# Cosmic Microwave Background past and future

June 3rd, 2016
28th Rencontres de Blois

Akito KUSAKA
Lawrence Berkeley National Laboratory

Light New Particle?

TeV

Higgs

$5^{th}$ force?

Yukawa

Inflation

$\nu$

Dark Energy

$\bar{B}/B$

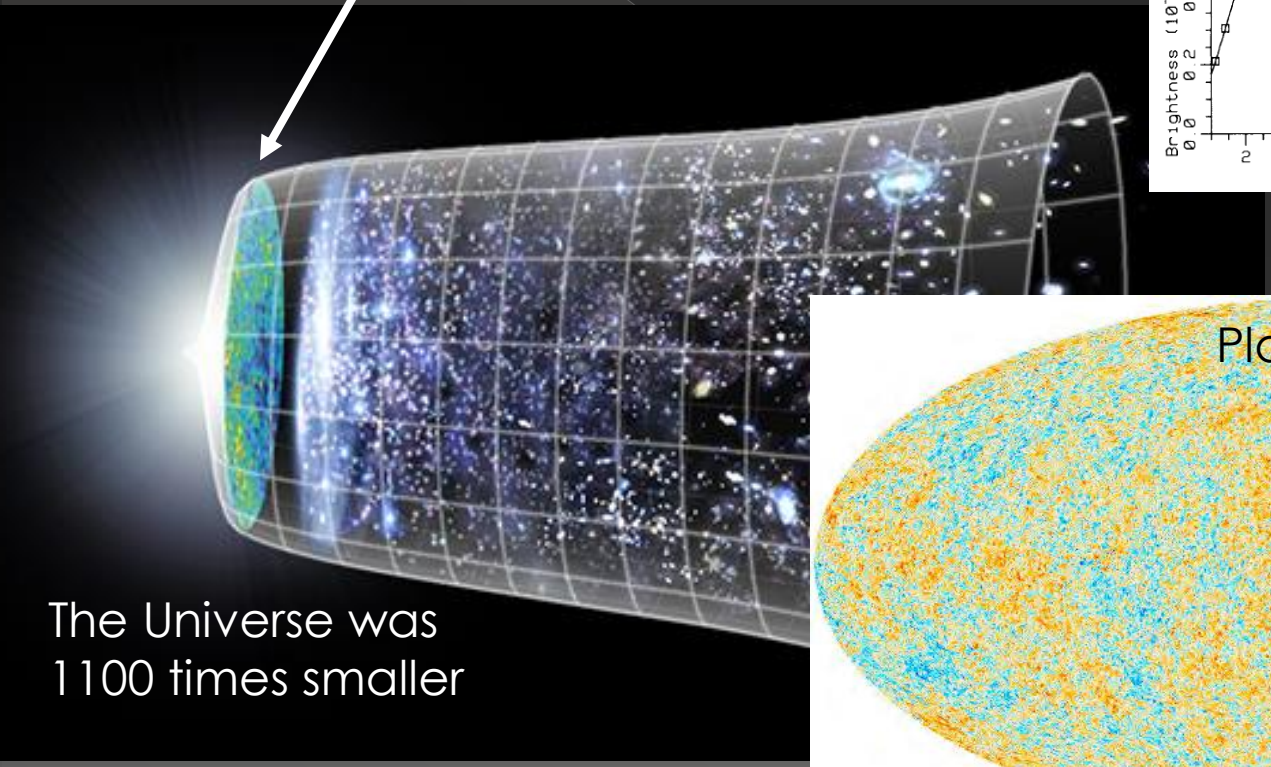
Dark Matter

My summary of "Snowmass Questions" 2014

# What is CMB?

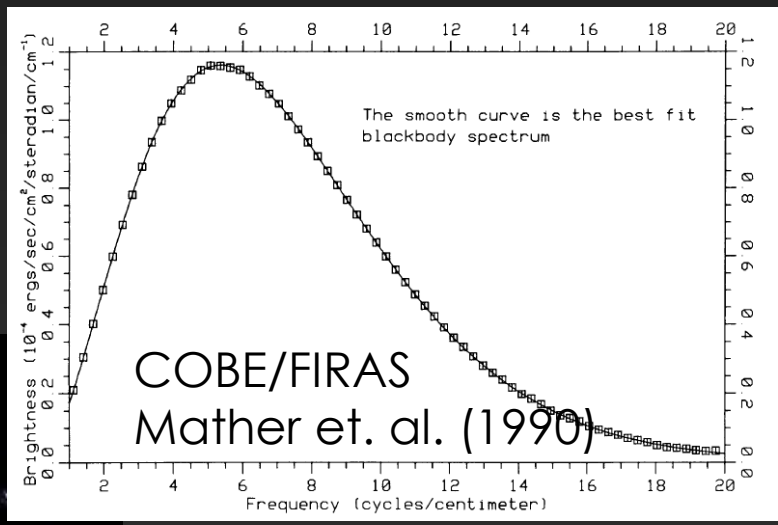
Light from Last Scattering Surface

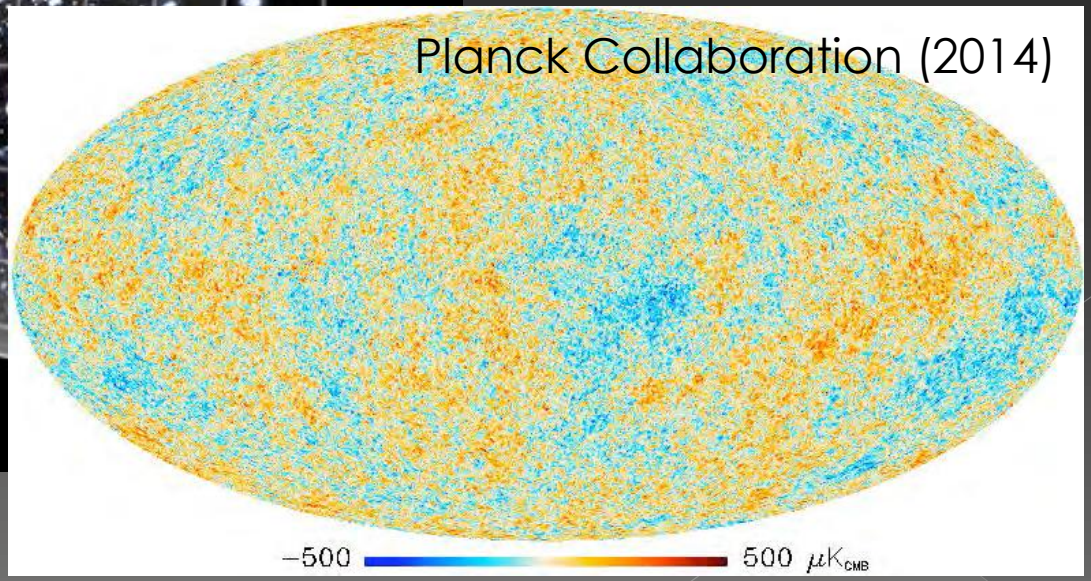
LSS: Boundary between plasma and neutral H



The Universe was
1100 times smaller

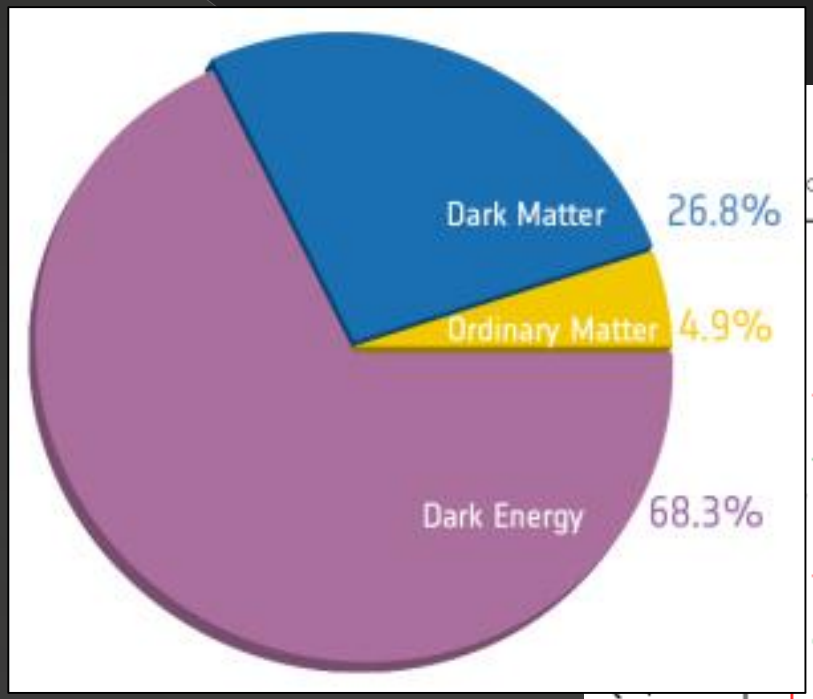
2.7K blackbody



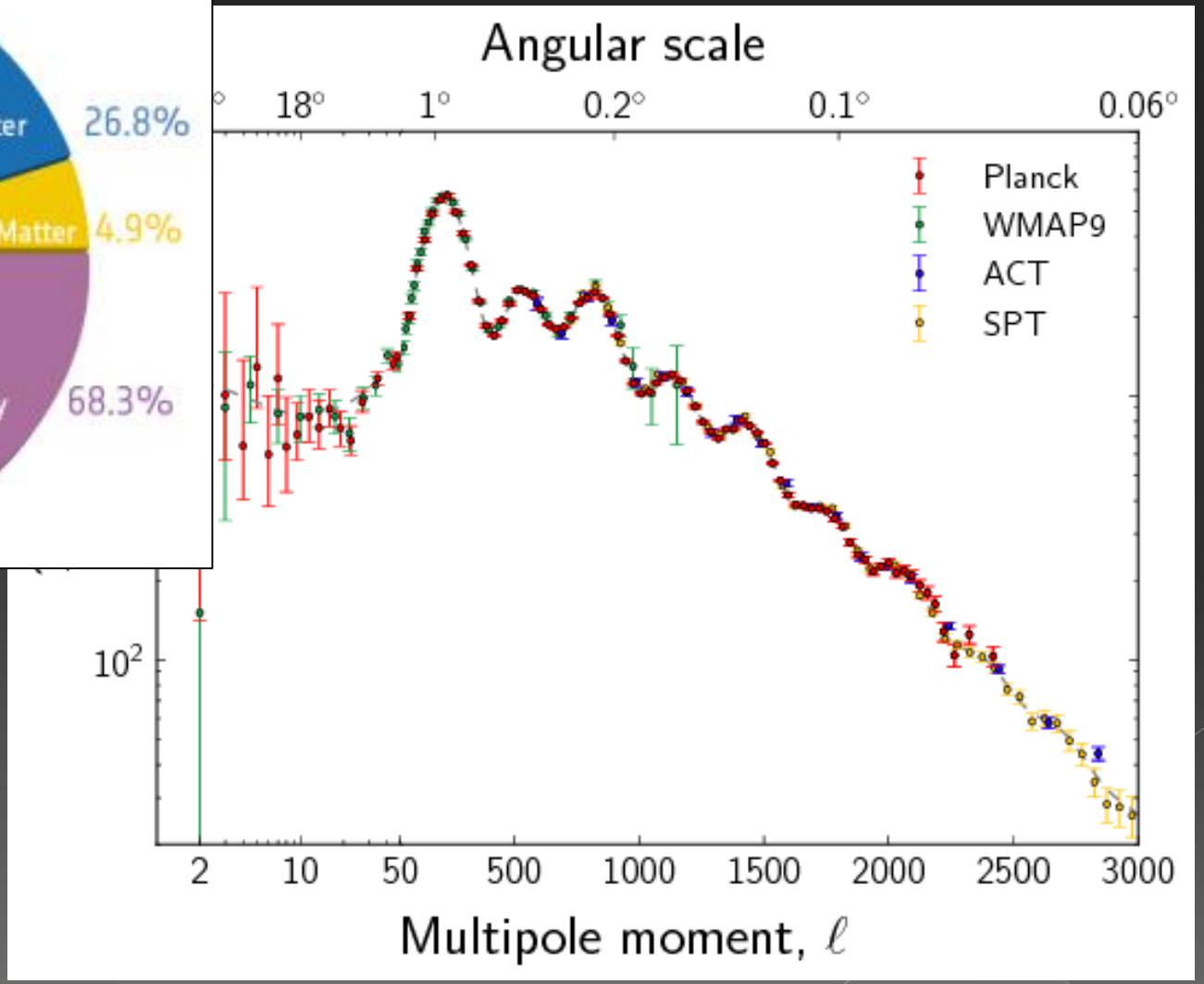

Fluctuations seeding "us"

# 2015




Planck Collaboration (2015)

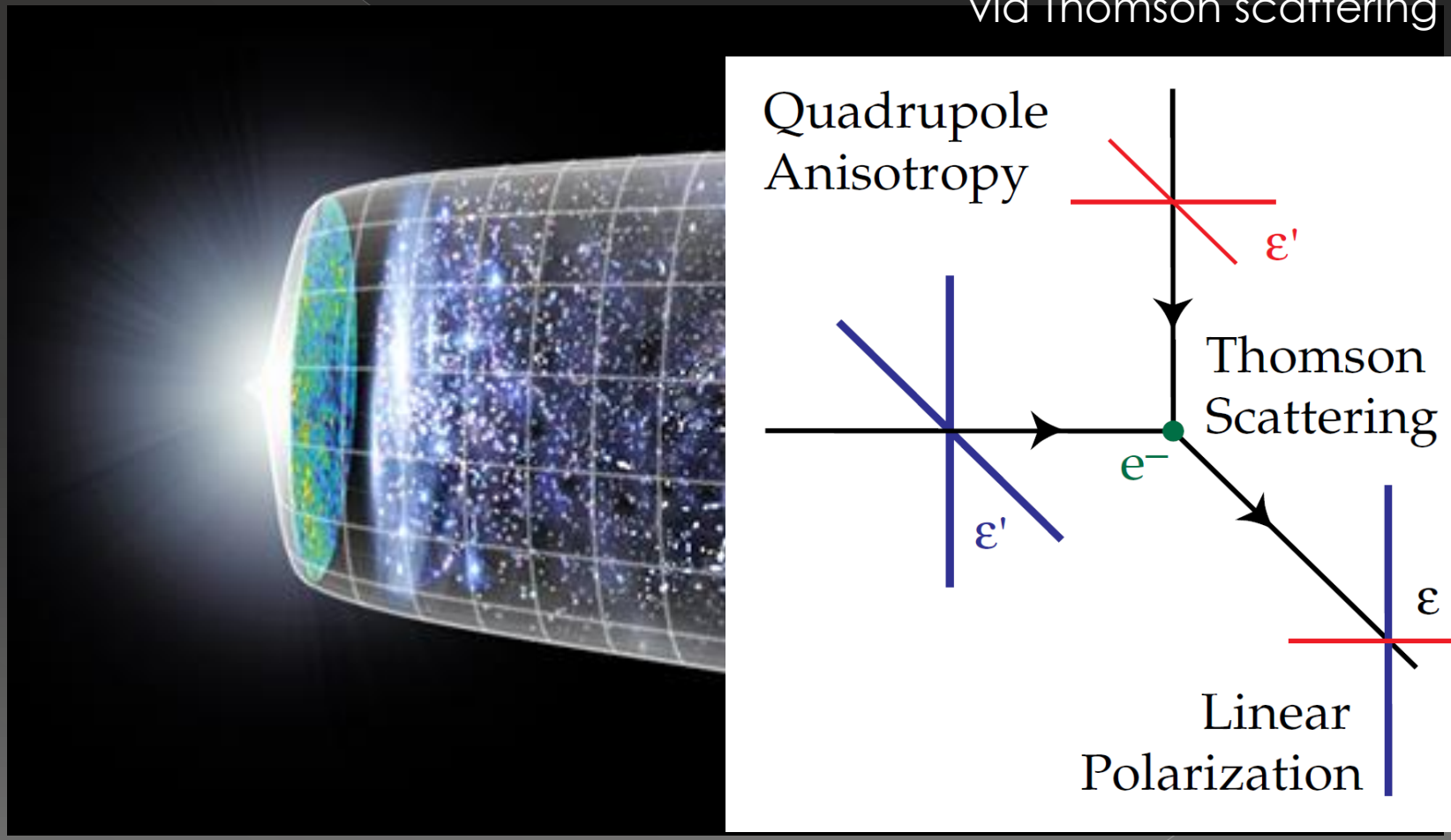
$\Omega_k = 0 \pm 0.005$ (w/ BAO)
Gaussian




Planck Collaboration (2014)

# Polarization

Quadrupole anisotropy creates linear polarization via Thomson scattering

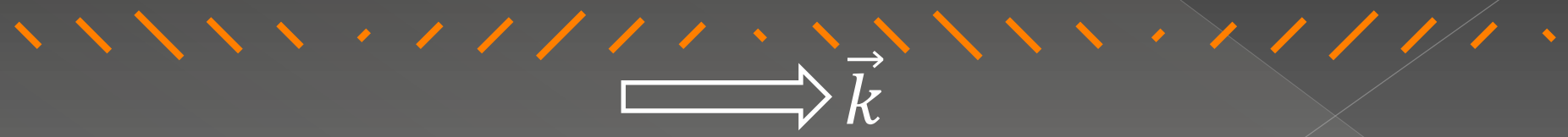



http://background.uchicago.edu/~whu/polar/webversion/polar.html

# Polarization – E modes and B modes

*E* modes: curl free component

*B* modes: divergence free component

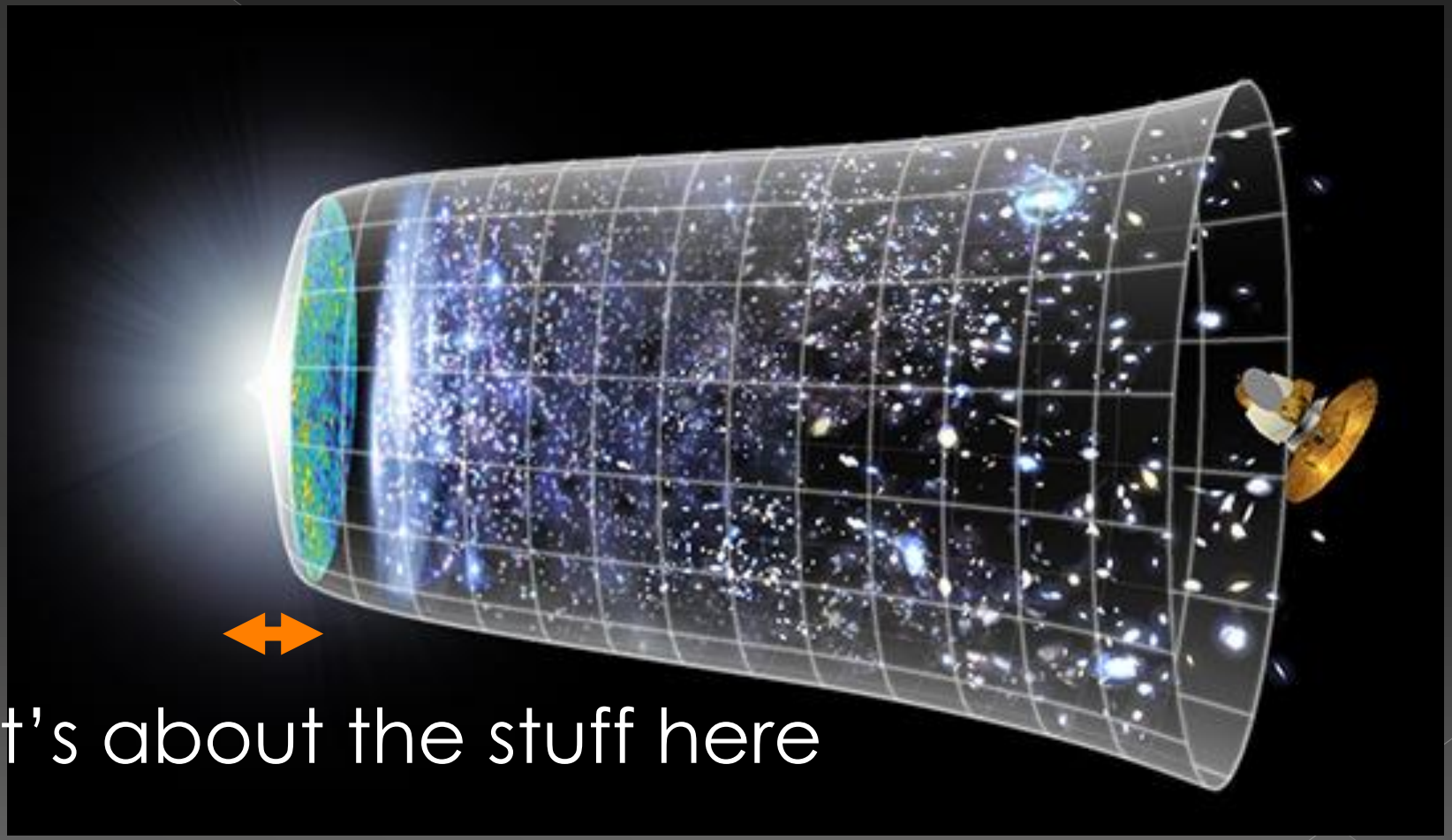


# CMB Polarization Science

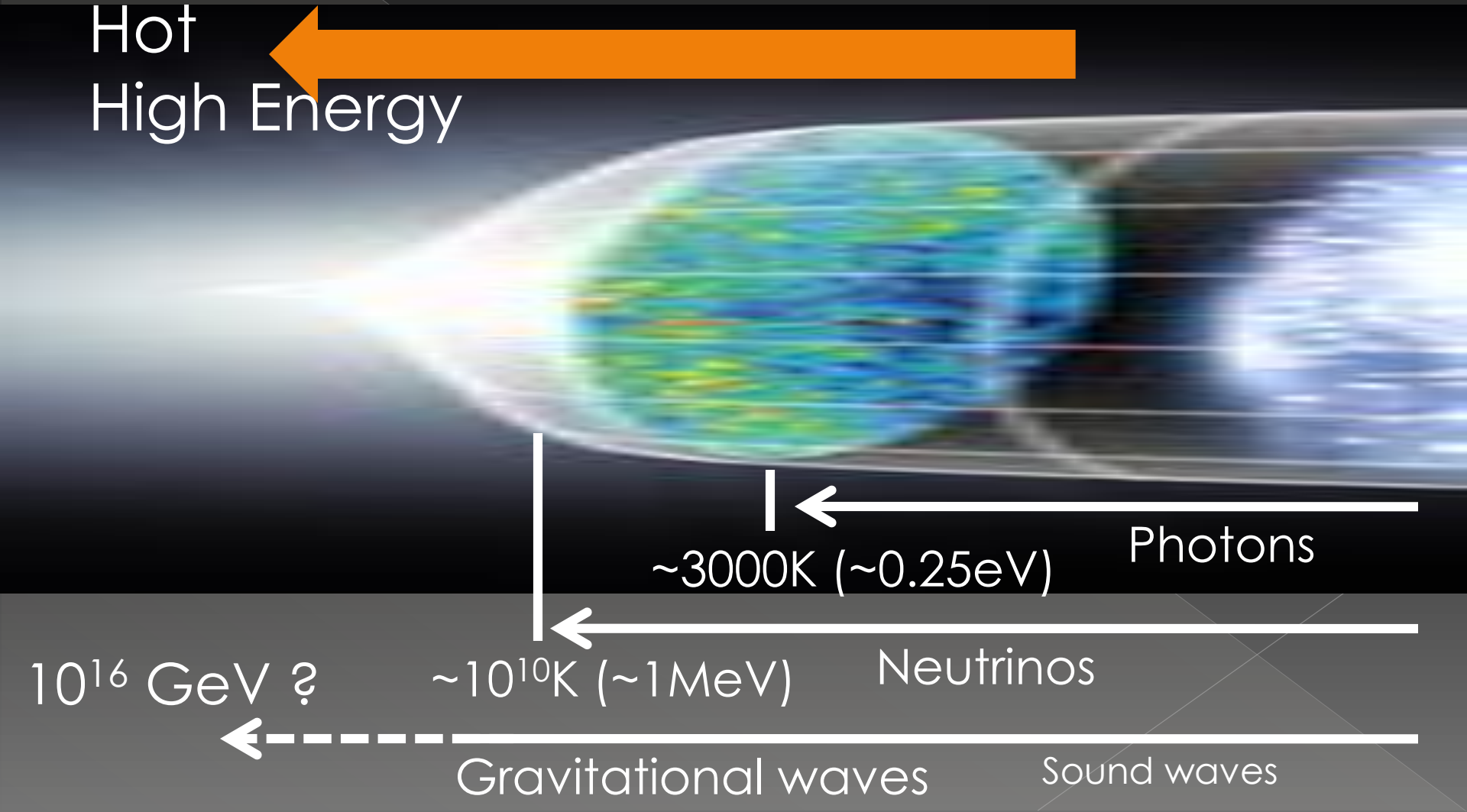
- Inflation / Gravitational Waves
- Gravitational Lensing / Neutrino Mass
- Light Relativistic Species

- And more…

# B-mode from Inflation



# A probe into the Early Universe



# Source of GW? : inflation

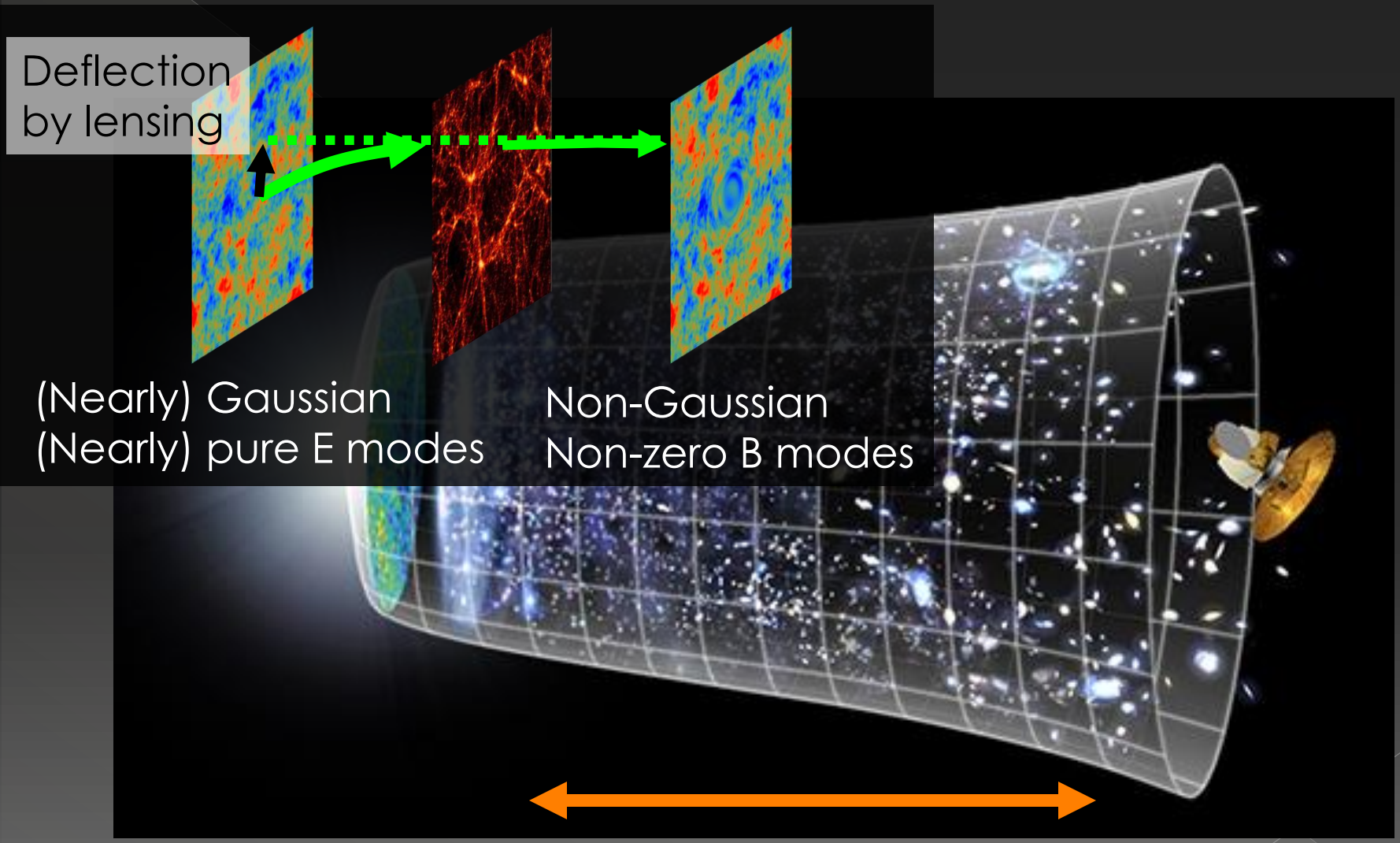
- Inflation
  - Rapid expansion of universe
- Quantum fluctuation of metric during inflation
  - Off diagonal component (T) → primordial gravitational waves

Unique probe into

gravity ←→ quantum mechanics connection

Ratio to S (on-diagonal): $r$=T/S

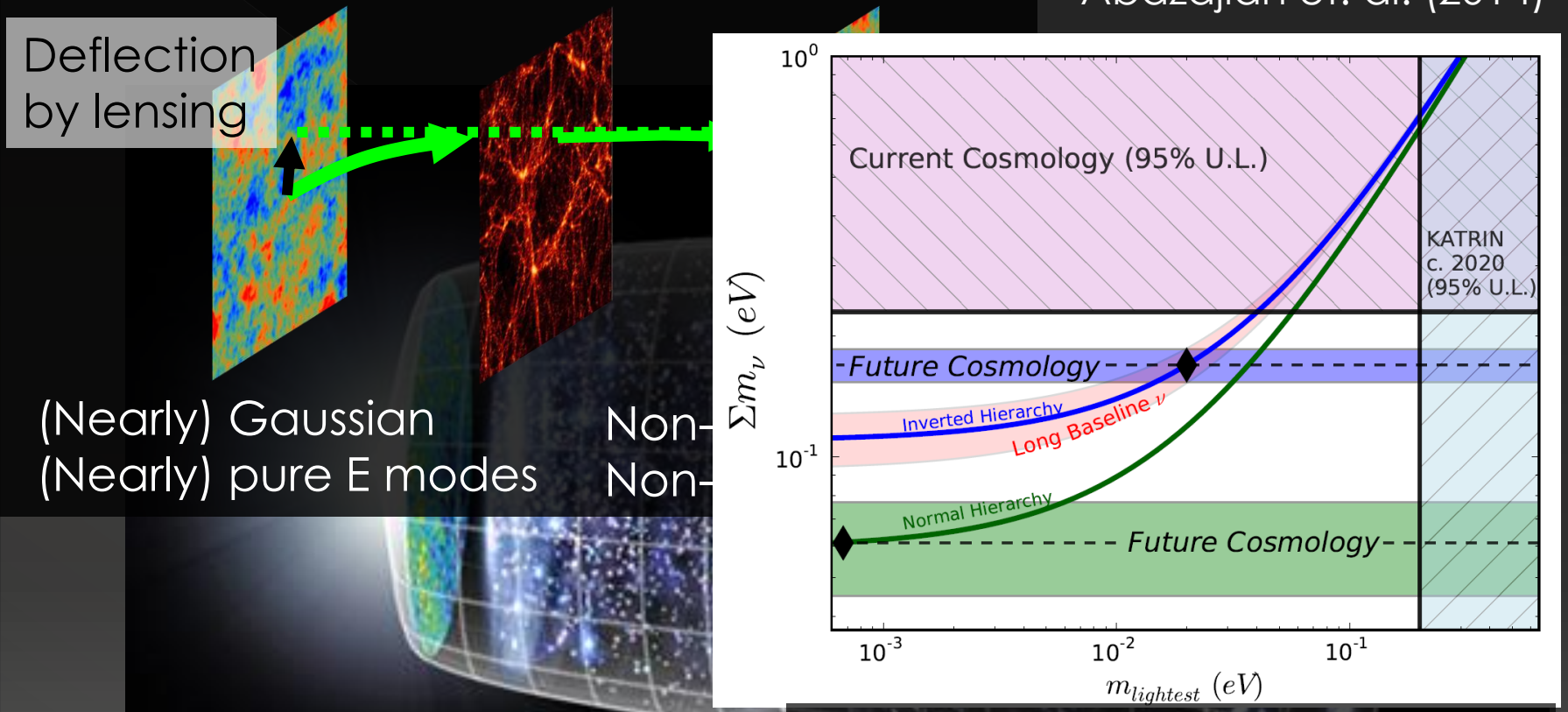
# Lensing B-mode




It's about the stuff here

# Lensing B-mode

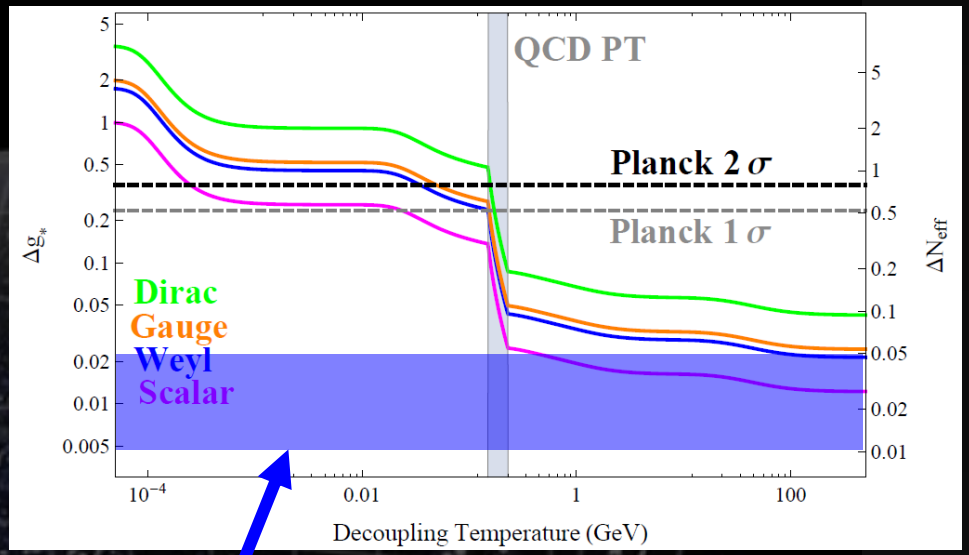
Abazajian et. al. (2014)




It's about the stuff here

# Extra Relativistic Species

$N_{eff}$ as a function of decoupling temperature of the extra species.

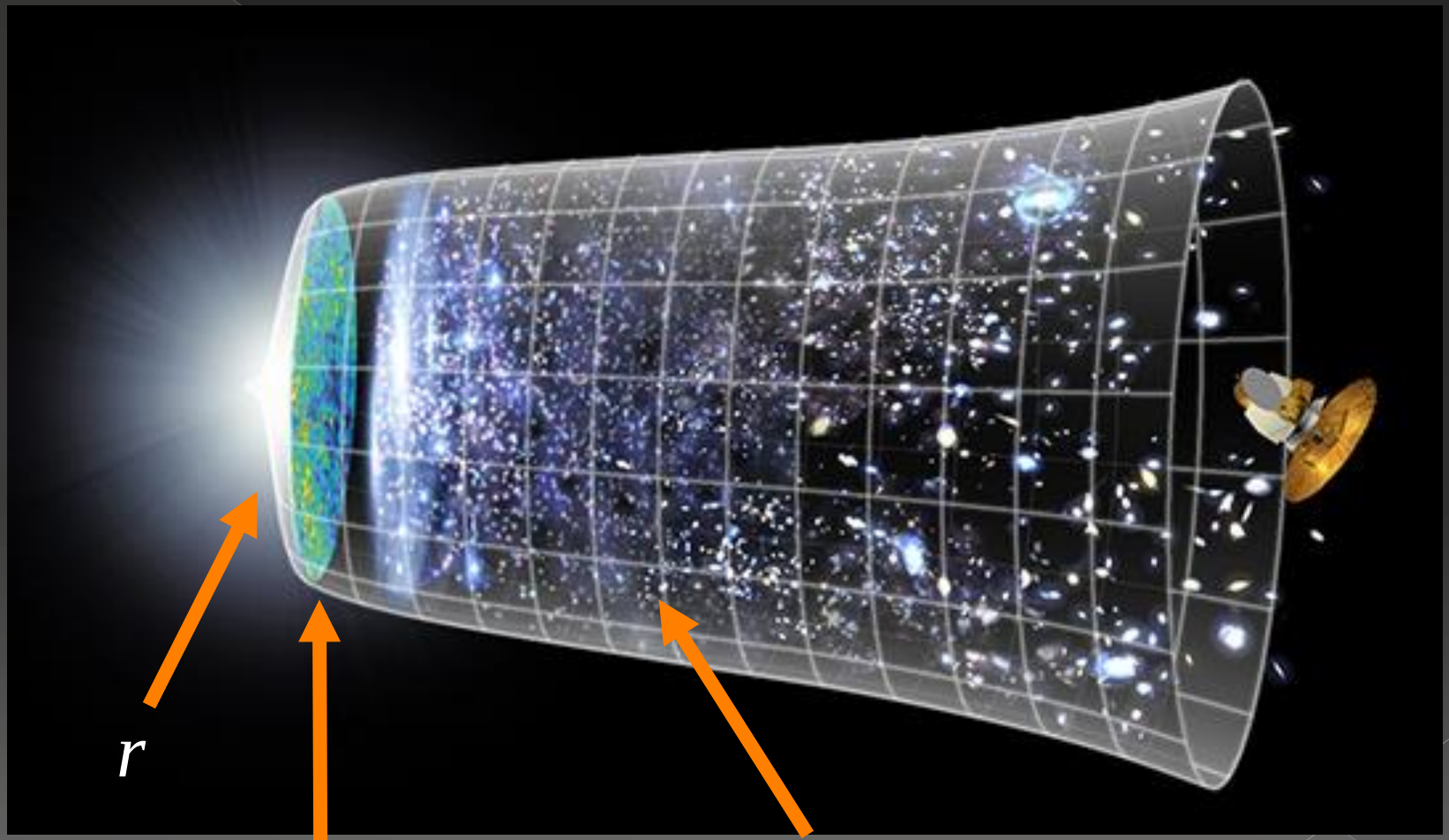



Brust et. al. (2013)

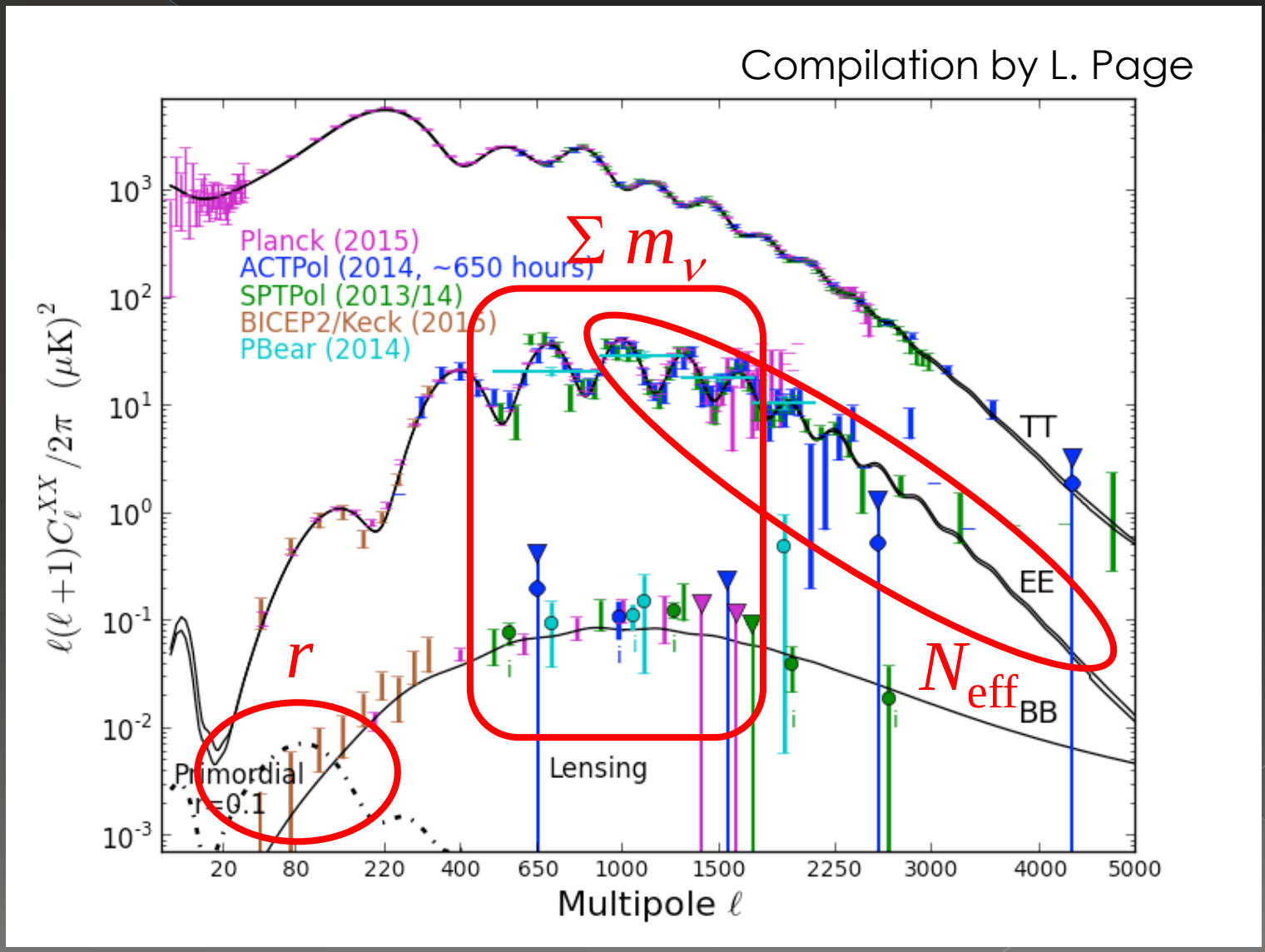
Reach of Stage 4 CMB experiment

It's about the stuff here

# CMB Polarization Science

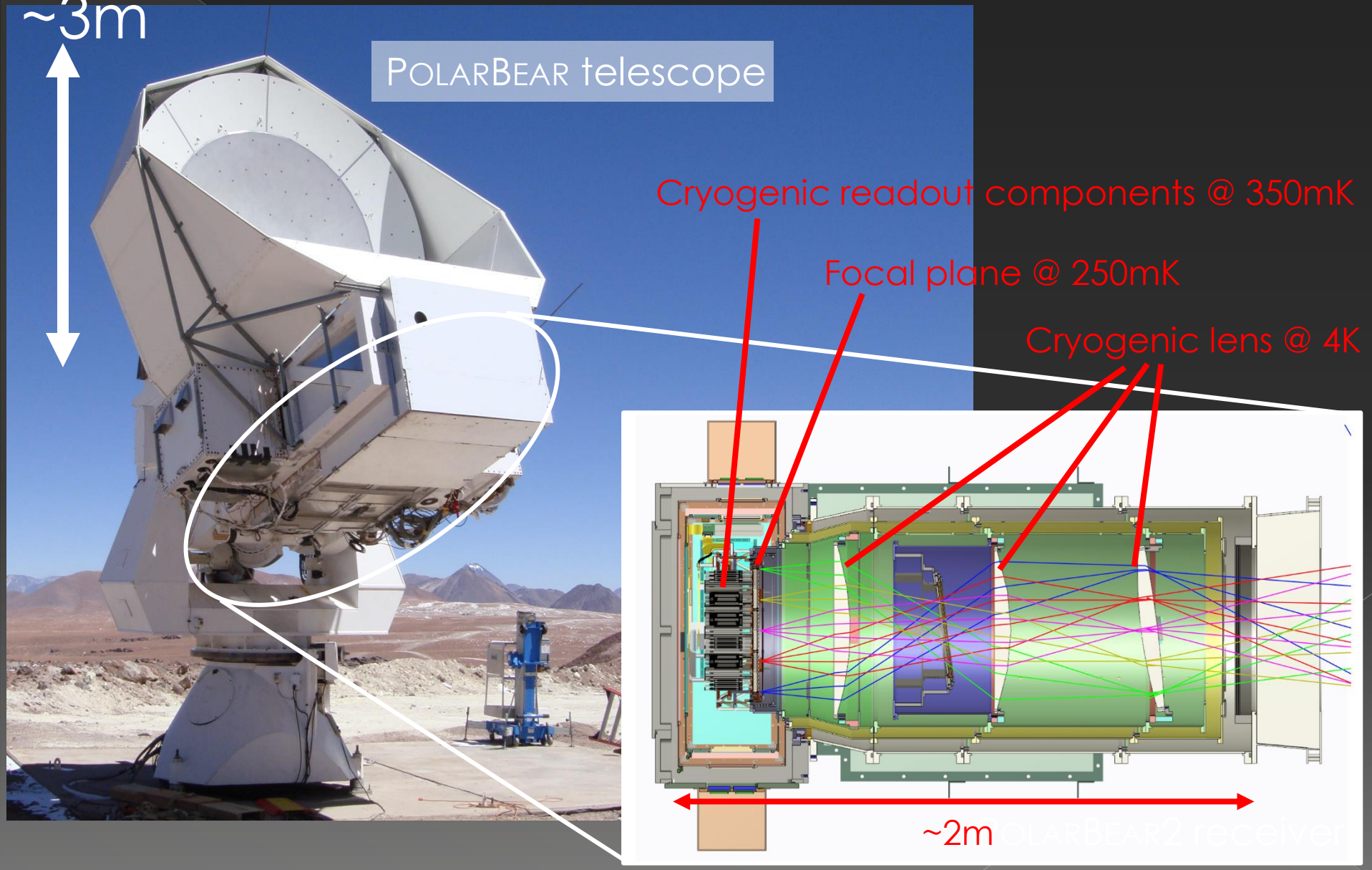


# CMB Polarization Science



# Experimental Approach

# A CMB Instrument

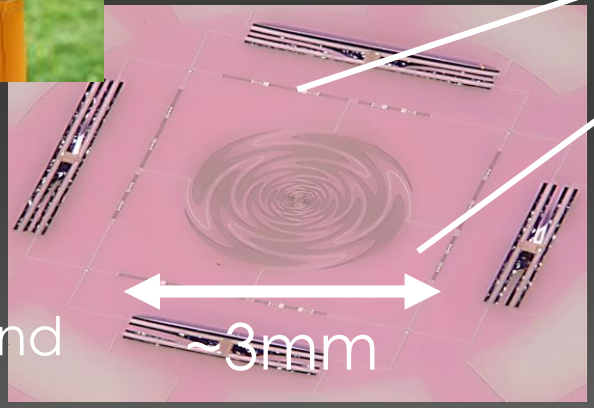


# A CMB Camera

Similar to this…

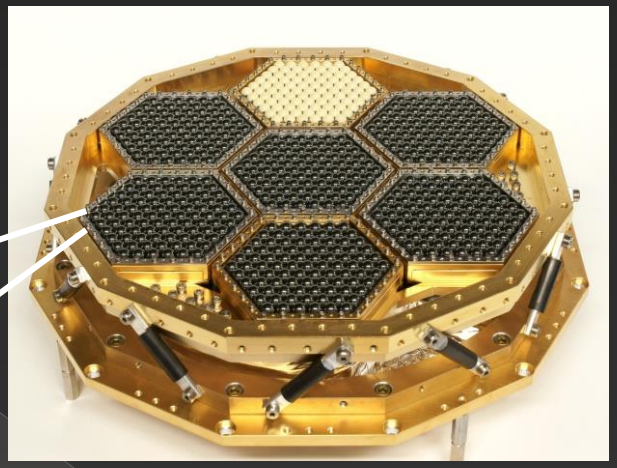
CMB Sensor

But in mm wave




$\Delta T \sim 300\mu K$
each second

Focal Plane

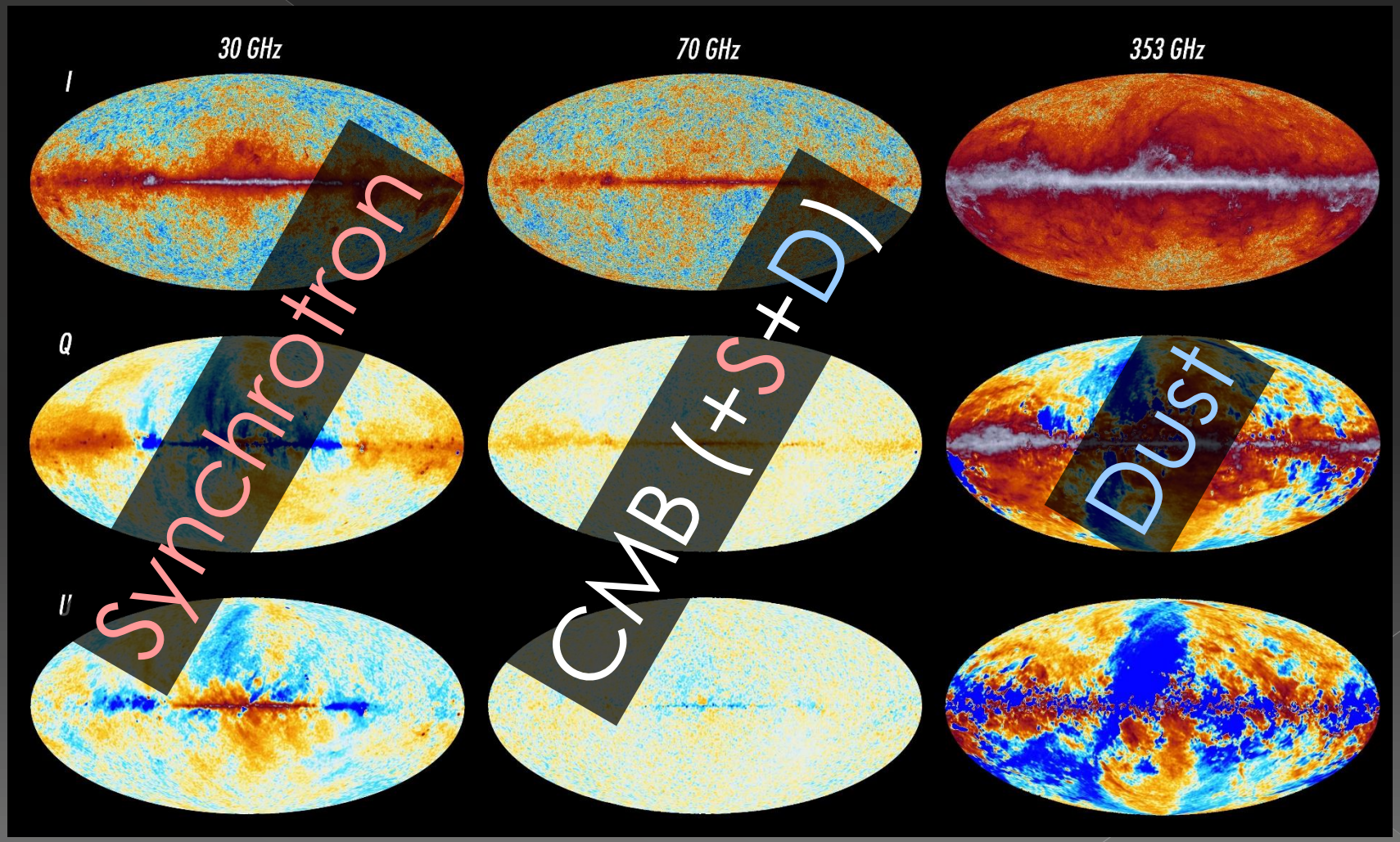


Under construction:
~50cm, ~10000 detectors
Next gen:
~2m(?), ~100000 detectors

Superconducting Transition Edge Sensors
Operating at 70 – 300 mK

# Foregrounds

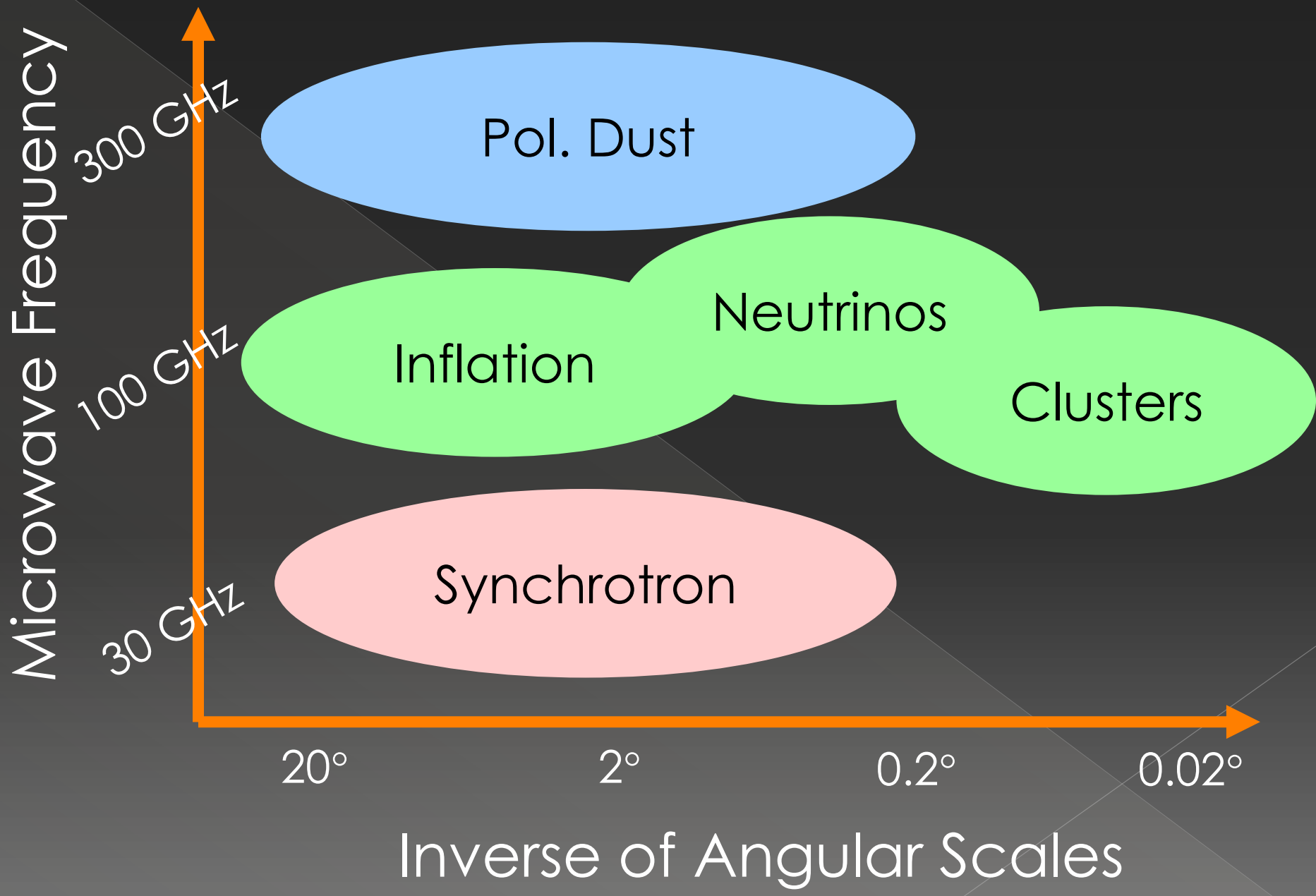
*Low frequency* ⟷ *High frequency*

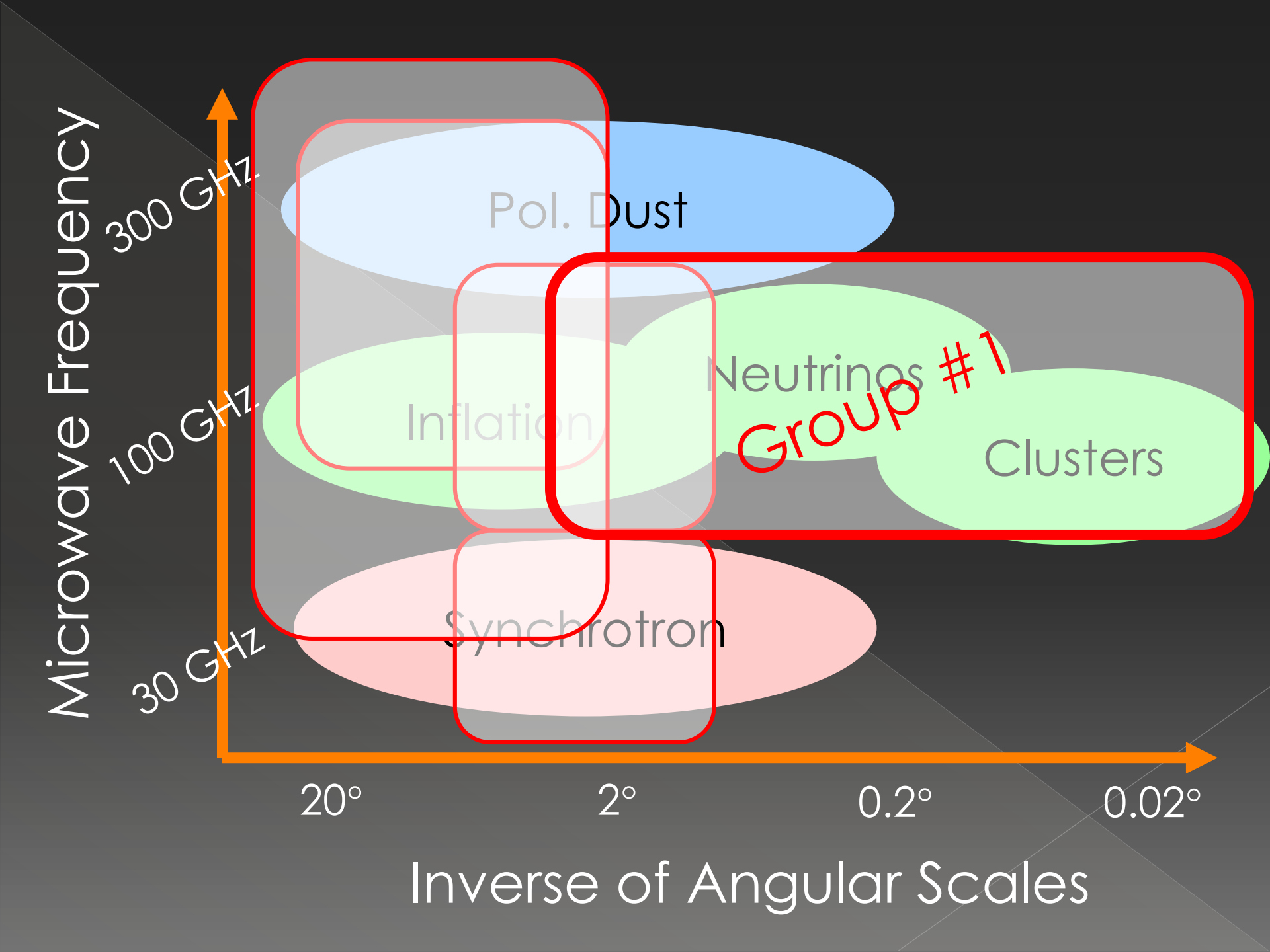



Planck Collaboration (2015)

# Review of Experiments

- Thanks to our collegues
  - C. Pryke (BICEP/Keck), T. Marriage (CLASS), O. Tajima (GroundBIRD), A. Tartari (QUBIC), R. Genova-Santos (QUIJOTE), C. Dickinson (C-BASS), S. Hanany (EBEX), J. Filippini (SPIDER), A. Kogut (PIPER), S. Staggs (ACTPol), A. Lee (Simons Array), B. Benson (SPT-3G), M. Hazumi (LiteBIRD), A. Kogut (PIXIE), C. Baccigalupi (Planck)
- But I am responsible for mistakes.


Microwave Frequency
300 GHz
100 GHz
30 GHz
Pol. Dust
Inflation
Neutrinos
Clusters
Synchrotron
20°
2°
0.2°
0.02°
Inverse of Angular Scales


Microwave Frequency
300 GHz
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20°
2°
0.2°
0.02°
Inverse of Angular Scales

# SPT: The 10-m South Pole Telescope

**2007: SPT-SZ**
960 detectors
100,150,220 GHz

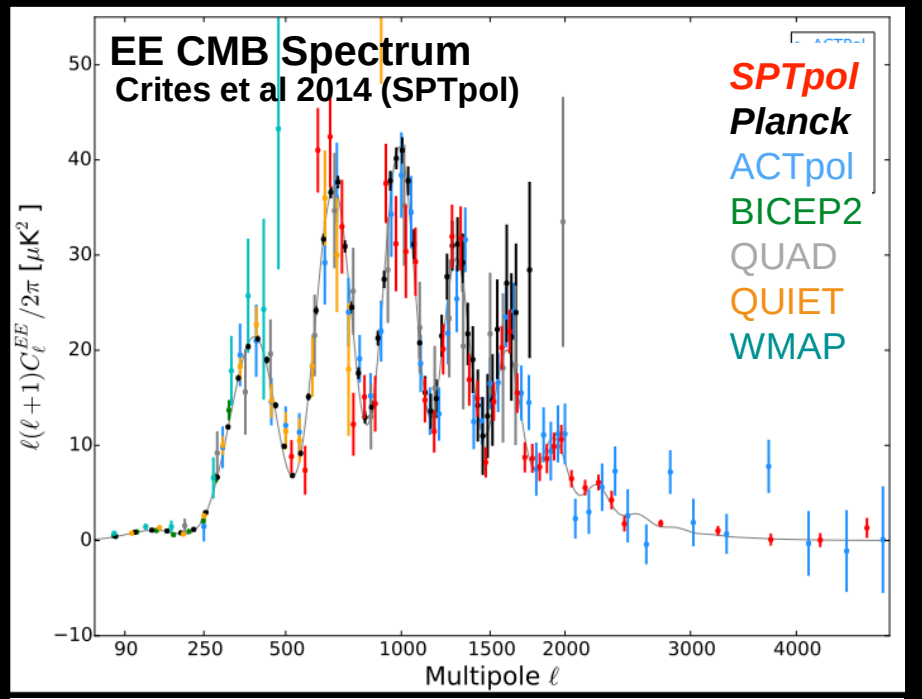
**2012: SPTpol**
1600 detectors
100,150 GHz

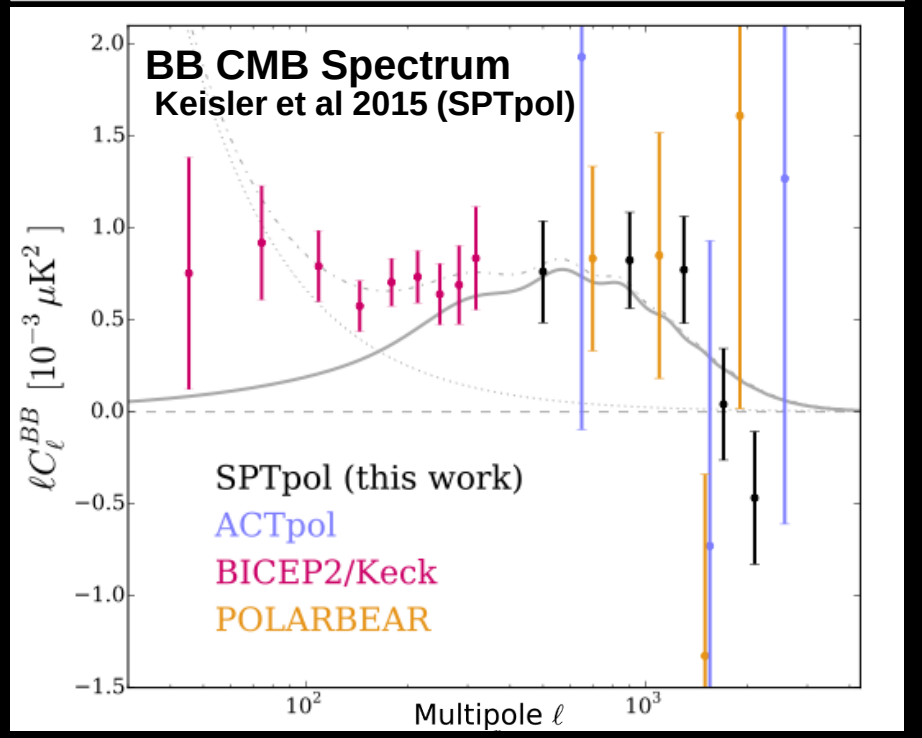
**2017: SPT-3G**
16,200 detectors
100,150,220 GHz

Funded By:

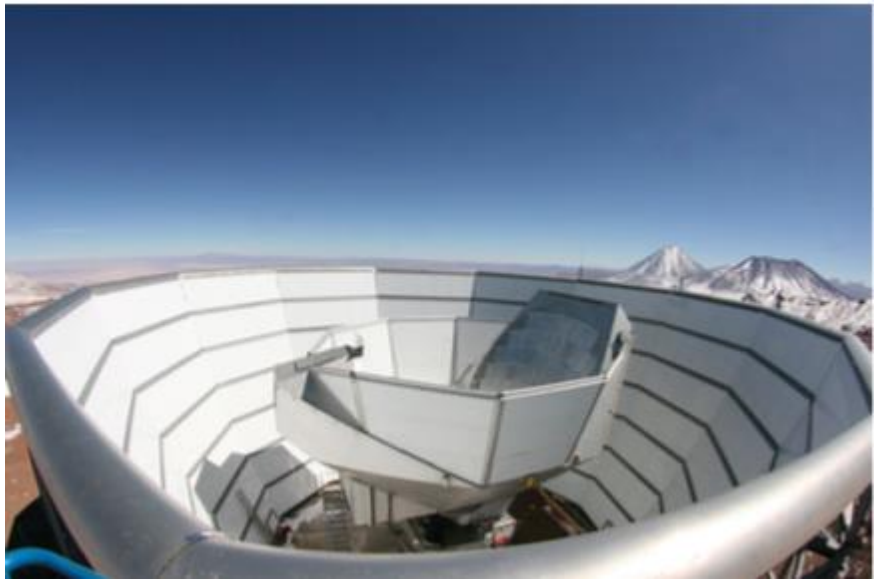
NATIONAL SCIENCE FOUNDATION

U.S. DEPARTMENT OF ENERGY



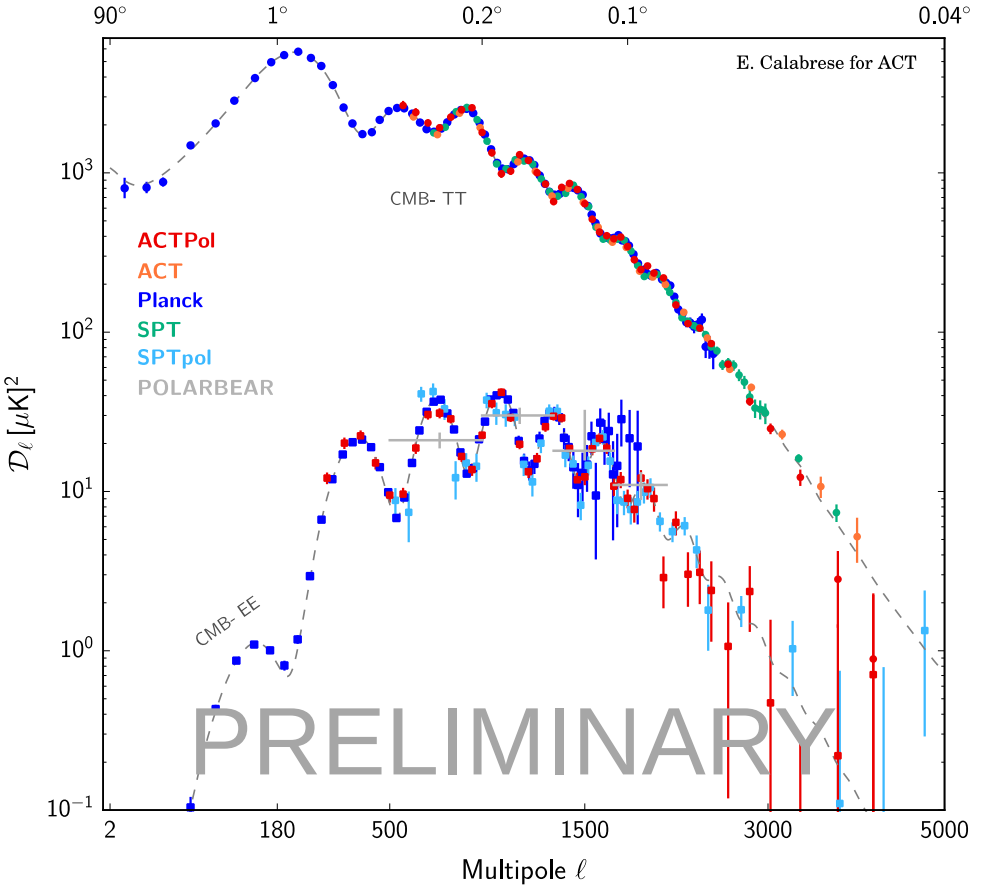
# Atacama Cosmology Telescope (ACT)



ACT: 6m telescope at 5200 m in Chile
ACTPol Camera: 2013-2015, 150 & 90 GHz

D56 Field: ~ 650 deg$^2$ , @ $\delta$ ~ -3°, RA ~ 15°

PRELIMINARY ACTPol SPECTRA
D56 Field
(12% of the ACTPol data)



# Simons Array

Simons Array (= 3x POLARBEAR-2)

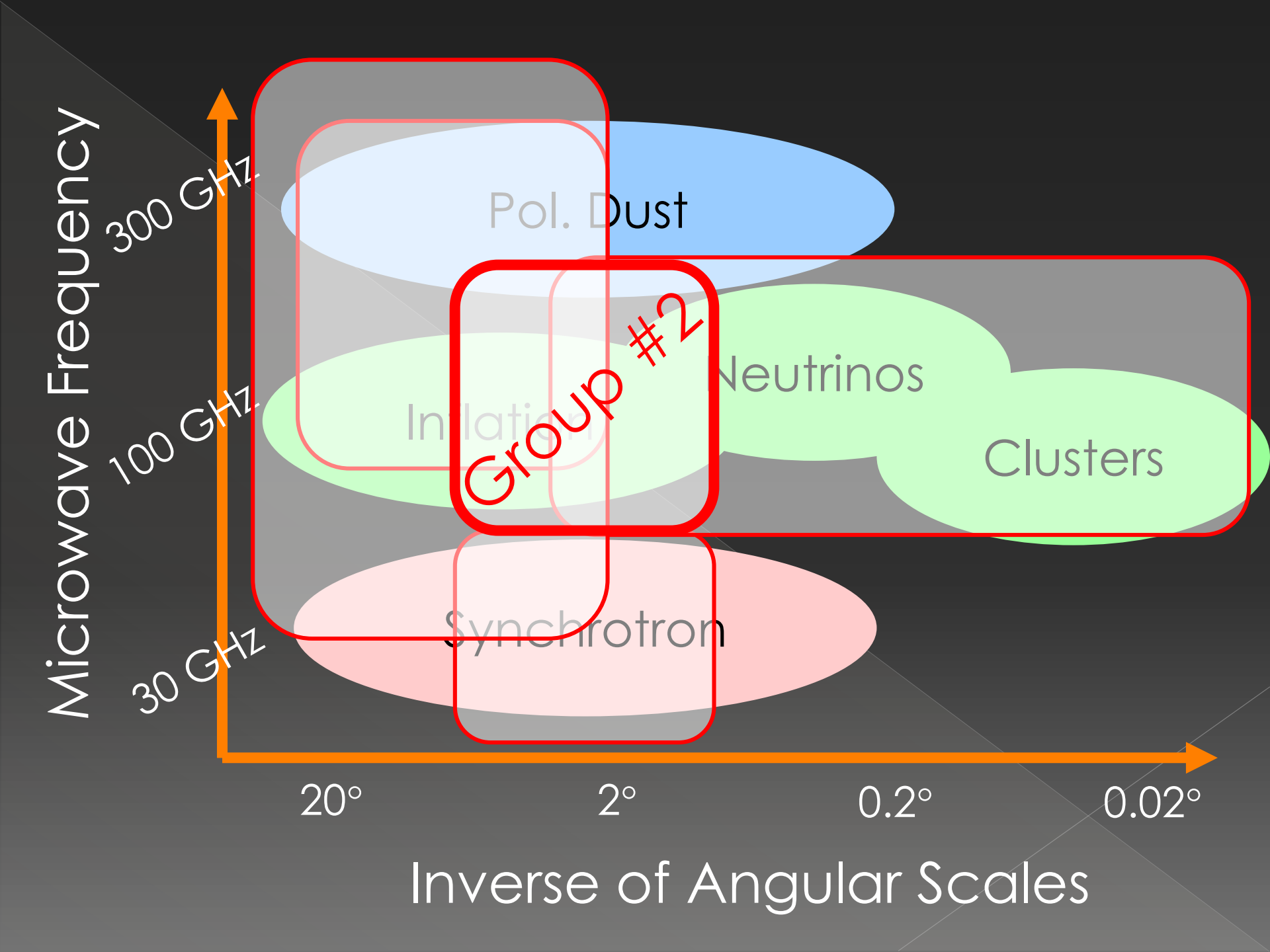
- 22,764 bolometers
- Resolution : 3.5’ @150GHz
- 4 frequency bands (95/150/220/280 GHz)
- Deep + Wide sky surveys ($f_{sky}$=65% visible)

Inflation

- $\sigma(r=0.1) = 6\times10^{-3}$ (w/foreground) $4\times10^{-3}$ (stat)

Neutrino mass

- $\sigma(\Sigma m_\nu) = 40$ meV (w/fground) 19 meV (stat) (w/ DESI-BAO)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Inverse of Angular Scales

## Stage 2

## Stage 3

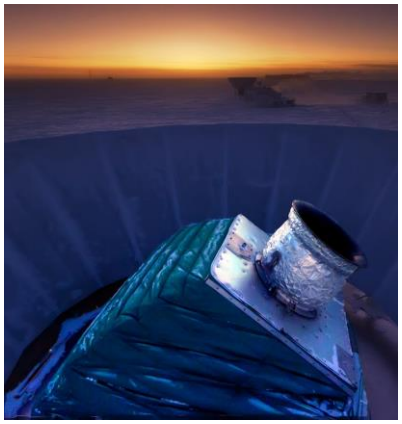
**BICEP2**
(2010-2012)

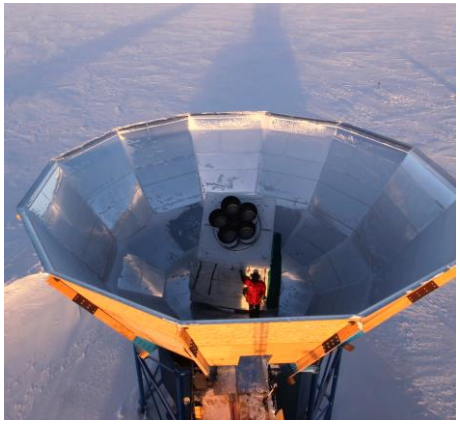
**Keck Array**
(2012-2017)

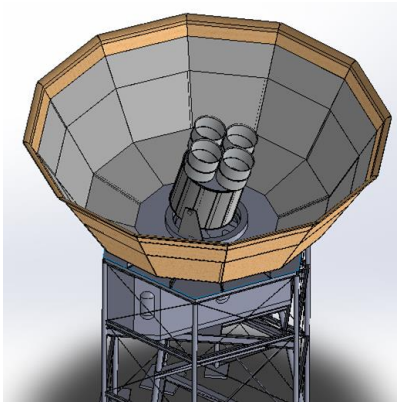
**BICEP3**
(2015-)

**BICEP Array**
(2018-)

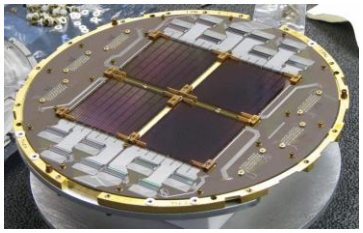
Telescope and Mount

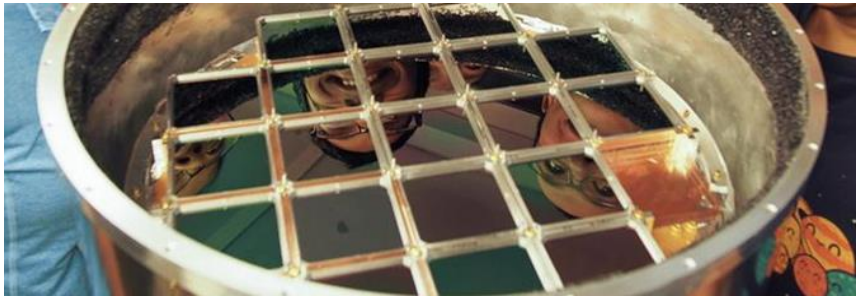




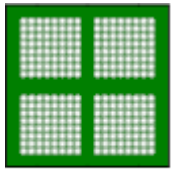


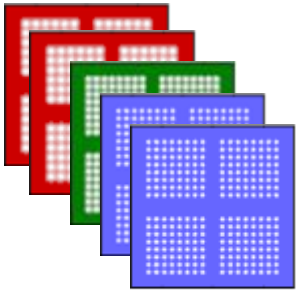
Focal Plane

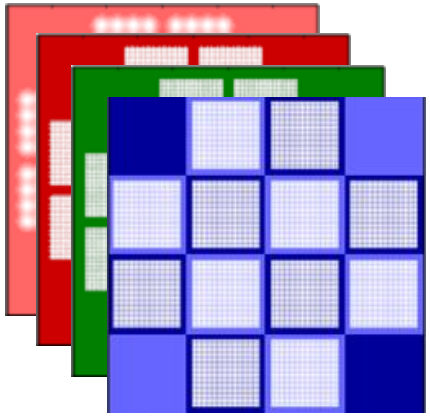




Beams on Sky





Stage 2

Stage 3

**BICEP2** (2010-2012)

**Keck Array** (2012-2017)

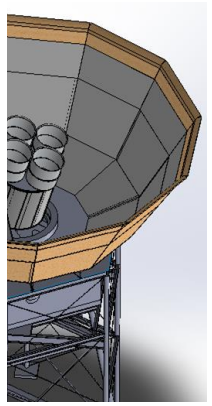
**BICEP3** (2015-)

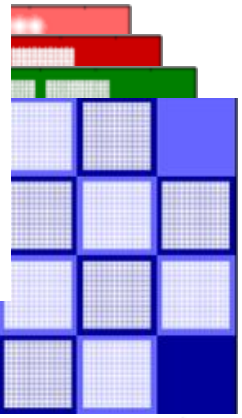
**BICEP Array** (2018-)

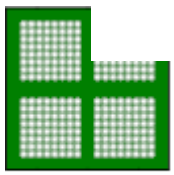
Telescope and Mount

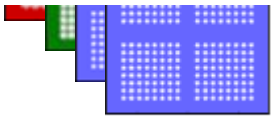
Focal Plane

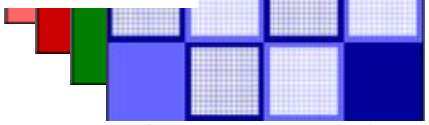
Beams on Sky







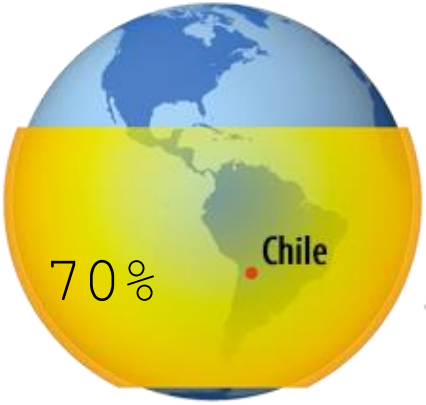



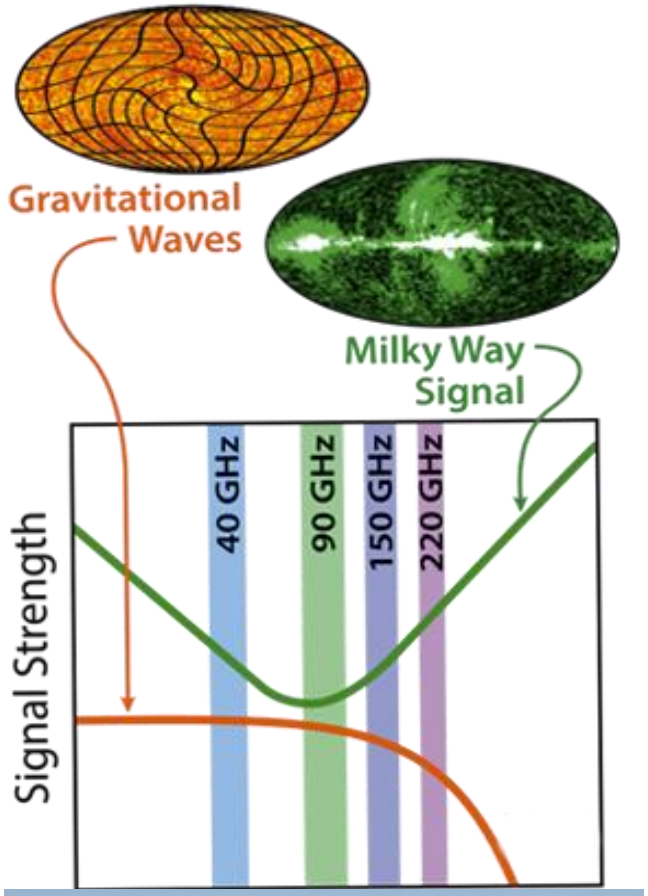


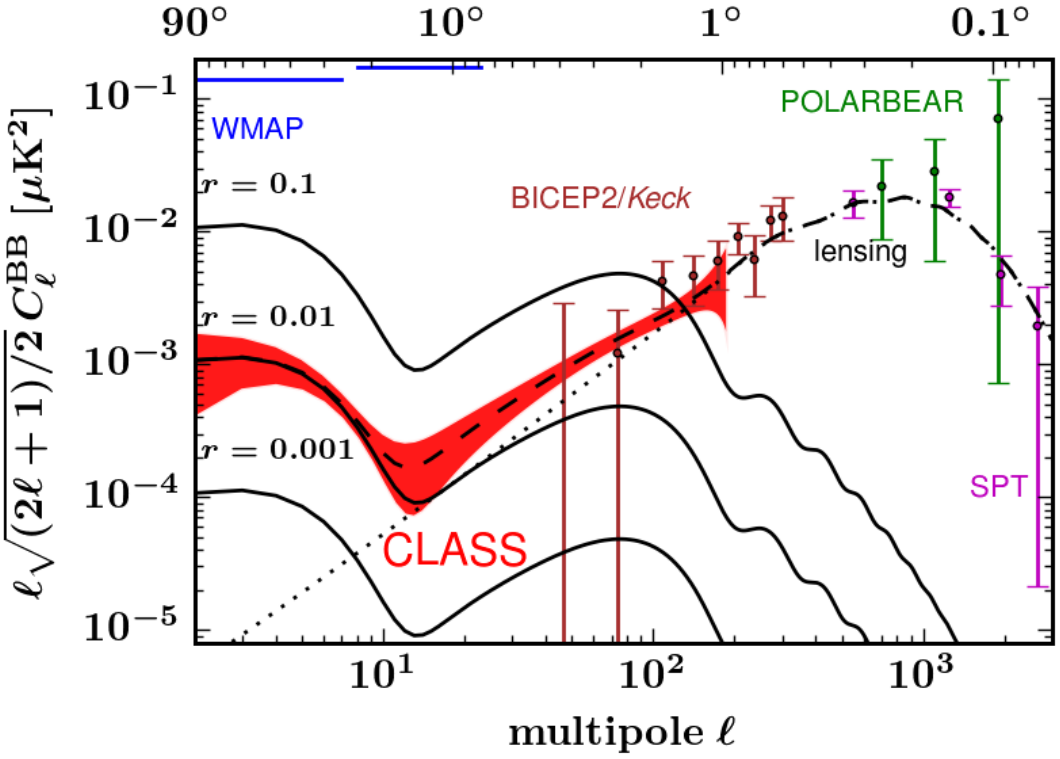
# CLASS

✓ Inflation

✓ Reionization

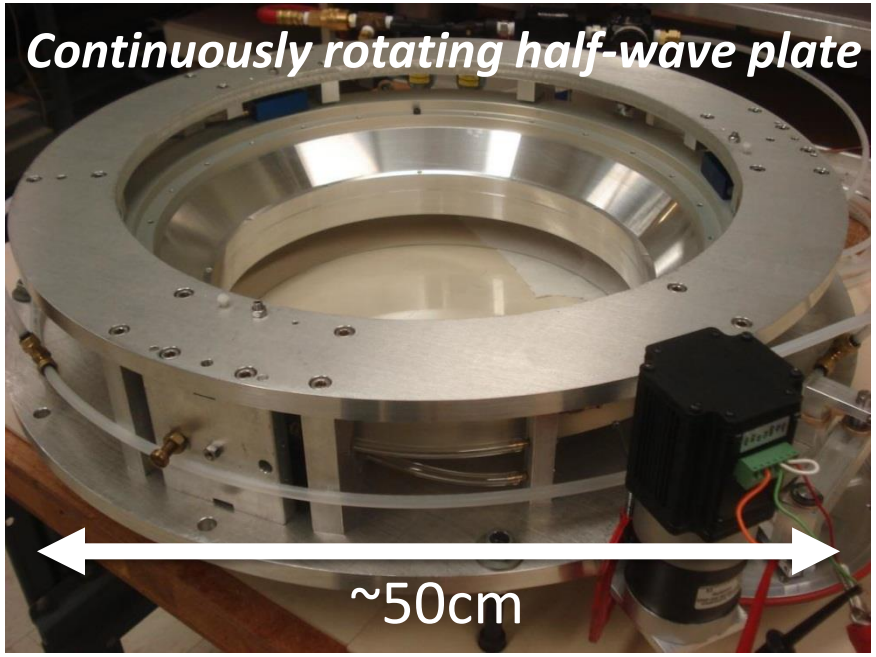


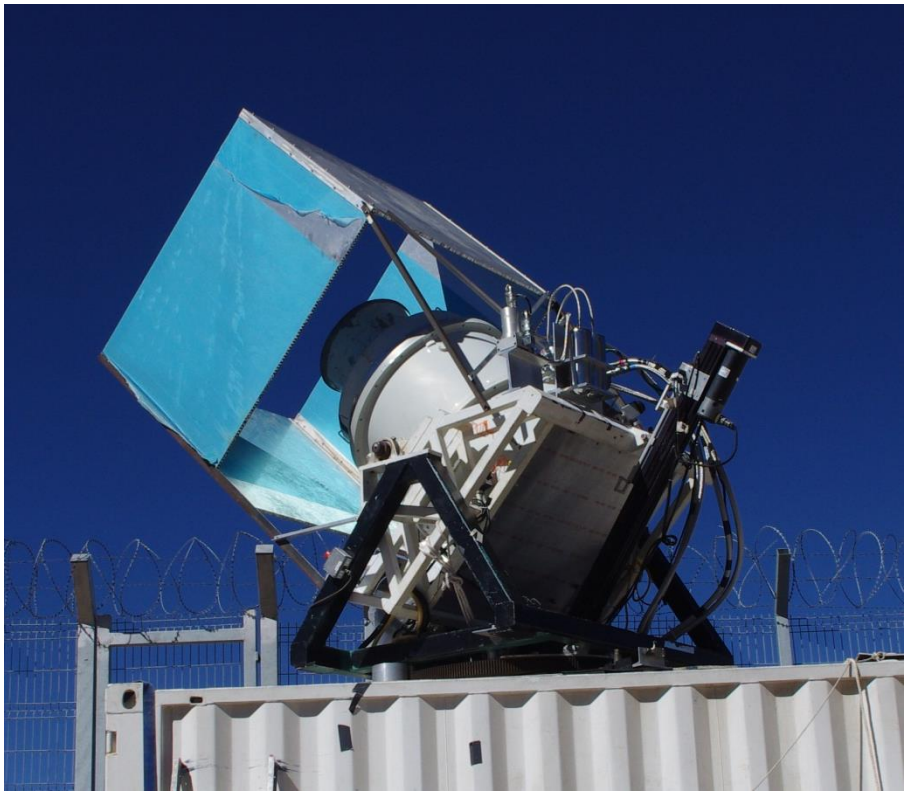



40 GHz Telescope

# Atacama B-mode Search (ABS)



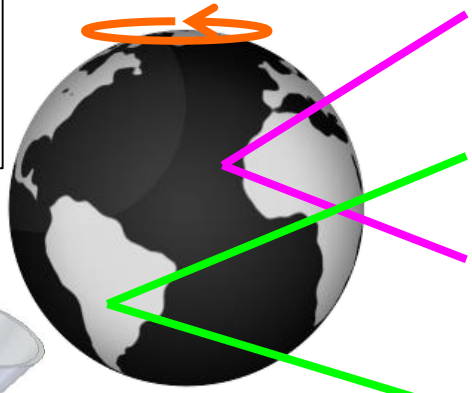



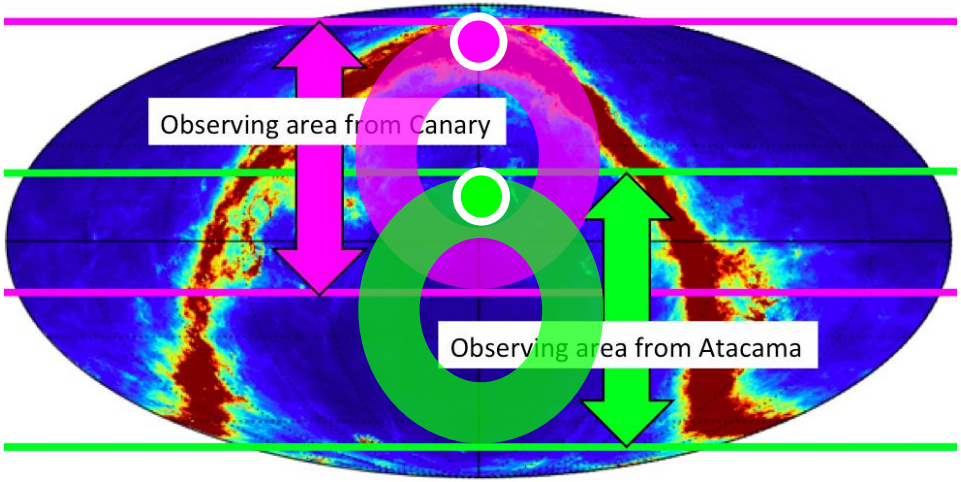
- TES bolometer at 150 GHz: 240 pixels / 480 bolometers
- 4K-cooled reflective optics
- Demonstration of continuously-rotating warm half-wave plate
  - Excellent stability [RSI, 85, 024501 (2014)] and systematics [arxiv:1601.05901 (2016)]
- Observation: 2012 – 2014

# **GroundBIRD** – *Satellite-like scan on the ground, but **super high-speed !***

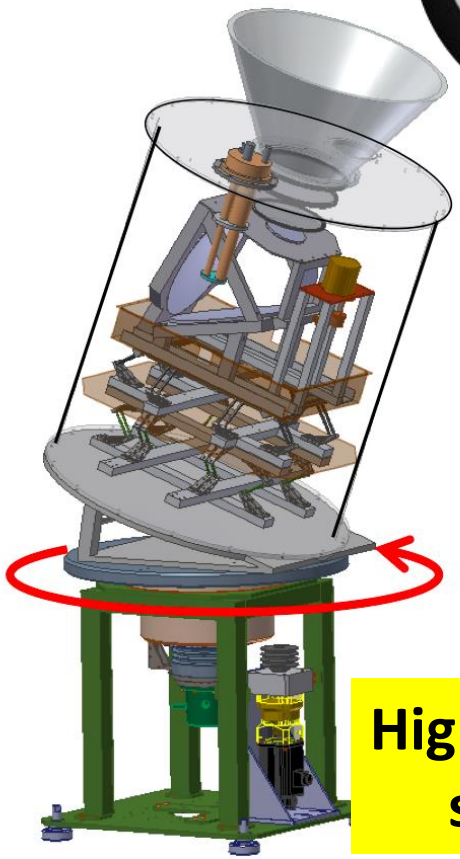
KEK, RIKEN, NAOJ
U-Tokyo, Tohoku U.,
Saitama U., Korea U.

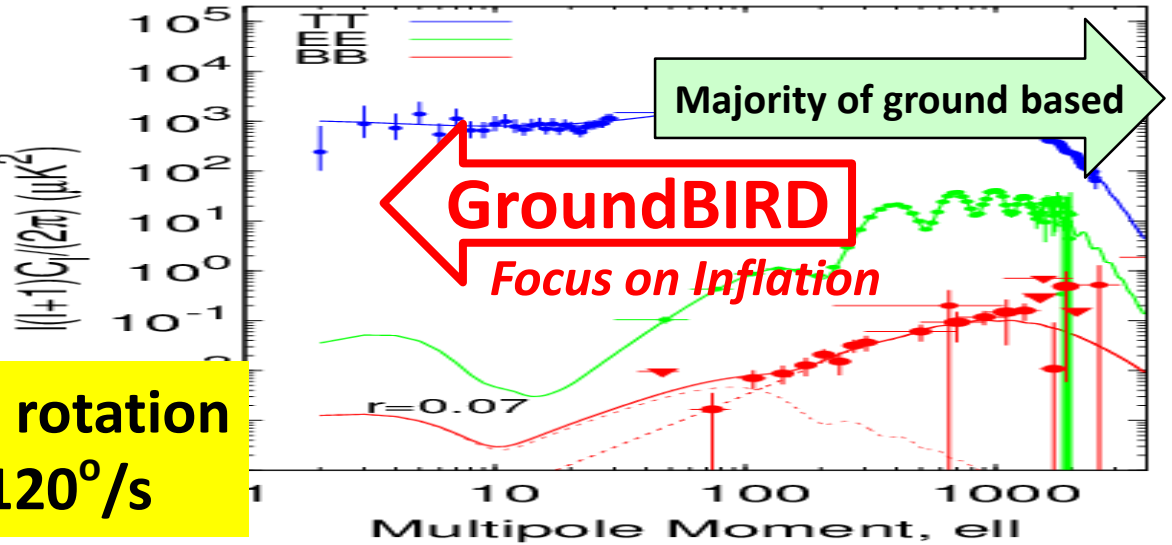
2017 ~ (@ Canary)





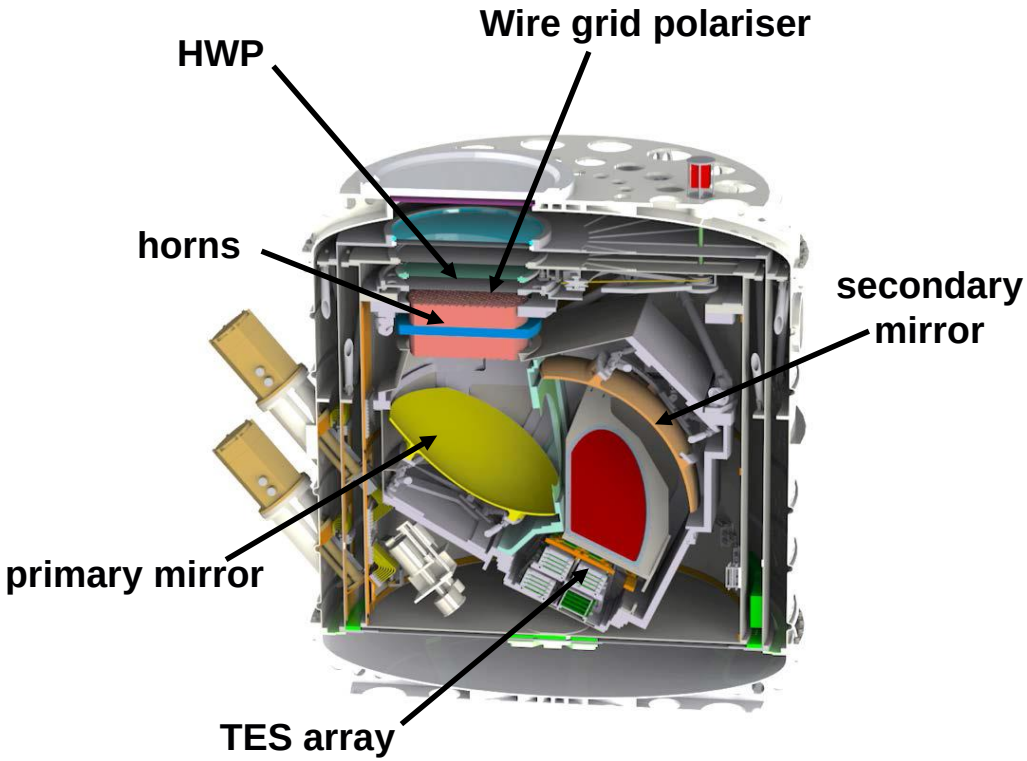

***High-speed rotation scan + Earth rotation → Large field obs.***
***Cover all-sky by two, e.g., Atacama Chile + Canary Islands***






**High-speed rotation scan of 120°/s**

The **QU** **B**olometric **I**nterferometer for **C**osmology




An original concept:

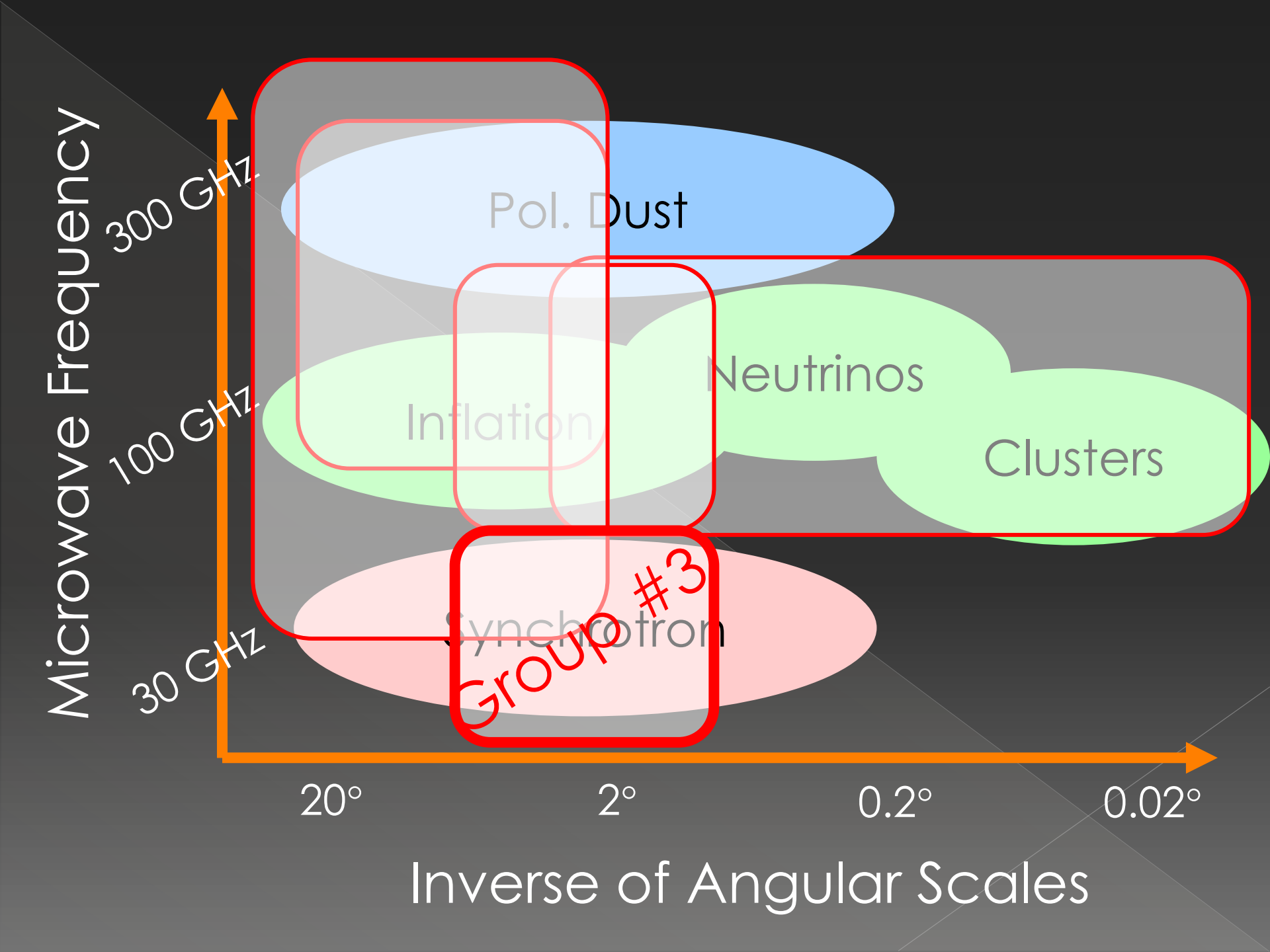
→ **A Fizeau adding interferometer**

- **400 dual band back-to-back horns (150-220 GHz) -> acting as a pupil plane spatial filter.**
- **A fast telescope (f/#~1.0)**
- **1024×2 NbSi TES arrays @ 300 mK**

→ **QUBIC 1st module: r=0.02 (95% CL) in 2020. In presence of dust (provided it's well described by a power law). With 30% time observing efficiency.**

→ **Start scientific operation in 2018.**

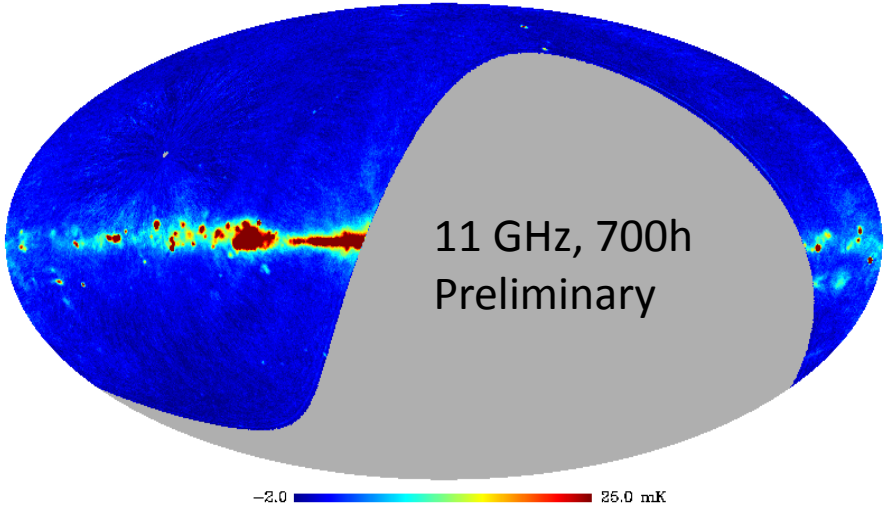
A.Tartari, et al., J Low Temp Phys 2016
E.S.Battistelli, et al., MNRAS 2012
The QUBIC Coll., AstroPart Phys 2011
S.Spinelli et al., MNRAS 2011


Microwave Frequency
300 GHz
100 GHz
30 GHz
Pol. Dust
Inflation
Neutrinos
Clusters
Synchrotron
Group #3
20°
2°
0.2°
0.02°
Inverse of Angular Scales

# QUIJOTE

- Teide Observatory (Tenerife, Spain), 2.4km asl
- **Two telescopes** and **three instruments**:
  - MFI (10-20 GHz) - observing since Nov 2012
  - TGI (30 GHz) – in commissioning since May 2016
  - FGI (40 GHz) - being manufactured
- Extension to full sky (from ZA). Building a MFI pixel
- 1-deg angular resolution.

- **Surveys**:
- Wide survey: 20,000 deg$^2$, ≈15 μK/deg$^2$ @ 11, 13, 17 and 19 GHz, ≤3 μK/deg$^2$ @ 30, 40 GHz
- Deep cosmological survey: 3×1,000 deg$^2$, ≈5 μK/deg$^2$ @ 11, 13, 17 and 19 GHz, ≤1 μK/deg$^2$ @ 30, 40 GHz (after 1 year)




- **Scientific goals**:
- B-modes down to r=0.05 (after 5 years), r=0.1 (after 1 year).
- Characterisation of the synchrotron and AME polarisations.

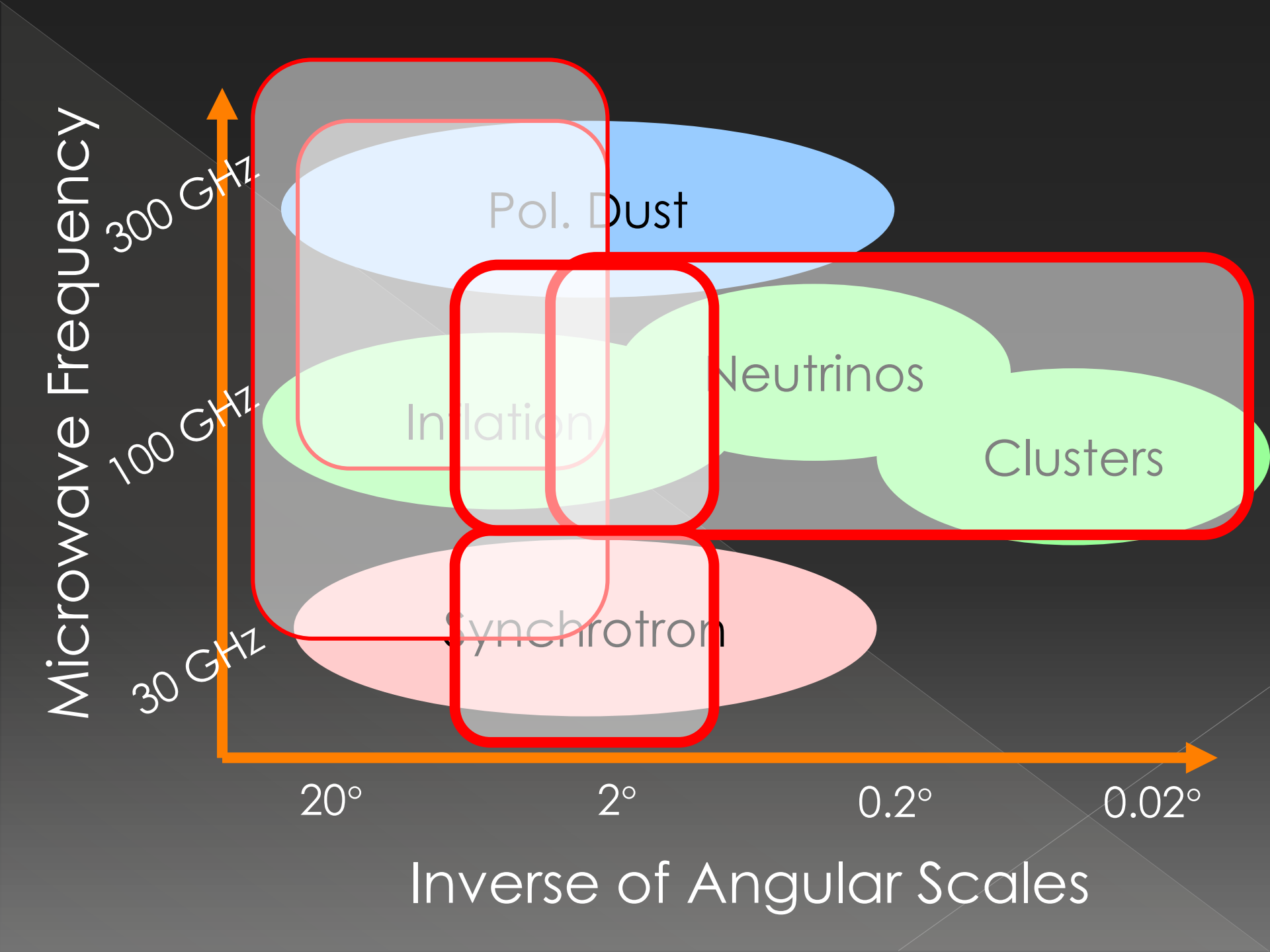
# C-BASS

- Collaboration: UK (Manchester/Oxford), U.S. (Caltech/JPL), South Africa (Rhodes, UKZN), Saudi Arabia (KACST)
- **Full-sky 5 GHz I/Q/U survey at 45 arcmin resolution, <0.1mK rms noise, with good calibration and minimal systematics**
- Careful attention to design details
  - Carefully balanced correlation receiver to reduce 1/f noise
  - Lowest noise C-Band low noise amplifiers
  - RFI notch filters
  - Foam cone support to reduce scattering
  - Under-illuminated low sidelobe matched beams
  - Absorbing baffles around reflectors
  - Fast scanning (4deg/s)
  - Digital spectral backend (Southern instrument)
  - …

California

South Africa

| | |
|---|---|
| Sky-coverage | All-sky |
| Angular resolution | 0.73 deg (43.8 arcmin) |
| Sensitivity | < 0.1mK r.m.s |
| Stokes coverage | I, Q, U, (V) |
| Tsys | ~20K, including sky |
| Frequency | 1 (0.7) GHz bandwidth, centered at 5 GHz |
| Northern site | OVRO, California<br>Latitude, 37.2 deg |
| Southern site | MeerKAT site, Karoo, South Africa<br>Latitude -30.7 deg |


Microwave Frequency
300 GHz
100 GHz
30 GHz
Pol. Dust
Inflation
Neutrinos
Clusters
Synchrotron
20°
2°
0.2°
0.02°
Inverse of Angular Scales

# CMB S4
# Stage-4 CMB Experiment

- O(500,000) detectors, multiple telescopes
  - More than x10 sensitivity increase over S3
- Science: Inflation, Neutrinos, Dark Radiation, Dark Energy, …
  - Large and Small angular scales.
  - 30 – 300 GHz
- Putting together the community

CMB S4 Collaboration Workshop at LBNL
~180 participants

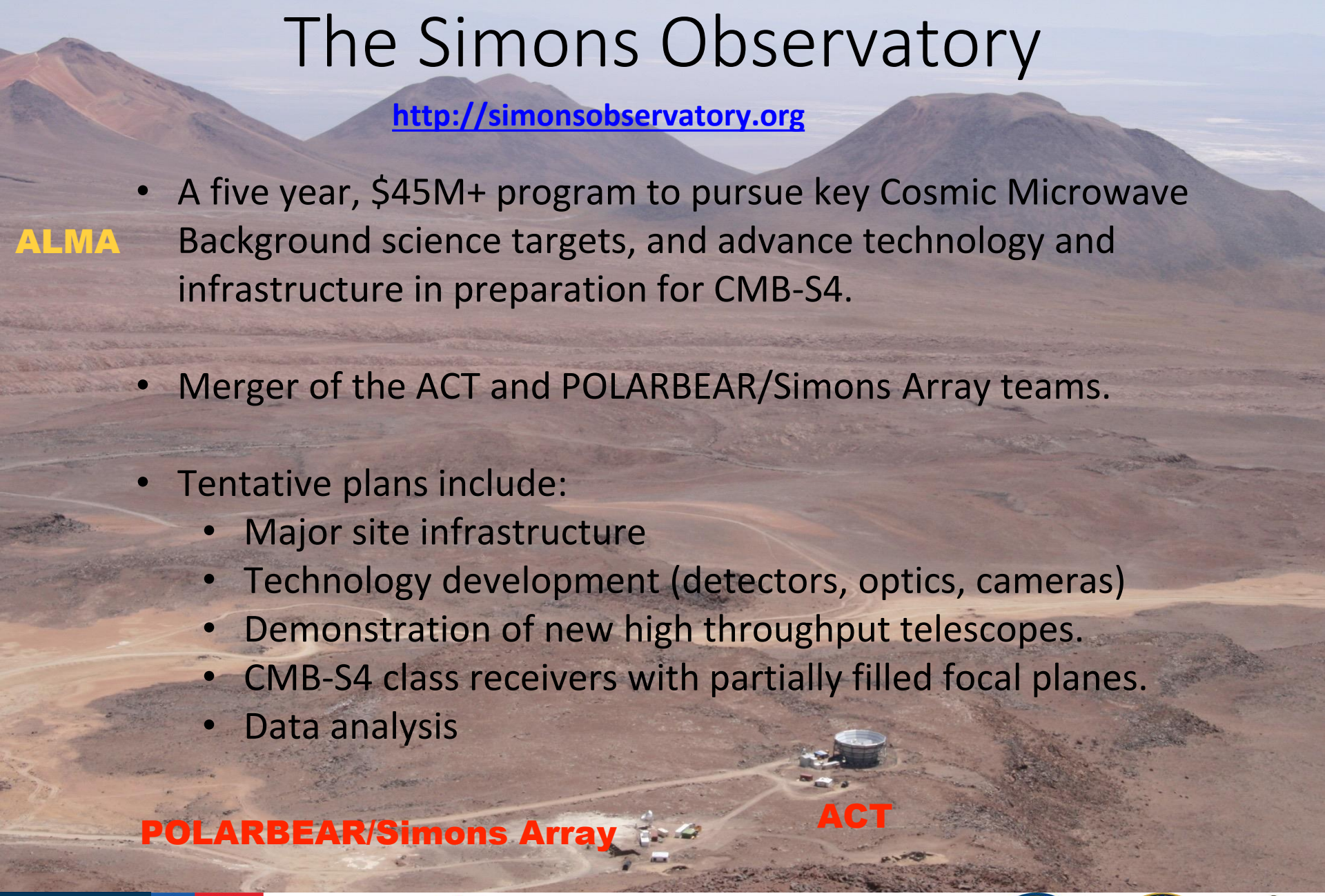
# The Simons Observatory

http://simonsobservatory.org

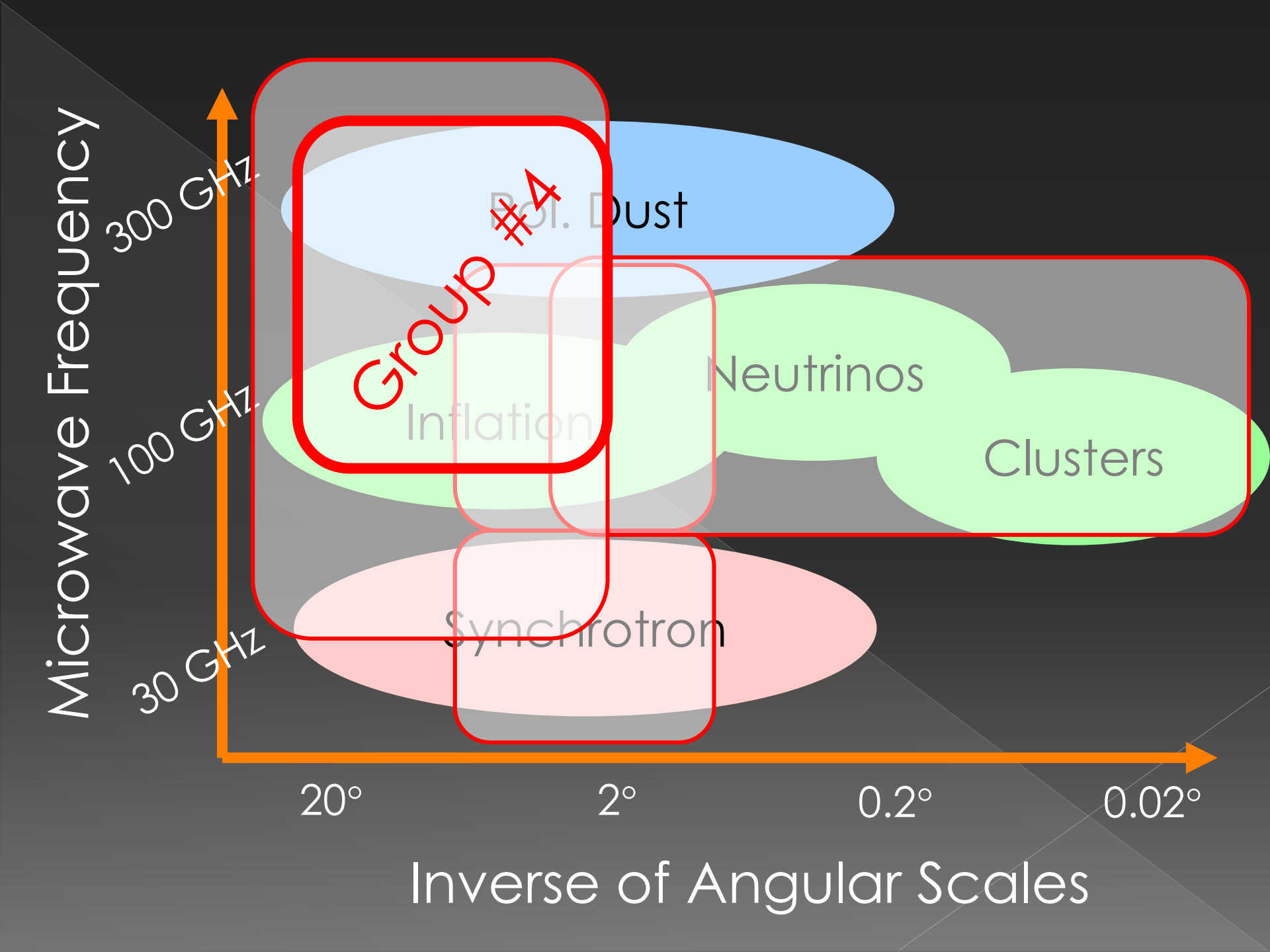
- A five year, $45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.

- Merger of the ACT and POLARBEAR/Simons Array teams.

- Tentative plans include:
  - Major site infrastructure
  - Technology development (detectors, optics, cameras)
  - Demonstration of new high throughput telescopes.
  - CMB-S4 class receivers with partially filled focal planes.
  - Data analysis



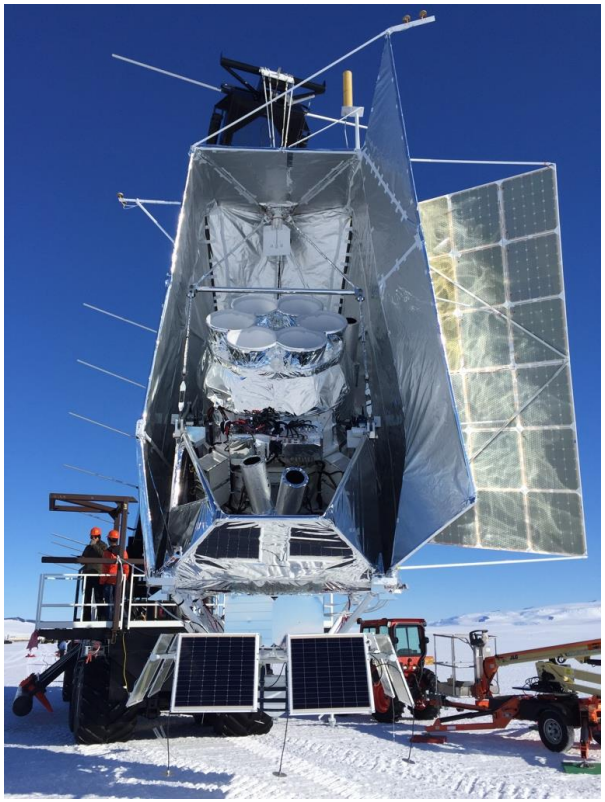

BERKELEY LAB CONICYT Ministerio de Educación HEISING-SIMONS FOUNDATION NSF Penn University of Pennsylvania PRINCETON UNIVERSITY SIMONS FOUNDATION


Microwave Frequency
300 GHz
100 GHz
30 GHz
Group #4
Rot. Dust
Inflation
Neutrinos
Clusters
Synchrotron
20°
2°
0.2°
0.02°
Inverse of Angular Scales

# SPIDER

## Payload

- Six monochromatic refractors (270 mm stop)
- Shared cryogenic vessel (1300L LHe, 4.2K and 1.6K)
- Sapphire half-wave plates, stepped every 12 hrs
- Fast (5˚ /s) sinusoidal azimuthal scan, elevation steps

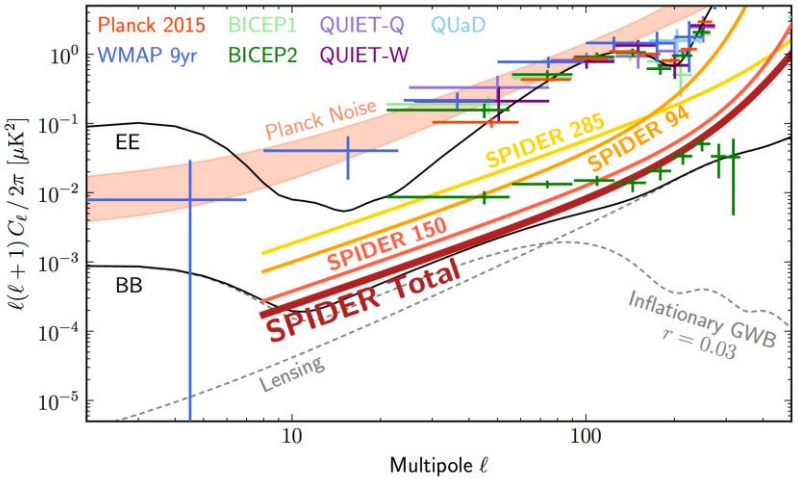


## First LDB Flight (Jan 1-18, 2015)

- 3 telescopes each at 94/150 GHz (42'/30' FWHM)
- 816/1488 JPL antenna-coupled TESs (+96 dark TESs)
- Sky coverage 12.3% (6.3%) geometric (hits-weighted)

## Second LDB Flight (2017-18)

- 2x 285 GHz NIST feedhorn-coupled receivers (512 TESs each)
- 1-2 broadband 270 GHz JPL receivers (512 TESs each)
- Hardware recovered; new flight cryostat in final leak testing



# EBEX in a Nutshell

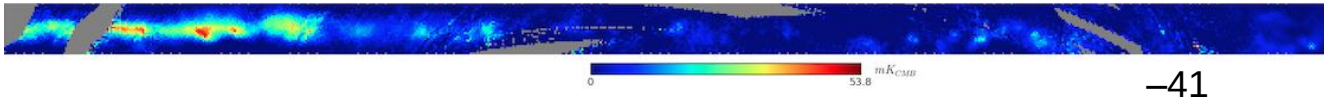
Sensitivity
- Conventional long duration
- Using ~1000 bolometric TES

CMB and Foregrounds
- 3 Frequency bands: 150, 250, 410 GHz

\ell space
- Resolution: 8’ at all frequencies

Polarimetry
- Polarimetry with continuously rotating half wave plate

Status
- 10 days of data collected in 1/2013 and are being analyzed



# Primordial Inflation Polarization Explorer (PIPER)

**Sensitivity**

- 5120 Detectors (TES bolometers)
- 1.5 K optics with no windows
- NEQ < 2 μK $s^{1/2}$ at 200, 270 GHz

**Systematics**

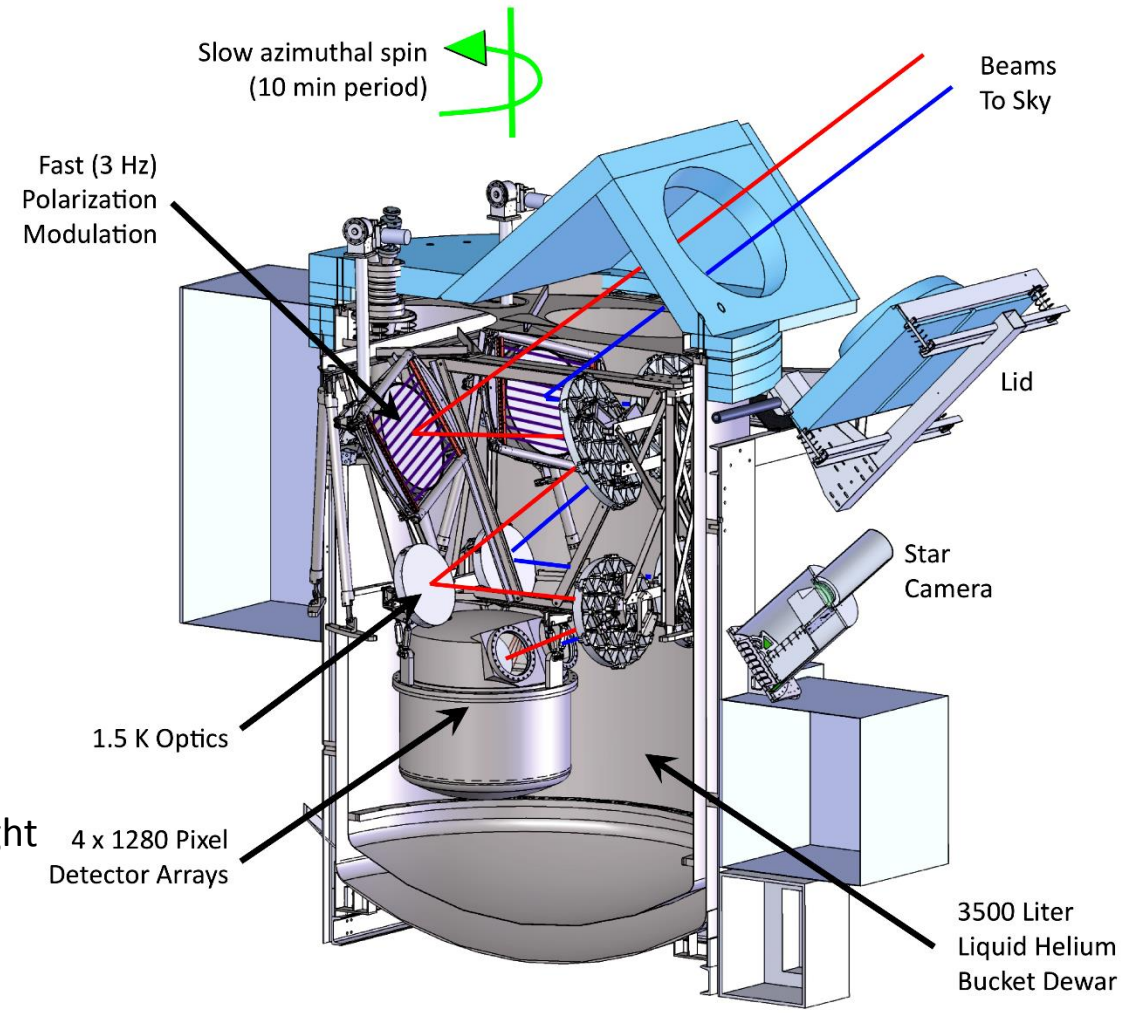
- Front-End polarization modulator
- Twin telescopes in bucket dewar

**Foregrounds**

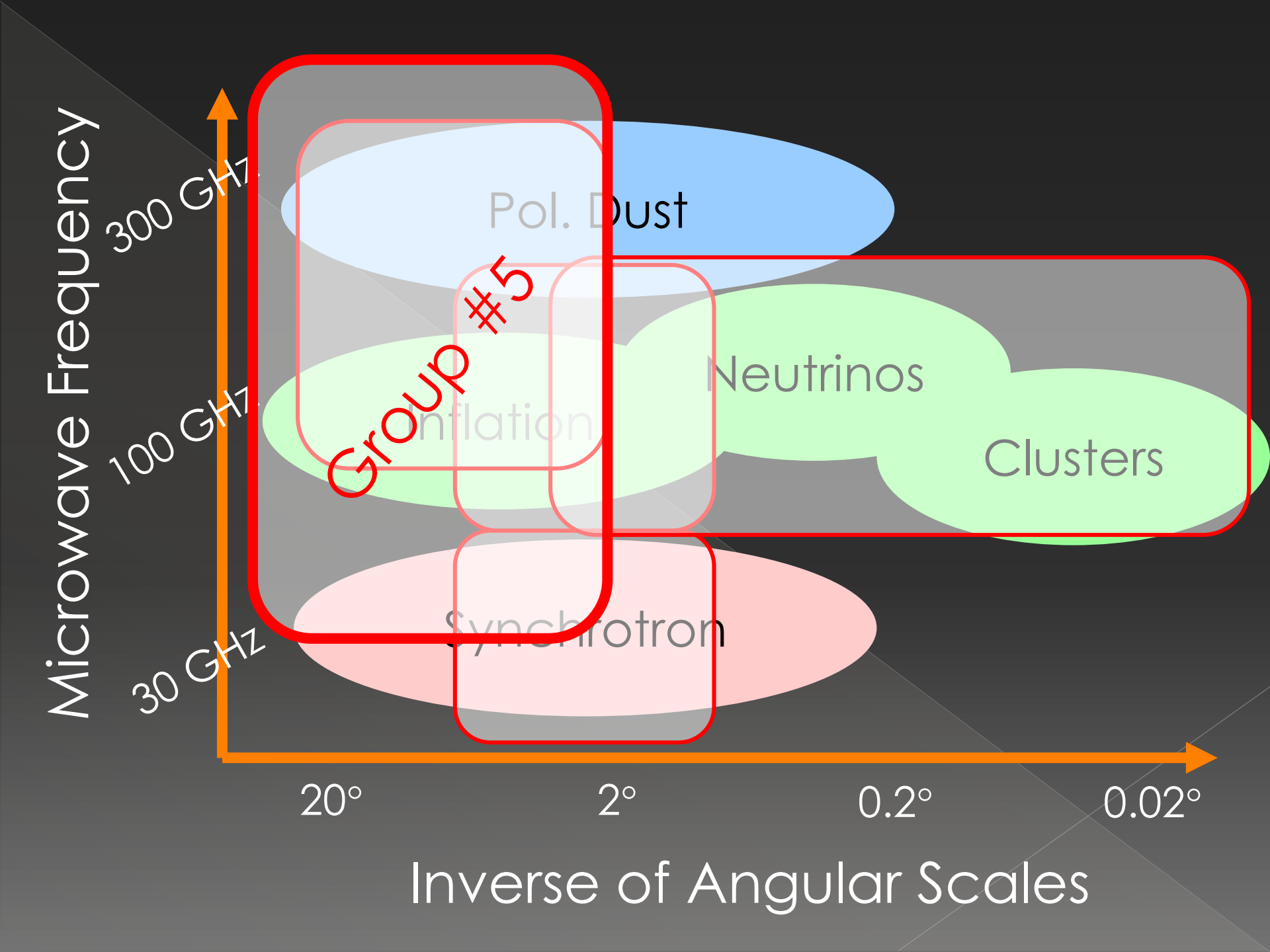
- 200, 270, 350, and 600 GHz
- Clearly separate dust from CMB

**Sky Coverage**

- Balloon payload, conventional flight
- 8 flights; half the sky each night

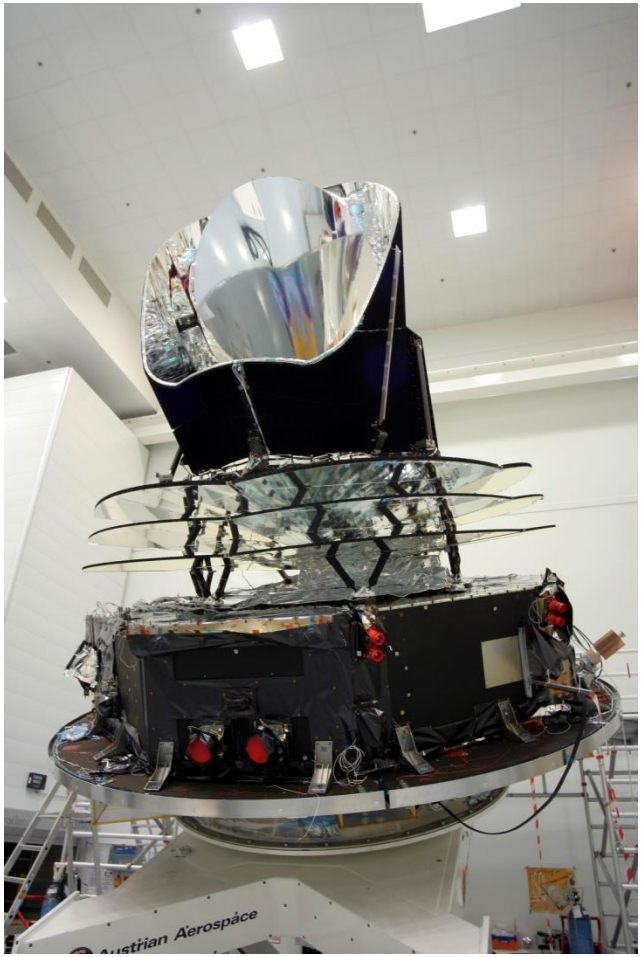



**Goal: Detect Primordial B-Modes with r < 0.01**

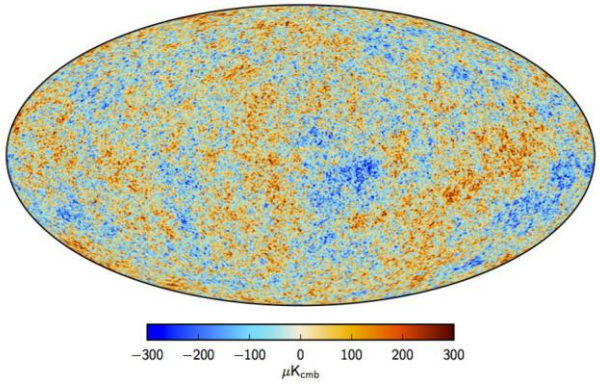

Microwave Frequency
300 GHz
100 GHz
30 GHz
Pol. Dust
Group #5
Inflation
Neutrinos
Clusters
Synchrotron
20°
2°
0.2°
0.02°
Inverse of Angular Scales

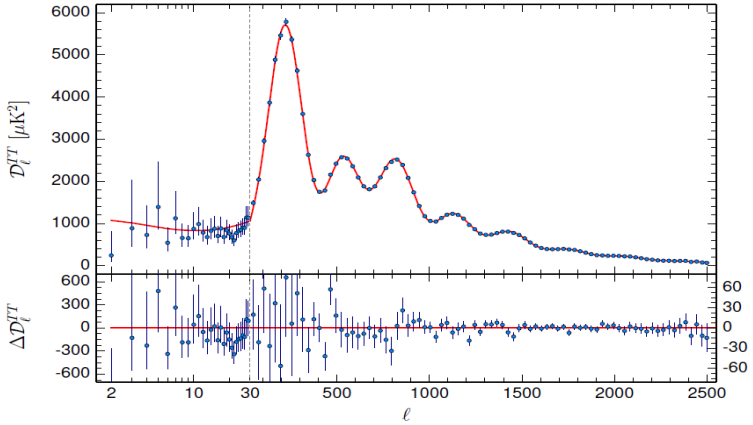
# The Planck Satellite

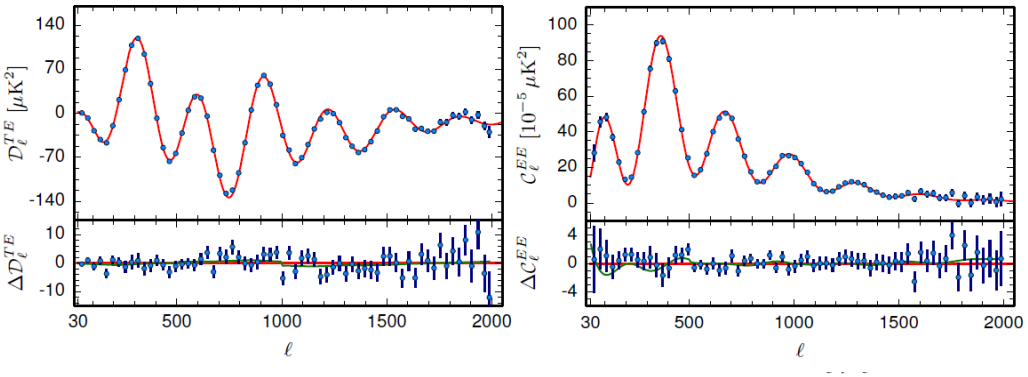
Hardware: ~600 ME, third generation CMB probe, ESA medium size mission, NASA (JPL, Pasadena) contribution on cooling systems
Low Frequency Instrument (LFI, Nazareno Mandolesi PI, instrument design and construction supervised by Marco Bersanelli) based on radiometer technology operating at three frequency channels, 30, 44, 70 GHz
High Frequency Instrument (HFI, Jean-Loup Puget PI) based on bolometer technology, operating at 100, 143, 217, 353, 545 GHz
All sky measurements, reaching 5 arcminutes angular resolution, sensitivity reaching 10 micro-K/resolution element
About 16 years (1993-2009) of design and construction
Two data processing centres, in Paris and Trieste, 2 data releases achieved (2013, 2015), 1 to go, foreseen for 2016
Next: main cosmological results
Not reported, implications for astrophysics, with tens of thousands of extra-Galactic source observed, hundreds of galaxy clusters
Complete description and links to deliverables, tpre-launch, 2013, 2015, intermediate papers available at www.cosmos.esa.int/web/planck



# Planck 2015: CMB



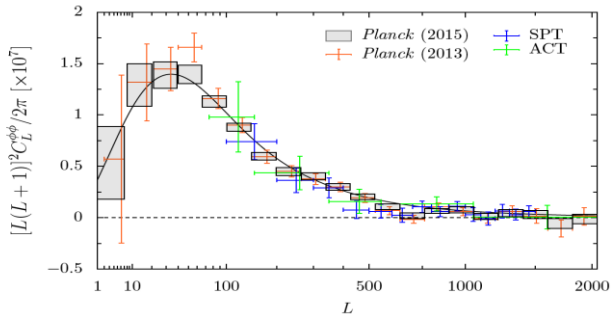




- Constraint to LCDM through cosmological parameter estimation
- Cross-correlation with LSS (CMB lensing, ISW, ...)
- Upper limit on neutrino masses
- Diffuse Galactic foreground polarization measurements for B-mode experiments
- Galactic populations through tens of thousands of sources
- Cosmological studies using galaxy clusters catalogues with hundreds of objects
- ...

Planck (+BAO)

$\Sigma m_\nu < 0.17\text{eV}$

$N_{\text{eff}} = 3.04 \pm 0.18$



# LiteBIRD - JAXA-led CMB polarization satellite

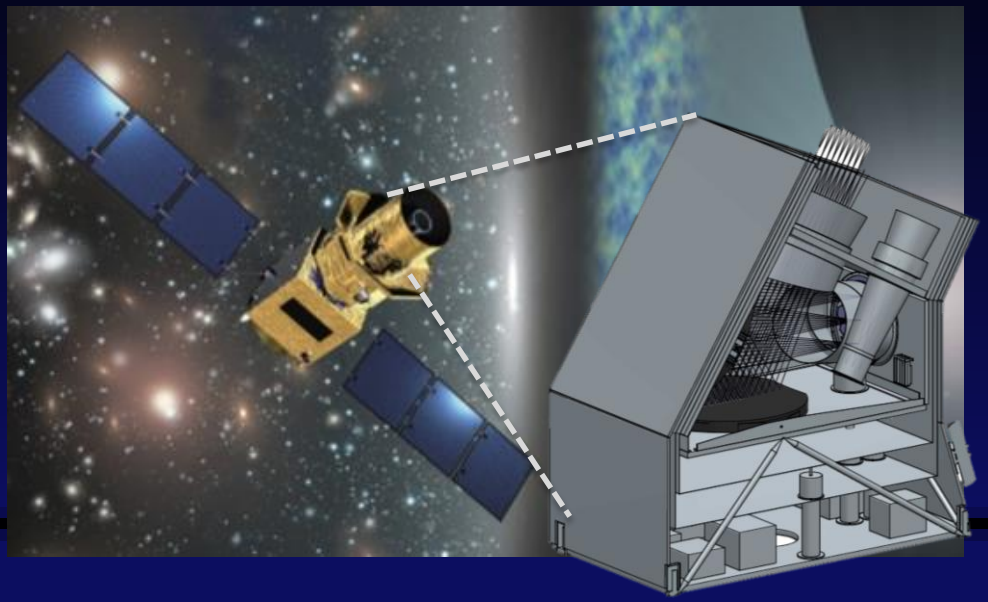
*Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection*

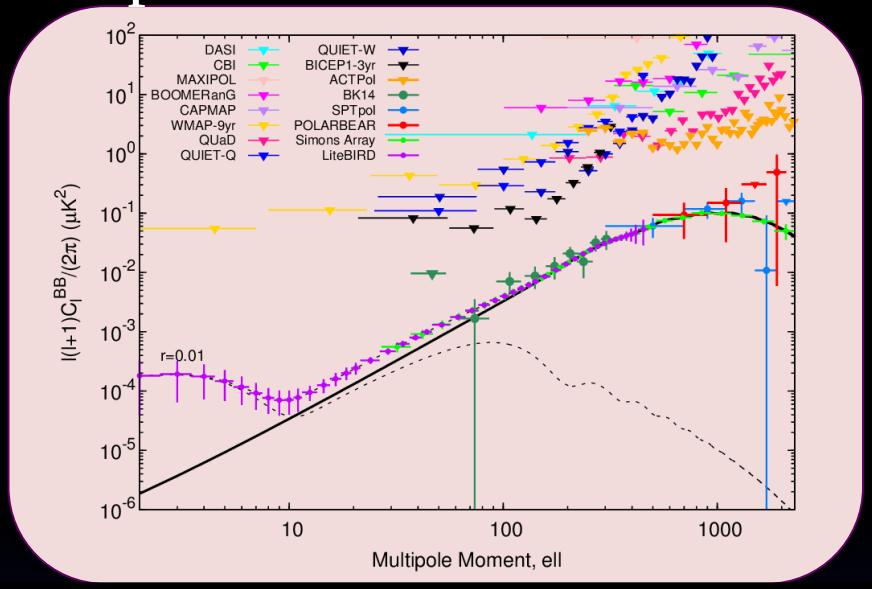
## Primacies

1. CMB polarization all-sky survey proposed in JFY14*
   - Also to NASA MO for US participation (Dec. 2014)
   - Both proposals passed initial down-selections (JFY15)
2. Full success
   - Total uncertainty on r, $\sigma(r=0) < 0.001$
   - Multipole coverage: $2 \leq \ell \leq 200$

***i.e. both bumps (reionization, recombination) detected with large ( >5sigma) significance if r > 0.01***

* JFY2014 = Japanese Fiscal Year 2014 = b/w Apr. 2014 and Mar. 2015

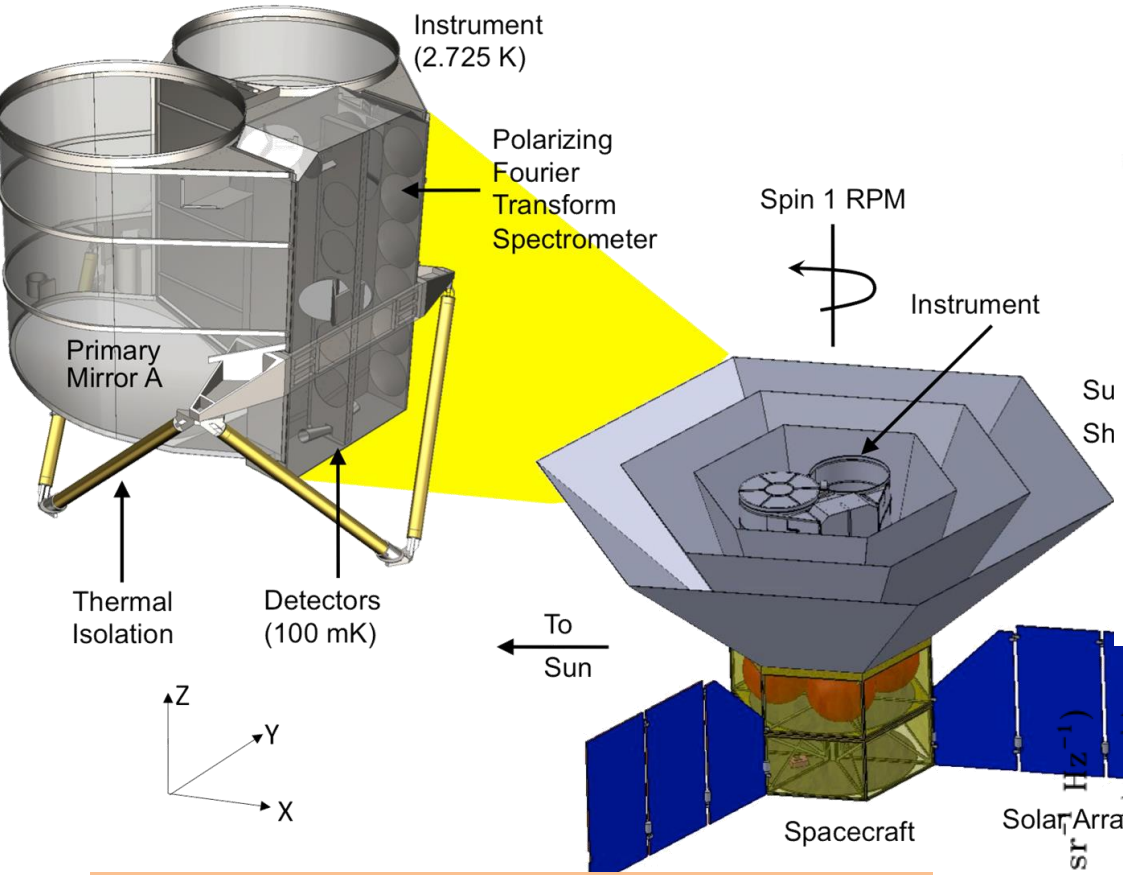


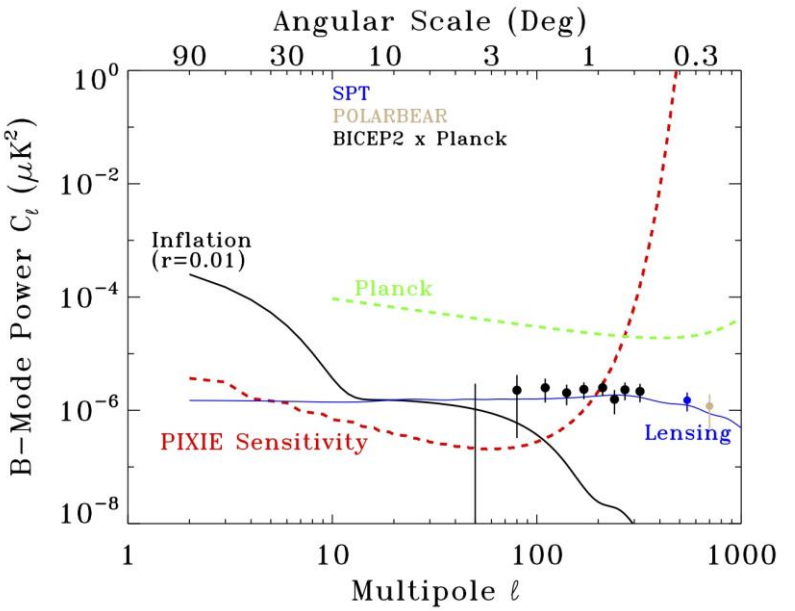


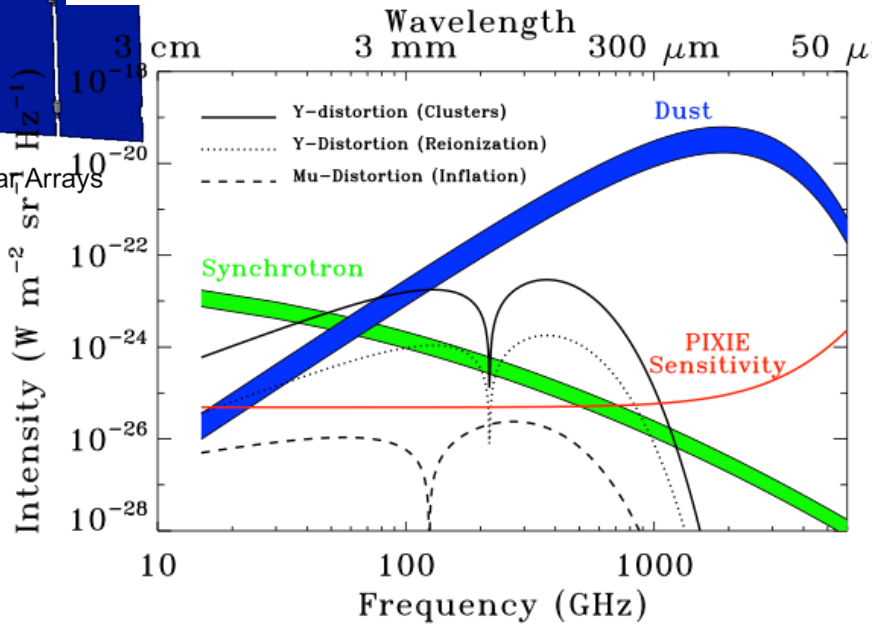

**Main specifications (Phase-A baseline design)**

| Item | Specification |
|---|---|
| Orbit | L2 halo orbit |
| Launch year (vehicle) | 2025 (H3 or H2A) |
| Observation (time) | All-sky CMB survey (3 years) |
| Mass | 2.2 t |
| Power | 2.5 kW |
| Mission instruments | • Superconducting detector arrays<br>• Continuously-rotating half-wave plate (HWP)<br>• Crossed-Dragone mirrors<br>• 0.1K cooling system (ST/JT/ADR) |
| Frequencies (# of bands) | 40 – 400 GHz (15 bands) |
| Data size | 4 GB/day |
| Sensitivity | 3 μKarcmin (3 years) with margin |
| Angular resolution | 0.5deg @ 100 GHz |

# PIXIE: Full-Sky Spectro-Polarimetric Survey




## Multiple Science Goals

- Inflation/GUT Physics
- Dark Matter
- Reionization/First Stars
- ISM and Dust Cirrus

B-mode: $r < 2 \times 10^{-4}$ ($1\sigma$)

Distortion $|\mu| < 10^{-8}$, $|y| < 5 \times 10^{-9}$

# Future Outlook

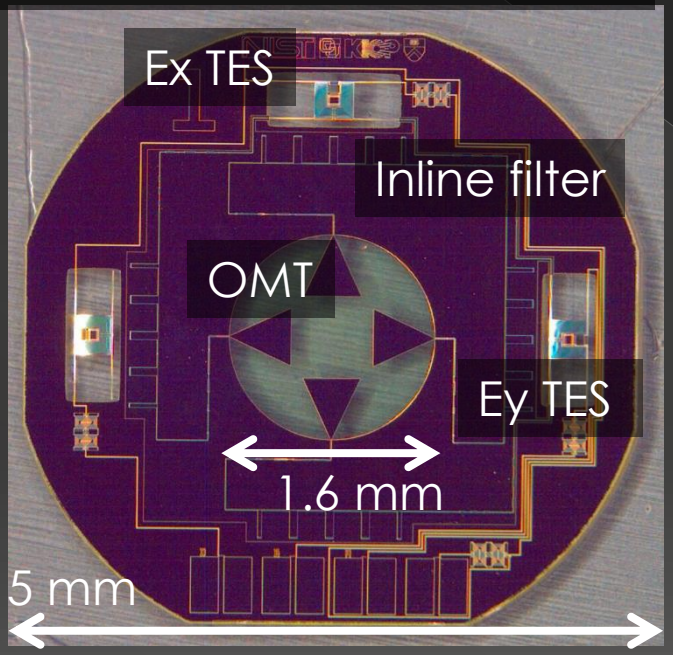
- Now – 2020: Stage 3 experiments
  - $\sigma(r) \sim 0.01$, depending on foregrounds
  - $\sigma(\sum m_\nu) \sim 50\text{meV}$, depending on BAO, $\tau$
- 2020 – 2030: CMB-S4, Satellites
  - $\sigma(r) \sim 0.001$
  - $\sigma(\sum m_\nu) \sim 20\text{meV}$, depending on $\tau$
  - $\sigma(N_{\text{eff}}) \sim 0.02$

# Summary

- Science of CMB polarization
  - Inflation – gravity and quantum mechanics
  - Gravitational lensing and neutrino mass
  - Extra relativistic species
- Current & Future
  - We are scaling up the instrument
  - Stage-3 experiments → Stage 4

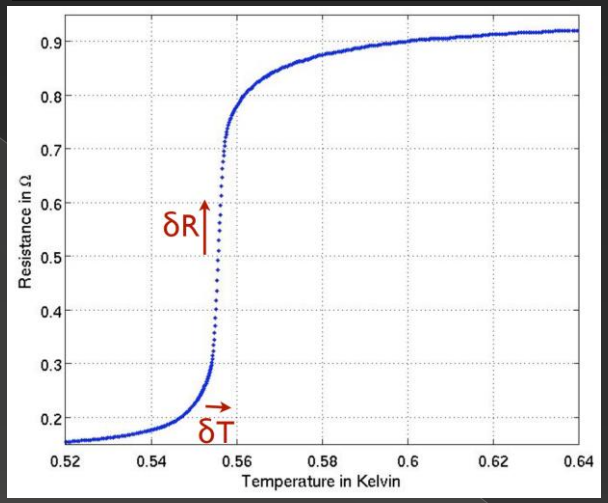
# (Some of) Key Technologies

## Polarization sensitive TES (from ABS experiment)



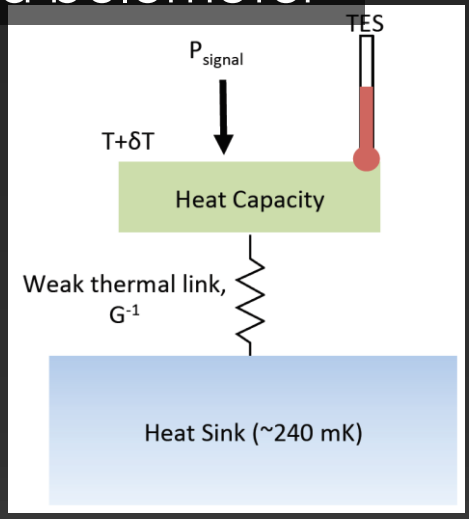

Fabricated at NIST

## TES resistance curve



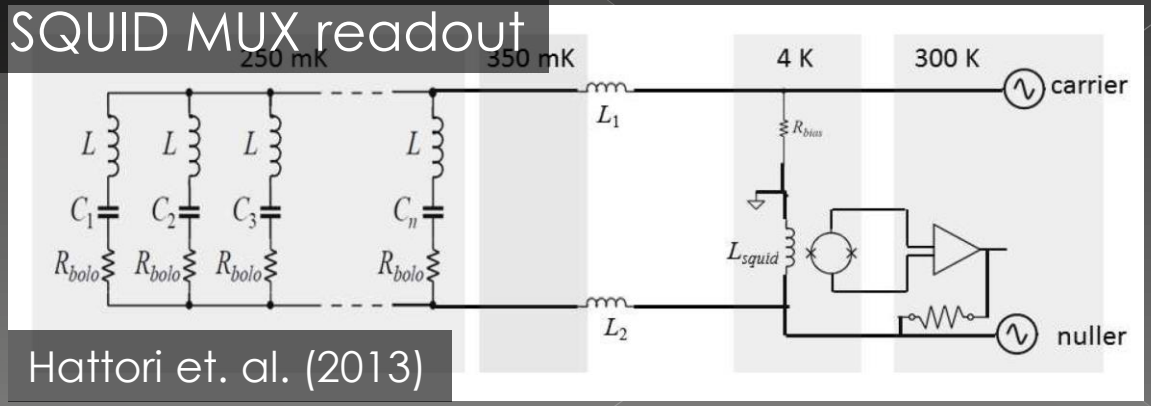

Irwin (1995)

## Schematic of a bolometer




Abazajian et. al. (2014)

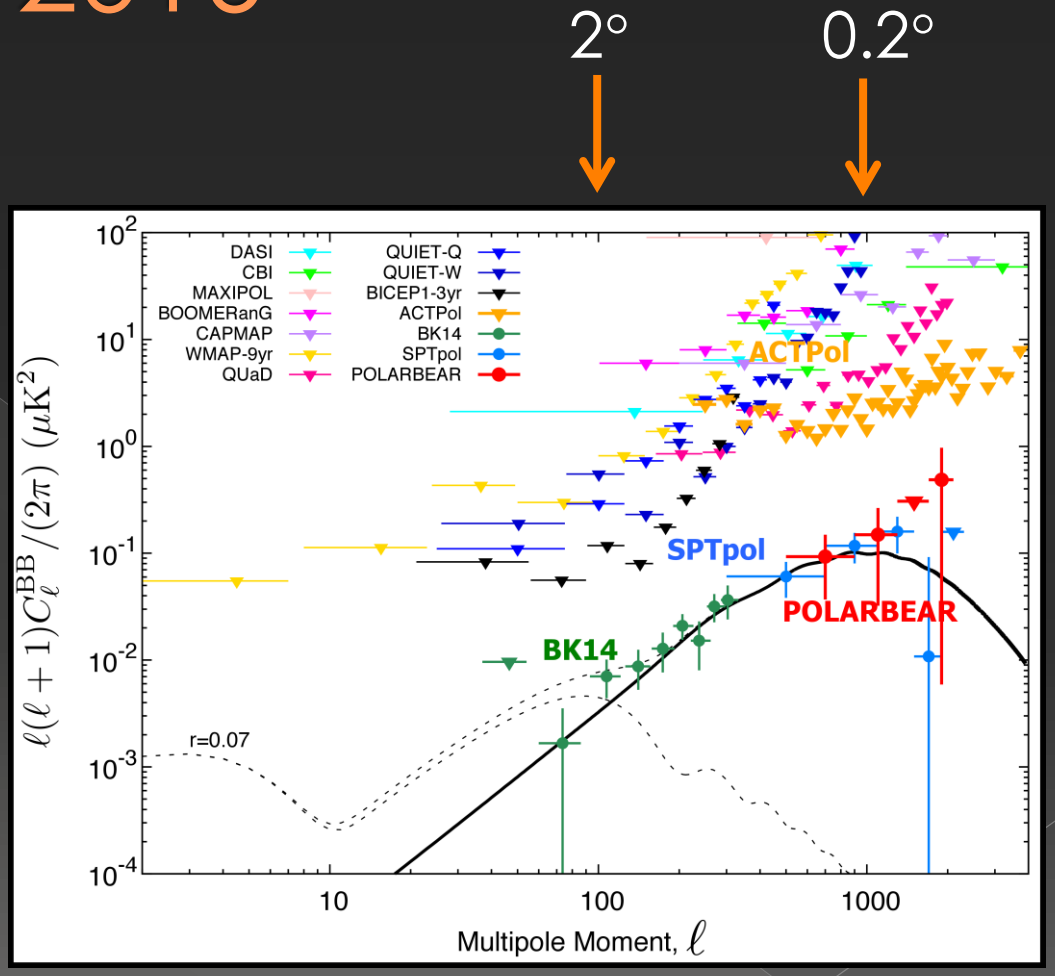
## SQUID MUX readout




Hattori et. al. (2013)

# Status as of 2016

- Gravitational lensing *BB* observed
  - Further improvement necessary for achieving interesting science.
- No significant *BB* from gravitational waves detected.

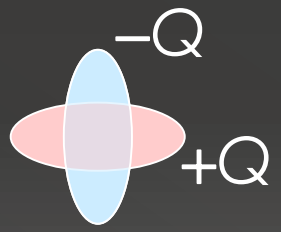


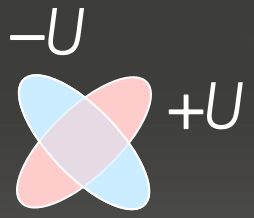

Plot by Yuji Chinone

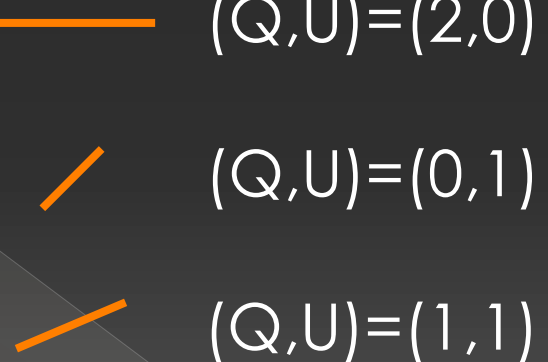
# Stokes parameters: I, Q, U, V

I: Intensity

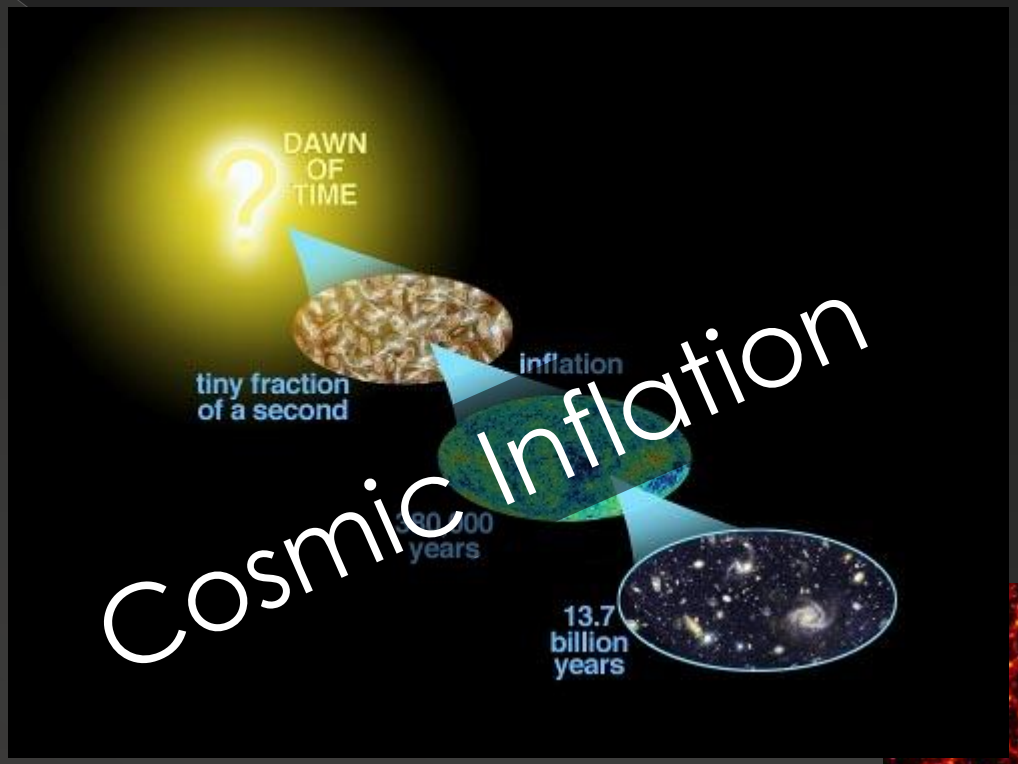
Q, U: Linear polarization



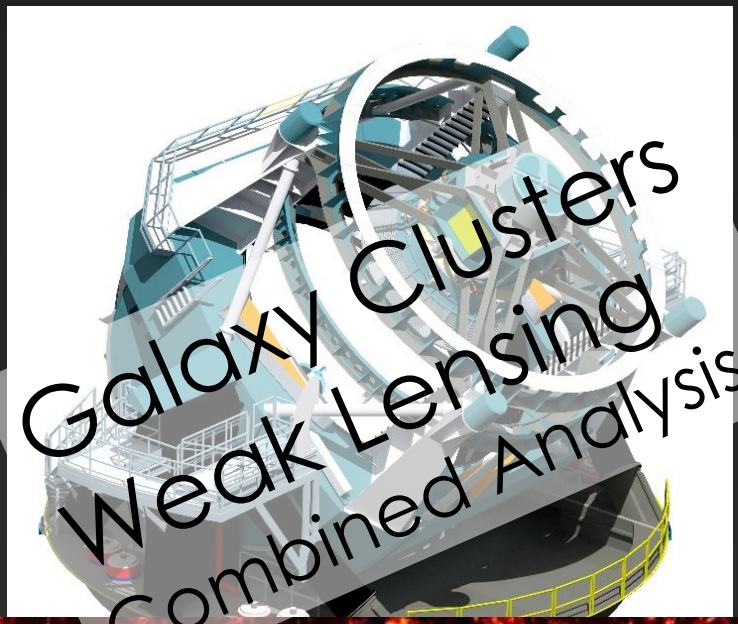



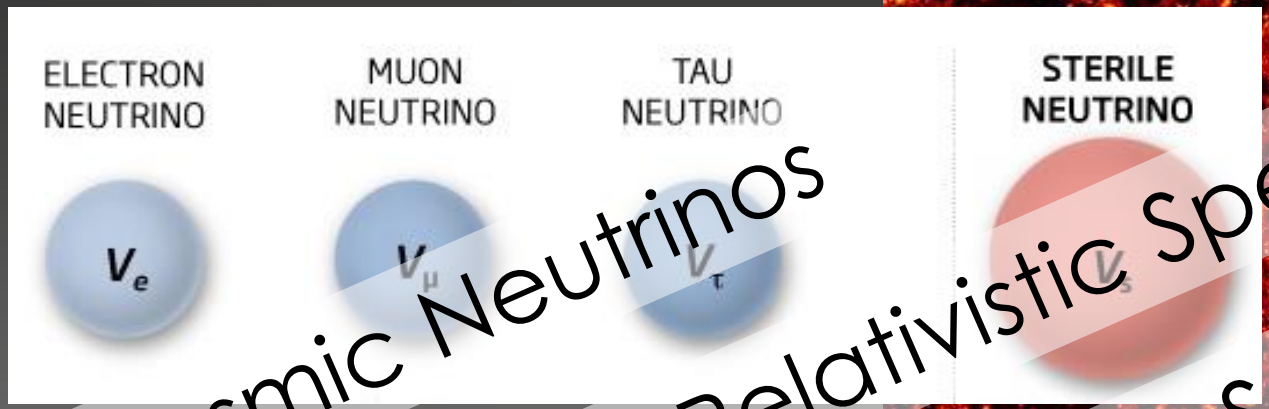

V: Circular polarization




Cosmic Inflation



Galaxy Clusters
Weak Lensing
Combined Analysis




Cosmic Neutrinos

Extra Relativistic Species

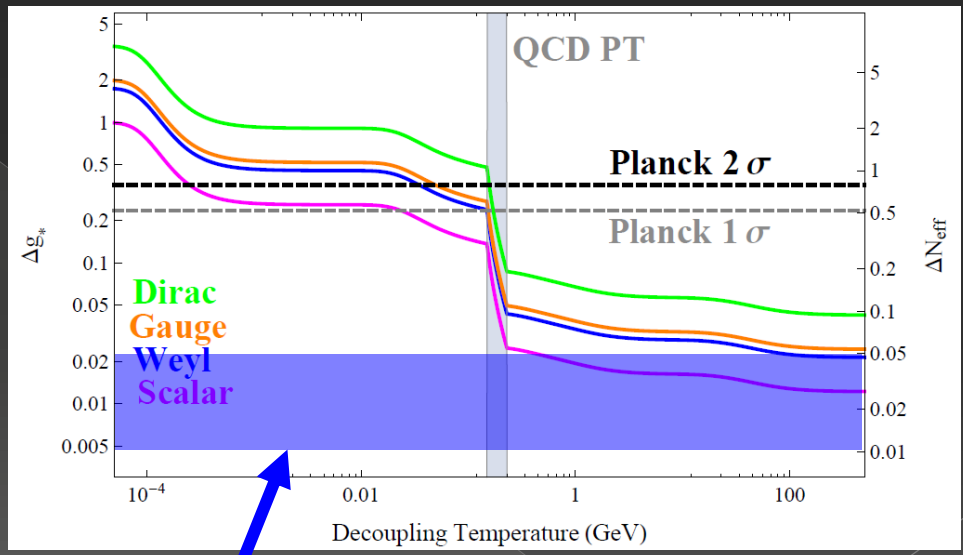
Large Scale Structure

# Extra Relativistic Species

Early universe = extremely clean thermal bath.

Additional relativistic species → impact on expansion history ~decoupling.

$N_{eff}$ as a function of decoupling temperature of the extra species.




Brust et. al. (2013)

Reach of Stage 4 CMB experiment

# Polarization – E modes and B modes

*E* modes: curl free component

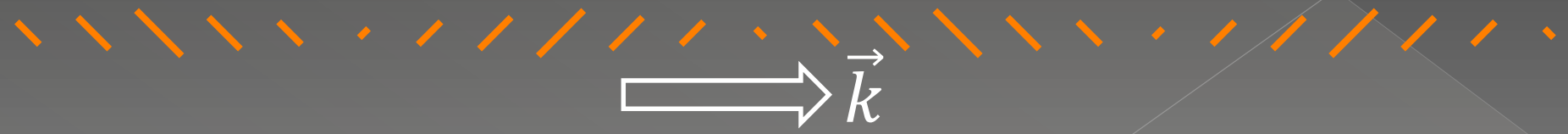
$$E(x,y) \propto \mathrm{div}(Q,U) \propto \left[\partial_x^2 - \partial_y^2\right] Q(x,y) + 2\partial_x \partial_y U(x,y)$$

$$\tilde{E}(k_x,k_y) = \cos 2\phi_k \, \tilde{Q}(k_x,k_y) + \sin 2\phi_k \, \tilde{U}(k_x,k_y) \qquad \phi_k = \arctan k_y/k_x$$

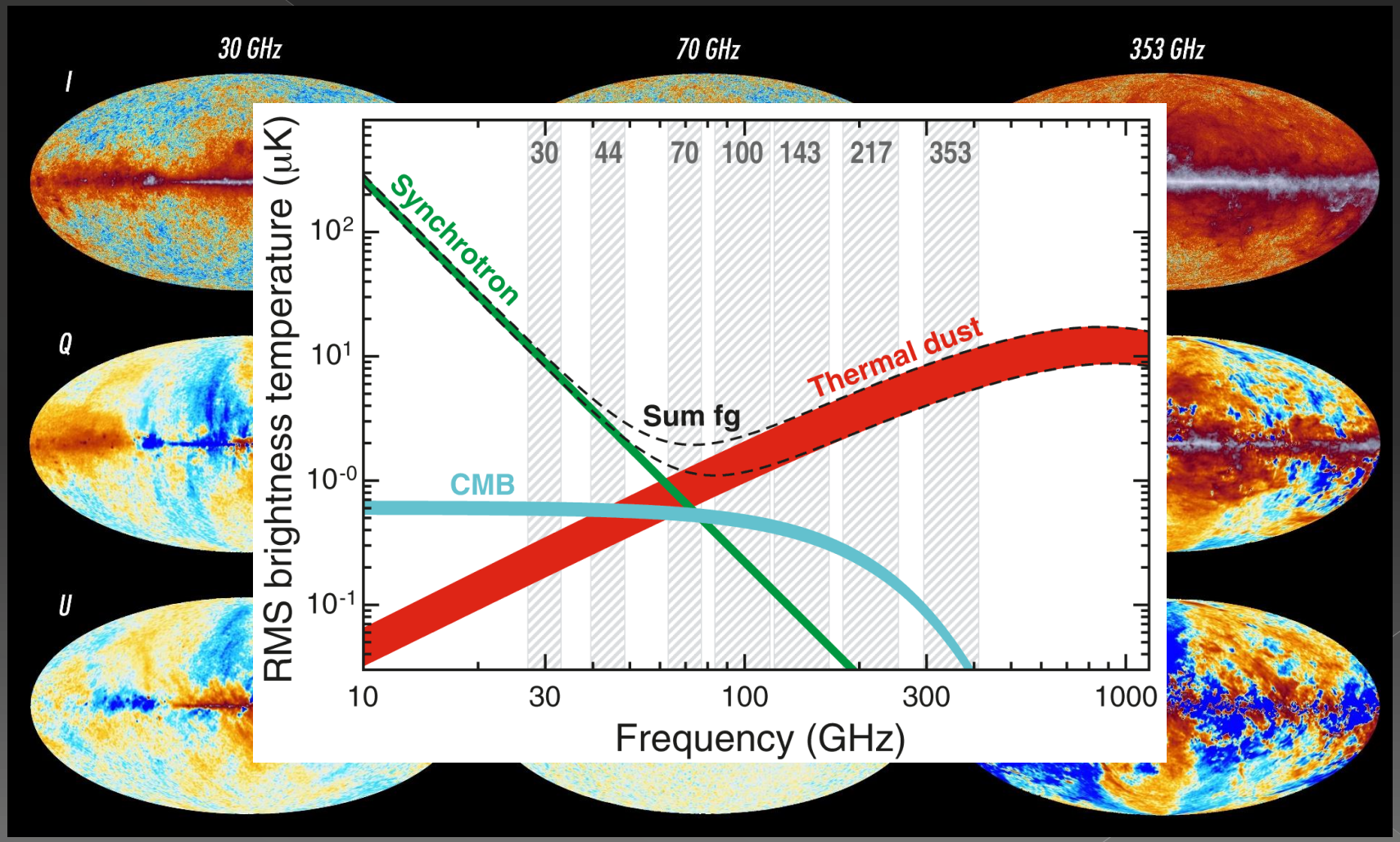
*B* modes: divergence free component

$$B(x,y) \propto \mathrm{rot}(Q,U) \propto -2\partial_x \partial_y Q(x,y) + \left[\partial_x^2 - \partial_y^2\right] U(x,y)$$

$$\tilde{B}(k_x,k_y) = -\sin 2\phi_k \, \tilde{Q}(k_x,k_y) + \cos 2\phi_k \, \tilde{U}(k_x,k_y)$$

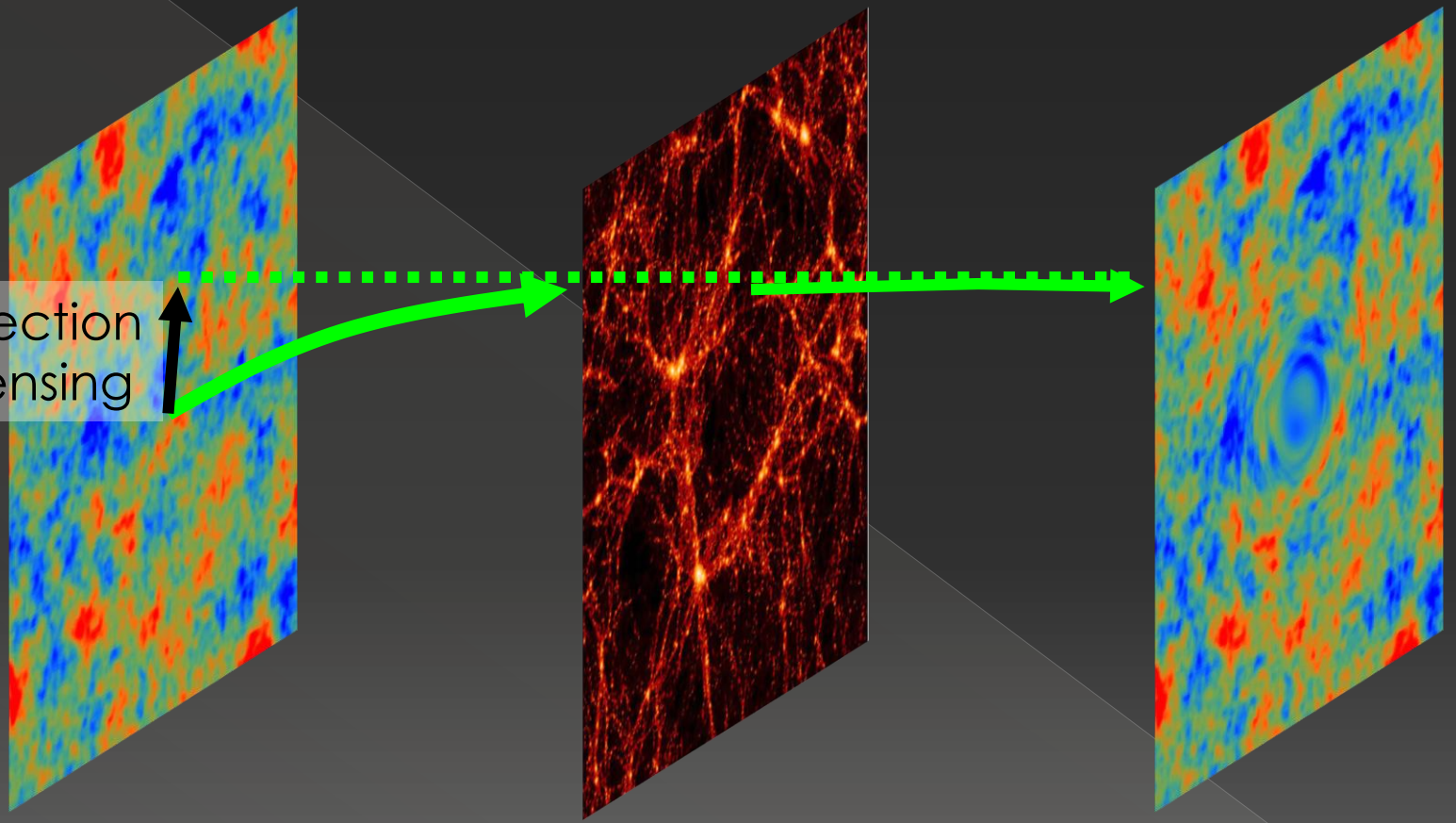


# Foregrounds




Planck Collaboration (2015)

# Deflection by "stuff" in between

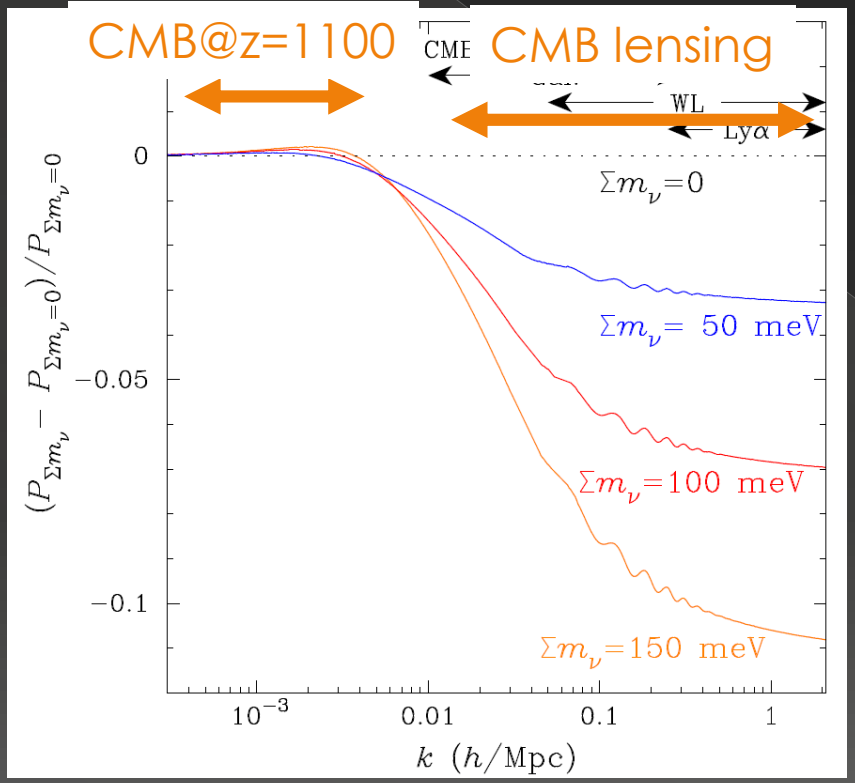


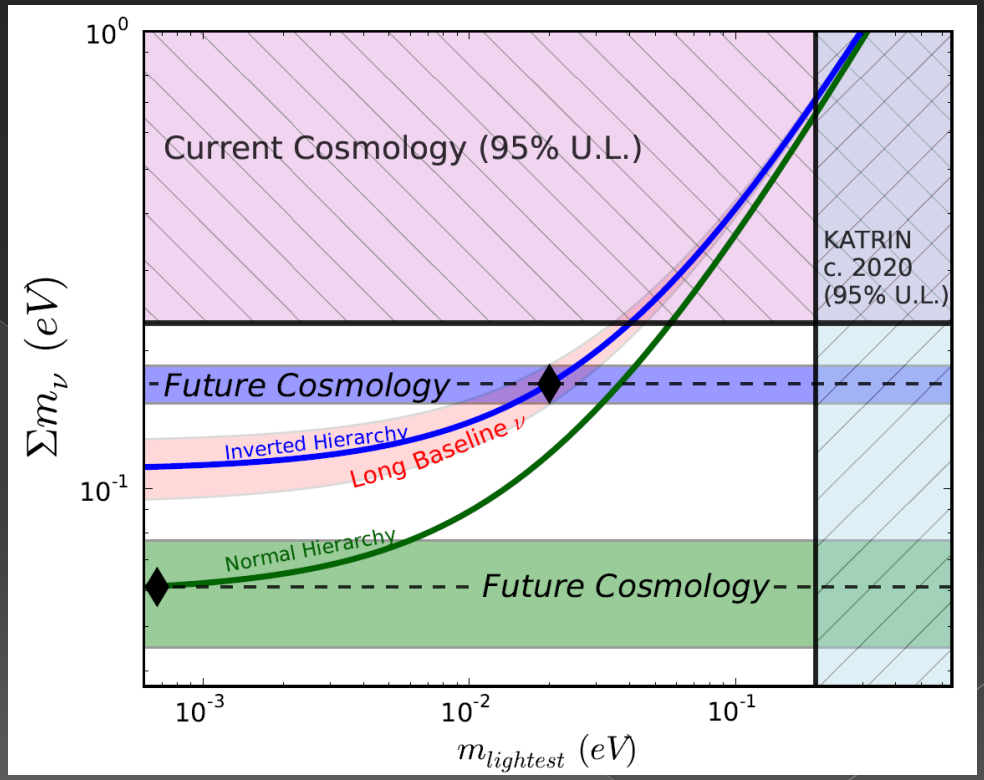

(Nearly) Gaussian
(Nearly) pure E modes

Non-Gaussian
Non-zero B modes

# Neutrino Mass

Abazajian et. al. (2014)

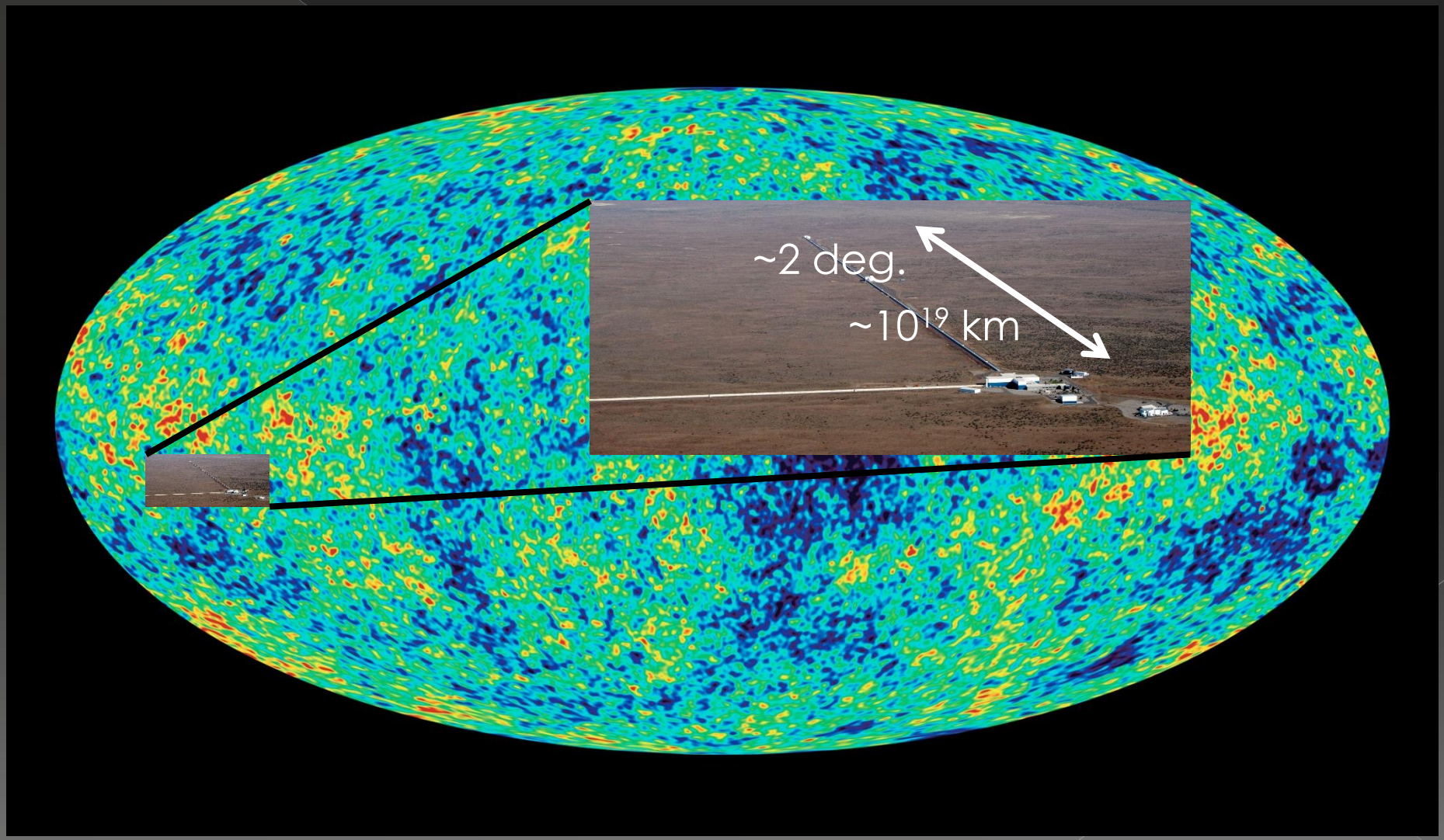


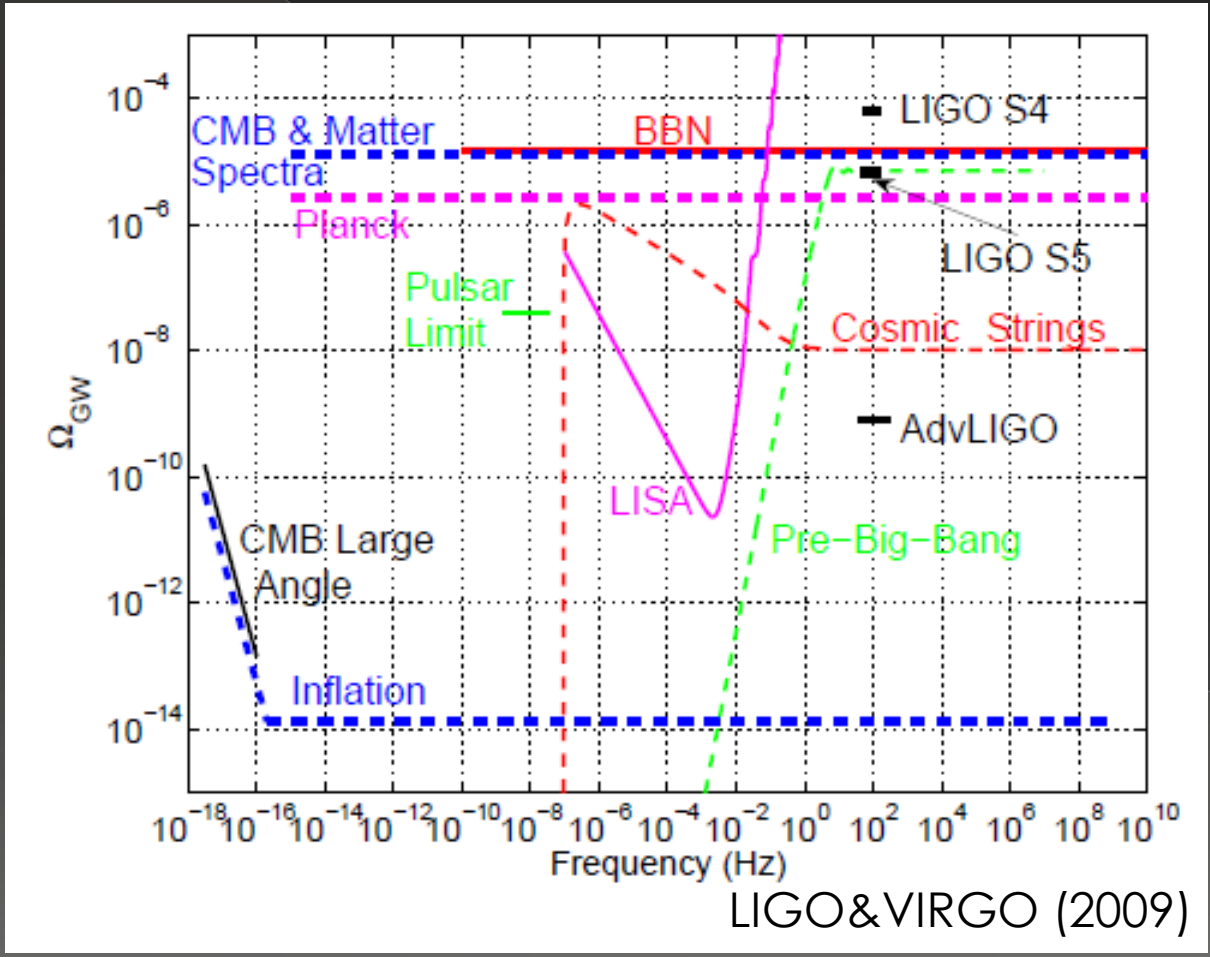

Primordial CMB + lensing measures reduction of fluctuation

Accurate mass measurement may resolve neutrino mass hierarchy.

# A huge GW detector



# Is it detectable? How?



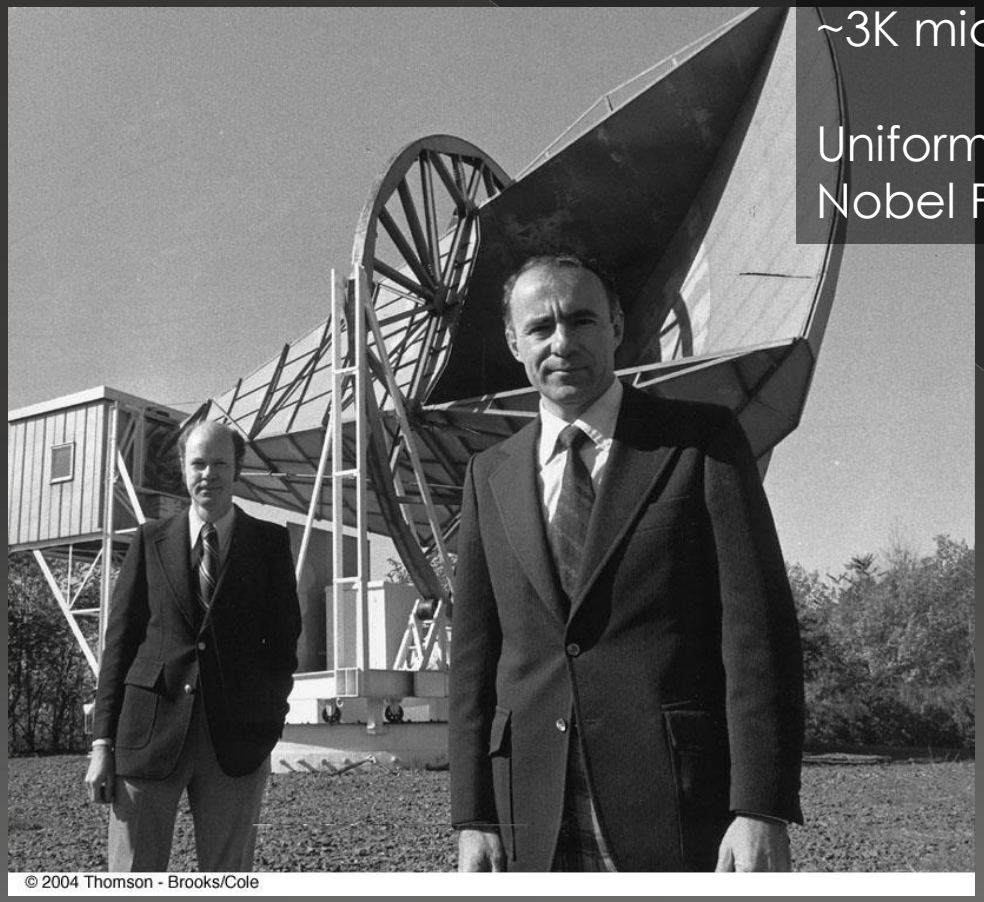

LIGO&VIRGO (2009)

w/ recent updates by
LIGO+VIRGO HF
Pulsar timing

CMB is a promising channel, r=0.001 is feasible.

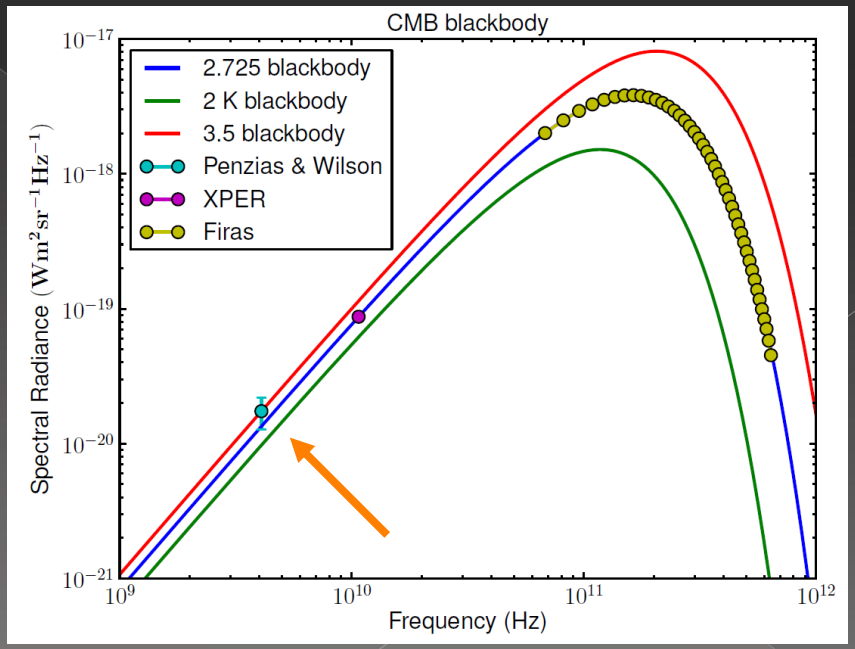
# 1965

# Arno Penzias & Bob Wilson



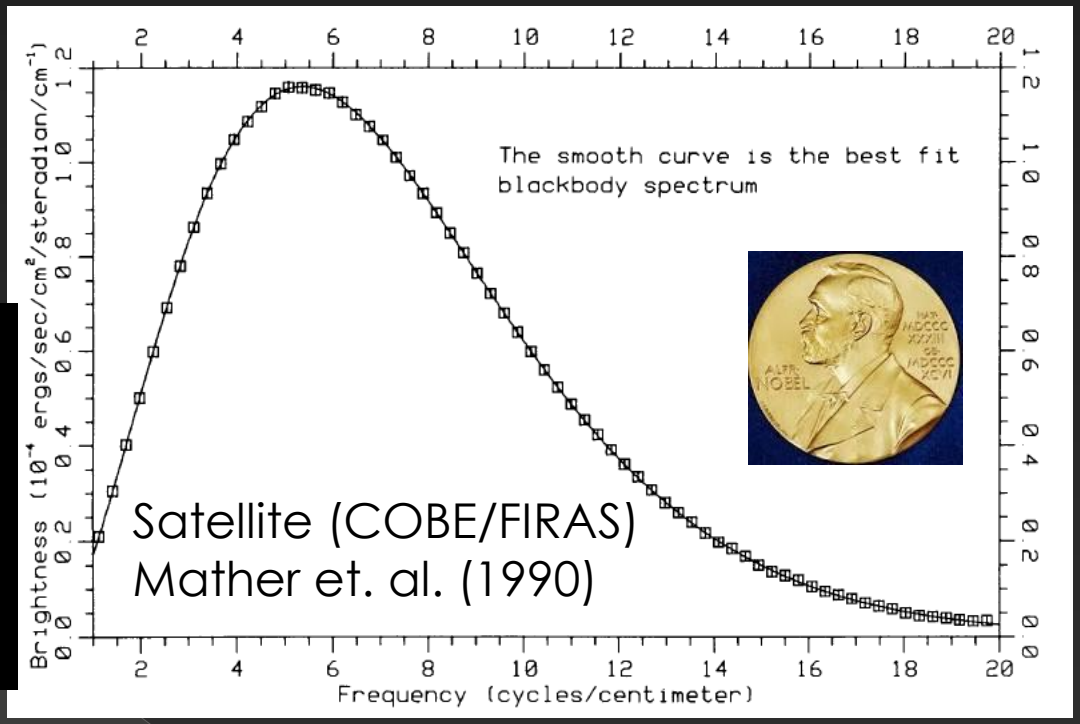

~3K microwave.

Uniform across the sky.
Nobel Prize (1978)



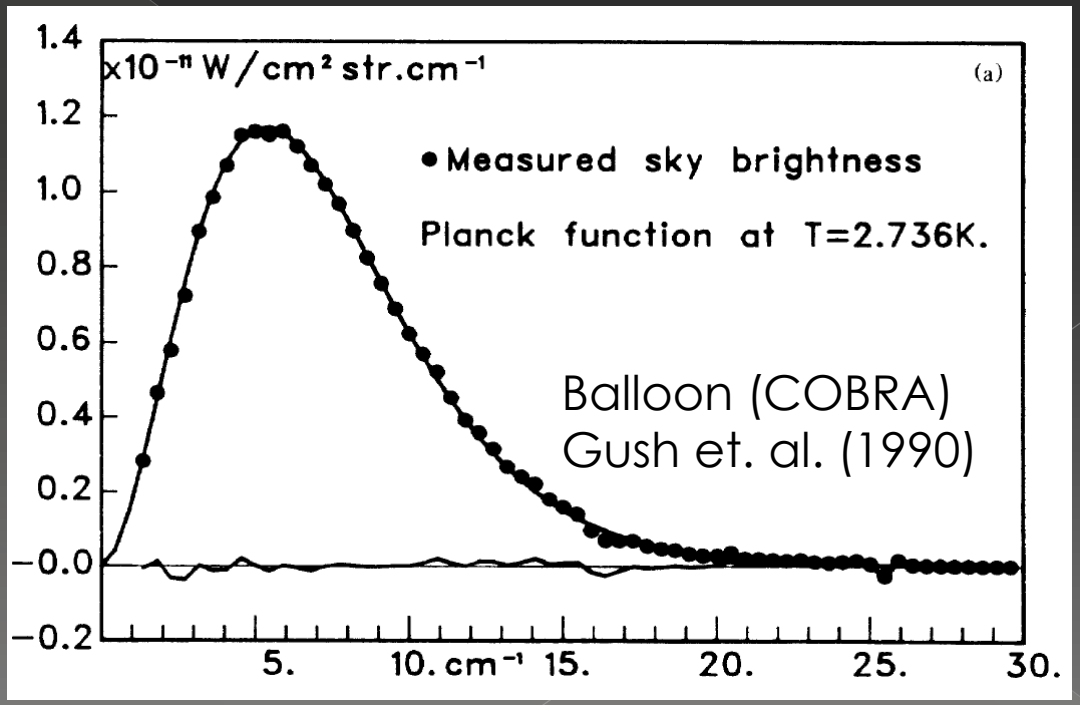

Plot from J. Appel's thesis (2012)

# 1990

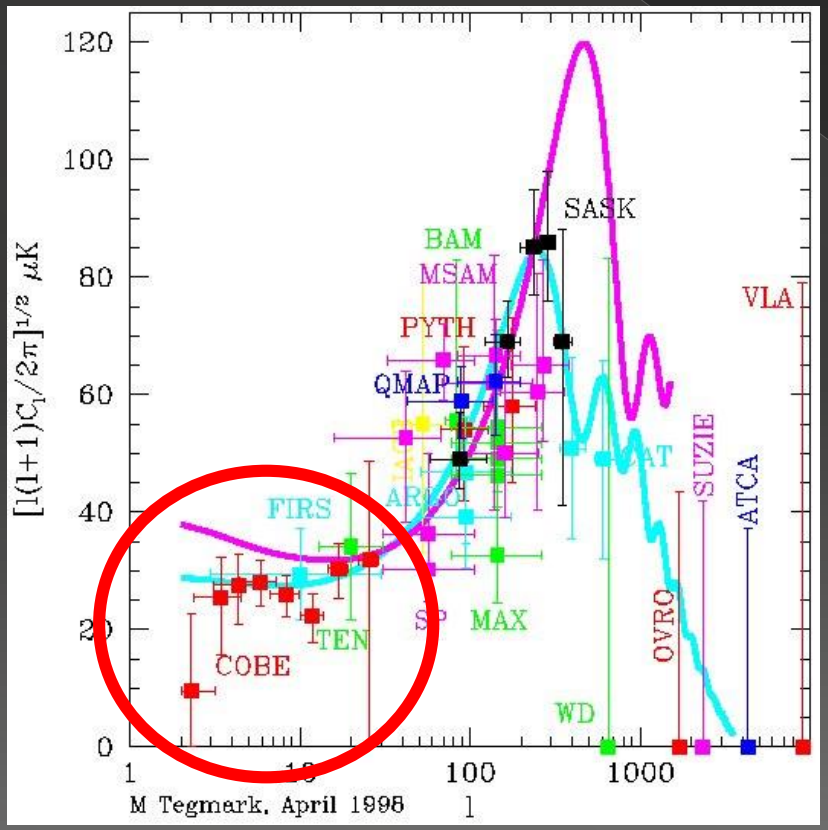


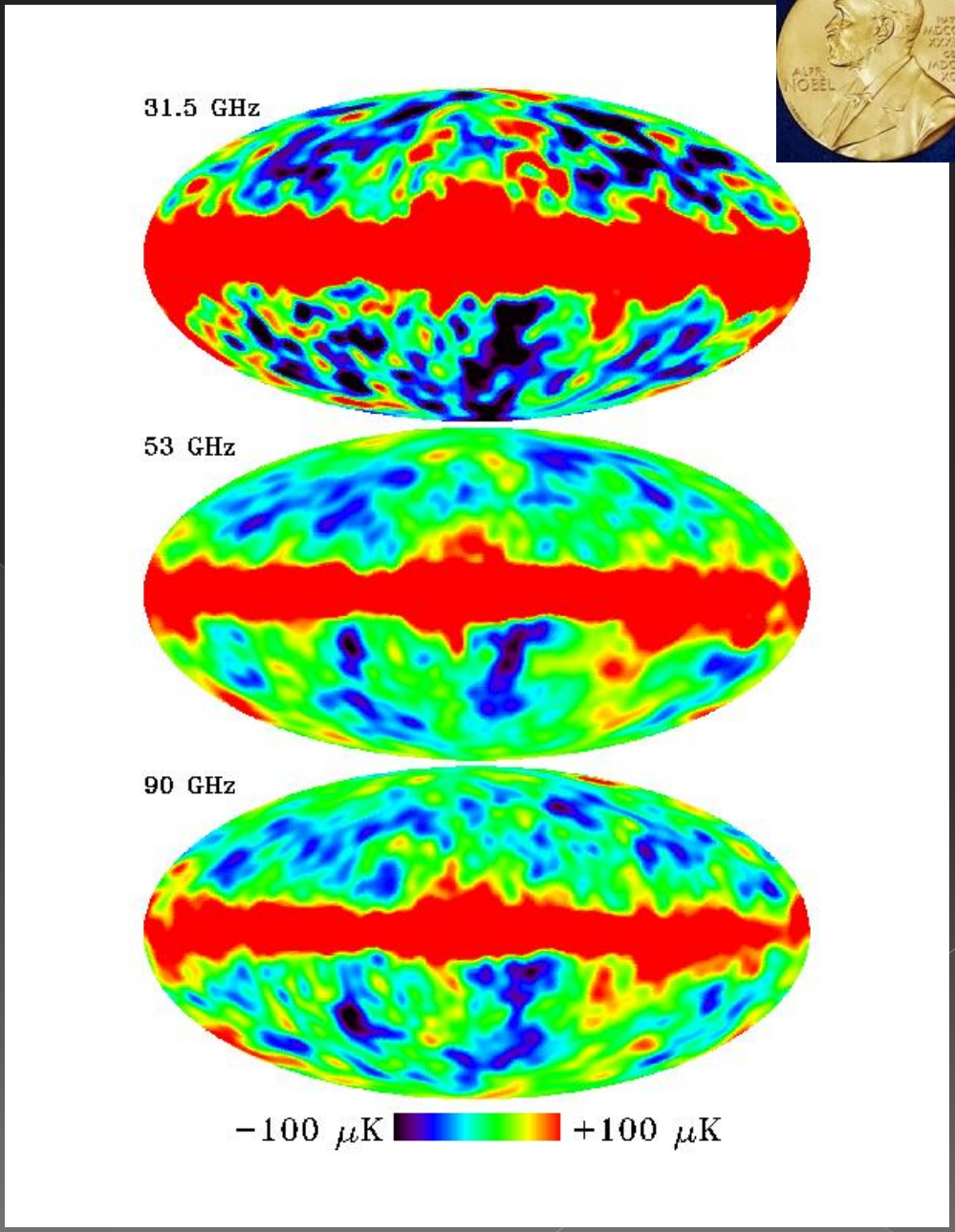

The most perfect blackbody in nature.

Strong support that this is not galactic foregrounds.



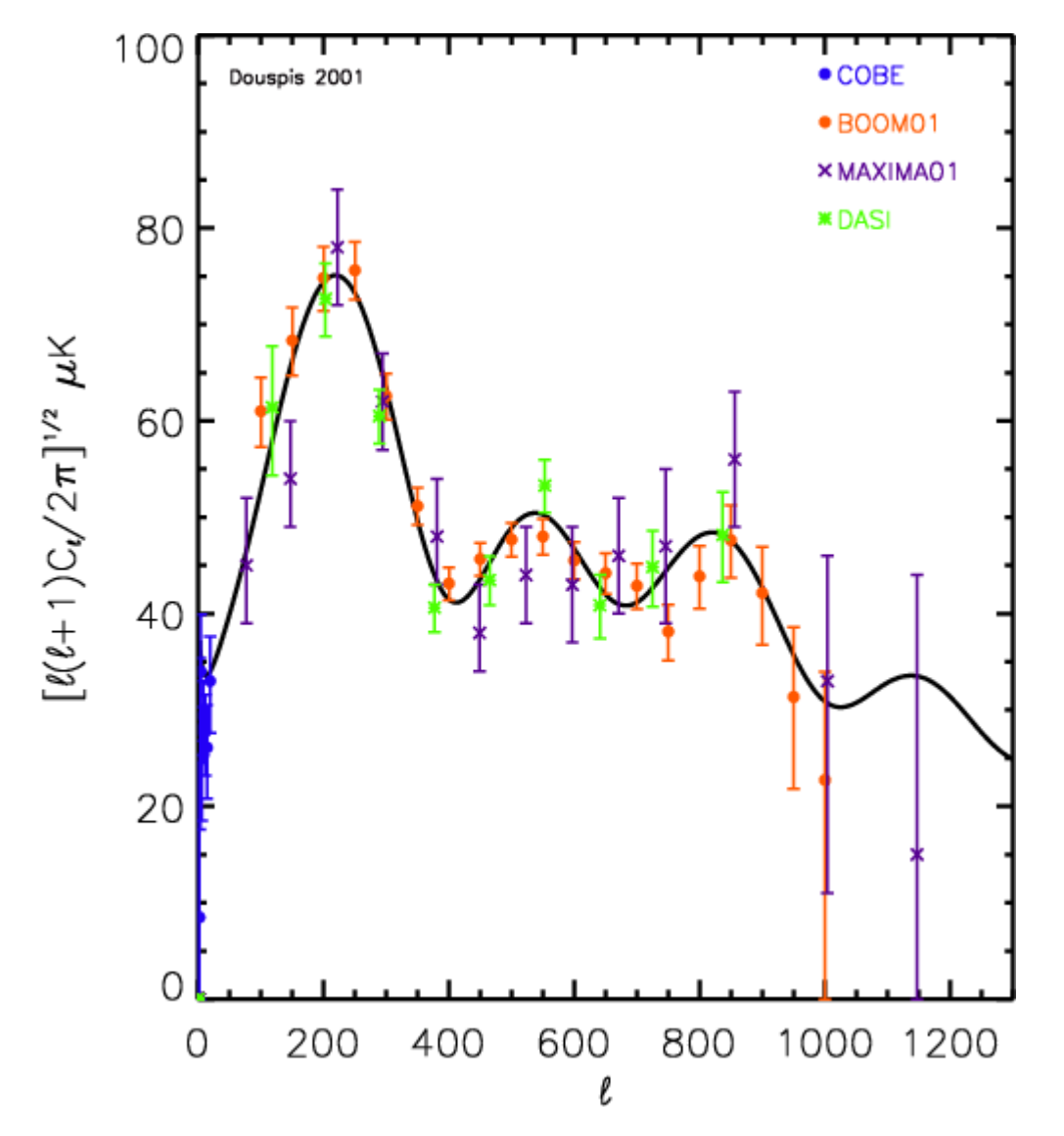
# 1992





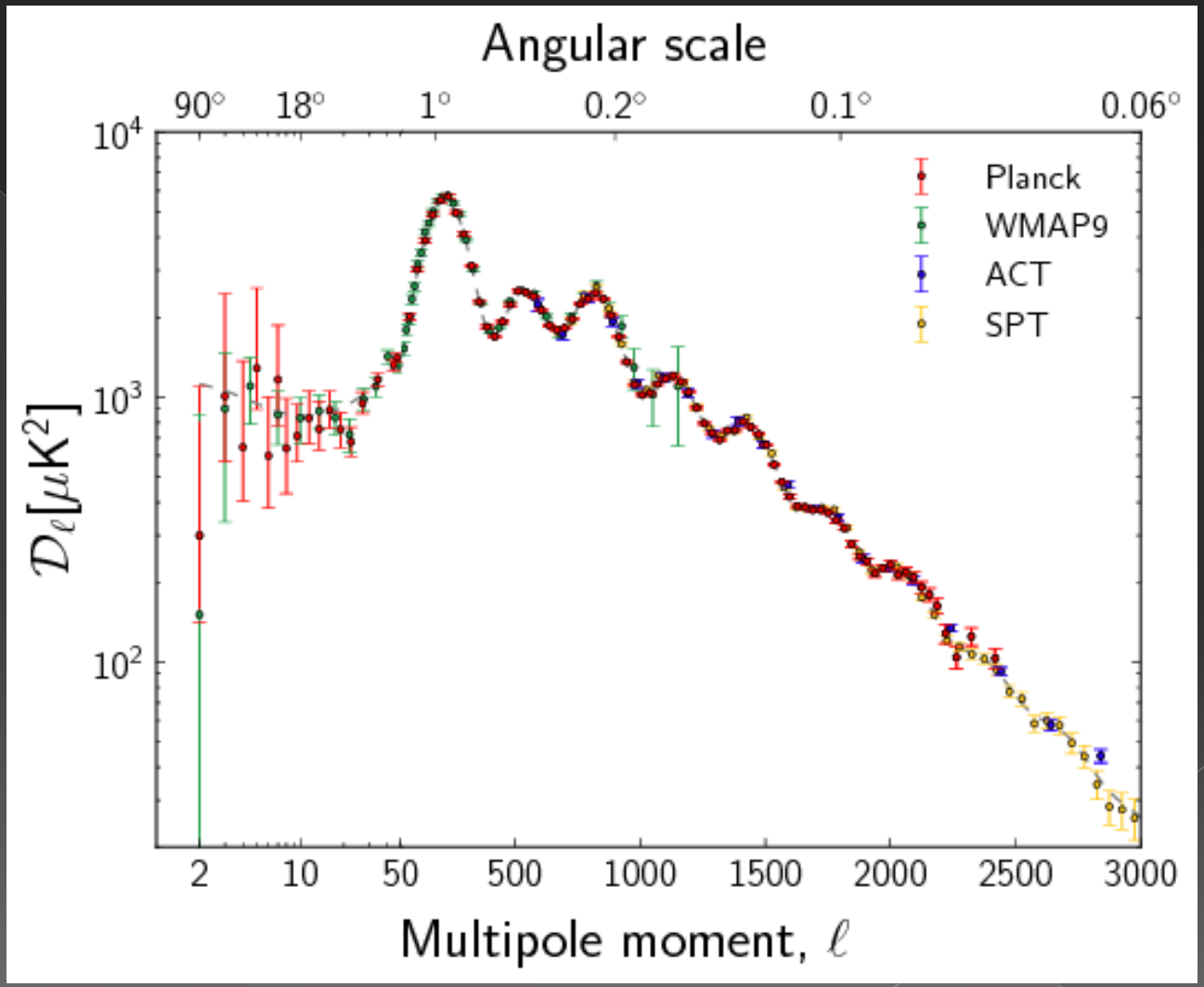

http://lambda.gsfc.nasa.gov/product/cobe/dmr_image.cfm

# 2001



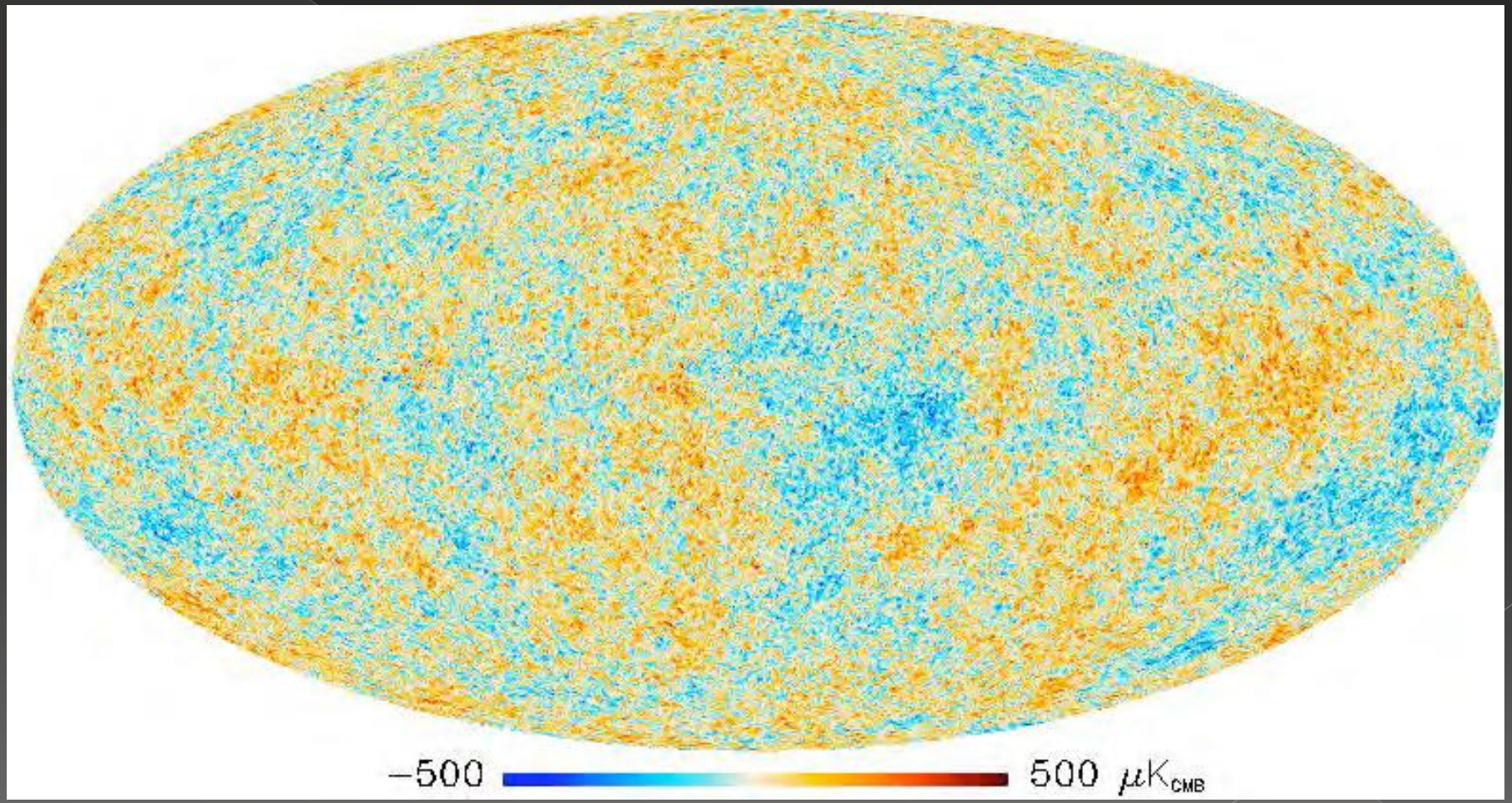

Douspis et. al. (2001)

# 2013



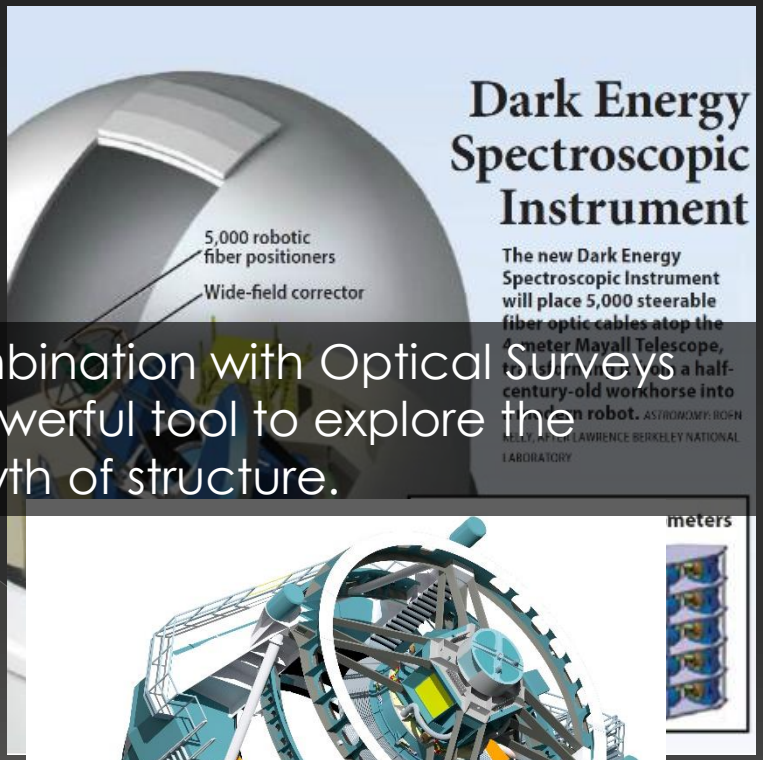

Planck Collaboration (2014)

# 2013

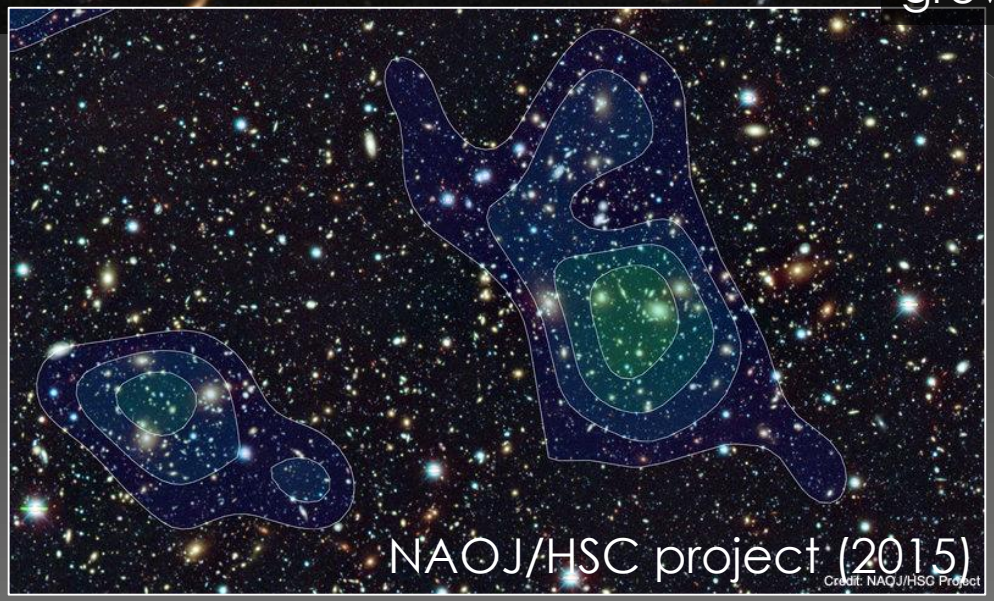



Planck Collaboration (2014)

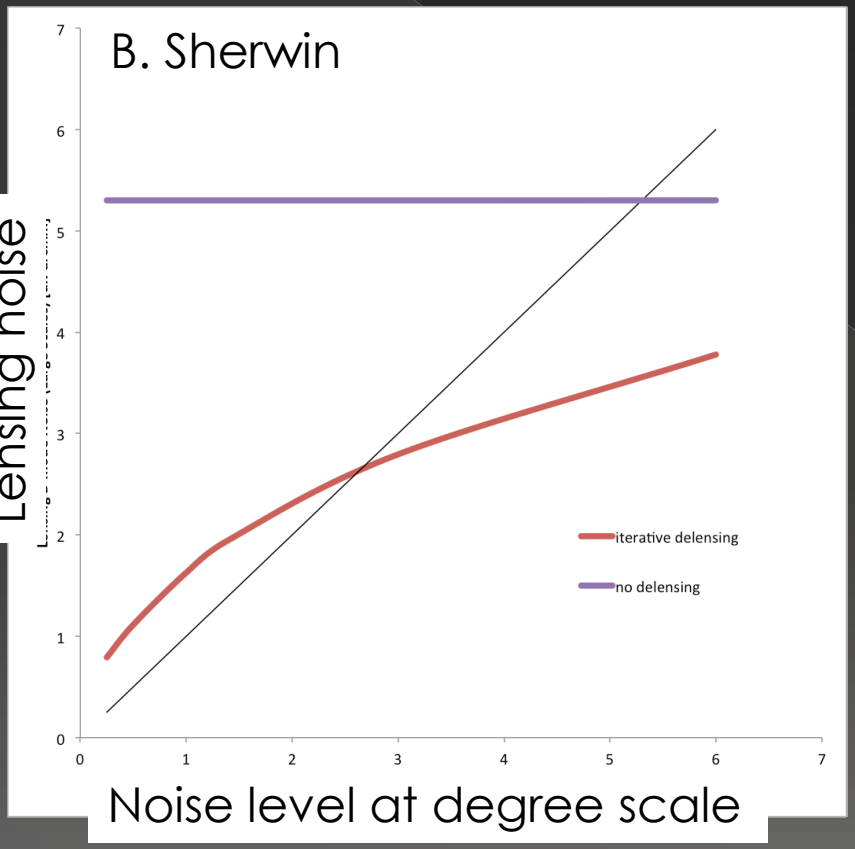
# Understanding Growth

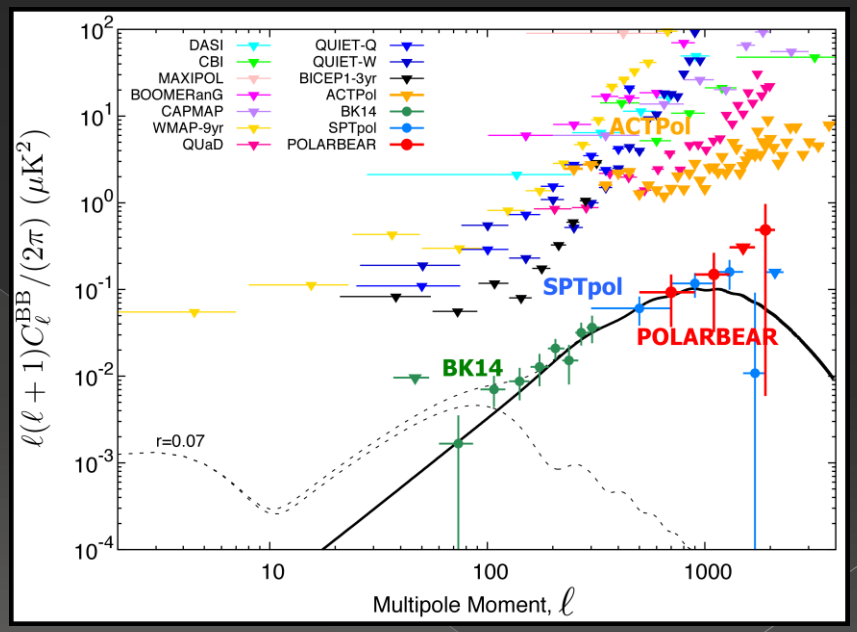



Combination with Optical Surveys
→Powerful tool to explore the growth of structure.



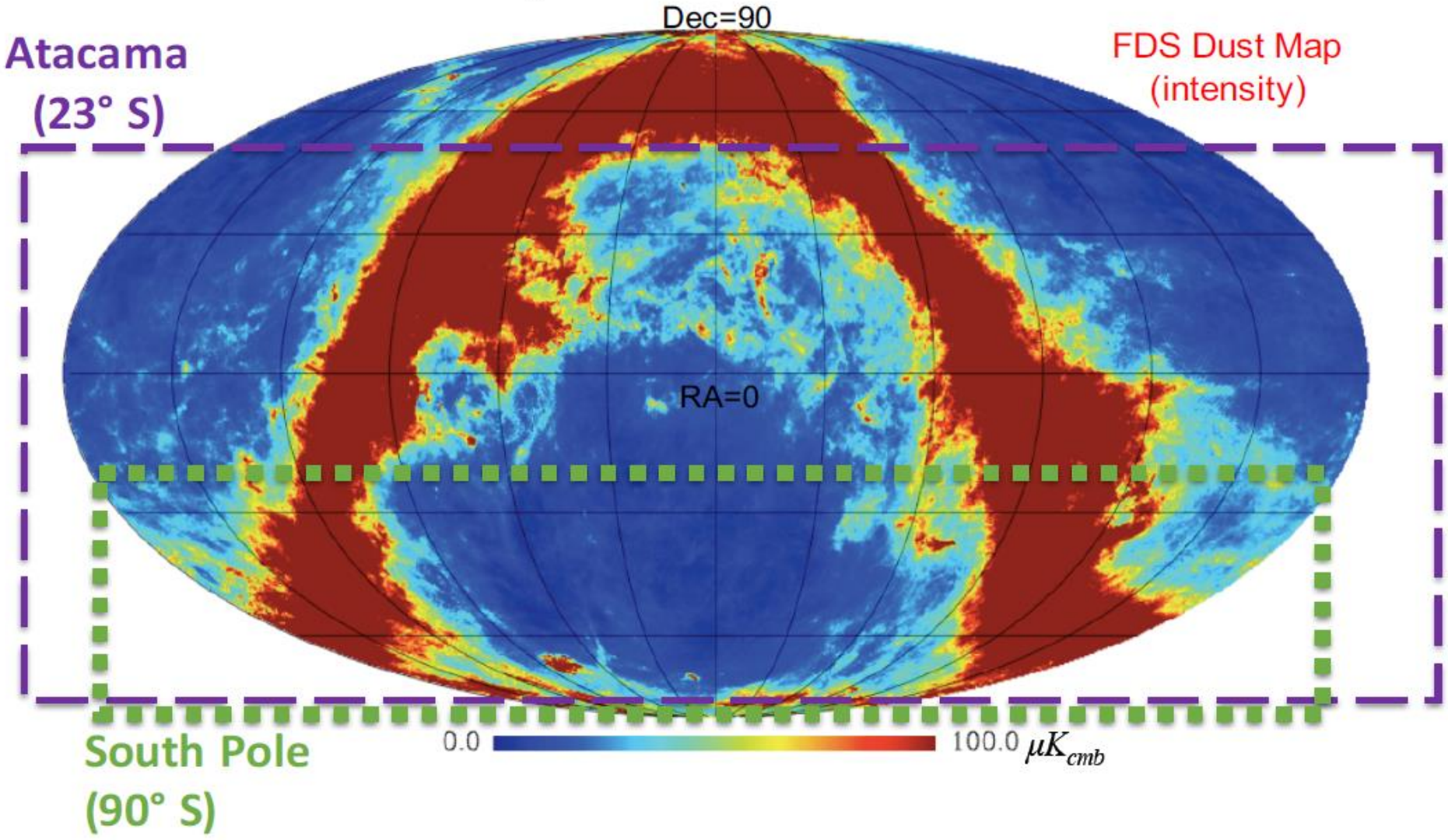
# CMB lensing
# both signal and noise source



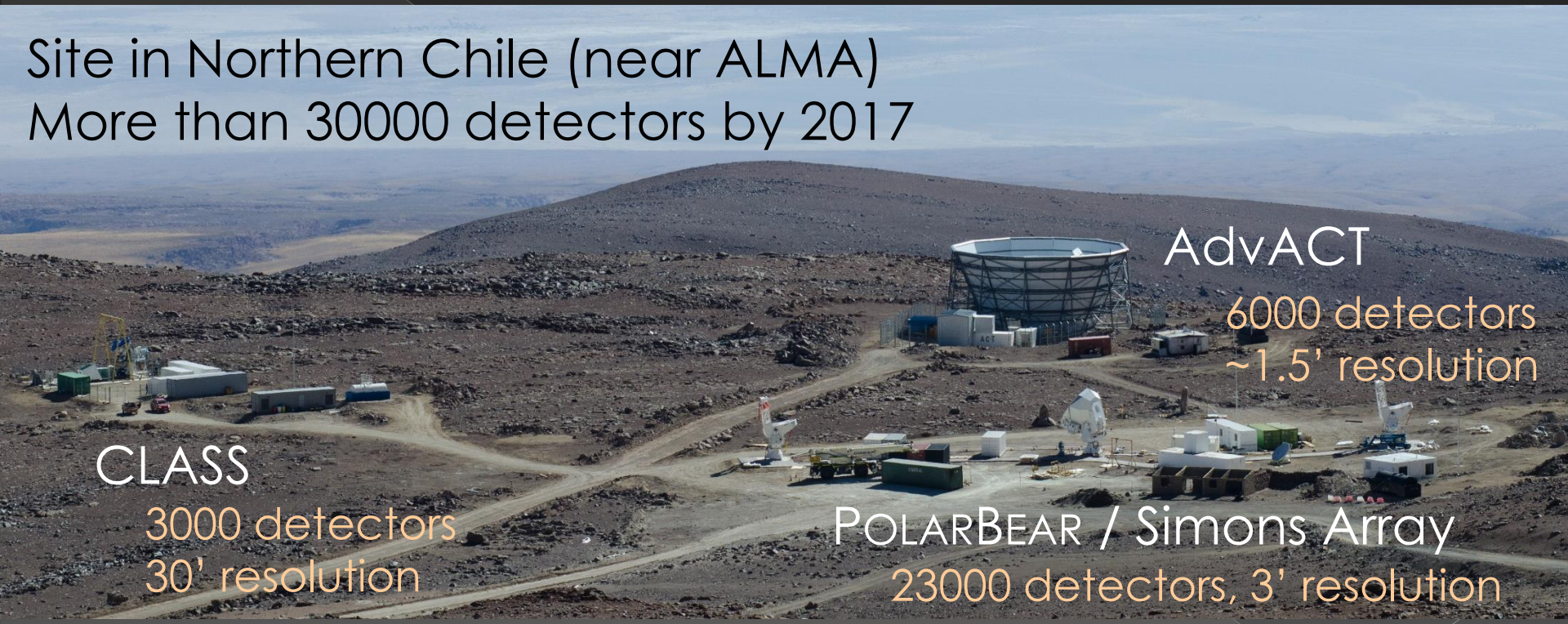




We will have to measure both arcminute and degree scales simultaneously.

# Sky coverage from CMB sites

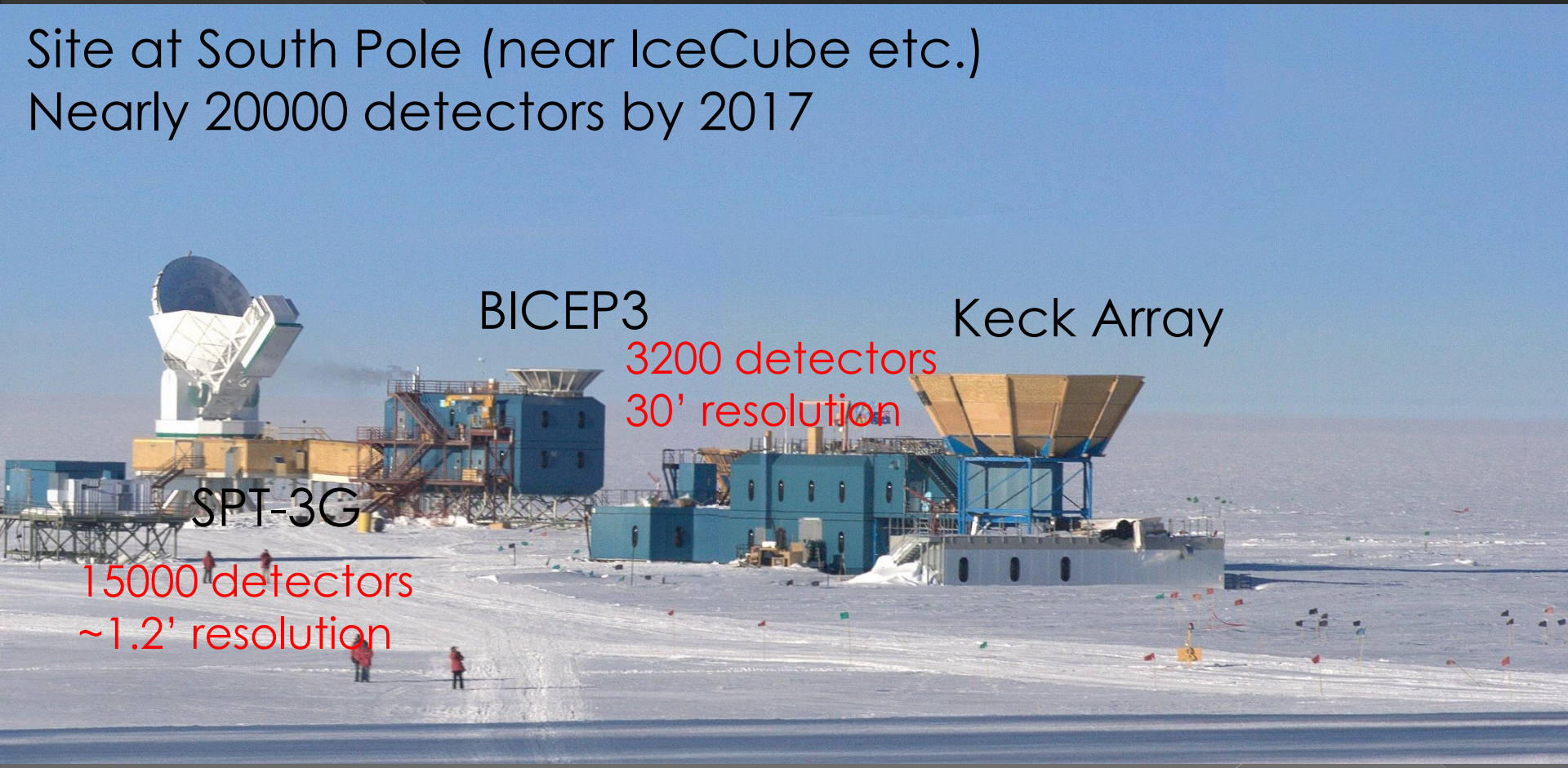


# Experiments



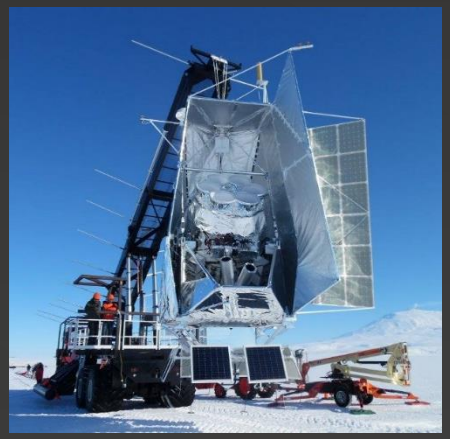
# Experiments

Site at South Pole (near IceCube etc.)
Nearly 20000 detectors by 2017

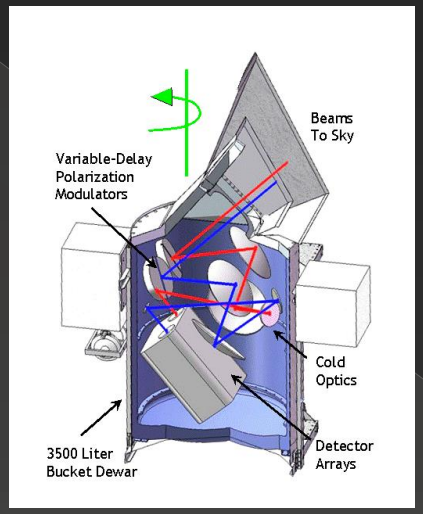


# Experiments

## Balloon



SPIDER (2015, ongling)

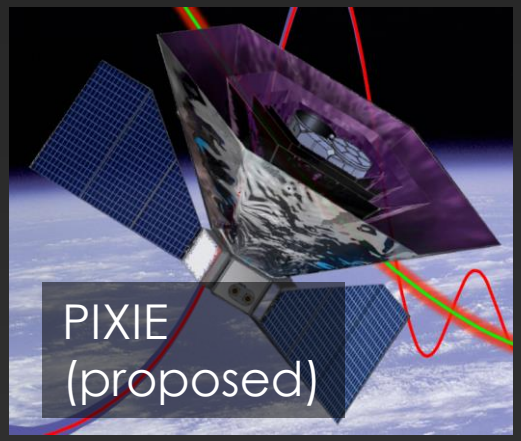



PIPER (2016?)

EBEX10k (proposed)

## Satellite

LiteBIRD
(proposed, 2025?)



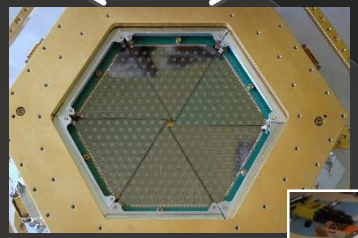
PIXIE
(proposed)

## Ground

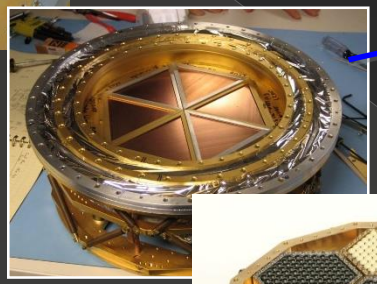
GroundBIRD
(2017~)

# History of evolution

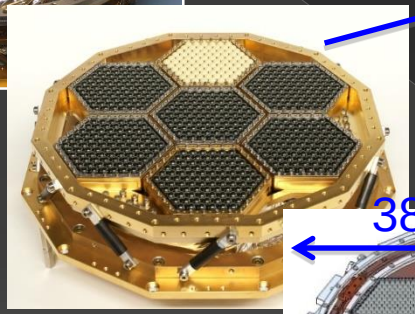
16 cm



APEX-SZ
330 detectors

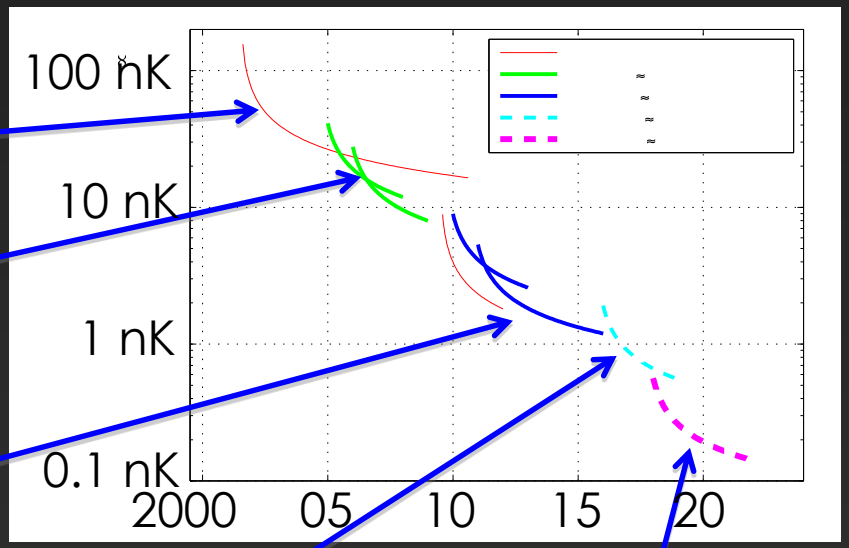


SPT-SZ
960 detectors

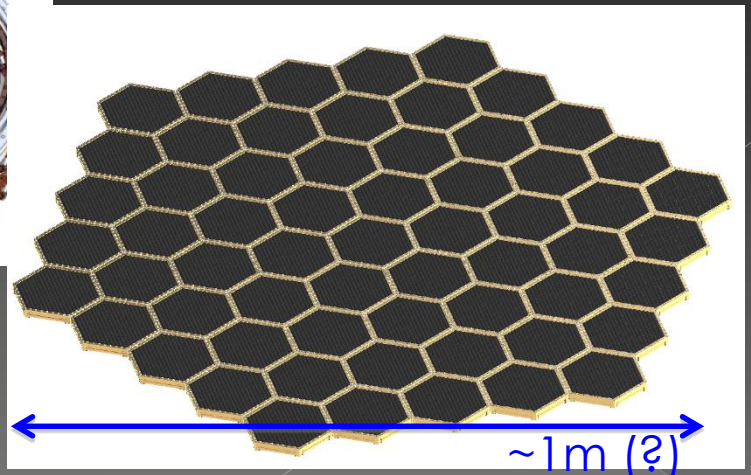


POLARBEAR-1
1274 detectors
Dual-Polarization

POLARBEAR-2
8,000 detectors
Dual-Polarization
2 Colors/pixel




*CMB S4*
~500k detectors



# Toward CMB S4
# Improving sensitivity x100

- Detector count increase ~$1/\sqrt{N_{det}}$
- Systematic error due to foregrounds
  - Multi-frequency observation mandatory
- Uncertainty due to physics
  - Lensing signal and delensing.
- Suppression of correlated noise
  - Noise averages down as $1/\sqrt{N_{det}}$ only for uncorrelated noise.
  - Environmental and instrumental sources.
- Systematic error due to instrument
  - Beam systematics mitigation.

# Path Toward Future w/ Biased Examples

# DOE is serious

**CMB-S4**

- As recommended by P5, we are planning to do CMB-S4
- A small funding wedge in FY18 would put us in line with the P5 recommended project timeline
- Will work with NSF to develop possibilities

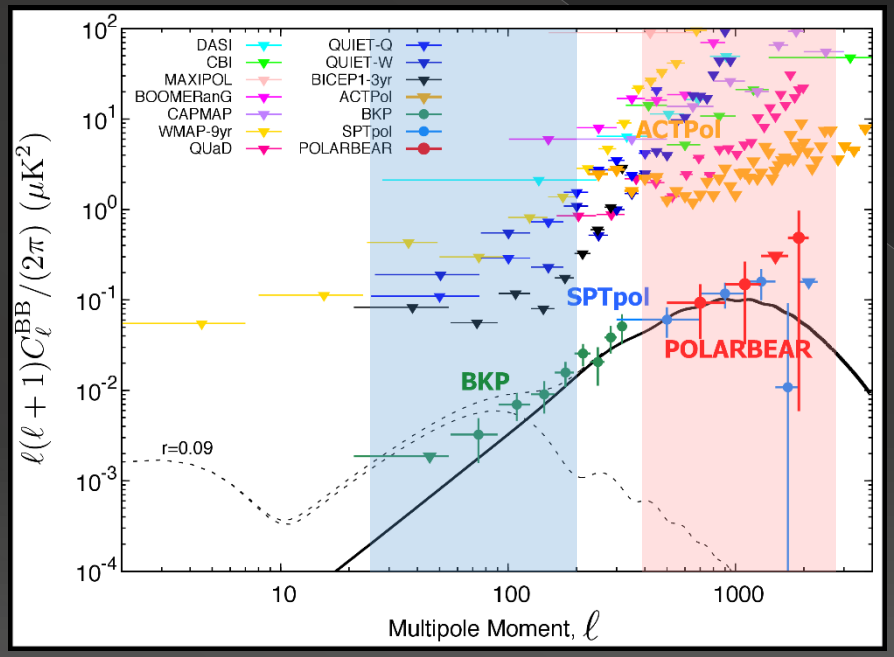
Kathy Turner's talk at AAAC meeting on Feb. 25, 2016

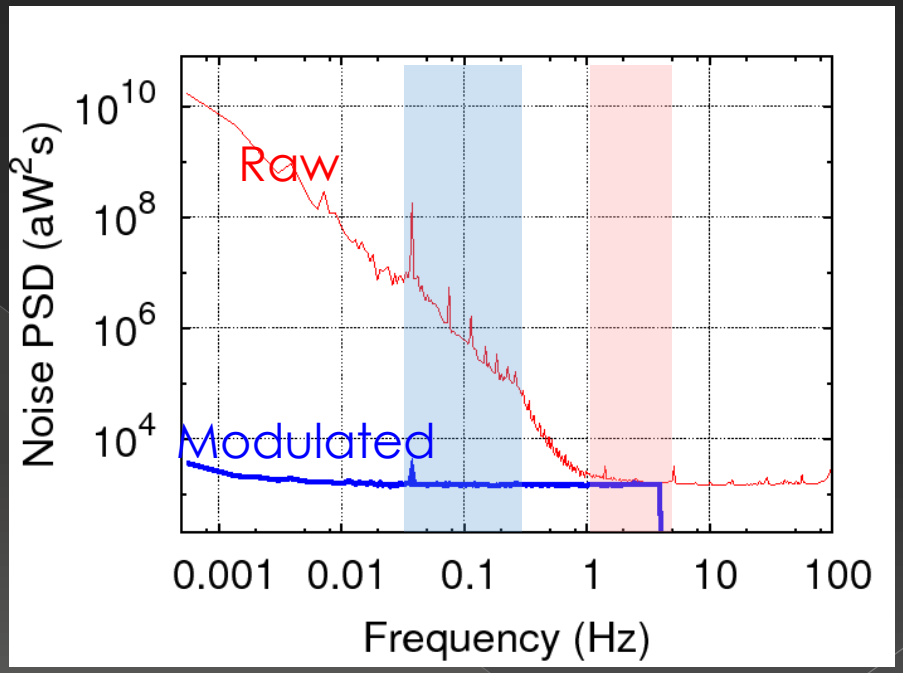
# Community is excited

CMB S4 Collaboration Workshop (Mar. 2016) at LBNL
~180 participants

Seeking for international partners
Japan is among the top on the list

# Why HWP is important?



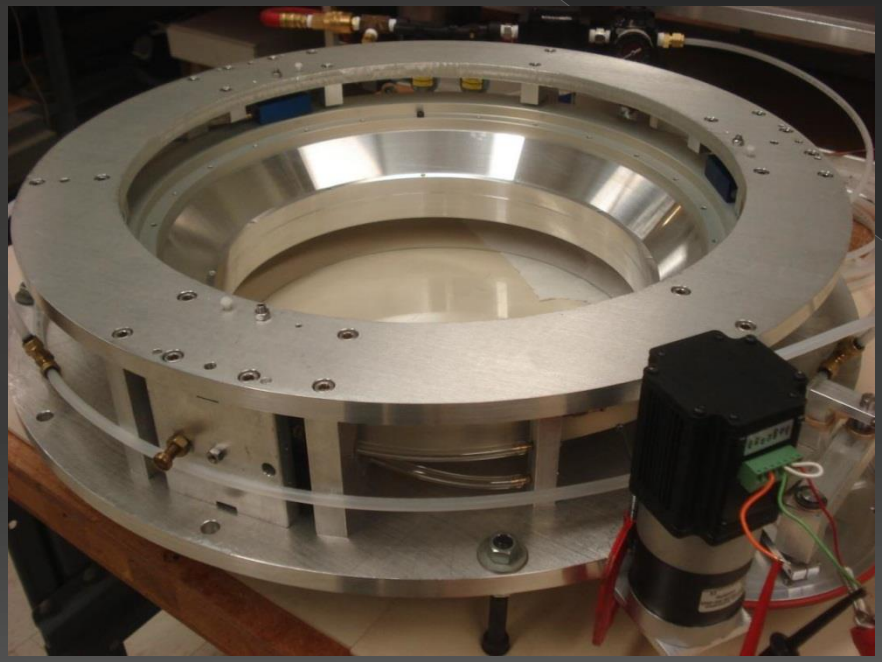

Two distinct angular scales:
- Gravitational Waves: 2-8 degrees
- Gravitational Lensing: 5-30 arcmin

Two distinct frequency ranges:
- Gravitational Waves: 50-250 mHz
- Gravitational Lensing: 1-6 Hz

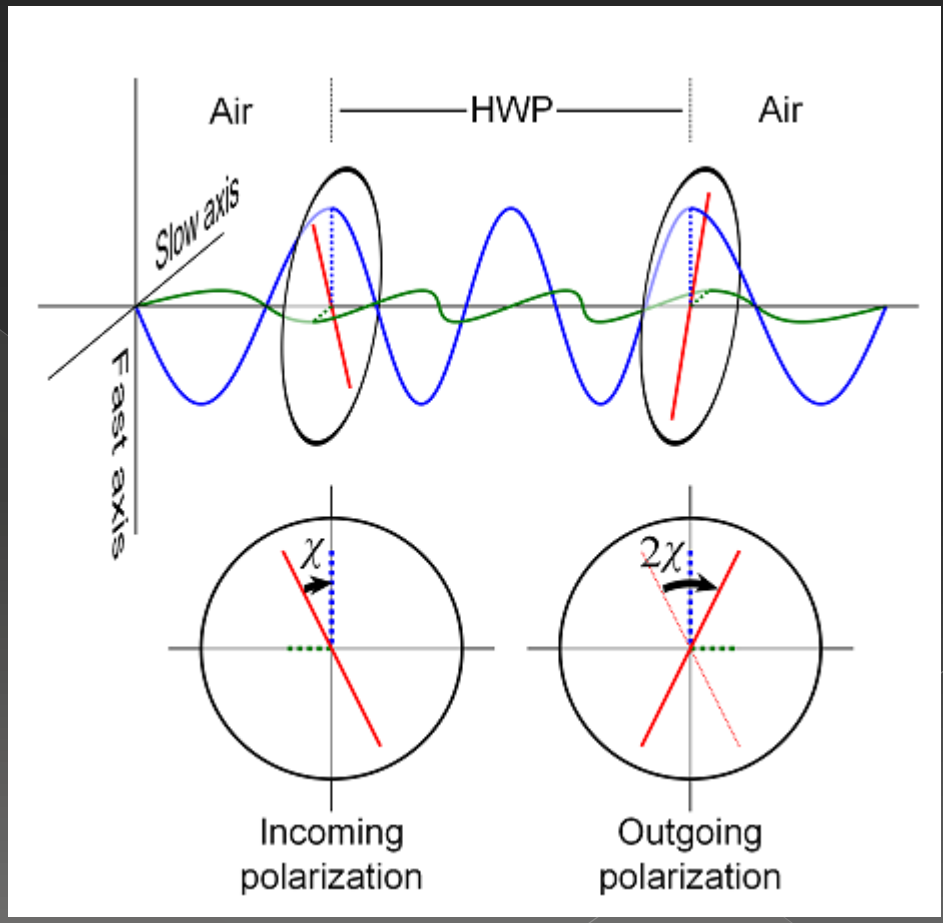
~0.5deg/sec scan

**Two orders of magnitude dynamic range**

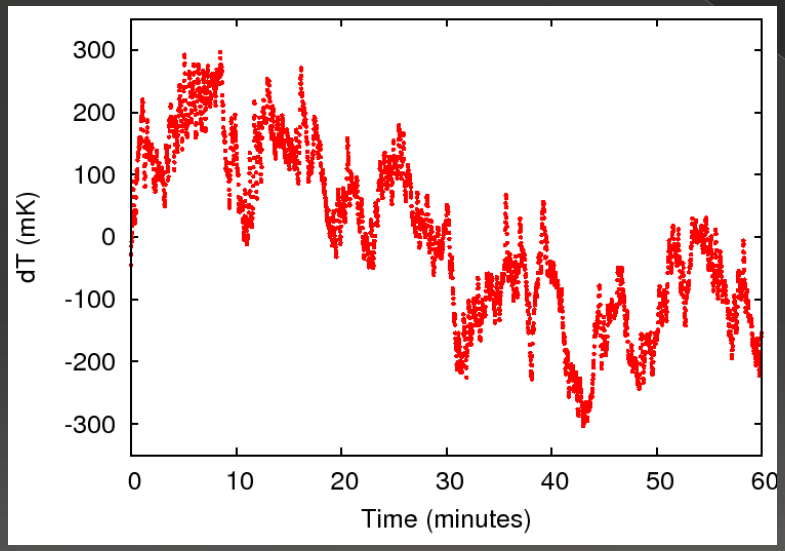
# Continuously rotating warm half-wave plate (ABS)



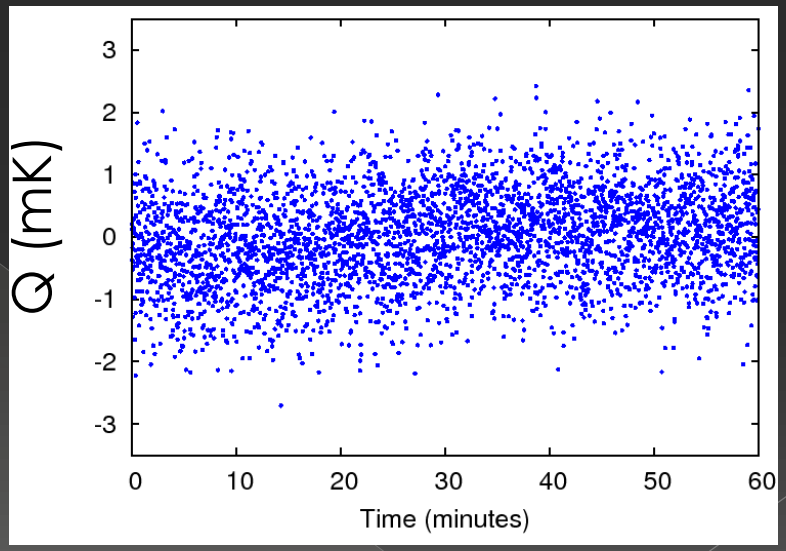
A-cut sapphire (D=330 mm)
$f$~2.5 Hz rotation
→ $f$~10 Hz modulation
Air-bearing → Stable rotation
No need for pair differencing



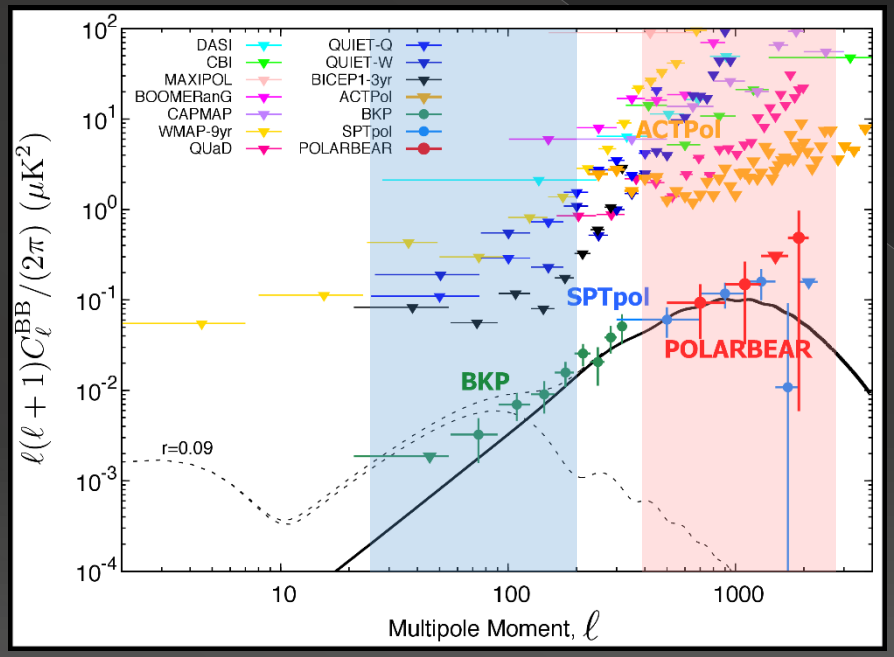
# Continuously rotating warm half-wave plate

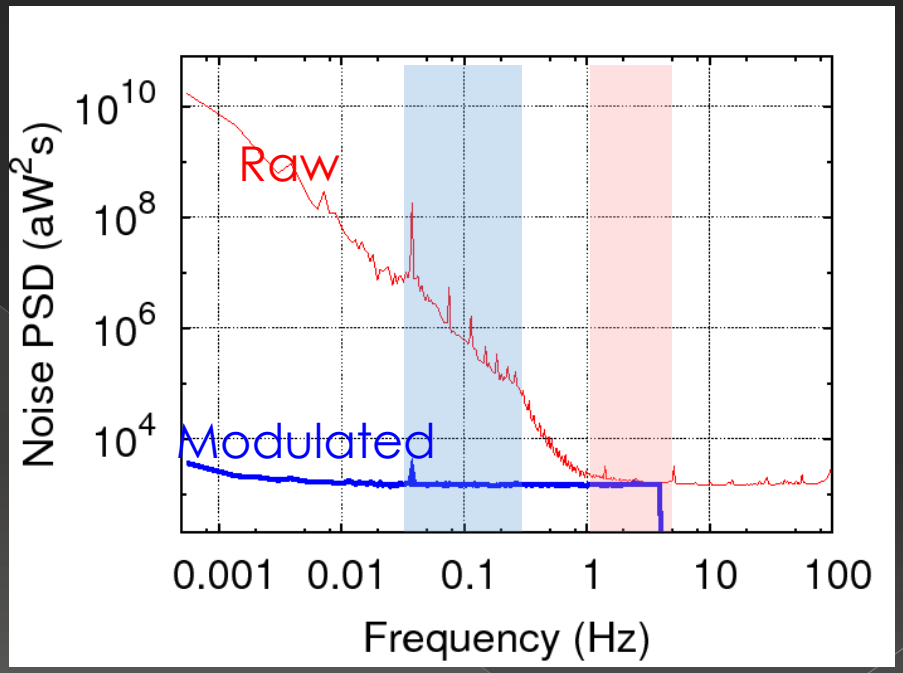



Demodulation



# Why HWP is important?

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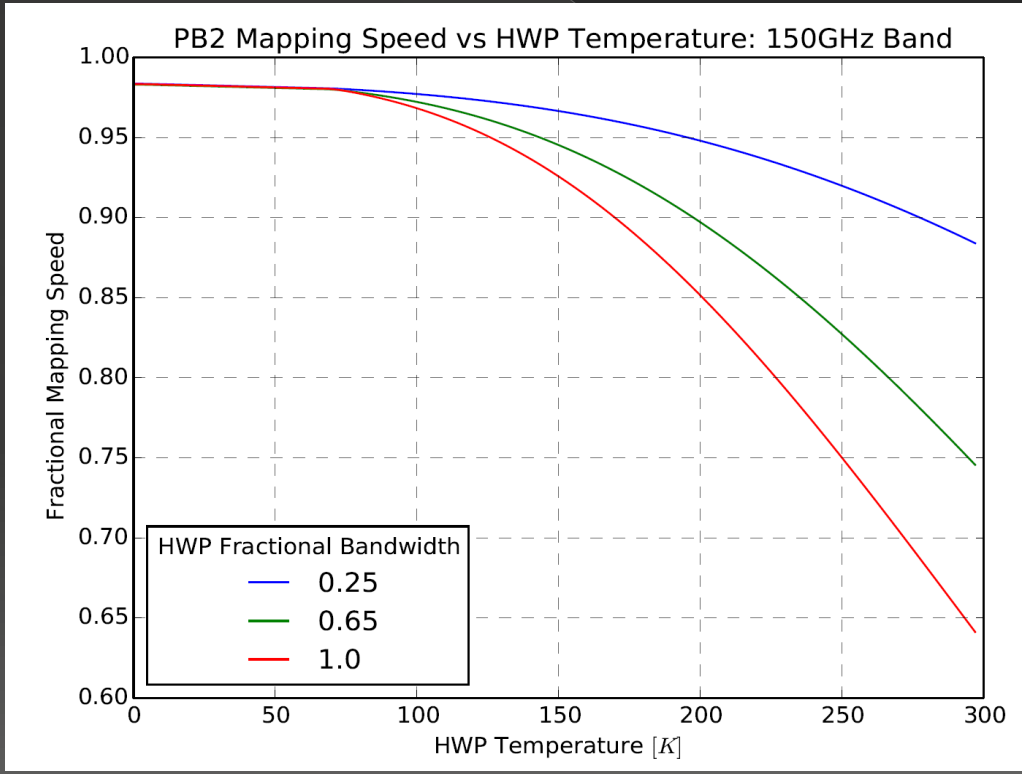
Two distinct frequency ranges:
- Gravitational Waves: 50-250 mHz
- Gravitational Lensing: 1-6 Hz

~0.5deg/sec scan

**Two orders of magnitude dynamic range**

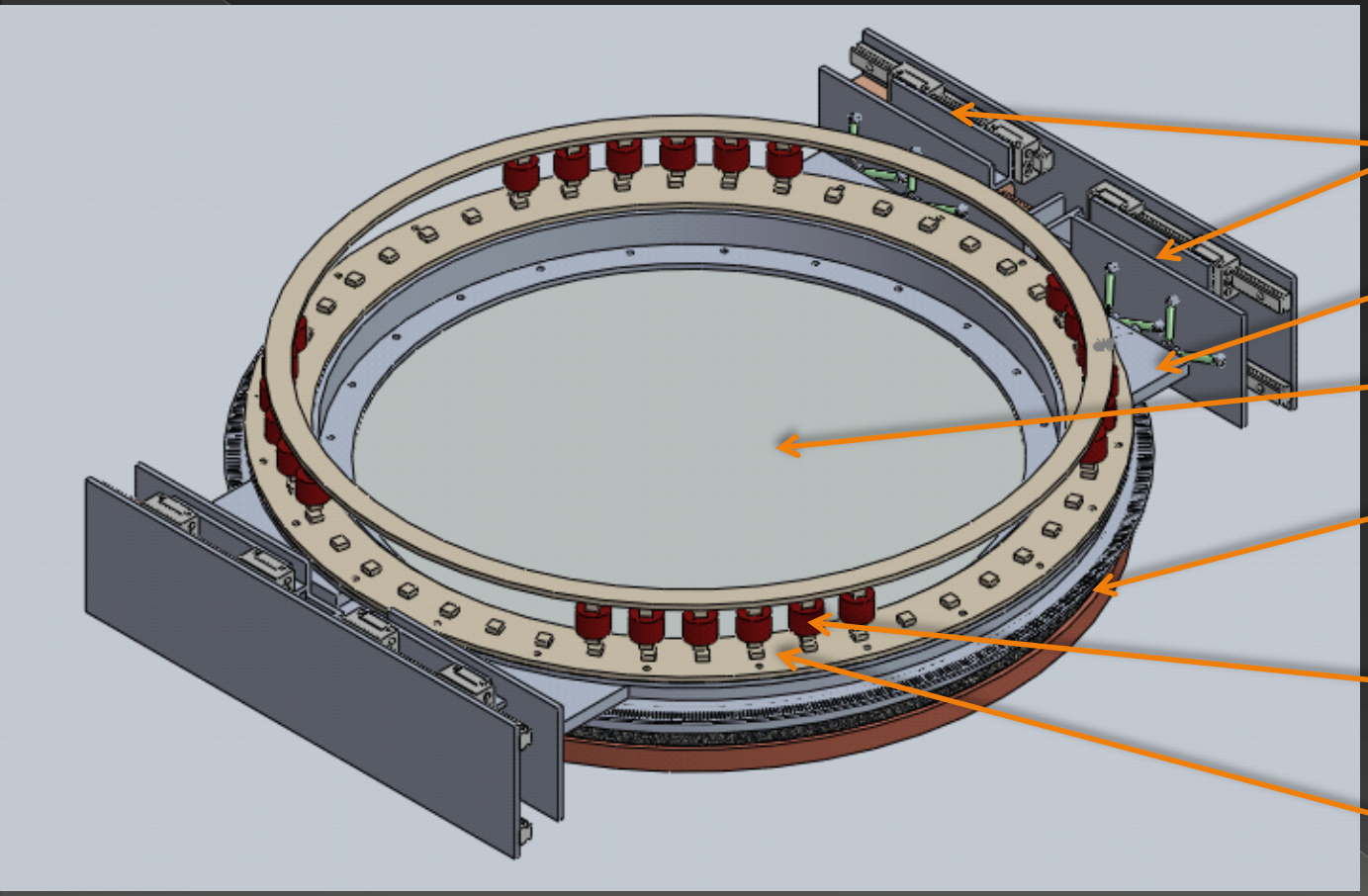
# HWP: Thermal loading




- When warm, the HWP (sapphire) radiates.
  - Sensitivity reduction
  - Esp. for large bandwidth
- Cryogenic HWP: two benefits
  - T drop → power drop.
  - Reduction of emissivity.

***Sensitivity improvement equivalent to 50% more detectors.***

# Baseline design

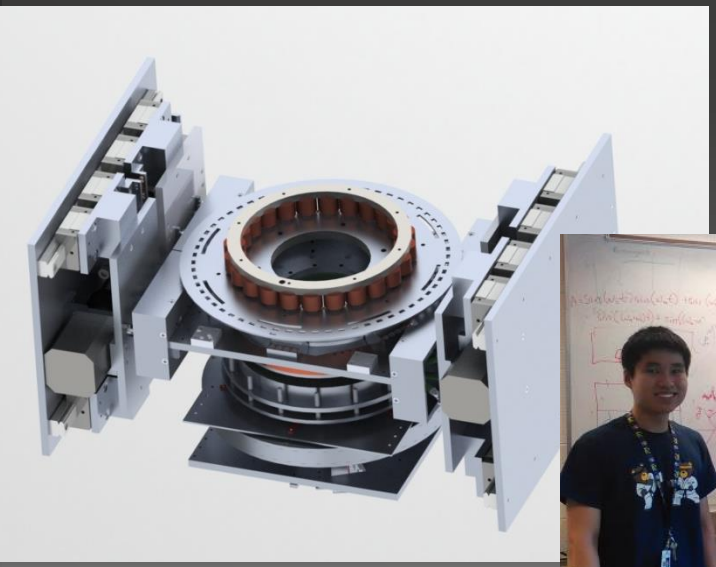



- Gripper used to align rotor and support the HWP when warm
- EM drive consists of 3-phase triplets of solenoids with a high-permeability core and monolithic return ring
- < 1nT B-field expected at the TES bolometers (~1m distance)
- Induced flux inhomogeneity at SMB expected to be < 0.5%

# Cryogenic HWP

- Establish design concept through a small prototype
- Fabricate full-scale system and test/evaluate with Simons Array as a test platform.

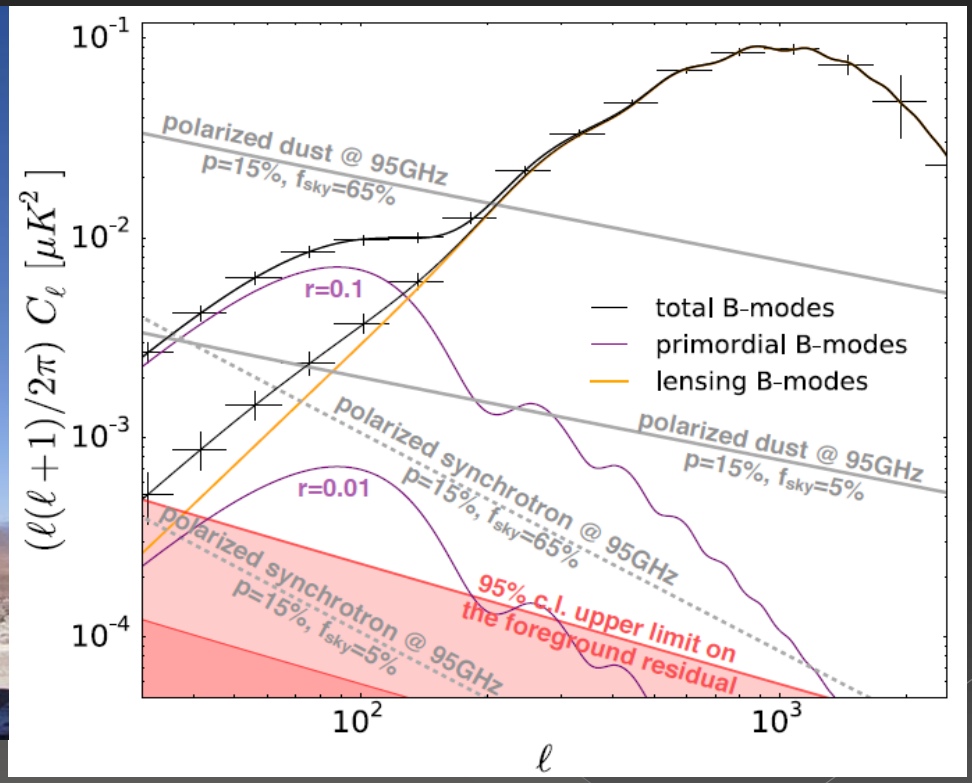
Prototype fabrication & evaluation



Team

Sapphire for full scale

# Near Future: Simons Array




Three 2.5m telescopes in Chile
~20000 detectors.
Multiple frequency coverage
95GHz, 150GHz, 220GHz, 280GHz.

$\sigma(r=0.1) \sim 6\times10^{-3}$

$\sigma(\Sigma m_\nu) \sim 40$ meV (w/ DESI BAO)

# POLARBEAR Collaboration

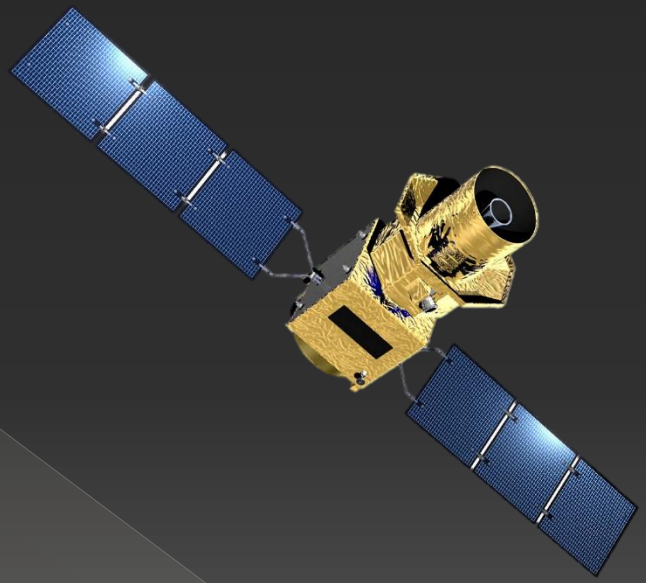
# Further future

## CMB S4 (2023~?)

Ultimate ground telescopes

$\sigma(\Sigma m_\nu) \sim 20\text{meV}, \sigma(r) \sim 0.001$

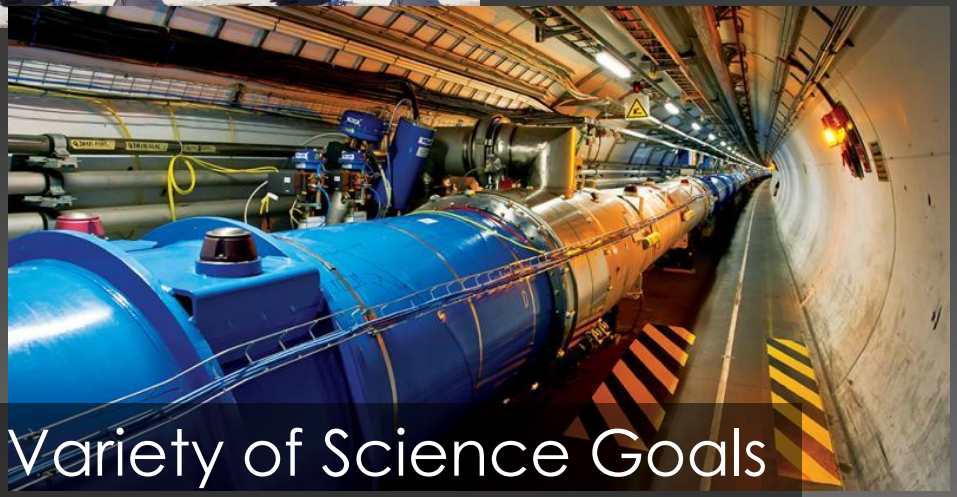
## LiteBIRD (2025~?)



Satellite for ultimate r ~0.001

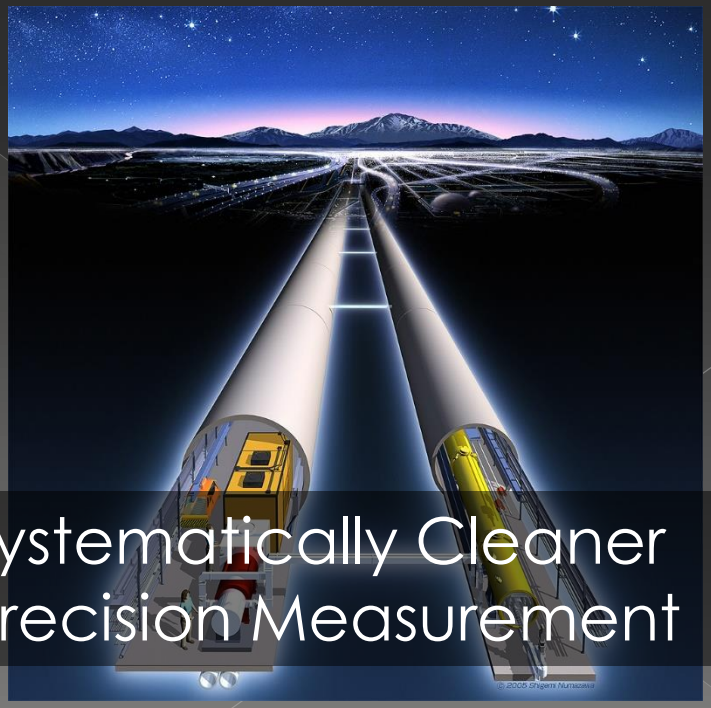
# Further future

## CMB S4 (2023~?)



Variety of Science Goals
More Discovery Potential

## LiteBIRD (2025~?)

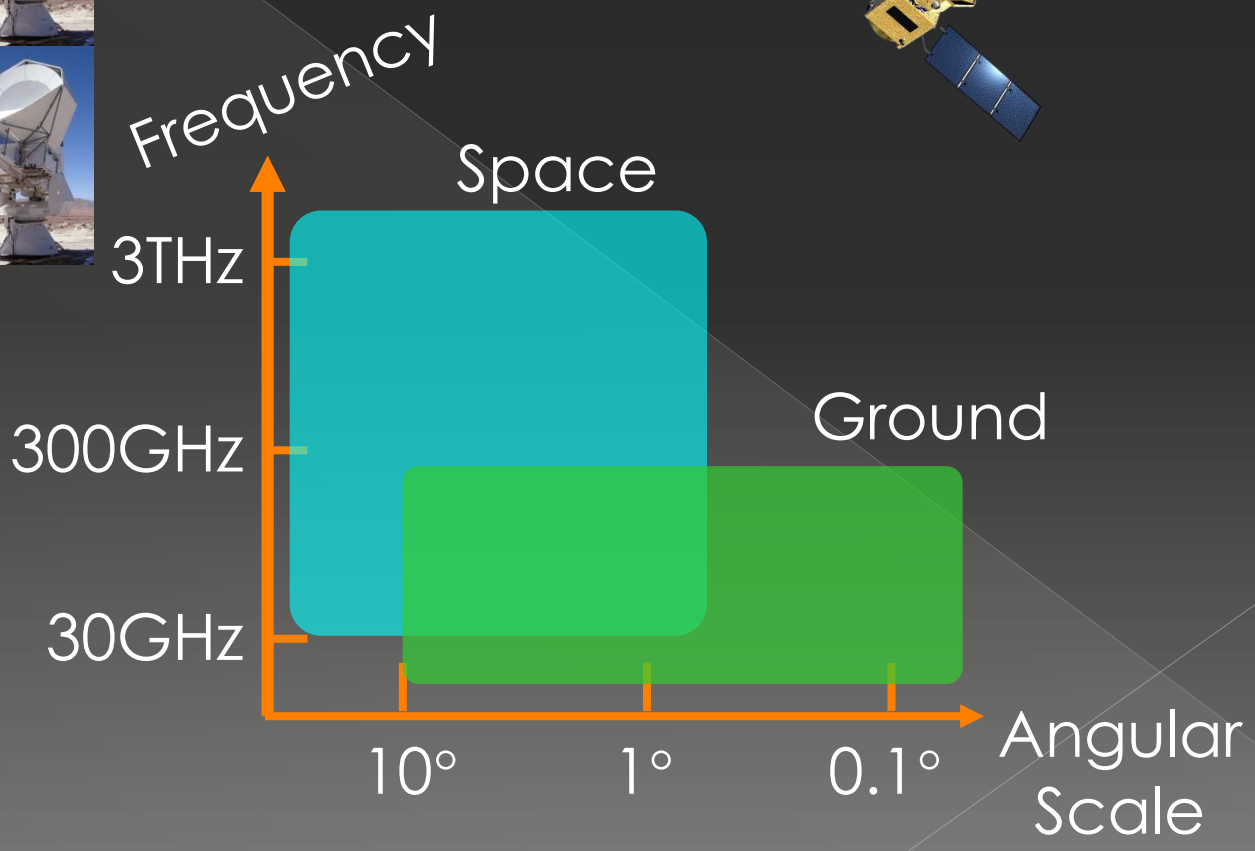


Systematically Cleaner
Precision Measurement

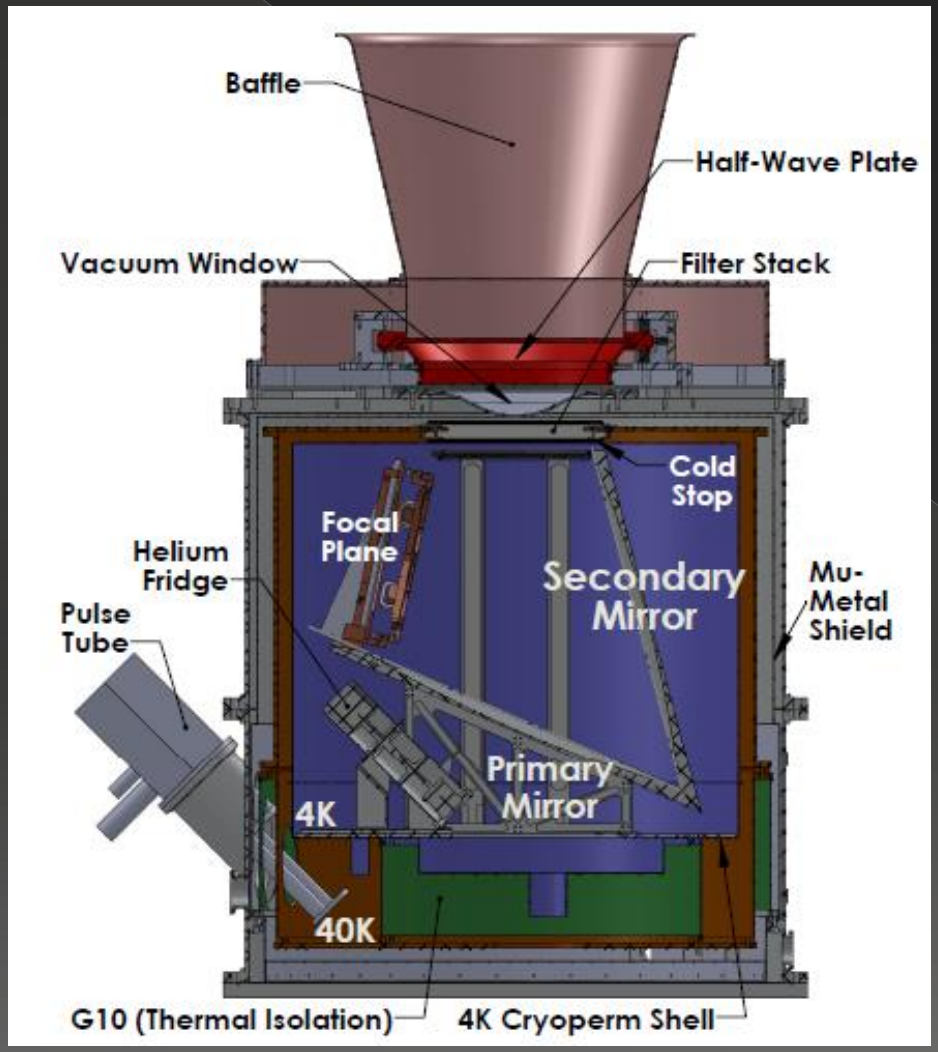
# Further future

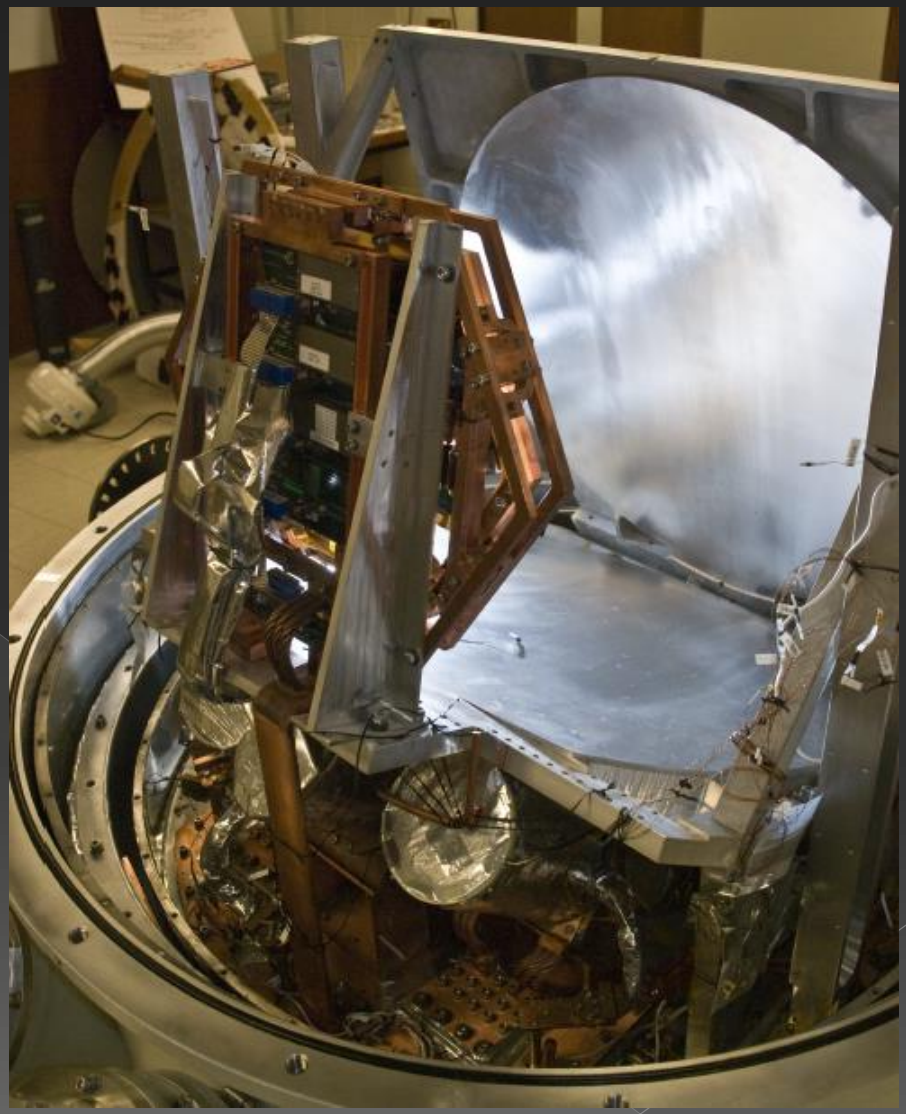
CMB S4 (2023~?)

LiteBIRD (2025~?)



# Optics

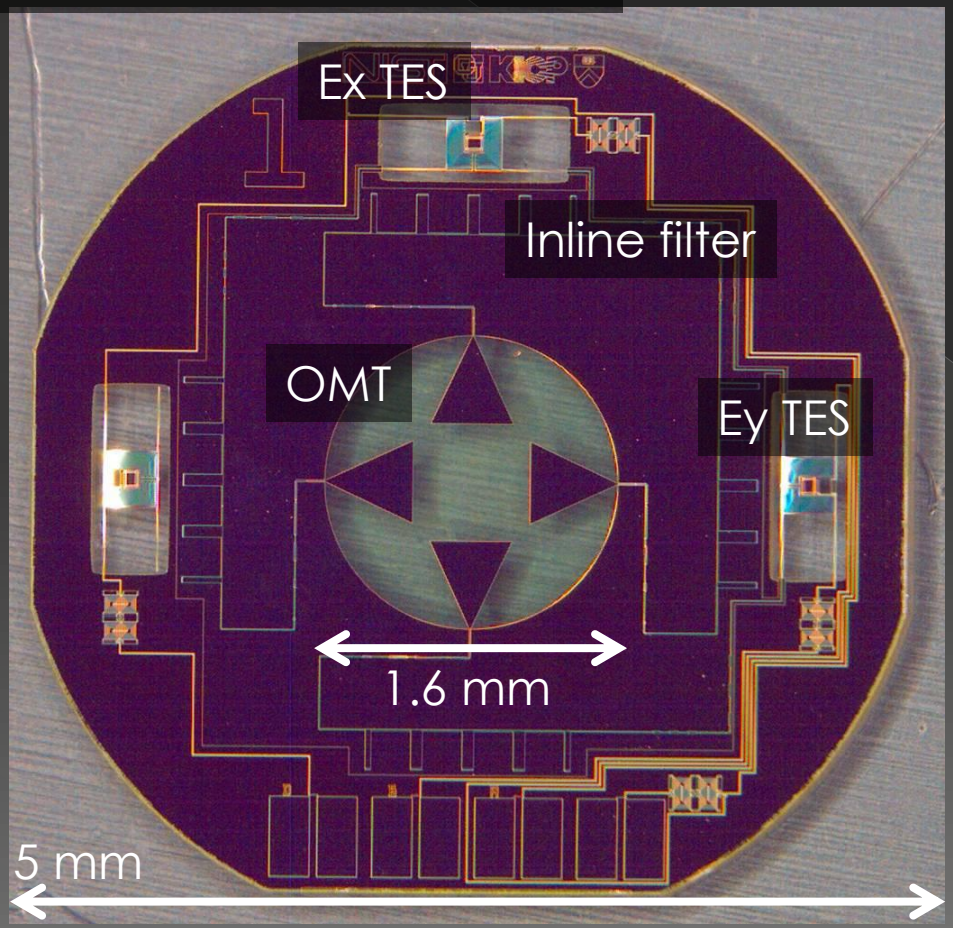


4 K cooled side-fed Dragone dual reflector.
~60 cm diameter mirrors. 25 cm aperture diameter.

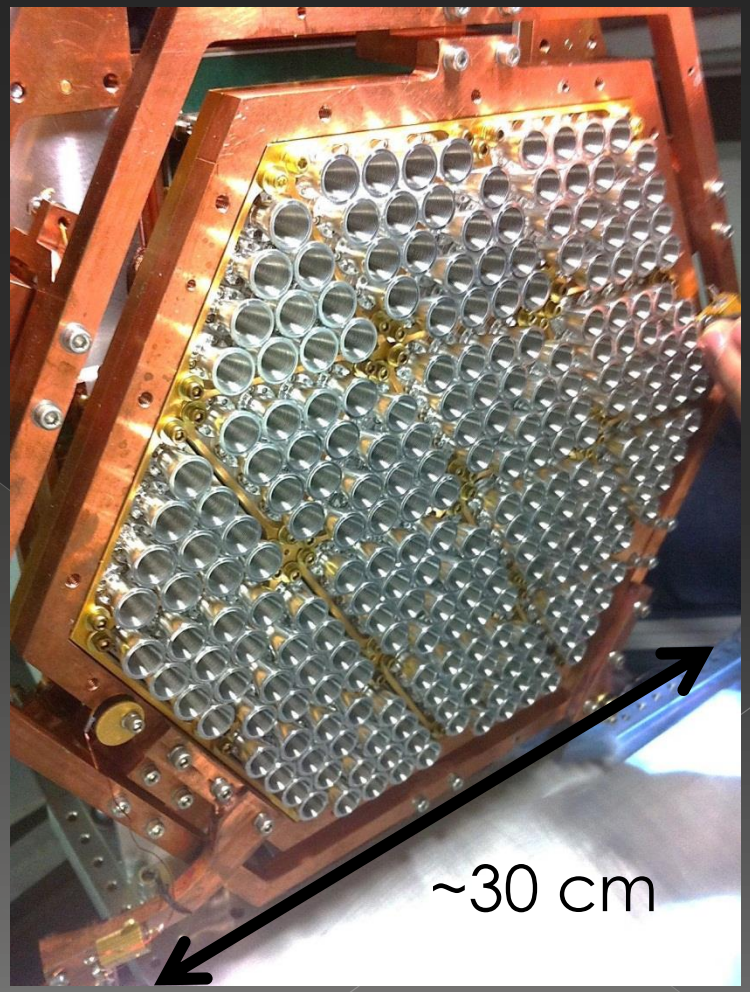
# ABS focal plane

Feedhorn coupled
Polarization sensitive TES

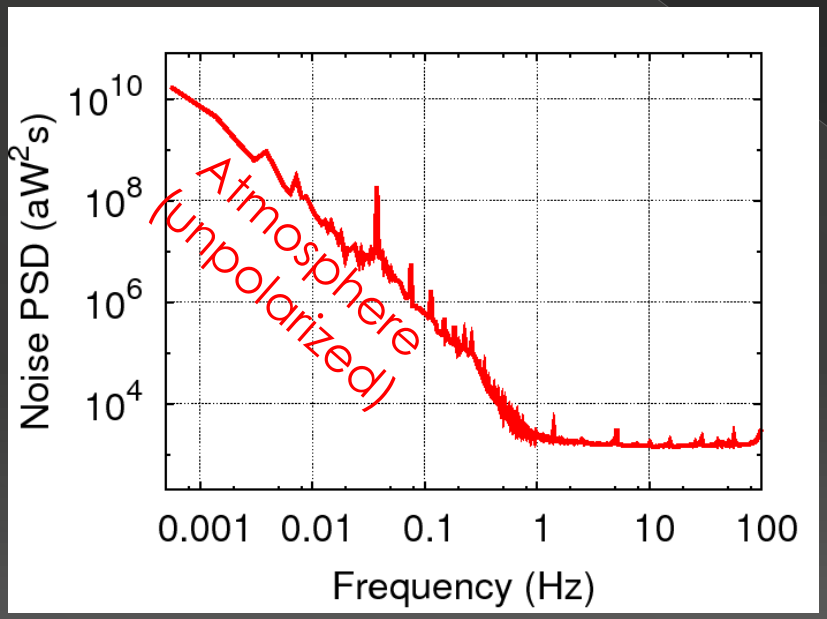


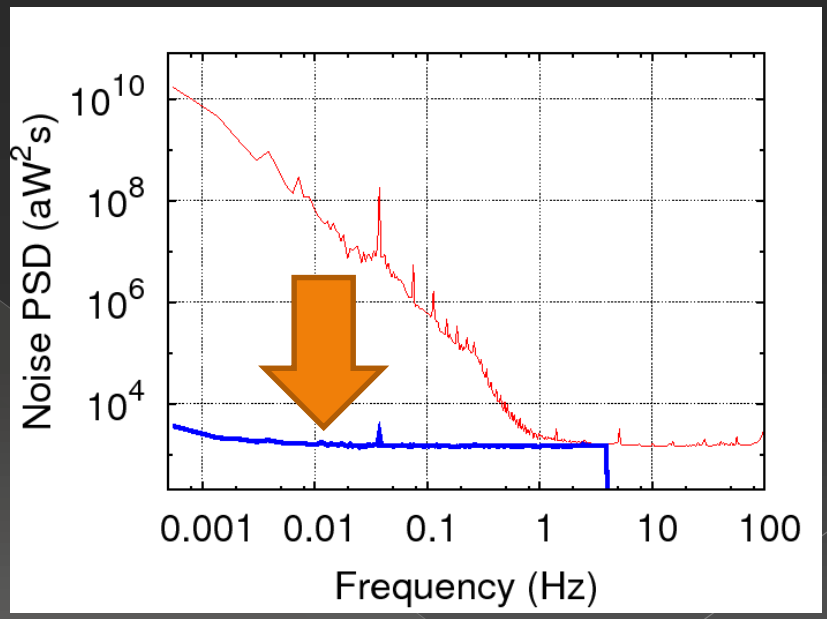

Fabricated at NIST

Focal plane ~300 mK



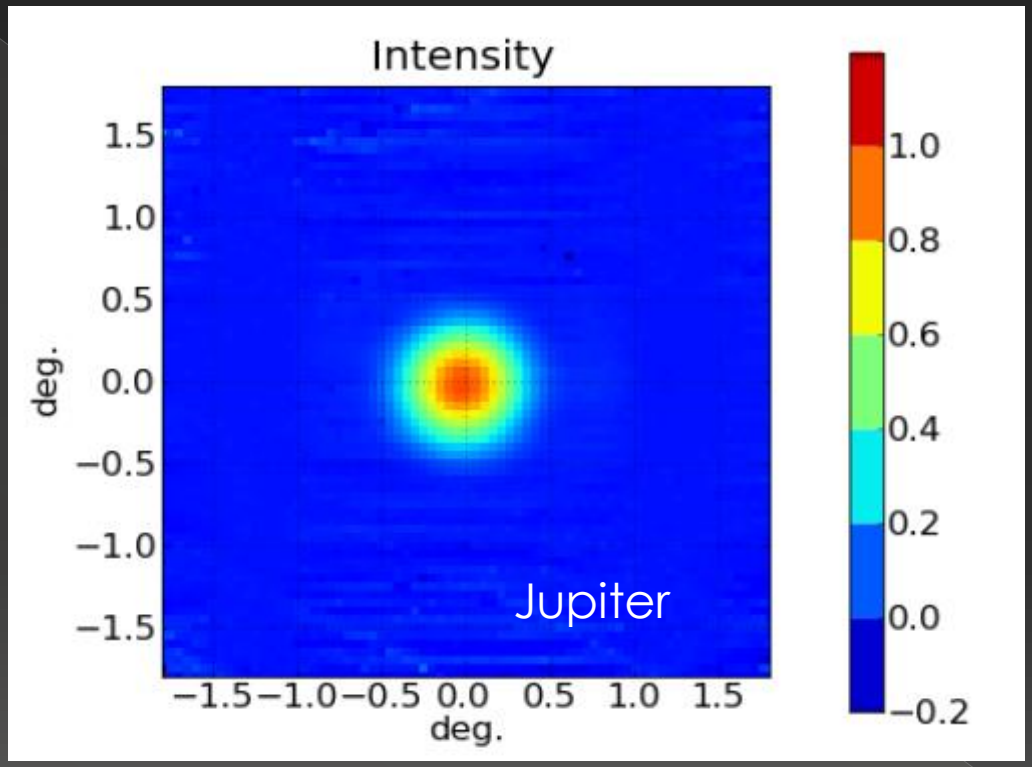
# Continuously rotating warm half-wave plate






ABS Collaboration
Kusaka, Essinger-Hileman et. al. (2014)

# Calibration: Beam




Beam
Point Spread Function (PSF)

# Calibration: Beam

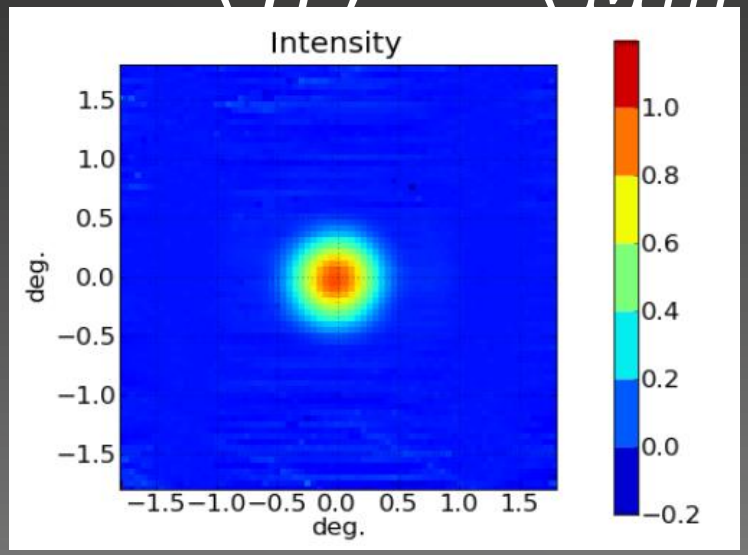
Observed

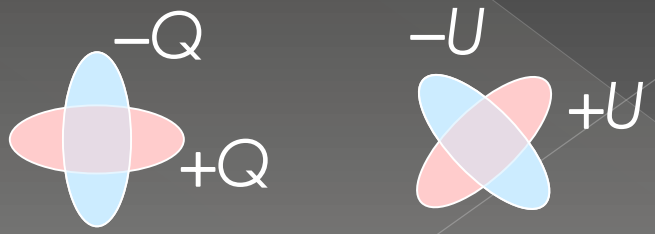
Instrument's response

True (Input)

$$\begin{pmatrix} \hat{I} \\ \hat{Q} \\ \hat{U} \end{pmatrix} = \begin{pmatrix} M_{II} & M_{IQ} & M_{IU} \\ M_{QI} & M_{QQ} & M_{QU} \\ M_{UI} & M_{UQ} & M_{UU} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \end{pmatrix}$$

$V$ (circular polarization) omitted



# Calibration: Systematics

Observed

Instrument's response

True (Input)

$$\begin{pmatrix} \hat{I} \\ \hat{Q} \\ \hat{U} \end{pmatrix} = \begin{pmatrix} M_{II} & M_{IQ} & M_{IU} \\ M_{QI} & M_{QQ} & M_{QU} \\ M_{UI} & M_{UQ} & M_{UU} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \end{pmatrix}$$

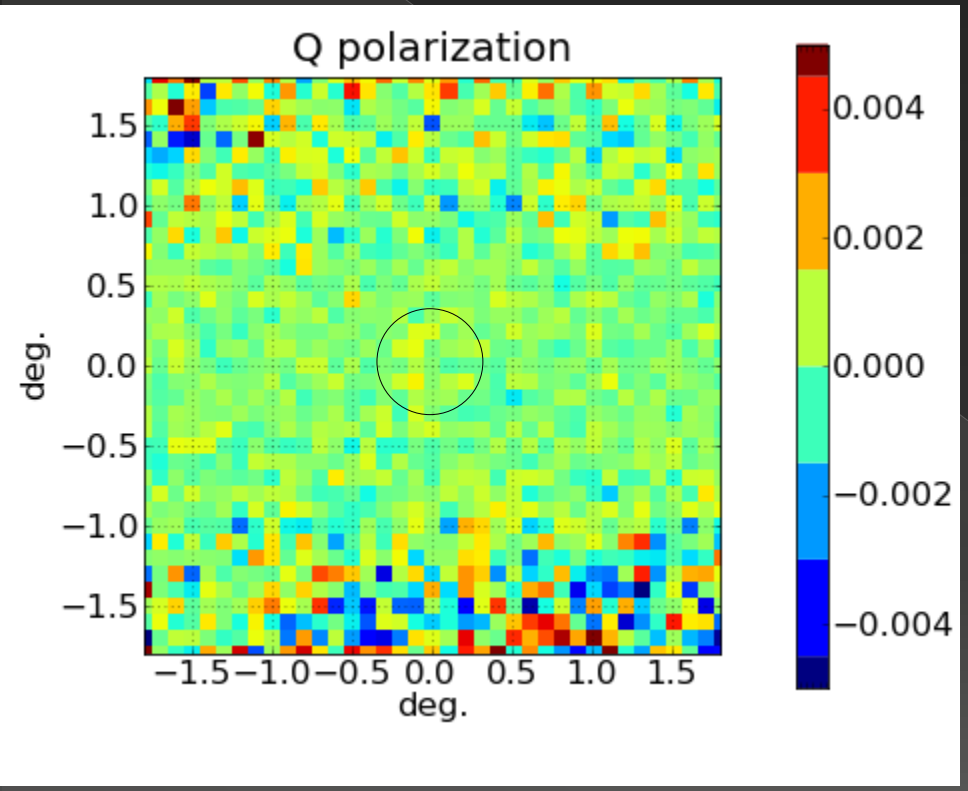
~ 100μK

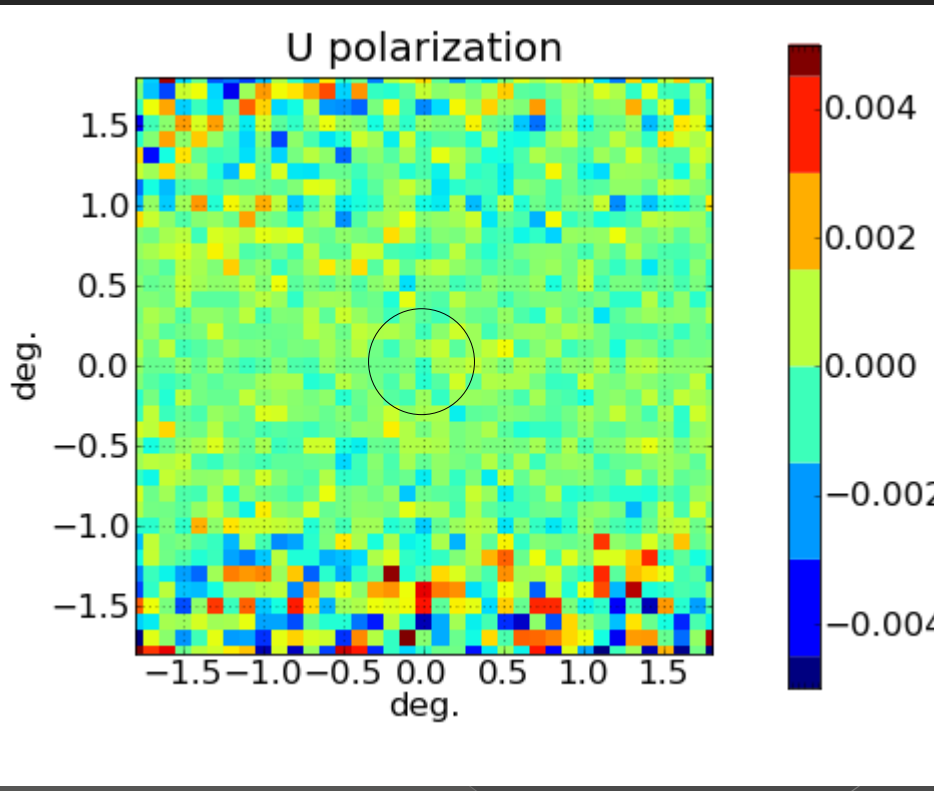
~ 1μK (E)

<0.1μK(B)

$V$ (circular polarization) omitted

# Beam Systematics

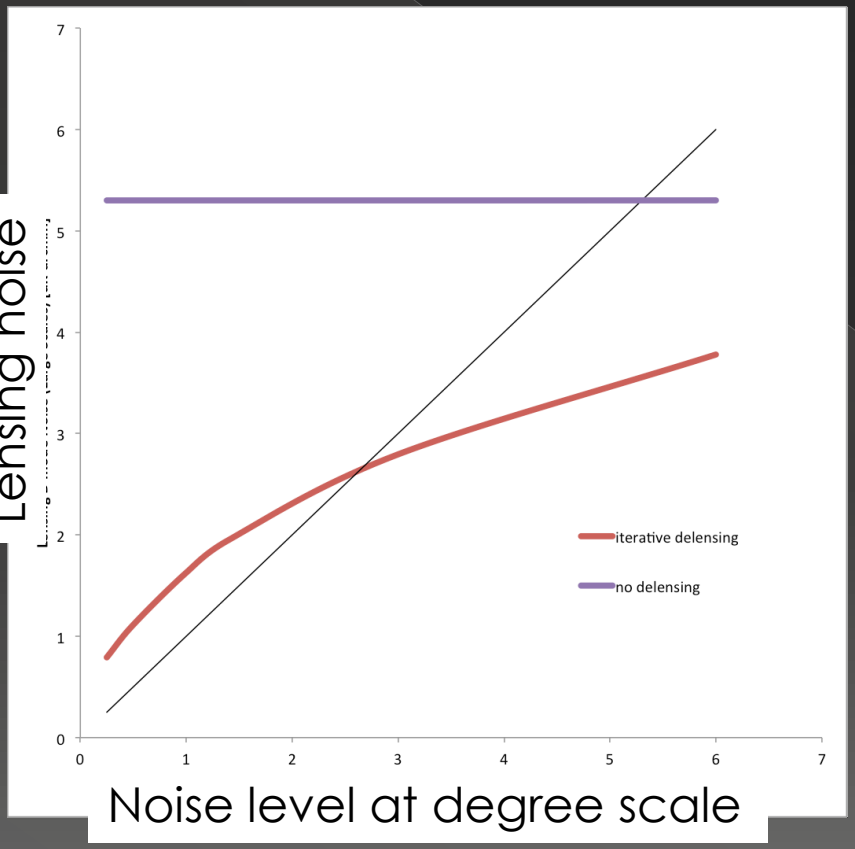


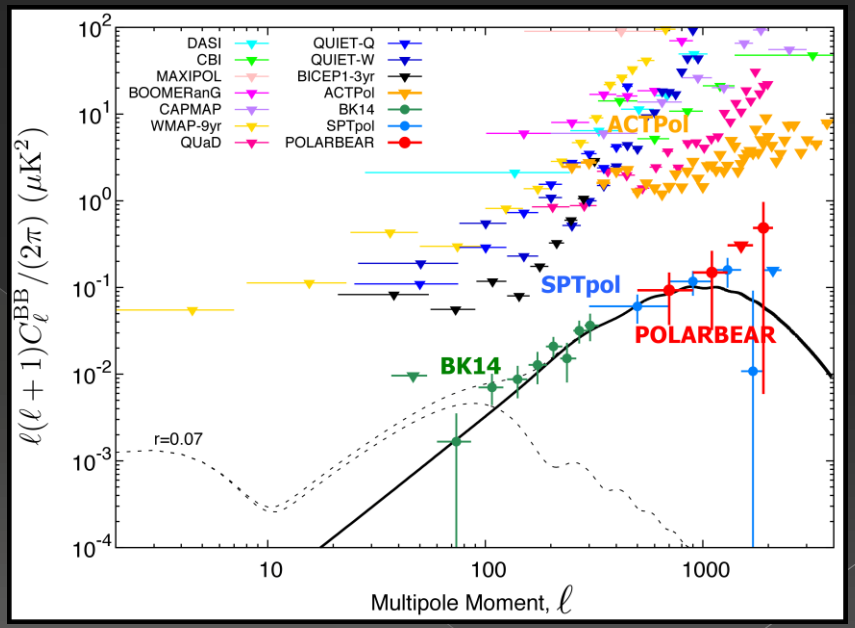




Leakage <~ 0.1% already at the map level
Monopole constrained to ~0.01%.

*Essinger-Hileman, Kusaka et. al. (2016)*

# CMB lensing
# both signal and noise source



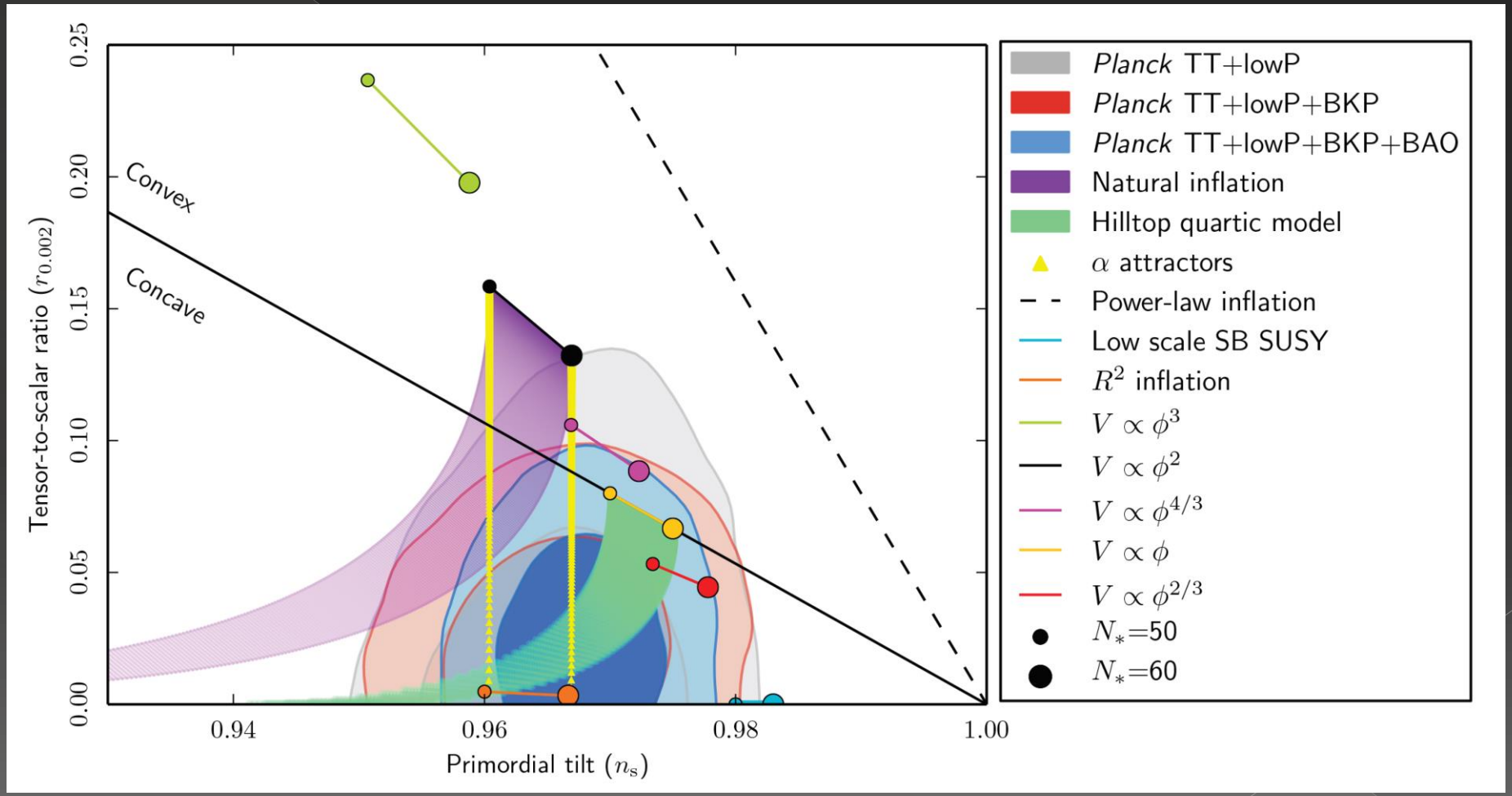




We will have to measure both arcminute and degree scales simultaneously.

# Introduction

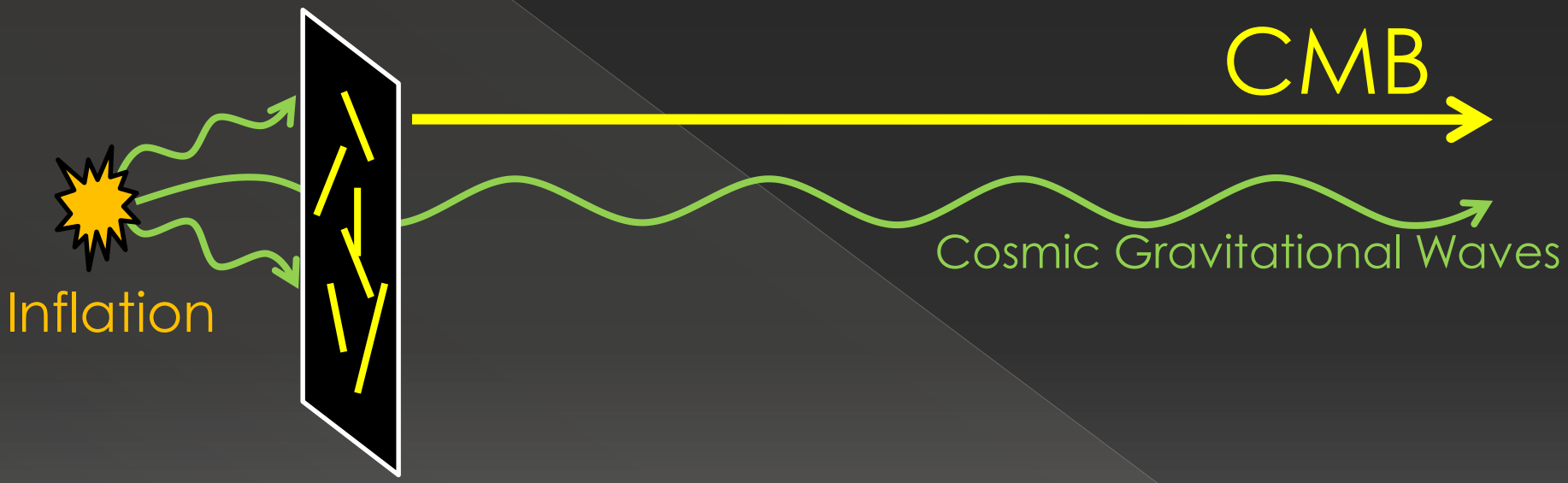
- High energy: $E$
  - LHC ~$10^4$ GeV, Cosmic rays ~ $10^{10}$ GeV
- Early Universe: $E[\mathrm{eV}] \sim 10^{-4} T\,[K]$ , $T \sim 3(1+z)$
  - Decoupling ~ $10^{-10}$ GeV
  - Matter radiation equality ~ $10^{-8}$ GeV
  - BBN ~ $10^{-3}$ GeV
  - Inflation ~ $10^{16}$ GeV?

# Tensor to Scalar ratio *r*




Planck Collaboration (2015)

# Is it detectable? How?




Last Scattering Surface

Screen for GW to put its fingerprint