Probing the History and Dynamics of the Universe with Polarized Signatures in the Cosmic Microwave Background

Suzanne Staggs
Princeton University
@PPPL, 23 Sept 15

CMB Polarization Reach

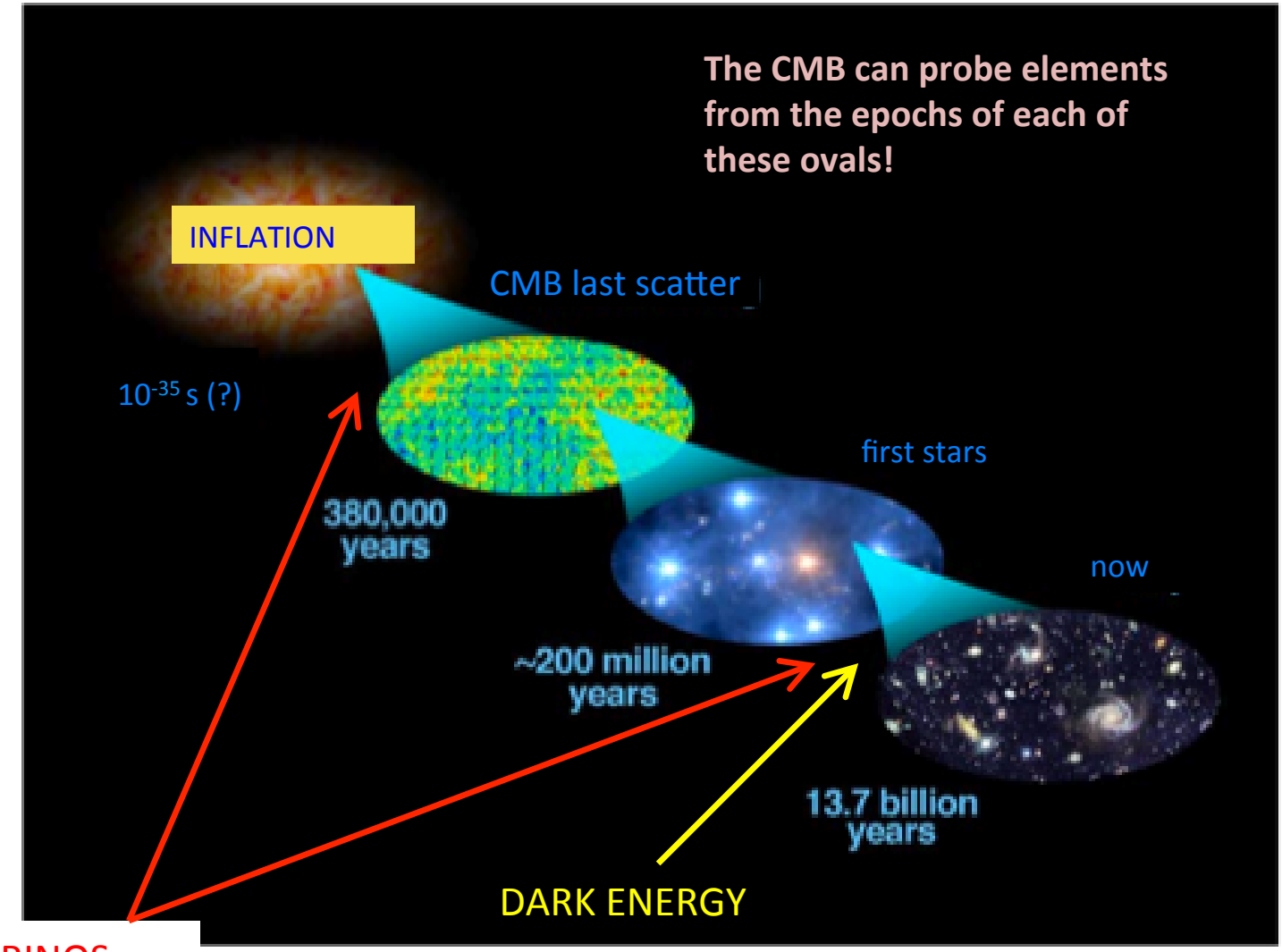
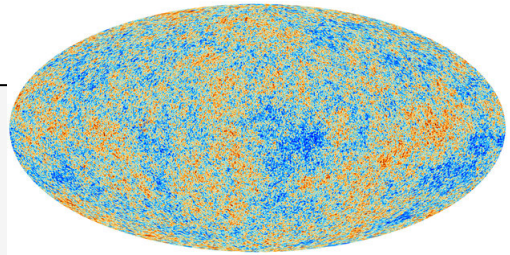


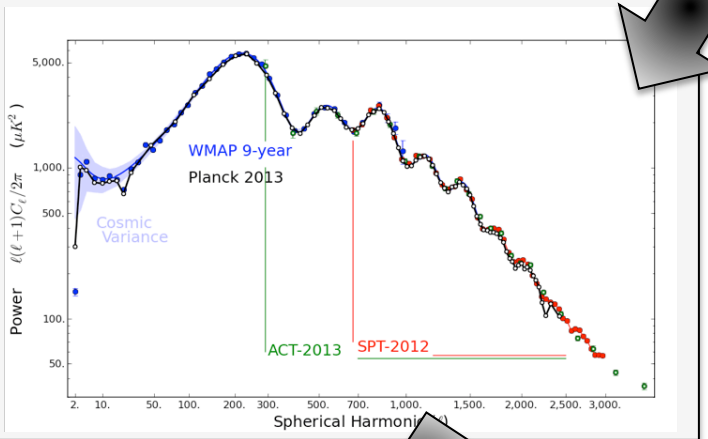
Figure adapted from the TFCR Report, 2005

The Cosmic Microwave Background and What It Can Yet Bring to the Party after 50 Years (Subtitle: Why You Should Still Be a Fan)

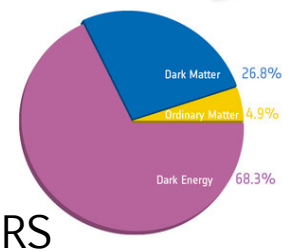


The CMB over the full sky – red and blue differ by ~ 1 mK; image courtesy of the ESA/Planck scientific team

POWER SPECTRUM
(the squared coefficients of an expansion in spherical harmonics, averaged over m)



BASIC COSMIC PARAMETERS



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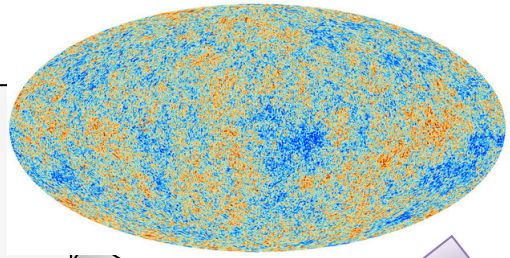

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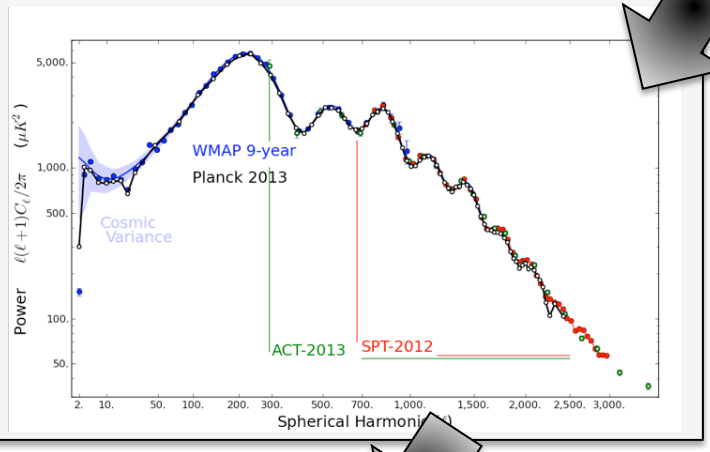
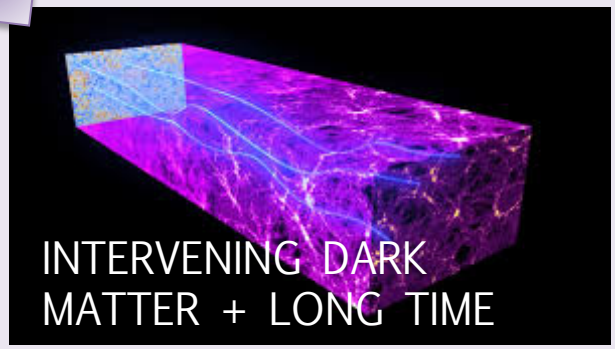
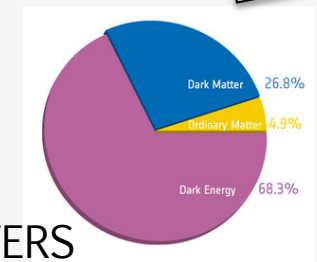


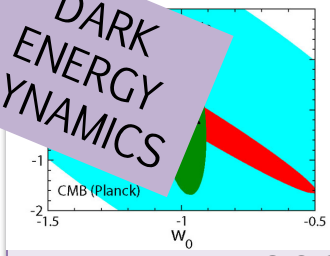


INTERVENING DARK MATTER + LONG TIME

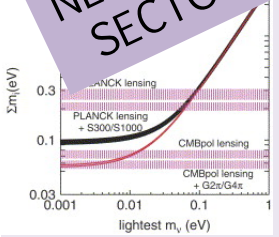
BASIC COSMIC PARAMETERS



DARK ENERGY DYNAMICS



NEUTRINO SECTOR



NEW COSMIC INTEL

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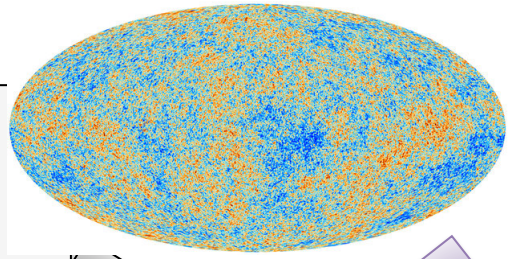

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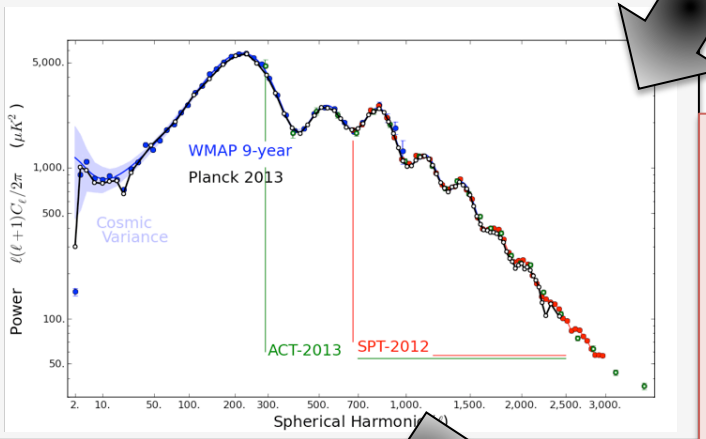
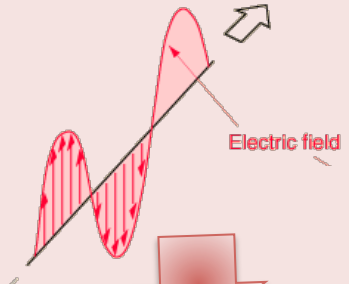
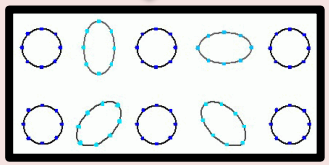
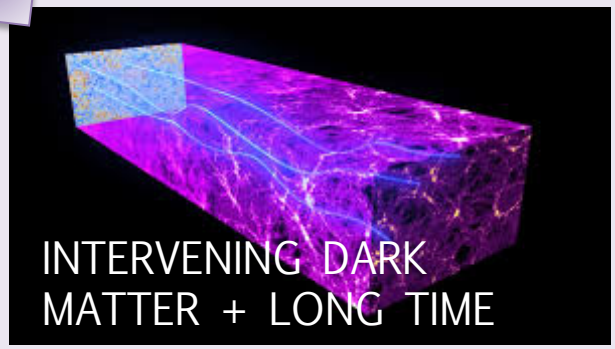


POLARIZATION PATTERNS





GW from INFLATION??



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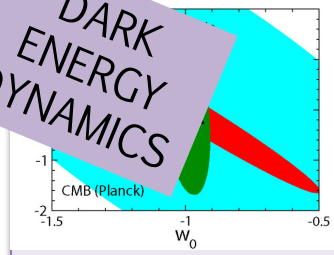

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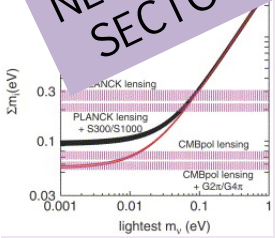

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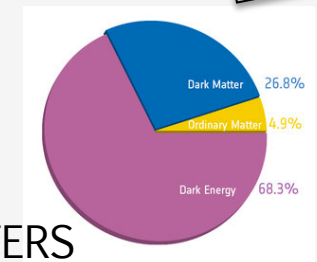
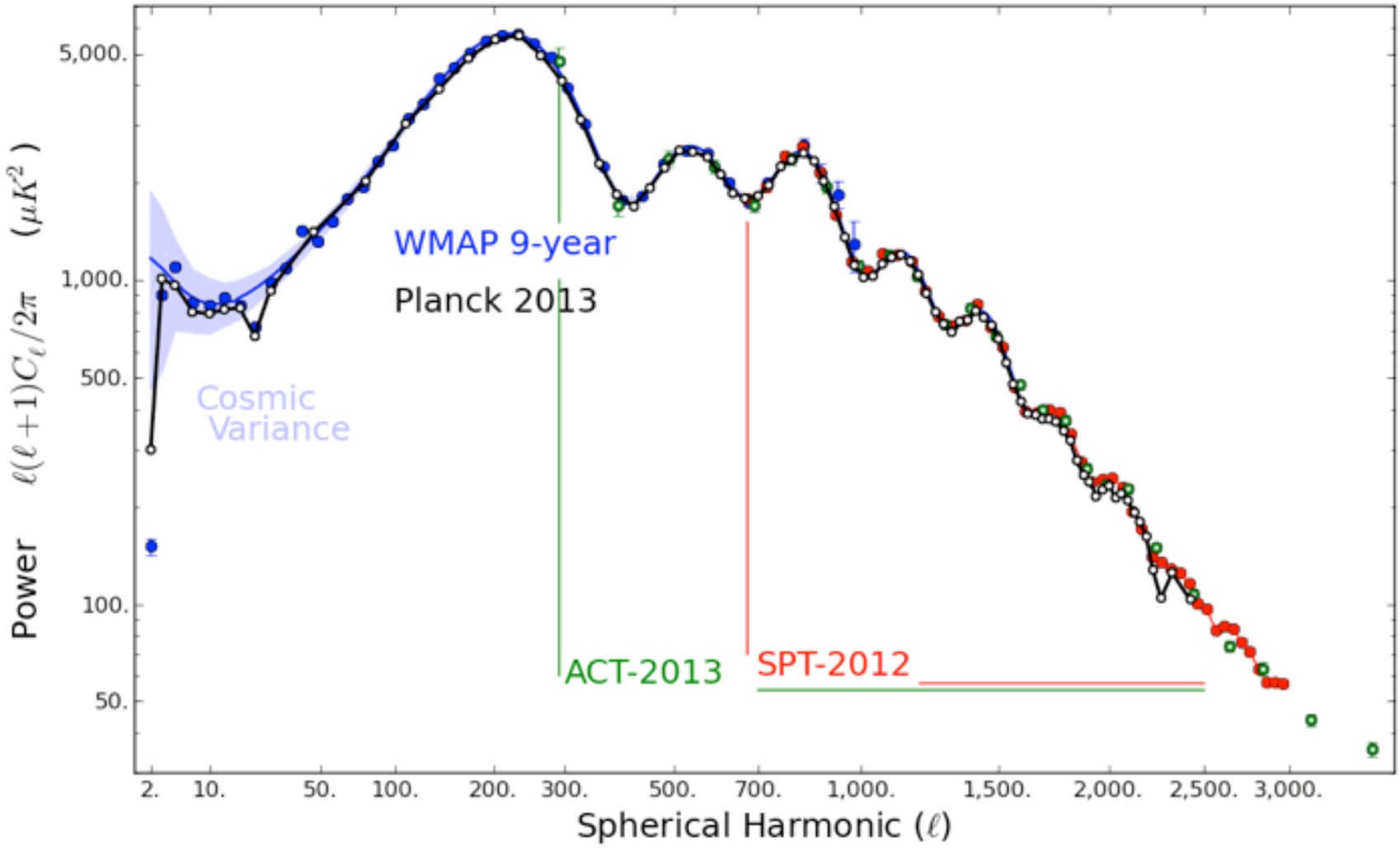


Six Parameter LCDM Fit to CMB TT



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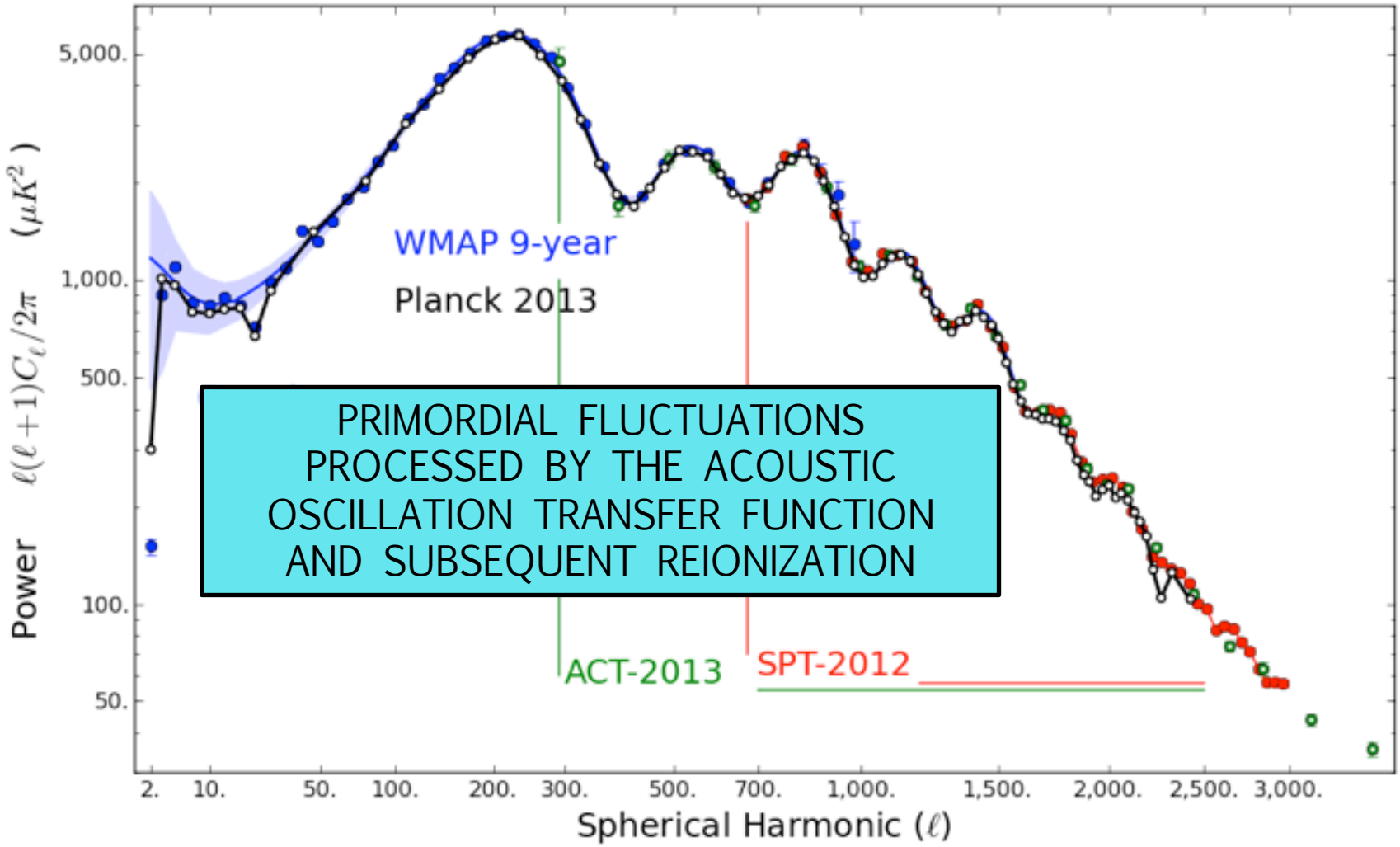

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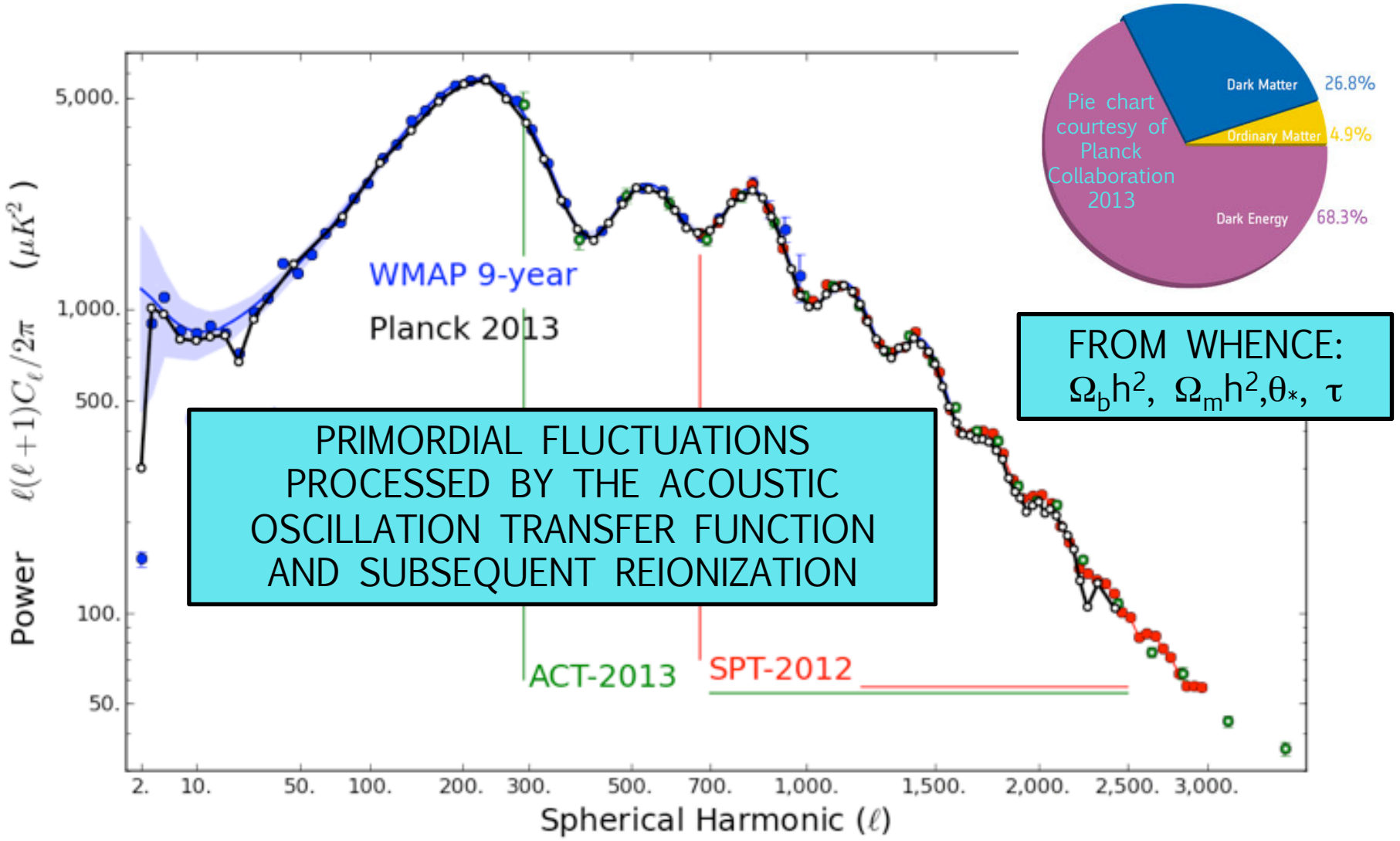
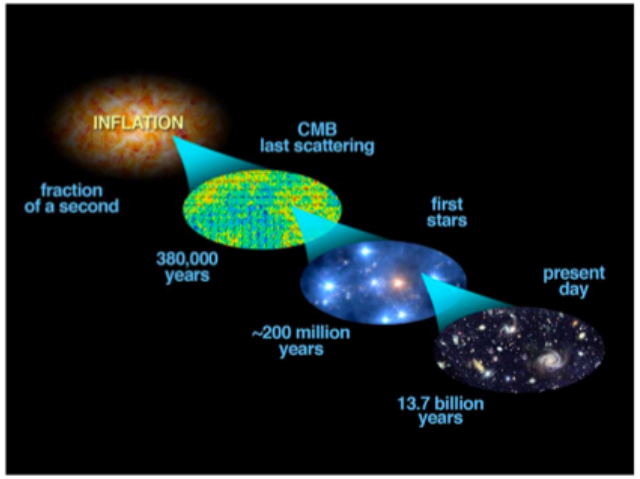


ΛCDM with inflation

Spatially flat expanding universe, currently dominated by vacuum energy from a cosmological constant causing accelerated expansion, with dark matter outmassing baryons 5:1. Structures formed by gravitational collapse (consistent with GR) from primordial Gaussian curvature fluctuations (adiabatic) with a nearly scale-invariant spectrum.

(Inflation predictions in blue)



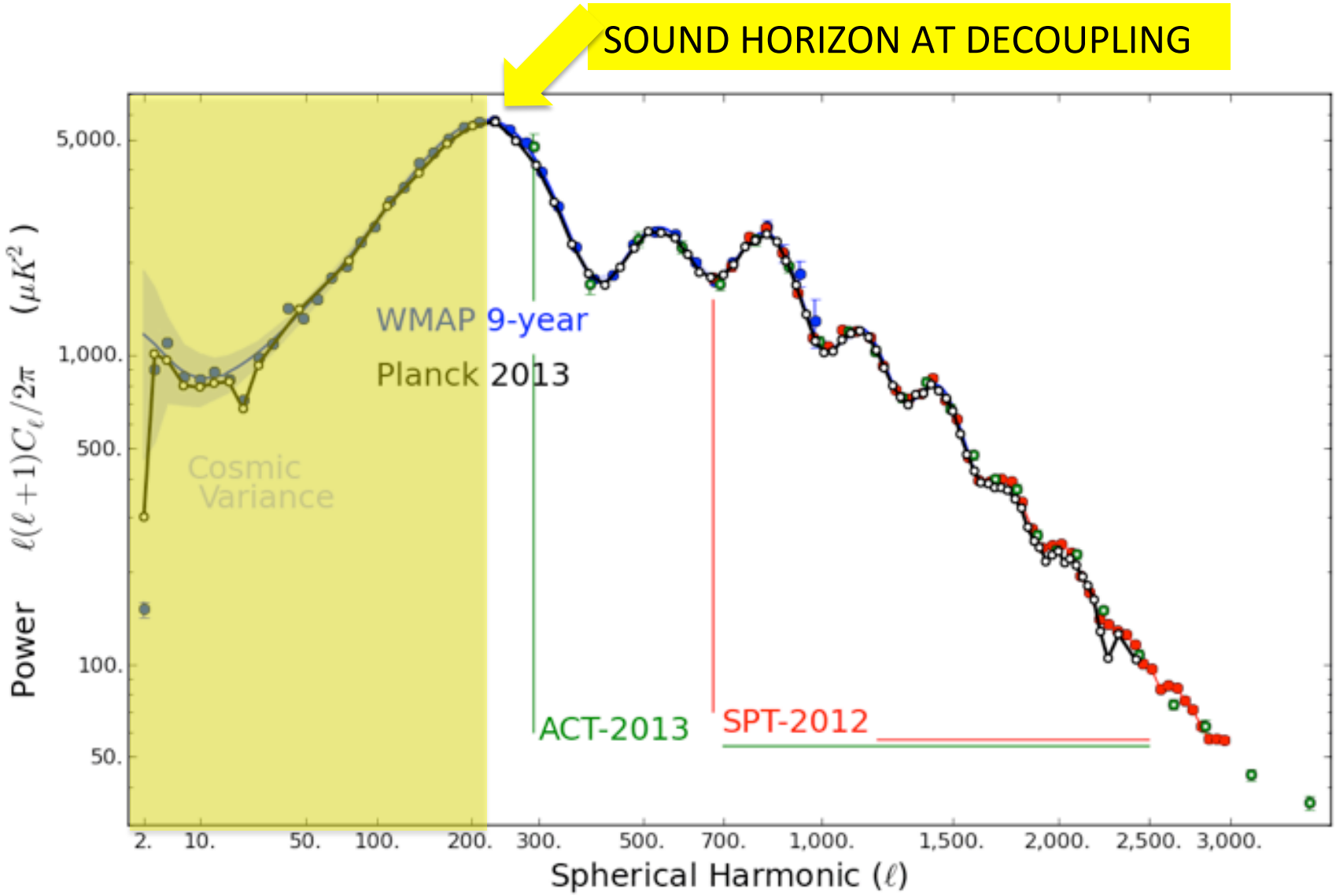
INFLATION POSITED TO EXPLAIN:

- Homogeneity at large scales
- Flatness
- Seeds for structure formation

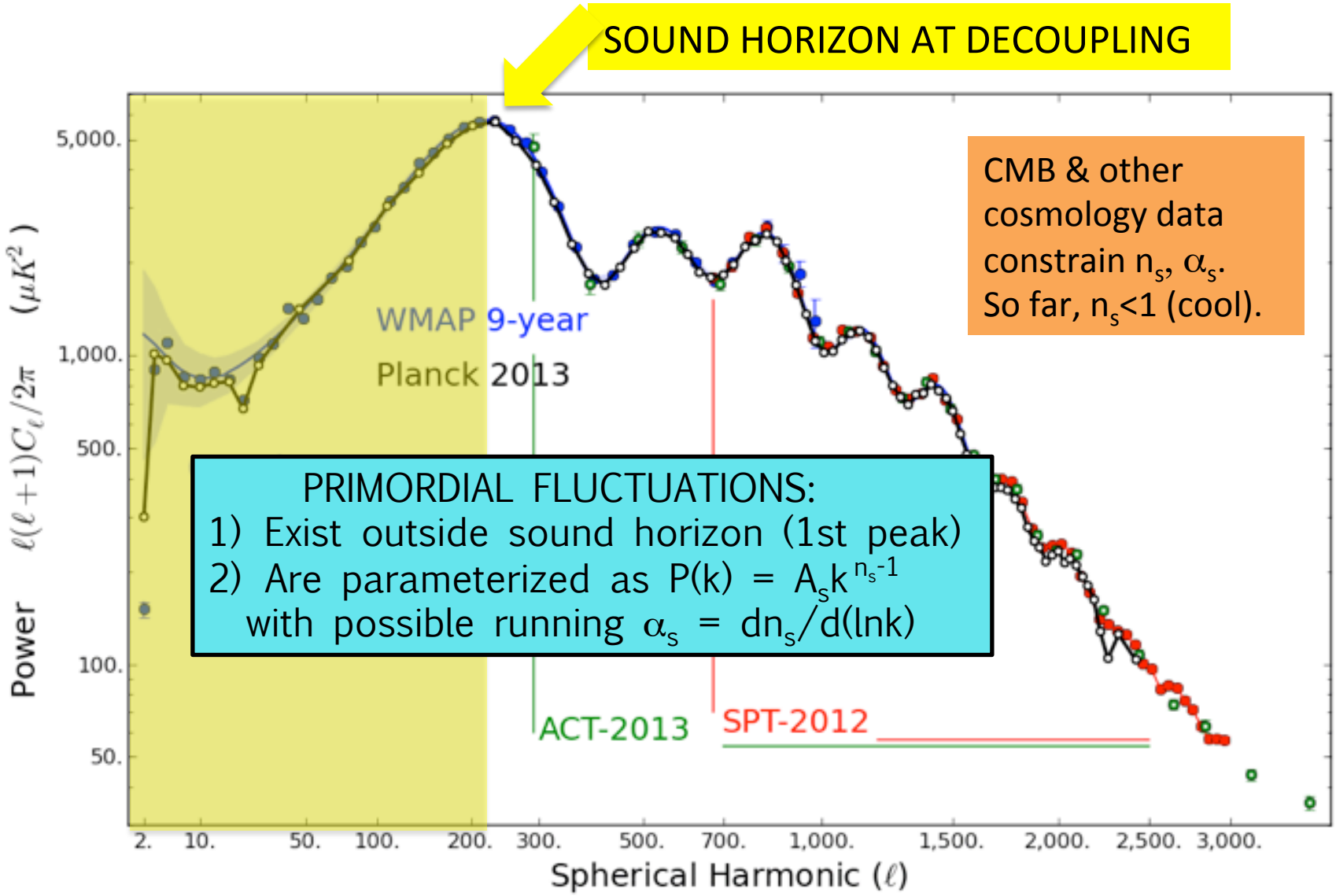
SIMPLEST MODELS PREDICT:

- Nearly scale-invariant spectrum
- Gaussian fluctuations
- Adiabatic fluctuations
- Gravity waves (unknown amplitude)

Inflation Hints from the CMB TT

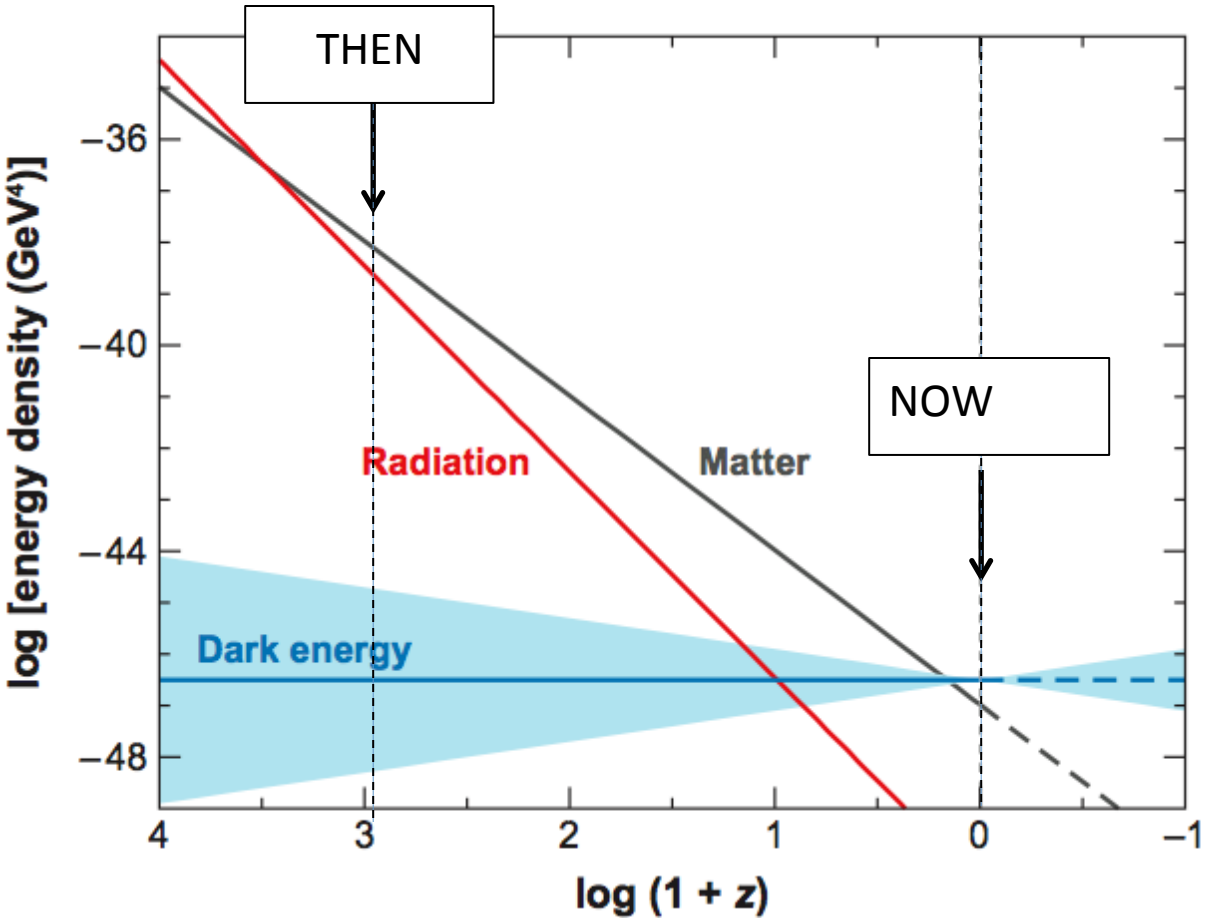


Inflation Hints from the CMB TT



Getting Here (now)
from There (then)

ΛCDM Then and Now



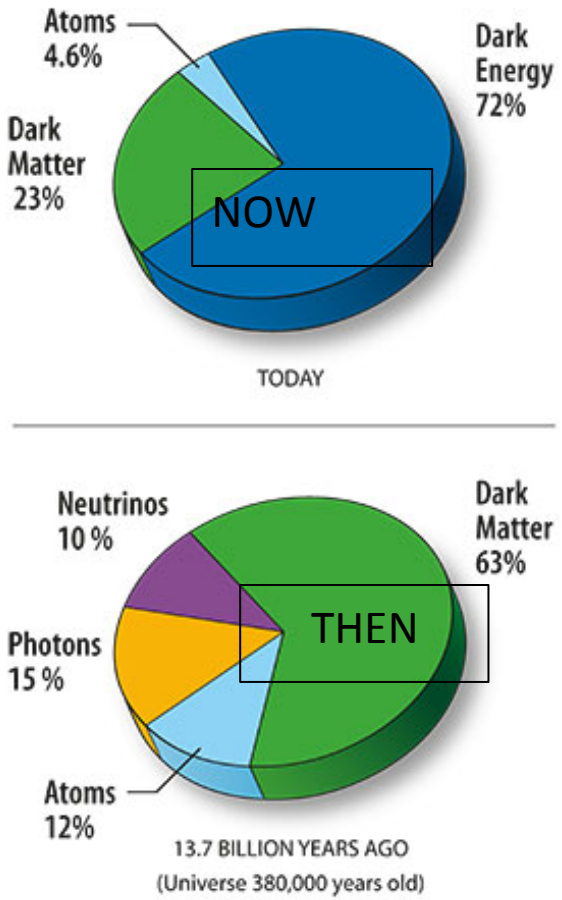
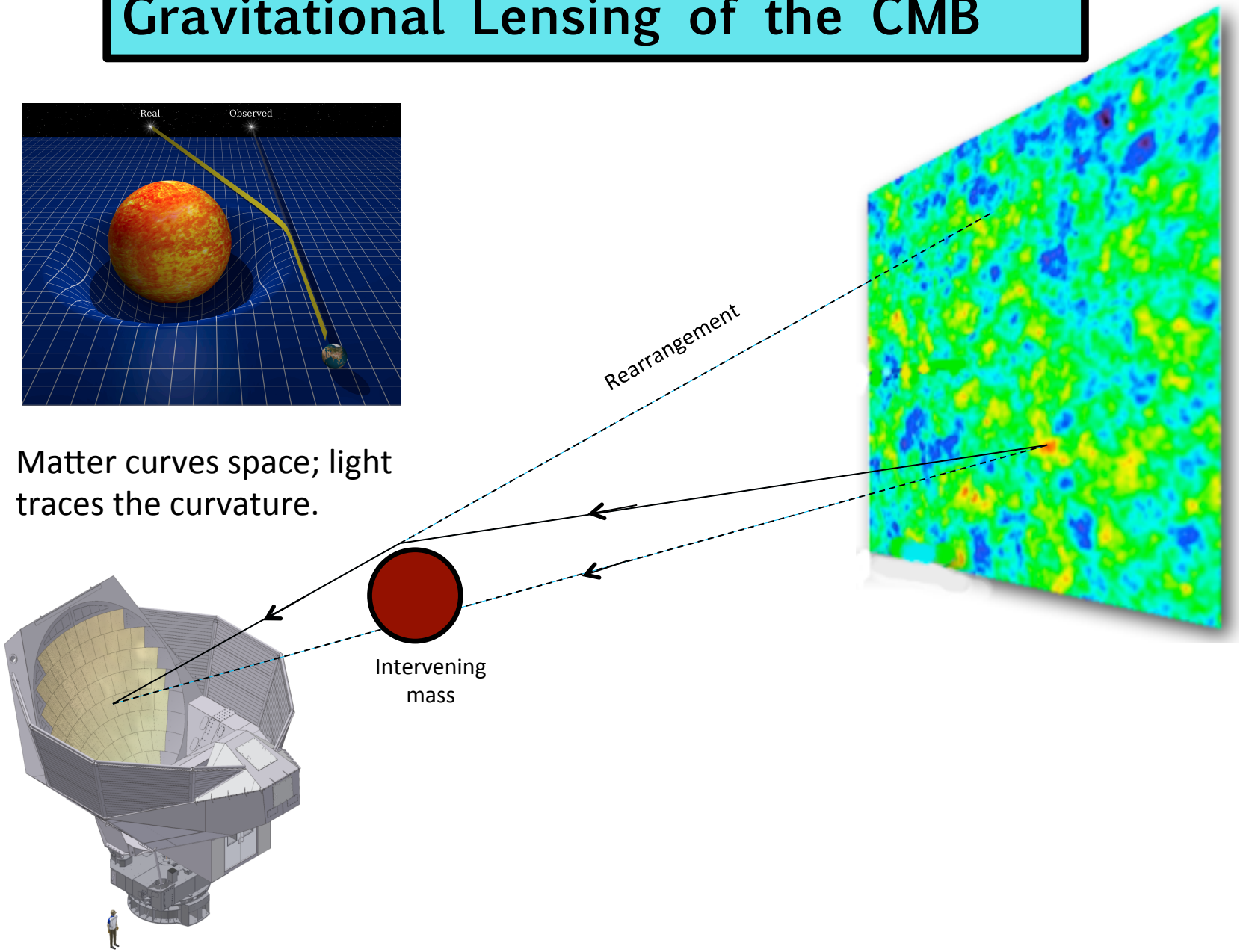


Figure from Frieman, Turner, Huterer ARAA 2008

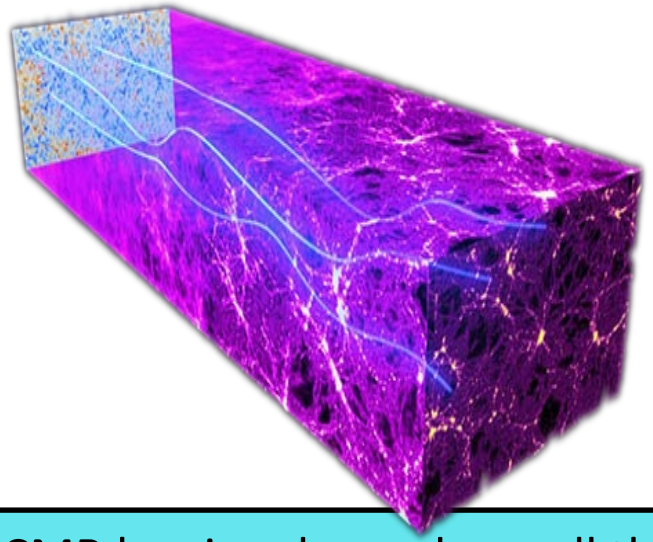
Illustrative numbers from WMAP5; courtesy WMAP science team.

Beyond the Power Spectrum: Gravitational Lensing of the CMB

Matter curves space; light traces the curvature.



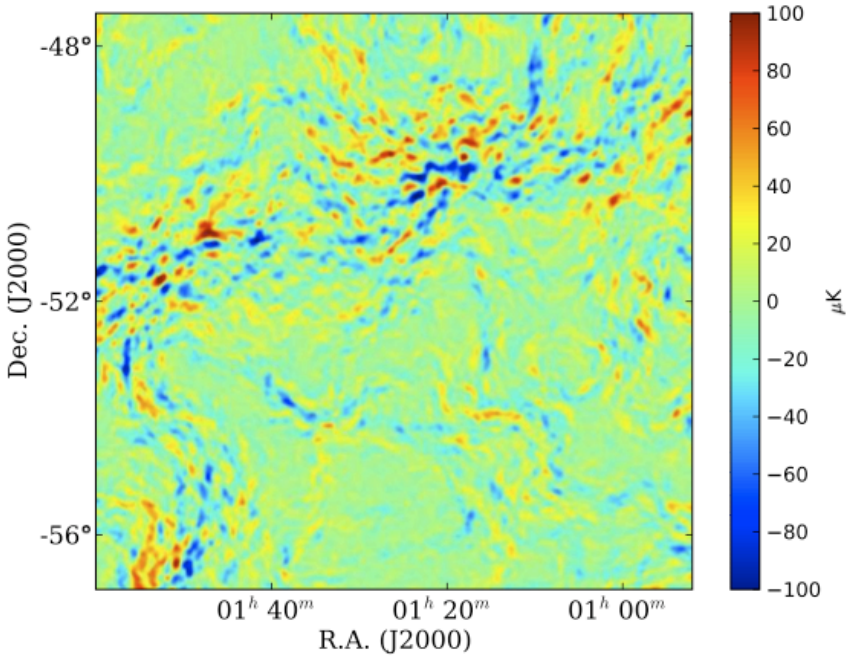
Why CMB Lensing Is Powerful



CMB lensing depends on all the mass from here to the CMB.

Structure is forming from gravitational collapse as the CMB traverses it.

Simulated difference between lensed and unlensed CMB in 10^ox10^o patch



Large & small scales are coupled.

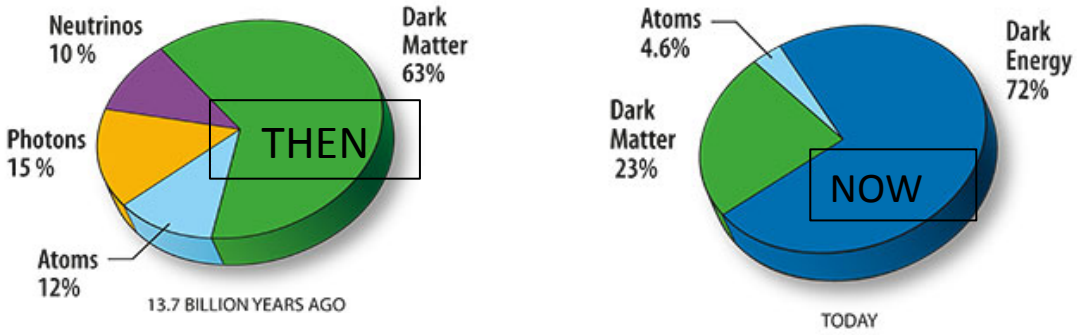
RULE OF 2-3: Typically ~ fifty 2-3' deflections, coherent over 2-3^o, mainly coming from redshifts of 2-3.

Das et al, 2011, 1103.2124 (PRL 107, 021301.)

CMB Lensing and Neutrinos

Small-scale CMB probes:

- the masses of neutrinos,
- the nature of dark energy, &
- the details of gravity.



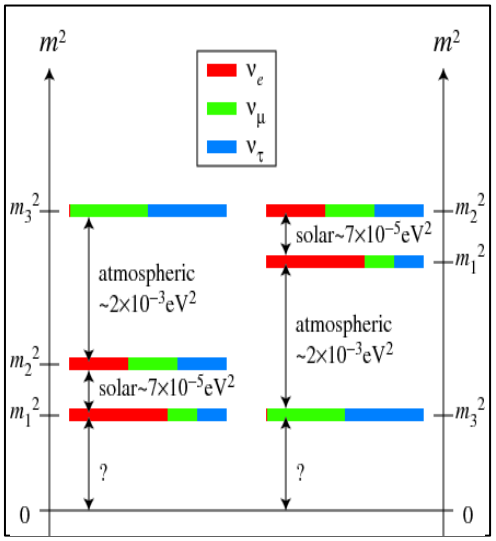
1. CMB lensing measures the amplitude of large angular scale structure.
2. Neutrinos eventually wander out of potential wells, taking their mass with them.
3. Effect is largest at small angular scales (probed by optical surveys).
4. More massive neutrinos suppress small-scale structure more.

The Excitement Of Neutrino Mass

Set limits on single masses In the lab

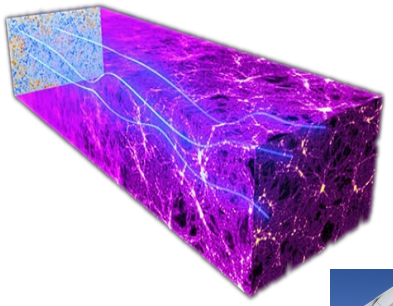
$^3H \rightarrow {}^3He^+ + e^- + \nu_e$

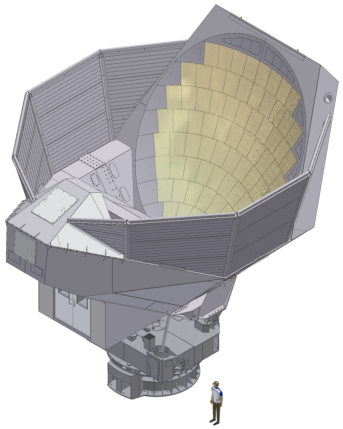
Measure mass **differences** from oscillation experiments



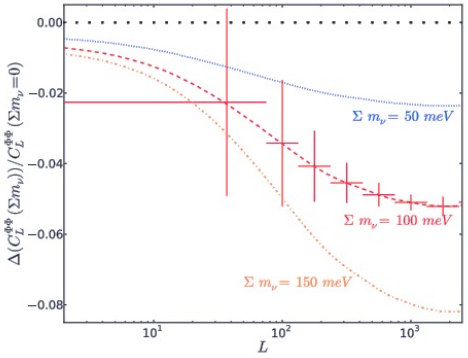
Minimum possible totals: 60 meV or 100 meV

Determine the sum of the masses with the CMB

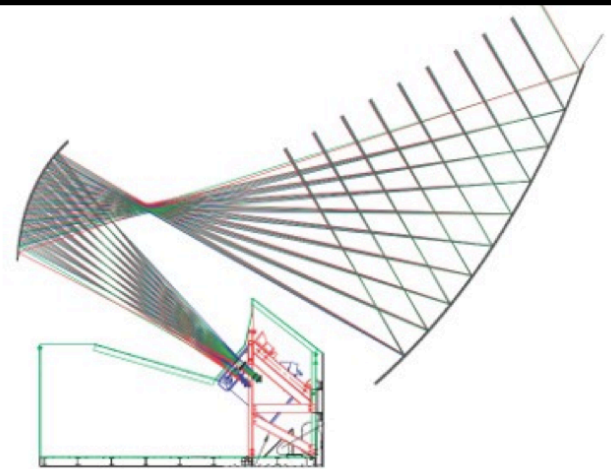




Lensing spectrum



The Atacama Cosmology Telescope



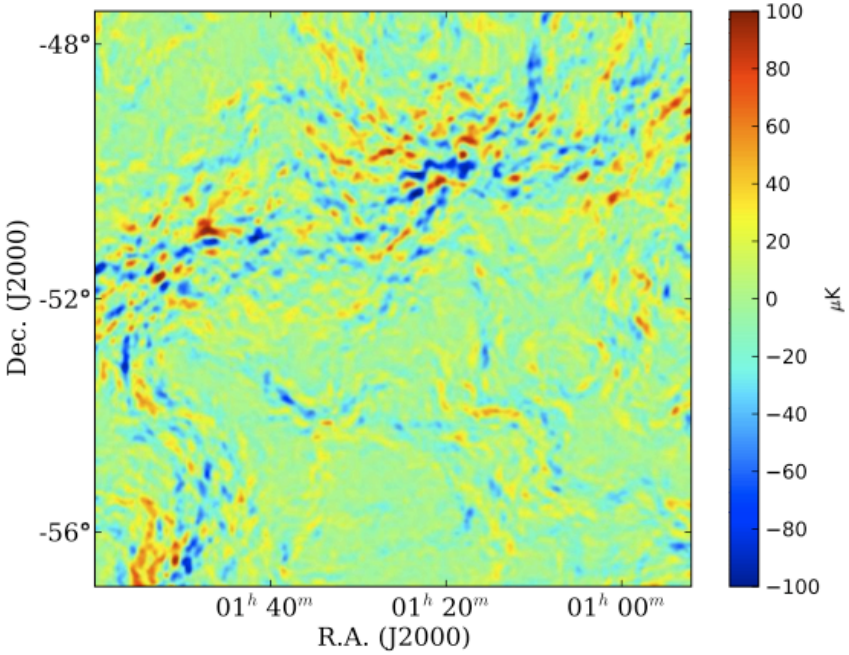
- 6m off-axis telescope
- Arcminute resolution

- 5200 m (high)
- Desert (dry)
- Latitude -23°

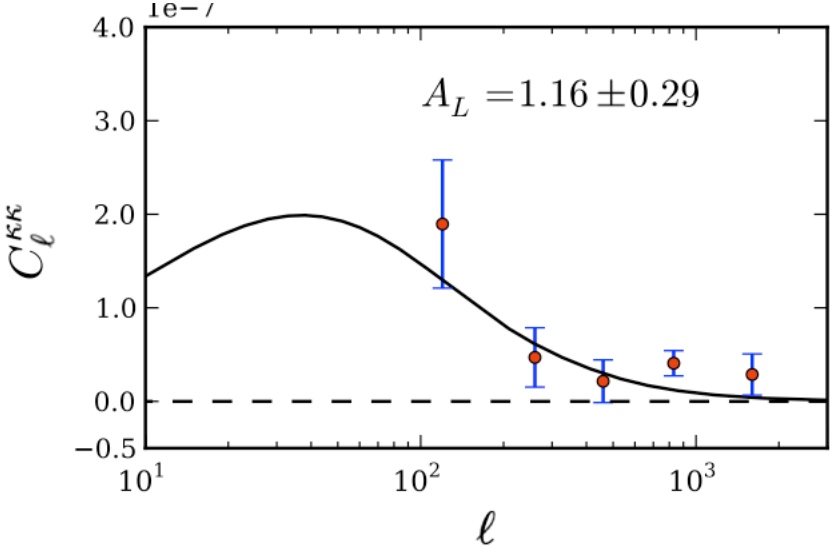
- 12 m groundscreen
- Large co-moving screen

Beyond the Power Spectrum:
First Detection of Gravitational Lensing from the CMB Alone

Simulated difference between lensed and unlensed CMB in 10°x10° patch



FIRST INTERNAL CMB LENSING DETECTION:
Data from ACT 4pt function



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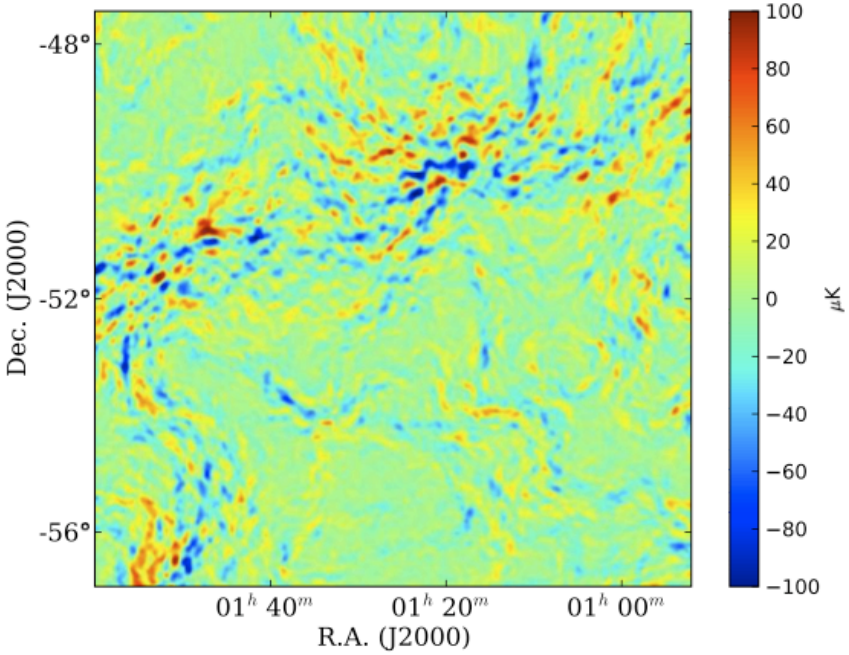
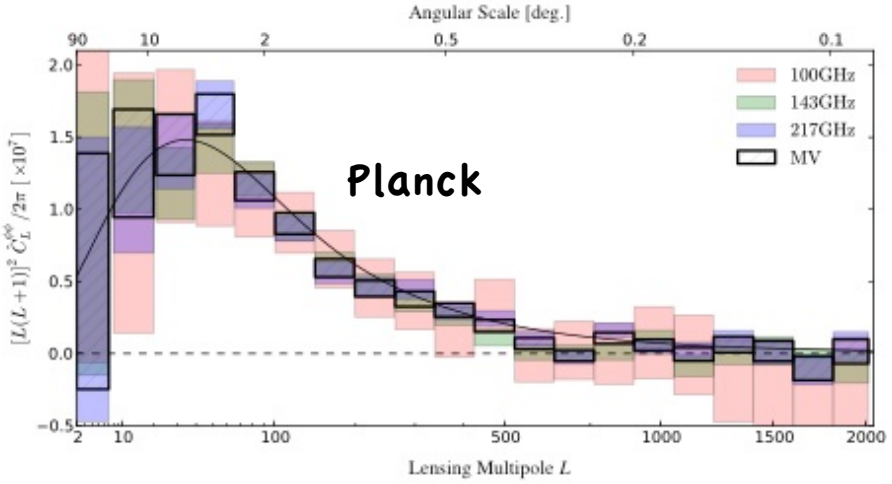


Great improvements on deflection power spectrum subsequently!



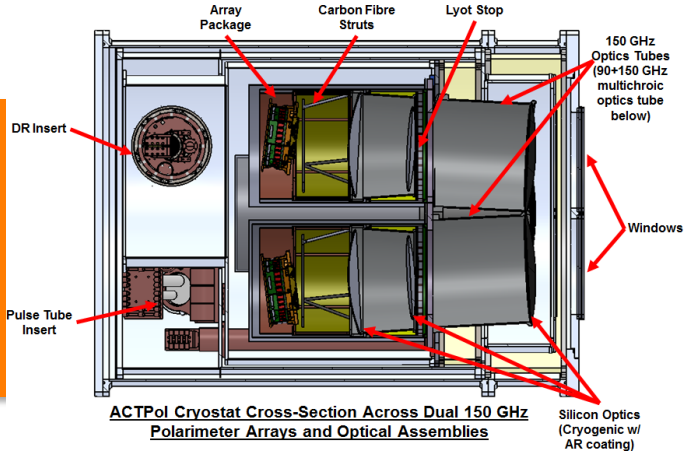
But, much more to come!

More Detail on ACTPol

The first generation camera on ACT measured only the intensity; the current generation also measures polarization!

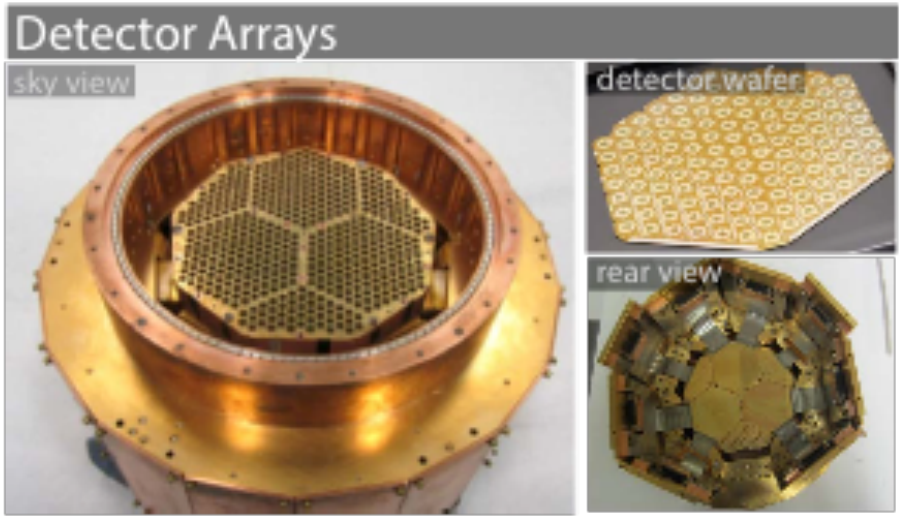
The ACTPol Camera

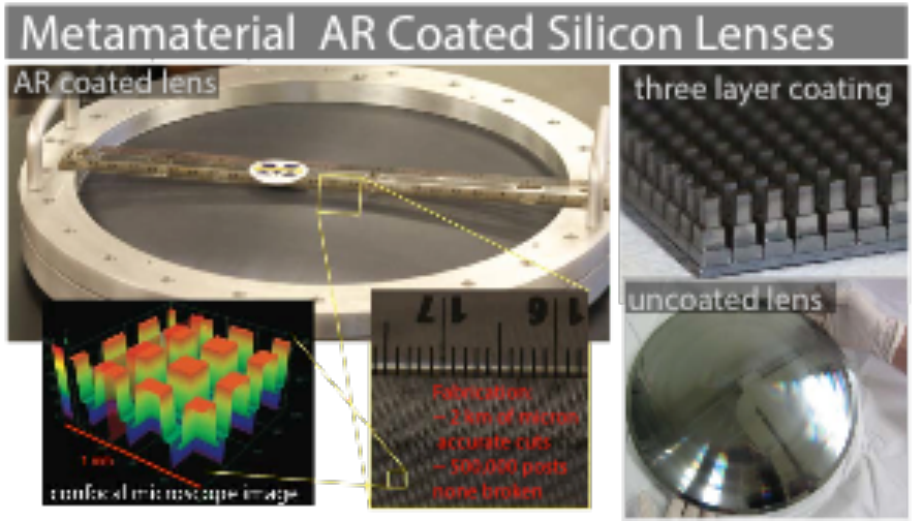
The Present: 2013-2015 ACTPol



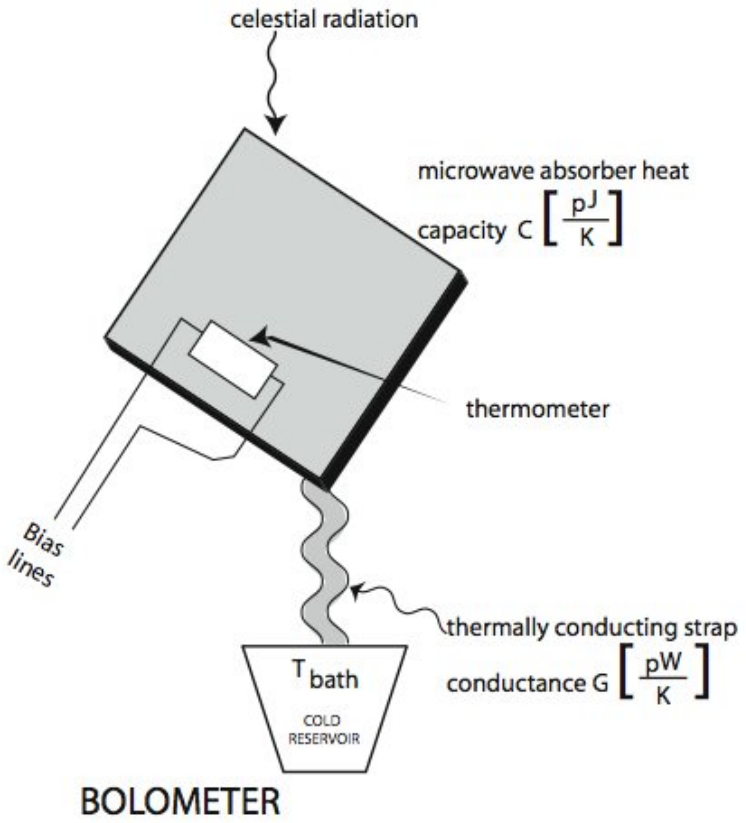
ACTPol Cryostat Cross-Section Across Dual 150 GHz Polarimeter Arrays and Optical Assemblies

Temperature & Polarization
Two bands: 146 & 90 GHz
90 mK dilution fridge
Round the clock observing

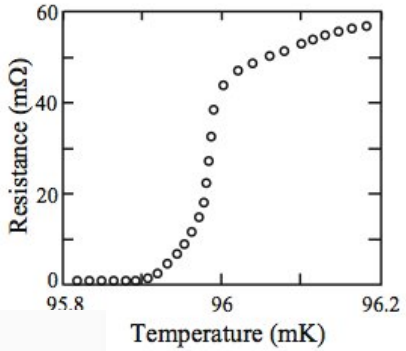


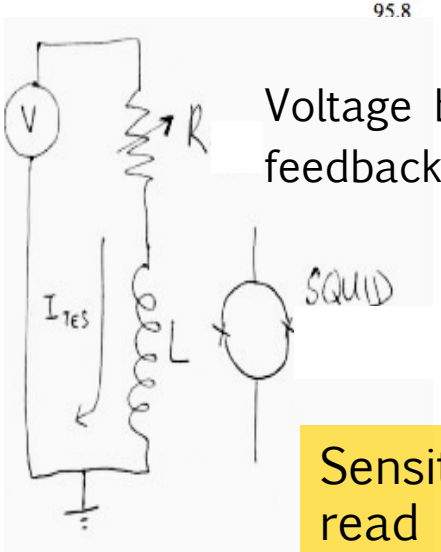


TES Bolometers



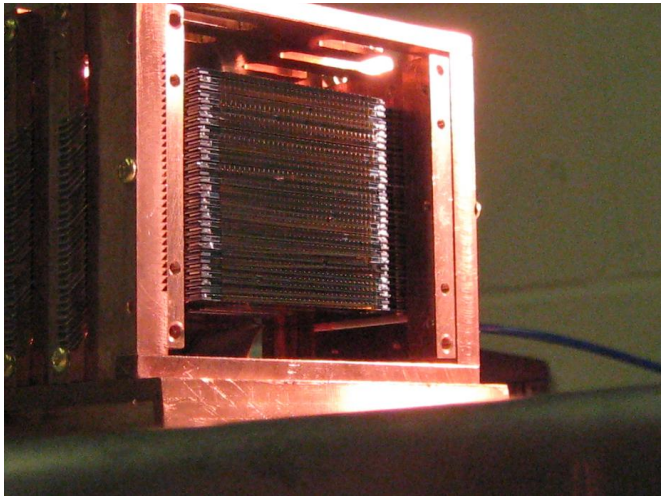
Use superconductor near T_c as thermometer!

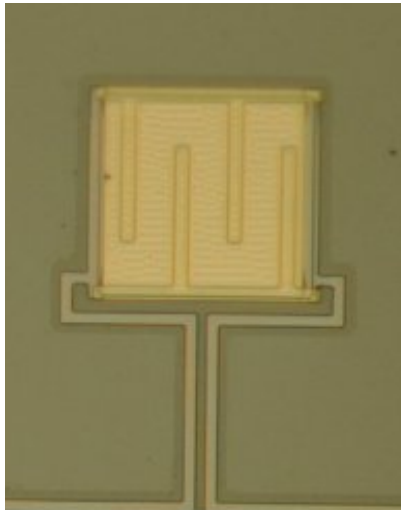


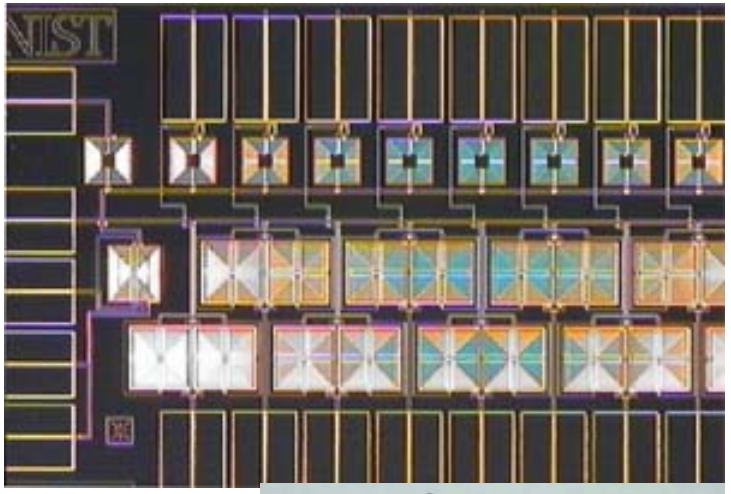


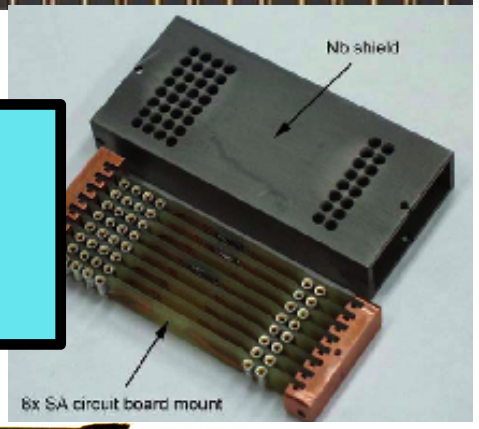
Voltage bias → electrothermal feedback!

Sensitive SQUIDs used to read out ΔI_{TES} via the flux coupled through the series inductance L.

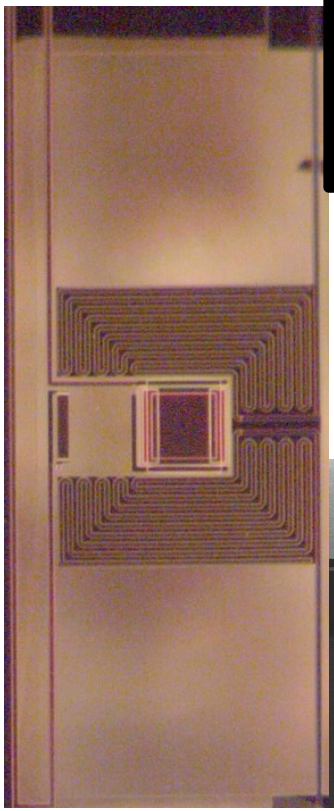


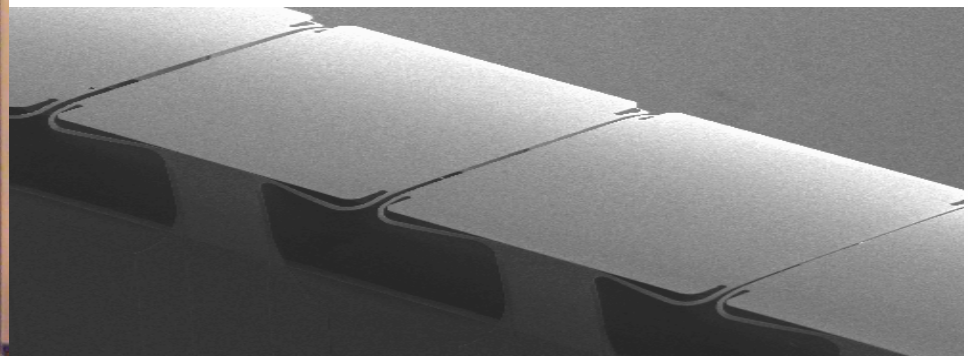


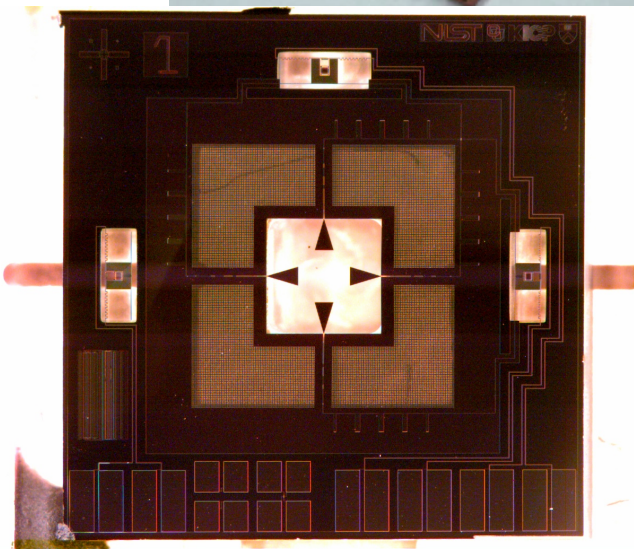




TES Bolometers and Readout (from ACT)

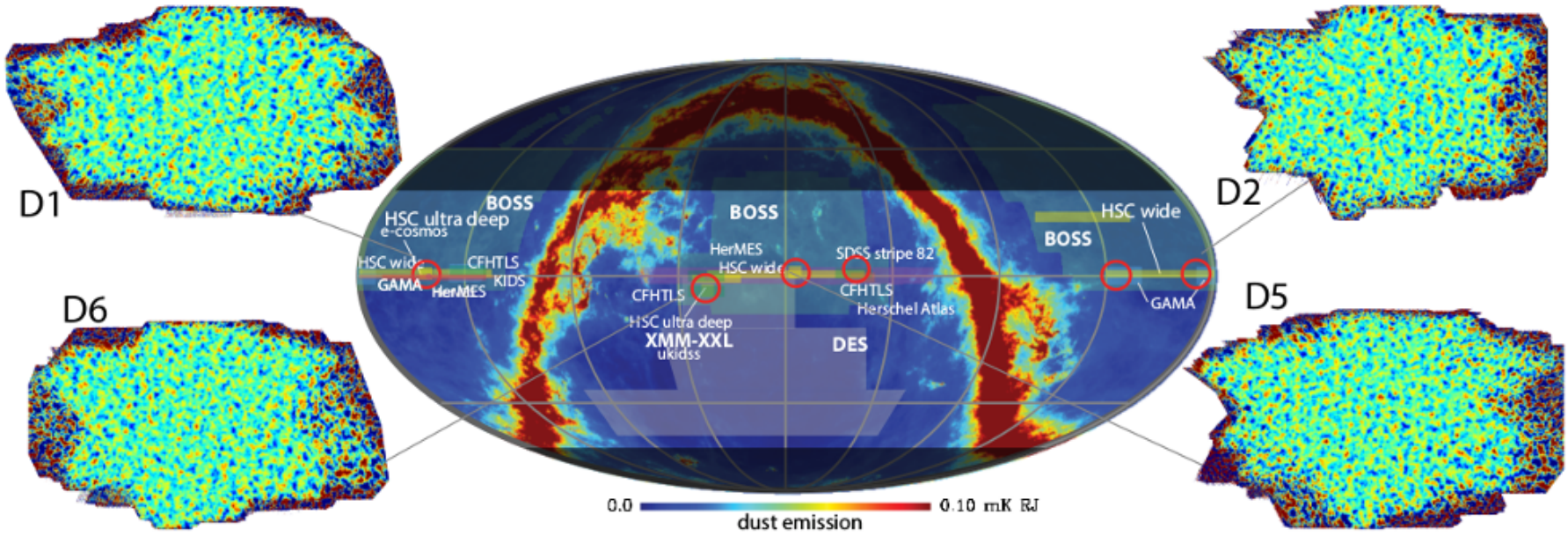






ACTPol First Season Observations

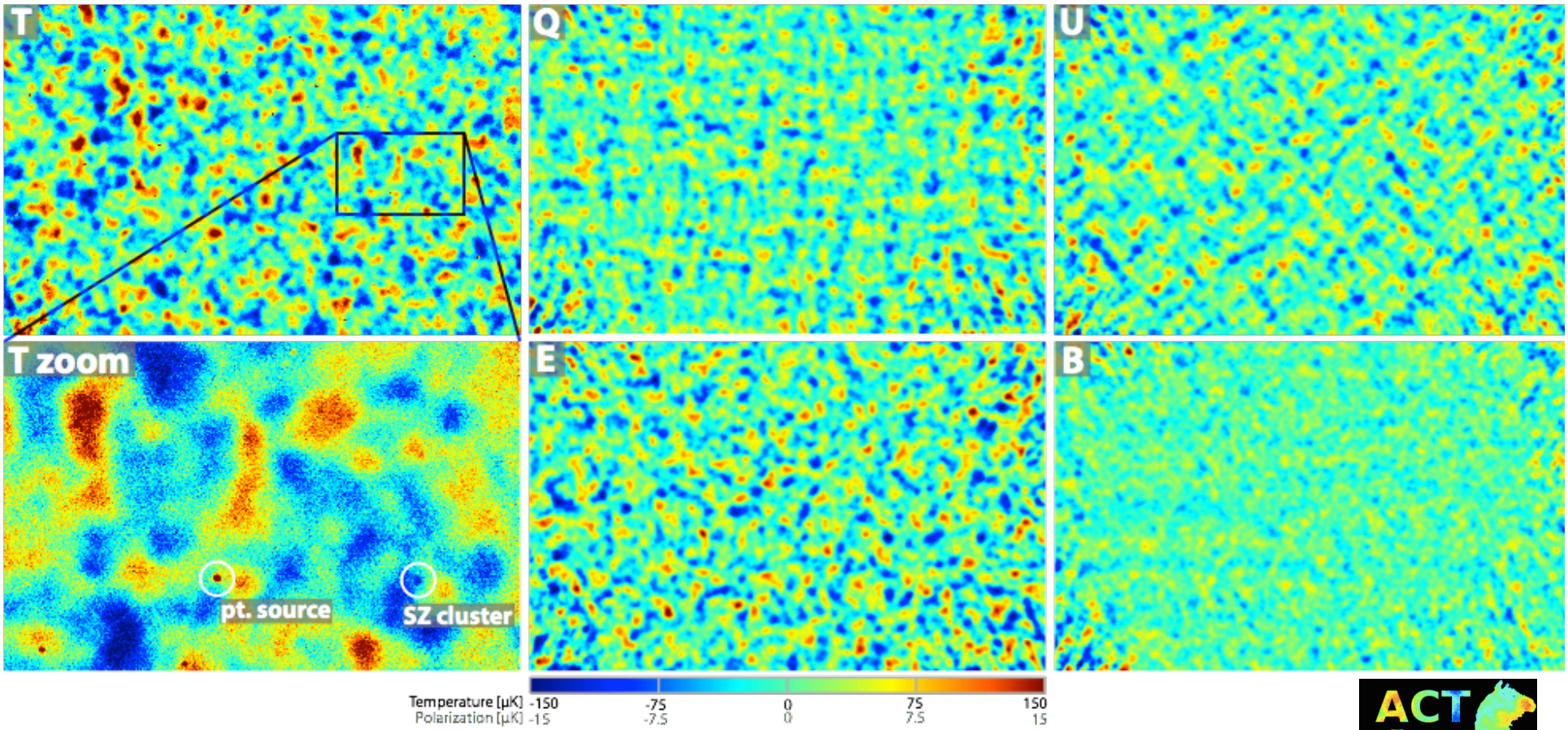
(Naess et al, JCAP10(2014)007)



- 11 Sept 2013 – 24 Dec 2013 (500 hrs)
- Only one 150 GHz array installed then
- Four ~ 70 deg^2 patches
- Overlap with other surveys for xcorr

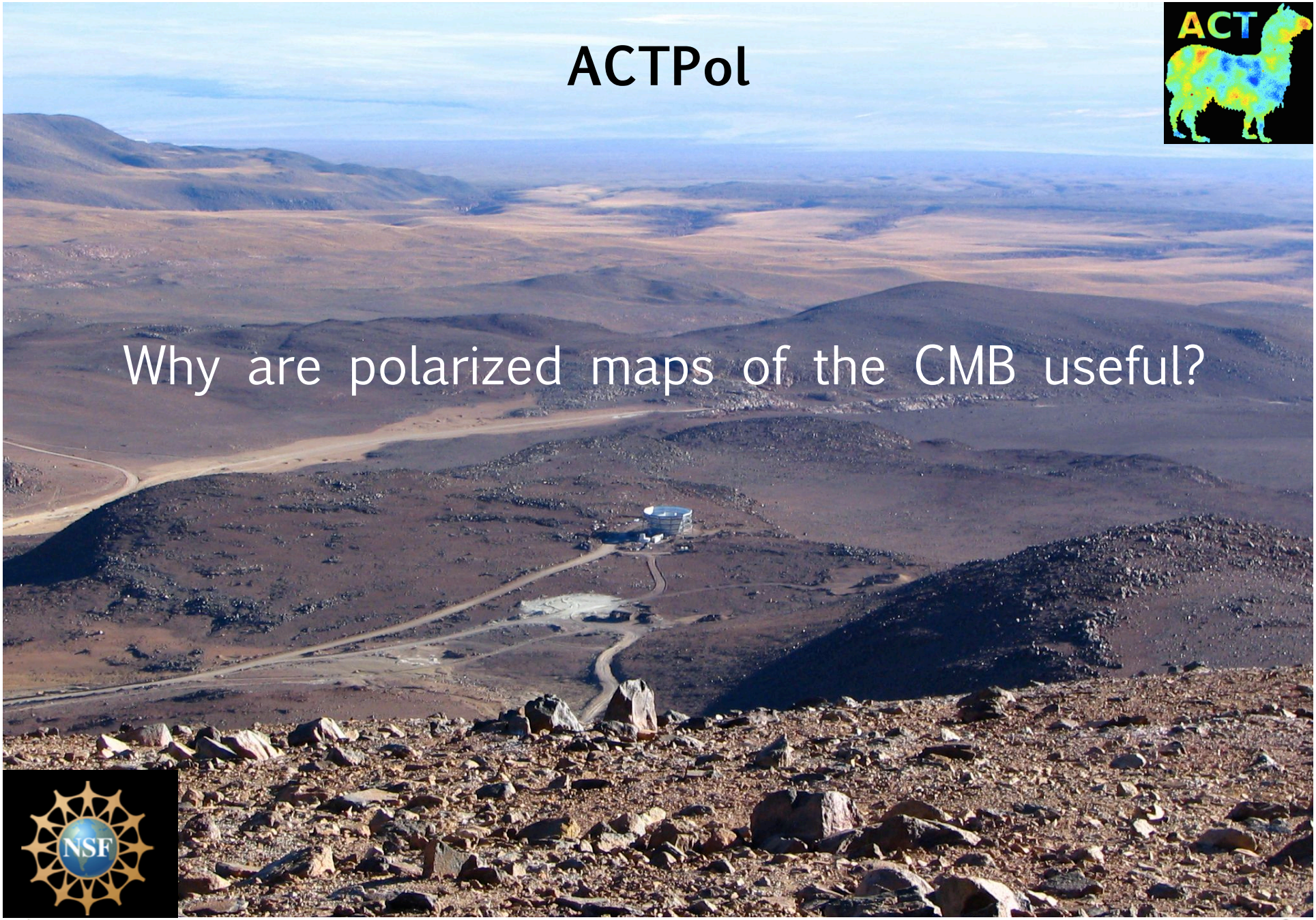
ACTPol First Season Observations

(Naess et al, JCAP10(2014)007)



- One of the 4 ACTPol fields: D6
- (Area ~ 60 deg^2)

ACTPol



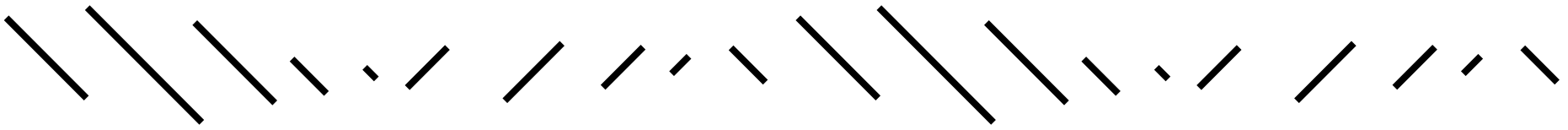
Why are polarized maps of the CMB useful?

Cartoon Visualization of E & B Single Fourier Modes

E-modes are symmetric wrt rotations around the wavevector...

k →

B-modes are **anti**-symmetric wrt rotations around the wavevector...



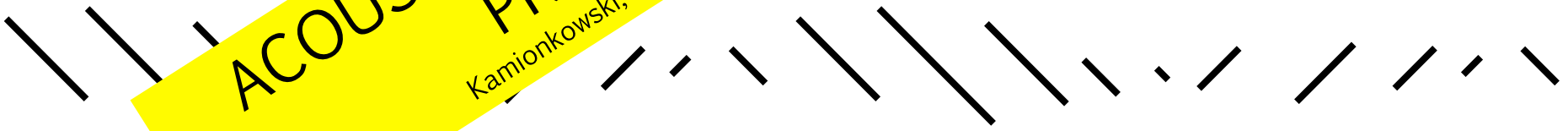
k →

Q,U are LOCAL; E,B are GLOBAL

Cartoon Visualization of E & B Single Fourier Modes

E-modes are symmetric wrt rotations around ...

B-modes are **anti**-s... ...ations around the wavevector...



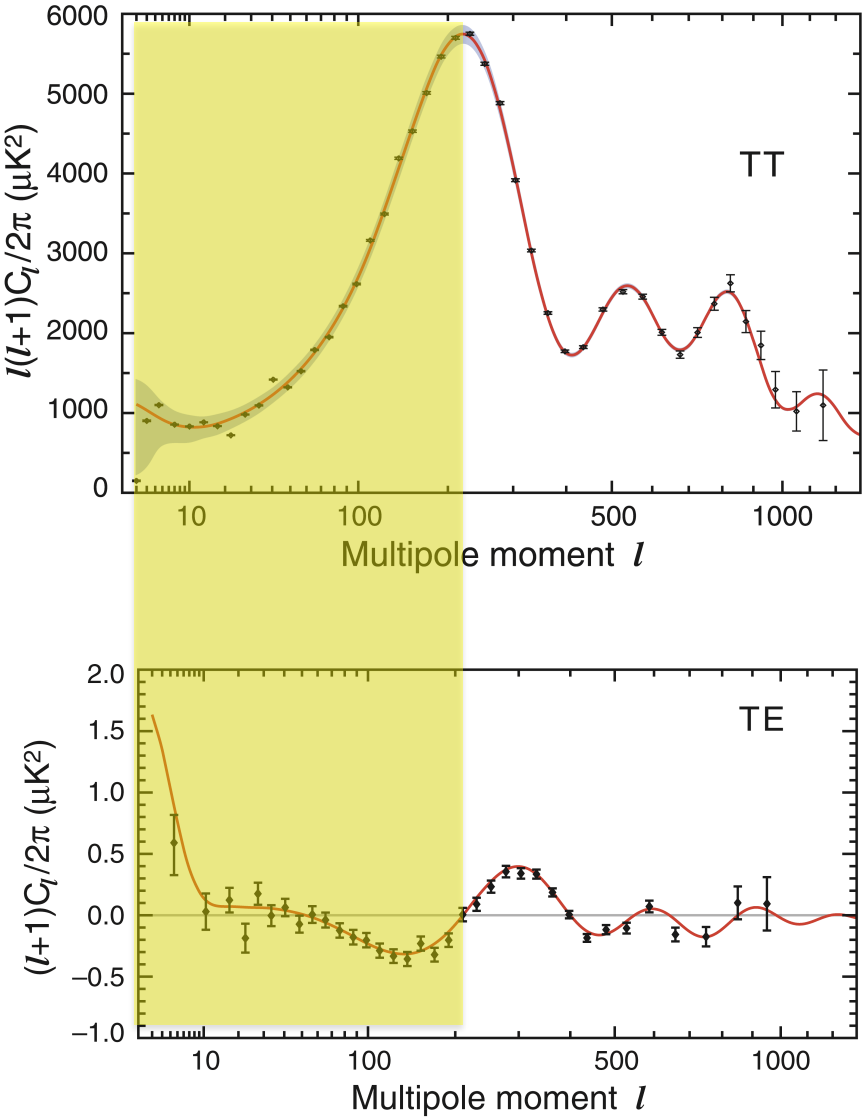
ACOUSTIC OSCILLATIONS (SCALAR MODES) PRODUCE ONLY E-MODES!

Kamionkowski, Kosowsky & Stebbins; 1997; Seljak & Zaldarriaga 1997

k →

Q,U are LOCAL; E,B are GLOBAL

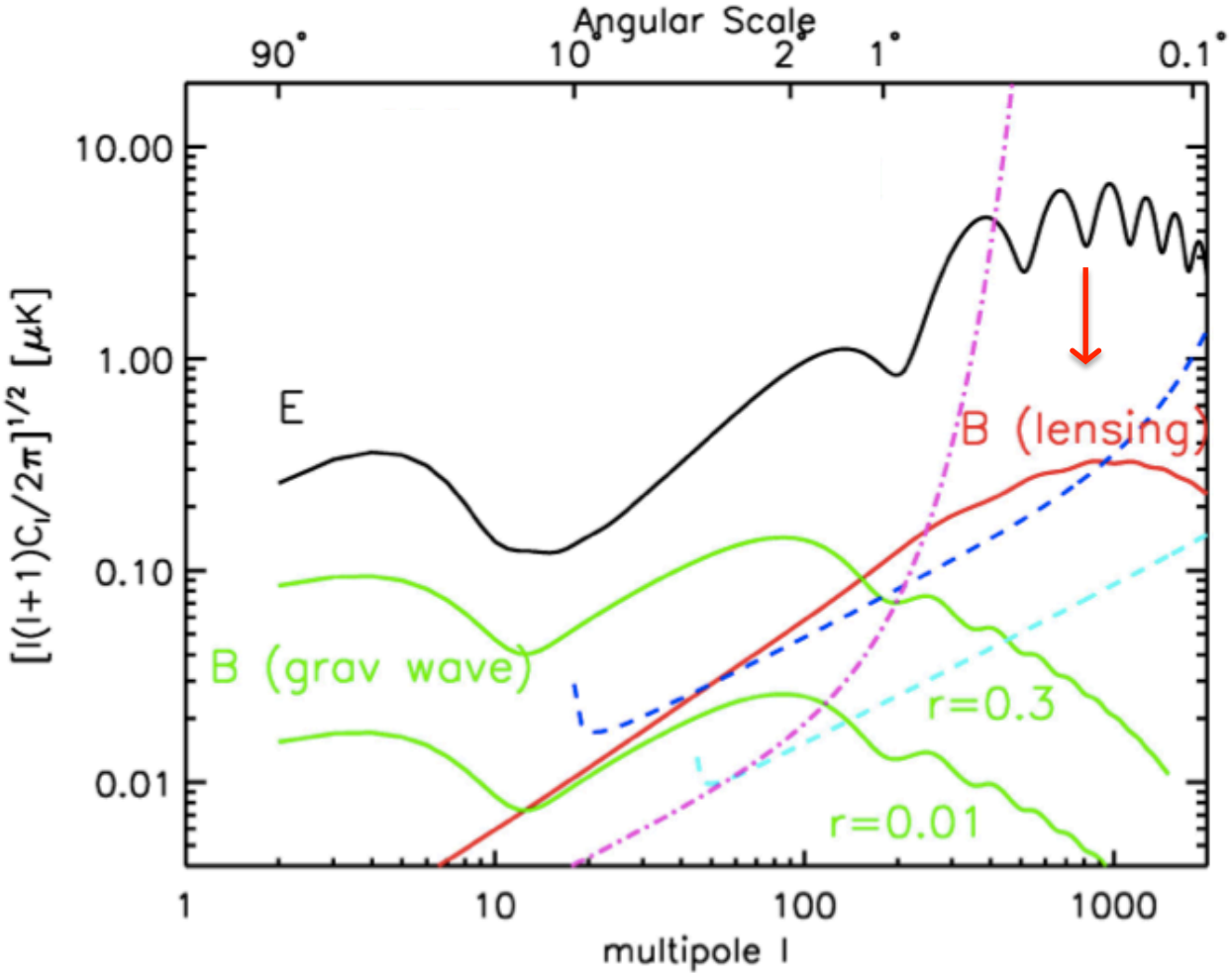
CMB Polarization Spectra & Inflation



PRIMORDIAL FLUCTUATIONS:
1) Exist outside sound horizon (1st peak)

- Evolving potential wells (ISW) could in principle explain low-l TT
- Polarization produced at surface of last scattering (and at the 10% level during reionization)
- TE (anti) correlations below l ~ 200 → superhorizon fluctuations!

B-modes: Inflation & Lensing

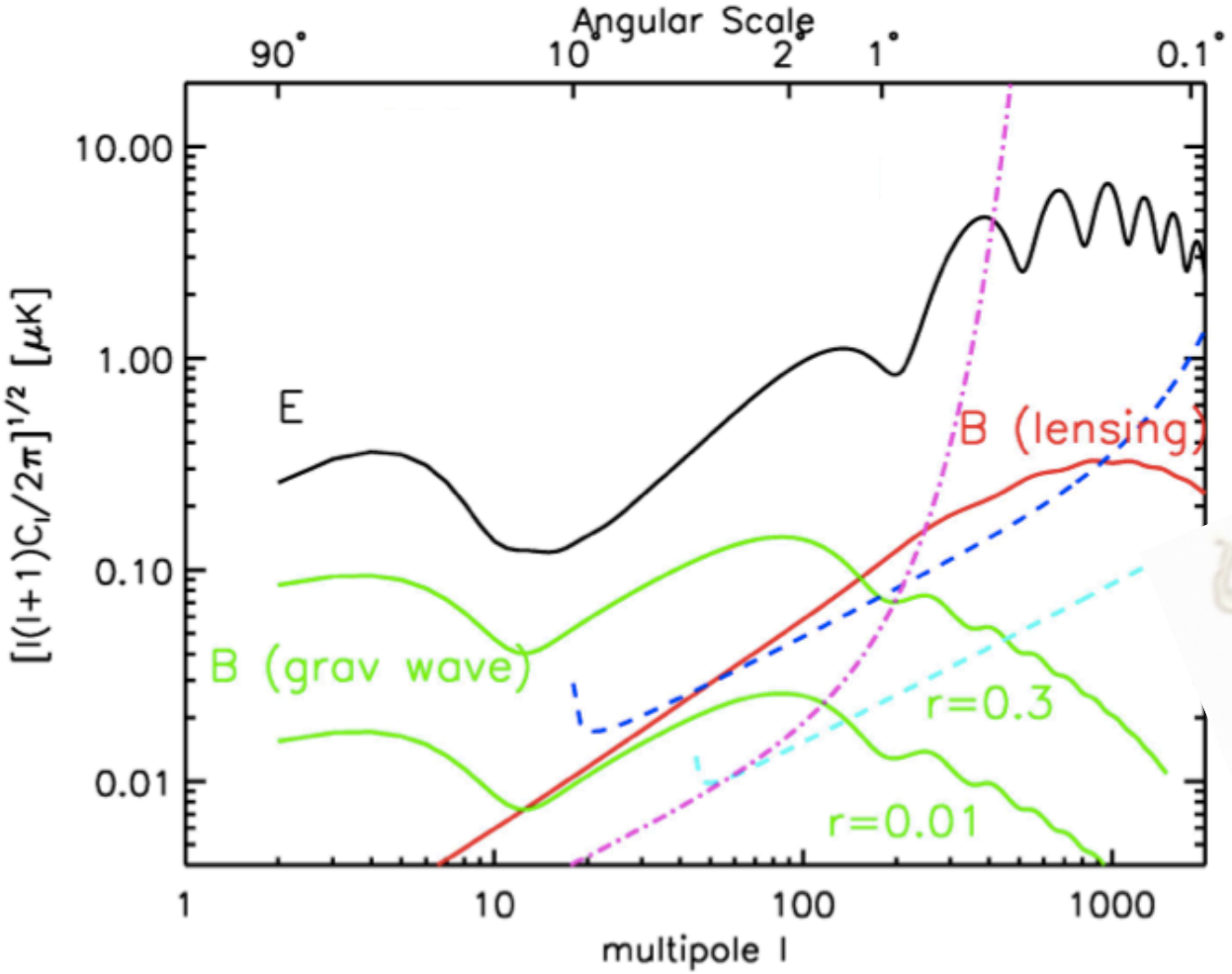


Gravitational lensing rearranges E-modes into B-modes.

The same mechanism that seeds the density fluctuations gives rise to gravitational waves, characterized by the ratio of their power spectra to that from the scalar fluctuations, r. A priori, r is not known.

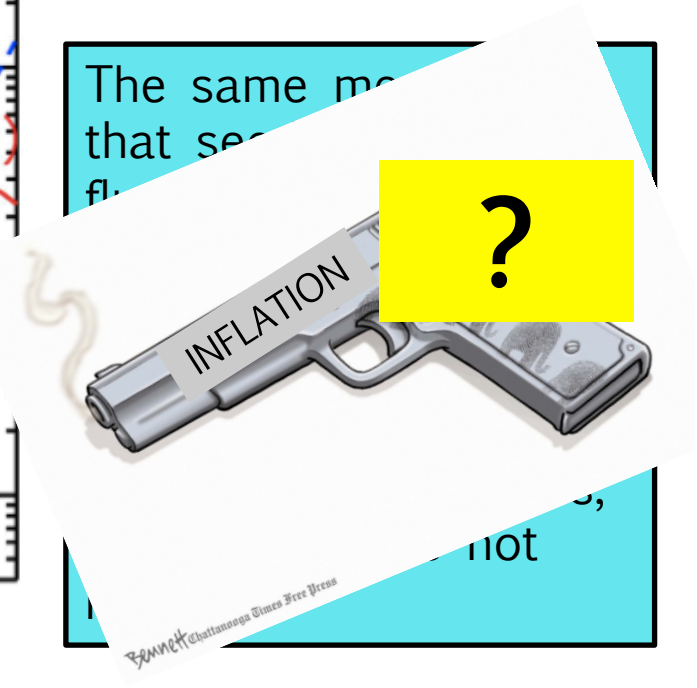
ARNPS 2007

B-modes: Inflation & Lensing



Gravitational lensing rearranges E-modes into B-modes.

The same m… that se… fl…

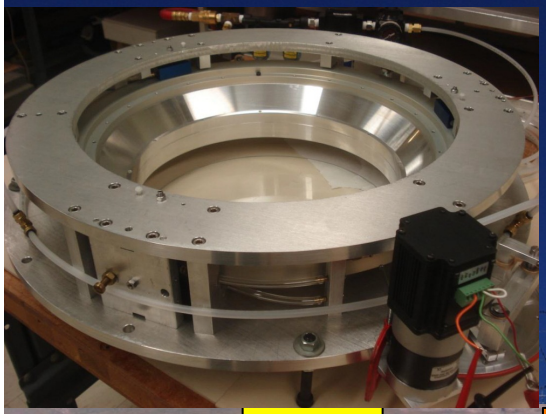


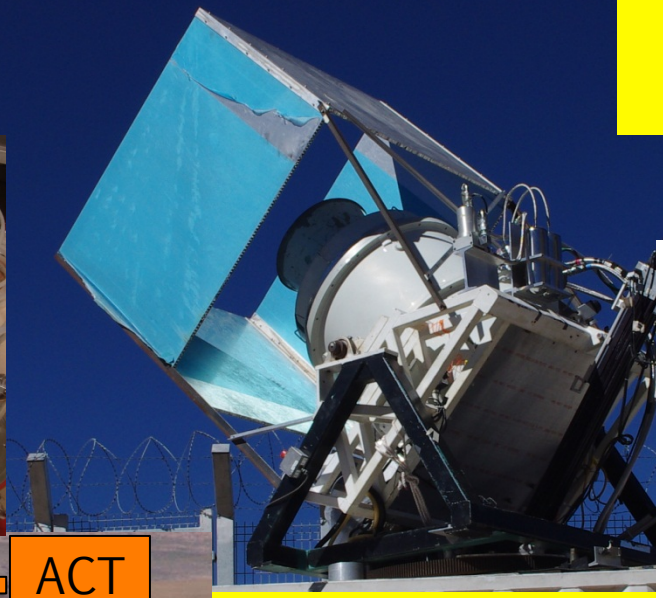
…not

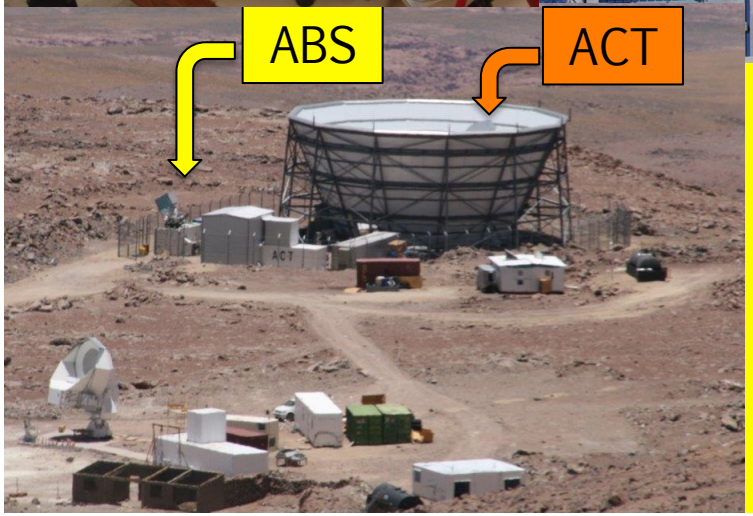
ARNPS 2007

Atacama B-mode Search (ABS)

GOAL: primordial B-modes;
150 GHz only

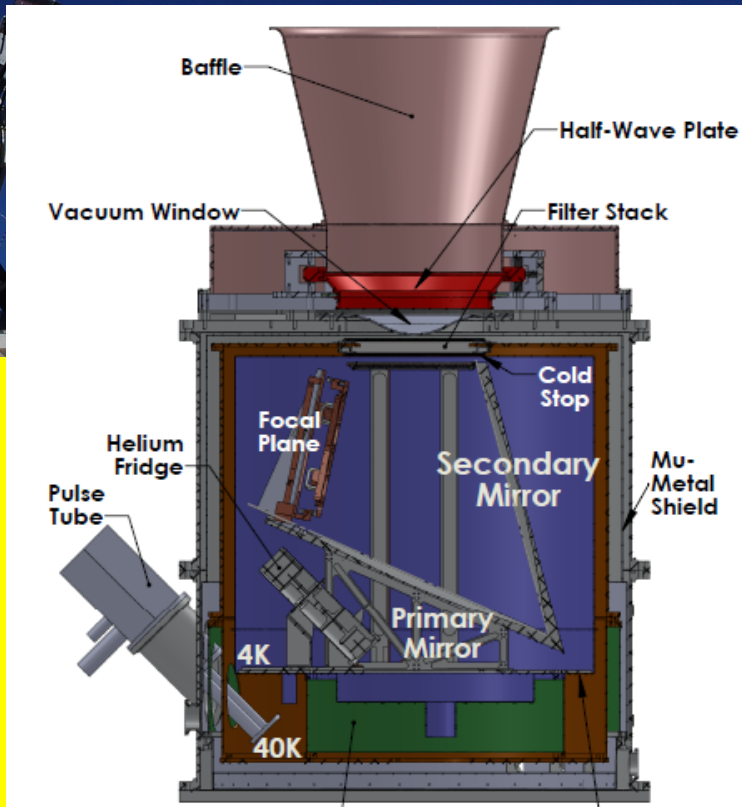




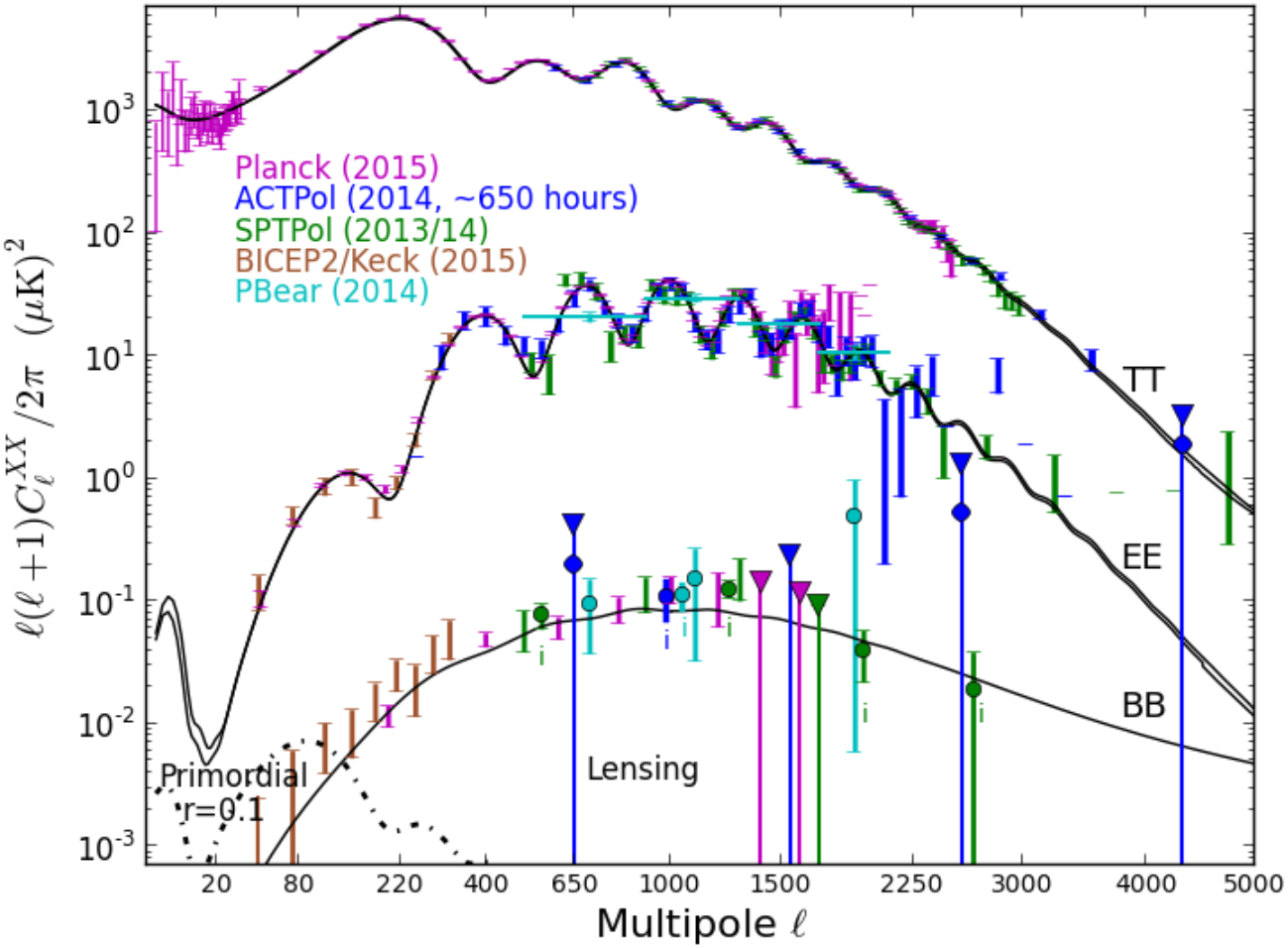


4 K CD* telescope;
~60 cm mirrors;
25 cm aperture;
300 K HWP.

*CD = Crossed-Dragone



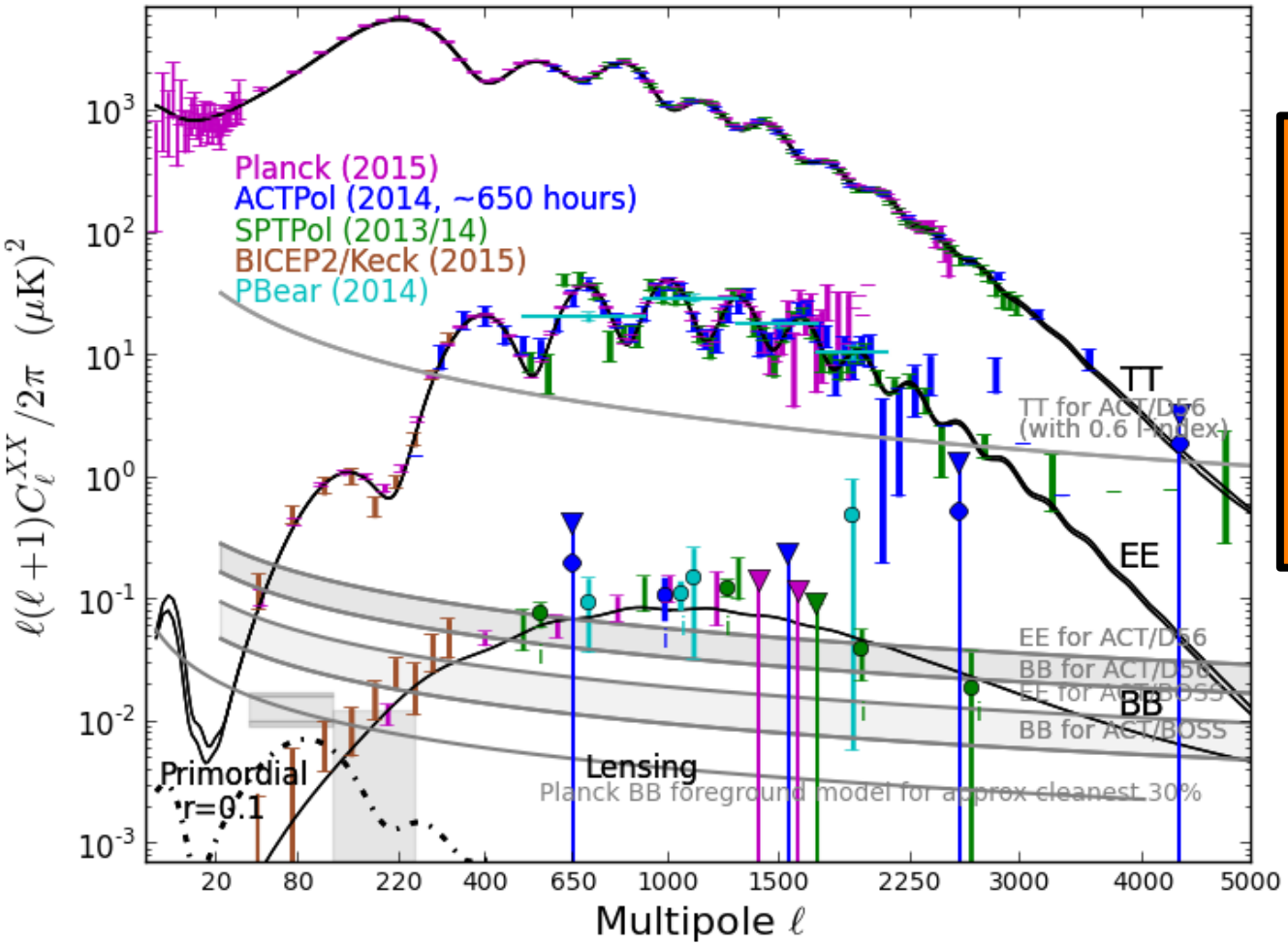
Spectra from ~ Past Year



BB data points are beginning to trace out the power spectrum from EE being converted to BB by gravitational deflection.

Figure courtesy of Lyman Page

Spectra from ~ Past Year

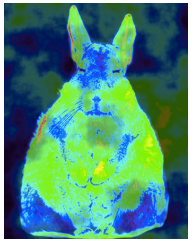


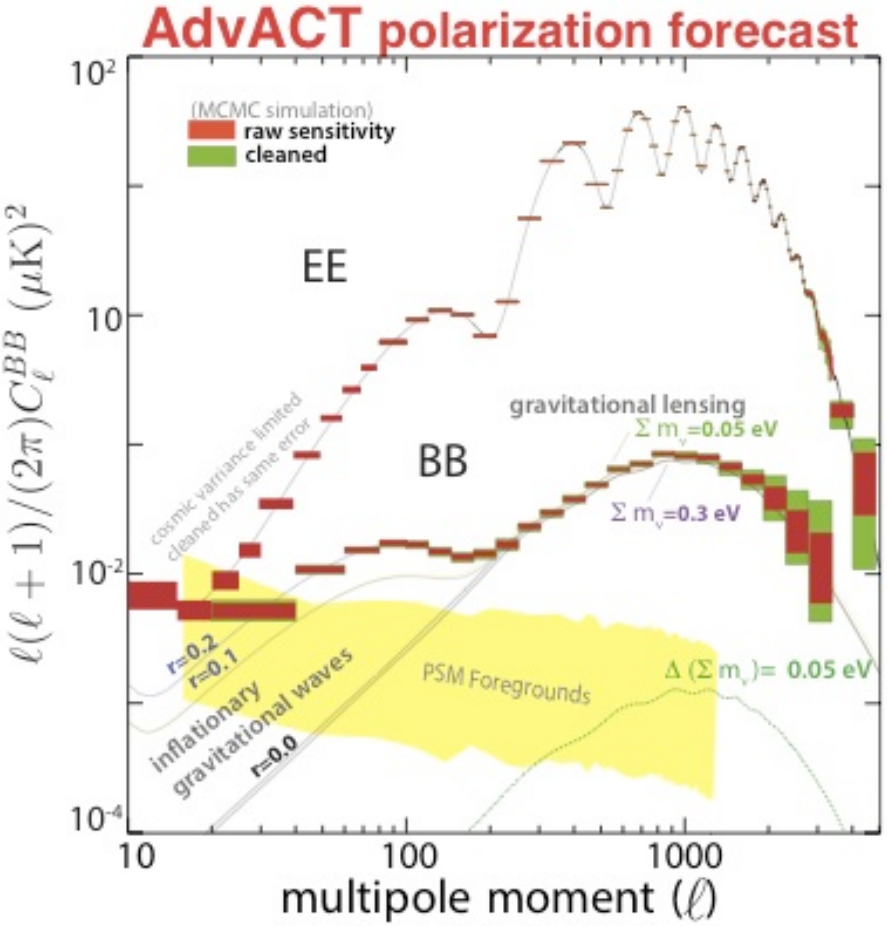
BB data points are beginning to trace out the power spectrum from EE being converted to BB by gravitational deflection.

Figure courtesy of Lyman Page

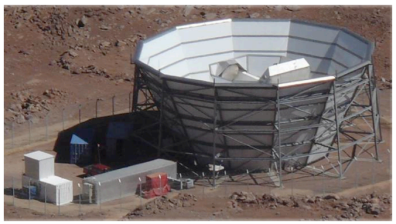
THE SEARCH FOR GRAVITATIONAL WAVES GOES ON!

Advanced ACTPol (AdvACT)

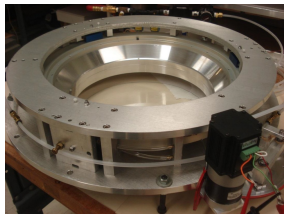


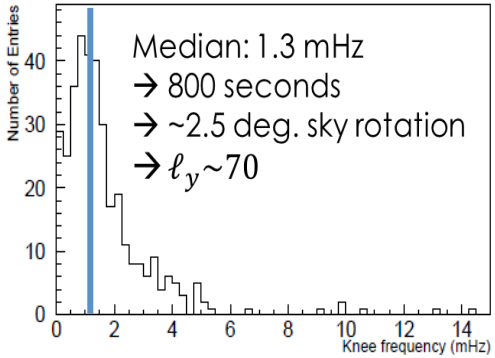


Funding started 9/1/2014
First observations 6/1/2016



+



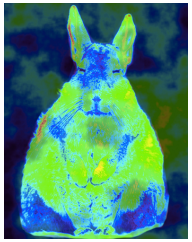


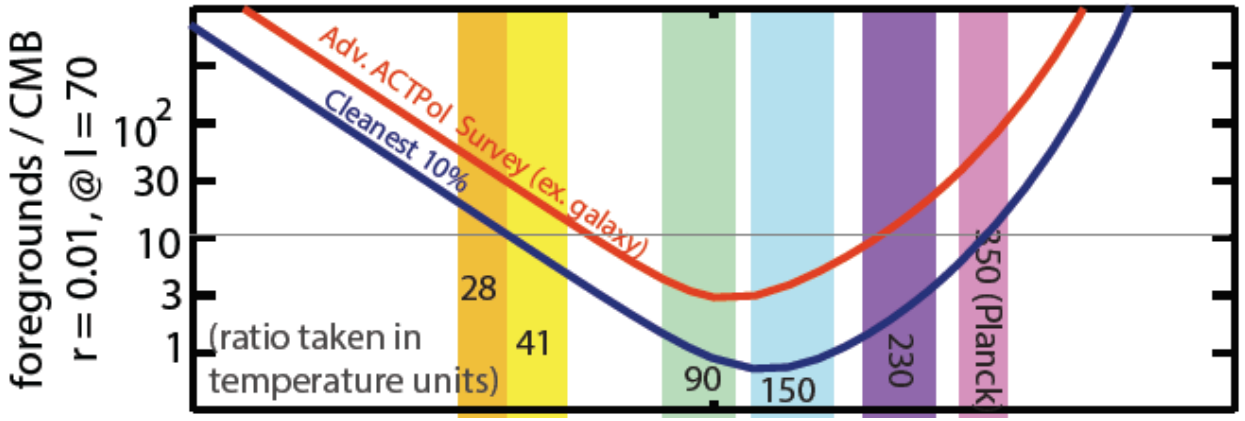
Fast polarization modulation to recover large scales

ABS on-sky performance

A ~half-sky survey in FIVE FREQUENCY BANDS with fast polarization modulation

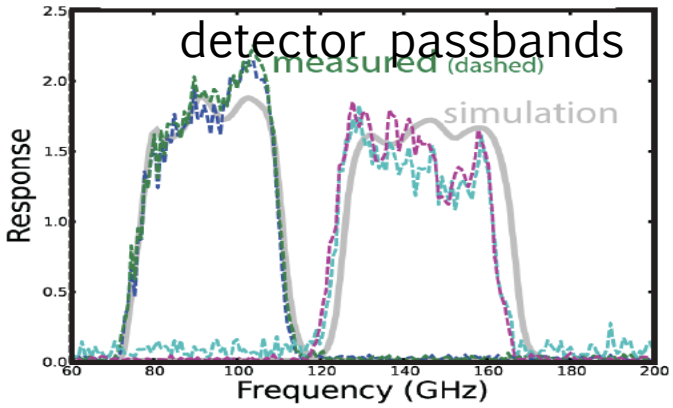
Advanced ACTPol (AdvACT)

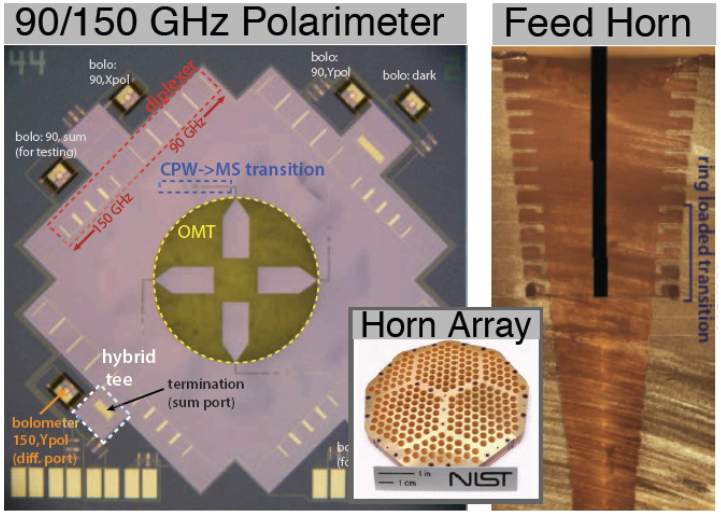




- Clean SYNCHROTRON AND DUST with five AdvACT bands + Planck-353-GHz.
- Projections on previous page were after cleaning!

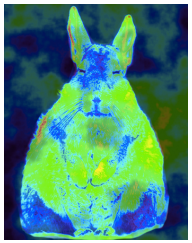
- New dichroic detectors
- Prototype array is now installed on ACT.

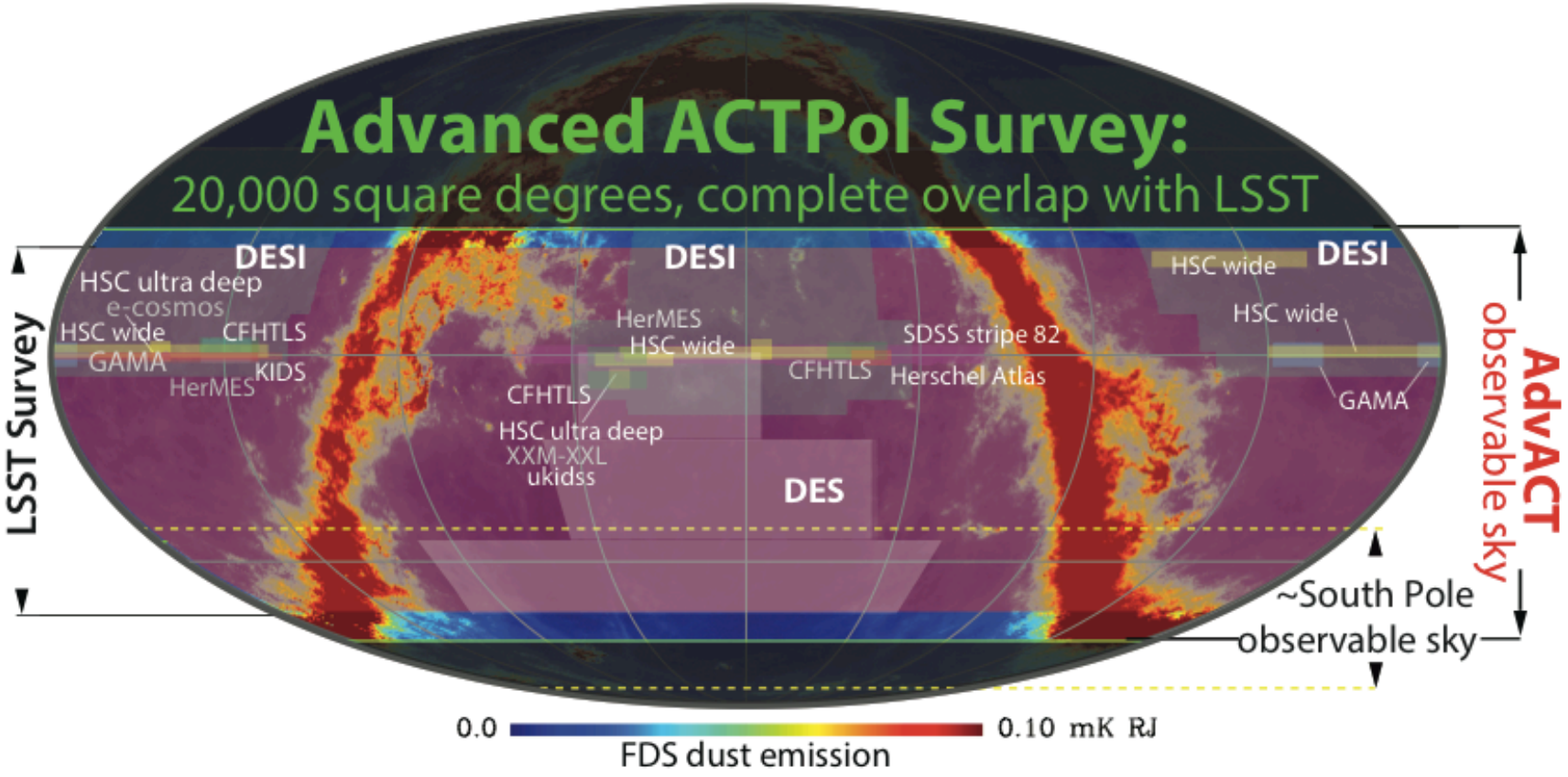




Datta et al., JLTP (2014)

AdvACT Survey Plans

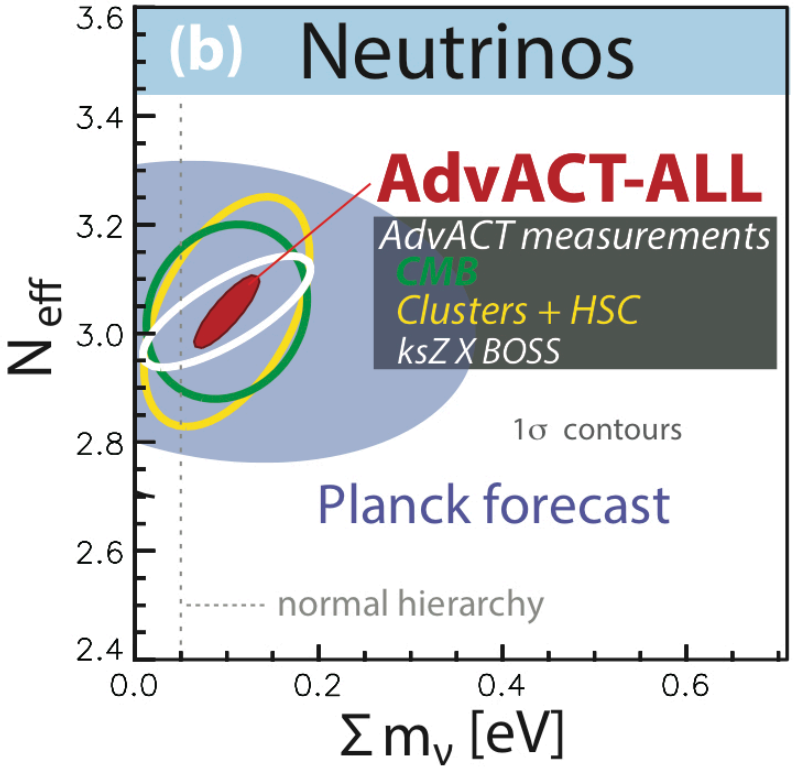




Complete overlap with DES, LSST & DESI survey regions

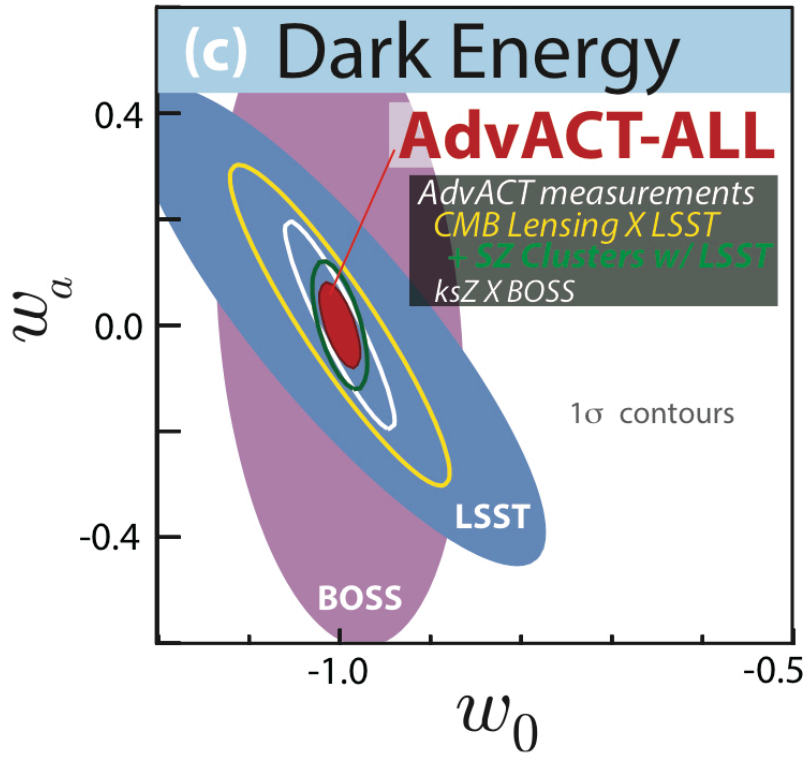
AdvACT Projections

(based on combining many analyses & cross-correlations)



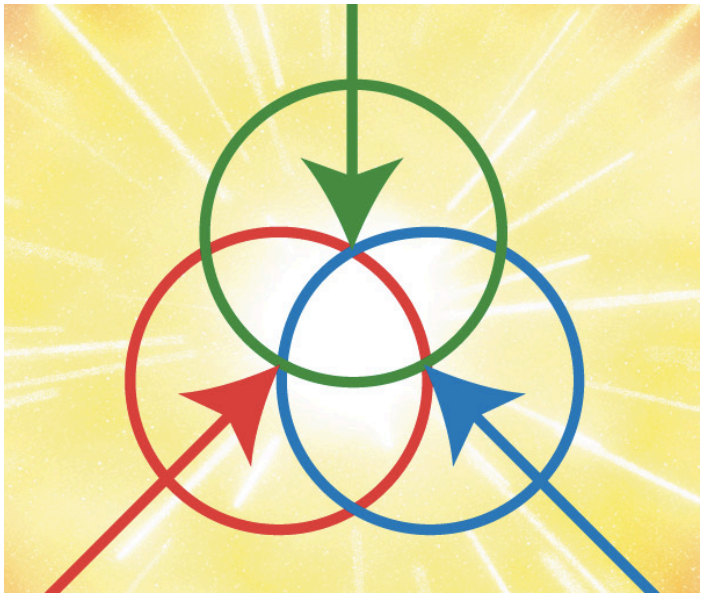
Projected to improve Planck limit on Σm_ν by 10x!

Projected to improve LSST's DE FOM by 20x!



The Future on Earth

CMB S4 & the DOE & NSF in the next few years …
Grand unification of CMB projects?



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