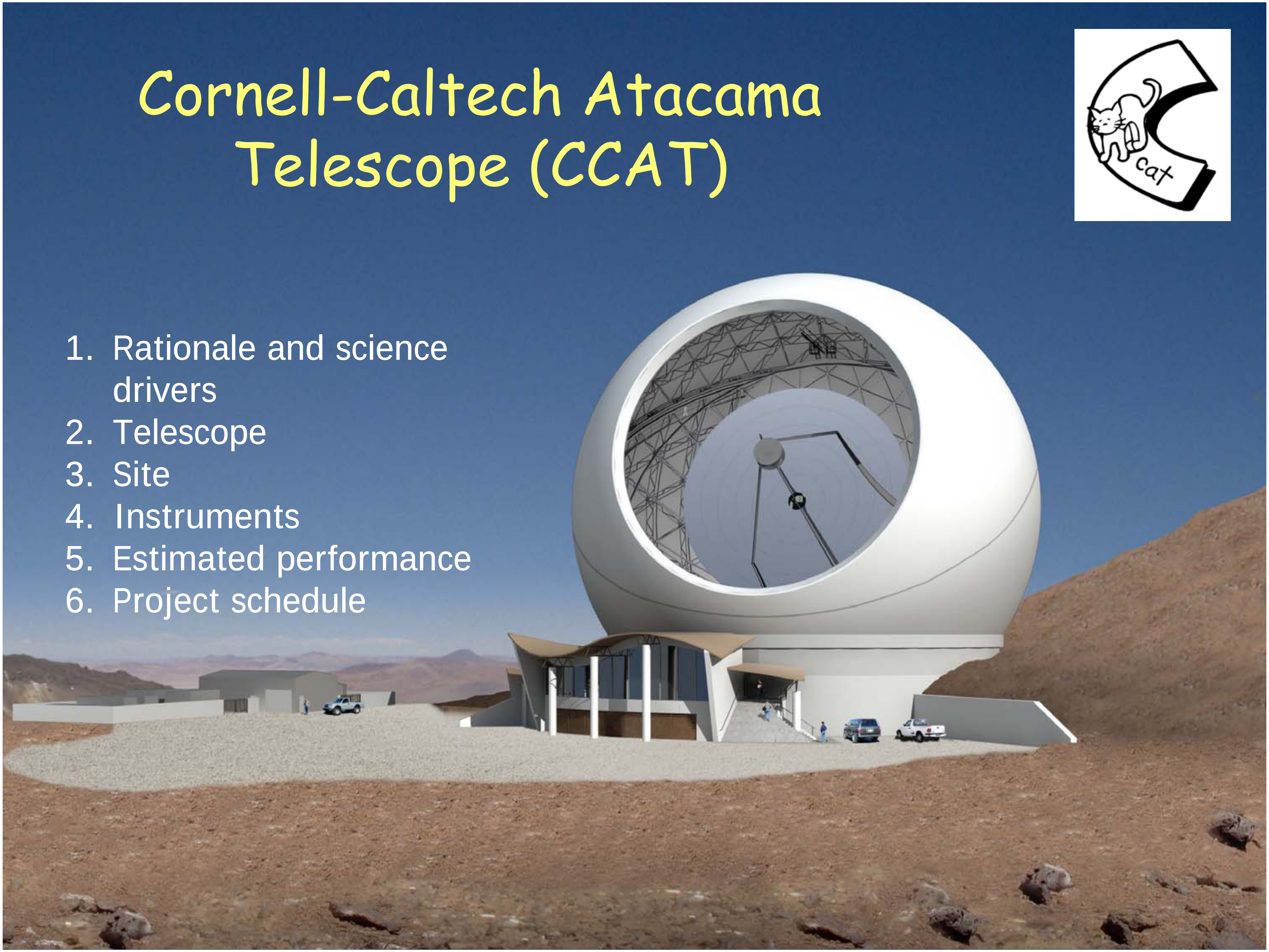
Cornell-Caltech Atacama Telescope (CCAT)



1. Rationale and science drivers
2. Telescope
3. Site
4. Instruments
5. Estimated performance
6. Project schedule

Why A Large Single Dish?

A timely convergence of Science, Technology, and Opportunity

- Many sources emit most of their energy in the FIR/submm
  - E.g. local and high-z galaxies, star forming cores
  - Important cooling lines for molecular clouds are in this region

- Submm technologies are progressing
  - First large format (> 10,000 pixel) bolometer arrays
  - Direct and heterodyne receivers approach the fundamental limits for sensitivity

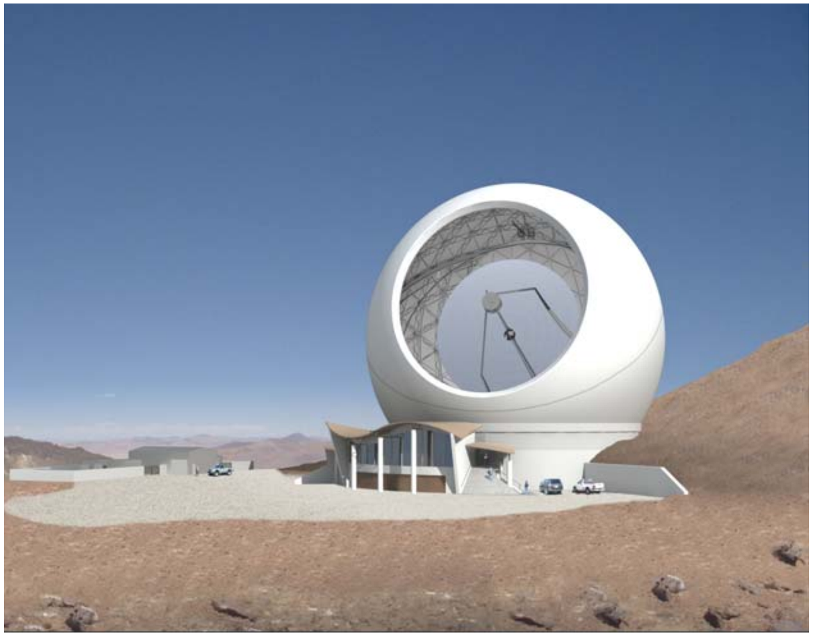
Why A Large Single Dish?

A timely convergence of Science, Technology, and Opportunity

- Opportunity
  - New submm sites have lower water vapour than Mauna Kea (e.g. Atacama, South Pole)
  - Close proximity to ALMA would foster natural synergies
  - A large submm telescope, delivering cutting edge science, is affordable... (fraction of cost of a space mission)

CCAT Proposal

A large single-aperture telescope located on a (very) dry site



Aperture: 25m

Wavelength range: 0.2 – 1mm+

Field-of-view: at least 25 arcmin^2

Instrumentation: wide-field imaging and spectroscopy

CCAT Science Strengths

- CCAT will be substantially larger and more and more sensitive than existing submillimetre telescopes

- It will be the first large submillimetre telescope designed specifically for **wide-field imaging**

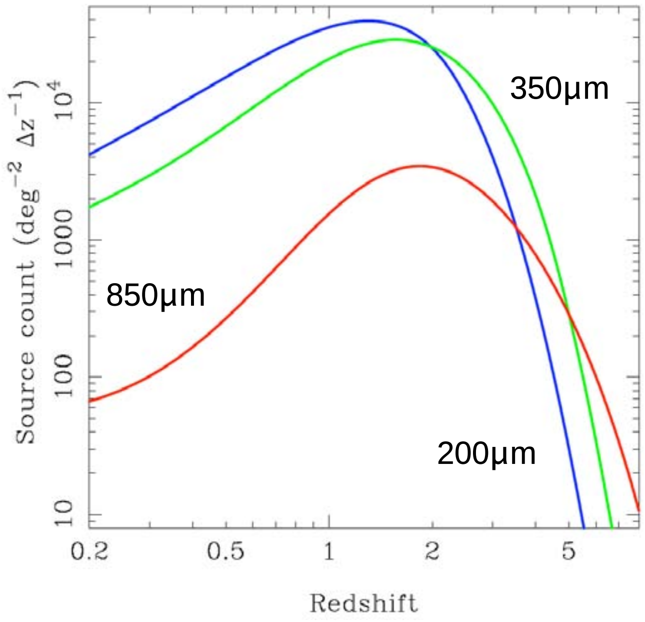
- It will complement ALMA
  - CCAT will be able to map the sky at a rate hundreds of times faster than ALMA

- CCAT will find galaxies by the tens of thousands

- It will map galaxy clusters, Milky Way star-forming regions, circumstellar disks etc.

Key Science Themes

Redshift distribution of galaxies that will be detected by CCAT at 1mJy



1. How did the first stars form?

- Detect hundreds of thousands of galaxies from the era of galaxy formation to provide a complete picture of this process

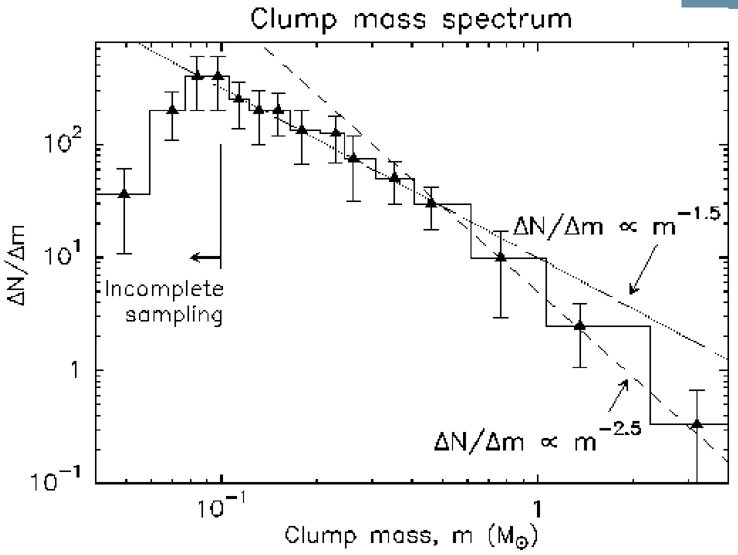
2. What is the nature of dark matter and dark energy?

- Image hundreds of clusters to provide an understanding how they form and evolve, and to constrain crucial cosmological parameters

Key Science Themes

3. How do stars form?

- CCAT will survey molecular clouds in our Galaxy to detect the (coldest) cores ($<0.1M_{Sun}$) that collapse to form stars



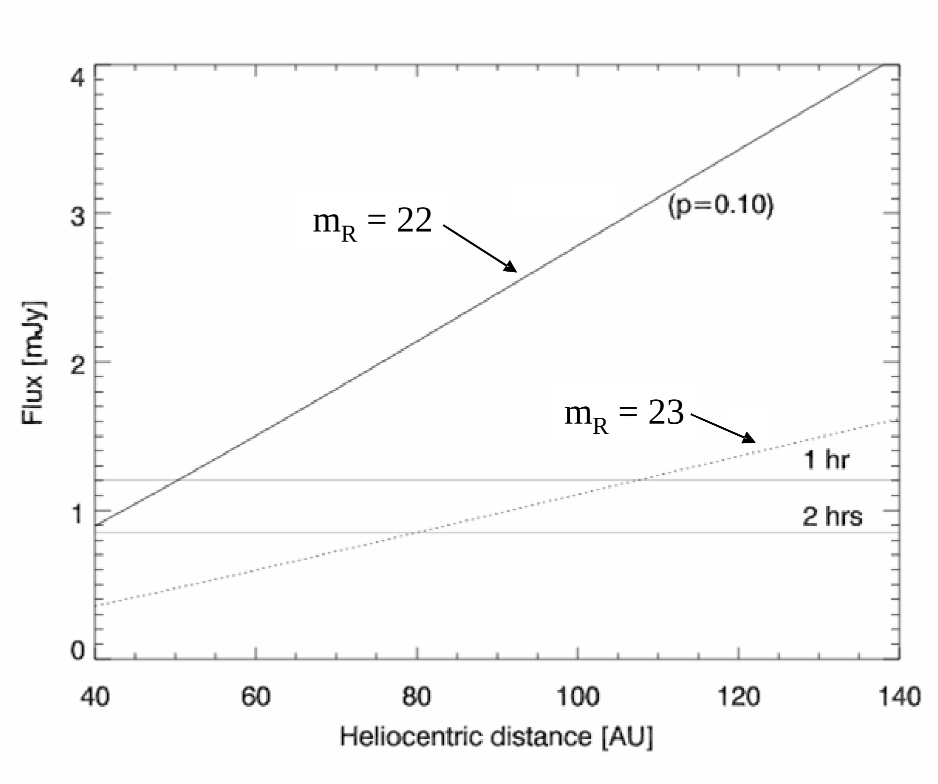
4. How do conditions in circumstellar disks determine the nature of planetary systems and the possibilities for life?

- Together with ALMA, CCAT will study disk evolution from the earliest (protoplanetary) to late (debris) stages

Key Science Themes

5. How did the Solar System form?

- CCAT will determine sizes and albedos for hundreds of KBOs, providing information to anchor models of the planetary accretion process that occurred in the early Solar System.



Science Steering Committee

Committee Charter:

- Establish top-level science requirements
  - Determine and document major science themes
- Flow down science requirements to facility requirements
  - Telescope, instrumentation, site selection criteria, operations, etc.

Science Steering Committee

Outputs:

- Science document
  - Write-ups on major science themes using uniform format (science goals, motivation/background, techniques, CCAT requirements, uniqueness and synergies)
- Requirements document
  - Specifies requirements for aperture, image quality, pointing, tracking, scanning, chopping, etc.

SSC Members

- Co-Chairs
  - Terry Herter (Cornell) and Jonas Zmuidzinas (CIT)
- Leads on Science Themes
  - Distant Galaxies – Andrew Blain (CIT)
  - Sunyaev-Zeldovich Effect – Sunil Gowala (CIT)
  - Local galaxies – Gordon Stacey (Cornell) + Shardha Jogee (UT)
  - Galactic Center – Darren Dowell (JPL/CIT)
  - Cold Cloud Cores Survey – Paul Goldsmith (JPL) + Neal Evans (UT)
  - Interstellar Medium – Jonas Zmuidzinas (CIT)
  - Circumstellar Disks – Darren Dowell (JPL/CIT)
  - Kuiper Belt Objects – Jean-Luc Margot (Cornell)
- Ex-officio members
  - Riccardo Giovanelli (Cornell), Simon Radford (CIT)

Selected (Key) Facility Drivers

Factor of ~6 over CSO

- Aperture (25m)
  - Sensitivity improves as $\propto D^2$ (hence time to a given S/N as D^{-4})
  - Confusion limit as $\propto D^{-a}$ (where a~2 and 1.2 at 350 and 850µm respectively)

- Field-of-view (5 × 5 arcmin; goal of 20 × 20...)
  - Major role of CCAT will be its unchallenged speed for moderate resolution surveys
  - Strongly complementing ALMA

JCMT is about 10 × 10

Selected (key) Facility Drivers

- Chopping/scanning
  - Modulate the signal by either chopping and/or scanning
  - Chopping secondary mirror (e.g. 1 arcmin at ~1Hz)
  - Scanning requires moderately large accelerations (0.2 deg/sec) for reasonable efficiency

- Pointing and guiding
  - Need accurate pointing particularly for spectrographs
  - Pointing goal is 2 arcsec rms with 0.5 arcsec offset accuracy
  - Guiding to maintain spectro-photometric accuracy

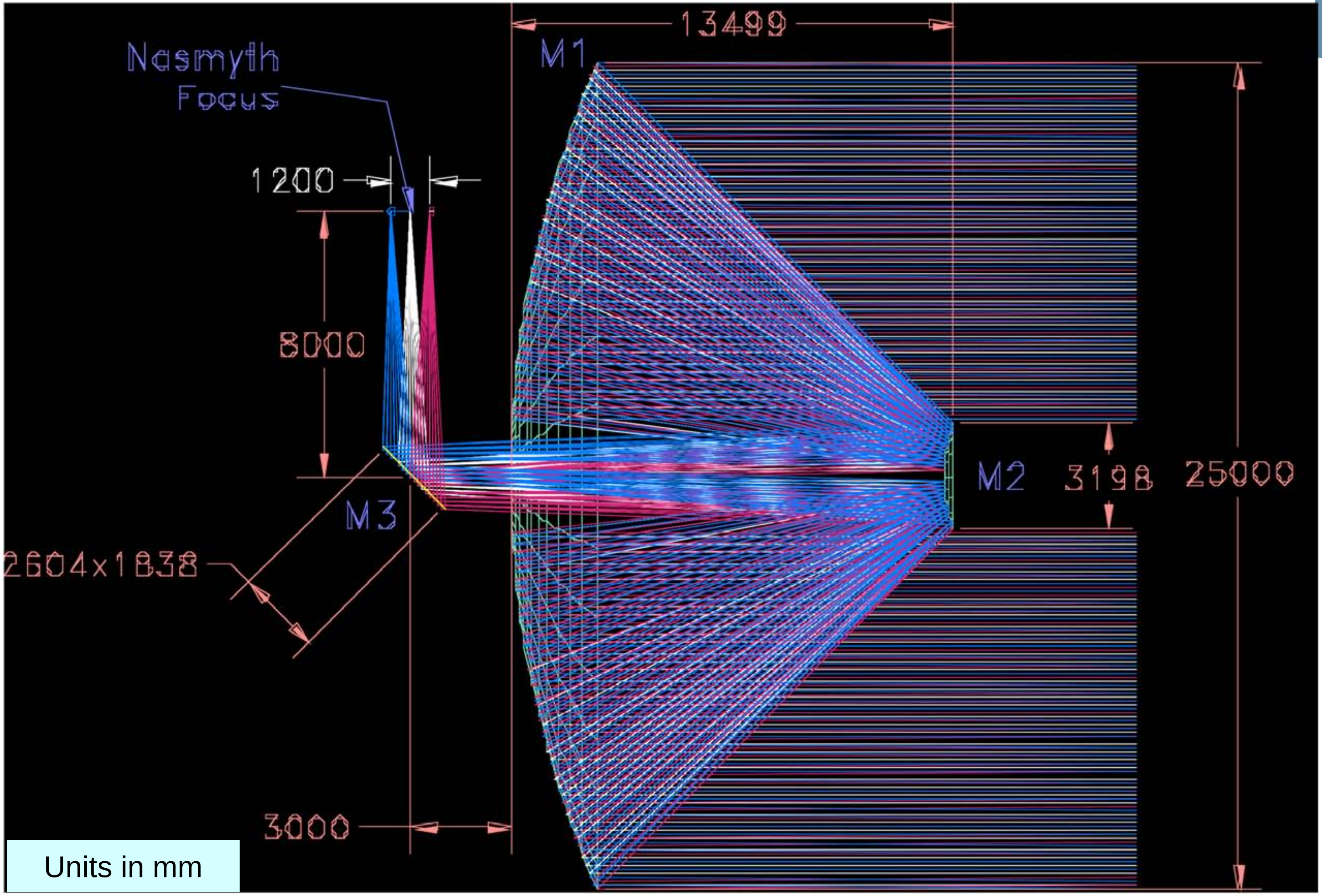
- Site quality
  - Provide significant observing time at 350/450µm

Optical Design Parameters

Design: **Ritchey-Chrétien/Nasmyth Focus**

Input Design Parameters	Symbol	Value	Units
Aperture Diameter	**D**	**25**	[m]
Primary Focal Ratio	***f1/D***	**0.6**	
System Focal Ratio	***f/#***	**f/8**	
Back Focal Distance	***B***	**11**	[m]
Field-of-View	**F-o-V**	**20**	[arcmin]
Minimum Operating Wavelength	λ_{min}	**200**	[μm]

Optical Layout



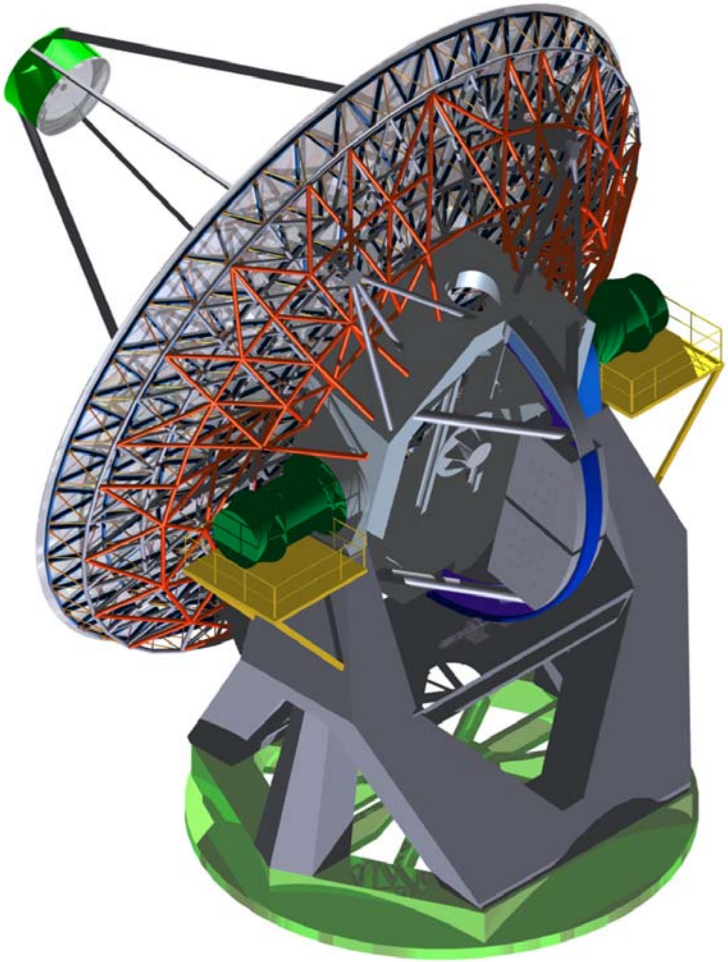
Units in mm

Telescope Design

- Design by Vertex RSI
- Uses approaches from radio and optical telescopes
- 210 panels in 7 rings, each panel about 1.7m

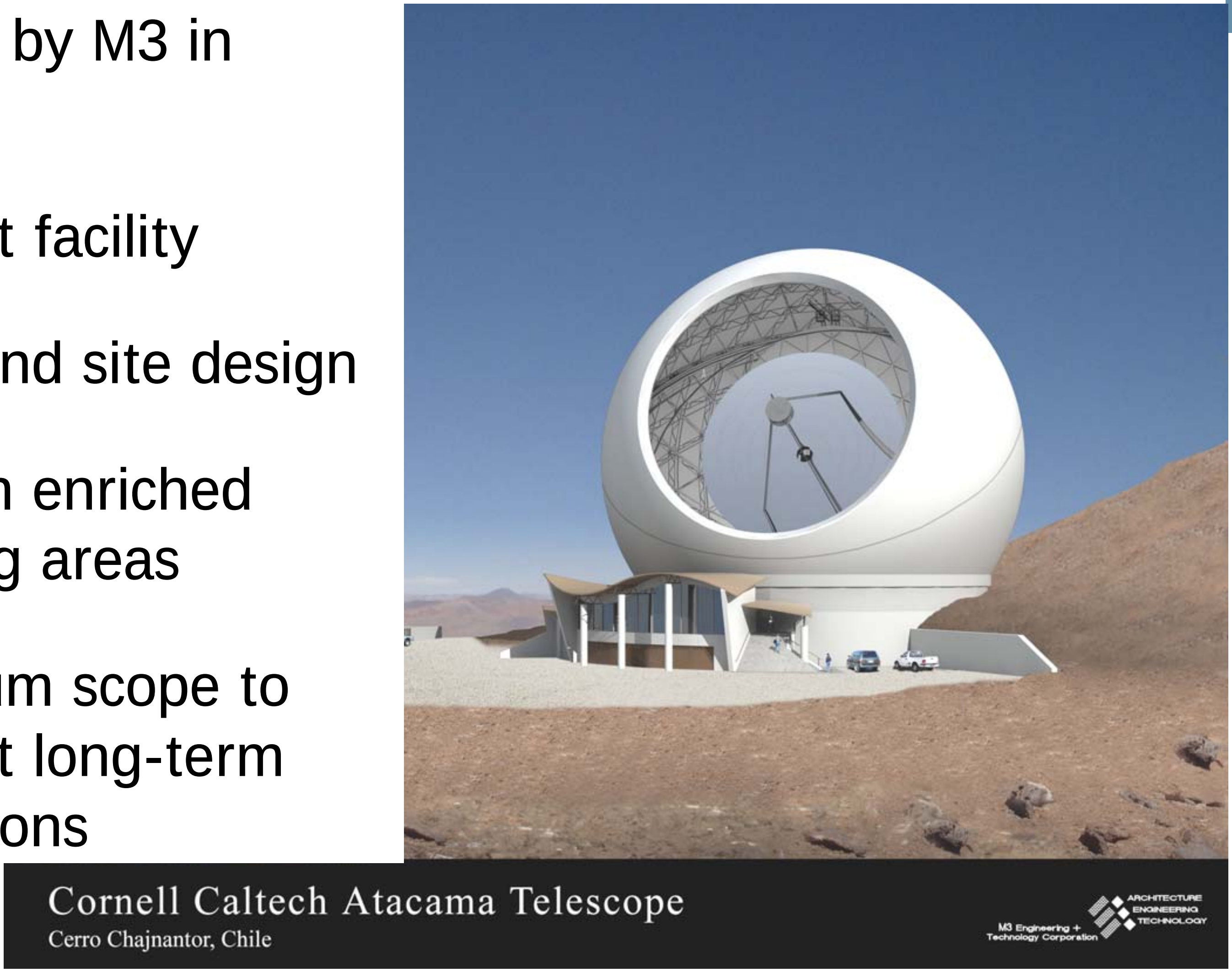
Mount Design

- Stainless steel truss (much cheaper than CPRP…)
- Commercial actuators will maintain the shape



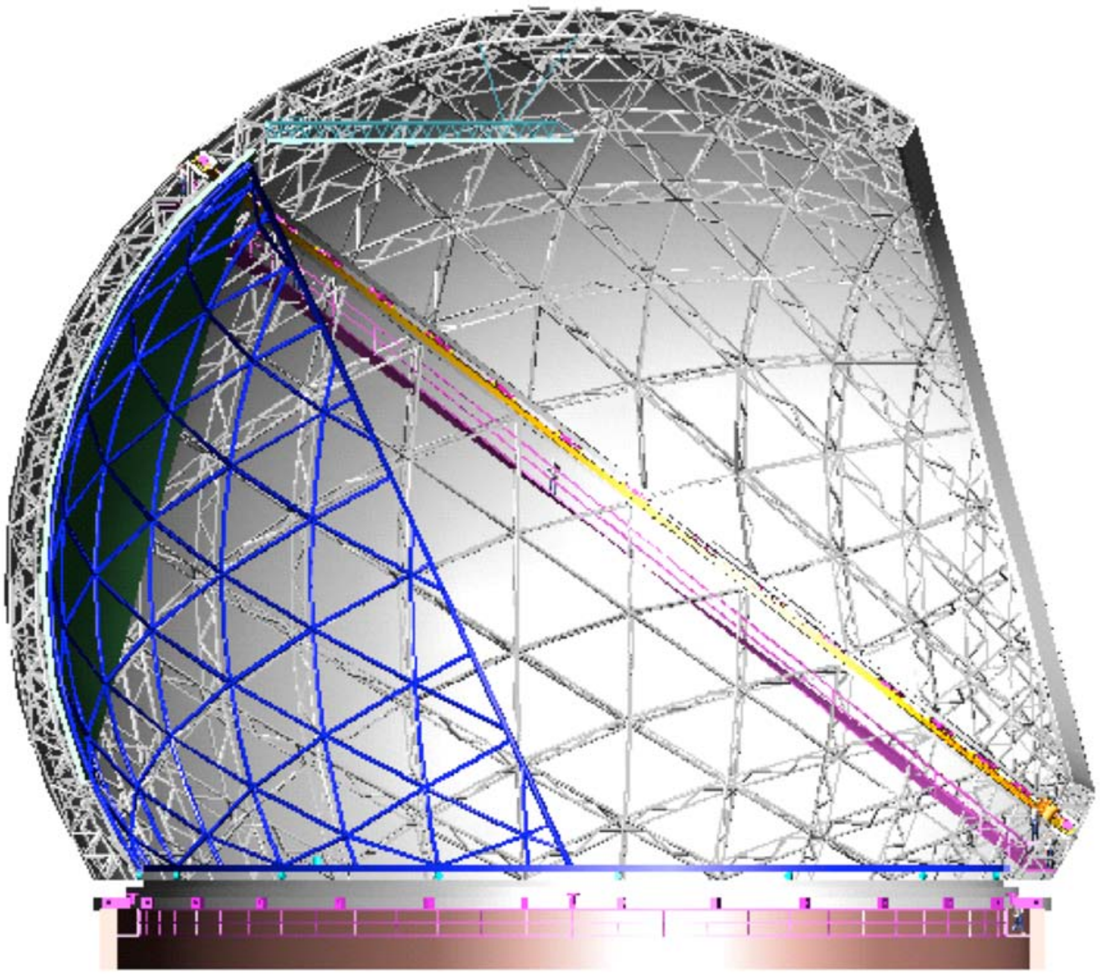
Telescope Facility

- Design by M3 in Tucson
- Summit facility
- Road and site design
- Oxygen enriched working areas
- Minimum scope to support long-term operations

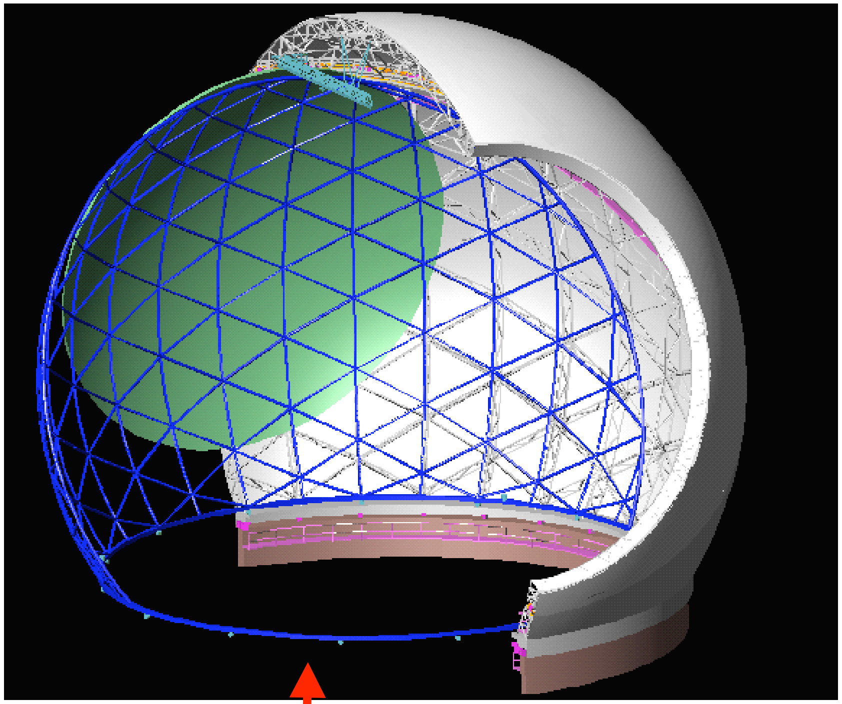


Telescope Dome Concept

- Calotte style 50m diameter at equator
- 30m aperture
- Rib and tie structure is highly repetitive
- Operation via two similar rotation stages
- Aperture sized to keep M2 2m inside dome

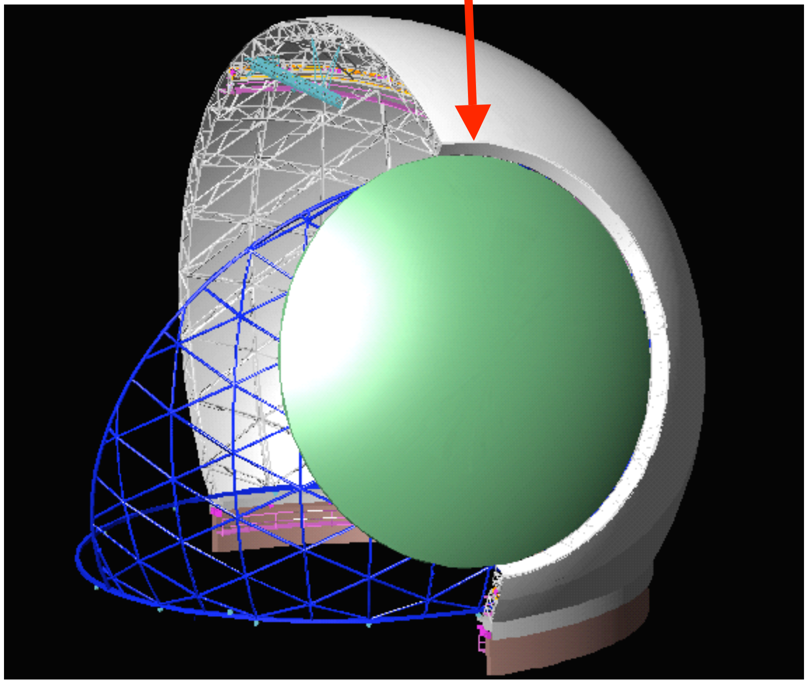


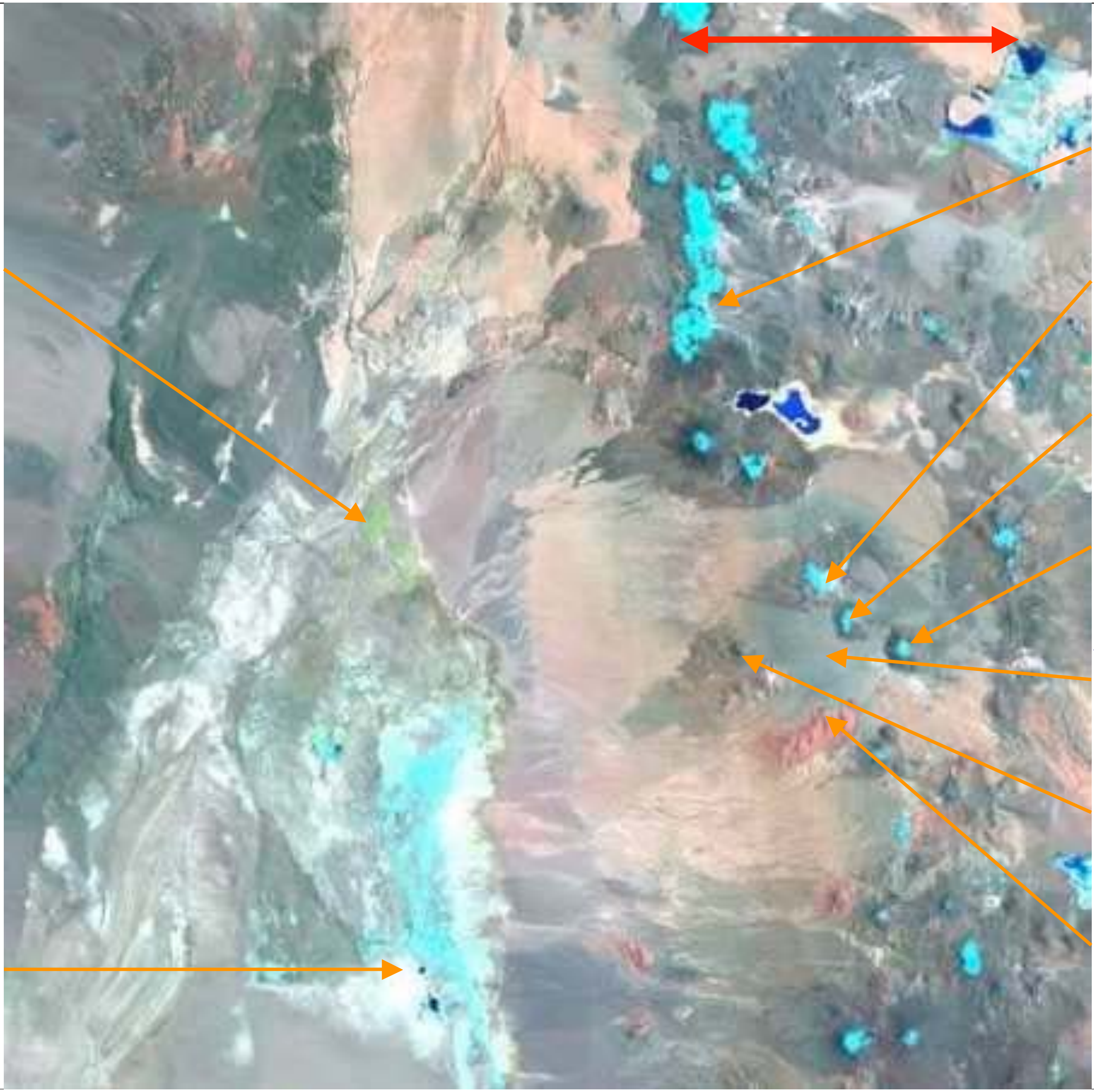
Telescope Dome Concept



Interior frame rotates independently of azimuth stage

Shutter uses mechanical and pneumatic seals to exclude weather





30 km

Cerro
Sairecabur
5500 m

Cerro
Toco
5600 m

Cerro
Chajnantor
5600 m

Cerro
Chascon
5675 m

ALMA,
CBI, APEX
5050 m

Cerro
Negro
5050 m

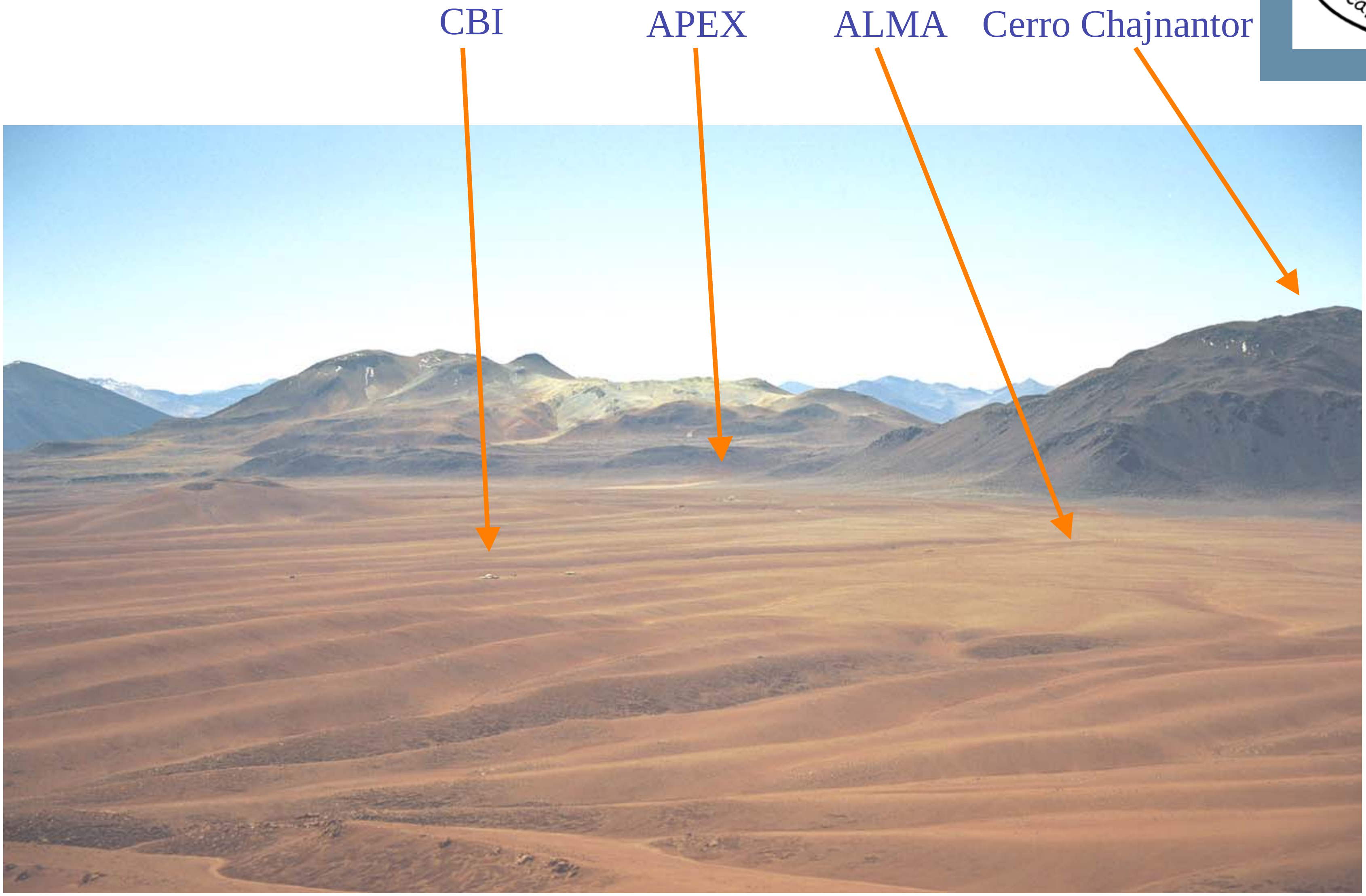
Cordon
Honar
5400 m

San Pedro
de Atacama
2400 m

Salar de
Atacama

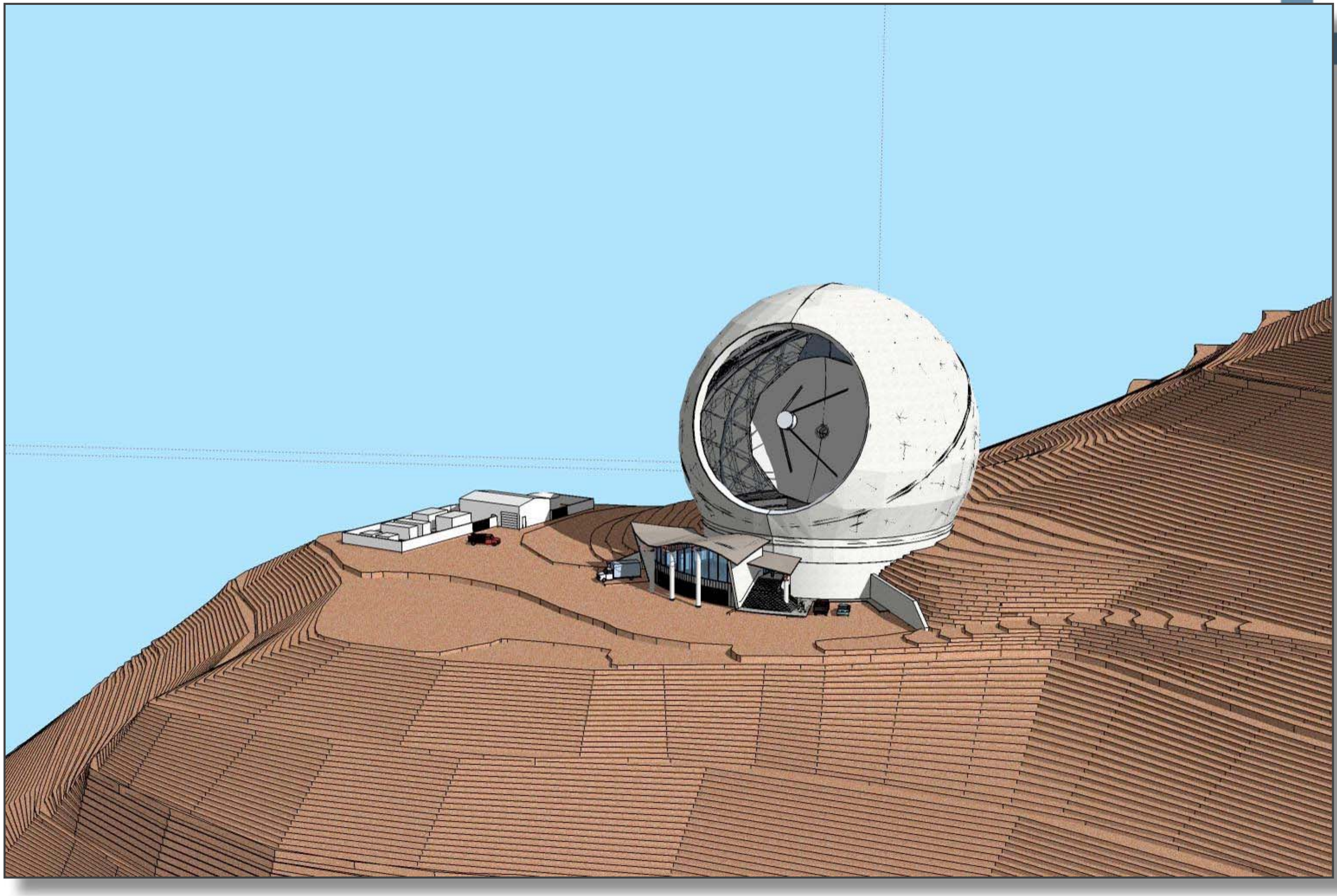
NASA/GSFC

Chajnantor Plateau (5000m)



CBI APEX ALMA Cerro Chajnantor

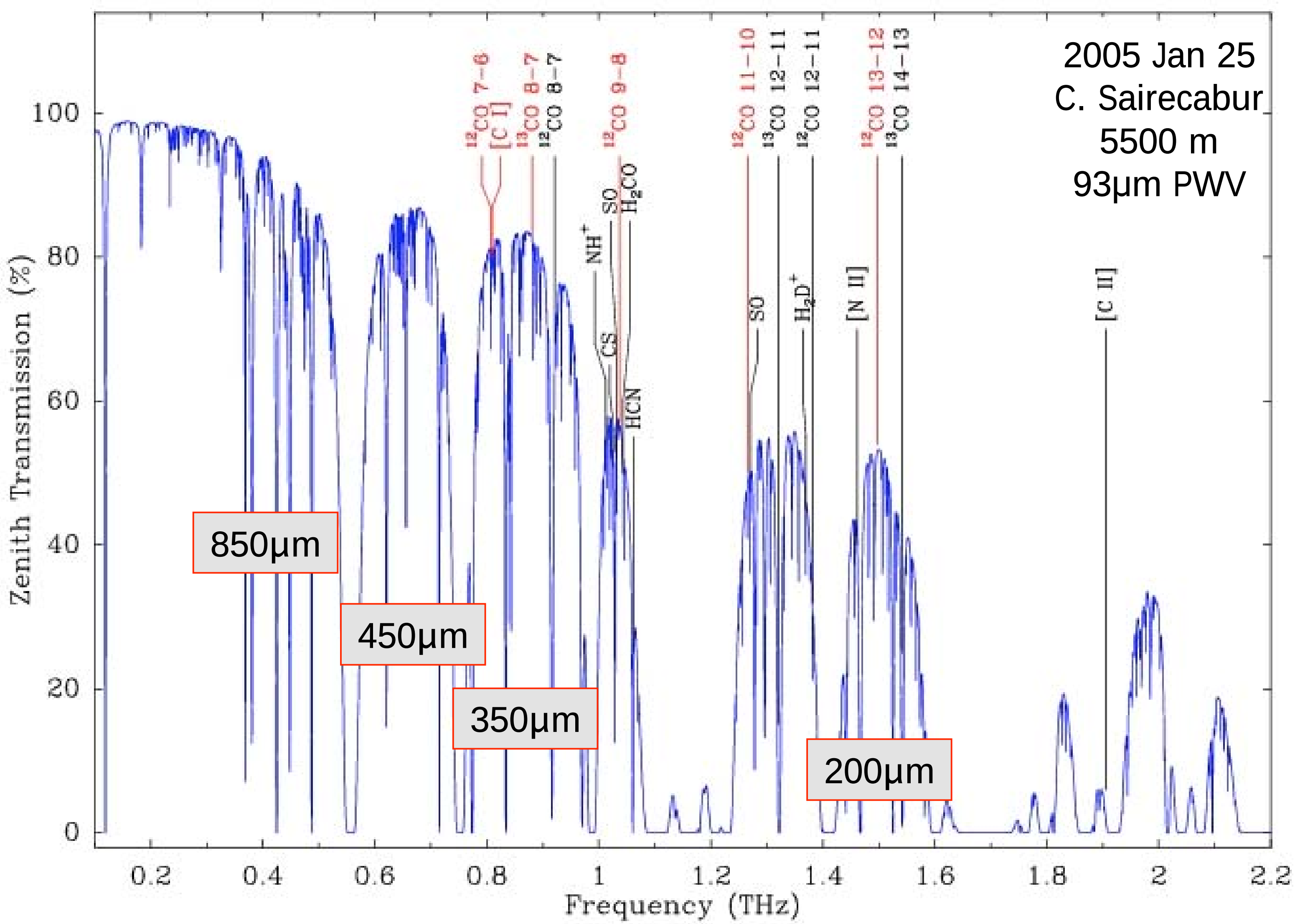
Site Plan: Aerial View



Mountain Facility

Site Plan: Aerial View

Submillimetre Transparency


2005 Jan 25
C. Sairecabur
5500 m
93µm PWV

850µm
450µm
350µm
200µm

Instruments

- First light instruments proposed to be wide-field cameras (not necessarily taking in entire F-o-V but having upgrade potential)

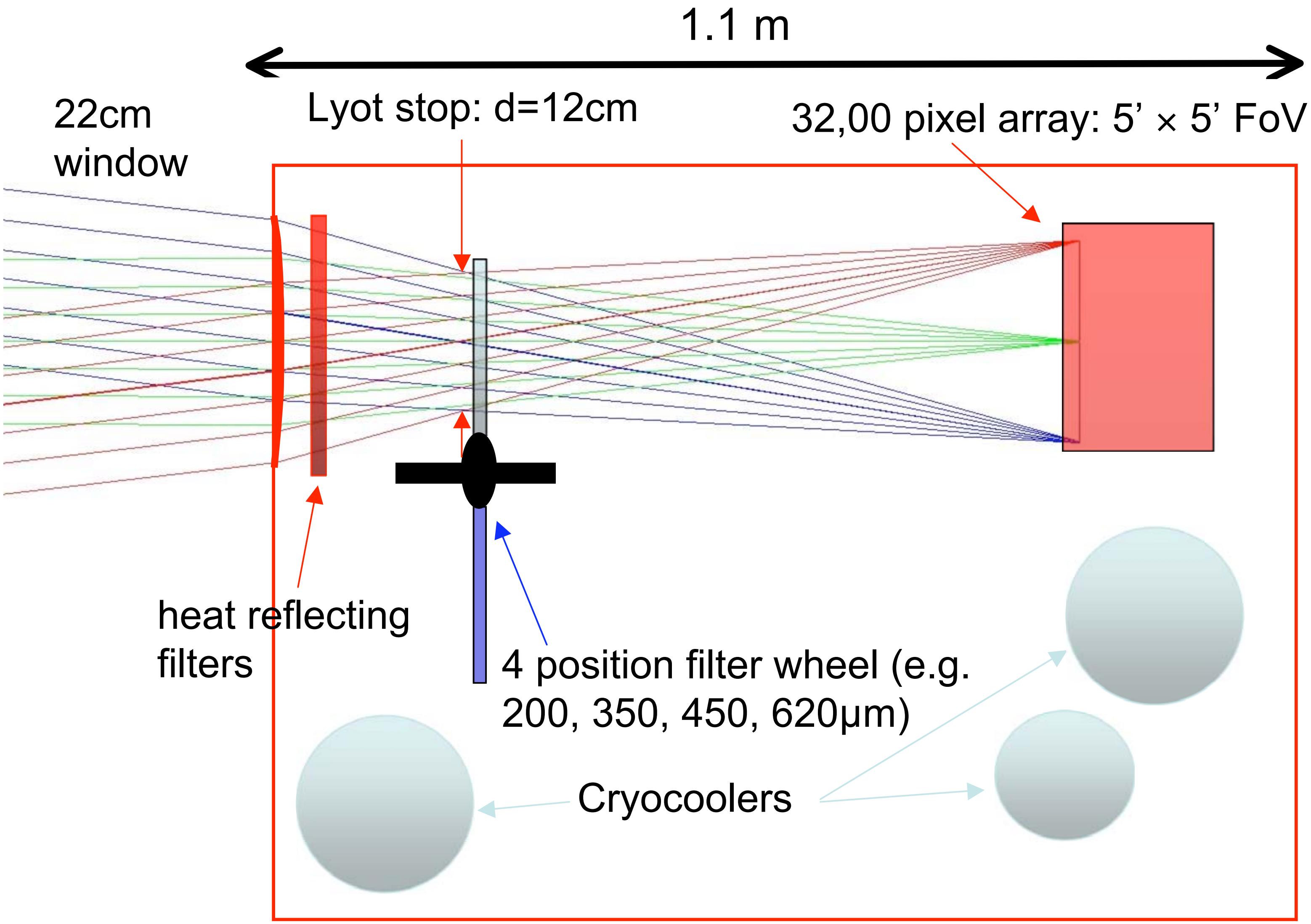
- Existing spectroscopic instruments (e.g. ZEUS, Z-spec) could also be used

- Most likely a call for second generation instruments at some point (multi-object spectrometers, array upgrades and a possible far-IR camera?!)

First Light Instruments

- Short Wavelength Camera (SW Cam)
  - F-o-V is ~5’ × 5’
    - For Nyquist sampling at 350μm this requires a 170 × 170 pixel array
    - 32,000 pixels, or 6 times that of SCUBA-2…
  - Primary bands are:
    - 200, 350, 450 and 620μm
    - Selection of bands driven by similar backgrounds and adequate sampling requirements
    - Filter wheel to change wavelengths

SW Cam Instrument Design



1.1 m

22cm window

Lyot stop: d=12cm

32,00 pixel array: 5’ × 5’ FoV

heat reflecting filters

4 position filter wheel (e.g. 200, 350, 450, 620μm)

Cryocoolers

First Light Instruments

- Long Wavelength Camera (LW Cam)
  - F-o-V from 10 × 10 (submm) to 20 × 20 arcmin (mm)
    - 1024 to 16,384 pixels depending on wavelength
  - Primary bands are:
    - 740 and 850μm, 1.1, 1.4 and 2mm
    - Backgrounds are lower so sensitivity requirements more of a challenge
    - Multifrequency operation using antenna coupled bolometer arrays

Detector Technology

The detection process is more formally split into two steps with the LW Cam arrays

- How light is routed from free space to detectors

Antenna coupled arrays

- What kind of detectors will be used?

TES or MKID detectors

Performance Comparison

Instrument	Wavelength (microns)	F-o-V (sq-arcmins)	NEFD (mJy)	FWHM (arcsec)	Confusion (mJy)
SCUBA	450	4.2	400	7.5	0.25
	850	4.5	80	14	0.5
SCUBA-2	450	50	100	7.5	0.25
	850	50	30	14	0.5
Laboca-S	350	4	250	7	0.3
Laboca	850	11	110	18	0.8
SPIRE	250	32	29	18	2.6
	350	32	34	25	3.8
	500	32	37	35	5.4
AzTec	1100	2.4	3.5	5.5	0.06
MAMBO-2	1200	10	30	10	0.2

The confusion level in this case is simply scaled by aperture area/wavelength from the (measured) SCUBA 850μm 1-σ level

Performance Comparison

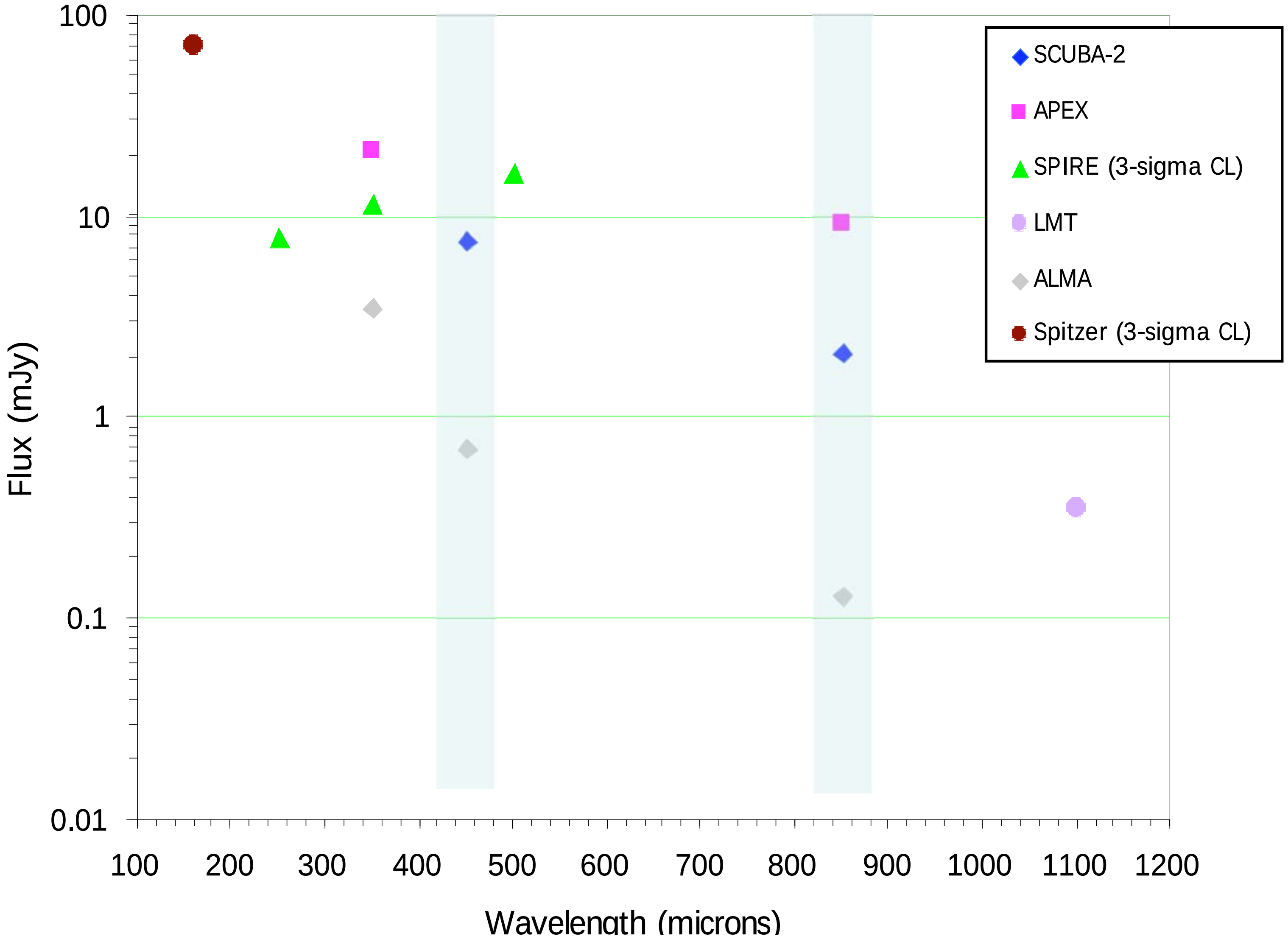
Instrument	**Wavelength (microns)**	**F-o-V (sq-arcmins)**	**NEFD (mJy)**	**FWHM (arcsec)**	**Confusion (mJy)**
ALMA*	450	0.0069	8	0.2	0.0002
	850	0.022	1.5	0.4	0.0004
CCAT	200	25	150	2	0.04
	350	25	14	3.5	0.07
	450	25	13	4.5	0.1
	850[1]	100	6	8.5	0.2

*Compact ALMA configuration

[1] Slightly undersampled

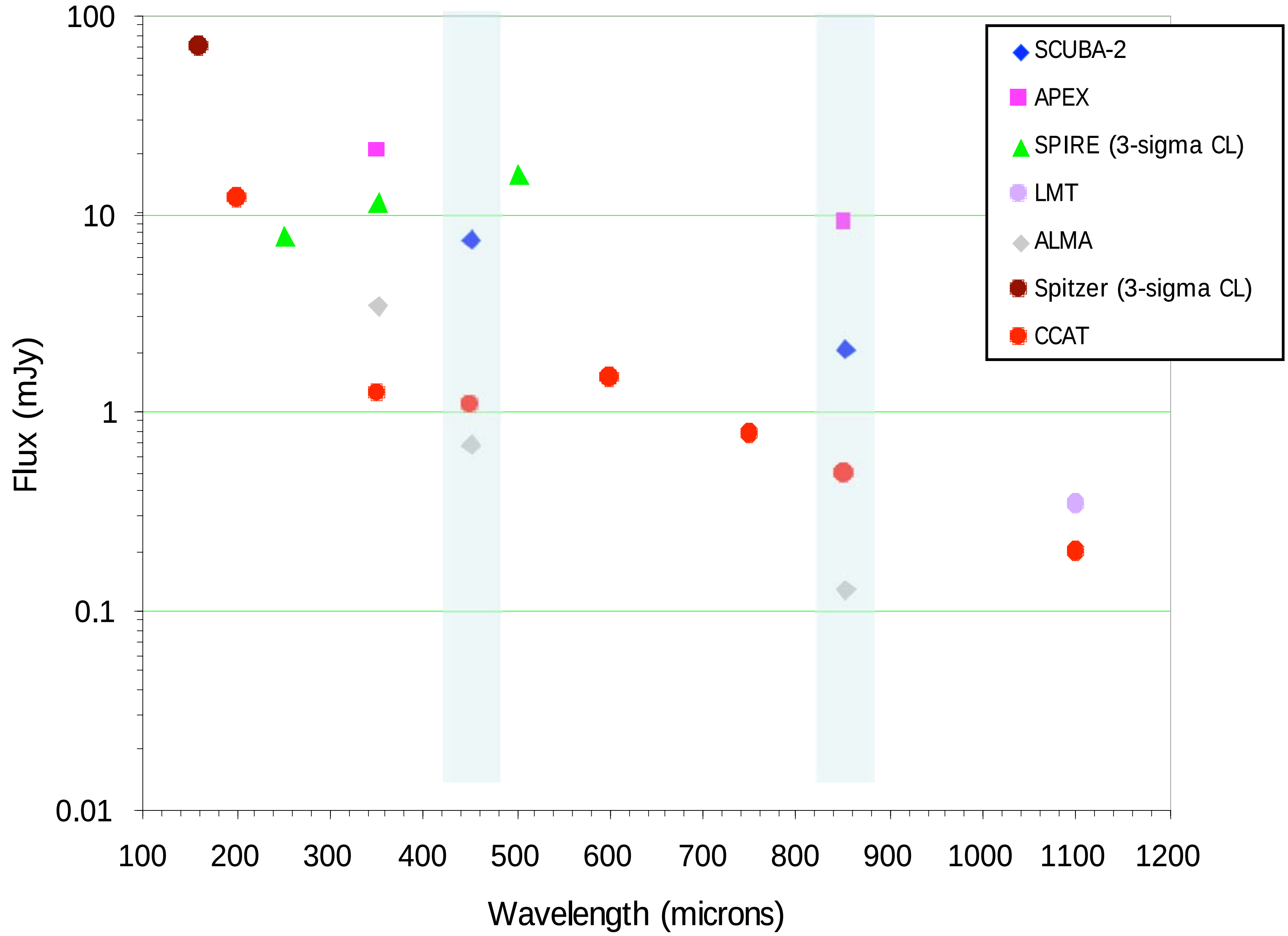
The confusion level in this case is simply scaled by aperture area/wavelength from the (measured) SCUBA 850μm 1-σ level

CCAT Sensitivity



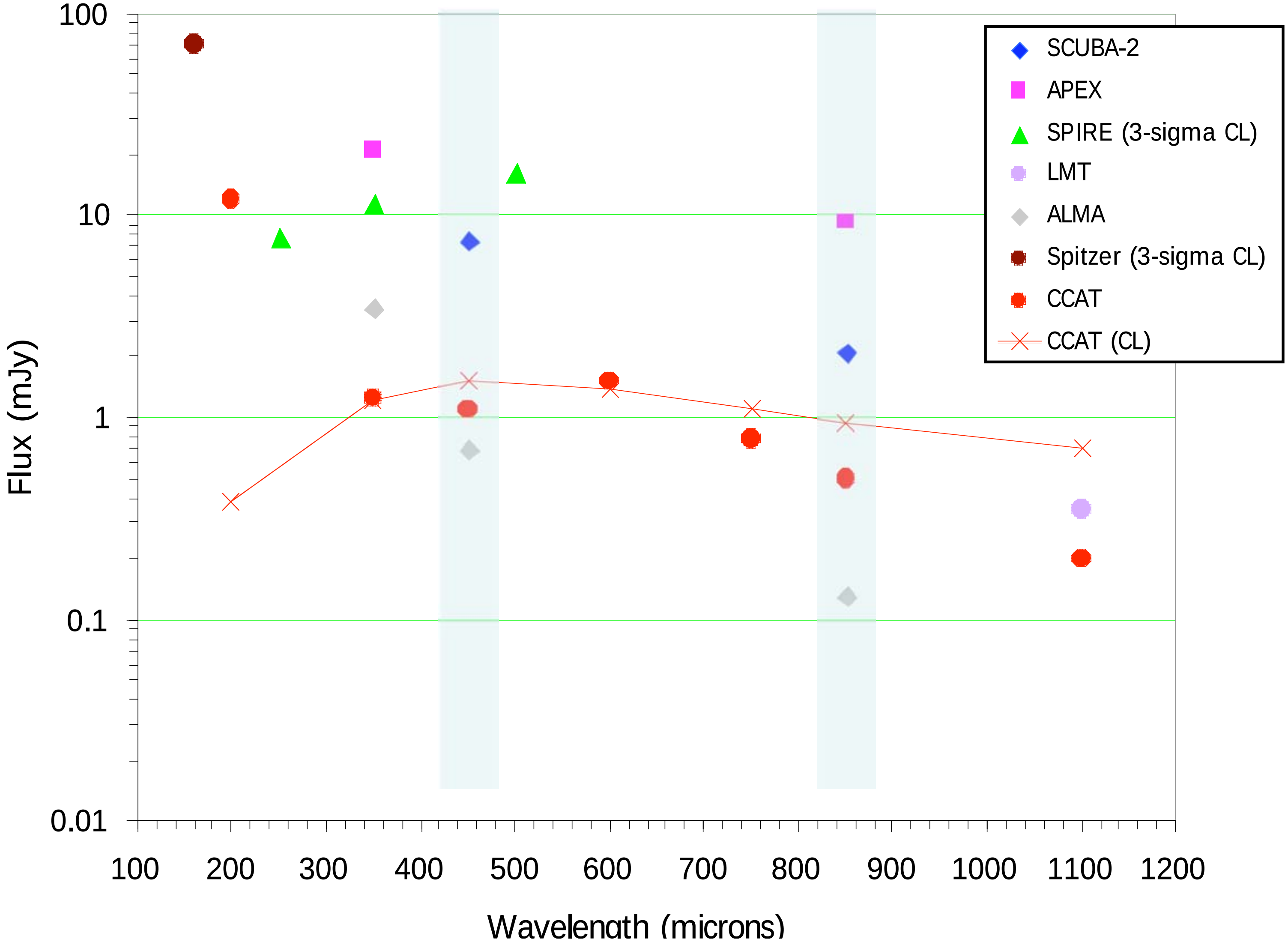
5σ, 1-hour sensitivities for various instruments

CCAT Sensitivity



5σ, 1-hour sensitivities for various instruments

CCAT Sensitivity



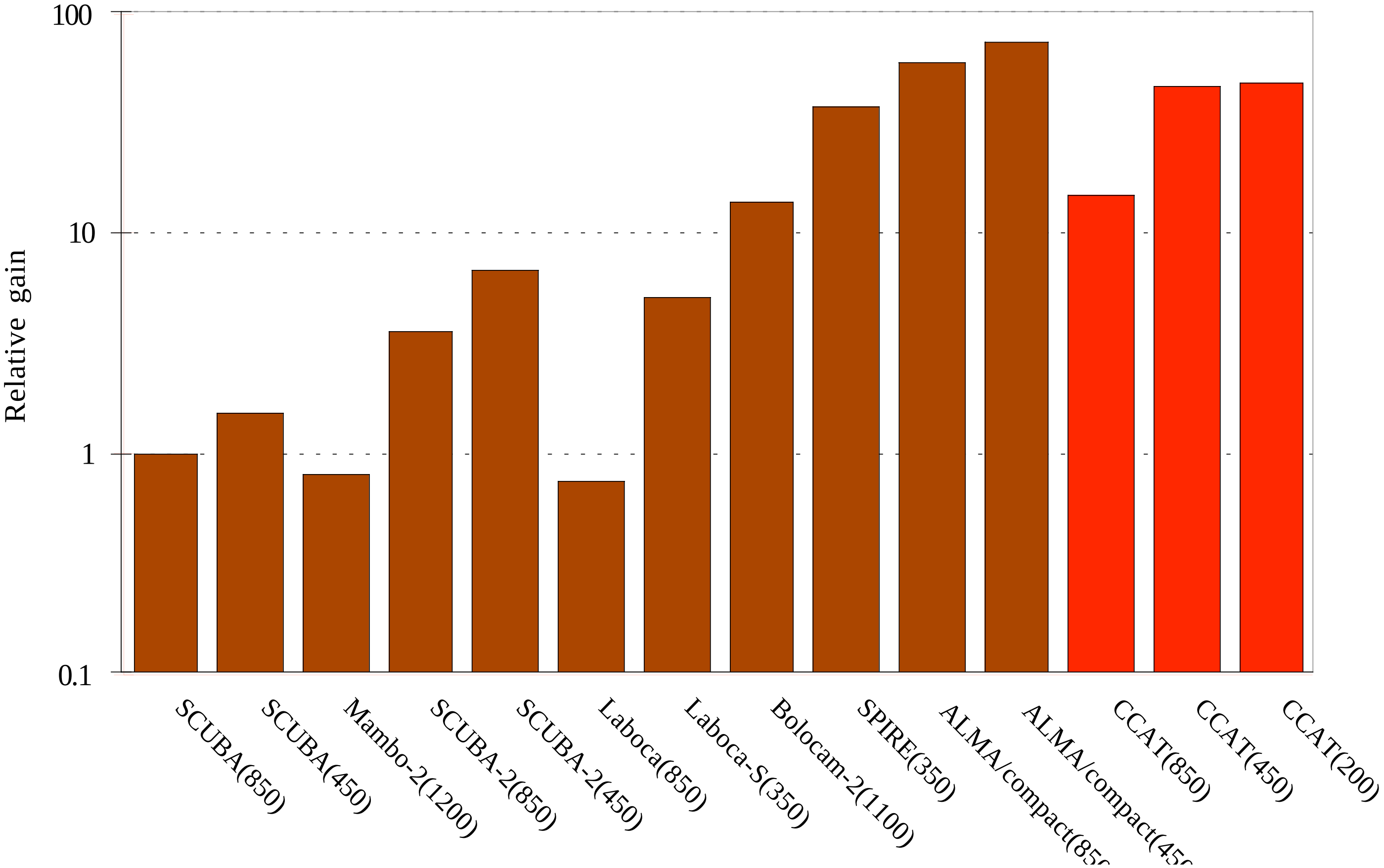
Confusion limit is 1 source per 30 beams and is calculated assuming CL is proportional to $D^{-\alpha}$ where $\alpha=2$ at 350μm and 1.2 at 850μm

Dust Mass Sensitivity

Dust at >30K and objects z<2 emission has a spectral index slope of ~2+β

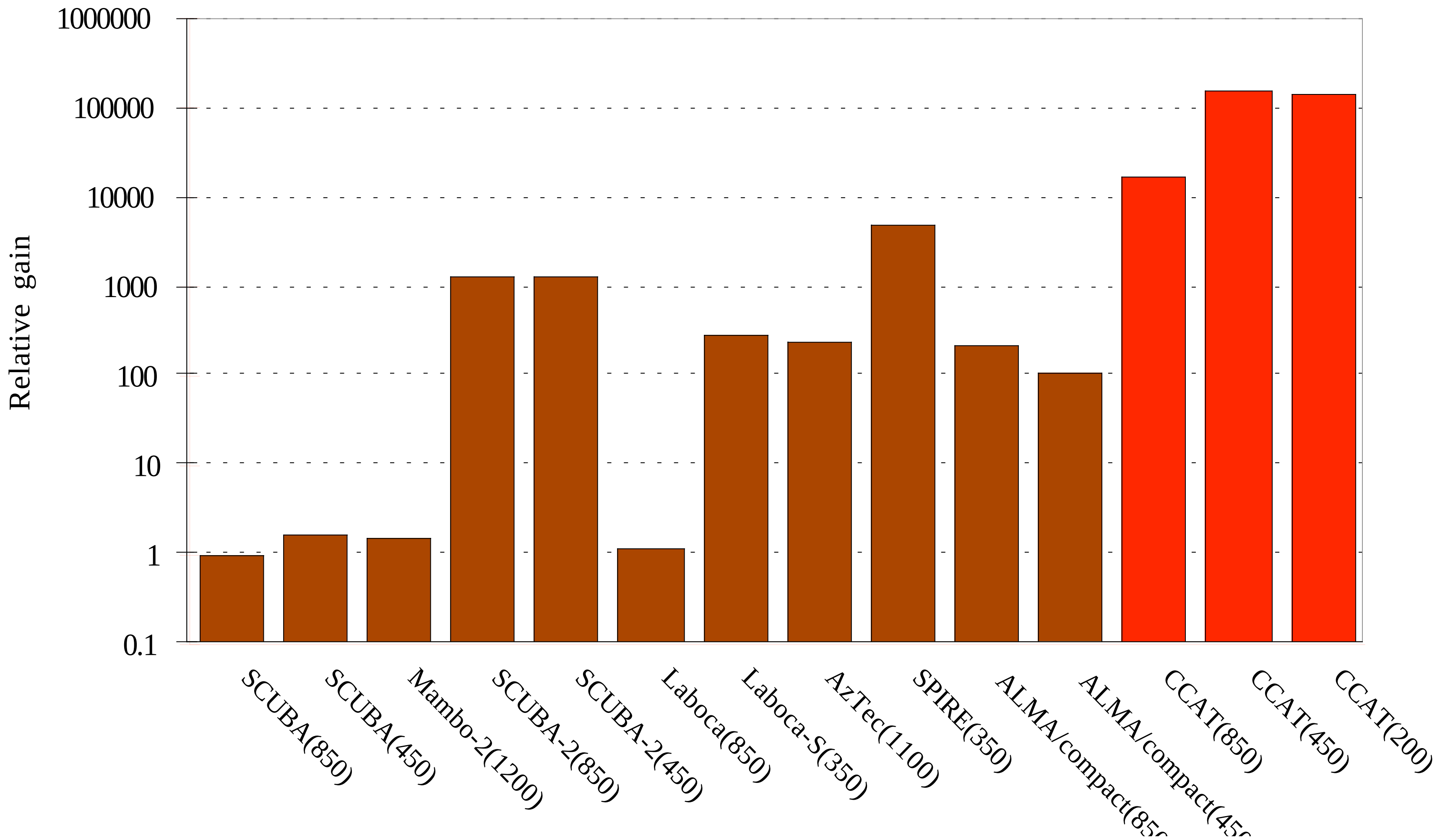
β=0 for a pure black-body, whilst β=2 for small ISM grains

Taking β=1 compute the relative gain of CCAT for a given mass of dust compared with other instruments



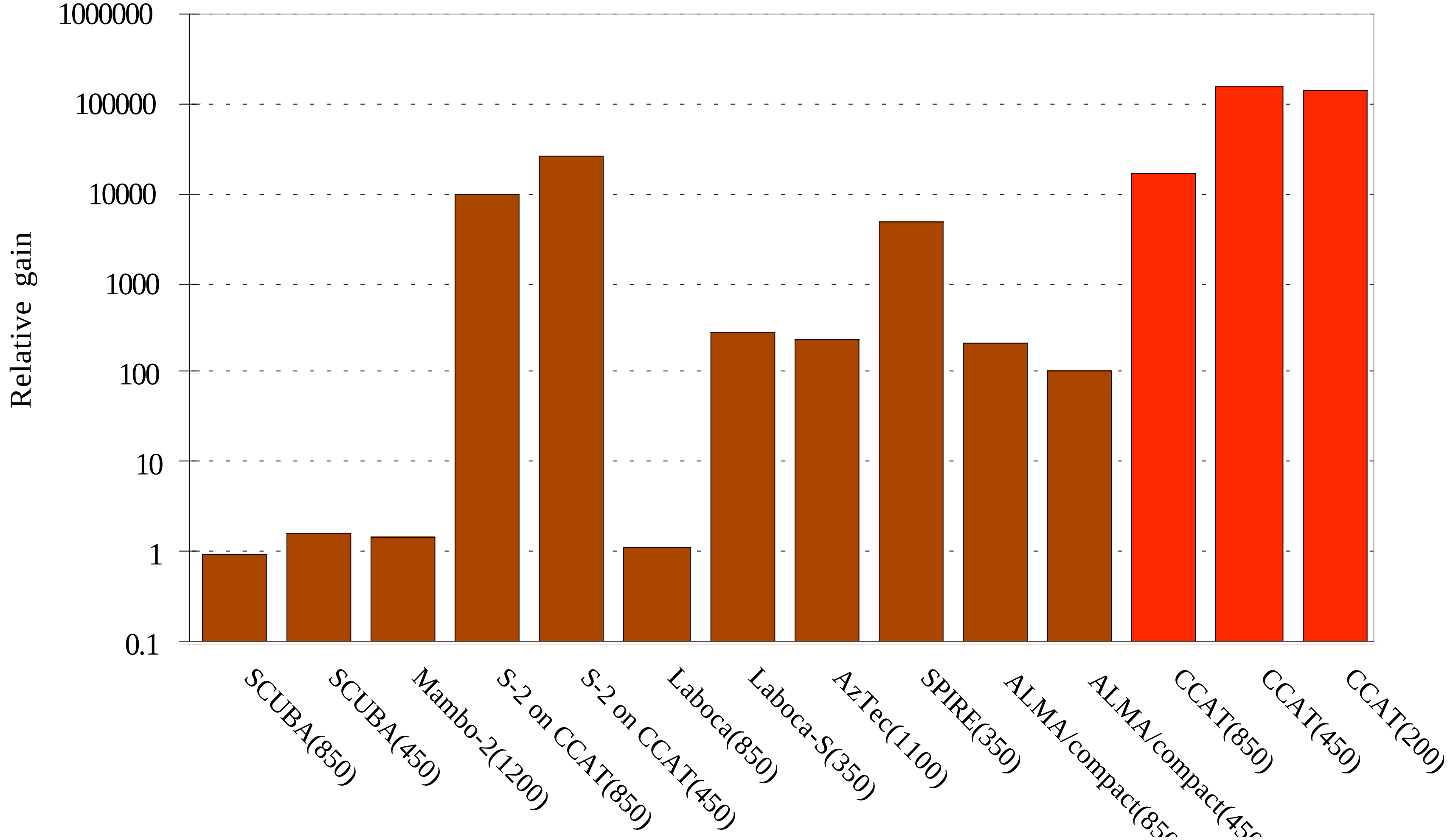
Relative to SCUBA at 850μm

Mapping Speed



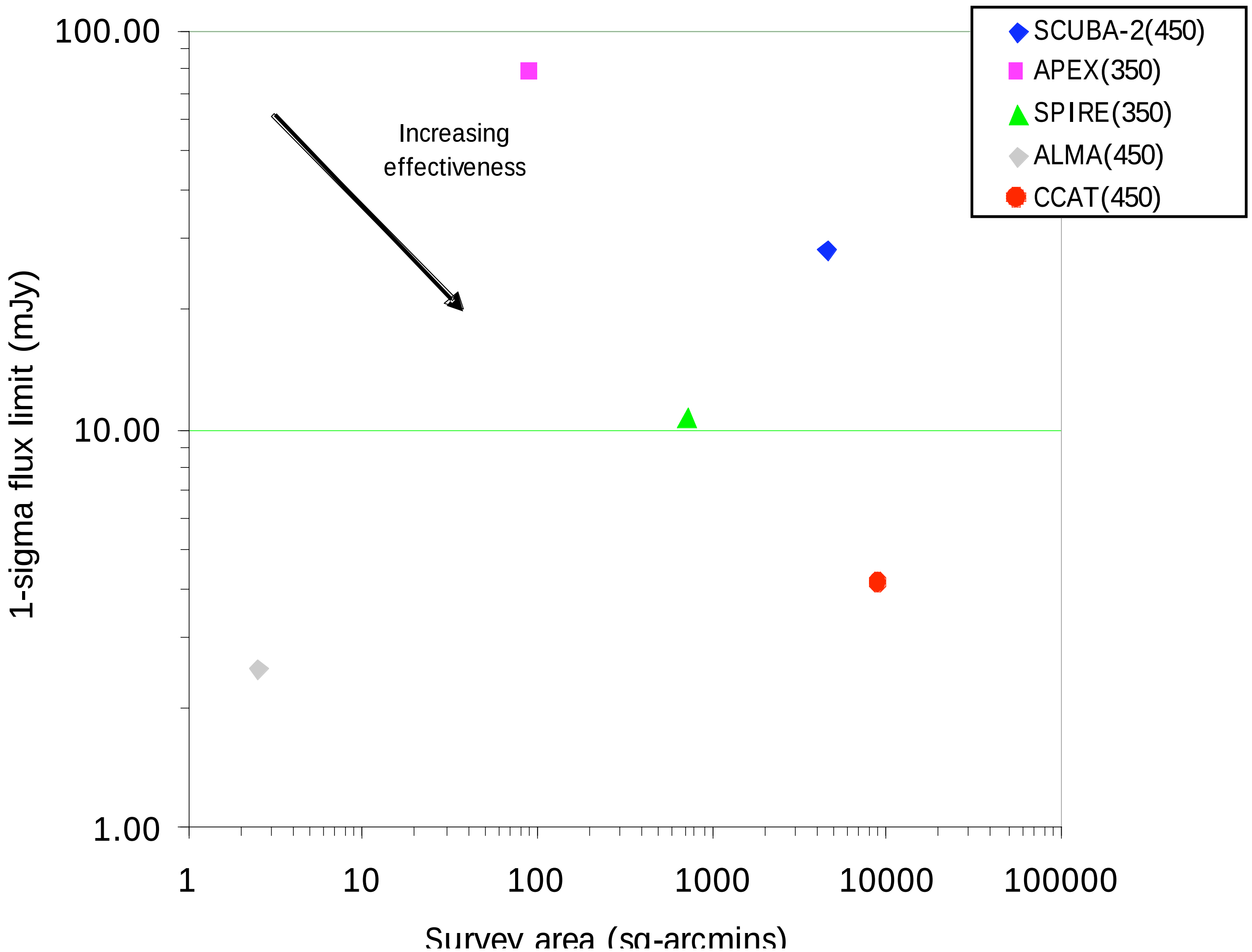
Large area mapping speeds assuming the same dust mass sensitivity (relative to SCUBA 850)

SCUBA-2 on CCAT



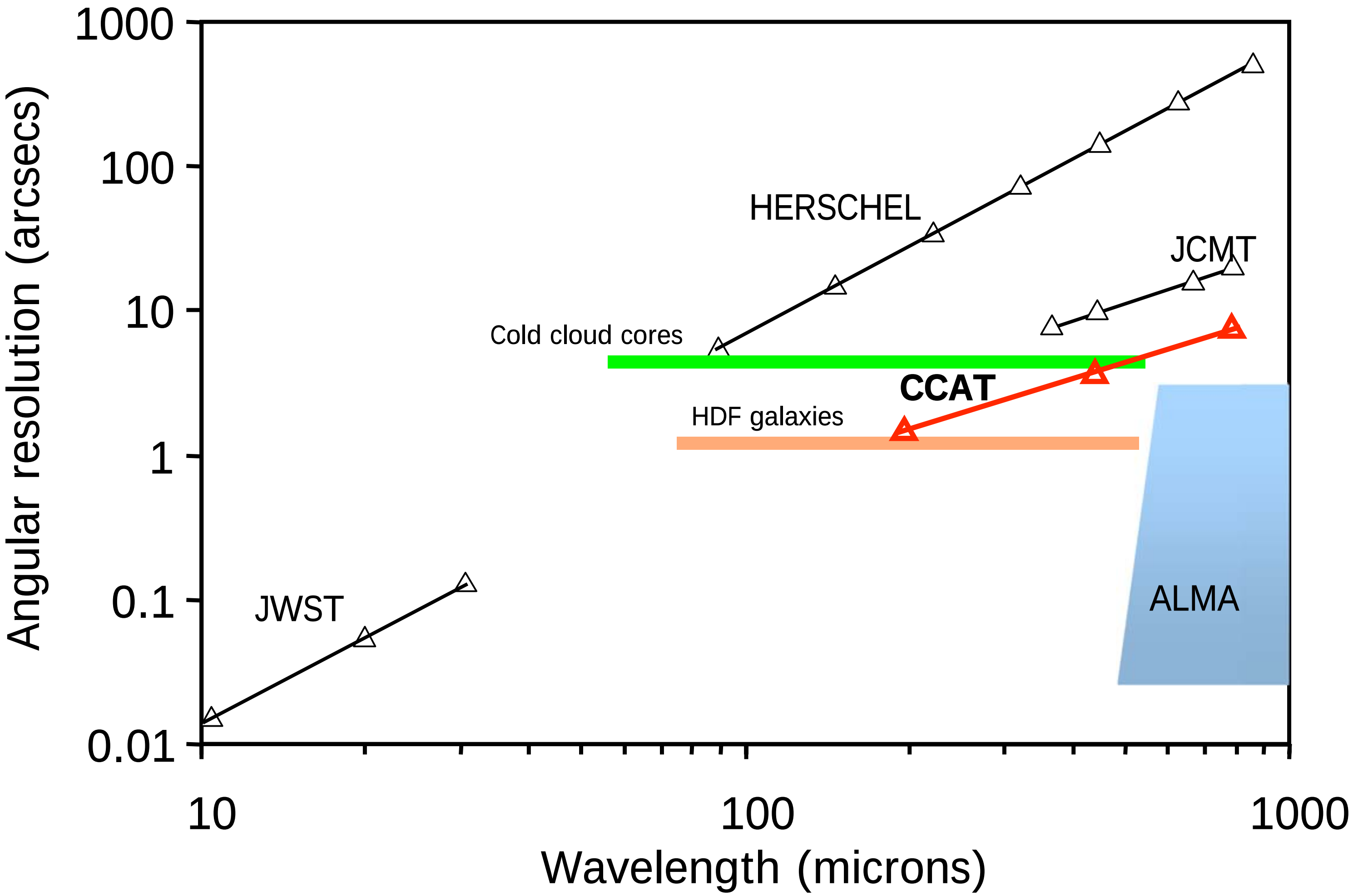
Assumes SCUBA-2 can achieve same sensitivity per pixel as CCAT instruments

Field Mapping



Flux limit versus area mapped assuming 10sec/pointing (no overheads)

Angular Resolution



Time Available To Observe

Band		Time to CL	Ref. PWV	Sairecabur (5500 m)			ALMA (5050 m)		
λ	ν			Time Available		CL fields	Time Available		CL fields
[µm]	[GHz]	[hr]	[mm]	[hr yr^{-1}]	[%]	[yr^{-1}]	[hr yr^{-1}]	[%]	[yr^{-1}]
200	1500	1248	0.26	281	3		84	1	
350	857	0.86	0.47	1936	22	2244	1084	12	1257
620	484	1.14	0.64	716	8	629	723	8	634
740	405	0.43	0.75	639	7	1488	690	8	1607
865	347	0.28	0.86	1223	14	4413	1205	14	4348
1400	214	0.30	1.00	1517	17	5093	1299	15	4361
Time (PWV < 1.1 mm)				6312	72		5084	58	

Number of hours/year (round the clock) available for observing at a given λ (PWV) for Sairecabur vs. the ALMA region. “CL fields” is the number of fields that can be observed to the confusion limit over a year. The “Total Time” is the sum of available hours and represents all time (day or night) with PWV < 1.1mm.

Observations at some wavelengths require similar conditions, e.g. 350/450µm, so they share a common range. Note that at MK, 350/450 observations are typically done when PWV <1 mm.

Project Phases and Schedule

- Feasibility/Concept Design Study
  - Oct 2005 – January 2006 $2m
  - Development of baseline concept and assessment of feasibility, initial cost estimate
- Engineering Concept Design
  - June 2006 – June 2007 $2-3m
  - Firm-up concept, key analyses, detailed and accurate cost estimate
- Development Phase
  - June 2007 – June 2011 ~$94-$95m
  - Detailed design, manufacture, integration
- Commissioning Phase
  - June 2011 – June 2012 ~$1m
  - Performance optimisation & handover to operations

Outstanding Questions?

By 2013 there will have been a number of large-scale surveys of the submm sky (SCUBA-2, Herschel etc)

- Is there a clear need for a wide-field imaging capability in the submm, and does CCAT provide this?
- At what level would we (the UK) be interested in joining the project?
- What areas can the UK contribute towards (science representation, design areas)?

Reserve Slides

SW Camera field-of-view

The telescope delivers a 20 arcmin diameter F-o-V so why are we designing to a 5 arcmin field?

- Science
  - The initial science can be delivered with 5 arcmin F-o-V cameras
- Image scale
  - Telescope delivers a 1.2m image for a 20 arcmin field – this would be quite challenging to couple onto a background limited camera

SW Camera field-of-view

The telescope delivers a 20 arcmin diameter F-o-V so why are we designing to a 5 arcmin field?

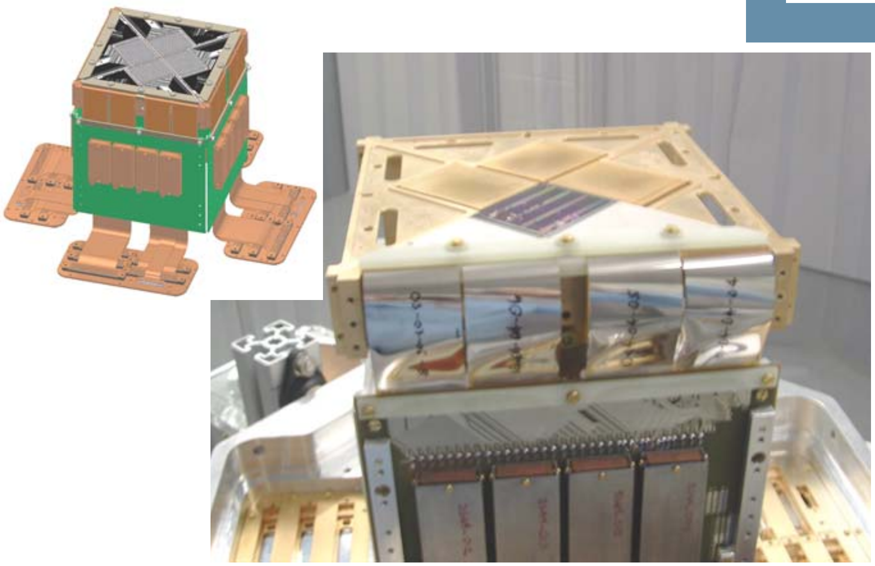
- Technology
  - Current, and near future technology suggests 32,000 pixels is a reasonable goal for the array – this can deliver Nyquist sampled images over a 25 sq-arcmin F-o-V at 350μm

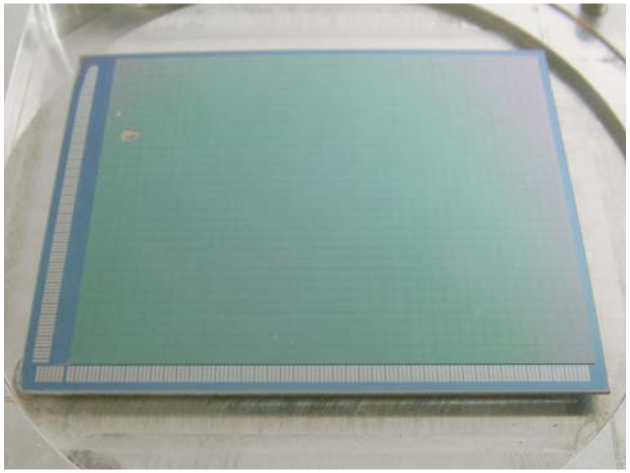
  - A 20’ F-o-V requires ***500,000 pixels*** at 350μm, – extremely expensive using today’s technologies

    - Future developments will greatly reduce the costs – therefore mega pixel cameras are postponed

Array Technology

- Baseline array technology is an extension of that developed for SCUBA-2
- Arrays easily deliver the requisite sensitivities ($<10^{-16}$ W/√Hz) for SW Cam wavebands
- 4 × (32 × 40) sub-arrays to make 5120 pixels – extend to 32,000 by using 25 edge-buttable sub-arrays





Antenna-coupled arrays

- Antenna-coupled arrays using a slot dipole architecture
- Device is broadband: can be made to cover 740µm to 2mm
- Bands are separated using microstrip bandpass filters
- Demonstrated to work in lab
- 16-pixel, 4 colour array under development using microstrip filters

Antenna coupled focal plane prototype device
Vertical lines are slots
Pie shaped structures connect to the microstrip taps that cross over the slots

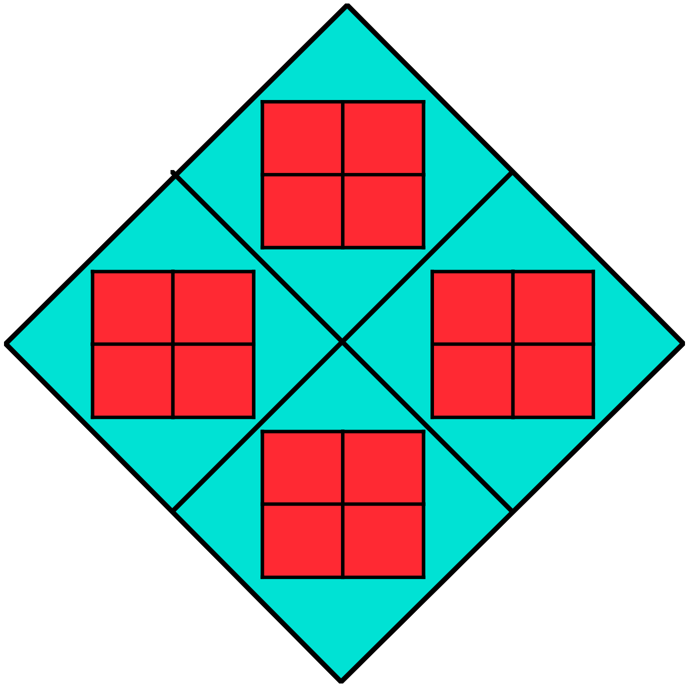
Under development within the CCAT consortium at Caltech/JPL

Pixel counts

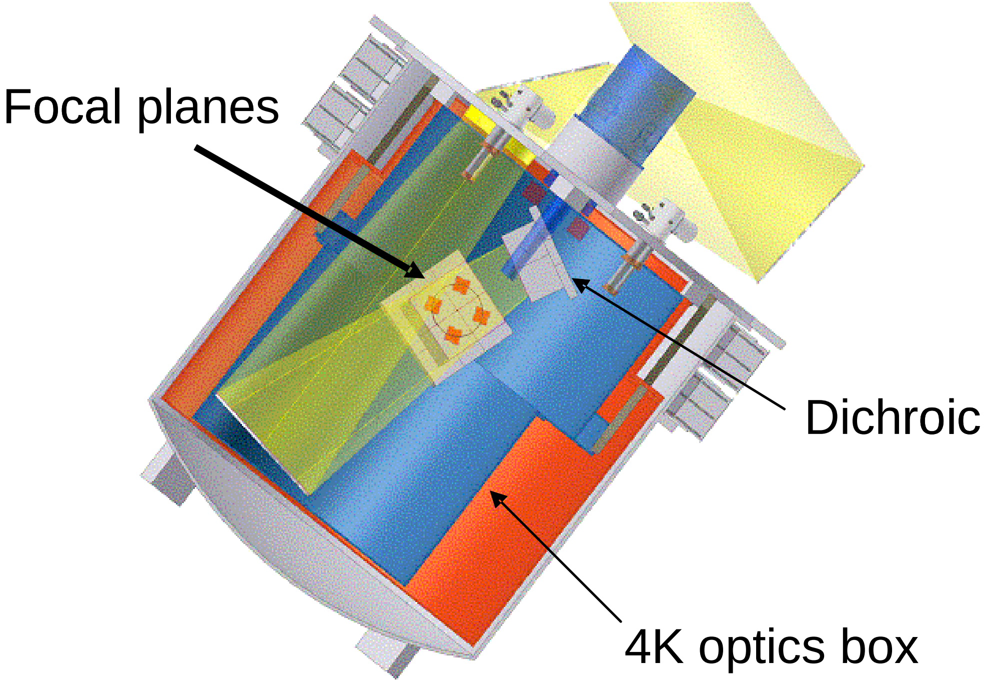
Field-of-view	Pixel spacing	200µm	450µm	850µm	Total number of pixels to build
~50-sq arcmins (SCUBA-2)	Fλ 0.5Fλ	–	64 × 64 (5120)	64 × 64 (5120)	~10k
5 × 5 arcmin (LST)	0.5Fλ	415 × 415 (178k)	185 × 185 (35k)	98 × 98 (9.5k)	~200k
10 × 10 arcmin (LST)	0.5Fλ	830 × 830 (700k)	370 × 370 (138k)	196 × 196 (38k)	~1000k

But pixels counts are not the only challenge: power dissipation in focal plane and number of read-out wires are just two others to mention…

Focal Plane Geometry



Focal plane geometry



🟥 Processed 6-inch wafer containing ~5000 pixels