Probing Inflation and Dark Energy with the Cosmic Microwave Background

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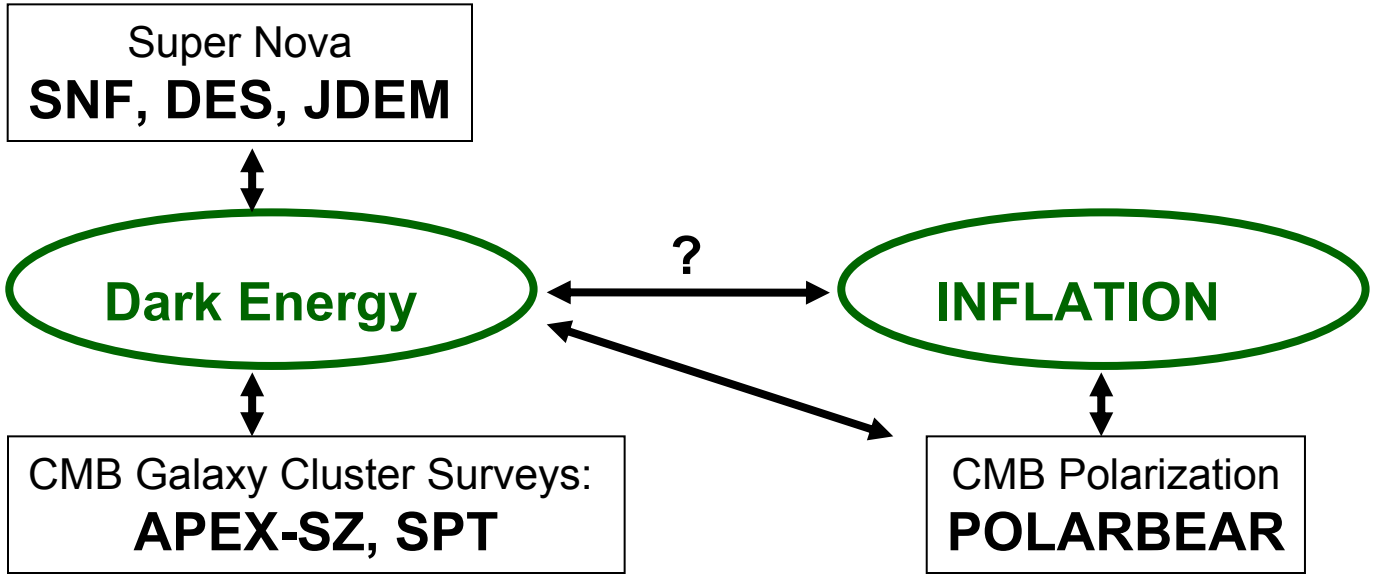
HEP-Cosmology Connection

- Common Questions:
  - What happens at the highest energies?
  - What are the fundamental particles?
  - How do we unify the forces?
- Cosmology: a new tool
  - Highest Energies => Early Universe
  - Test masses probe gravity, e.g. Dark Energy
  - Tests of String Theory?

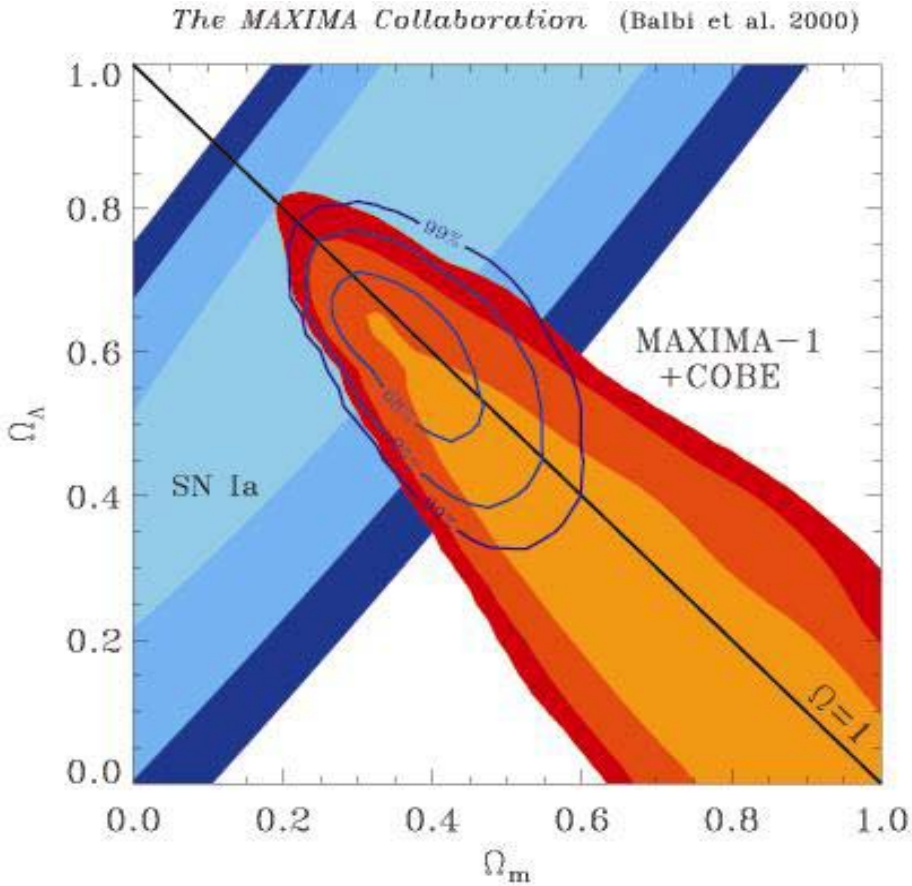
A Coherent Program



LBNL/Campus Partnership

- Integrated program combines efforts at LBNL + UCB
  - Complementary strengths of National Lab and University
- Strong program in theory and data analysis
  - Collaboration with NERSC
  - Strong role on Planck satellite analysis
- New instrumentation enables new experiments
  - APEX-SZ, South Pole Telescope - LBNL building array readout
    - Galaxy Cluster Search - probe Dark Energy
  - POLARBEAR - DOE lead role
    - CMB Polarization - probe Energy Scale of Inflation

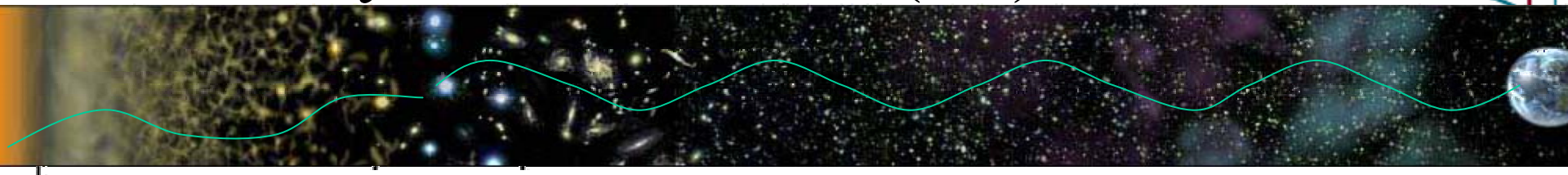
Berkeley CMB Experience



- MAXIMA: Strong Role in establishing peaks
  - Low systematic uncertainties
- Flat Geometry
  - => Critical for Dark Energy
- All Agencies: DOE, NSF (CfPA), NASA

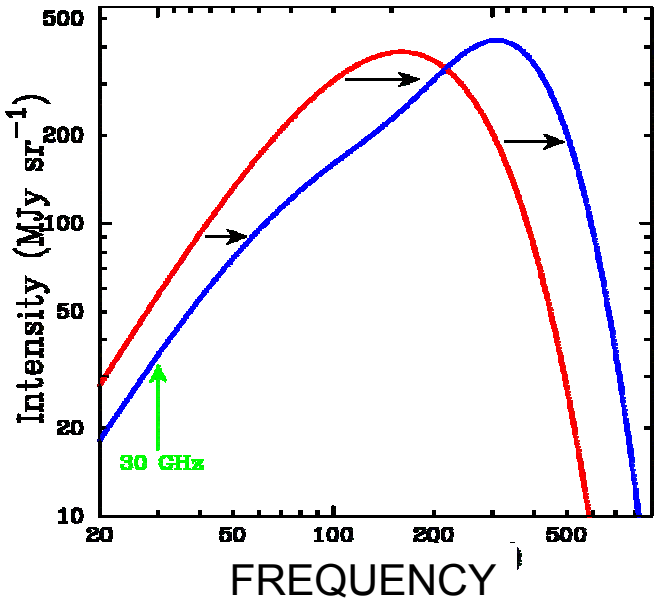
Galaxy Cluster Searches with the Sunyaev-Zel'dovich Effect

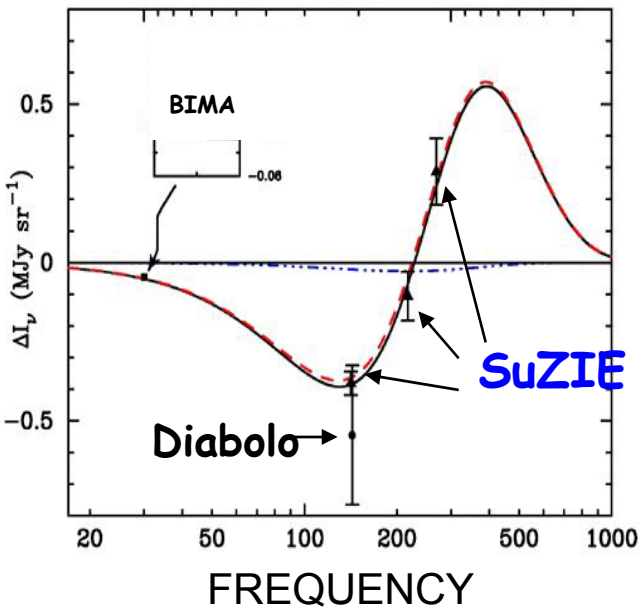
The Sunyaev-Zel'dovich (SZ) Effect



379,000 years

Prese

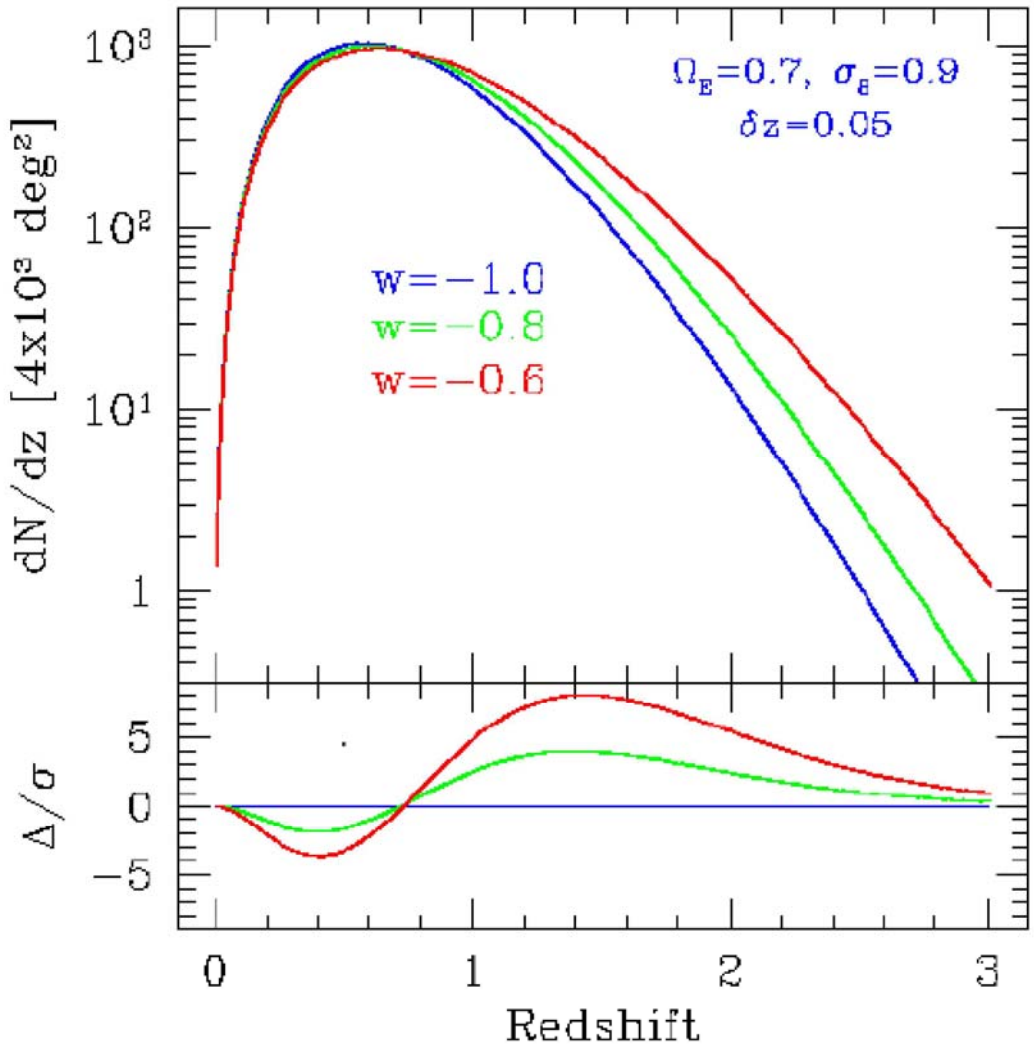




Compared to weak lensing, x-rays, optical:

- Signal independent of redshift
- Low false positive rate: deep potential well needed

Galaxy Cluster Surveys Probe Dark Energy



Atacama Pathfinder Experiment (APEX-SZ)

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

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

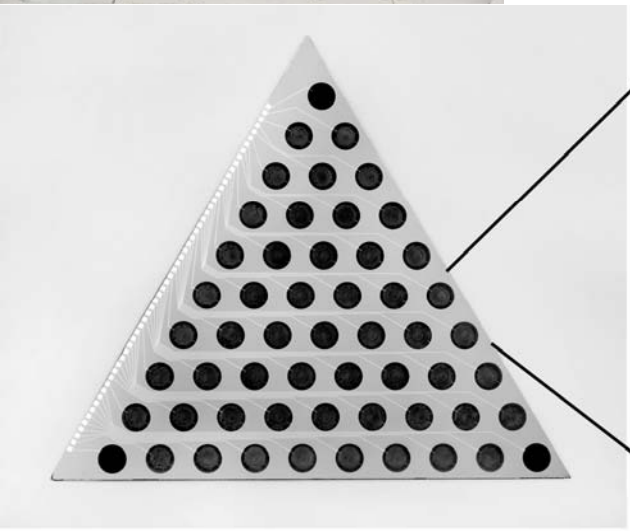
Berkeley SZ Receiver:

- 330 Bolometer array
- funded by NSF Astronomy
- Discover ~1000 Clusters/2yrs
  - Mass limit > 4×10^{14} M_0
- First Light *Fall 2005*.
- LBNL responsible for readout
- Probe of Dark Energy

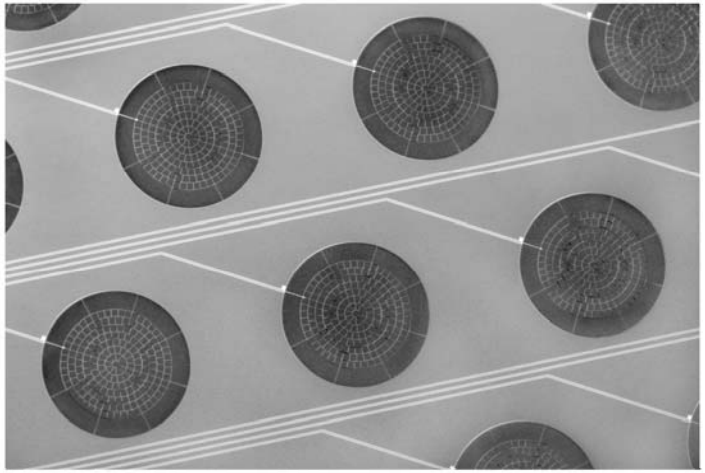
New APEX Hardware

reimaging optics
(LBNL Machine Shop)

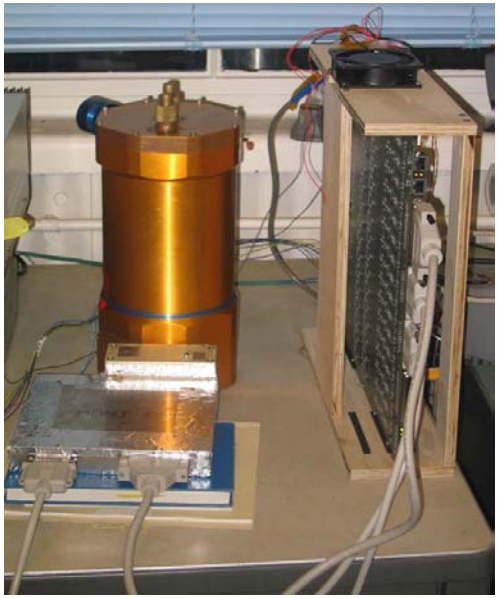
Bolometer Array
Prototype



7.5 cm

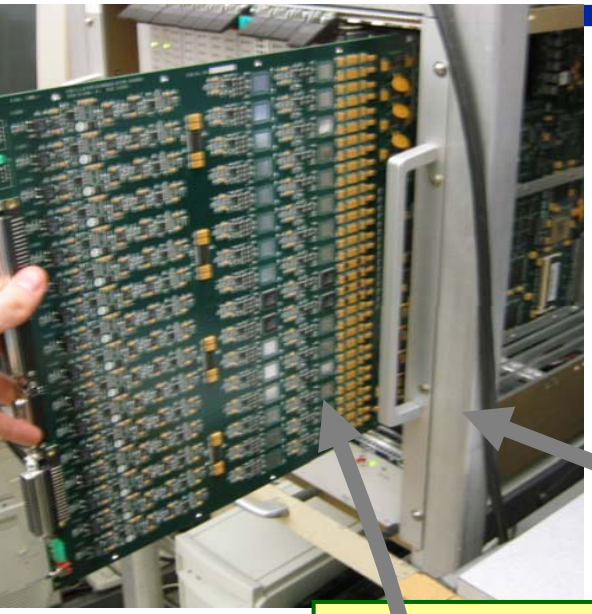


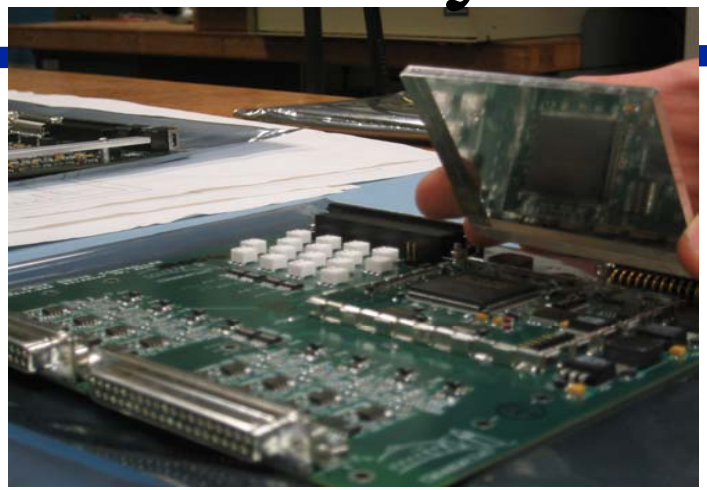
5 mm

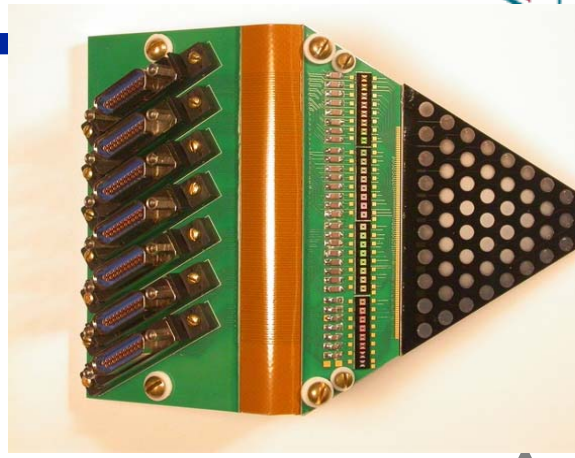


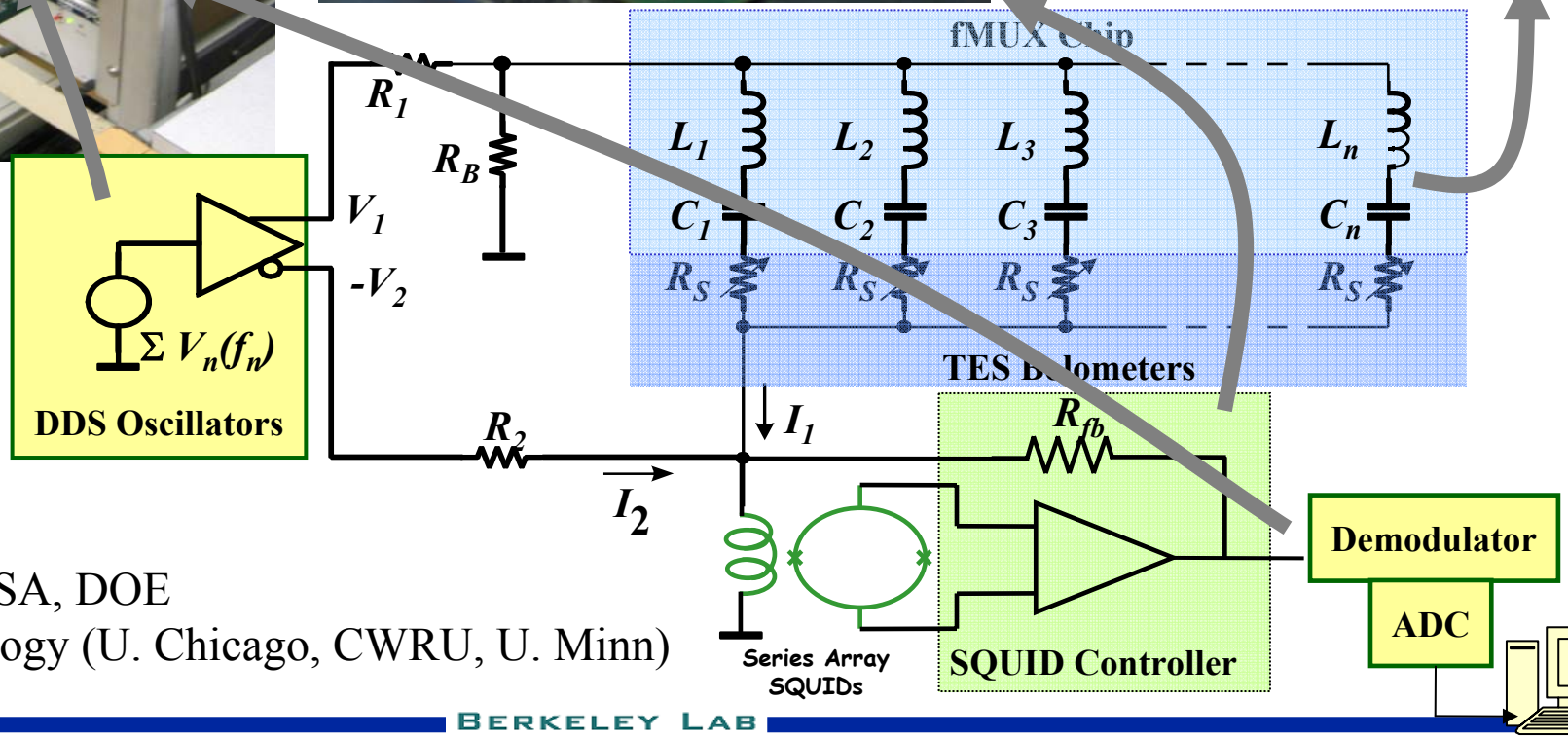
End-to-end test
of readout @
LBNL

Readout System





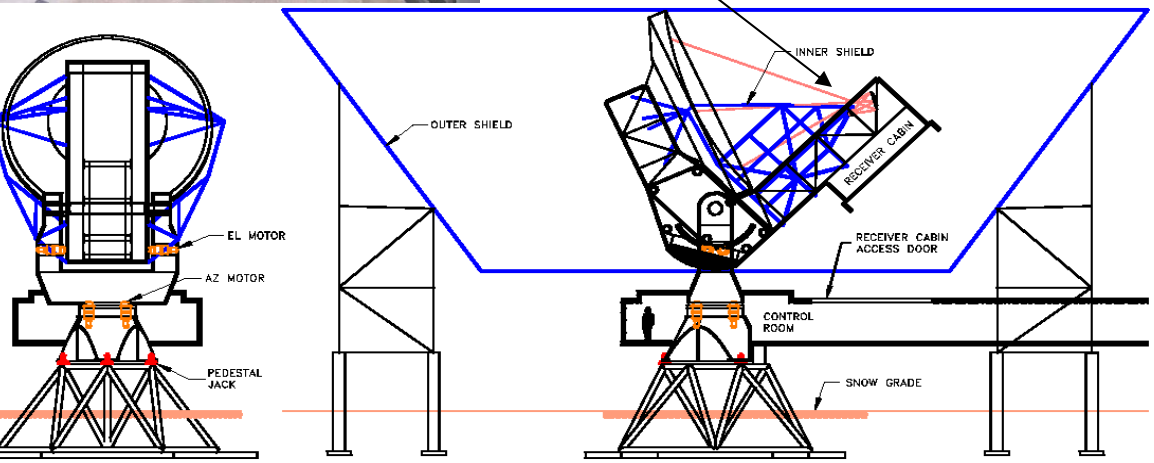


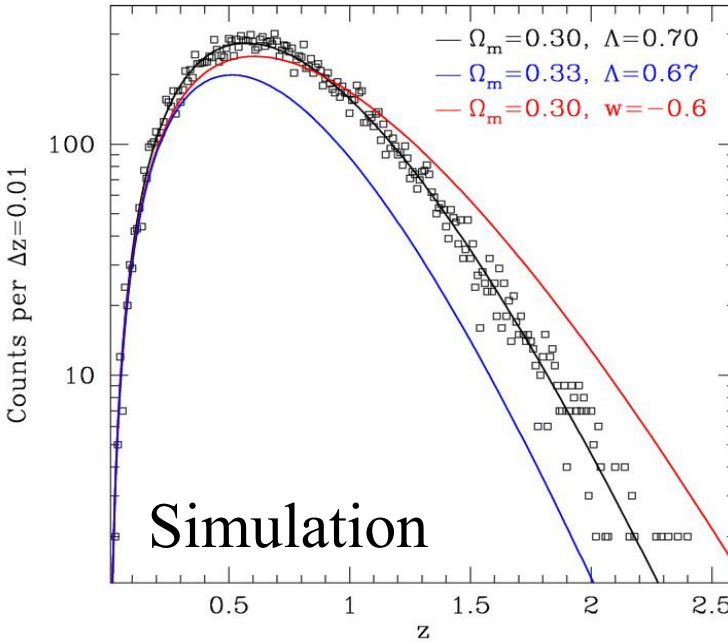


tial Work: NSF
velopment: NASA, DOE
porting Technology (U. Chicago, CWRU, U. Minn)

South Pole Telescope (SPT)

U. Chicago, UC Berkeley, Case, U. Illinois, LBNL, SAO





10 m off-axis telescope

1000 horn-coupled bolometers

10 μK/pix+4000 deg^2 => ~3 x10^4 clusters

Optical Followup with DES

NSF-OPP funded: First Light early 2007

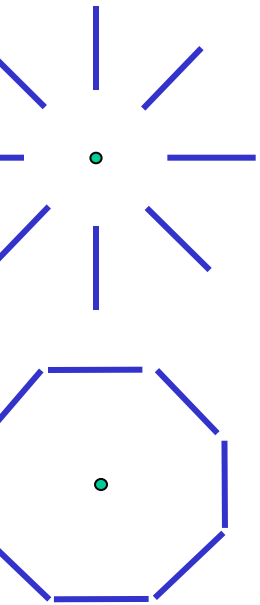
LBNL responsible for readout electronics

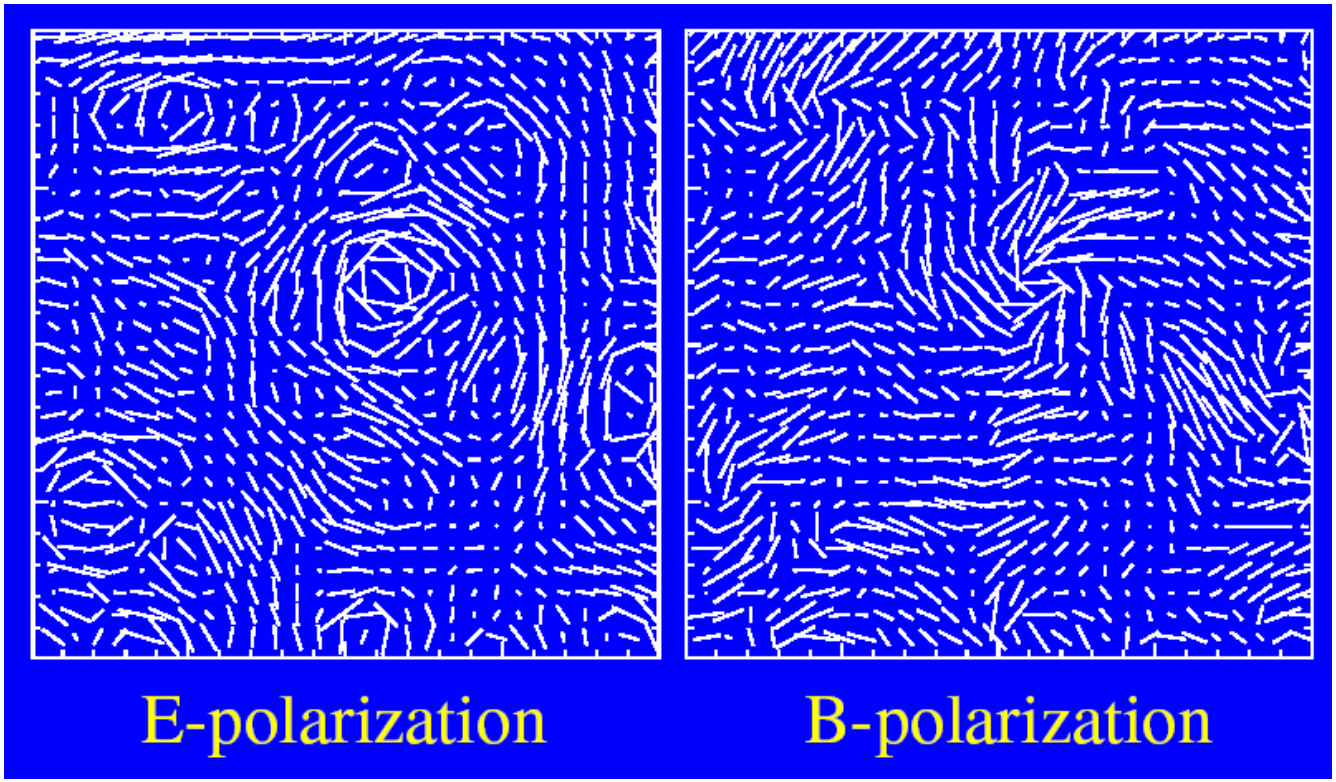
CMB Polarization

Polarization Patterns

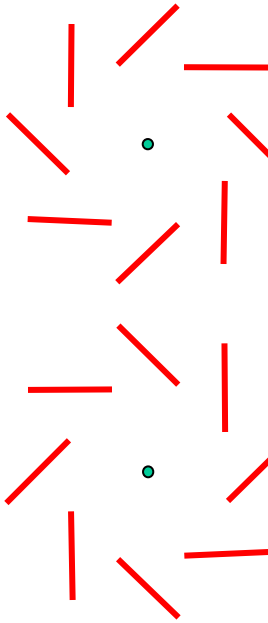
- Polarization Generation by Thompson Scattering

E-mode





B-mode

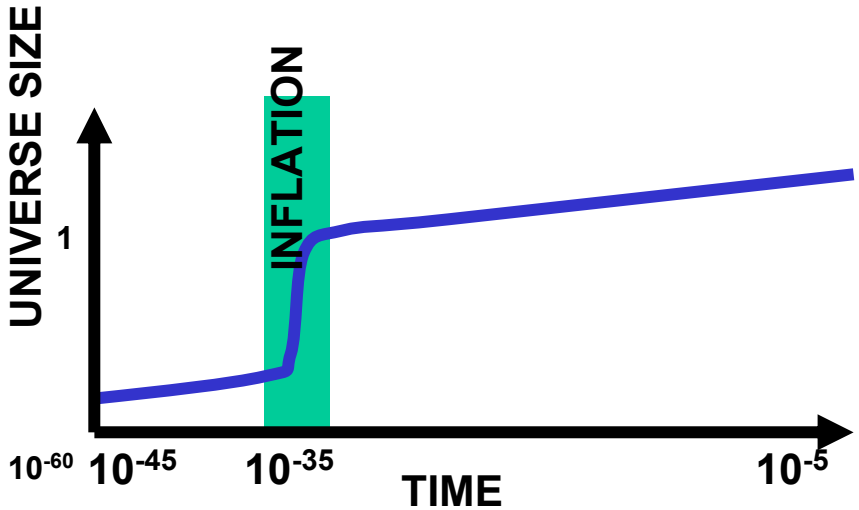


Wayne Hu

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

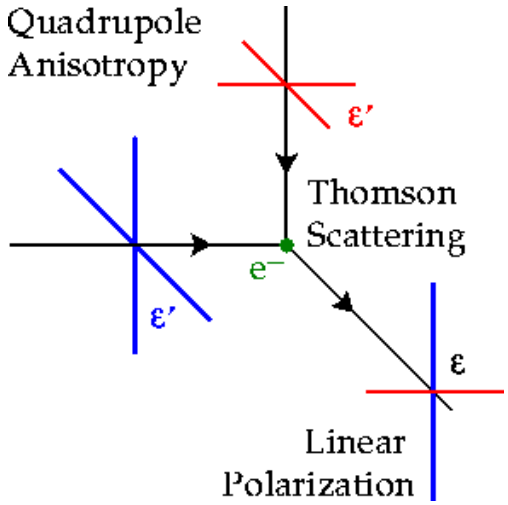
Physics of Inflation

- Inflation is a faster-than-light expansion of space-time
  - Naturally gives flatness and observed horizon scale



- Driven by vacuum energy
- Scalar Potential with associated particle -- Inflaton
- What is the Energy Scale?
  - Many theorists suggest 10^{16} GeV, If so, Inflation <==> GUT
- Is Inflation related to current acceleration??

Gravity Waves from Inflation



Linear polarization from Thompson scattering (same as with light from sky)

Linear Polarization comes from anisotropic photon flux

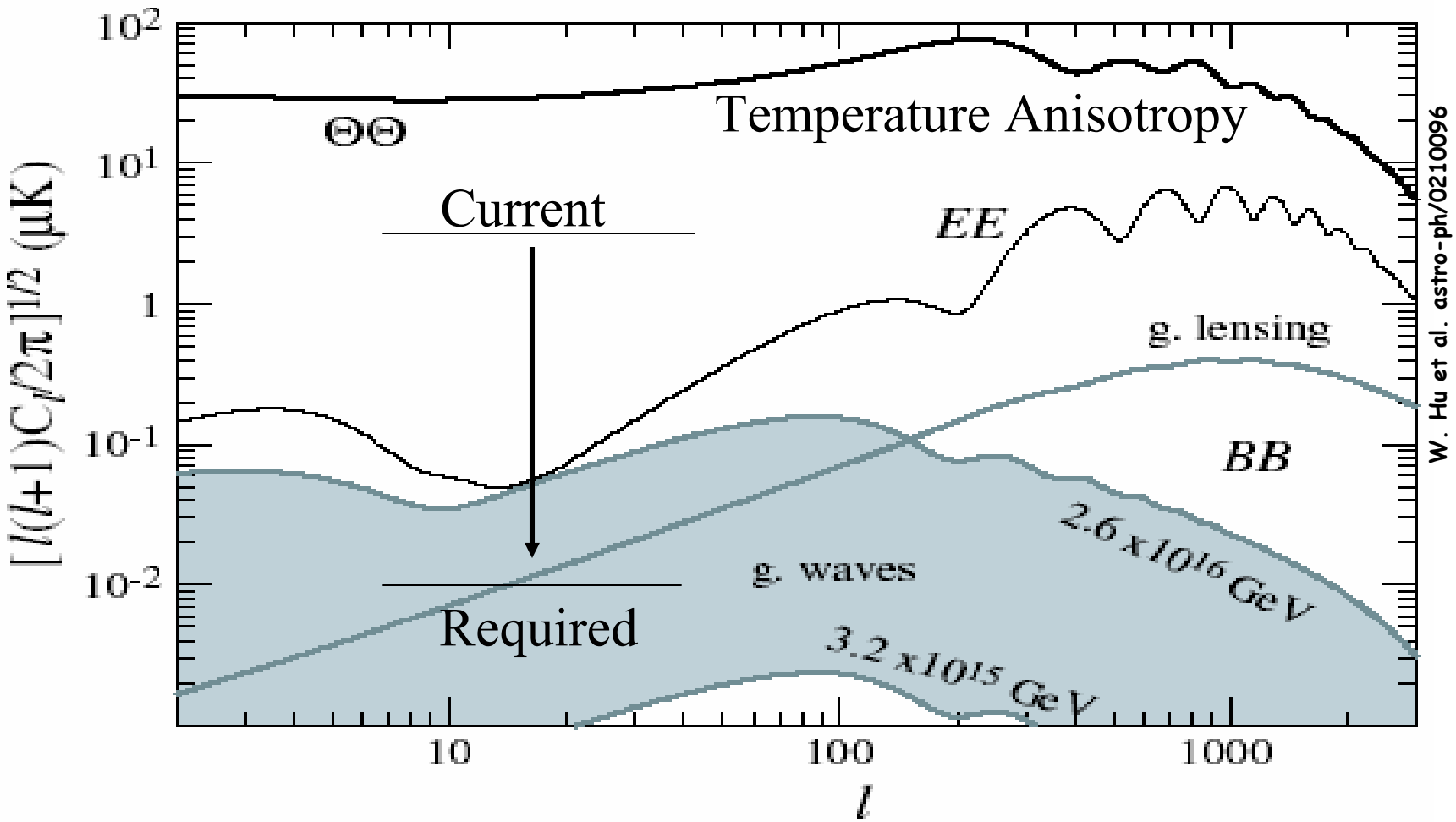
- Gravity waves create an anisotropic flux
- Gravity waves have handedness, and polarization patterns therefore do too (B-mode)

Amplitude of B-mode gives Energy Scale

- One possibility: GUT level 10^{16} GeV
- 12 orders of magnitude higher energy than accelerators!

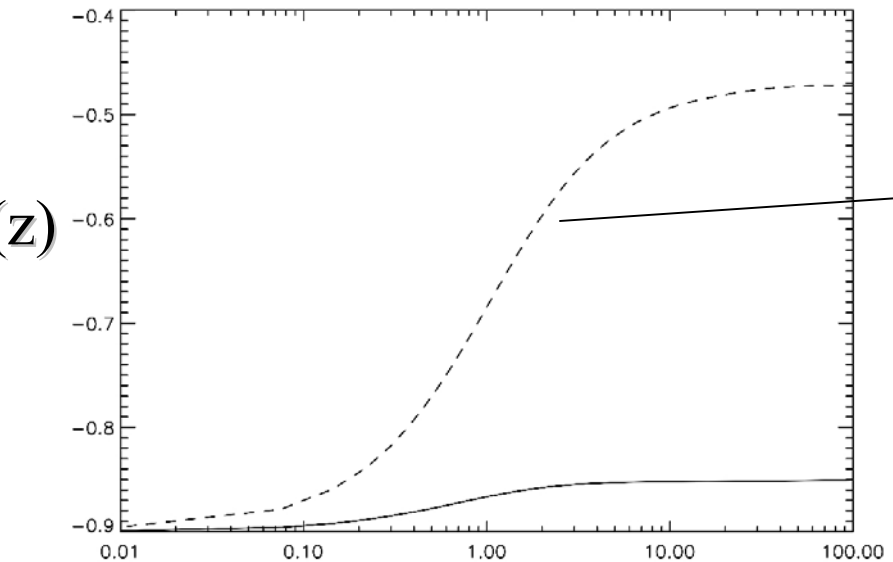
Quantum Gravity Regime

CMB Polarization Spectra

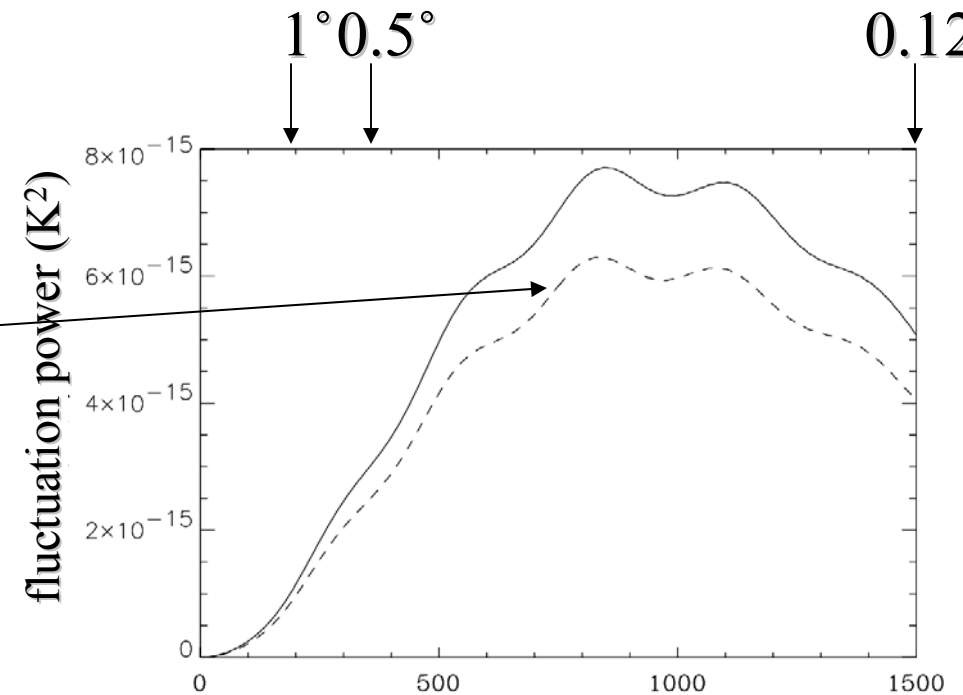


Dark Energy History and B-mode lensing

Example models



redshift z

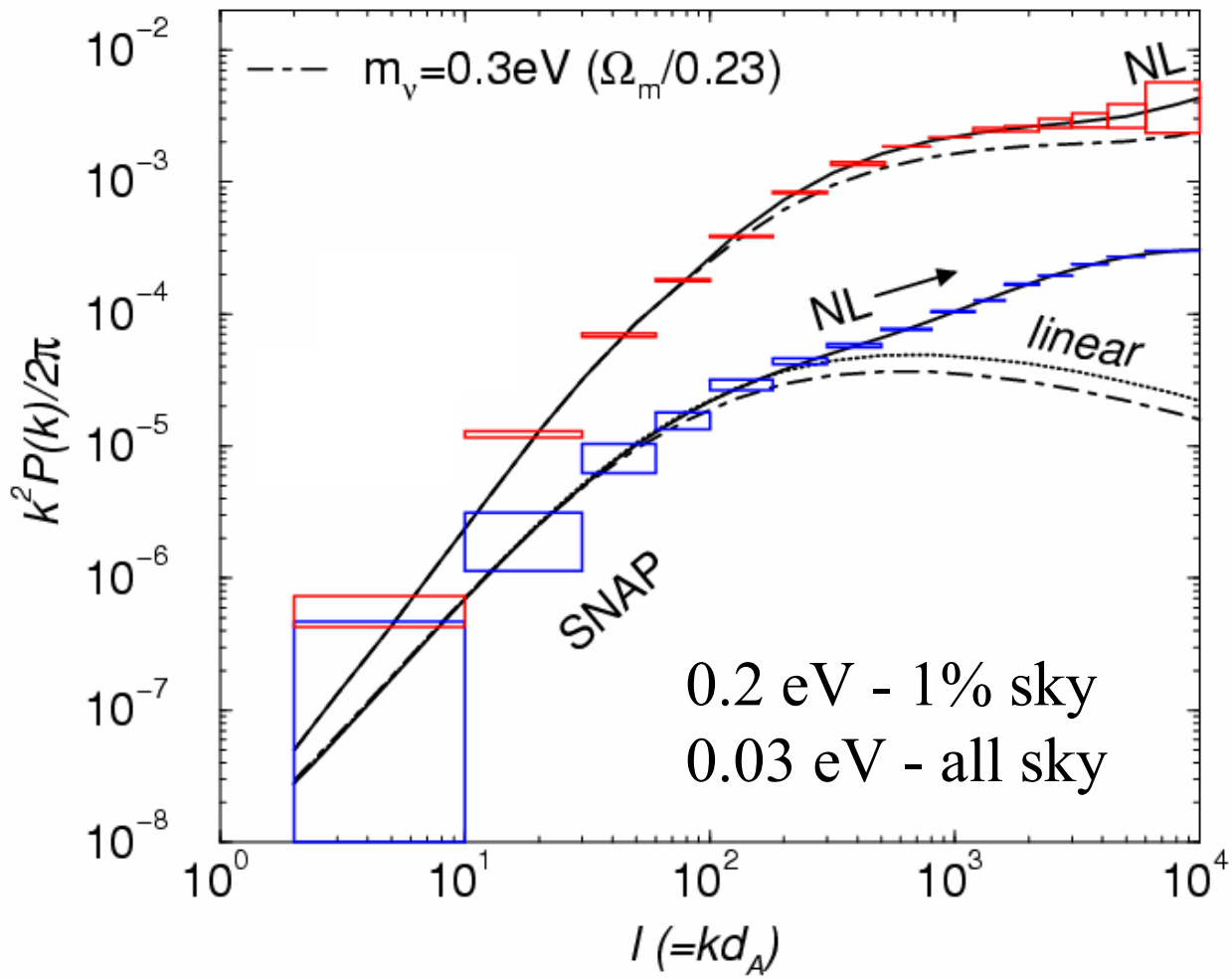


multipole l

- Early appearance of dark energy
  - => early acceleration
    - => delays structure formation
      - => reduces lensing power

V. Acquiviva and C. Baccigalupi (2005

Sum of Neutrino Masses from Lensing

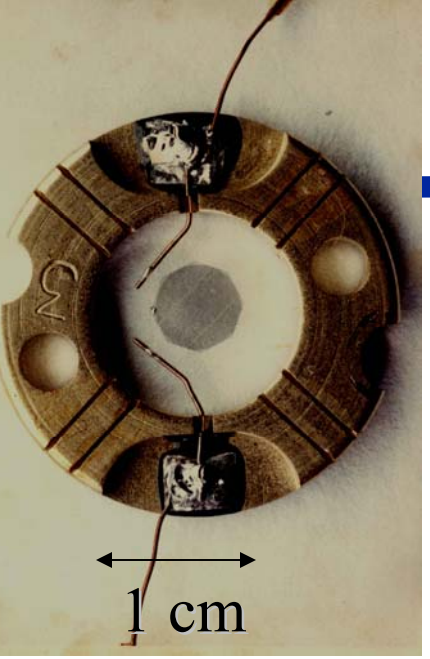


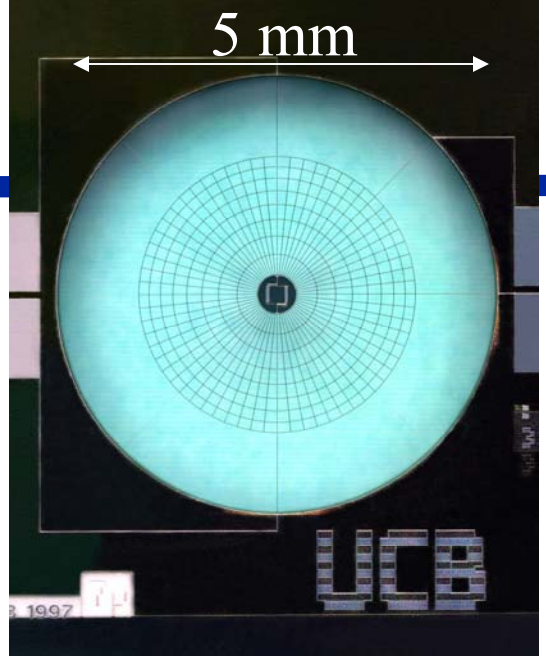
POLARBEAR (LBNL, UCB, UCSD)

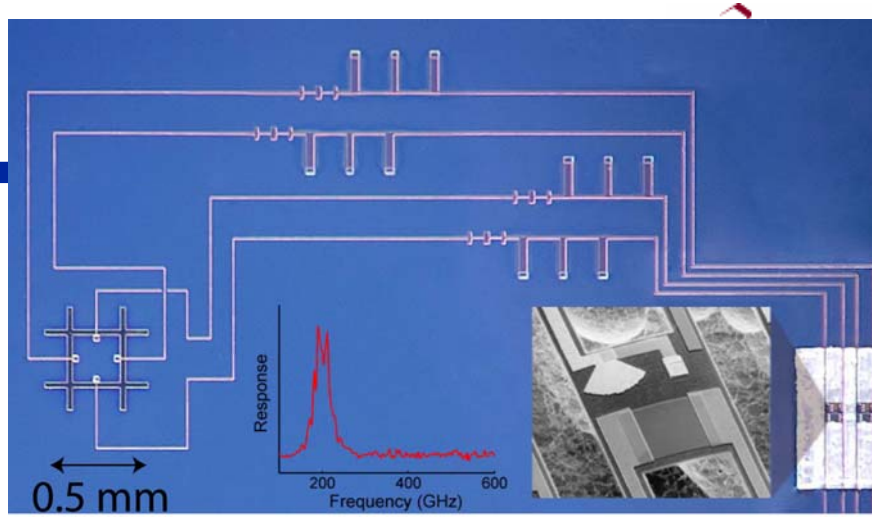
- Ground-Based 3 meter Telescope at Atacama Chile
  - Optimized for CMB Polarization
    - Characterize E-modes
    - Search for B-modes
- Novel Technology
- Ready for Construction
  - R&D under LDRD funding
  - Positive Review from SAGENAP
  - $6M over 5 years
  - Invited to Propose to DOE/NSF

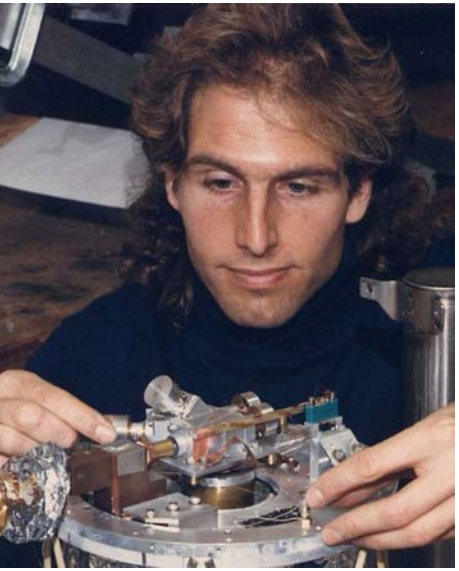
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

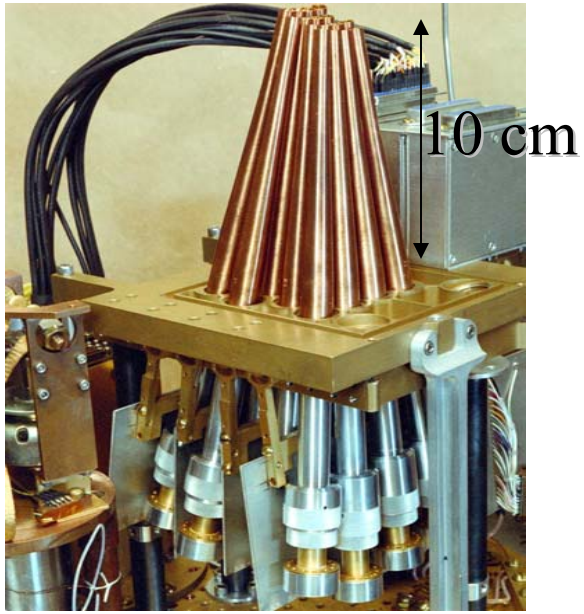
3m Telescope Design

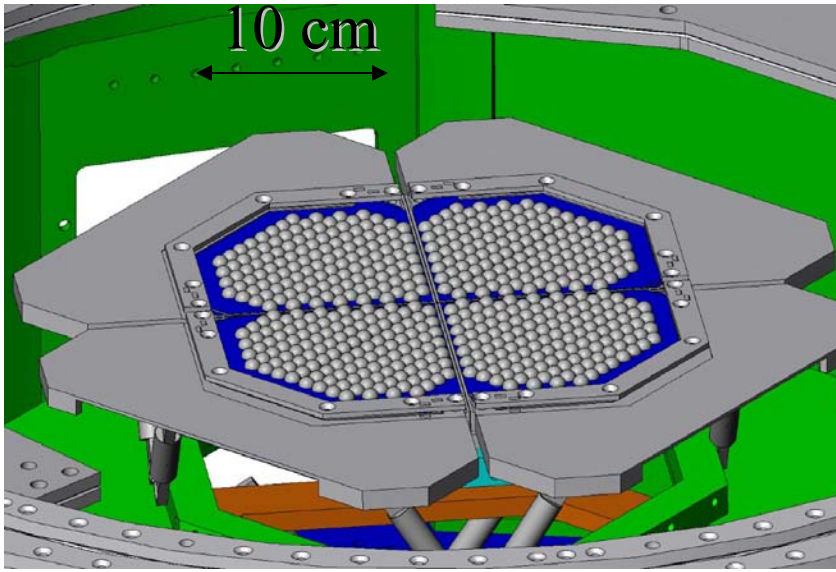






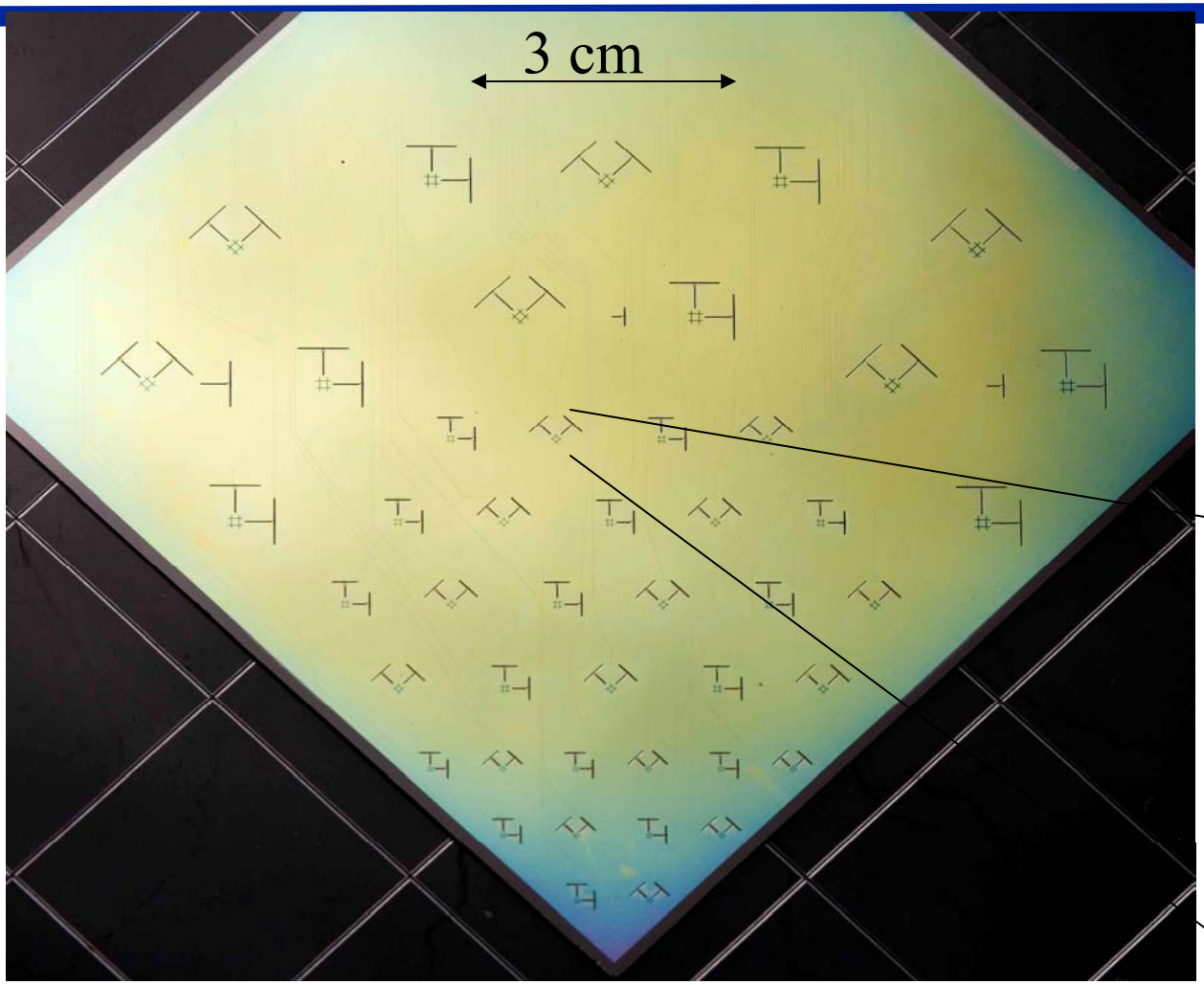


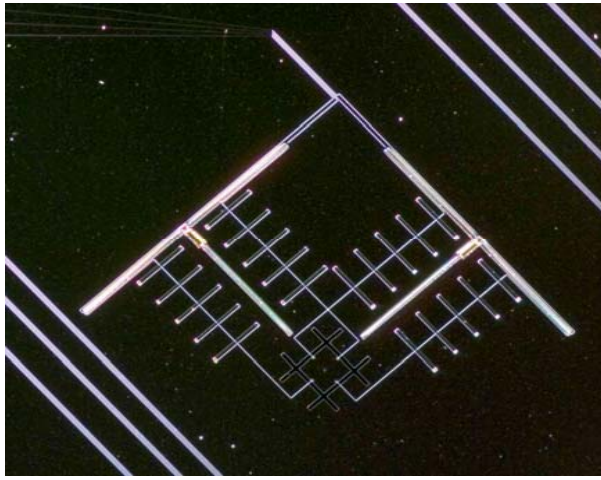




1980's 1990's 2000's

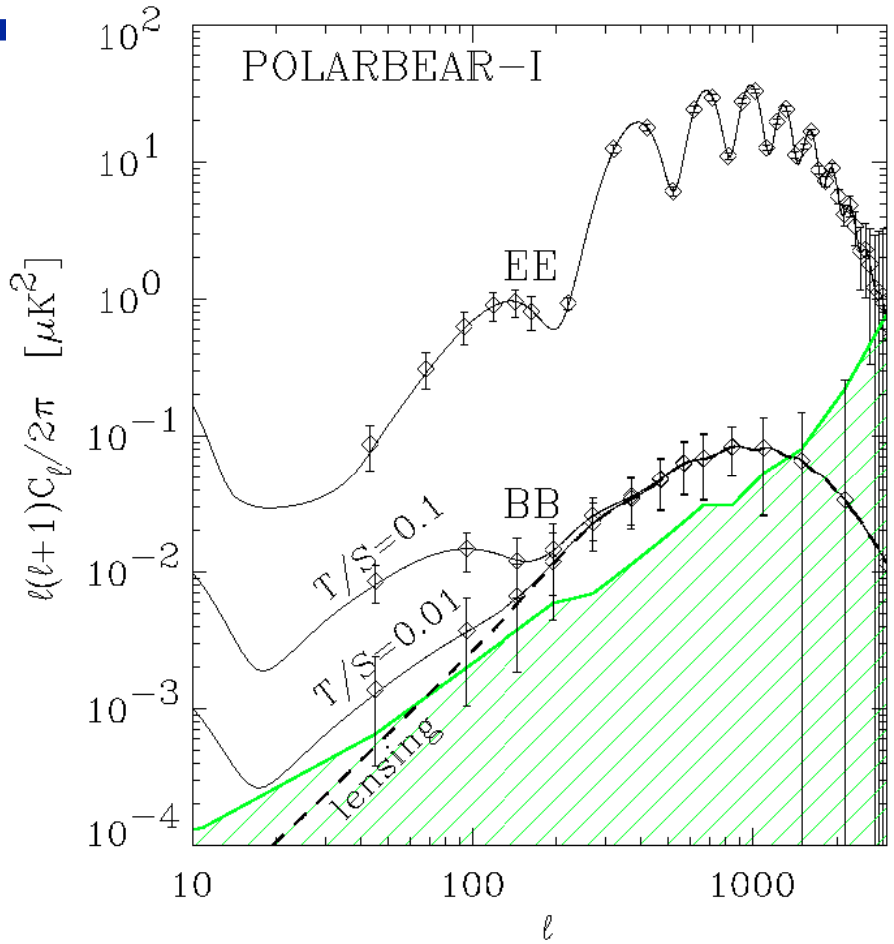
Antenna Coupled Arrays

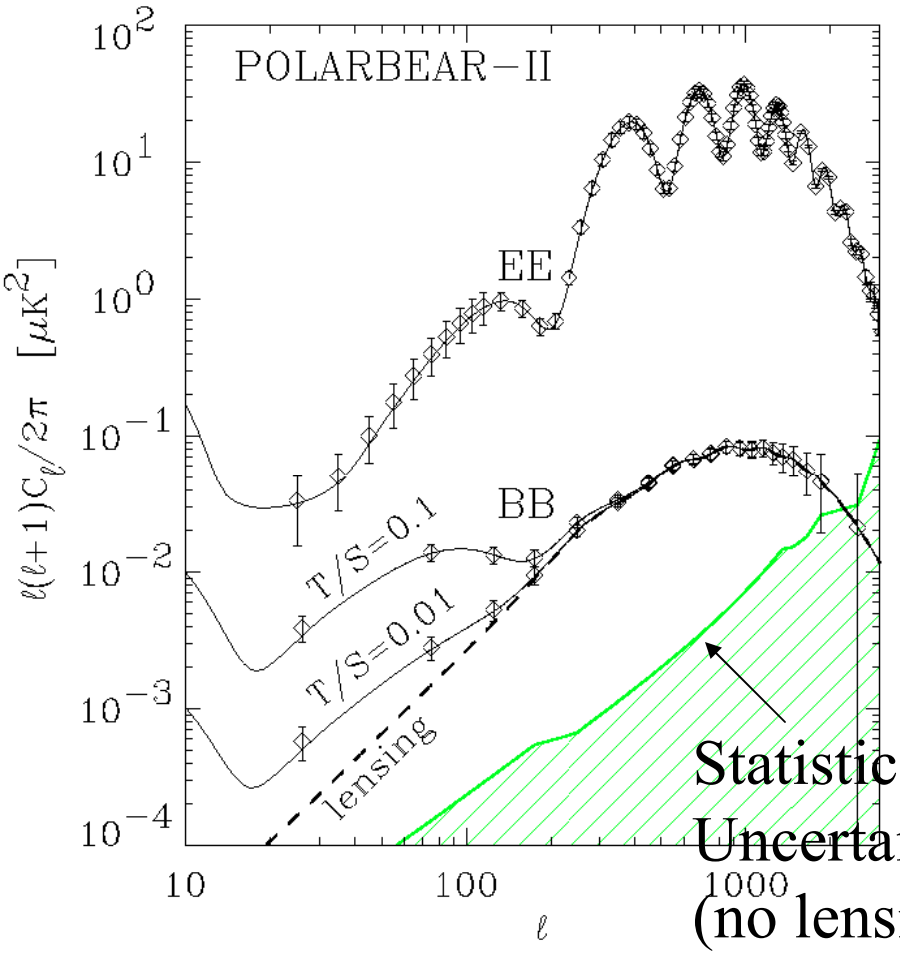




Single-color, dual-pol at 90, 150, 220 GHz

POLARBEAR Sensitivity





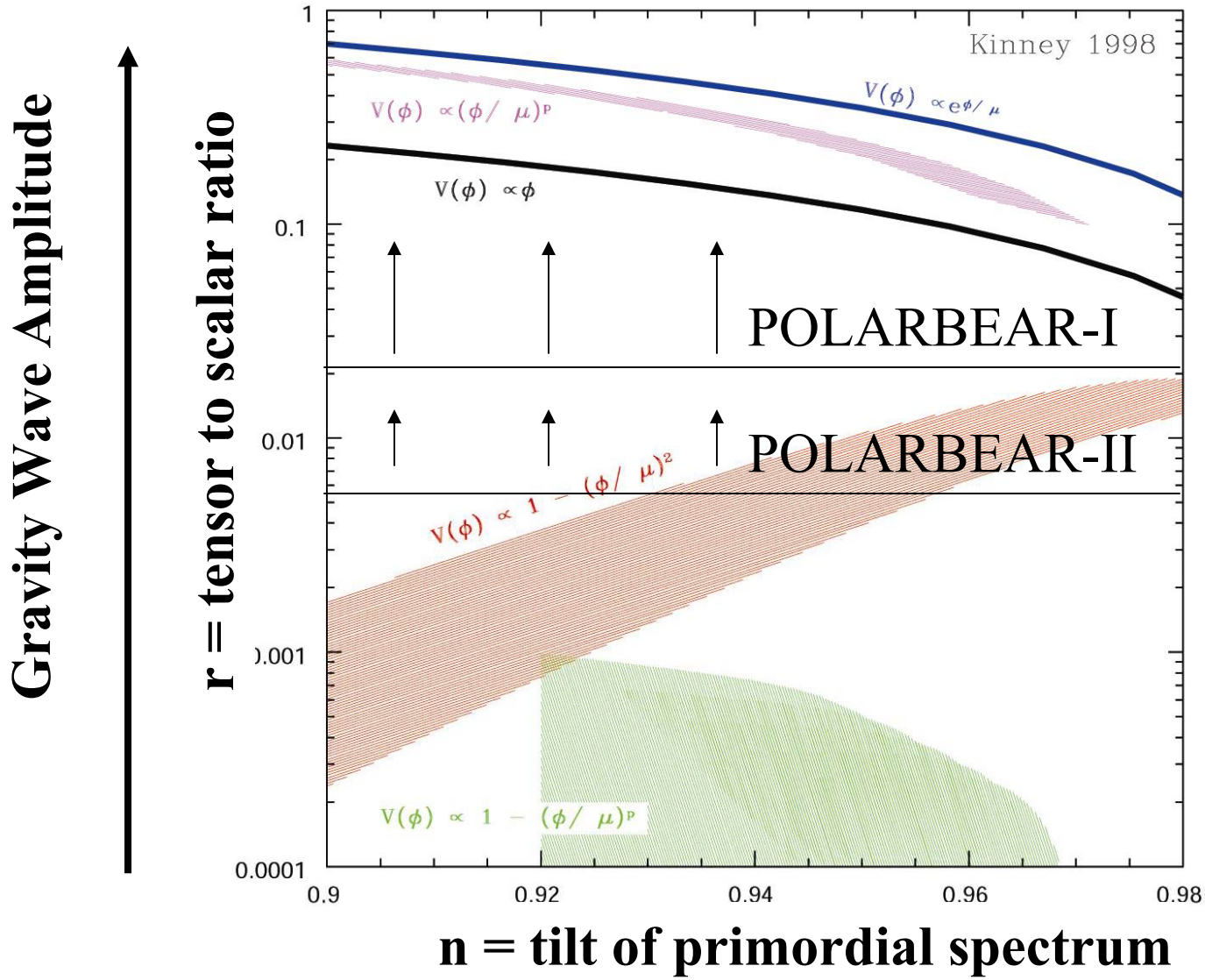
Statistical
Uncertaint
(no lensing

- Large Arrays + 3 Years Integration

  ==> 10^5 Effective Integration Time compared to MAXIMA

- Conservative Estimate using Achieved Sensitivity

PolarBeaR Performance



(300 Bolometer
@ 300 mK)

(1200 Bolomete
@ 300 mK)

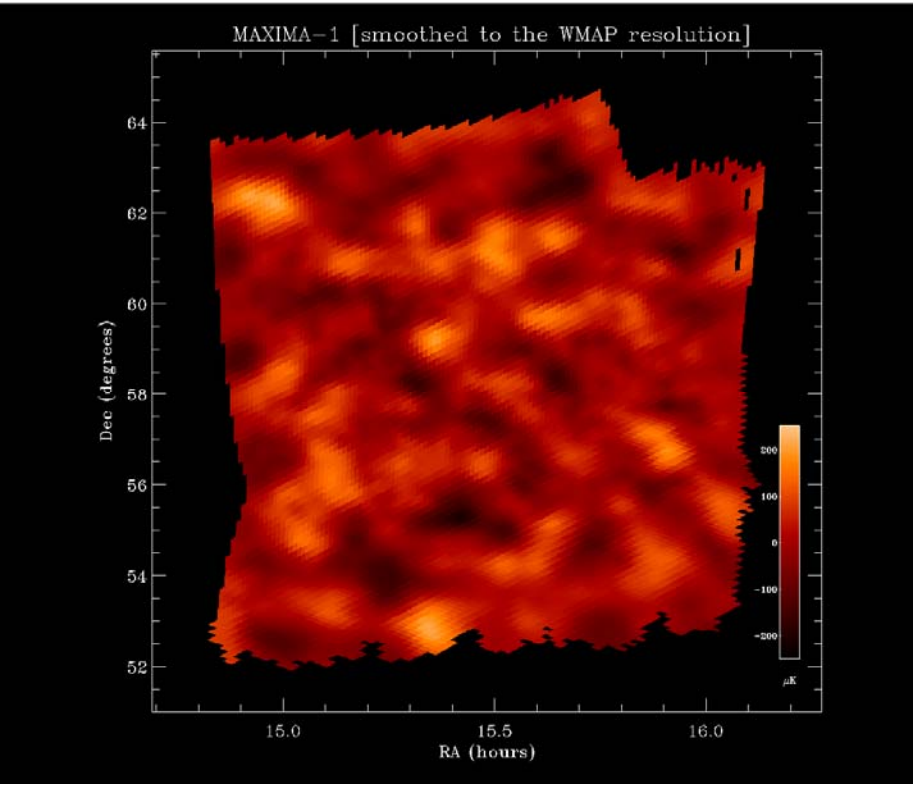
Includes Effect
of Lensing

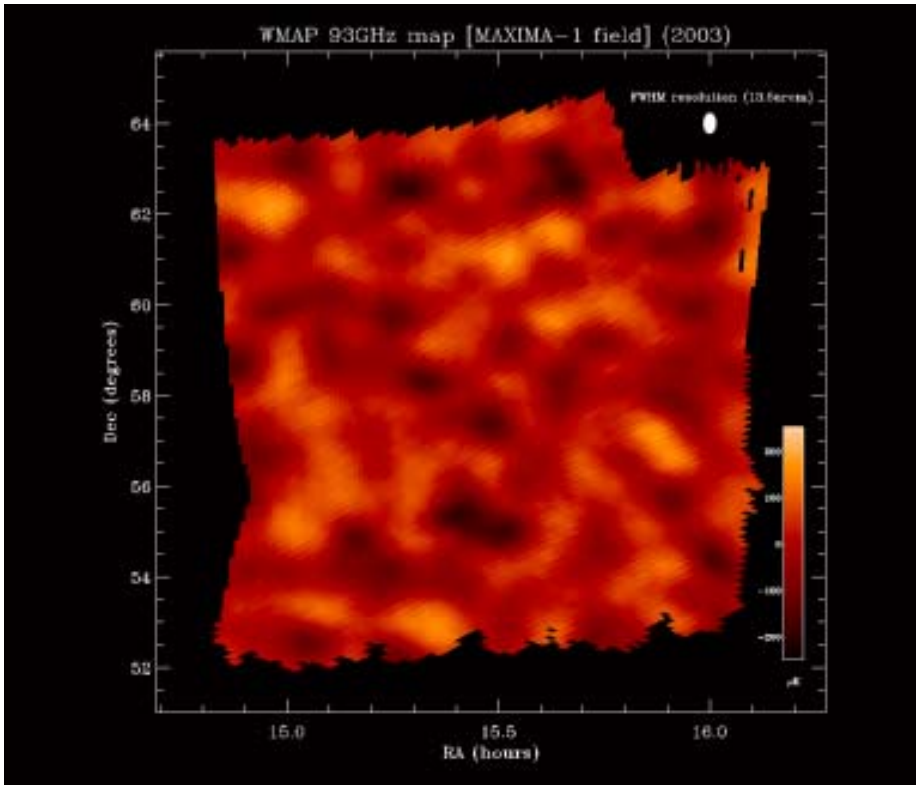
Systematic Uncertainties

- Polarization signals are small!
  - Use multiple levels of switching (chopping)
  - Use the rotation of the earth to vary polarization angle
  - Design the optics with low spurious polarization

- And there are bright foreground objects everywhere!
  - The nearby ground => use stringent shielding
  - The galaxy => use multiple frequencies to discrimination unique CMB spectrum

MAXIMA and WMAP





Statistically Consistent Measurements

SAGENAP Report

"In summary, POLARBEAR Represents a novel and highly promising technique to attack the important scientific questions addressed by measurements of polarization of the CMB. The group is strong and it has a good track record."

"We believe POLARBEAR is a project that merits funding and it should be considered by the agencies in the broader picture of the future of CMB measurements to be provided by the [tri-agency] CMB Roadmap study."

OMB CMB (Weiss) Taskforce

- ***"DOE has played a significant role over the years in supporting CMB anisotropy and spectrum observations through the program at Berkeley."***
- ***"The necessary receiver technology takes the CMB field into an area where DOE, NASA and NIST have prior experience in developing large format arrays."***
- ***"NIST, NASA, NSF and DOE funded groups are making significant contributions to detector development, and we urge continued and strong support for these efforts. Detector development is a particularly appropriate area for increased involvement by DOE in CMB research."***
- ***"We therefore recommend, as a highest priority, that DOE, NASA and NSF cooperatively plan and carry out a phased program of ground-, balloon- and space-based measurements of the polarization of the cosmic background radiation, with primary emphasis on mapping the B-mode, gravitational wave, signals in the CMB, to a sensitivity limited only by our ability to model the astrophysical foregrounds."***

LBNL and Future CMB Experiments

- LBNL has an irreplaceable role in the CMB Field
  - Expertise with large-scale detector systems
  - Expertise with large data sets
- Current: LBNL responsible for array readout
  - APEX, SPT
- Future: POLARBEAR
  - Lead role for DOE
  - A leap in capability beyond funded experiments
  - Positively reviewed proposal
  - Pathfinder for CMBPOL Satellite

END

Technology Development

- LBNL and Campus work as one group
- Novel LBNL contributions
  - current summing MUX architecture + design
  - shunt feedback SQUID amplifier
  - theory + process for selecting SQUID parameters
  - computer-controlled multi-channel SQUID electronics
  - multi-channel demodulator, digitizer + data readout
    - Direct Digital Synthesis low-noise carrier generators
    - high dynamic range readout
- LBNL responsible for APEX-SZ and SPT readout

CMB Polarization Satellite

Physics Division
BERKELEY LAB

One of three "Einstein Probes" will be "CMBPOL"

Berkeley/LBNL/CIT/JPL et al. in Study Phase

LBNL infrastructure allows strong role for Berkeley

– Critical mass for large project scale

POLARBEAR : testbed for potential CMBPOL technology + observations