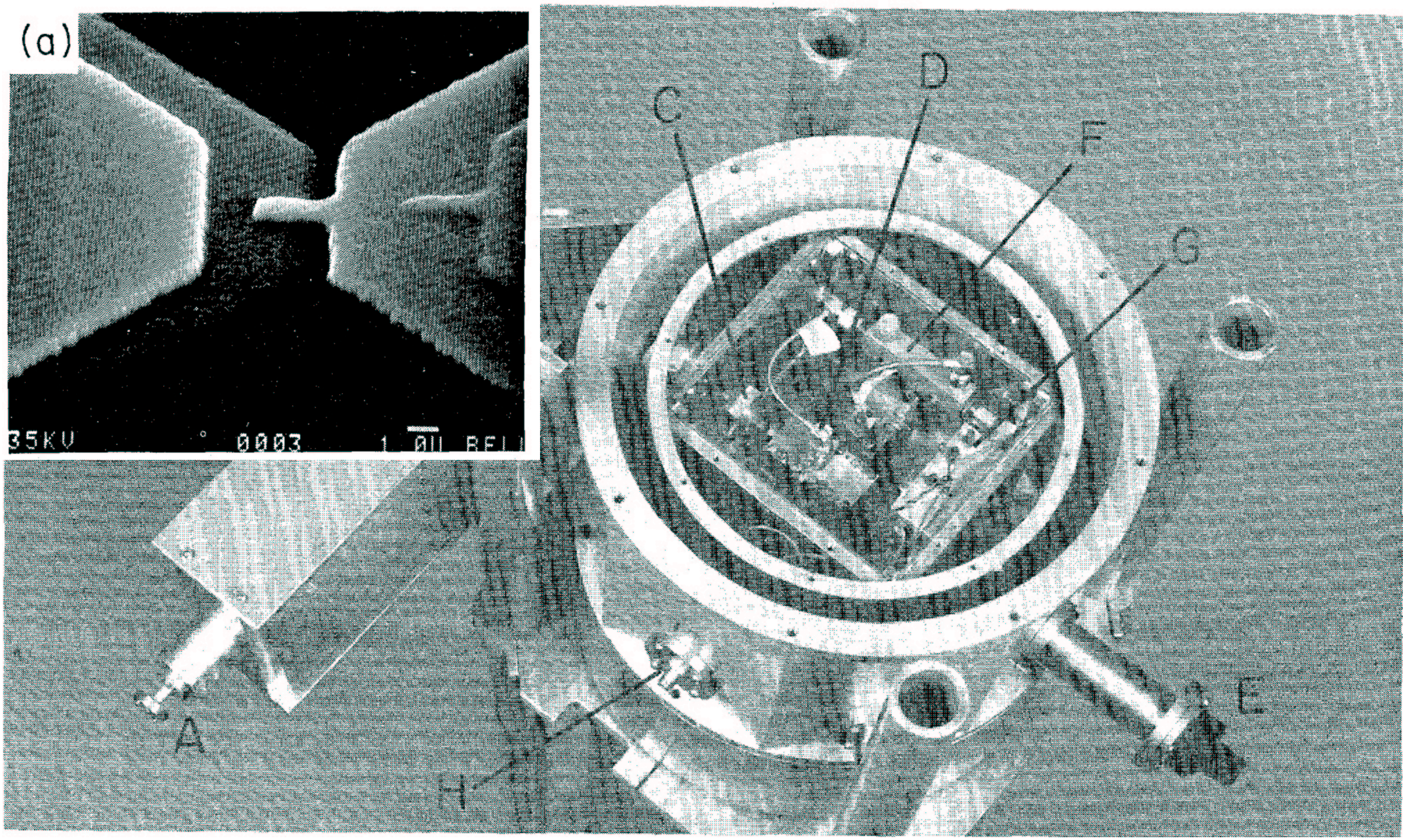
CSO SIS Receivers, MKID Camera, and CCAT

Jonas Zmuidzinas

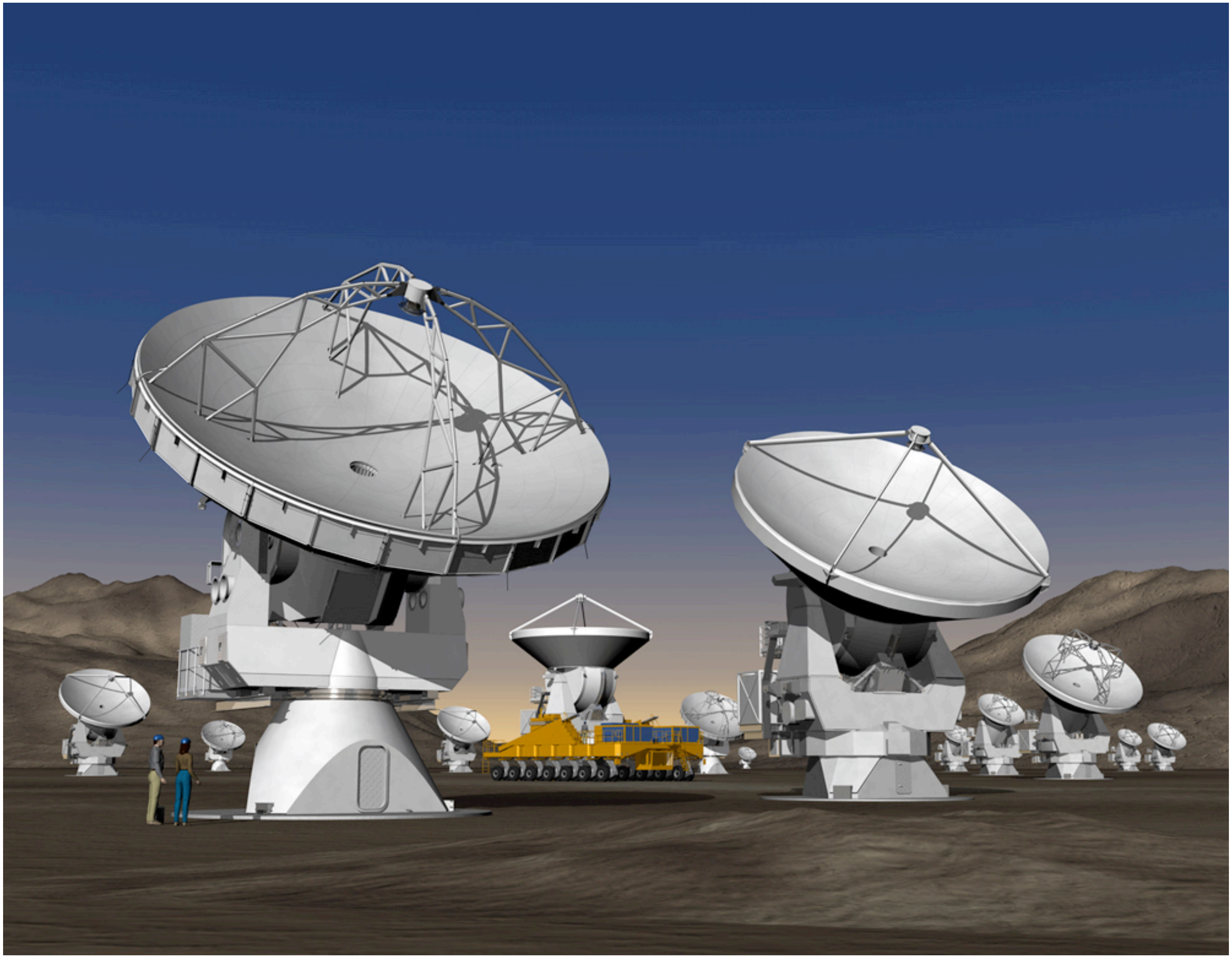
SIS Receiver Development

- Very strong effort at CIT/JPL
- SIS mixer co-invented by Tom Phillips (1979)
  - Sensitivity can approach the quantum limit ($T_n = h\nu/k$)
  - Revolutionized mm/submm astronomy
  - Enables ALMA, HIFI-Herschel
- CIT/JPL are world leaders in SIS technology
  - Devices produced at JPL Microdevices Laboratory (MDL)
  - Design: "Supermix" + commercial EM software
  - Pioneered use of NbTiN superconductors, AlN tunnel barriers
  - CSO has lowest-noise 800-900 GHz receiver (200 K DSB; all-NbTiN)
  - Development/production of 1.2 THz SIS for HIFI-Herschel (Band 5)
  - SOFIA instrument: CASIMIR, SIS to 1.4 THz

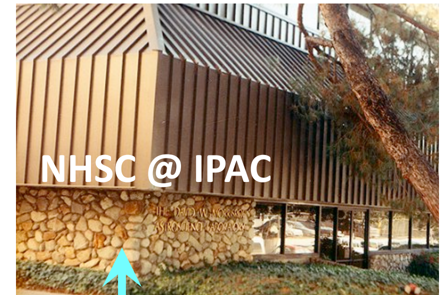
100 GHz SIS at OVRO, 1979, T. Phillips et al.

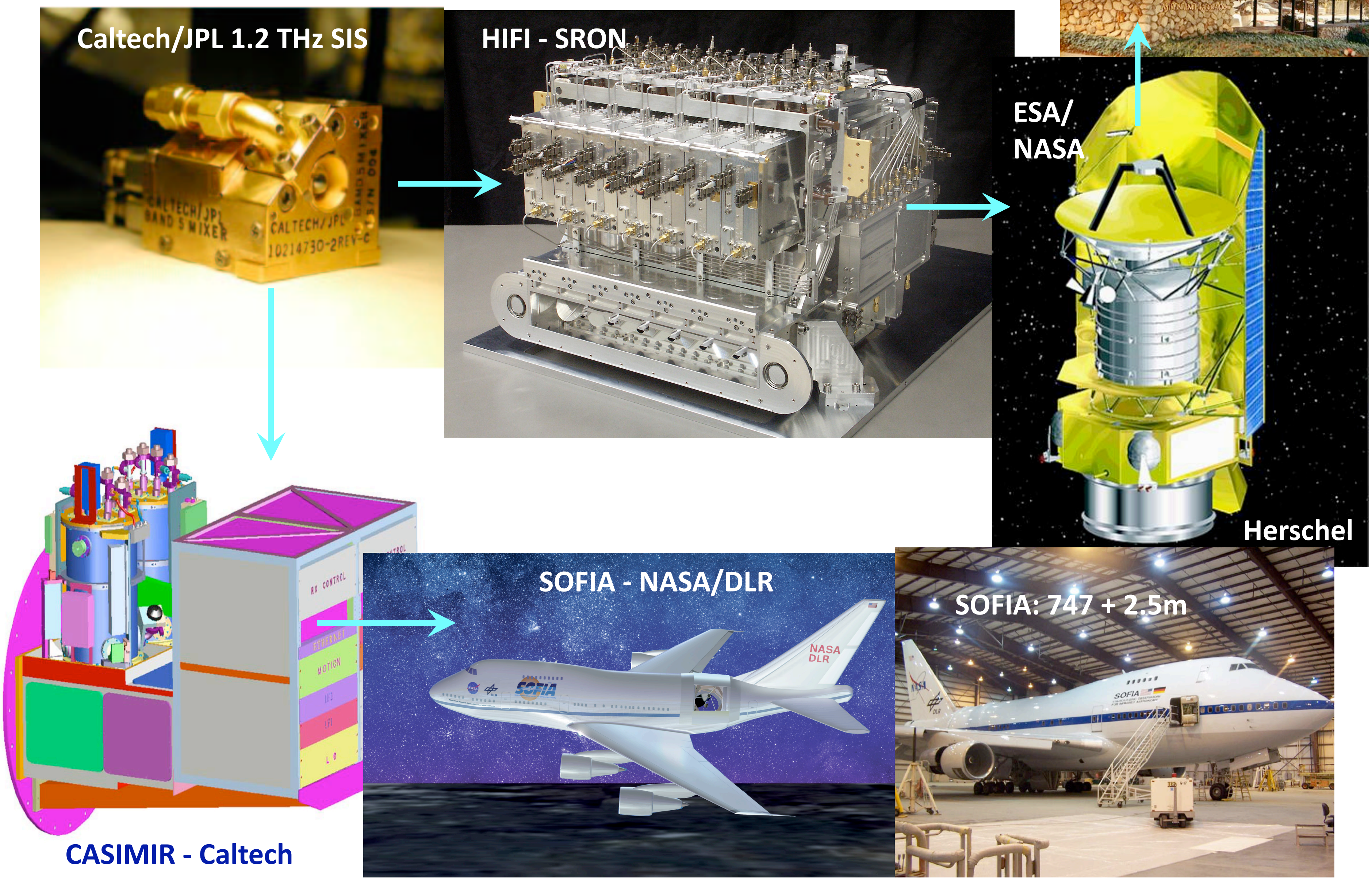


SIS mixers enable ALMA

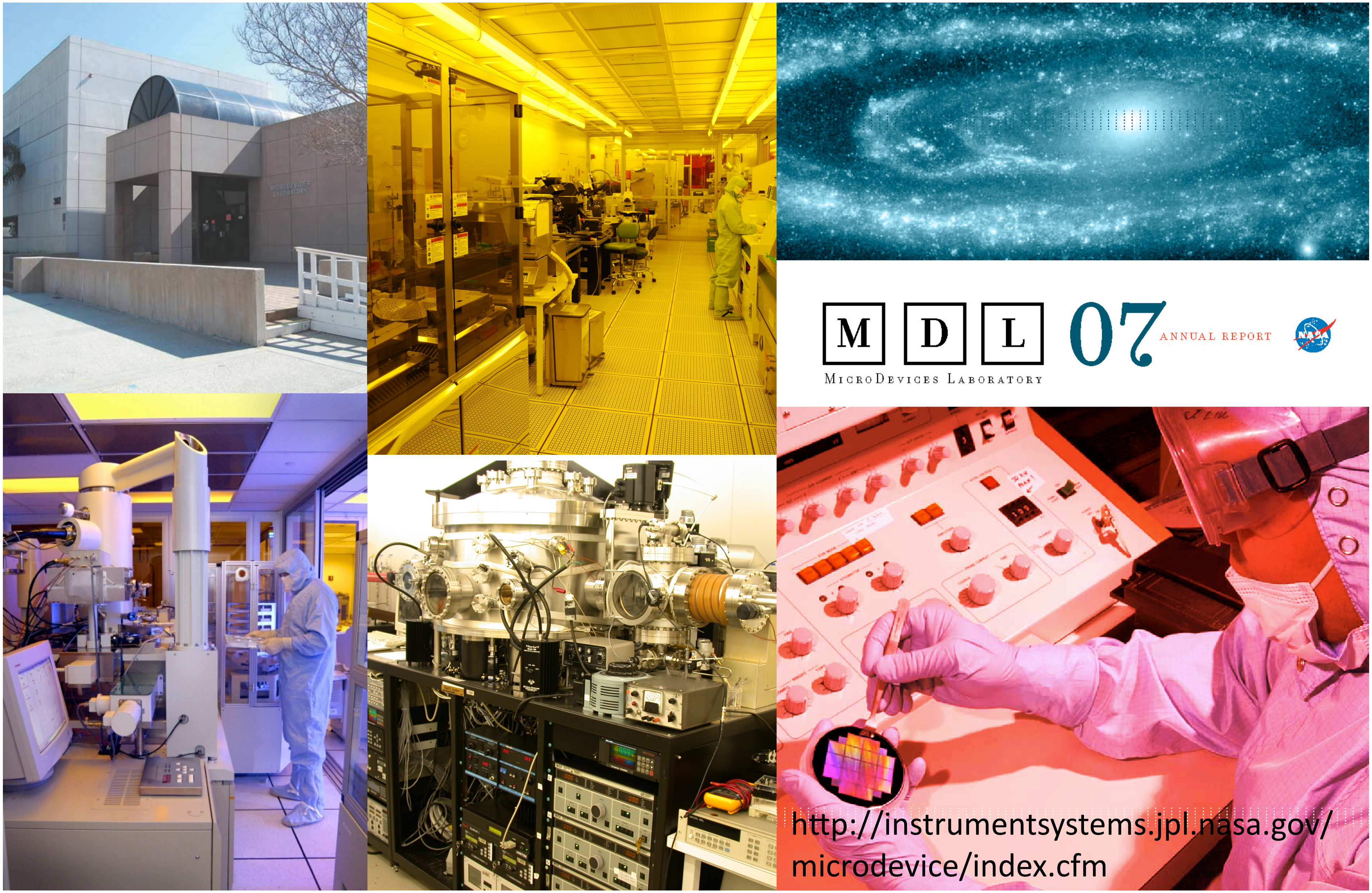


Herschel and SOFIA



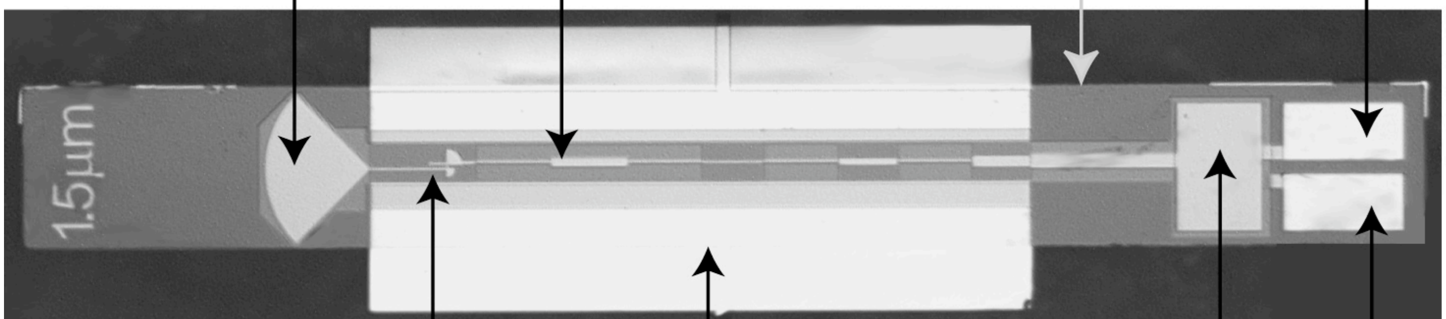


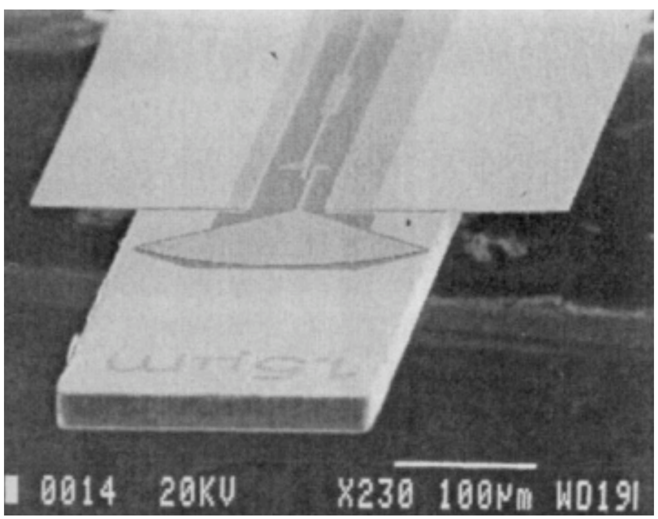
Device fabrication at JPL's MDL

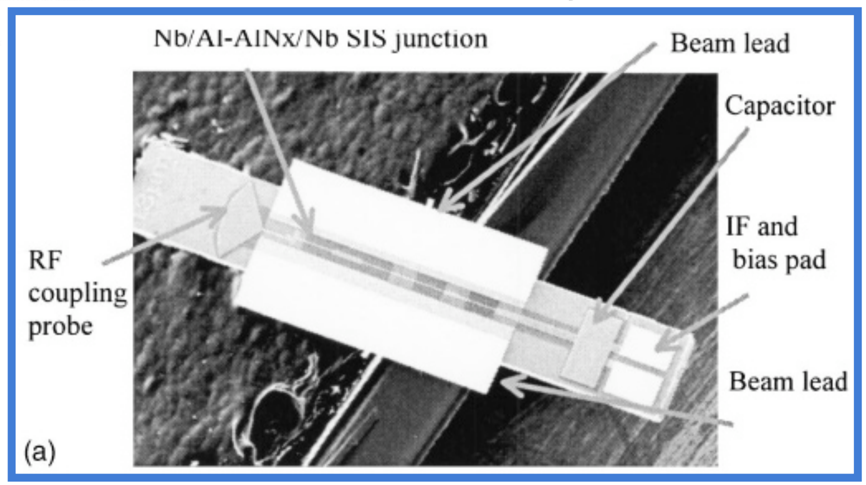


http://instrumentsystems.jpl.nasa.gov/microdevice/index.cfm

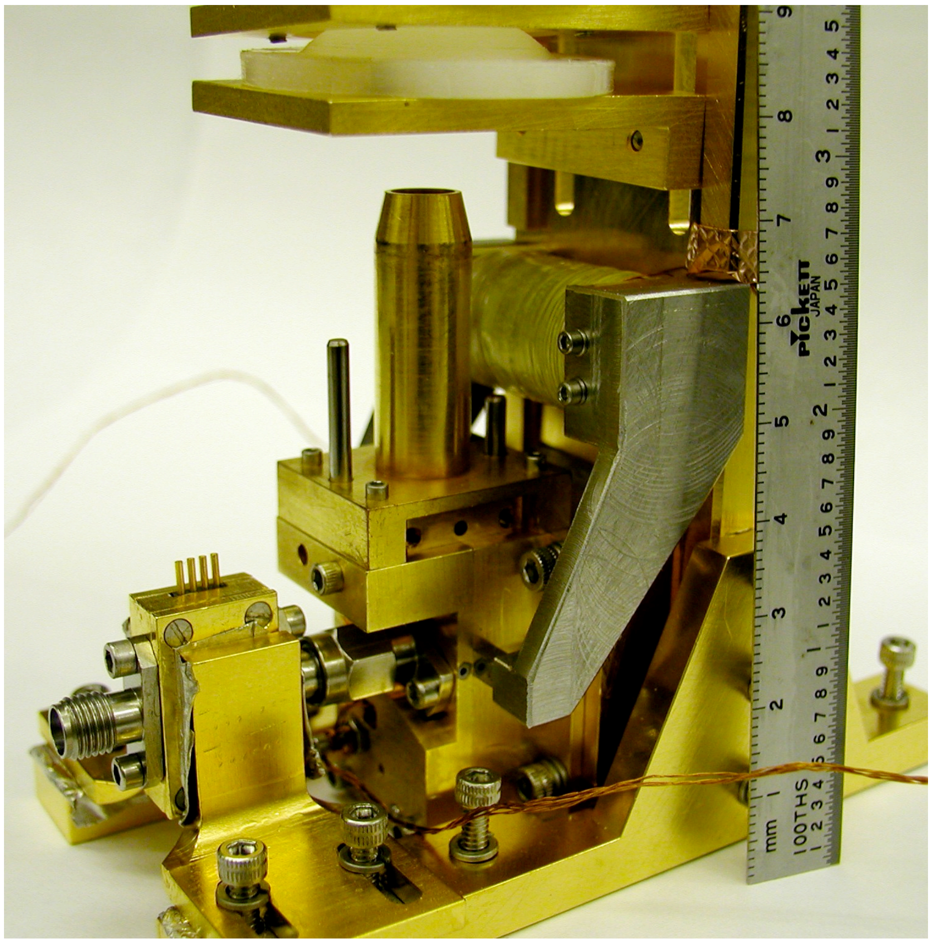
SIS chip: thin silicon with beam leads





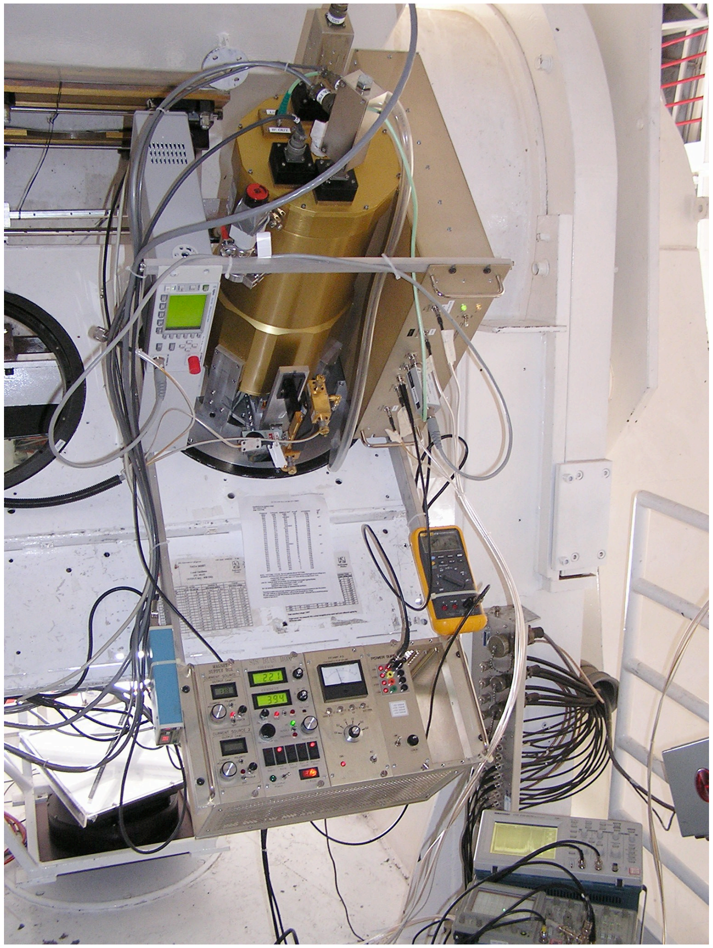


ZRx: ultra-wideband mixer



- All-new design
- 3D EM solver (HFSS) + Supermix
- 180-300 GHz RF bandwidth
- 4-20 GHz IF output
- Fixed-tuned
- New waveguide probe
- Nb/AlN/Nb SIS junction
- Thin (25 μm) silicon substrate
- Beam leads for grounding
- 4-12 GHz MMIC LNA (S. Weinreb)
- Sideband-separating version now demonstrated at JPL (J. Ward)

ZRx + WASP: 12 GHz IF bandwidth



180-300 GHz SIS receiver
Fixed-tuned mixer, synthesized LO
F. Rice + C. Sumner

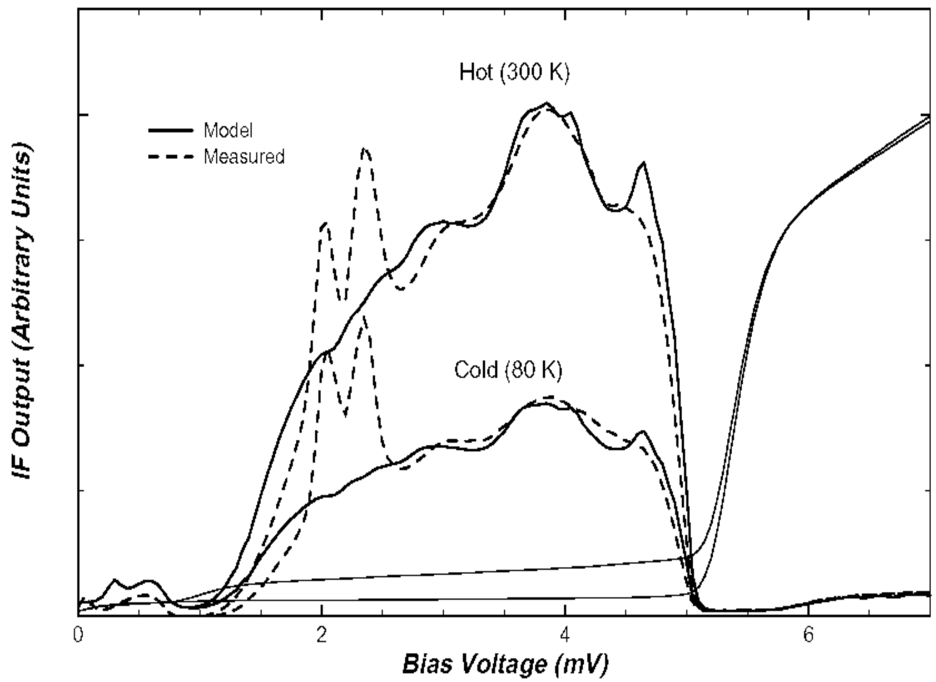
WASP II: 4 × 3.5 GHz analog correlator
Andy Harris, U Md
Future: sideband separating receiver with wideband digital backend

Supermix simulation software

Powerful circuit modeling tool:

- C++ class library
- 47,000+ lines of code
- Linear and nonlinear modeling
- Arbitrarily complex designs
- Superconducting transmission lines
- SIS junctions – Tucker theory
- Developed at Caltech, 1997 to present
- Most powerful tool available for SIS development
- Freely available to the community

SuperMix website:
www.submm.caltech.edu/supermix



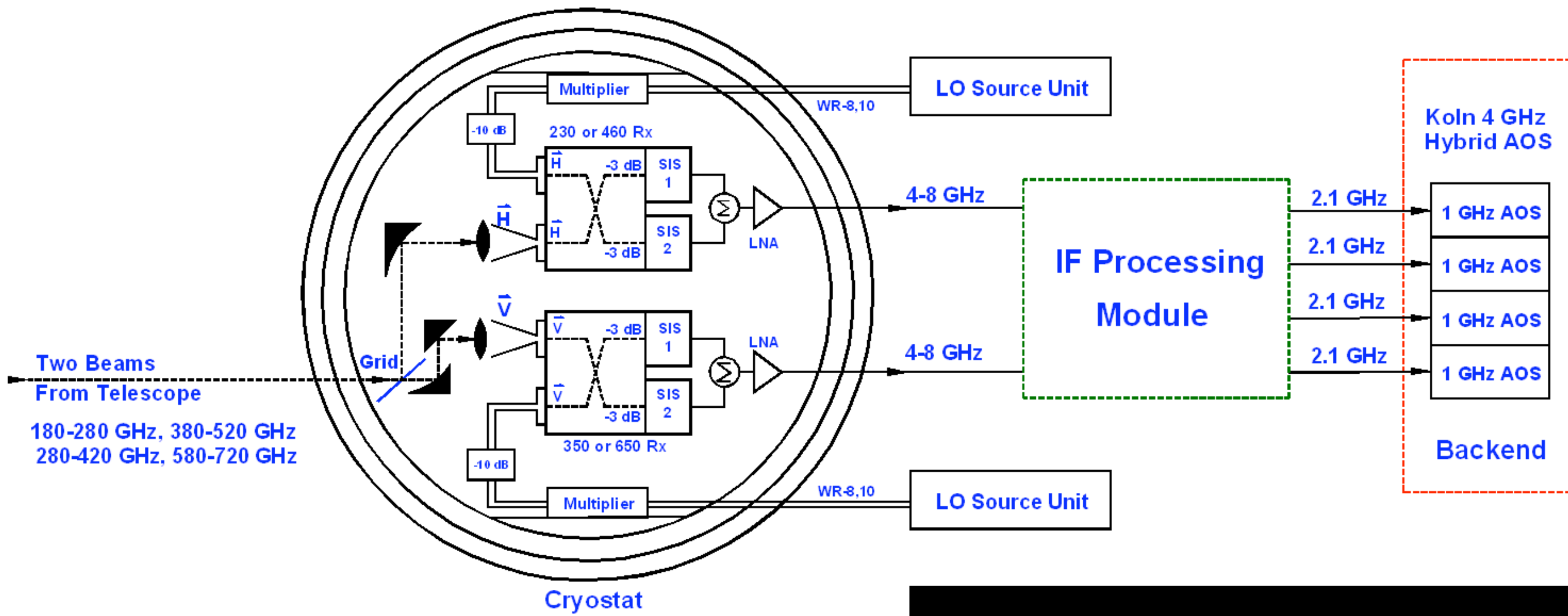
F. Rice, J. Ward, G. Chattopadhyay, J. Zmuidzinas

Facility Receiver Upgrade

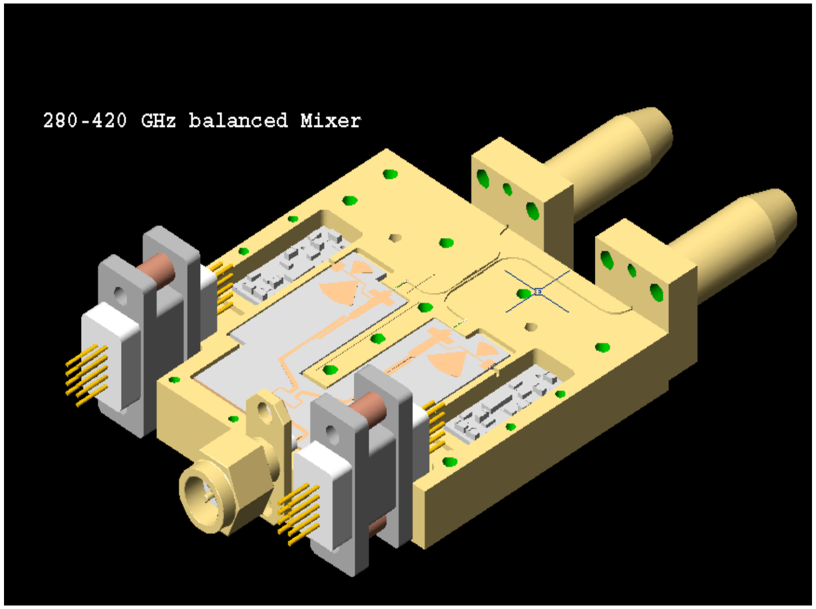
J. Kooi & A. Kovacs

- Goals:
  - Fixed-tuned operation
  - Synthesized LOs
  - 4 - 8 GHz IF
  - Dual-frequency operation
  - Link with SMA
  - High-sensitivity 350 GHz band Rx

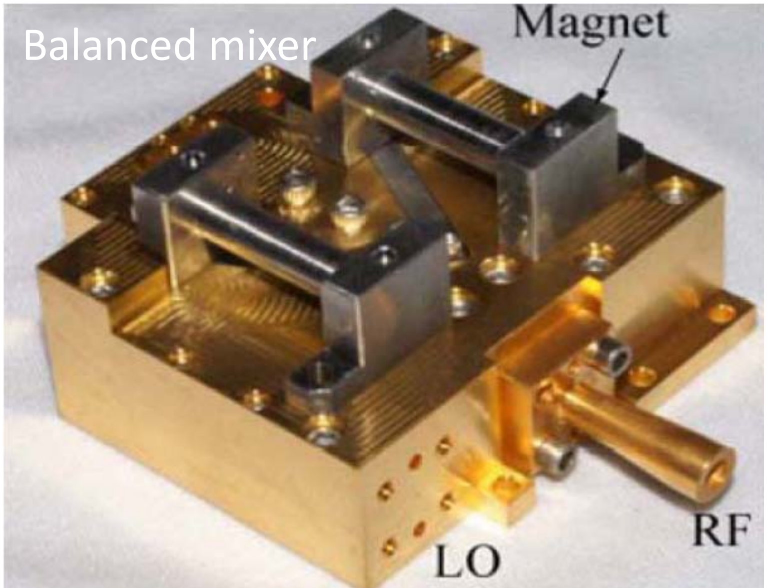
Facility Receiver Layout

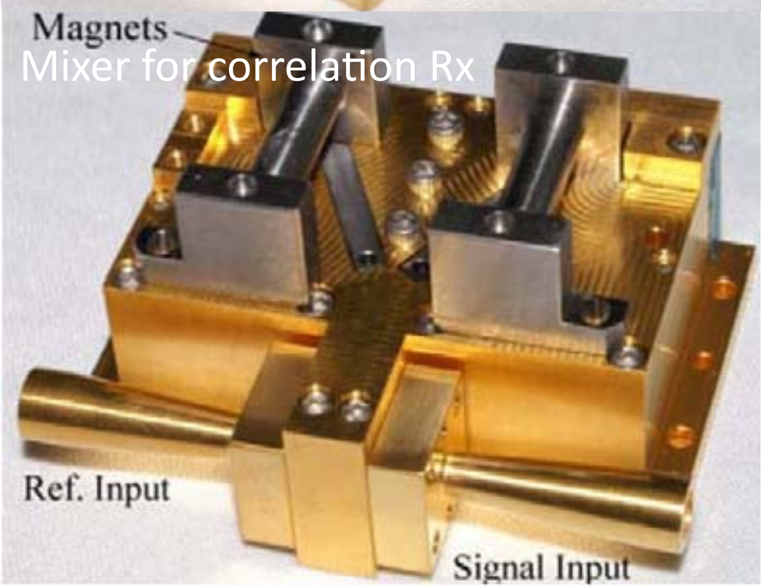


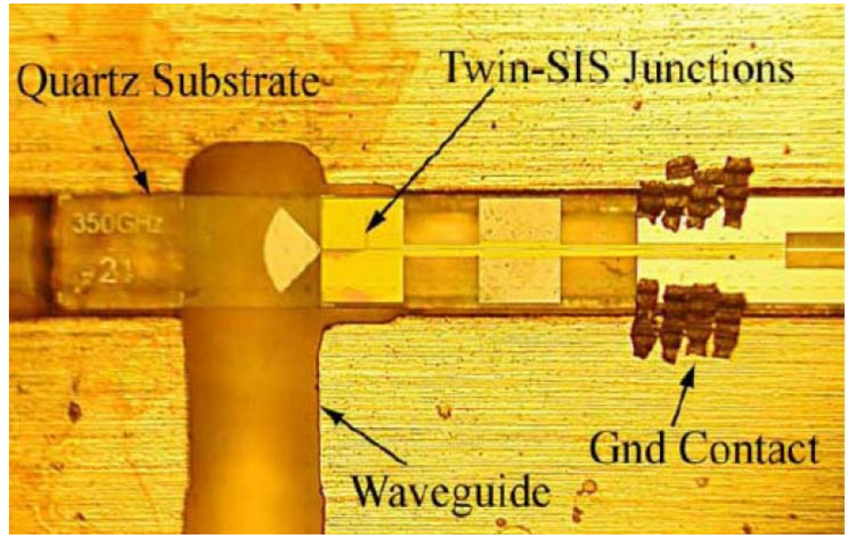
- Key Features:
  - Dual frequency operation
  - 180-280 & 380-520 GHz
  - 280-420 & 580-720 GHz
  - Pointing, more science
  - 4-8 GHz IF band
  - Balanced mixer design -> LO noise cancellation

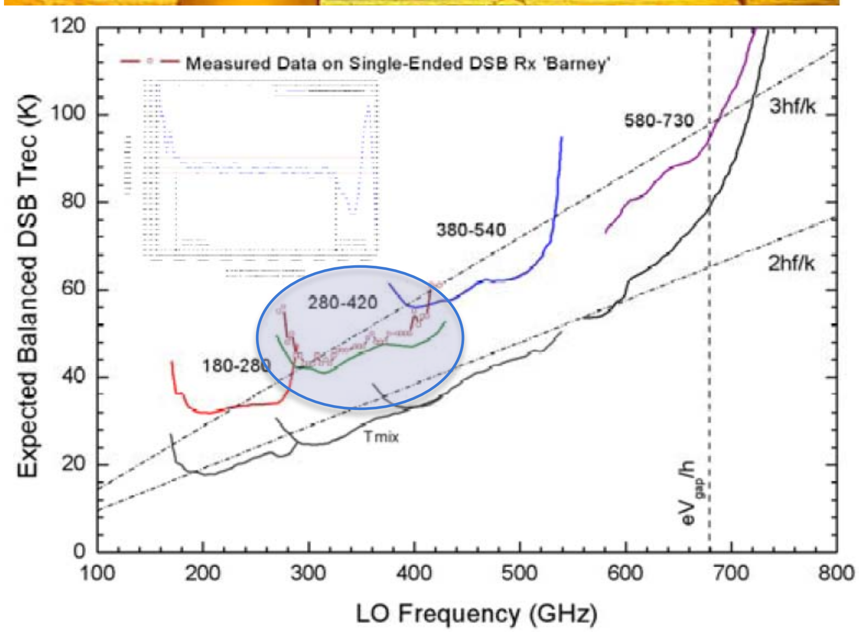


Facility receiver components







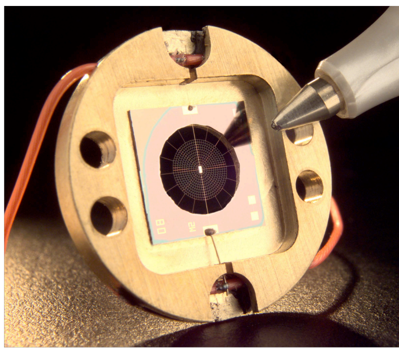


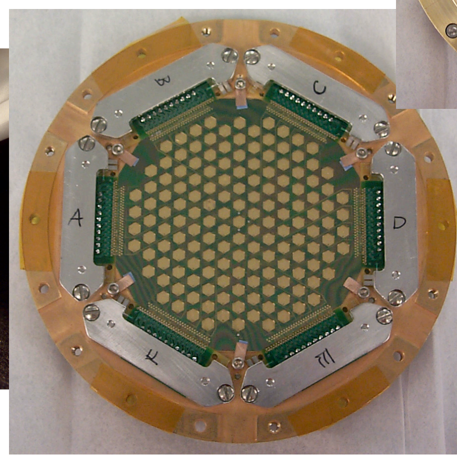
MKID Camera for CSO

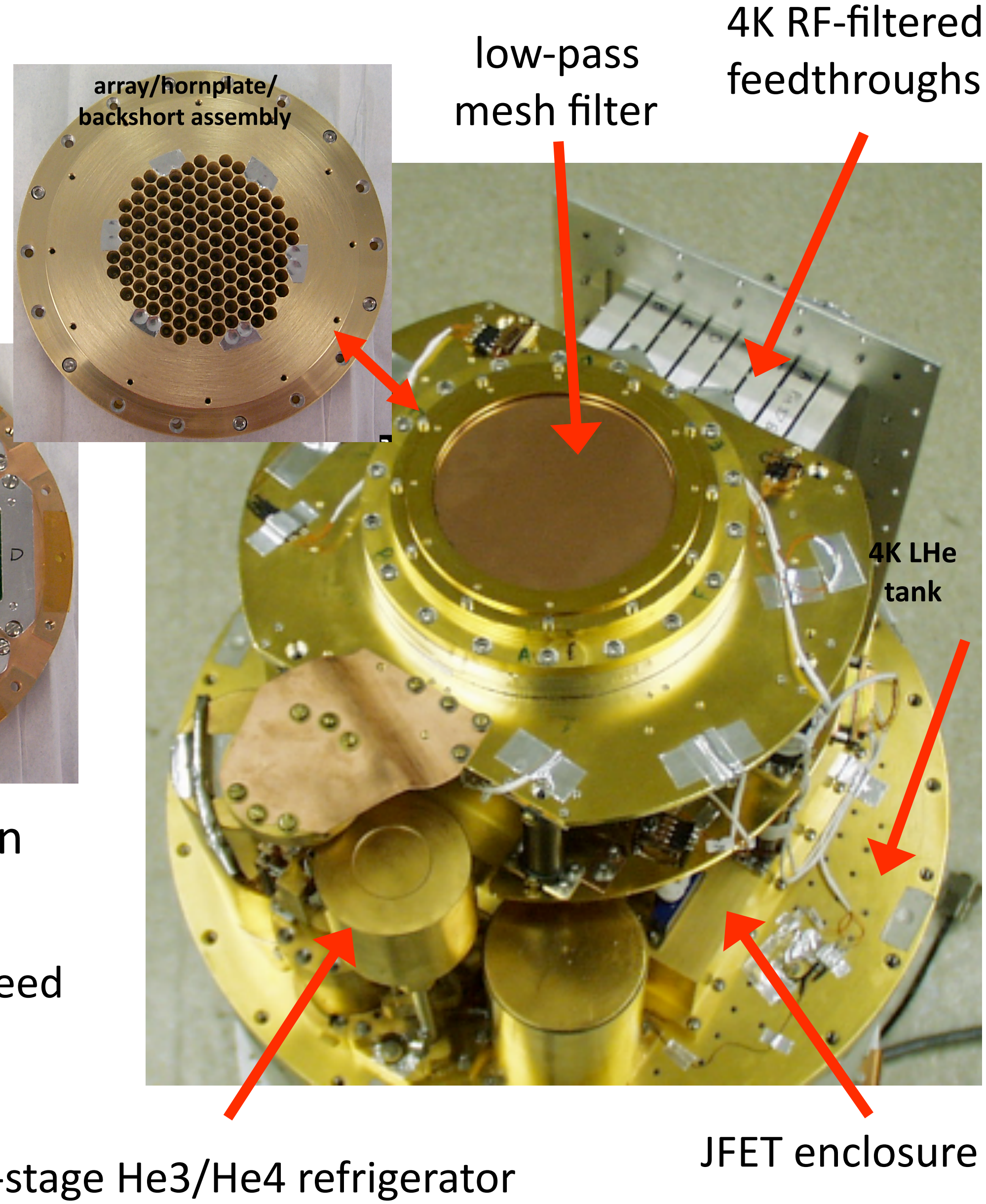
- Replacement for BOLOCAM
- 24 x 24 array = 576 spatial pixels
- Multicolor operation
  - Each spatial pixel has simultaneous response in four bands, 1.3, 1.1, 0.85, and 0.75 mm
  - 4 x 576 = 2304 detectors total
- Combines broadband planar antennas, on-chip filtering, and MKIDs for detection
  - all invented & developed at CIT/JPL
- Frequency-multiplexed microwave readout
- MUCH simpler than TES + SQUID mux (SCUBA 2)

Bolocam - Golwala, Glenn, Bock, Lange et al.

- Observation bands:
  - 125-165 GHz: thermal SZ
  - 225-300 GHz: dusty sources
- 144-pixel JPL/MDL spiderweb bolometer array at 250 mK







- NTD Ge thermistor + Si_3N_4 isolation
- Array architecture:
  - Large FOV (8’) => high mapping speed
  - Sky subtraction enabled by beam overlap through atmosphere
- AzTEC = BOLOCAM 2

MKIDs - superconducting resonators

f, Q are temperature-dependent

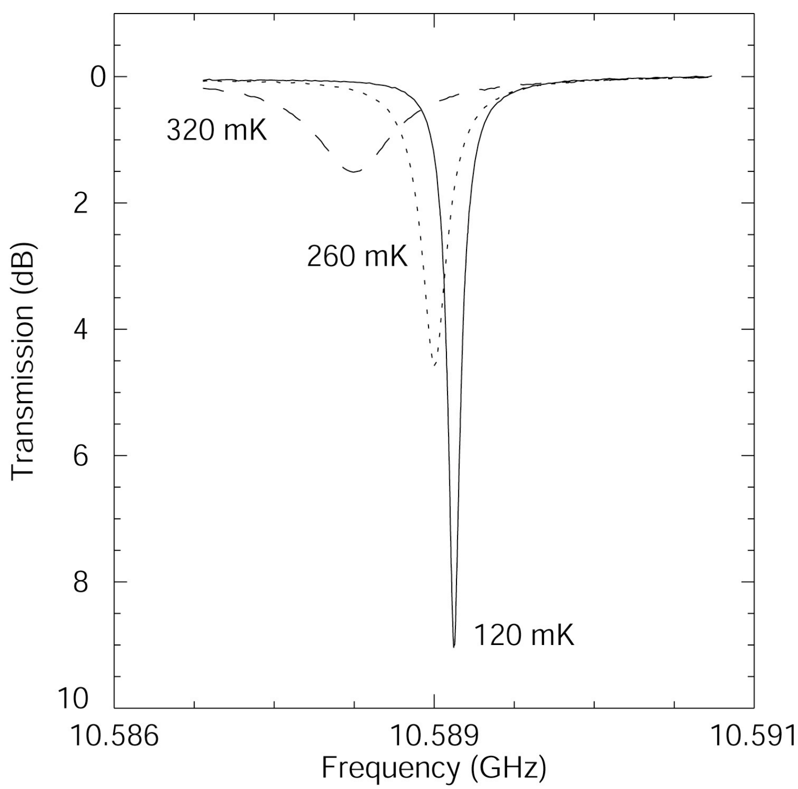
CPW - "coplanar waveguide"

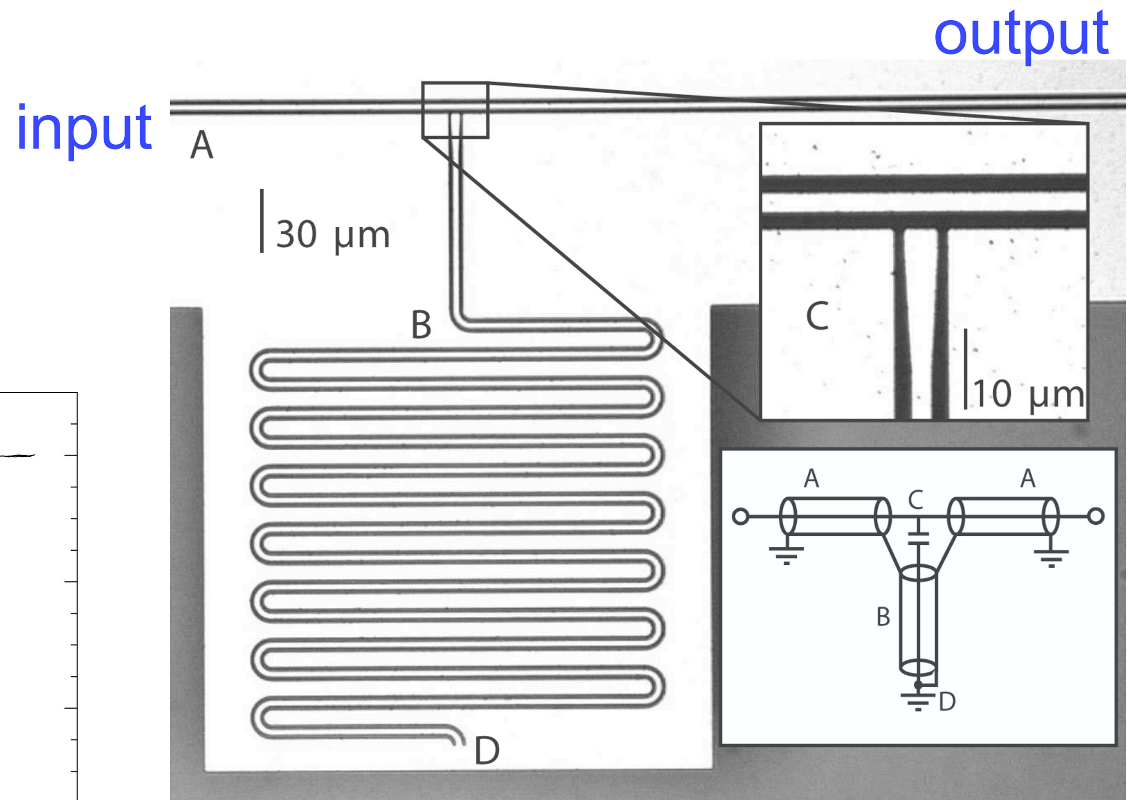
Aluminum on sapphire

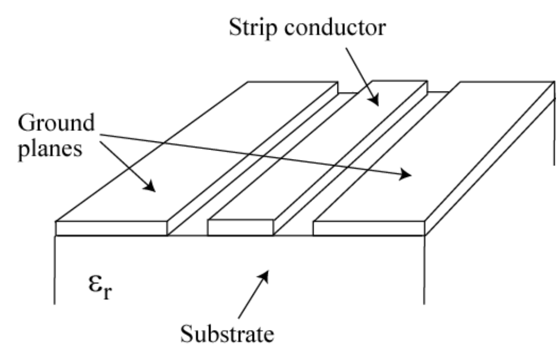
t = 200 nm, L = 3mm

V = 2000 μm^3

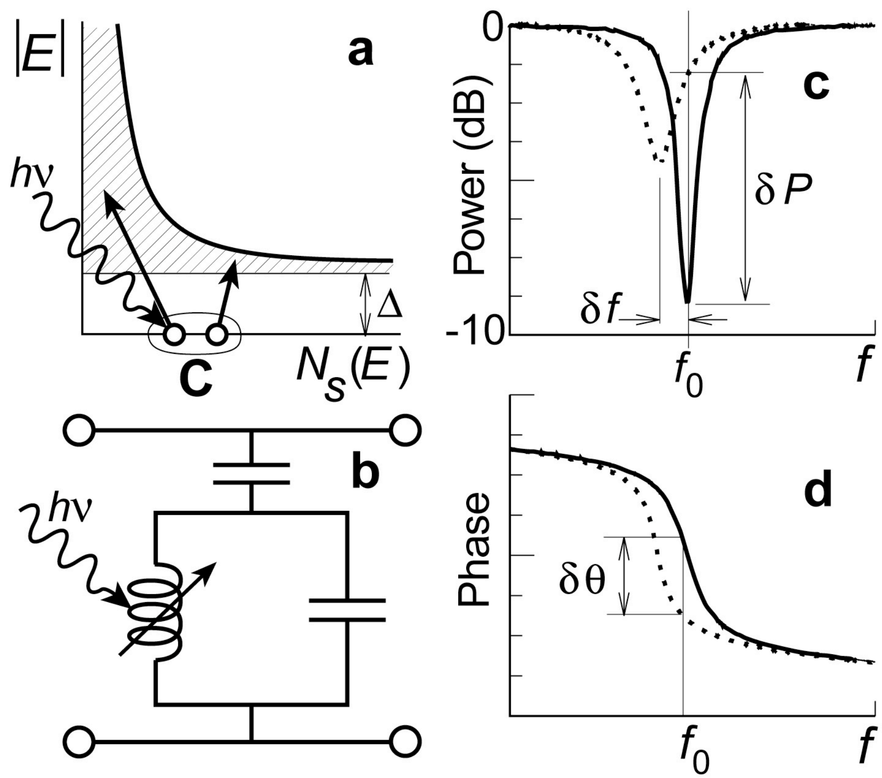
f_{res} = 10 GHz, Q = 55,000

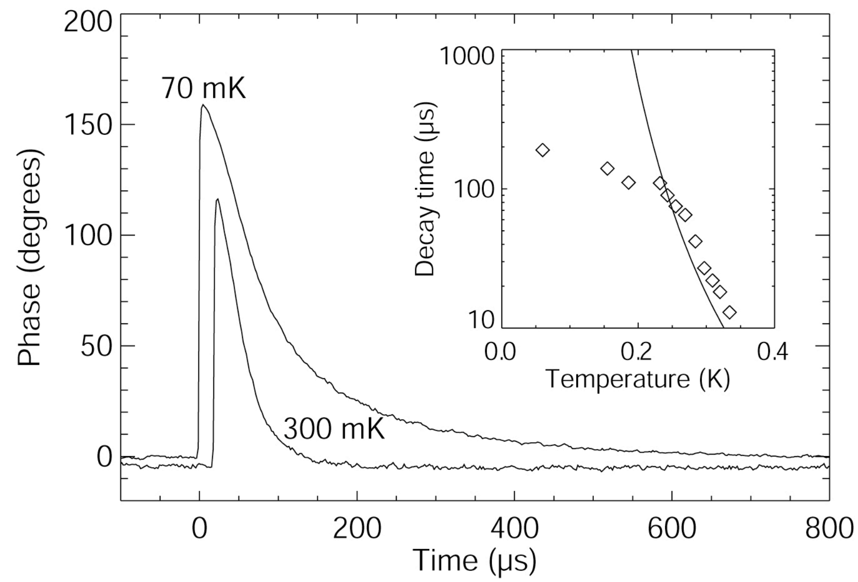






Photon detection: MKIDs





Pulses from 6 keV photons

MKID proof of principle

letters to nature

A broadband superconducting detector suitable for use in large arrays

Peter K. Day[1], Henry G. LeDuc[1], Benjamin A. Mazin[2], Anastasios Vayonakis[2] & Jonas Zmuidzinas[2]

[1] *Jet Propulsion Laboratory, Pasadena, California 91107, USA*
[2] *California Institute of Technology, 320-47, Pasadena, California 91125, USA*

Cryogenic detectors are extremely sensitive and have a wide variety of applications[1–3] (particularly in astronomy[4–8]), but are difficult to integrate into large arrays like a modern CCD (charge-coupled device) camera. As current detectors of the cosmic microwave background (CMB) already have sensitivities comparable to the noise arising from the random arrival of CMB photons, the further gains in sensitivity needed to probe the very early Universe will have to arise from large arrays. A similar situation is encountered at other wavelengths. Single-pixel X-ray detectors now have a resolving power of $\Delta E < 5$ eV for single 6-keV photons, and future X-ray astronomy missions[7] anticipate the need for 1,000-pixel arrays. Here we report the demonstration of a superconducting detector that is easily fabricated and can readily be incorporated into such an array. Its sensitivity is already within an order of magnitude of that needed for CMB observations, and its energy resolution is similarly close to the targets required for future X-ray astronomy missions.

NATURE | VOL 425 | 23 OCTOBER 2003 | www.nature.com/nature

See also:

news and views

Applied physics

To catch a photon

Daniel E. Prober

Astronomers crave a detector sensitive enough to detect a single photon and determine its energy. A new single-pixel device can do this, and could also be built up into a large array suitable for a telescope.

PHYSICS

Seeing Single Photons

A SUPERCONDUCTING WAY TO SPOT PHOTONS ONE BY ONE BY GRAHAM P. COLLINS

SCIENTIFIC AMERICAN JANUARY 2004

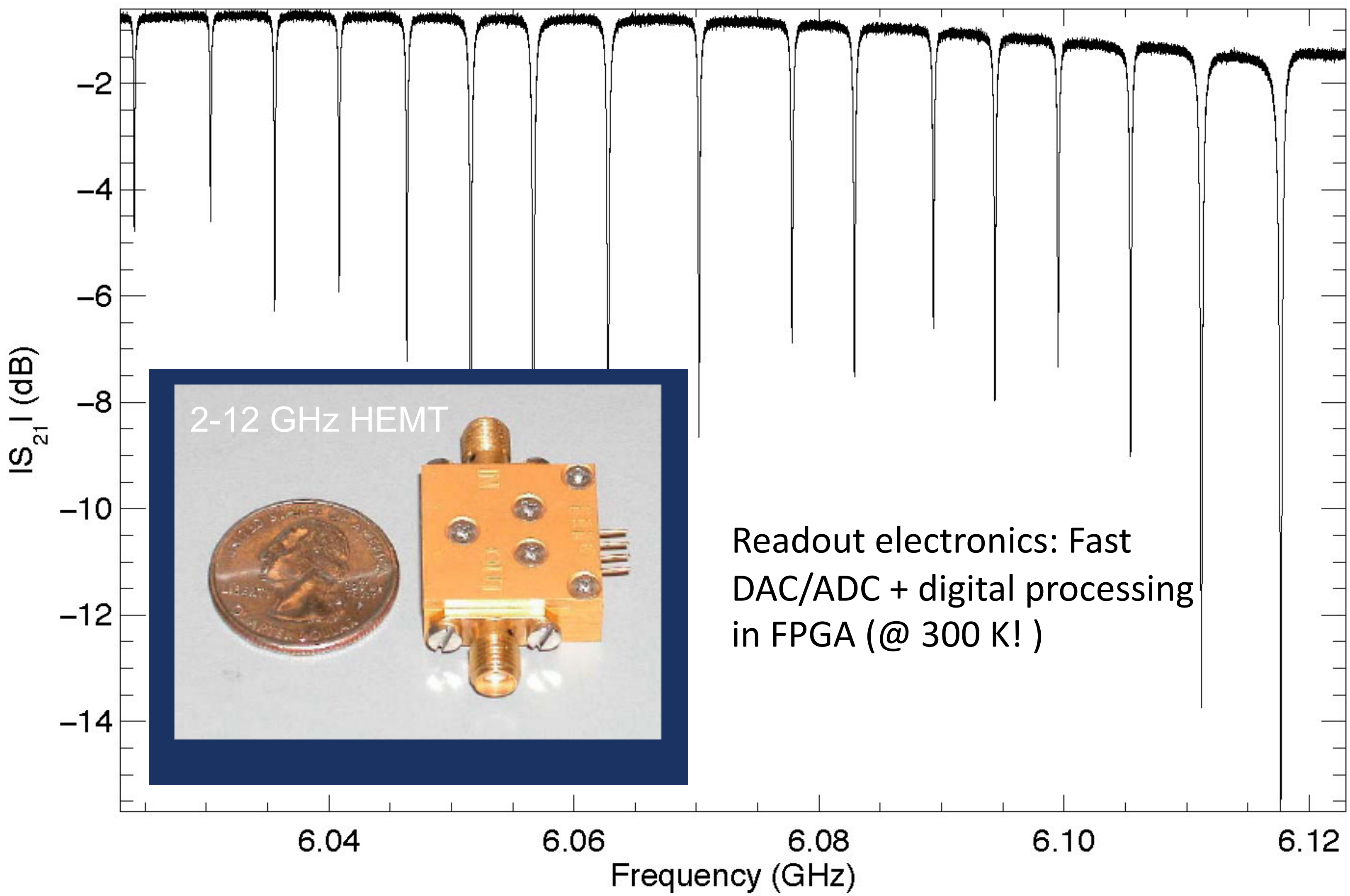
Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics

A. Wallraff[1], D. I. Schuster[1], A. Blais[1], L. Frunzio[1], R.- S. Huang[1,2], J. Majer[1], S. Kumar[1], S. M. Girvin[1] & R. J. Schoelkopf[1]

[1] *Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520, USA*
[2] *Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*

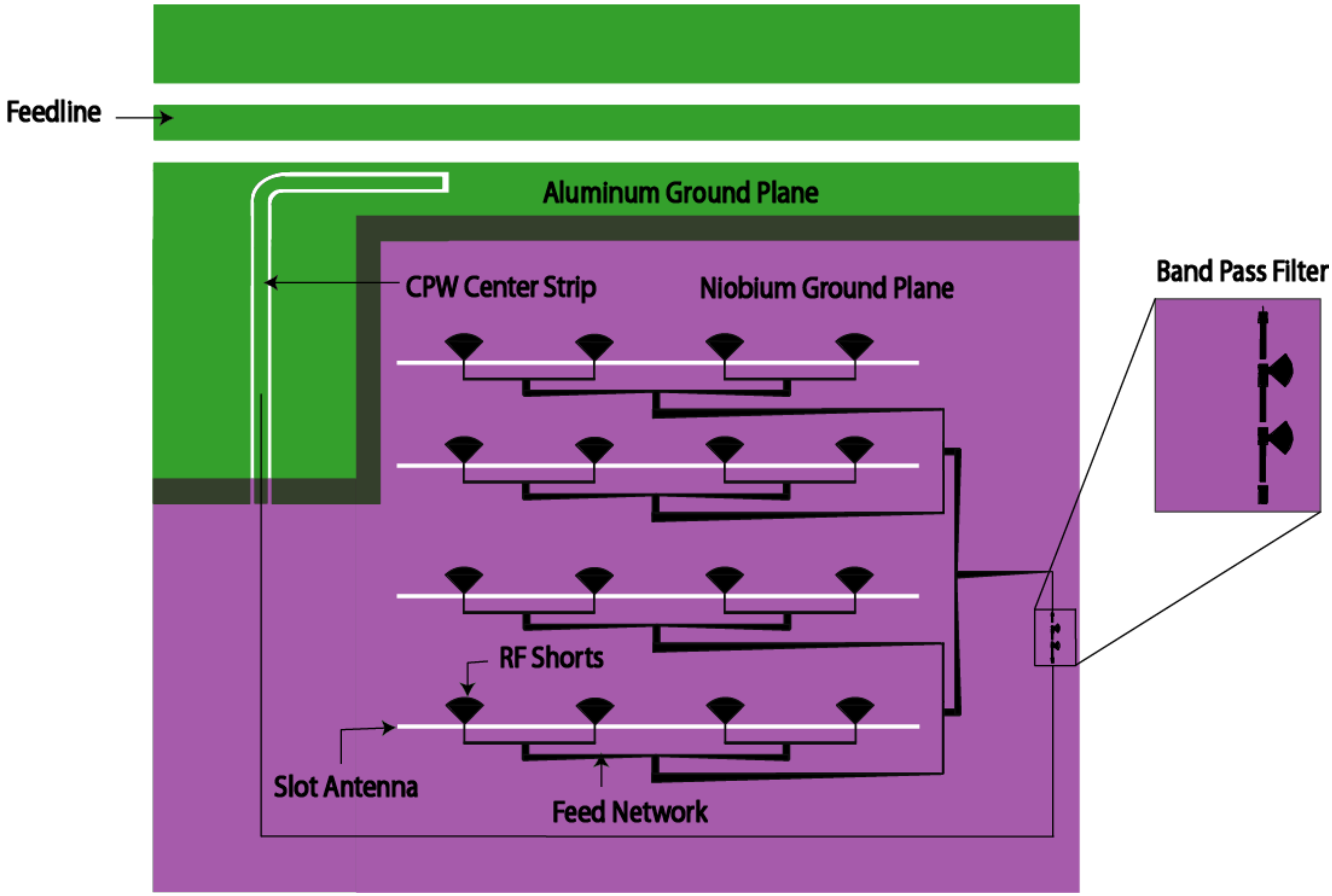
NATURE | VOL 431 | 9 SEPTEMBER 2004 |

Frequency multiplexing



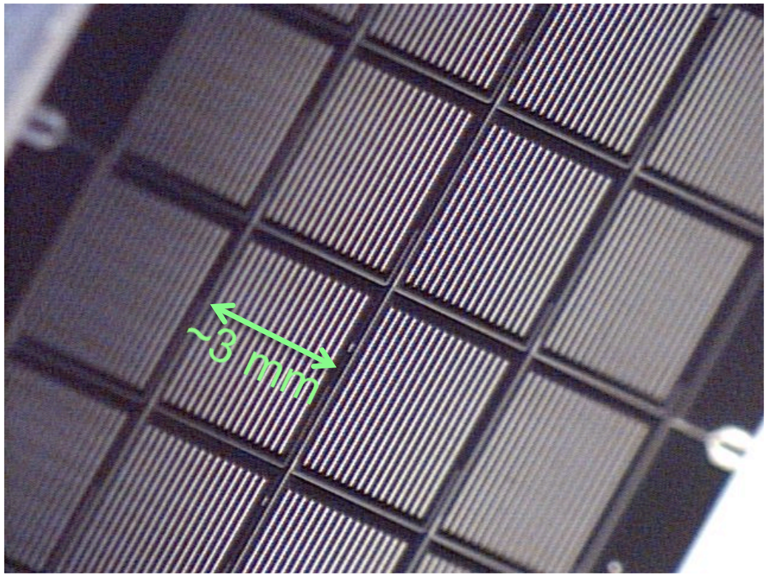
Readout electronics: Fast DAC/ADC + digital processing in FPGA (@ 300 K!)

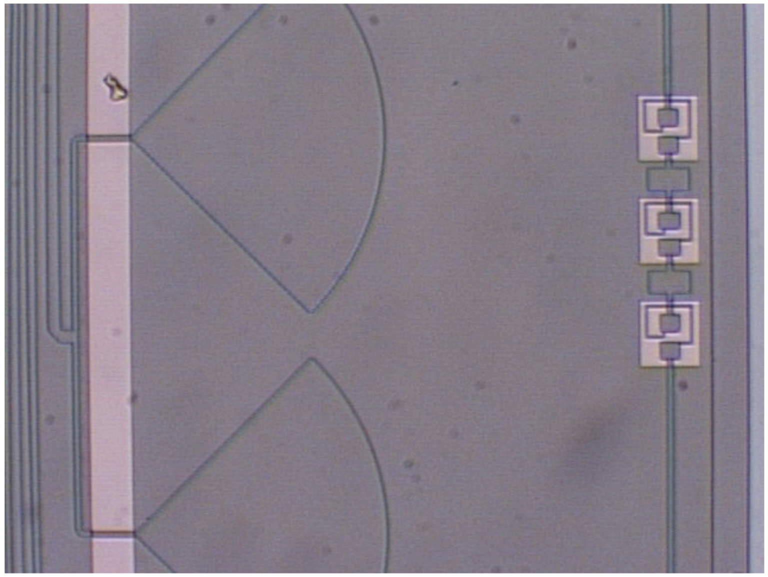
Antenna-coupled submm MKID

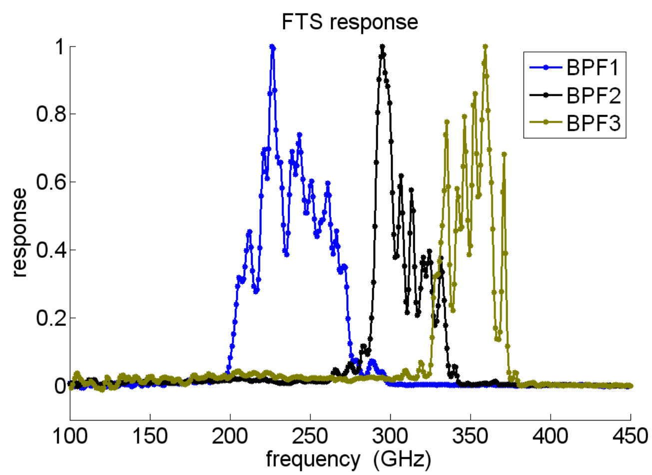


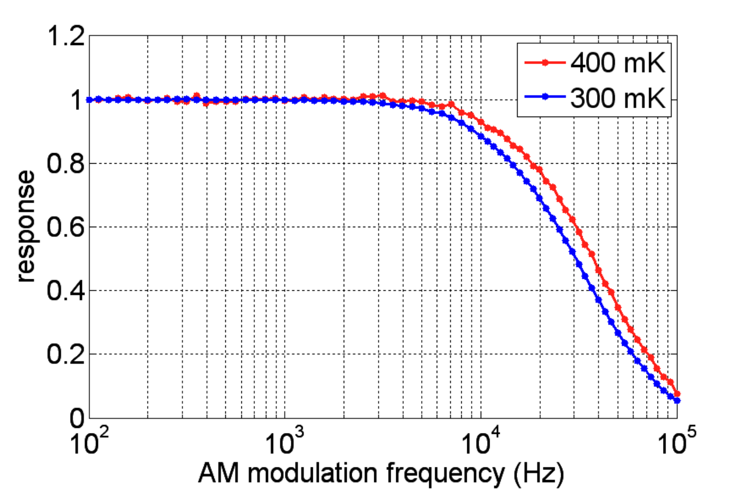
Attenuation length of $Nb/SiO_2/Nb$ microstrip lines is around 60 cm at 300 GHz!

4x4 antenna-coupled MKID array

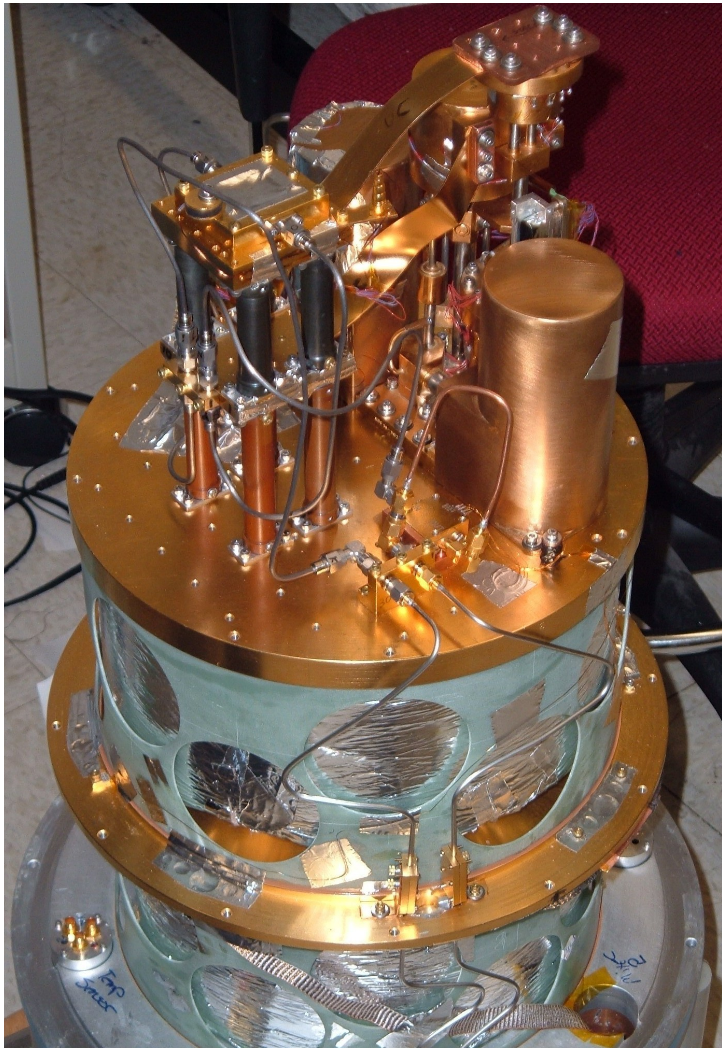


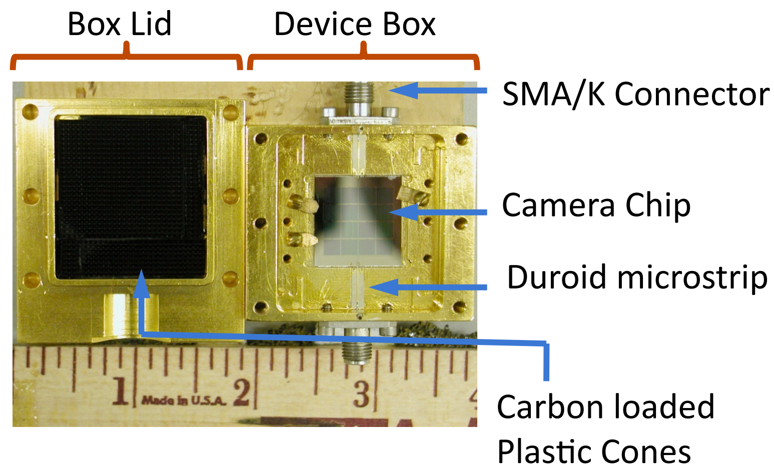


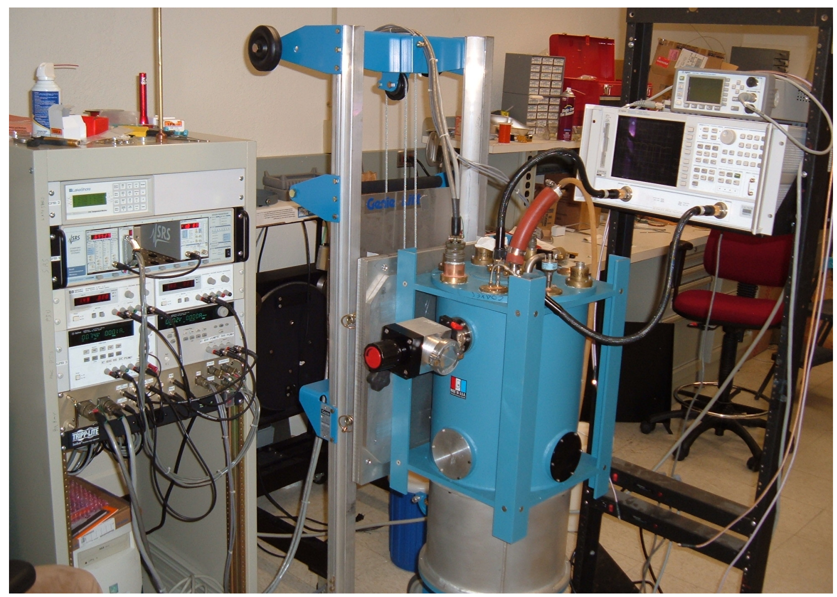




2007: demonstration camera for CSO

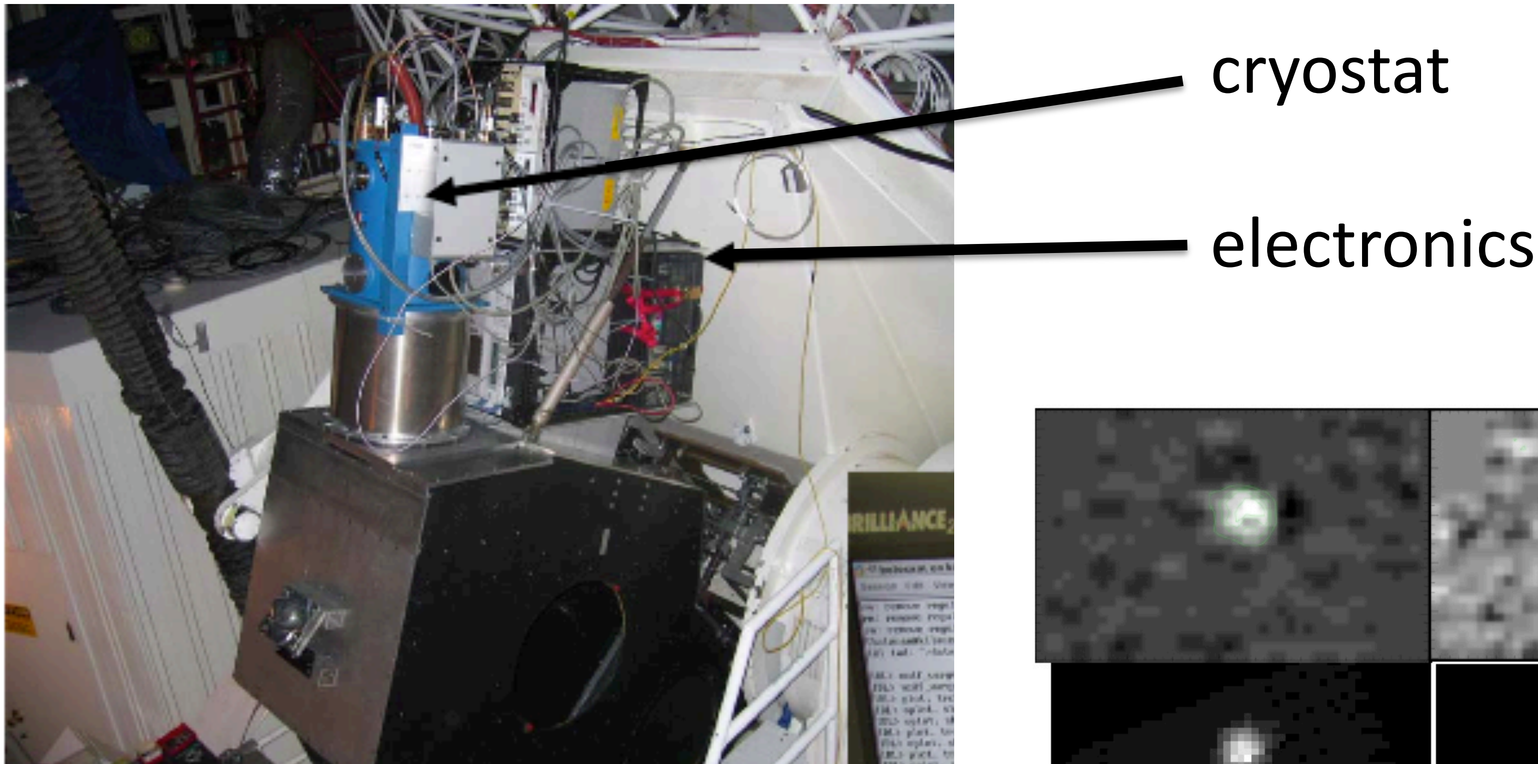


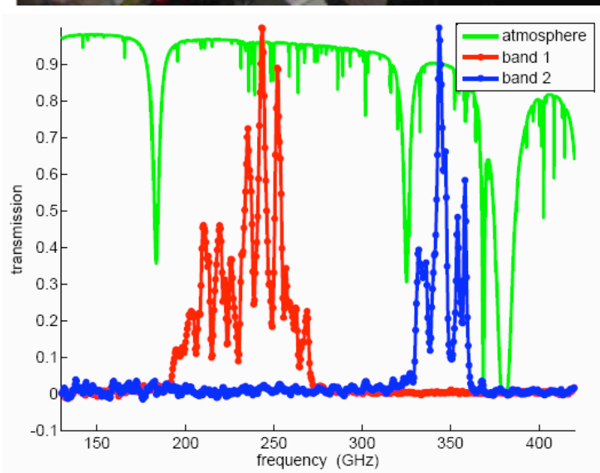




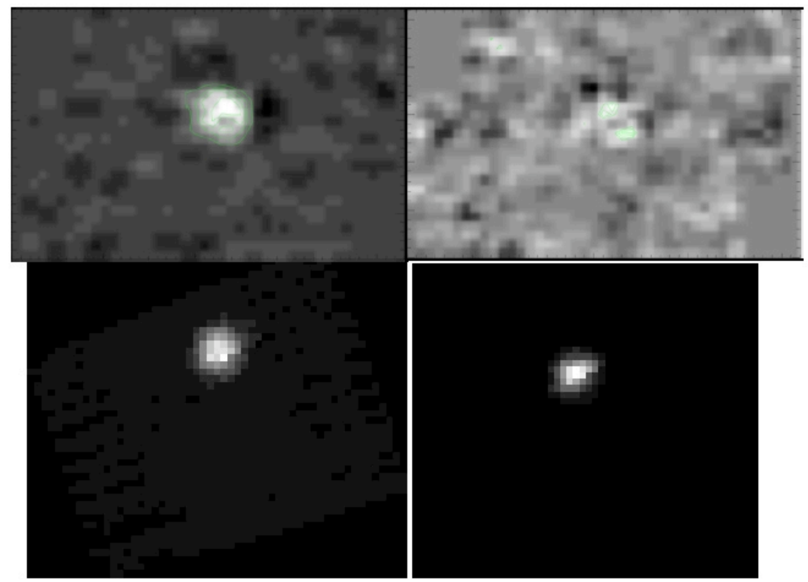
Demonstration camera for CSO
4x4x2 color array, 1.3 & 0.85 mm

April 2007 at CSO





FTS response, two-color pixels (no AR coatings on optics)



First-light images (G34.3, Jupiter)

MKID Camera Status - I

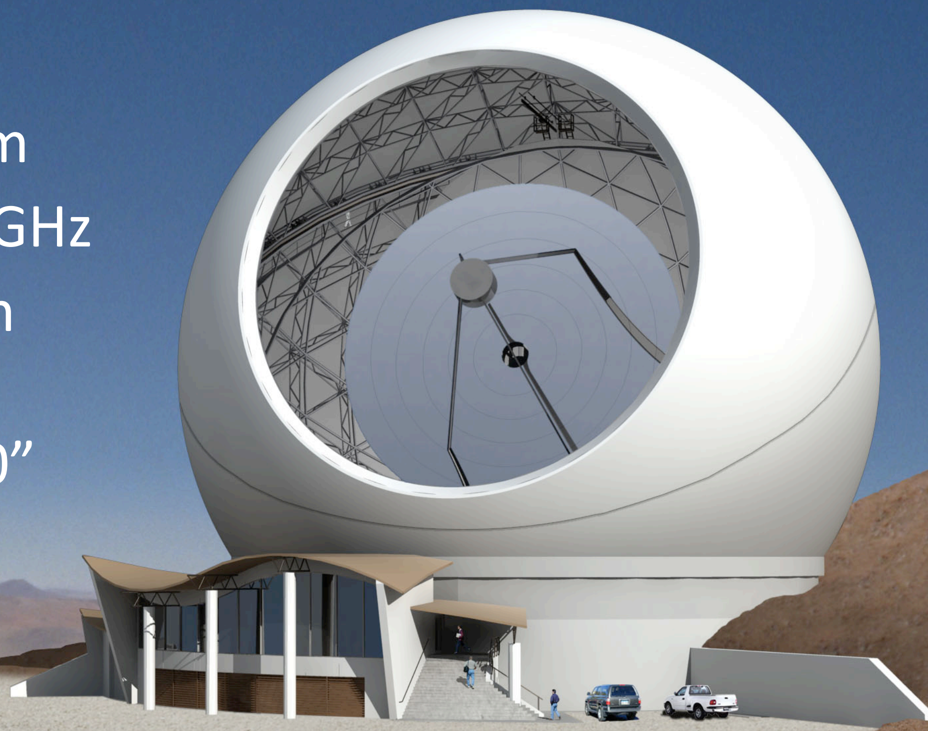
- Funding
  - NSF ATI: PI, J. Glenn; co-PI, S. Golwala (Colorado personnel + hardware)
  - Moore Foundation - Lange/Golwala/Zmuidzinas (Caltech students, demo camera)
  - NASA & JPL: MKID & array development, cryogenic system assembly & test
- Personnel
  - Caltech: Czakon*, Gao, Golwala, Noorozian*, Vaillancourt, Vayonakis*, Zmuidzinas
  - Colorado: Glenn, Maloney*, Schlaerth*
  - JPL: Day, LeDuc, Mazin, Nguyen, Sayers
- MKID Performance
  - High efficiency verified at JPL (~50%)
  - Measured beam patterns, filter passbands agree with predictions
  - Physical mechanism of noise is now understood; predictive, quantitative model available
  - New resonator designs show 10x lower noise – BLIP operation expected at CSO

MKID Camera Status - II

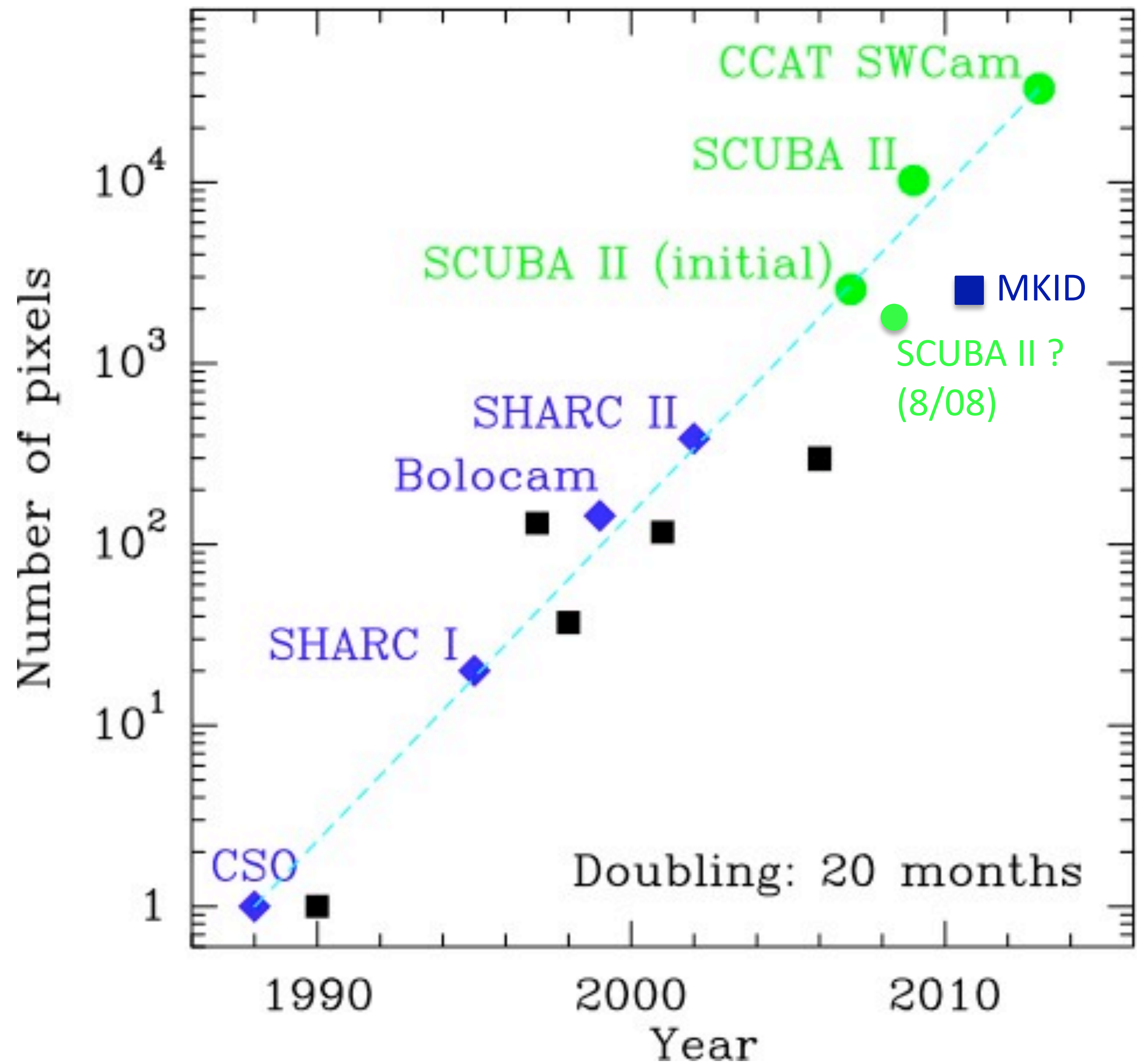
- Schedule
  - Significant BOLOCAM heritage: optics, mechanical mounting, software pipeline, …
  - $^{3}He/^{3}He/^{4}He$ refrigerator delivered 7/08 (250 mK; S. Chase)
  - Cryostat + 4 K pulse tube delivery expected this month (8/08)
  - First 12 x 6 array "tile" design to be finalized in fall '08 – updated antenna & resonator designs
  - Detailed instrument design in progress: optics, focal plane layout, etc.
  - Contract for readout electronics expected 8/08 (Omnisys – DAC/ADC/FPGA turnkey system)
  - Instrument completion expected in mid-2010
- Future prospects
  - New MKID designs are being developed that should allow very large (5-10 kilopixel) 350 μm arrays – SHARC 3 ?

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
  - Active surface !
- Angular resolution 2-20”
- Survey instrument:
  - Wide field of view
  - *Large submm cameras*
  - *Spectrometers*



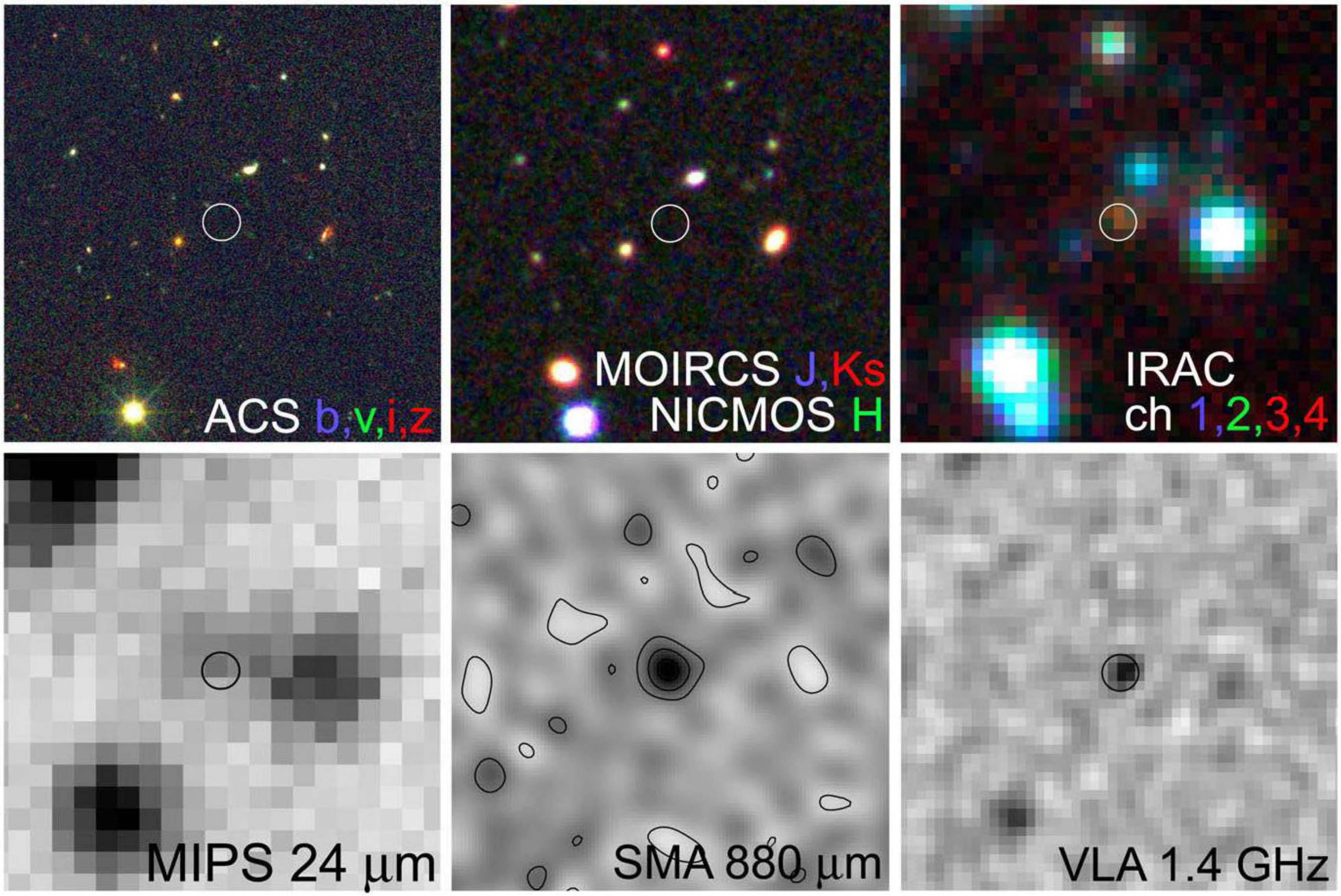
Exploit revolution in submm array technology



CCAT Science Case

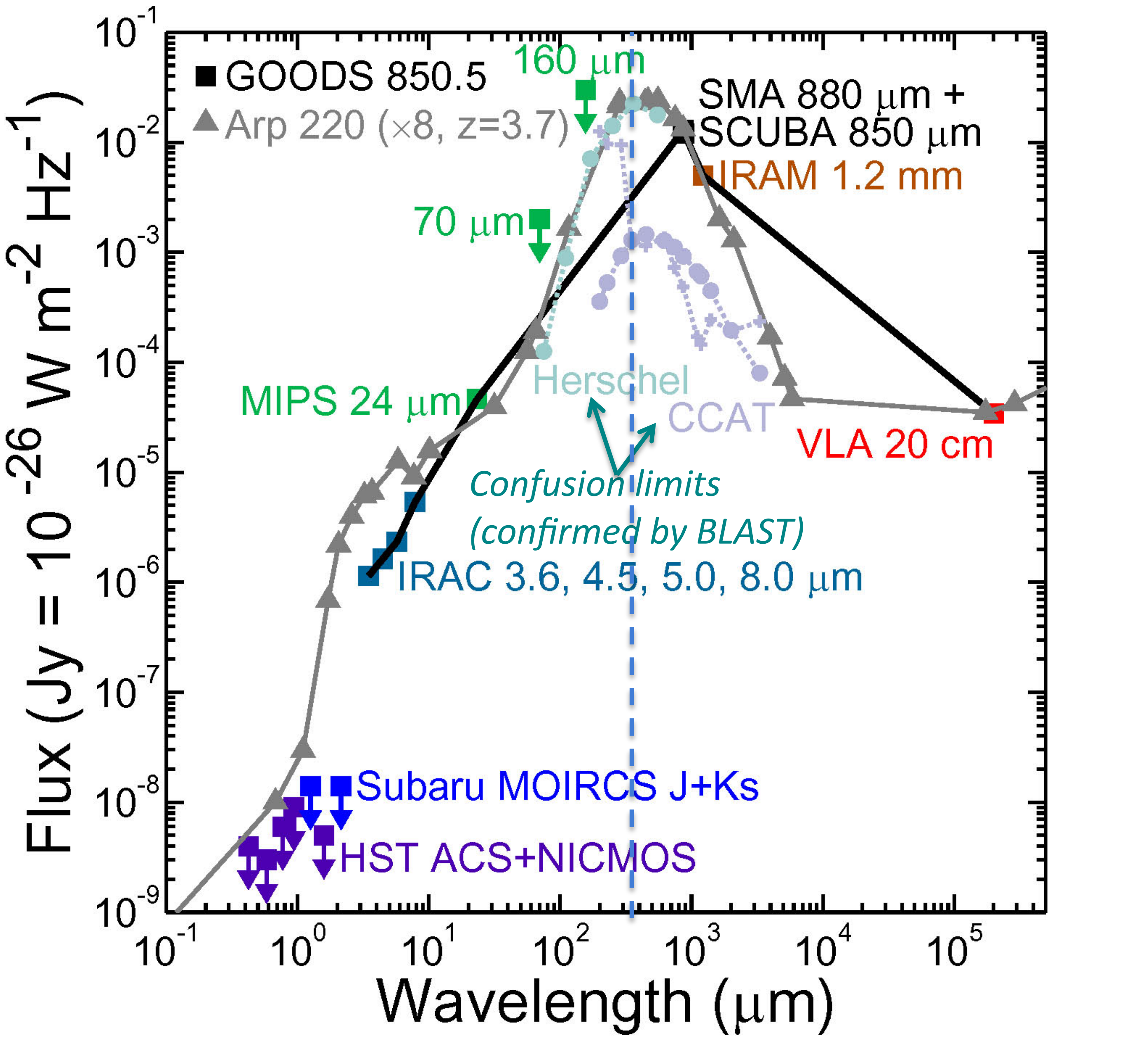
- Submm survey instrument - essential complement to ALMA
- Submm galaxies – beyond the "tip of the iceberg"
  - Submm galaxies → role of mergers in galaxy formation and evolution
  - Need 350 μm flux to constrain luminosity
  - Collecting area + 10 μm rms + site = SENSITIVITY
  - 50% time available for 350 μm = SURVEYS
  - 25m gives angular resolution of 3".5 @ 350 μm
    - reduce CONFUSION LIMIT
    - Improve IDENTIFICATION
  - wide wavelength range = SED
  - Surveys + sensitivity = large catalogs = RARE OBJECTS
- Much more: star formation, CMF studies, SZE, debris disks, KBOs, polarimetry, spectroscopy…
- See www.submm.org

Example: a SCUBA source, GOODS 850-5



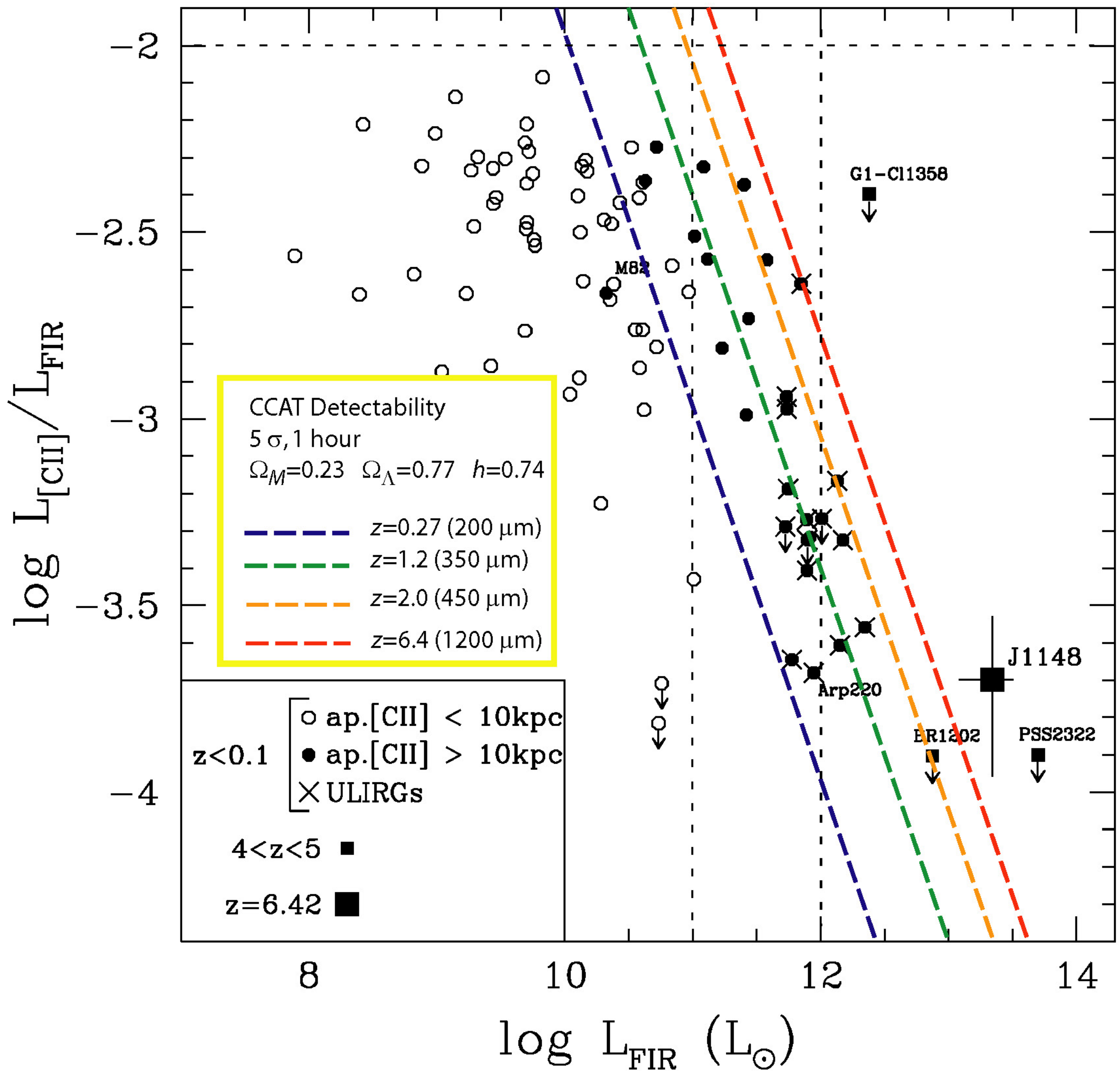
GOODS 850-5: a six decade "panchromatic" view

- Wang, Barger Cowie, 5/22/08
- Second brightest submm source in Goods field is *invisible* to HST and Subaru, and is very faint in IRAC, MIPS, and VLA images
- Luminosity: 8 x Arp 220 is around 2 x 10^{13} L_{solar}
- Lots of questions !
  - z = ? Optical/IR spectroscopic redshift not forthcoming
  - z=3.7 seems ok for radio, mm, submm fluxes…
  - …but higher z for better match to near-IR, optical?
  - Where is the peak, and what really is the luminosity?
  - Can we use submm spectroscopy for determining the redshift?
  - How many more of these are there ??

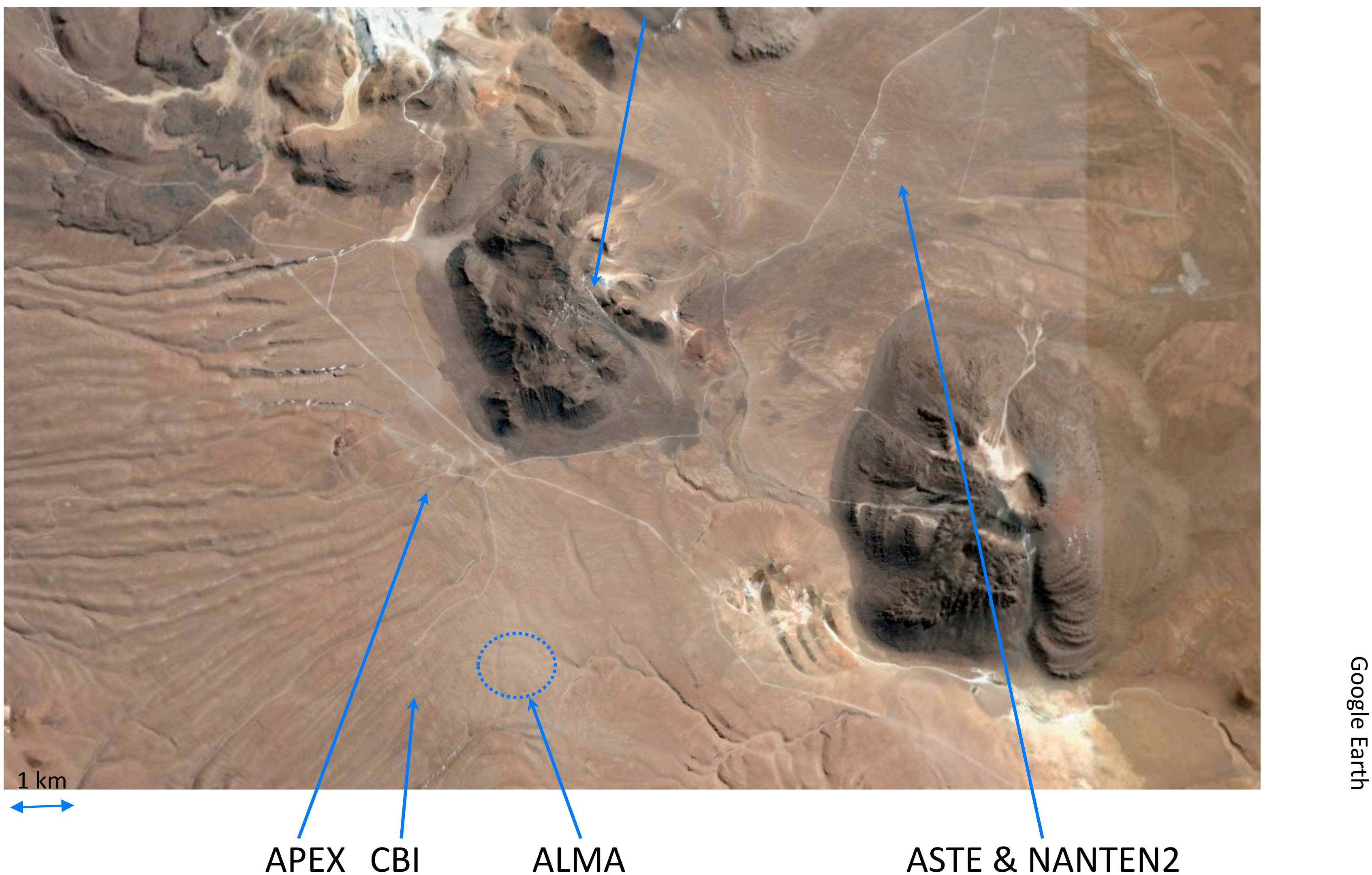


158 μm C+ line is detectable at high z with CCAT

- Multiobject grating spectroscopy ?
- See submm.org



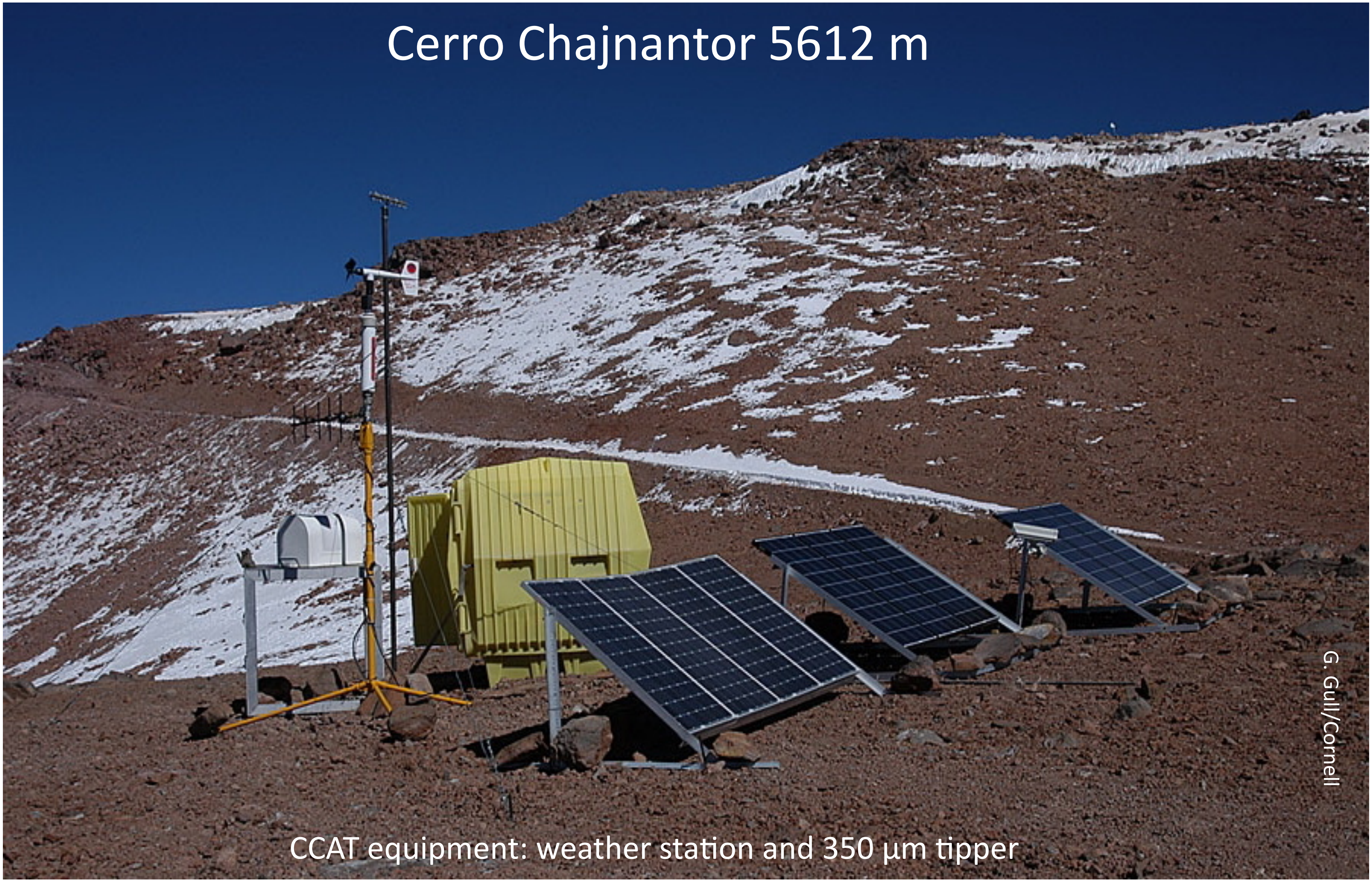
Cerro Chajnantor 5612 m




Cerro Chajnantor 5612 m
View SW from ASTE; access road constructed by U. Tokyo
G. Gull/Cornell


Cerro Chajnantor 5612 m
CCAT equipment overlooking ASTE & NANTEN2 @ 4800 m
C. Gull/Cornell

Cerro Chajnantor 5612 m



CCAT equipment: weather station and 350 µm tipper

Atmospheric Transparency

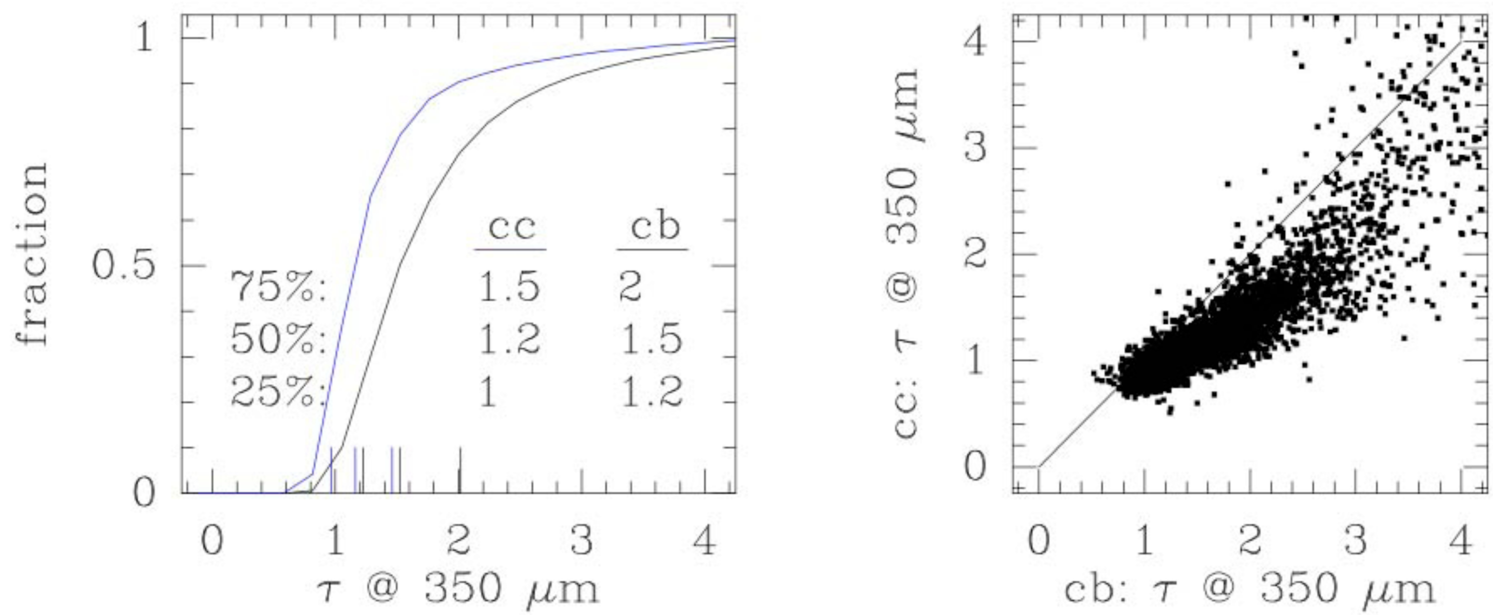


Fig. 8. Cumulative distributions and correlation of 350 μm optical depth (τ) measured simultaneously from 2005 May to 2006 November with two tipping radiometers, one on Cerro Chajnantor (cc) and the other at the Chajnantor plateau (cb).

- Radford et al. 2008, Proc. SPIE, in press (available at submm.org)

CCAT Organization

- Personnel
  - Interim Board (9 members)
  - Director: Riccardo Giovanelli (Cornell)
  - Project Manager: Tom Sebring (Cornell)
  - Deputy PM: Simon Radford (Caltech)
  - Project Scientists: Terry Herter (Cornell) & Jonas Zmuidzinas (Caltech)
- Interim partnership
  - Caltech/JPL, Colorado, Cornell
  - Canada, UK, + Germany (Koln/Bonn)
  - Major partners have 2 seats on interim board
  - Caltech board members: Anneila Sargent and Tom Soifer
- Working towards establishing CCAT nonprofit corporation

CCAT Progress and Status

- 2004-06 Feasibility Study ($2M)
  - Caltech/JPL + Cornell; $1M each
  - Jan 2006 review panel (Bob Wilson, chair)
  - Estimated cost: $100M including two instruments (long & short-wavelength cameras)
- 2006-2008 Partnership Formation
  - Interim partnership established July 2007
  - Kickoff meeting in Waterloo
- FY07-09
  - JPL engineering study of active surface (around $250k/yr)
  - Continued support for PM at Cornell
- 2009 – Begin Detailed Engineering Phase
  - Goal is $10M over two years
  - Funding proposals submitted by partners
  - Continue fundraising for construction
- 2011 – Begin Construction
- NSF participation ?
  - Provide share of operating cost in exchange for broader community access ? (CSO model)
  - To be discussed by Glenn committee (CCAT statement for Decadal Survey)
  - Will seek external input !