Measuring the Cosmic Microwave Background with the South Pole Telescope and Future Instruments

CaJAGWR Seminar — April 24th, 2018

Abigail Crites
National Science Foundation Astronomy and Astrophysics Postdoctoral Fellow at Caltech

Image Credit: Planck

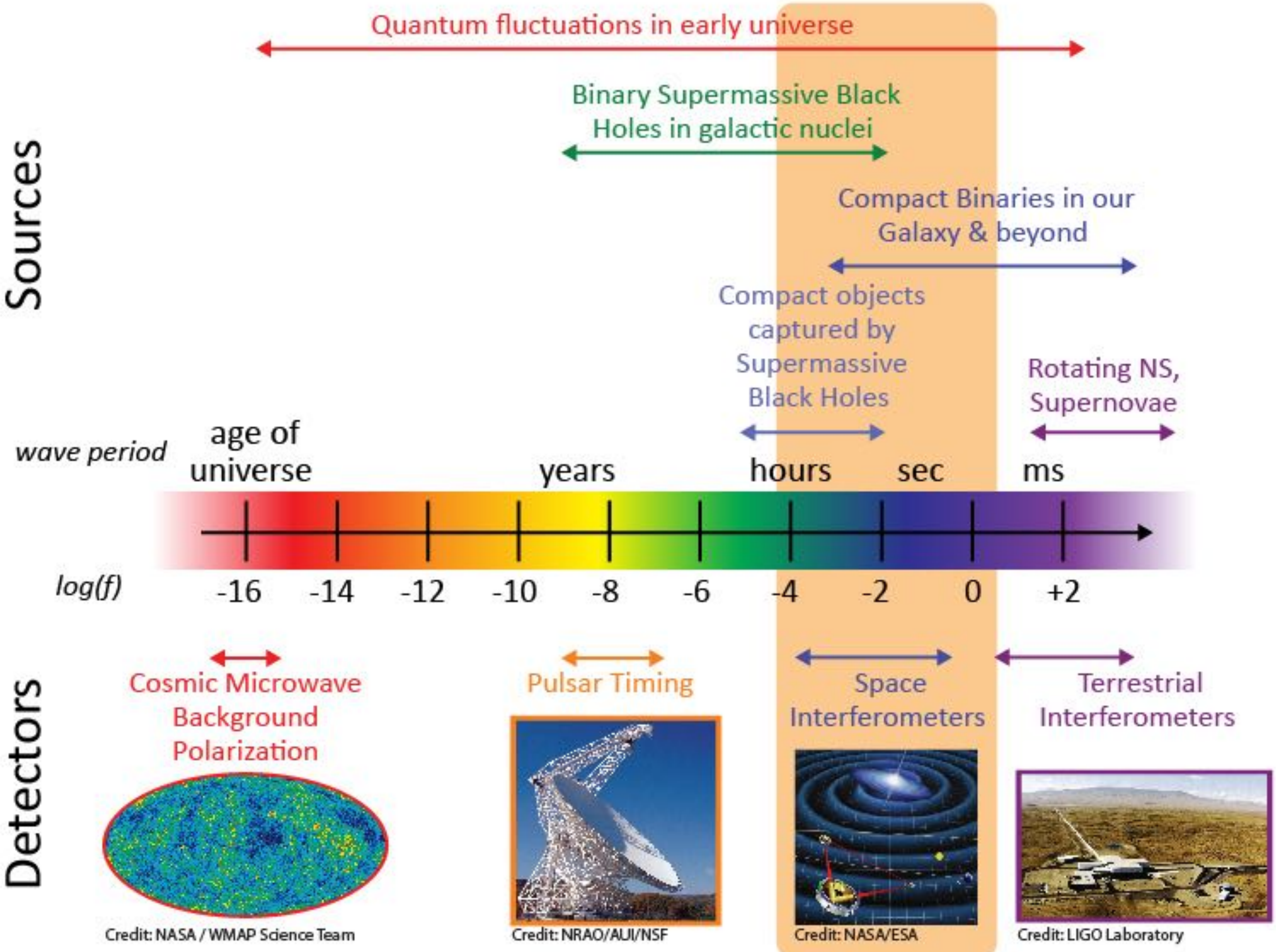
Objective:

detect signatures from inflationary gravitational waves in the cosmic microwave background (CMB)

↓

probe physics of the universe fractions of a second after the big bang

The Gravitational Wave Spectrum



Slide Credit: https://lisa.nasa.gov/

The Cosmic Microwave Background

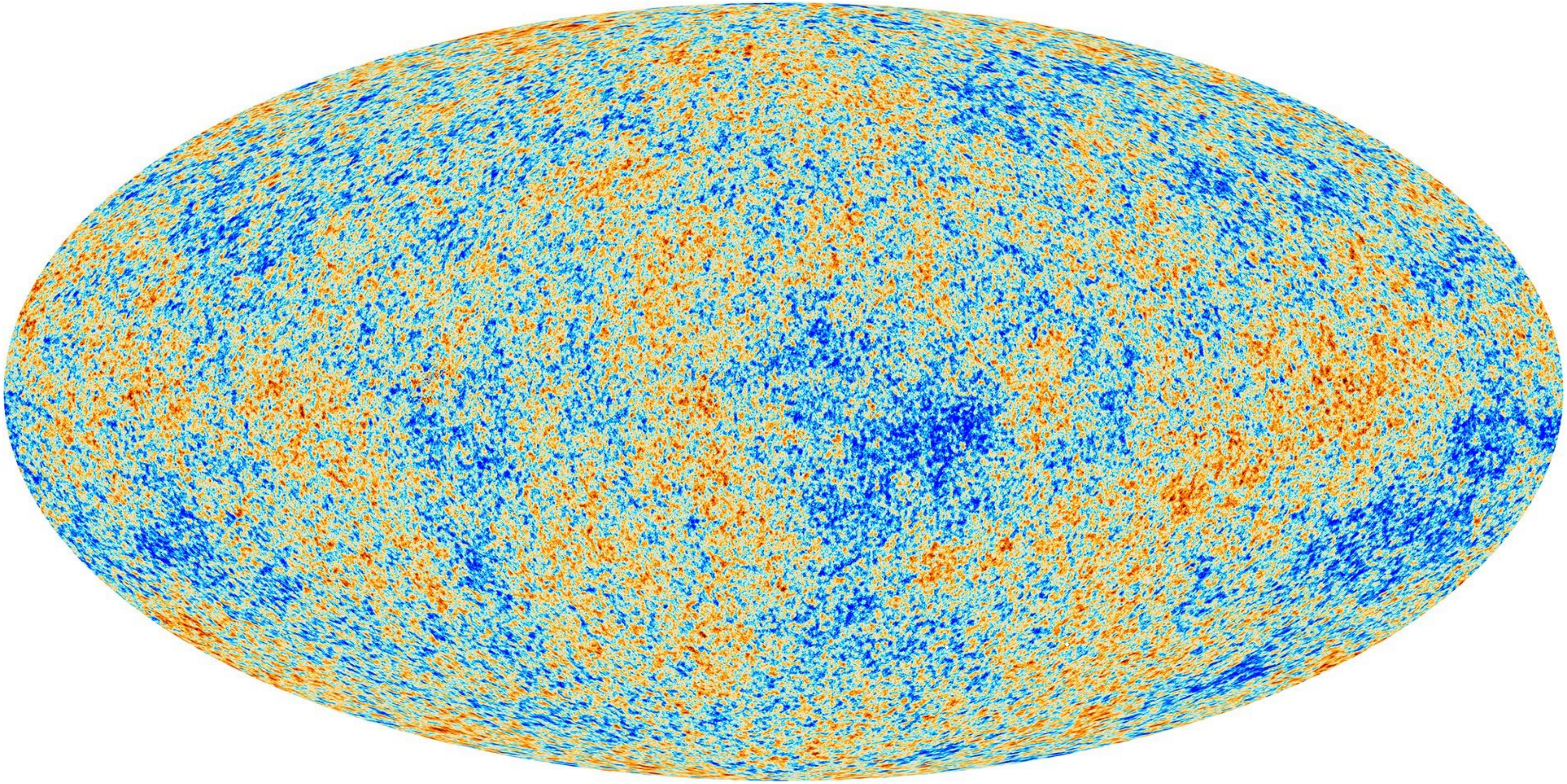


Image Credit: Planck

Observing the Early Universe:

(what makes it challenging)

1. The signals we are trying to measure are very tiny.

2. The wavelength of the light is different than what we measure with our eyes and every day cameras.

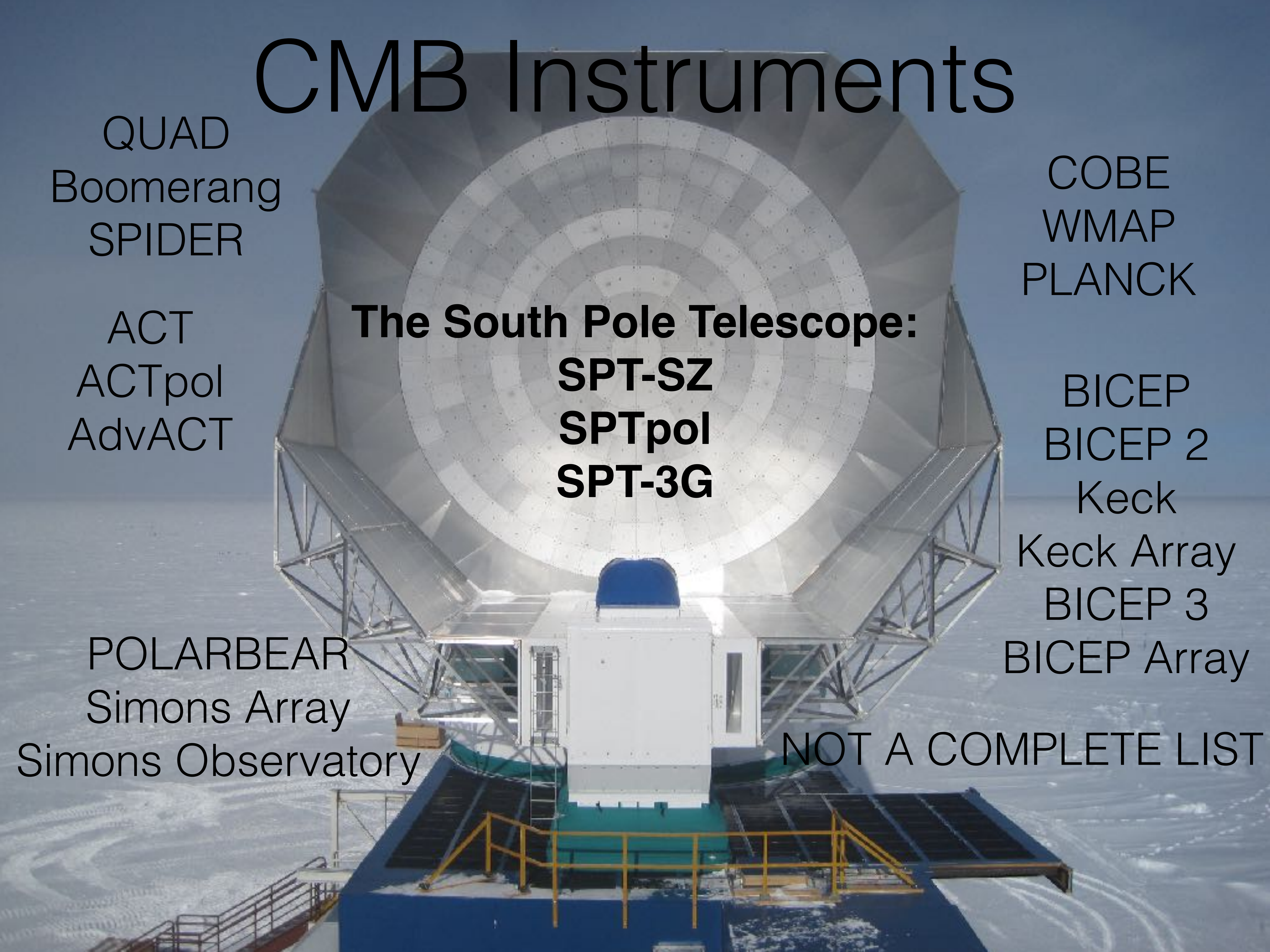
(typical wavelengths = 1 - 3 mm)

(and what makes it worthwhile)

1. We can probe physics when the universe was less complicated.

2. We can probe high energy physics that is hard to create in the modern universe.

CMB Instruments



QUAD
Boomerang
SPIDER

ACT
ACTpol
AdvACT

POLARBEAR
Simons Array
Simons Observatory

The South Pole Telescope:
SPT-SZ
SPTpol
SPT-3G

COBE
WMAP
PLANCK

BICEP
BICEP 2
Keck
Keck Array
BICEP 3
BICEP Array

NOT A COMPLETE LIST

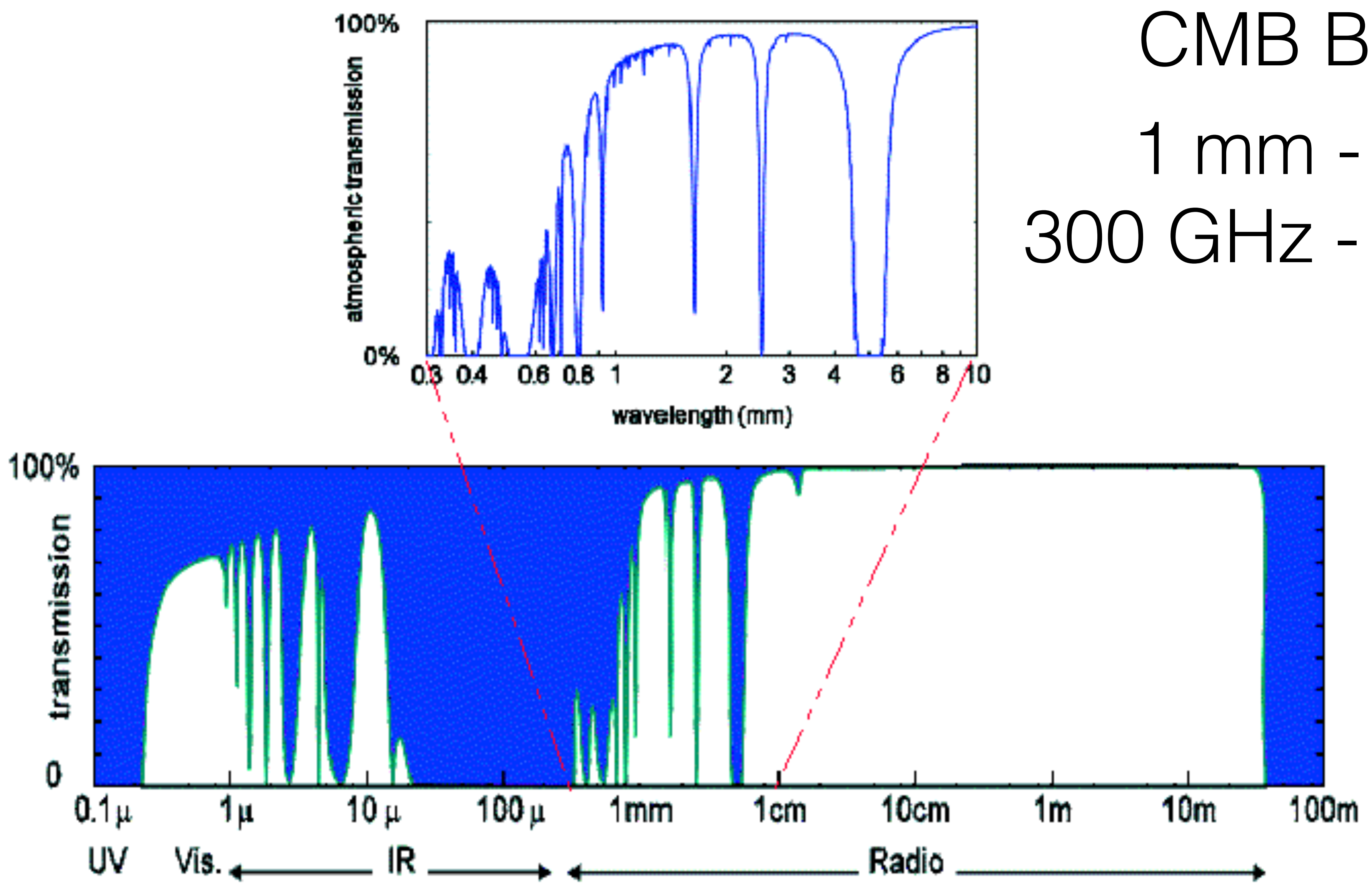
What do you need for a successful CMB instrument?

Observing Site — the atmosphere is one of the biggest sources of noise

Sensitivity — how faint are the signals you can measure

Resolution — what scale objects you can measure

What do you need for a successful CMB instrument?



CMB Bands:

1 mm - 3 mm
300 GHz - 100 GHz

Image Credit: Credit: IRAM, France

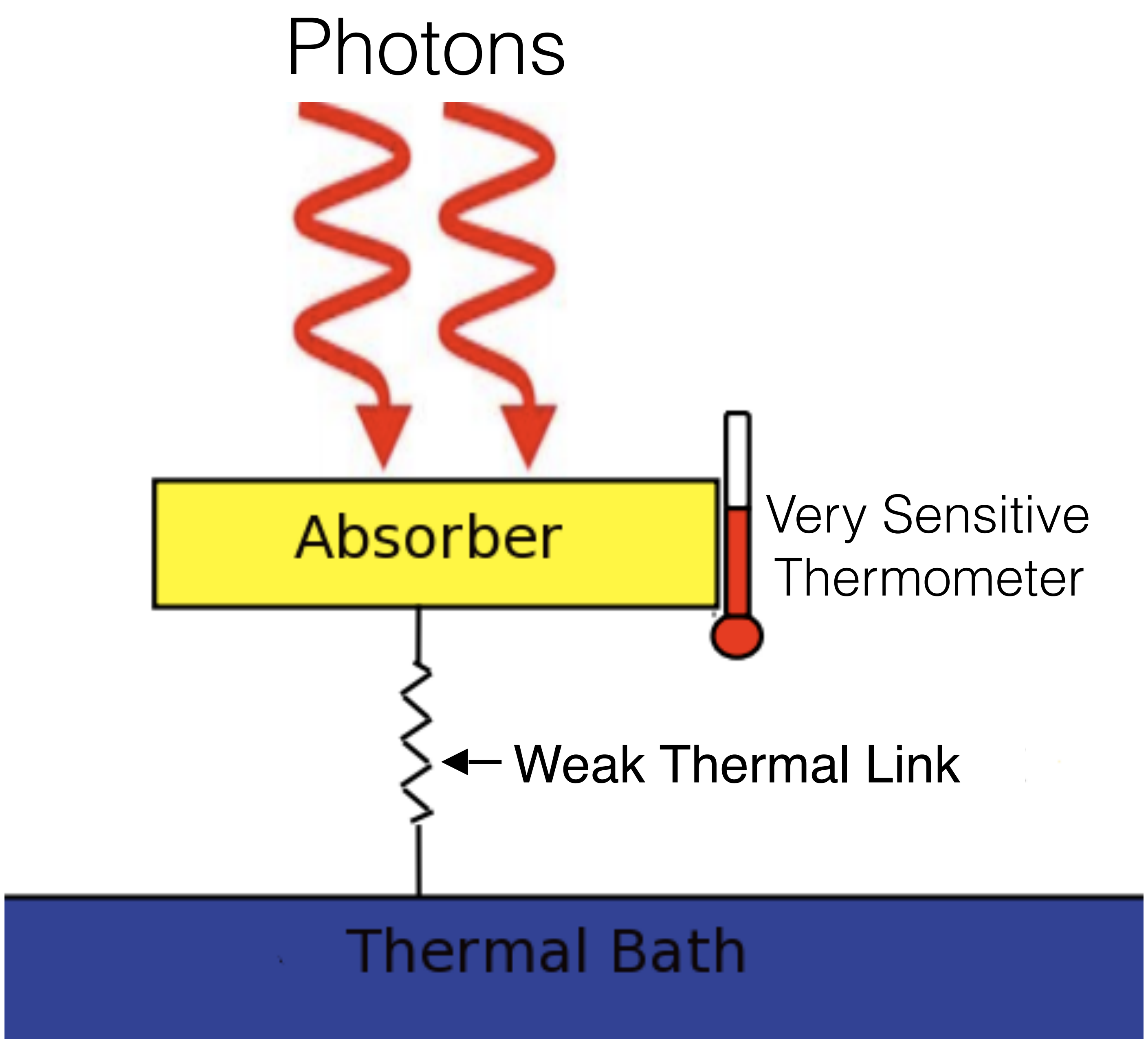
Photo Credit: Forest Banks

What do you need for a successful CMB instrument?

Sensitivity — lots of detectors with very low noise that work at these frequencies

Key Technology: Superconducting Transition Edge Sensor (TES) Bolometer

Key Technology:
Superconducting Transition Edge Sensor (TES) Bolometer



Key Technology: Superconducting Transition Edge Sensor (TES) Bolometer

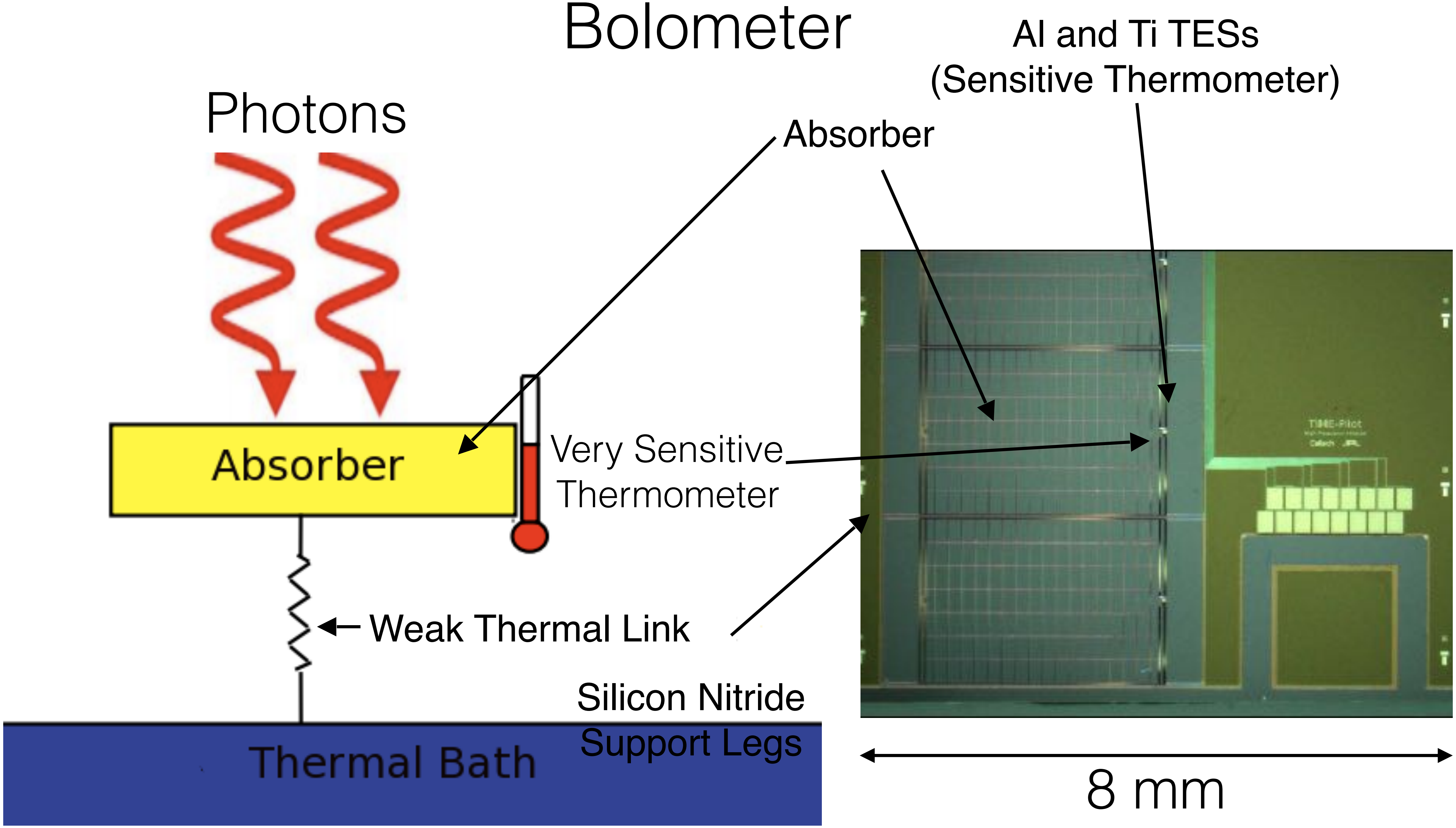
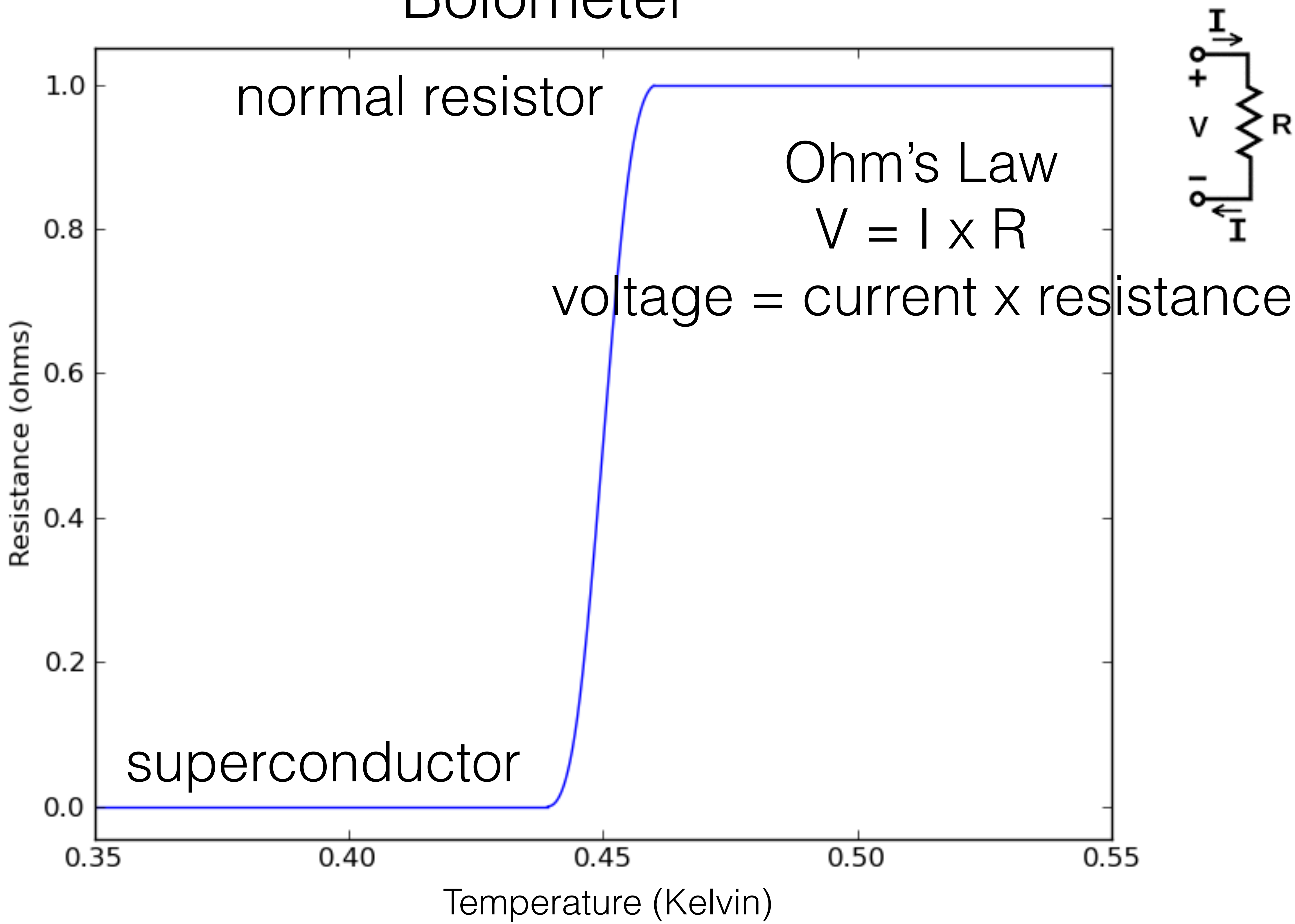
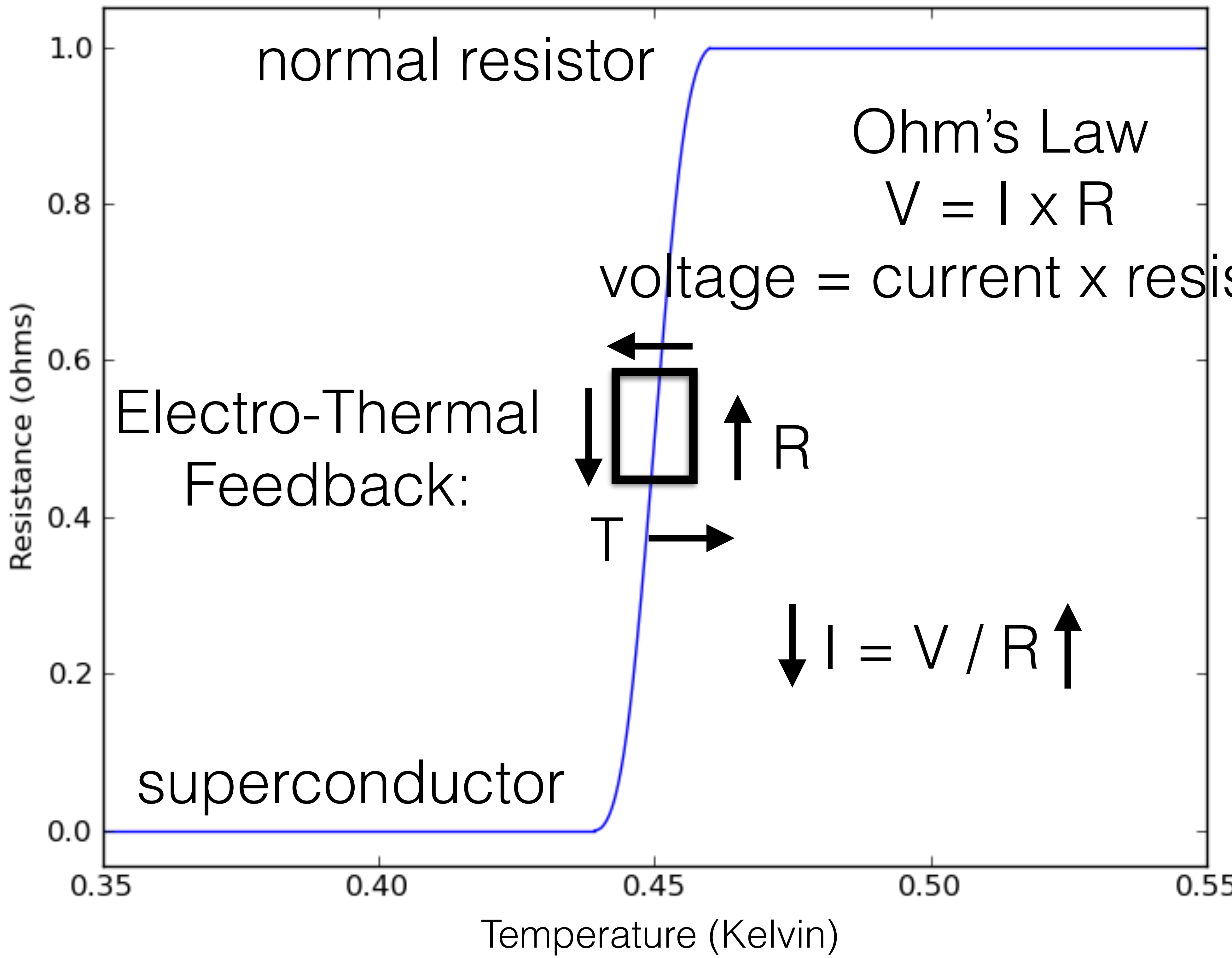


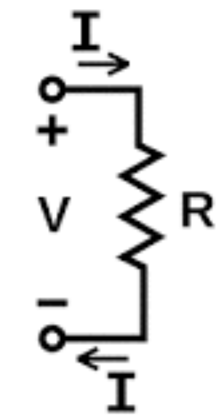
Image Credit: TIME Collab.

Key Technology:
Superconducting Transition Edge Sensor (TES) Bolometer

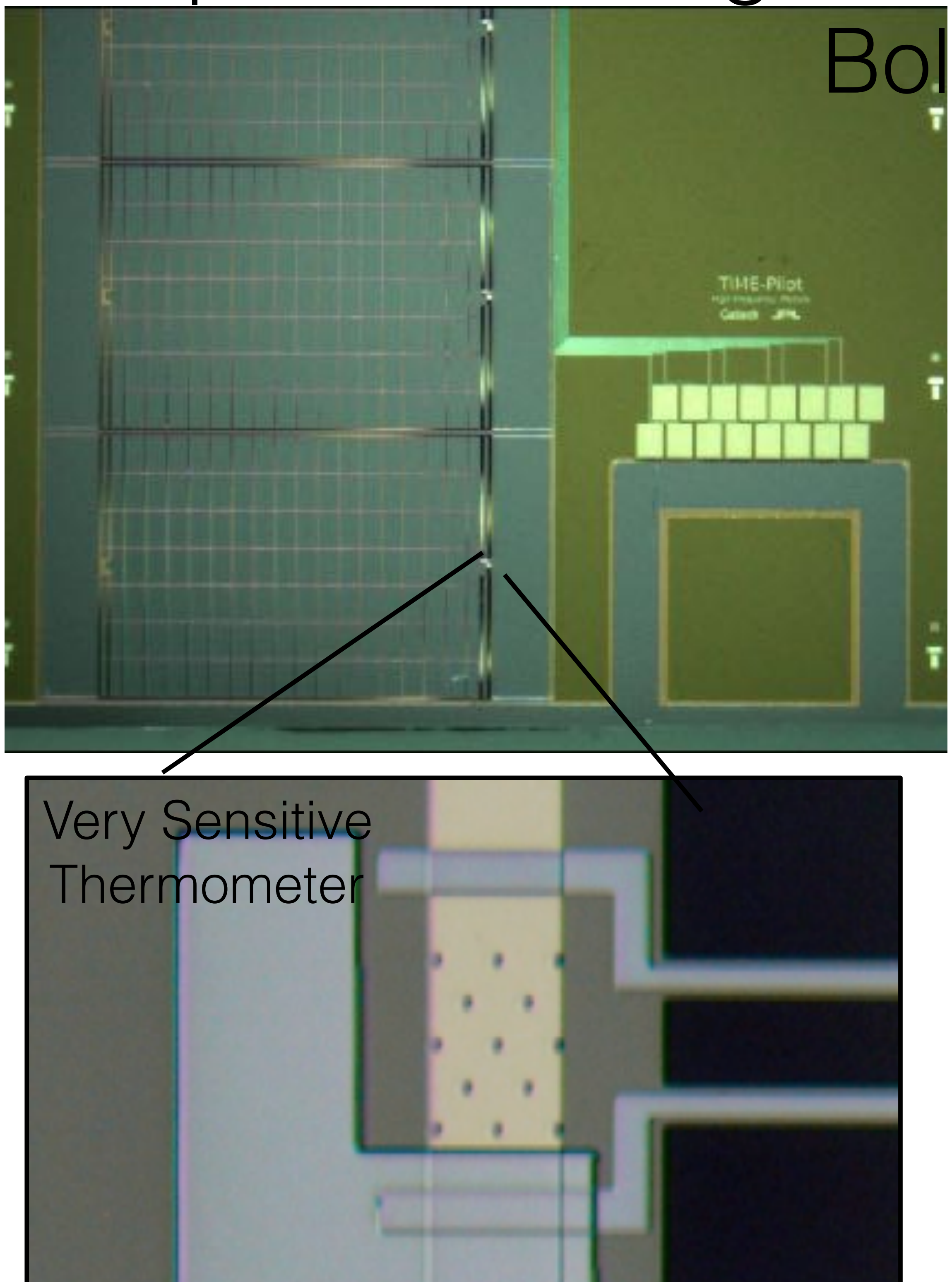


Key Technology:
Superconducting Transition Edge Sensor (TES) Bolometer





Key Technology:
Superconducting Transition Edge Sensor (TES) Bolometer



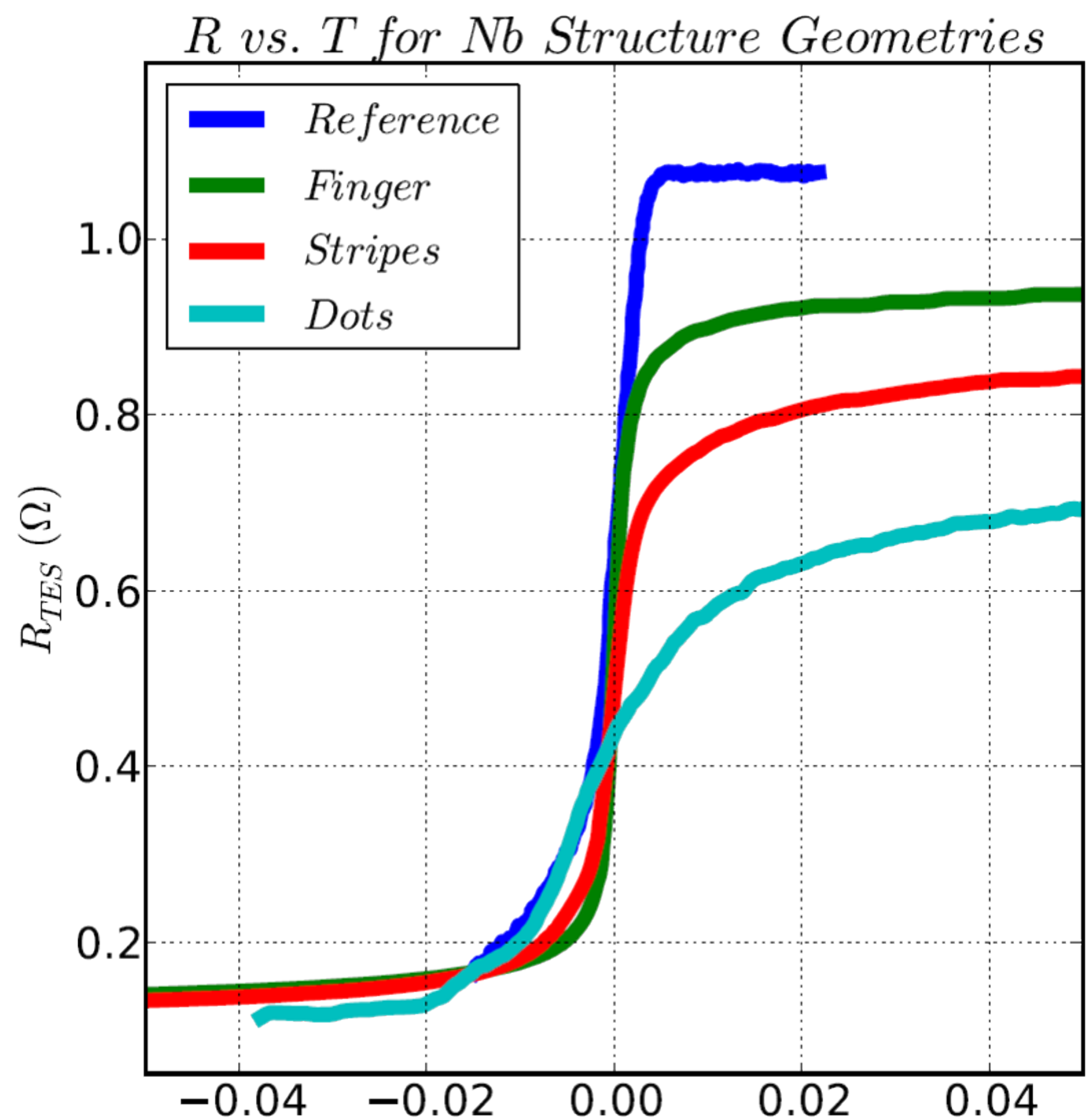
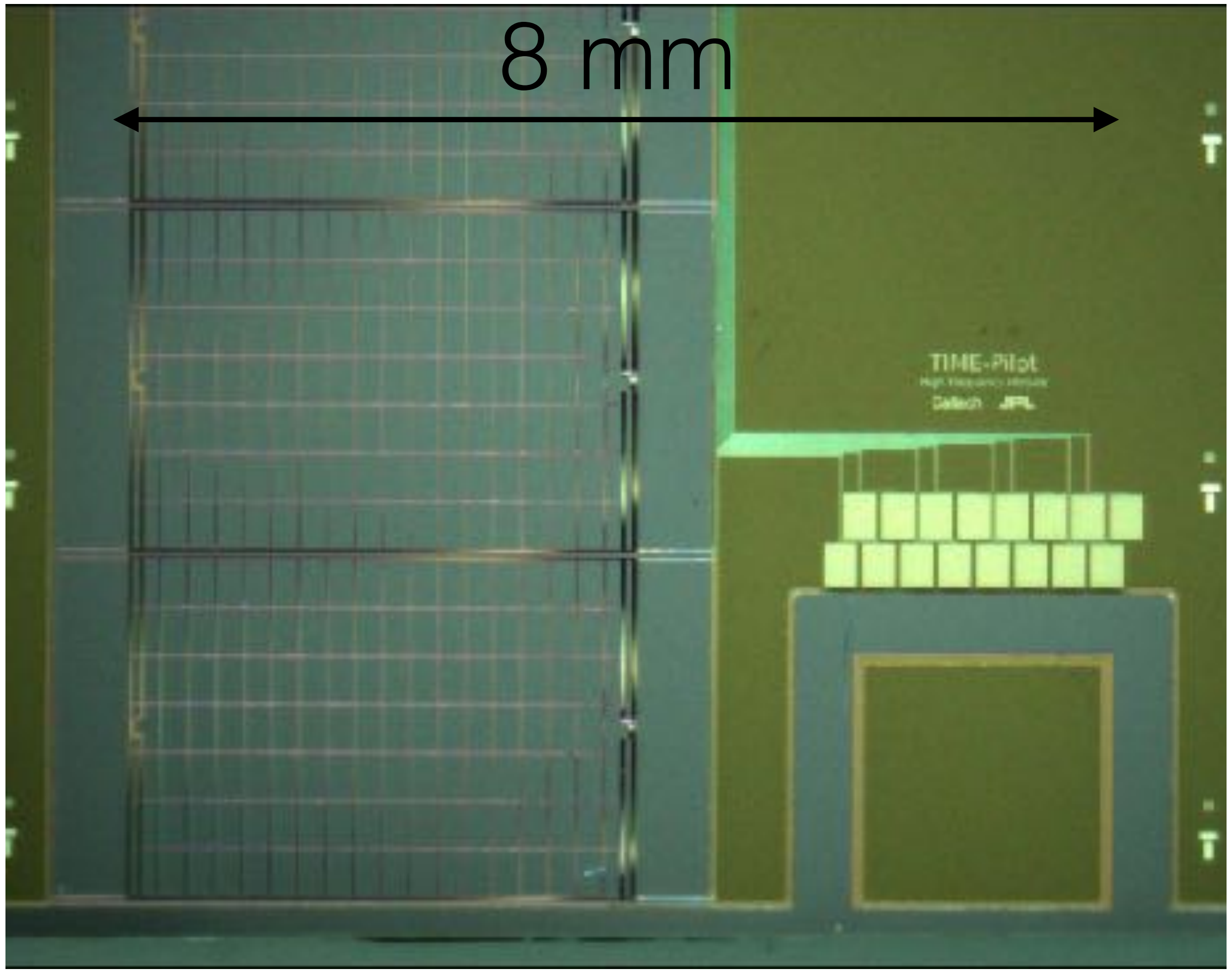


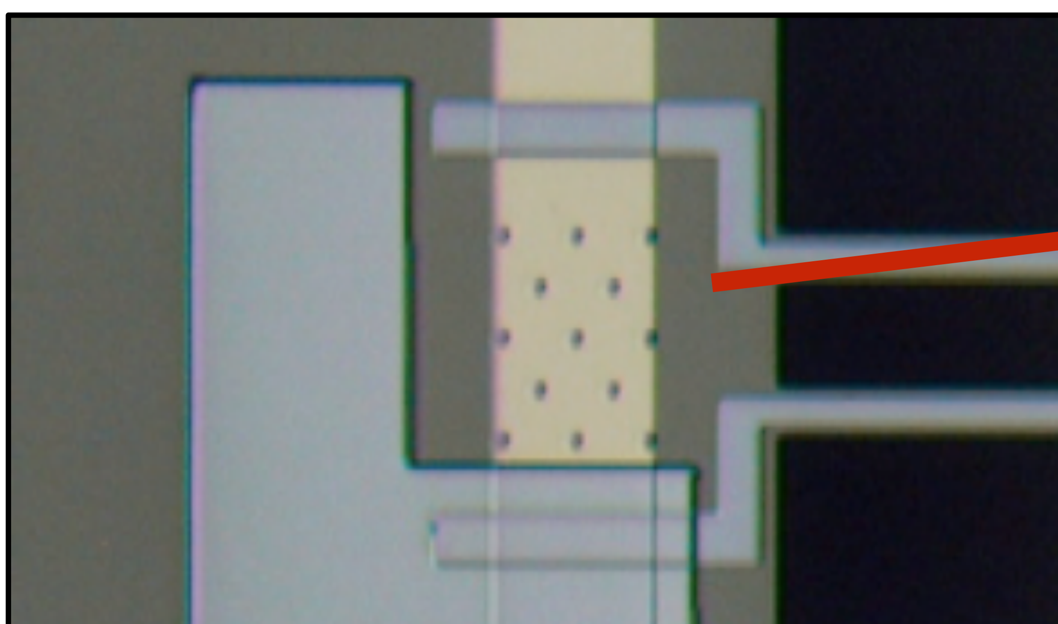
Image and figure Credit: TIME Collab., George et al 2014

“Lots of Detectors”

	2010-2015	2015-2019	2020 — 2025
CMB Experiment Stage	II	III	IV
Number of TES Detectors	~1000’s	~ 10,000	~500,000

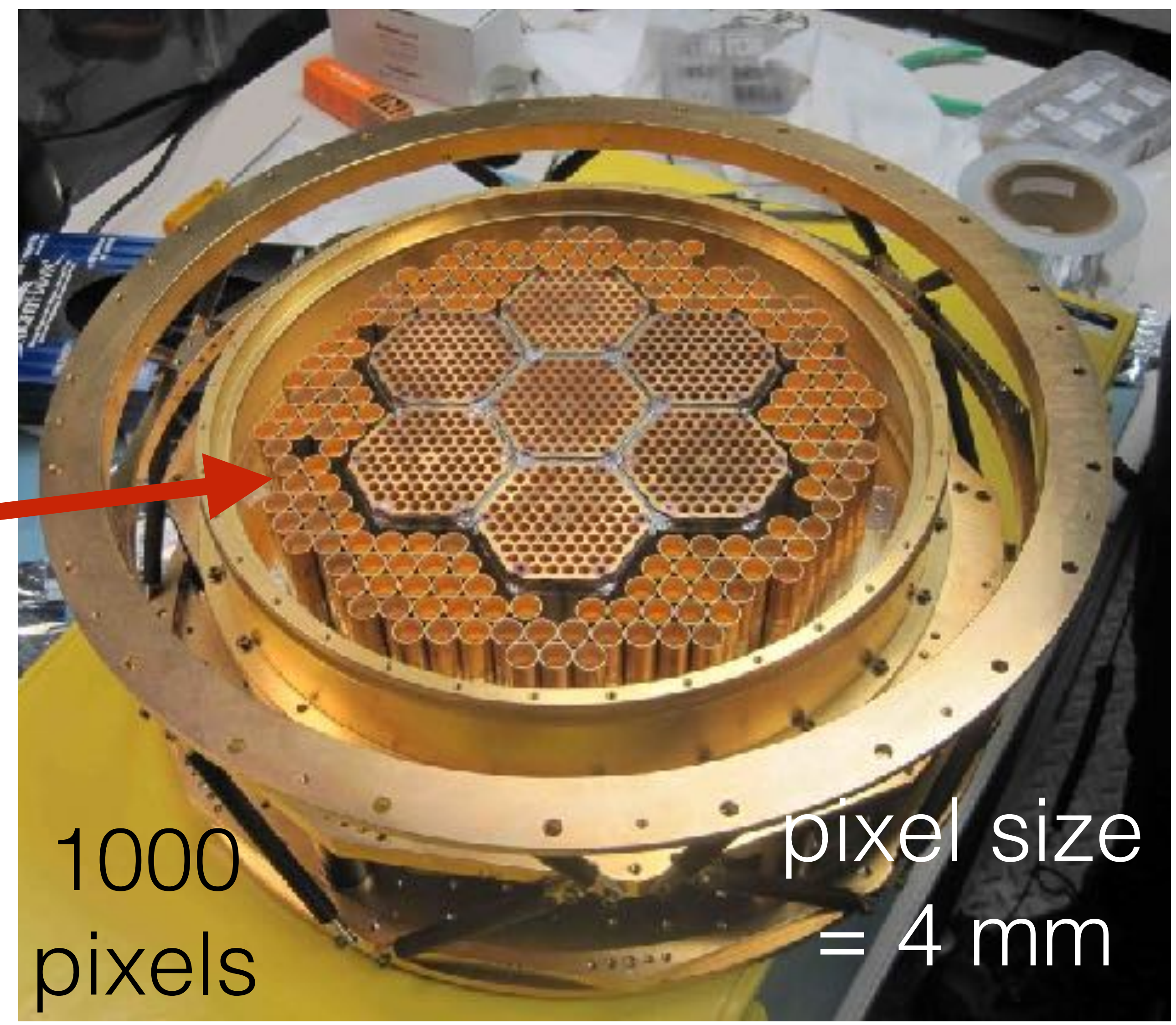


Transition Edge Sensor

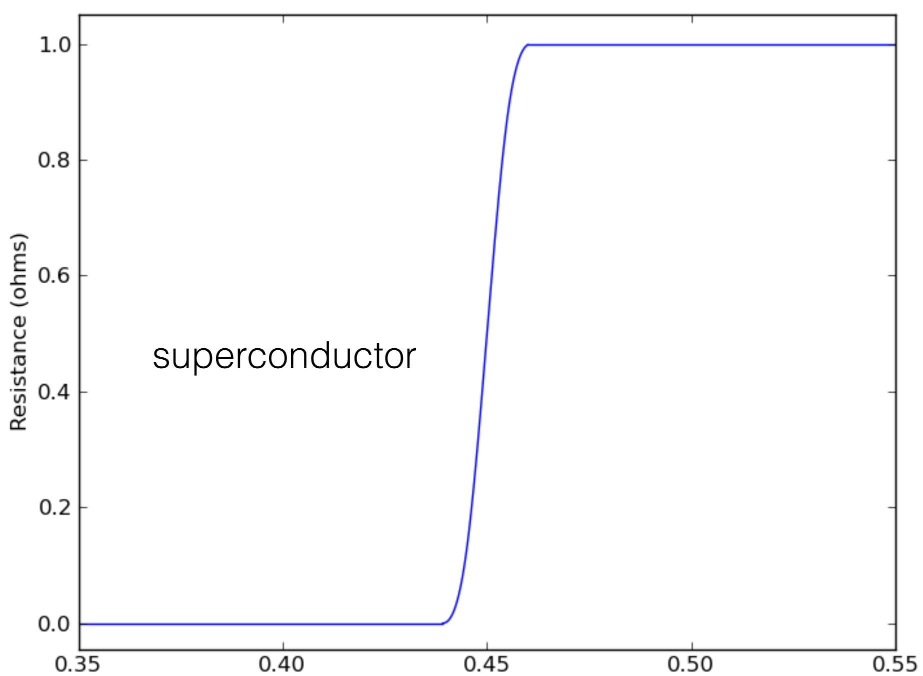


> 1 million pixels

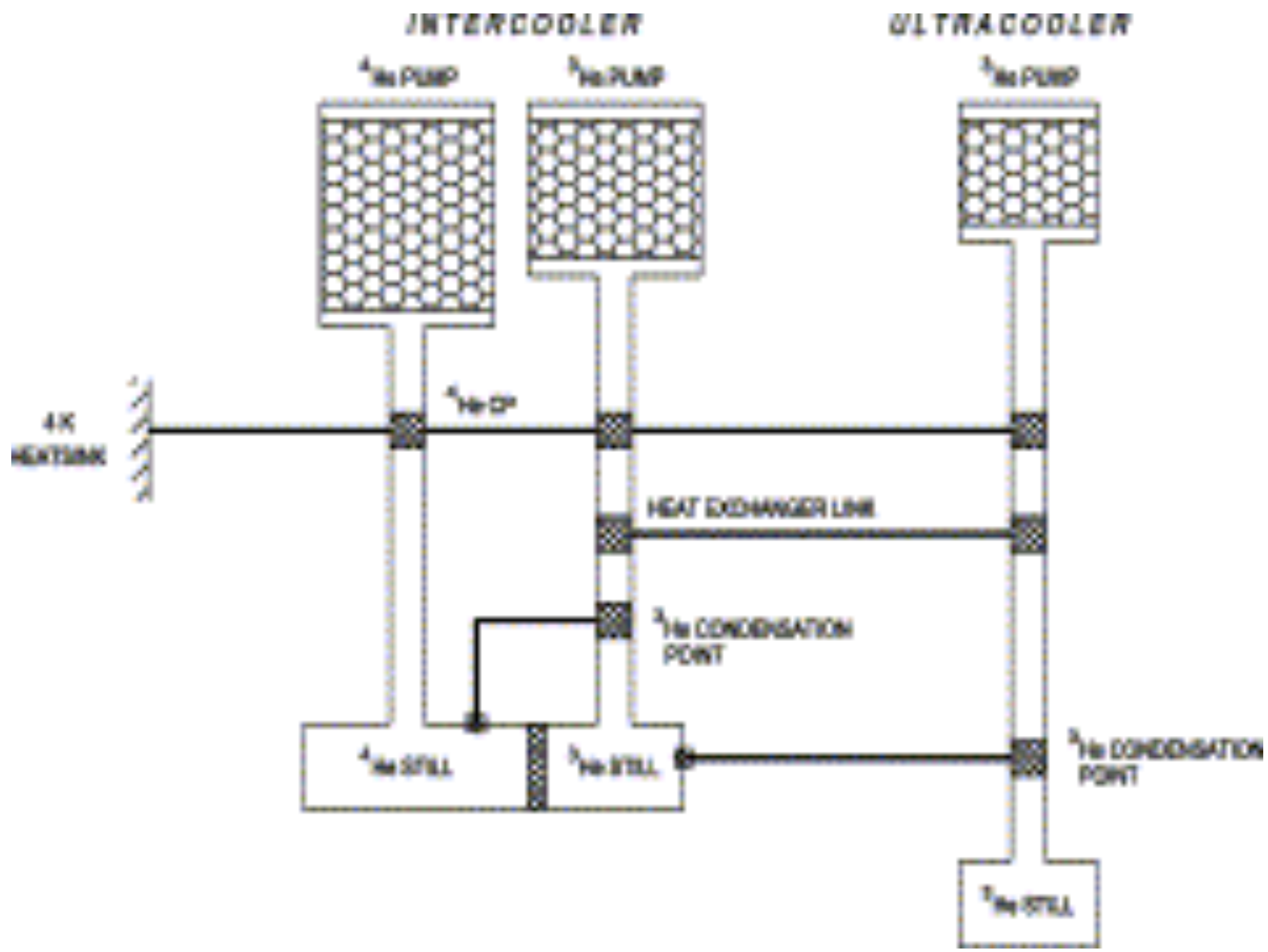
pixel size = 4 um



Cryogenics



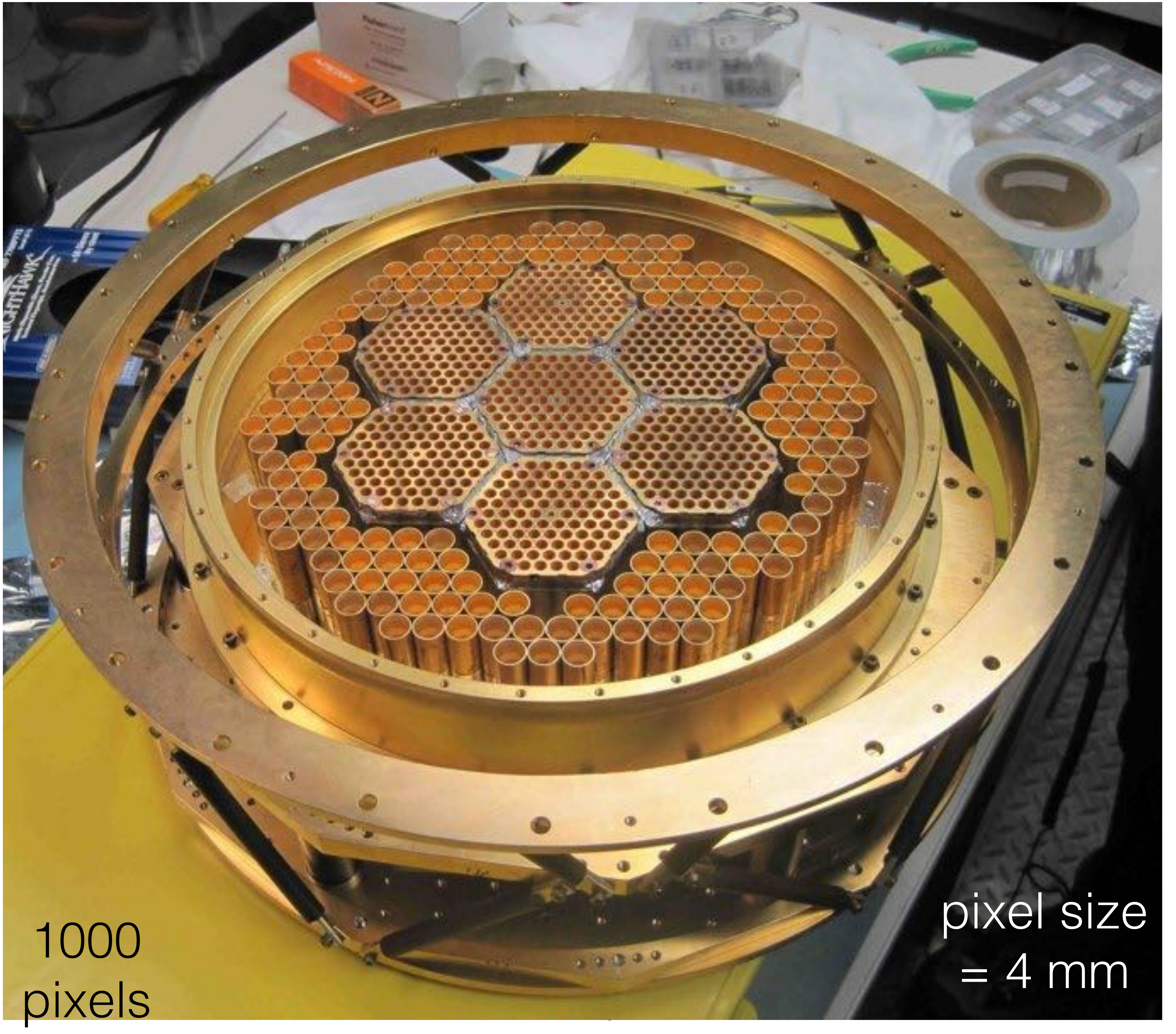
Temperature (Kelvin)

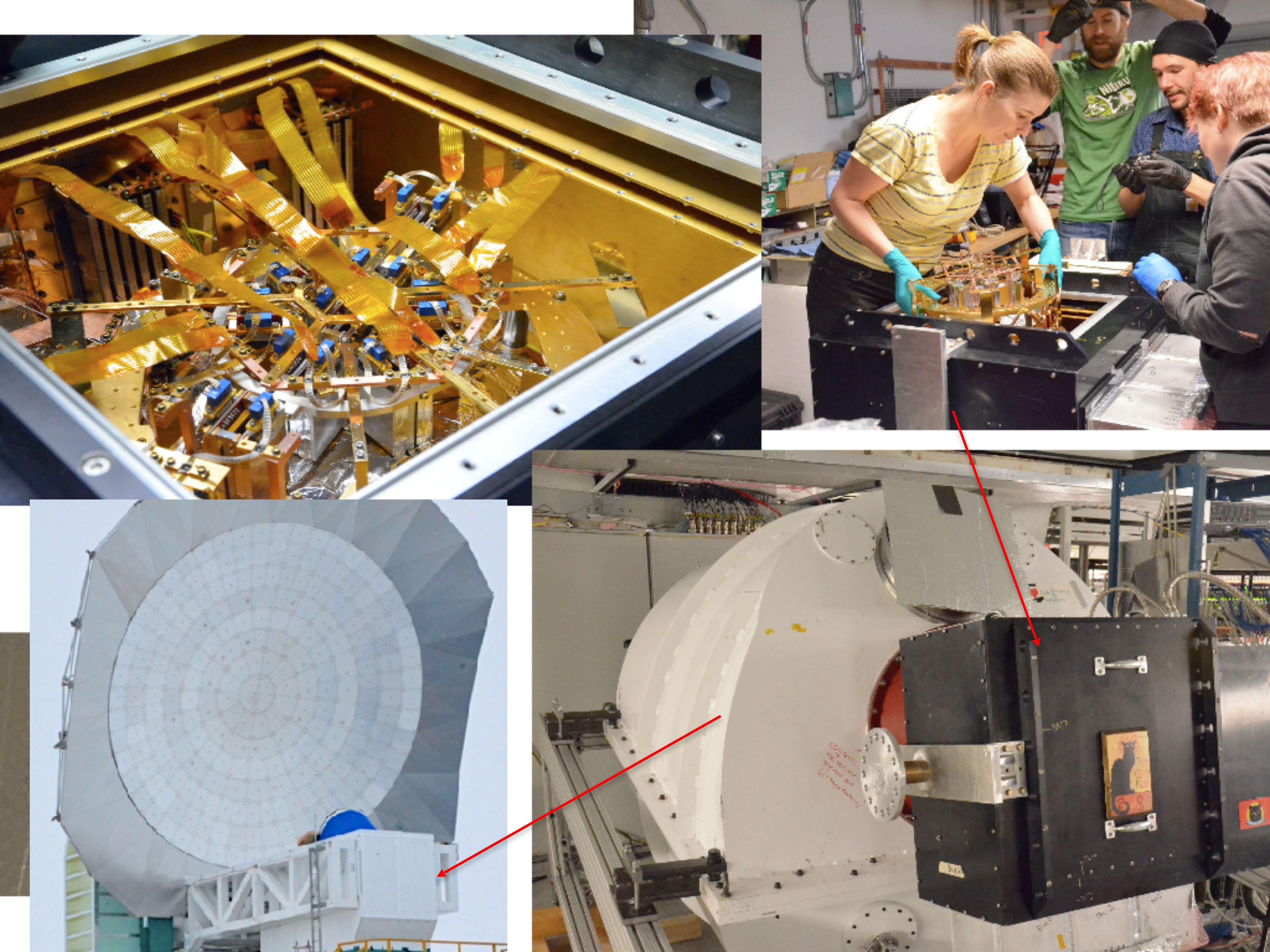


3He Sorption Refrigerator

Image Credit: Bhatia et al. 2000


PROBES

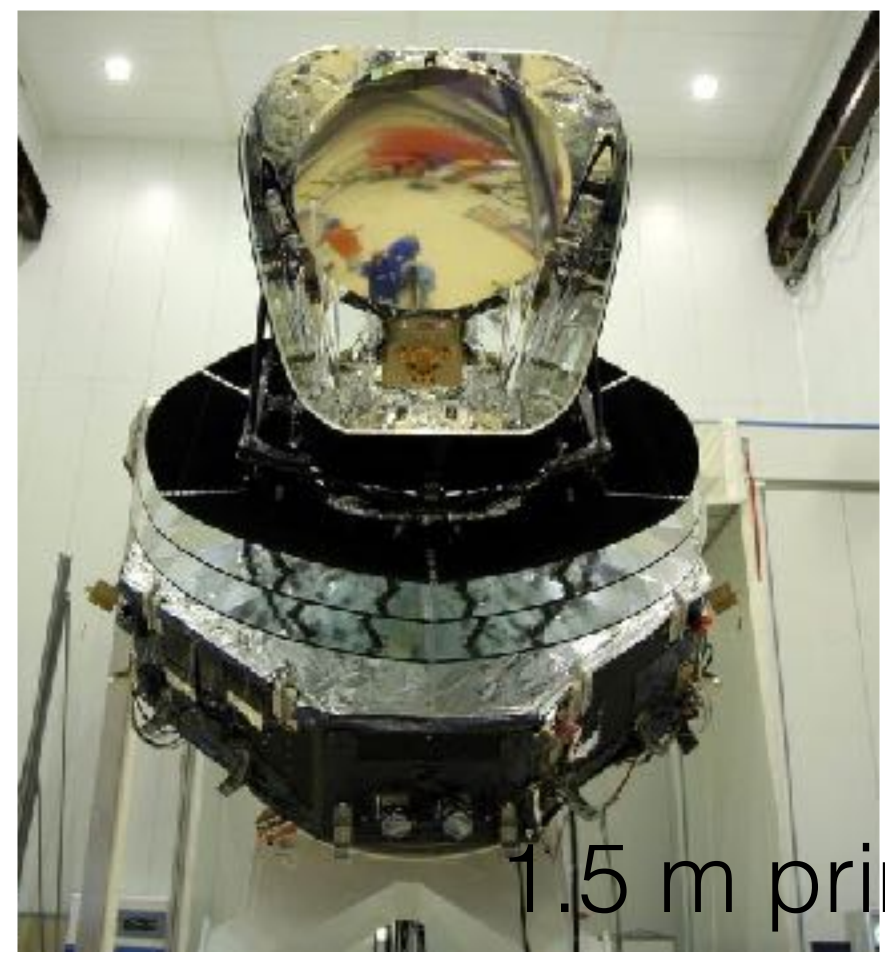

pixel size
= 4 mm
1000
pixels



What do you need for a successful CMB instrument?

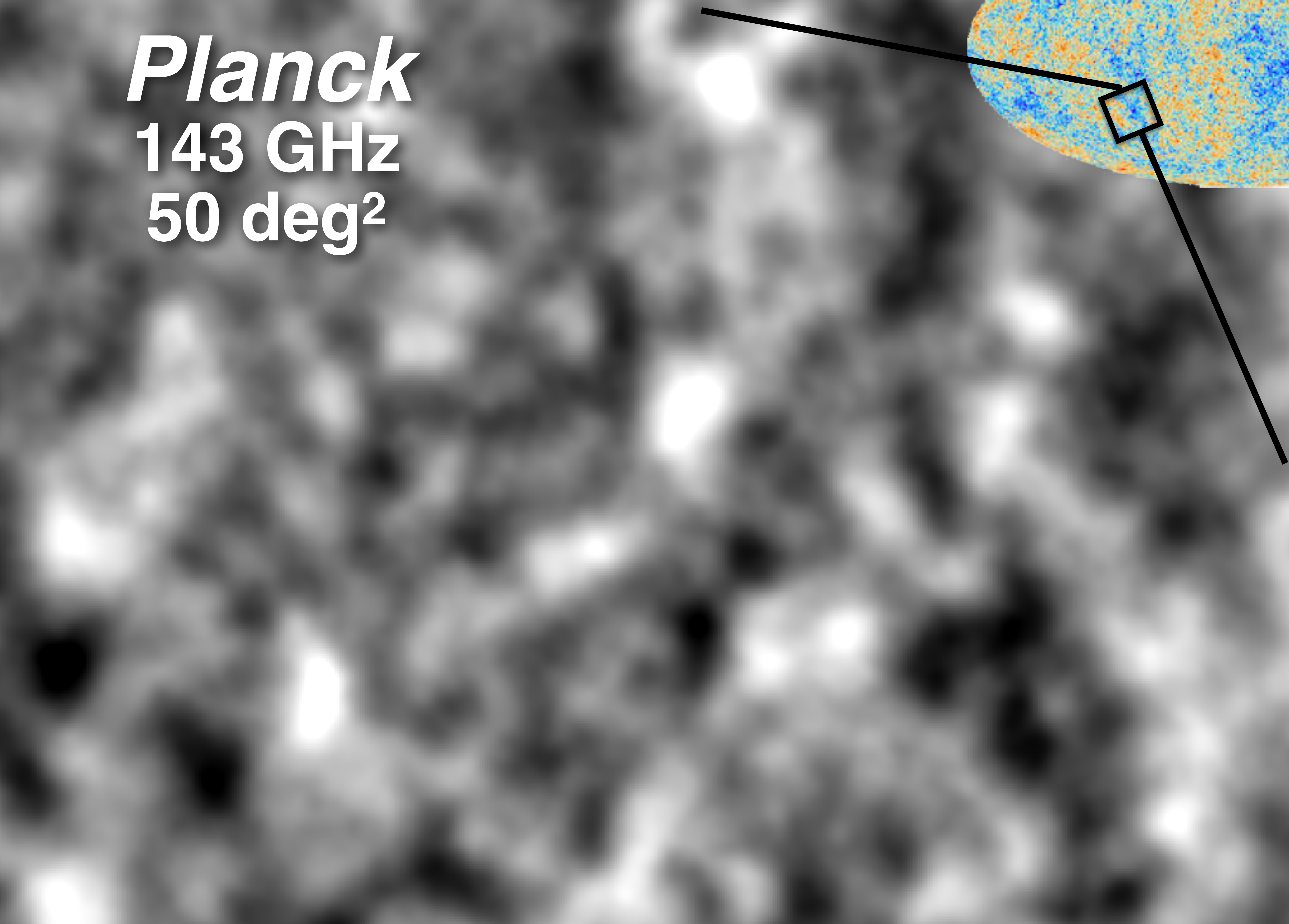
Resolution — what scale objects you can measure

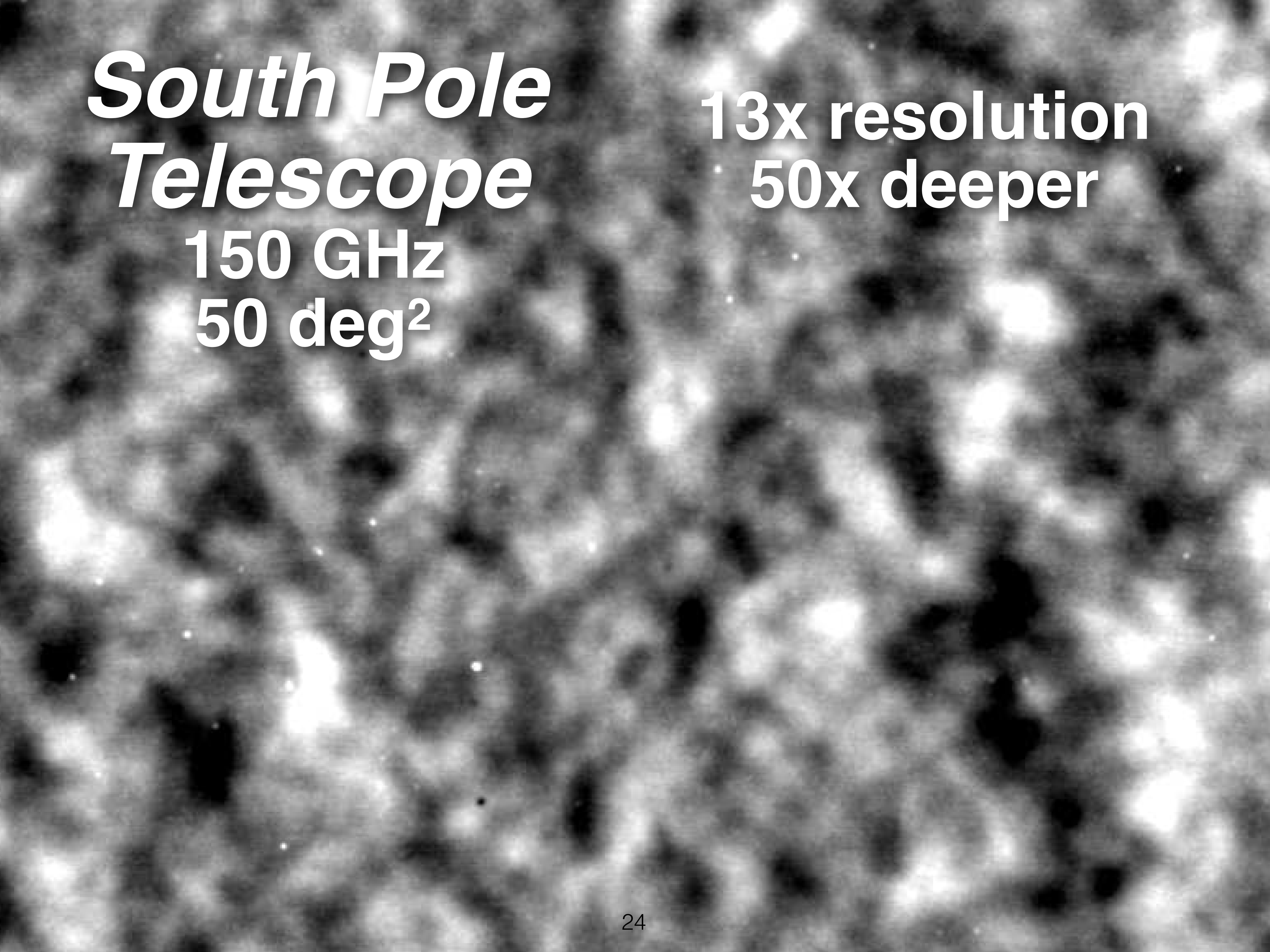
Image Credit: SPT



1.5 m primary mirror

Image Credit: ESA


Planck
143 GHz
50 deg²


South Pole Telescope
150 GHz
50 deg²
13x resolution
50x deeper

Science Objectives

0. Constrain the Cosmological Parameters Describing our Universe "Lambda CDM Cosmology"

- Will the universe expand forever, or will it collapse?
- Is the universe dominated by exotic dark matter?
- What is the shape of the universe?
- How and when did the first galaxies form?
- Is the expansion of the universe accelerating rather than decelerating?

Credit: NASA WMAP

Science Objectives

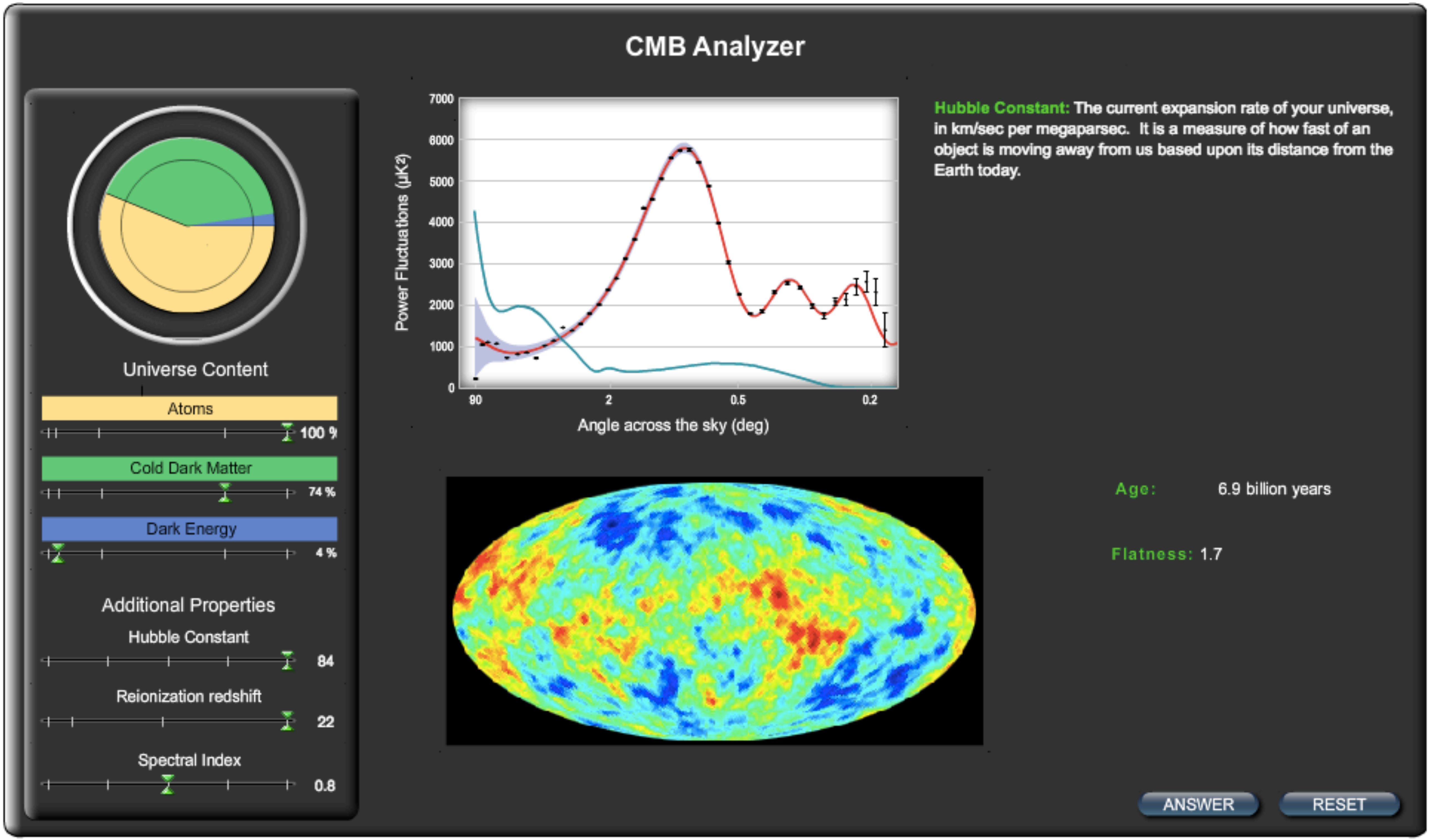
0. Constrain the Cosmological Parameters Describing our Universe "Lambda CDM Cosmology"

What are the parameters the CMB constrains?

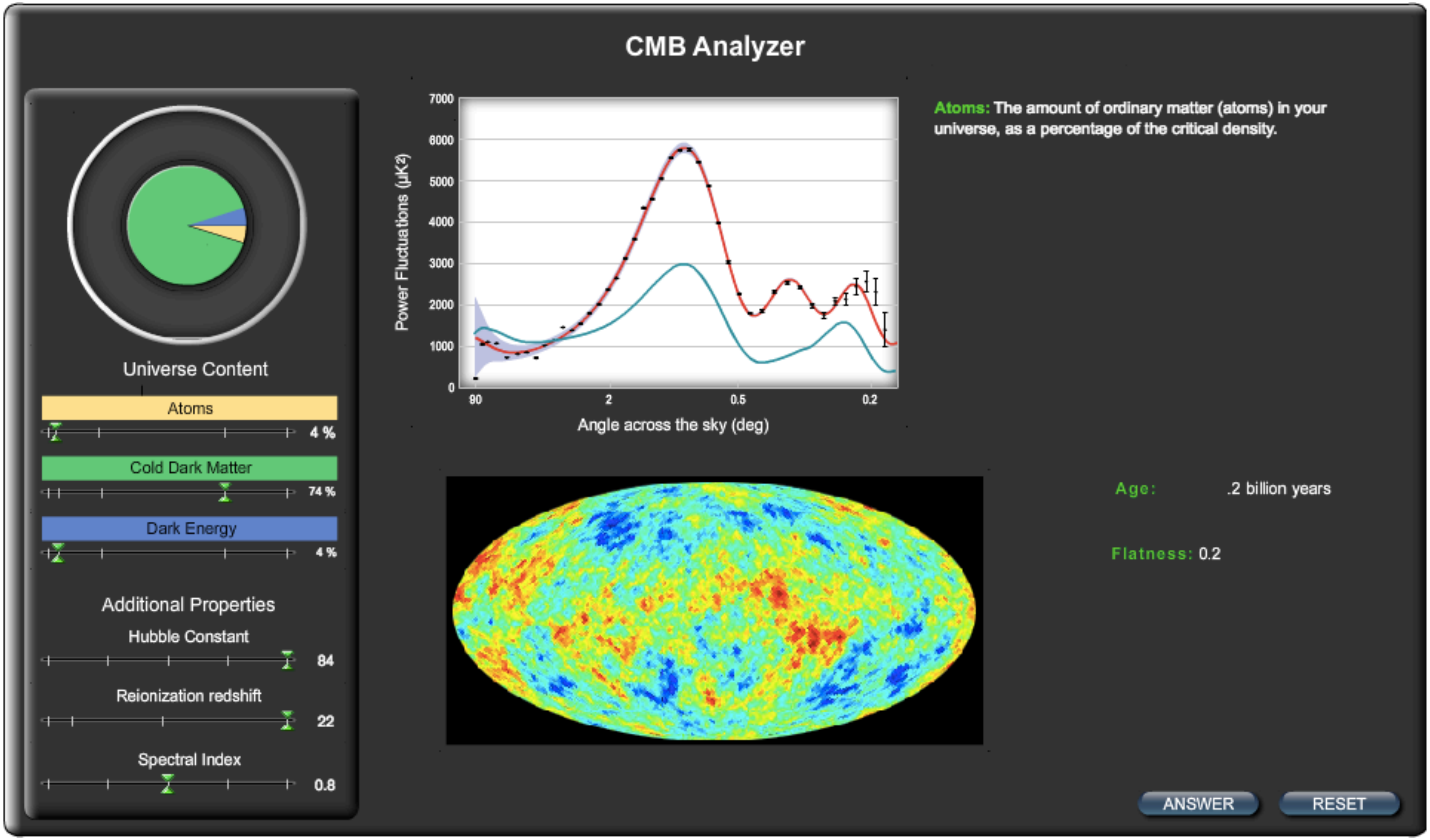
Atoms (Baryons)
Dark Matter
Dark Energy

Hubble Constant
Reionization Redshift
Spectral Tilt

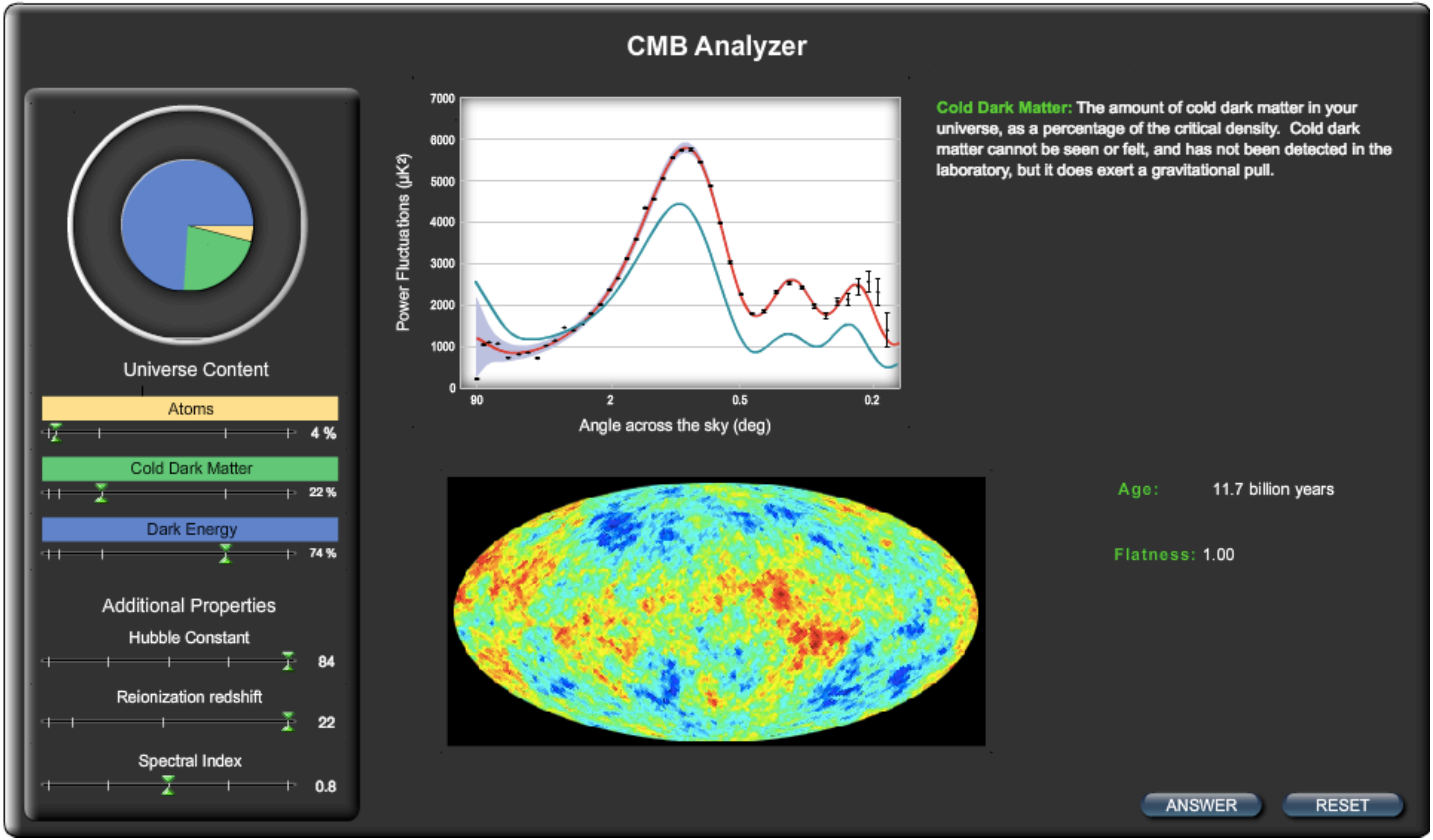
Credit: NASA WMAP



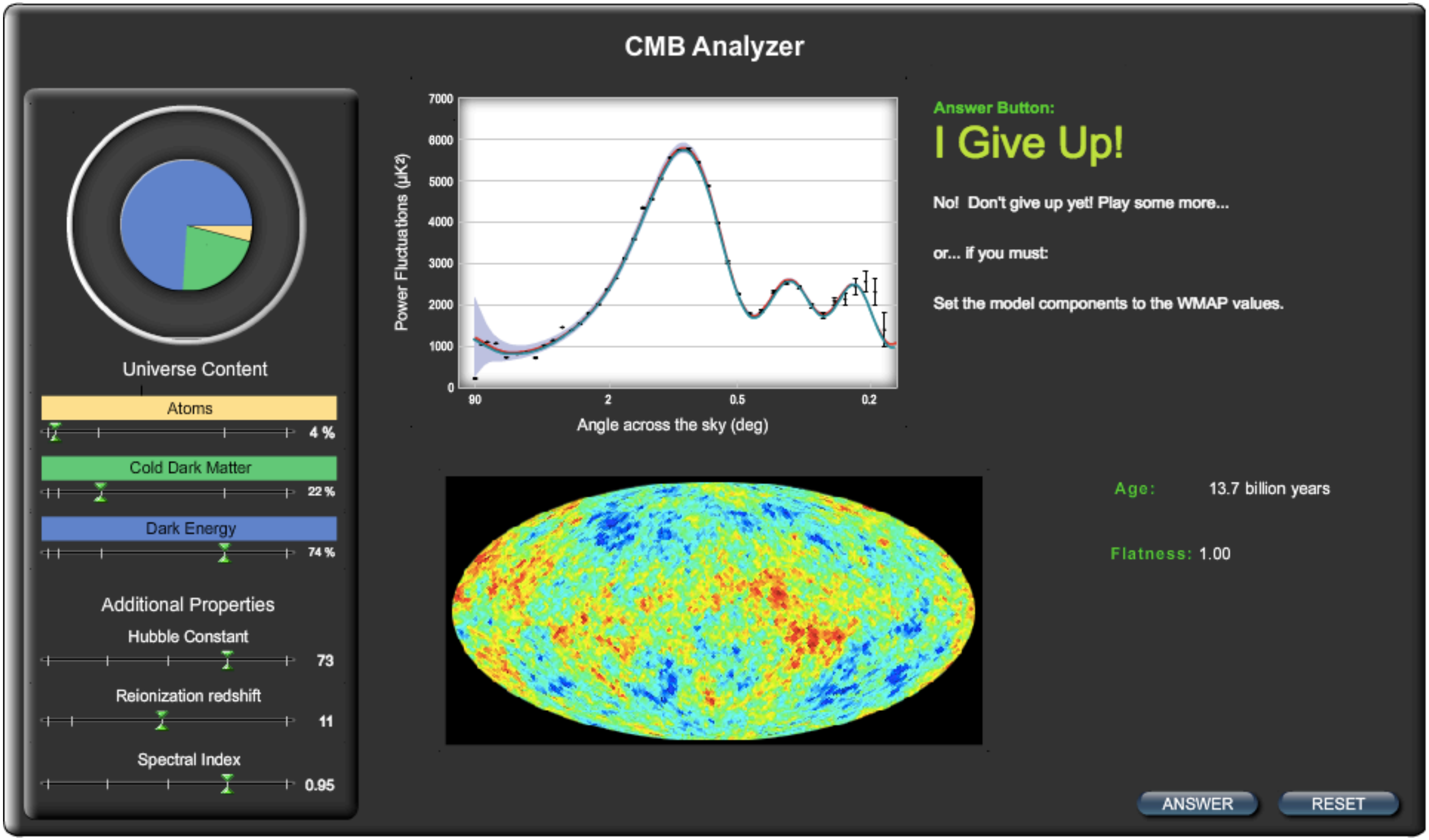
https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html



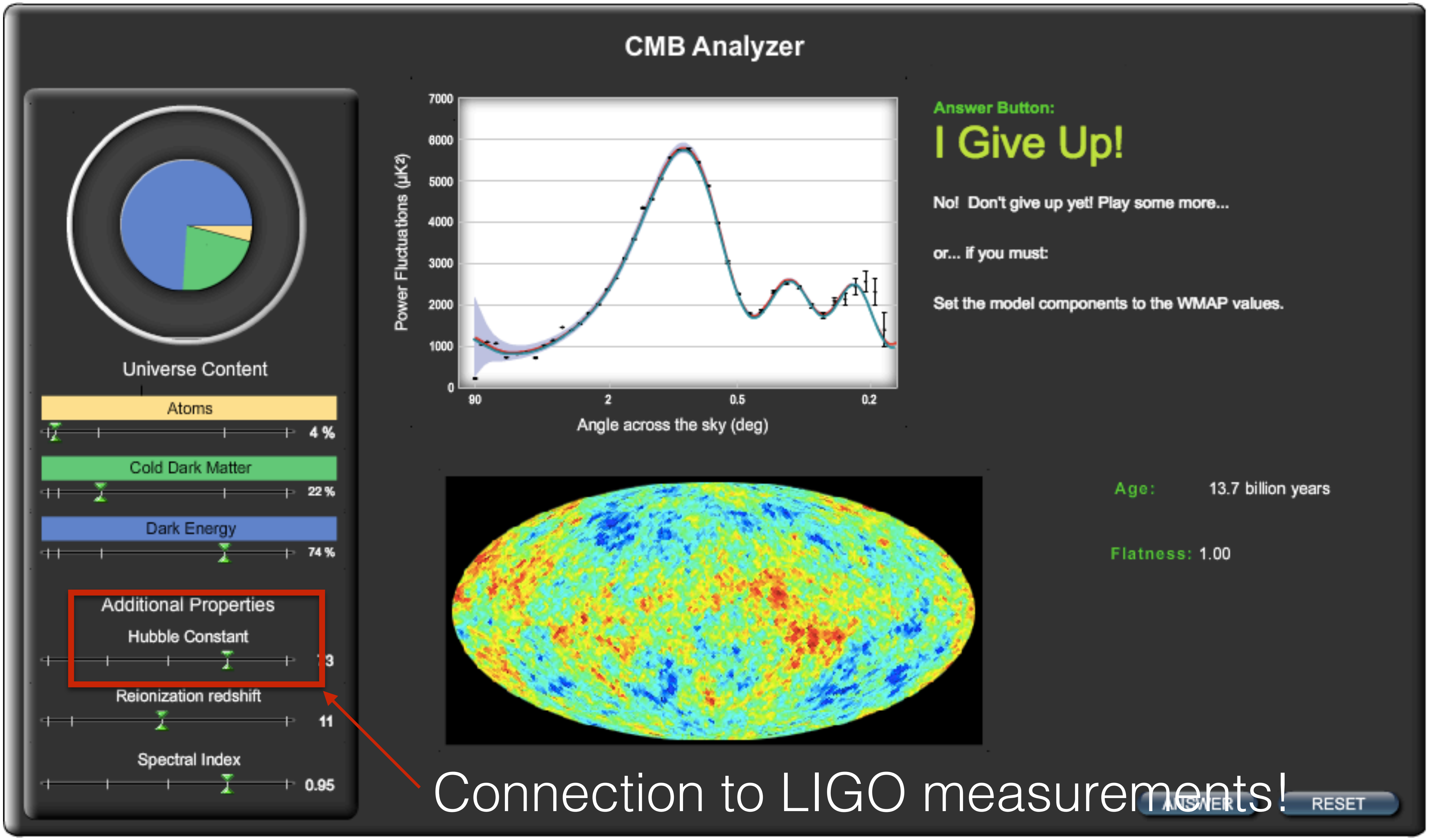
https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html



https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html



https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html



Connection to LIGO measurements!

https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html

LIGO vs. CMB Measurements of the Hubble Constant, Ho

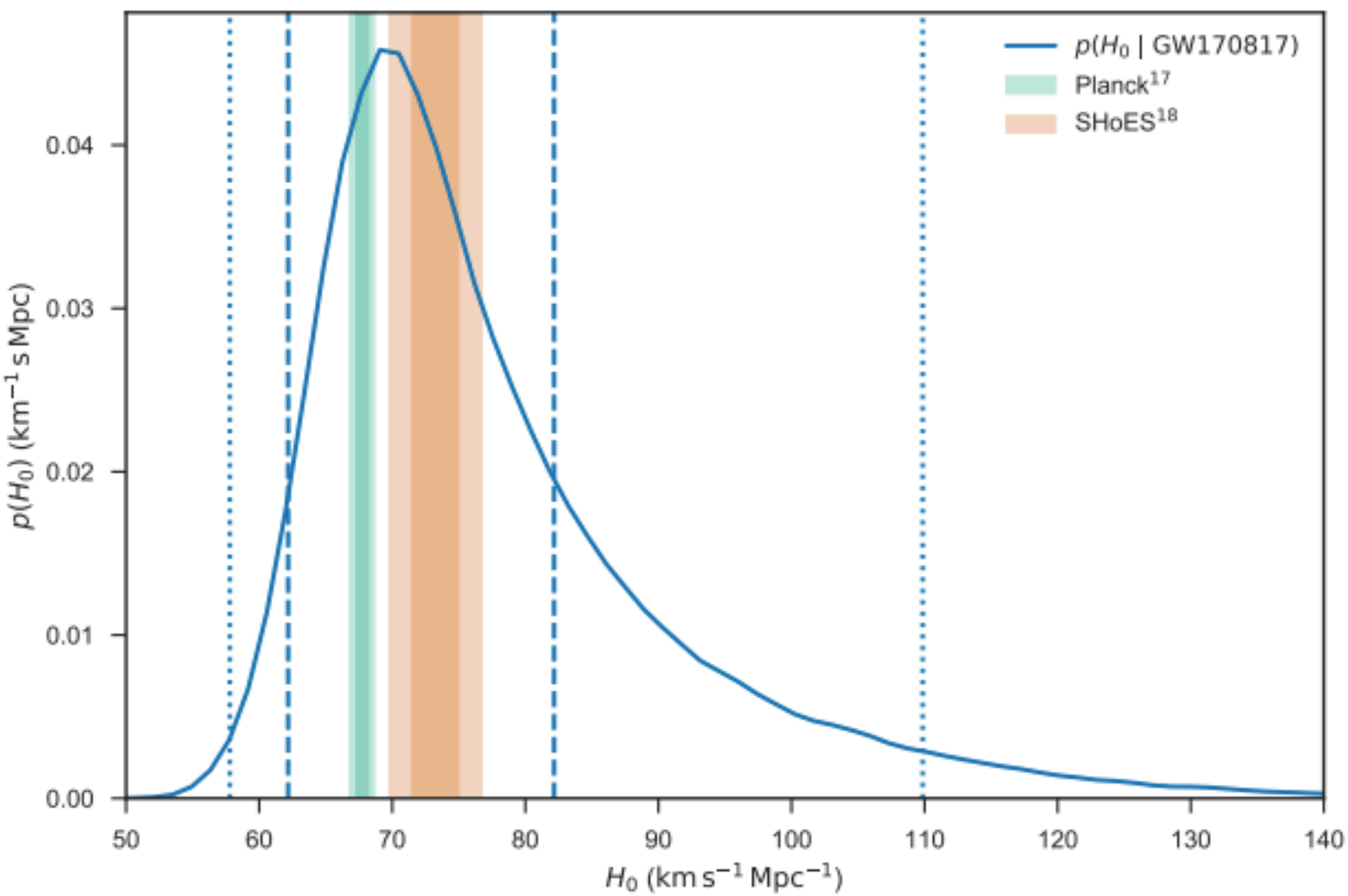


Figure Credit:
The Ligo Scientific Collaboration And The Virgo Collaboration, The 1m2h Collaboration, The Dark Energy Camera Gw-em Collaboration And The Des Collaboration, The Dlt40 Collaboration, The Las Cumbres Observatory Collaboration, The Vinrouge Collaboration, The Master Collaboration, Et Al.

Science Objectives

1.

detect signatures from inflationary gravitational waves in the cosmic microwave background (CMB)

probe physics of the universe fractions of a second after the big bang

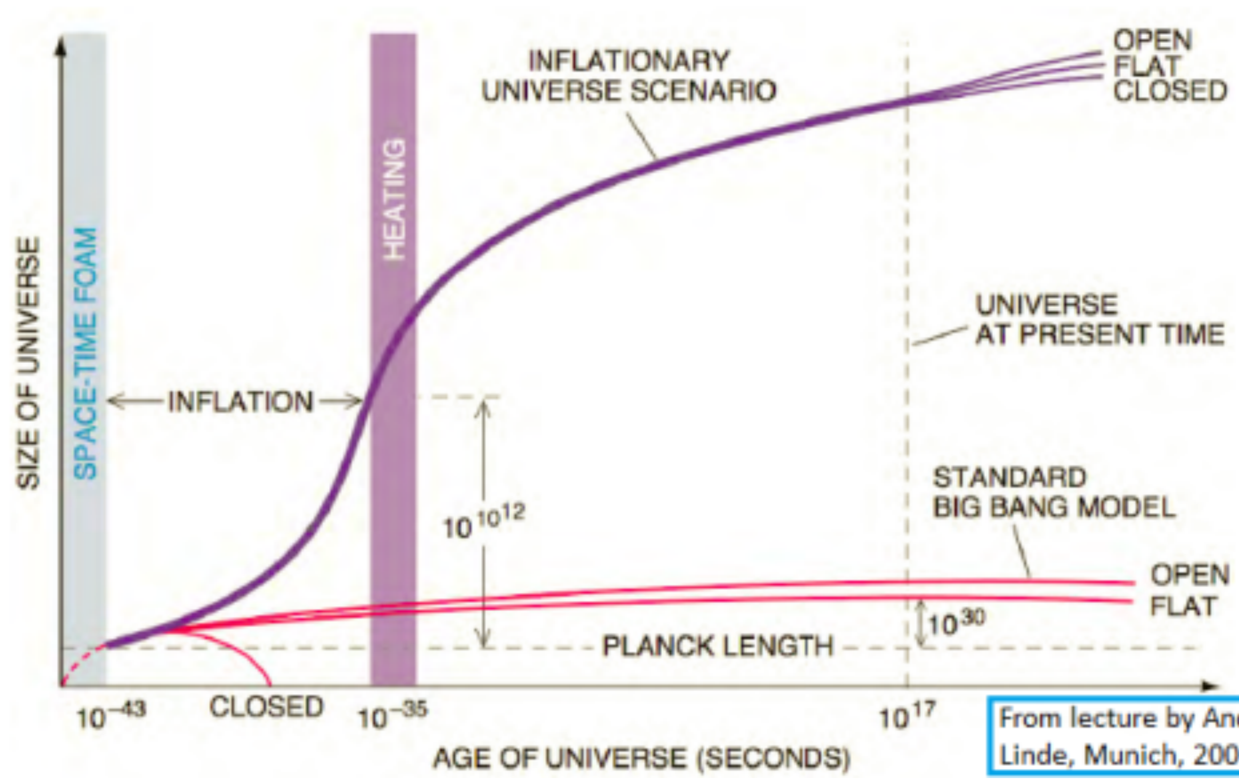
Science Objectives

1.

Why is the universe homogeneous?
Why is the universe flat?

Inflation?!

inflation is as exponential expansion of the universe in the first fractions of a second after the big bang



From lecture by Andrei Linde, Munich, 2007

Science Objectives

2.

measure gravitational lensing
of the CMB by matter in our universe

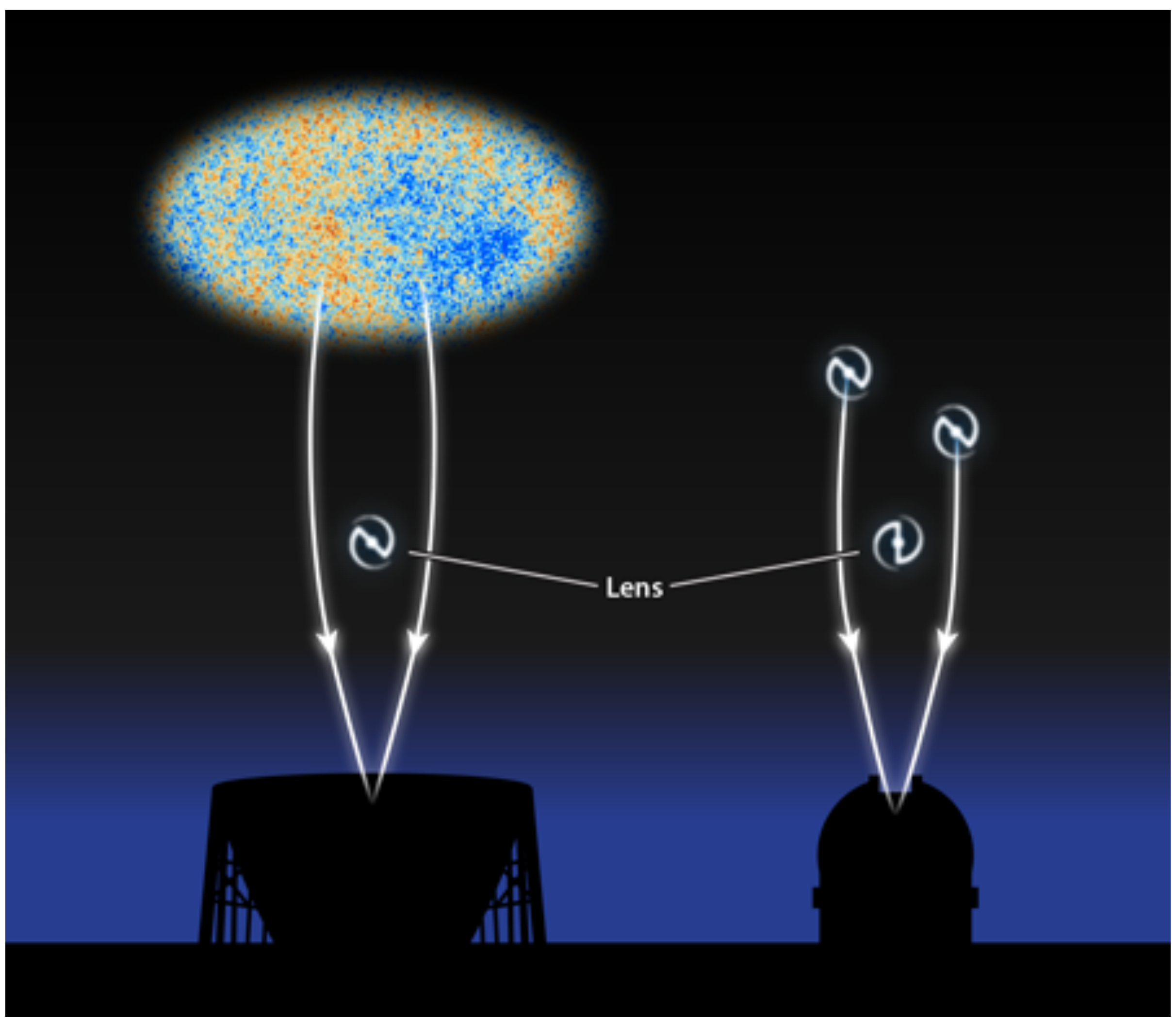


Image Credit: Stompor et al 2015

Properties of neutrinos
affect the structure in our
universe!

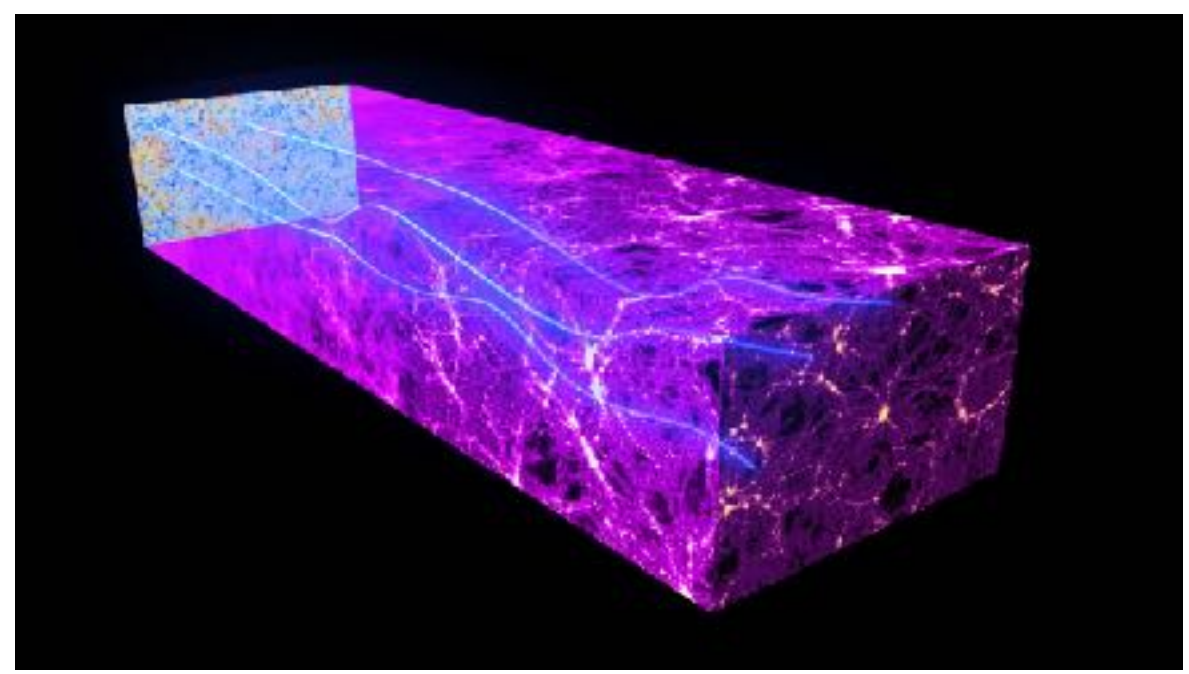
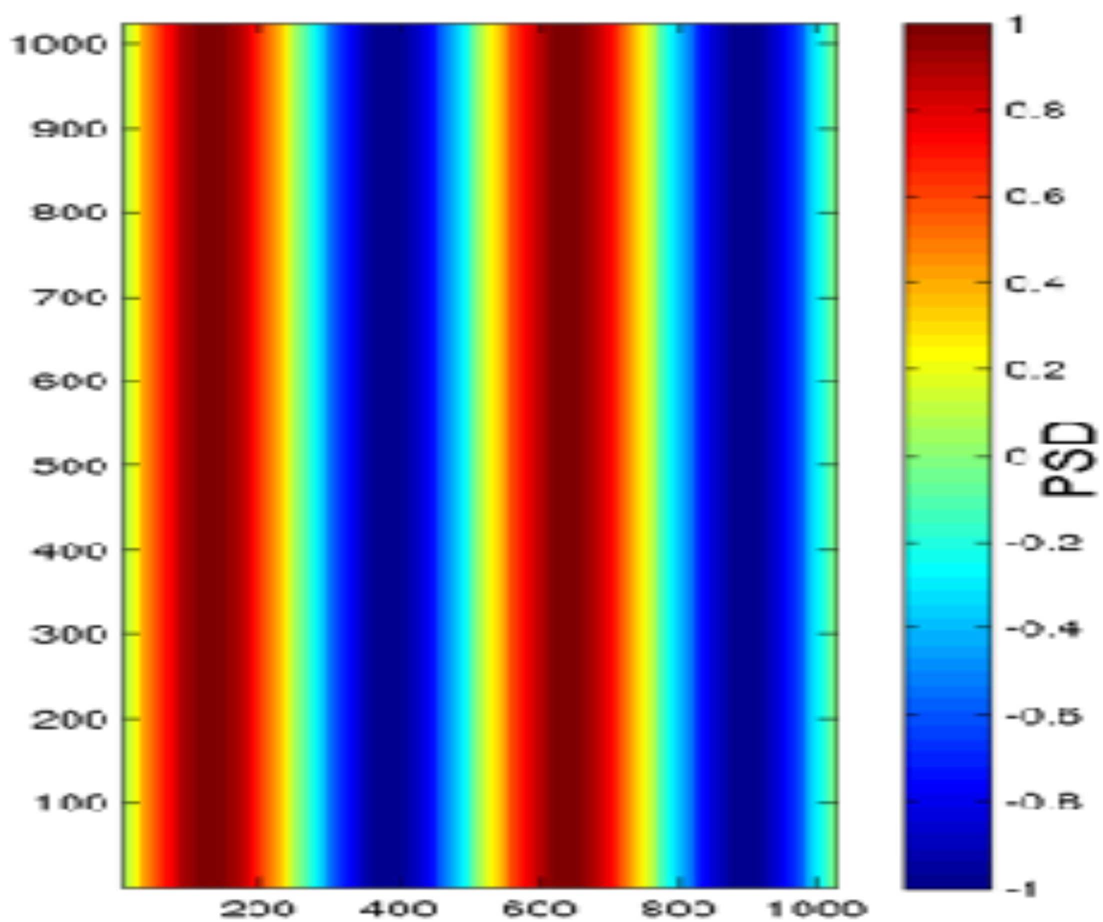


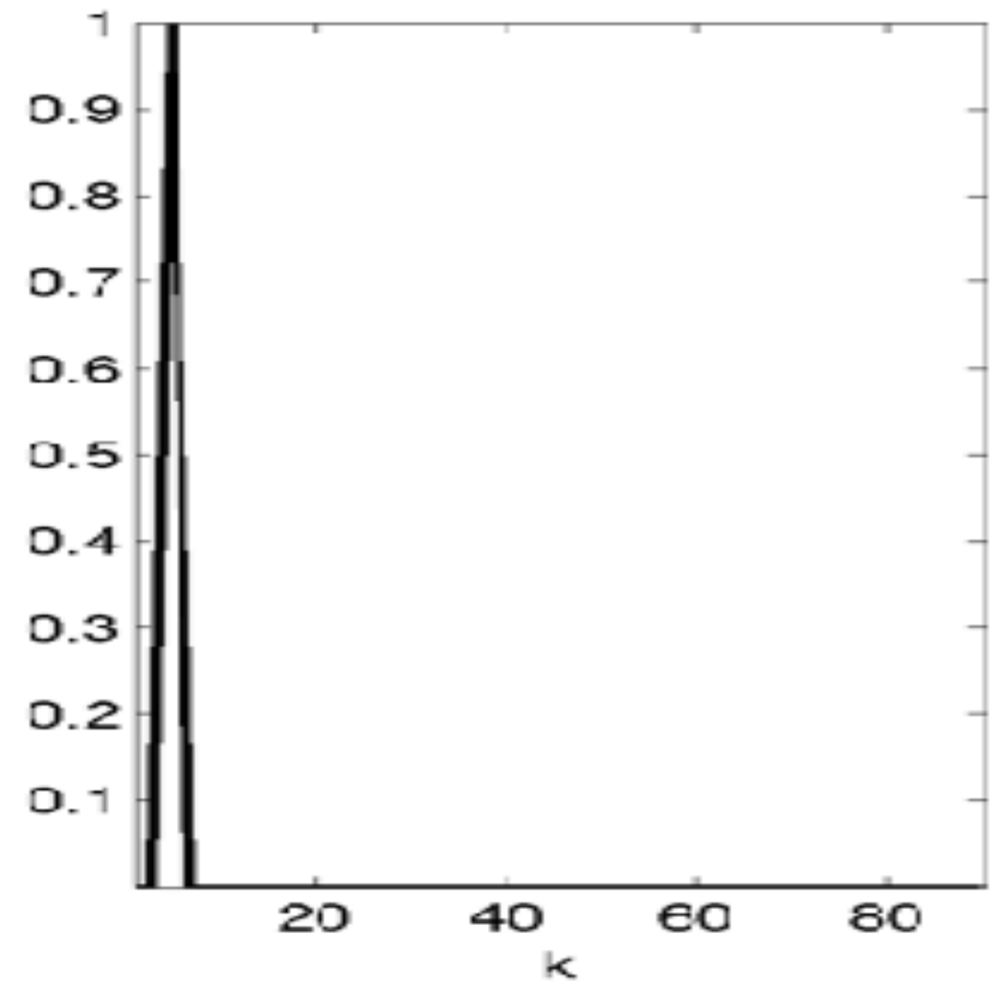
Image Credit: Planck

Understanding the Power Spectrum of the CMB

If the sky looks like this



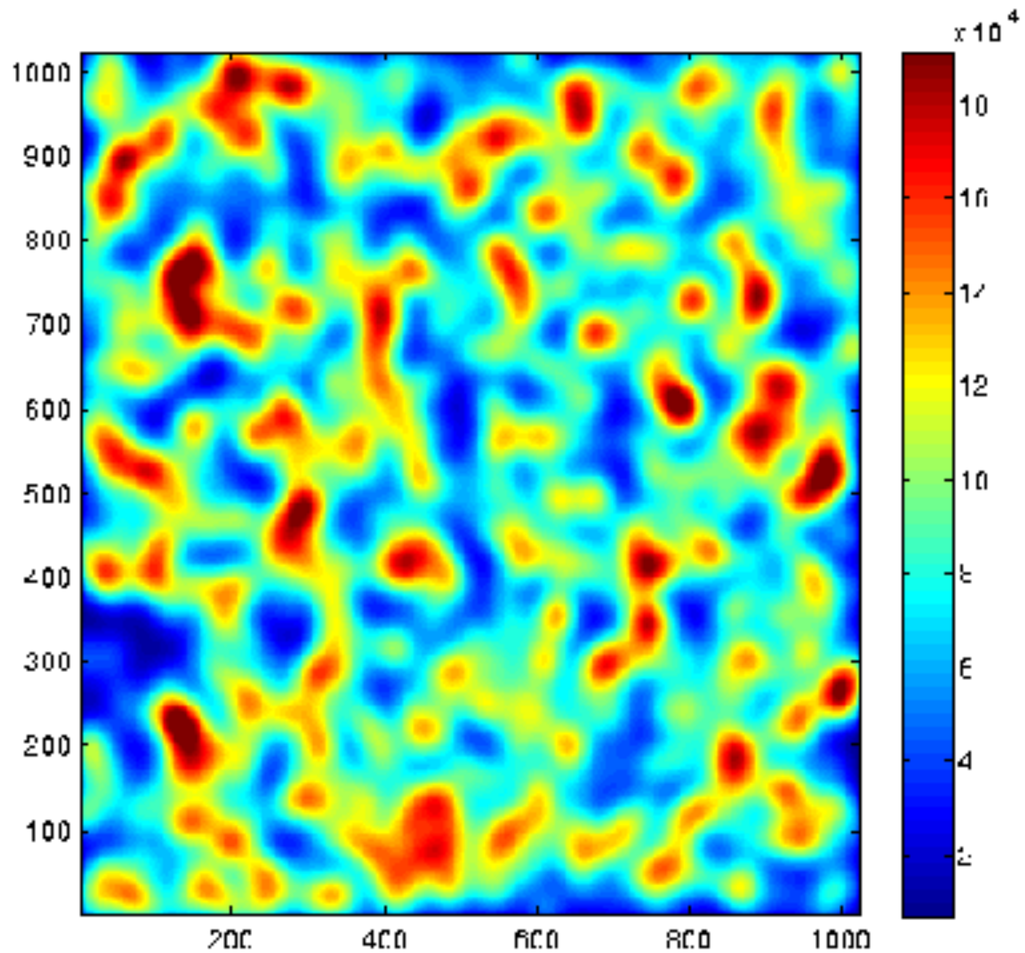
The power spectrum looks like this:



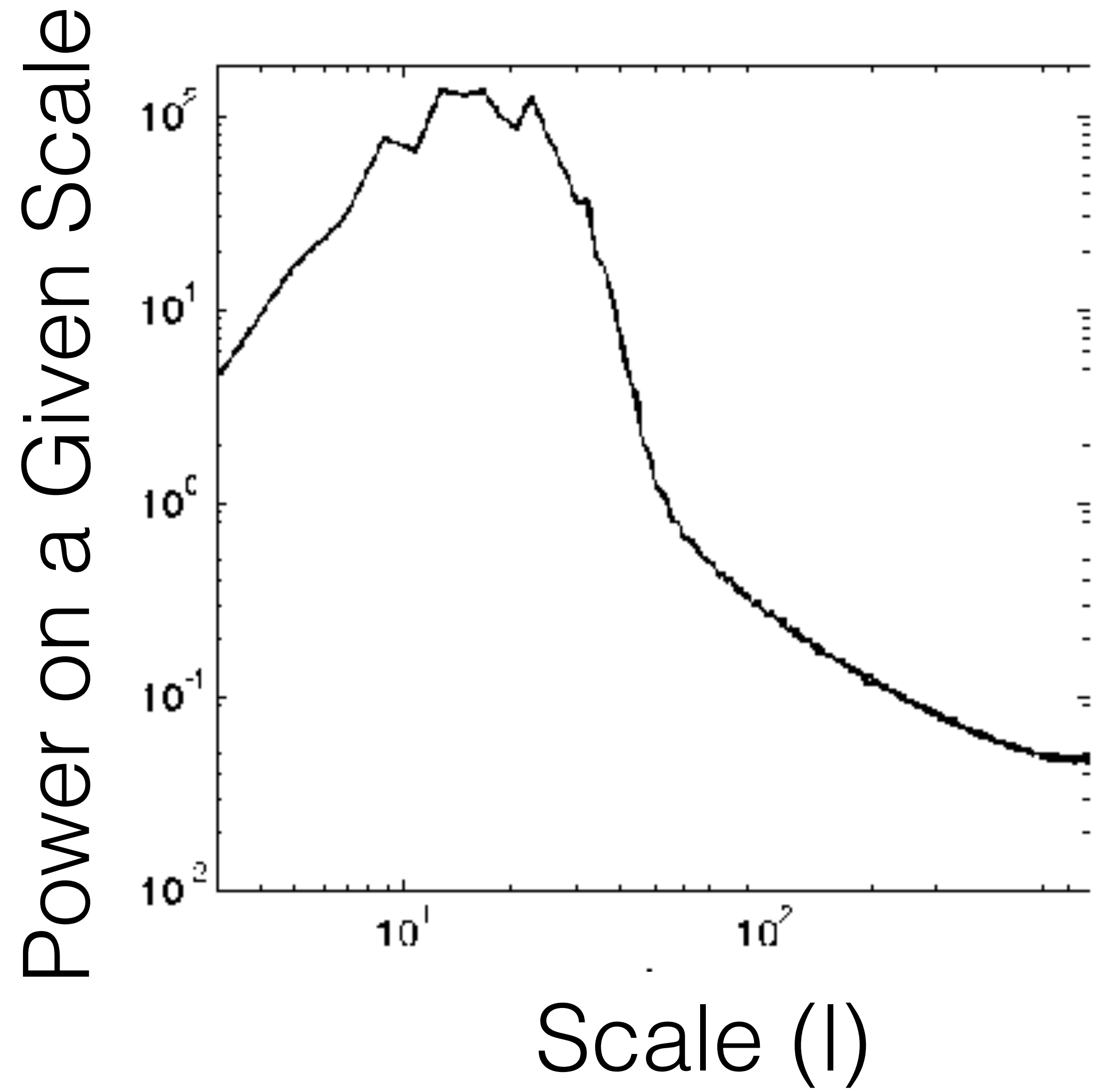
Power spectrum slides courtesy of Phil Korngut

Understanding the Power Spectrum of the CMB

If the sky looks like this



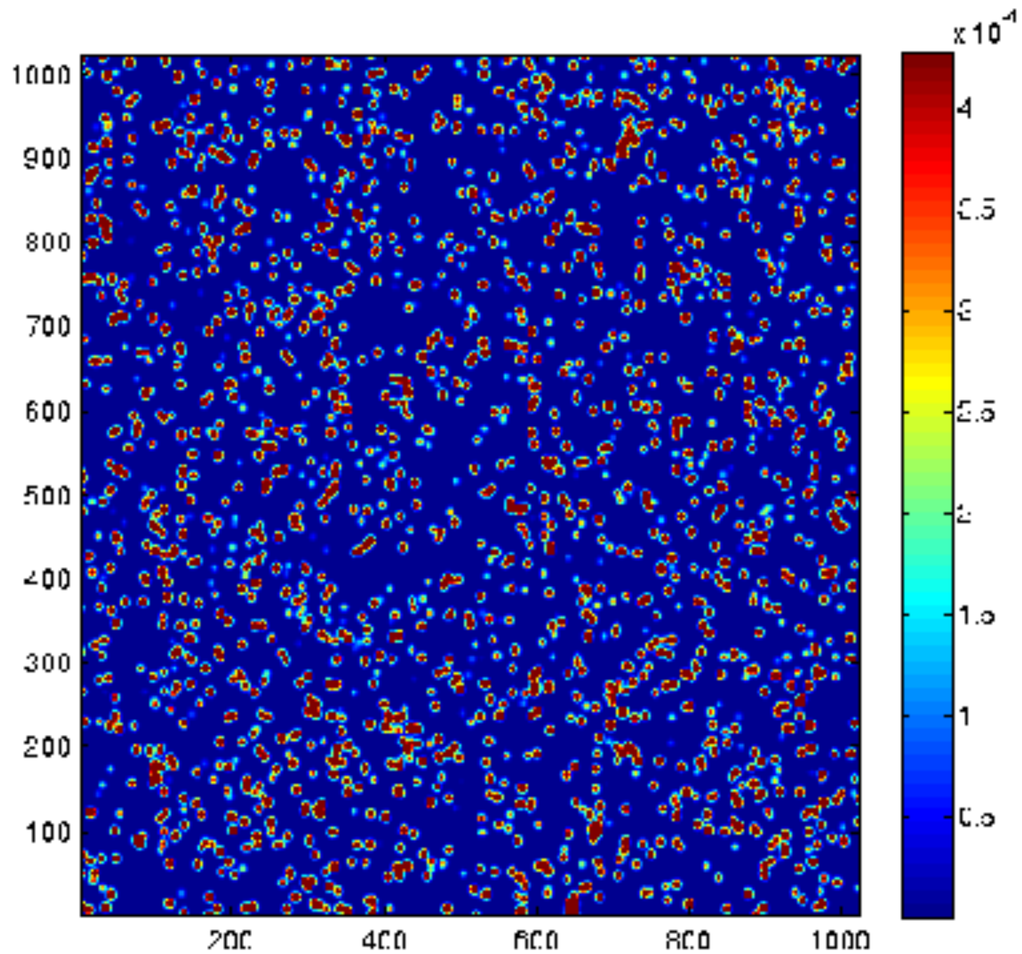
The power spectrum looks like this:



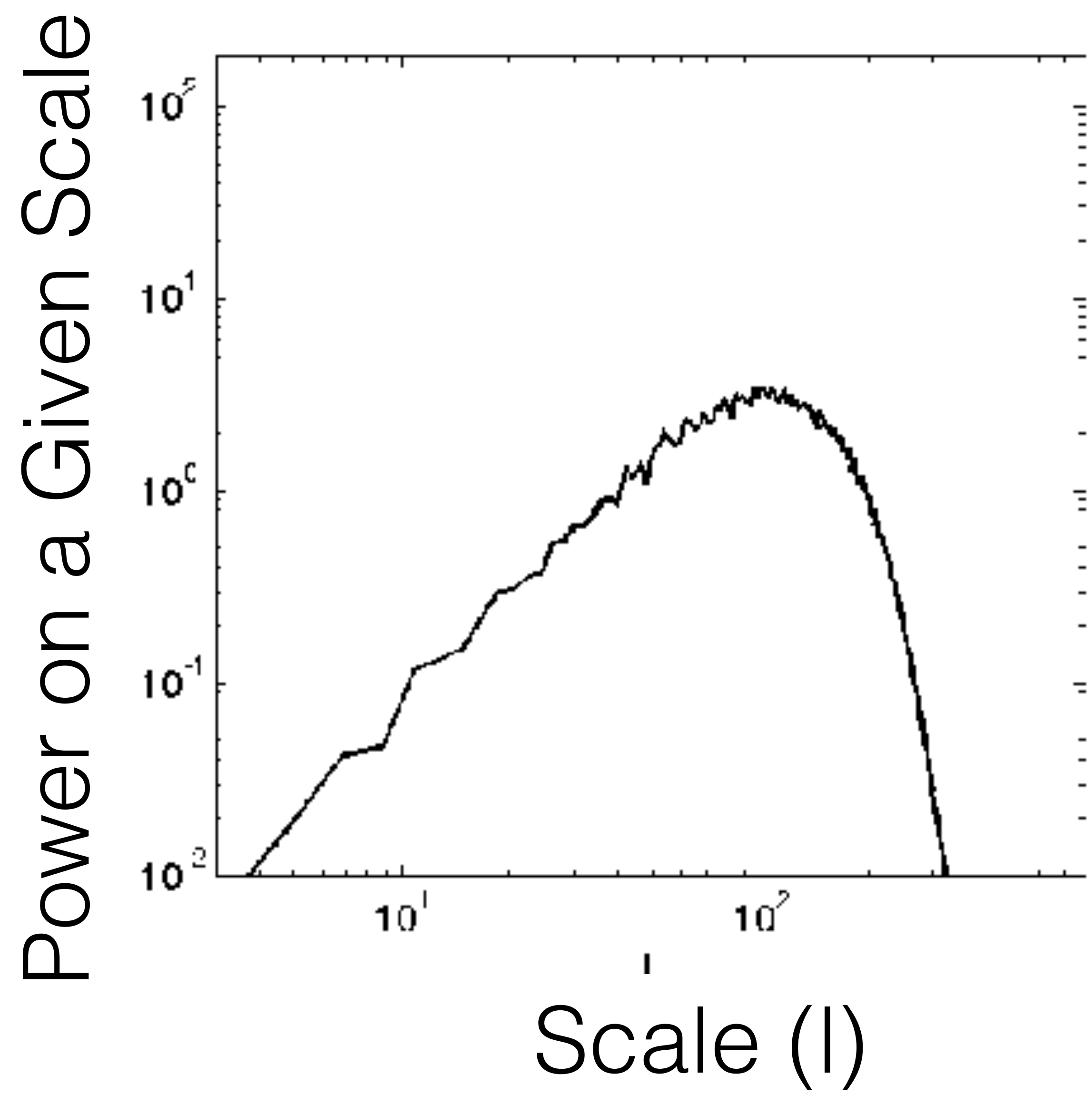
Power spectrum slides courtesy of Phil Korngut

Understanding the Power Spectrum of the CMB

If the sky looks like this



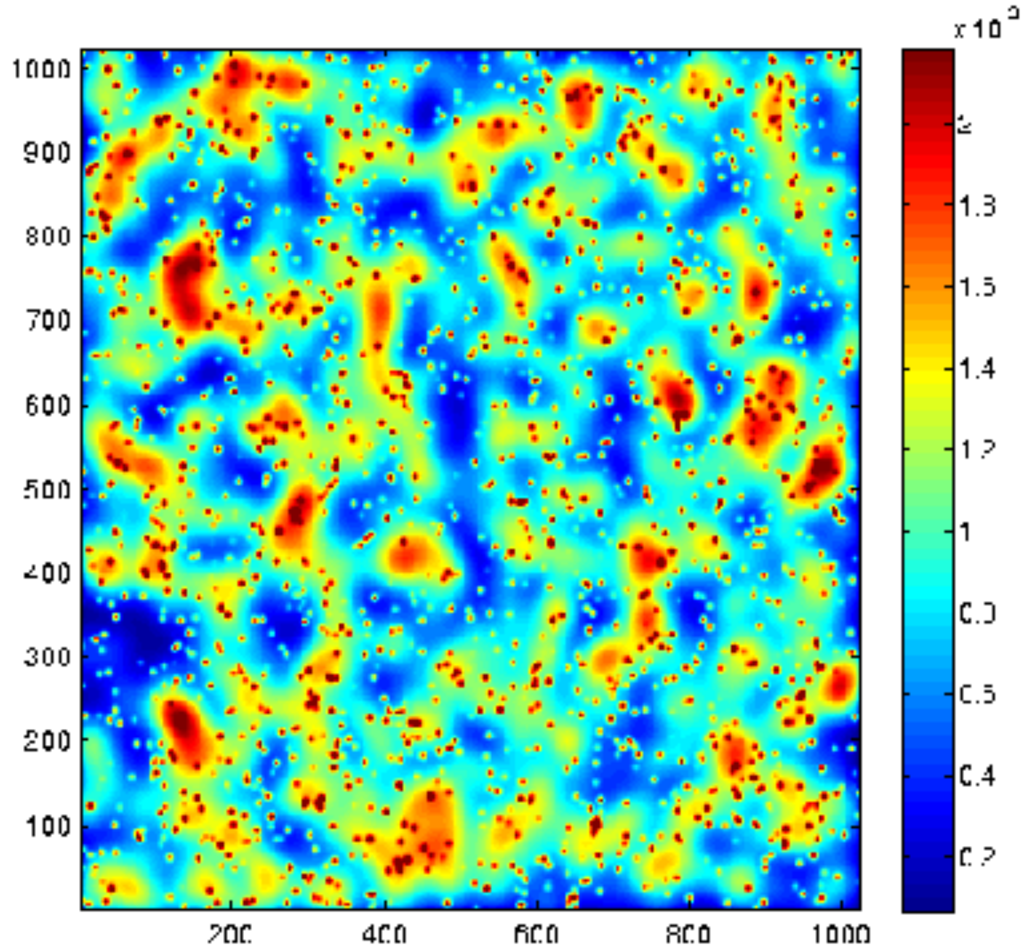
The power spectrum looks like this:



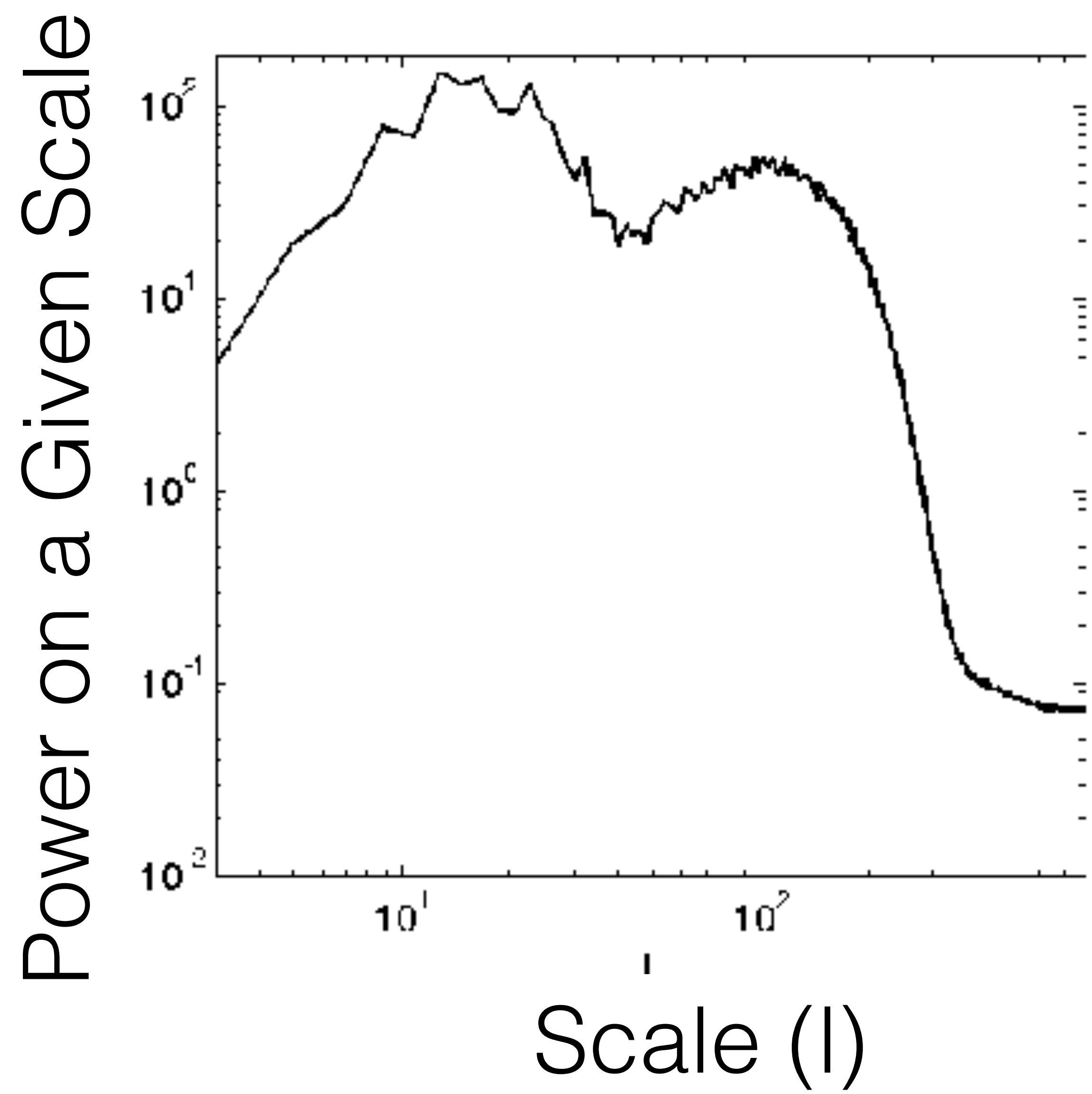
Power spectrum slides courtesy of Phil Korngut

Understanding the Power Spectrum of the CMB

If the sky looks like this



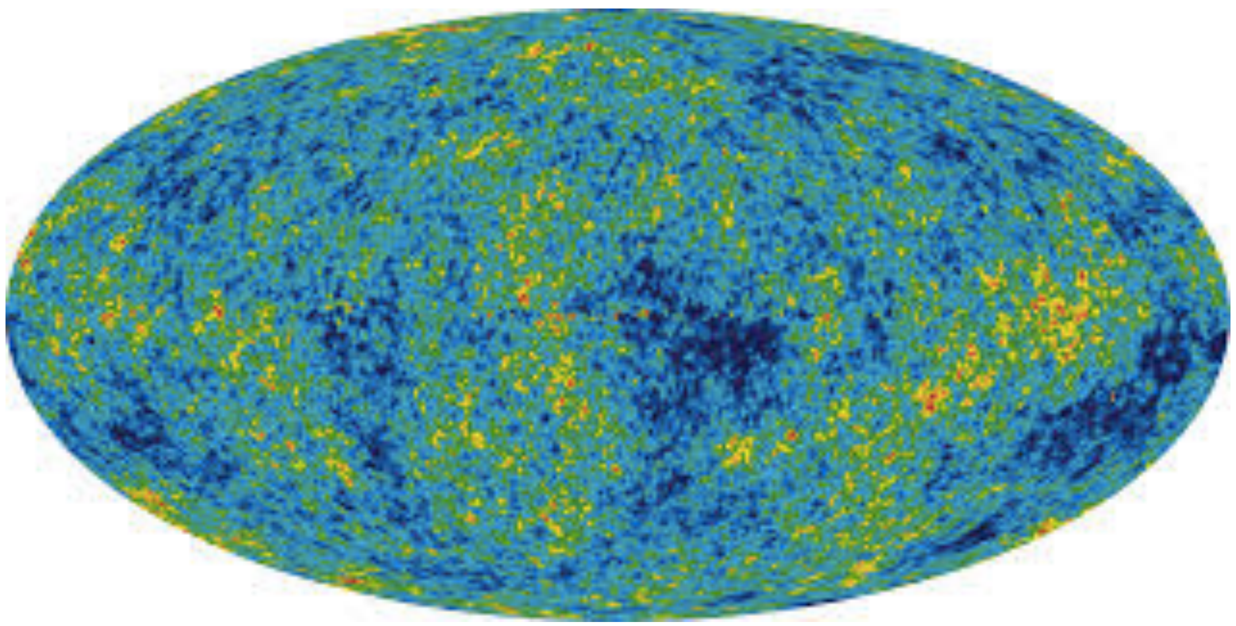
The power spectrum looks like this:

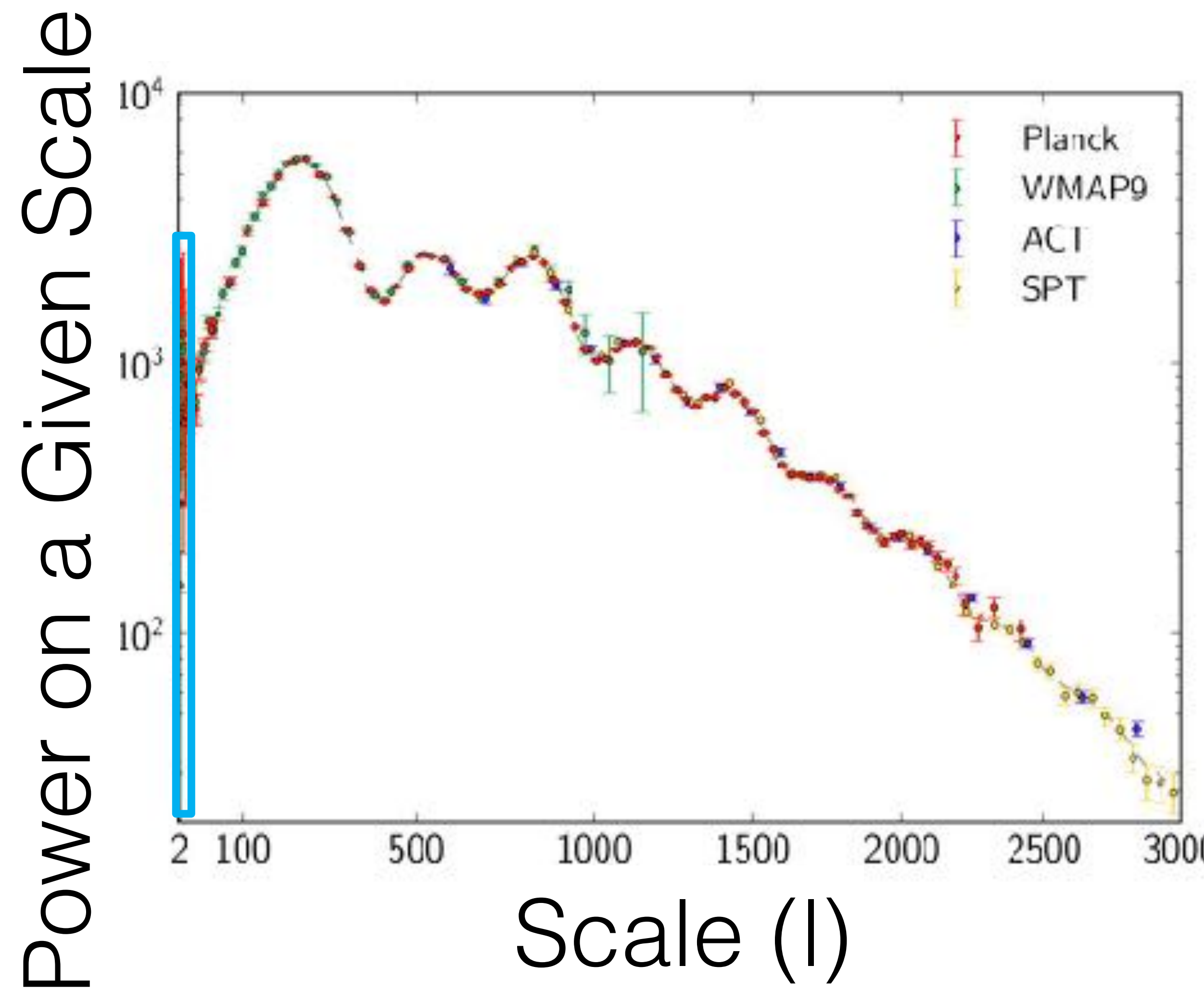


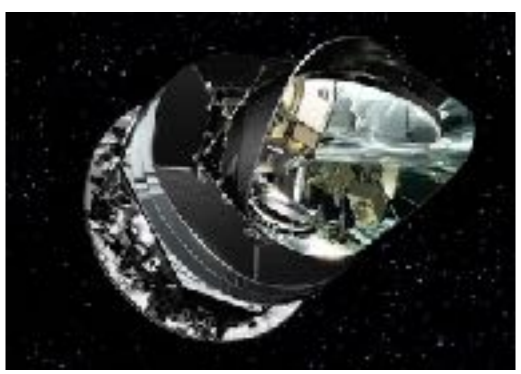
Power spectrum slides courtesy of Phil Korngut

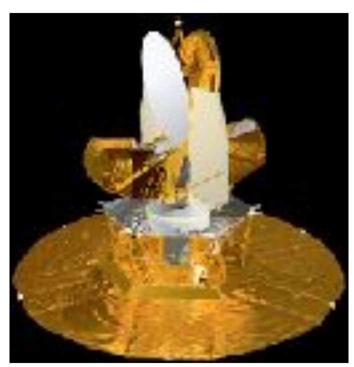
The sky looks like this

And the power spectrum looks like this!









Planck Collaboration Cosmological parameters[12]

	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ±0.000 14
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ±0.0010
	Age of the universe	t_0	13.799 ±0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude, k_0 = 0.002 Mpc^{-1}	Δ_R^2	2.441 $^{+0.088}_{-0.092}$ × 10^{-9}[15]
	Reionization optical depth	τ	0.066 ±0.012

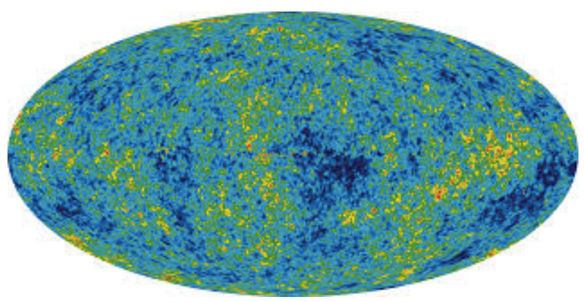
Credit: Planck, wikipedia

What do you need for a successful CMB instrument?

ability to detect the polarization of the CMB signal

CMB Polarization

Thomson scattering generates linear polarization.



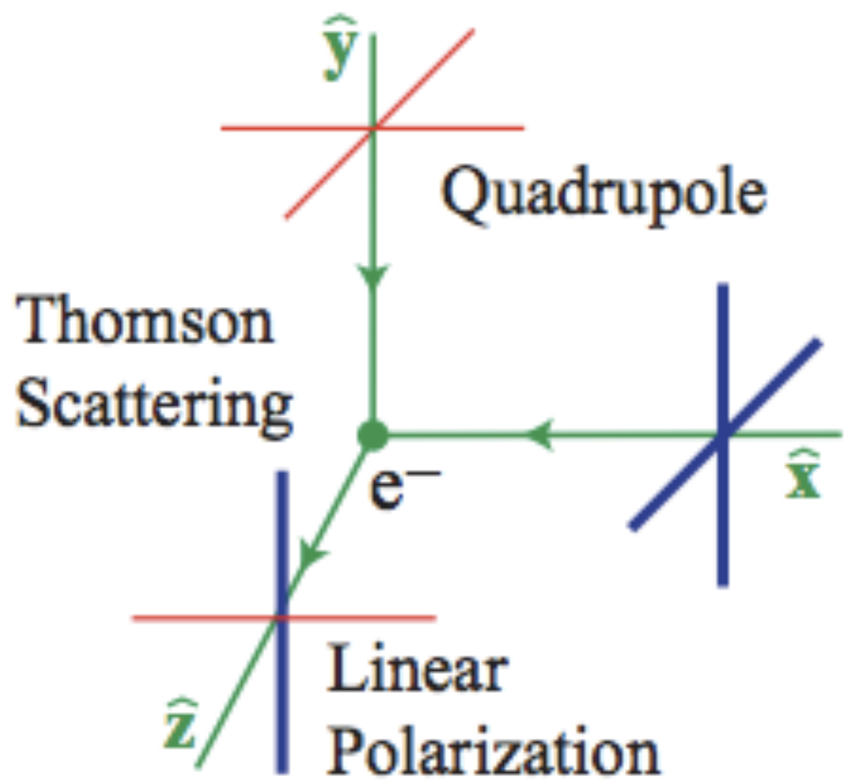


Image Credit: Hu and Dodelson, 2001

The CMB polarization can be decomposed in to E-modes and B-modes

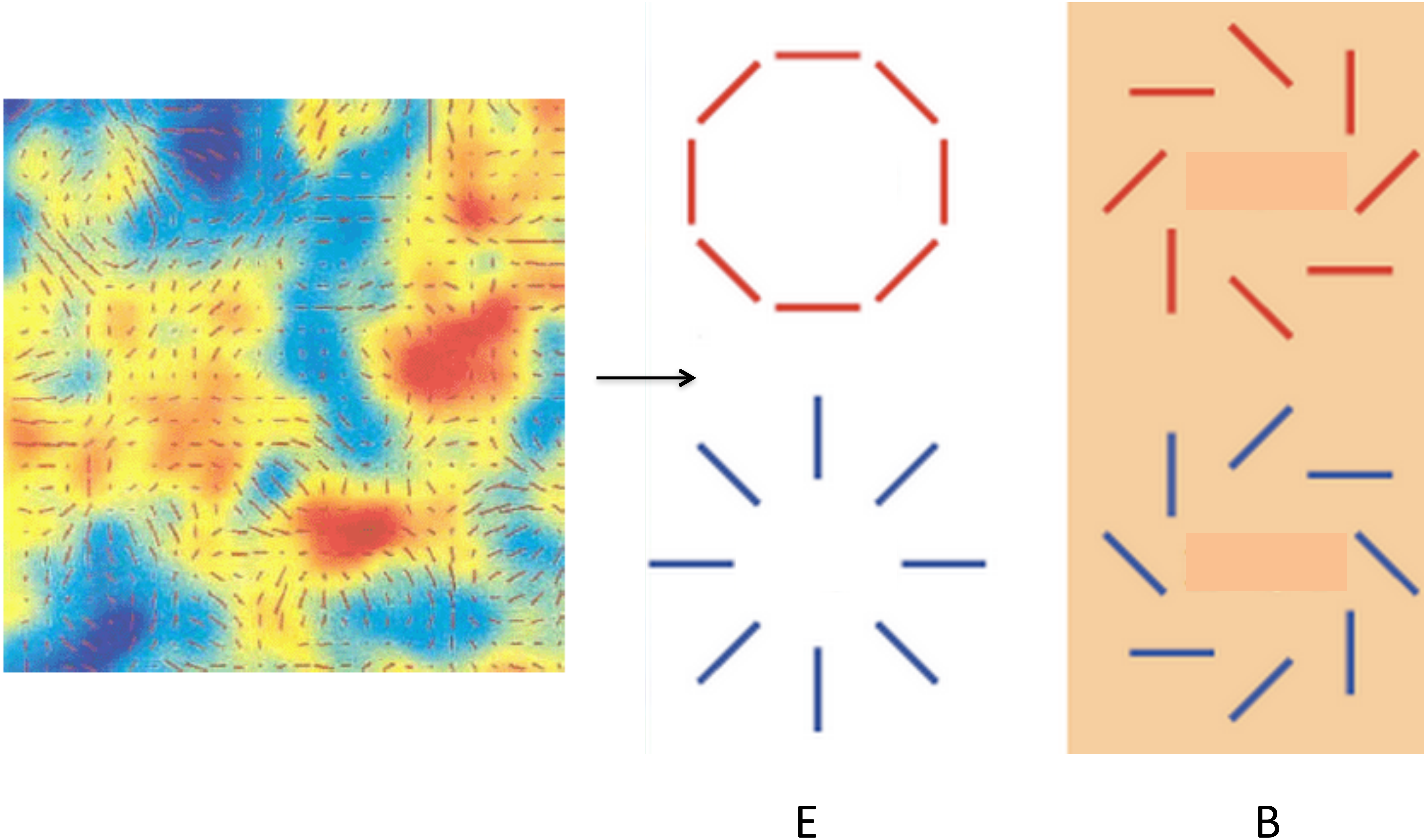
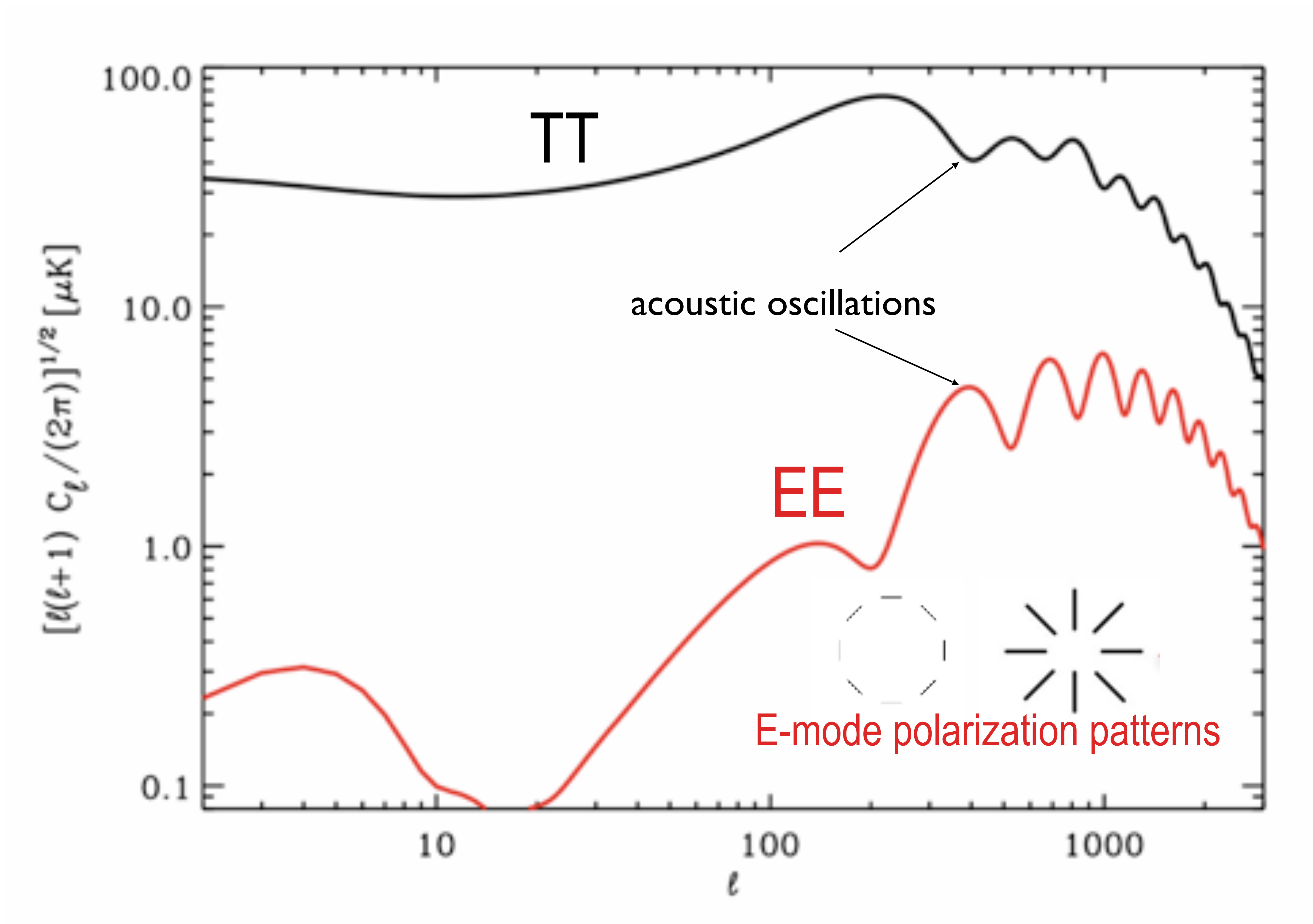
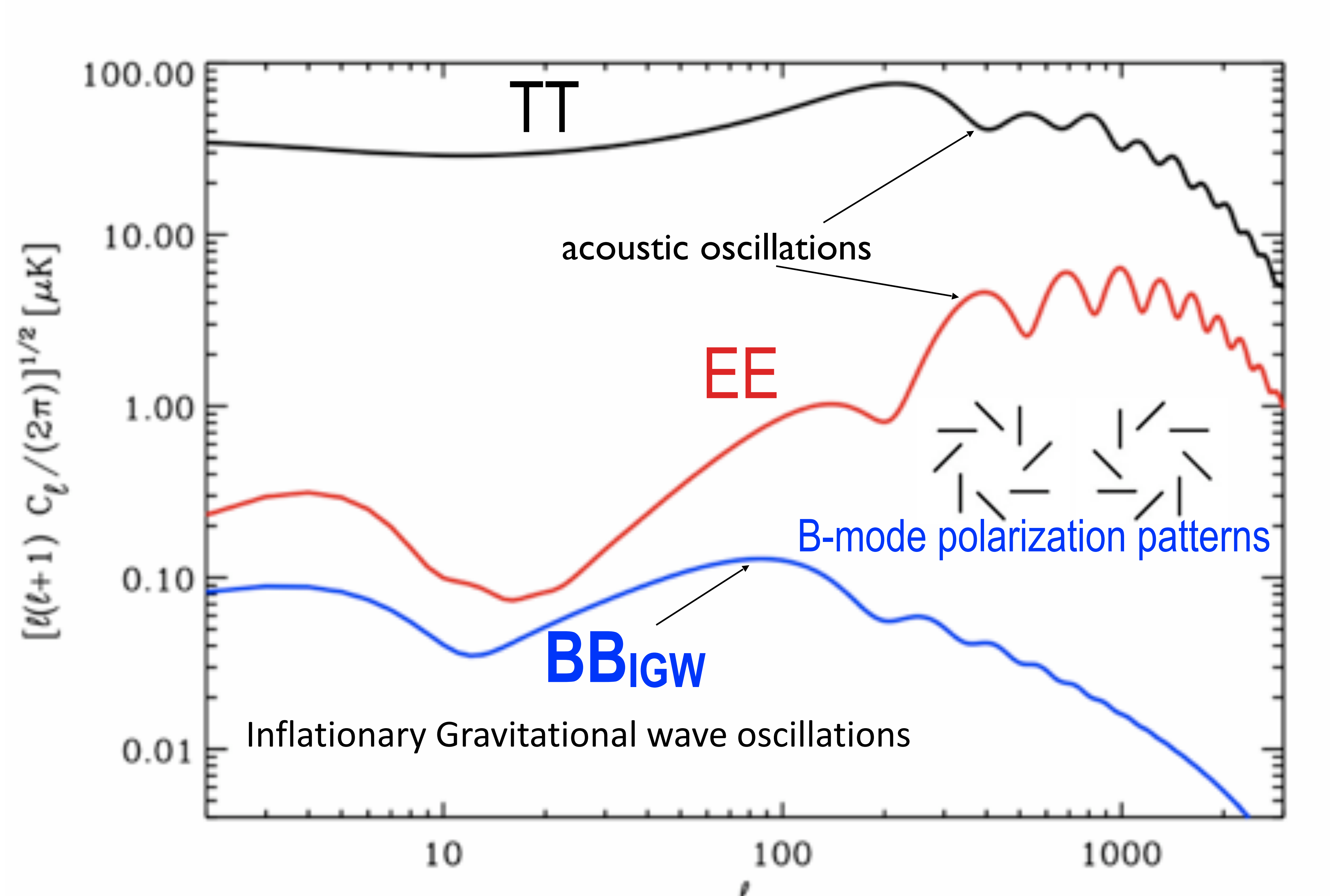


Image Credit: Seljak and Zaldarriaga

The TT and EE spectra probe acoustic oscillations in the early Universe



The BB spectrum probes gravitational waves from inflation!



BB auto- and cross-frequency spectra between BICEP2/Keck Array (150 GHz) and Planck (217 and 353 GHz), BKP find a 95 % upper limit of $r < 0.12$. (A Joint Analysis of BICEP2/Keck Array and Planck Data)

Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO's First Observing Run

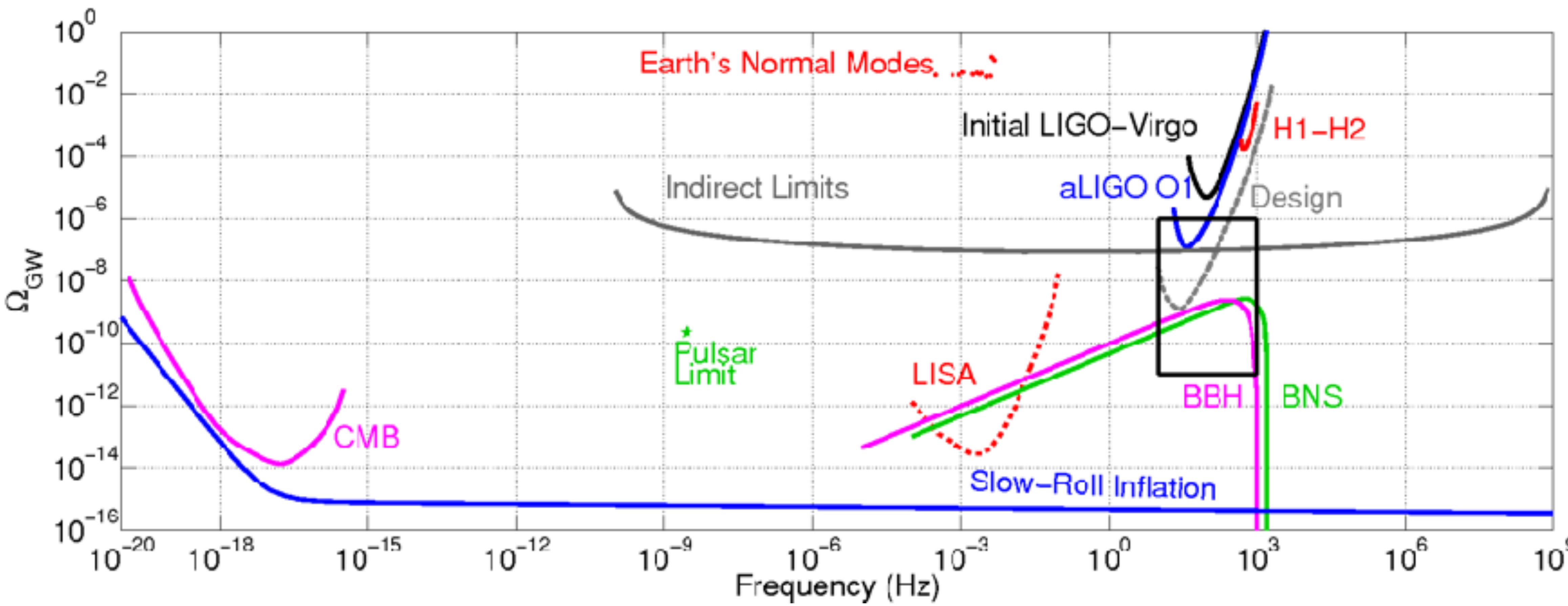
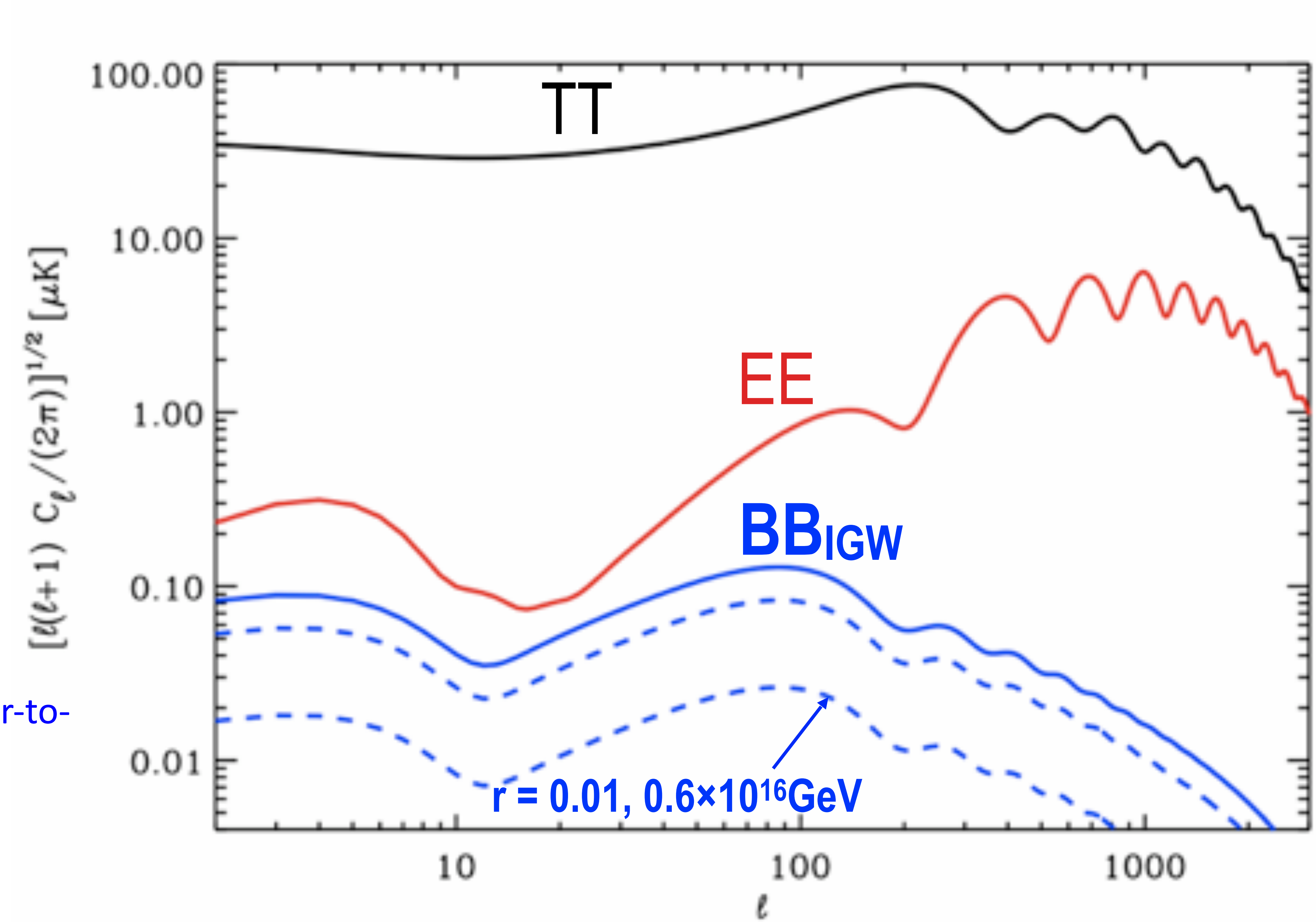


Figure Credit: LIGO Scientific and Virgo Collaborations, 2017

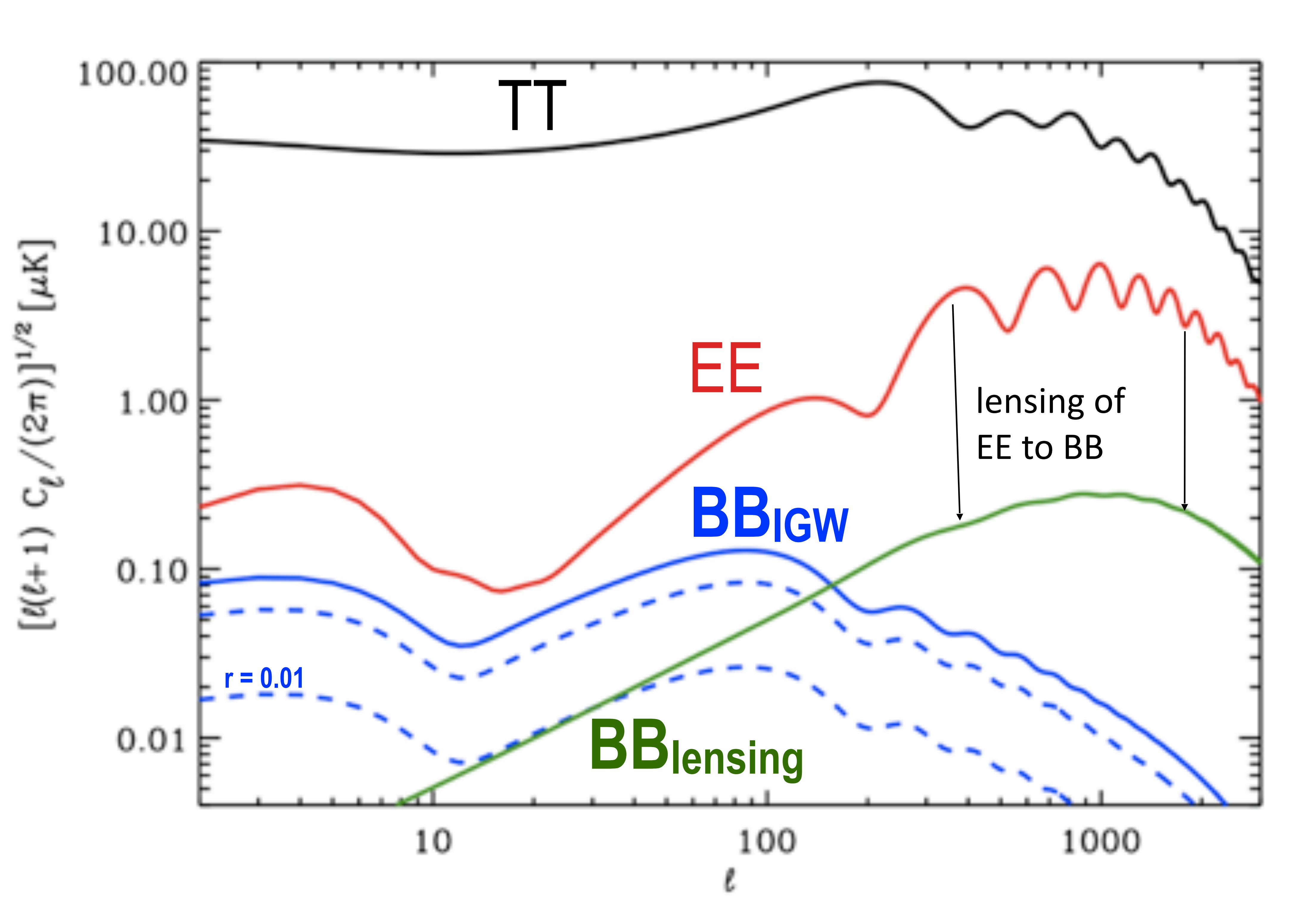
The amplitude of the gravity wave signal depends on the energy scale of inflation



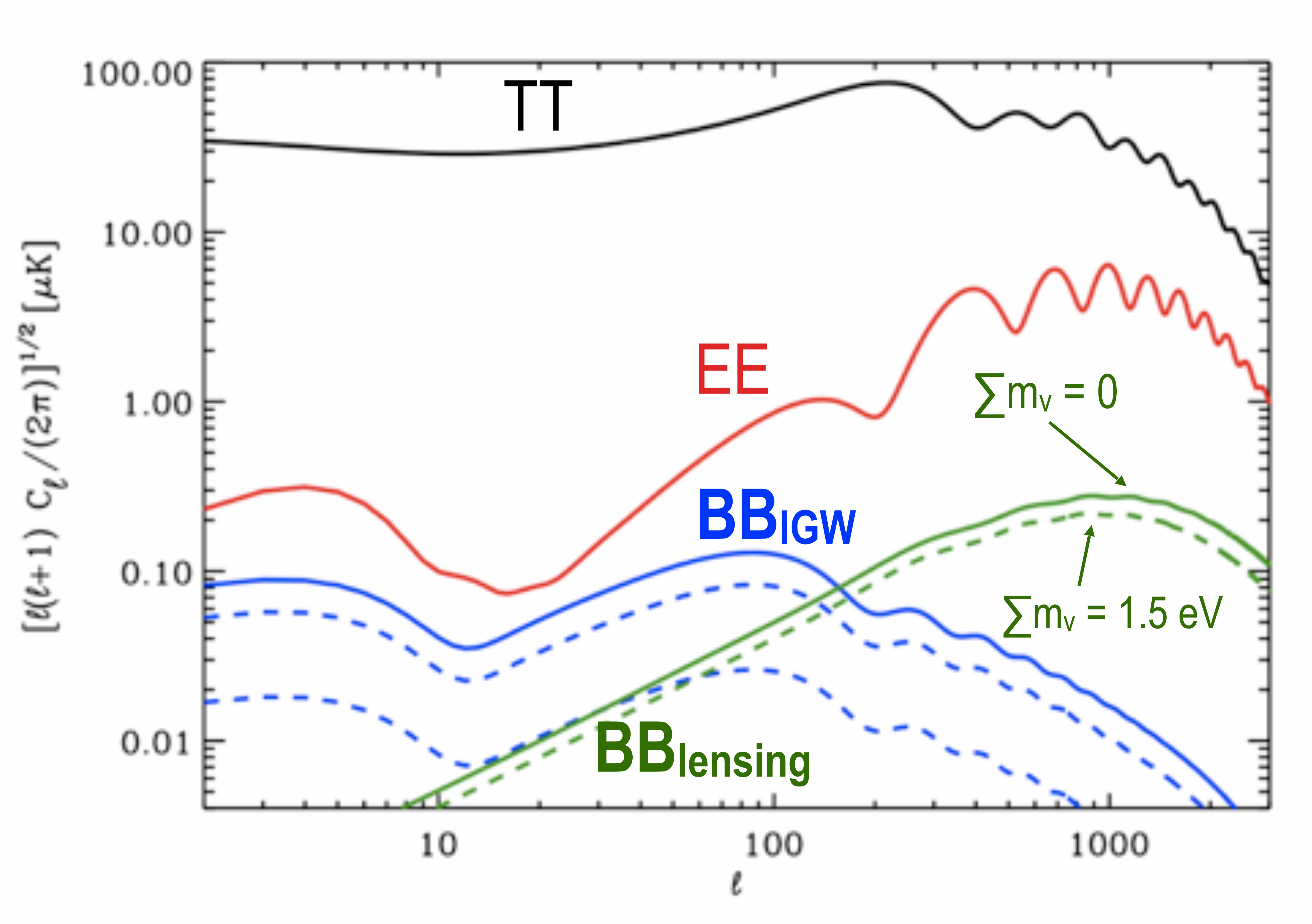
r == Tensor-to-scalar ratio

BB auto- and cross-frequency spectra between BICEP2/Keck Array (150 GHz) and Planck (217 and 353 GHz), BKP find a 95 % upper limit of r < 0.12. (A Joint Analysis of BICEP2/Keck Array and Planck Data)

Gravitational lensing of the CMB creates a BB signal at small angular scales



Neutrino mass affects lensing – CMB can measure $\sum m_\nu$



CMB Polarization B-Mode Lensing Power Spectrum and Neutrino Mass

- direct implication of massive neutrinos is a non-zero hot dark matter (HDM)
- this suppresses the power spectrum due to neutrinos free streaming below the matter-radiation equality scale

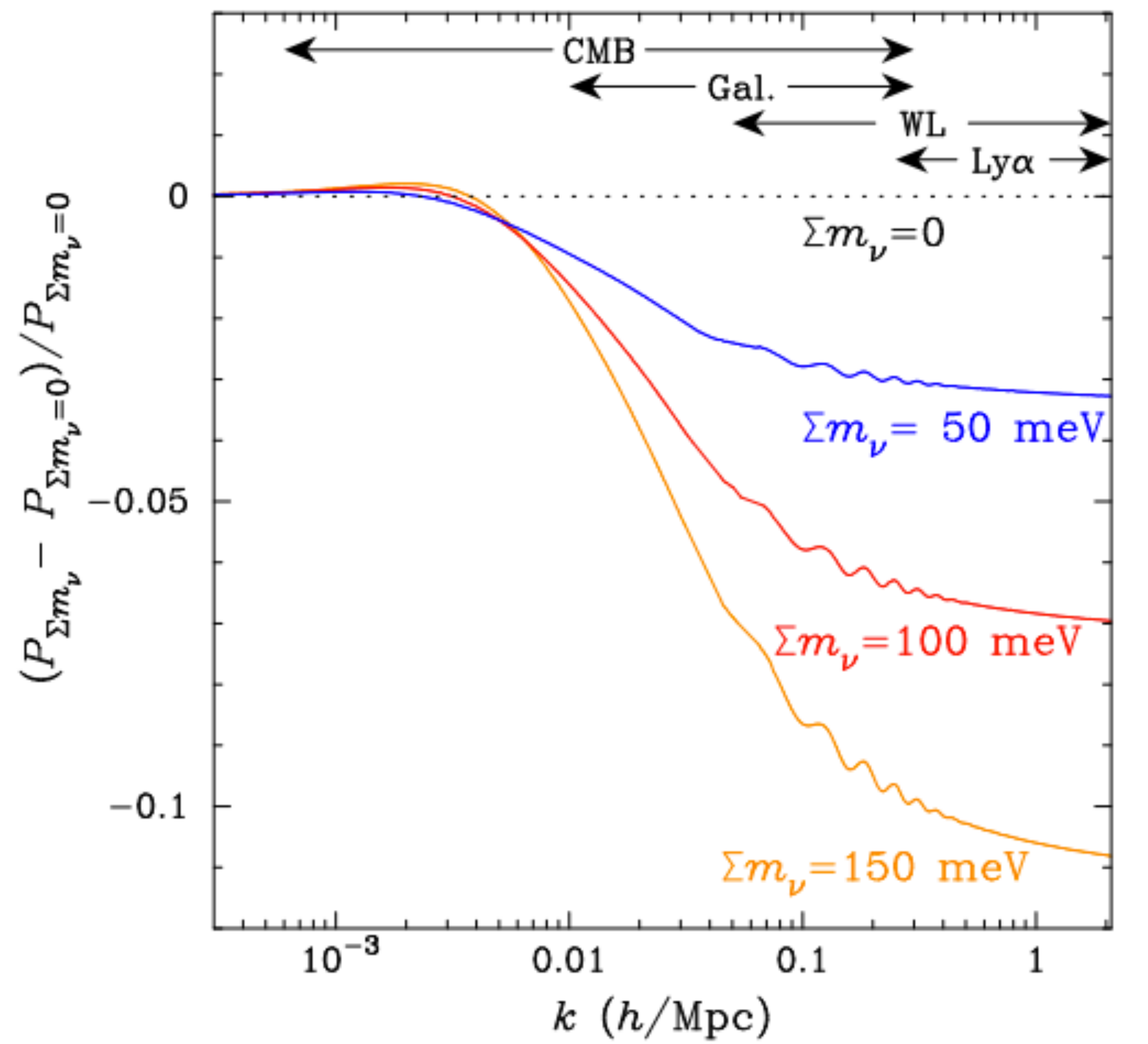
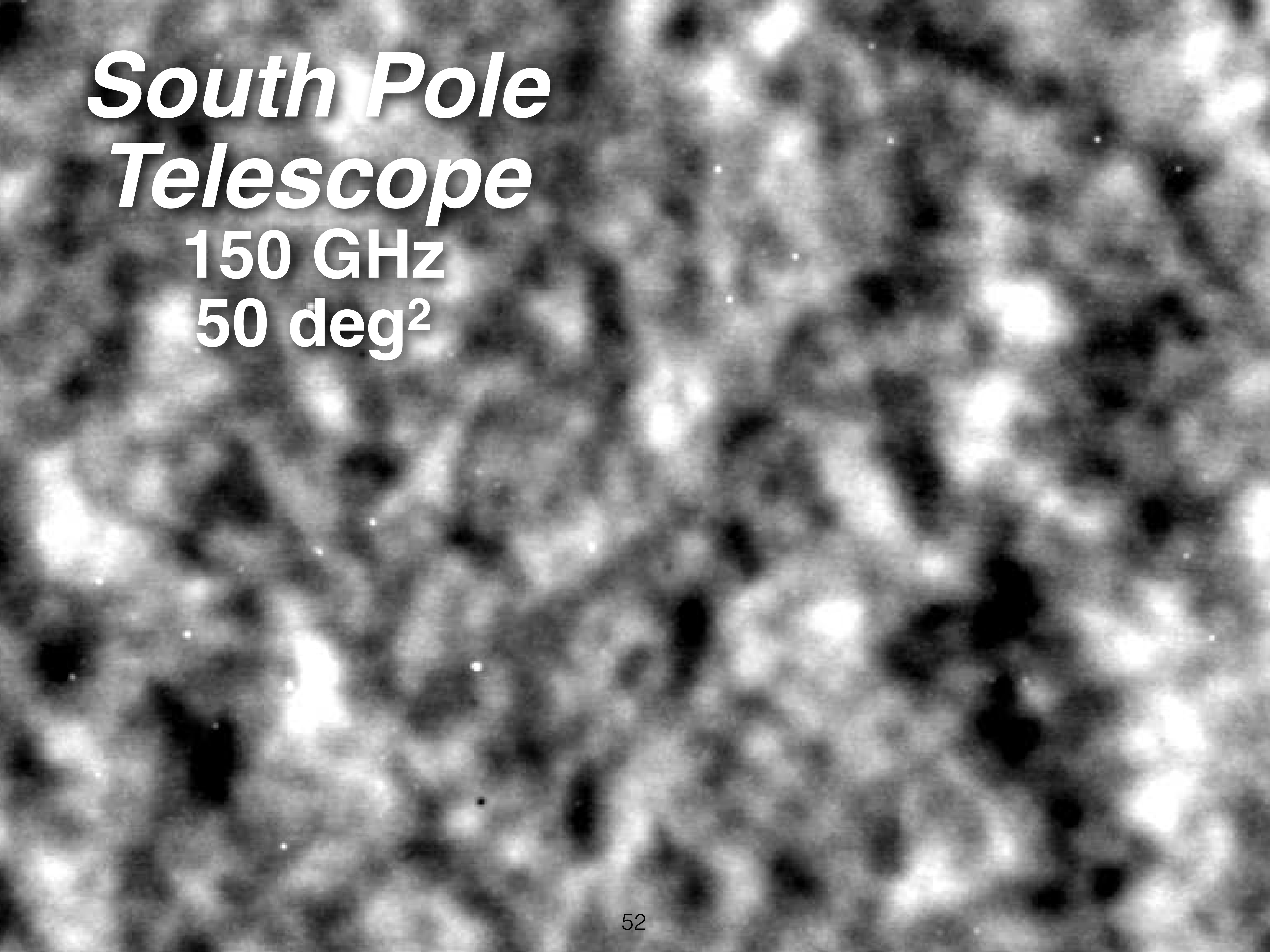


Image Credit: Abazajian et al, 2014

How do we make this measurement in practice?


South Pole
Telescope
150 GHz
50 deg²

Time Ordered Data to Maps

Outline of a CMB map making pipeline

1. Read in raw data

2. Interpolate over short pointing glitches and timestream dropouts

3. cut on elnod response, both pixels partners being live, pointing and flagged bolometers (squid off, zero bias, etc).

4. Process data: relative calibration, polynomial subtraction

5. Time stream rms cut (removes very noisy timestreams), other cuts (glitchy timestreams.

6. Make left and right going scan maps

7. Make sum and difference maps for each observation

6. Make cuts of noisy maps

8. Coadd maps in to bundles of ~20 maps

Raw Data

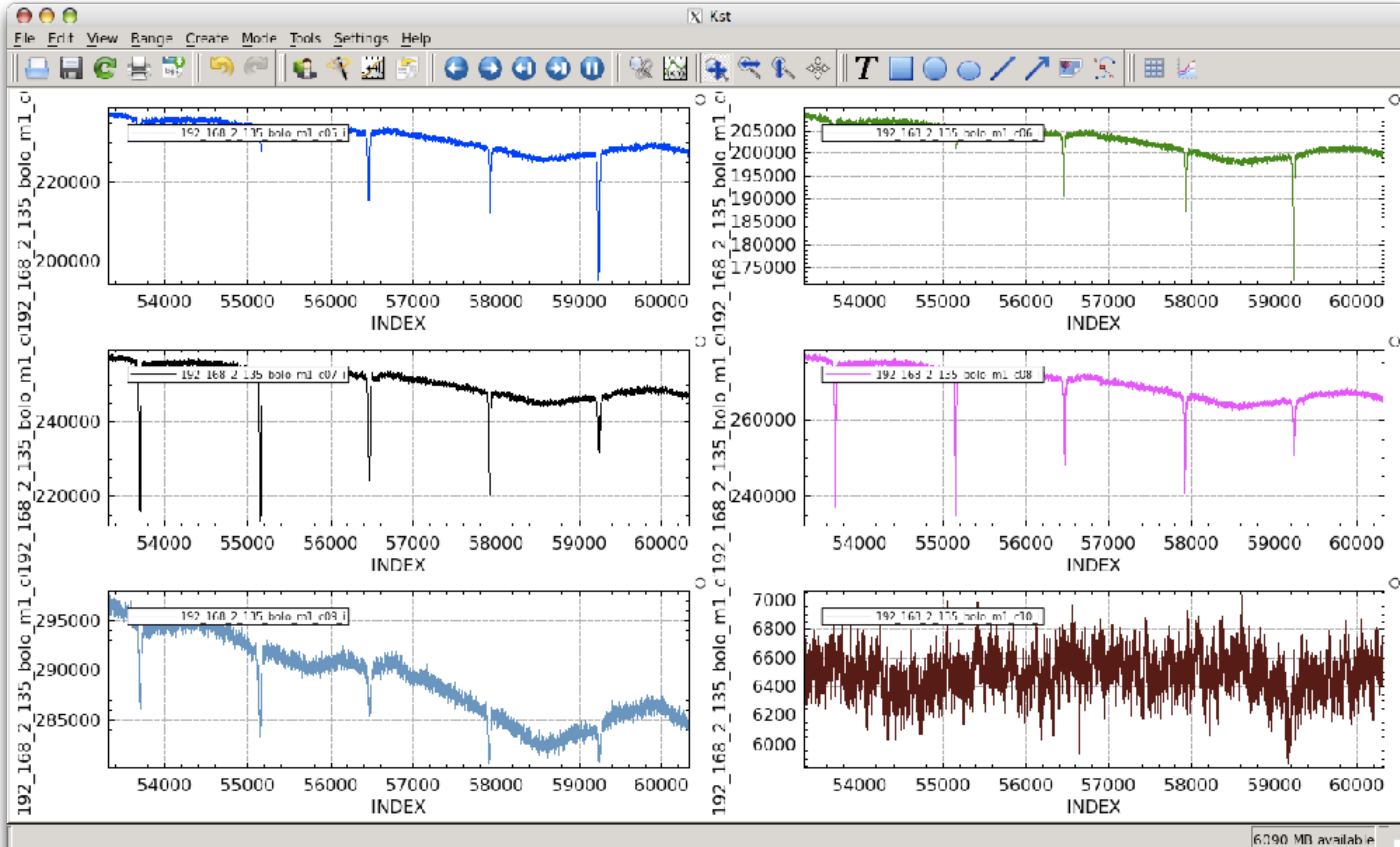
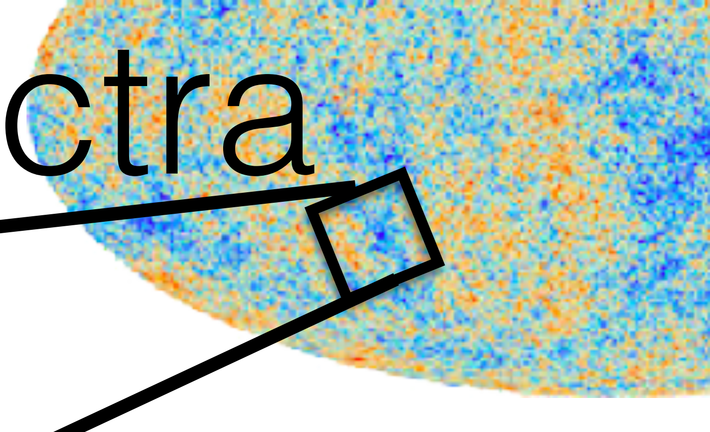
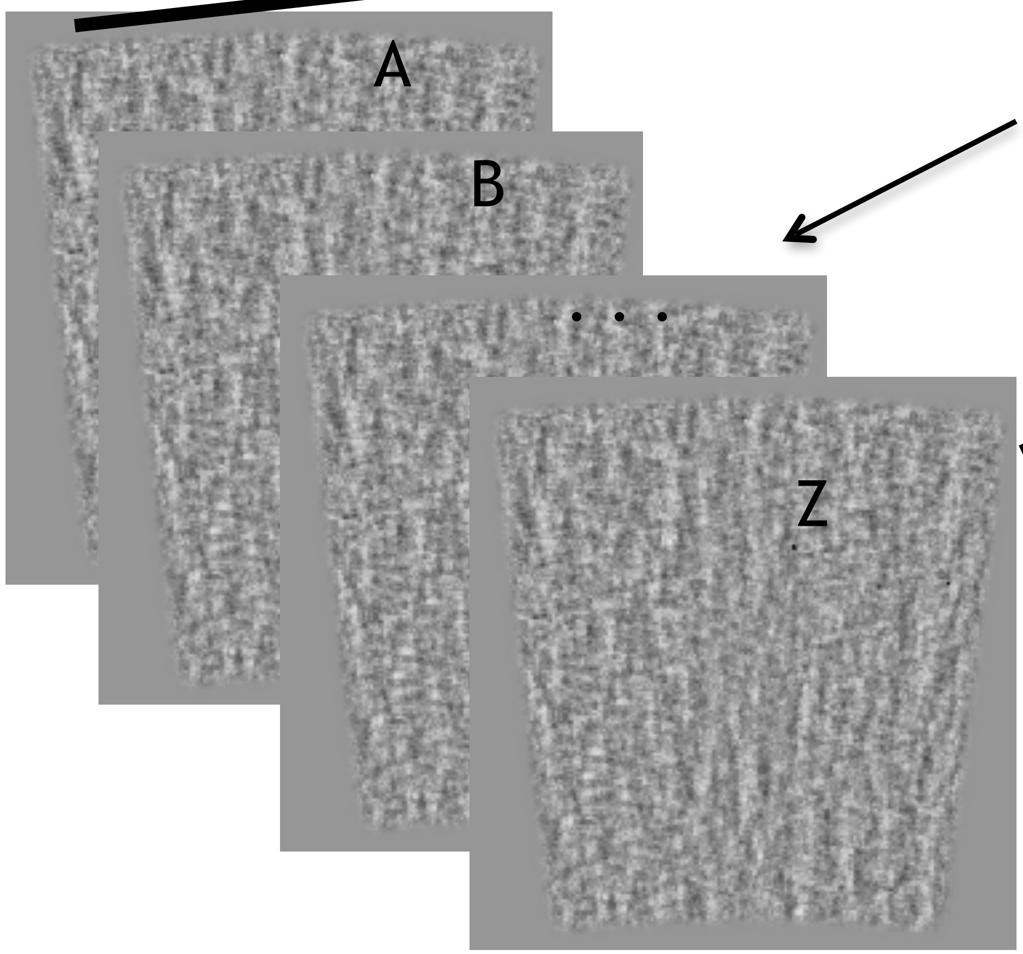


Image Credit: https://pole.uchicago.edu/blog/

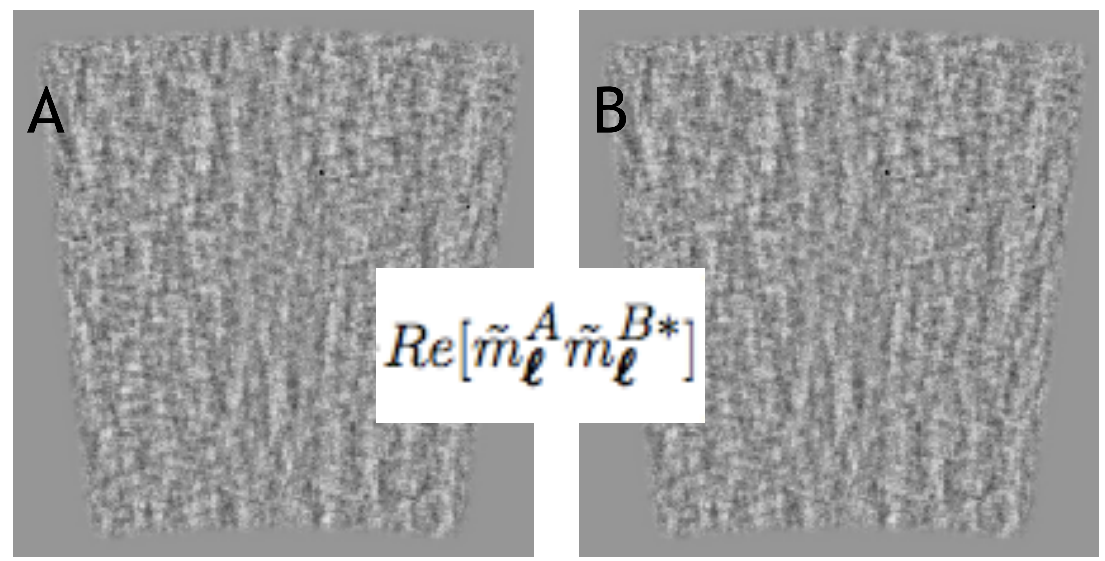
Maps to Power Spectra



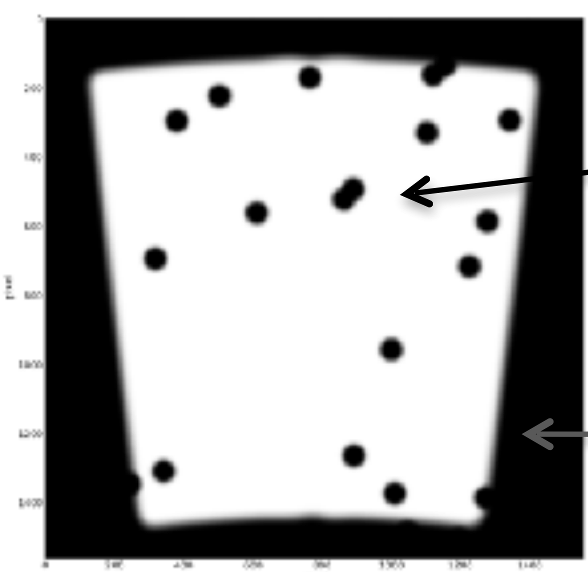


Set of South Pole Telescope Polarization maps

Cross-correlate pairs of maps



$Re[\tilde{m}_{\boldsymbol{\ell}}^{A}\tilde{m}_{\boldsymbol{\ell}}^{B*}]$



Mask bright point sources

Apodize the map edges

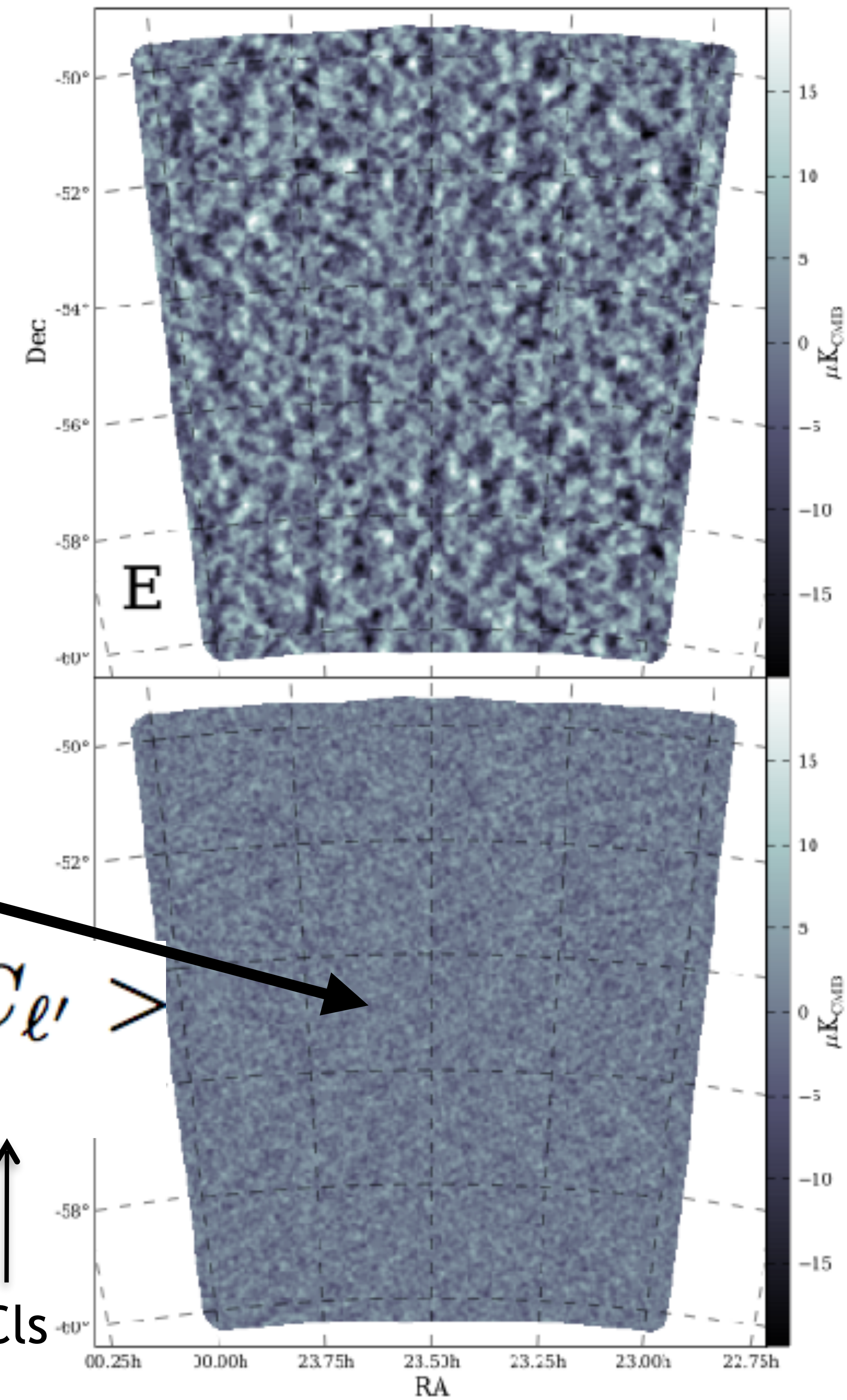
$$\widehat{D}_b^{AB} \equiv \left\langle \frac{\ell(\ell+1)}{2\pi} Re[\tilde{m}_{\boldsymbol{\ell}}^{A}\tilde{m}_{\boldsymbol{\ell}}^{B*}] \right\rangle_{\ell \in b}$$

Described in Lueker et. al. 2009 arXiv:0912.4317

Maps to Power Spectra

Outline of a CMB power spectrum pipeline

1. Cross-correlate pairs of maps
2. Correct resulting spectra for telescope beam
3. Correct for filtering effects and mode mixing from the cut sky
4. Calculate errors
5. Check for Systematic Errors



$$< \tilde{C}_\ell^{ii} >= \sum_{\ell'} M_{\ell\ell'}[W] F_{\ell'} B_{\ell'}^2 < C_{\ell'} >$$

Transfer Function

Measured Cls

Mode Mixing

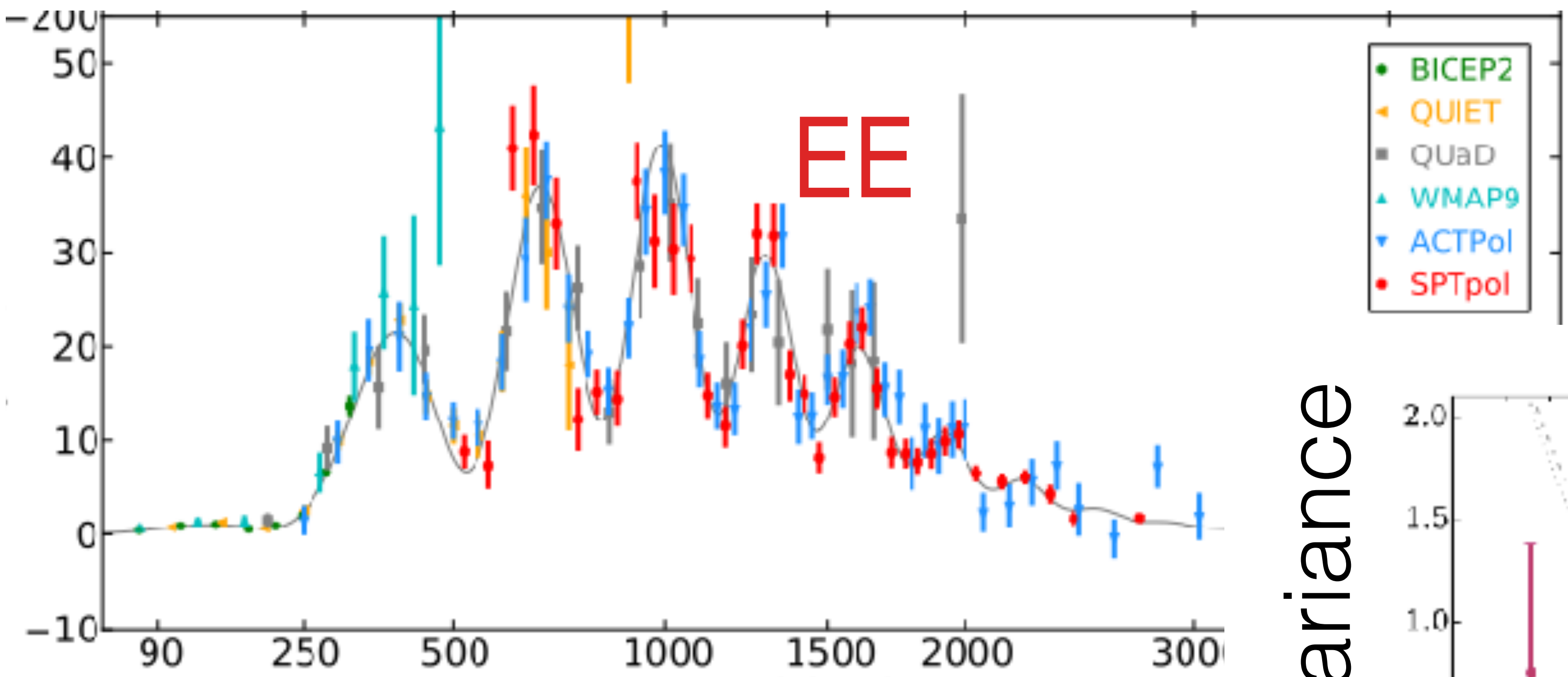
Beam

True Cls

The Angular Power Spectrum of the Cosmic Microwave Background

Crites et al. 2015

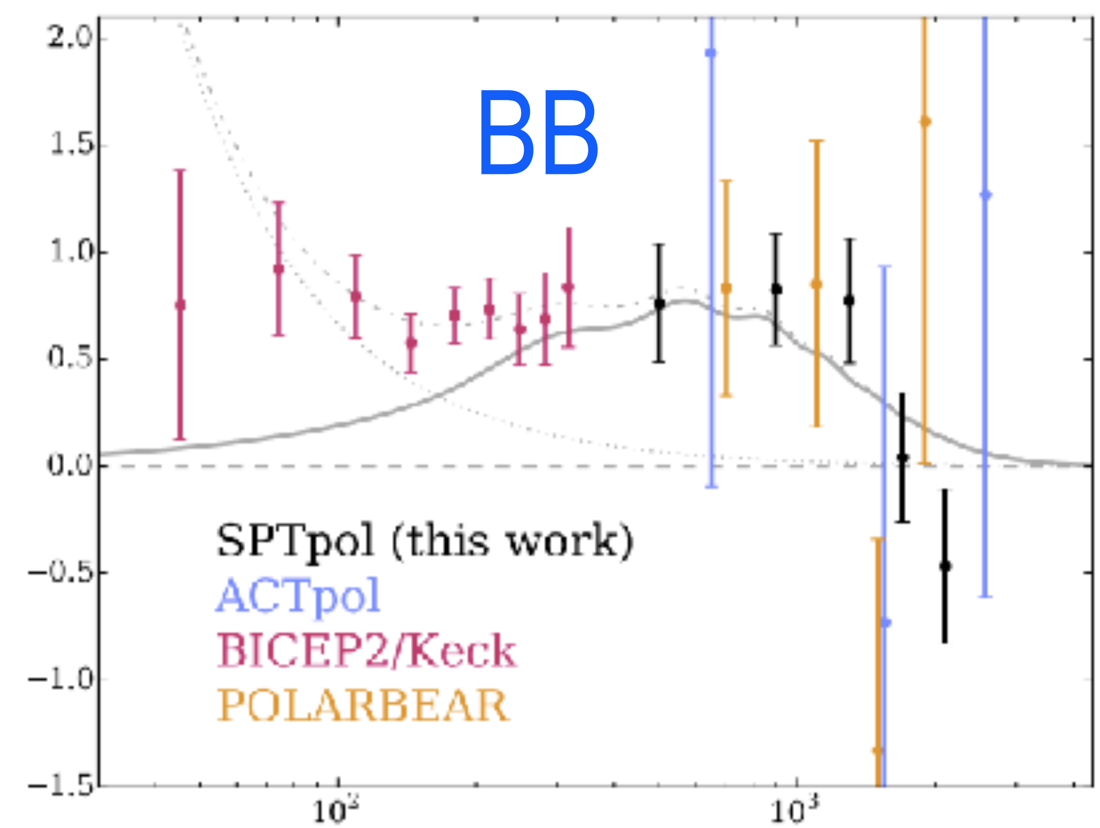
Polarized Variance



Angular Scale

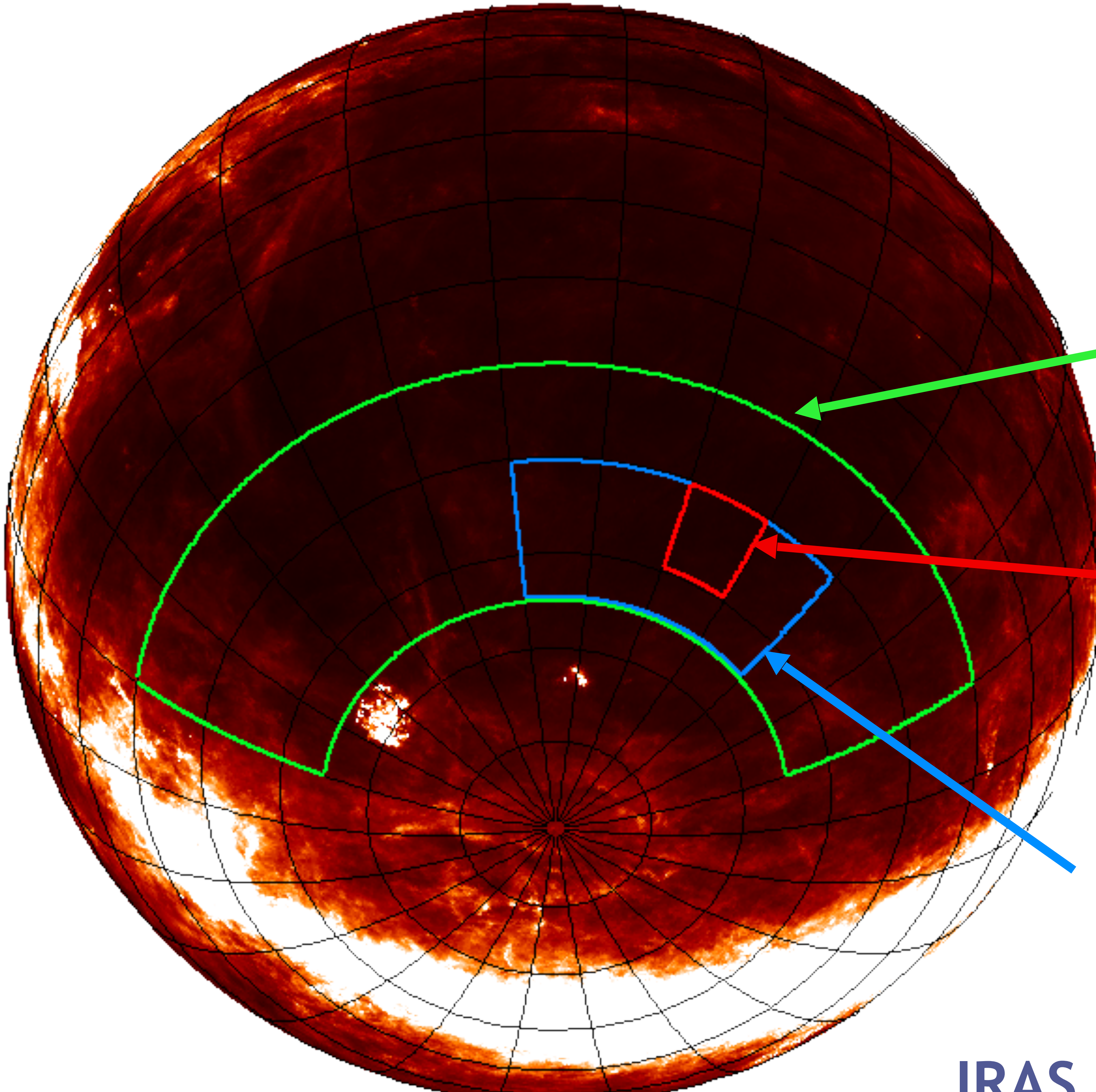
Keisler et al. 2015

Polarized Variance



Angular Scale

SPTpol Survey Fields



Also SPT-3G Field

SPT-SZ

Entire survey,
2500 deg²

Deep Field

First year,
100 deg²

Survey Field

Three years,
500 deg²

Also BICEP/ Keck Field

IRAS from Schlegel et al. 1998

4+ years of SPTpol data

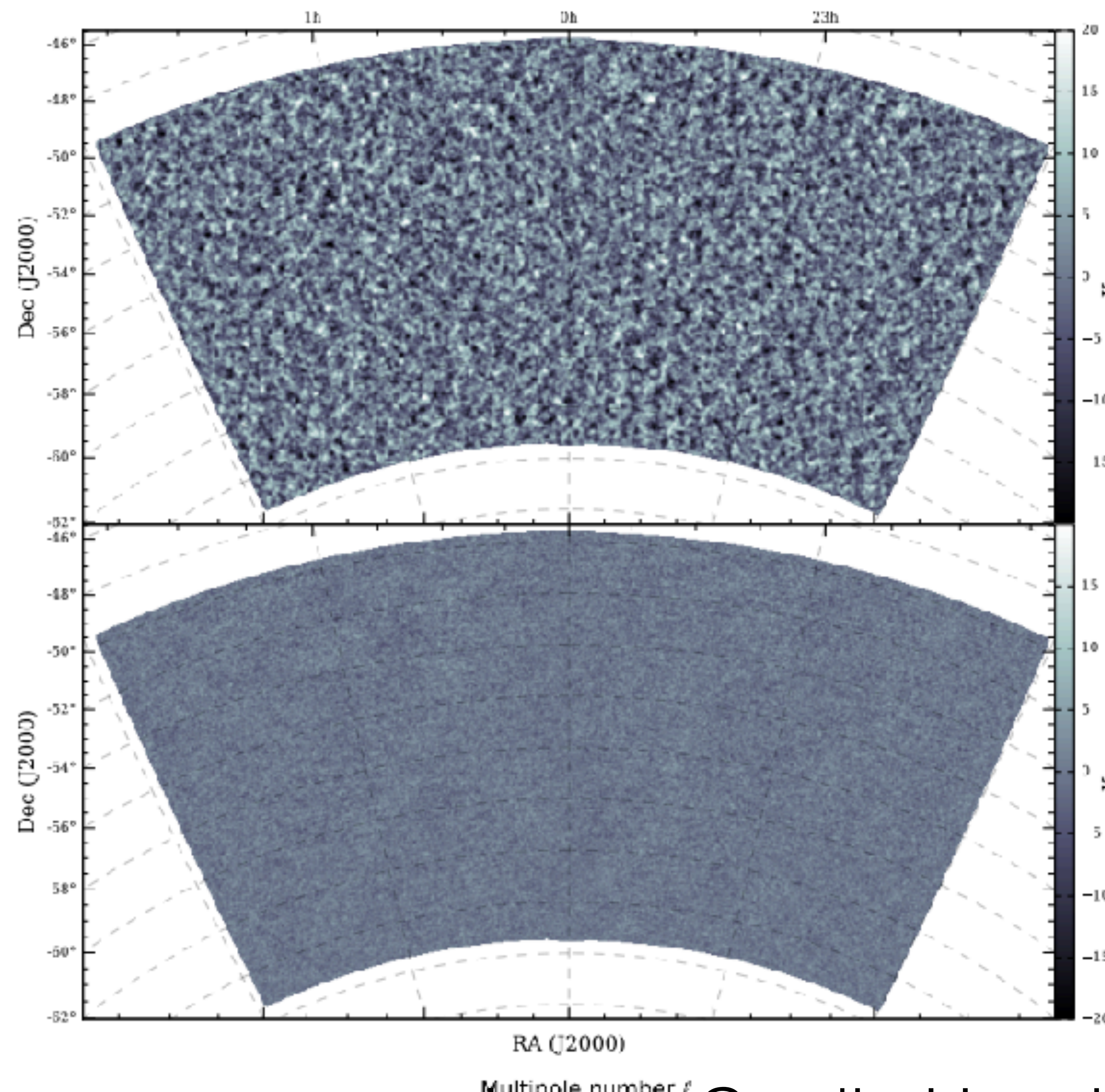


Image Credit: Henning et al, 2017

4+ years of SPTpol data

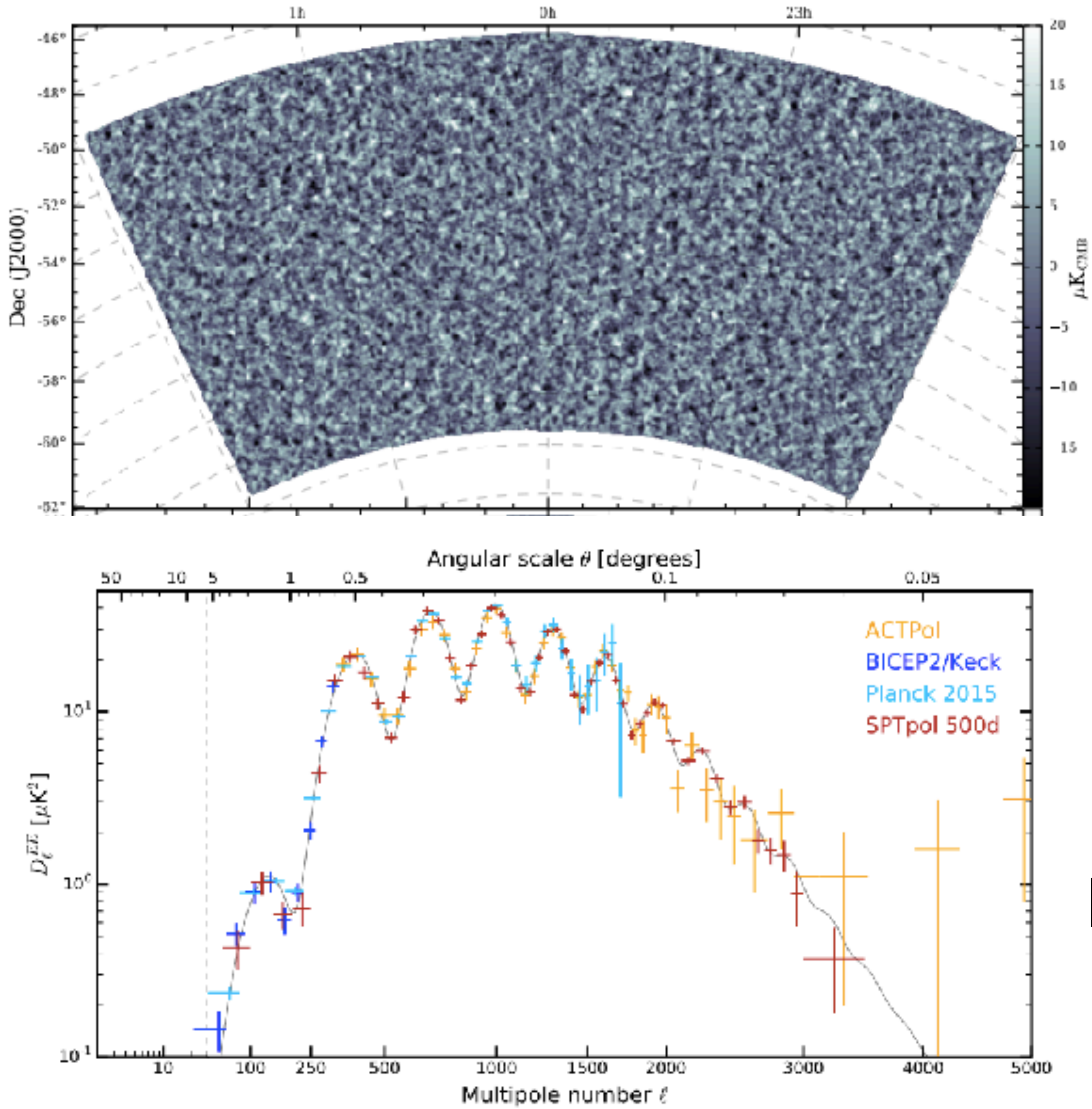


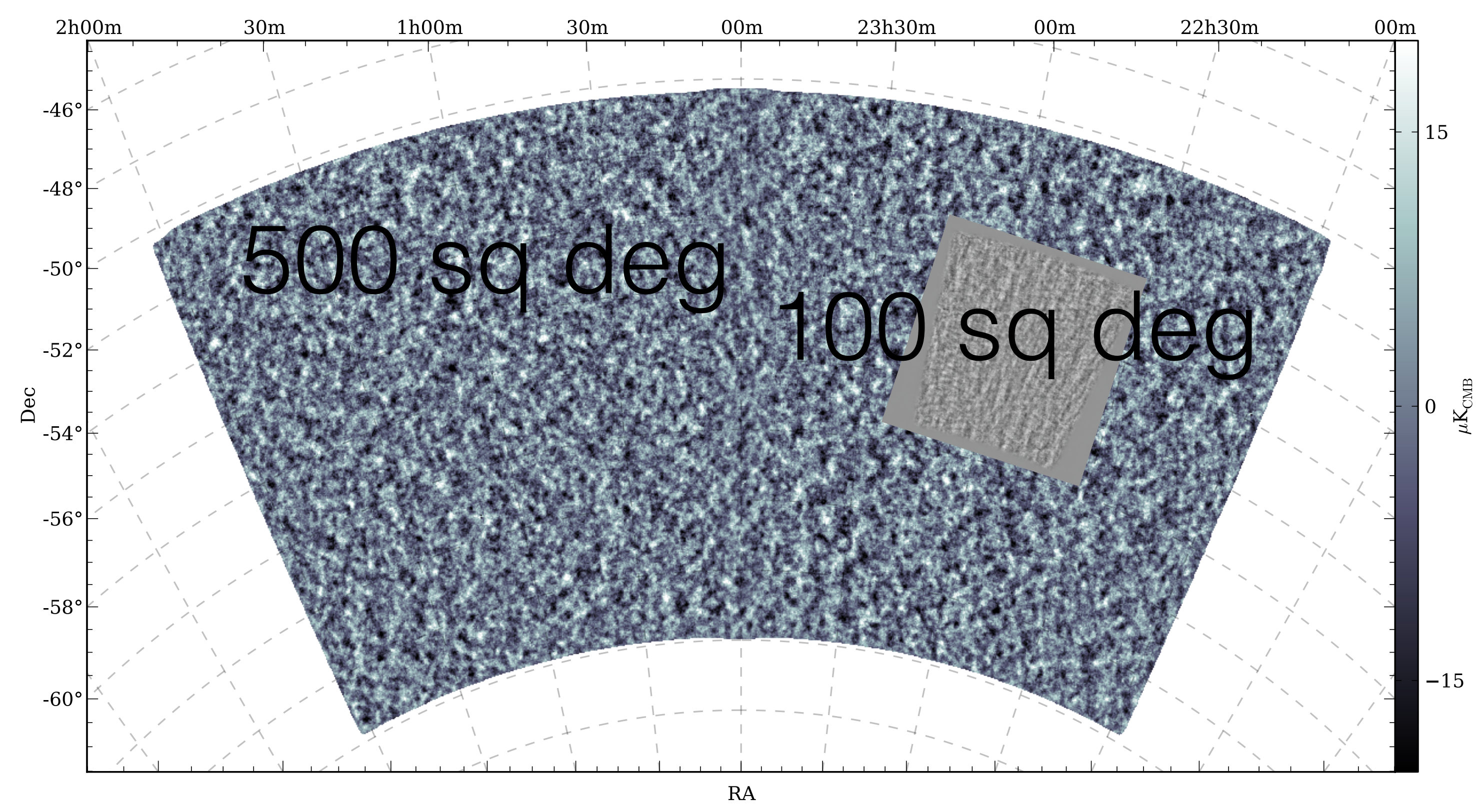
Image Credit: Henning et al, 2017

Science from SPTpol

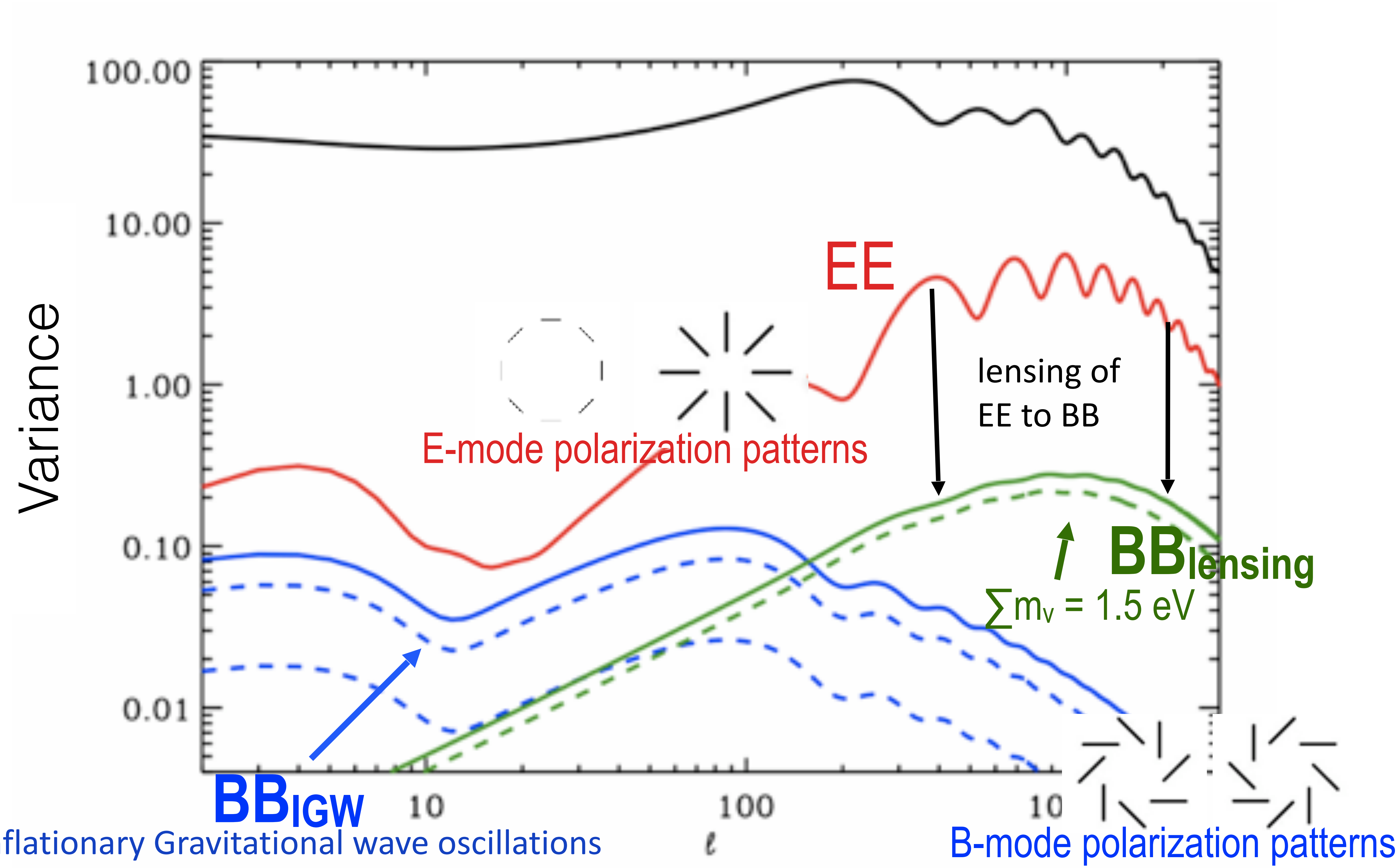
Hanson et al. 2013 — Detection of lensing with Hershel
Crites et al. 2015 — 100 sq deg EE
Keisler et al. 2015 — 100 sq deg lensing BB

Story et al. 2015 — 100 sq deg Lensing
Manzotti et al. 2017 —
100 sq deg delensing with SPTpol and Hershel

Henning et al. 2017— 500 sq deg EE
Sayre et al. in prep — 500 sq deg BB



What's Next For CMB?



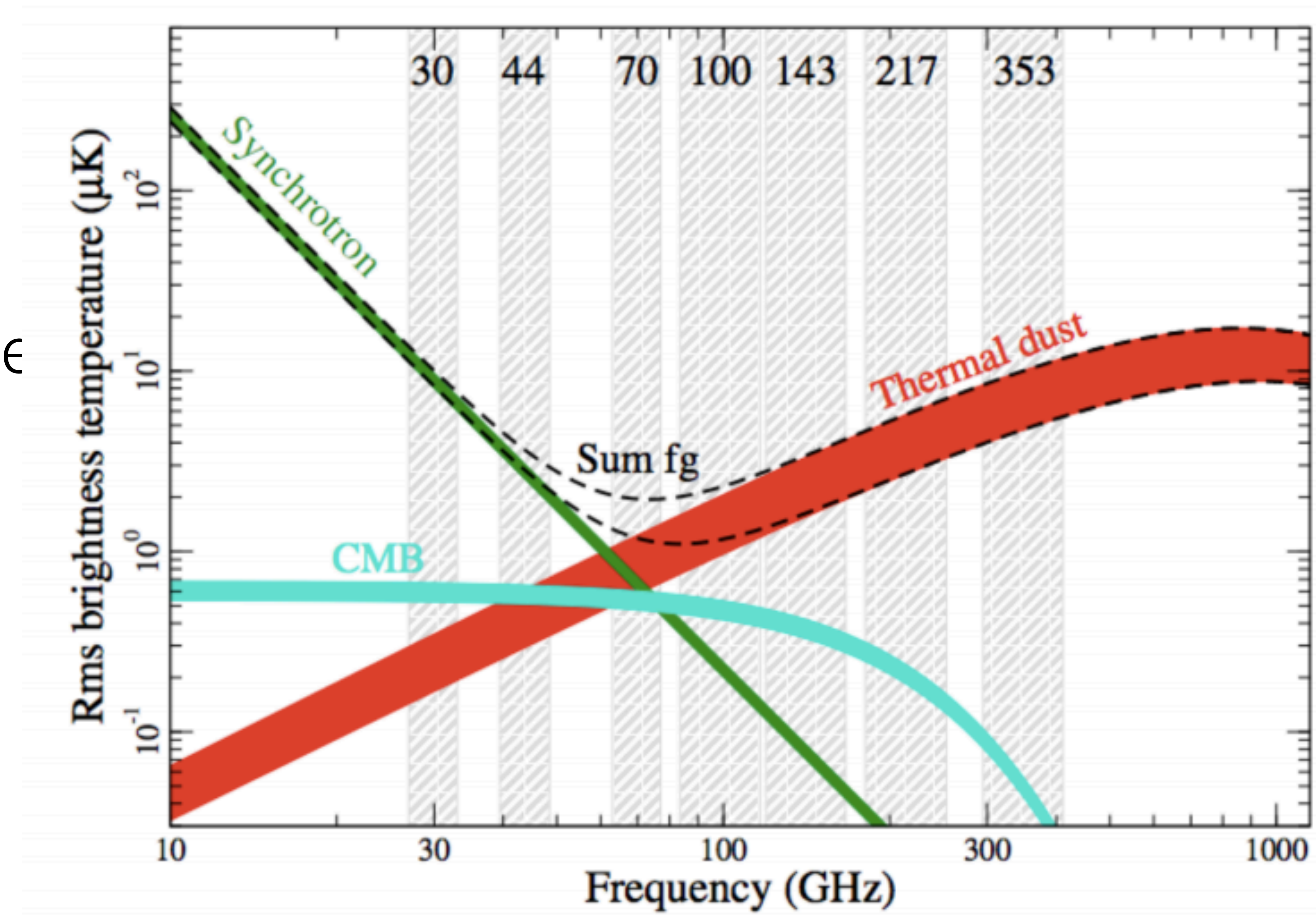
What's Next For CMB?

One big challenge: Foregrounds

↓

we need to measure the signal at many frequencies!

What's Next For CMB?



we … es!

Image Credit: Dickenson et al 2016

What's Next for CMB

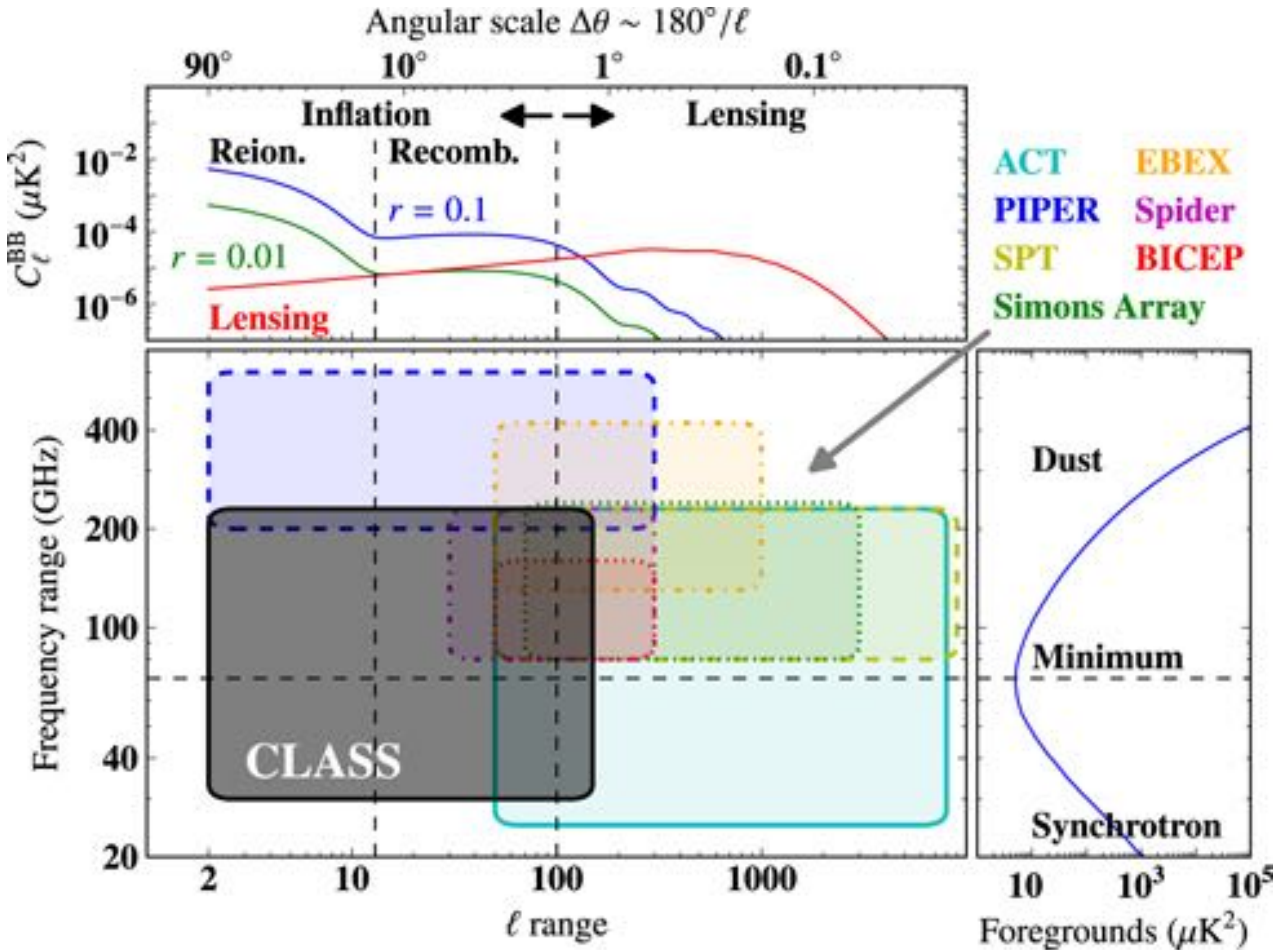
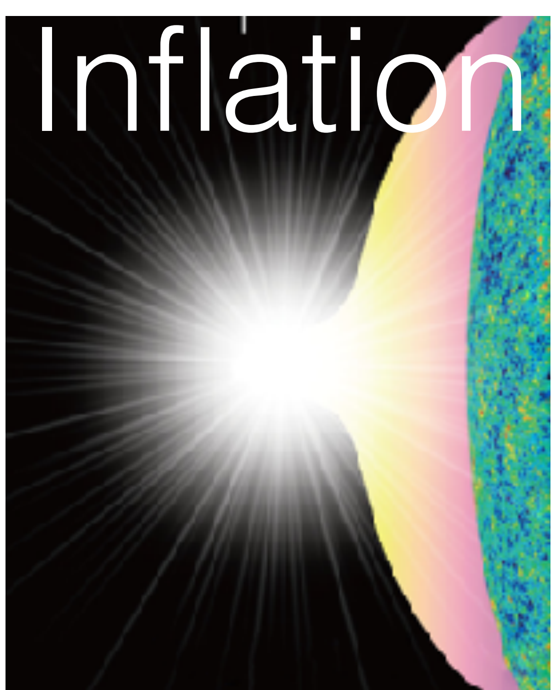
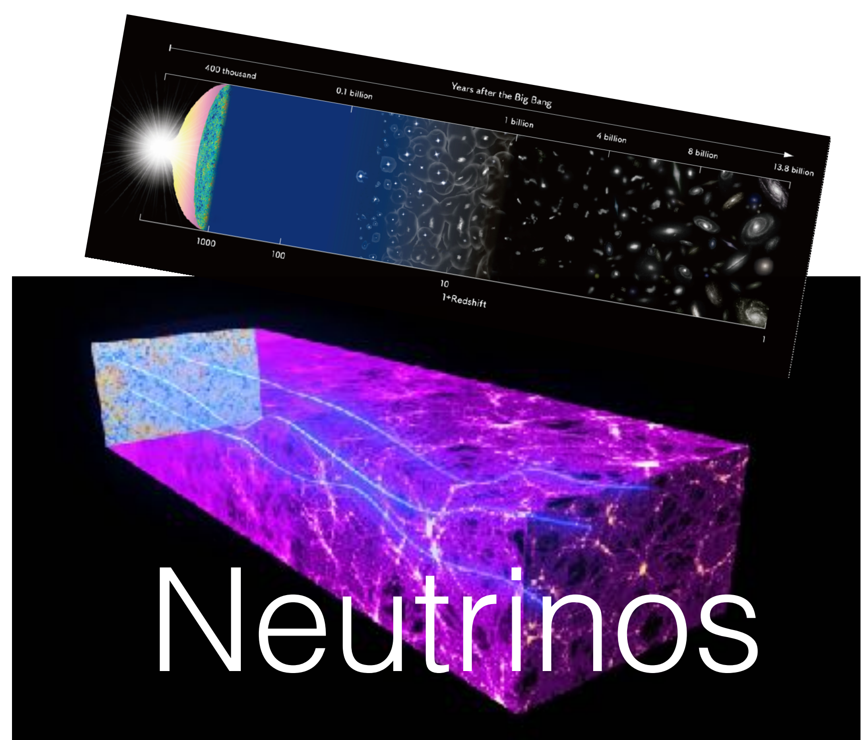


Image Credit: Watts et al 2015

What's Next For CMB?

CMB-S4 will have a profound impact on our understanding of fundamental physics!

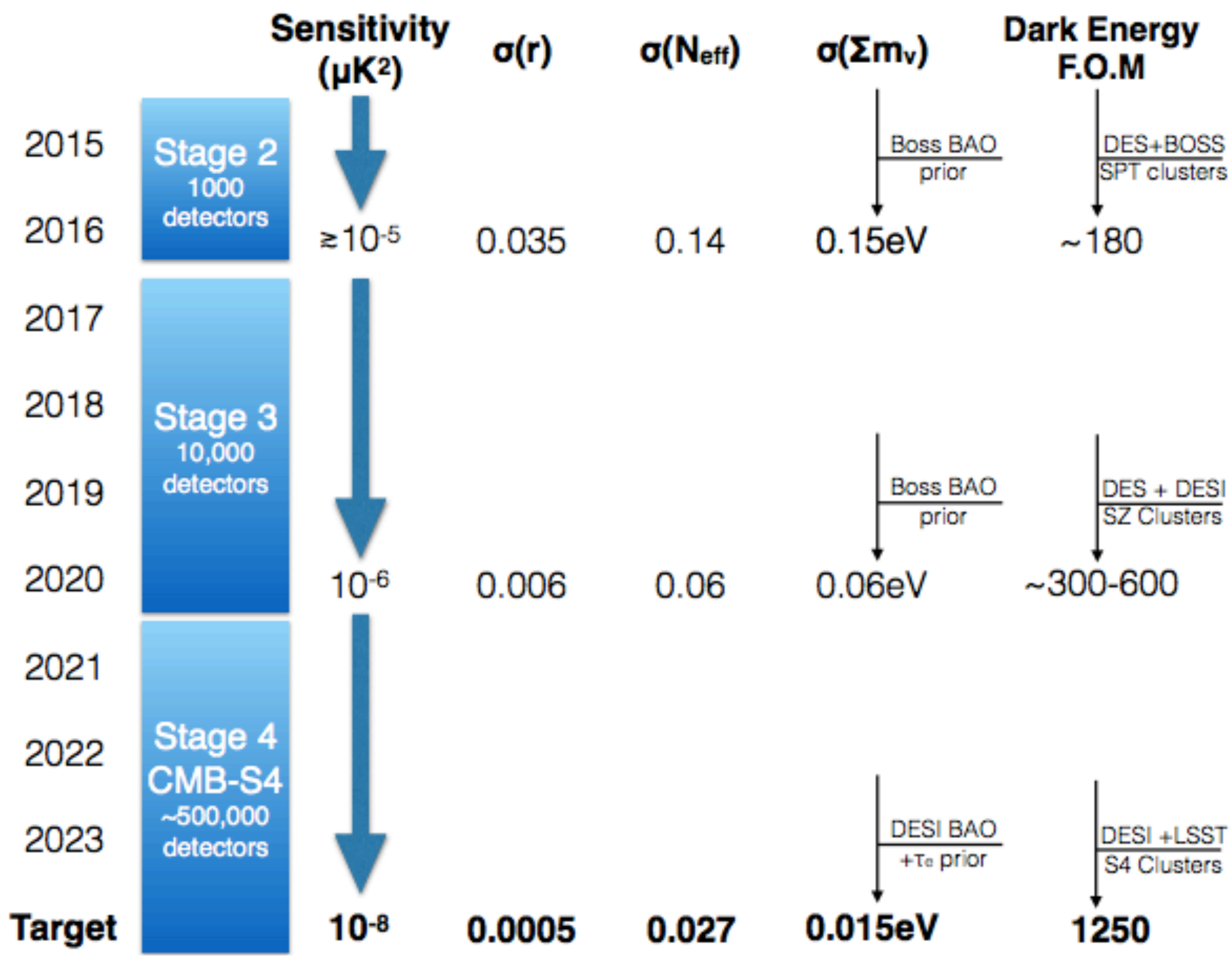




… and more!

CMB Stage 4

CMB-based Cosmological Constraints With CMB Stage 4



Credit: CMB Technology Book arxiv:1706.02464

Conclusions: Measurements of the Cosmic Microwave Background

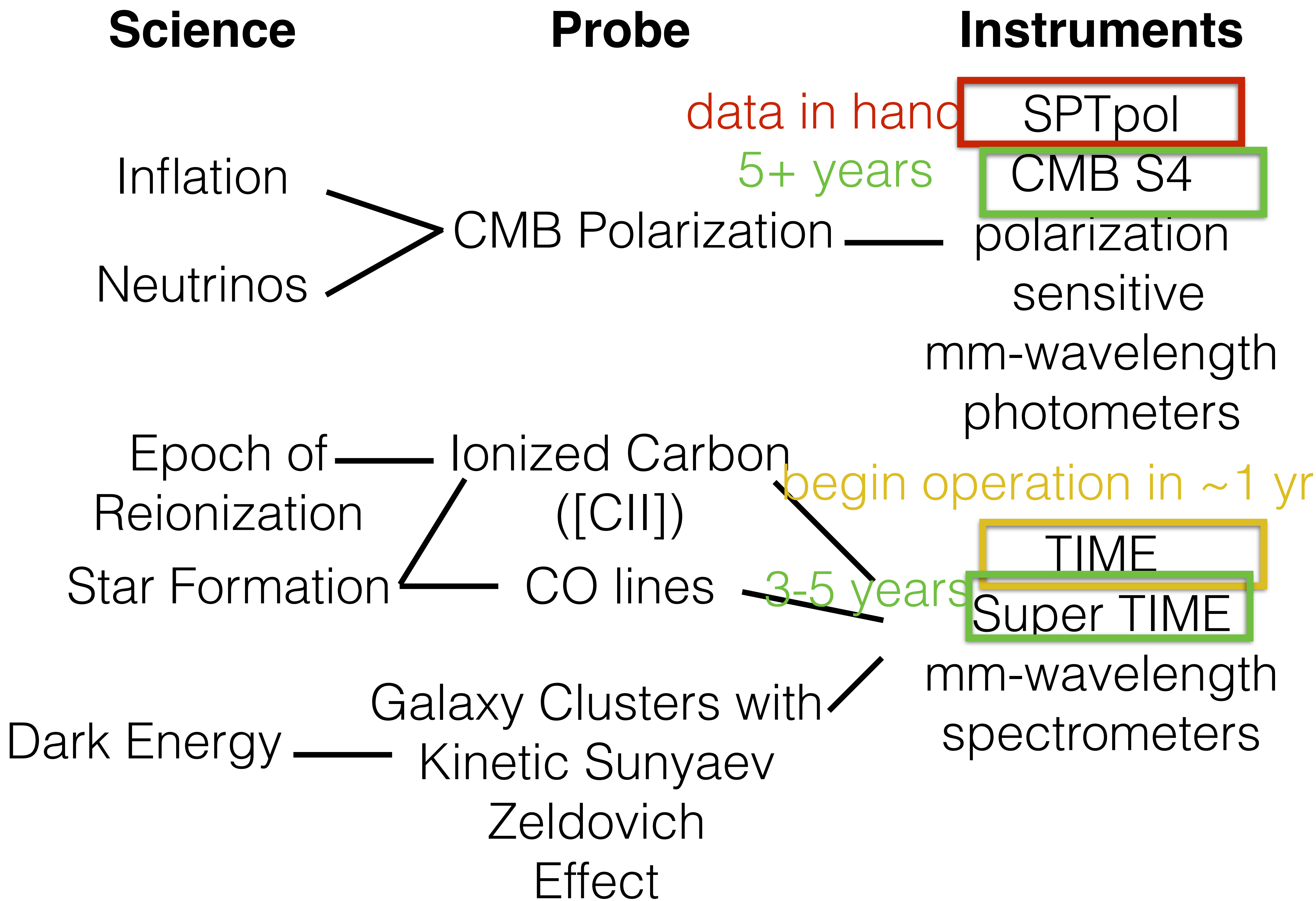
Polarization sensitivity to probe new physics

Many, many detectors to make measurements of faint signals

Many frequencies to remove foregrounds

Science: Inflation, neutrinos, Ho, dark energy!

My Science Interests



Thank You!


GEOGRAPHIC
SOUTH POLE
ROALD AMUNDSEN
DECEMBER 14, 1911
"So we arrived and were able to plant our flag at the geographical South Pole."
ROBERT F. SCOTT
JANUARY 17, 1912
"The Pole. Yes, but under very different circumstances from those expected."