Submillimeter astronomy at Caltech: CCAT and CSO

J. Zmuidzinas

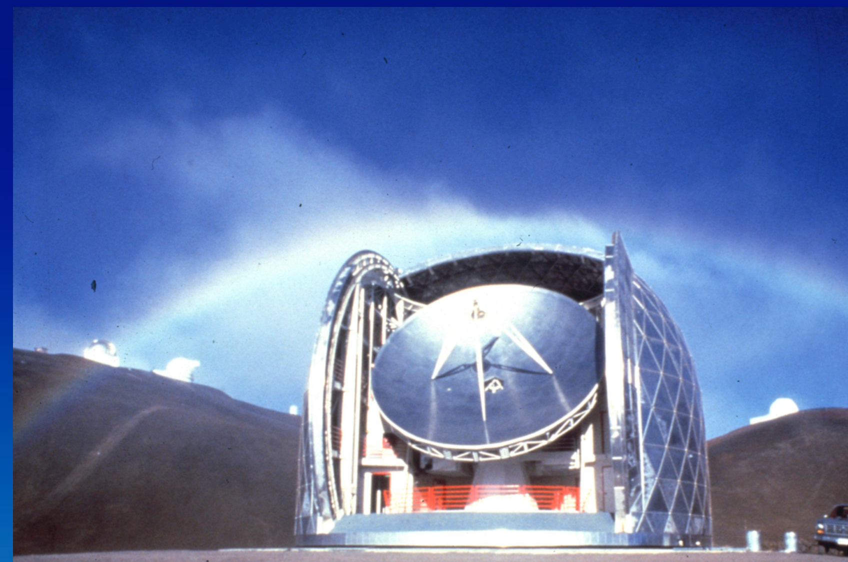
February 4, 2008

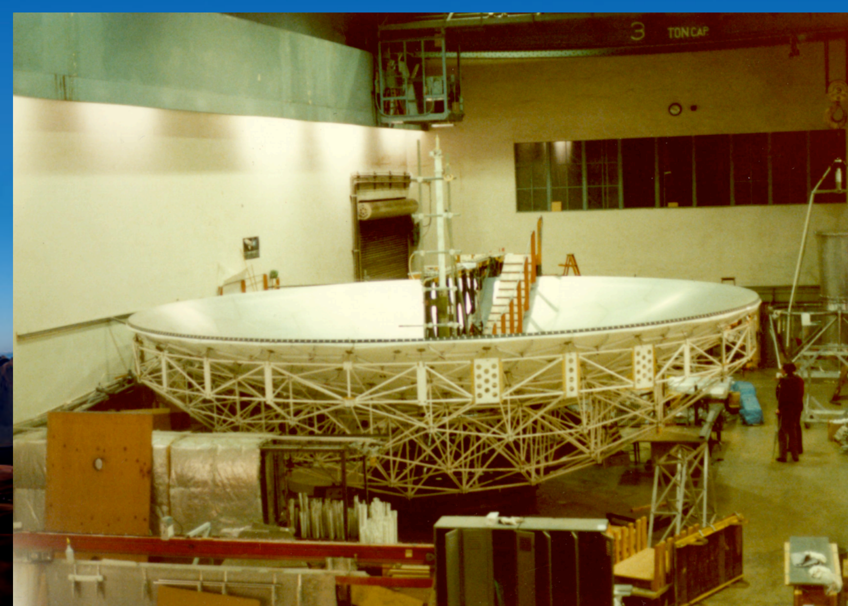
CCAT Organization

- Director
  - Riccardo Giovanelli, Cornell
- Project Manager
  - Tom Sebring, Cornell
- Deputy Project Manager
  - Simon Radford, Caltech
- Project Scientists
  - Terry Herter (Cornell) and Jonas Zmuidzinas (Caltech)
- Interim Board
  - Anneila Sargent (chair), Tom Tombrello (Caltech)
  - Joe Veverka, Joe Burns (Cornell)
  - Web Cash (acting chair; Colorado)
  - Ian Robson, Colin Vincent (UK)
  - Mike Fich, Mark Halpern (Canada)

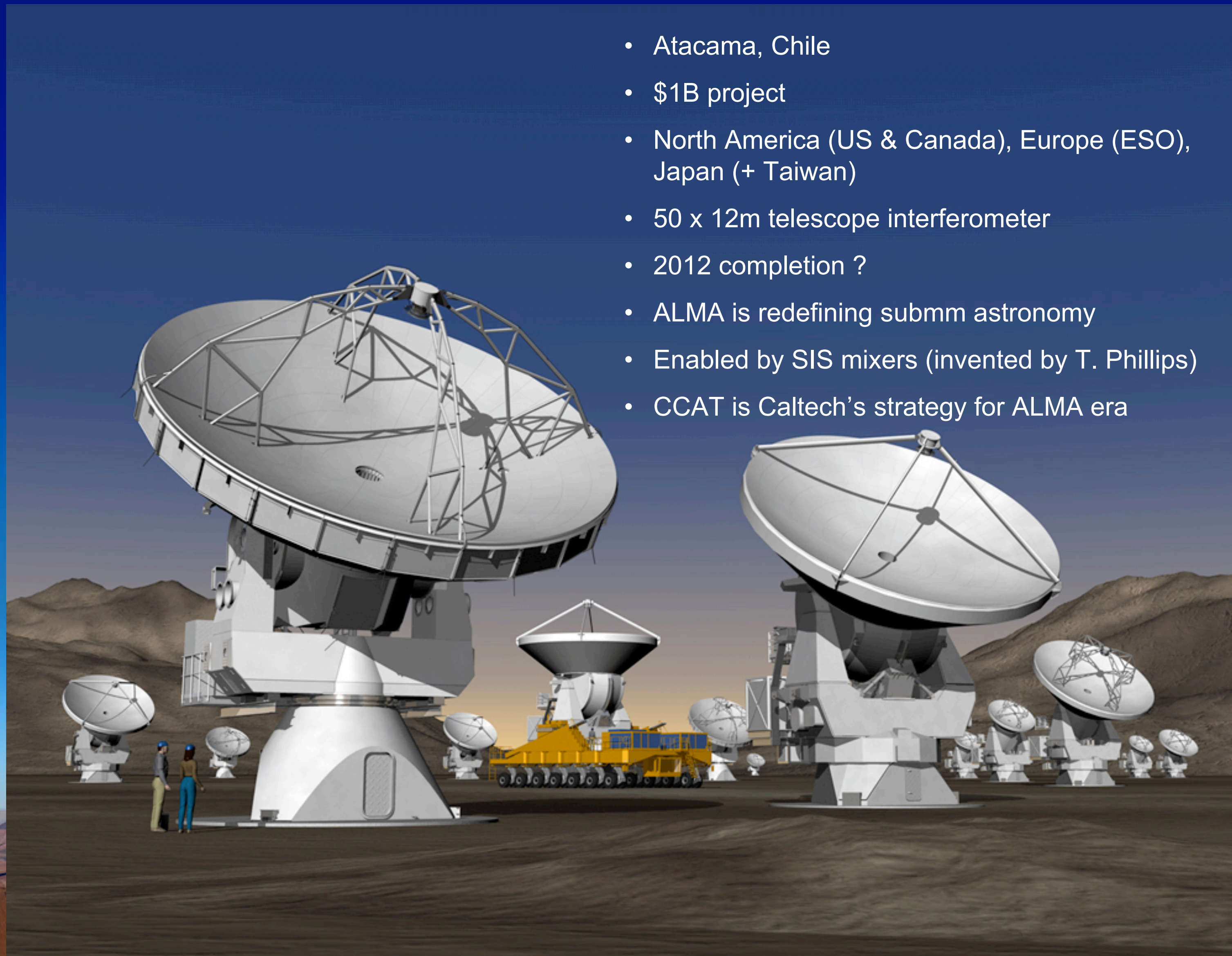
The Caltech Submillimeter Observatory

- Mauna Kea, HI
- 4100 m altitude
- 10.4 m diameter Leighton telescope
- 0.3 to 2 mm wavelengths
- Active surface
- NSF supported
- #1 ranking in Aug ‘05 review of NSF UROs, with CARMA
- Detector testbed for Herschel, Planck space missions (JPL)
- Operating since 1987
- T. G. Phillips, Director
- Active faculty: Blain, Blake, Golwala, Phillips, Sargent, Zmuidzinas
- 44 CSO PhD’s + 33 in progress





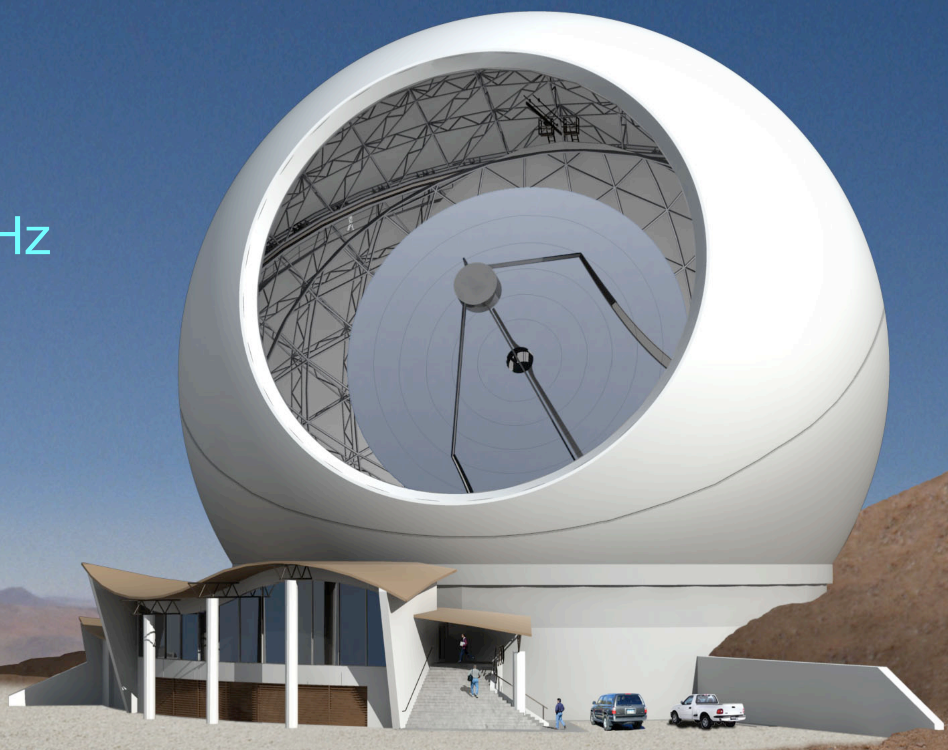
ALMA: a challenge and an opportunity



- Atacama, Chile
- $1B project
- North America (US & Canada), Europe (ESO), Japan (+ Taiwan)
- 50 x 12m telescope interferometer
- 2012 completion ?
- ALMA is redefining submm astronomy
- Enabled by SIS mixers (invented by T. Phillips)
- CCAT is Caltech’s strategy for ALMA era

CCAT: a 25m submillimeter telesope

- Cerro Chajnantor, Atacama, Chile, 5600m
- Cornell, Caltech/JPL, +partners
- Wavelengths 2 - 0.2 mm
- Frequencies 150-1500 GHz
- Surface accuracy 10 μm
- Angular resolution 2-20”
- Survey instrument:
  - Wide field of view
  - Large submm cameras
- Coincident with ALMA
- www.submm.org

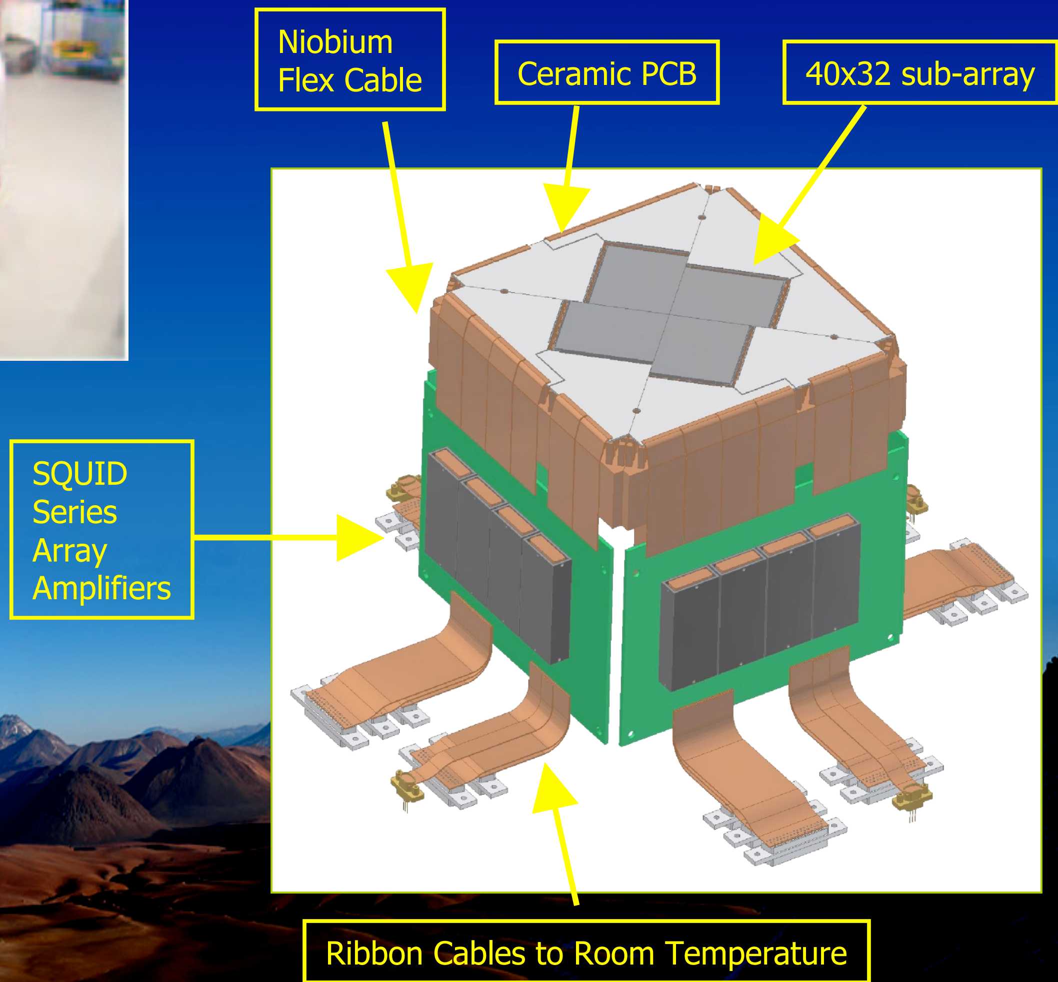


McCray committee report

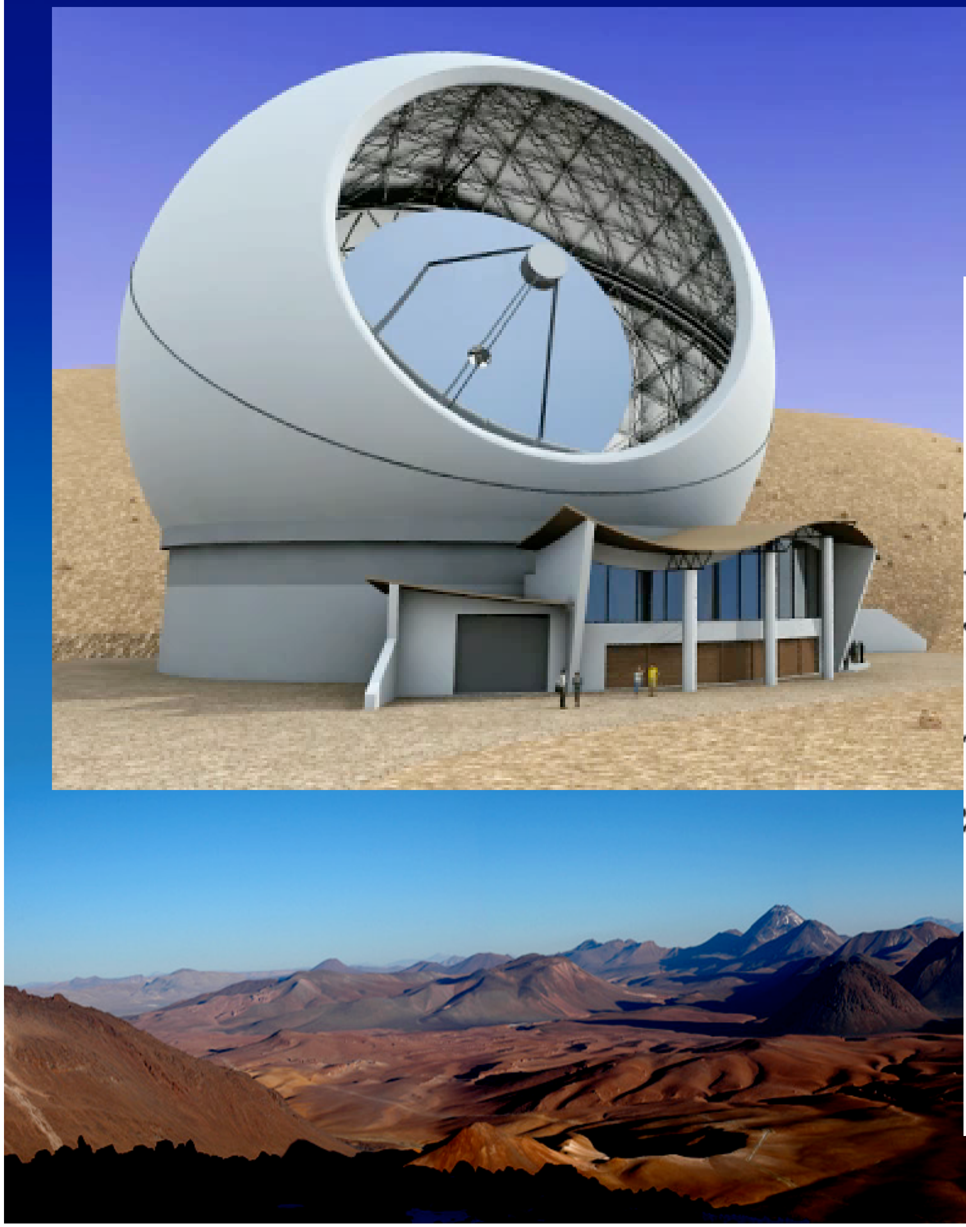
- “Future of US radio astronomy”, to inform decadal survey
- Convened by AUI
- Backer, Carilli, Gaensler, Genzel, Gnedin, Haynes, Heinz, Hewitt, Lazio, Readhead, Sargent, Wilcots, Wong, + Lo, Brown + Jack Burns (Exec. Sec’y)
- Importance of surveys in general
- CCAT/LMT surveys needed for ALMA science

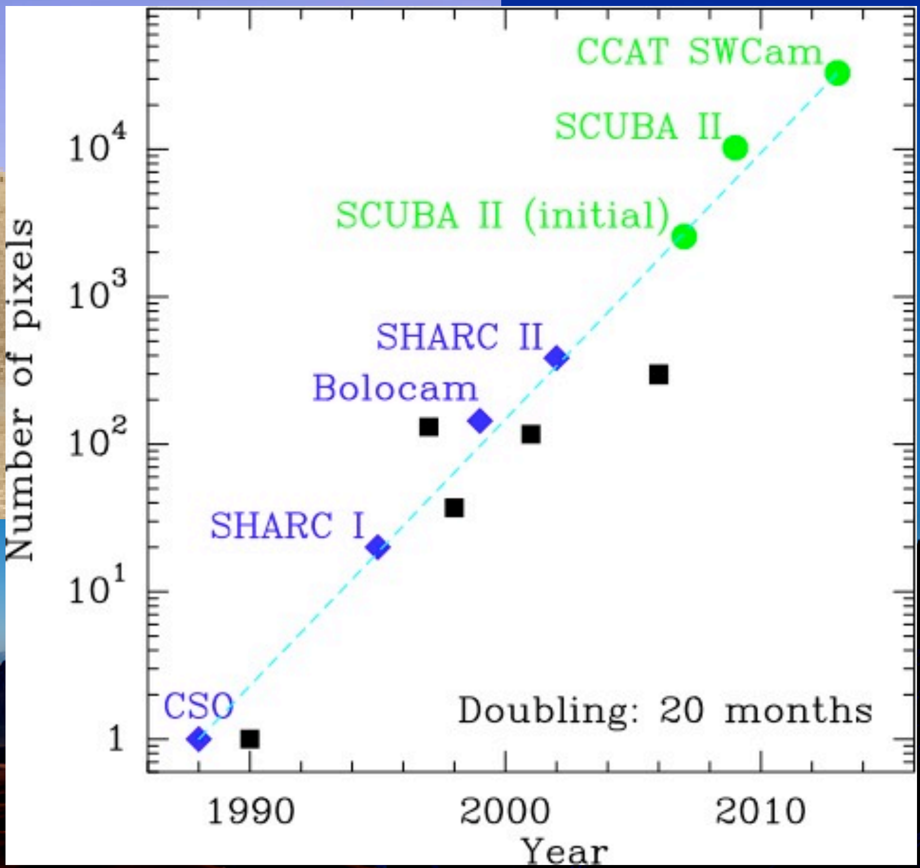
UK's SCUBA 2: multiplexed superconducting detector arrays

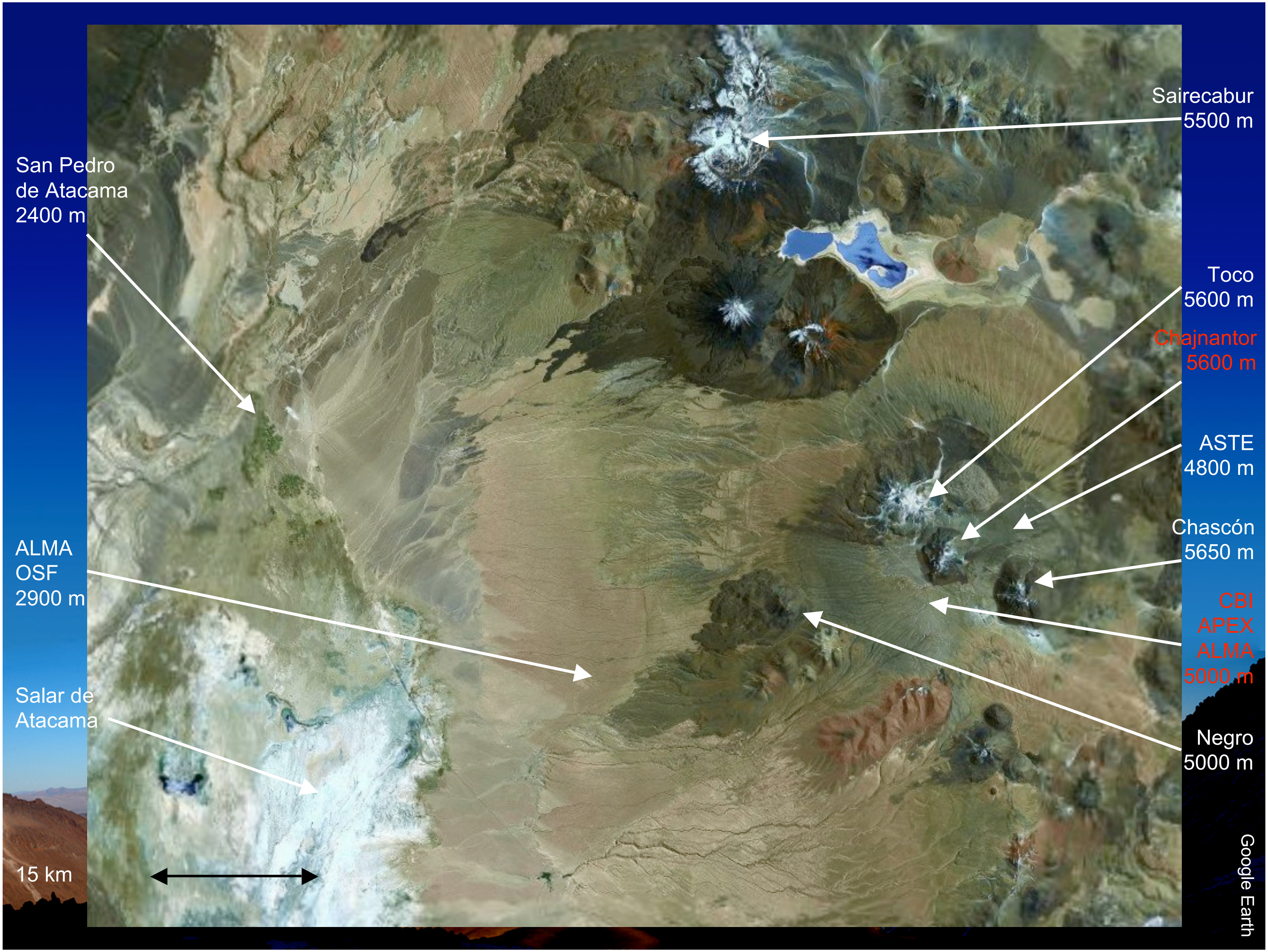
- 5000 close-packed pixels
- 450/850 μm
- 15m JCMT, Mauna Kea
- Cost: ~$40M
- Status: ship to JCMT in early '08
- Credit: W. Holland, UKATC



CCAT will exploit the revolution in submm array technology

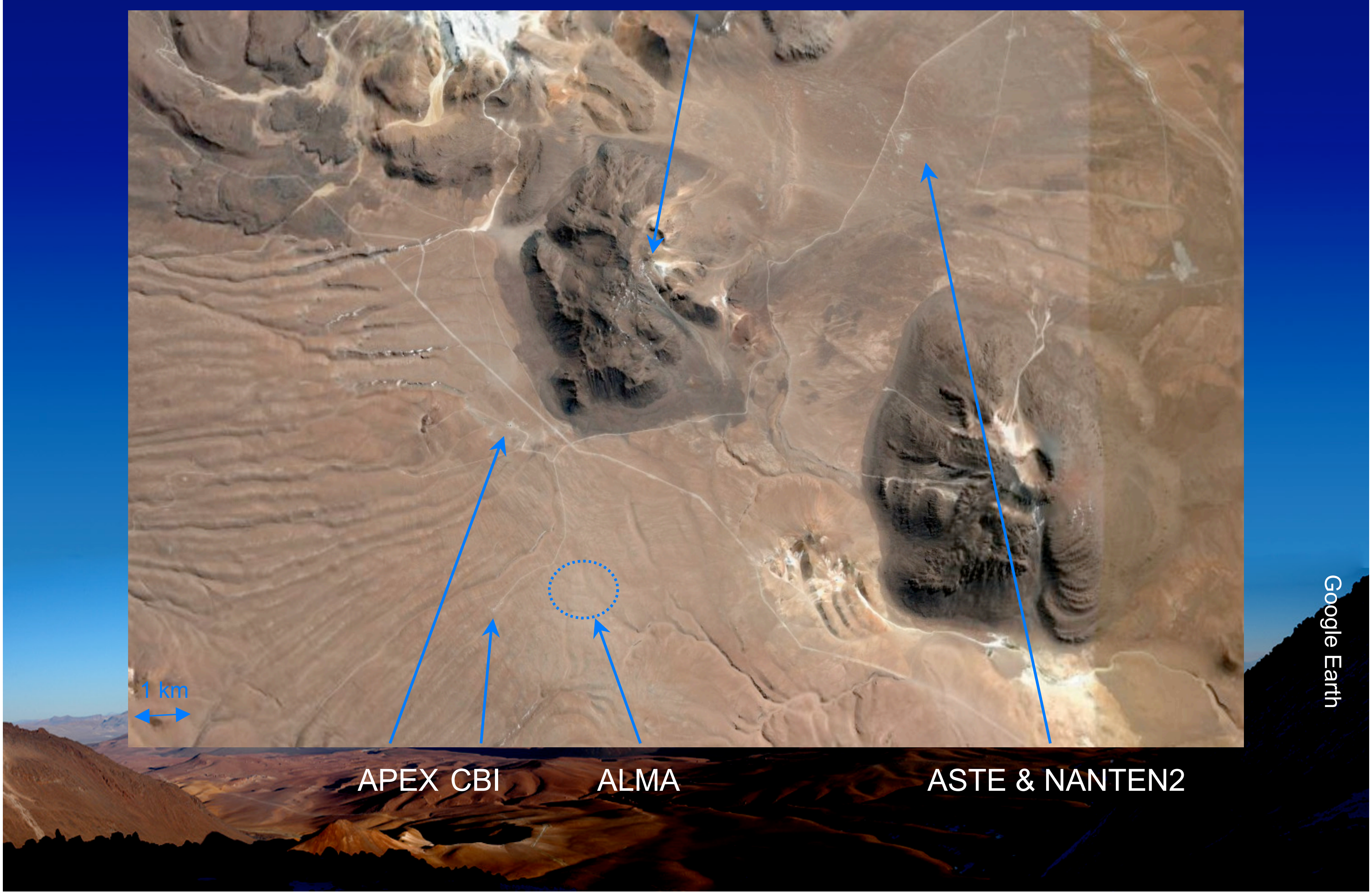






Sairecabur
5500 m
San Pedro
de Atacama
2400 m
Toco
5600 m
Chajnantor
5600 m
ASTE
4800 m
Chascón
5650 m
ALMA
OSF
2900 m
CBI
APEX
ALMA
5000 m
Salar de
Atacama
Negro
5000 m
15 km
Google Earth

Cerro Chajnantor 5612 m



Cerro Chajnantor 5612 m

View SW from ASTE; access road constructed by U. Tokyo


Cerro Chajnantor 5612 m
G. Gull/Cornell

Cerro Chajnantor 5612 m

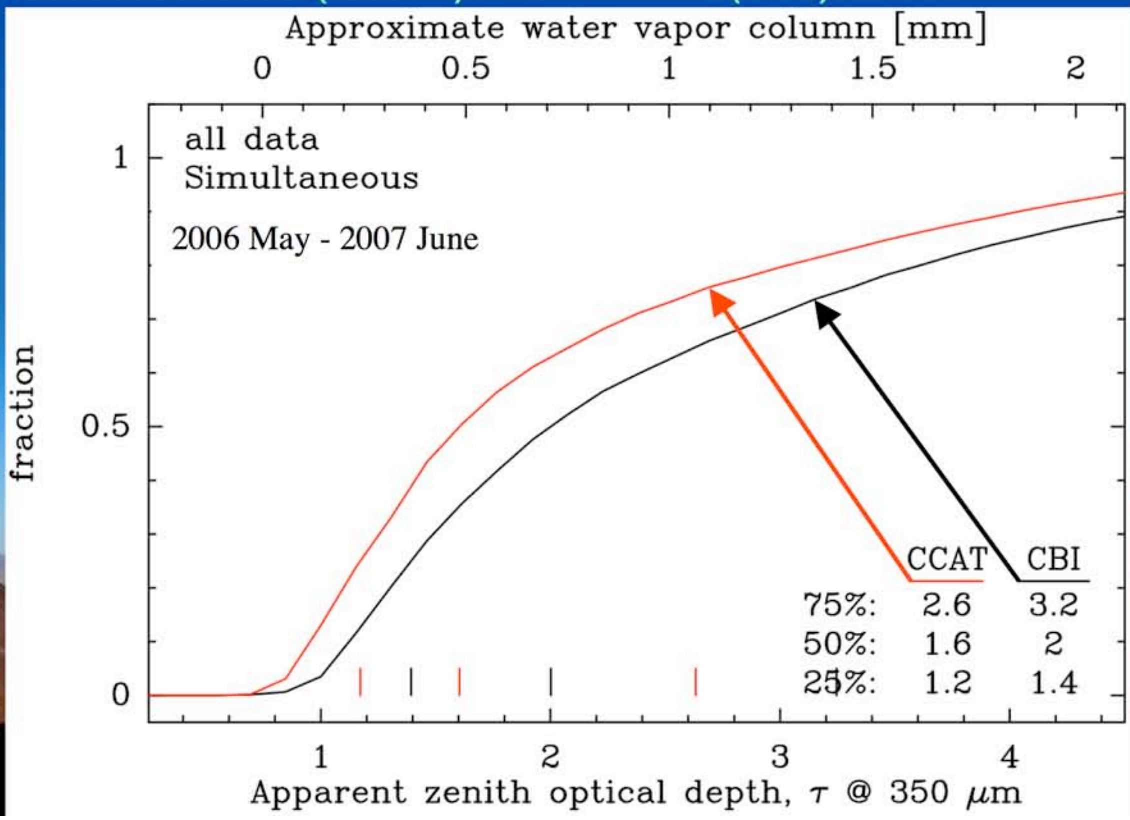
CCAT equipment overlooking ASTE & NANTEN2 @ 4800 m

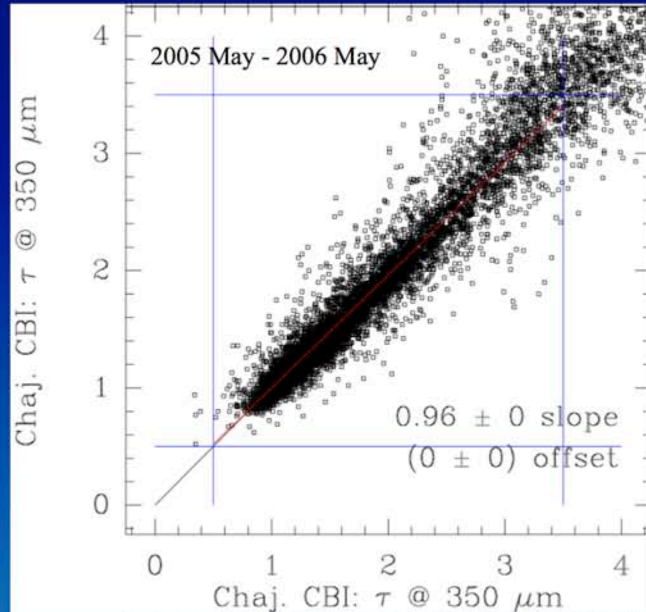
Cerro Chajnantor 5612 m

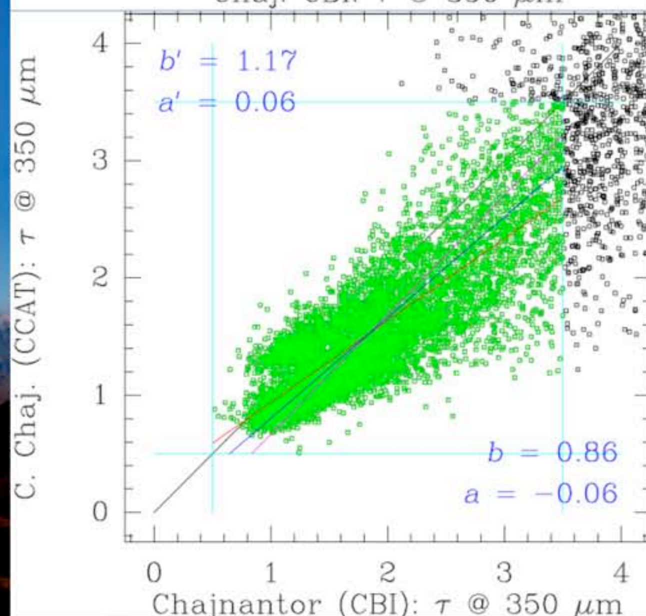
CCAT equipment: weather station and 350 μm tipper

Better 350 µm Transparency

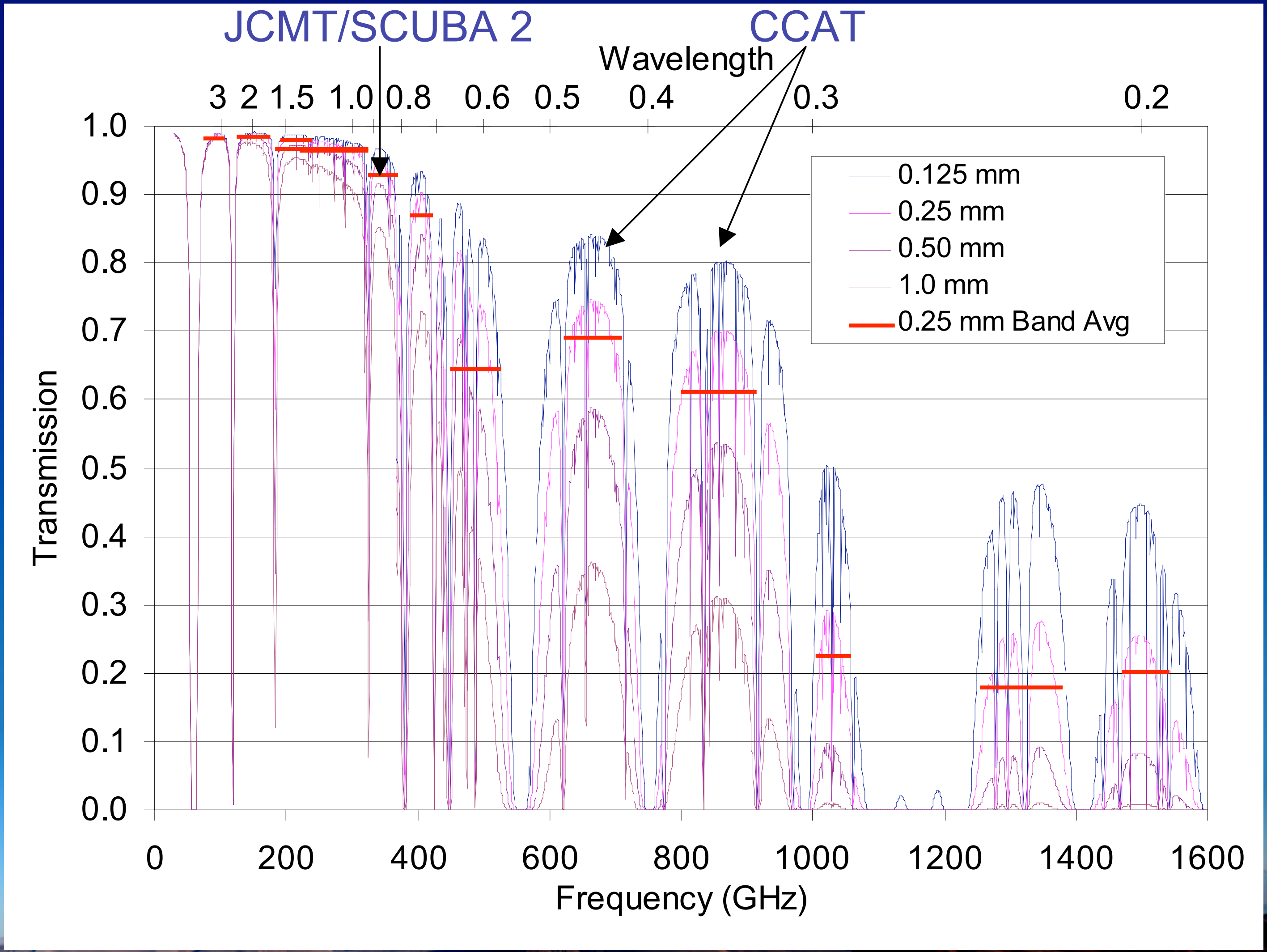
- Two Tippers: CCAT (5600 m) & CBI (5050 m)
- Side-by-Side at CBI: Same Values
- Better Transparency at CCAT
- Less Water Vapor at CCAT
  - $\tau_{off} \approx 0.5$
  - Slope ∝ PVW
  - PWV(CCAT) ≤ 70% PWV(CBI)







Atmospheric Transmission

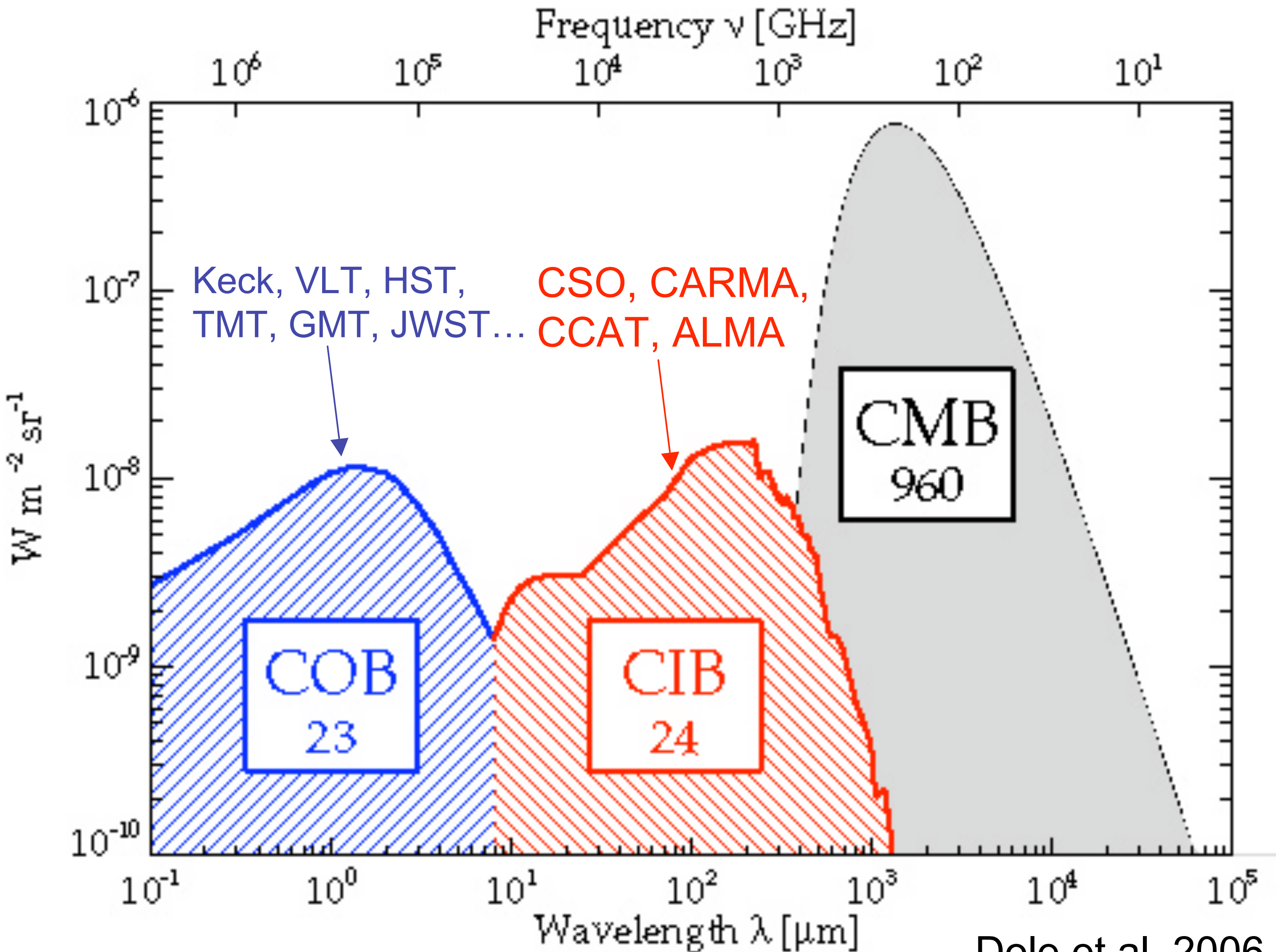


Atmospheric transmission for different amounts of precipitable water vapor. The horizontal red bars represent the adopted bandpasses and the average transmission for 0.25 mm PWV.

CCAT Science

- Lots of information available on submm.org !
- Topics
  - Cosmology (SZ, dark energy)
  - Galaxy formation and evolution (submm galaxies)
  - Nearby galaxies
  - Star formation
  - Exoplanets: debris disks
  - Solar system: Kuiper belt objects, …
- CCAT strengths
  - will be premier facility for mm/submm imaging, surveys
  - wide FOV + large-format cameras (1 mm - 200 μm)
  - Excellent site = high sensitivity, 50% time at 350 μm
  - 25 m aperture = high sensitivity, good resolution (3".5 @ 350 μm), low confusion
  - multi-object, wideband, R~1000 spectroscopy ?
  - narrow-band, $R\sim10^6$, imaging (100 pixel?) spectroscopy ?
- Perfect complement to ALMA
  - CCAT continuum point-source sensitivity well matched to ALMA
  - ALMA best for high-res imaging & spectroscopy in small FOV (17" @ 850 μm)
  - Prediction: ALMA will have poor continuum mosaicing ability

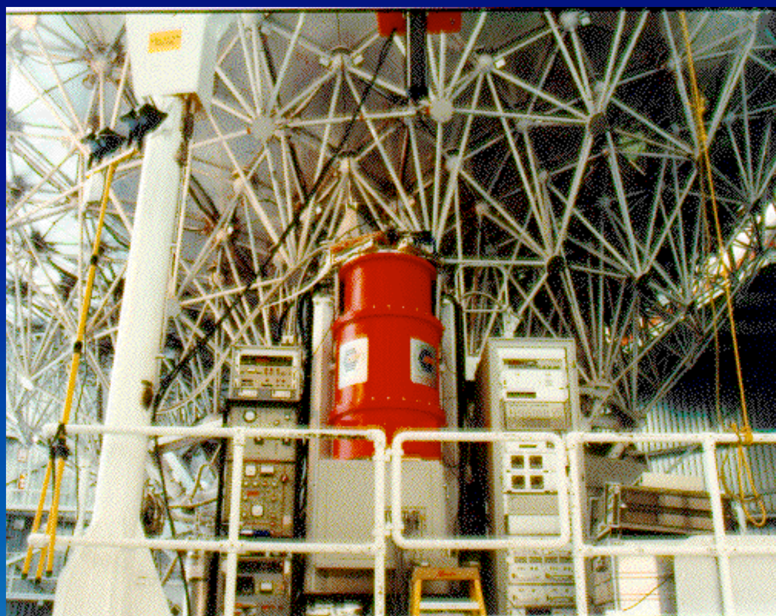
Half of the energy from stars ends up in far-IR/submm

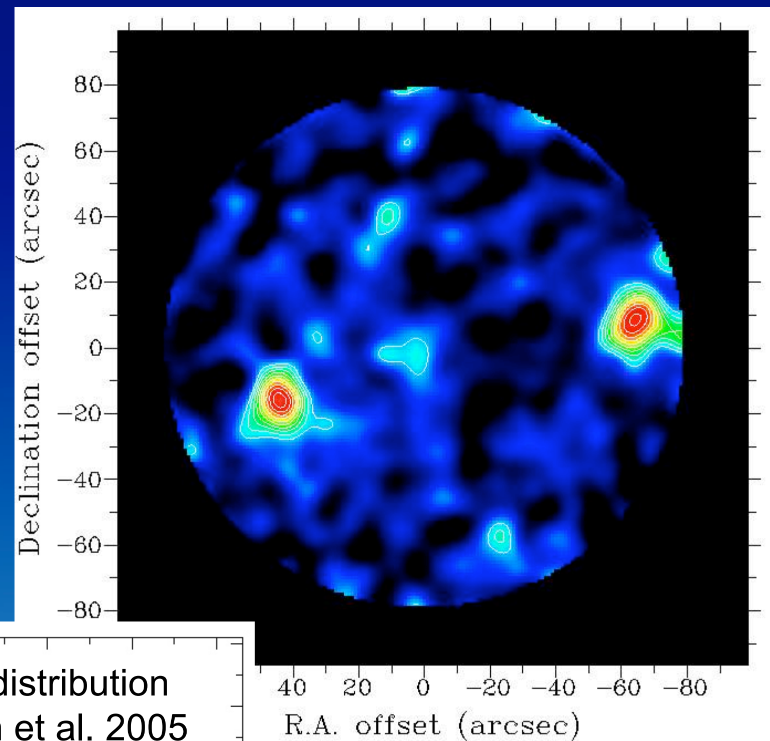


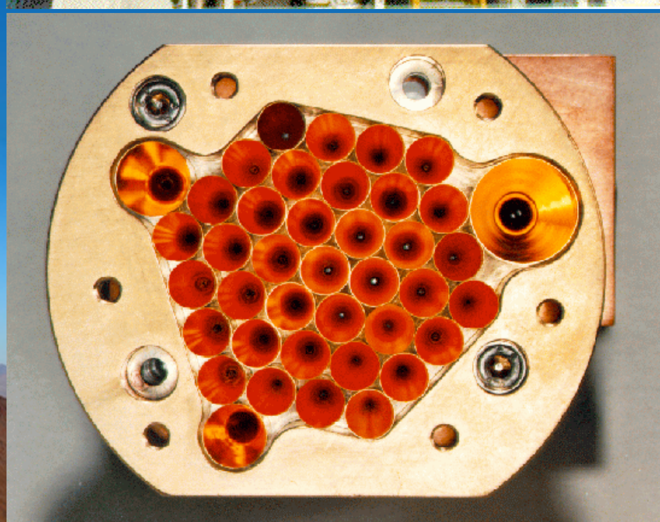
Dole et al. 2006

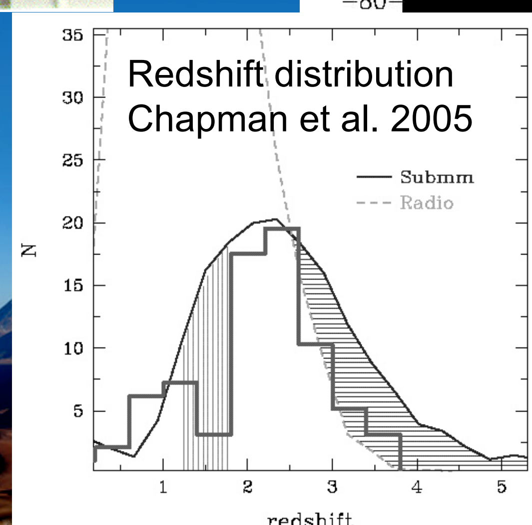
1997: SCUBA discovers submm galaxies

Smail, Ivison, Blain ApJ 490, L5

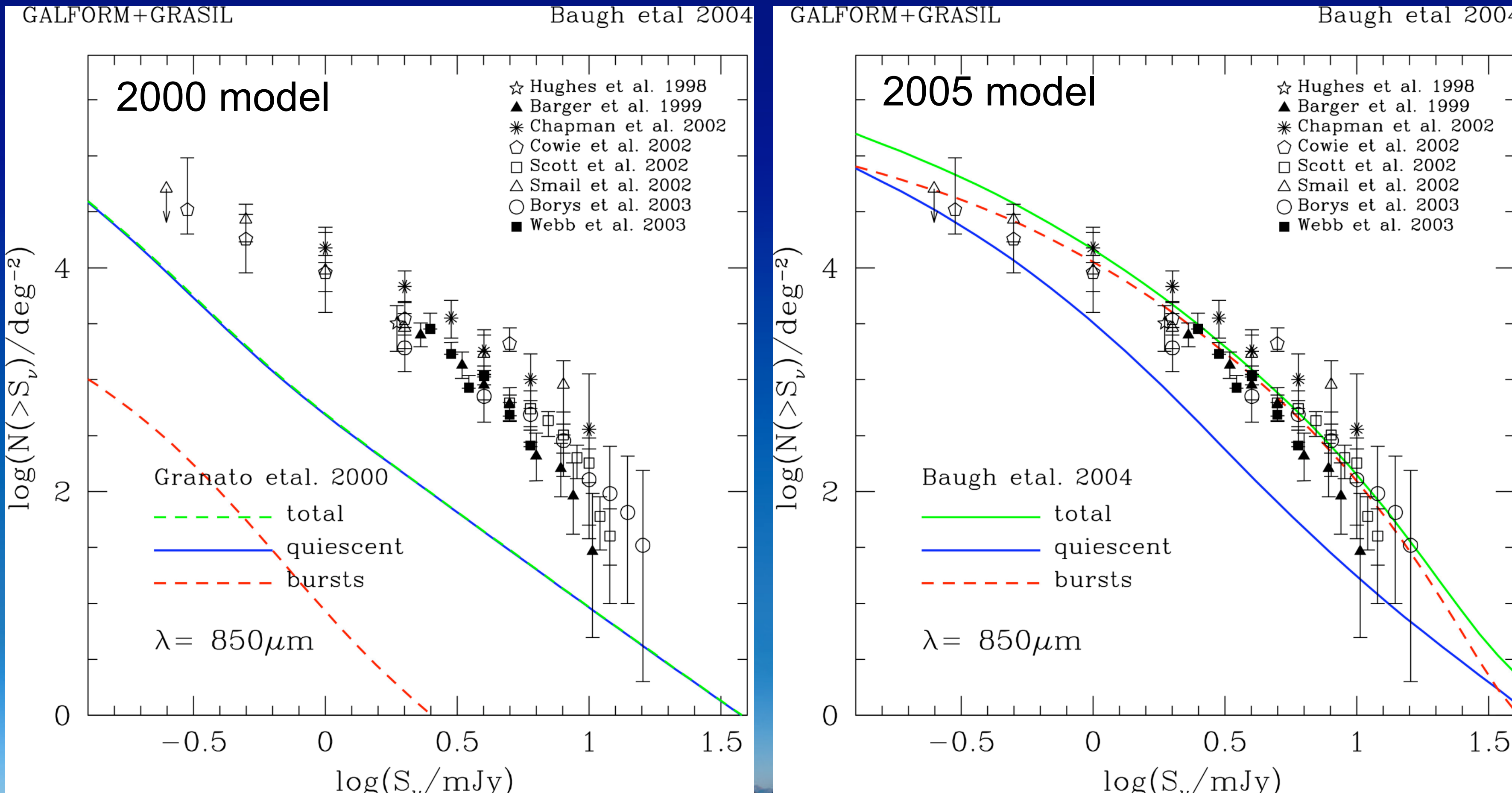








Submm galaxies are far more numerous than predicted (Frenk/Durham/GALFORM - A. Benson, SRA)



"Old" model matched optical data reasonably well…

…but submm data required drastic changes in assumptions regarding star formation in mergers

UKATC visit

- June/July 2007 (6 weeks)
- supported by SUPA
- Seminar + informal talk at UKATC
- Visits to:
  - Heriot-Watt (+Cunningham)
  - Scottish Microelectronics Centre (Edinburgh)
  - Cambridge (seminar)
  - St. Andrews (seminar)
  - Glasgow (+ Cunningham)
  - Durham (+ Robson, Ivison)

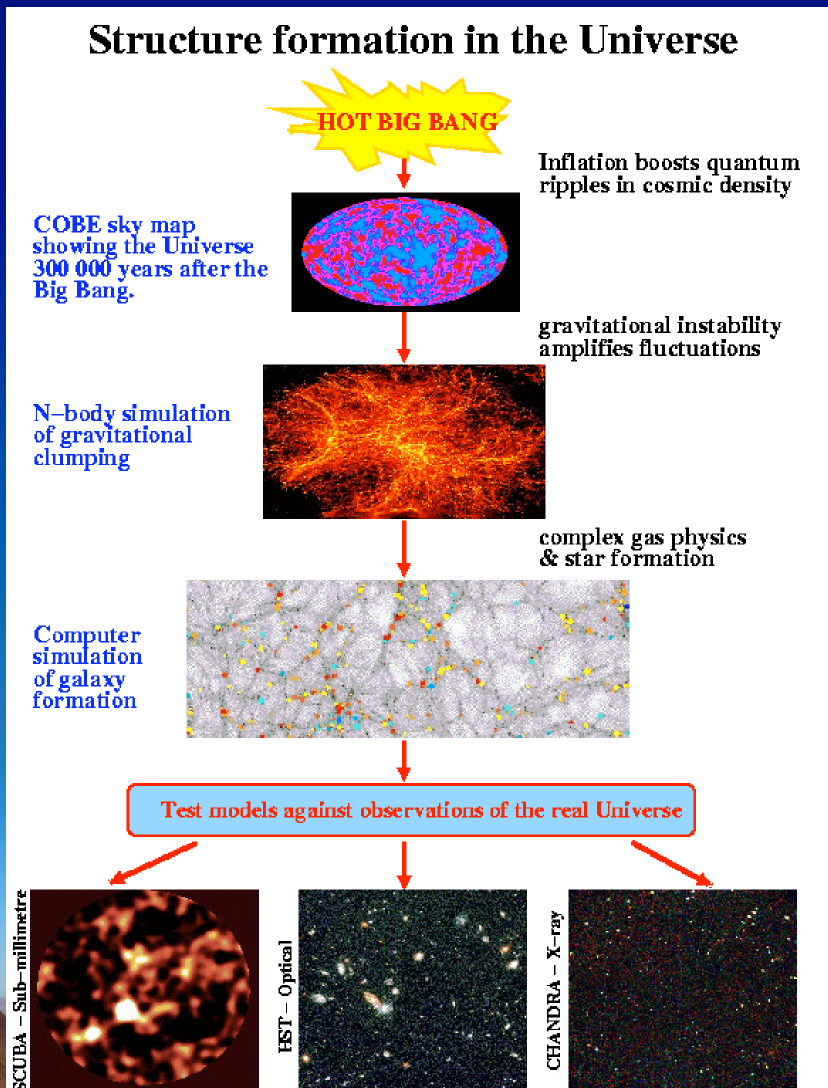
From Cedric Lacey:

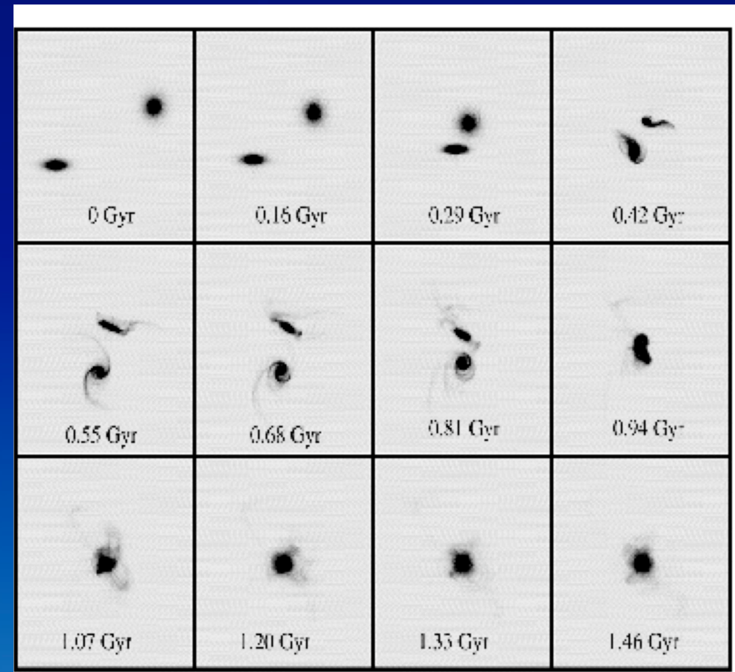
Dear Jonas,

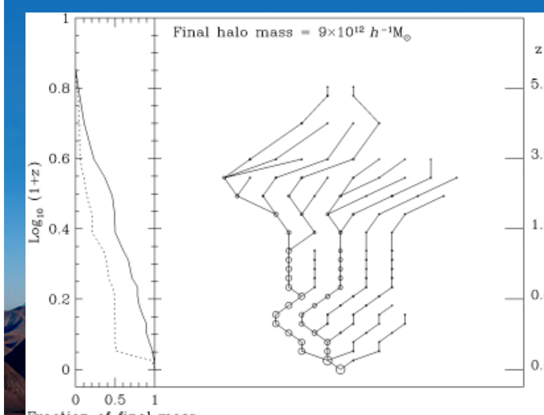
Our meeting together last week was very interesting. The group of us in Durham have decided that I should coordinate the input to the CCAT science case from the galaxy formation modelling using GALFORM+GRASIL. Mark Swinbank, Carlton Baugh, Ian Smail and Carlos Frenk will also be involved. If I remember correctly, you were most interested in the following predictions from the models: (1) number counts and redshift distributions at 350 um; (2) the use of the 350/850 um flux ratio as a means of selecting high-z SMGs as dropouts. Was there anything else which I've forgotten?

Best wishes, Cedric

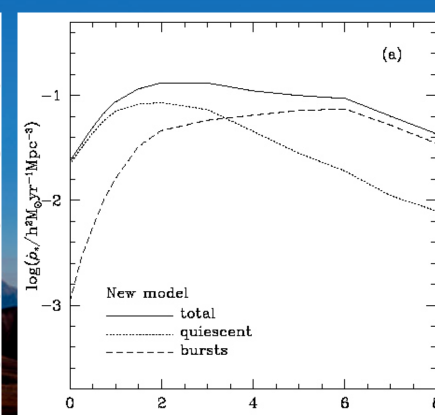
Mergers are key to understanding galaxy formation



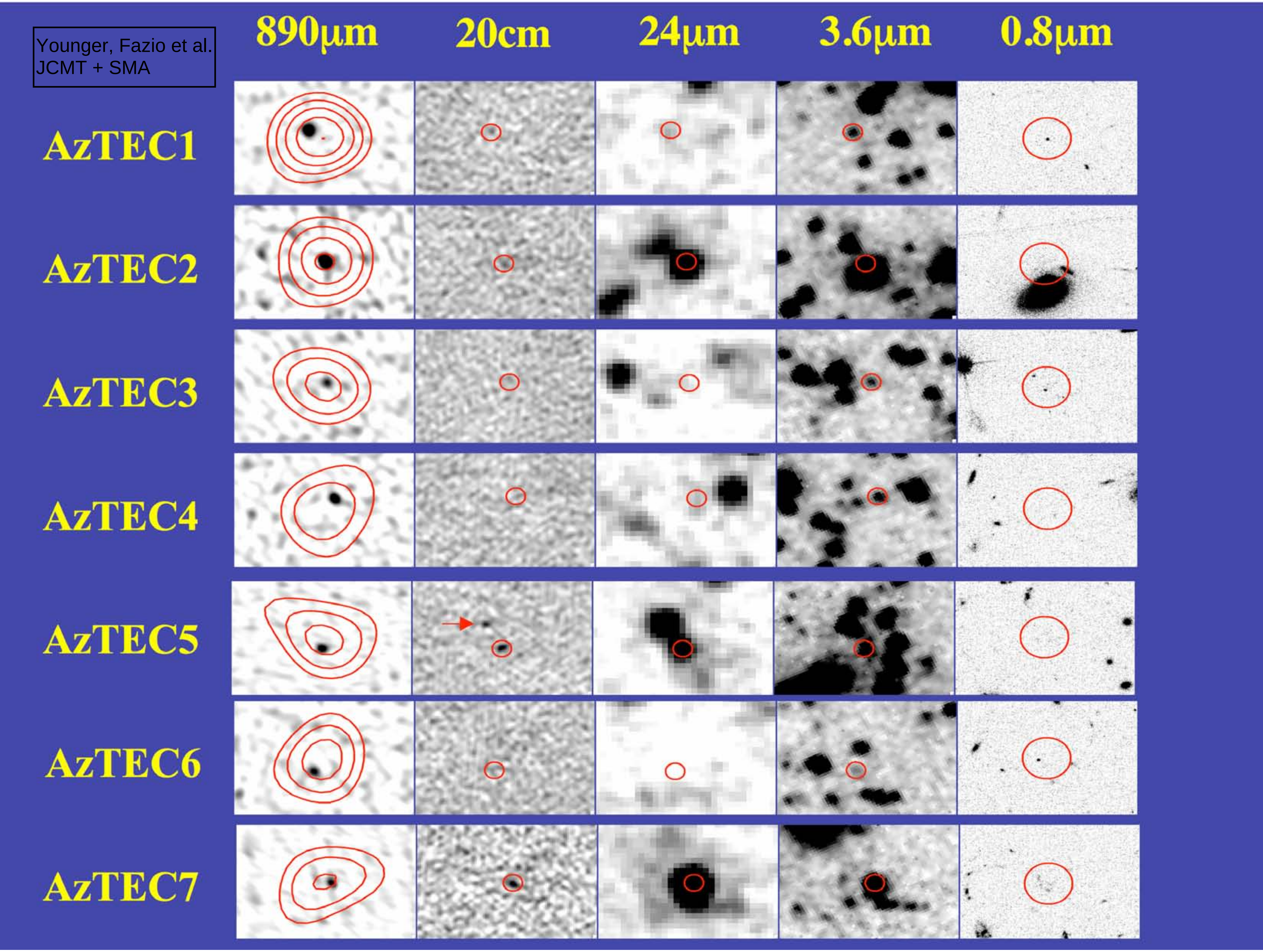




Merger tree



Mergers dominate star formation for z>3.5 ?

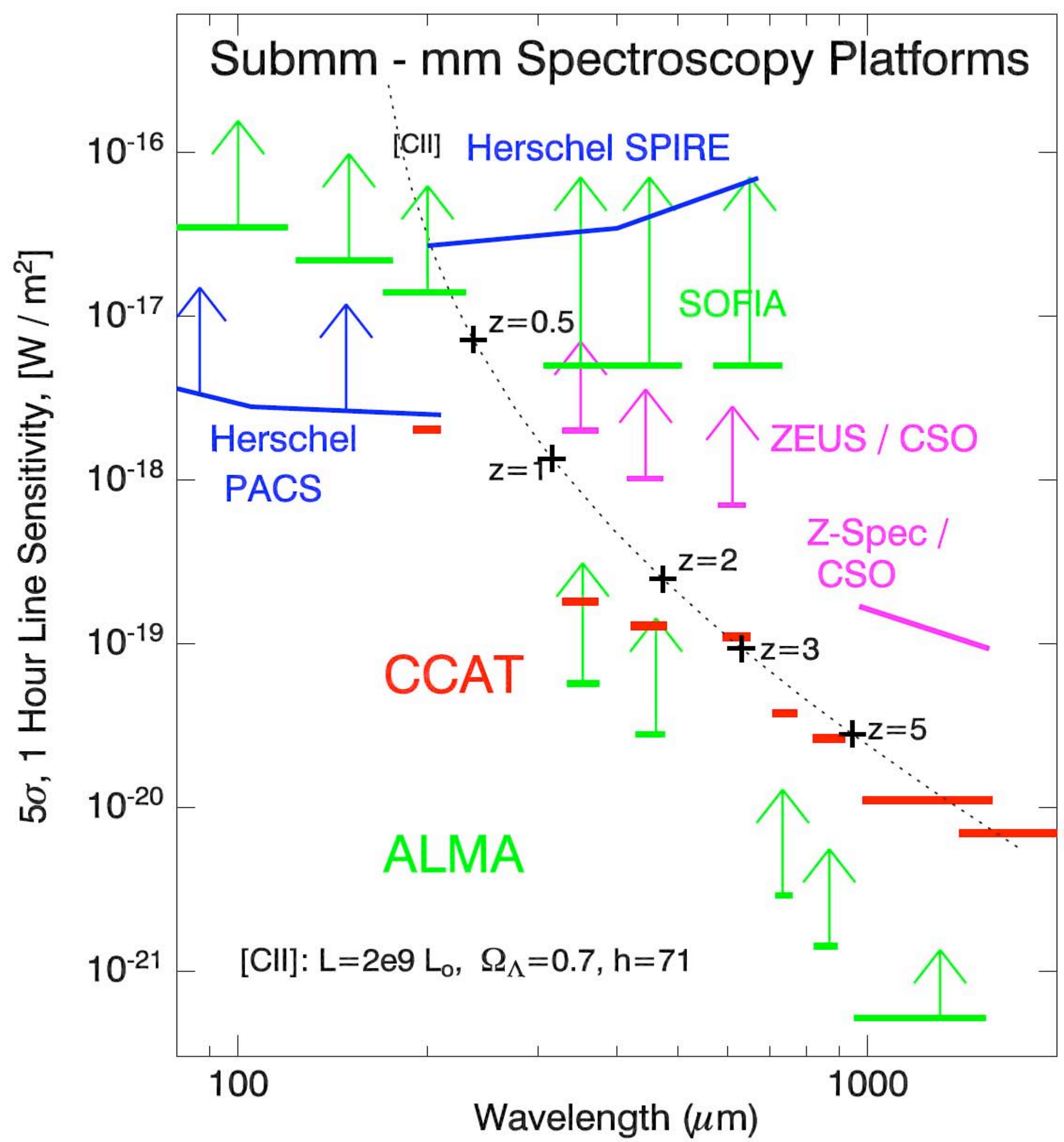


Younger, Fazio et al.
JCMT + SMA
890μm
20cm
24μm
3.6μm
0.8μm
AzTEC1
AzTEC2
AzTEC3
AzTEC4
AzTEC5
AzTEC6
AzTEC7

Submm galaxies: what's next ?

- Need to go fainter
  - Existing detections (SCUBA/2, MAMBO, Bolocam) are finding only the most luminous objects - just the "tip of the iceberg"
  - Hierarchical formation: mergers are smaller at higher redshifts
  - Need better sensitivity (aperture, site)
- Need better angular resolution in surveys
  - beat confusion limit: 3".5 for CCAT/350 μm vs. 15" for JCMT/850 μm
  - Much smaller error circle + higher source density for efficient follow-up
- Need larger surveys for better statistics, clustering studies
  - Faster mapping, better sensitivity (aperture, site)
  - Larger cameras, telescope with wider FOV
- Need multiple wavelengths
  - Constrain luminosity, redshift
  - 350 μm point near peak of SED for z~2
  - 350/450 μm "dropouts" as candidates for z > 4 ?
- Spectroscopy, redshifts ?

CCAT Spectroscopic Sensitivities



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

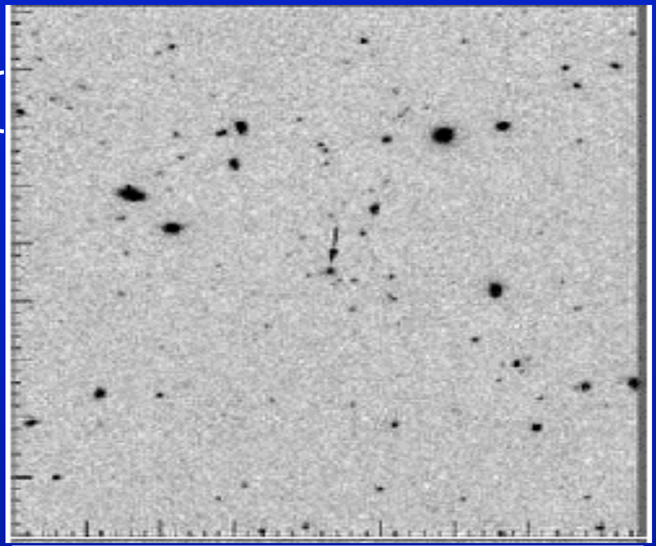
CCAT less sensitive than ALMA, but with full window bandwidth, CCAT can carry out spectroscopic surveys on galaxies with comparable speed.

Can be even faster if coupling many galaxies at once.

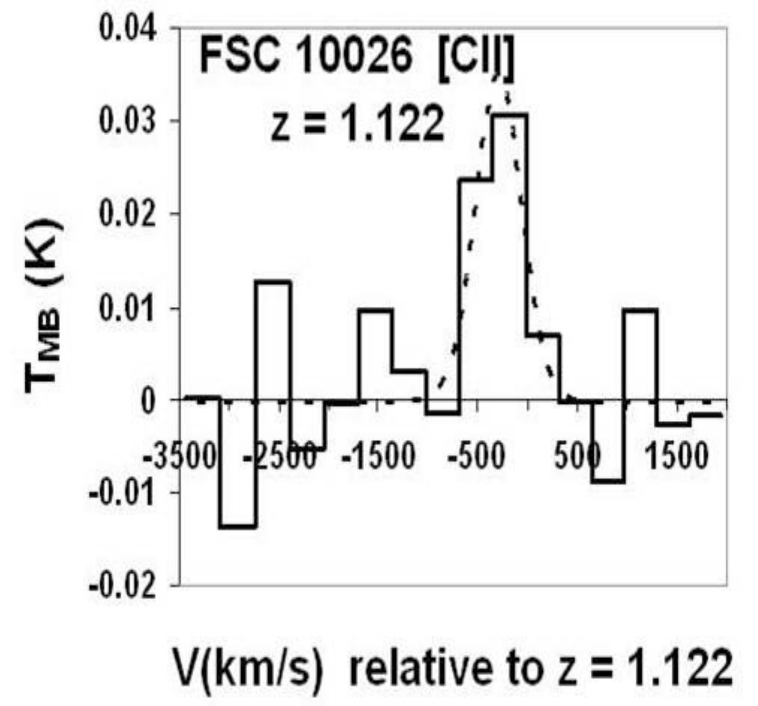
ZEUS on the CSO

C+ in an IRAS Galaxy at z = 1.12

25”



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



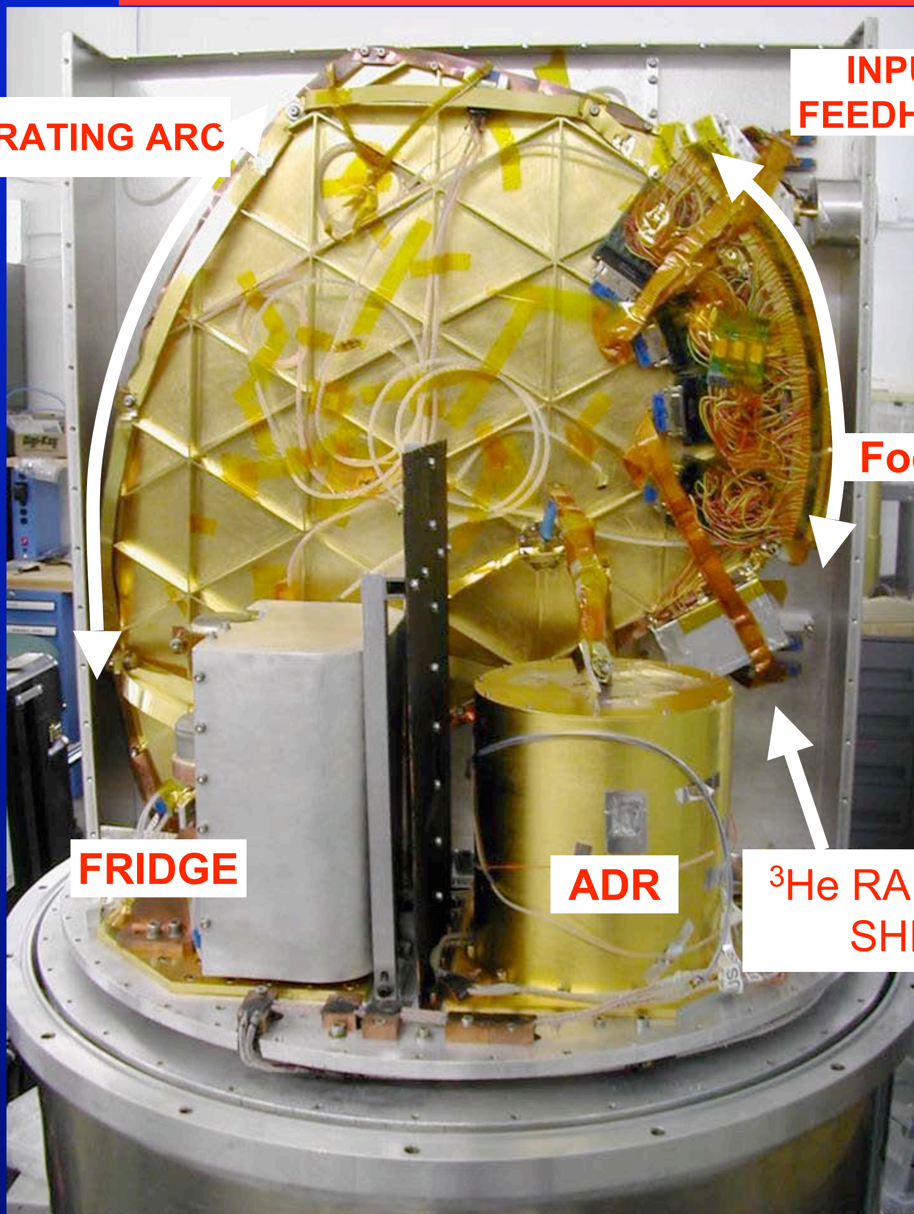
ZEUS/CSO (Hailey-Dunsheath et al. 2007)

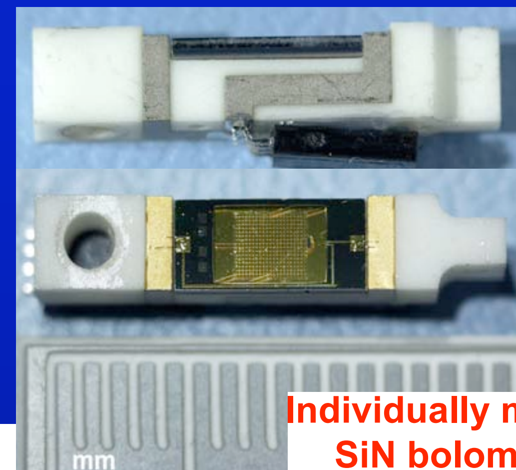
- Detected [CII] line (S/N = 6.4) FSC10026+4949 using ZEUS on the CSO (t_{int} ~ 1 hour, $t_{l.o.s.}$ ~ 20%)
- $L_{far\text{-}IR} \sim 6.5\times10^{13}\ L_\odot$ (Duncan et al. 2004) and $L_{[CII]} \sim 4.5 \times 10^{10}\ L_\odot$

$$\Rightarrow R \sim 7\times10^{-4}$$

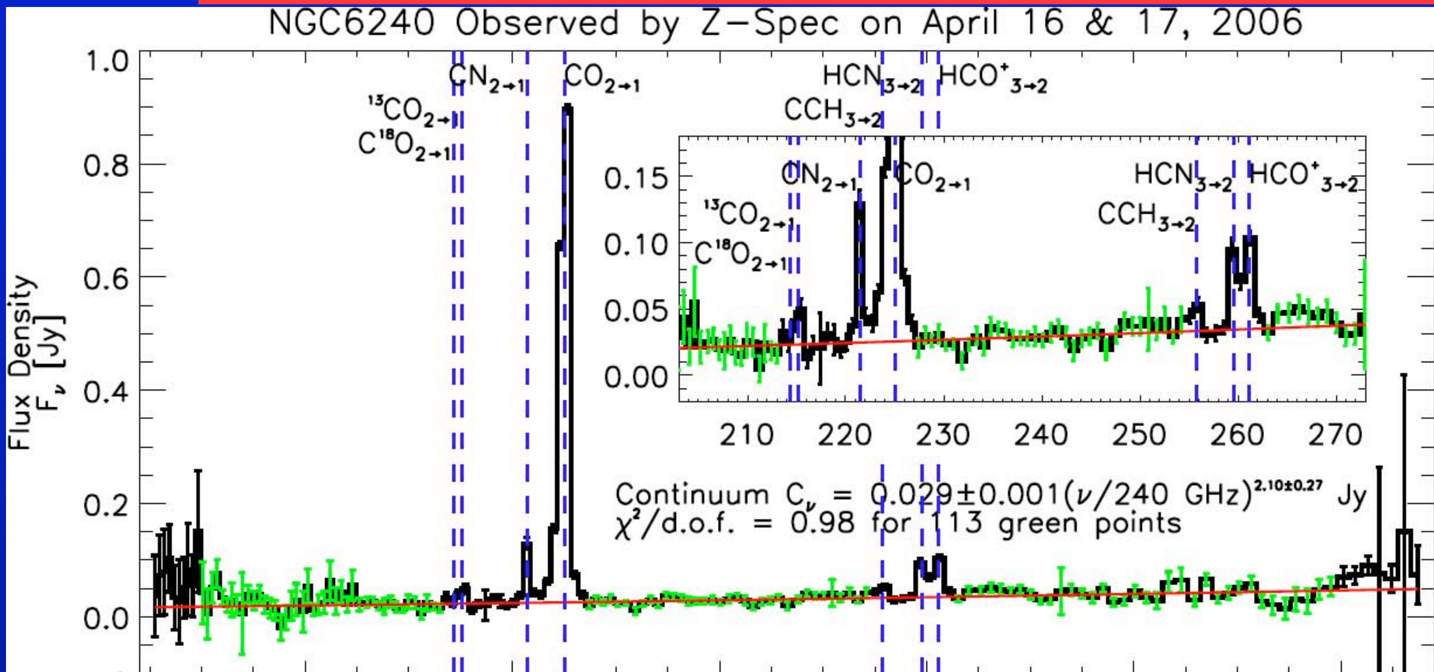
Gordon Stacey

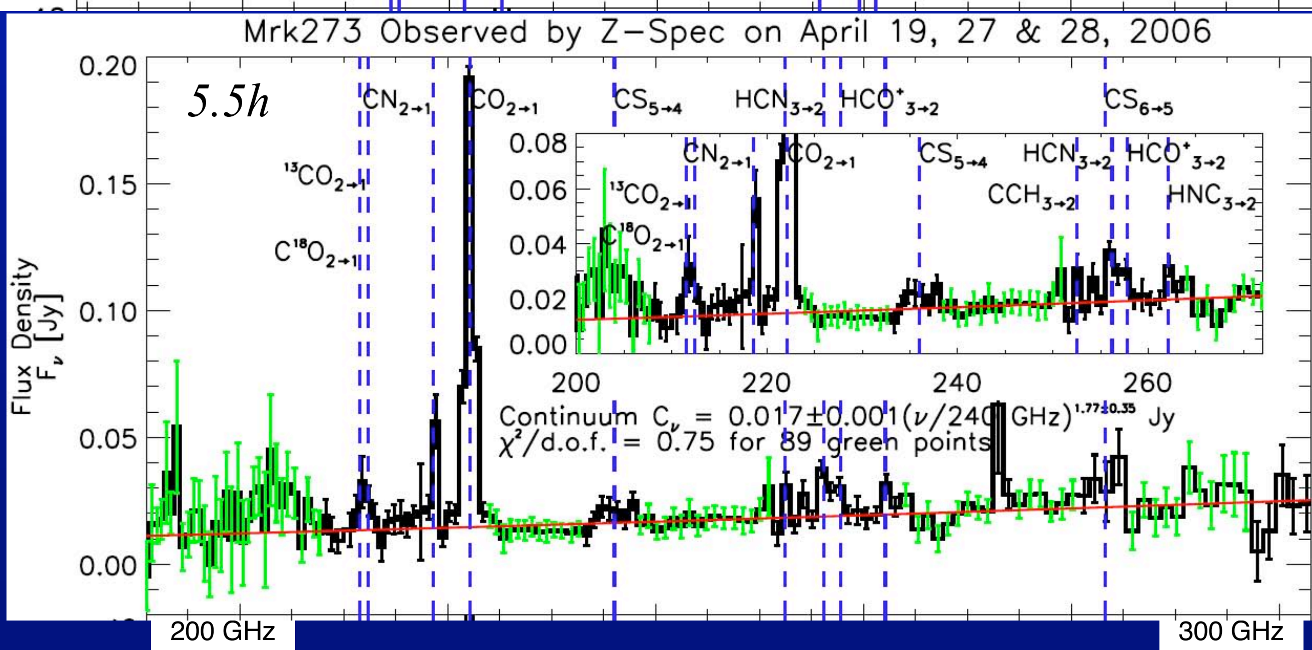
True broadband spectroscopy in the submillimeter: Z-Spec, a 1st order grating covering 190-305 GHz.





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





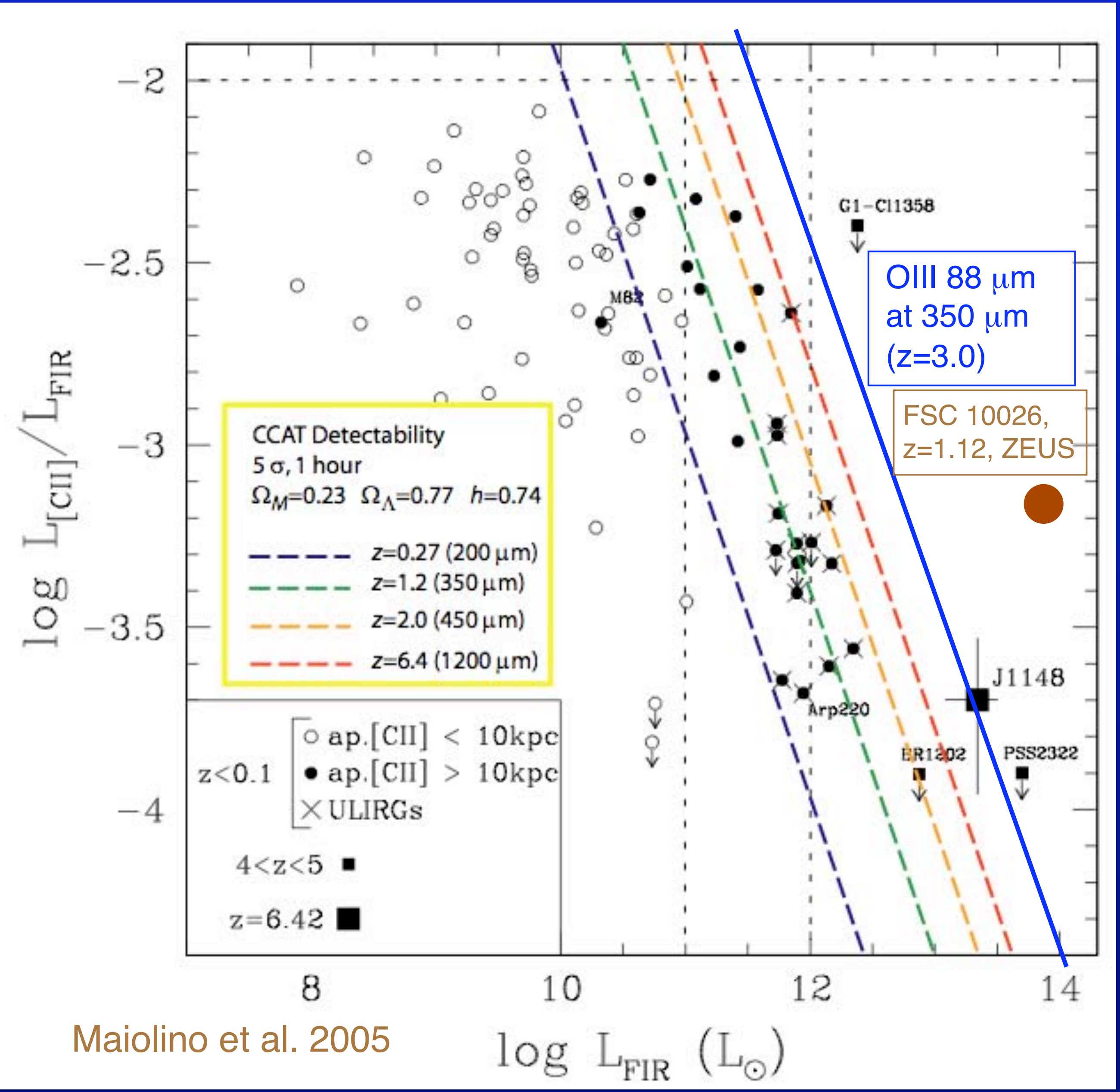
ULIRG spectroscopy for CO, isotopes, density tracers.

Lieko Earle Ph.D. dissertation

High-redshift observations coming.

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

Redshifted C+ Detectability with CCAT



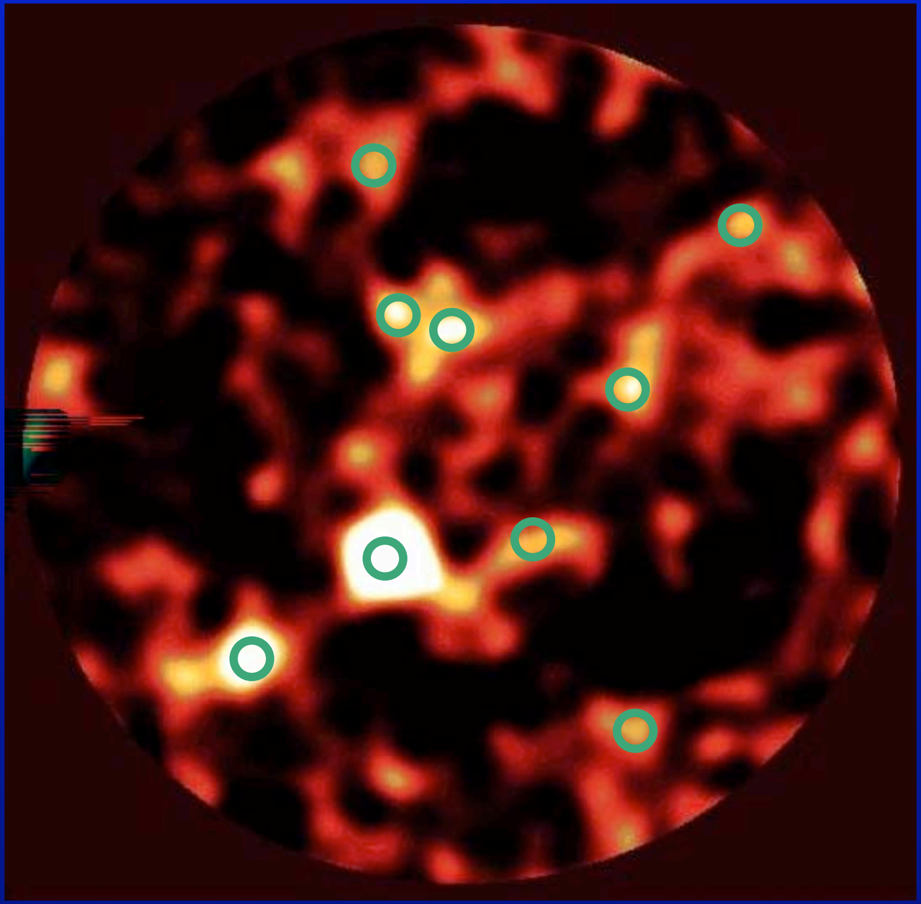
Maiolino et al. 2005

- *Constant C+ luminosity (log L_{C+}~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_{line} > 0.003*

Both waveguide and free-space echelle grating spectrometers could accommodate a mulit-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

CCAT Instrumentation Status

- Original plan:
  - long λ camera, 1.5 - 0.7 mm
  - Short λ camera, 450, 350, 200 μm
- NSF funding for CSO MKID camera, 24x24 x4 color long- λ array (Glenn, Golwala, Zmuidzinas)
- SCUBA 2 potential first light instrument
  - reconfigure for 450 & 350 μm
- Delay CCAT short λ camera ?
- Build a spectrometer instead ? C+ redshifts ?

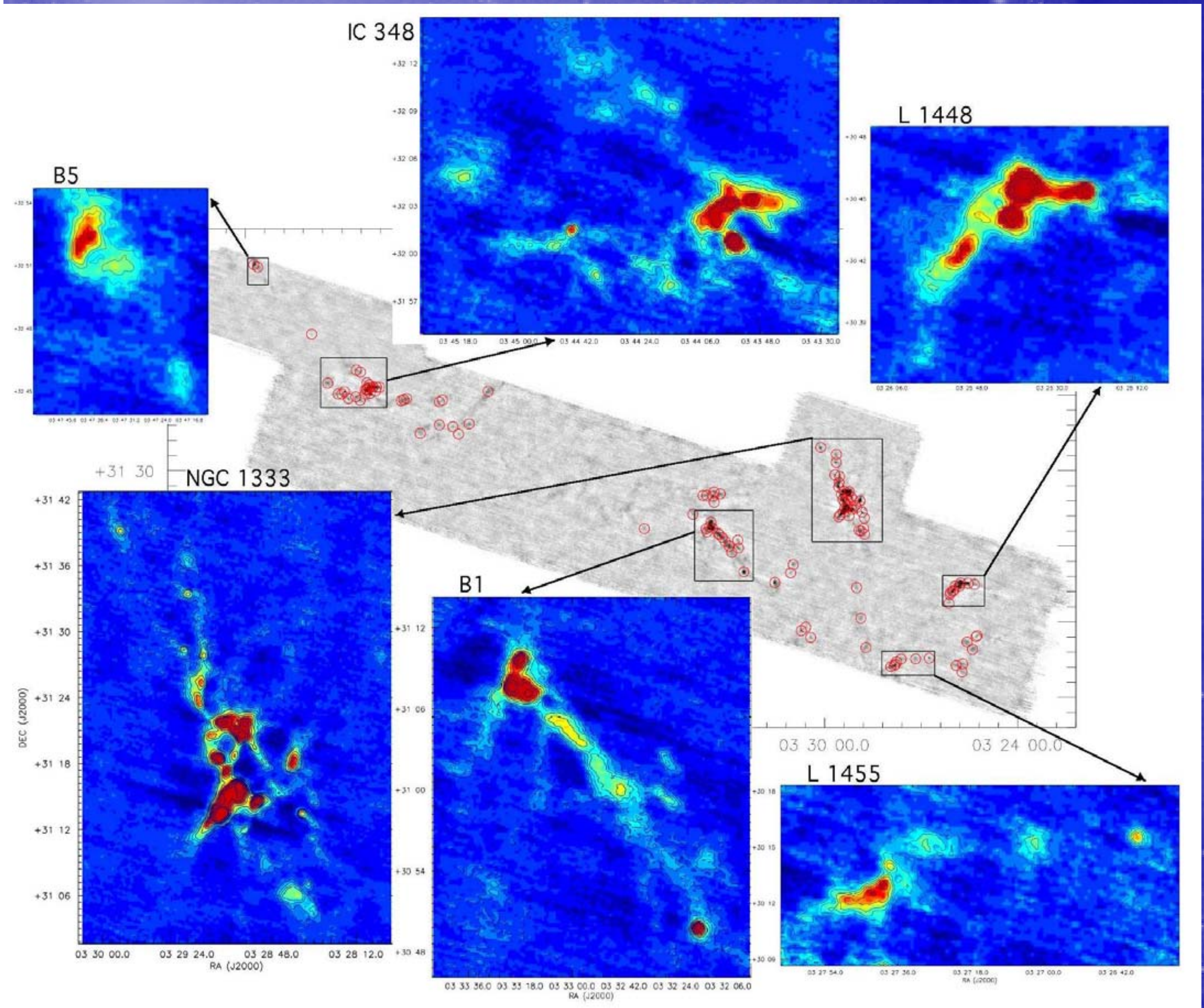
CCAT spectroscopy meeting

- Dates: May 13-14, 2008
- Theme
  - Spectroscopy with CCAT: Science and Instrumentation Opportunities
- Location: U. Colorado, Boulder
- Organizers: J. Glenn, S. Radford, JZ
- Compiling list of potential speakers
- Looking for suggestions !

AAS Special Session

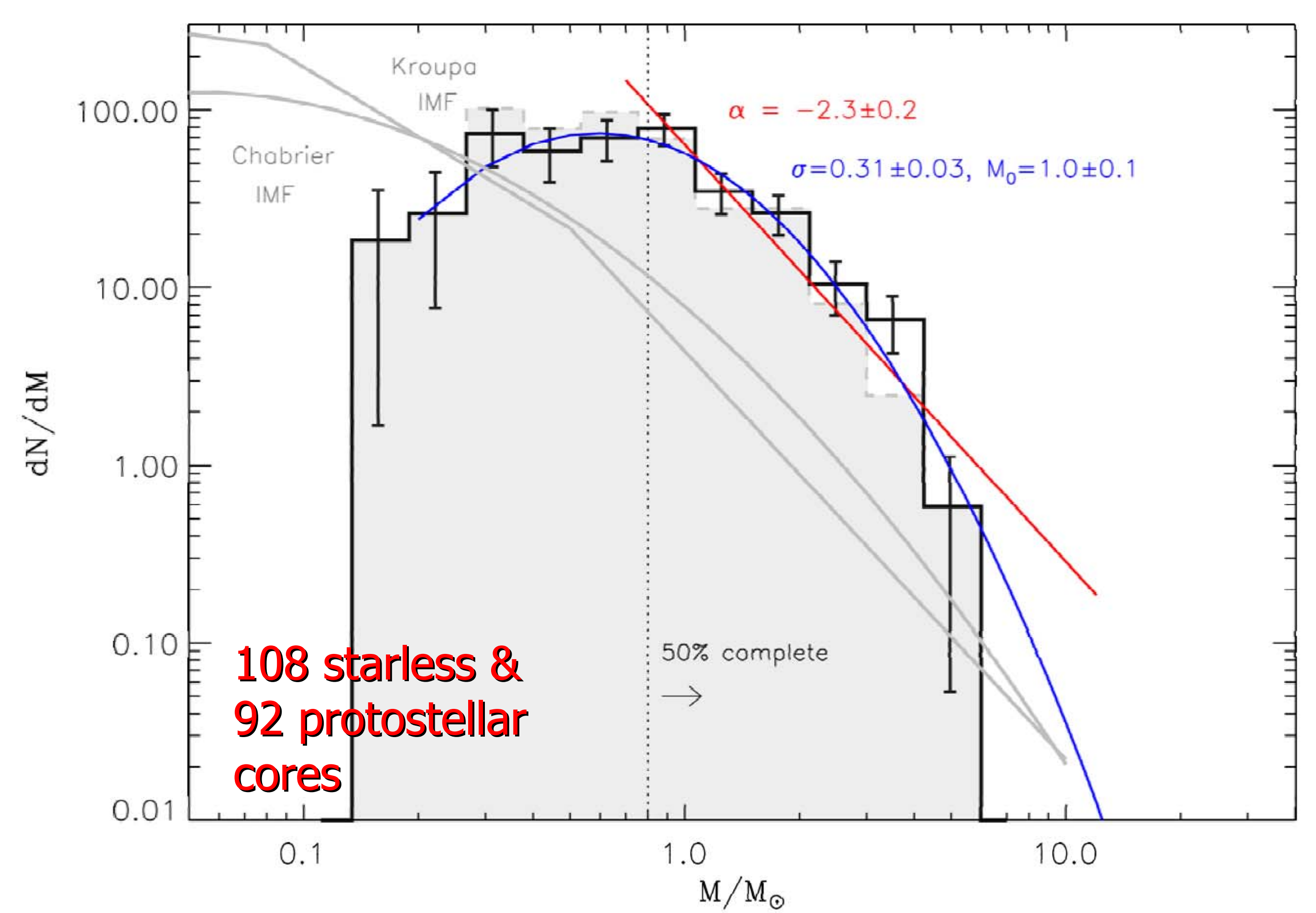
- “Present and Future Wide Field Submillimeter Surveys”
- AAS Austin, January 10
- Organized by Simon Radford
- Speakers
  - Wayne Holland: galactic, near-term
  - Mark Halpern: extragalactic, near-term
  - Andrew Blain: extragalactic, future
  - Jason Glenn: galactic, future
  - Riccardo Giovanelli: CCAT

Results from the Bolocam c2d Survey



Perseus molecular cloud complex (Bolocam, λ = 1.1 mm; Enoch, et al. 2006)

Perseus, Rho Ophiuchus, & Serpens: Bolocam + *Spitzer*

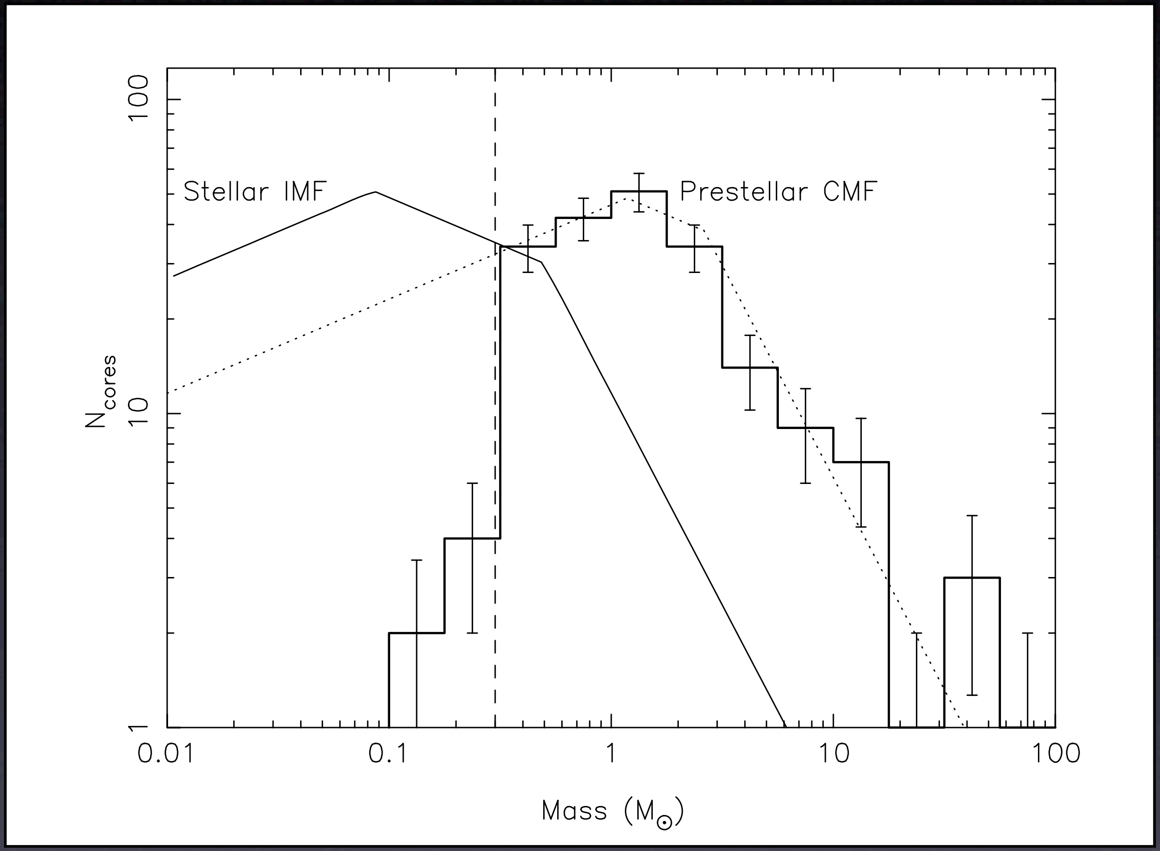


Tantalizing results that require large, deeper surveys to address further:

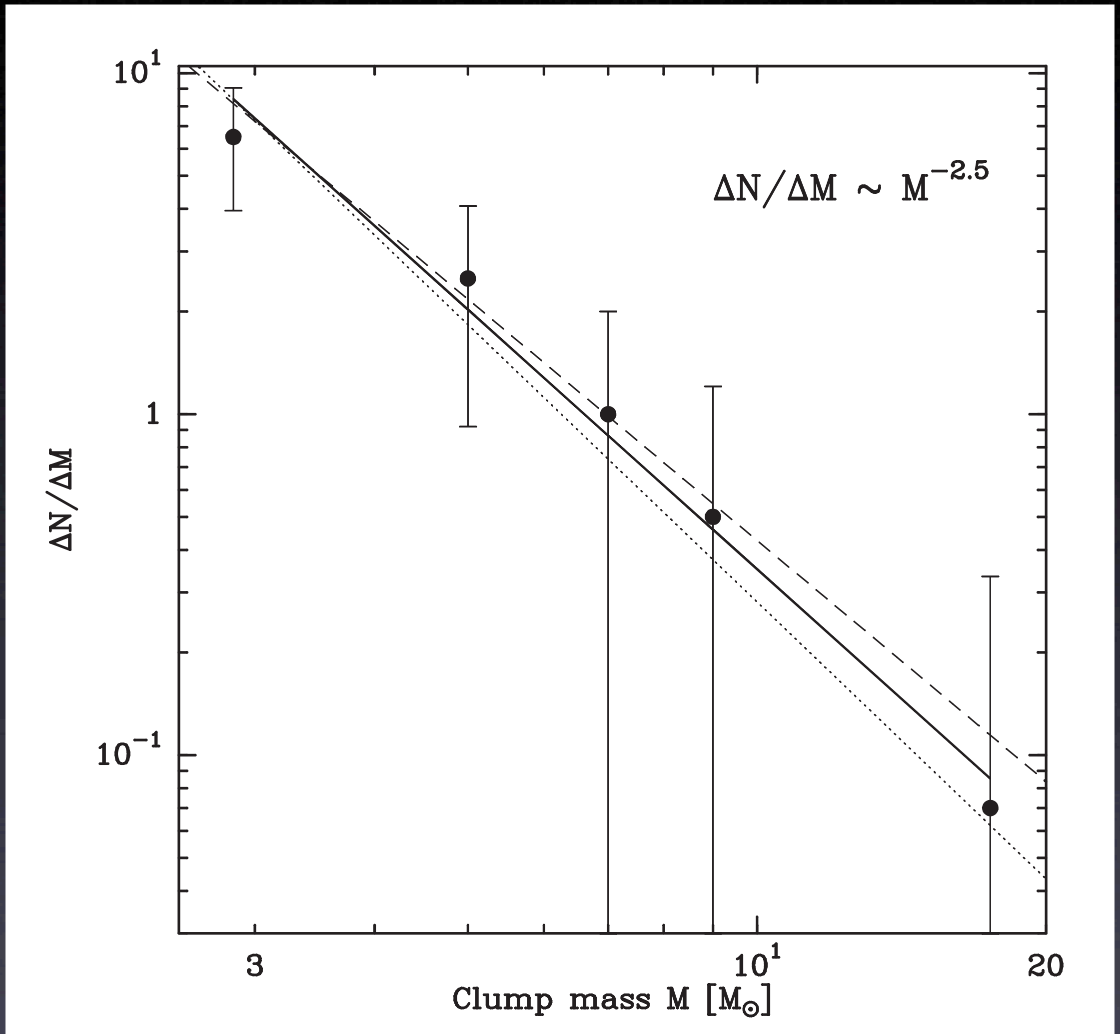
- MF similar power law to IMF
- ≥25% core-to-star efficiency
- Can (magnetic) turbulent fragmentation explain the core mass function?

Enoch et al., in prep.; Enoch et al. 2006, Young et al. 2007, Enoch et al. 2007

Linking clump mass to IMF



Nutter & Ward-Thompson 2007

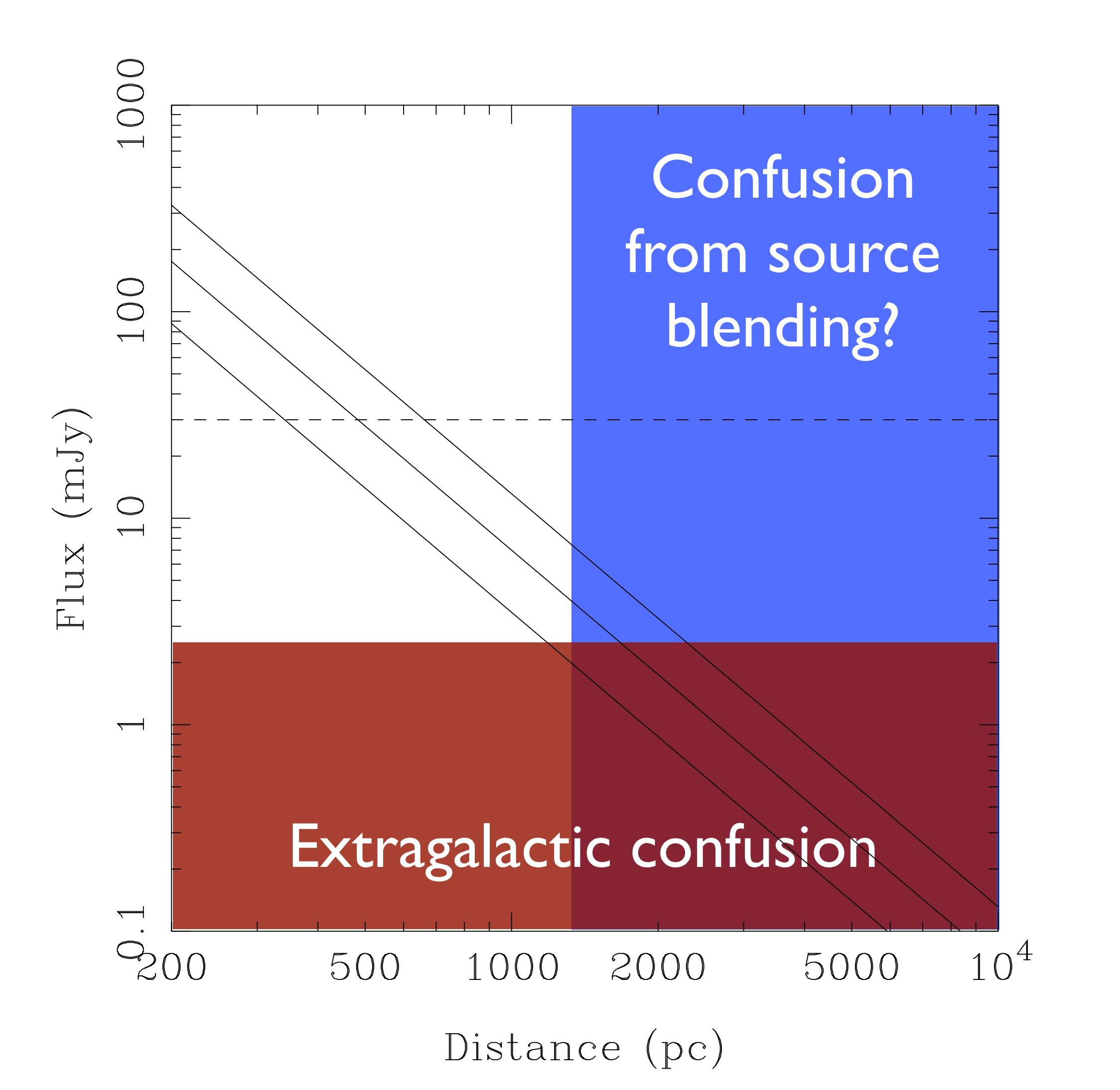


Beuther & Schilke 2004

A major goal is to understand the link between clumps and the IMF.

- limited by lack of statistics at high & low mass end
- limited by sensitivity at low mass end
- limited by angular resolution at very high mass end

JCMT survey parameter space



Solid lines show 850 μm flux vs distance for 0.04, 0.08, 0.15 solar mass core

Dashed line is JCMT Gould Belt Survey 3σ detection limit

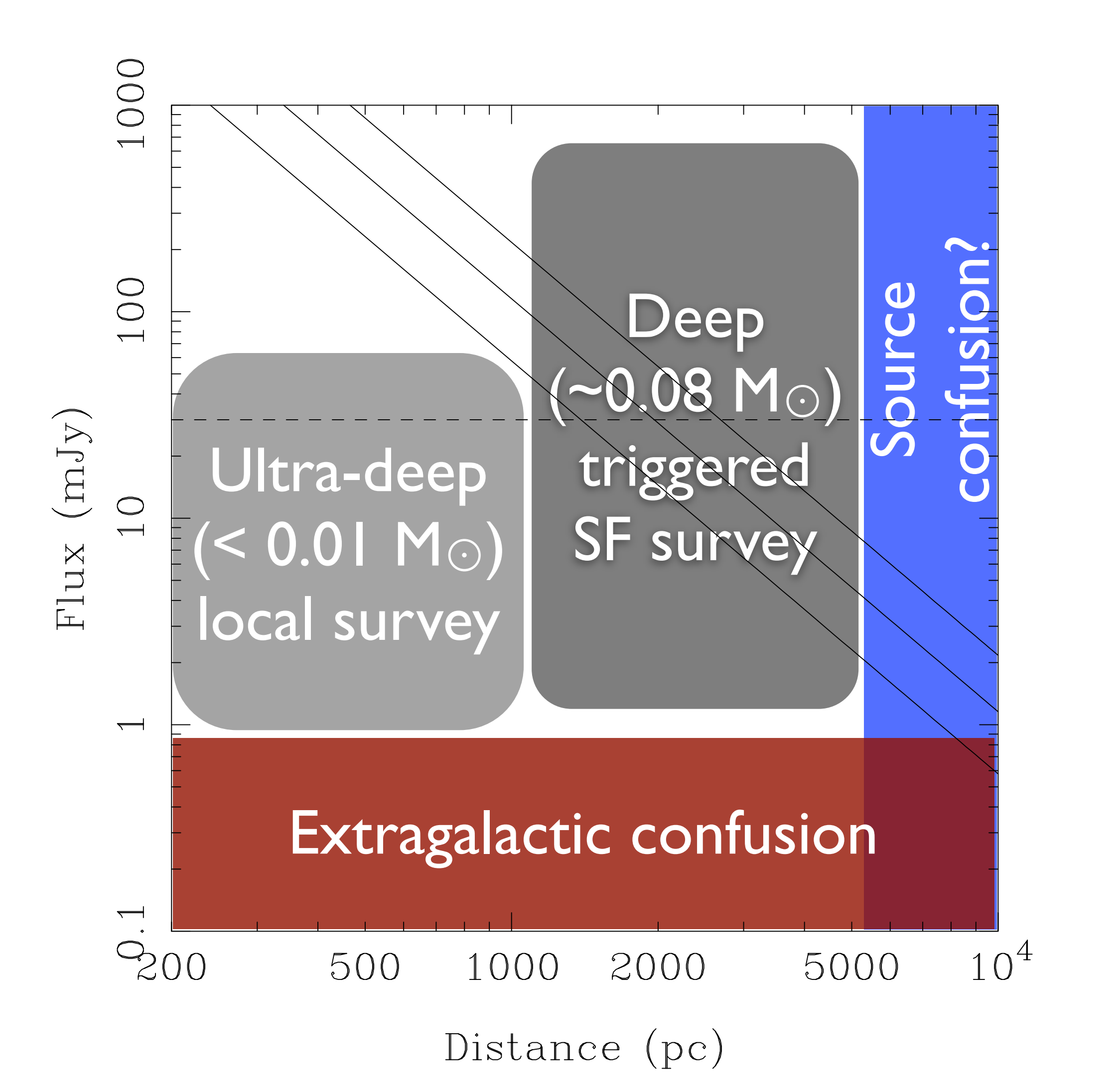
There are two major limitations to the survey parameter space.

Sensitivity: beyond ~1.5 kpc low-mass cores blend into extragalactic confusion limit.

Resolution: beyond ~ 1.5 kpc low-mass cores blend with each other. (IRAS 16293 type objects are confused even at 500 pc)

While *Herschel* is not sensitivity-limited it is very much confusion-limited.

CCAT survey parameter space



Solid lines show 350 μm flux vs distance for 0.04, 0.08, 0.15 solar mass core

Dashed line is JCMT Gould Belt Survey 3σ detection limit

CCAT's improved angular resolution & sensitivity removes these limitations for a large fraction of the Galactic survey parameter space.

Working at 350 μm improves mass sensitivity by an order of magnitude.

Two previously unstudied regimes become accessible:

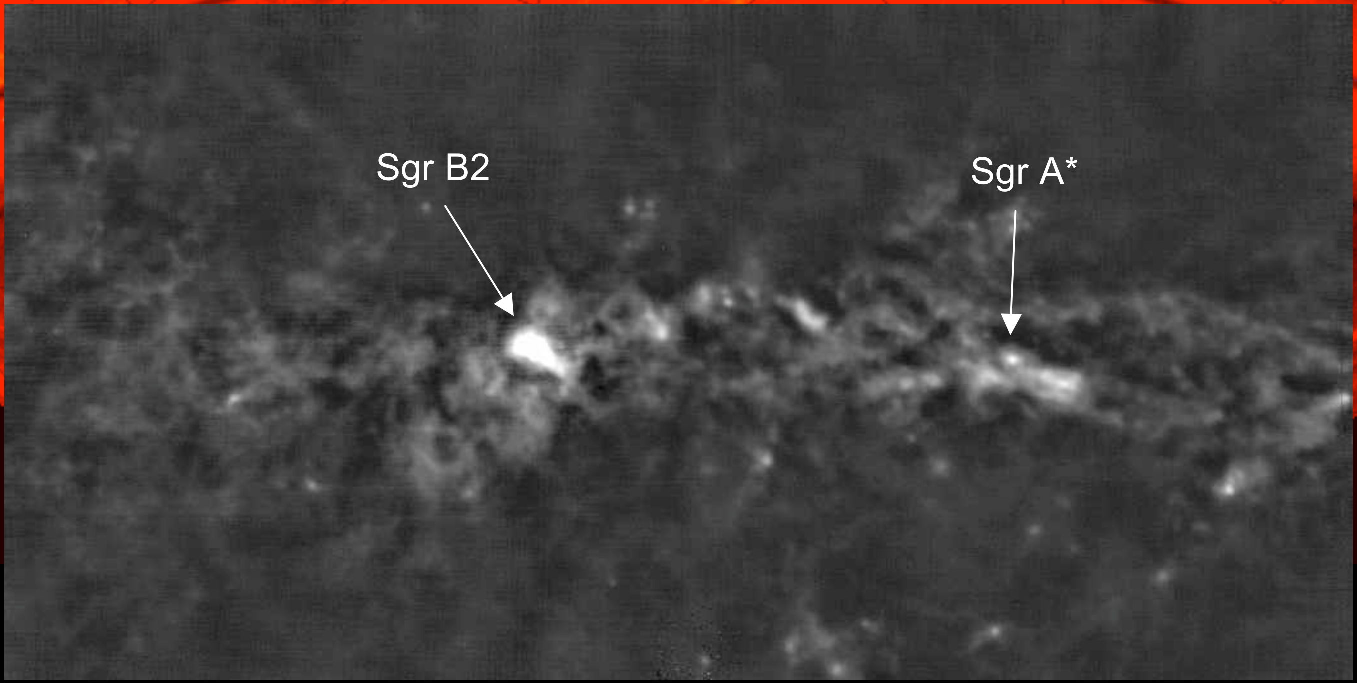
- Ultra-deep survey of local clouds for 0.01 M☉ objects (free-floating planets?)
- Surveys of nearby HII regions to study how triggering affects the formation of solar and sub-solar mass stars

CCAT Galactic Plane Survey

In ~200 hours CCAT will be able to survey the “inner” Galactic Plane to a level that will find all of the star forming regions (ie. cool dust), not just the massive star regions (i.e. warm or hot dust)...

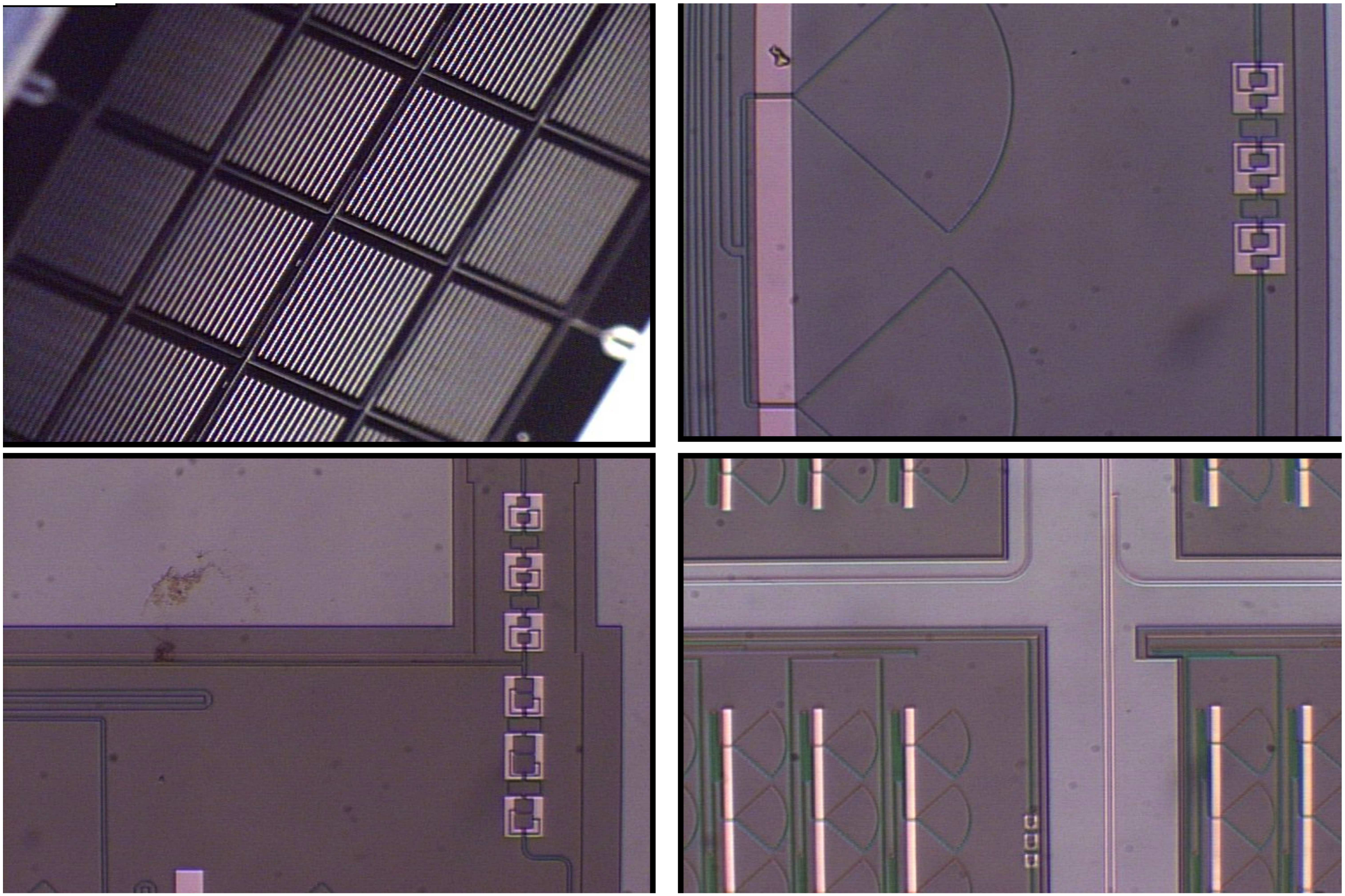
BoloCAM Galactic Plane Survey

- Dec 2007: ~150 sq-degrees of the Galactic Plane surveyed
- Detected >5,000 dense cloud cores (3σ = 15−30 mJy)
- Follow-up SHARC observations of selected cores (CS 5-4)



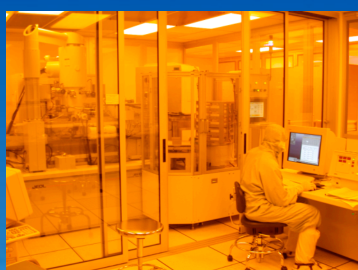
Galactic Center with BoloCAM at 1.1mm (Courtesy John Bally/Jason Glenn)

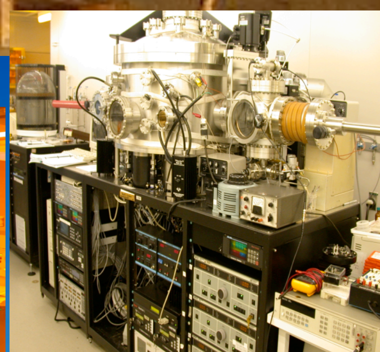
4×4 dual-color submm MKID array

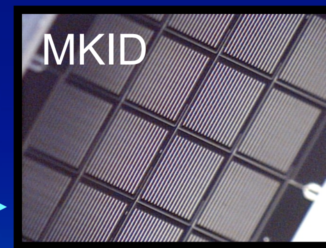


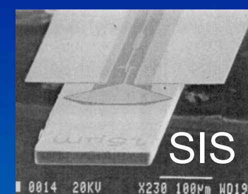
JPL Microdevices Laboratory (MDL)

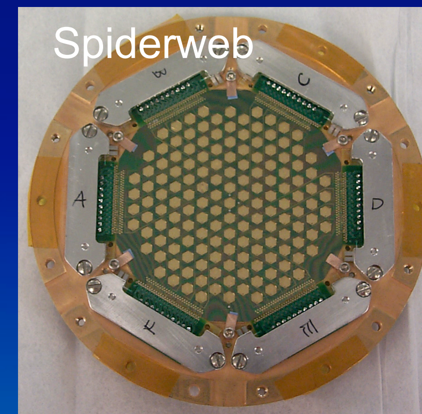
Detectors for Astrophysics



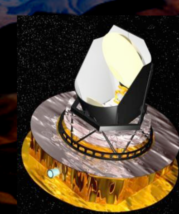






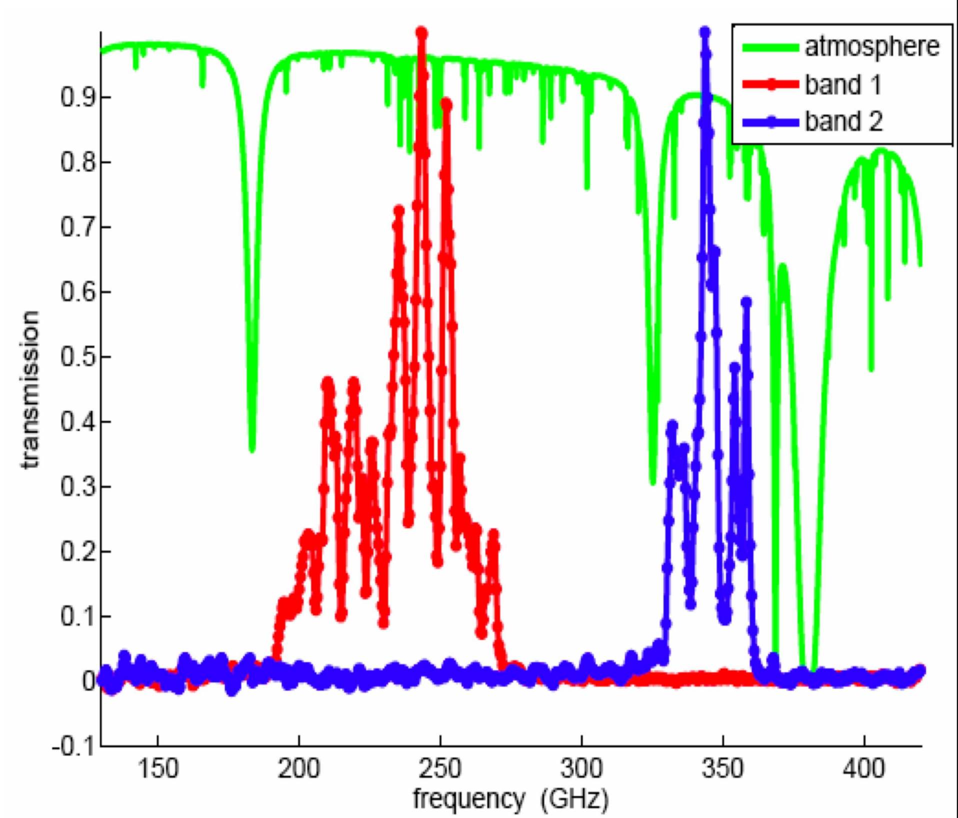


- Constructed in late 1980's: Lew Allen, Tom Phillips
- 38,000 sq. ft. facility
- Class 10 to 100,000
- Dedicated equipment for superconducting devices
- E-beam & UV stepper lithography



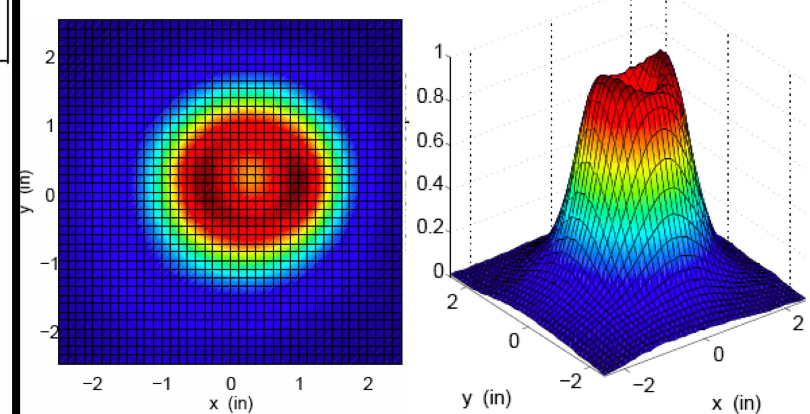
PLANCK,
HERSCHEL,
+ future space missions

Frequency response and antenna patterns

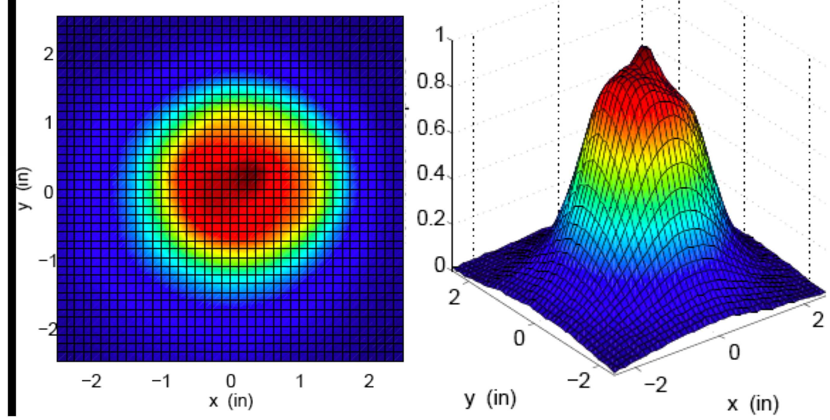


(Taken *before* Zitex AR coating applied on PTFE filters/lens)

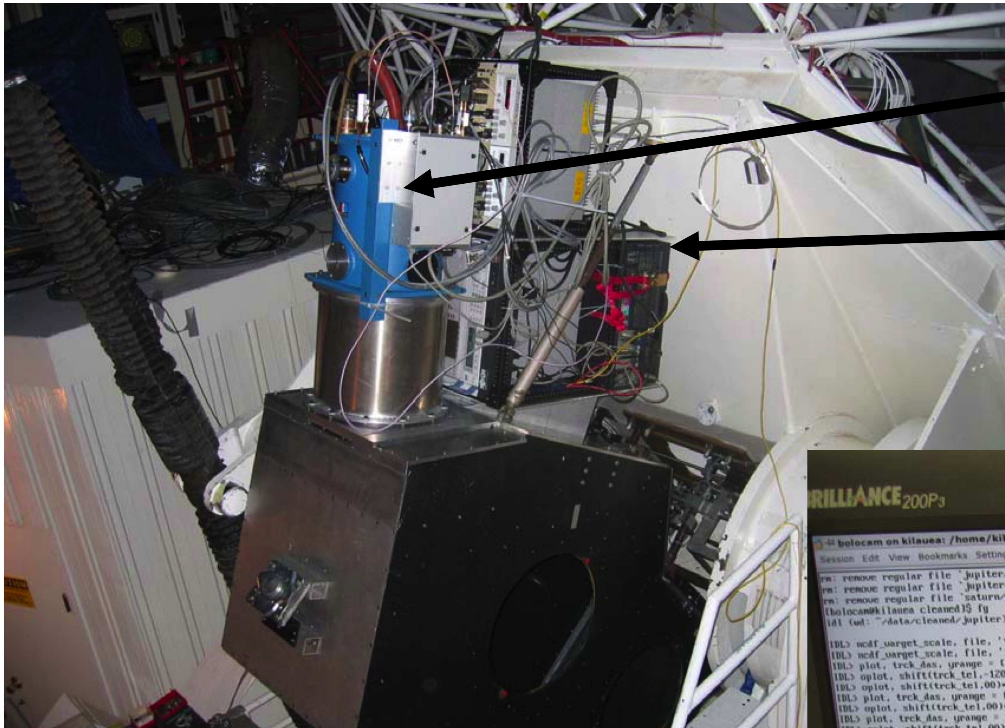
Band1



Band2



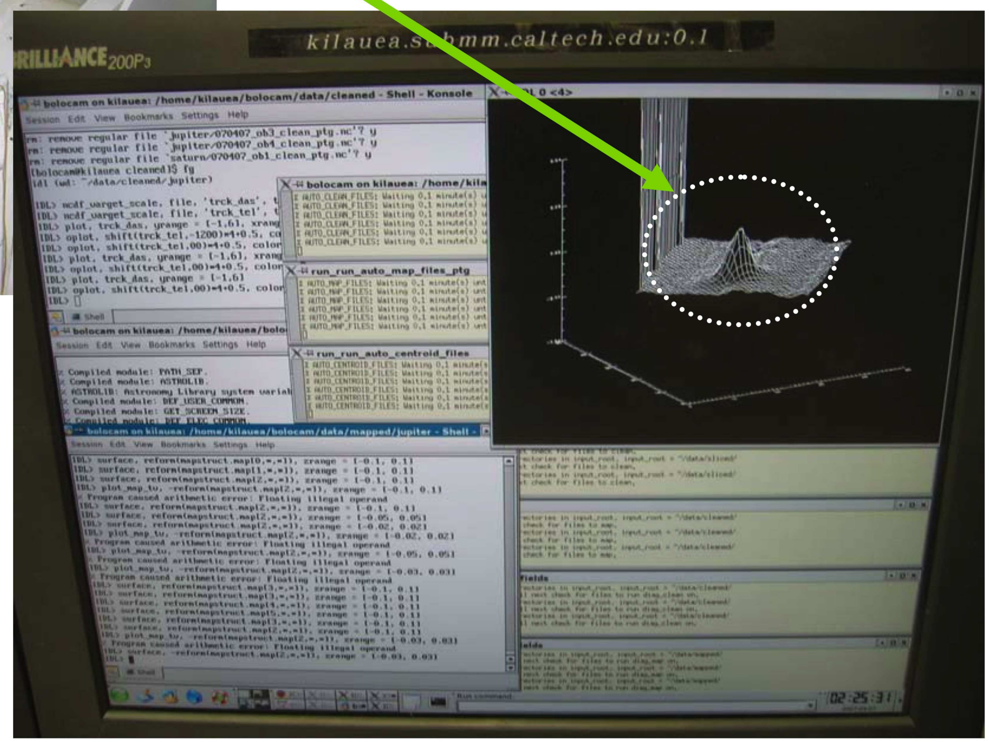
Demo at the Caltech Submillimeter Observatory (CSO)



DemoCam dewar mounted on optics box

Instrument racks

First light: detection of Jupiter with MKIDs!



Future plans: build a 600 pixel, multi-color camera.

The MKID camera for the CSO (NSF ATI + Moore)

- Jason Glenn, PI; Sunil Golwala, co-PI
- 24×24 array $=$ 576 spatial pixels
- Four colors/bands: λ =1.3, 1.1, 0.85, and 0.75 mm
- $576 \times 4 = 2304$ MKID resonators
- Focal plane: 4×4 mosaic of 6×6 ($\times 4$) tiles
- Each $6 \times 6 \times 4$ tile has 144 MKIDs total
- 2.8 MHz per MKID $\rightarrow$ 400 MHz bandwidth per tile

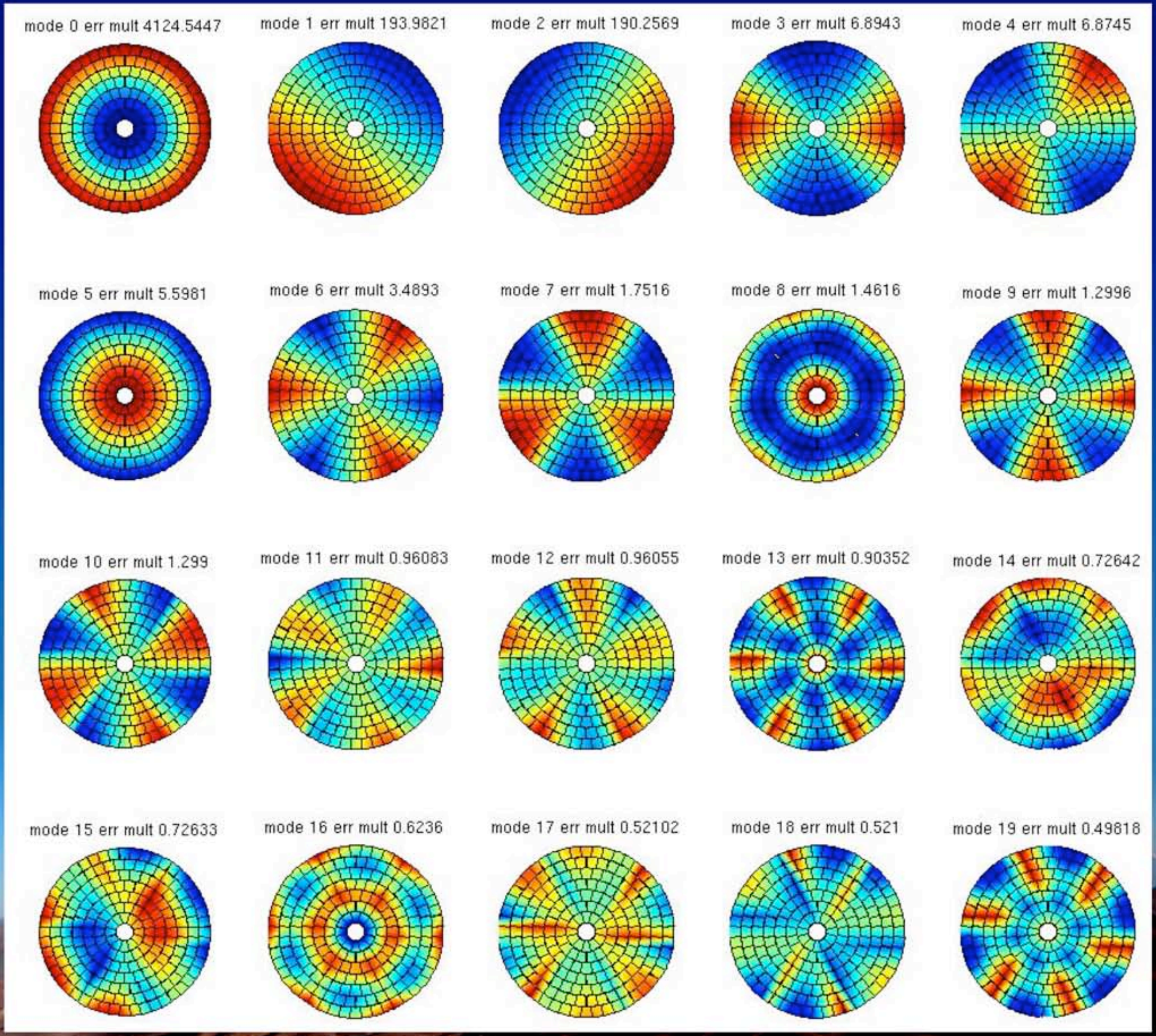
JPL and CCAT

- JPL long-wavelength missions
  - IRAS
  - Spitzer
  - Herschel/Planck
  - MIRI/JWST
  - WISE
  - BLISS, SAFIR, SPIRIT, … ?
- Werner, Yorke, Langer, Goldsmith; CLWA
- IPAC
- Strong detector and instrumentation capability
  - Microdevices laboratory (MDL)
  - Detectors for Herschel/Planck
  - CSO instruments: Z-spec, Bolocam, heterodyne (SIS) + MKID camera
  - CCAT as testbed for detectors/arrays/instruments for future missions
- Active/adaptive optics
  - JWST, TMT
  - October 2006: 3-year study of CCAT active surface, $0.8M

CCAT active surface study

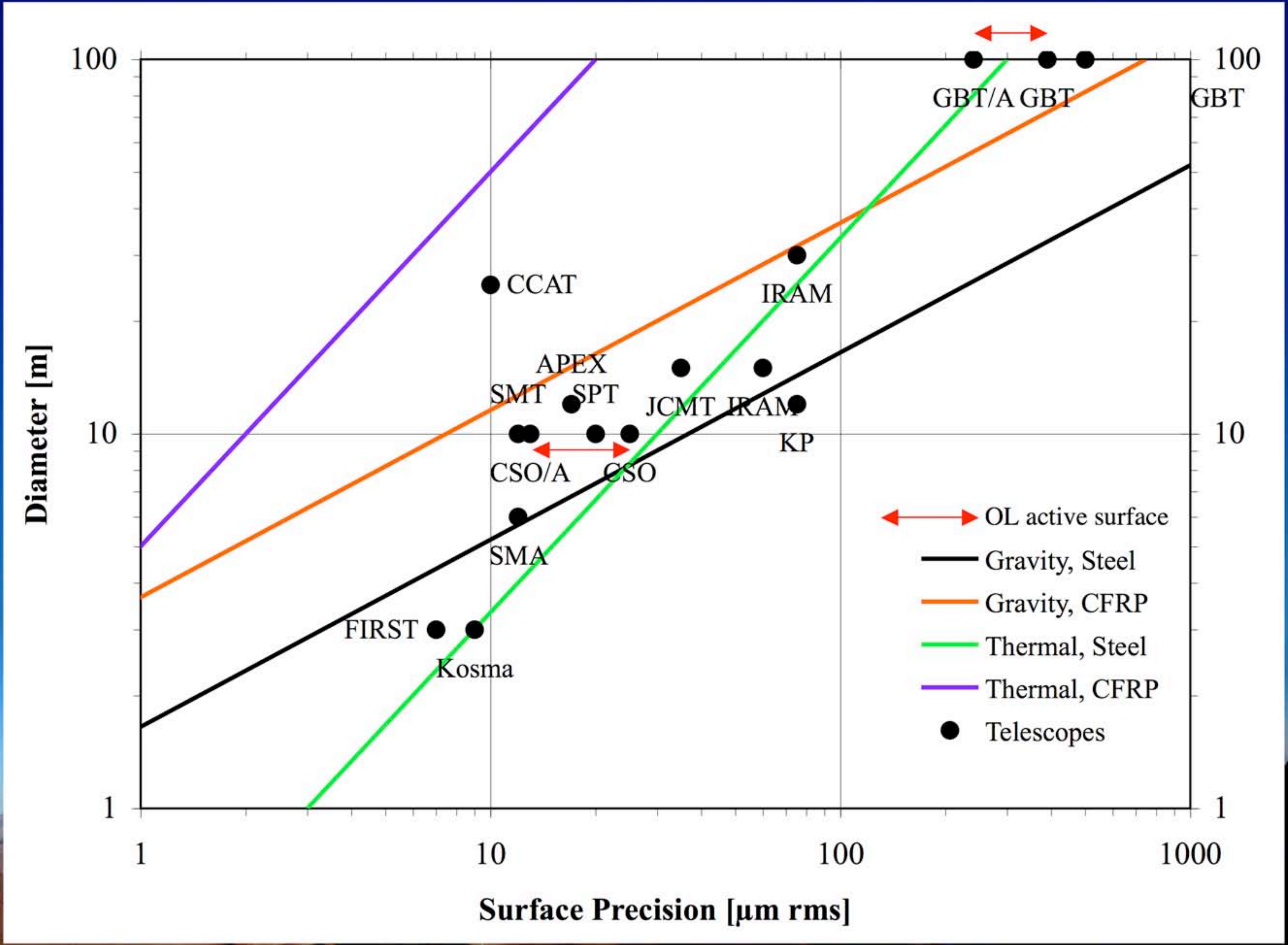
- David Woody (OVRO), Dan McDonald (JPL), Paul Goldsmith (JPL), Eri Cohen (JPL), + SR, JZ
- CCAT problem is different than Keck & TMT
  - much lower cost
  - no zerodur, no whiffletrees
  - panel thermal deformations can lead to large surface errors
  - CCAT surface accuracy of 10 μm rms is smaller than the segment piston error that can be tolerated for seeing-limited operation in visible
  - Cannot use visible light reflected from panels to help alignment
- CCAT active surface problem not resolved satisfactorily by the end of the feasibility study
- JPL funded a follow-on study of CCAT active surface
  - Three years, \$0.8M total
  - Led by Paul Goldsmith
  - JPL: Dan McDonald, Eri Cohen, others
  - Caltech: David Woody (OVRO), + SR, JZ

CCAT *f* = 0.4 Mirror Modes



Displacement sensors on 55 mm fingers

Passive Telescope Limits



Rafted panel concept for primary reflector segments

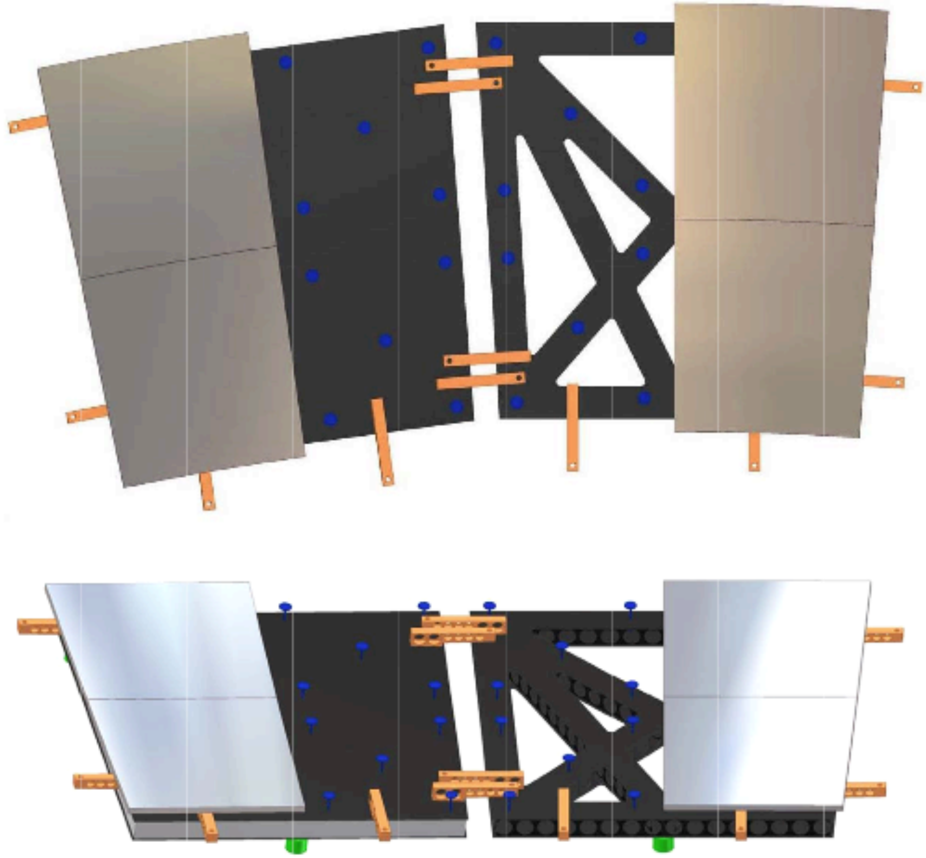


Fig. 1. Views from secondary and from the vertex of the model of two rafts around the perimeter of CCAT. The frame on the right is a light weight all CFRP beam construction while the left frame is a simple CFRP Al-honeycomb CFRP sandwich. The four reflecting tiles on each raft are mounted on five hand adjustable supports shown in blue. The edge sensors are standard gap sensors mounted on CFRP arms shown in orange. The rafts are mounted on three computer controlled adjusters shown in green.

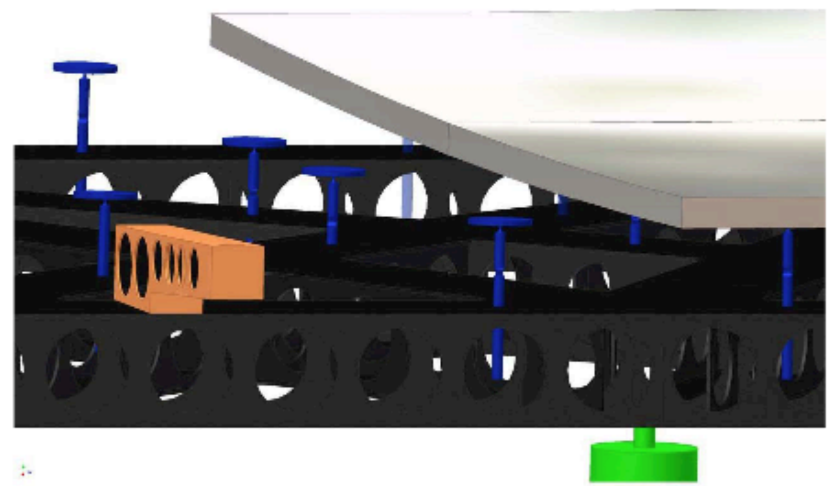


Fig. 2. Close up view of tile standoffs shown in blue.

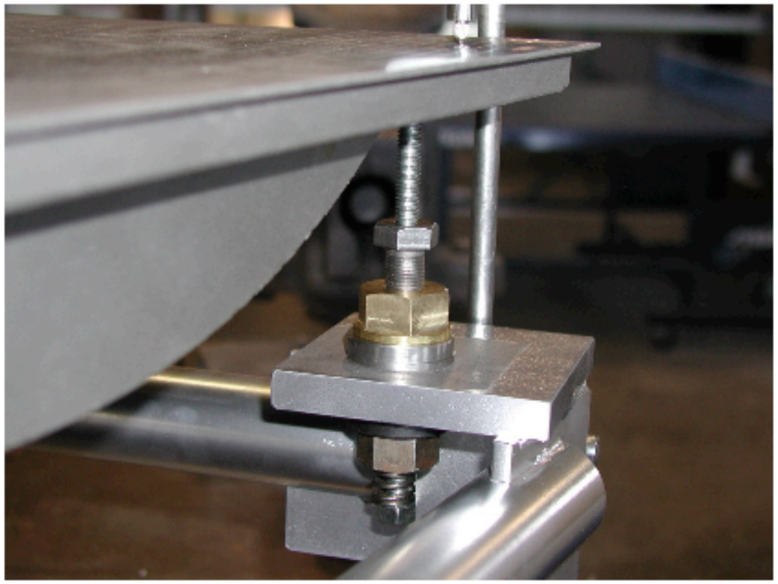


Fig. 3. Differential screw panel adjustable standoff used for the SZA panels.

Status - active surface study

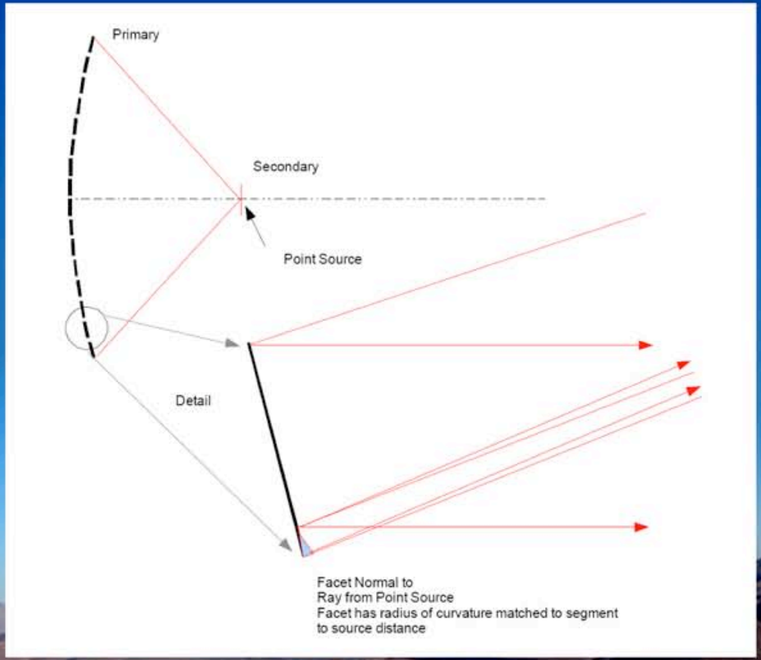
- Detailed error budget developed
- Thermal deformation (“cupping”) of segments is a major issue
- Rafted panel concept (Woody) readily achieves the required surface accuracy, 10 μm rms
- Need edge sensors + angle sensors
  - several concepts being evaluated
- Ready to proceed into detailed design & cost study

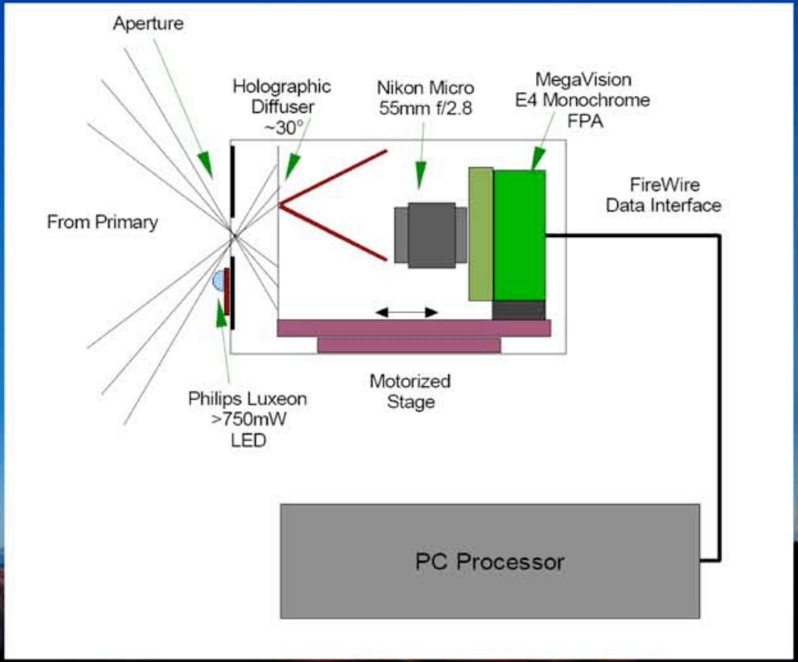
Rafted Tiles	design #1	design #2	design #3	design #4	design #5	design #6	design #7
	ML tiles	ML lite wt	ML 4xcorr	Al raft cor	CMA 4xcor	TT 4xcorr	all Al 4xcorr
tile RMS errors, 3 point support							
areal density	10.10	4.50	10.10	10.10	4.00	6.47	13.55
gravity	3.38	4.24	3.38	3.38	2.07	1.75	7.40
wind	2.11	6.93	2.11	2.11	3.28	1.74	5.44
temperature change	0.03	0.03	0.03	0.03	0.00	0.01	0.05
thermal cupping	0.97	0.97	0.97	0.97	0.01	2.50	0.29
lateral Trms	0.34	0.34	0.34	0.34	0.34	0.07	0.34
manufacturing	2.00	2.00	8.00	2.00	8.00	8.00	8.00
aging	0.10	0.10	0.10	0.10	0.10	0.10	0.10
net tile error, 3 point	4.57	7.63	9.00	4.57	8.59	8.74	11.44
tile RMS errors, 5 point suppot							
gravity	0.84	1.08	0.84	0.84	0.52	0.46	1.86
wind	0.53	1.48	0.53	0.53	0.82	0.43	0.86
temperature change	0.01	0.01	0.01	0.01	0.00	0.00	0.01
thermal cupping	0.48	0.48	0.48	0.48	0.00	1.25	0.14
lateral Trms	1.70	1.70	1.70	1.70	1.70	0.37	1.70
manufacturing	1.00	1.00	4.00	1.00	4.00	4.00	4.00
aging	0.05	0.05	0.05	0.05	0.05	0.05	0.05
net tile error, 5 point	2.26	2.73	4.49	2.26	4.45	4.26	4.80
standoff errors							
gravity [microns]	0.09	0.16	0.09	0.09	0.07	0.12	0.24
thermal [microns]	0.45	0.45	0.45	0.45	0.45	0.45	0.45
adjustment [microns]	1.41	1.41	1.41	1.41	1.41	1.41	1.41
net standoff errort	1.49	1.49	1.49	1.49	1.49	1.49	1.60
sub-frame errors							
sub-frame areal density	12.60	6.30	12.60	15.14	6.30	6.30	9.90
total raft areal density [kg/m^2]	23.33	10.96	23.33	26.87	10.61	13.06	23.76
gravity, including segment wt	4.31	2.83	4.31	4.78	2.74	3.37	3.02
wind	1.16	1.62	1.16	1.16	1.62	1.62	0.80
Temp change	0.02	0.02	0.02	0.02	0.02	0.02	0.02
thermal cupping	0.14	0.10	0.14	0.03	0.10	0.10	0.10
lateral Trms	0.01	0.01	0.01	1.81	0.01	0.01	0.01
aging	0.40	0.40	0.40	0.40	0.40	0.40	0.40
net subframe error	4.48	3.29	4.48	5.19	3.21	3.77	3.15
primary figure maintence							
surface error from edge sensors	0.56	0.70	0.56	0.81	0.70	0.70	0.47
surface error from angle sensors	1.17	1.07	1.17	1.23	1.07	1.11	1.06
net surface maintenance error	1.73	1.77	1.73	2.04	1.76	1.81	1.63
total primary 1/2WFE	5.52	4.86	6.74	6.20	5.95	6.14	6.14
other non-primary surface 1/2WFE							
primary support	4.86	4.86	4.86	4.86	4.86	4.86	4.86
secondary	3.49	3.49	3.49	3.49	3.49	3.49	3.49
tertiary	3.49	3.49	3.49	3.49	3.49	3.49	3.49
wavefront measurement	4.17	4.17	4.17	4.17	4.17	4.17	4.17
total other contrib. 1/2WFE	8.1	8.1	8.1	8.1	8.1	8.1	8.1
total telescope 1/2WFE	9.78	9.43	10.52	10.18	10.03	10.15	10.14

Table 1. Bottom up error budget for rafted tiles. The spreadsheet is quite extensive and only the key summary rows are shown.

Segment Tilt Sensor

- Optical system measures segment tilts
- Complements edge sensors
- Improves mirror control
- Concept design by Adaptive Optics Associates





CCAT History

- 9/2003: Cornell-Caltech workshop (Pasadena)
- 3/2004: $2M study phase initiated by Cornell/Caltech MOU
  - 50/50 split between Caltech, JPL
- 1/2006: Feasibility study report completed (376 pages)
  - review panel gives “thumbs up”
  - Cost estimate $100M = $80M + $20M, **need partners**
- 7/2006: Partnership meeting (Cornell)
- 10/2006: JPL initiates 3-year study of CCAT active surface ($800k)
- 12/2006: Instrumentation workshop (Caltech)
- 6/2006: Interim Partnership Agreement signed by U.K. (UKATC Edinburgh), Canada (U Waterloo & UBC), U Colorado
- 7/2007: First meeting of the CCAT Interim Board (Waterloo)
  - A. Sargent elected chair
- 1/2008: Second meeting of Interim Board (Caltech)

Current Status

- Nominal partnership levels:
  - Cornell, UK, Canada at 20-25%; Caltech at 20%; Colorado at 5-10%
- Project is gaining visibility
  - AAS special session, Austin, January 2008
  - McCray report, “Future of Radio Astronomy”
  - Numerous visits, colloquia, etc.
- Strong interest among partners
  - Letter of intent from Bud Peterson, Chancellor, U. Colorado
  - Letter of interest for 10% share from German consortium (J. Stutzki, U. Koln; F. Bertoldi, U. Bonn)
  - U. Texas, U. Wyoming, … ?
- Challenges
  - Interim funding (e.g. Radford now only 20% on CCAT)
  - Detailed study phase ?

Why CCAT ?

- Heritage
  - Neugebauer, Leighton, Phillips, …
  - TMSS, IRAS, OVRO/CARMA, CSO, Spitzer, Herschel, …
- Strong instrumentation capability
  - Microdevices Laboratory is a leader in this area
  - exploit rapidly developing technology
- Future JPL missions
- Science
  - basic cosmological parameters are now known
  - inflation + CMB polarization, dark energy, etc. are interesting *physics* problems
  - galaxy & star formation are central problems of modern *astrophysics*
    - strongly interrelated
    - will be a major focus over next several decades
  - CCAT submm observations will provide essential information
  - ALMA provides powerful follow-up opportunities
- Are we up for the challenge ?