Dorothea Samtleben,
NIKHEF, Amsterdam

Measuring the Cosmic Microwave Background Radiation

News from the oldest light

The Cosmic Microwave Background Radiation

- Expectations, measurements and mysteries of its

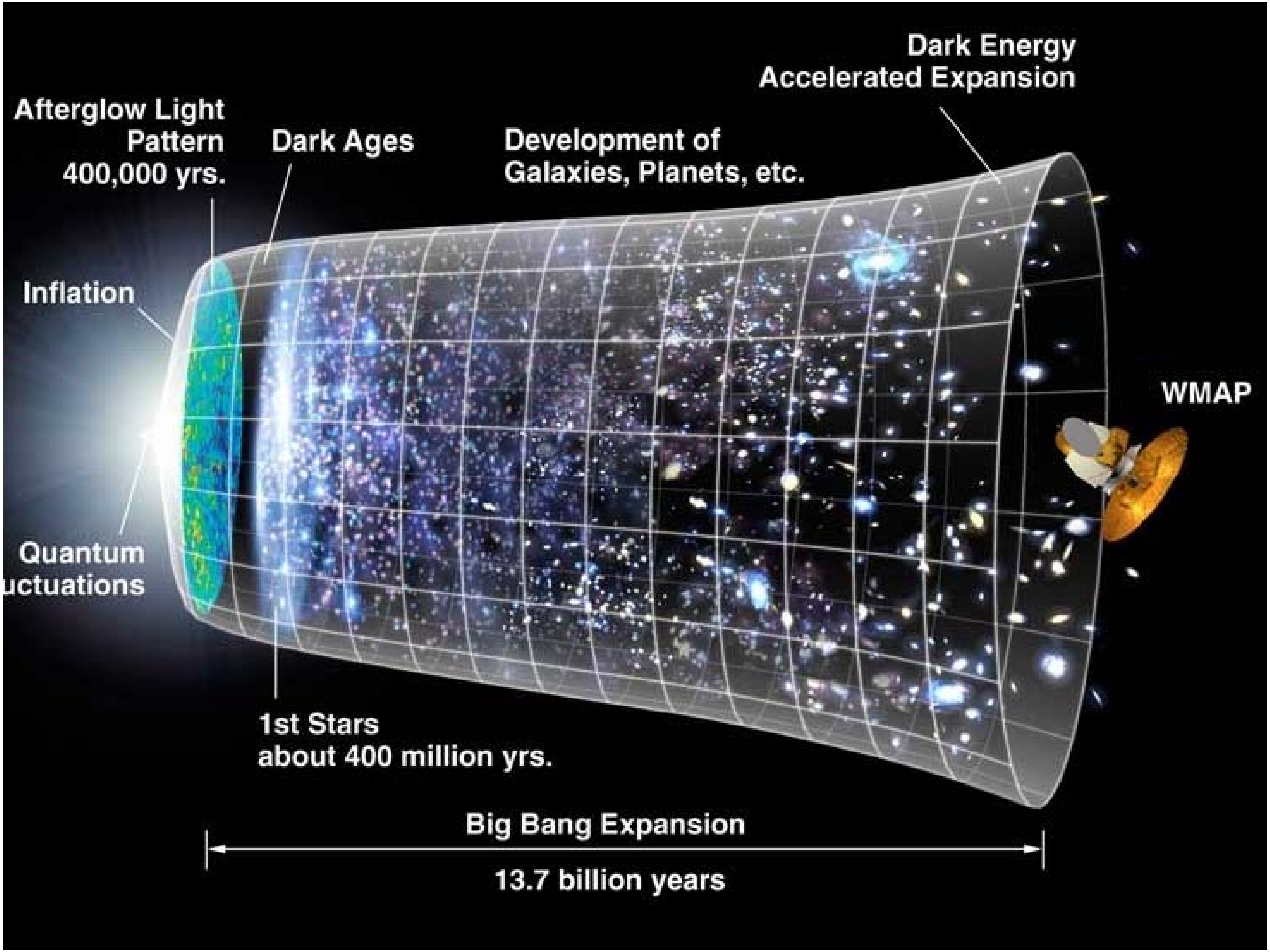
  * Temperature Anisotropies

  * Polarization Anisotropies

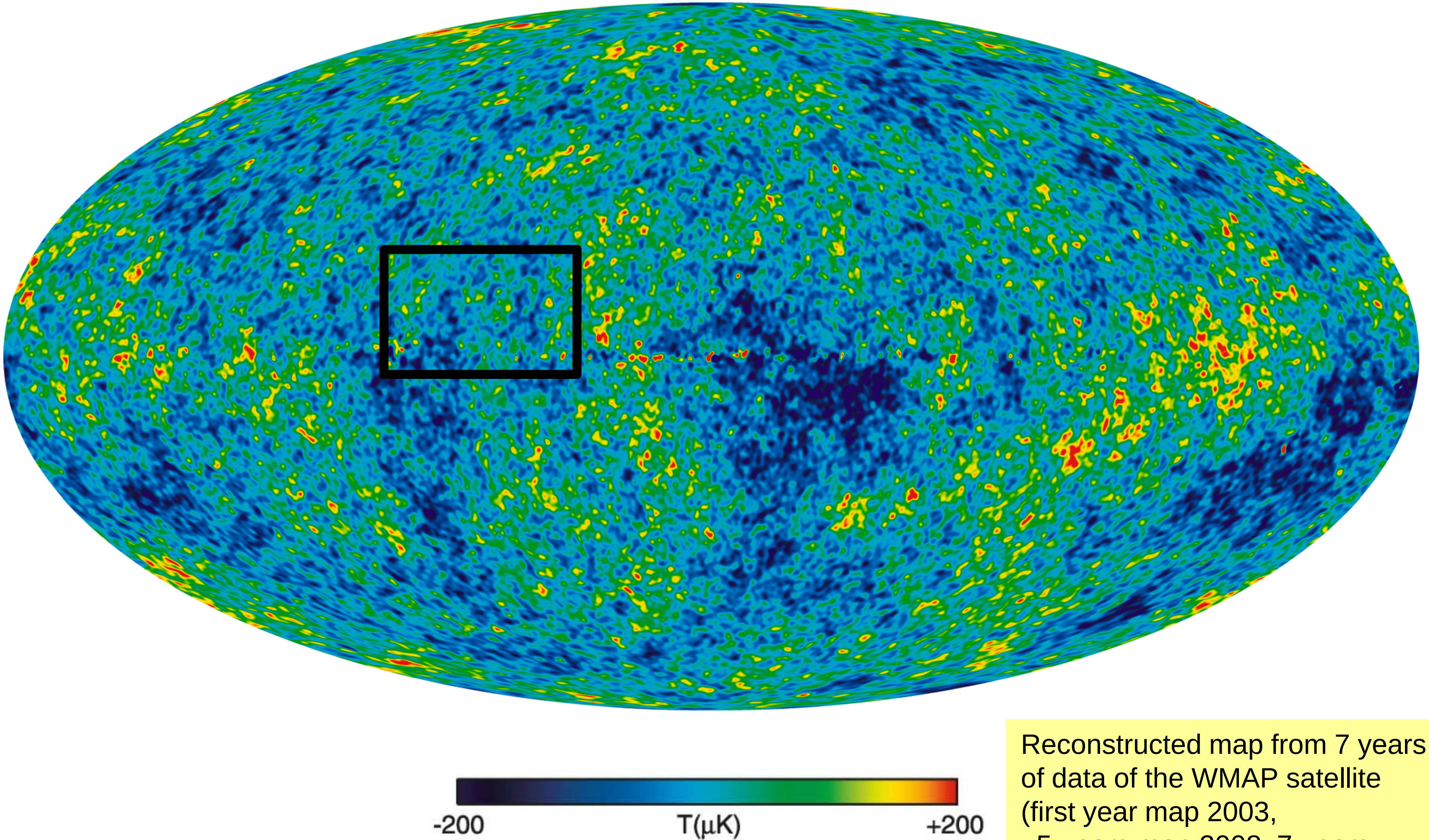
- Future prospects

  * Ground-based and satellite experiments

  * The Q/U Imaging ExperimenT (QUIET)

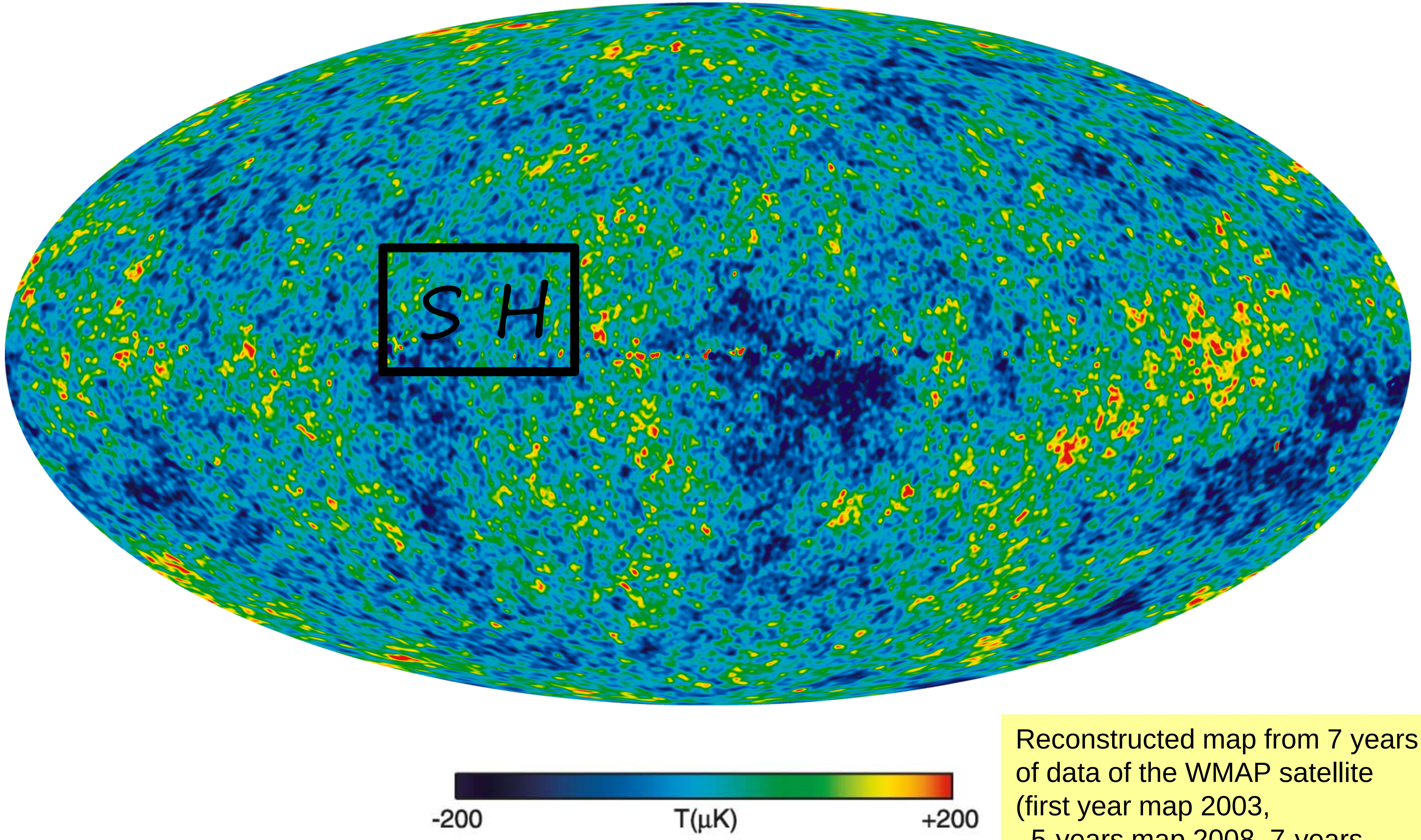

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
uctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

The oldest light



Reconstructed map from 7 years of data of the WMAP satellite (first year map 2003, 5-years map 2008, 7-years map 2010)

The oldest light



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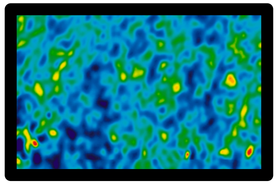


Stephen Hawking‘s initials found in sky map (Lyman Page)

Be careful with the interpretation of the data!

Accoustic Oscillations

Density oscillations in charged plasma
driven by gravitation and radiation pressure

Sound horizon during recombination determines
size of fluctuations

Pattern of primordial fluctuations
(determined by inflation)

Energy densities of baryonic/dark matter

Curvature of space

Scattering due to Reionization,
lensing by mass in line of sight
(Neutrino Mass, Dark Energy play a role)

→ Pattern of CMB fluctuations

Description of anisotropies

- Statistical properties of CMB predictable
- Representation by spherical harmonics Y_{lm}

Temperature: $$T(\theta,\varphi) = \sum a_{lm} Y_{lm}(\theta,\varphi)$$

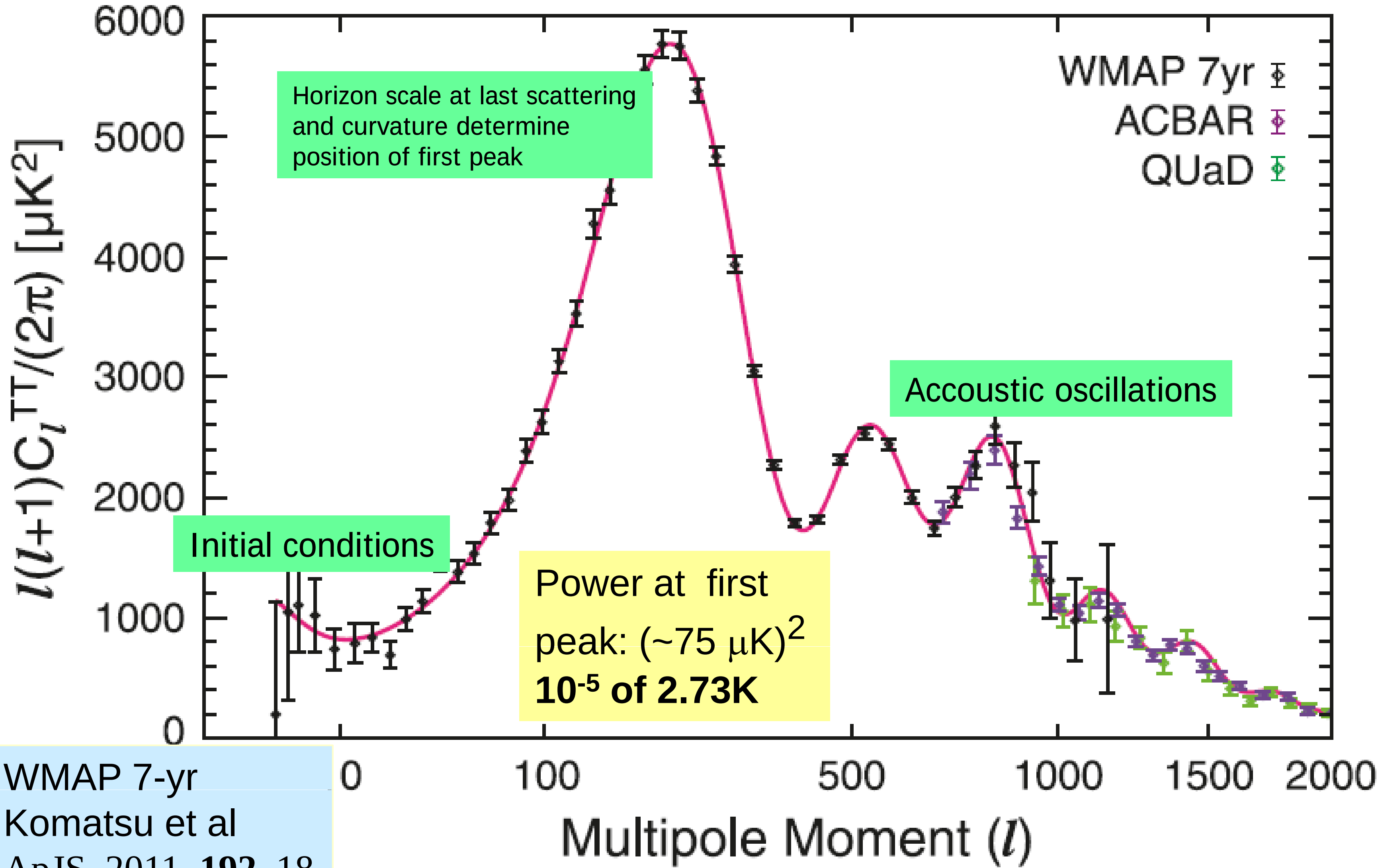
Definition for coefficients: $$C_l = < a_{lm} a_{lm}^* >$$

Variance (observable): $$\Delta T^2 = \frac{l(l+1)}{2\pi} C_l$$

Information compressed in power spectrum

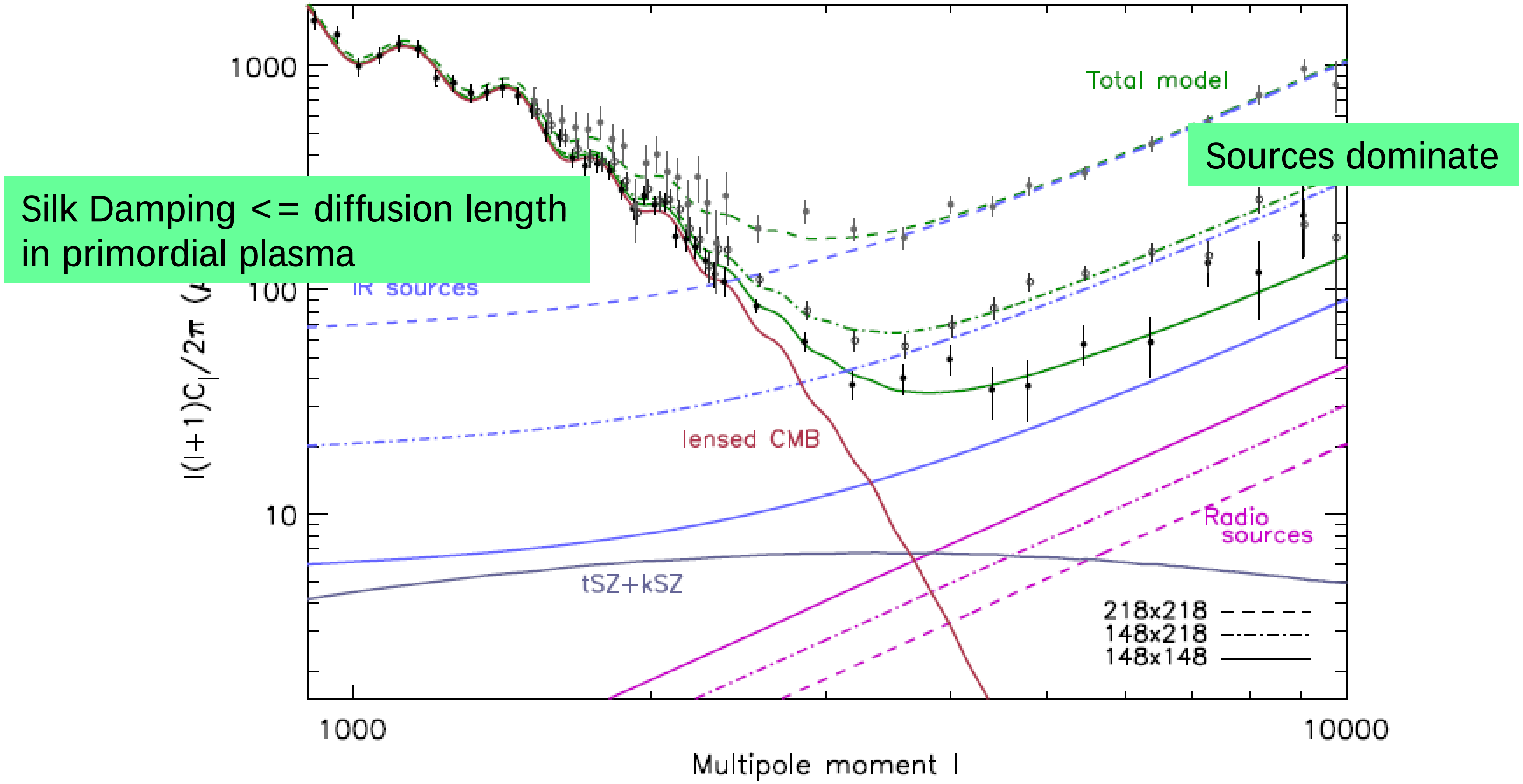
Caveat: The power spectrum contains all information of the field only for an isotropic gaussian field!

Temperature Power Spectrum

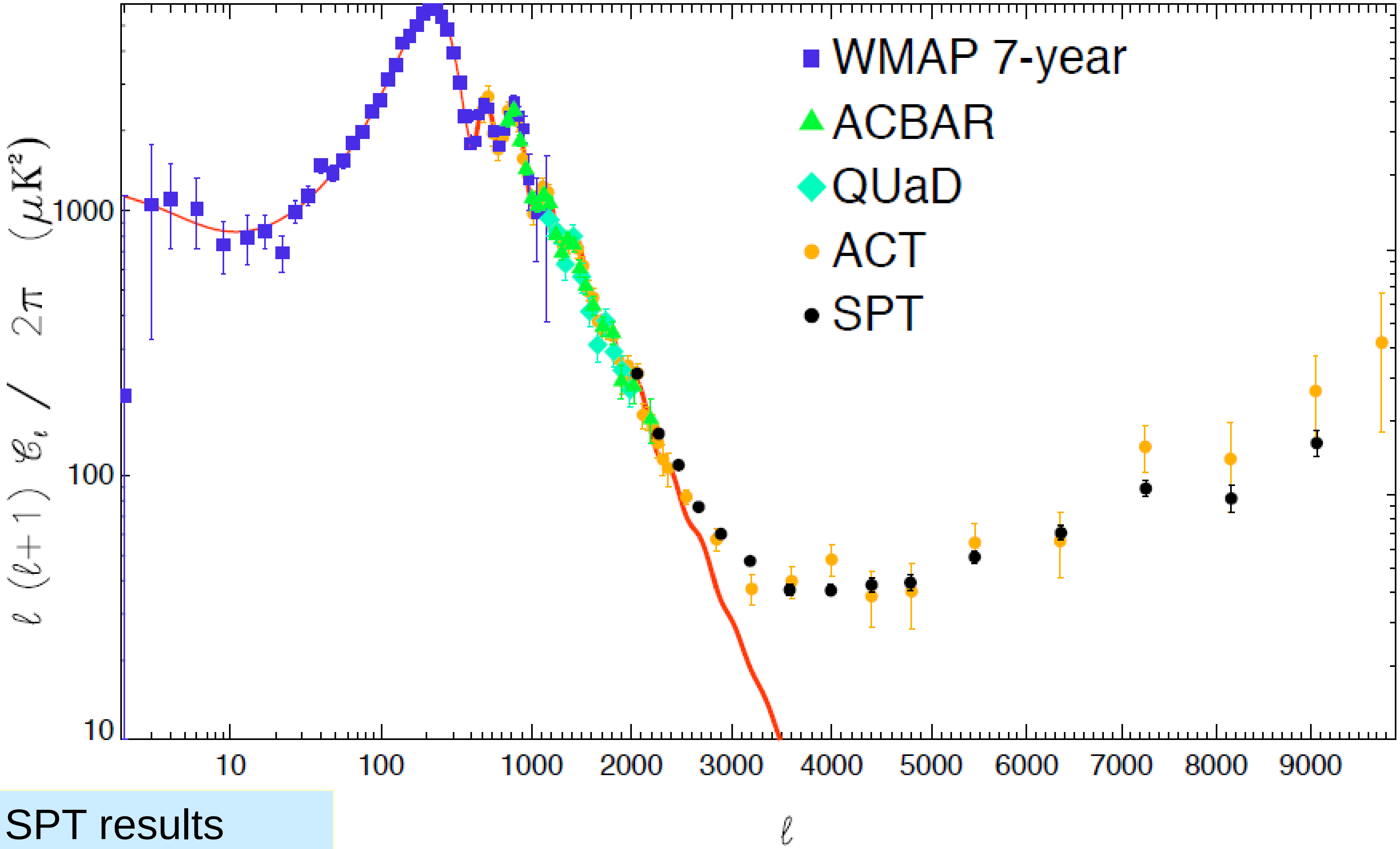


WMAP 7-yr
Komatsu et al
ApJS, 2011, **192**, 18

Temperature Power Spectrum



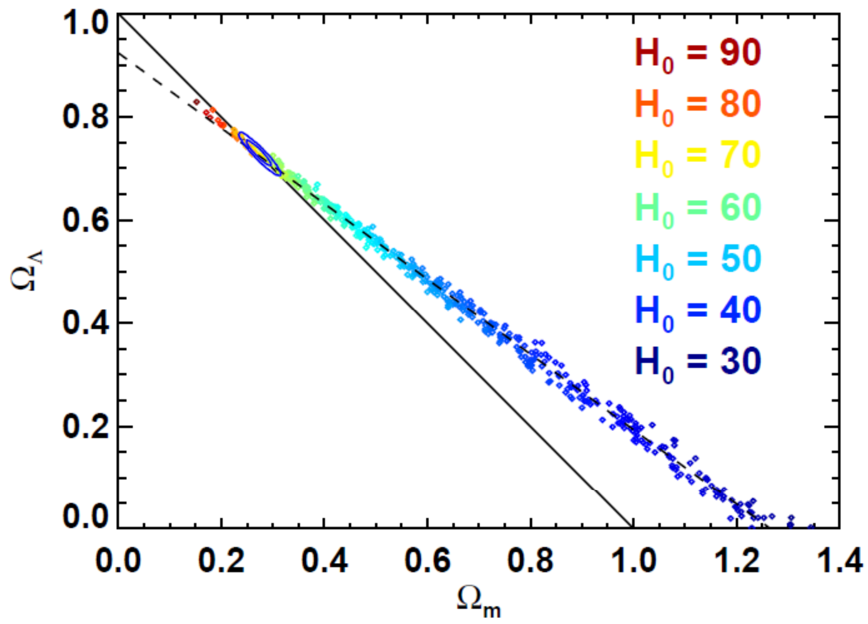
ACT power spectra
Dunkley et al
arXiv 1009.0866



SPT results
Shirokoff et al
arXiv 1012.4788

CMB confirms ΛCDM

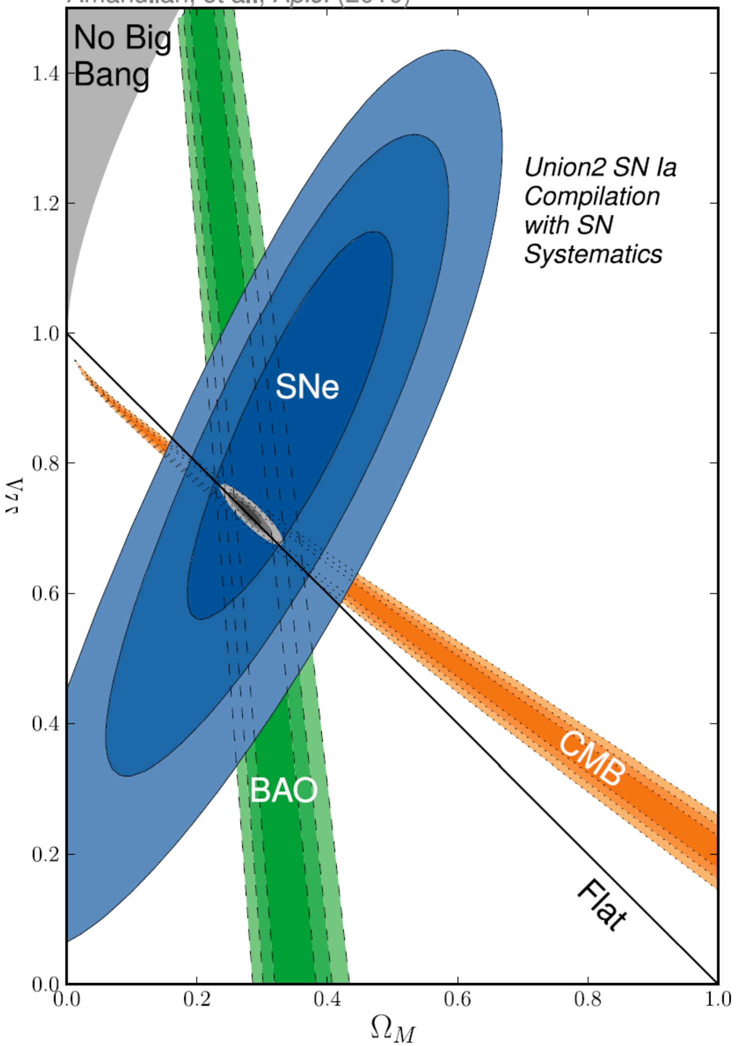
- Degeneracies don‘t allow a completely autonomous determination of all parameters
- CMB data complementary to other cosmological observations



WMAP CMB also consistent with NO dark energy but Hubble constant would have to be 30 km/s/Mpc!

WMAP 7-year publication

Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)

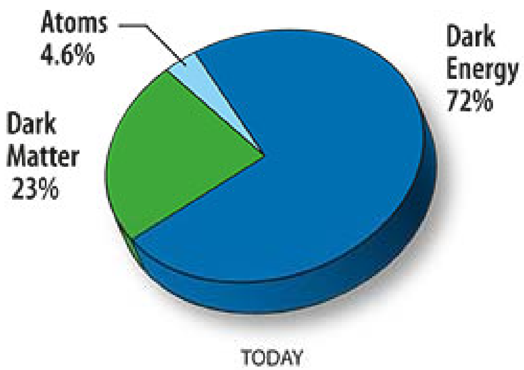


Precision cosmology

ACT+WMAP+H0+BAO evaluation of ΛCDM

Label		Parameter[a]	ΛCDM	ΛCDM $+ dn_s/d\ln k$	ΛCDM $+ r$	ΛCDM $+ N_{\rm eff}$
Baryon density	ary	$100\Omega_b h^2$	2.222 ± 0.047	2.206 ± 0.047	2.237 ± 0.048	2.238 ± 0.046
Cold dark matter density		$\Omega_c h^2$	0.113 ± 0.0034	0.1148 ± 0.0039	0.1117 ± 0.0033	0.140 ± 0.015
Dark energy density		Ω_Λ	0.724 ± 0.016	0.713 ± 0.019	0.729 ± 0.017	0.715 ± 0.017
Slope		n_s	0.963 ± 0.011	1.017 ± 0.036	0.970 ± 0.012	0.983 ± 0.014
Optical depth		τ	0.086 ± 0.013	0.095 ± 0.016	0.086 ± 0.015	0.086 ± 0.014
Amplitude		$10^9\Delta^2_{\mathcal{R}}$	2.46 ± 0.09	2.39 ± 0.10	2.40 ± 0.10	2.44 ± 0.09
	Extended	$dn_s/d\ln k$		-0.024 ± 0.015		
Tensor to scalar ratio		r			< 0.19	
Number of relativistic species		$N_{\rm eff}$				4.56 ± 0.75
	Derived	σ_8	0.813 ± 0.022	0.820 ± 0.023	0.811 ± 0.022	0.885 ± 0.039
		Ω_m	0.276 ± 0.016	0.287 ± 0.019	0.271 ± 0.017	0.285 ± 0.017
		H_0	69.9 ± 1.4	69.1 ± 1.5	70.4 ± 1.5	75.5 ± 3.0

Dunkley et al, arXiv 1009.0866

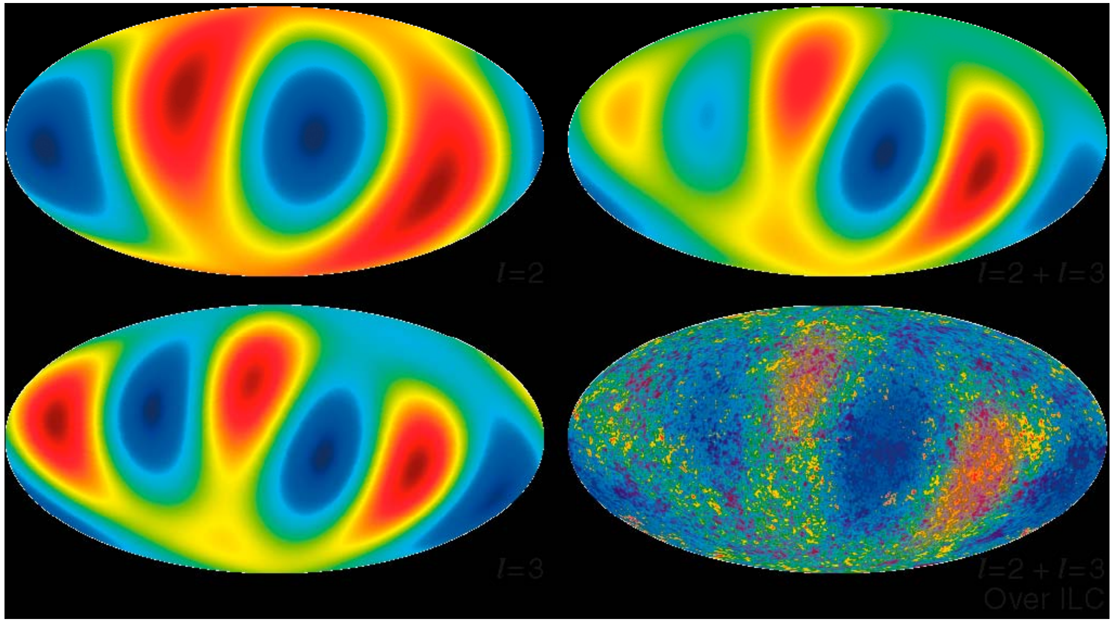


Only a few percent error on the main cosmological parameters

Features in the data?

quadrupole

octopole

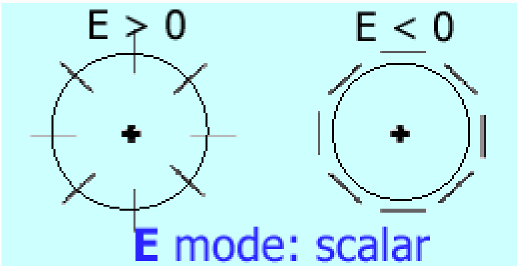


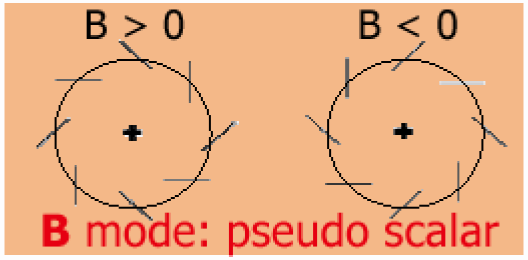
quadrupole
+octopole

- Alignment of quadrupole & octopole with ecliptic plane
  - subtraction of modelled Integrated Sachs Wolfe effect might help
- Lack of large scale power?
  - possibly estimators on cut sky suboptimal
- Odd-even multipole asymmetry (no cosmology known)
- Possibly systematic time calibration error (quadrupole then not cosmological!)?

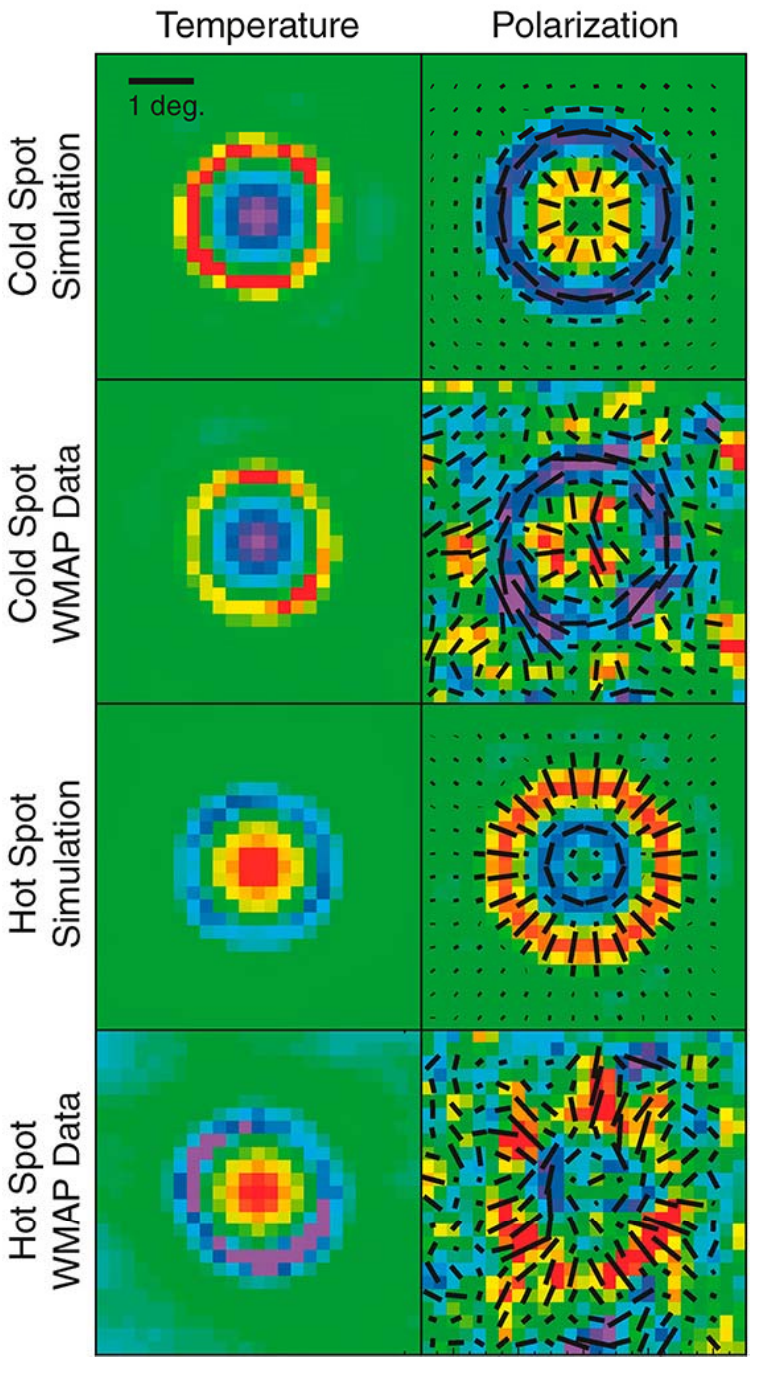
Different Polarization patterns

Division of Polarization into gradient (E-mode) and curl component (B-mode)





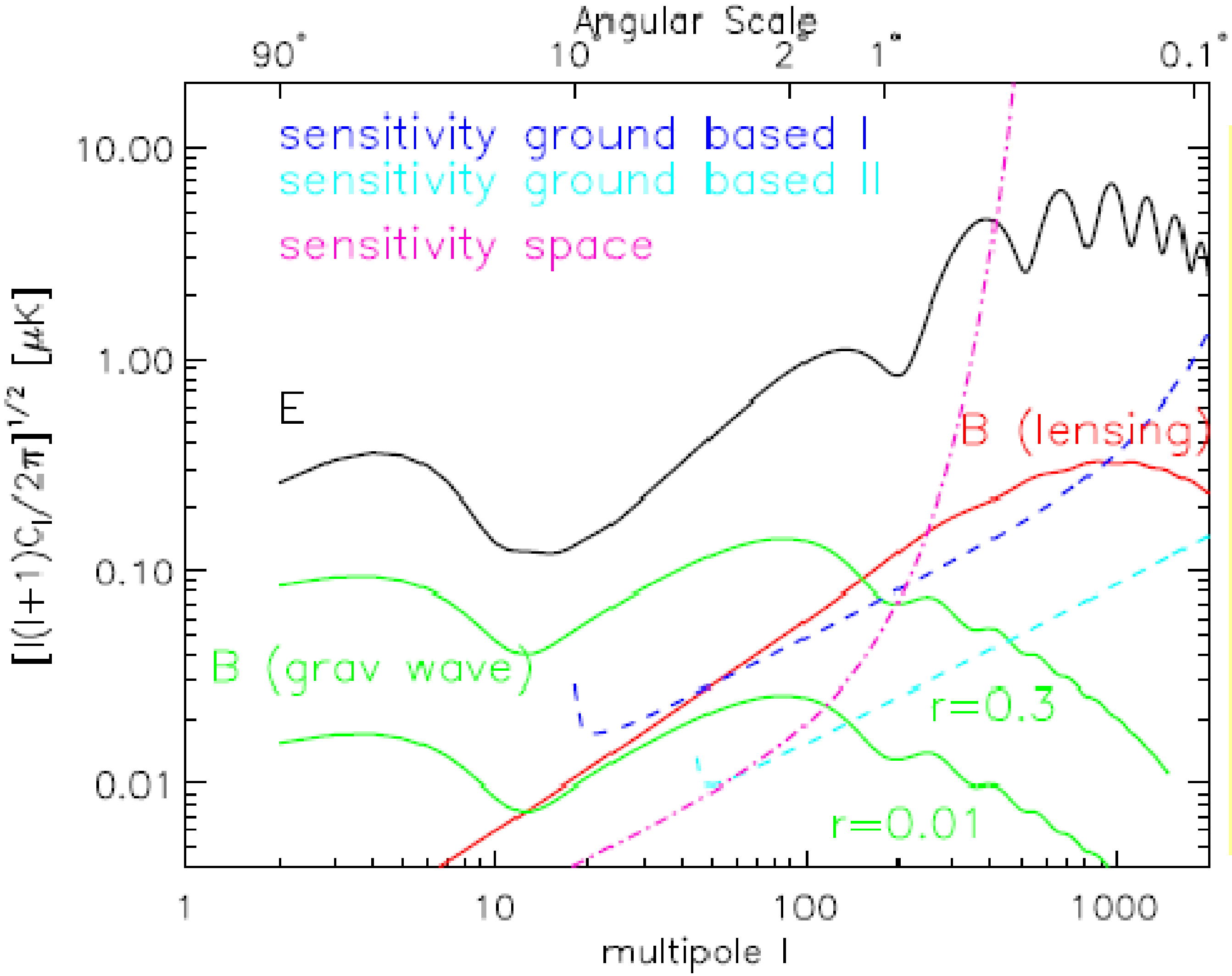
Density fluctuations	E-modes
Gravity waves	E- and B-modes, amplitude determined by energy scale of inflation (often linked to GUT scale)
Gravitational lensing	E-modes appear as B-modes



WMAP 7-year stacked hot/cold spots: Expected tangential/radial pattern visible

Polarization pattern reflects velocity flow from high to low density (hot->cold)

Power spectra expectation for Polarization



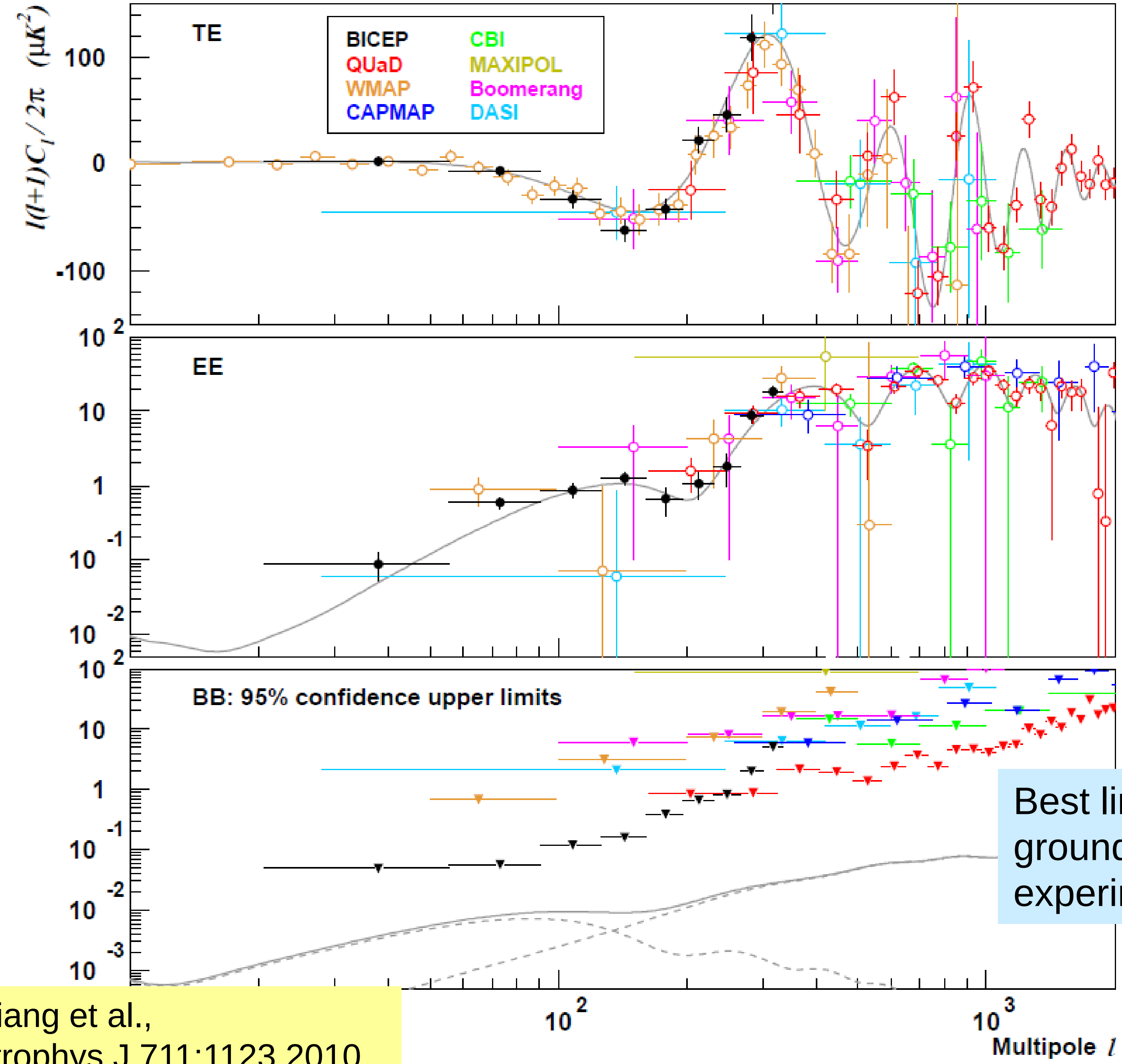
Size of E-mode power factor of 10 below temperature anisotropy

Size of B-mode power at least a factor of 10 below E-mode power

Size of B-modes from Primordial Gravity Waves still unknown

parametrized by Tensor-to-Scalár Ratio r=T/S

Energy Scale of Inflation linked to r=*T/S*: $V^{1/4} = 3.3 * 10^{16} \quad (T/S)^{1/4}$ GeV



Best limits from ground-based experiments

Chiang et al., Astrophys.J.711:1123,2010

Inflationary parameters

Inflation expectations consistent with measurements:
- Flatness
- Homogeneity
- Isotropy
- Nearly scale invariant fluctuations

Primordial power spectrum: $P(k) \propto k^{n_S}$

Slow roll inflation requires n_s slightly different from 1

Relation between r=T/S and n_s and inflationary potential $V(\Phi)$:

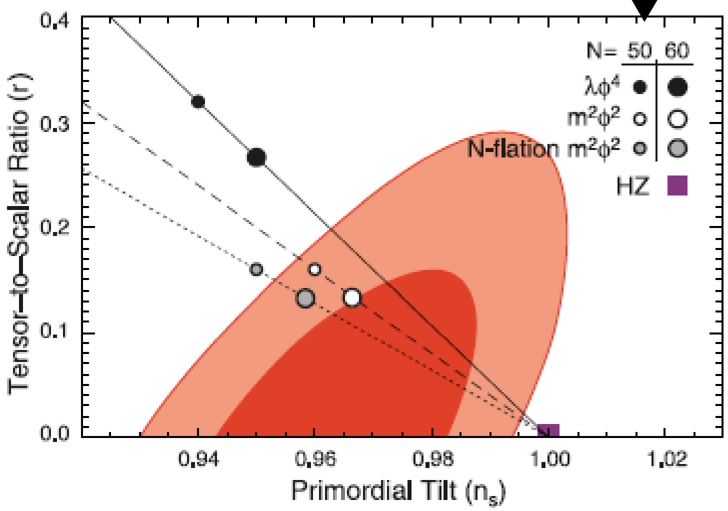
$$n_S = 1 - 6\varepsilon + 2\eta$$
$$r = 16\varepsilon$$
$$\varepsilon \propto (V')^2, \quad \eta \propto V''$$

Inflationary parameters

Inflation expectations consistent with measurements:
- Flatness
- isotropic
- gaussian field
- nearly scale invariant

Different inflationary models

Primordial power spectrum: $P(k) \propto k^{n_S}$



Relation between r=T/S and ns and inflationary potential V(Φ):

$$n_S = 1 - 6\varepsilon + 2\eta$$

$$r = 16\varepsilon$$

$$\varepsilon \propto (V')^2, \quad \eta \propto V''$$

Contours show WMAP+BAO+SN

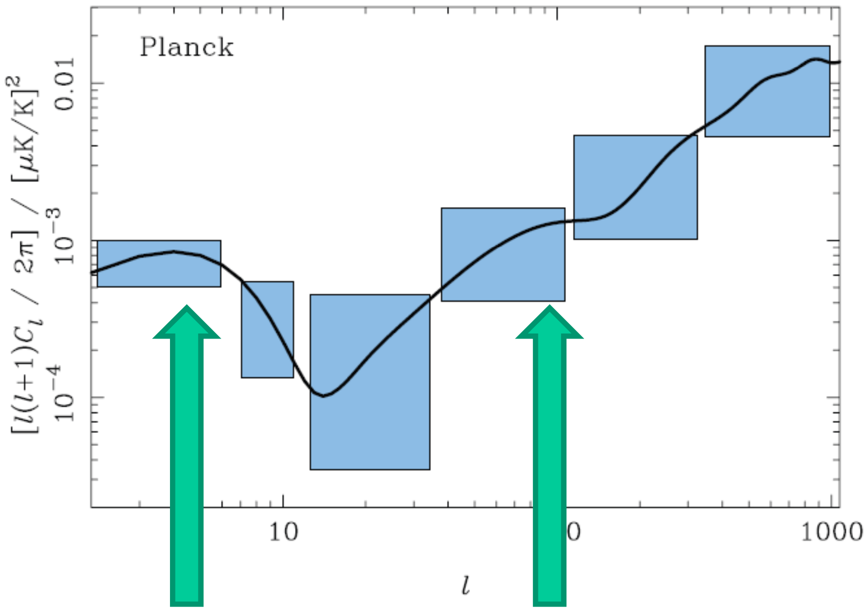
r<0.19 (95%) ACT+WMAP7+BAO+SN
r<0.72 (95%) BICEP (from polarization alone)

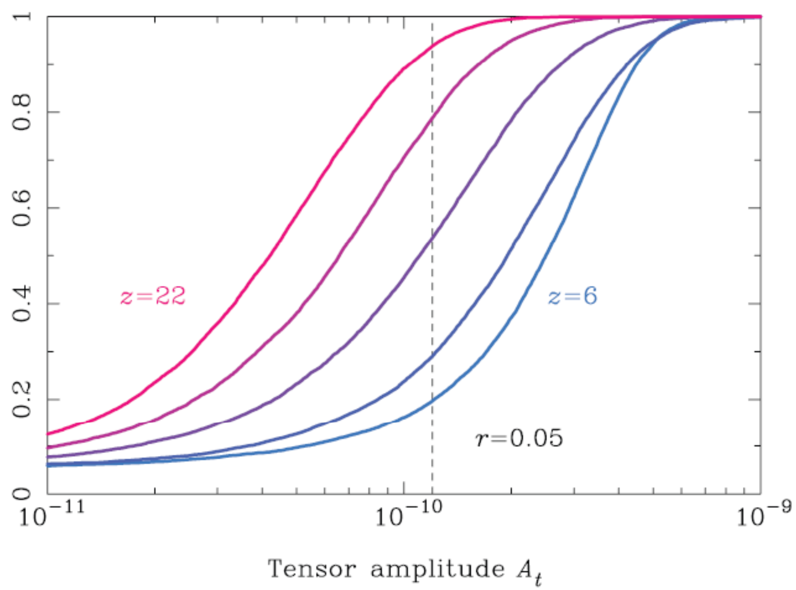
n_S = 0.97+-0.012 WMAP7+ACT+H0+BAO

Expectations for the satellite Planck for measuring *r*

B-mode spectrum for r=0.1
(plus lensing of E-modes)

Detection probability for r for
different redshifts of reionization





Main sensitivity for r
of satellite experiments

Ground-based experiments
contribute here

From Planck Bluebook

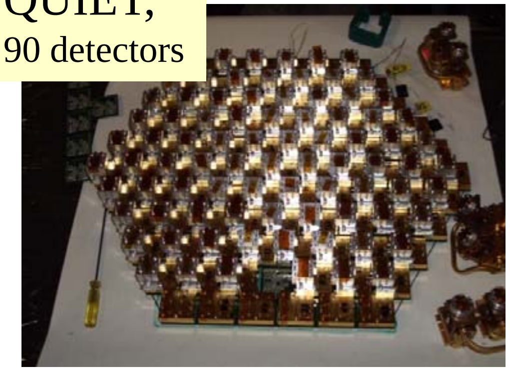
Challenges of the future

High precision measurements of temperature and polarization power spectra

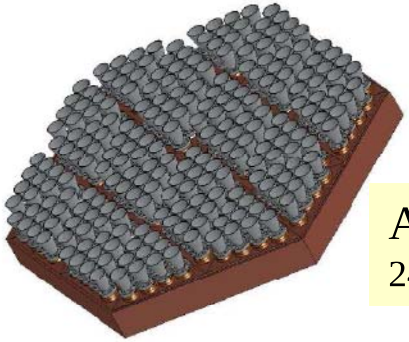
receivers operate close to fundamental limits

=> large receiver arrays

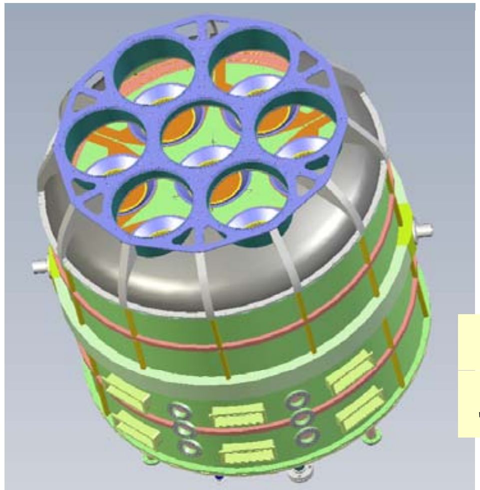
QUIET,
90 detectors



South Pole Telescope
960 detectors

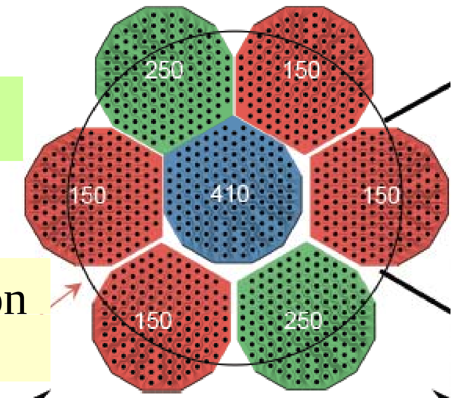


ABS,
240 detectors



SPIDER, balloon
512 detectors

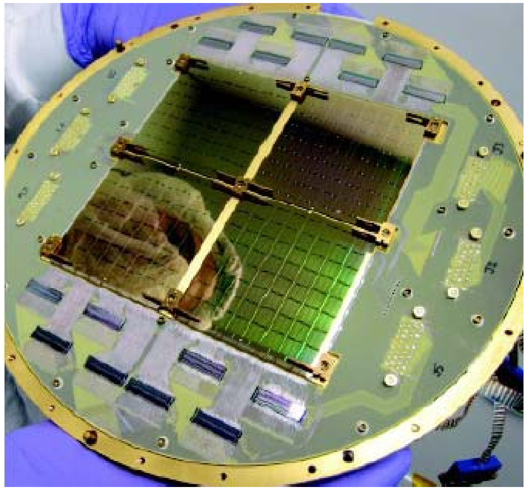
Not a complete list of experiments!



EBEX, balloon
738 detectors

BICEP -> KECK array
large bolometer arrays at the South Pole

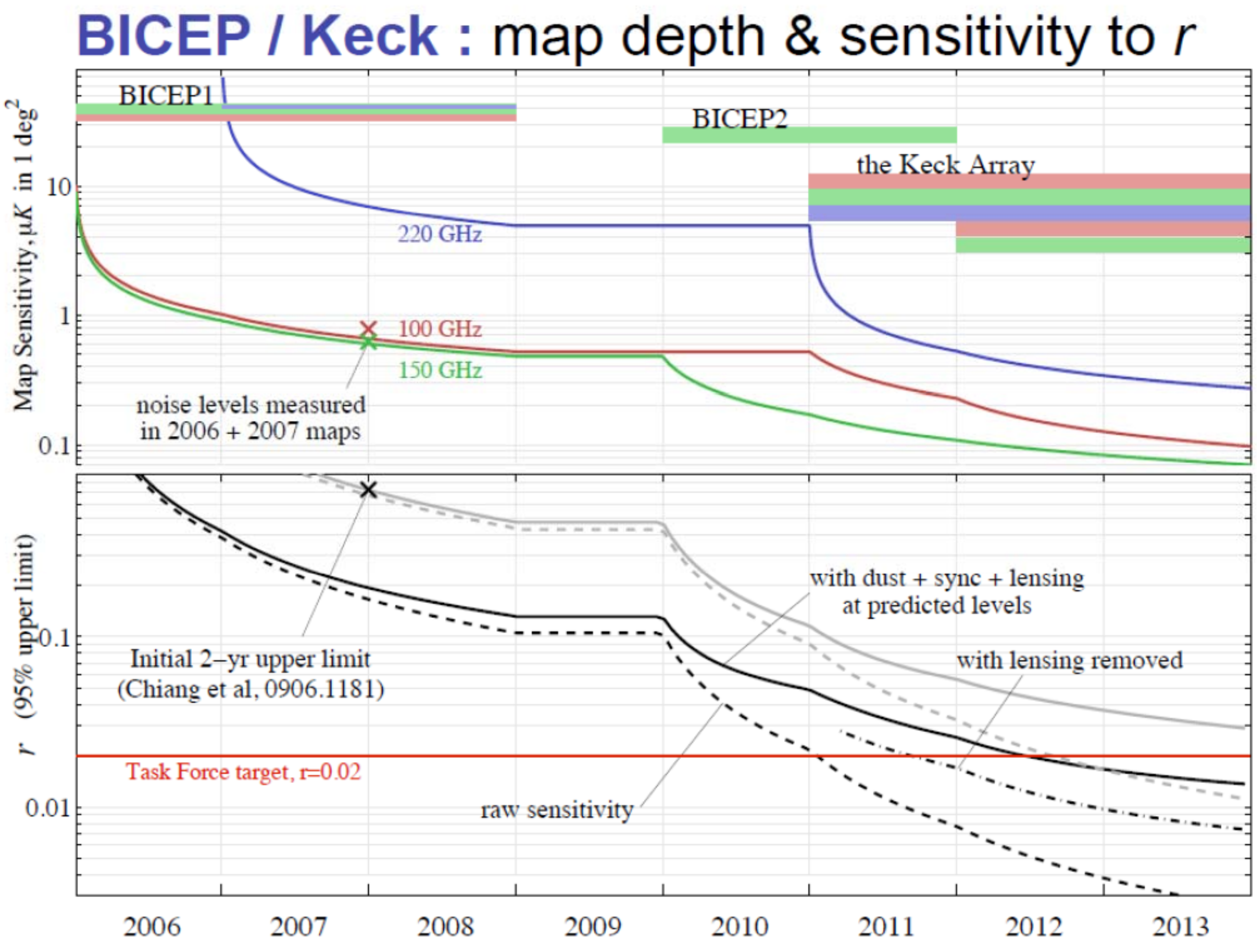
BICEP 1 , 3 years data til 2008
48 detectors @150 GHz



BICEP 2, deployed 2009
512 detectors @150 GHz
TES antenna coupled arrays

Keck array ,
3x512 detectors @150 GHz
deployed Nov 2010
2x512 detectors @100/220 GHz
planned for Nov 2011

BICEP -> KECK array
large bolometer arrays at the South Pole



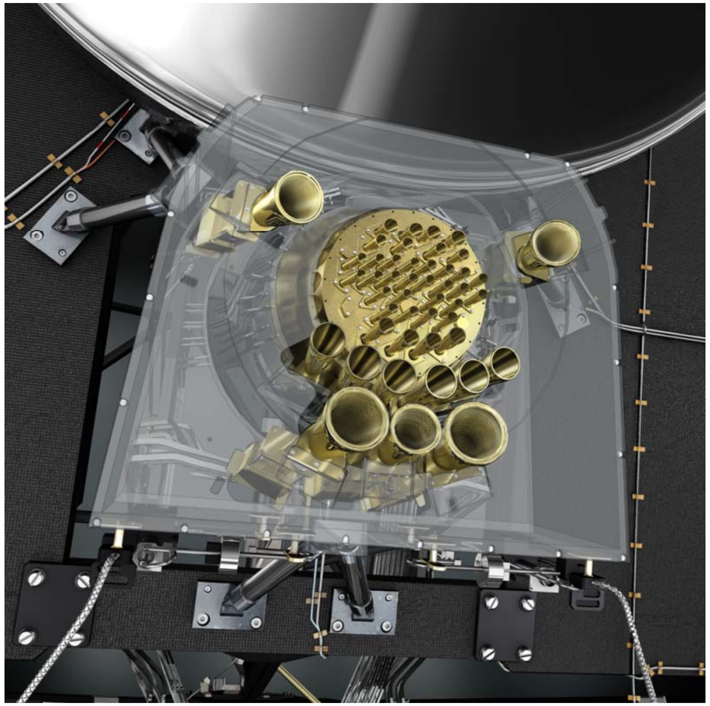
John Kovac

Satellite experiment Planck

Low **F**requency **I**nstrument **(LFI):**
HEMT arrays at 30, 44, 70 GHz

High **F**requency **I**nstrument **(HFI):**
Bolometer arrays at100,143, 217, 353, 545, 857 GHz

Launch May 2009 to L2



Planck Focal Plane
Image credit: ESA

Expectations for Planck

Cold dark matter density

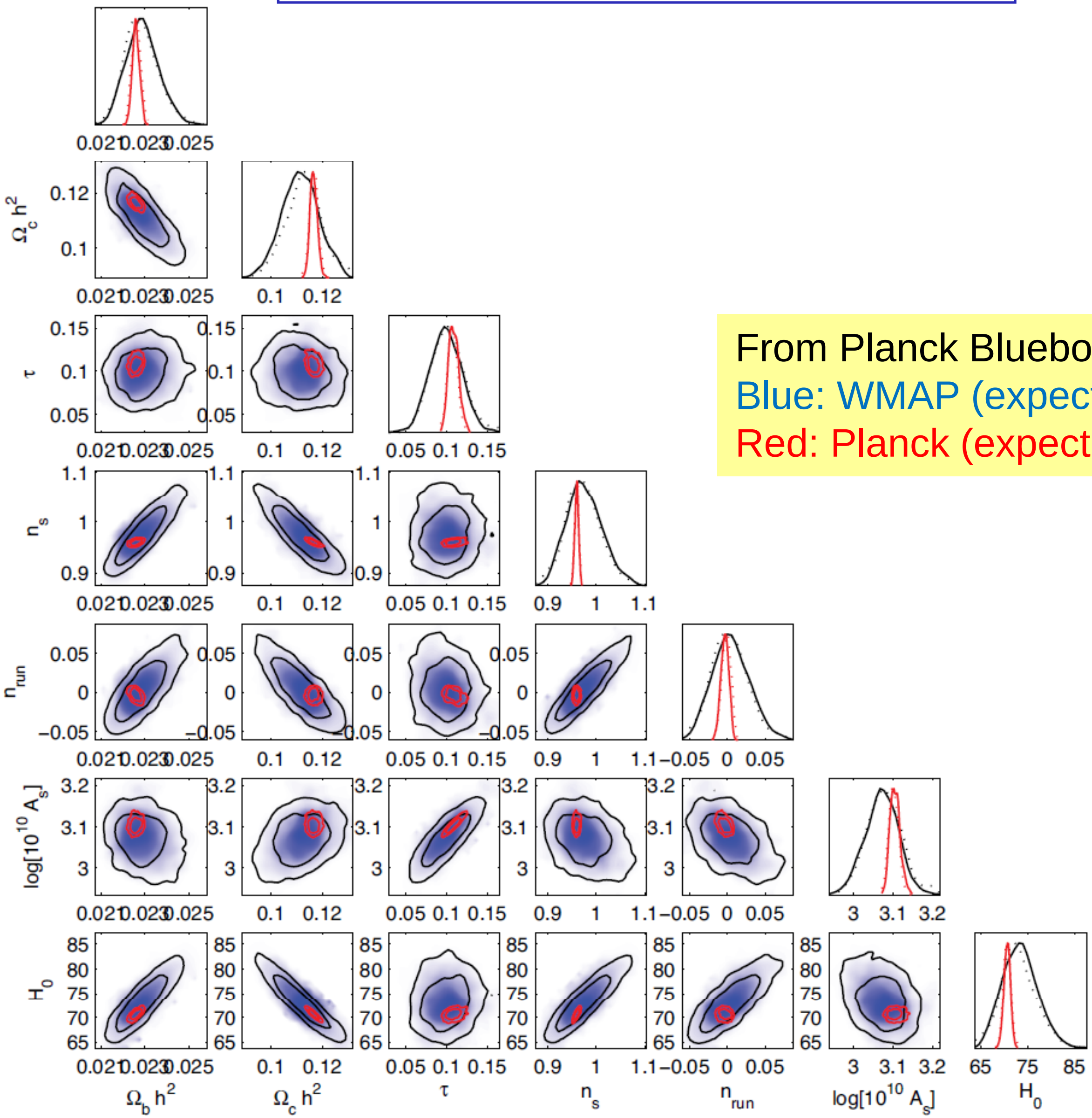
Optical depth

Slope

Running index

Amplitude

Hubble constant

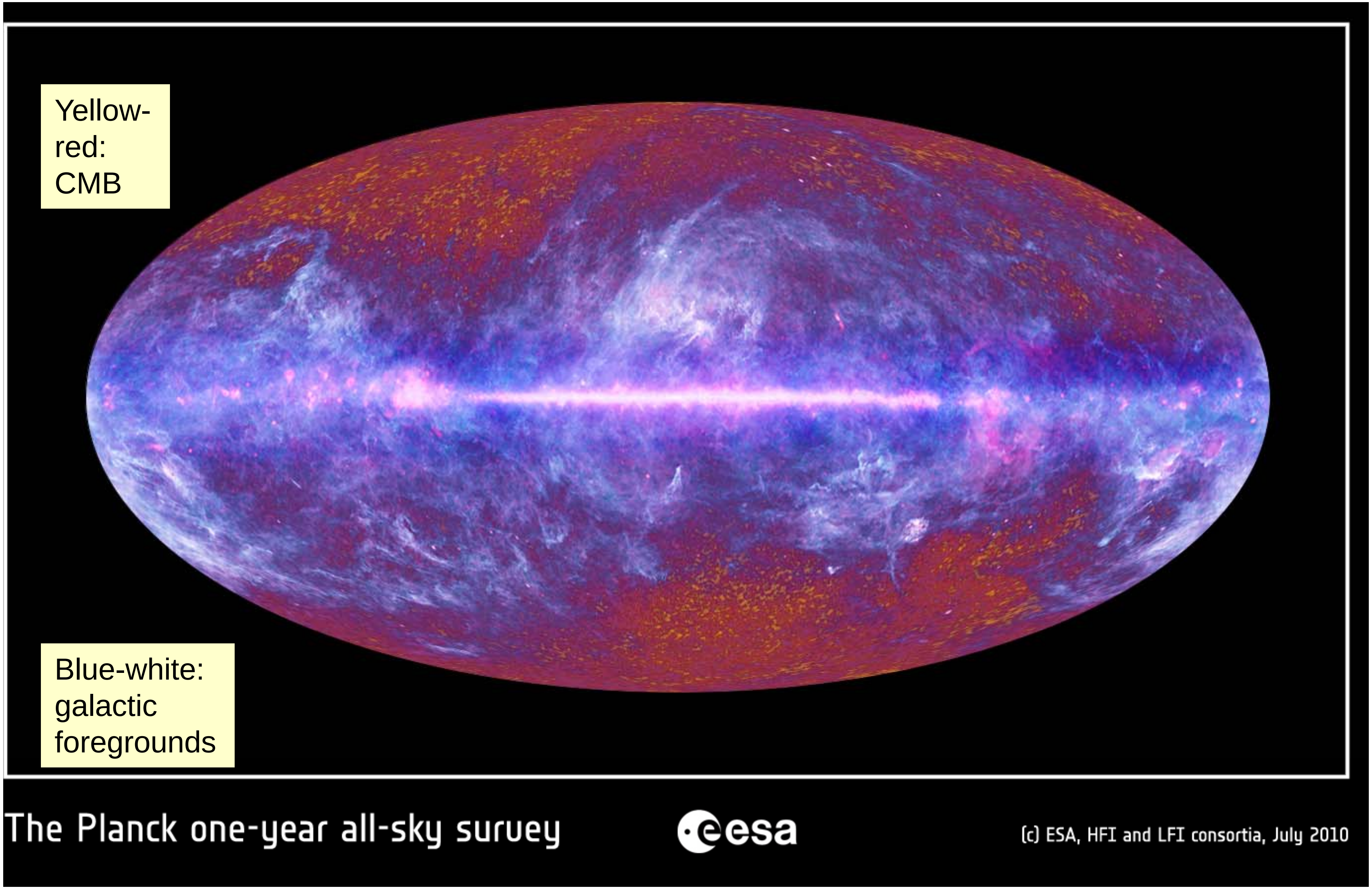


From Planck Bluebook (prediction 2005)

Blue: WMAP (expectation for 4 years)

Red: Planck (expectation for 1 year)

First Image from Planck
(satellite launched May 2009)



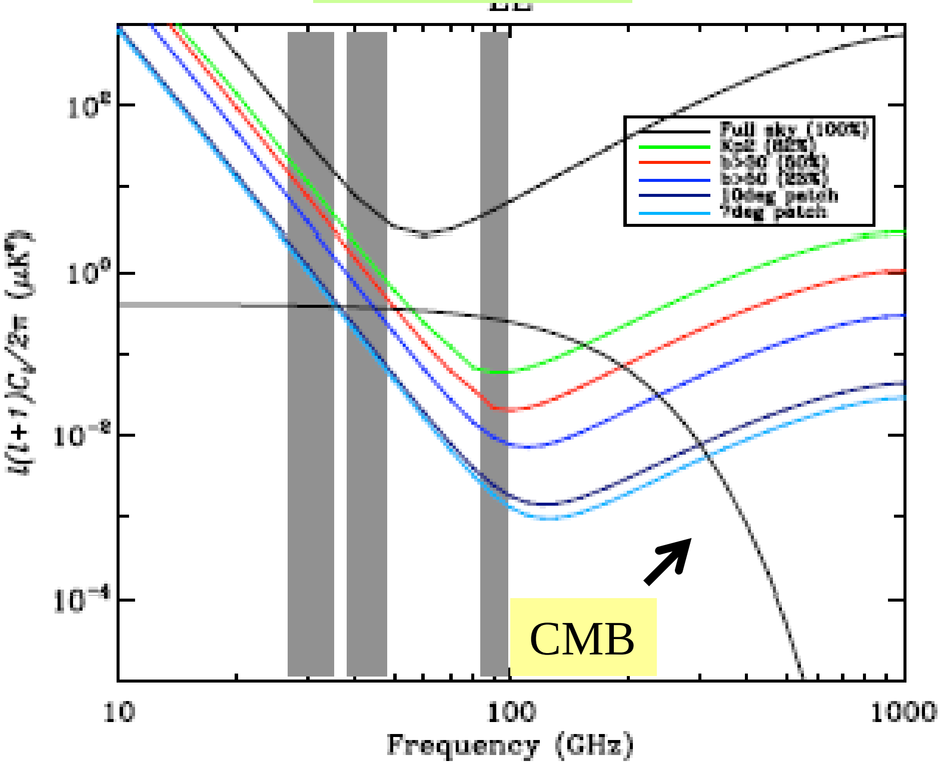
Impact of foreground

Foreground contamination as function of frequency

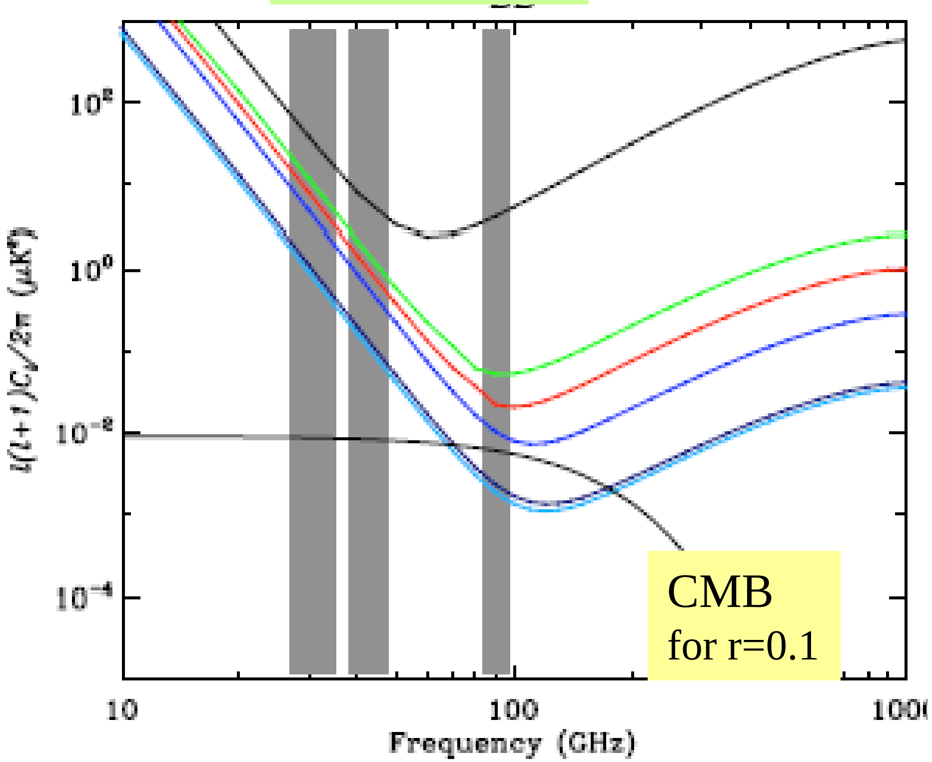
Different colors: different fractions of sky

Multifrequency measurements help separating the foregrounds from CMB

E-mode power

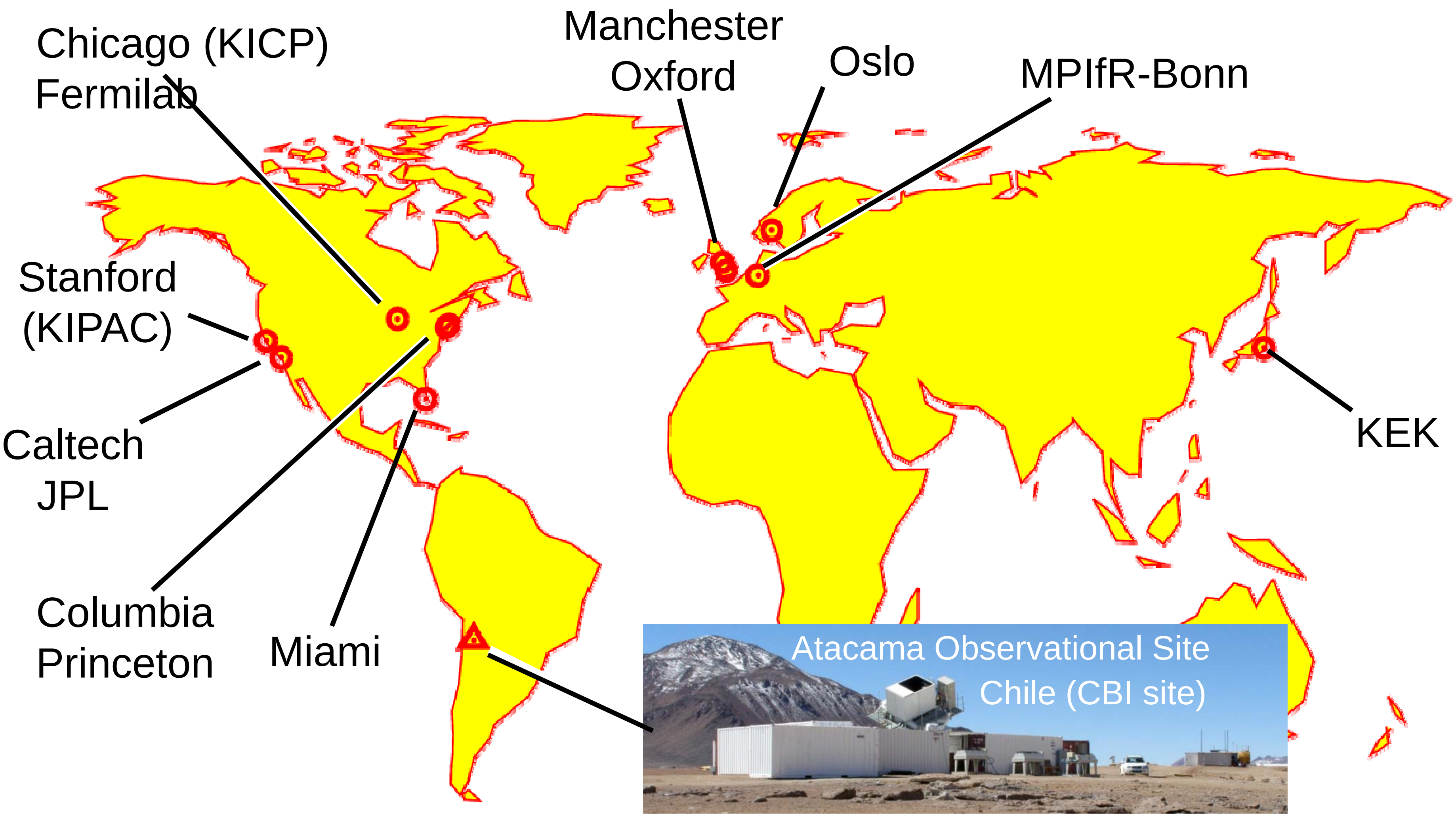


B-mode power



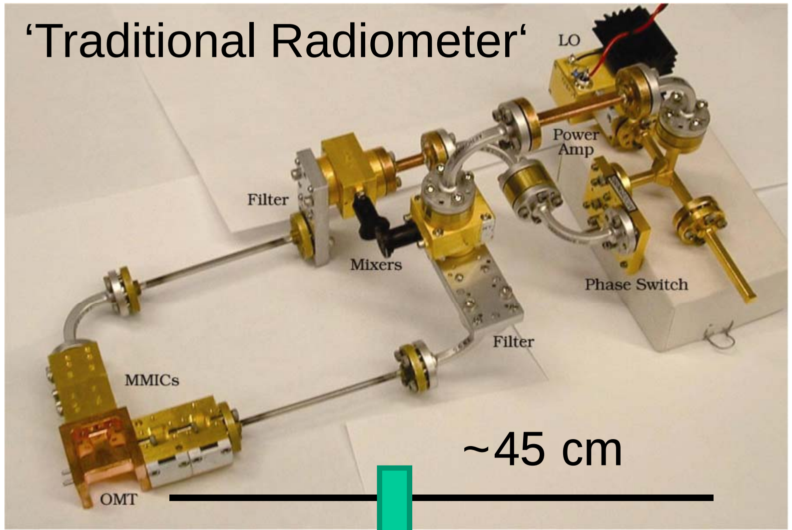
Results from using Planck Sky Model
(Clive Dickinson)

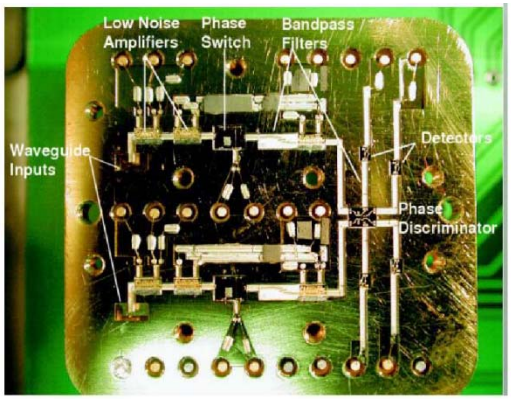
Q/U Imaging ExperimenT Collaboration



5 countries, 13 institutes, ~30 people

Q/U Imaging ExperimenT (QUIET)





2.5cm

'Radiometer on a chip'

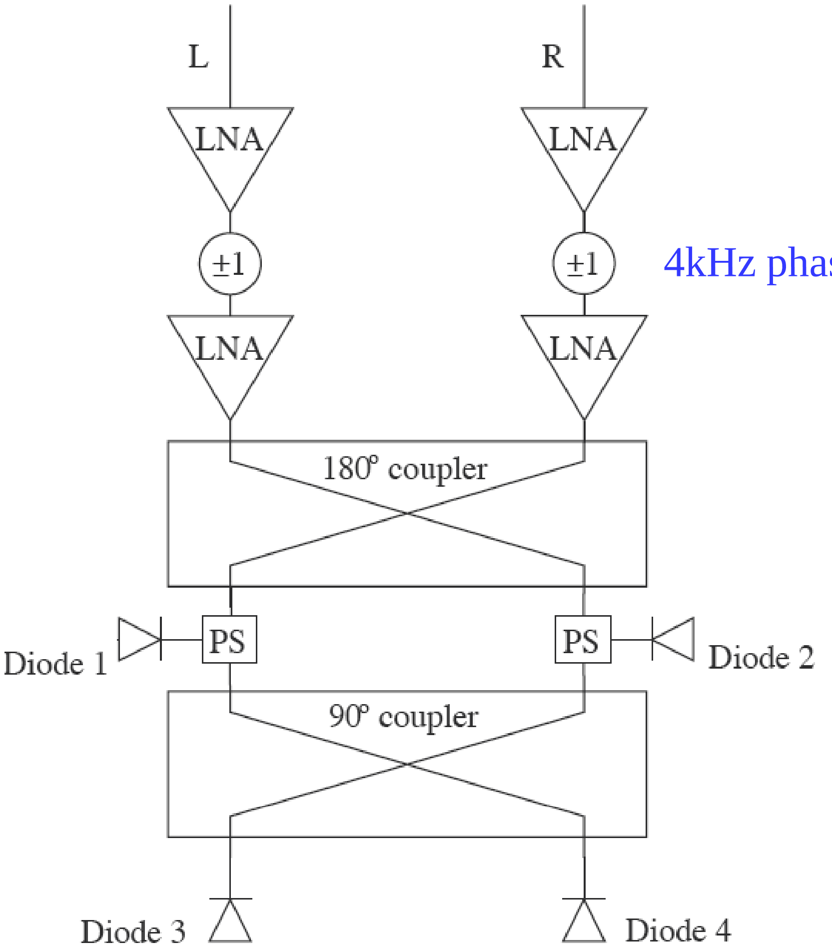
Produced by JPL (based on developments for Planck LFI), Todd Gaier

Radiometer on a chip:

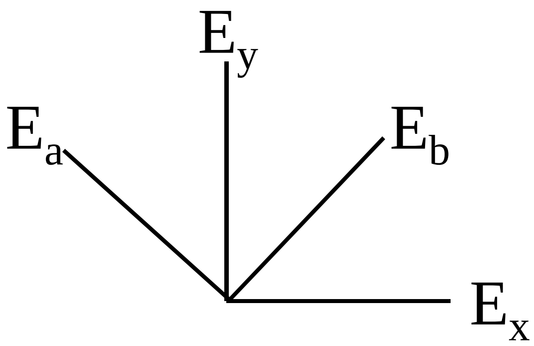
- Automated assembly and optimization
- Large array of correlation polarimeters

- Only ground-based effort using coherent detectors
- Measuring Q/U simultaneously in each pixel
- Complementing frequencies from other experiments

QUIET L/R Correlator: Simultaneous Q/U measurements



4kHz phase switching



Differencing of phase-switched data streams at 4kHz and 50Hz protects against various instrumental systematics

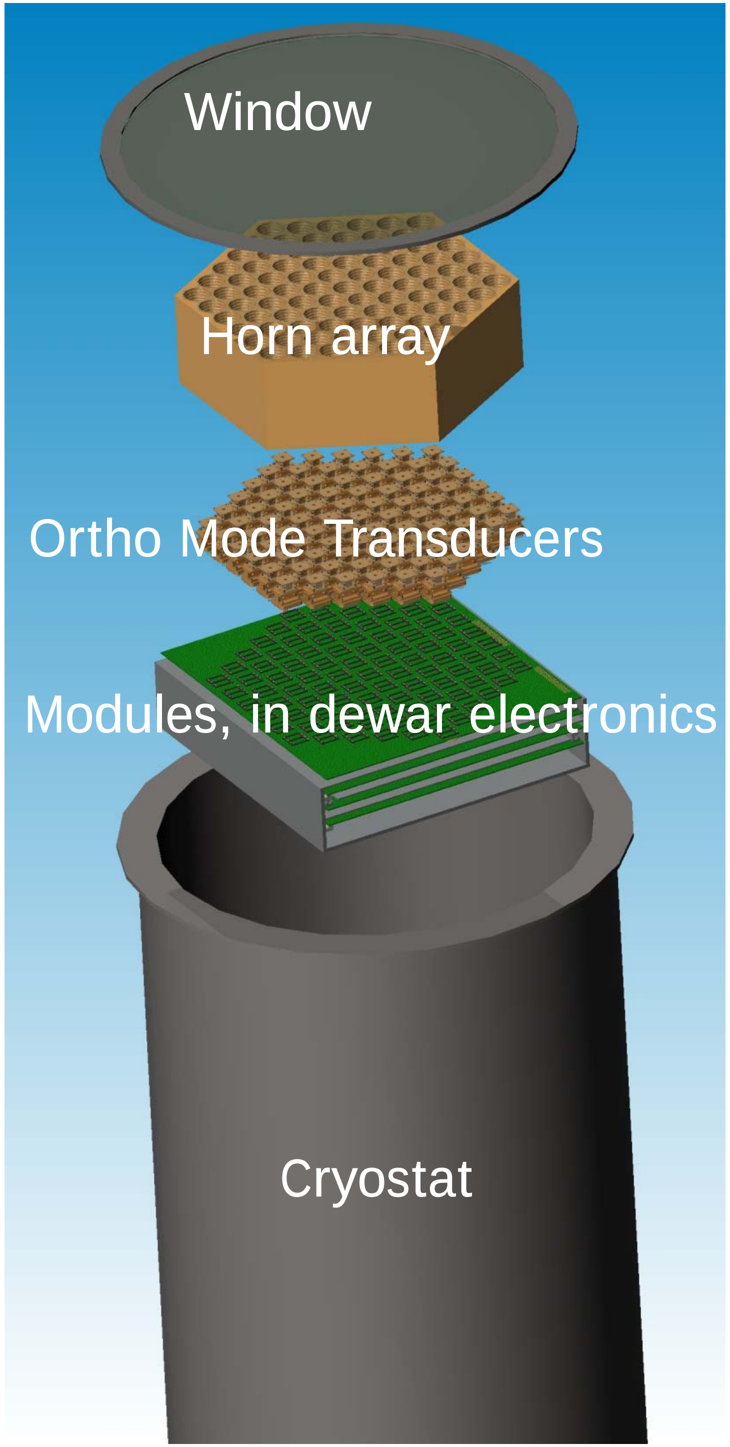
$$|L \pm R|^2 = |(E_x + iE_y) \pm (E_x - iE_y)|^2 = \underline{4E_x^2, 4E_y^2}$$

Q

$$|(L \pm R) + i(L \mp R)|^2 = |L \mp iR|^2 = |L|^2 + |R|^2 \mp 2\,\mathrm{Im}(RL^*)$$

$$\mathrm{Im}(RL^*) = \mathrm{Im}(E_x + iE_y)^2 = 2E_xE_y = \underline{E_a^2 - E_b^2}$$

U



Receivers for QUIET

Large receiver arrays in cryostats in the Atacama Desert

84+6* pixel 90 GHz
FWHM 13'
array sensitivity: 70 $\mu K\sqrt{s}$

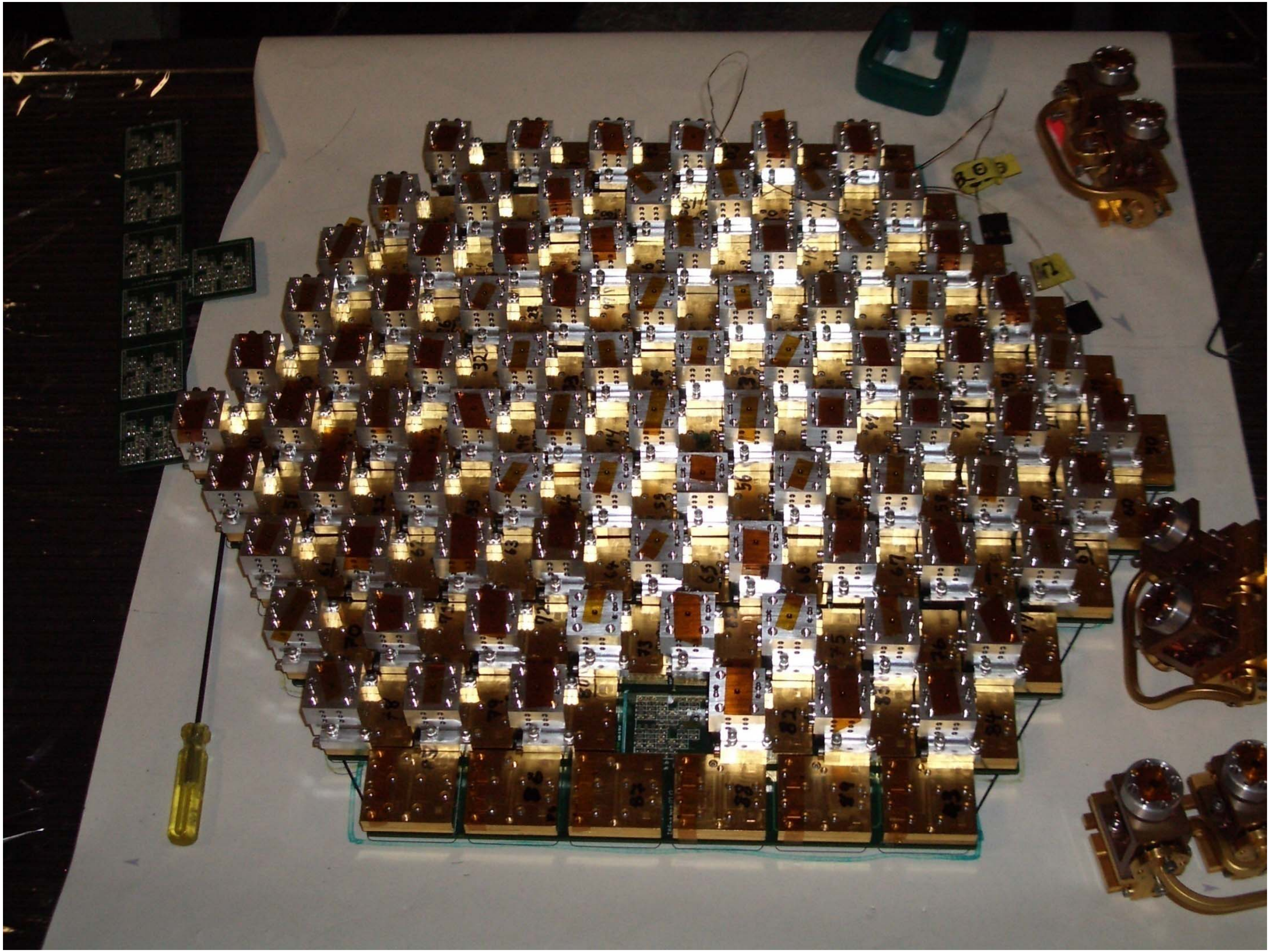
17+2* pixel 40 GHz
FWHM 28'
array sensitivity: 60 $\mu K\sqrt{s}$

* 6 (2) pixels are Total Power Pixels in the W (Q) band array

Phase I, in Chile 2008-2010

397 pixel 90 GHz
61 pixel 40 GHz
18 pixel 30 GHz

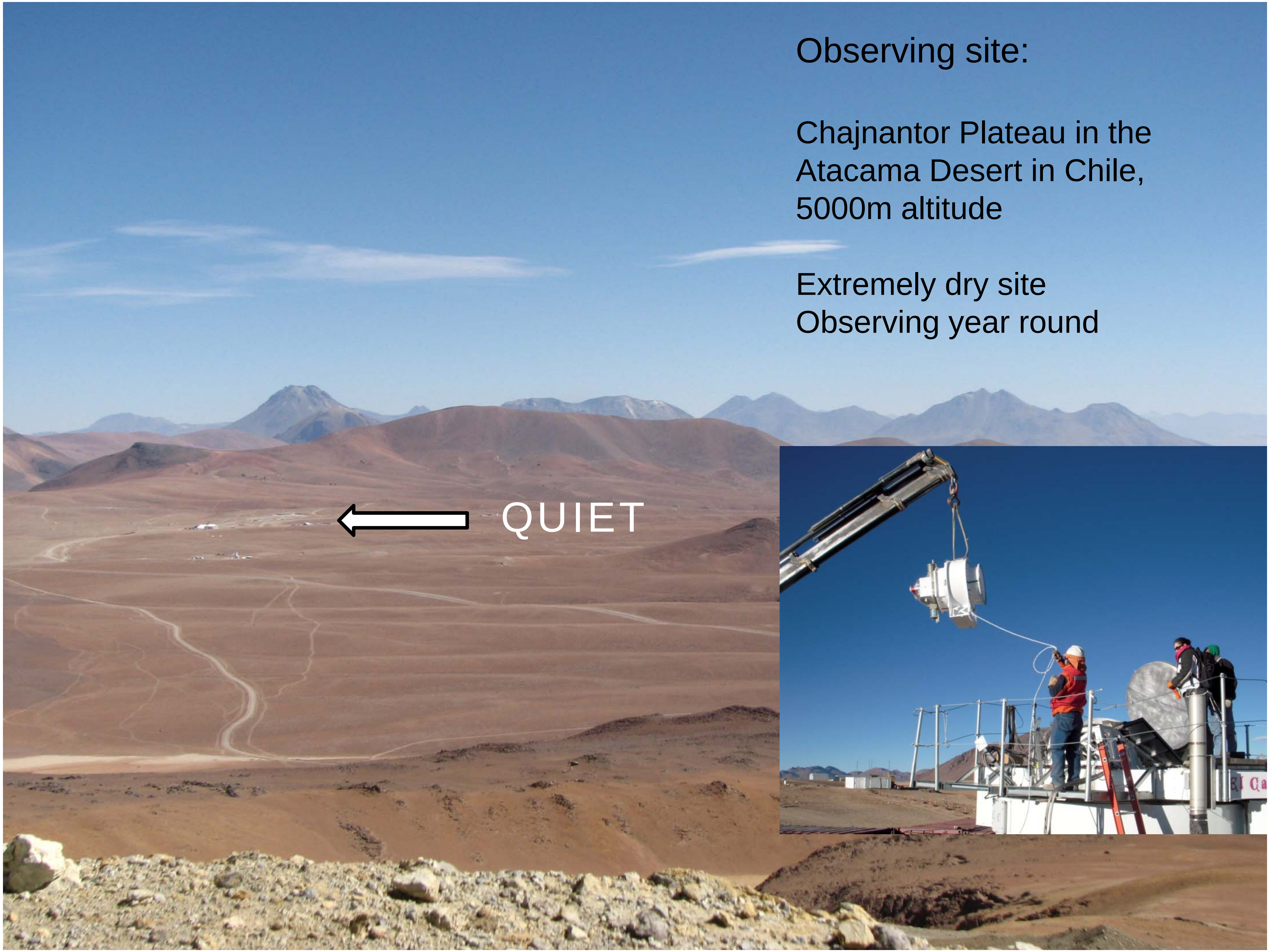
Phase II 2011++ (planned)



Observing site:

Chajnantor Plateau in the Atacama Desert in Chile, 5000m altitude

Extremely dry site
Observing year round

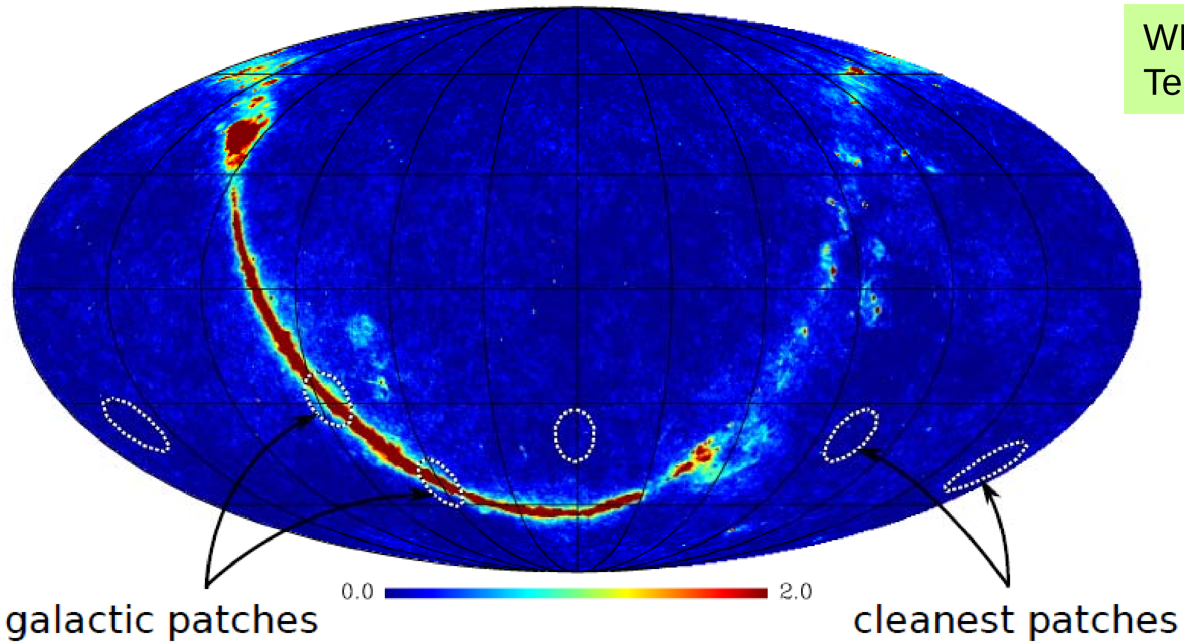


Observations

Q-band (40 GHz): Oct 2008 - mid 2009, 4000 hours
W-band (90 GHz): mid 2009 - end 2010, 7600 hours

Choice of 4x250 square degree patches:

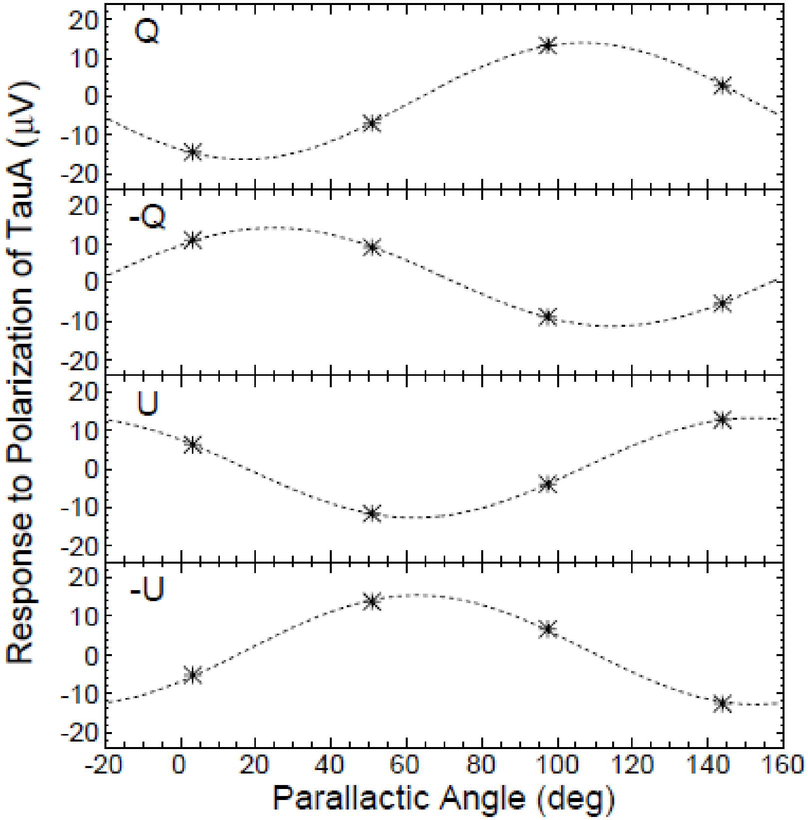
- Low foreground regions in coordination with ABS, Polarbear
- Distribution to allow continuous scanning



WMAP Q-band
Temperature map

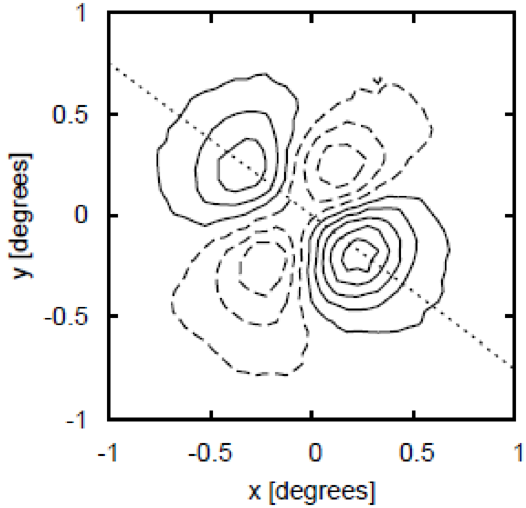
Calibration

Tau A (Crab nebula, supernova remnant)
Parallactic angle vs. response



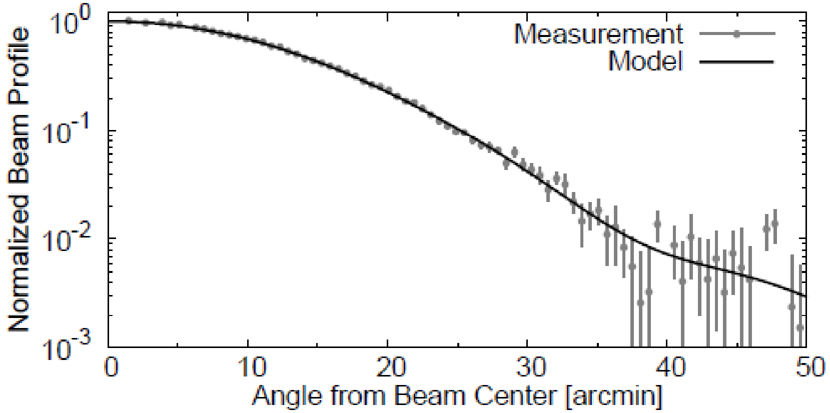
Gain (~6%/scan), polarization angle (check)

Moon
(polarization map)



Polarization angle (syst. ~3%)

Tau A beam map



FWHM = 27.3'

Analysis

- Two independent pipelines using different methods:

  A: Pseudo Cl (flexible and fast, using Monte Carlo methods)
  B: Maximum Likelihood (unbiased maps, computing intensive)

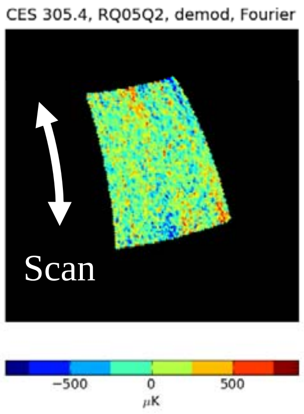
- Blind Analysis: Null Tests had to pass before unblinding real power spectra

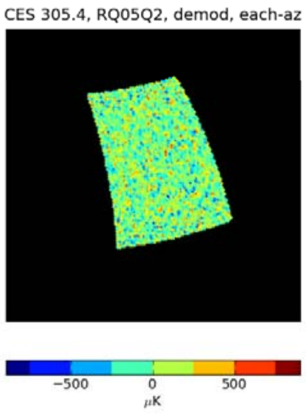
- Q-band data analysis finalized, starting W-band data analysis

- Main data selection based on agreement of data stream with noise model (evaluated on power spectrum)

- Instead of N^{-1} filter we introduce cutoff around f_{scan} with little loss of sensitivity
  - Pipeline A: in azimuthal domain

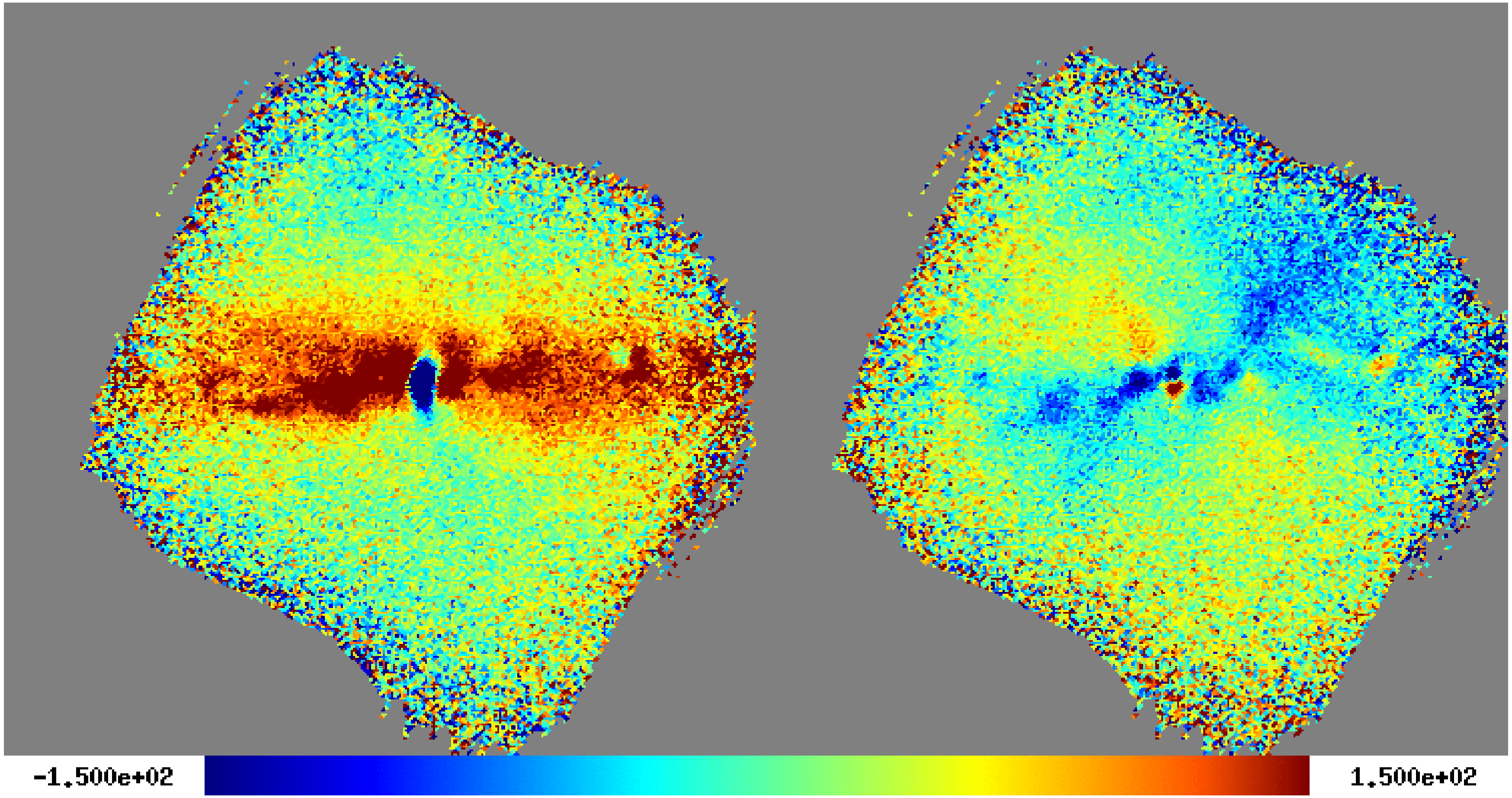
Naive N^{-1} filter





Our filter

QUIET vs WMAP – galactic center

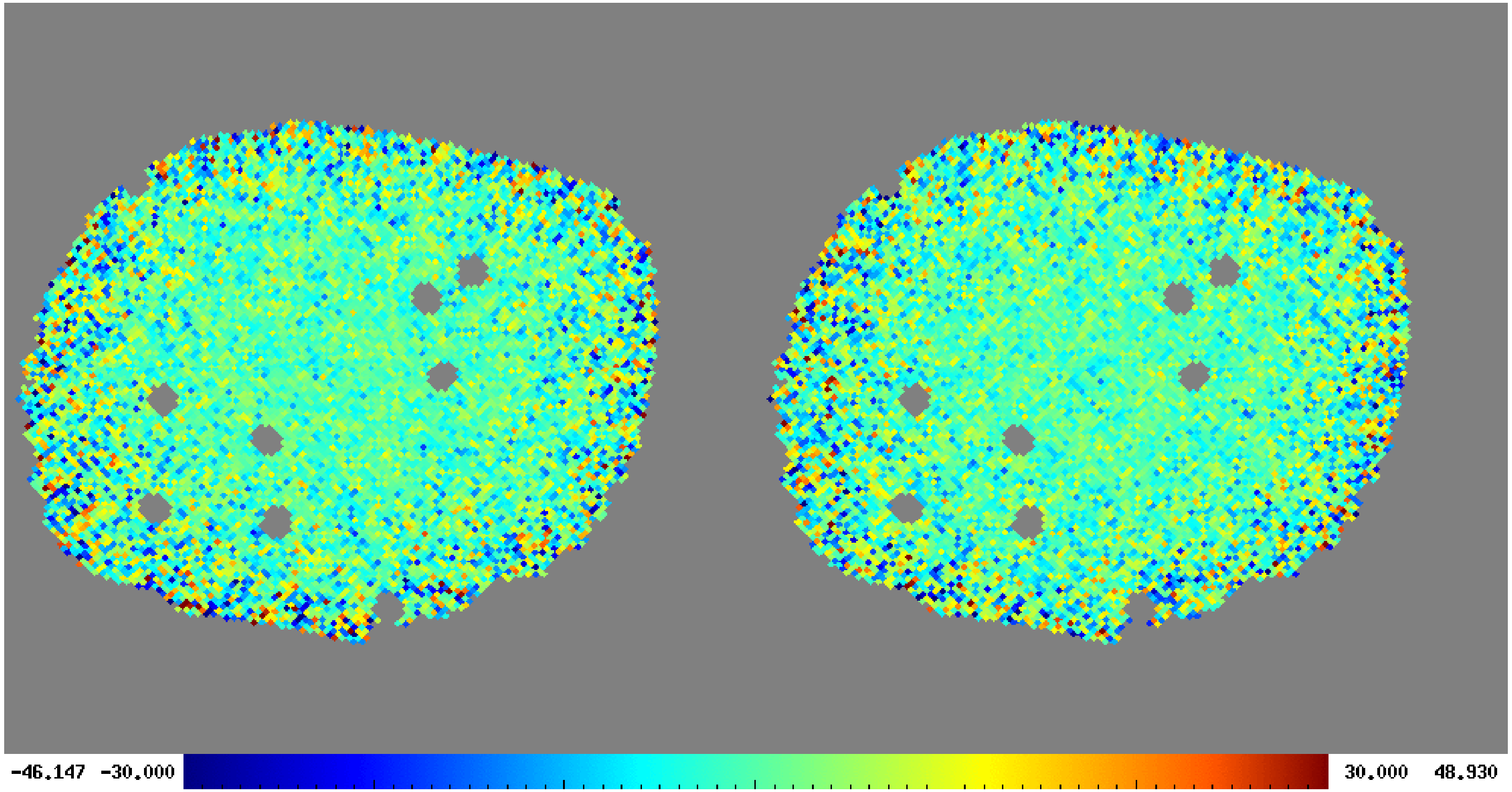


Stokes Q

Q-band

Stokes U

QUIET vs WMAP – CMB patch



Stokes Q   Q-band   Stokes U

Polarization maps ~3 times deeper than Planck!

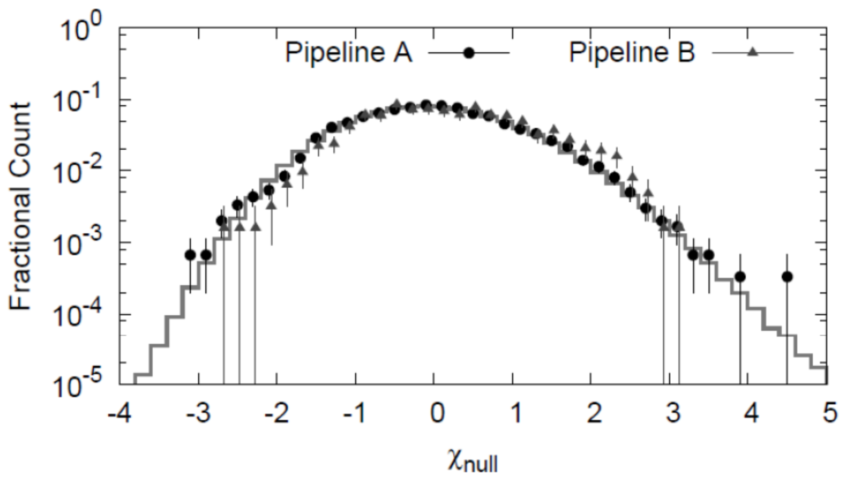
Blind analysis

- Suite of 42 Null Tests:
  - Division of Data into two subsets (e.g. first/second half, day/night)
  - Power Spectrum for difference map
  - χ^2 distributions sensitive to outliers
  - χ sensitive to systematic shifts

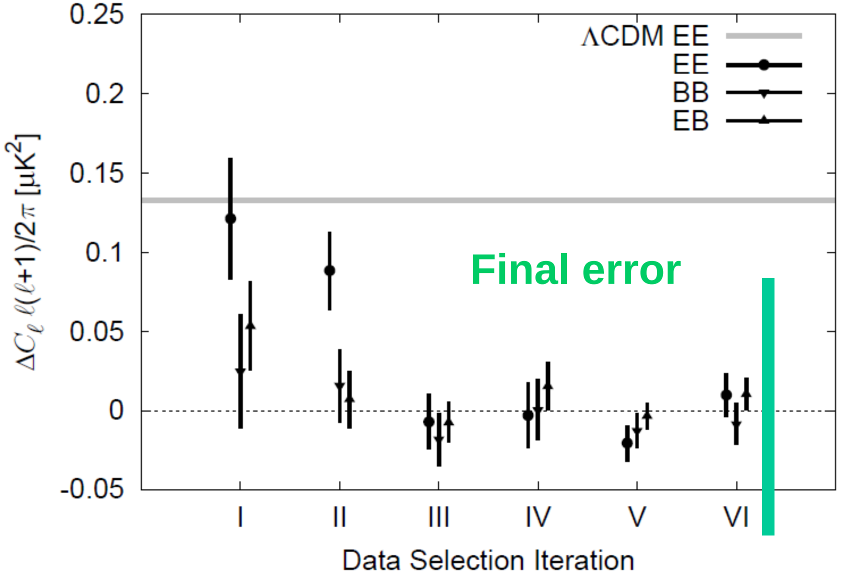
- 'Unblinding' of Power Spectrum for undifferenced maps only
  once Null Tests pass!

- First use in CMB experiment!

- Cross-correlating maps from different azimuth-deck divisions reduces external contaminations (e.g. ground)



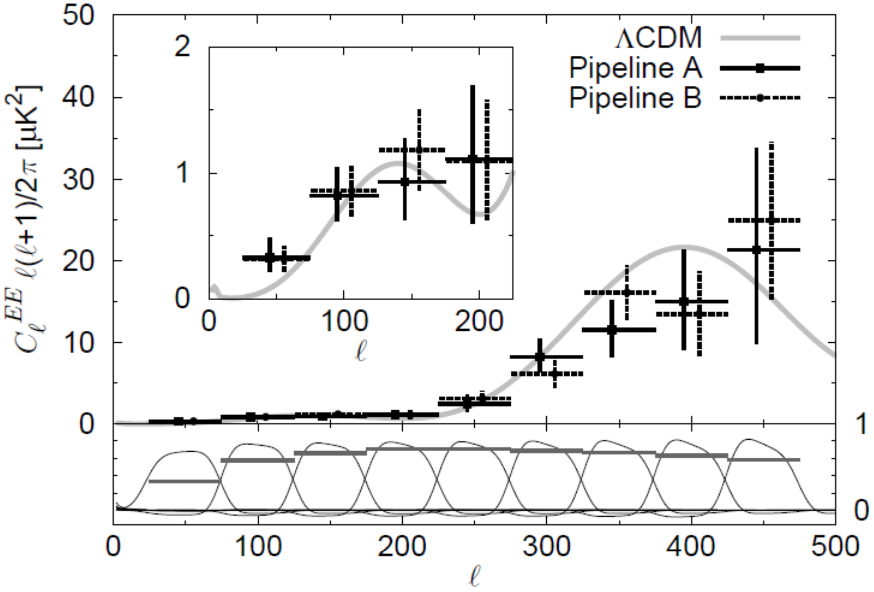
Impact of cut variation:
6 (of 33) iterations:



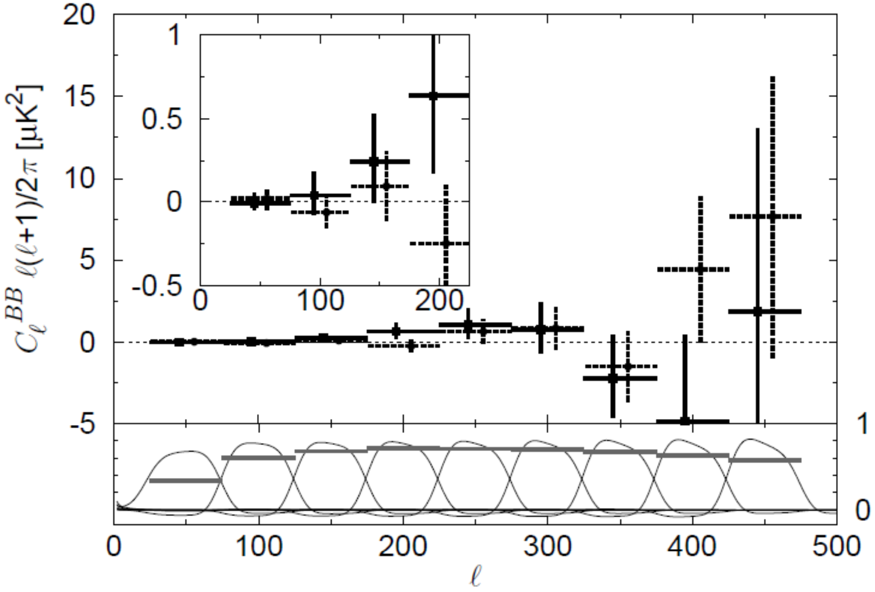
- Consistency between iterations
- Consistency between patches

CMB polarization results

EE power



BB power

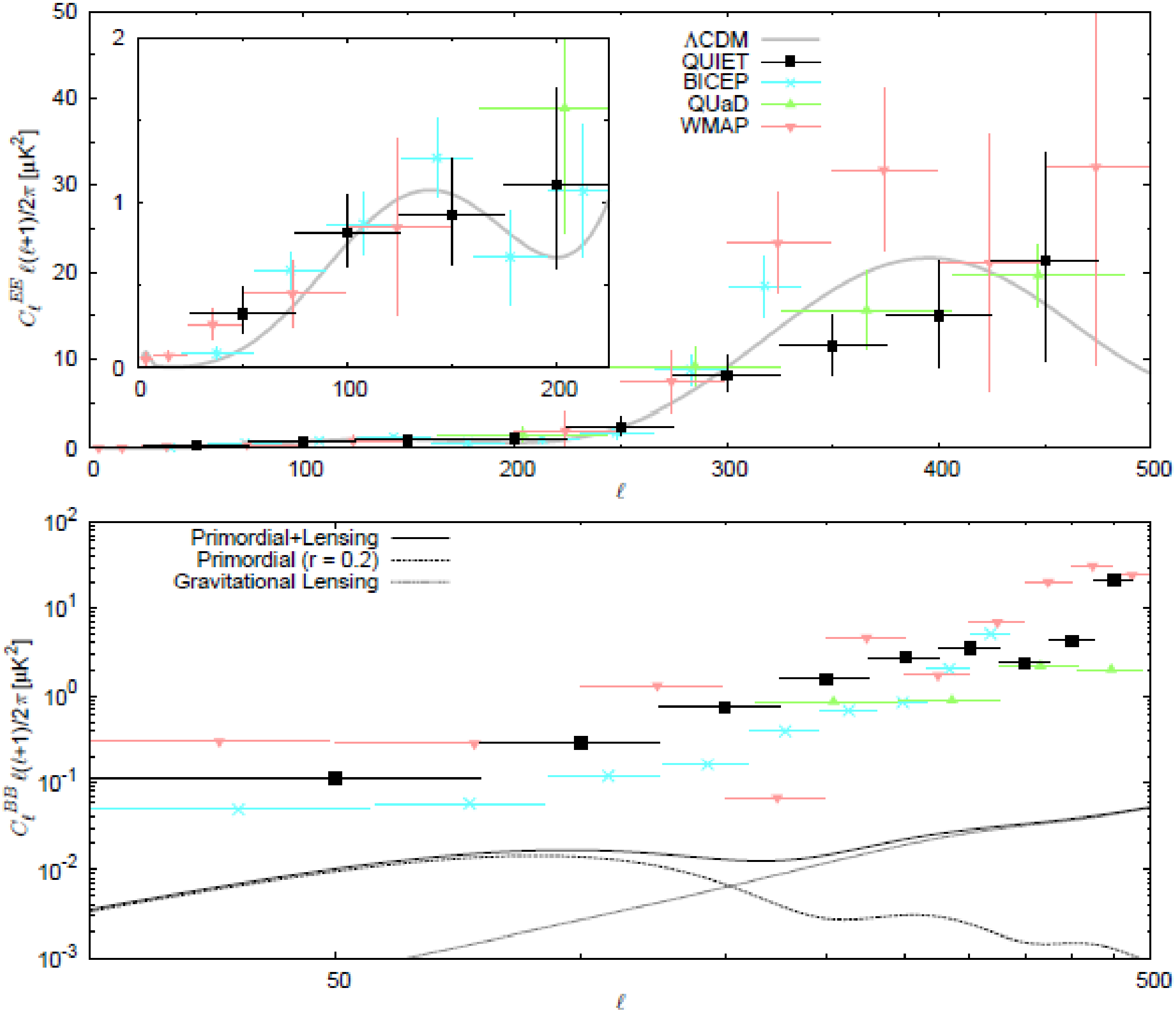


Results from 1839 (1934) hours on 4 CMB patches using 17 receivers

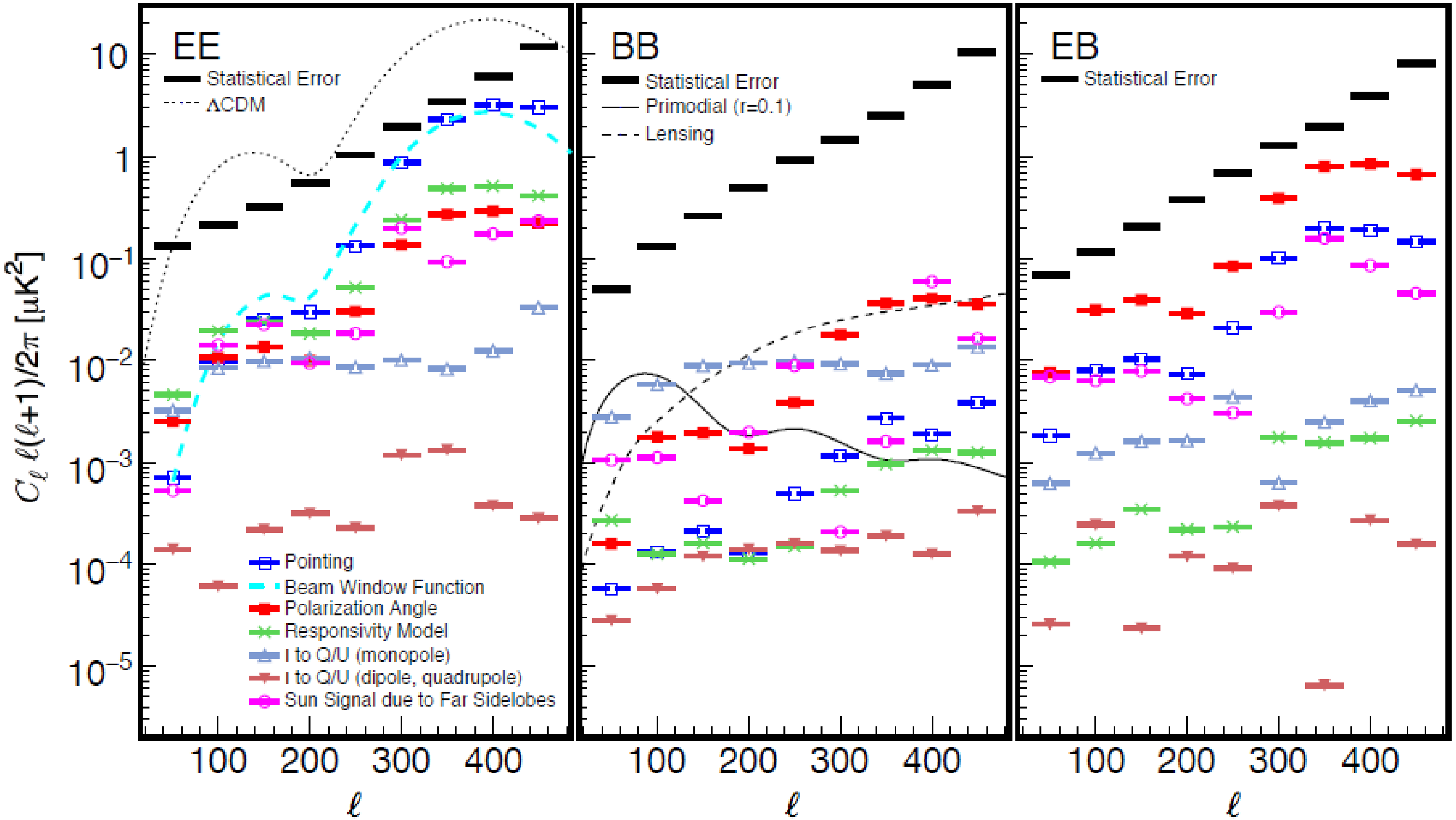
- Two pipelines show consistent results
- Consistent with ΛCDM
- No detection of B-mode power

Comparison to other experiments

- First confirmation of E-mode peak around l=100 at low frequency
- B-mode limits between BICEP and WMAP
- Limit on r:
  - $r=+0.35^{+1.06}_{-0.87}$
  - r<2.2 (95% C.L.)



Systematic errors



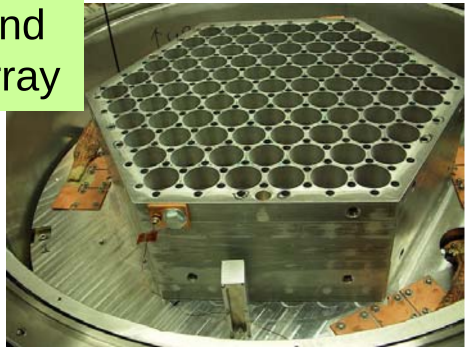
- Error dominated by statistical error
- Largest systematic at BB low l due to leakage (from optics) I->Q/U
- Size of errors for BB <r=0.1,

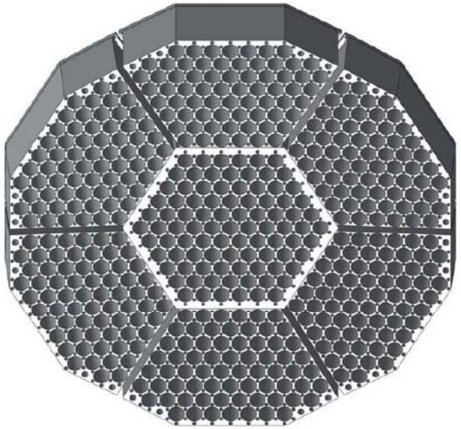
  => Smallest systematics reported to date from any CMB experiment

  => proves potential of our technology for future experiment

Future Prospects

Phase-I W-band
91-element array





499-
element
array

- W-band data in hand
  => twice of Q-band

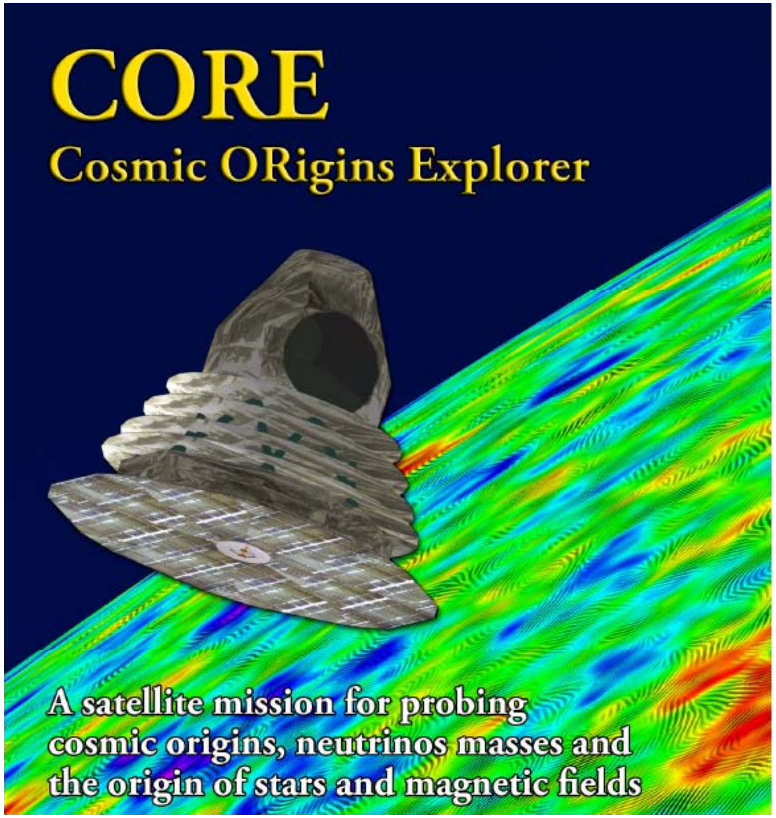
- Improve detectors T_noise<40K

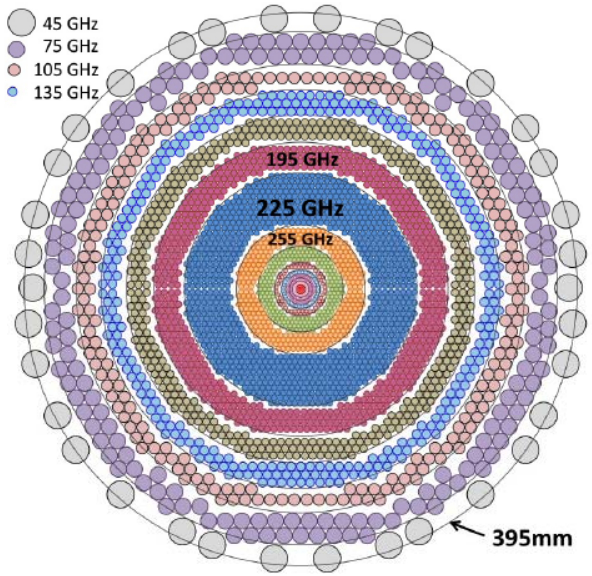
  => 500 element array $<10\mu K\sqrt{s}$
  => **$\sigma(r)<0.01$ by 2 yrs**

Beyond Planck

15 frequencies 45-795 GHz
30 times higher sensitivity than Planck

New satellite proposal in response to the European Space Agency Cosmic Vision 2015-2025 Call





Reach r=0.001

Constrain summed neutrino masses <0.03eV

Map magnetic field to sub-parsec scales

Summary

Measurements of the Cosmic Microwave Background Radiation have helped establishing our current cosmological model

Experiments are underway with significantly increased sensitivites compared to previous efforts, challenge to control foregrounds and systematics at unprecedented levels

Sensitive polarization measurements offer a unique window to the earliest moments in the Universe (inflation)

Already able to cover an interesting part of the phase space of inflationary modelsbe over the next few years

Exciting times ahead!