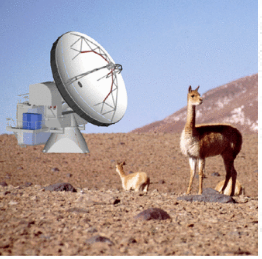
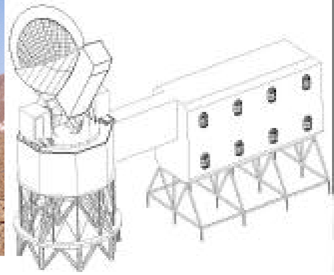
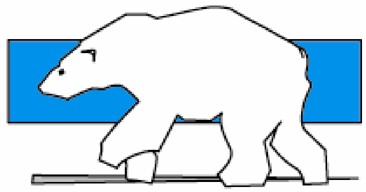






Physics Division
BERKELEY LAB

Cosmic Microwave Background Observational Program at Berkeley

Senior Scientists

John Clarke (LBNL,UCB)
William Holzapfel (UCB)
Adrian Lee (LBNL,UCB)
Paul Richards (UCB)
George Smoot (LBNL,UCB)
Helmuth Spieler (LBNL)
Martin White (LBNL,UCB)

Engineers

John Joseph (LBNL)
Chinh Vu (LBNL)

Scientists

Julian Borrill (Staff NERSC)
Sherry Cho (Postdoc UCB)
Matt Dobbs (Fellow LBNL)
Nils Halverson (Postdoc UCB)
Radek Stompor (Staff NERSC)
Huan Tran (Fellow UCB)

+ ~8 Graduate Students
1 Undergraduate

Outline

Detector Technology Development

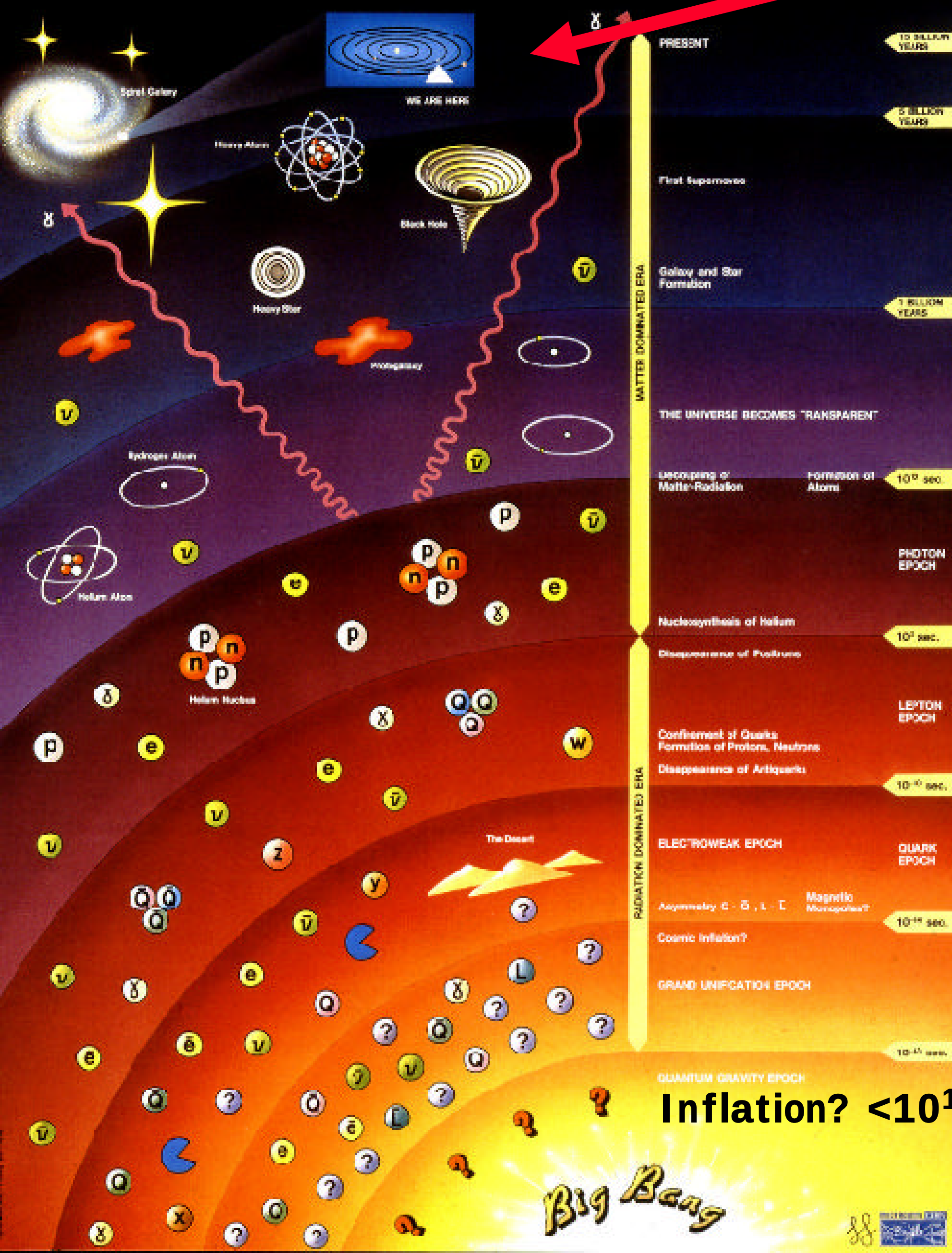
- Large Scale Bolometer Arrays
- Antenna coupled devices
- Frequency domain multiplexer

Experimental Program

- CMB Polarization as a probe of inflationary Scales
  - Maxima (2000) → Maxipol (2002/3)
  - Polarbear (2005/6) [Proposal Pending]
- Galaxy Cluster Searches using the Sunyaev Zel'dovich (SZ) Effect
  - Atacama Pathfinder Experiment (APEX) SZ Receiver (2004) [Funded]
  - South Pole Telescope (2006) [Funded]

History of the universe

You are here



← NOW (15 Billion years)

← Stars form (1 Billion years)

CMB & B mode polarization

← Atoms Form (300 000 years)

← Nuclei Form (180 seconds)

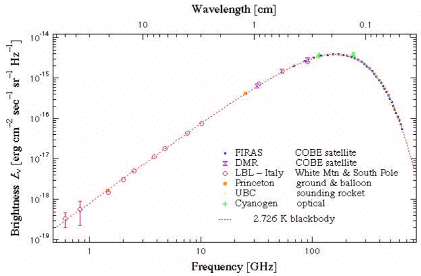
← Protons and Neutrons Form (10^{-10} sec)

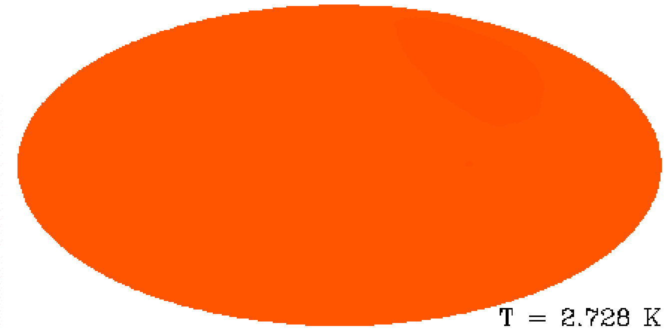
← Quarks Differentiate (10^{-34} sec ?)

Inflation? <10^{16} GeV

LHC probes physics relevant to the universe at age 10^{-14} sec.

- CMB is a near perfect black body, 2.7º K

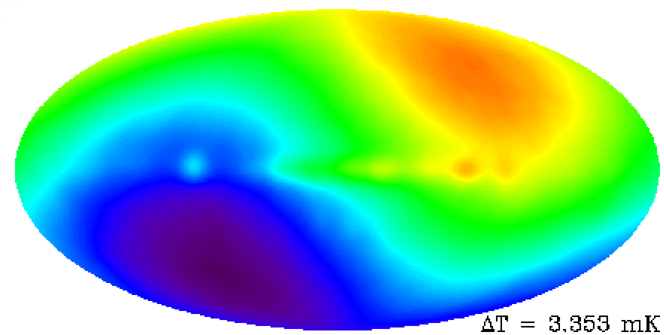




Cobe 1992

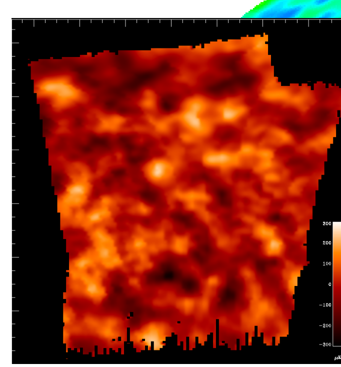
- Dipole Anisotropy 10^{-3}

  (our motion in the CMB `rest frame')

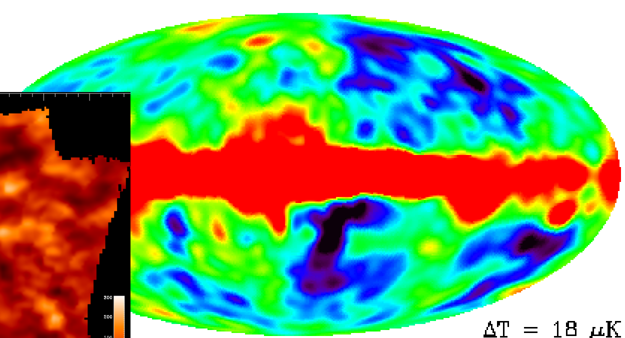


Cobe 1992

- Temperature Anisotropy 10^{-5}

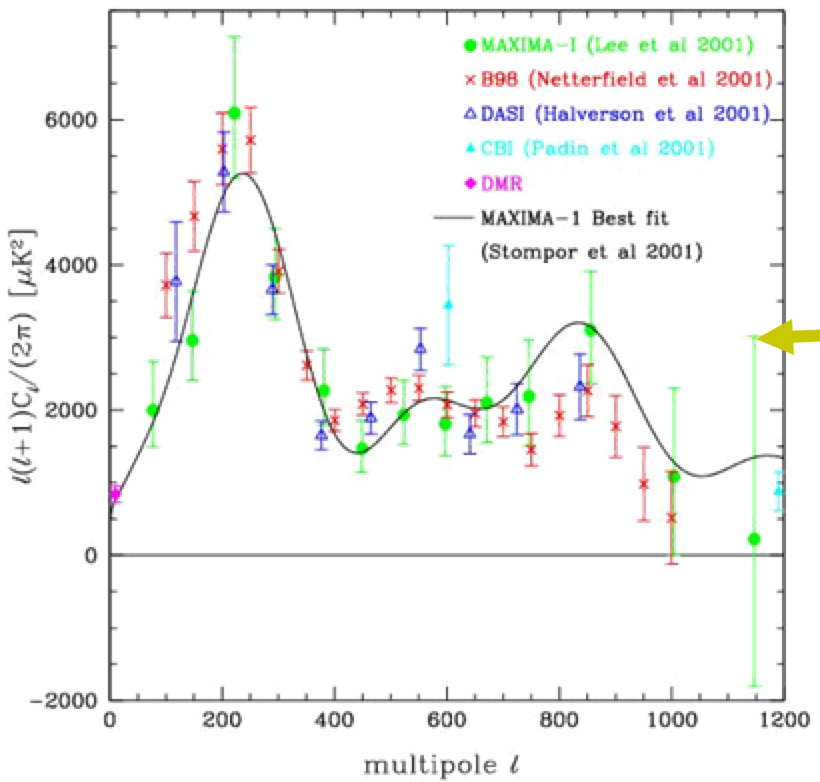


Maxima 2001



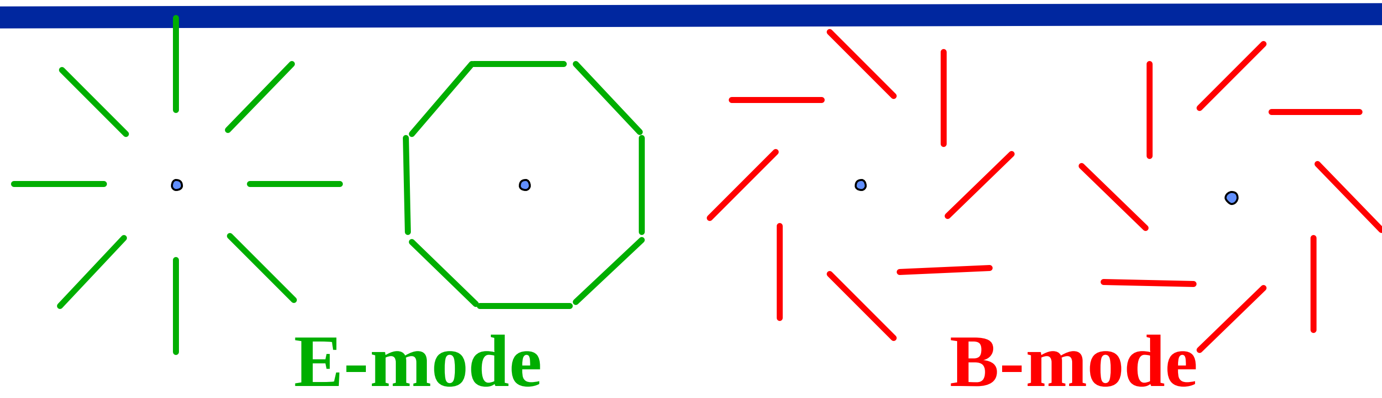
Cobe 1992

Where We Stand Today



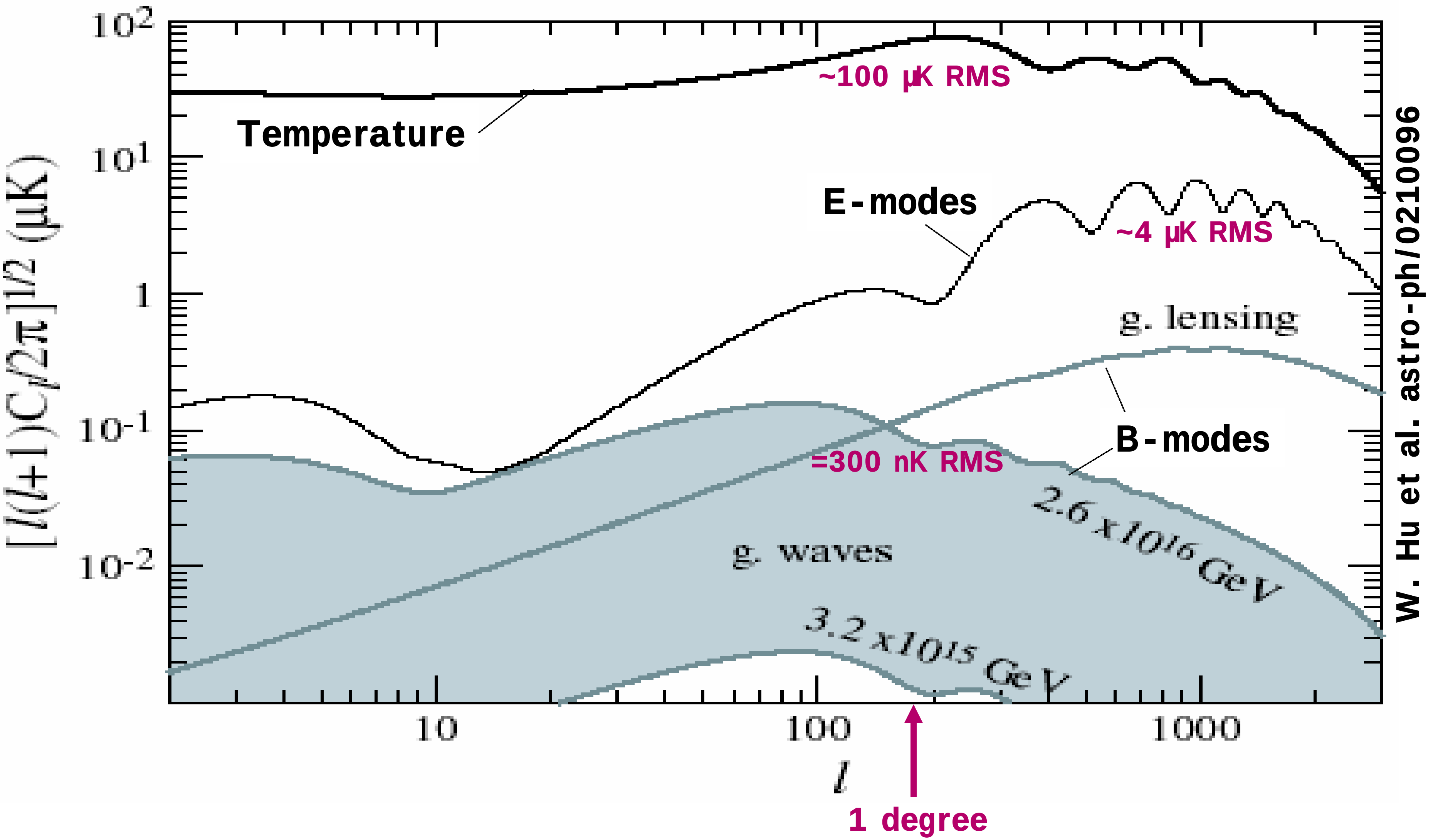
- CMB Blackbody Temperature
  - ✓ Observed
  - ✓ Well Characterized
- CMB Temperature Anisotropy
  - ✓ Observed
  - ✓ (mostly) Well Characterized
- CMB E-mode Polarization
  - ✓ Observed (?)
  - ❑ Well Characterized
- CMB B-mode Polarization
  - ❑ Observed
  - ❑ Well Characterized
- CMB SZ cluster surveys
  - ✓ Observed
  - ❑ Counted and Mapped

CMB Polarization



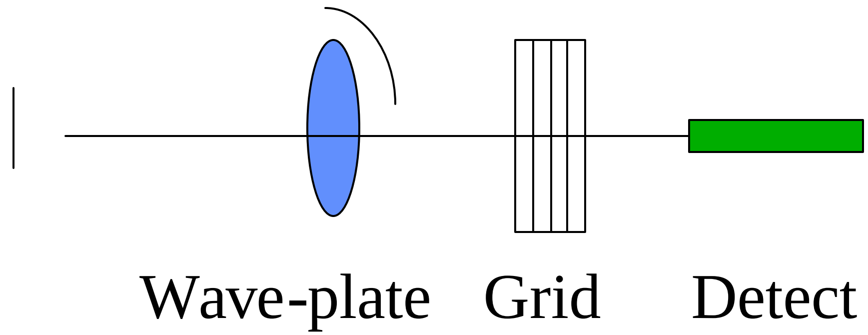
- Thomson scattering at time of last scattering polarizes EM radiation ➔ Anisotropy yields net polarization, "E-modes" (scalar perturbations).
- Gravity waves put stress on photon-baryon fluid, tensor perturbations ➔ generation of curl component in CMB-pol, "B-modes"
  - "Smoking gun" of Inflation
  - Amplitude of B-modes proportional to Inflationary scale (probe of GUT energy scales)
- Defects and strings give vector perturbations ➔ B-modes *(observational string theory??)*

CMB Polarization



Current Observation Program: E-mode POLARIZATION with MaxiPOL

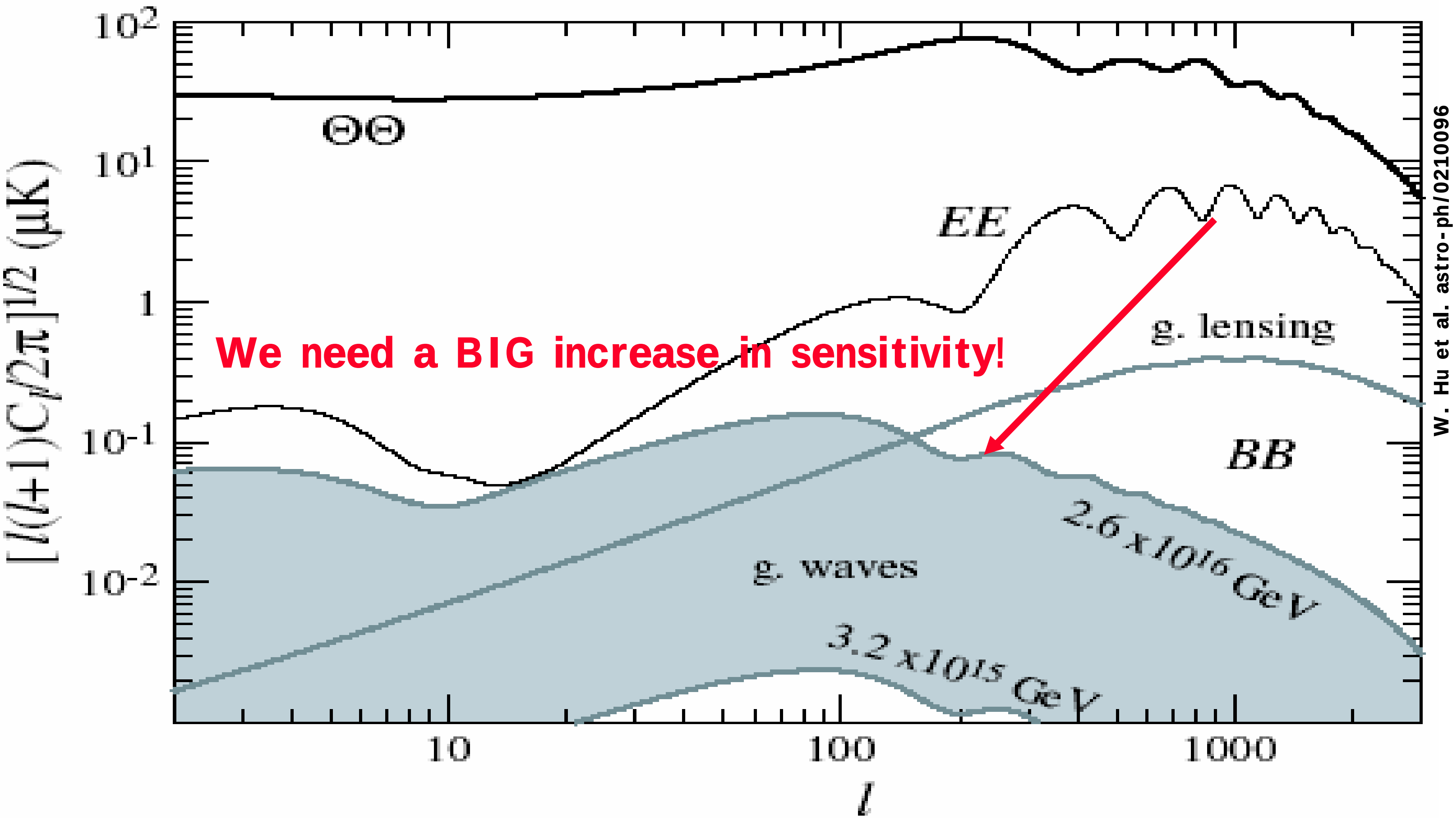
- Next step for POLARIZATION, MaxiPOL
  - GOAL: detection of E-mode polarization
  - Natural evolution of MAXIMA



    - 2 Hz half-wave plate and wire grid (both stokes parameters measured using a single beam on the sky)
    - ~36 hour balloon flight
  - Fall 2002 flight: instrument worked well, but suffered telemetry failure.

    Fly again in Spring 2003.

CMB Polarization



Large Scale Bolometer Arrays

Physics Division
Berkeley Lab

- Bolometer technology is approaching the photon statistics limit.
  - We can't do better by building a better bolometer.
  - Next step:
    1. Increase integration time by going to ground based observations.

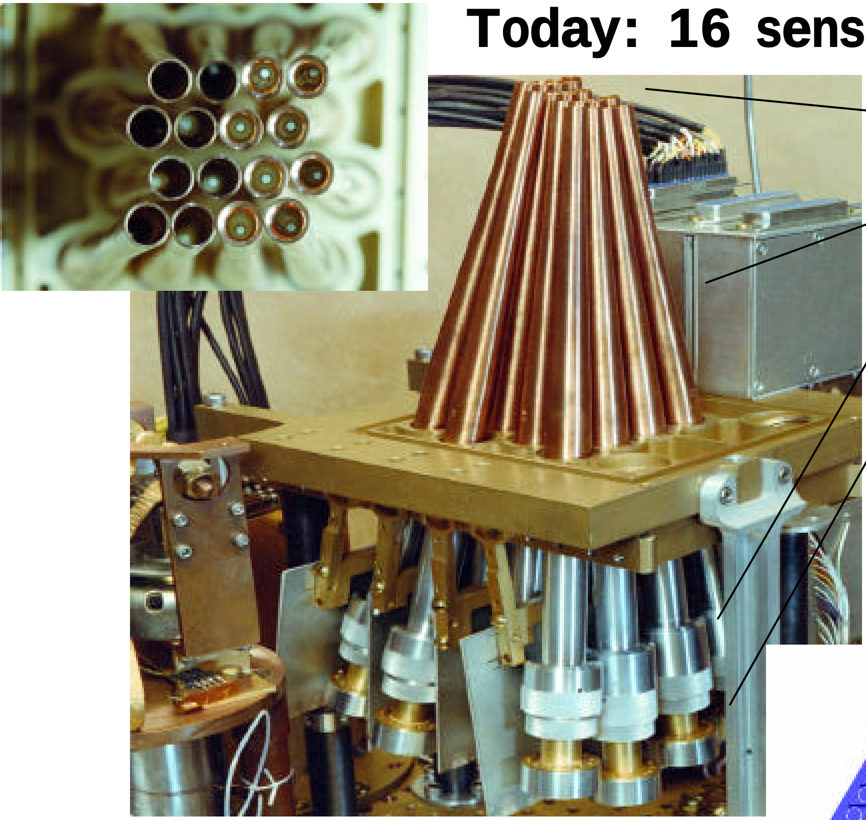
       (atmospheric disturbances are not polarized– common mode effect cancels out.)
    2. Make many measurements at once using large scale bolometer arrays **(thousands of pixels)**

- Superconducting Transition-edge Sensor (TES) Bolometer Arrays

  (TES: key development here at Berkeley)
  - Electrothermal feedback ➔ Fast, linear response and higher sensitivity
  - SQUID preamplifier low noise power, low power dissipation (1 nW/device), low input impedance
  - Entire fabrication is by photolithography
  - Frequency domain multiplexer readout in development

Large Scale Bolometer Arrays

Today: 16 sensor Maxipol Array



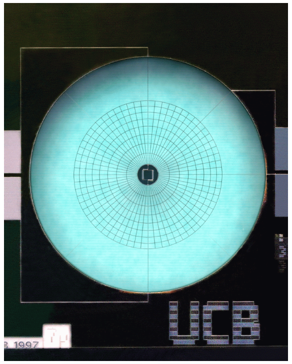
Focal plane horns

Waveguides

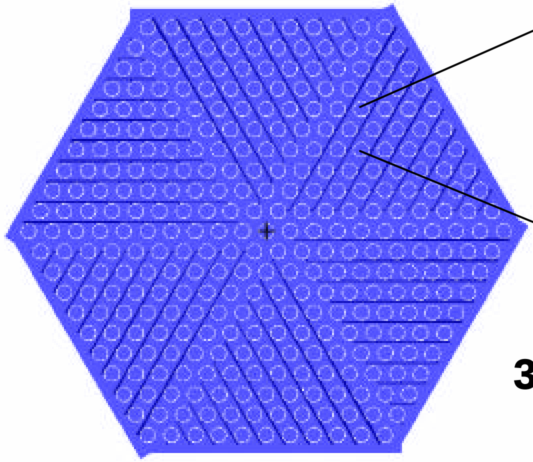
Filters

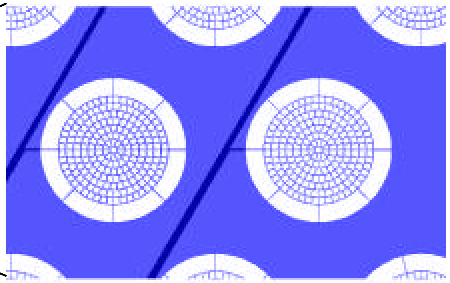
Bolometers

3.5 mm



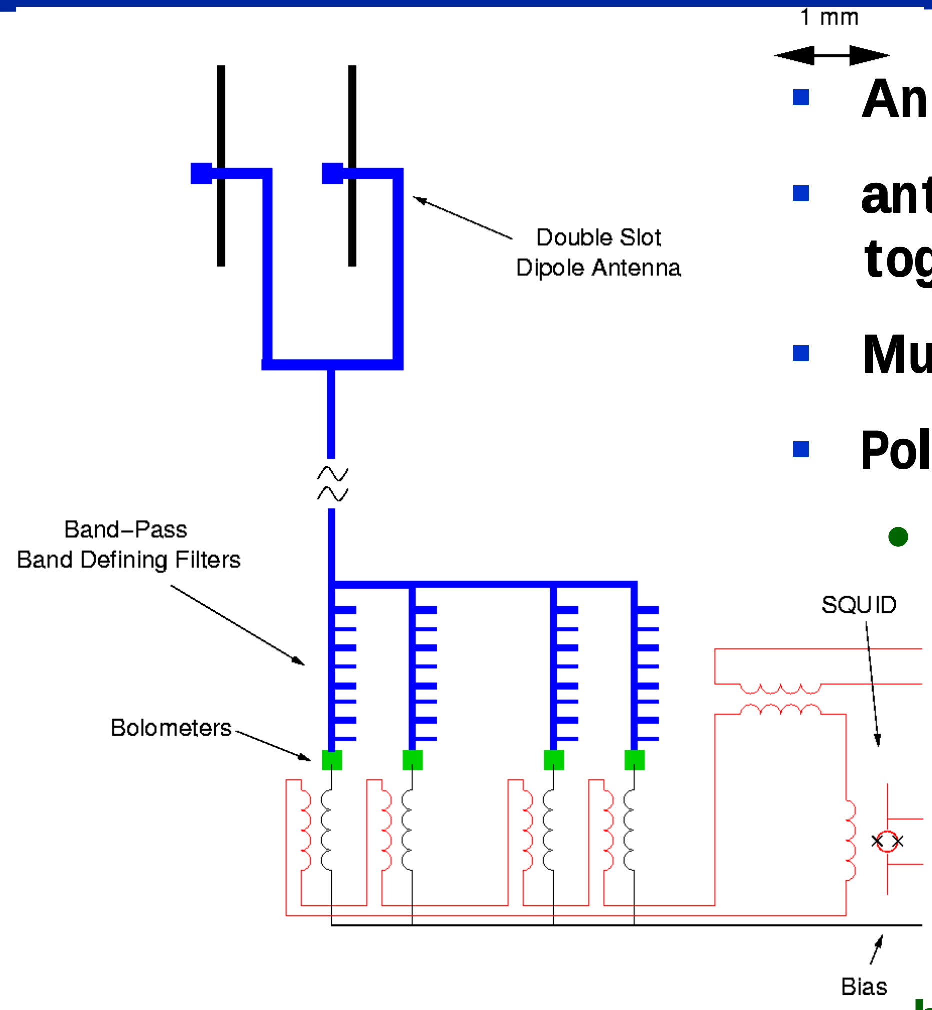
Next Step: Photolithographic manufacture of Bolo Arrays





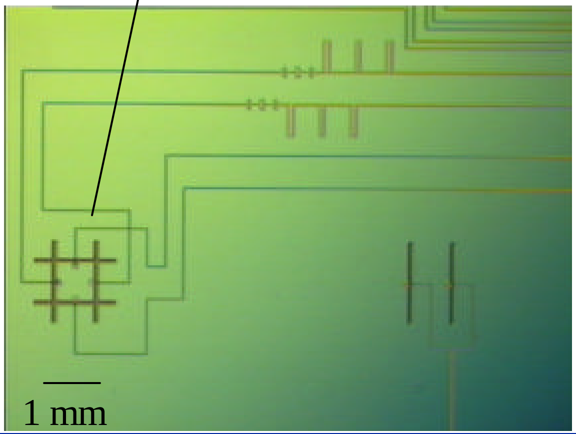
300 Element Spider web TES bolometer array for APEX

Antenna-coupled Bolometer Diagram



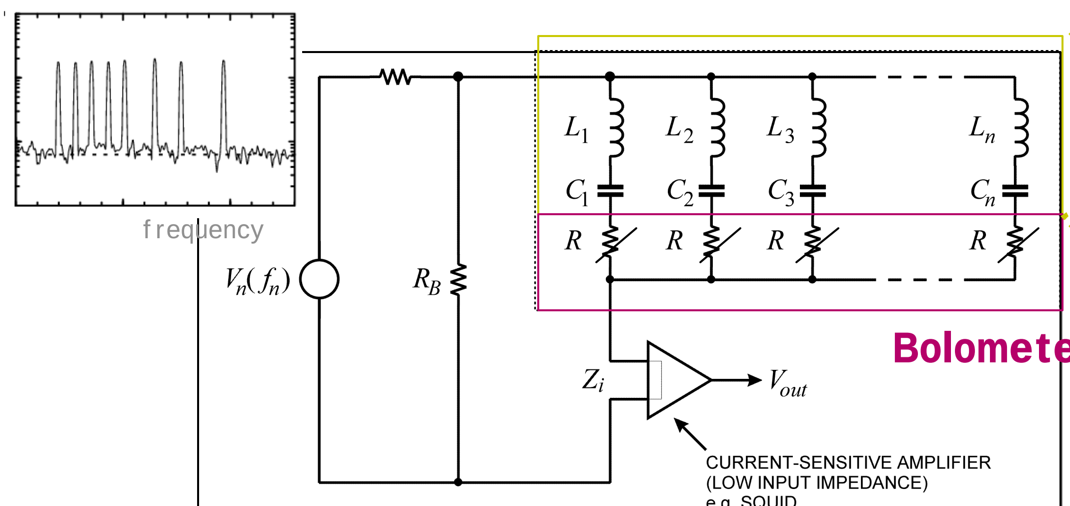
- Antenna provides directivity
- antenna, filters, bolometers packaged together below lens
- Multicolor → multiple bands per pixel.
- Polarization sensitive
  - dual polarization by placing 2 crossed dipole arrays in same pixel

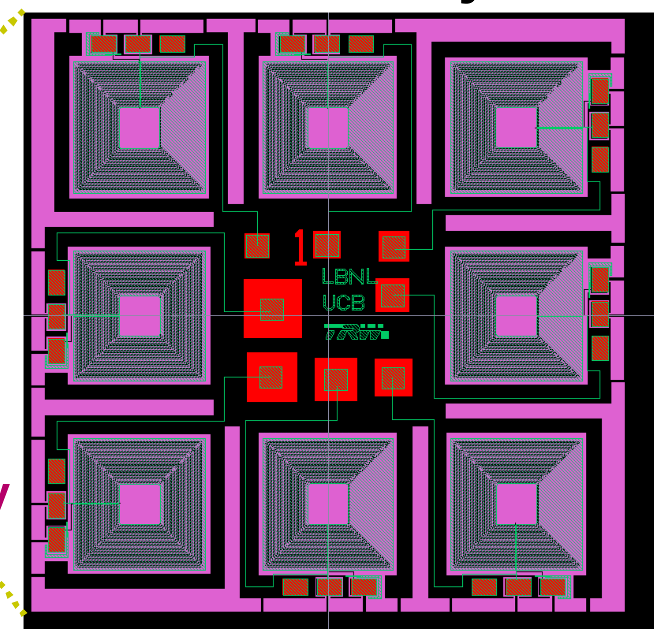
Prototype pixel fabricated, being tested now



SQUID Readout Multiplexing

- Key Element: Readout Multiplexing
  - maintain exquisite sensor sensitivity, continuous readout
  - test chip of 8-channel Multiplexer (LBNL, UCB, TRW)
- **cited as a Physics Highlight in APS *Physics News in 2001***
- April 2002: **MUX demonstrated together with LLNL in x-ray bands** (Cunningham et al., APL 2002 (LBNL-50193))



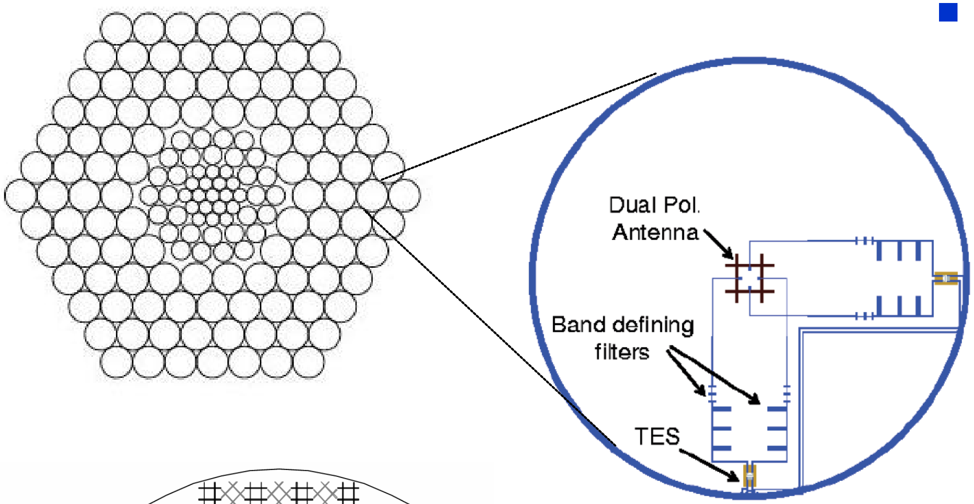


POLARBEAR

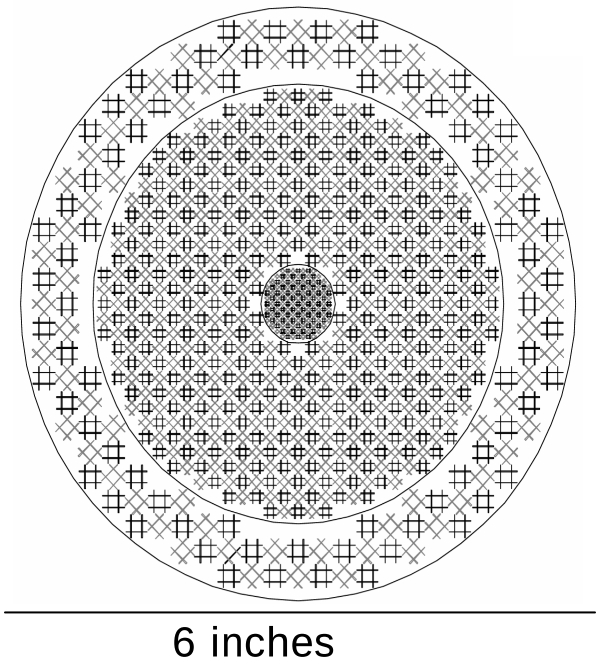
(NSF Proposal submitted summer 2002)

- Ground-Based at South Pole
  - atmospheric emission is nearly unpolarized
  - ➔ increase observation time from few hours ➔600 days.
- Large Scale Array of Antenna coupled TES Bolometers
  - antennae, filters & bolos manufactured photolithographicaly on Si wafers
  - Ground based + arrays ➔factor 10^5 increase in integration time (including lower sensitivity on the ground)
- Use existing Viper telescope
- Characterize E-modes
- Search for B-modes, the “smoking gun” of inflation

POLARBEAR Focal Plane



- Polarbear I Focal plane
  - 150 pixels x 2 polarizations =300 bolo's at 300 mK
  - 3 bands, 150,250,350 GHz

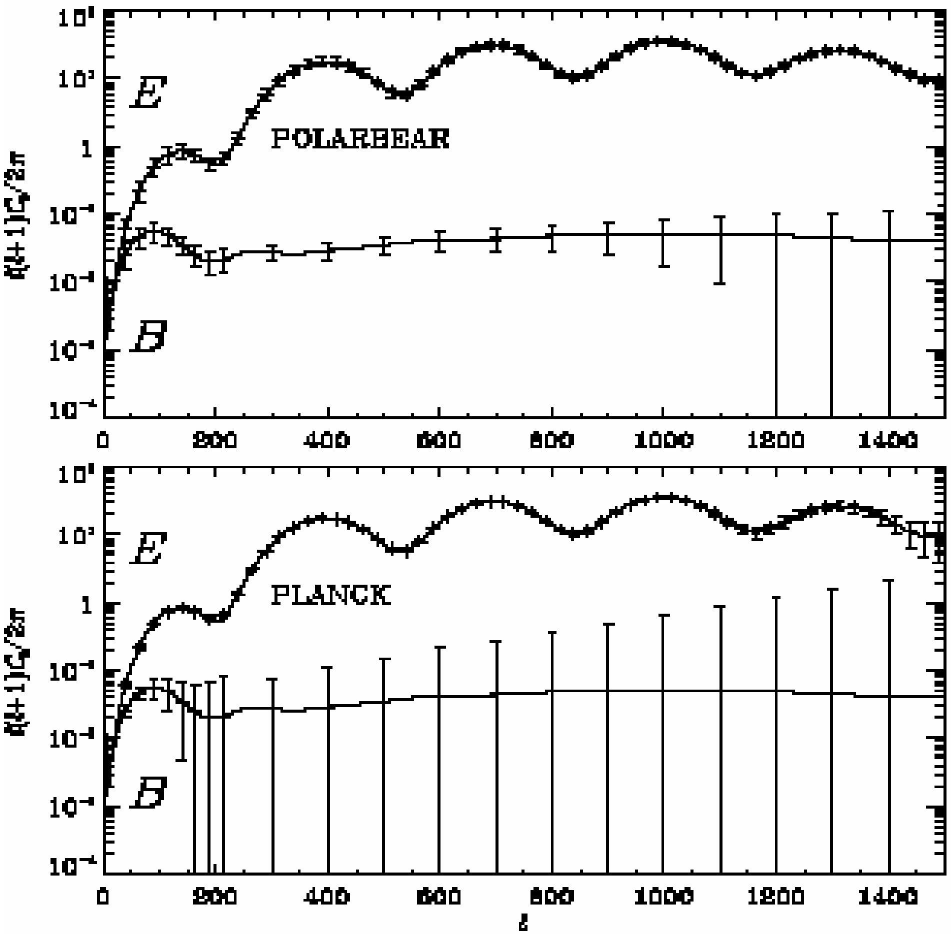


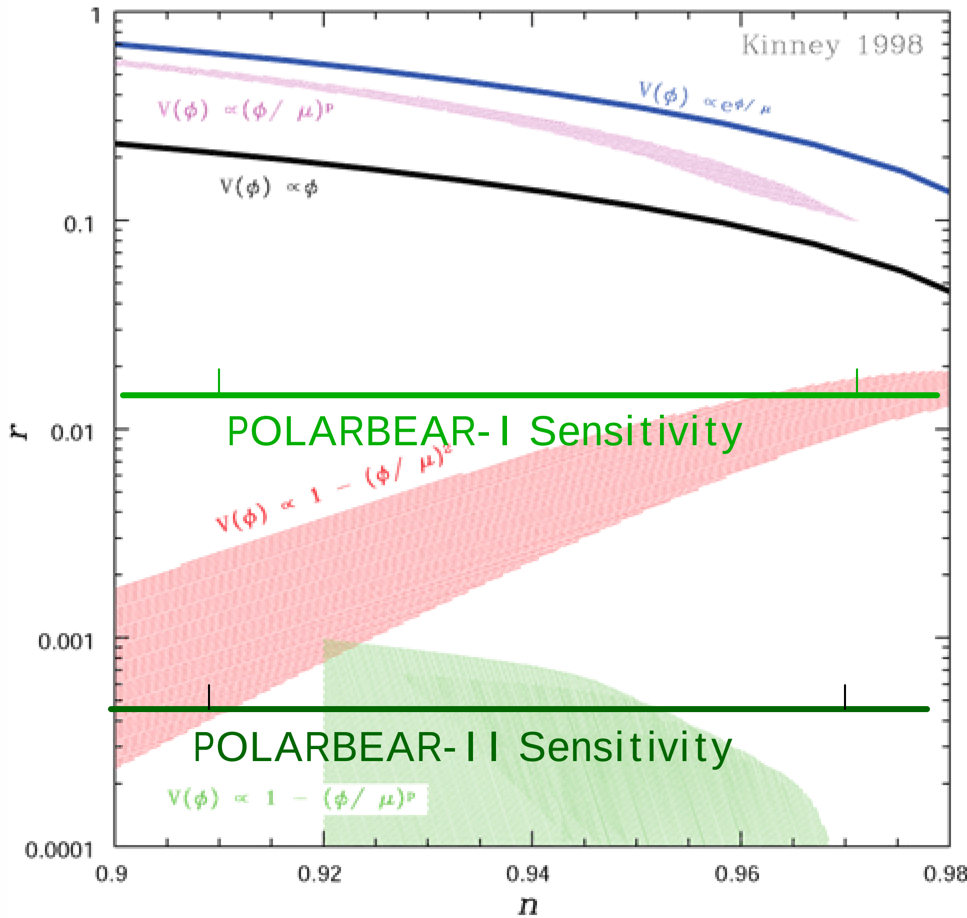
- Polarbear II Focal plane
  - 900 pixels, 3000 bolometers
  - Full use of 150 GHz Field-of-view

POLARBEAR Systematic Controls

- Multiple levels of differencing, many time scales
  - Subtraction of signals from orthogonal antennas
  - Rotation of polarization, e.g half-wave plate
  - Scan telescope
  - Rotation of sky
  - Repeat over day/night and larger time scales
- Low side-lobe response telescope
- High SNR helpful for systematic tests
  - Compare e.g. halves of data

POLARBEAR Performance





3 years observing
(Assuming a Tensor to Scalar ratio r=T/S=0.35)

3 yrs x 25% duty
➔ 200 nK/pixel on 10 x 10 deg^2

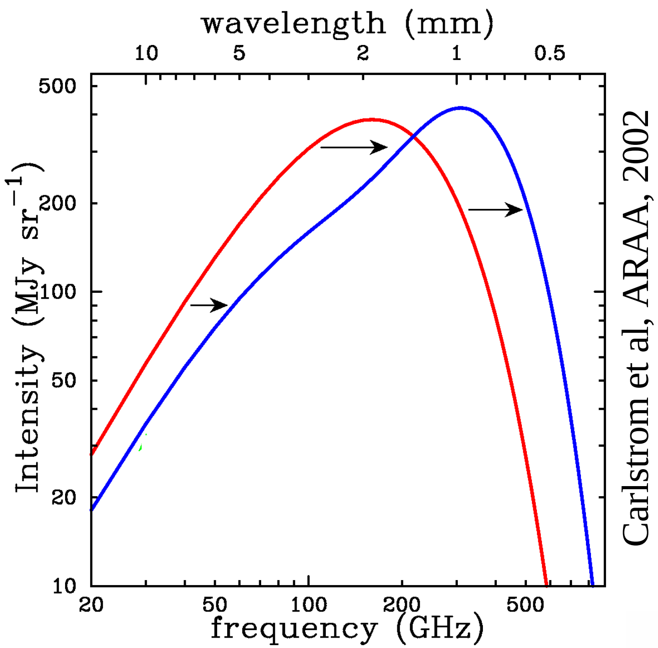
PolarBear Schedule

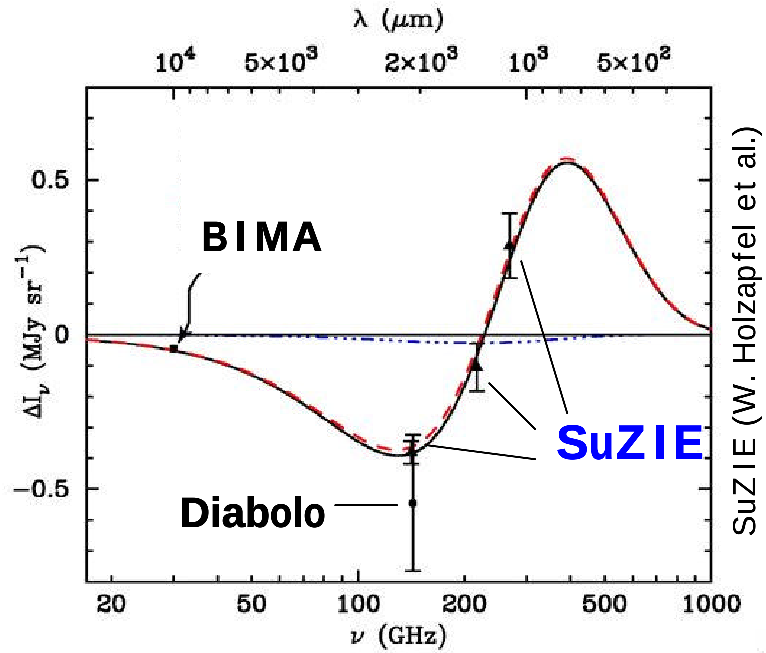
- Now→ 2005
  - Antenna coupled bolo array and Multiplexer development, fabrication
- 2005/6
  - Observations with 300 channels, individually read out with SQUIDS.
- 2007
  - Observations with 3000 multiplexed channels

Seed funding from LBNL LDRD.

Proposal submitted summer 2002 to NSF Polar Programs.

Sunyaev Zel'dovich Effect



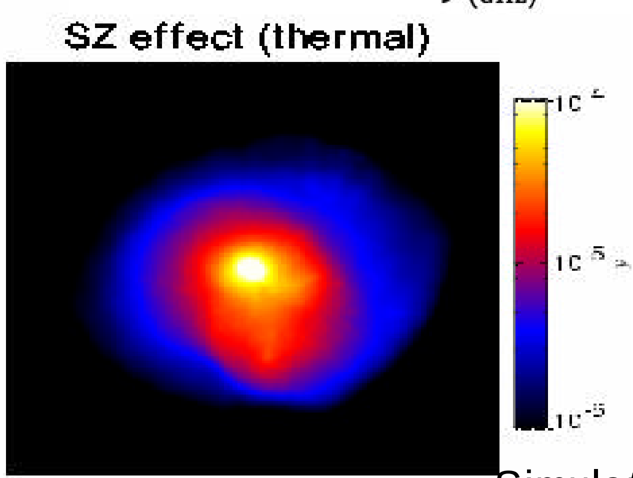


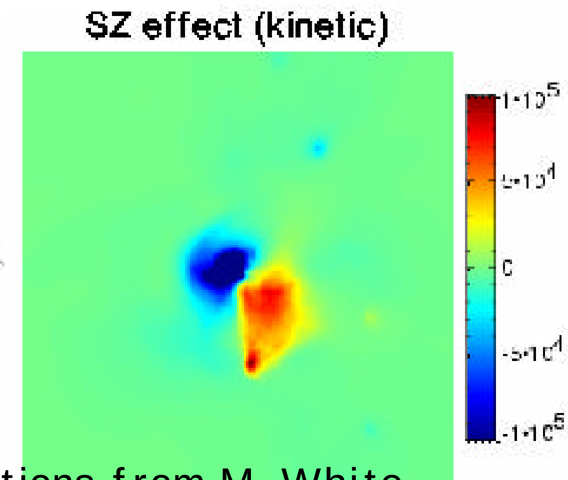
Measured deviation from Black body spectrum.

Dotted line: Kinetic SZ

Thermal SZ: Inverse Compton Scattering in the hot inter galactic medium "kicks" CMB photons up to higher energy.

Kinetic SZ: doppler shift due to cluster motion.

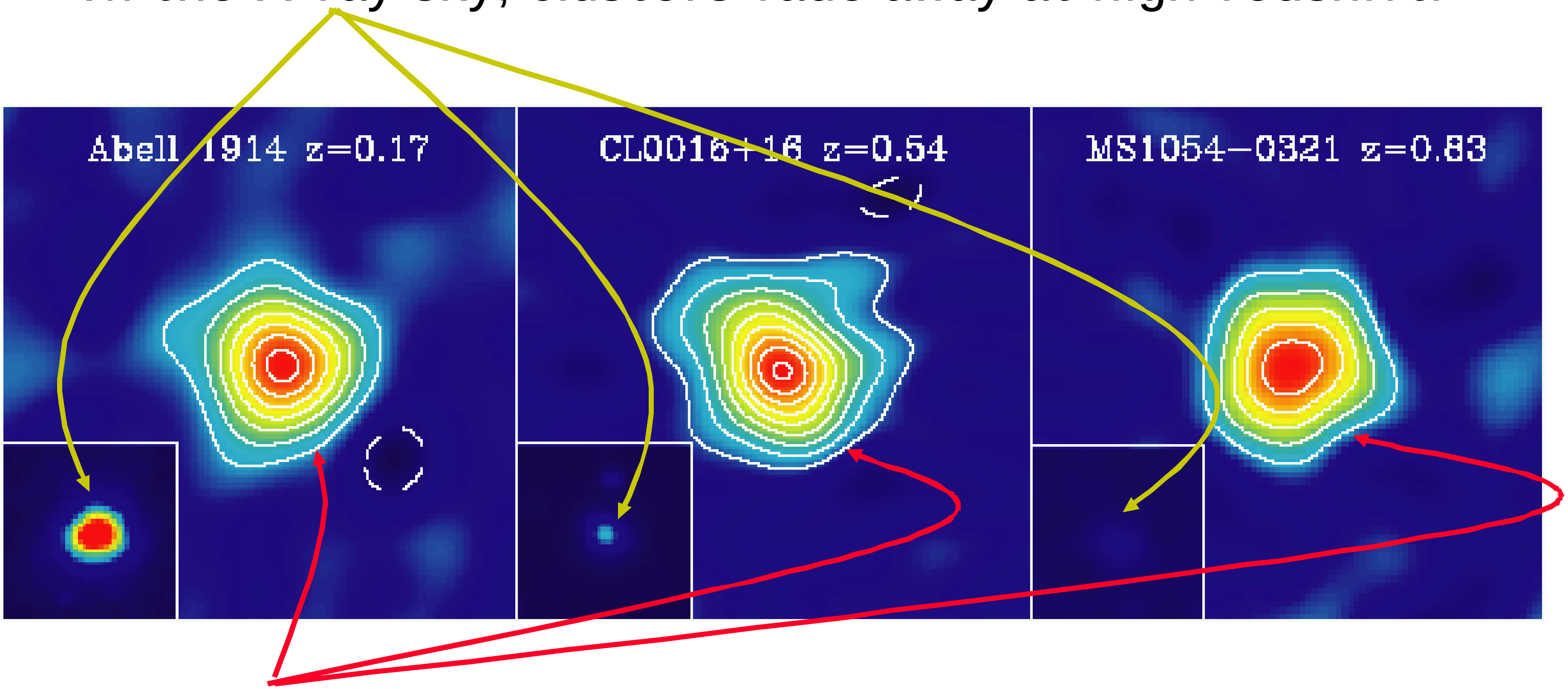




Simulations from M. White.

Sunyaev Zel'dovich Effect is Independent of Distance

- In the X-ray sky, clusters fade away at high redshift.

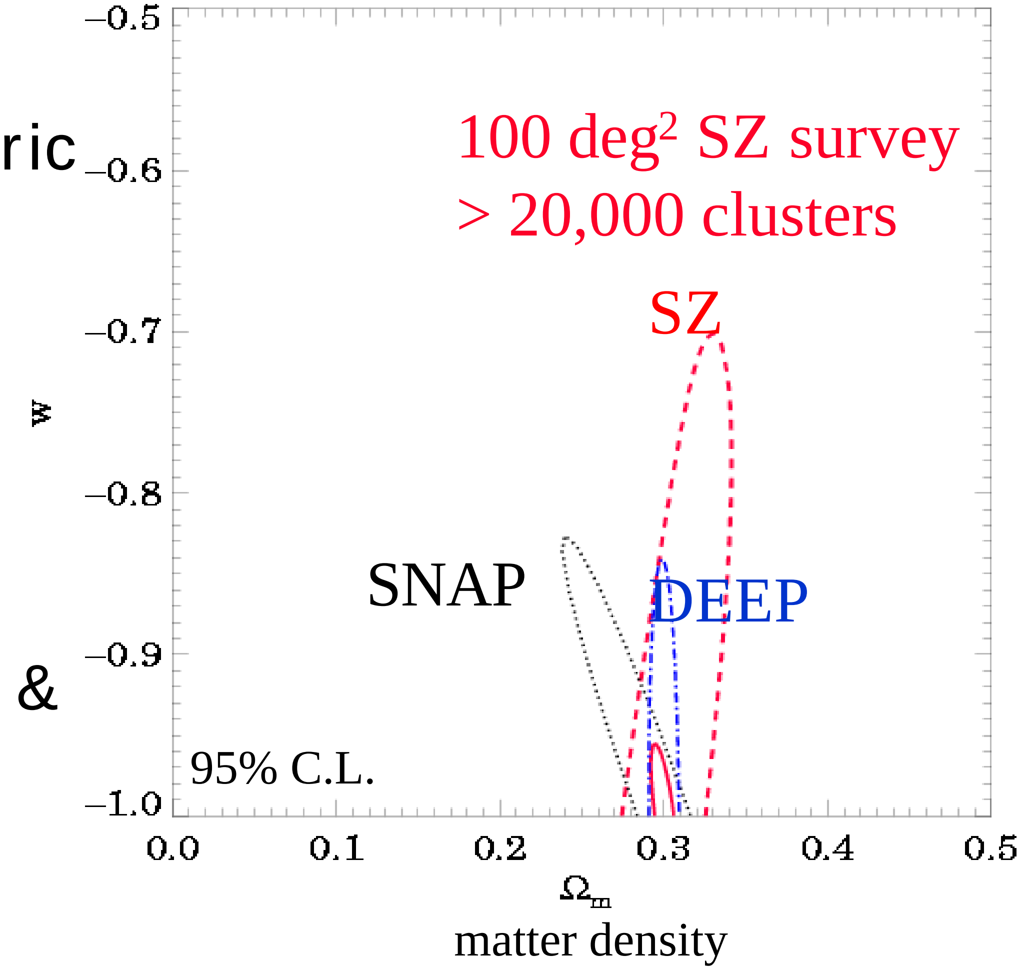


- SZ observations are independent of redshift

→ ***Clusters can be seen at any distance.***

Sunyaev Zel'dovich Effect

- Growth of structure depends on cosmology.
- SZ cluster counts together with photometric redshifts determine cluser dN/dz
  - constrain dark energy equation of state, w
  - constrain matter density, O_M
- Complementary to DEEP & SNAP results
  - different systematics
  - different correlations

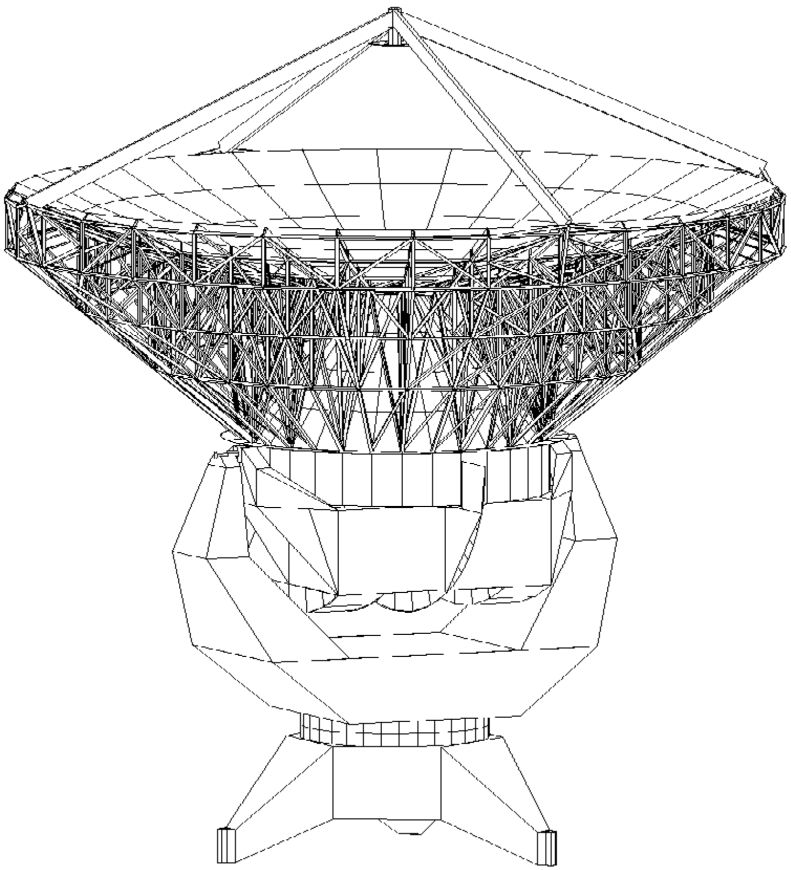


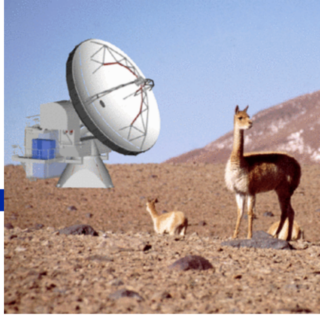
APEX Sunyaev Zel'dovich Receiver

Physics Division
BERKELEY LAB

- 300 Element Bolometer array
  - superconducting transition edge sensors (TES)
    - 250 pixels observing at 2mm
      - where the ratio of the thermal SZ signal to the combination of atmospheric and detector noise is maximum
    - 50 pixels observing at 1.4mm (217 GHz)
      - coincides with the null of the thermal SZ effect
      - and the peak in the kinetic SZ effect.
- Noise: 250 µK vs at 2mm.
- will thus measure one square degree of sky to an RMS of 10 µK per three hours of observation!

Atacama Pathfinder Experiment (APEX)





Telescope

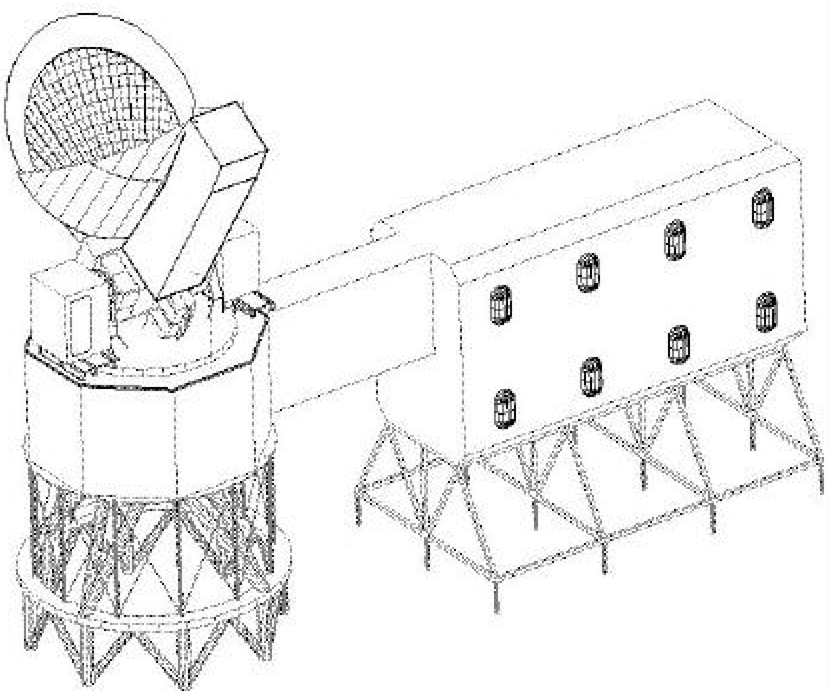
- Located at 16,500 feet in the Chilean andes.
- 12m on-axis ALMA prototype
- 45” resolution at 150 GHz
- 30’ field-of-view
- Use in drift scanning mode
- Telescope funded and under construction by **MPIfR/ESO/Onsala.**

Berkeley SZ Receiver **funded by NSF astronomy, 2002.**

- **First Light January 2004.**

• 25% of Telescope time will be dedicated to Berkeley SZ Receiver

South Pole Telescope



- ~3000 pixel focal plane (multiplexed)
- 8m, off-axis design
- 1.3' resolution
- 1 deg. Field of view
- 100% time SZ observations
- Best mm-wave site
- First light 2006
- Funded by NSF Polar Programs (Chicago, Berkeley, Case Western, SAO)

APEX/SPT are complementary: APEX will be operational 2-3 years before SPT, but SPT will have ~5x faster cluster finding rate.

Technology Development Crucial

- **We are breaking new ground in several areas**
  - **integrated sensor arrays**
  - **cryogenic readout multiplexing**
    - **Frequency-Domain Multiplexing for bolometer readout**
    - **SQUID arrays with large dynamic range + bandwidth**
  - **Our technology is scalable, economical, and robust**
- **Individual elements demonstrated as proof-of-principle**
- **Challenges**
  - **sufficient engineering effort**
  - **infrastructure for fabrication of sensor arrays**
  - **maintain our technology lead**

Facility for Superconducting Sensor Arrays

- **Establish infrastructure capable of fabricating very high yield TES sensor arrays.**
  - **natural evolution of the TES bolometers (a Berkeley technology)**
  - **existing facilities on campus not adequate**
- **augment the existing LBNL Silicon MicroSystems lab to accommodate production of large superconducting sensor arrays**
  - **extends our current facility to frontier technology**
  - **establishes technology base in the engineering division**
- **LDRD strategic proposal submitted and plant funds requested (Jun 2002).**

Summary

- **The Berkeley observational CMB program is going after the next generation CMB science:**
  - **Polarization** with **Maxipol** & **POLARBEAR** experiments
  - **SZ cluster surveys** with **APEX** and **South Pole Telescope**
- **These experiments require a leap forward in sensitivity, which will be provided by our instrumentation advances**
  - monolithically fabricated large scale arrays of bolometers
  - antenna coupled devices
  - multiplexed readout

  ➔ **Proof-of-concept prototypes of all elements fabricated, and now being tested.**

  ➔ **We're moving into the engineering phase.**