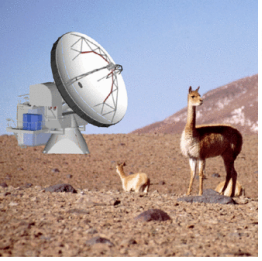
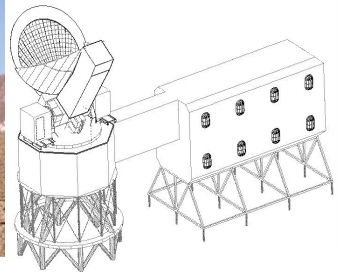
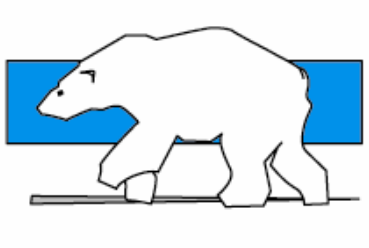

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Cosmic Microwave Background Program at Berkeley

Senior Scientists

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

Engineers

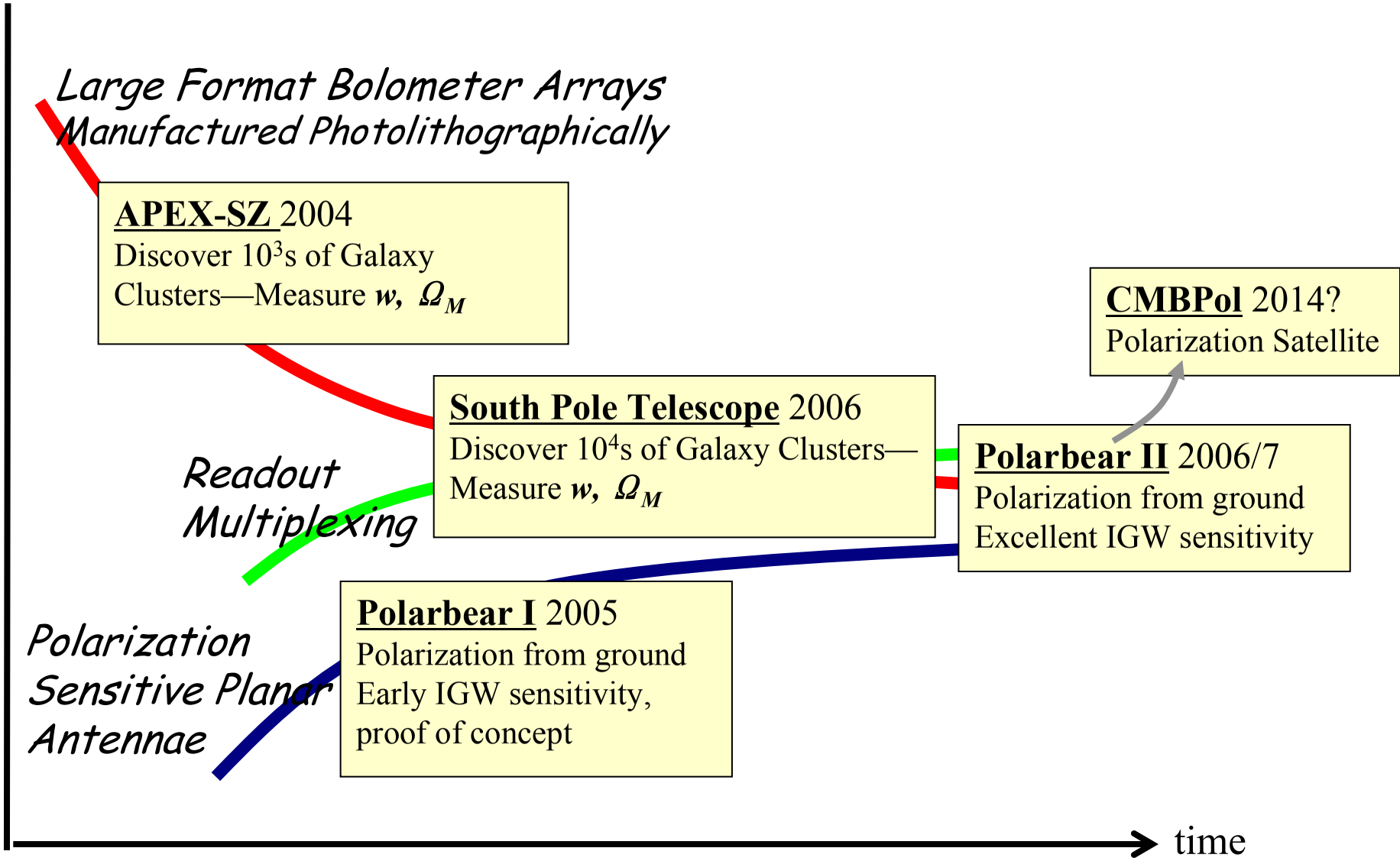
John Joseph (LBNL)
Chinh Vu (LBNL)

Scientists

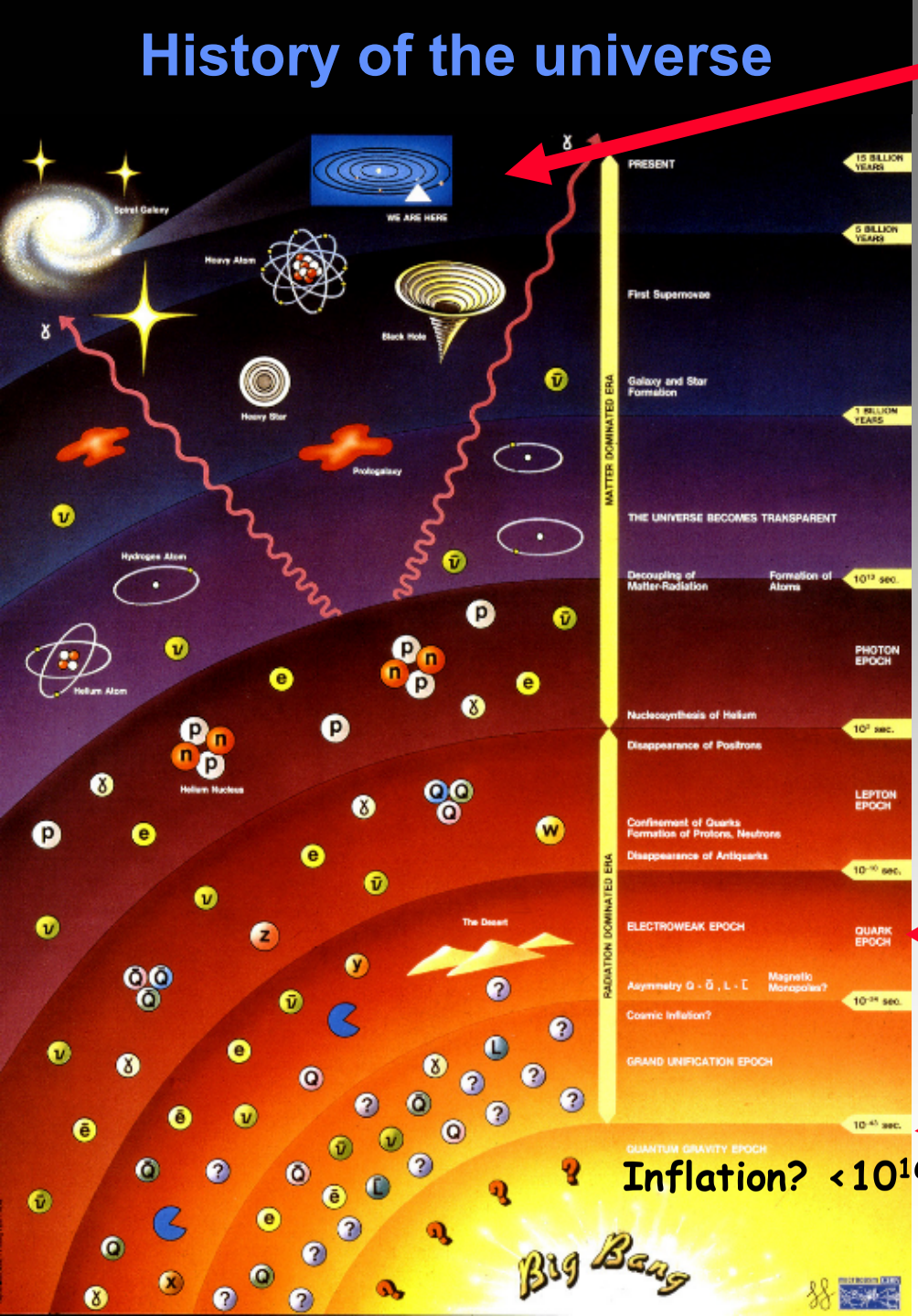
Alex Amblard (UCB)
Julian Borrill (LBNL NERSC)
Chris Cantalupo (LBNL NERSC)
Sherry Cho (UCB)
Matt Dobbs (LBNL)
Nils Halverson (UCB,SSL)
Radek Stompor (LBNL NERSC)
Huan Tran (UCB)

+ ~10 Graduate Students
Few Undergraduates

New Instrumentation↔New Experiments



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)

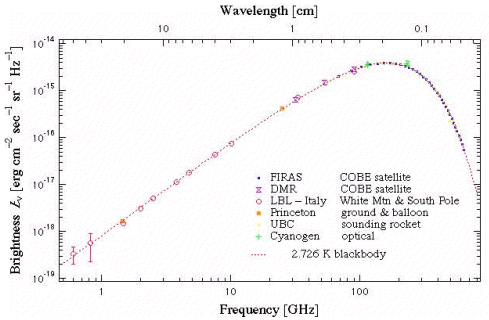
←Quarks Differentiate (10^{-34} sec ?)

Inflation? $<10^{16}$ GeV

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

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

  (≠0 monopole)

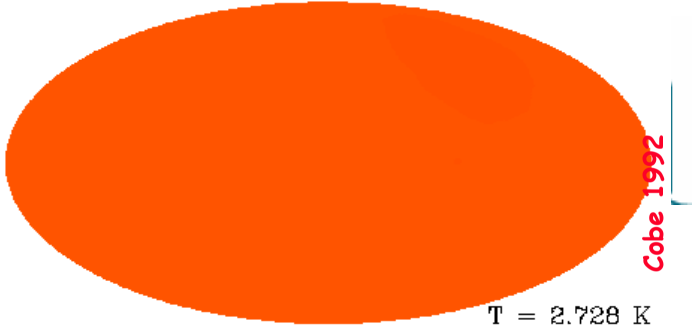


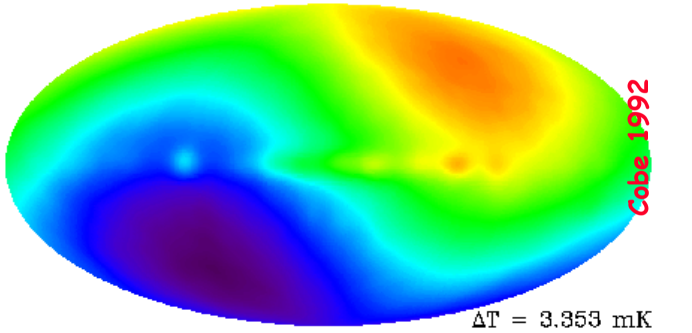
- Dipole Anisotropy 10^{-3}

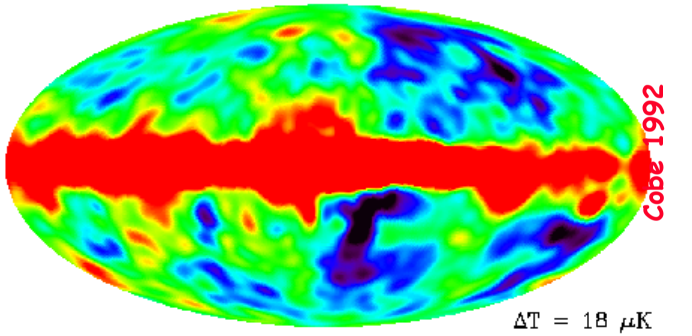
  (≠1 dipole)

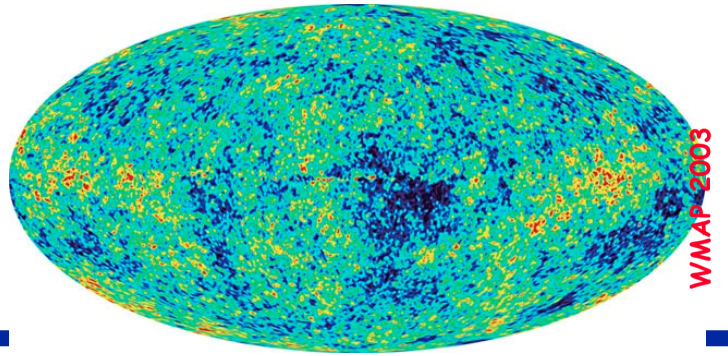
  (our motion in the CMB `rest frame')

- Temperature Anisotropy 10^{-5}

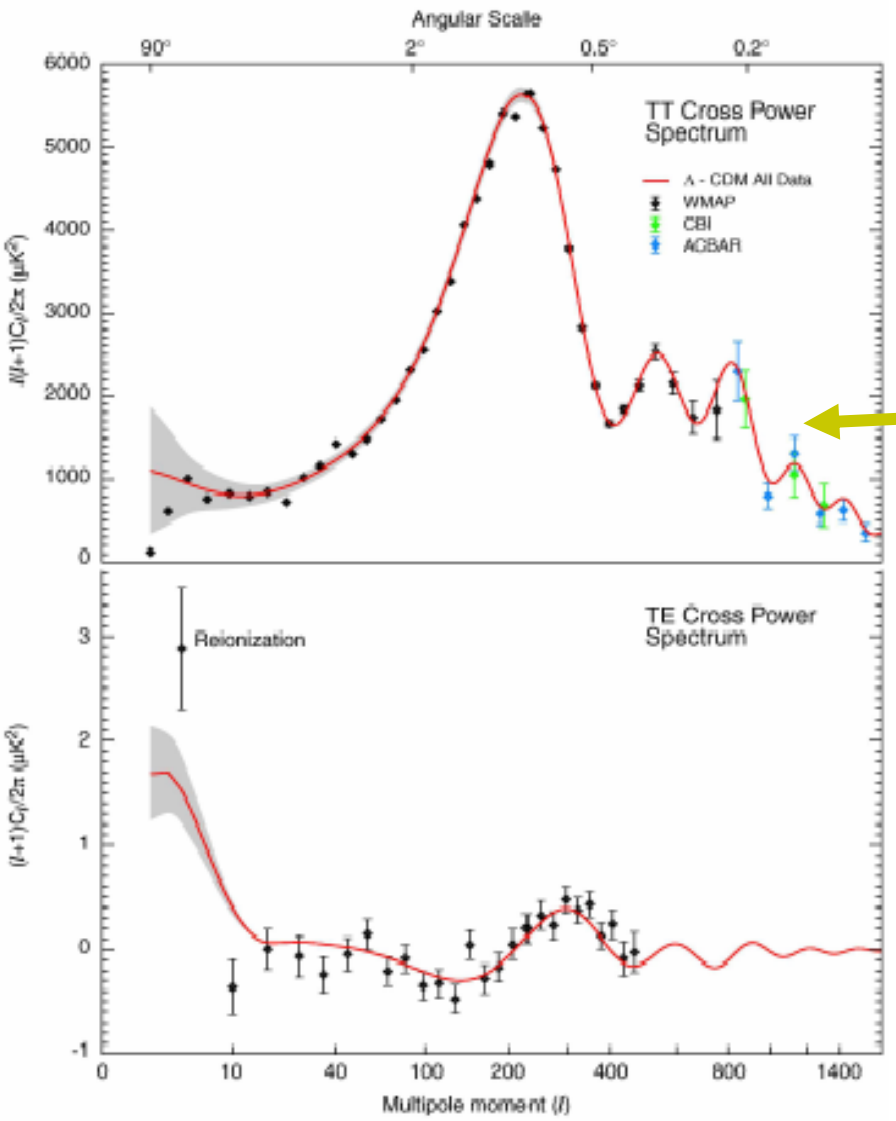








Where We Stand post-WMAP



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

Science Endorsed by Nat. Review Panels

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Quarks to the Cosmos report questions from the ***Turner panel***:

1. What is the dark matter?
2. What is the nature of the Dark Energy?
3. How did the universe begin and how did its present LSS form?
4. …

Barish/Bagger Long Range HEP Planning Report

"origins of dark energy and dark matter are important components of a broader program of cosmological measurements including the CMB and LSS…"

…"more than one approach will be necessary to understand the nature of dark energy"

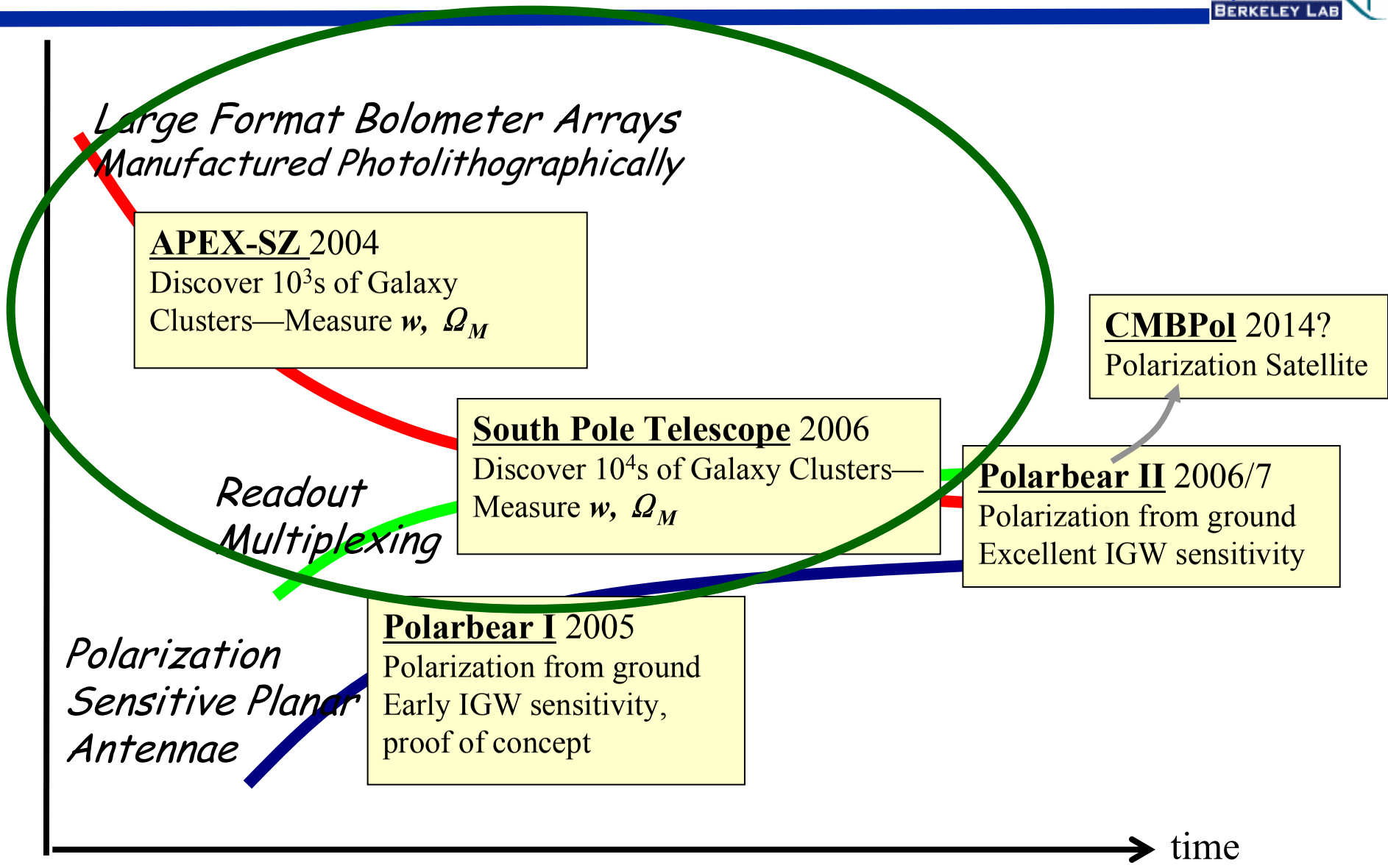
Independent confirmation of the ***w*** measurement
APEX-SZ
• **South Pole Telescope**

Precise measurement of ***w, w'*** with **SNAP**

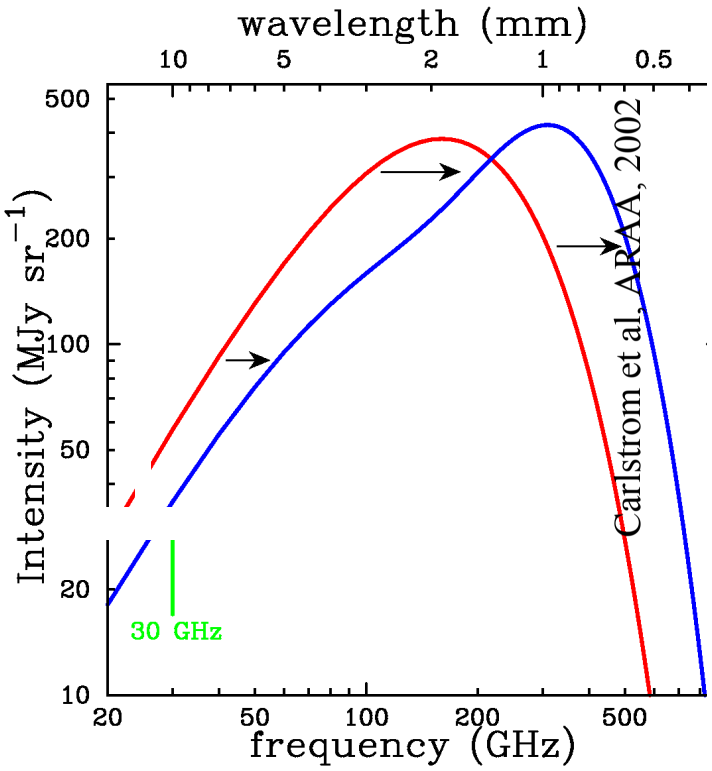
Inflationary Gravity Waves in the CMB Polarization
• **POLARBEAR**
• **CMBPol Satellite**

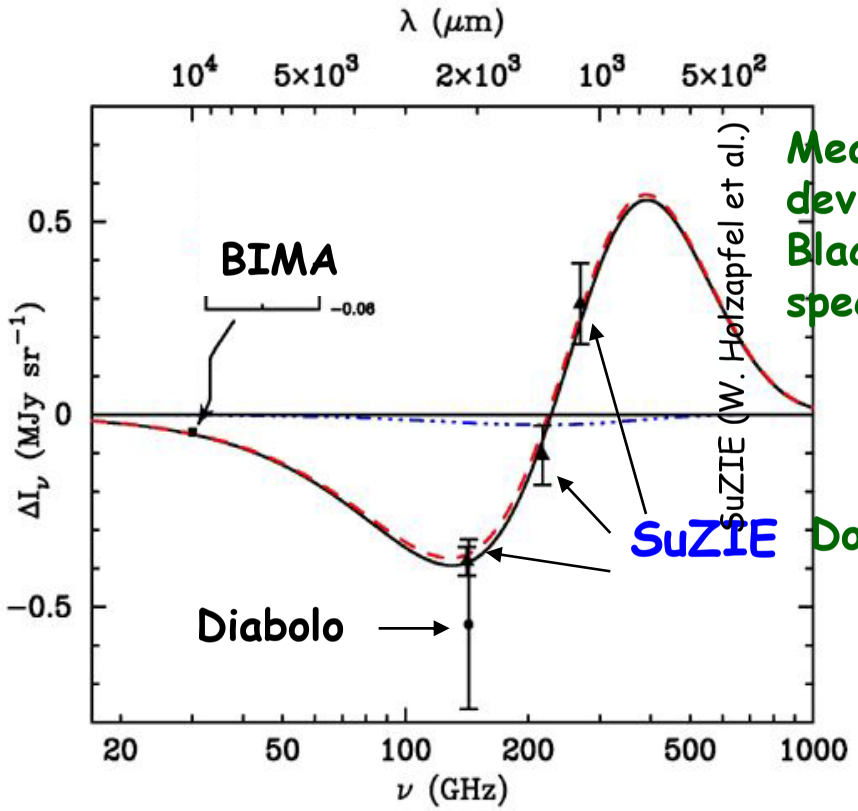
Charles Shank, 2003 State of LBL Address
"…laboratory goal to understanding the nature of Dark Energy."

New Instrumentation↔New Experiments



Sunyaev Zel'dovich Effect





Measured deviation from Black body spectrum.

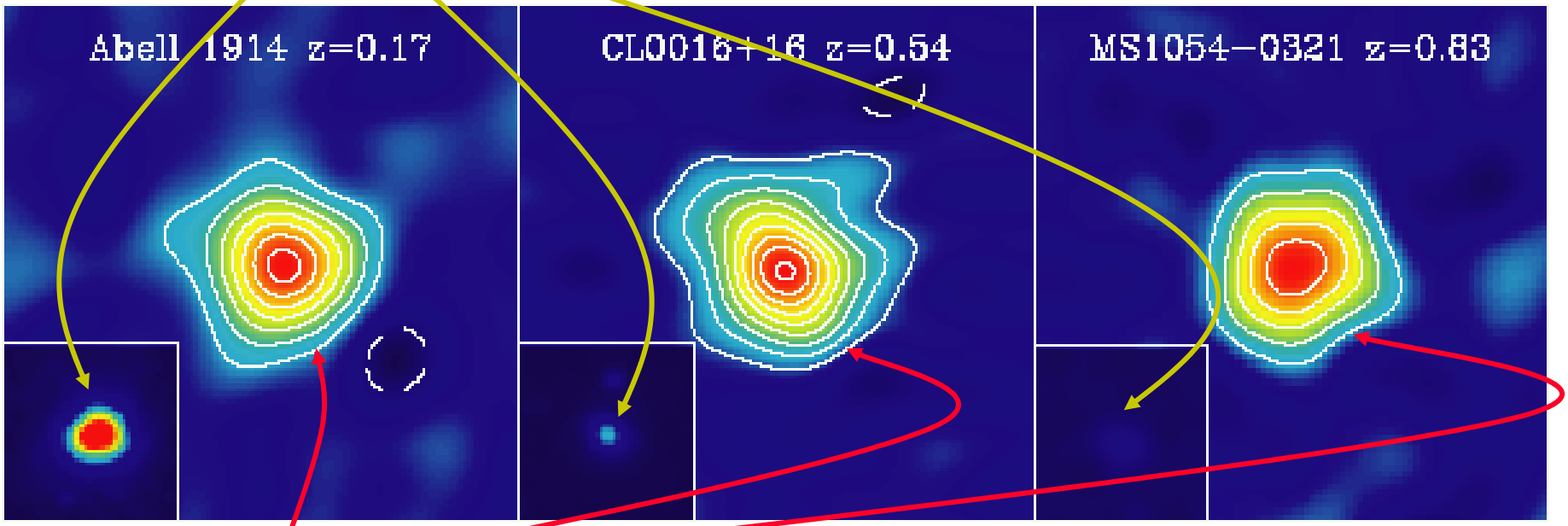
Dotted line: Kinetic SZ

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.

Sunyaev Zel'dovich Effect is Independent of Distance

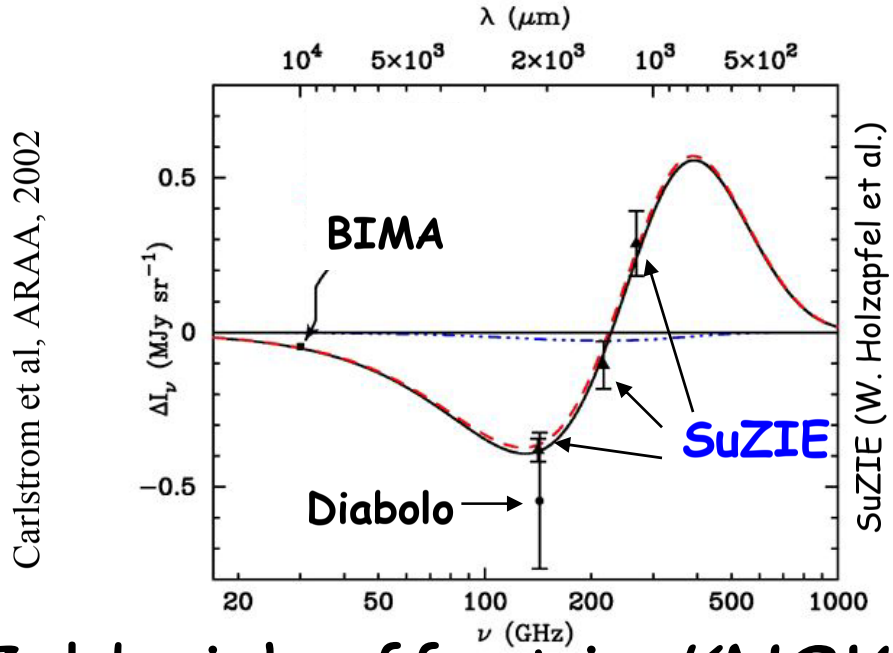
- In the X-ray sky, clusters fade away at high redshift.



- SZ observations are independent of redshift

→ *Clusters can be seen at any distance.*

SZ State-of-the-Art TODAY

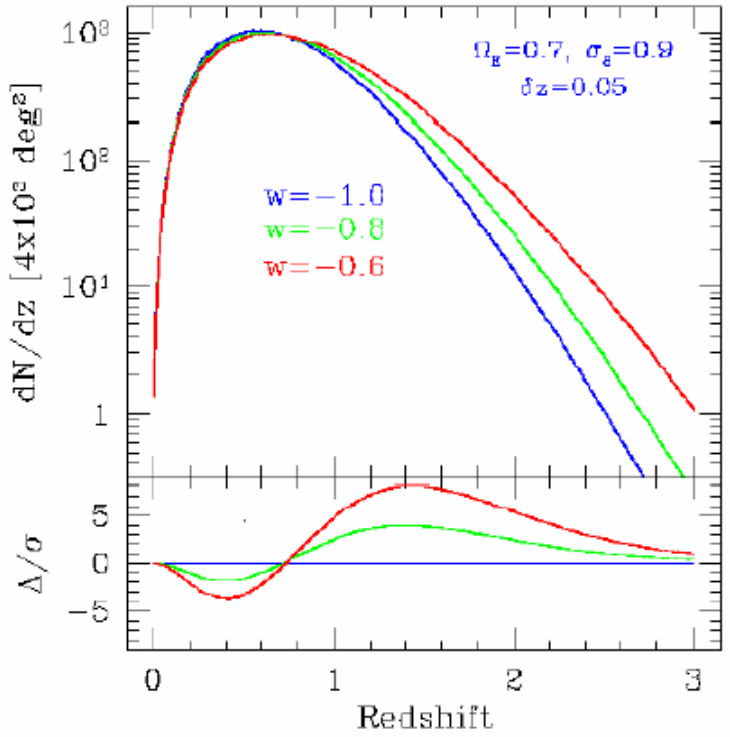


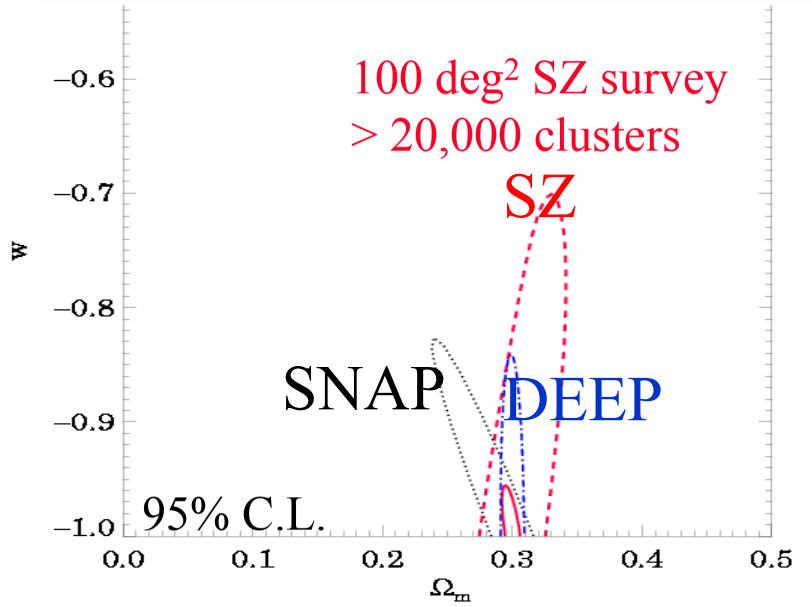
- Sunyaev Zeldovich effect in *KNOWN* galaxy clusters observed.
- No clusters have been *DISCOVERED* with SZ yet.
- No observation of kinetic SZ yet.

Simulations from M. White.

SZ Effect

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



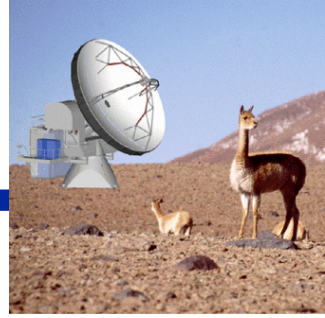


- Instrumentation development #1:
  - *Large Scale Bolometer Arrays manufactured Photolithographically*
- Implementation:
  - *APEX-SZ Galaxy Cluster Survey*

APEX Sunyaev Zel'dovich Receiver

- Bolometer technology is approaching the photon statistics limit.
  - We can't do better by building a better bolometer.
    1. Increase integration time by going to ground based observations.
    2. Make many measurements at once using large scale arrays
- APEX-SZ: 320 Element superconducting transition edge sensor array
- Noise: 250 μK $\sqrt{s}$ at 2mm.
- will thus measure one square degree of sky to an RMS of 10 μK per three hours of observation!
- discover ≈ 5000 Galaxy Clusters in 250 degrees^2
  - Mass limit of 4×10^{14} Solar Masses

Atacama Pathfinder Experiment (APEX)



Mechanical Installation in Chile Completed.

Telescope

- Located at 16,500 feet in the Chilean Andes.
- 12m on-axis ALMA prototype
- 45" resolution at 150 GHz
- 30' field-of-view
- Telescope funded and under construction by **MPIfR/ESO/Onsala.**

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

- **First Light *Fall 2004*.**

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

Physics Division
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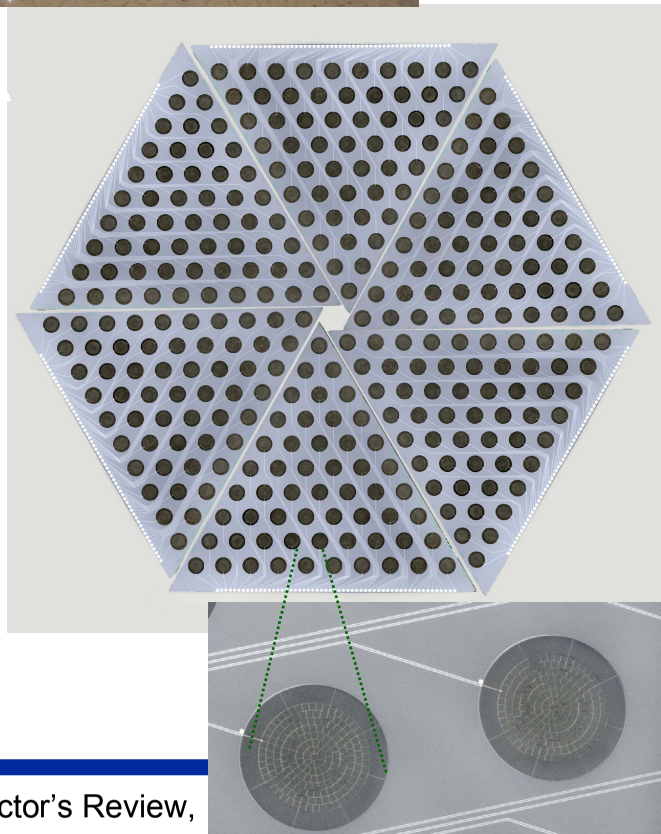
Since last year's review:

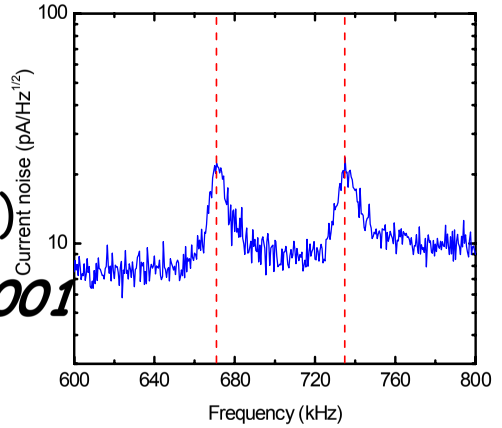
- Pulse tube cooler technology proven
  - noise characteristics carefully studied and understood
  - eliminates need for liquid cryogens $\Rightarrow$ remote operation
- 55 element Spider-web TES Bolometer array fabricated and tested.
  - demonstrates our abilities for large scale photolithographic production
- Prototypes for each element of readout system tested.

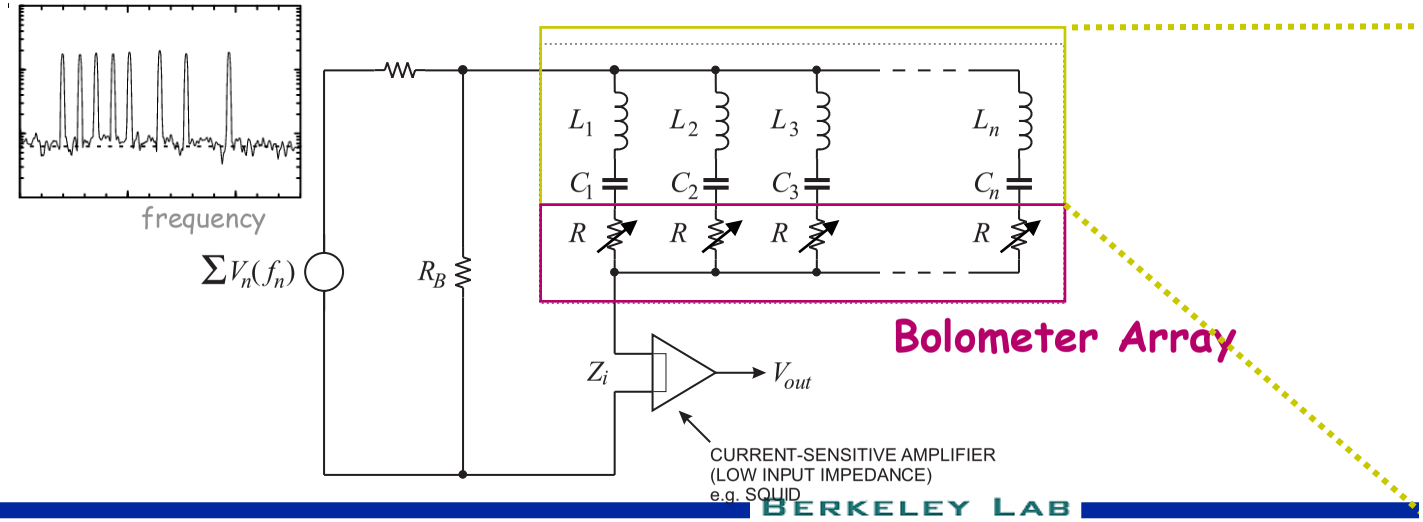


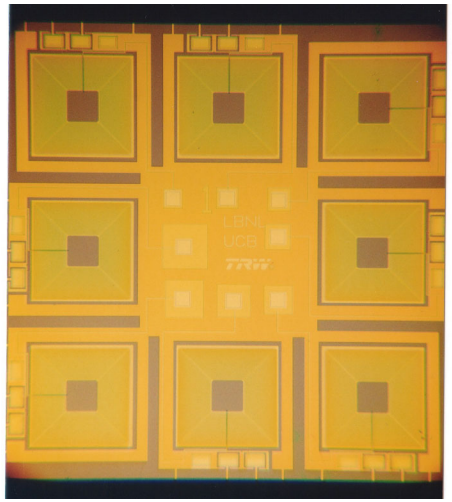
- Instrumentation development #2:
  - *Frequency Domain Multiplexing*
- Implementation:
  - *South Pole Telescope*

SQUID Readout Multiplexing

- Key Element: Readout Multiplexing
  - maintain 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))
- LTD 2003: **noise properties of MUX demonstrated with CMB bolometer**



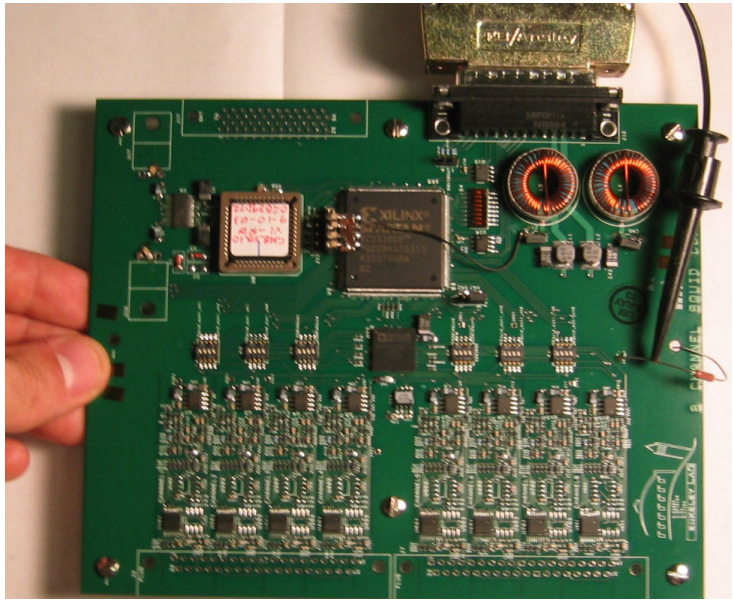




Since last year's review:

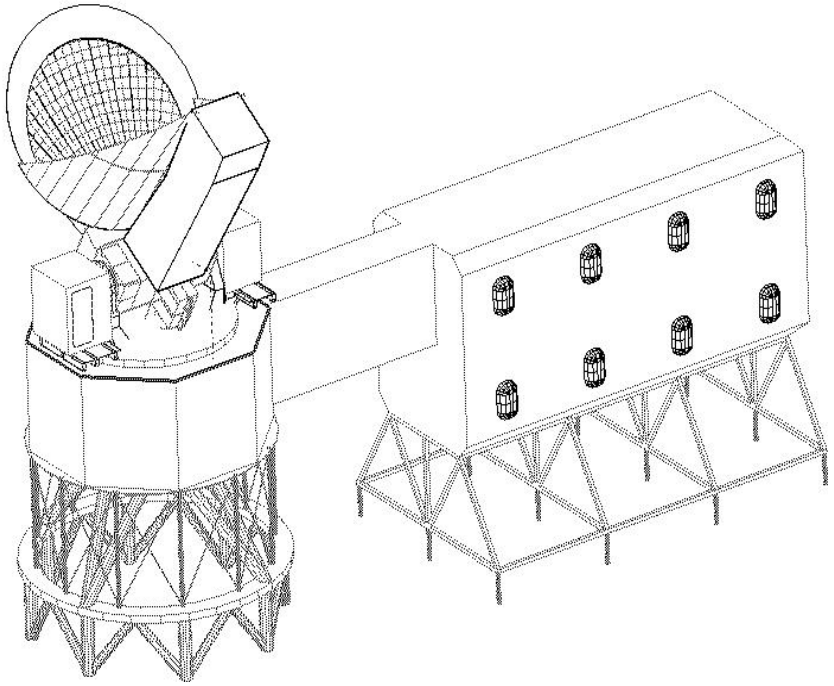
- Prototype readout electronics fabricated and tested.
  - "Module Zero" SQUID controllers in hand and operating.
  - Prototype Osc/Demod board tested
  - "Module Zero" Osc/Demod boards in layout phase
    - in hand in ~ month

- **Computer controlled mixed Analog / Digital SQUID readout Electronics**



- **Exploit unique capabilities of LBL for large scale detector development.**

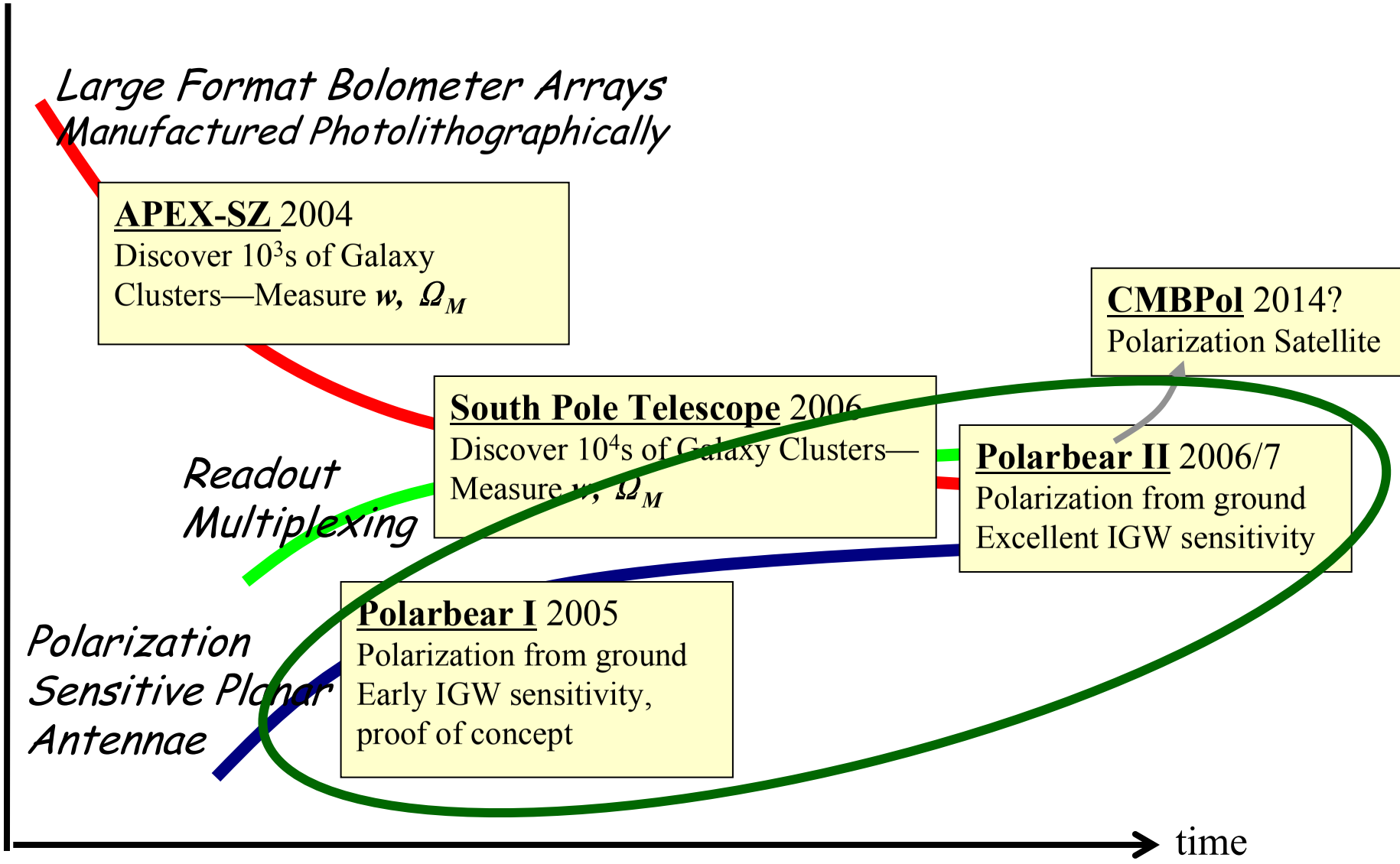
South Pole Telescope



- 1000 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.

New Instrumentation↔New Experiments



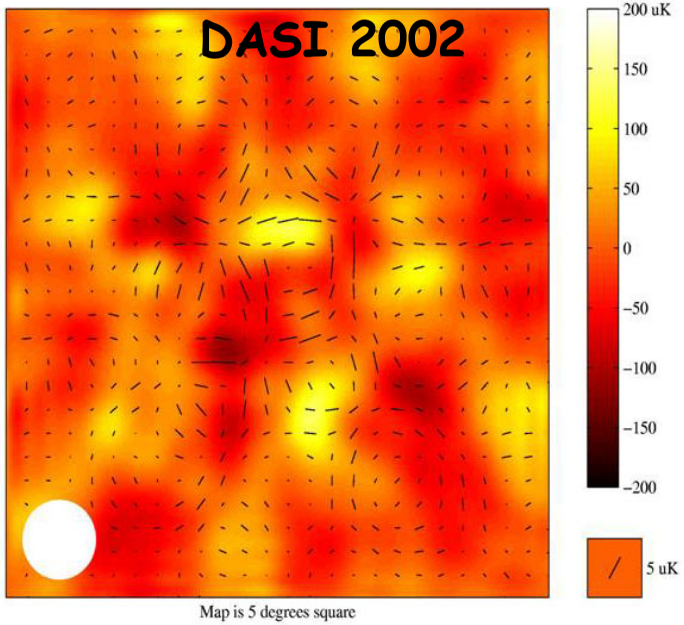
Why measure CMB Polarization?

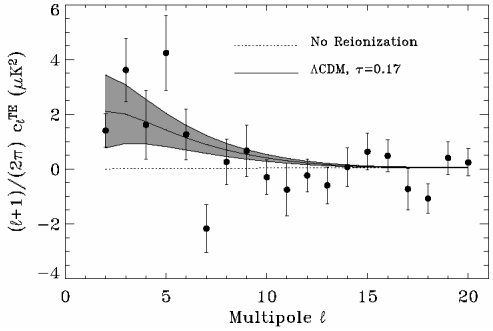
- scalar, vector & tensor fields carry more information than the temperature anisotropies alone.

→ measure cosmo parameters better

- measure the reionization epoch, which produces a large degeneracy in the Temp spectrum

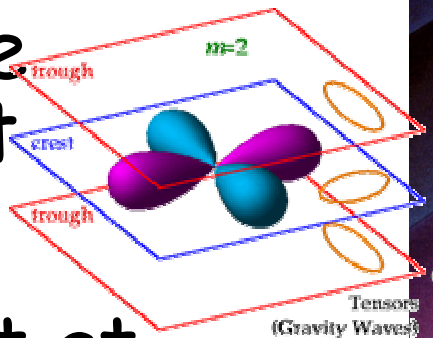
- measure gravity wave amplitude… the smoking gun of inflationary models.

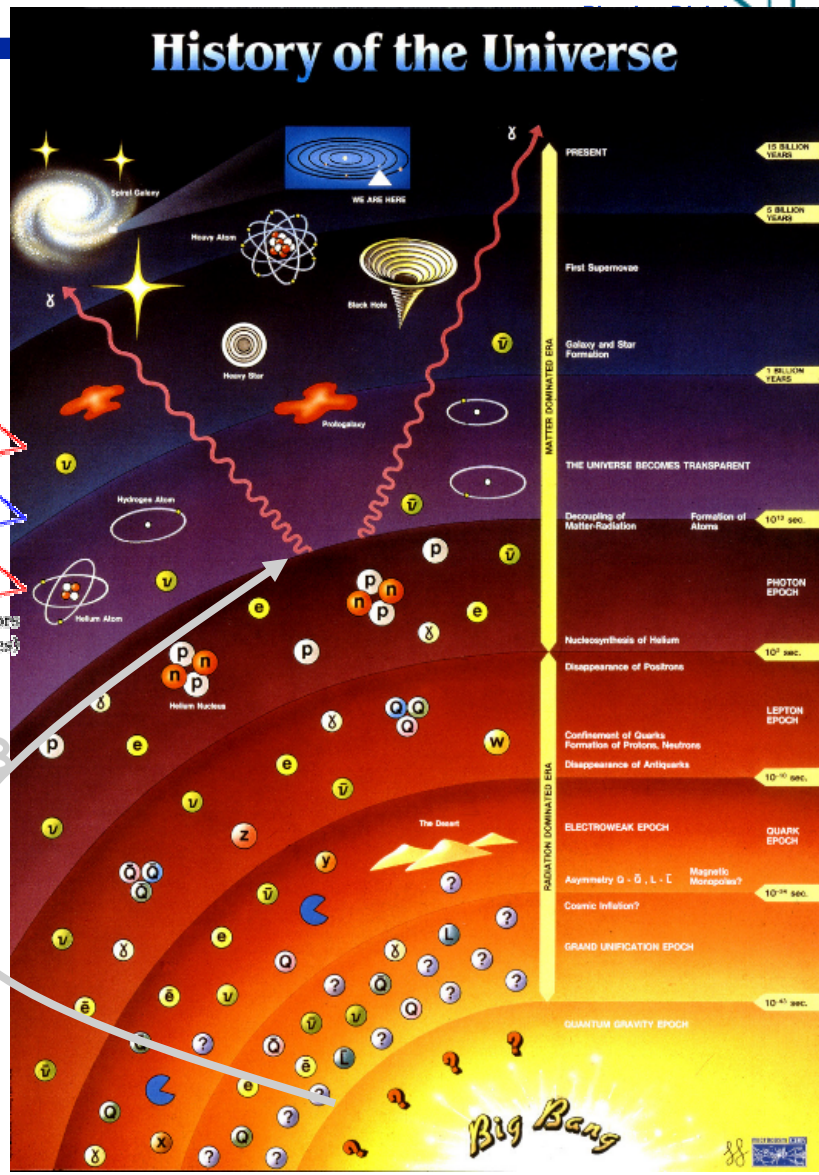




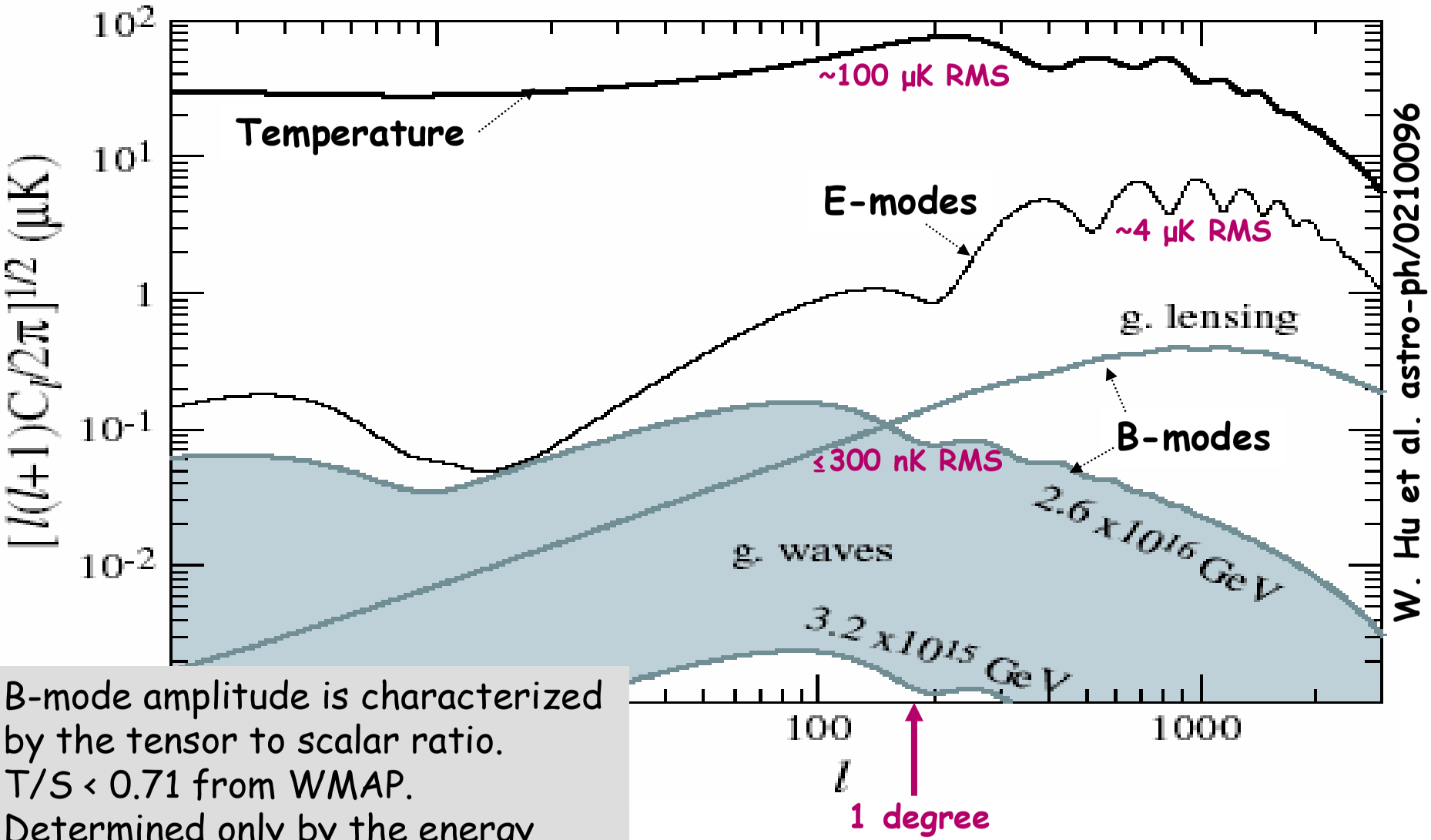
Inflationary Gravity Waves

- Just as the CMB gives the fingerprint of the universe at the surface of last scattering,
- the fingerprint at the time of inflation (10^{-38}? s) is encoded on the ***inflationary gravity wave background*** (IGB).





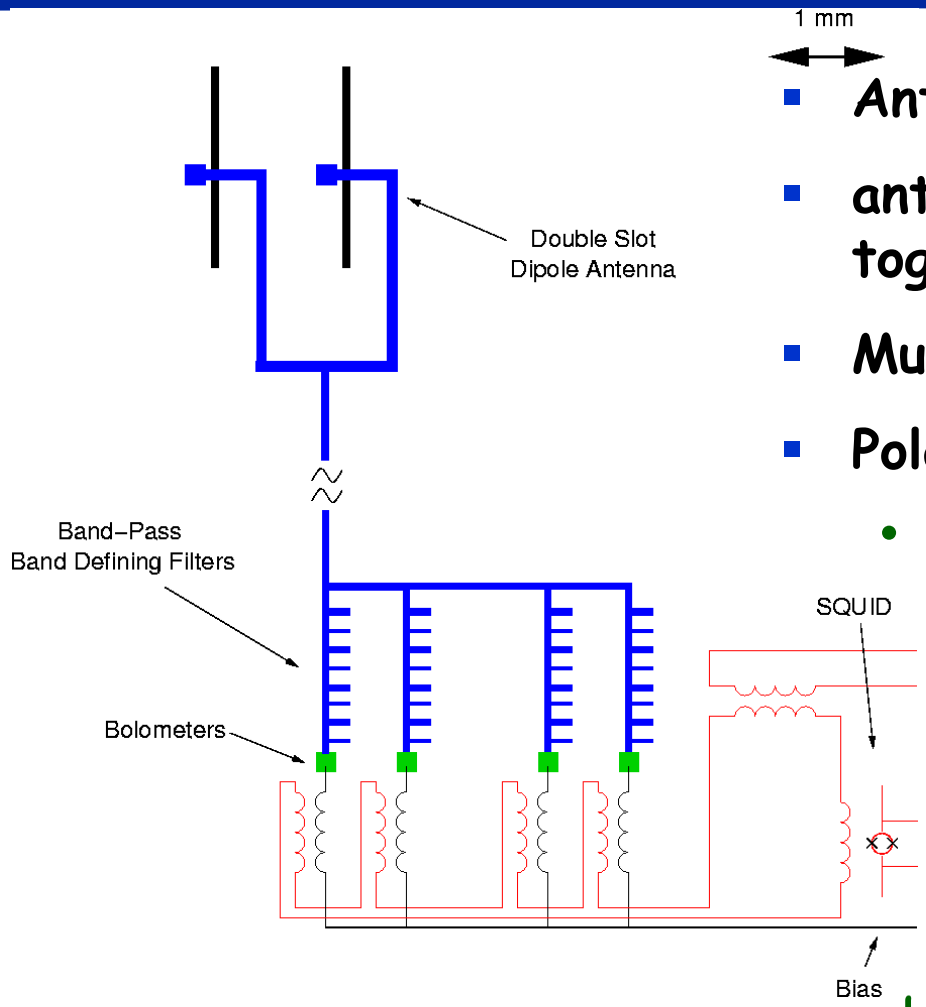
Polarization Power Spectrum



B-mode amplitude is characterized by the tensor to scalar ratio. T/S < 0.71 from WMAP. Determined only by the energy scale of inflation.

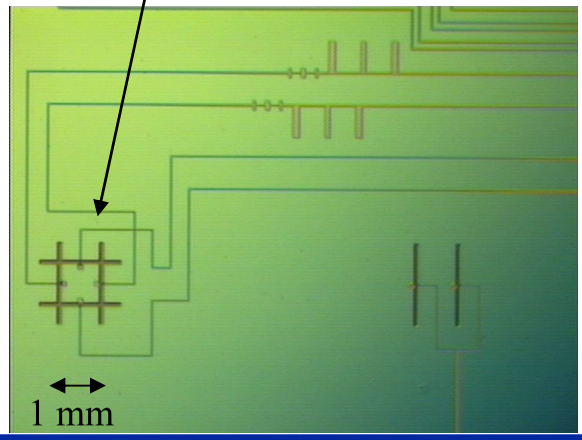
- Instrumentation development #3:
  - ***Polarization Sensitive Antenna Coupled Bolometers***
- Implementation:
  - ***POLARBEAR I***
- Instrumentation development #1+2+3:
  - ***POLARBEAR II***

Antenna-coupled Bolometer Diagram

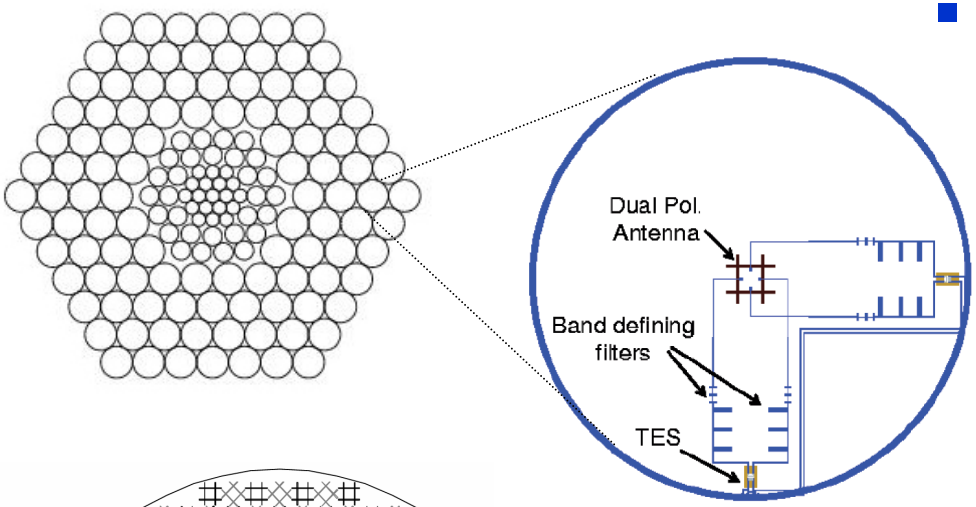


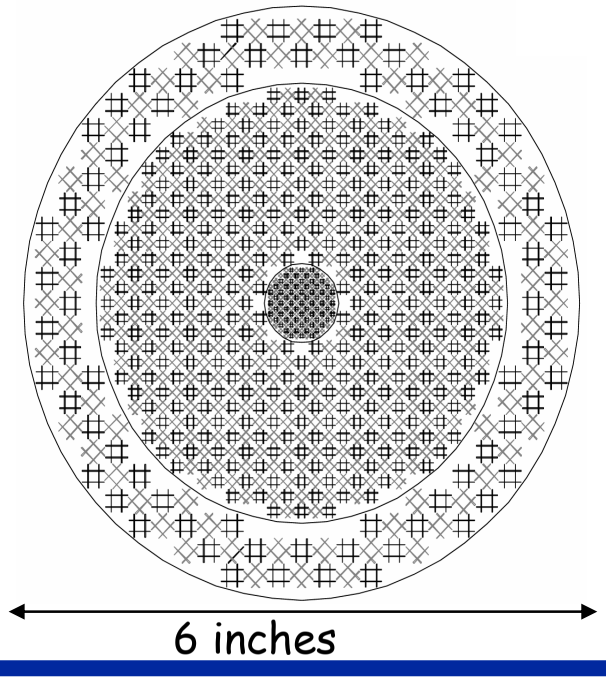
- Antenna provides directivity
- antenna, filters, bolometers packaged together below lens
- Multicolor → multiple bands per pixel.
- Polarization sensitive
  - dual polarization by placing 2 crossed dipole arrays in same pixel

Prototype pixel fabricated, being tested now



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

Since last year's review:

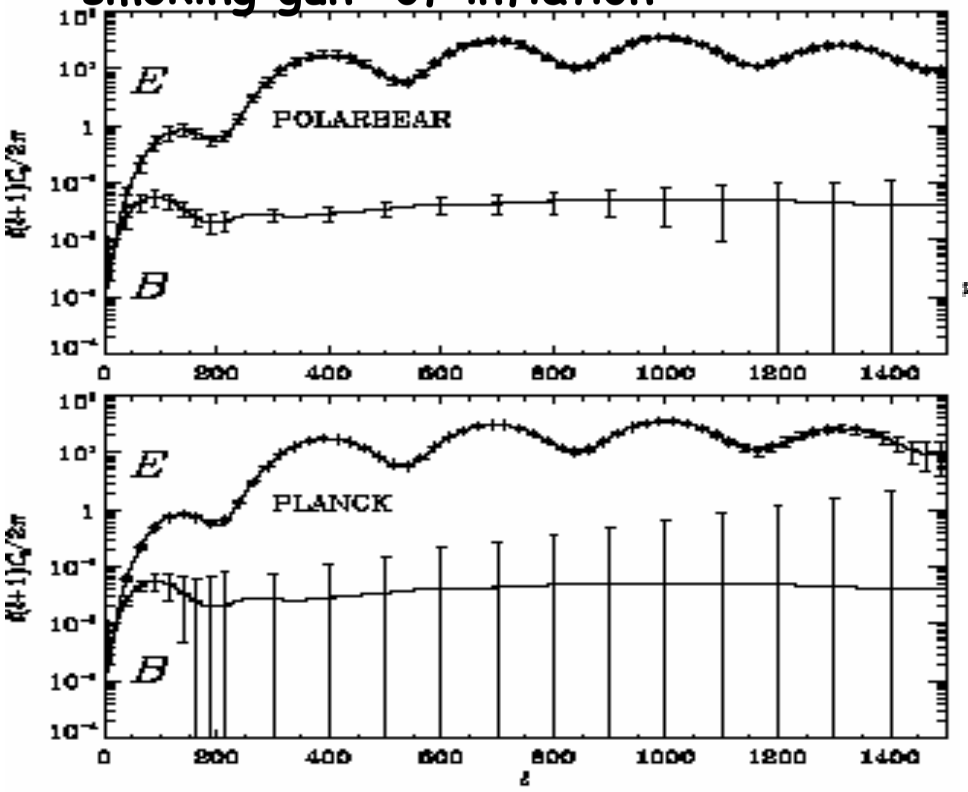
- dipole slot antenna coupled bolometer has been successfully fabricated
  - beginning testing phase.
- Optics design complete.
- Candidate telescope designs assessed.
- Site selection & evaluation.
  - White Mtn- good observing conditions, easily accessible to Berkeley for Bolo-array prototyping.

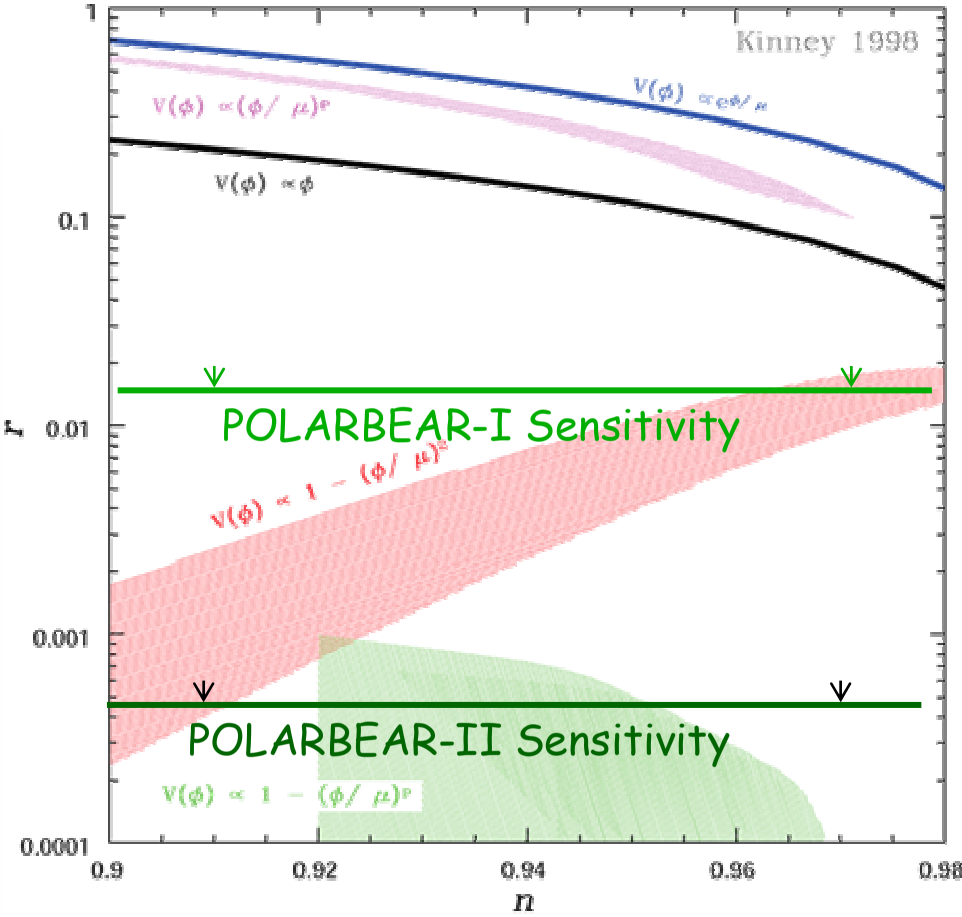
POLARBEAR

- Could achieve first light in 2005 from White Mountain, CA with a ~3m primary
  - atmospheric emission is nearly unpolarized.
  - large sky coverage for primordial gravity waves
  - sufficient resolution to measure and subtract out gravitational lensing signal.
  - staged deployment – 300 elements, upgrade to fMUX 1000s of elements.
  - multi-frequency polarization sensitive antenna coupled toTransition Edge Sensor bolometers
- testing facility for future satellite technologies, systematics, and foreground measurements.

POLARBEAR Performance

- Characterize E-modes
- Search for B-modes, the "smoking gun" of inflation

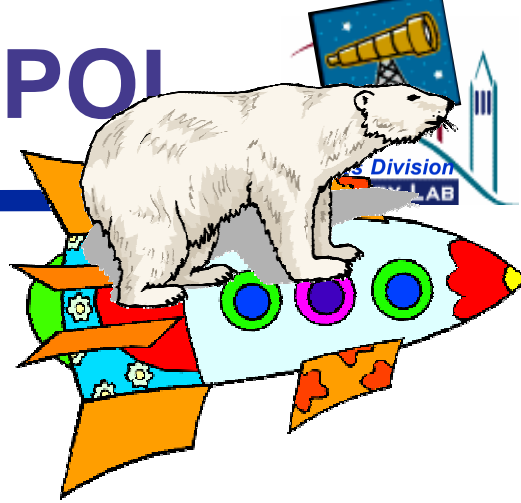




3 years observing
(Assuming a Tensor to Scalar ratio r=T/S=0.35)

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

Einstein Probe Satellite: CMBPOL



- SPACE: the final-frontier
  - Are POLARBEARs space-worthy?
- Proposals for concept studies submitted.
  - Five Berkeley collaborators (Lee = CO-I) on joint JPL/Berkeley/Caltech/Chicago proposal
- 2013-16 launch with cost cap ~$500M
- lots of R&D between now and then
- upcoming polarization facilities (e.g. POLARBEAR) will be test-beds for CMBPOL instrumentation.

(a few of) The Polarization Experiments

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now

- DASI (interferometer at the South Pole)
- Boomerang / MAXTD (balloon based ...pes)
- WMAP NASA ...re 2001-5
- Bicep (S... ...le 2004/5
- POL... ...AR (Califor... ground based
- C... ...D (South P... ground based
- Planck ES... ...atellite (2007-)
- CMB... ...Probe Satellite (2013/16)

Competition is fierce.
In terms of technology and leveraging, Berkeley is positioned as a leader.

Computing & Data Analysis

Physics Division
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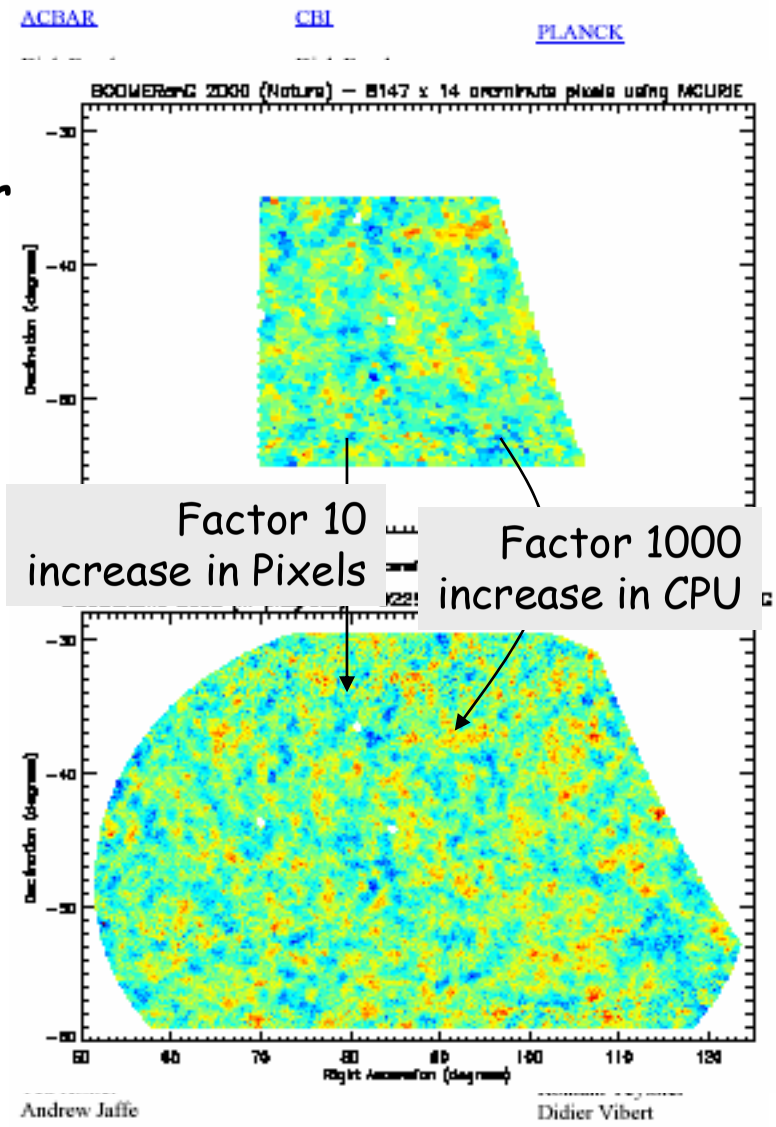
- **NERSC expertise and computing power is used extensively by CMB community**
  - Seaborg: ~6000 processor (1.5 GFlops, 1-4 GB each) IBM SP3 Massively Parallel Computer
  - HPSS Storage, 850 TB
- **Since Last Year, MADCAP3 Released:**
  - Microwave Anisotropy Dataset Comp Analysis Package, Ver 3 implemented for SP3
  - polarization capability
  - multiple datasets, Planck size datasets
- **Planck Surveyor, 2007**
  - responsibility for software, algorithm development, calibration, and treatment of systematics
  - ESA/NASA has recognized importance of NERSC
    - **2 Planck funded NERSC positions +postdoc**
    - **50 team members using NERSC facilities**



E-mode POLARIZATION with MaxiPOL

- The Polarization sensitive balloon-borne followup to MAXIMA flew in May 2003

- GOAL: detection of E-mode polarization
- First half-wave plate polarimeter
  - modulated polarization key for systematics

- NERSC Facilities and staff currently analyzing data

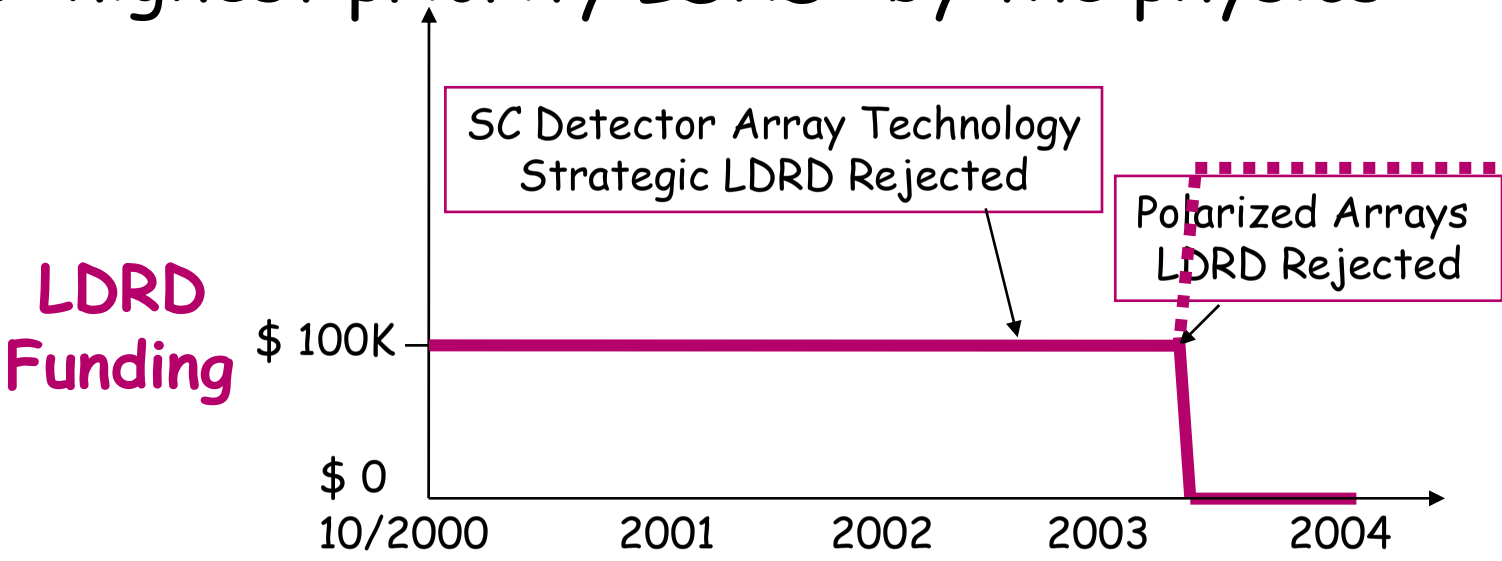
→ Expect results soon.

Technology Development is Crucial

- Berkeley CMB Group is a world leader in CMB instrumentation, observations, analysis and results.
  - excellent synergy between Campus & LBL.
- NASA/NSF is funding basic Bolometer development
  - no funding for engineering large scale systems / production facilities.
- Berkeley National Lab's unique contribution is expertise in large detector systems.
  - large scale integrated sensor arrays & readout multiplexing.
  - experienced engineers are essential
- Superconducting Detector Fabrication Facility progressing:
    - Identified Space, Floor plan, & equipment requirements
    - Start date deferred to 2005.

LDRD Funding for CMB Technology

- from Director's Review Last year:
  - "technology development relies heavily on LDRD funds from LBNL... require a significant infusion of LDRD funds in 2003 and 2004... We recommend that LBNL use LDRD funds toseed the technology development for the approved experiments."
- Rated as "highest priority LDRD" by the physics division.



Summary

- strong ongoing CMB program that combines the strengths of university and National Lab.
- Science goals of CMB program have been endorsed by two National Advisory Panels and given the highest priority by the community.
- LBL has a focused instrumentation development path, providing key cosmology measurements at each step
- next generation CMB measurements rely on technology development
- Physics Div's unique contributions to this field need lab support.
  - Berkeley is in a unique position to take leadership role in Polarization science.
  - modest increase in funding will allow POLARBEAR to proceed expeditiously
  - positions LBL to play major role in (post-SNAP) future CMBpol satellite