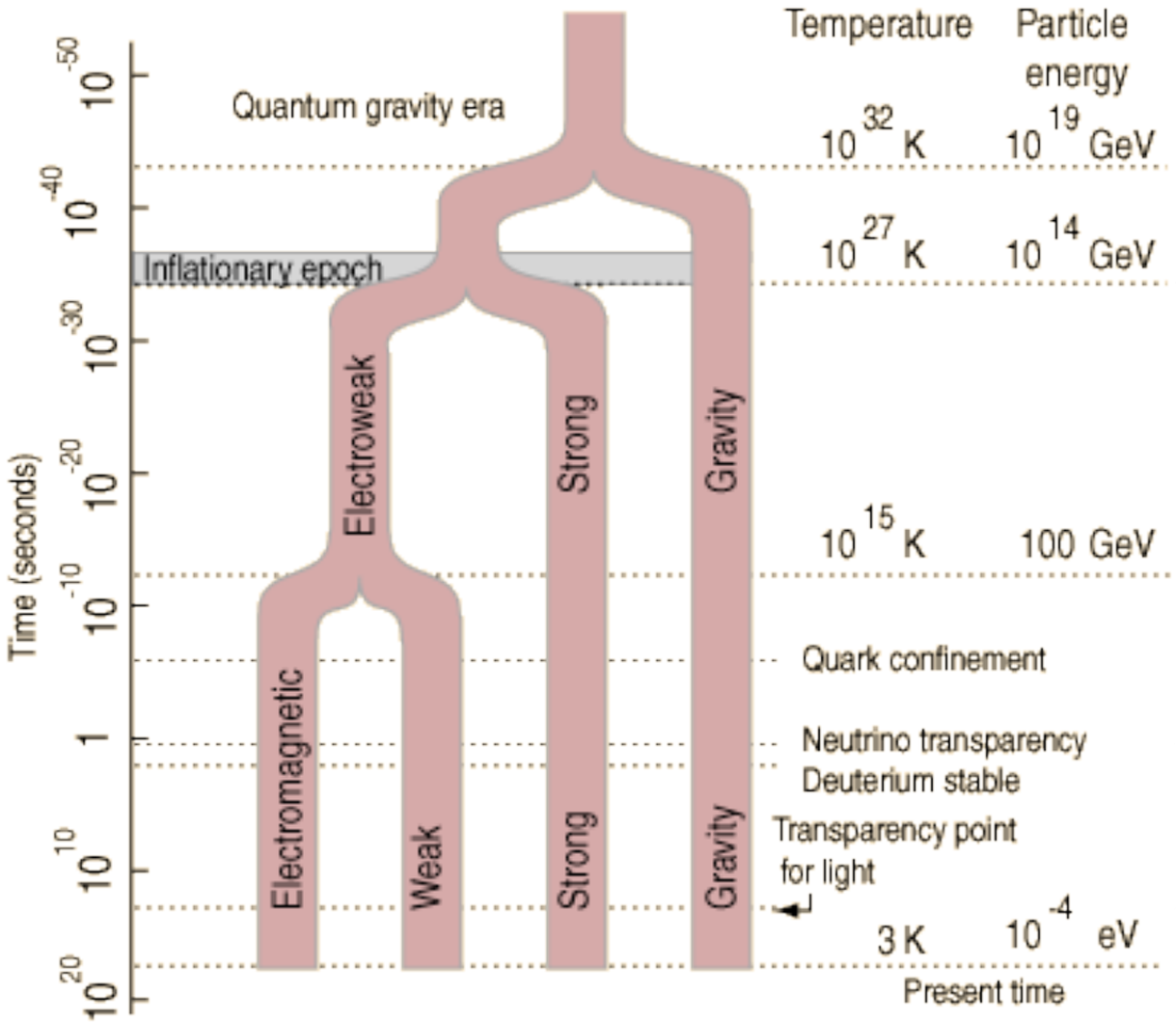
Cosmology with the Cosmic Microwave Background: New Results and Future Prospects

John Carlstrom
Kavli Institute for Cosmological Physics
University of Chicago

Photo credit: Daniel Luong-van

Early universe as a HEP lab

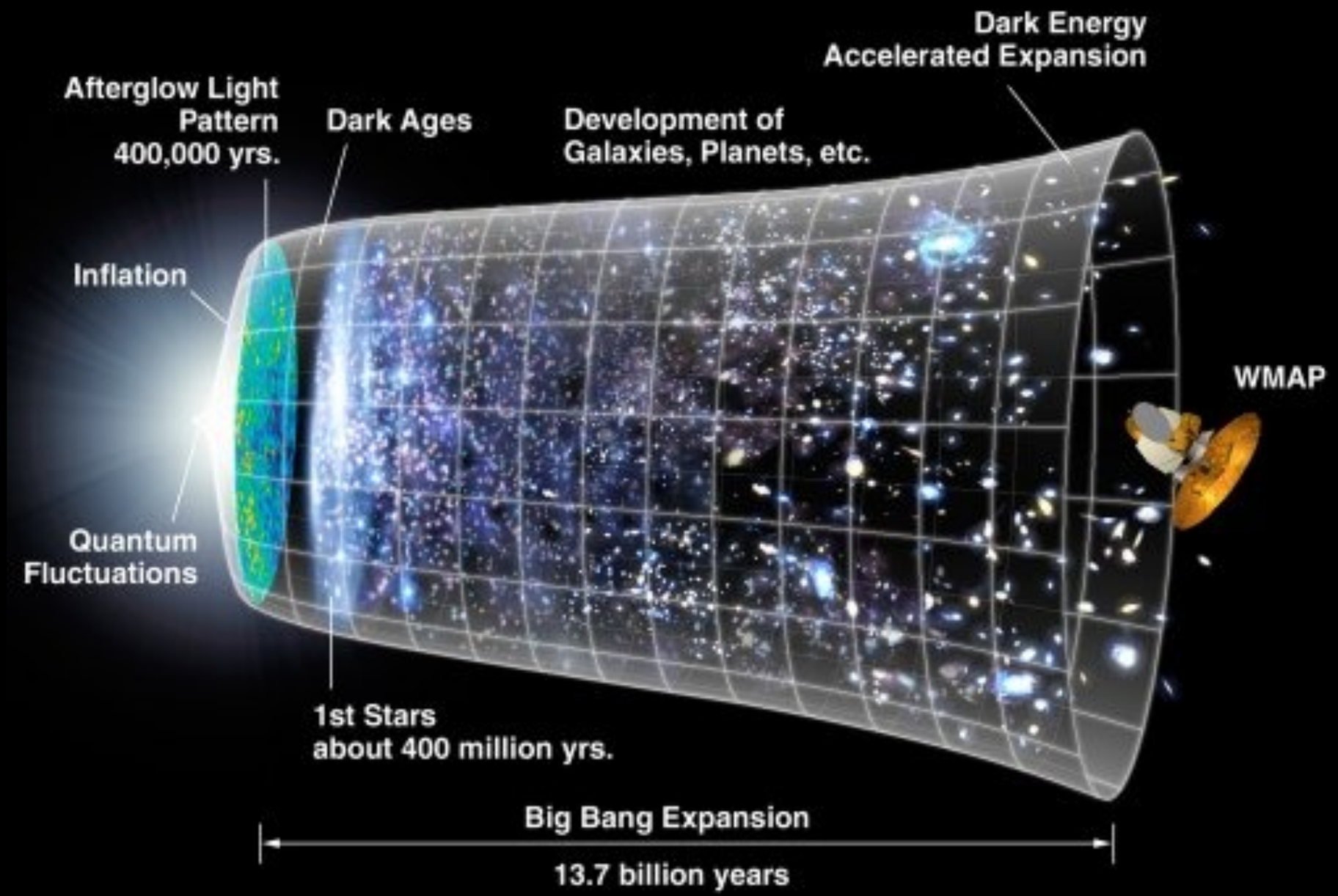


Inflation

Cosmic neutrino background

Cosmic microwave background

CMB measurements probe cosmology, astrophysics and fundamental physics

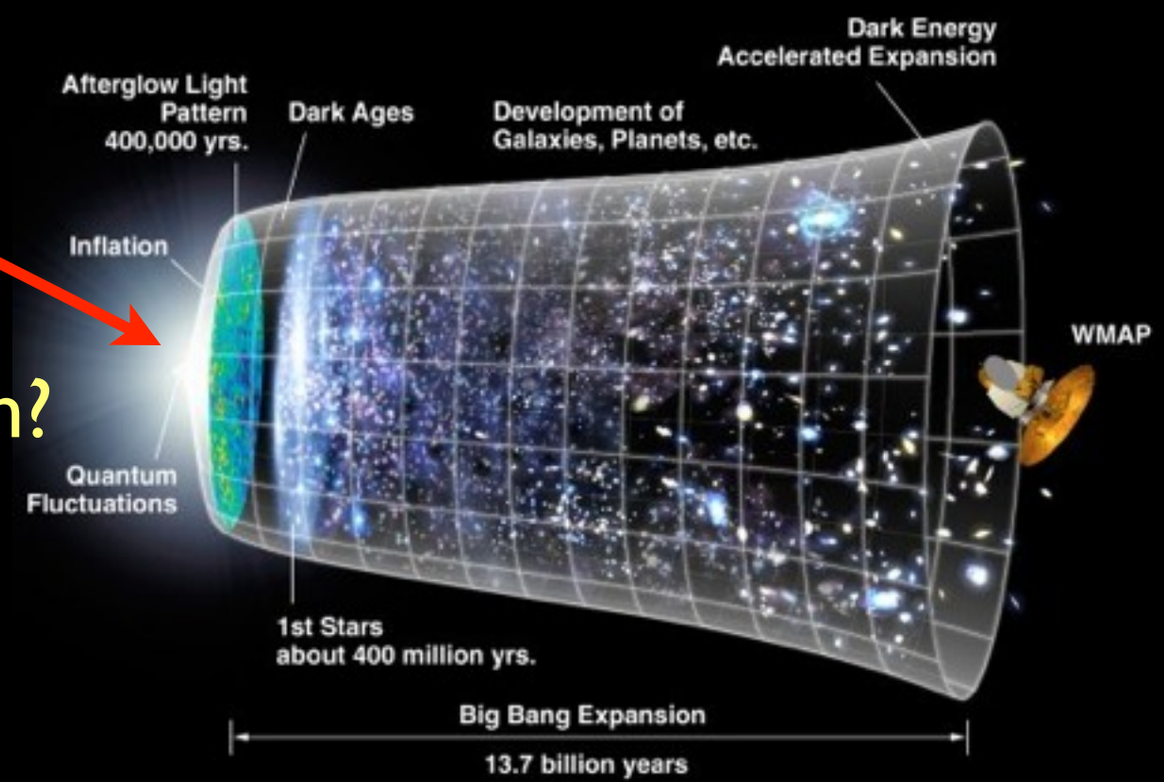


NASA/WMAP Team

Inflation?

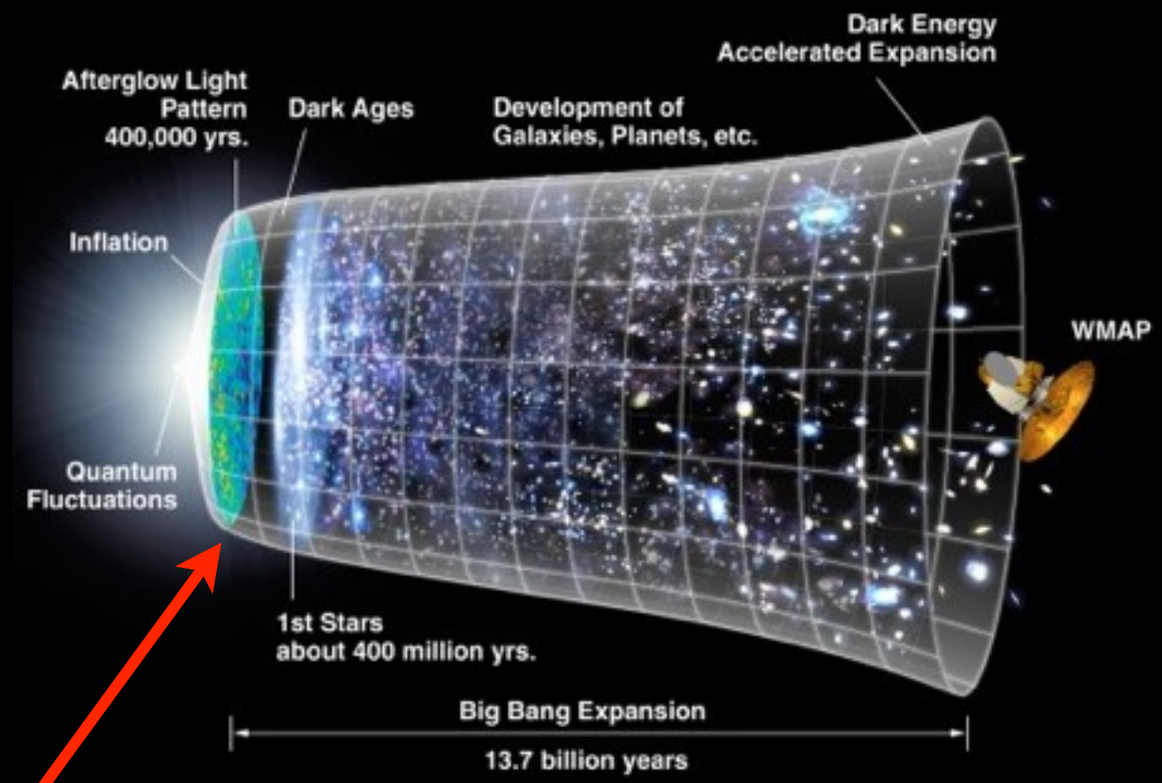
Universe expands by $>e^{60}$
solving smoothness problem,
flatness and more..

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



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

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

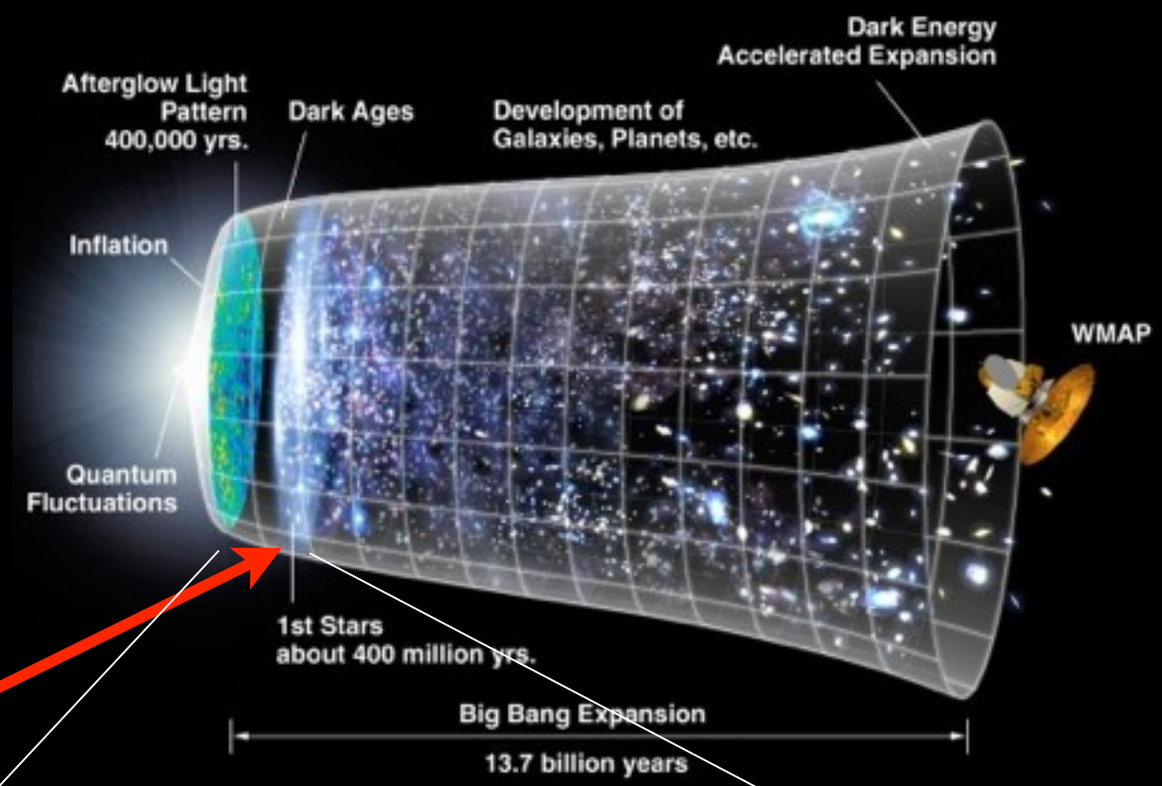


Physics at recombination

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

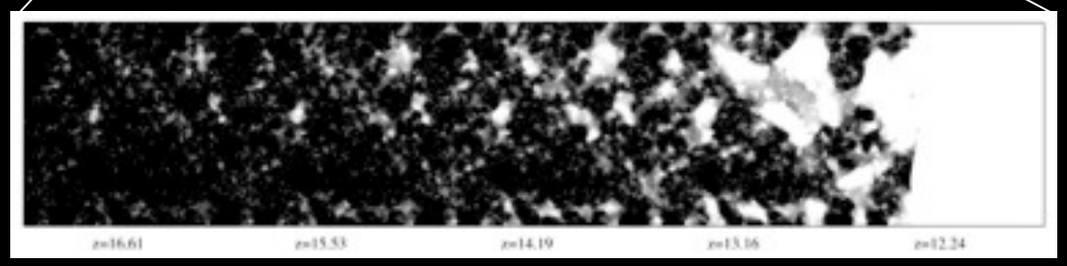
- Measure primordial fluctuations
- Inventory stuff in the universe
- Number of relativistic species, helium abundance

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



Reionization

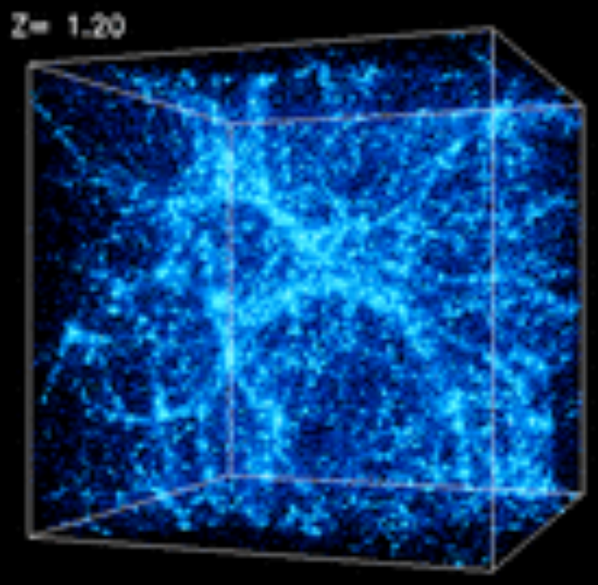
First stars(?) start producing
UV photons. Hydrogen is reionized.



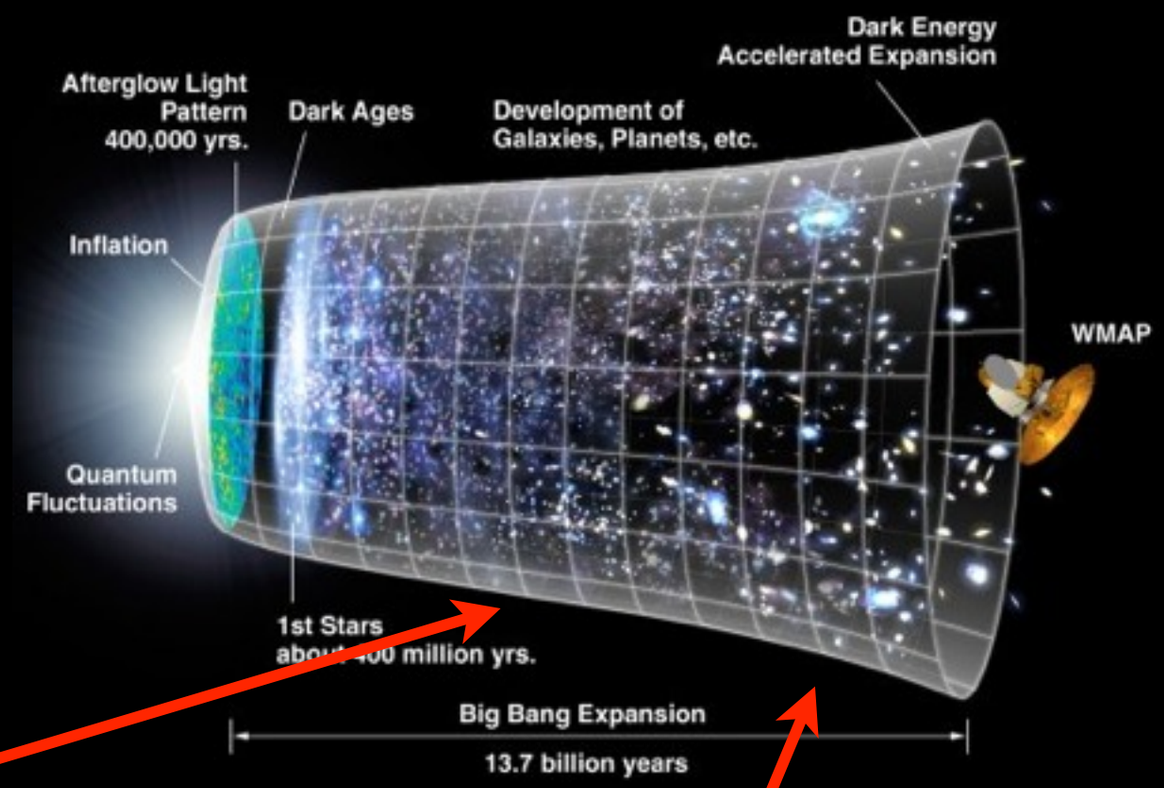
Patchy reionization, Zahn et al, 2005

How did it proceed?
Are star forming galaxies sufficient to power reionization?

➡ *measure 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

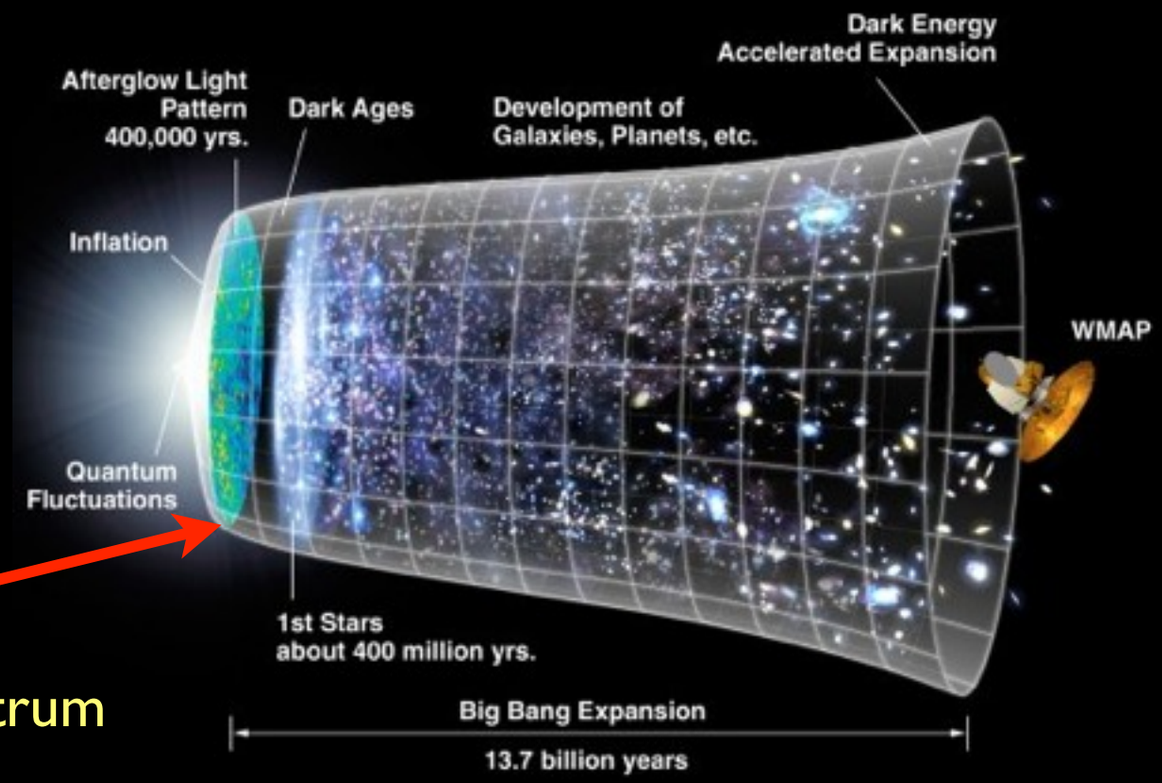
Dark energy begins accelerating the expansion of the Universe.

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

➡ *map dark matter through lensing of the CMB*

➡ *evolution of Galaxy Clusters through thermal SZ effect*

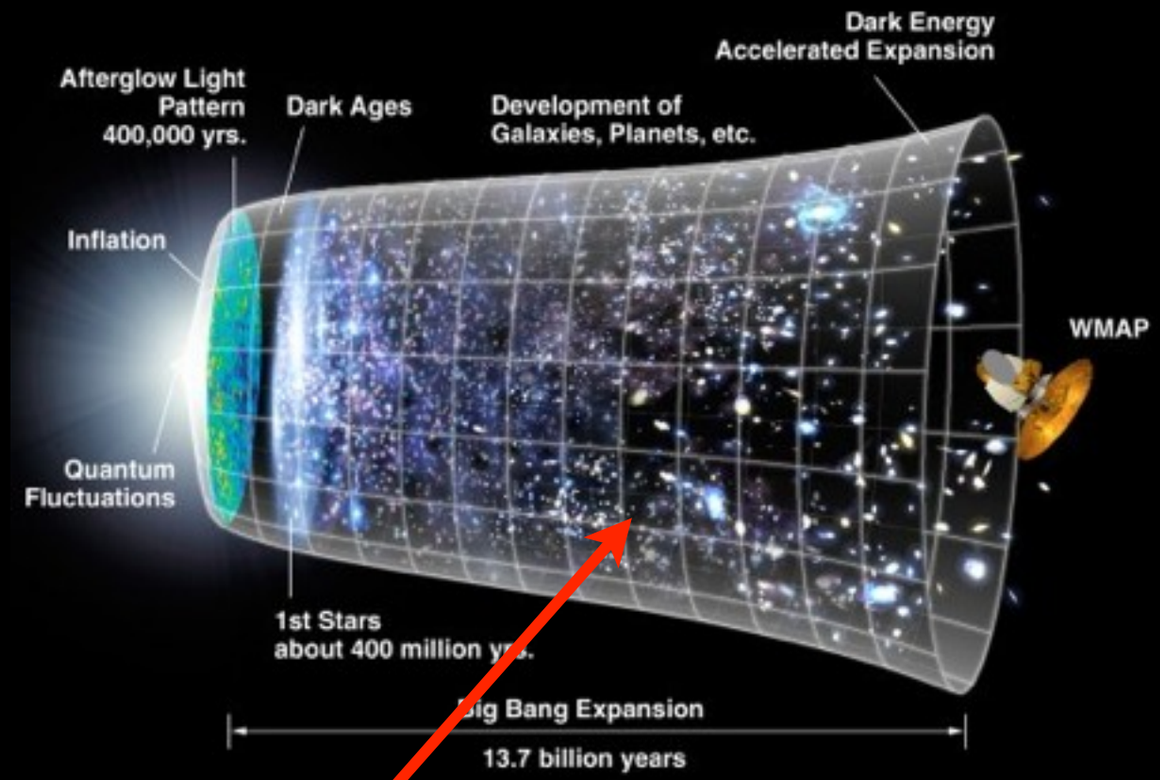
E.g., Neutrino constraints

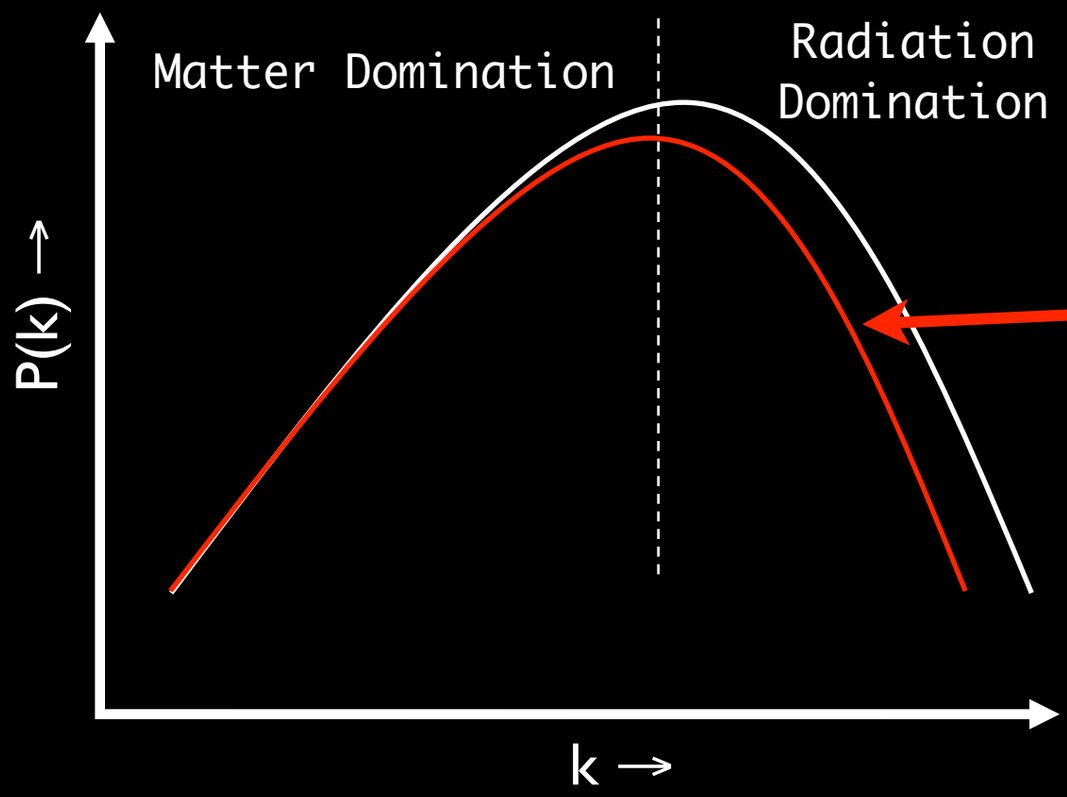


Dark Radiation

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

E.g., Neutrino constraints



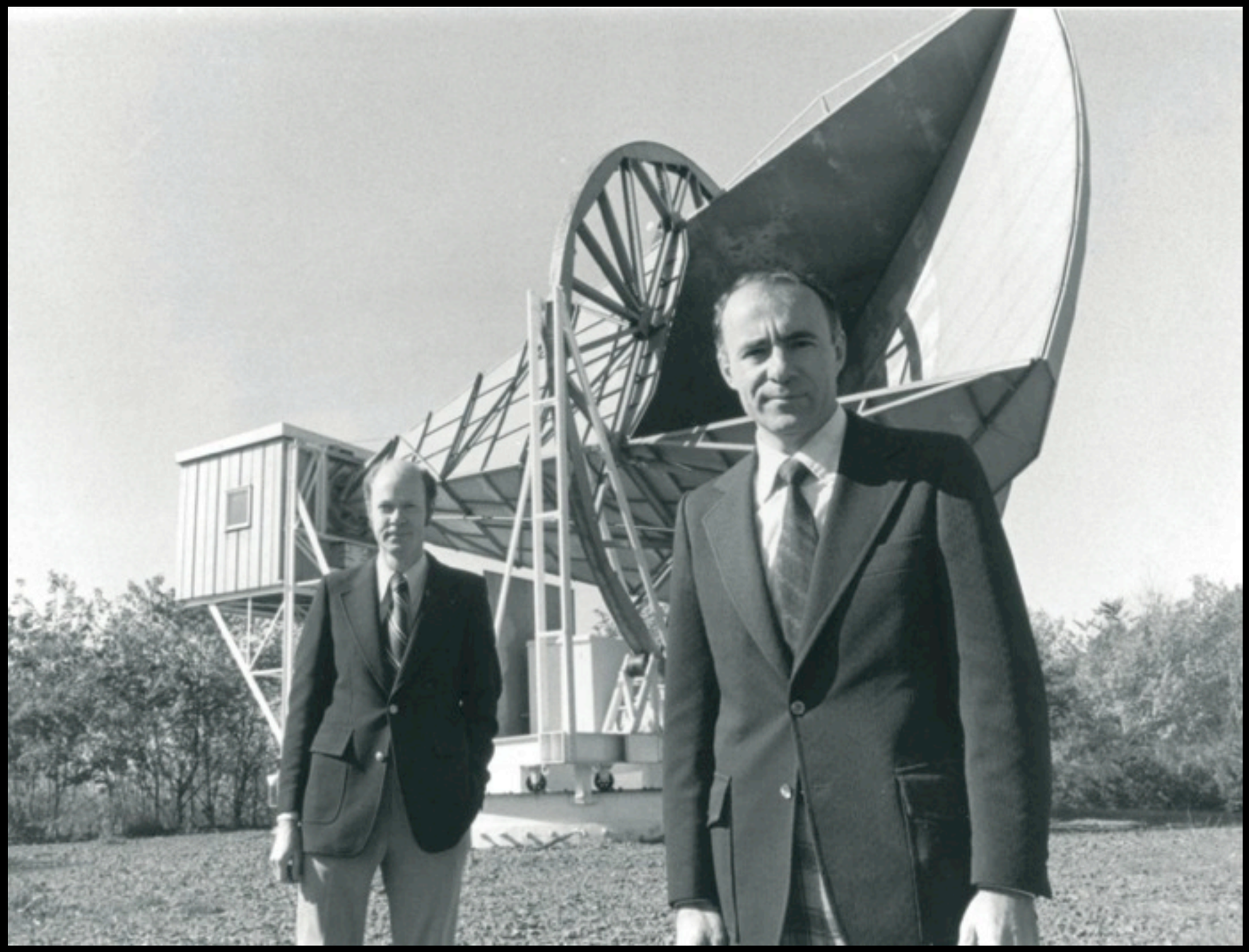


$\Sigma m_\nu > 0$

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

Discovery of the Cosmic Microwave Background

50 yrs ago



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

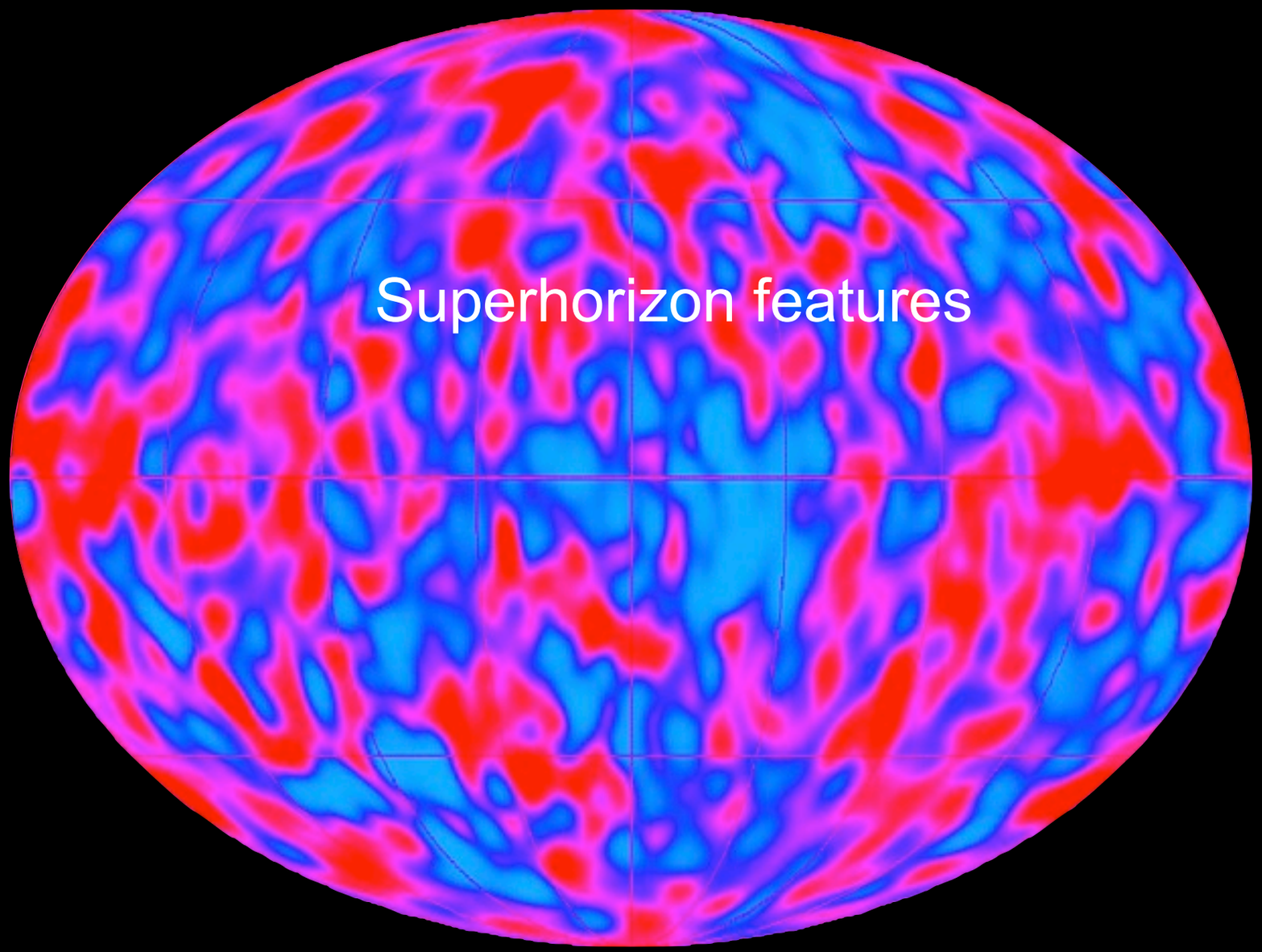
"smoking gun" evidence for a <u>Hot Big Bang</u>

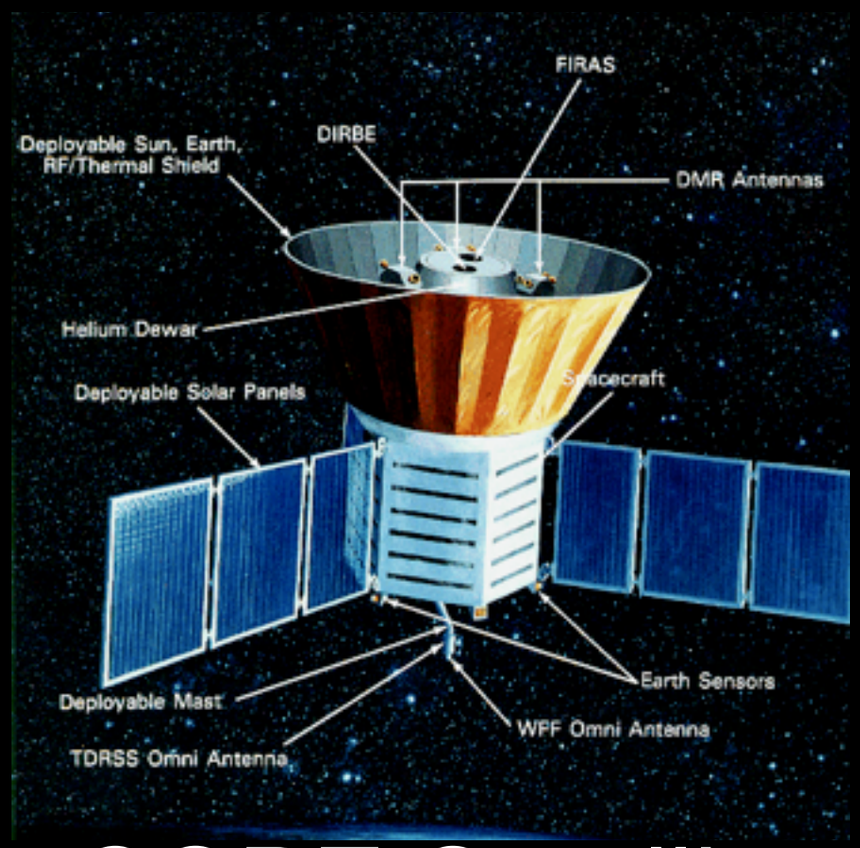
Received 1978 Nobel Prize

Enormous impact on Cosmology

Structure in background discovered in 1992

20 yrs ago

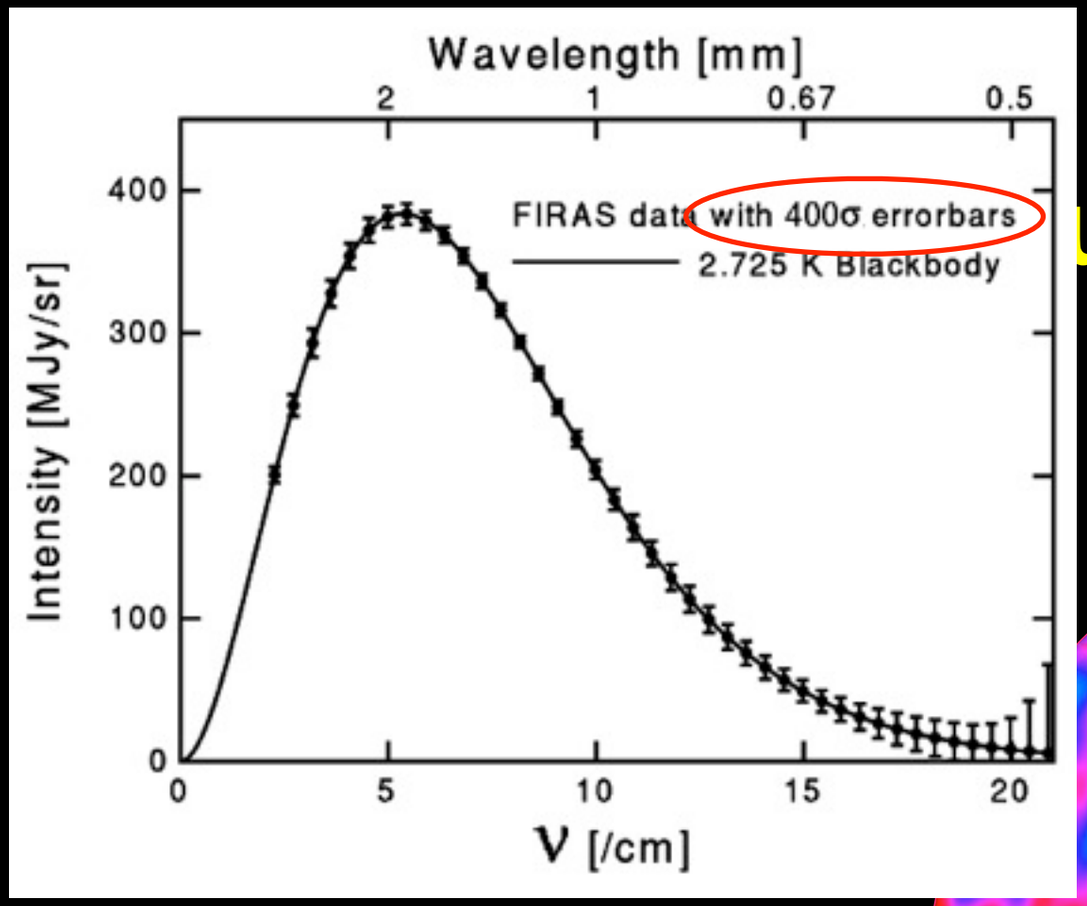




COBE Satellite

Smooth to a part in 10^5

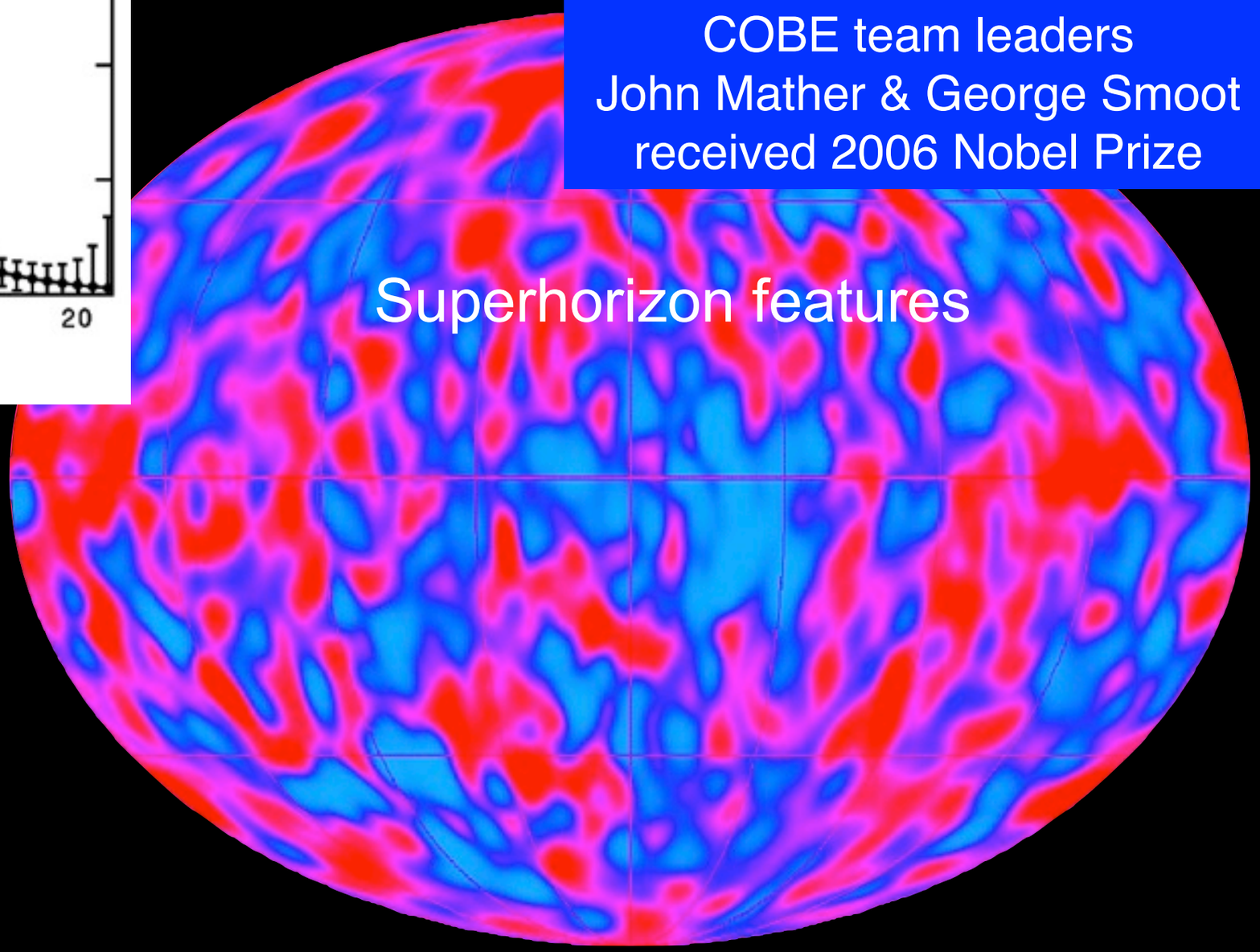
the smoothness problem -
led to Inflation theory



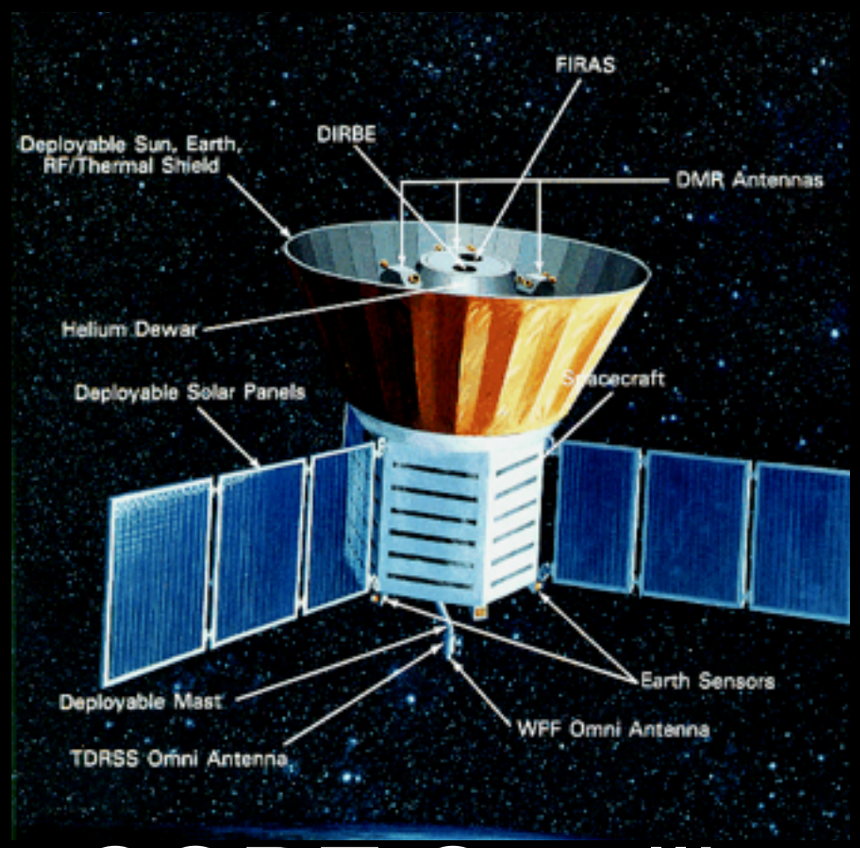
und discovered in 1992

20 yrs ago

COBE team leaders
John Mather & George Smoot
received 2006 Nobel Prize



Superhorizon features



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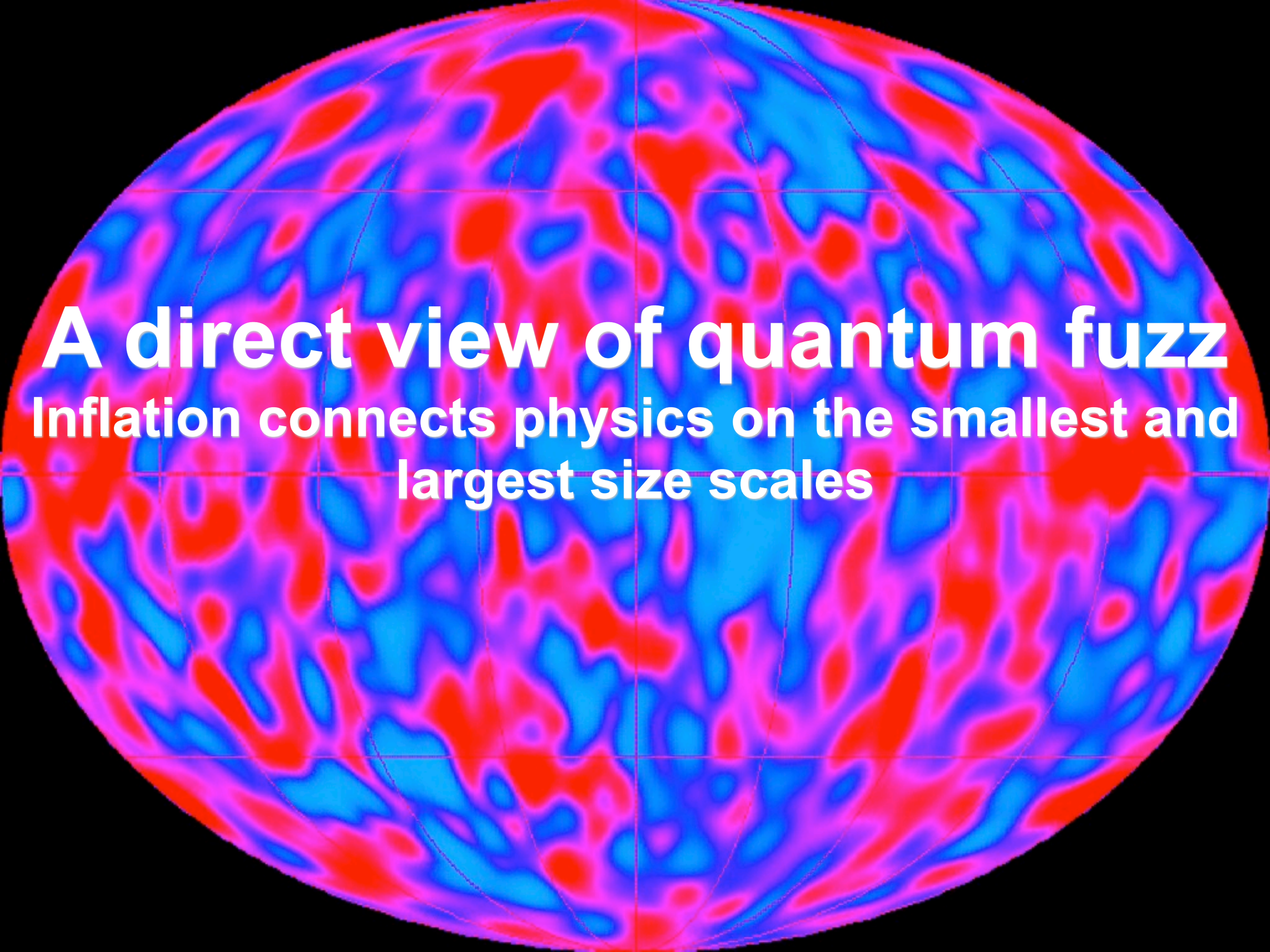
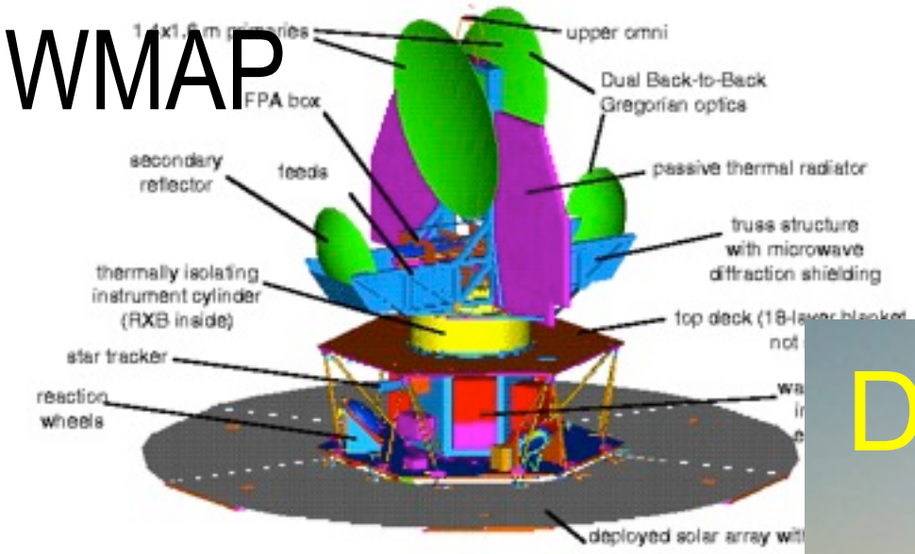


A direct view of quantum fuzz

Inflation connects physics on the smallest and largest size scales

WMAP



TOCO

Experiments w/ tens of detectors circa 1995-2005

DASI

ACBAR

VSA

QUaD

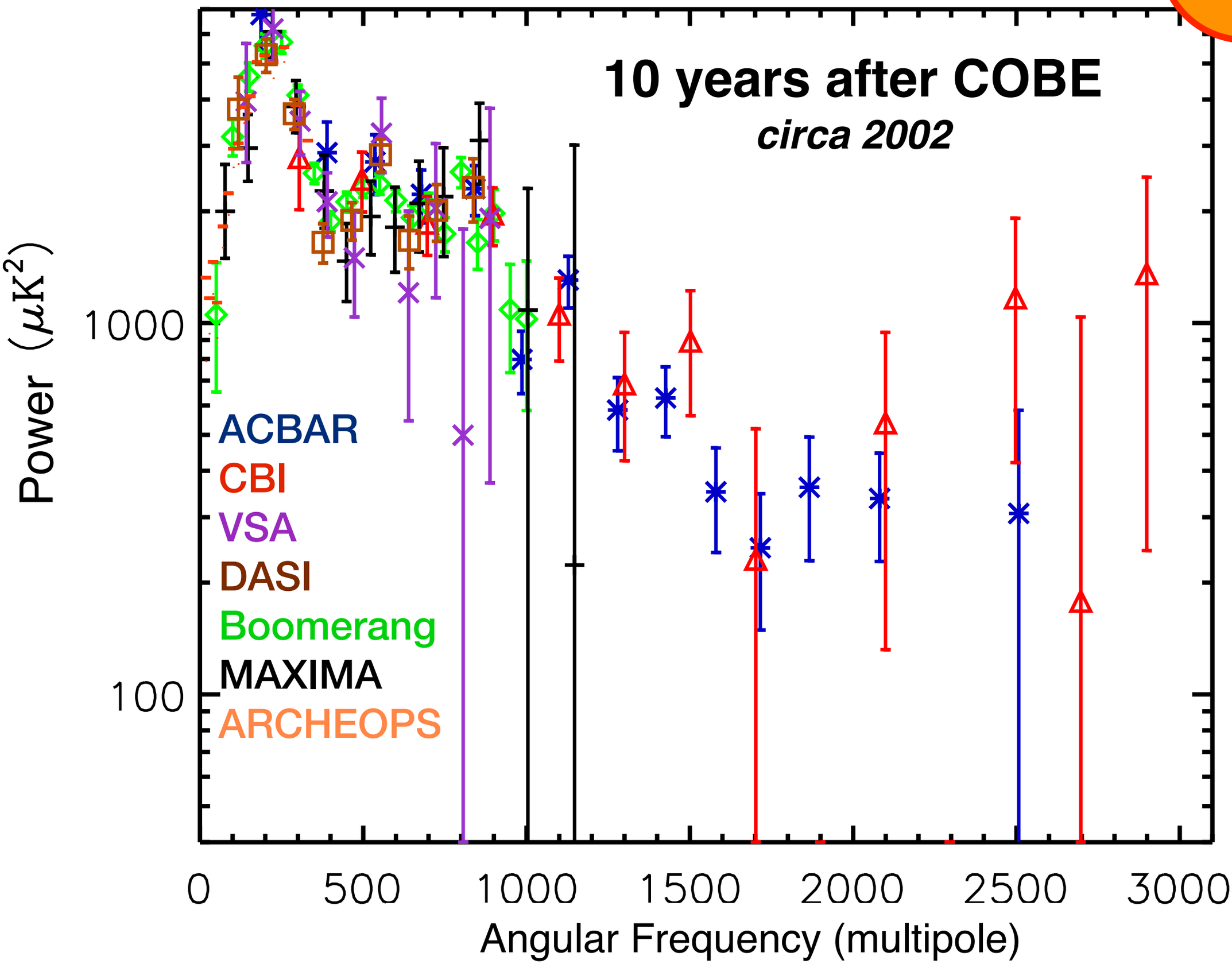
BOOMERanG

Maxima

CBI

Experimental Progress

12 yrs ago



Experimental Progress

12 yrs ago

10 years after COBE

circa 2002

ACBAR
CBI
VSA
DASI
Boomerang
MAXIMA
ARCHEOPS

Power (μK^2)

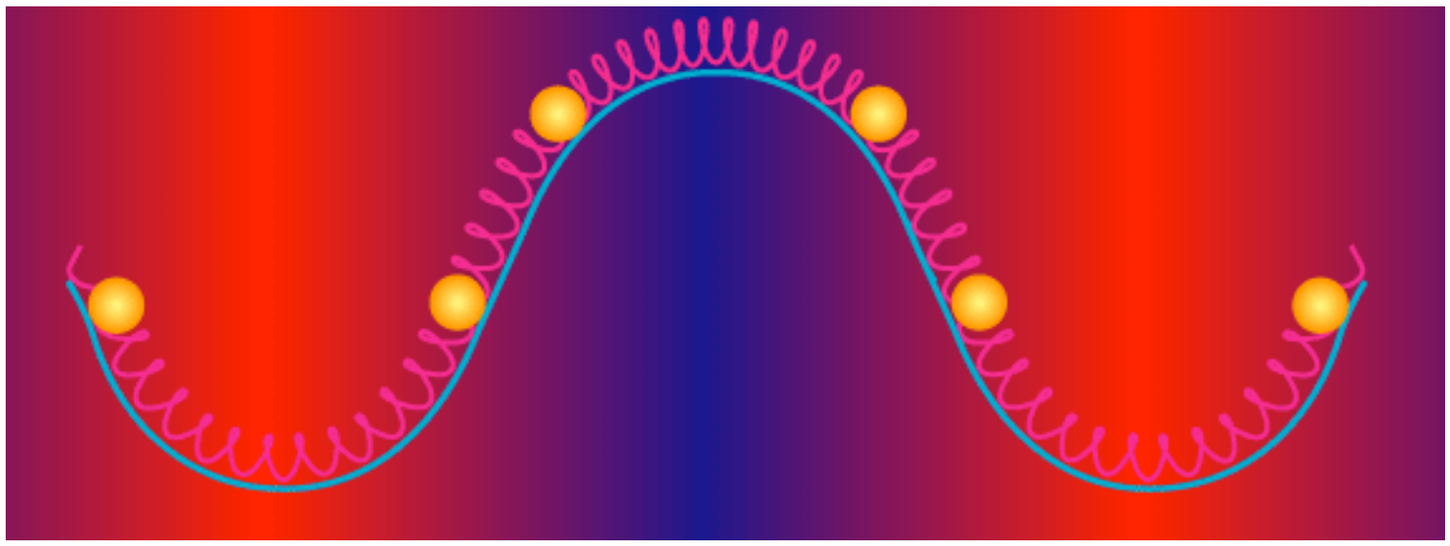
1000

100

0 500 1000 1500 2000 2500 3000

Angular Frequency (multipole)

Acoustic Oscillations



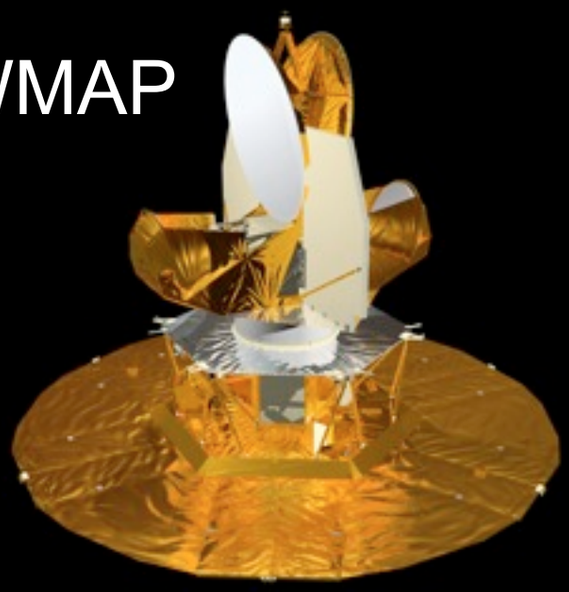
from Wayne Hu's web site

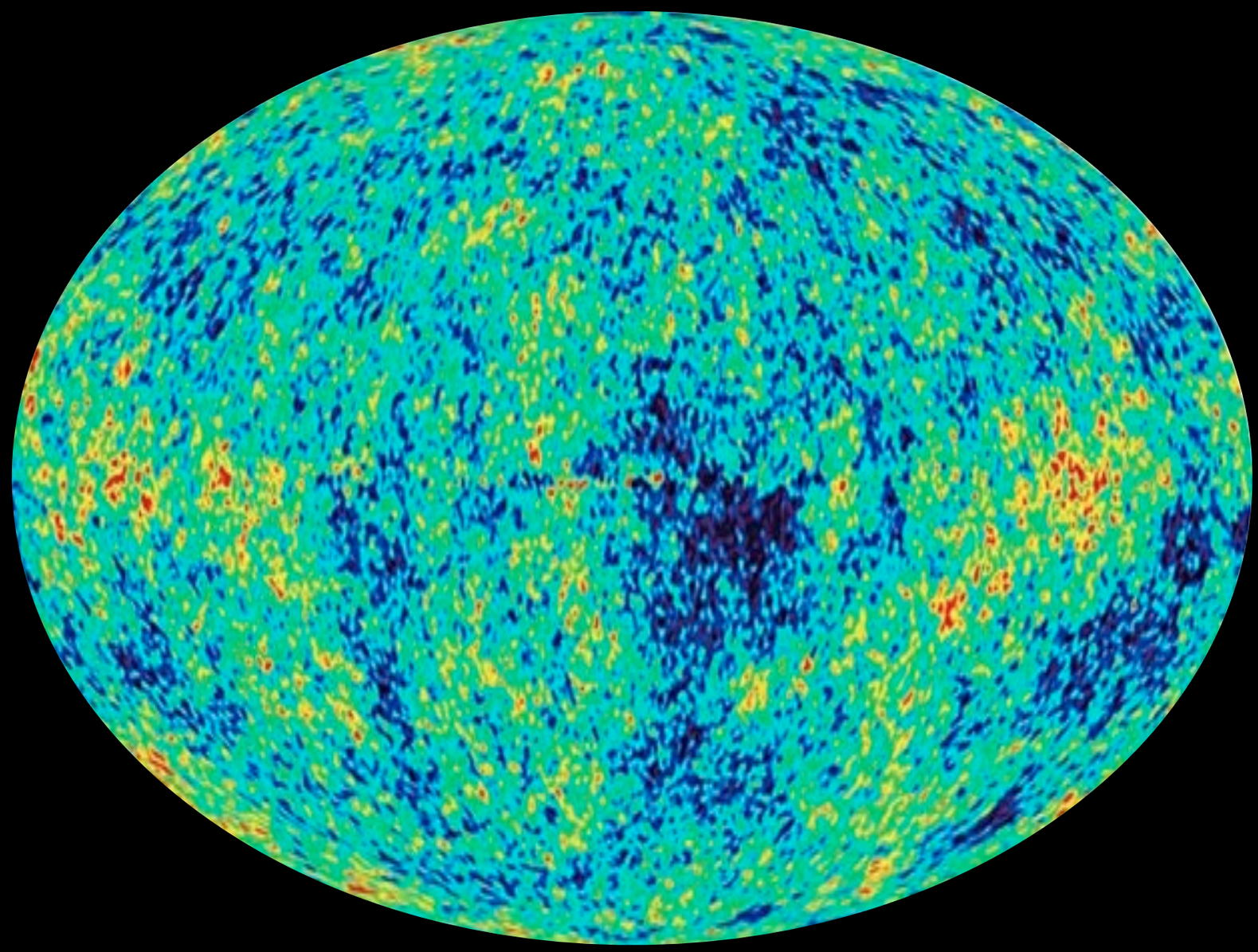
Wilkinson Microwave Anisotropy Probe (WMAP)

10 yrs ago

David Wilkinson
1935-2002

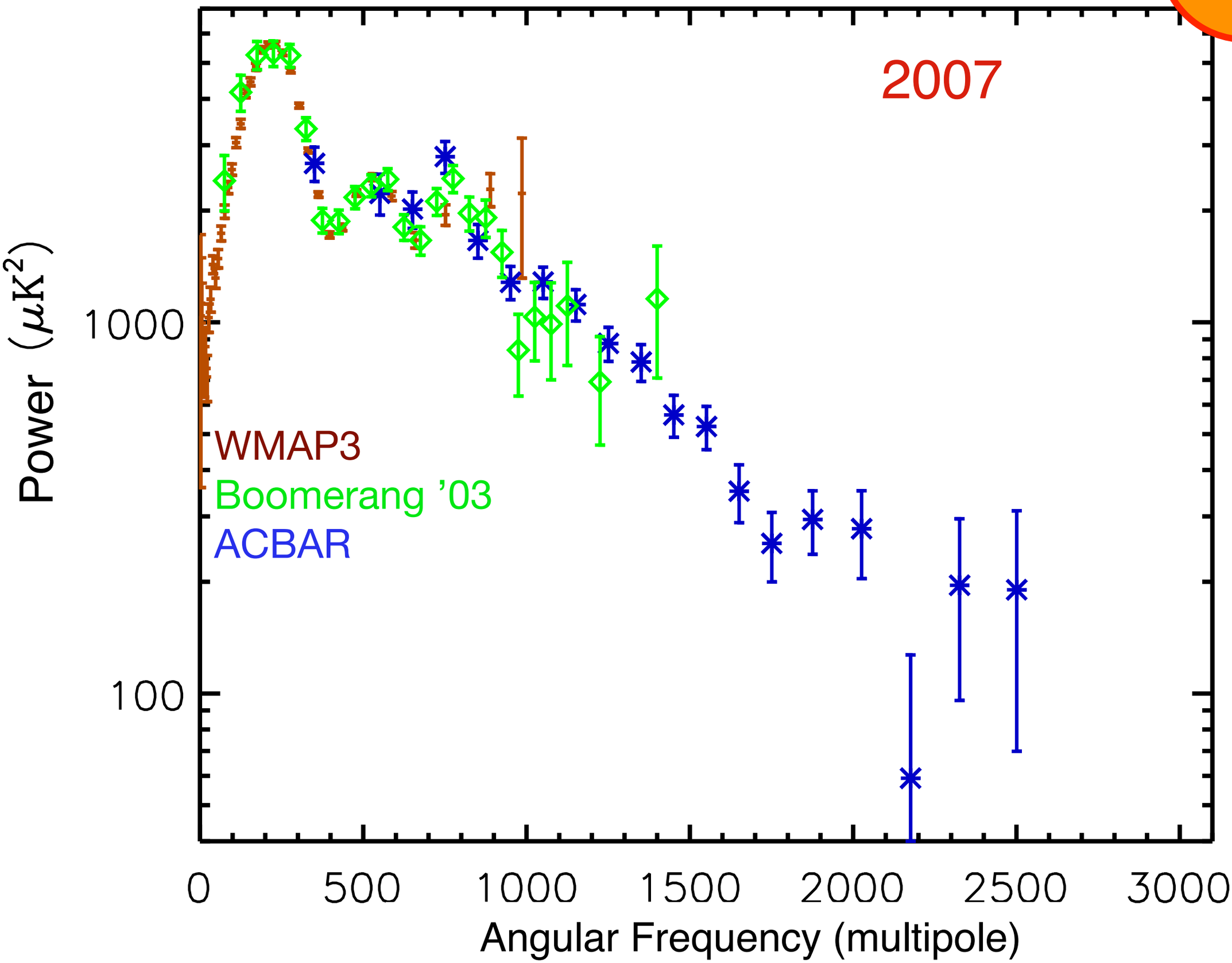
WMAP





Strong Experimental Progress

5 yrs ago



ACT and SPT

Dedicated Telescopes for fine angular scale
CMB temperature and polarization

6m Atacama Cosmology Telescope
http://www.physics.princeton.edu/act/

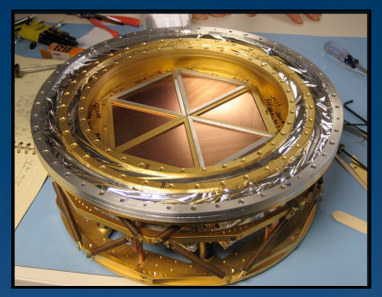
10m South Pole Telescope
http://pole.uchicago.edu

- Exceptional high and dry sites for dedicated CMB observations.
- Exploiting ongoing revolution in low-noise bolometer cameras

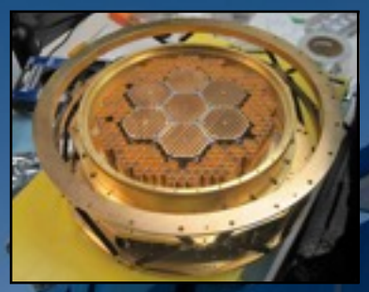
The South Pole Telescope (SPT)

- 10-meter sub-mm quality wavelength telescope
- At **100**, **150**, **220** GHz, angular resolution of **1.6**, **1.2**, **1.0** arcmin

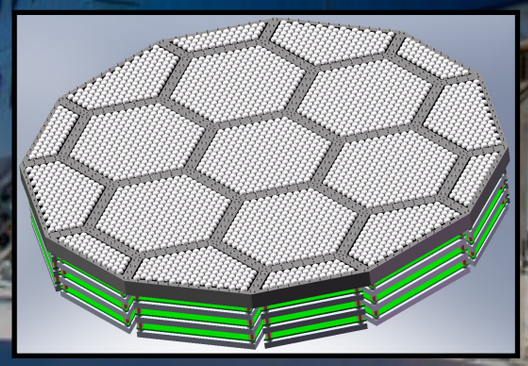
2007: SPT-SZ
960 detectors (UCB)
100,150,220 GHz



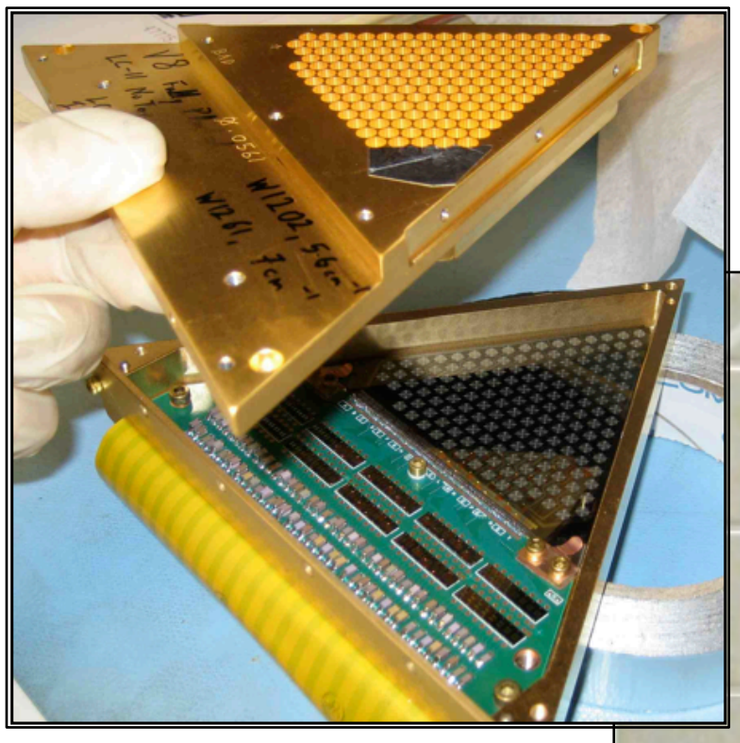
2012: SPTpol
1600 detectors
100,150 GHz
+Polarization

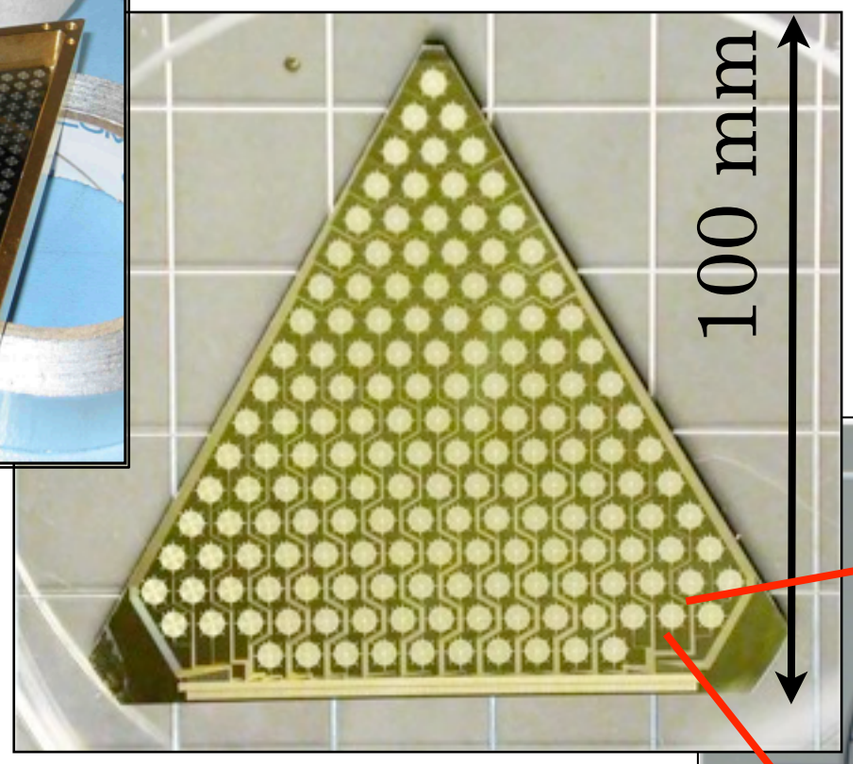


2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization

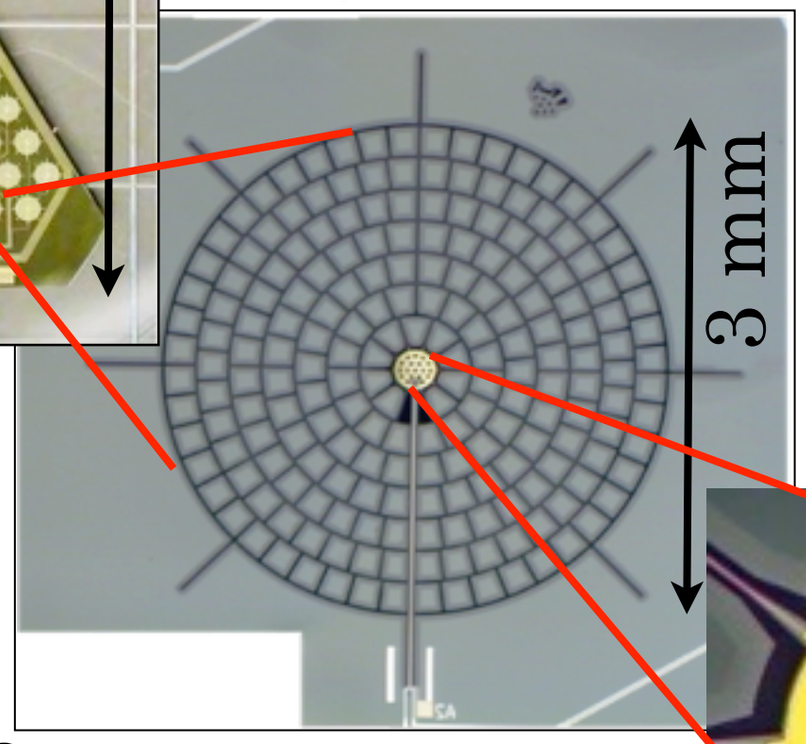


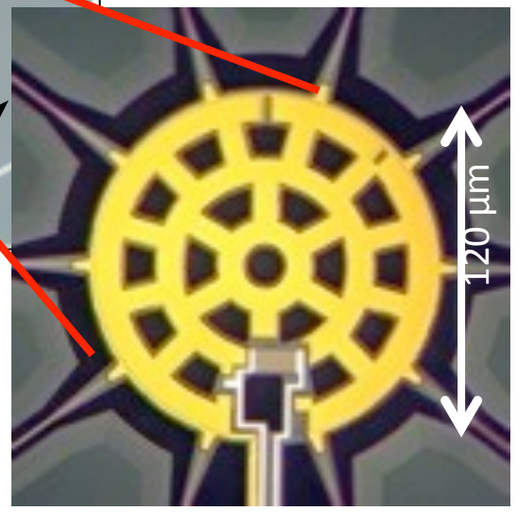
SPT-SZ Bolometer Array





Fabricated by Erik Shirokoff and Sherry Cho at UC-Berkeley





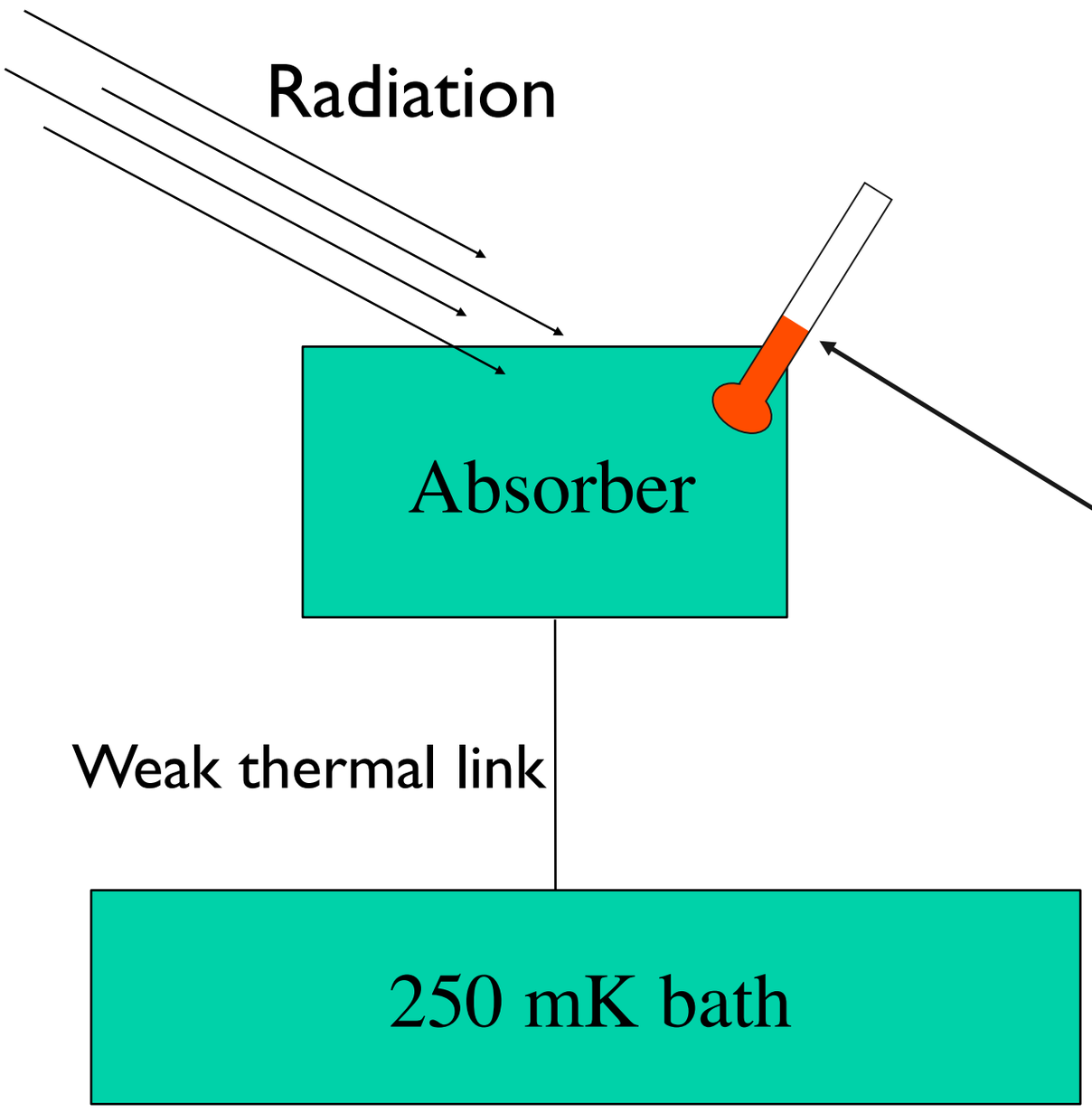
160 pixel bolometer array

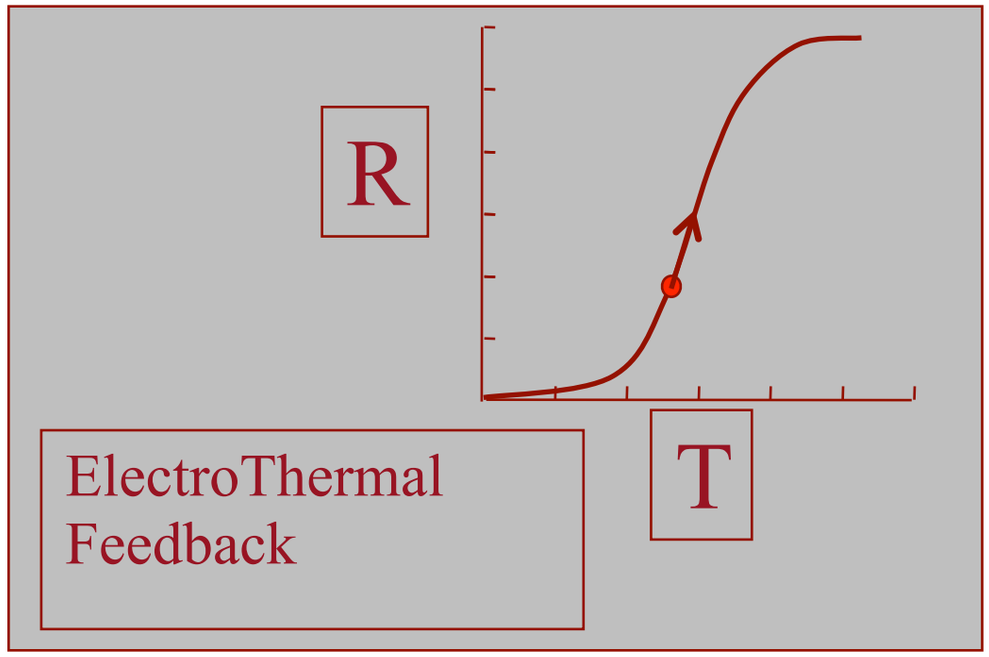
SiN substrate with gold absorber

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!

The South Pole Telescope Collaboration

Funded By:

Funded by:

Argonne NATIONAL LABORATORY

Berkeley Lab

Cardiff University

Prifysgol Caerdydd

NIST

SLAC National Accelerator Laboratory

KICP Kavli Institute for Cosmological Physics at the University of Chicago

Berkeley University of California

Case Western Reserve University

McGill

Colorado University of Colorado at Boulder

Stanford University

The University of Chicago

LMU Ludwig-Maximilians-Universität München

Harvard-Smithsonian Center for Astrophysics

UC Davis University of California

Fermilab

U.S. Department of Energy

KAVLI

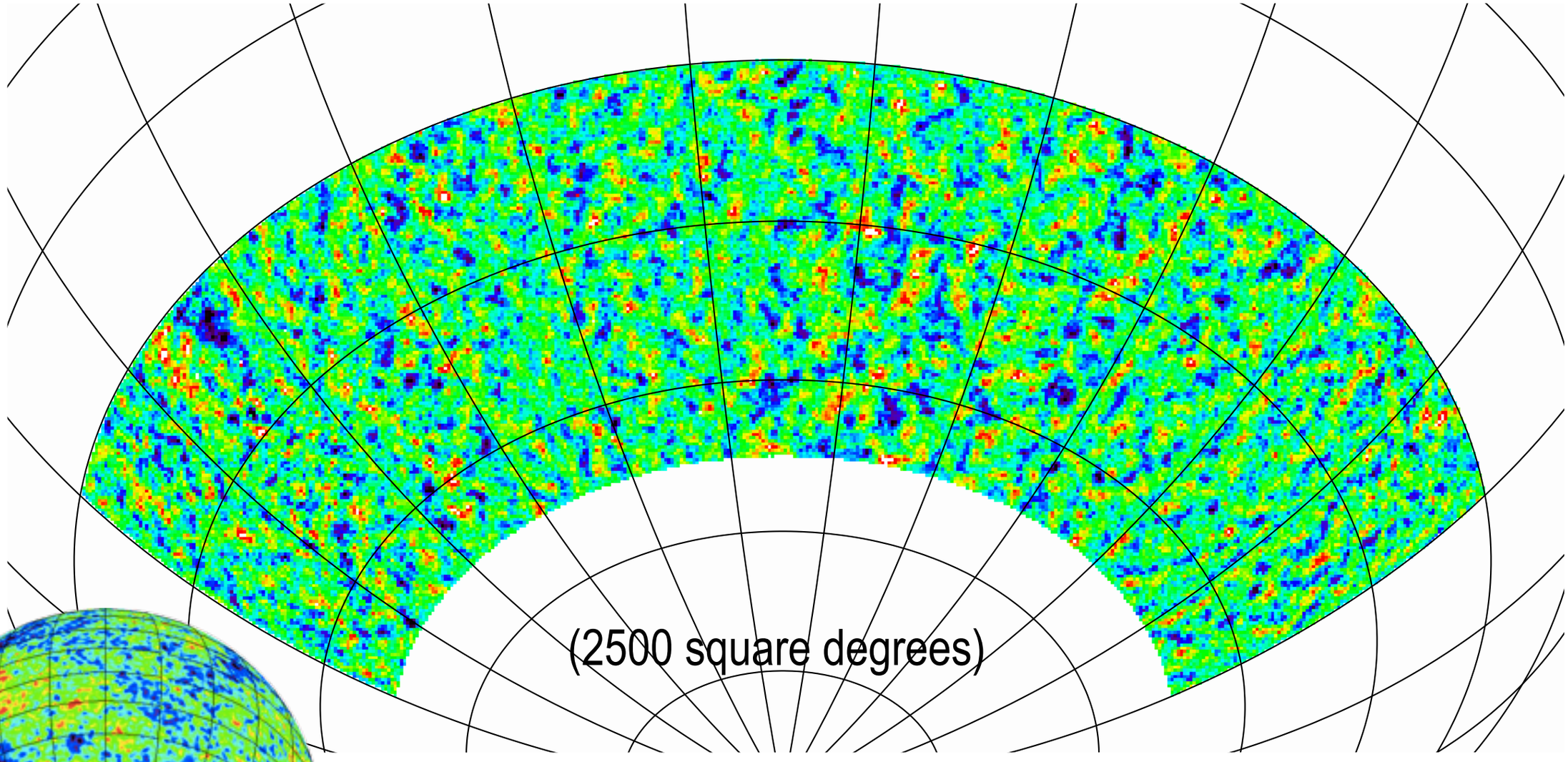
Gordon and Betty Moore Foundation

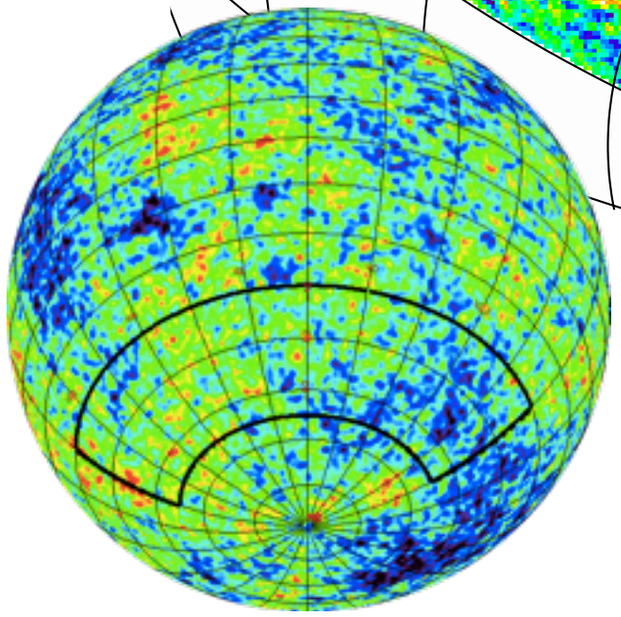
SPT has produced the

highest resolution and sensitivity map of the CMB

covering 1/16 of the sky

2 yrs ago



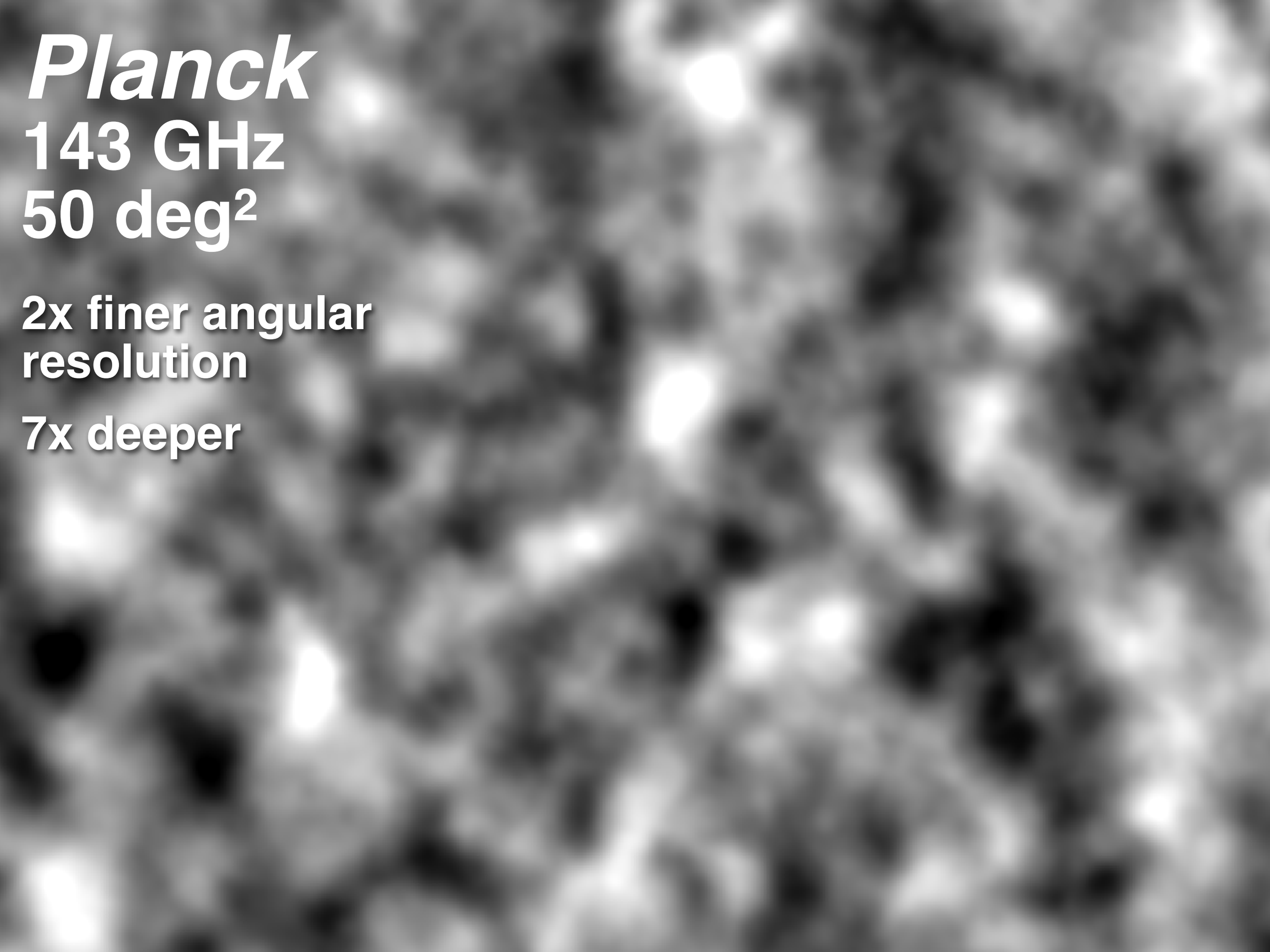


WMAP lower resolution full sky map with SPT area marked

Survey depths:

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

WMAP
94 GHz
50 deg^2

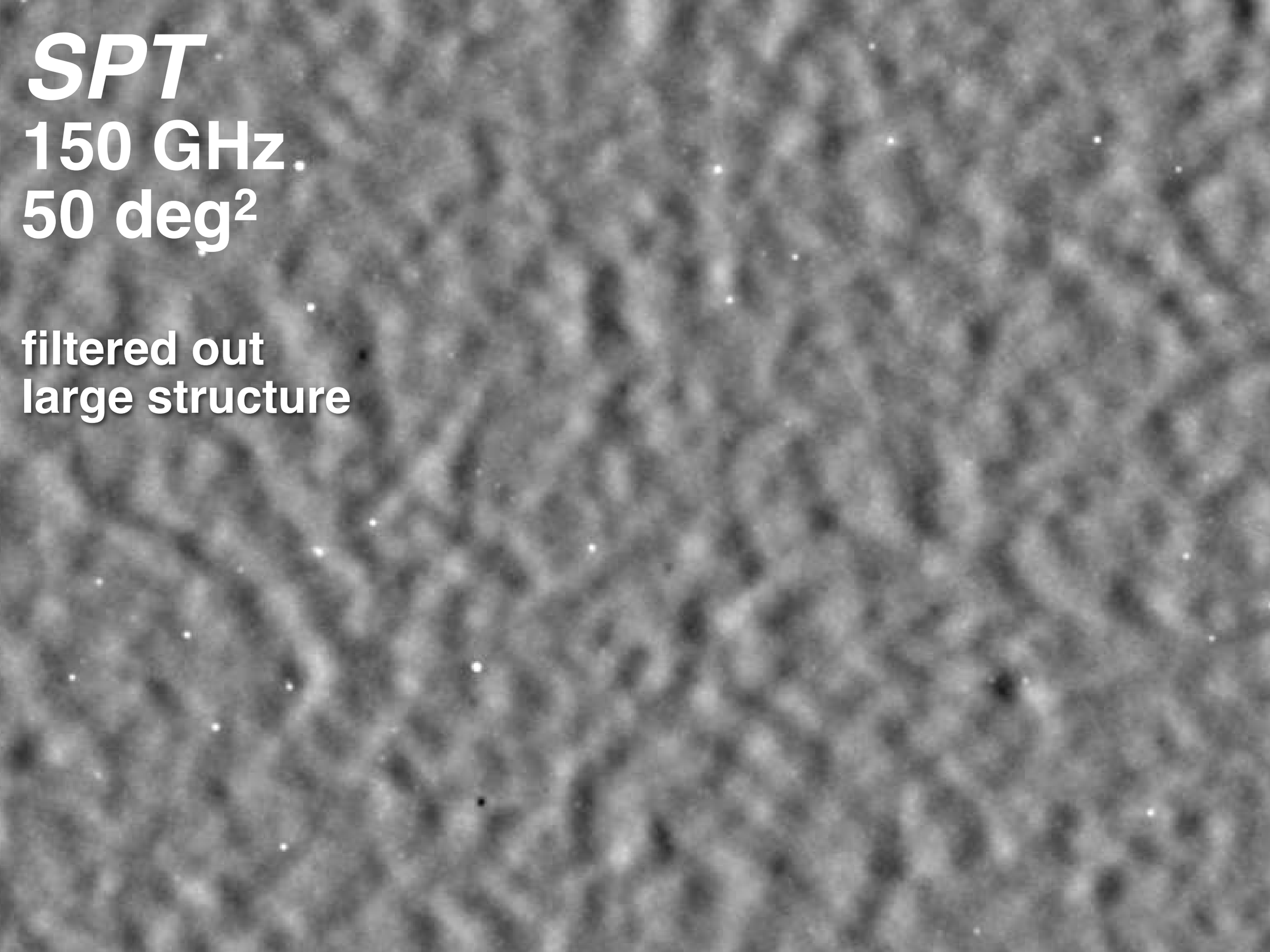

Planck
143 GHz
50 deg²
2x finer angular resolution
7x deeper

SPT

150 GHz
50 deg^2

13x finer angular resolution

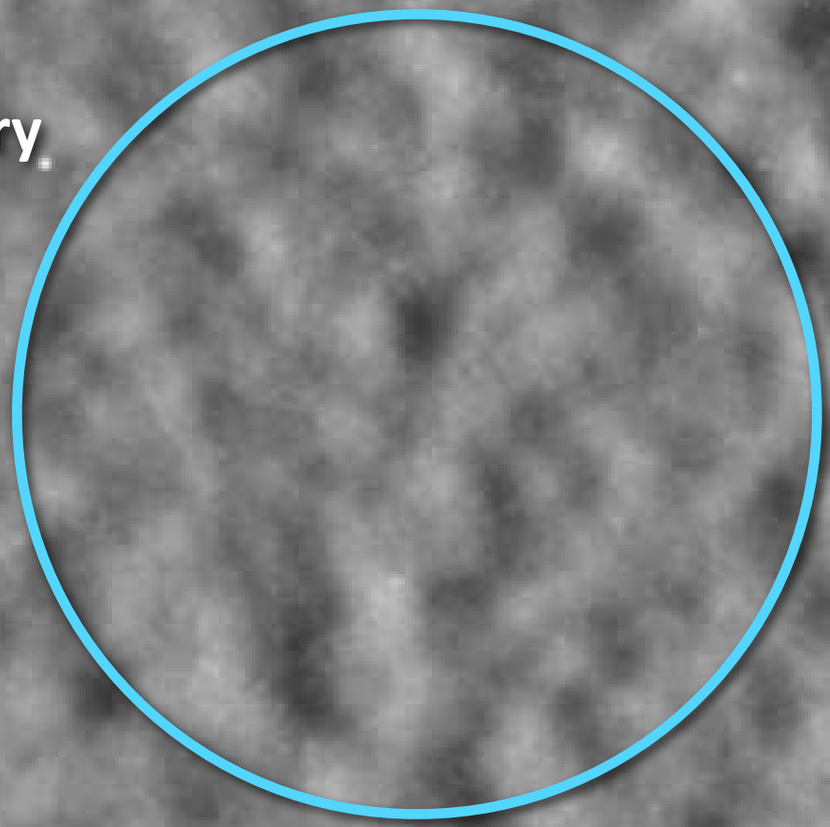
50x deeper


SPT
150 GHz
50 deg²
filtered out
large structure

SPT
150 GHz
50 deg^2

CMB Anisotropy

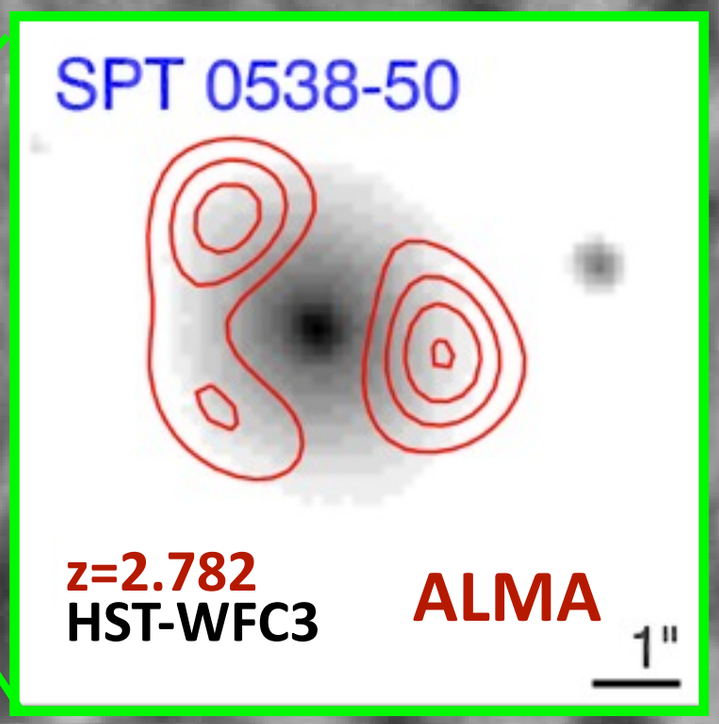
Primordial and secondary anisotropy in the CMB

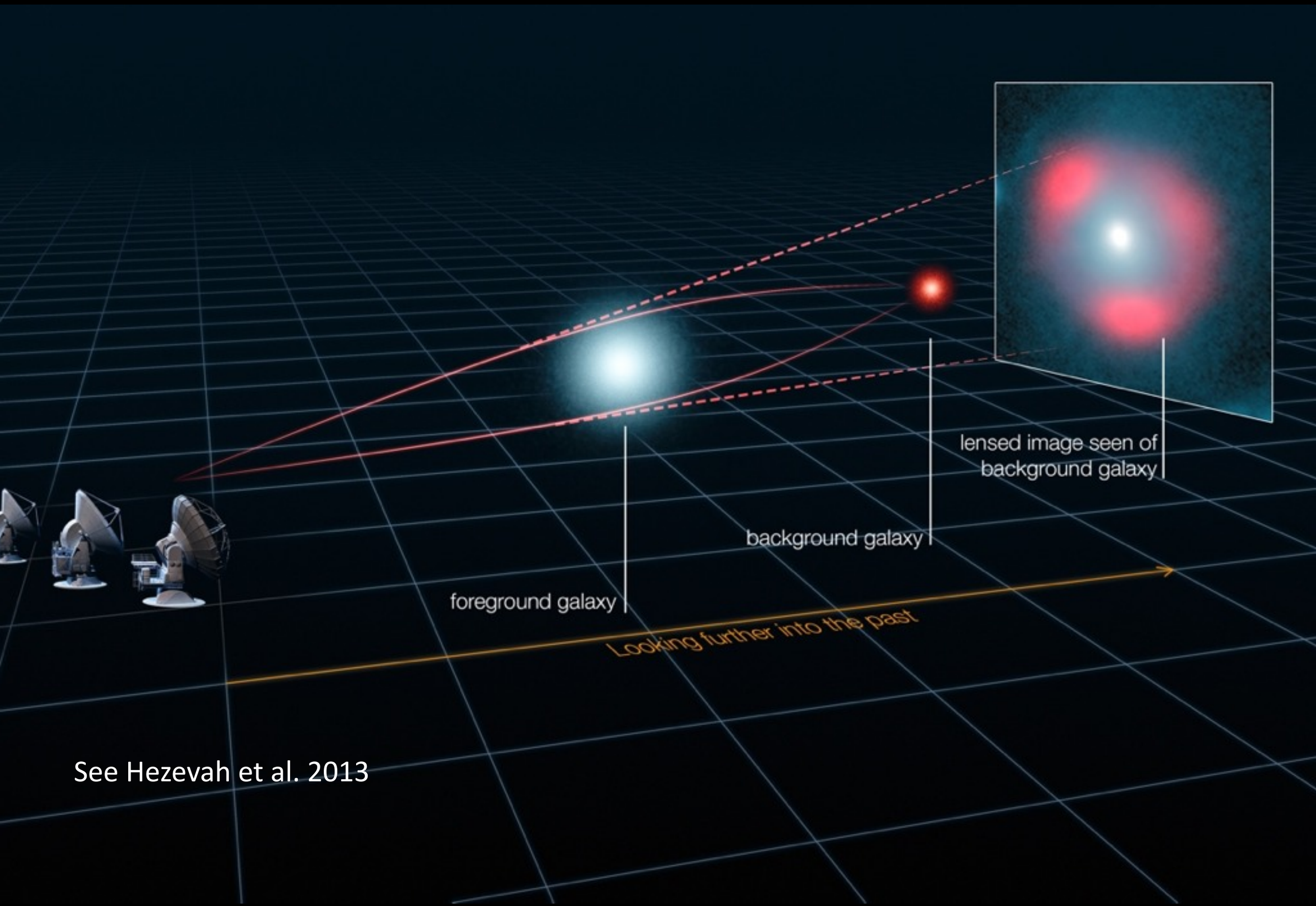


SPT
150 GHz
50 deg^2

Point Sources

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



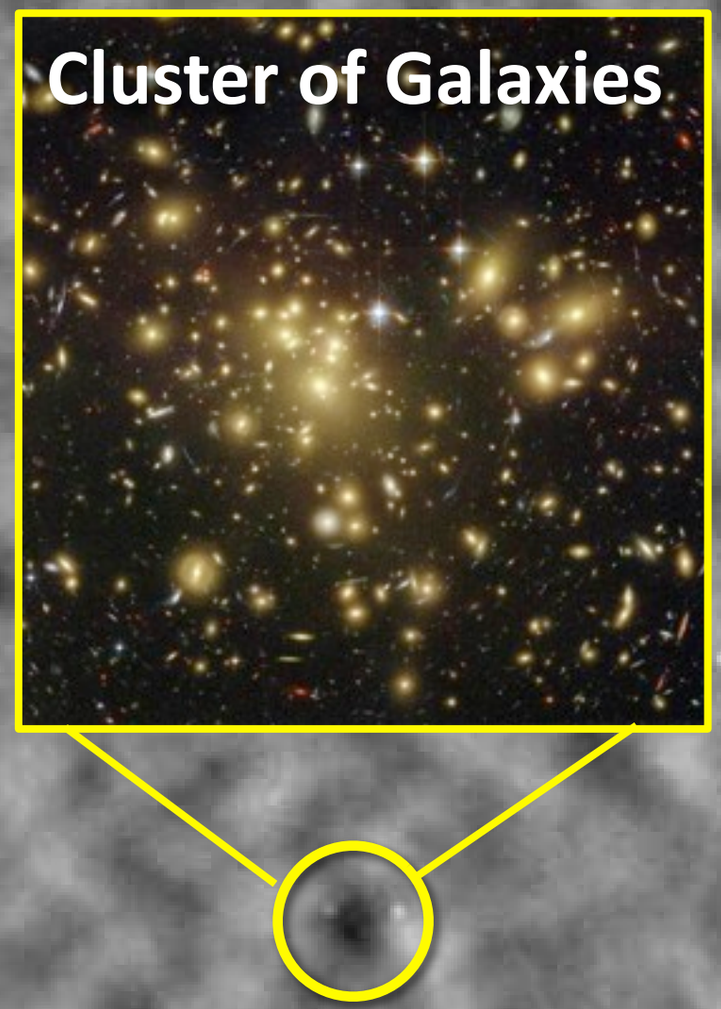


See Hezevah et al. 2013

SPT
150 GHz
50 deg²

Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies



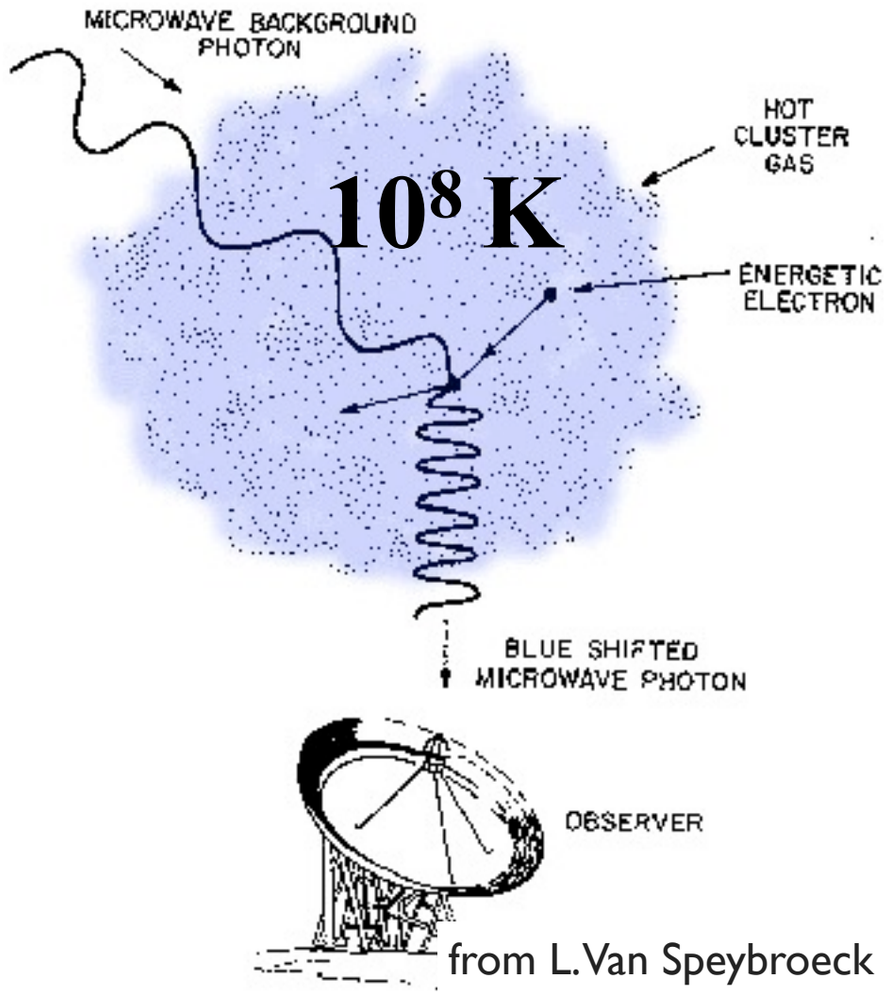
Sunyaev-Zel'dovich (SZ) Effect

CMB photons provide a backlight for structure in the universe.

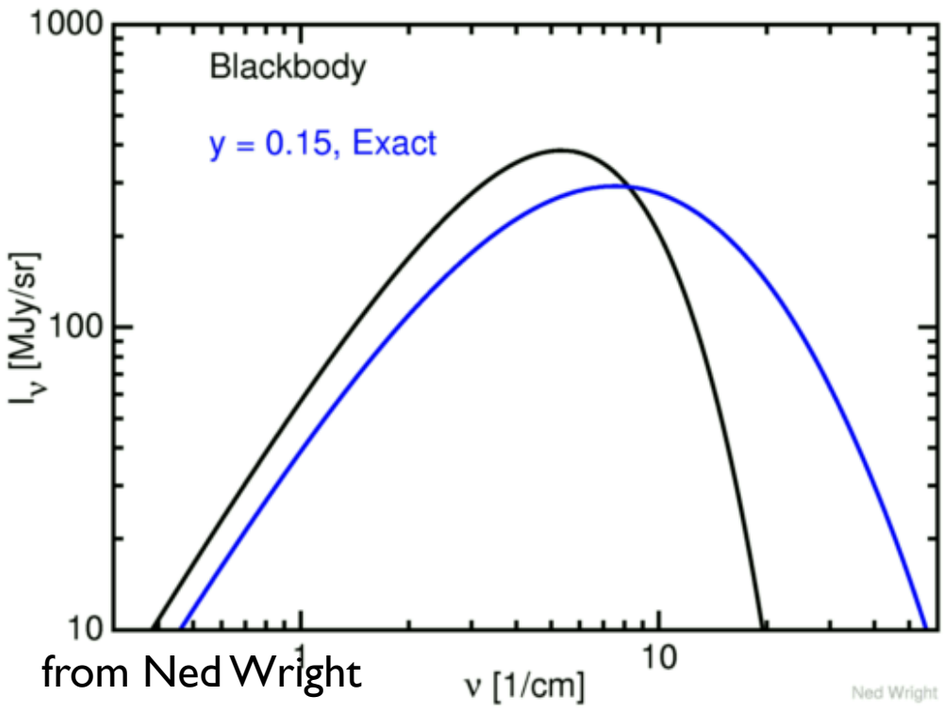
~1% of CMB photons traversing a massive galaxy cluster scatter.

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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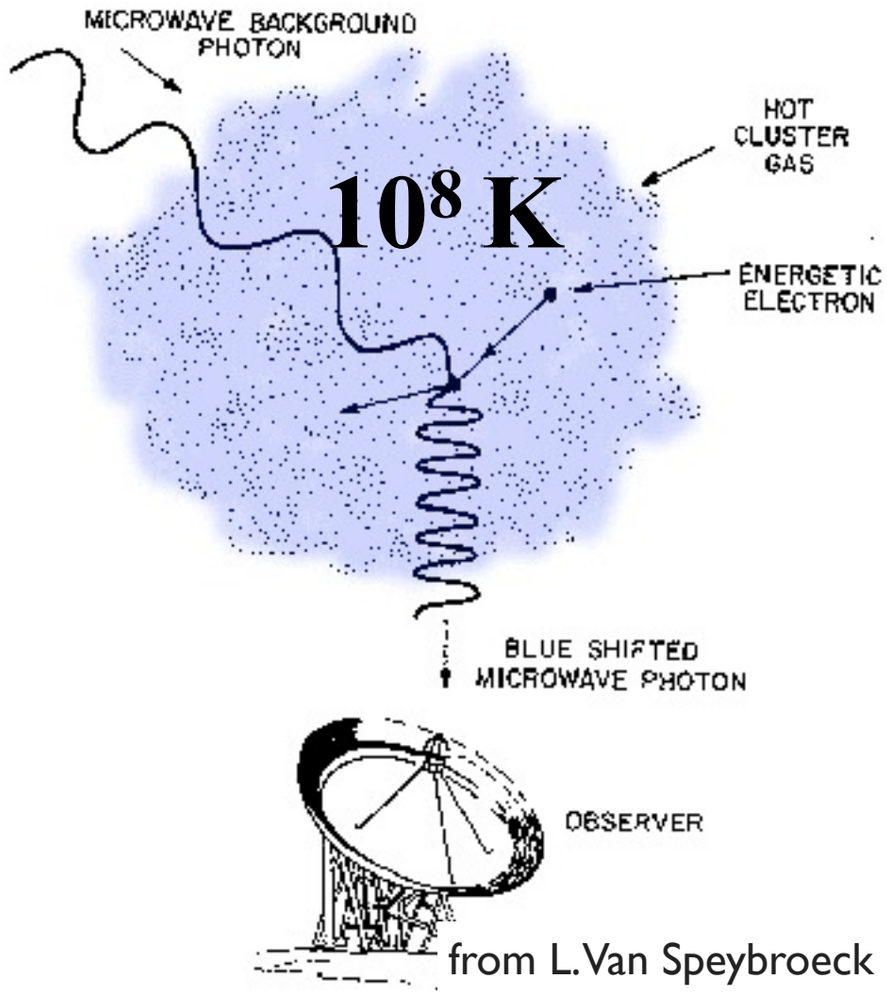

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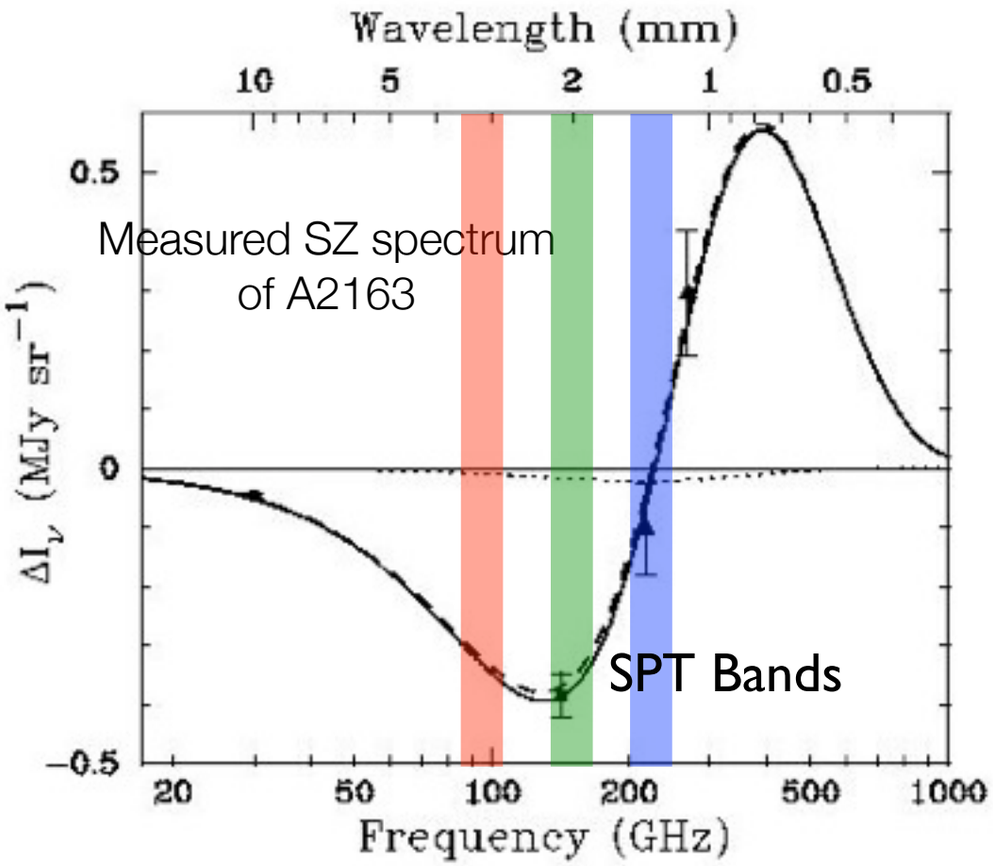

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Dark Energy and Cluster Cosmology

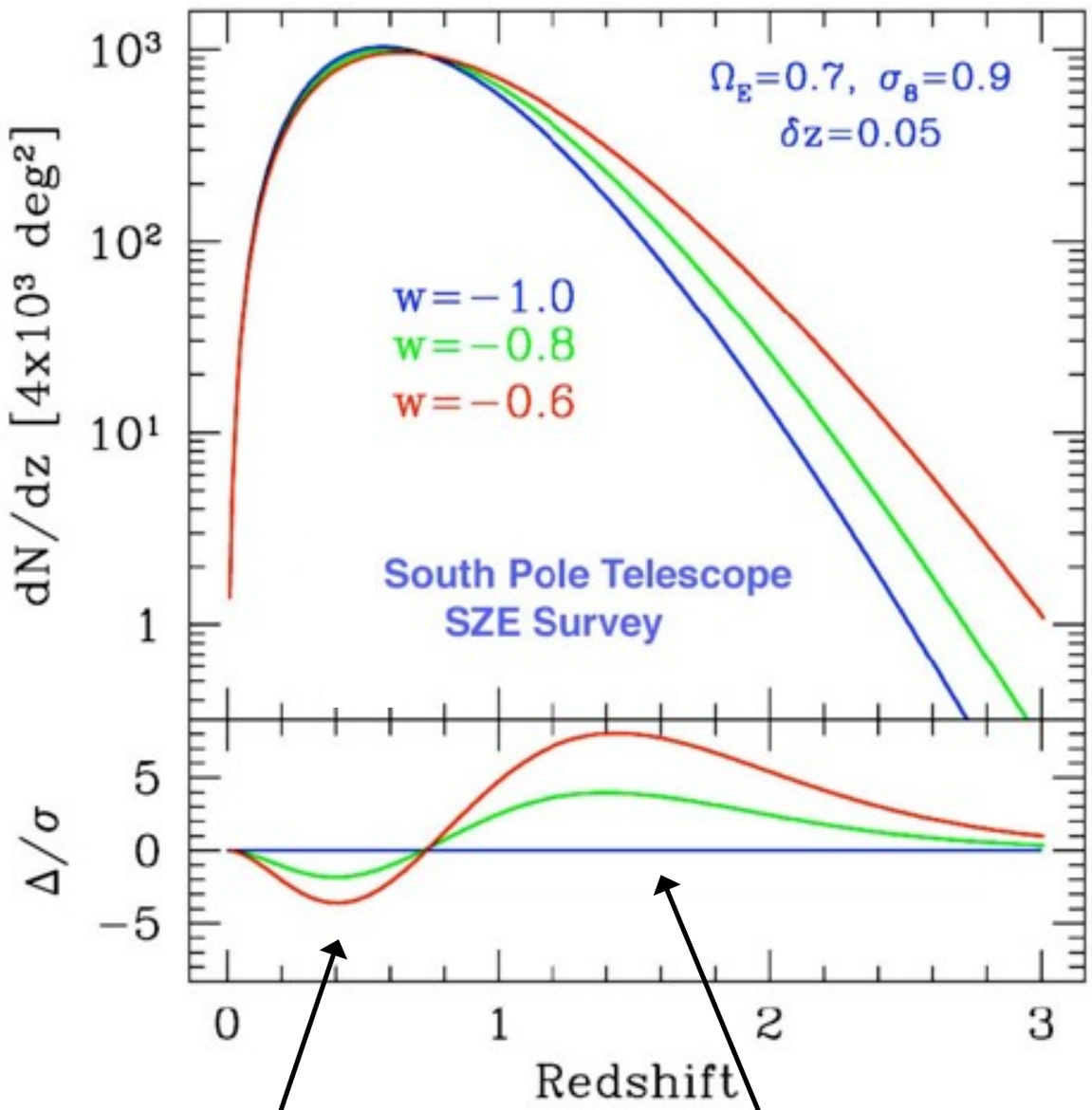
- Abundance of clusters is sensitive to the **dark energy equation of state, $w = p/\rho$**
- If dark energy was due to a cosmological constant then **w = -1**

Cluster Abundance: dN/dz

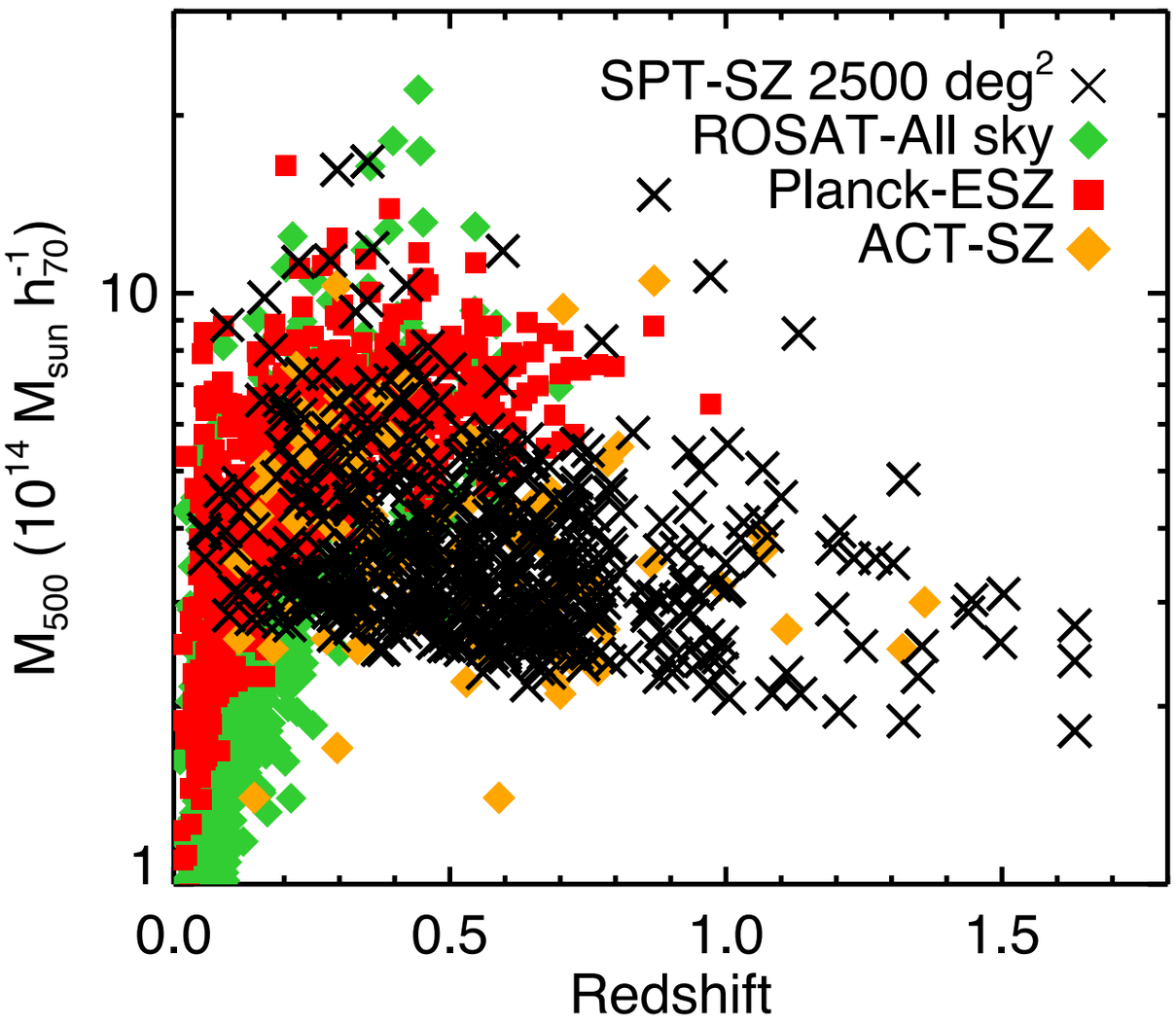
$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

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

Depends on:
Rate of Expansion, *H(z)*



SZ Cluster Surveys: Mass vs Redshift

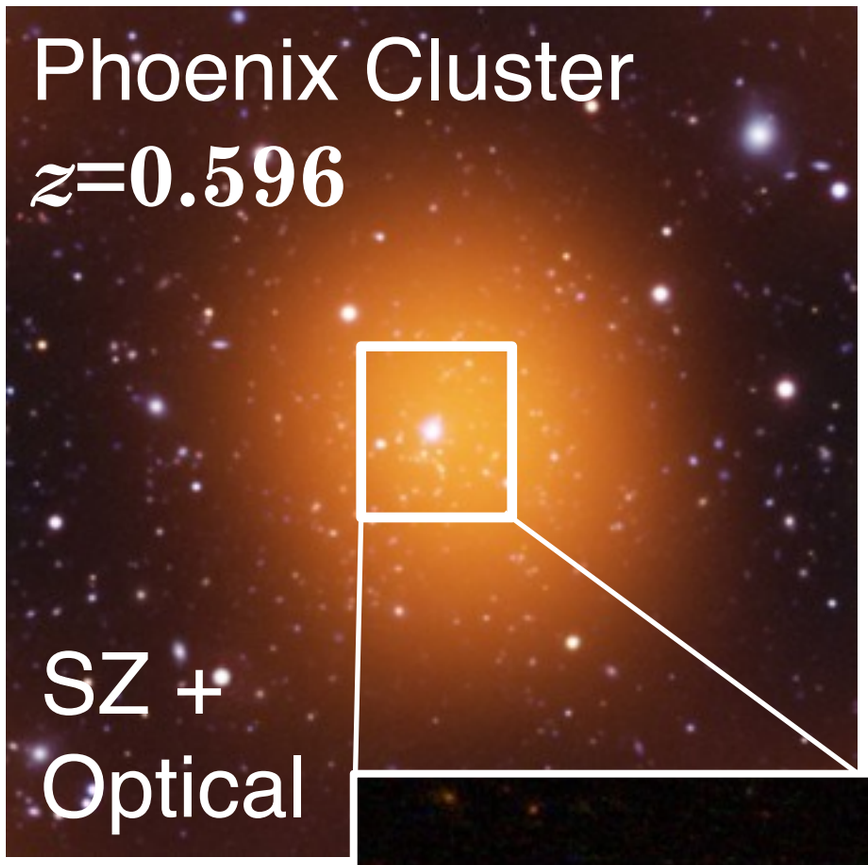


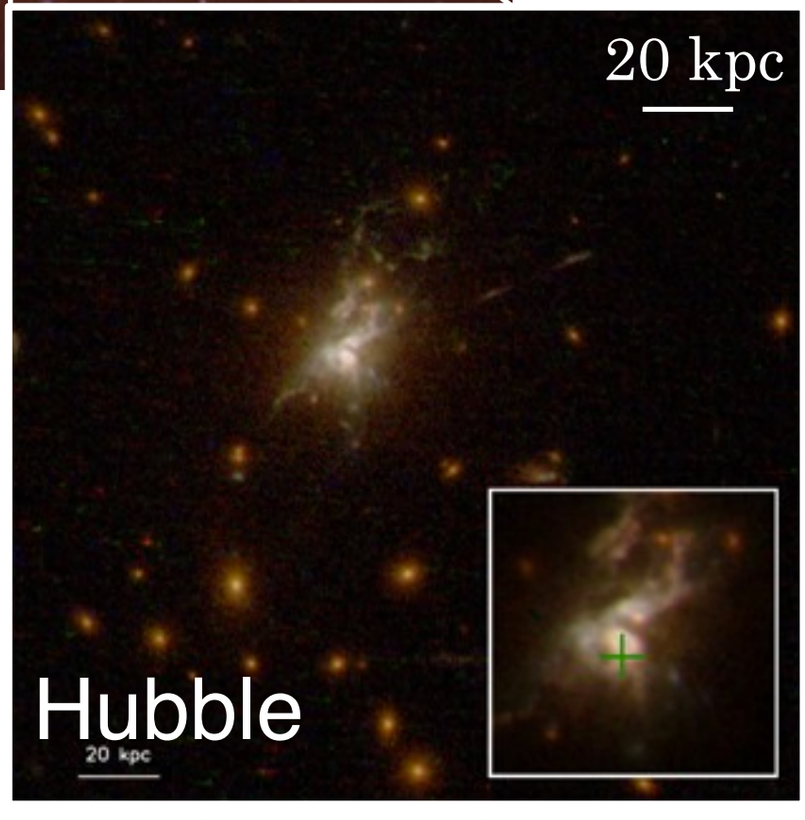
	Area (deg²)	Depth (uK-arcmin)	$N_{clusters}$
Planck	All-sky	45	861
SPT	2500	17	508
ACT	950	23-40	91

- The SZ effect uniquely finds all the massive, high-redshift clusters along the line of sight in the observable universe.
- ***First SZ-discovered cluster found in 2008*** *(SPT, Staniszewski et al)*
- ***SPT has more than doubled the number of z > 0.5 massive clusters***

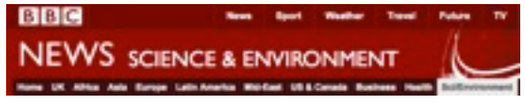
Lots of discoveries.

E.g., SPT-CL J2344-4243: *The "Phoenix Cluster"*





- **Most X-ray luminous cluster known**
- **Largest star formation rate observed in a cluster's brightest central galaxy**: (~800 +/- 40 Msun / year)
- **Star formation efficiency of ~30%;** "classical" X-ray cooling rate of 2850 Msun / year is efficiently turning into stars



Galaxy cluster's 'starburst' surprises astronomers

Astronomers have seen a huge galaxy cluster doing what until now was only theorised to happen: making new stars.

Most galaxy clusters - the largest structures in the Universe - are "red and dead", having long since produced all the stars they can make.

But cluster formation should, according to theory, include a cooling phase, resulting in blue light from new stars.

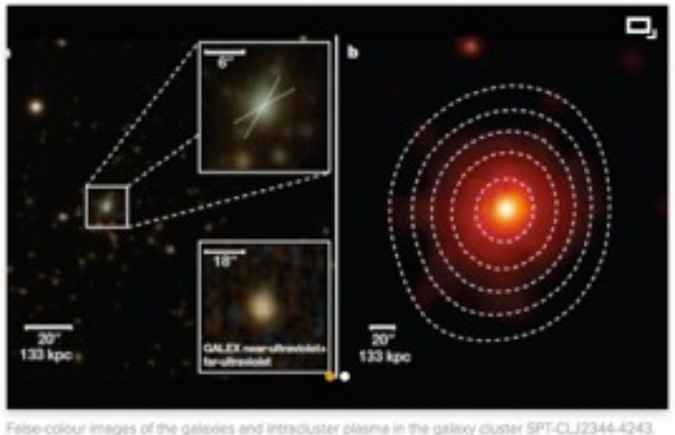
Writing in Nature, researchers say they have seen evidence that the enormous Phoenix cluster makes 740 stars a year.

In our own Milky Way, only one or two new stars are made each year.

The cluster, some seven billion light-years away, is formally called SPT-CL J2344-4243 but the researchers h for the constellation in which it lies.

AUG. 17, 2012

Massive "Phoenix Cluster" Supersizes Star Creation



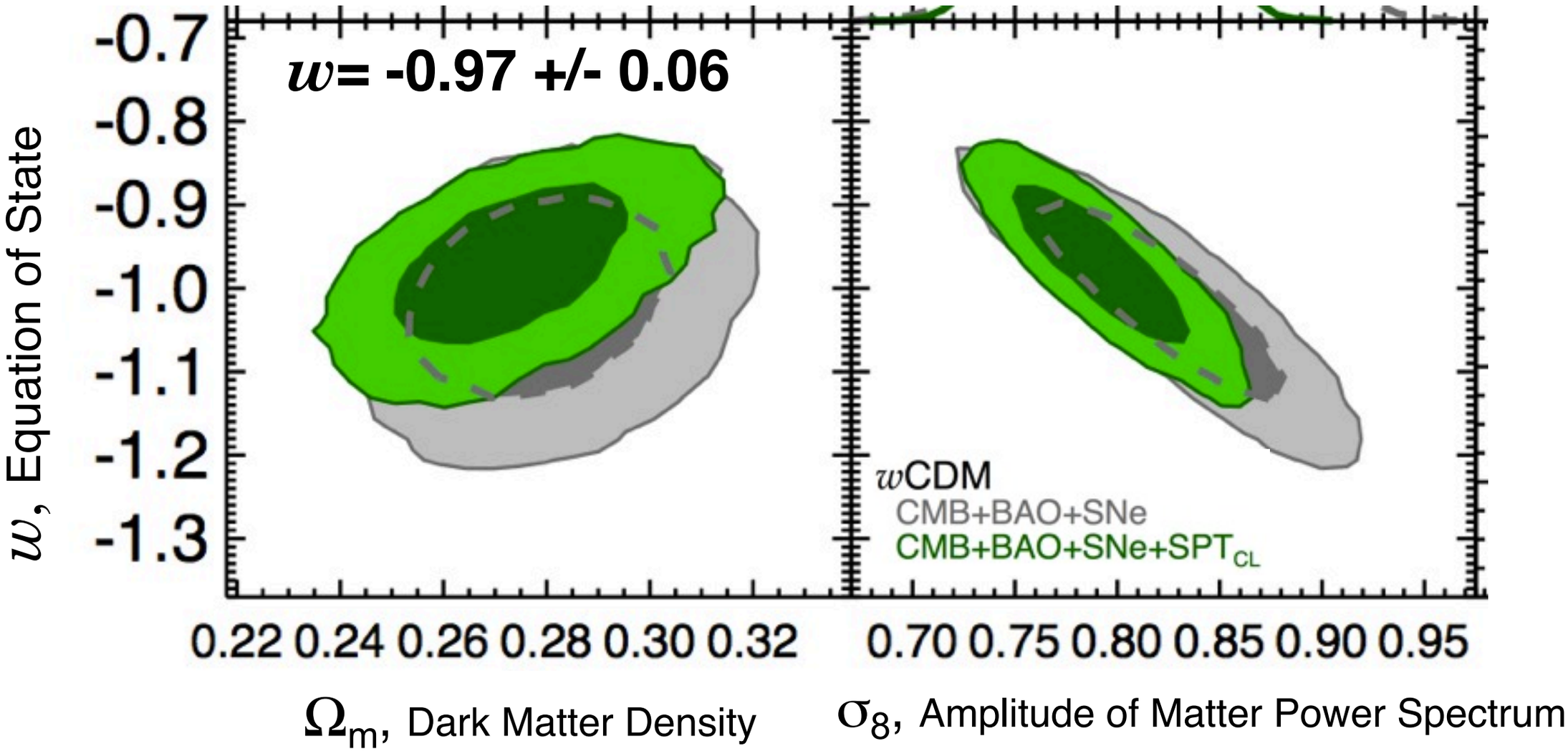
False-colour images of the galaxies and intracluster plasma in the galaxy cluster SPT-CL J2344-4243. Figure 1 of "A massive, cooling-flow-induced starburst in the core of a luminous cluster of galaxies" published in *Nature* Vol 488, 349-352 (August 16, 2012).

(SPT) McDonald et al. (2012, 2013)

Initial wCDM Constraints

Using only first ~5% of survey (18 clusters)

SPT$_{CL}$ data improved dark energy (w,Ω_m) constraints by factor of 1.5, but already limited by mass calibration



68, 95% Confidence Contours

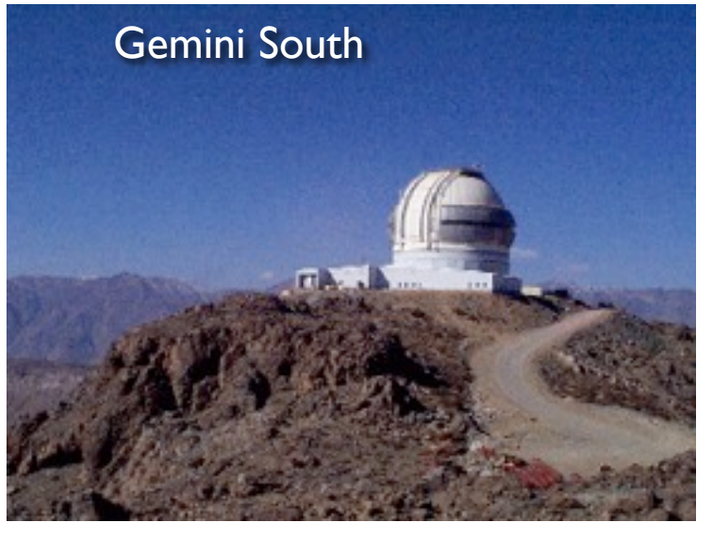
CMB: WMAP7 + SPT (Komatsu et al 2011, Keisler et al. 2011)
BAO: (Percival et al. 2010)
SNe: (Amanullah et al. 2010)

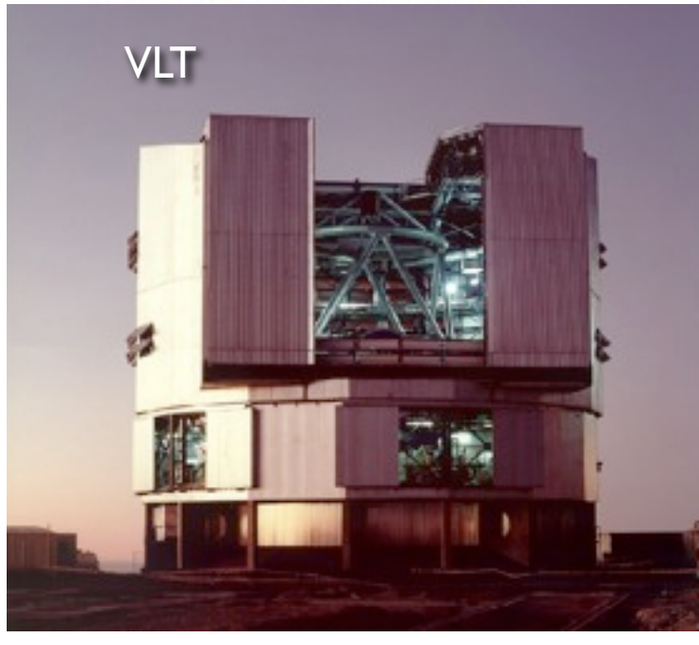
Benson et al 2011,
arXiv: 1112.5435

Mass Calibration

- **Multi-wavelength mass calibration campaign, including:**

1. **X-ray** with Chandra and XMM; 2.1 Msec 80 cluster Chandra XVP award, PI: Benson
2. **Weak lensing** from Magellan ($0.3 < z < 0.6$) HST ($z > 0.6$)
3. **Dynamical masses** from NOAO 3-yr survey on Gemini ($0.3 < z < 0.8$)(PI:Stubbs); VLT at ($z > 0.8$) (PI: Mohr)



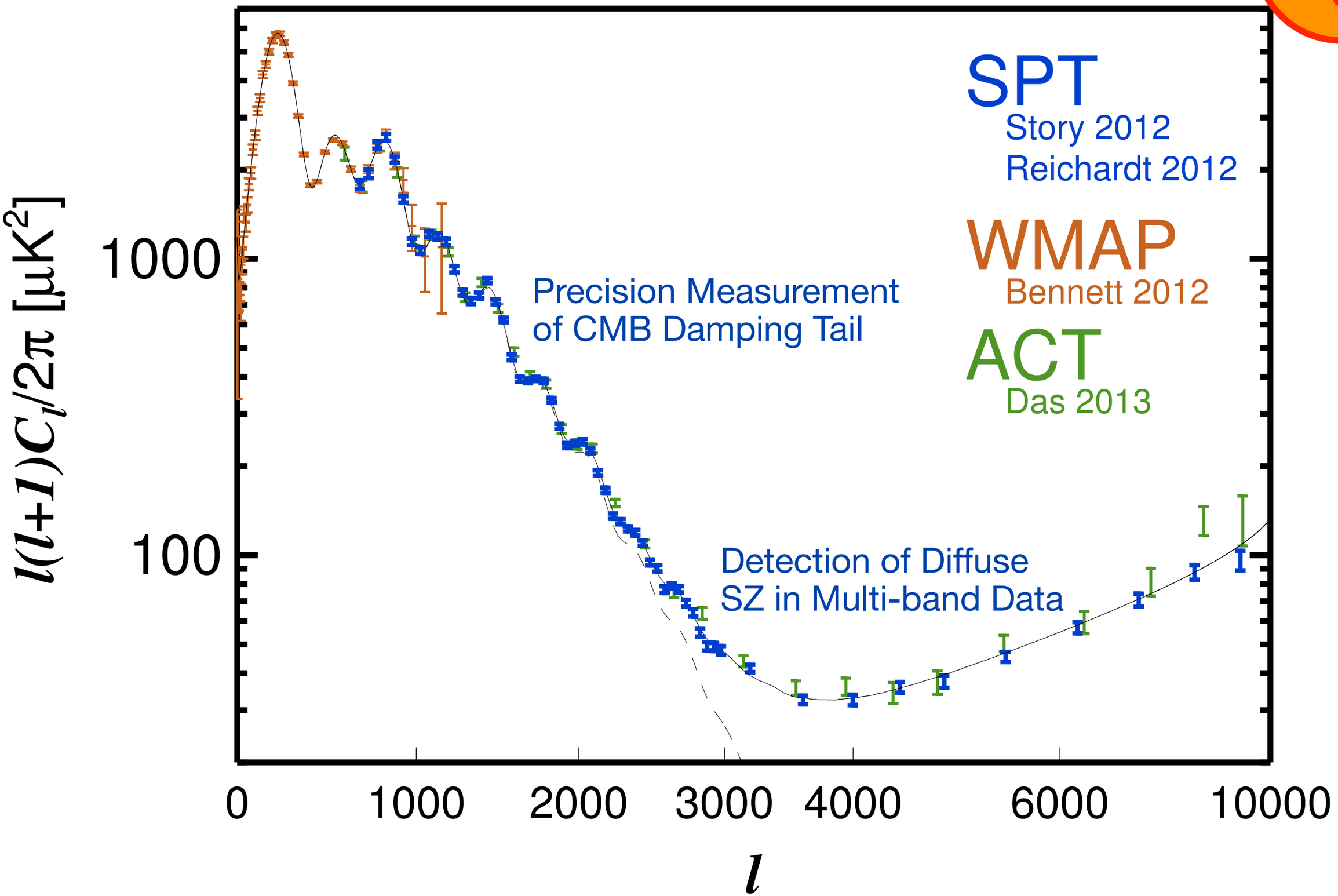


Dark Energy Survey (DES) and SPT

- 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)
- **The DES Survey began on August 31, 2013**
  - DES will detect ~100,000 clusters at $0 < z < 1$
  - ***Strong complementarity with SPT cluster survey and SPT CMB lensing; the combination will improve cluster constraints on dark energy by ~100x***

The "pre-Planck" CMB Power Spectrum

1 yr ago



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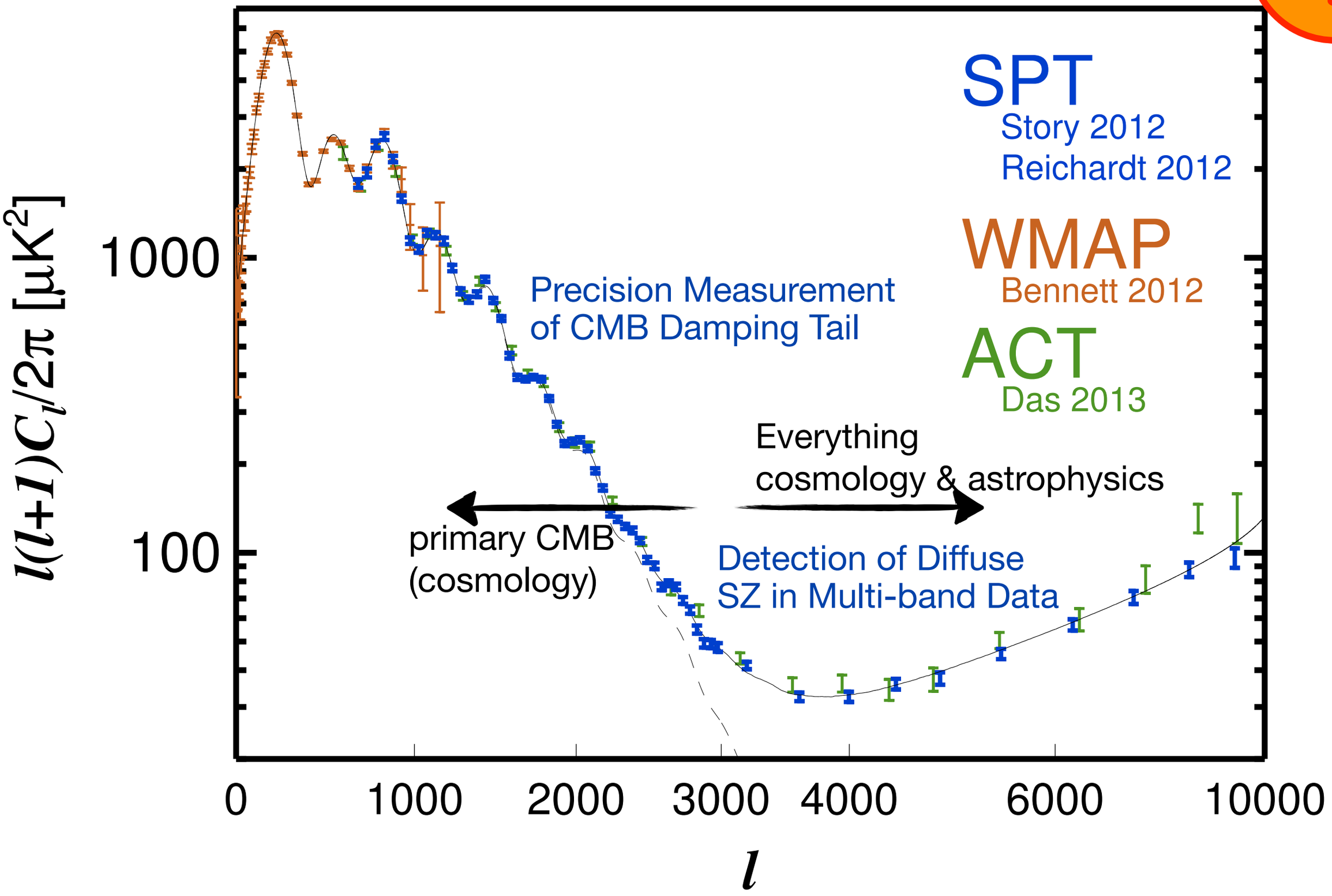
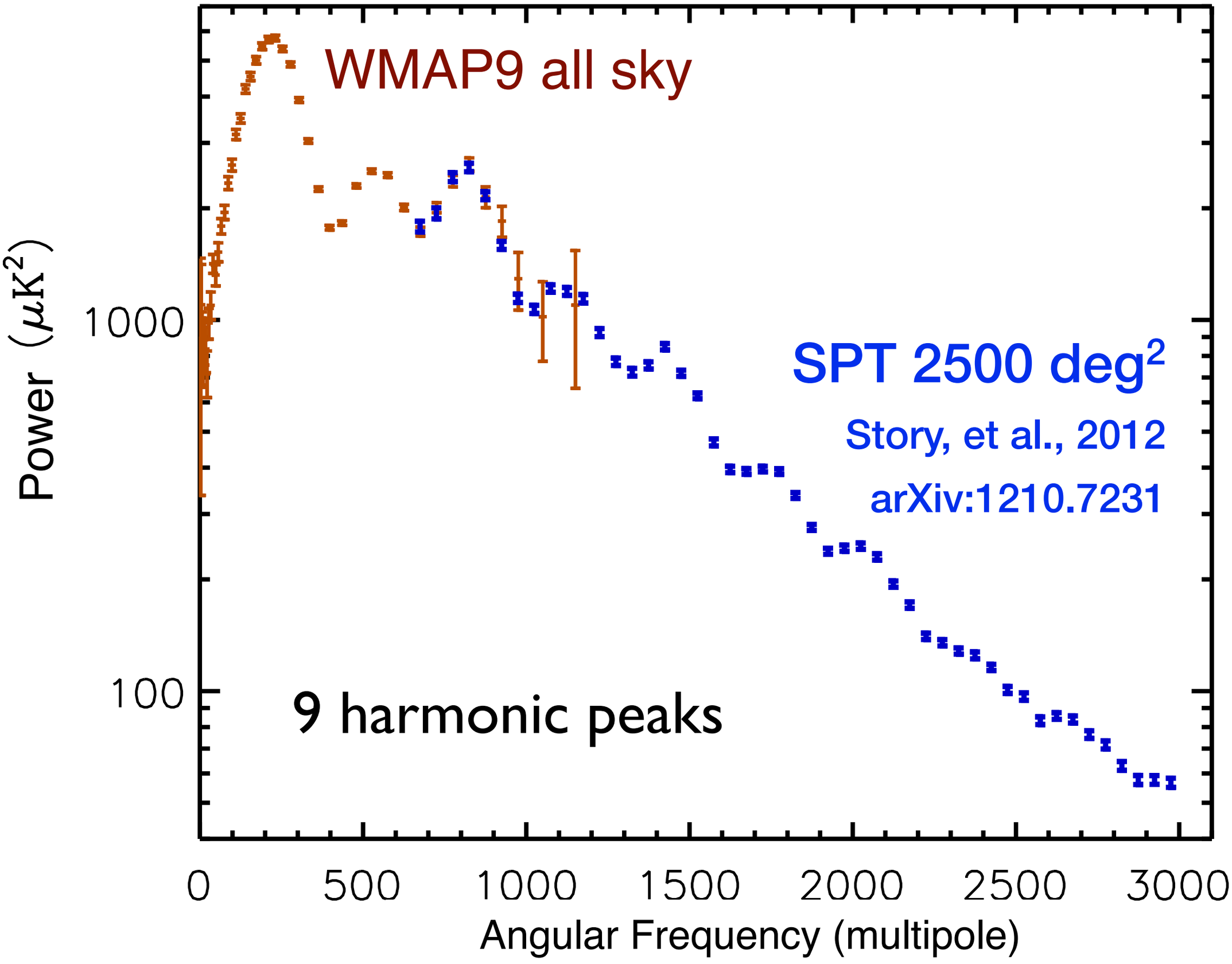
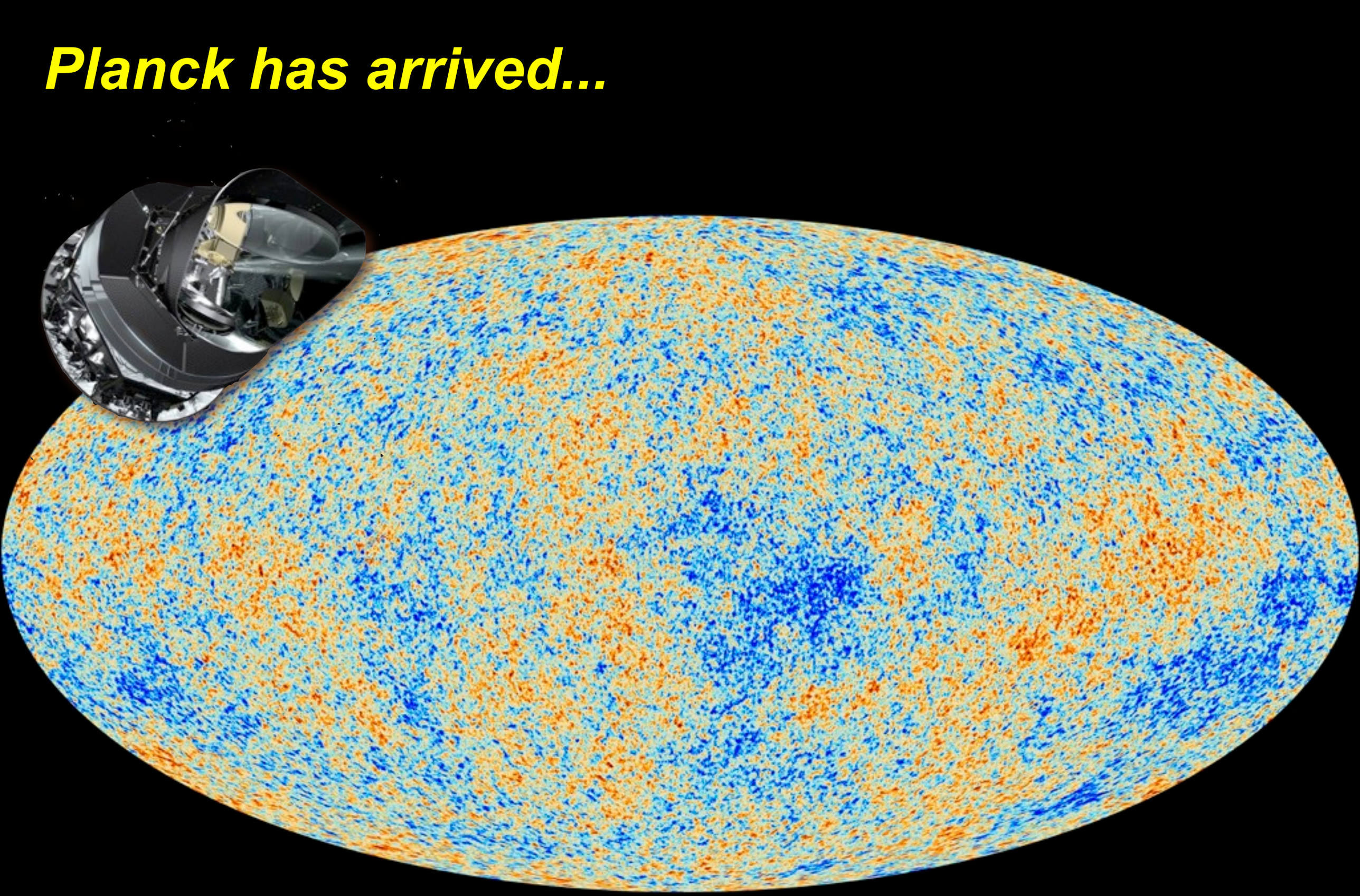


The "pre-Planck" CMB Power Spectrum

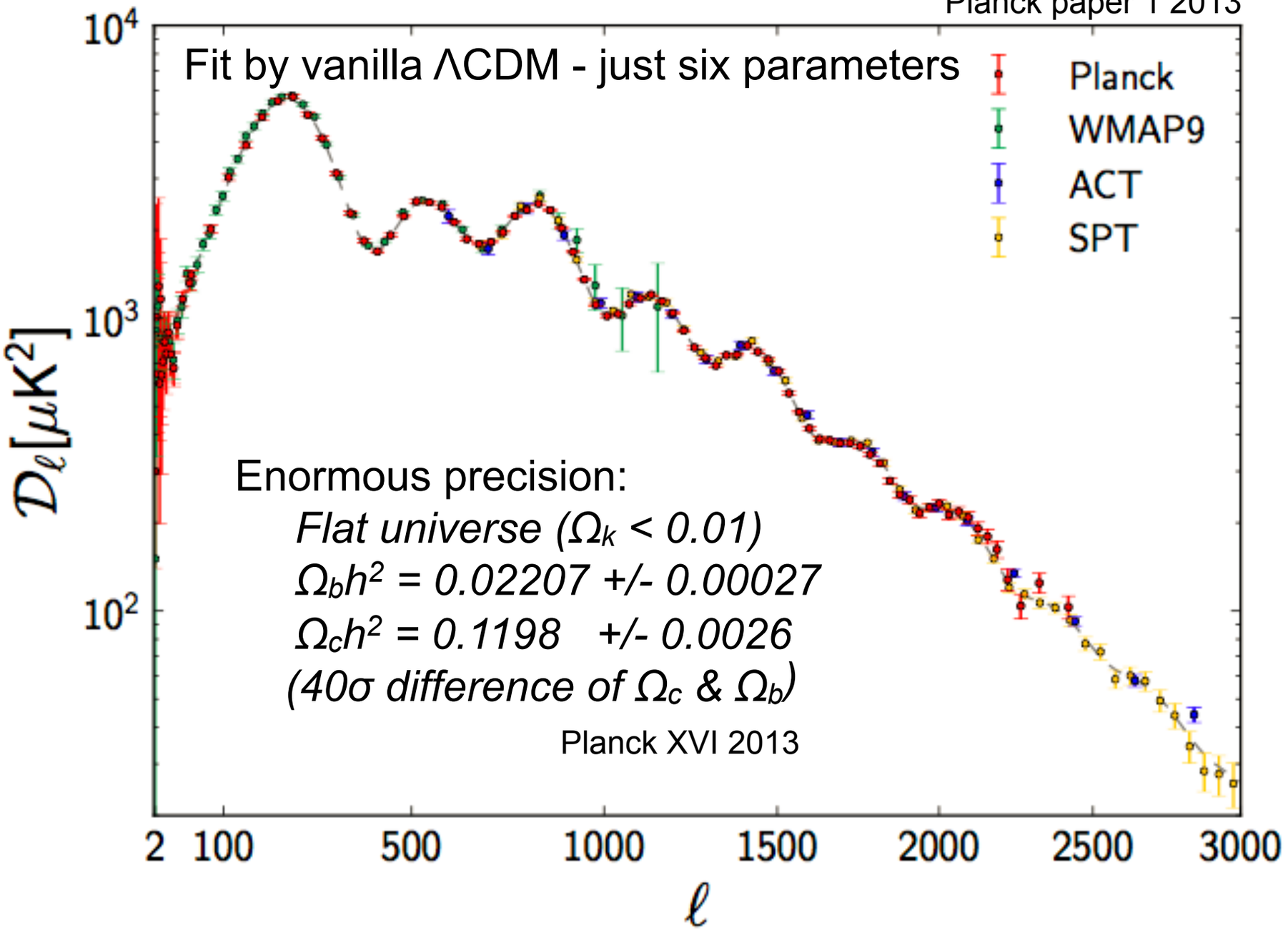


Planck has arrived...



Primary CMB anisotropy - remarkable agreement

Planck paper 1 2013



Enormous precision:

Flat universe ($\Omega_k < 0.01$)

$\Omega_b h^2 = 0.02207$ +/- 0.00027

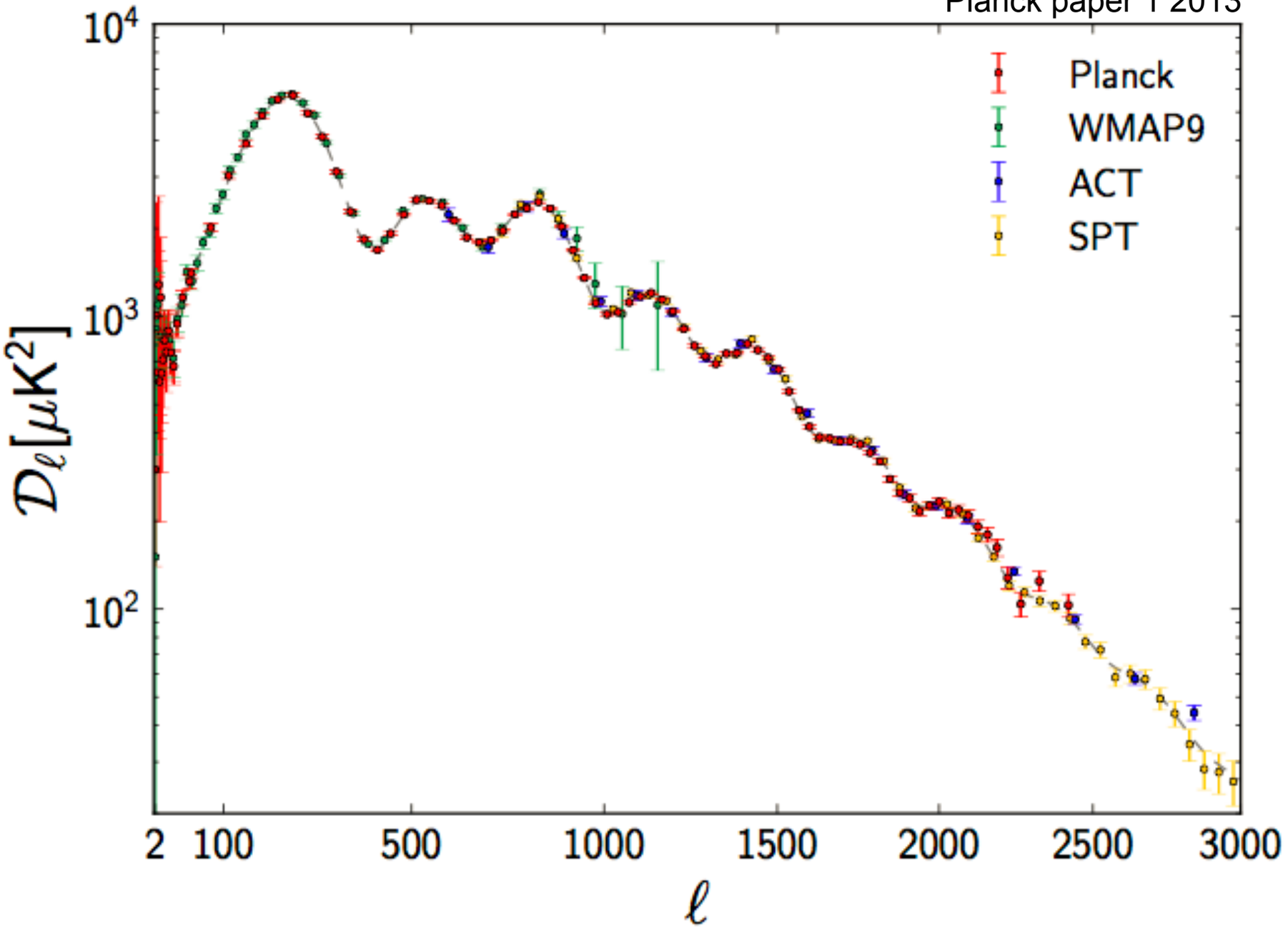
$\Omega_c h^2 = 0.1198$ +/- 0.0026

(40σ difference of Ω_c & Ω_b)

Planck XVI 2013

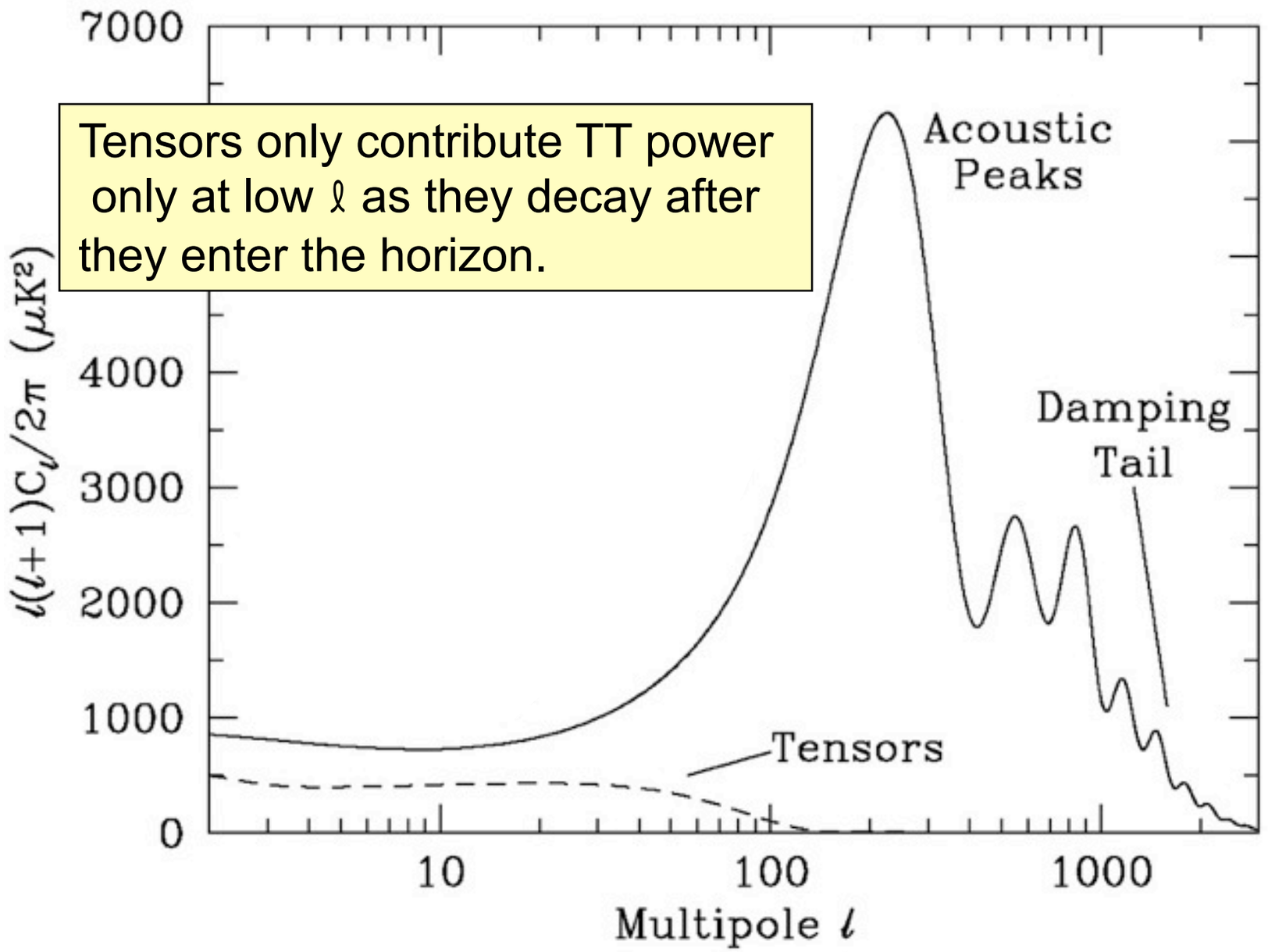
Primary CMB anisotropy - remarkable agreement

Planck paper 1 2013



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



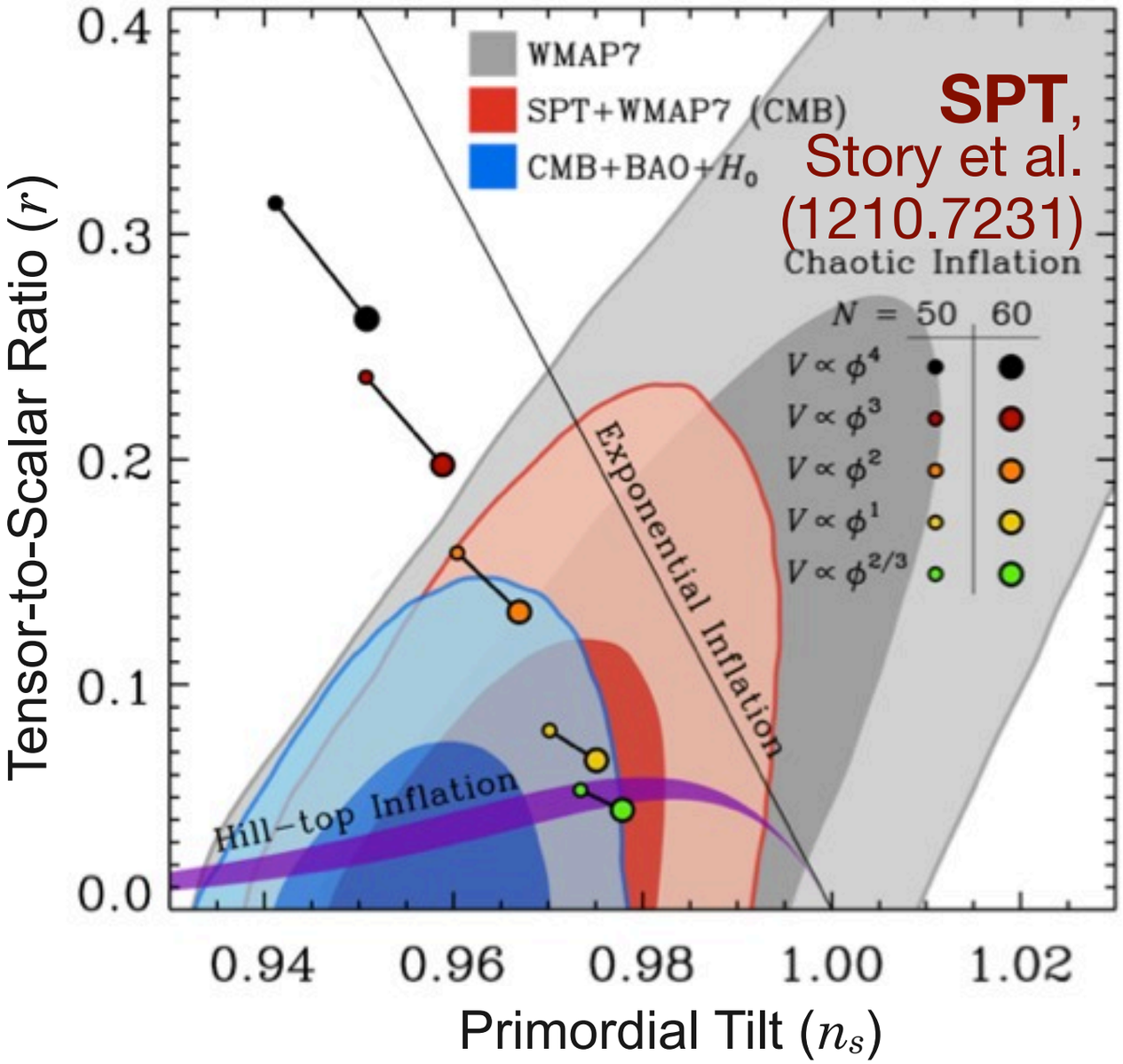
Tensors only contribute TT power only at low ℓ as they decay after they enter the horizon.

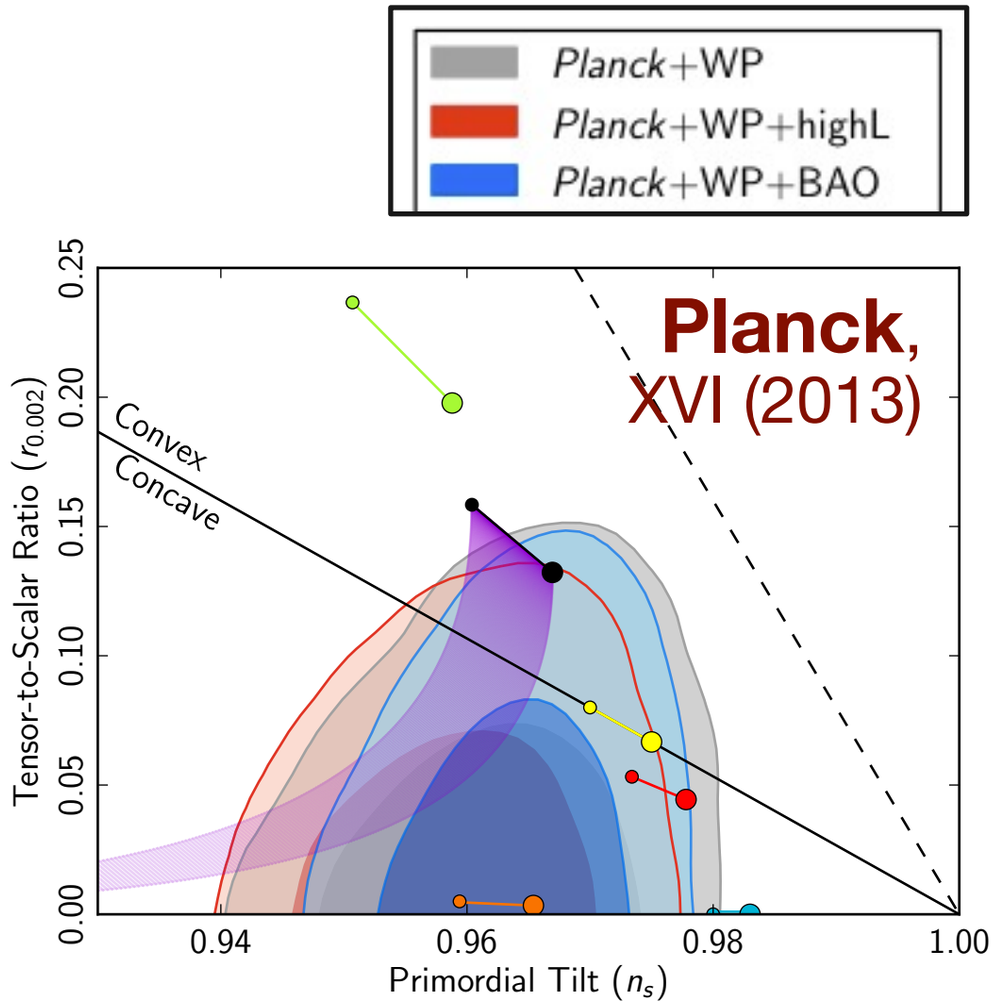
$$r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}$$

$$V^{1/4} = 1.06 \times 10^{16}\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

plot taken from Ned Wright's web pages

Constraining inflationary models
joint r and n_s limits





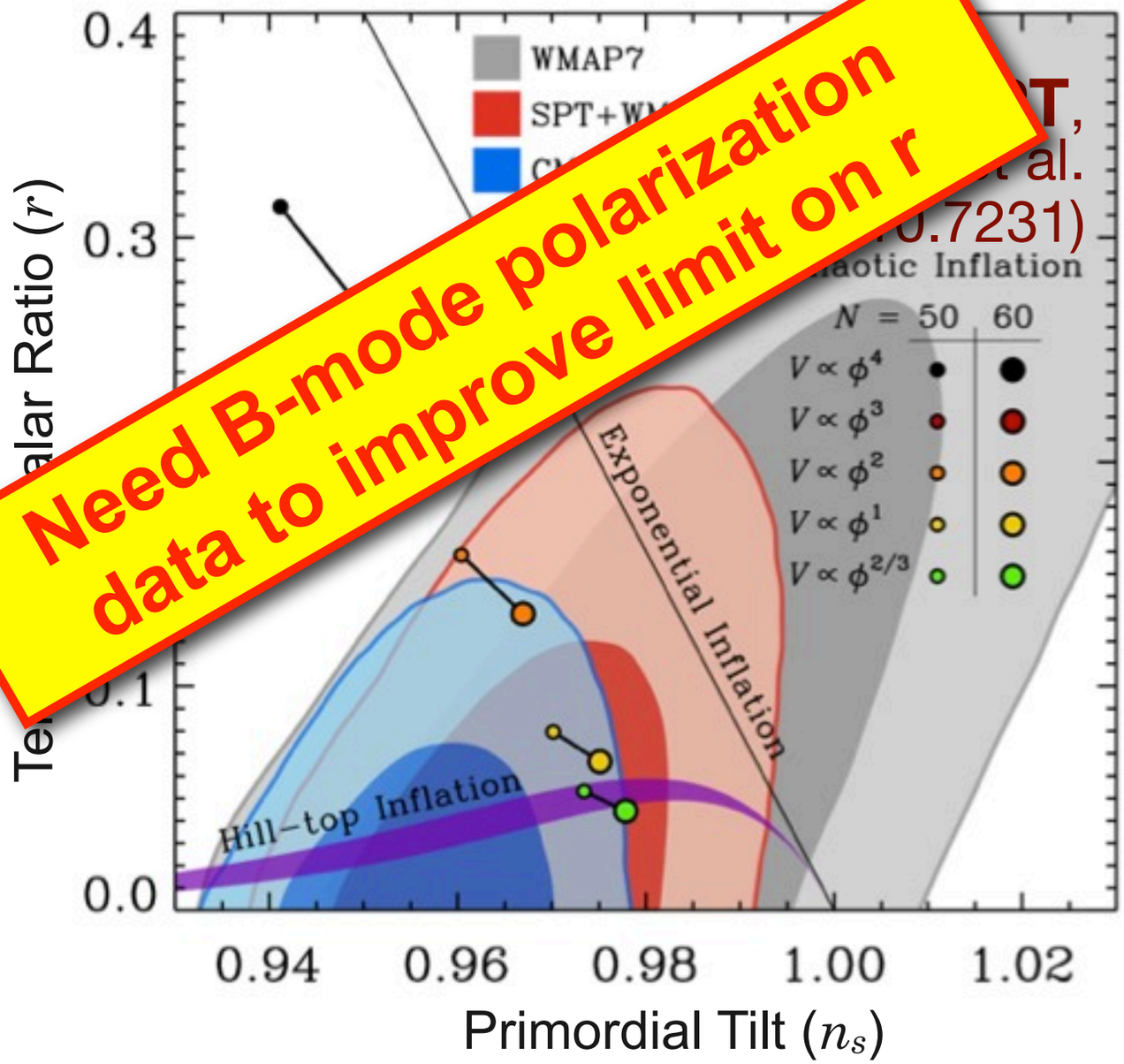
Spectral Index of Primordial Fluctuations

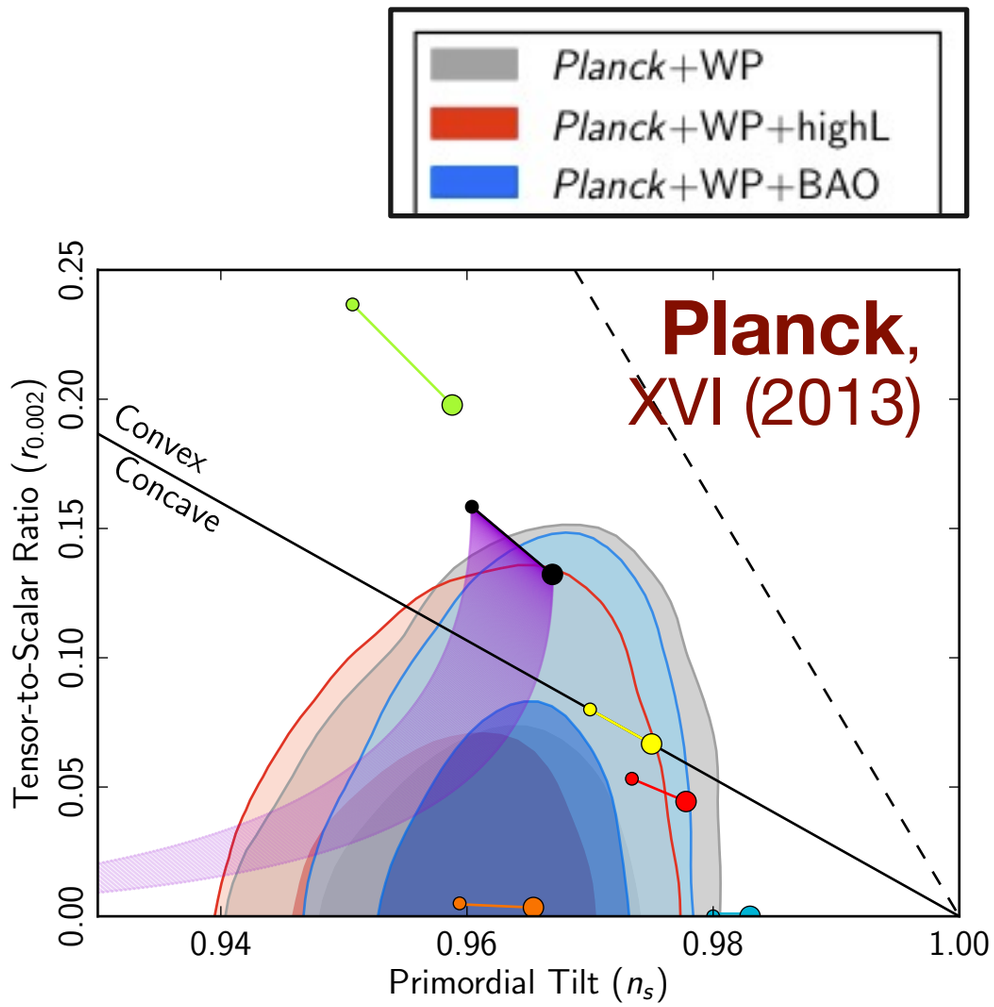
$$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1} \qquad r \equiv \frac{\Delta_h^2}{\Delta_R^2}$$

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

Constraining inflationary models
joint r and n_s limits

Need B-mode polarization data to improve limit on r





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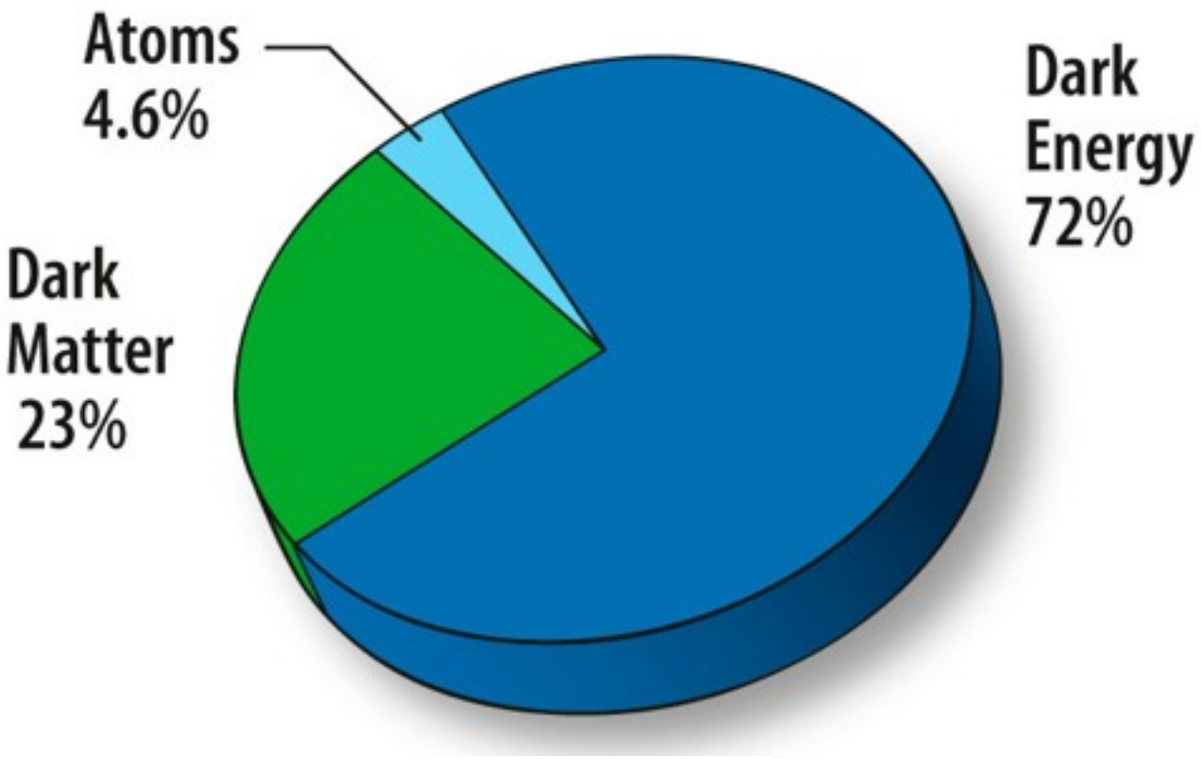
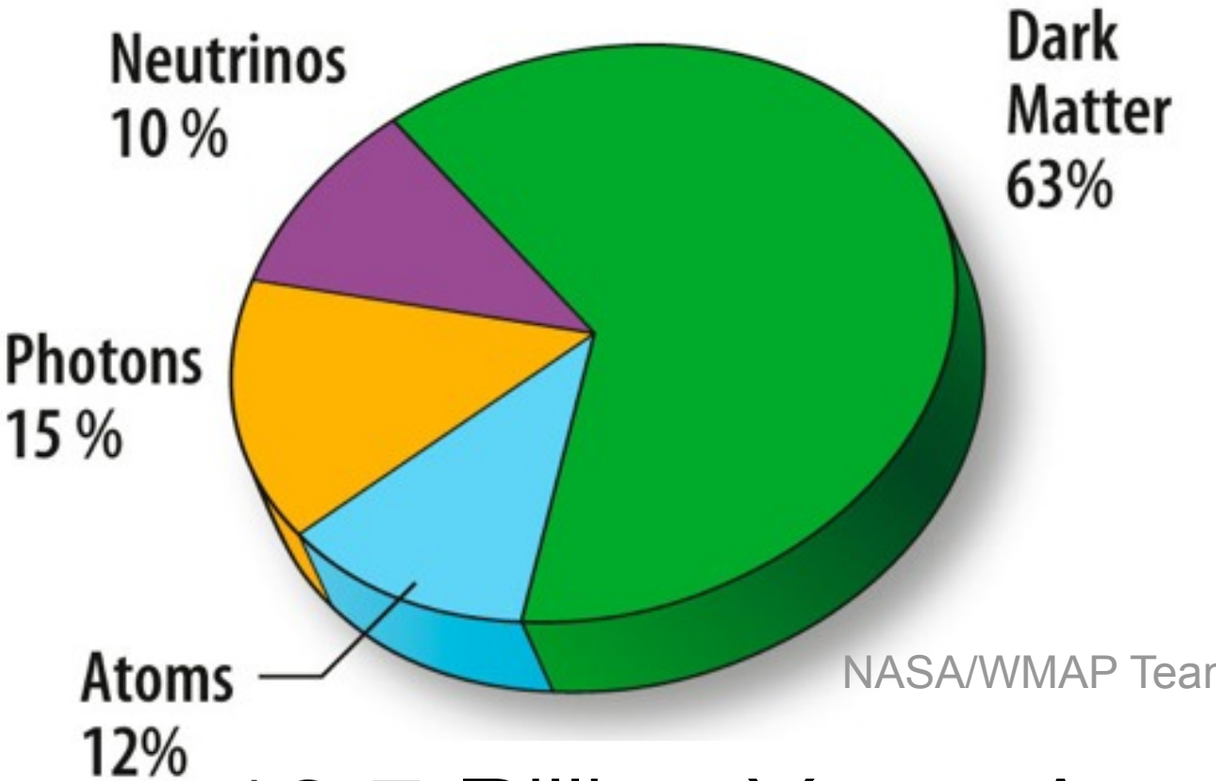
Inflation evidence $n_s \neq 1$ at over 5σ

The Energy Density of the Universe:
Today vs 13.7 Billions years ago



TODAY



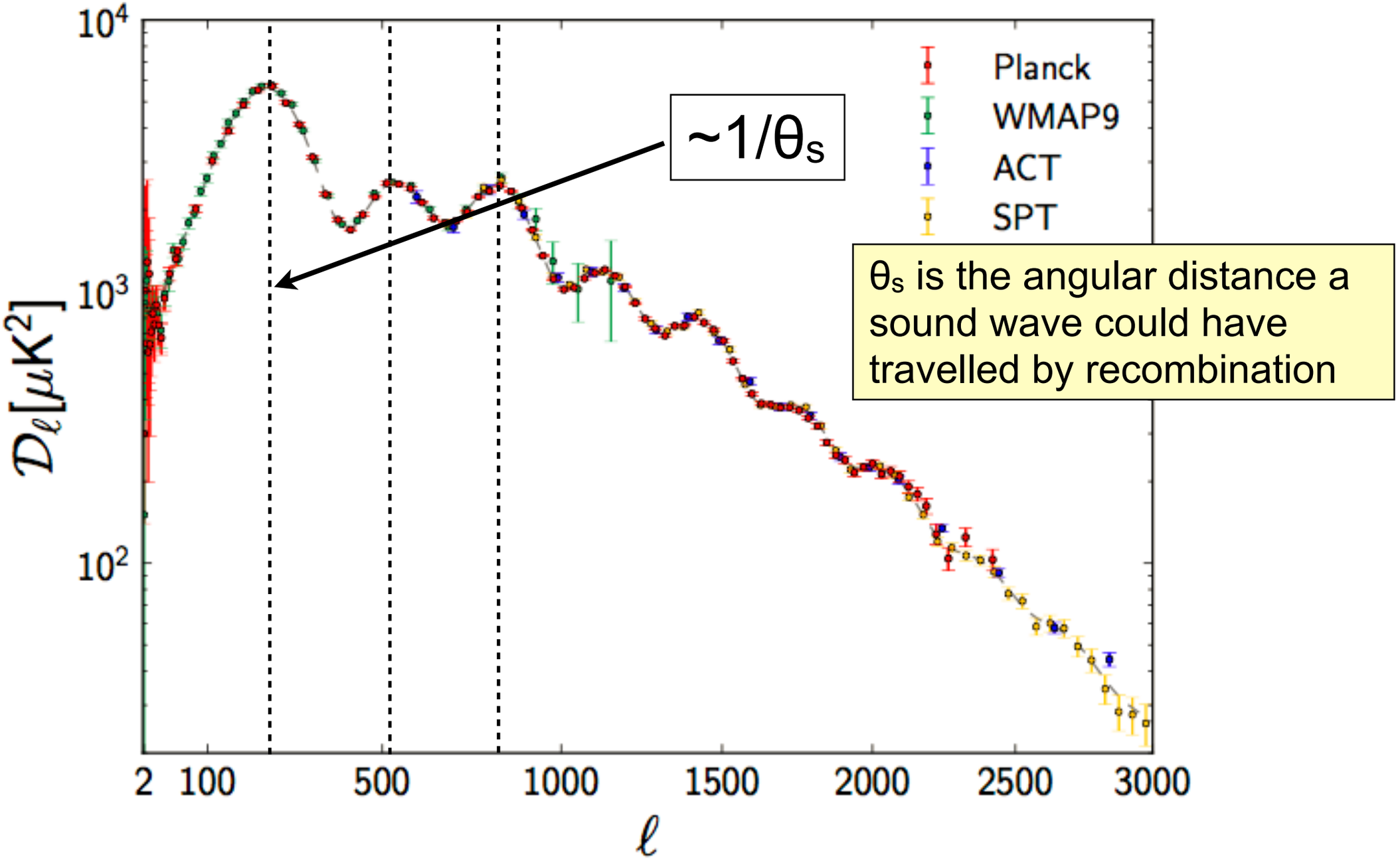
13.7 Billion Years Ago
(Universe 380,000 years old)

- *Neutrinos are the most abundant particle after photons*
- *There is a **"Cosmic Neutrino Background"** that decoupled at 1 sec and which we can detect indirectly in the CMB.*

$$\Omega_\nu h^2 = \Sigma m_\nu / 92\text{eV} \rightarrow \Omega_\nu \gtrsim 0.4\%$$

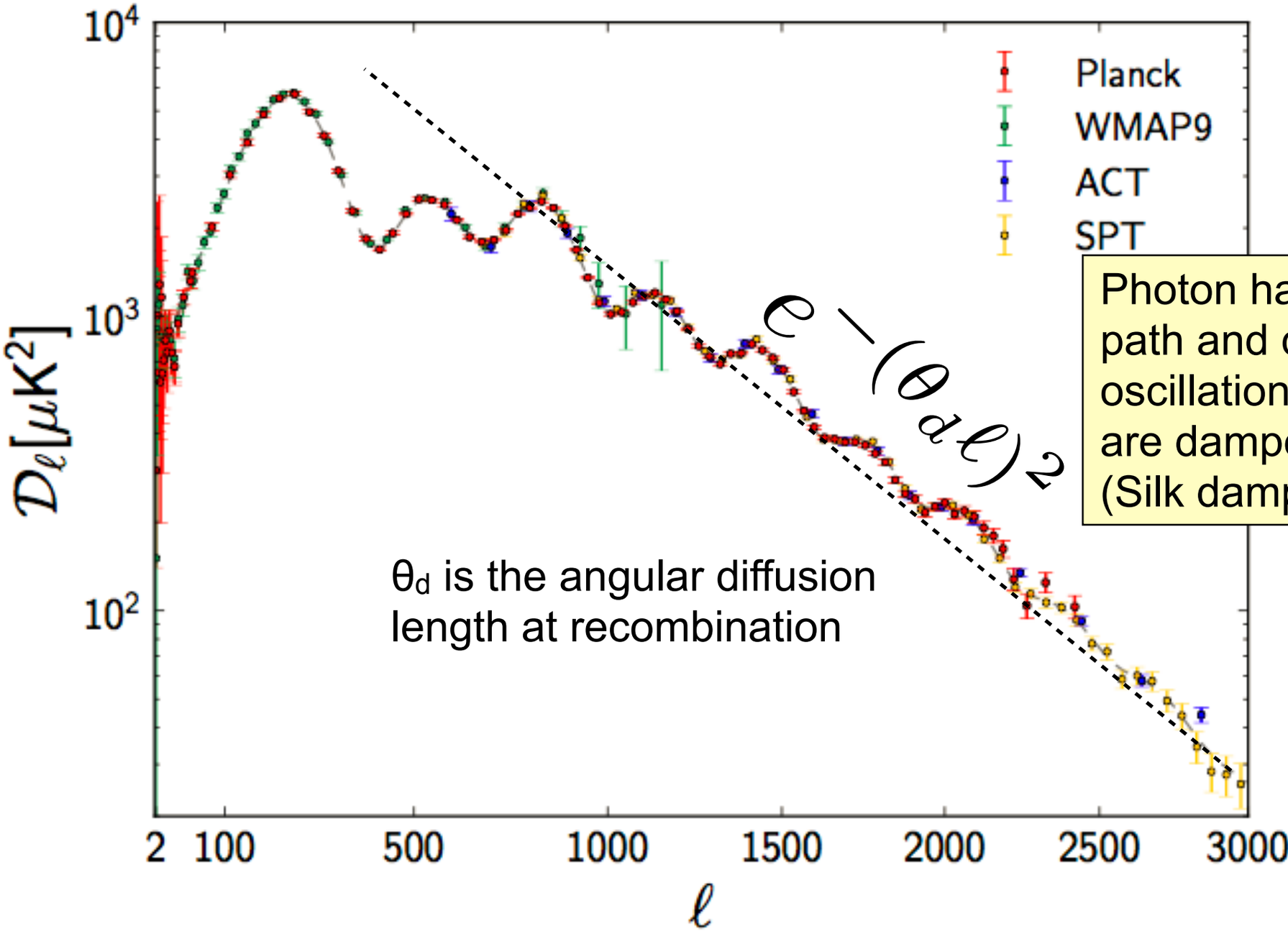
Primary CMB anisotropy

Improves precision of sound horizon, θ_s, & provides larger lever arm



θ_s is the angular distance a sound wave could have travelled by recombination

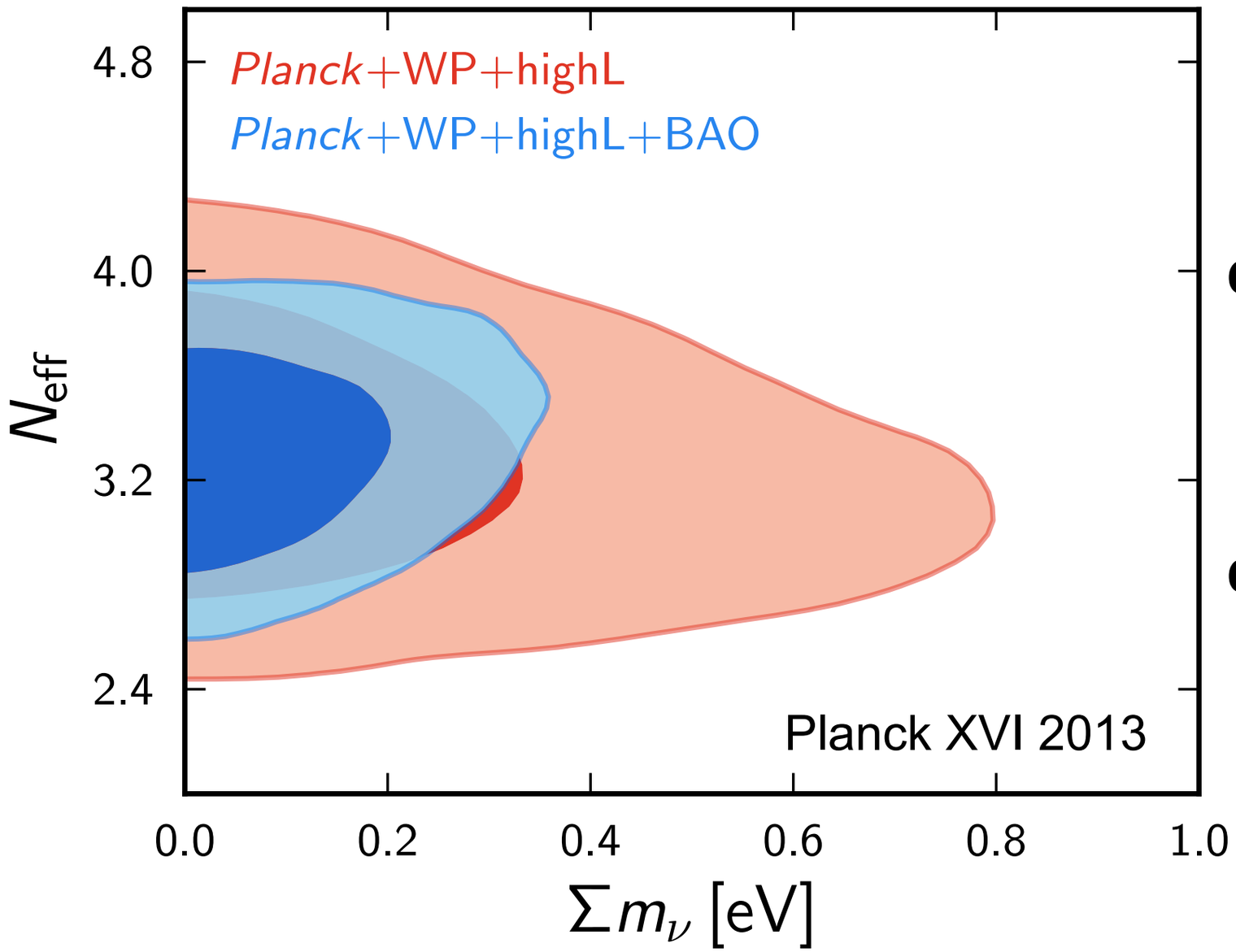
And most importantly provides determination of the damping scale, θ_d



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

$$\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H_,^{0.5}$$ so ratio is sensitive energy density.

Constraining model extensions:
joint Dark Radiation (N_{eff}) and Σm_ν constraints



$\sigma(N_{eff}) = 3.36 \pm 0.34$

(10σ detection of cosmic neutrino background)

$\sigma(\Sigma m_\nu) < 0.23$eV at 95% C.L.

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

Constraining model extensions:
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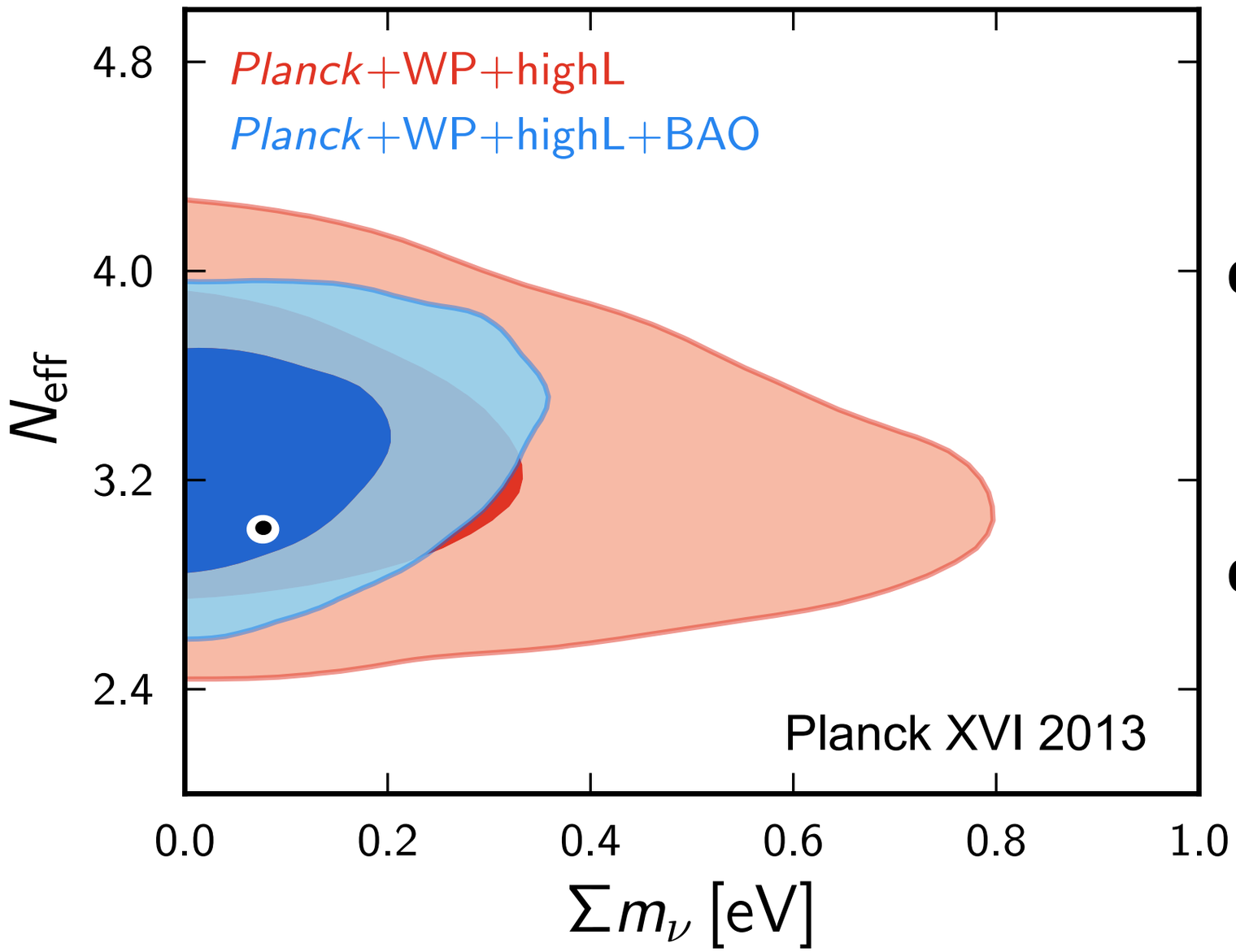

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CMB lensing

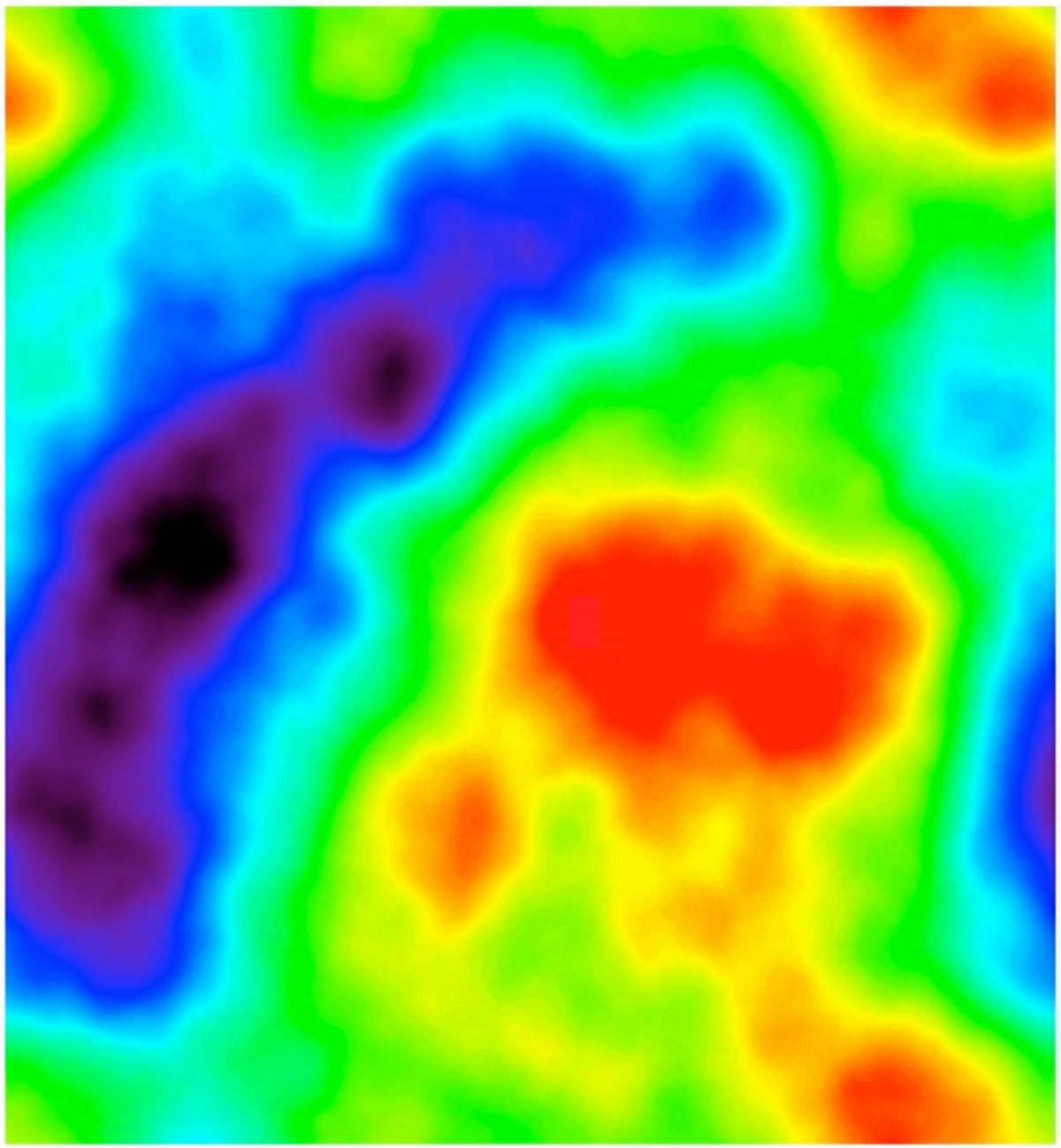
Large-Scale Structure Lenses the CMB

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

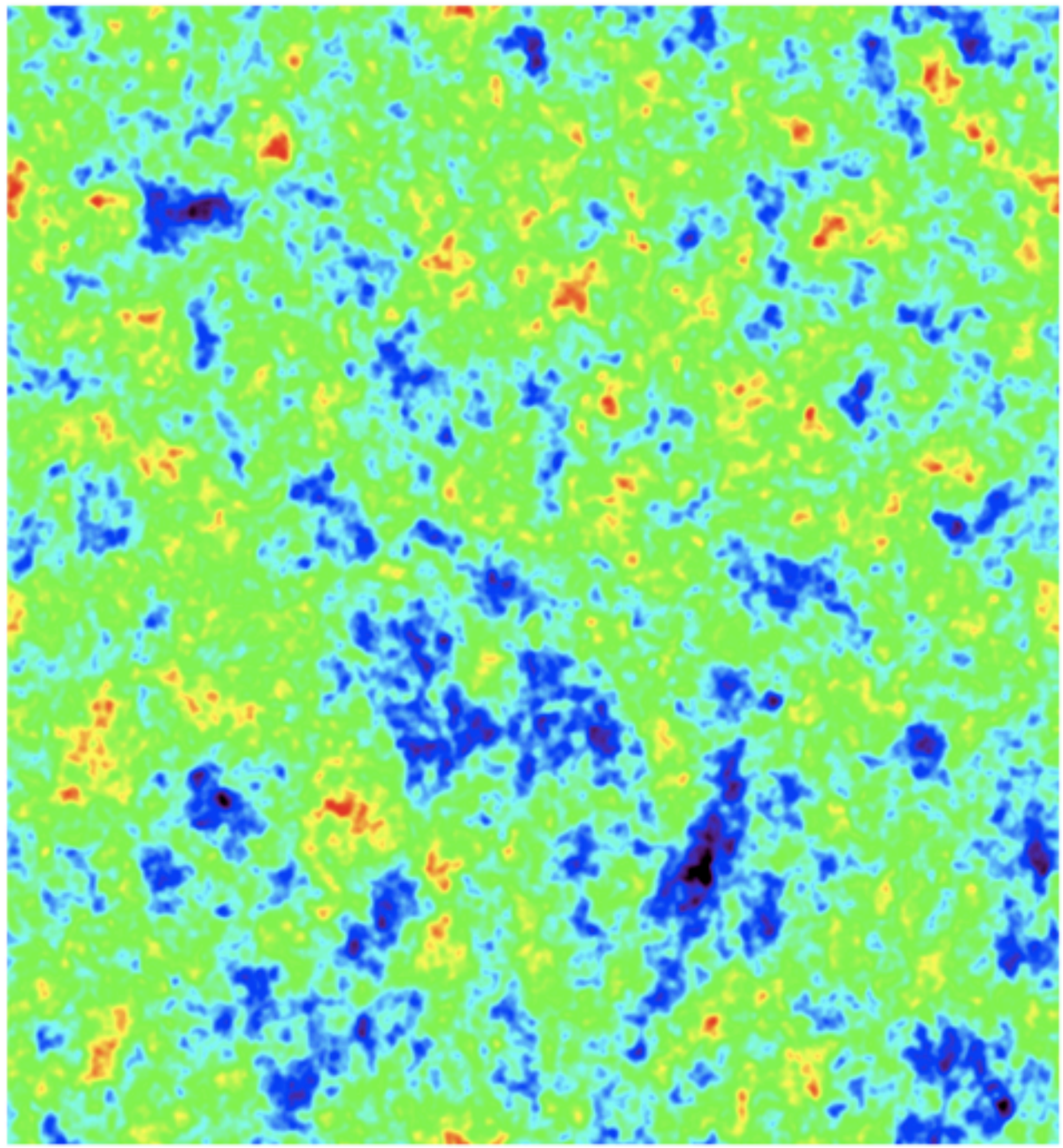
graphic from ESA Website

Lensing of the CMB

17°x17°



lensing potential

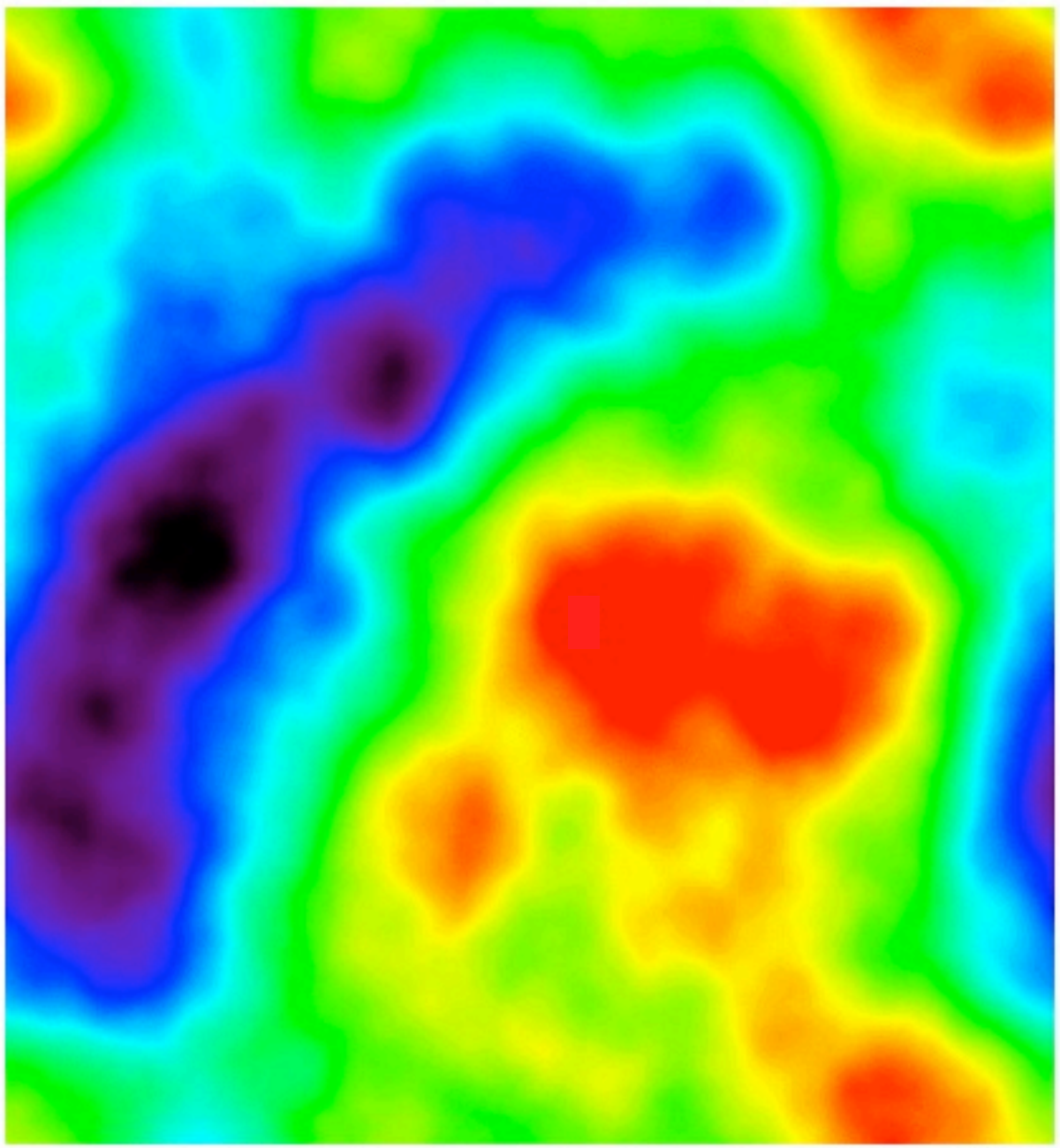


unlensed cmb

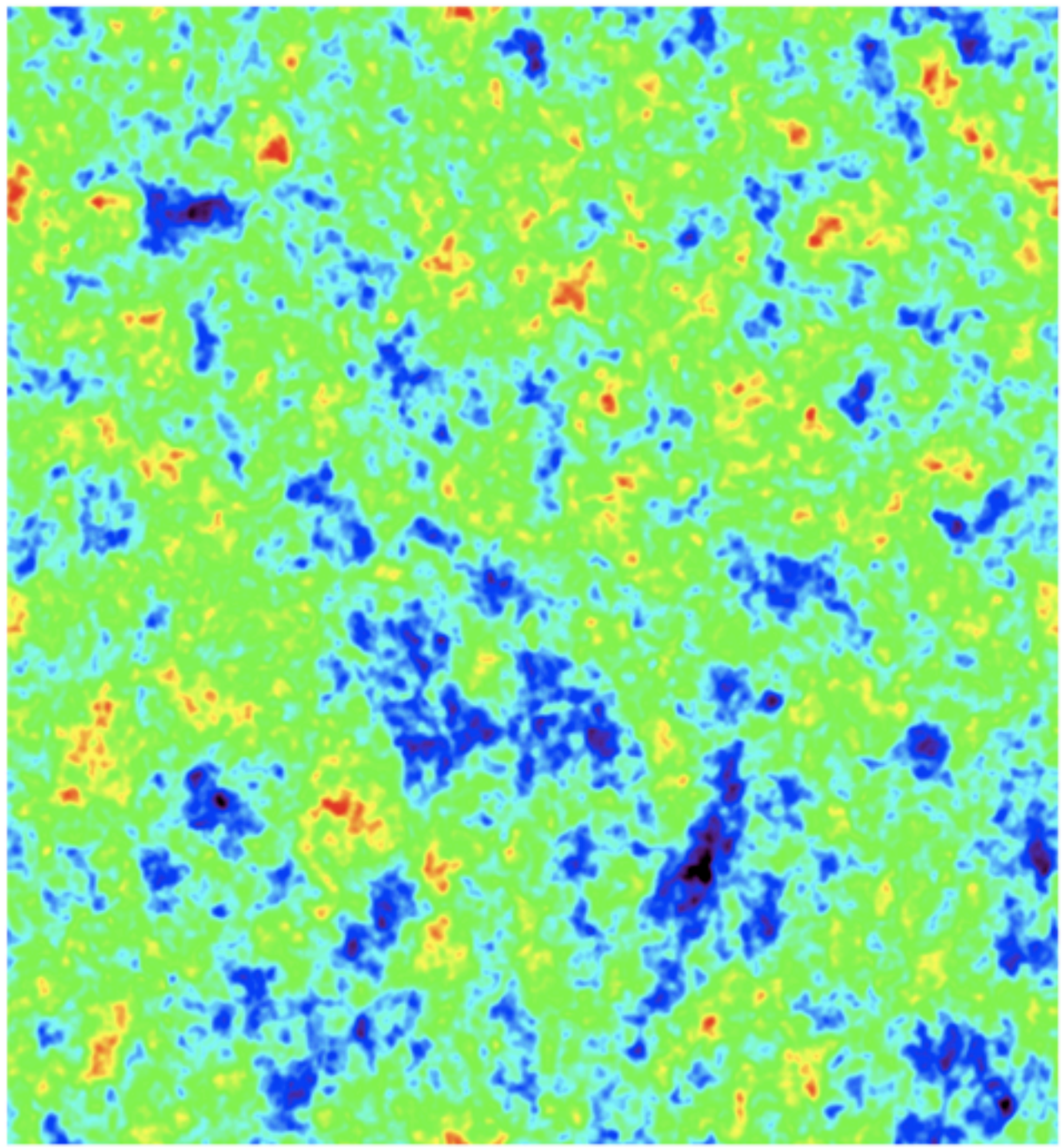
from Alex van Engelen

Lensing of the CMB

17°x17°



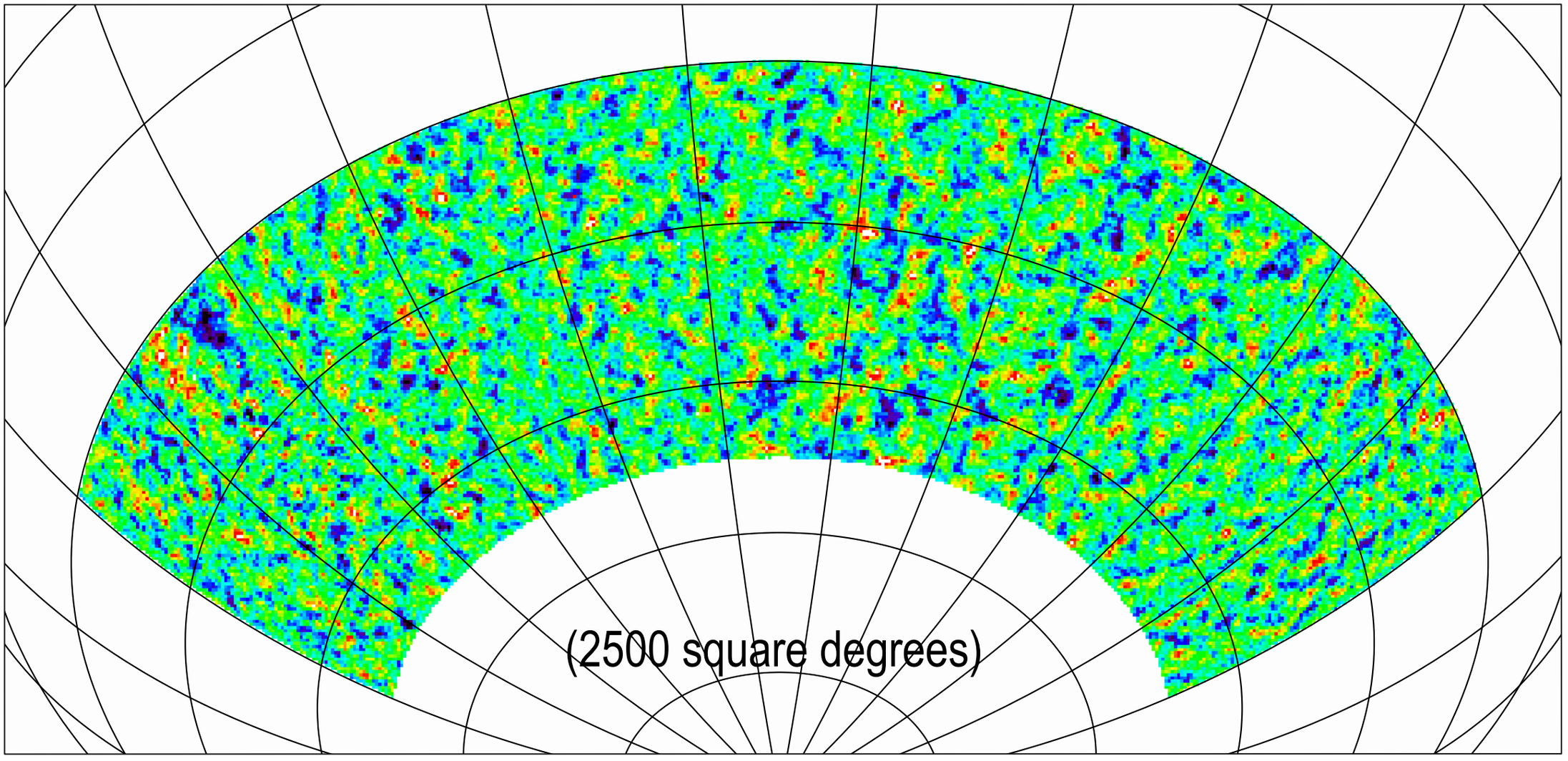
lensing potential



lensed cmb

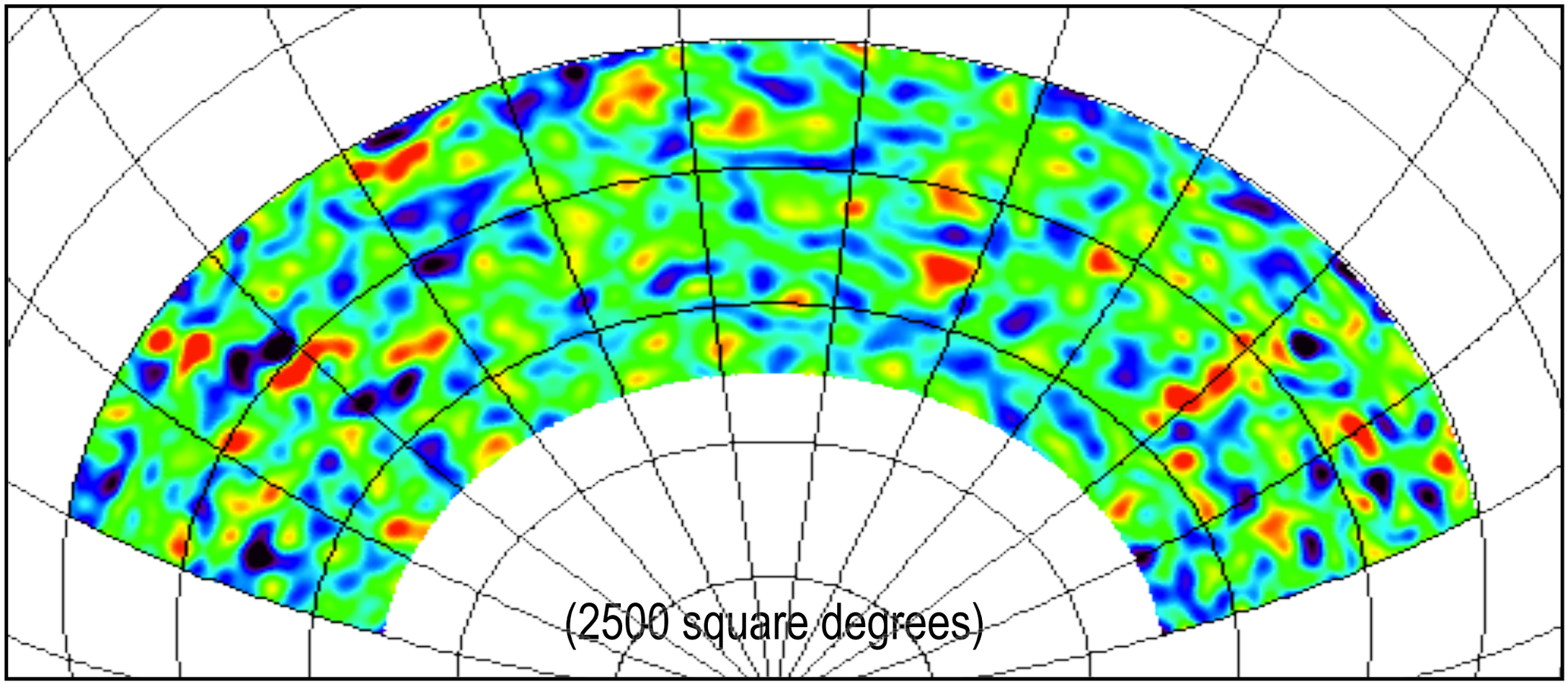
from Alex van Engelen

SPT CMB Anisotropy Map



SPT CMB Lensing Map

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



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

SPT CMB Lensing Ma

reconstruction of the mass proje

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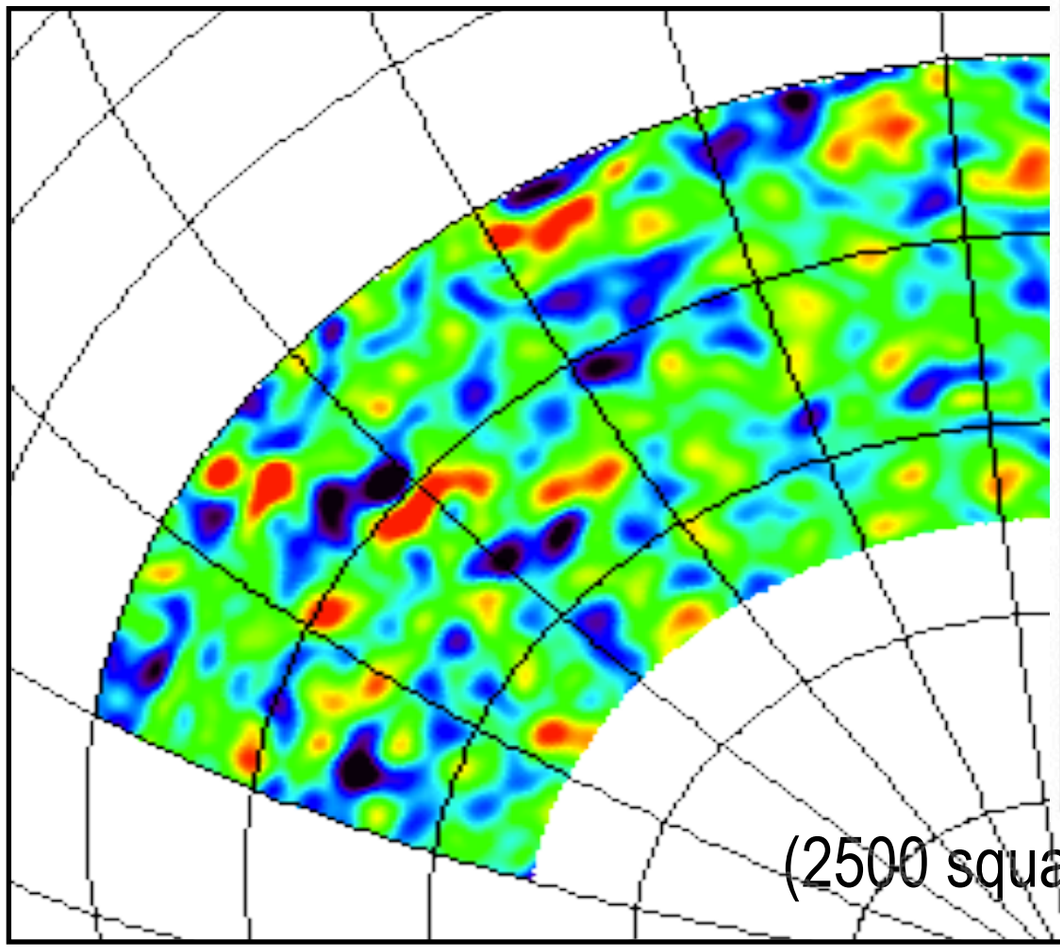
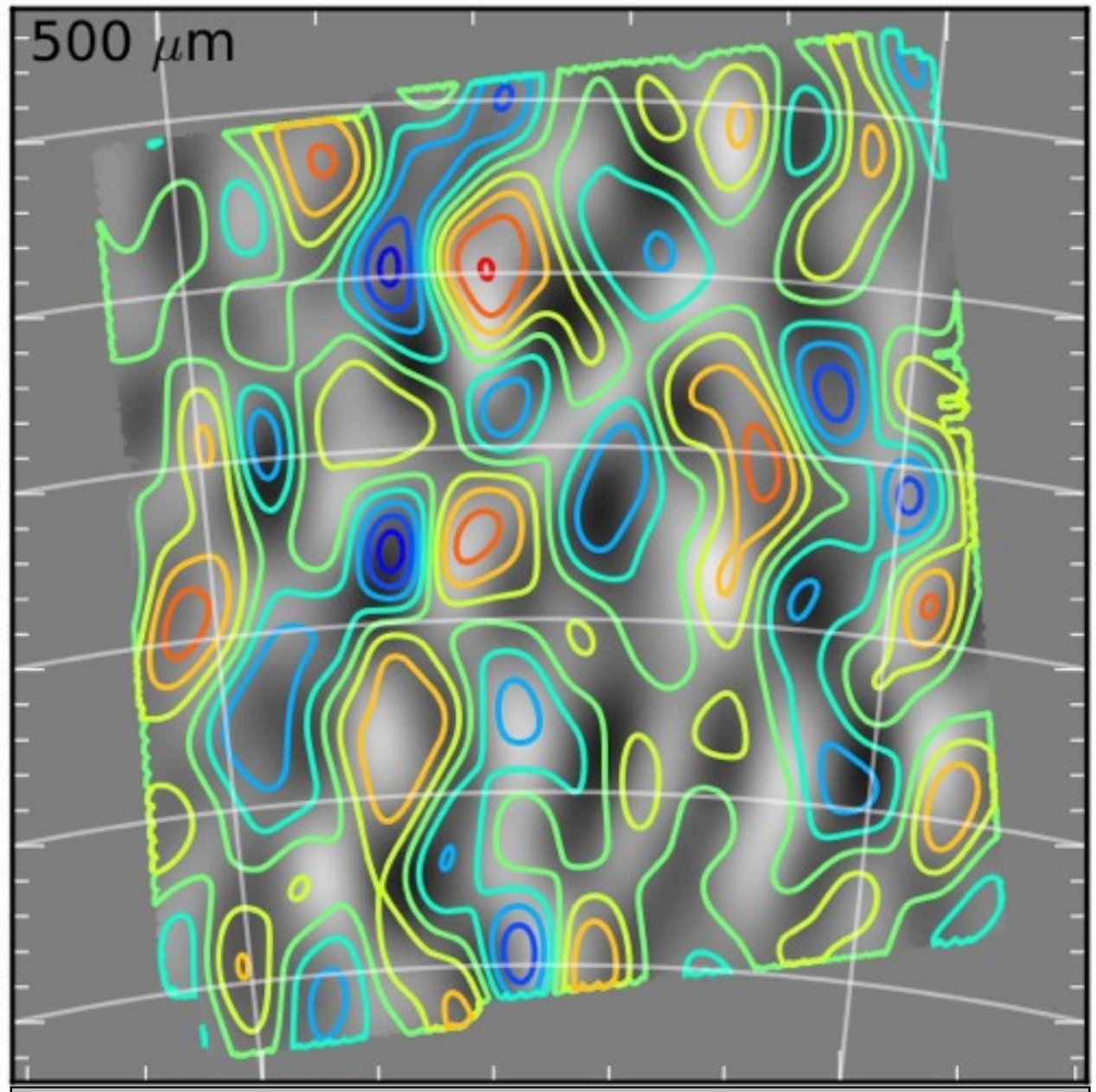
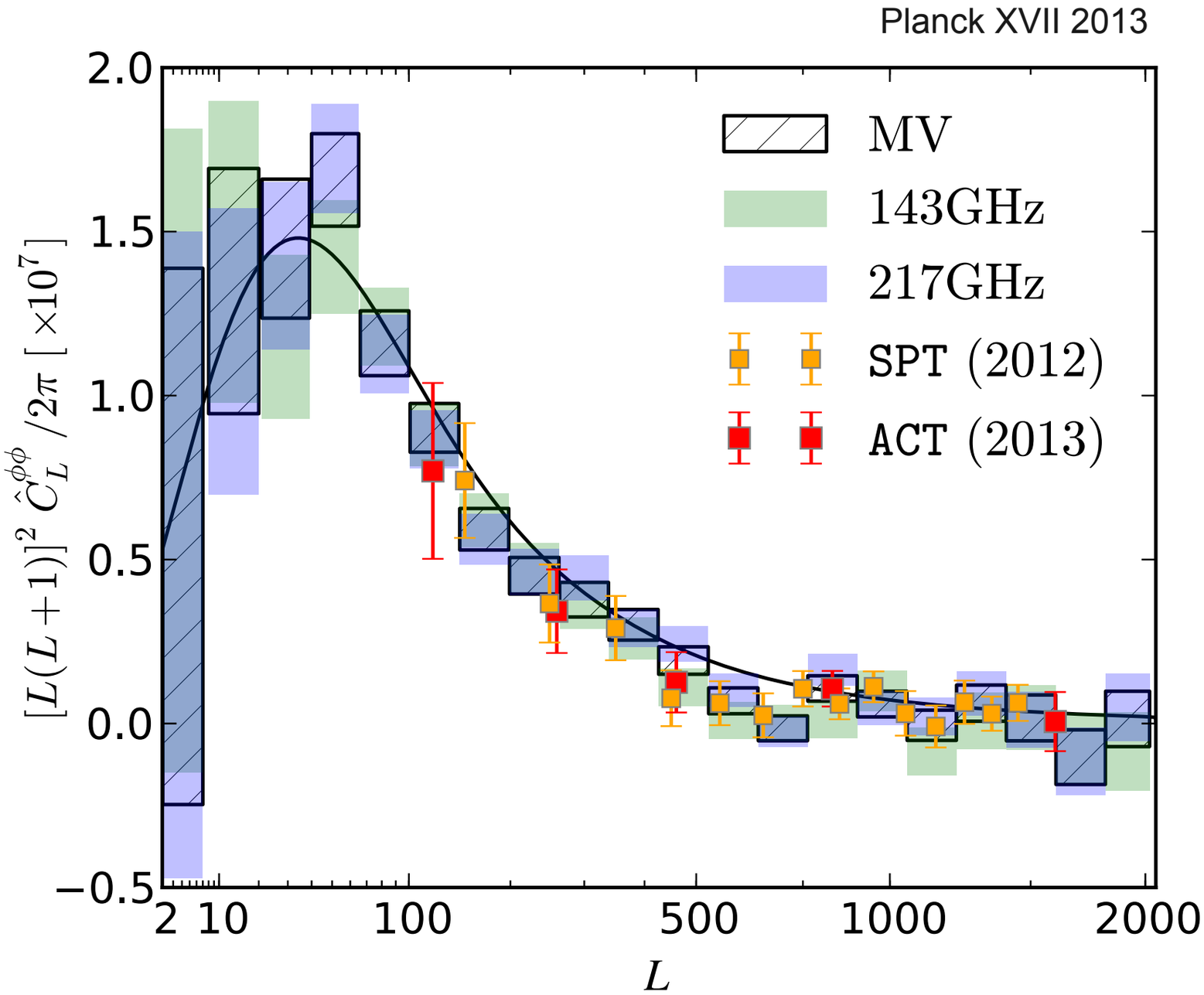




Correlation of matter traced by CMB lensing (contours, SPT) and distribution of high z galaxies (grayscale; Herschel 500 um) [arXiv:1112.5435]

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

CMB lensing power spectrum



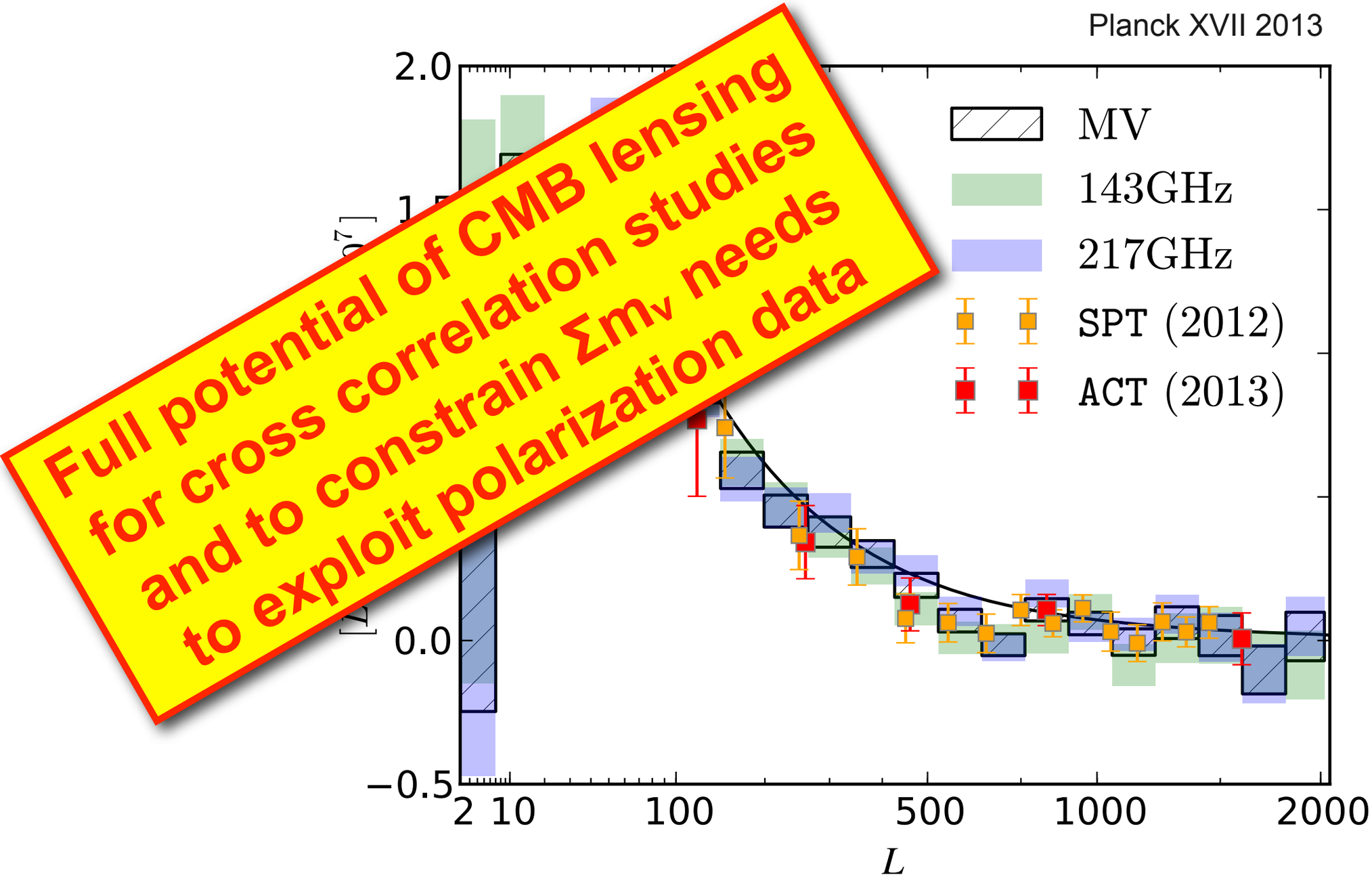
Sensitive to the neutrino masses

$\sum m_\nu$ = 0.1 eV → 5% amplitude of spectrum

Polarization gives additional lensing sensitivity and is a cleaner probe.

B_{lens} modes are only sourced by lensing.

CMB lensing power spectrum



Full potential of CMB lensing for cross correlation studies and to constrain Σm_ν needs to exploit polarization data

Sensitive to the neutrino masses

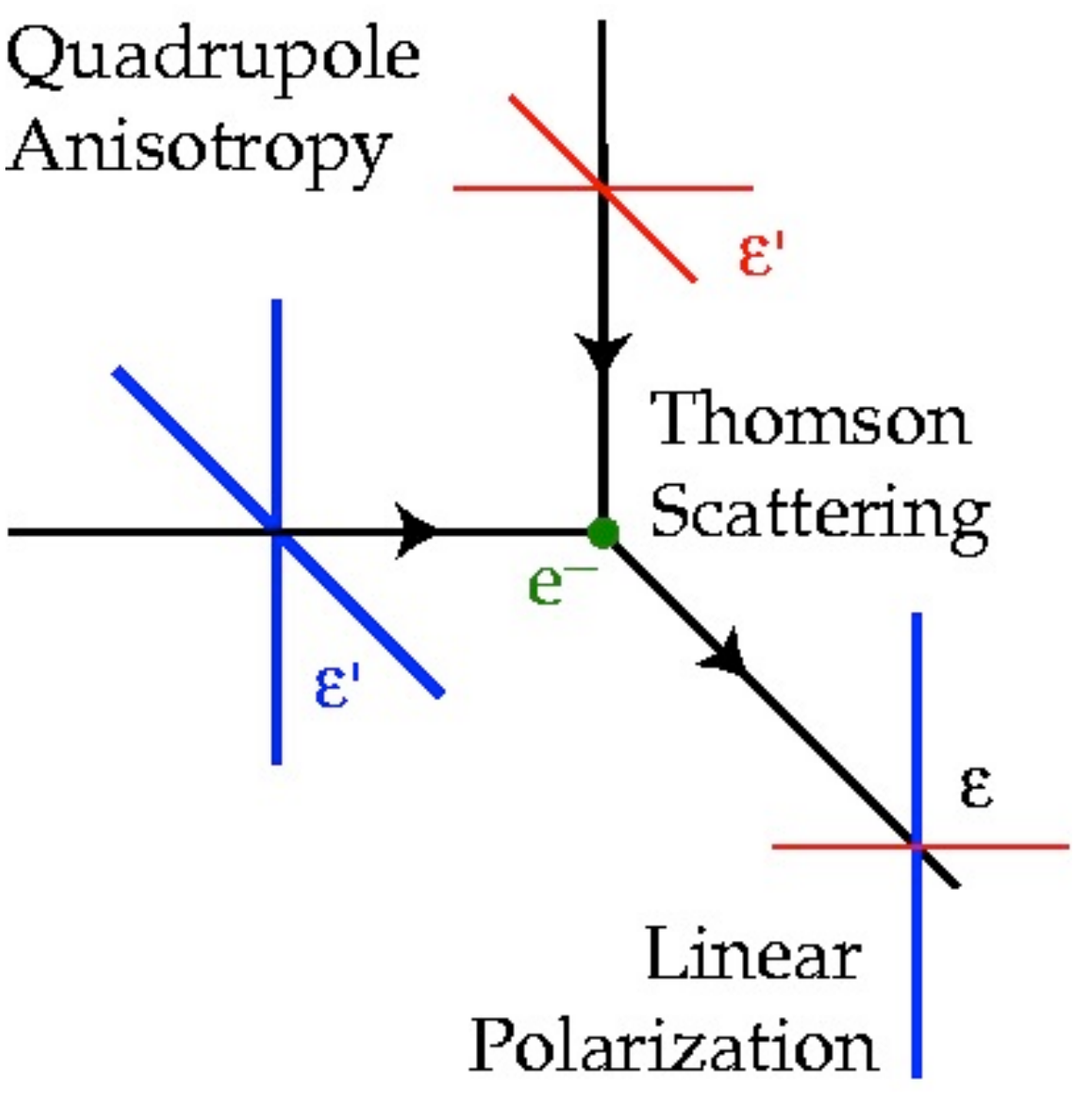
$\sum m_\nu$ = 0.1 eV → 5% amplitude of spectrum

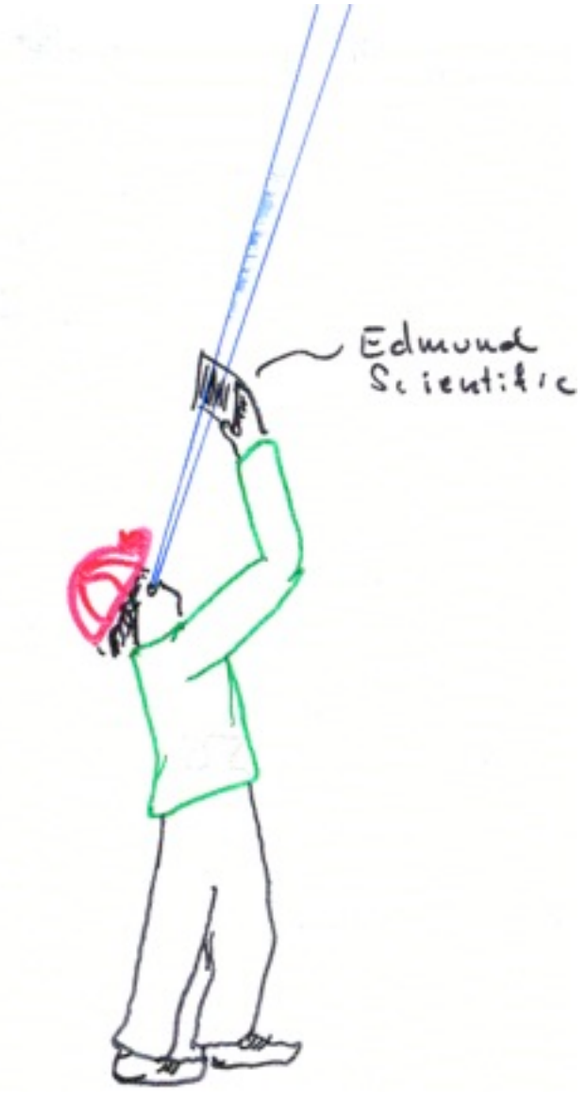
Polarization gives additional lensing sensitivity and is a cleaner probe.

B_{lens} modes are only sourced by lensing.

Polarization of the CMB

Due to Thomson scattering –
CMB must be polarized

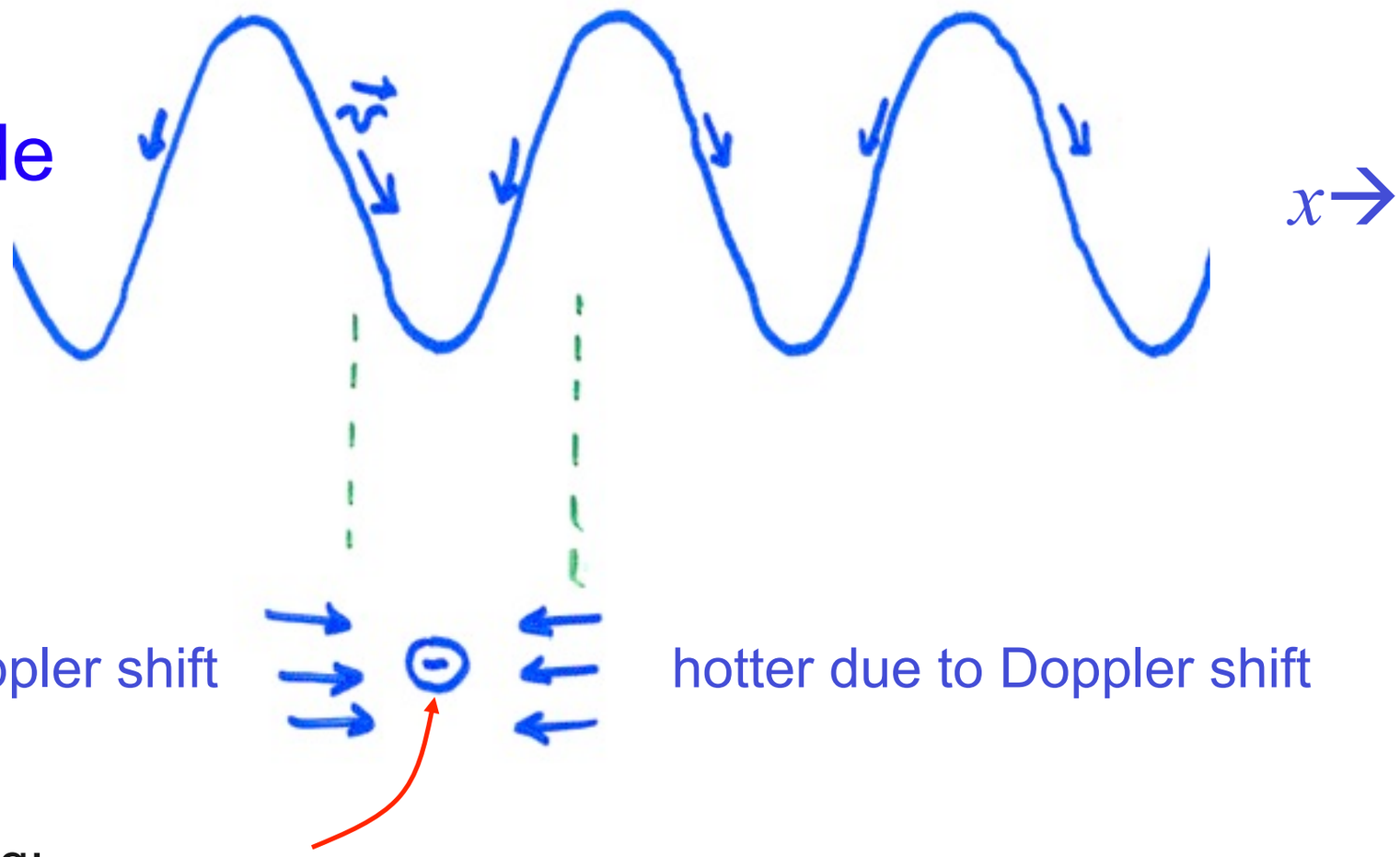




from W. Hu's web page

Generating CMB polarization

Density mode



Before decoupling:

- electron ‘sees’ only a local monopole

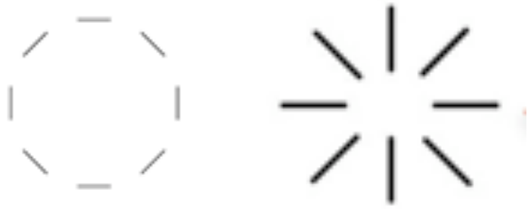
During decoupling:

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

E-mode from density modes (scalar fluctuations)

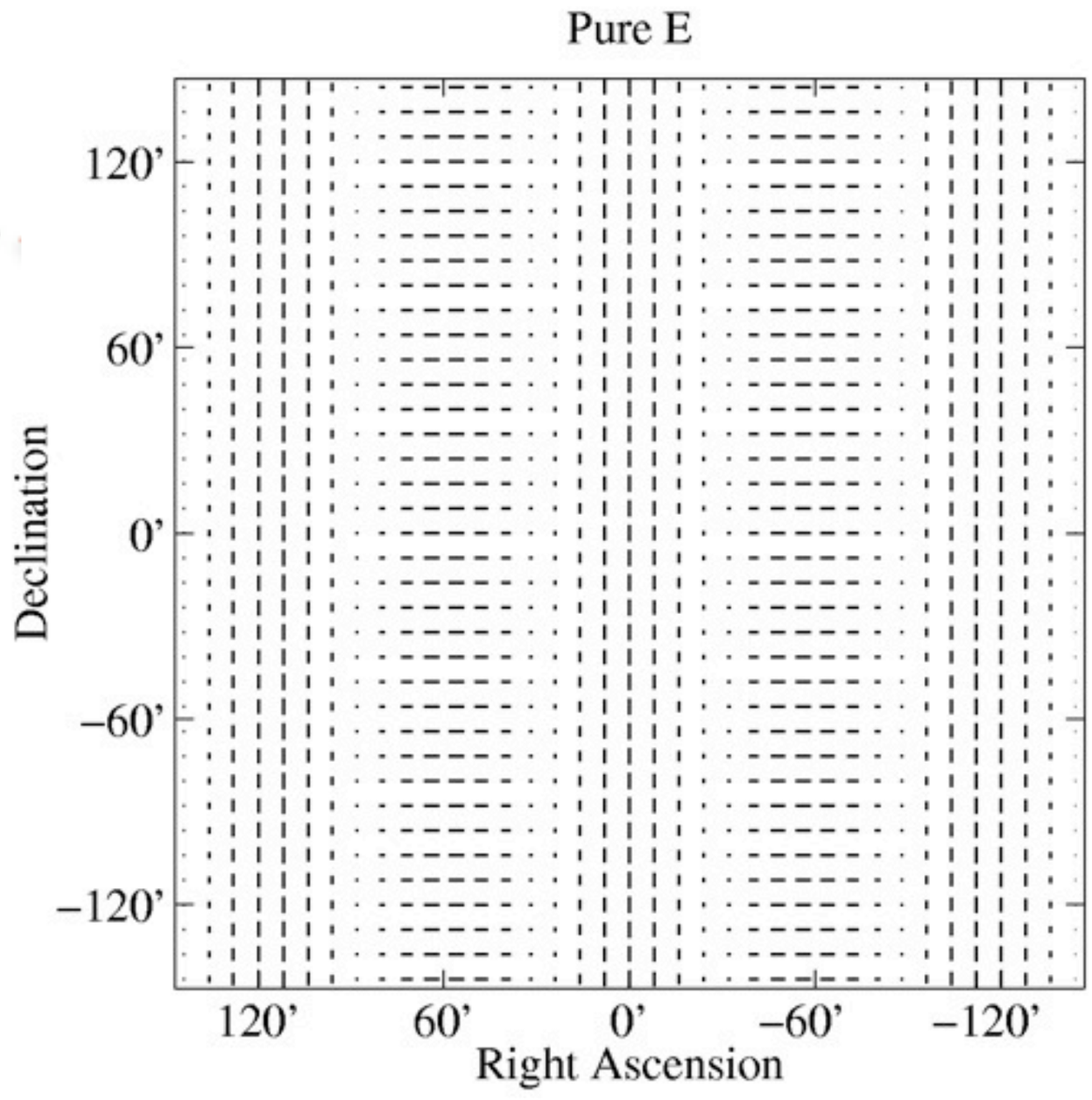
E-mode Polarization (Curl free)

Polarization parallel & perpendicular to wave vector



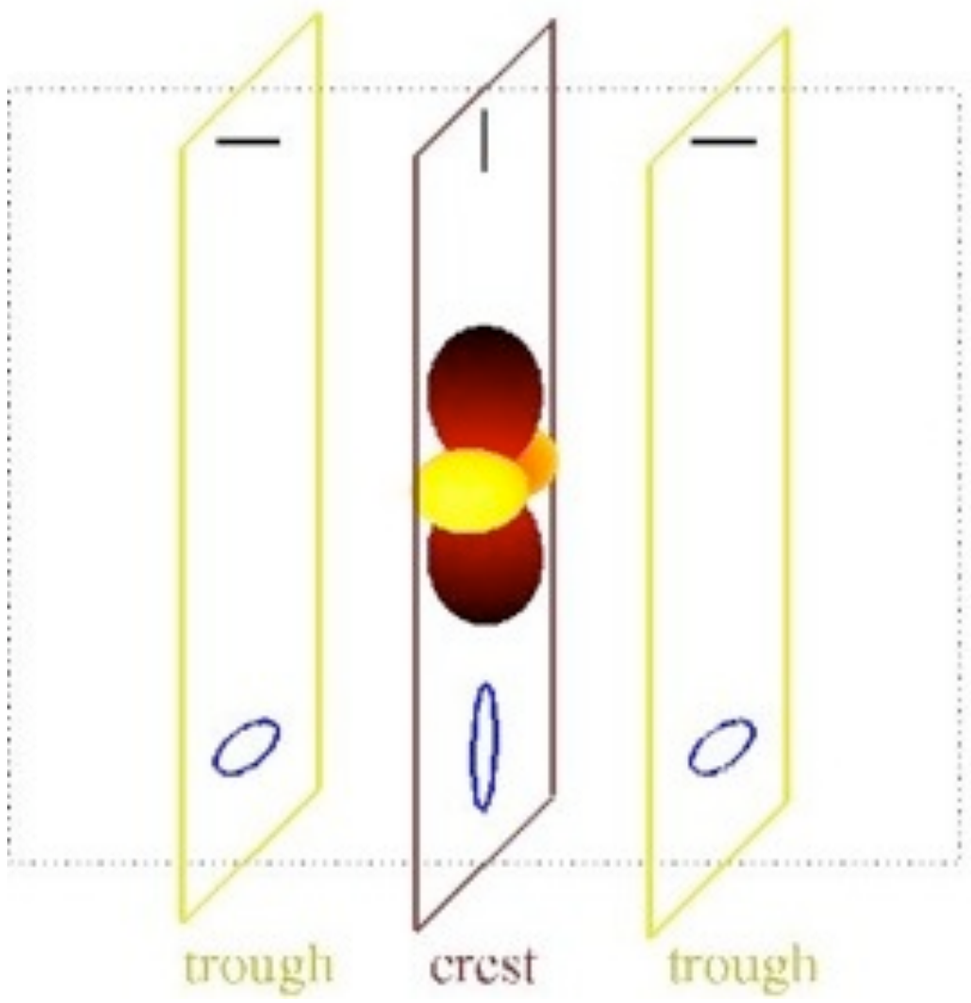
Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization



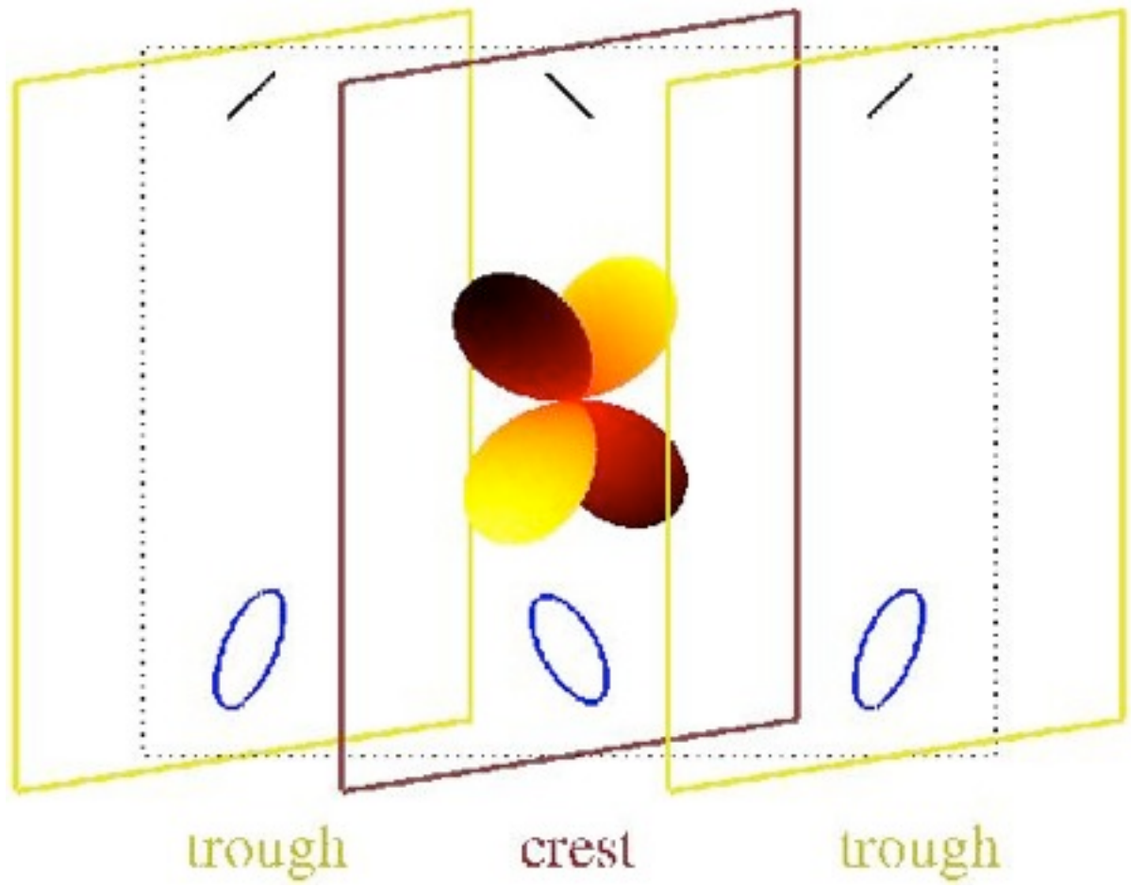
Gravitational wave induced CMB polarization

'+' 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)

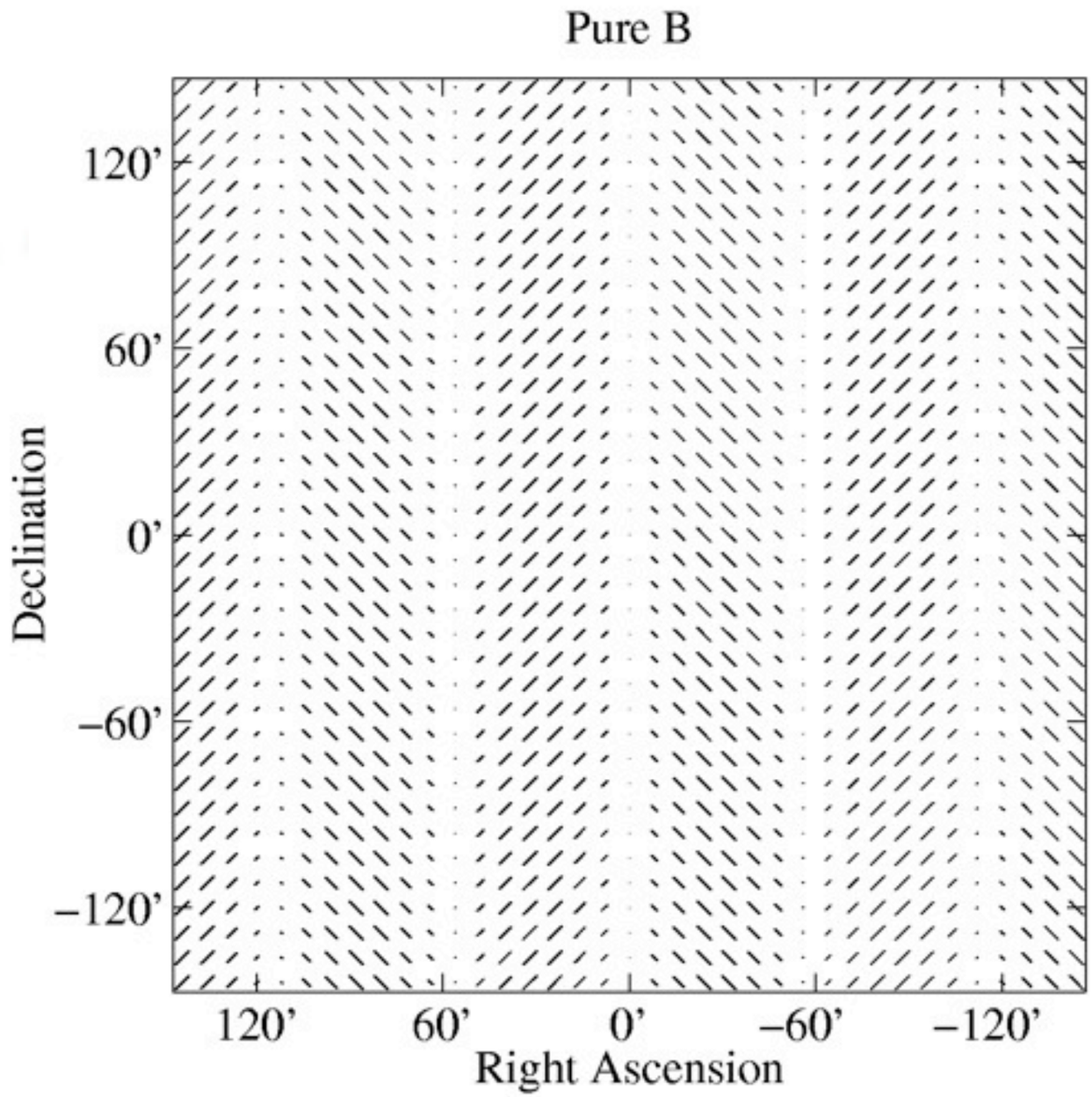
Polarization oriented ±45 degrees to wave vector

Odd parity, div free

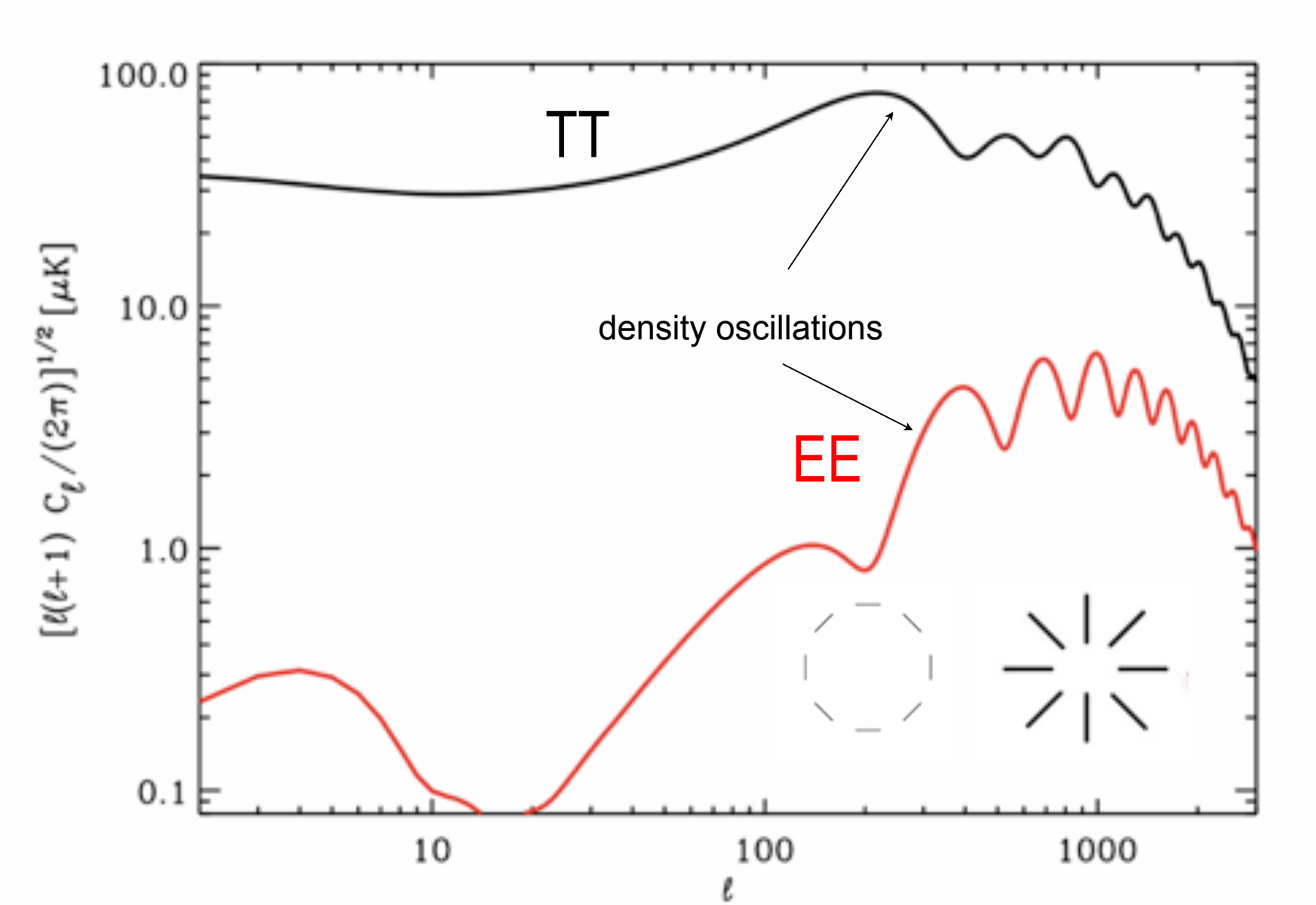
NOT generated by density fluctuations

Generated by gravitational waves sourced by Inflation in the first instants of the universe, 10^{-35} seconds, at ~ GUT energies.

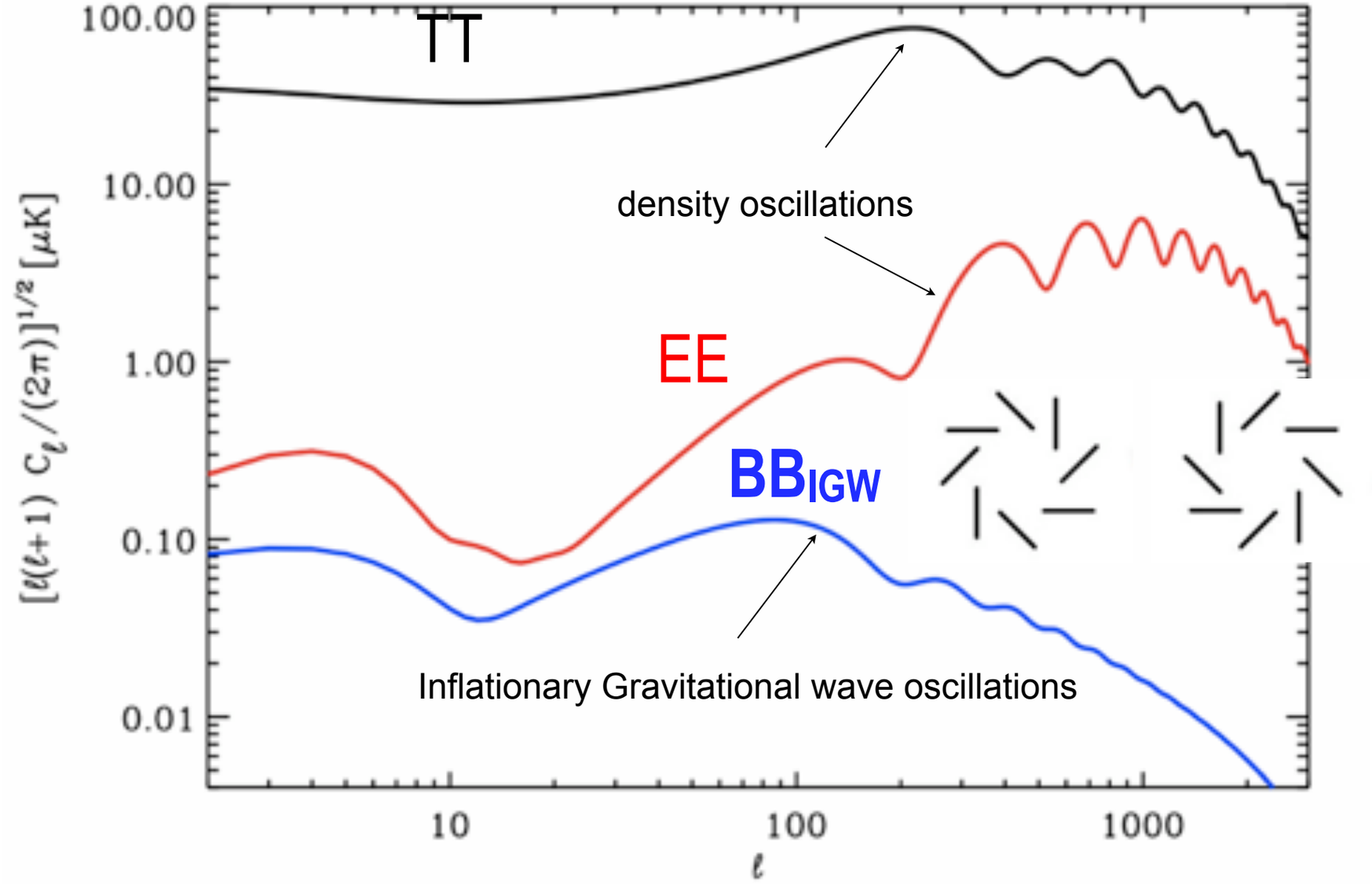
"Smoking gun" test of Inflation and direct measure of its energy scale



CMB polarization:
the next frontier for lensing & inflation



CMB polarization:
the next frontier for lensing & inflation



CMB polarization:
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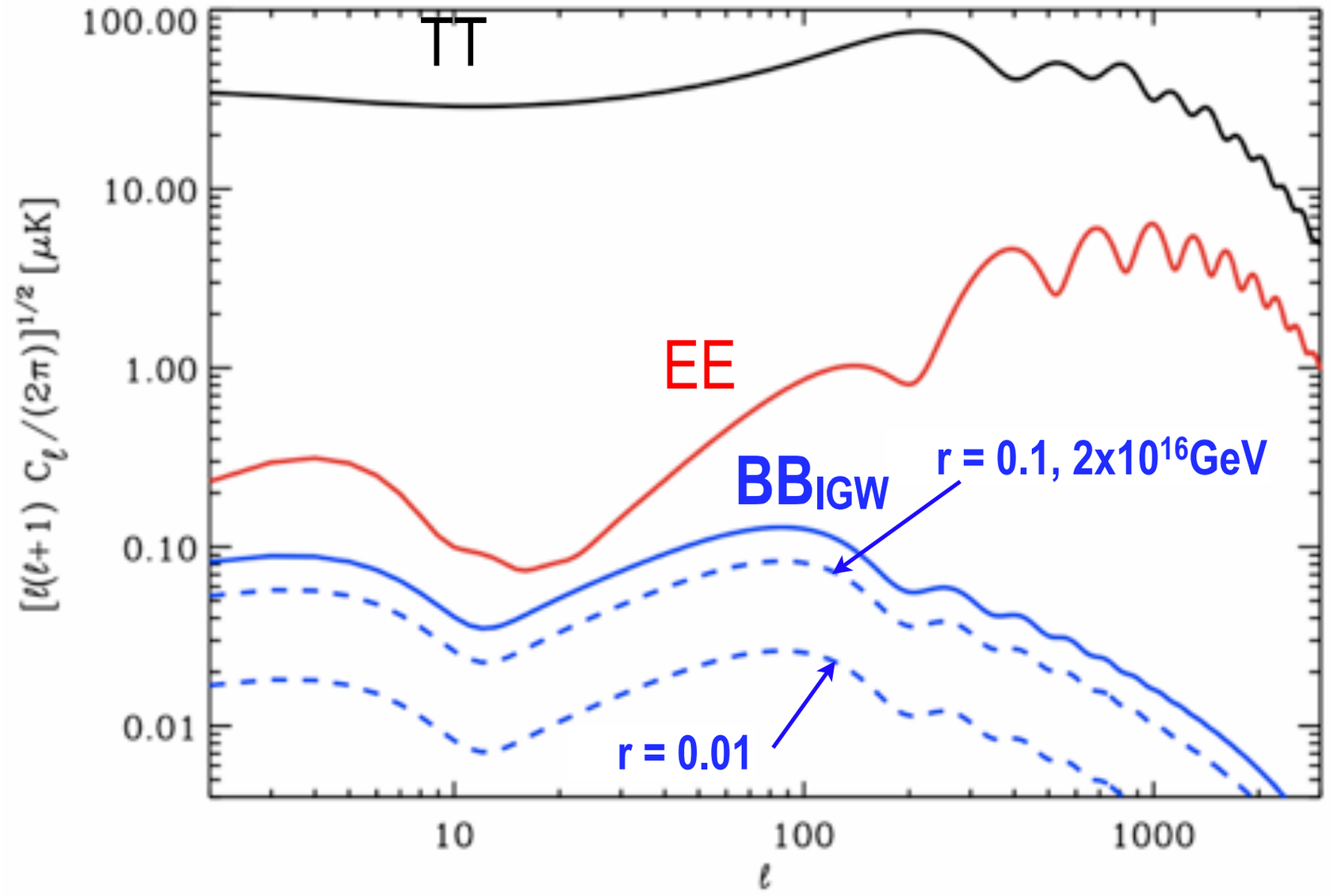
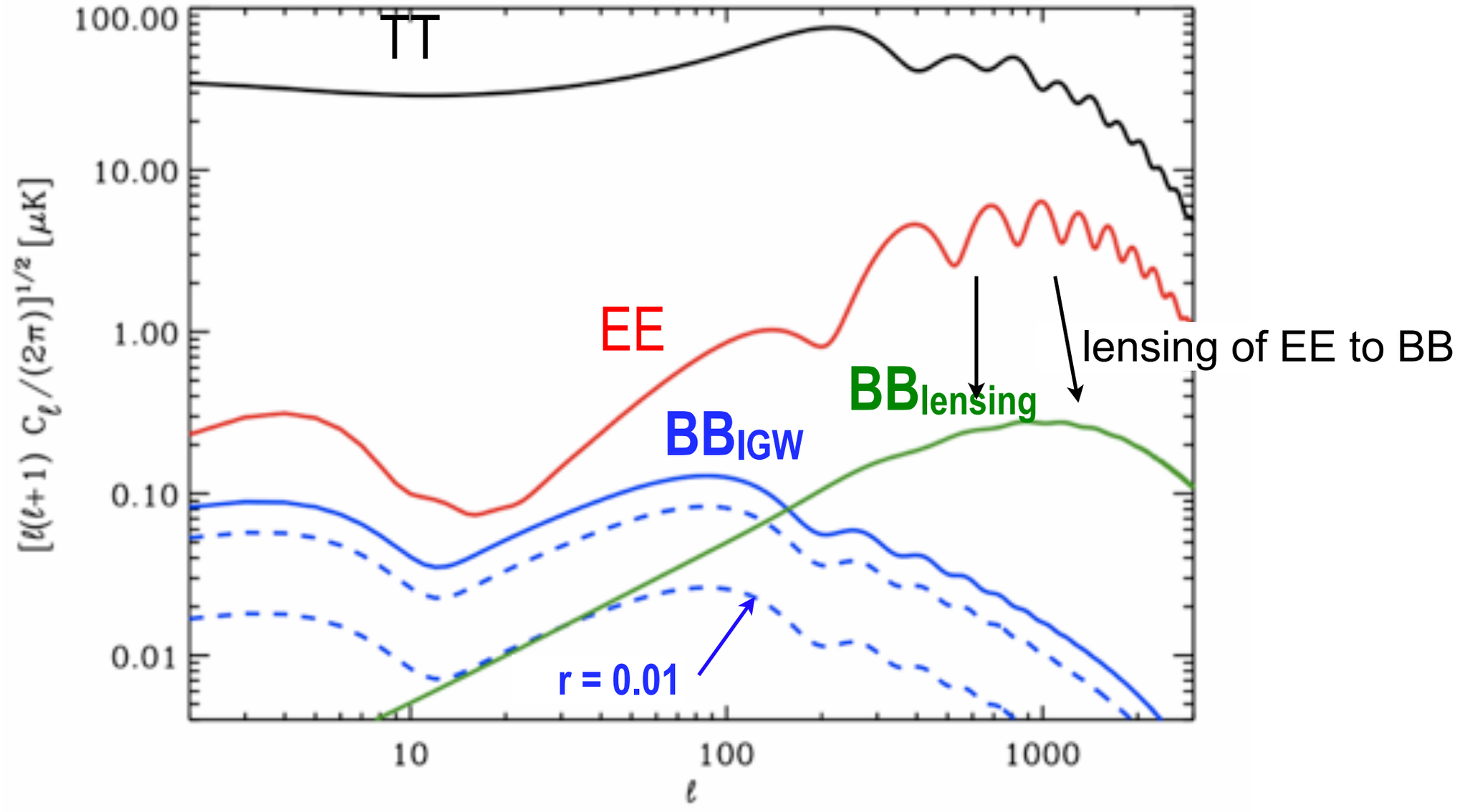
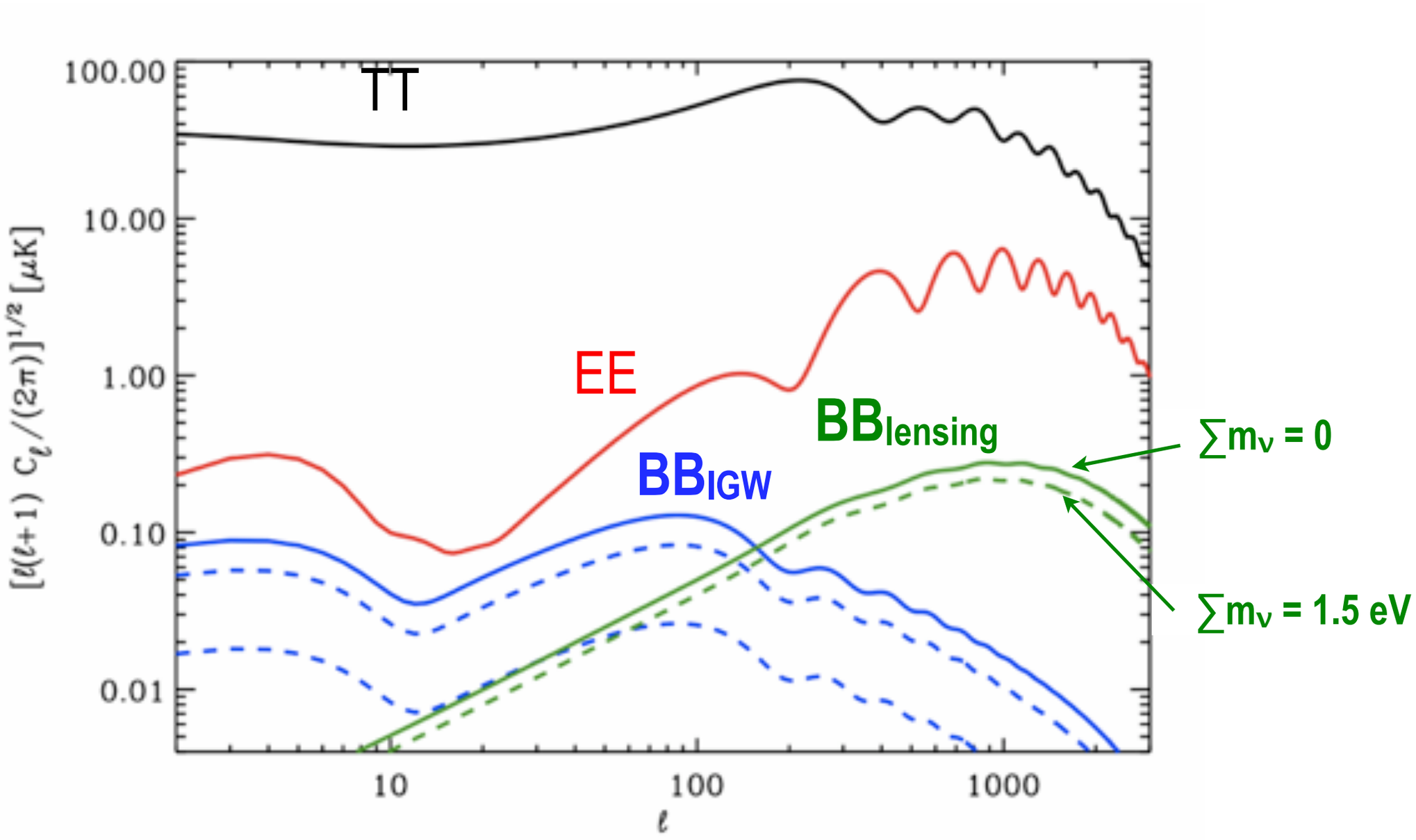


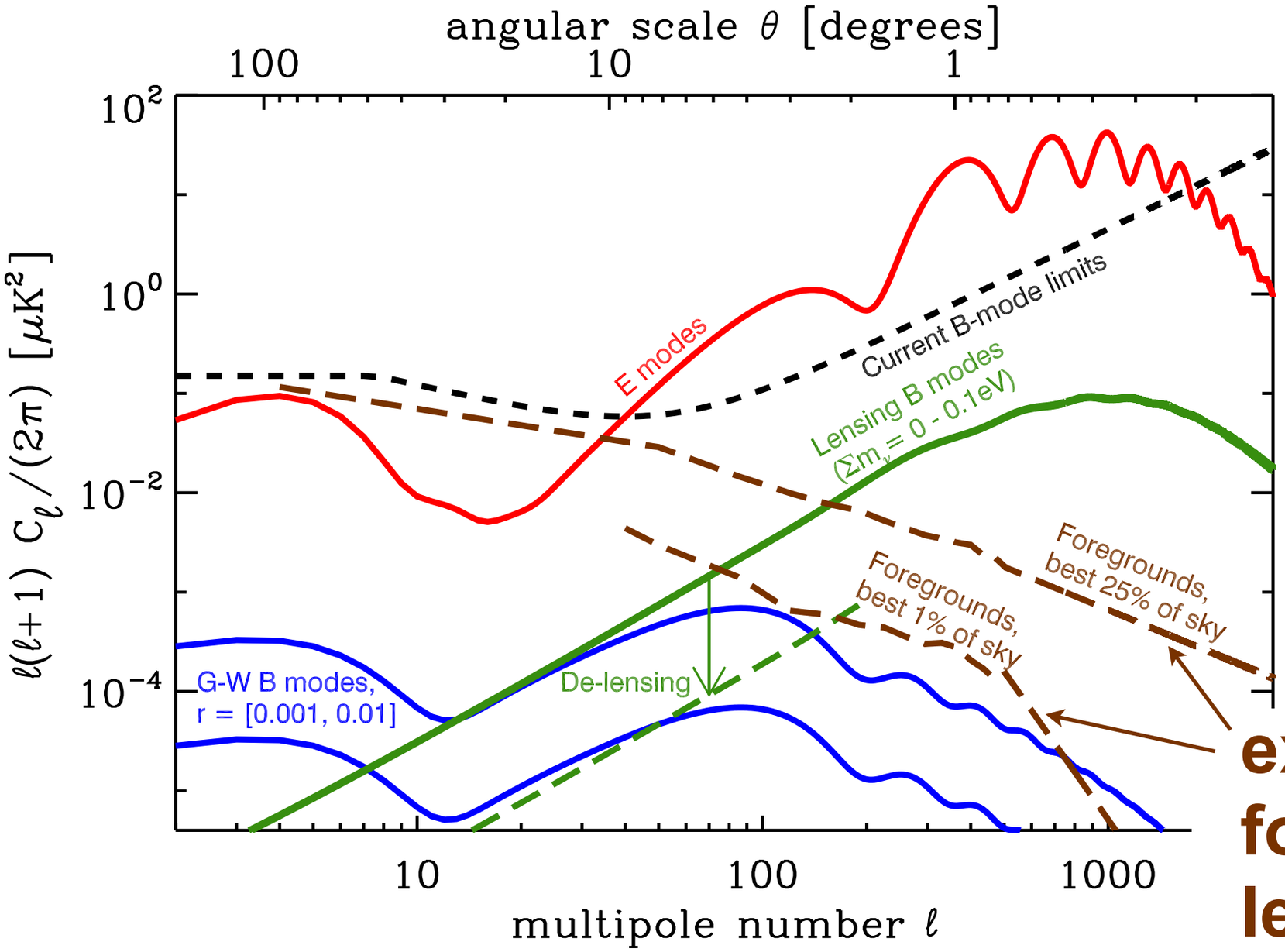
CMB polarization:
the next frontier for lensing & inflation



CMB polarization:
the next frontier for lensing & inflation



CMB polarization:
the next frontier for lensing & inflation



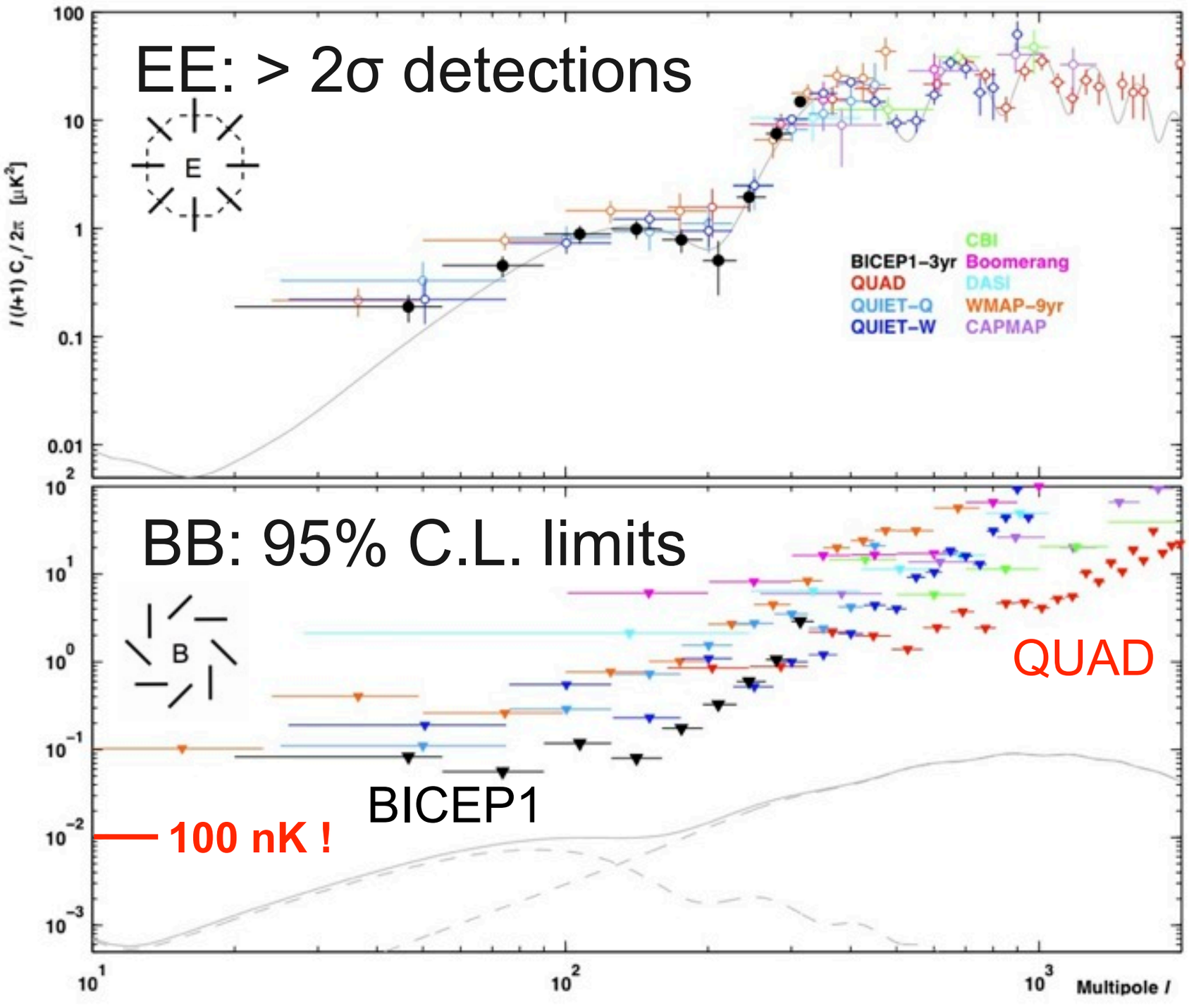
expected foreground levels

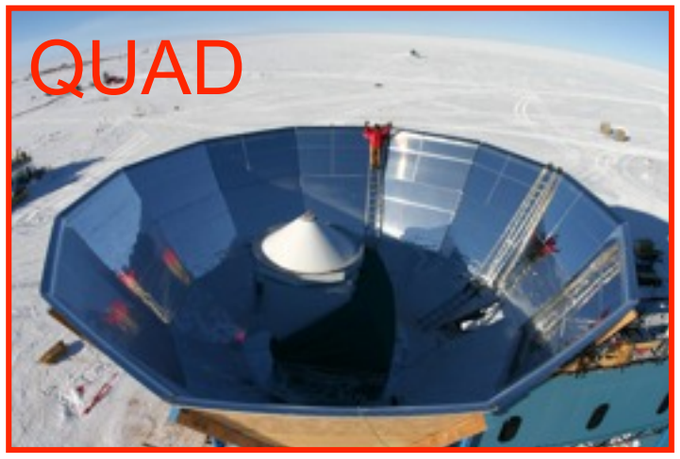
Shifted and expanded scale: 0.001 < r < 0.01

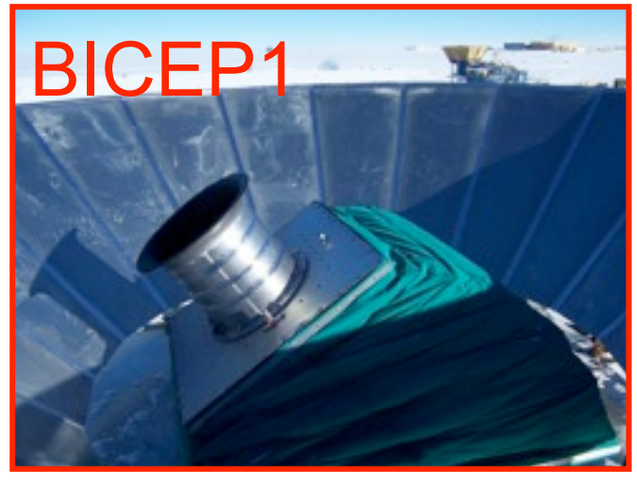
Figure from Snowmass planning document arXiv:1309.5381

Status of B-mode experiments

Barkats et al., arXiv:1310.1422

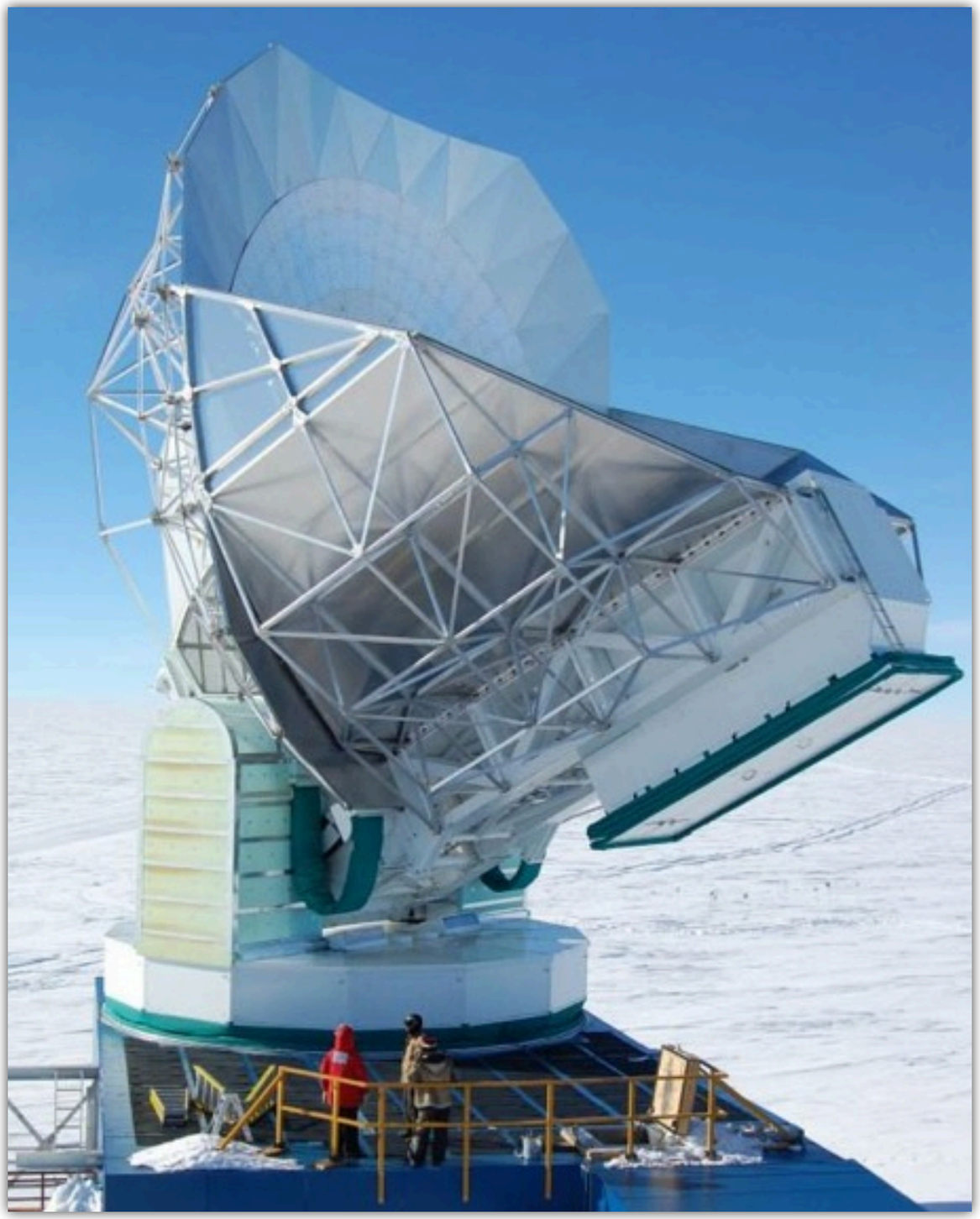






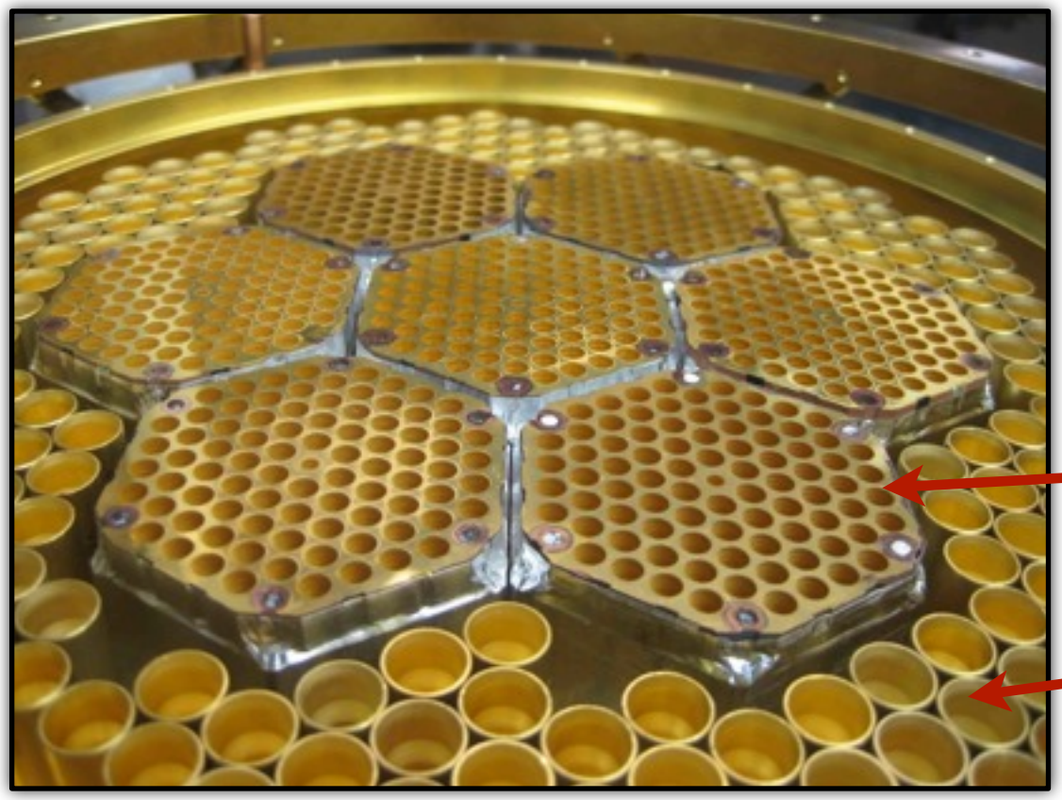
SPTpol:

polarization-sensitive camera on SPT



Status:

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



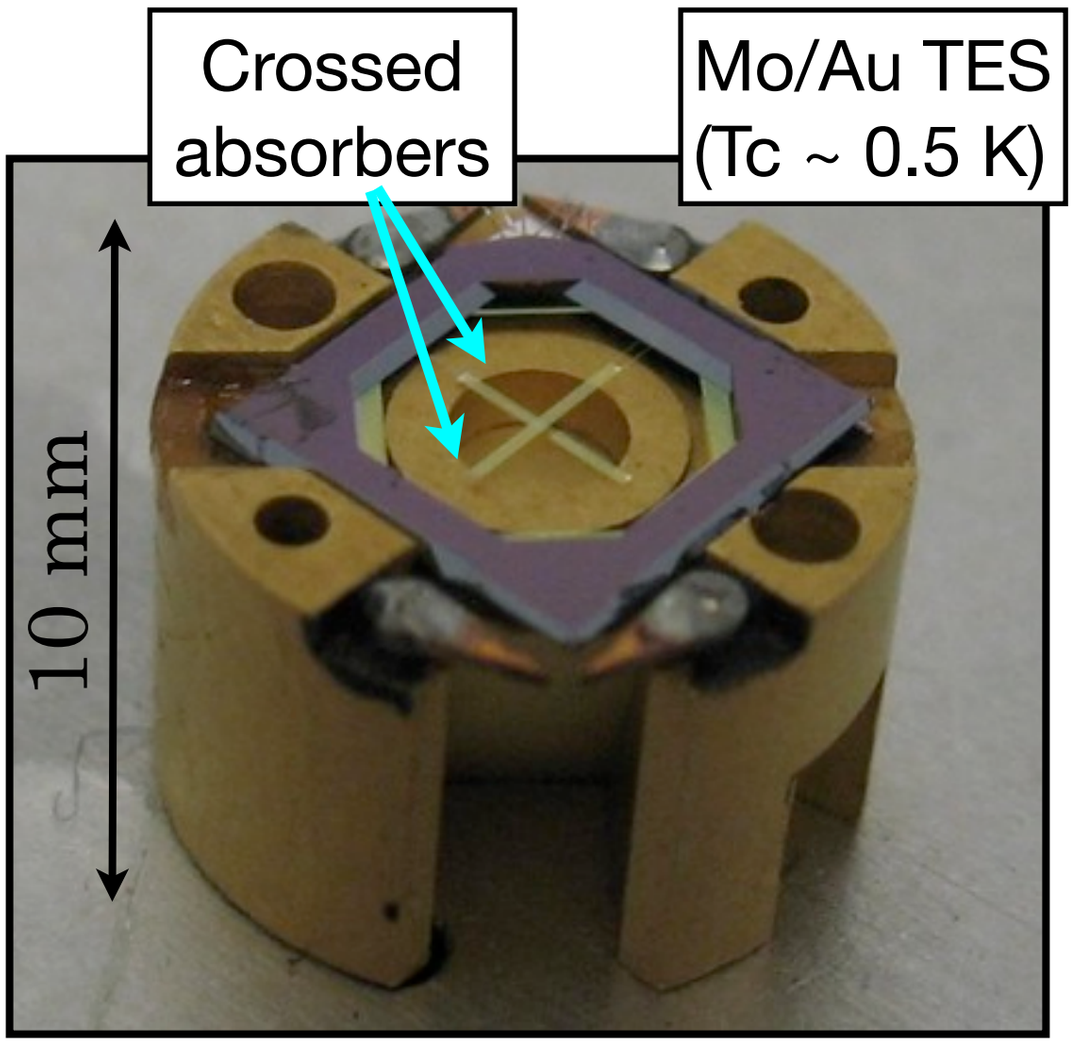
(1176x) **150 GHz** detectors (NIST)

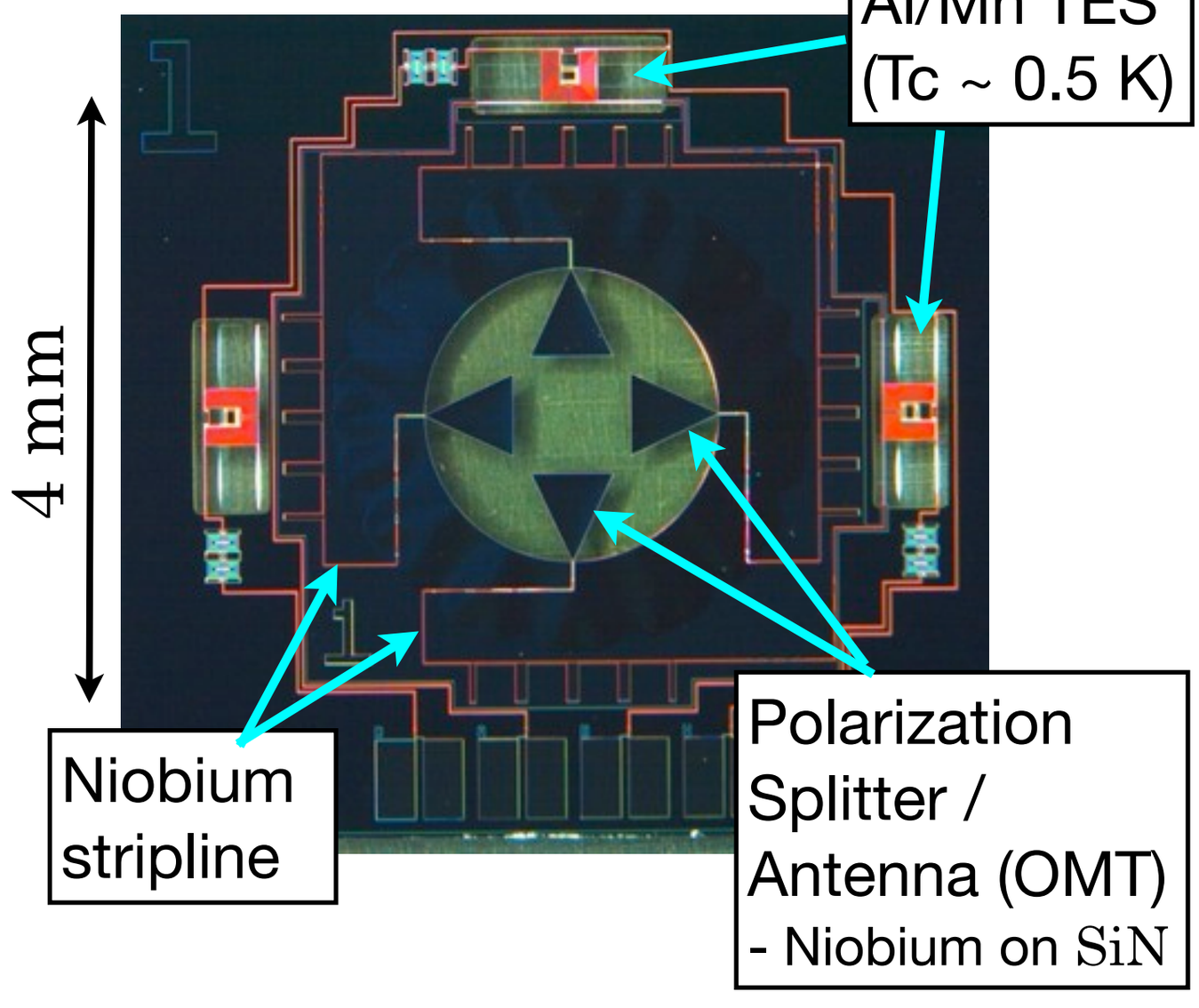
(360x) **100 GHz** detectors, (Argonne National Labs)

SPTpol: Detectors

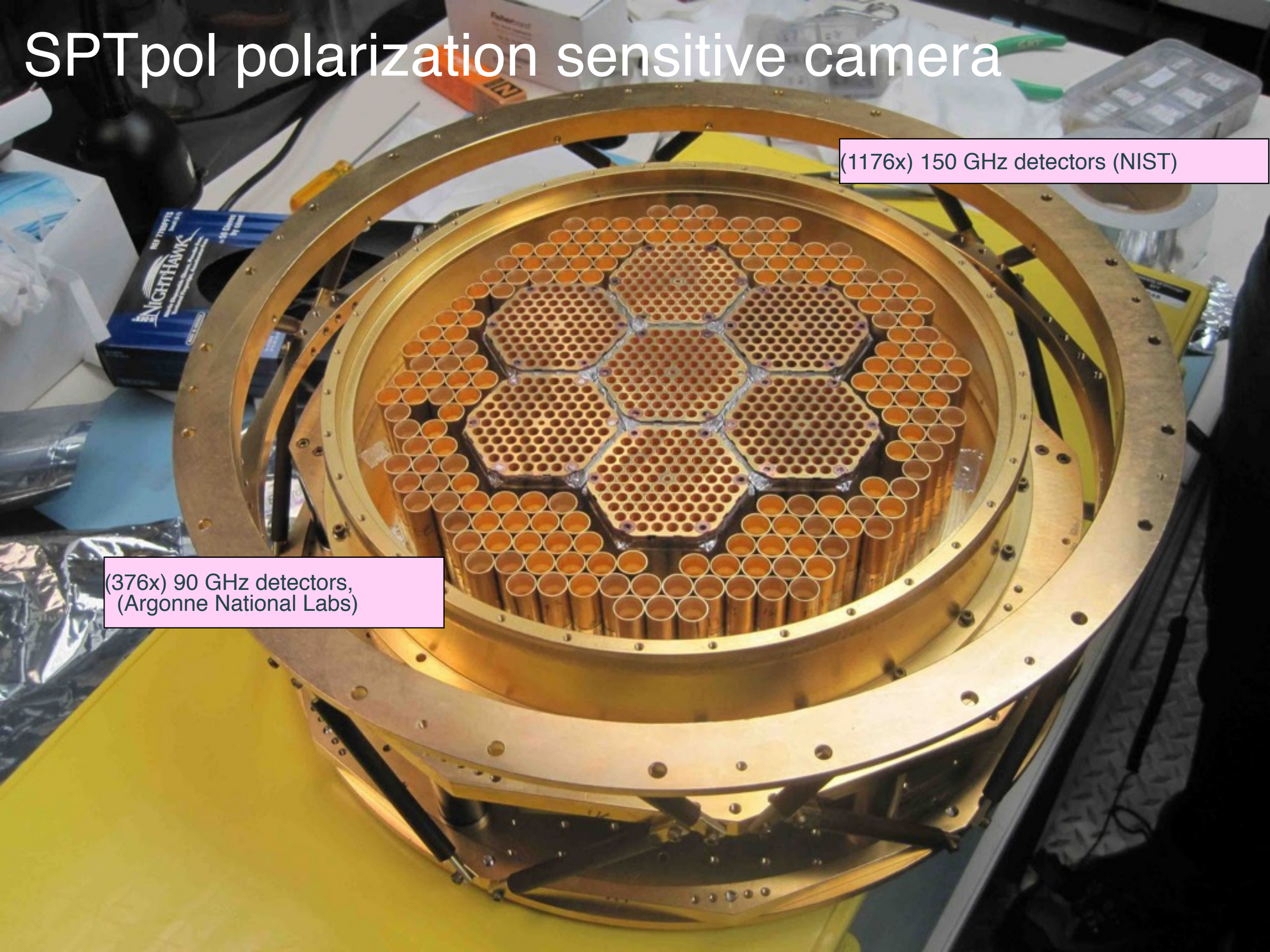
SPTpol used two different detectors technologies

- At 90 GHz, individual pixels, crossed absorbers with TES made at Argonne
- At 150 GHz, array of antenna-coupled TES made at NIST (Boulder)





SPTpol polarization sensitive camera



(1176x) 150 GHz detectors (NIST)

(376x) 90 GHz detectors,
(Argonne National Labs)

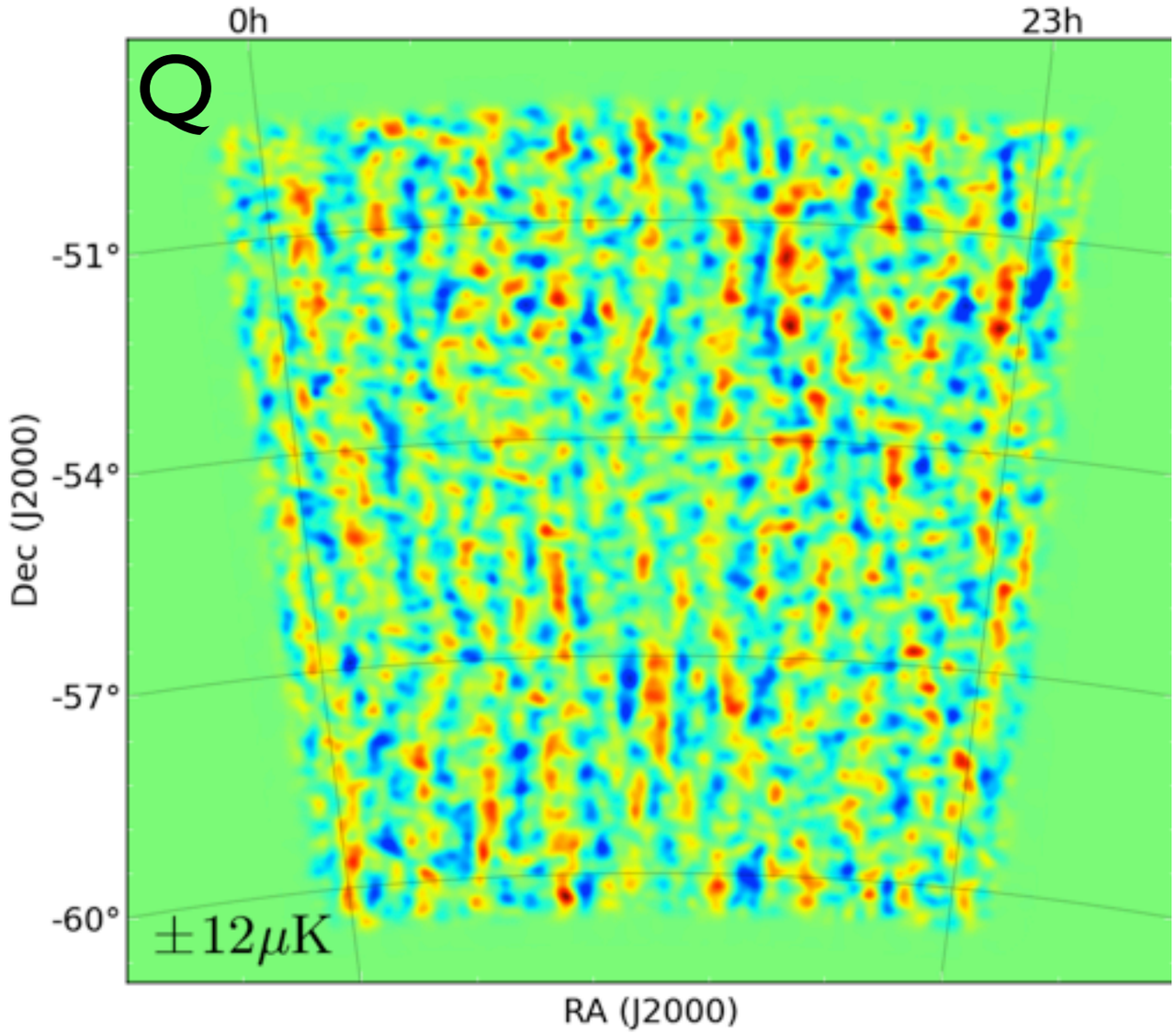
on sensitive camera

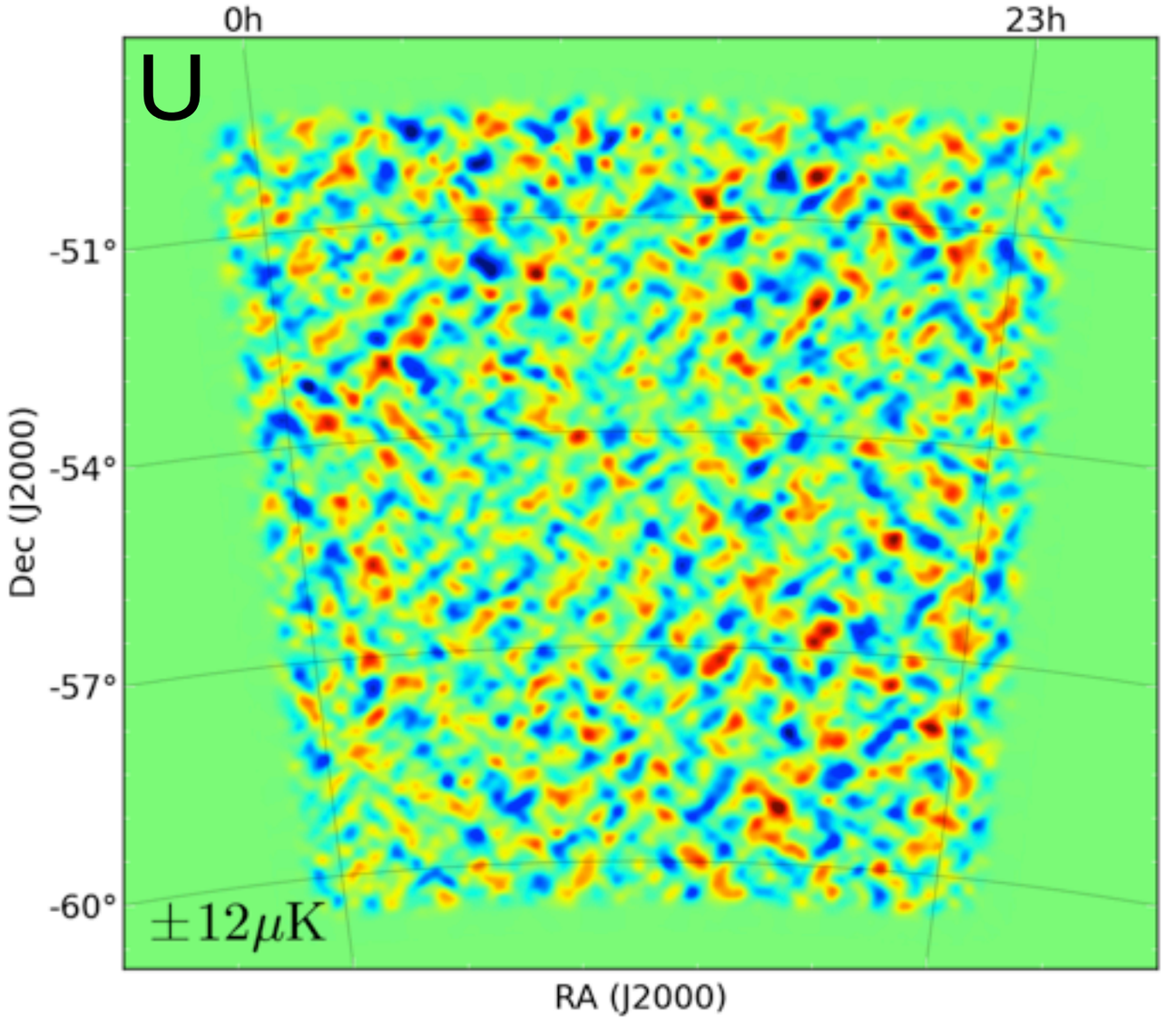
(1176x) 150 GHz detectors (NIST)

(376x) 90 GHz detectors,
(Argonne National Labs)

SPTpol 1st light January 2012

SPTpol 100 deg^2 Deep Field from 2012

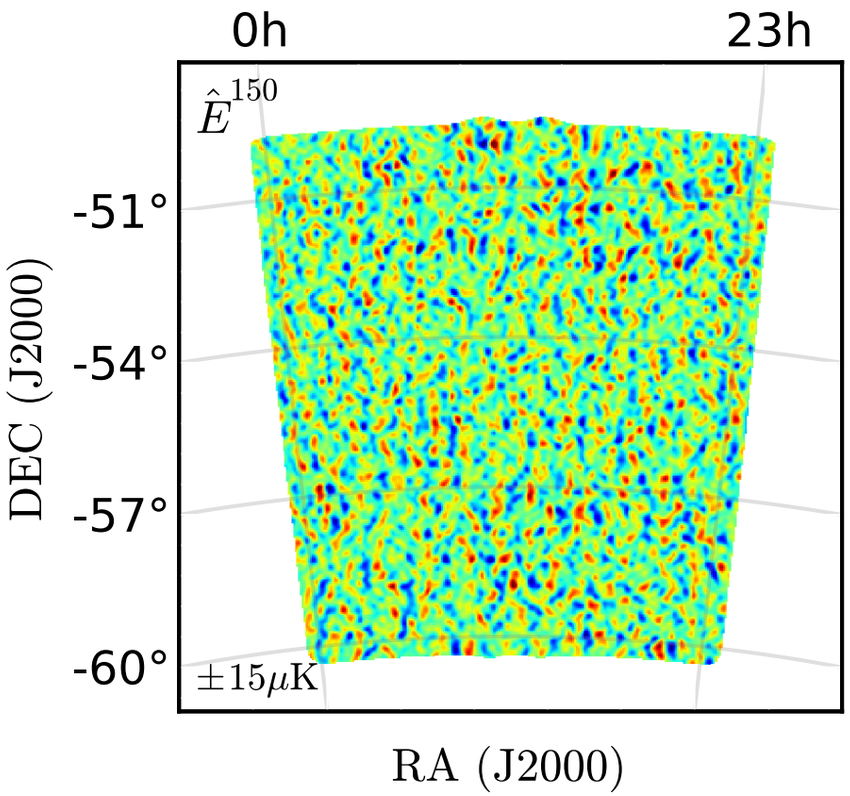




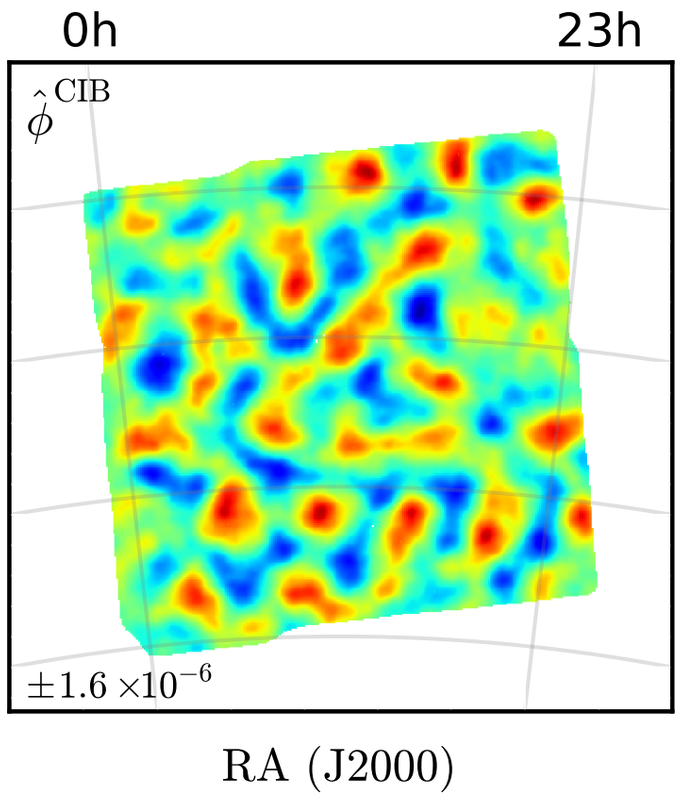
E-mode polarization visible by eye
in150 GHz Stokes Q & U maps

SPTpol Detection of CMB B-mode Polarization

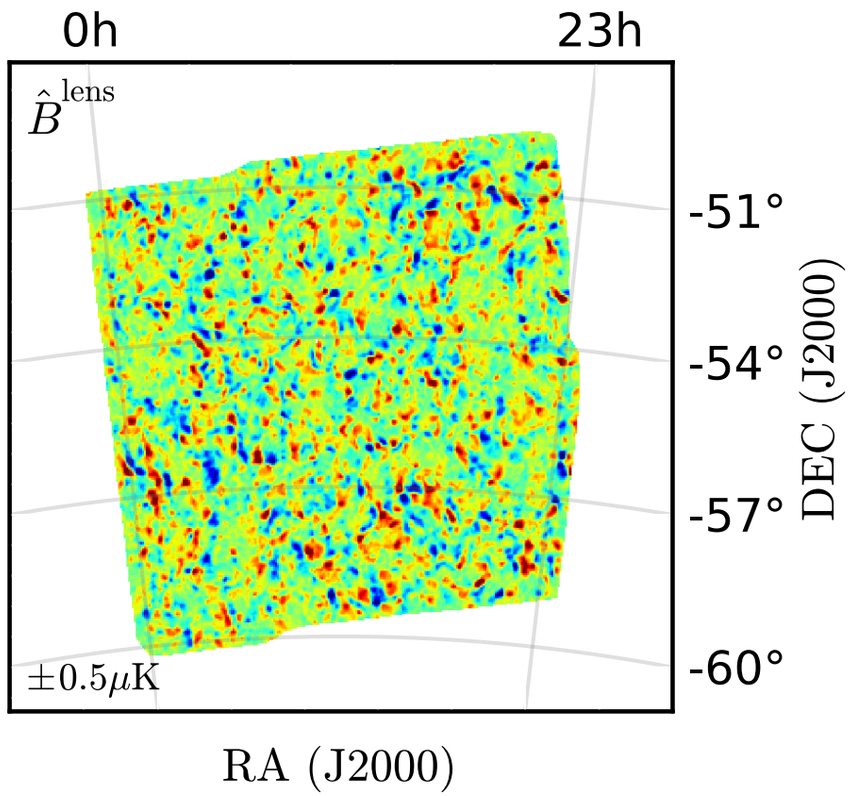
SPTpol Measured E-mode polarization



Lensing Potential from Herschel CIB



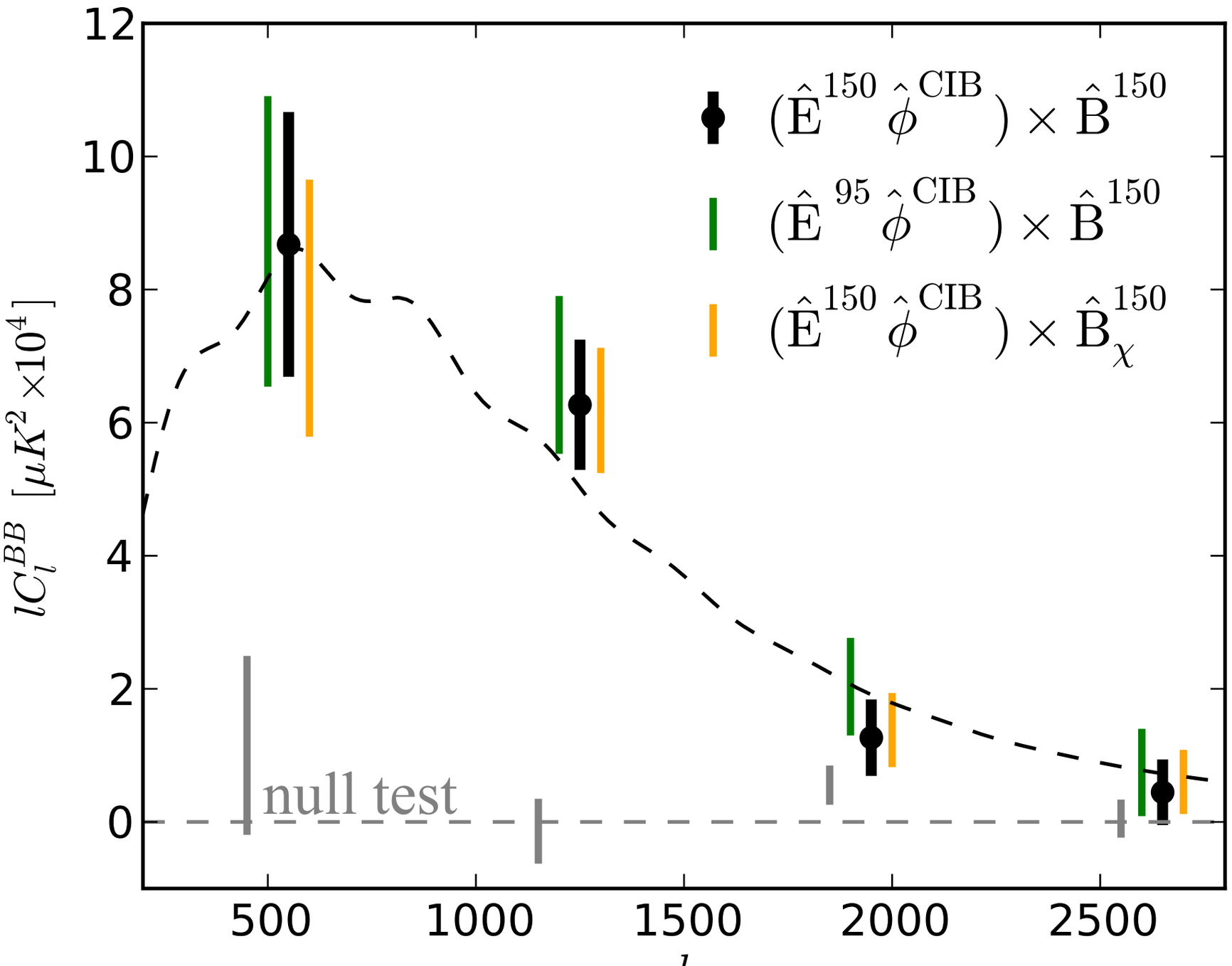
Predicted B-mode polarization

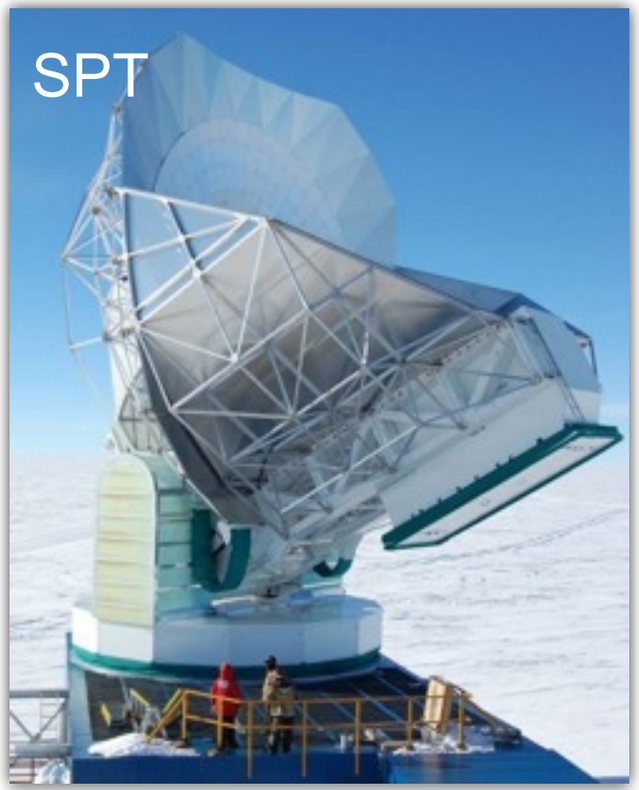


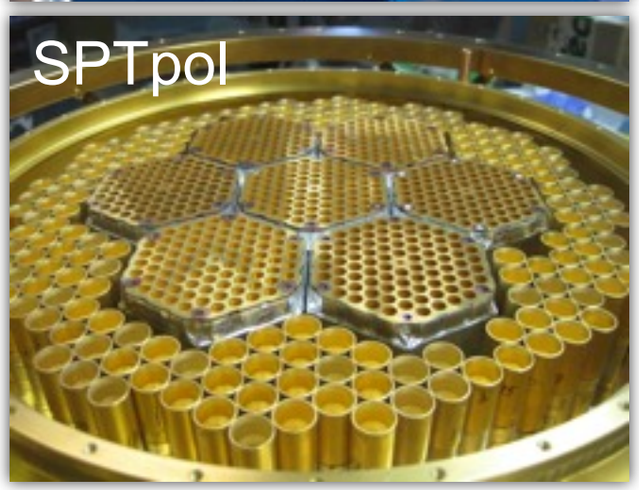
B-mode template to correlate with SPT B-mode map

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

SPTpol Detection of lensing B-modes!

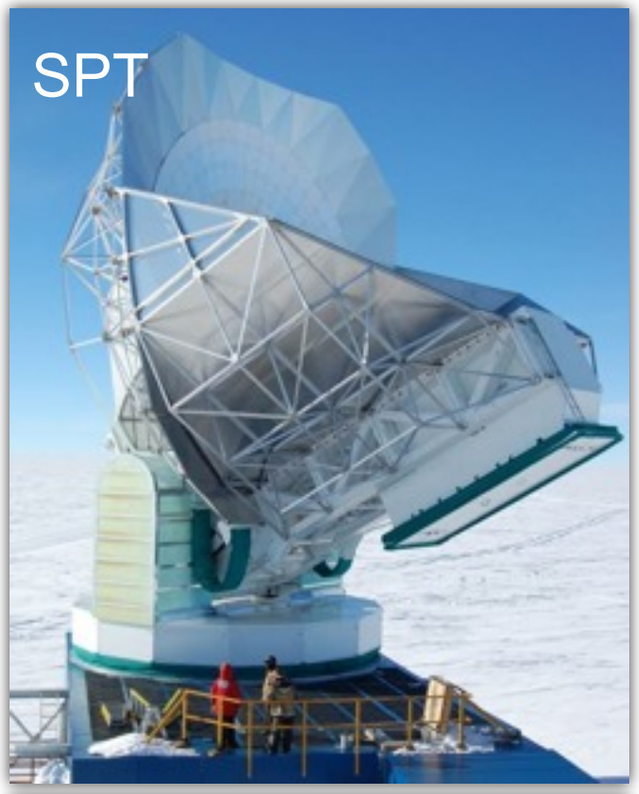


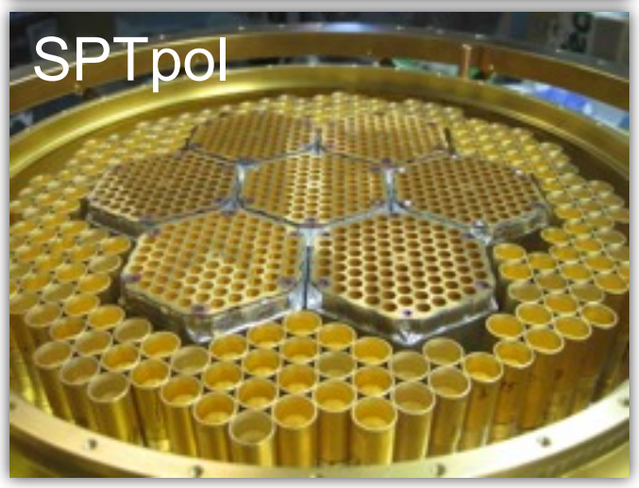




SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)
Also recently detected by Polarbear arXiv:1312.6645 & 1312.6646

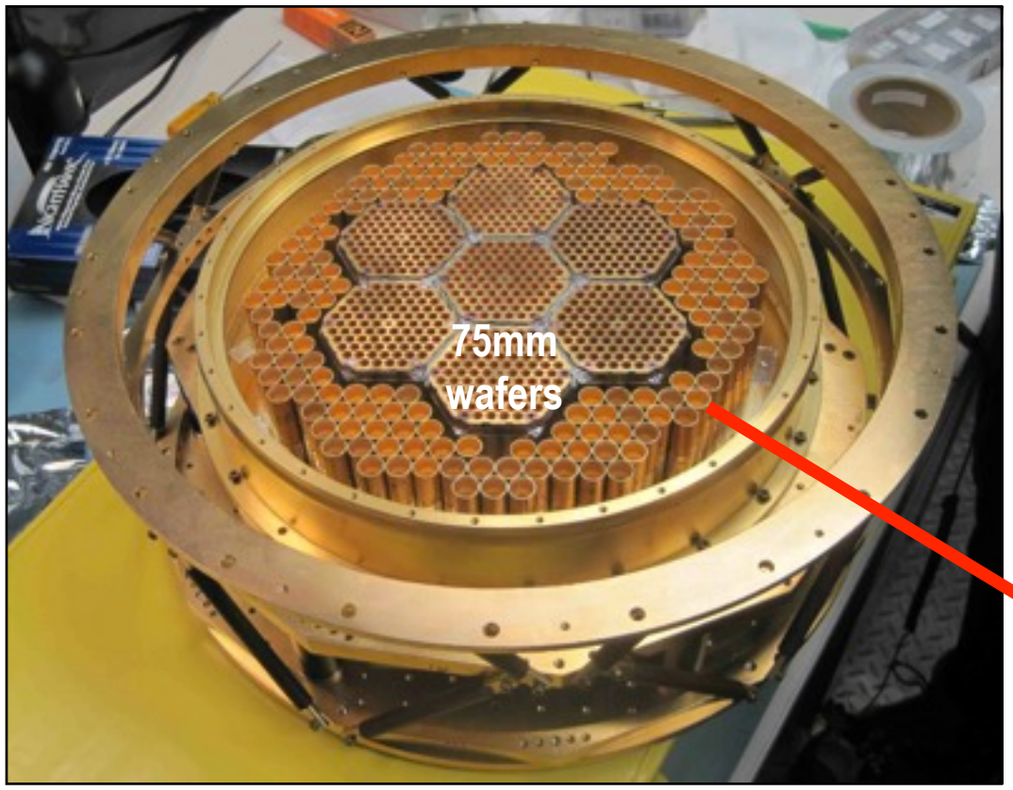
SPTpol Detection of lensing B-modes!





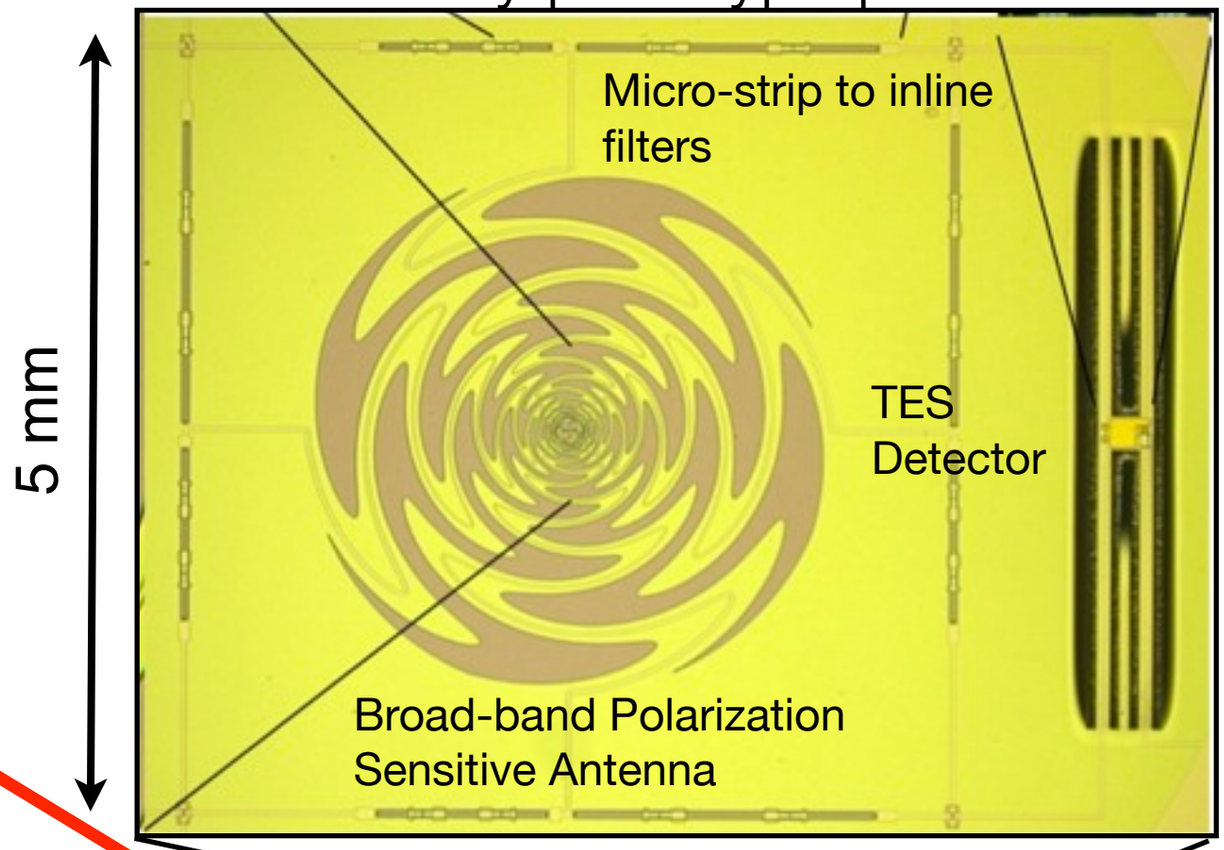
SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)
Also recently detected by Polarbear arXiv:1312.6645 & 1312.6646

next: SPT-3G

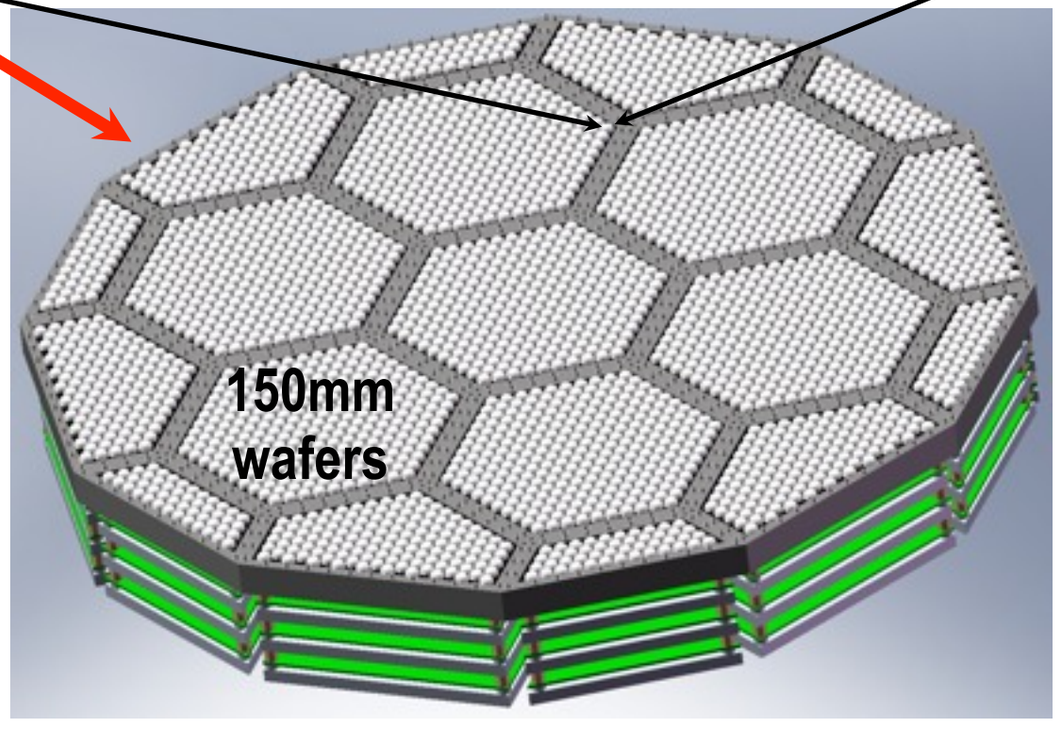


2012: SPTpol Stage II
1600 detectors (ANL/NIST)

UC Berkeley prototype pixel



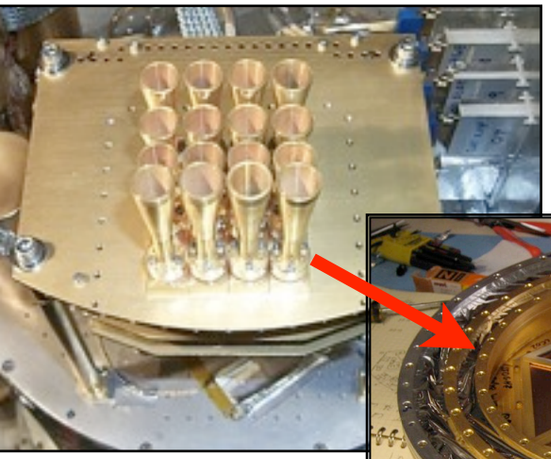
ANL, LBNL, SLAC, Polarbear and SPT teams working on Stage II to Stage III detector advance based on 3-band, dual polarization pixel.



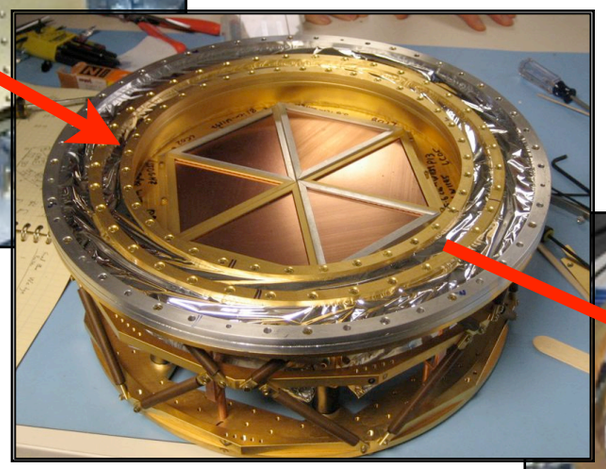
2016: SPT-3G Stage III 4x larger area
15,234 detectors at T = 250mK

Whats next? Evolution of CMB Focal Planes

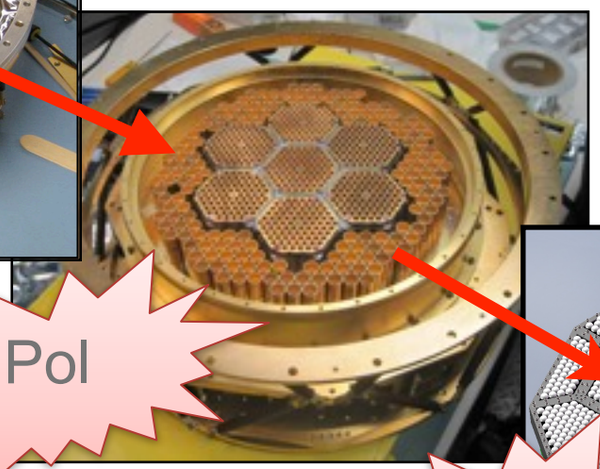
2001: ACBAR
16 detectors



2007: SPT
960 detectors

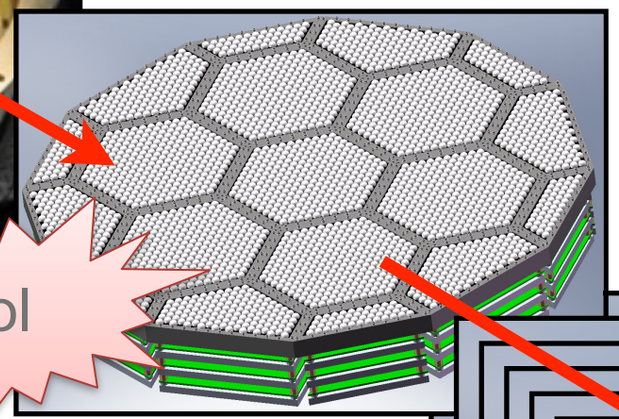


Stage-2
2012: SPTpol
~1600 detectors



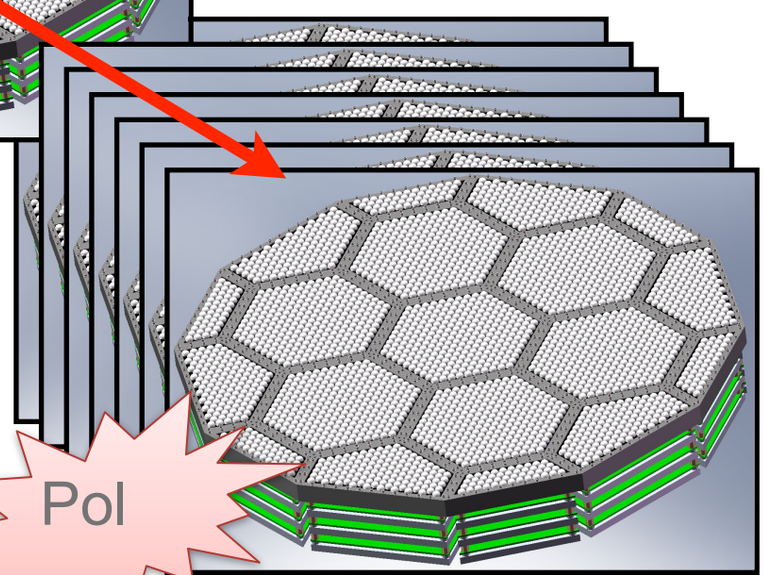
Pol

Stage-3
2016: SPT-3G
~15,200 detectors



Pol

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

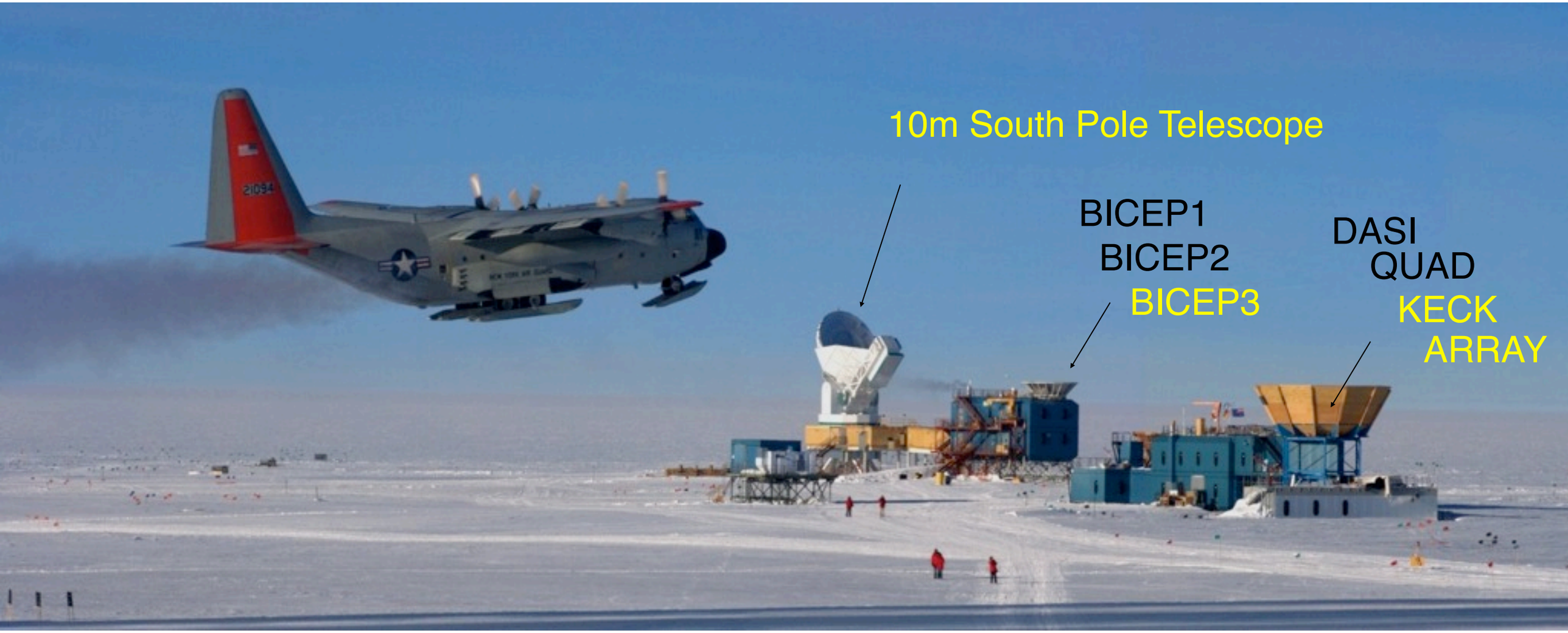


Pol

CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

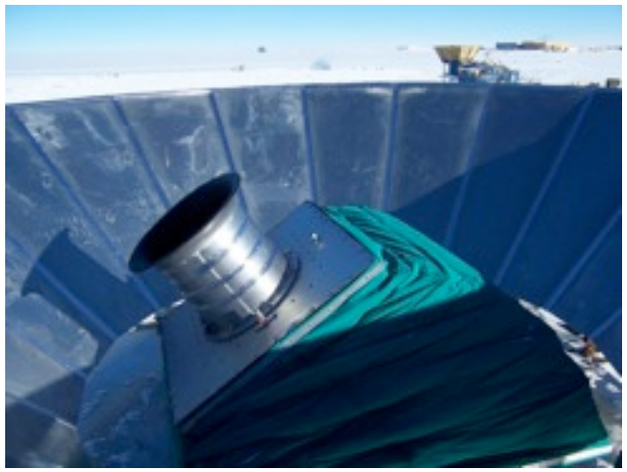
Detectors have been background limited by photon “shot” noise.
Sensitivity improvements are made by having ***more detectors.***

Also amazing progress by the BICEP/KECK team on degree beam CMB polarization measurements



Observing same sky fields as SPTpol at degree angular resolution to target inflationary B modes
→ combined SPT/BICEP/KECK data will lead to best constraints

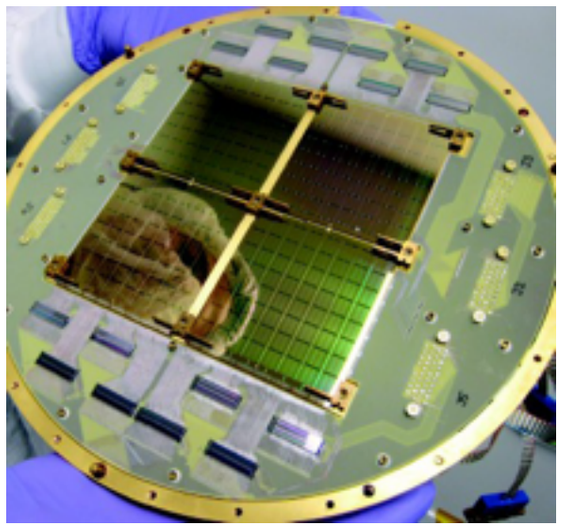
BICEP1
2006-2008



50 @ 100 GHz
48 @ 150 GHz

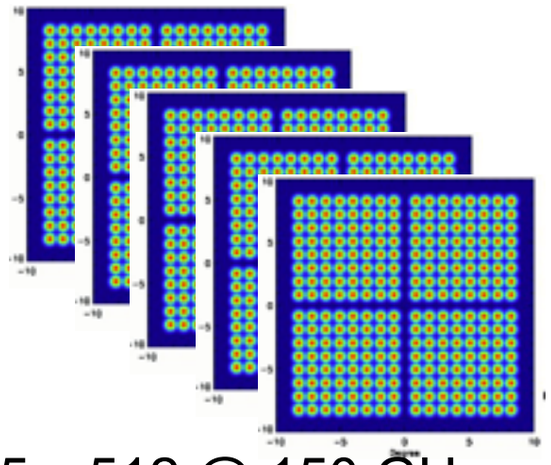
Current best limits on
Inflationary polarization

BICEP2
2010-2012



512 @ 150 GHz
JPL

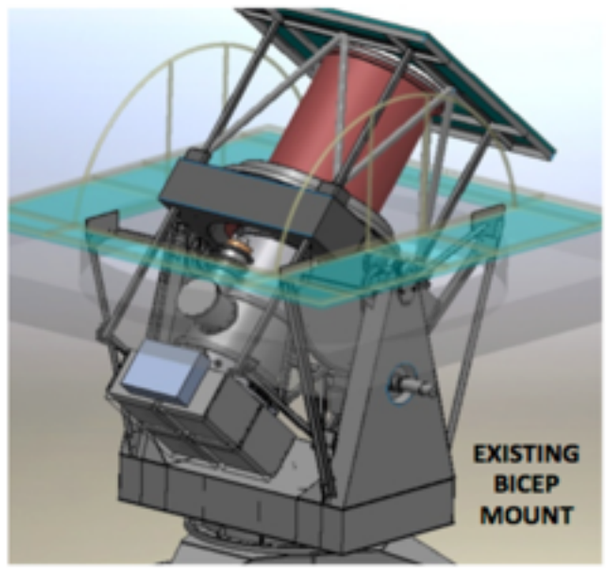
Keck Array
on DASI mount

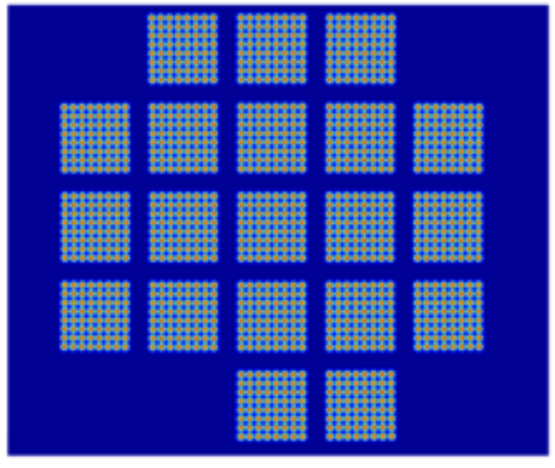


5 x 512 @ 150 GHz

\+

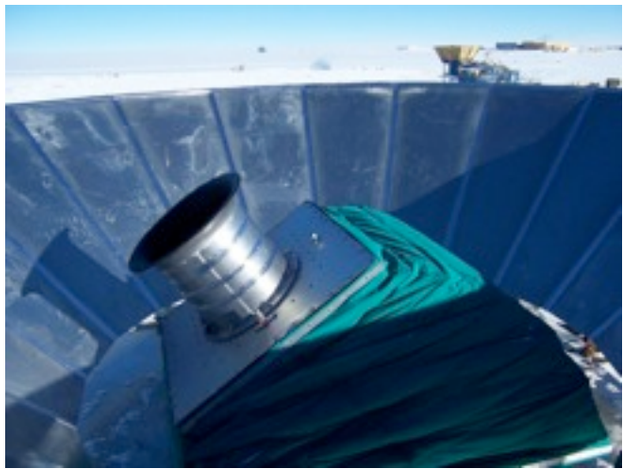
BICEP3
2015





2056 @ 100 GHz

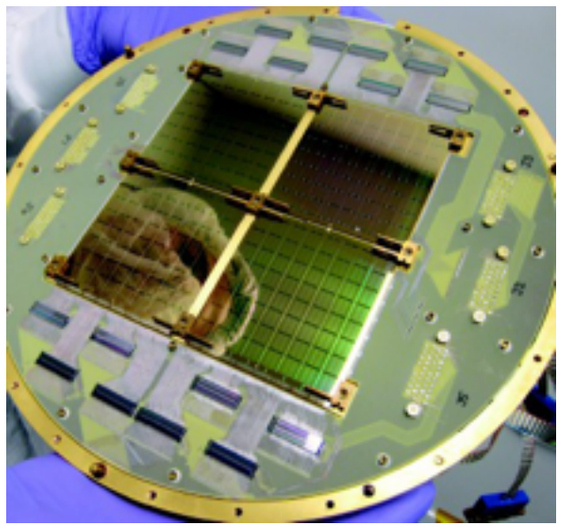
BICEP1
2006-2008



50 @ 100 GHz
48 @ 150 GHz

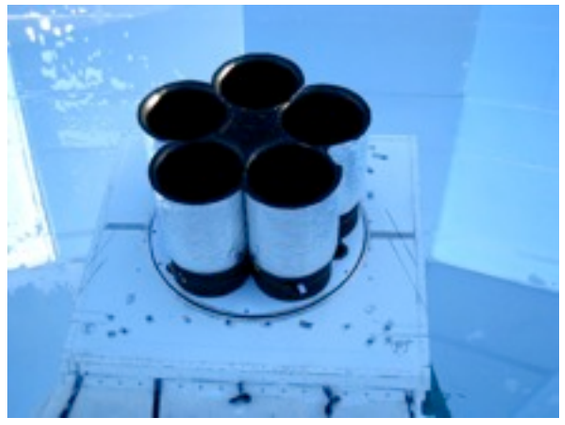
Current best limits on
Inflationary polarization

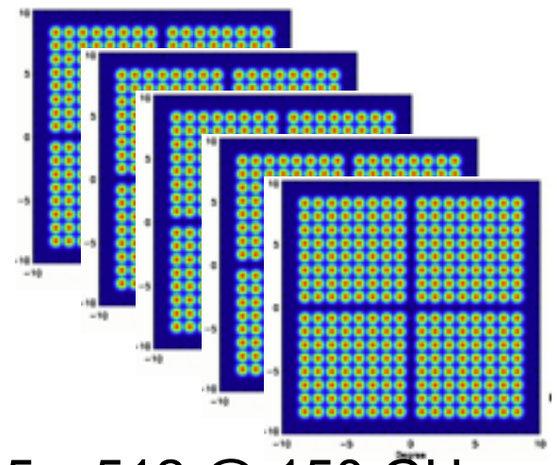
BICEP2
2010-2012



512 @ 150 GHz
JPL

Keck Array
on DASI mount

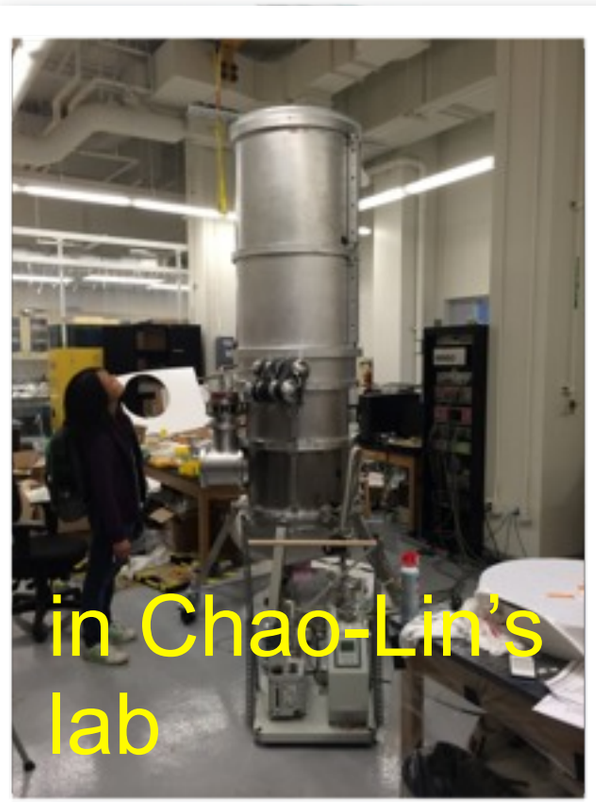


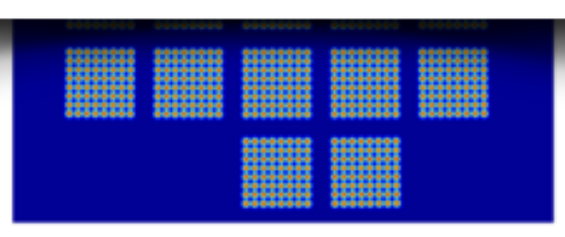


5 x 512 @ 150 GHz

\+

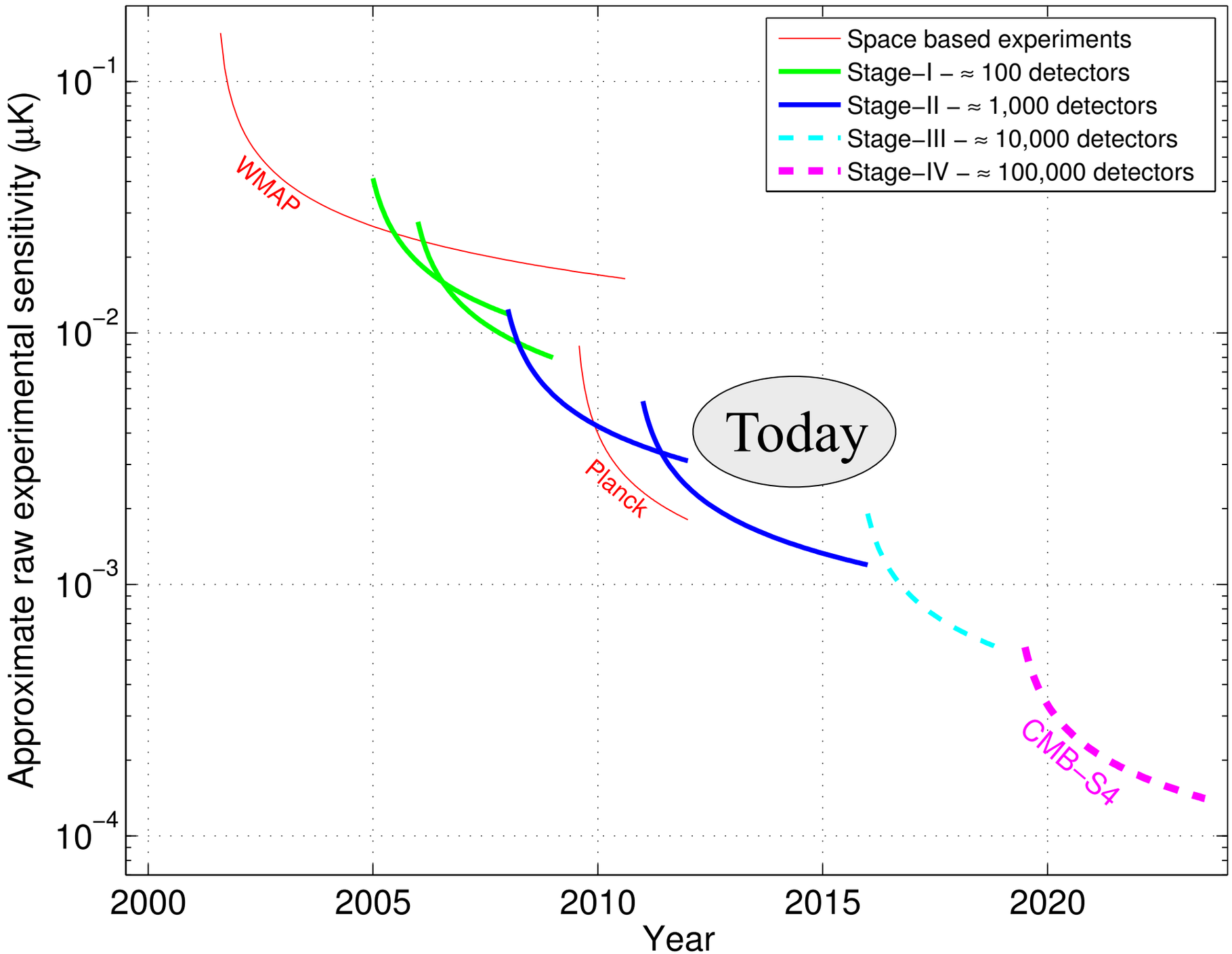
BICEP3
2015





2056 @ 100 GHz

CMB Experimental Stages



Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB-S4: A CMB Stage 4 Experiment

- **Experimental Configuration:**
  - 200,000 - 500,000 detectors on multiple platforms
  - Spanning 40 - 240 GHz for foreground removal
  - < 3 arcmin resolution required for CMB lensing, neutrino science

- **Two Nested Surveys:**
  - Inflation survey (~few% of sky)
  - Neutrino survey (~half of sky)

- **Target noise of ~1 uK-arcmin depth over half the sky, starting in 2020**

Primary technical challenge will be from the scaling of the CMB detector arrays

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

Projected CMB Constraints

	$\sigma(r)$	$\sigma(N_{\rm eff})$	$\sigma(\Sigma m_\nu)$
Current CMB	**0.10**	**0.34**	**117 meV**
2016 Stage 2: SPTpol	0.03	0.12	96 meV
2020 Stage 3: SPT-3G	0.01	0.06	61[a] meV
2024 Stage 4: CMB-S4	**0.001**	**0.02**	**16[b] meV**

[a] Includes BOSS prior
[b] Includes DESI prior

The CMB measurements will achieve important benchmarks:

- Energy scale of inflation? Test large vs small field inflation
- Dark Radiation? New physics in neutrino or dark sector?
- Cosmological detection of neutrino mass, Σm_ν.

Snowmass: CF5 Neutrinos + Inflation documents arXiv:1309.5383, 1309.5381, see also Wu et al., arXiv:1402.4108

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 "dark radiation"?

What are the neutrino masses?

What is dark energy?

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

Thanks

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