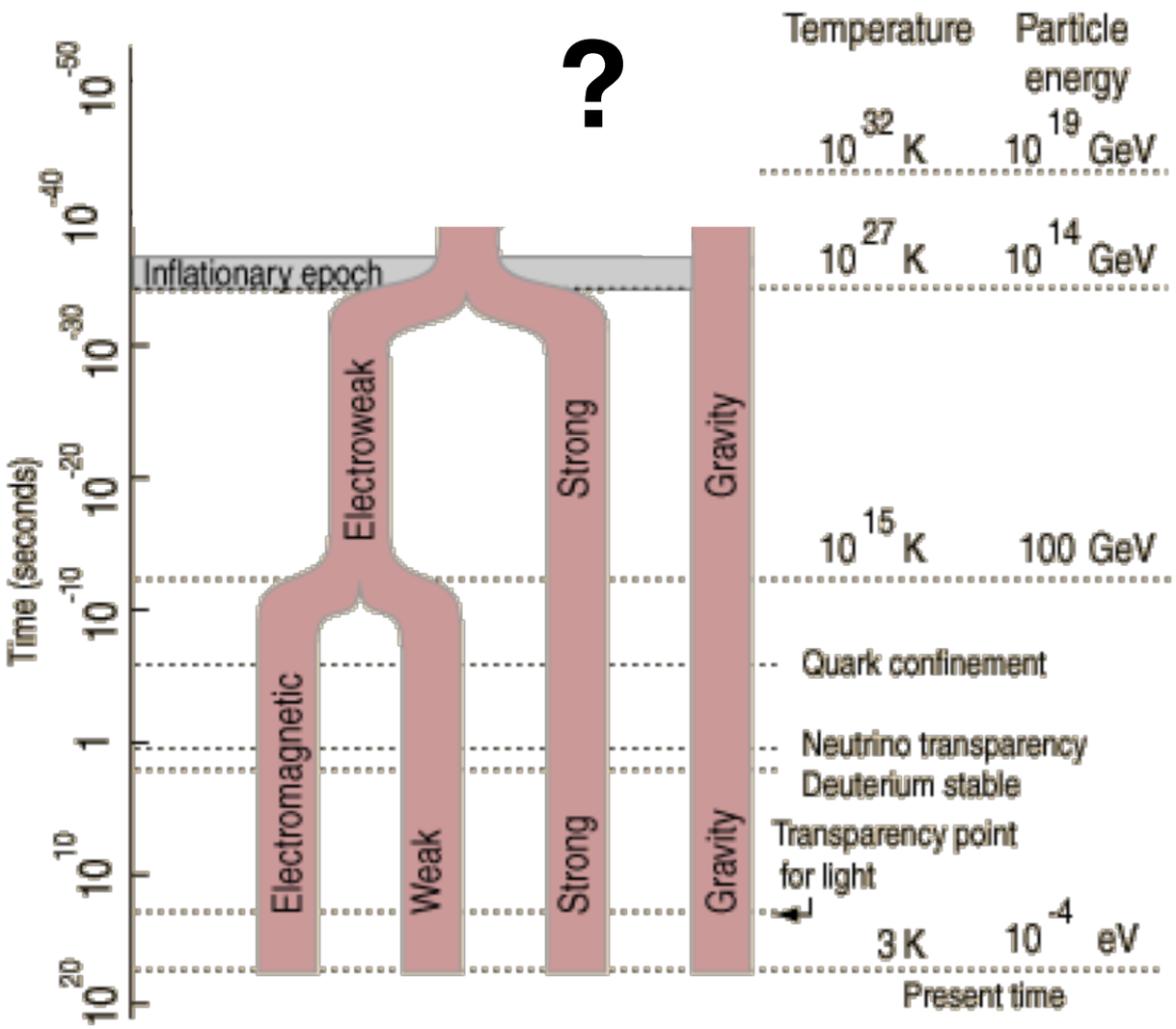
Physics and Cosmology with the Cosmic Microwave Background

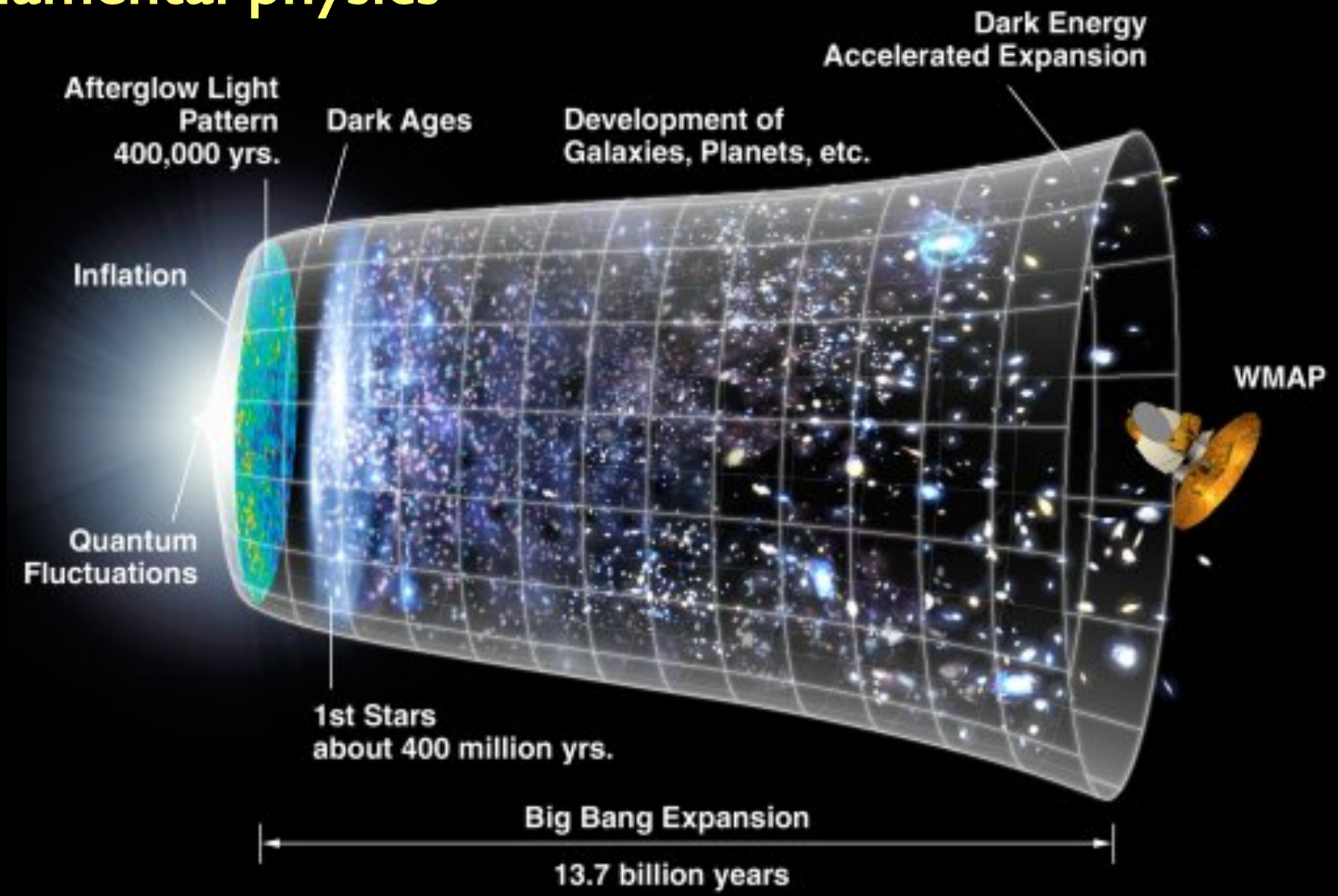
John Carlstrom
University of Chicago

Photo credit: Jason Gallicchio

Universe as a Physics Laboratory



CMB measurements probe cosmology, astrophysics and fundamental physics

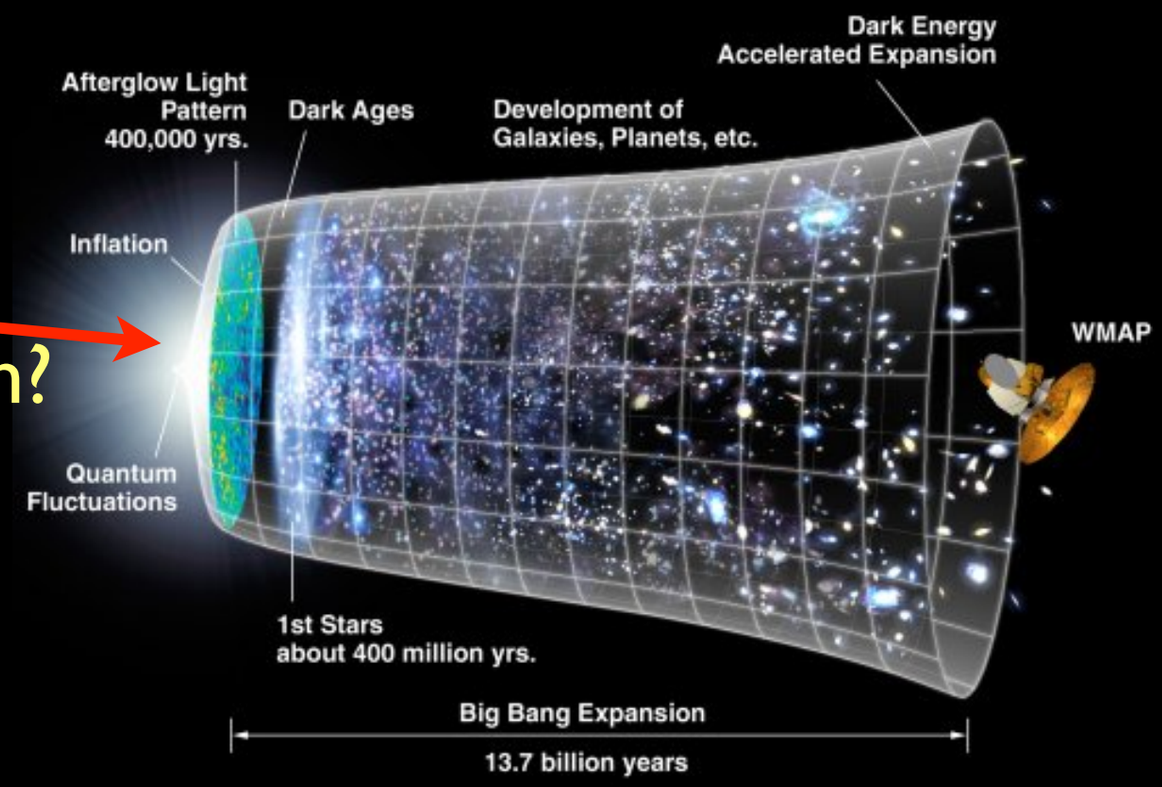


NASA/WMAP Team

Inflation?

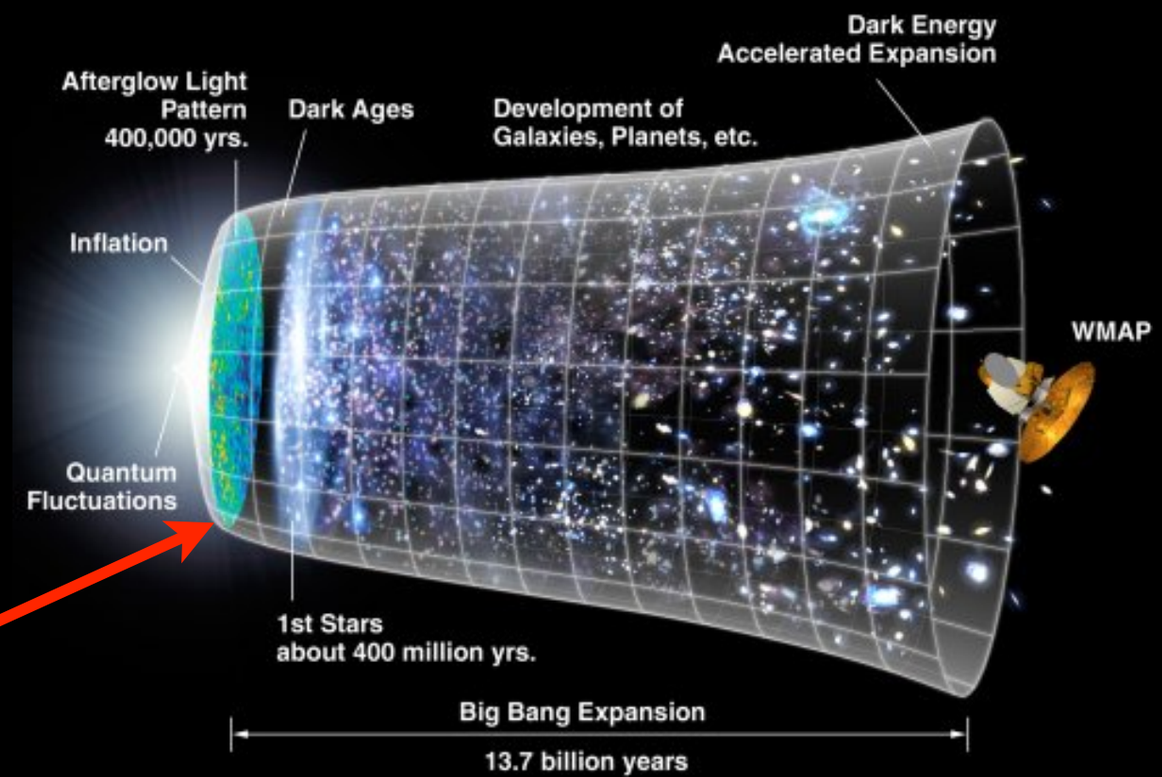
Universe expands by $>e^{60}$
solving smoothness problem,
flatness and more..

What drove inflation?
What is the energy scale of inflation?



- spectral index of primordial fluctuations, n_s
- non-Gaussianity?
- constrain tensor to scalar fluctuations
- detect inflationary gravitational waves?

➡ *through precision temperature and ultra-sensitive polarization measurements of the primary CMB anisotropy*



Physics at recombination

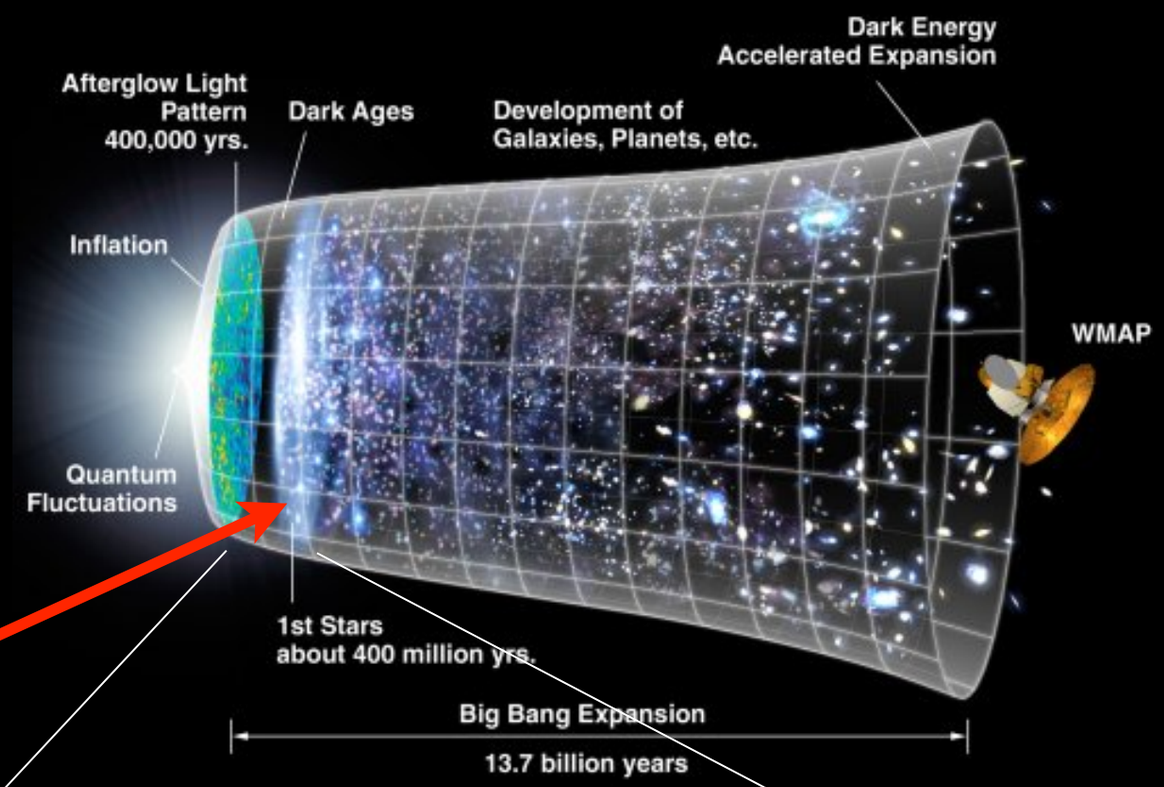
Universe cools enough to form neutral H.
Photons start free-streaming

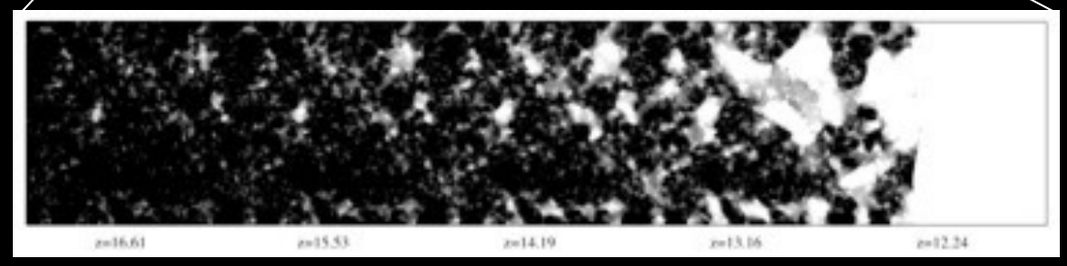
- Measure primordial fluctuations
- Inventory stuff in the universe
- Number of relativistic species, helium abundance
- Recombination history; energy injection

➡ *through precision measurement of CMB power spectrum to fine angular scales, i.e., covering the "damping" tail*

➡ *eventually through spectral distortions and recombination lines*

Reionization "Cosmic Dawn"

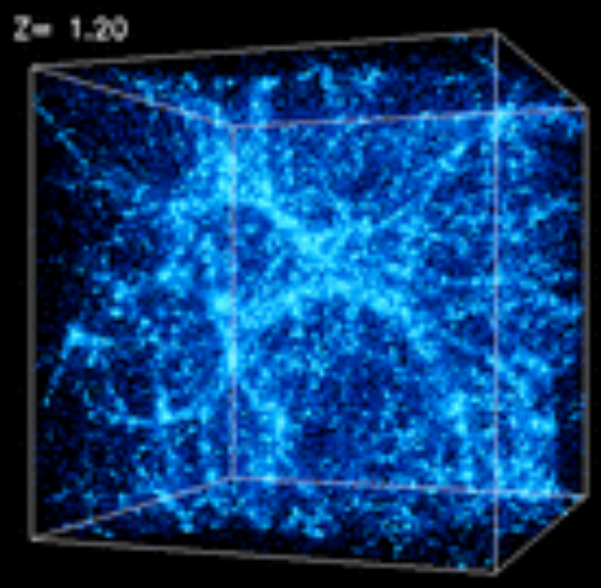




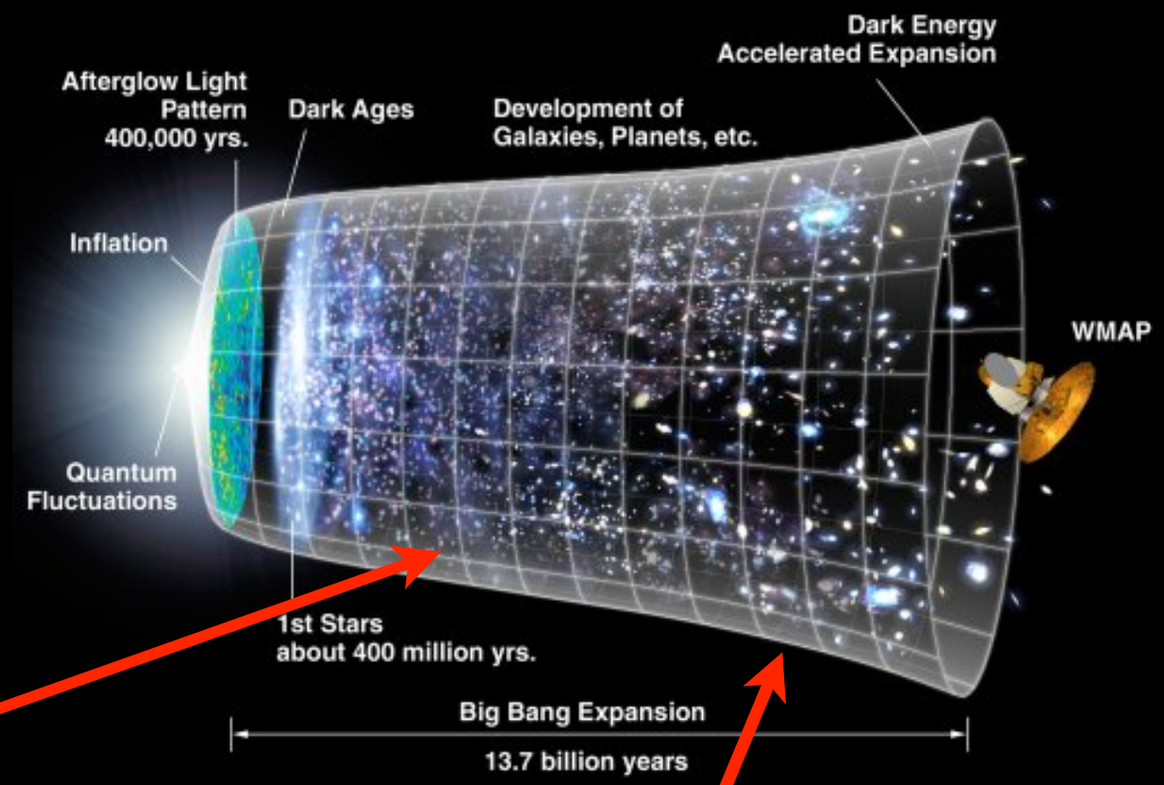
Patchy reionization, Zahn et al, 2005

When and how did it proceed?

- ➡ *through measurement of CMB polarization imprint of reionization on large angular scales*
- ➡ *through measurements of the diffuse kinematic SZ effect on small angular scales*



Credit: Kravtsov



Structure Formation

Gravitational collapse creates increasingly large structures

- What is dark matter?
- Masses of the neutrinos

Cosmic Acceleration

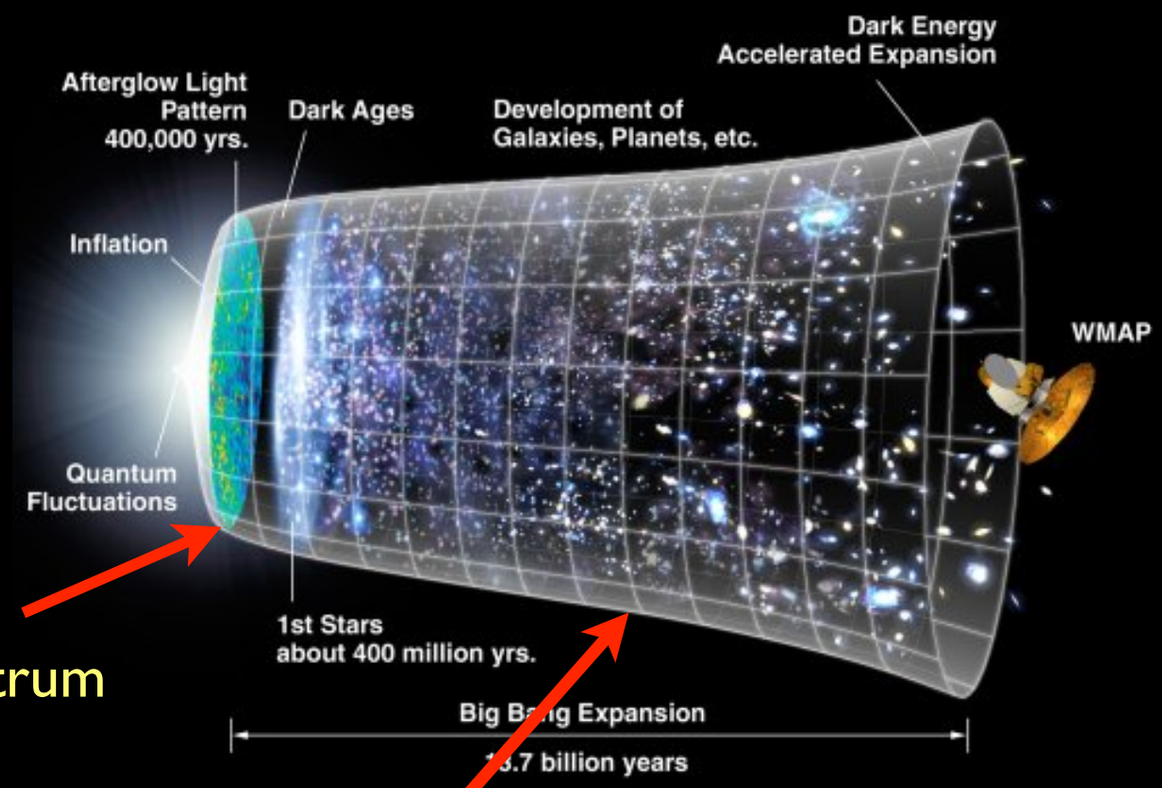
Dark energy begins accelerating the expansion of the Universe.

- Is dark energy dynamic or a cosmological constant?
- Is GR correct on large scales?

➡ *structure formation through lensing of the CMB and kinematic SZ effect*

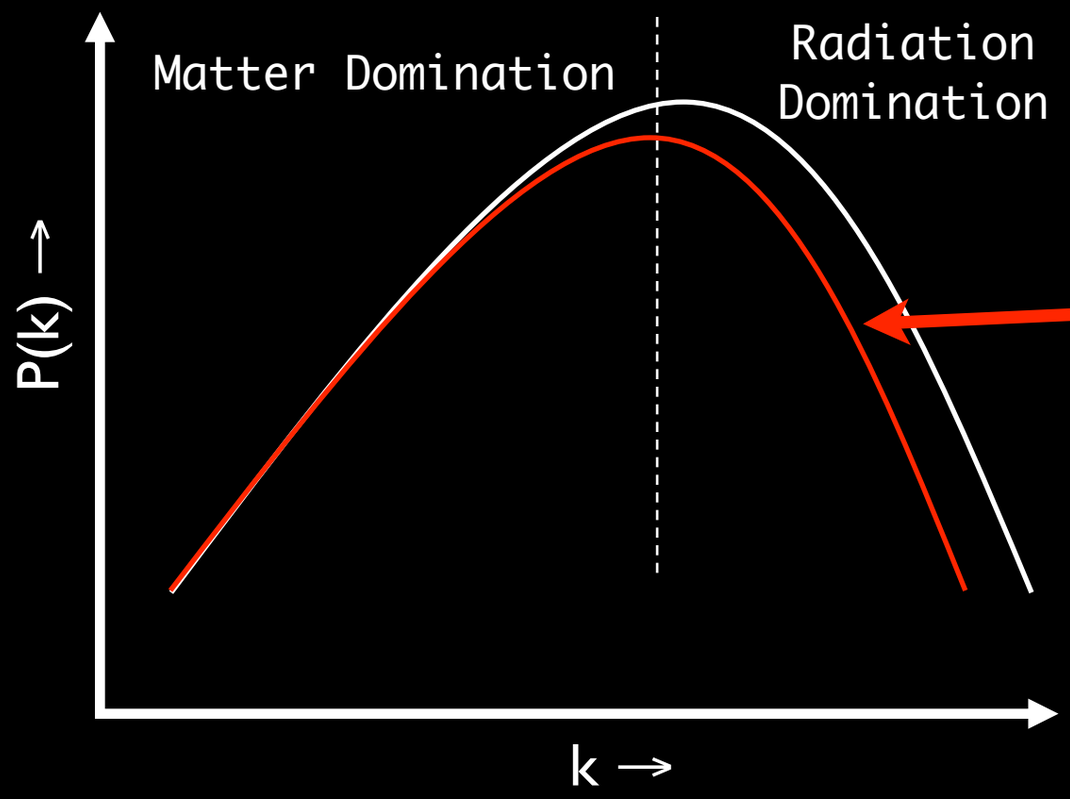
➡ *measure evolution of Galaxy Clusters through thermal SZ effect*

E.g., Neutrino constraints



Dark Radiation

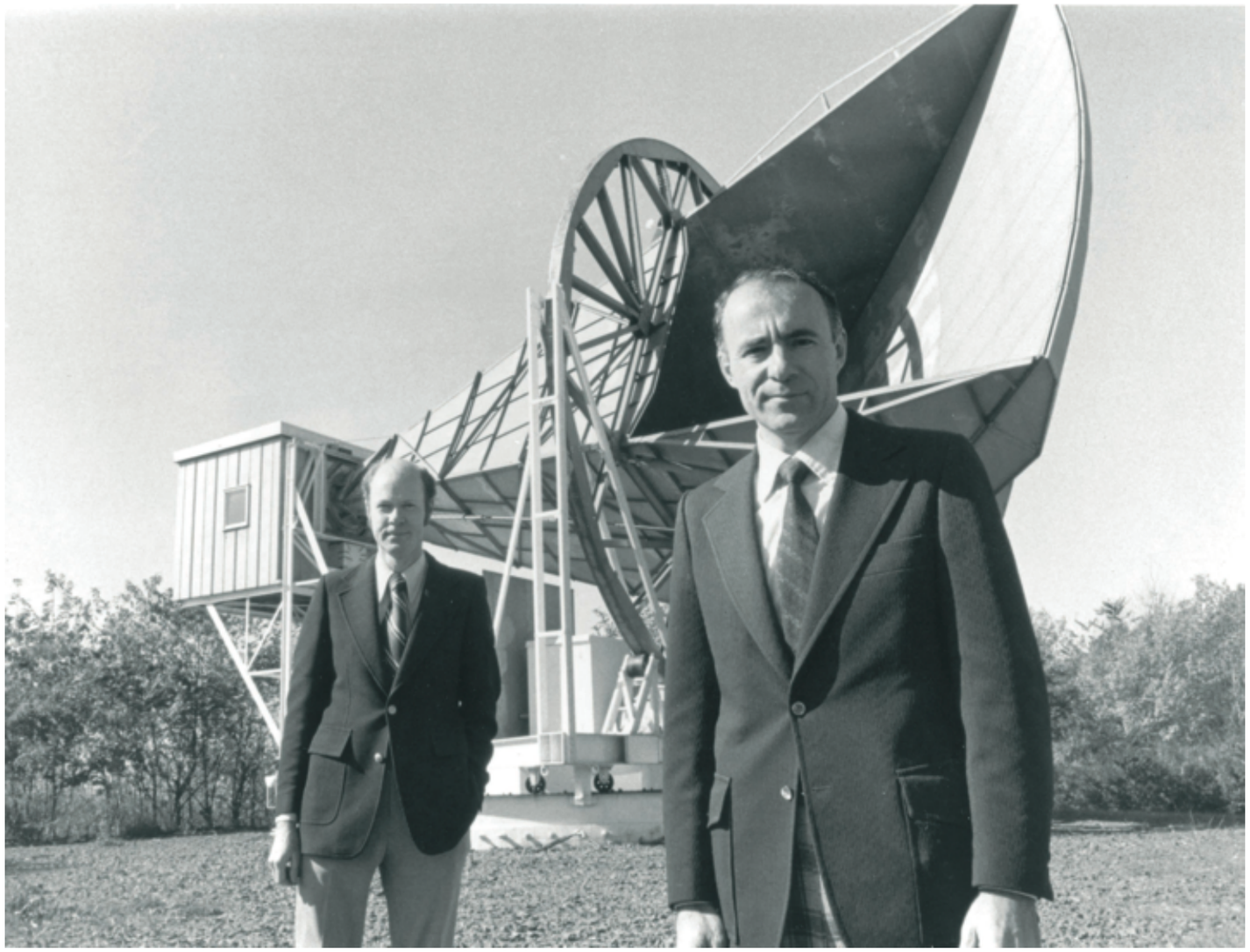
N_{eff} - effective number of relativistic species
uniquely impacts intrinsic CMB power spectrum



$\Sigma m_\nu > 0$

Sum of the neutrino masses
impacts growth of large scale structure,
i.e., the matter power spectrum measured
by CMB lensing.

2015 marks the 50 year anniversary of the Discovery of the Cosmic Microwave Background



Arno Penzias & Robert Wilson in front of the 20ft Bell Labs antenna used to discover the microwave background in 1965

"smoking gun" evidence for a Hot Big Bang

1978 Nobel Prize

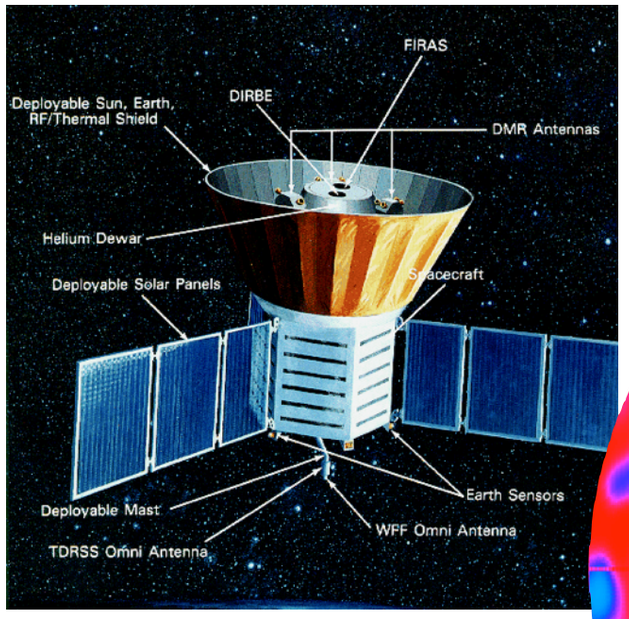
Enormous impact on Cosmology

Penzias & Wilson pp 419 [ApJ 142, 1965]
Dicke, Peebles, Roll & Wilkinson pp. 414
Following the work of Alpher, Gamov, Herman and others in 1940-50s

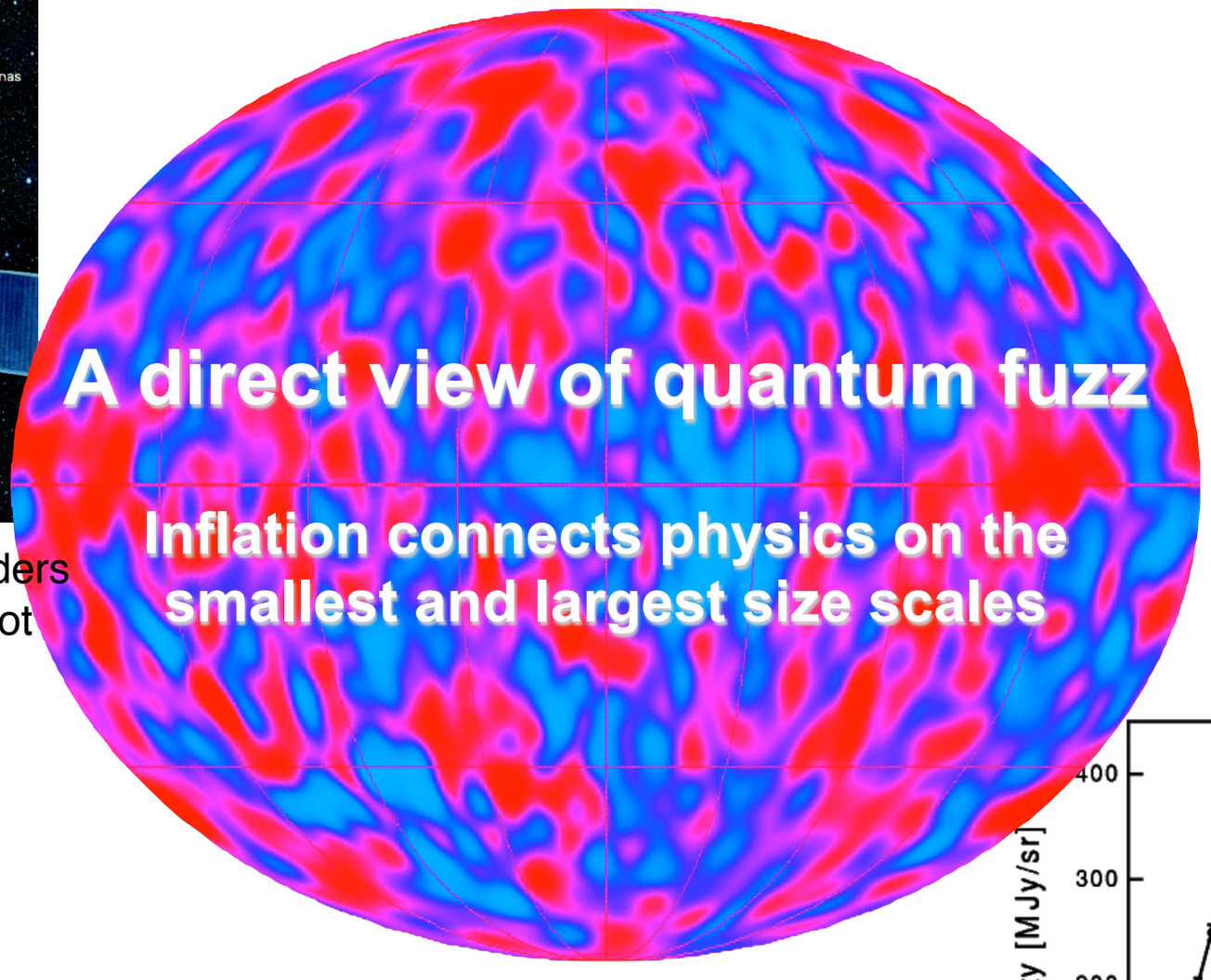
23 years ago

Discovery of CMB Anisotropy

COBE Satellite



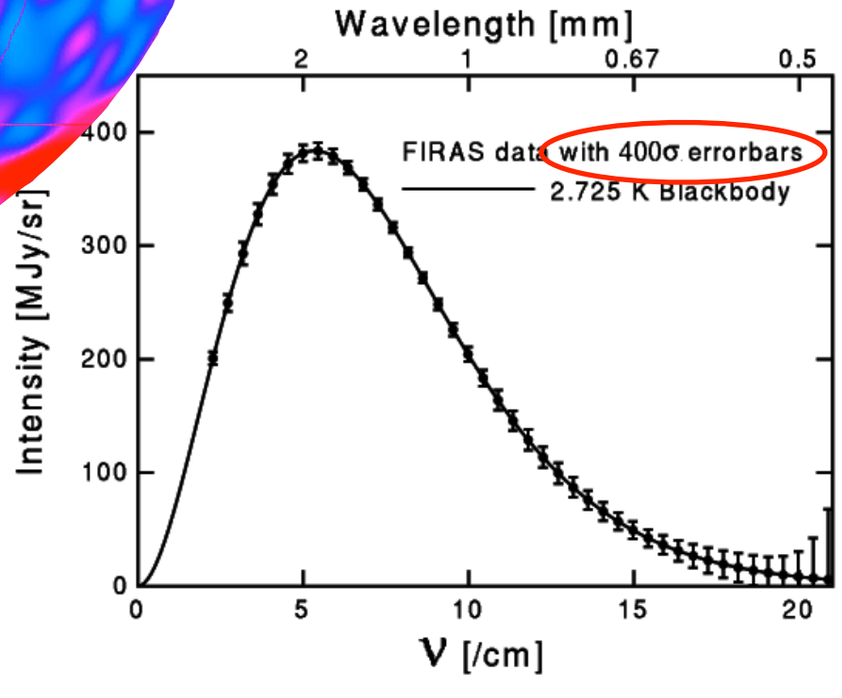
2006 Nobel Prize to Team leaders
John Mather & George Smoot



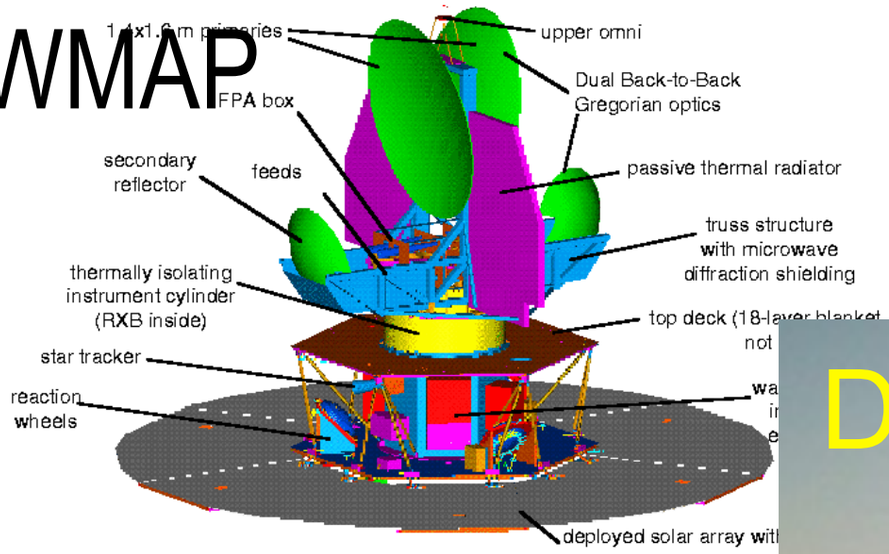
2006 Nobel Prize
John Mather
George Smoot

Isotropic to a part in 10^5

motivated inflationary
quantum mechanical origin
of our universe



WMAP



TOCO

Experiments w/ tens of detectors circa 1995-2005

DASI

ACBAR

VSA

QUaD

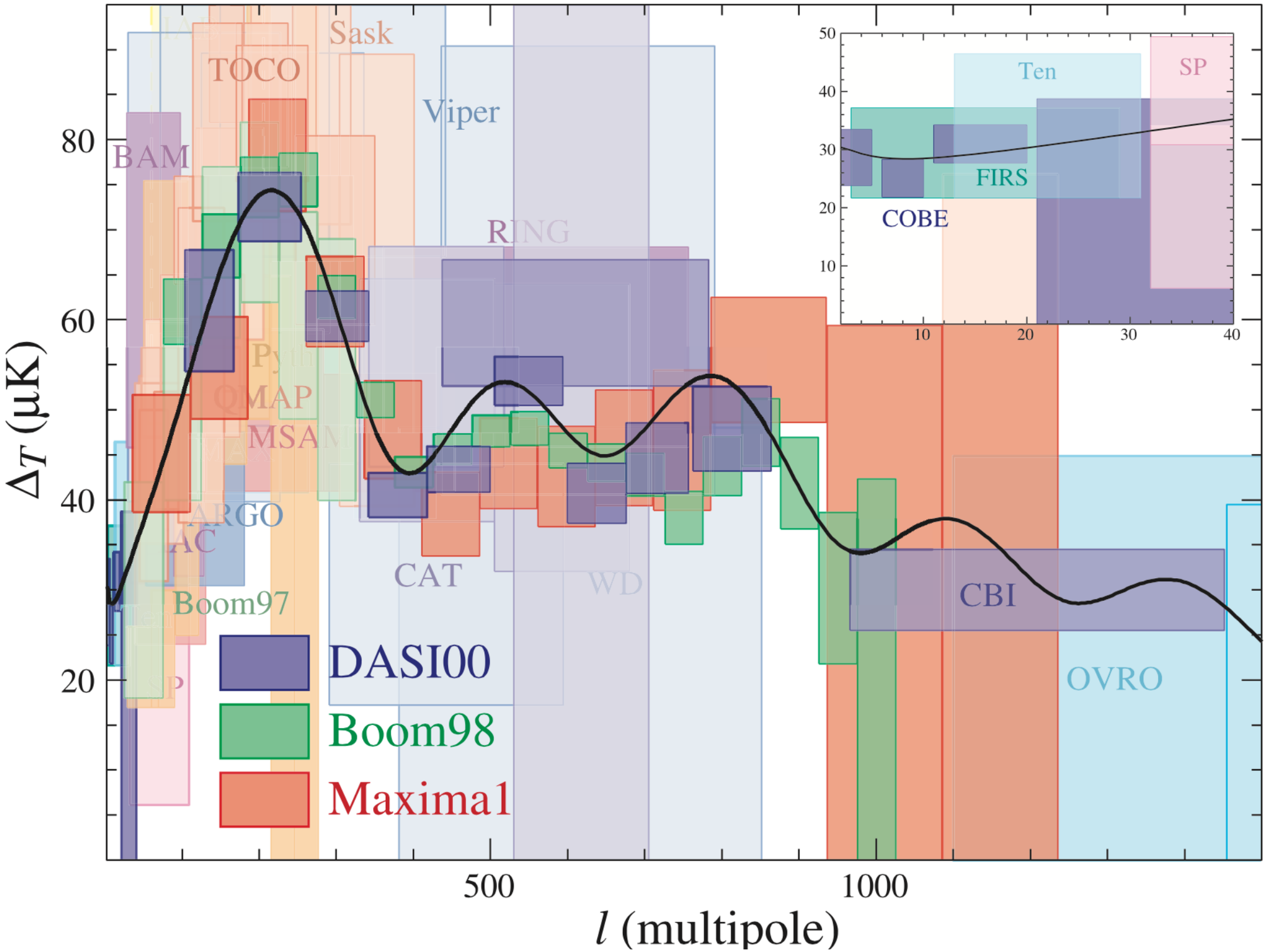
BOOMERanG

Maxima

CBI

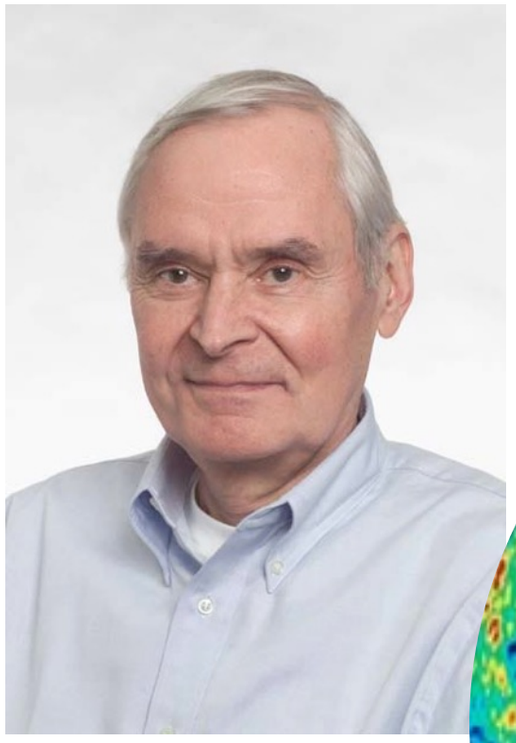
10 years after COBE

circa 2002

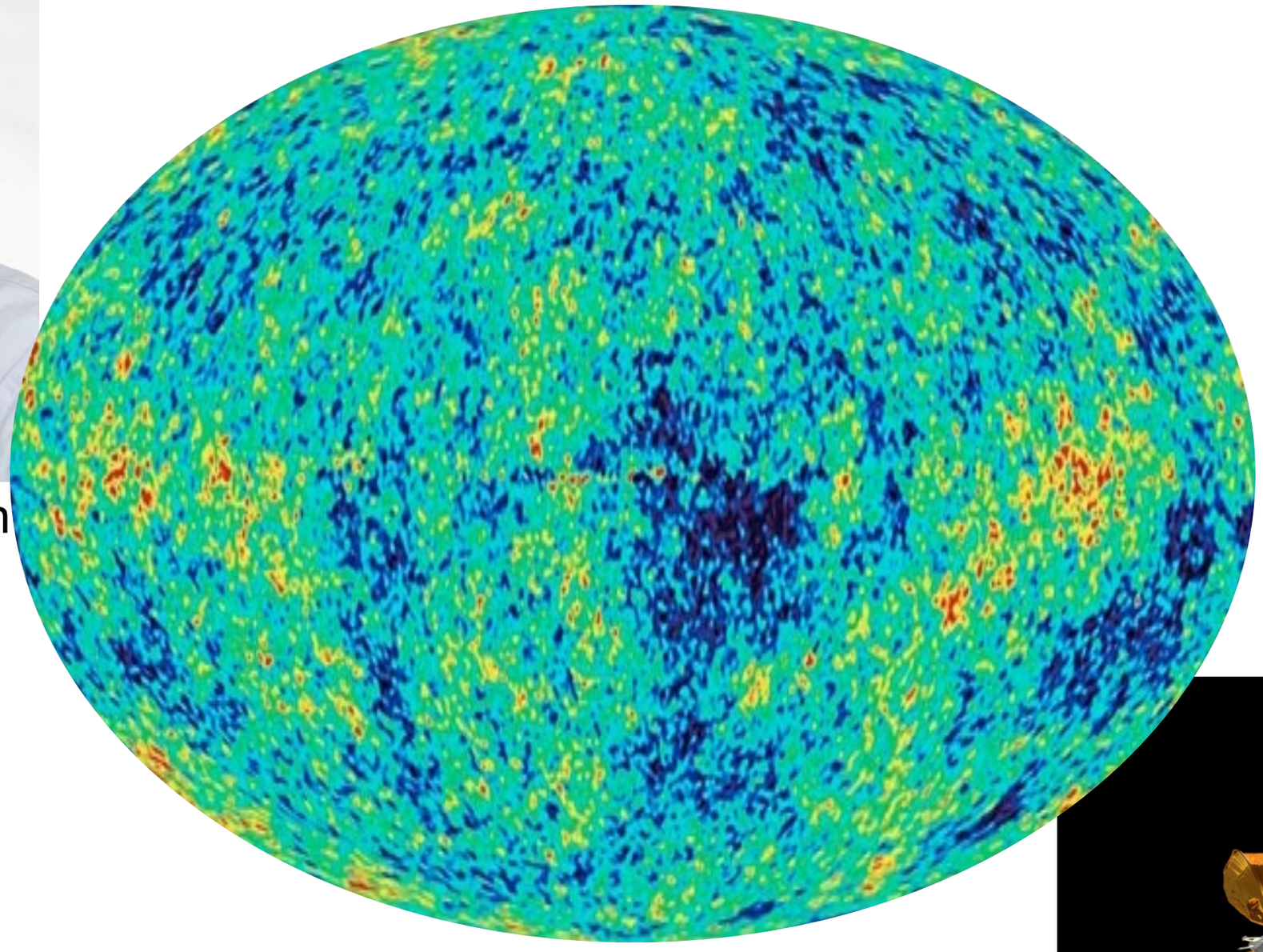


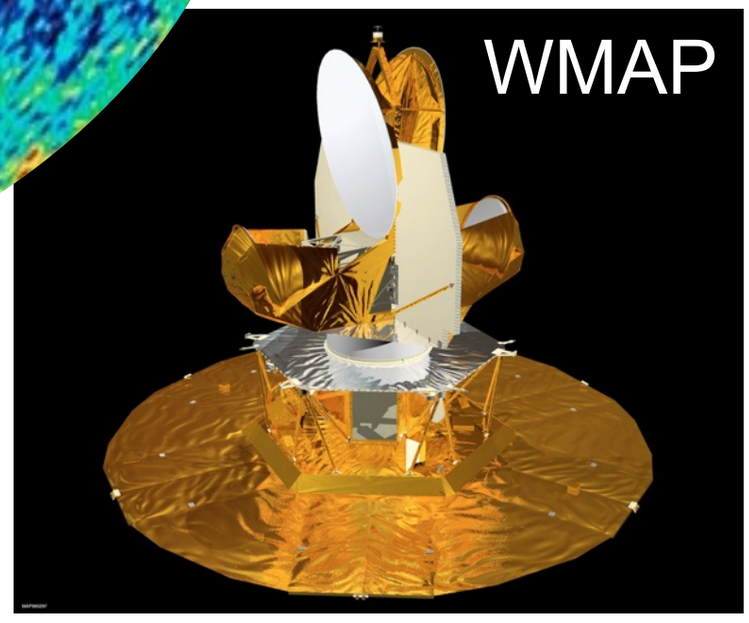
Compilation from Hu & Dodelson 2002, *ARAA* 40, 171

Wilkinson Microwave Anisotropy Probe (WMAP)

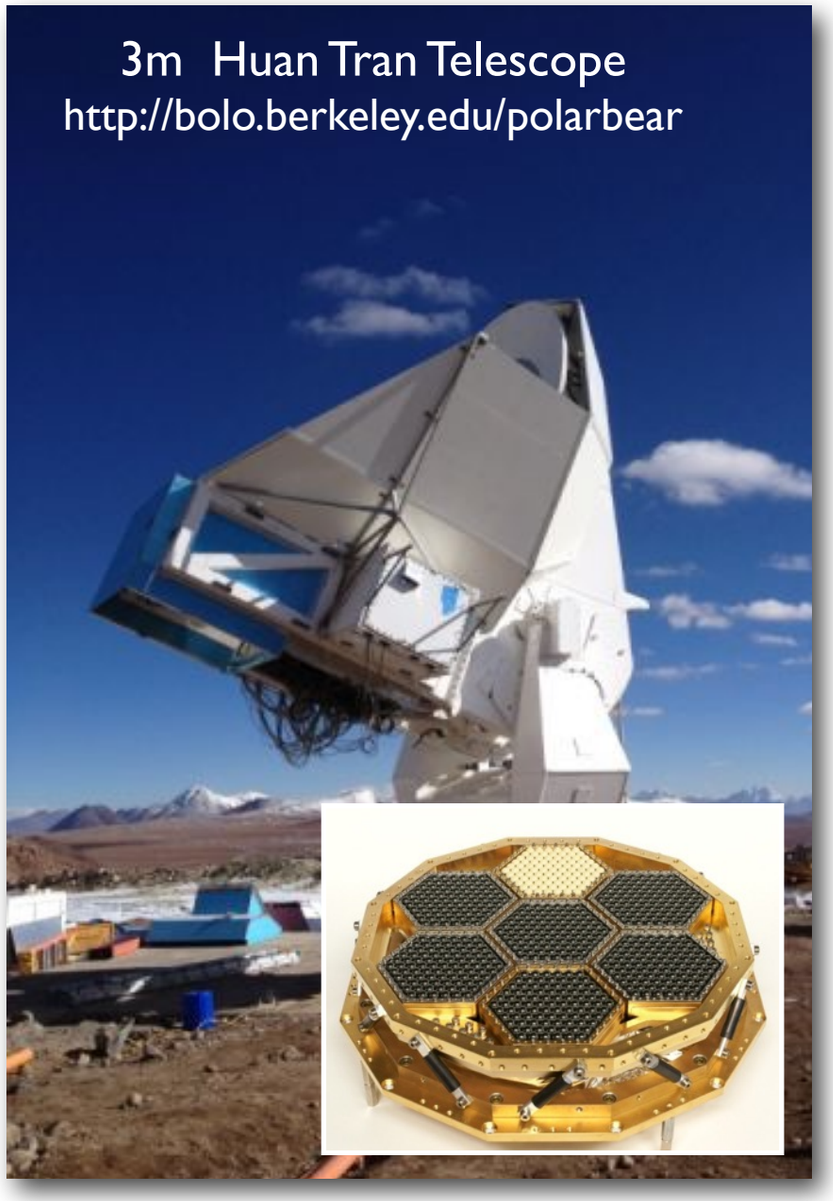


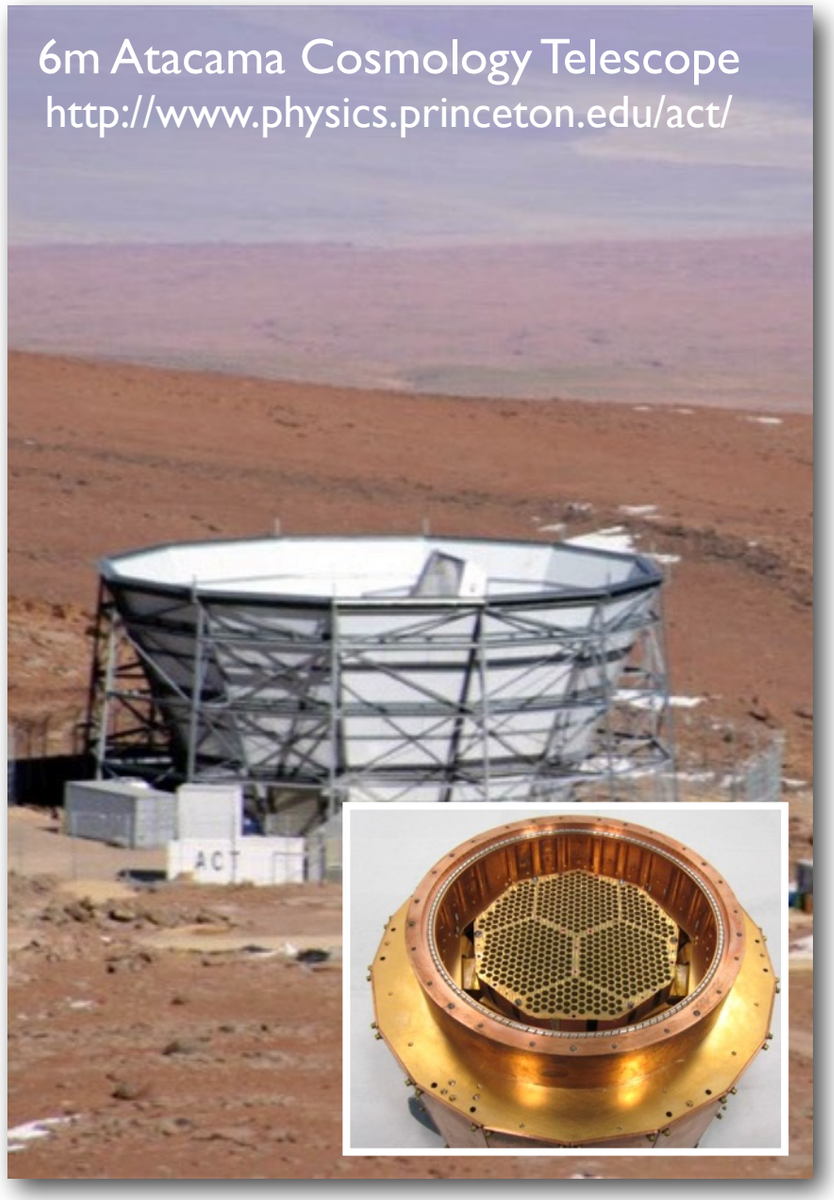
David Wilkinson
1935-2002

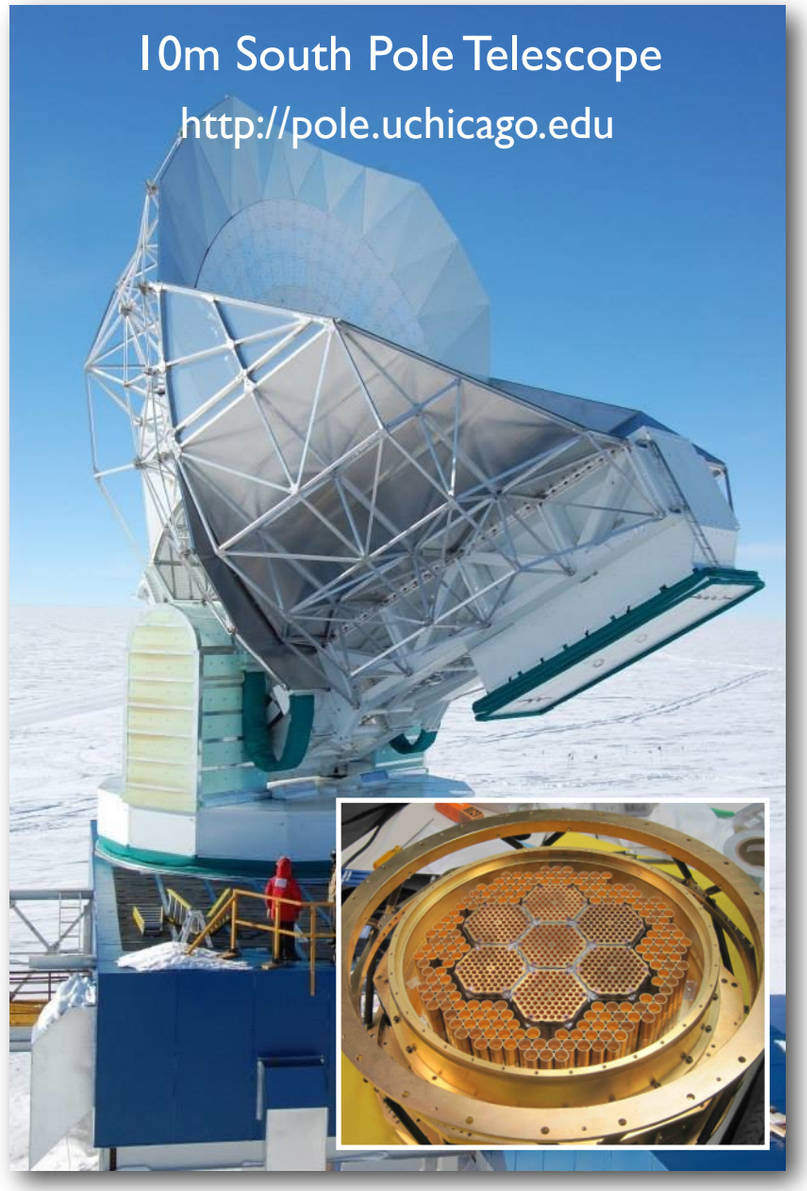




Dedicated Telescopes for fine angular scale CMB measurements







Exceptional high and dry sites for dedicated CMB observations.

Exploiting and driving ongoing revolution in low-noise bolometer cameras

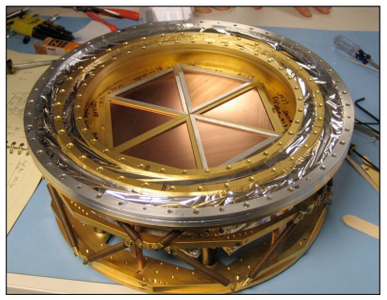
The South Pole Telescope (SPT)

A very high-tech 10-meter submm wave telescope

100 **150** **220** GHz and
1.6 **1.2** **1.0** arcmin resolution

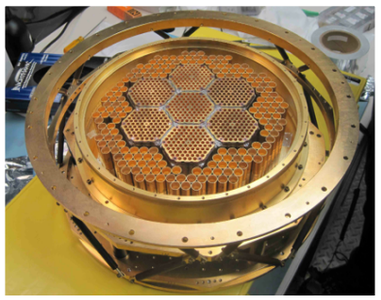
2007: SPT-SZ

960 detectors (UCB)
100,150,220 GHz



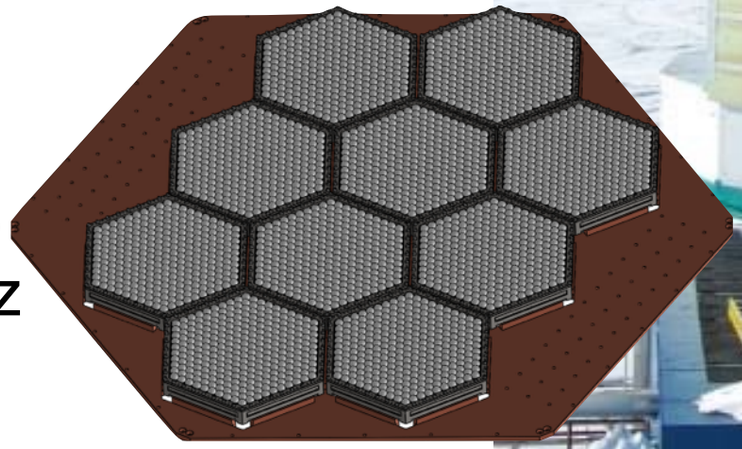
2012: SPTpol

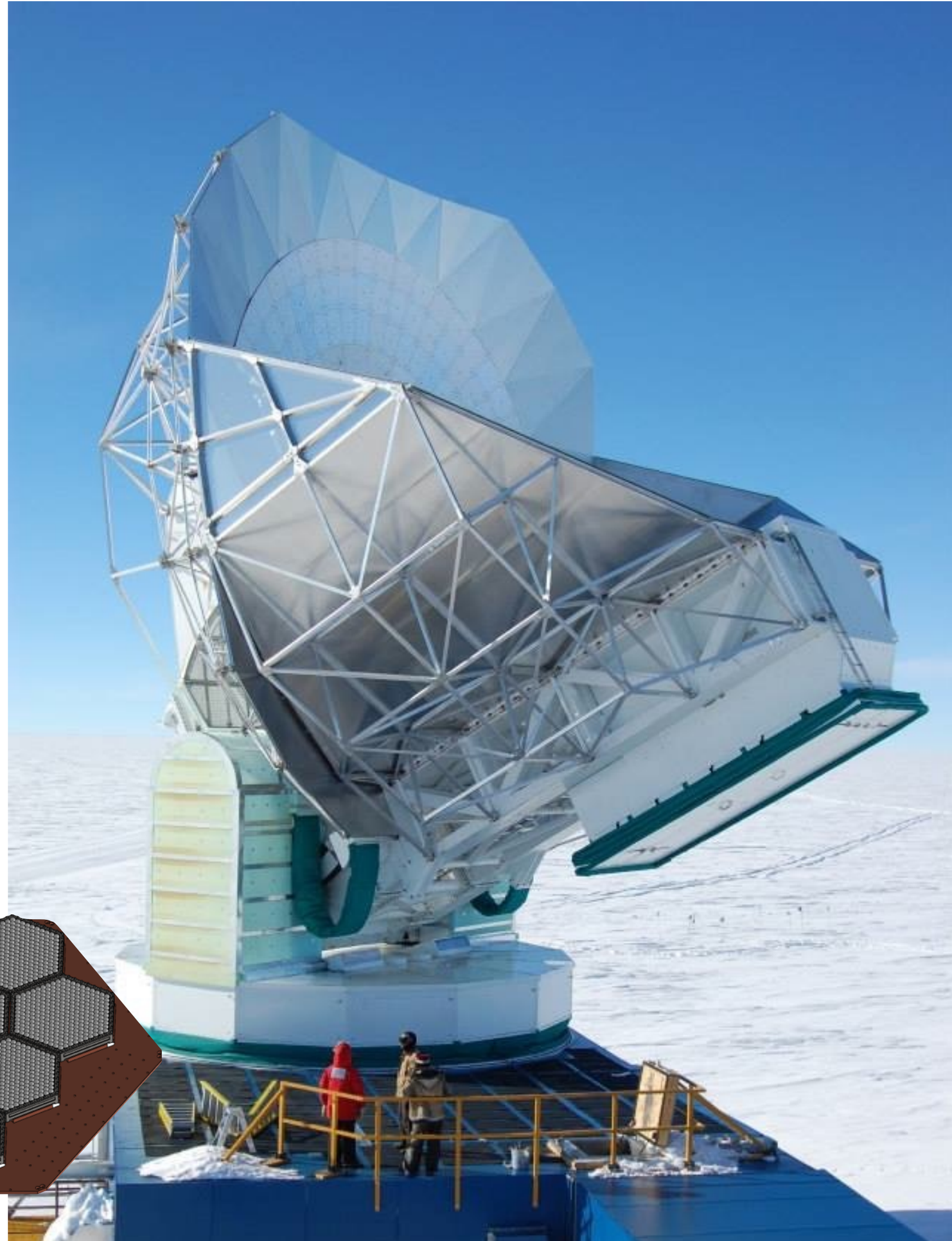
1600 detectors
100,150 GHz
+Polarization



2016: SPT-3G

16,400 detectors
100,150, 220 GHz
+Polarization





The South Pole

The South Pole (and Station)

The "Dark" Sector

~1 km

IceCube

SPT

Keck

BICEP

Why the South Pole?

- **Extremely dry, stable atmosphere**.
- High altitude ~ 10,500 feet.
- Sun below horizon for 6 months.
- Unique geographical location - We can observe the clearest view through our Galaxy 24/7, actually 24/7/52
- Excellent support from National Science Foundation research station

The South Pole Telescope Collaboration

Argonne NATIONAL LABORATORY

BERKELEY LAB

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

NIST

SLAC NATIONAL ACCELERATOR LABORATORY

Funded By:

U.S. DEPARTMENT OF ENERGY

KICP
Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

Berkeley University of California

Case CASE WESTERN RESERVE UNIVERSITY

McGill

Colorado University of Colorado at Boulder

STANFORD UNIVERSITY

KAVLI

THE UNIVERSITY OF CHICAGO

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Harvard-Smithsonian Center for Astrophysics

UC DAVIS UNIVERSITY OF CALIFORNIA

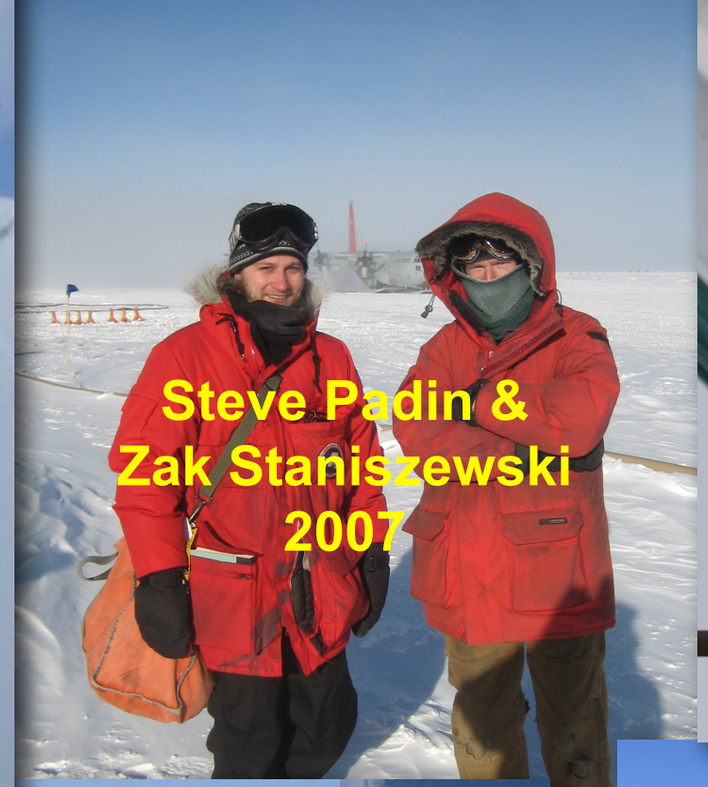
Fermilab

NSF

GORDON AND BETTY MOORE FOUNDATION

Our Heroes, the SPT Winterovers

Dana Hrubes 2008



Steve Padin & Zak Staniszewski 2007

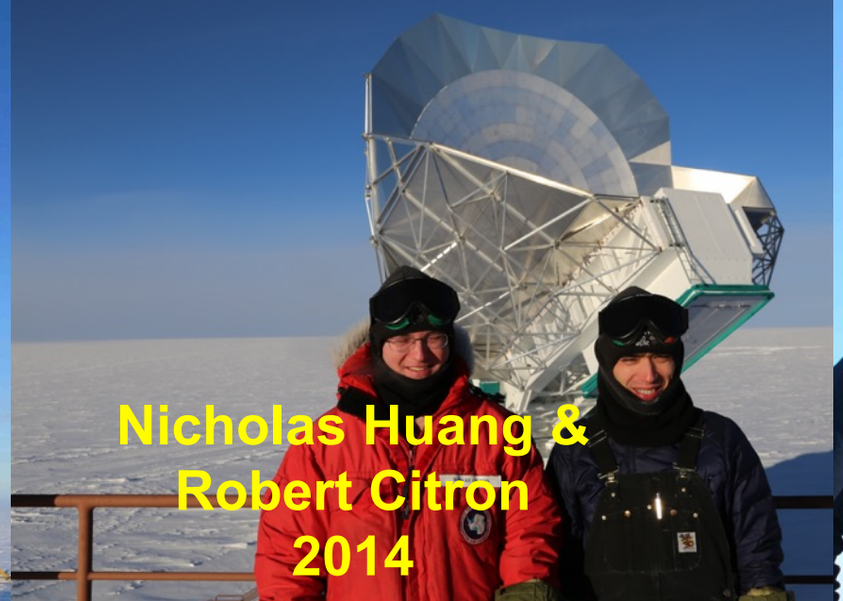
Ross Williamson & Erik Shirokoff 2009

Keith Vanderlinde 2008

Dana Hrubes & Daniel Luong-van 2010 & 2011 !

Cynthia Chiang & Nicholas Huang 2012

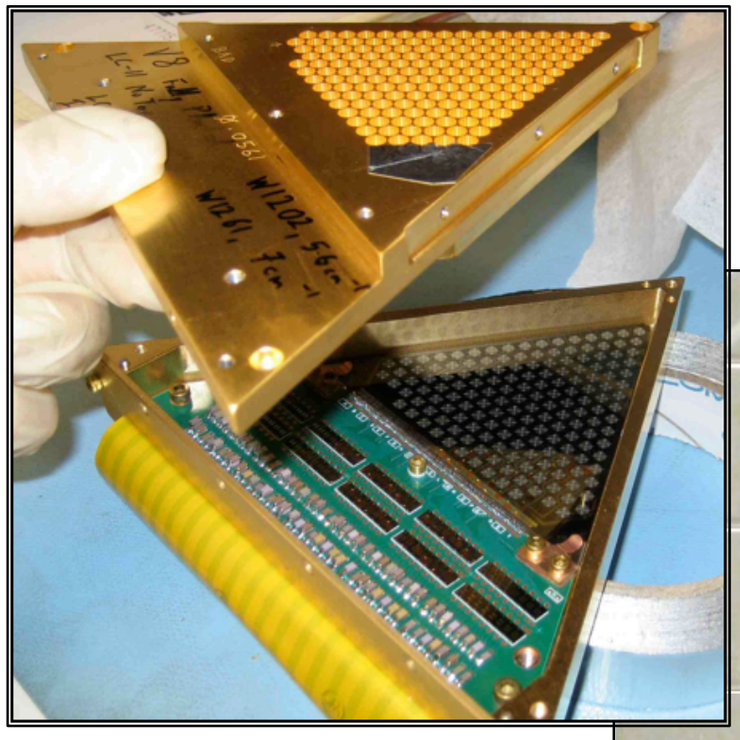
Dana Hrubes & Jason Gallicchio 2013

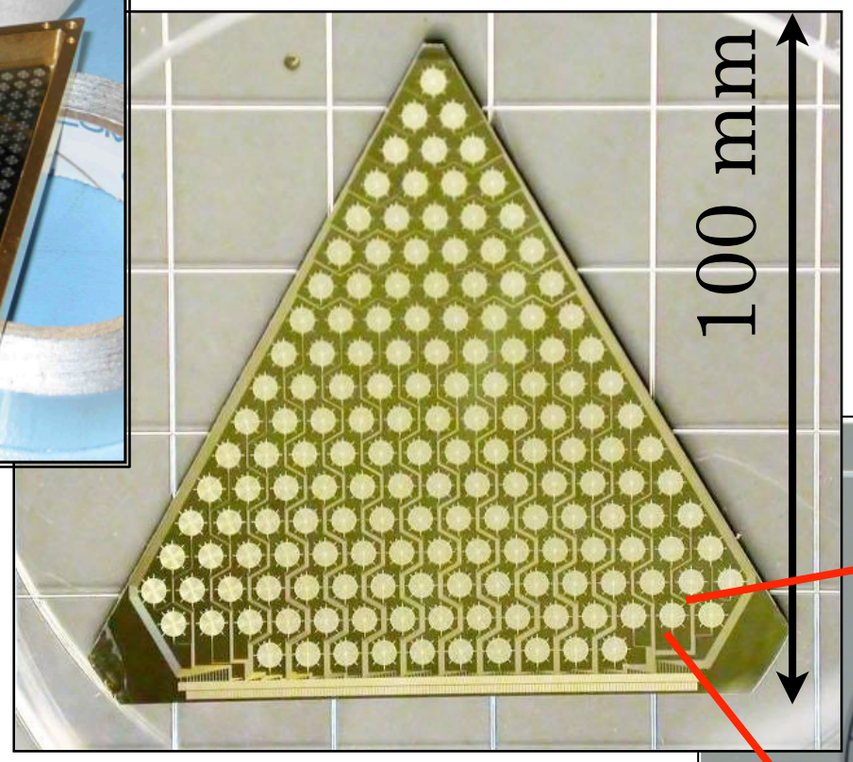


Nicholas Huang & Robert Citron 2014

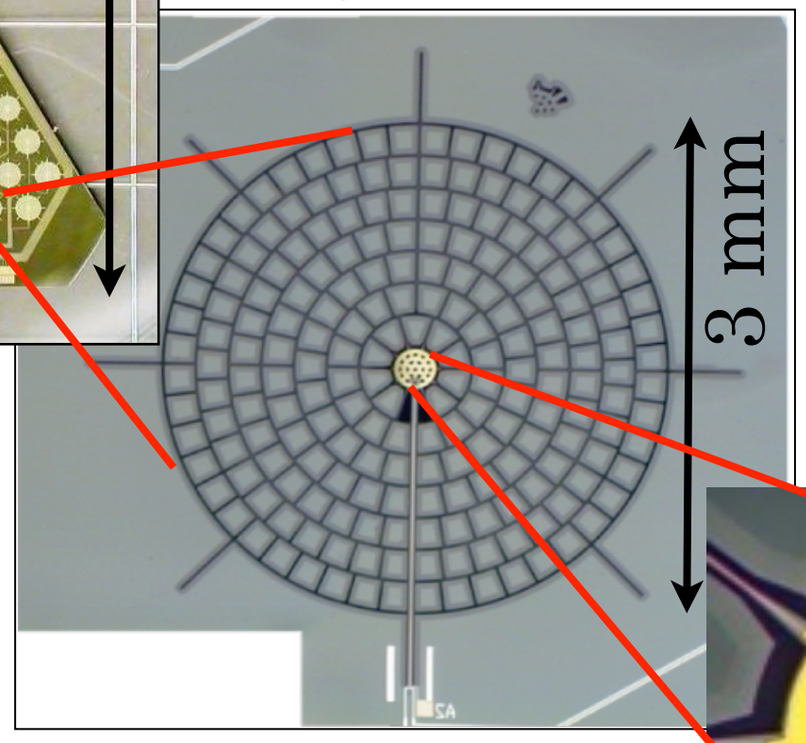
Charlie Sievers & Todd Veach 2015

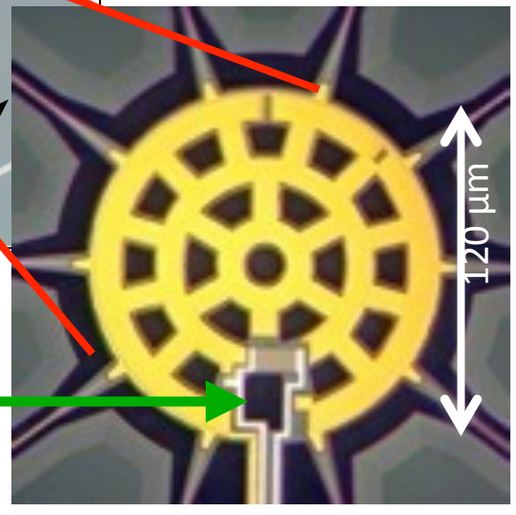
First SPT Bolometer Array





Fabricated by Erik Shirokoff and Sherry Cho at UC-Berkeley





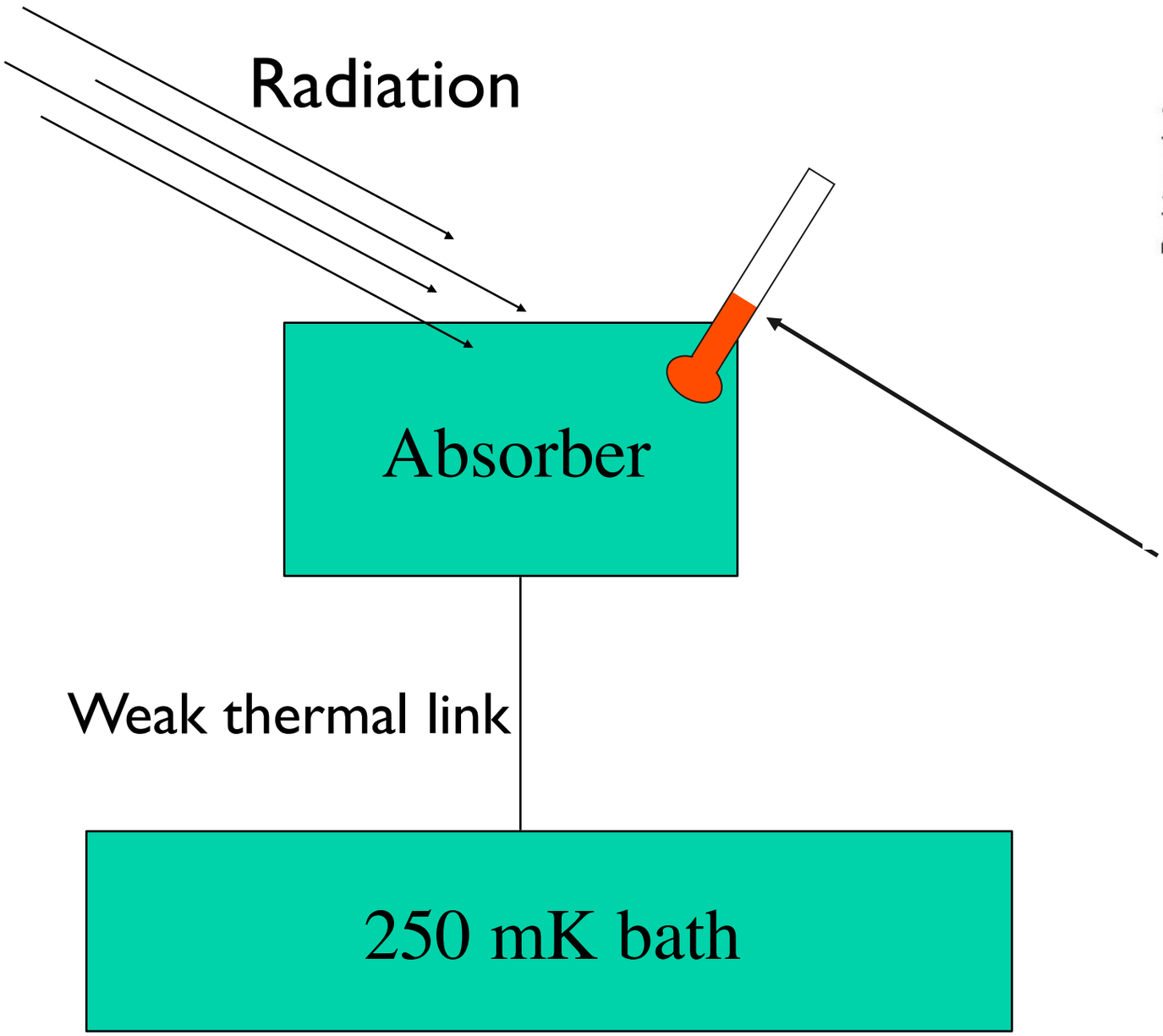
160 pixel bolometer array wedge

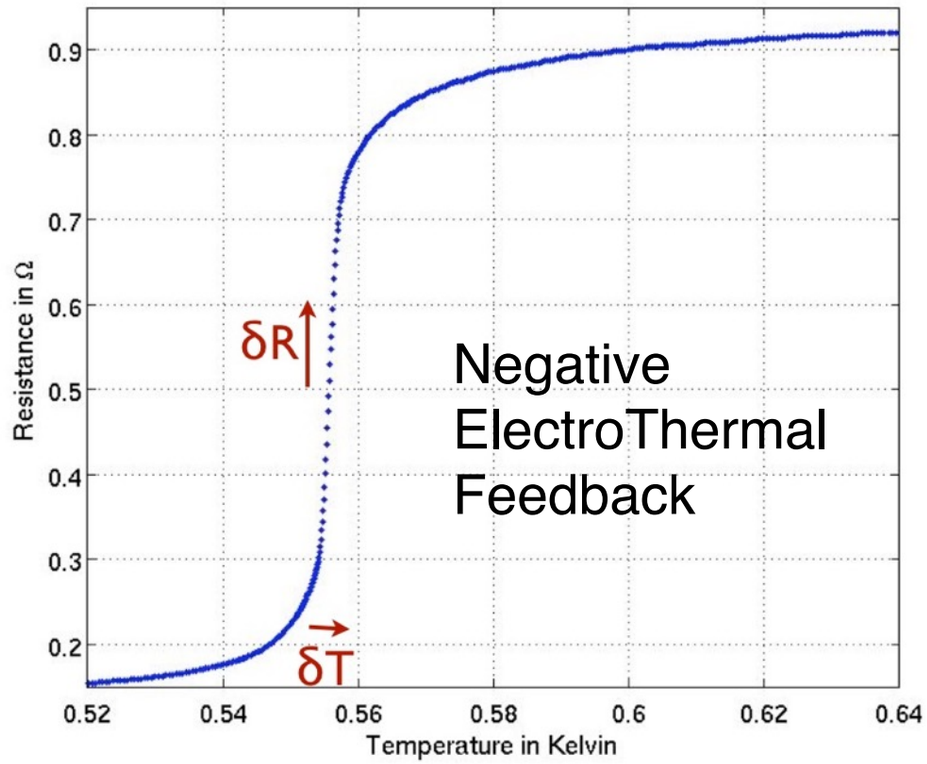
SiN substrate with gold absorber

Al/Ti transition edge sensor (TES) with a transition temperature of 500 mK

Transition Edge Sensors (TES)

Scalable, background limited, broadband bolometric detectors.





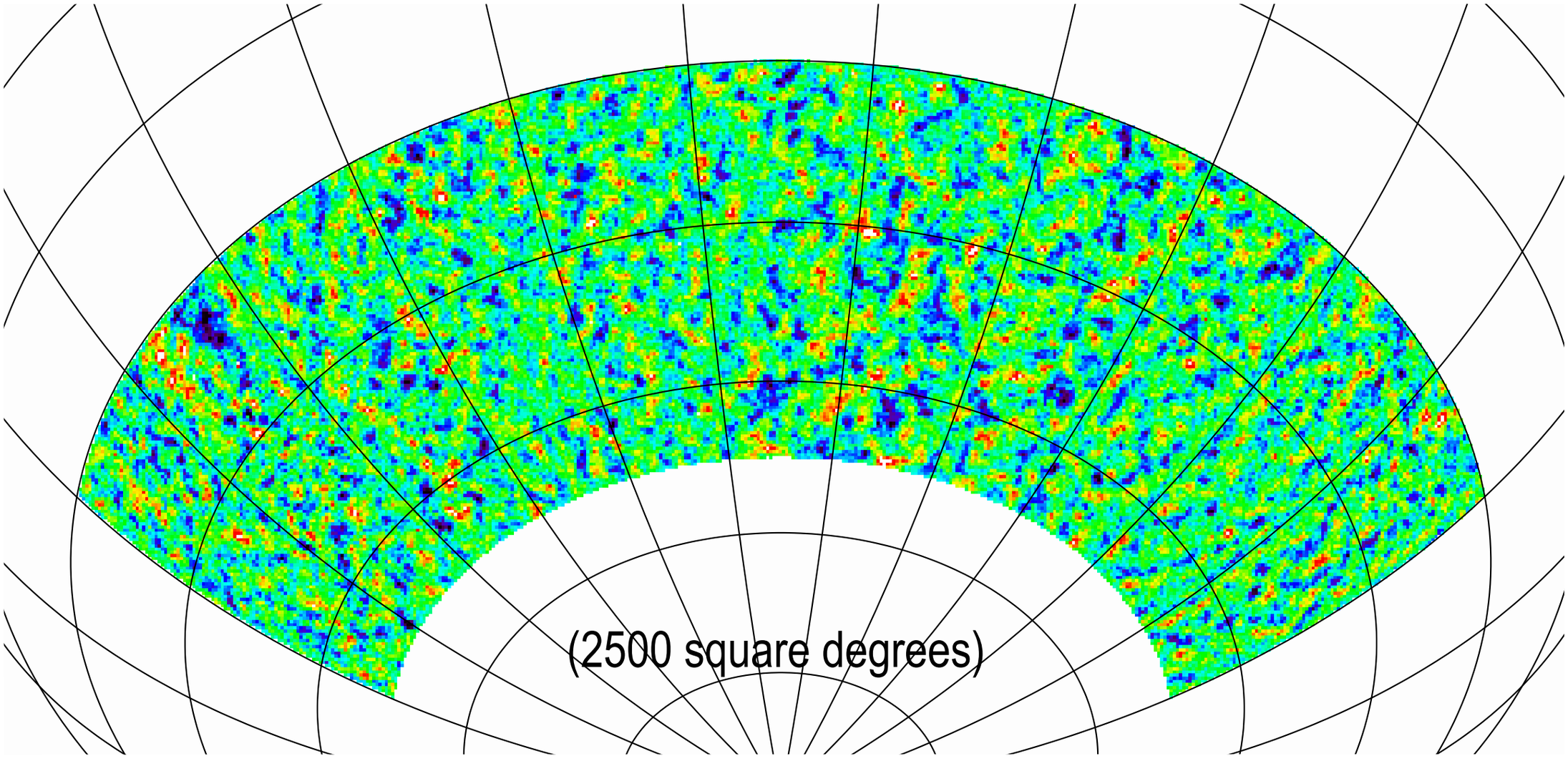
Thermometer: Voltage biased transition edge sensor (TES).

Measure incident power (pW) by change in bias current using SQUIDS.

Apparent simplicity is deceptive!

Credit: Jose-Francisco Salgado

First SPT survey completed in 2011
High resolution and sensitivity map of the CMB
covering 1/16 of the sky



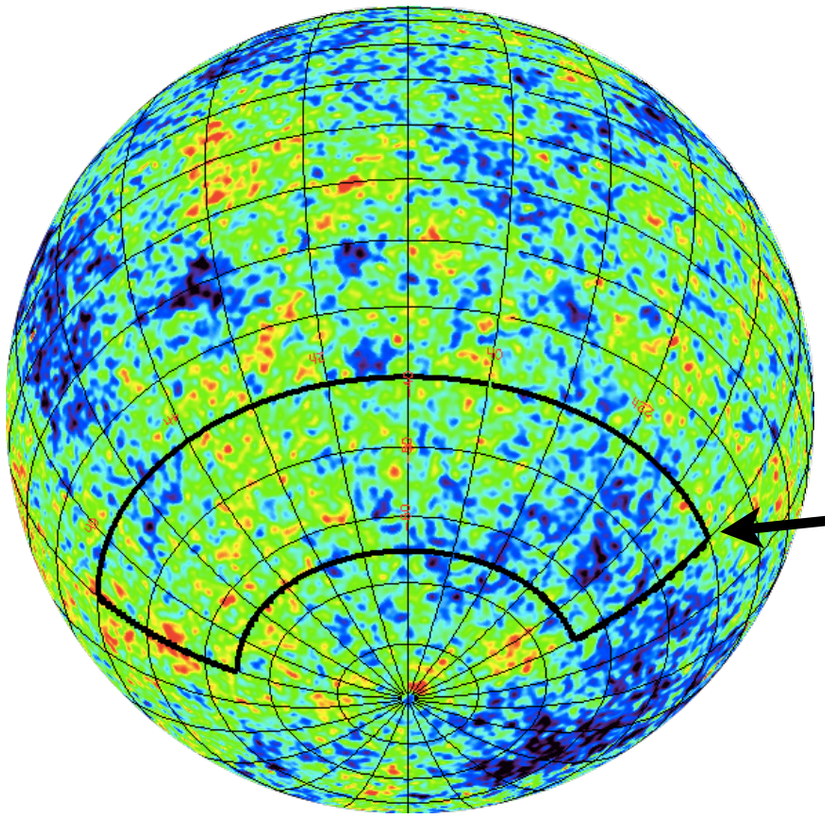
Survey depths:

- 90 GHz: 42 uK_{CMB}-arcmin
- 150 GHz: <18 uK_{CMB}-arcmin
- 220 GHz: 85 uK_{CMB}-arcmin

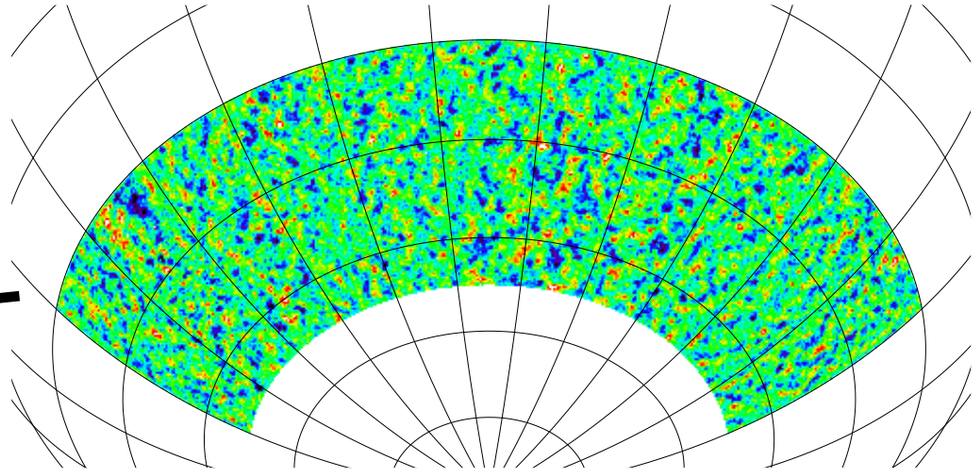
Complementary ground and space CMB measurements

All sky, large angular scales, extended frequency coverage, precise calibration

Deep targeted fields, high resolution, implement new technology

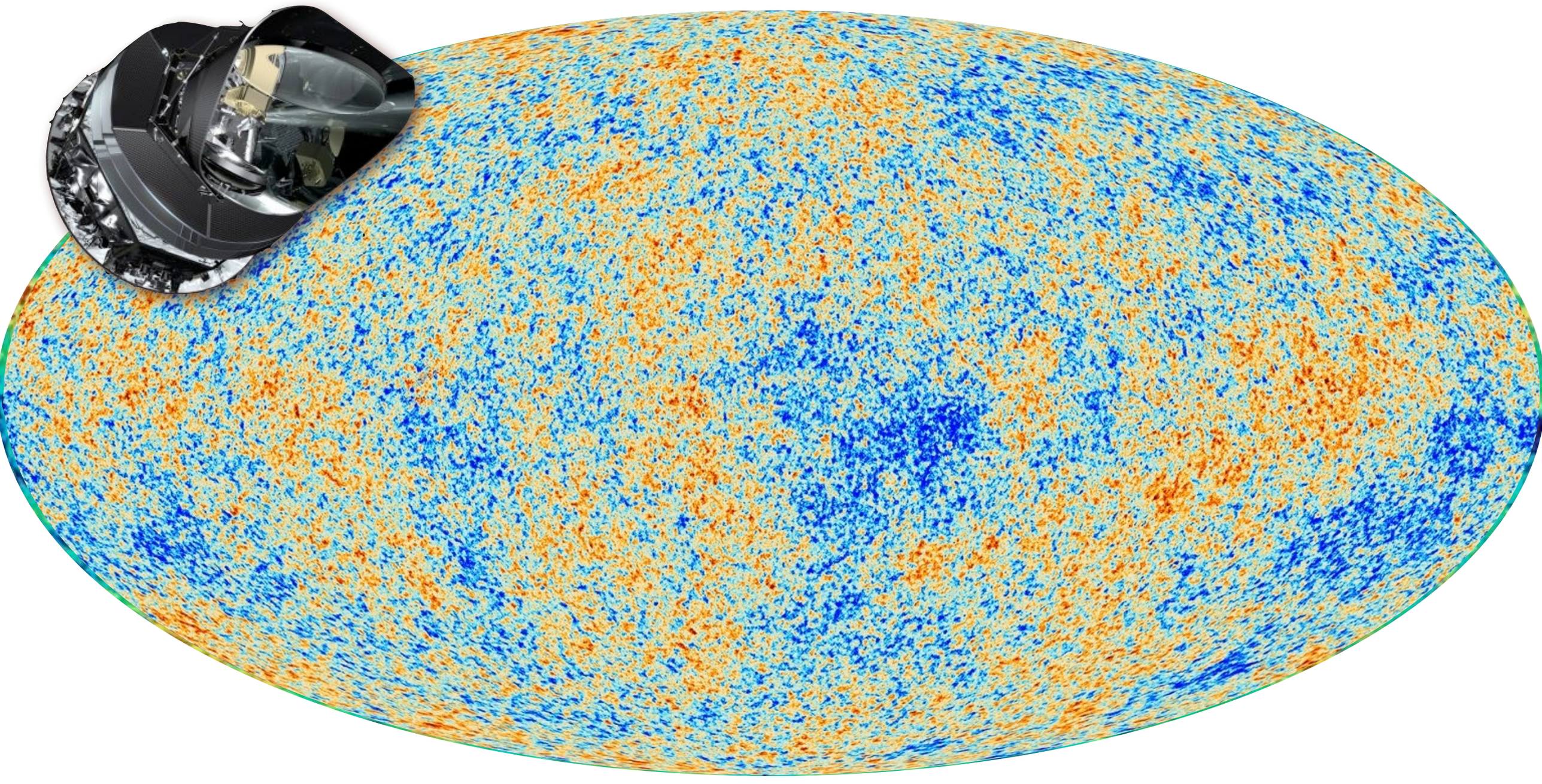


WMAP full sky map
with SPT area marked

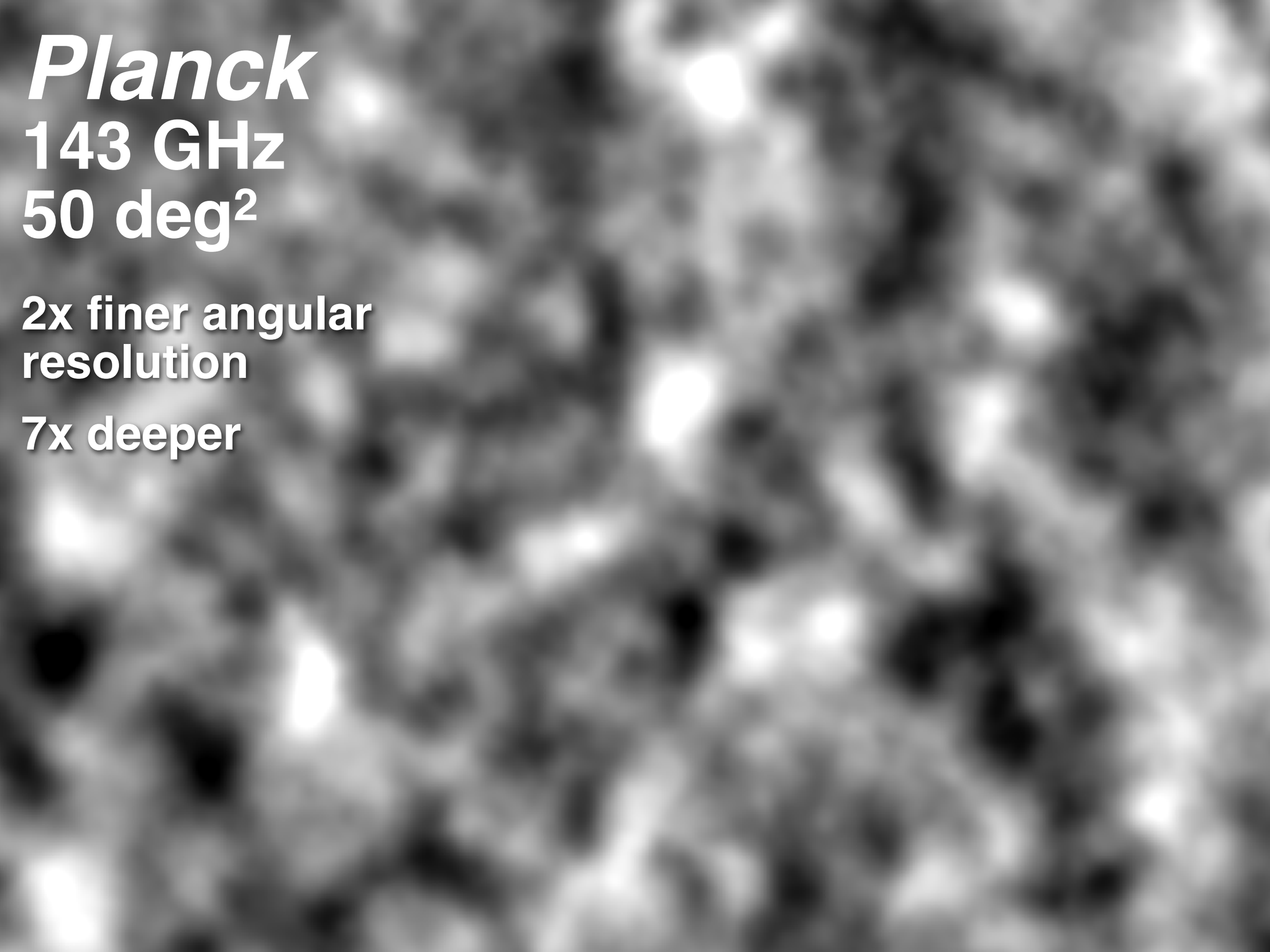


SPT-SZ 2500 deg^2 Survey

Planck



WMAP
94 GHz
50 deg^2


Planck
143 GHz
50 deg²
2x finer angular resolution
7x deeper

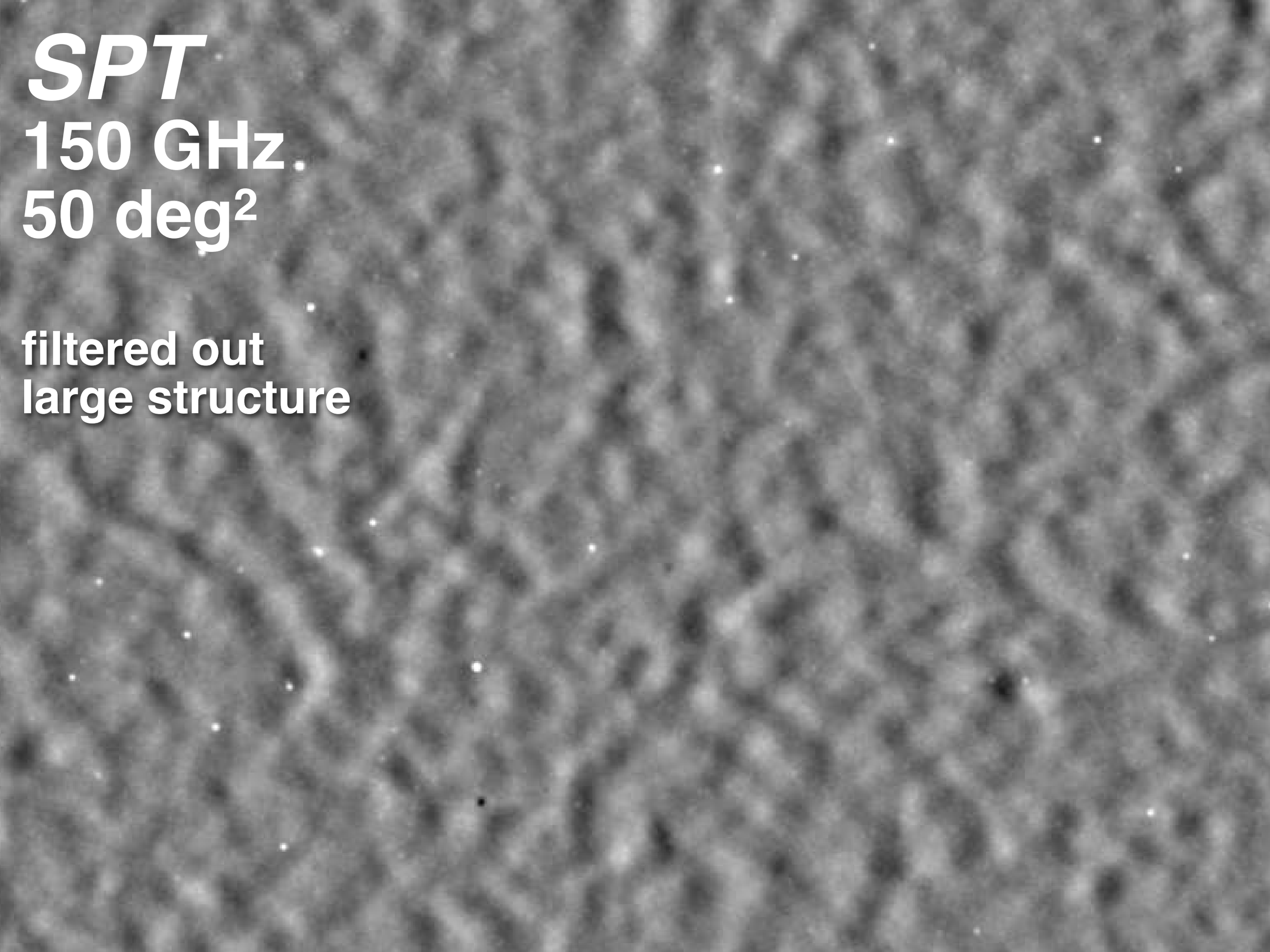
SPT

150 GHz

50 deg^2

13x finer angular resolution

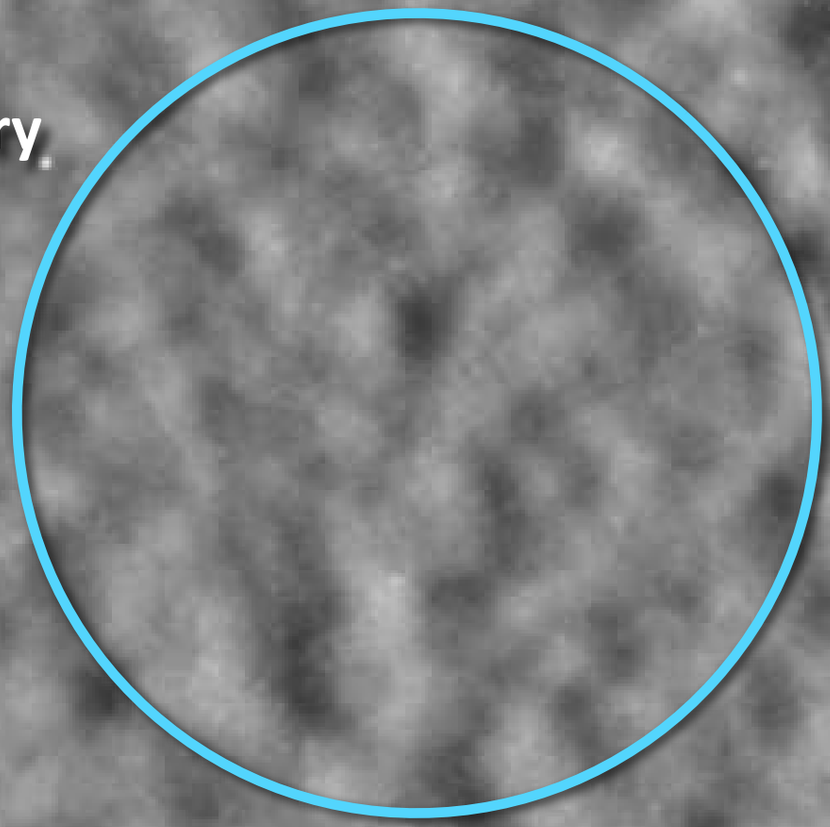
50x deeper


SPT
150 GHz
50 deg²
filtered out
large structure

SPT
150 GHz
50 deg^2

CMB Anisotropy

Primordial and secondary anisotropy in the CMB



SPT
150 GHz
50 deg^2

Point Sources

Active galactic nuclei, and the most distant, star-forming galaxies

SPT
150 GHz
50 deg²

Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies

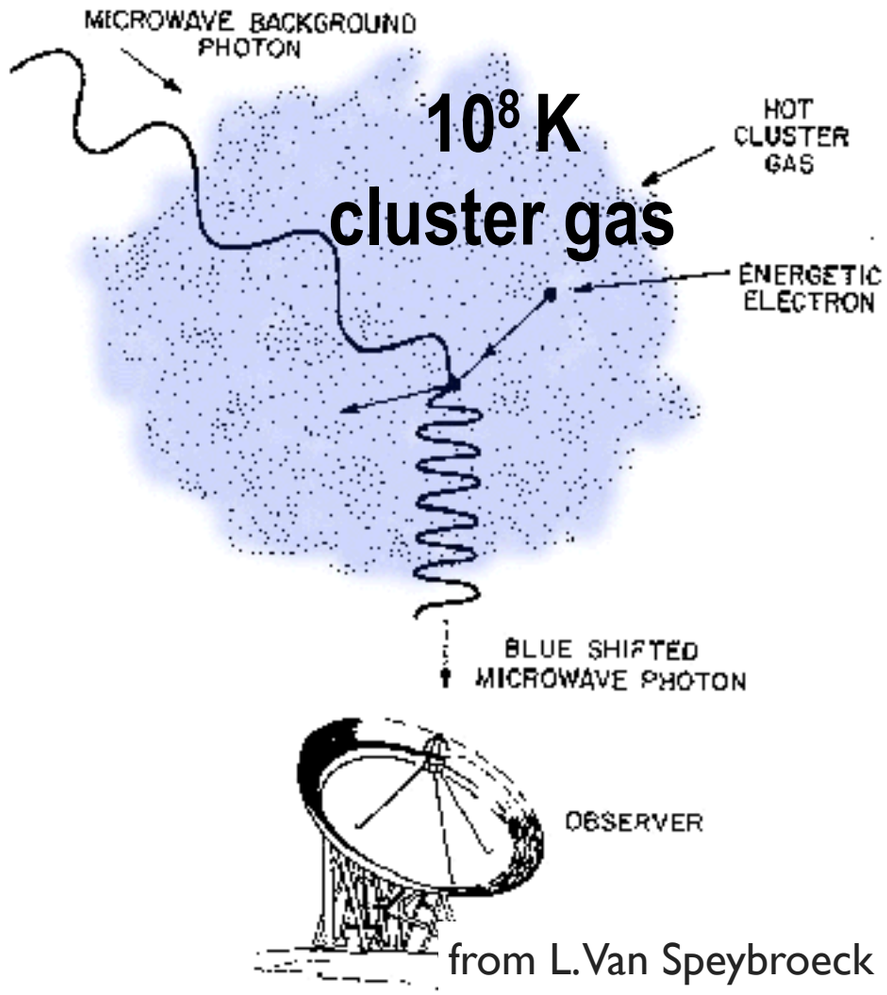
Sunyaev-Zel'dovich (SZ) Effect

CMB photons provide a backlight for structure in the universe.

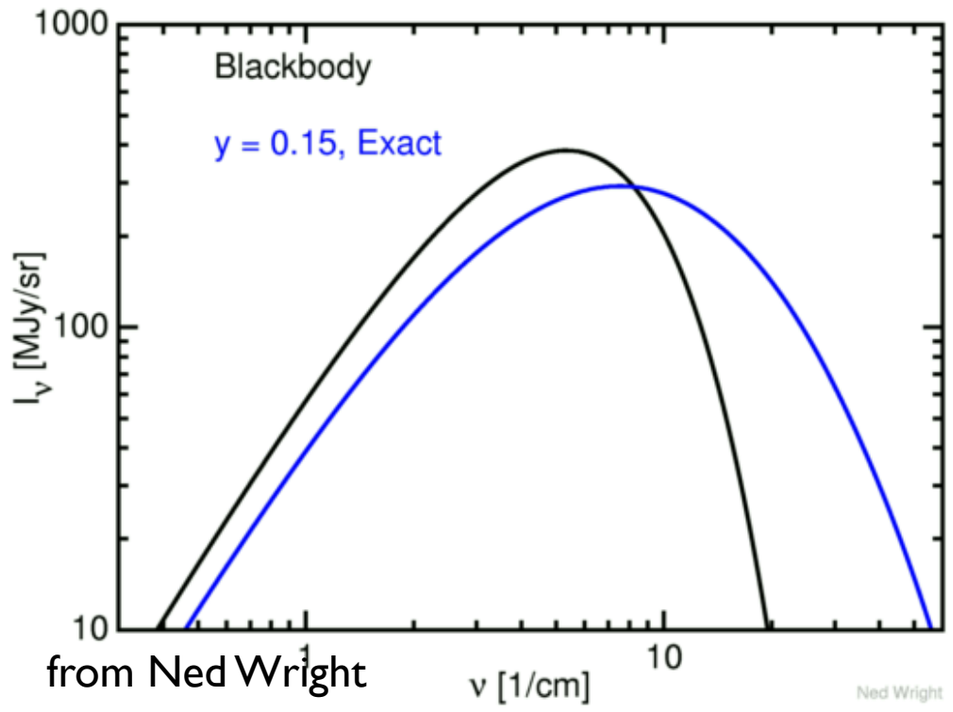
~1% of CMB photons traversing a massive galaxy cluster scatter.

Thermal SZ effect (tSZ) spectral "y" distortion due to inverse Compton scattering.

Kinematic SZ effect (kSZ) due to cluster moving with respect to the CMB



from L. Van Speybroeck



from Ned Wright

Two important points:

1) SZ effect is a measure of total thermal energy, so good mass proxy.

2) Surface brightness of the SZ effect is independent of redshift!

→ an excellent tool for studying cosmology

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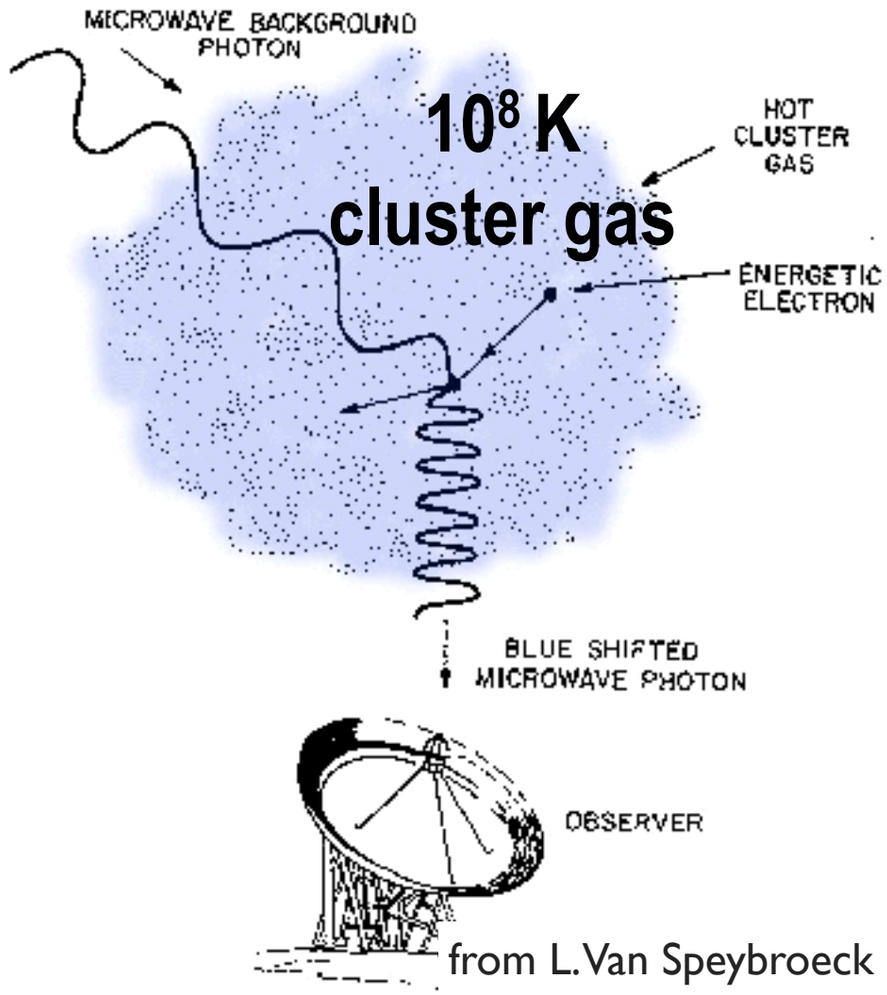

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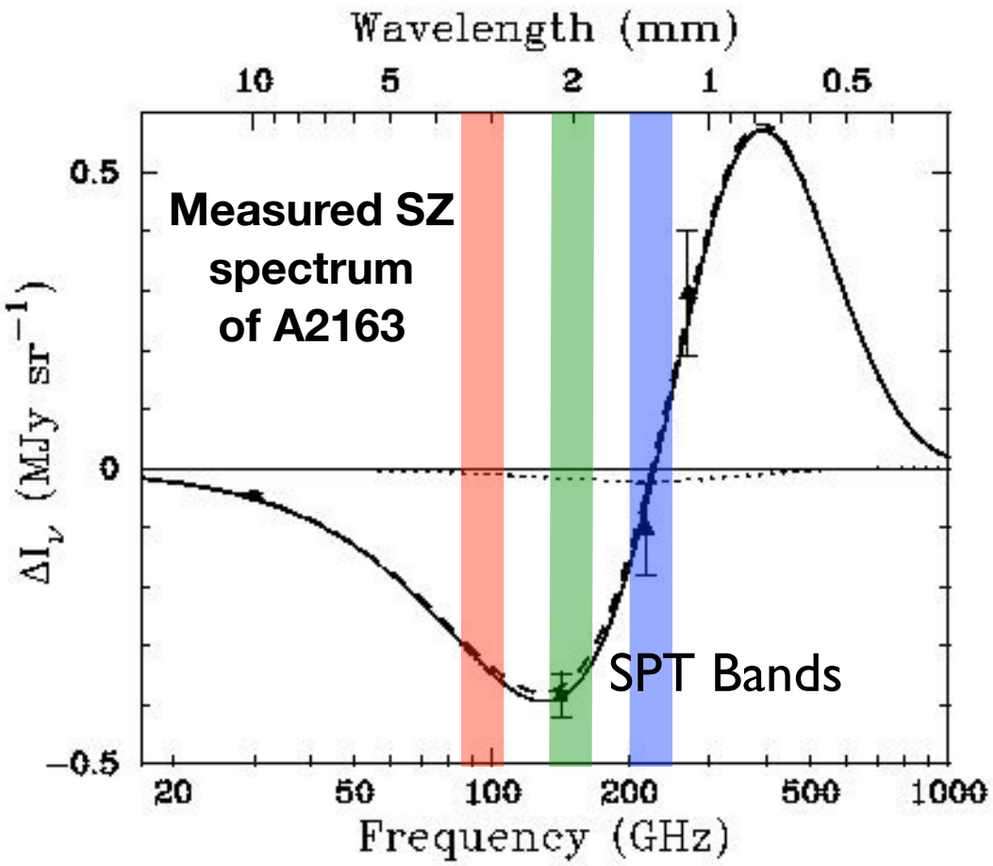

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Dark Energy and Cluster Cosmology

• Abundance of clusters is sensitive to **dark energy** through geometry and growth of structure.

Cluster Abundance: dN/dz

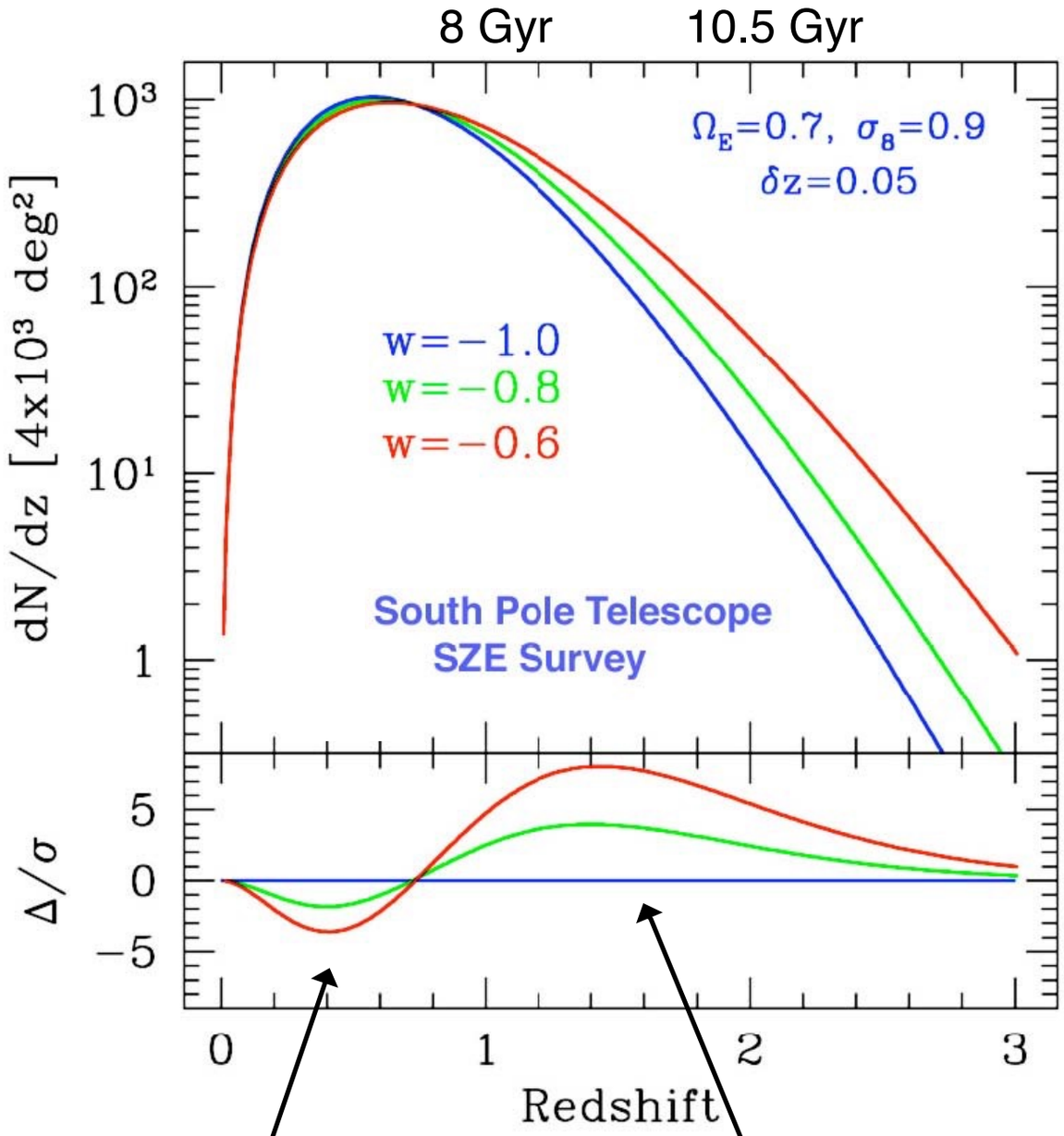
$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

Depends on:

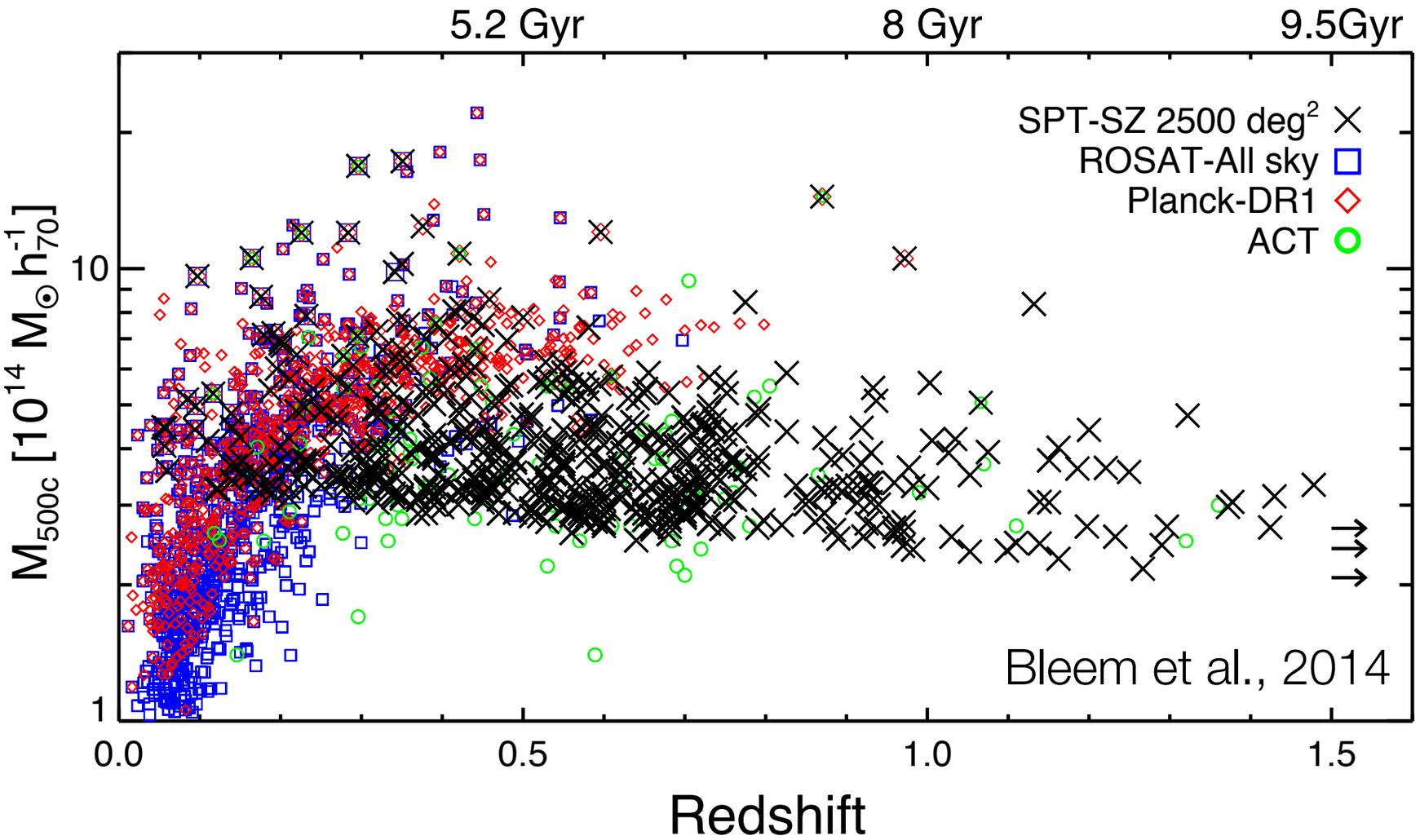
Matter Power Spectrum, σ_8
Growth Rate of Structure, *D(z)*

Depends on:

Rate of Expansion, *H(z)*

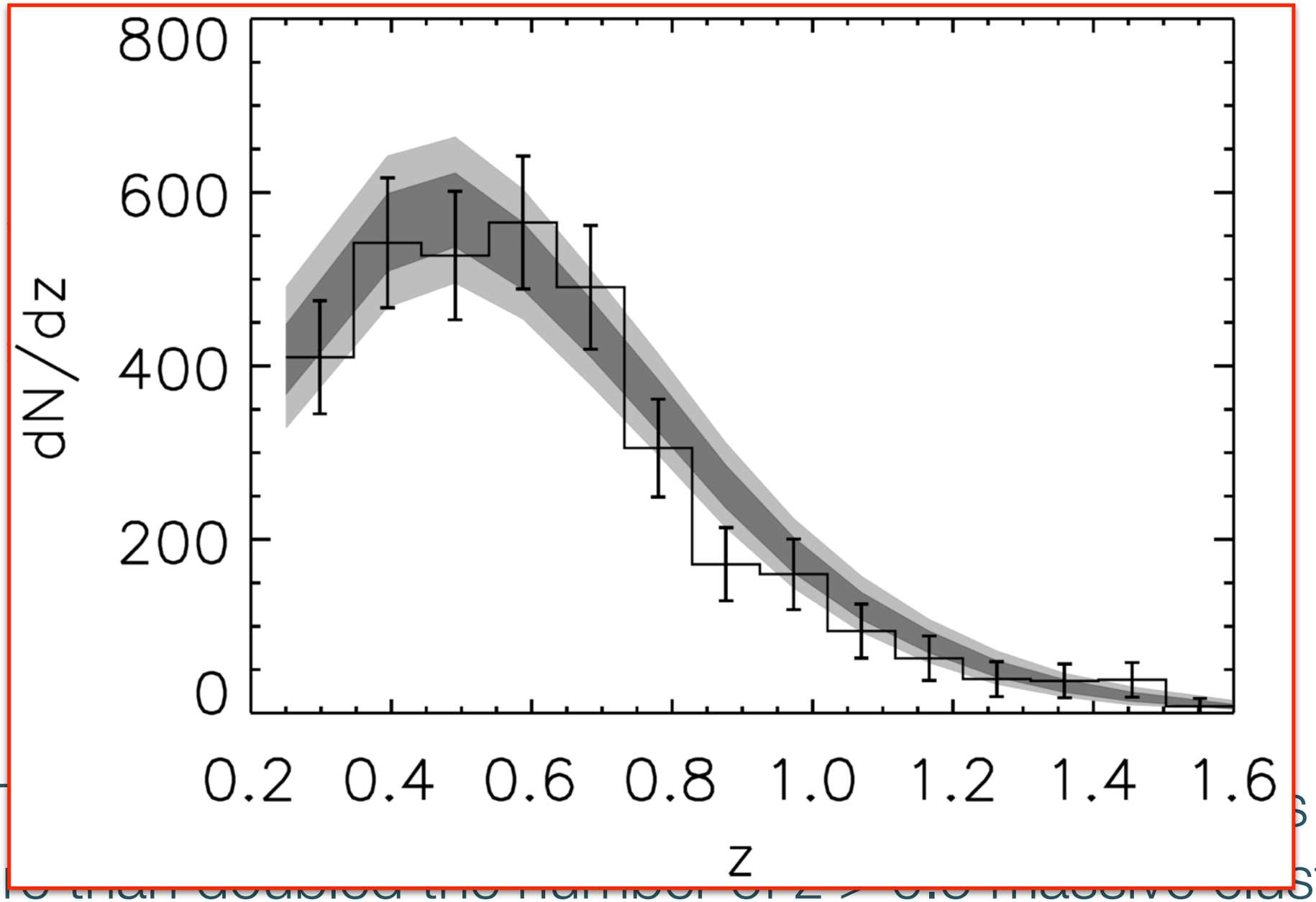


Sunyaev-Zel'dovich (SZ) effect discovered clusters



- SPT made 1st SZ discovery of cluster in 2008 and has more than doubled the number of $z > 0.5$ massive clusters.
- **Cosmological constraints limited by cluster mass calibration.**

Sunyaev-Zel'dovich (SZ) effect discovered clusters



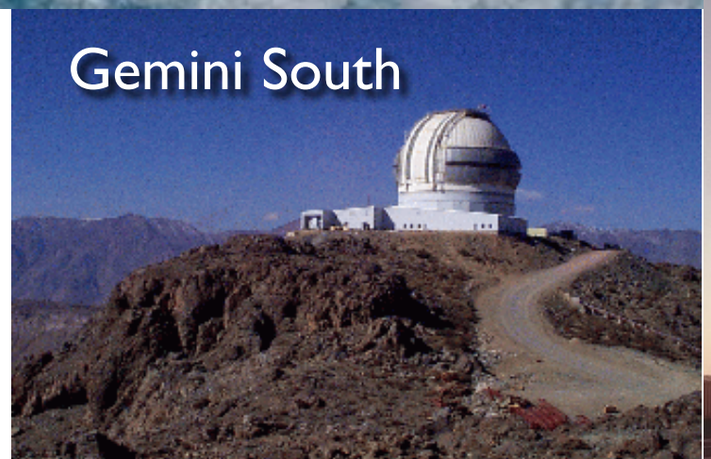
- SP[illegible]s
  mo[illegible]sters.
- **Cosmological constraints limited by cluster mass calibration.**

Mass Calibration of SPT clusters

Multi-wavelength Observations

1. **X-ray** with Chandra and XMM
2. **Weak lensing** from Magellan ($0.3 < z < 0.6$) and HST ($z > 0.6$)
3. **Dynamical masses** from NOAO 3-year survey on Gemini ($0.3 < z < 0.8$), and VLT at ($z > 0.8$)

>100 SPT clusters with proposed or approved measurements with each method



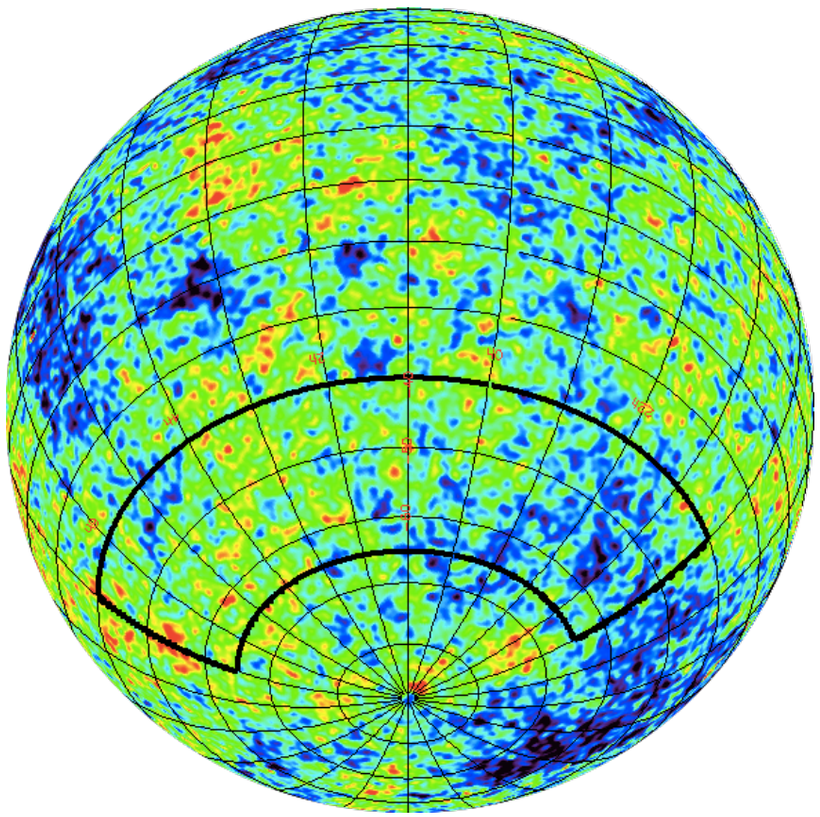
Synergy with Dark Energy Survey

- DES: a 5-year optical survey to image 5000 deg^2, including entire SPT-SZ survey area
- Multiple probes of dark energy (cluster survey, weak lensing, BAO, Supernovae)

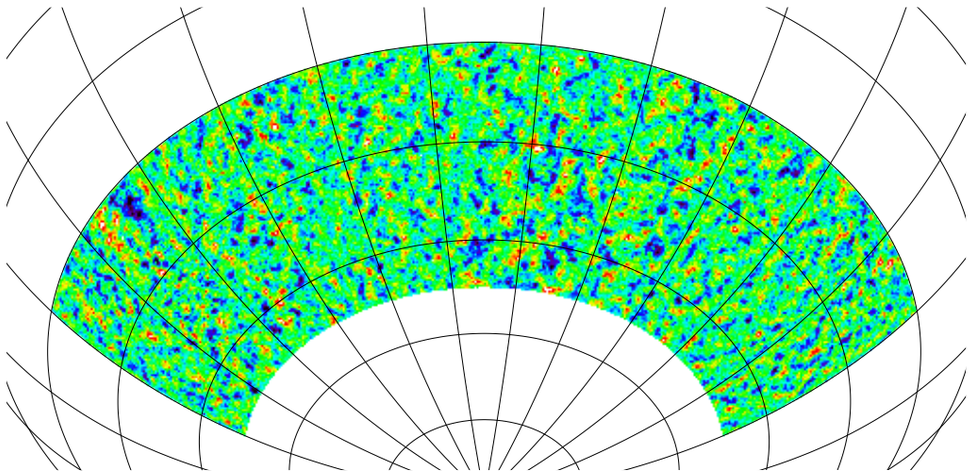
Strong complementarity with SPT cluster survey and SPT CMB lensing; the combination will improve cluster constraints on dark energy by ~100x

Already a vibrant joint DES + SPT analysis group.

From maps to angular power spectra



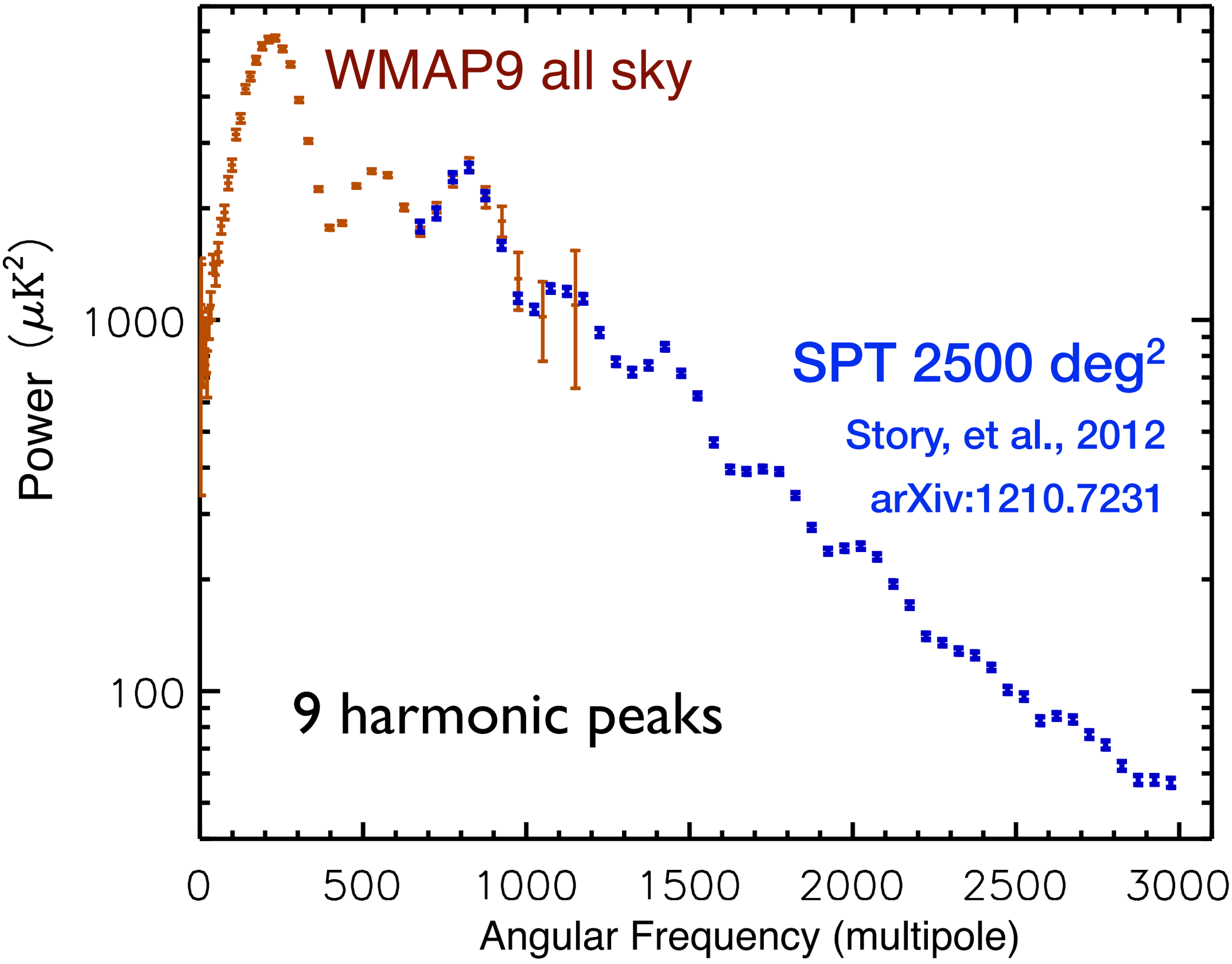
WMAP full sky map
with SPT area marked

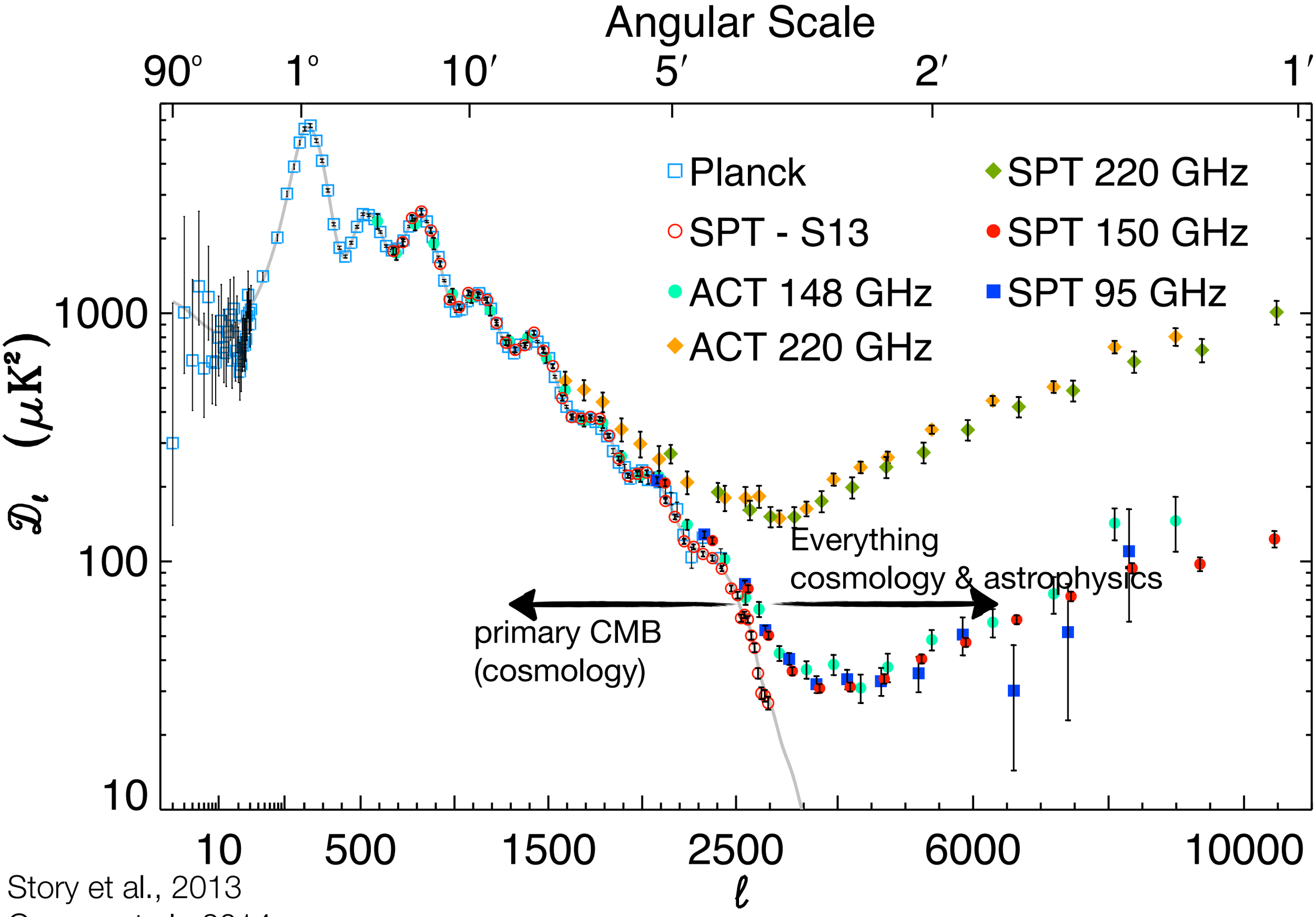


SPT-SZ 2500 deg^2 Survey

Transform

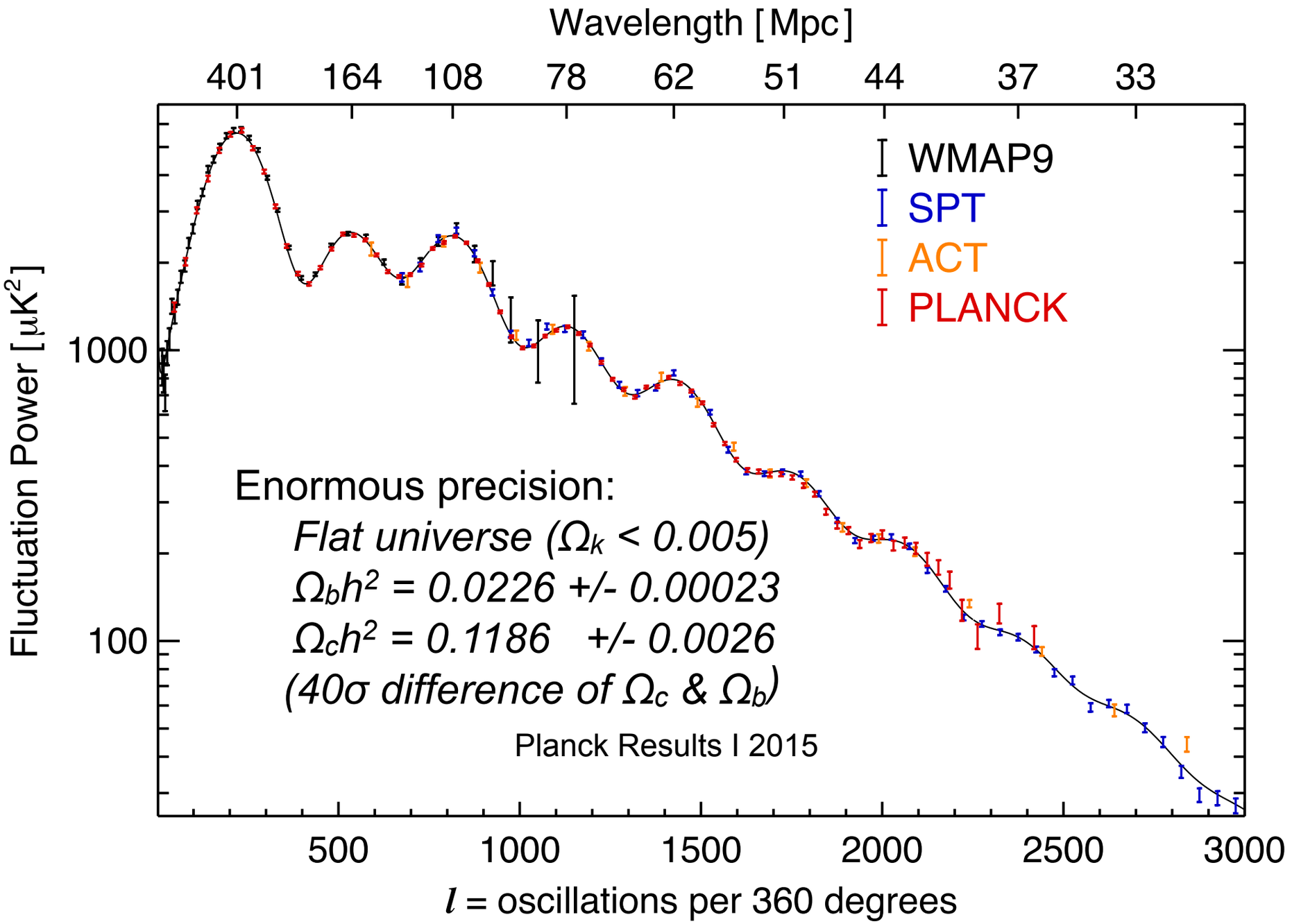
"pre-Planck" CMB Power Spectrum





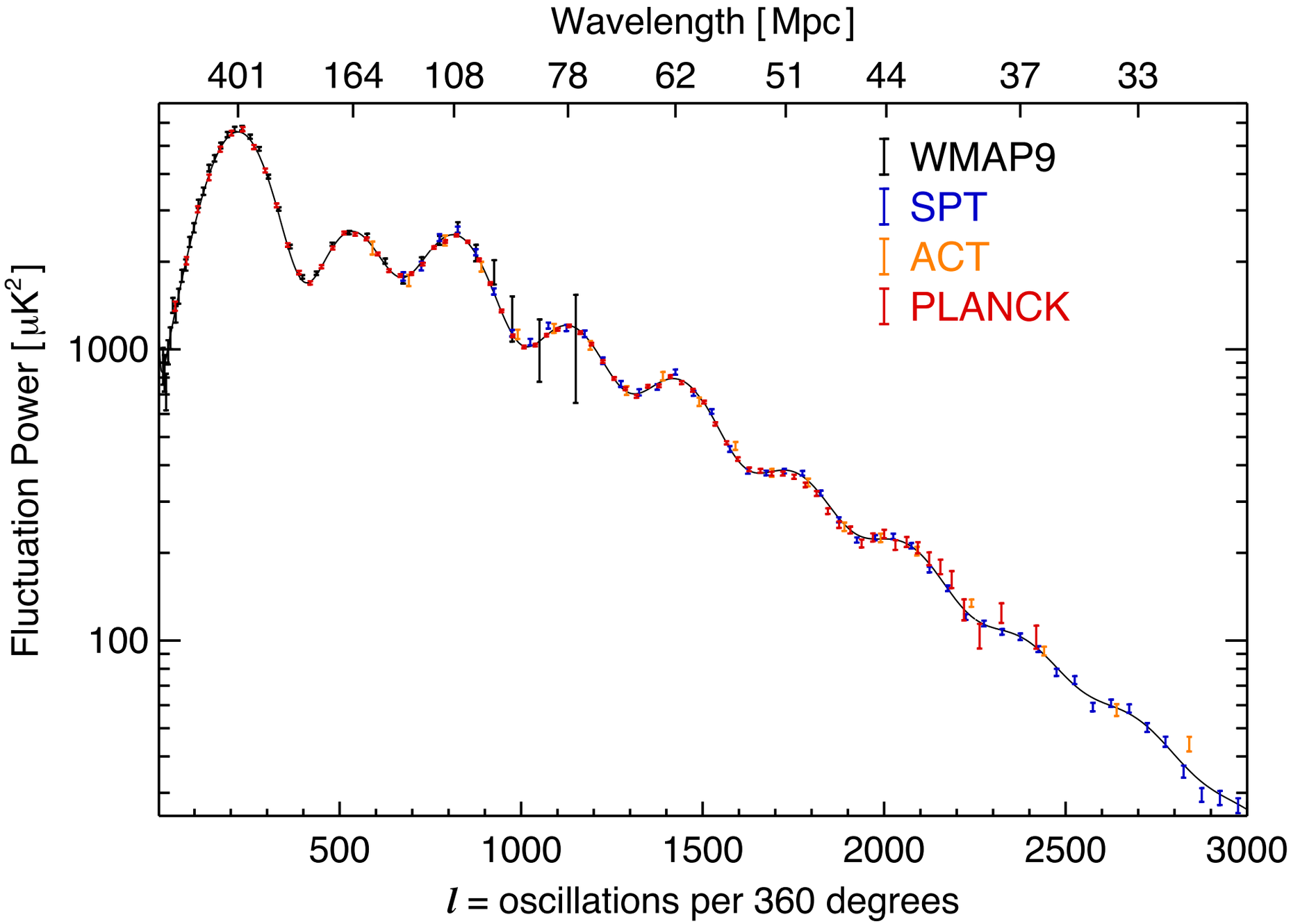
Story et al., 2013
George et al., 2014
Das et al., 2014

Primary CMB anisotropy - remarkable agreement
Enormous precision



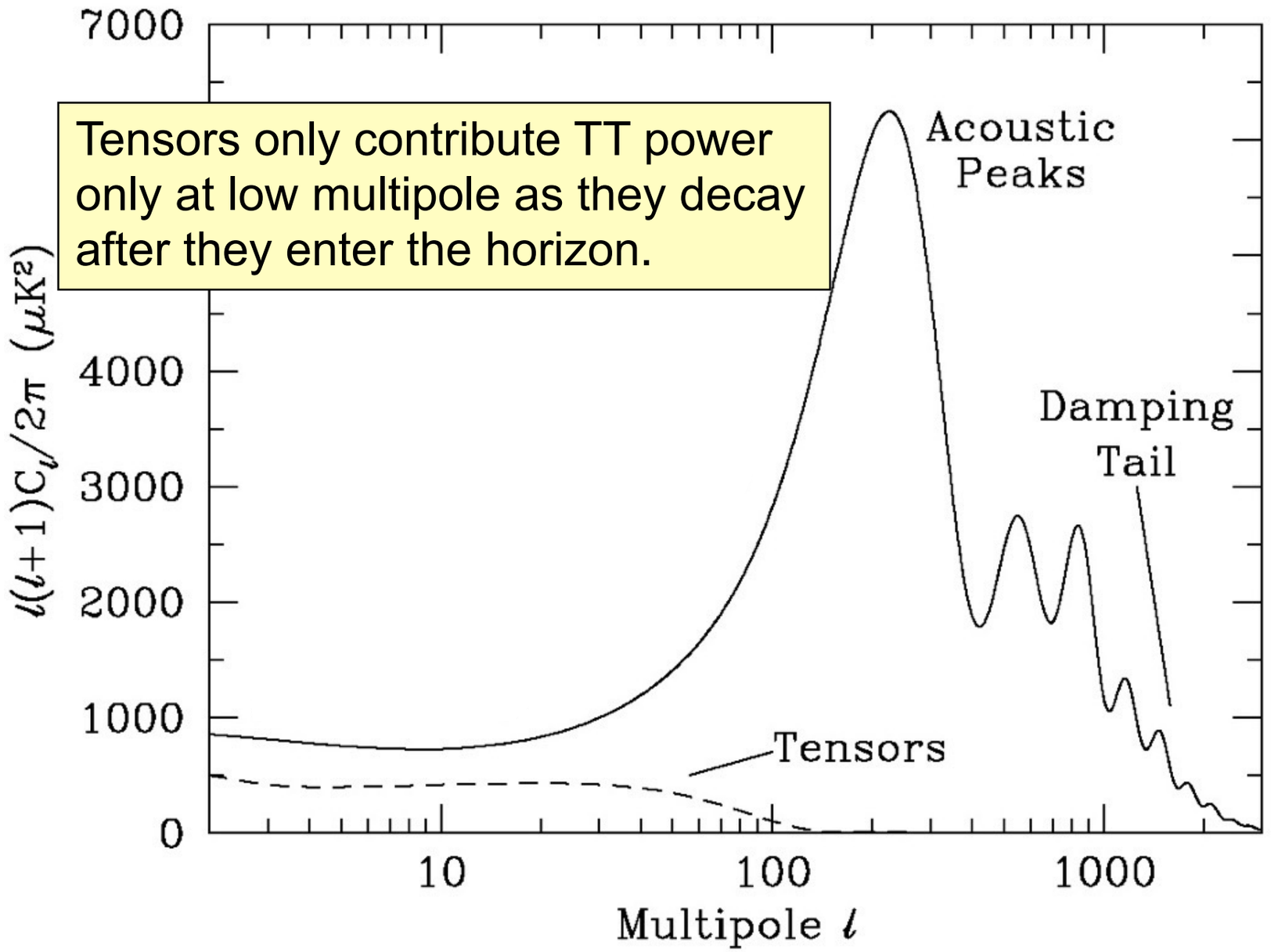
Fit by vanilla ΛCDM - just six parameters: $\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ Δ^2_R n_s τ

Primary CMB anisotropy - remarkable agreement Enormous precision



Inflation checks: Geometrical flat universe; Superhorizon features; acoustic peaks/adiabatic fluctuations; departure from scale invariance; inflationary gravitational waves (tensors)

setting limit to tensor perturbations i.e., primordial gravitational waves

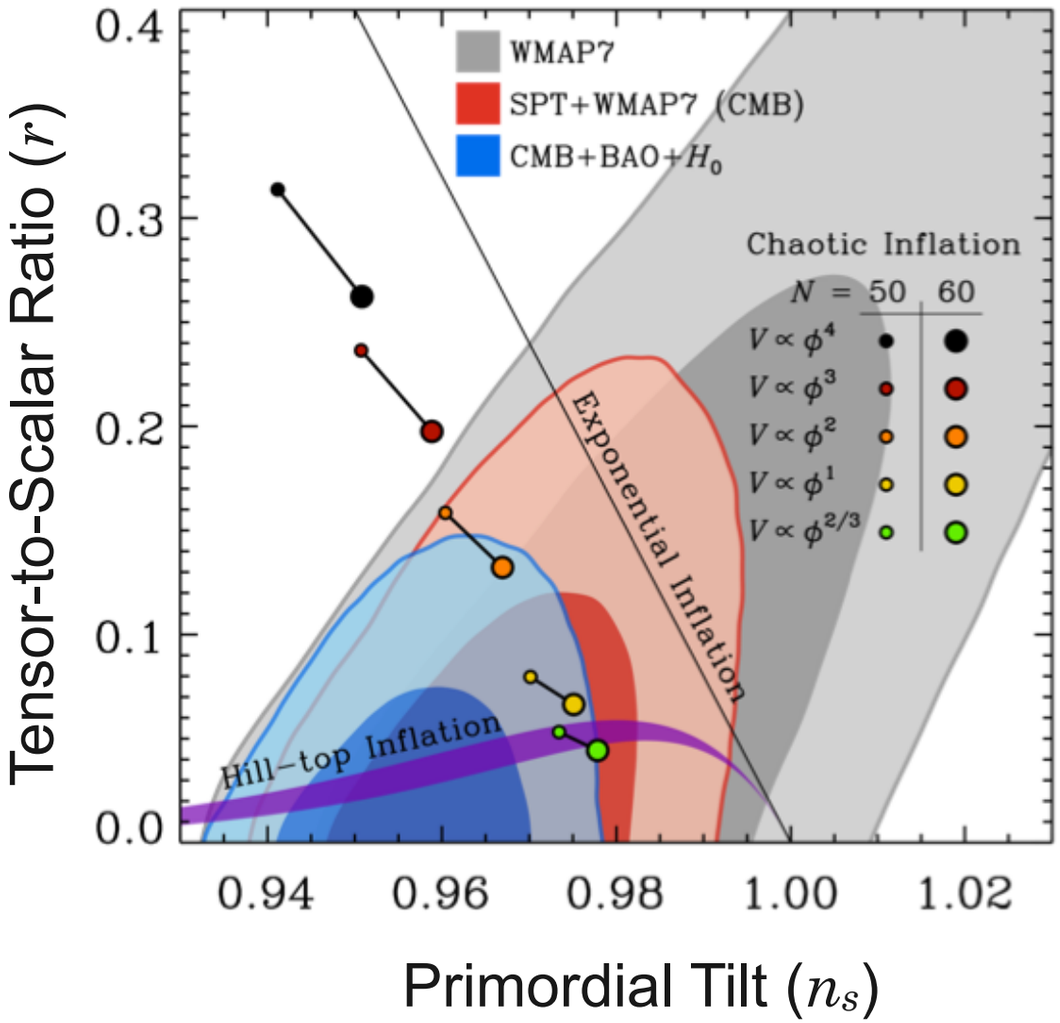


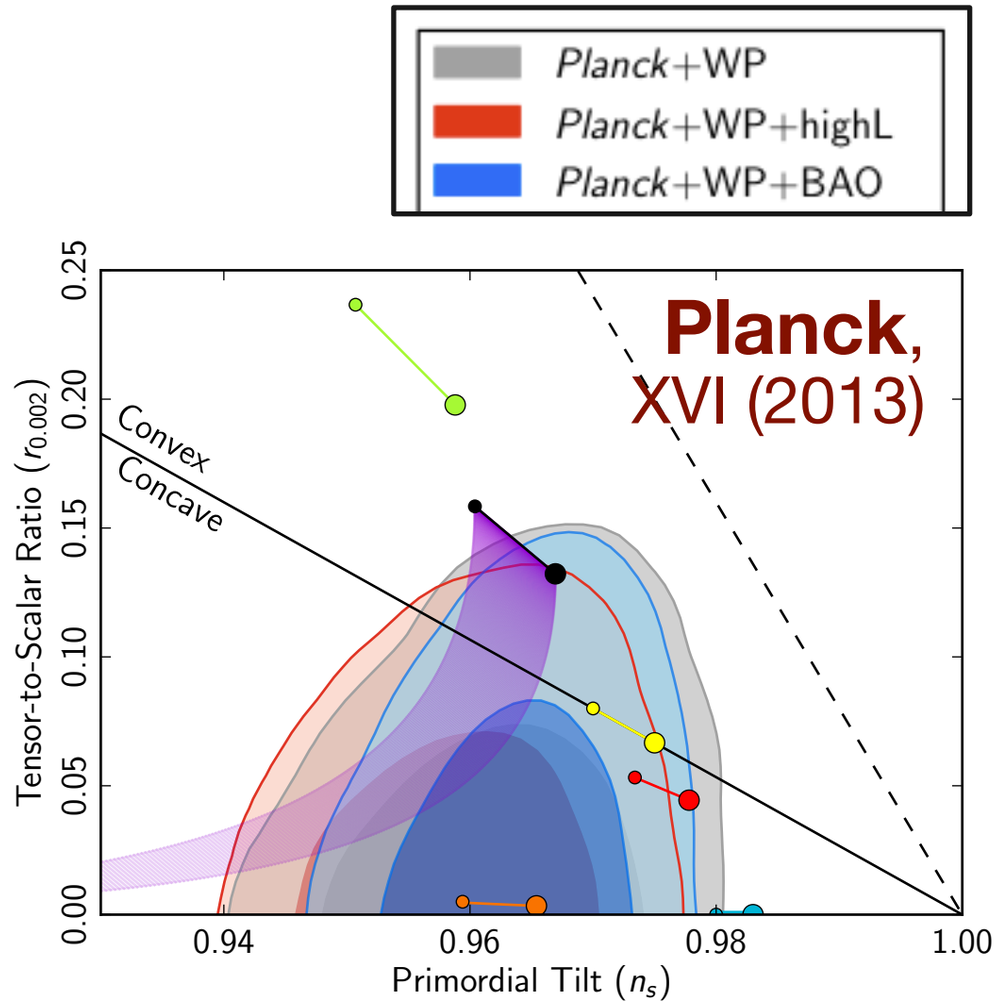
$$r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}$$

plot taken from Ned Wright's web pages

Constraining inflationary models
joint r and n_s limits

SPT Story et al., 1210.7231





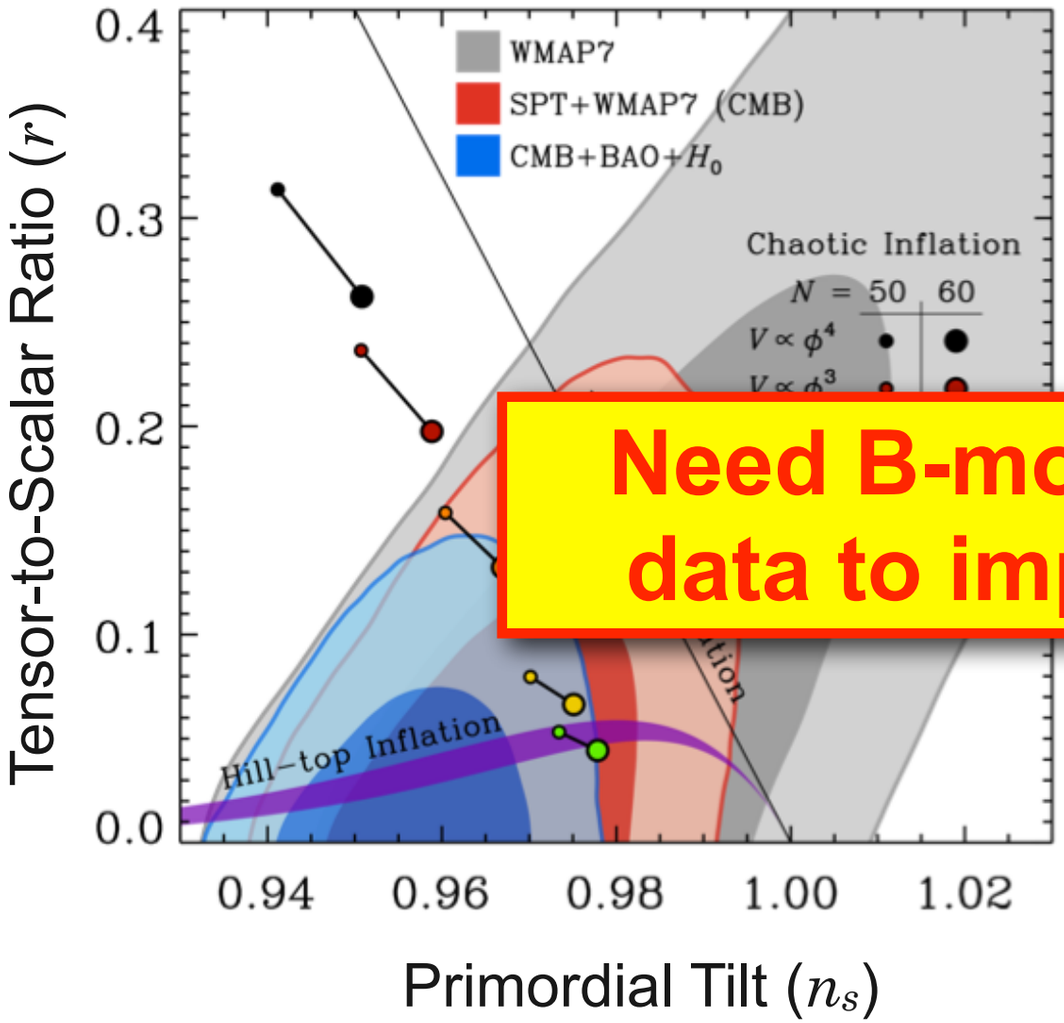
Spectral Index of Primordial Fluctuations

$$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1} \qquad r \equiv \frac{\Delta_h^2}{\Delta_R^2}$$

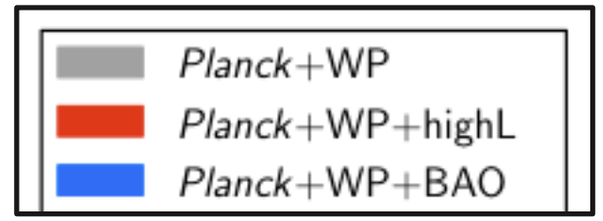
Inflation evidence
$n_s \neq 1$ at over 5σ

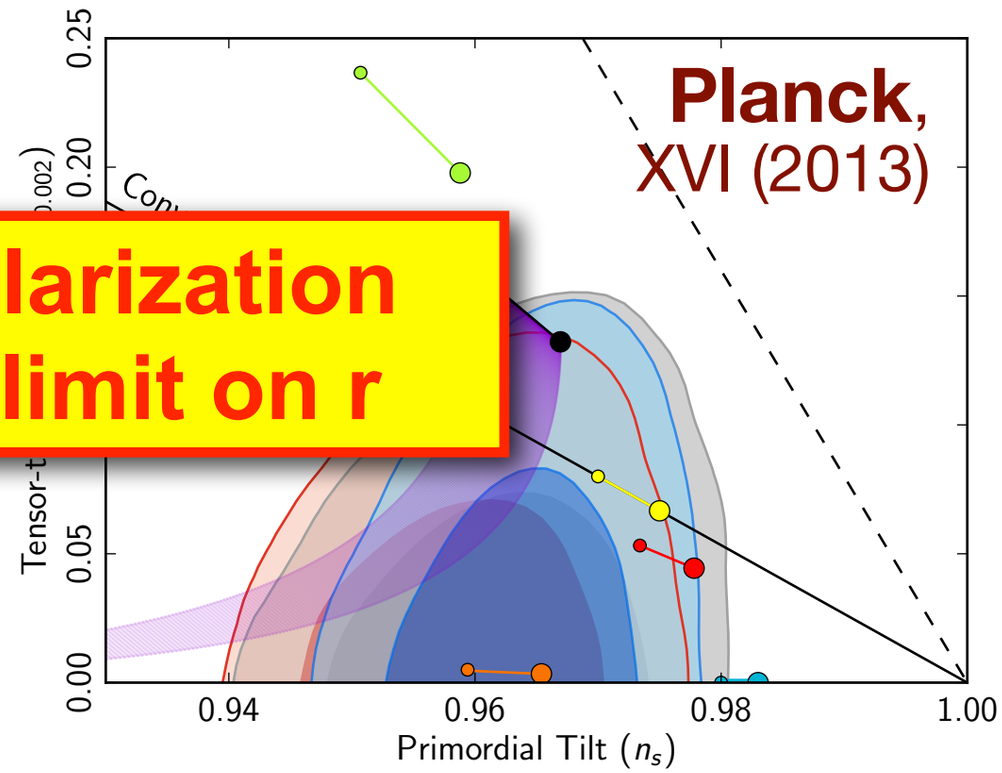
Constraining inflationary models
joint r and n_s limits

SPT Story et al., 1210.7231



Need B-mode polarization data to improve limit on r





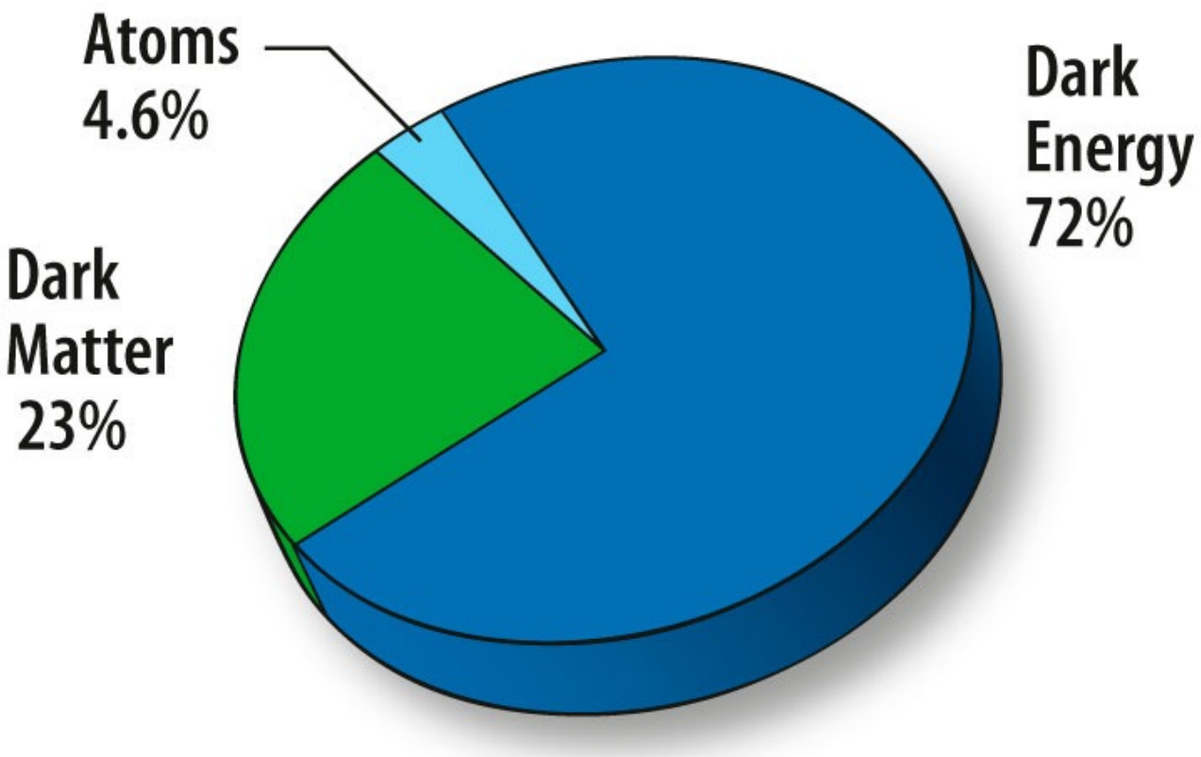
Planck, XVI (2013)

Spectral Index of Primordial Fluctuations

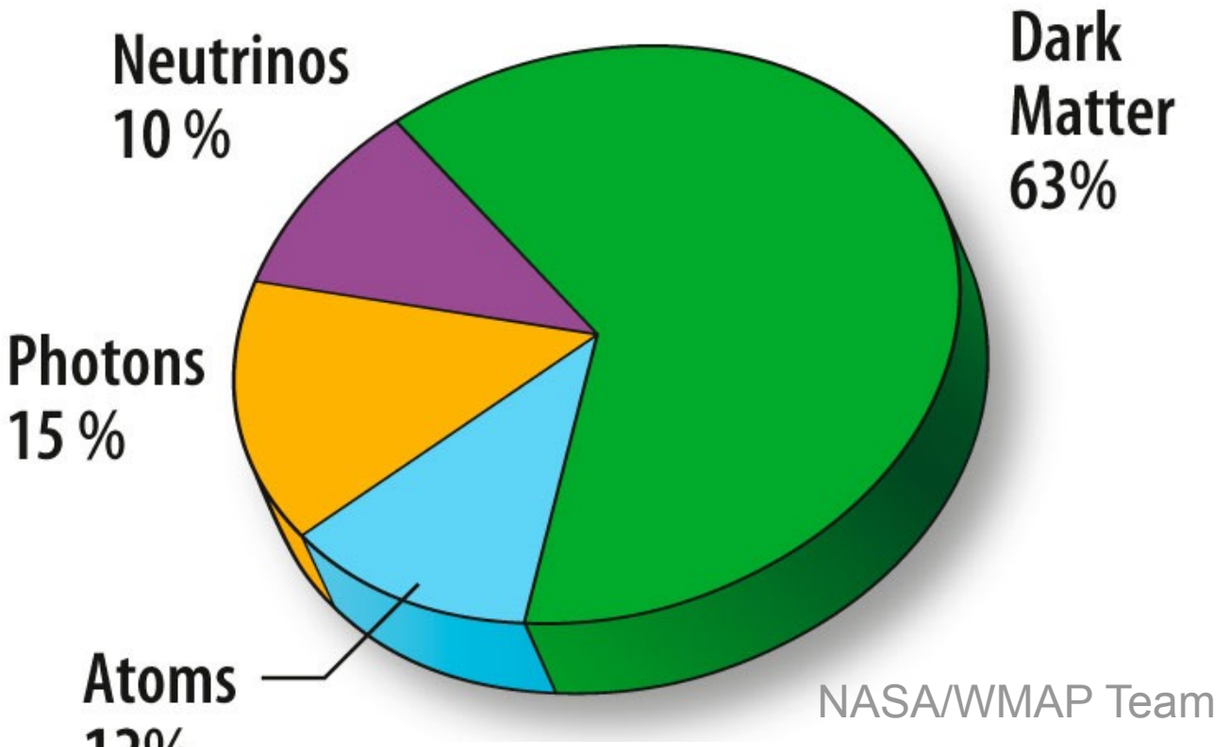
$$\Delta^2_R(k) = \Delta^2_R(k_0)\left(\frac{k}{k_0}\right)^{n_s-1} \qquad r \equiv \frac{\Delta^2_h}{\Delta^2_R}$$

Inflation evidence $n_s \neq 1$ at over 5σ

Neutrinos - now and then



TODAY

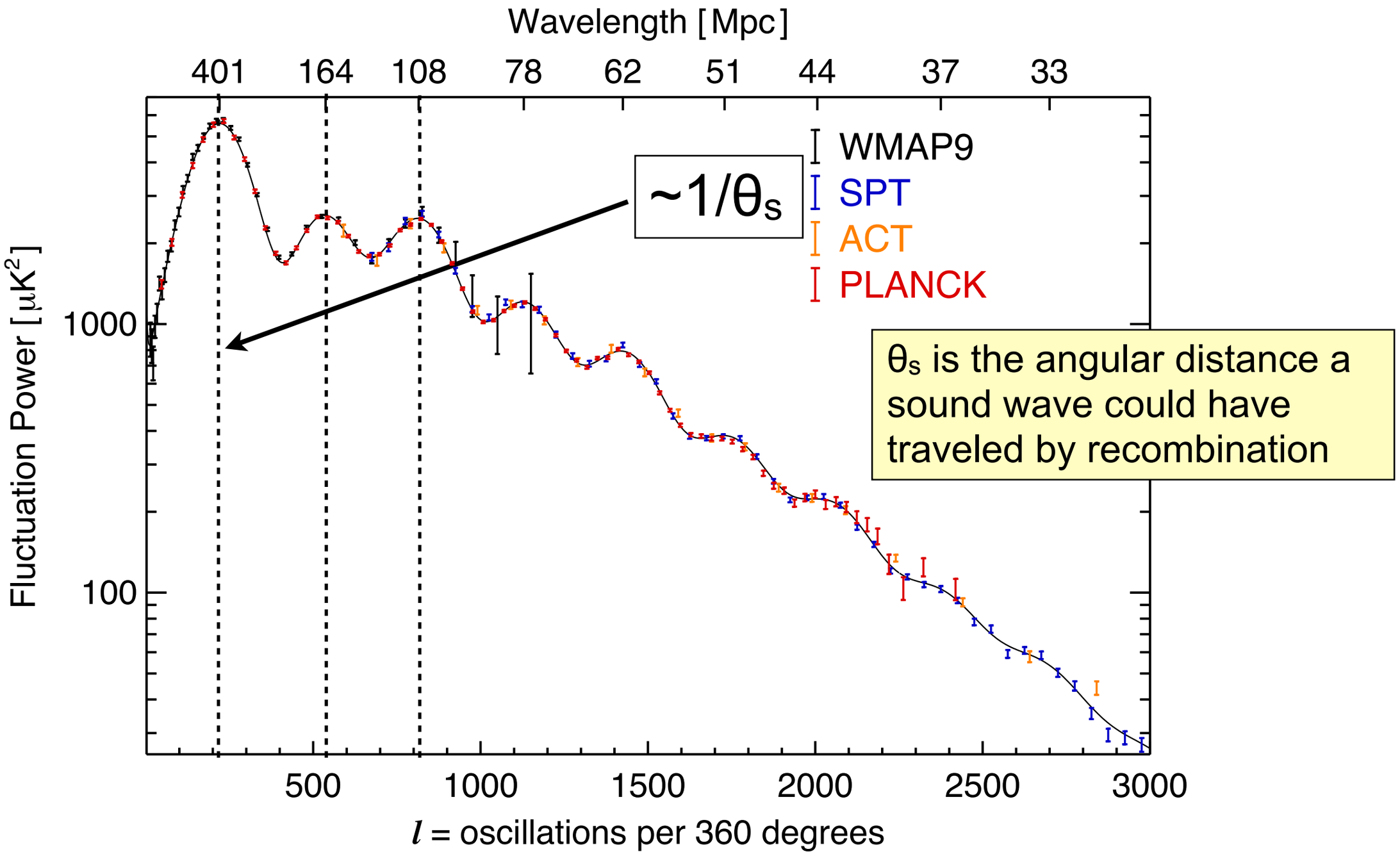


13.7 Billion Years Ago
(Universe 380,000 years old)

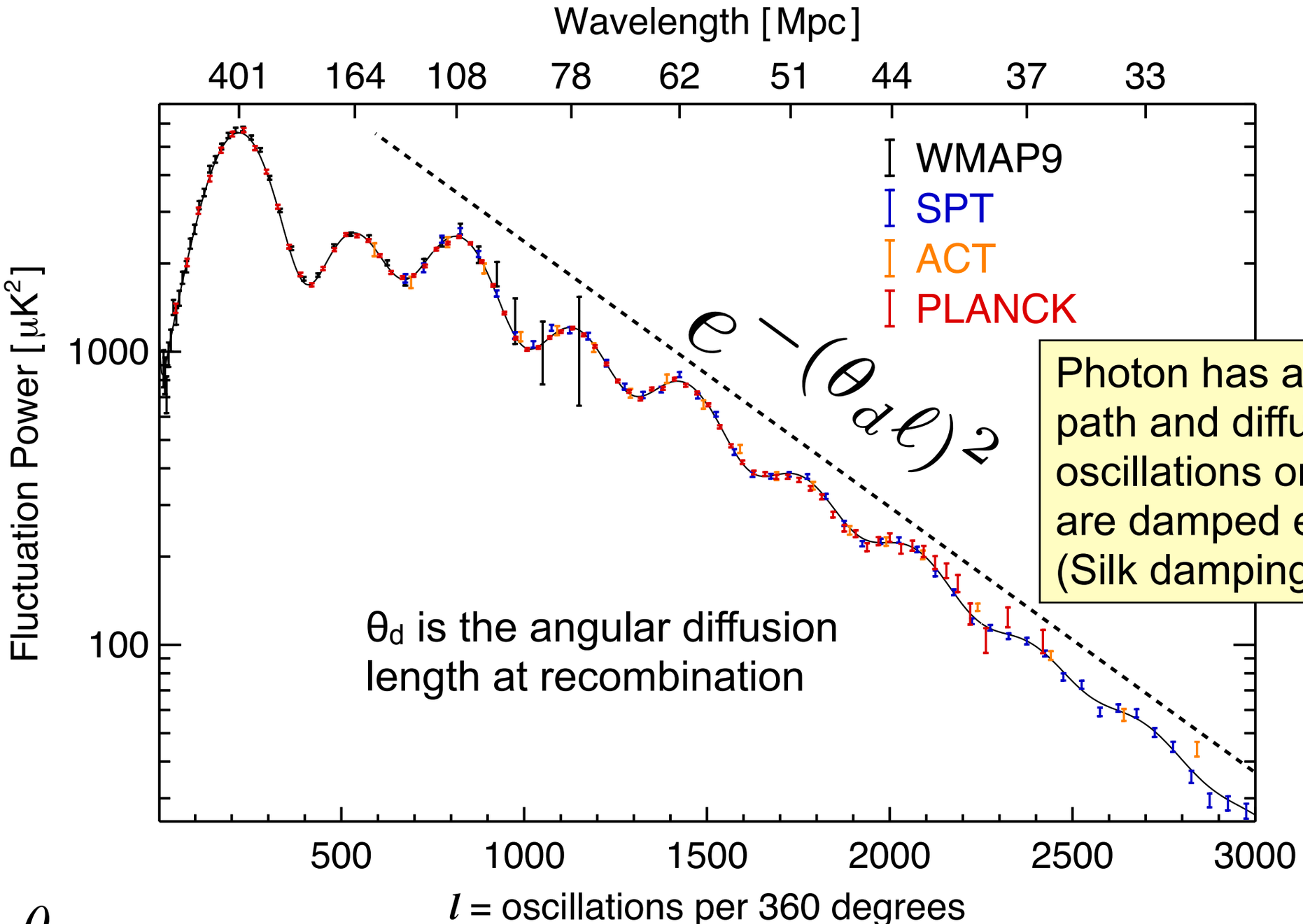
- *Neutrinos are the most abundant particle after photons*
- *The **"Cosmic Neutrino Background"** decoupled at 1 sec and can be detected indirectly in the CMB.*

$$\Omega_\nu h^2 = \Sigma m_\nu / 93\text{eV} \rightarrow \Omega_\nu \gtrsim 0.4\%$$

Two scales: sound horizon, θ_s



and the damping scale, θ_d

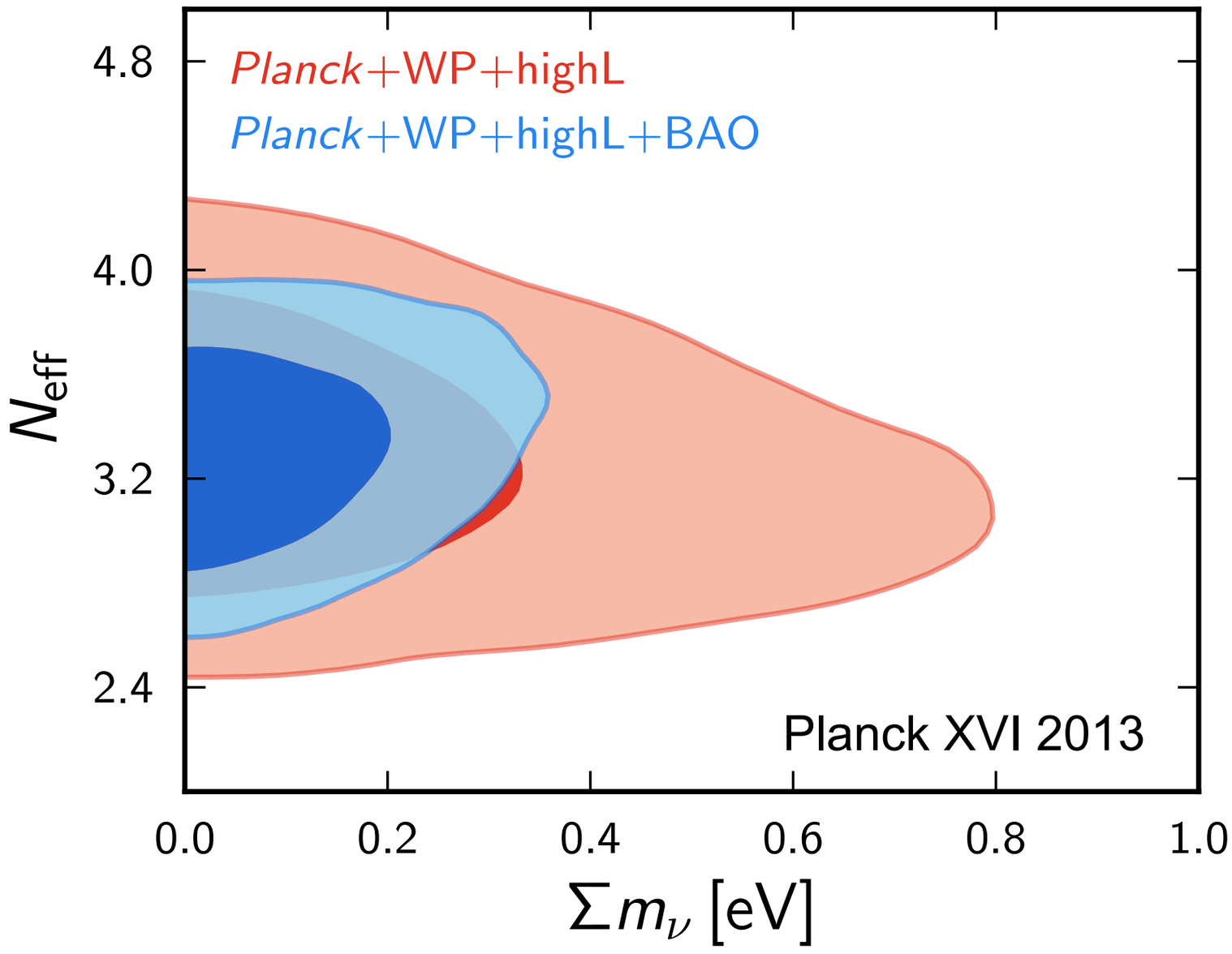


Photon has a mean free path and diffuses. So, oscillations on small scales are damped exponentially. (Silk damping)

$$\frac{r_s}{r_d} = \frac{\theta_s}{\theta_d} \propto t_{exp}^{0.5},$$ so sensitive to energy density, through Friedman eq. $$t_{exp} = \frac{1}{H} = \sqrt{\frac{3c^2}{8\pi G\rho}}$$

Give constraints on Dark Radiation (N_{eff})

Joint Dark Radiation (N_{eff}) and Σm_ν constraints



Planck 2015:

N_{eff} = 3.15±0.23

(>10σ detection of cosmic neutrino background)

Σm_ν < 0.23eV

at 95% C.L.

(N_{eff} and Σm_ν constraints depend on choice of external data sets.)

N_{eff} is the effective number of relativistic species; it measures the extra relativistic energy relative to photons.
For standard 3 neutrinos N_{eff} =3.046.

CMB lensing

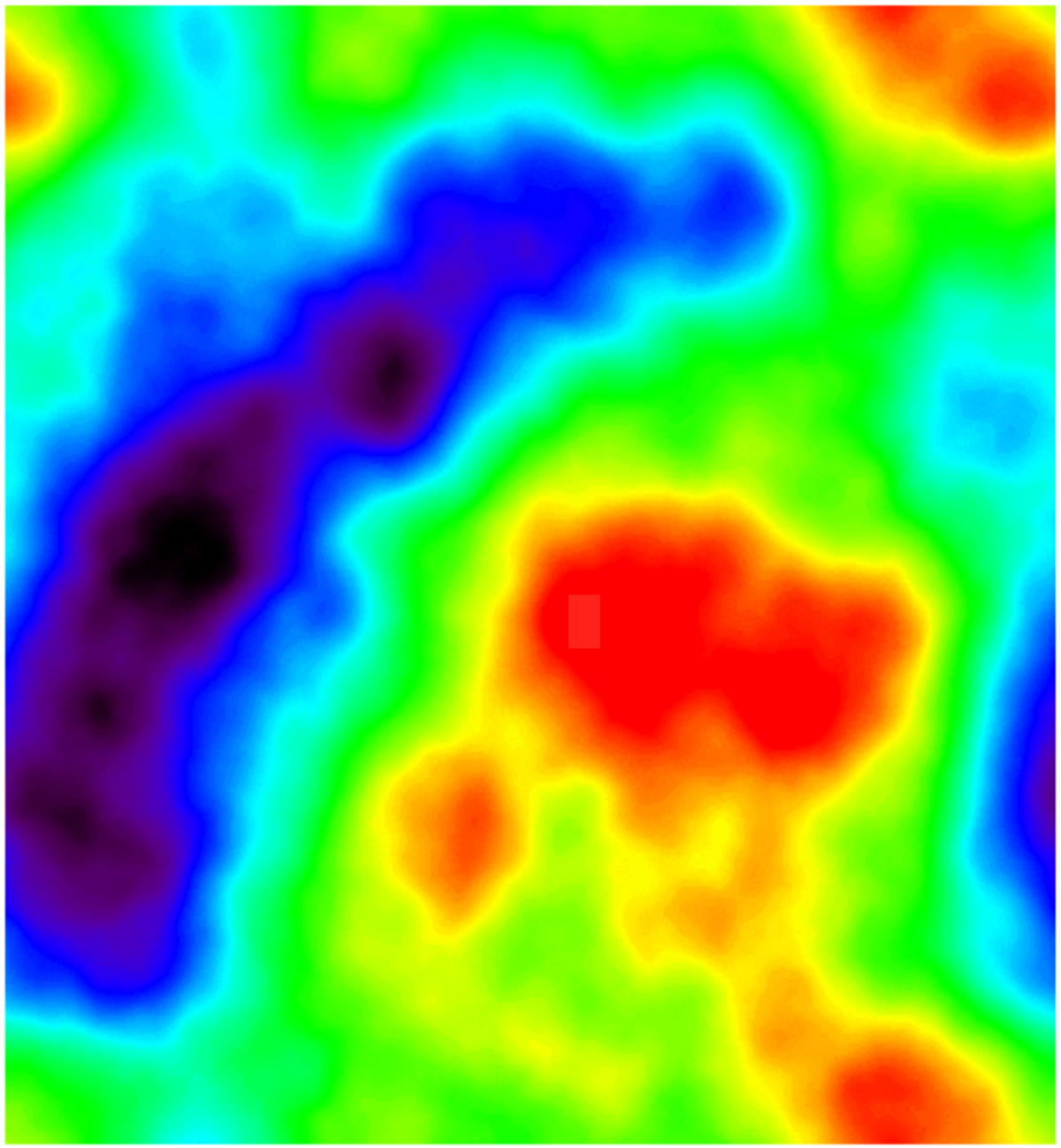
Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree (~300 Mpc) scales

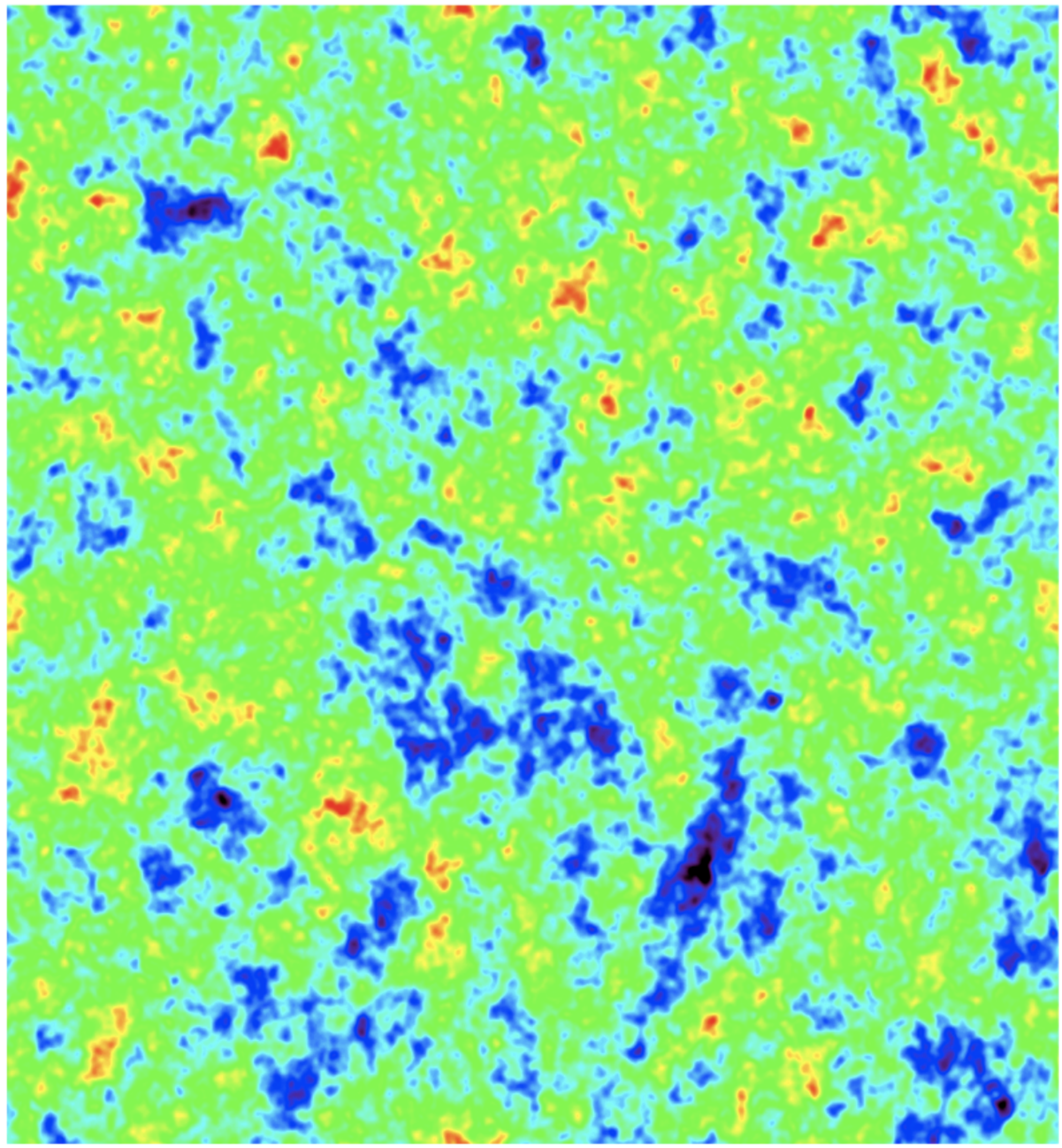
graphic from ESA Website

Lensing of the CMB

17°x17°



lensing potential

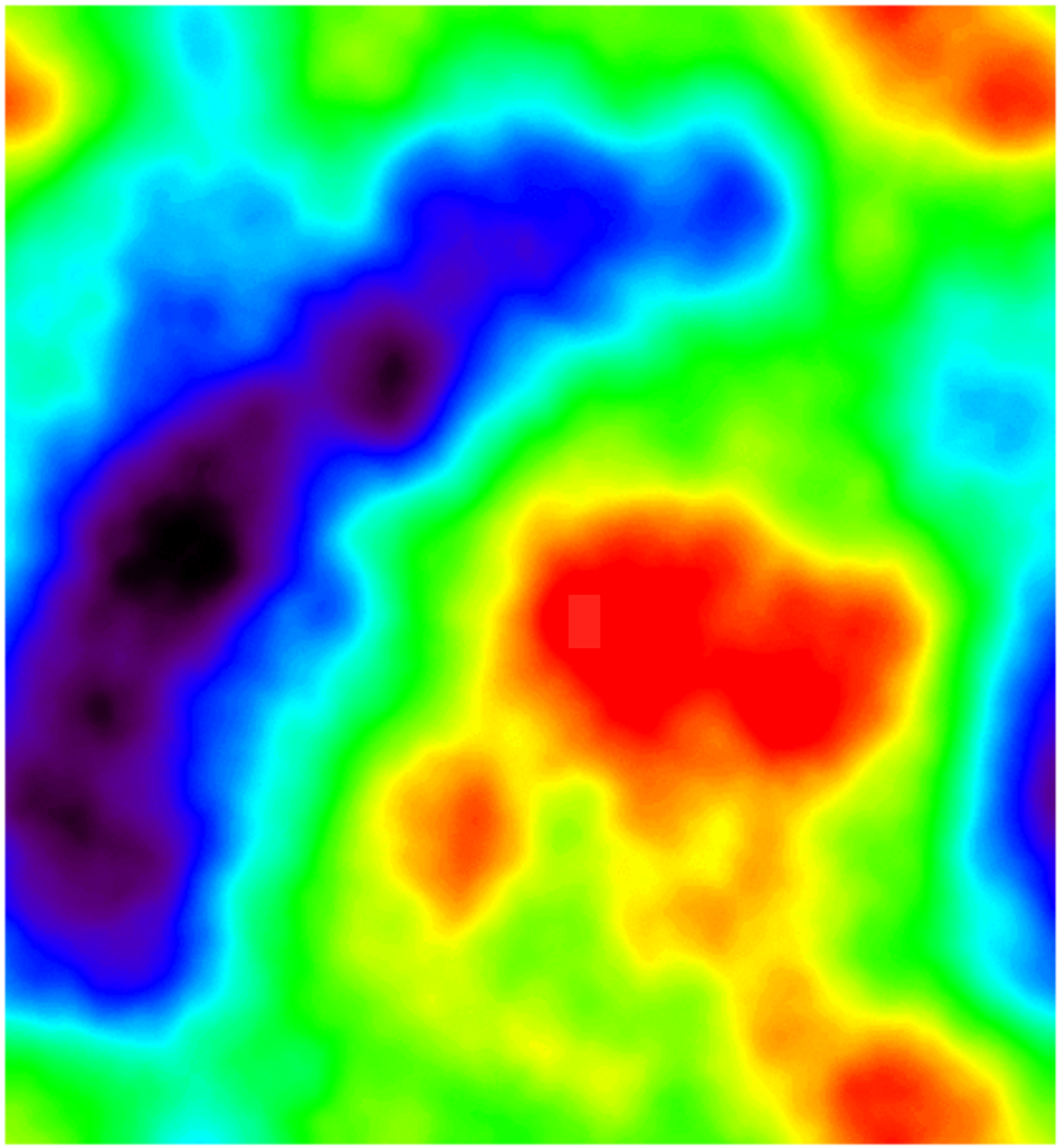


unlensed cmb

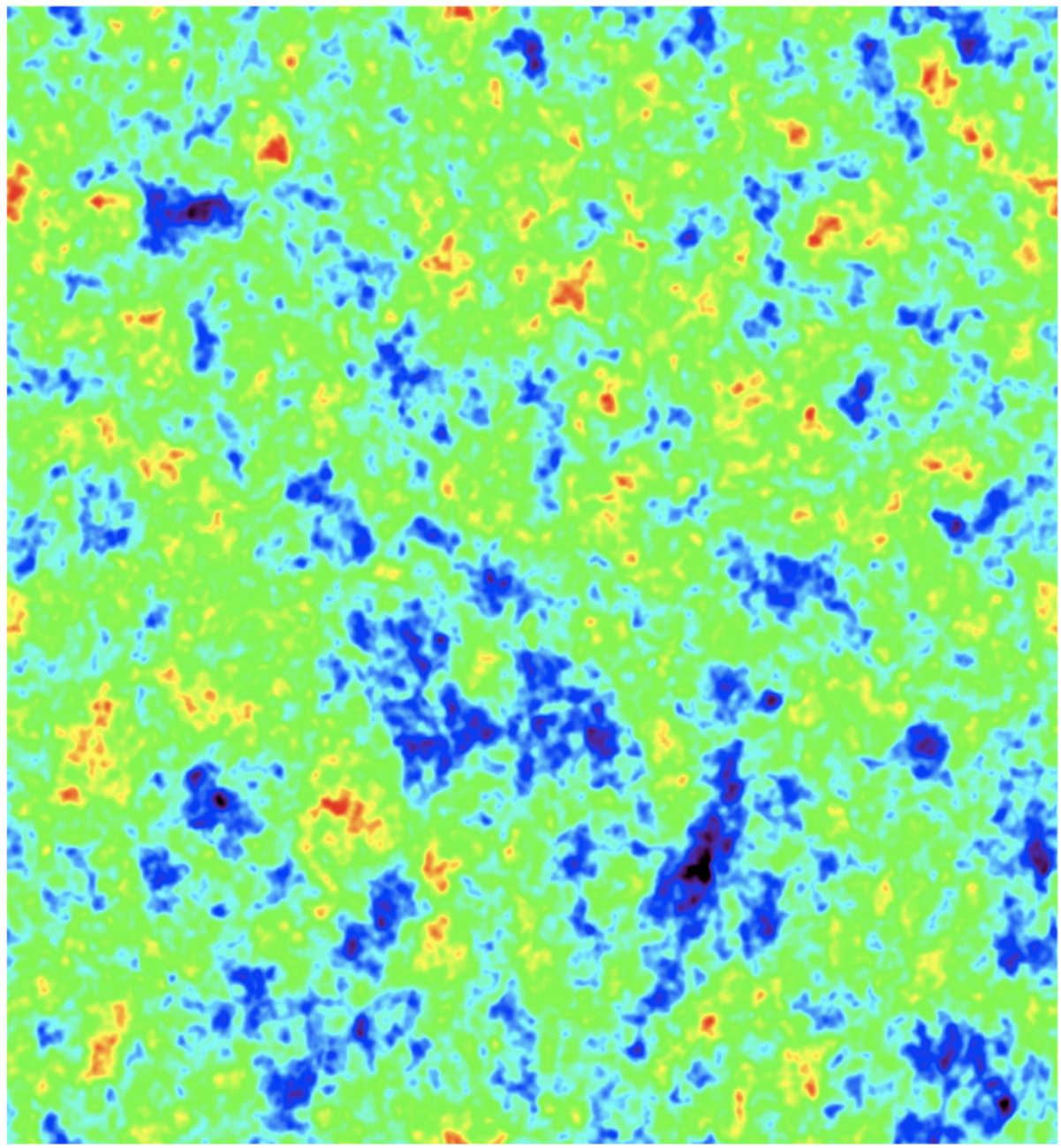
from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential



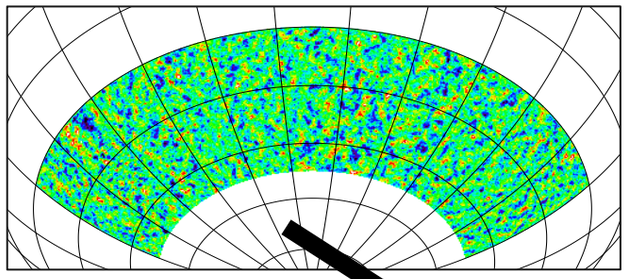
lensed cmb

from Alex van Engelen

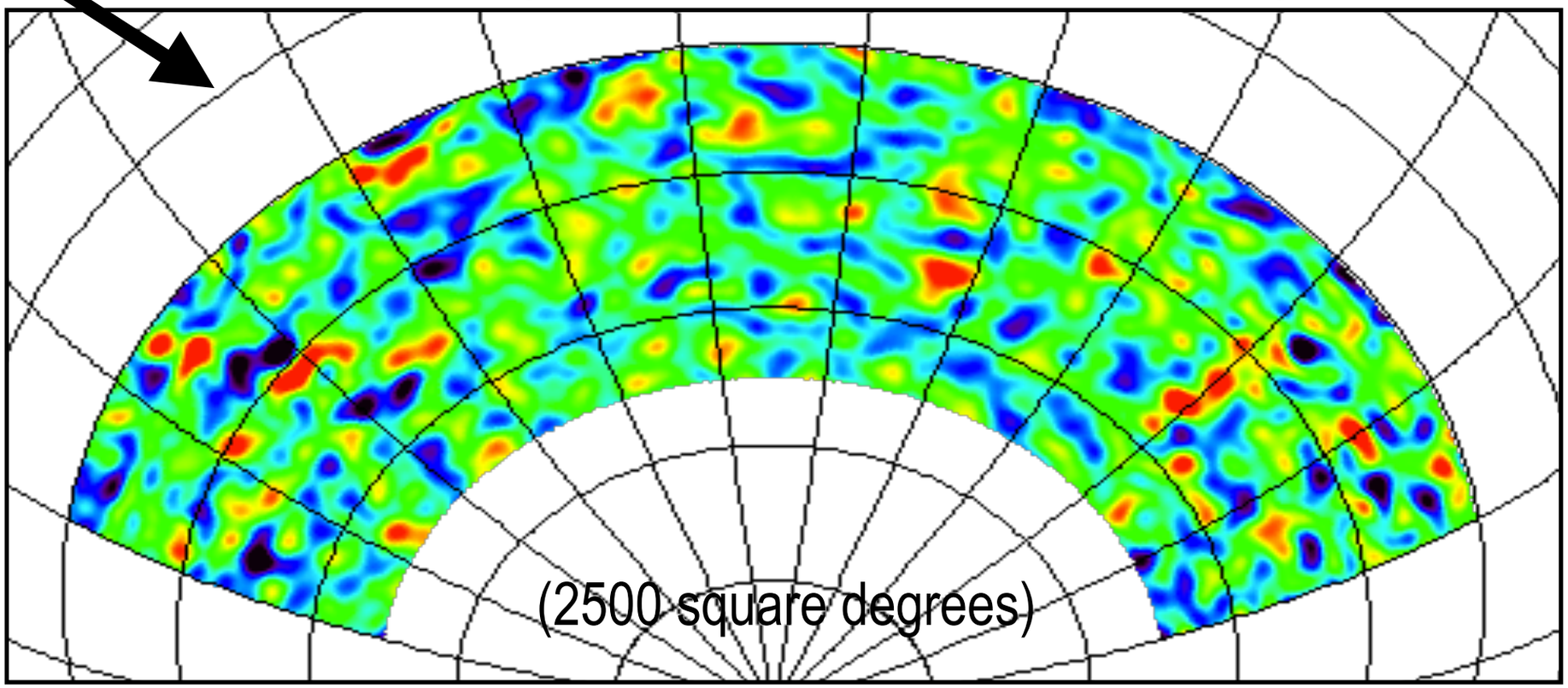
SPT CMB Lensing Map

reconstruction of the mass projected along the line of sight to the CMB.

SPT CMB MAP



Lensing convergence map smoothed to 1° res
from CMB lensing analysis of SPT 2500 deg^2 survey



SPT CMB Lensing Map

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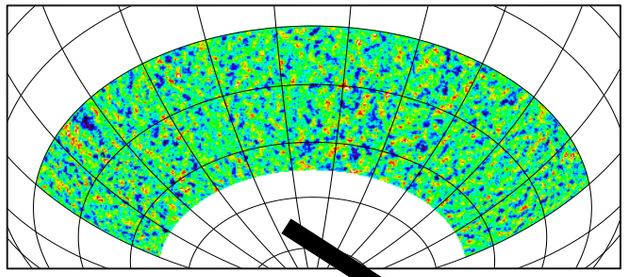
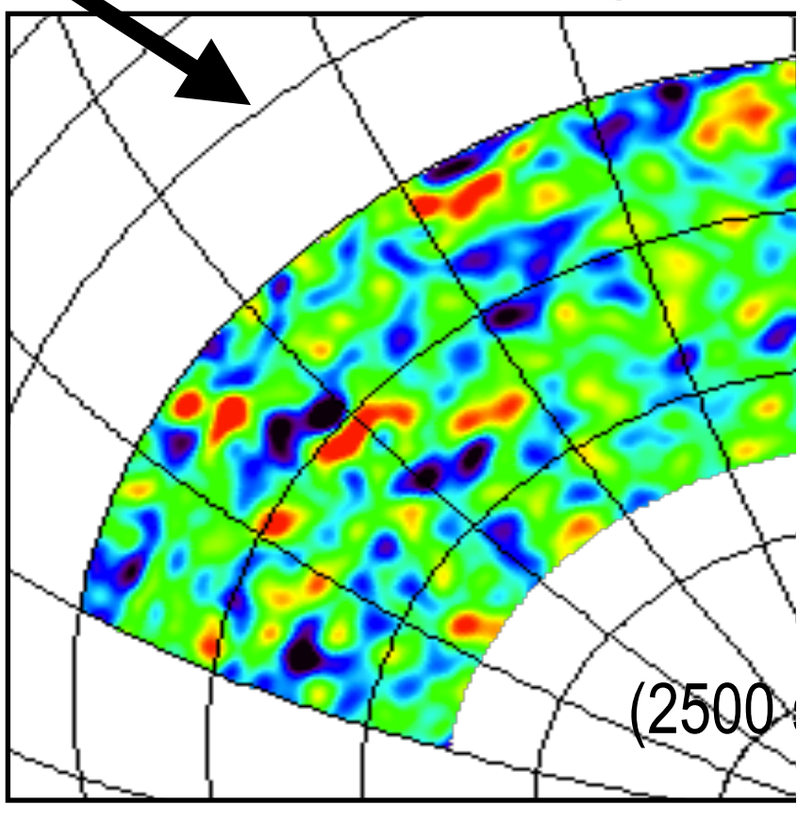
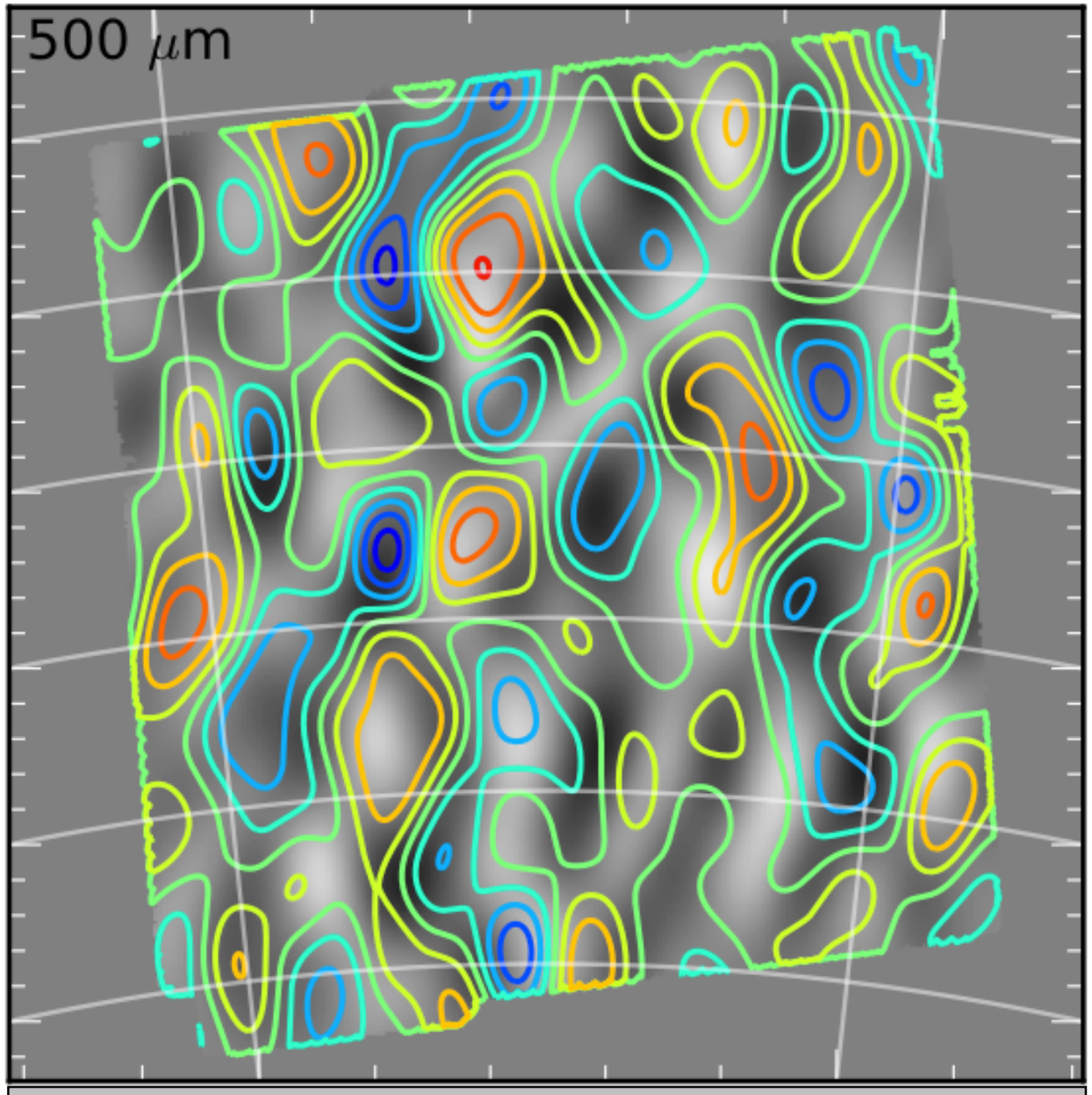
SPT CMB MAP



Lensing convergen
from CMB lensing anal



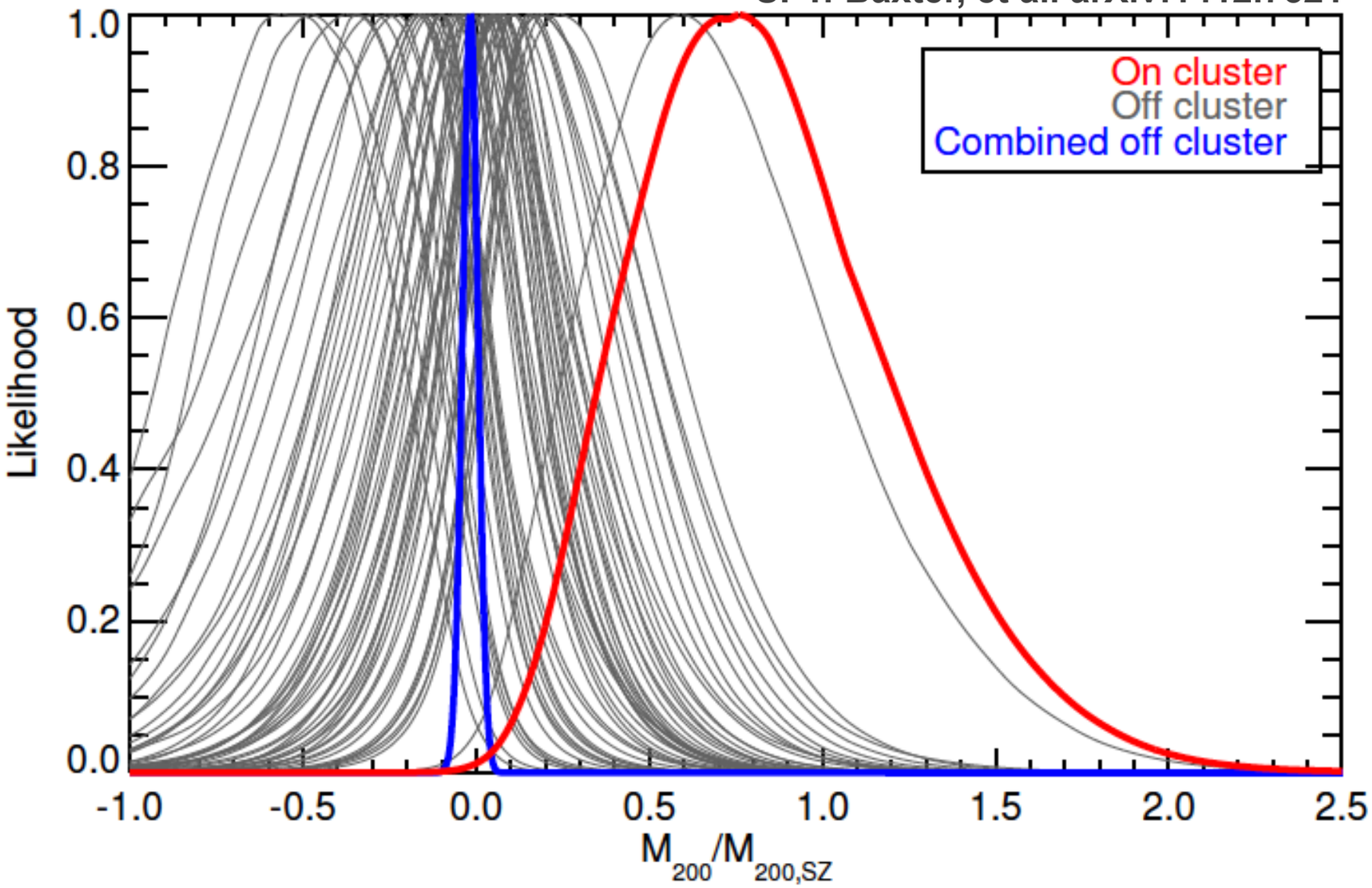


Correlation of matter traced by CMB lensing (contours, SPT) and distribution of high z galaxies (grayscale; Herschel 500 um) [arXiv:1112.5435]

A nice trick: CMB Cluster Lensing

- Stack of the 520 clusters detected in SPT-SZ survey
- ~3-sigma detection of lensing
- Masses agree with SZ-estimated masses

SPT: Baxter, et al. arXiv:1412.7521

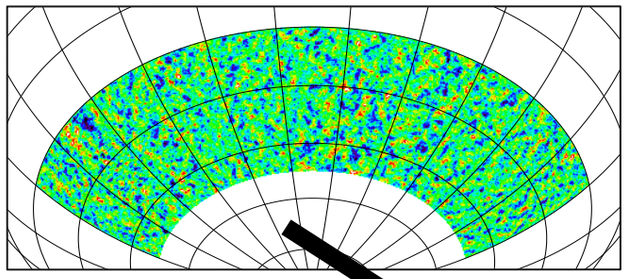


Opens up a new way to measure cluster masses

SPT CMB Lensing Map

reconstruction of the mass projected along the line of sight to the CMB.

SPT CMB MAP



Lensing convergence map smoothed to 1° res
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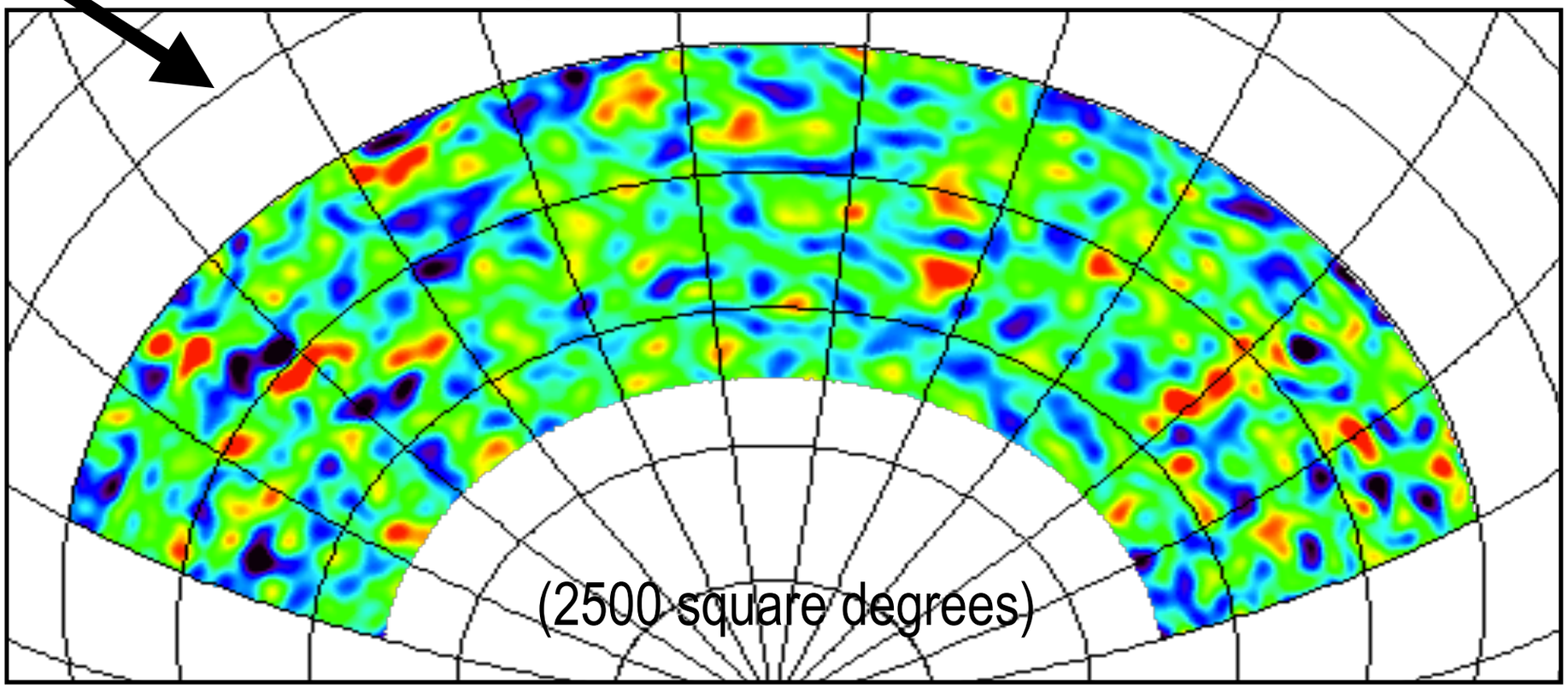
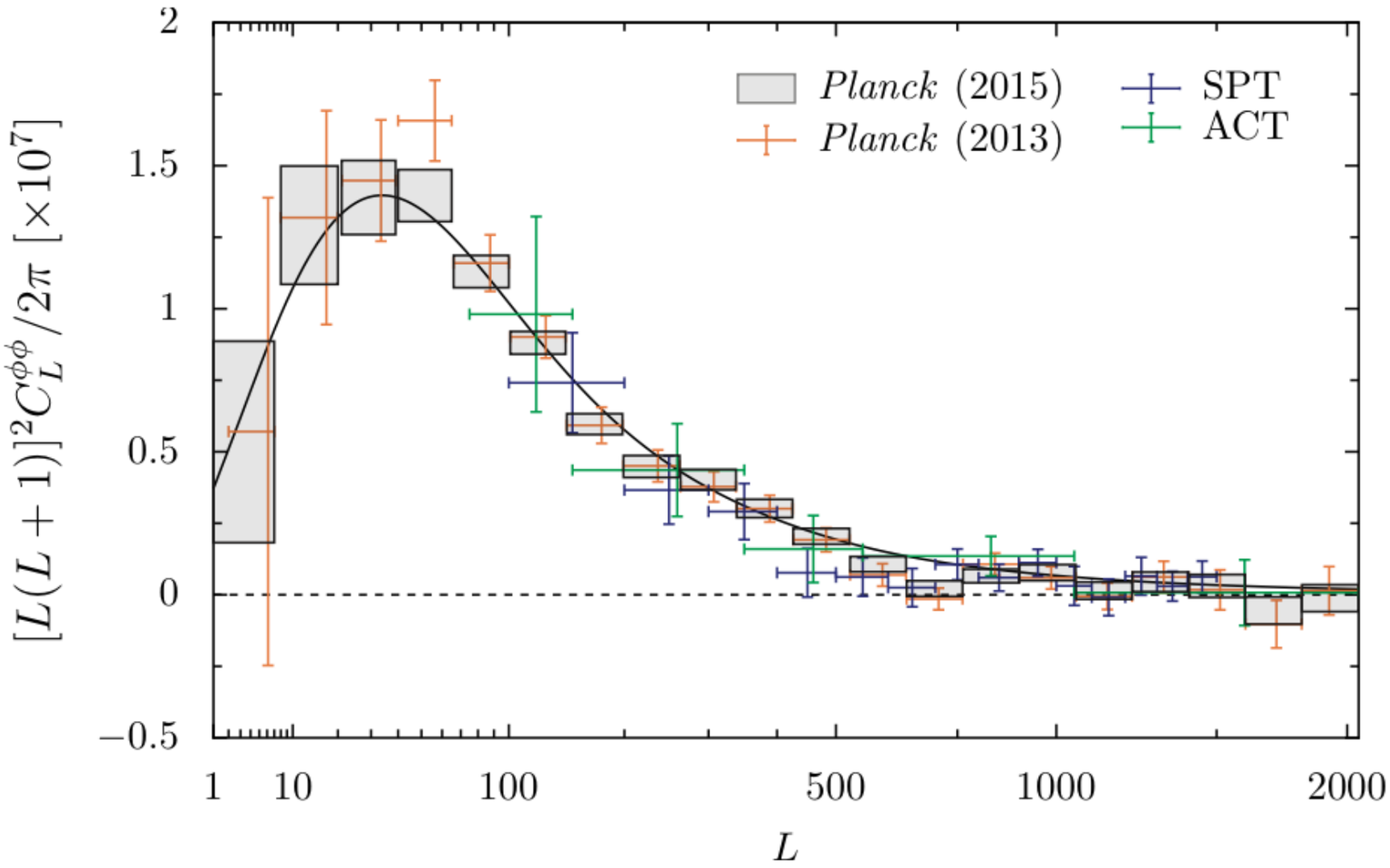


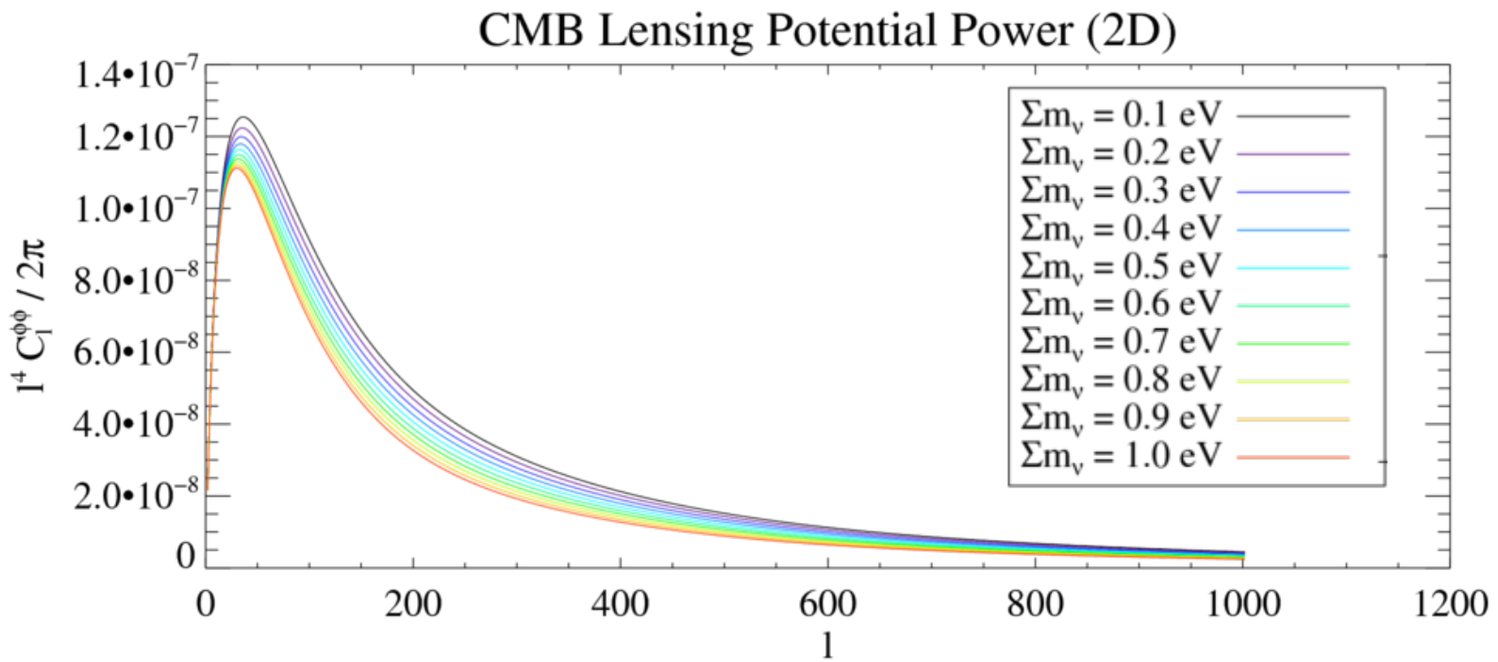
Transform

CMB lensing power spectrum

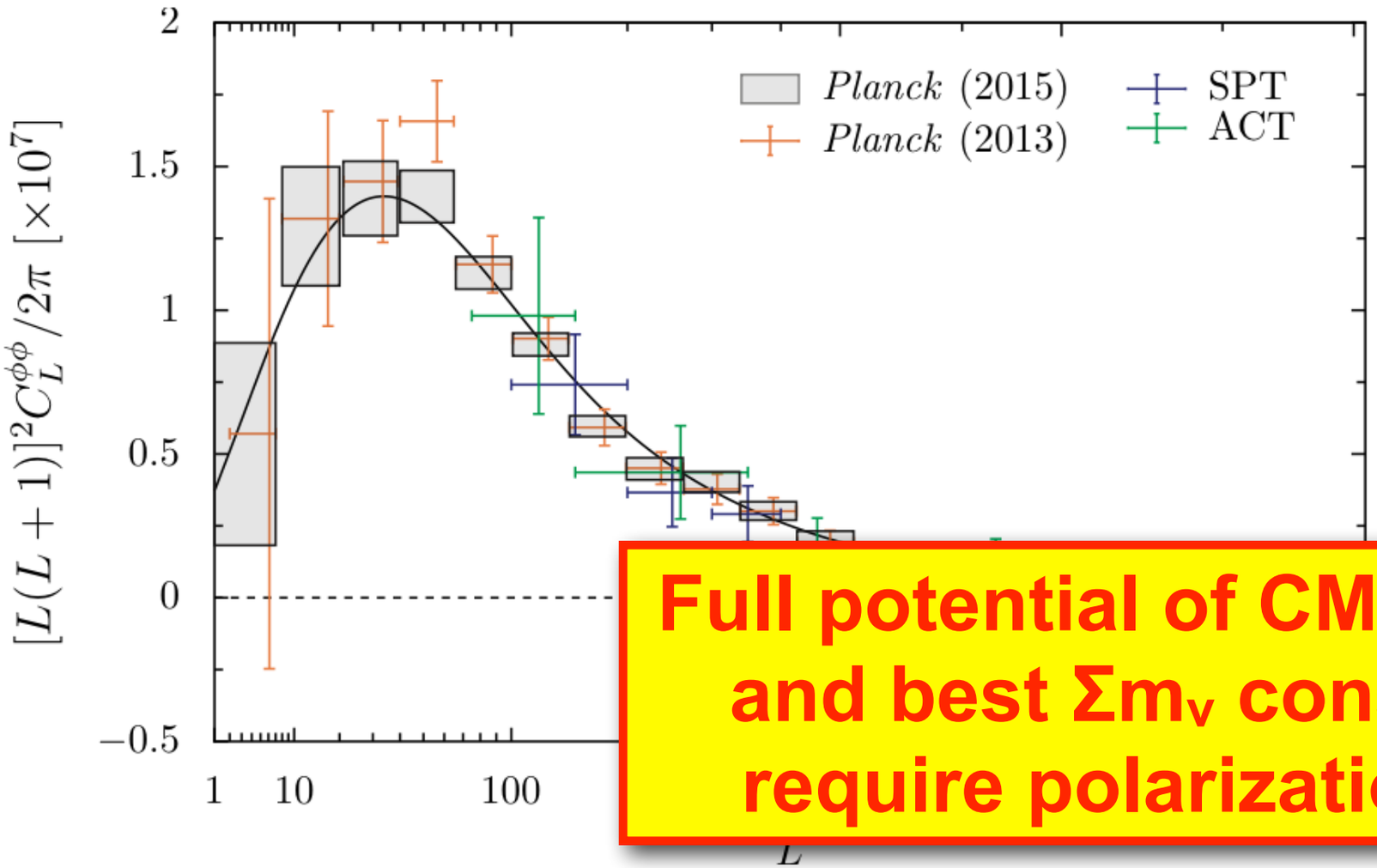


Sensitive to neutrino masses

CMB Polarization provides additional lensing sensitivity and is cleaner probe.



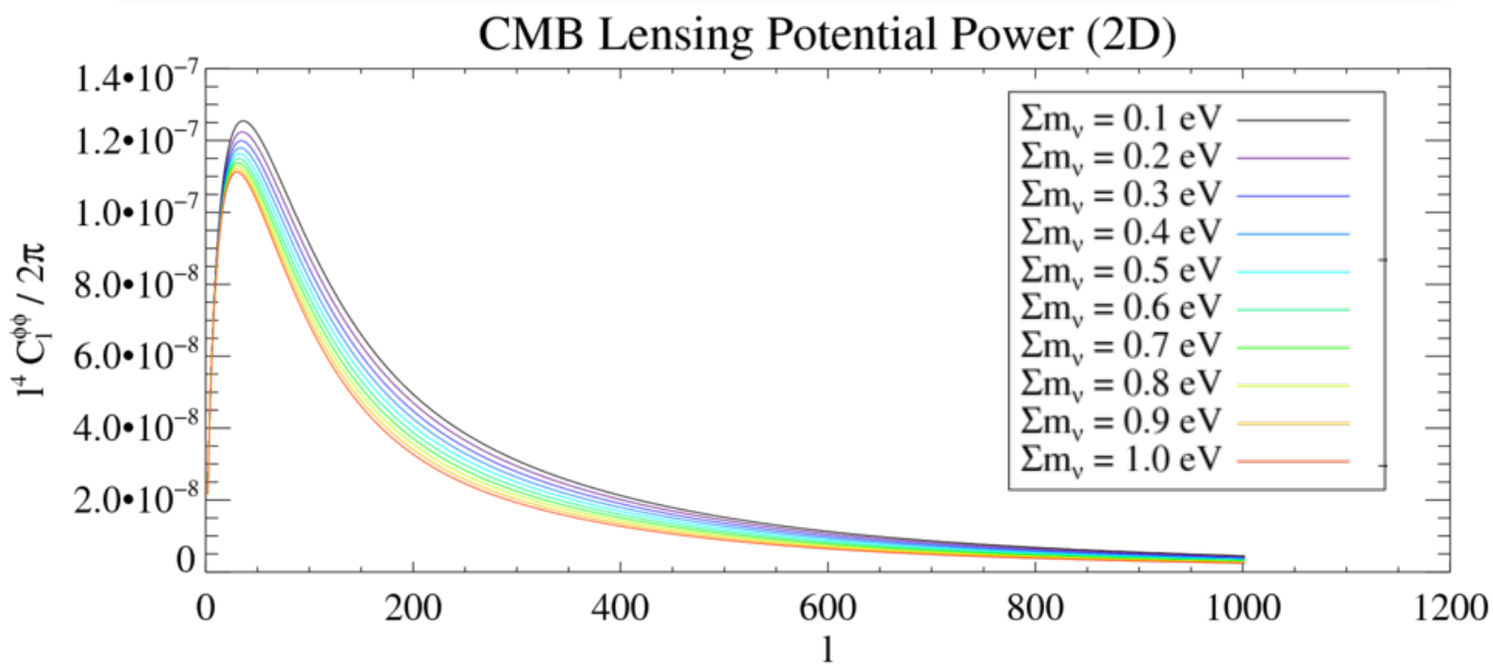
CMB lensing power spectrum



Full potential of CMB lensing and best Σm_ν constraints require polarization data

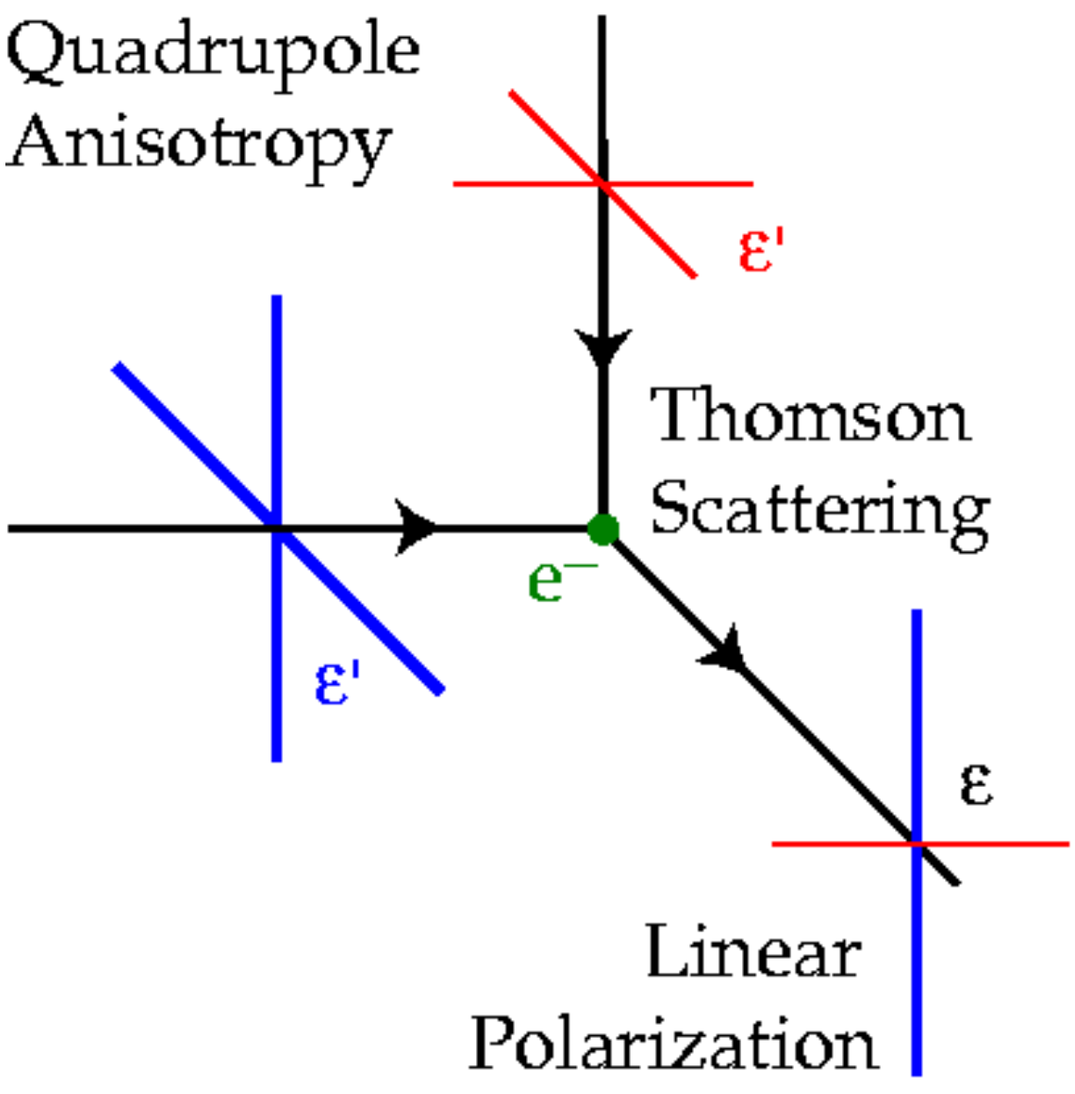
Sensitive to neutrino masses

CMB Polarization provides additional lensing sensitivity and is cleaner probe.



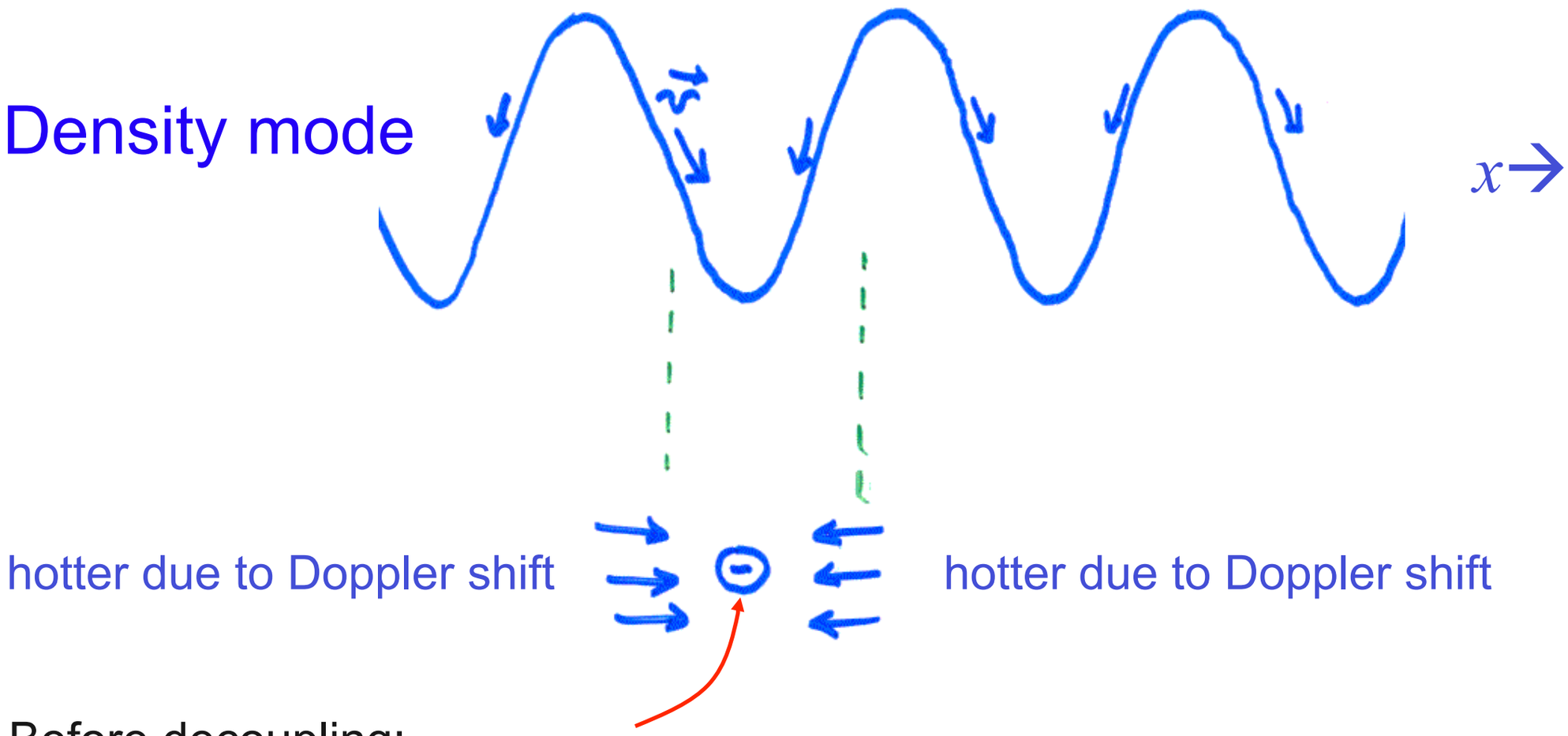
Polarization of the CMB

Due to Thomson scattering –
CMB must be polarized



from W. Hu's web pages

Generating CMB polarization



Before decoupling:

- electron ‘sees’ only a local monopole

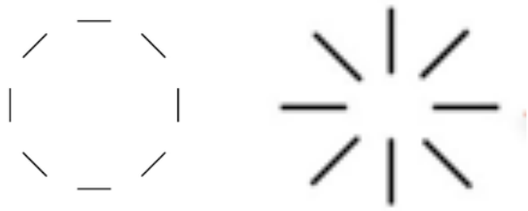
During decoupling:

- mean free path increases and electron ‘sees’ quadrupole
- scattered light is polarized

E-mode from density modes (scalar fluctuations)

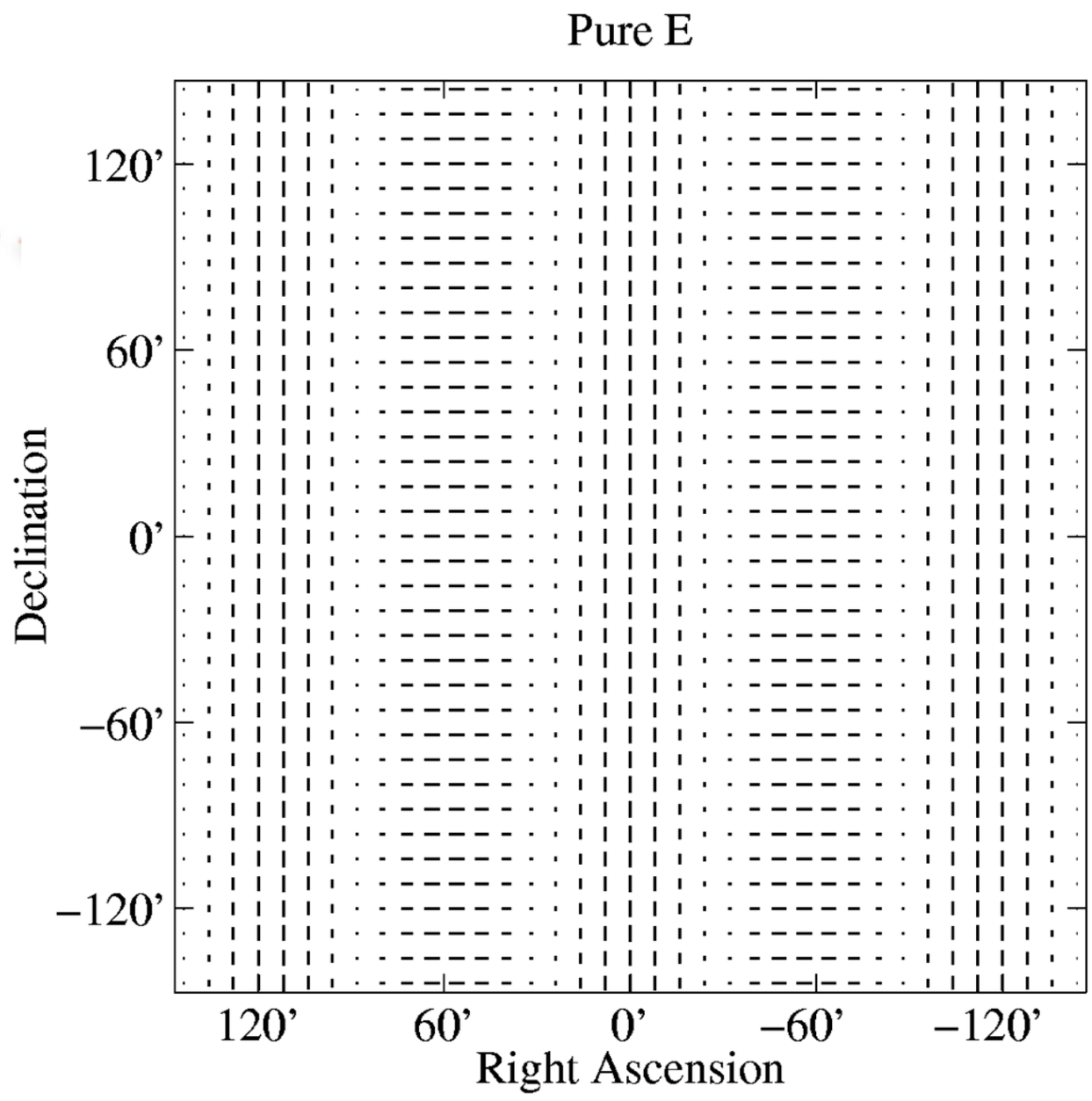
E-mode Polarization (Curl free)

Polarization parallel & perpendicular to wave vector



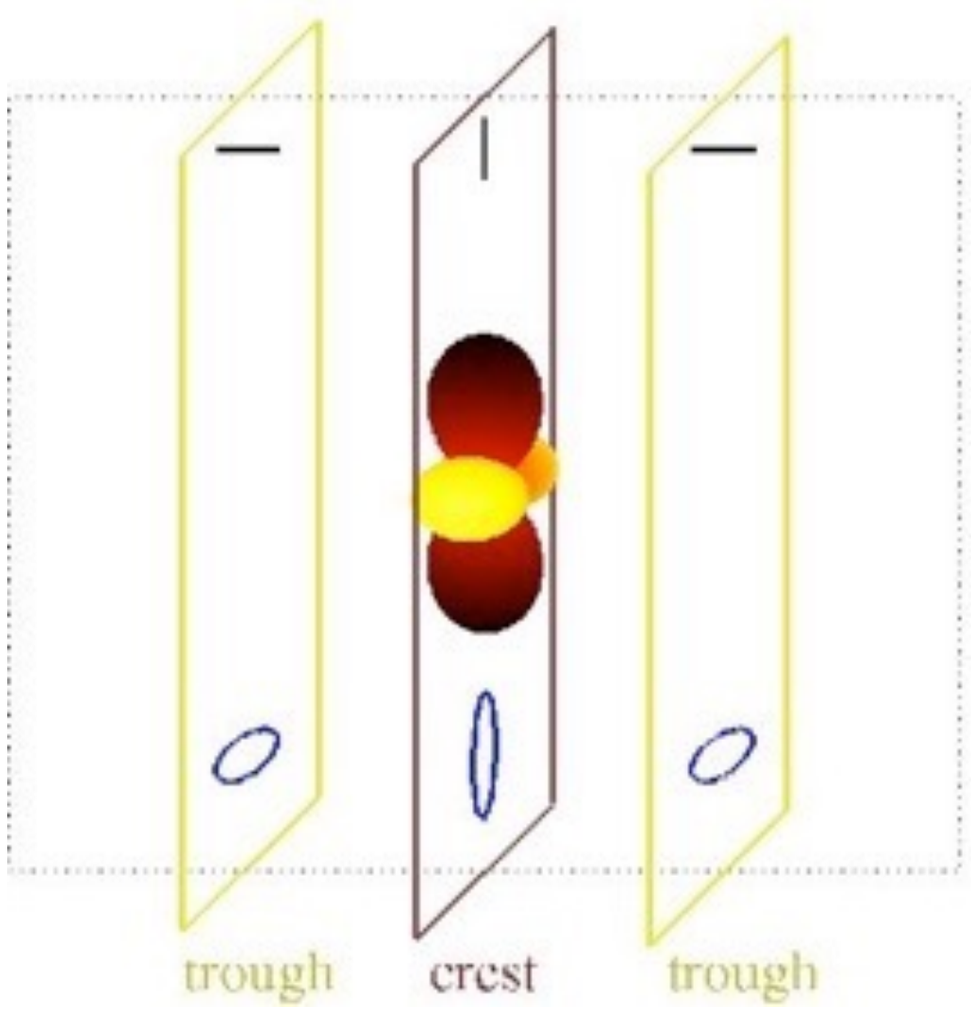
Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization



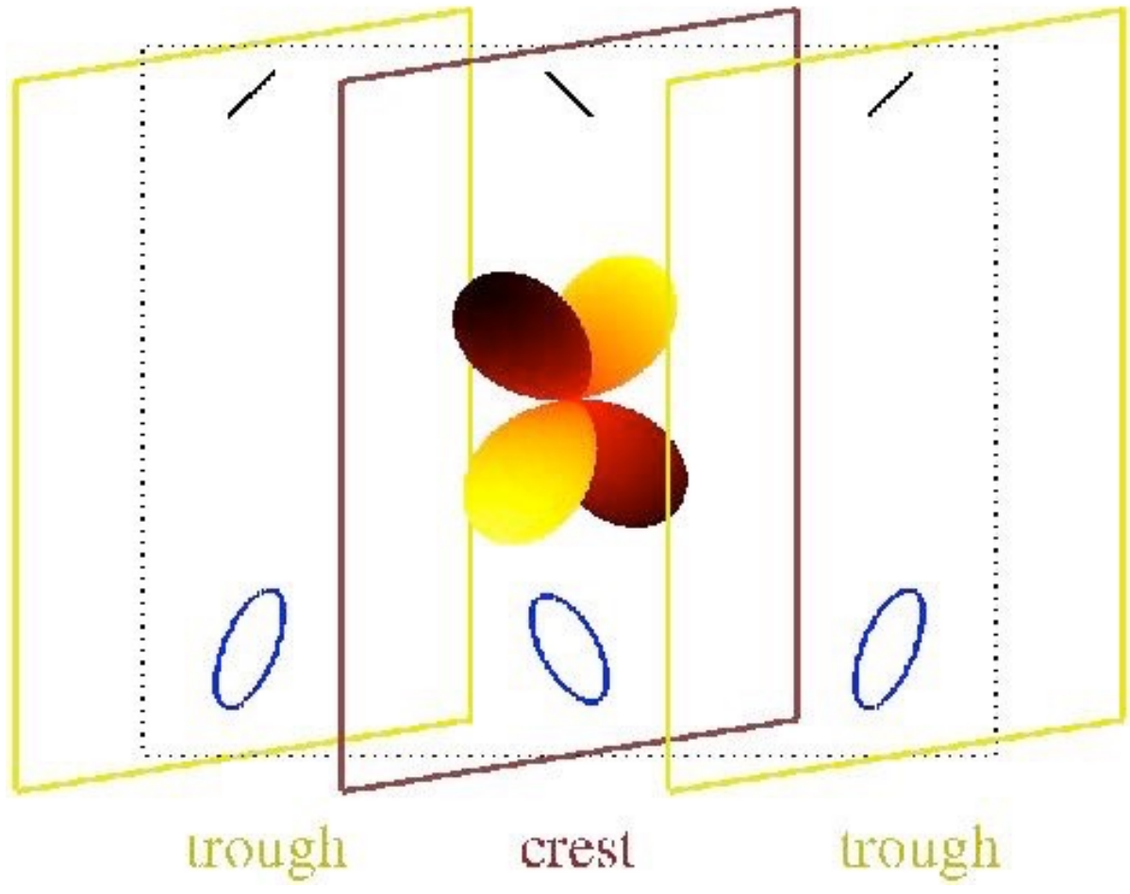
Gravitational wave induced CMB polarization

'+' mode, $\vec{k}$ parallel



E-mode

'×' mode, $\vec{k}$ not parallel



B-mode
(Inflationary GW B-modes)

Figure from John Kovac's thesis

B-mode Polarization (div free)

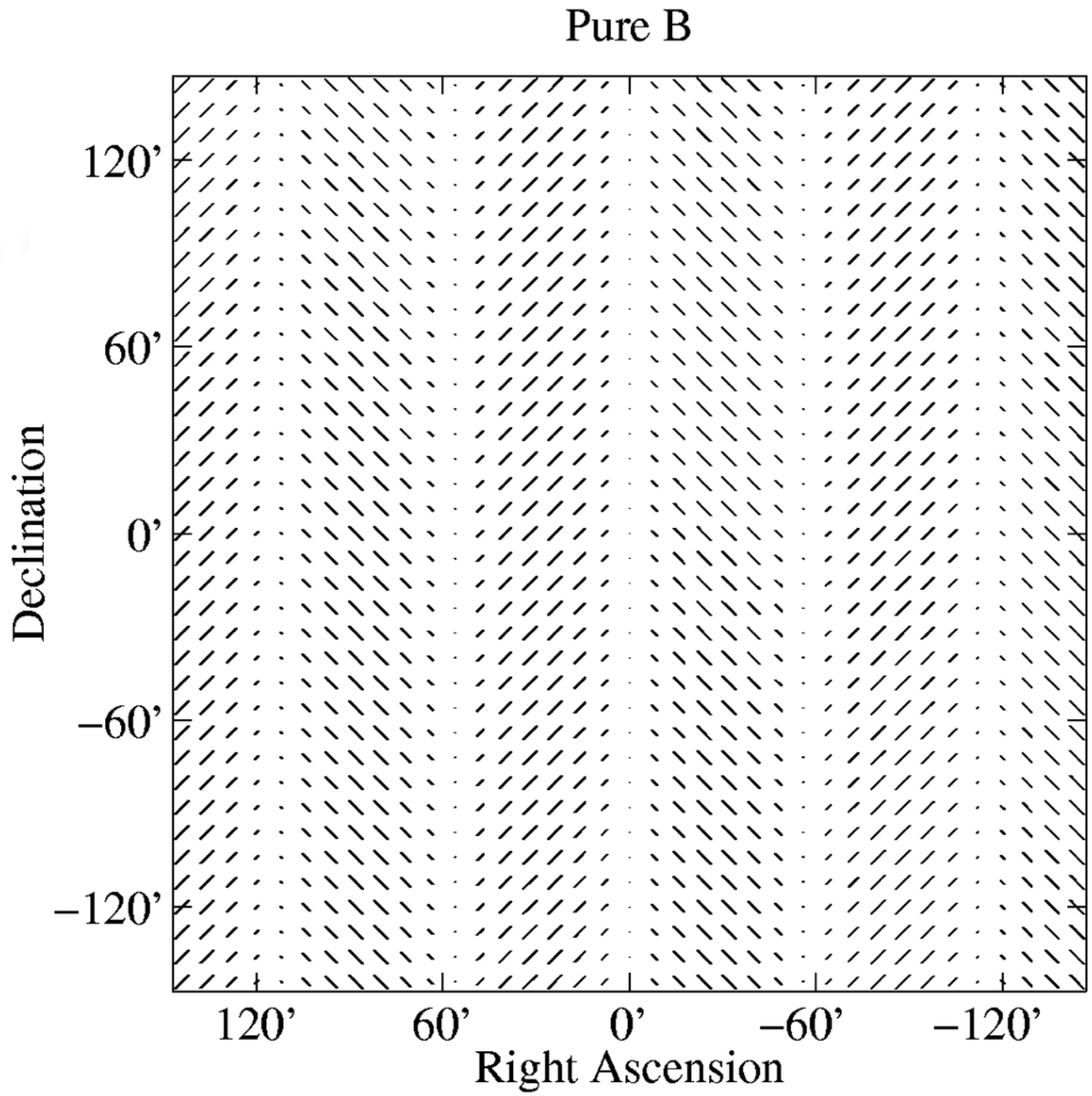
Polarization oriented ±45 degrees to wave vector

Odd parity, div free

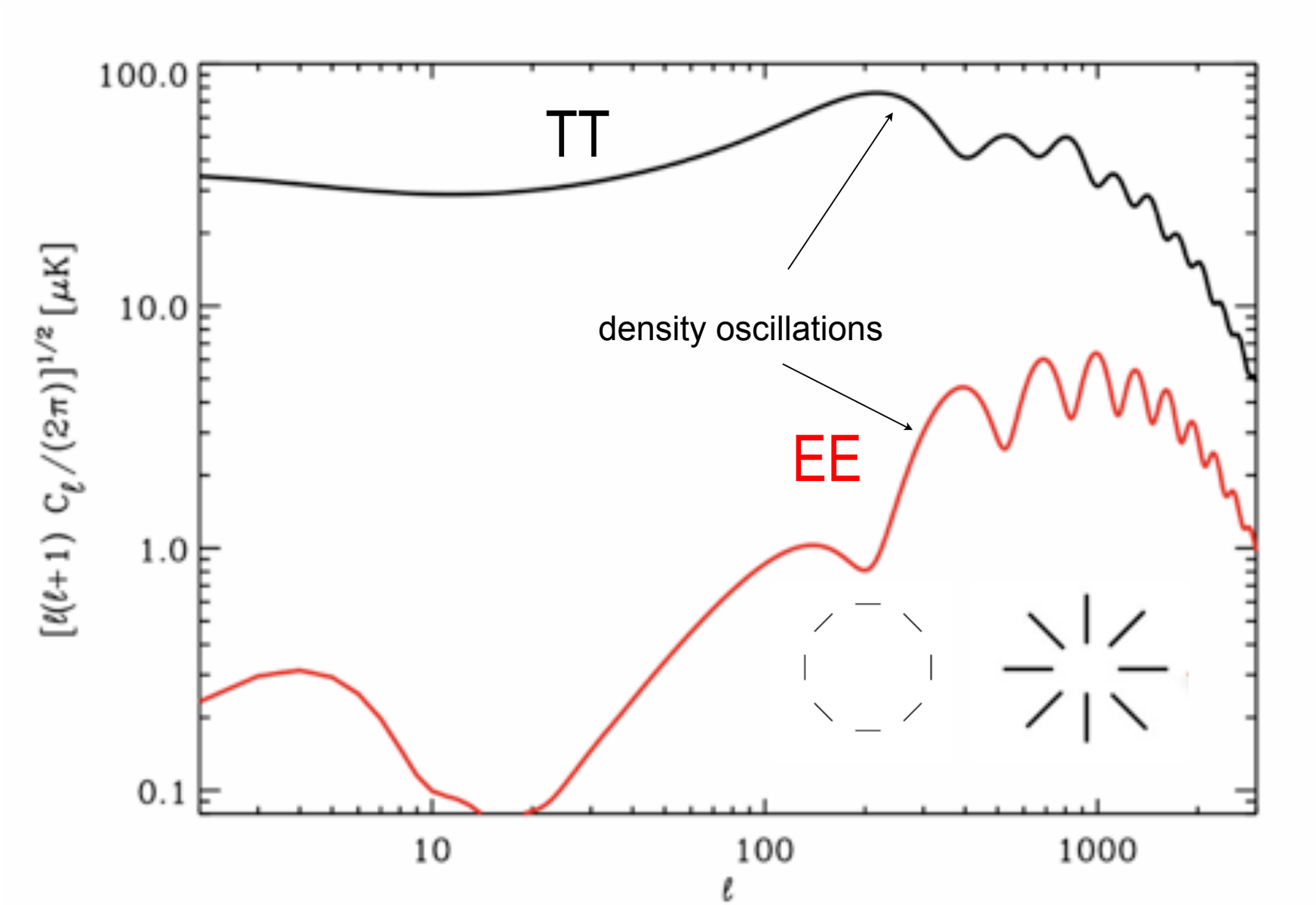
NOT generated by density fluctuations

Generated by gravitational waves sourced by Inflation in the first instants of the universe, 10^{-35} sec at $\lesssim 10^{16}$ GeV

Key test of Inflation and direct measure of its energy scale



CMB polarization:
the next frontier for lensing & inflation



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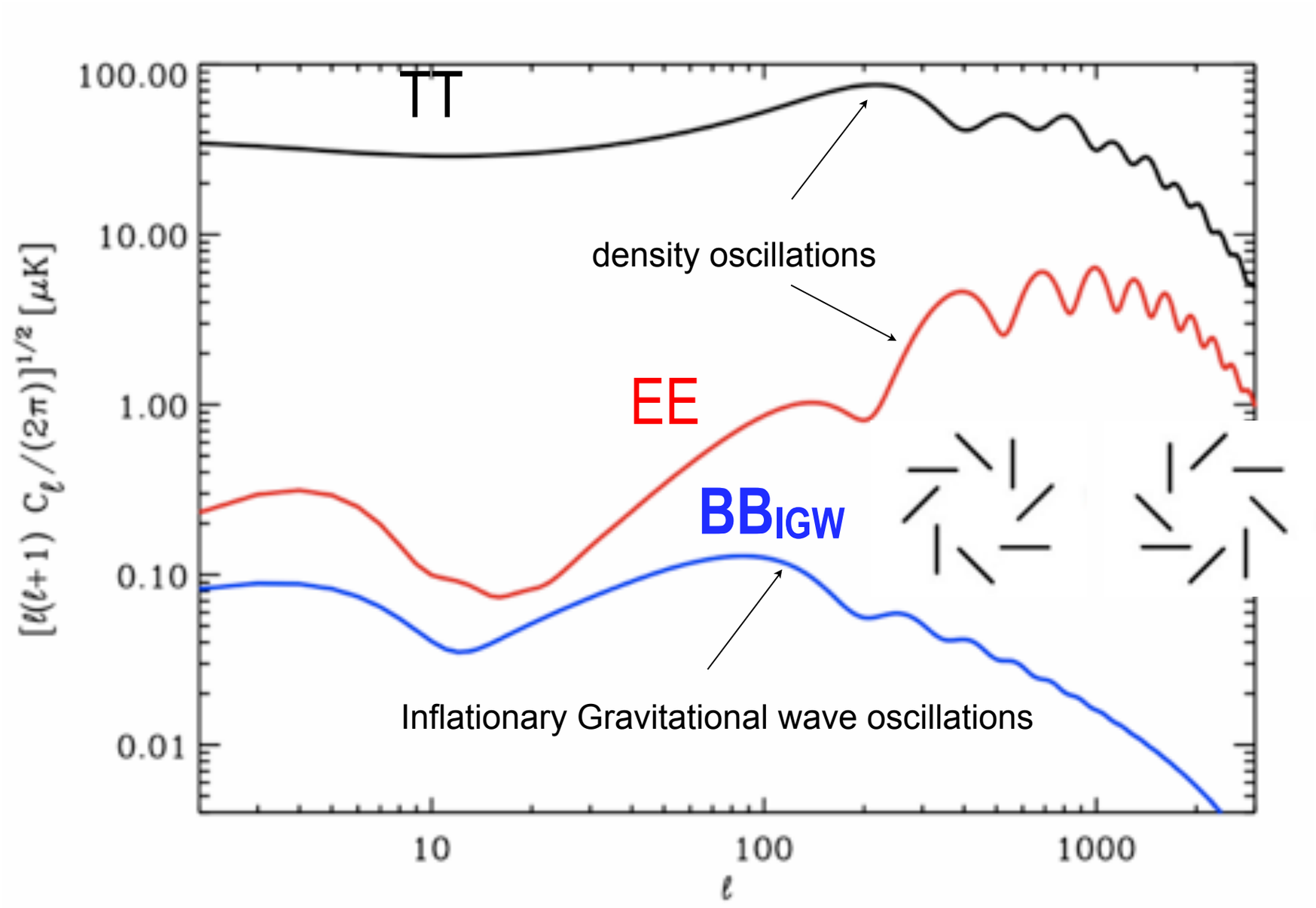
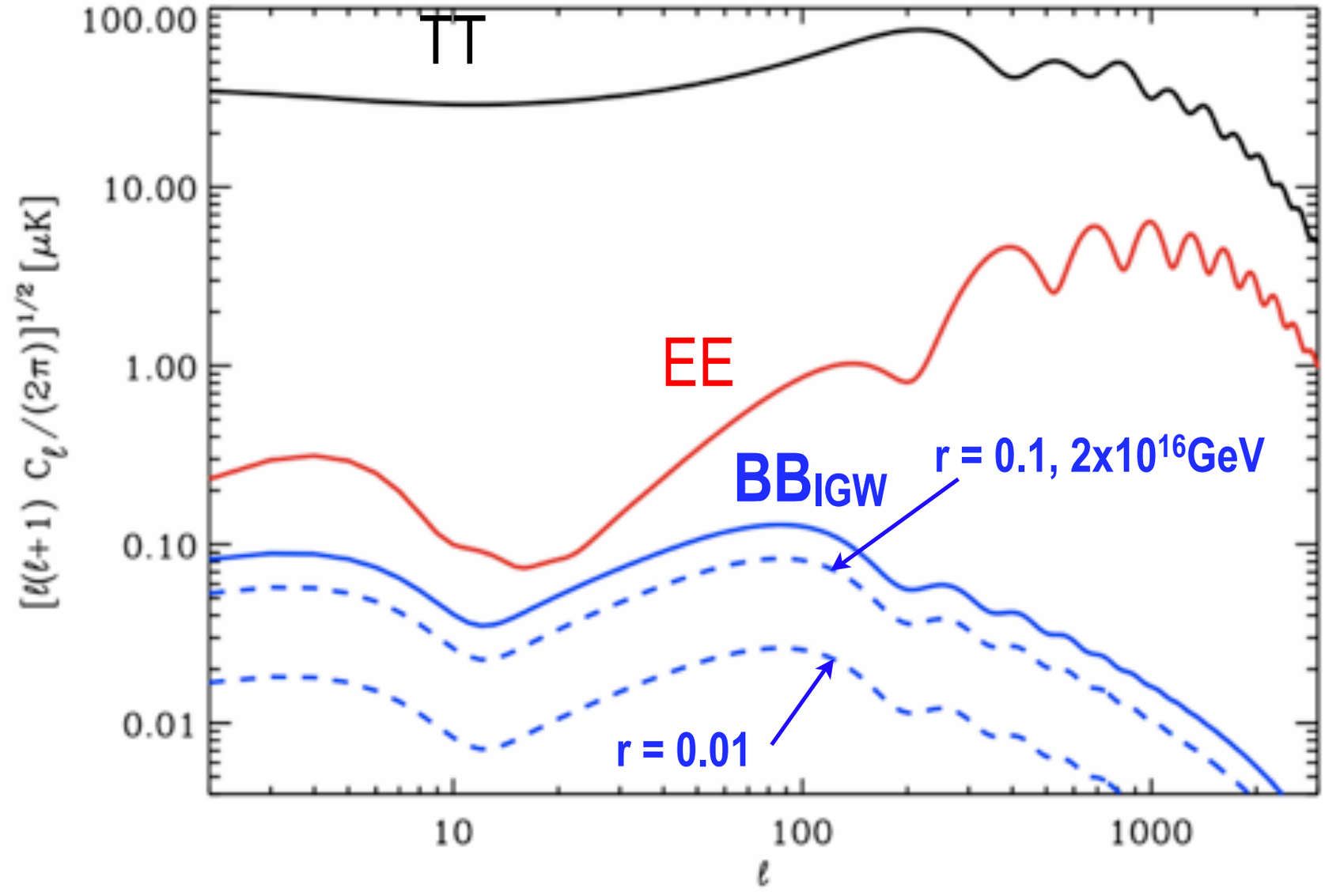
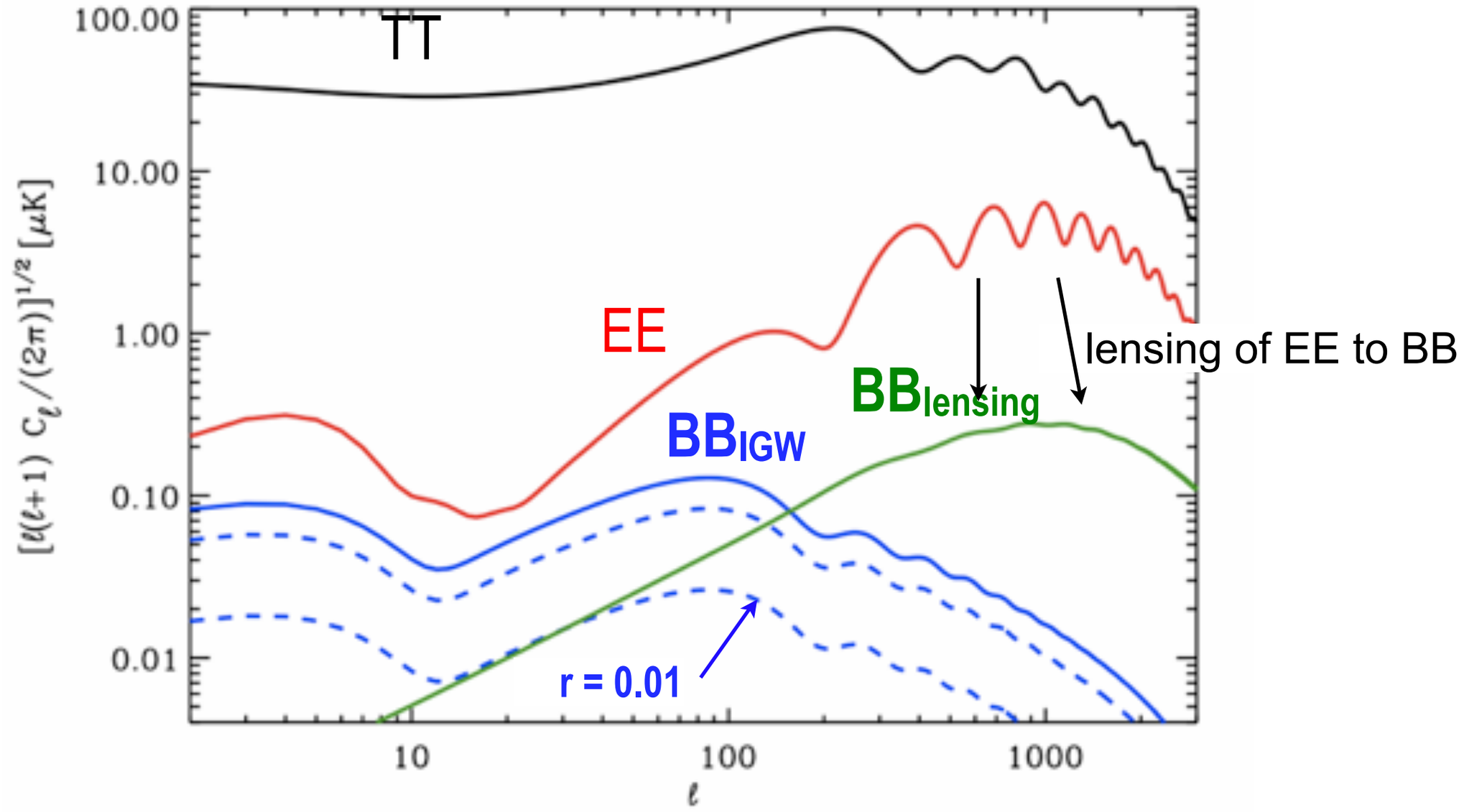


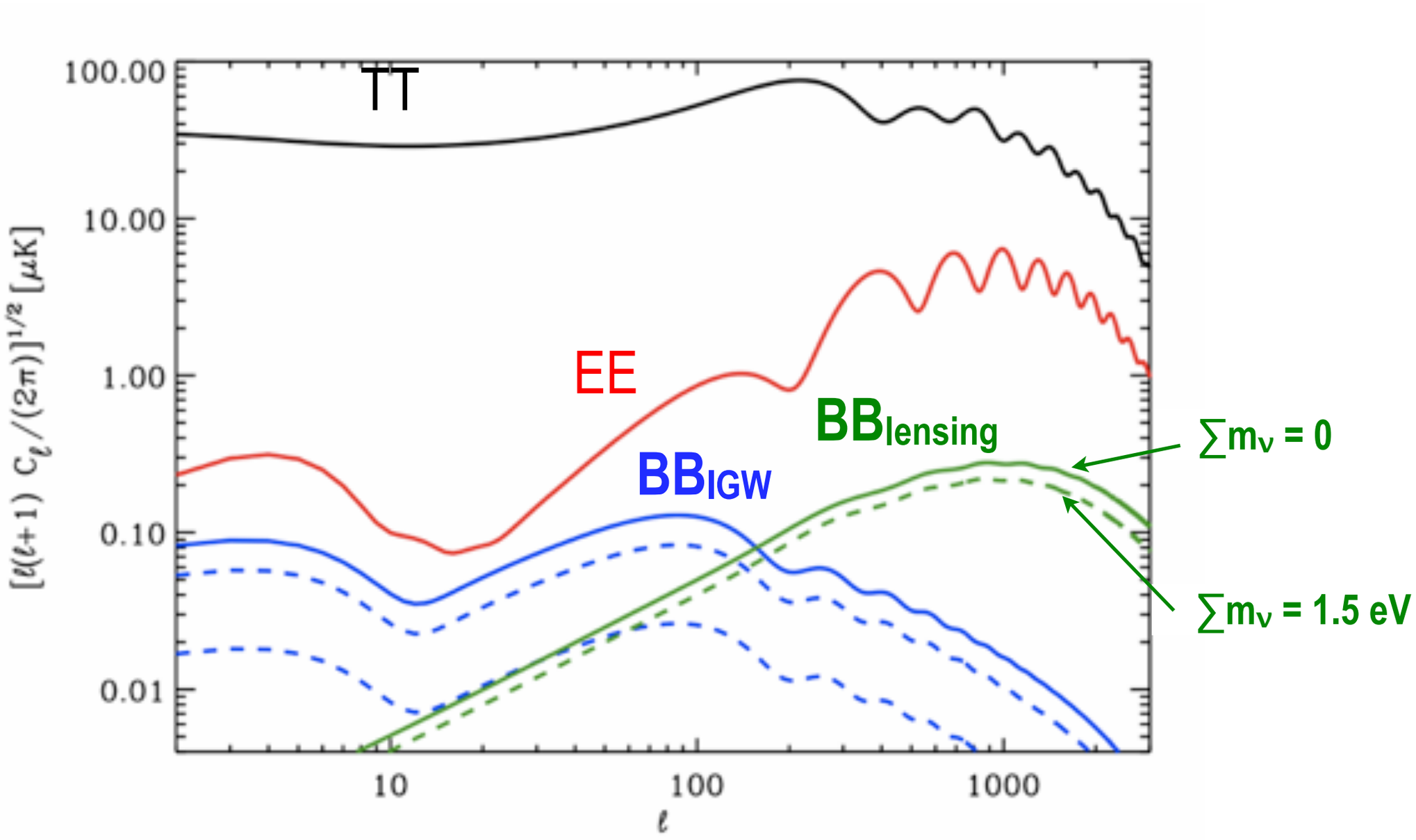
CMB polarization:
the next frontier for lensing & inflation



CMB polarization:
the next frontier for lensing & inflation

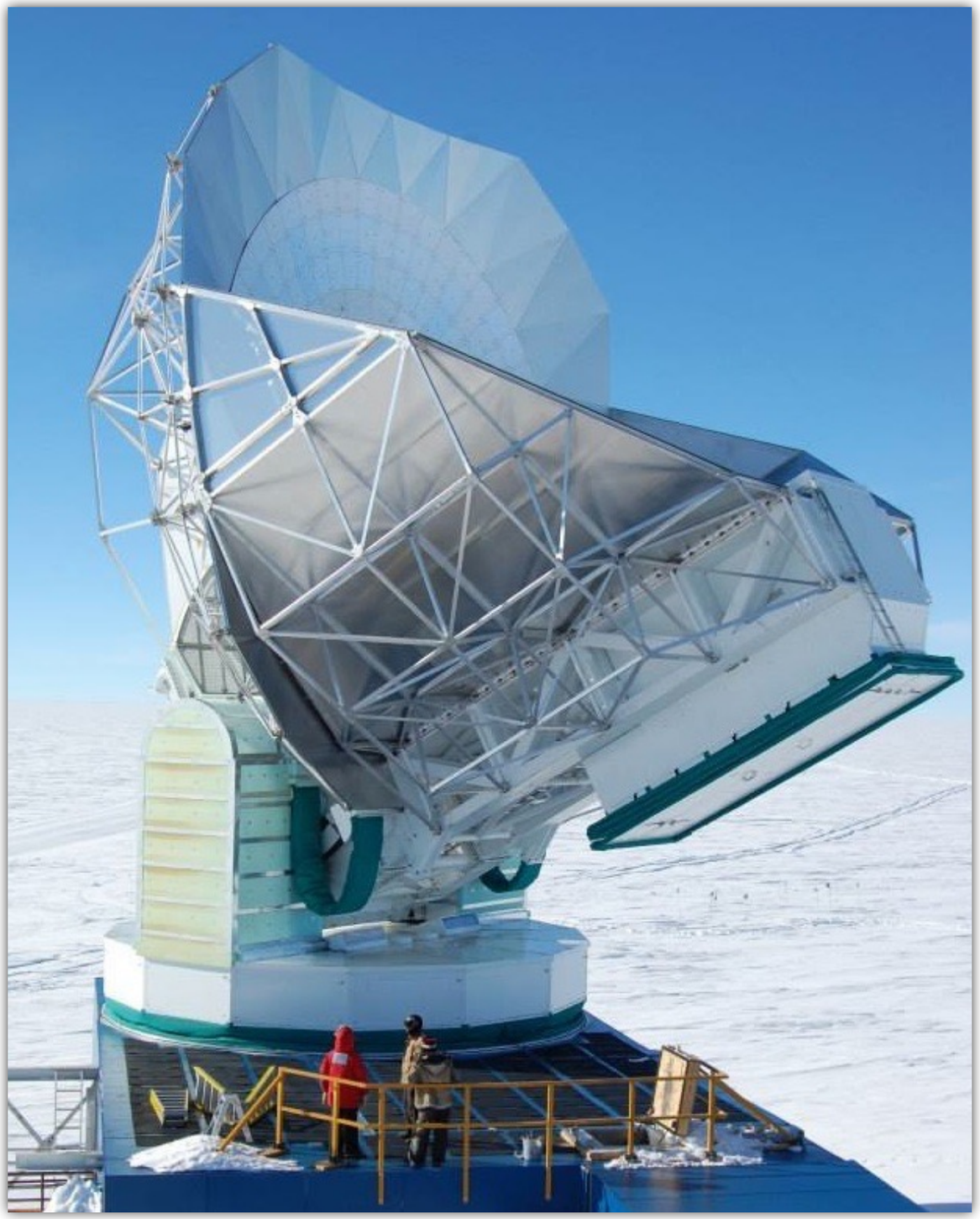


CMB polarization:
the next frontier for lensing & inflation



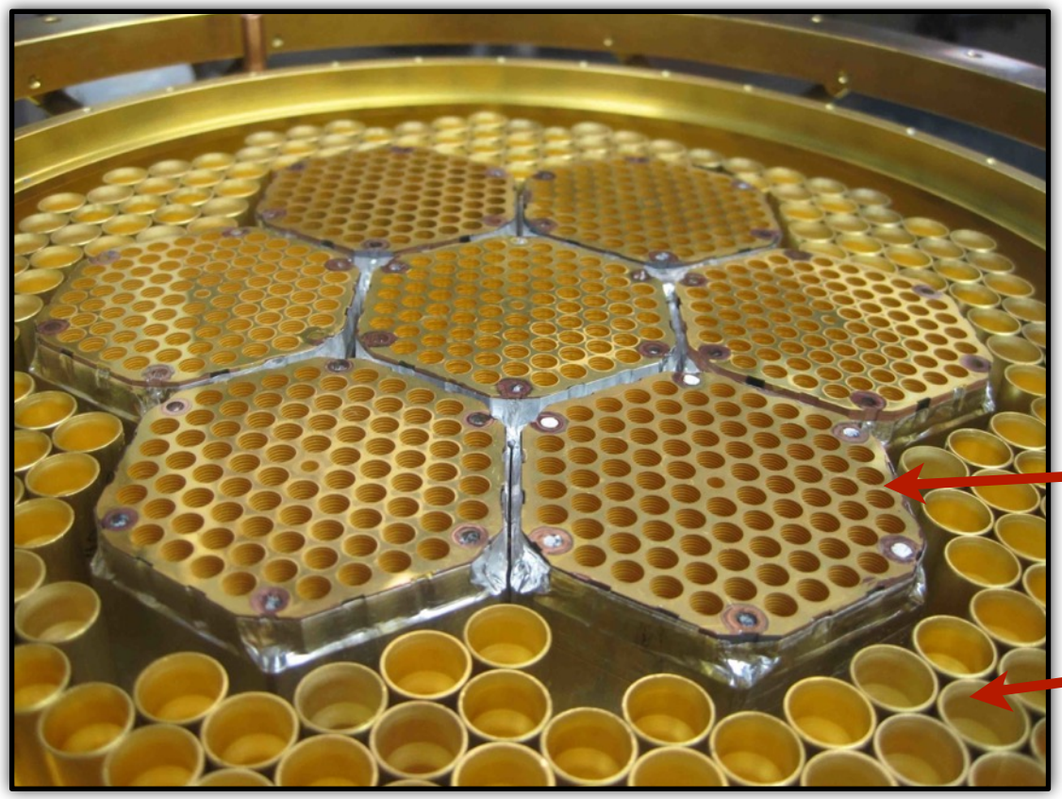
SPTpol:

polarization-sensitive camera on SPT



Status:

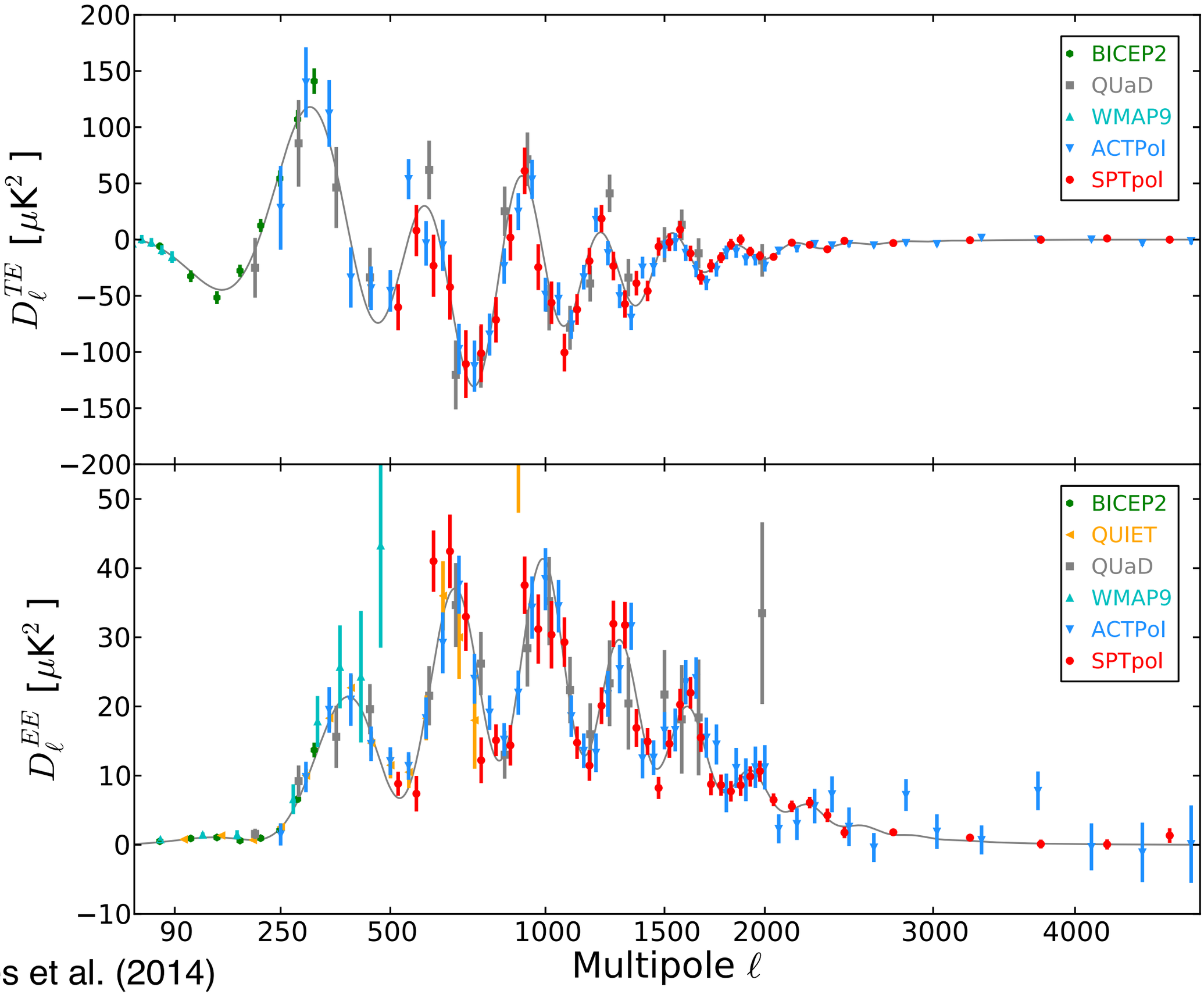
- **First light Jan. 26, 2012**
- **500 deg² survey to ≲6 uK-arcmin depth** *(3x deeper than SPT-SZ)*
- **3 yrs of 4 yr survey done**



(1176x) **150 GHz** detectors (NIST)

(360x) **100 GHz** detectors, (Argonne National Labs)

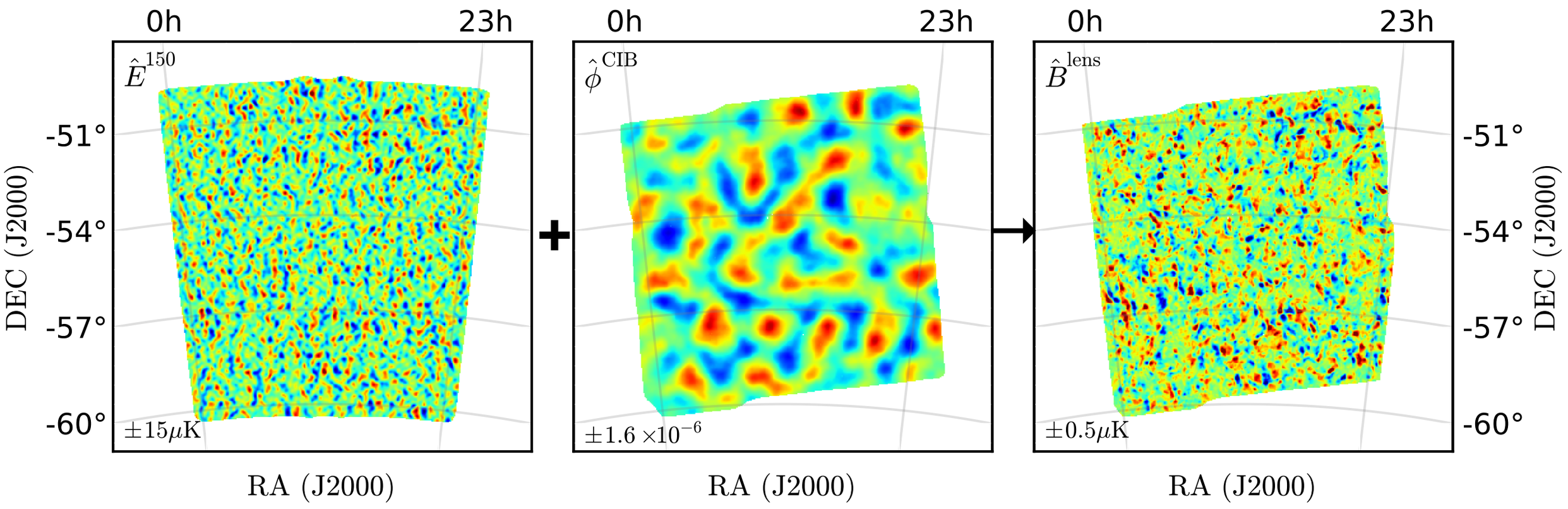
TE, EE Compilation Power Spectrum



Crites et al. (2014)

SPTpol: 1st Detection of CMB B-mode Polarization

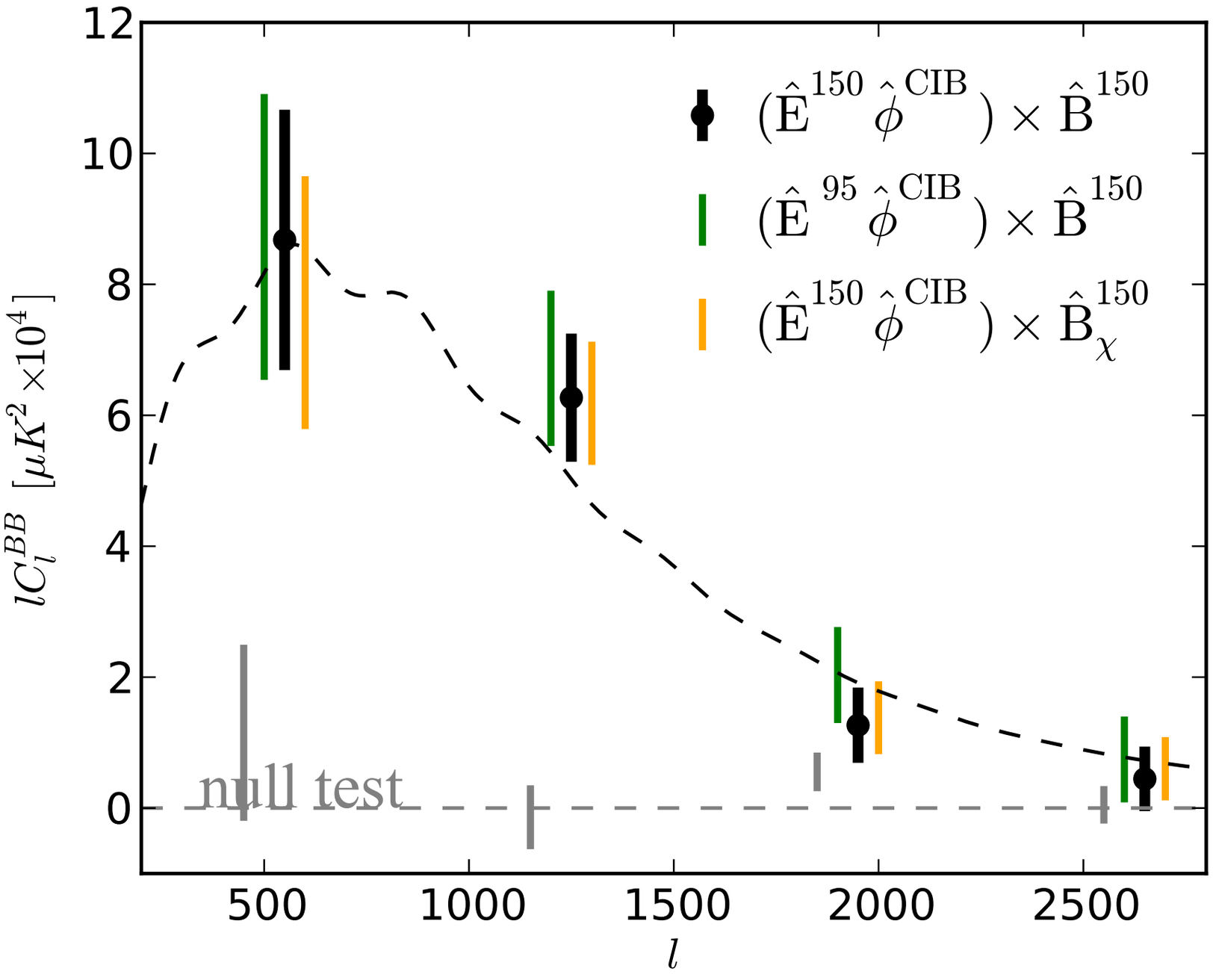
SPTpol Measured E-mode polarization + **Lensing Potential from Herschel CIB** → **Predicted B-mode polarization**

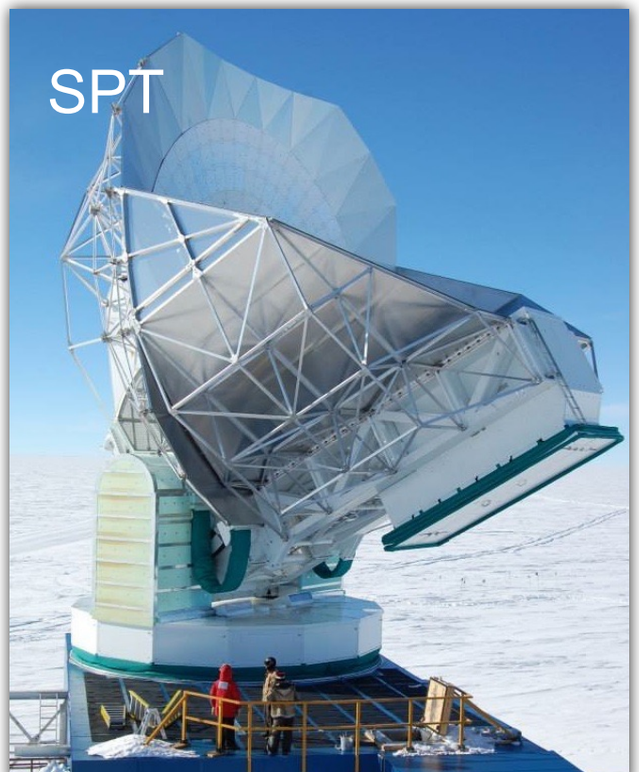


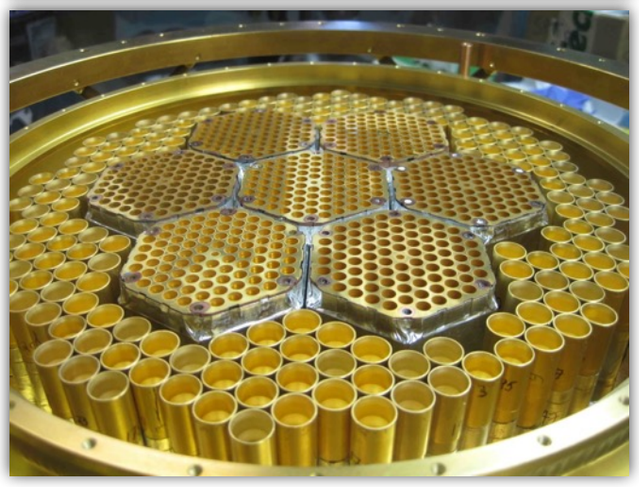
B-mode template to correlate with SPT B-mode map

SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)

SPTpol: 1st Detection of CMB B-mode Polarization

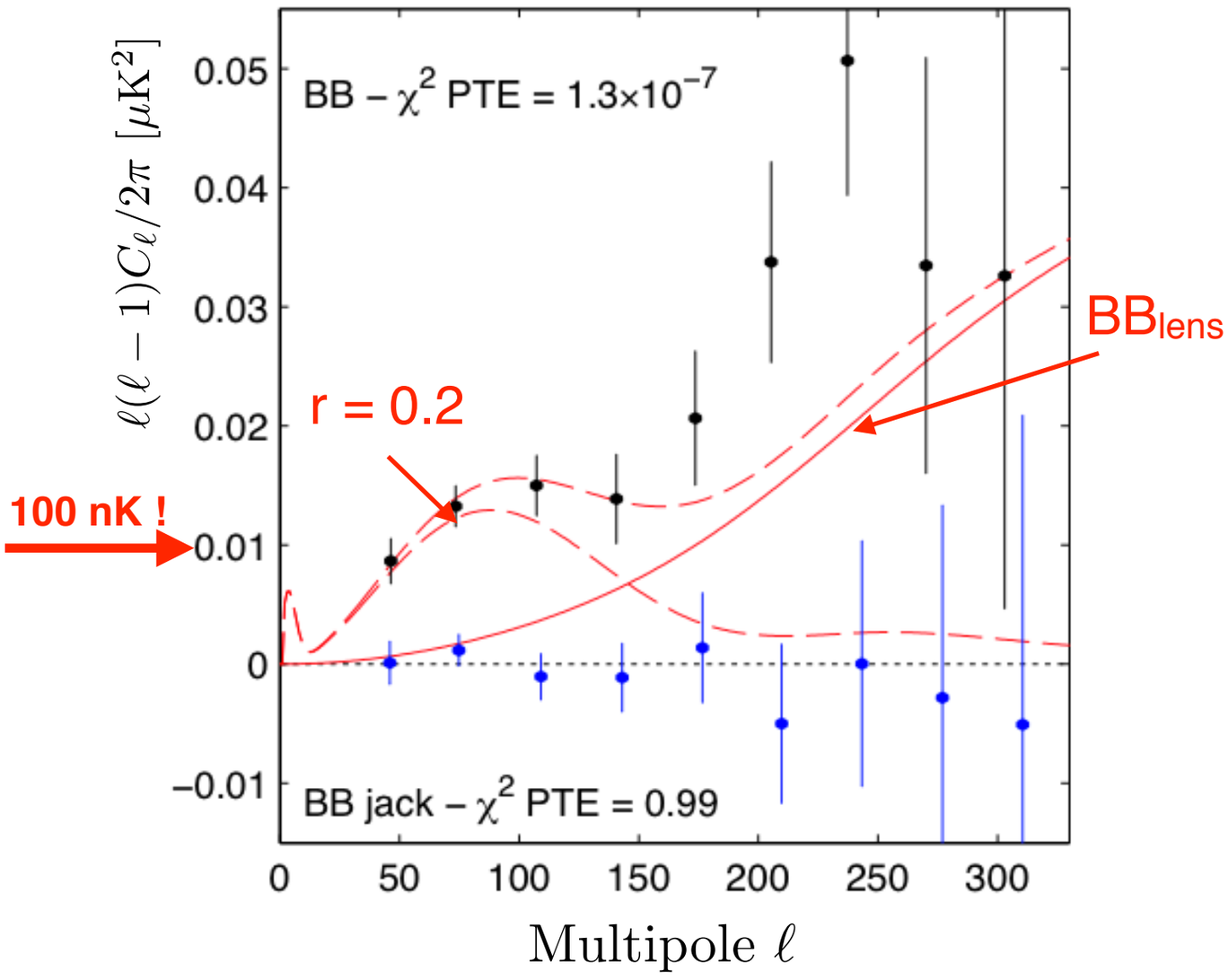




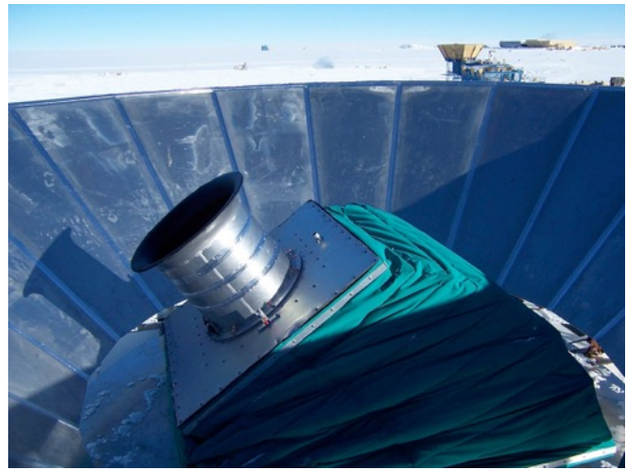


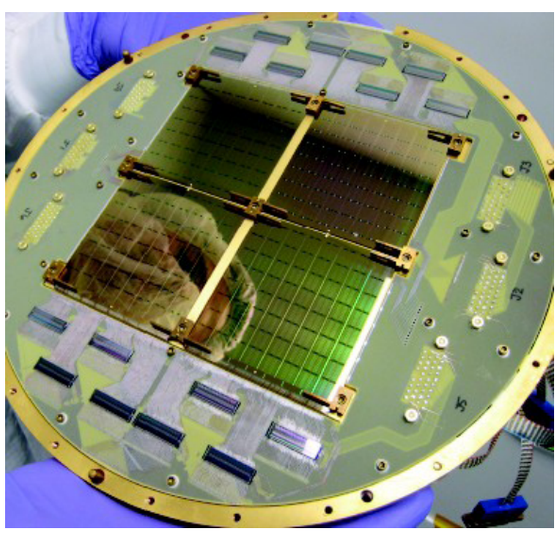
SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)
Also detected by Polarbear arXiv:1312.6645 & 1312.6646

Inflationary B modes?
BICEP2 results



BICEP2
2010-2012

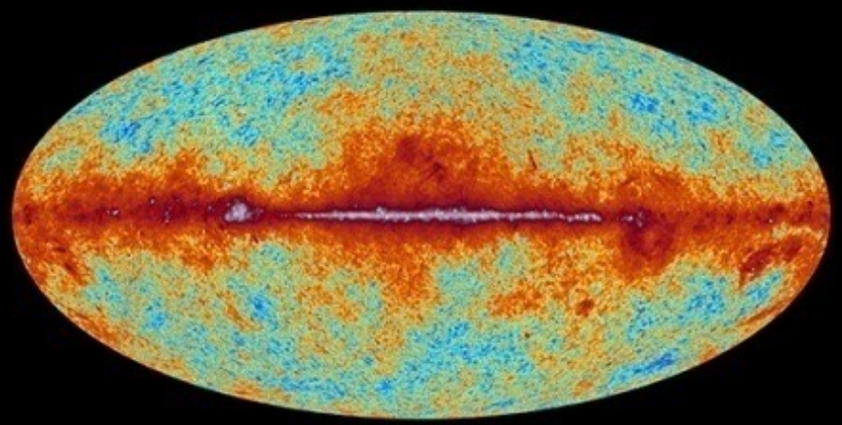




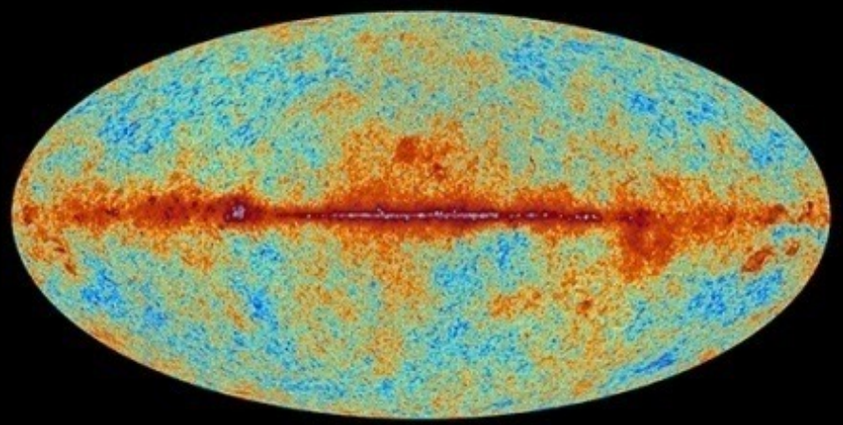
512 pixels @ 150 GHz
JPL

CMB & Foregrounds

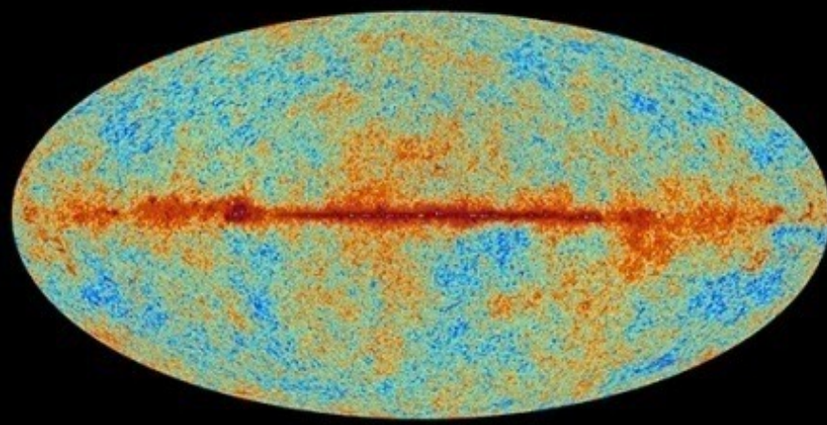
We had been very fortunate for primary CMB anisotropy.



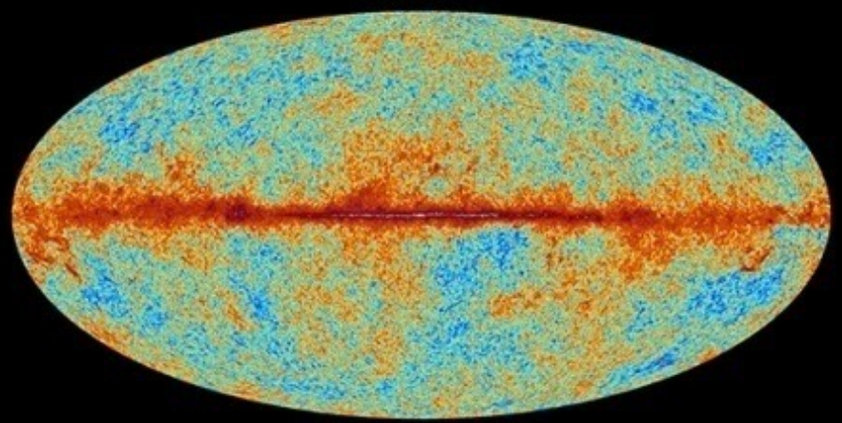
30 GHz



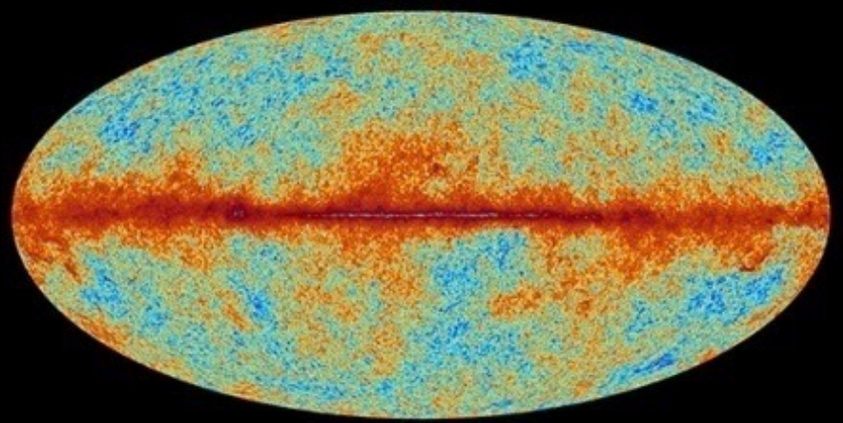
44 GHz



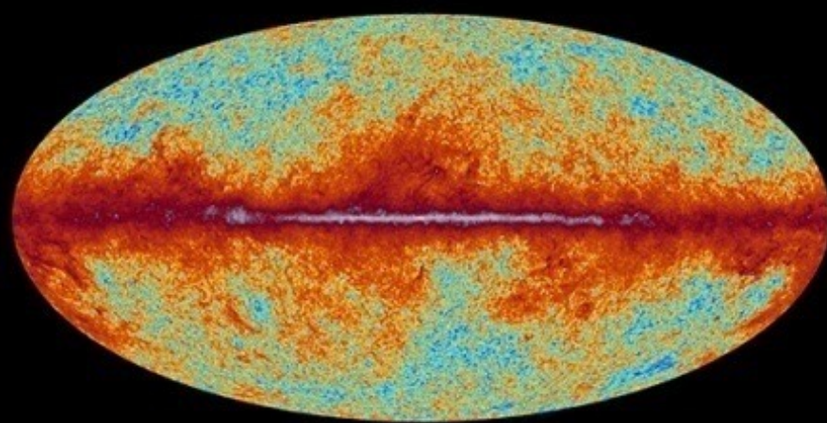
70 GHz



100 GHz

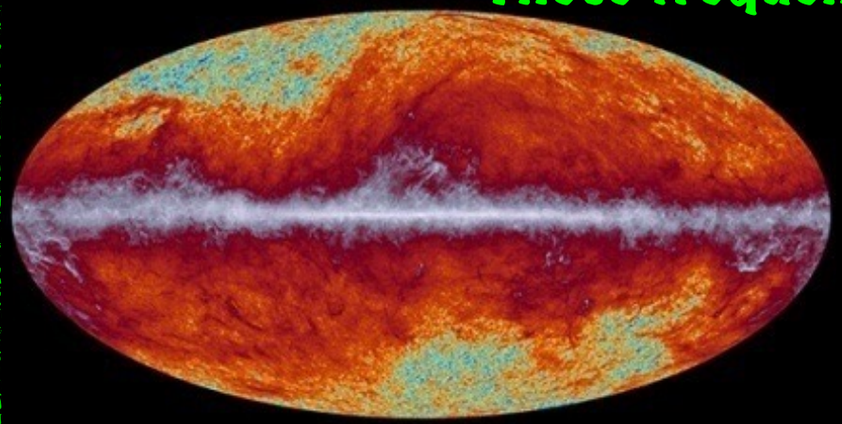


143 GHz

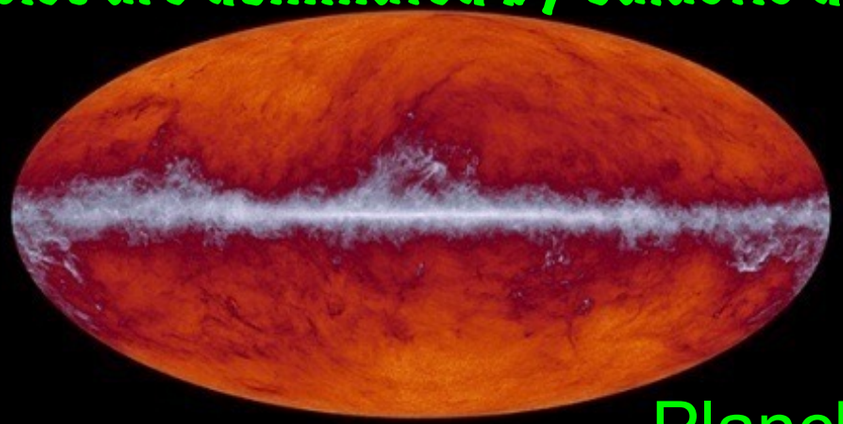


217 GHz

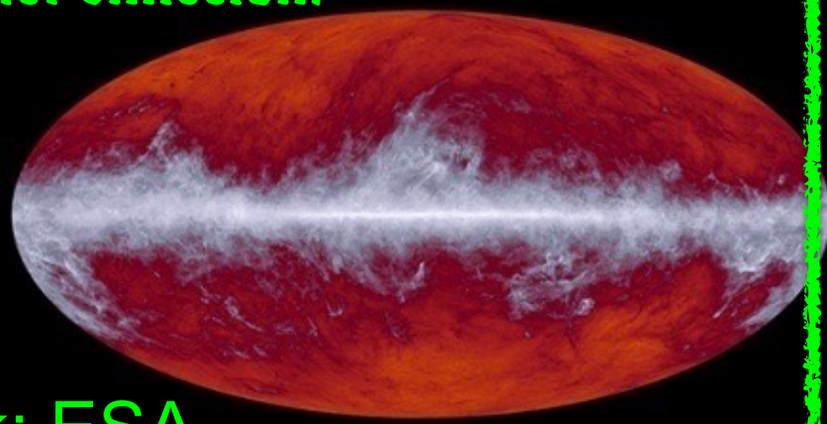
These frequencies are dominated by Galactic dust emission.



353 GHz



545 GHz

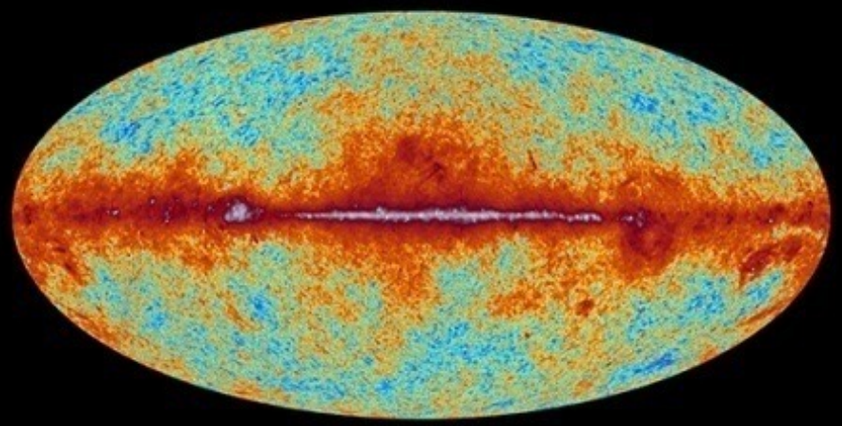


857 GHz

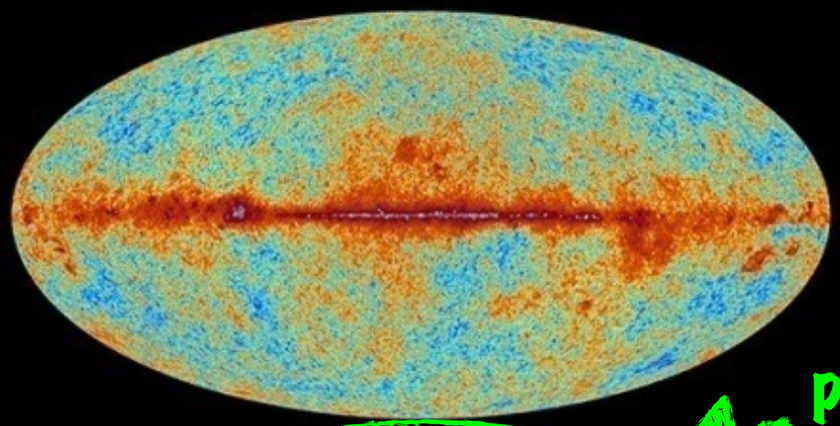
Planck: ESA

CMB & Foregrounds

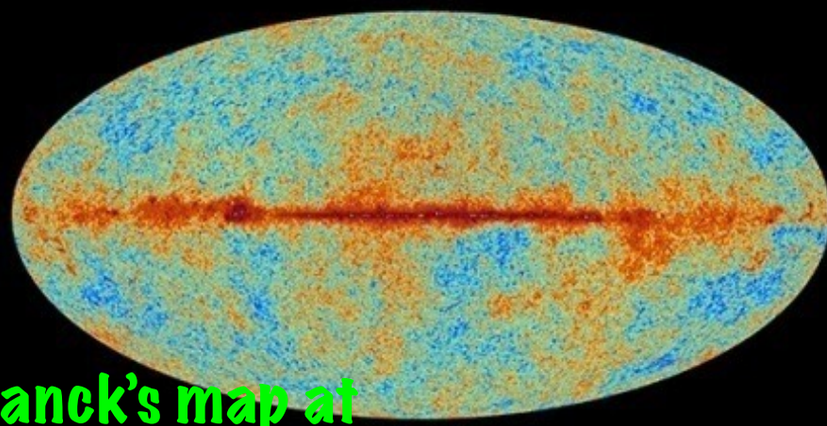
We had been very fortunate for primary CMB anisotropy.



30 GHz

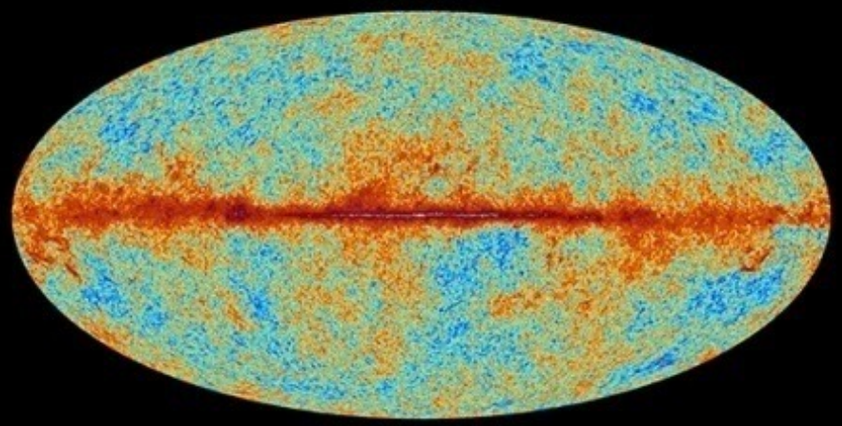


44 GHz

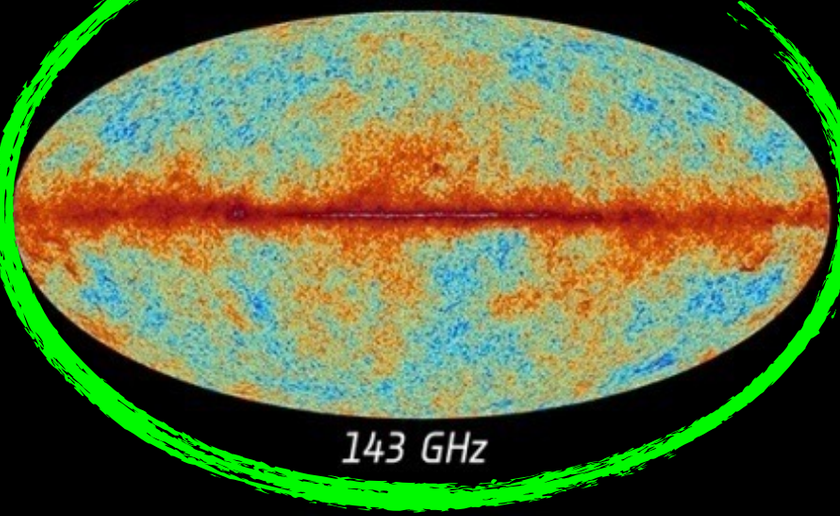


70 GHz

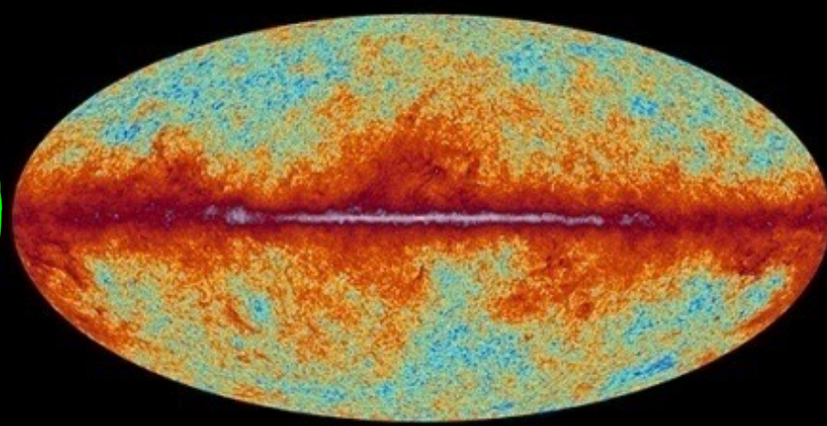
Planck's map at BICEP's frequency



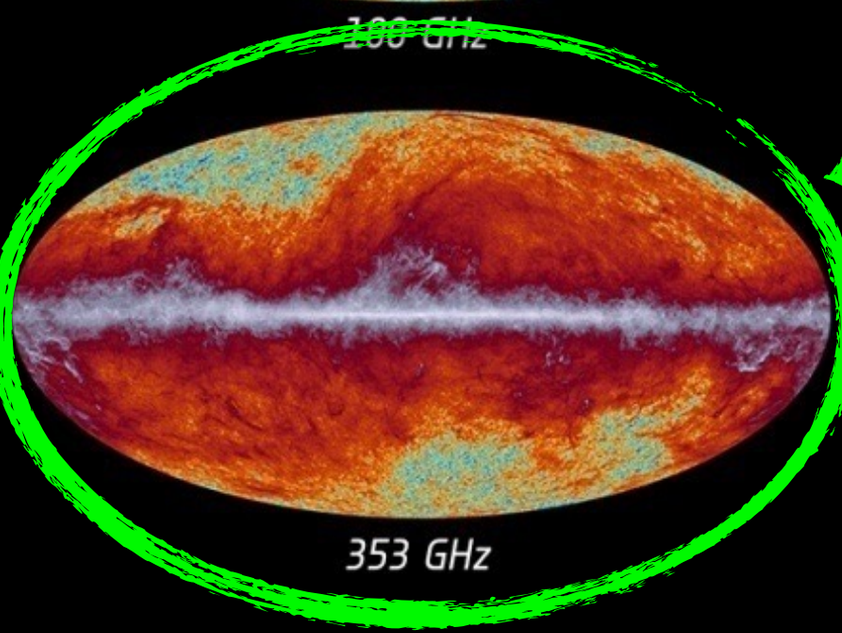
100 GHz



143 GHz

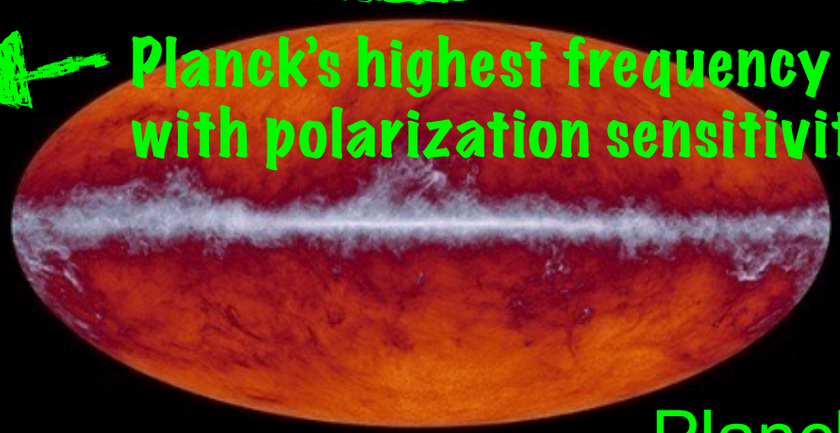


217 GHz

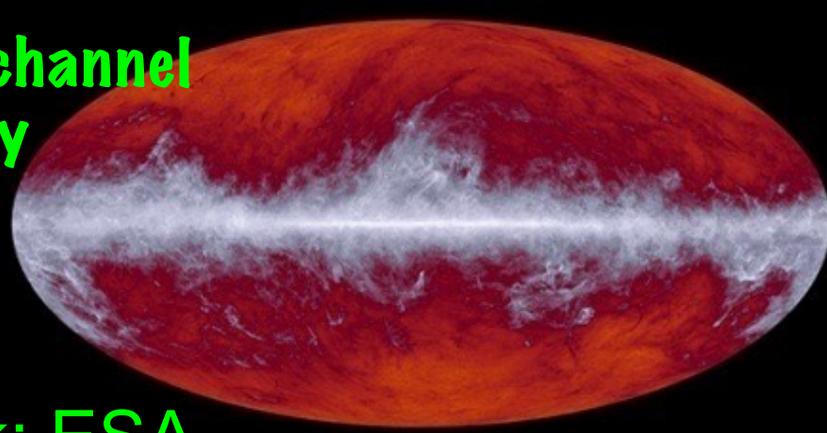


353 GHz

Planck's highest frequency channel with polarization sensitivity



545 GHz

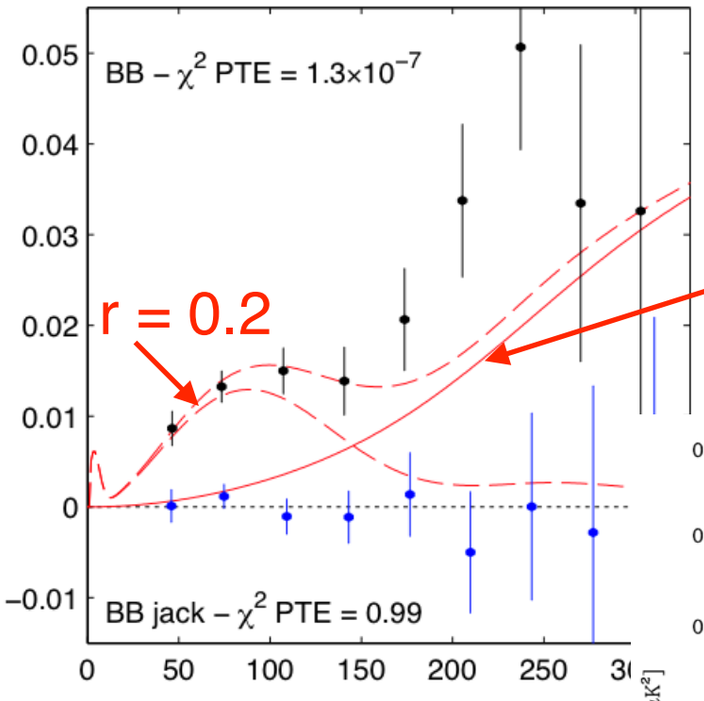


857 GHz

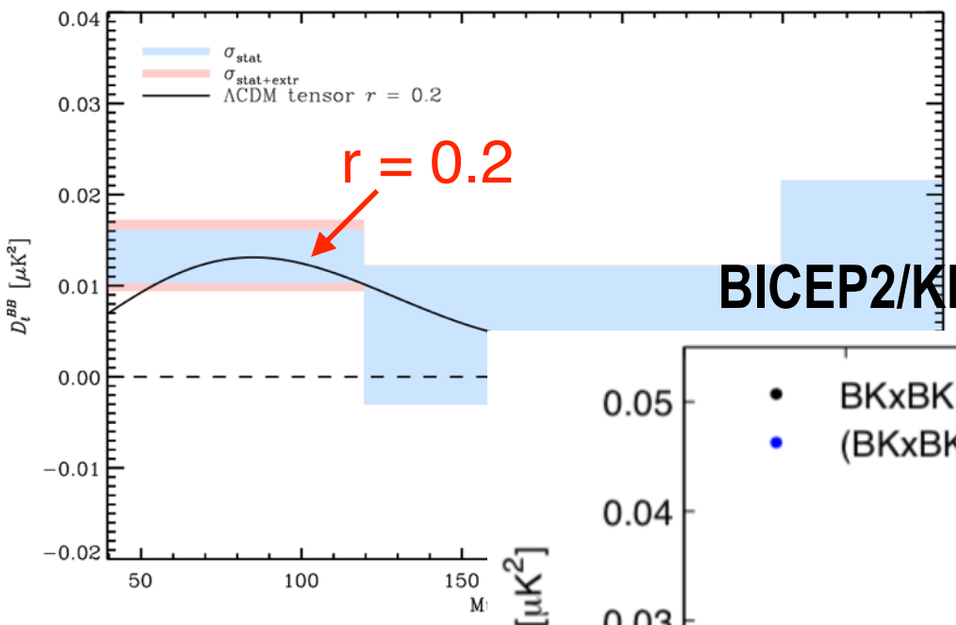
Planck: ESA

Inflationary B modes?

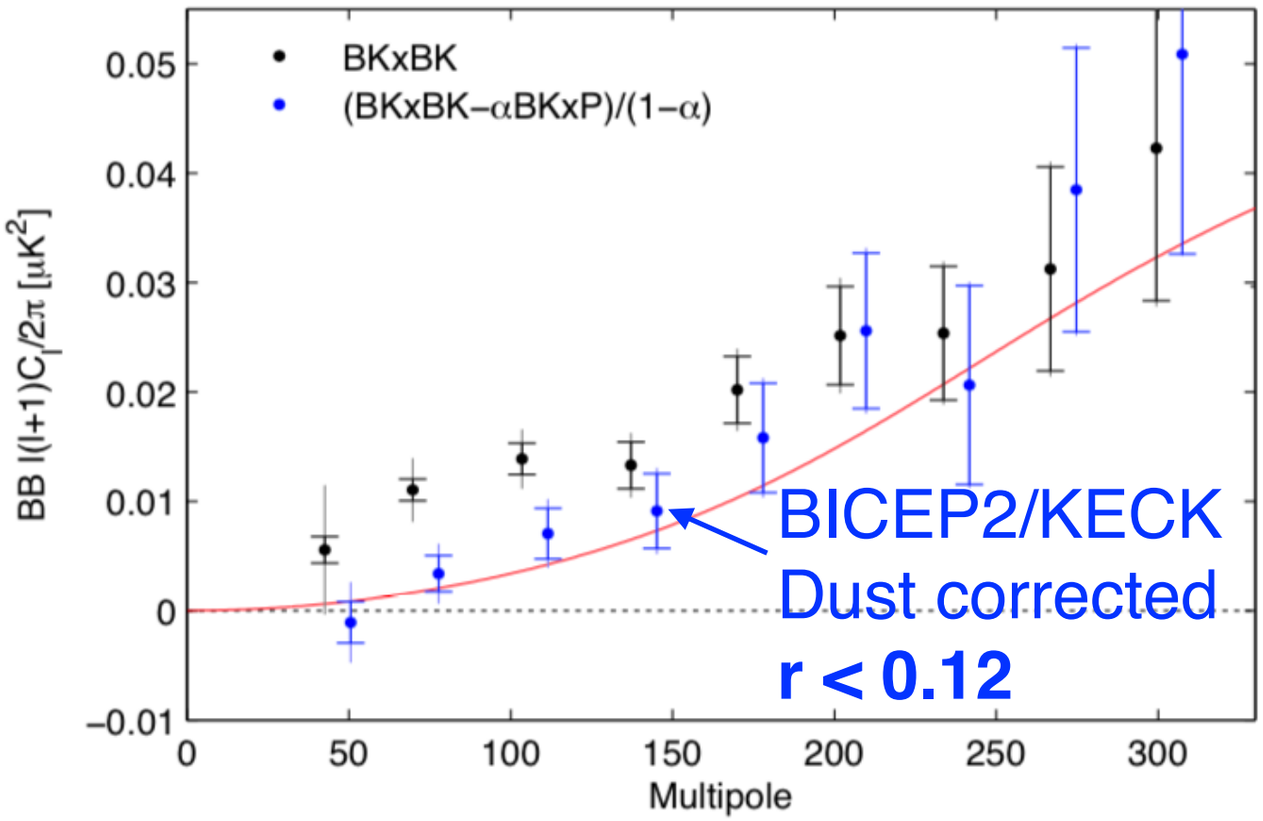
BICEP2 PhyRevLett



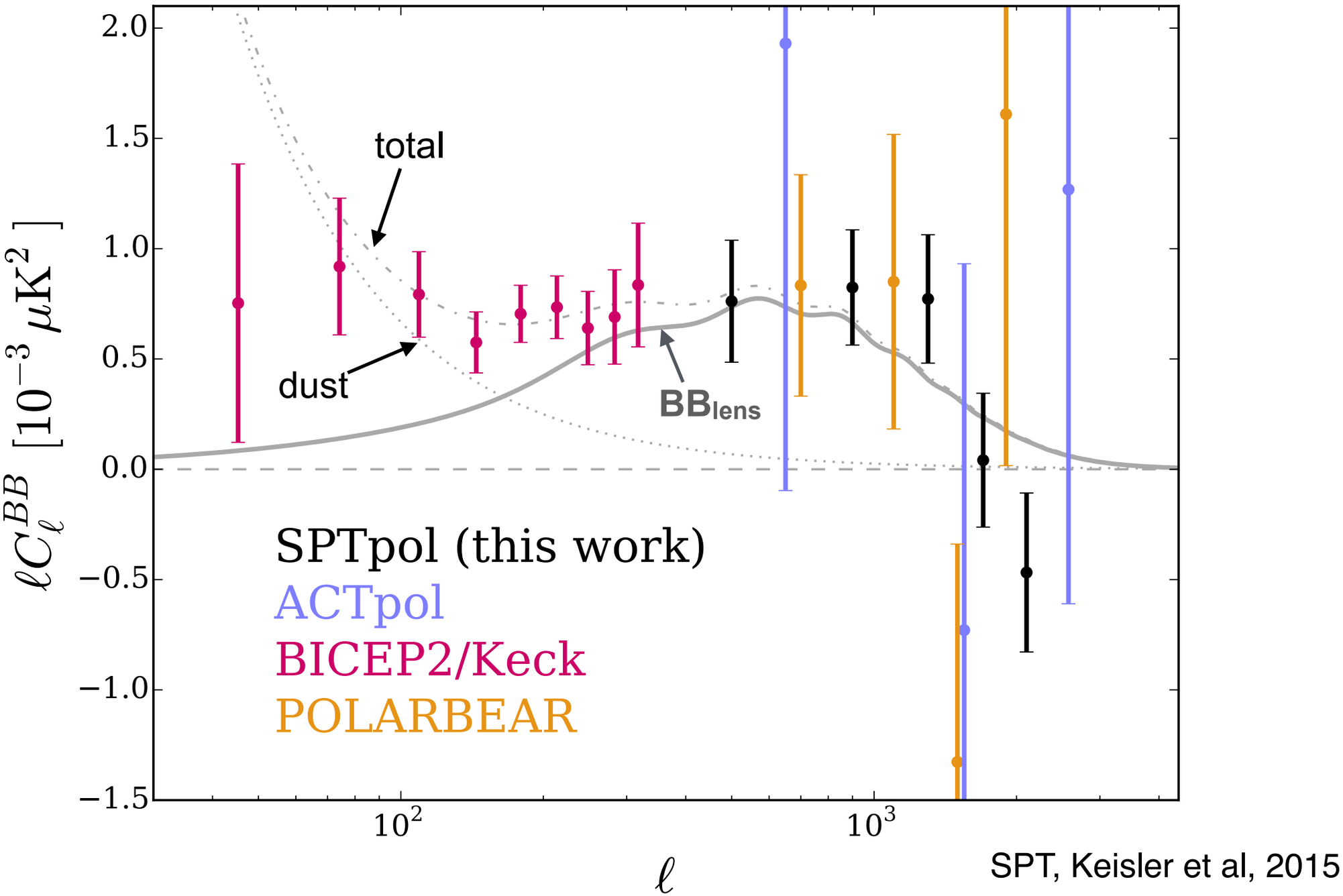
***Planck* estimate of dust B-mode level at 150 GHz in BICEP2 field**



BICEP2/KECK x Planck (arXiv:1502.00612)



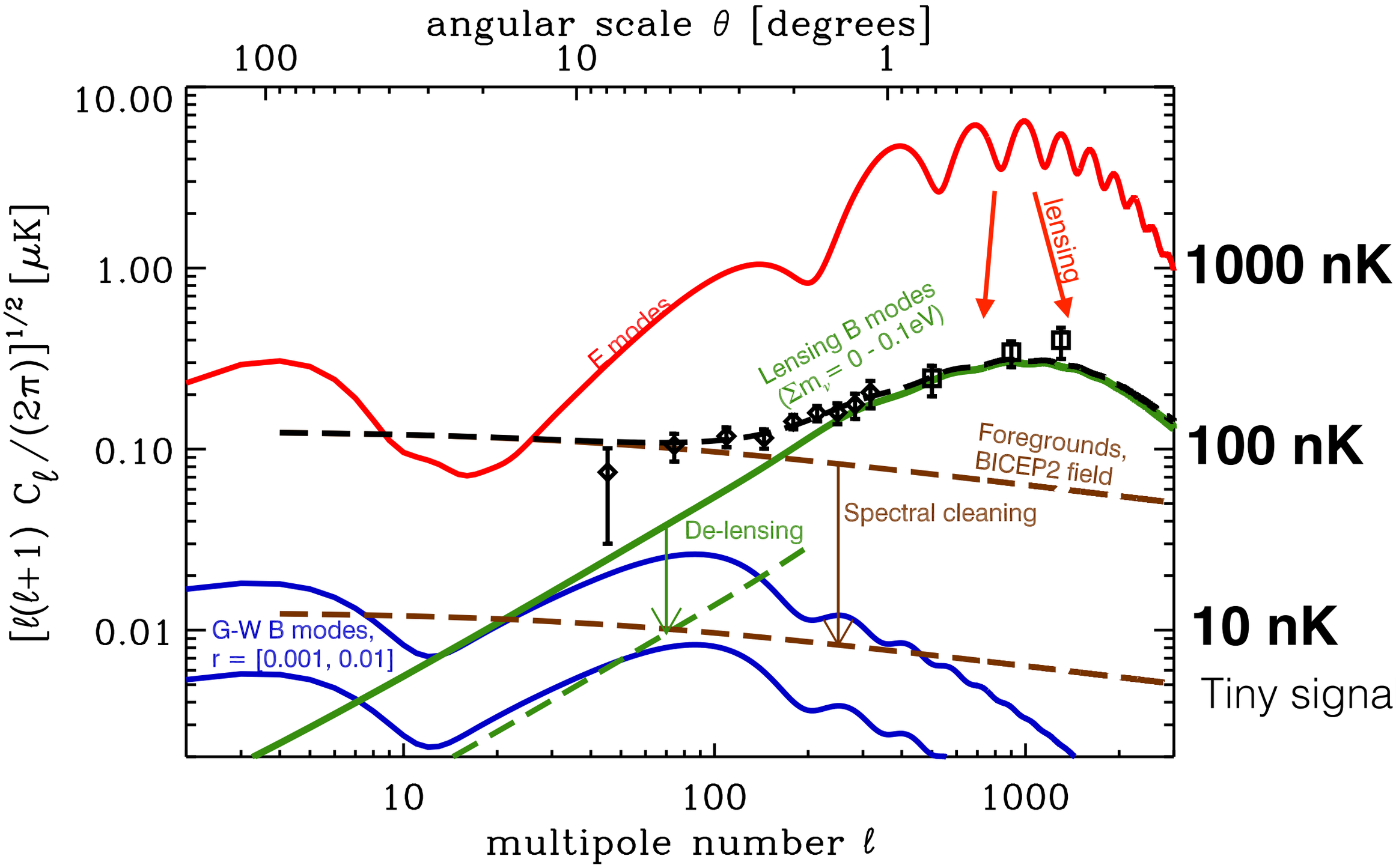
BB Compilations



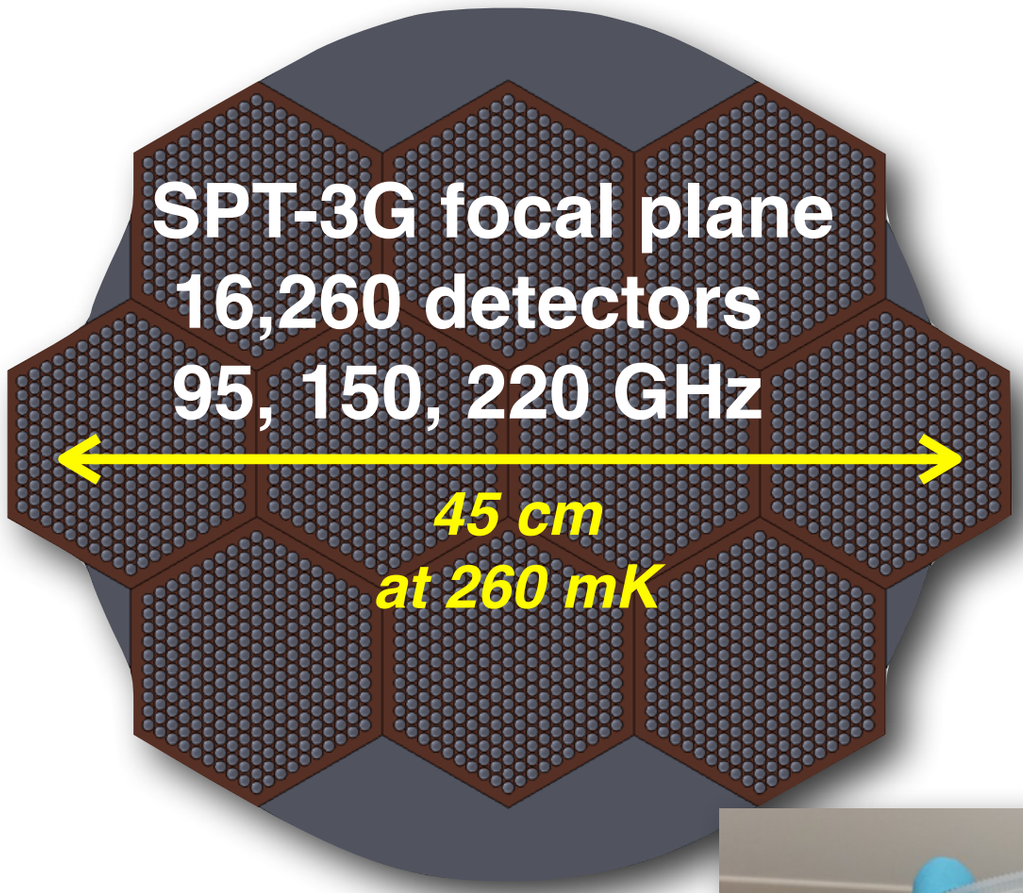
SPT, Keisler et al, 2015

Rapid progress! Still a long, long way to go.

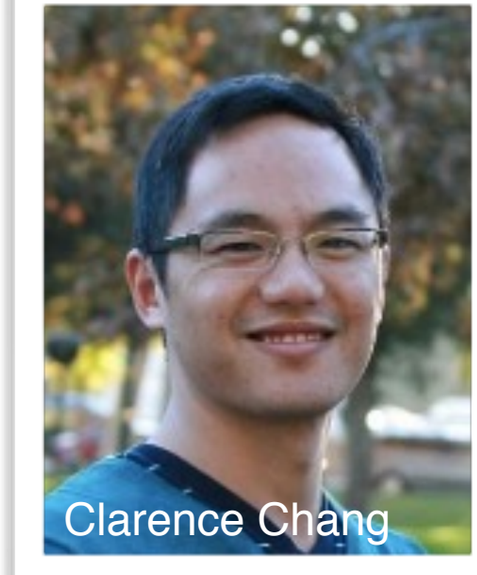
Chasing inflationary B modes

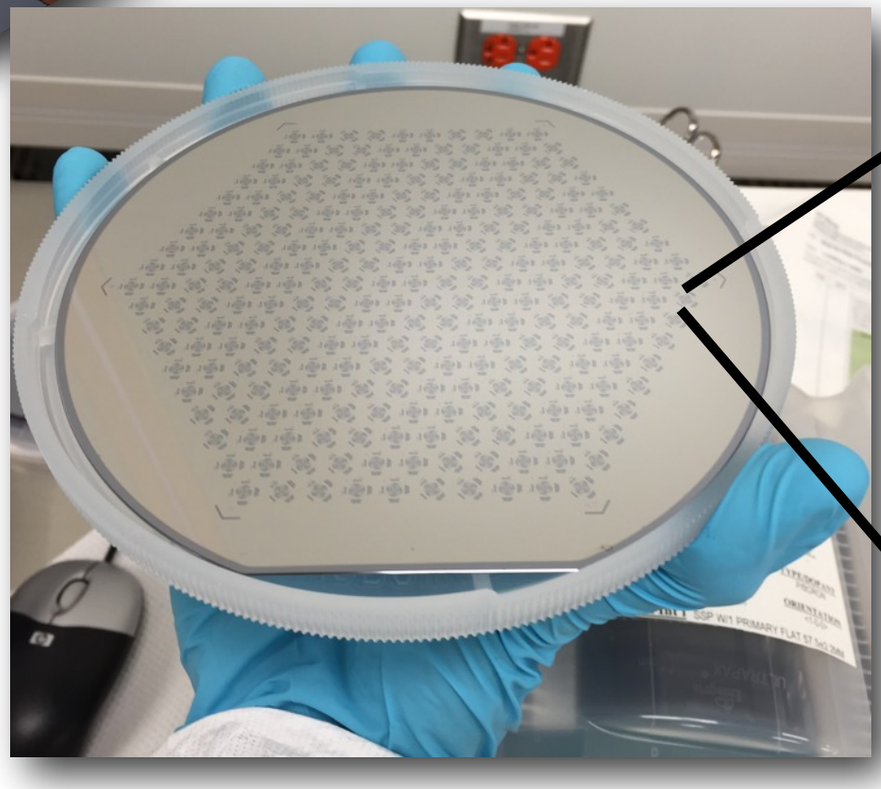


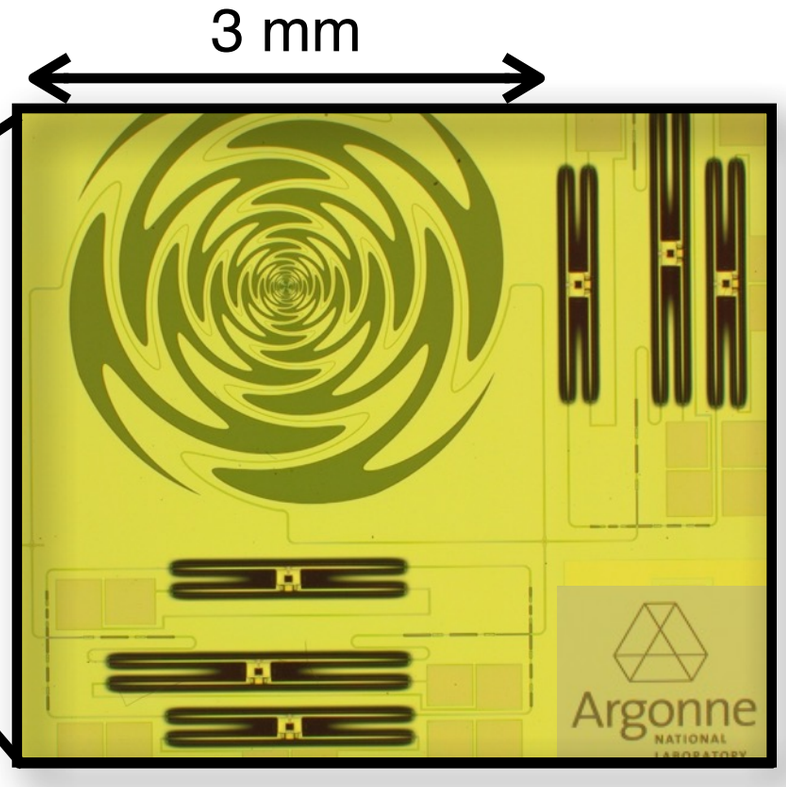
Plans for SPT: 10x leap with multichroic pixels



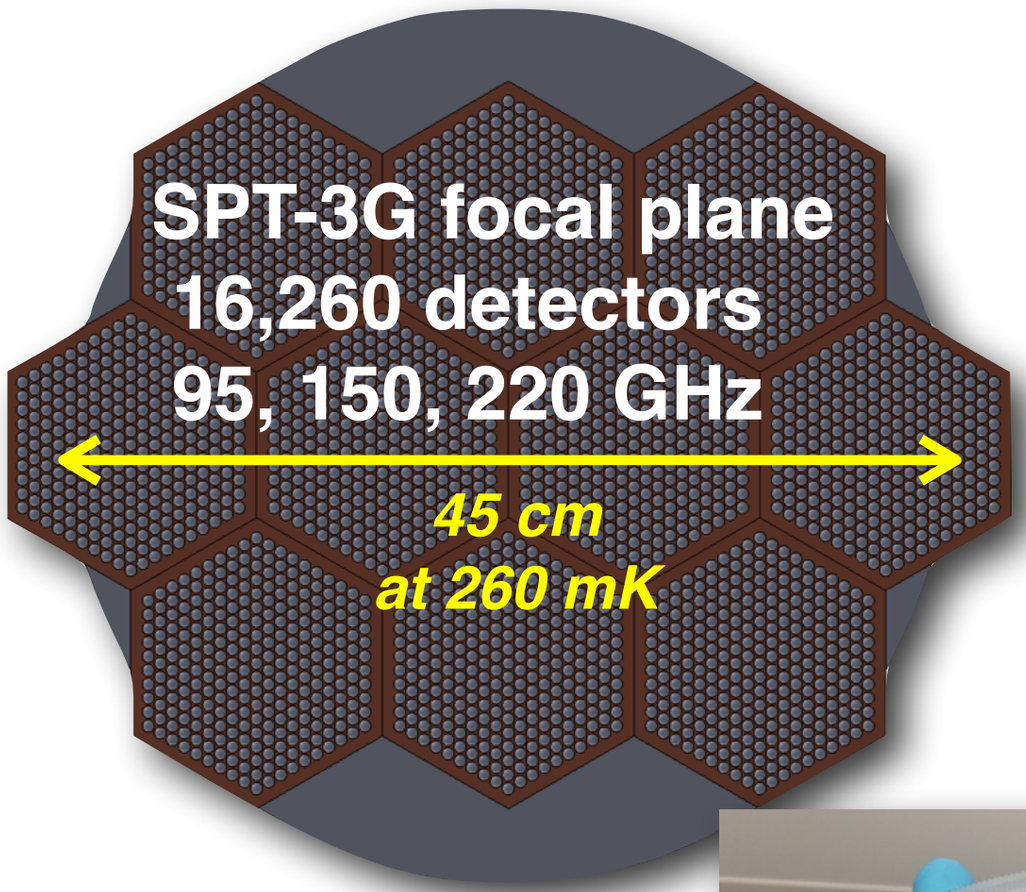
- Detector fabrication at Argonne National Labs on 6” silicon wafers led by C. Chang
- Using lenslet coupled, 3-band sinuous antenna coupled TES detector design from UCB (Suzuki et al, 1210.8256)
- 68x frequency multiplexed SQUID readout (McGill), using SQUIDs from NIST-Boulder





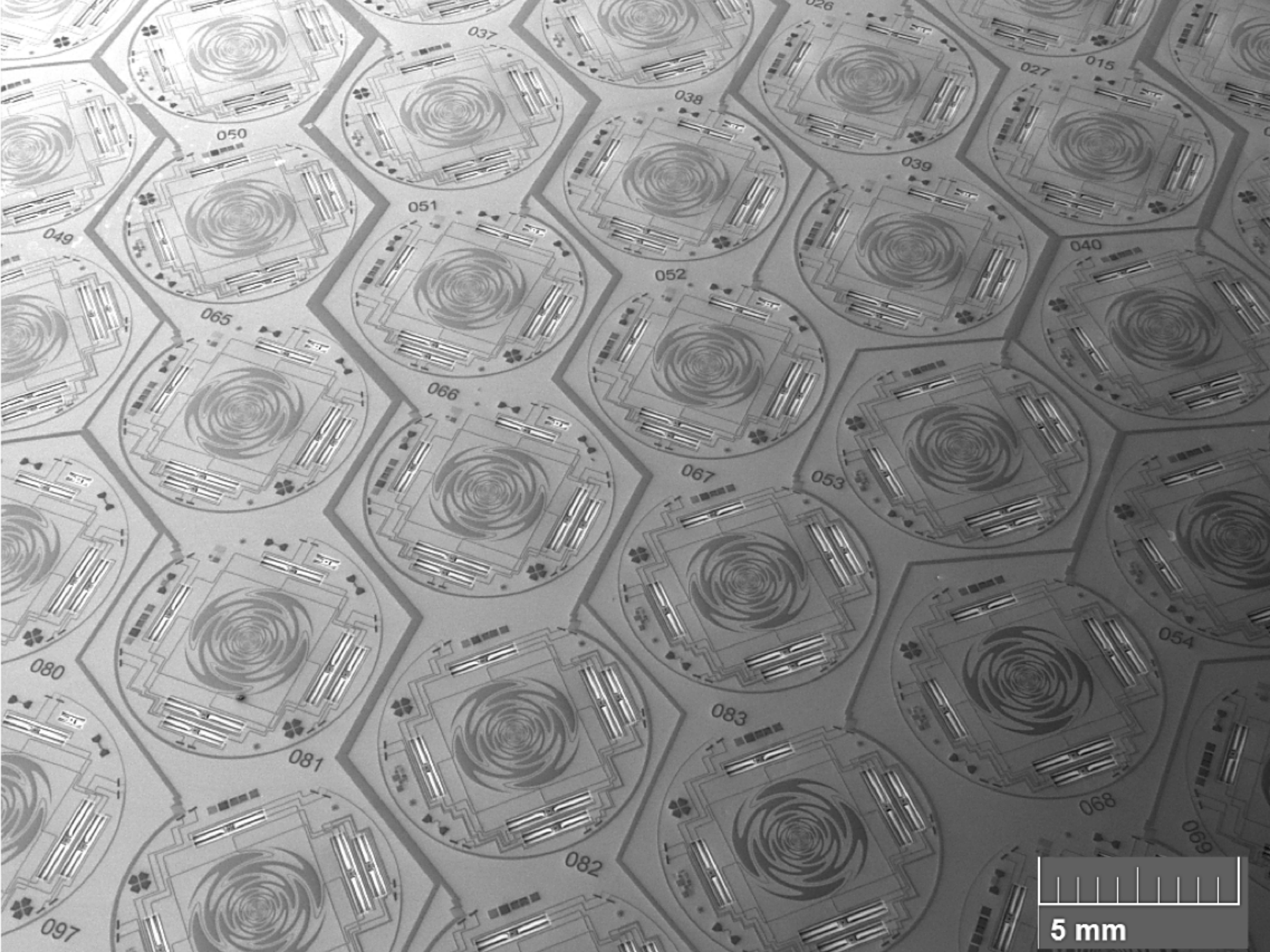


Plans for SPT: 10x le s

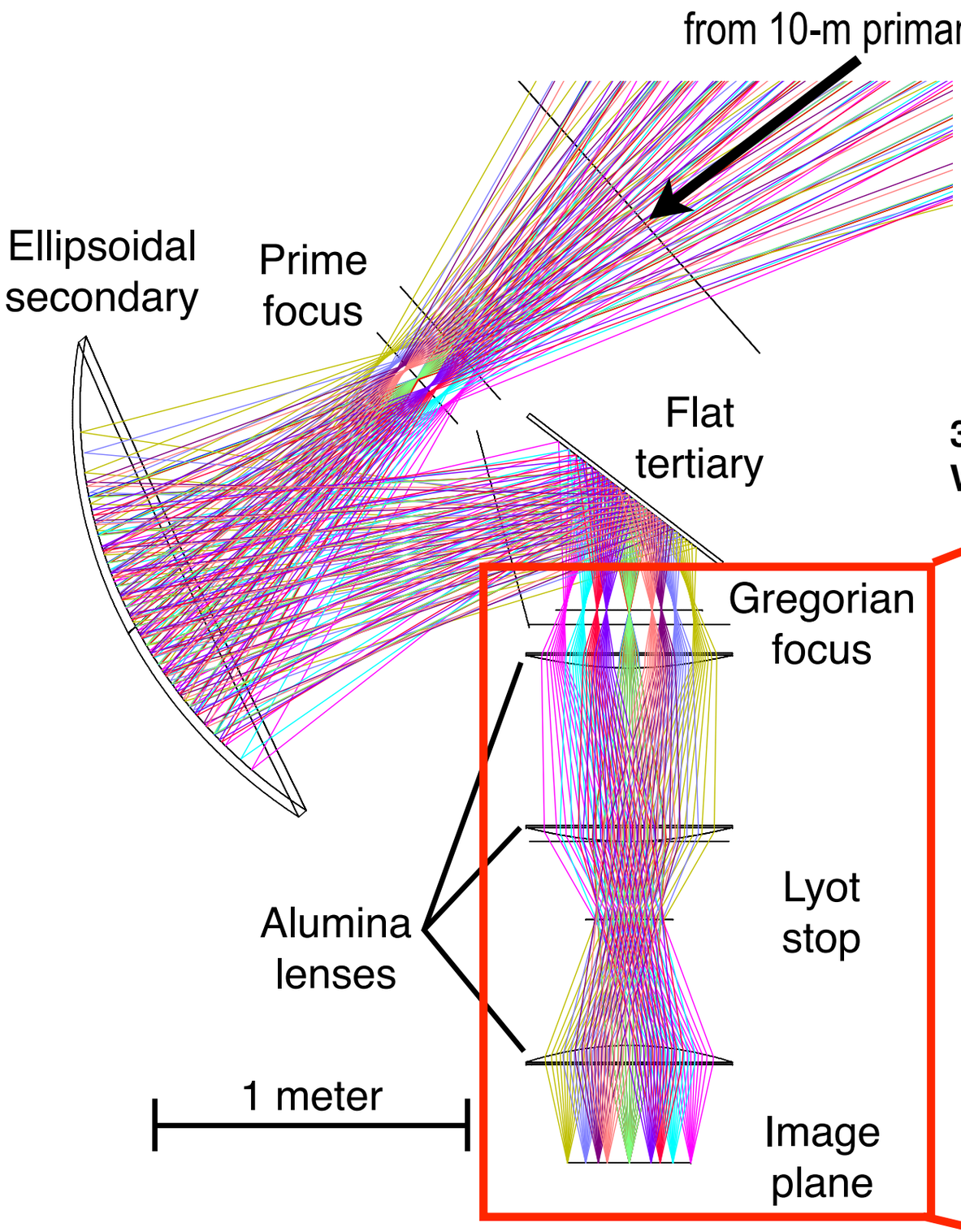



Clarence Chang

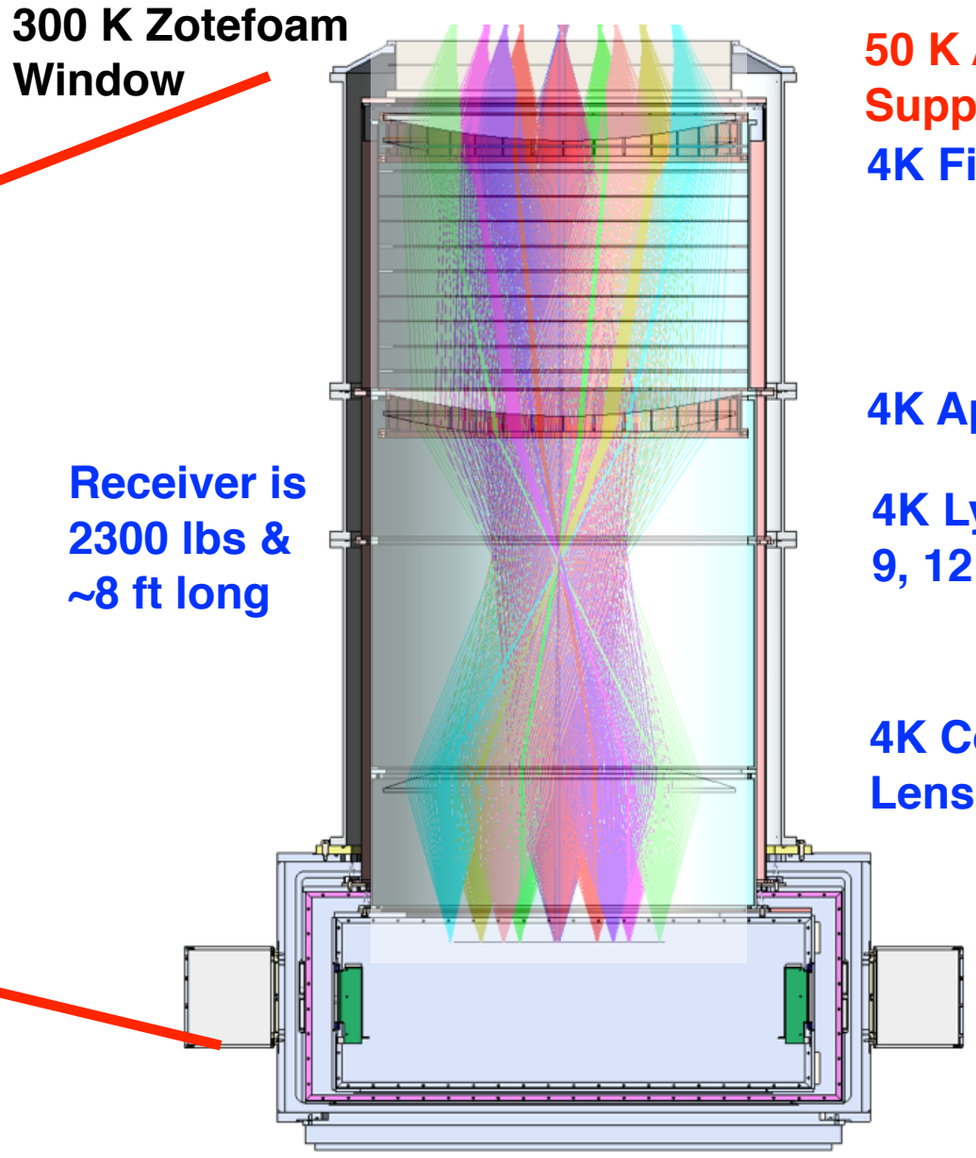
lt


037
026
027
015
038
050
039
049
051
040
052
065
066
067
053
080
054
081
083
068
082
097
5 mm

SPT-3G - New Optics & Receiver

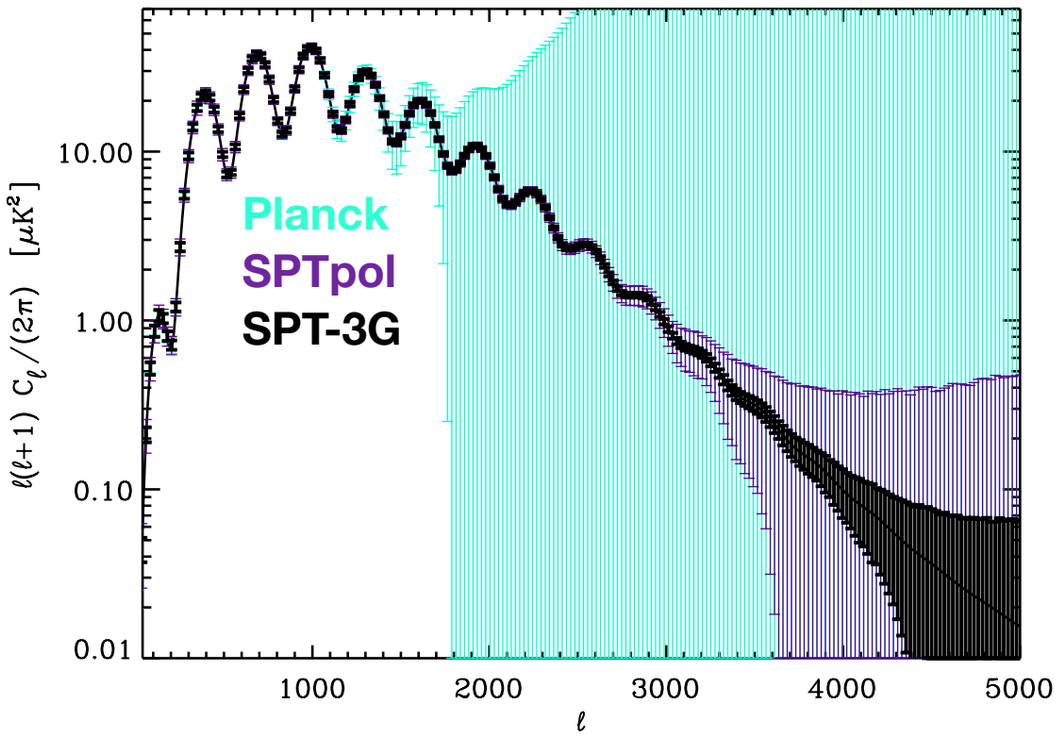


New receiver design and integration led by Benson at Fermilab, with Hogan Nguyen, Sasha Rahlin and Donna Kubik

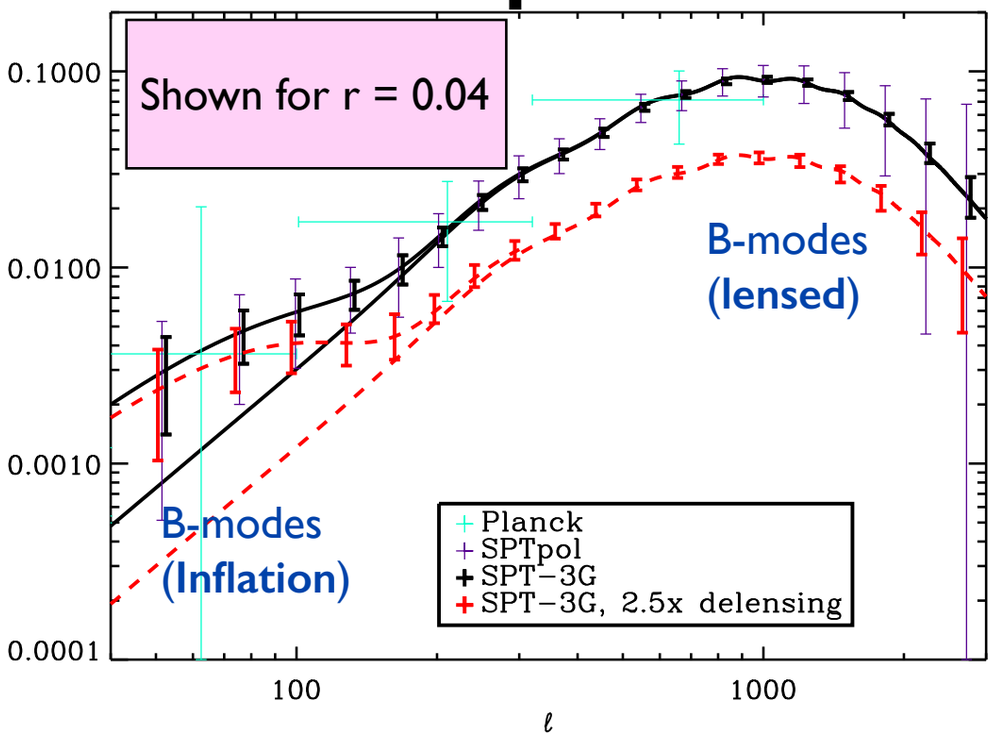


SPTpol and SPT-3G projections

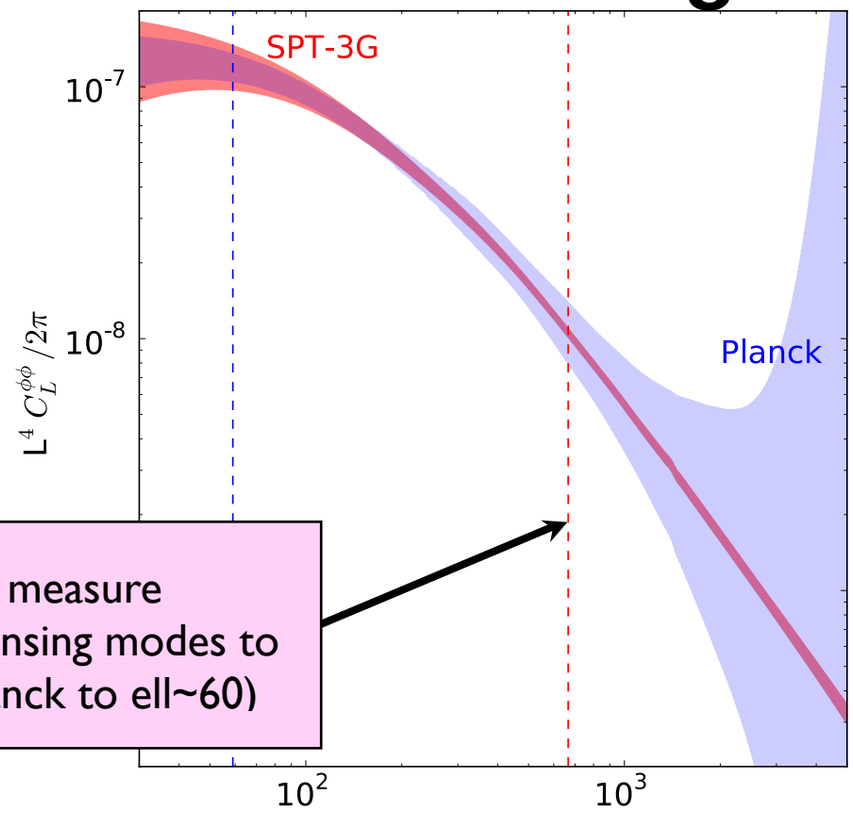
EE-Spectrum



BB-Spectrum



CMB Lensing



SPT-3G will measure individual lensing modes to ell~700 (Planck to ell~60)

Projections

(w/Planck priors)

	SPTpol (2015)	SPT-3G (2019)
σ(r)	0.028	0.011
$\sigma(N_{eff})$	0.117	0.058
$\sigma(\Sigma m_\nu)$	0.096 eV	0.061 eV*

* includes BOSS prior

CMB-Stage 4 experiment: CMB-S4

Because there is a lot more to learn from the CMB.

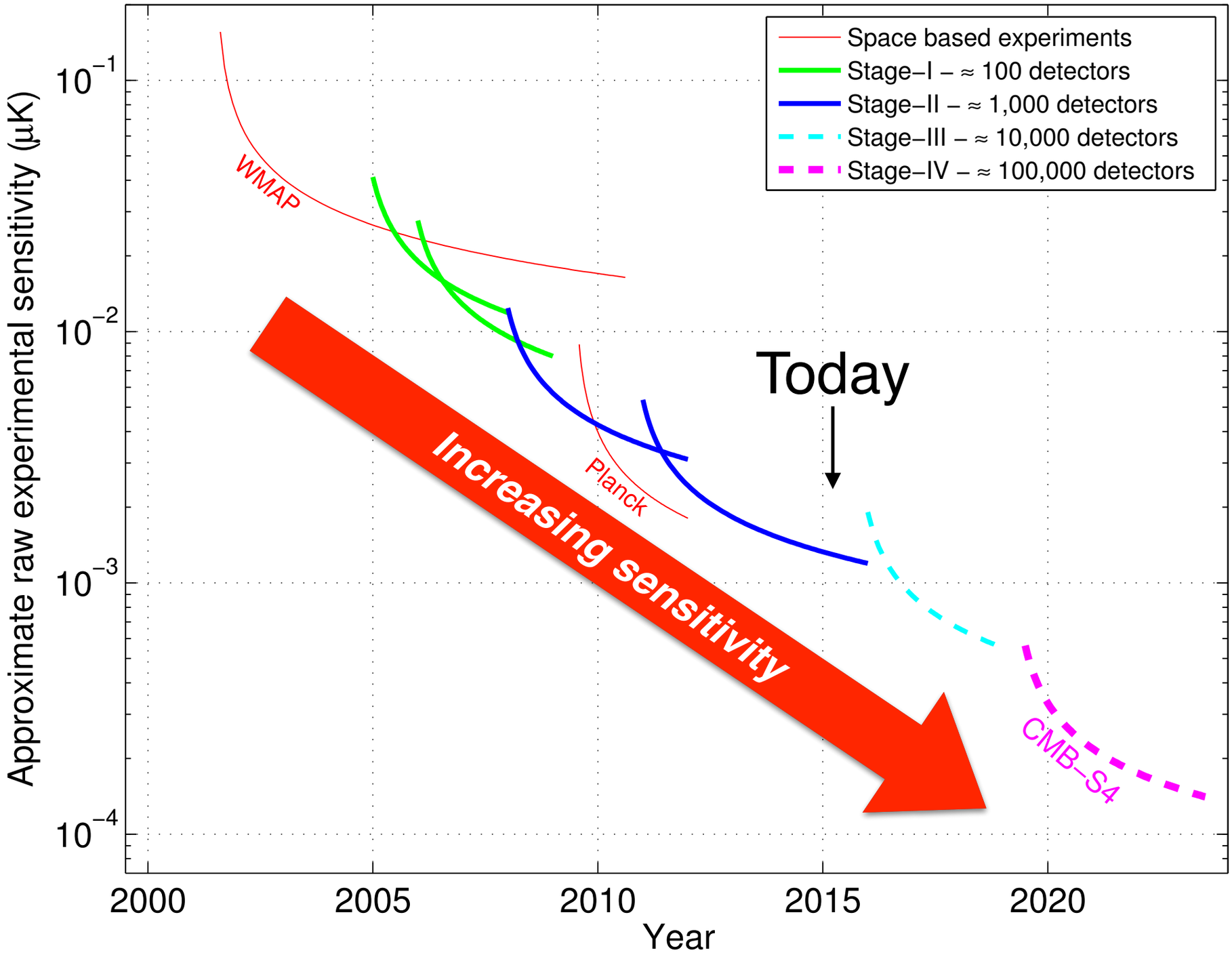
CMB-S4: a plan to build a coherent ground-based program working with, and building on, CMB stage II & III projects.

Participation includes, ***but is not limited to:***

- the ACT, BICEP/KECK, SPT, Polarbear,… CMB Stage 2 & 3 teams and their international partners

- Argonne, FNAL, LBNL, SLAC, NIST U.S. national labs and the high energy physics community.

The next step - Stage 4



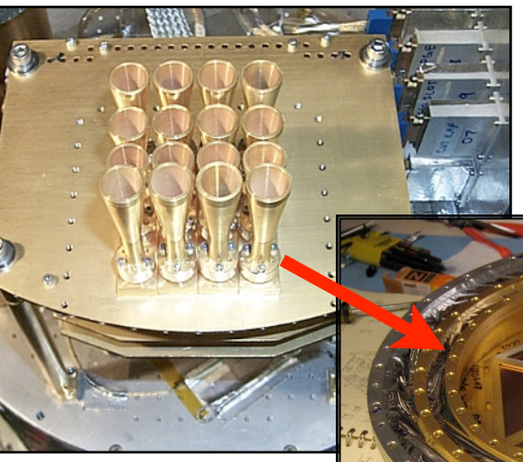
future Satellite?

A Moore's Law of CMB sensitivity

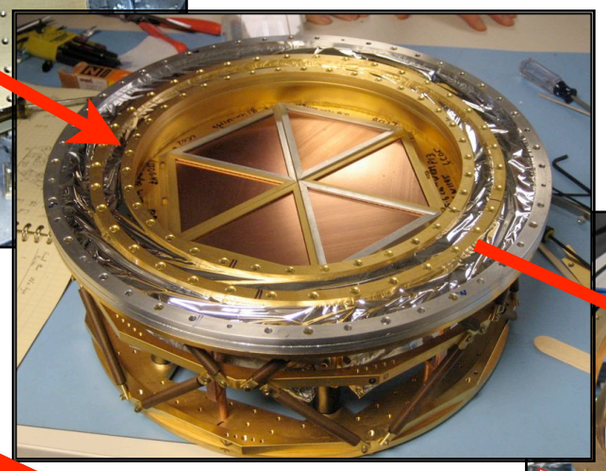
Snowmass: CF5 Neutrinos Document arxiv:1309.5383

CMB-S4: A coordinated community wide program to put 200,000 to 500,000 detectors spanning 40 - 240 GHz on multiple telescopes and map over 20,000 deg^2 of sky

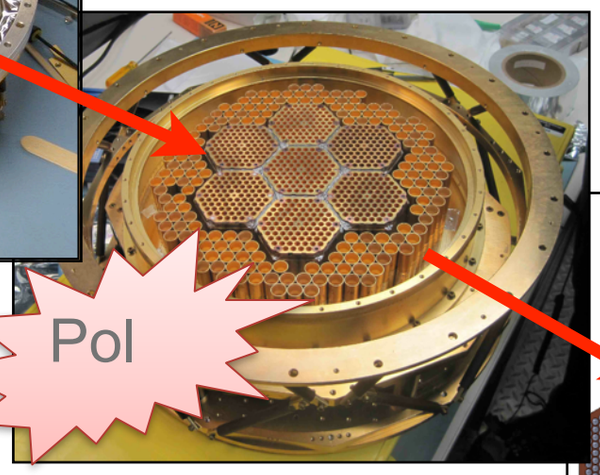
2001: ACBAR
16 detectors



2007: SPT
960 detectors

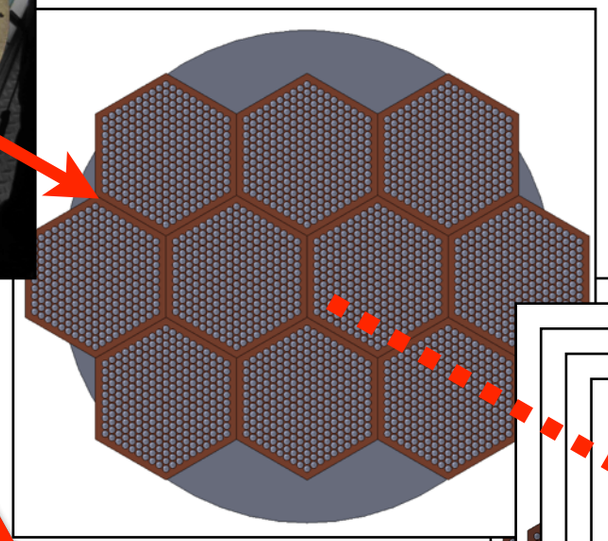


Stage-2
2012: SPTpol
~1600 detectors

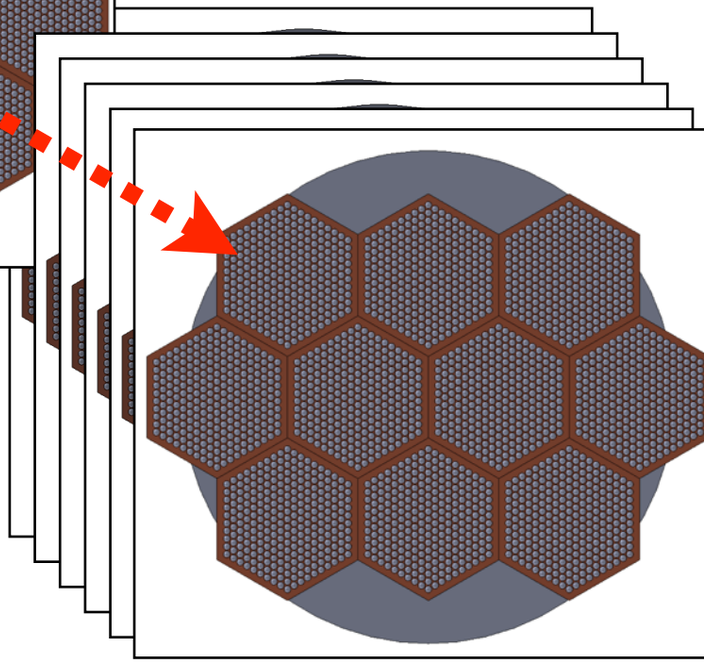


Pol

Stage-3
2016: SPT-3G
~16,000 detectors



Stage-4
2020?: CMB-S4
200,000+ detectors

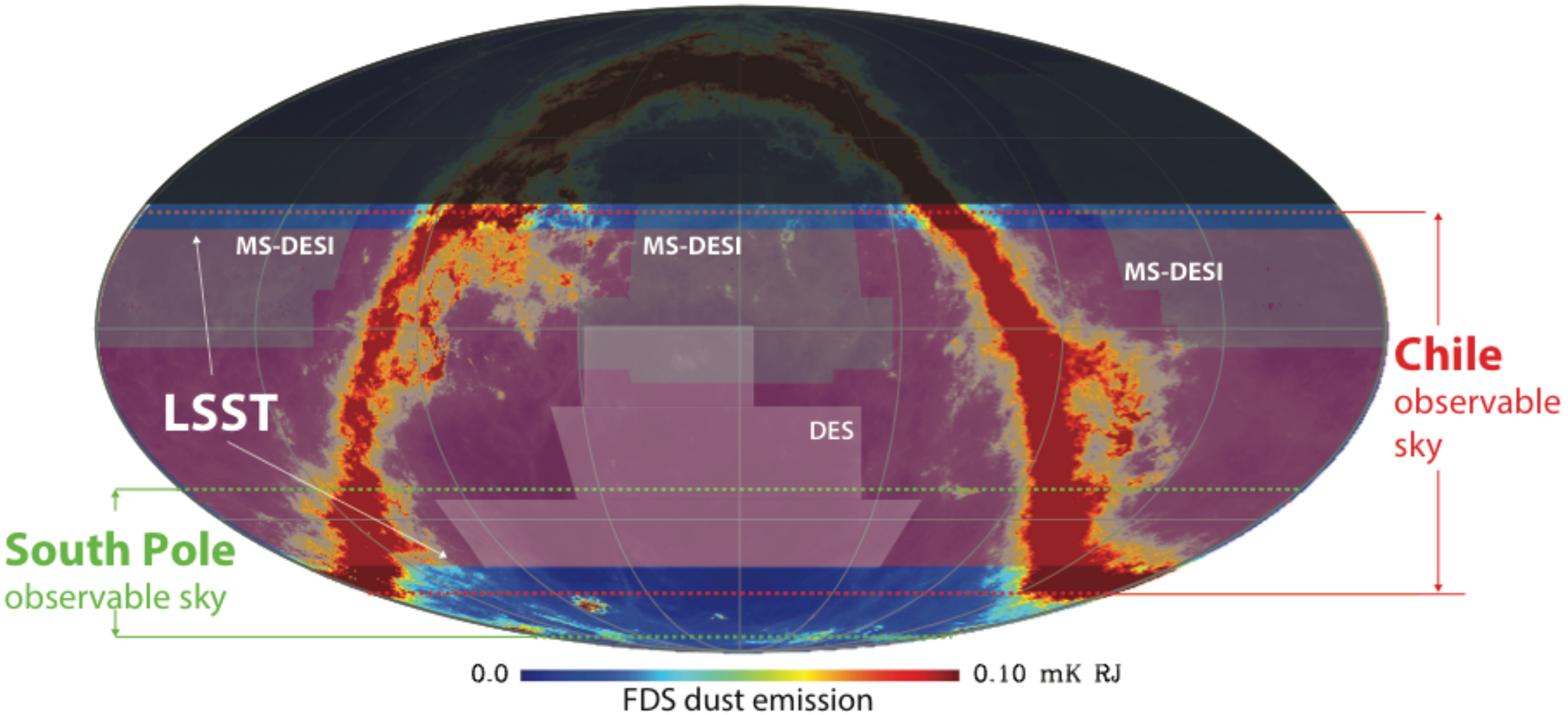


increasing detector count

Maintaining Moore's Law: focal planes are saturated so go to parallel processing with multiple telescopes

Multiple platforms exploiting superb, established sites at Chile and South Pole and possibly add Northern site(s)

Critical to overlap with LSST, MS-DESI, etc.



Slide from Jeff McMahon

CMB polarization timeline

- 2013: Stage II experiments detect lensing B-modes (**SPTpol)**
- now: $r \lesssim 0.12$ CMB B-modes **(BICEP2/KECK with *Planck)***
- 2013-2016: Stage II experiments (**SPTpol)**

  $\sigma(r)\sim0.03$, $\sigma(N_{eff})\sim0.1$, $\sigma(\Sigma m_\nu)\sim0.1$eV
- 2016-2020: Stage III experiments (**SPT-3G)**

  $\sigma(r)\sim0.01$, $\sigma(N_{eff})\sim0.06$, $\sigma(\Sigma m_\nu)\sim0.06$eV*

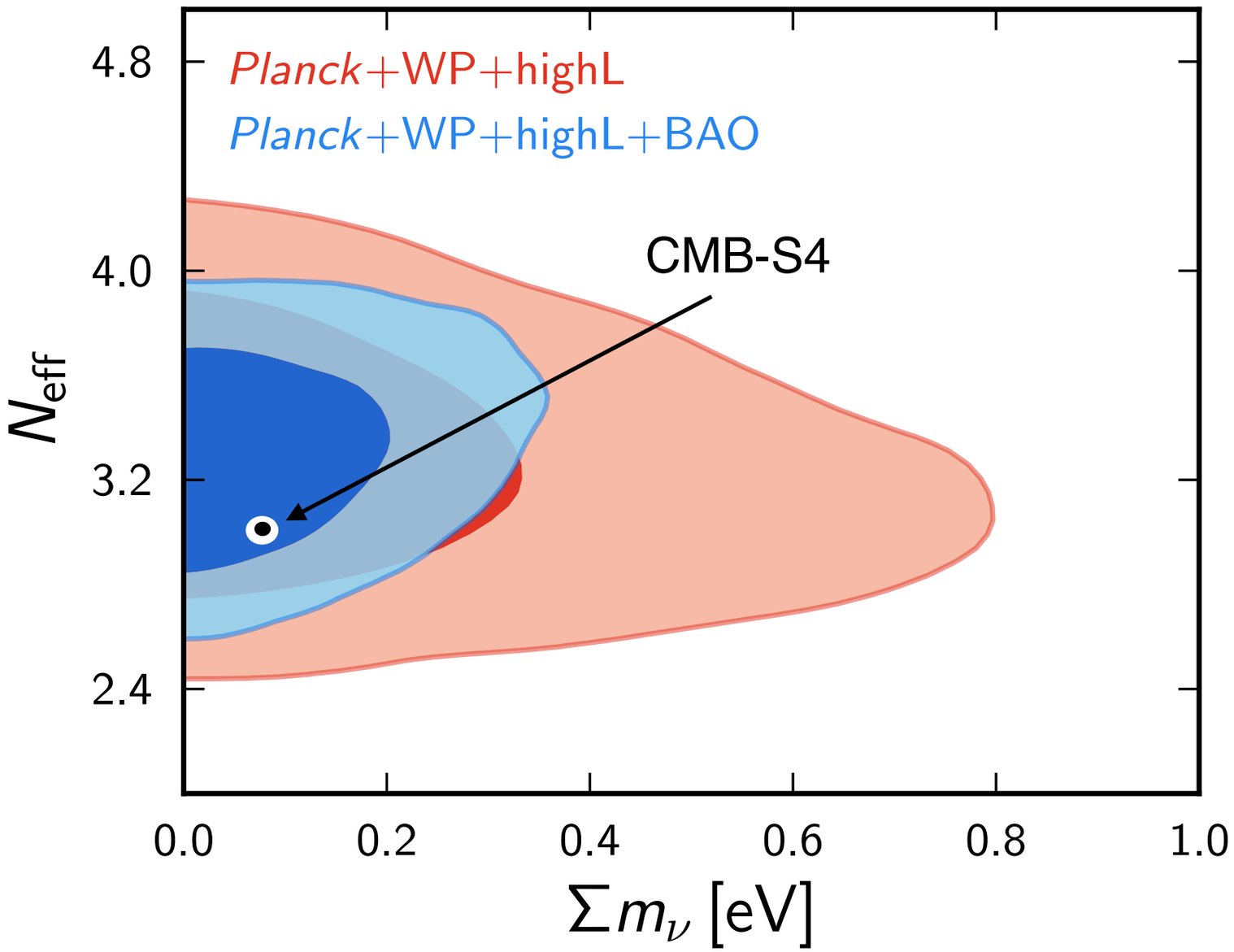
- 2020-2025: Stage IV experiment, **CMB-S4**

  $\sigma(r) = 0.001$, $\sigma(N_{eff}) = 0.020$, $\sigma(\Sigma m_\nu) = 16$ meV

  each crosses a critical threshold for physics

* includes BOSS prior

N_{eff} - Σm_ν projections for CMB-S4



σ(Σm_ν) = 16 meV
(with DESI BAO)

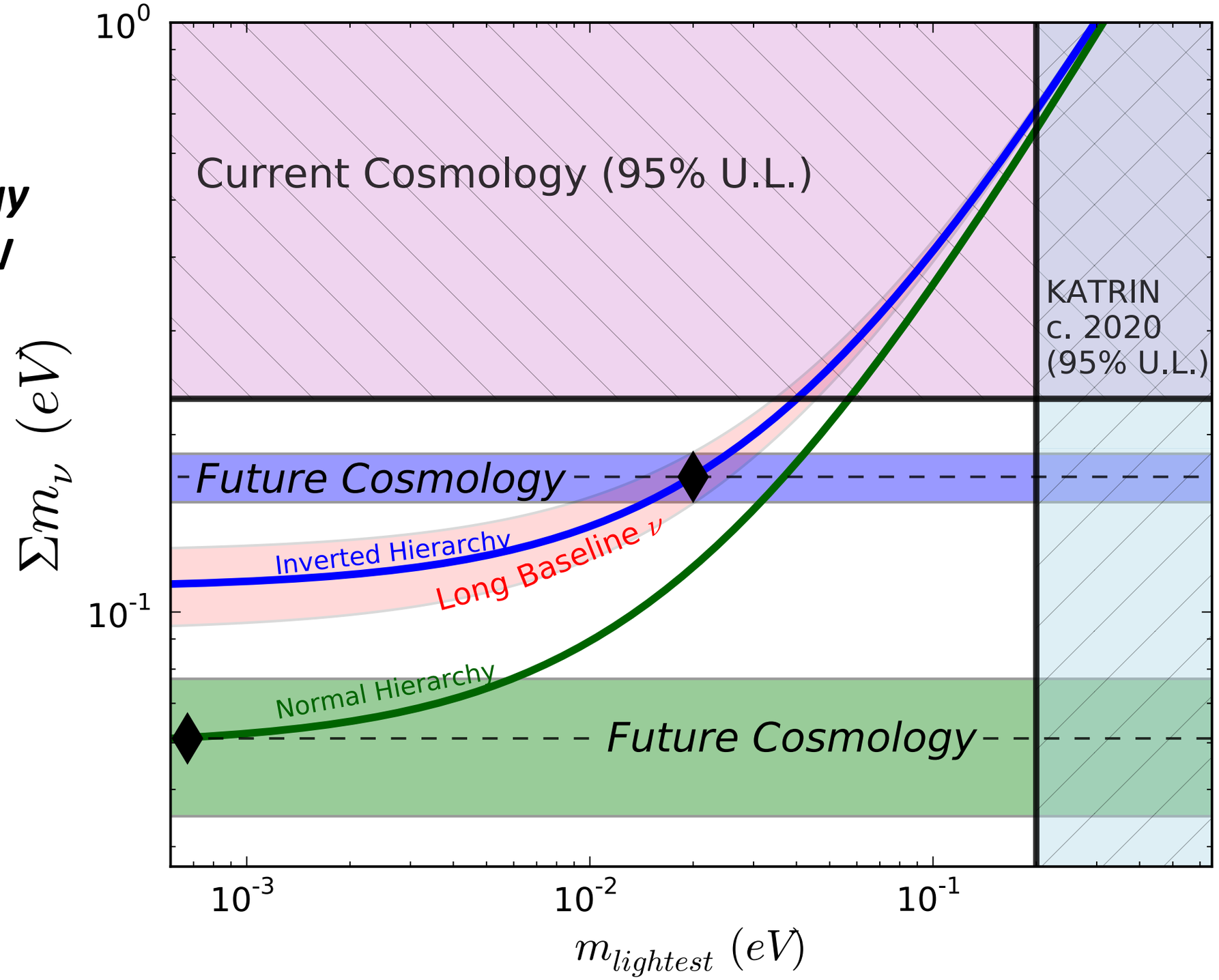
σ(N_{eff}) = 0.020
CMB is the only probe of N_{eff}

Our forecasters: J. Errard, P. McDonald, A. Slosar K. Wu, O. Zahn

Combined Neutrino mass constraints

Future Cosmology

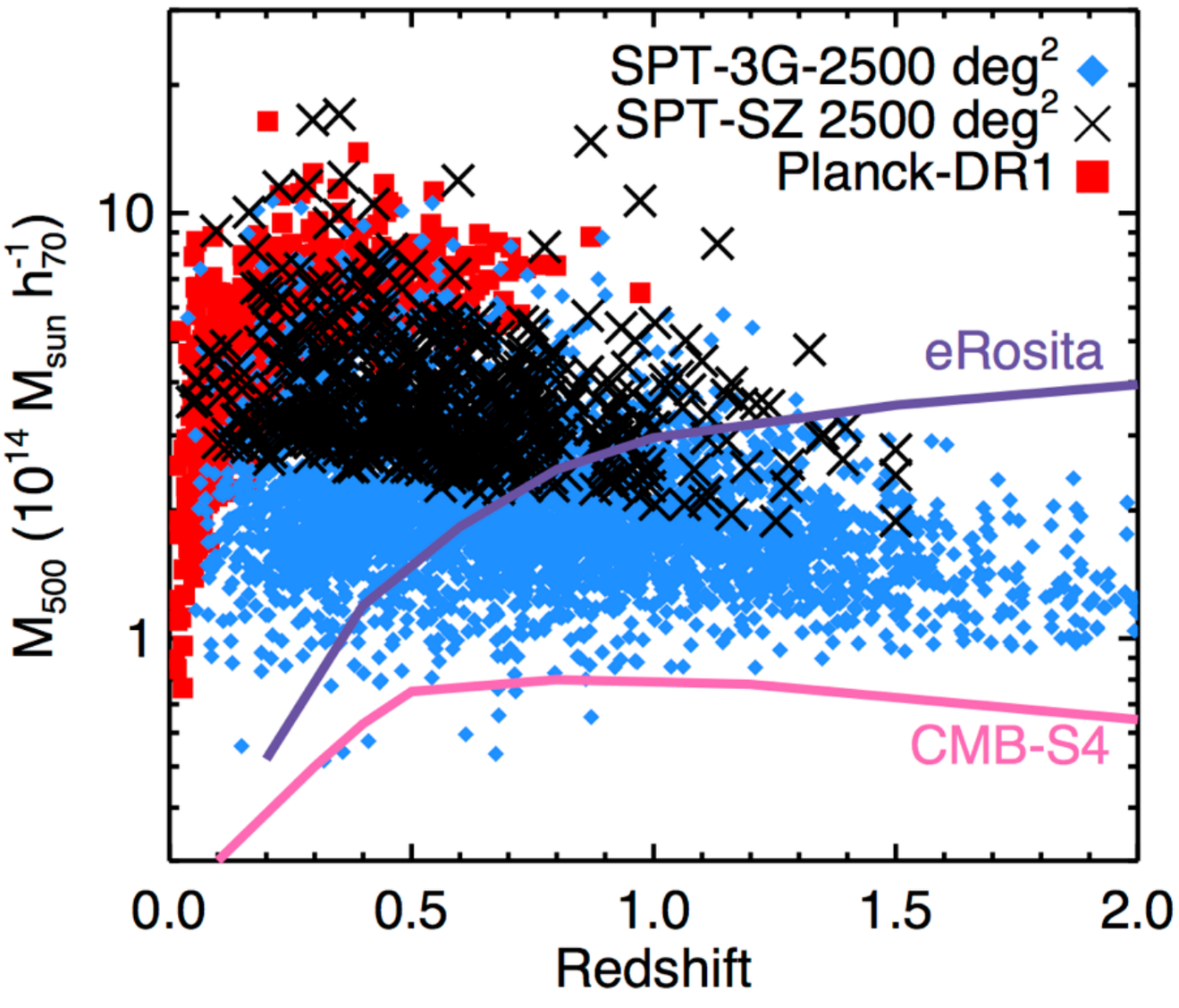
$\sigma(\Sigma m_\nu) = 16$ meV



"use cosmology to tighten the noose" Boris Kayser

CMB Sunyaev-Zel'dovich Cluster Surveys

Cluster Mass vs Redshift for CMB/SZ Experiments



SPT-SZ/pol: $N_{\rm clust}$ **~ 1,000**

SPT-3G: $N_{\rm clust}$ **~ 10,000**

CMB-S4: $N_{\rm clust}$ **~ 100,000**

CMB lensing can directly calibrate cluster mass:

SPT-3G: $\sigma(M) \sim 3\%$

CMB-S4: $\sigma(M) \sim 0.1\%$

making SZ cluster cosmology an extremely powerful probe of structure formation and dark energy

SPT-3G Collaboration

Last words

We have learned a great deal from the CMB and will learn even more in the future,

Did the universe start with an epoch of inflation?

What is the energy scale of inflation?

Is there excess "dark radiation"?

What are the neutrino masses?

What is nature of dark energy?

Is GR correct on large scales?

with lots of great astrophysics and new discoveries on the way.

Thanks

For more information and SPT publications see pole.uchicago.edu