Going to the End of the Earth to Learn About the Beginning of the Universe:

New Results from the South Pole Telescope

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(University of Chicago)

Outline

1) Cosmology and the CMB
- CMB measurements from the South Pole

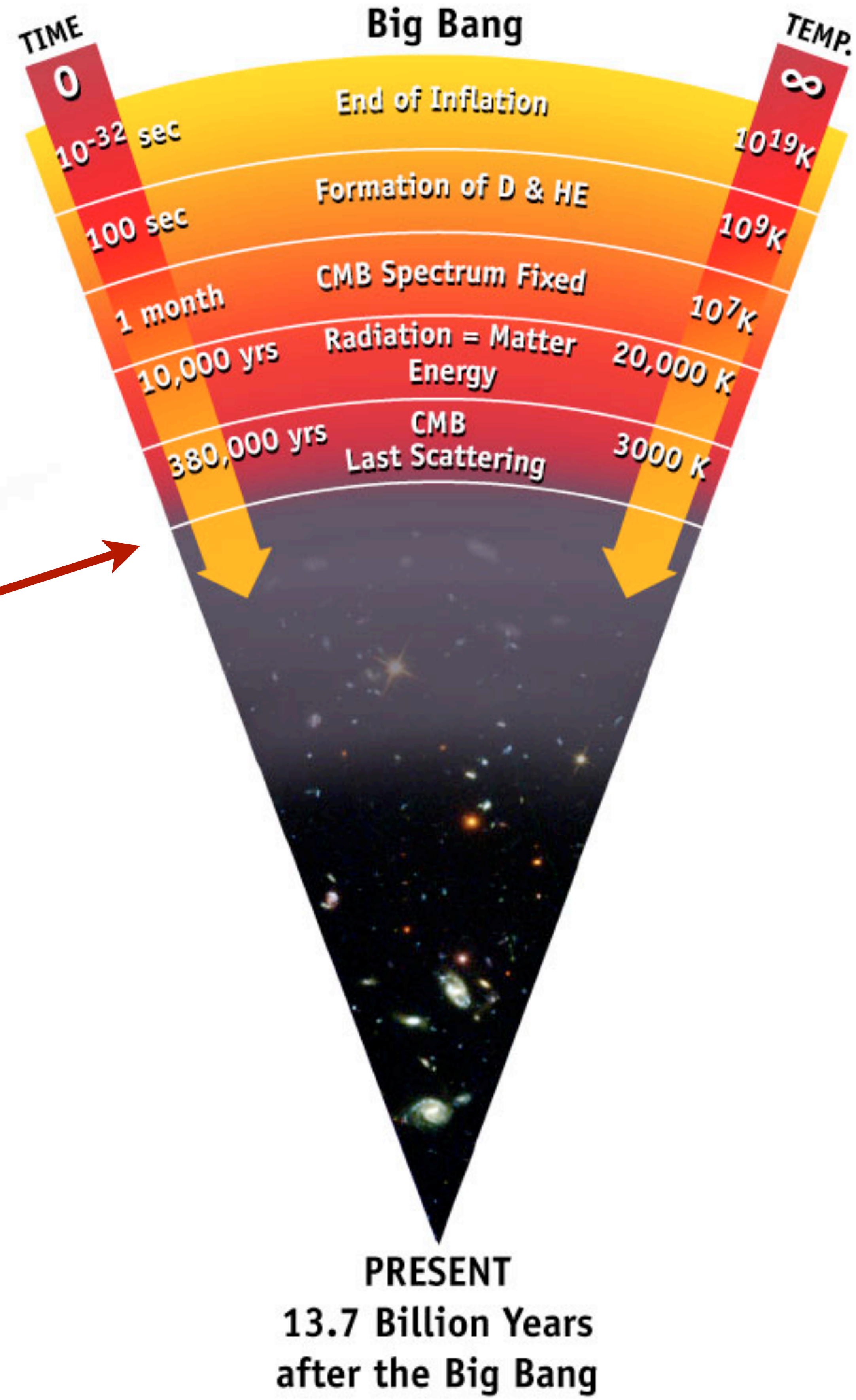
2) The South Pole Telescope (SPT) and new results:
- The Sunyaev-Zel'dovich Cluster Survey
- Primordial CMB anisotropy
- Constraints on Dark Energy and Neutrinos

3) Whats next? SPTpol
- CMB polarization constraints on Inflation, test of physics at 10^{16} GeV

We Live In An Exciting Time for Cosmology

- We have a ***testable*** model that describes the evolution of our Universe from a hot, dense state

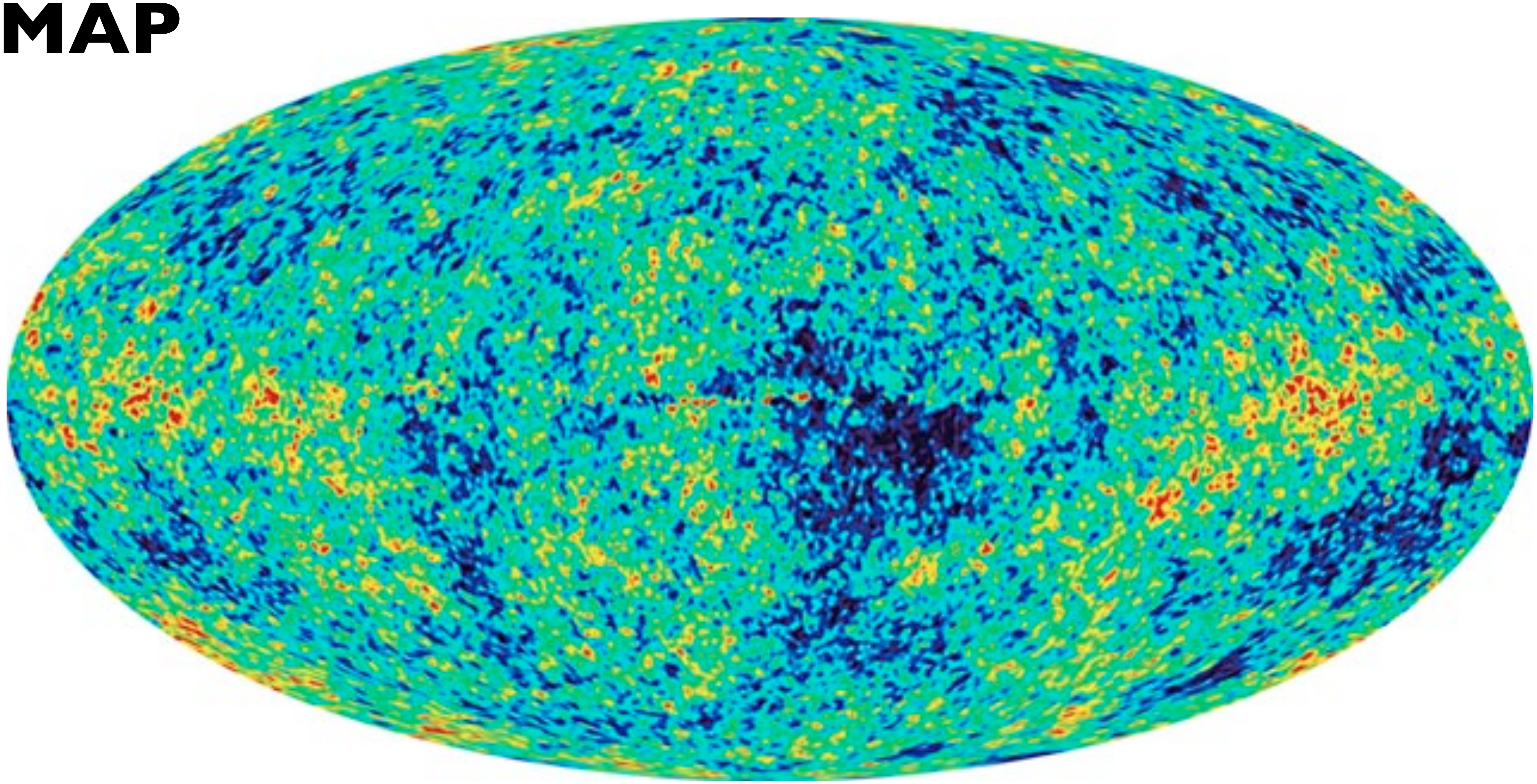
- Our strongest constraints come from the **Cosmic Microwave Background (CMB)**, which provides a snapshot of the infant Universe as it was 14 billion years ago (400,000 years after the Big Bang)



The CMB Power Spectrum

Encoded within the primordial CMB power spectrum is information regarding the Universe's **initial conditions**, its **geometry** (flat vs curved), and its **content** (baryons, dark matter)

WMAP



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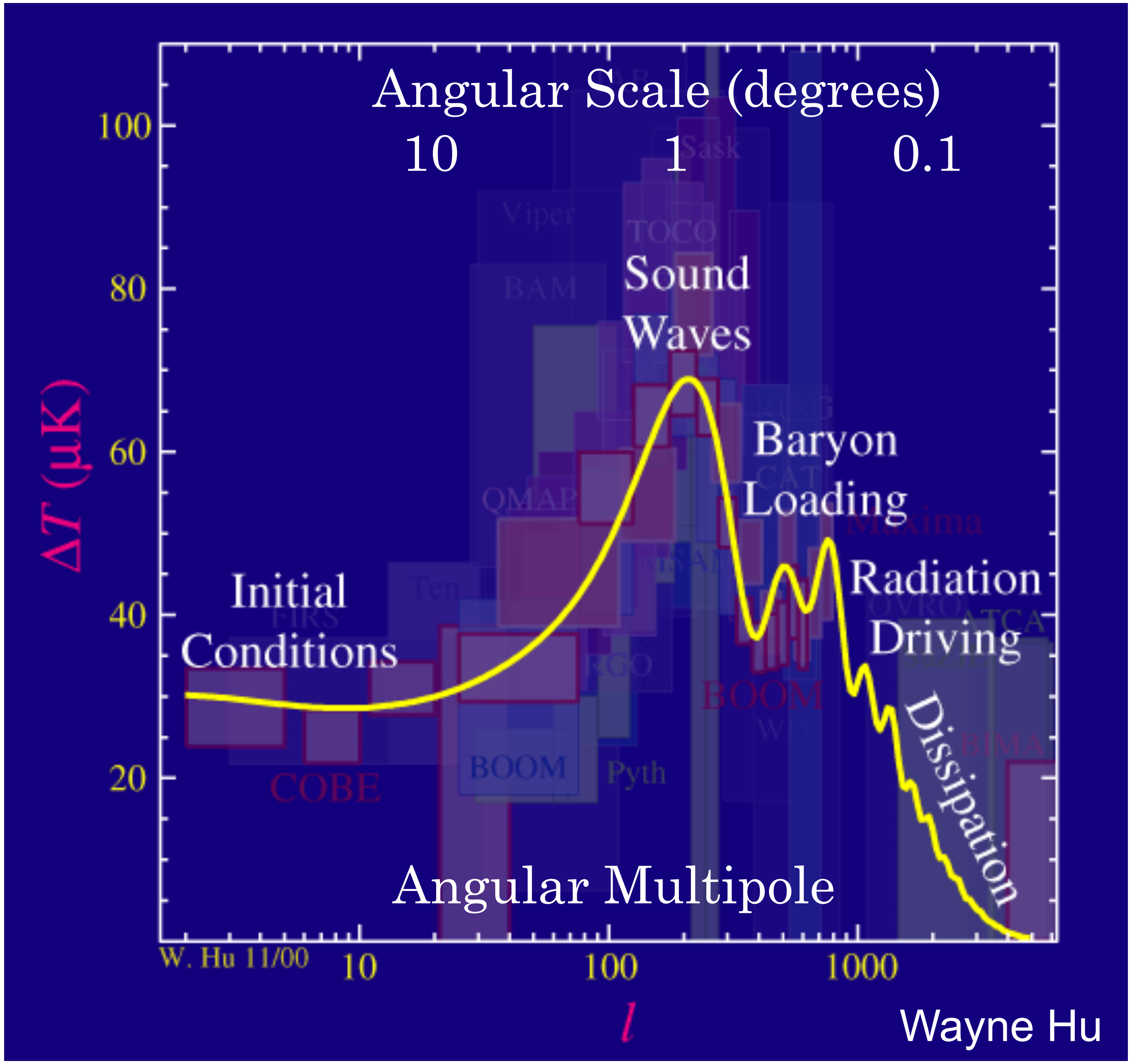
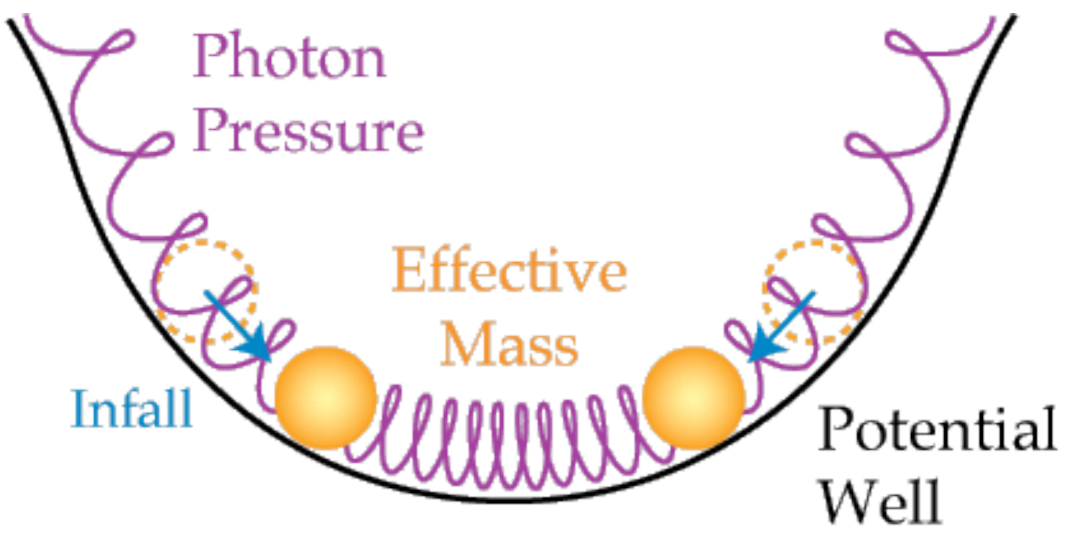
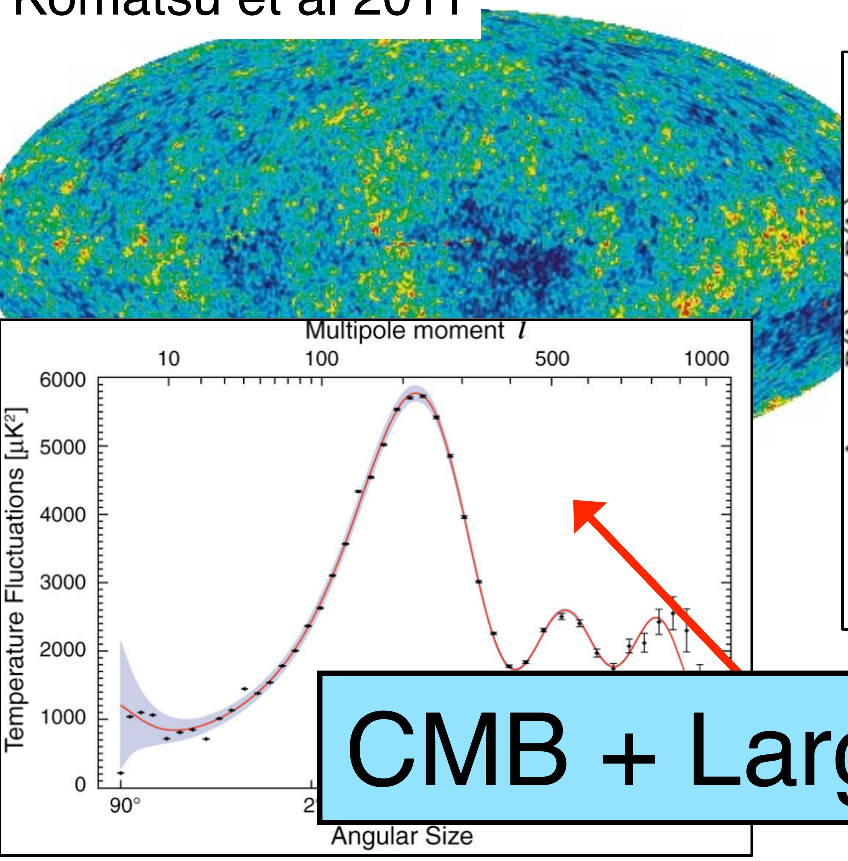




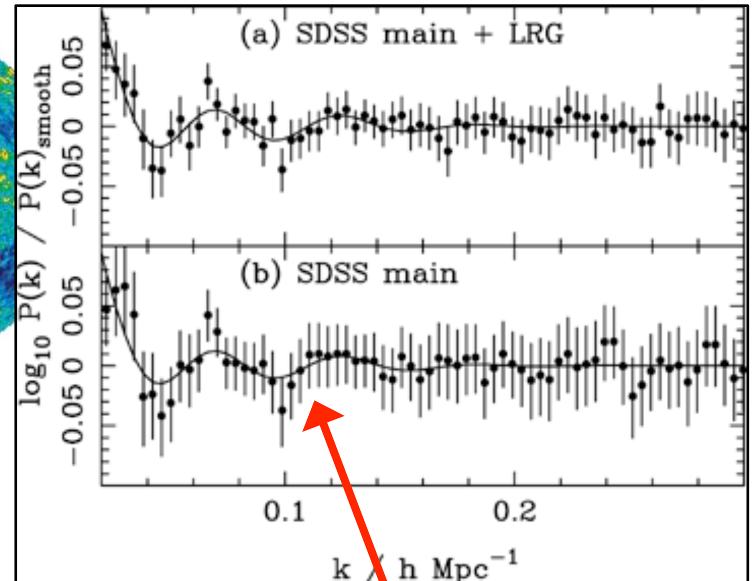
Peaks in power spectrum generated by acoustic oscillations in ~3000 K plasma

Today's Cosmology

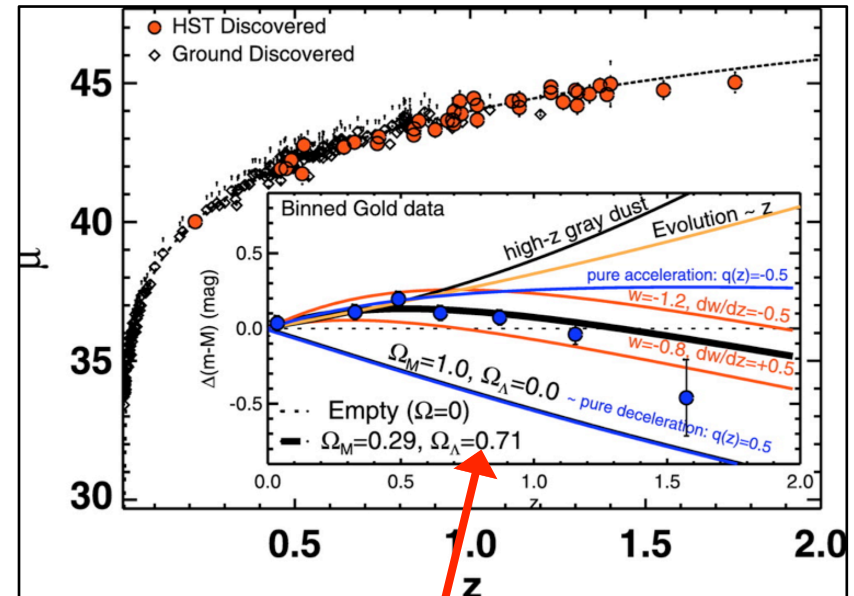
Komatsu et al 2011



Percival et al 2011



Amanullah et al. 2010



CMB + Large Scale Structure + Supernova

- Precision constraints on the content, evolution of the Universe.
- Only ~4% "ordinary" matter, the rest is fit well by a model with **Dark Matter** and **Dark Energy**, and a early period of exponential **Inflation**

Ω_b = 0.0444 +/- 0.008

Ω_{DM} = 0.224 +/- 0.010

Ω_Λ = 0.732 +/- 0.025

Big Questions Remain!

1. Dark Energy

   - What drives cosmic acceleration? Vacuum energy? Do its properties evolve with redshift? Is General Relativity correct on large scales?

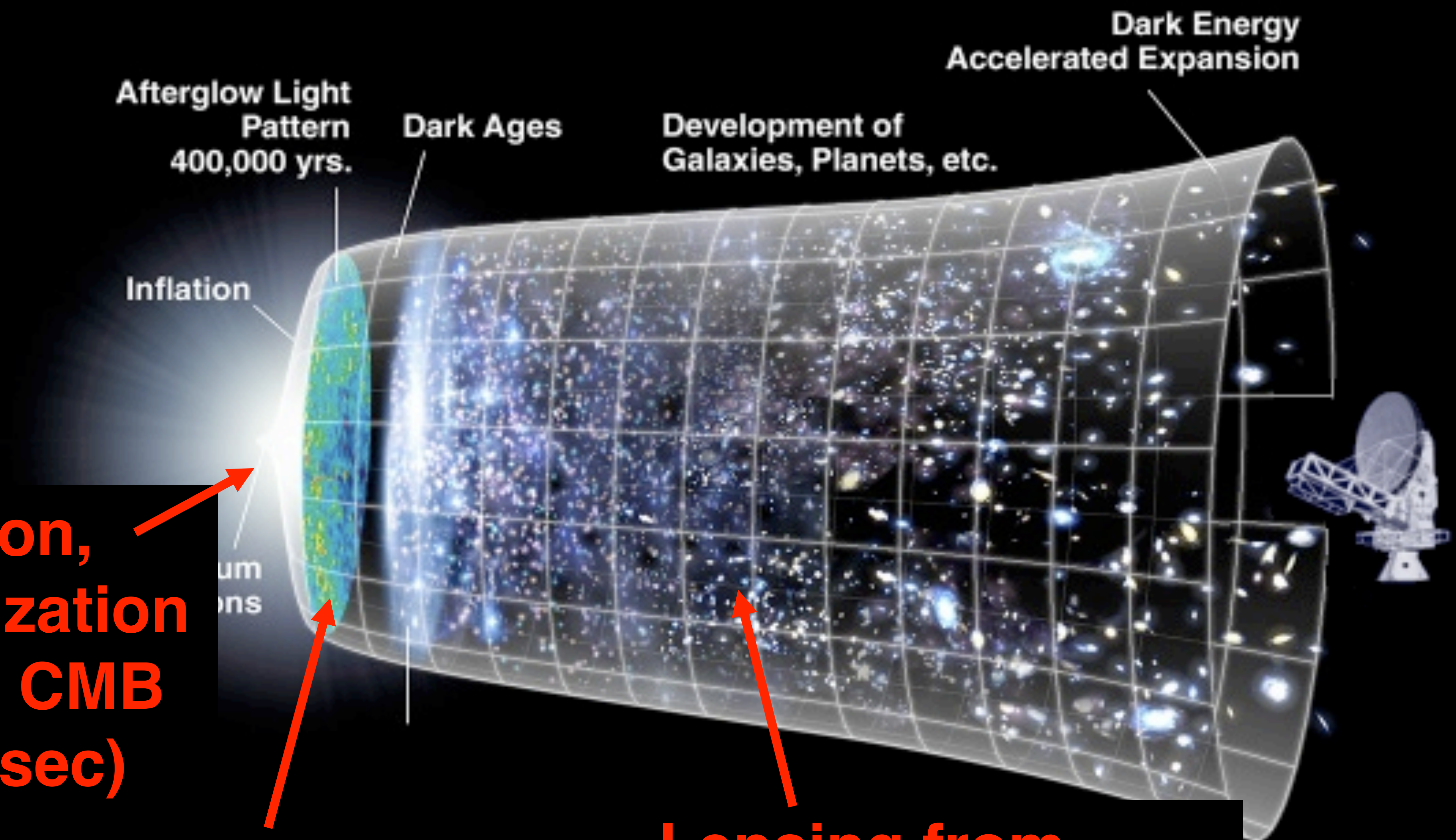
2. Dark Matter

   - Particle-based explanation for dark matter? What are they: WIMPs, axions, etc.? Remaining questions for neutrinos: How massive? Any additional unknown species?

3. Inflation

   - Can we observationally confirm Inflation? What physics was responsible for it? What other paradigm can replace it?

The CMB is a Unique Tool to Answer these Questions

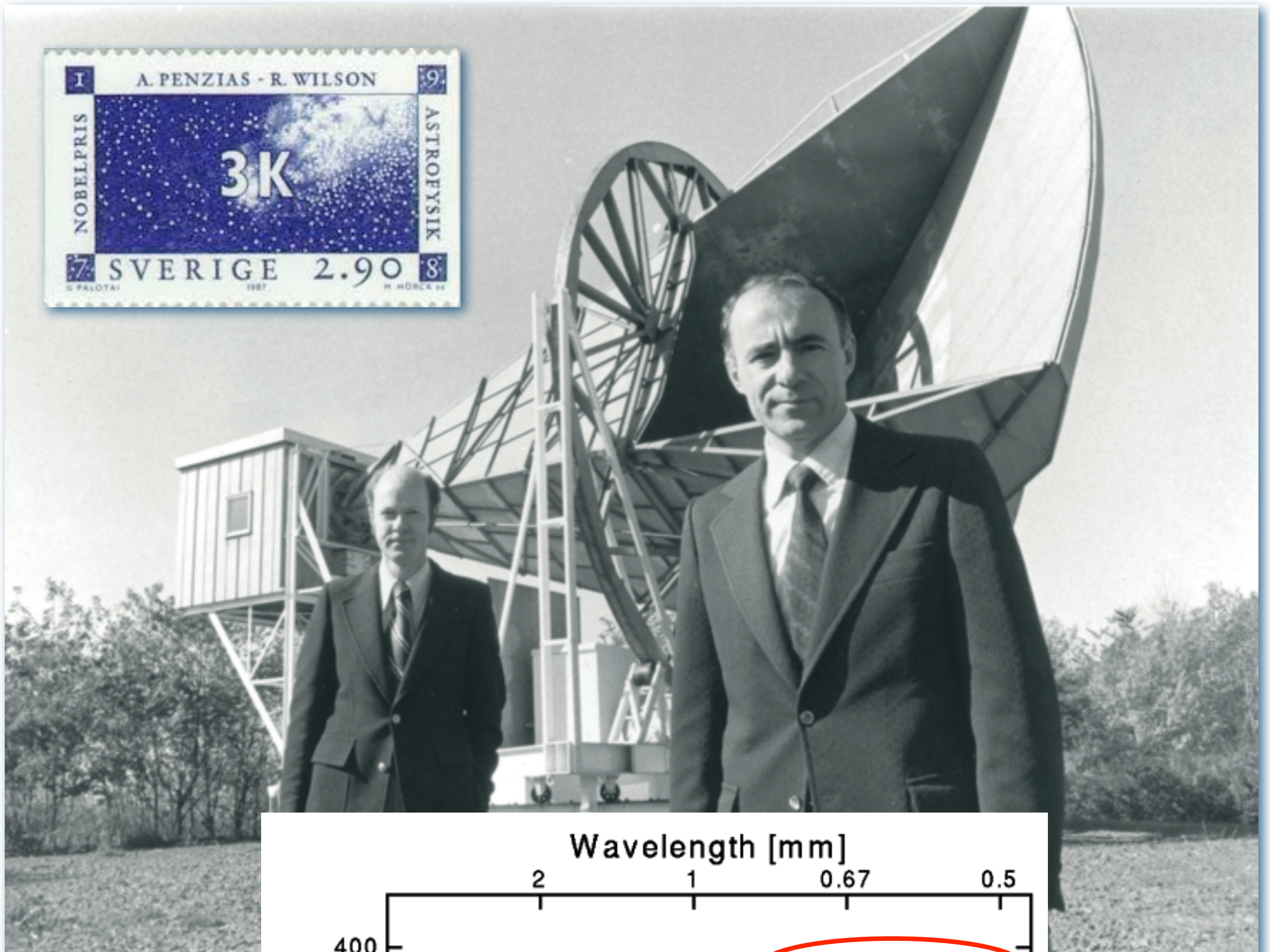


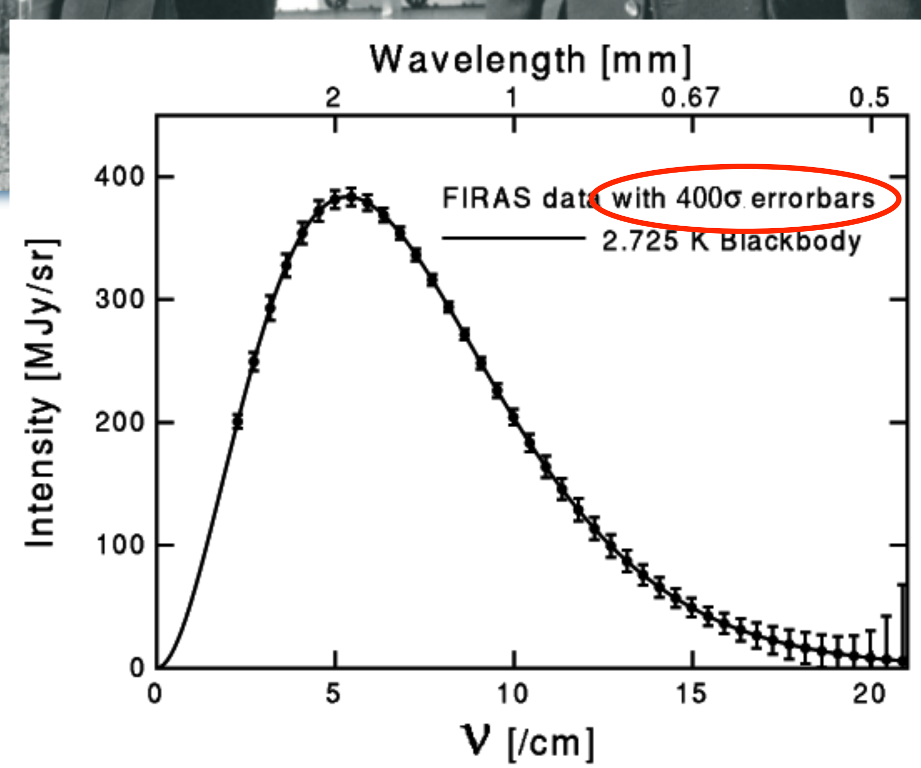
Inflation, Polarization of the CMB (10^{-34} sec)

CMB (400,000 years)

Lensing from structure, clusters of galaxies (1-14 billion years)

Discovery of the Cosmic Microwave Background (CMB)





"Smoking Gun" evidence for the Big Bang

Penzias & Wilson 1964

Received 1978 Nobel Prize

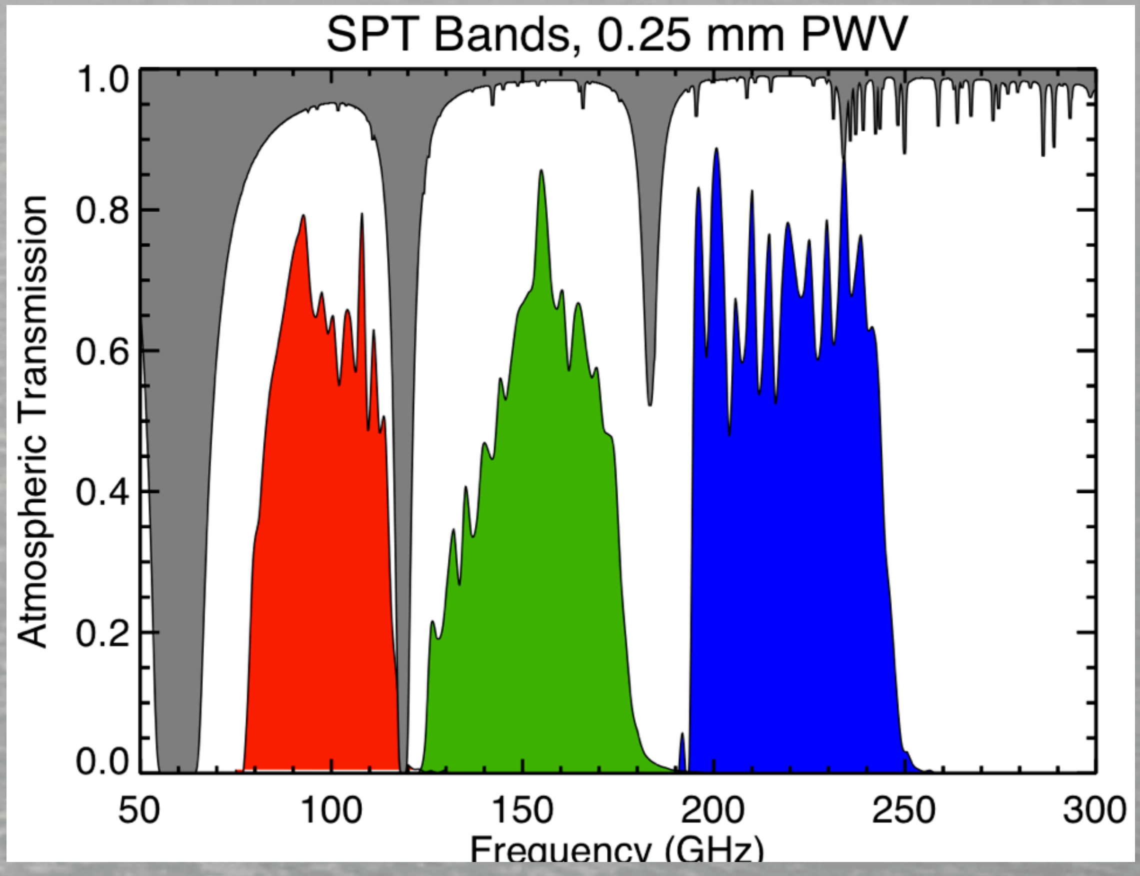
- **Isotropic** and **uniform**, and **very bright!**
  - >90% of Universe's electromagnetic energy is in CMB
- Nearly perfect 2.7 K blackbody

Why Observe the CMB from the South Pole?

South Pole Telescope (SPT)

South Pole Environment

- High Altitude (~10,000 ft)
- Extremely Dry
  - Precipitable Water Vapor in Winter is ~4x < than Chile, ~6x < than Hawaii
- Stable Atmosphere
  - ~30x less power from atmospheric fluctuations at large angular scales compared to ALMA site in Chile



1986-1987: First CMB efforts at Pole

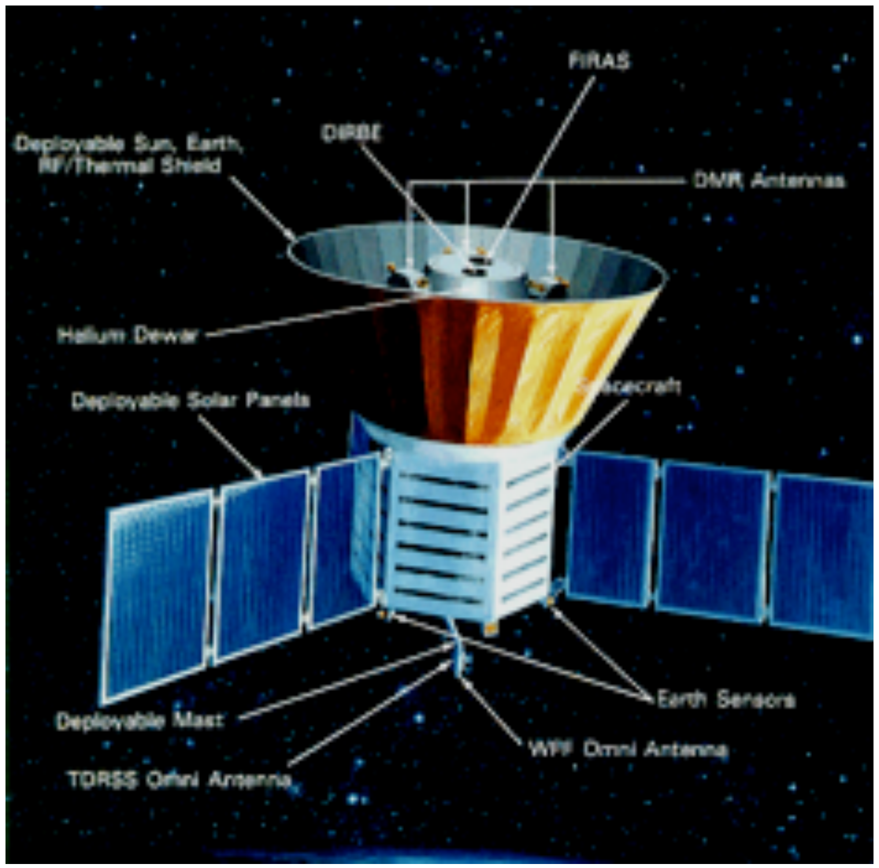
1986-89: First attempts to measure CMB by Bell Labs + Princeton experiment (Dragovan, Pernic, Stark). Verified quality of the South Pole site.

1989-1992: Berkeley experiment, led by George Smoot (future Nobel Prize winner)

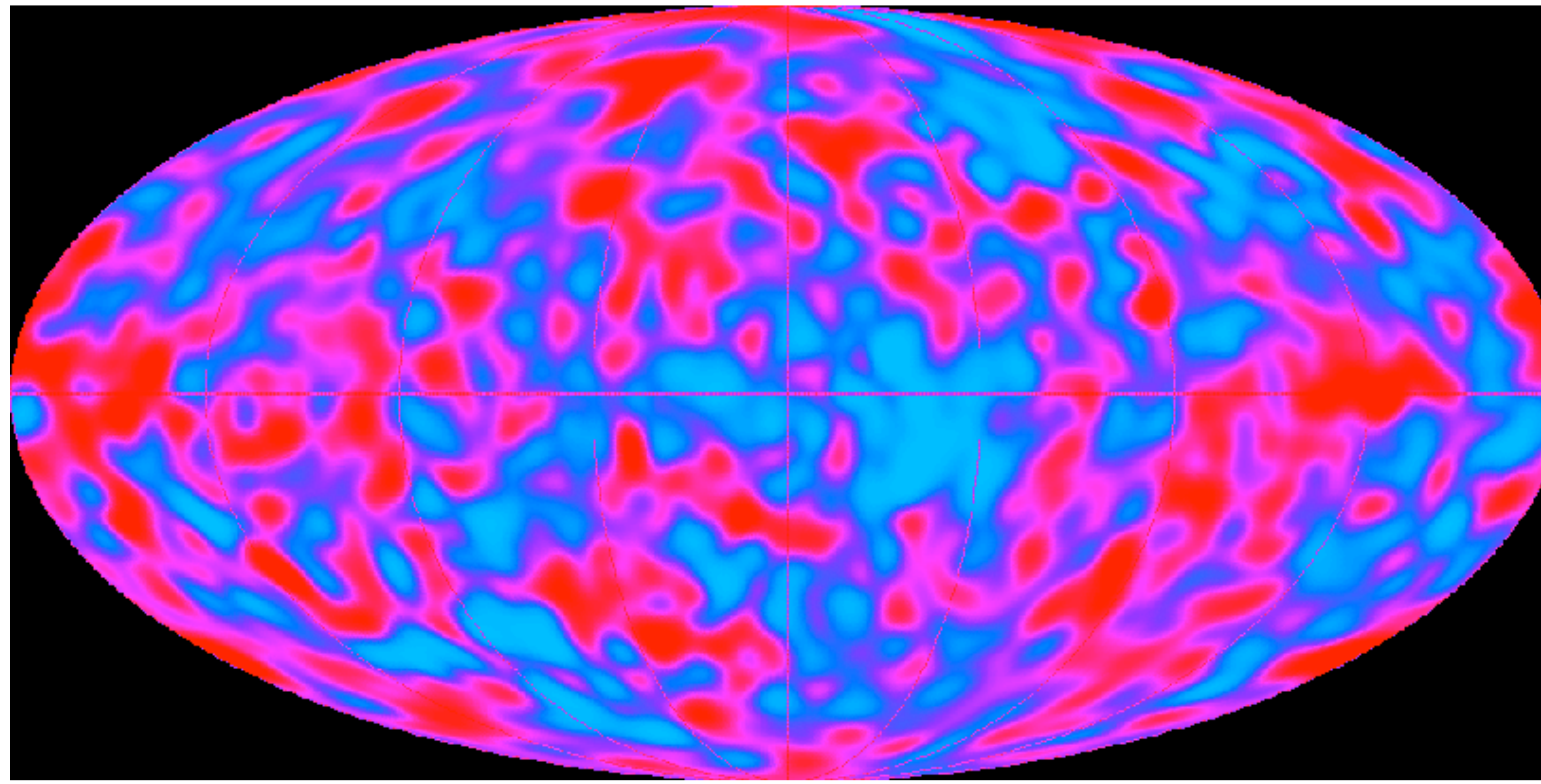
1988-1994: Groups from UC-Santa Barbara (Lubin) and Princeton (Peterson) deployed experiments

Structure in Background Discovered in 1992

COBE Satellite
(launched 1987)



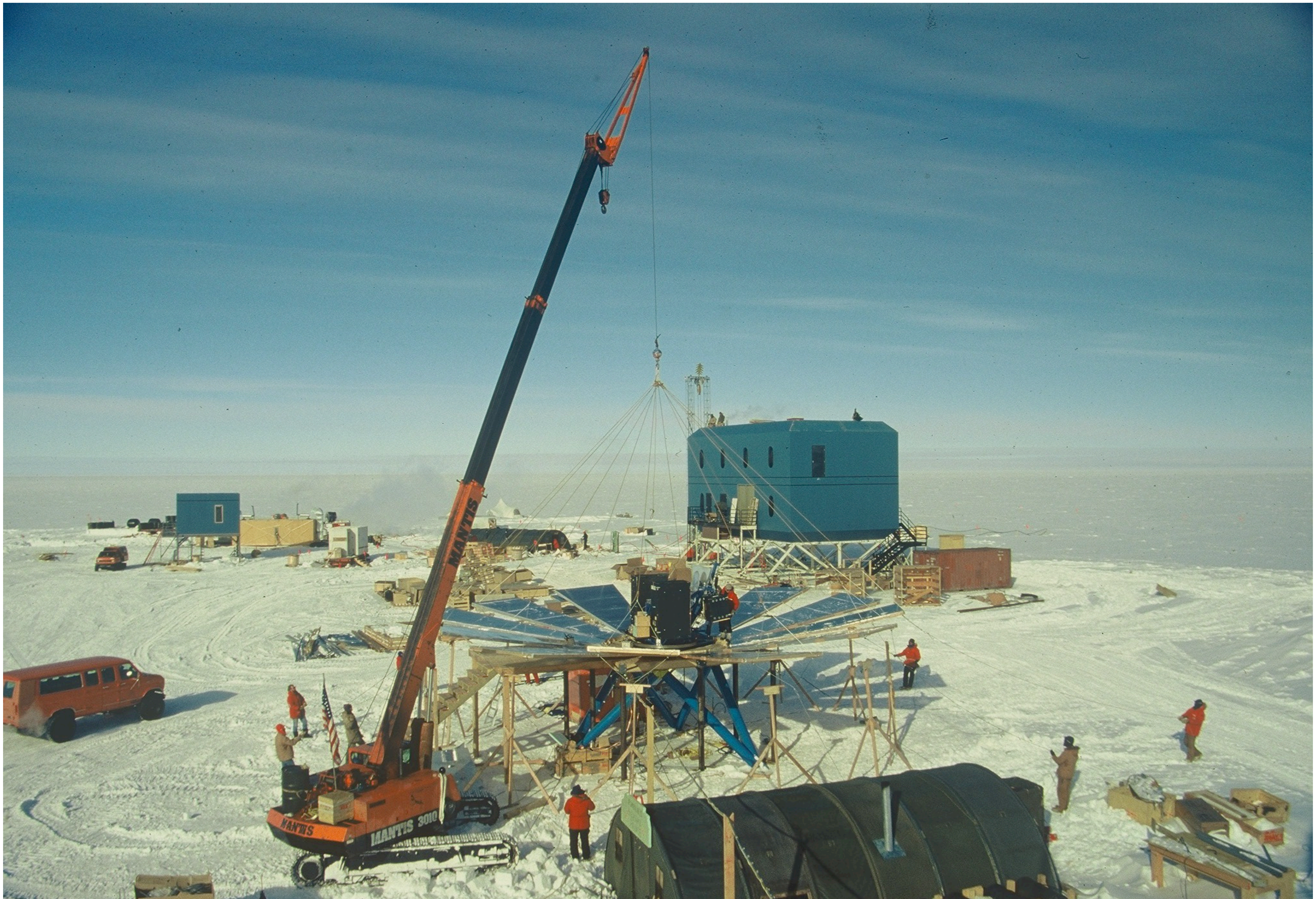
Map of the CMB



~30 μK fluctuations in 2.7 K CMB

COBE team
John Mather & George Smoot
Received 2006 Nobel Prize

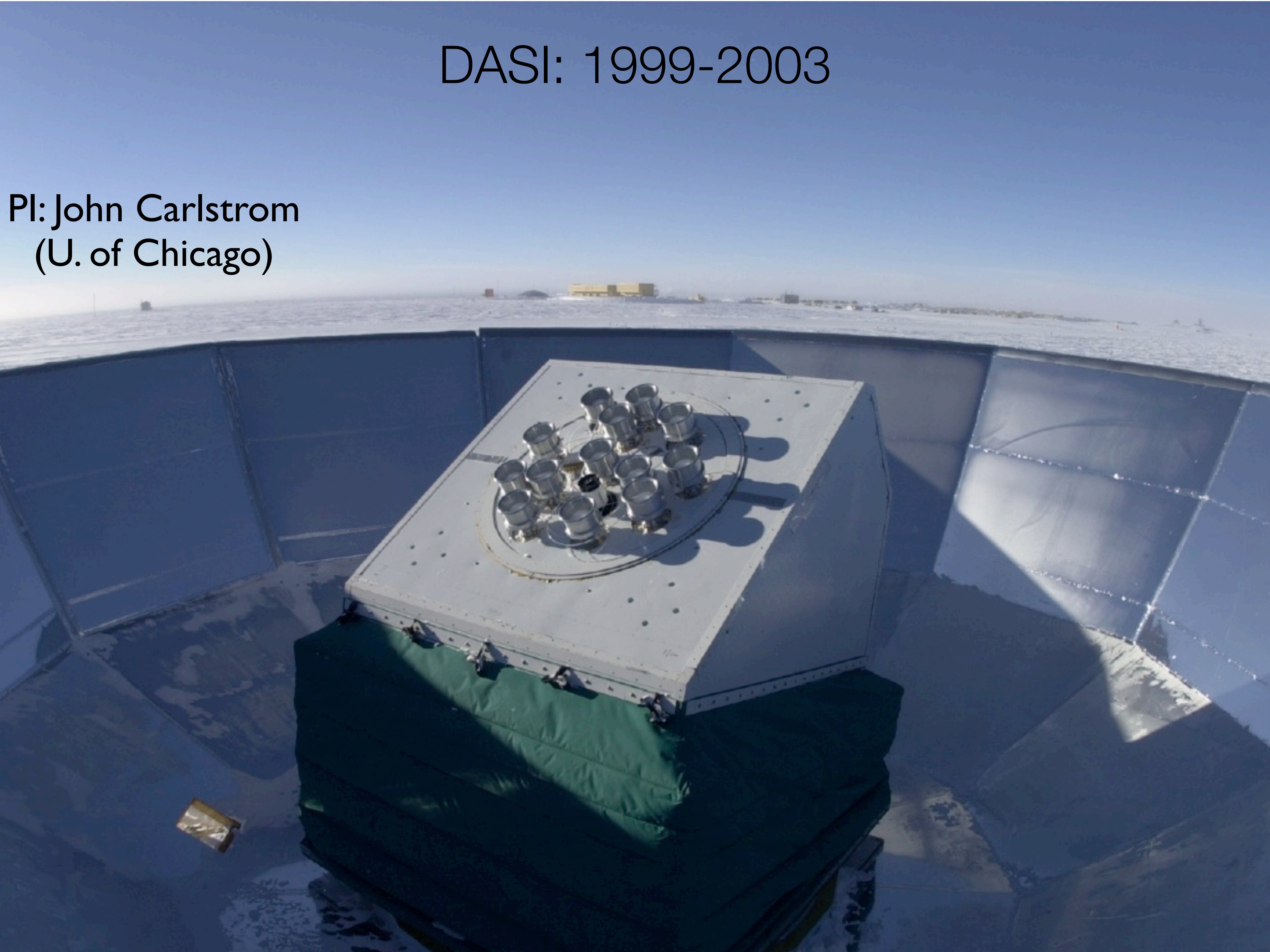
Python (1992-97): first “permanent” CMB installation at South Pole



1994: Python had first Winter-Over operations for a CMB experiment

DASI: 1999-2003

PI: John Carlstrom
(U. of Chicago)



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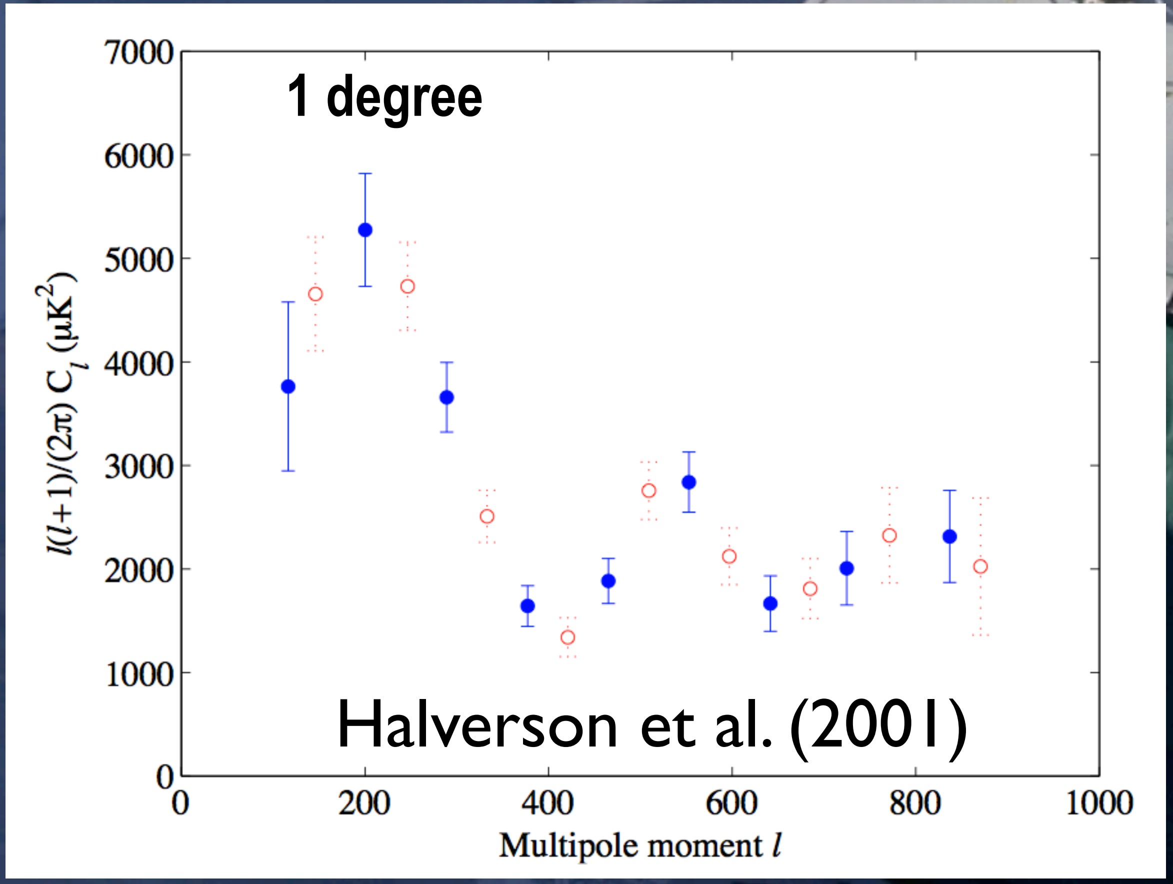
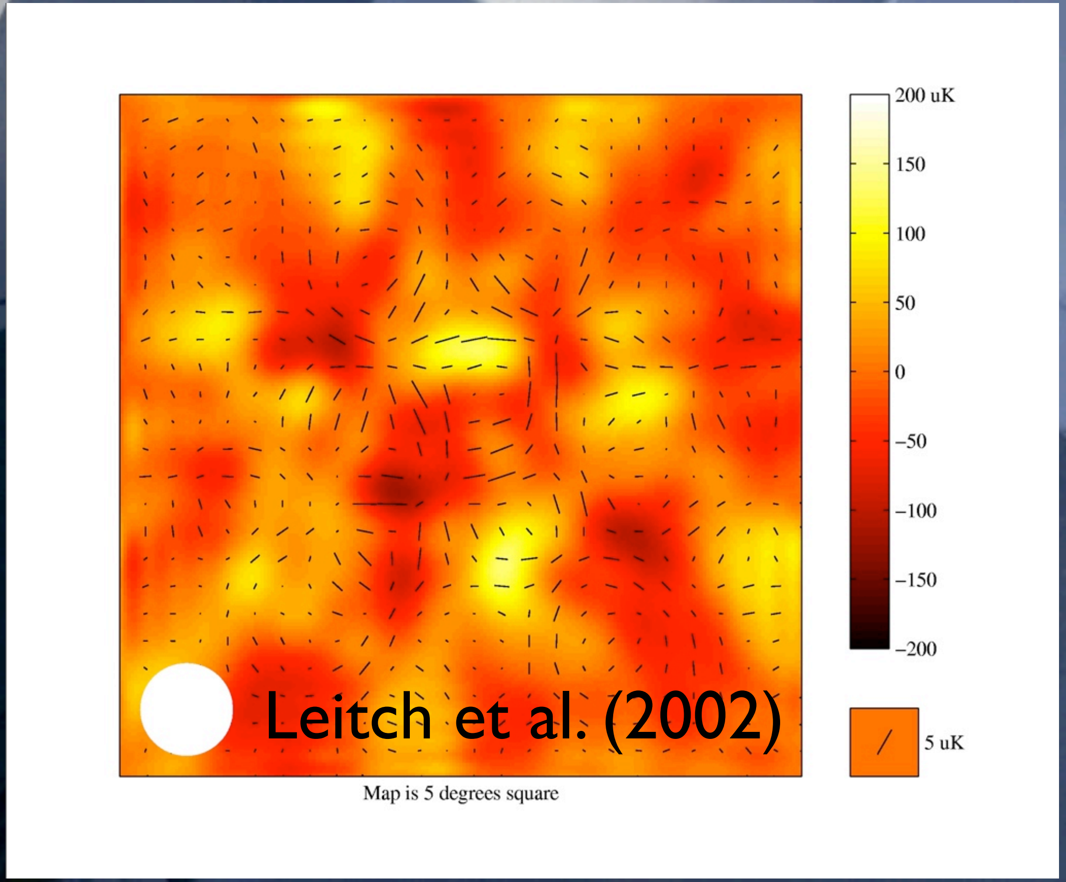
Early detection of harmonic structure in the CMB

First detection of the polarization of the CMB

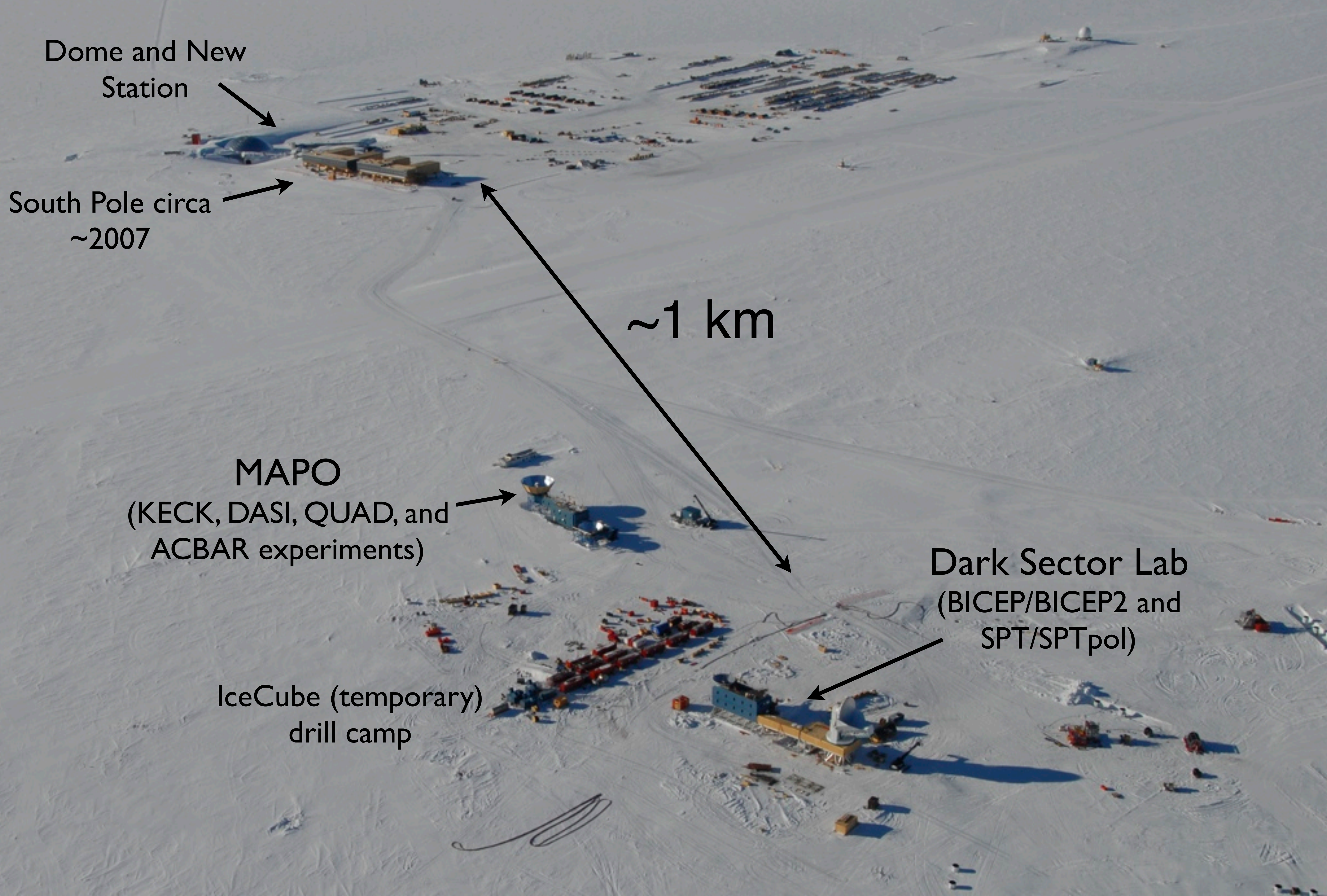





South Pole Telescope
January 7, 2007

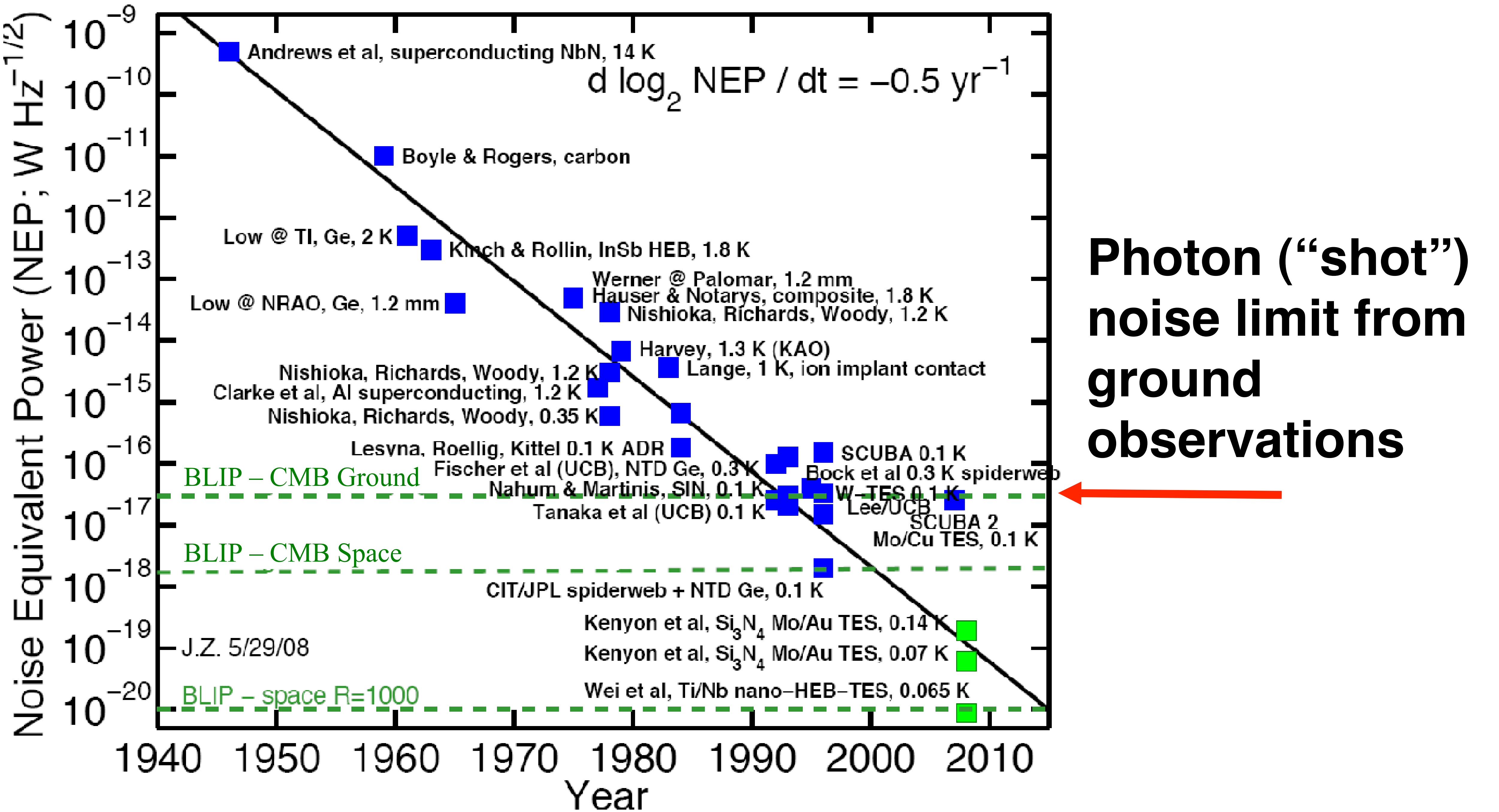
The South Pole has led ground-based measurements of the CMB for the past decade

February 3, 2007: South Pole



Evolution of CMB Detectors

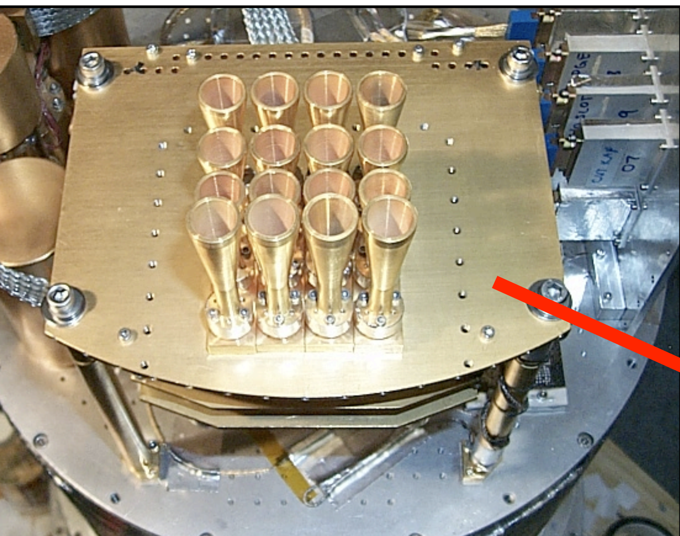
CMB science results have been driven by advances in detector technologies



Plot from J. Zmuidzinas

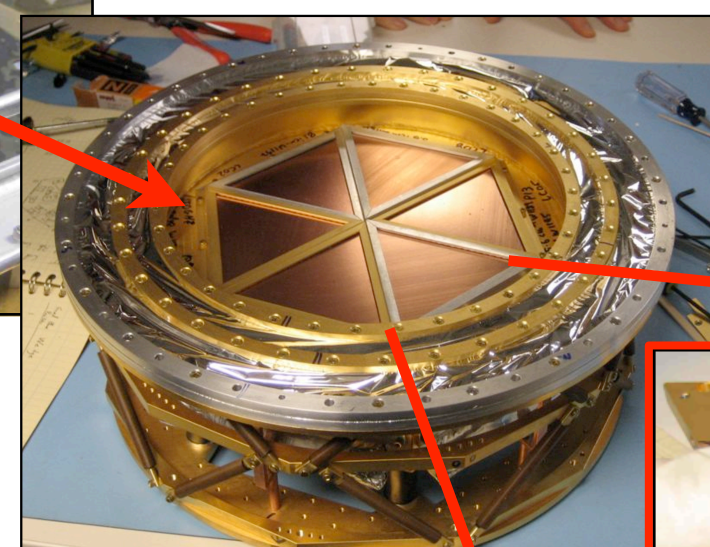
Evolution of Detector Focal Planes

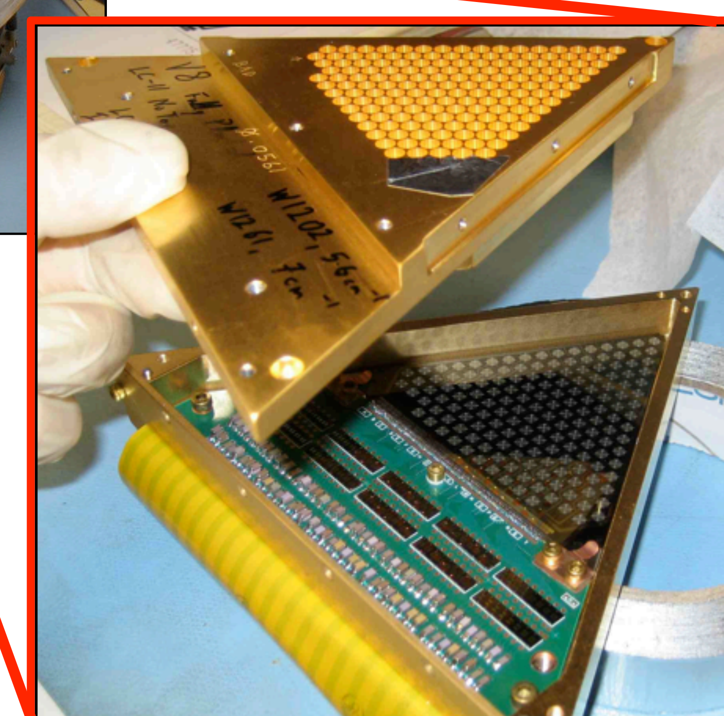
2001: ACBAR
16 detectors



2005: BICEP
~100 detectors

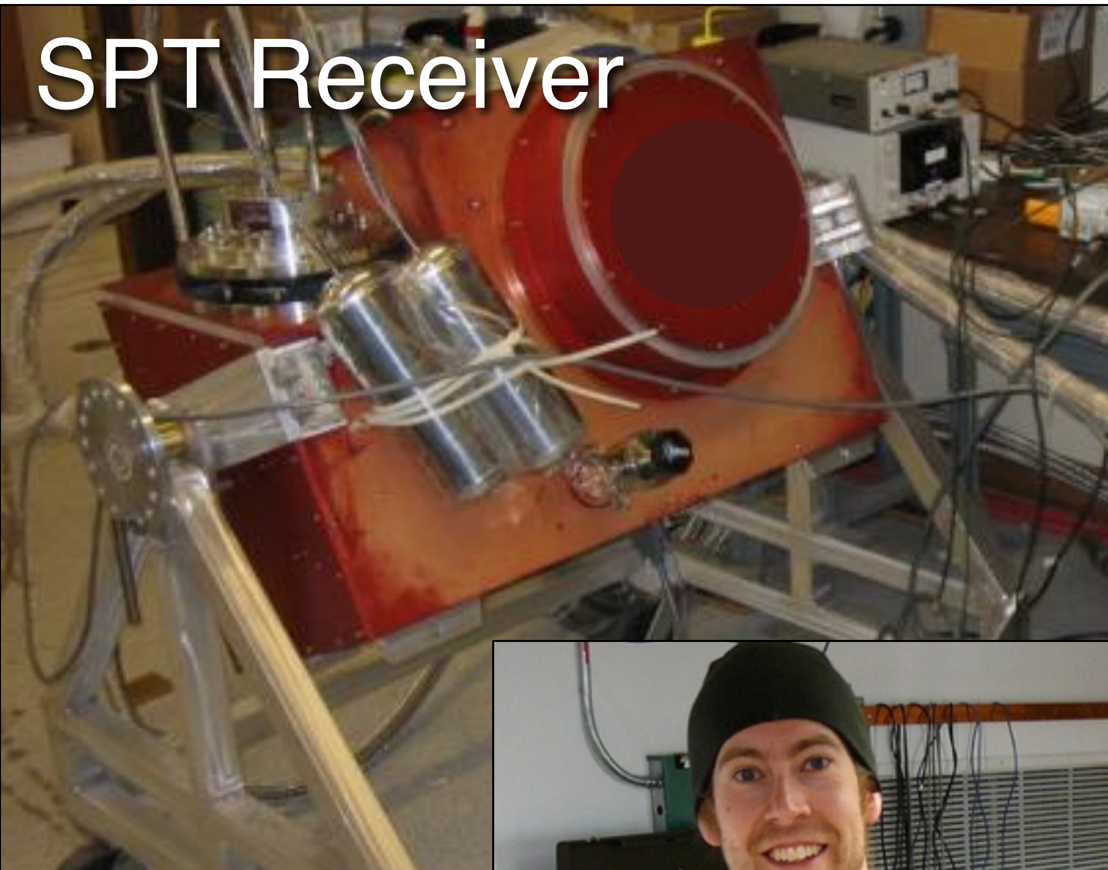
2007: SPT
960 detectors





ACBAR was one of the first experiments to deploy a photon ("shot") noise limited detector, since then we've just been trying to make more of them

SPT Receiver



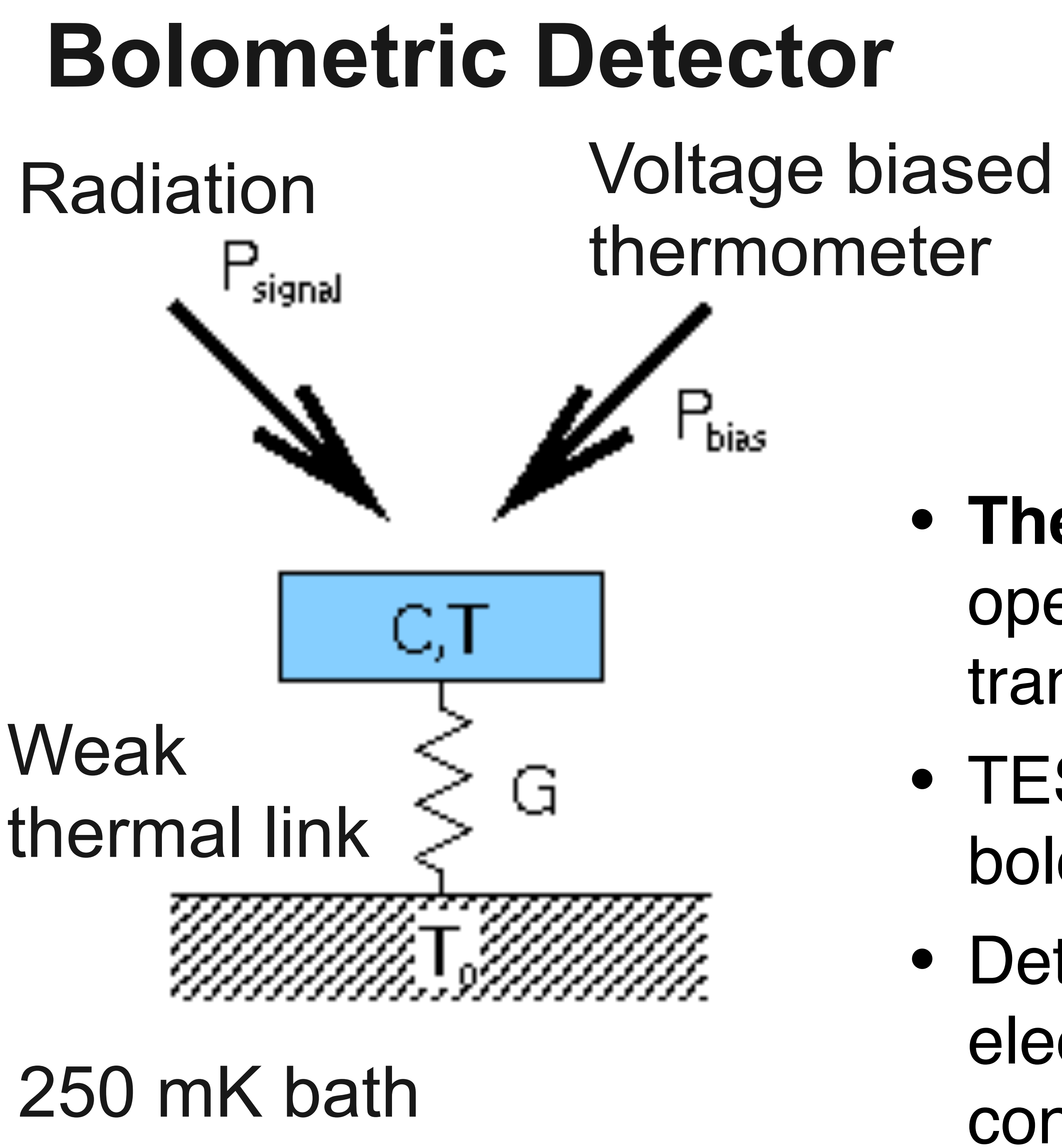
SPT Focal Plane

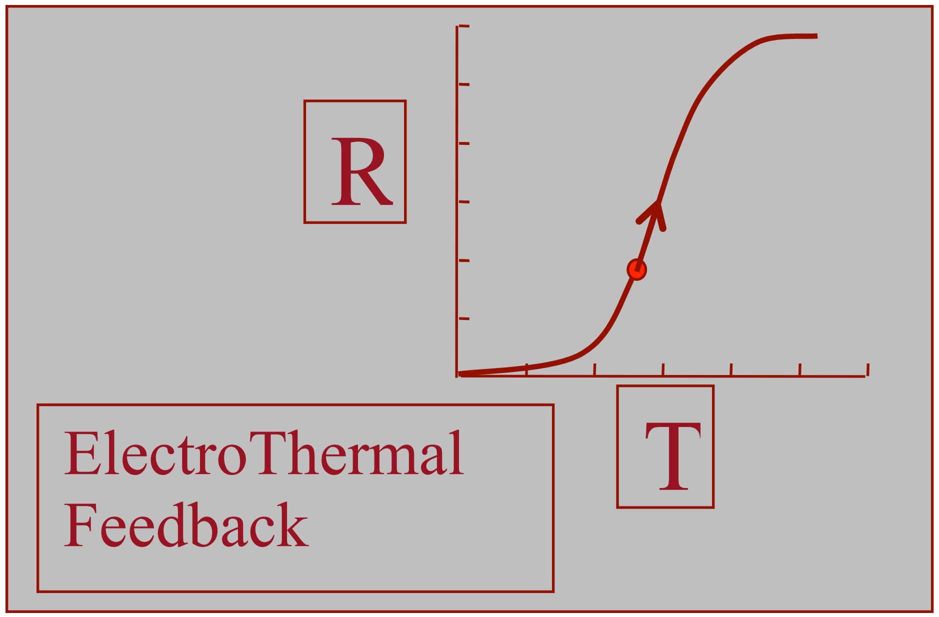
- Built at UC-Berkeley
  - an effort that I worked on from 2004-2008

- Required development of several **key technologies**:

  1) **Pulse Tube Coolers**
  2) **Superconducting (TES) bolometers**
  3) **Multiplexed low-noise SQUID readout electronics**

Need scalable detectors:
Transition Edge Sensors (TES)

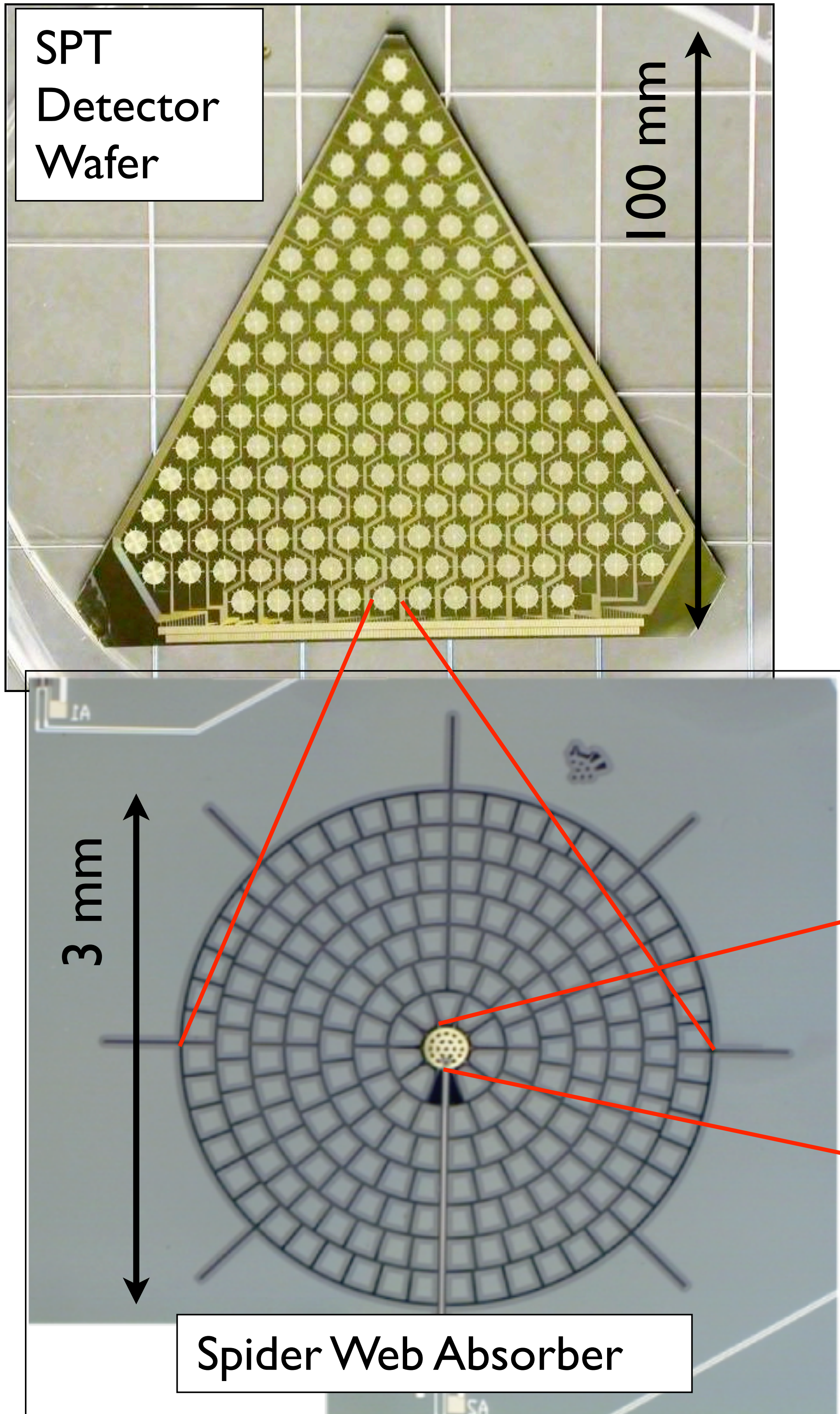


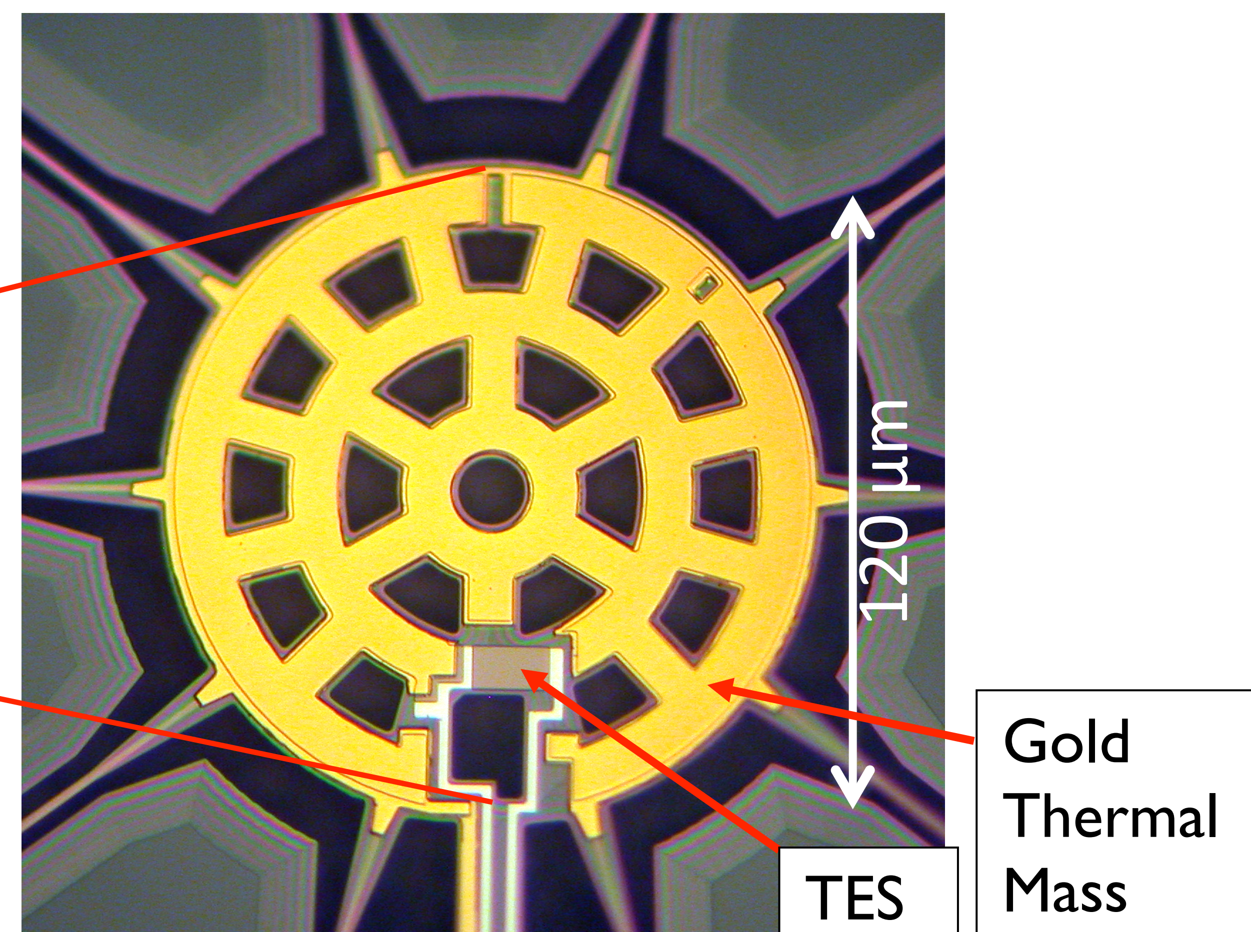


- **Thermometer:** Voltage biased TES operating at superconducting transition (~500 mK)
- TES's can be fabricated on bolometer, and
- Detector has electrical negative electrothermal feedback to maintain constant power; improves detector linearity and speed

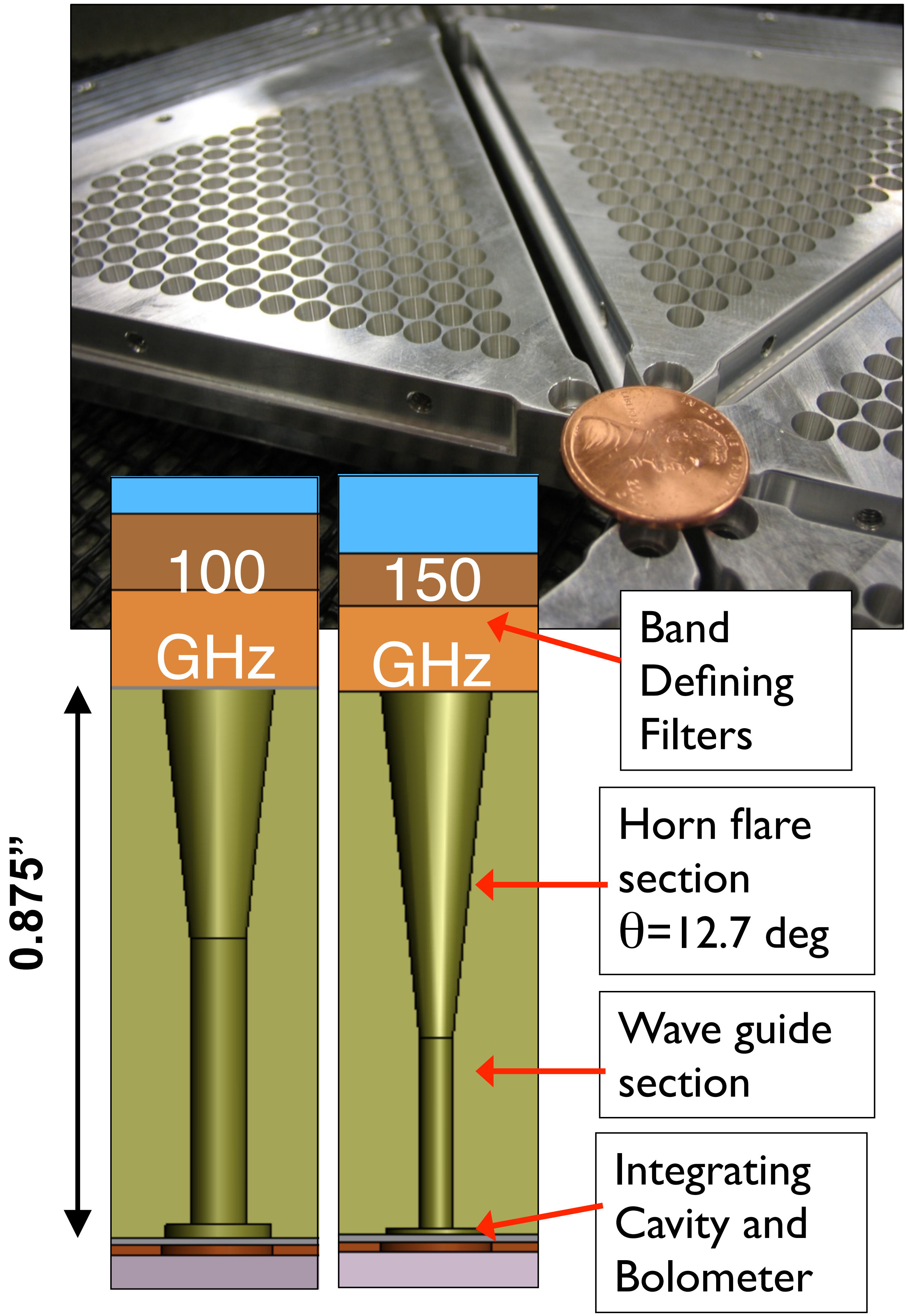
SPT Detector Wafer

- Fabricated at UC-Berkeley
- 160 bolometers per wafer
- Al-Ti bi-layer (TES) with Tc = 0.55 K
- Electrical time constant of ~1 ms
- Wafer thickness tuned to observing frequency/wavelength

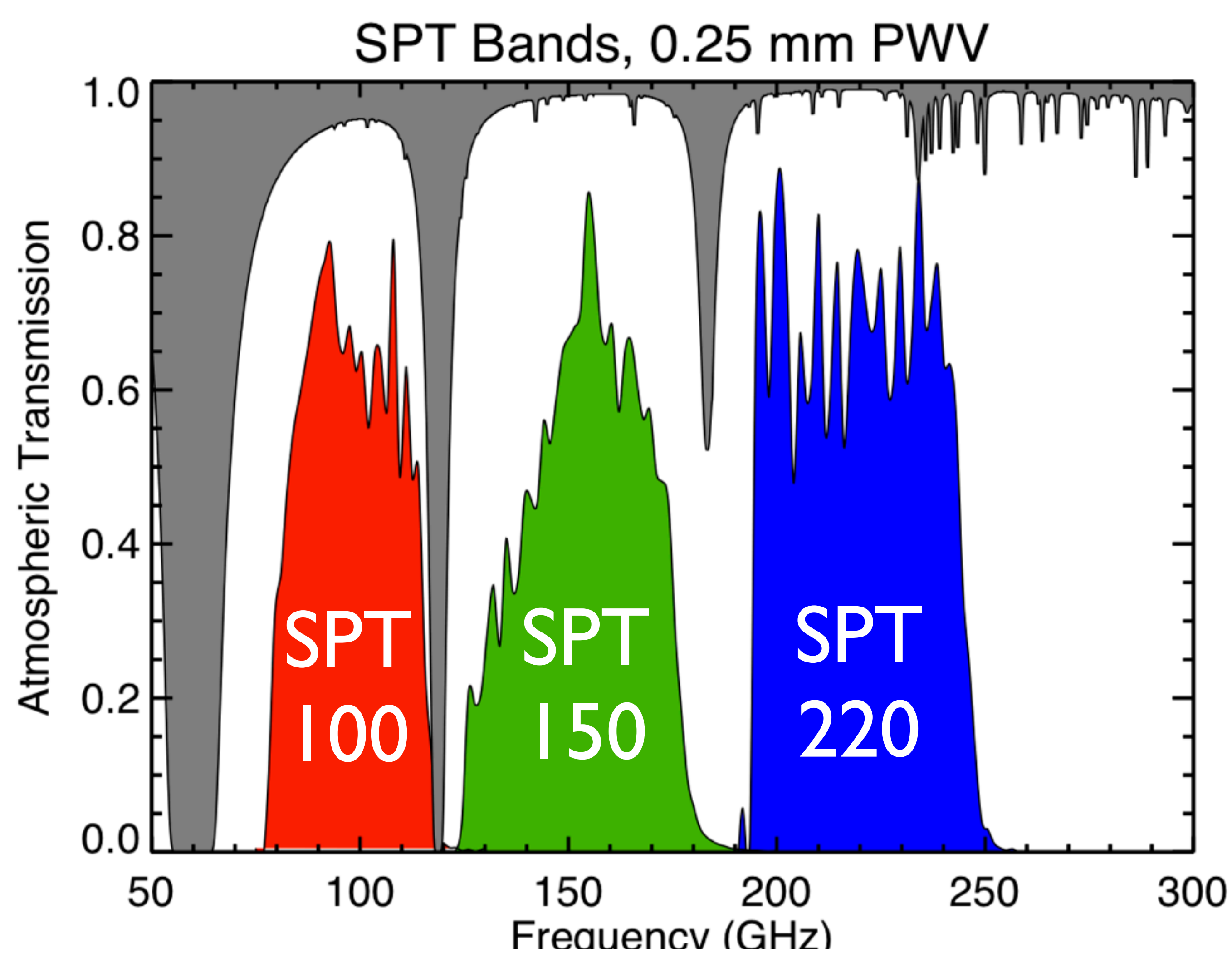




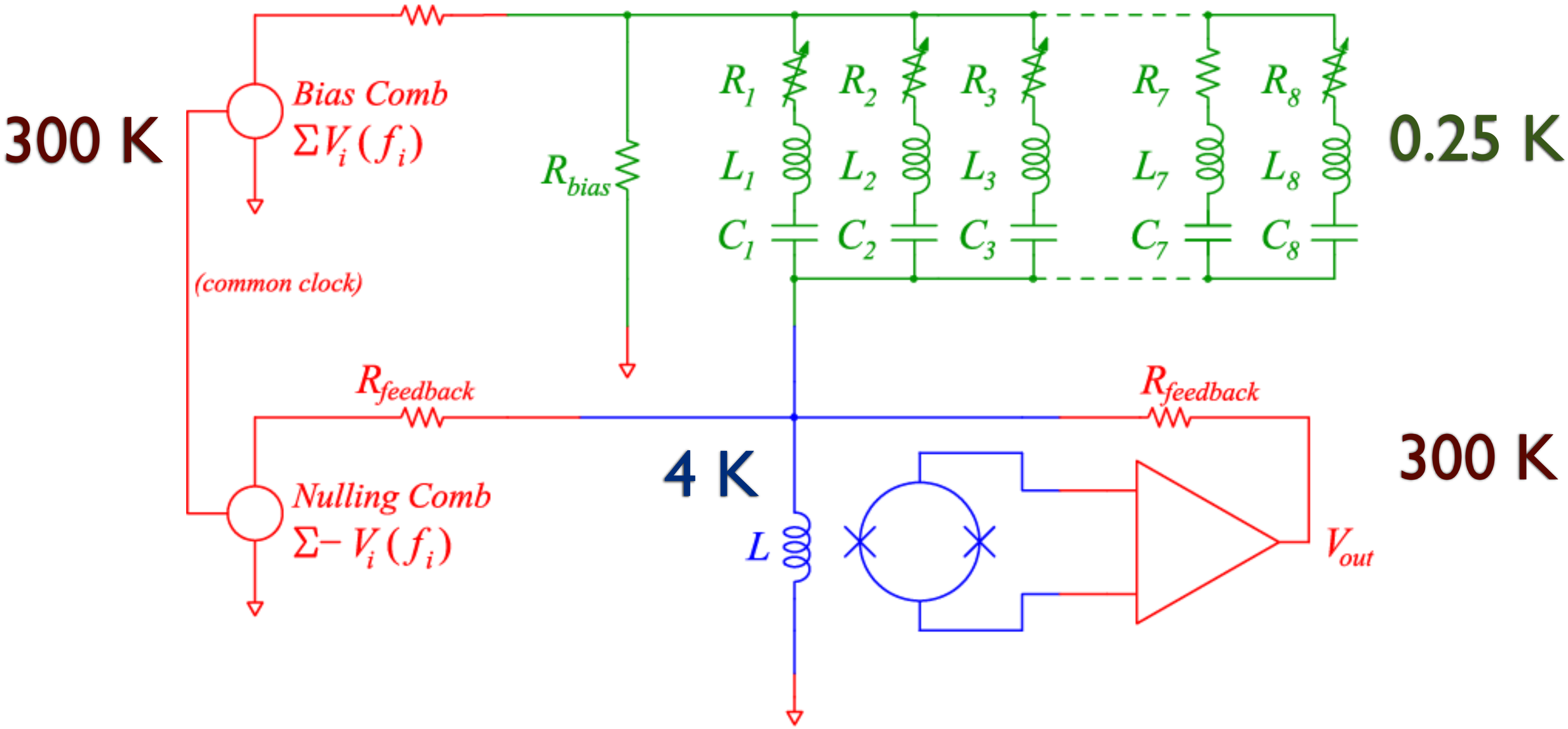
SPT Focal Plane Optics



- Light coupled to the detectors thru a machined conical horn array, with a waveguide, and integrating cavity
- Bands set by waveguide diameter on the low frequency edge and metal-mesh filters on the high-edge



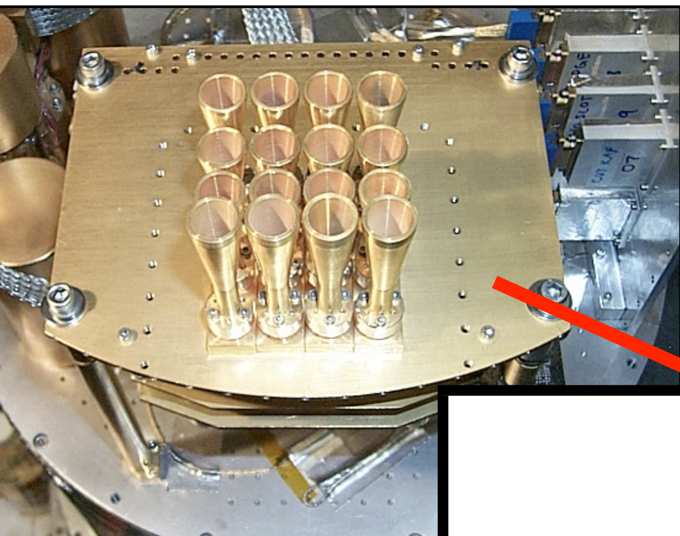
Frequency Domain Multiplexing (fMUX)



- Developed current summing fMUX at UC-Berkeley and Lawerence Berkeley Labs (LBL)
- AC Bias a row of detectors with comb of frequencies between 300-950 kHz
- Crosstalk determined by Q of LC resonance (designed to be $< 1\%$)
- Null current thru SQUID to improve its dynamic range and linearity

Evolution of Detector Focal Planes

2001: ACBAR
16 detectors



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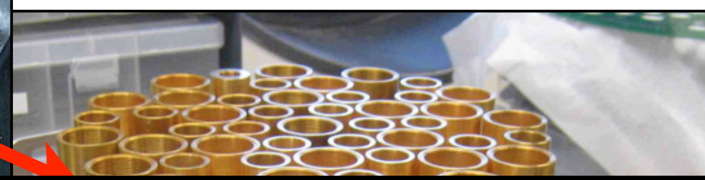
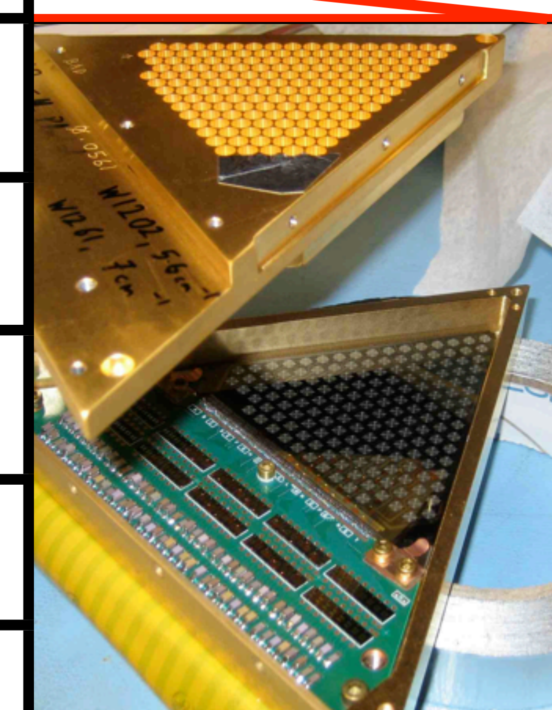


2007: SPT
960 detectors

	NET (noise equivalent temperature) (μK CMB s$^{0.5}$)	**Mapping Speed**
ACBAR	90	**1**
BICEP	57	**5**
ACT	30	**9**
SPT	18	**30**
SPTpol	14	**50**



ACBAR w
to deploy
detector,
trying to r

The South Pole Telescope:
a mm-wave observatory

- **10 meter diameter** primary mirror
  ~1 arcminute resolution
- **1st camera SPT-SZ (2007-2011)**
  - 1000 bolometers.
    three “colors”: 3.2, 2.0, 1.4 mm
- **2nd camera: SPTpol (2012-?)**
  - 1600 bolometers. polarization-sensitive. 2 bands: 3.2, 2.0 mm

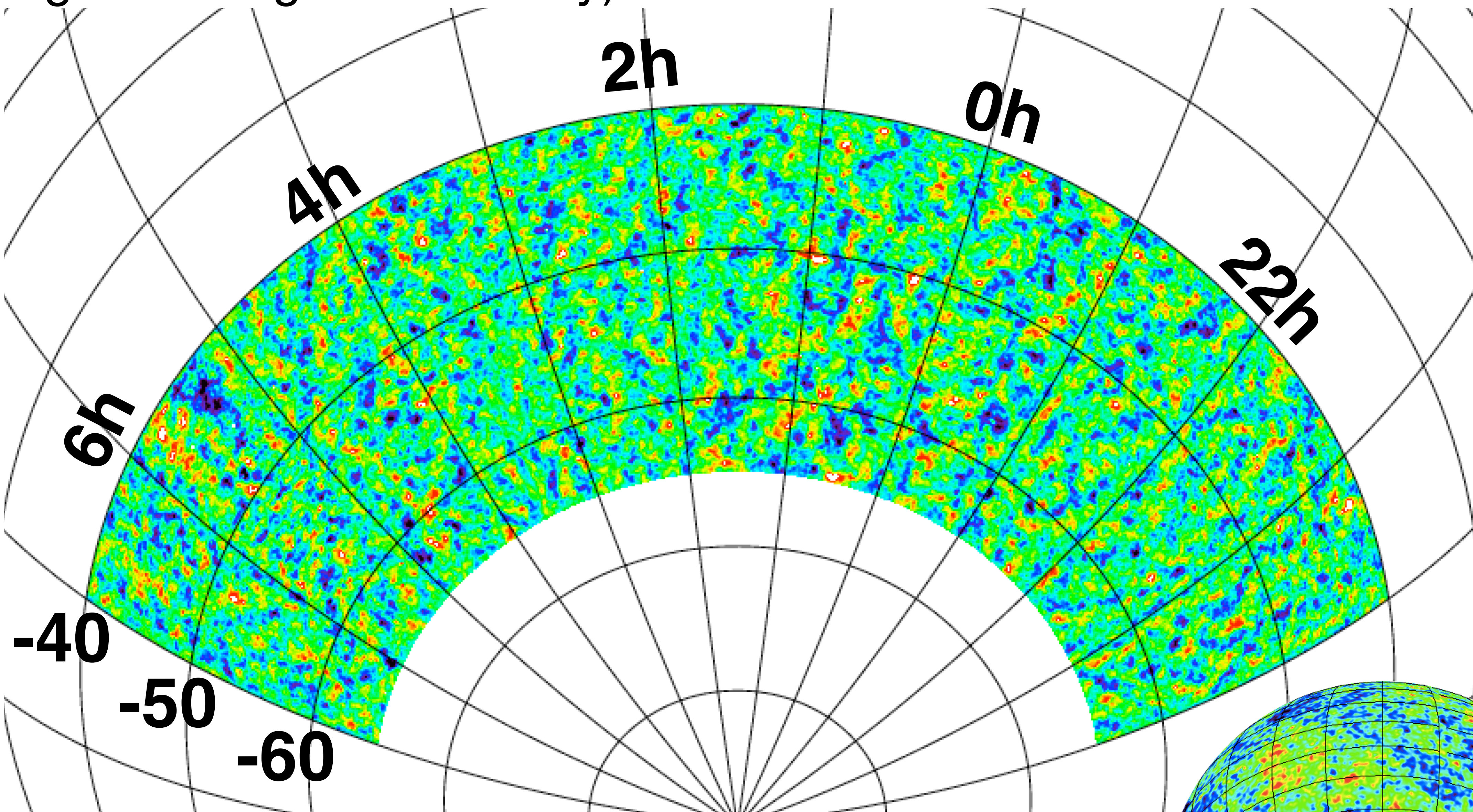
Chicago
Berkeley
Case Western
McGill
Boulder
Harvard
Caltech
Munich
Michigan
Arizona
...

photo by Dana Hrubes

The SPT-SZ Survey (2007-2011):

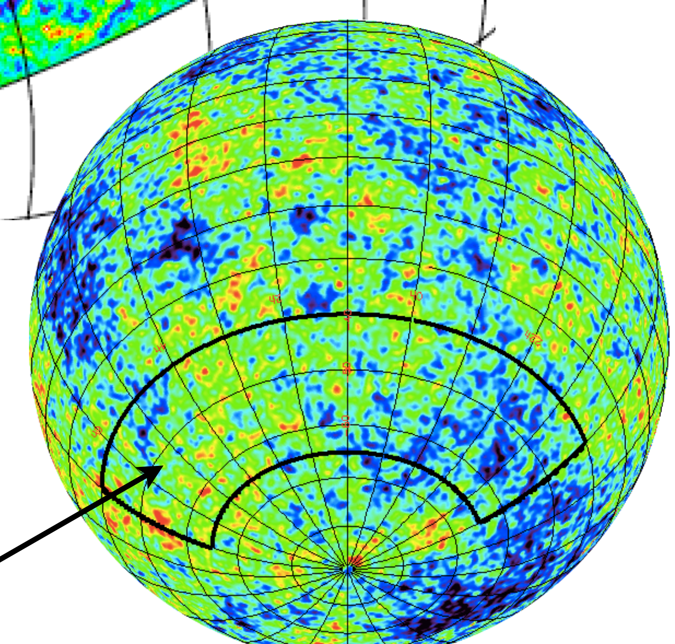
The highest resolution and sensitivity map of the CMB

(covering 2500 deg² ~ 6% of sky)



Final survey depths of:

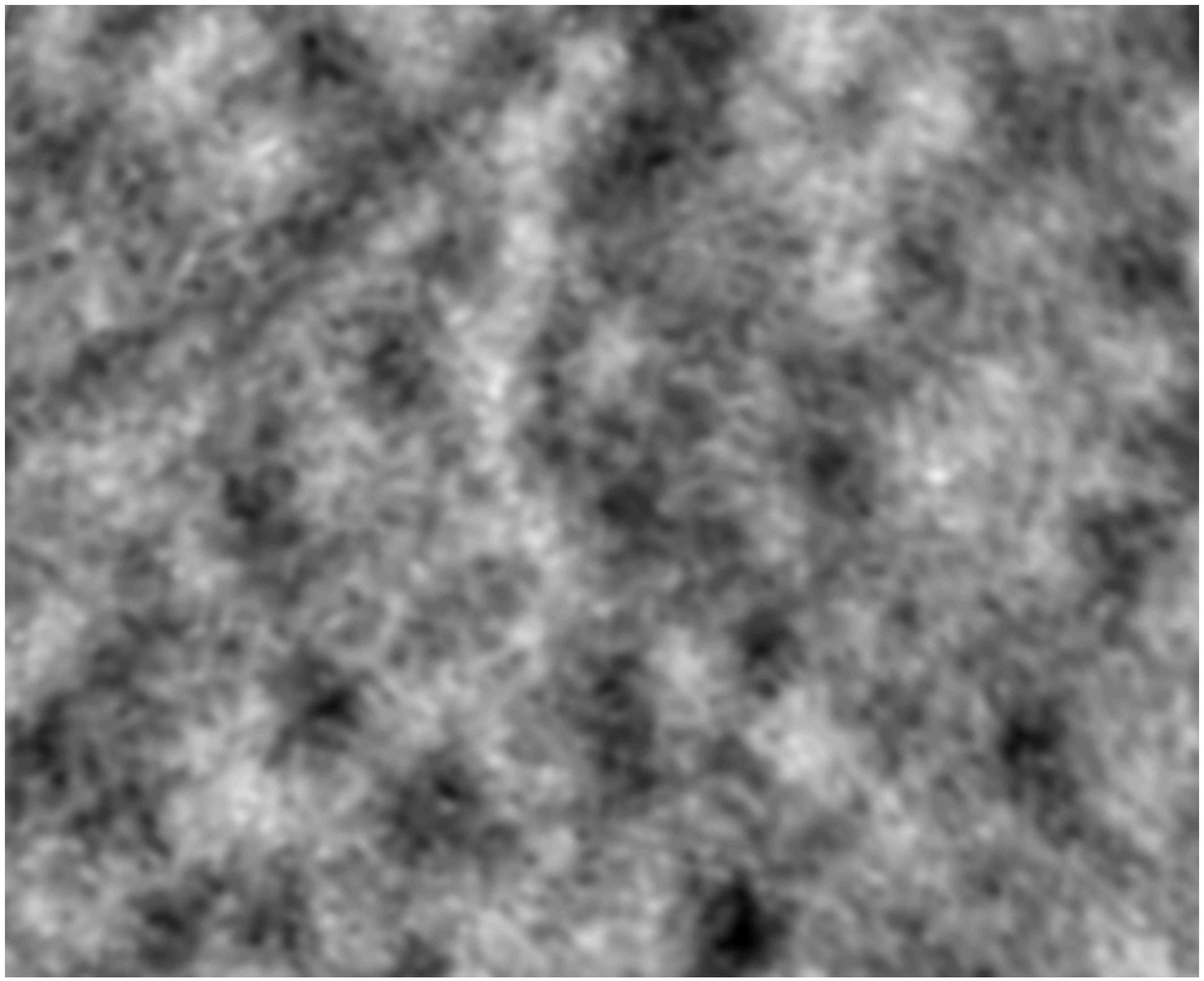
- 90 GHz: 40 uK_{CMB}-arcmin
- 150 GHz: 18 uK_{CMB}-arcmin
- 220 GHz: 80 uK_{CMB}-arcmin



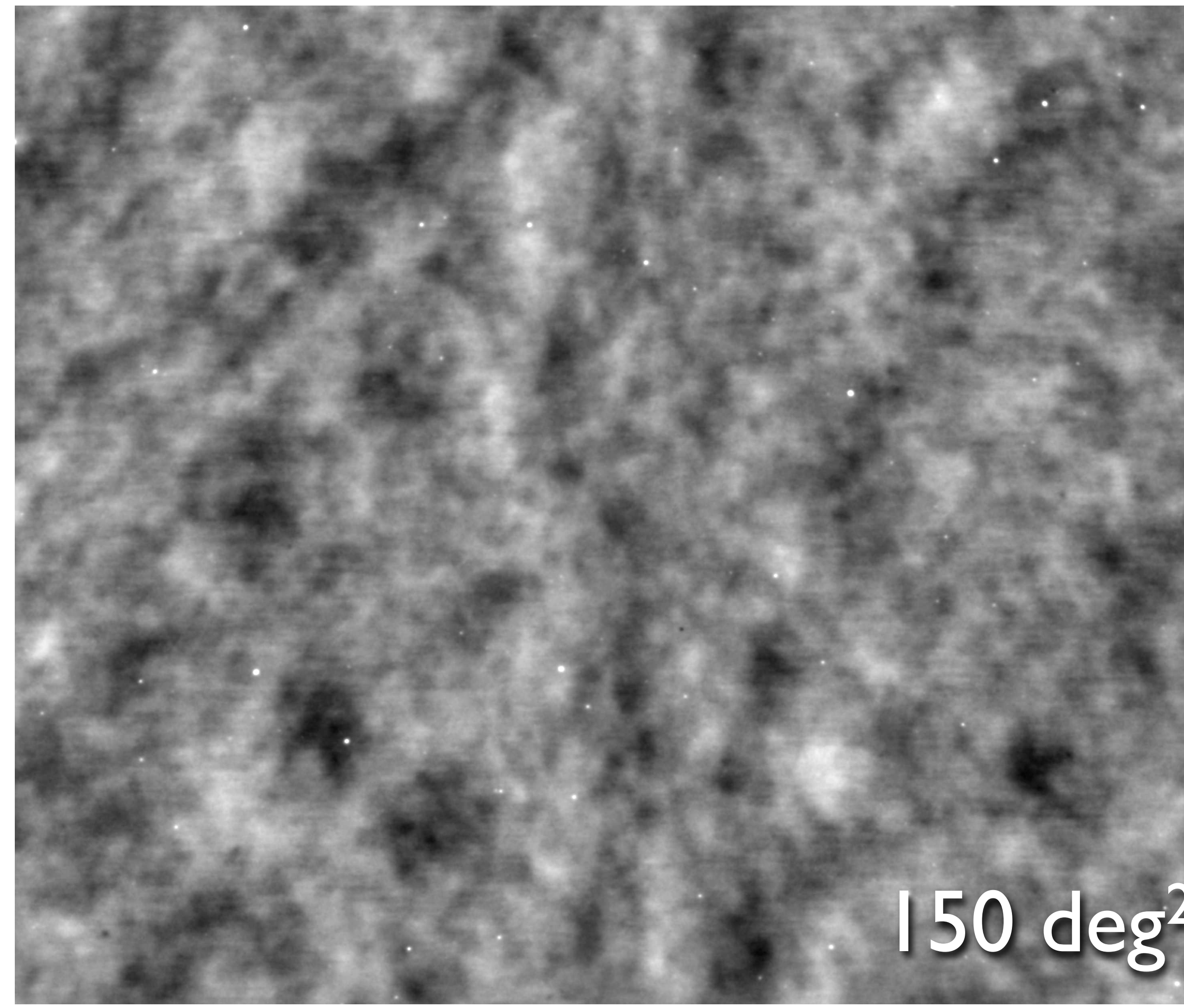
WMAP lower resolution full sky map with SPT area marked

The CMB as observed by WMAP and SPT

WMAP



SPT



SPT relative to WMAP:

13x smaller beam (13’ vs 1’)

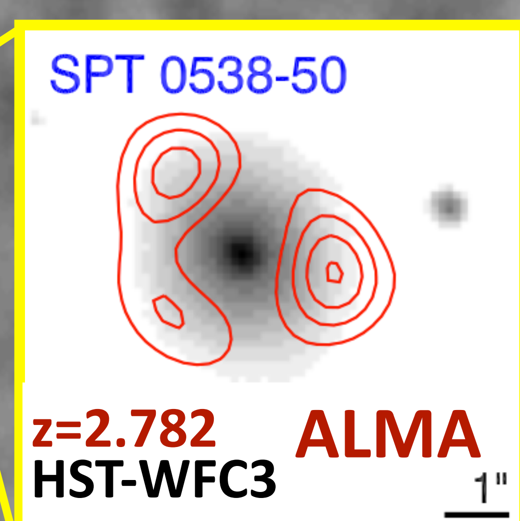
17x deeper (300 uK-arcmin vs 18 uK-arcmin)

Zoom in on an SPT map

50 deg² from 2500 deg² survey

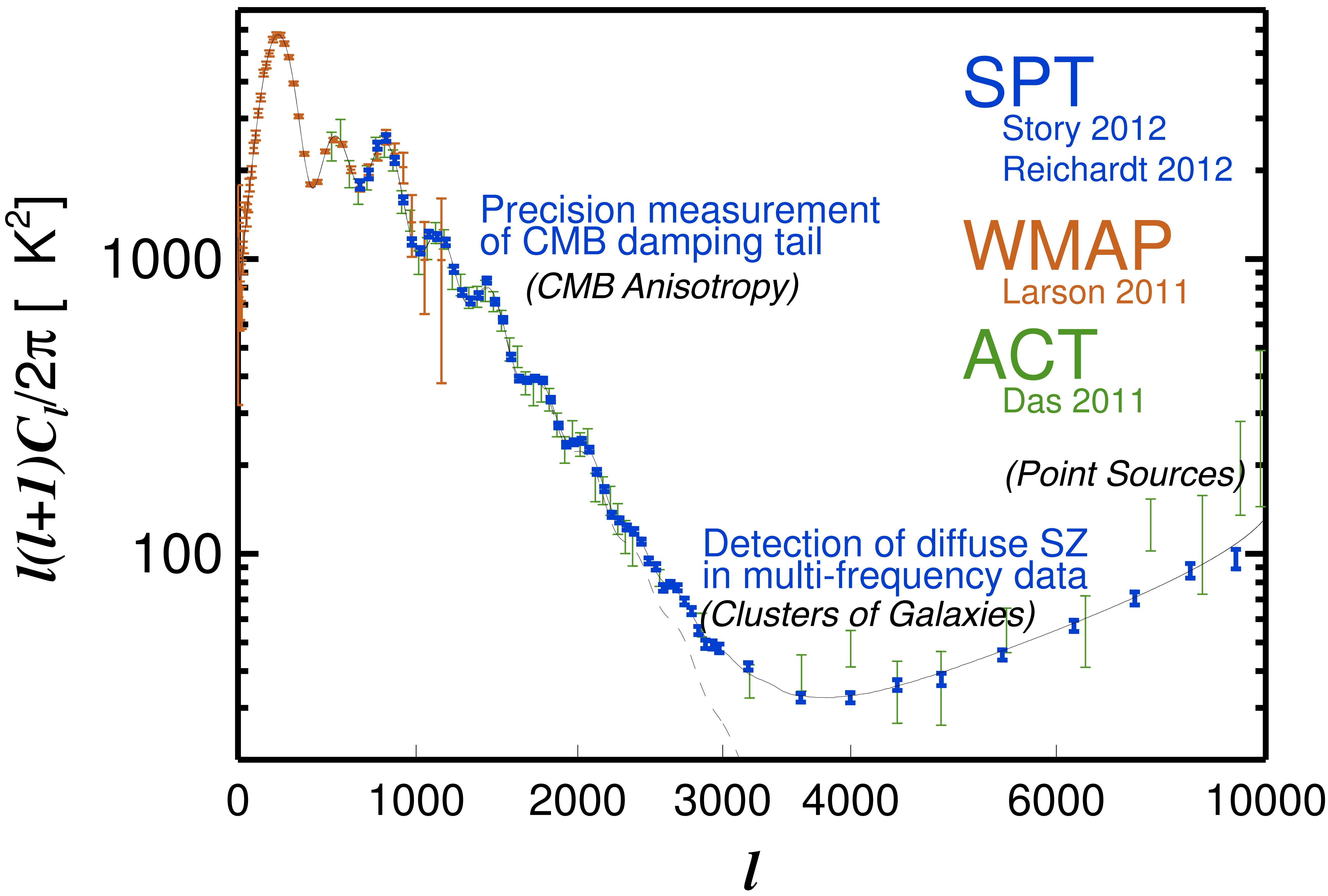
CMB Anisotropy - Primordial and secondary anistropy in the CMB

Point Sources - High-redshift dusty star forming galaxies and synchrotron AGN



Clusters - High signal to noise SZ galaxy cluster detections as "shadows" against the CMB!

SPT: CMB Power Spectrum



SPT Science

1. **SPT Cluster Survey**
   - Testing Dark Energy
2. **SPT: CMB Power Spectrum**
   - Constraints on Neutrinos
3. **SPTpol: CMB Polarization**
   - Constraining Inflation

SPT Science

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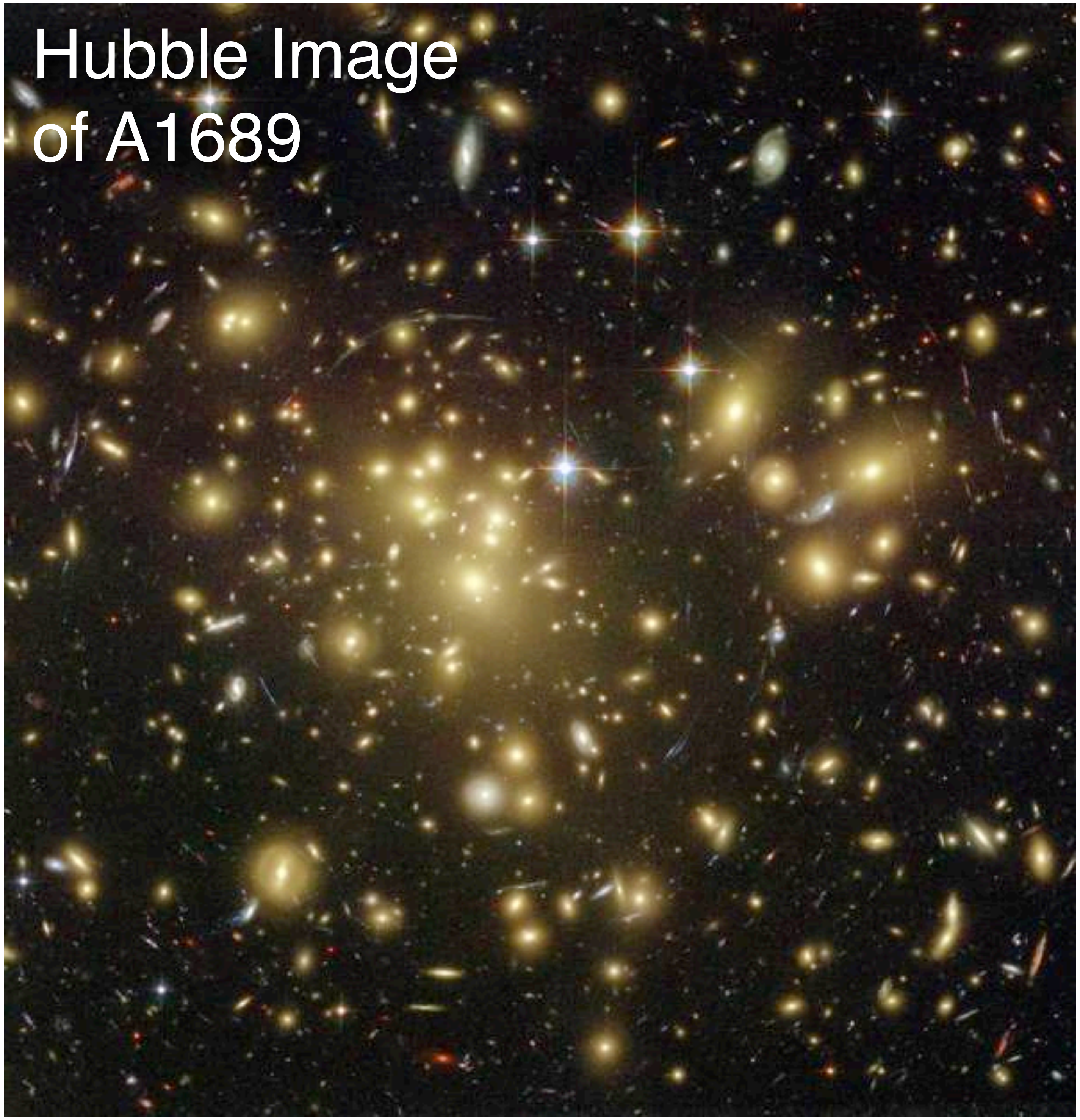
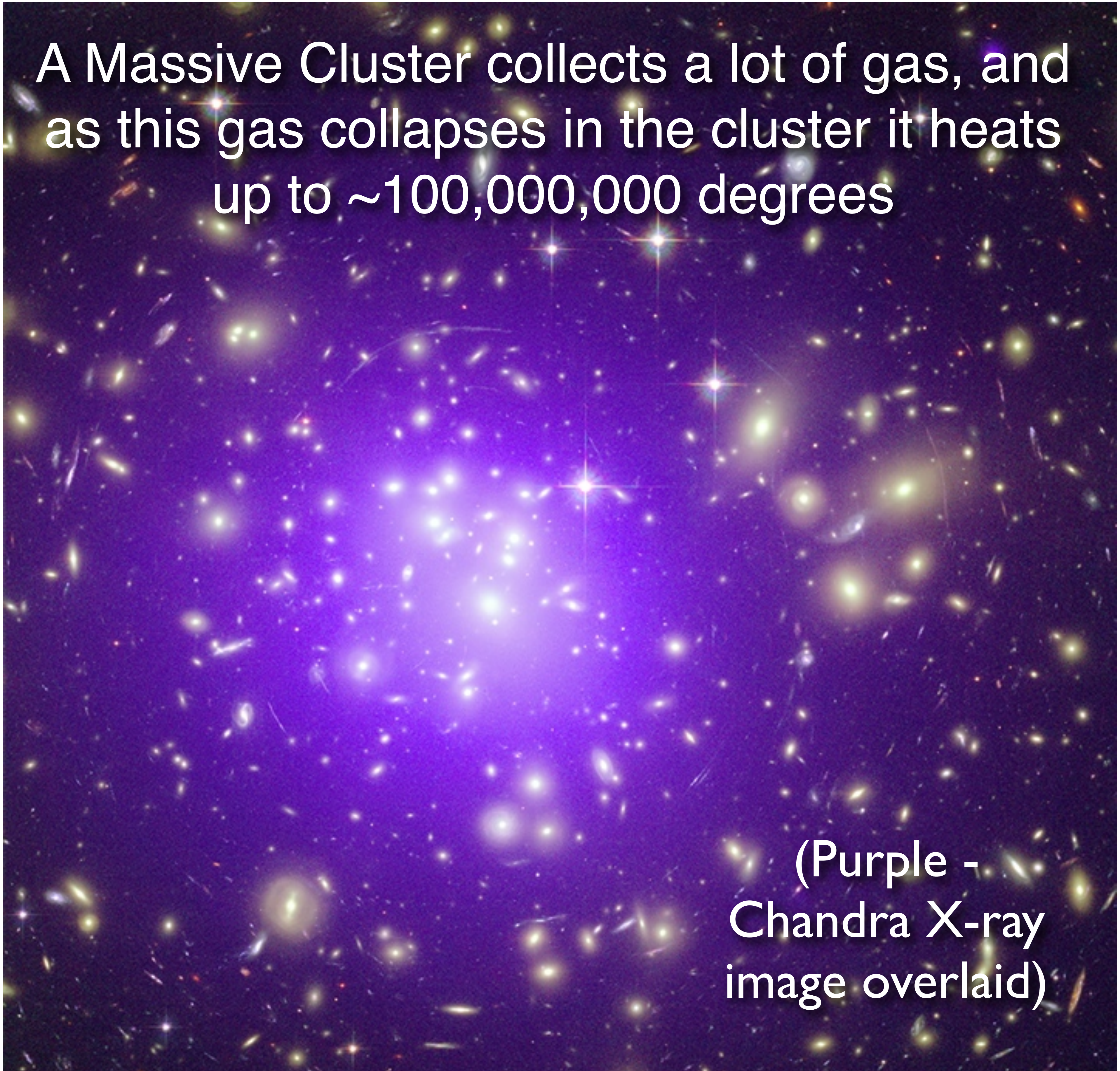
Clusters of Galaxies

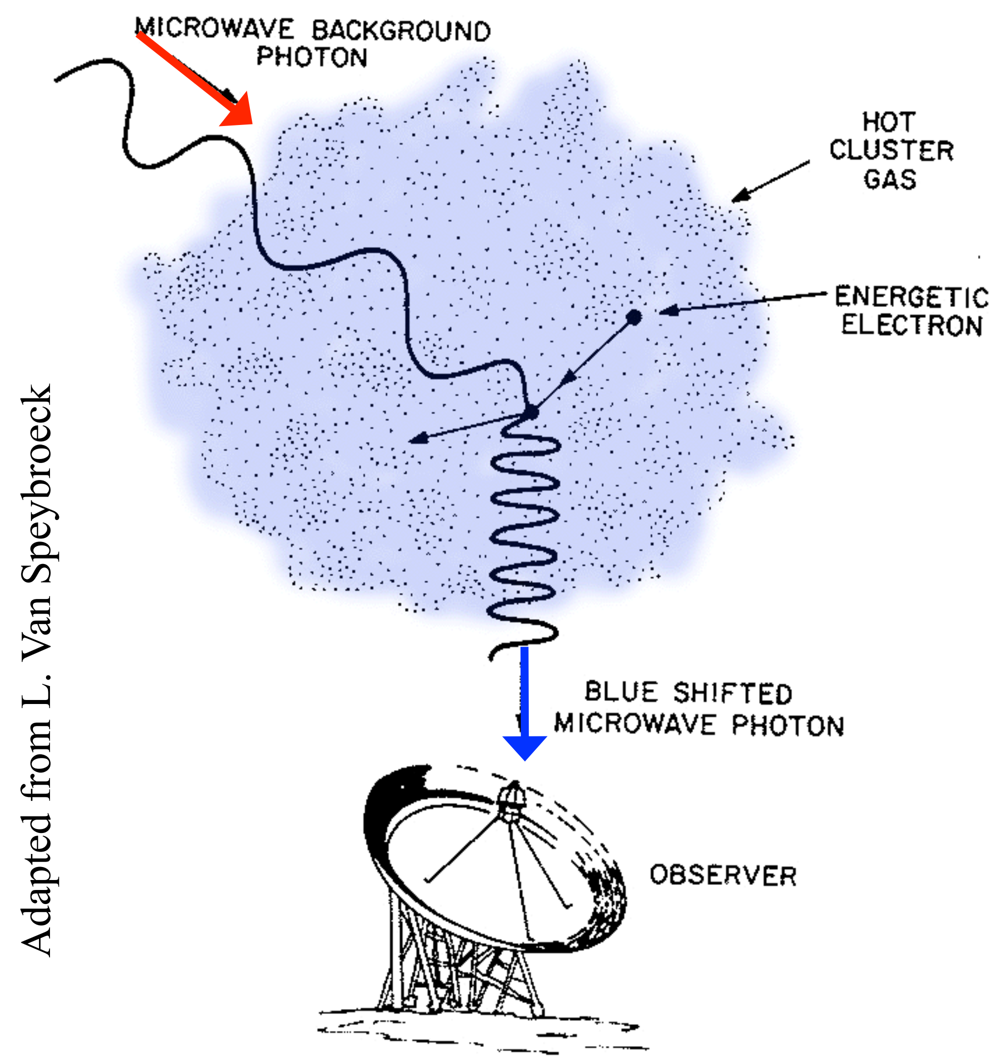


- They are the most massive, rare objects in the Universe - **this makes clusters very sensitive to cosmology**
- The biggest clusters contain **thousands of galaxies**, and take billions of years to form
- One of the few tracers of structure big enough to "feel" dark energy

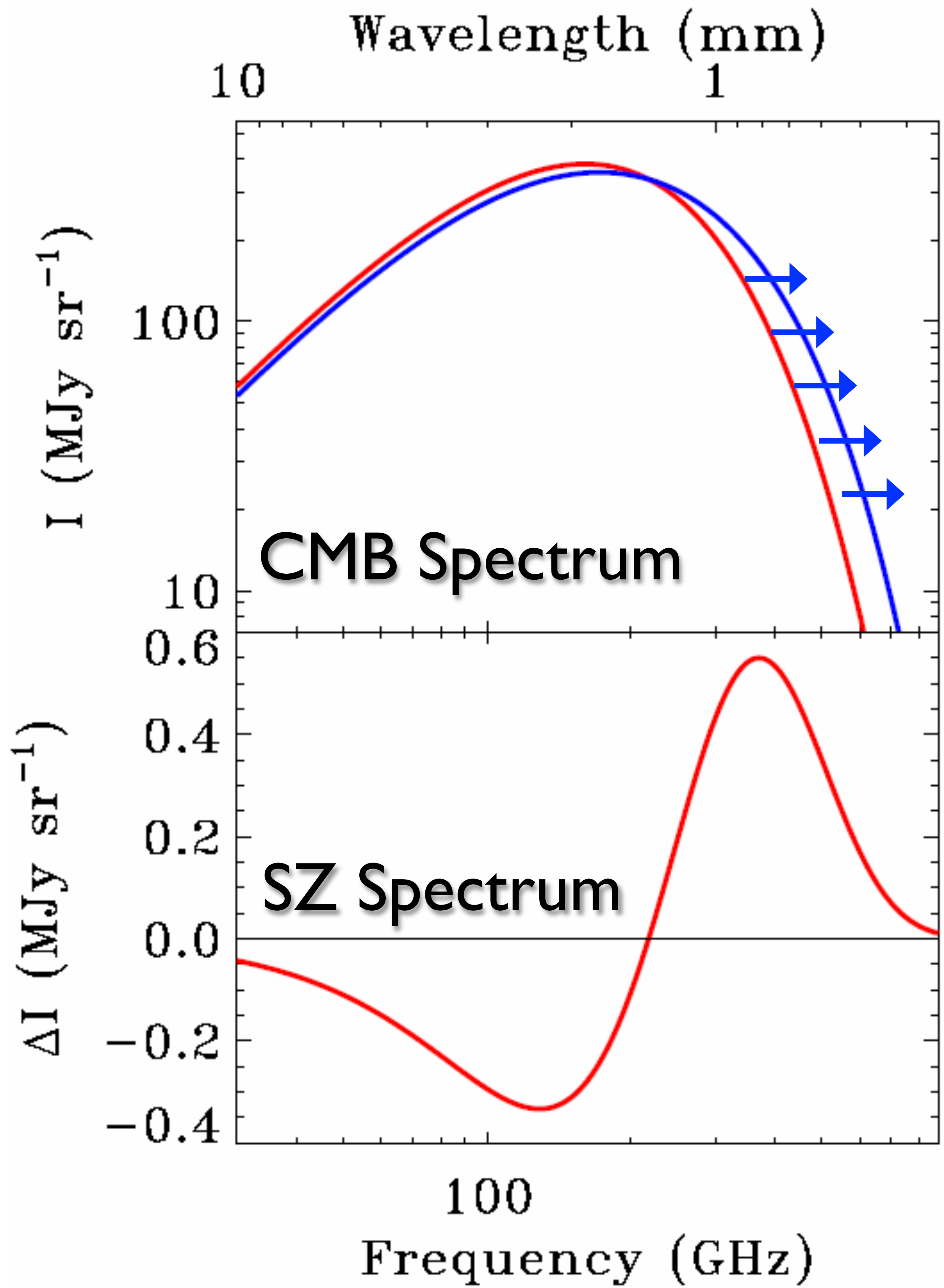
Baryons Are Mostly in the Form of Hot Gas



The Sunyaev Zel'dovich (SZ) Effect

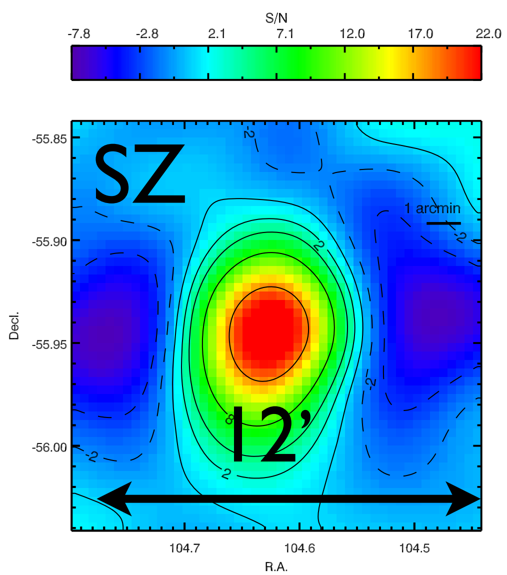


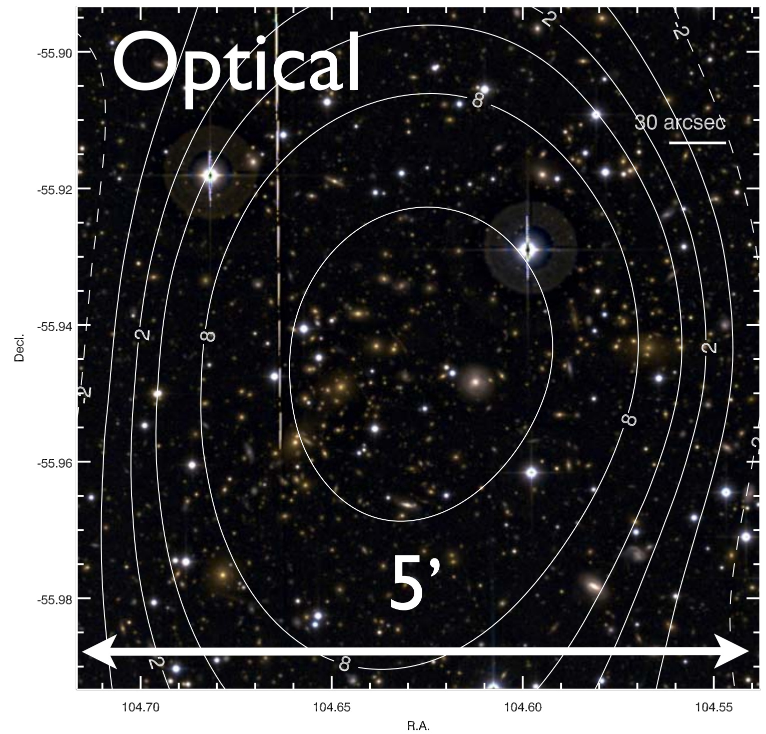
- Towards a massive cluster, ~1% of CMB photons scatter off of intra-cluster gas
- SZ Surface Brightness is redshift independent



Example Massive SPT Clusters

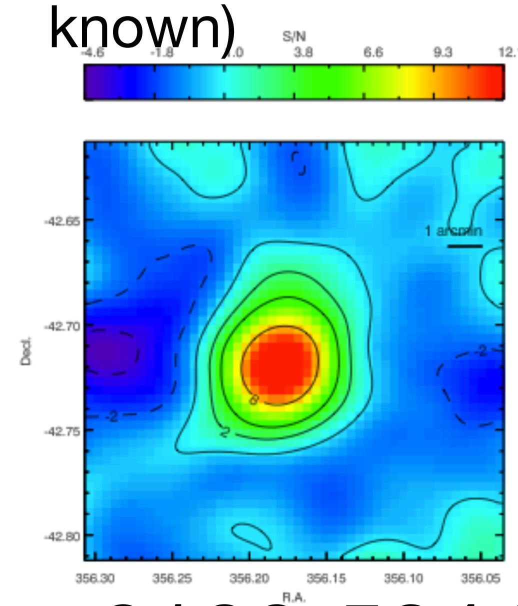
0658-5358 (z=0.30) (Bullet)

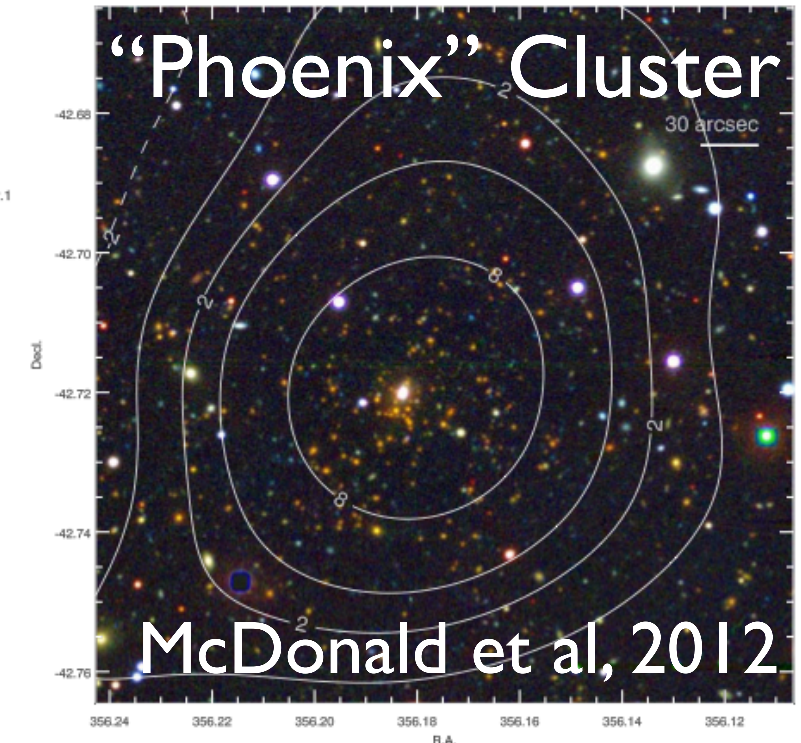




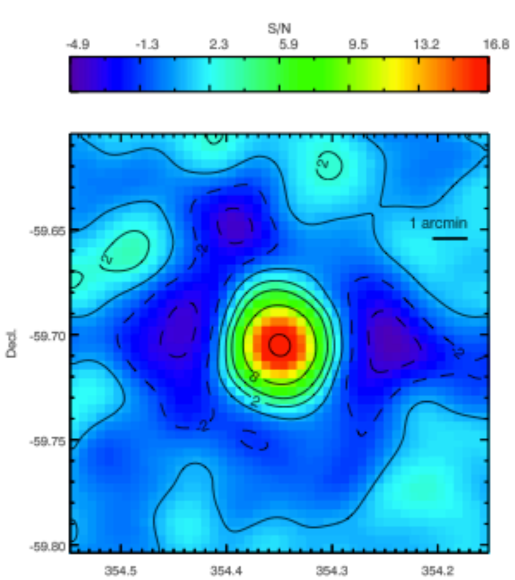
2344-4243 (z=0.60)

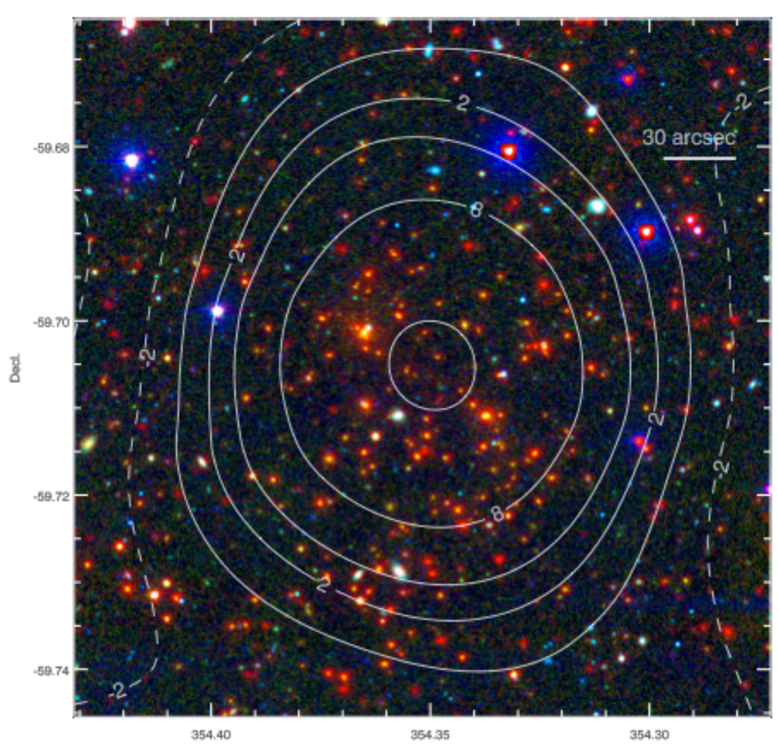
(Most X-ray luminous cluster known)





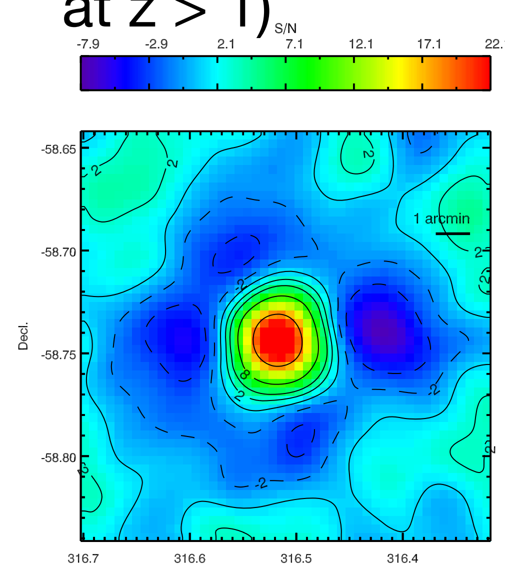
2337-5942 (z=0.78)

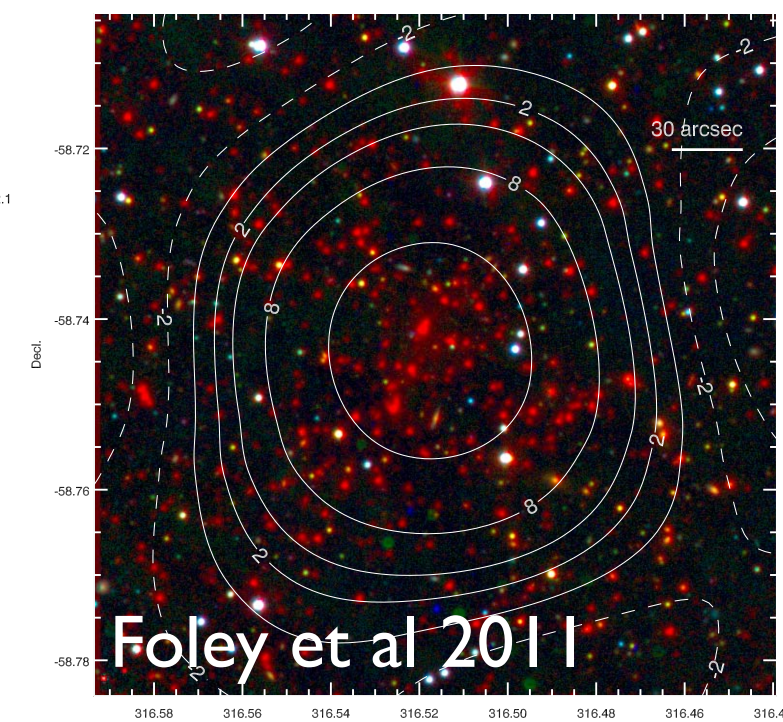




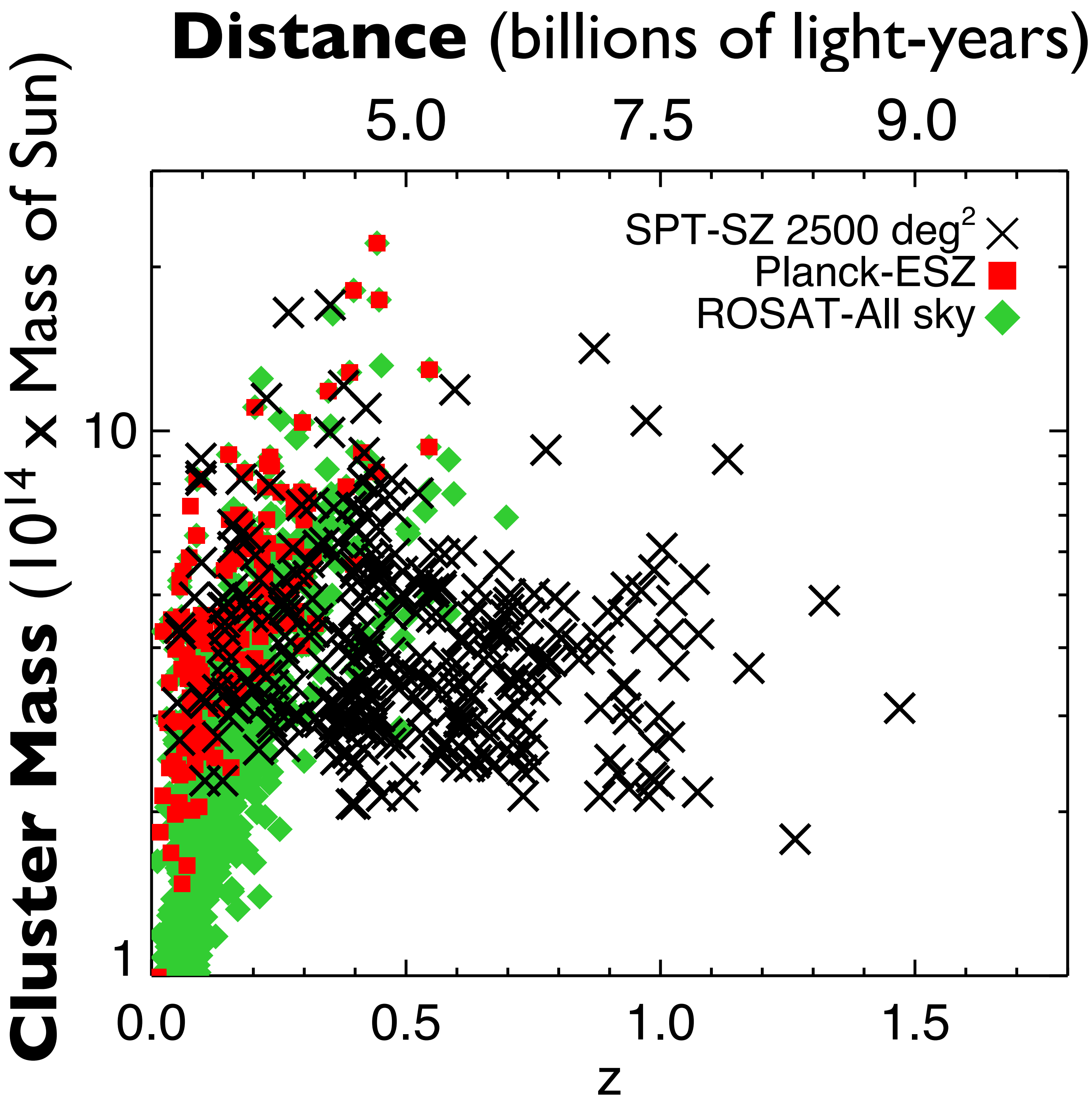
2106-5844 (z=1.13)

(Most massive cluster known at z > 1)





SPT Cluster Sample Properties



- SPT efficiently finds massive, distant clusters; about 400 new clusters of galaxies discovered by SPT.
- They are typically **one million-billion** (10^{15}) **times the mass of the Sun**, and
- Median redshift of 0.55
- SPT has more than doubled the number of known distant, comparably massive clusters at $z > 0.4$

See, Reichardt et al 2012, arXiv:1203.5775

brief detour: Today's Cosmology - ΛCDM

6 parameter ΛCDM Cosmological Model

$\Omega_\mathrm{b} h^2$: Baryon Density $\Omega_\mathrm{c} h^2$: Cold Dark Matter Density Ω_Λ : Dark Energy Density	} Content of Universe
n_s : Scalar Tilt Δ_R : Scalar Amplitude	} Primordial Power Spectrum
τ : Optical Depth to Reionization	} Astrophysical

This basic 6 parameter model fits all our astrophysical data very well!

brief detour: Today's Cosmology - ΛCDM

6 parameter ΛCDM Cosmological Model

$\Omega_b h^2$: Baryon Density
$\Omega_c h^2$: Cold Dark Matter Density
Ω_Λ : Dark Energy Density
} Content of Universe

n_s : Scalar Tilt
Δ_R : Scalar Amplitude
} Primordial Power Spectrum

τ : Optical Depth to Reionization } Astrophysical

This basic 6 parameter model fits all our astrophysical data very well!

Remember though, big questions remain! We would like to test extensions to this model and see what else we find!

Dark Energy and Cluster Cosmology

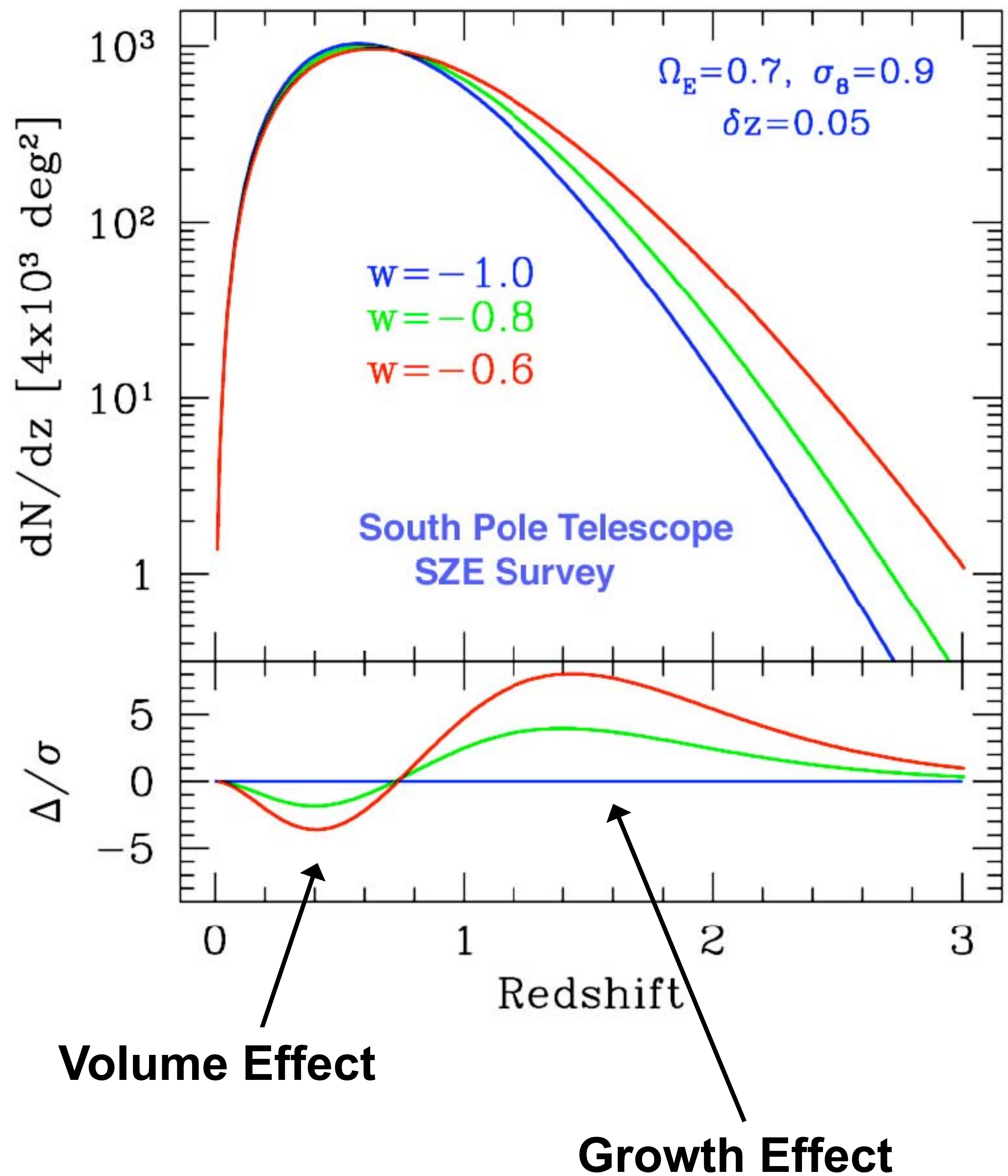
- Abundance of clusters is sensitive to the **dark energy equation of state, $w = p / \rho$**
- If dark energy was due to a cosmological constant then w = -1

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)*

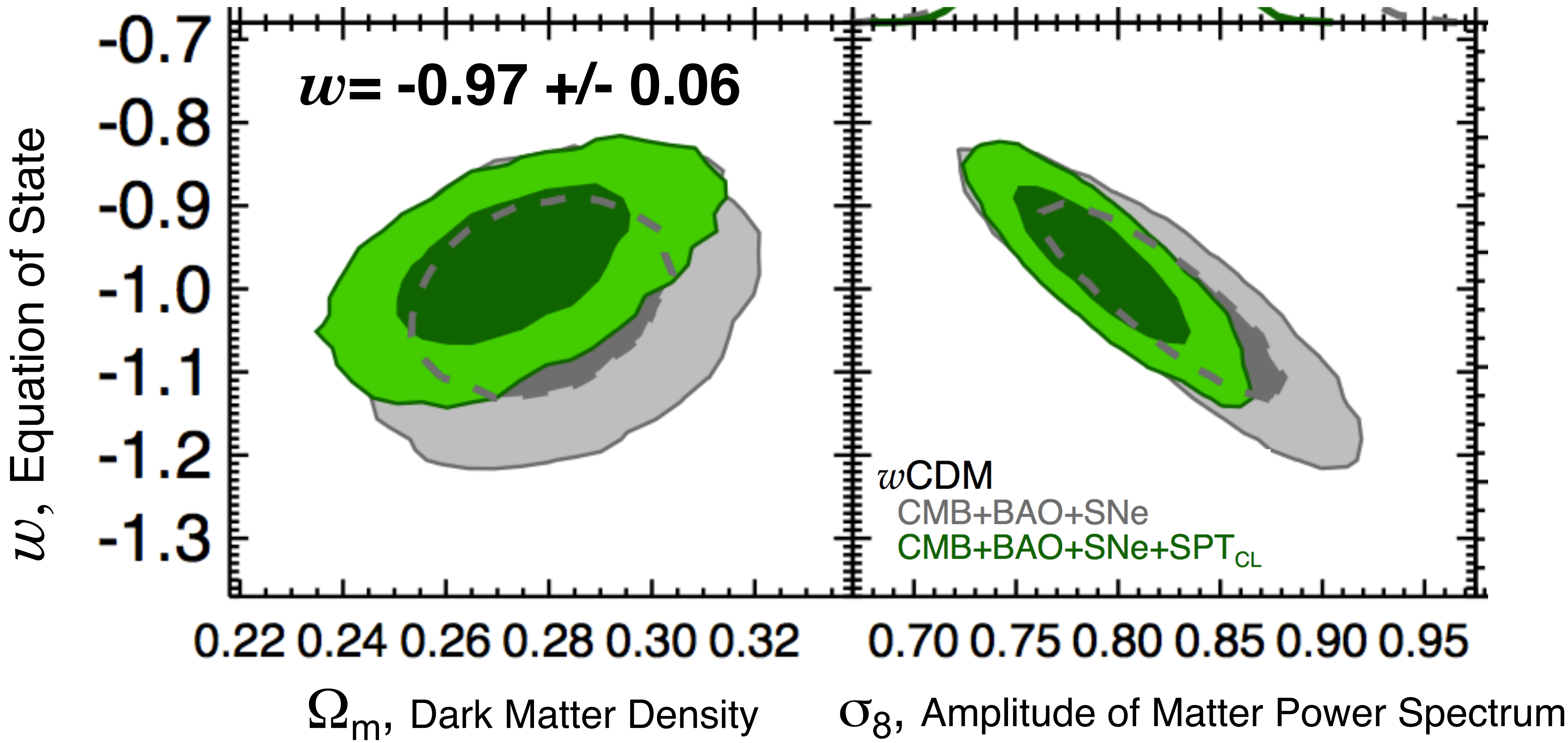
Depends on:
Rate of Expansion, *H(z)*



wCDM Constraints

Test Constraints with 18 clusters (~5% of survey)

SPT_{CL} data improves dark energy (w,Ω_m) constraints by factor of 1.5

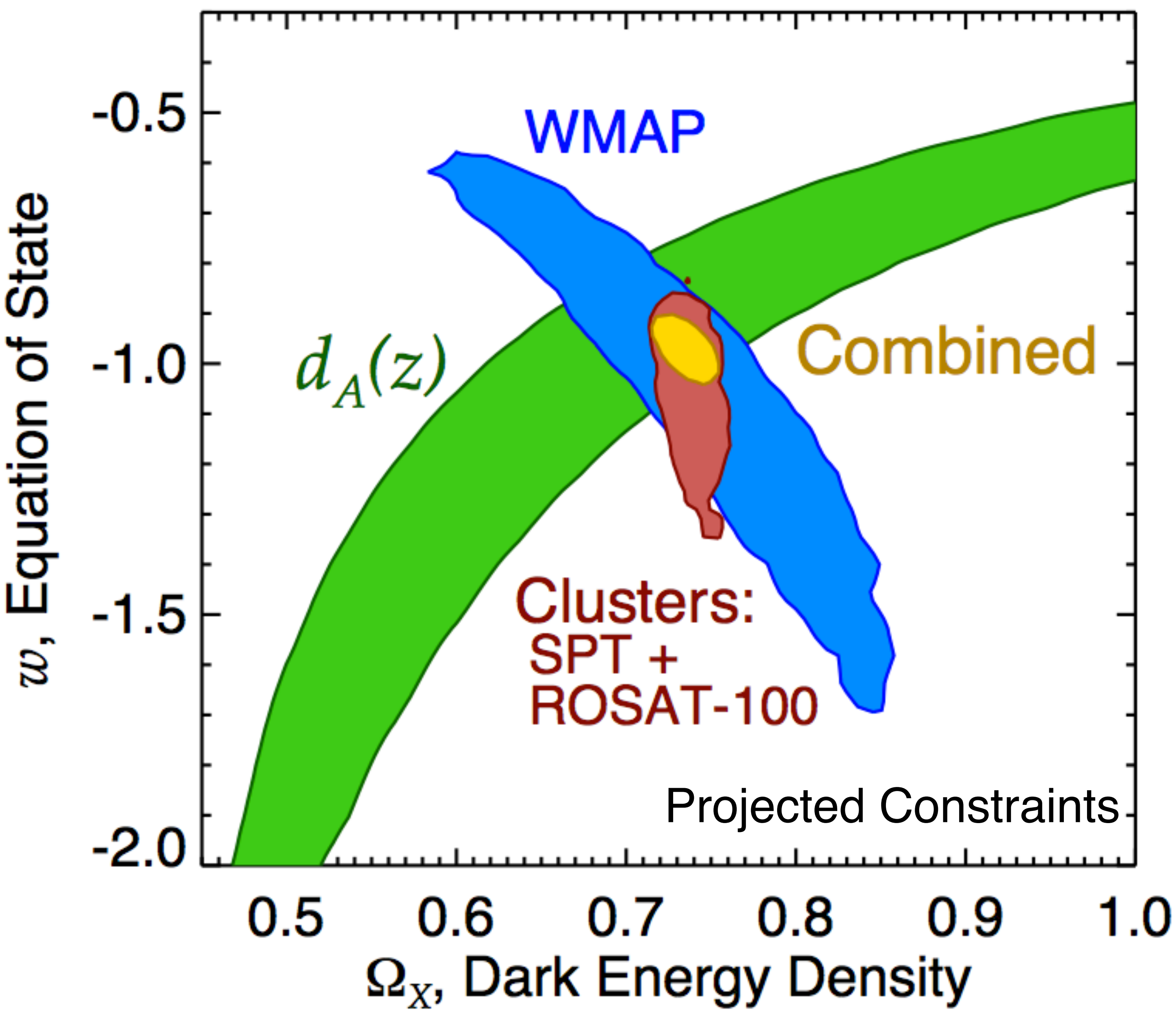


w, σ_8, Ω_m - 68, 95% Confidence Contours

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

SPT Cosmological Constraints:
2500 deg^2 (projected)



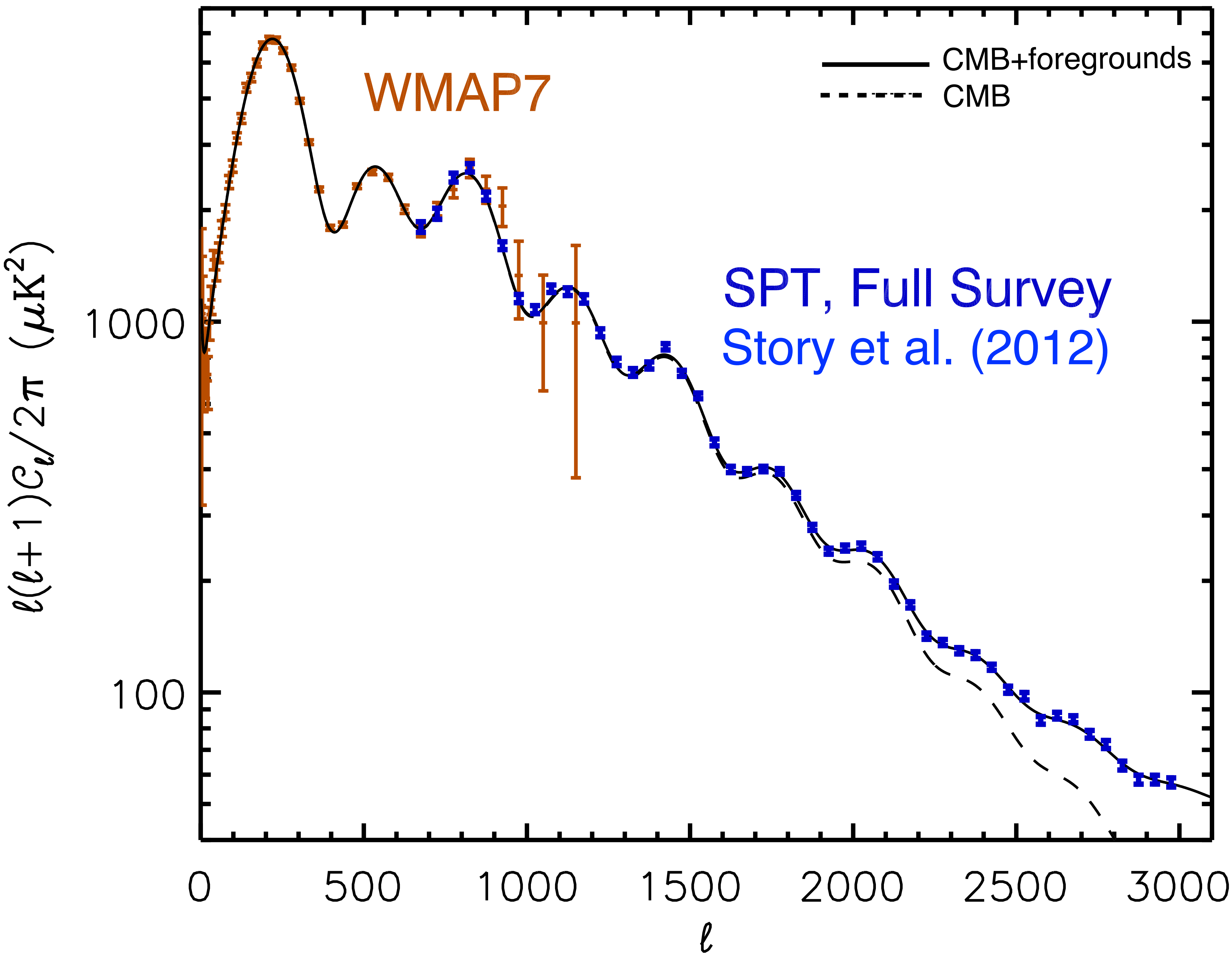
-Constrain δw ~ 5%, ****independent**** of *geometric cosmological constraints*** *from Supernova, BAO*

- *Systematic test of dark energy paradigm*

SPT Science

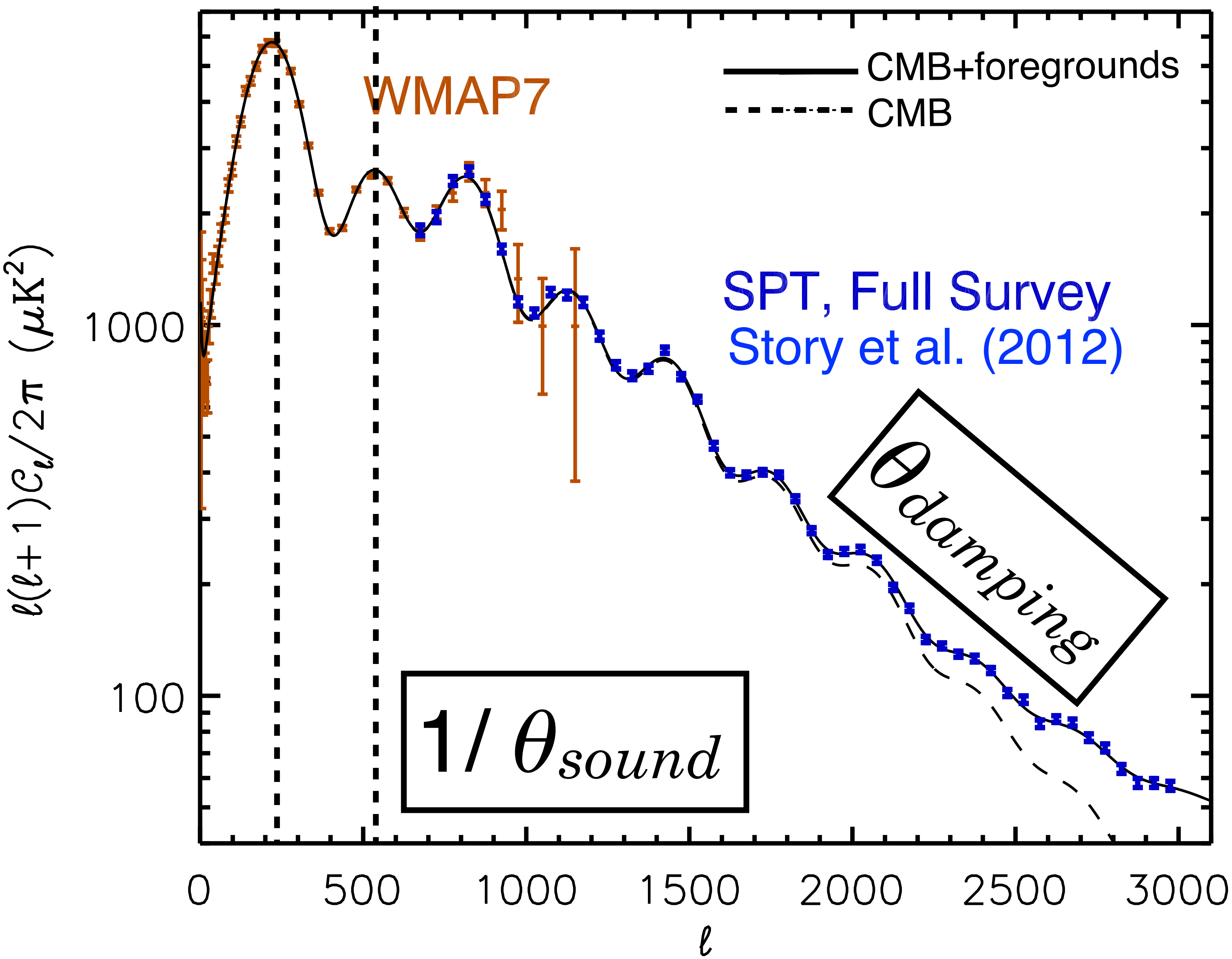
1. **SPT Cluster Survey**
   - Testing Dark Energy
2. **SPT: CMB Power Spectrum**
   - Constraints on Neutrinos
3. **SPTpol: CMB Polarization**
   - Constraining Inflation

SPT: CMB Power Spectrum



Beyond ΛCDM:

The Number of Neutrino Species



Each scale depends on expansion rate, or Hubble constant (H), differently:

$$\theta_s \propto H^{-1}$$

$$\theta_d \propto H^{-0.5}$$

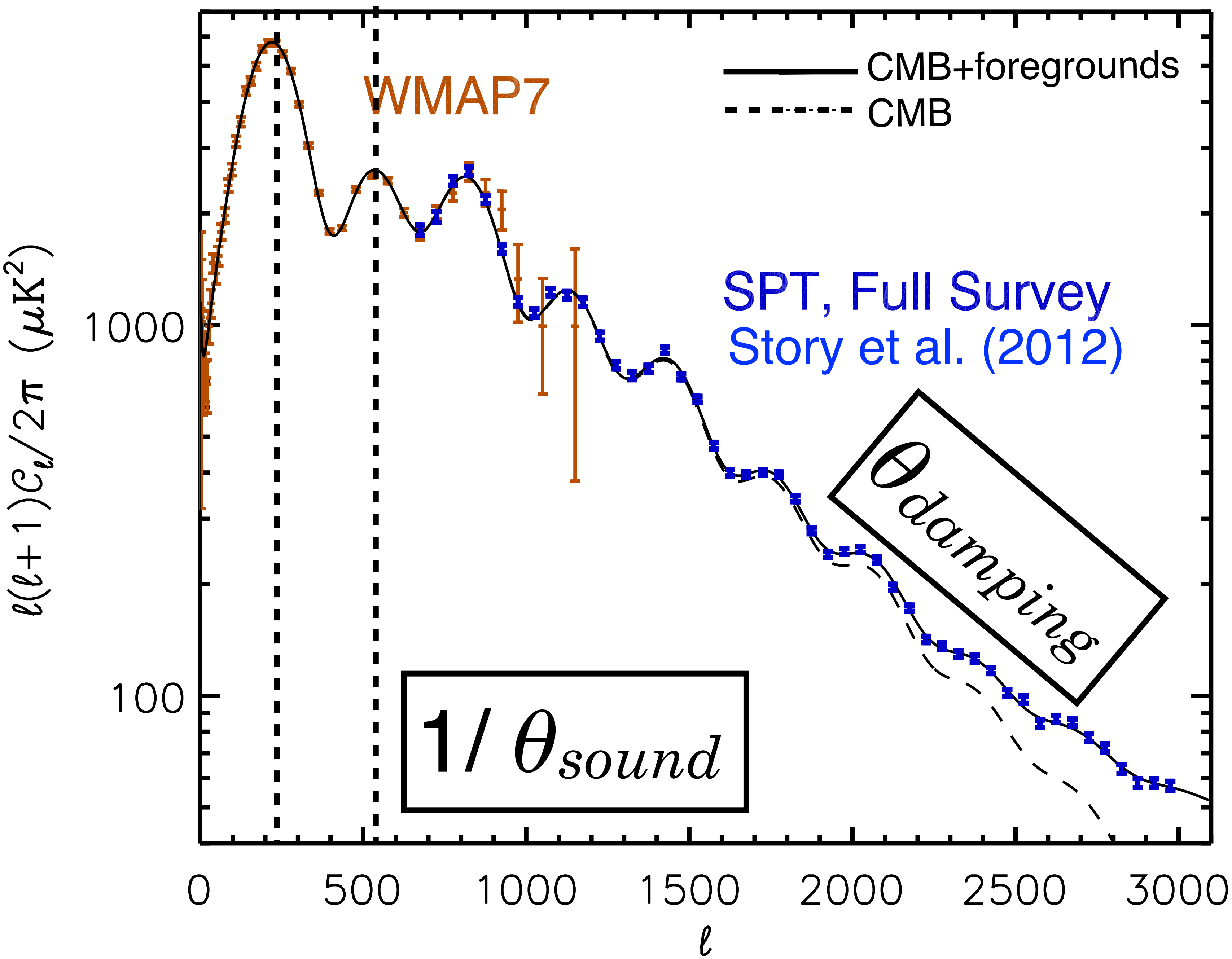
- "damping" is a diffusion process for the CMB photons, i.e., a random walk

$$\boxed{\frac{\theta_d}{\theta_s} \propto H^{0.5}}$$

A measure of the Hubble constant (H) at 400,000 years after the Big Bang!

Beyond ΛCDM:

The Number of Neutrino Species



- In early universe, neutrinos would have thermalized with other matter and radiation
- When the CMB was emitted, the universe was ~13% neutrinos (by energy density)
- Additional relativistic particle species (e.g., neutrinos) would increase relativistic energy density and affect the Universe's expansion rate

The Number of Effective Relativistic Species: $\boldsymbol{N_{\mathrm{eff}}}$

Neff is the *effective number of relativistic species.*

$$N_{\mathrm{eff}} \equiv \frac{\rho_\nu}{\rho_\gamma} \left(\frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \right)$$

The standard value is **Neff = 3.046**

This is

3.000 for the 3 neutrino species,
0.046 for energy injected by electron/positron annihilation.

Neff > 3.046 could correspond to a new particle species that is relativistic prior to recombination and has an energy density comparable to the standard neutrinos.

Beyond ΛCDM:

No Neutrinos vs. Standard Neutrinos?

Simple test: compare maximum likelihood in N_ν=0 model to that in N_ν=3.046 model

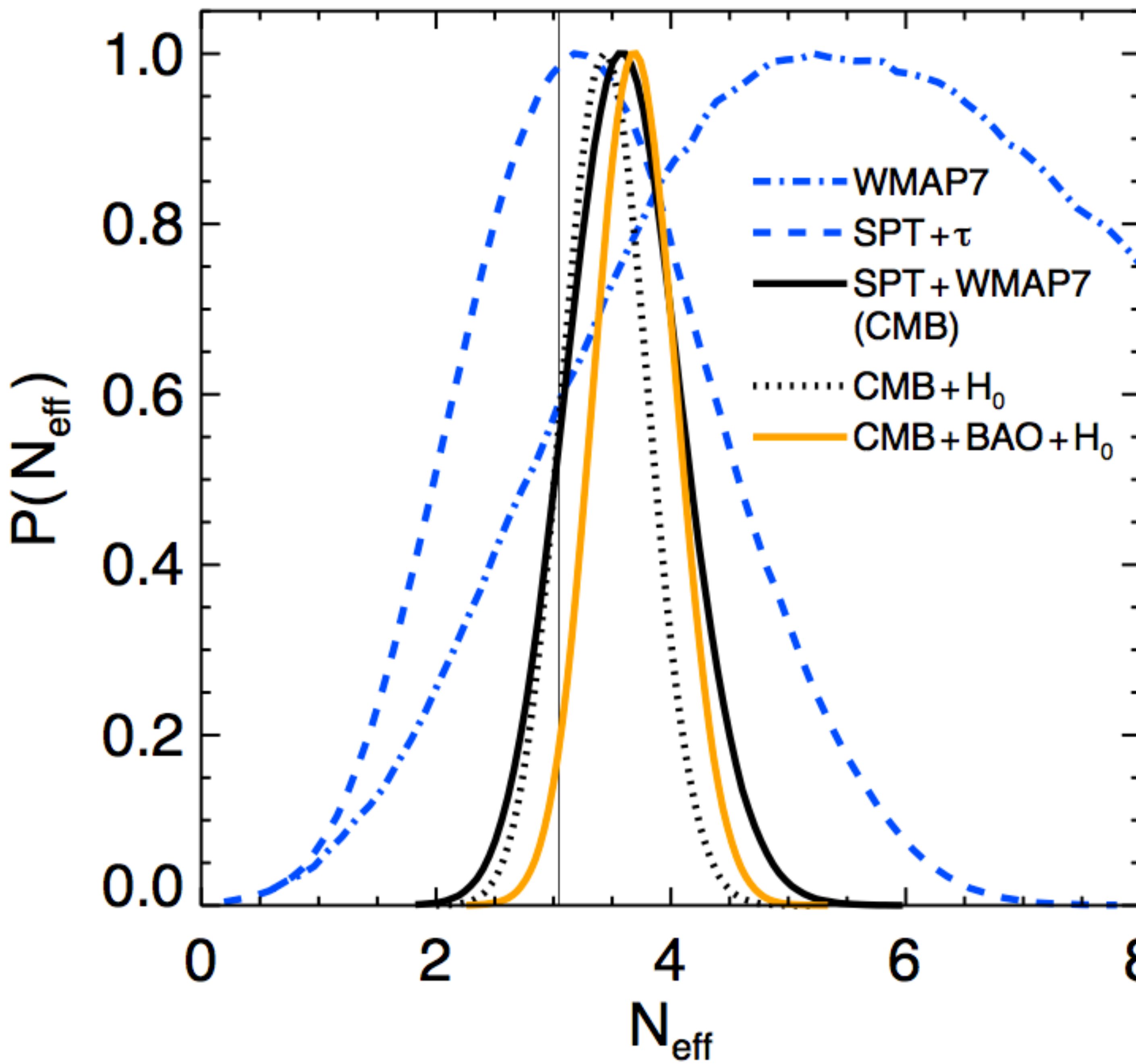
Standard neutrinos are preferred over no neutrinos preferred by $\delta\chi^2 = 56.3$, i.e. 7.5-σ

The CMB strongly detects presence of neutrinos in early universe.

SPT Collab:
Hou et al 2012,
arXiv: 1212.6267

Beyond ΛCDM:

Constraints on the Number of Neutrinos



SPT Collab:
Hou et al 2012,
arXiv: 1212.6267

Neff = 3.62 +/- 0.48	**(WMAP7 + SPT)**	(1.2σ higher than 3.046)
Neff = 3.71 +/- 0.35	**(WMAP7 + SPT + BAO + H_0)**	(1.9σ higher than 3.046)

WMAP9

The WMAP9 and most-recent SPT power spectrum papers (Hou et al. 2012) came out within days each other, how do they compare?

CMB-only constraints on Neff:

Neff = 3.89 +/- 0.67	**(WMAP9 + eCMB)**
Neff = 3.62 +/- 0.48	**(WMAP7 + SPT)**

("eCMB" driven by old SPT data)

However, when the WMAP9 data set added the same BAO and H0 data as the SPT papers, their results changed significantly:

Neff = 3.26 +/- 0.35	**(WMAP9 + eCMB + BAO + H_0)**
Neff = 3.71 +/- 0.35	**(WMAP7 + SPT + BAO + H_0)**

Huh?

WMAP9

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~~**Neff = 3.26 +/- 0.35**~~	~~**(WMAP9 + eCMB + BAO + H_0)**~~
Neff = 3.71 +/- 0.35	**(WMAP7 + SPT + BAO + H_0)**

There was a bug in the WMAP9 paper in how they included BAO in their Neff constraint! (corrected on arxiv 30-Jan-2013)

Neff = 3.80 +/- 0.40	**(WMAP9 + eCMB + BAO + H_0)**
Neff = 3.71 +/- 0.35	**(WMAP7 + SPT + BAO + H_0)**

(corrected WMAP9 result)

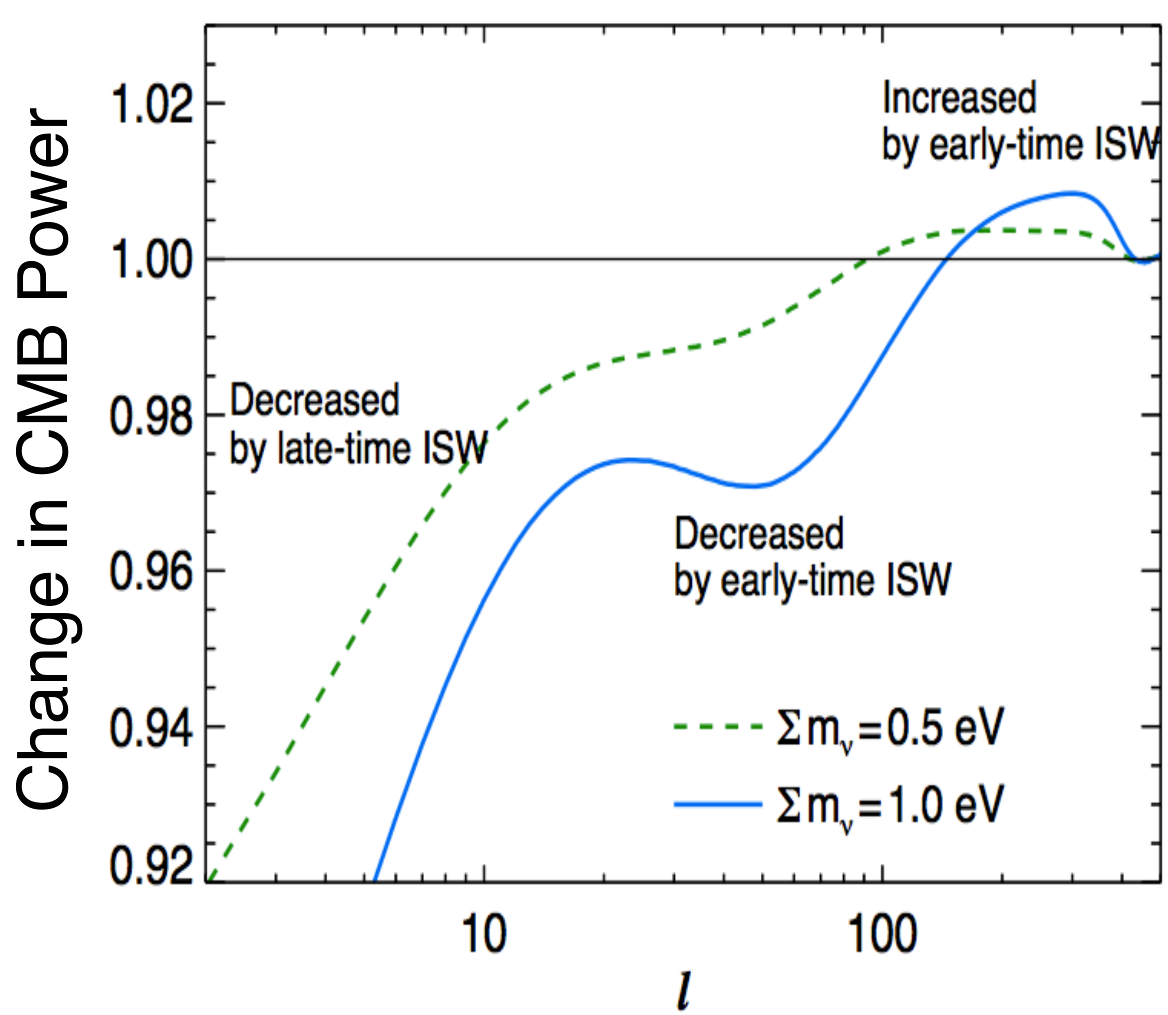
Neutrino Mass (Σm_ν) Constraints

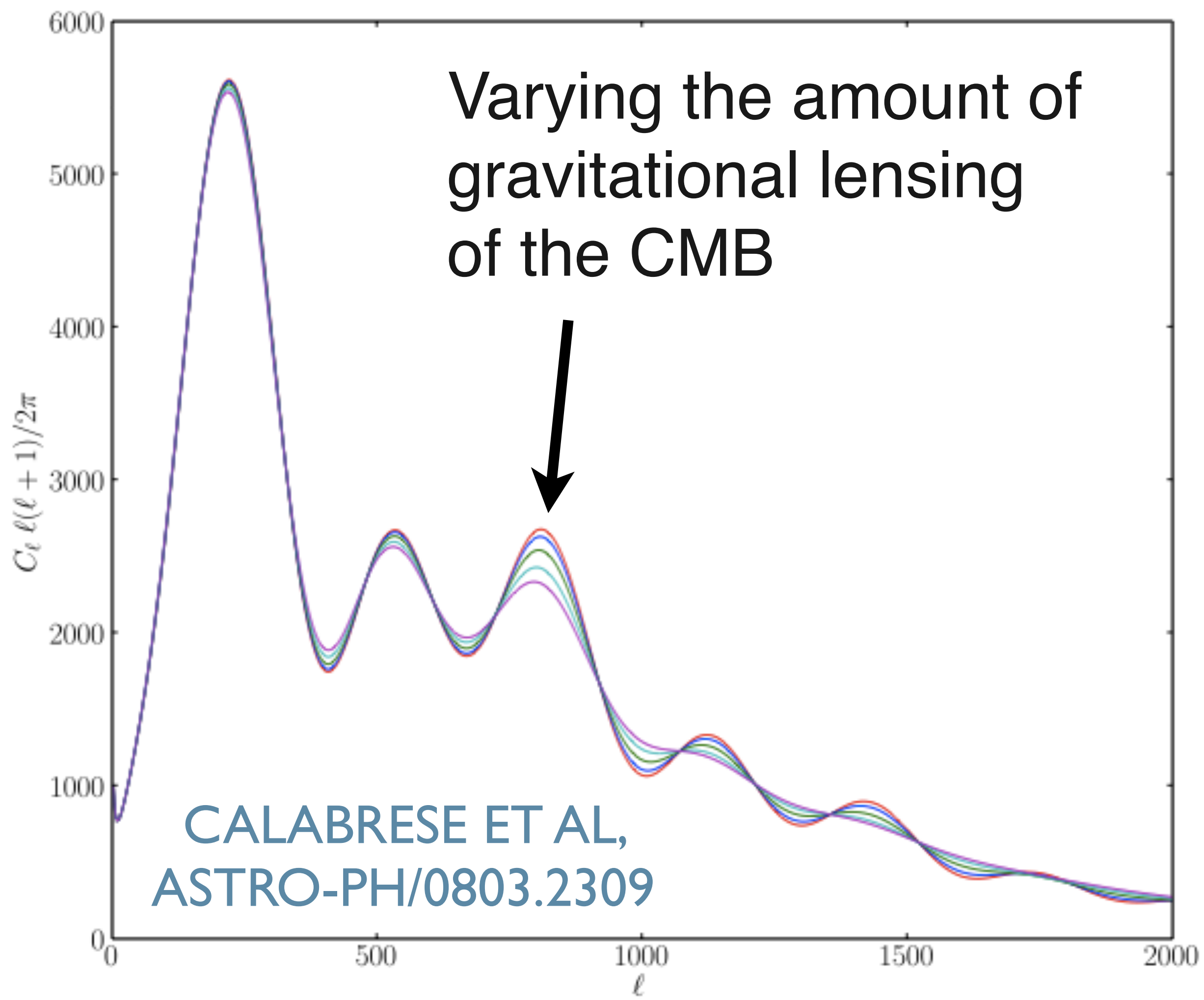
From a combination of terrestrial neutrino-oscillation and double Beta decay experiments, we know the mass of the neutrino is:

$$0.06 < \Sigma m_\nu < 1.8 \text{ eV}$$

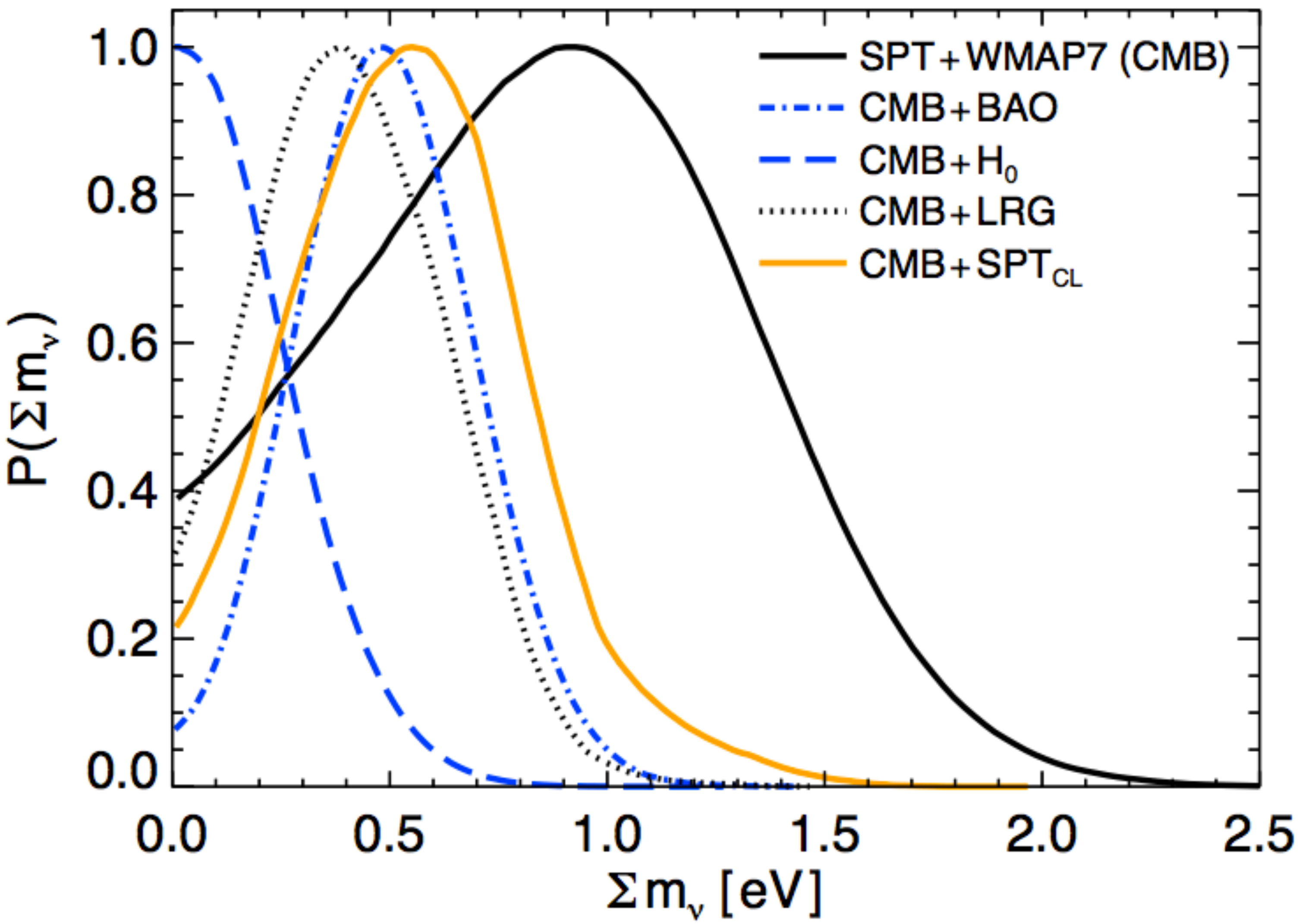
* Cosmology is mainly sensitive to the sum of the neutrino masses, Σm_ν.

* Massive neutrinos affect the CMB through the Integrated-Sachs Wolf (ISW) effect, and lensing / smearing of CMB peaks





Neutrino Mass (Σm_ν) Constraints



- CMB data has a **mild preference for positive neutrino mass**
- Adding other cosmological measurements can break degeneracies in the CMB data

H0 = Hubble Constant } Expansion Rate

BAO = Baryon Acoustic Oscillations } Geometry

SPT_{CL} = SPT Clusters

LRG = Luminous Red Galaxies } Measurements of Cosmic Structure

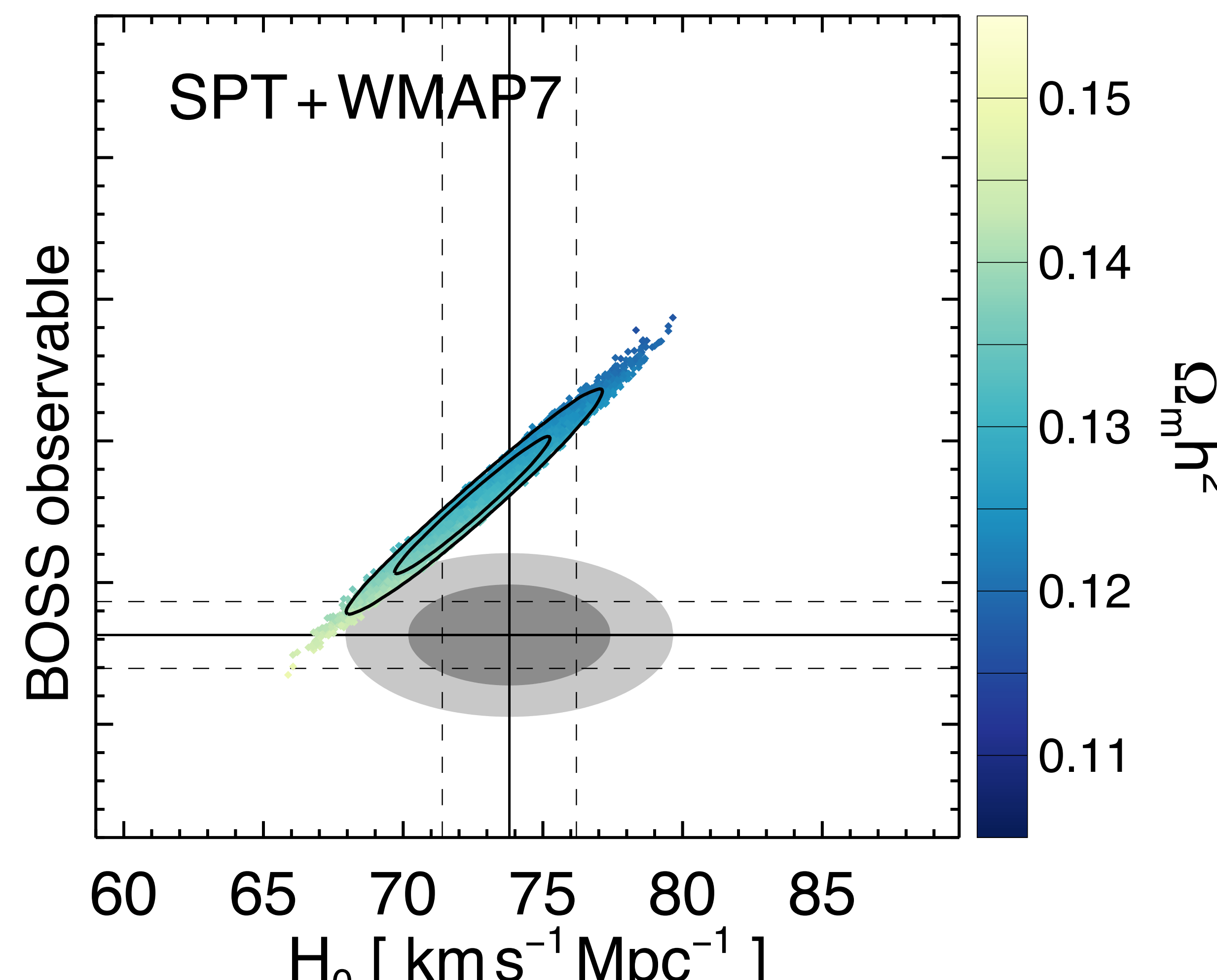
brief detour: Hubble Constant (H0) and BAO data

H0 — Riess et al 2011

BAO —
BOSS (z=0.57), Anderson et al 2012
SDSS (z=0.35), Padmanabhan et al 2012
WiggleZ (z=0.44-0.73), Blake et al 2011

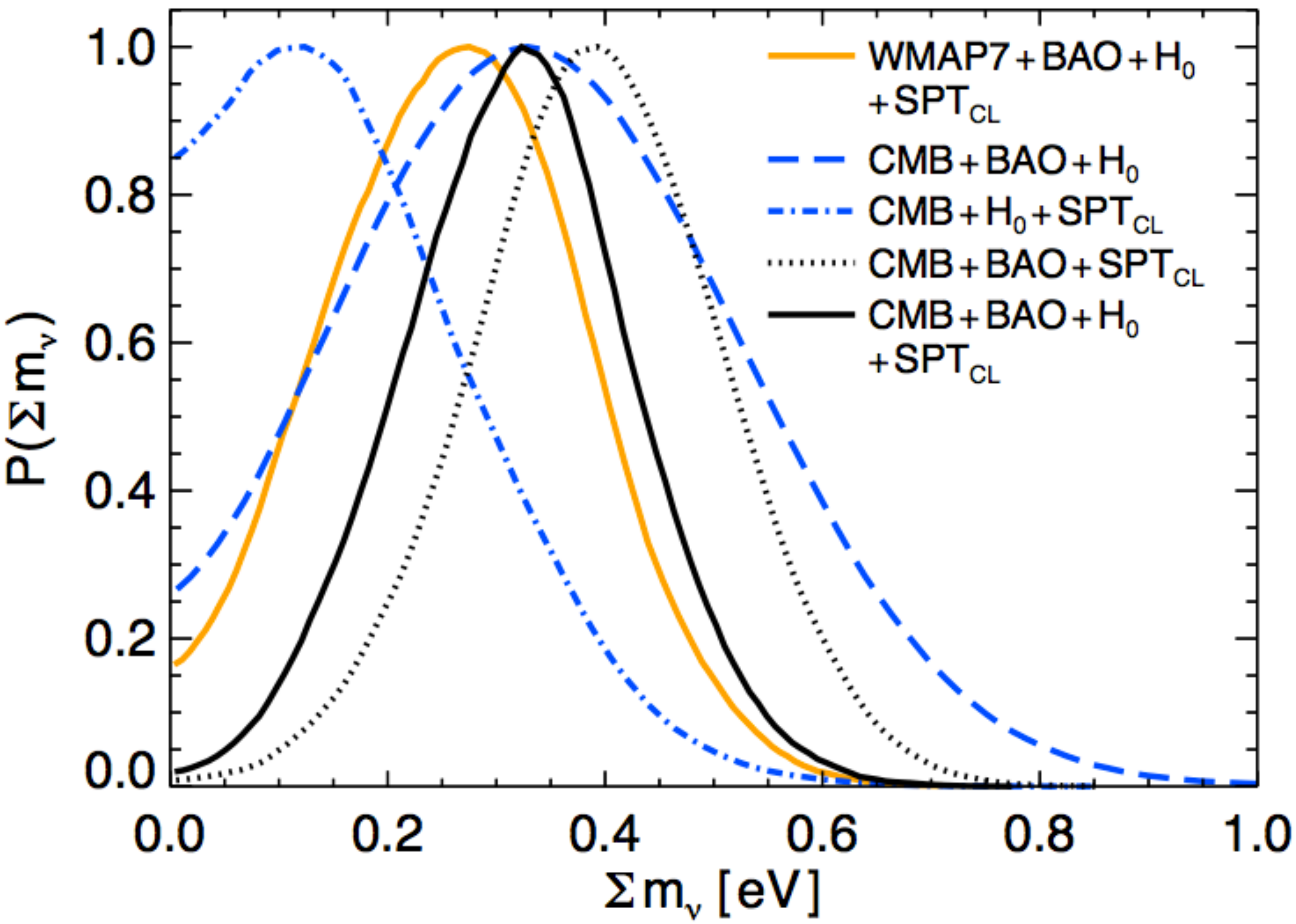
There is some ~2-sigma tension between CMB, H0, and BAO.

This is true in LCDM, and in most other models.



(see Hou, Reichardt, Story, Follin, Keisler, et al, 1212.7231)

Neutrino Mass (Σm_ν) Constraints



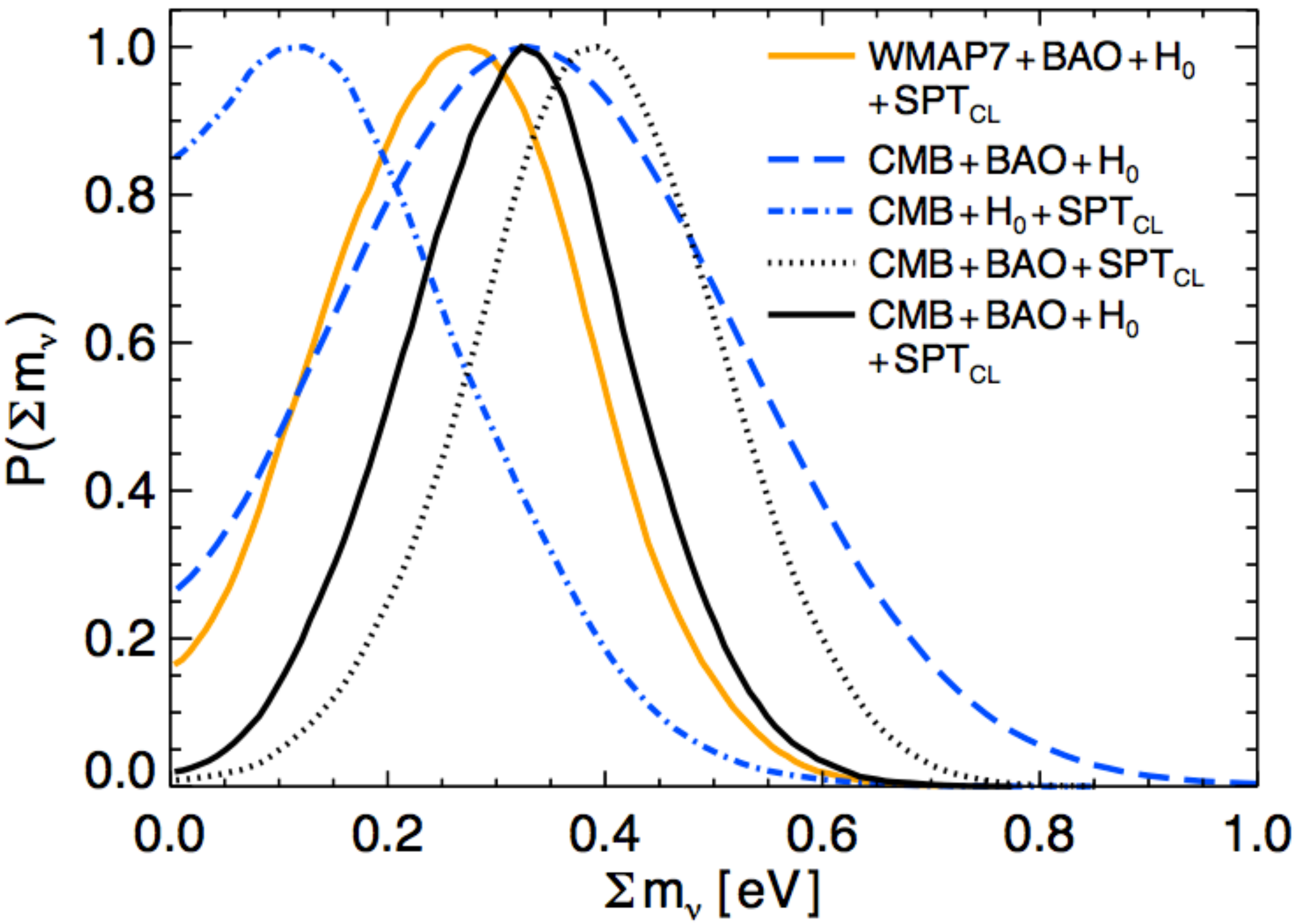
Adding all the cosmological data together:

$$\Sigma m_\nu = 0.32 \pm 0.11 \text{ eV}$$
(CMB+BAO+H0+SPT_{CL})

How does it depend on which data sets we use?

- All of the CMB, BAO, and SPT_{CL} data sets have slight (~1-sigma) preferences for non-zero neutrino mass
- However, remove BAO data, and the preference for the combined data set goes away

Neutrino Mass (Σm_ν) Constraints



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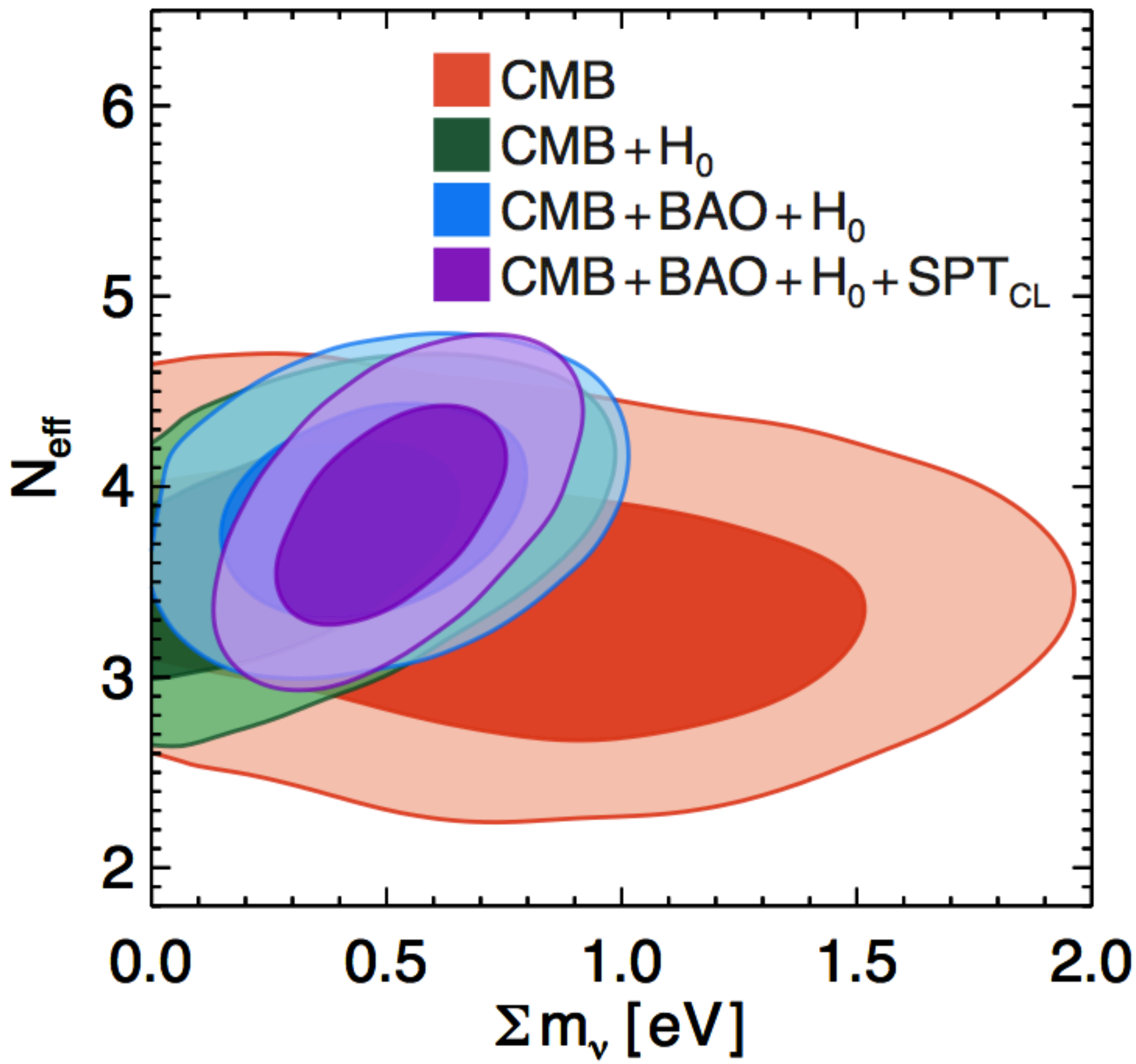
- However, remove BAO data, and the preference for the combined data set goes away

Take away: There are data combinations that yield a 3σ "detection" of neutrino mass, at ~0.3 eV or ~6X the minimum Σm.

Will this hold up with future CMB/BAO/H0/LSS data?

Neutrino Mass and the Number of Relativistic Species



We can also let the mass and number of relativistic species both be free parameters:

$N_{\rm eff}$ = 3.86 +/- 0.37

Σm_ν = 0.51 +/- 0.15 eV

2.2-σ preference for $N_{\rm eff} > 3.046$

3.3-σ preference for $\Sigma m_\nu > 0$ eV

SPT Collab:
Hou et al 2012,
arXiv: 1212.6267

SPT Science

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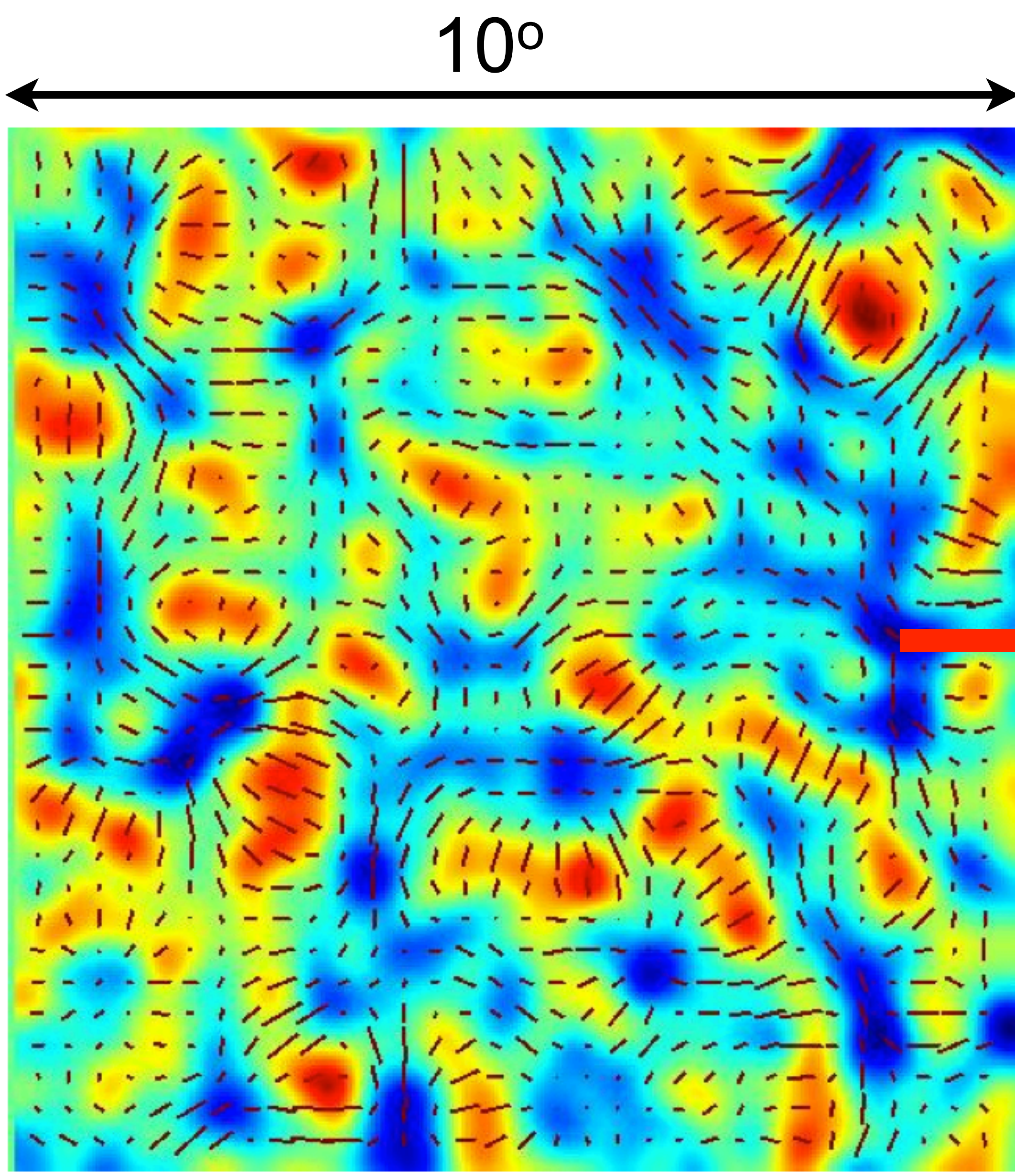
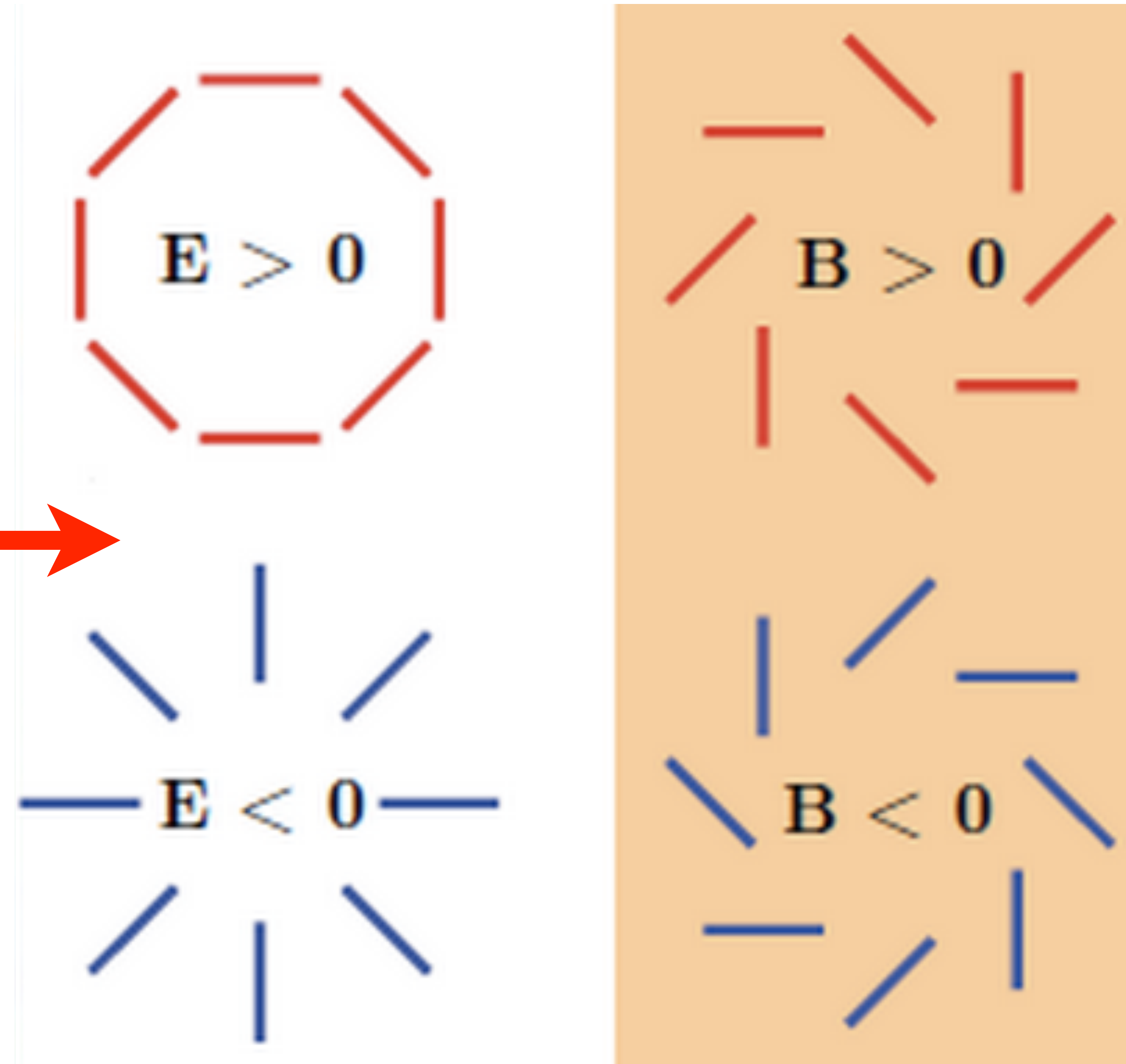
   - Constraining Inflation

The Next Frontier:
The Polarization of the CMB

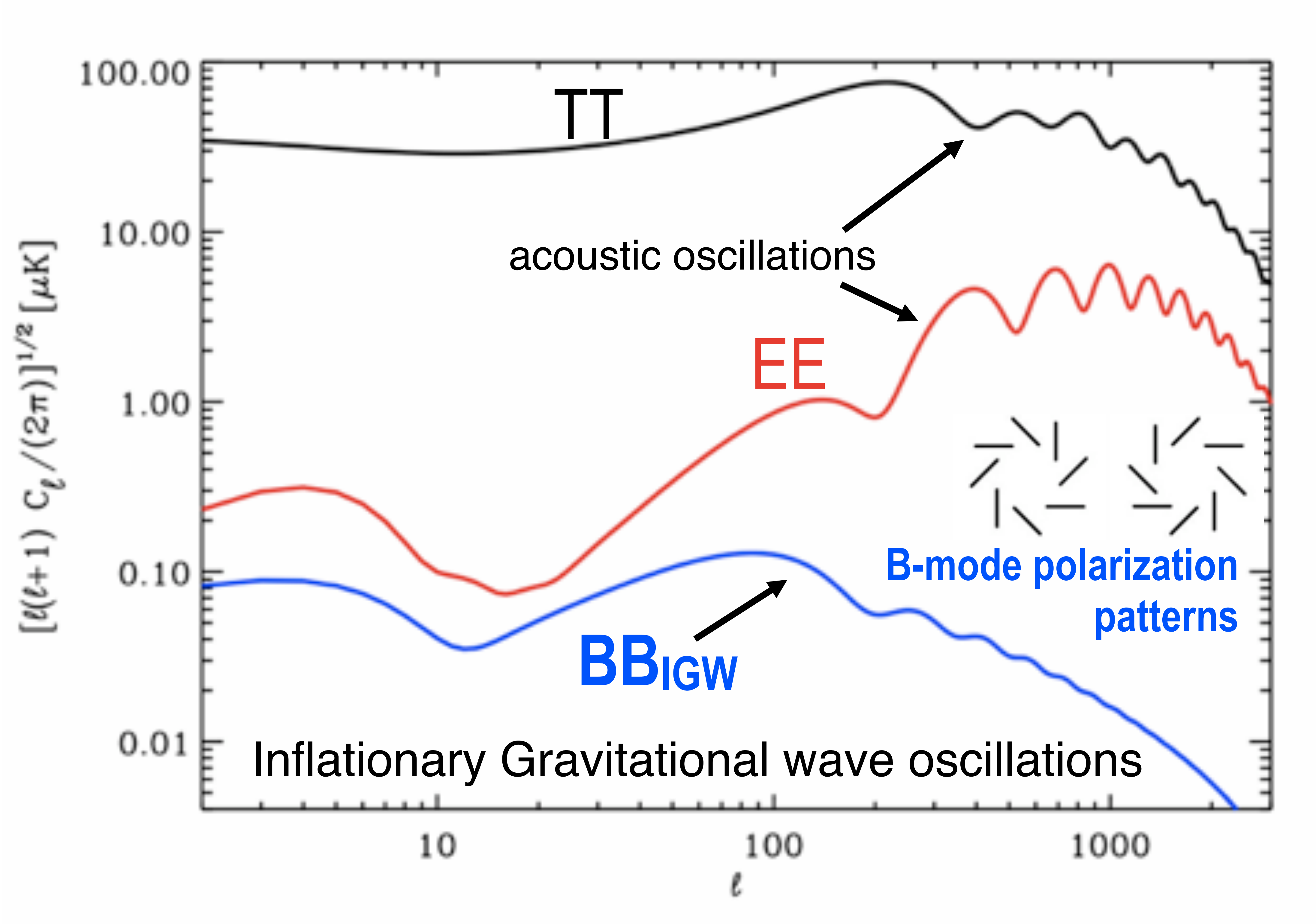




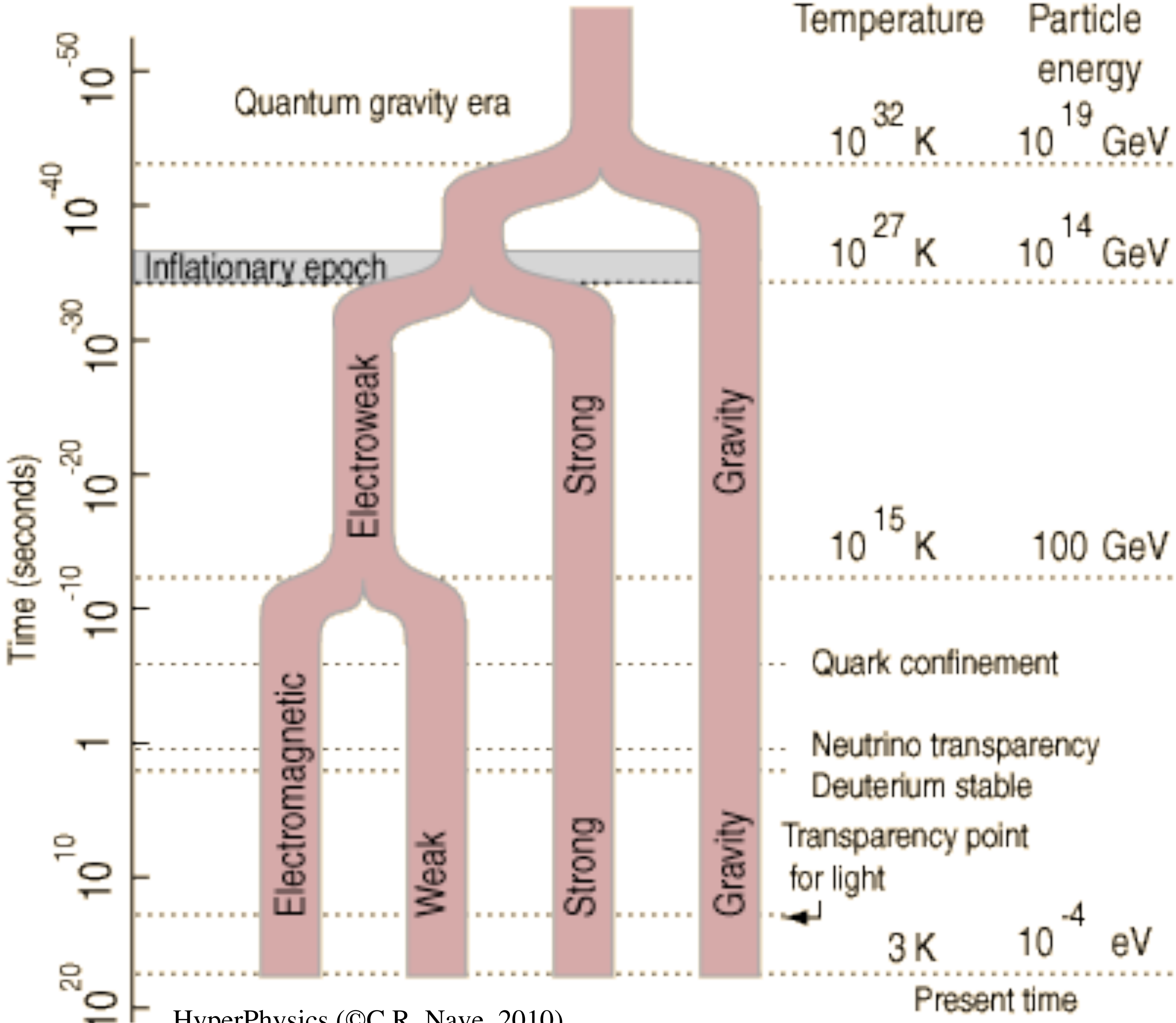
E-modes:
Even Parity

B-modes:
Odd Parity

The BB spectrum probes gravitational waves from Inflation!

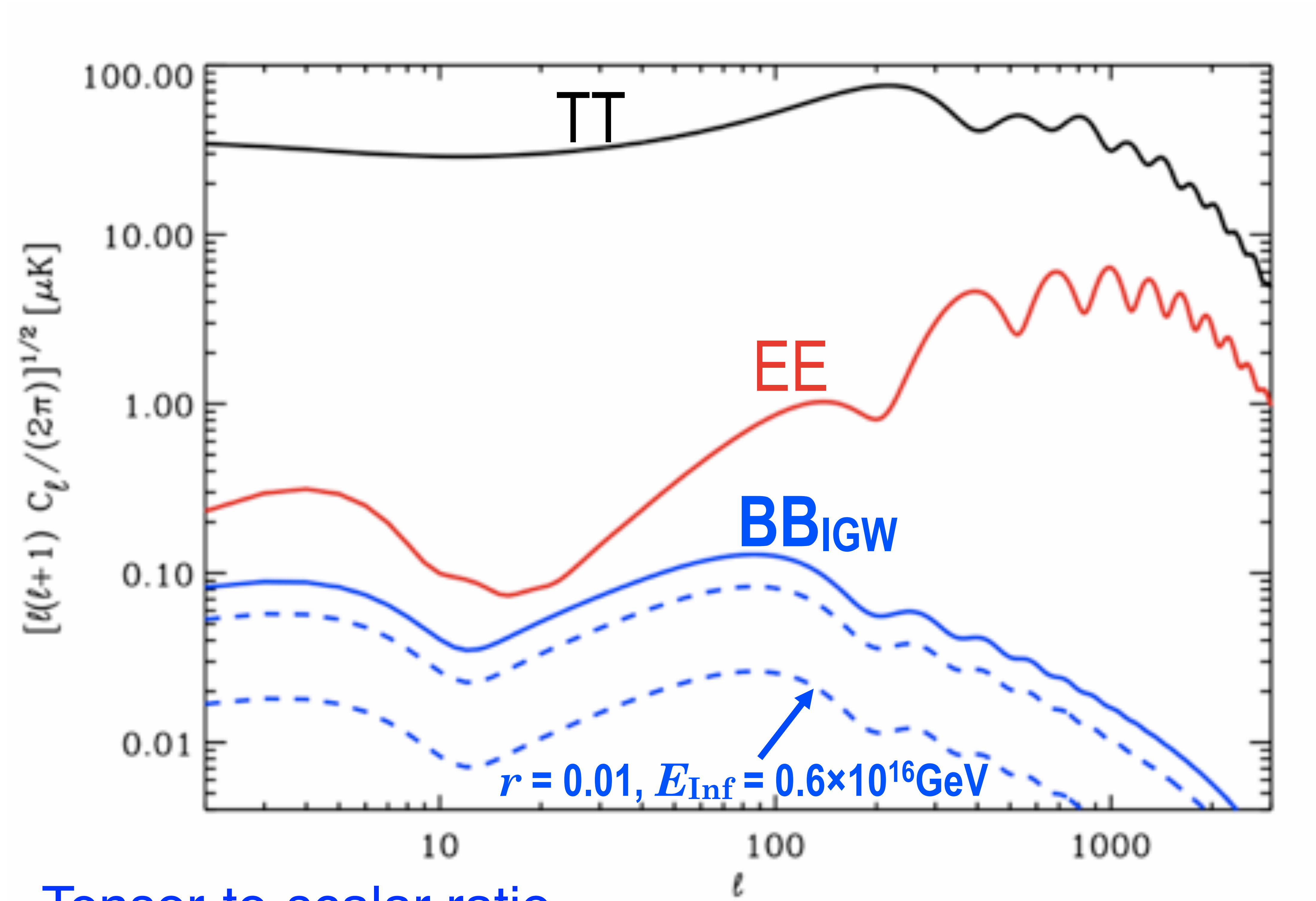


Early universe as an High-Energy Physics lab



HyperPhysics (©C.R. Nave, 2010)

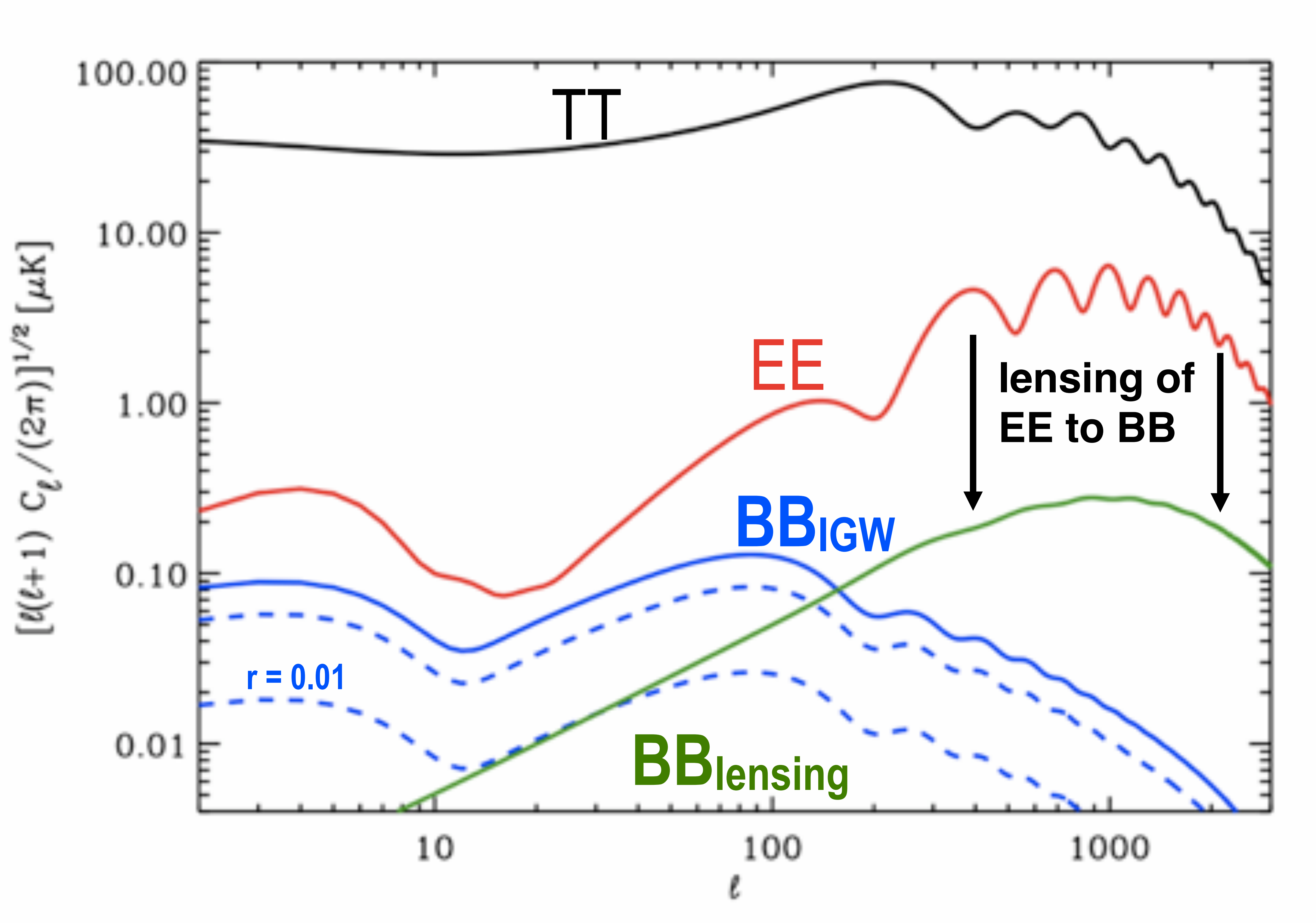
The amplitude of the gravity wave signal depends on the energy scale of Inflation



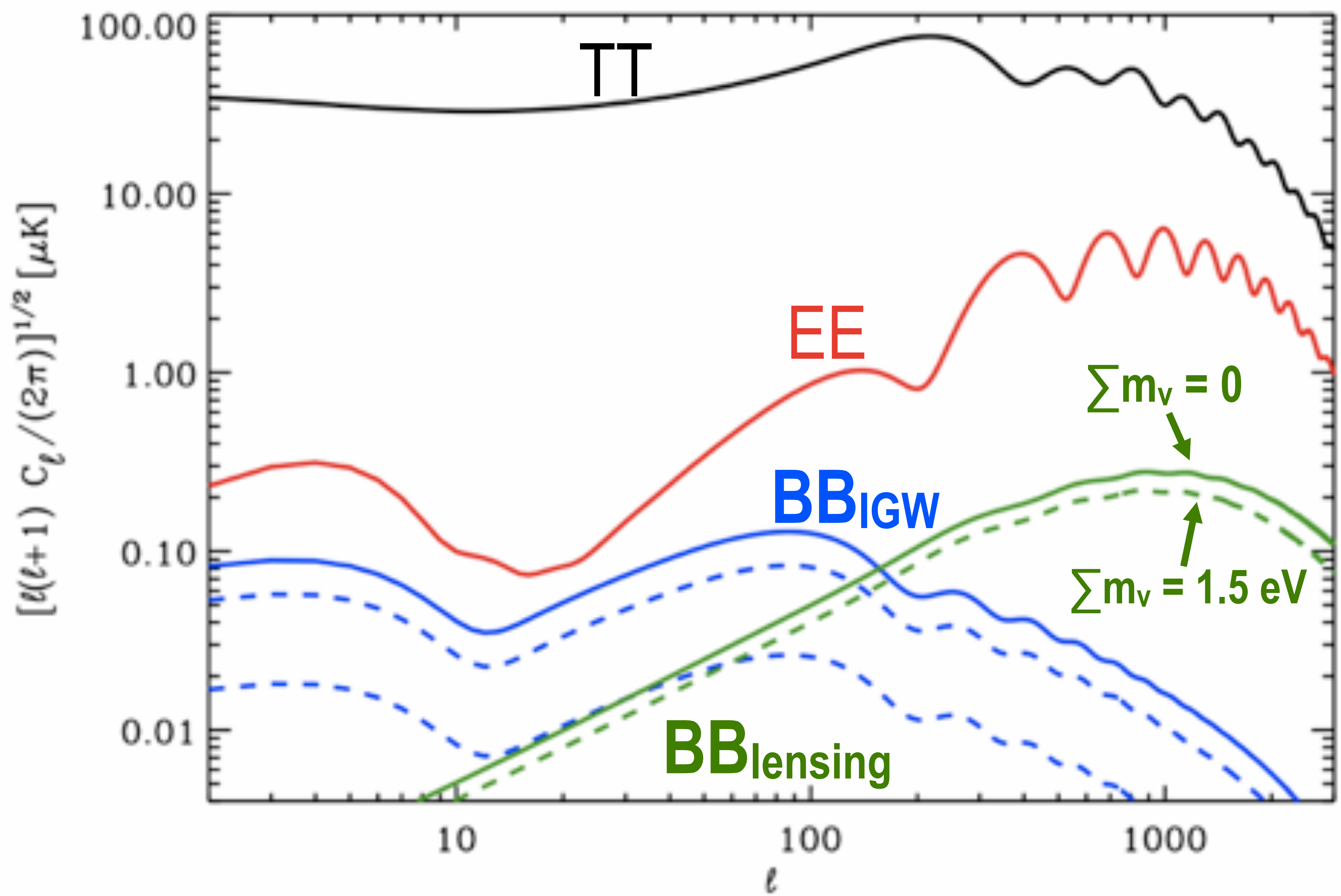
r == Tensor-to-scalar ratio

$E_{\rm Inf}$ == Energy scale of Inflation

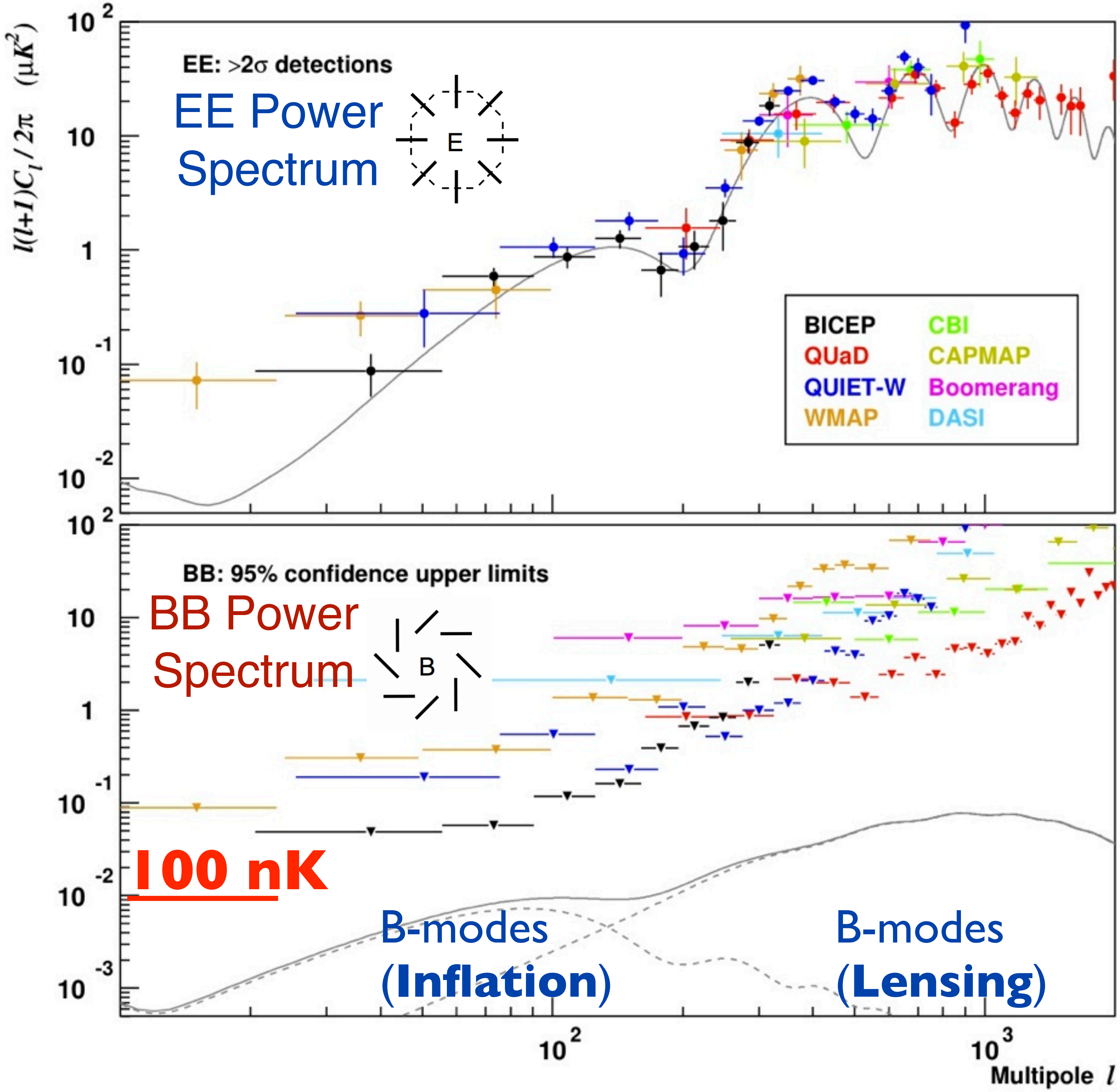
Gravitational lensing of the CMB creates a BB signal at small angular scales



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



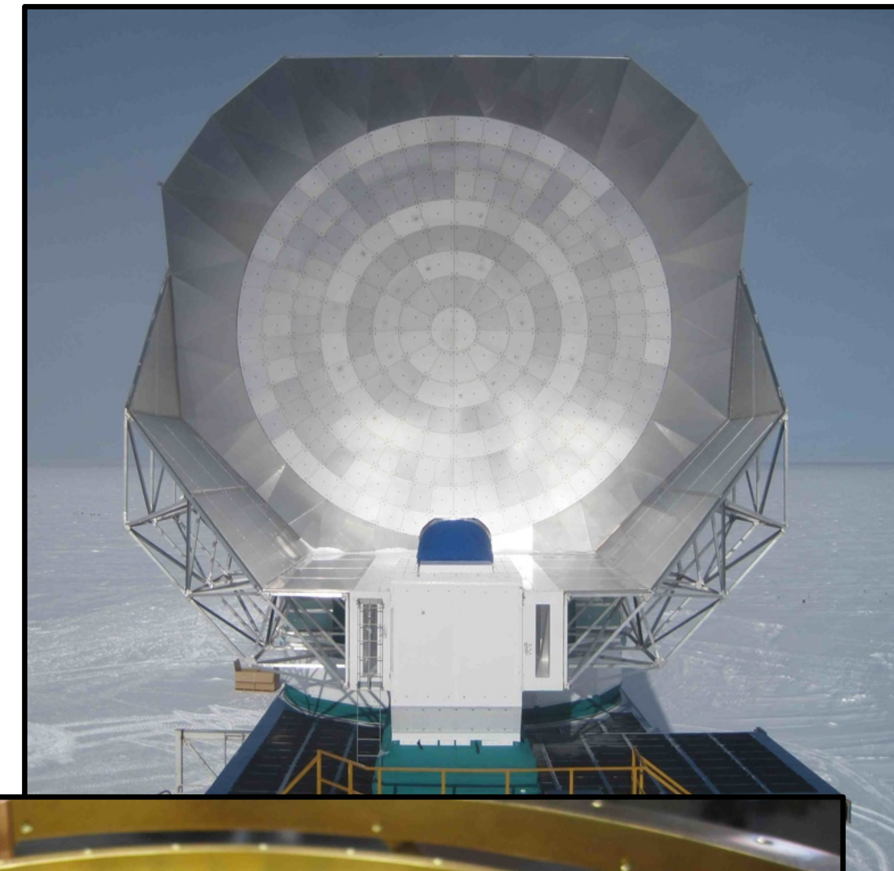
Current State of CMB Polarization Measurements



all points are upper limits!

Compilation by Cynthia Chiang

SPTpol:
A *new* polarization-sensitive camera for SPT



Science from SPTpol -

"B-mode" CMB Polarization:

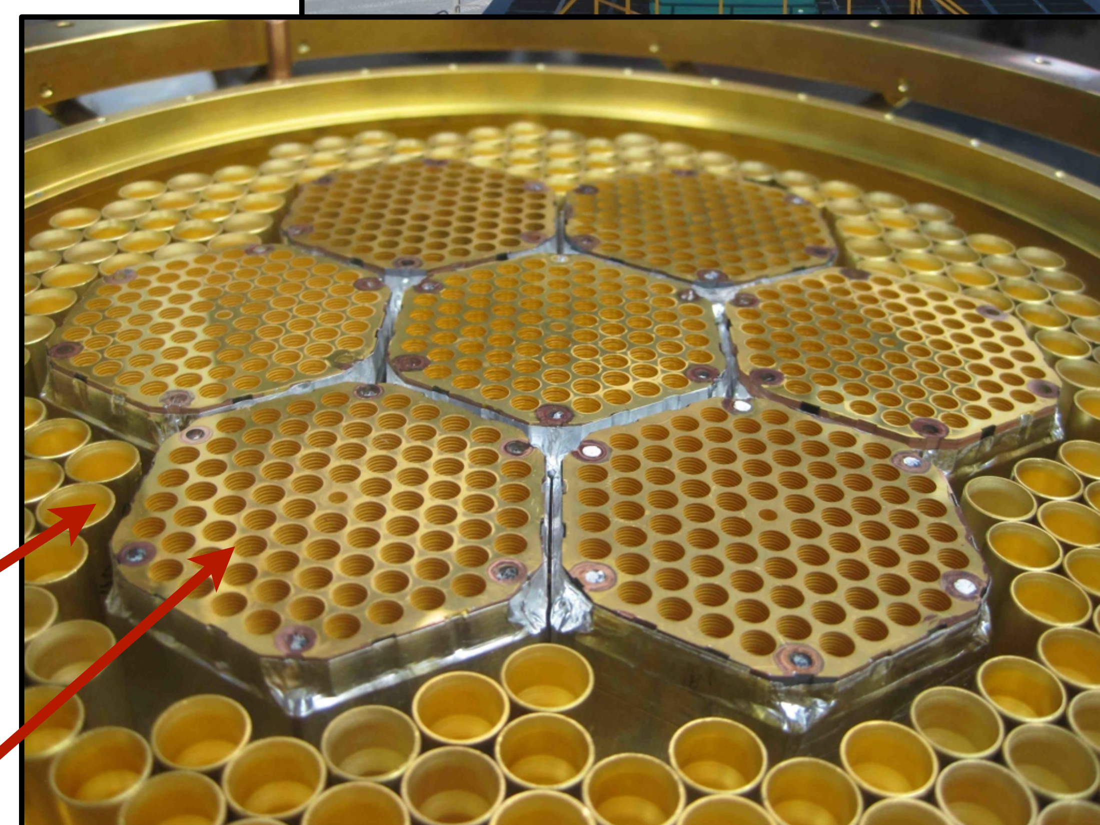
1. Detection of "B-mode" power spectrum
2. Neutrino mass from CMB lensing
   +/- 0.1 eV constraint from CMB alone!
3. Energy scale of inflation

Temperature Survey:

4. Deeper cluster survey

Status:

- First light Jan. 26, 2012.
- Started a 4-year, 600 deg^2 survey
- **Finished 1st year of survey!**

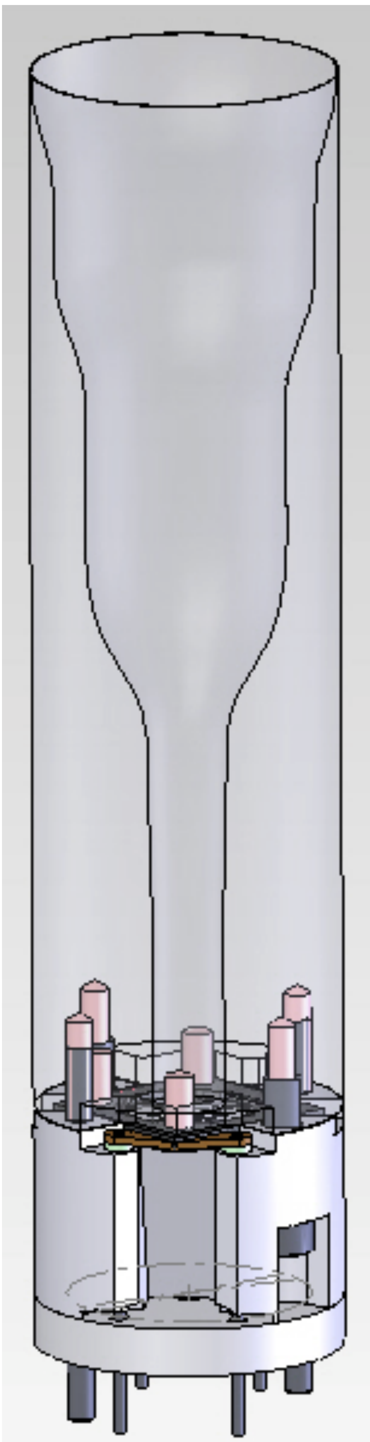


(360x) 100 GHz detectors,
(Argonne National Labs)

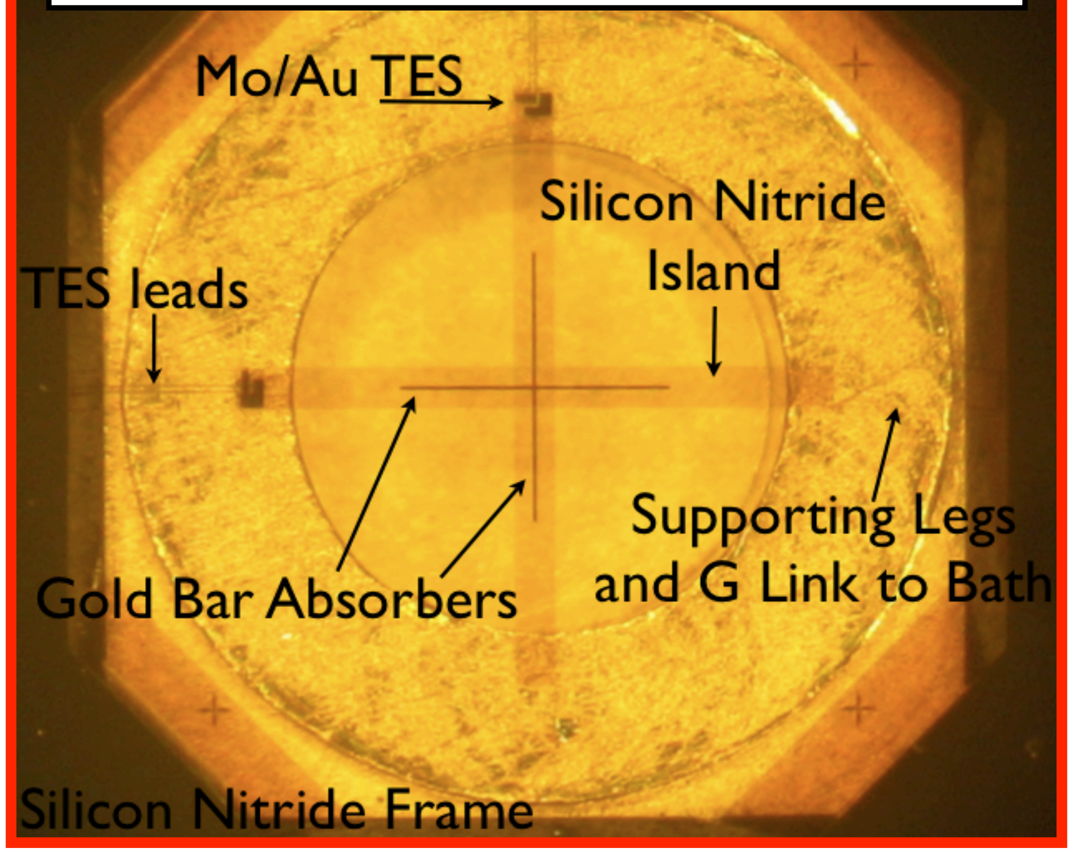
(1176x) 150 GHz detectors (NIST)

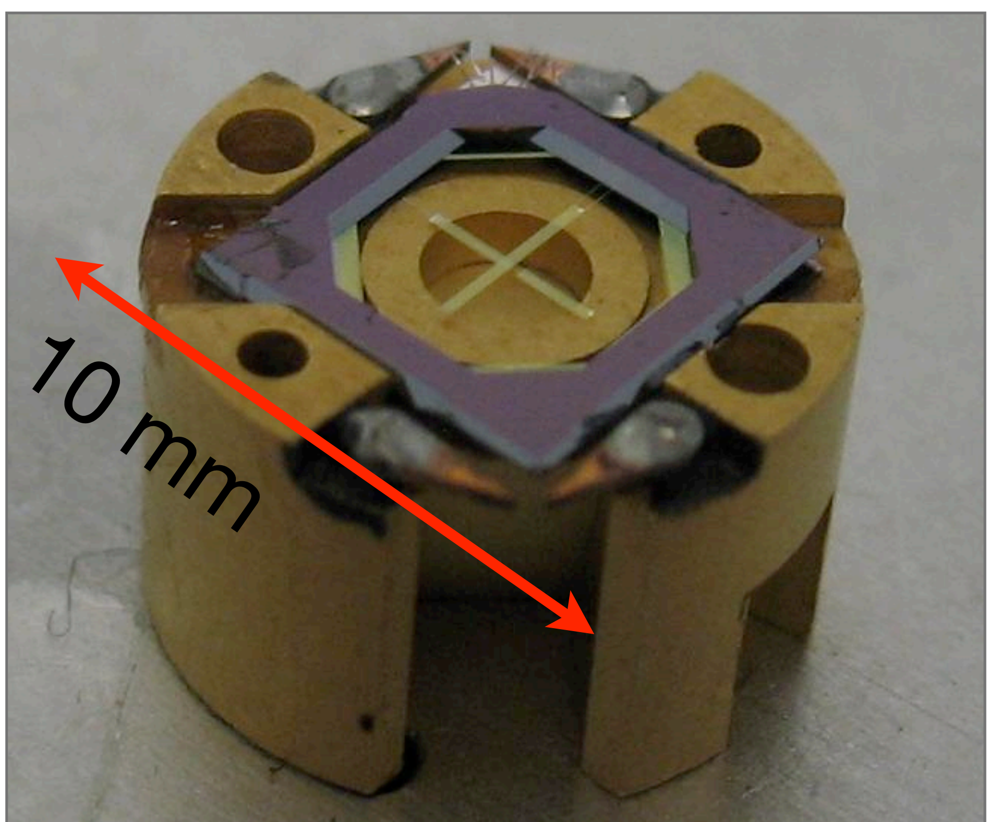
SPTpol: 100 GHz Detectors

Argonne NATIONAL LABORATORY

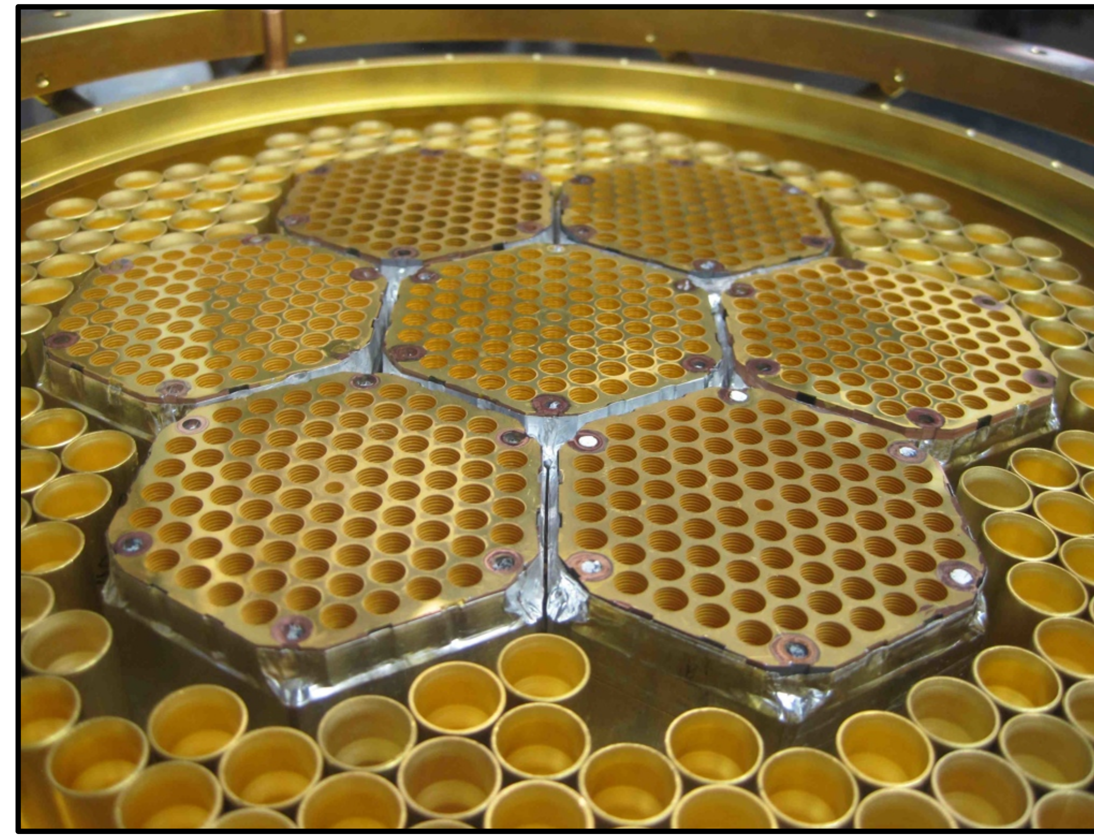


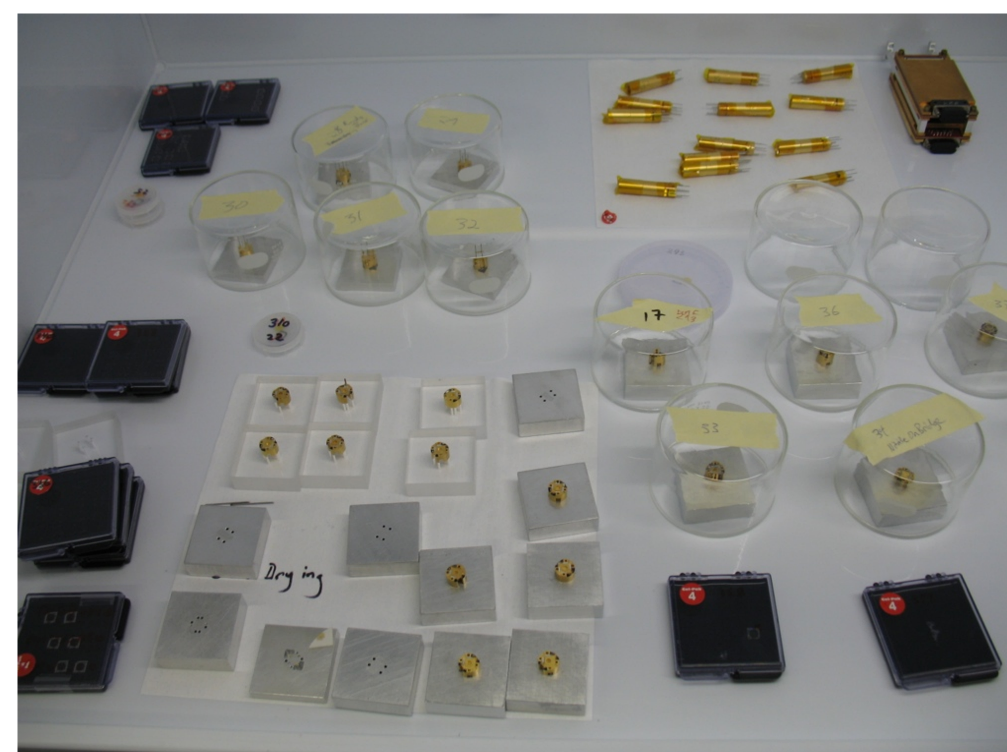
Argonne 100 GHz Pixel



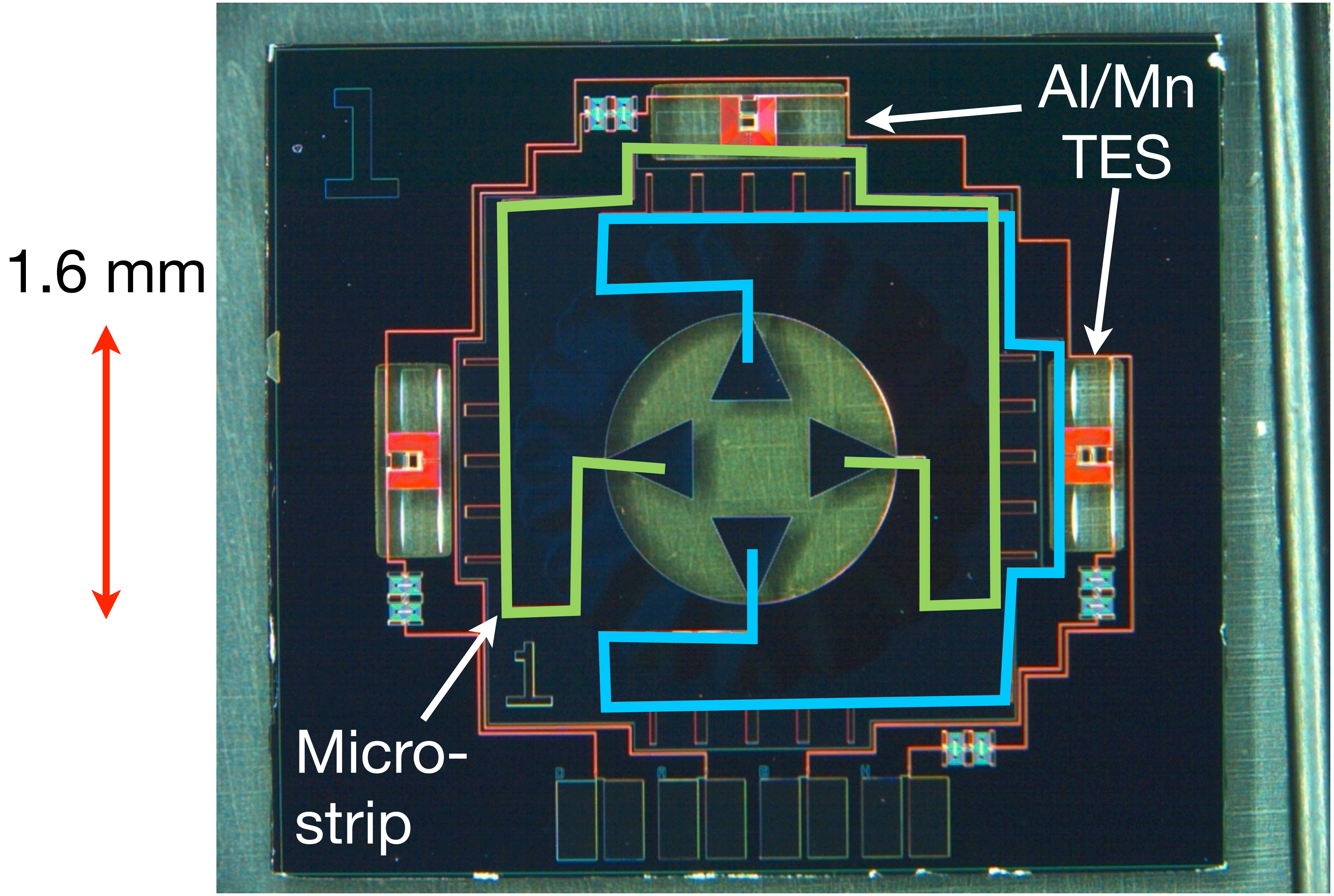


SPTpol Focal Plane





SPTpol: 150 GHz Detectors



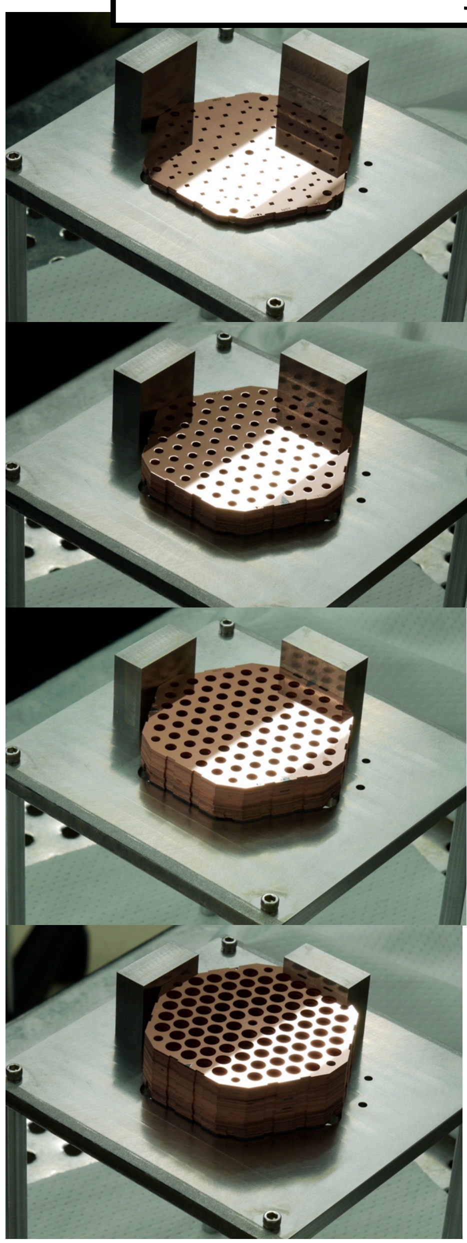
Superconducting Orthomode Transducer (OMT) separates two linear polarizations onto superconducting microstrip

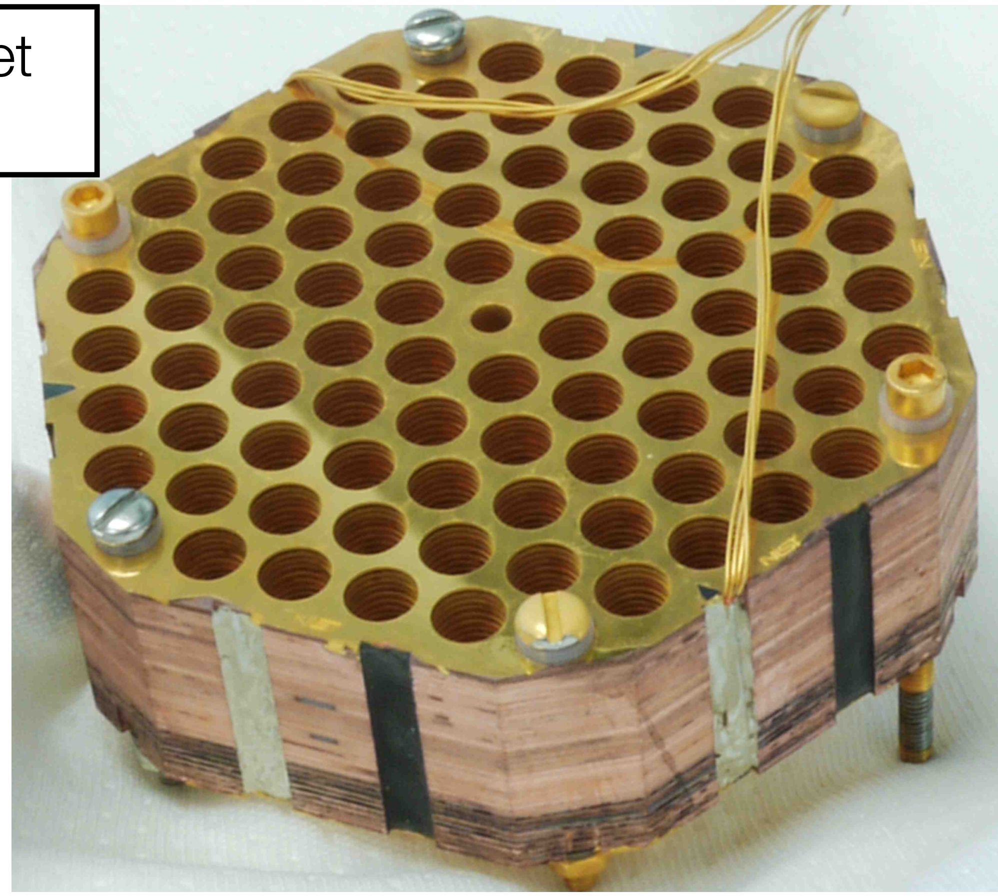
NIST

SPTpol: 150 GHz Detectors

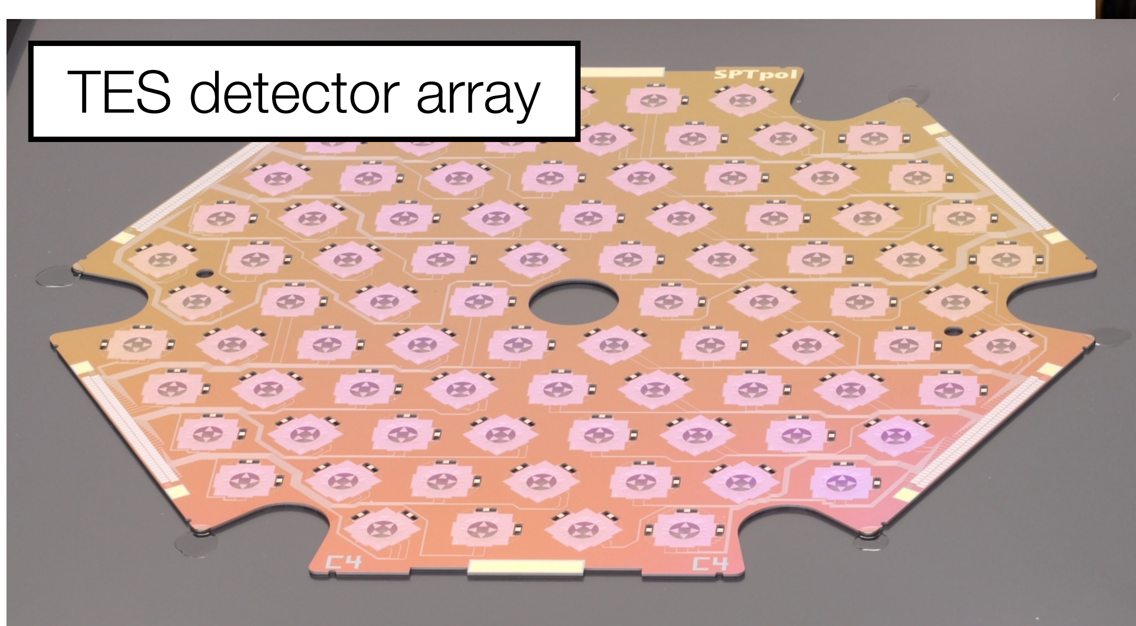
SPTpol Focal Plane

Silicon Platelet horn array





TES detector array

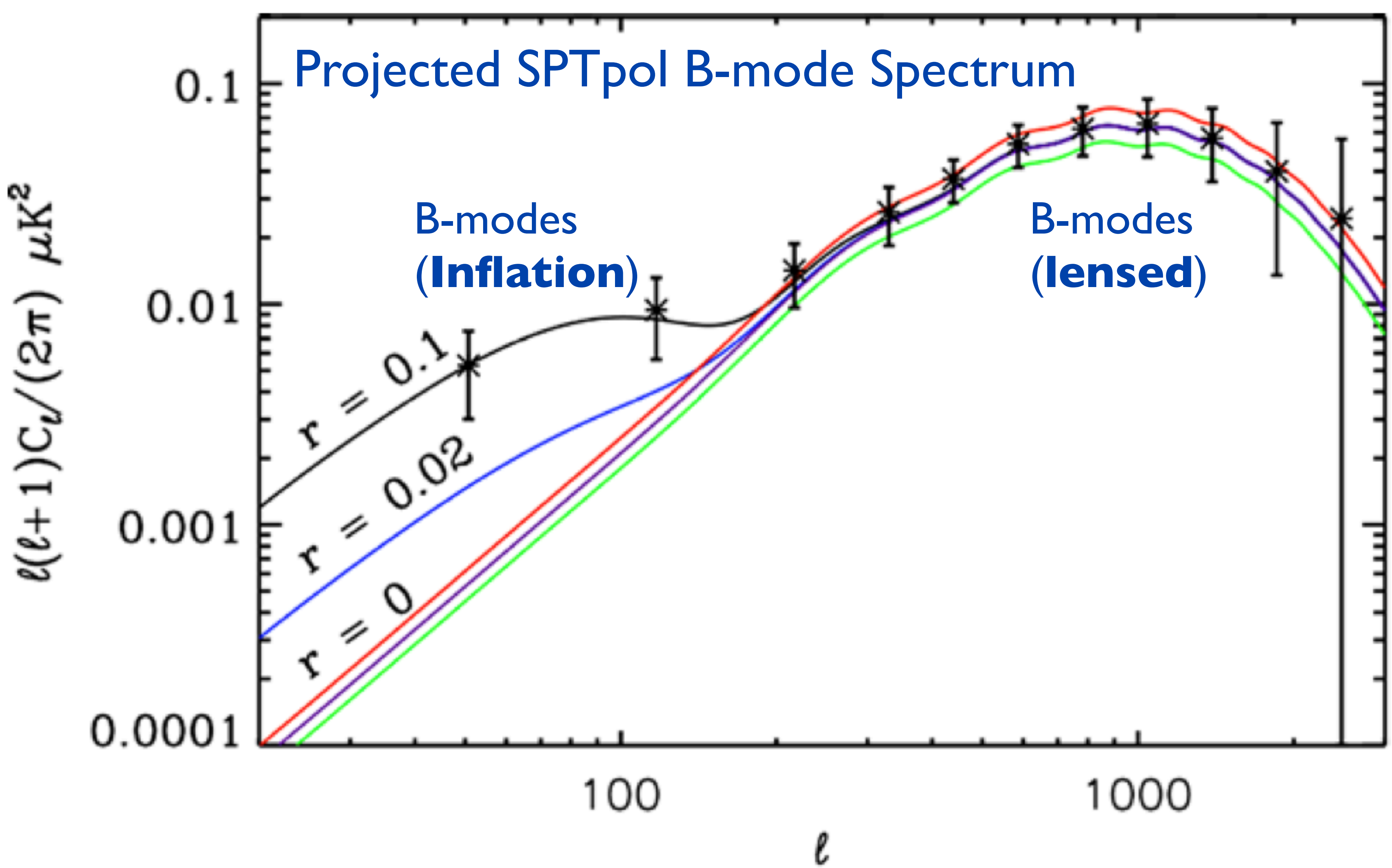


NIST

SPTpol (Projected) B-mode Power Spectrum

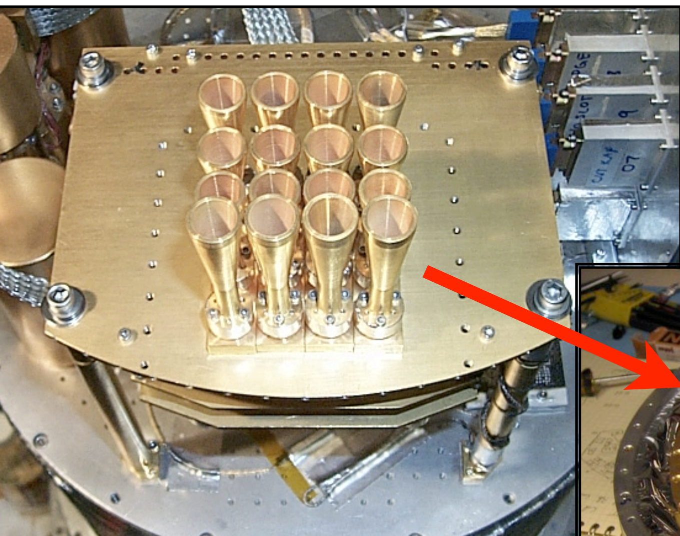
SPTpol already has enough data to make the **first-ever detection of B-modes!** The 4-year 600 deg² SPTpol survey will constrain:

- $r < 0.03$ ($E_{\rm inf} < 0.8 \times 10^{16}$ GeV) at 95% confidence
- $\delta(\Sigma m_\nu) = 0.15$ eV

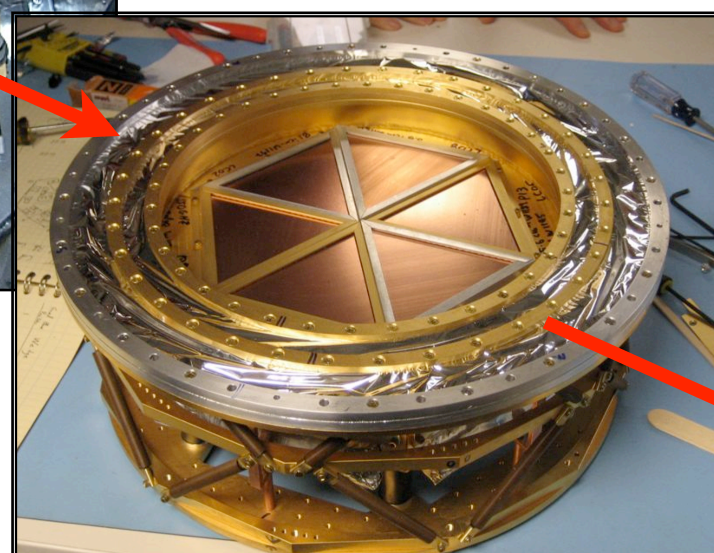


SPT-3G: The Next Generation Camera for the SPT

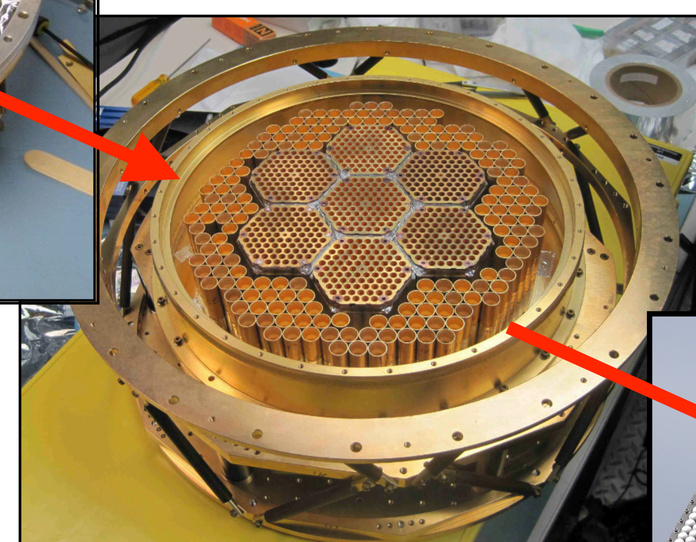
2001: ACBAR
16 detectors



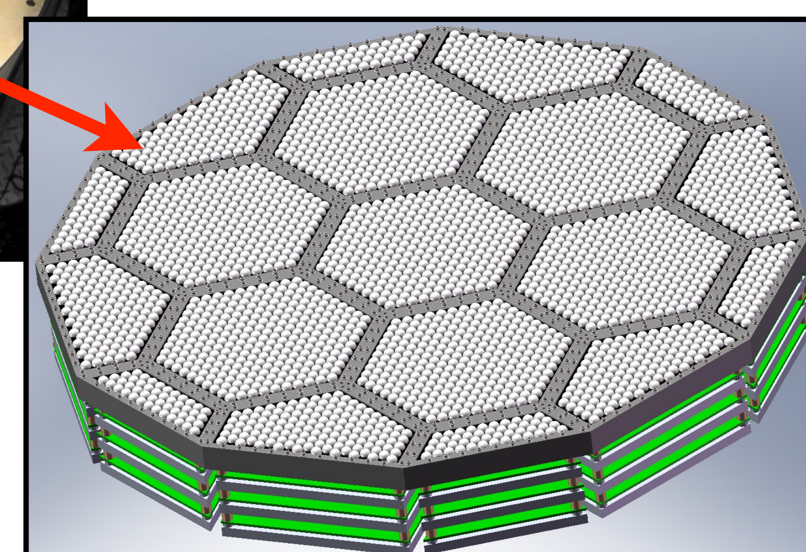
2007: SPT
960 detectors



2012: SPTpol
~1600 detectors

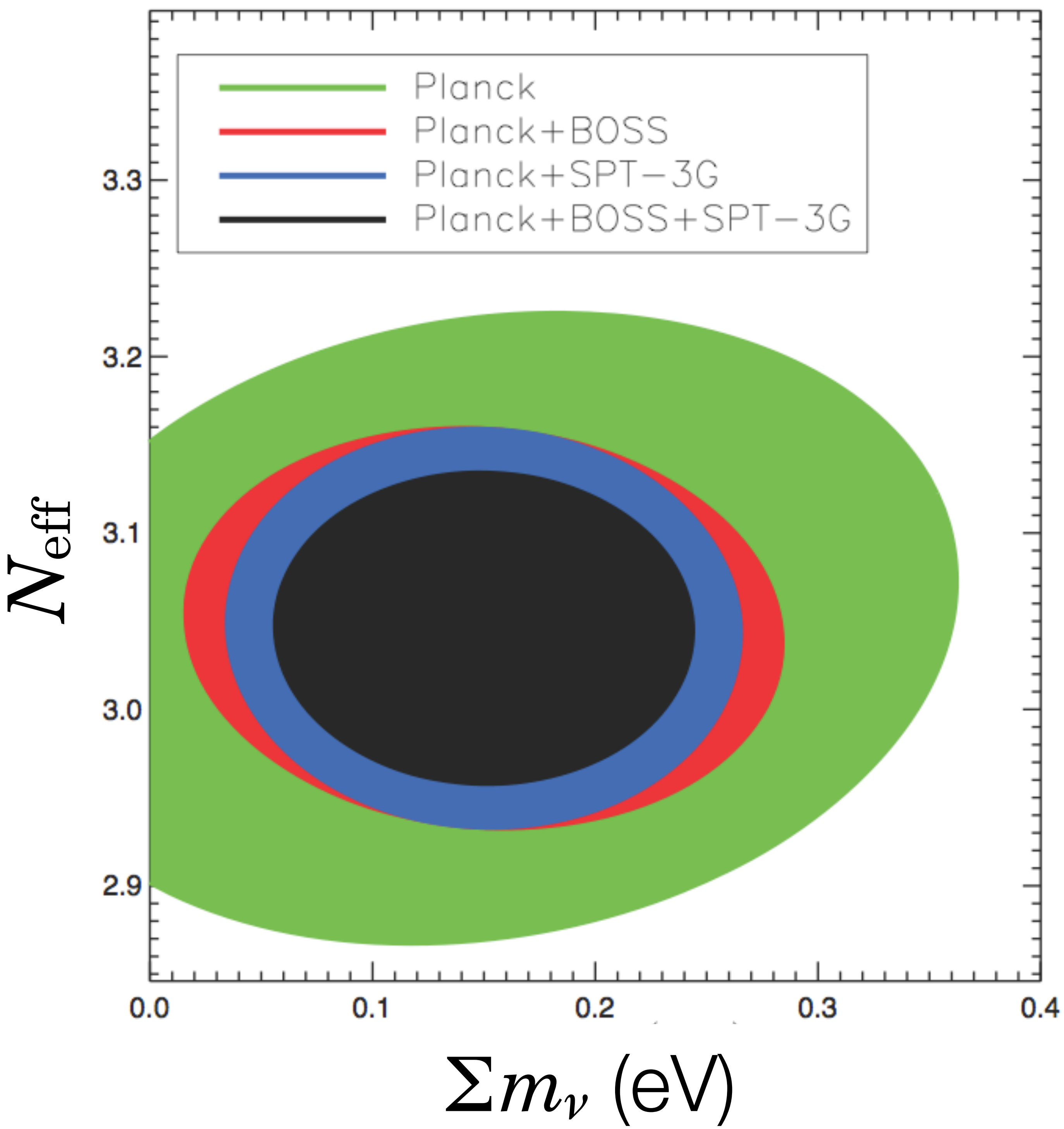


2016: SPT-3G
~15,200 detectors



ACBAR was one of the first experiments to deploy a photon (“shot”) noise limited detector, since then we’ve just been trying to make more of them

Future CMB Neutrino Constraints



- First **Planck** satellite results will be coming out by April 1st, 2013 (this year!)
- Planck + SPTpol (using CMB alone) will constrain:

$$\delta(N_{\rm eff}) = 0.12$$
$$\delta(\Sigma m_\nu) = 0.10 \text{ eV}$$

- Constraints will **improve by factor of two with SPT-3G** experiment!
  - $\delta(\Sigma m_\nu) = 0.05$ **eV!**
  - At lower limit of oscillation experiments!

Credit: C. Reichardt, G. Holder, G. Simard

Summary

- **Dark Energy:** SPT cluster survey will constrain equation of state, w, to +/-5% without geometric probes -> systematic test of dark energy

- **Number of Neutrino Species:** CMB power spectrum detects neutrinos at 7.5-σ, with interesting hints of an additional species (Neff=3.71 +/- 0.35). Within ~1 year, constraints will improve to δNeff = +/- 0.12 with Planck + SPTpol data.

- **Sum of Neutrino Masses:** Cosmology constrains the sum of neutrino masses to $\delta(\Sigma m_\nu)$ = +/- 0.11 eV. CMB-only data will be at this level of constraint with Planck, and improved by over two with future CMB polarization constraints.

- **Energy Scale of Inflation:** New CMB polarization experiments will place new constraints on energy level, or possibly detect, the energy scale of inflation.


Thank You!