Testing Fundamental Physics with CMB Polarization (and other RMS Measurements) in the Next Decade

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From NWNH

FRONTIERS OF KNOWLEDGE

New fundamental physics, chemistry, and biology can be revealed by astronomical measurements, experiments, or theory and hence push the frontiers of human knowledge.

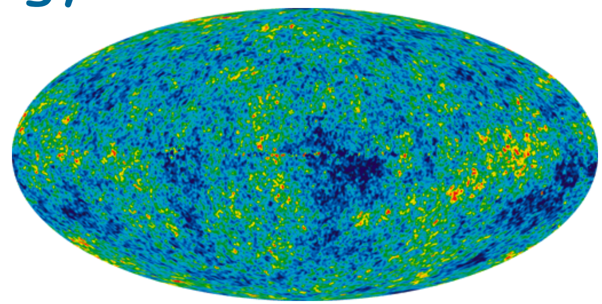
Science frontier questions in this category are:

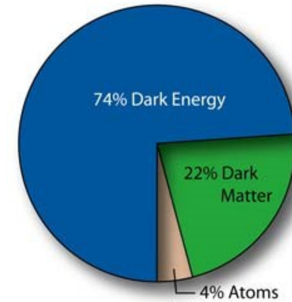
- ***Why is the universe accelerating?***
- ***What is dark matter?***
- ***What are the properties of the neutrinos?***
- ***What controls the masses, spins and radii of compact stellar remnants?***

Some thoughts about the next decade

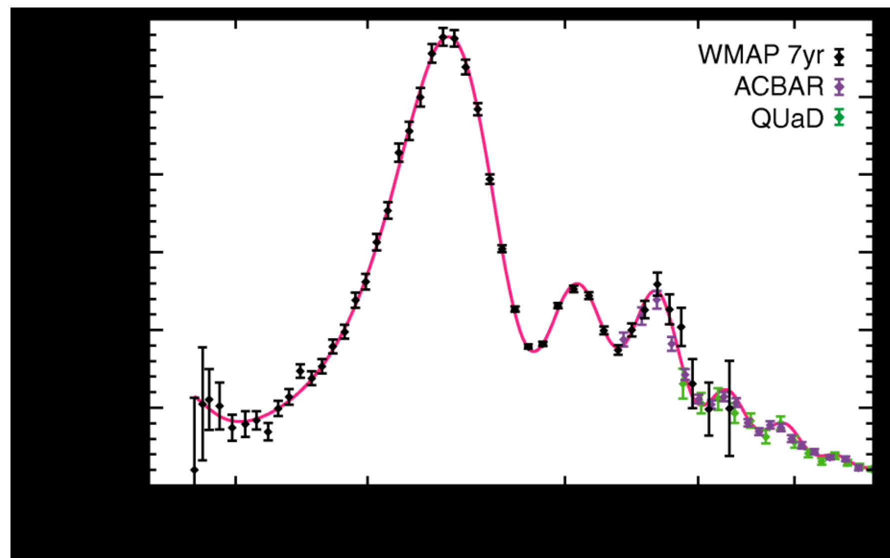
- Moving from phenomenology to detailed tests of physics theories

Image Credit: X-ray: NASA/CXC/M.Markevitch et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al. Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.





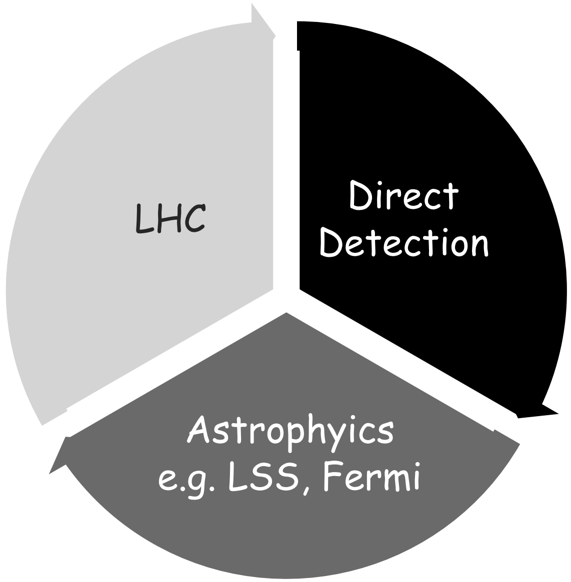
Credit: WMAP team



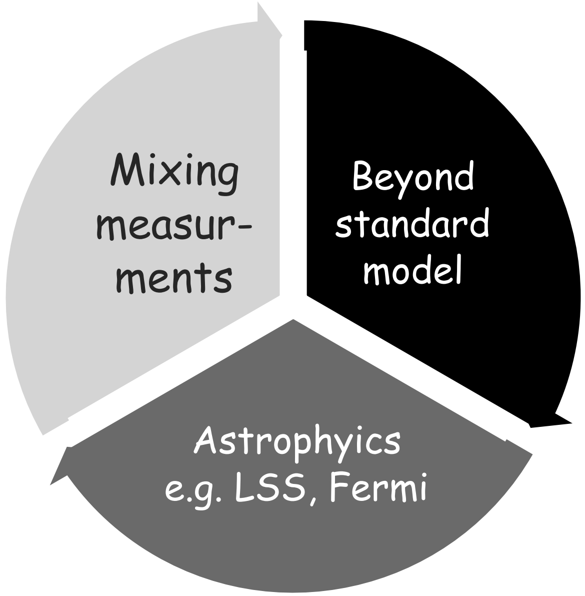
What is dark energy?
What caused inflation?

Many examples at the boundary of astrophysics and particle physics

- Example 1: The nature of dark matter



- Example 2: Neutrino mass



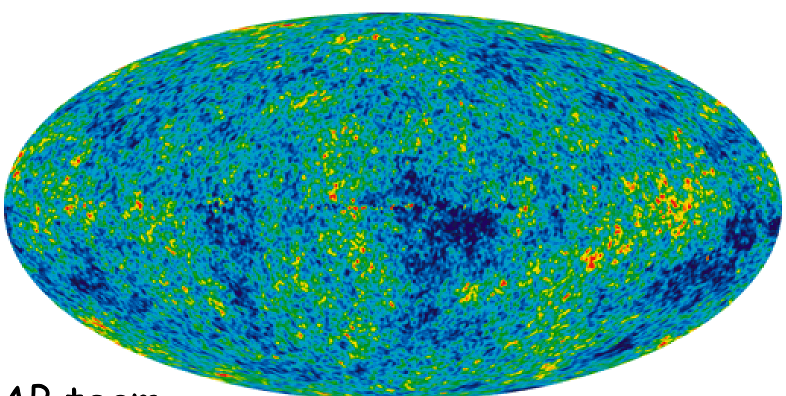
Many examples of where RMS will contribute

- CMB measurements to quantitatively probe inflation and exotic physics in the early universe
- Understanding the role of feedback on the formation of structure (AGN, synchrotron in galaxy clusters etc.)
- Probing particle acceleration (e.g Fermi/WMAP haze)
- Radio transients associated with gravitational wave events
- …and many more

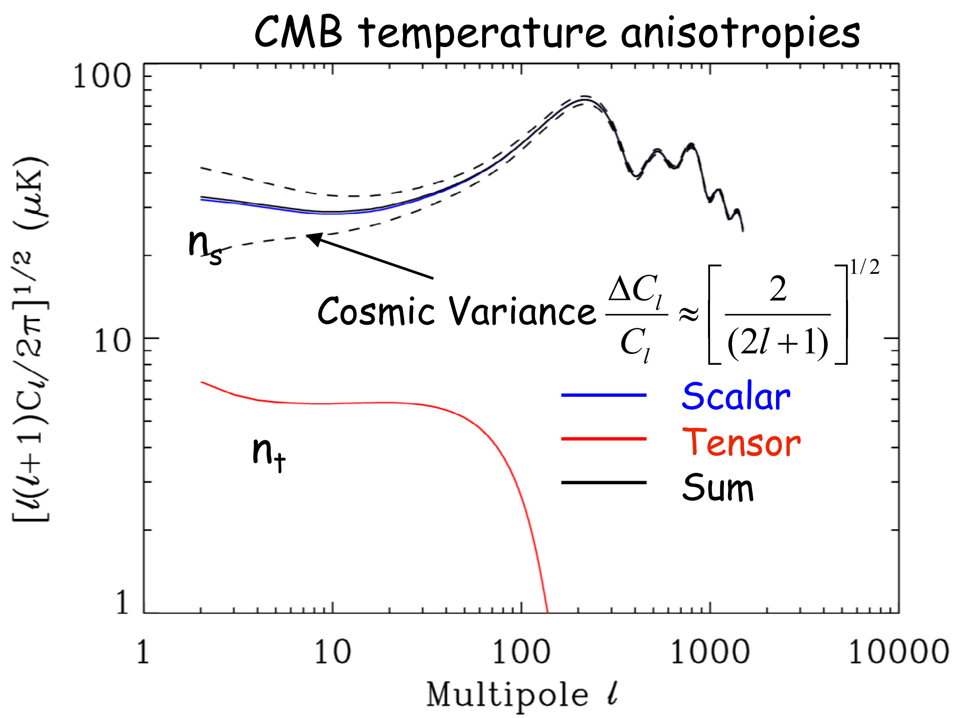
Example: Using the CMB to quantitatively probe inflation in the early universe.

- Scalar fluctuations (density fluctuations) are known to exist and are produced during inflation.
- Tensor fluctuations (gravitational waves) may be generated during inflation
- Relative proportions depend on the exact model of inflation

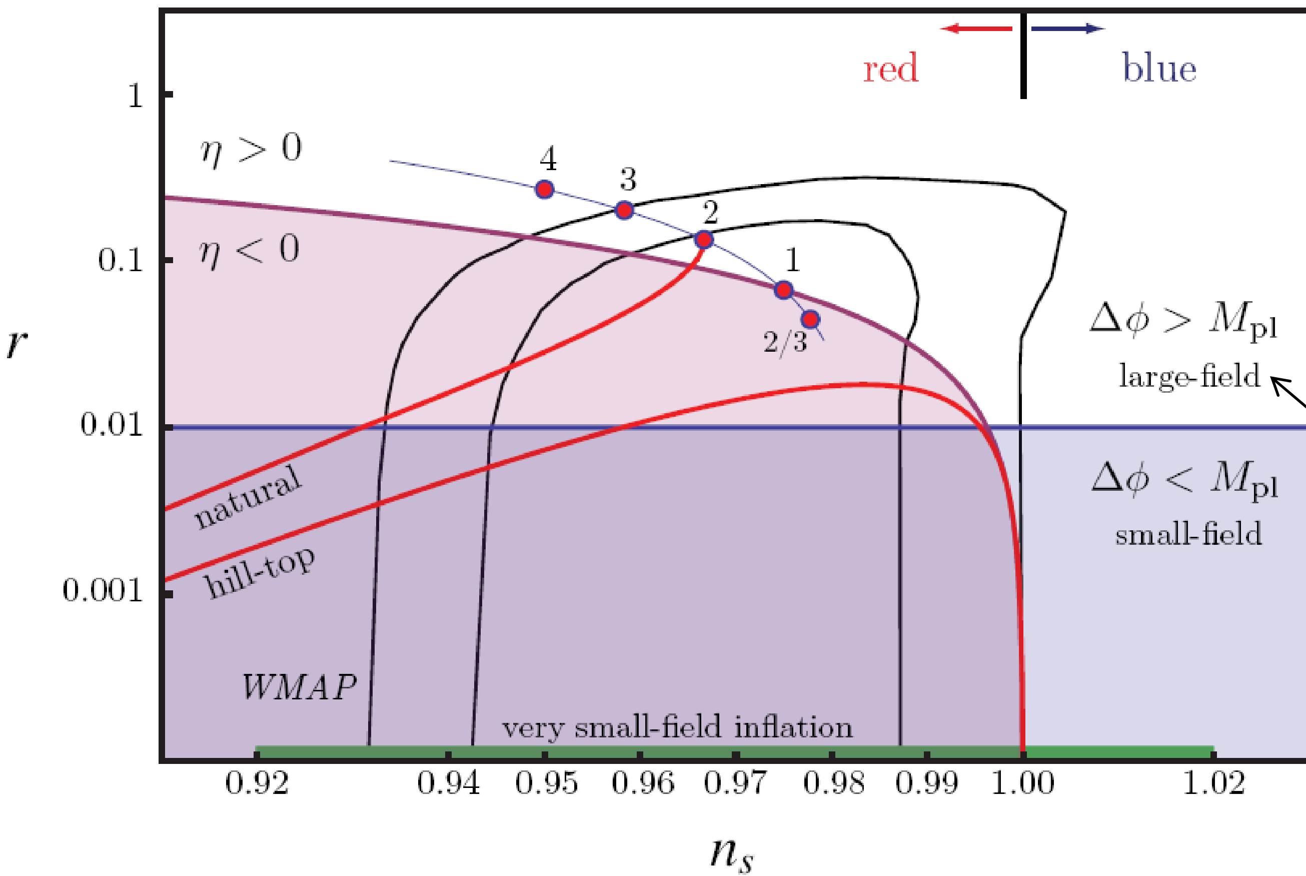
-- See review Baumann et al., arXiv:0811.3919



WMAP team



The allowed model space is large!



Detectable with upcoming Experiments!

Baumann et al.,arXiv:0811.3919

Example of WMAP measurements of r and n_s

"Precision cosmology"

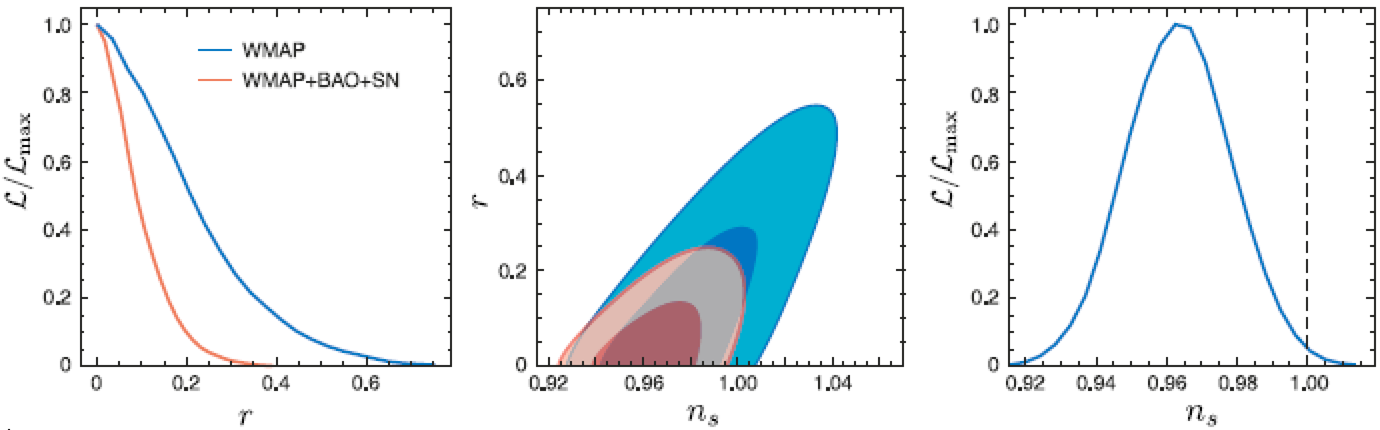


Figure 7: *WMAP* 5-year constraints on the inflationary parameters n_s and r [14]. The *WMAP*-only results are shown in blue, while constraints from *WMAP* plus other cosmological observations are in red. The third plot assumes that r is negligible.

Parameter	5-year *WMAP*	*WMAP*+BAO+SN
n_s	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.013}_{-0.013}$
n_s	0.986 ± 0.022	0.970 ± 0.015
r	< 0.43	< 0.22
n_s	$1.031^{+0.054}_{-0.055}$	$1.017^{+0.042}_{-0.043}$
α_s	-0.037 ± 0.028	$-0.028^{+0.020}_{-0.020}$
n_s	$1.087^{+0.072}_{-0.073}$	$1.089^{+0.070}_{-0.068}$
r	< 0.58	< 0.55
α_s	-0.050 ± 0.034	-0.058 ± 0.028

$$\alpha_s \equiv \frac{dn_s}{d\ln k}$$ Running spectral index

$$r \equiv \frac{P_t}{P_s}$$ Tensor-scalar ratio

Komatsu et al., arXiv:0803.0547

Where things are…

Label	Definition	Physical Origin	Value
Ω_b	Baryon Fraction	Baryogenesis	0.0456 ± 0.0015
$\Omega_{\rm CDM}$	Dark Matter Fraction	TeV-Scale Physics (?)	0.228 ± 0.013
Ω_Λ	Cosmological Constant	Unknown	0.726 ± 0.015
τ	Optical Depth	First Stars	0.084 ± 0.016
h	Hubble Parameter	Cosmological Epoch	0.705 ± 0.013
A_s	Scalar Amplitude	Inflation	$(2.445 \pm 0.096) \times 10^{-9}$
n_s	Scalar Index	Inflation	0.960 ± 0.013

See review Baumann et al., arXiv:0811.3919

Where we would like things to be

Label	Definition	Physical Origin	Current Status	Section
A_s	Scalar Amplitude	V, V'	$(2.445 \pm 0.096) \times 10^{-9}$	§3.4
n_s	Scalar Index	V', V''	0.960 ± 0.013	§3.4
α_s	Scalar Running	V', V'', V'''	only upper limits	§3.4
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ω_k	Curvature	Initial Conditions	only upper limits	§6.2
$f_{\rm NL}$	Non-Gaussianity	Non-Slow-Roll, Multi-Field	only upper limits	§5.3
S	Isocurvature	Multi-Field	only upper limits	§5.4
$G\mu$	Topological Defects	End of Inflation	only upper limits	§6.1

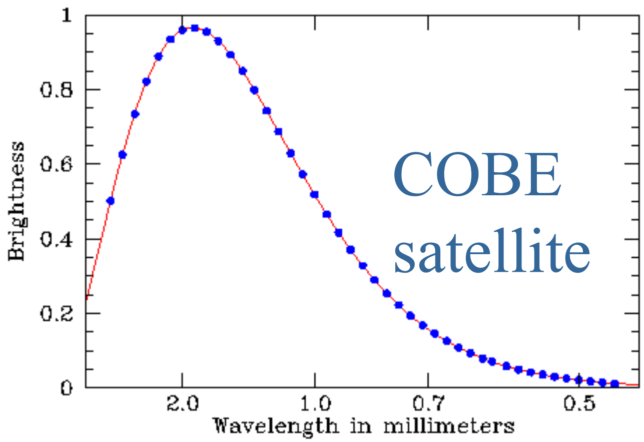
See review Baumann et al., arXiv:0811.3919

CMB polarization measurements will play a major role in determining these parameters

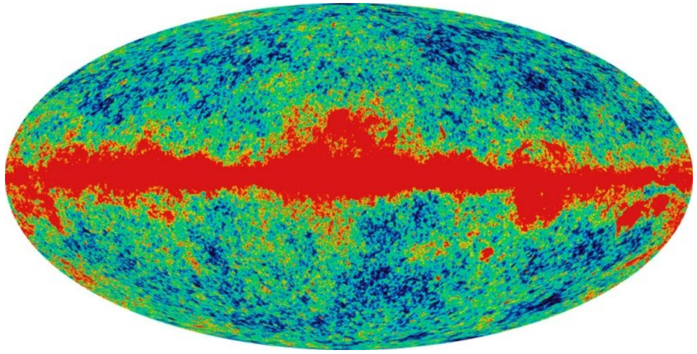
$$V(\phi) = V|_\star + V'|_\star (\phi - \phi_\star) + \frac{1}{2} V''|_\star (\phi - \phi_\star)^2 + \frac{1}{3!} V'''|_\star (\phi - \phi_\star)^3 + \cdots$$

Polarization is the third measurable property of the CMB

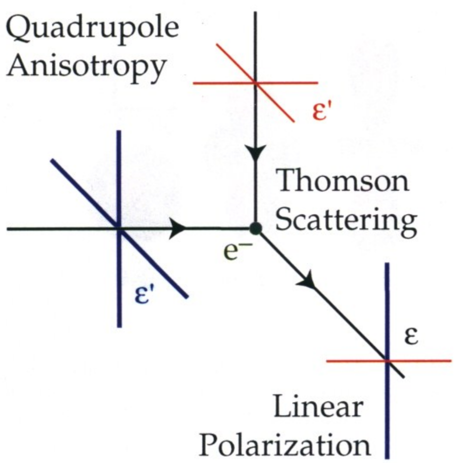
- Frequency spectrum



- Spatial temperature variations:



WMAP satellite 2003

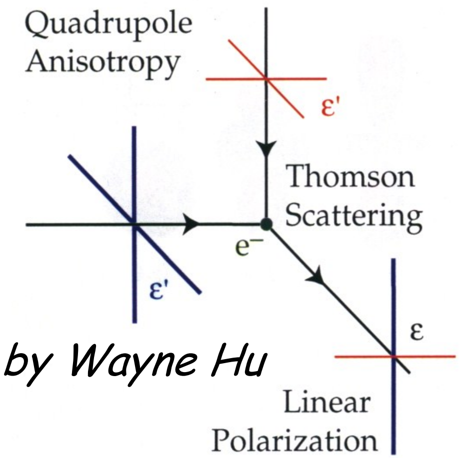


Picture by W. Hu

- Polarization generated by Thomson scattering
- The polarization percentage is high (around 10%), but the signal is still very weak
- The physics is well-understood
- Precision cosmology equally feasible using polarization

Polarization patterns on the sky depend on the source of the temperature anisotropies

- Only quadrupoles at the surface of last scattering generate a polarization pattern

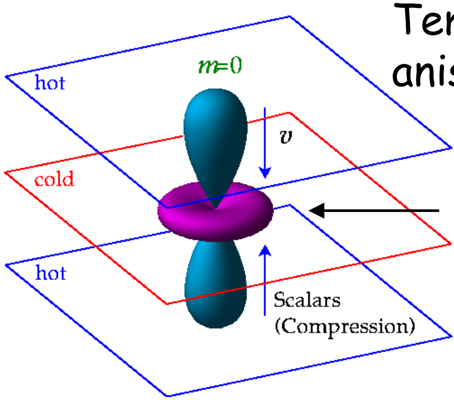


Pictures by Wayne Hu

Pictures by Wayne Hu

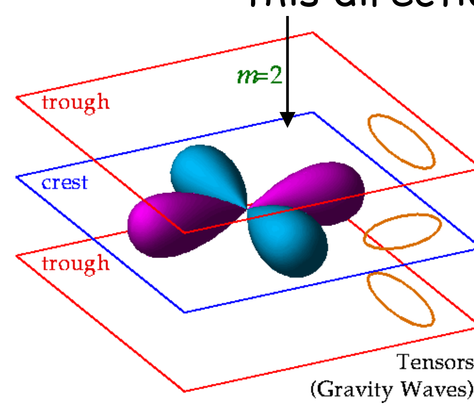
Temperature anisotropy

Quadrupole viewed in this direction

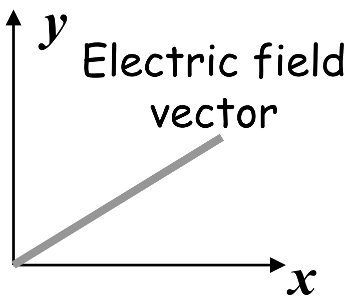


Quadrupole viewed in this direction

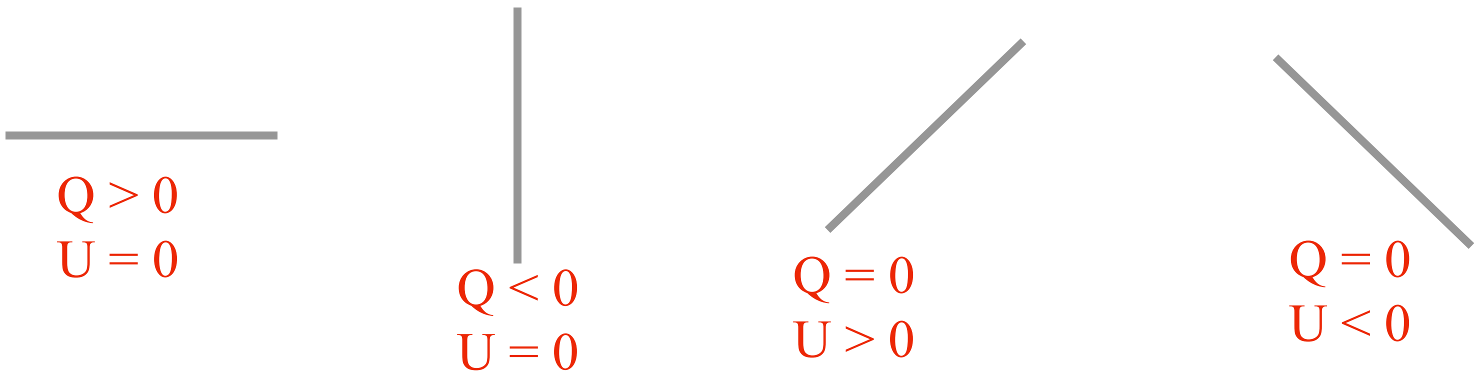
Temperature anisotropy



Relating polarization to observables

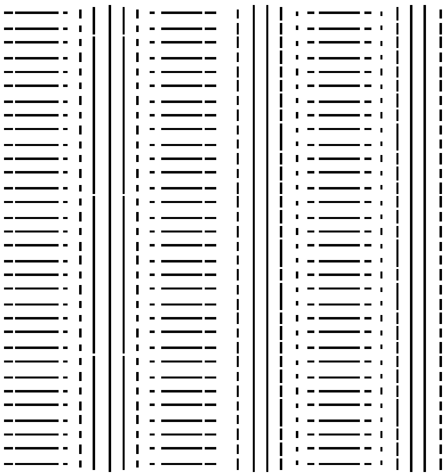


- The observables are Stokes parameters I, Q and U
  - Circular polarization (parameter V) is not expected

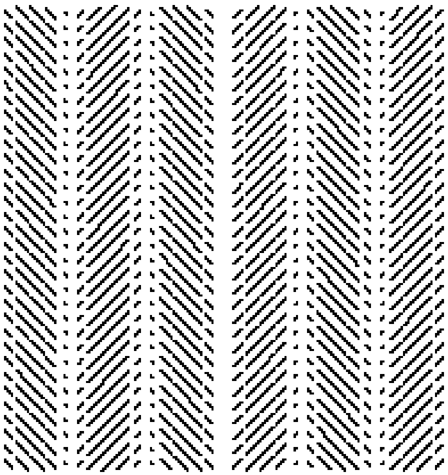


- But Q and U depend on the local coordinate system
  - Rotate coordinates by 45°, Q becomes U and vice versa
- Need an observable that is independent of coordinate system.

“E” and “B” modes

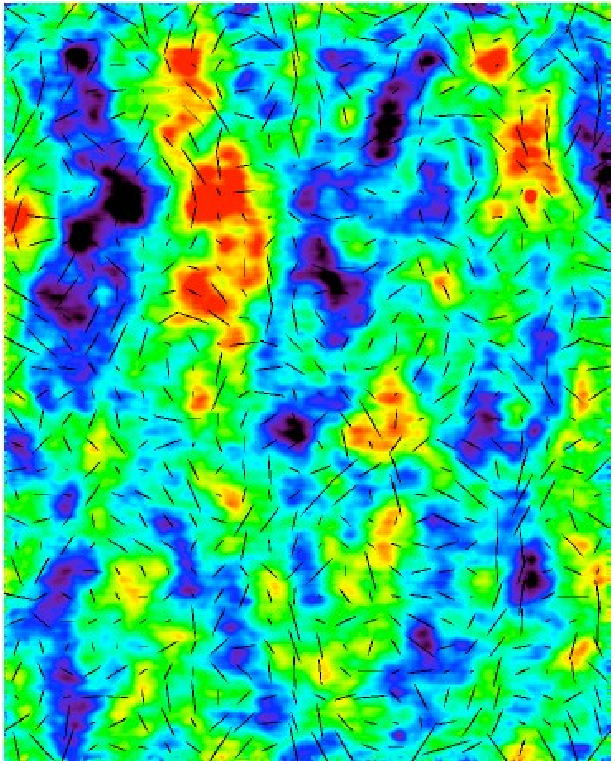


E Fourier mode



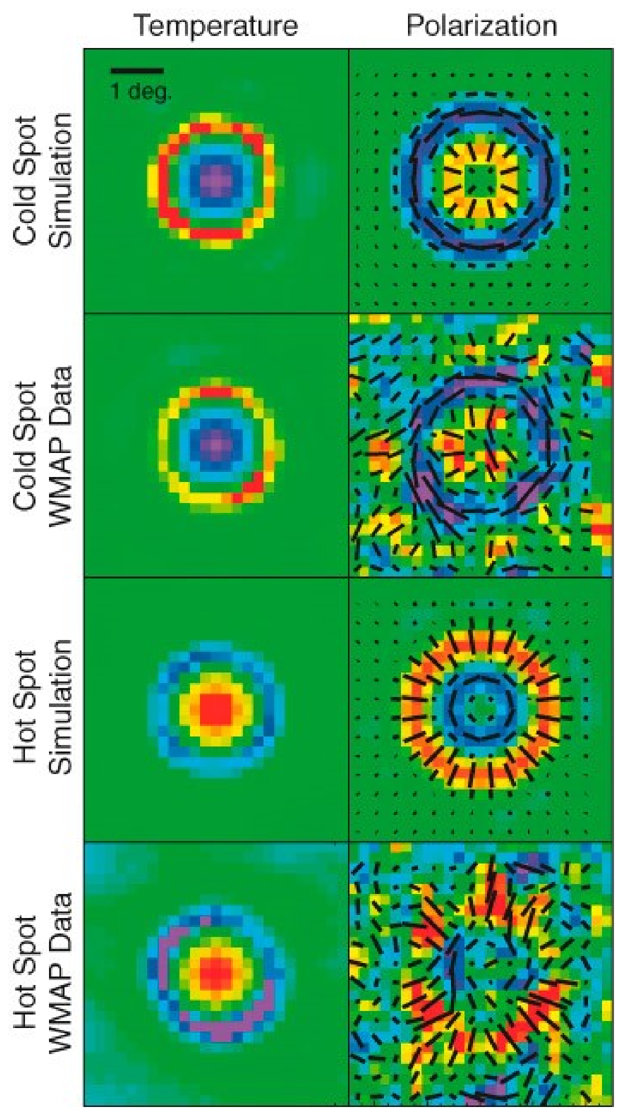
B Fourier mode

See, e.g. Bunn, 2005



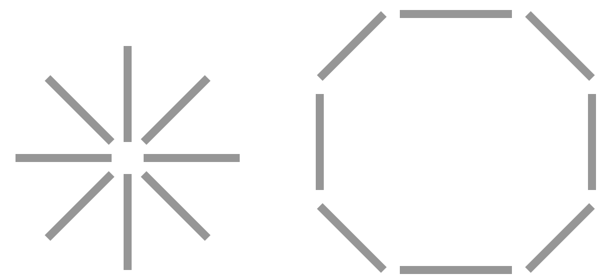
QUaD data – see later

E-modes as seen by WMAP (7-year)

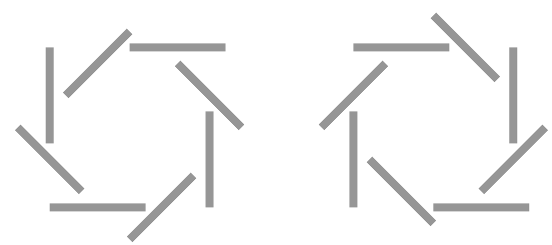


Credit: NASA / WMAP Science Team

- Stacked hot and cold spots in the 7-year maps



E modes



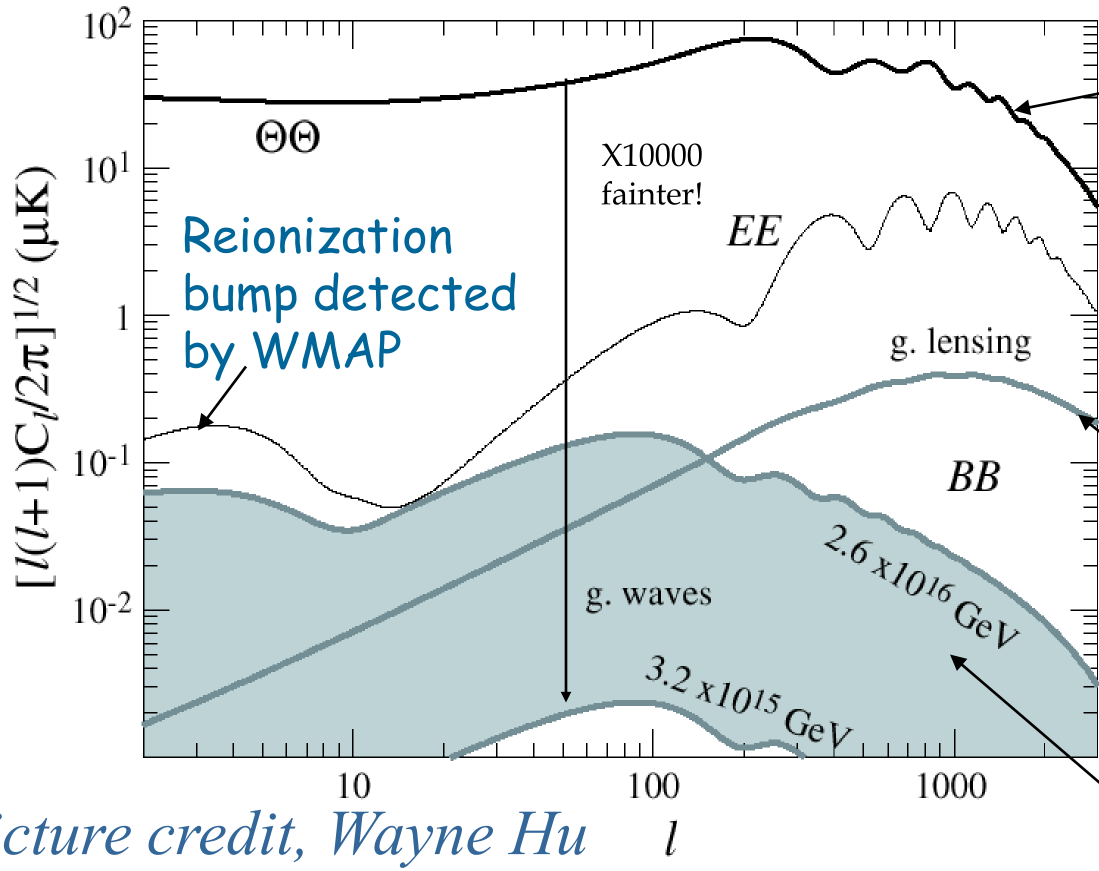
B modes

ONLY FROM GRAVITATIONAL WAVES

Aim of CMB polarization measurements

- Stronger constraints on a host of cosmological parameters from *E*-modes
  - E.g. Optical depth, τ, and redshift of reionization from WMAP
- Measure (or set limits to) parameters of inflation from *B* modes:
  - E.g ratio of tensor/scalar modes, r
  - Spectral index of tensor fluctuations, n_t
  - Other effects e.g. non-gaussinity
- Probe dark energy parameters and neutrino mass through lensing of *E*-modes to *B*-modes, also CMB temperature anisotropies

Polarization measurements require greater sensitivity than temperature measurements...



Temperature spectrum mapped by WMAP

Gravitationally lensed E-modes probe large scale structure formation

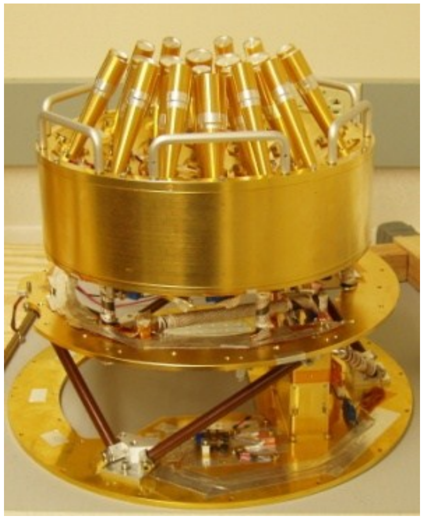
Projected effect of a gravitational wave background

Picture credit, Wayne Hu

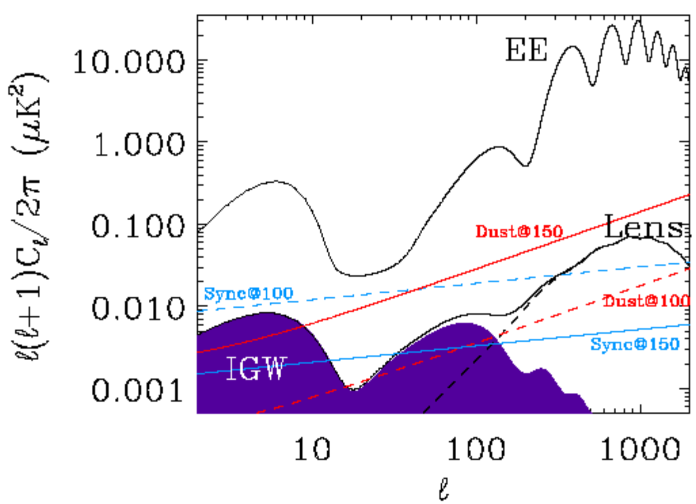
The range shown for the gravitational wave background spans the maximum allowable level from COBE, and the minimum detectable from CMB measurements

Example: The QUaD Experiment 2004-2007

- Used polarization-sensitive bolometers (also in Planck, BICEP)
- Specifically designed to measure CMB polarization

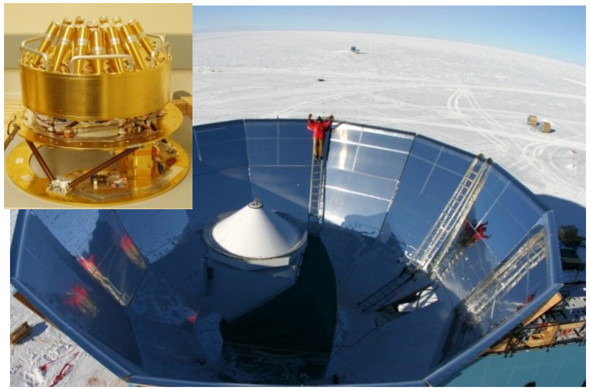


QUaD 31-pixel Camera



Freq (GHz)	Beam (arcmin)	No. feeds
100	6.3	12 (9)
150	4.2	19 (17)

The QUaD team



Stanford University/KIPAC
-- **Sarah Church (US PI)**, Melanie Bowden, Keith Thompson, Ed Wu

University of Chicago/KICP
-- **Clem Pryke (Data Analysis Leader)**, Tom Culverhouse, Robert Friedman

Caltech
-- Andrew Lange, John Kovac, Erik Leitch, Angiola Orlando

JPL/IPAC
-- Jamie Bock, Ben Rusholme, Mike Zemcov

NASA Goddard
-- Jamie Hinderks

Chicago/SouthPole
-- Robert Schwarz

Cardiff University
-- **Walter Gear (UK PI)**, Peter Ade, Sujarta Gupta, Abigail Turner

University of Edinburgh
-- Andy Taylor

University of Cambridge
-- Michael Brown

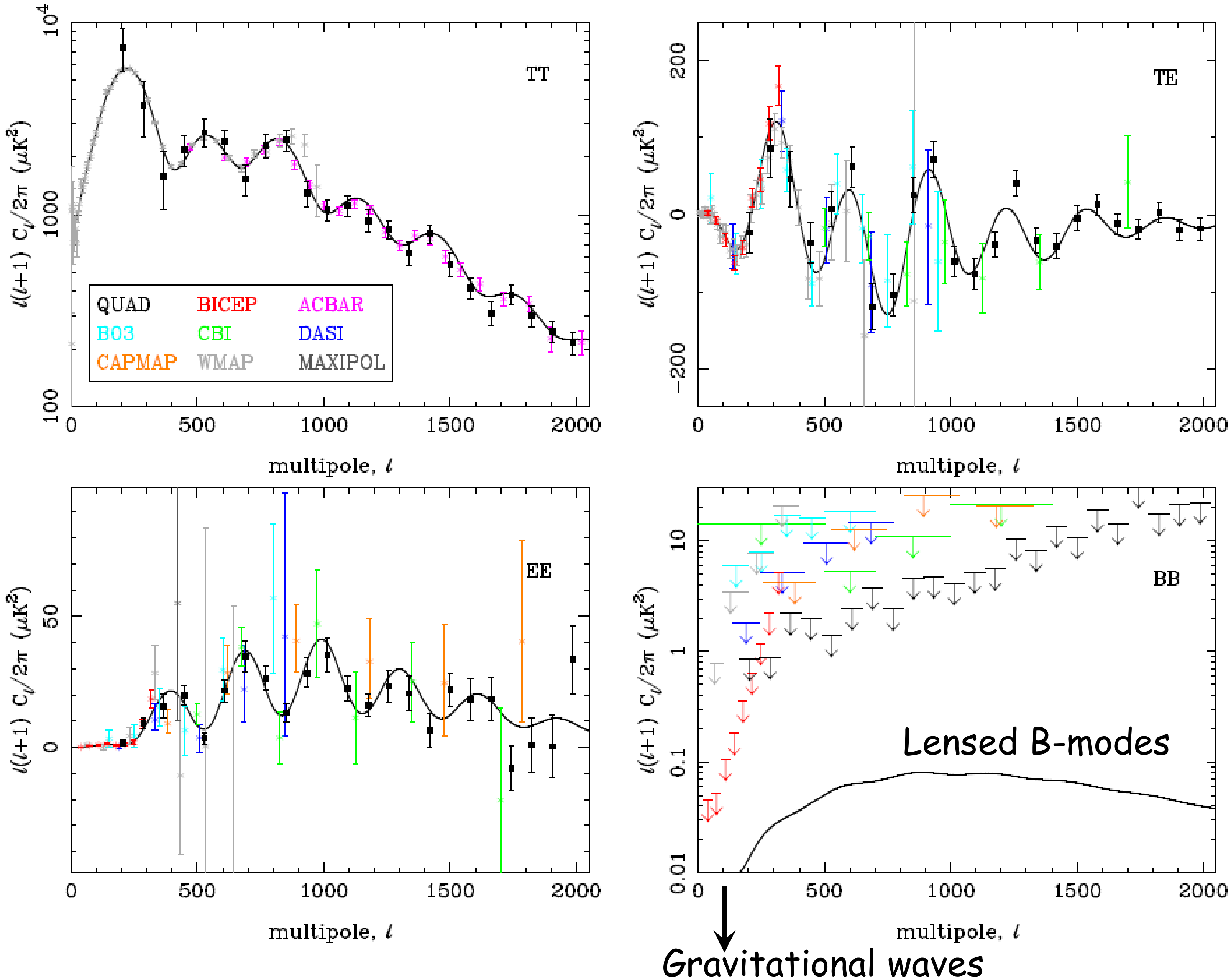
Laboratoire APC/CNRS
-- Ken Ganga

Universidade Técnica de Lisboa
-- Patricia Castro

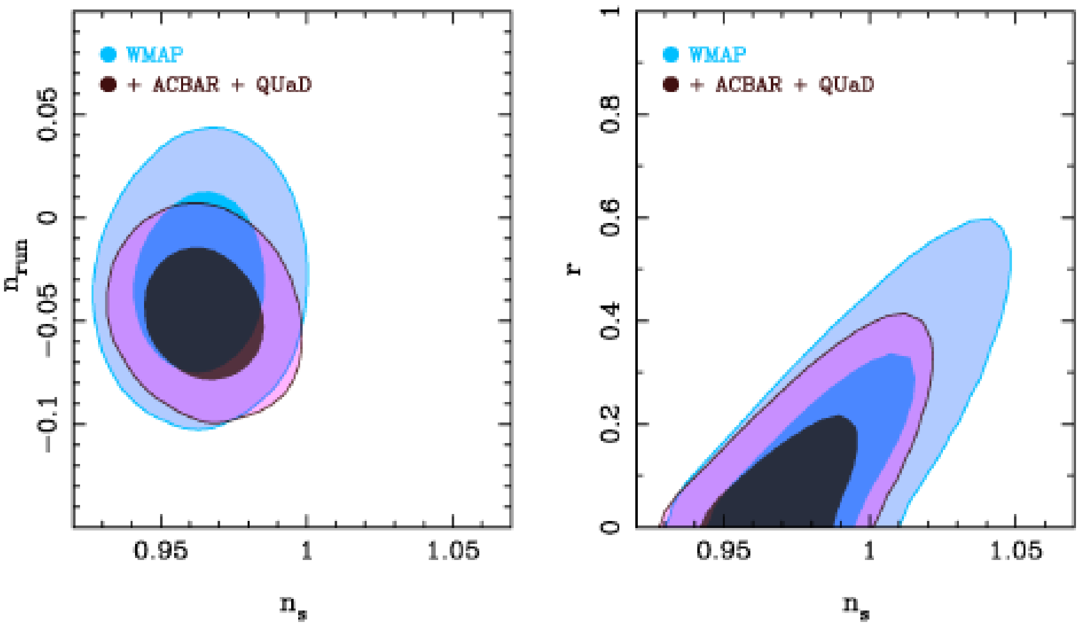
Manchester University
-- Lucio Piccirillo, Simon Melhuish

Maynooth College, Ireland
-- Anthony Murphy, Creidhe O'Sullivan, Gary Cahill

Status of power spectrum measurements circa 2009 (Brown et al., arXiv:0906.1003)

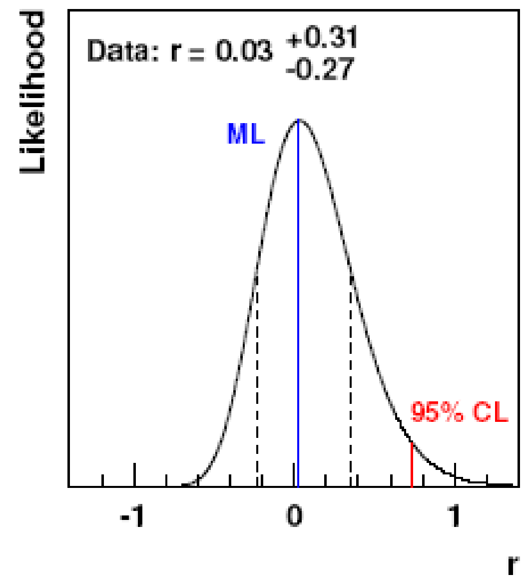


Inflationary parameters from CMB measurements



WMAP (5 year) + QUaD plus ACBAR, with r inferred from n_s

Brown et al., arXiv:0906.1003



Best *direct* limit from B-modes – BICEP experiment

Chiang et al.

arXiv: 0906.1181

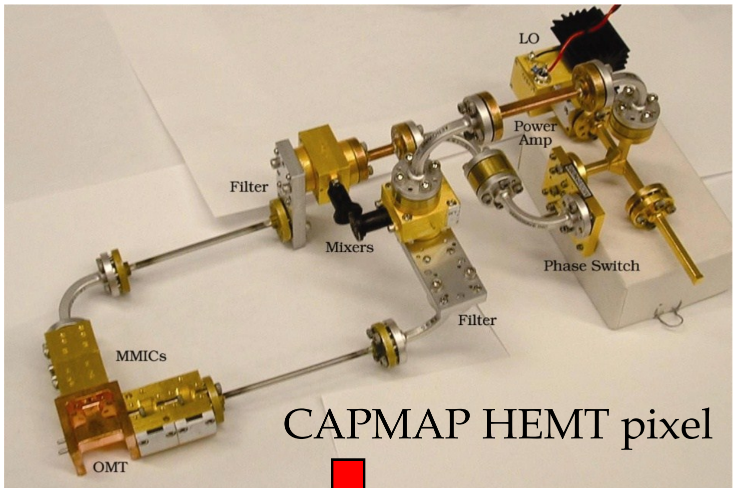
$r < 0.7$ (95% conf.)

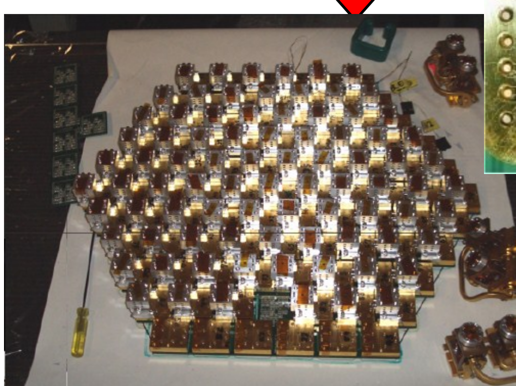
The experimental landscape going forward

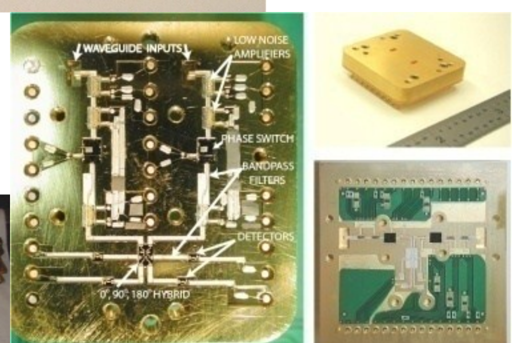
- Experiments fielding or under construction
  - Planck (bolometers, HEMTs)
  - QUIET II (HEMTs)
  - EBEX (Bolometers)
  - Keck (Bolometers)
  - Polarbear (Bolometers)
  - SPTpol (Bolometers)
  - ABS (Bolometers)
  - ACTpol (Bolometers)
  - Spider (Bolometers)
  - PIPER (Bolometers)
  - + others I may have forgotten (the field is large…)
- **Reduction of systematics will be key**
  - We need to try different techniques and technologies
  - We need wide frequency coverage to understand foregrounds

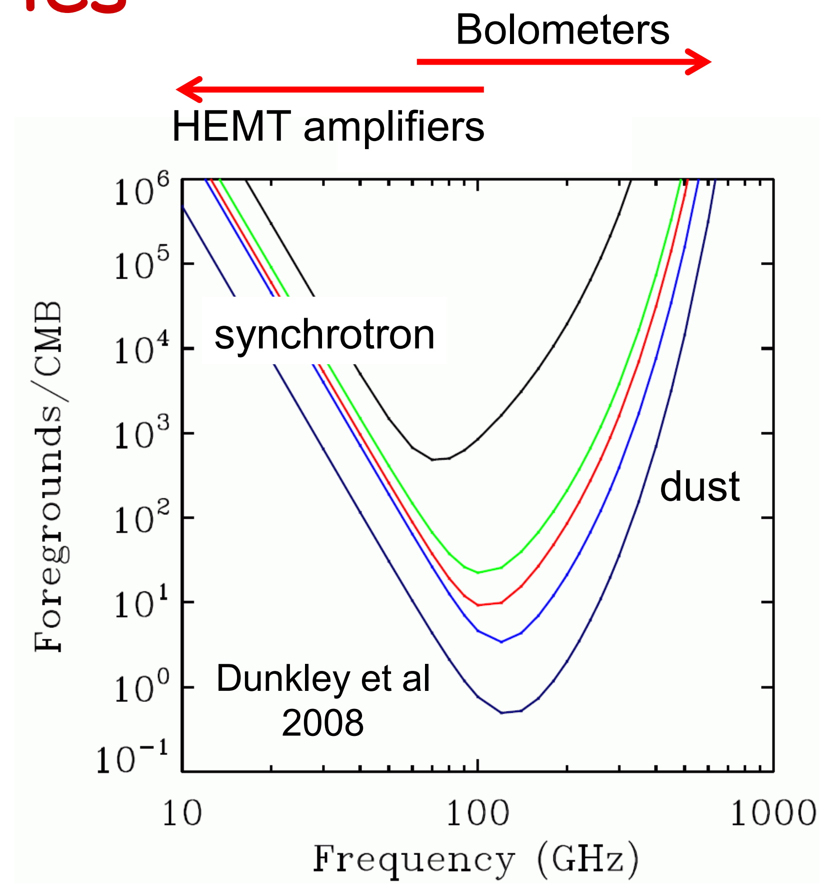
Detector developments will drive new experiments and discoveries

"Hand-crafted" pixels





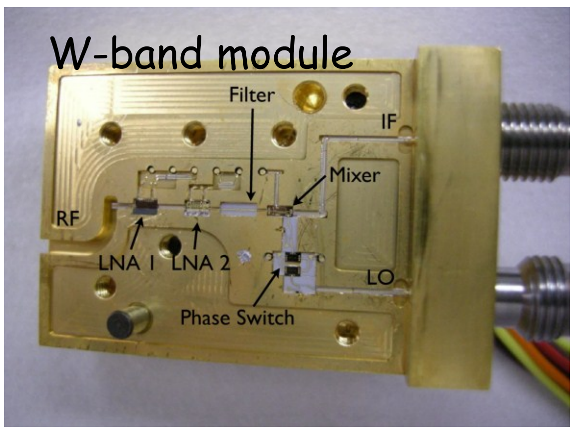




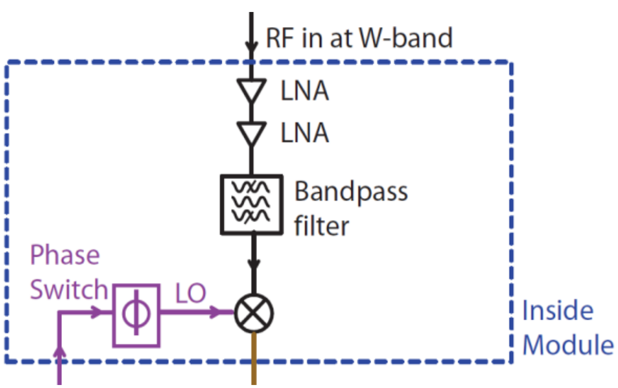
MMIC HEMT arrays for the Quiet experiment manufactured at JPL

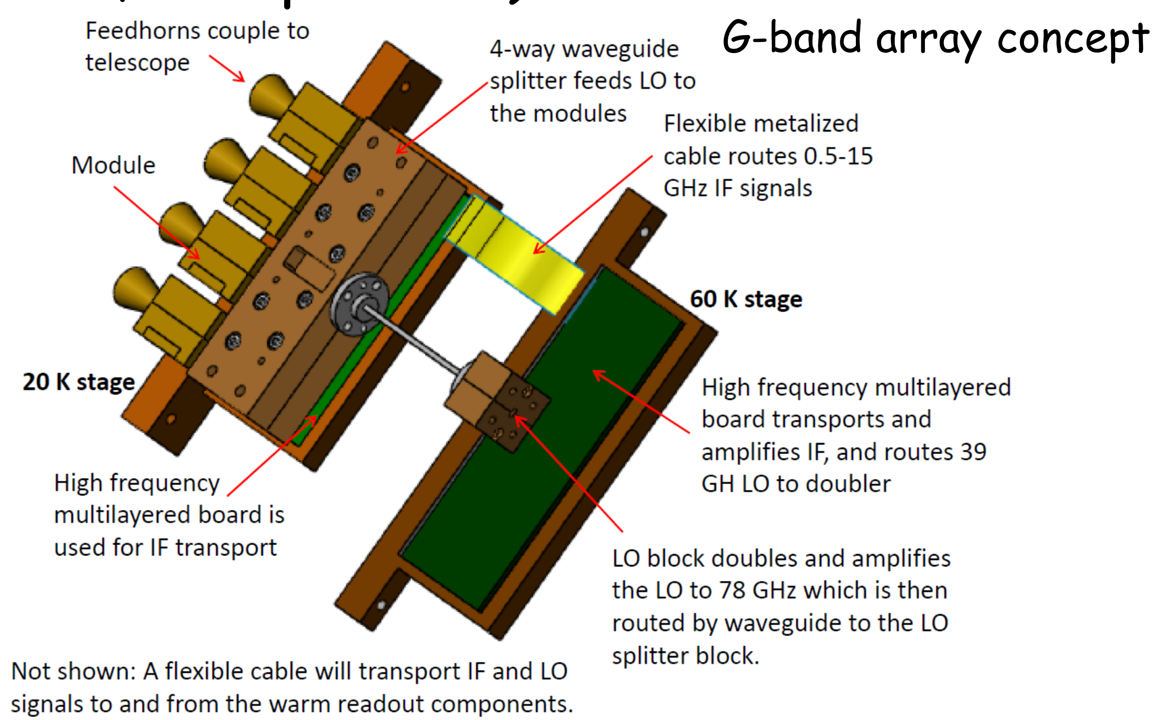
MMIC arrays for CMB and other science

- Focal plane arrays (FPAs)
  - CMB polarization interferometry
  - High resolution measurements of the Sunyaev-Zel'dovich effect using interferometers equipped with FPAs
  - W-band and G-band spectrocopy

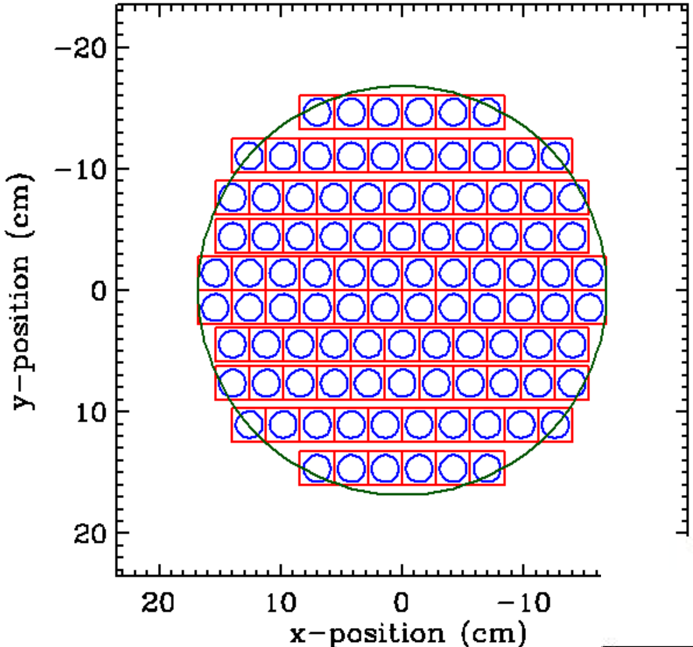


Stanford, Caltech, JPL, Maryland (see Sieth, Voll posters)

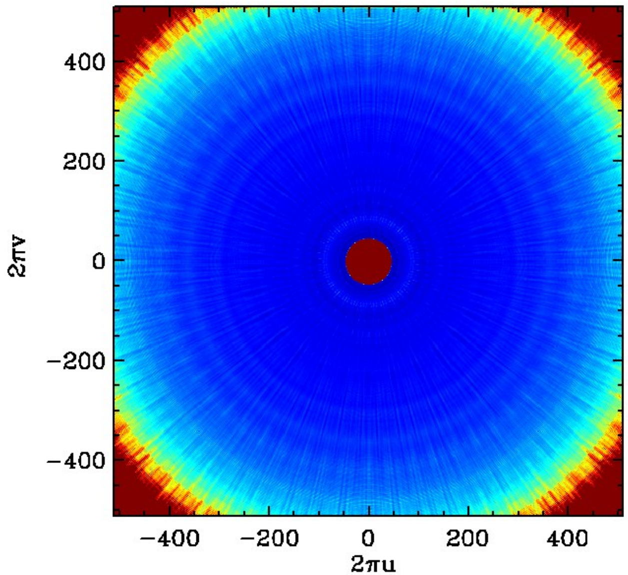


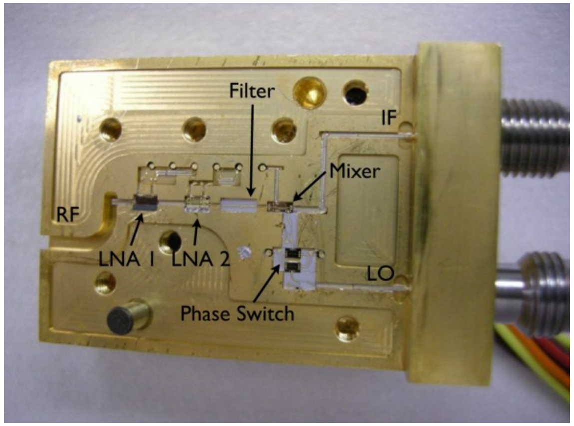


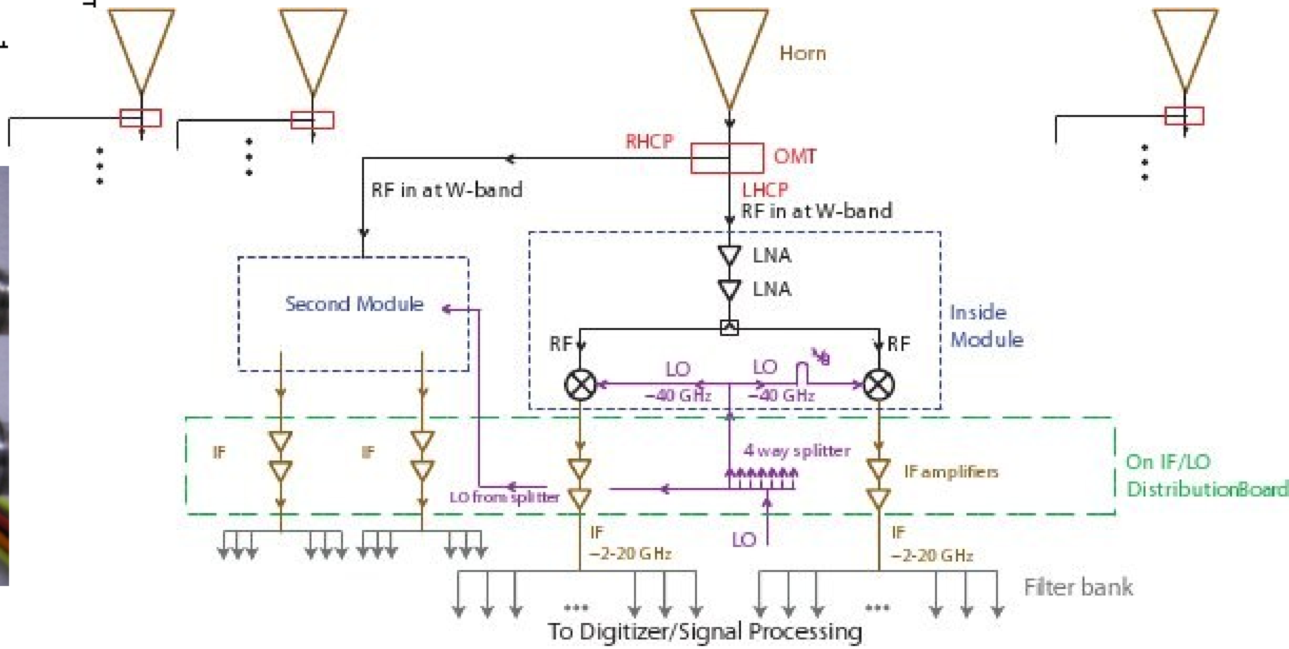
Strawman design, B-mode interferometer



uv-coverage





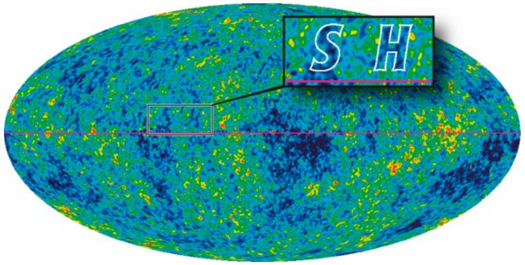


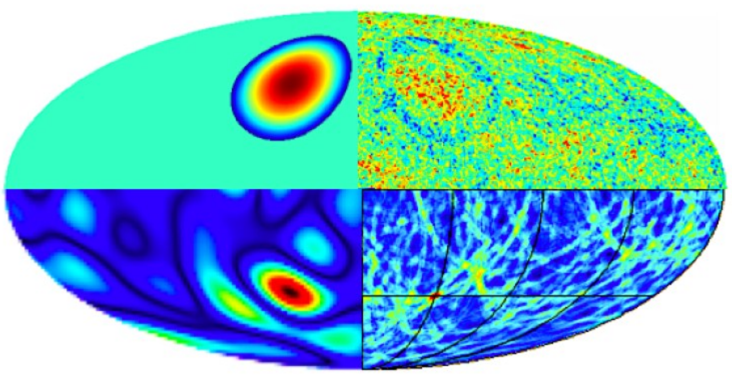
We need to be prepared to confront our data with more speculative physics

- Signature of the "Bubbles" from eternal inflation
- Temperature patch is pure E-mode but different radial dependence to those from density modes
- We need careful and ongoing analysis to properly test these predictions. See for example:

  Bennett et al., 2011, arXiv:1001.4758v2

Credit: WMAP team





Simulations, Feeney et al. 2010

Conclusions

- The CMB is still one of the cleanest probes that we have of conditions in the early universe.
- Future measurements will set limits on inflationary parameters…
  - n_s n_t – scalar and tensor spectral indices
  - $\alpha = dn_s/d\ln k$ -- running spectral index
  - r -- tensor/scalar ratio
  - Non-gaussianity – a whole other talk there…….
- ..as well as other cosmological parameters and secondary sources of anisotropy
  - E.g. neutrino mass, Sunyaev-Zel'dovich effect
- Look for results from future experiments, especially Planck in the next few years
- **A B-mode detection using 2 completely different experimental methods would be transformative**