Bolometers and the Big Bang

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LBNL Physics Division

Bolometers and CMB at Berkeley

Berkeley Physics and LBNL

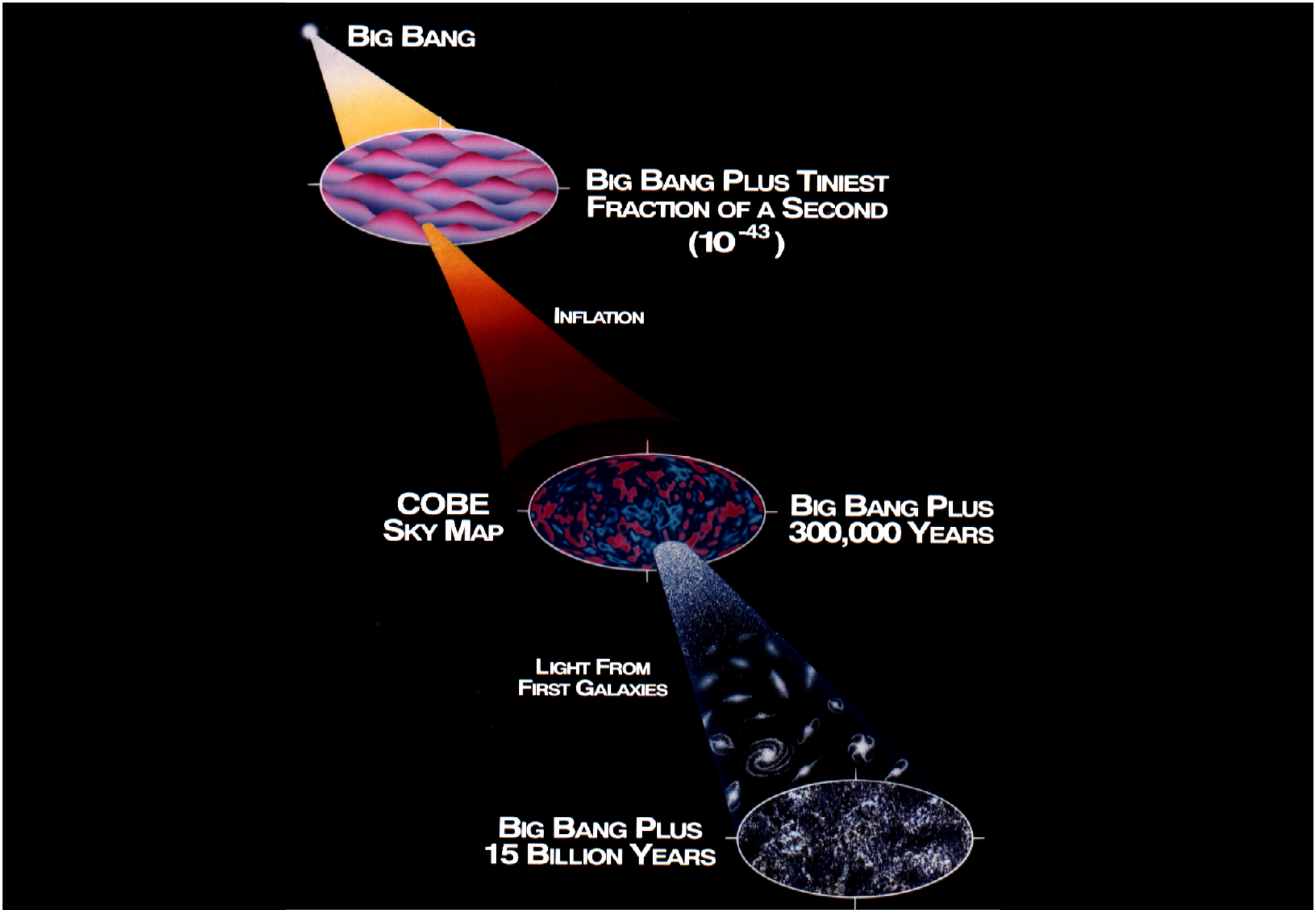
Kam Arnold
Brad Benson
Sherry Cho
John Clarke
Matt Dobbs
Greg Engargiola
Nils Halverson
Bill Holzapfel
Zigmund Kermish
Trevor Lanting
Martin Leuker
Adrian Lee
Jared Mehl
Mike Myers
Roger O'Brient
Tom Plagge
Paul Richards
Dan Schwan
Erik Shirokoff
Helmuth Spieler
Huan Tran
Erin Quealy

Blue = Senior Personnel at Berkeley

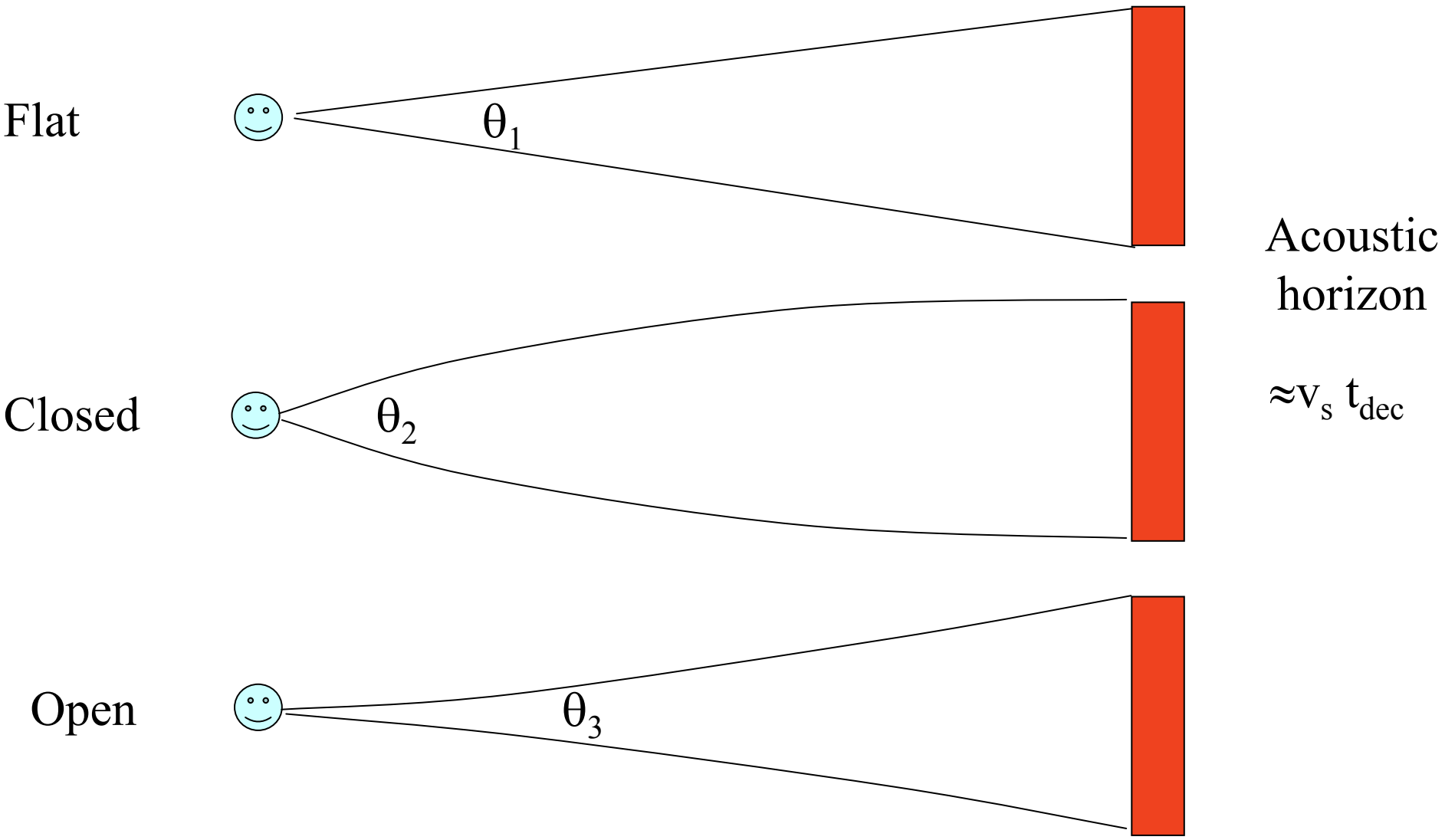
Outline

- Science: Cosmic Microwave Background (CMB)
  - CMB Temperature Anisotropy
  - CMB Polarization Anisotropy
  - Galaxy Clusters as Probe of Cosmology
- Technology: Superconducting Bolometers
  - Transition-Edge Sensors
  - Monolithic Millimeter-Wave RF Circuits
  - SQUID Readout and Multiplexing
- Connections to Other Fields
  - Calorimeters (Optical, x-ray, gamma-ray, Dark Matter)

Science: Observations of the CMB


BIG BANG
BIG BANG PLUS TINIEST FRACTION OF A SECOND (10^{-43})
INFLATION
COBE SKY MAP
BIG BANG PLUS 300,000 YEARS
LIGHT FROM FIRST GALAXIES
BIG BANG PLUS 15 BILLION YEARS

Measuring curvature of the universe with the CMB...



Structure on an angular scale of 1° (l=200) expected for a flat universe...

MAXIMA Team

Berkeley

Amedeo Balbi
Julian Borrill
Andrew Jaffe
Adrian Lee
Bahman Rabii
Paul Richards
George Smoot
Radek Stompor
Celeste Winant
Proty Wu

Minnesota

Shaul Hanany
Brad Johnson

Caltech/JPL

Jamie Bock
Viktor Hristov
Andrew Lange
Enzo Pascale

Rome

Paolo de Bernardis

Florence

Andrea Boscaleri

Toronto

Barth Netterfield

QMWC

Peter Ade

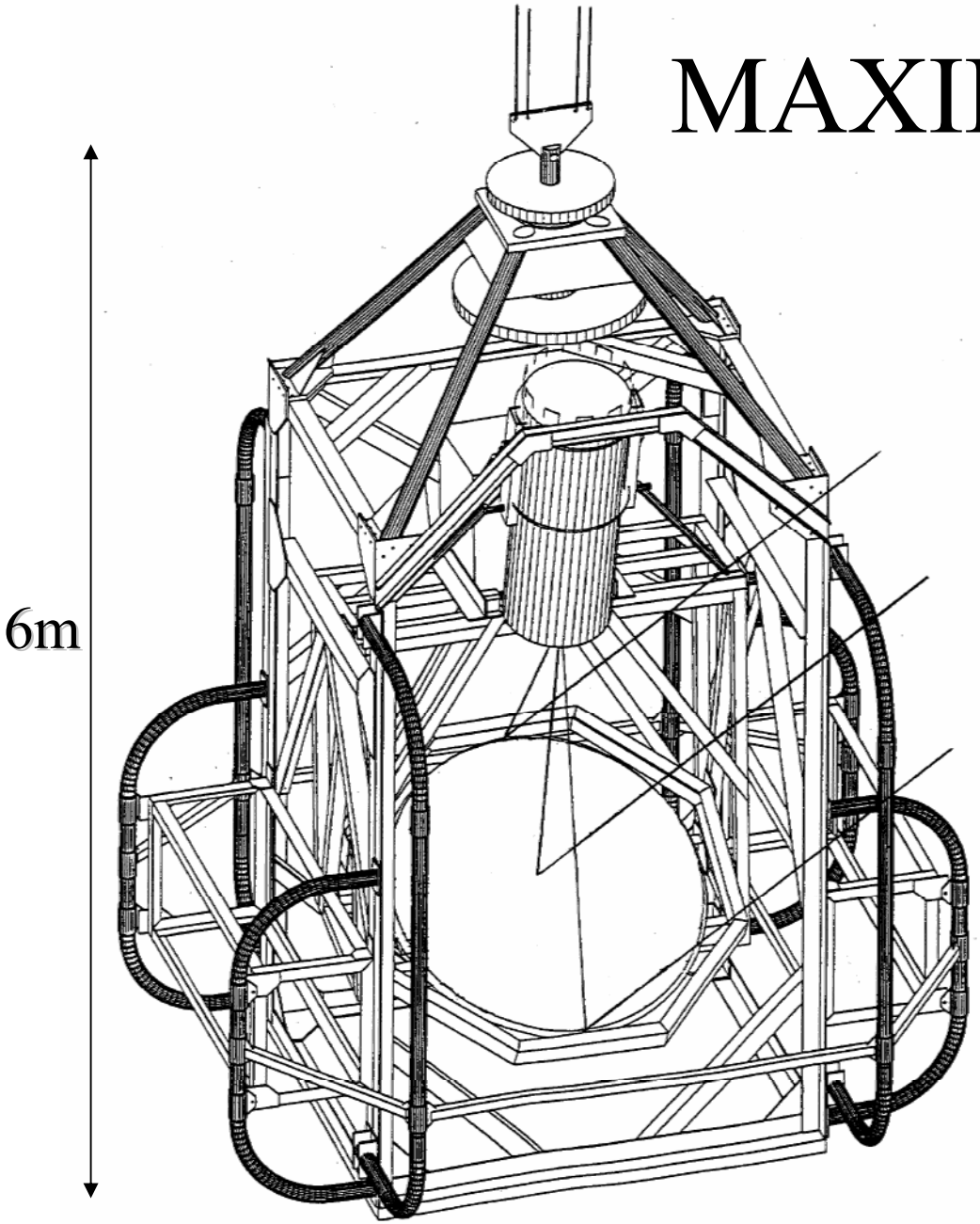
Cardiff

Phil Mauskopf

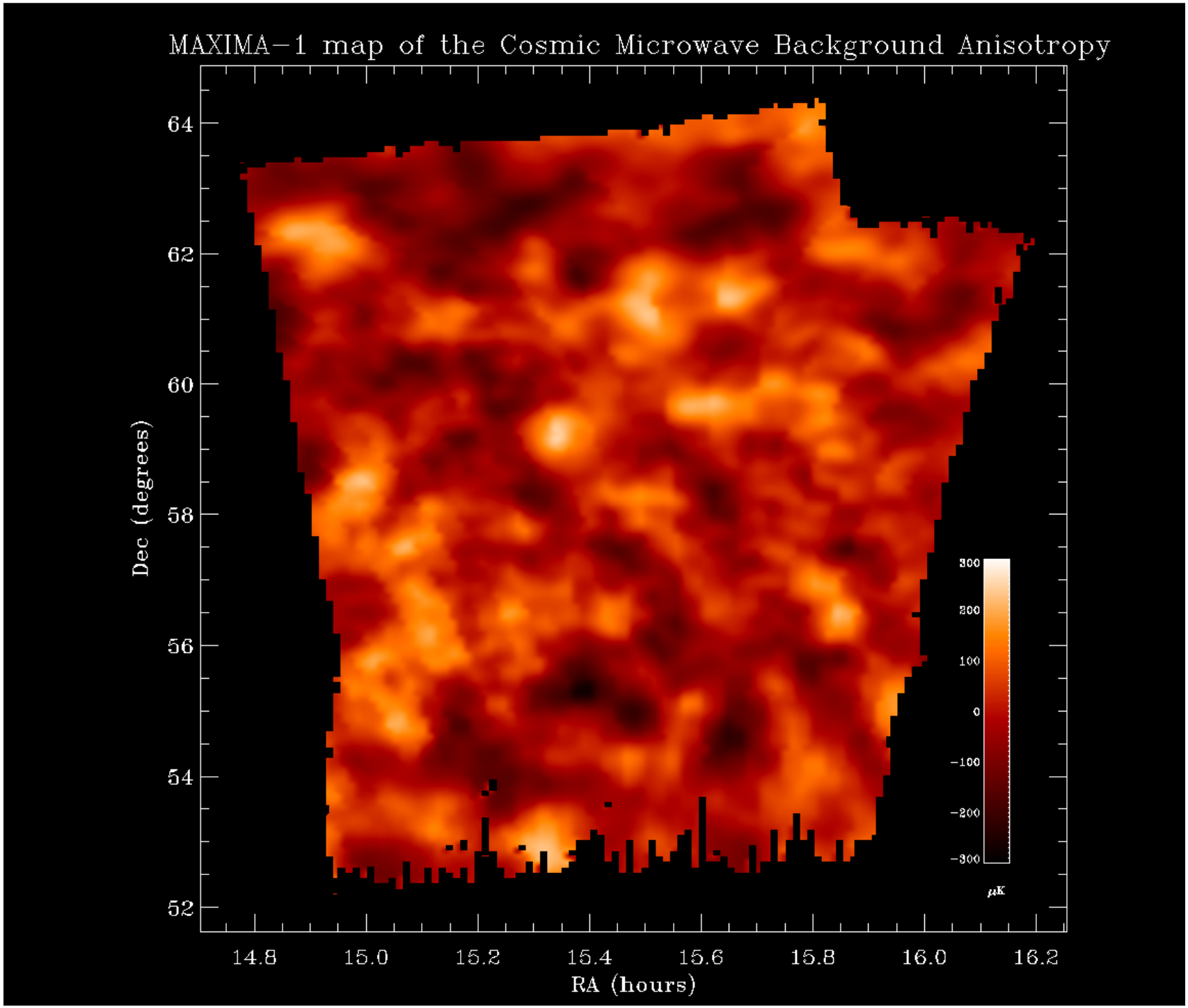
Oxford

Pedro Ferreira

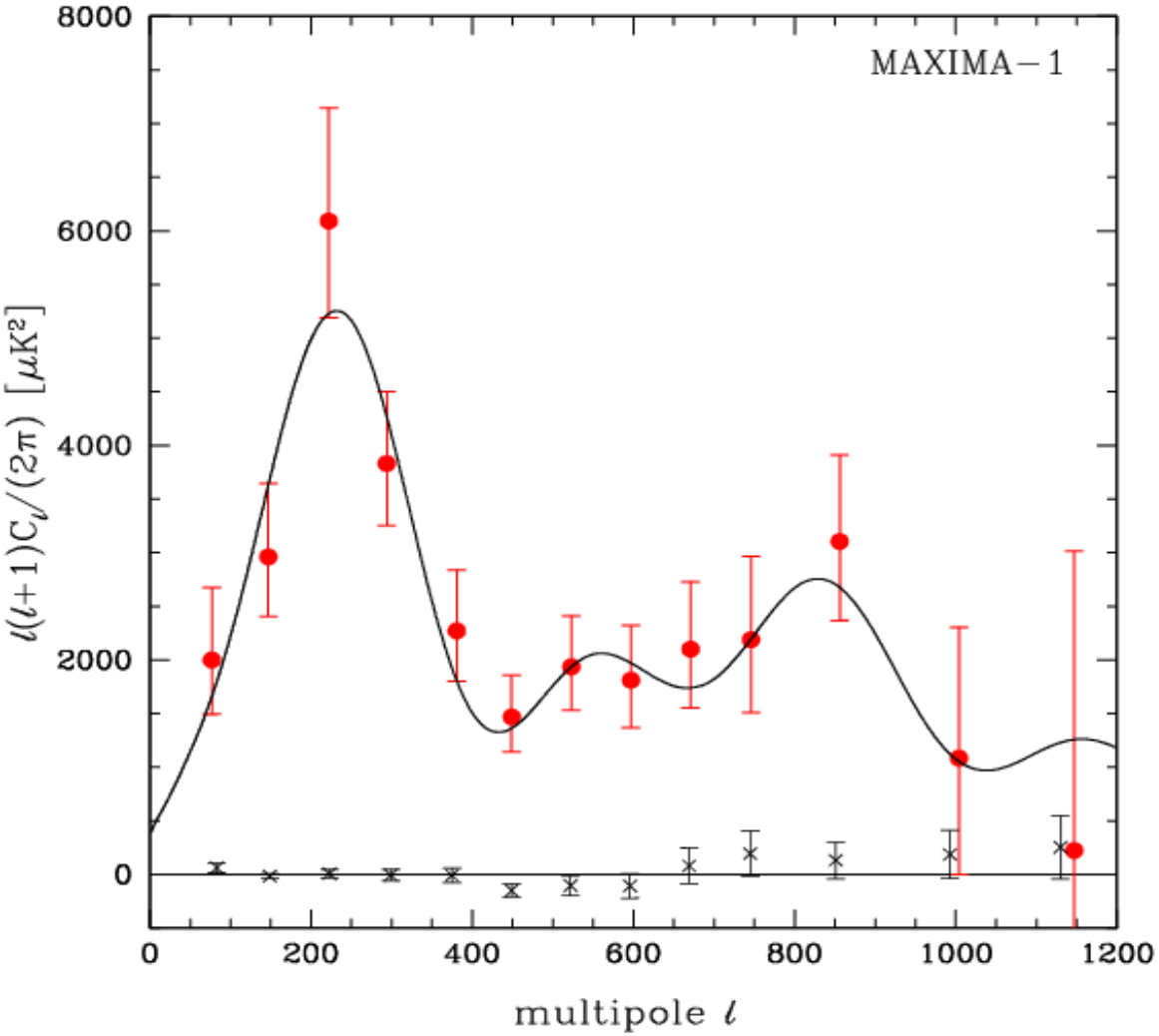
MAXIMA Balloon Gondola



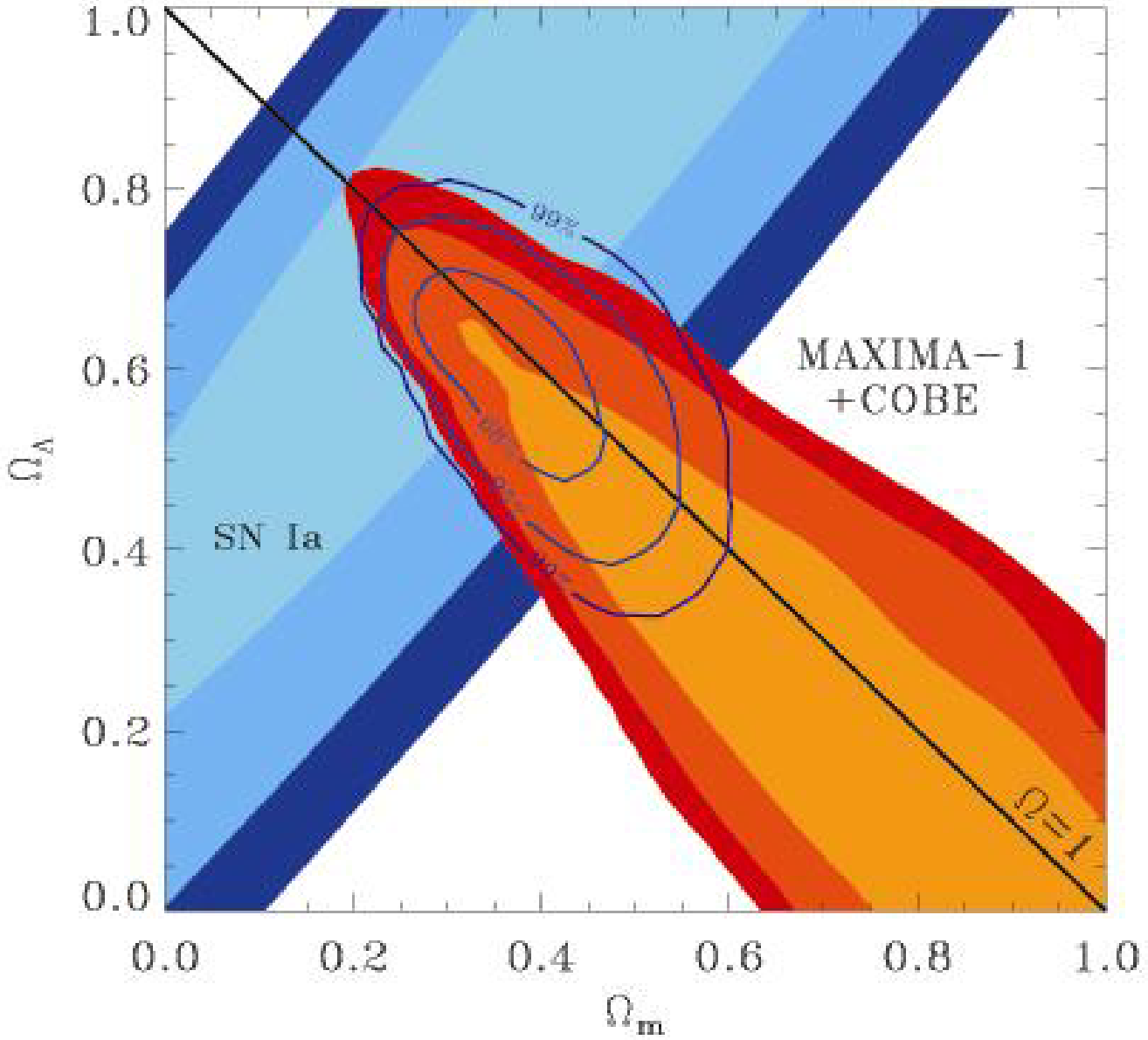



MAXIMA−1 map of the Cosmic Microwave Background Anisotropy
Dec (degrees)
64
62
60
58
56
54
52
14.8
15.0
15.2
15.4
15.6
15.8
16.0
16.2
RA (hours)
300
200
100
0
−100
−200
−300
μK

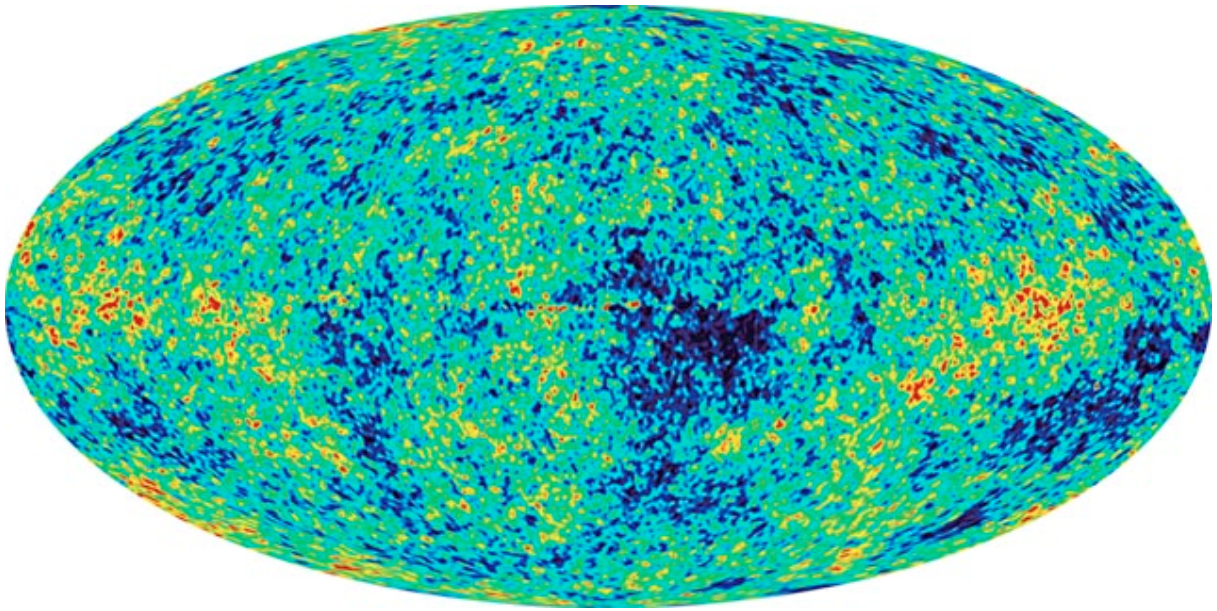
MAXIMA power spectrum

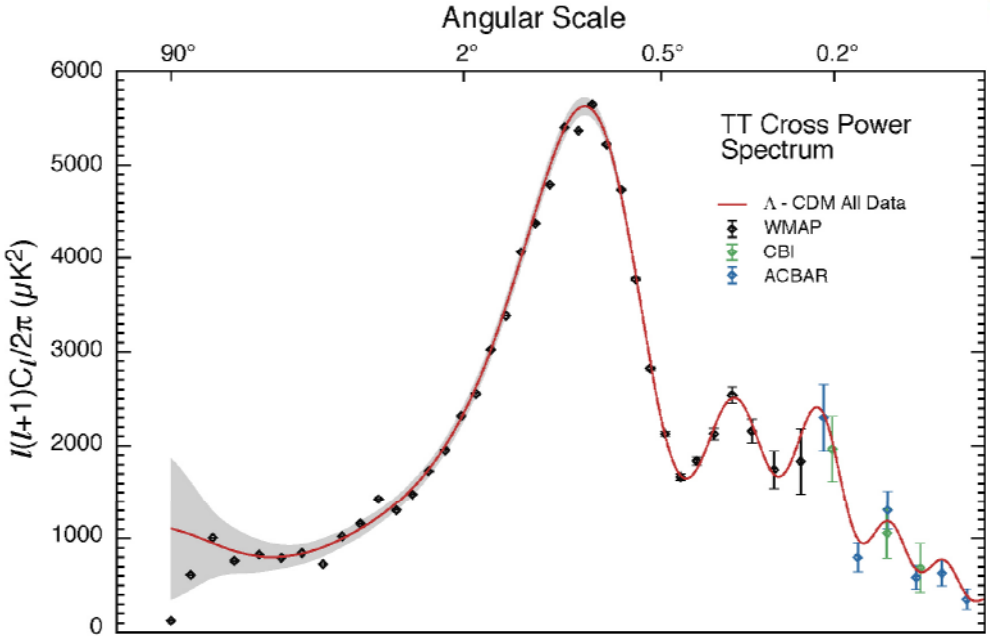


The MAXIMA Collaboration (Balbi et al. 2000)



WMAP





$$\Omega_{TOT} = 1.02 \pm 0.02$$

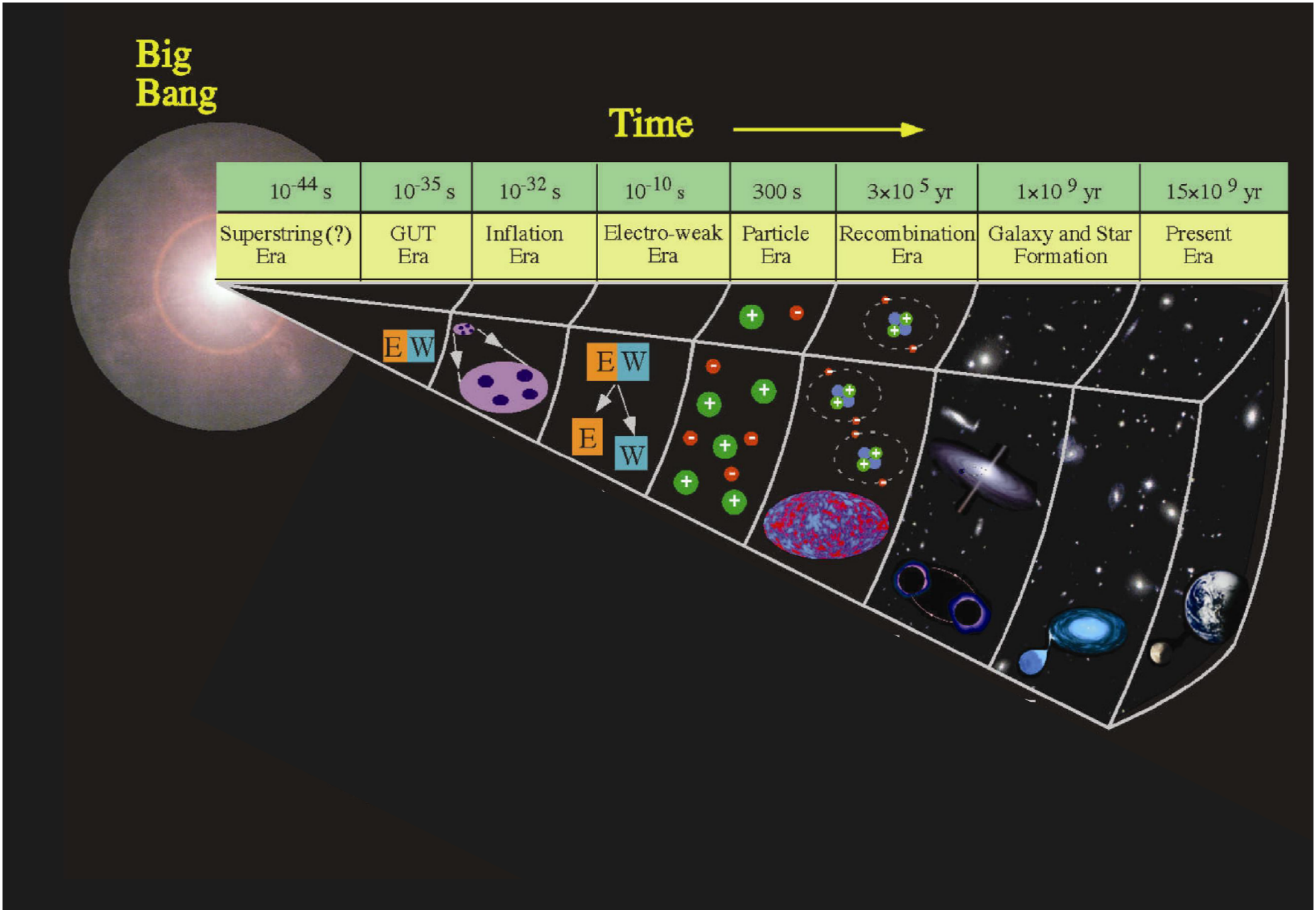
$$\Omega_M = 0.29 \pm 0.07$$

$$\Omega_B = 0.047 \pm 0.006$$

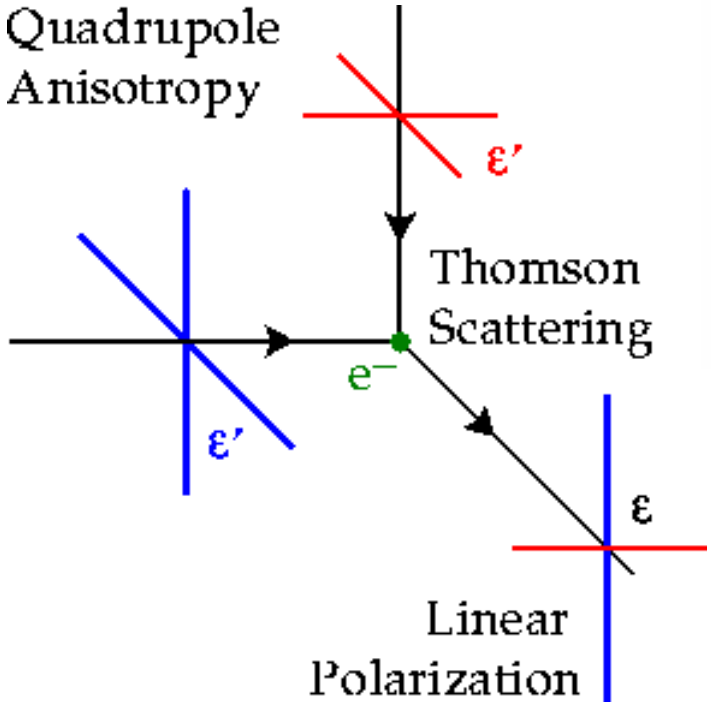
$$t_0 = 13.4 \pm 0.3\ Gyr$$

(WMAP only, Spergel et al.)

Polarization


Big Bang
Time
10-44 s
10-35 s
10-32 s
10-10 s
300 s
3×10 5 yr
1×10 9 yr
15×10 9 yr
Superstring (?) Era
GUT Era
Inflation Era
Electro-weak Era
Particle Era
Recombination Era
Galaxy and Star Formation
Present Era
E
W
E
W
E
W

Polarization Generation

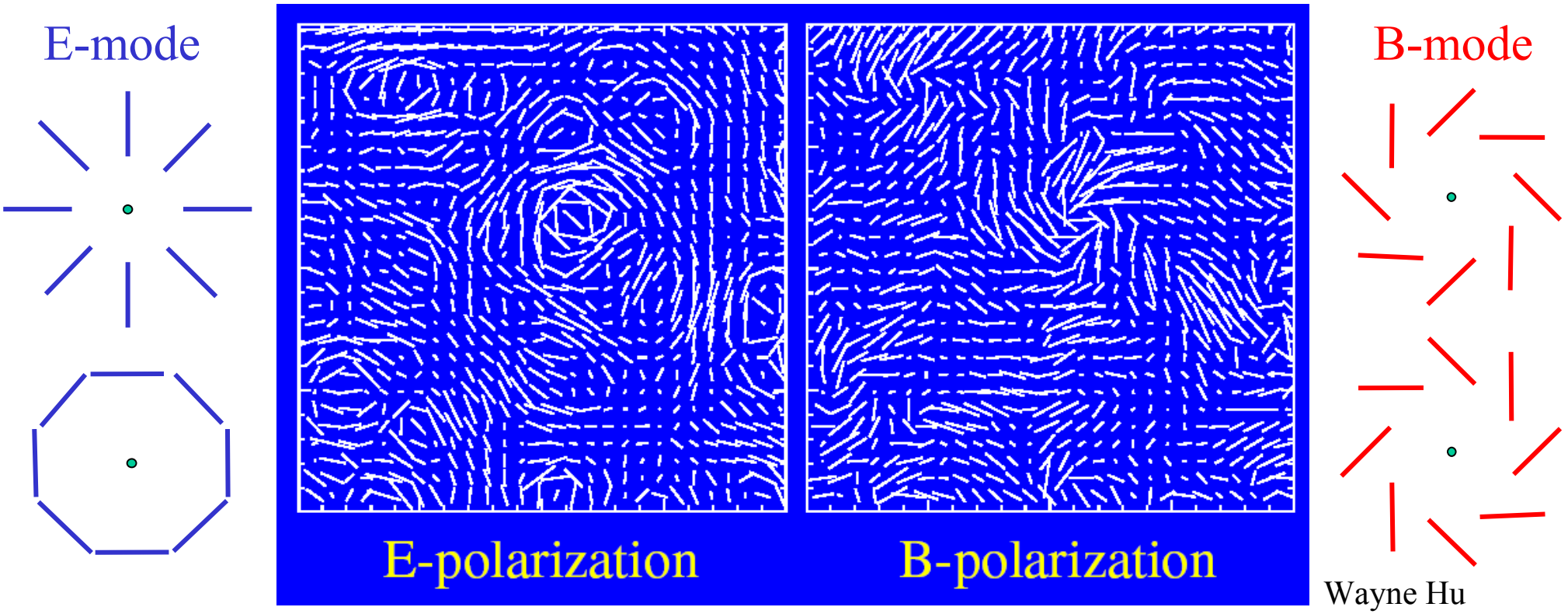



H.Edens

- Quadrupole intensity => linear polarization

Polarization Patterns

- Polarization Generation by Thompson Scattering

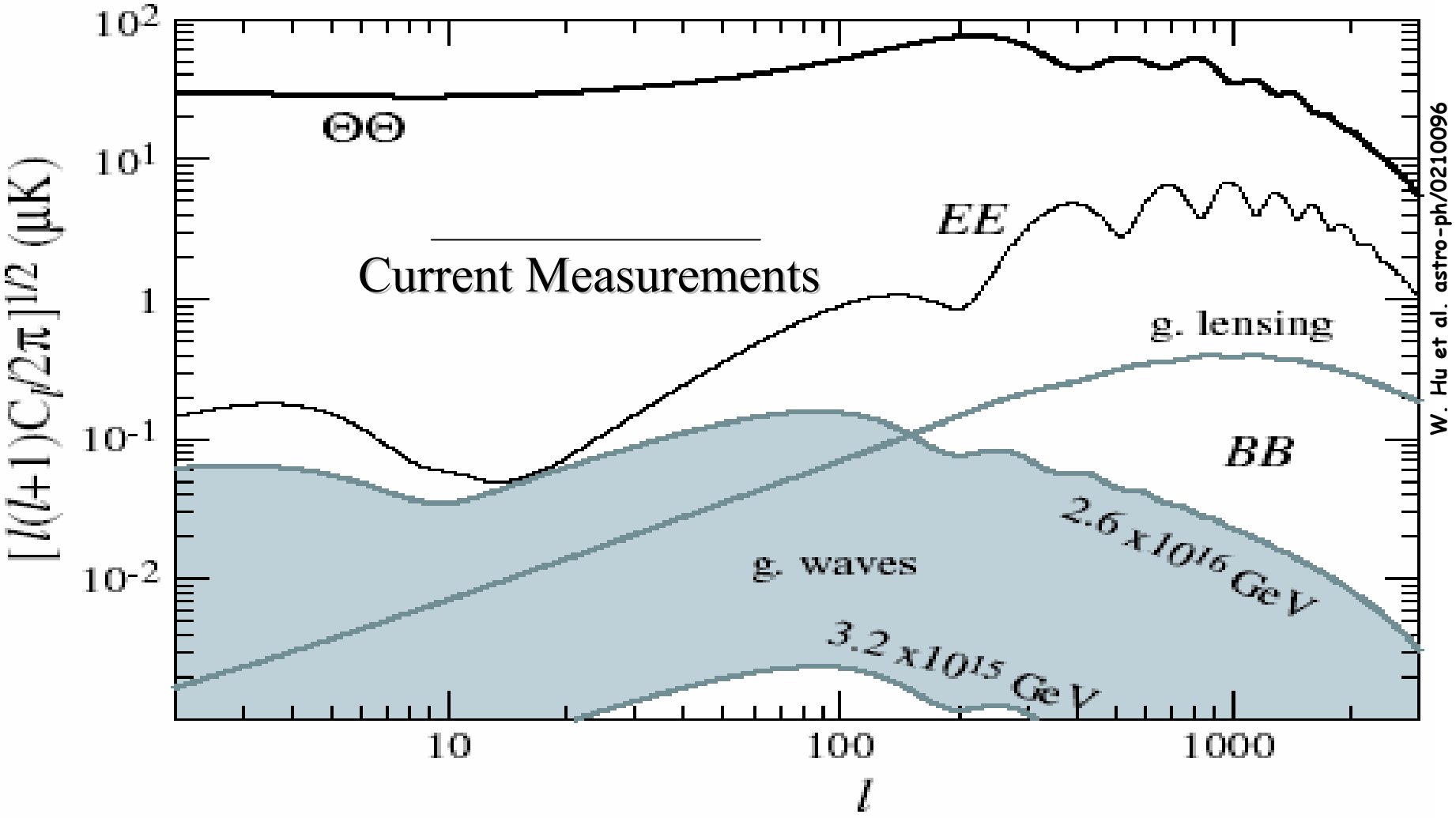


- Density fluctuations give scalar perturbations => E-mode
- Gravity waves give tensor perturbations => B, E modes

Gravity Waves from Inflation

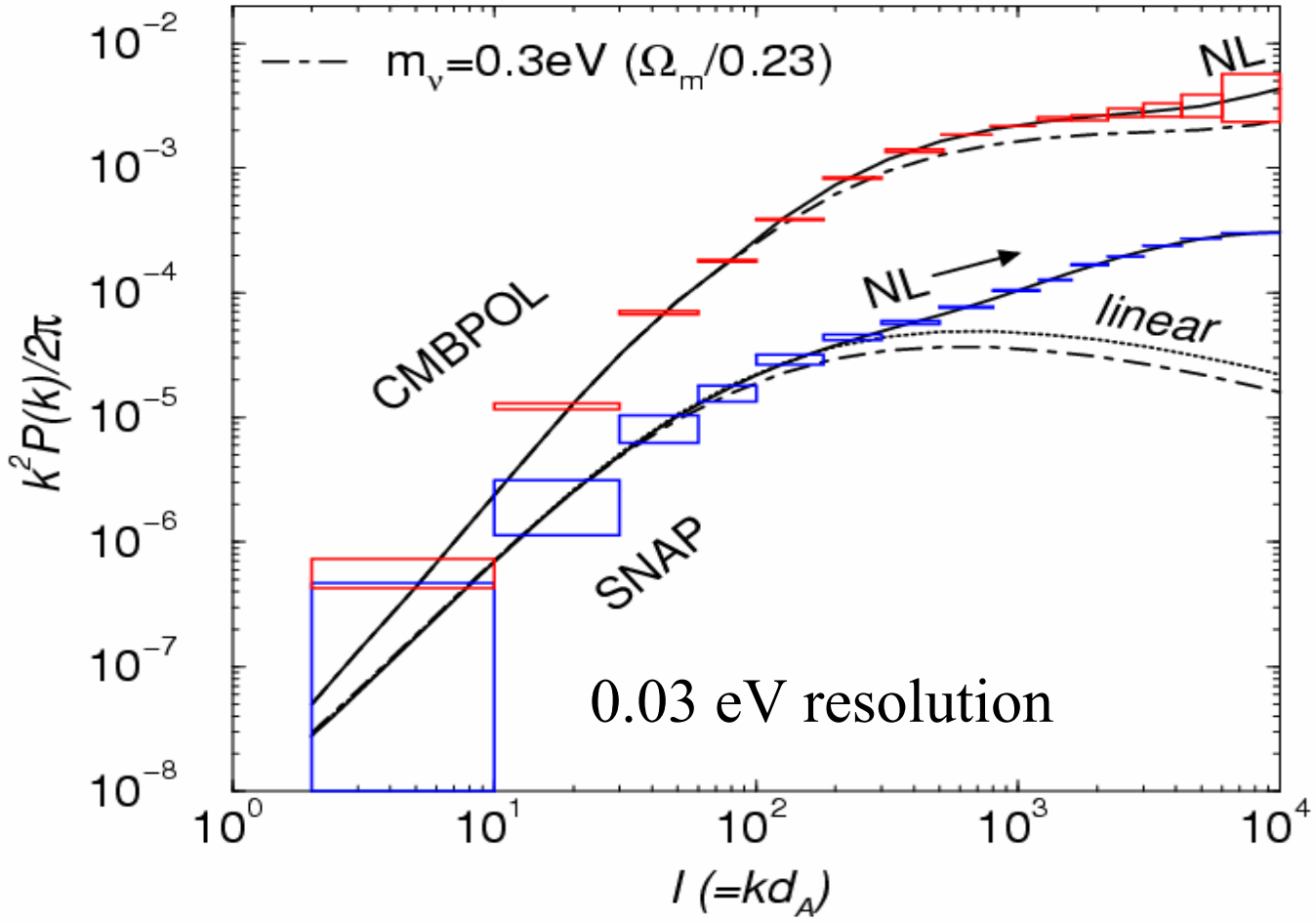
- **Gravity waves put stress on photon-baryon fluid**
  - Generation of B-mode polarization
- **Detection => "smoking gun" of inflation**
- **Amplitude of B-mode gives Energy Scale**
  - One possibility: GUT level 10^{16} GeV
  - 12 orders of magnitude higher energy than accelerators!
- **Quantum Gravity Regime**

CMB Polarization Spectra



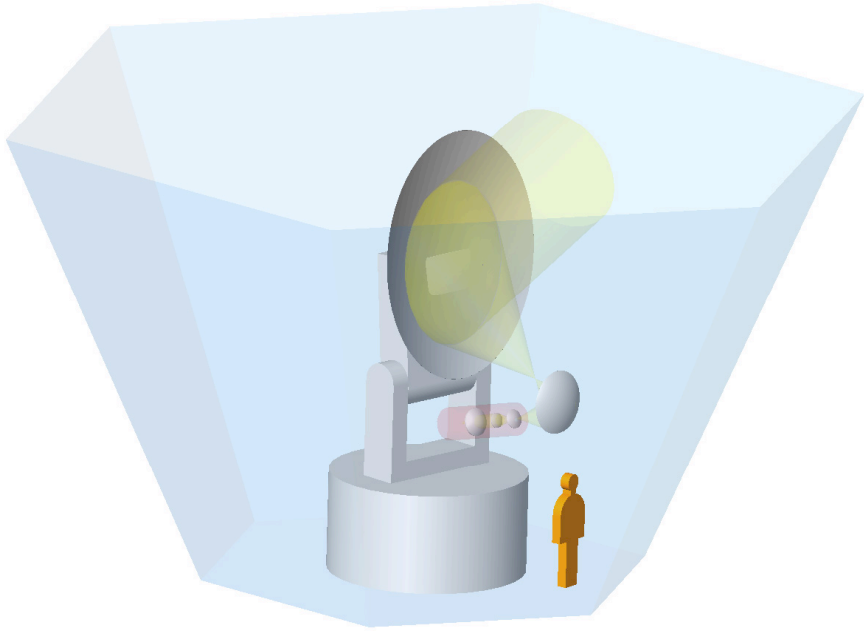
We need a large increase in sensitivity!

Sum of Neutrino Masses from Lensing

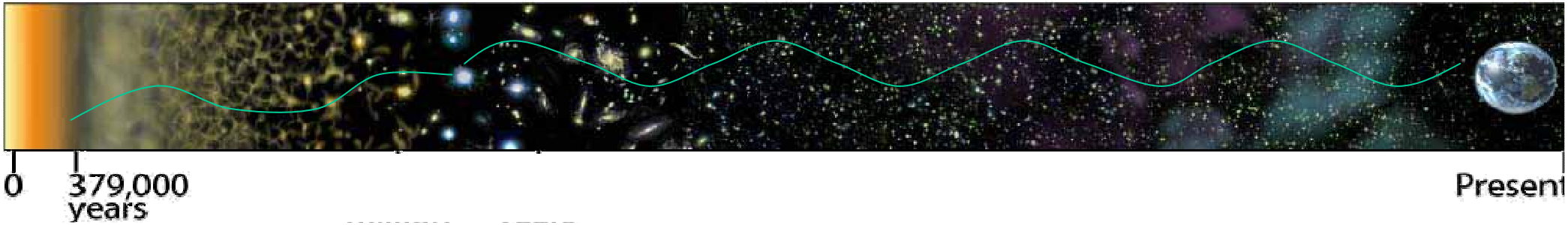


POLARBEAR

- Experiment using 3 meter Telescope at White Mountain CA
  - Characterize E-modes, B-mode Lensing
  - Search for Inflationary B-modes
- First Light mid 2006
  - LDRD seed funding (2001-2003)
- 90, 150, 220 GHz
- 4’ beam @ 150 GHz

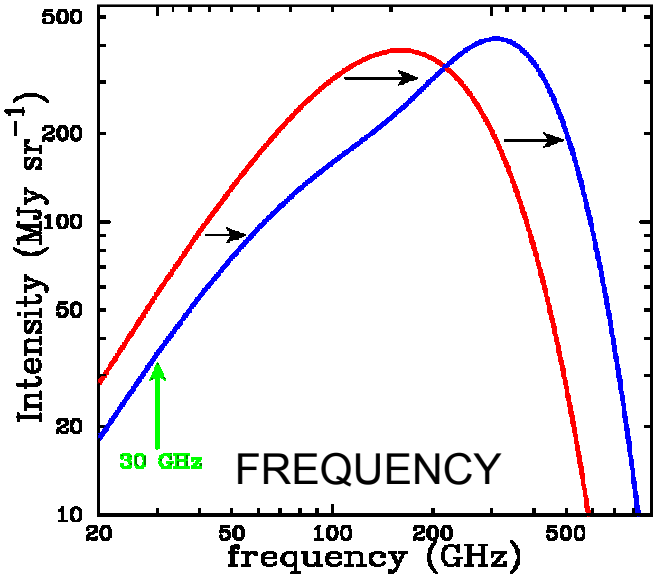


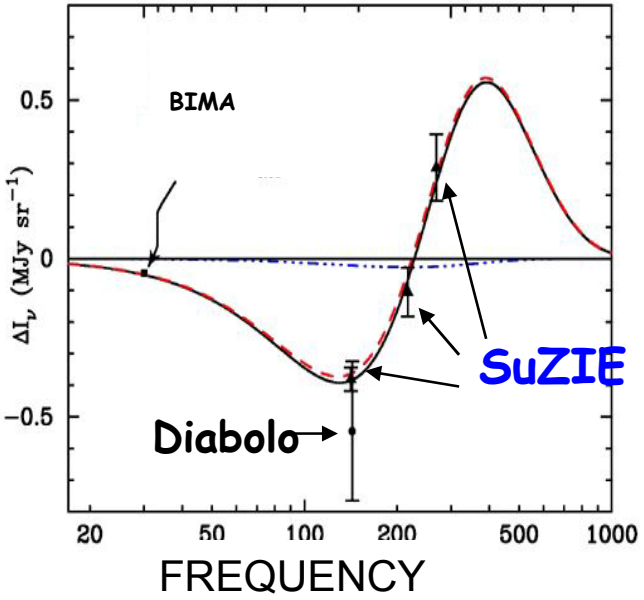
Galaxy Clusters



CMB photons are used to backlight structure in the universe.

- **1-2% of CMB photons traversing galaxy clusters are inverse Compton scattered to higher energy– the *Sunyaev Zeldovich Effect*.**





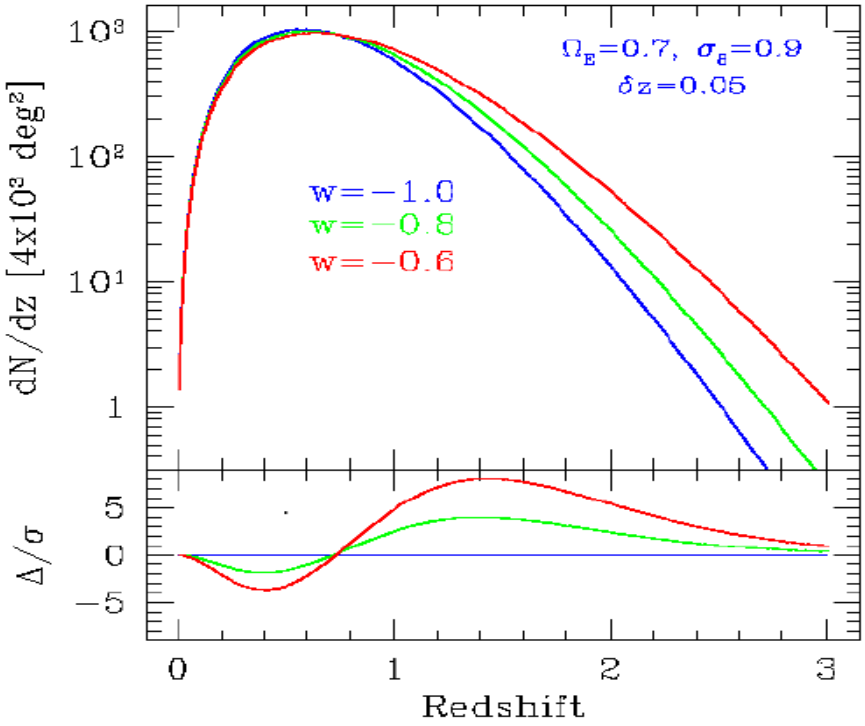
- **Tool for mapping expansion history**

Galaxy Cluster Surveys Probe Dark Energy

Cluster surveys probe
(1) **volume-redshift relation**,
(2) **abundance evolution**,
(3) **structural evolution**

need sensitivity at redshifts > 1

==> **SZ Effect**
signal independent of
redshift in relevant range



Atacama Pathfinder Expt (APEX-SZ)



- 16,500 feet in Chilean Andes.
- 12m on-axis ALMA prototype

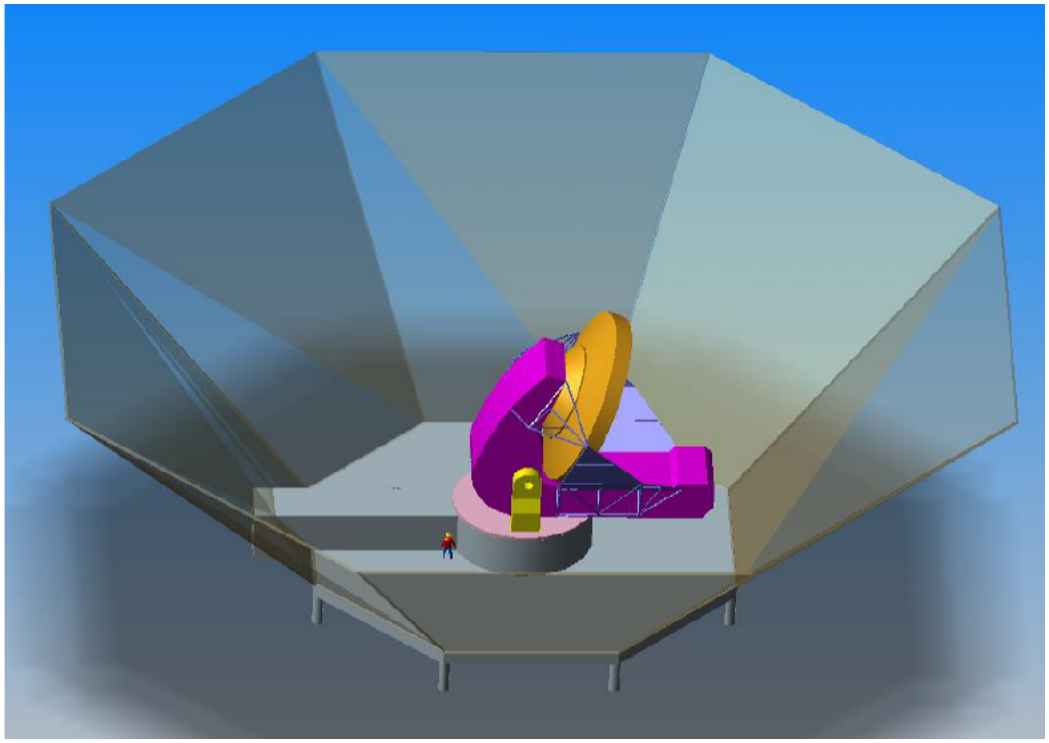
Berkeley SZ Receiver:

- 330 Bolometer array
- 25% telescope time
- **Discover 2000 Clusters/2yrs**
  - Mass limit > 4×10^{14} M_0
- **First Light *2005*.**



UC Berkeley/LBNL,
MPI-Bonn/Munich,
Cardiff

South Pole Telescope



Chicago/CWRU/
SAO/UC Berkeley/LBNL

- 10m off axis telescope
- Dedicated to CMB observations
- 10x faster mapping than APEX
- deploy January 2007

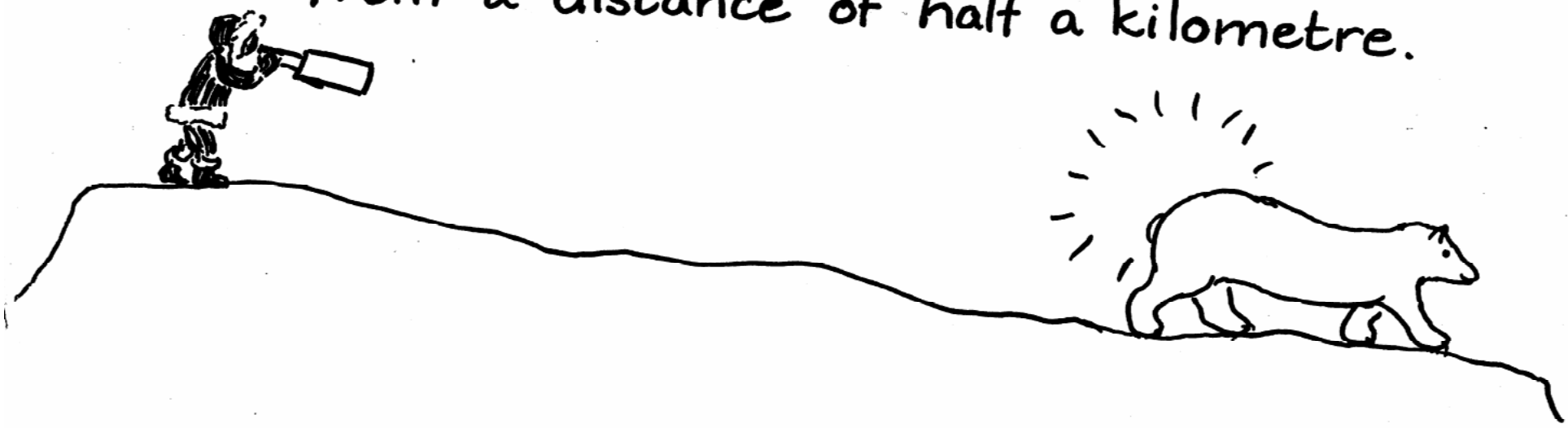
Berkeley:

- 1000 Bolometer array
- cryogenics
- **LBNL responsible for readout**

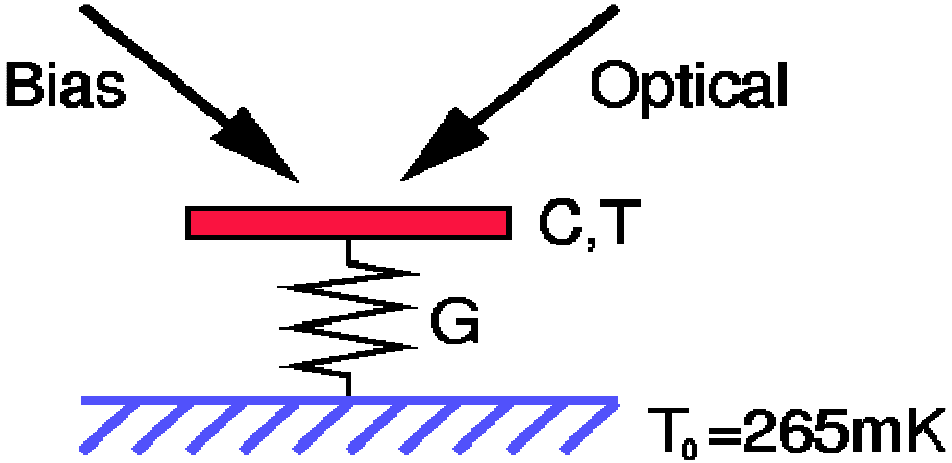
Technology: Superconducting Bolometers

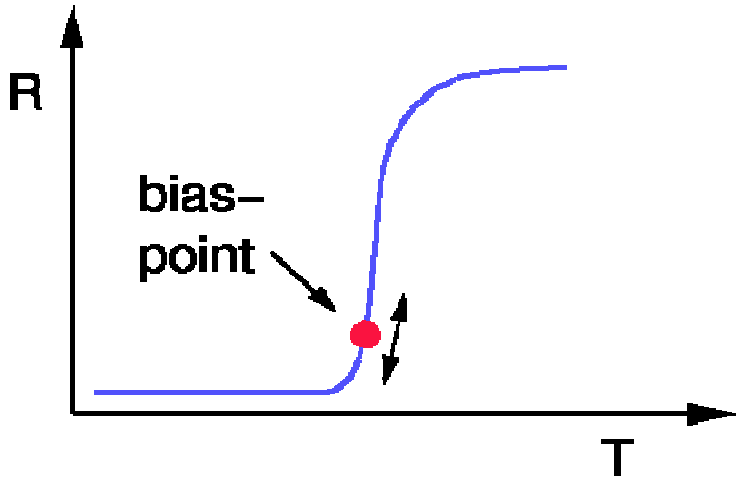
The Bolometer.

S.P. Langley invented the Bolometer,
Which is really a sort of thermometer.
It can measure the heat
Of a polar-bear's seat,
From a distance of half a kilometre.



Transition-Edge Sensor (TES)
Superconducting Bolometer

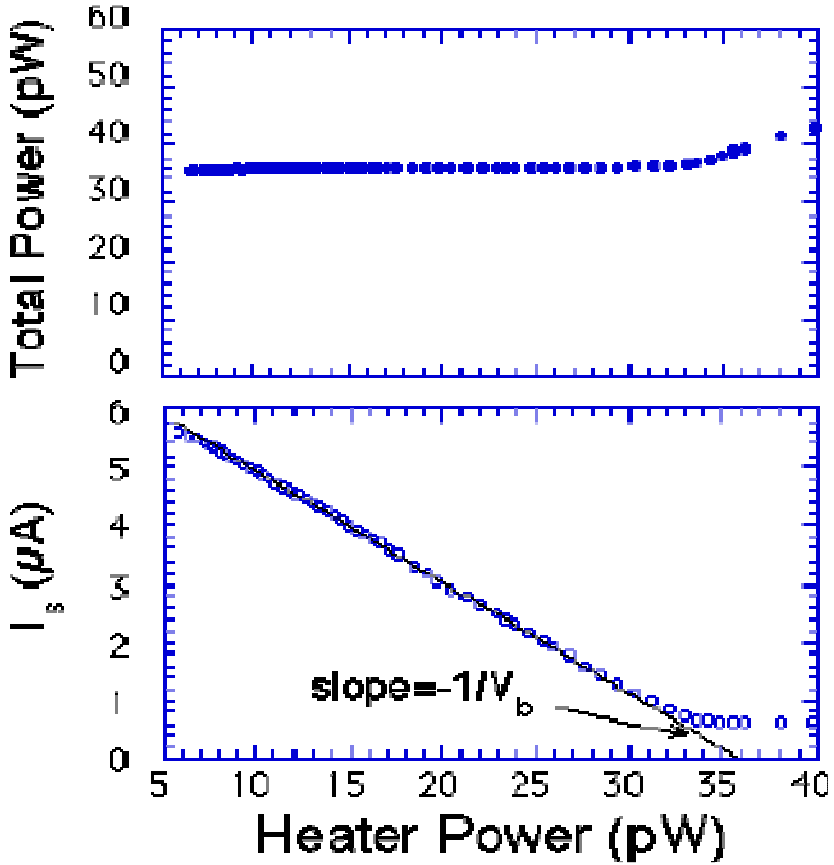




$$P_{total} = P_{opt} + P_{bias}$$

$$P_{bias} = V_{bias}^2/R$$

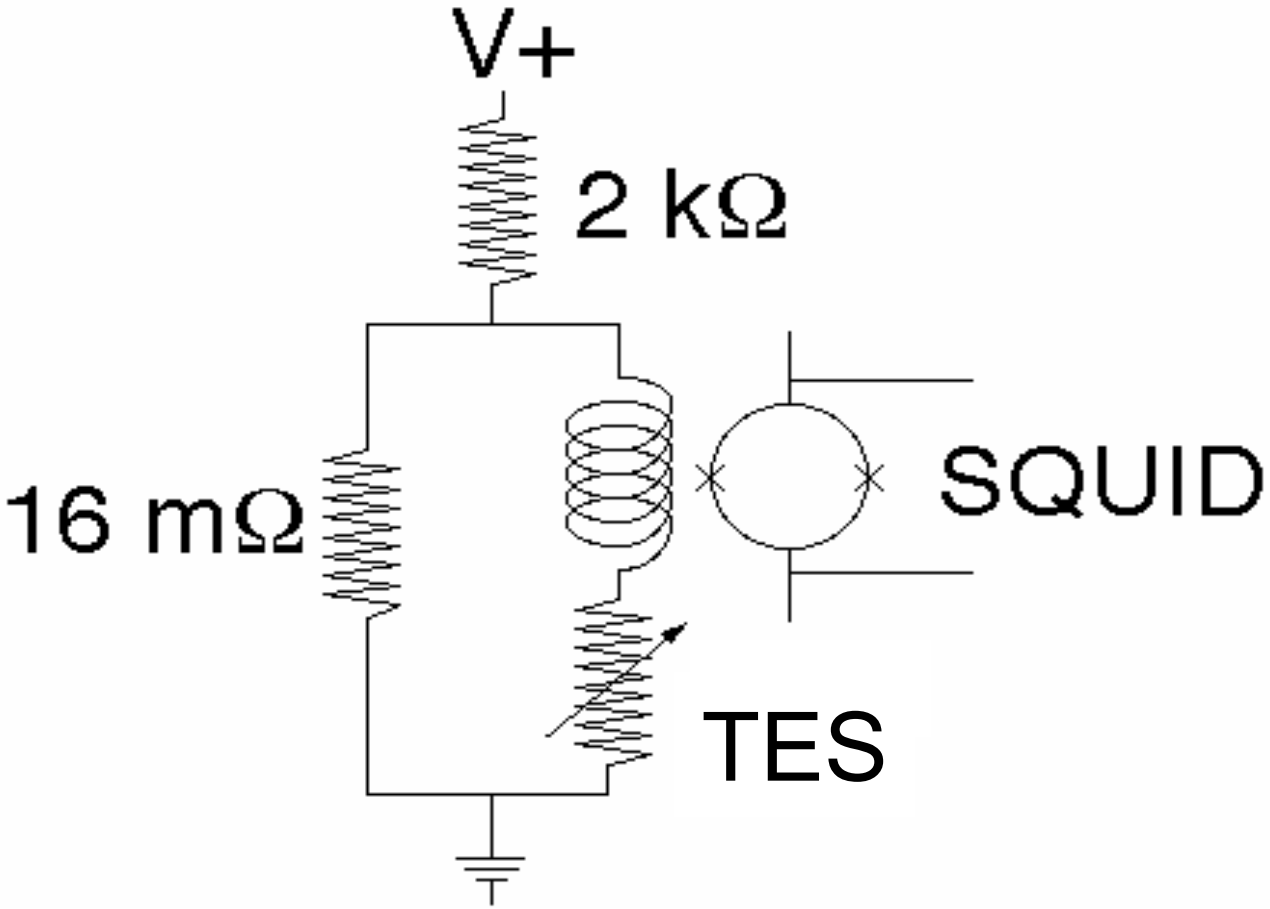
Electrothermal Feedback



Feedback holds Power Constant

$$S_I \equiv \frac{dI}{dP_{Bias}} = \frac{1}{V_B}$$

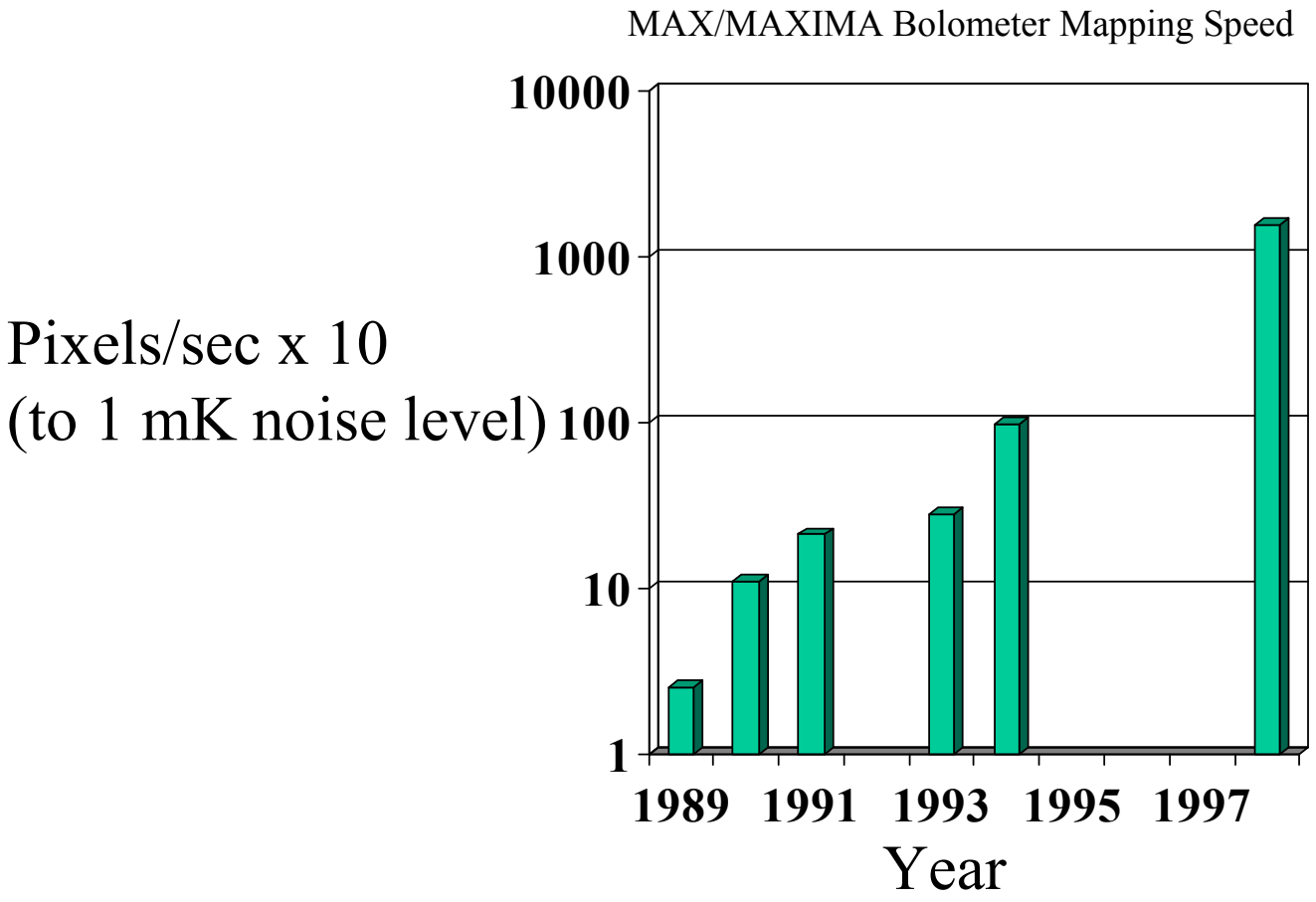
TES Bias and Readout



- SQUIDs: low noise and low power dissipation

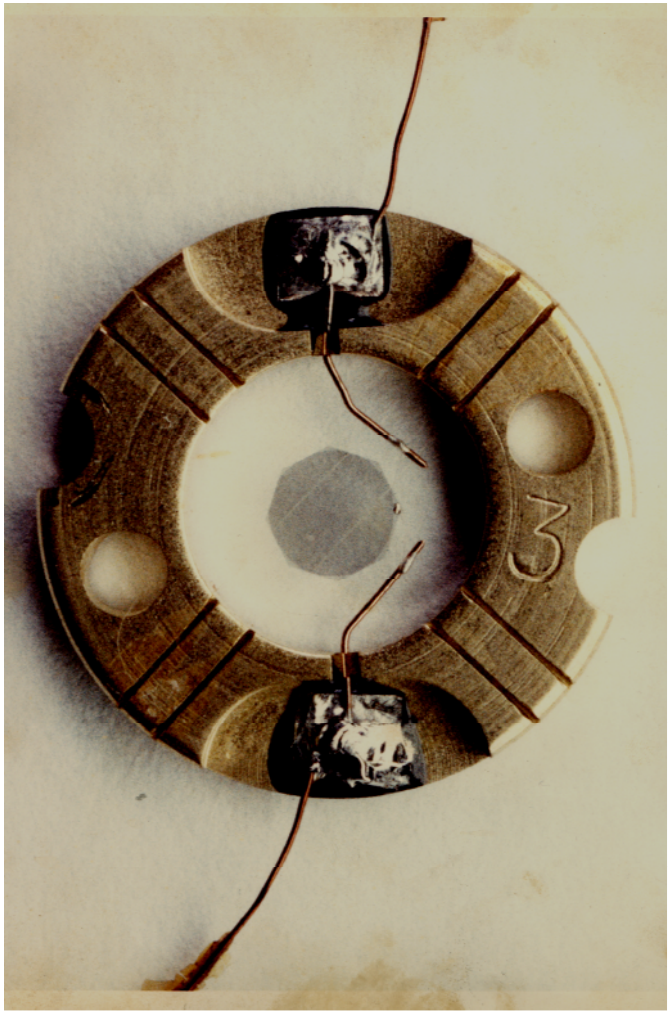
Bolometer Mapping Speed

- 30 years: 8 order increase in mapping speed ($1/NET^2$)
  - doubling time is one year!



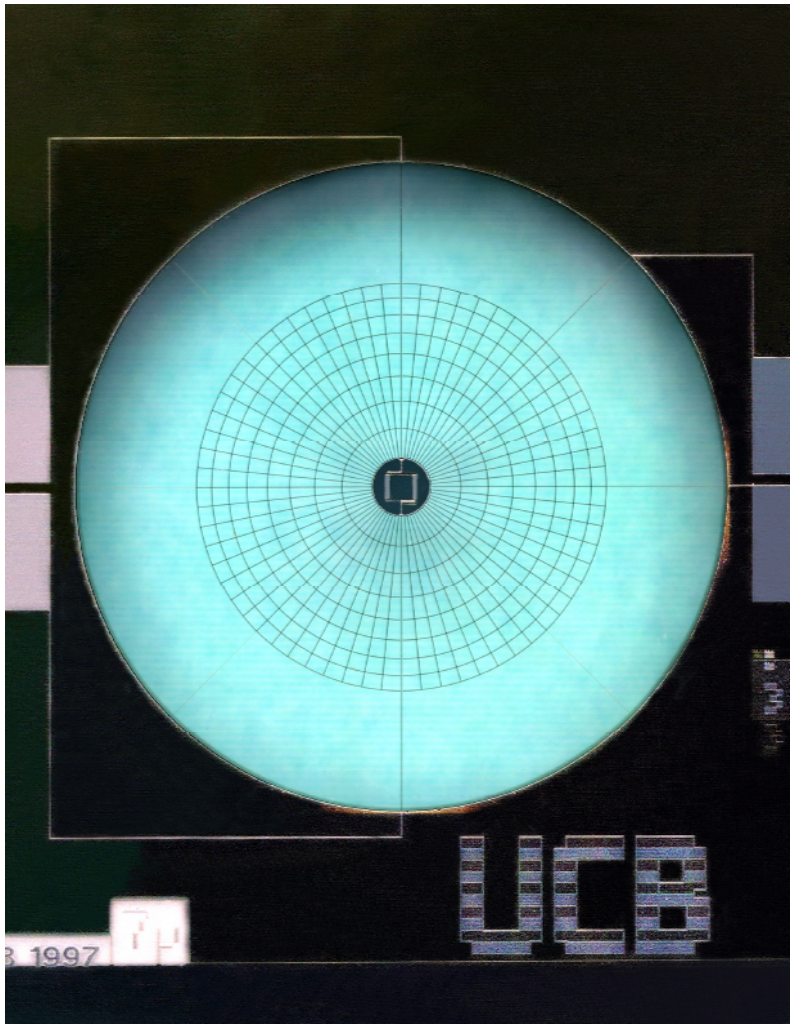
Monolithic Bolometers

5 mm



1990

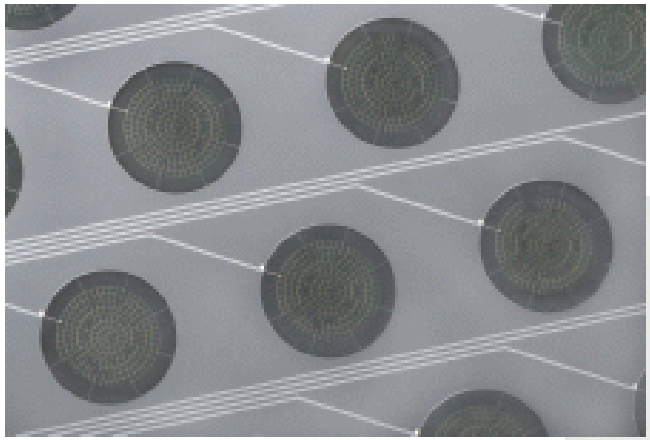
5 mm

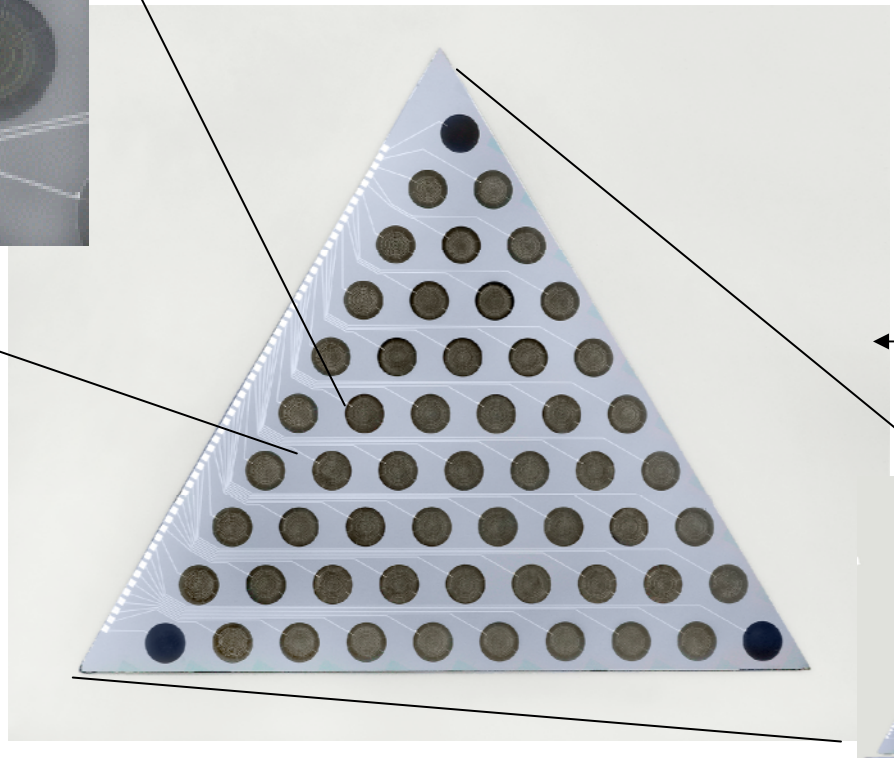


1997

Berkeley TES Spiderweb Arrays

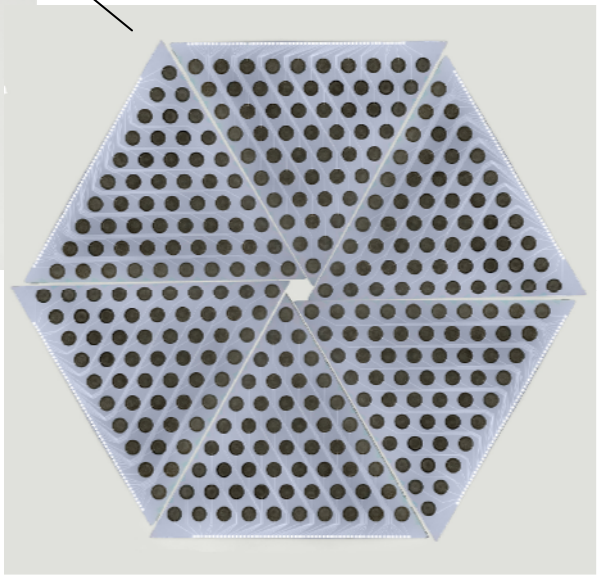
APEX-SZ, SPT, EBEX





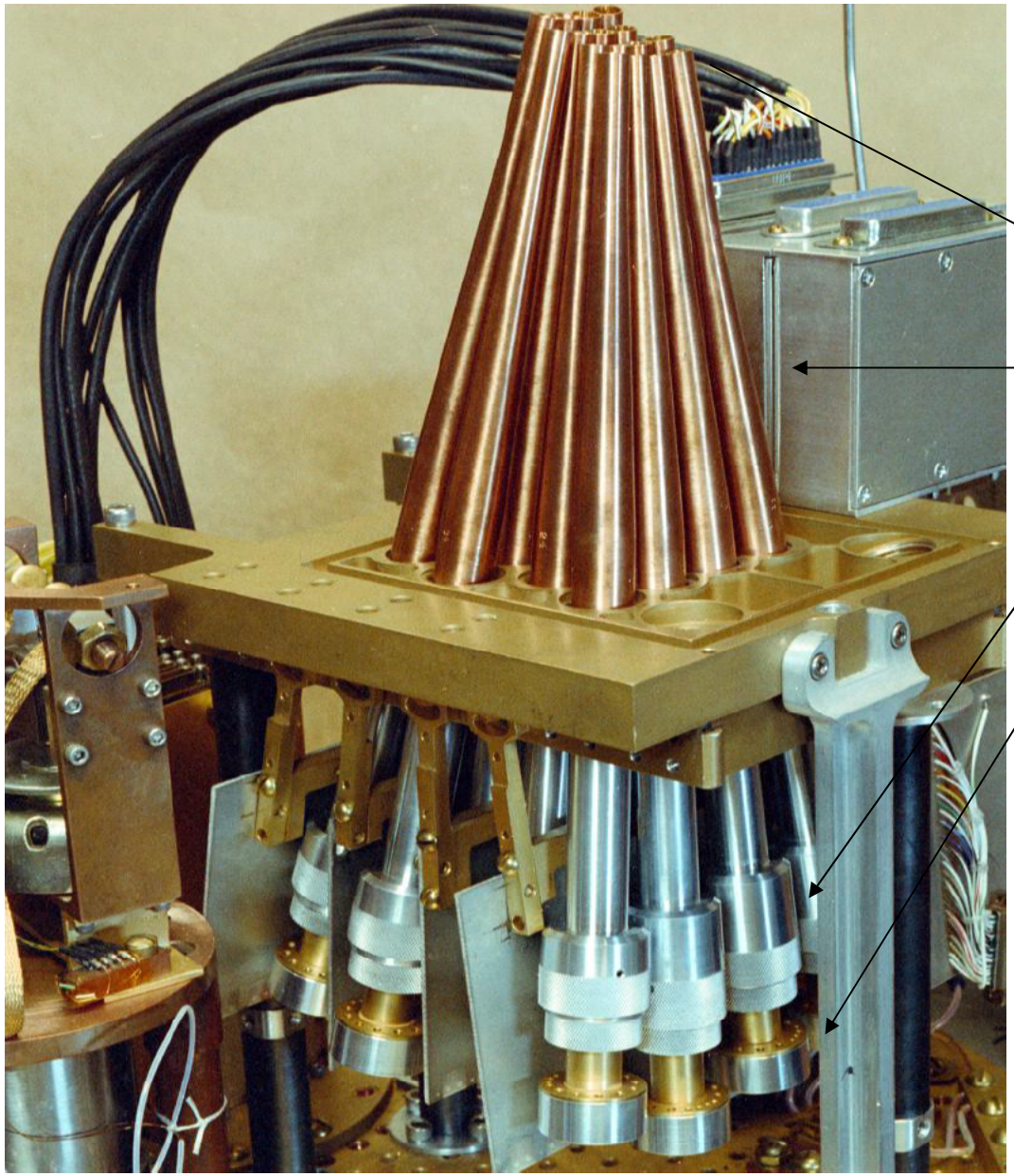
5”

*Artist’s concept

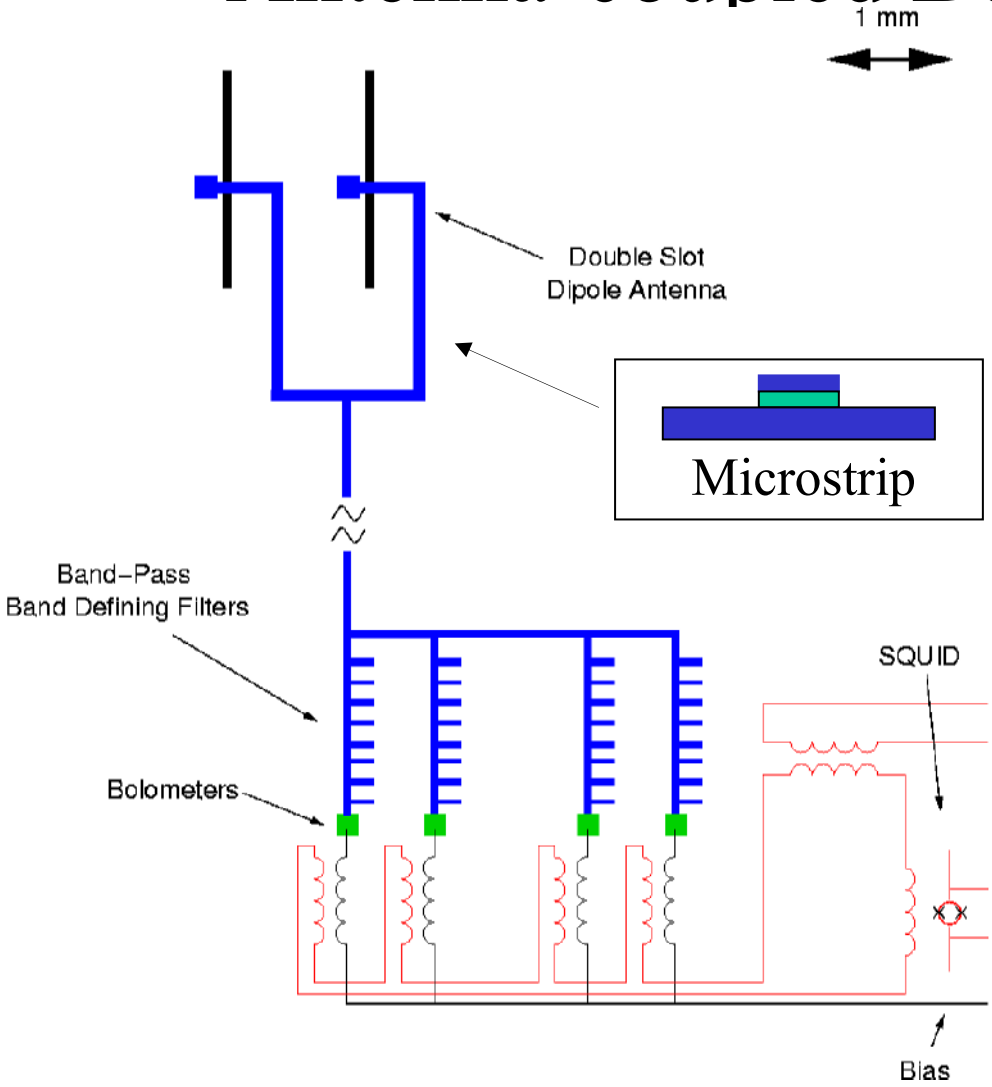


Monolithic Millimeter-Wave Circuits

MAXIMA Array

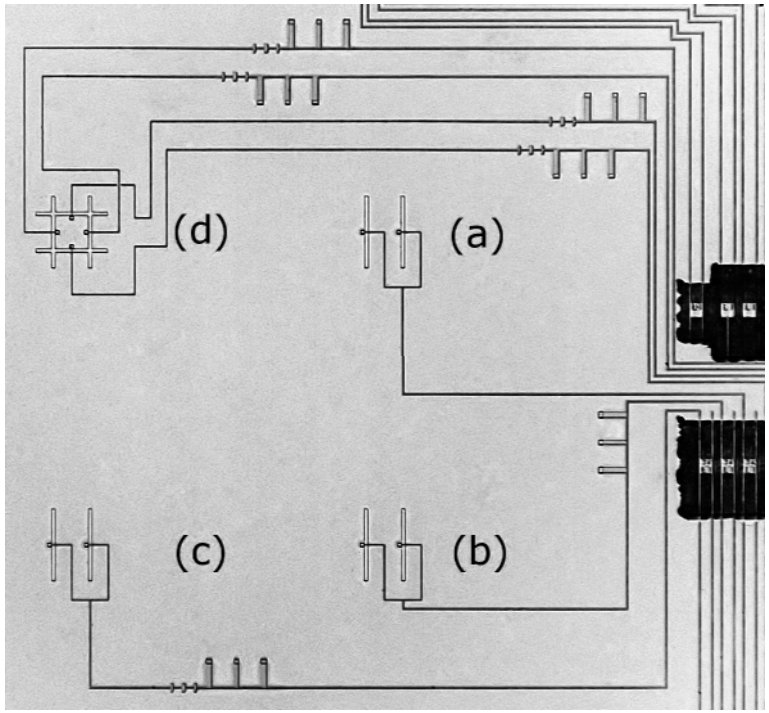


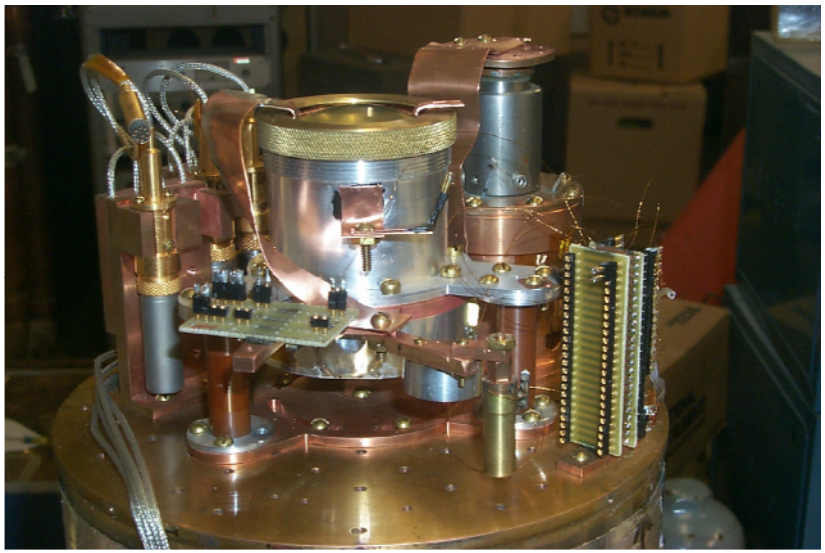
Antenna-coupled Bolometer Diagram

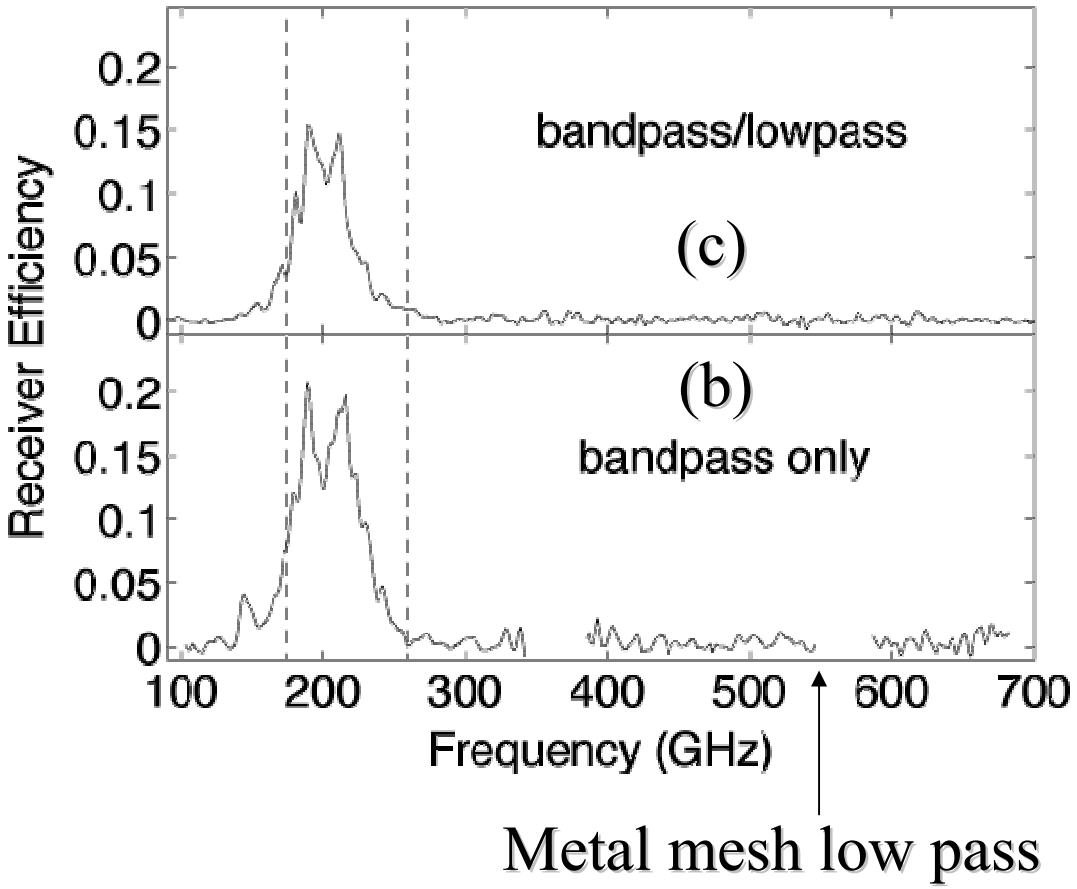


- Antenna provides directivity
- On-chip filters
- Multicolor pixels
- Polarization sensitive

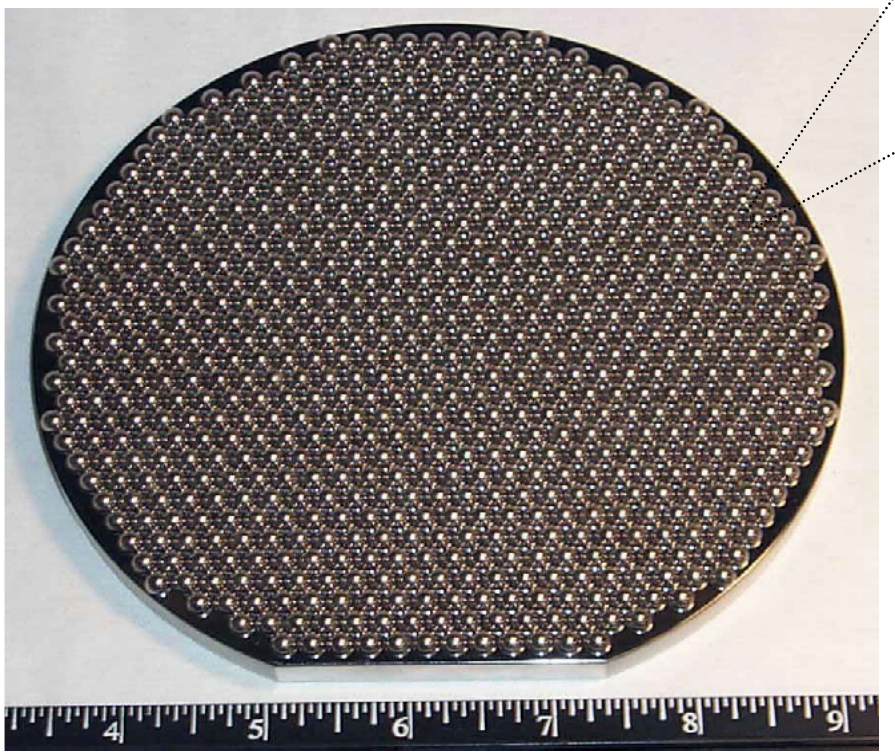
New Technology: Radiometer on Chip

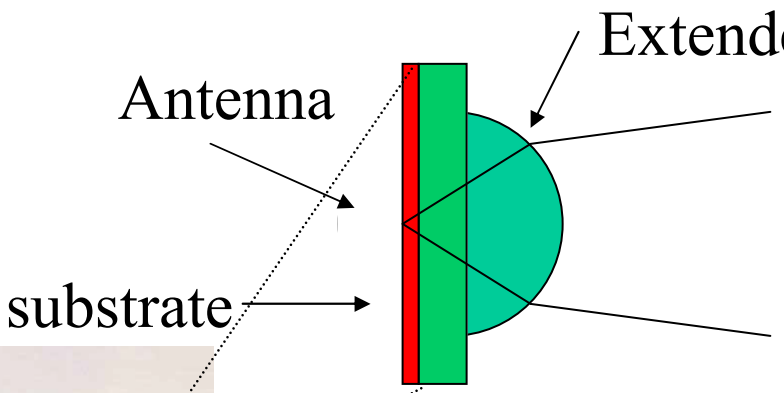




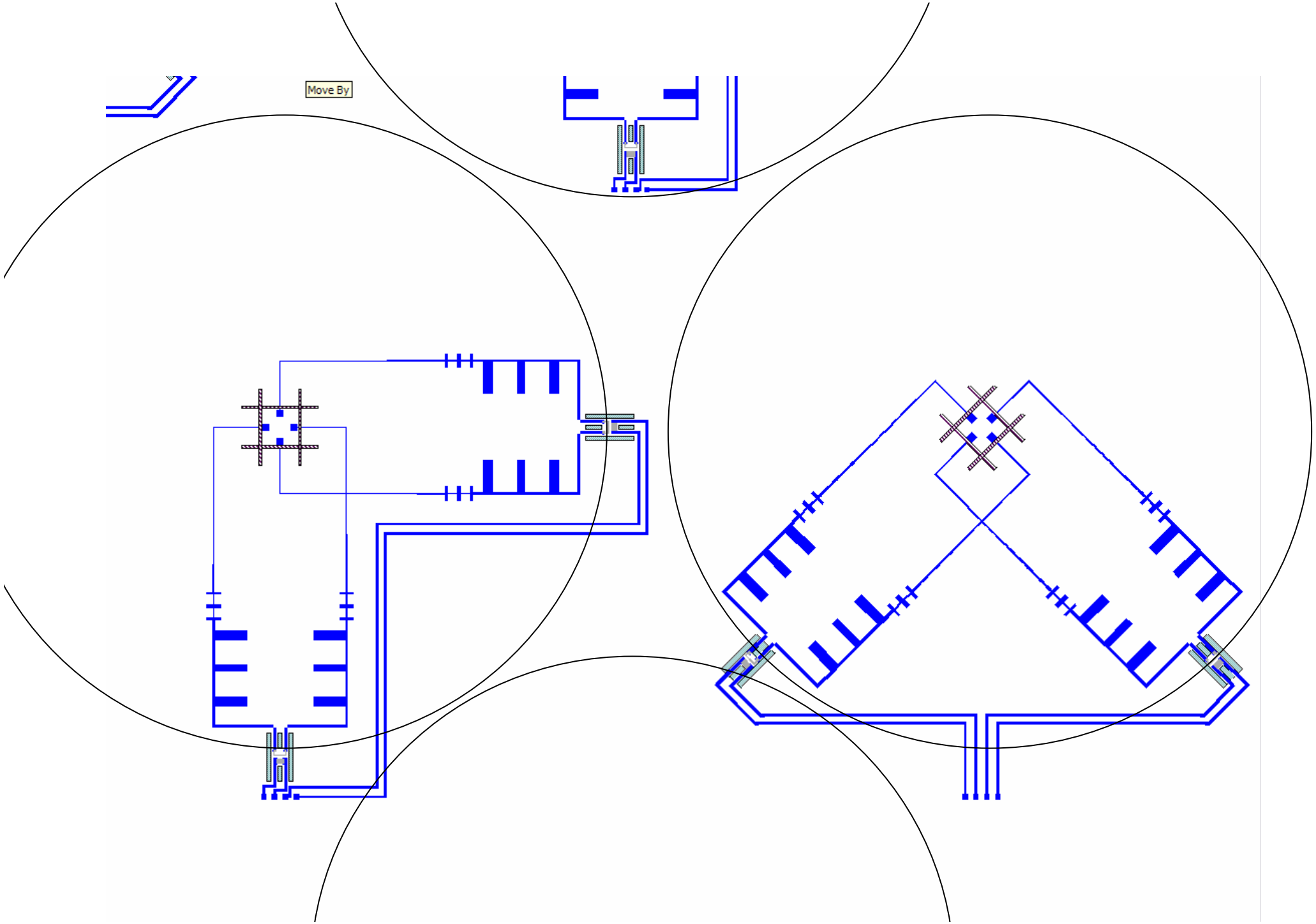


Monolithic Array with Lenslets



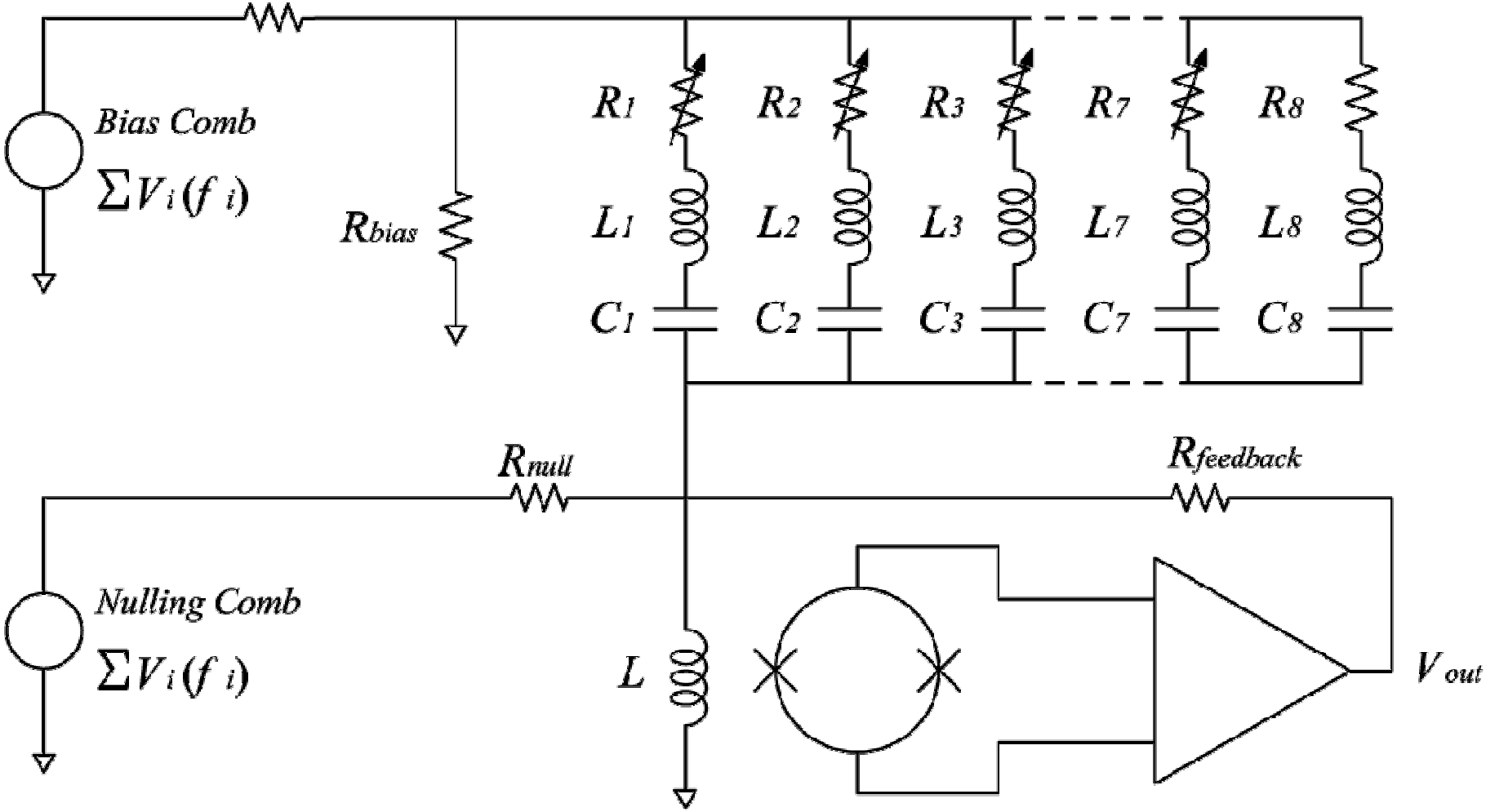


- Well developed for e.g. SIS mixer work
  - High antenna gain
  - Forward radiation pattern
- Efficient coupling to telescope
  - 80-90% achieved: Similar to scalar horn


Move By

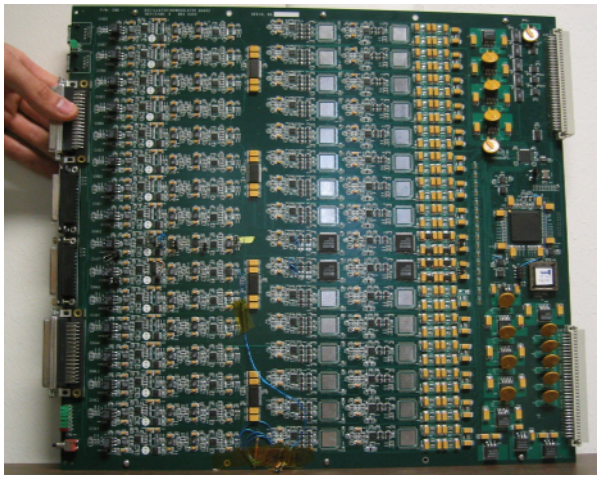
Frequency Multiplexed SQUID Readout

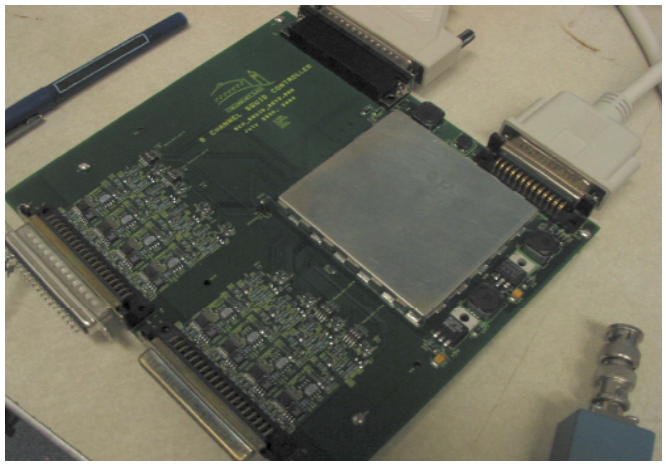
Frequency-Domain MUX

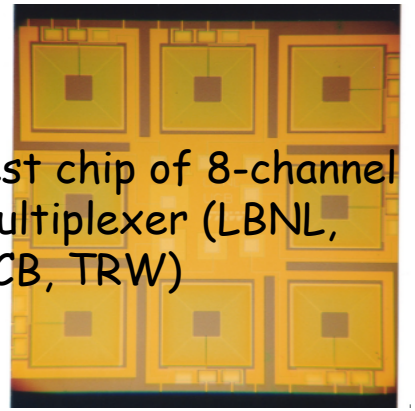


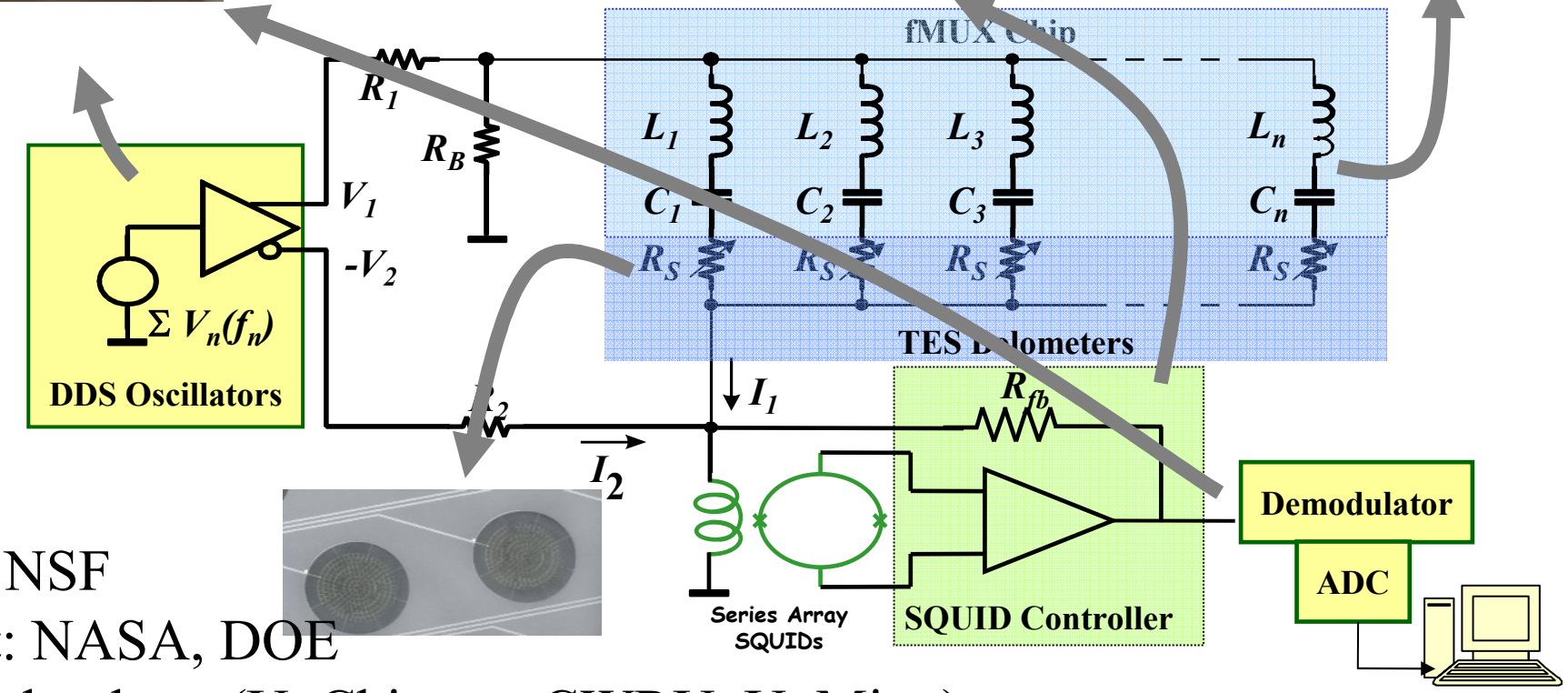
- Zero Power Dissipation at Base Temp
- Simple: One SQUID array per row
- Robust to vibration

Berkeley Freq-Domain Multiplexer



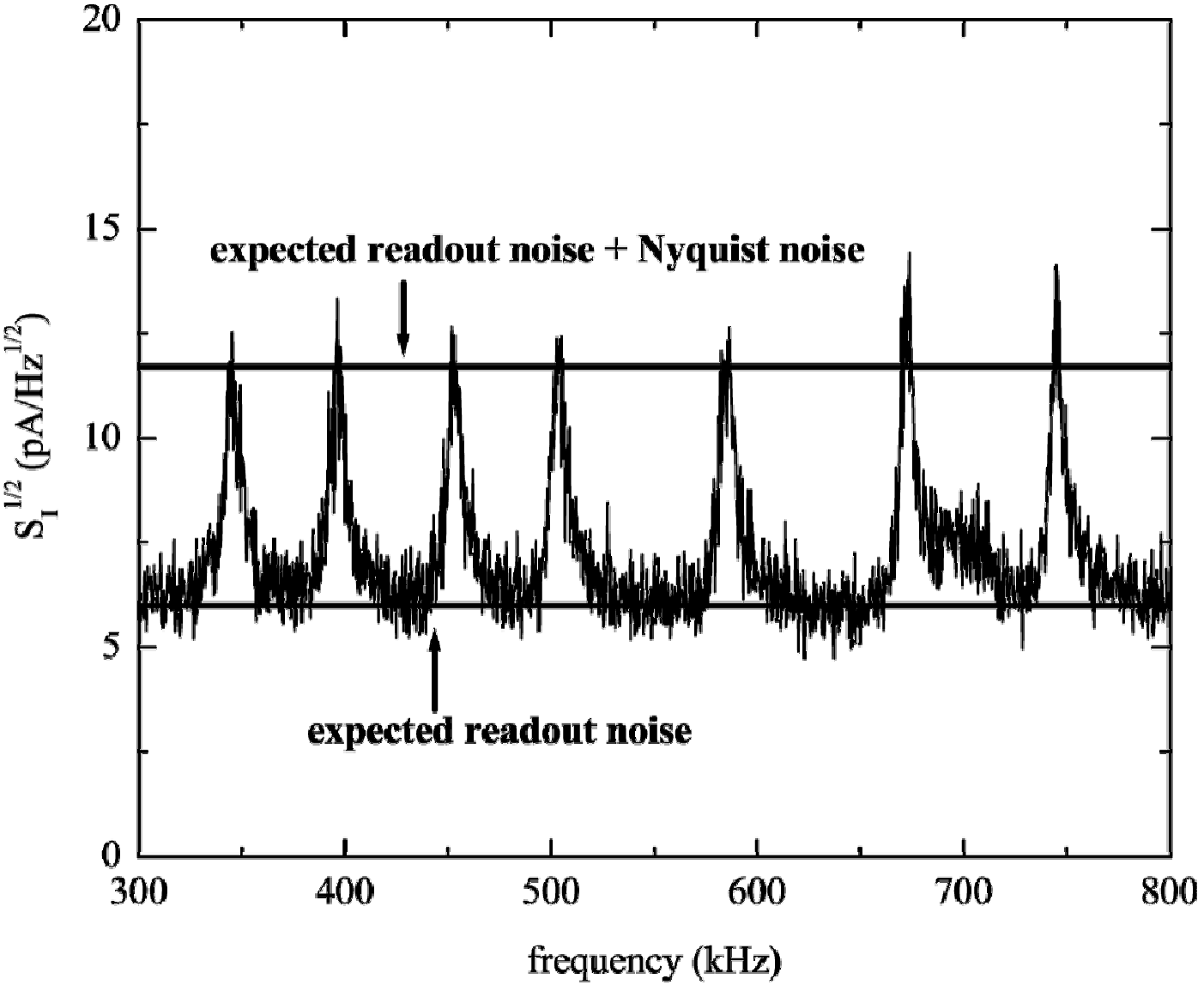




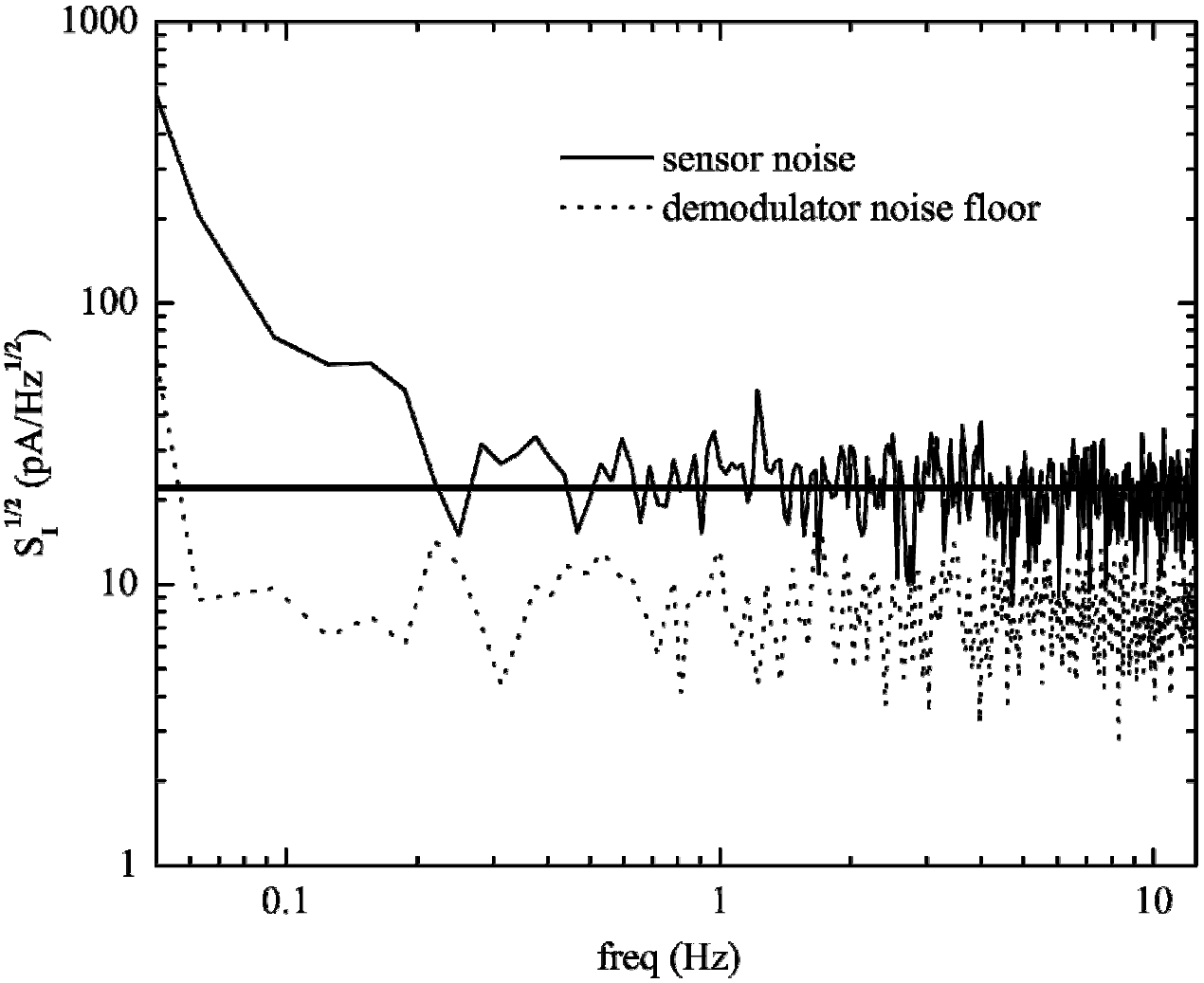


Initial Work: NSF
Development: NASA, DOE
Exporting Technology (U. Chicago, CWRU, U. Minn)

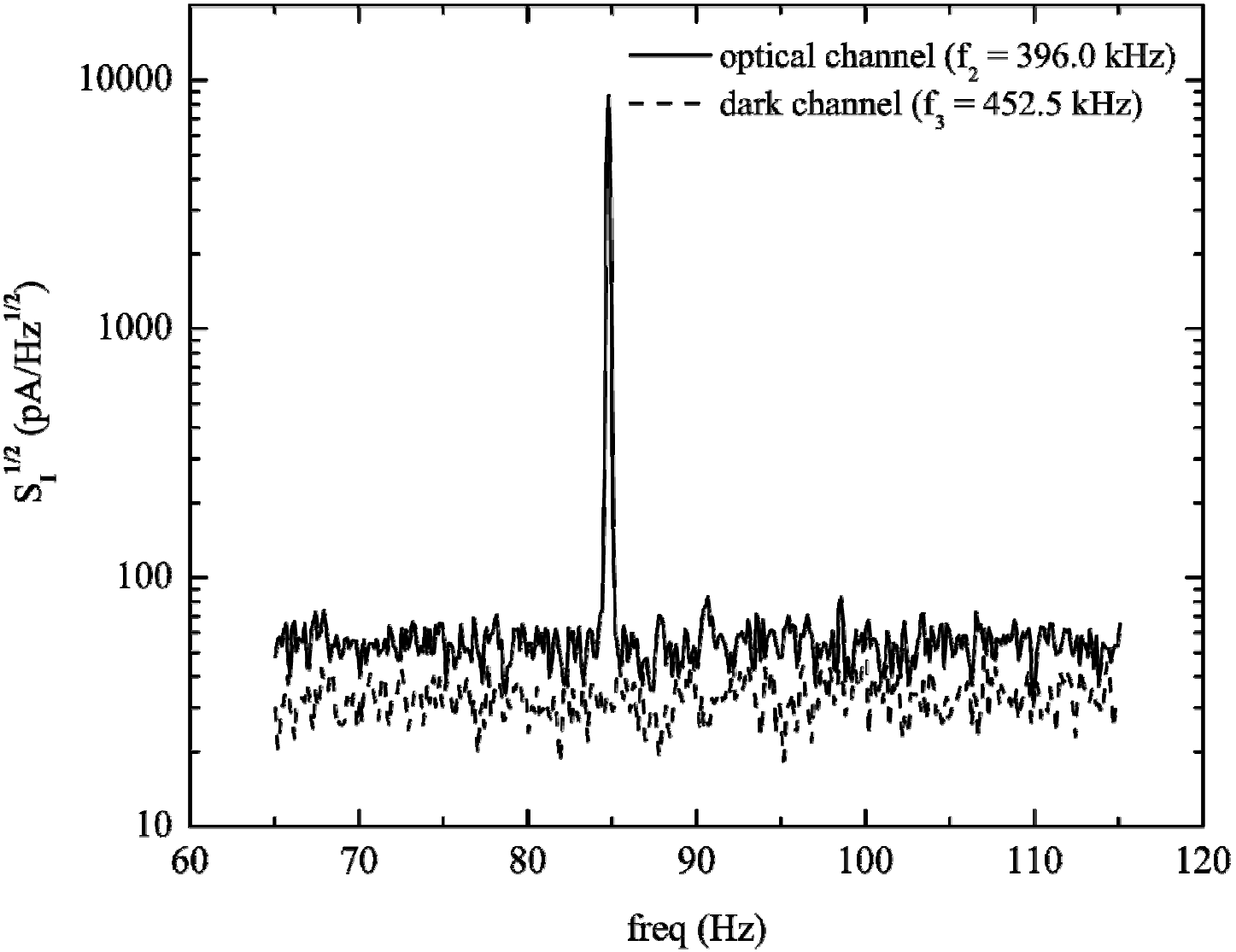
Pre-demodulation Ouput



Demodulated Output



Crosstalk Measurement

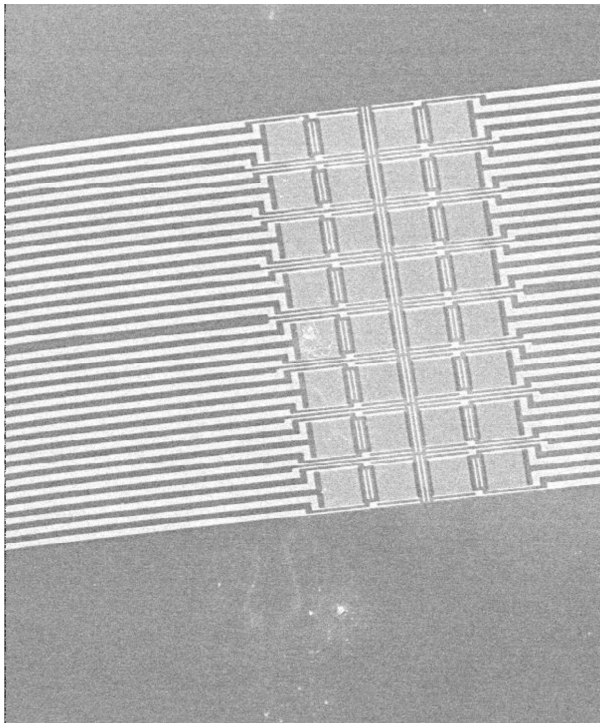


Future MUX Work

- Observational Test of MUX System
- Increase MUX Factor 8 => 32
- Add Cold Amplifier Stage
  - # MUXed Channels Dramatically Increases
  - Wire Length Restriction

Other TES Applications

Optical Photon Detection (e.g. Cabrera @ Stanford)

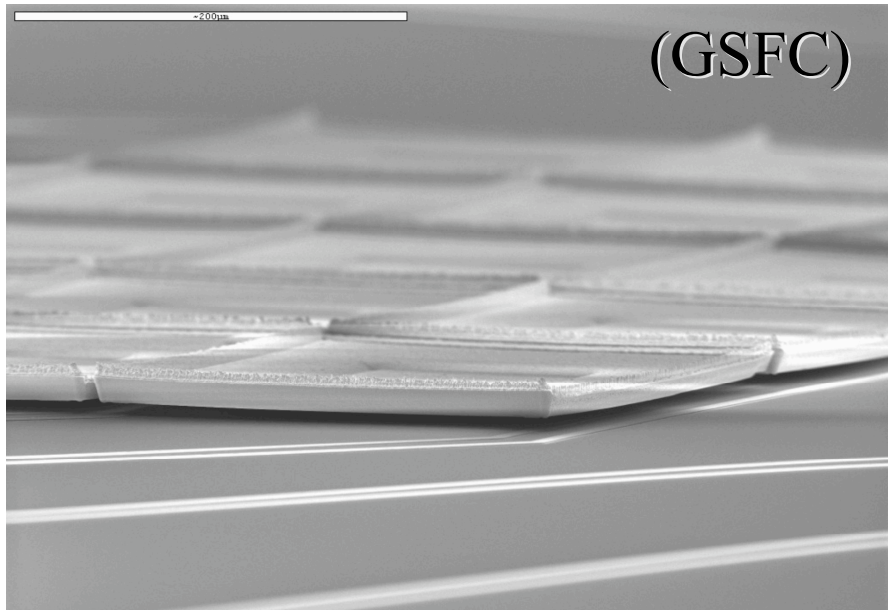


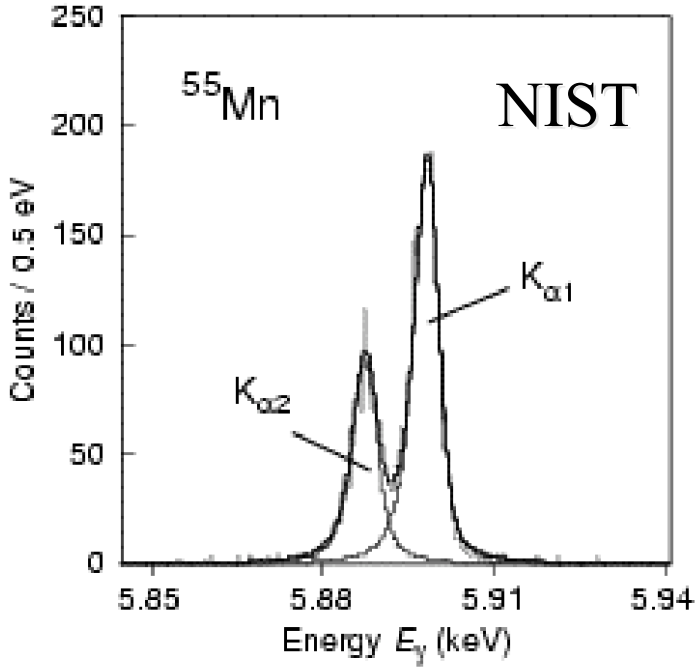
- UV-IR Photons Detected as Pulses
- Simultaneous Imaging, Energy, Arrival Time
- Energy Resolution ~ 0.2 eV @ 2.33 eV
- Time Resolution ~ 1 μs

$$\Delta E_{FWHM} = 2.35\sqrt{kT^2C\sqrt{8n}/\alpha}$$

(TES Calorimeter)

Soft X-ray Calorimetry (e.g. GSFC and NIST)



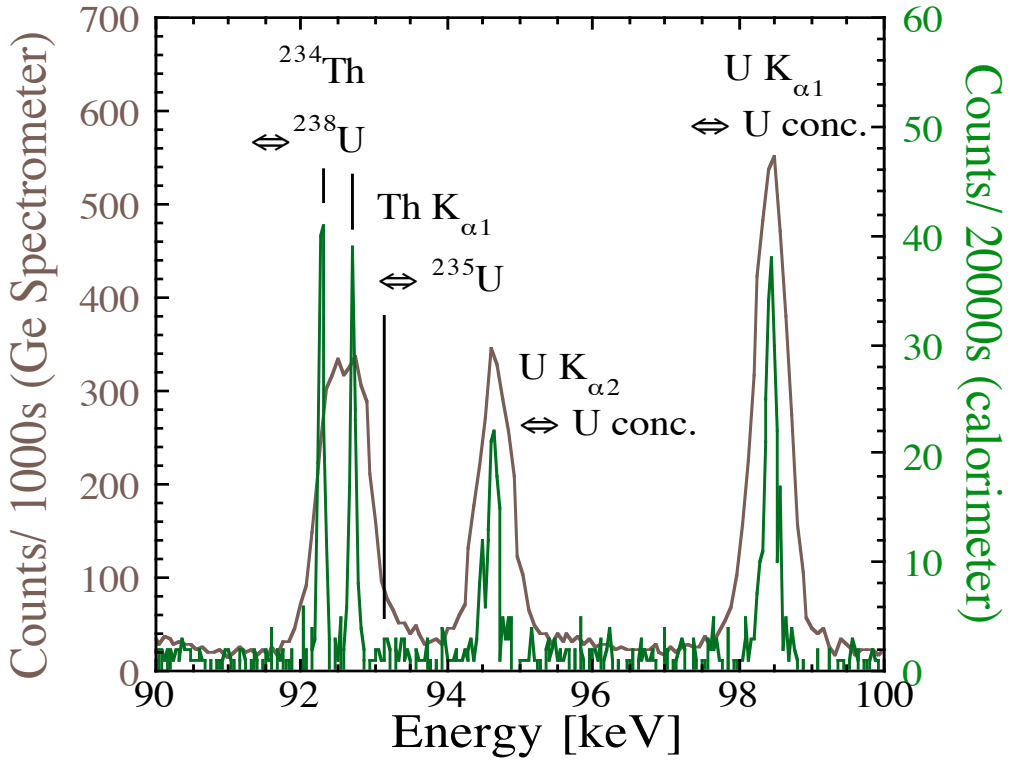


- X-ray Calorimeters for Astronomy/Materials Analysis
- Resolution 2.4 eV @ 6 keV (NIST)
- Friedrich, Cramer et al. Supercon. Tunnel Junct. (high rate)

High-Resolution γ-Ray Spectroscopy

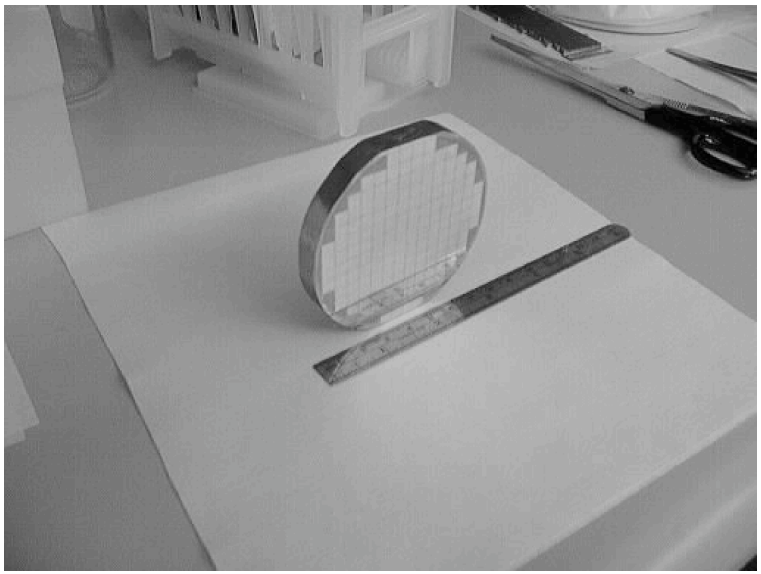
Uranium enrichment:
90eV FWHM

Superconducting γ-ray spectrometers enable high-resolution spectroscopy in cases where Ge detectors are fundamentally limited by device physics.

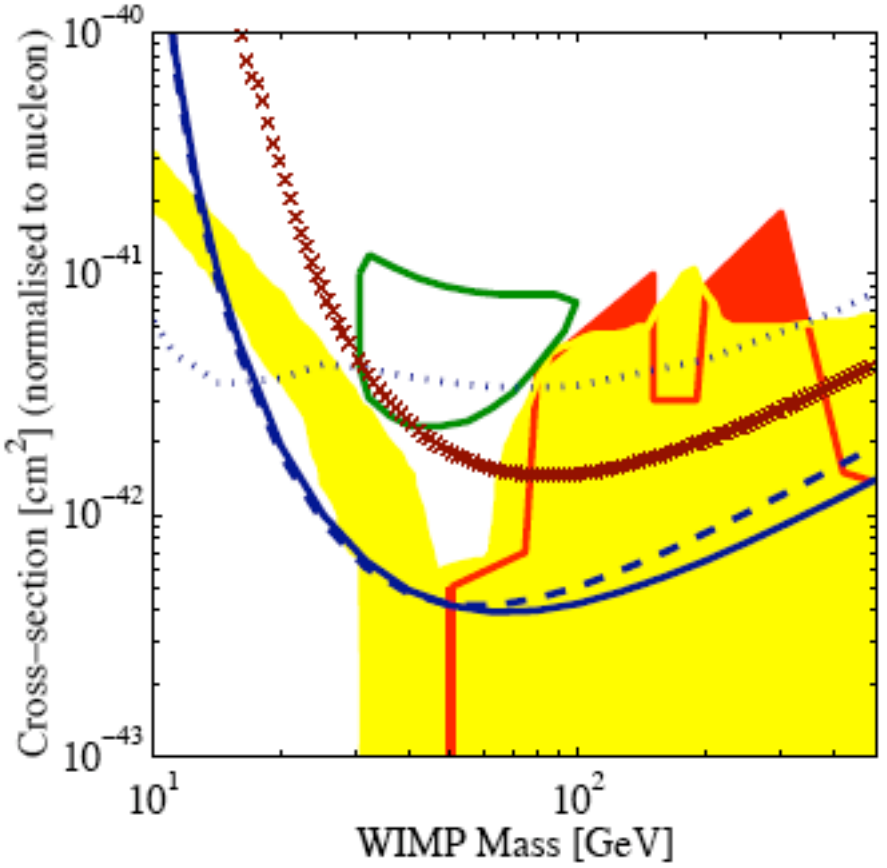


Analyzing similar-energy gamma lines increases precision of isotope ratio measurements, as errors from energy dependent self-absorption, shielding, detector efficiency are reduced.

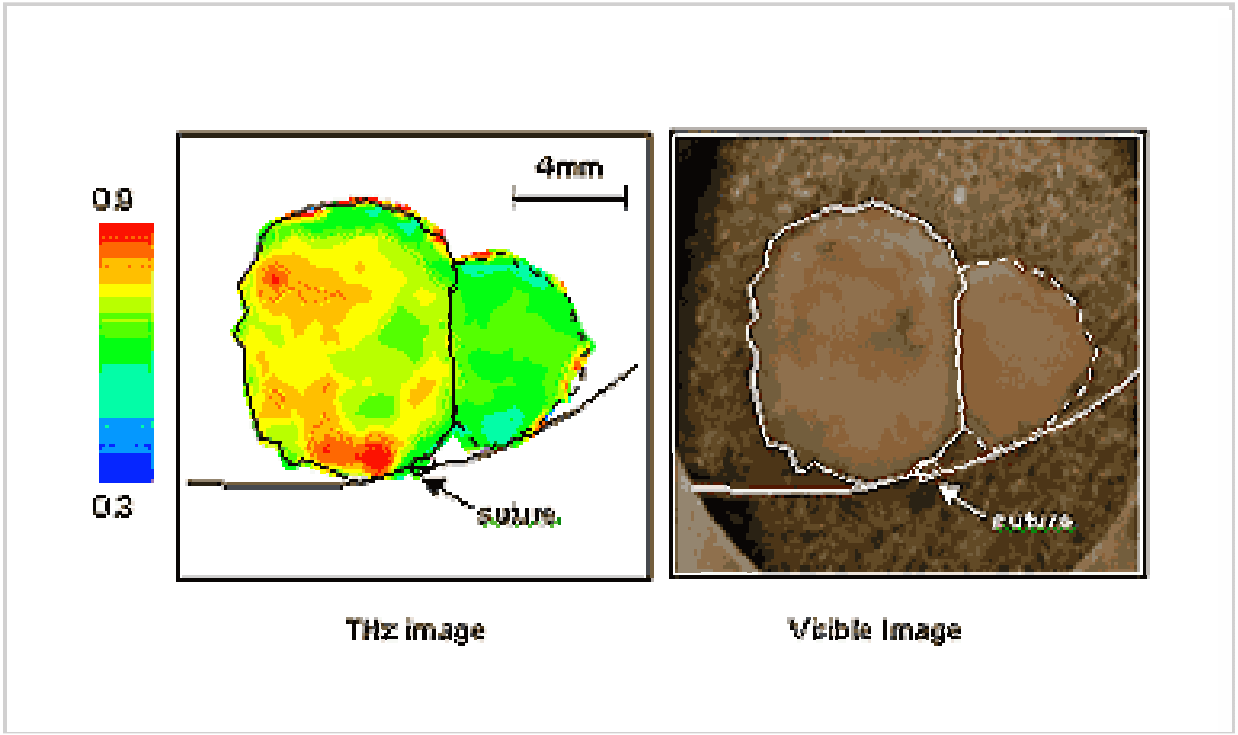
Dark Matter (WIMP) Detection (CDMS Group)







THz Imaging





- THz (Sub-mm) Imaging
  - Medical Imaging: THz penetrates outer skin
  - Concealed Weapons

Conclusions

- Great Science Potential with CMB
  - Polarization: Physics of Inflation
  - Clusters: Matter Density, Dark Energy
- Superconducting Bolometer Arrays
  - Large Monolithic Arrays
  - Integrated Antennas, Filters, Detectors
  - SQUID Multiplexing
- Many Applications
  - Optical to Gamma-Ray, Dark Matter