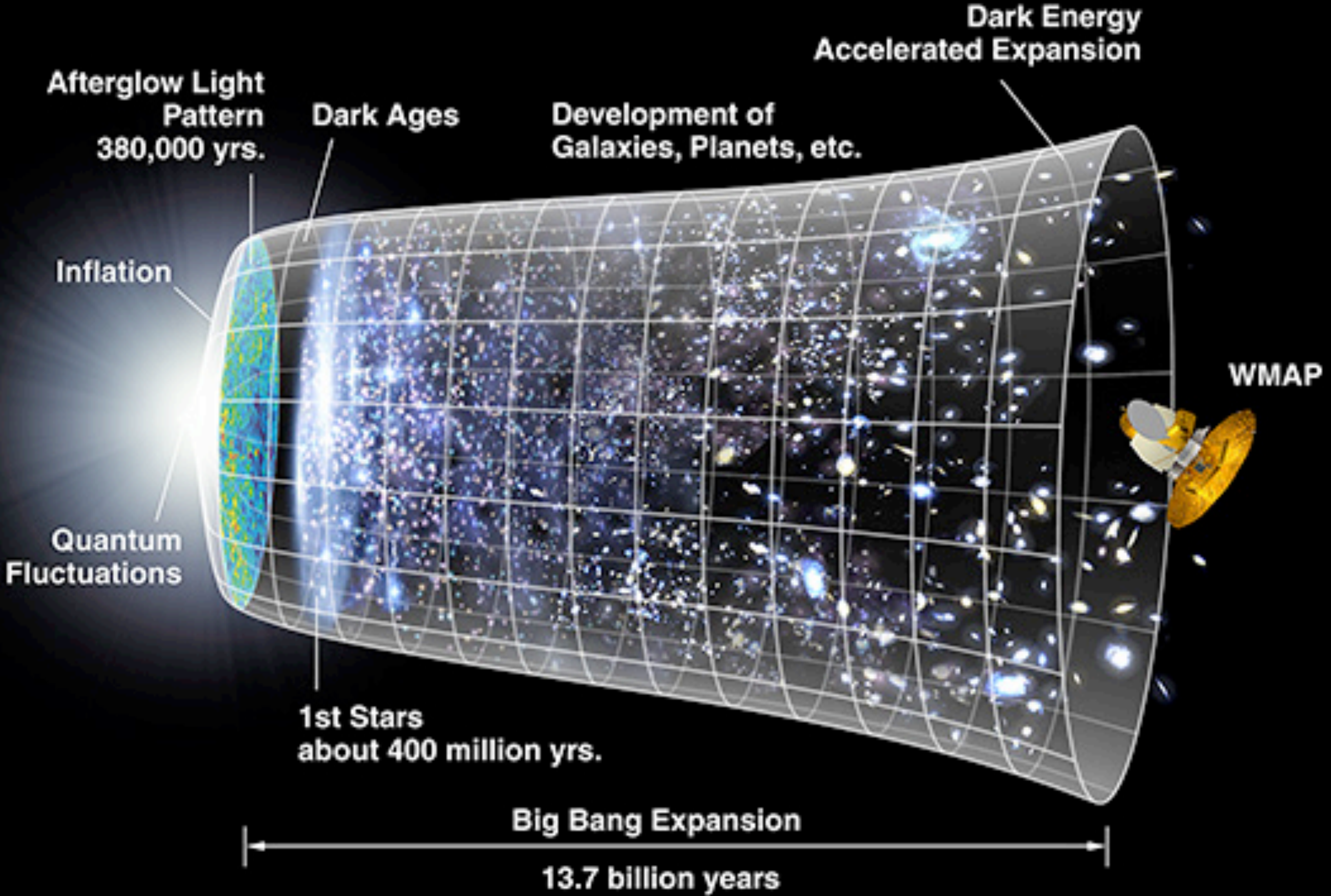
Tomotake Matsumura, IPNS/KEK

# RECENT DEVELOPMENTS IN CMB RESEARCH

# Outline

- Science with CMB
- Review of recent results
- Ongoing and future CMB experiments

# History of the Universe




http://map.gsfc.nasa.gov/

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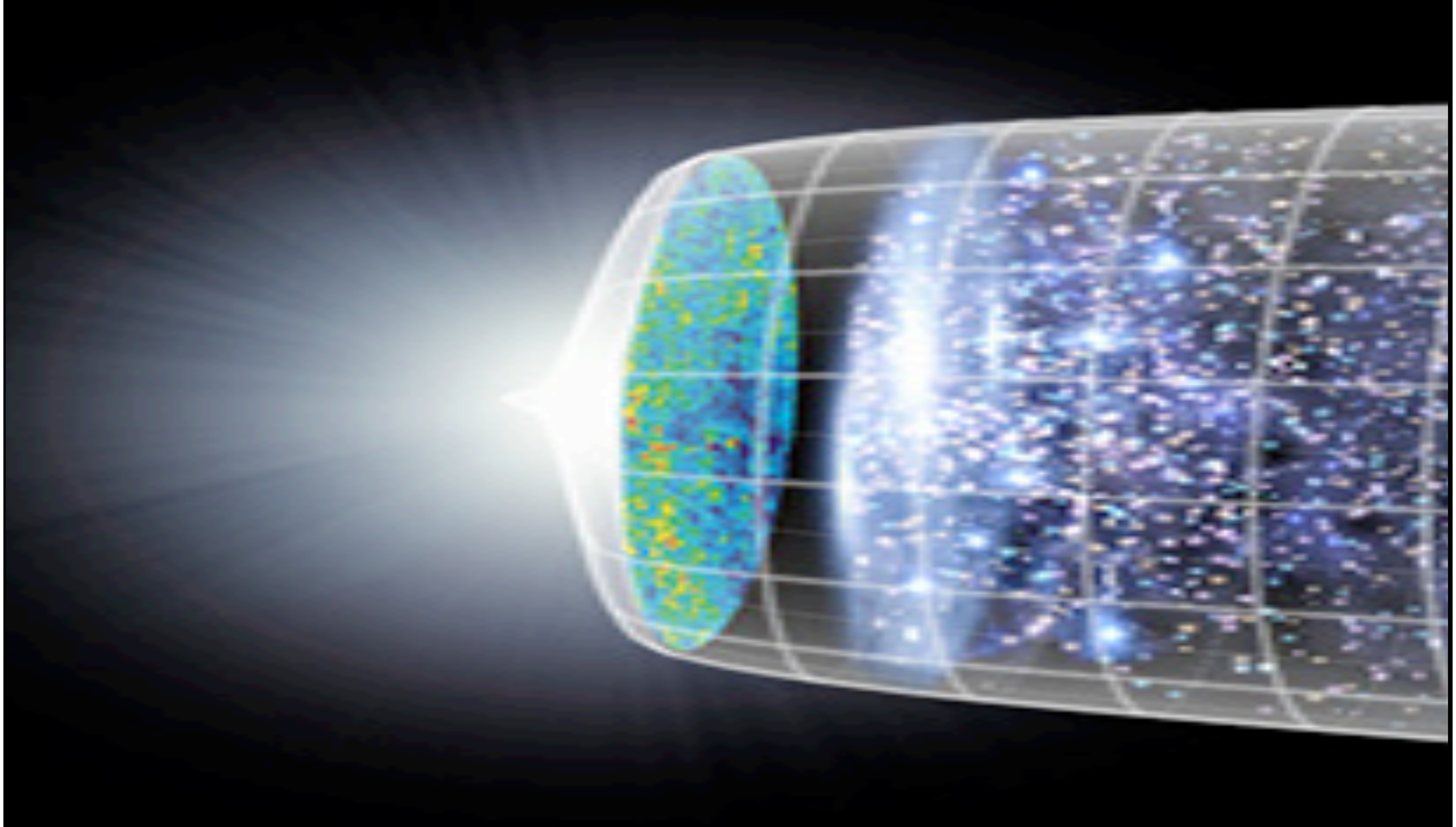
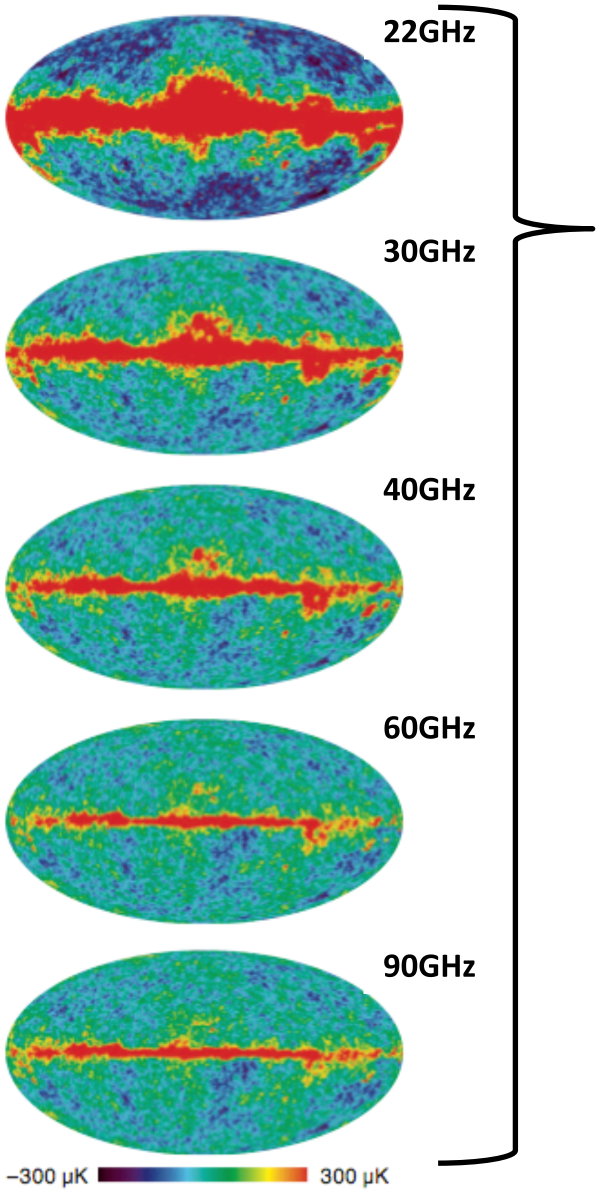


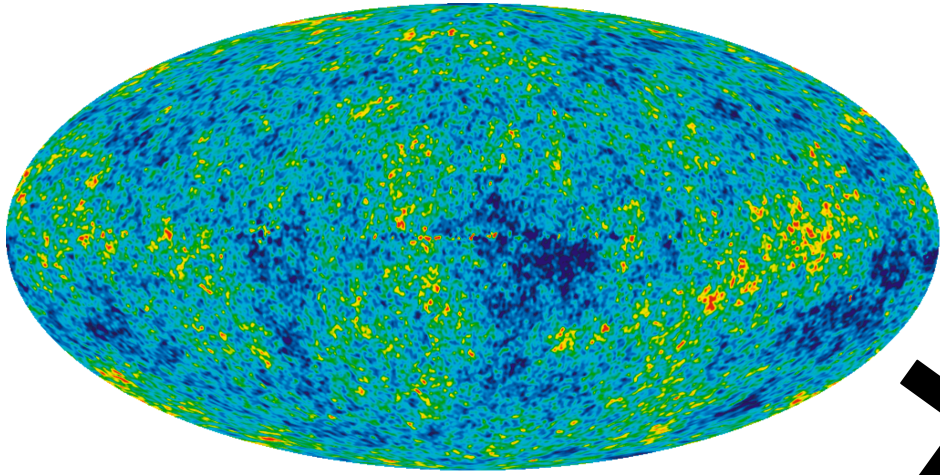
http://map.gsfc.nasa.gov/

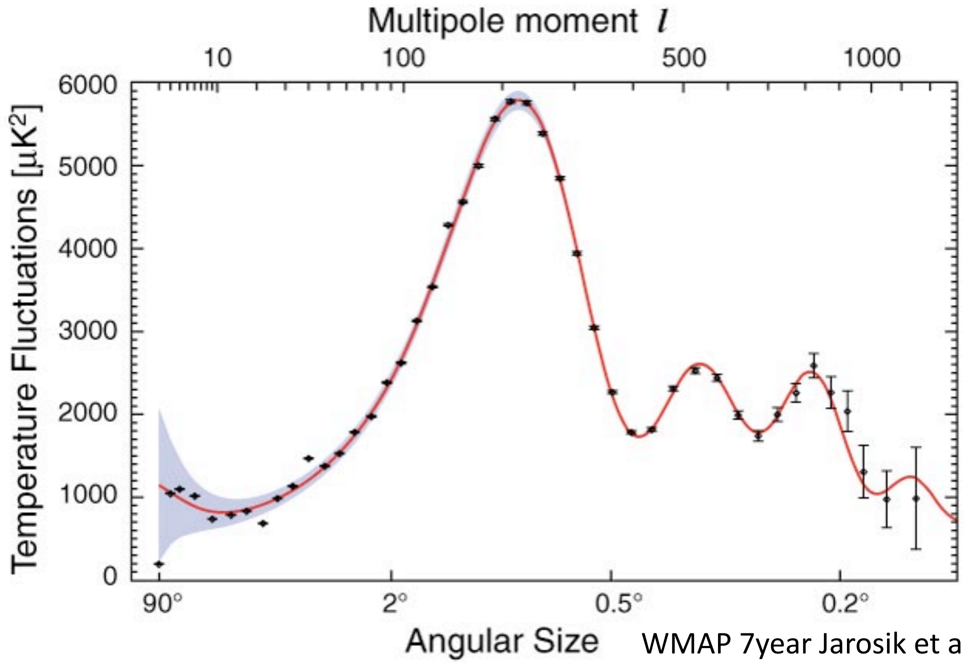
# What are we chasing after?

# B-mode

# From the real sky to the physics of early Universe in one slide






WMAP 7year Jarosik et al.

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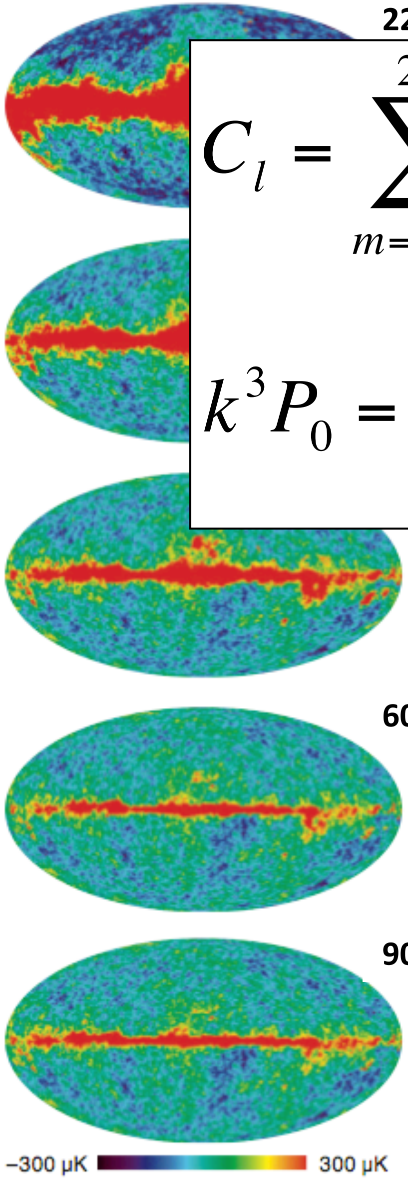


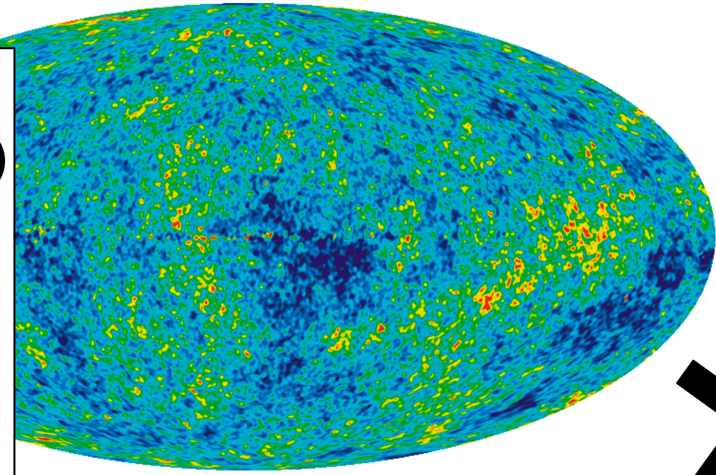

22GHz

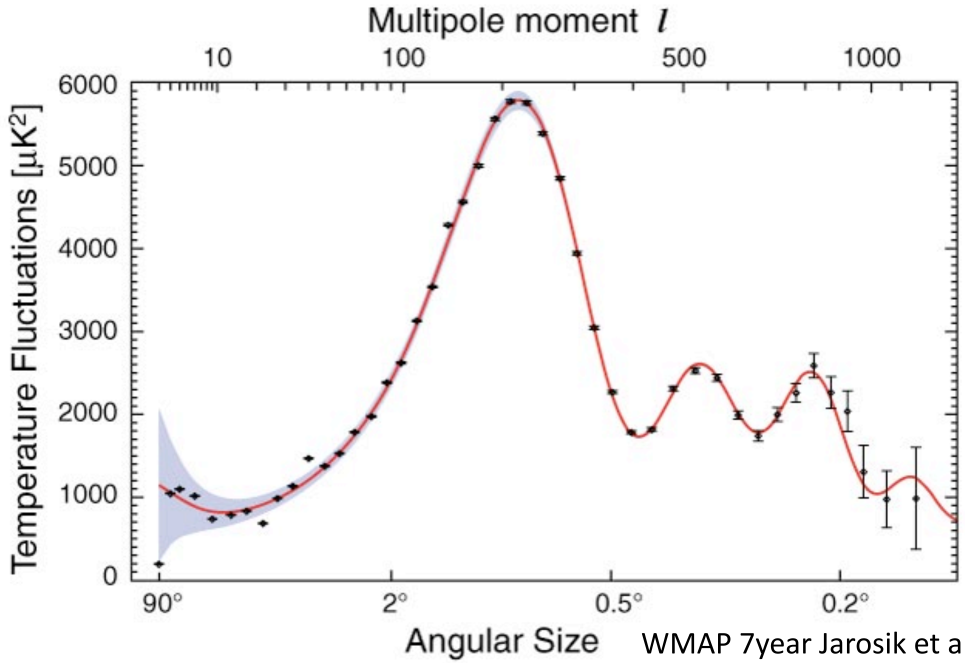
60GHz

90GHz

$$C_l = \sum_{m=-2}^{2} \int dk T_m(l,k) P_m(k)$$

$$k^3 P_0 = A_s \left( \frac{k}{H_0} \right)^{n_s - 1}$$






WMAP 7year Jarosik et al.

# Inflation

- **Inflation is introduced to explain**
  - why the Universe has the scale invariant initial condition
  - why the Universe is flat
  - why the Universe is uniform

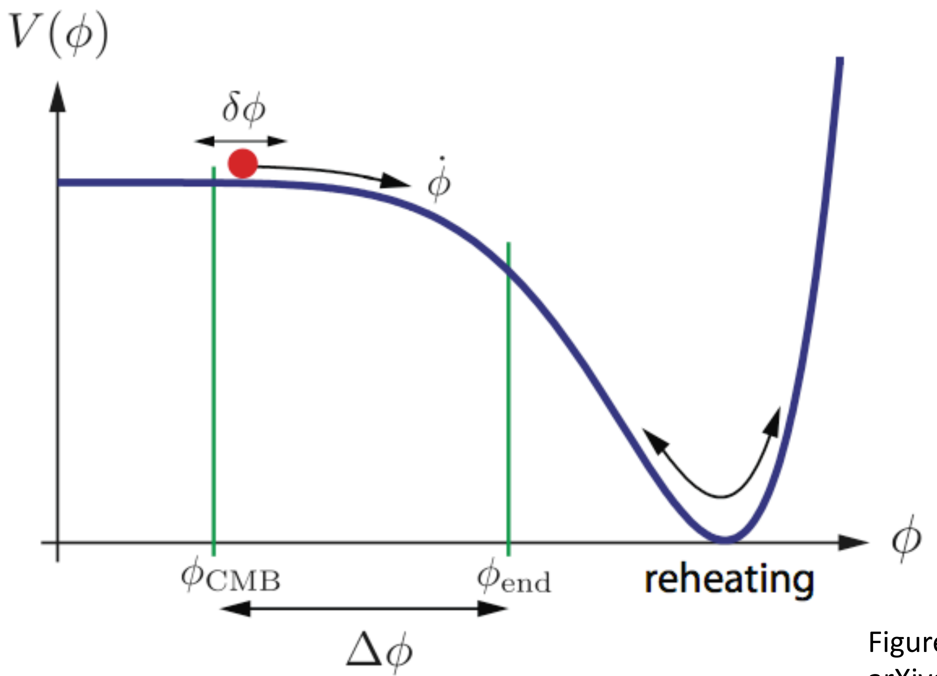



Figure from Braumann arXiv:0907.5424

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- Simple inflation models relate the energy scale of the inflation and the strength of the primordial gravitational wave.

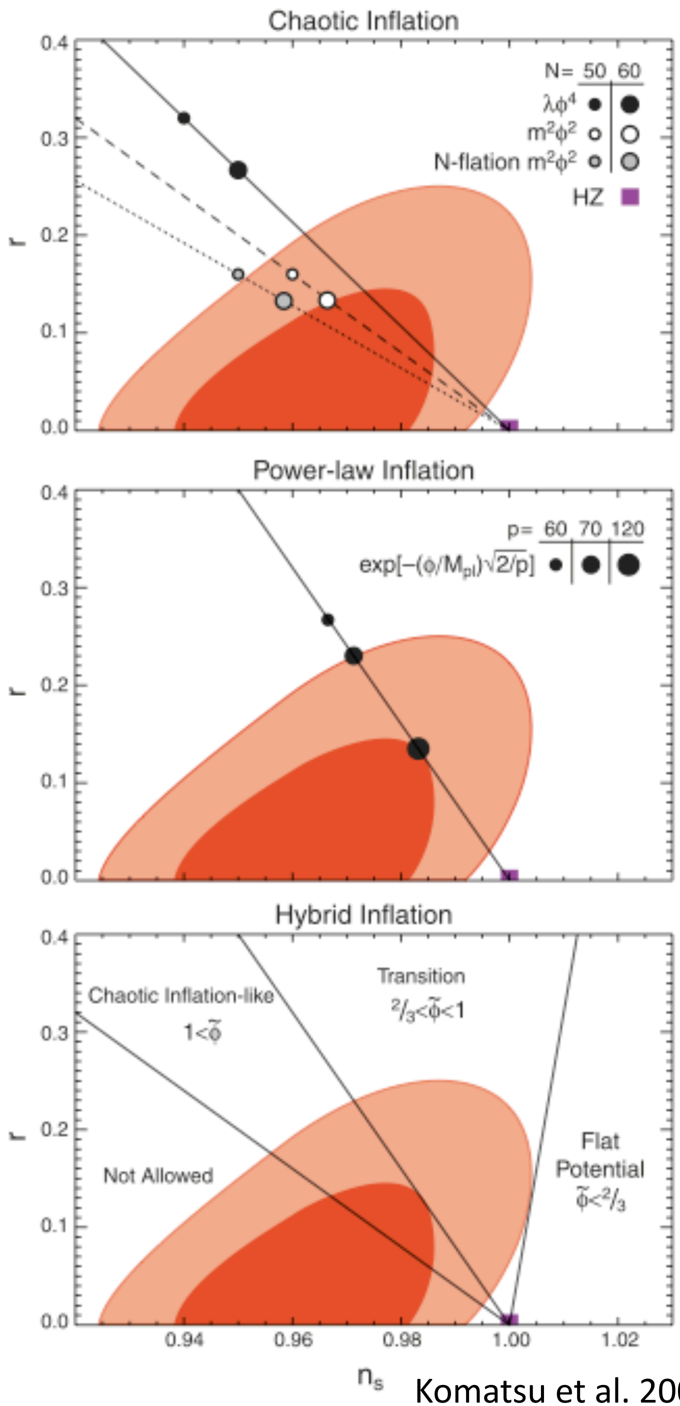
$$V^{1/4} = 3.3 \times 10^{16}\, r^{1/4}\ \mathrm{GeV}$$

where we define a parameter $r$, the tensor-to-scalar ratio.

# Tenor-to-Scalar ratio

WMAP put a constraint to the tensor-to-scalar ratio, $r$ <0.24, Komatsu et al. (2011) using temperature anisotropies in CMB.

This allows to start excluding some of the inflationary models.




Komatsu et al. 2009

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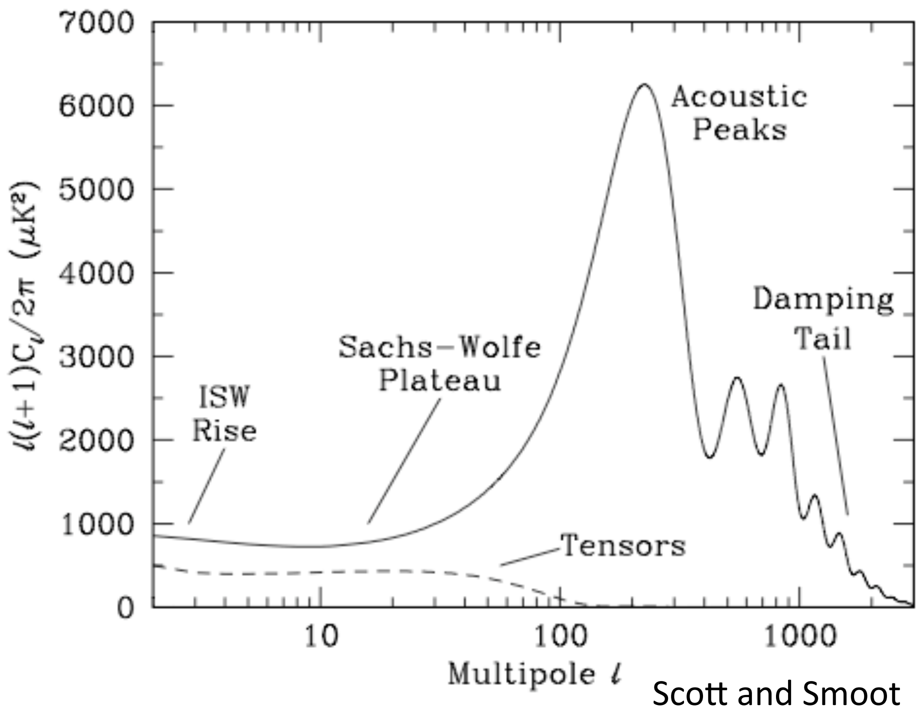
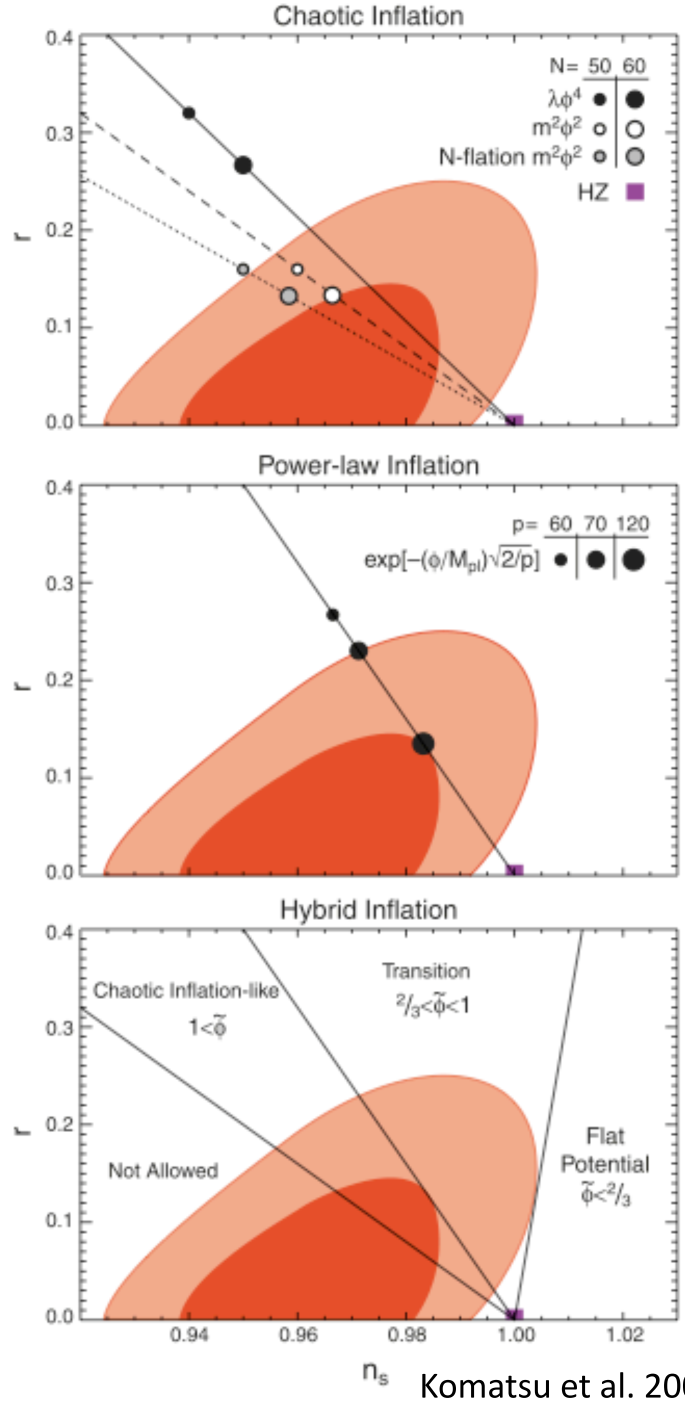
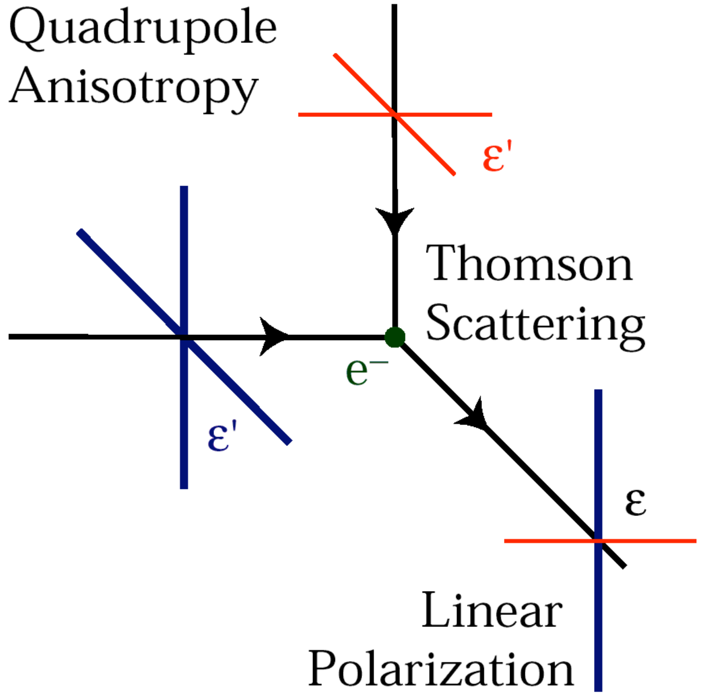



Scott and Smoot
arXiv:astro-ph/0601307



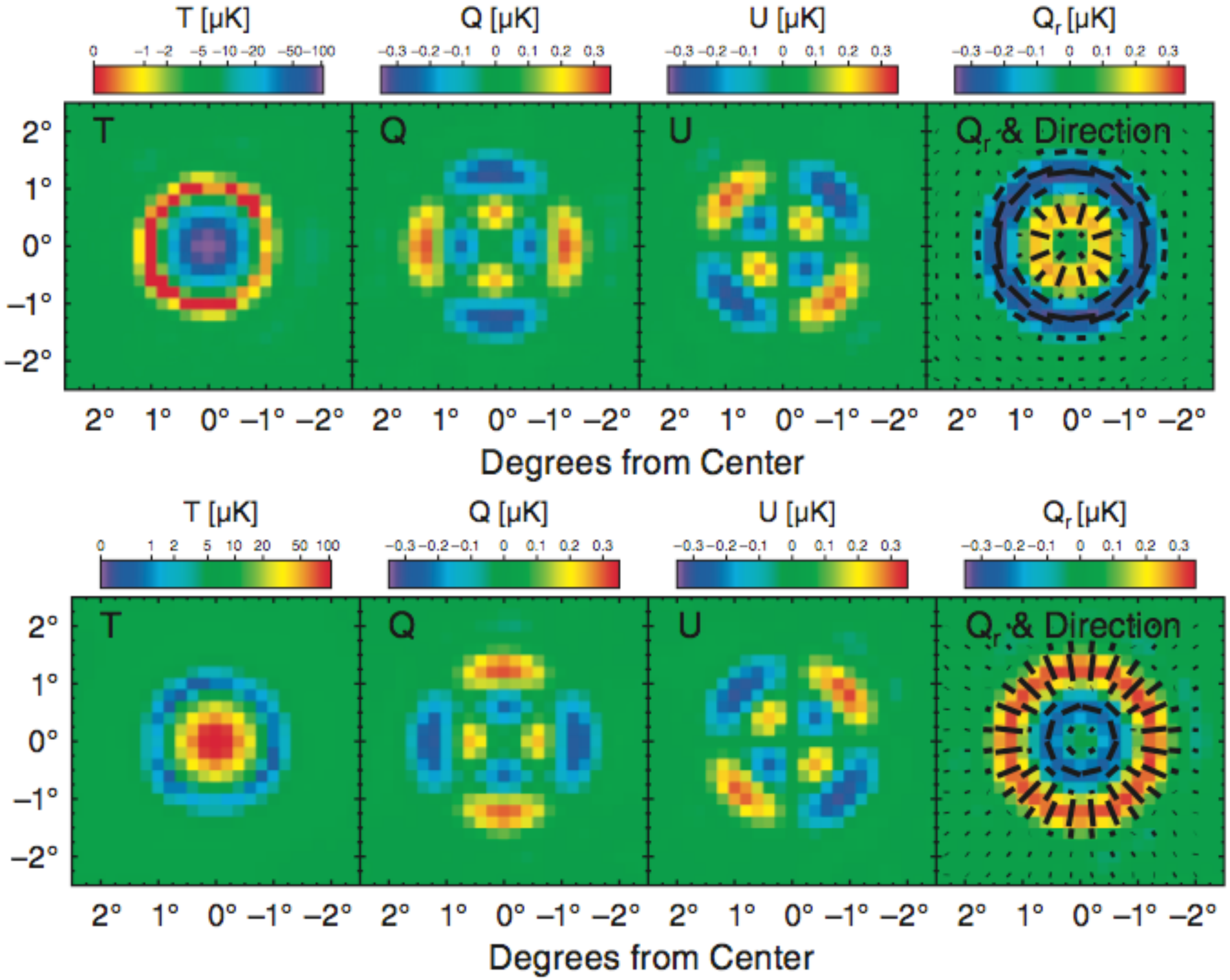

Komatsu et al. 2009

# Polarization



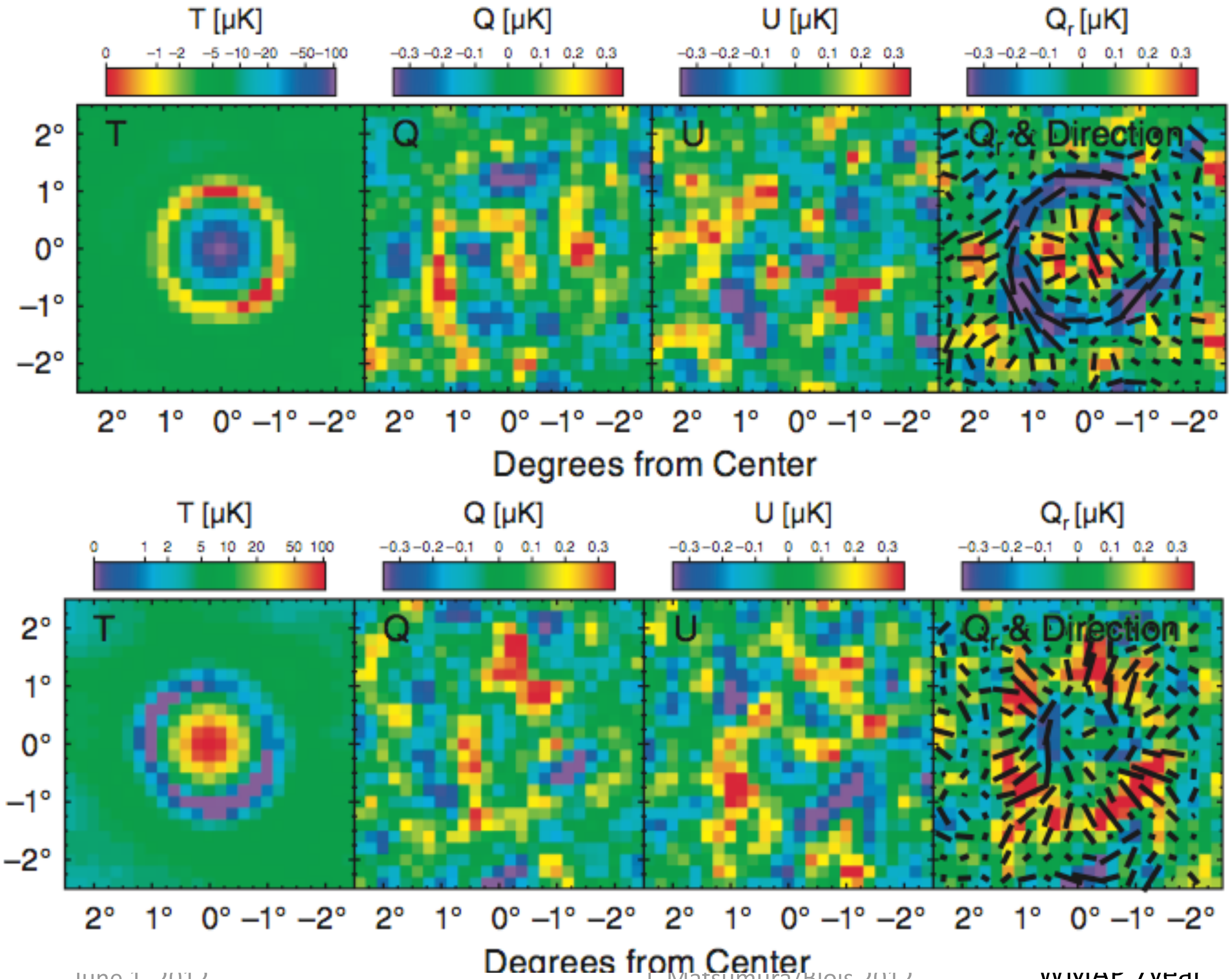

- CMB polarization is expected to be linearly polarized.
- Quadrupole pattern around the scattering center creates the linearly polarized light.
- Sources of the quadrupole pattern:
  - **Primordial density perturbation**
    - → **E-mode**
  - **Primordial gravitational wave originated from inflation**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

# Polarization




Komatsu et al. 2011

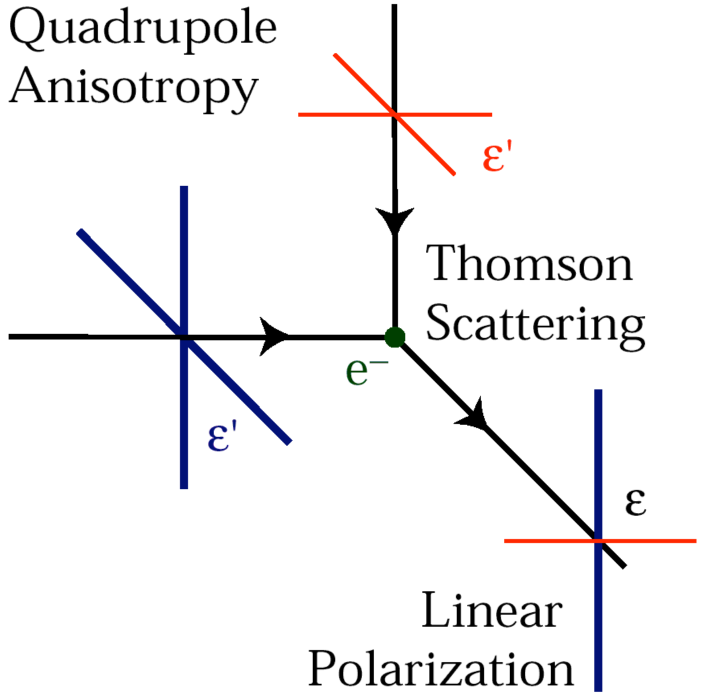
# Polarization




Komatsu et al. 2011

WMAP 7year

# Polarization

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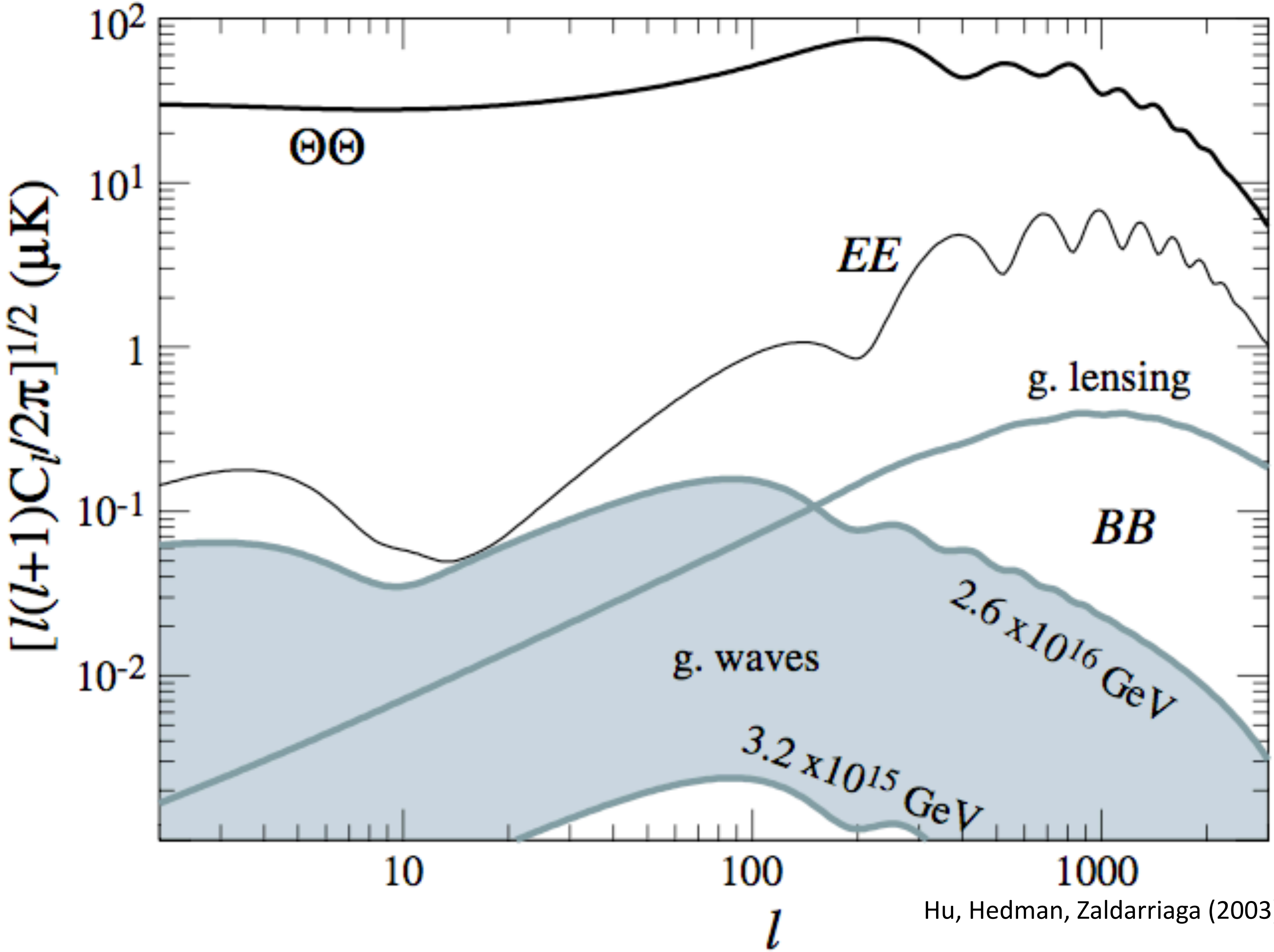
**Warning!**

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.

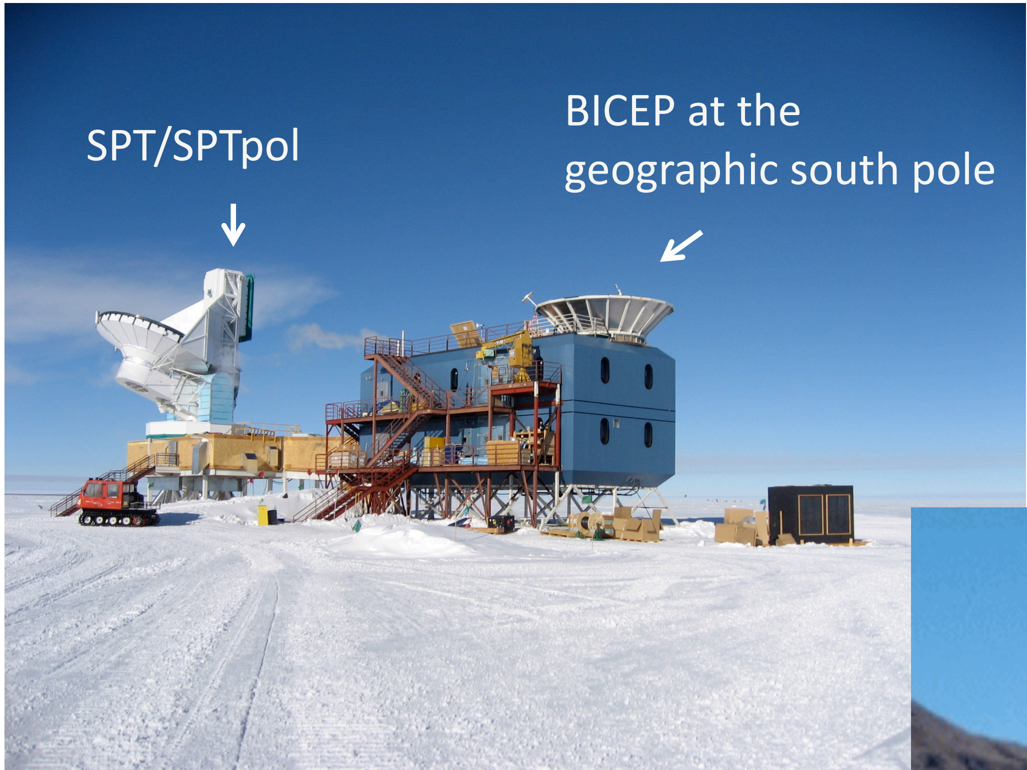

WMAP 7year

# Polarization

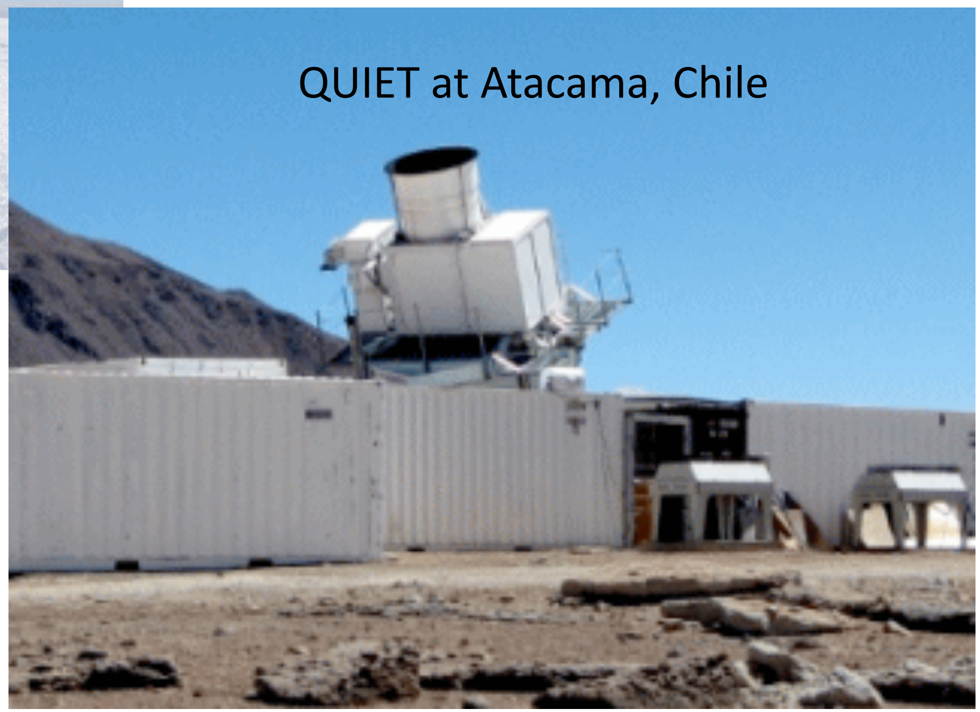



Hu, Hedman, Zaldarriaga (2003)

# Tenor-to-Scalar ratio using B-mode

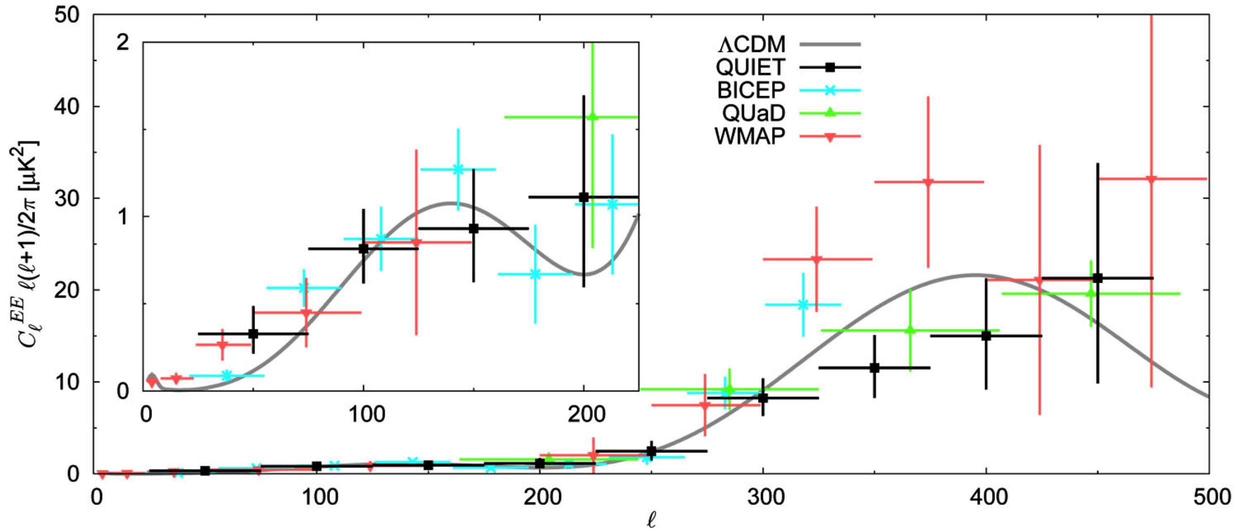



**Current best limit on $r$**
WMAP+SPT $r$ <0.21. Keisler et al.



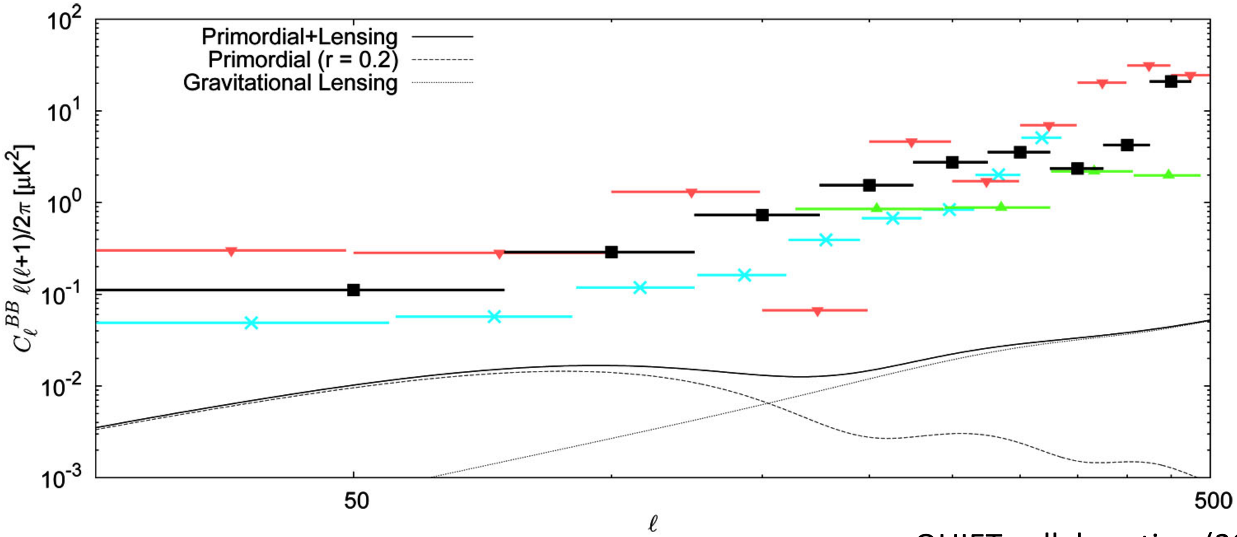

**Currently these two leading experiments put the upper limit on $r$ using B-mode polarization.**

# Tenor-to-Scalar ratio using polarization




**Current best limit on $r$**
WMAP+SPT $r$ <0.21

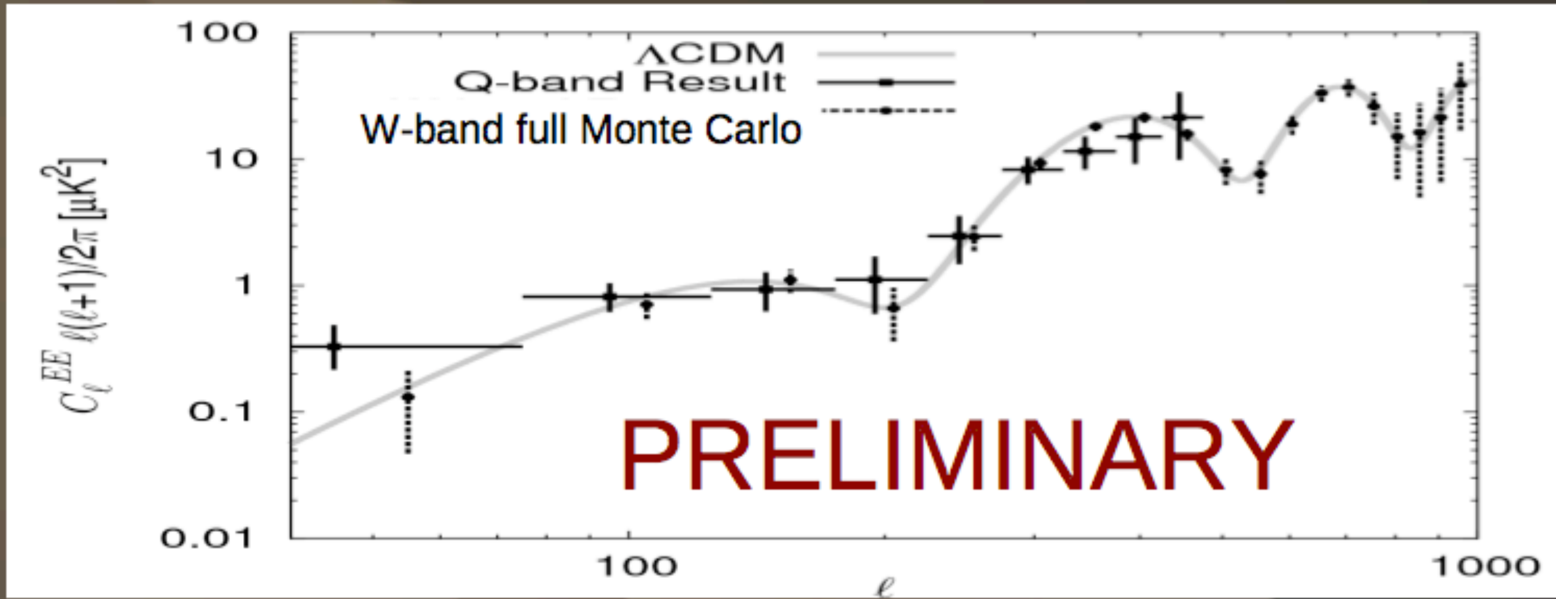
**Current best limit from BB power spectrum**
BICEP-I two year data,
$r$ <0.72. Chiang et al. (2010)

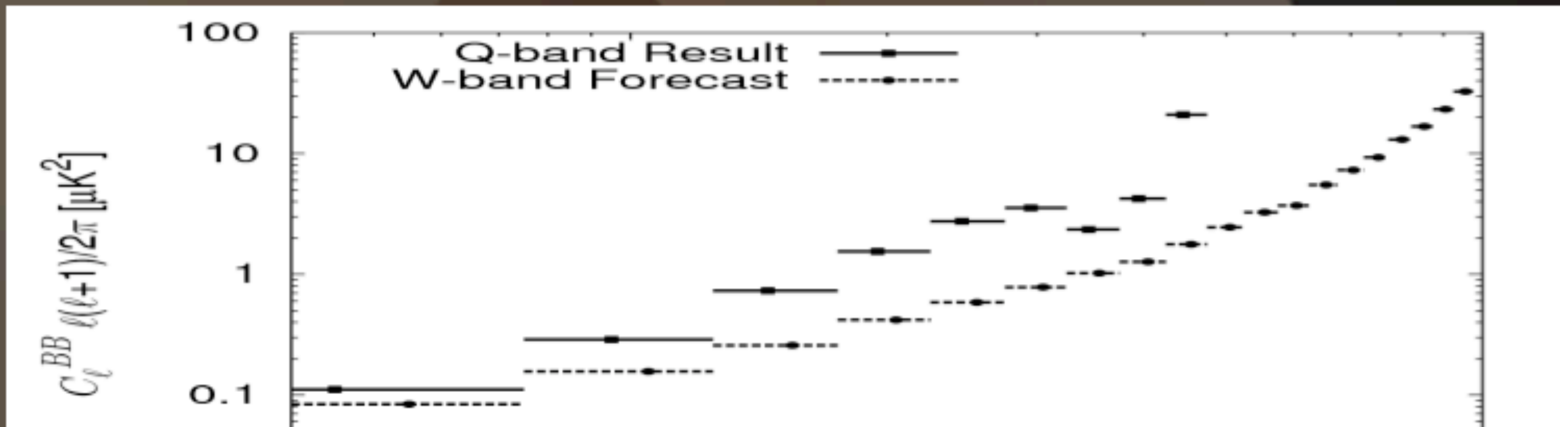



QUIET collaboration (2010)

Very big community wide efforts to probe this deeper.

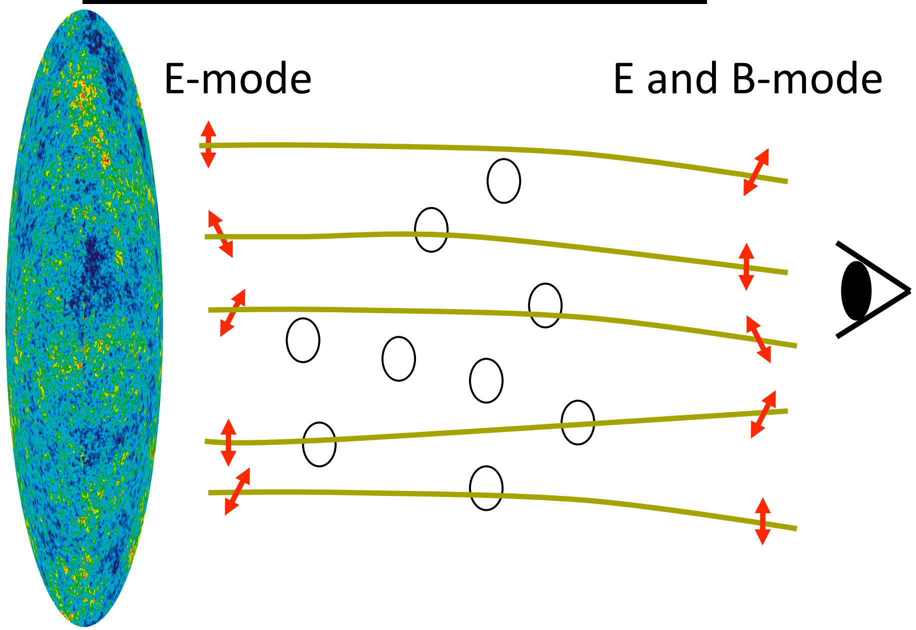
# W-band Forecast Result




**QUIET, W-band**
**Slide from Immanuel Buder presented in Blois 2012**

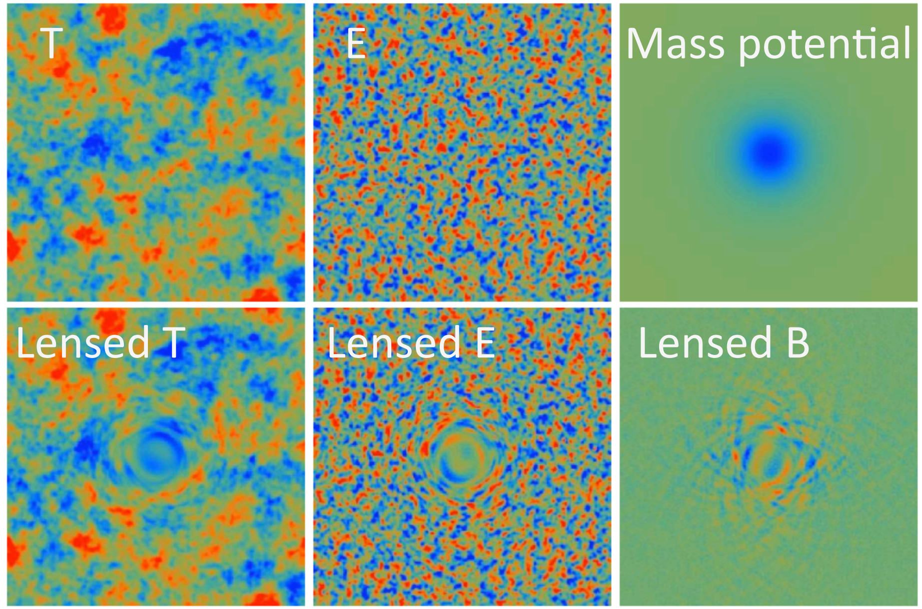
# CMB Lensing



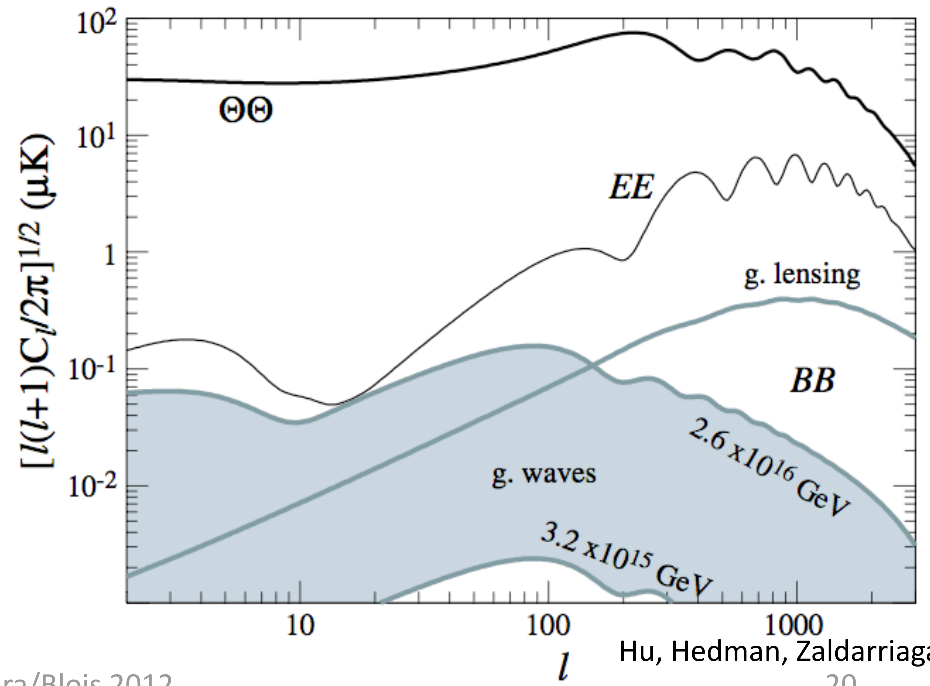

The lensing field smears the power at scale below the free stream length.

The lensing field mix E and B
and also mix the modes.

This is annoying “foreground” for the primordial gravitational wave B-mode hunting, but it contains rich physics in itself.




Hu and Okamoto (2002)



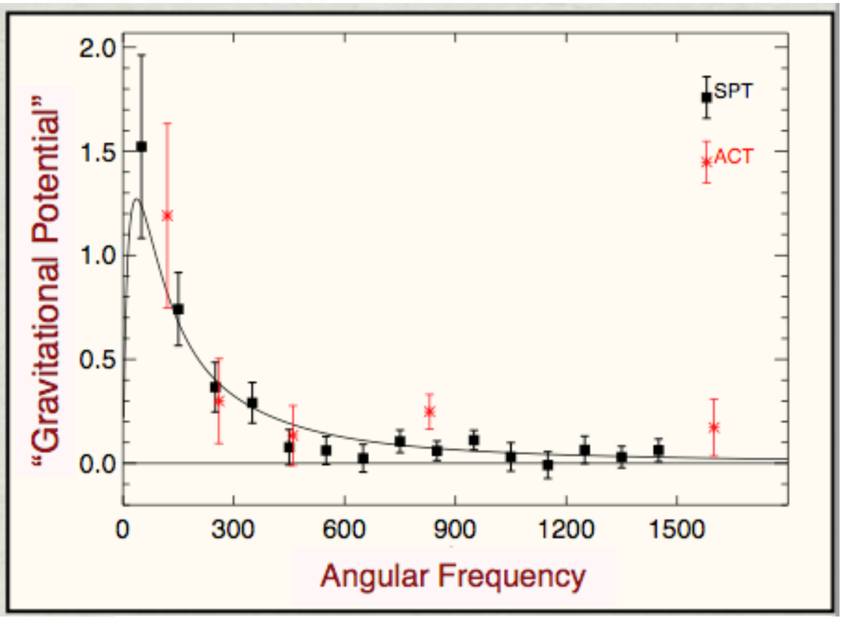

Hu, Hedman, Zaldarriaga

# Detection of lensing effect in CMB temperature

Slide from R. Kleisler, presented in Blois 2012.

- **Gravitational lensing of CMB**
  - First >5σ detections in last year.
  - 20-30σ in next year, similar to Planck.
  - Sensitive to sum of neutrino masses.

(see Van Engelen et al, 1202.0546)

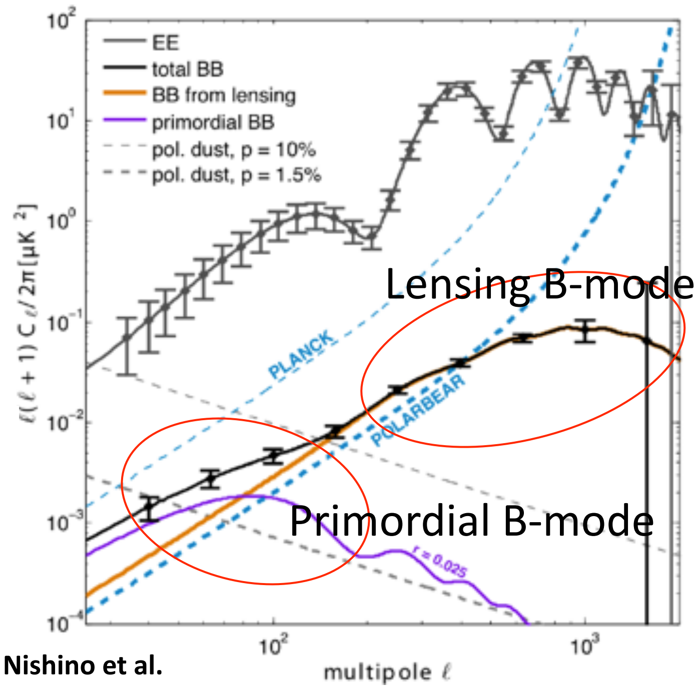



**WMAP 7year puts constraint $\Sigma m_\nu < 0.58$ (95%CL)**
**Planck forecast of error in $\Sigma m_\nu$ is 150meV.** (Planck bluebok)

**Upcoming: Constraining the mass of neutrino and dark energy using lensing B-mode polarization**

**Example with POLARBER→**

Sensitive to sum of neutrino mass: 75 meV (68%C.L.) (combined with Planck)




Nishino et al.

# <u>Ongoing B-mode Experiments</u>

# Challenges in the next generation CMB experiments

## Science goals

## Need more statistics

- Large array detector experiments
- Large sky coverage

## Need to control systematics

- Instrumental systematics
  - Beam shape, gain, polarization angle, and many others
- Foreground emission

# Challenges in the next generation CMB experiments

## Science goals

## Need more statistics

– Large array detector experiments→ >1000 detectors
– Large sky coverage→ smaller $1/f$ noise and fast scan

## Need to control systematics

– Instrumental systematics→ simpler design, improve calibration techniques
    • Beam shape, gain, polarization angle, and many others
– Foreground emission→ broad frequency coverage

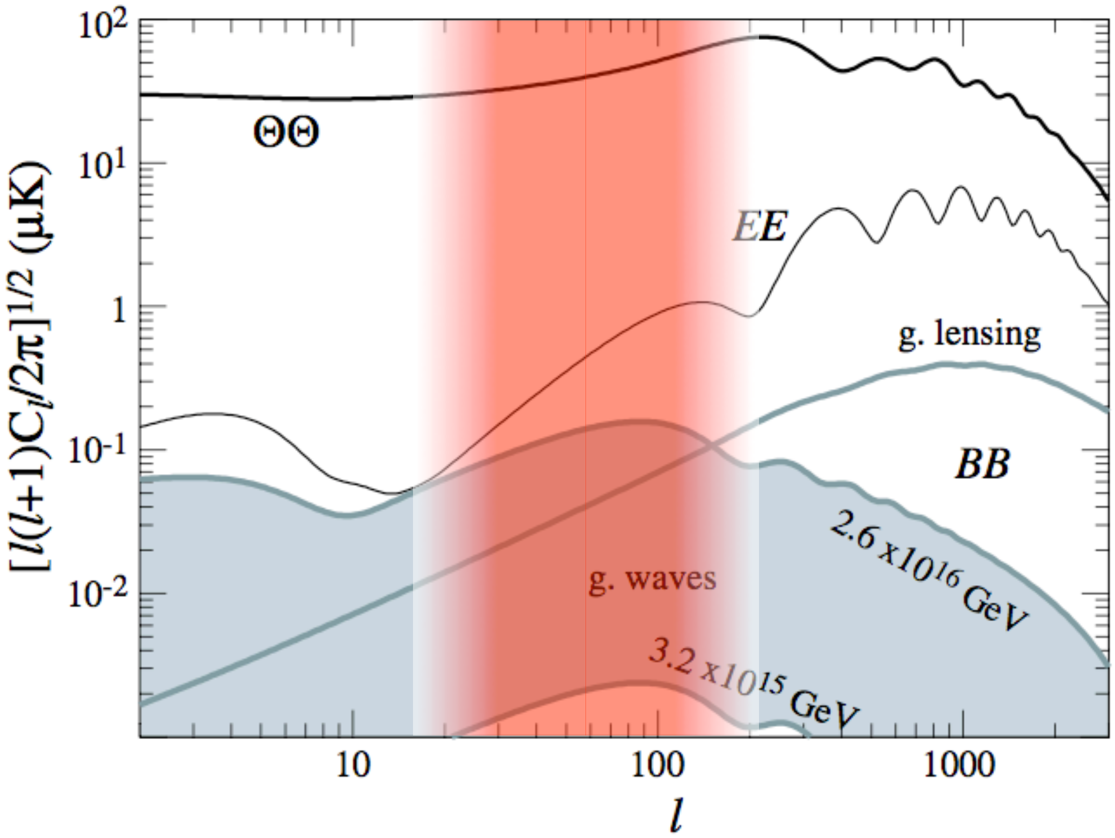
# Ongoing and next generation experiments

**Low *l* range experiments**
ABS, BICEP, BICEP-II, Class, GroundBIRD, Keck, SPIDER

**Mid *l* range experiments**
EBEX, POLAR, POLARBEAR

**High *l* range experiments**
ACTpol, SPTpol

***l* ≥ 2 (Satellite)**
Core, EPIC, LiteBIRD, Pixie, Planck




Full sky

Small patch

Satellite

Small telescope

Large telescope

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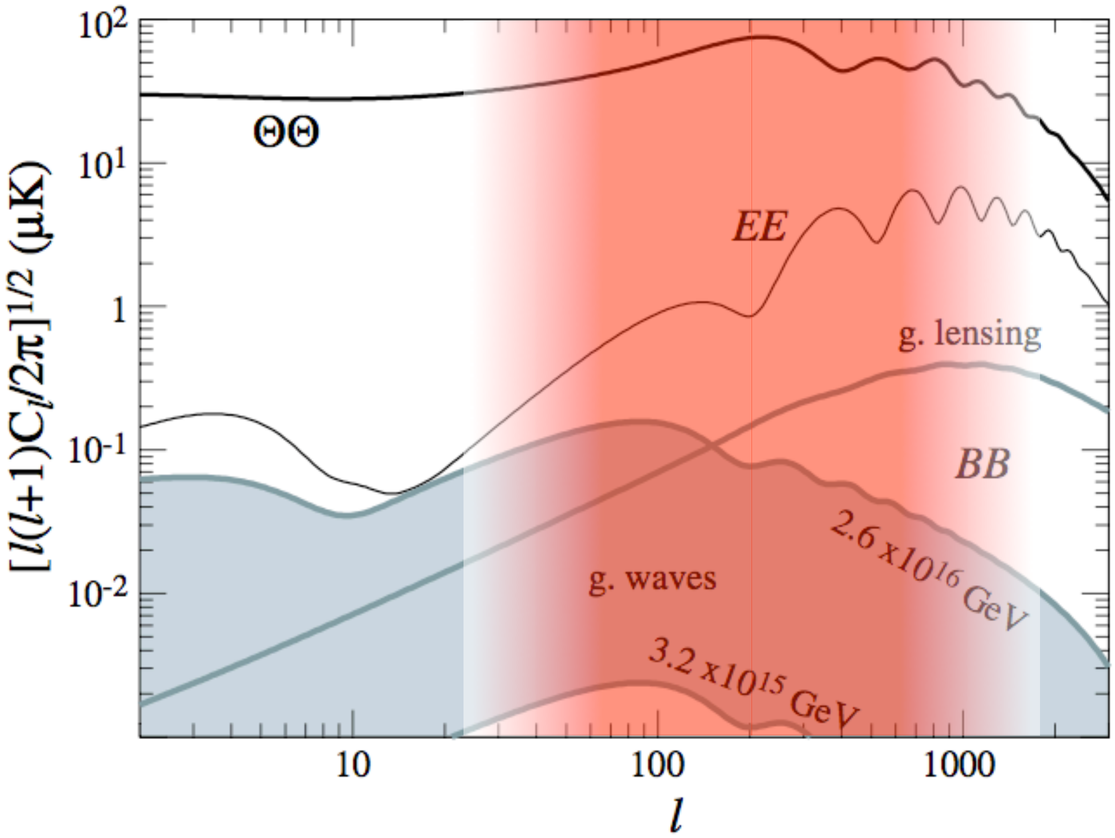


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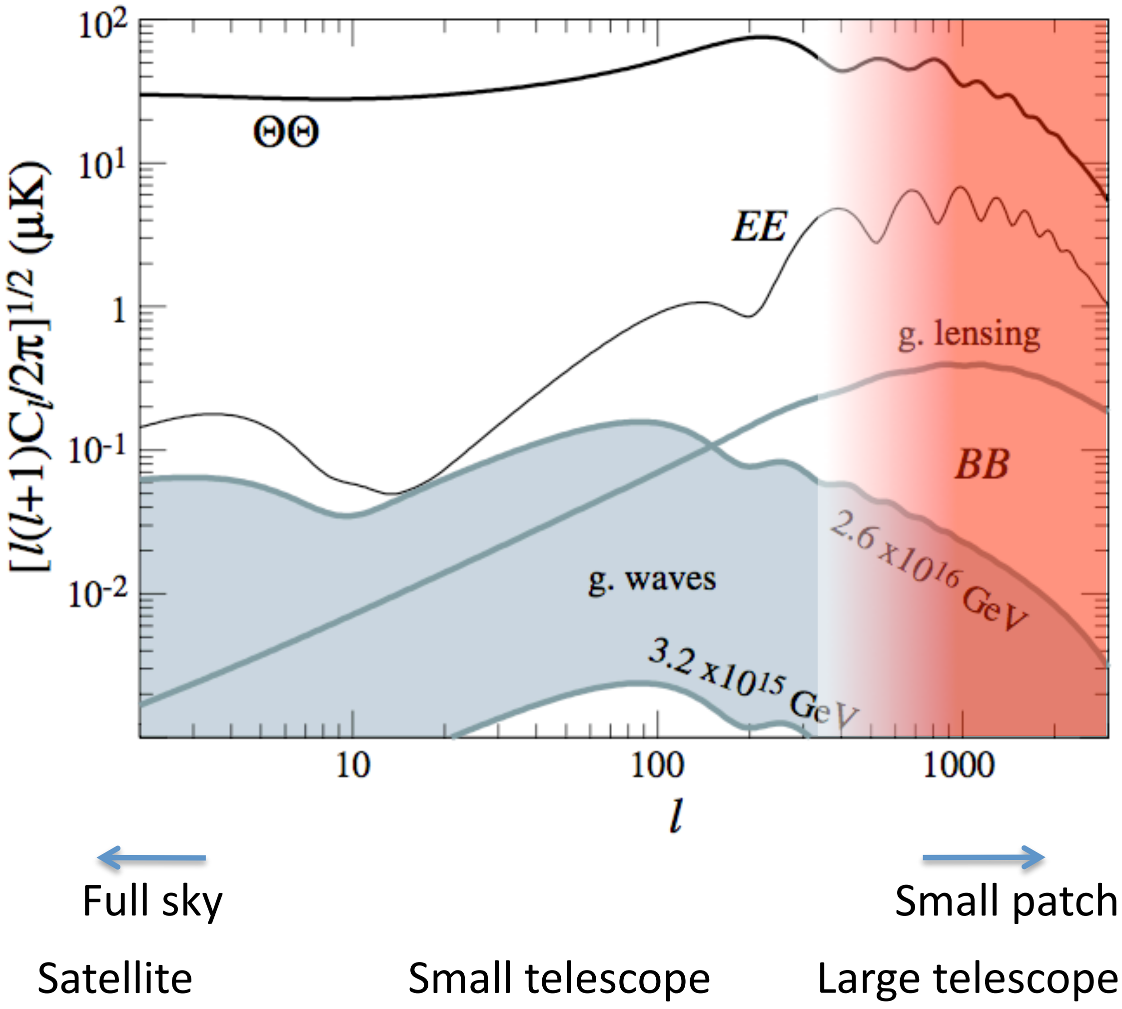

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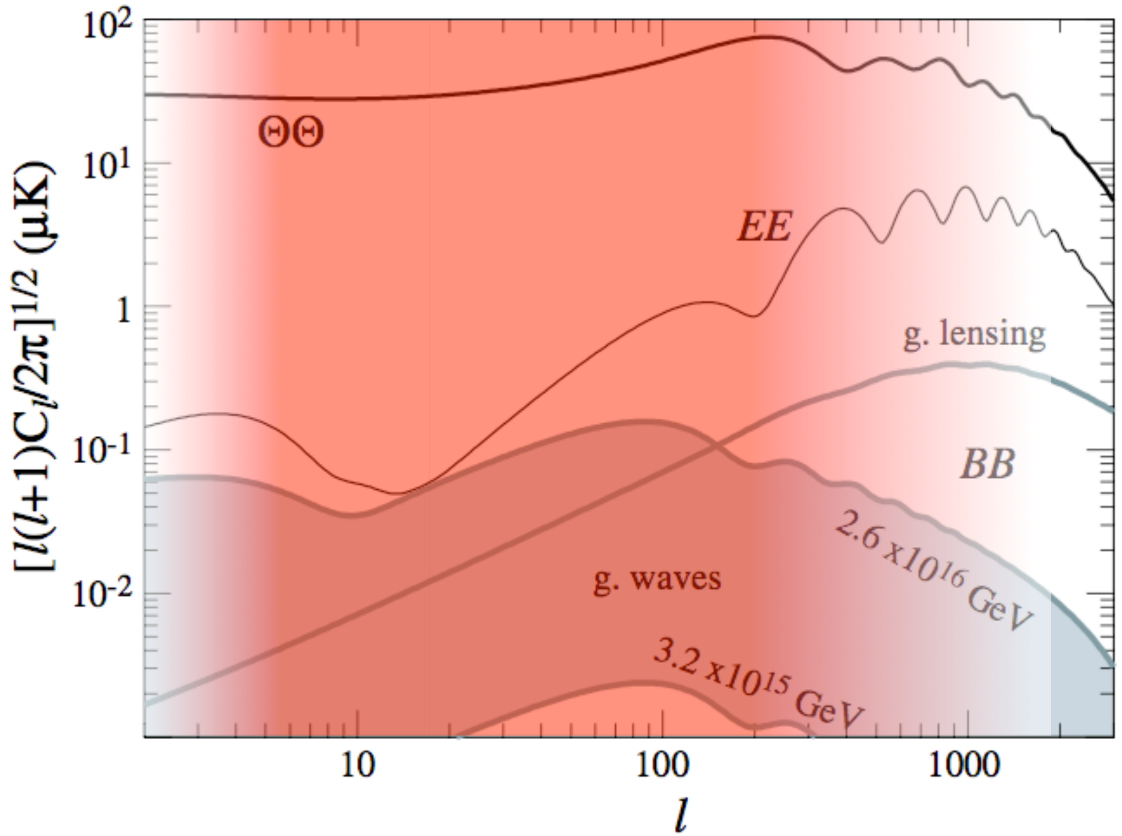


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Small patch

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Small telescope

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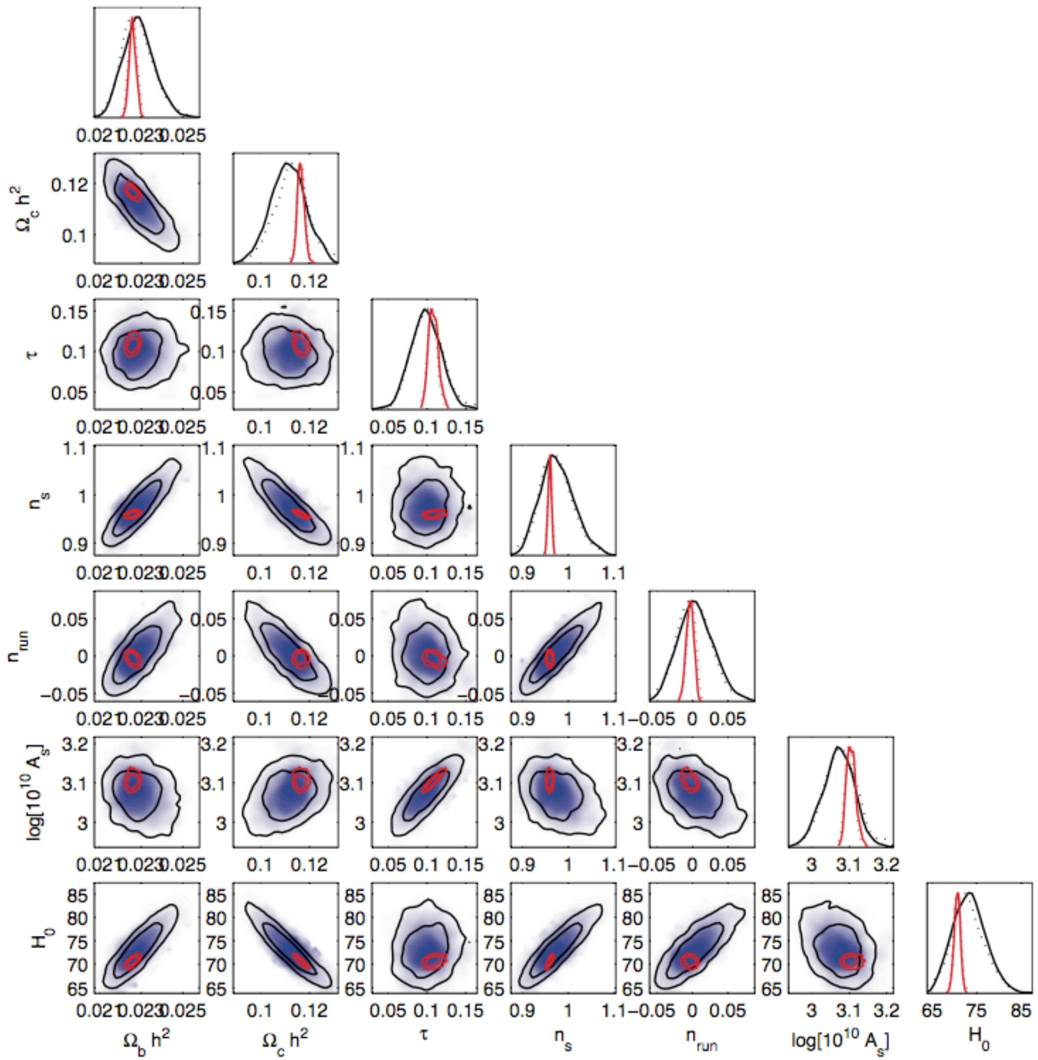
# Planck

François Couchot presented the hot and cold plots of CMB from Planck ir this Blois 2012.

We expect the huge improvement oı number of cosmological parameters.

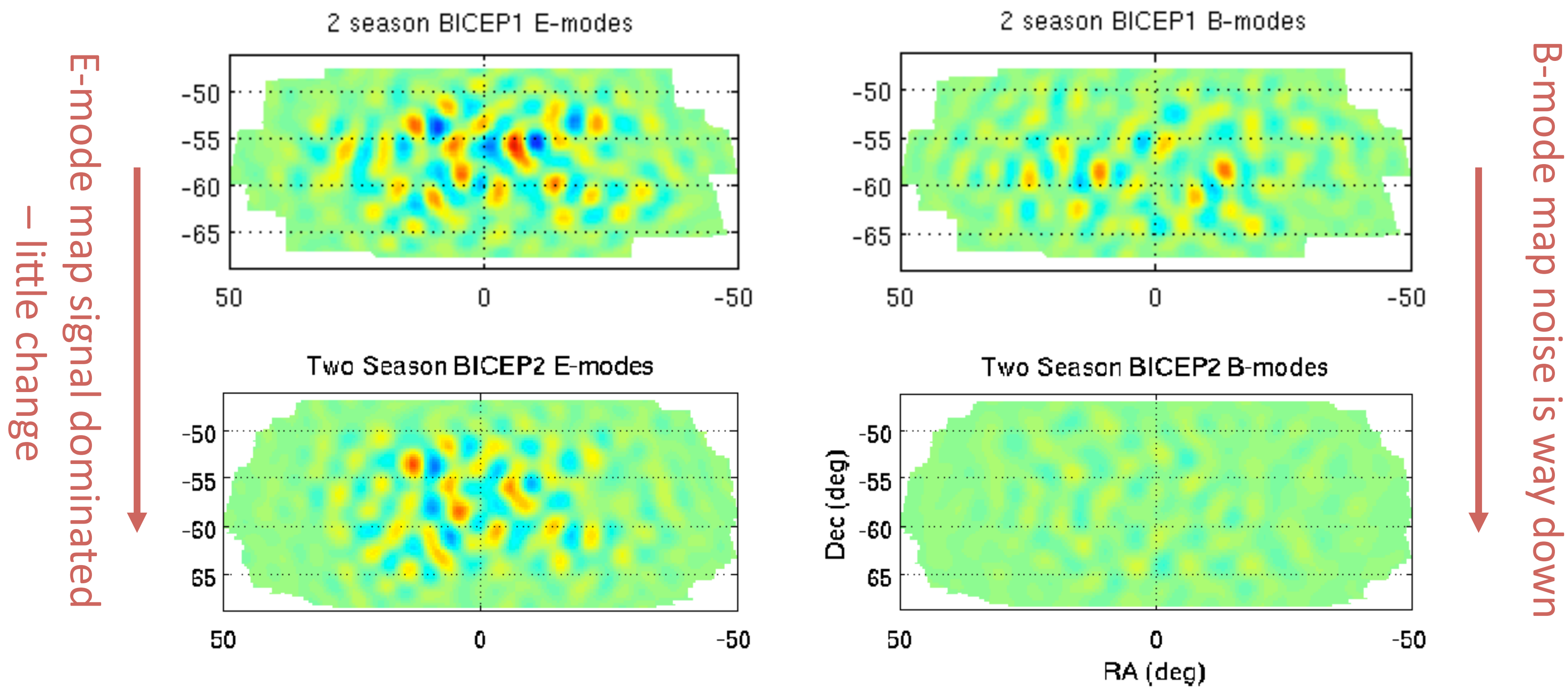
We also expect to learn about (polarized) foreground emission oveı wide range of frequency, 30-857GHz

The temperature results are expecte to be released in early 2013.




Figures from Planck Bluebook

# BICEP1 vs BICEP2 E/B Maps




• These BICEP1 maps correspond to a limit r<0.72 (95%), from Chiang et al 2009 and still the world's best published limit from B-modes.

• These *preliminary* BICEP2 maps already reach noise levels corresponding to limits of r<0.1 (signal under analysis)

Slide from J. Kovac.

# Keck-Array (aka SPUD)

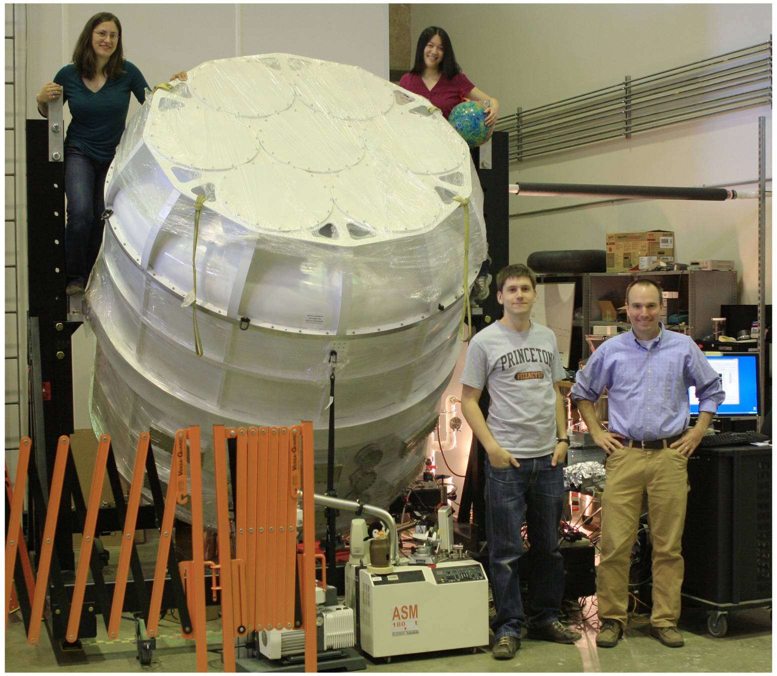
- SPUD is five BICEP2 like receivers on the old DASI/QUaD platform
- Enough sensitivity @150GHz to reach r=0.02 by 2014
- SPUD will detect a B-mode – cosmological or otherwise! Starting phased switch this year to other frequencies to follow up

Slide from J. Kovac.

# SPIDER

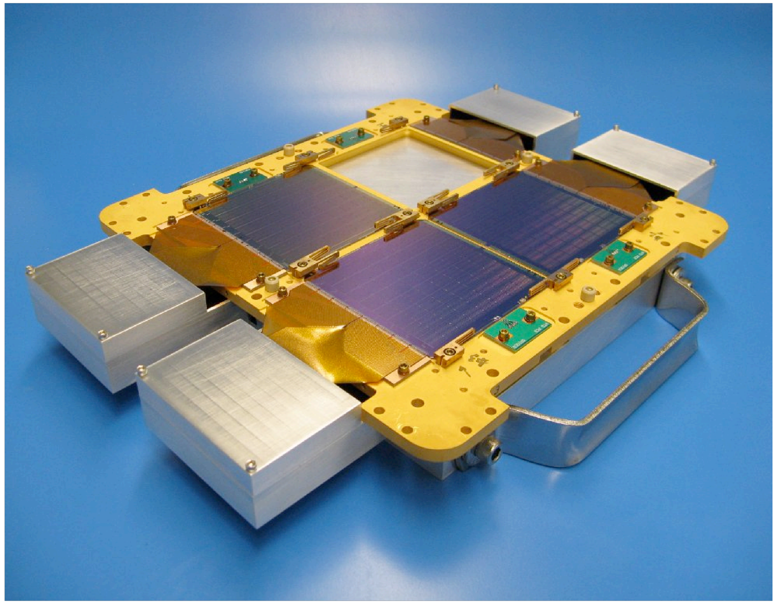
Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization

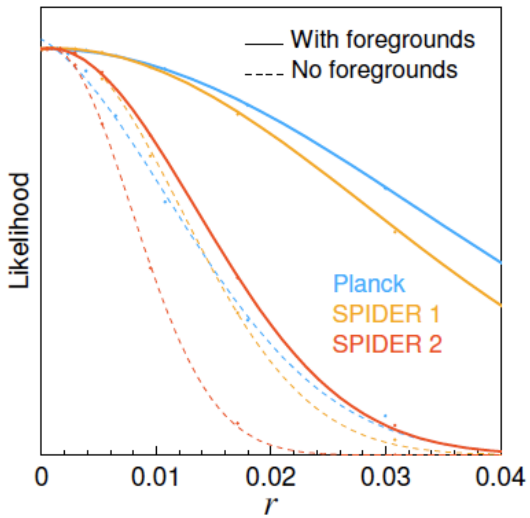
- Long duration (20+ day cryogenic hold time) balloon borne polarimeter
- Sensitive to scales from 20° to 0.5°
- Instrumental sensitivities 5x that of Planck
- Polarization modulation and survey redundancy
- Technical Pathfinder: solutions appropriate for a space mission

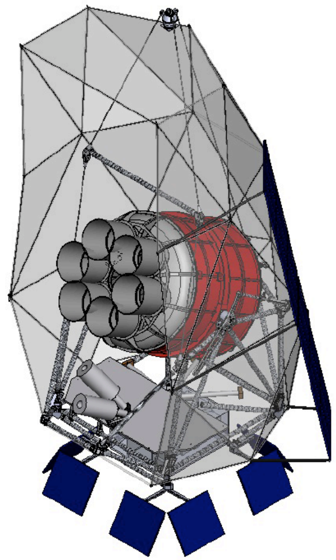


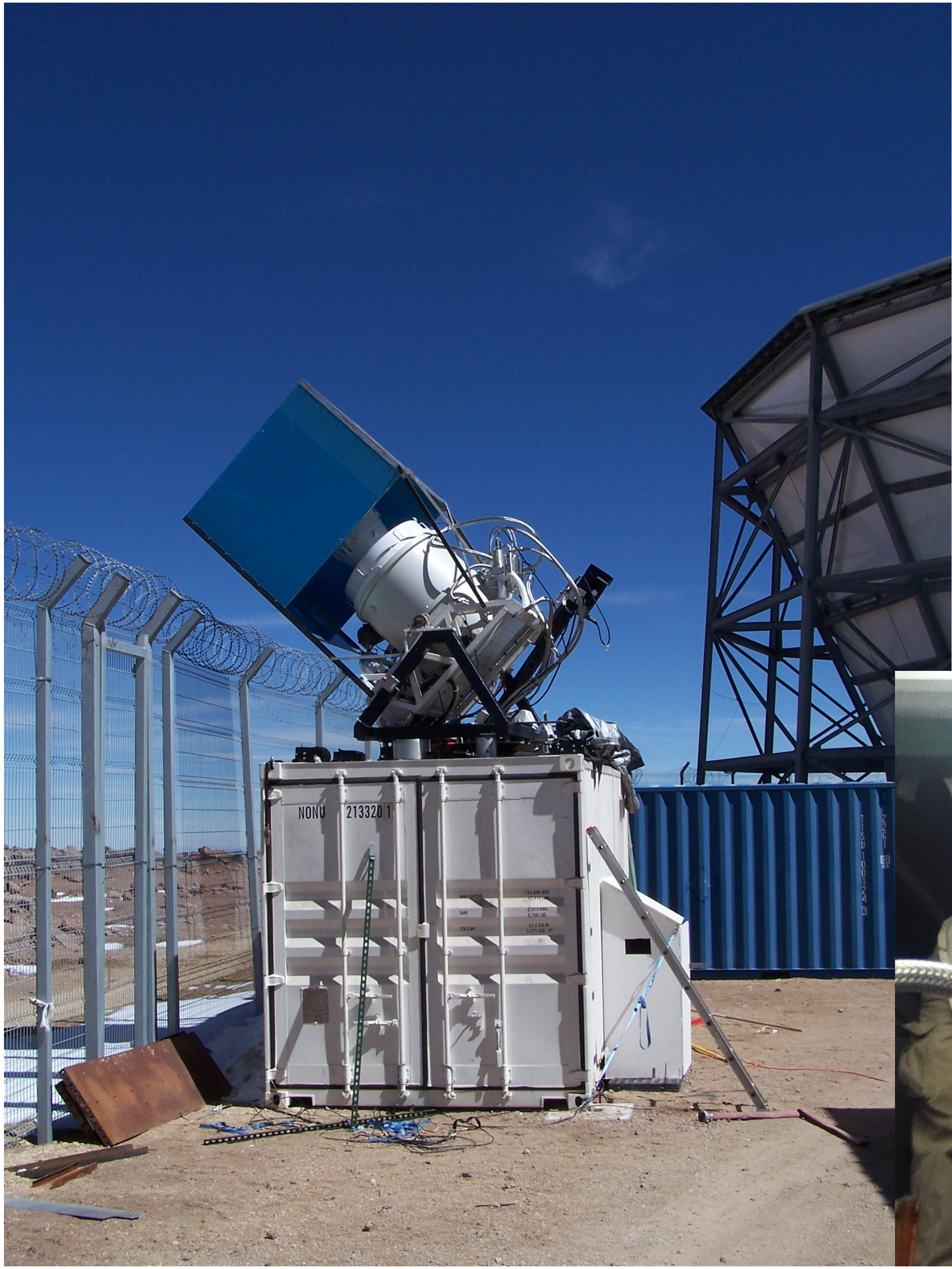
*Spider:*

- 94/150 GHz flight in 2013 (~2600 detectors)
- 8% full sky, 0.27/0.20 $\mu K_{CMB}/deg^2$
- Probing Inflation at r ~ 0.03
- Detecting weak lensing
- Detecting Galactic polarization
- Technology demonstration
- Training for young scientists





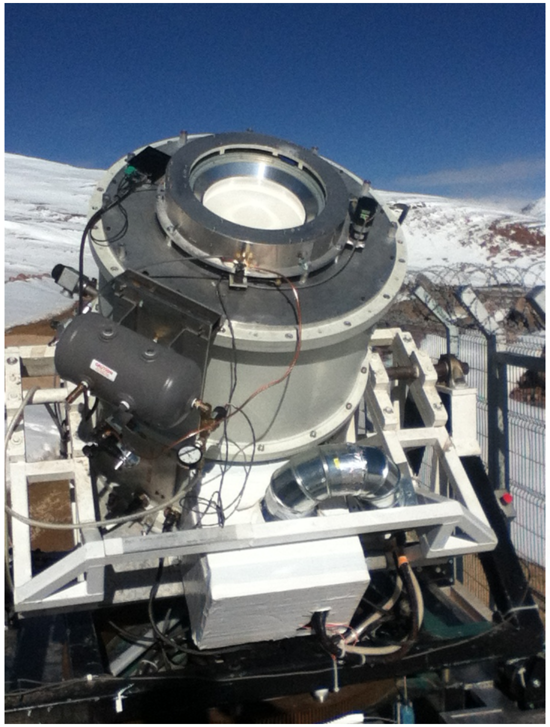


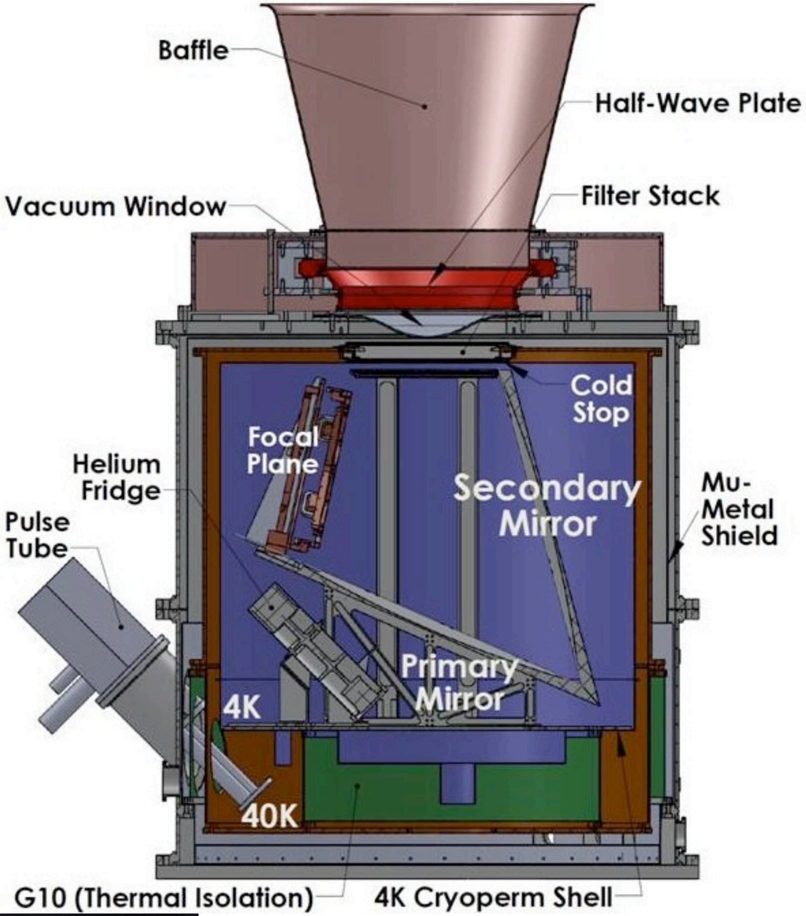

# Status of ABS

## 30 May 2012

- Arrived in Chile 1/15/2012.
- First light (moon) ~ 2/28/2012
- Calibrations, etc are ongoing
- Princeton, NIST, JHU

First Deployment Team

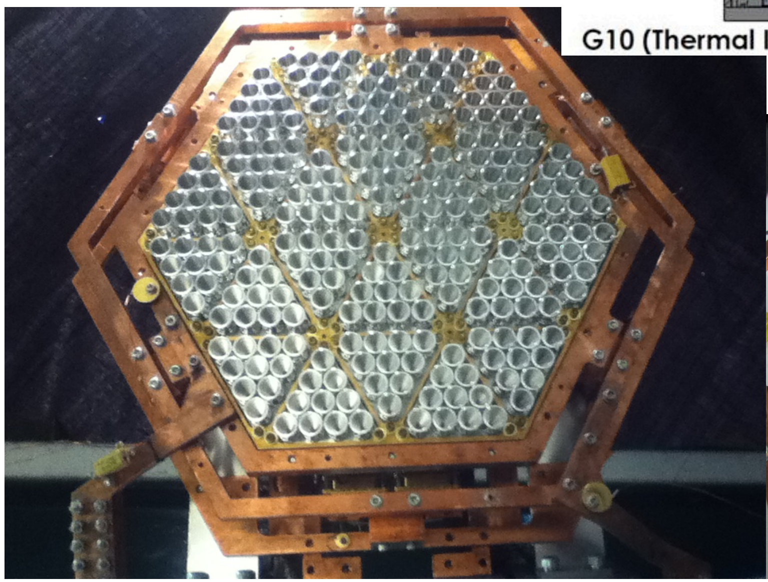


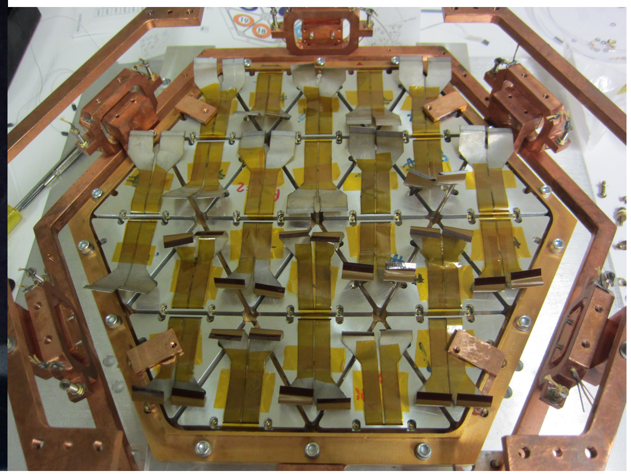



# ABS

Atacama B-mode Search

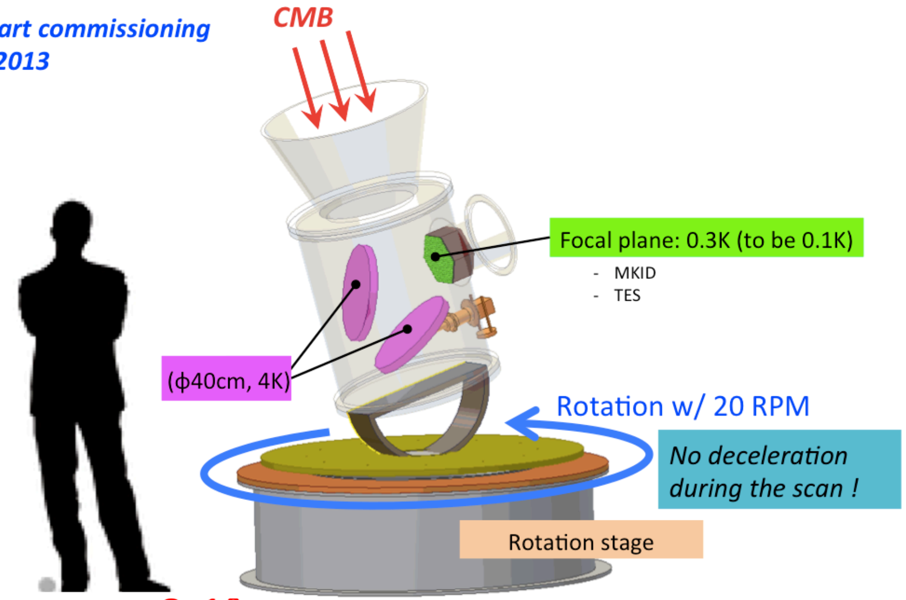
*All 150 GHz
*Low foreground parts of sky
* ~ 35 microK rt(s)
*Cold mirrors
*Warm continuously rotating HWP
*300 mK TES-based polarimeters
*Machined Al feeds





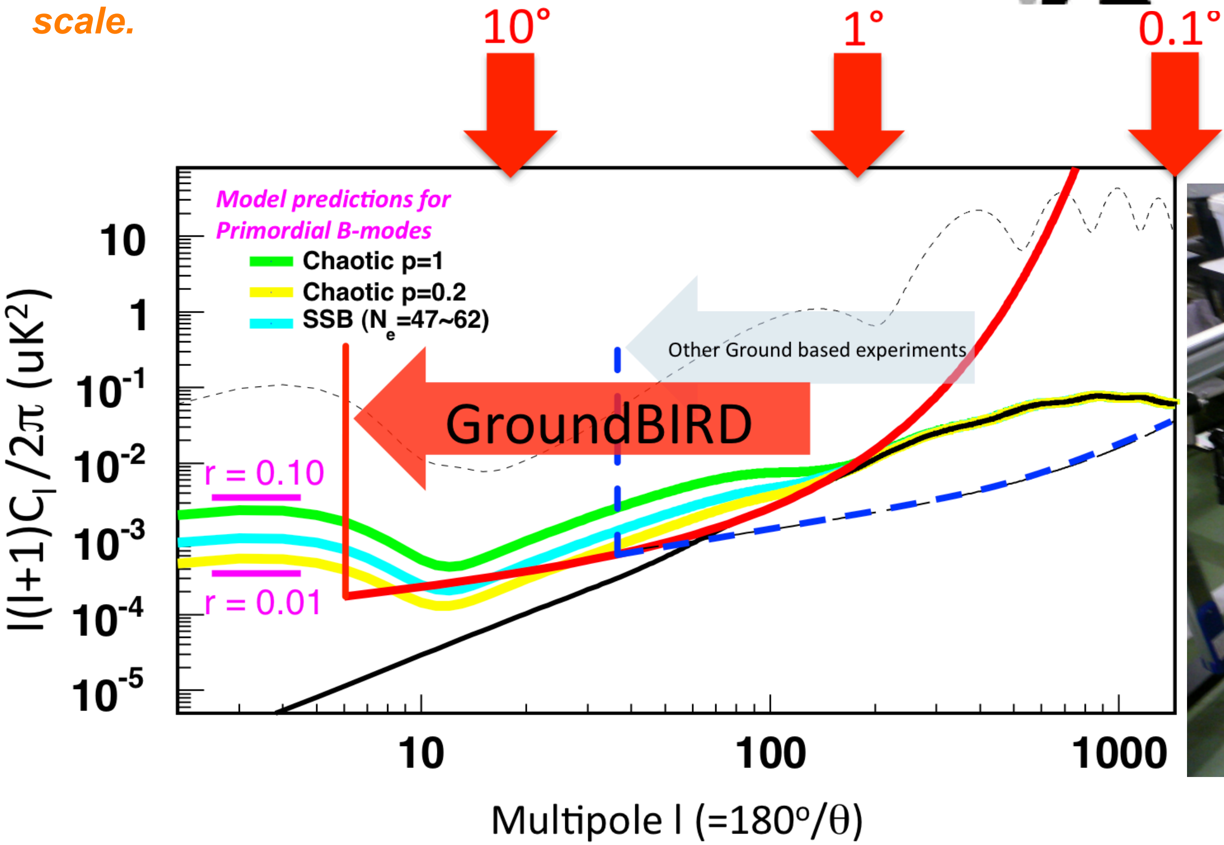
# GroundBIRD

*start commissioning ~2013*

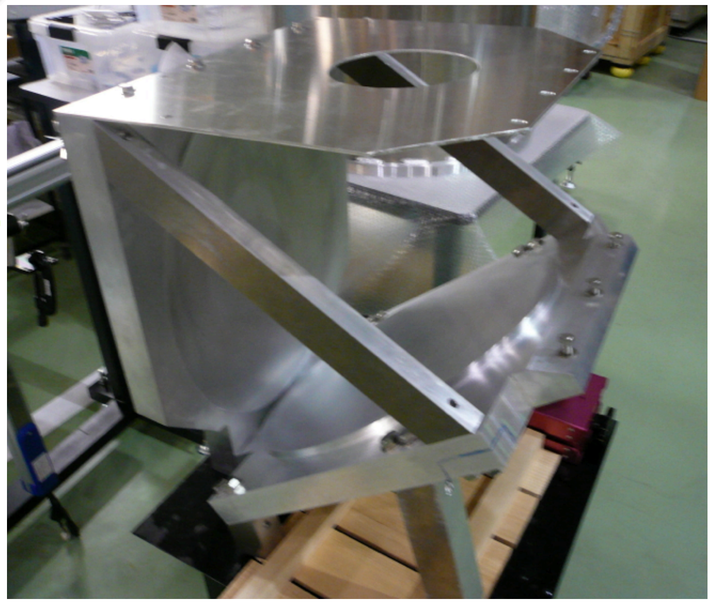



- ◆ Measurements of the primordial B-modes at a large angular scale directly constrain inflation models !!

***Large area of observation allows us to measure the B-mode power at a large angular scale.***

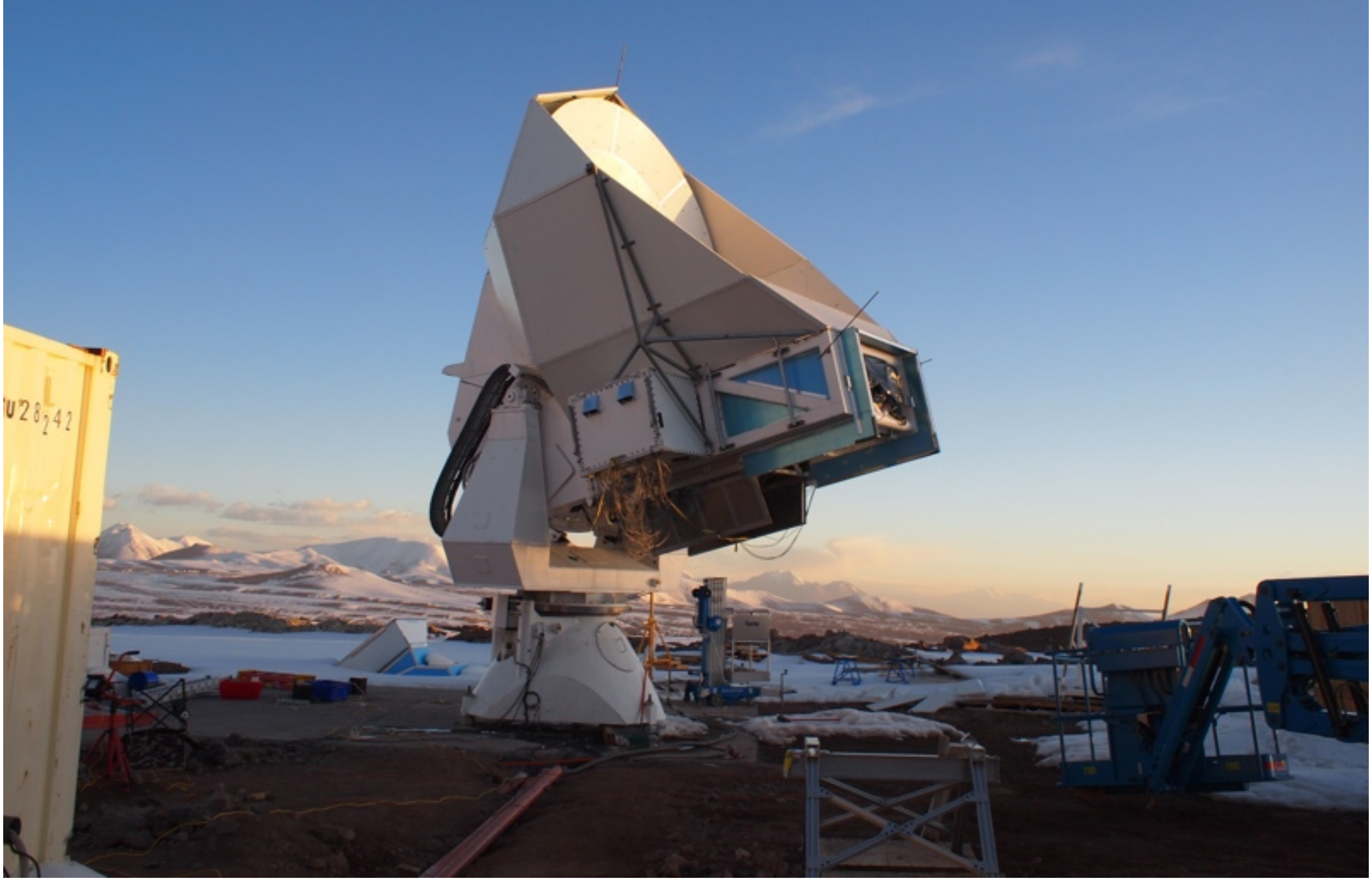



◆ Mirrors



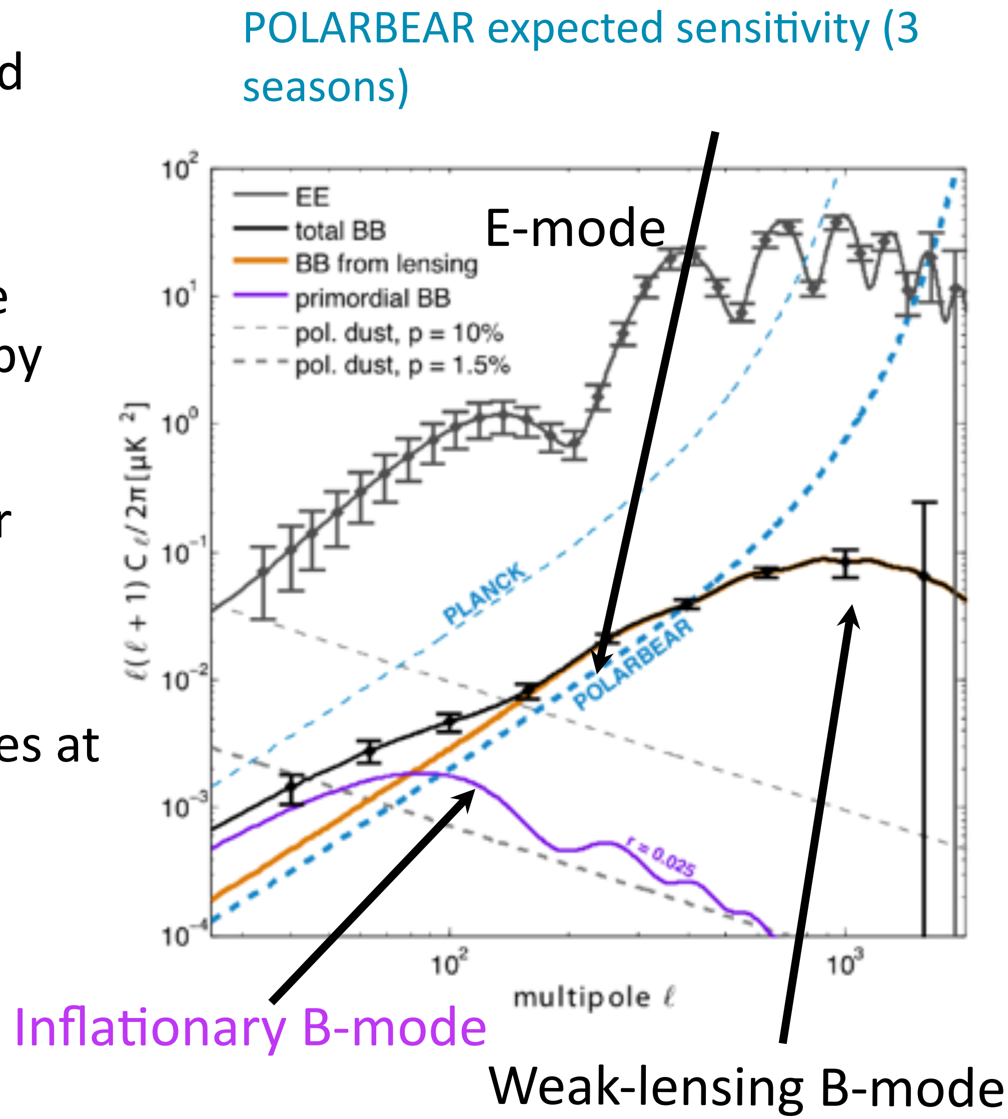
**From KEK O. Tajima**

# The POLARBEAR Experiment

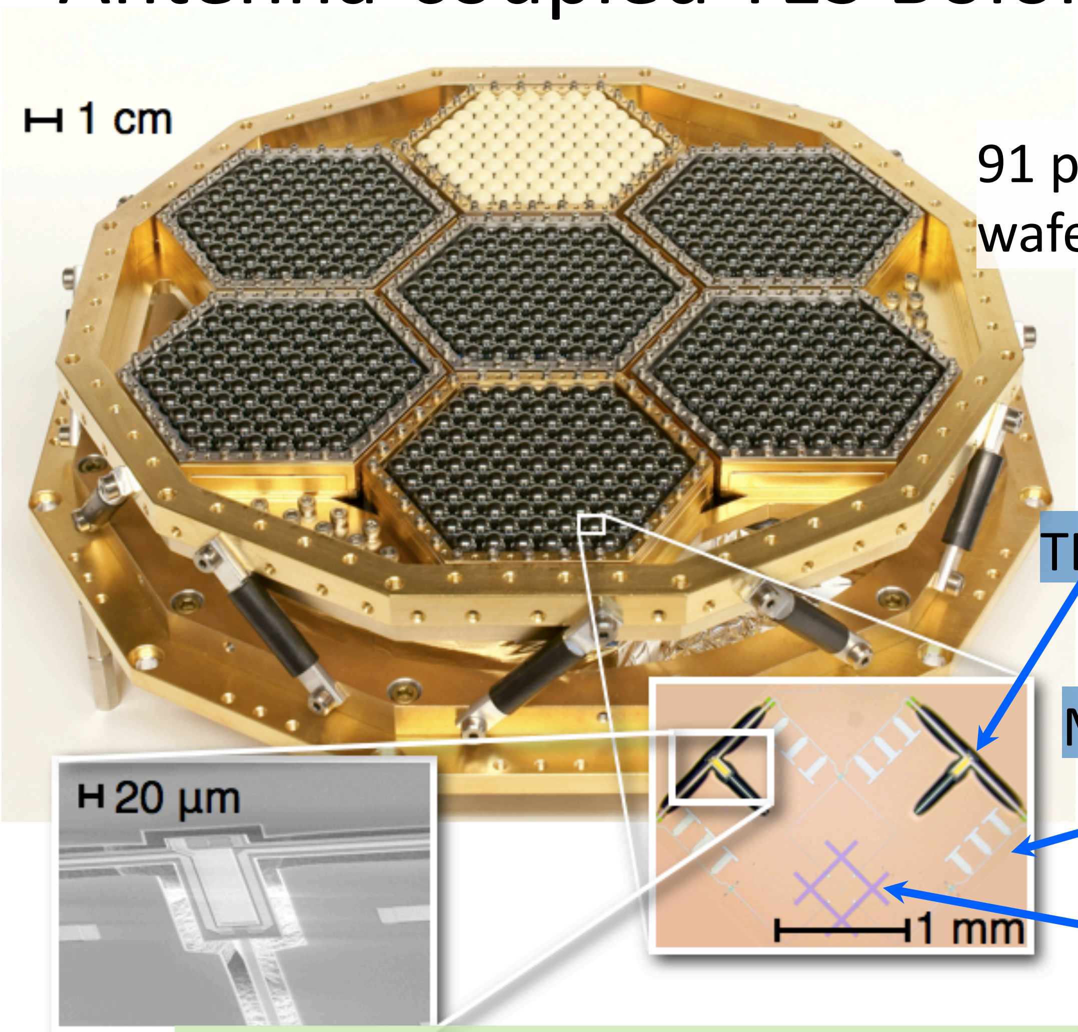


# POLARBEAR Science Goals

- POLARBEAR will measure CMB polarization with unprecedented high precision
- Prove the epoch of inflationary cosmology by detecting B-mode polarization pattern generated by primordial gravitational wave
  - sensitivity for scalar to tensor ratio *r*=0.025 (95%CL)
- Weak lensing by large scale structure also generates B-modes at smaller angular scales
  - Sensitive to sum of neutrino mass: 75 meV (68%C.L.) (combined with Planck)



# Antenna-coupled TES Bolometer Arrays




91 pixels (182 bolometers) per wafer under AR-coated lenslets

TES bolometer

Microstrip Filter (150GHz)

Dual-Polarization Slot Antenna

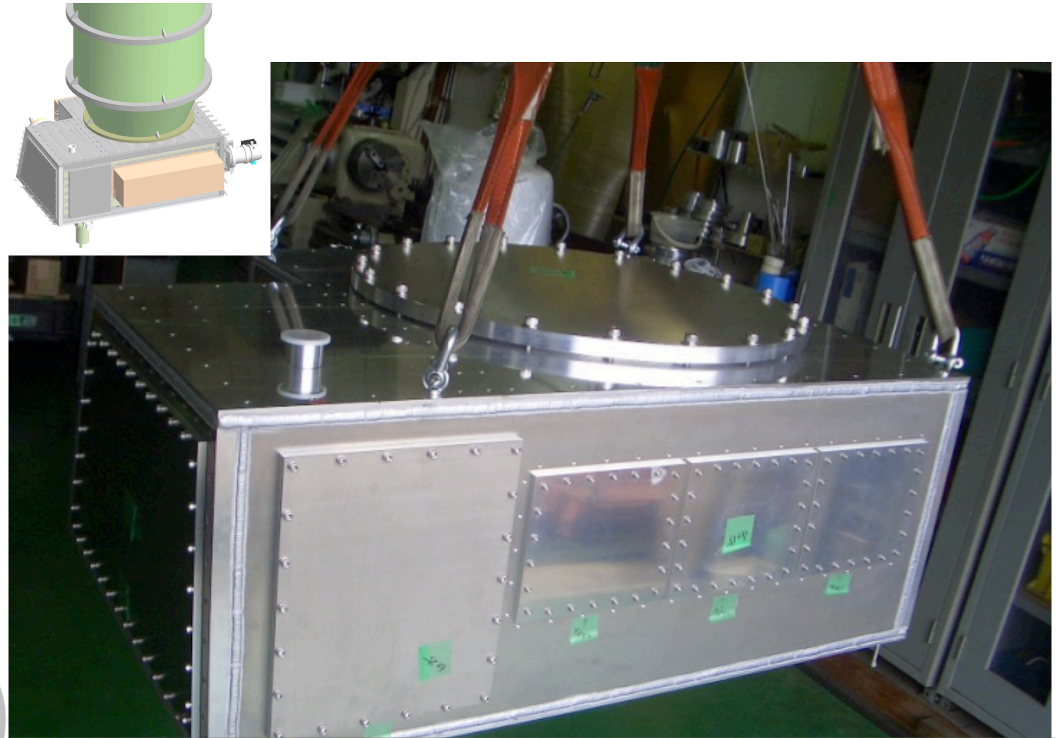
Total: 7 wafers ⇔ 637 pixels (1274 bolos)
Expected Array Sensitivity: ~13 µK√s

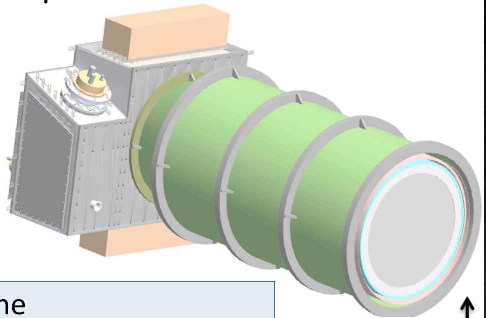
# POLARBEAR2

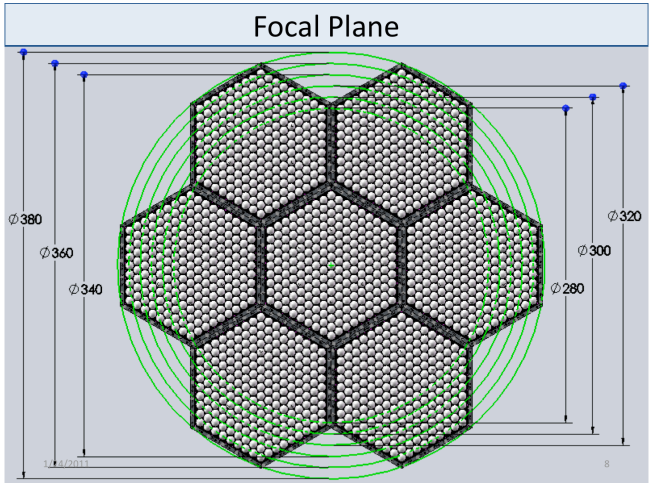
The upgrade version of POLARBEAR
and KEK lead the receiver construction.

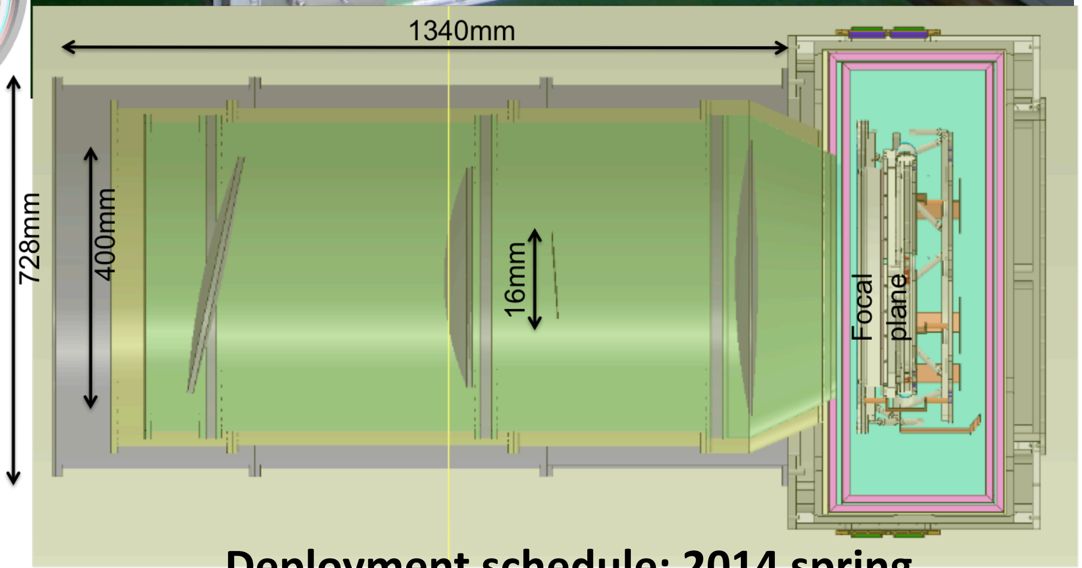
## Baseline design

- Frequency at 90 and 150GHz (3.5 arcmin at 150GHz)
- Total # of bolometers, 7588 (32 MUX)
- Going to the existing POLARBEAR telescope
- Two PTCs, receiver and optics tube.



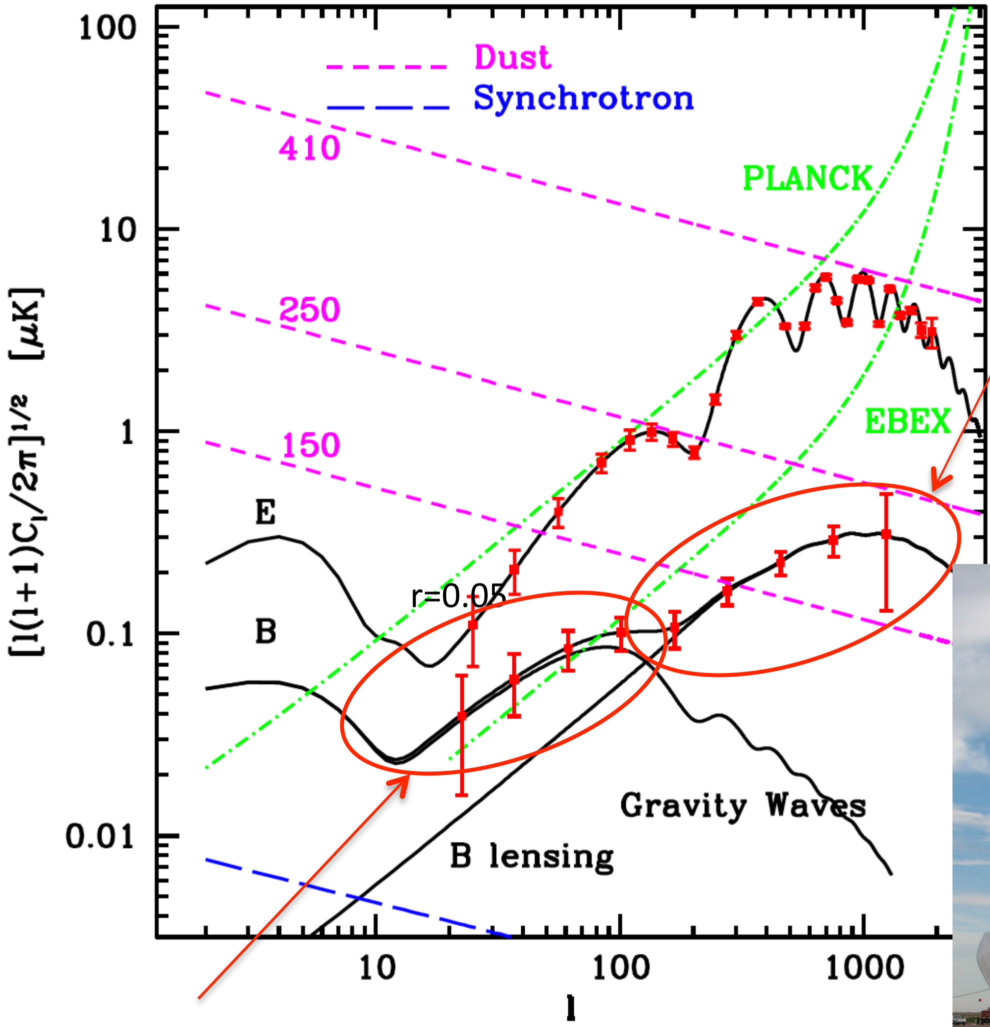





**Deployment schedule: 2014 spring**

# *EBEX*




Signal magnitude predicted within ~20%

Nearly guaranteed signal

Determination can constrain neutrino masses

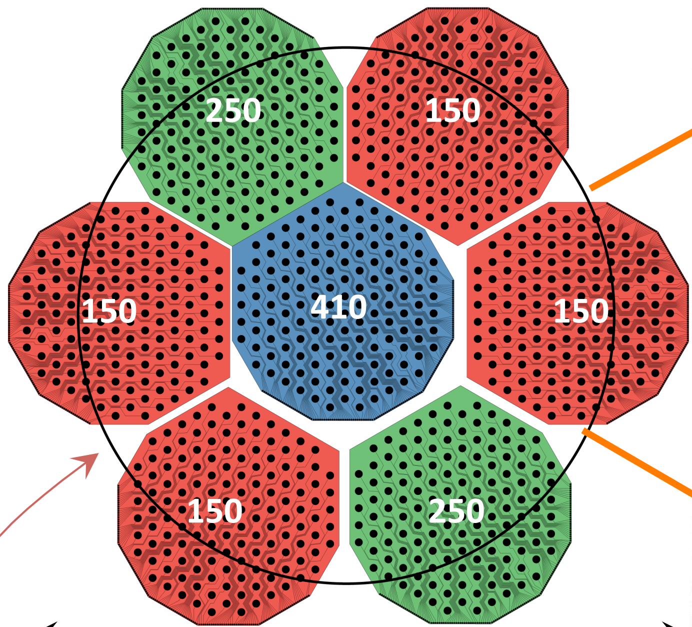
and dark energy EOS

Goal: 2σ upper limit on r=0.04

Current limit: r<0.21

# *Layout of One Focal Plane*

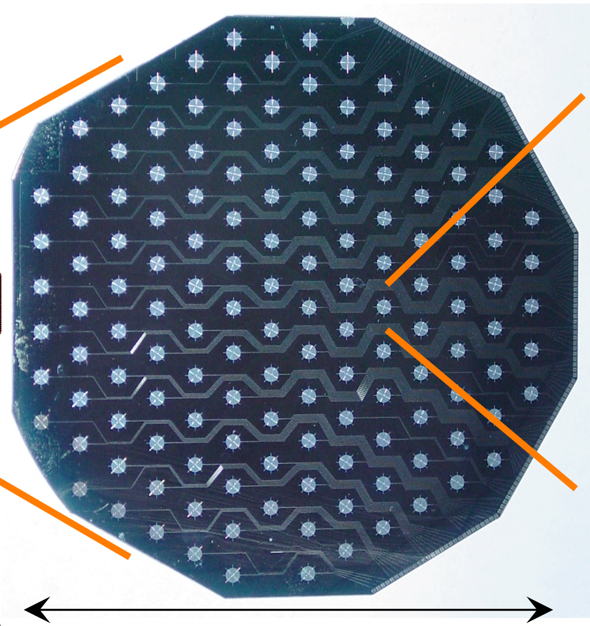
782 element array




30 cm

Strehl>0.9 at 250 GHz

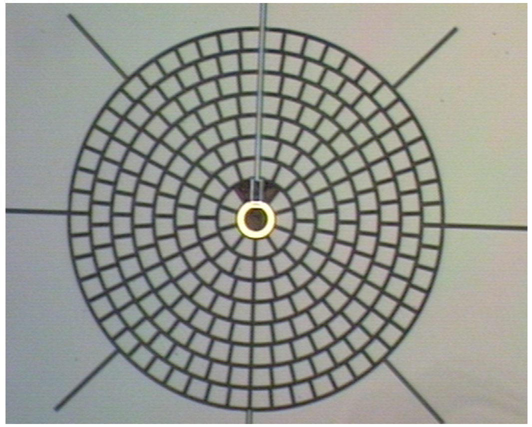
140 element decagon



8.6 cm

Single TES

Lee, UCB



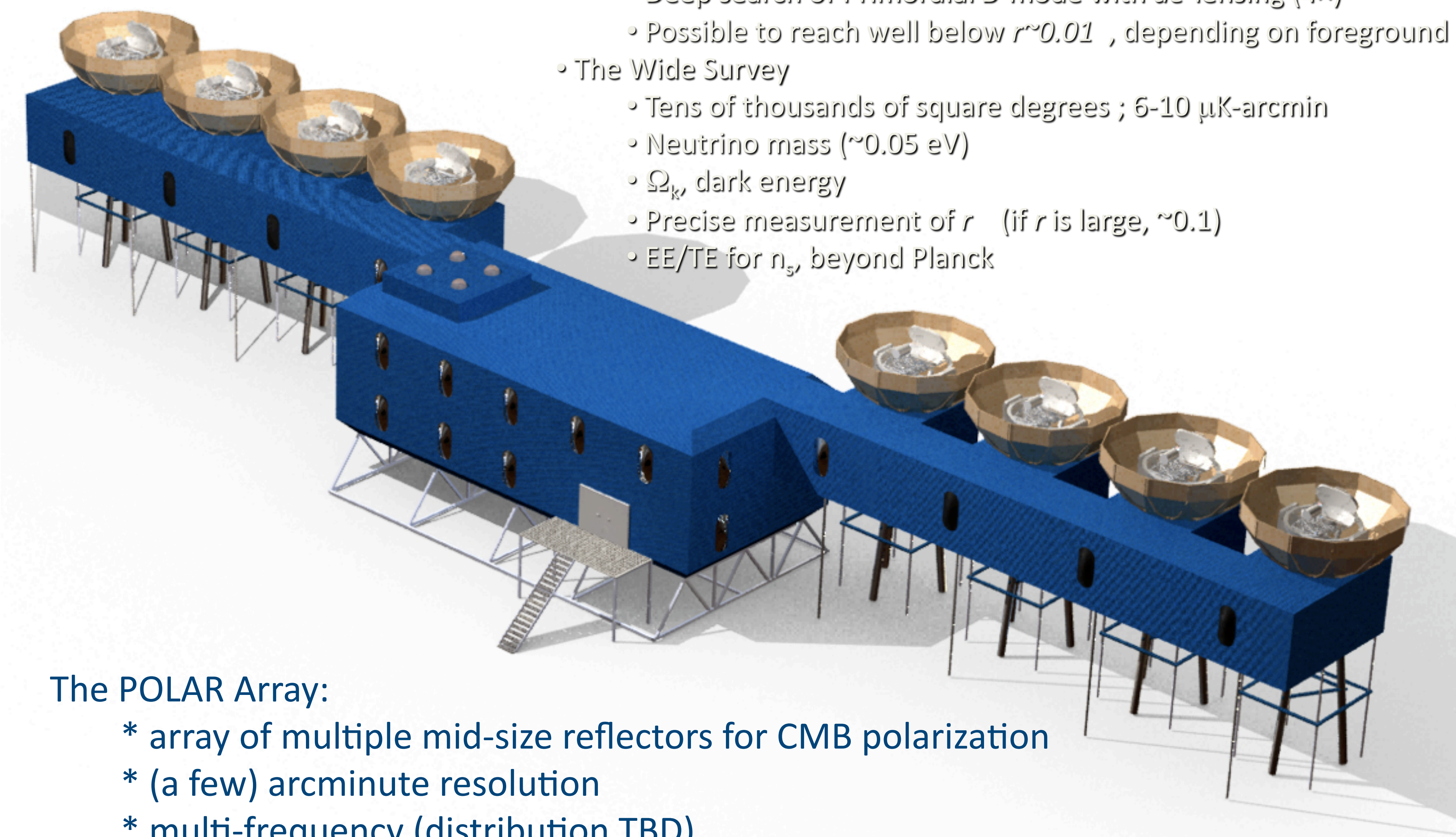
2.1 mm

- Total of 1564 transition edge sensor bolometers
    - Bath temperature = 0.27 K

**Hardware being integrated for 12/2012 flight.**

# POLAR Array

- The Deep Survey
  - 400 square degrees ; 1 μK-arcmin
  - Deep search of Primordial *B*-mode with *de*-lensing (4×)
  - Possible to reach well below *r~0.01* , depending on foreground
- The Wide Survey
  - Tens of thousands of square degrees ; 6-10 μK-arcmin
  - Neutrino mass (~0.05 eV)
  - $\Omega_k$, dark energy
  - Precise measurement of *r* (if *r* is large, ~0.1)
  - EE/TE for $n_s$, beyond Planck



The POLAR Array:

* array of multiple mid-size reflectors for CMB polarization
* (a few) arcminute resolution
* multi-frequency (distribution TBD)
* 10% the survey speed of CMBPOL

# Even after Planck, CMB Polarization presents great scientific opportunities, most of which can be accessed from the ***ground***

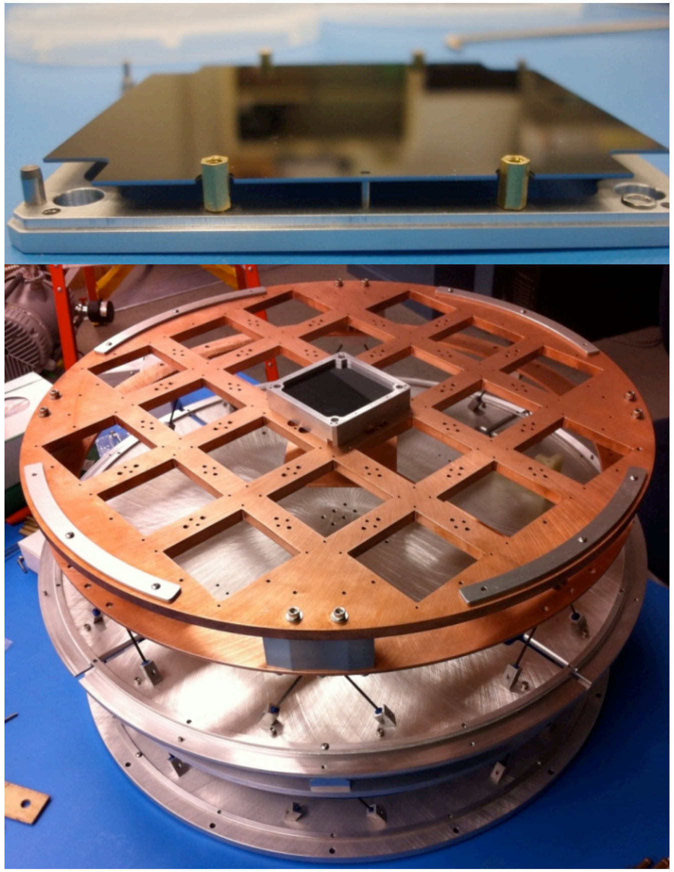
*gravitational waves*

- Tensor mode perturbation is a prediction of Inflation
- Search to *r*~0.03 at single freq.
- Search to *r*~0.01 w/ multi-freq. and lensing removal
- Precise measurement of *r*, if *r*~0.1

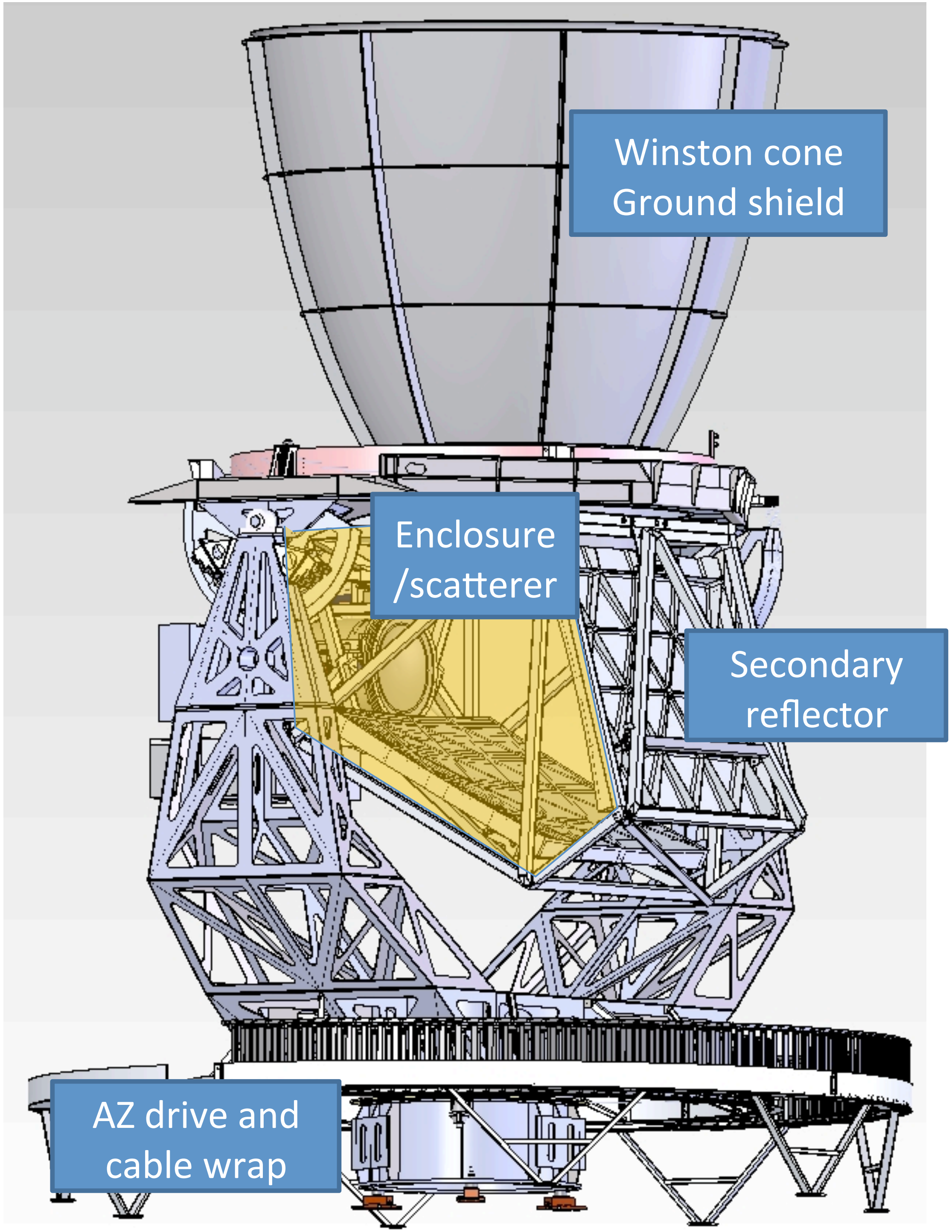
*gravitational lensing*

- A Large Scale Structure exp. at high redshift (*z*~3)
- Sensitive to neutrino mass, dark energy, spatial curvature
- Cross correlation with other astronomical measurements
- Bias calibration for optical galax. surveys

# POLAR-1 (pathfinder)

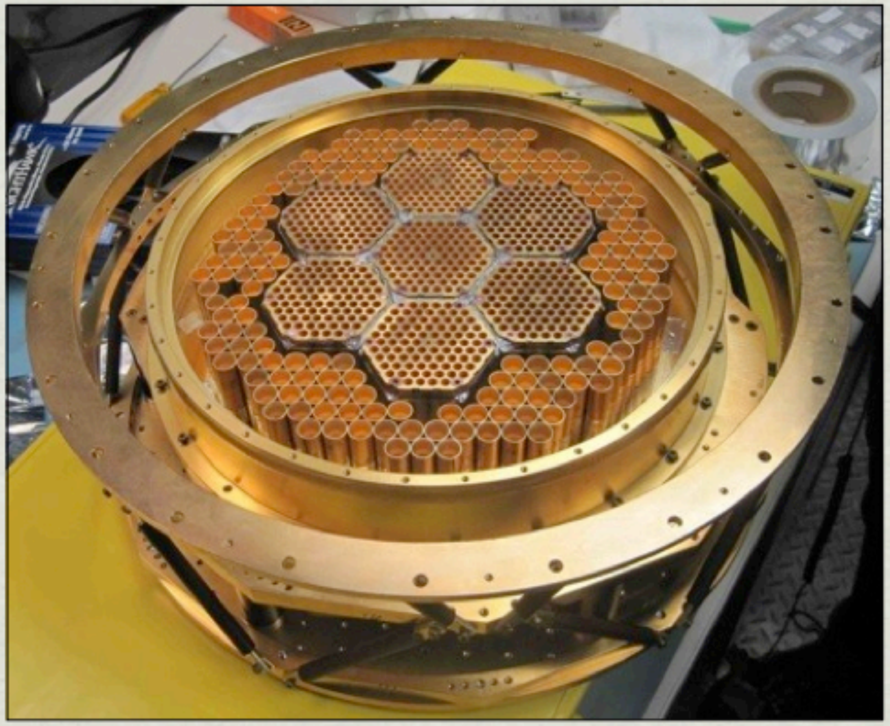


- Modular focal units, tiled together to form large focal plane
- Large $A\Omega$, simple optics
- Spillover scatterer + Winston shield
- Boresight angle rotation
- Aiming for 2013 deployment



# SPT-pol

## A new *polarization*-sensitive camera for SPT



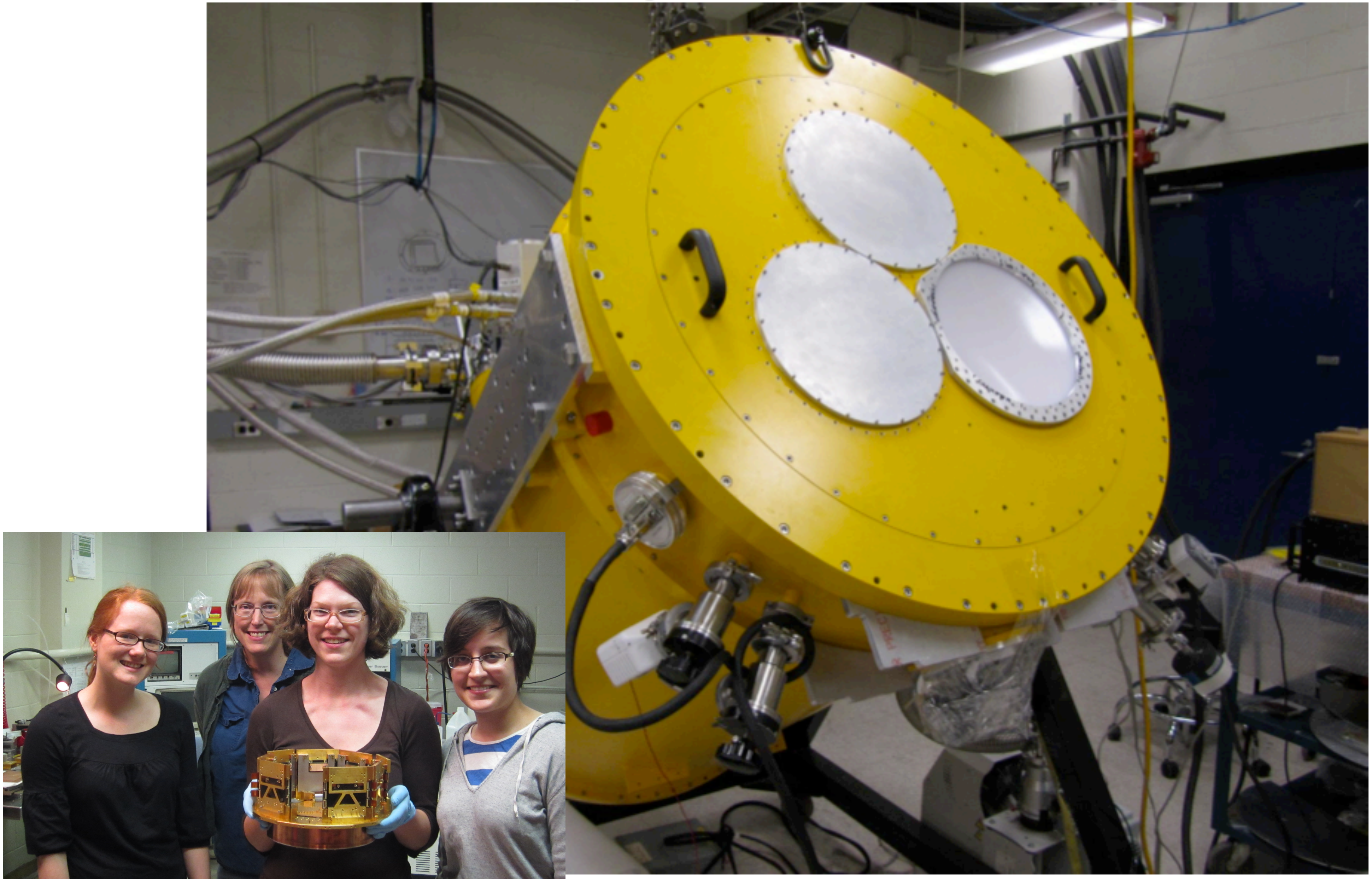
### Science targets:

- first measurement of "B-mode" polarization of CMB
- constrain neutrino mass
- constrain energy scale of inflation

### Status:

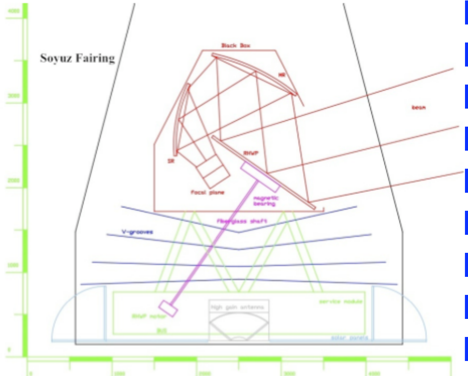
- *First light was seen in Jan. 2012.*
- Operating well.
  Potential to detect "lensing B-modes" using 2012 data.

# ACTPol PA1 Optics Tube Installation:
## Vacuum Pumping and Cooldown Configuration



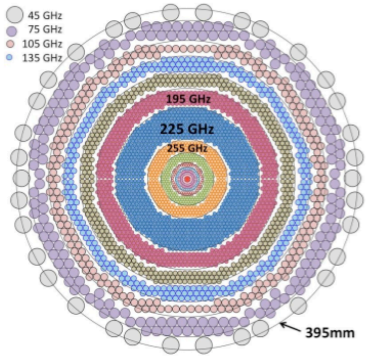
# CMB satellite after Planck

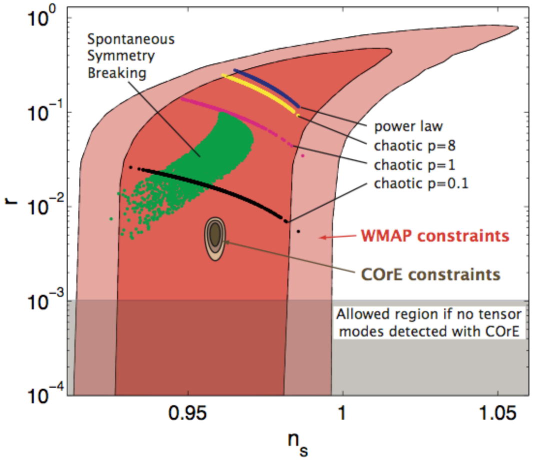
**COrE** is proposed to ESA within Cosmic Vision 2015-2025.




| $\nu$ | $(\Delta\nu)$ | $n_{det}$ | $\theta_{fwhm}$ | Temp (I) $\mu K$·arcmin | | Pol (Q,U) $\mu K$·arcmin | |
|---|---|---|---|---|---|---|---|
| $GHz$ | $GHz$ | | arcmin | RJ | CMB | RJ | CMB |
| 45 | 15 | 64 | 23.3 | 4.98 | 5.25 | 8.61 | 9.07 |
| 75 | 15 | 300 | 14.0 | 2.36 | 2.73 | 4.09 | 4.72 |
| 105 | 15 | 400 | 10.0 | 2.03 | 2.68 | 3.50 | 4.63 |
| 135 | 15 | 550 | 7.8 | 1.68 | 2.63 | 2.90 | 4.55 |
| 165 | 15 | 750 | 6.4 | 1.38 | 2.67 | 2.38 | 4.61 |
| 195 | 15 | 1150 | 5.4 | 1.07 | 2.63 | 1.84 | 4.54 |
| 225 | 15 | 1800 | 4.7 | 0.82 | 2.64 | 1.42 | 4.57 |
| 255 | 15 | 575 | 4.1 | 1.40 | 6.08 | 2.43 | 10.5 |
| 285 | 15 | 375 | 3.7 | 1.70 | 10.1 | 2.94 | 17.4 |
| 315 | 15 | 100 | 3.3 | 3.25 | 26.9 | 5.62 | 46.6 |
| 375 | 15 | 64 | 2.8 | 4.05 | 68.6 | 7.01 | 119 |
| 435 | 15 | 64 | 2.4 | 4.12 | 149 | 7.12 | 258 |
| 555 | 195 | 64 | 1.9 | 1.23 | 227 | 3.39 | 626 |
| 675 | 195 | 64 | 1.6 | 1.28 | 1320 | 3.52 | 3640 |
| 795 | 195 | 64 | 1.3 | 1.31 | 8070 | 3.60 | 22200 |

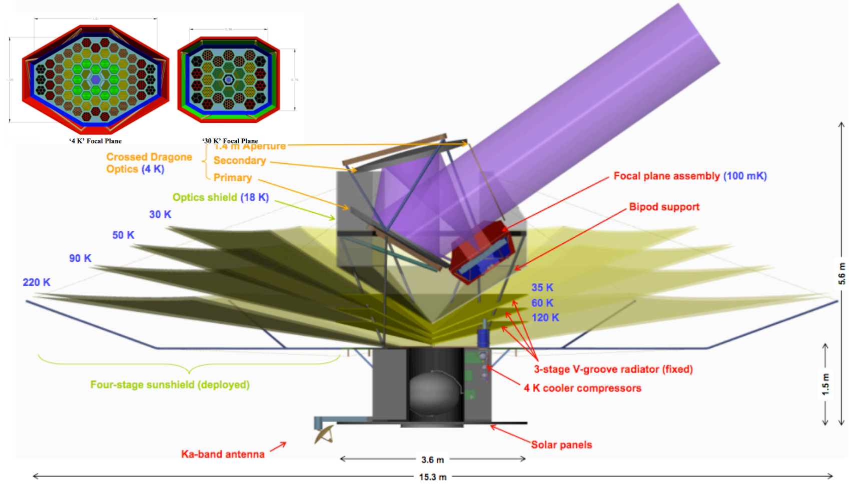
COrE summary (4 year mission)




From COrE white paper

**EPIC-IM,** US(JPL) based CMB satellite.



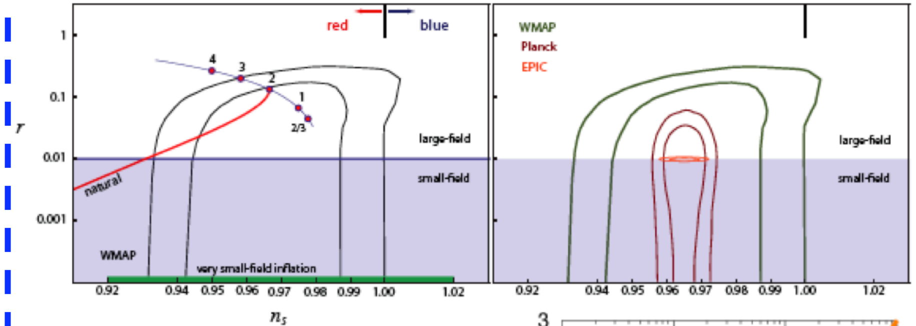
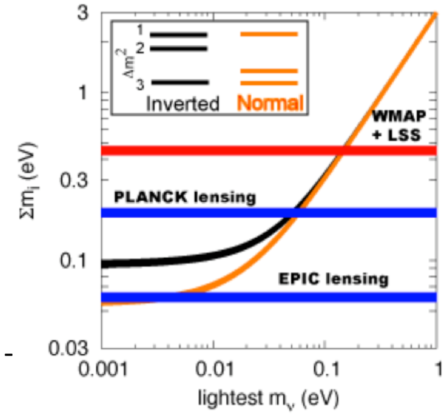



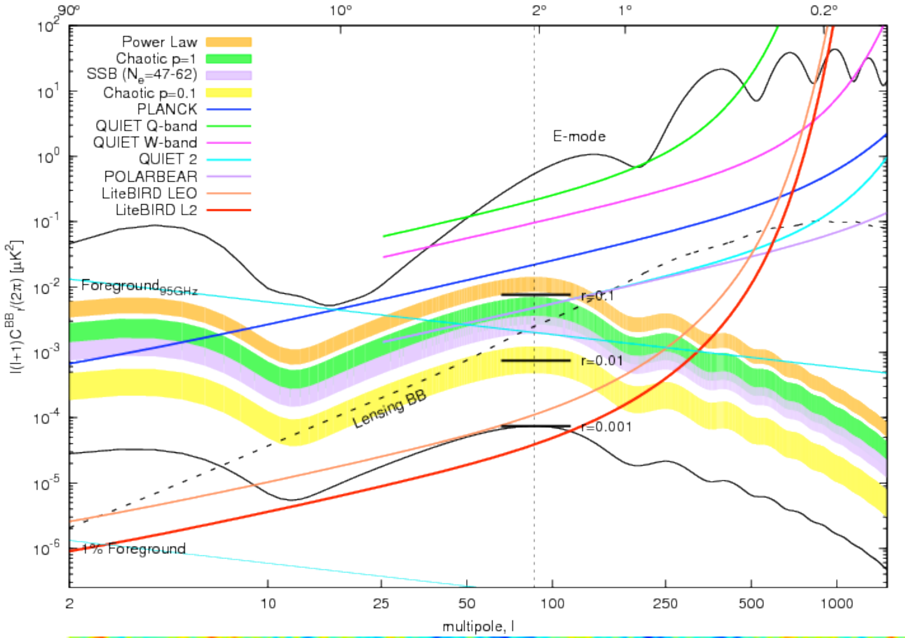

Table 3.2 EPIC-IM Bands and Sensitivities

| Freq [GHz] | $\theta_{FWHM}$ [′] | 4 K Telescope Option: $N_{bol}$[a] [#] | NET [μK√s] bolo[b] | NET [μK√s] band[c] | $w_p^{-1/2}$ [μK-′][d] | $\delta T_{pix}$[e] [nK] | 30 K Telescope Option: $N_{bol}$[a] [#] | NET [μK√s] bolo[b] | NET [μK√s] band[c] | $w_p^{-1/2}$ [μK-′][d] | $\delta T_{pix}$[e] [nK] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | 28 | 84 | 84 | 9.2 | 14 | 83 | 24 | 83 | 17 | 26 | 150 |
| 45 | 19 | 364 | 71 | 3.7 | 5.7 | 34 | 84 | 70 | 8 | 12 | 69 |
| 70 | 12 | 1332 | 60 | 1.6 | 2.5 | 15 | 208 | 60 | 4.1 | 6.4 | 37 |
| 100 | 8.4 | 2196 | 54 | 1.1 | 1.8 | 10 | 444 | 55 | 2.6 | 4.0 | 24 |
| 150 | 5.6 | 3048 | 52 | 0.9 | 1.4 | 8 | 516 | 57 | 2.5 | 3.8 | 23 |
| 220 | 3.8 | 1296 | 59 | 1.6 | 2.5 | 15 | 408 | 77 | 3.8 | 5.8 | 34 |
| 340 | 2.5 | 744 | 100 | 3.7 | 5.6 | 33 | 120 | 220 | 20 | 30 | 180 |
| 500 | 1.7 | 1092 | 350 | 10 | 16 (140)[f] | 8[g] | 108 | 1500 | 170 | 260 (2000)[f] | 140[g] |
| 850 | 1.0 | 938 | 15000 | 280 | 740 (70)[f] | 7[g] | 110 | 250k | 24k | 40k (3000)[f] | 340[g] |
| **Total[h]** | | **11094** | | **0.6** | **0.9** | **5.4** | **2022** | | **1.5** | **2.3** | **13** |

From Study of the Experimental Probe of Inflationary Cosmology - Intermediate Mission for NASA's Einstein Inflation Probe

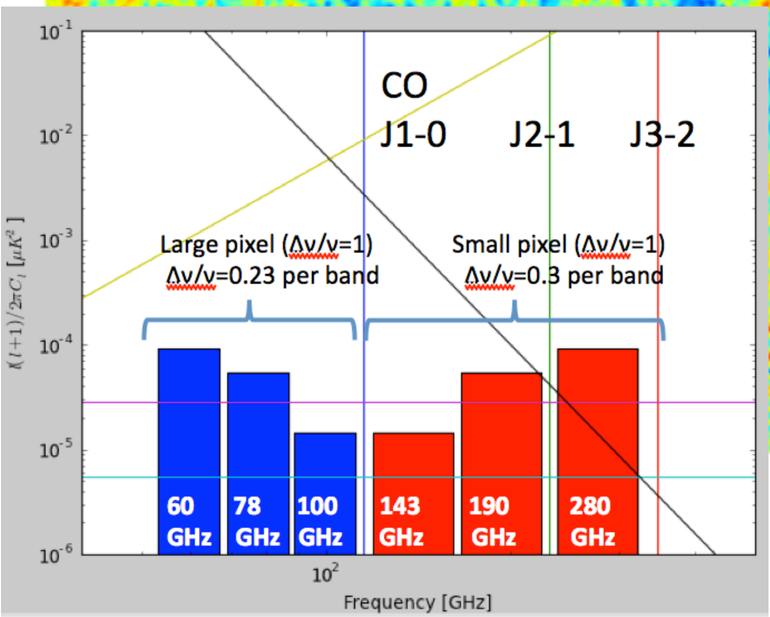


# CMB satellite after Planck: LiteBIRD

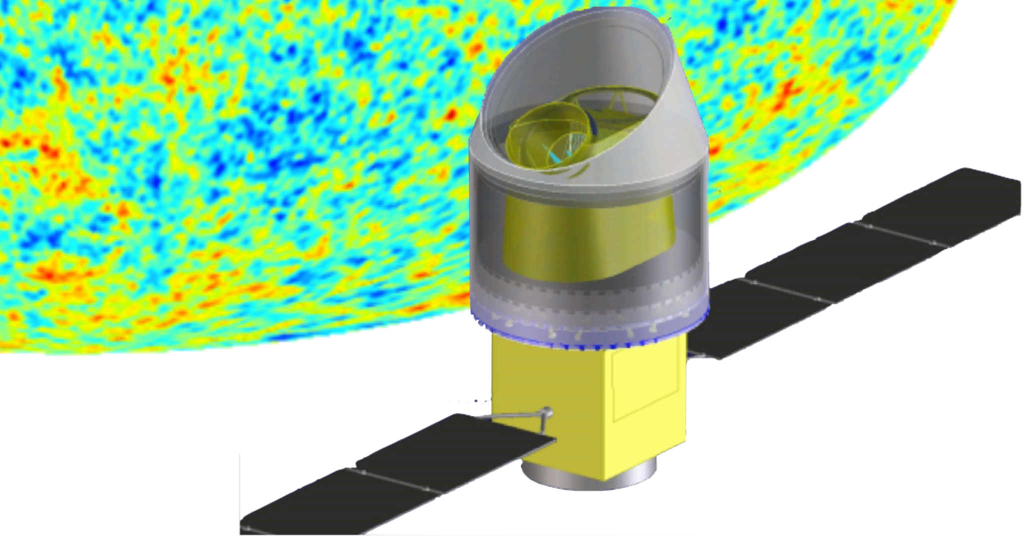



**LiteBIRD** probes the footprint of the inflation in the CMB polarization with the sensitivity of $\boldsymbol{\delta r}$**>0.001**. This enables us testing major single field inflation models ($r$>0.002 from the Lyth bound).

The design philosophy is to minimize the satellite size and maximize the sensitivity to the primordial B-mode detection.




**LiteBIRD: A small CMB satellite probing the primordial gravitational-wave B-mode**



# Summary

The measurements of the CMB already started to constrain some models of inflation. The current WMAP+SPT limit is $r$ <0.21.

A number of ground based and balloon-borne CMB polarization experiments are observing, deploying, and in design stage. Their aim is $r \sim 0.01$.

The CMB future satellite concepts are put together to pursue for the ultimate measurements of B-mode polarization, $r \sim 0.001$.

Lensing B-mode also provides a tool to study such as neutrino mass.