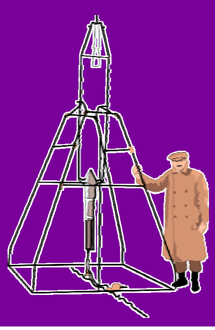
Cryogenic Detectors for Astrophysics
Far-IR, Submillimeter, and CMB

Harvey Moseley

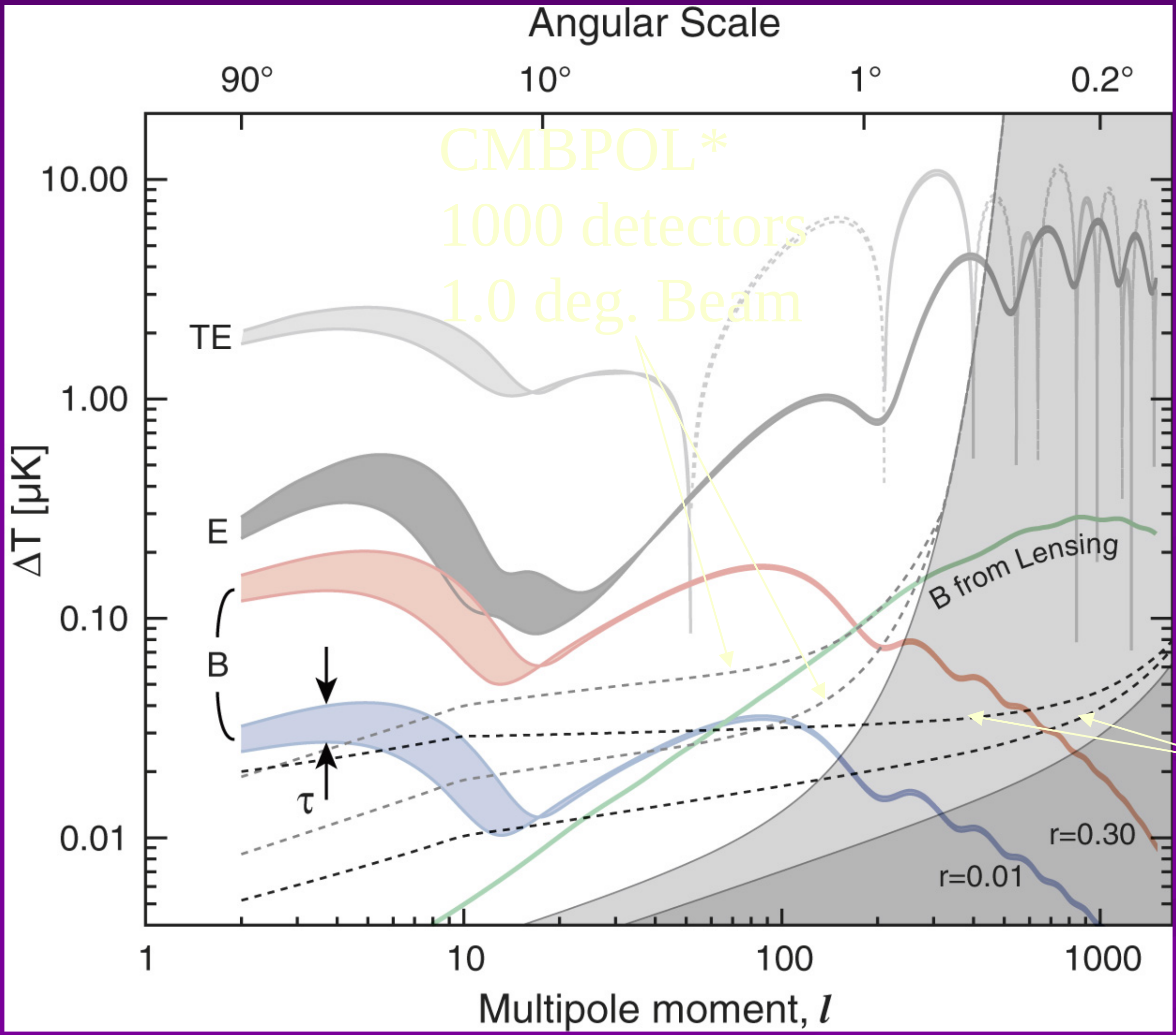
NASA/GSFC



Science Objectives

- Test Inflationary models, particle physics at the highest energies
  - Inflation should leave imprint in polarization of CMB (B-mode polarization), its magnitude related to energy scale of inflation.
- Test models for structure formation in the early universe
  - Galaxy clustering and correlations driven by dark matter

CMB polarization is a unique probe of Inflation

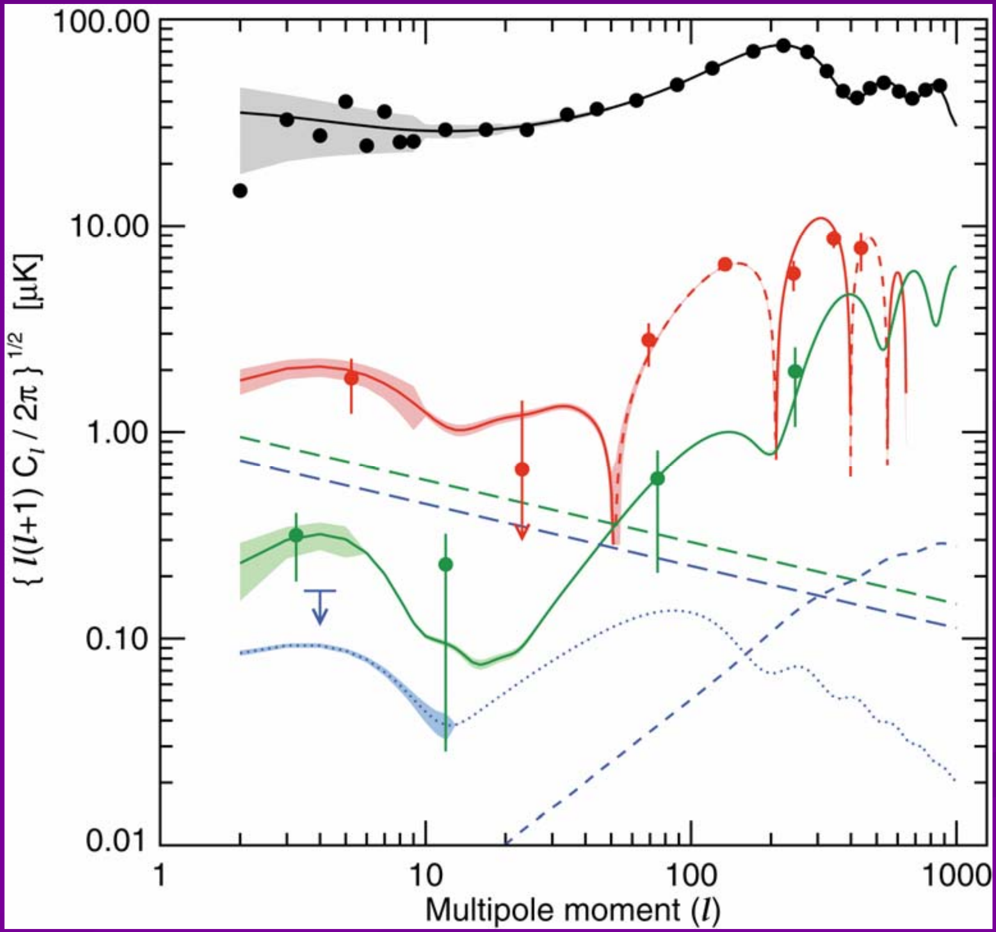


CMBPOL*
2000 detectors
0.1 deg. Beam

*2 lines span foreground uncertainty

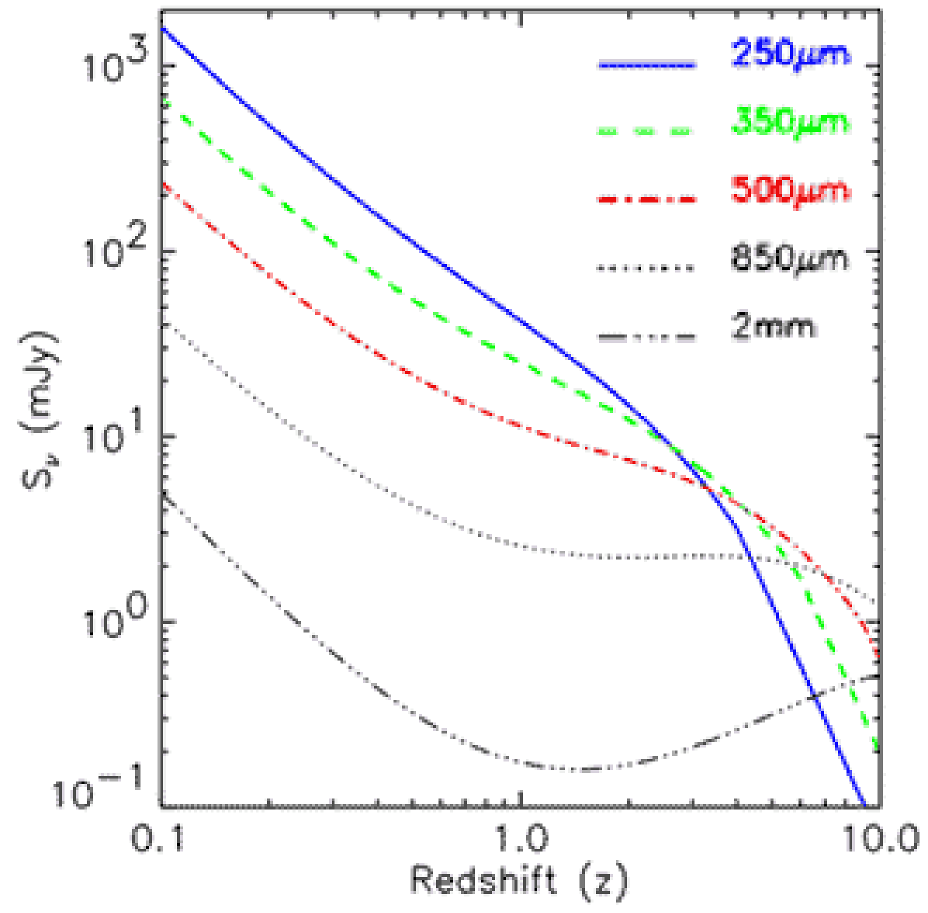
WMAP Results Important Step in Understanding CMB Polarization

- WMAP has detected E-mode polarization at large angles, and sets significant limits on B-Mode
- Spectral slope is significant less than 1; theorists see smoking gun of inflation?
  - Resolution will require B-Mode measurement



The High z Universe is Easily Observed at Sub-mm and mm

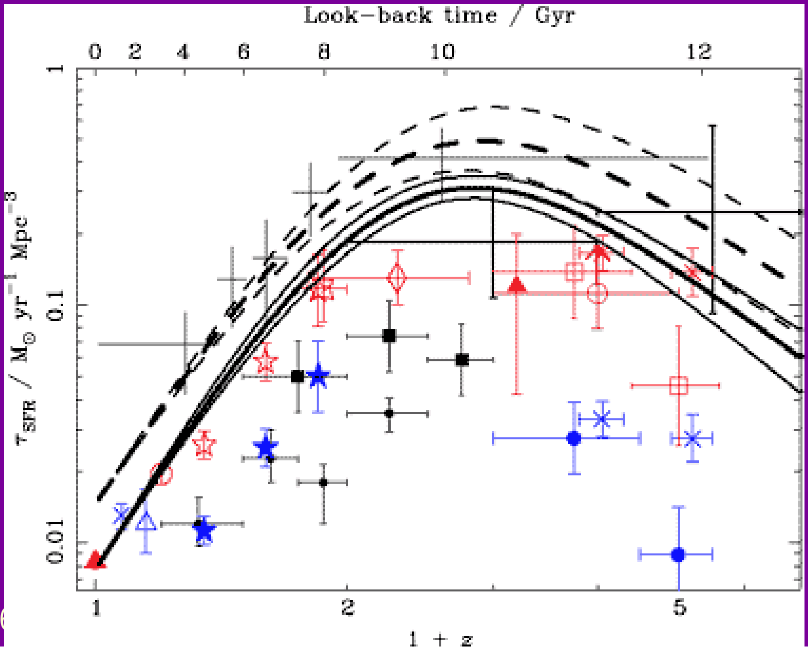
- The Inverse K-correction results in very small variation of galaxy brightness with redshift.
- Multicolor imaging or spectroscopy are essential for sorting the sources by z



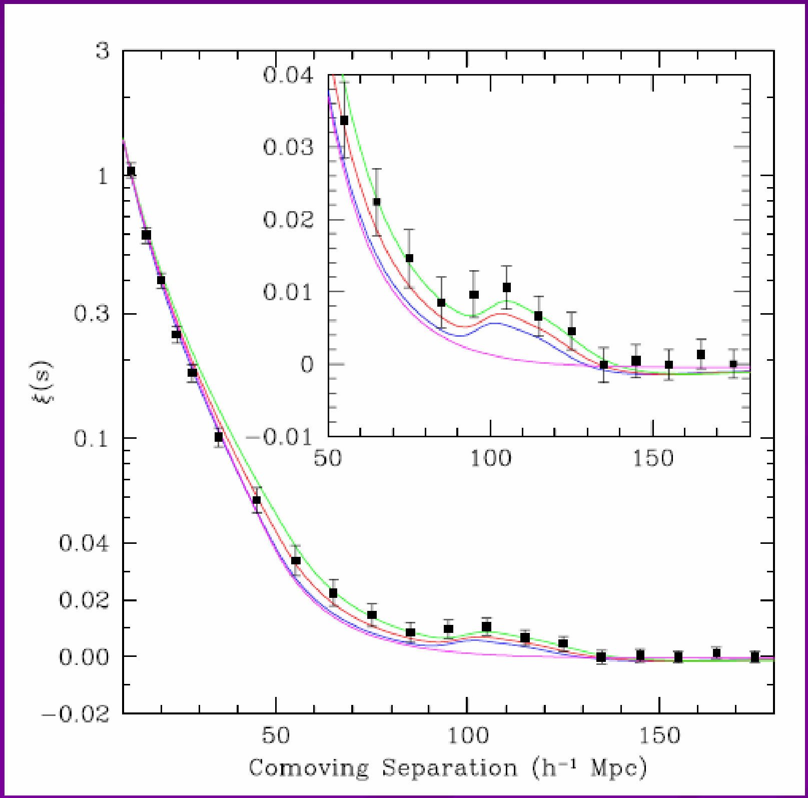
Devlin

Submillimeter/MM Surveys Show Evolution of Early Universe

- Surveys can determine star formation rate in the early universe.
- With adequate spectroscopy, can be used to track growth of structure



Smail et al.



Eisenstein et al.

Observing Facilities

Sensitivity

- Thermal detectors operating at 0.1 K can reach background limit with margin over the peak of the CMB
  - Cryo cooling to 0.1 K is well developed
  - Raw sensitivity is easily reached by semiconducting and TES bolometers
- STJs, KIDS, can, in principle, reach similar sensitivity at 0.3 K

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

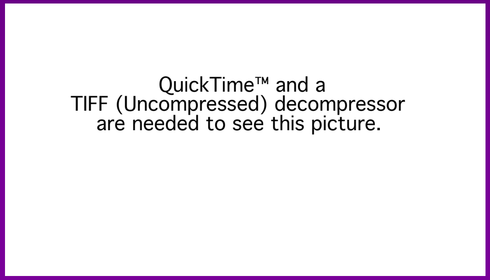
Both Objectives Require Large Arrays of High Performance Detectors

- Sensitivity limits set by photon statistics from cosmic backgrounds.
  - Present generation of bolometers operating near 0.1 K can reach background limits for imaging
- Both objectives require large arrays of such detectors to do large area surveys in practical times
  - CMBPol -> ~ 1000 channels of background limited detectors in a high performance polarimeter
  - SMM Galaxy survey ~ 1000's of detectors for imaging, higher sensitivity detectors for spectroscopy; spectroscopy detectors need significant development

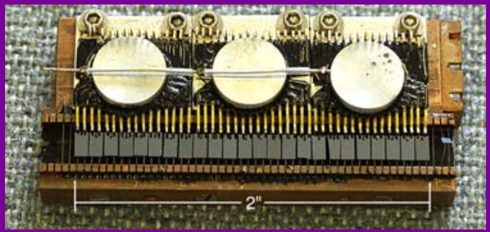
History

Evolution of GSFC Bolometers

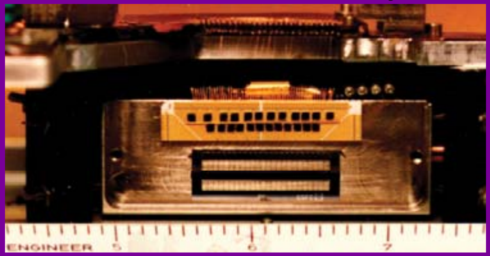
- COBE-FIRAS
  - 1 pixel, handmade – *mid 1980's*

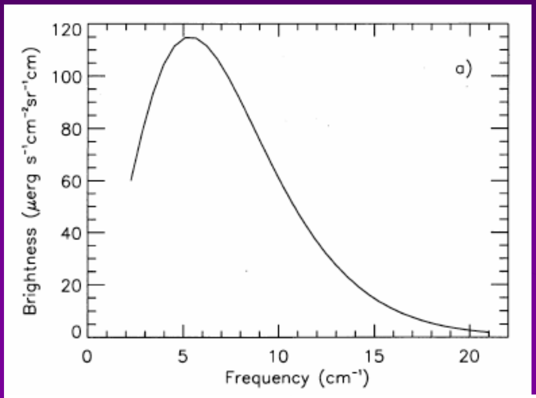


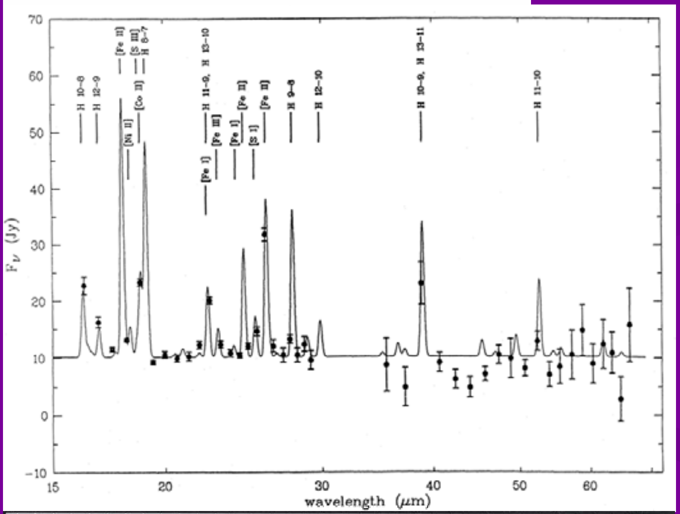
- KAO spectrometer
  - 24 pixels, handmade –*1987*

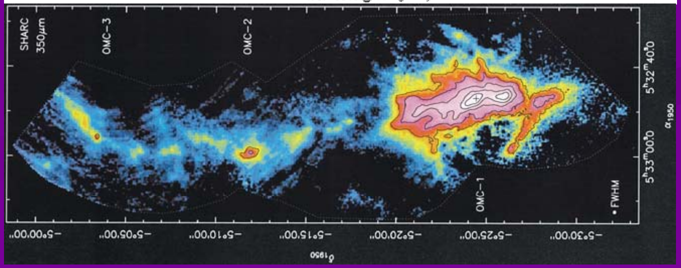


- SHARC I
  - 24 pixels, micromachined – *early 1990's*

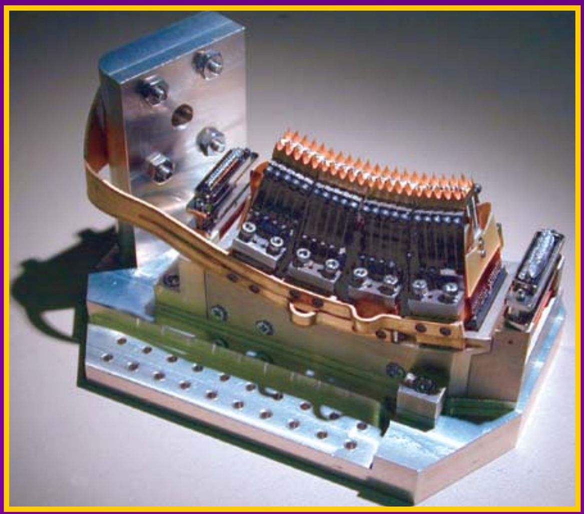


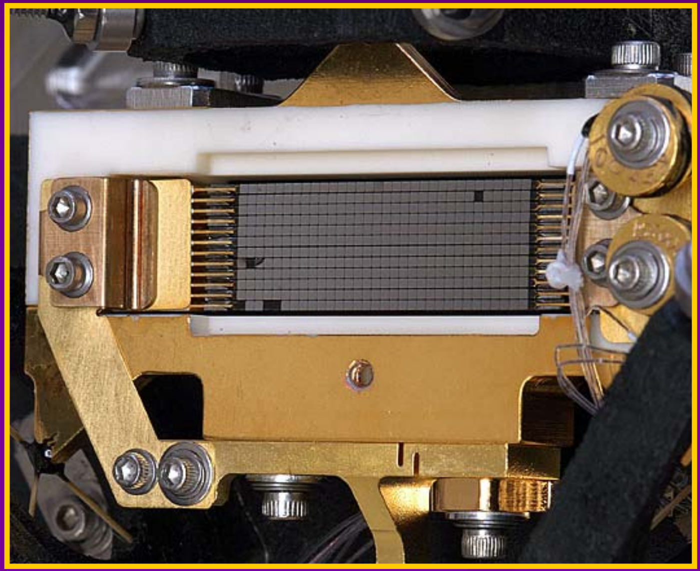


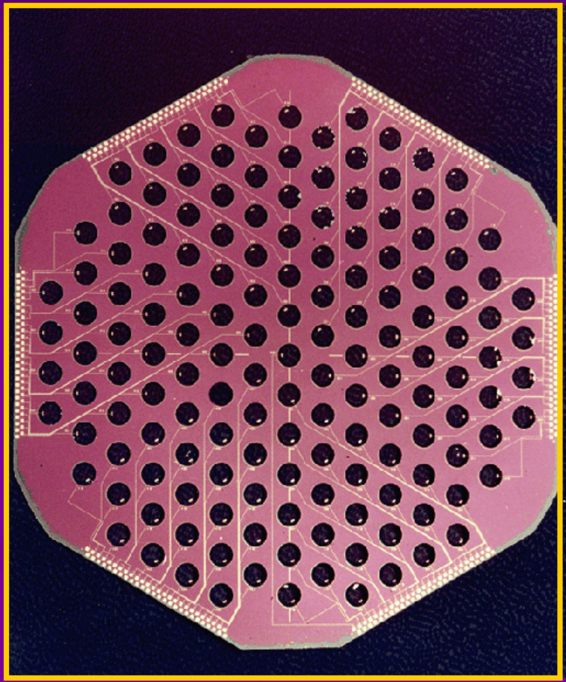




Examples of Detector Arrays





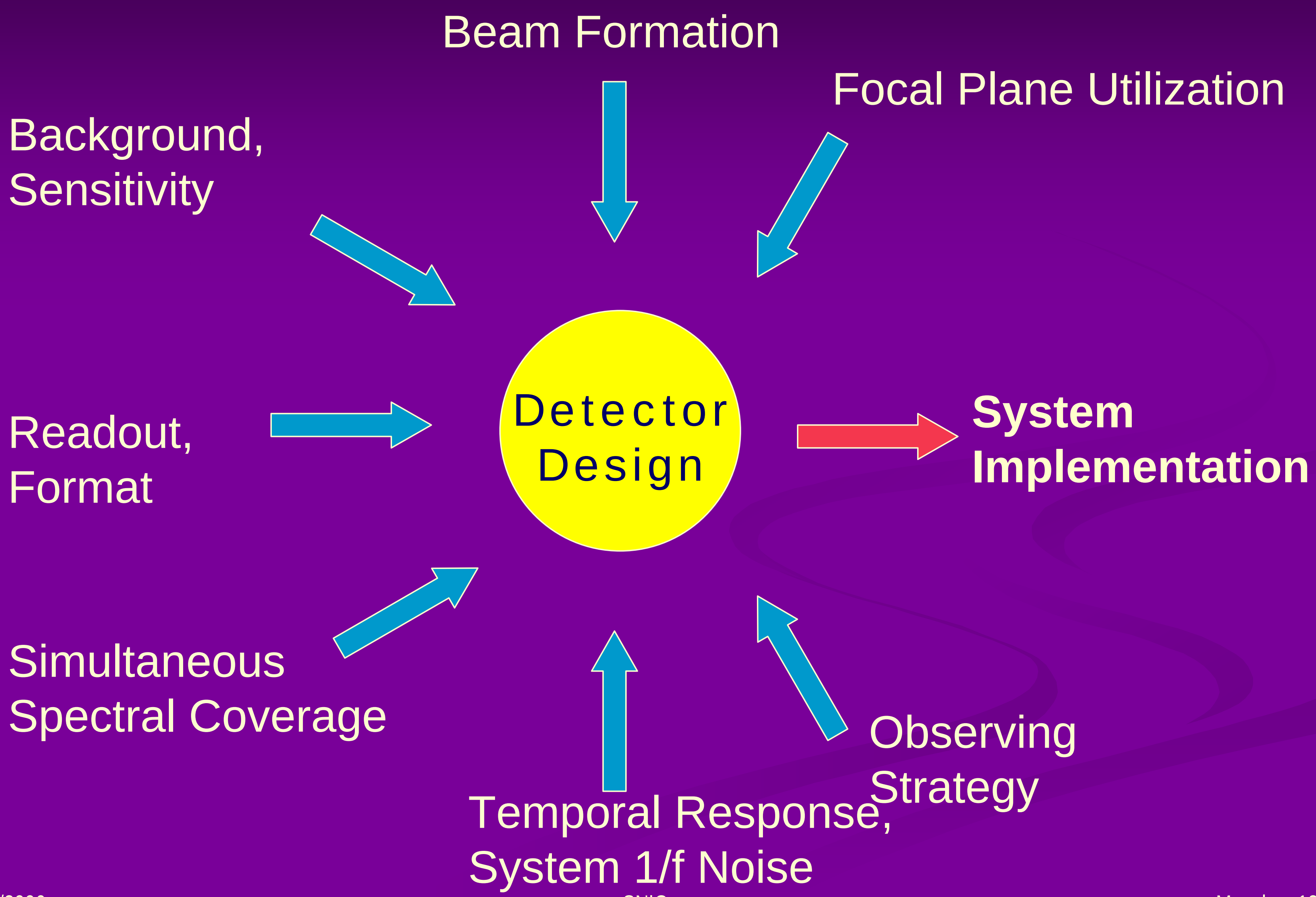


Spitzer/MIPS
100 Element
Flight Array
(U. of Arizona)
160µm

SOFIA/HAWC
384 Element
Flight Array
(GSFC)
50-450µm

Herschel/SPIRE
144 Element
Prototype Array
(Caltech/JPL)
200-1000µm

Motivation



Beam Formation
Focal Plane Utilization
Background,
Sensitivity
Readout,
Format
Detector
Design
System
Implementation
Simultaneous
Spectral Coverage
Observing
Strategy
Temporal Response,
System 1/f Noise

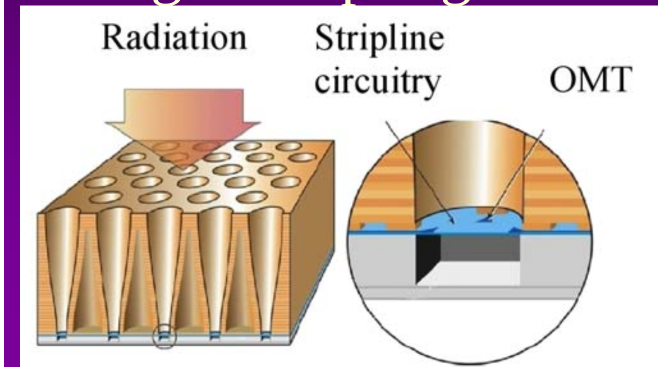
Development Process
The Path to Kilopixel Arrays and Beyond

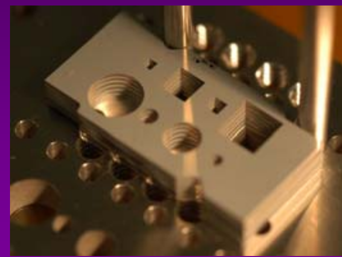
- Choice of Architecture
  - Radiation Coupling
  - Level of integration
- EM Modeling of coupling, filtering, transmission, detection
- Thermal/Mechanical design of detector
  - Mather (1982, 1984), Irwin (1996)
- Fabrication and test of components
- Integration
- Test of system

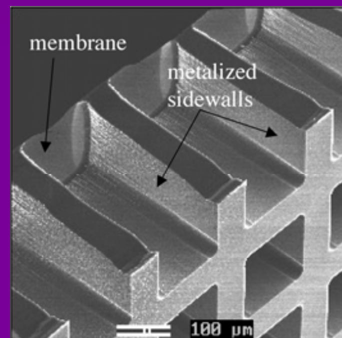
Microstrip Components for CMBPol

NASA
GSFC

- Light coupling method:

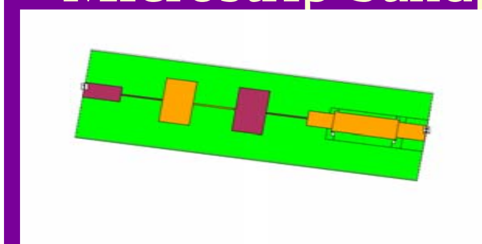


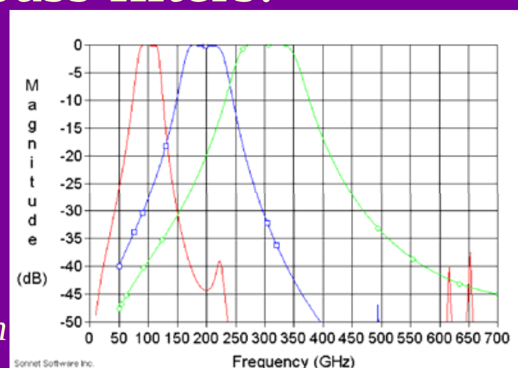




Platelet feed horn & planar OMT light collection concept (above). Test of stacked thru-wafer Si waveguides (top right). Membranes over Si waveguides (right).

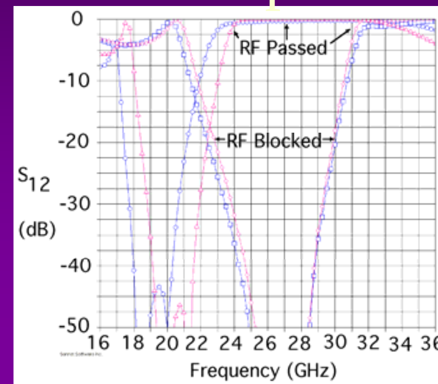
- Microstrip bandpass filters:

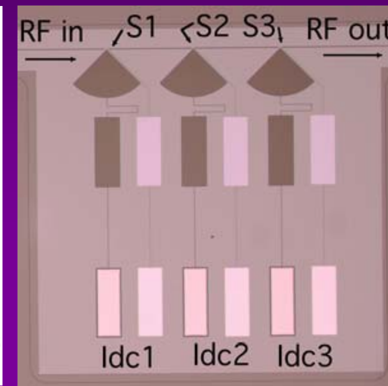




Bandpass filters designed for three measurement bands with low high frequency leakage.

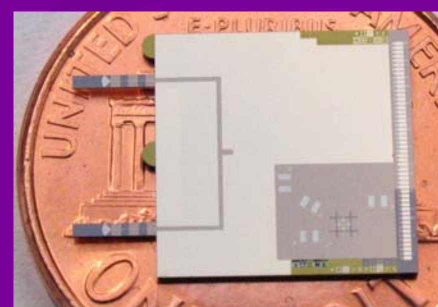
- On-chip modulation:

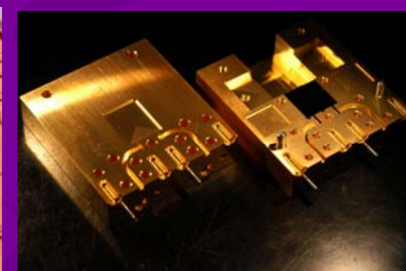




Predicted behavior (left) and photo (right) of prototype millimeter-wave microstrip switch device based on variable inductance of Josephson junction.

- Laboratory tests with VNA:

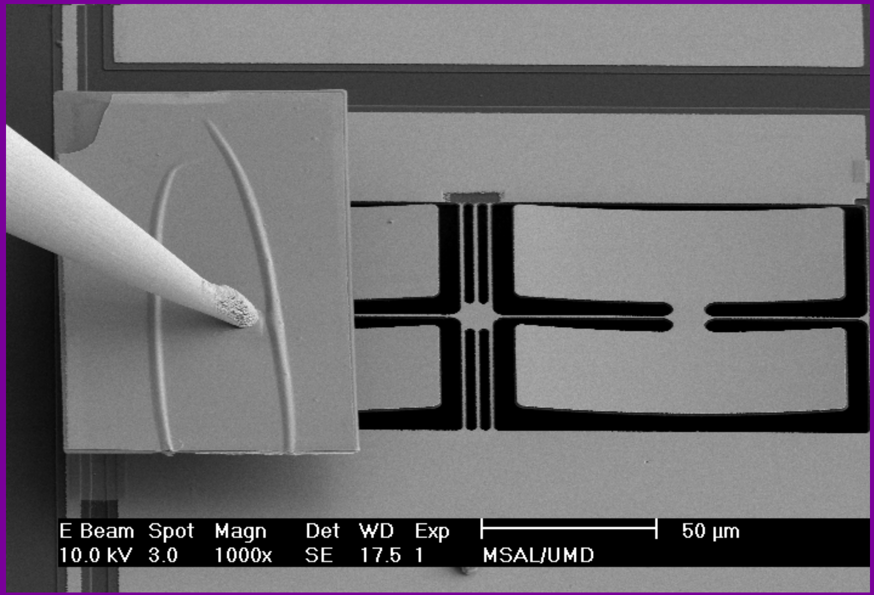


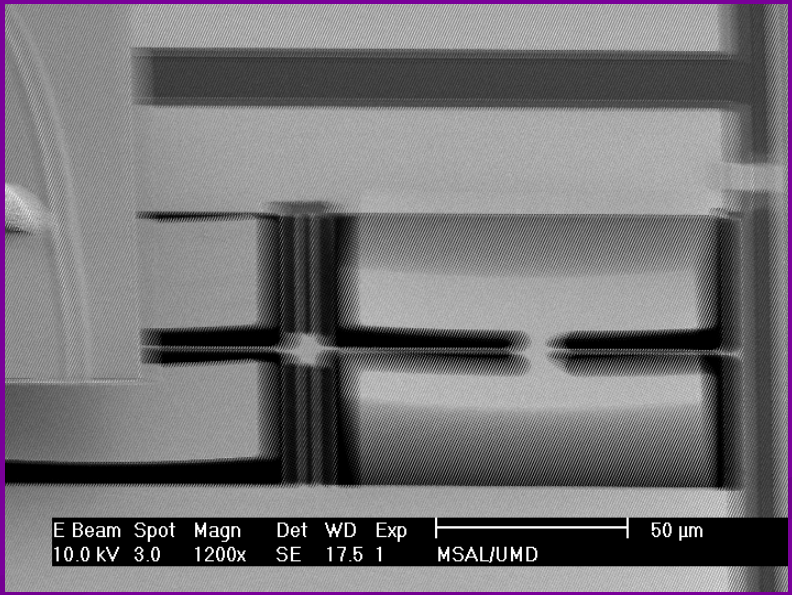


Chip with 100 GHz waveguide probe antennas (above) fits in split block (top right). Package with K-connectors allows tests up to 40 GHz (right).

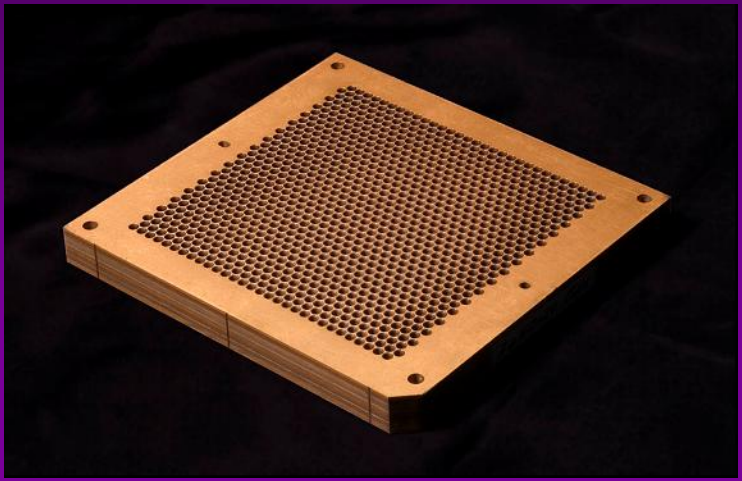
Mechanical Characterization

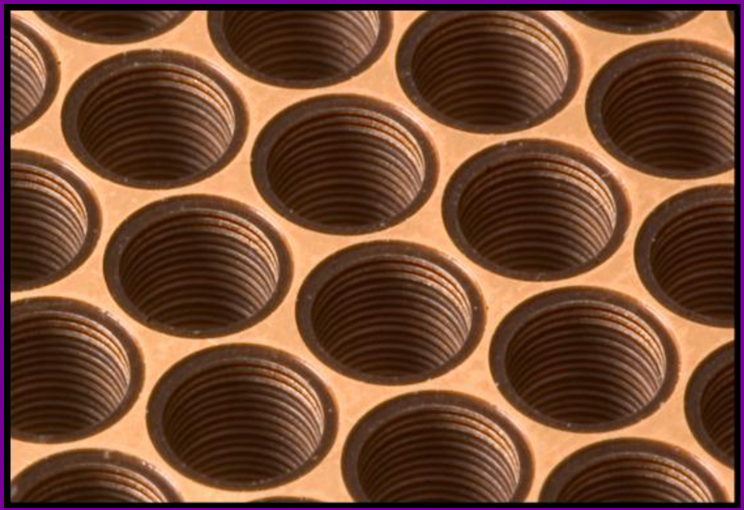
- **Mechanical-Amplifier device for measurement of mechanical properties of detector materials (Si Nitride in this case)**

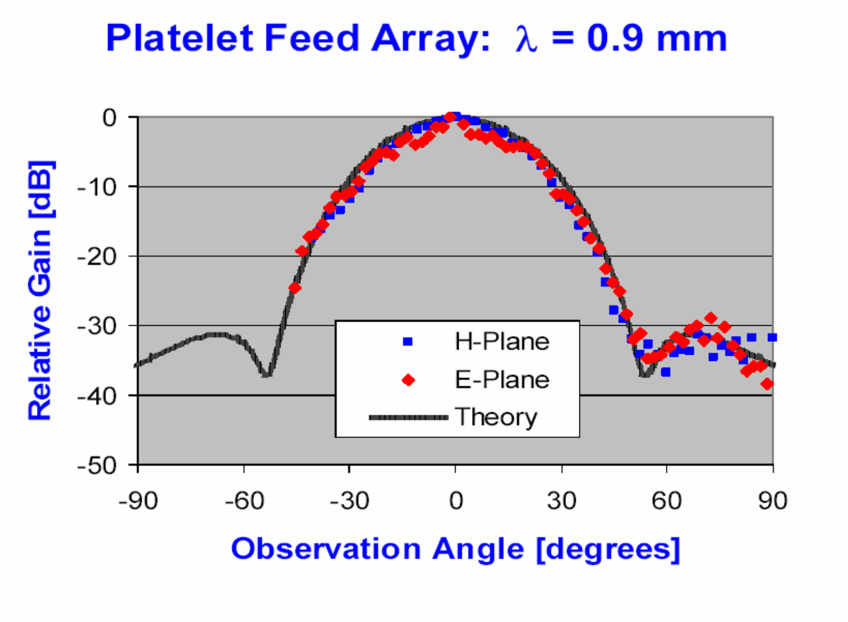




WR02.2 Platelet Feed Array:







Return Loss for elements sampled better than 20 dB across test band…

Movie of the computed current density $J_y(x,y,t)$:

QuickTime™ and a
Video decompressor
are needed to see this picture.

x-axis, along the slots

y-axis, perpendicular to slots

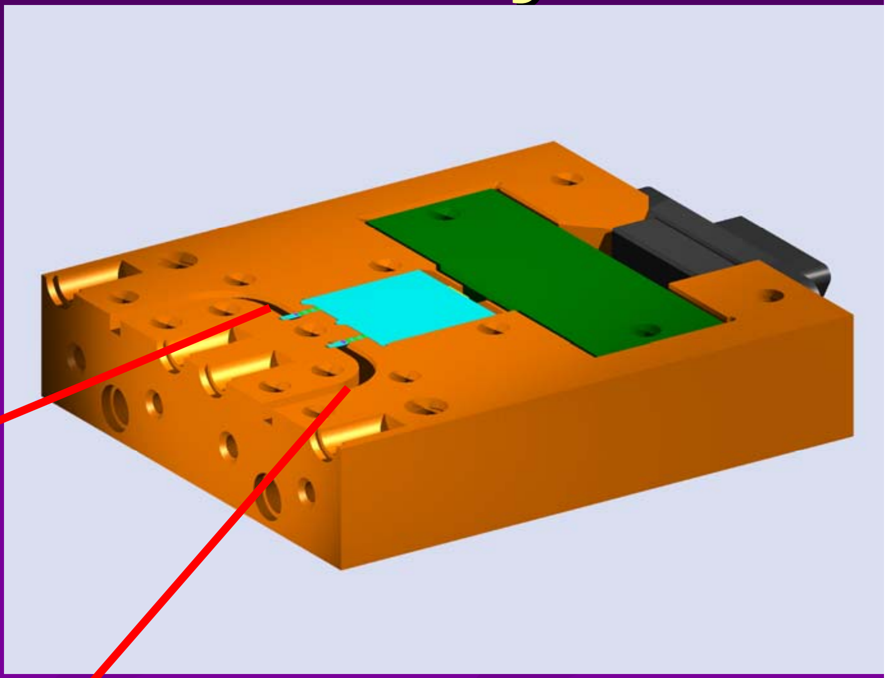
(slots are at $y = \pm 0.25$, $-0.5 < x < 0.5$, and have width 0.04)

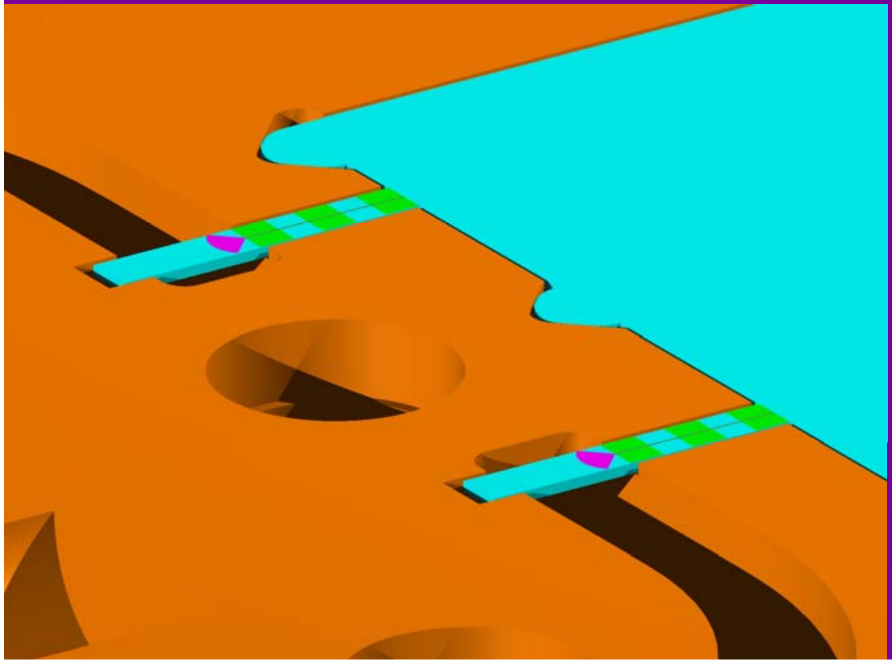
VNA/Microstrip Test Facility

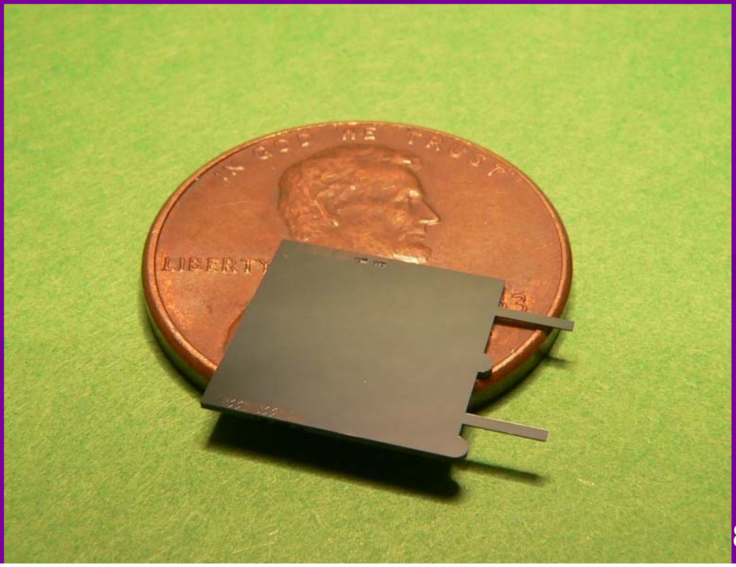
Waveguide/Microstrip Probe

Superconducting Test Capability

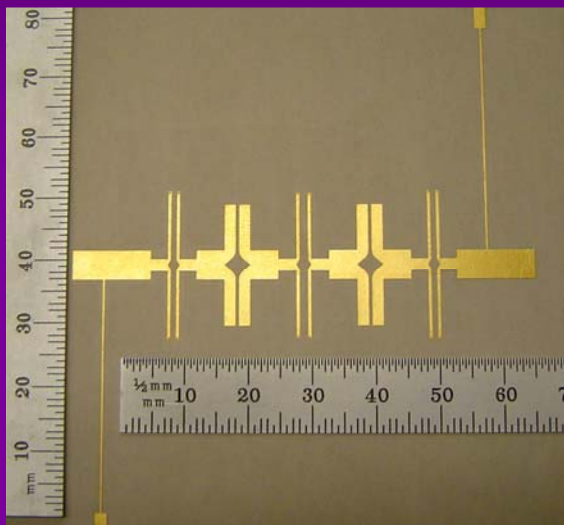
Rapid characterization with VNA



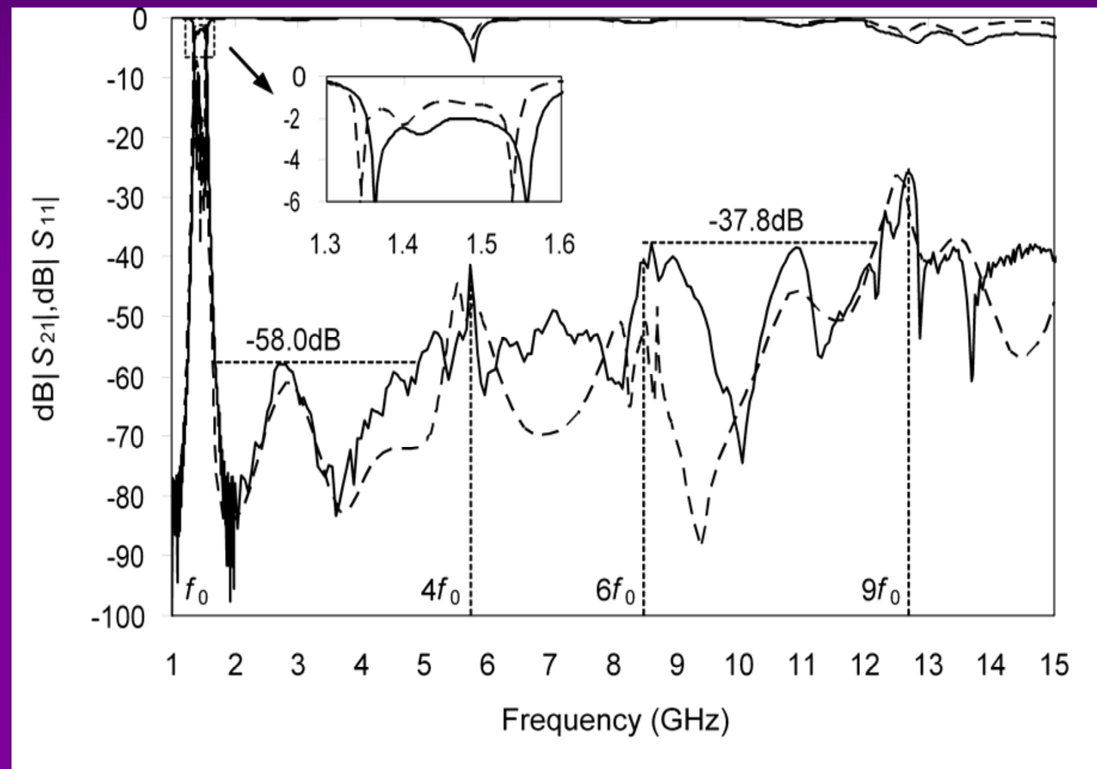




Double Split-End Quarter-wave SIR Filter



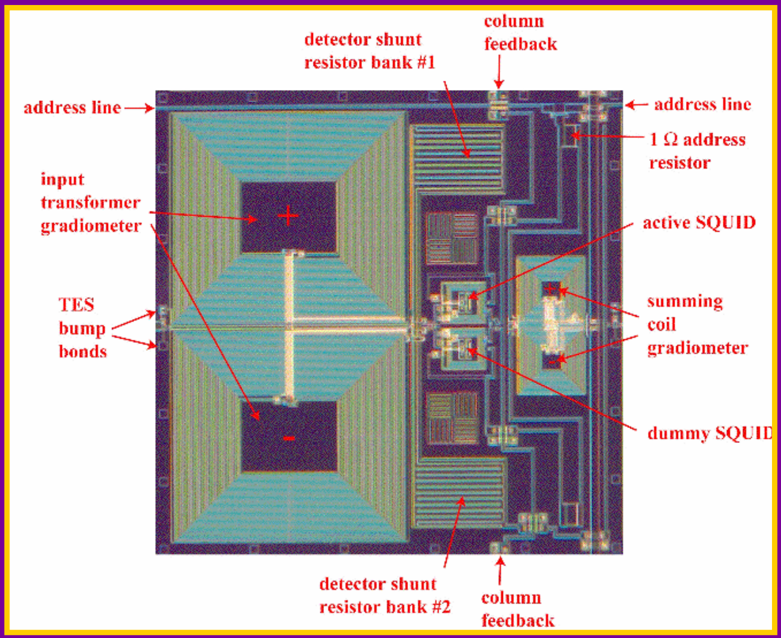
REFERNCE: U-yen, K., Wollack, E.J., Doiron, T., Papapolymerou, J., Laskar, J., "A Planar Bandpass Filter Design with Extended Rejection Bandwidth Using Double Split-end Stepped Impedance Resonators," 2006, IEEE Microwave Methods and Techniques, Vol. 55, No. 3, pp. 1237-1244.

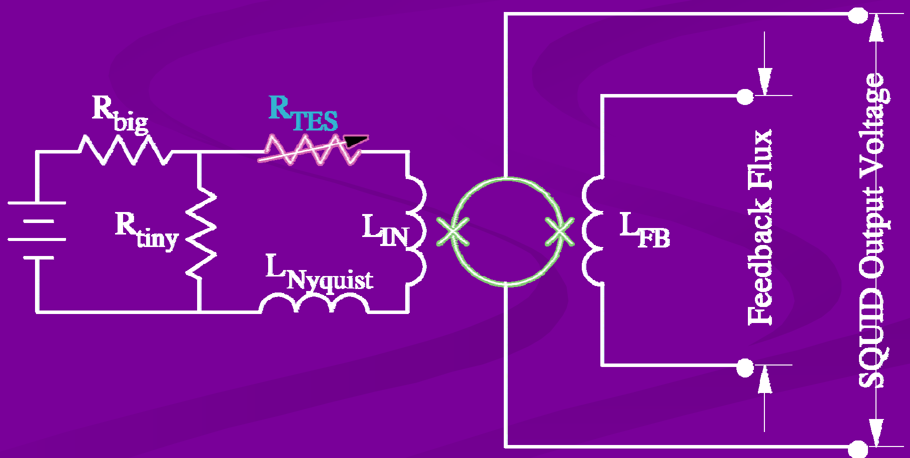


Normal metal quarter-wave SIR (Stepped Impedance Resonator) filter design prototype with large stop band. Frequency response of dB|S_{21}| (solid line) and dB|S_{11}| (dash line) of filter with 3 transmission zeros placed around the lowest spurious frequency (at 5.65GHz) and 4 transmission zeros place around the second lowest frequency (at 8.47GHz).

SQUID Amplifiers

- SQUID amplifiers are well-matched to TES detectors
- Operate at detector temperature
- Low noise makes multiplexing feasible





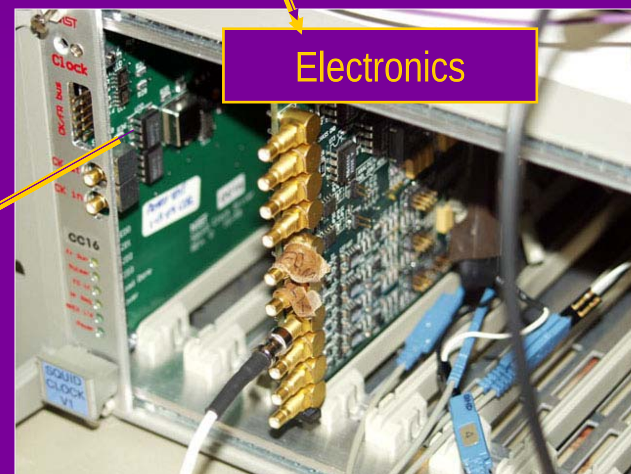
GSFC-NIST Collaboration

GSFC

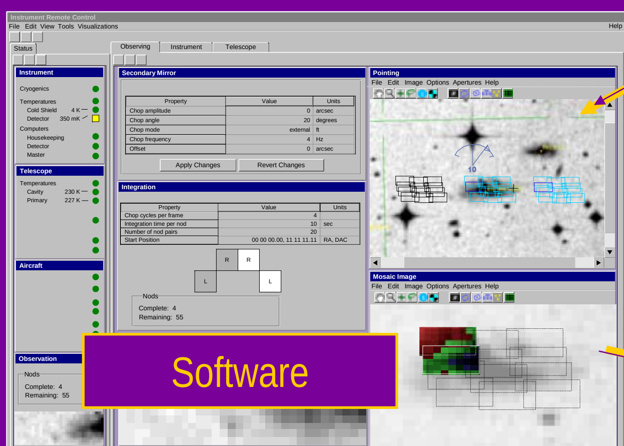
Detector

NIST

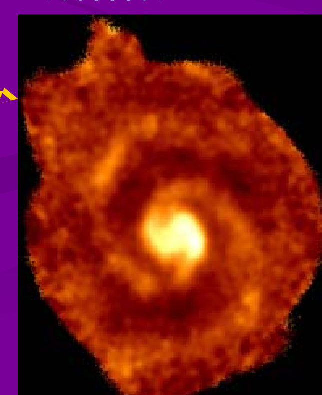
SQUIDs



Electronics



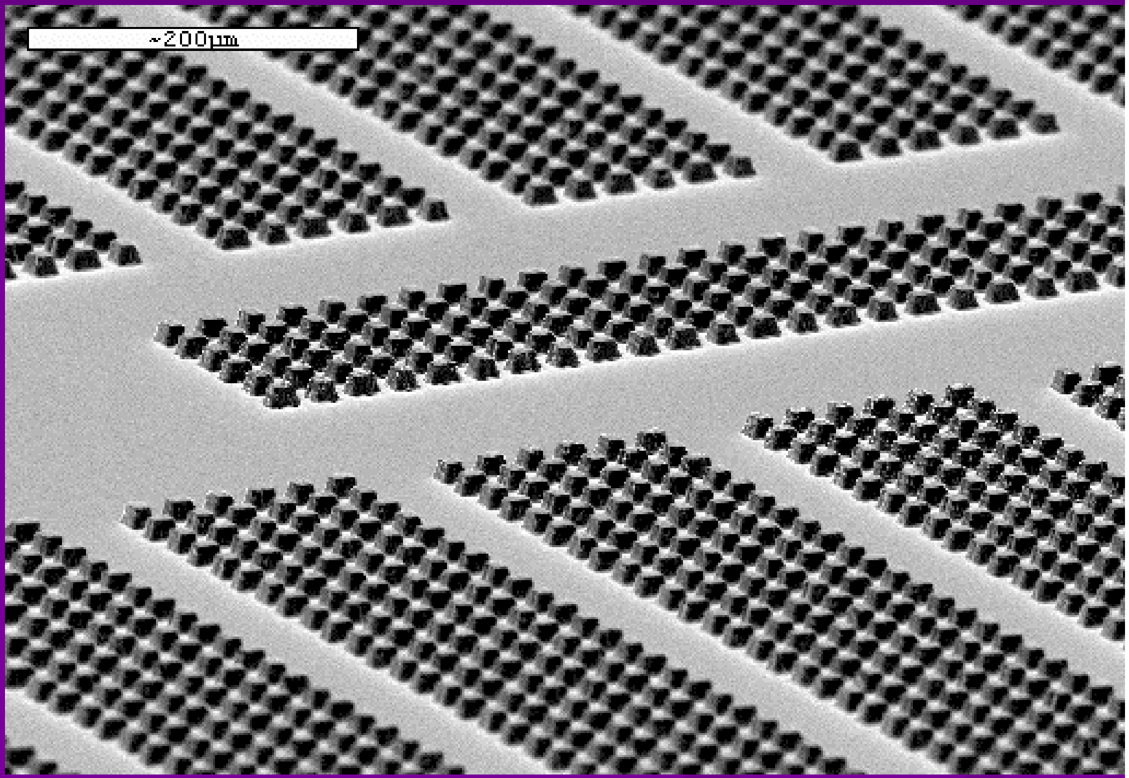
Software



Science

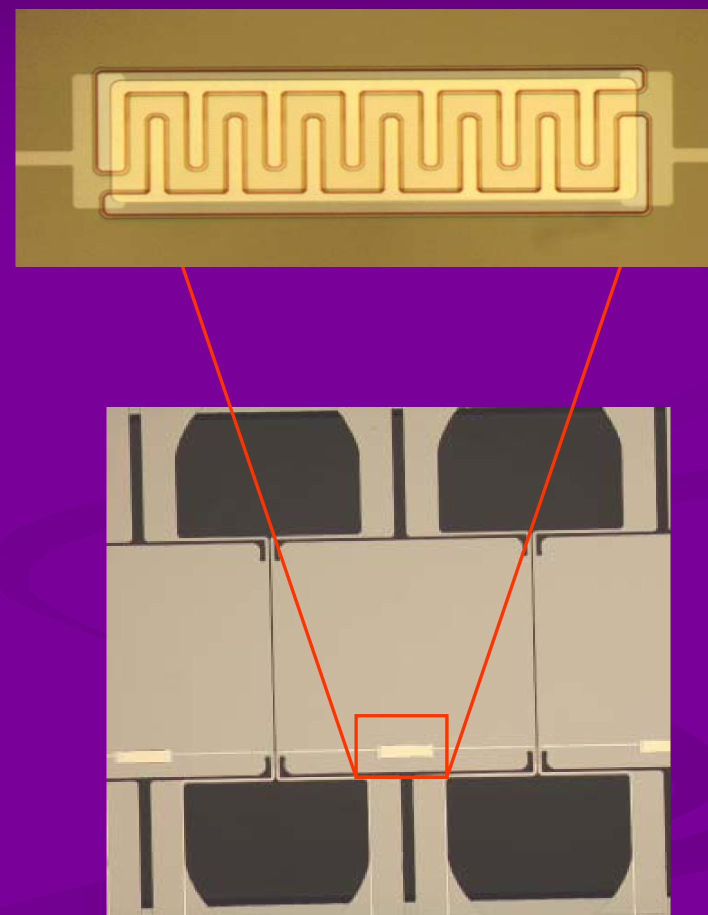
Integrating Detector to SQUID Mux

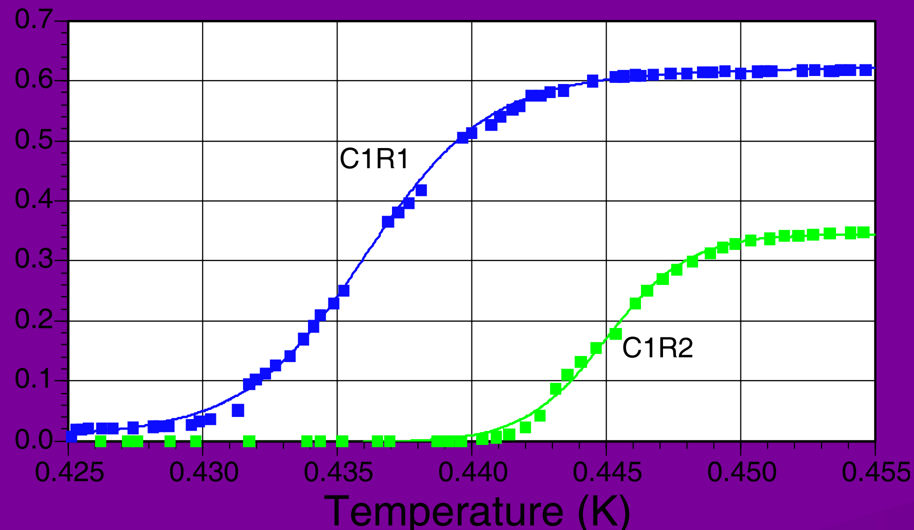
- Following the SCUBA II development, we have extended the bump bonding to allow one-sided bumps to thin substrates



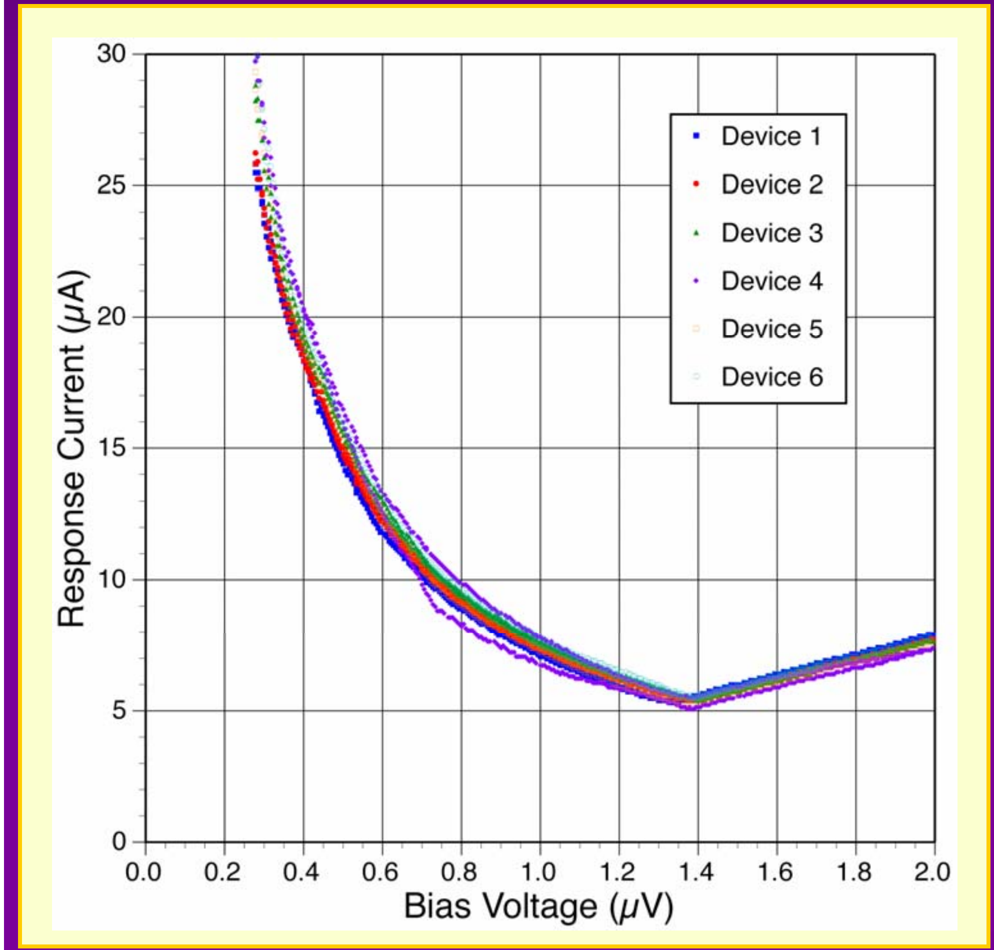
Transition Edge Sensor Bolometers

- One highly credible approach to meeting future pixel count and sensitivity requirements is with superconducting transition edge sensor (TES) bolometers.



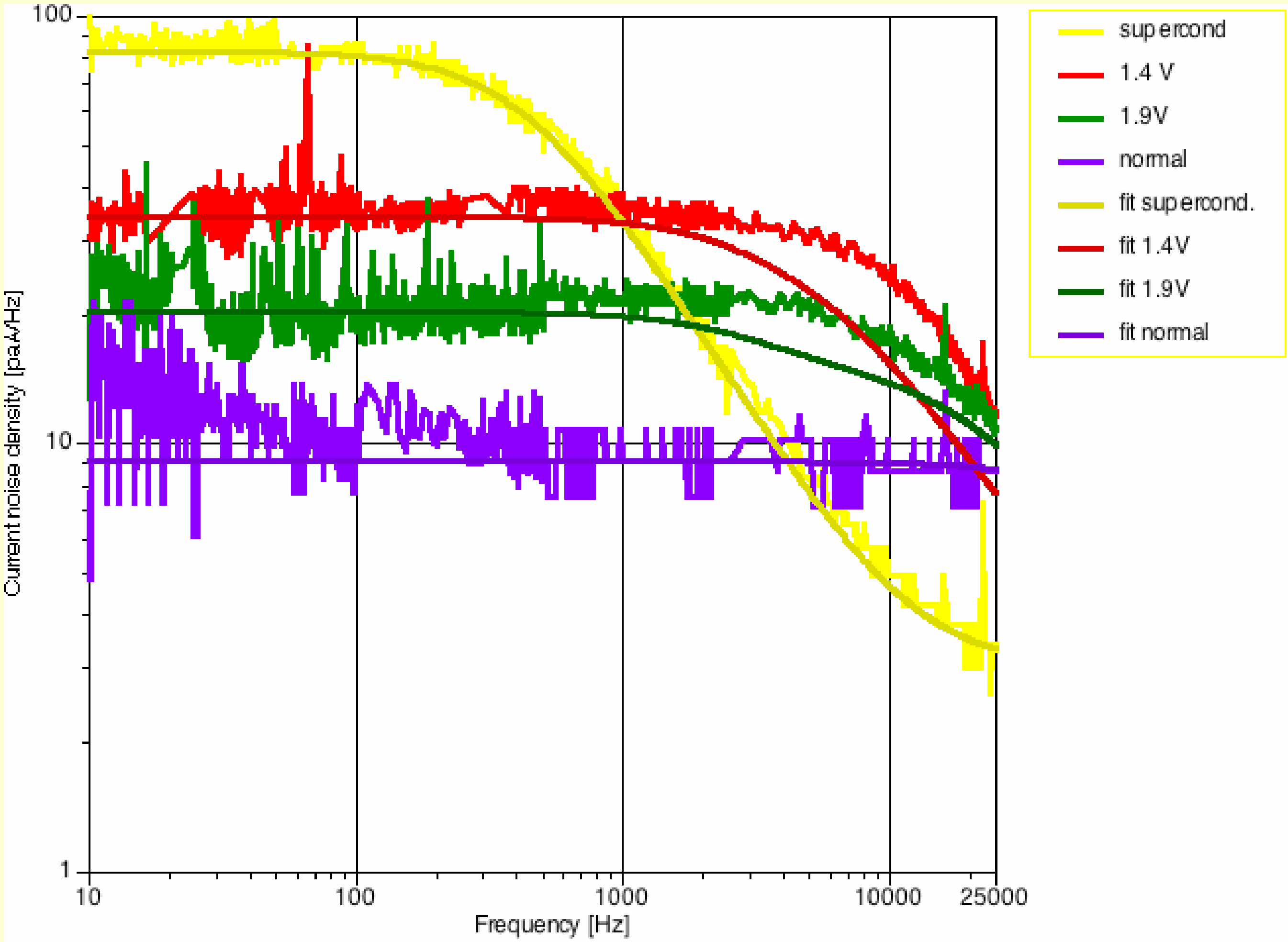


Detector I-V Curves



- Normal region at high voltage provides ohmic definition of zero point
- S/C region is hyperbolic

Detector Noise

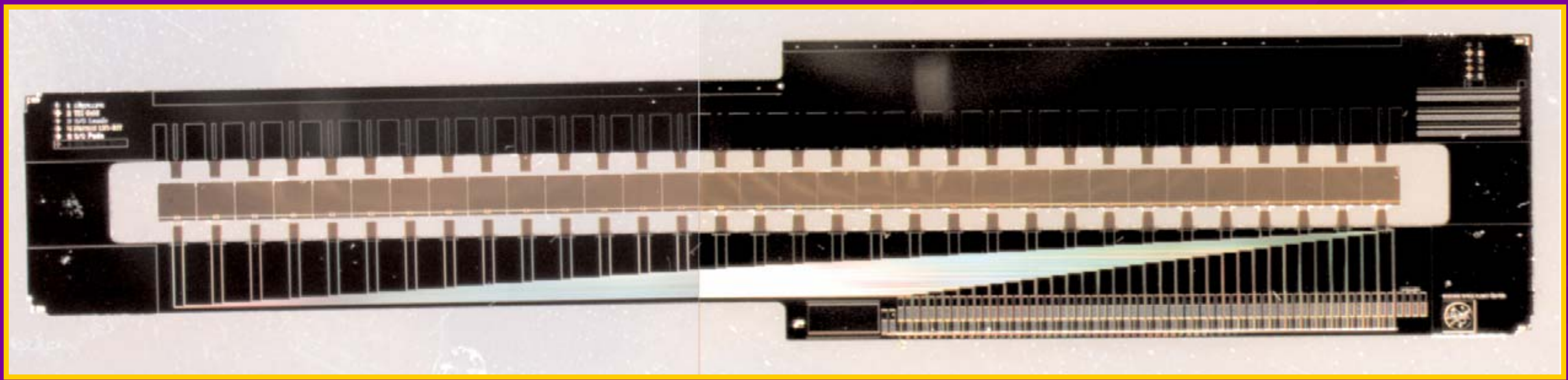


Noise very close to theoretical limit!

TES Pop-up Bolometer Array

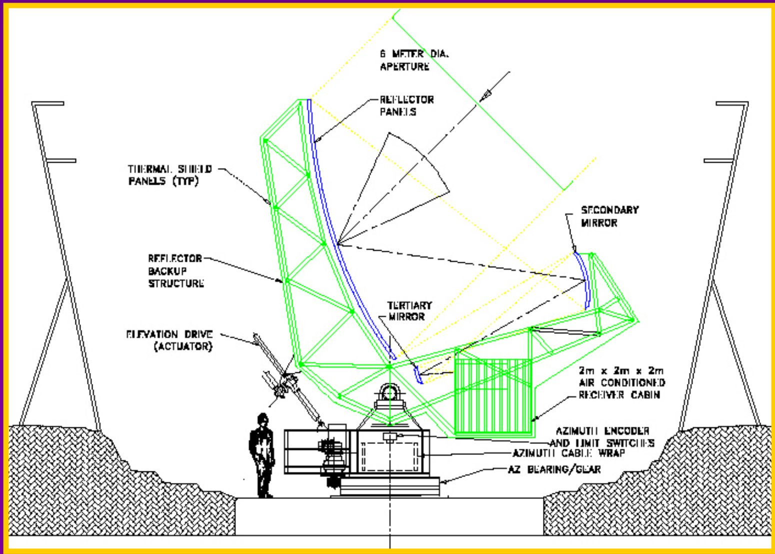
1 x 32 TES arrays have been produced for ACT;

device characterization in progress.



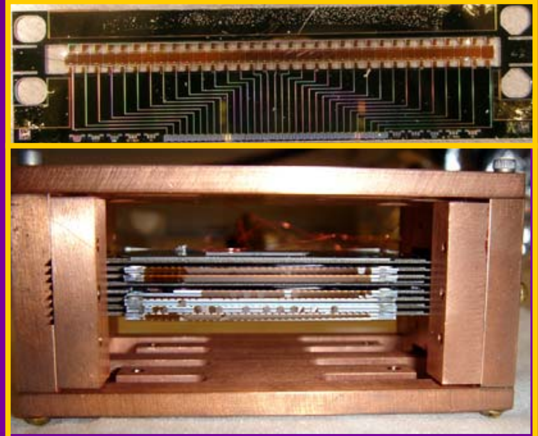
ACT - Atacama Cosmology Telescope

U. Wales - Cardiff, U. Colorado, Columbia, CUNY, Haverford, NASA/GSFC, NIST, U. Penn., Princeton, Rutgers, UBC, U. de Catolica, U. Mass. - Amherst, U. Toronto



Observations:

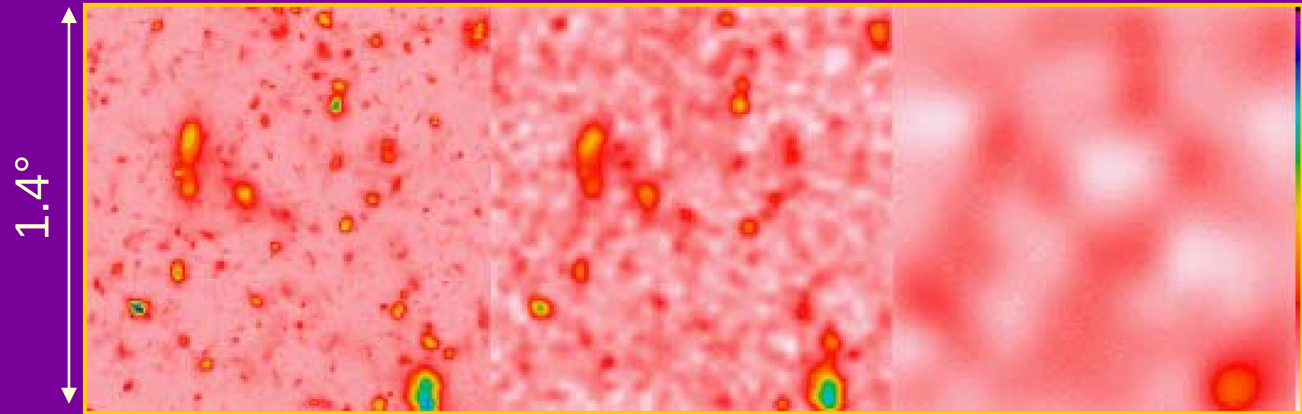
- •CMB: *l*>1000
- •Cluster (SZ, KSZ
- •X-rays, & optical)
- •Diffuse SZ
- •OV
- •Lensing



ACT camera will consist of 3 1024-element arrays from GSFC

Science:

- •Growth of structure
- •Eqn. of state
- •Neutrino mass
- •Ionization history
- •Power spectrum

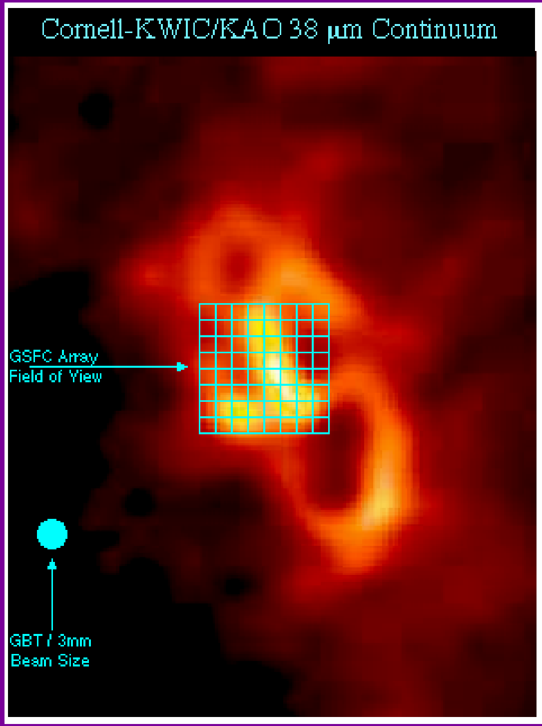


SZ Simulation **MBAC on ACT** **PLANCK**

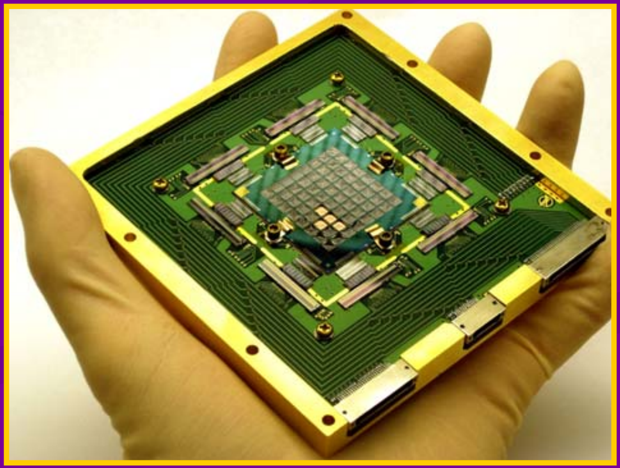
GBT 3mm Camera

U.Pennsylvania, NASA/GSFC, NIST, NRAO, U. Wales - Cardiff

- First NRAO bolometer camera
- Sensitivity ~500μJy in 1 s
- Great for extragalactic surveys - very sensitive
- Can do amazing Galactic science - high resolution



- 3.3mm wavelength, 8x8 array
- Features 64 pixels = 32'' x 32'' FOV, with 8'' resolution



NASA GSFC

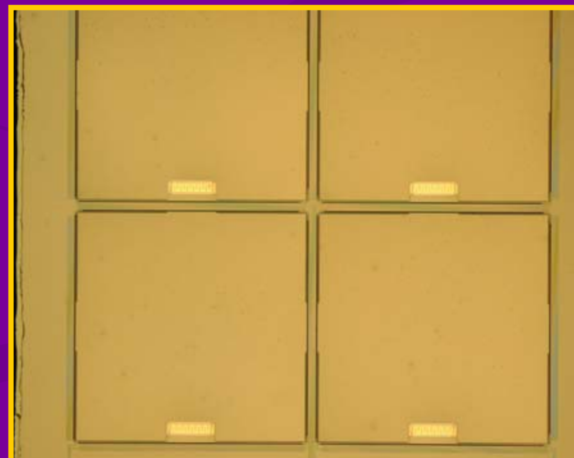
Goddard/IRAM 2mm Camera "GISMO"

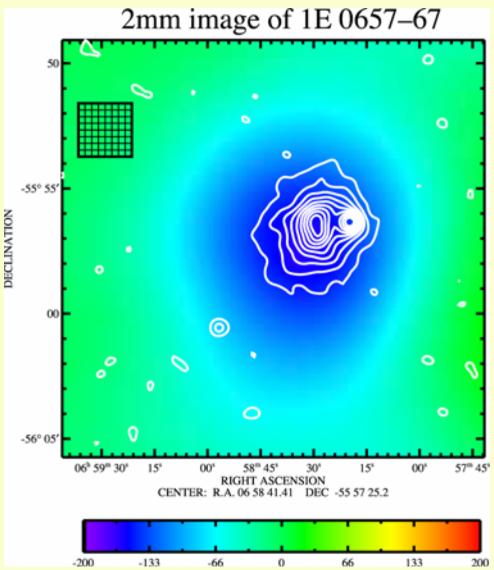
NASA/GSFC, IRAM, NIST

- Hybrid bolometer/readout camera
- Sensitivity ~1mJy in 1 min on 10 sq. arcmin FOV
- Great for extragalactic followup - high-z instrument
- Can do amazing Galactic science - rapid mapping

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

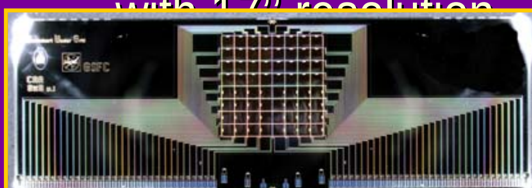
Above: IRAM 30m telescope
Below: enlargement of pixels





SZ cluster: high res image in 1 night

- 2mm wavelength, 8x16 array
- Features 128 pixels = 2.2' x 4.4' FOV, with 17" resolution



8x8 prototype array

Summary

- Highly integrated arrays of kilopixels of background limited detectors are required to address the studies of CMB polarization and to characterize the epoch of initial star formation
- Elements of the system design are generally understood well enough to optimize analytically and produce the desired component
  - Exceptions:
    - TES noise not understood in a fundamental way
    - Thermal conductance in small structures still determined by iteration
- Overall thermal/mechanical design must be carefully done
- Completing this next generation of detector is within technical reach
  - Build now, or wait for perfection?
  - Large engineering project, needs concerted effort