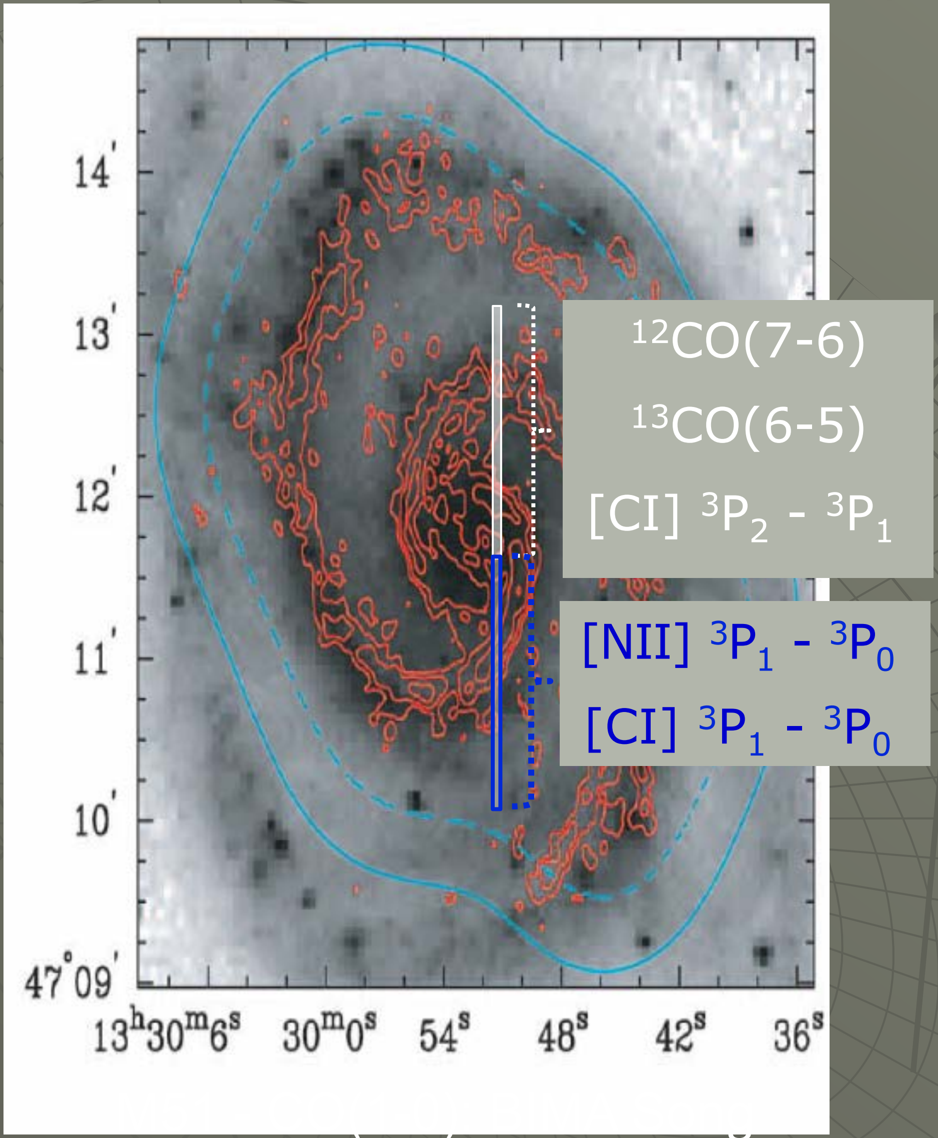
ZEUS-2 Focal Plane Array: Natural Spatial Multiplexing

CCAT

- Upgrading to (3) NIST 2-d TES bolometer arrays
- Backshort tuned
- 5 lines in 4 bands *simultaneously*
  - 215 μm (1.5 THz)
  - 350 μm (850 GHz)
  - 450 μm (650 GHz)
  - 625 μm (475 GHz)
- Imaging capability (9-10 beams)
- Simultaneous detection of [CII] and [NII] in z ~ 1-2 range
- *First light in Januar 2012 on CSO with 400 um array only*
- *APEX later in 2012*



Spectral Imaging Capabilities



(Helfer et al. 2003)

- Astrophysics
  - [CI] line ratio: Strong constraints on T
  - $^{13}CO(6-5)$ line: Strong constraints on CO opacity
  - [NII] line: Cooling of ionized gas, and fraction of [CII] from ionized media
- Mapping Advantages
  - Spatial registration "perfect"
  - Corrections for telluric transmission coupled
  - *Expected SNR for the five lines comparable*

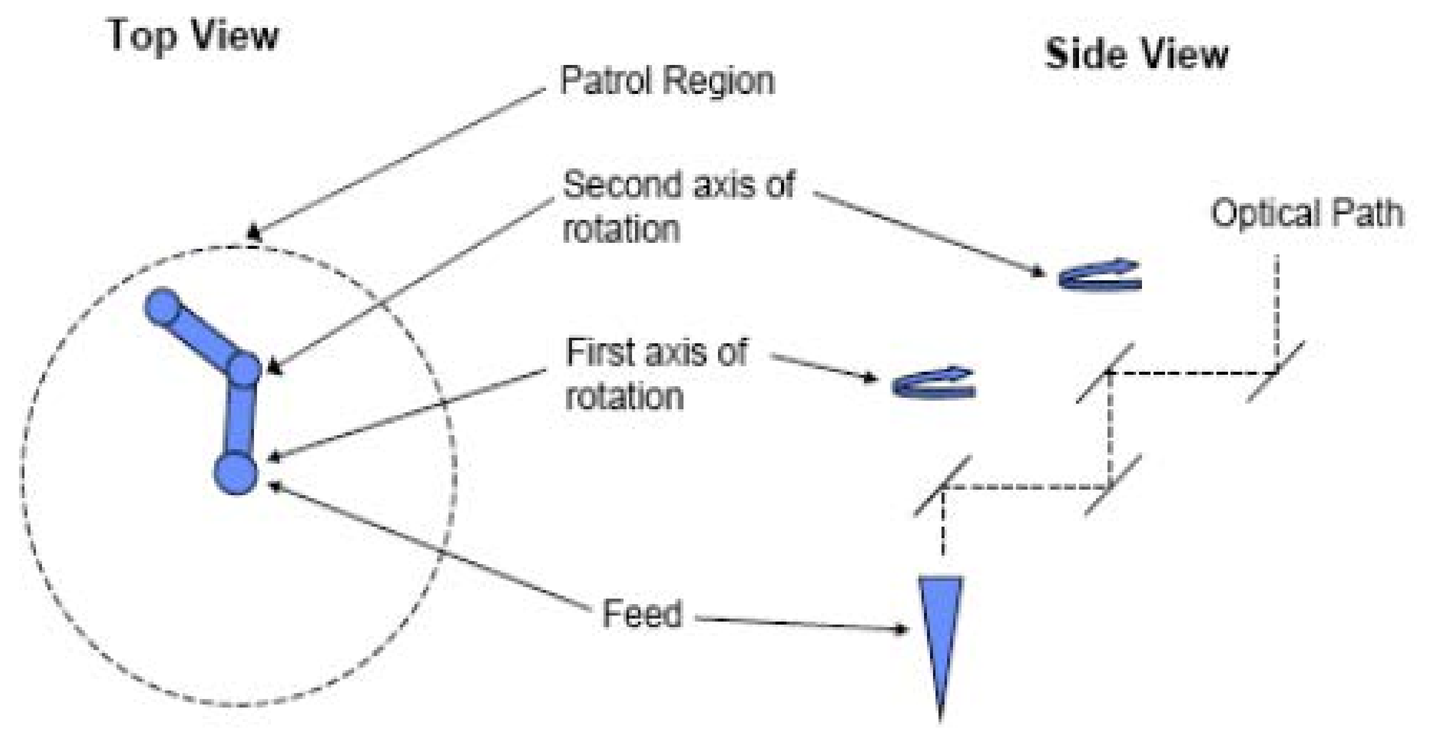
A Long Slit Free Space Spectrometer

- ZEUS-2 is in 5th order at 350 um - BW ~ 8%
- RP~1000 ⇒ 20 cm collimated beam ⇒ 0.6 m dewar
- Could build a 1st order free space grating spectrometer – BW 160%
- RP~1000 ⇒ 60 cm collimated beam ⇒1.5 to 1.8 m dewar
- Advantages
  - Flat focal plane
  - Transmits both polarizations
  - Beams “dense-packed” but readily adapted to multi-object spectroscopy

Multi-Object Spectrometers

- Free-space spectrometers like ZEUS-2 are trivially made into 1 (or 2) - d imaging systems, so it naturally becomes a multi-object spectrometer if we can “pipe” the light in.
- If configured in one band (say 350/450 μm), then the usable FoV of ZEUS-2 is > 20 beams
- To avoid source confusion, could configure with 10 feeds
- Z-Spec’s modularity also lends itself well to multi-beam configurations through stacking of the planar waveguides.

Light Pipes: Quasi-optical Approach



Goldsmith
and
Seiffert

- Periscope based Multi-Object Spectrometer
- Useful for observations of sources which have a low spatial density on the sky
- Patrol regions over the focal plane assigned to each receiver
- Low transmission losses since only four reflections

Confusion ⇒ [CII] = FIR Continuum Detection Limits

- ZEUS Survey of 24 – z ~ 1 to 2 galaxies shows [CII]/ FIR continuum ~ 0.2%
- Line/continuum ~ 10:1
- CCAT confusion limit: 1 mJy

⇒ 10 mJy in line × 1.9 THz/1000/(1+z)

or 1 × 10^{-19} W/m^2 – easily detectable (10σ/4hrs) with ZEUS – like spectrometers on CCAT

- An image slicer grating (IFU) spectrometer might well be quite useful – sources are crowded

Is CCAT Spectroscopy Really Necessary?

- CCAT will be the source finder for ALMA
    - Detect sources with CCAT continuum
    - Detect sources and redshifts in spectral lines with CCAT
    - Spatially (and spectrally) resolve lines with ALMA
    - CCAT spectrometers are competitive for line searches
        - Transparency and dish surface wins up to 2
        - System temperature wins a factor of 2 to 3
        - Bandwidth: 10 settings vs. 1 setting per window
        - 25 m dish vs. 12 m – wins a factor of 4
        - ∴ CCAT is equivalent to 2*2.5*4 = 20 antennas ⇒ takes $(64/20)^2$ = 10 times longer for CCAT, but CCAT covers entire band – ***so it comes out even***

But – CCAT will have multi-object spectrometers!

Summary

- CCAT's facility first light instruments will consist of:
  - Submm camera with > 50,000 pixels covering > 5' FoV
  - Mm-wave camera with > 50,000 pixels covering ~ 20' FoV
  - Multi-object broad band direct detection spectrometers
- In addition we expect other "contributions" including
  - Heterodyne receivers and arrays
  - Specialize direct detection spectrometers (e.g. IFU, FPI)
  - Polarimeters