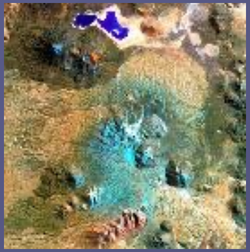
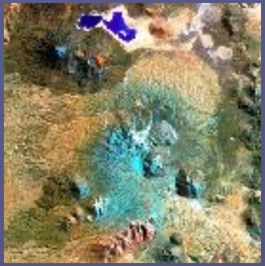


CCAT

Design, Science and SOFIA Synergy

Gordon Stacey
Cornell University



What is CCAT:

- A 25meter submillimeter telescope that will operate at wavelengths as short as $\lambda = 200\ \mu m$, an atmospheric limit.

Why 25m?

- Match ALMA sensitivity at submm regime
- Integration time to confusion at 350 um > 1 hr
- Better than 0.5" source positioning

- It will be located in a desert environment, at very high elevation (5600m, or 18400 ft)

- Designed for maximal synergy with ALMA

- It will take advantage of the fastest-developing detector technology of any spectral range, opening up the last, largely untapped frontier of ground-based astronomical research

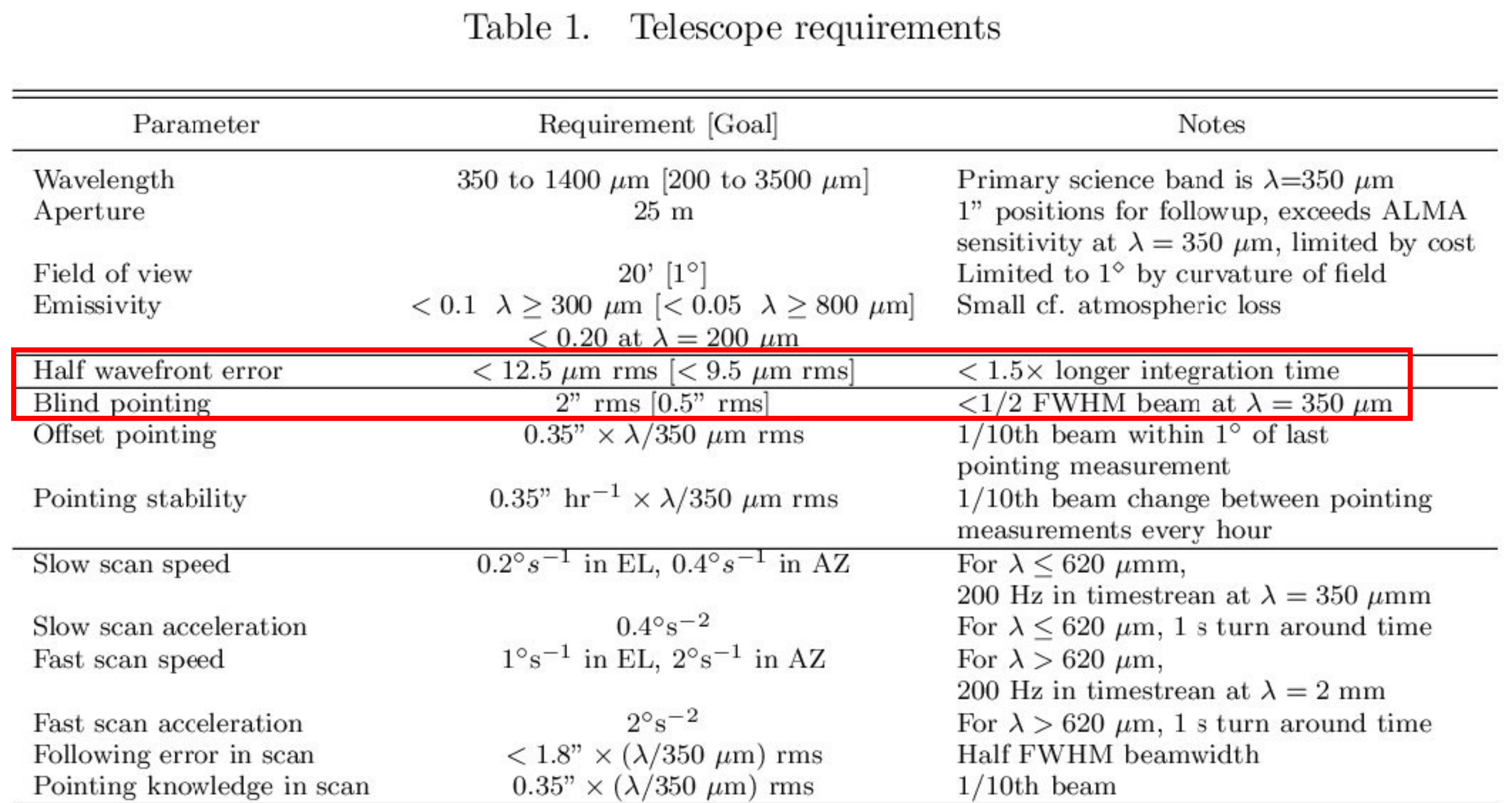
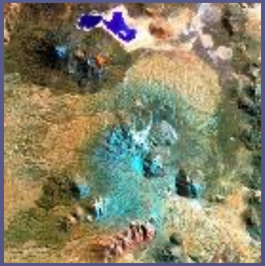


Table 1. Telescope requirements

Parameter	Requirement [Goal]	Notes
Wavelength	350 to 1400 μm [200 to 3500 μm]	Primary science band is λ=350 μm
Aperture	25 m	1" positions for followup, exceeds ALMA sensitivity at $\lambda = 350$ μm, limited by cost
Field of view	20' [1°]	Limited to 1° by curvature of field
Emissivity	< 0.1 $\lambda \geq 300$ μm [< 0.05 $\lambda \geq 800$ μm] < 0.20 at $\lambda = 200$ μm	Small cf. atmospheric loss
Half wavefront error	< 12.5 μm rms [< 9.5 μm rms]	$< 1.5\times$ longer integration time
Blind pointing	2" rms [0.5" rms]	$<$1/2 FWHM beam at $\lambda = 350$ μm
Offset pointing	0.35" $\times$ λ/350 μm rms	1/10th beam within 1° of last pointing measurement
Pointing stability	0.35" hr^{-1} $\times$ λ/350 μm rms	1/10th beam change between pointing measurements every hour
Slow scan speed	0.2°s^{-1} in EL, 0.4°s^{-1} in AZ	For $\lambda \leq 620$ μmm, 200 Hz in timestrean at $\lambda = 350$ μmm
Slow scan acceleration	0.4°s^{-2}	For $\lambda \leq 620$ μm, 1 s turn around time
Fast scan speed	1°s^{-1} in EL, 2°s^{-1} in AZ	For $\lambda > 620$ μm, 200 Hz in timestrean at $\lambda = 2$ mm
Fast scan acceleration	2°s^{-2}	For $\lambda > 620$ μm, 1 s turn around time
Following error in scan	< 1.8" $\times$ (λ/350 μm) rms	Half FWHM beamwidth
Pointing knowledge in scan	0.35" $\times$ (λ/350 μm) rms	1/10th beam



What is CCAT:

- A 25meter submillimeter telescope that will operate at wavelengths as short as λ = 200 micron, an atmospheric limit.

Why 25m?
- Match ALMA sensitivity at submm regime
- Integration time to confusion at 350 um > 1 hr
- Better than 0.5" source positioning

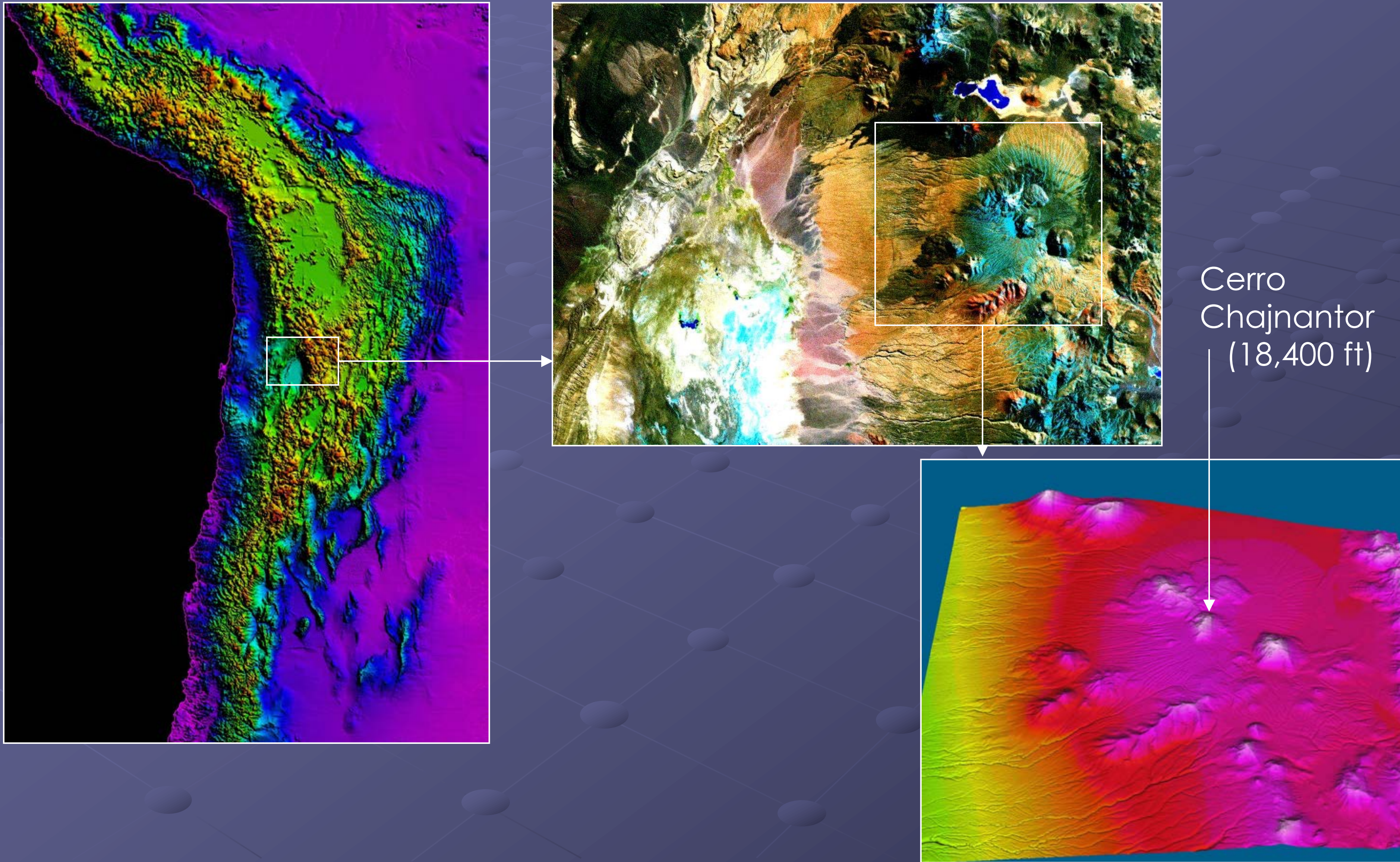
- It will be located in a desert environment, at very high elevation (5600m, or 18400 ft)

- Good fraction of time with PWV<0.5mm

- Designed for maximal synergy with ALMA

- It will take advantage of the fastest-developing detector technology of any spectral range, opening up the last, largely untapped frontier of ground-based astronomical research

At the driest, high altitude site you can drive a truck to



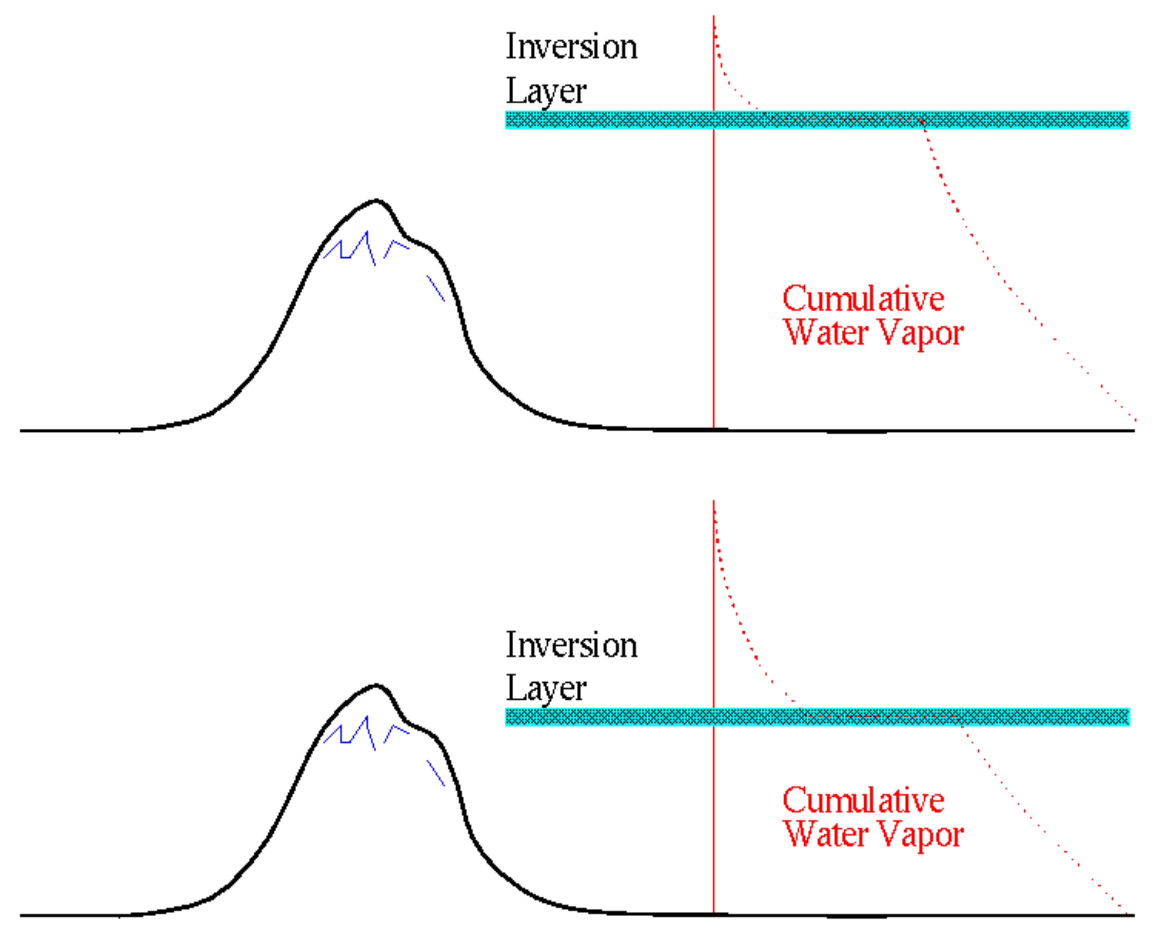
Cerro Chajnantor (18,400 ft)

Is it really worth going just (!)
2000 ft (13%)
higher than ALMA?

A little gain in PWV by going to summit

PWV=precipitable water vapor

B most PWV below summit; great gain by going to summit



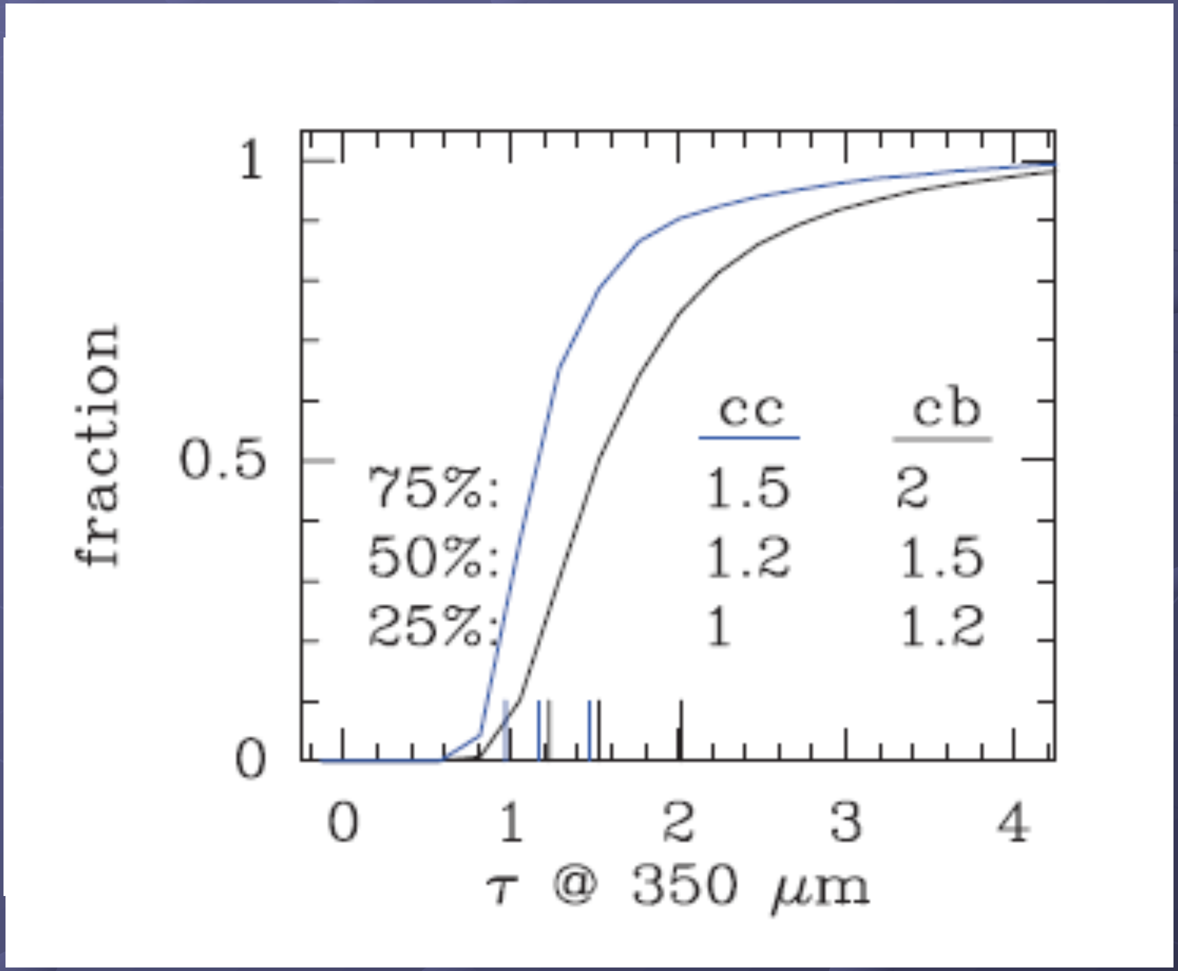
T-inversion layers form above extended plateaus. Much of the PWV gets trapped under them.
Is it worth focusing on surrounding summits?
YES! if case B occurs a fair fraction of the time.

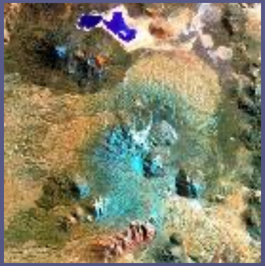
Median WV Distribution over Chajnantor

From radiosondes:

The median WV scale height Is h=1.135 km

However, it becomes shallower at night…





What is CCAT:

- A 25meter submillimeter telescope that will operate at wavelengths as short as $\lambda = 200$ micron, an atmospheric limit.

Why 25m?
- Match ALMA sensitivity at submm regime
- Integration time to confusion at 350 um > 1 hr
- Better than 0.5" source positioning

- It will be located in a desert environment, at very high elevation (5600m, or 18400 ft)

- Good fraction of time with PWV<0.5mm

- Designed for maximal synergy with ALMA

- Wide FoV; fast surveyor

- It will take advantage of the fastest-developing detector technology of any spectral range, opening up the last, largely untapped frontier of ground-based astronomical research

Synergy with ALMA

ALMA will deliver very high spatial resolution, but only over a very small Field of View:

➔ Will reveal fine detail, ONE SOURCE at a time

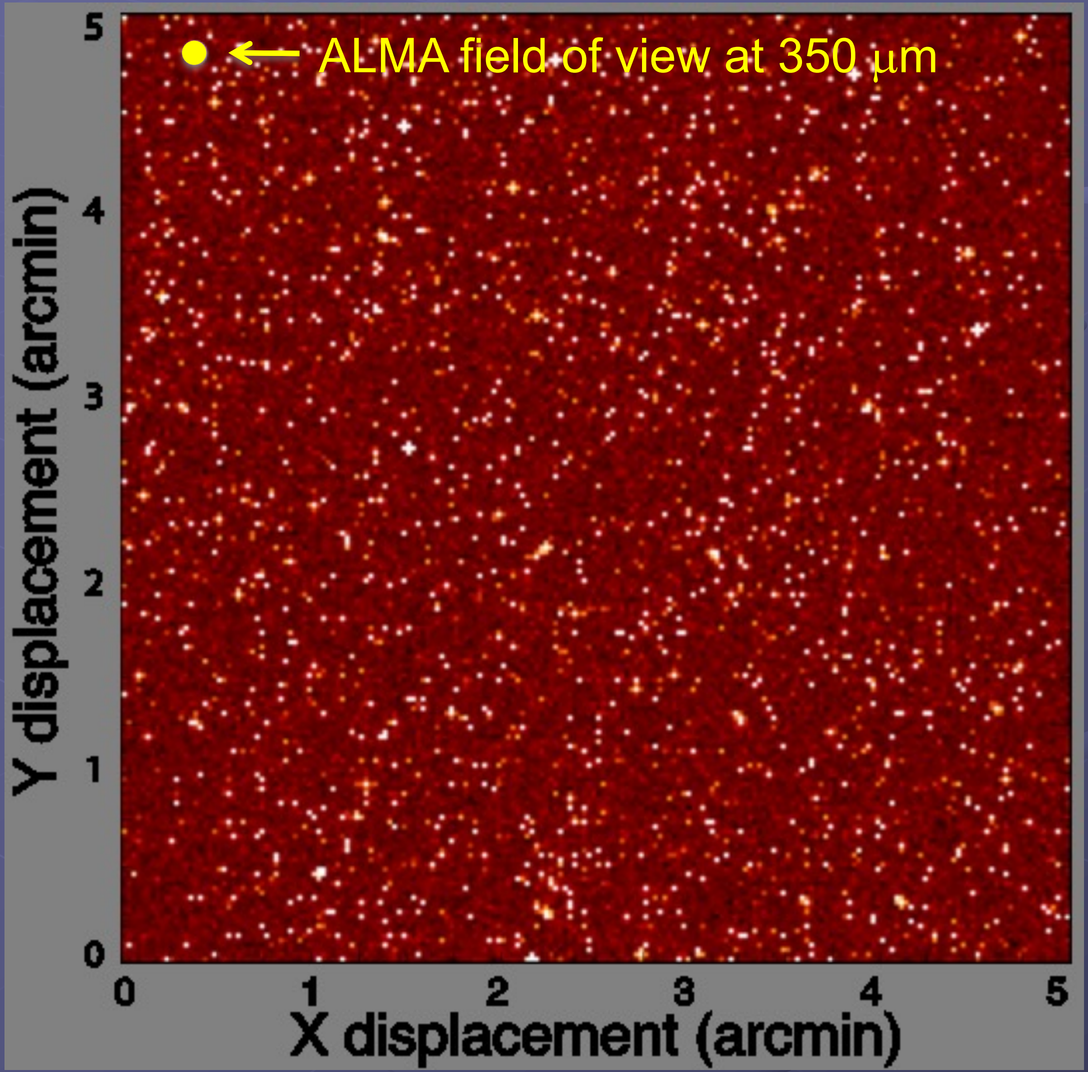
CCAT will not match ALMA in angular resolution; it will however match it in sensitivity and will have a Field of View > 240,000 times larger

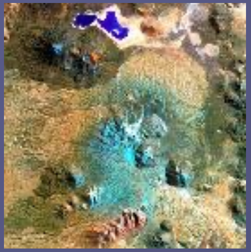
➔ Fast Surveyor (MANY objects at a time)

Large scale projects coordinated between the two facilities?

CCAT & ALMA

CCAT's instantaneous field of view (350 μm, 48 kpix 1st light camera)





Who is CCAT?

A joint project of Cornell University,
the California Institute of Technology
the University of Colorado,
the Universities of Waterloo & British Columbia,
the Universities of Bonn & Cologne,
and Associated Universities, Inc.
…

Brief Timeline-1

• 2003 :	Cornell invites Caltech to dance, Workshop in Pasadena
• 2004:	MOU signed by Caltech and Cornell, Project Office established, Feasibility Study
• 2006:	Feasibility Study Review

Feasibility Study Review

Review Panel:
- Robert Wilson (Harvard-Smithsonian, Chair)
- Mark Devlin (Penn)
- Fred Lo (NRAO)
- Matt Mountain (STScI)
- Peter Napier (NRAO)
- Jerry Nelson (UCSC)
- Adrian Russell (ALMA, NA)

> "CCAT is an important and timely project that will make fundamental contributions to our understanding of the processes of galaxy, star and planetary formation, both on its own and through its connection with ALMA. It should not wait."

Brief Timeline-2

2003 :	Cornell invites Caltech to dance, Workshop in Pasadena
2004:	MOU signed by Caltech and Cornell, Project Office established, Feasibility Study
2006:	Feasibility Study Review
2006-2010:	Expand partnership, finalize site selection, review high risk issues, initiate engineering design, consolidate consortium, Astro2010
2010-2013:	Engineering Design Phase, Critical Design Rev.
2013-2017:	Construction → First light

Friday the 13th of August brings good news from Astro2010

New Worlds, New Horizons in Astronomy and Astrophysics

Committee for a Decadal Survey of Astronomy and Astrophysics

National Research Council

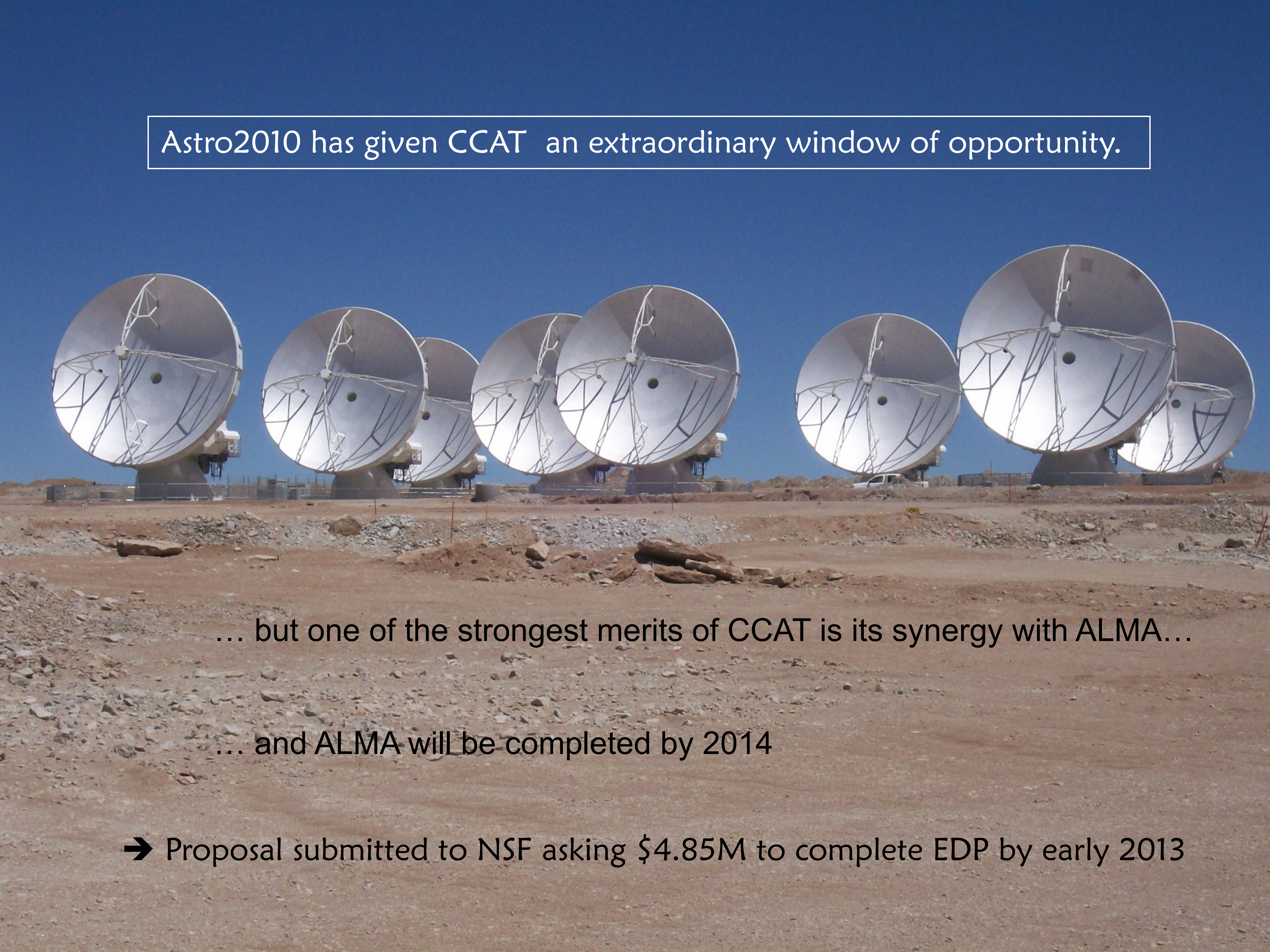
Quoting Astro2010:

The Section Recommendations for New Ground-Based Activities - Medium Projects, page 7-37, starts with:

"Only one medium project is called out, because it is ranked most highly. Other projects in this category should be submitted to the Mid-Scale Innovations Program for competitive review."

The one project is CCAT.

In pages 1-12 and 7-38: *"CCAT is called out to progress promptly [. . .] because of its strong science case, its importance to ALMA and its readiness."*



Astro2010 has given CCAT an extraordinary window of opportunity.

… but one of the strongest merits of CCAT is its synergy with ALMA…

… and ALMA will be completed by 2014

➔ Proposal submitted to NSF asking $4.85M to complete EDP by early 2013

CCAT Cost

CCAT was asked to provide Astro2010 detailed information to be used for the CATE process carried out by the Aerospace Corp.

Their estimates of the cost and time to completion of construction were higher than the project team's:

➔ $140M vs. $110M

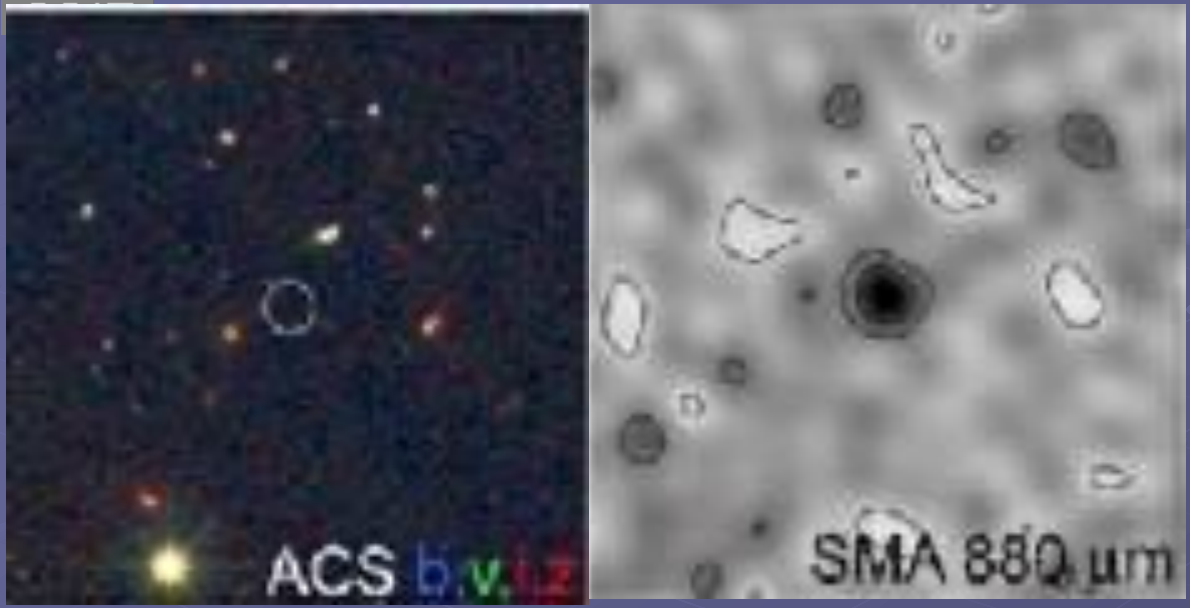
➔ 2020 vs. 2017

Engineering Design Phase goal: reduce error in estimate

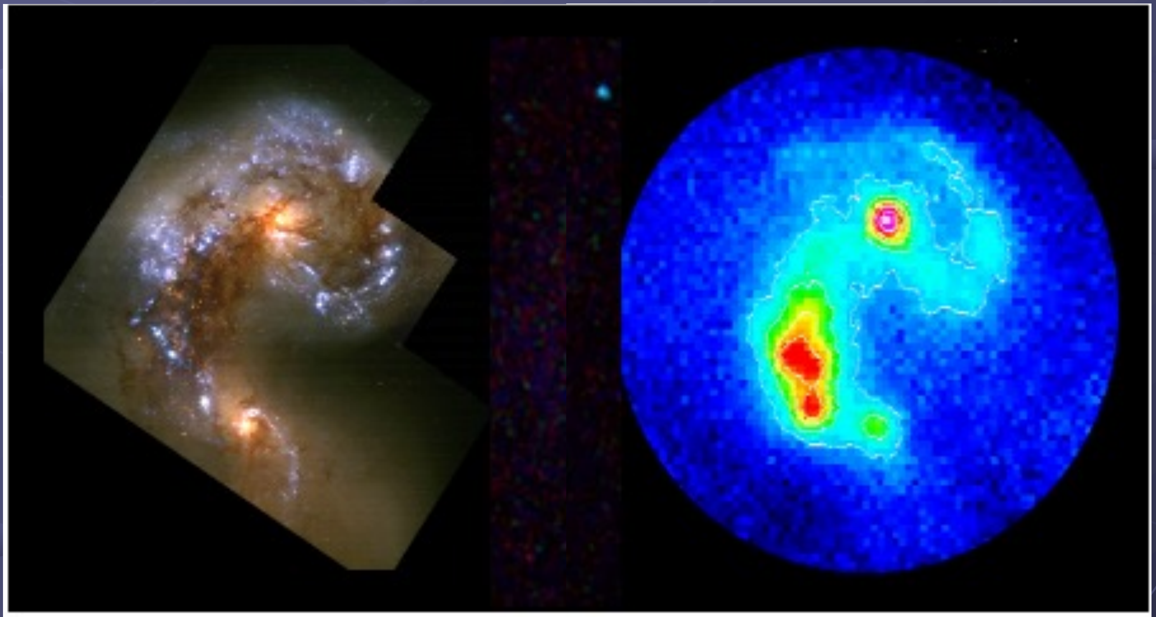
Over last 5 yr the CCAT project $ burn rate has been $1-2M/yr,
adding up to > $6.7M,
fully funded by partners.

Scientific Motivation for CCAT

The Universe is Dusty



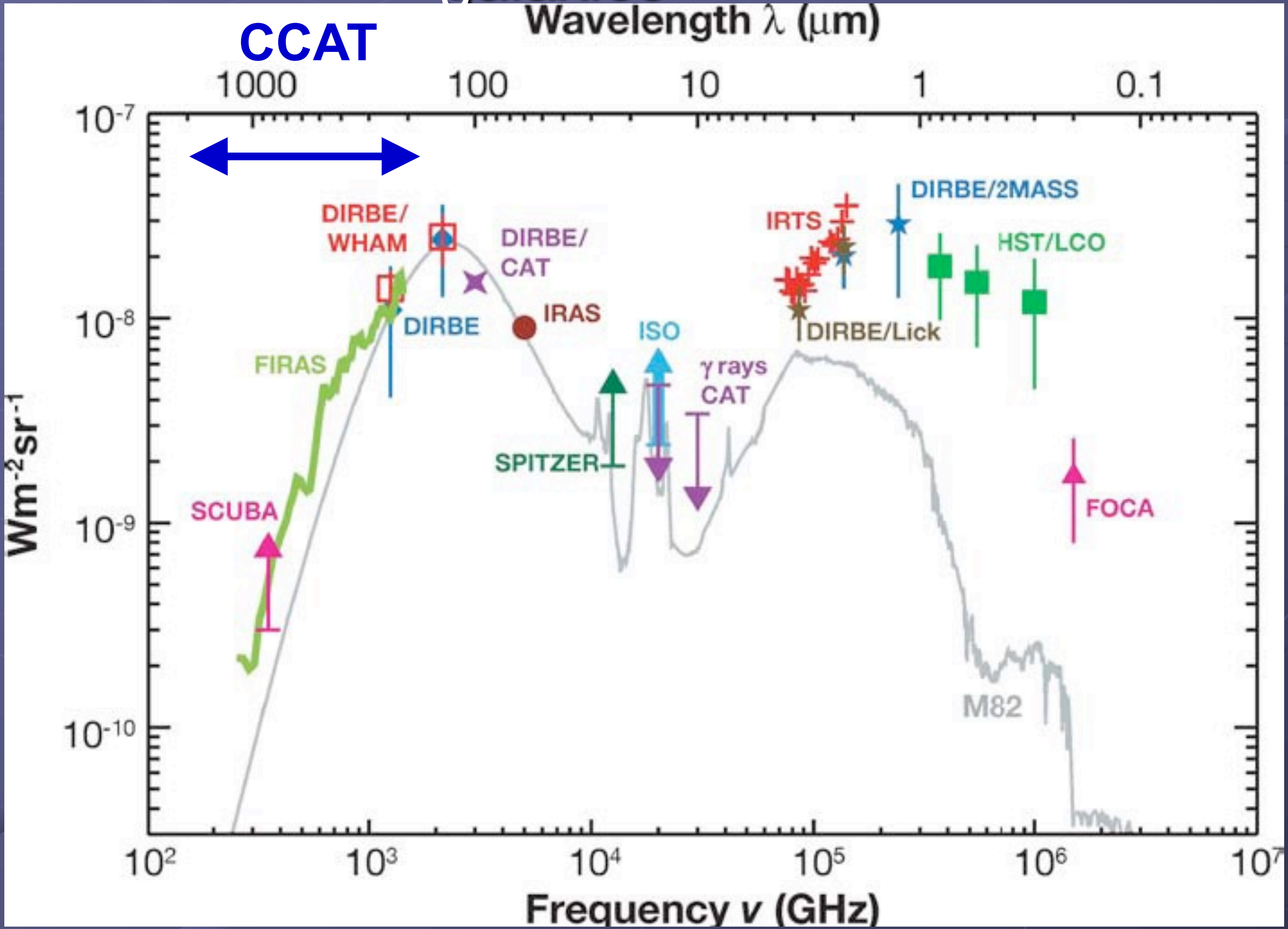
Goods 850-5 (z=4.1) in optical (Hubble, left) and submm (SMA, right)



Antenna Optical (Hubble, left) and submm (SHARC/CSO, right)

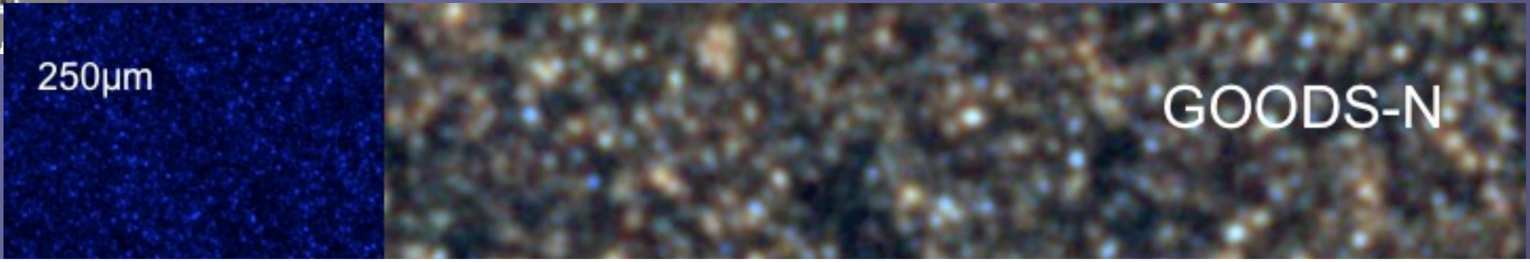
It is so dusty that half the energy of stars integrated over the history of the universe is reprocessed by dust into the far-IR submm bands!
Throughout cosmic time, stars formed in dust obscured galaxies

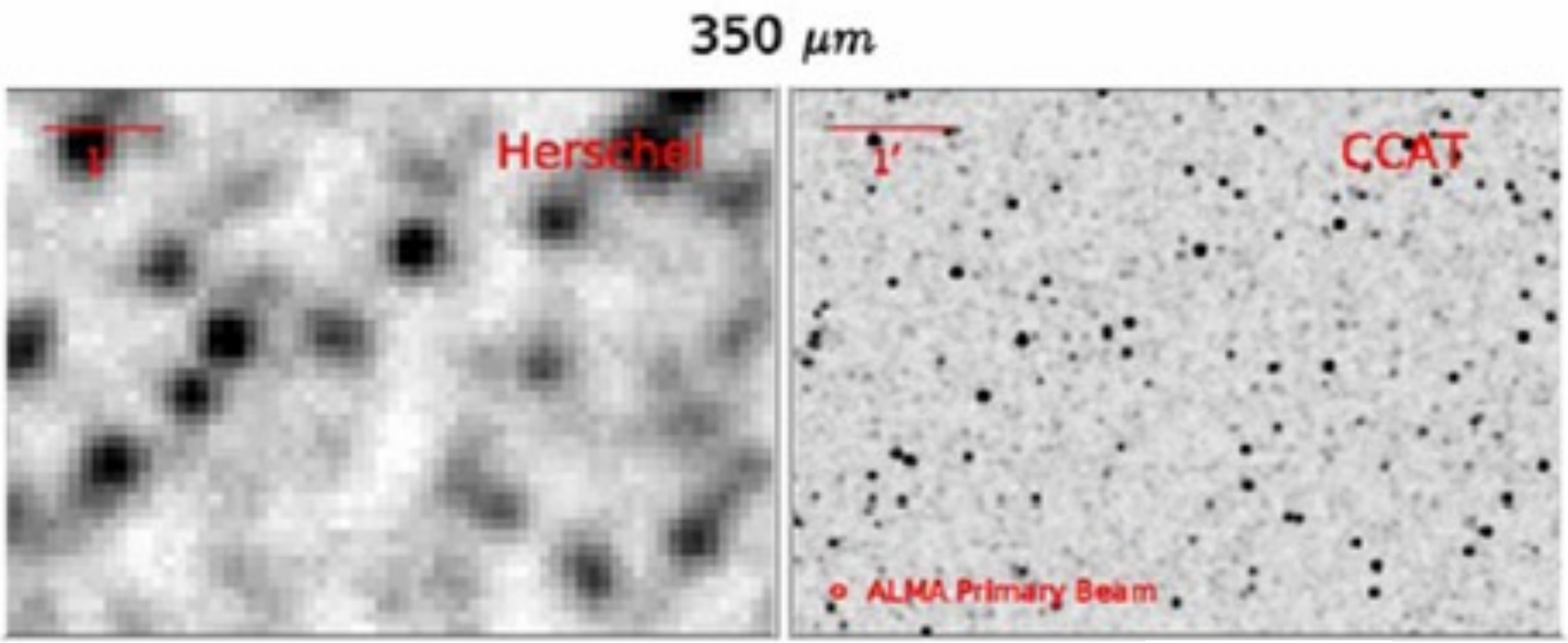
COBE (1996)



Lagache,
Puget, &
Dole 2005

The Universe is Confused

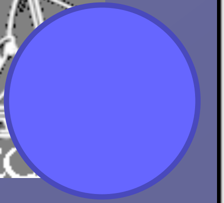




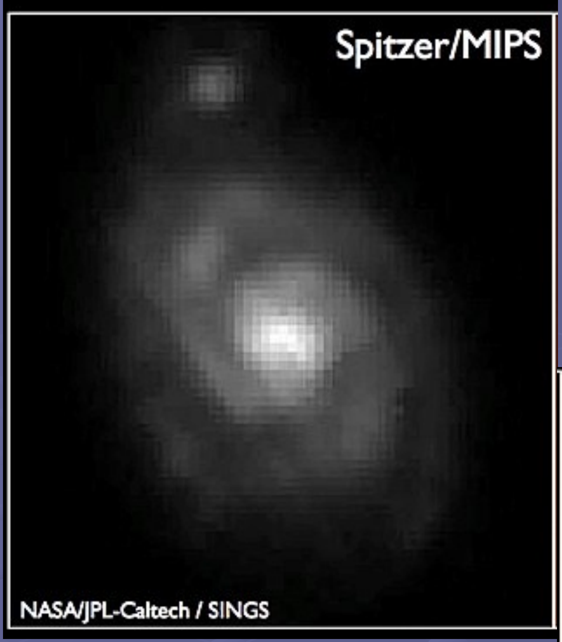
P. Maloney

Herschel/SPIRE

Bigger *IS* better

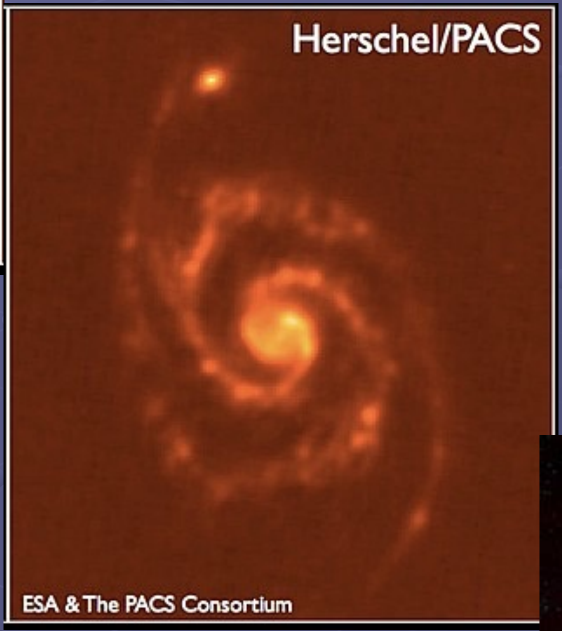


Herschel



NASA/JPL-Caltech / SINGS

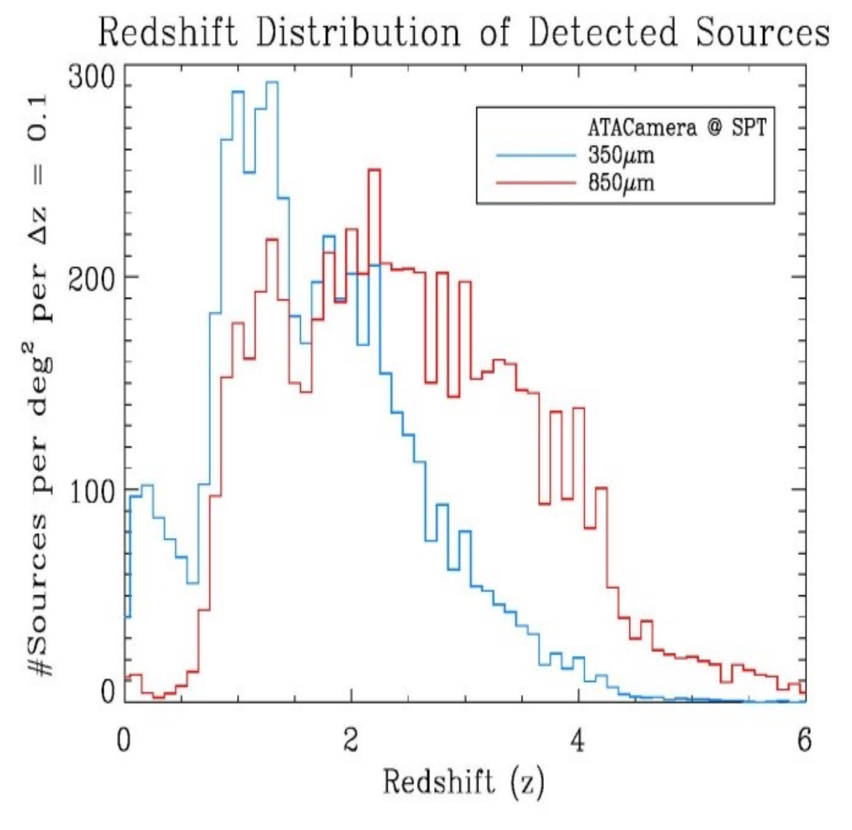
CSO/SPT/JCMT



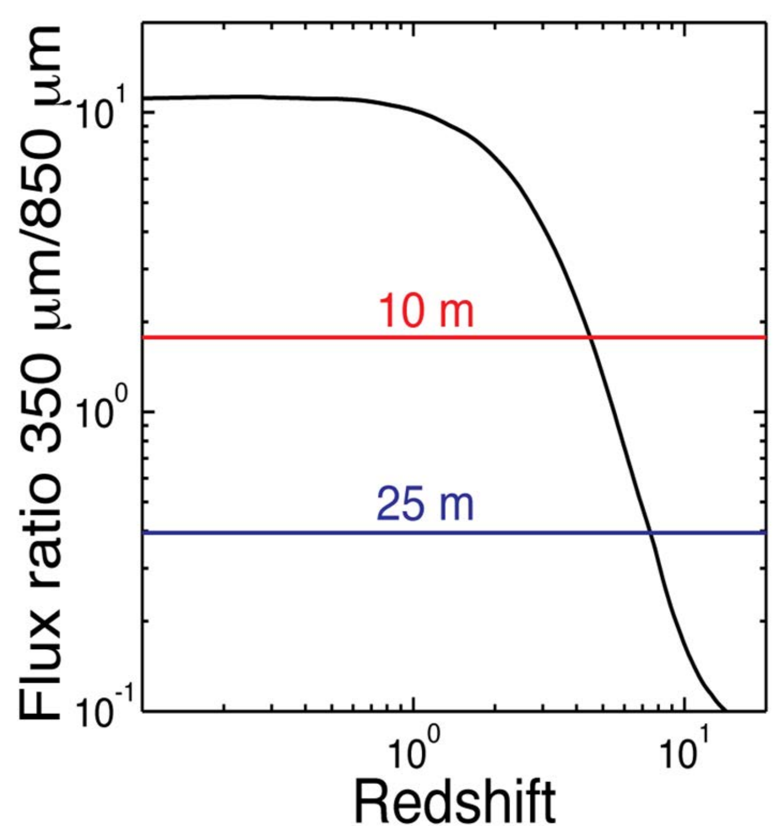
ESA & The PACS Consortium

CCAT

Most Distant is Better Still...

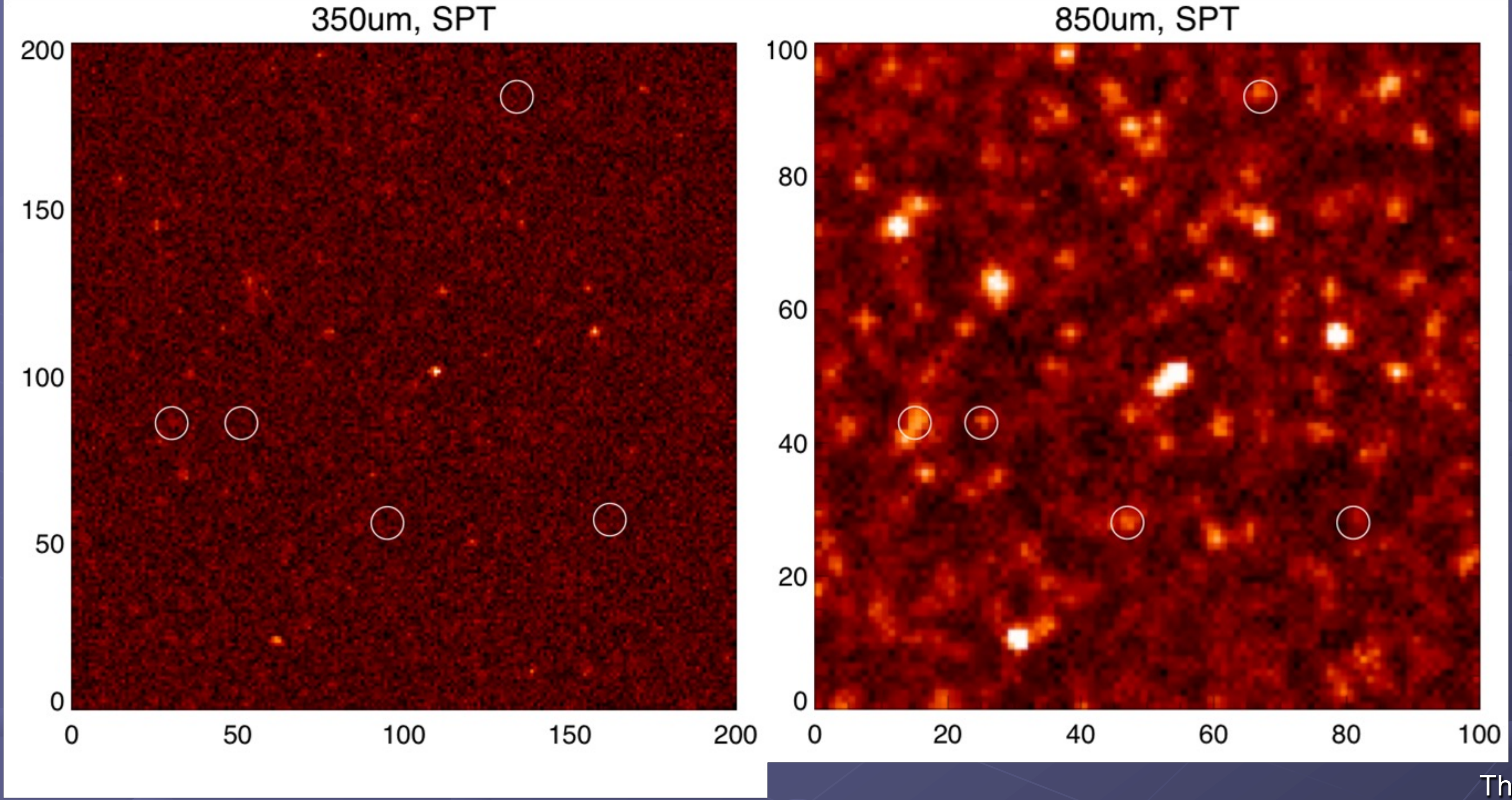


Redshift distribution of sources for ATACamera on SPT at 350 and 850 μm.



350/850 μm flux density ratio for a $10^{12} L_\odot$ galaxy as a function of redshift.

To find the distant ones, look for drop-outs



- Simulated ATACamera on SPT at 350 and 850 μm – 4 hours/pixel
- Circled sources: >5 σ detections at 850 μm that drop out at 350 μm
- There are the 85 - 350 μm drop-outs in the image.

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

Baseline CCAT Instrumentation

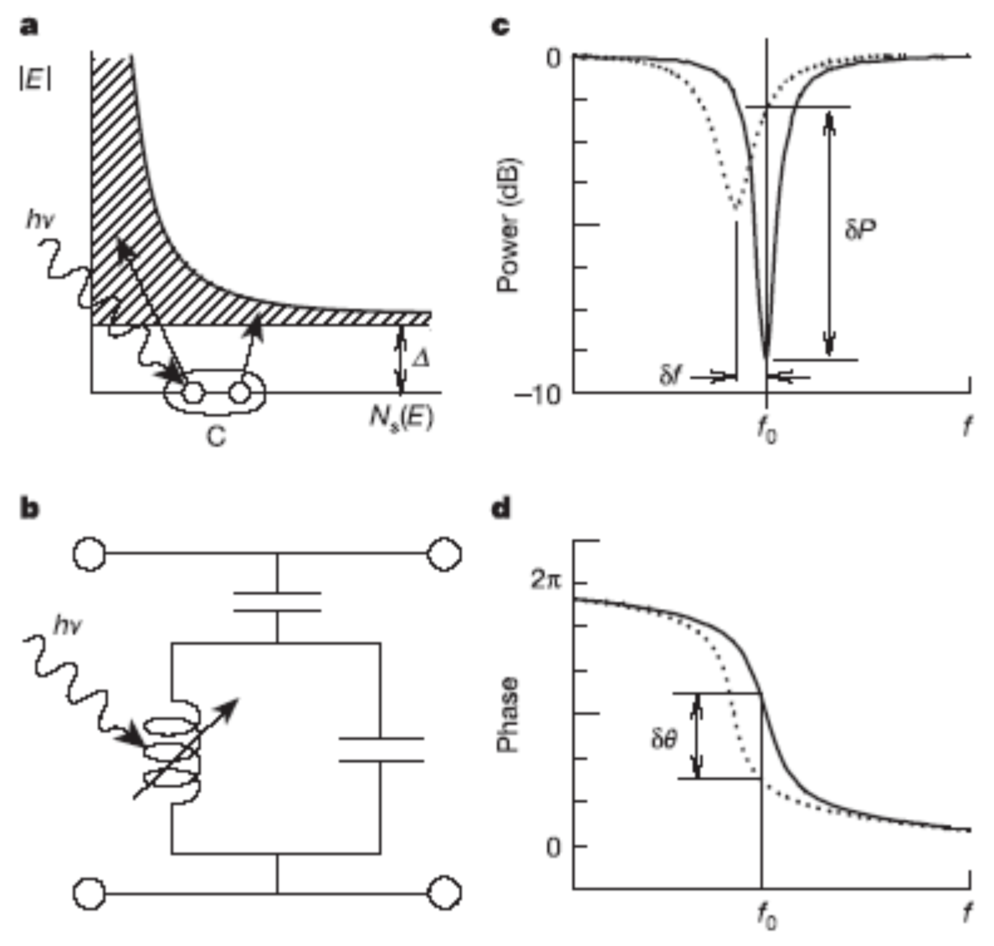
- Three Primary Science Instruments
  - Submillimeter wave camera
  - Near millimeter wave camera
  - Multi-object direct detection spectrometer
    - Z-spec
    - ZEUS/ZEUS-2
  - Transferred, and future instrumentation
    - Full FoV cameras
    - Heterodyne spectrometers/arrays

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
- Detectors likely MKID arrays
- Advanced Technology Array Camera

ATACamera

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

Predicted Sensitivity

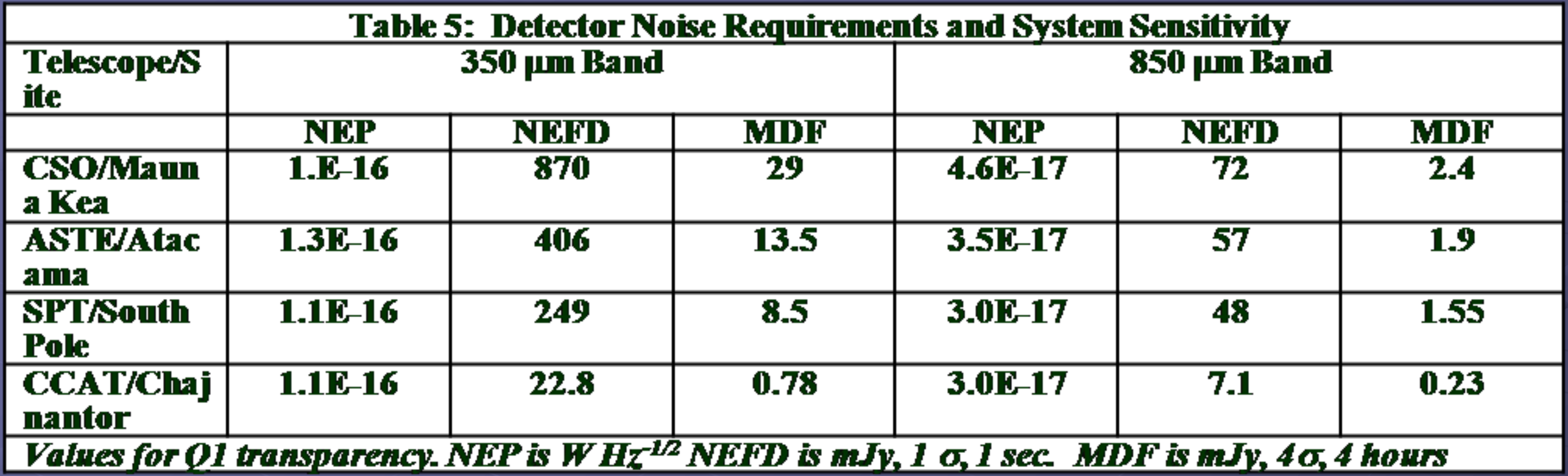


Table 5: Detector Noise Requirements and System Sensitivity

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

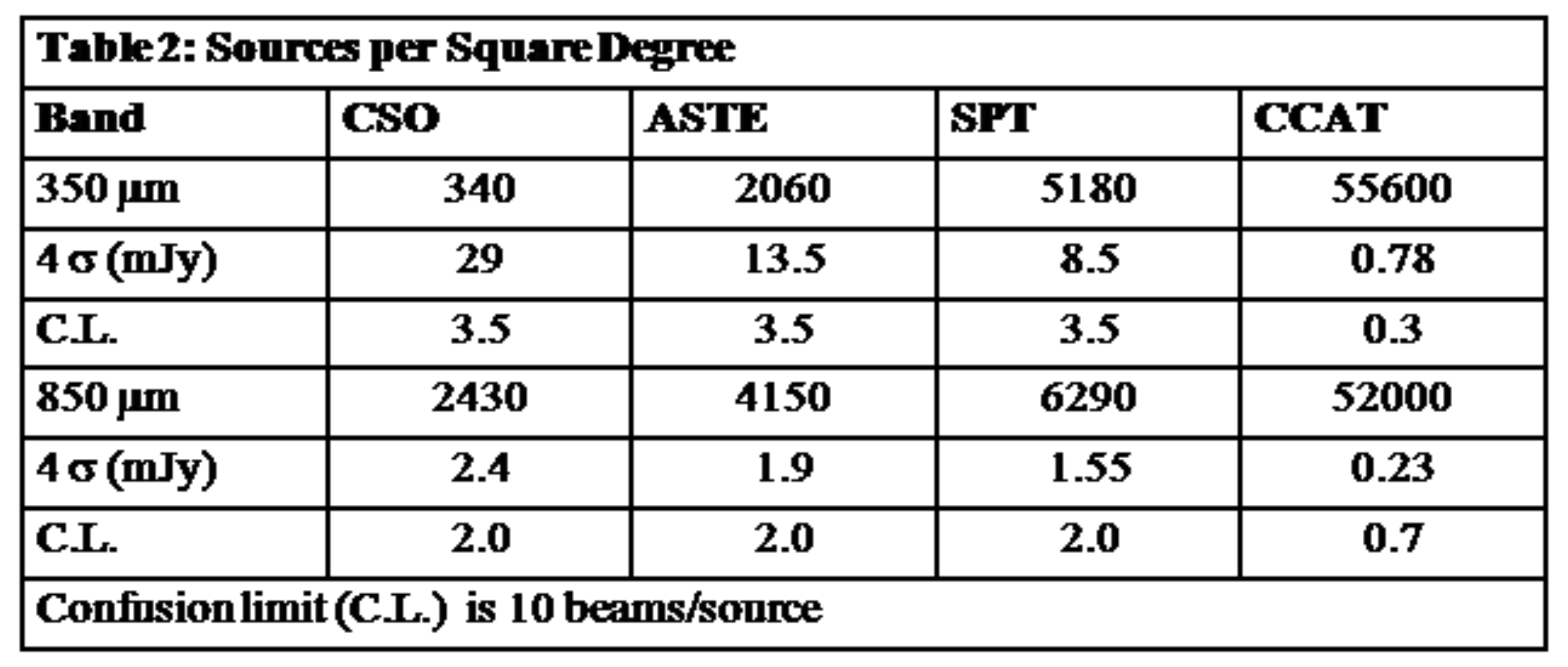


Table 2: Sources per Square Degree

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

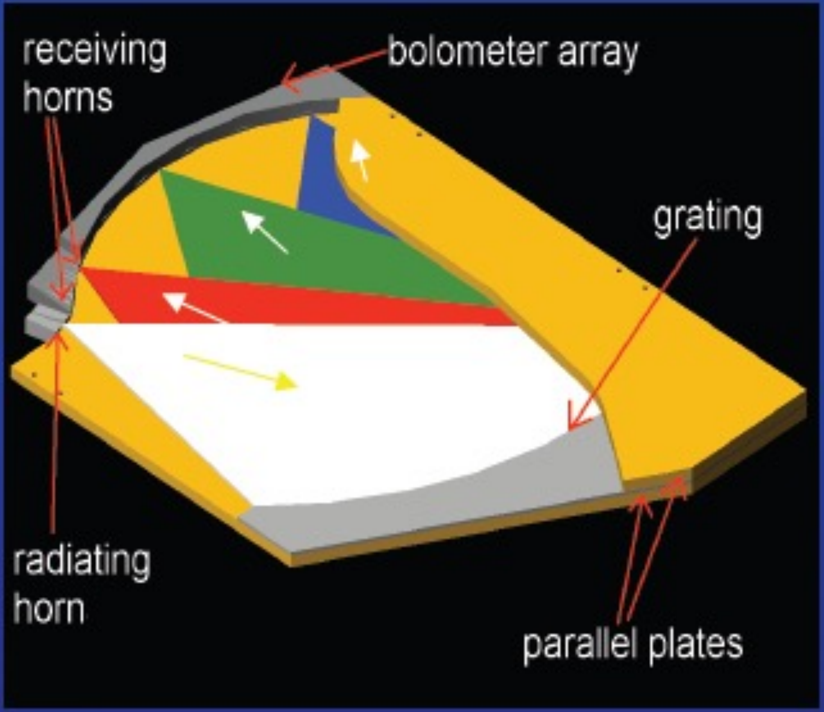
Transmillimeter Wave Camera –Sunil Golwala

- Low wavelength Camera for CCAT
- Antenna-coupled arrays of bolometers
  - 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

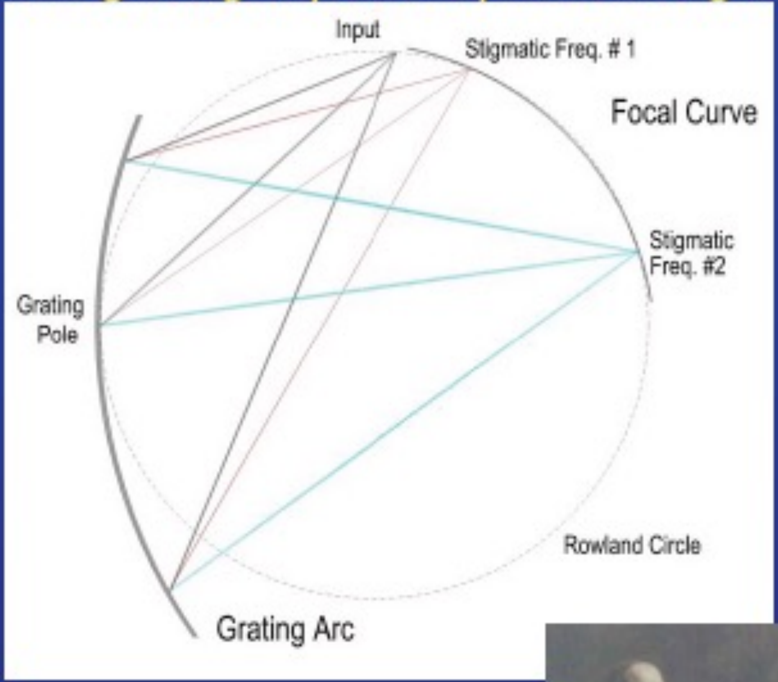
Direct Detection Spectrometers

- 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

Compact Waveguide Spectrometer: Z-spec



curved grating in parallel plate waveguide



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

- 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

Z-Spec as a Redshift Engine

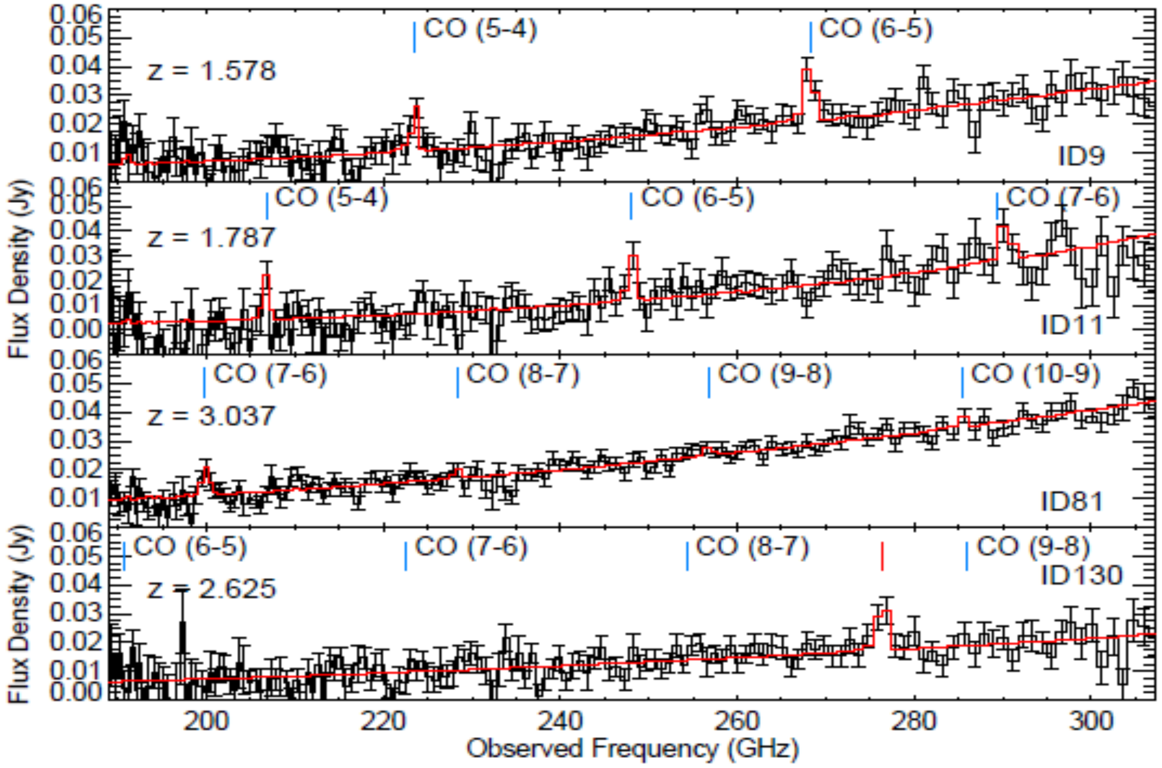


Fig. 1.— The Z-Spec spectra of four submillimeter bright H-ATLAS galaxies. The fit to the continuum and CO lines at the measured redshift is overplotted in red, and the positions of the strongest lines falling in the Z-Spec bandpass are indicated by the vertical blue lines. The line indicated in red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

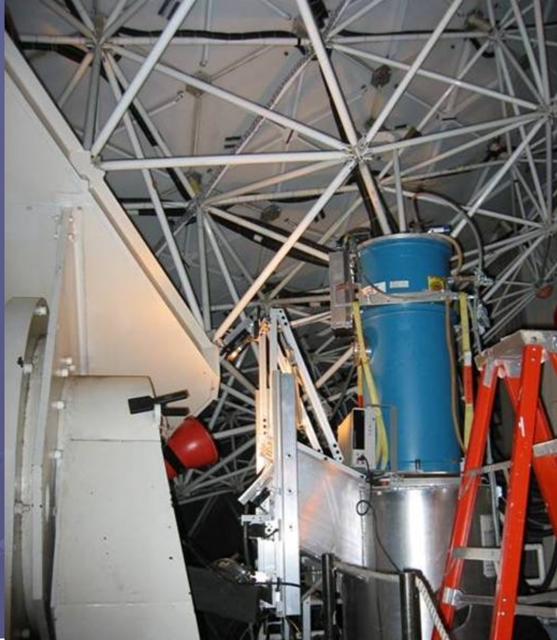
- Broad bandwidth is very useful for determining redshifts of submm galaxies
- Observed (redshifted) spacing between CO rotational lines given by:

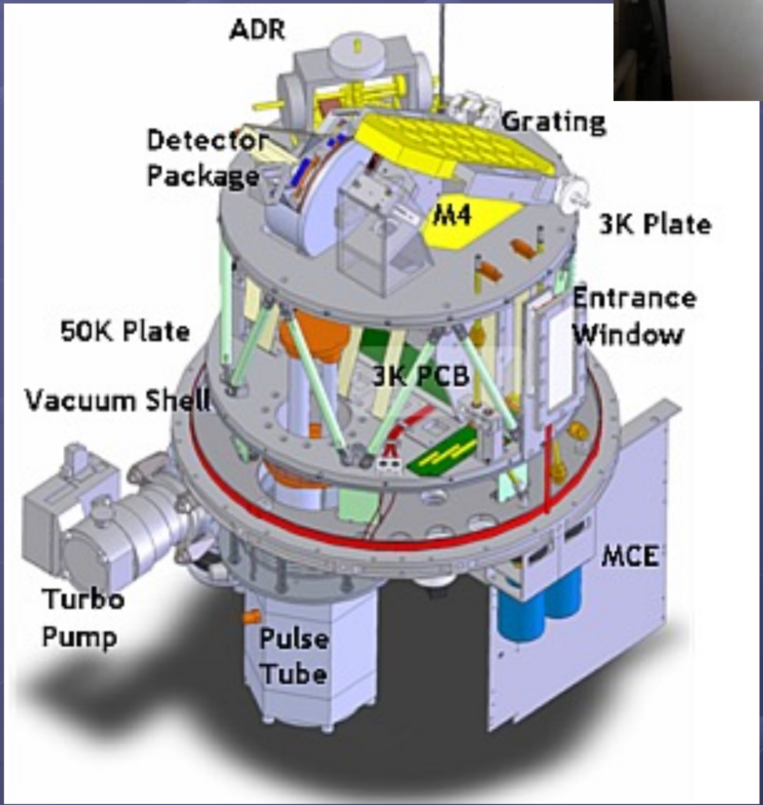
$\Delta\nu$ = 115 GHz/(1+z)

Lupu et al. 2010

Free-space Spectrometers: ZEUS and ZEUS-2

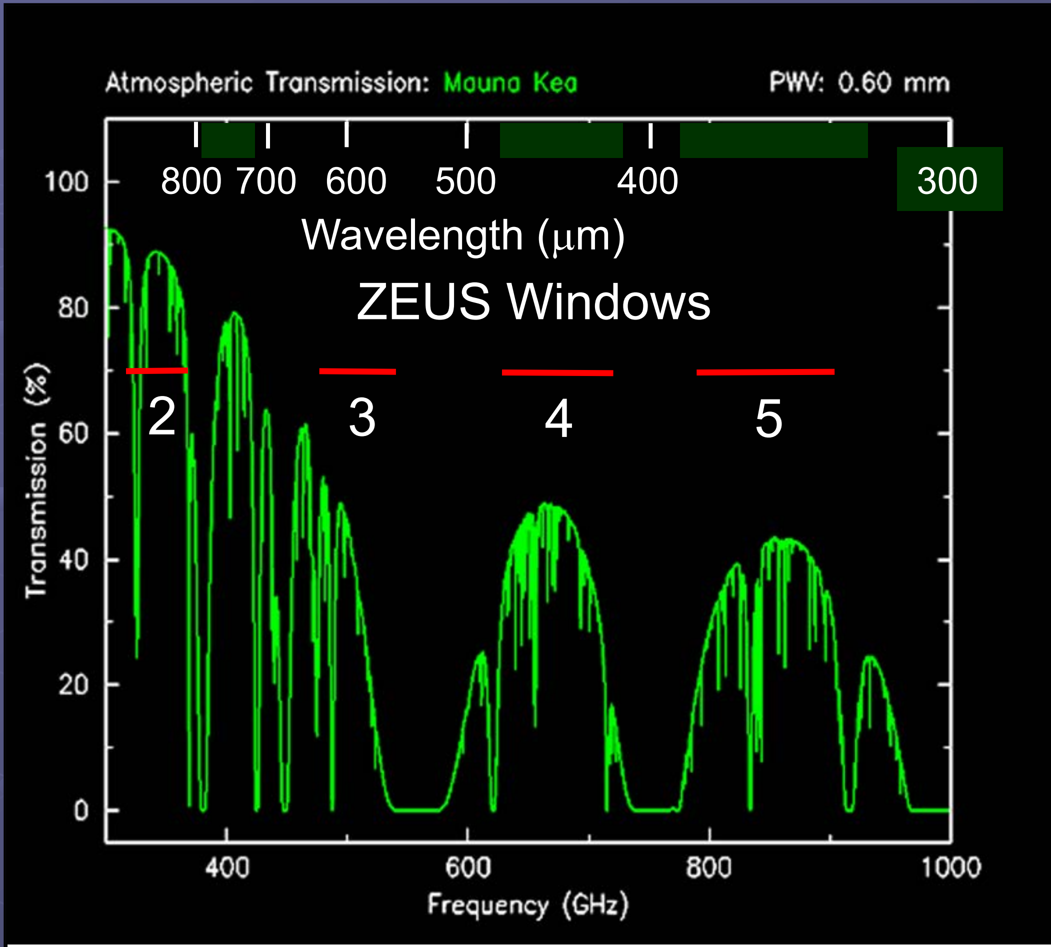
- $R \sim 1000$
- 40 GHz BW
- $T_{rec} < 40$ K (SSB)





Design Choices

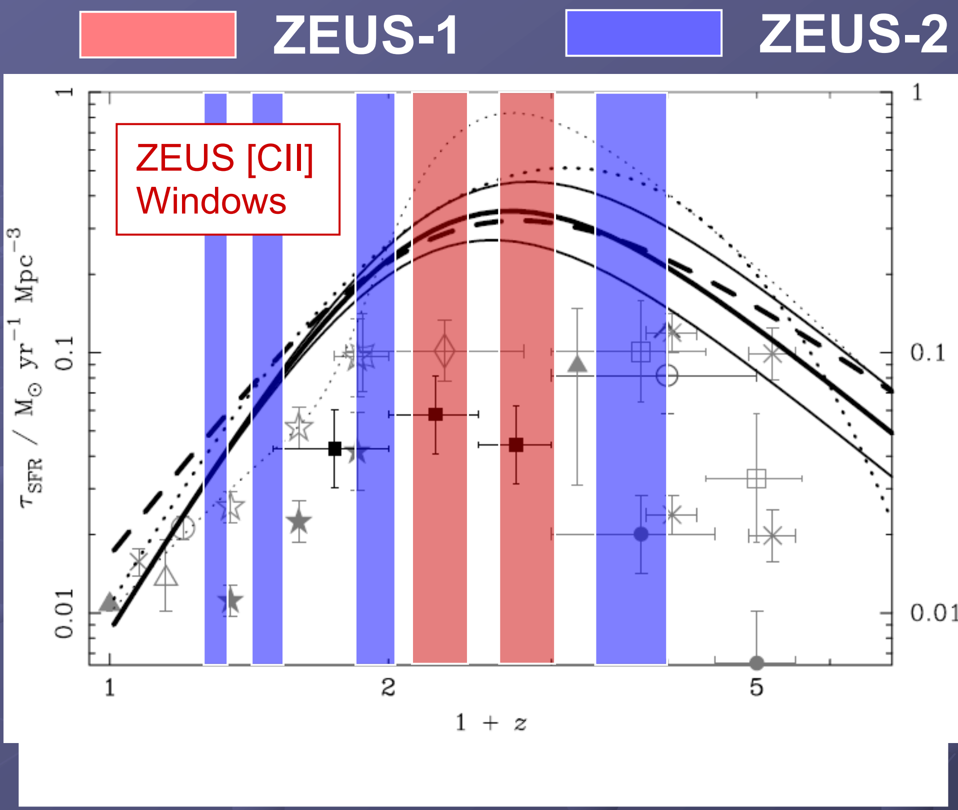
- Choose R ≡ λ/Δλ ~ 1000 optimized for detection of extragalactic lines
- Near diffraction limit:
  - Maximizes sensitivity to point sources
  - Minimizes grating size for a given R
- Long slit in ZEUS-2
  - Spatial multiplexing
  - Correlated noise removal for point sources
- Choose to operate in n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



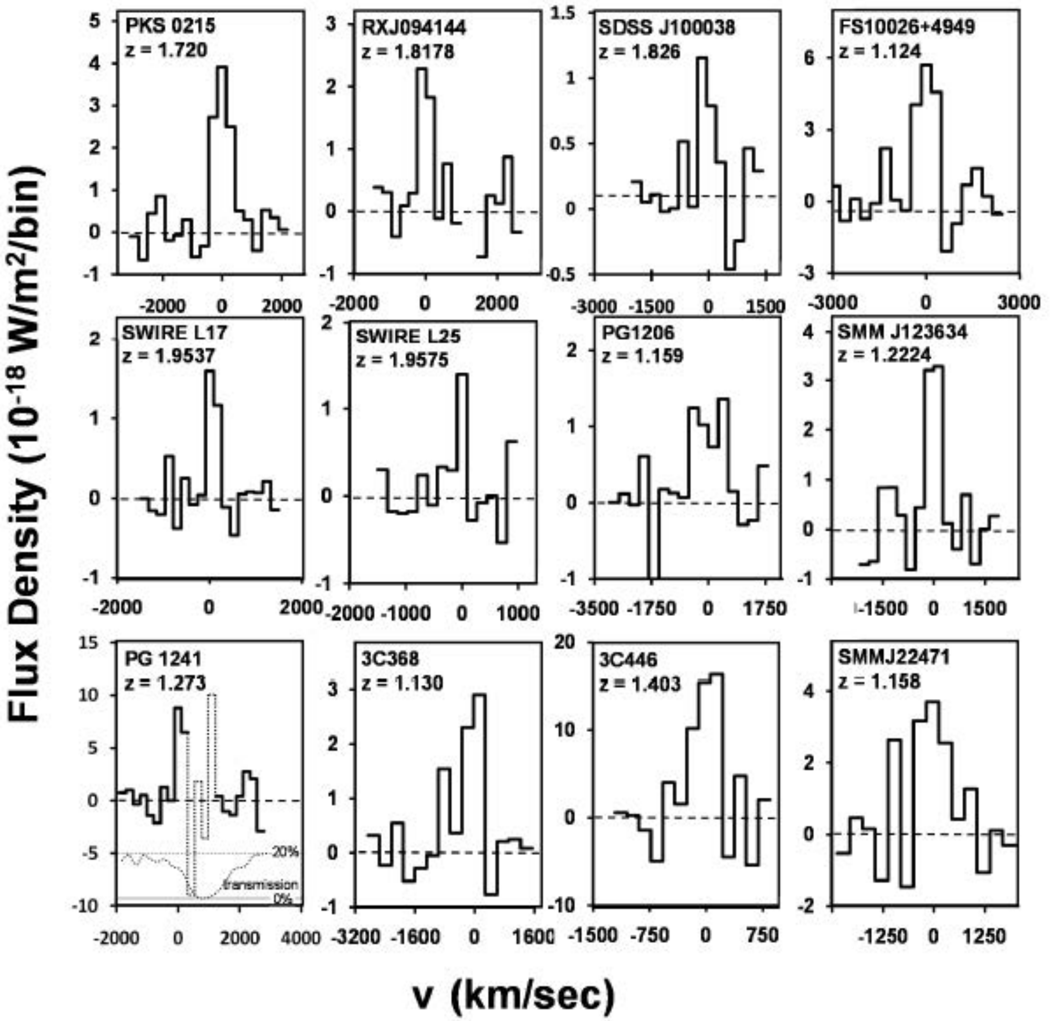
ZEUS spectral coverage superposed on Mauna Kea windows on an excellent night

ZEUS 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



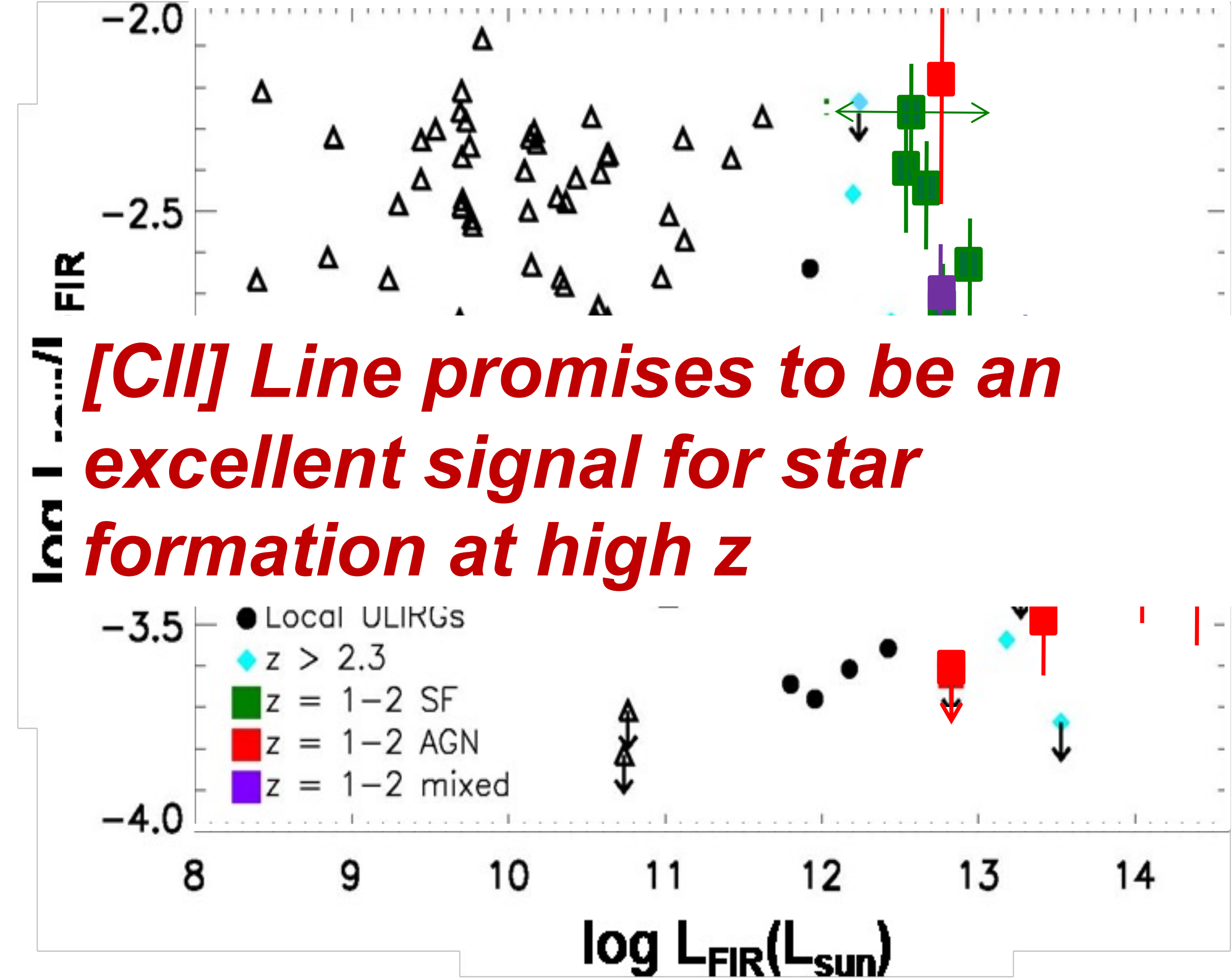
With ZEUS-2 at Chajnantor we can extend these studies from z >4 to 0.25 -- tracing the history of star formation from 12 Gyr ago, through its peak 10 Gyr ago to the present epoch



- The [CII]/FIR continuum ratio traces FUV radiation fields
- Find:
  - starbursters at z ~ 1-2 have M82-like FUV fields ⇒ very extended starbursts
  - Starformation enveloped galaxies at this epoch of galaxy assembly

- Find some AGN are also enveloped in kpc scale starbursts
- But by comparing with the [OII] line (e.g. Ferkinhoff et al. 2010) we find AGN starbursts are younger – AGN stimulates starbursts…

Results: The [CII] to FIR Ratio



[CII] Line promises to be an excellent signal for star formation at high z

SB-D:

R = 2.9±0.5 ×10^{-3}

AGN-D:

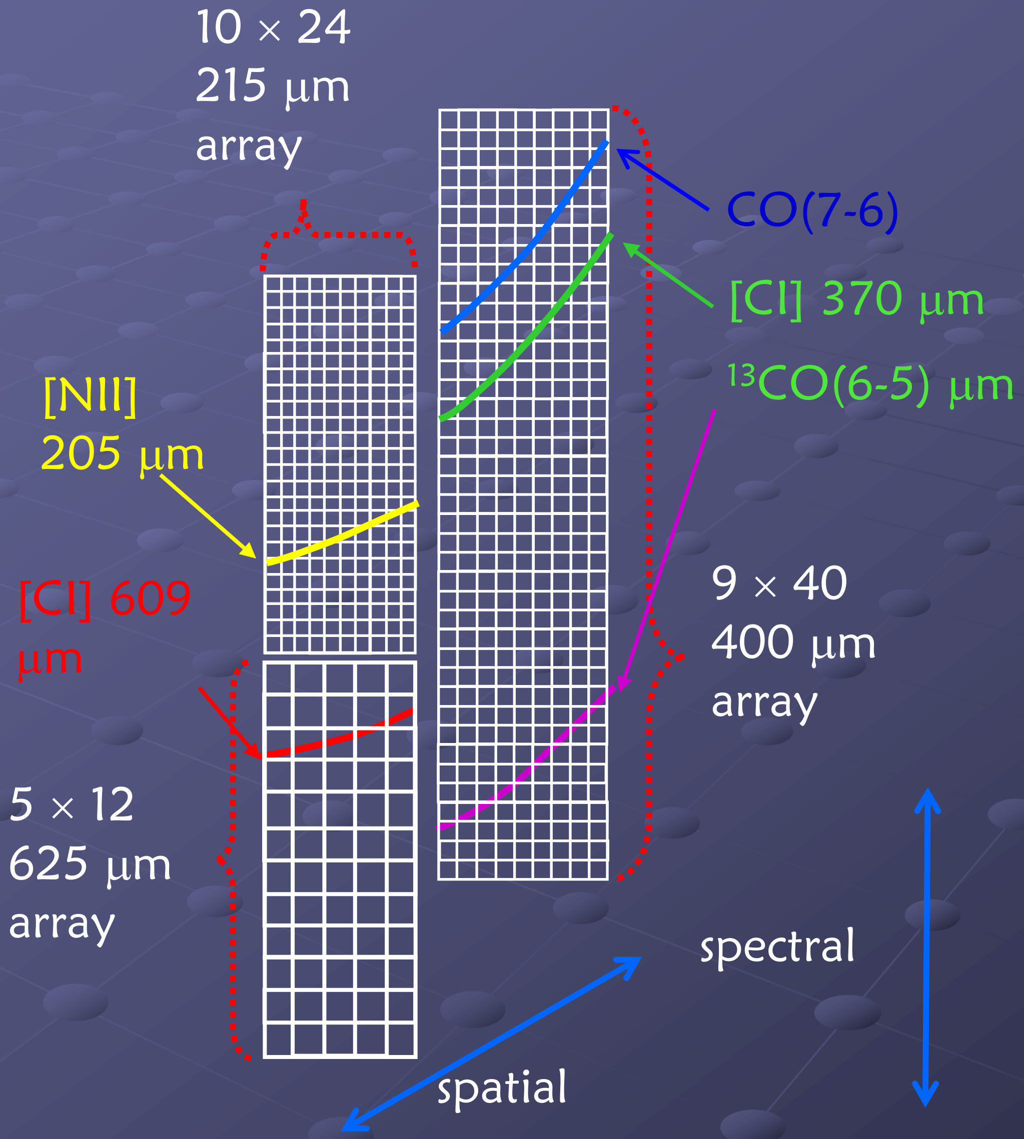
R = 3.8±0.7×10^{-4}

Mixed – in between

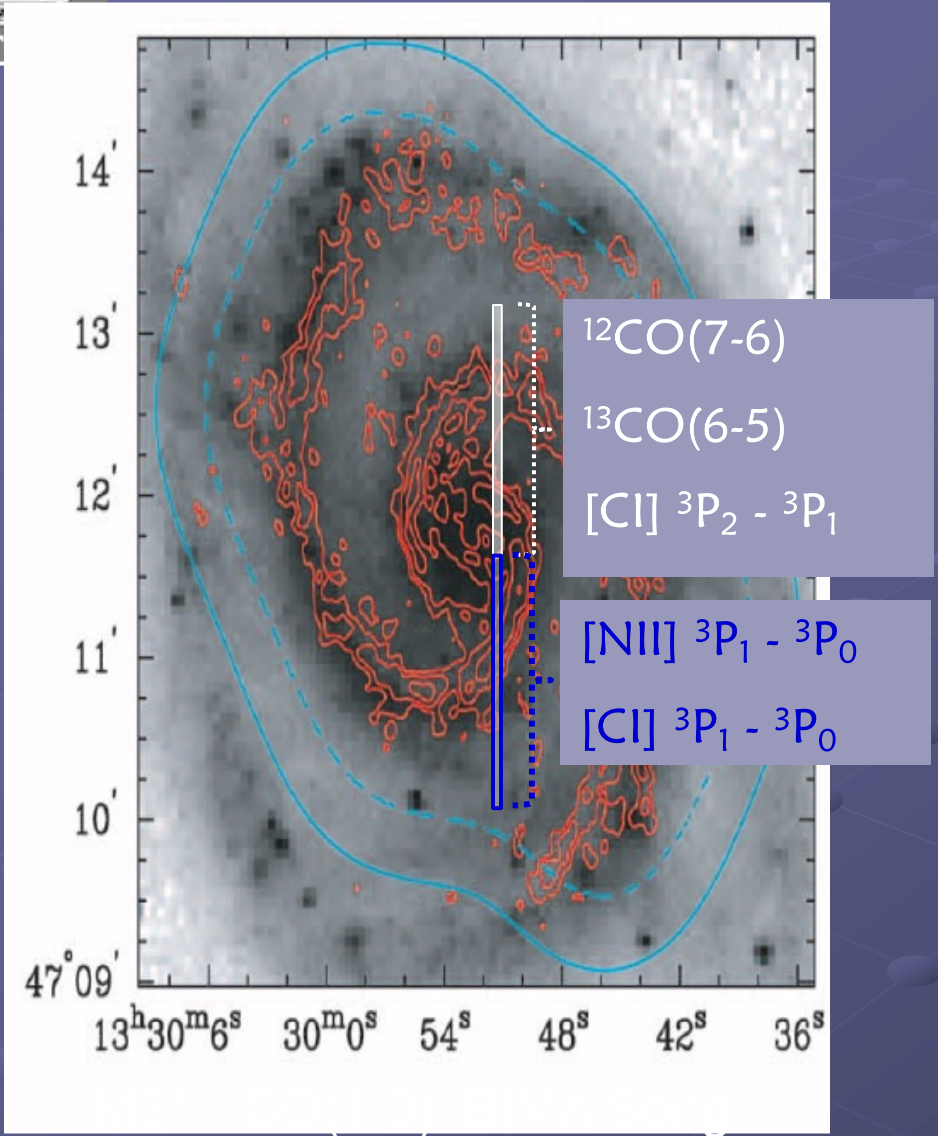
SB-D to AGN-D ratio is ~ 8:1

ZEUS-2 Focal Plane Array: Natural Spatial Multiplexing

- 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 April 2011 on CSO with 400 um array only*
- *APEX later in 2011*



Spectral Imaging Capabilities



^{12}CO(7-6)

^{13}CO(6-5)

[CI] $^3P_2$ - $^3P_1$

[NII] $^3P_1$ - $^3P_0$

[CI] $^3P_1$ - $^3P_0$

(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*

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.

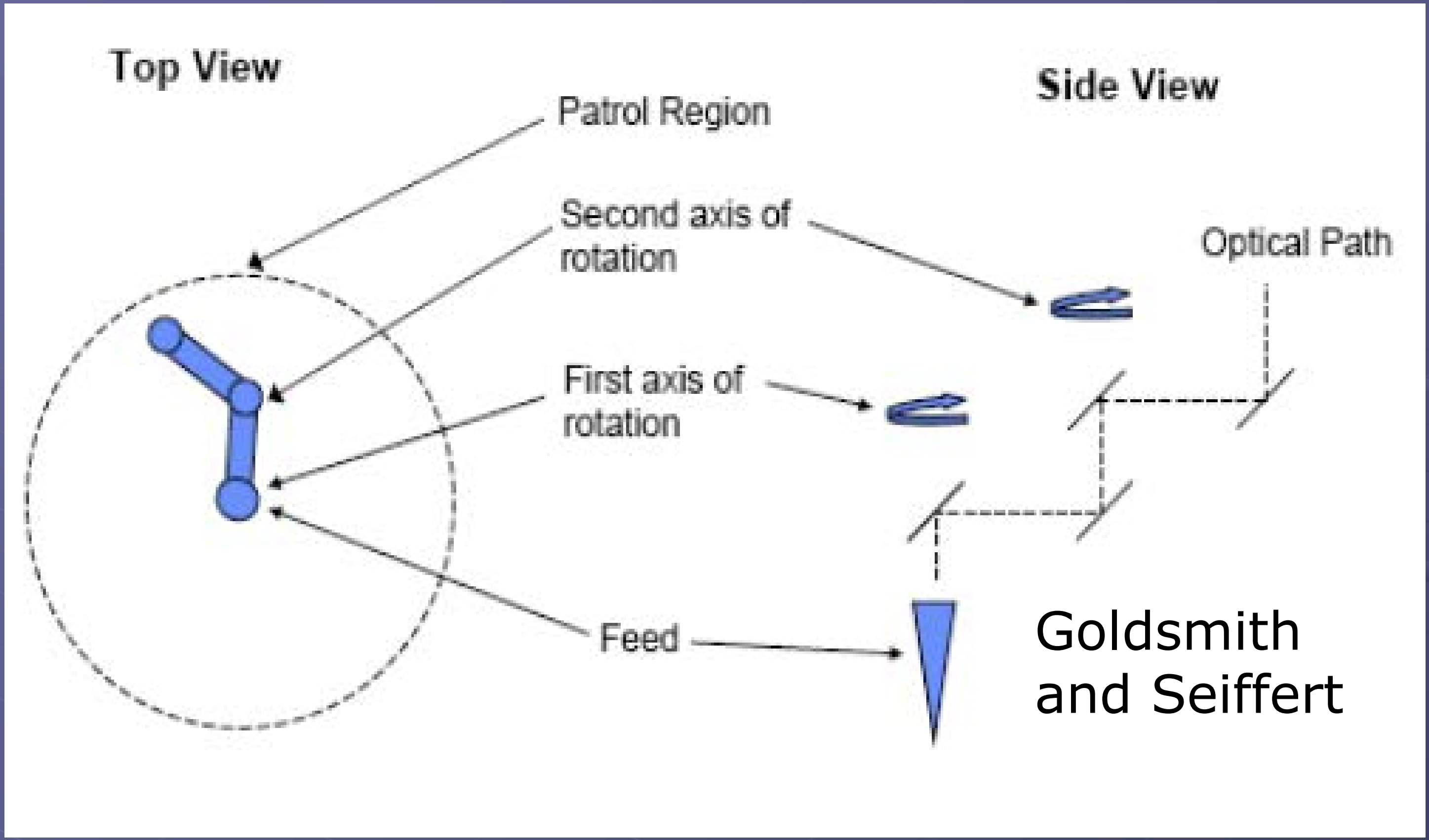
Confusion ⇒ [CII] = FIR Continuum Detection Limits

- ZEUS Survey of 13 – z ~ 1 to 2 galaxies shows [CII]/FIR continuum ~ 0.2%
- Line/continuum ~ 10:1
- CCAT: 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 spectrometer would be quite useful – sources are crowded

Light Pipes: Quasi-optical Approach



Goldsmith and Seiffert

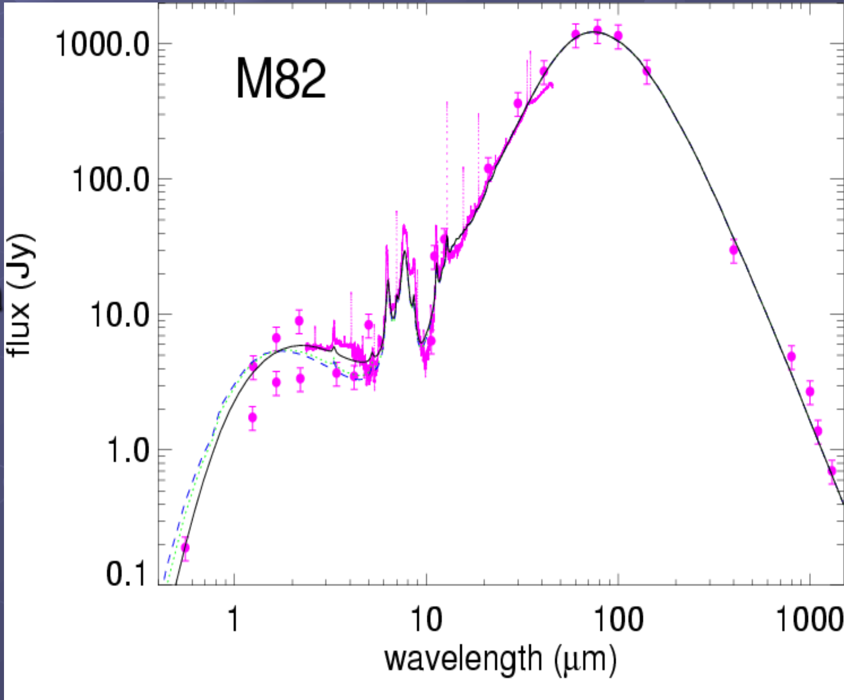
- Periscope based Multi-Object Spectrometer
- Useful for observations of sources which have a low spatial density on the sky
- Patrol regions over the focal plane assigned to each receiver
- Low transmission losses since only four reflections

SOFIA Synergy: Lines

- Bright fine-structure lines of roughly equal luminosity for most galaxies
  - [CII] 158 μm
  - [OIII] 52 and 88 μm
  - [OI] 63 and 146 μm
  - [NII] 122 and 205 μm
  - [NIII] 57 μm
- Within the windows, CCAT much (25 ×) more sensitive
- CCAT can't do these lines at until $z > 1$
  - More modest z purview of SOFIA – trace the evolution in star formation rate
  - Complementary lines for high z (albeit somewhat higher L) sources.

SOFIA Synergy: Continuum

- CCAT ~ 25 × more sensitive, but SED rises towards shorter wavelengths – factors of >10 – so that SOFIA can trace further down the luminosity function than in the lines – however, there will be some K correction going on…
- Local Universe :
  - 60 μm (SOFIA) ~ 6”
  - 38 μm (SOFIA) ~ 4” – but flux down
  - 350 μm (CCAT) ~ 4”
- Constrains dust SED
  - Temperature
  - Dust properties
  - Dust mass
  - Luminosity



SOFIA Synergy: Galactic Science

- CCAT will survey tens of square degrees in the Milky Way – sampling different environments
    - Sensitive to clumps capable of forming 0.01 $M_\odot$ stars
    - Angular resolution sufficient to resolve 0.05 pc clump to 1 kpc
    - Multicolor imaging to get dust T and mass
    - Follow-up spectroscopy in molec ular lines and [CI] to probe dynamics, physical conditions of star-forming cloud
- SOFIA will:
    - Trace dust SED to < 38 μm – vitally important if $T_{dust} > 10$ K
    - Enable observations of far-IR FS lines
    - Enable observations of important infall tracers for protostellar candidates: e.g. water (via isotopes), OH, [OI], [FeII], [SI]…

SUMMARY

- CCAT is in the design study phase
  - Looking for more partners
  - first light anticipated in 2017
- Great synergy with both:
  - ALMA
    - finder – scope
    - high spatial resolution follow-up of interesting sources
  - SOFIA
    - important obscured spectral lines
    - Dust SED