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Probing the physics of early Universe using CMB polarization

The recent results from BICEP2 and POLARBEAR, and future path using a satellite

History of the Universe

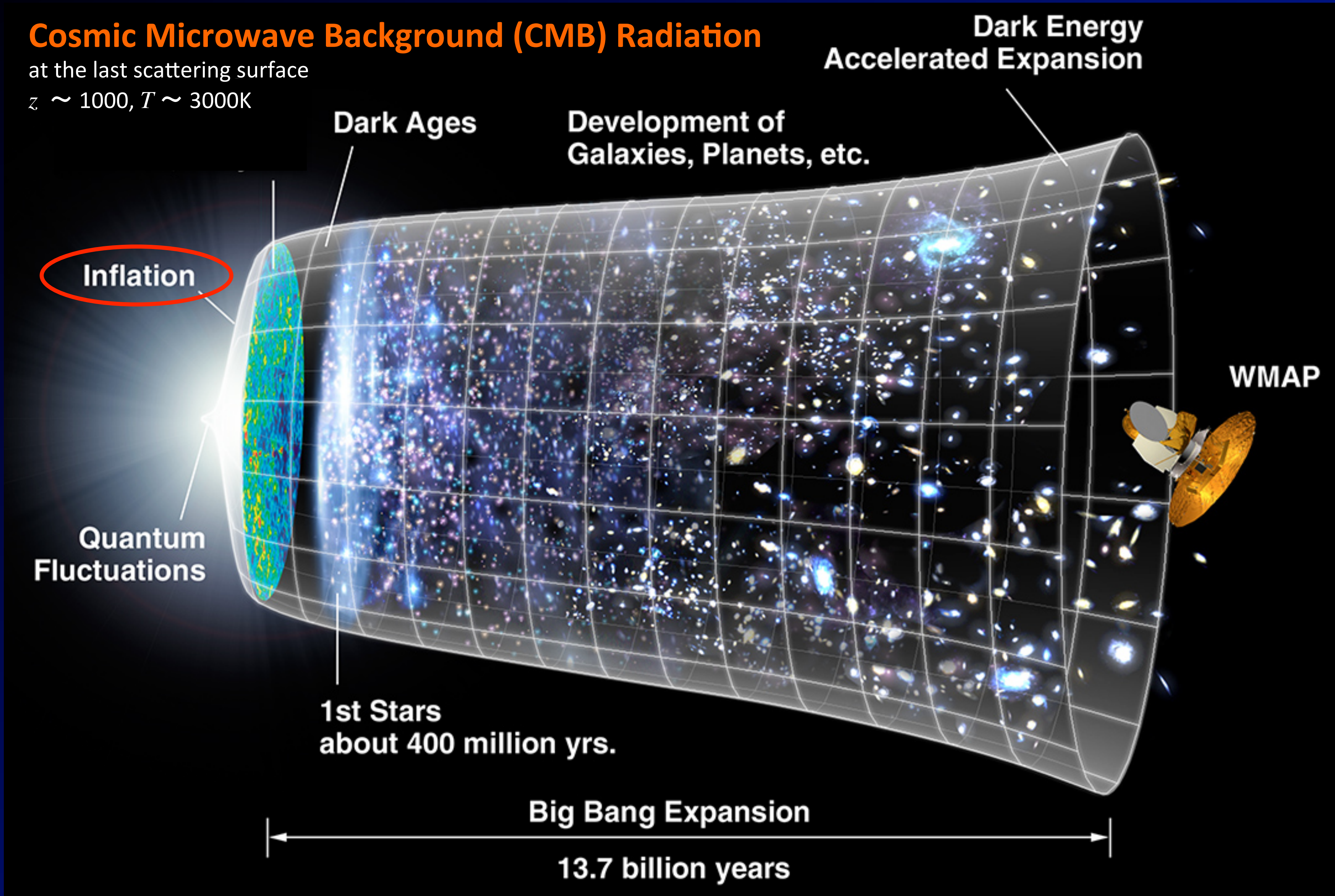
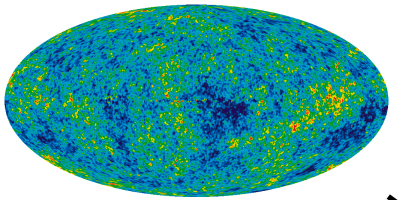


Figure from http://lambda.gsfc.nasa.gov/ (modified)

Only 6 parameters to describe the current ΛCMD paradigm

Initial condition
A_s, n_s

Propagation of plasma
$\Omega_b h^2$: Baryon
$\Omega_c h^2$: Cold dark matter



h: **Hubble constant**

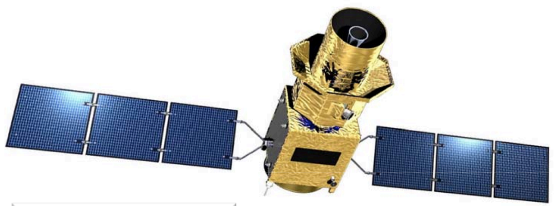
Before recombination
$e + \gamma \rightleftarrows e + \gamma$

Recombination (z～1000、T～3000)
$e + p \rightarrow H + \gamma$

Today CMB appears as 3K (λ=2mm) black body radiation.

Reionization
τ

Observer



Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

From Planck 2013 results. I. Overview of products and scientific results

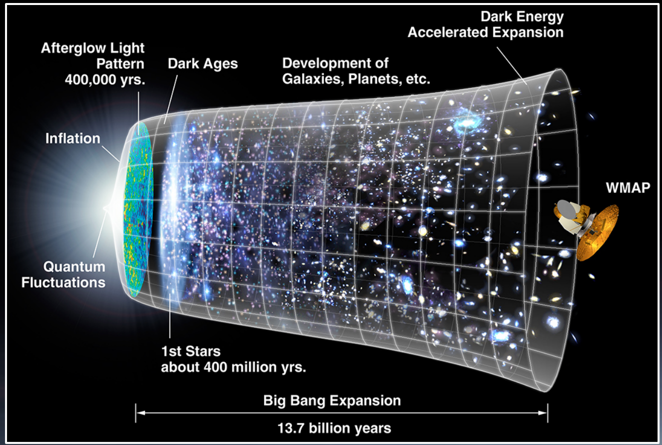
Beyond the standard

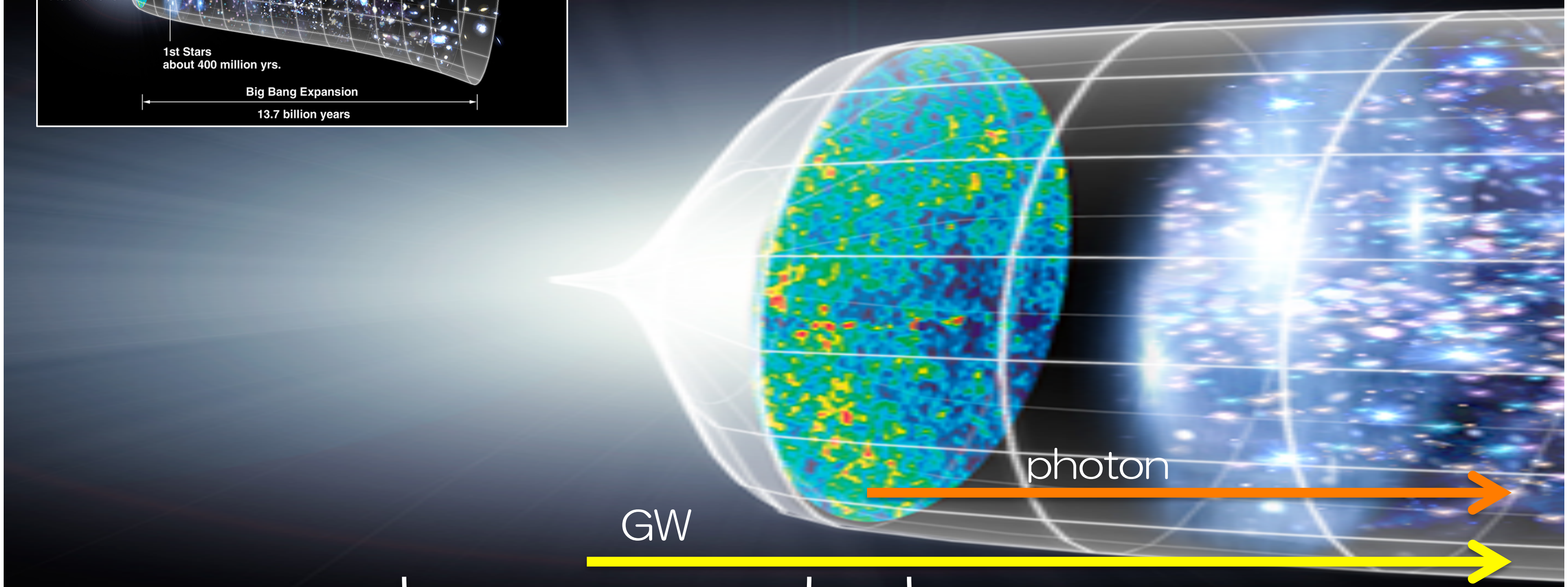
- Unsolved problems in the standard Big Bang cosmology
  - Where does the seed of the structure come from?
  - Flatness problem
  - Horizon problem
  - Monopole problem
  - ・・・

The idea of inflation can resolve all of these at once. AND, there are many circumstantial evidences that support the existence of inflation but no 'direct' confirmation yet.

The measurements of the CMB polarization have a sensitivity to probe the inflation. Let's hunt this!

What do we learn from the CMB polarization beyond ΛCDM?





Probing inflation

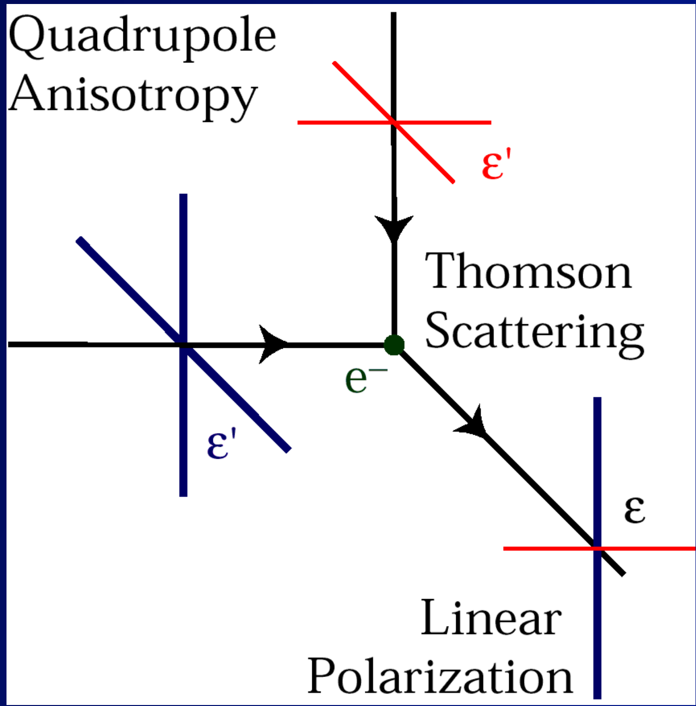
If inflation exists, the primordial gravitational wave has imprinted the particular CMB polarization pattern, called B-mode.

Probing the gravitational potential of the large scale structure

The CMB polarization (E-mode) is lensed and this effect produces B-mode pattern.

Polarization

- CMB polarization is expected to be linearly polarized.
- Quadrupole pattern around the scattering center creates the linearly polarized light.
- Sources of the quadrupole pattern:
  - **Primordial density perturbation**
    - → **E-mode**
  - **Primordial gravitational wave originated from inflation**
    - → **E-mode and B-mode**



Warning!

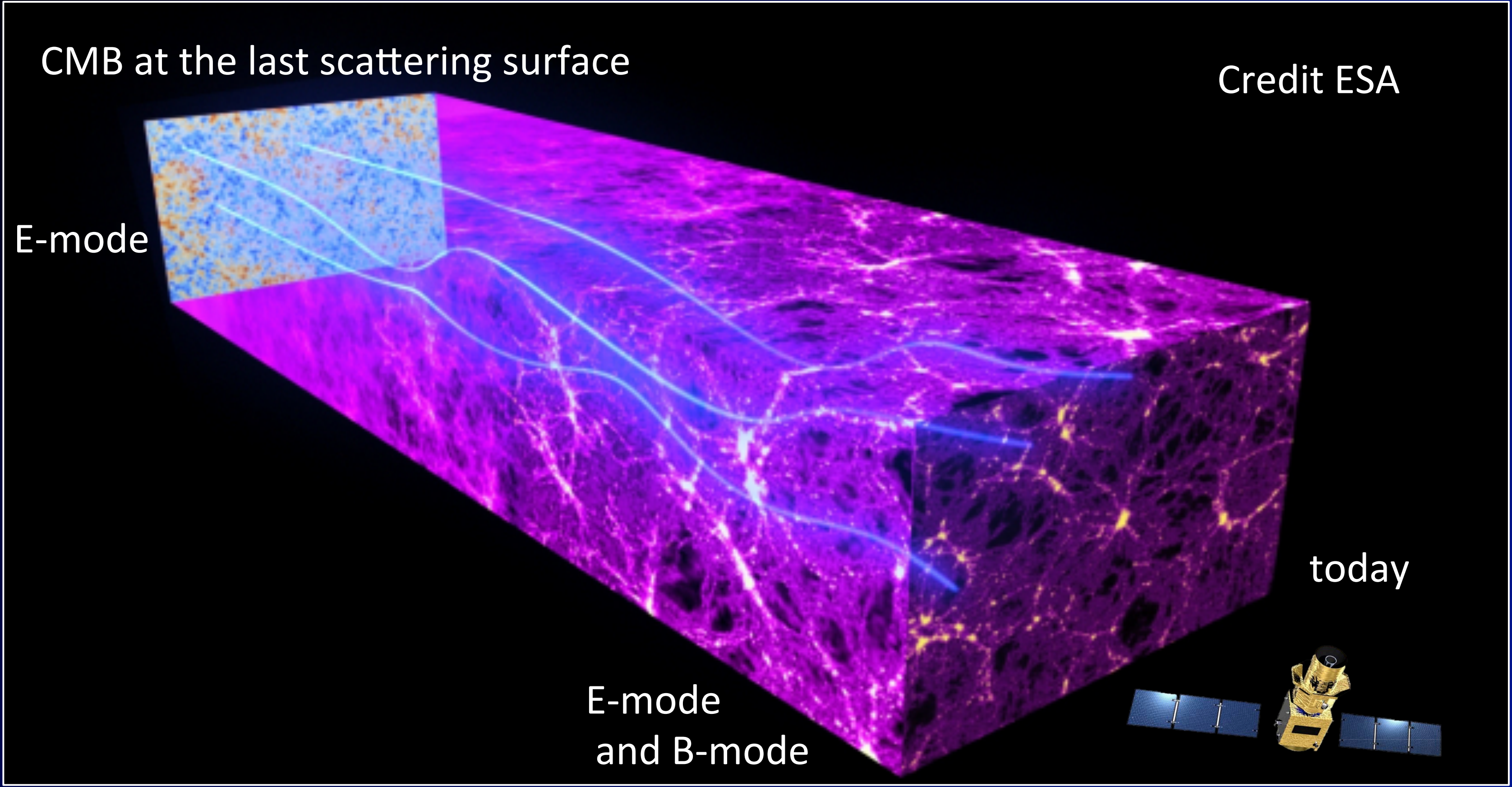
The detection of B-mode pattern does not necessary guarantee for the detection of primordial gravitational wave B-mode.

- The weak gravitational lensing mixes the E-mode and B-mode.

- The polarized galactic emission also creates B-mode pattern.

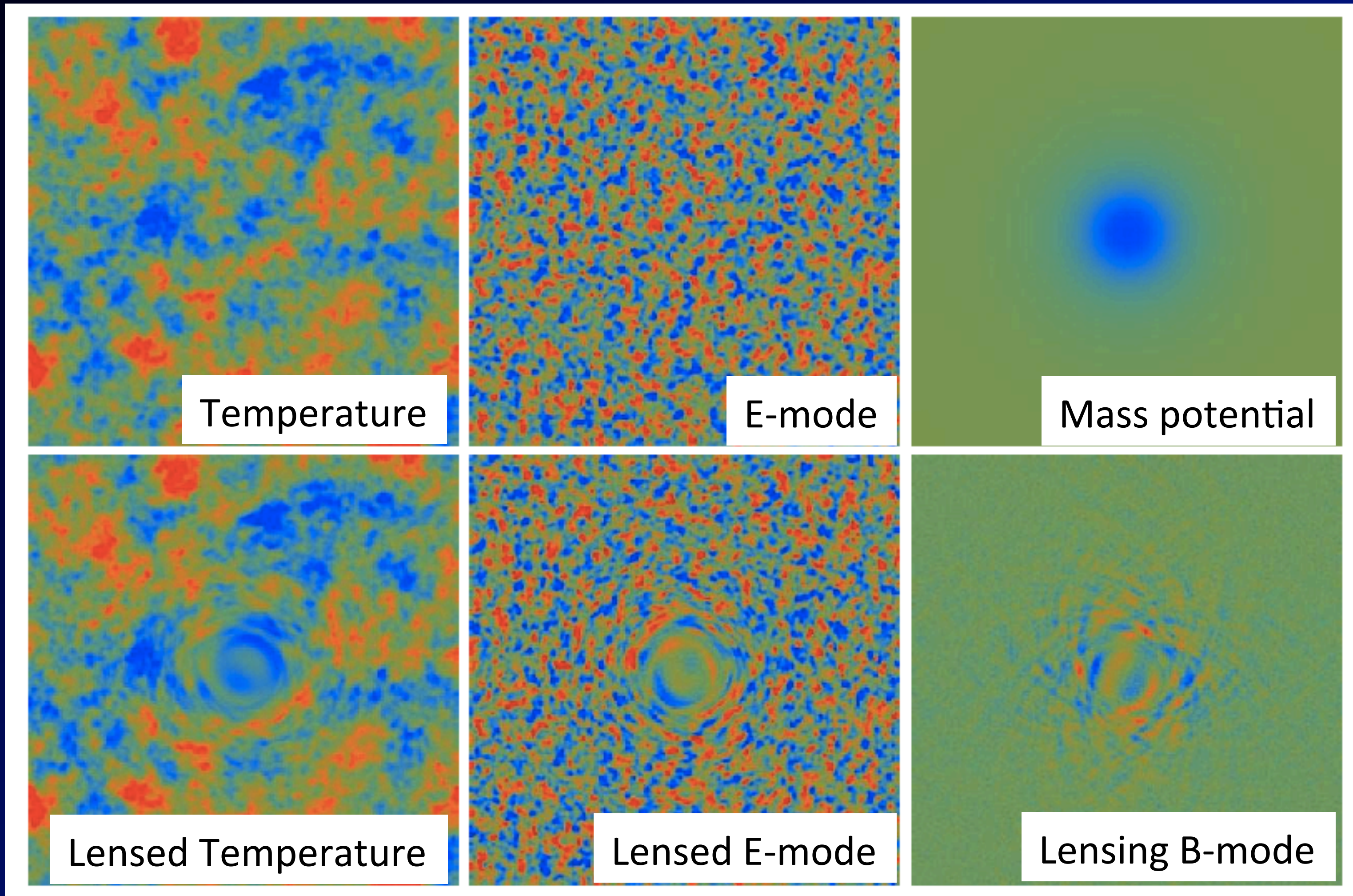
WMAP 7year

CMB as a probe of the LSS



- The CMB photons travel through the potential of the large scale structure and weak gravitationally lensed.
- The effect is prominent at around z ～ 2 while the effect is integrated through out the history of the universe since the last scattering surface.
- Sensitive to the sum of the neutrino mass and dark energy via the LSS potential.

Effect on CMB from lensing



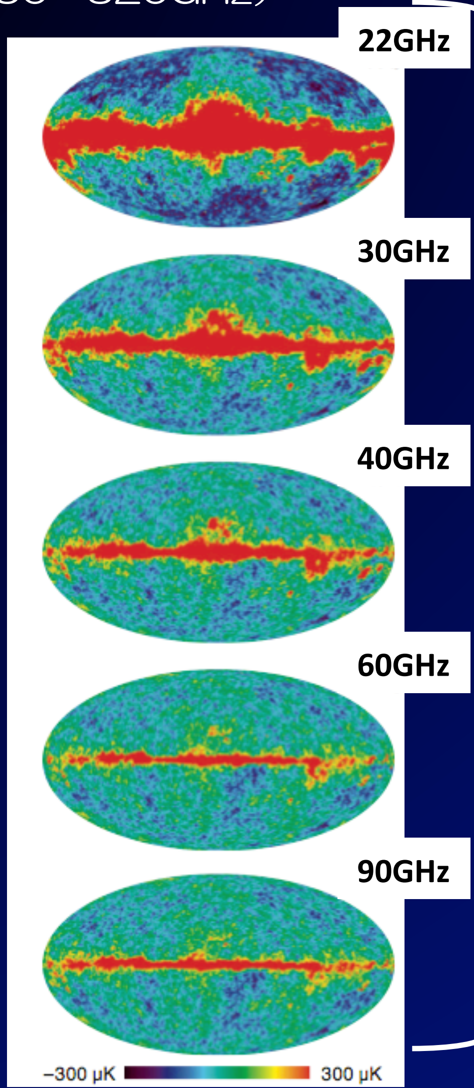
Hu & Okamoto (2002)

From measurements to science product

LiteBIRD

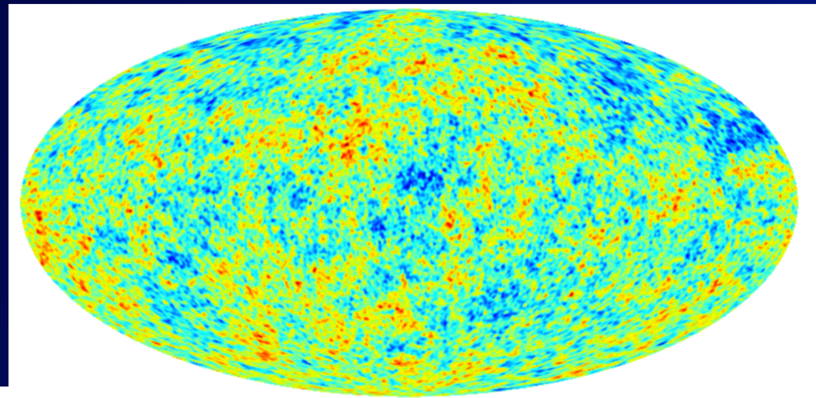
Data process

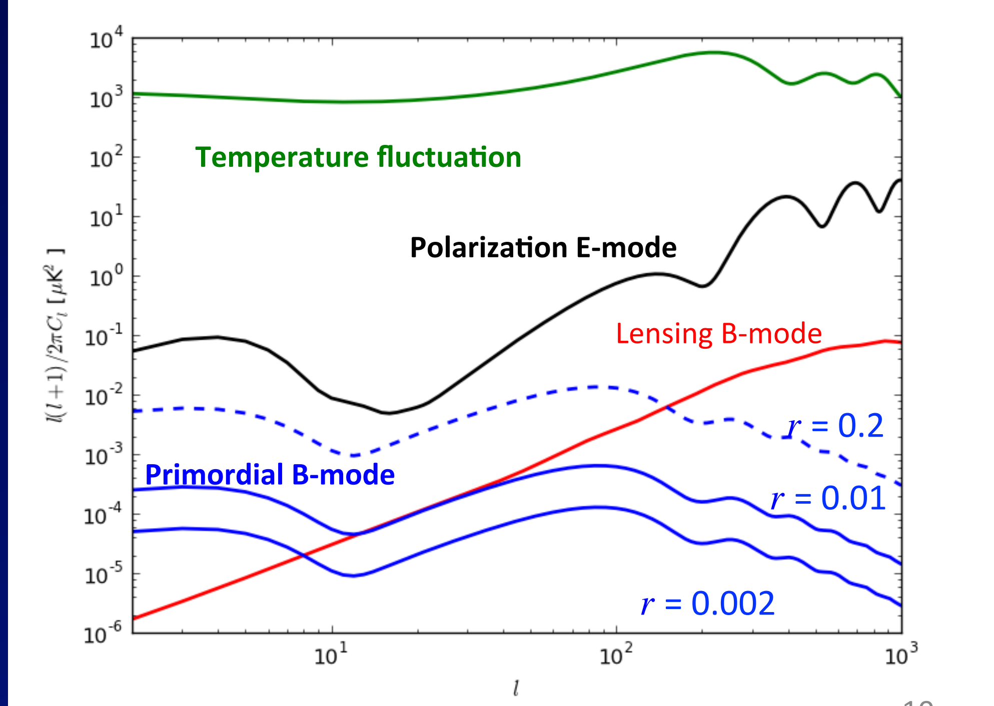
Map at various observing frequencies
（50～320GHz）

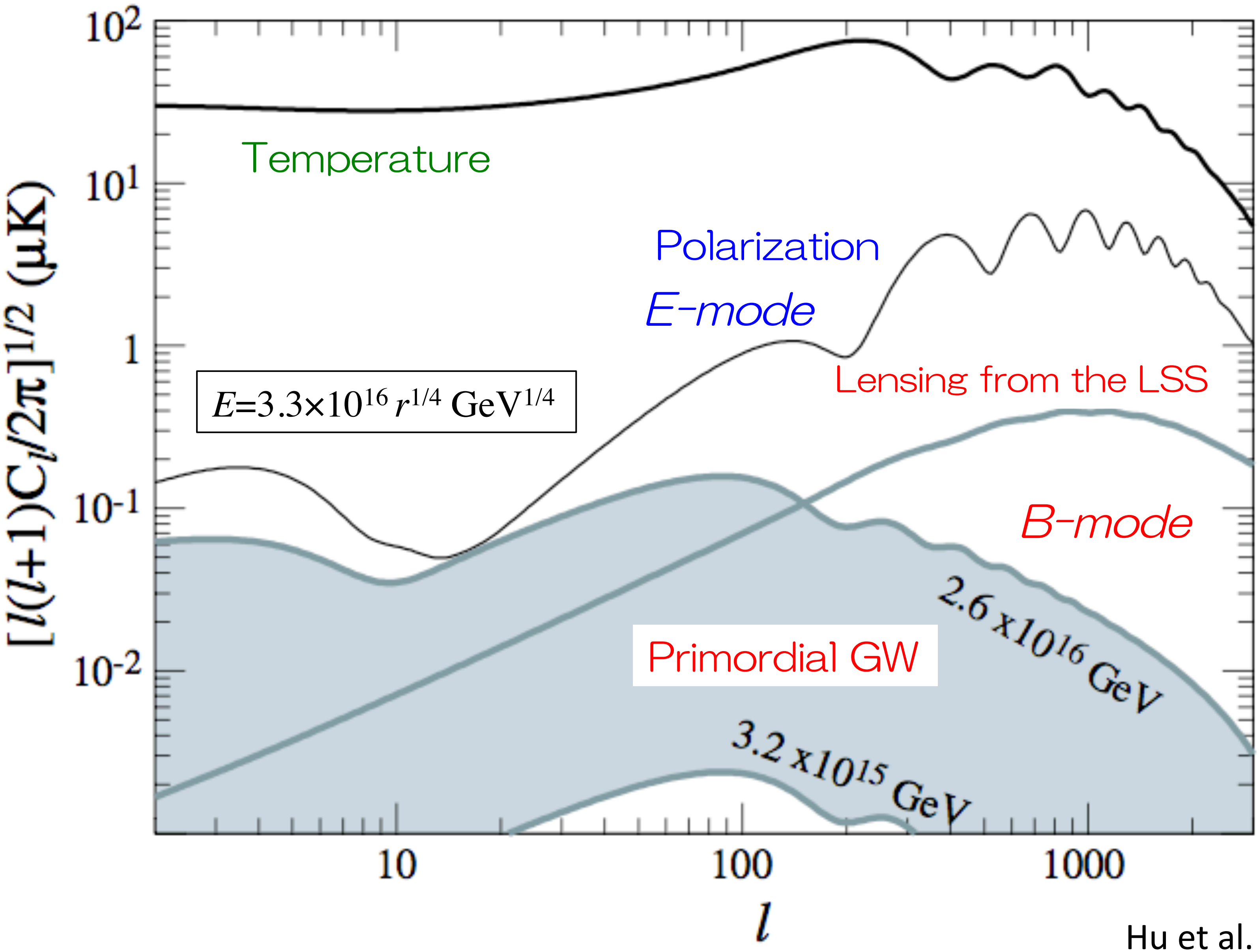


Maps from WMAP as an example

CMB only map



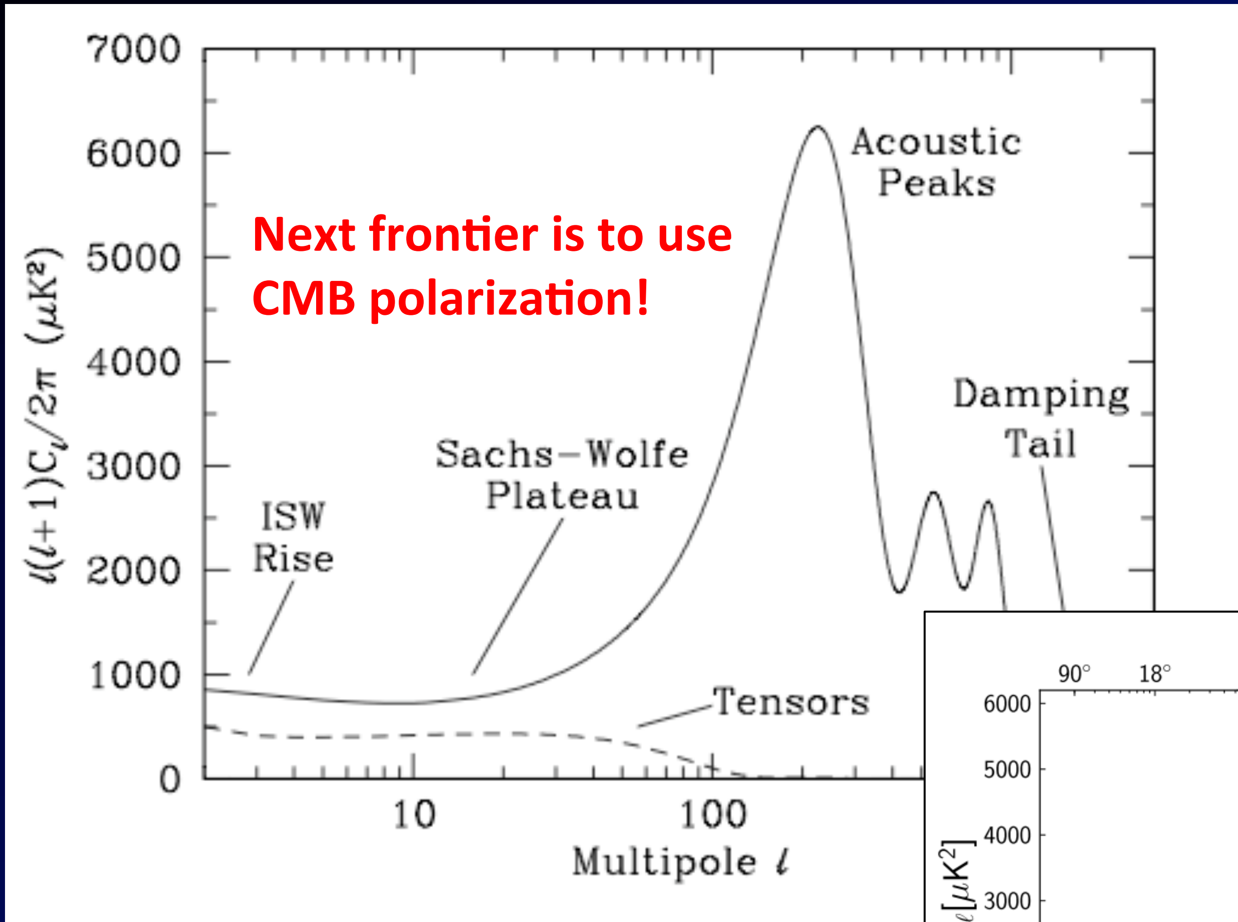




10^2
10^1
1
10^{-1}
10^{-2}
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
Temperature
Polarization
E-mode
Lensing from the LSS
$E=3.3\times10^{16}\, r^{1/4}$ GeV$^{1/4}$
B-mode
2.6 x10^{16} GeV
Primordial GW
3.2 x10^{15} GeV
10
100
1000
l

Hu et al.

Current (2013) status of the B-mode hunting

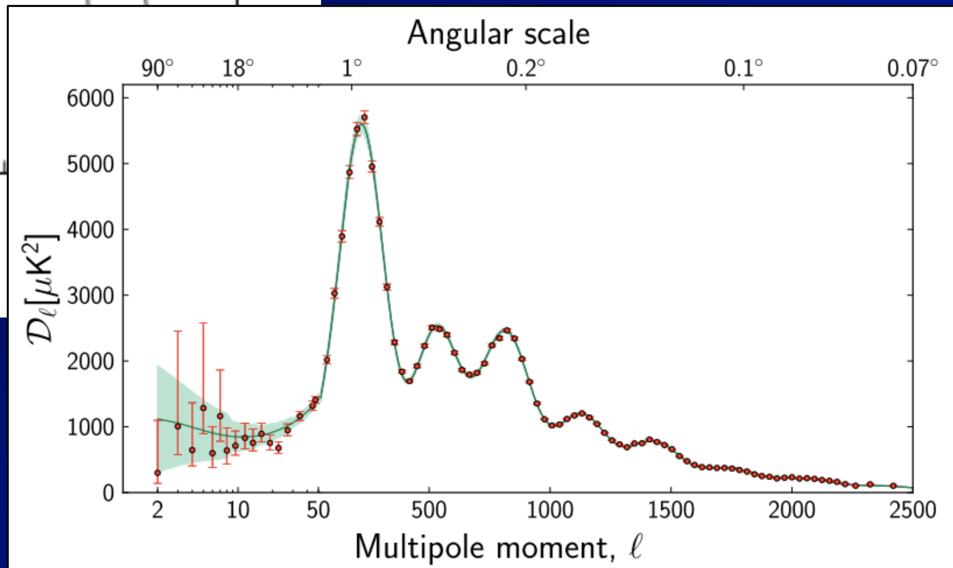


Next frontier is to use CMB polarization!

Limit from the temperature fluctuation

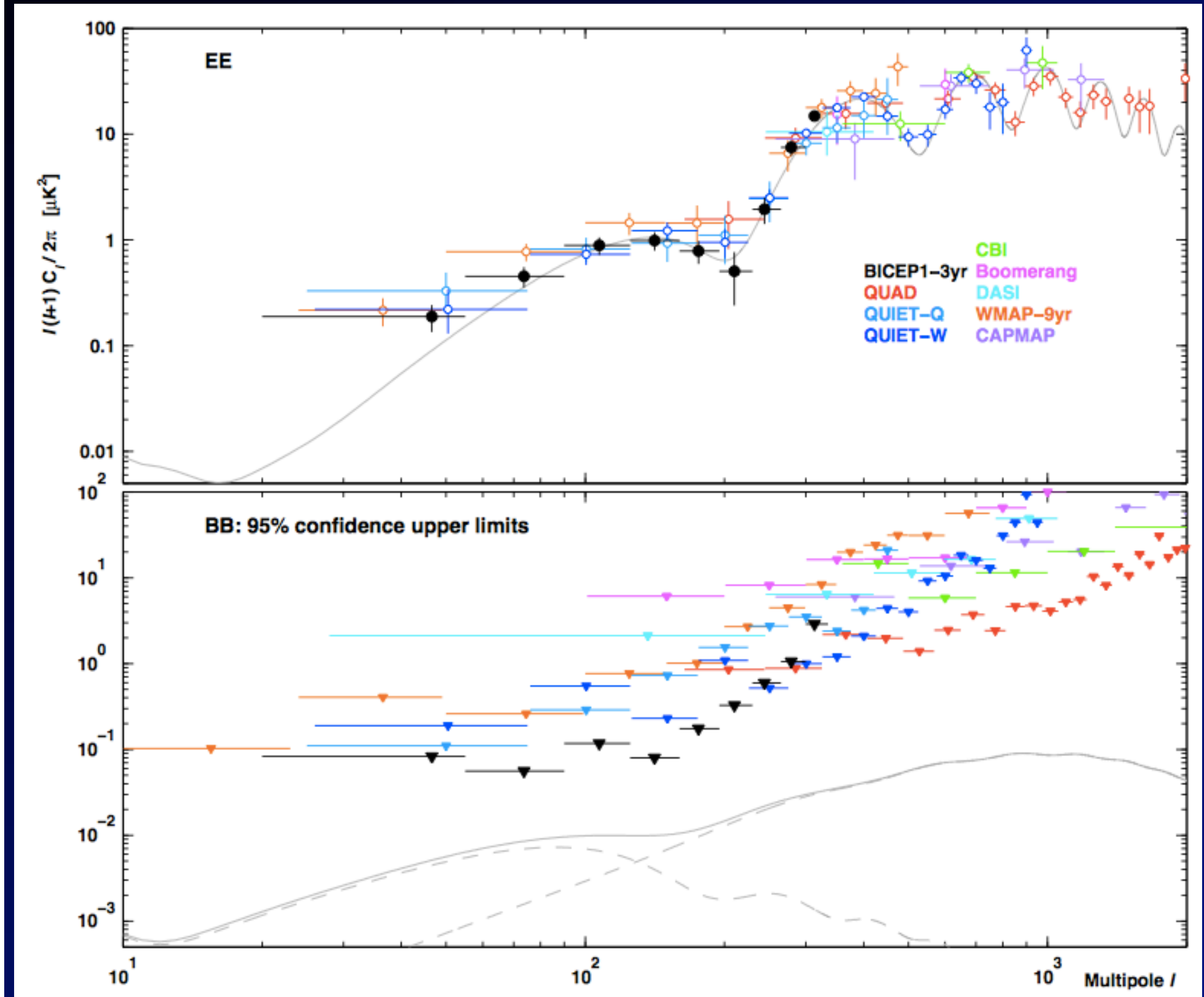
Planck+WMAP+high$l$

r <0.11 (95%C.L.)



Planck2013

Current (2013) status of the B-mode hunting



BICEP-I three year data Barkats et al. (2013)

Limit from the temperature fluctuation Planck+WMAP+high$l$
r <0.11 (95%C.L.)

Limit from the polarization BICEP-I three year data, r <0.70. Barkats et al. (2013)

Community wide effort/ race to detect this B-mode first!

Huge progresses since the end of 2013

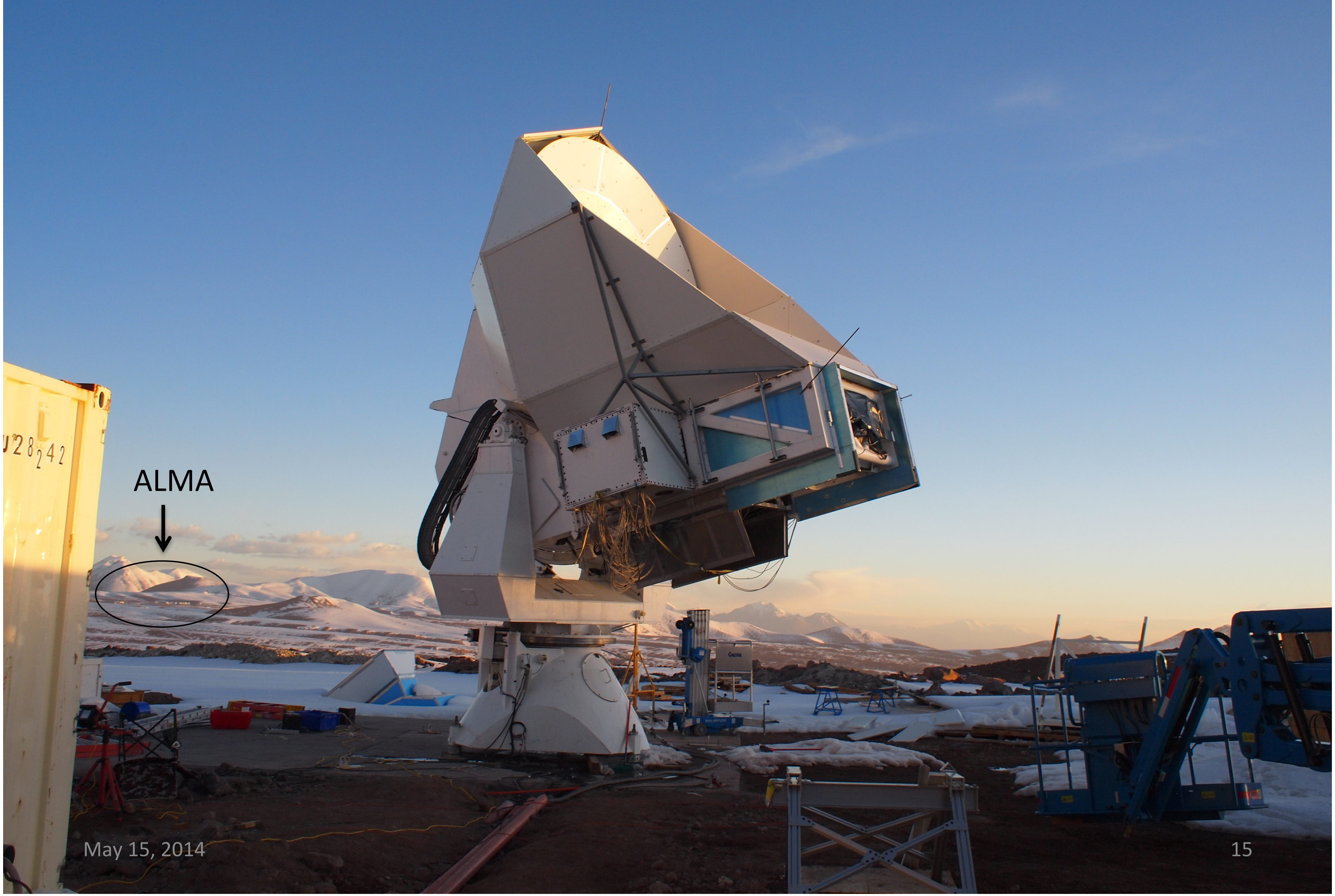
POLARBEAR @ Chile

- Beam size： 3.5 arcmin.
- Observing band： 150GHz (λ～2mm)
- Detector： 1274 Transition Edge sensor bolometers
- Modulation：Sky＋HWP
- Atacama desert in Chile（5200m）
- 1 year eq. of observations

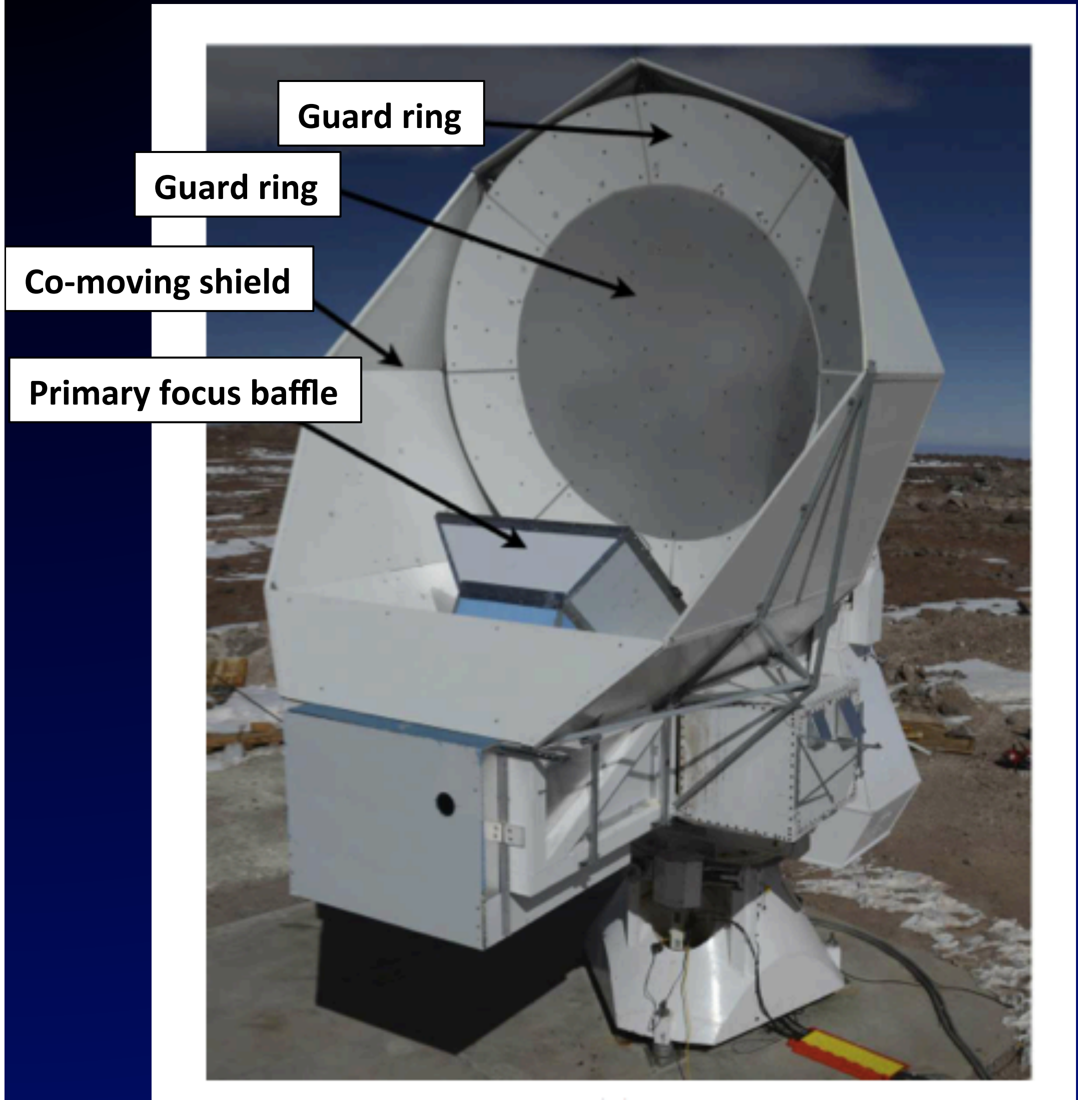
BICEP2 @ South pole

- Beam size：30 arcmin.
- Observing band： 150GHz (λ～2mm)
- Detector： 512 TES
- Modulation： Telescope
- Geographic South Pole（～3000m）
- Three years of observation

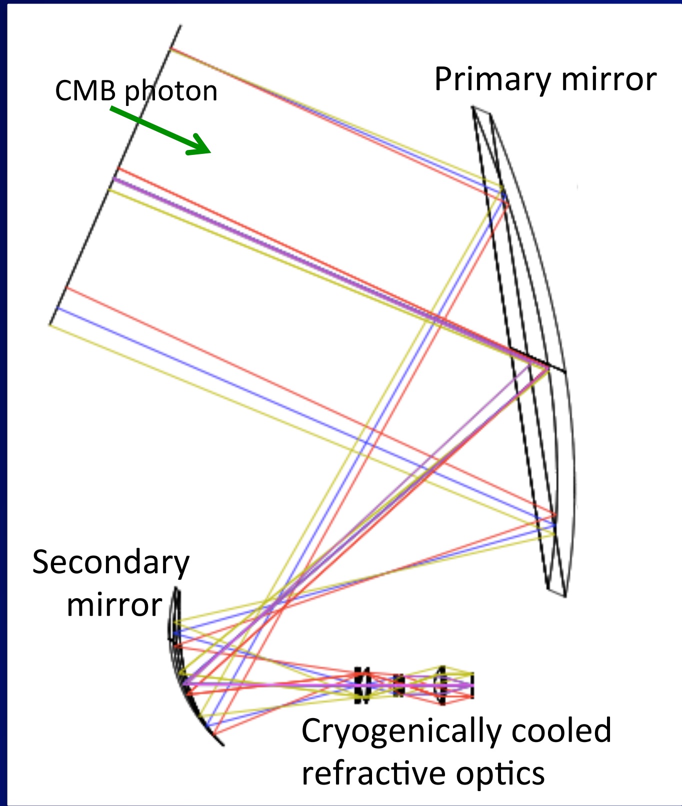
POLARBEAR, hunting the lensing B-mode



Telescope overview

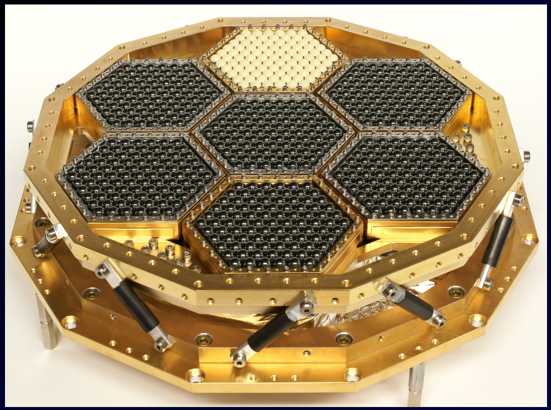


Huan Tran telescope

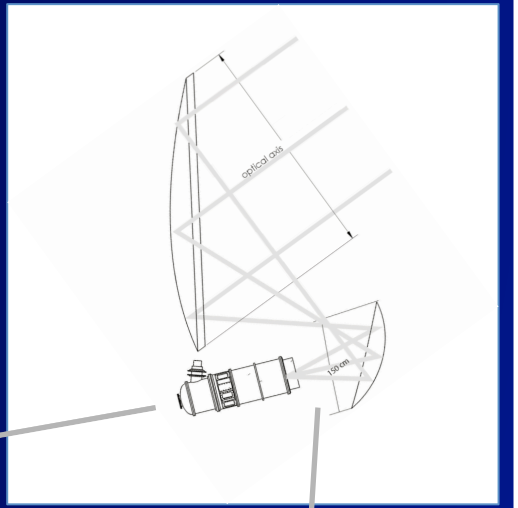


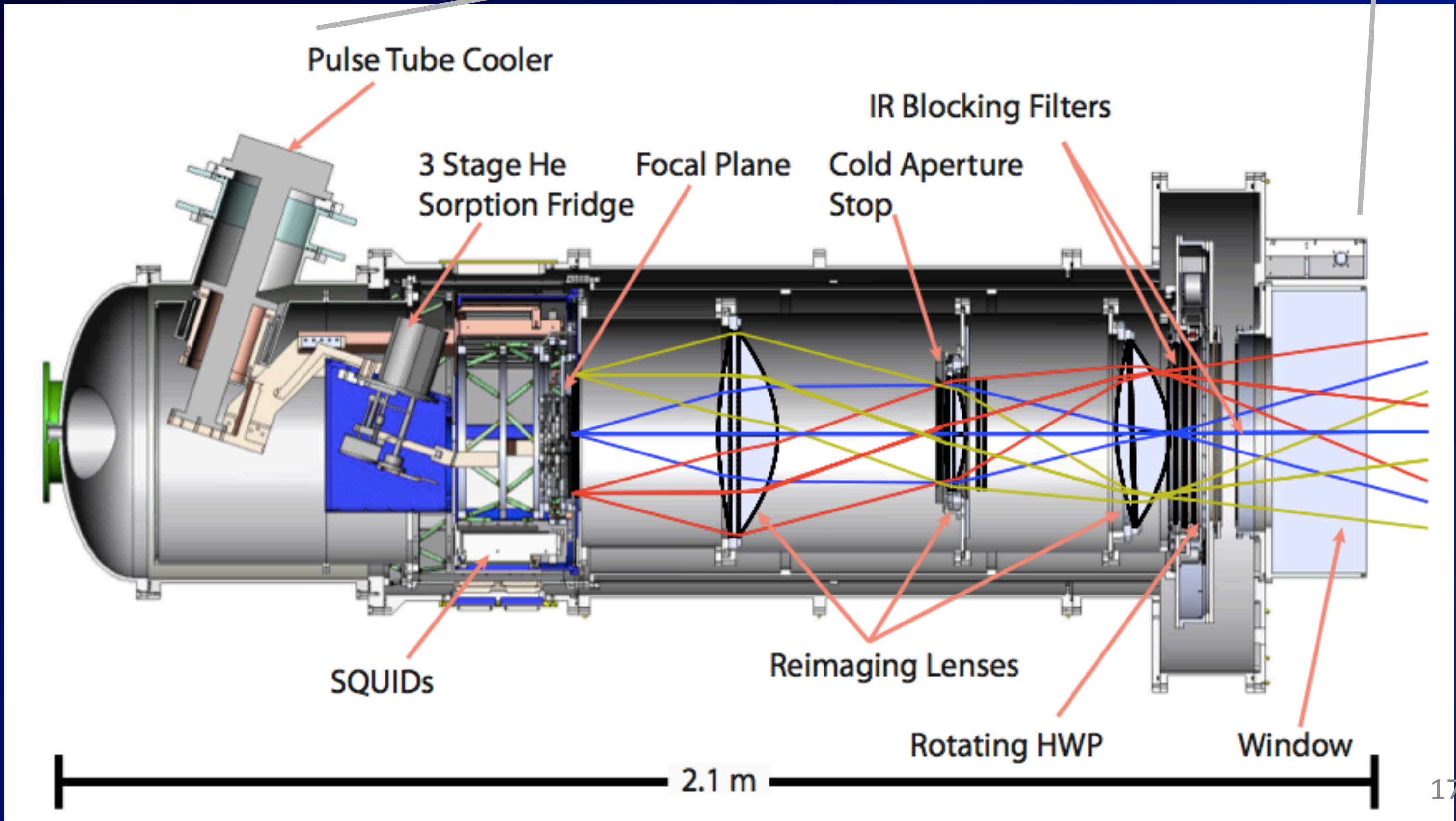
A primary mirror diameter of 3.5m creates the beam on the sky with 3.5 arcmin (FWHM) angular resolution at 150 GHz.

Receiver and detector array

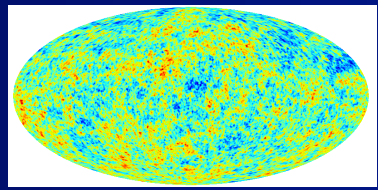


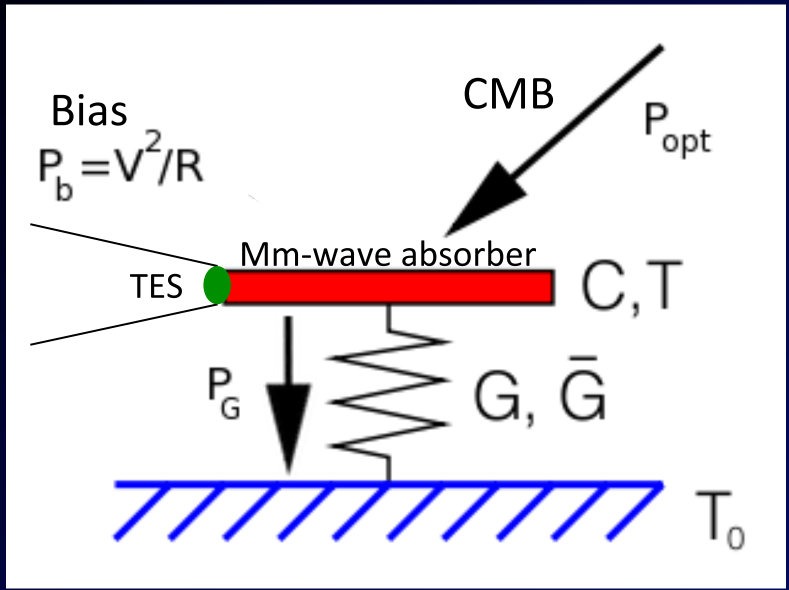
- The refractive optical elements are cooled at 4K.
- The focal plane consist of the 1276 transition edge sensor bolometers cooled at 250mK.

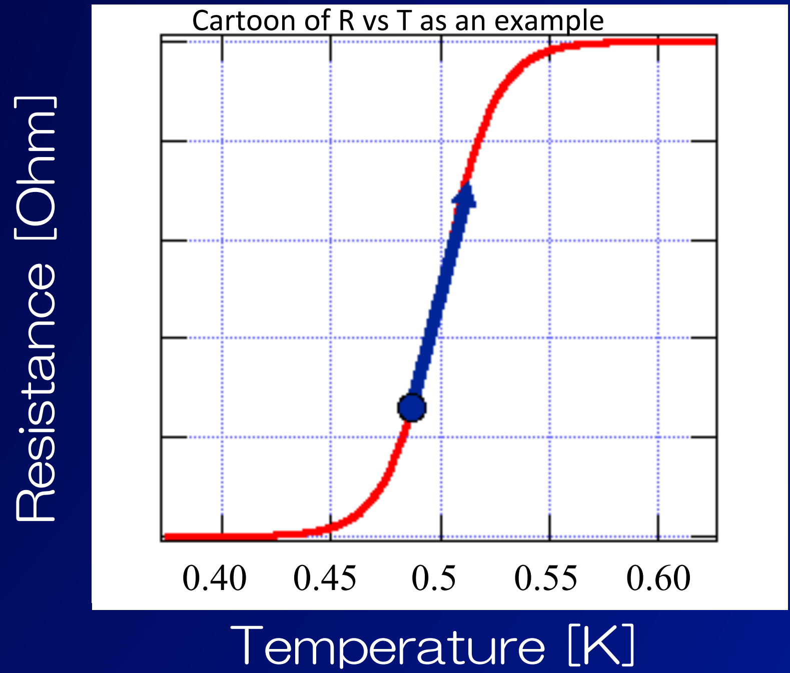




Principle of the TES bolometers







http://web.mit.edu/ (modified)

From energy conservation

$$P_{opt} + P_{bias} = G(T_{bolo} - T_0)$$

$$P_{opt} + \frac{V^2_{bias}}{R} = G(T_{bolo} - T_0)$$

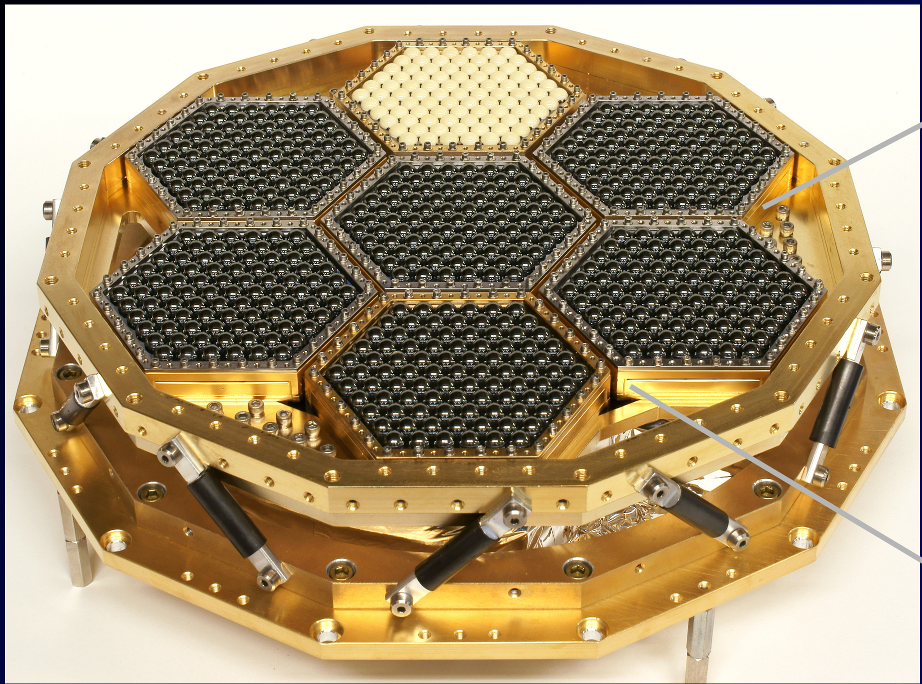
Our goal is to measure the spatial variation of the CMB on top of 3 K.

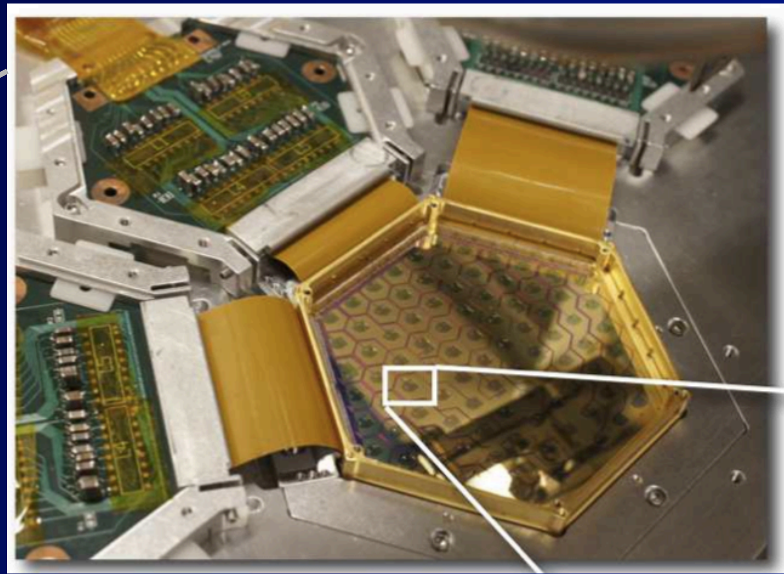
δP from sky → δT of TES → δR

With constant voltage bias, this translates to δI (current)

We now use SQUID to measure the change of the curren, δI → δΦ (flux) → δV.

Focal plane, detector module, and TES



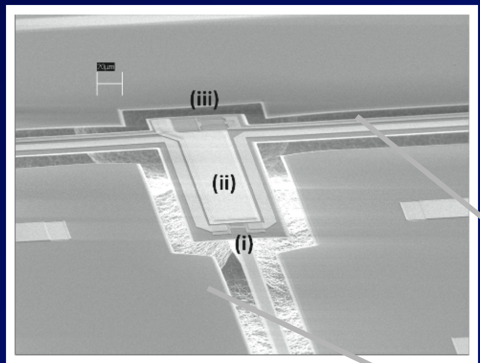


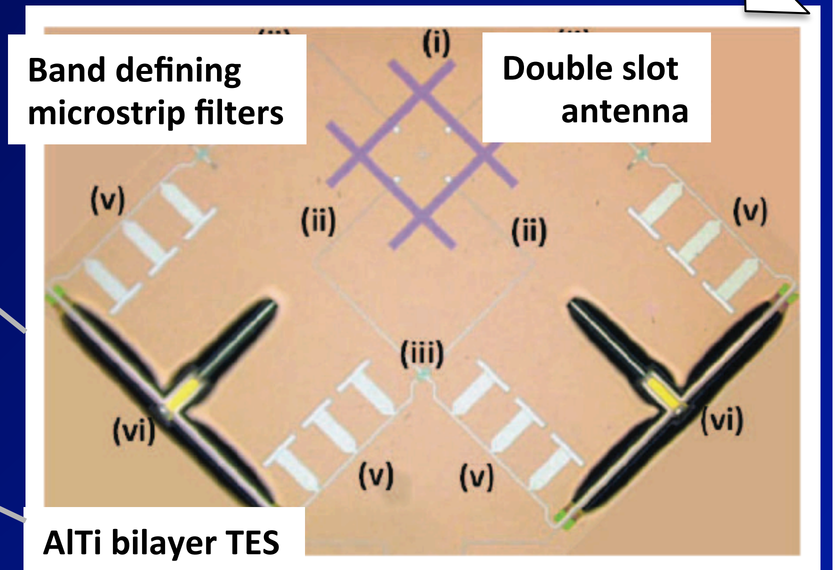
The 1 module has 91 pixels (=182 TESs.)

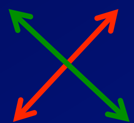
The 7 modules comprises the focal plane, 1274 TESs.

Yield: 80%.

NET per bolo: 550 $\mu K\sqrt{s}$
NET per array: 21 $\mu K\sqrt{s}$



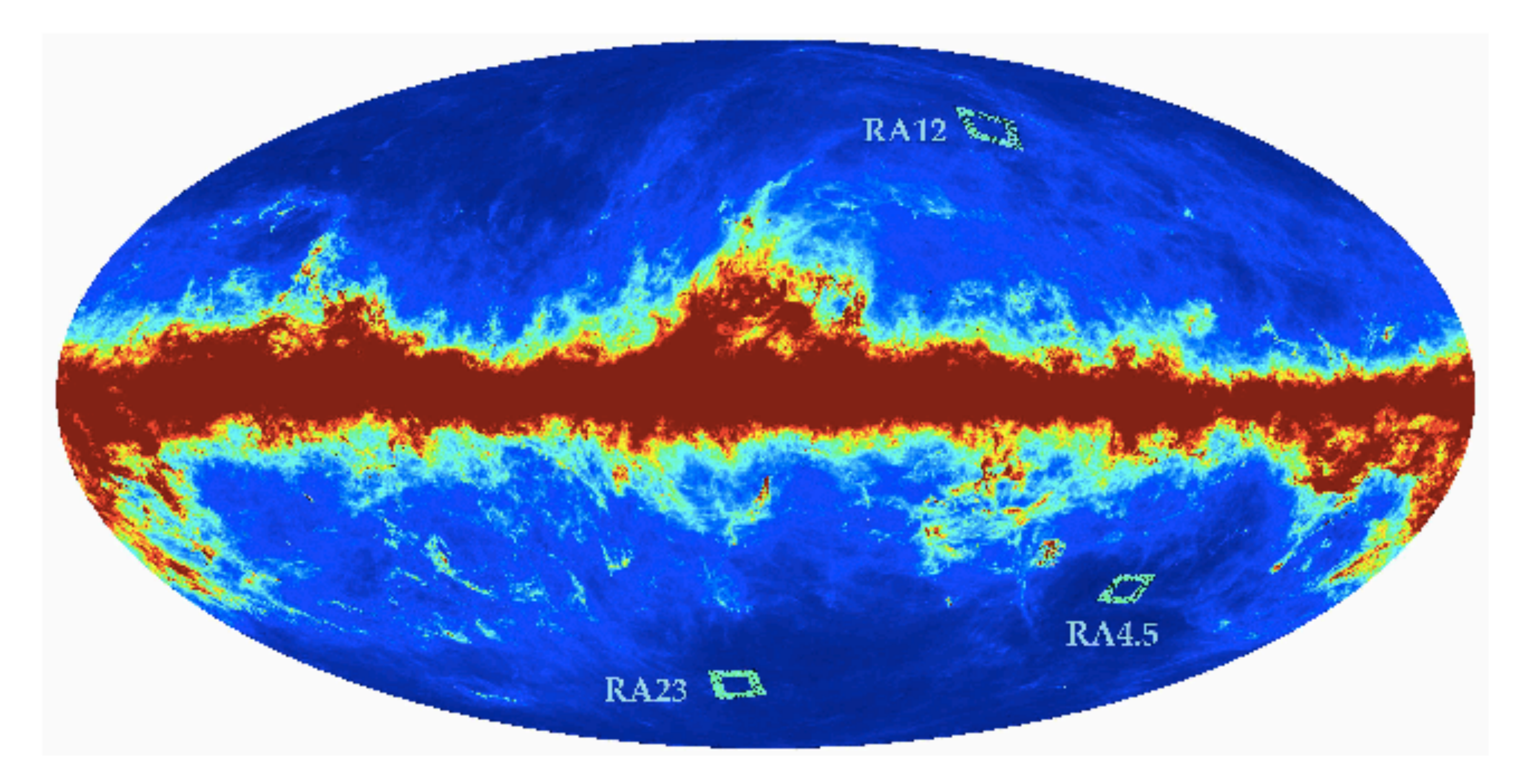




Measure the two orthogonal polarization states simultaneously.

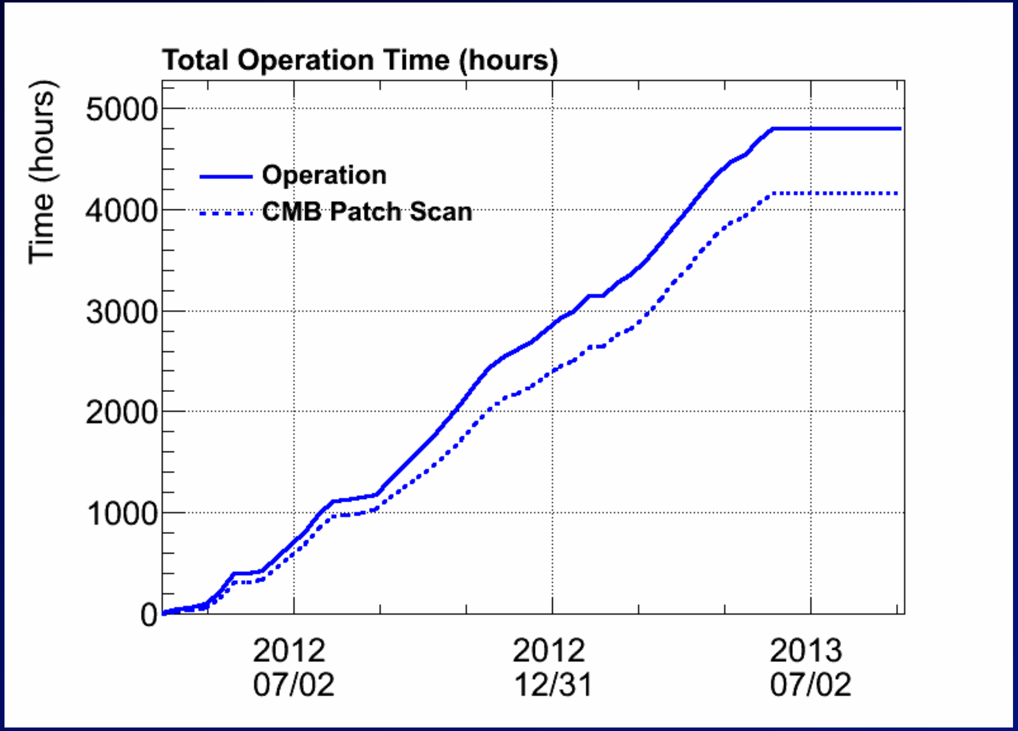
Observing region

Maximizing the observational time at the "dust free" area on the sky.
We choose the sky area of 3° ×3° . Optimize for the lensing detection.
Overlap with other CMB and CIB measurements.



Observations

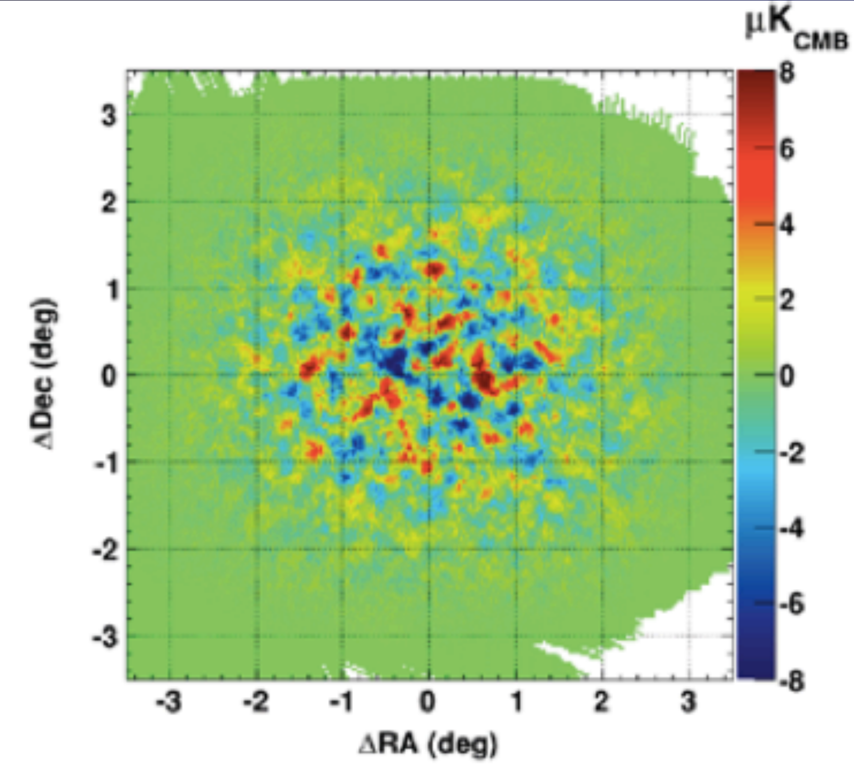
- 2010-Summer: Engineering run at CA, USA.
- 2011-Fall: Construction of Chile site, building the telescope, install the receiver
- 2012-Jan: First light
- 2012-May: Start the CMB observations.

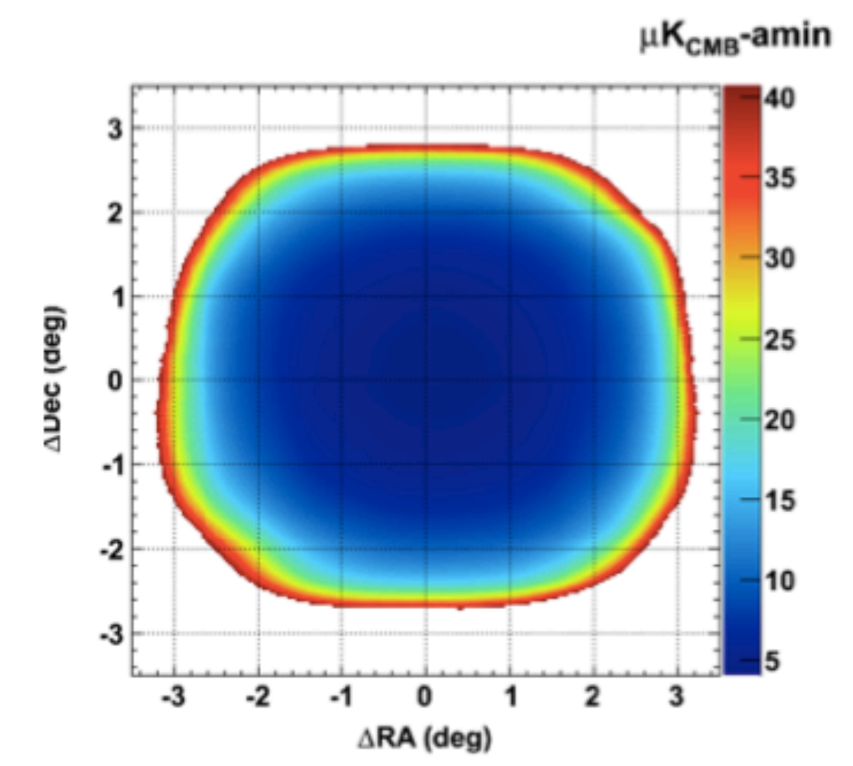


During the time between 2012-May and 2013-June, POLARBEAR accumulated 3300 hours of CMB data.

From this point, the results are analyzed from these data.

CMB map





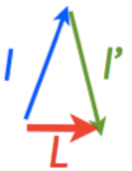
Polarization sensitivity of 5 μK・arcmin.

Analysis for gravitational lensing effect

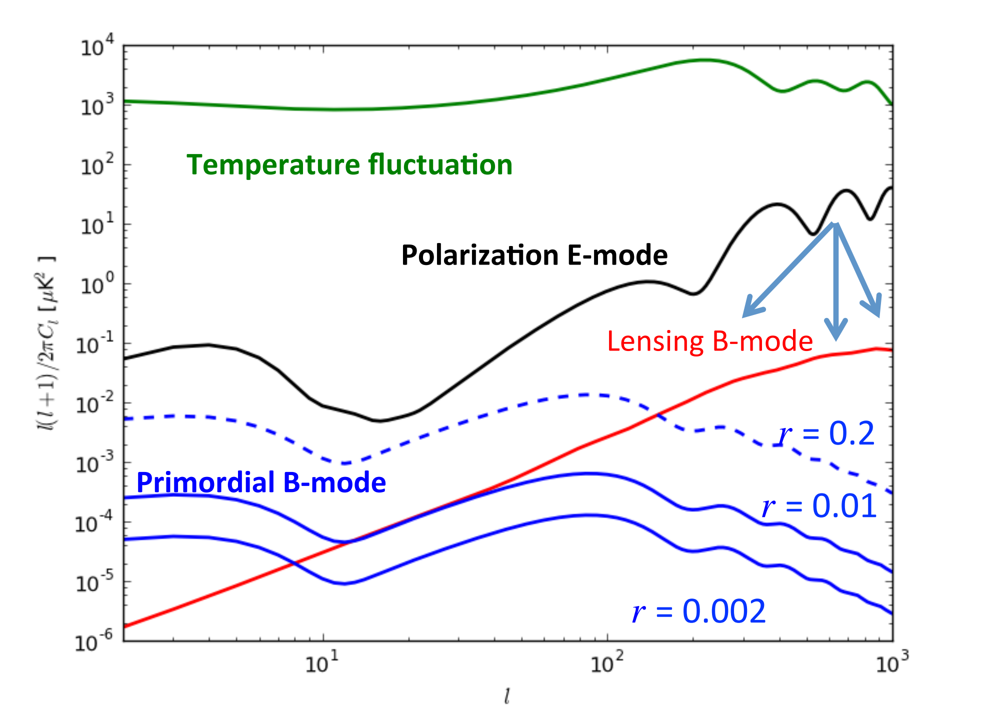
Effect of lensing mix E-mode and B-mode and they are NOT 1-to-1 in ell space.

$$\underline{d_{EE}}(\mathbf{L}) \propto \sum_{\mathbf{l}} \underline{E(\mathbf{l})}\,\underline{E(\mathbf{l}')}$$

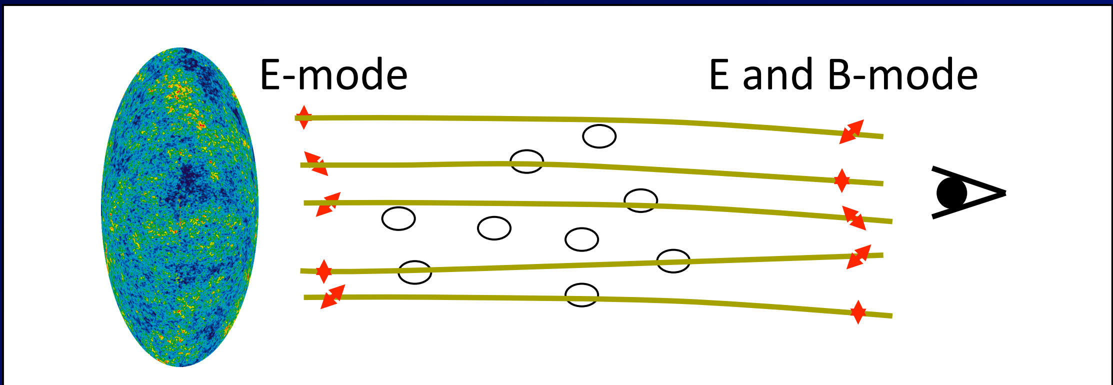
$$\underline{d_{EB}}(\mathbf{L}) \propto \sum_{\mathbf{l}} \underline{E(\mathbf{l})}\,\underline{B(\mathbf{l}')}$$



(Hu, Okamoto, 2002)

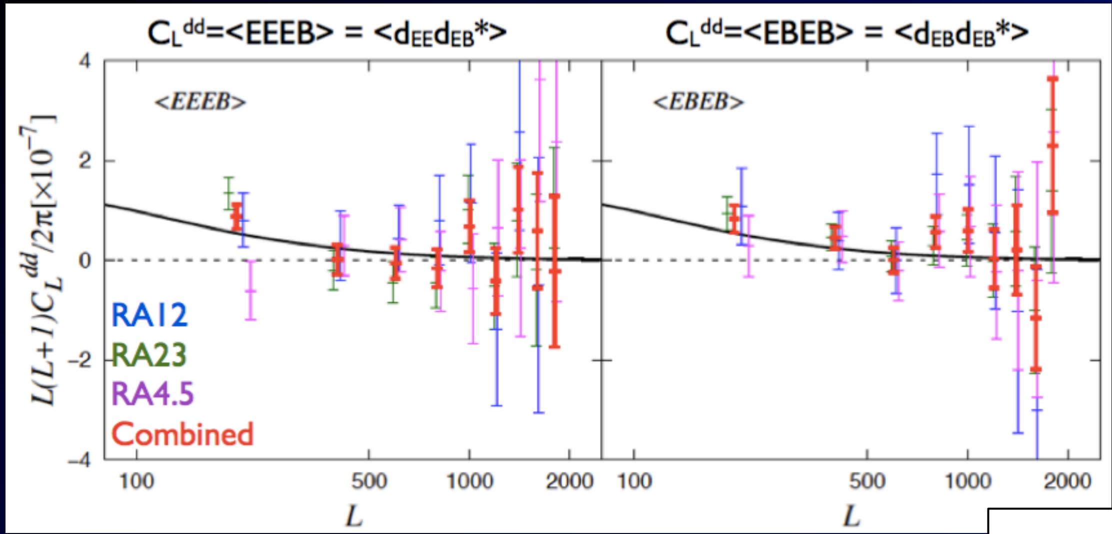


The magnitude of the correlation between E and B gives the magnitude of the lensing deflection.



About 2 arcmin of the deflection due to the lensing effect.

Lensing power spectrum



arXive:1312.6646

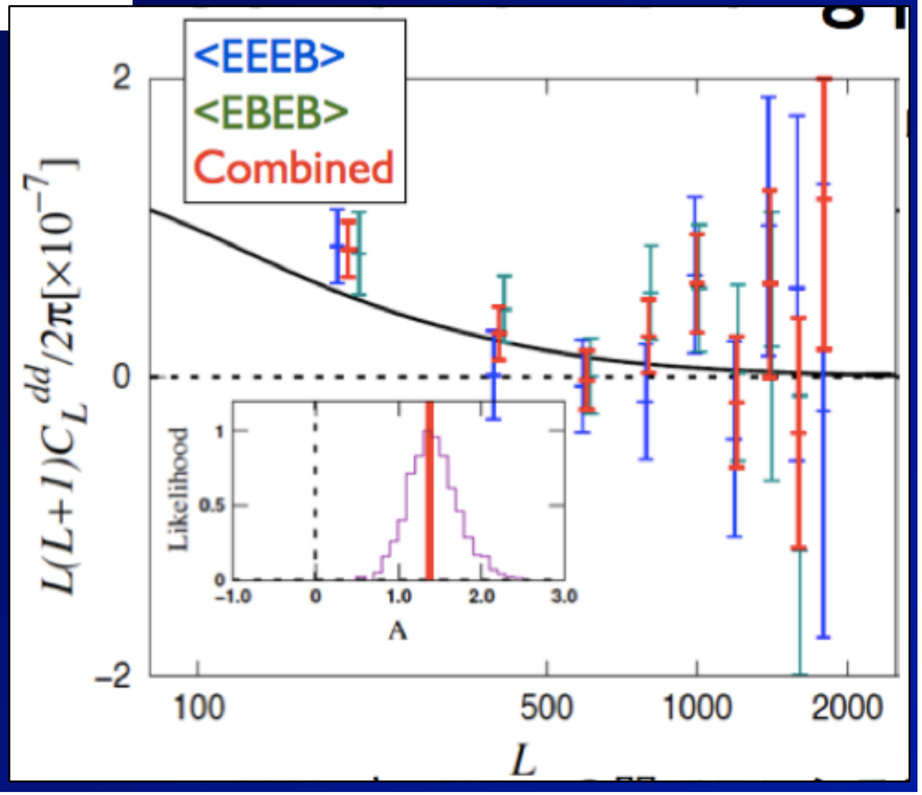
$$C_l^{dd} = <dx\, dx'^*>$$

Auto-correlation of the lensing deflection field. (4-point correlation)

The convention is to express the magnetite of lensing effect with A, where A=1 is ΛCDM with WMAP9.

A = 1.37 +/- 0.30 (stat.) +/- 0.13 (sys.)

- The results from <*EEEB*> and <*EBEB*> are consistent.
- Exclude no-lensing scenario with 4.2σ.
- The first results from the CMB data alone.

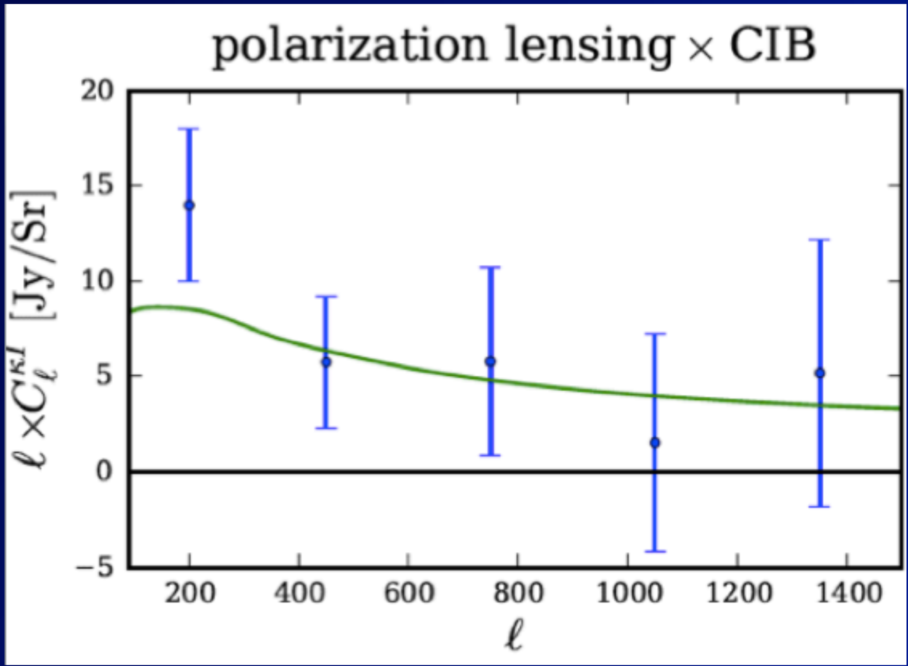


Cross correlation with CIB

arXive:1312.6645

C_l^{dl} = <dx CIB>

Cross-correlation of the lensing deflection field and Cosmic Infrared Background)



CIB in our patch is estimated from Herschel/ SPIRE (500μm).
CIB is a good tracer of the matter distribution at around z = 1〜3.

Exclude the null correlation.

- evidence for gravitational lensing of the CMB polarization at a statistical significance of 4.0σ.
- evidence for the presence of a lensing B-mode signal at a significance of 2.3σ.

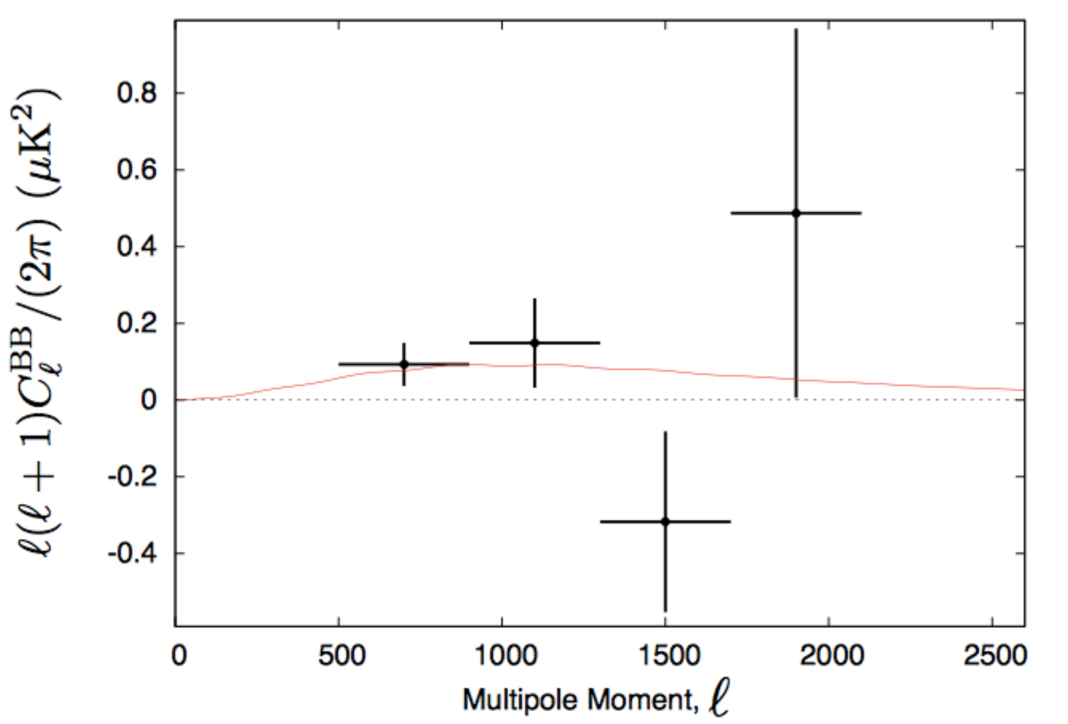
The result is consistent with ΛCDM and the result from SPTpol (Hanson et al, 2013) that is reportedly previously from this work.

CMB B-mode auto-correlation

arXiv:1403.2369

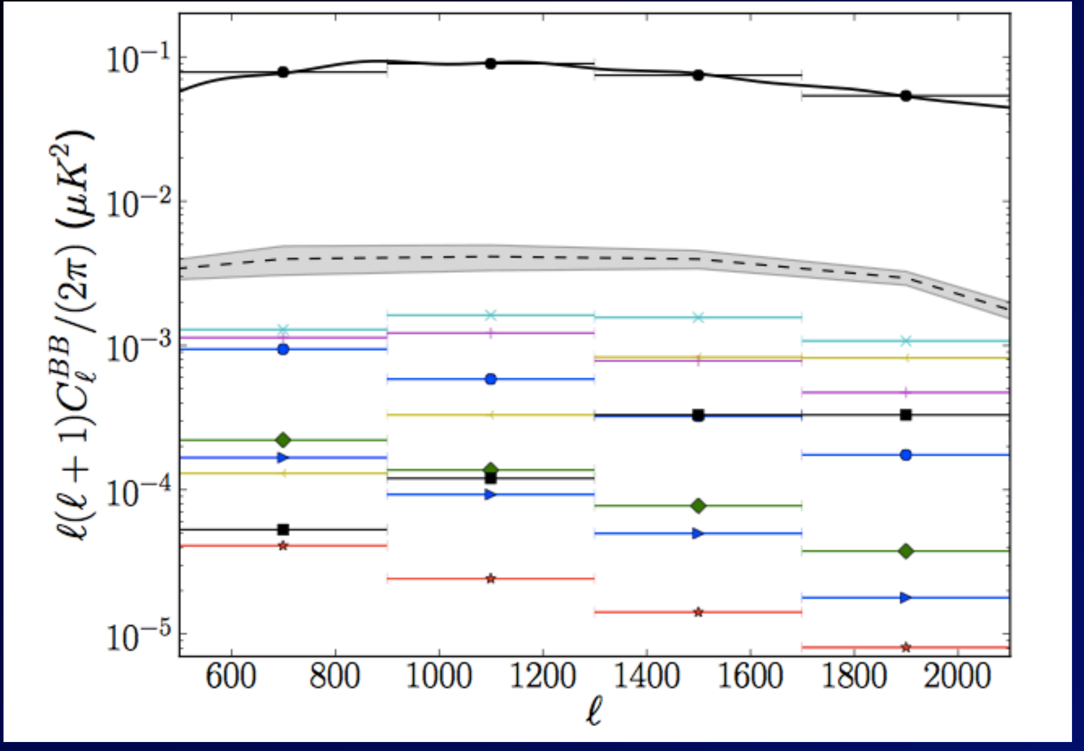
A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-Degree Scales with POLARBEAR

$$A_{BB} = 1.12 \pm 0.61(\mathrm{stat})^{+0.04}_{-0.10}(\mathrm{sys}) \pm 0.07(\mathrm{multi})$$



Systematic effect evaluations

Instrumental origin



Sources of the instrumental systematic effects

- Pointing direction
- Detector pair direction
- Polarization angle
- Beam shape
- Cross talk
- Gain

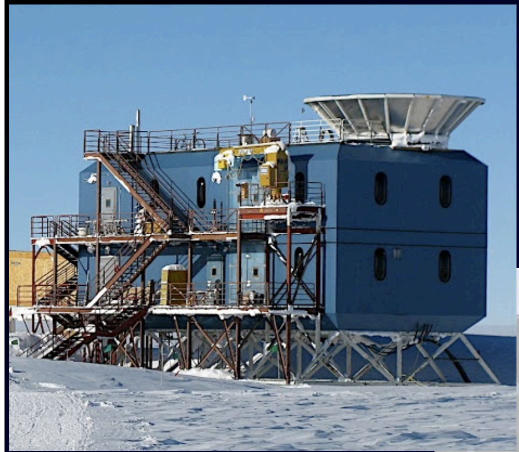
Foreground

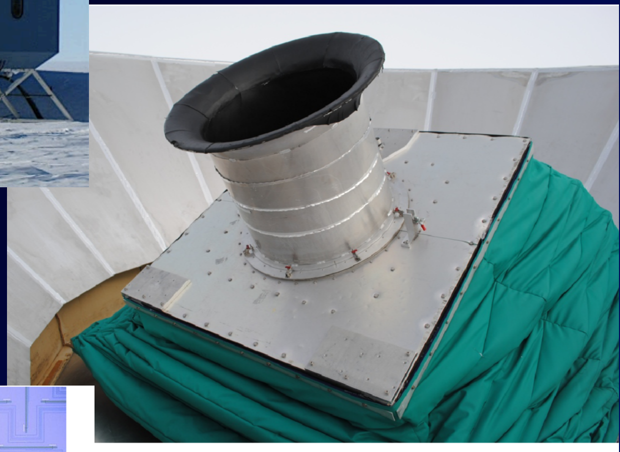
Foreground	Predicted power in $\ell(\ell+1)C_\ell^{BB}/2\pi$ (10^{-4} μK^2)			
	500-900	900-1300	1300-1700	1700-2100
Galactic dust	15	9.2	6.7	5.3
Galactic synchrotron	0.7	0.5	0.5	0.4
Radio galaxies	4.9	12	22	36
Dusty galaxies	2.8	4.5	6.5	8.7
Total bias	23	26	36	50

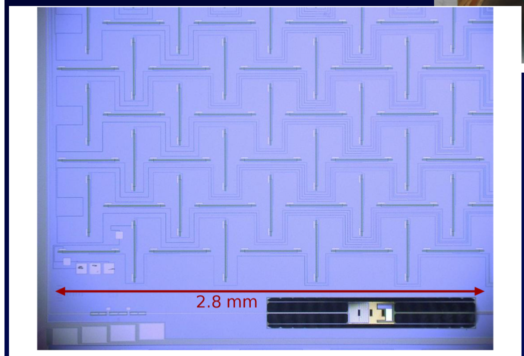
Recent report from BICEP2

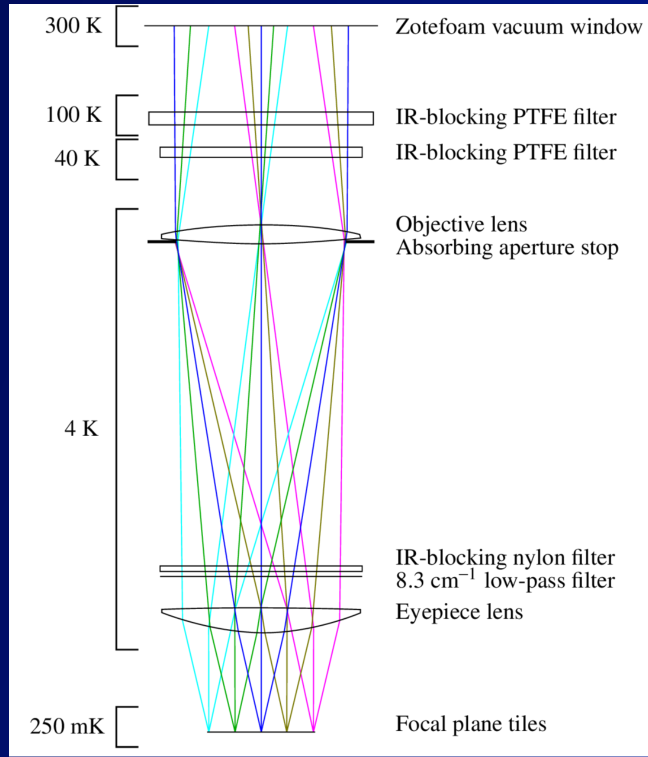
See more details in www.bicepkeck.org

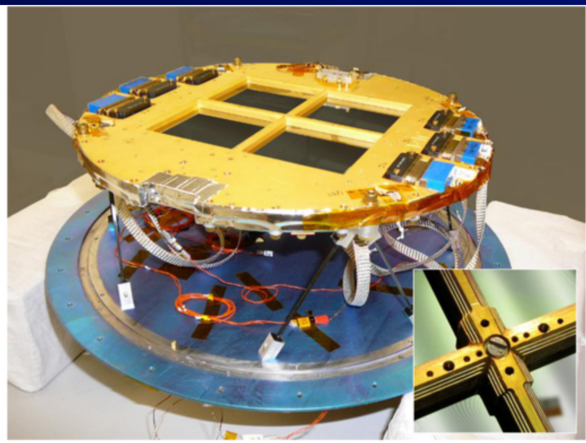
Brief overview

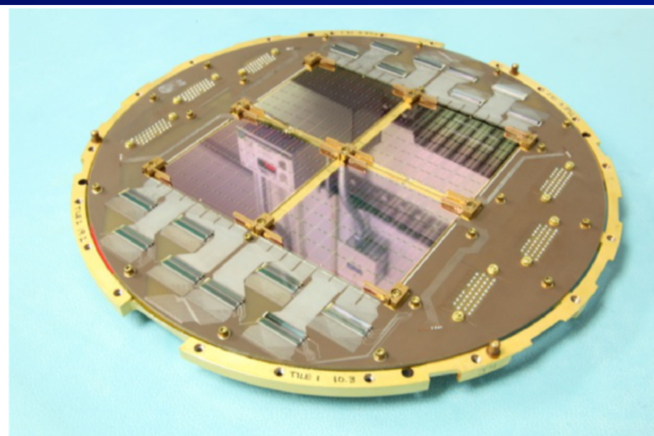




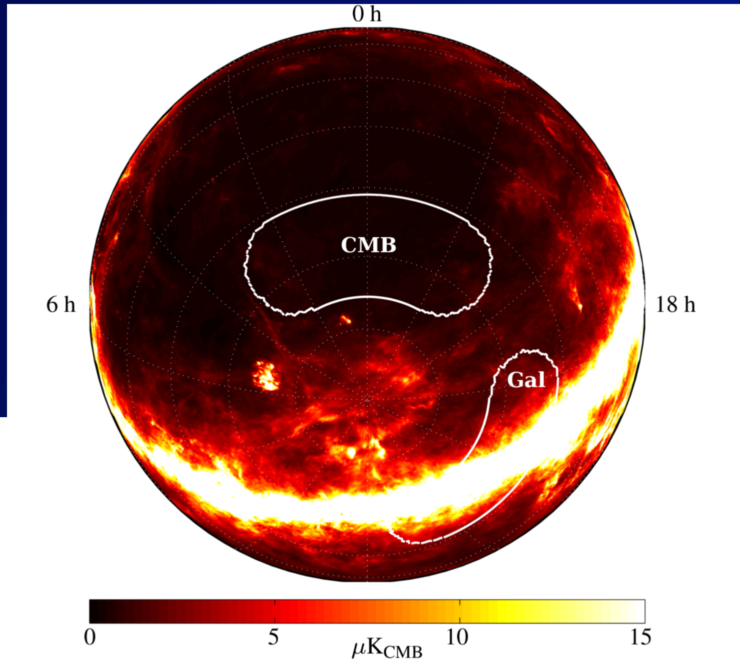


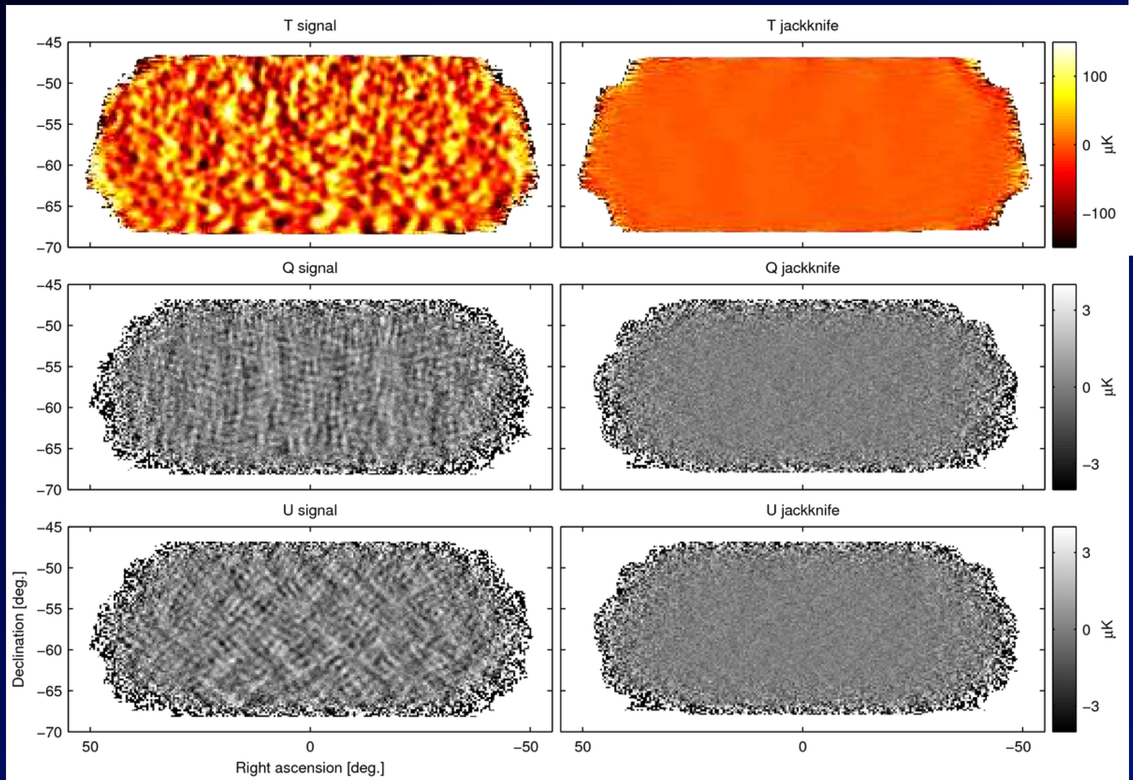




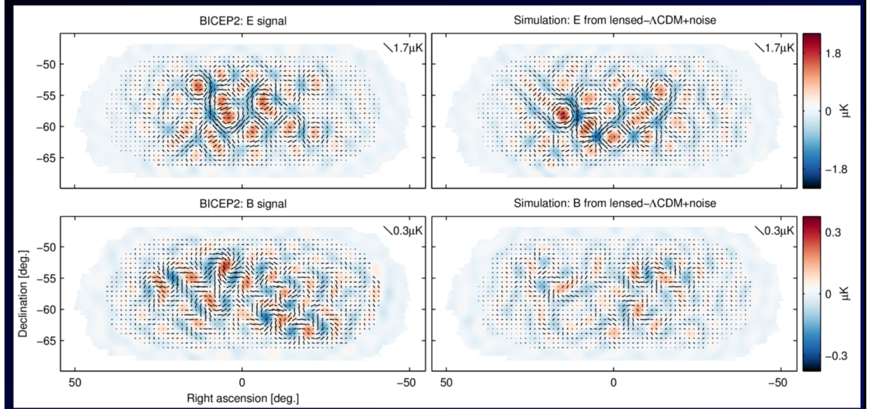


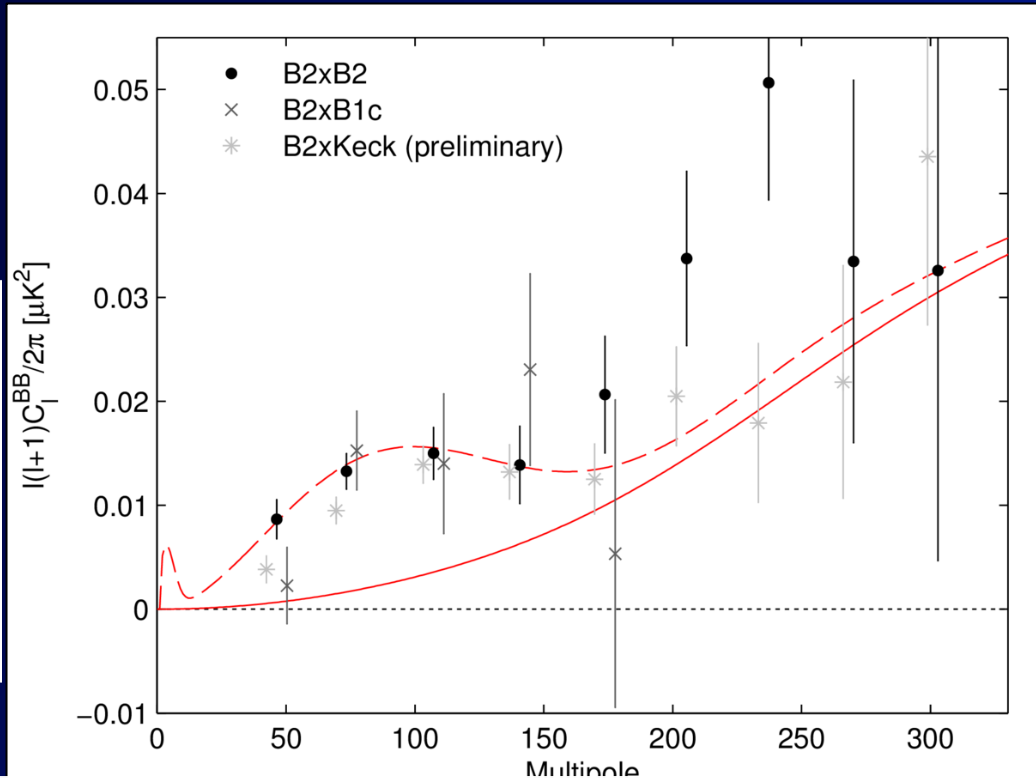
Map

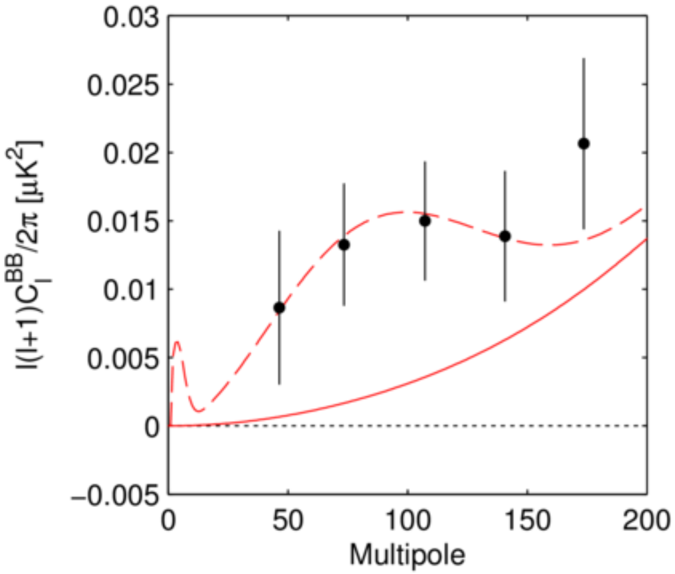

0 h
6 h
18 h
CMB
Gal
0
5
10
15
μK_{CMB}

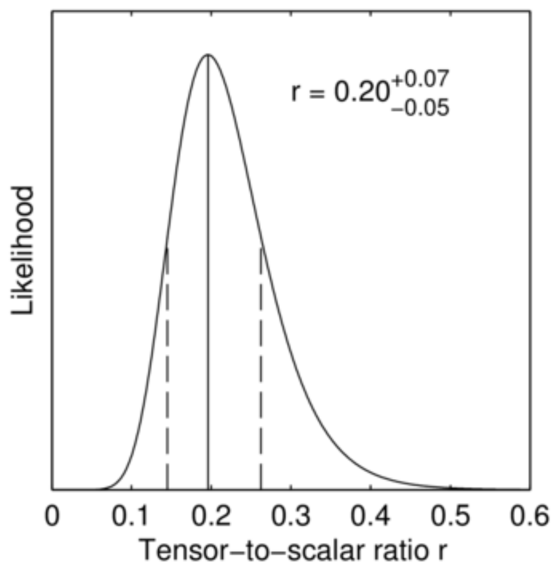

T signal
T jackknife
Q signal
Q jackknife
U signal
U jackknife
−45
−50
−55
−60
−65
−70
100
0
−100
3
−3
μK
Declination [deg.]
50
0
−50
Right ascension [deg.]

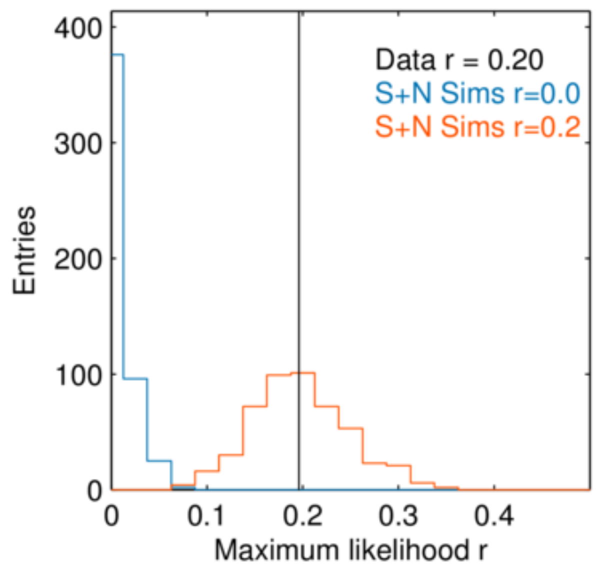
Map and power spectrum



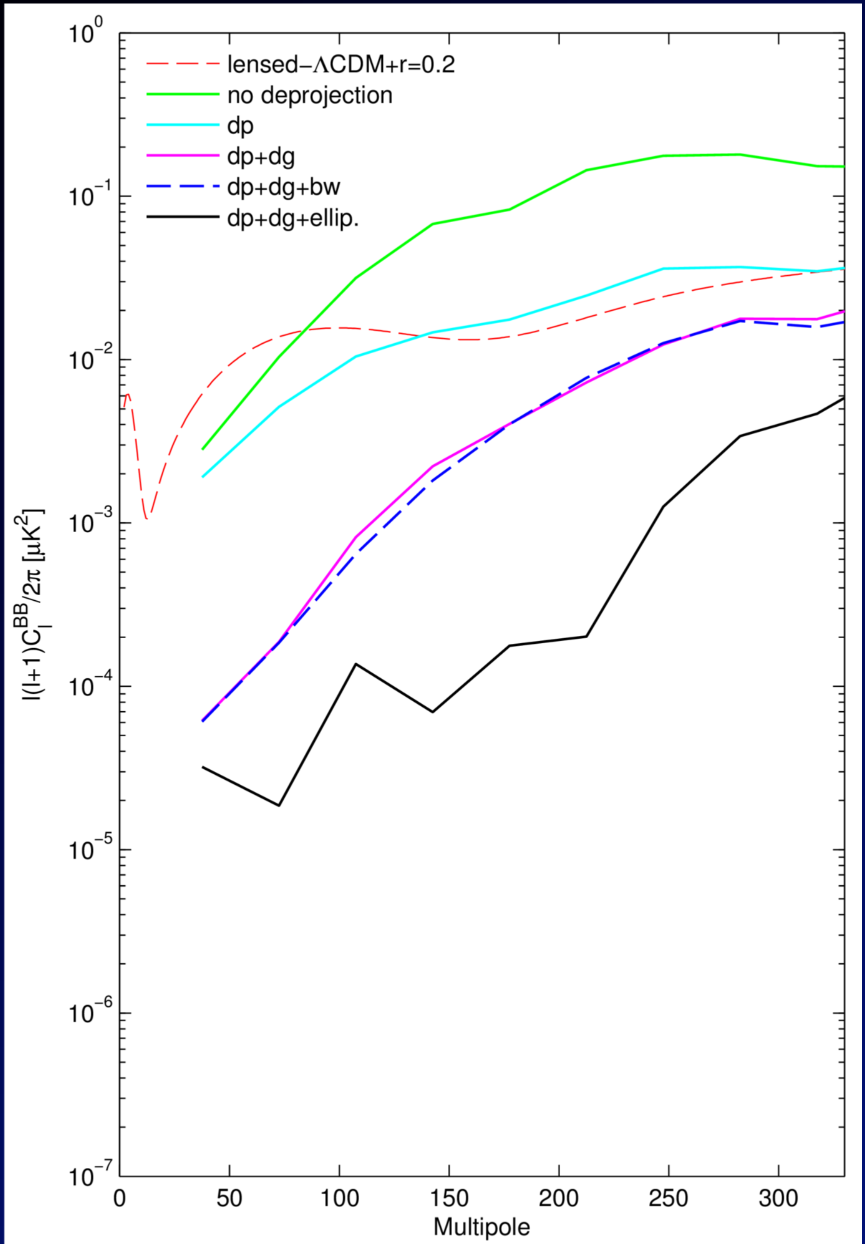


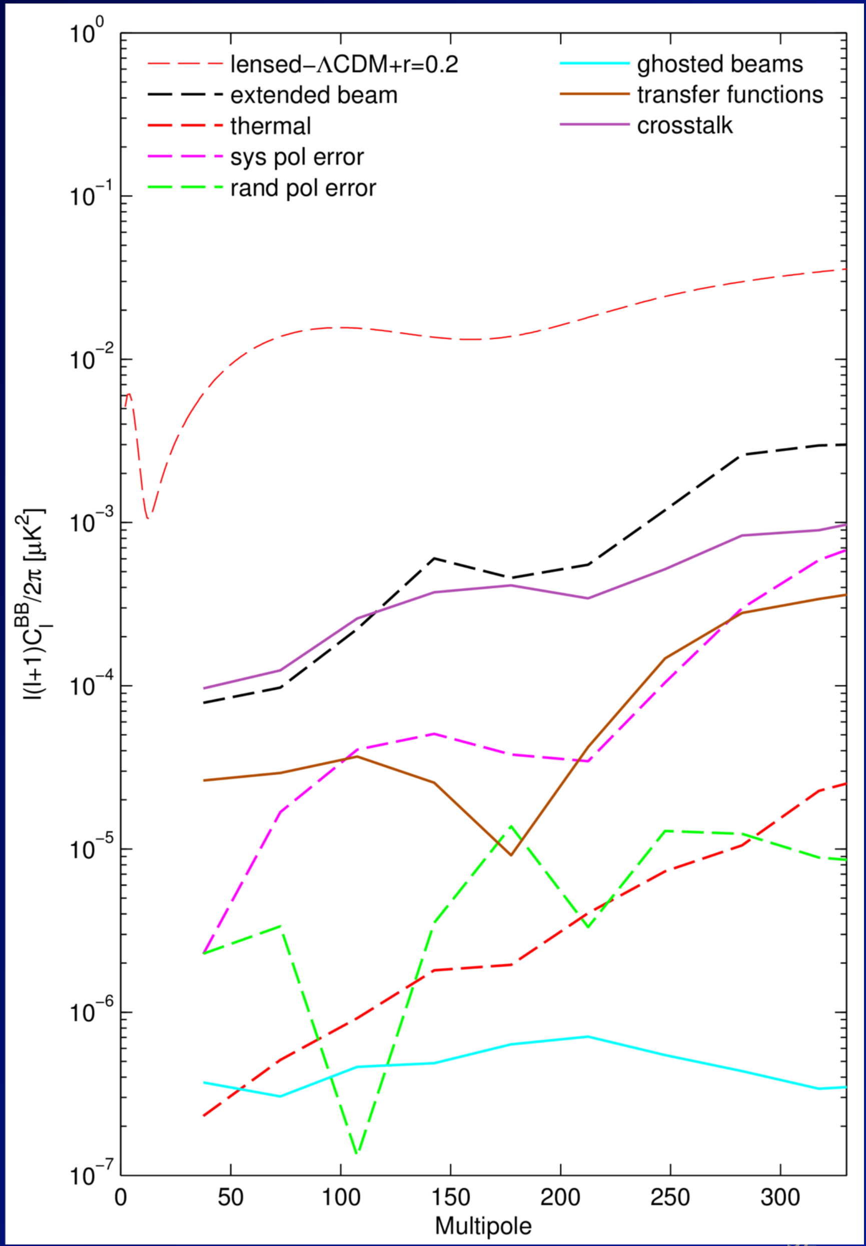




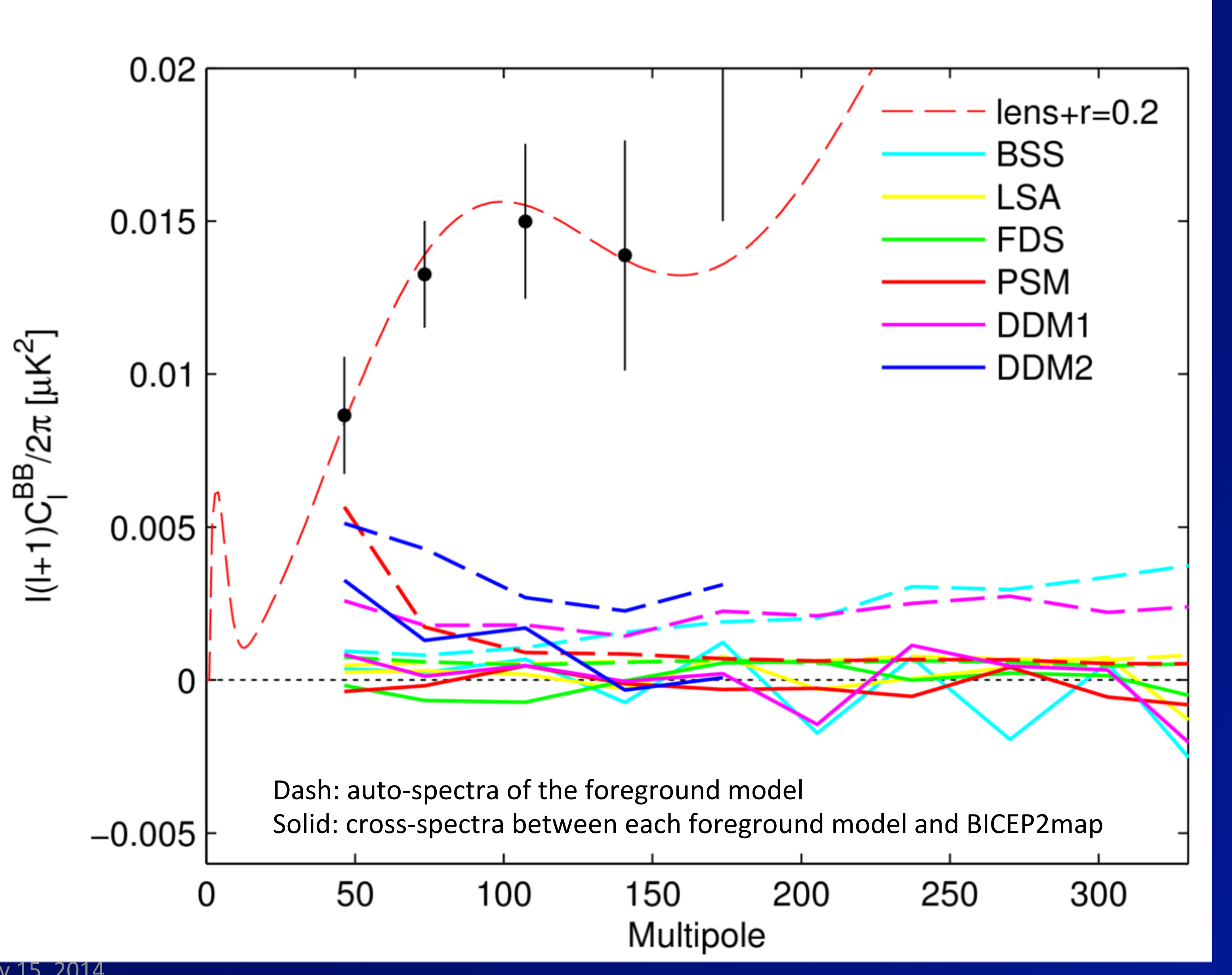


Systematic effects

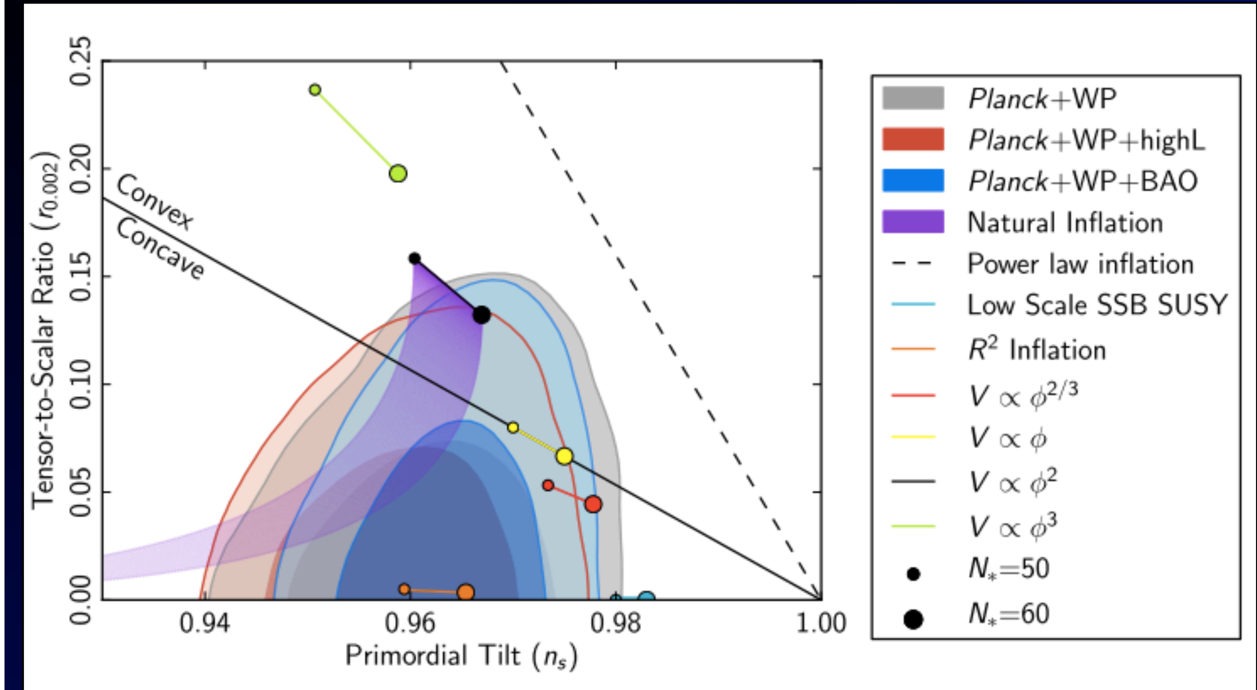




Foregrounds



Cosmological implications

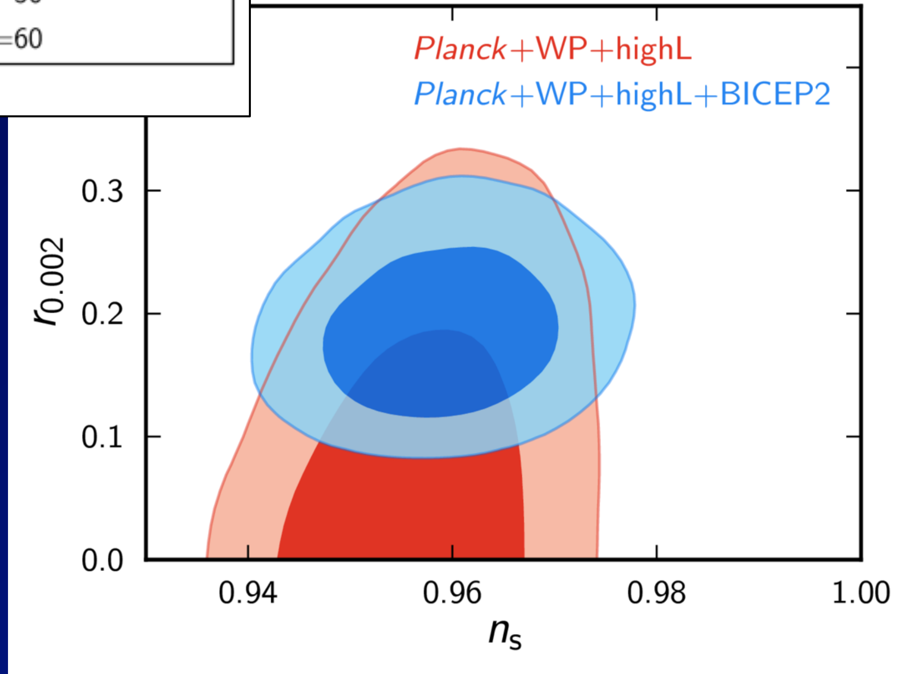


From Planck2013 results I

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1+\frac{1}{2}\, dn_s/d\ln k \ln(k/k_*)+\frac{1}{6}\, d^2n_s/d\ln k^2(\ln(k/k_*))^2+\ldots}$$

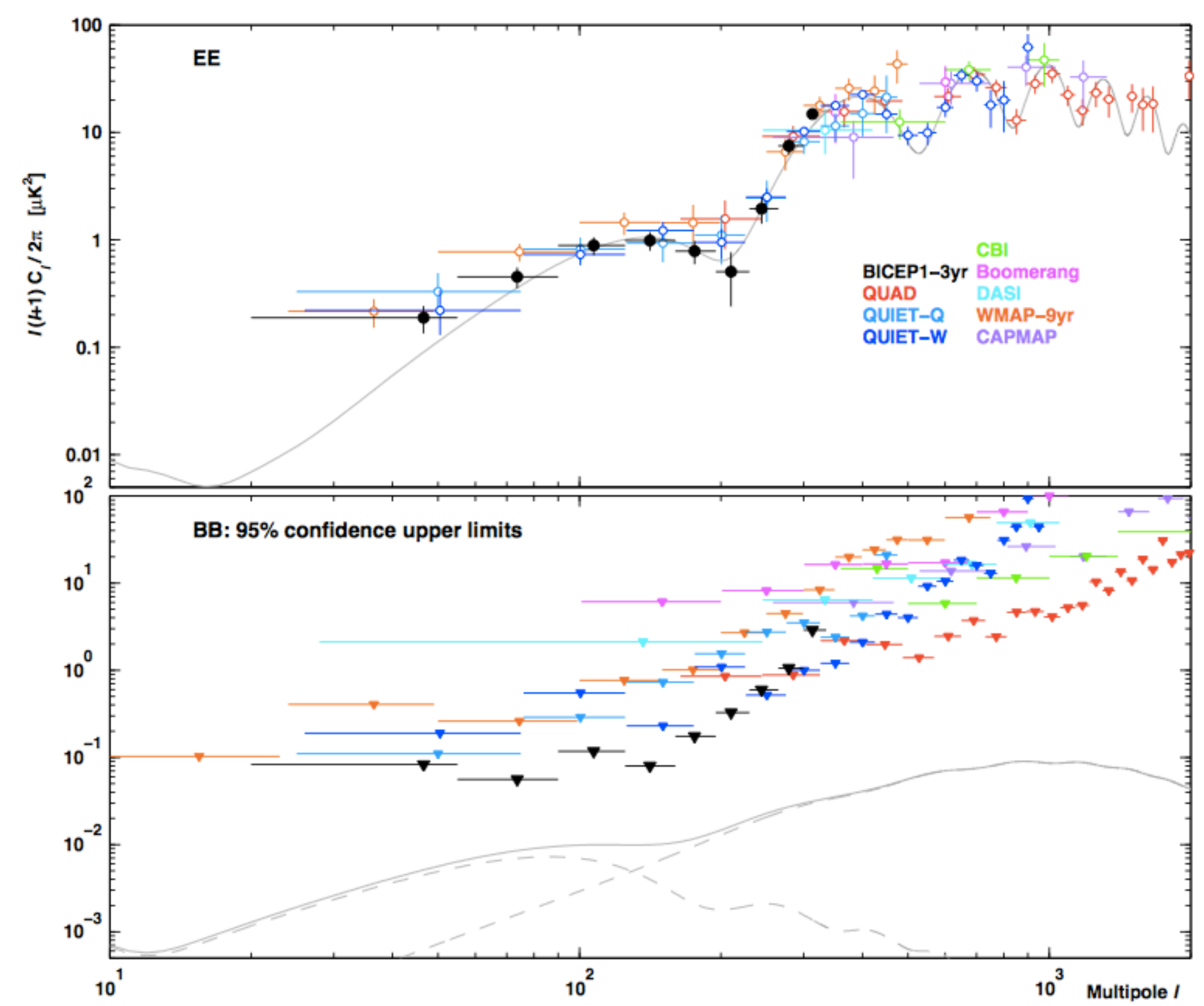
$$\mathcal{P}_t(k) = A_t \left(\frac{k}{k_*}\right)^{n_t+\frac{1}{2}\, dn_t/d\ln k \ln(k/k_*)+\ldots},$$

From Planck2013 results XXII



From BICEP2

Reminder: status of the B-mode hunting in 2013



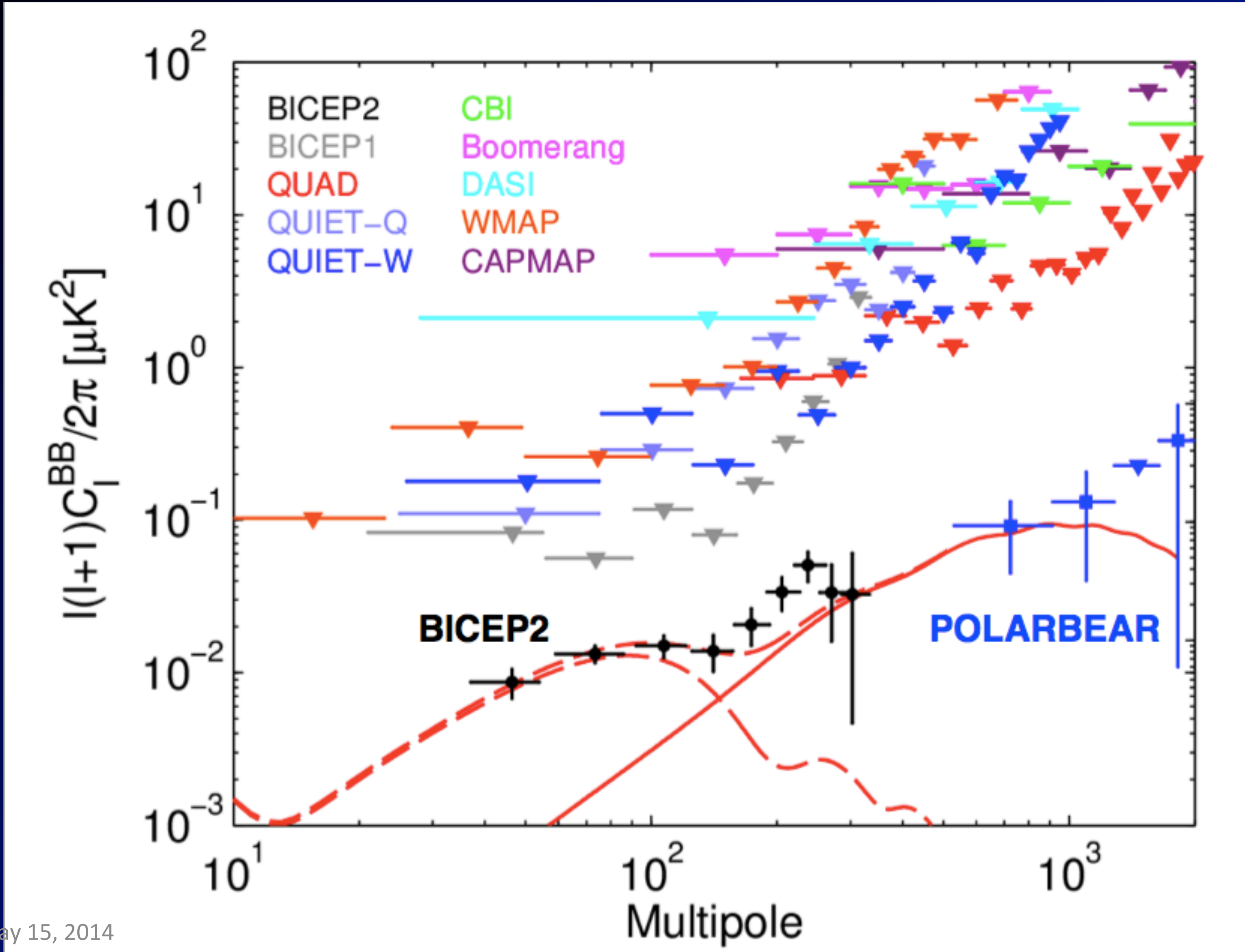
BICEP-I three year data Barkats et al. (2013)

Limit from the temperature fluctuation Planck+WMAP+high$l$
r <0.11 (95%C.L.)

Limit from the polarization BICEP-I three year data, r <0.70. Barkats et al. (2013)

Community wide effort/ race to detect this B-mode first!

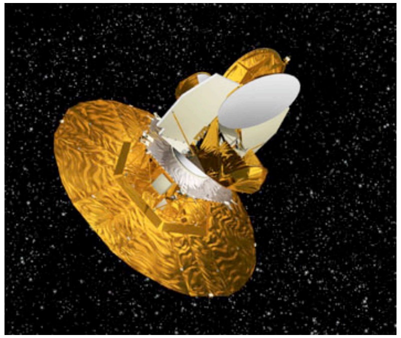
After the POLARBEAR and BICEP2



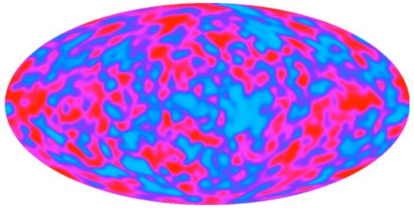
Summary so far

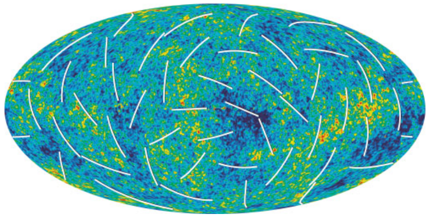
- The results from POLARBEAR
  - Consistent with ΛCDM cosmology. Continue the observations for higher sensitivity and probe the physics of the summ of the neutrino mass and dark energy.
- The results from BICEP2
  - Big surprise!
  - Tension in the reported r and the r limit from temperature anisotropy using Planck and other experiments.
  - The deviation from the ΛCDM above $l > 200$.
  - Further observations using multi-color and wider sky region are awaited.
- Anyhow…
  - We enter the new era of observational cosmology using the CMB B-mode polarization.

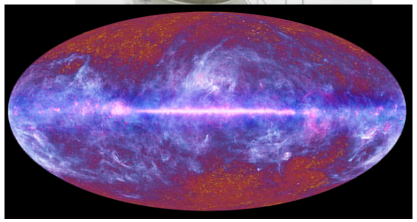
CMB satellites



Next generation
CMB satellite

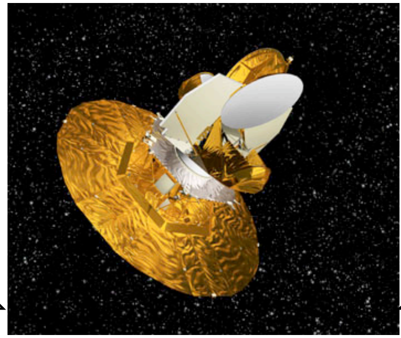




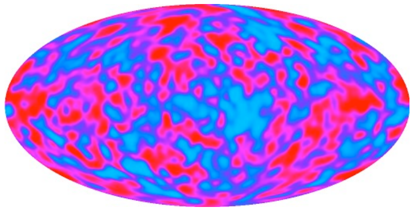


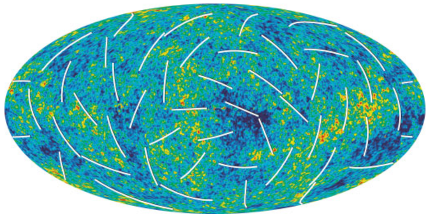
COBE (1989)	**WMAP (2001)**	**Planck (2009)**
Band		
32–90GHz	23–94GHz	30–857GHz（353GHz）
Detectors		
6 radiometers	20 radiometers	11 radiometers + 52 bolometers
Operation temperature		
300/140 K	90 K	100 mK
Angular Resolutino		
~7°	~0.22°	~0.1°
Orbit		
Sun Synch	L2	L2

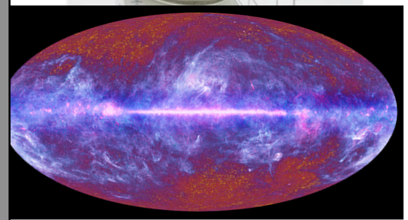
CMB satellites



Next generation CMB satellite







COBE (1989)

Band
32–9

Dete
6 rad

Oper
300/

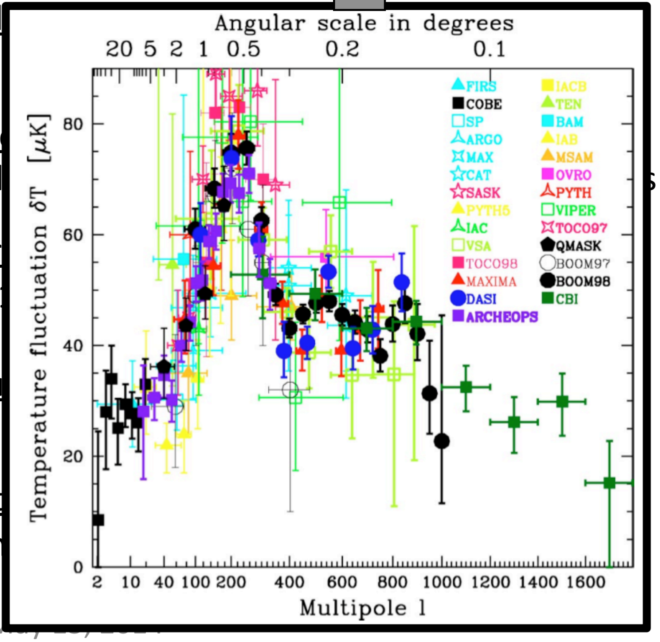
Angu
~7°

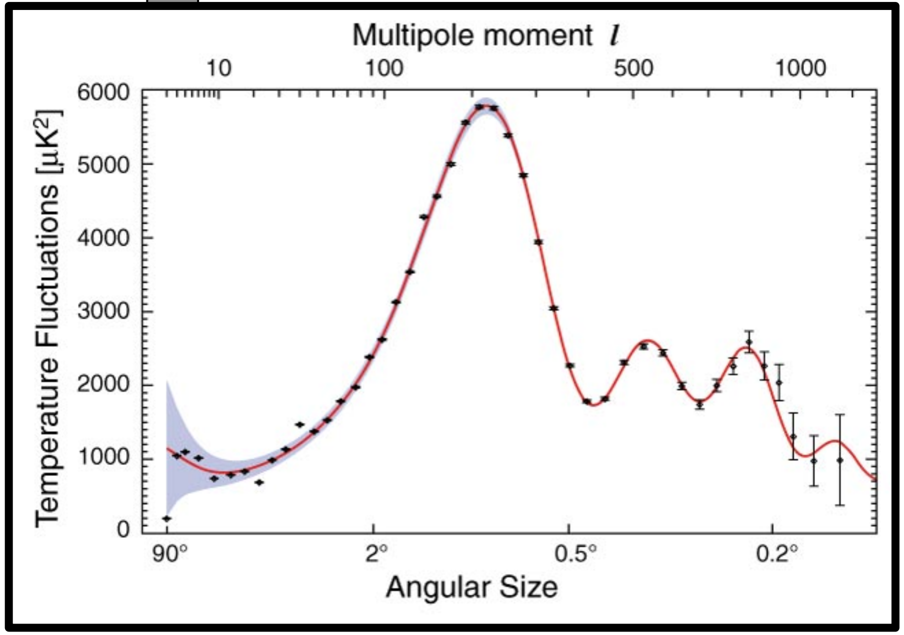
Orbit
Sun

WMAP (2001)

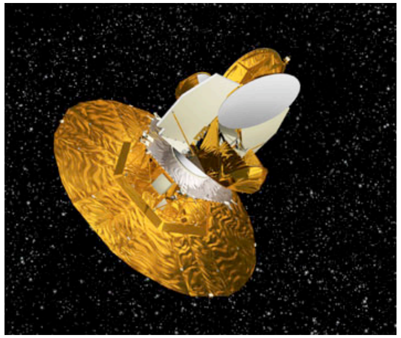
s

Planck (2009)

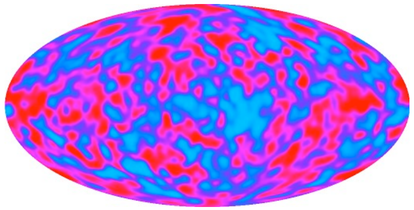


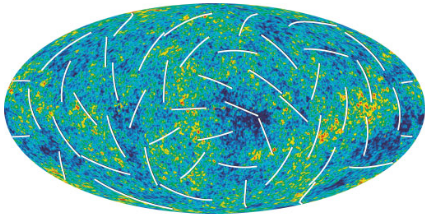


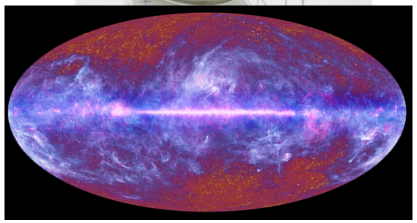
CMB satellites



Next generation CMB satellite



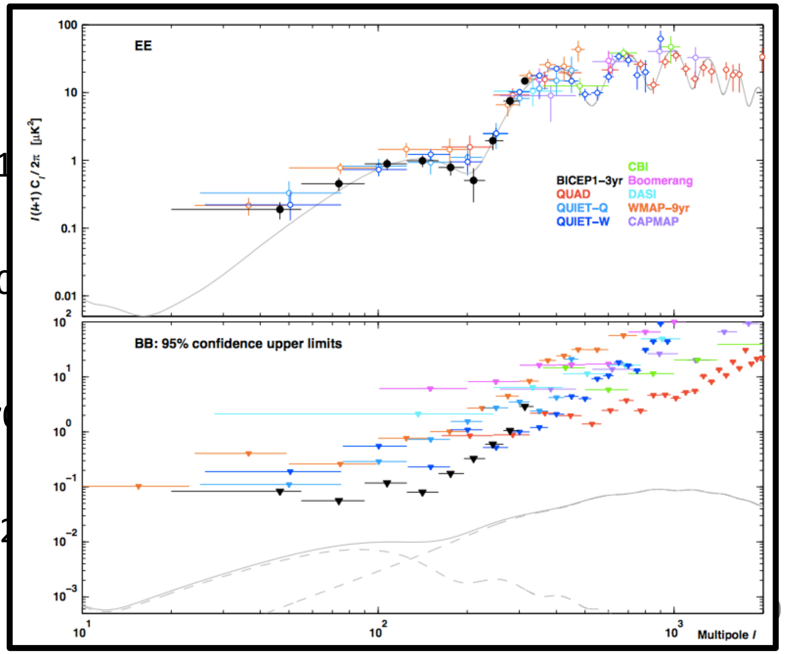




	COBE (1989)	**WMAP (2001)**	**Planck (2009)**
Band	32–90GHz	23–94GHz	
Detectors	6 radiometers	20 radiometers	1
Operation temperature	300/140 K	90 K	10
Angular Resolutino	~7°	~0.22°	~(
Orbit	Sun Synch	L2	L2

EE

BB



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Archive > Volume 509 > Issue 7500 > News Feature > Article

NATURE | NEWS FEATURE

Cosmology: First light

The left-over radiation from the Big Bang has given up what may be its last great secret about the early Universe, but astronomers are determined to mine more from this primordial prize.

Joanne Baker

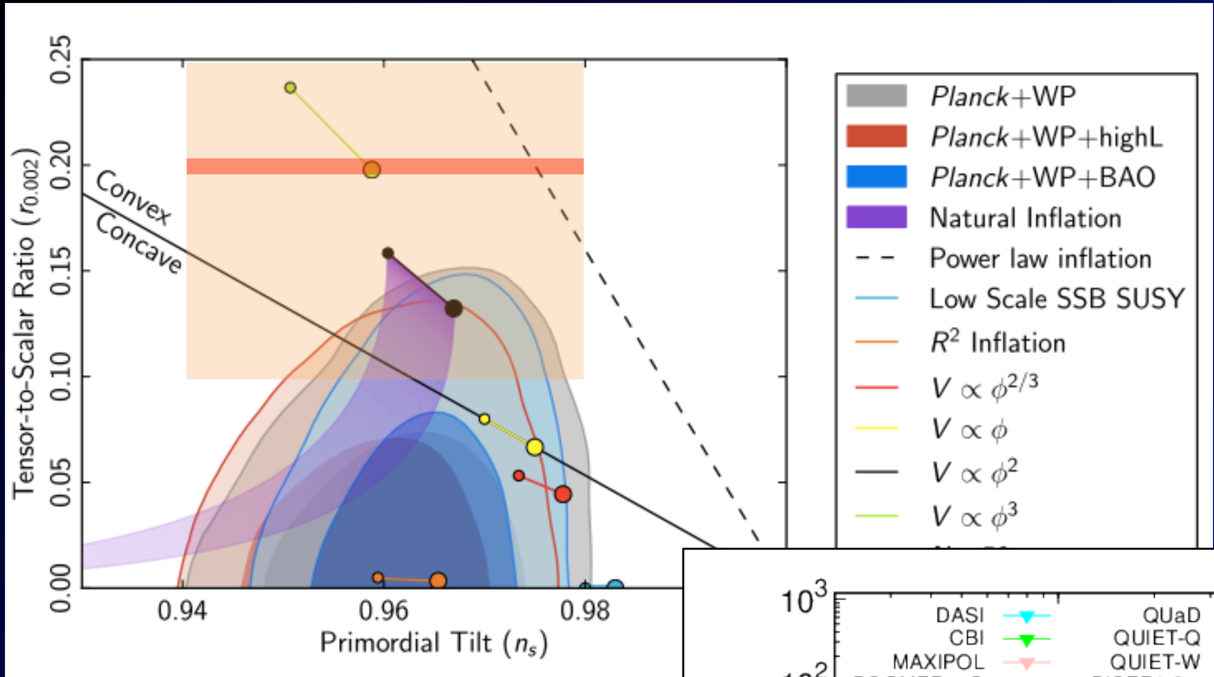
14 May 2014

Top Story

But such complicated proposals are expensive and difficult to realize, Efstathiou says. 'Keep it simple' is now his mantra. He would like to see a small mission dedicated to observing B modes on large angular scales, thus targeting the gravitational-wave signature alone. In effect, it would be a BICEP2 experiment in space, says Peter Ade at Cardiff University, UK, who has built detectors for ground-based experiments and Planck. The technology is mature and he thinks such a mission could be ready in five years.

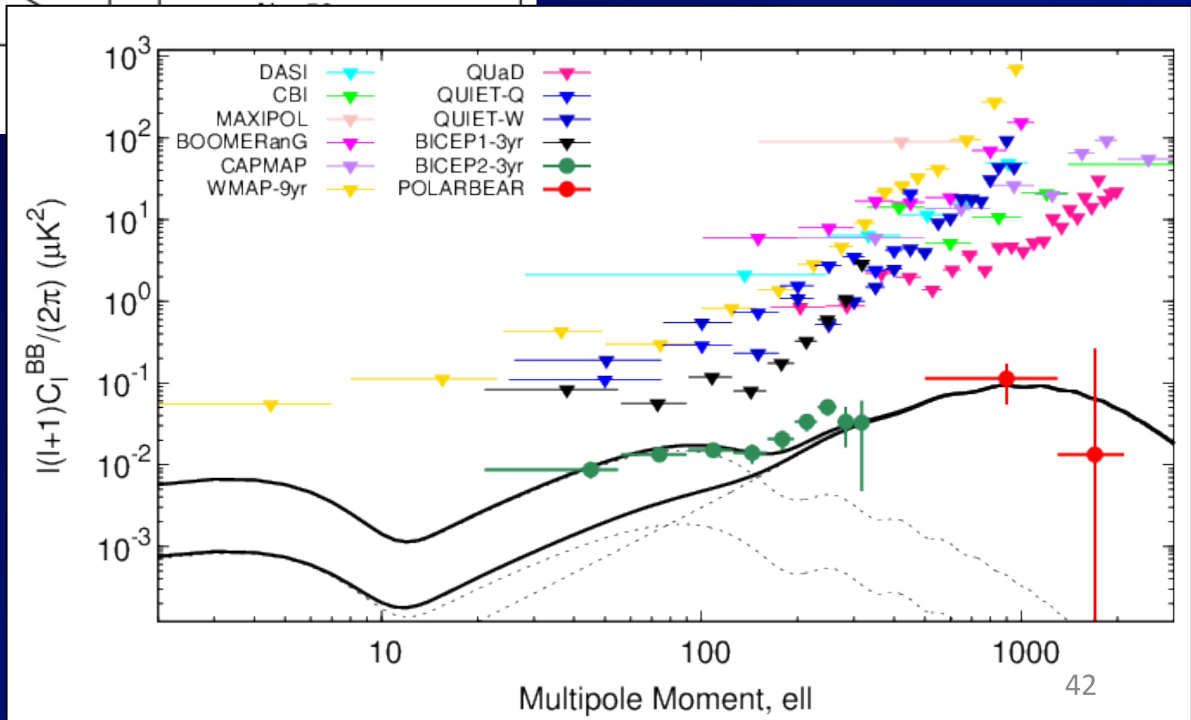
A Japanese-led satellite proposal called LiteBIRD could be just such a mission. Proposed by physicists in Japan, in collaboration with experimenters in the United States, Germany and Canada, the project could be launched in the early 2020s if it received some US$100 million in funding. In the meantime, the researchers are developing a ground-based experimental version, called GroundBIRD.

What's the role for upcoming exp?

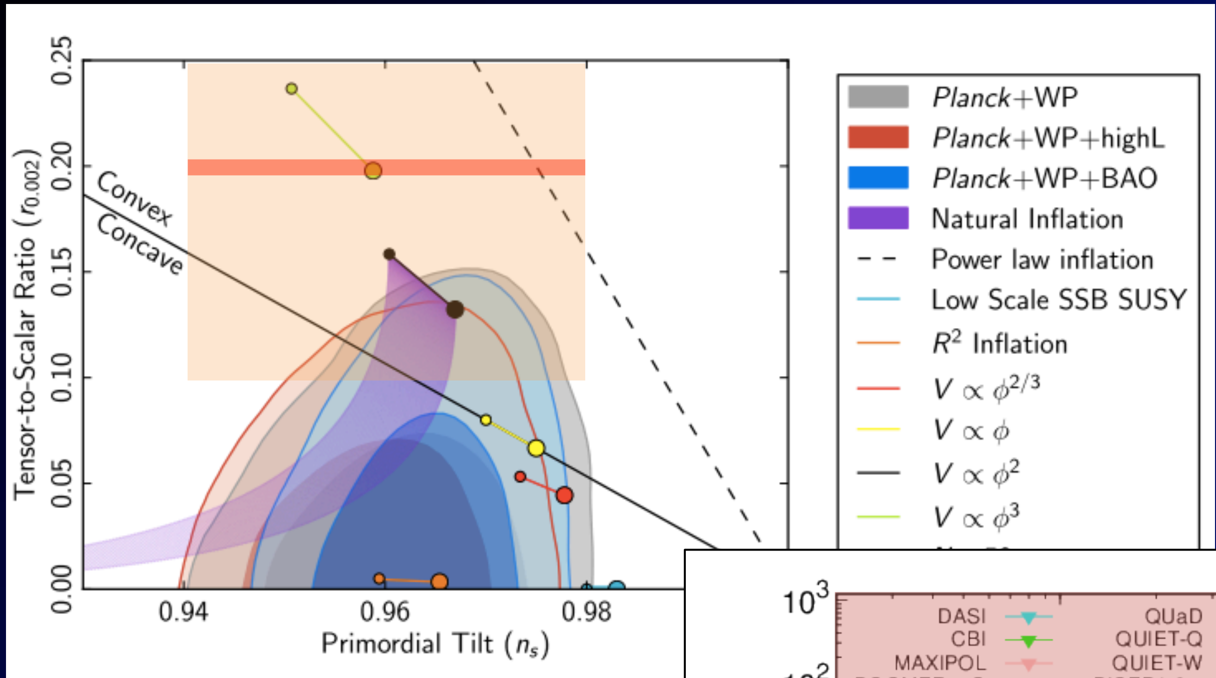


A next few years would be tremendously important for verifications from the ground and balloon.

The obs. from the ground has access to the limited sky area. Need a full sky? A satellite is the way to go.



What's the role for upcoming exp?



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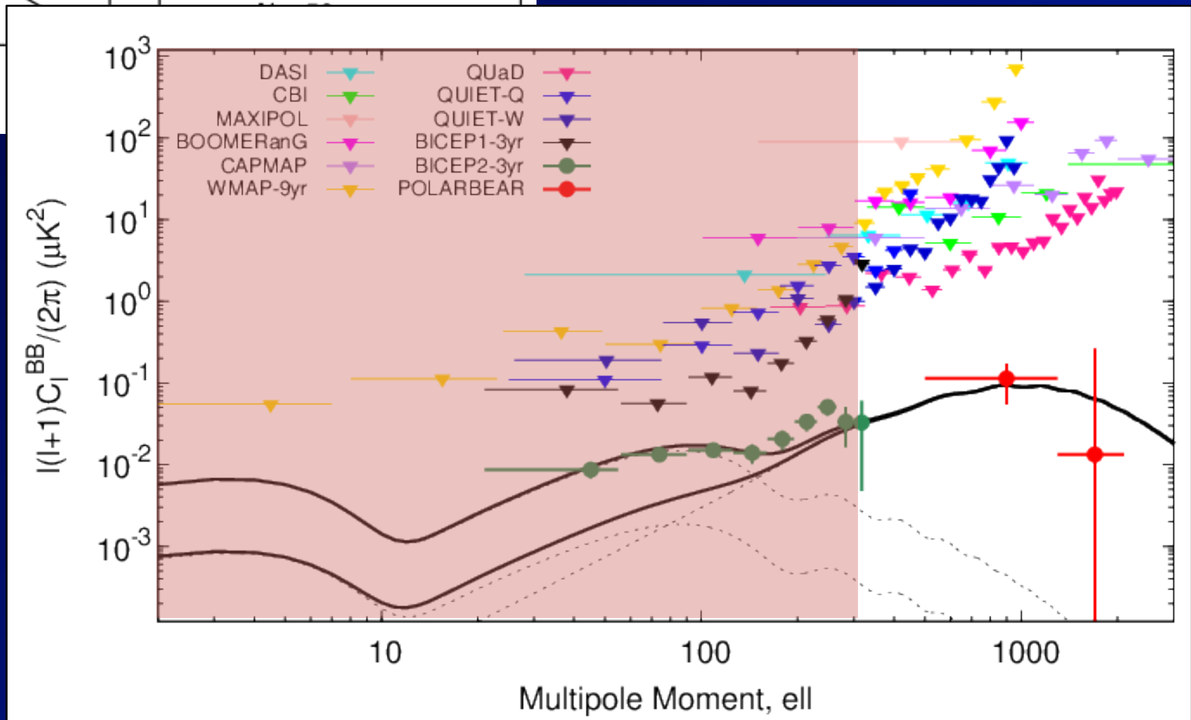


LiteBIRD is a small satellite mission that probes the inflationary B-mode with a sensitivity of δr =0.001.
If r =0.2, LiteBIRD can determine a few % accuracy, i.e. pinpoint the inflation model.
Precision cosmology!

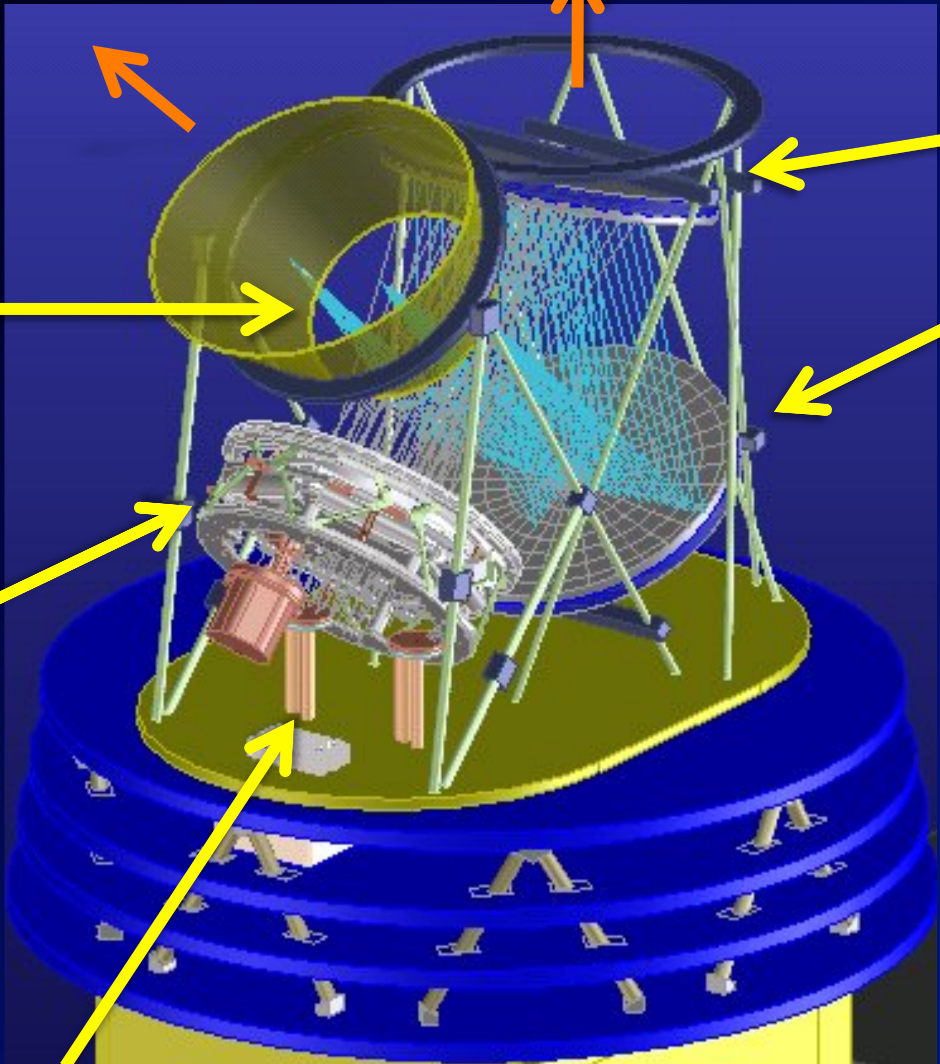
The science goal of LiteBIRD

The science goal of LiteBIRD is to test the well motivated inflationary models with the sensitivity of $\delta r < 0.001$.

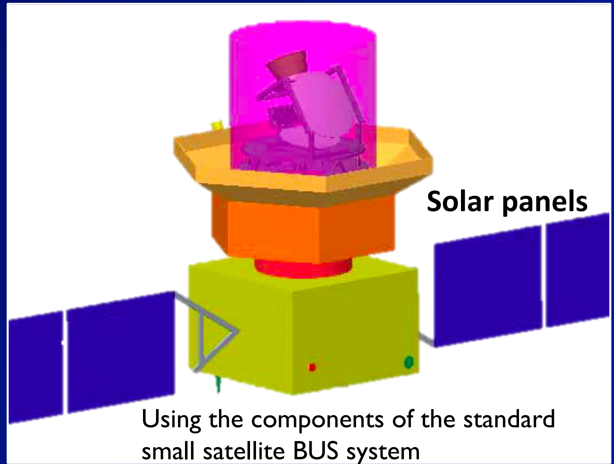
Instrumental specifications

- **Frequency coverage 60-270 GHz**
  - **→ multi-color observations without using external data**
- **Angular resolution: 30 arcmin（@150GHz）**
  - **→ < 1 m telescope**
- **Sensitivity: 2 uK・arcmin**
  - **→ kilo pixel superconducting detector array**
- **All sky survey**
  - **→ spin type scanning strategy**

LiteBIRD overview

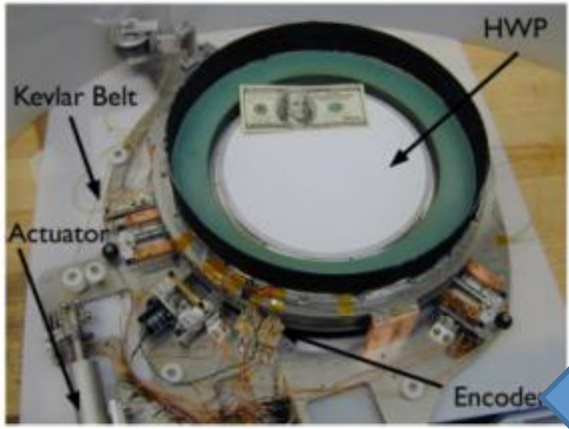


Warm launch with the cryogenic system developed for Astro-H.



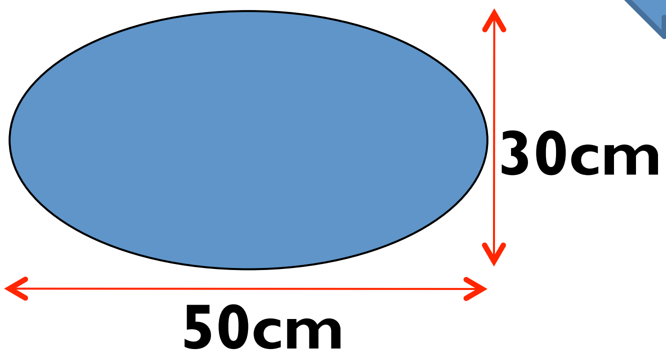
Optics

Half-wave plate

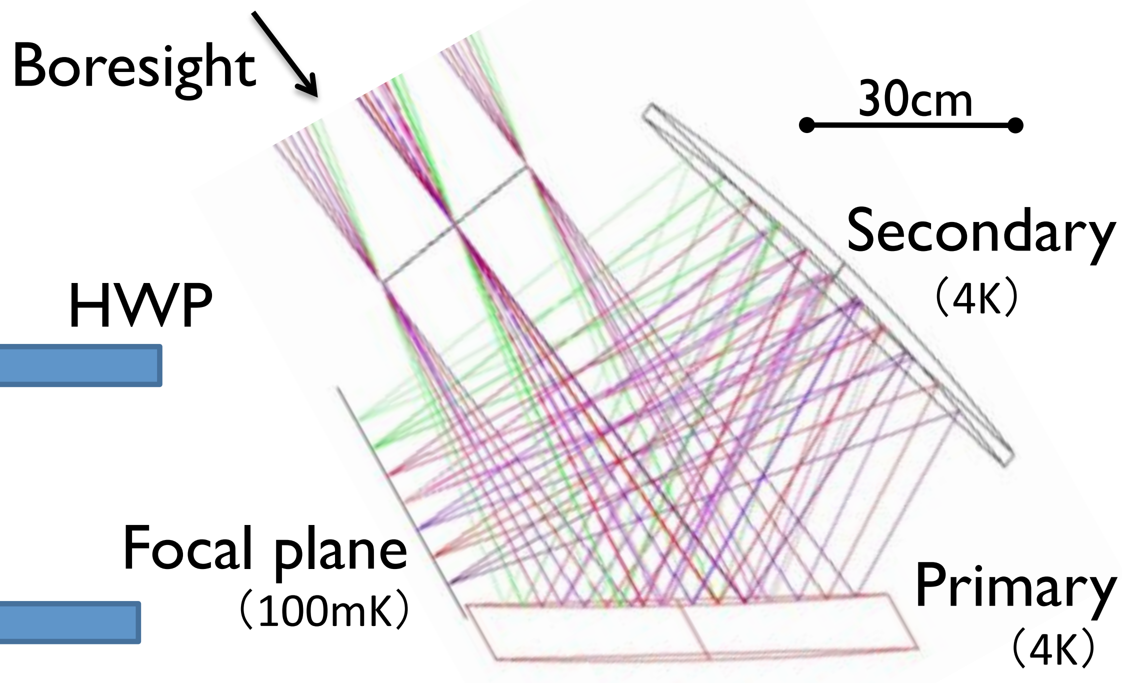


High TRL by the use in the balloon-borne CMB experiment, EBEX

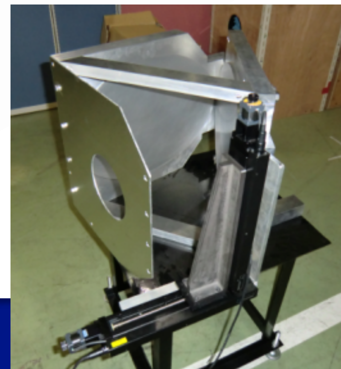
Available focal plane size



Cross Dragone telescope



Prototype beam test

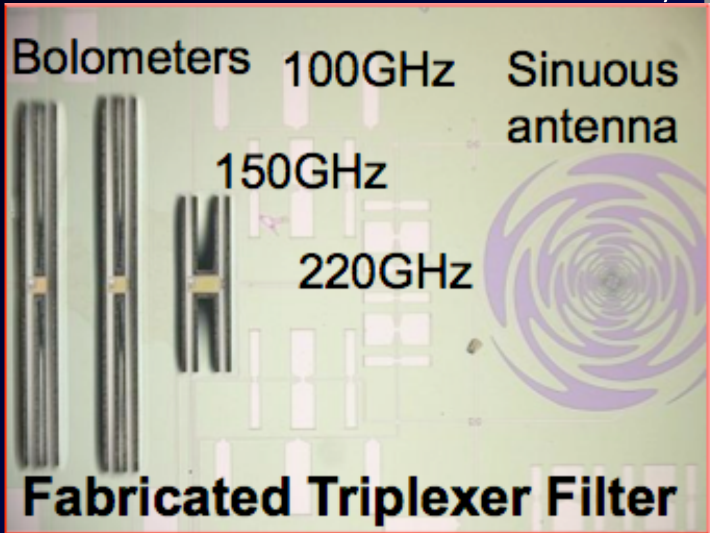


Detector option

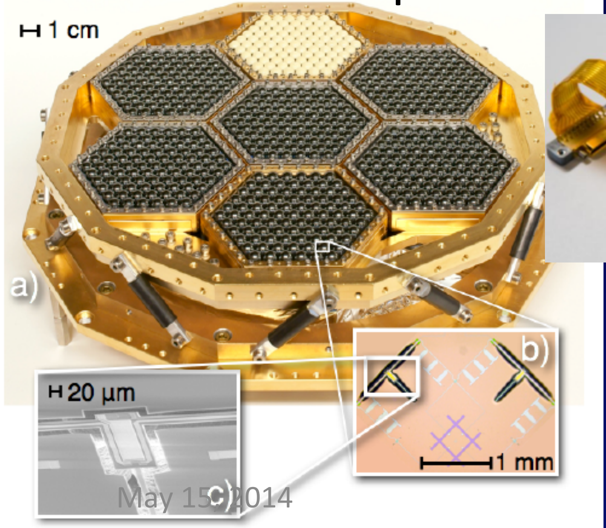
TES option

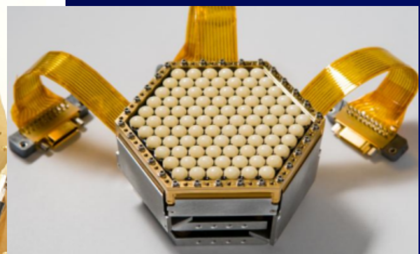
- **High TRL by use of the ongoing CMB experiments**

From UCBerkeley



POLARBEAR1 focal plane

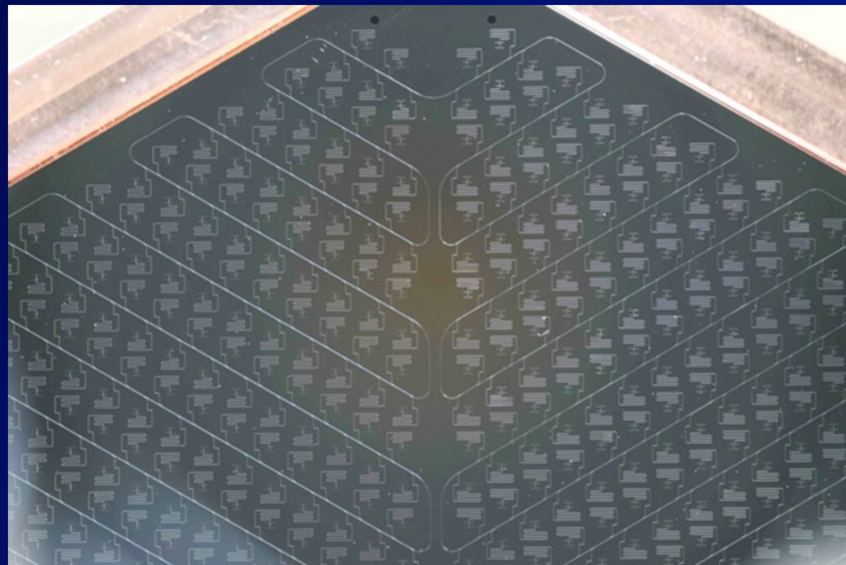


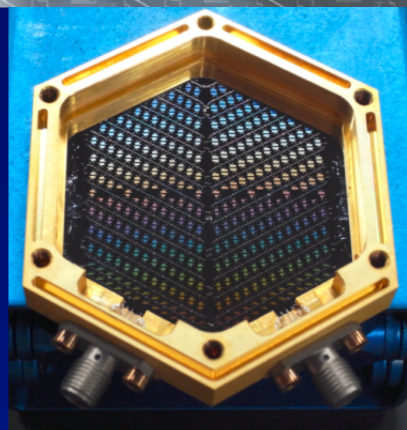


MKID option

- Higher mux factor
- Larger dynamic range

600 MKID sensor（@ 220GHz）





From NAOJ

Development is underway with the collaboration of KEK, NAOJ, Okayama, Riken

Foreground removal and observing bands

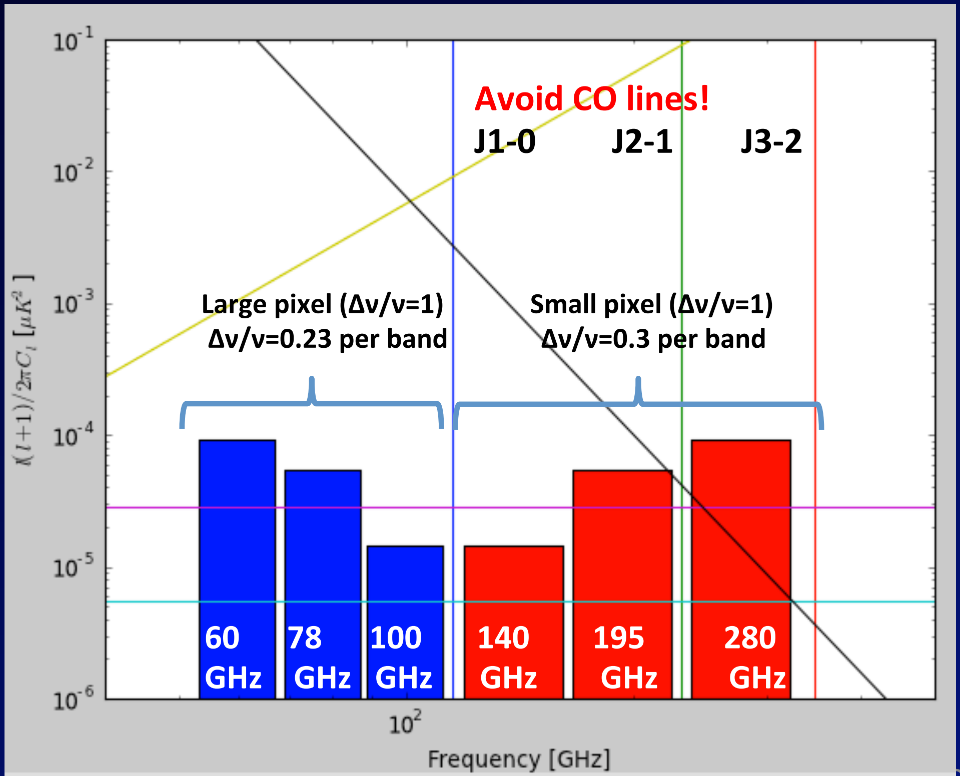
According to N. Katayama and E. Komatsu,

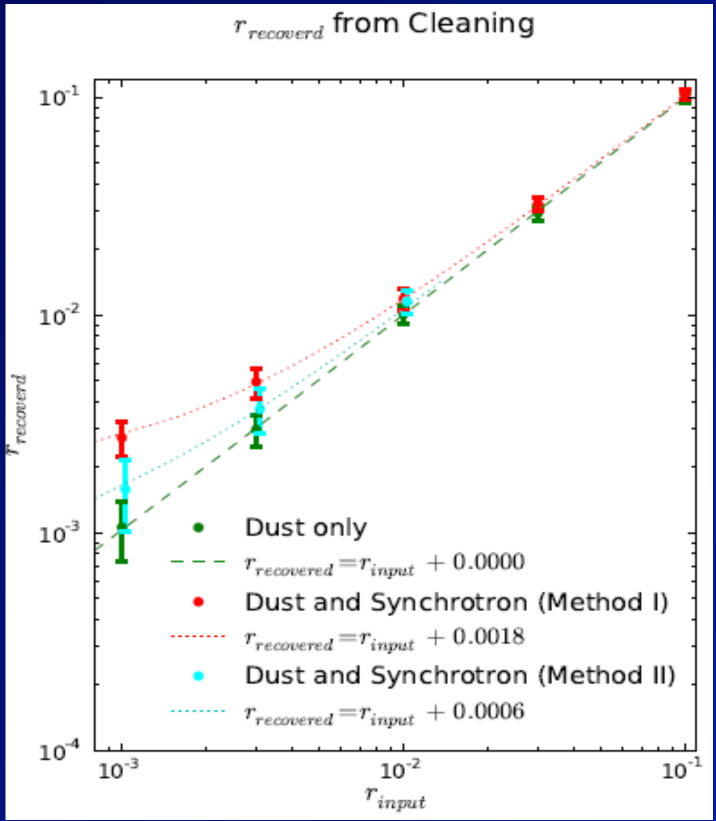
(ApJ 737, 78 (2011), arXiv:1101.5210),

the pixel-based polarized foreground removal using template method (model independent) indicates that we need

→ ≥ 5 bands in 50-270GHz

The subtraction of the dust and synchrotron emissions with the three bands (60, 100, 240 GHz) was demonstrated with very small bias, r~0.0006.

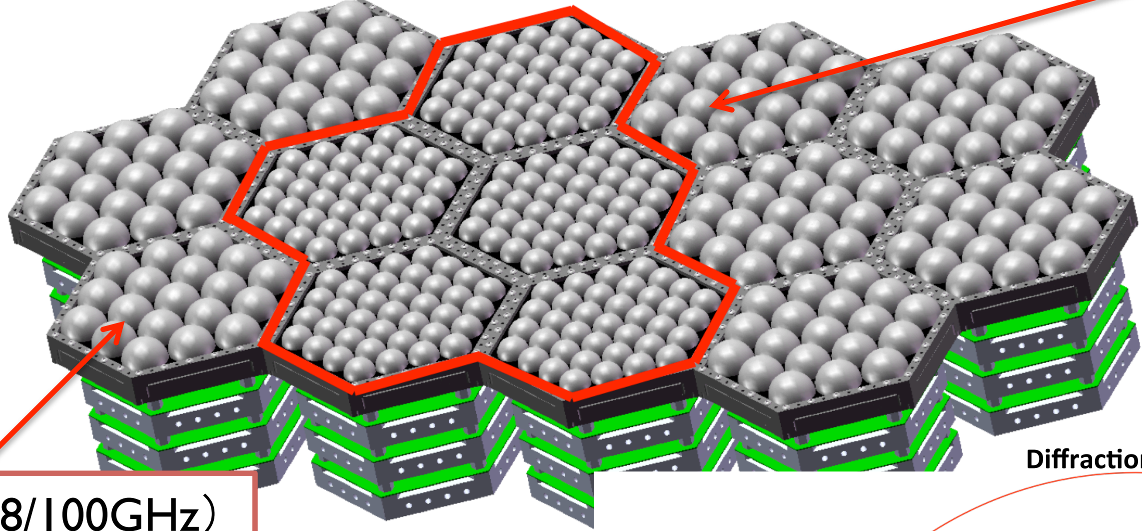




Focal plane design

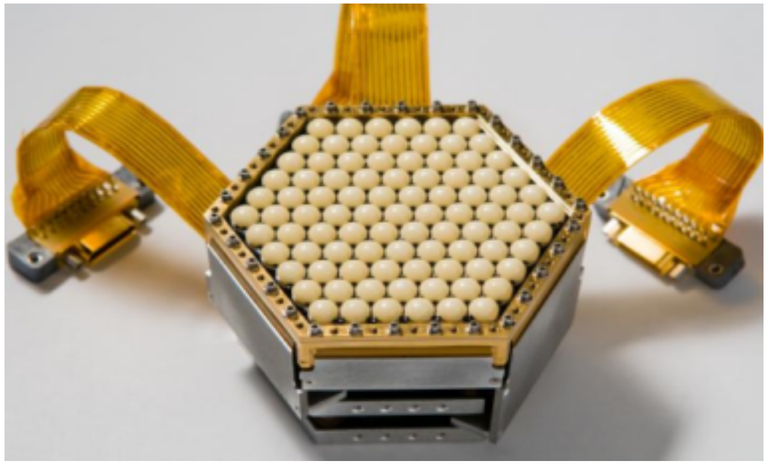
tri-chroic (140/195/280GHz)

UC Berkeley TES option

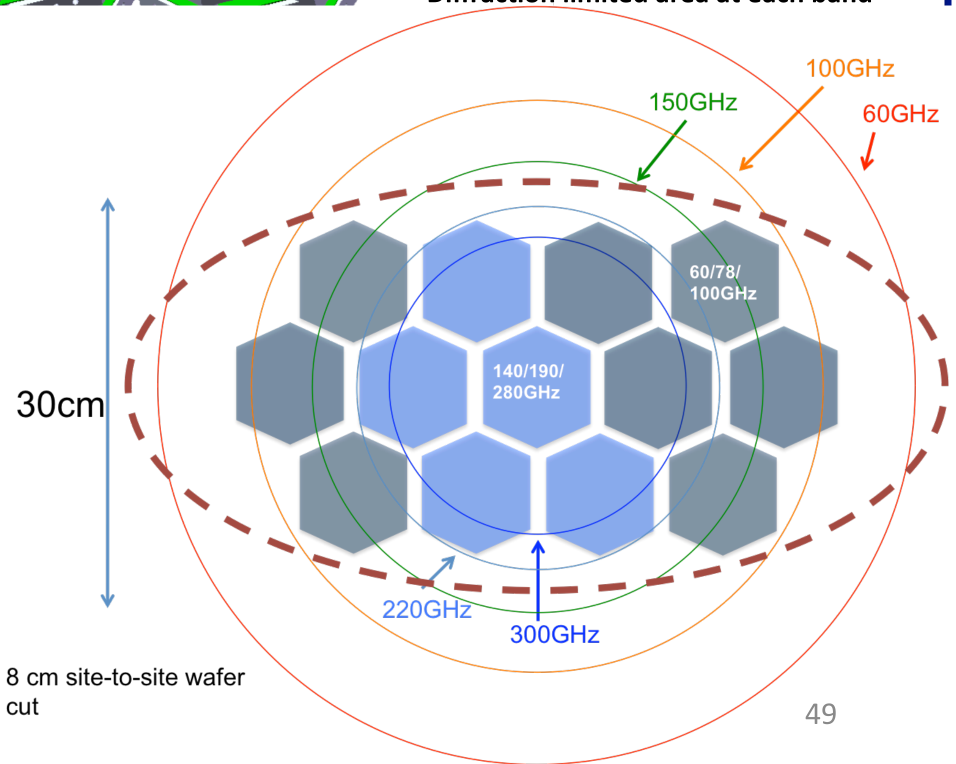


T_{bath} = 100mK

tri-chroic (60/78/100GHz)



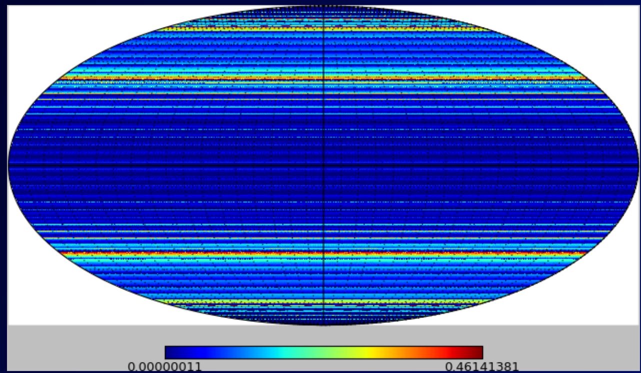
Diffraction limited area at each band



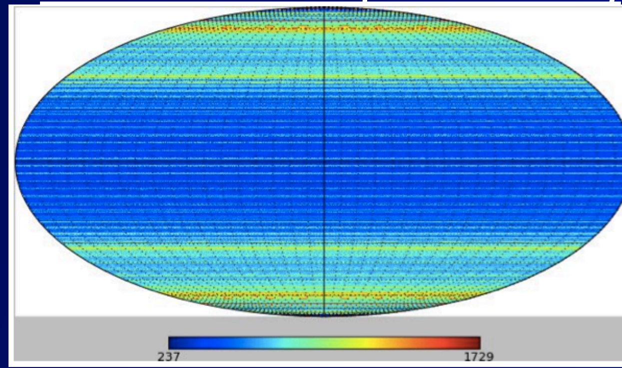
Orbit and scan strategy（L2）

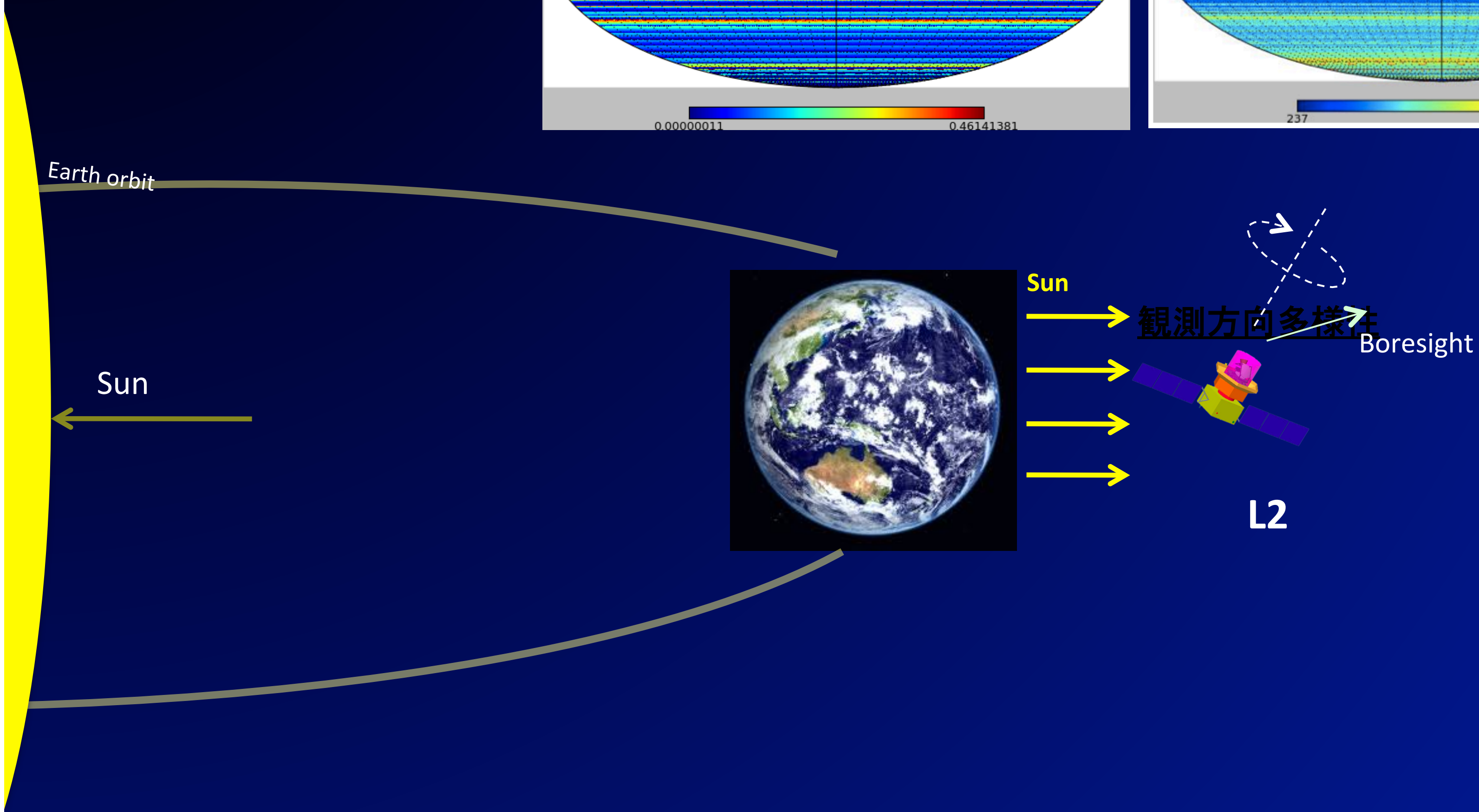
半年で全天をカバー

Good crosslink

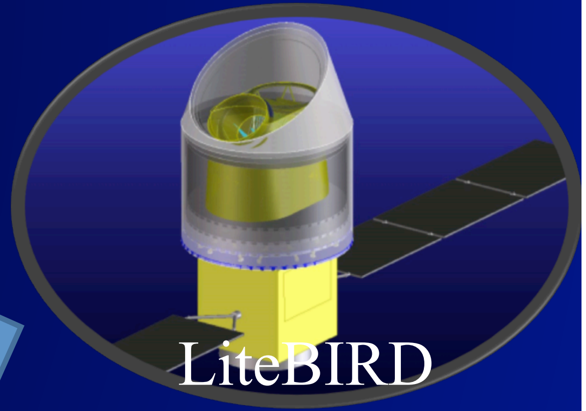


Observational time spatial uniformity





LiteBIRD roadmap

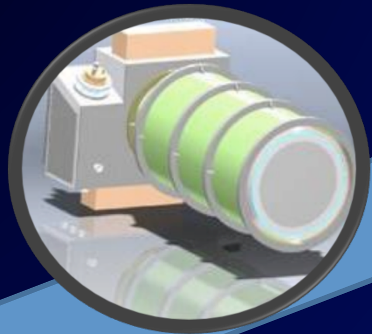


LiteBIRD

Launch target 2020s

- Detector and readout: TES bolometer
- Mitigation of the 1/f and systematics using HWP

POLARBEAR-2



POLARBEAR

GroundBIRD

- Detector and readout: MKID
- LiteBIRD optics

The ground based experiments pave the path to LiteBIRD while they also produce the science results.

Support from astronomy and high energy physics communities

- Japan Radio Astronomy Forum identified LiteBIRD as one of the high priority missions.
- Japanese High Energy Physics (HEP) community has also identified CMB polarization measurements and dark energy survey as two important areas of their “cosmic frontier”.
- LiteBIRD is selected as one of the JutenOgataKenkyuKeikaku in 2014 Science Council of Japan.

Summary

- POLARBEAR measures the lensing BB signal.
- BICEP-2 announced the detection of inflationary B-mode.
- Entering new era to the real precision cosmology. A small satellite mission proposal LiteBIRD can pinpoint the inflation model.