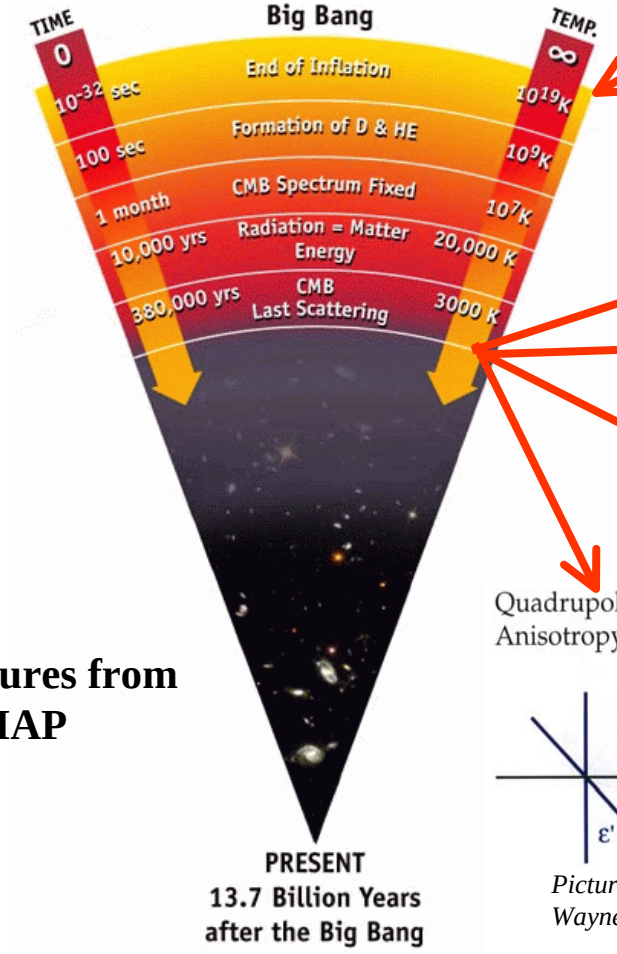
QUaD and Development for Future CMB Experiments

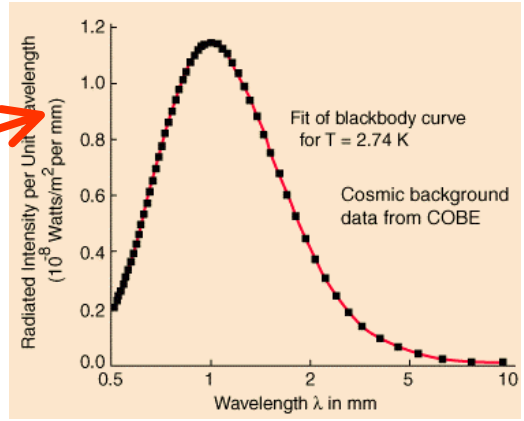
S. Church

C-L Kuo

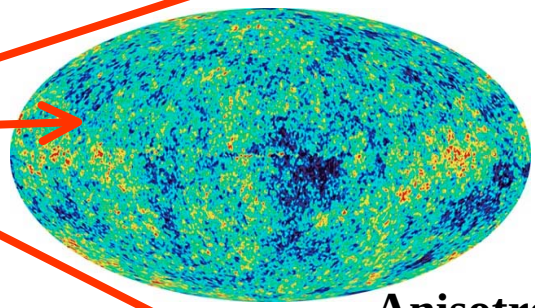
The Cosmic Microwave Background



Inflationary physics?

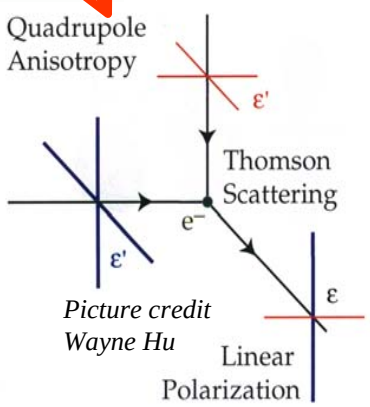


blackbody spectrum



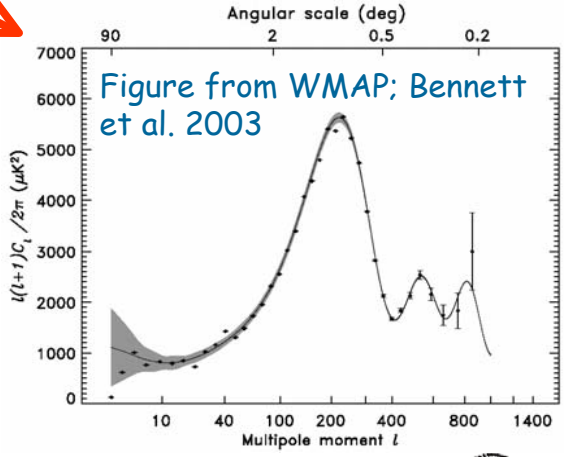
Anisotropies in temperature

Pictures from WMAP

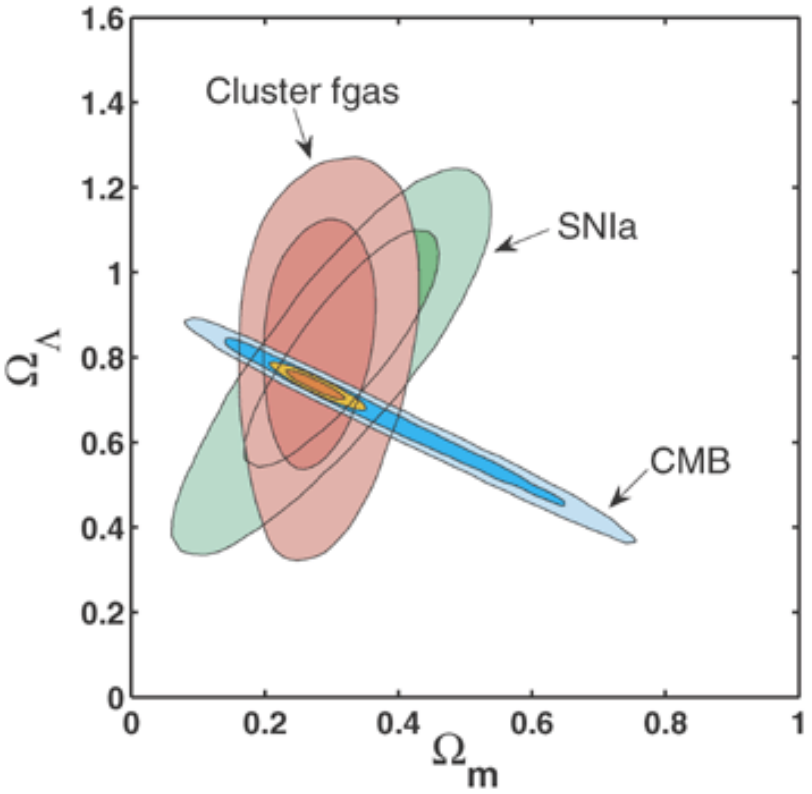


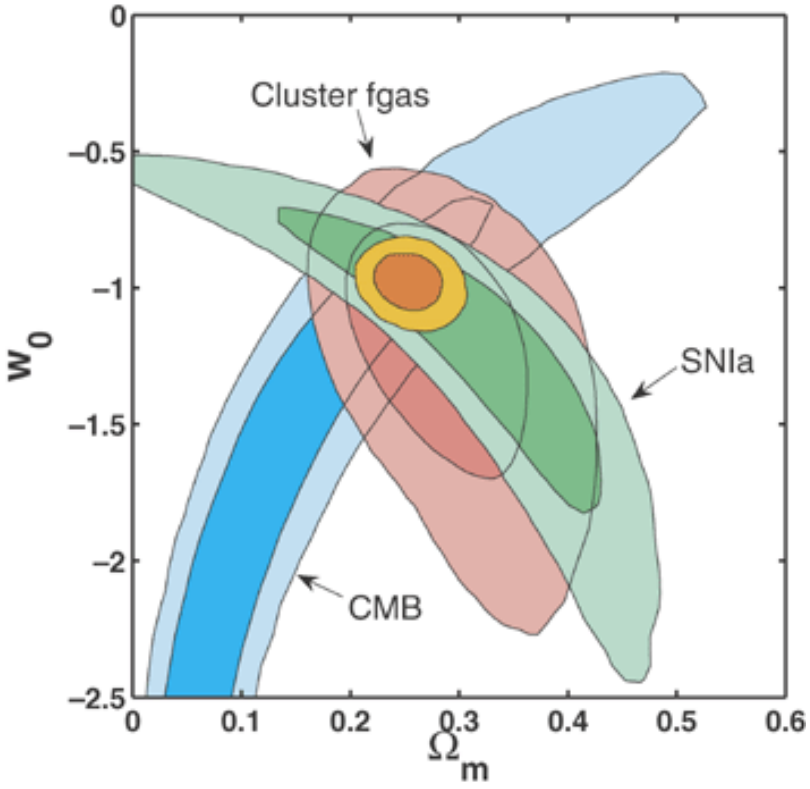
Picture credit Wayne Hu

Polarization



CMB has been very effective at constraining cosmological parameters





Especially when combined with other data sets

See Allen talk

The constraining power of the CMB comes from…

* Straight-forward physics ⇒ accurate theoretical predictions with cosmological quantities as the free parameters
* **Measurements are the key**
* Precision measurements ⇒ "precision cosmology"
* **Potential to constrain inflation through direct parameter measurement**

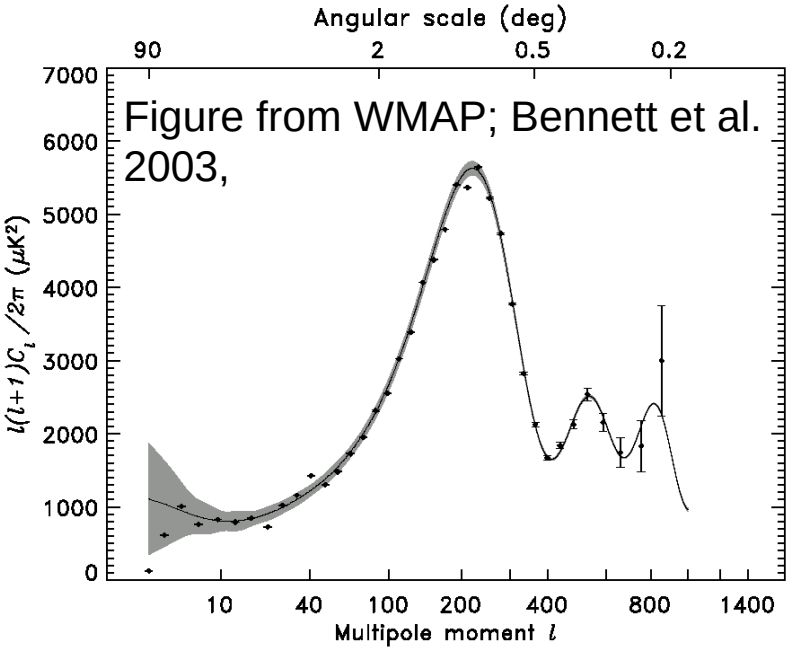


Figure from WMAP; Bennett et al. 2003,

TABLE 7

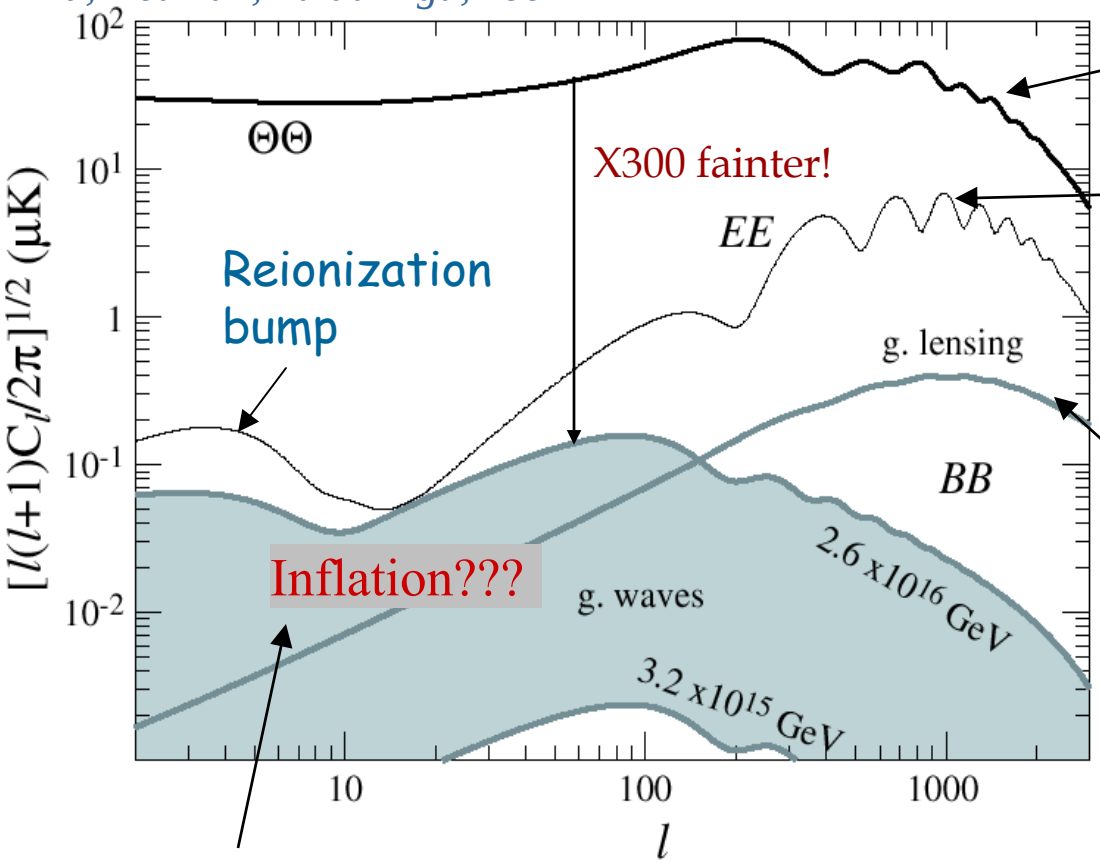
BEST-FIT INFLATIONARY PARAMETERS (*WMAP* DATA ONLY)

Parameter	ΛCDM + Tensor	ΛCDM + Running + Tensors
$\Omega_b h^2$	0.0233 ± 0.0010	0.0219 ± 0.0012
$\Omega_m h^2$	$0.1195^{+0.0094}_{-0.0093}$	0.128 ± 0.011
h	0.787 ± 0.052	0.731 ± 0.055
n_s	$0.984^{+0.029}_{-0.028}$	1.16 ± 0.10
$dn_s/d\ln k$	Set to 0	-0.085 ± 0.043
r	<0.65 (95% CL)	<1.1 (95% CL)
τ	0.090 ± 0.031	$0.108^{+0.034}_{-0.033}$
σ_8	0.702 ± 0.062	0.712 ± 0.056

Table from Spergel et al. 2007

The Science

Hu, Hedman, Zaldarriga, 2002



Temperature spectrum

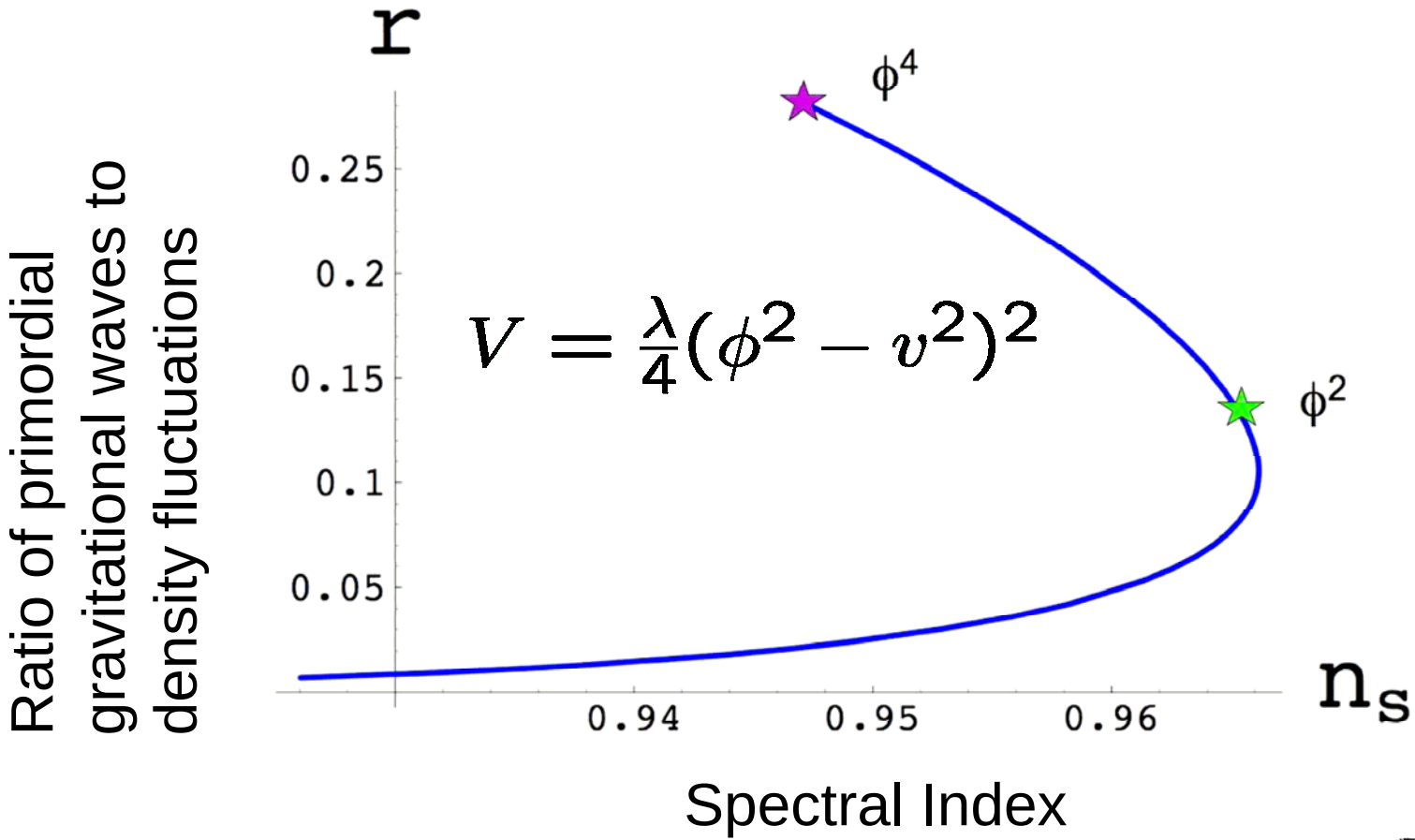
E-mode polarization (no parity) from density fluctuations

Gravitationally lensed E-modes (dark energy, massive neutrinos)

B modes (parity) from primordial gravitational waves (Blue shading spans current limits and minimum detectable from CMB)

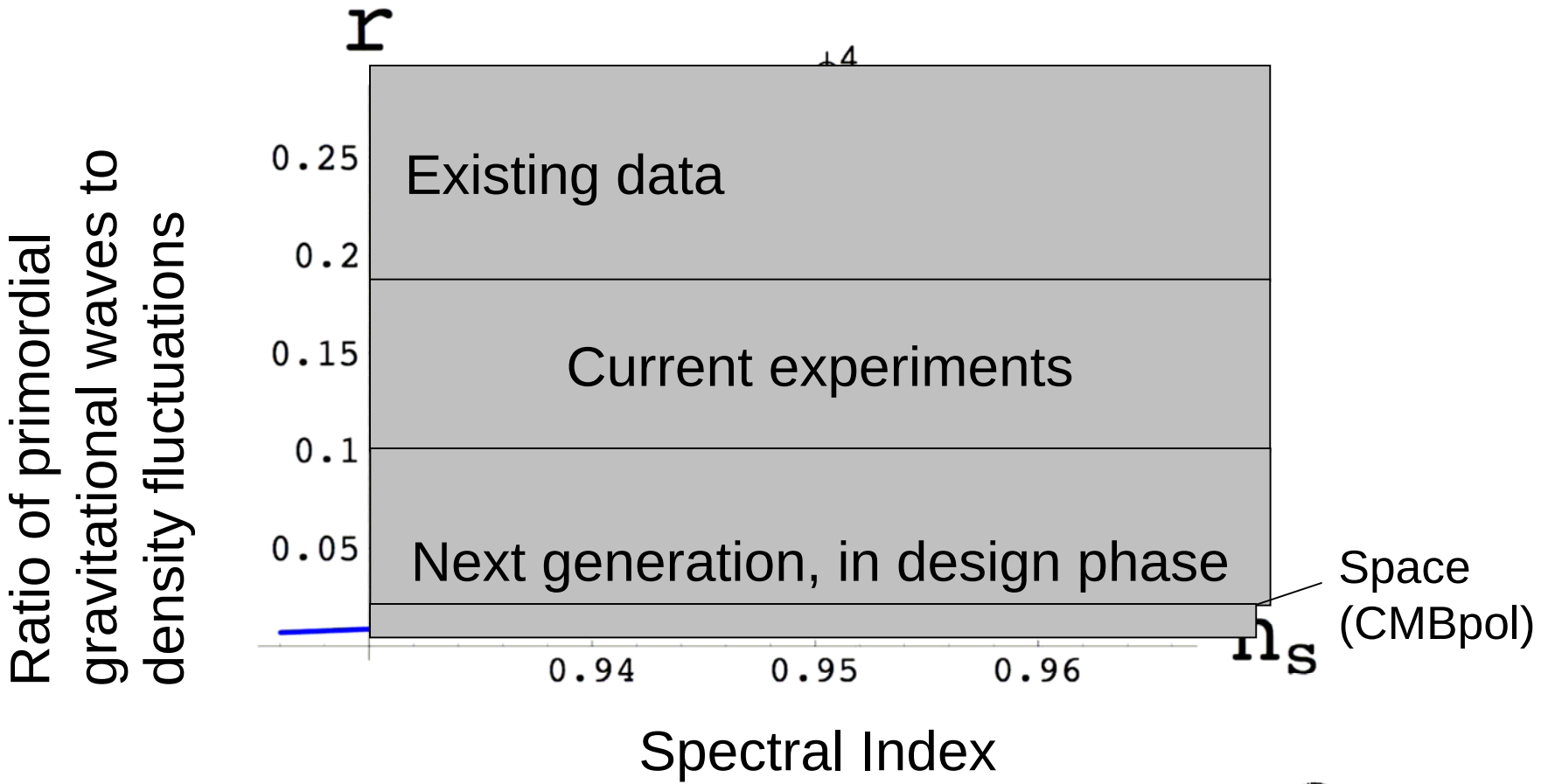
One particular class of inflationary models

Figure from Kallosh, Stanford Institute for Theoretical Physics

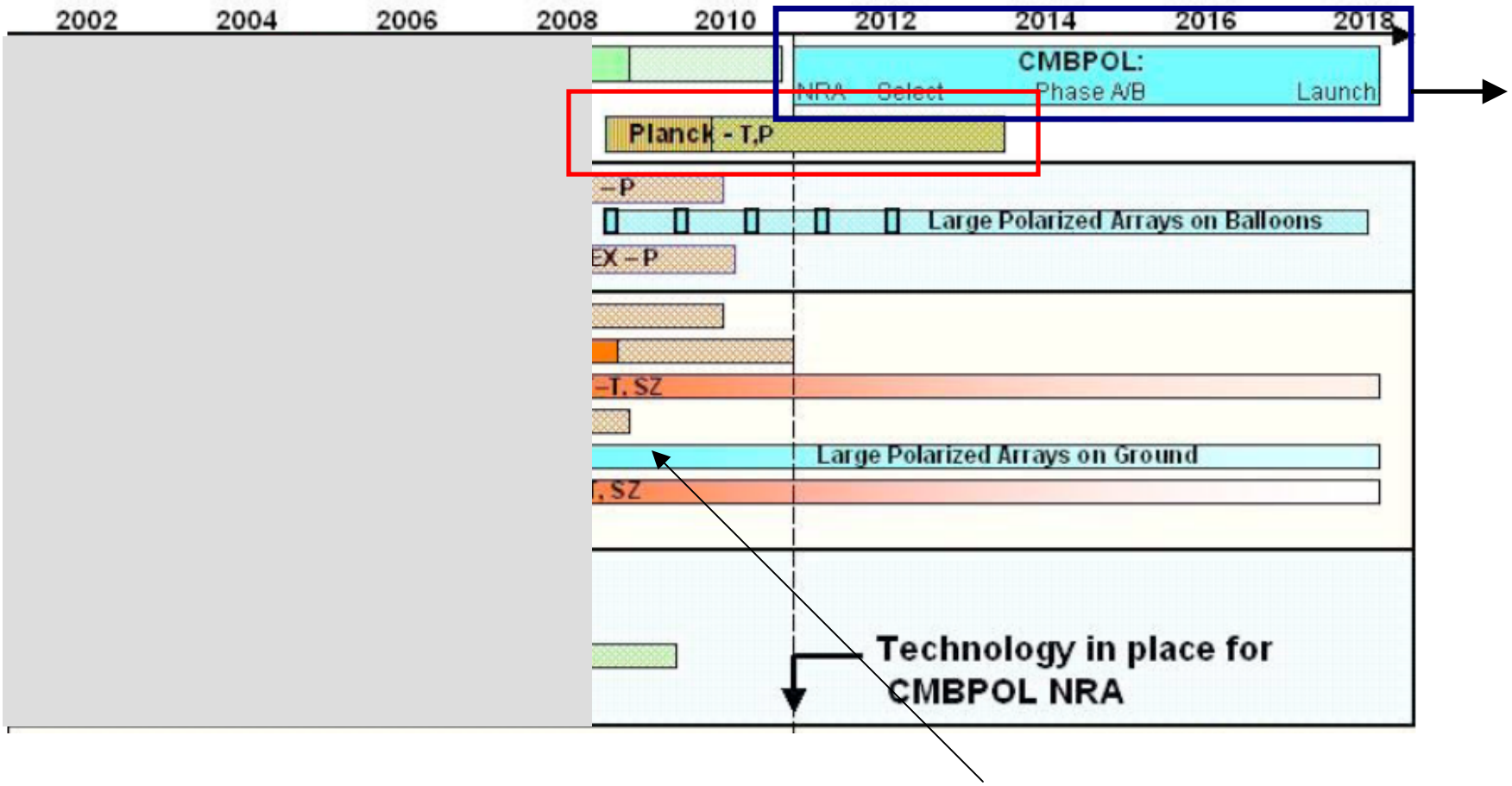


The Goal

Figure from Kallosh, Stanford Institute for Theoretical Physics



The experimental landscape circa 2005 (NASA/NSF/DOE taskforce on CMB research)



KIPAC experiments in development --CHIP, SPUD

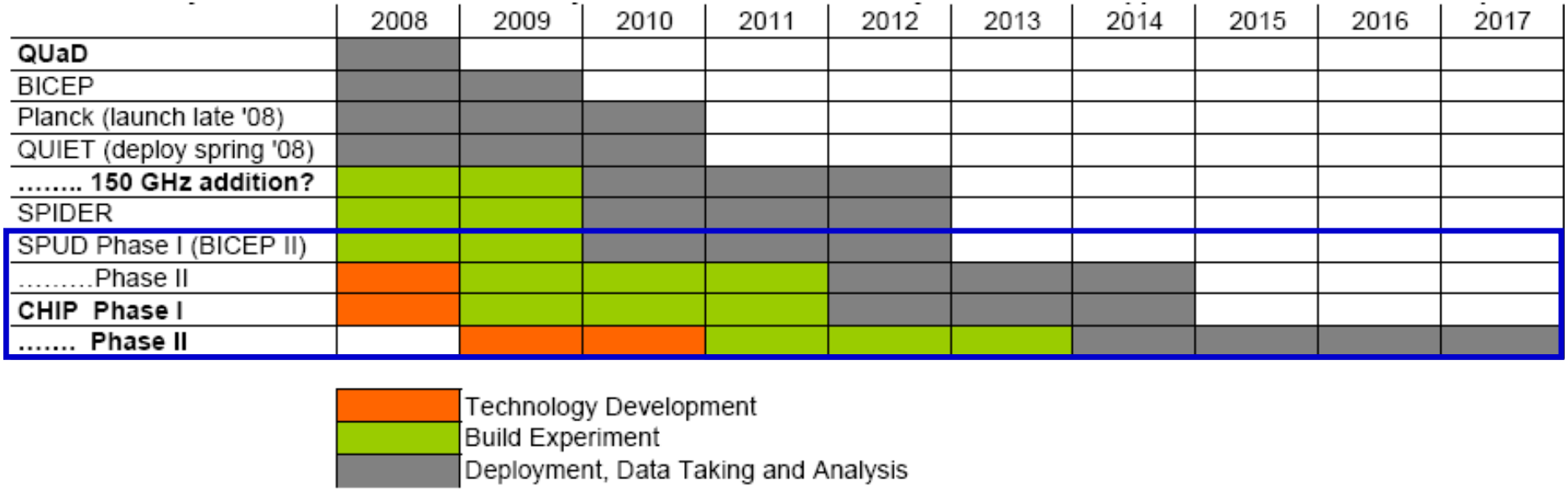
The Challenge

* Beyond $r \sim 0.1$ can only come from deploying very large numbers of detectors -- 1000's rather than 100's
  - Optimum experimental design not yet determined
  - Careful system engineering needed to minimize systematic effects **that will otherwise dominate** (signal < 1pt in 10^8 of background)
  - Data sets will comprise tens of thousands of time streams compared to few tens for current expts.
  - Project size and analysis complexity will increase
  - Project management/data distribution issues
* **Requires a change in culture from small collaborations, few postdoc/grad students**

Complementary approaches being pursued at KIPAC for next generation experiments

* Large format radio interferometers based on coherent amplifier technology
  - Excellent control of systematics
* Large-format arrays of transition-edge sensor bolometric detectors
  - high instantaneous sensitivity

Projects with KIPAC Involvement



* **NSF/NASA funded**
  - **Intellectual connection to SLAC where core capabilities can benefit experimental design e.g. RF design, systems engineering, large format FPGA-based and analog electronics**
* **These will be large, multi-institutional, possibly international collaborations**

Activities with intellectual matches to SLAC

* RF design
  - Low-noise radio amplifier modules suitable for mass-reproduction.
  - On-chip antennas and filters for 30-300 GHz
* Digital and Analog Electronics
  - FPGAs or ASICs for large correlators – 10^7 correlations
  - SQUID amplifier readout and multiplexing for SPUD TES detectors
* Systems engineering and end-to-end characterization and calibration
* Handling of very large data sets
* Analysis and signal processing methods to provide believable detection of very small signals in large backgrounds (1 pt in 10^8)

CHIP – an interferometer for measuring CMB polarization

KIPAC

Sarah Church

Judy Lau

Stephen Osborne

Patricia Voll

Ed Wu

John Fox

Daniel van Winkle

Sami Tantawi

Jet Propulsion Lab

Todd Gaier

Pekka Kangaslahti

Charles Lawrence

Ian O'Dwyer

Lorene Samoska

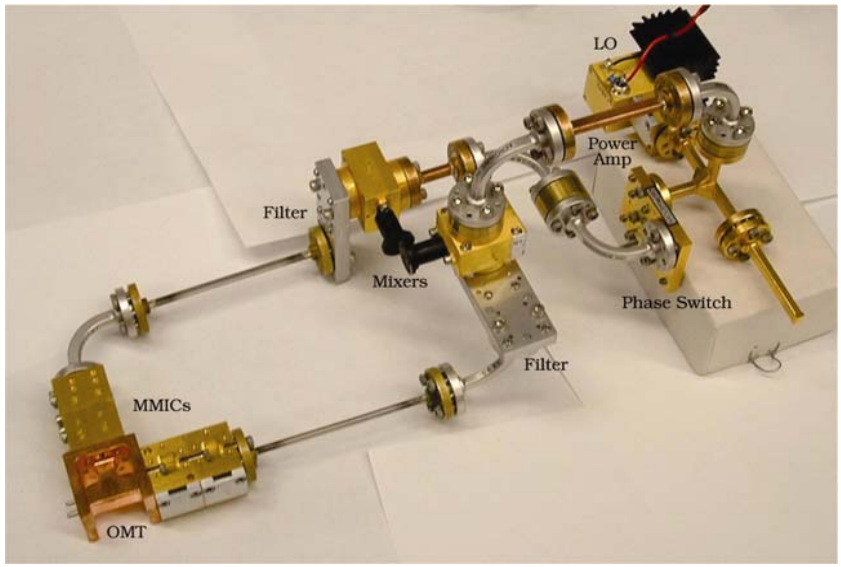
Caltech

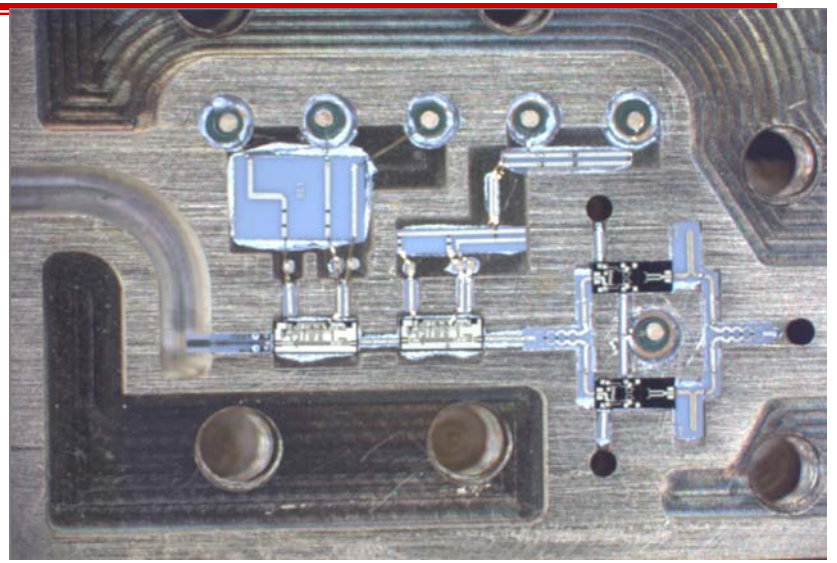
Tim Pearson

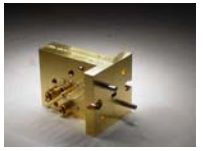
Tony Readhead

- Currently Stanford/NASA funding
- Fledgling collaboration with SLAC
  - RF design of low cross-talk antennas
  - Systems design for large format, low cross-talk, analog electronics (10^4 channels)
  - FPGA/ASIC correlator, 10^7 correlations

New development: advances in miniaturization of coherent detector technology (JPL/KIPAC)



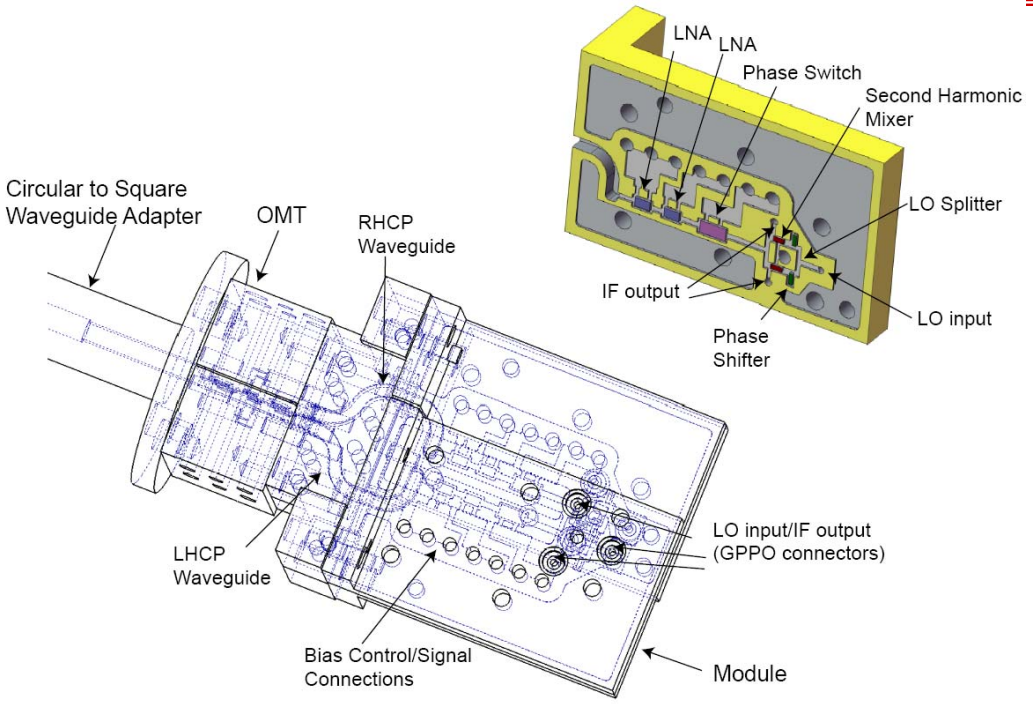


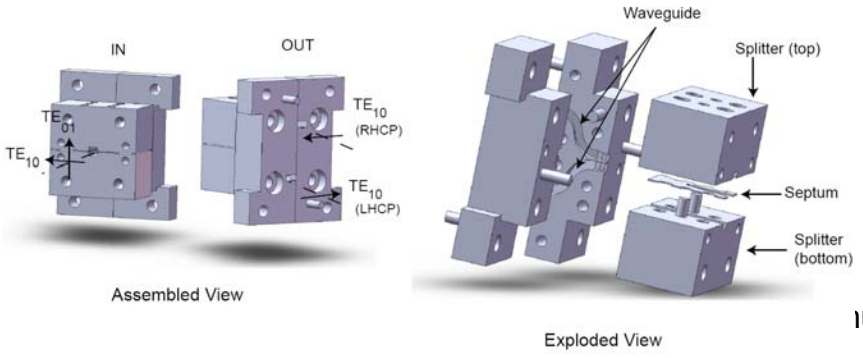


1.5 in

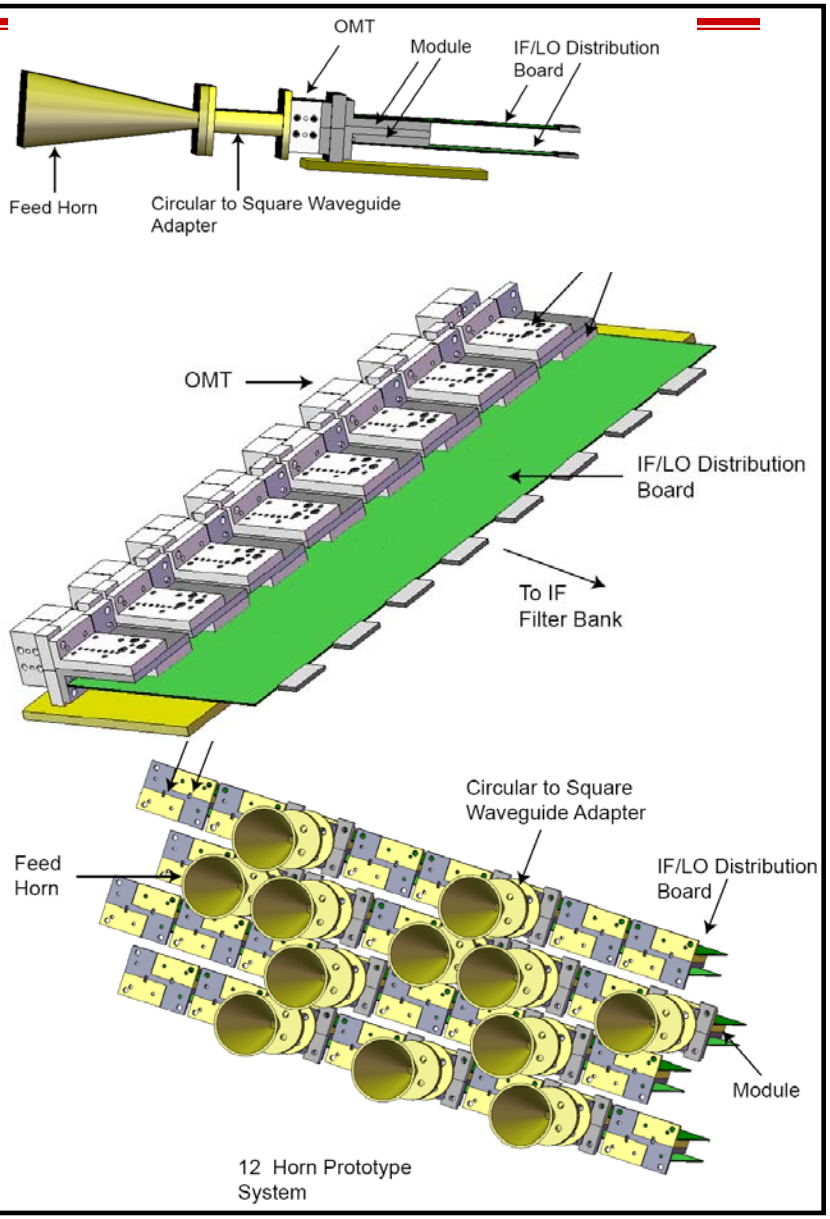
* JPL/KIPAC collaboration is developing 90 GHz MMIC amplifier modules for CHIP
* Amplifier technology can be extended to 150 GHz, possible to 220 GHz, covering all of the frequency range of interest

Prototype array is being designed



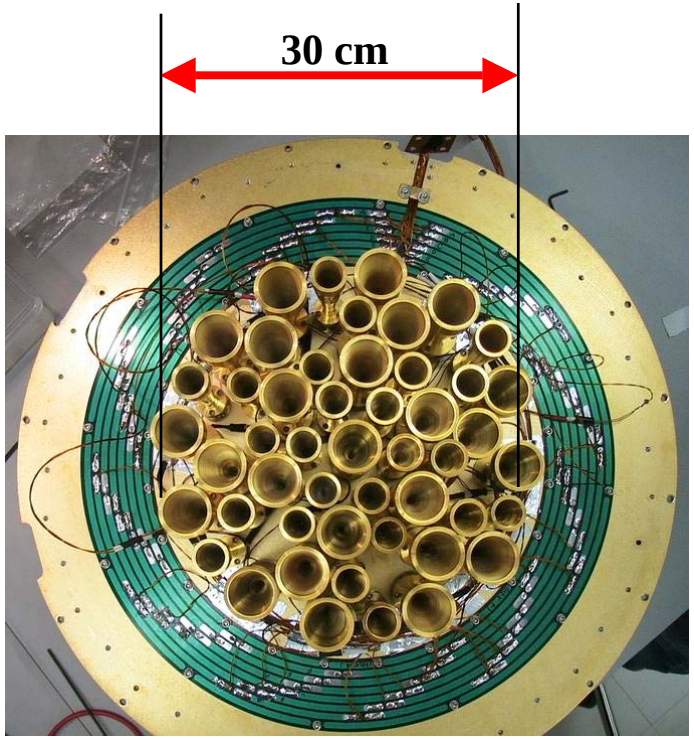


ıual Program



Advances in Bolometric Polarimeters (Kuo)

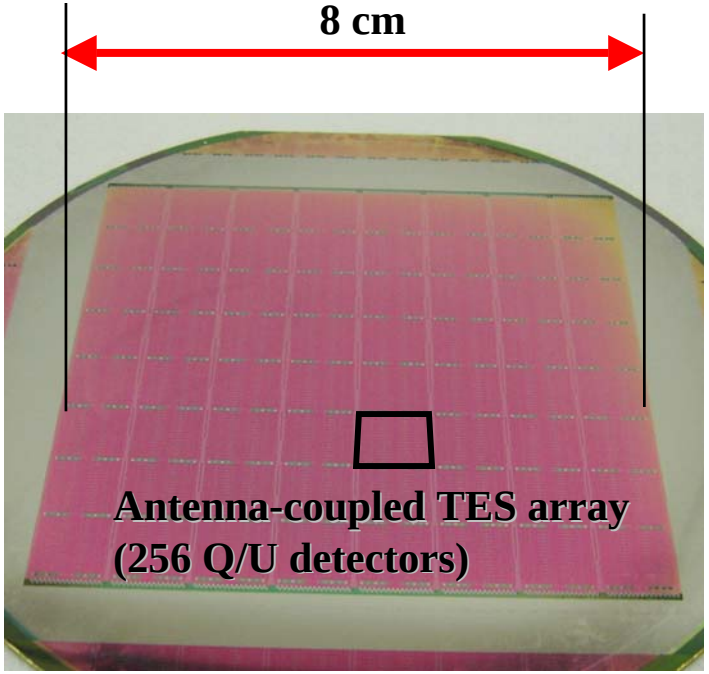
The state-of-the-art (QUAD, BICEP)



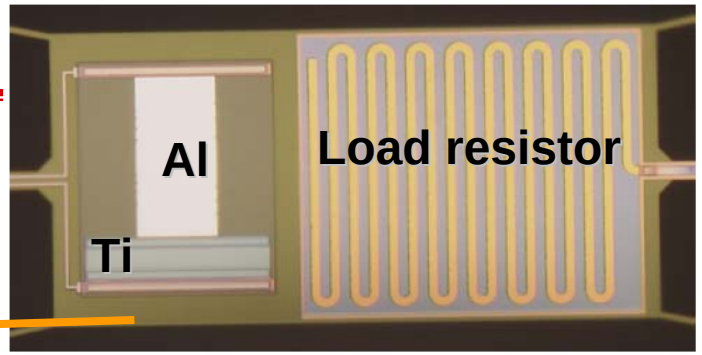
BICEP focal plane (98 detectors)

The future:

- To integrate all these components on a Si wafer → mass production
- TES enables SQUID multiplexed read-out; need high speed FPGA/ASIC readout – intellectual match to SLAC expertise

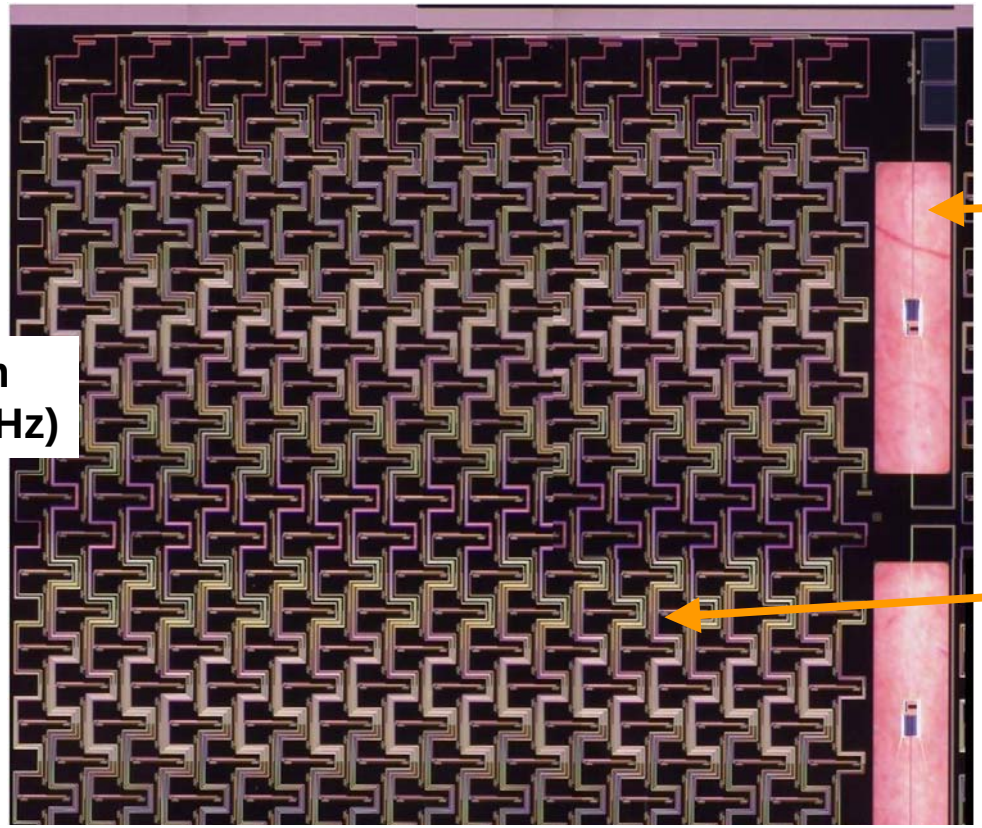


Enabling Technology for Bolometric Experiments (Antenna Coupled Bolometers)

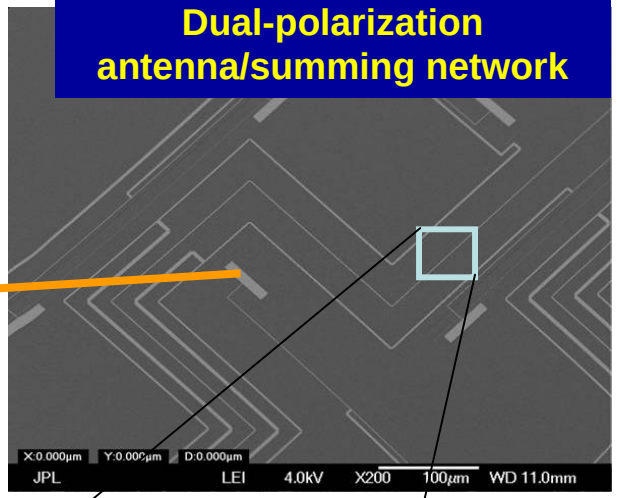


Dual-Tc TES bolometer

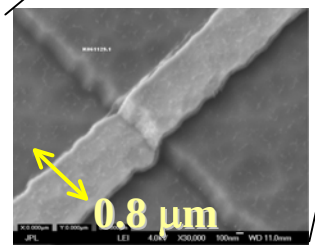
Dual-polarization antenna/summing network



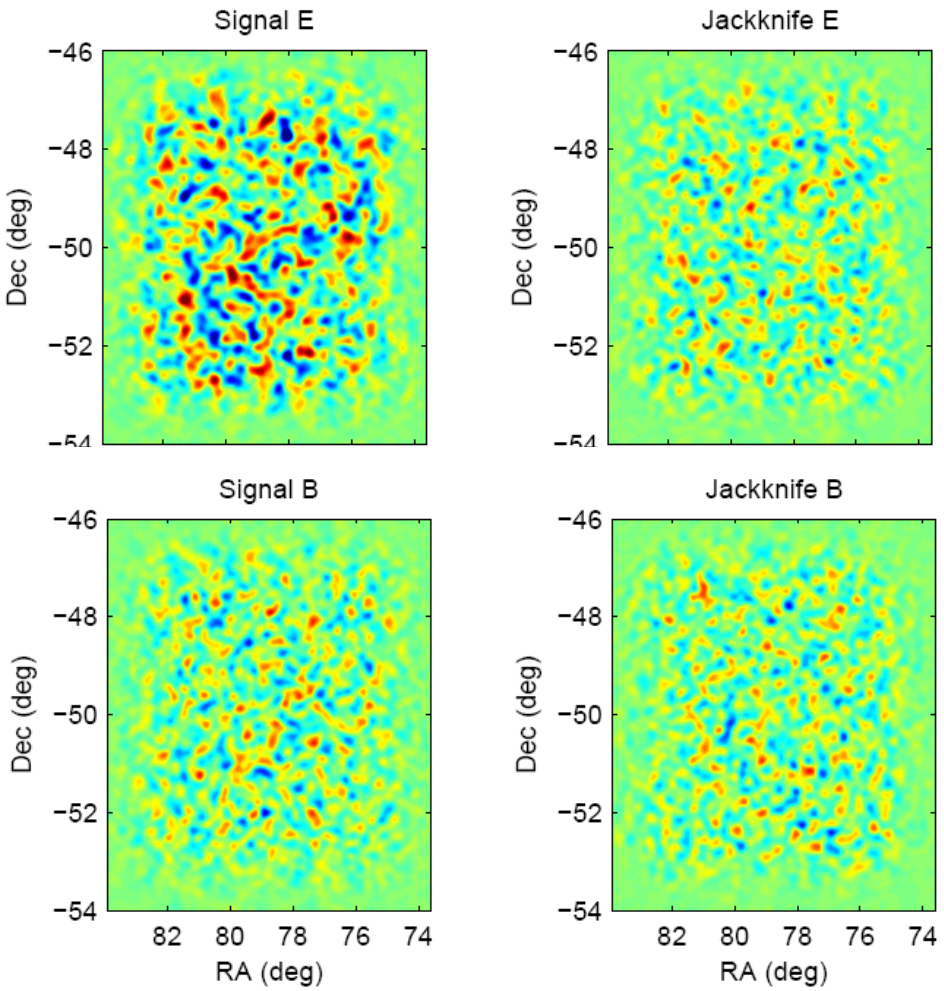
7.5 mm (150 GHz)

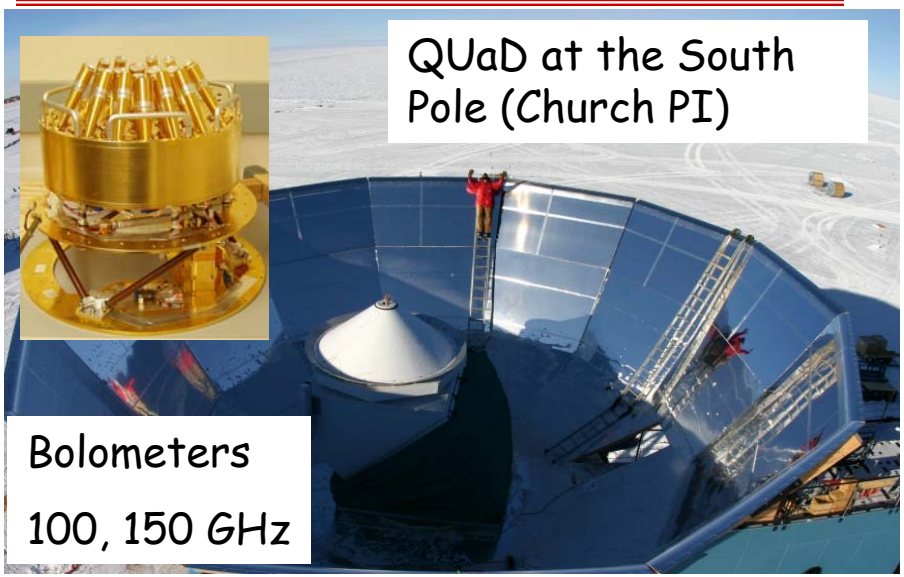


Pictures from JPL microlab, KIPAC effort includes digital backend (Kuo)



Precision Measurements of CMB polarization have been made at KIPAC

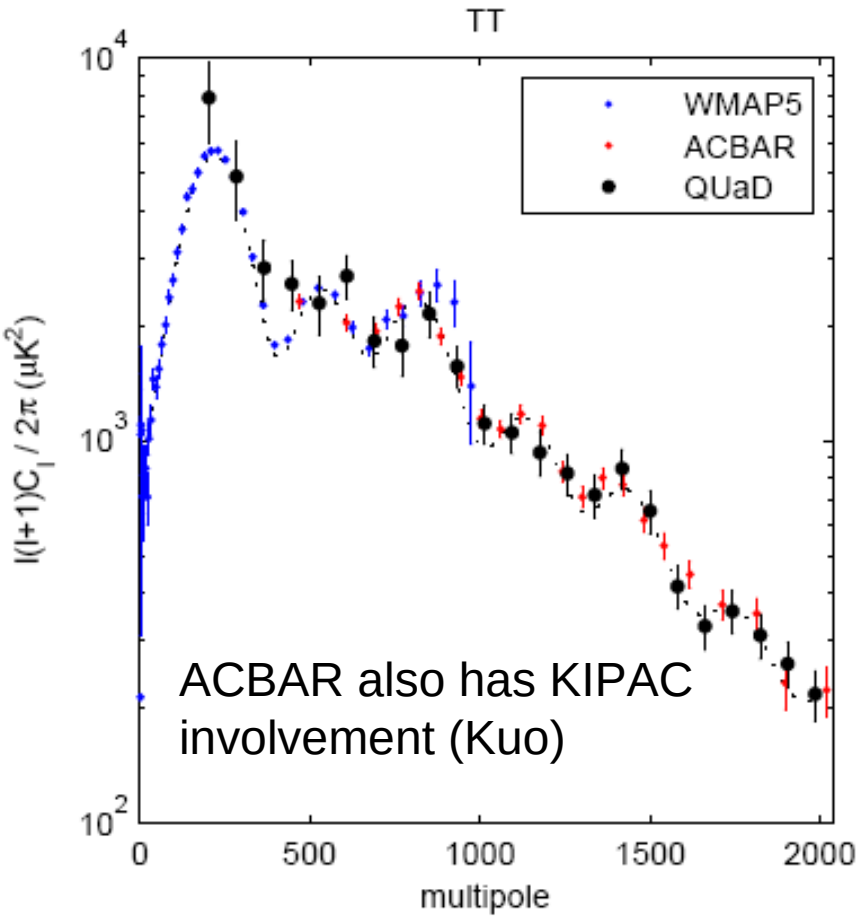




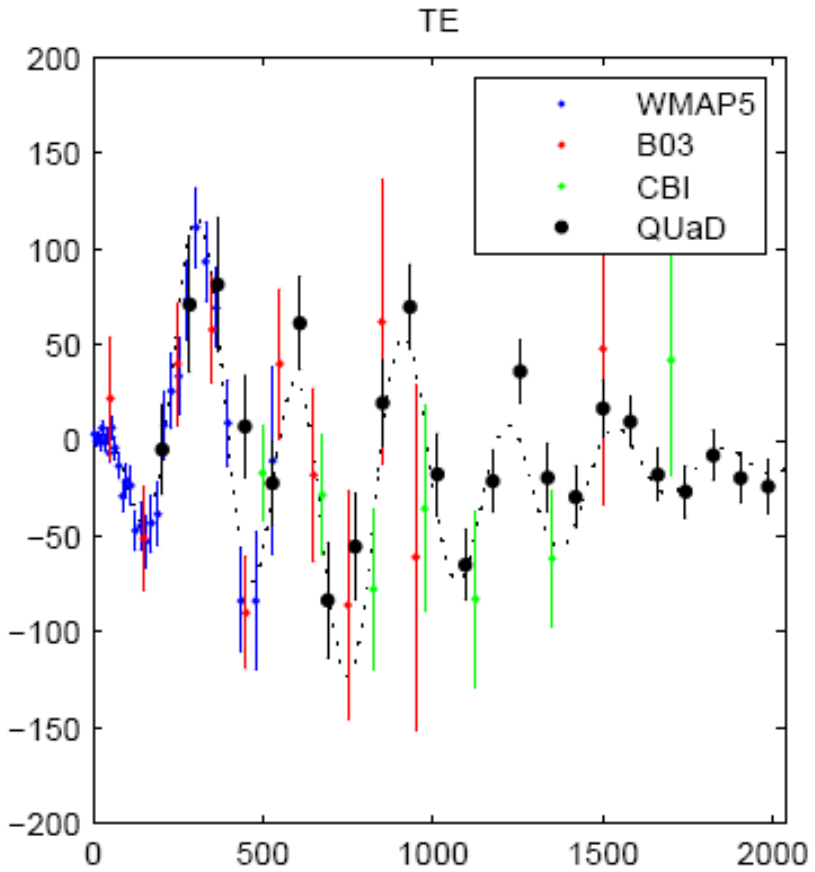
- Stanford University
- U. of Wales, Cardiff
- Caltech
- JPL
- U. of Chicago
- N.U.I Maynooth
- U. of Edinburgh
- Collège de France

Funded NSF, PPARC (UK), Enterprise Ireland

QUaD data

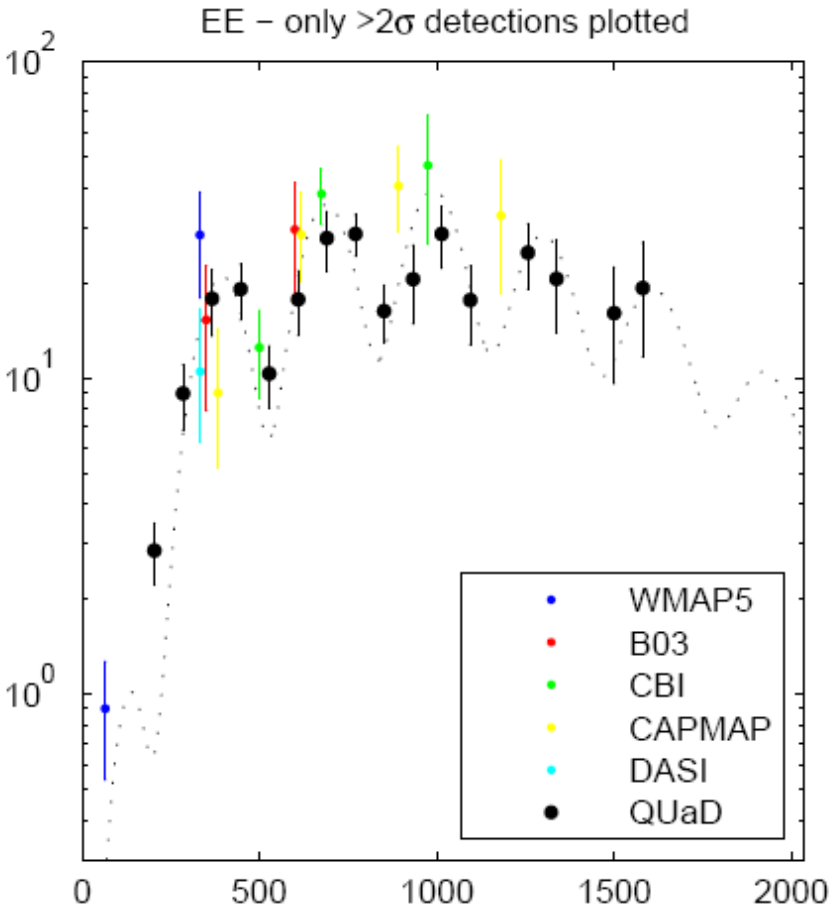


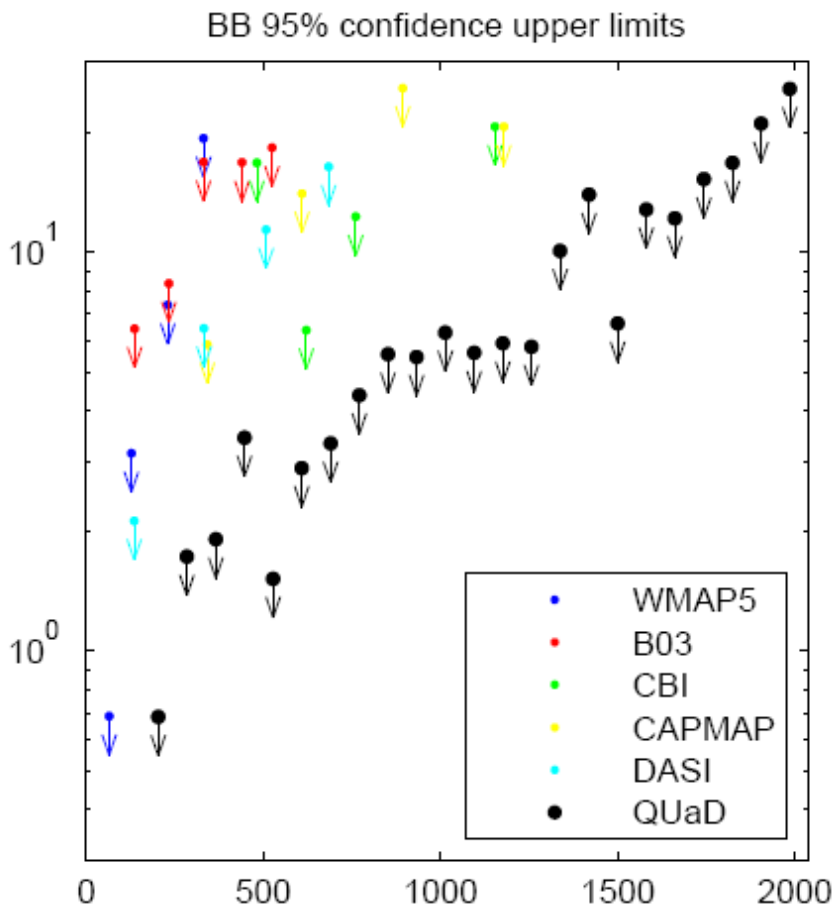
ACBAR also has KIPAC involvement (Kuo)



Multiple peaks in the various power spectra

QUaD data


EE – only >2σ detections plotted
10^2
10^1
10^0
0
500
1000
1500
2000
WMAP5
B03
CBI
CAPMAP
DASI
QUaD


BB 95% confidence upper limits
10^1
10^0
0
500
1000
1500
2000
WMAP5
B03
CBI
CAPMAP
DASI
QUaD

Summary

* The CMB is still the best astrophysical probe of conditions in the very early universe
* Offers a means to probe physics beyond the standard model e.g. inflation
* **KIPAC is already a center for CMB research**
* Strong intellectual connection to SLAC in
  - Technology development
  - Data handling and analysis
  - Project management
* Potential for KIPAC to lead the next generation of experiments culminating in a space mission