CCAT

Gordon Stacey

Cornell University

Gull

CCAT Scientific Inspiration

- Measure and characterize the history of star formation in galaxies through cosmic time
  - Photometric surveys to resolve the FIR background
  - Spectroscopic surveys characterizing the energy sources: stellar populations, shocks and AGN activity
- Probe the astrophysics of galaxy clusters through the Sunyaev-Zel’dovich effect (S-Z)
- Characterize the star formation process locally through submm-wave spectroscopy and dust continuum emission
  - Over 10’s of degree scales and through 5 orders of magnitude in scale for in the Milky Way
  - Complete maps over a variety of environments in nearby resolved galaxies

CCAT Implementation

Requirements:

- 25 meter telescope
- high surface accuracy (10 μm RMS goal)
- superb astronomical site: Cerro Chajnantor at 5617 m

– Resolves the CIRB

– Beam ~λ(μm/100) (“)

– Enables accurate astrometry for follow-up

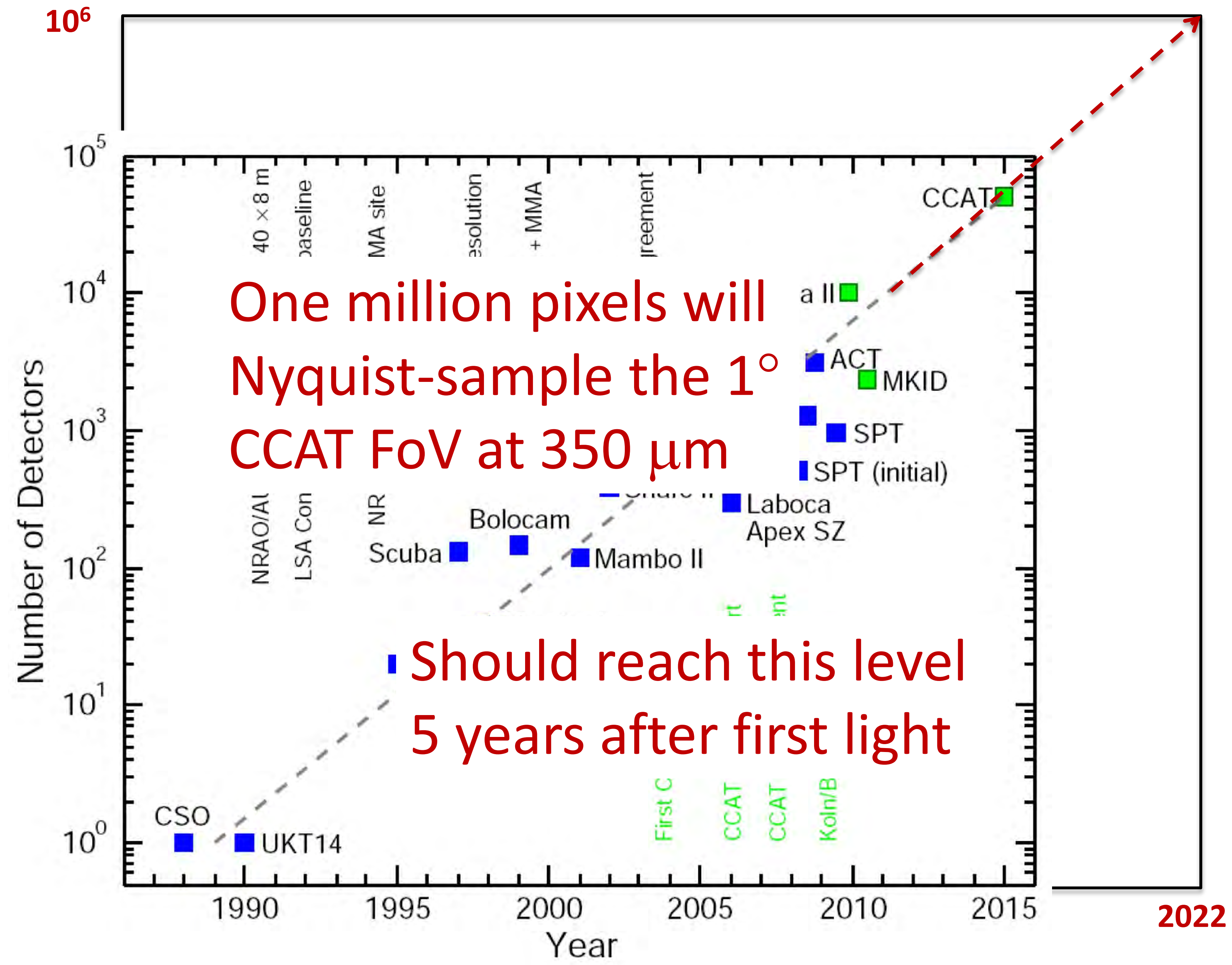
– Can reach the confusion limit at 350 μm in a few hours

– Point source sensitivity comparable to ALMA in short submm bands: *discovery and follow-up*

CCAT Implementation

Requirements:

- 25 meter telescope
- high surface accuracy (10 μm RMS goal)
- superb astronomical site: Cerro Chajnantor at 5617 m
  - Highly accessible
- Wide (1°) field of view
- 20 year lifetime
  - Takes advantage of technological innovations
  - Look towards future with growth of detector technology
  - Simultaneous mounting and use of instrumentation



One million pixels will Nyquist-sample the 1° CCAT FoV at 350 μm

Should reach this level 5 years after first light

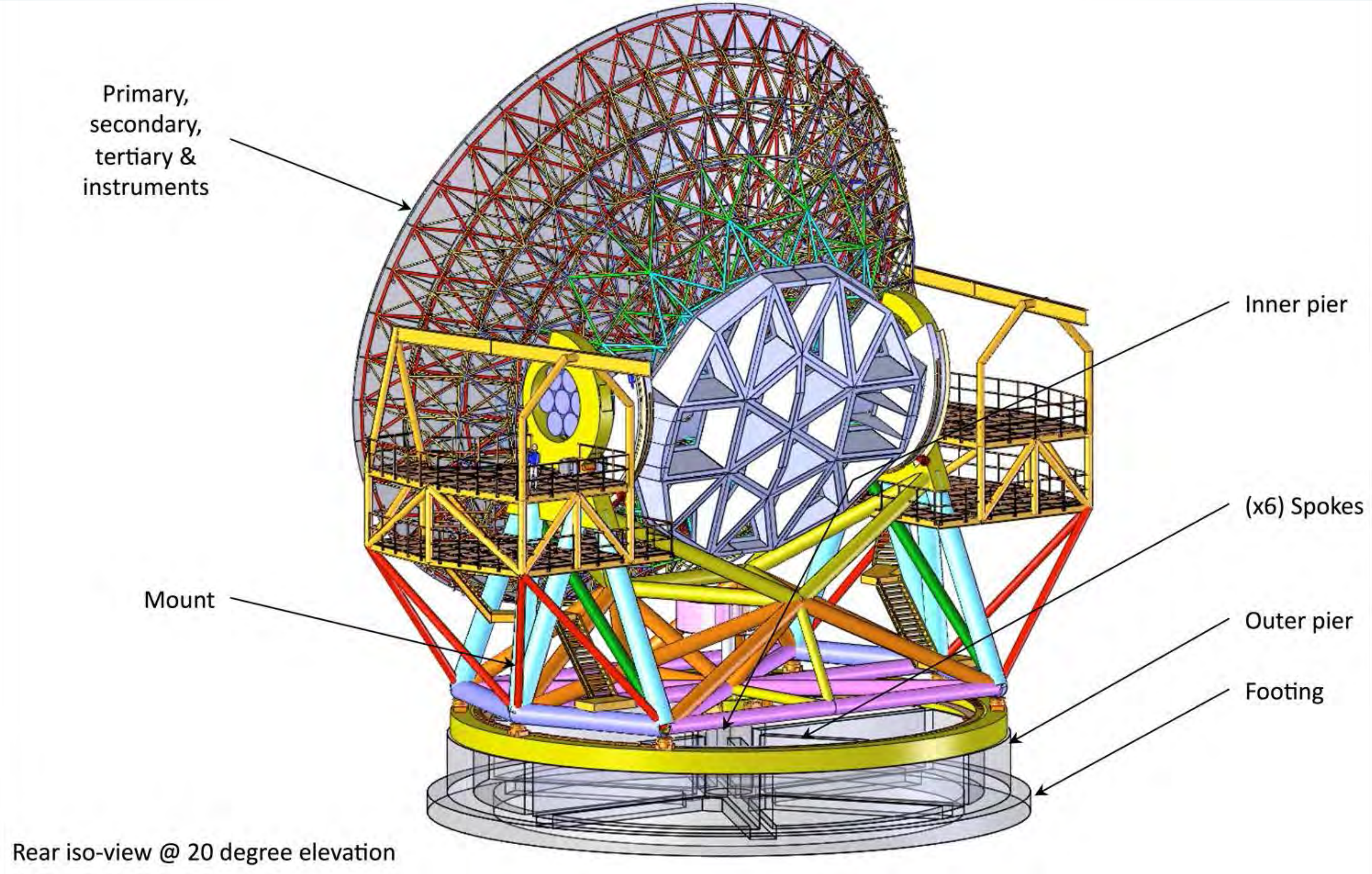
Telescope Design

CCAT

- Aperture 25 m
- Wavelength 350 µm – 3300 µm (200 µm goal)
  - Beam size 3.5 arcsec @ 350 µm
- Field of view 1° circular
- Half Wave Front Error < 12.5 µm rms

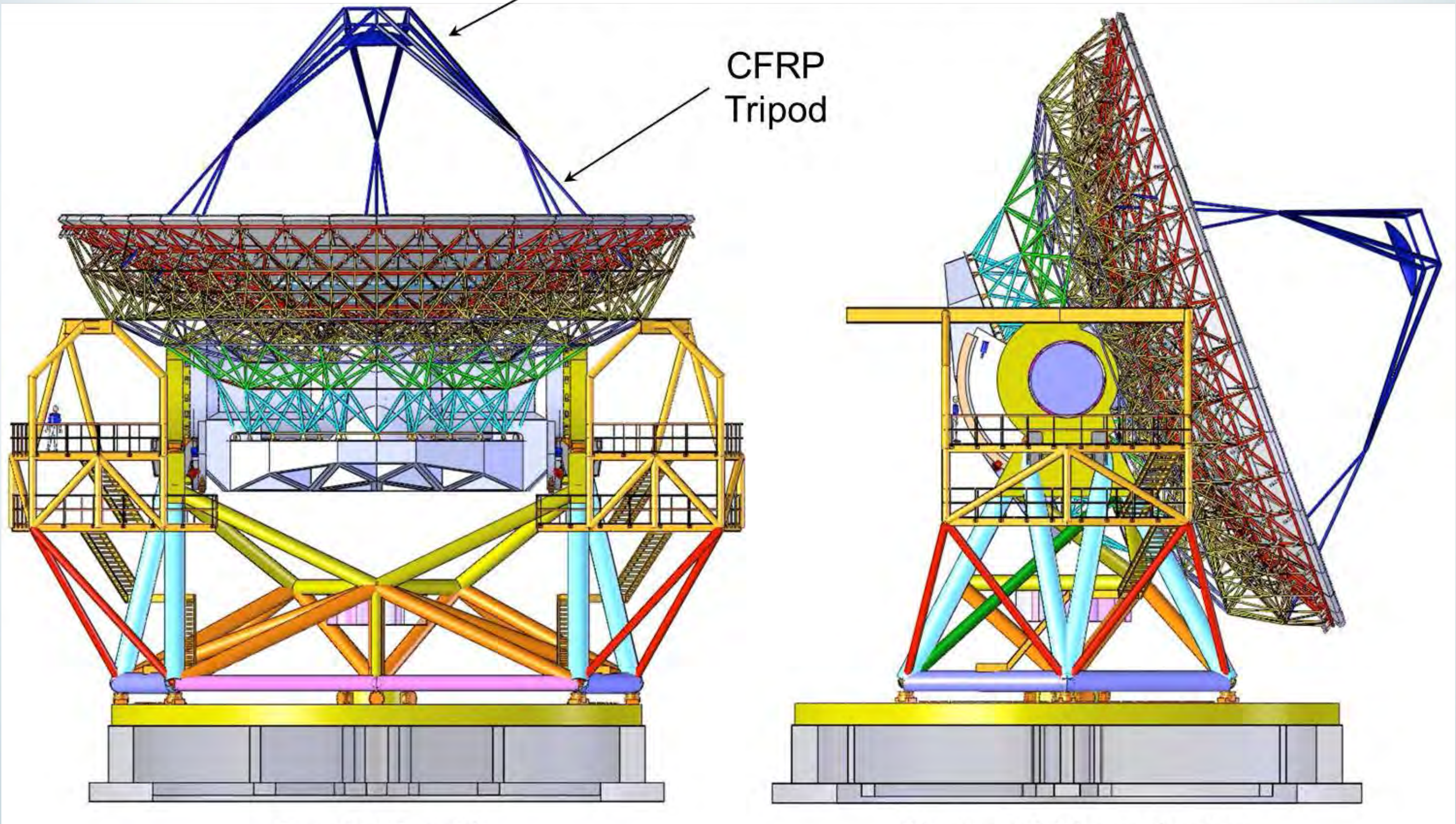
- Gregorian optics, Nasmyth instruments
- Active primary mirror
  - Al tiles on CFRP subframes, CFRP/invar truss
  - Open loop design, provision for closed loop
- Insulated steel Az/El mount, fast scan speed
- Enclosure: protection from wind, Sun

CCAT Rear View



Rear iso-view @ 20 degree elevation

CCAT Side Views



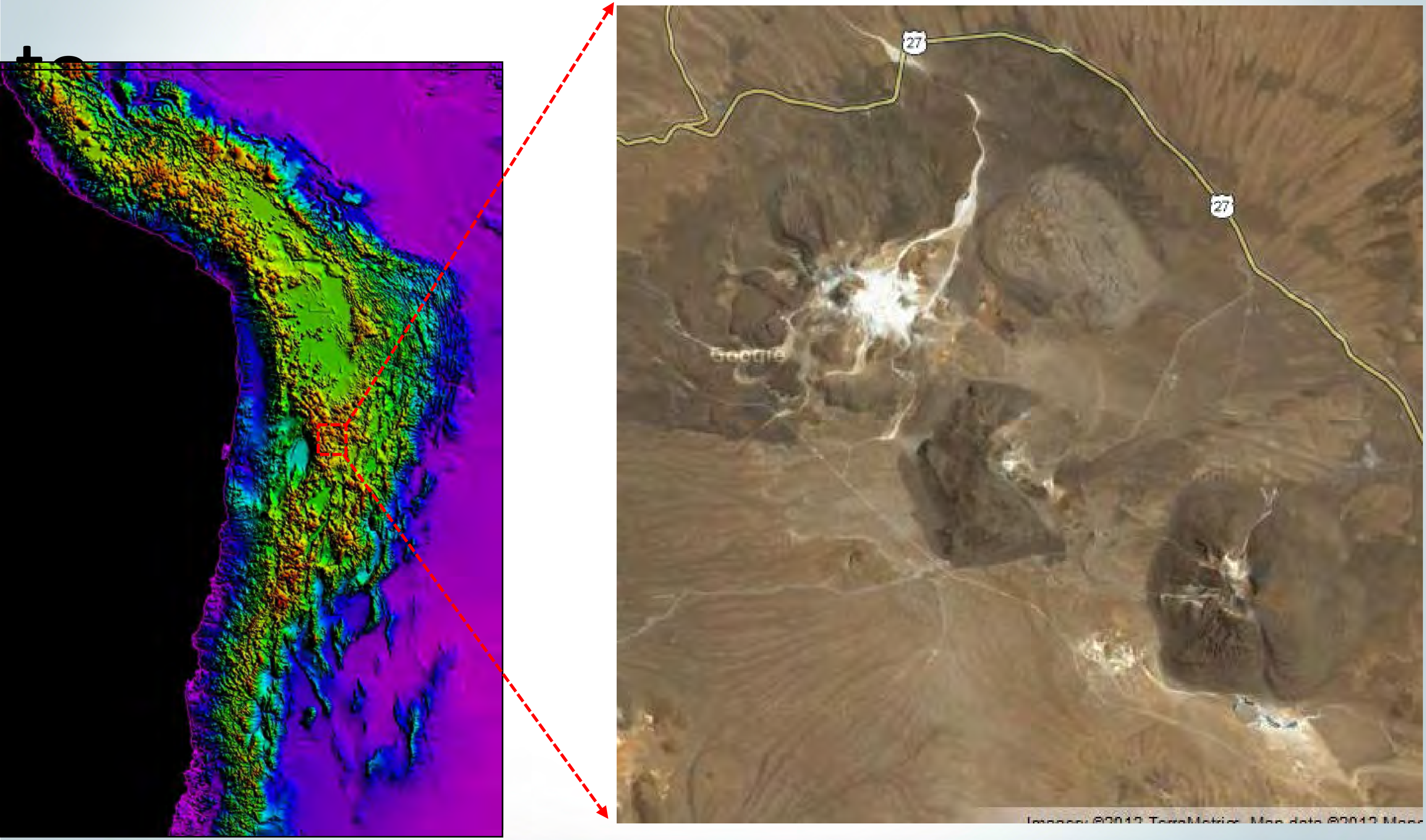
Aplanatic Gregorian

CFRP Tripod

Rear view @ zenith

Side view @ 20 degree elevation

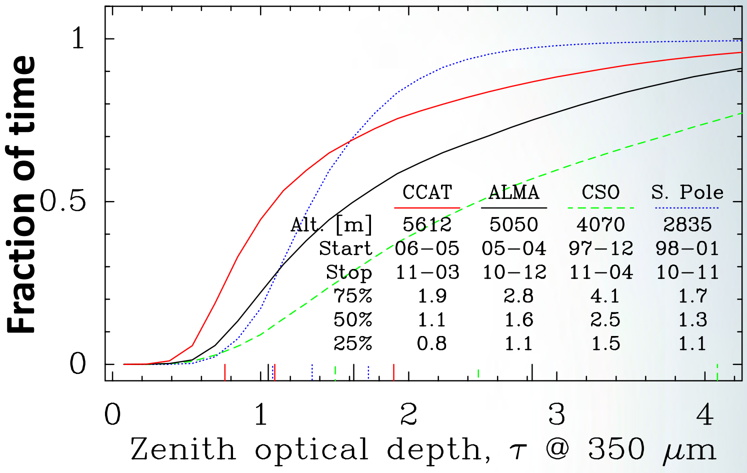
The Site: the driest, high altitude site to which one can drive a truck to

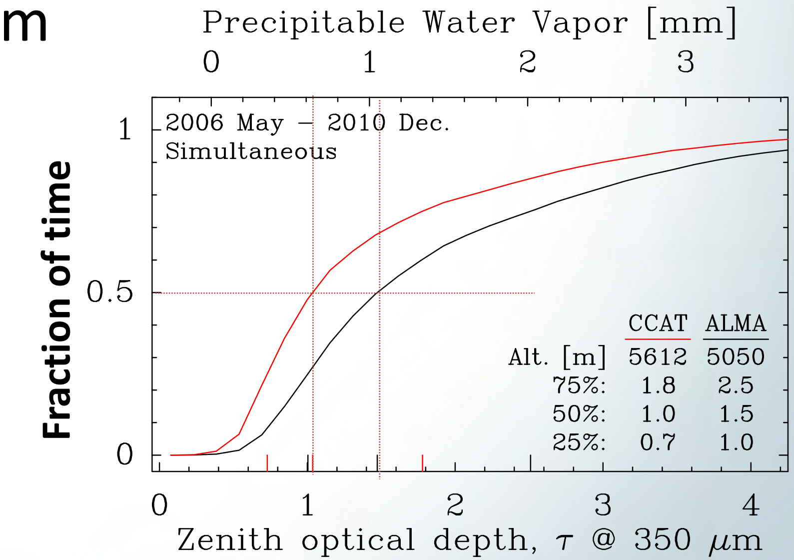


Looking *Down* on the ALMA Site

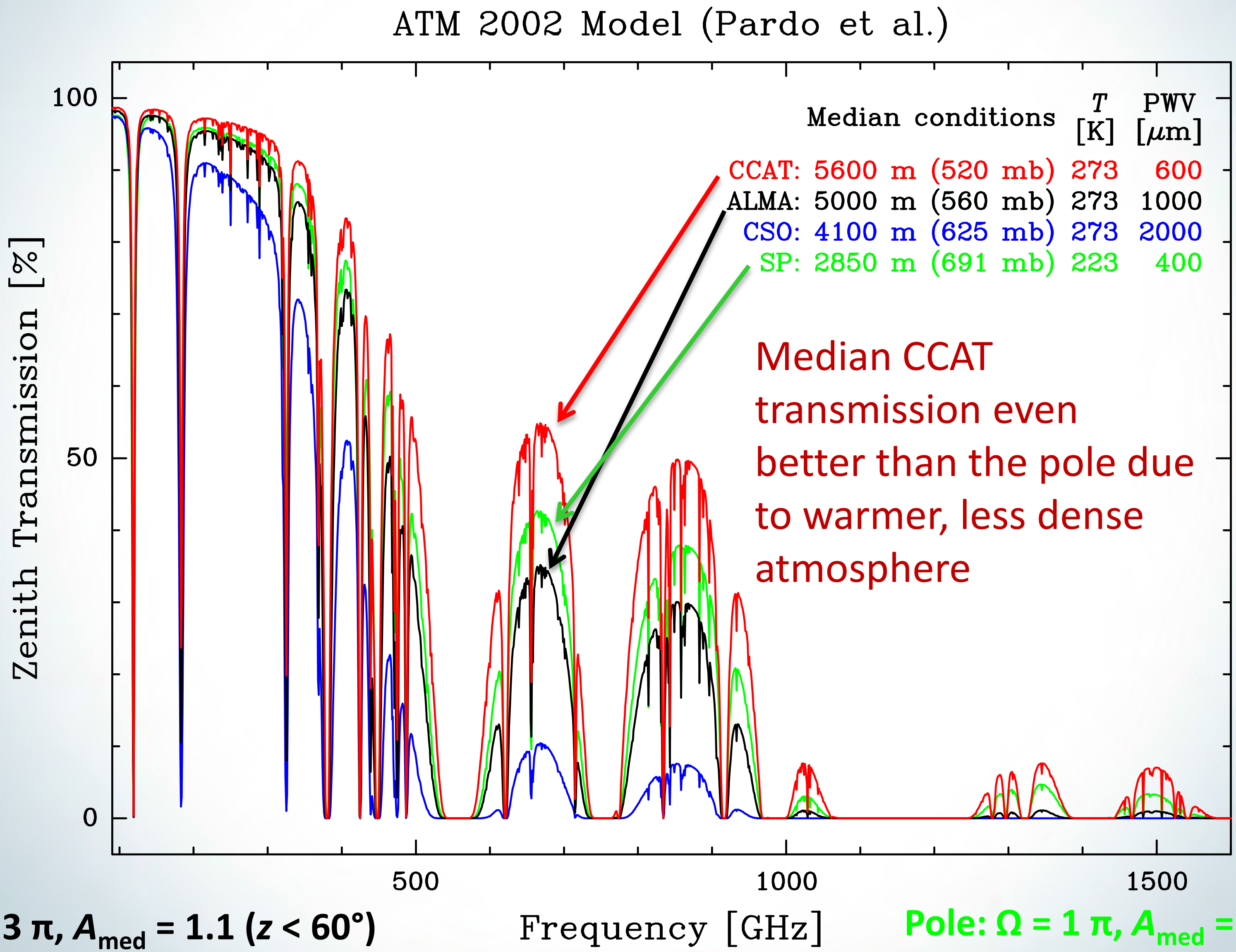
Why the Extra 600 Meters?

- Submillimeter sensitivity is all about telluric transmission
- Simon Radford has been running tipping radiometers at primary sites for more than a decade –
- Simultaneous period for CCAT vs. ALMA site: median is 0.6 vs. 1.0 mm $H_2O \Rightarrow$ *factor of 1.4 in sensitivity*





Median Conditions

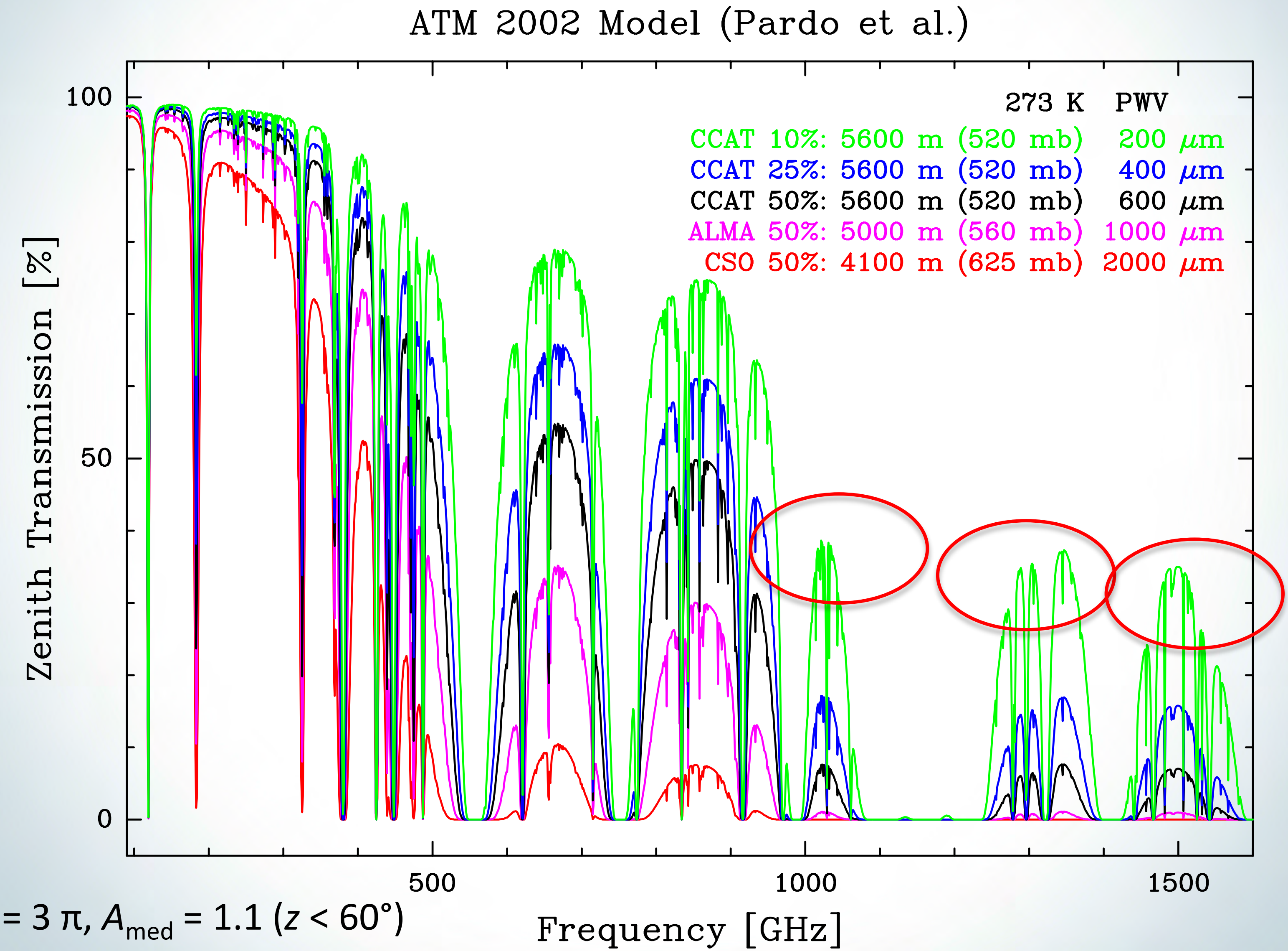


Median CCAT transmission even better than the pole due to warmer, less dense atmosphere

$\Omega = 3\pi$, $A_{\text{med}} = 1.1$ ($z < 60°$)

Pole: $\Omega = 1\pi$, $A_{\text{med}} = 1.4$ ($z < 60°$)

Top 10% Opens up THz Windows



$\Omega = 3\pi$, $A_{\mathrm{med}} = 1.1$ ($z < 60°$)

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  - Photometric surveys to resolve the FIR background
  - Spectroscopic surveys characterizing the energy sources: stellar populations, shocks and AGN activity
- Probe the astrophysics of galaxy clusters through the Sunyaev-Zel’dovich effect (S-Z)
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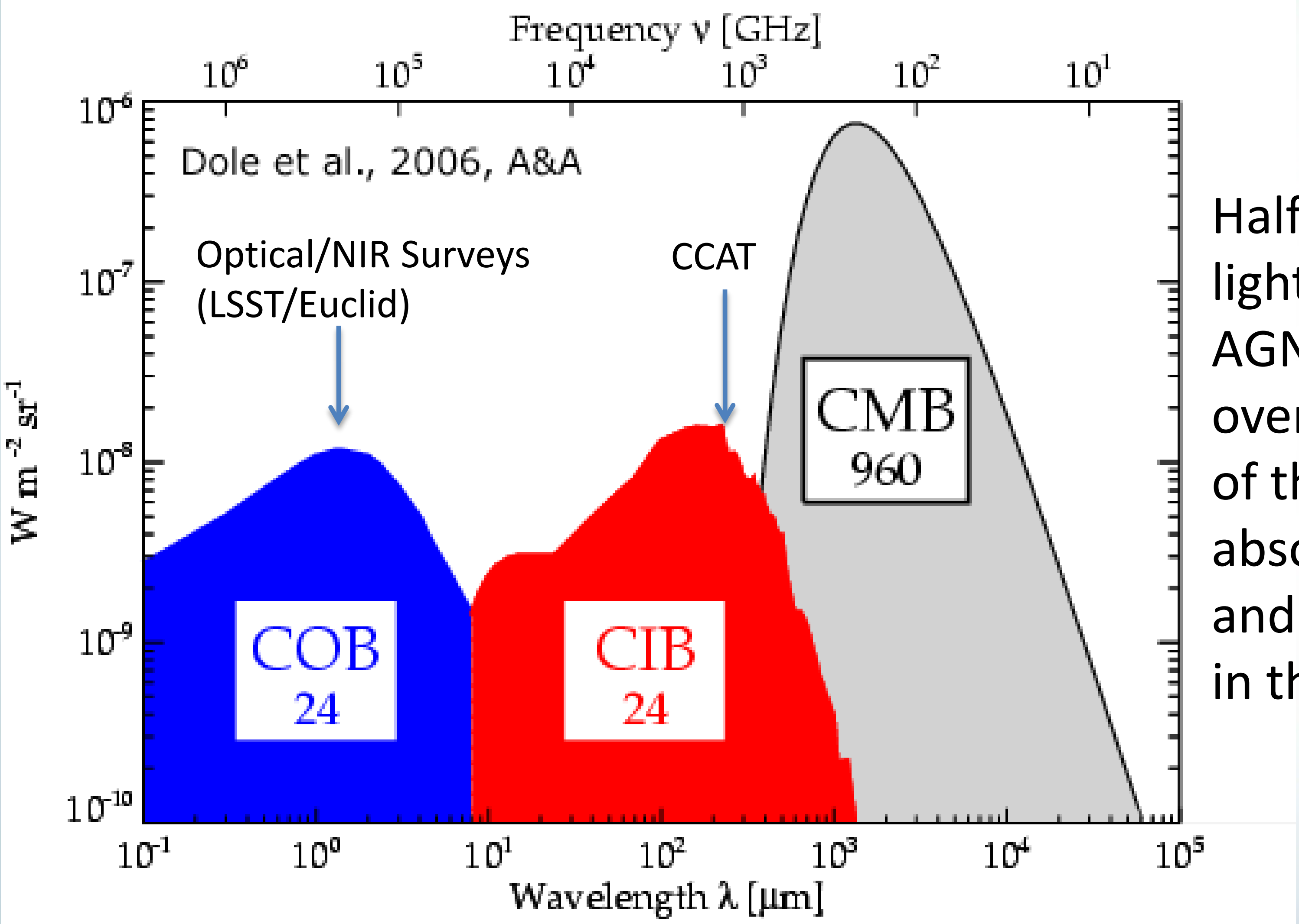
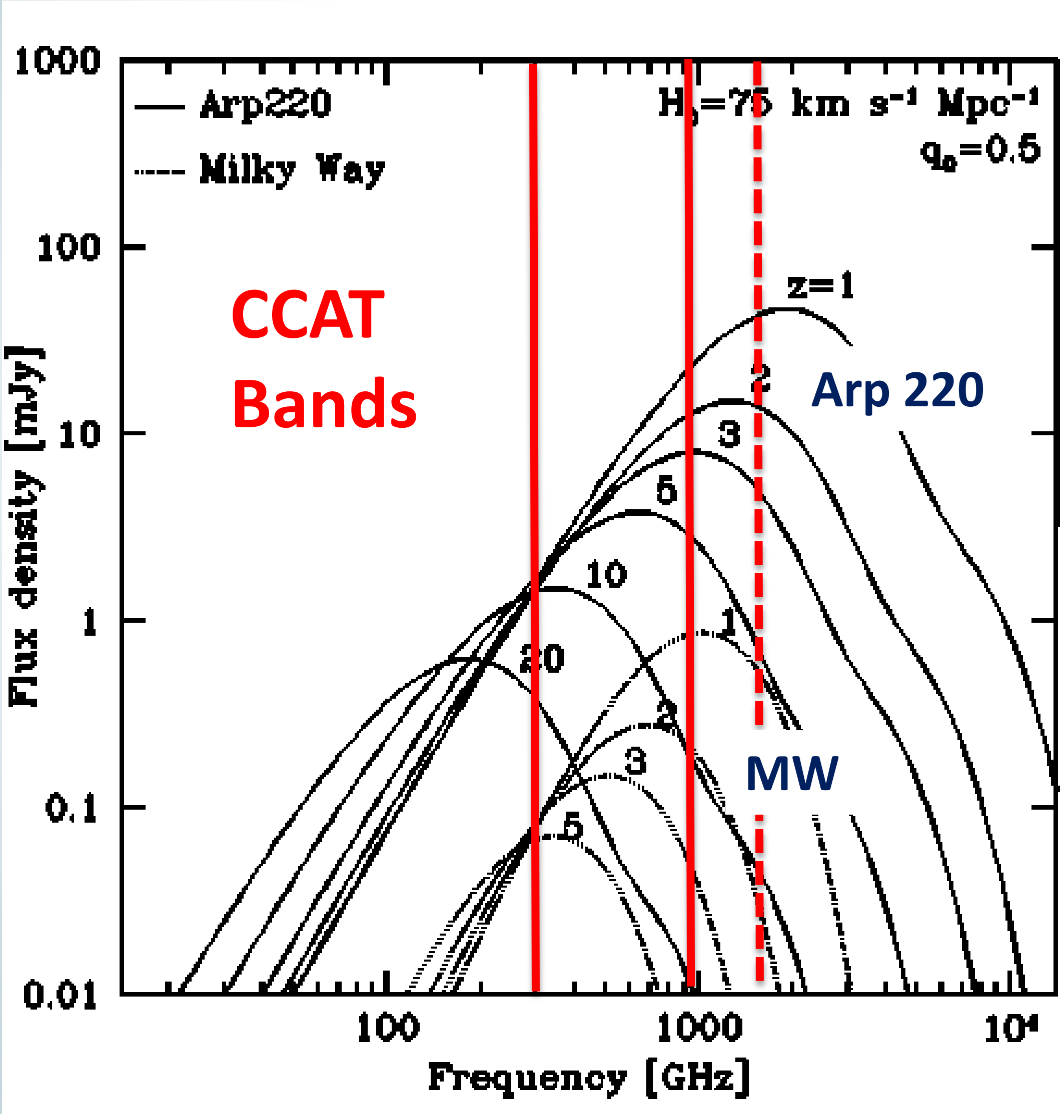
  - Over large scales and through 5 orders of magnitude in scale for in the Milky Way
  - Complete maps over a variety of environments in nearby resolved galaxies

Photon Energy Density of the Universe



Half the optical light of stars and AGN produced over the history of the Universe is absorbed by dust and re-radiated in the FIR band

CCAT Characterizes Luminosity

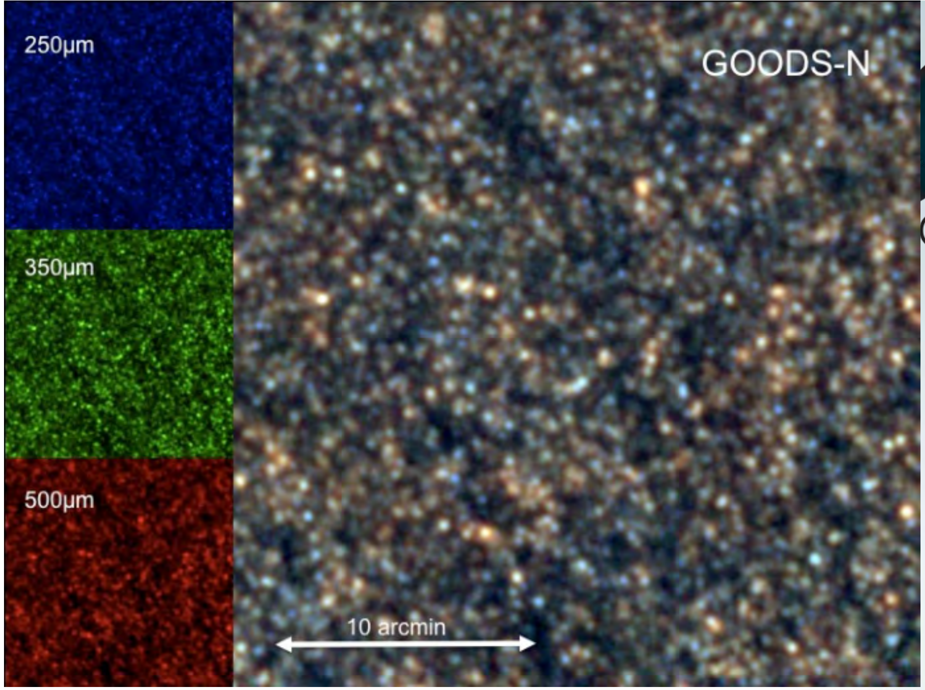


- CCAT measures the L_{FIR} for star forming galaxies at z > 1
- For most cases this is:
  - Nearly the bolometric luminosity
  - Good estimate for star formation rates
  - Note that 850 μm flux is insensitive to z, whilst 350 μm flux is quite sensitive

Red-shifted SEDs from Paul van der Werf's web-page

Confusion

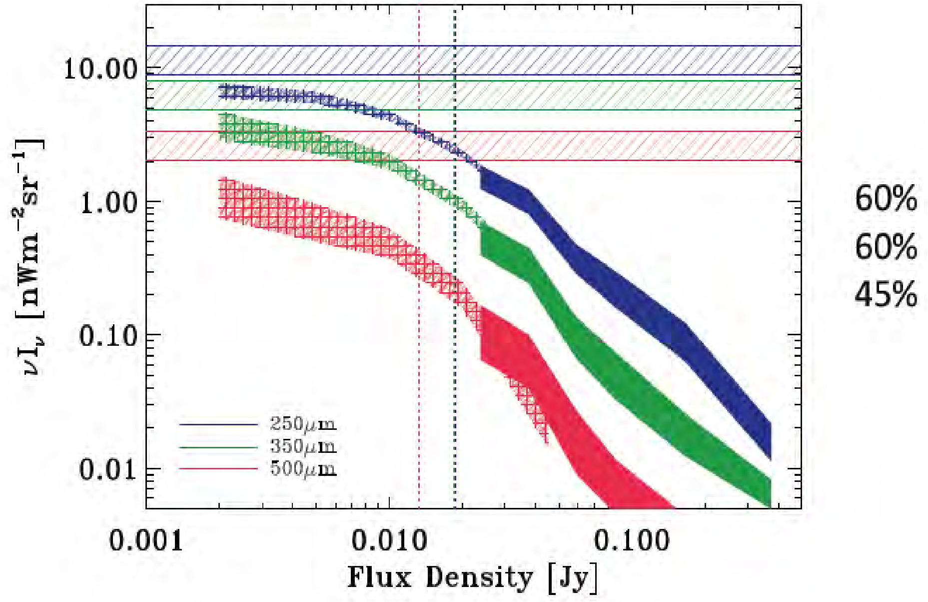
- The large CCAT aperture breaks the confusion limit
- Herschel surveys limited to ~ 25 mJy confusion limit ⇒ resolve the CIRB at 10% level
- Statistically inferred at 50% level to 2 mJy/beam
- 25 m CCAT resolves directly sources at ~0.5 to 1 mJy level in few hours at 350 μm
- → large (10-20$^{(\circ)2}$; 350 μm) per year surveys into the most active epoch of assembly of galaxies and large scale structures in the Universe
- ~ million sources/year



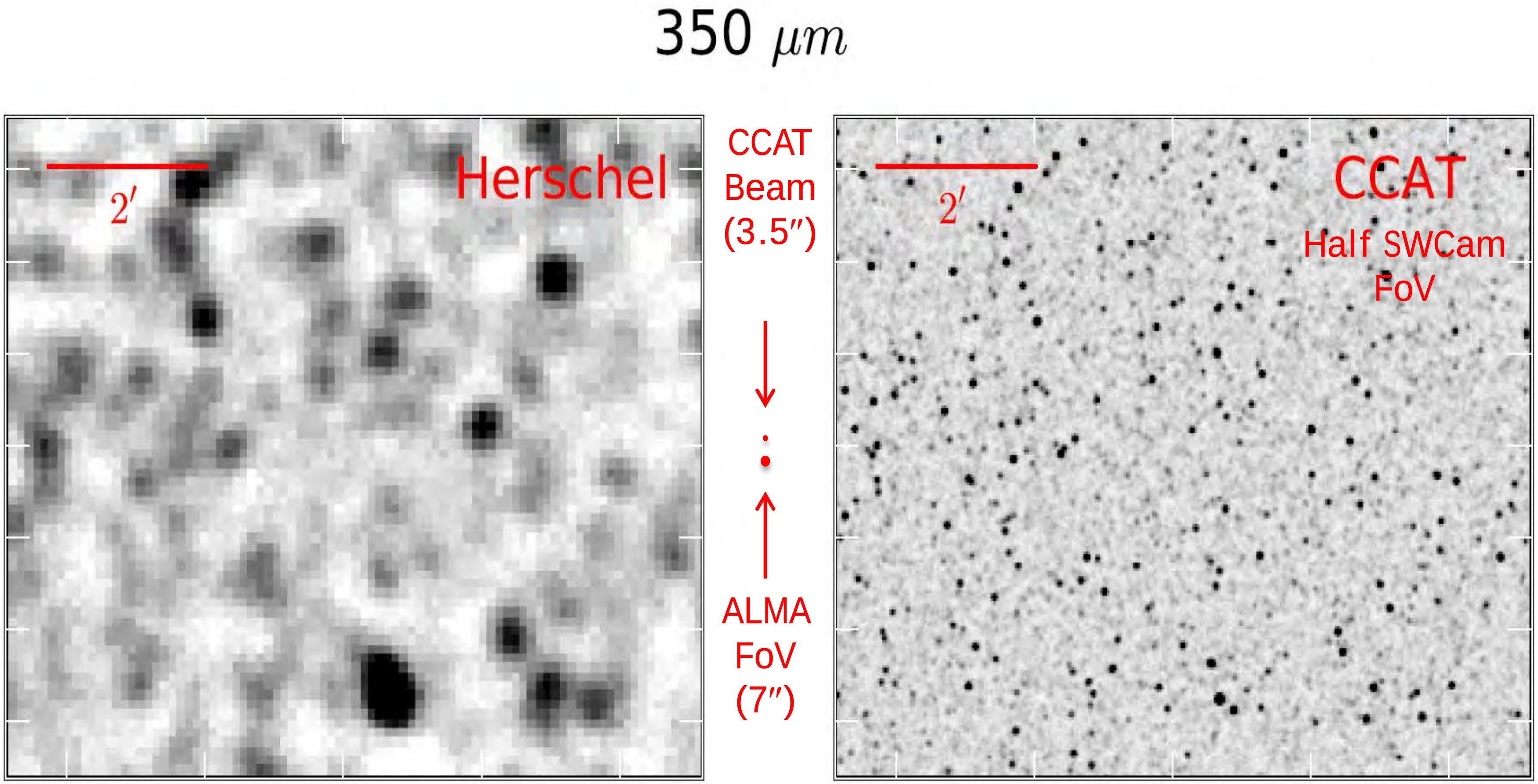
HerMES Lockman Hole North

Oliver et al. (2010, 2011)

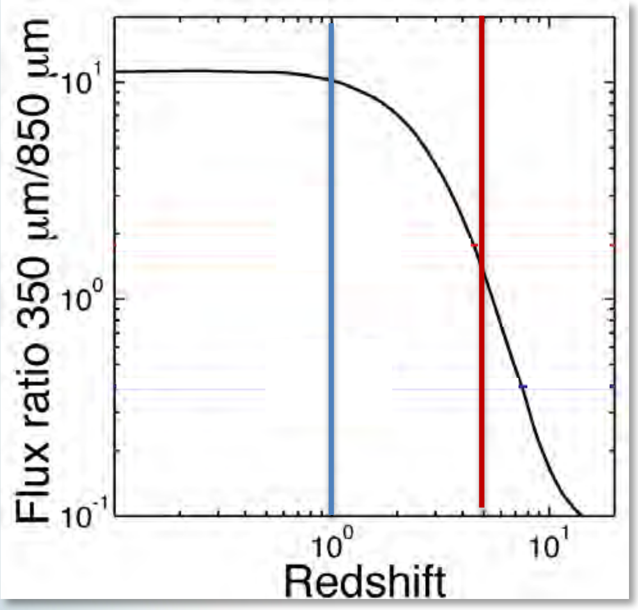
See Patanchon et al. (2010), Glenn et al. (2011)

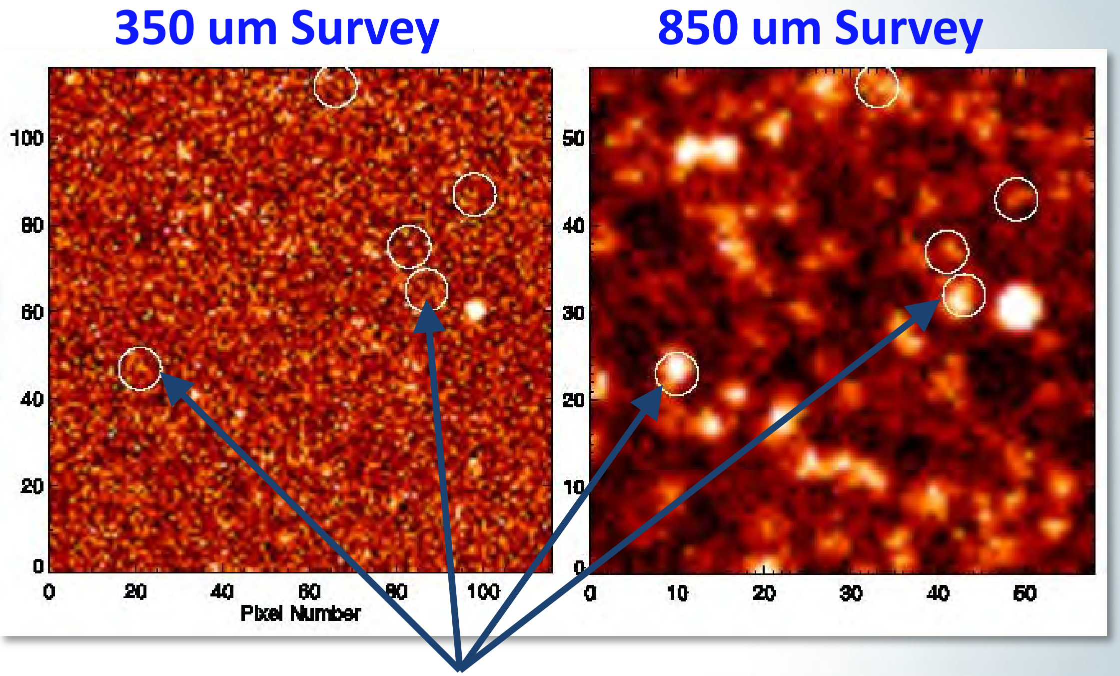


Confusion: 25 m vs. 3.5 m telescopes



Identifying the Highest Redshift Sources: 350 μm Drop-outs



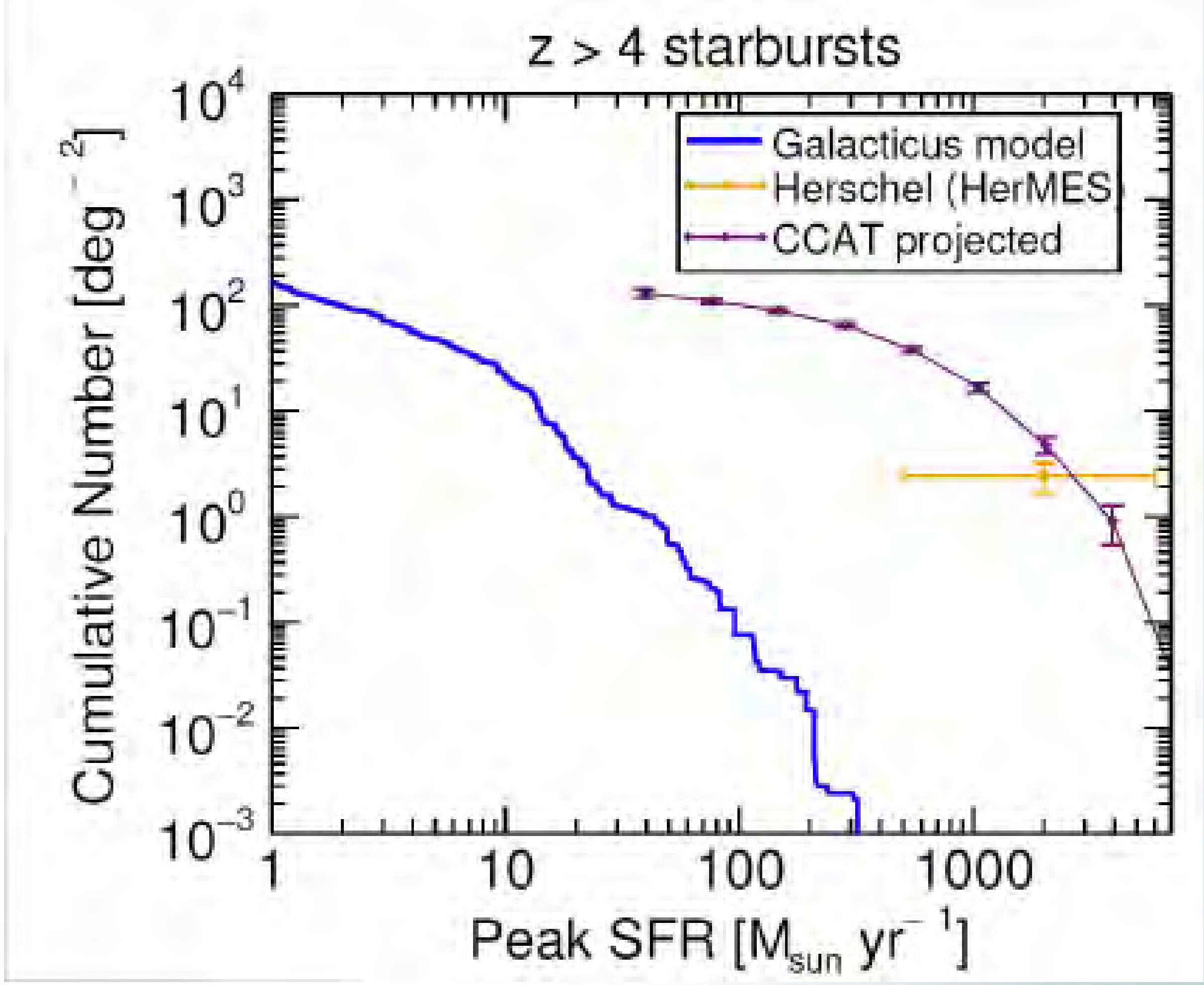

350 um Survey

850 um Survey

>5σ 850 μm detection, 350 μm non-detections, or "drop-outs"

Identifying the High z Sources: Challenging Structure Formation Models

- The number of z > 4 galaxies forming stars at 1000 $M_\odot$ ***already*** discovered by Herschel already large
- CCAT will further challenge the structure formation models

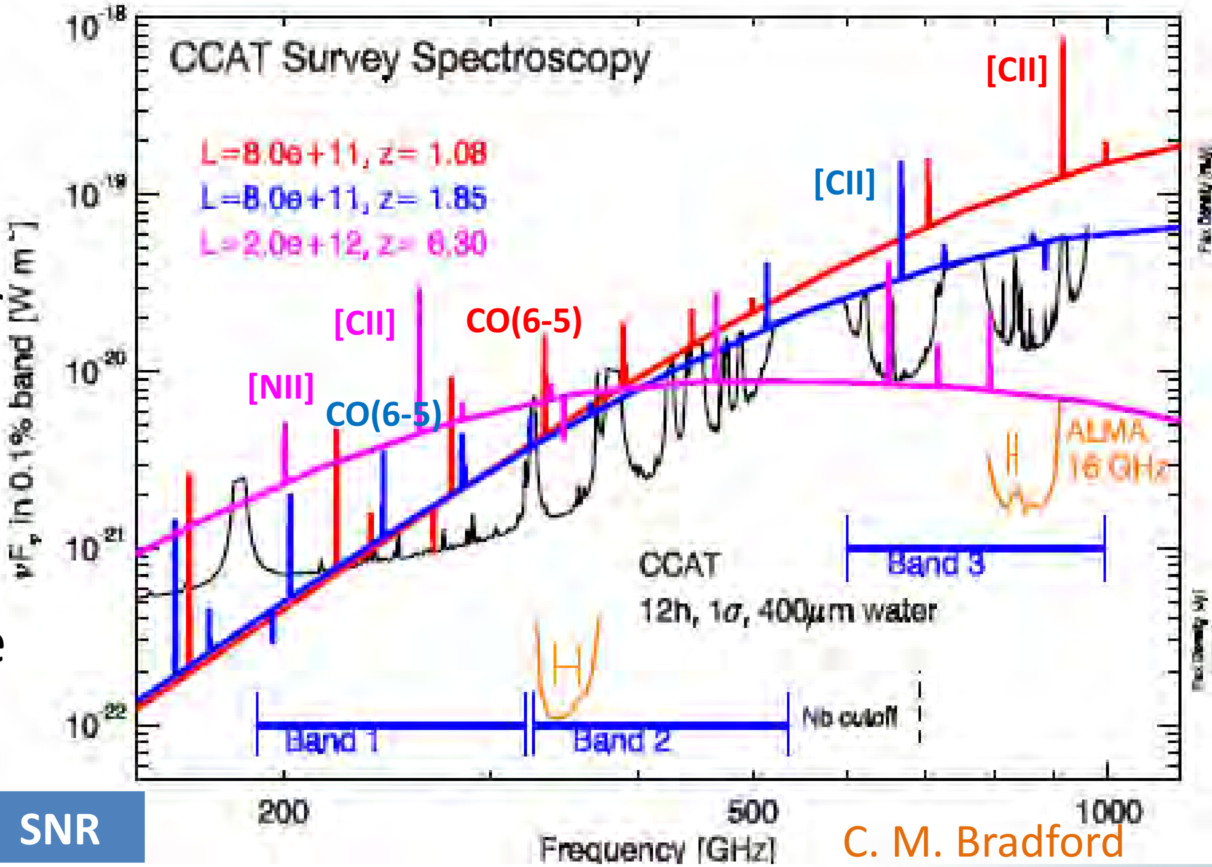


Spectroscopic Redshifts

- Determined with multi-object, large bandwidth, direct detection spectrometers
  - Spacing of CO lines: 115 GHz/(1+z)
  - FIR fine structure lines, especially [CII]
- Most sources detectable in the continuum are detectable in the 158 μm[CII] line (if transmitted):
  - For $L_{[CII]}/L_{FIR} = 1\text{-}2\times10^{-3}$; [CII]/158 μm continuum ~ 5-10:1
  - Photometric BW/Spectroscopic BW ~ 1000/10
  - $\Rightarrow$ sensitivity ratio ~ sqrt(1000/10) = 10:1
  - $\Rightarrow$ line is ~ detectable as the continuum
- CO lines roughly 5 times harder to detect, but the detection of multiple lines helps significantly

Spectroscopy

- X-Spec: a very broad (50%) BW spectrometer
- [CII] much easier to detect…
- Multiple CO lines help, and uniquely determine the redshift



C. M. Bradford

Redshift	L(FIR)	Line	SNR
1.15	8×10^{11}	[CII]	75
		CO(6-5)	12
1.85	8×10^{11}	[CII]	18
		CO(6-5)	4
6.3	2×10^{12}	[CII]	30
		[NII] 205 μm	6

ALMA 5 to 10 times more sensitive per spectral tuning (1/25-1/100 time), but:

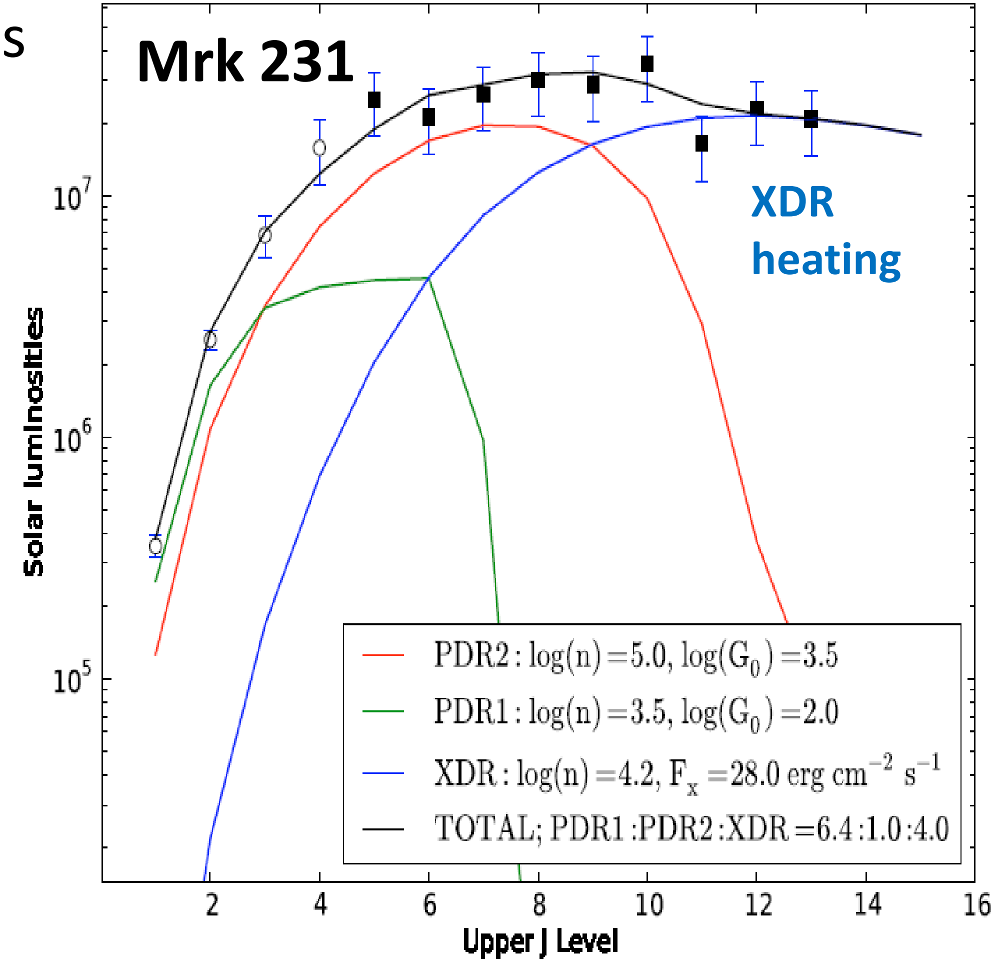
- Several (5-10) tunings are necessary
- CCAT spectrometer is multi-object

⇒ z determination is more efficient with >10 object CCAT spectrometer

Far-IR/submm Spectral Probes

- CO SED constrain molecular gas mass reservoir and the sources of gas heating
  - Stellar FUV heating (PDRs)
  - Cosmic rays
  - Micro-turbulent shocks: mid-J
  - XDR heating: high-J

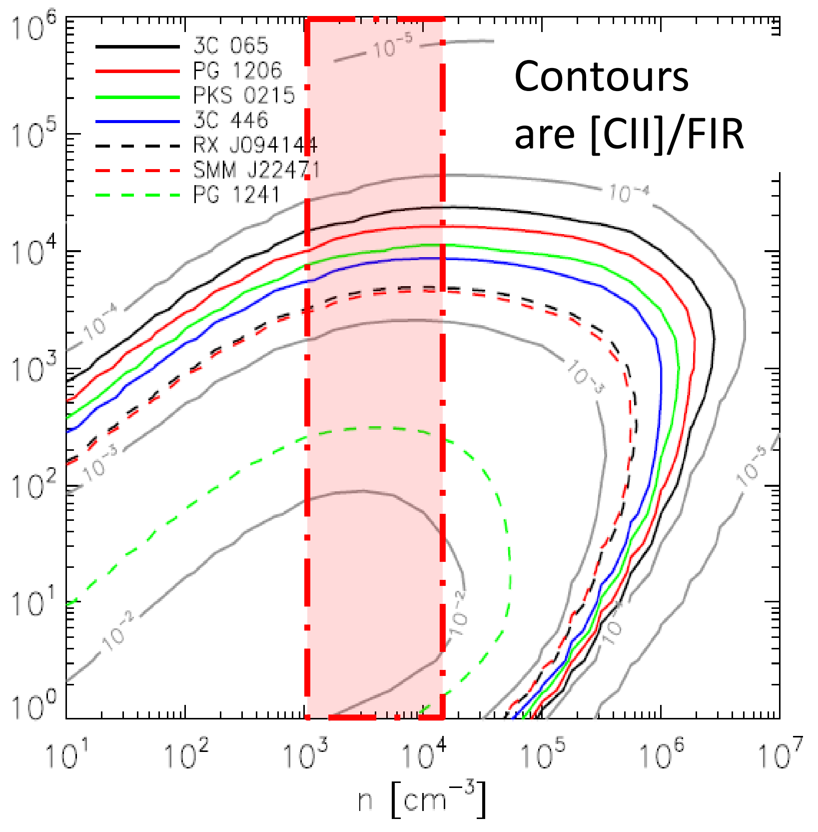
  Smoking Gun for AGN Tori
- FIR fine-structure lines
  - Extinction free probes
  - Insensitive to T (in HII regions)
  - Collisionally excited at modest n
  - Very bright, excellent probes of physical parameters of the gas and the stellar radiation fields.



van der Werf et al. 2010

Far-IR Fine-Structure Line Science

- [CII] 158 μm mostly arises in PDRs on neutral clouds exposed to stellar FUV
- [CII]/FIR yields the *intensity* of the ambient FUV radiation field, G_o
- Observed FIR intensity relates to the modeled G_o by the beam filling factor $\Rightarrow$ the [CII]/FIR ratio indirectly yields the *size* of star formation regions
- First surveys found star formation occurs on kpc scales enveloping redshift 1-2 star forming galaxies



Contours are [CII]/FIR

Hailey-Dunsheath et al. 2010, Stacey et al. 2010

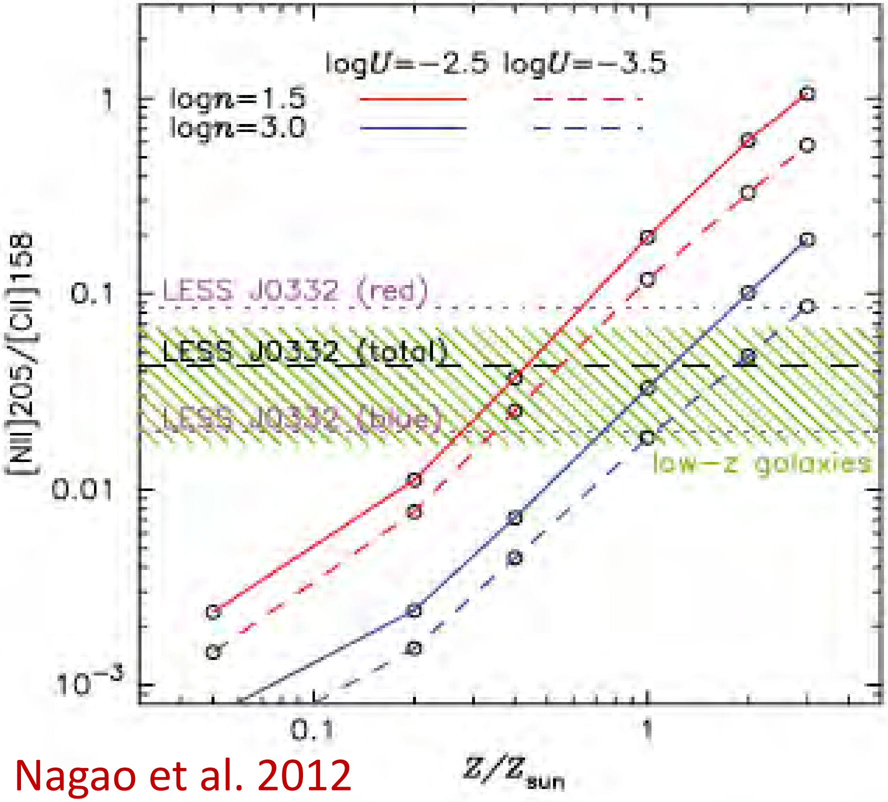
Consistent with cold accretion and Schmidt-Kennicutt star formation law – not major merger induced

Far-IR Line-Structure Line Science

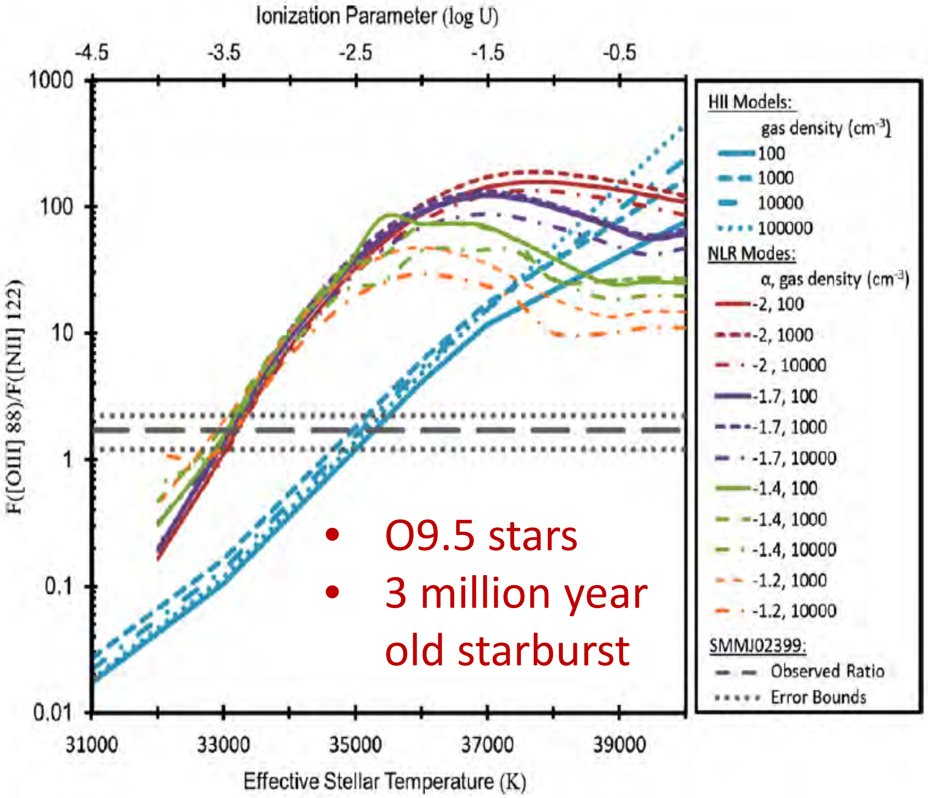
- [NII] (122 and 205 μm) lines count ionizing photons
- With [CII] yields fraction of [CII] from HII regions, or with other F-S lines and FIR, and PDR modeling, metalicity

- O^{++} (35 eV); N^{+} (14.5 eV)

  ⇒ [OIII]/[NII] yields hardness of the radiation field ⇒ Age of starburst



Nagao et al. 2012



- O9.5 stars
- 3 million year old starburst

Ferkinhoff et al. 2011

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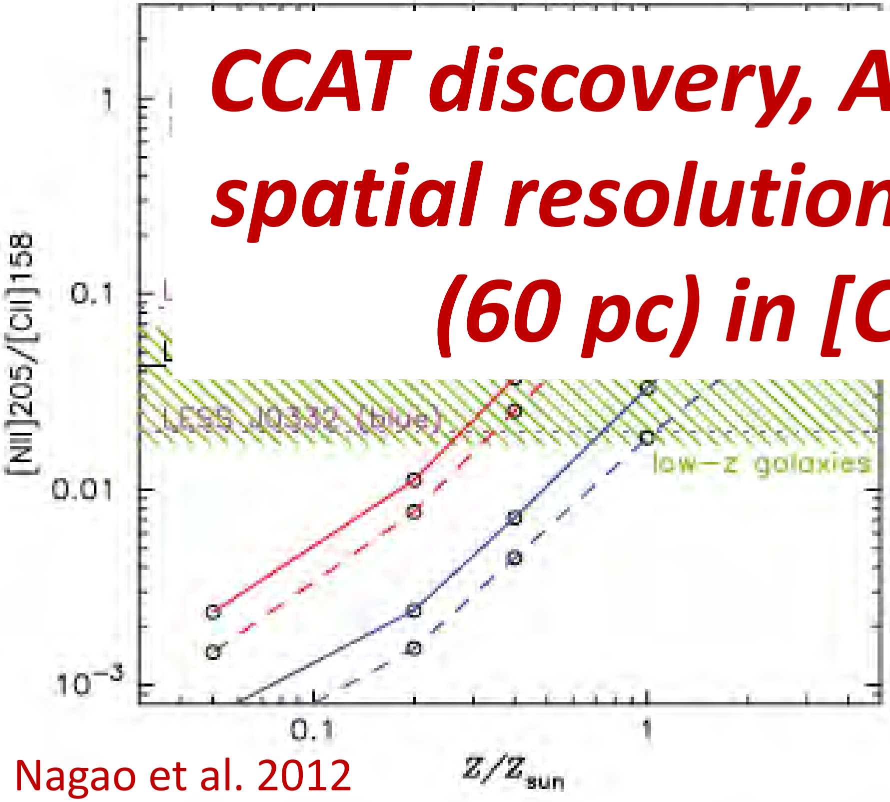
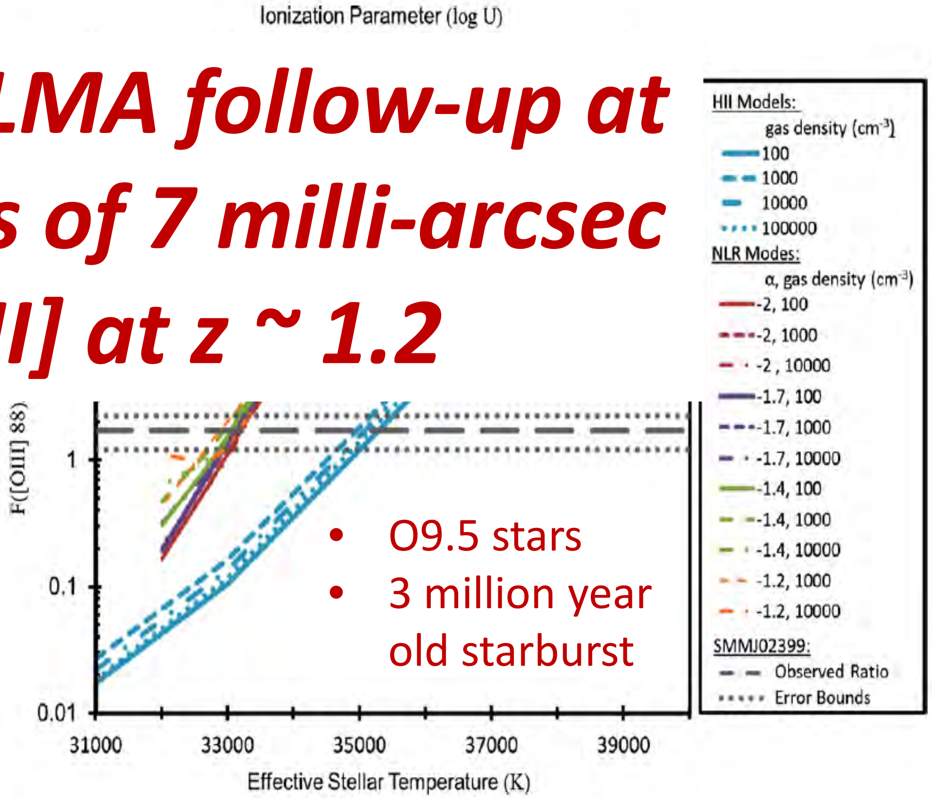
CCAT discovery, ALMA follow-up at spatial resolutions of 7 milli-arcsec (60 pc) in [CII] at z ~ 1.2



Nagao et al. 2012



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CCAT Cosmology and Cluster Science

- Sunyaev-Zel'dovich signal from CMB photons interact with hot cluster gas
- Multiple contributions to observed signal: both SZ and astrophysical
  - Thermal, kinetic, and relativisitic SZ
  - Sub-mm and radio galaxies
- Multi-frequency operations and high angular resolution are critical to disentangle the various components

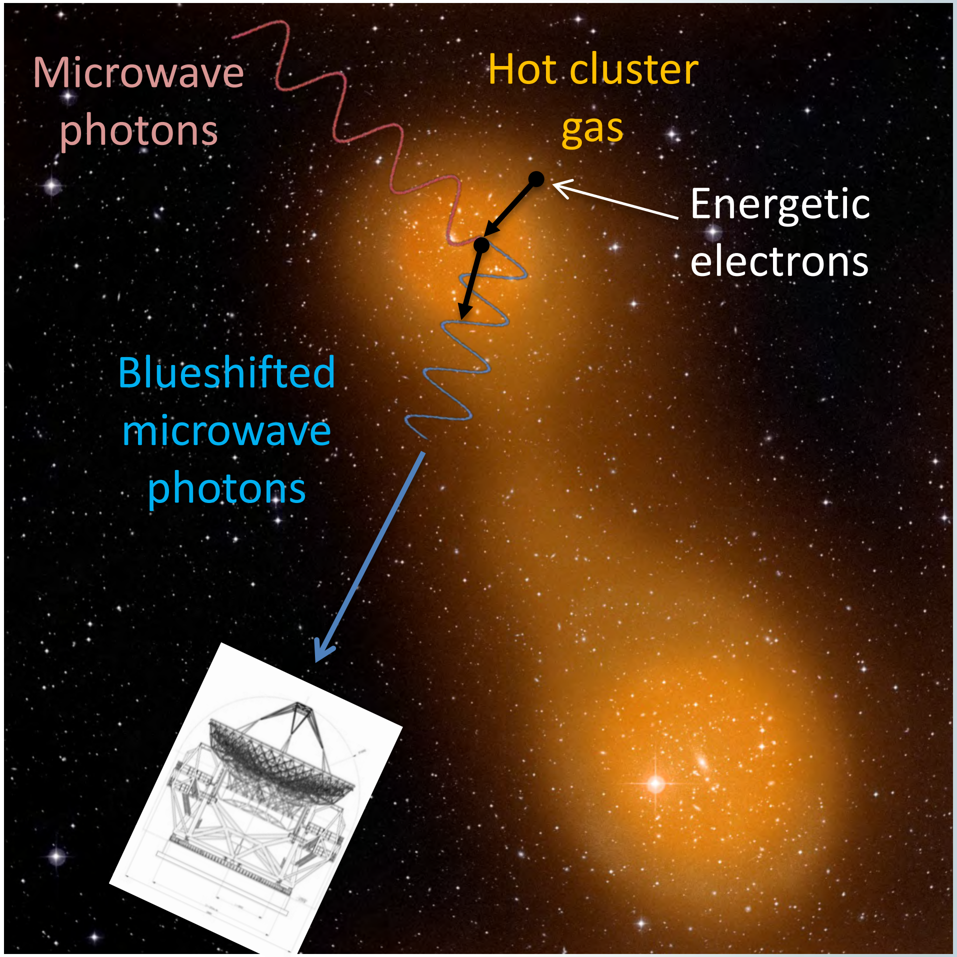
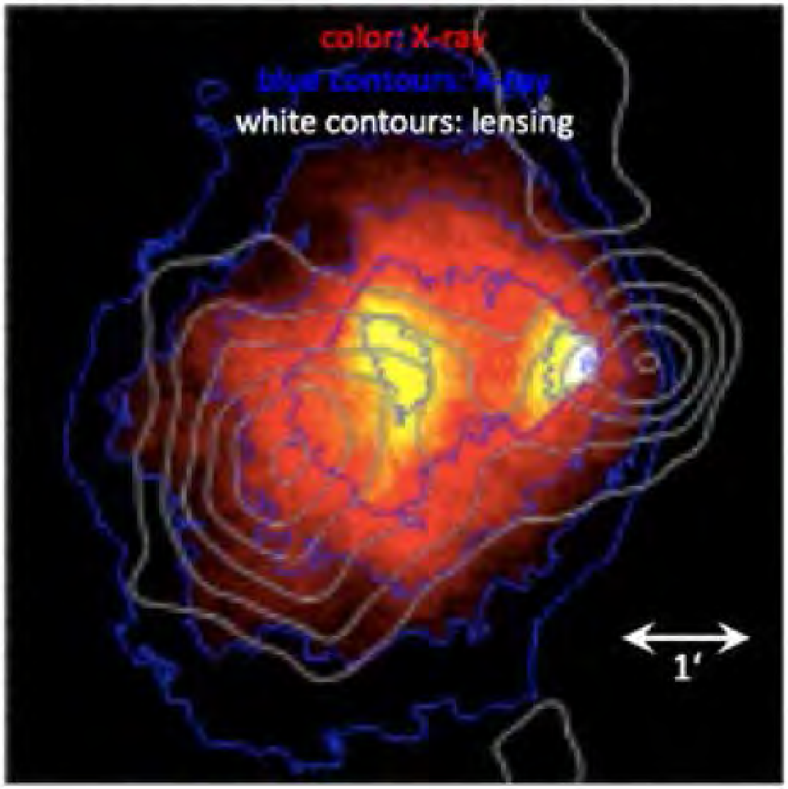
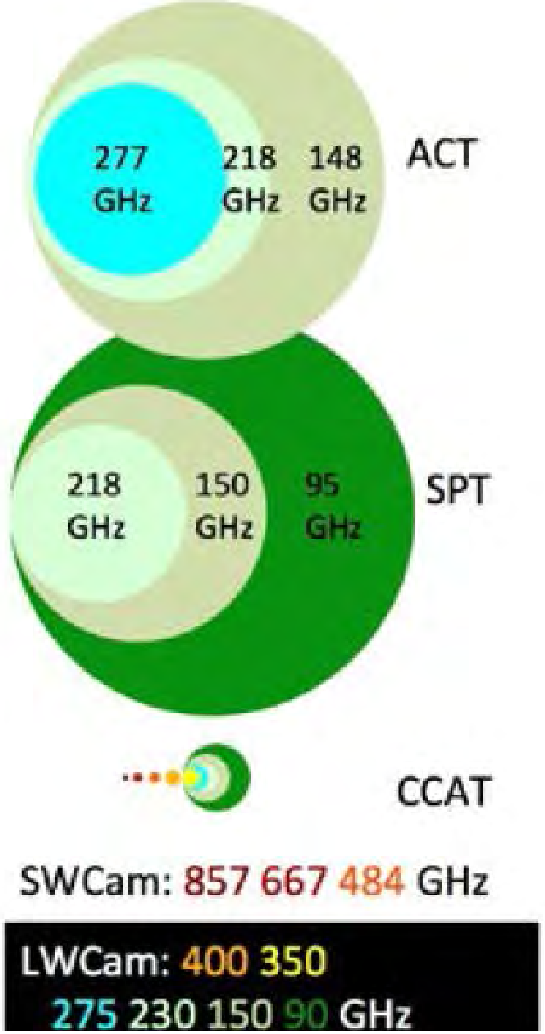


Image credit: ESA Planck Collaboration and STScI Digitized Sky Survey

High Spatial Resolution is the Key

Composite image of the Bullet Cluster





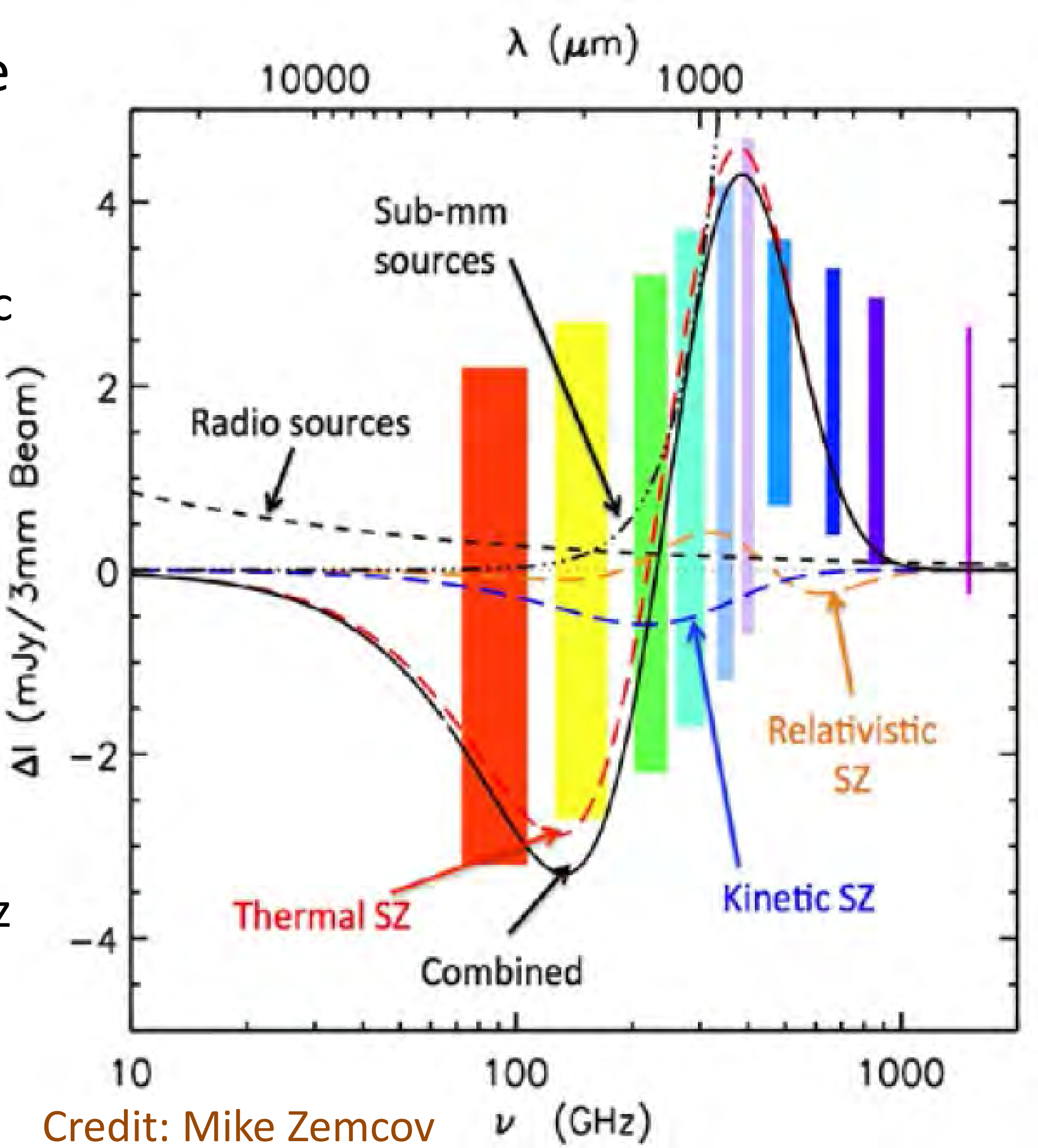
Credit: Tony Mroczkowski & Sunil Golwala

- CCAT's measures hot gas distribution at arcsec resolution within clusters enabling:
  - Improved cosmological constraints
  - Cluster astrophysics:
    - Shocks due to mergers
    - Relativistic ejecta from BH accretion disks

CCAT

Multi-color SZ Studies

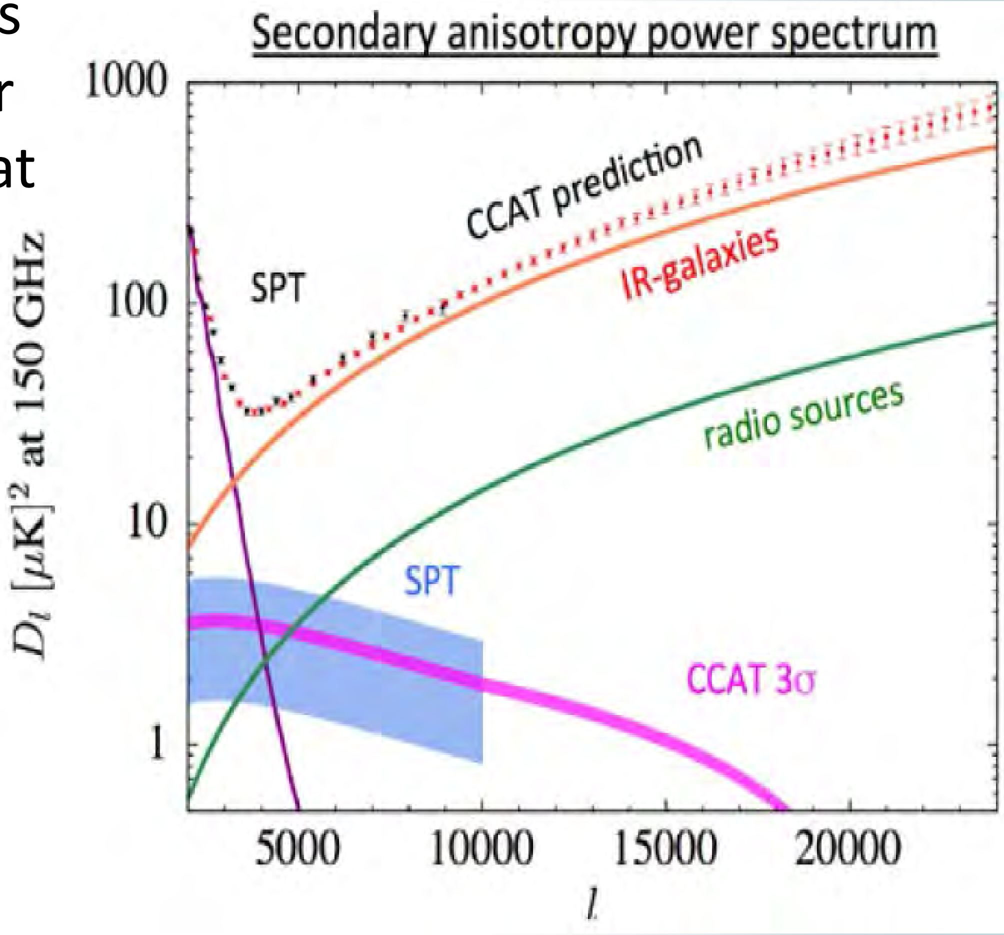
- CCAT has multi-band coverage so that multiple competing signals can be disentangled
  - Thermal, kinetic, and relativisitic SZ
  - Sub-mm and radio galaxies
- Isolating distinct SZ components ⇒ CCAT delivers SZ cluster masses without calibration from X-ray measurements
  - Very important at high z were X-ray or lensing data is sparse



Credit: Mike Zemcov

Cosmology with CCAT

- CCAT disentangles and resolves SZ $\Rightarrow$ CCAT measures SZ power spectrum to greater accuracy at smaller scales
  - Kinetic-SZ $\Rightarrow$ measure motions of H bubbles during EOR constraining EOR duration
  - Kinetic-SZ measures cluster motions $\Rightarrow$ tests how these most massive objects move in cosmological gravitational fields
  - Probes gravity on cosmic scales leading to insights on dark energy.



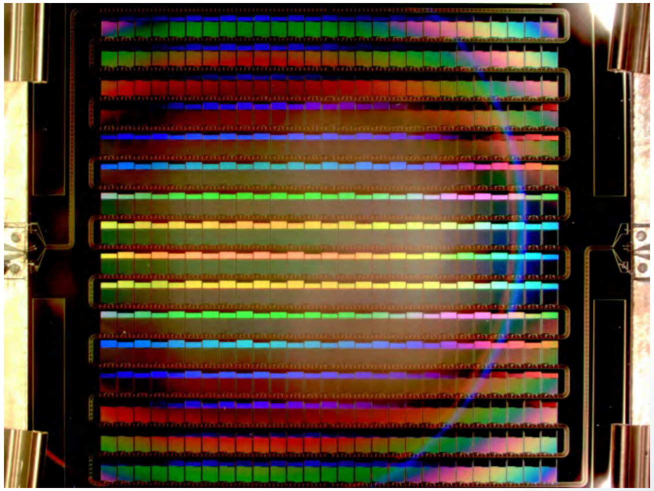
Projected CCAT CMB secondary anisotropy power spectrum. Credit: Miriam Ramos-Ceja & Kaustuv moni Basu

Instrumentation Plans

Four instruments are in preliminary design phase, all multi-institutional :

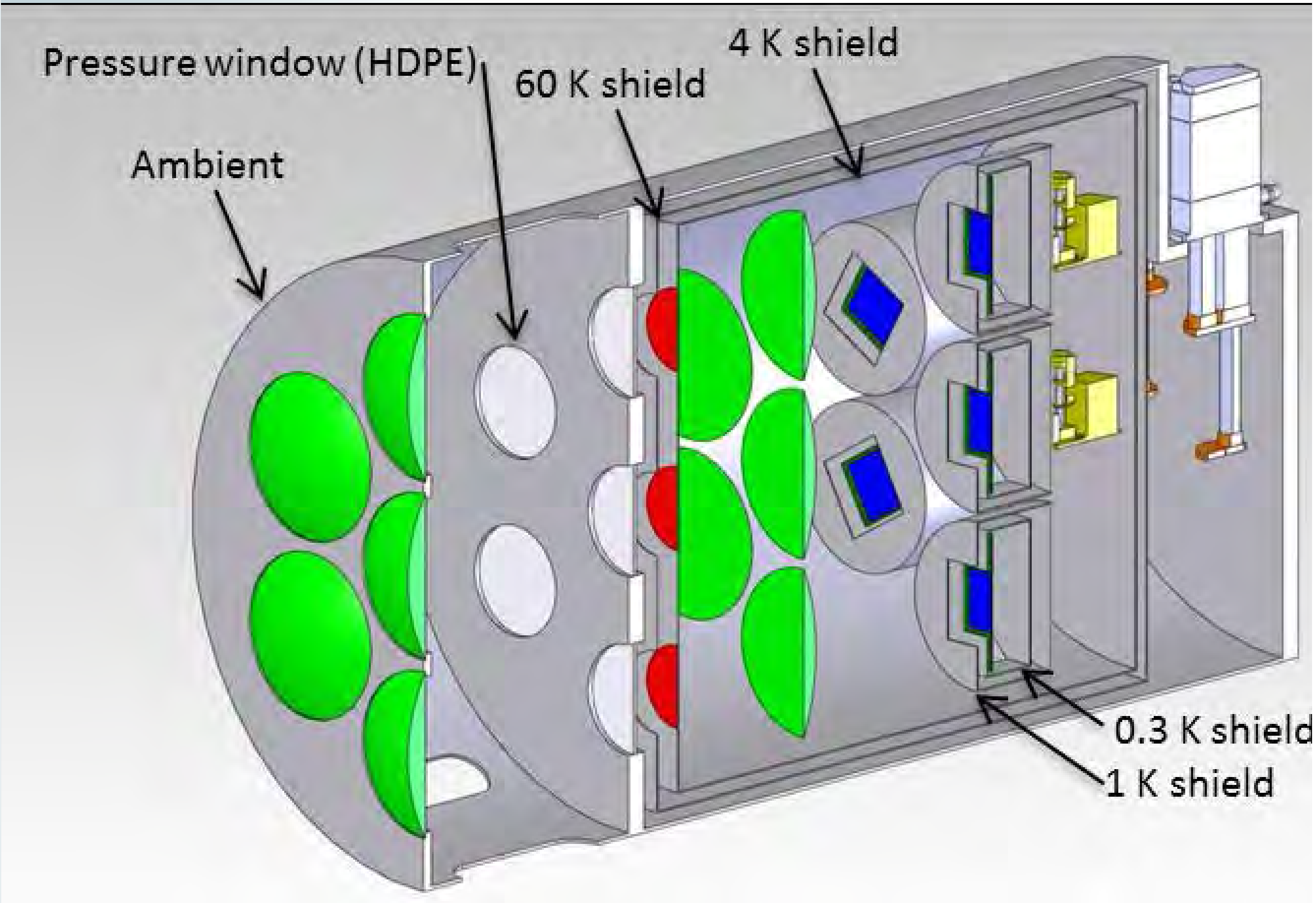
- Short Wavelength Camera (PI: G. Stacey, Cornell) (*)
- Long Wavelength Camera (PI: S. Golwala, Caltech) (*)
- Direct Detection MOS (PI: M. Bradford, JPL) (*)
- Heterodyne Feed Array (PI: J. Stützki, Köln)

(*) Direct detection instruments MKIDs are technology of choice: they are intrinsically multiplexable, and can be implemented into large format arrays with relatively simple readout electronics.



432 pixel TiN MKID array for MAKO/SWCam (Caltech/JPL)

Short Wavelength Camera (SWCam)

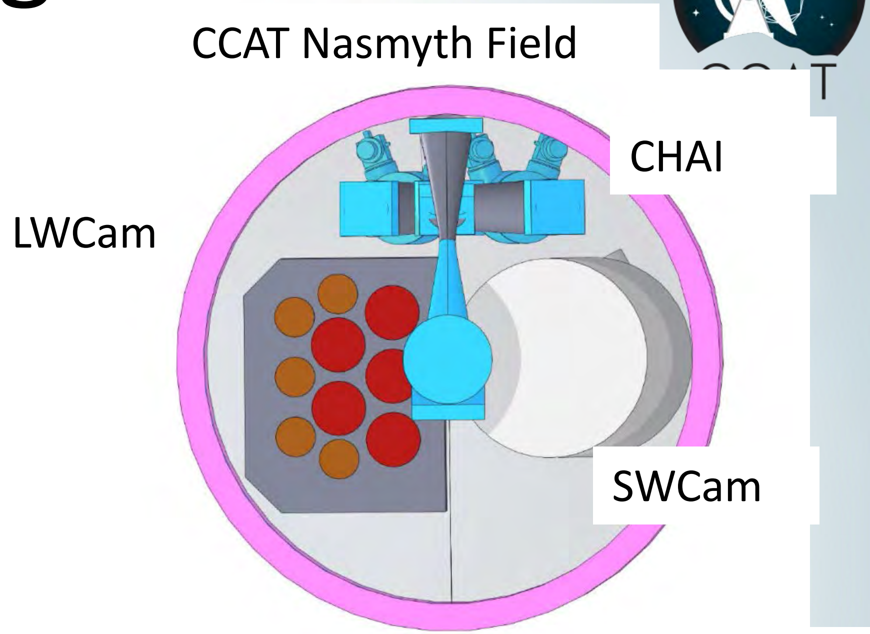


- 7 planar subarrays ~ 9000 pixels each @ 2.9” p.s. ⇒ 63,000 pixel submm camera w/ 13’ FoV
- Primary bands 350 and 450 µm; secondary bands 200 & 850 µm
- Meandering inductor coupled direct absorption MKID arrays

CCAT

Long-Wavelength Camera

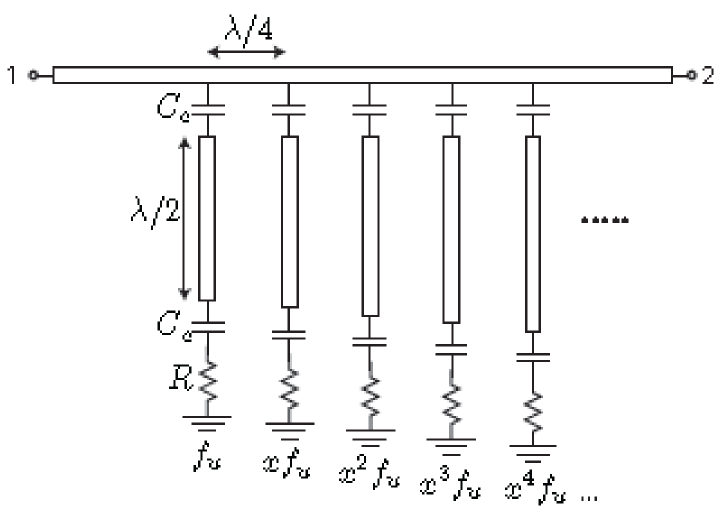
- PI: Sunil Golwala
- Primary Observing Bands
  - Between 750 µm and 3.3 mm
  - 6 sub-arrays
  - 20’ FoV
  - ~ 40,000 pixels
- Technology
  - Antenna coupled MKID detectors
  - TES/feed-horn coupled backup



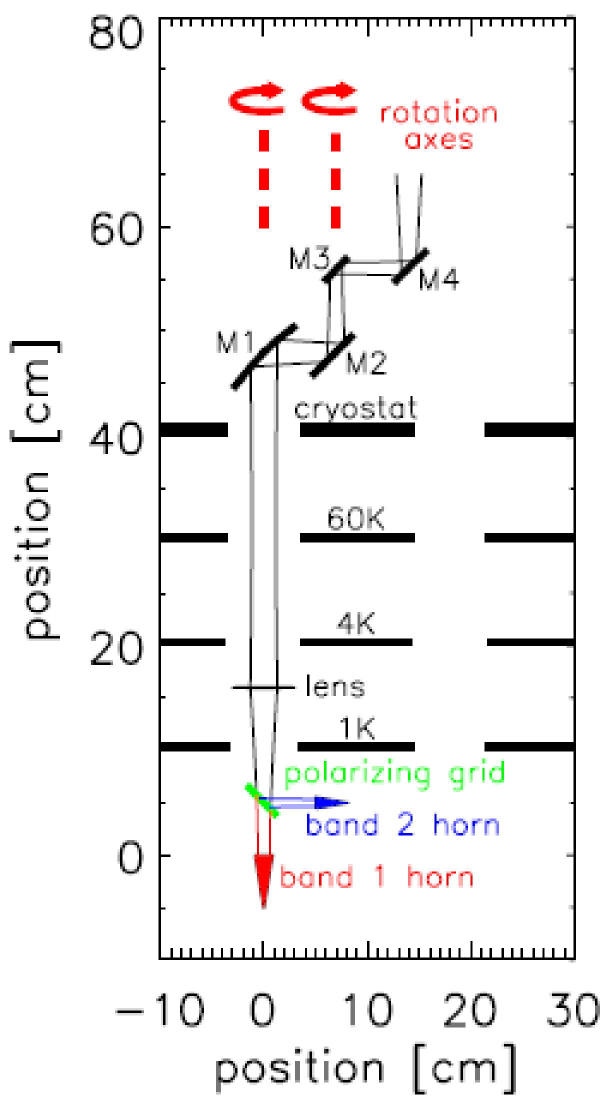
λ [μm]	ν [GHz]	$\Delta\nu$ [GHz]	Per-Pixel Sensitivity [mJy $s^{1/2}$]	Number of Pixels
750	400	30	18	16384
850	350	34	10	16384
1100	275	95	2.4	4096
1300	230	62	2.2	4096
2000	150	47	2.3	1024
3300	90	35	2.7	1024

X-Spec: A Multi-Object Spectrometer for CCAT

- PI: Matt Bradford
- Spectral coverage: 195 GHz – 520 GHz in 2 bands
- Redshifts from CO lines at z ~ 0 to 3, fine-structure lines at z ~ 3 to 10
- Resolving power: 400 – 700
- Simultaneous spectra: Between 20 and 300 beams on the sky likely fixed beam positions for larger formats
- Technology: “on-chip” filter bank architecture with MKID readouts
- Fed with swinging arm twin periscopes



X-S bject Spectrometer CCAT



- PI:
- Spe – 520 GH
- Re ~ 0 to 3, f 3 to 10
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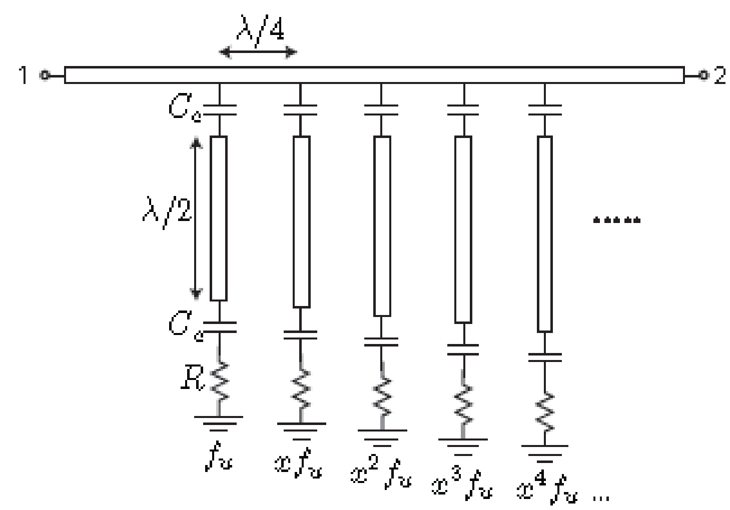

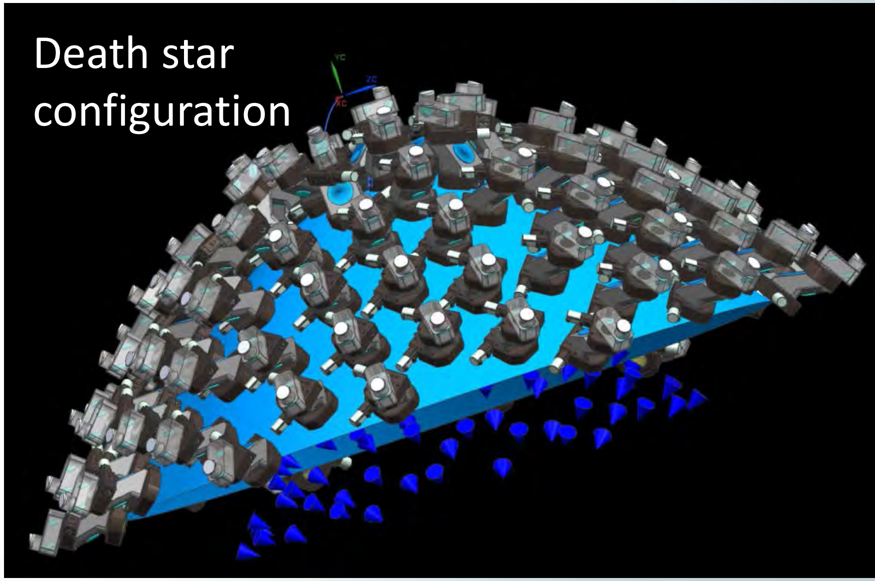

Death star configuration

CHAI: CCAT Heterodyne Array Instrument

- PI: Jürgen Stutzki
- Heterodyne, dual frequency array
- Operating bands: 500 GHz (600 μm) and 850 GHz (350 μm)
  - 2’ × 2’, 14” spacing at 600 μm
  - 1’ × 1’, 8” spacing at 370 μm
  - Mid-J CO; ^{13}CO, and [CI] F-S lines in Galactic star formation regions and nearby galaxies
  - Comets in the HDO 1_{10}-1_{01} 509 GHz line
- 64 (baseline), 128 (goal) pixels in each band

CCAT Consortium Members

- Cornell University (*)
- California Institute of Technology(*)/Jet Propulsion Laboratory
- University of Colorado(*)
- University of Cologne(*) + University of Bonn
- Canadian consortium(**):
  - U. of Waterloo, U. of British Columbia, U. of Toronto, Dalhousie U., McGill U., of Western Ontario, McMaster U. and U. of Calgary
- Associated Universities, Inc.
- U.S. National Science Foundation

(*) Signers of CCAT Consortium Agreement and members of CCAT Corp.
(**) Members of Canada Corp., which is in process of joining CCAT Corp.

Project Timeline

- October 2003: Partnership Workshop in Pasadena
- Feb 2004: MOU signed by Caltech, JPL and Cornell
- 2005: Project Office established
- 2006: Feasibility Study Review
- 2007-2010: Consortium consolidation, design development. Site selection completed
- 2010: First-ranked mid-scale project by Astro2010
- 2010 Nov: $11M donation by Fred Young (Cornell)
- 2011 Feb: Jeff Zivick takes over as Project Manager
- 2011 Jun: NSF Award of $4.5M toward CCAT Engineering Design
- 2011 Nov: Universities of Köln/Bonn awarded $9M by German Foundation for CCAT
- 2011-2013: Detailed Engineering Design (EDP) underway ($12.7M)
- September-2013: Preliminary Design Review
- 2013-2017: Construction and First Light

CCAT