Probing the Cosmic Frontier with the Cosmic Microwave Background: Current Status and Future Challenges

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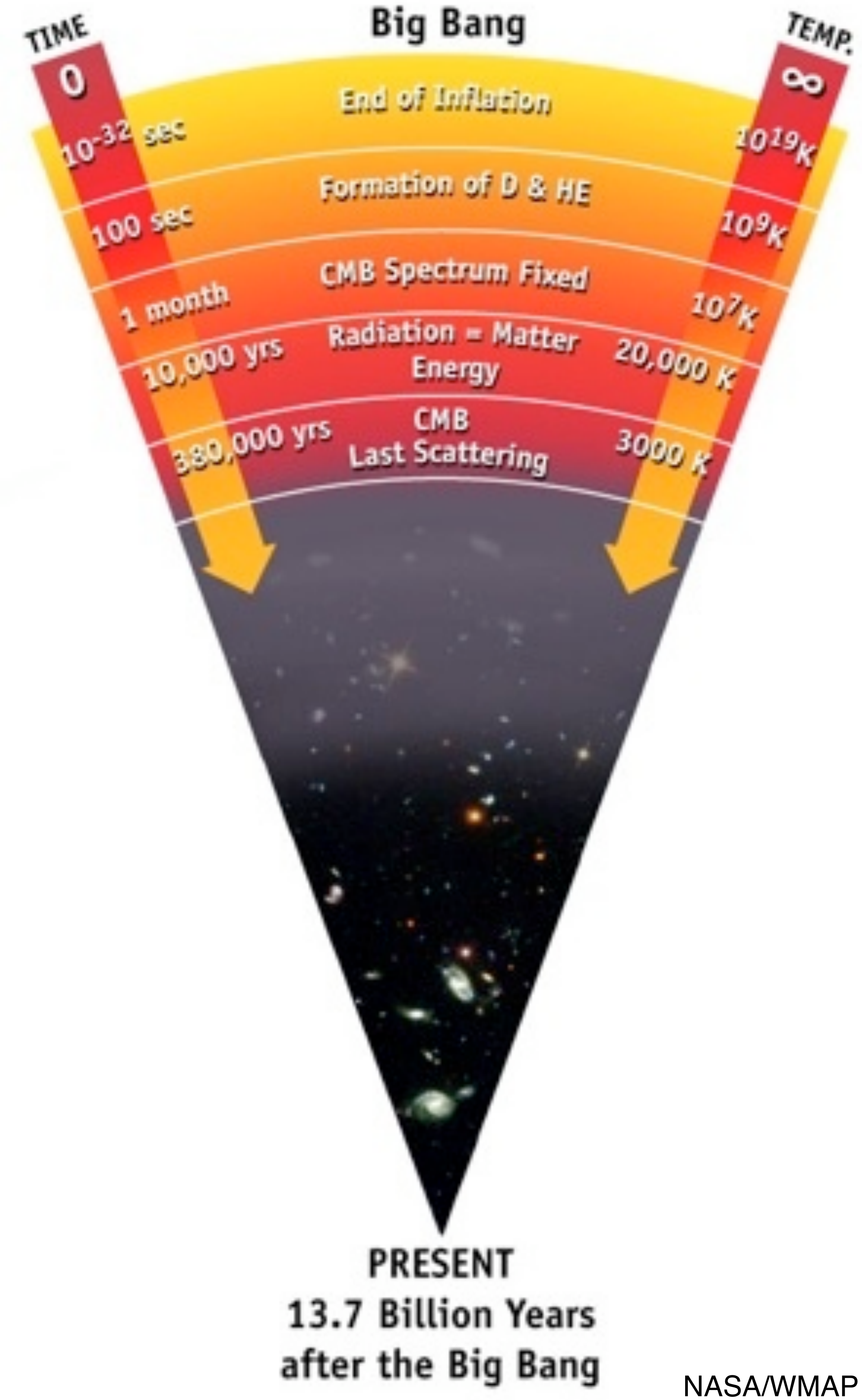
It is an exciting time for cosmology

We now have a model that describes the evolution of our Universe from a hot and dense state.

We are able to make precise predictions and test them with powerful new experiments.

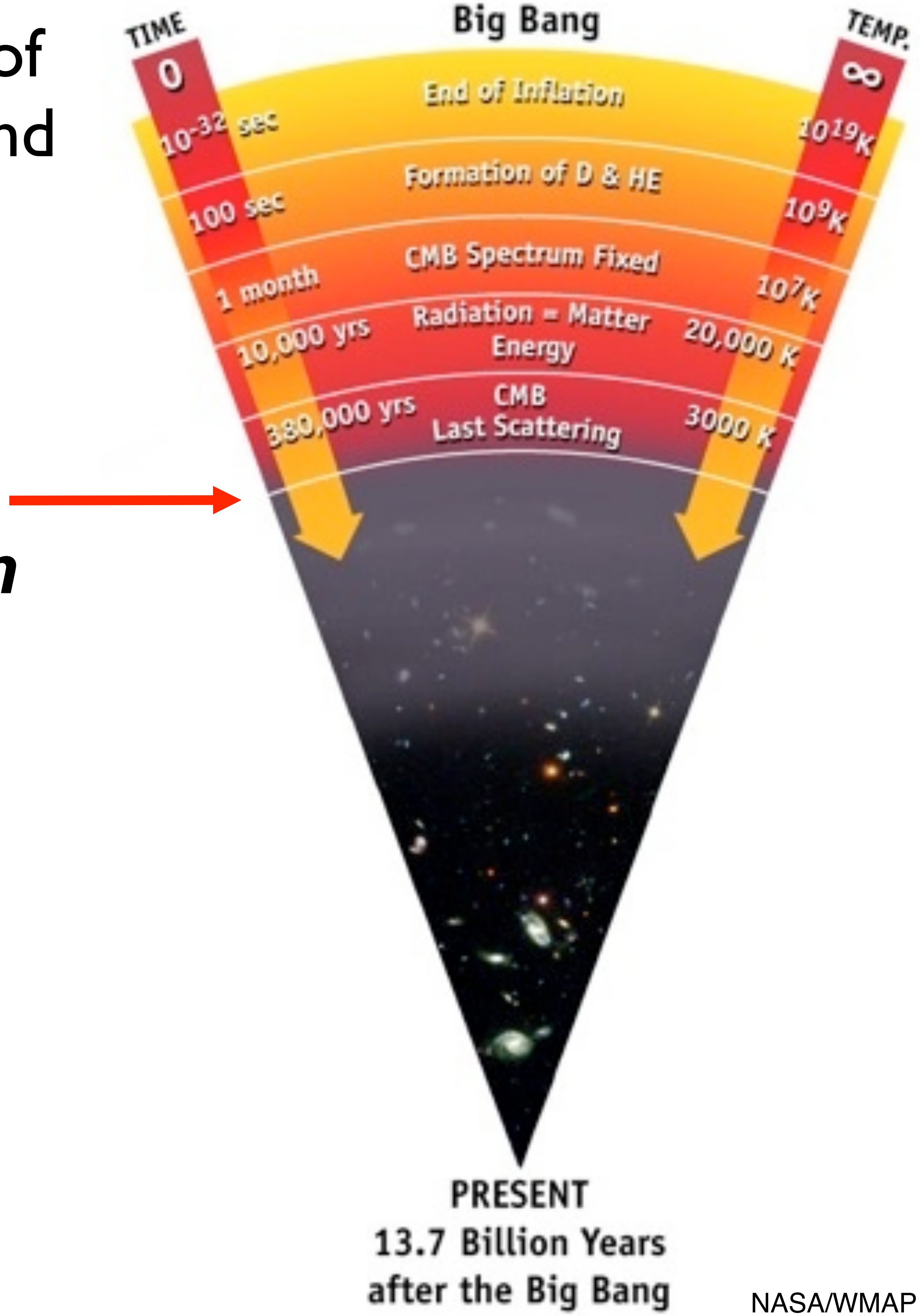
The model has some unusual features - new physics - Dark Matter, Dark Energy, and starts with a period of Inflation



NASA/WMAP

Much of the model has been determined from measurements of the Cosmic Microwave Background (CMB) radiation

Measurements of the CMB provide a snapshot of the universe as it was 14 billion years ago.



NASA/WMAP

Discovery of the Cosmic Microwave Background

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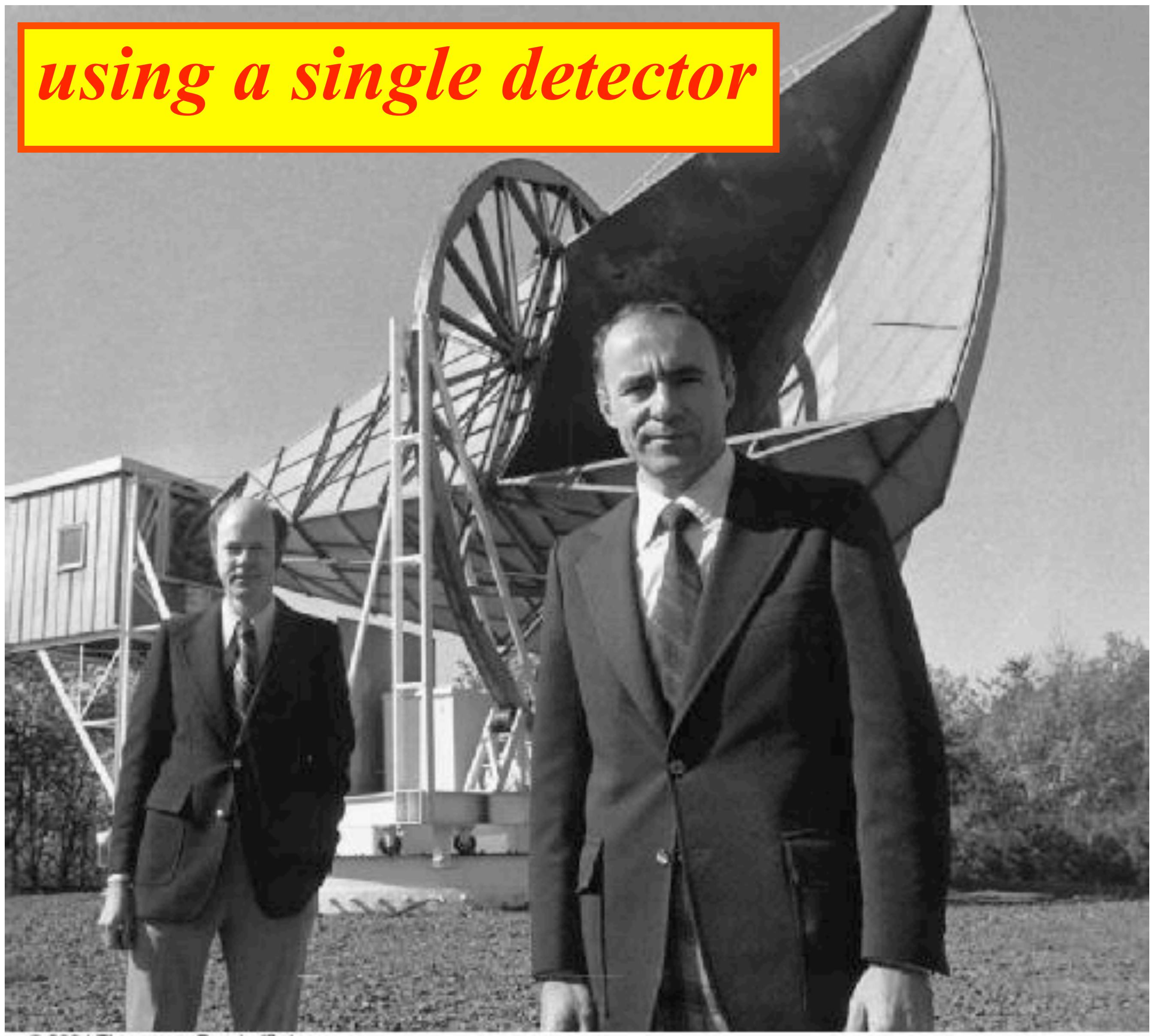
“smoking gun” evidence for a <u>Hot Big Bang</u>

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

Received 1978 Nobel Prize

Enormous impact on Cosmology

Discovery of the Cosmic Microwave Background



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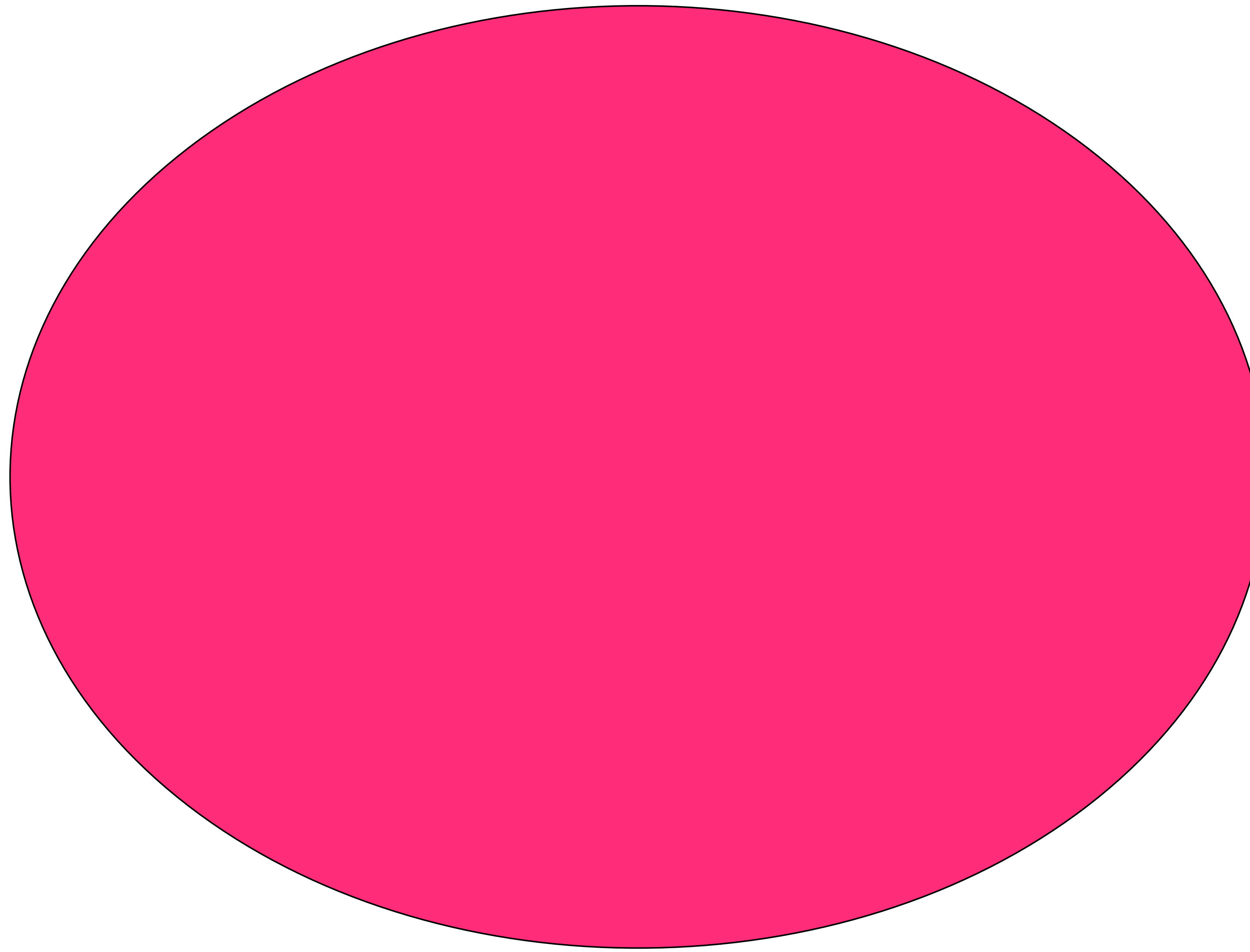
Structure in background discovered in 1992

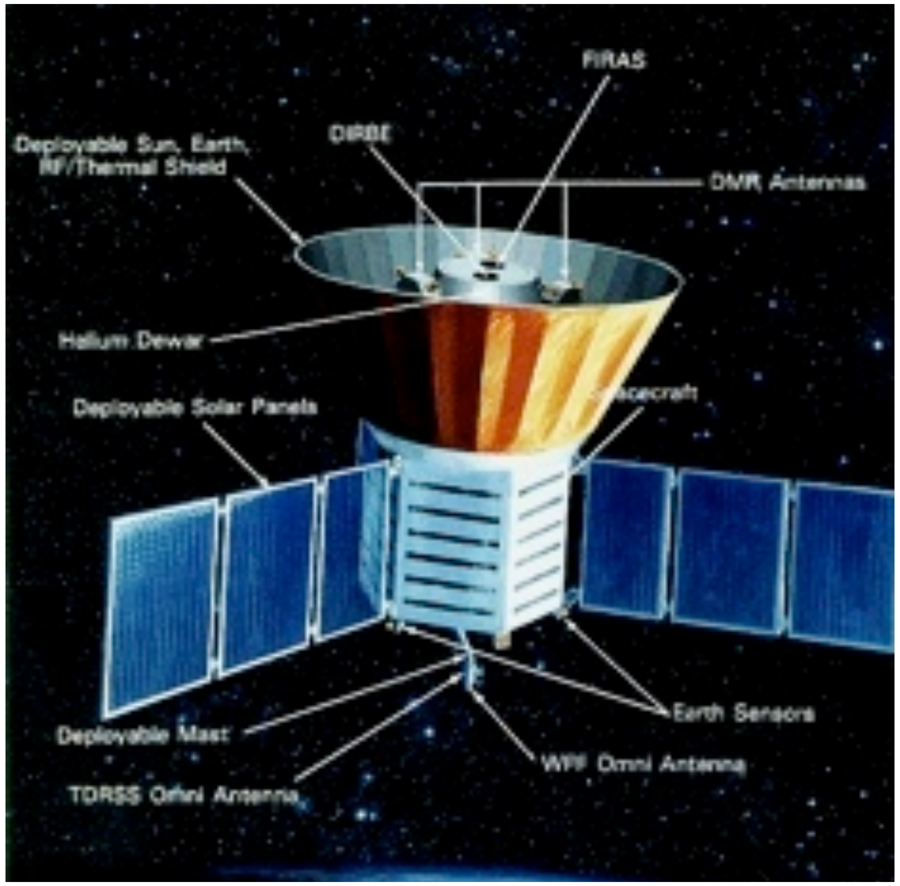
COBE Satellite



Uniform to a part in 10^5

the smoothness problem - led to Inflation theory

Structure in background discovered in 1992



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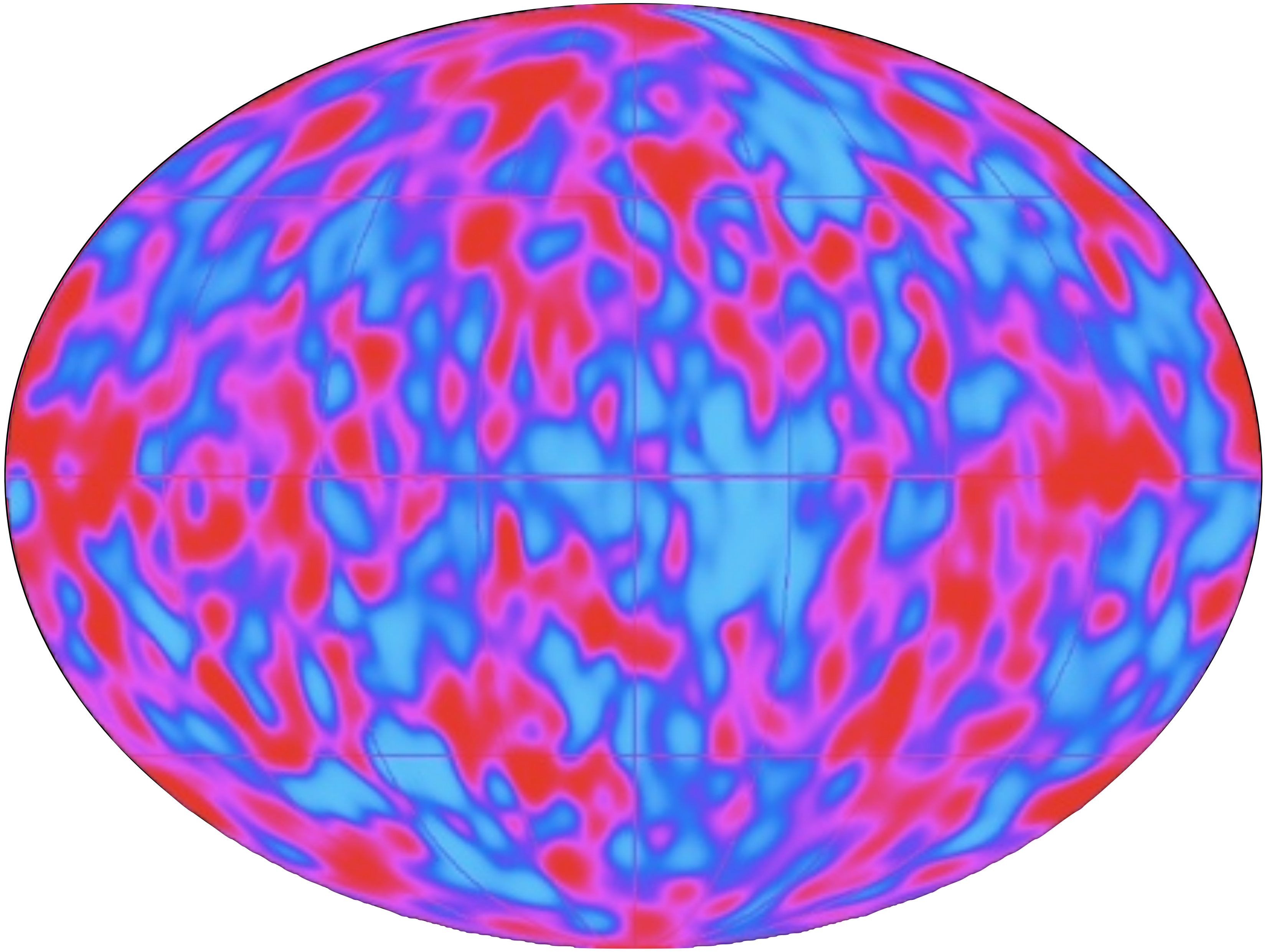

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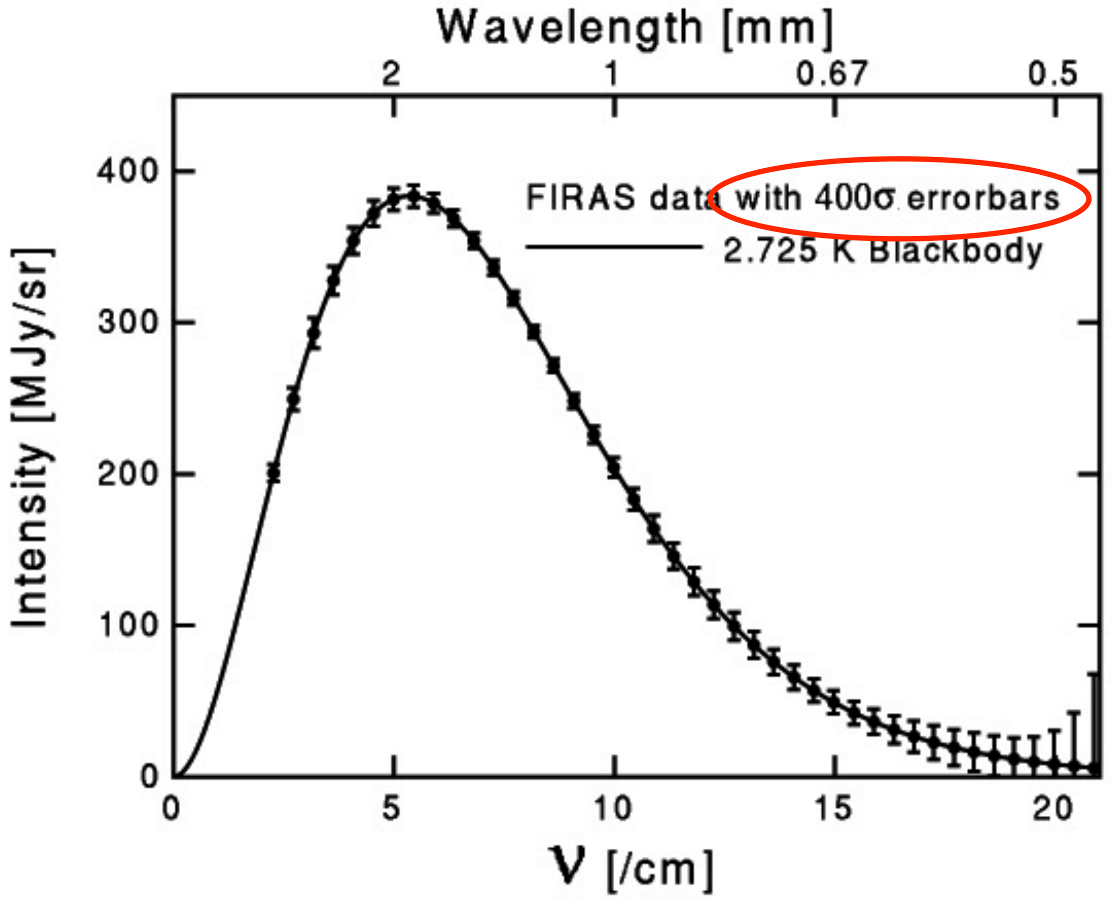
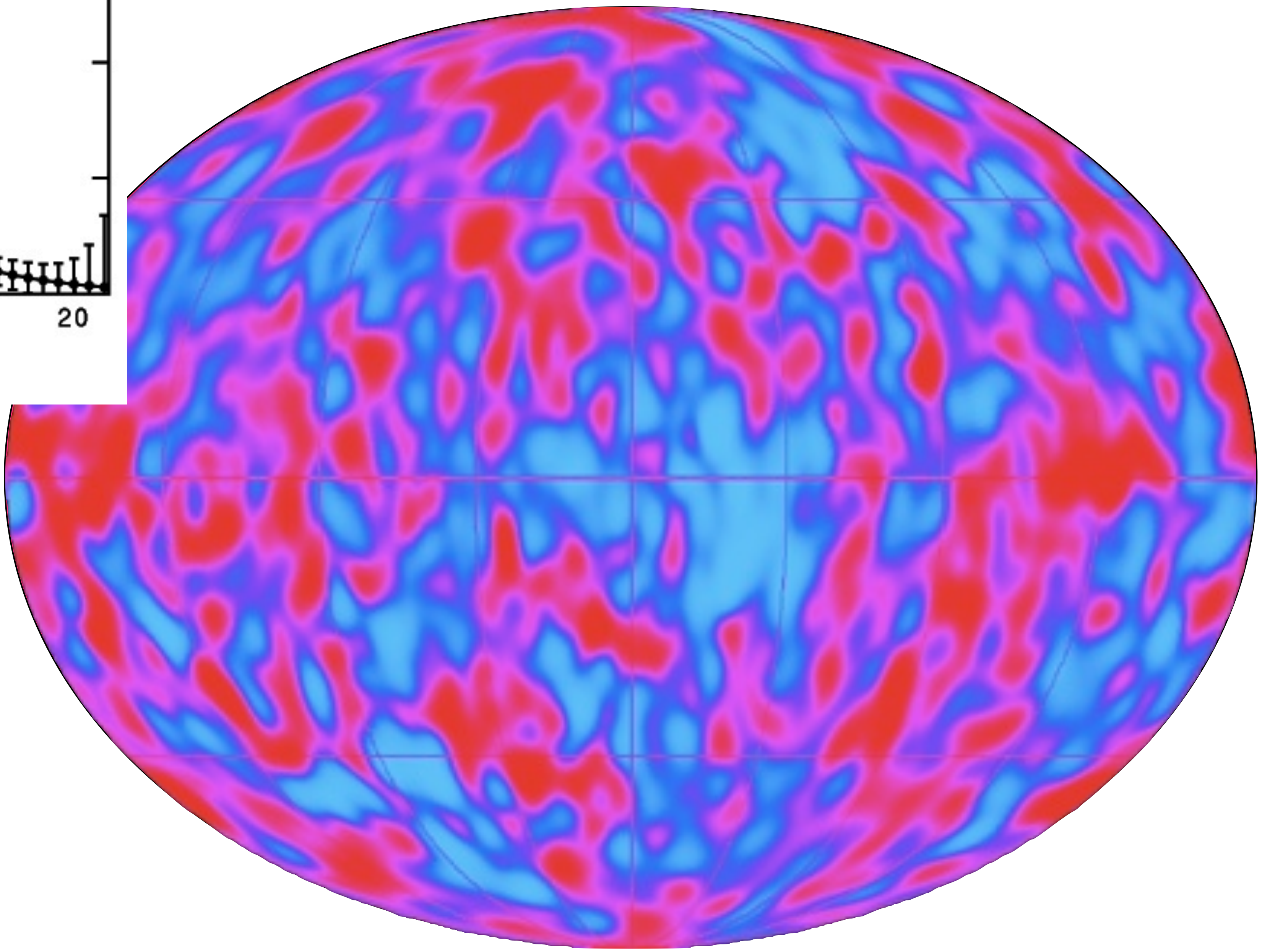
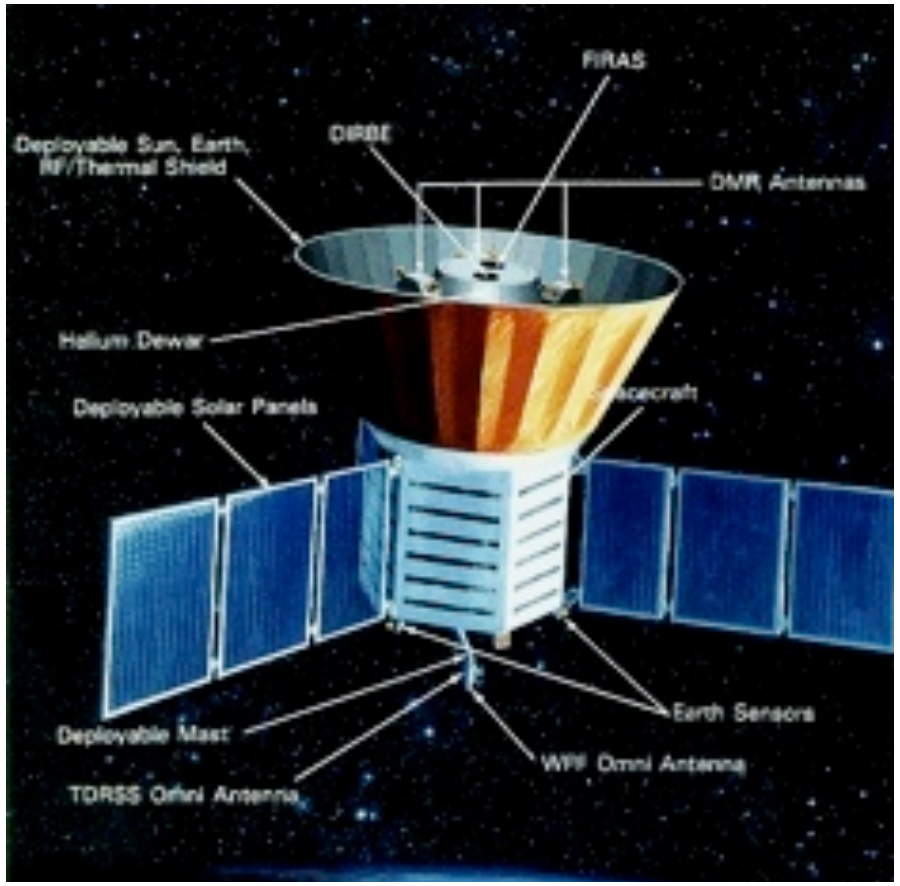


round discovered in 1992





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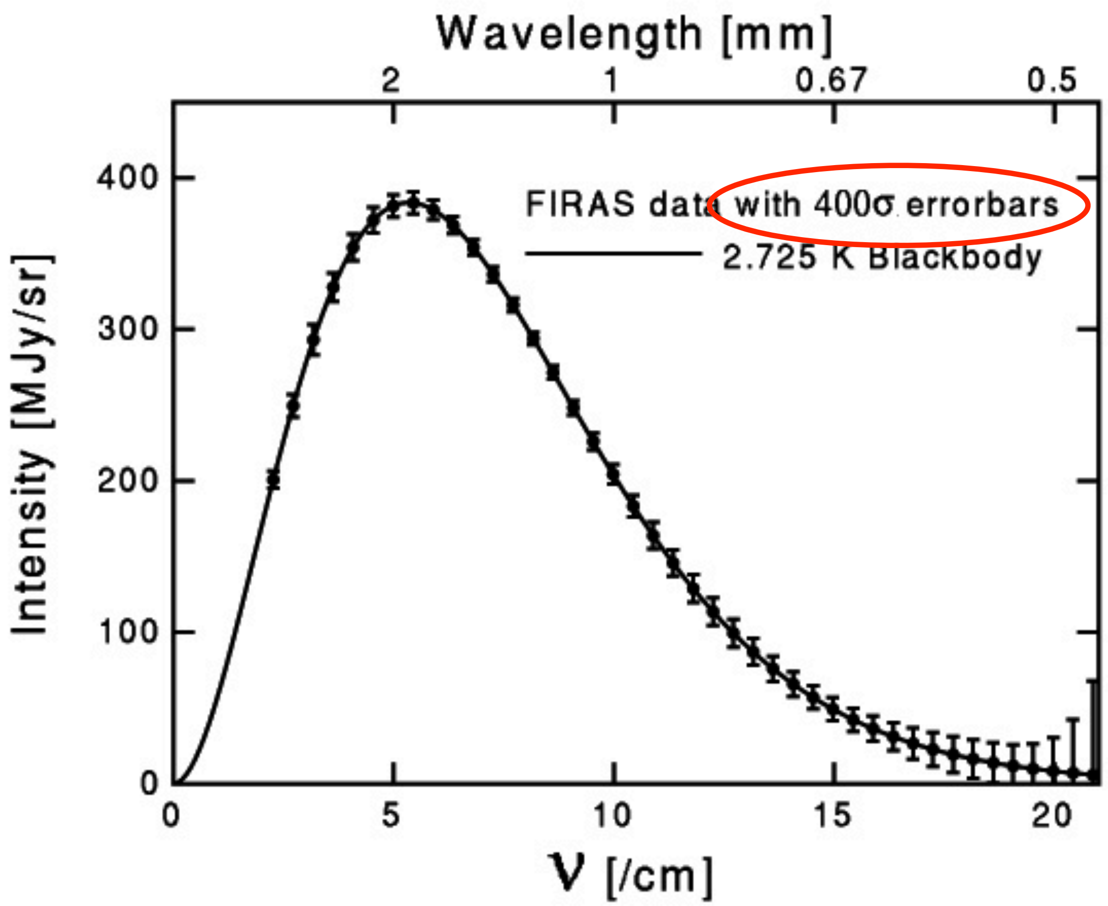
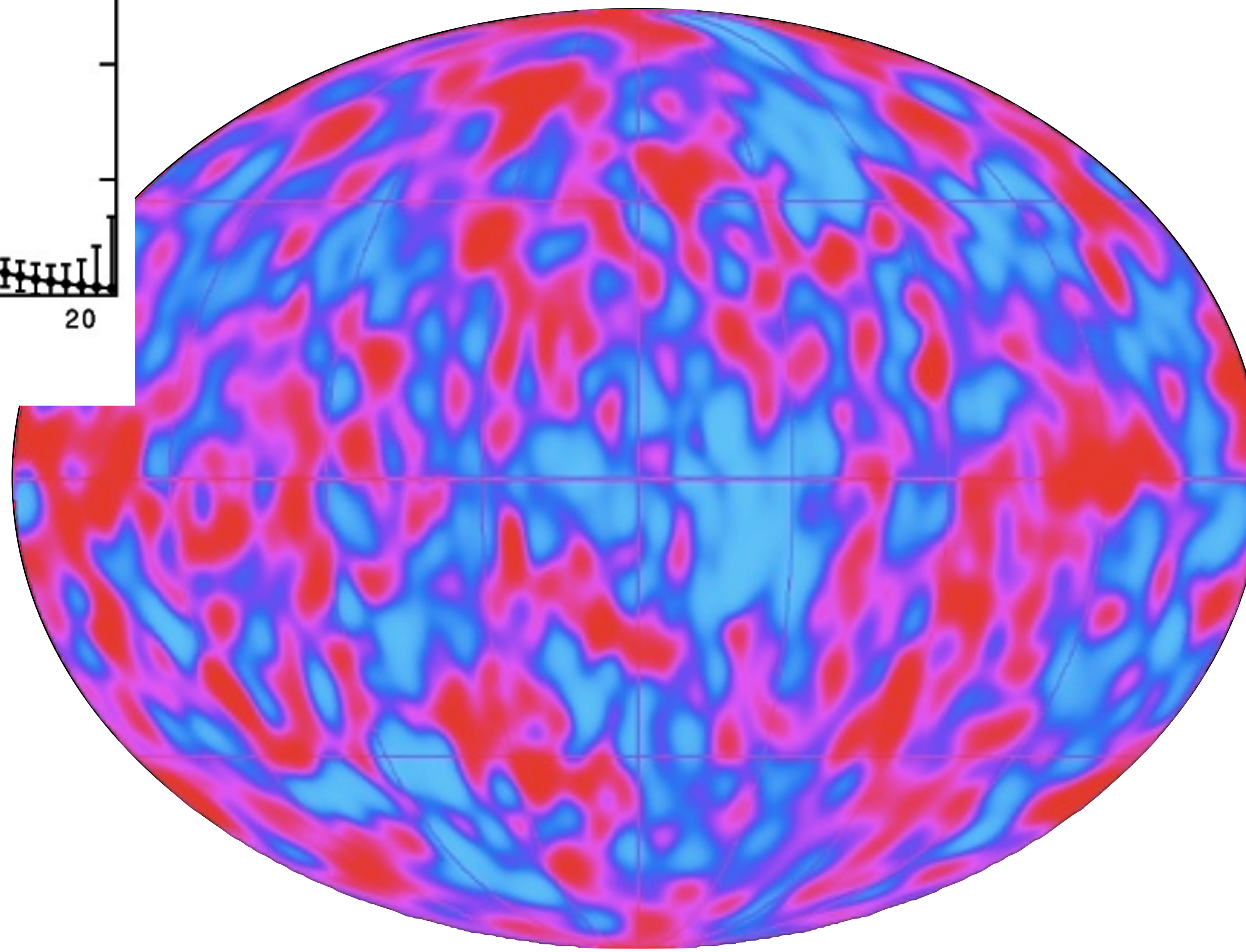


round disc

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



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the smoothness problem -
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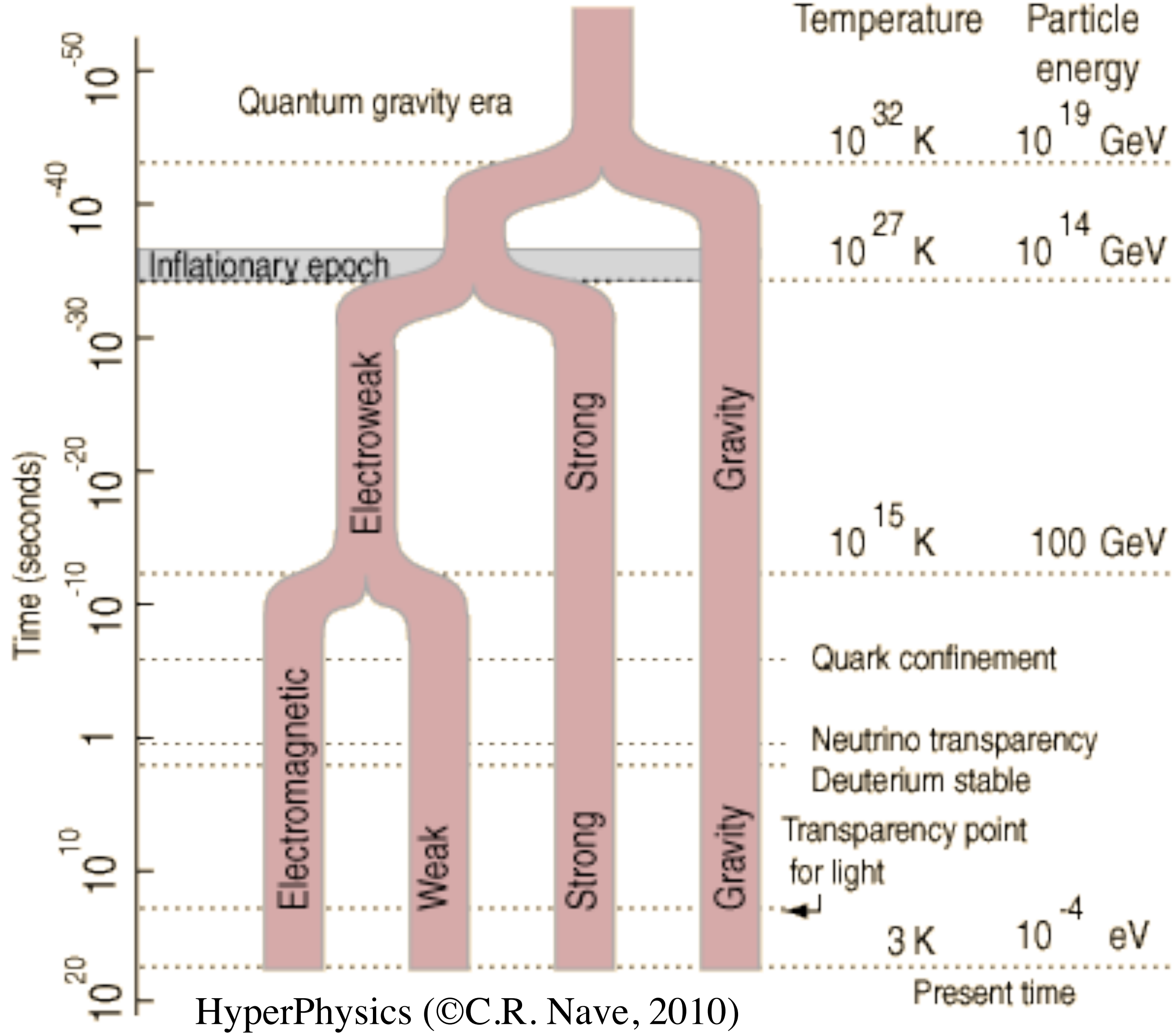
Early universe as an HEP lab



HyperPhysics (©C.R. Nave, 2010)

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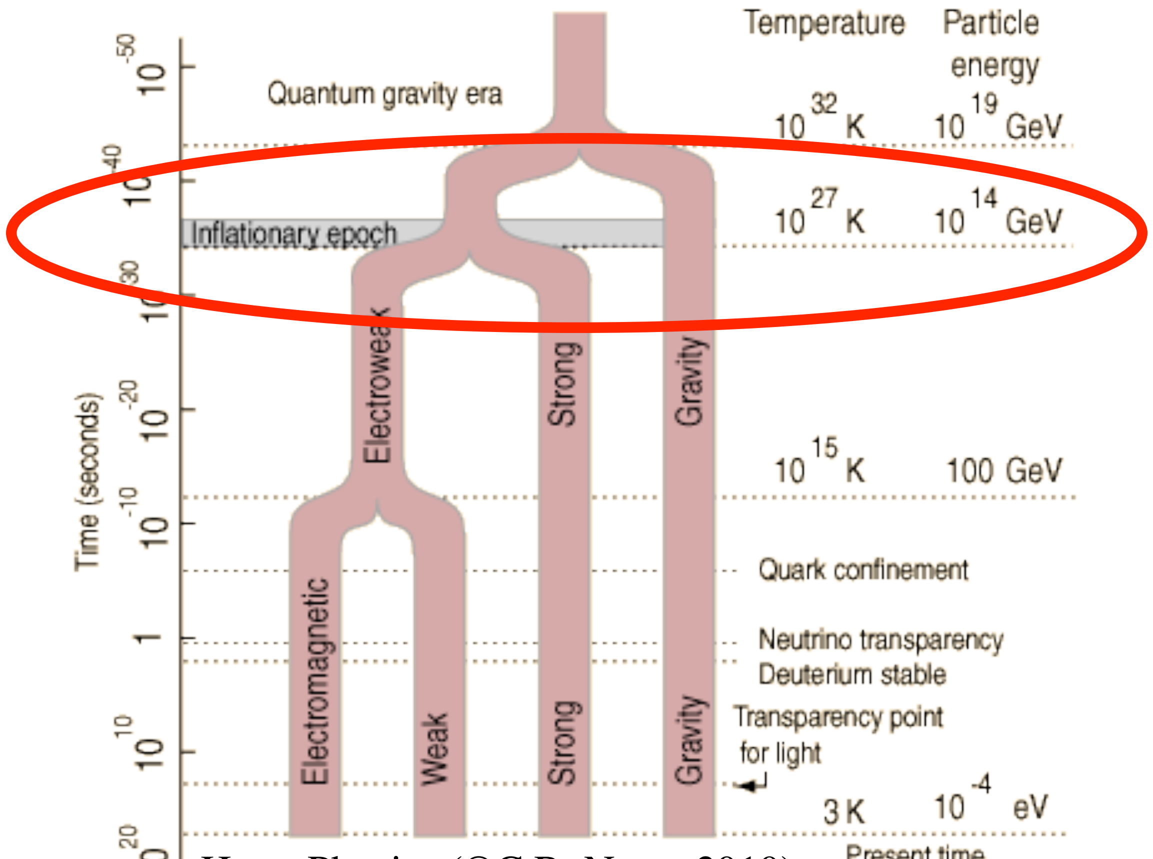

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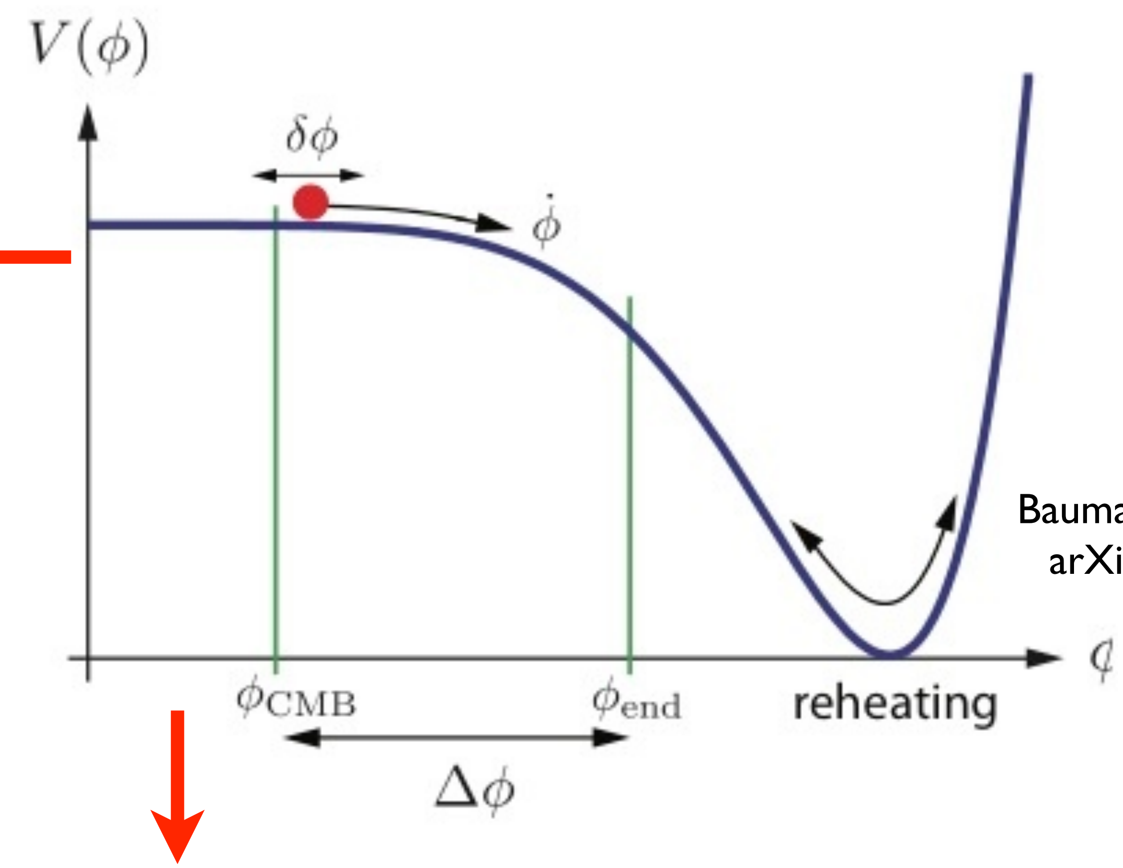


Baumann et al. 2008
arXiv:0811.3919

Inflation generates

- Density (scalar) fluctuations:

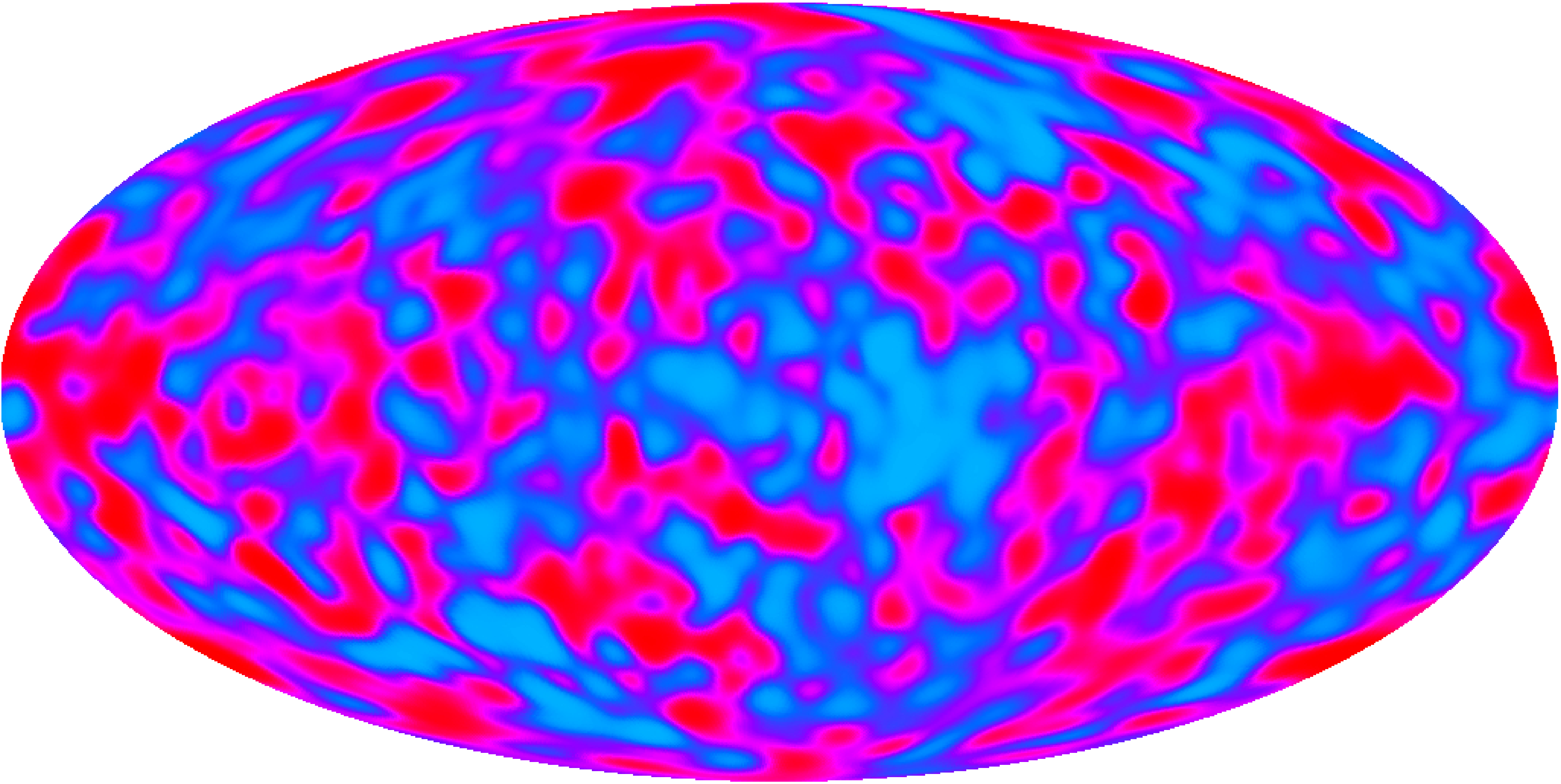
$$P_s(k) = \mathbf{A_s} k^{(\mathbf{n_s} - 1 + \frac{1}{2}\alpha_\mathbf{s} \ln k)}$$

- Gravitational wave (tensor) fluctuations:

$$P_t(k) = \mathbf{A_t} k^{\mathbf{n_t}}$$

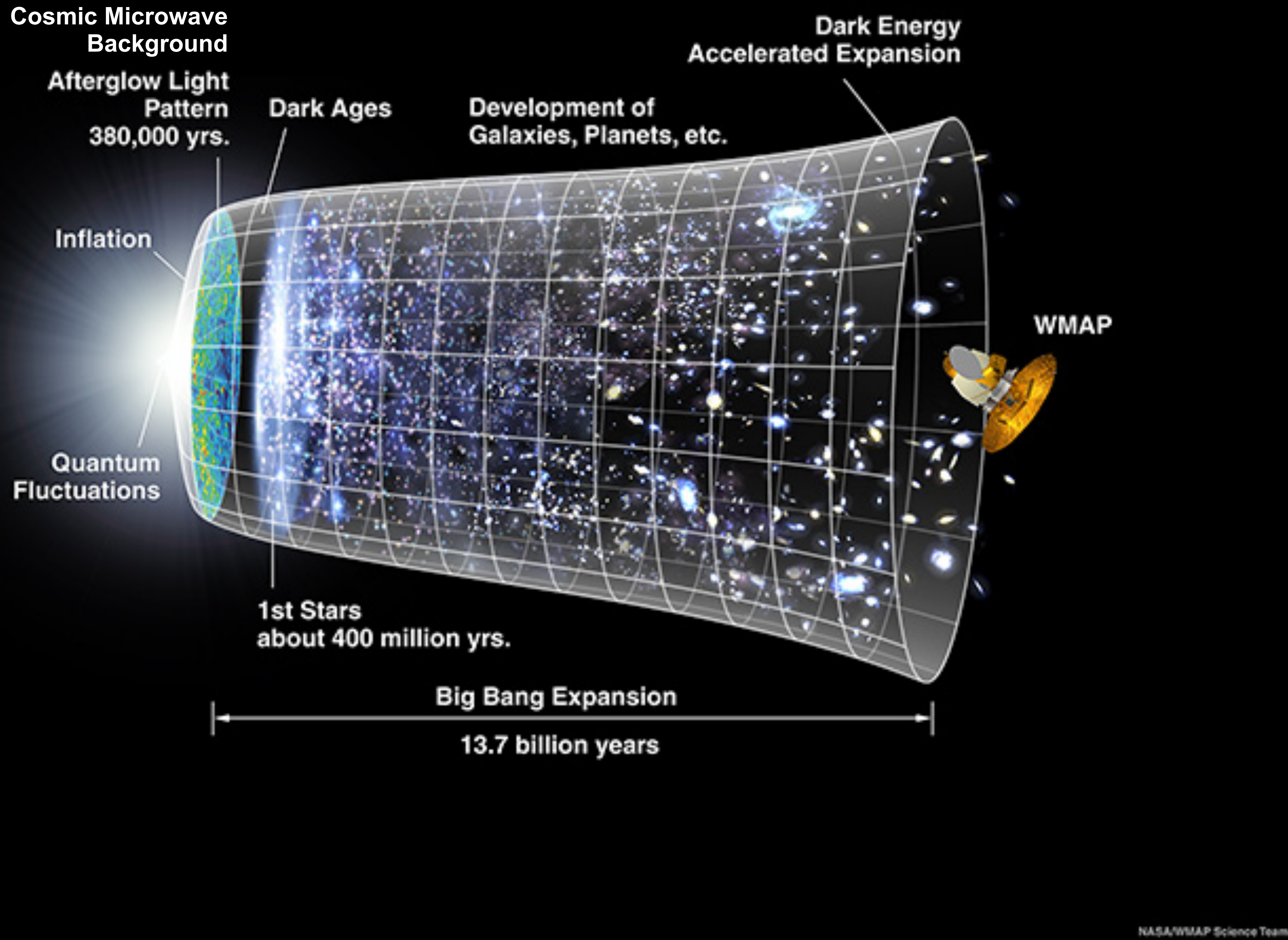
A_s, n_s, α_s, A_t, n_t are measurable and related to the shape of the inflaton potential

$r \equiv A_t/A_s$ determines the energy scale



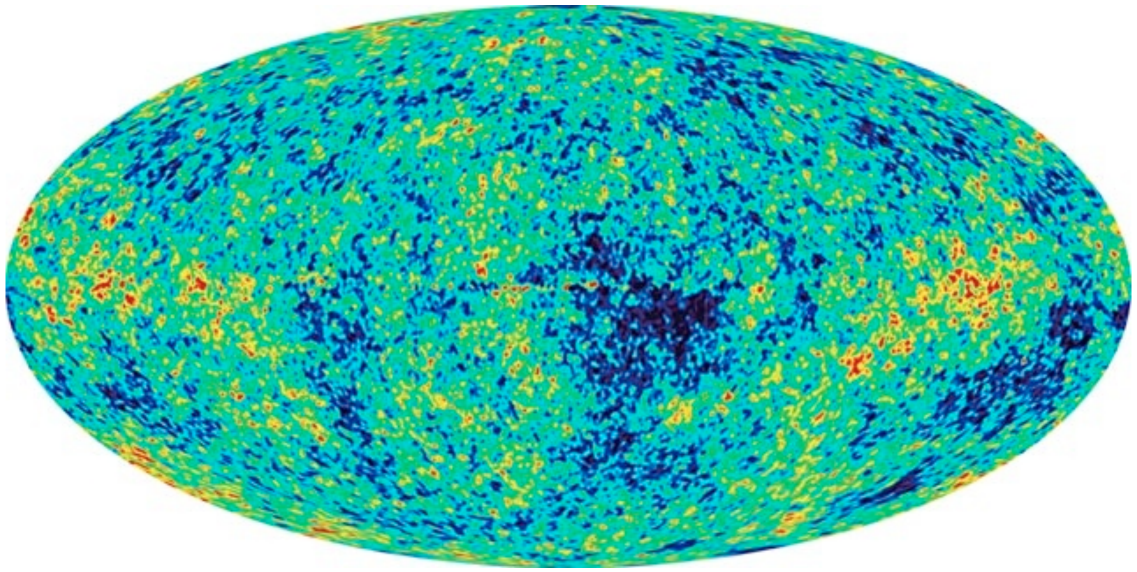
Superhorizon features

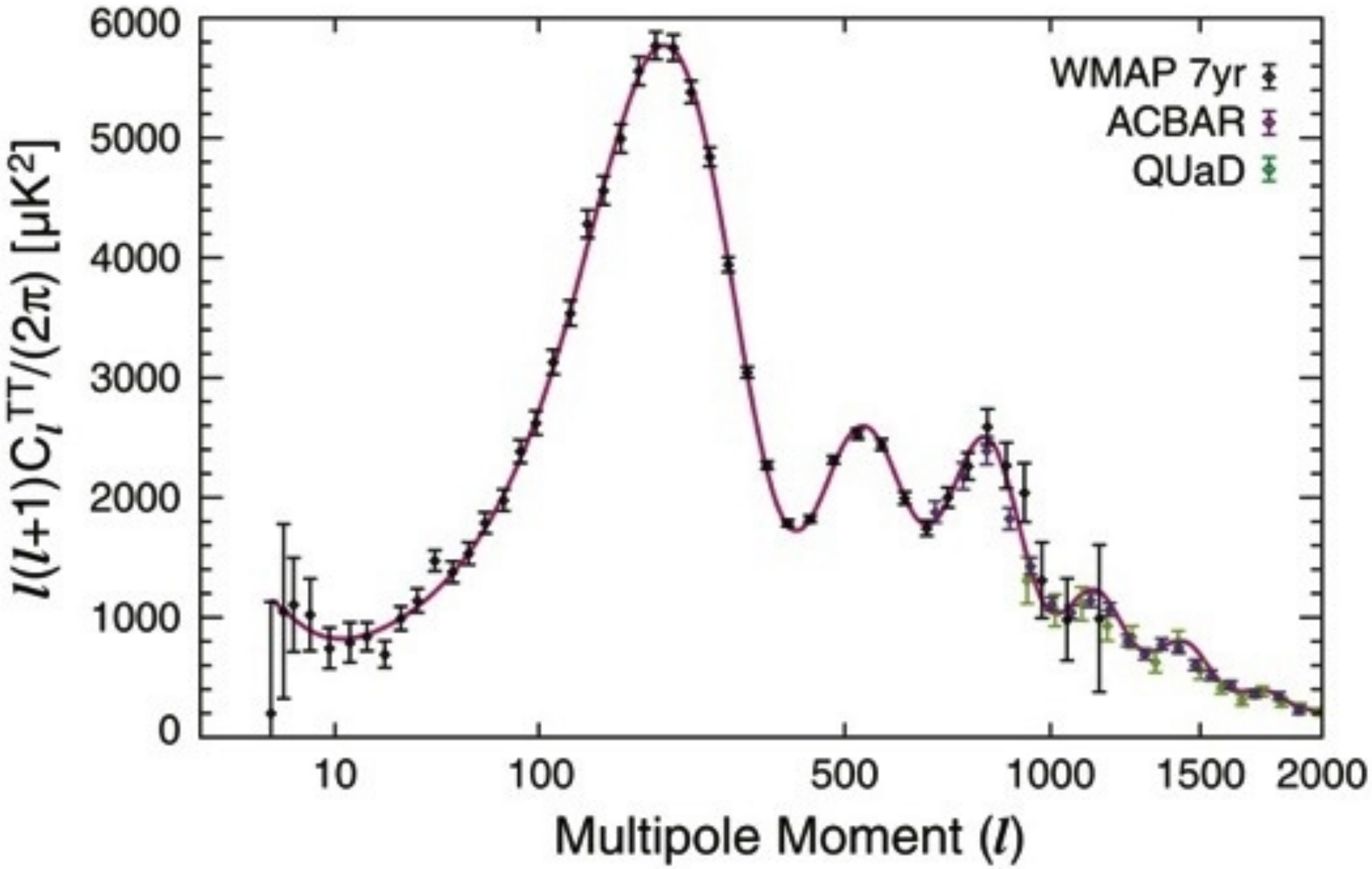
Connecting the smallest and largest scales in the universe


Cosmic Microwave Background
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
Quantum Fluctuations
WMAP
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Experiments w/ tens of detectors circa 1995-2005

Incredible progress with CMB





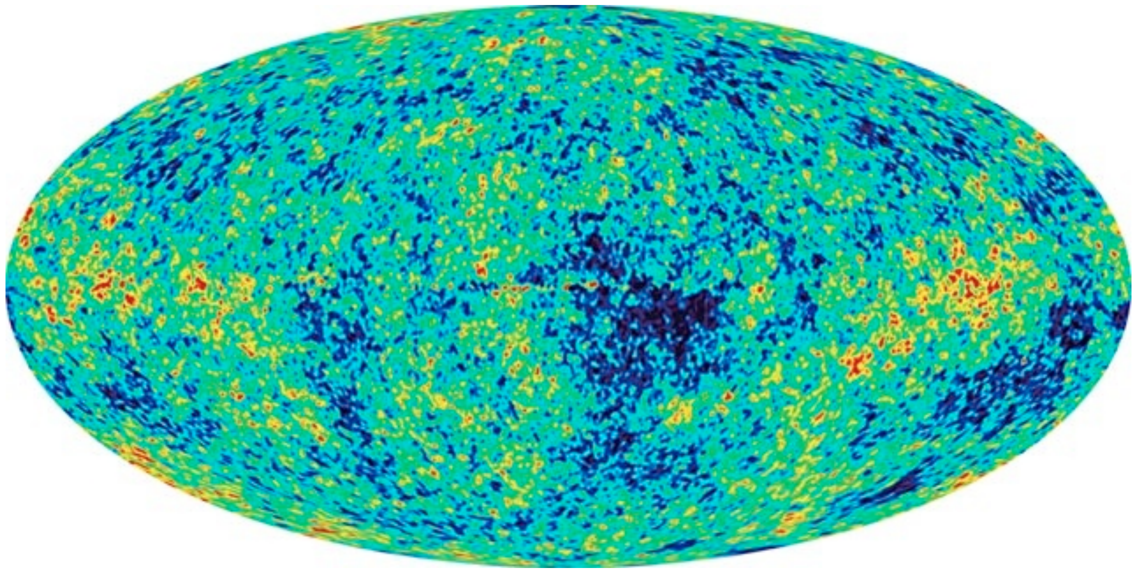
Line is fit to a flat ΛCDM cosmology model with just six parameters:

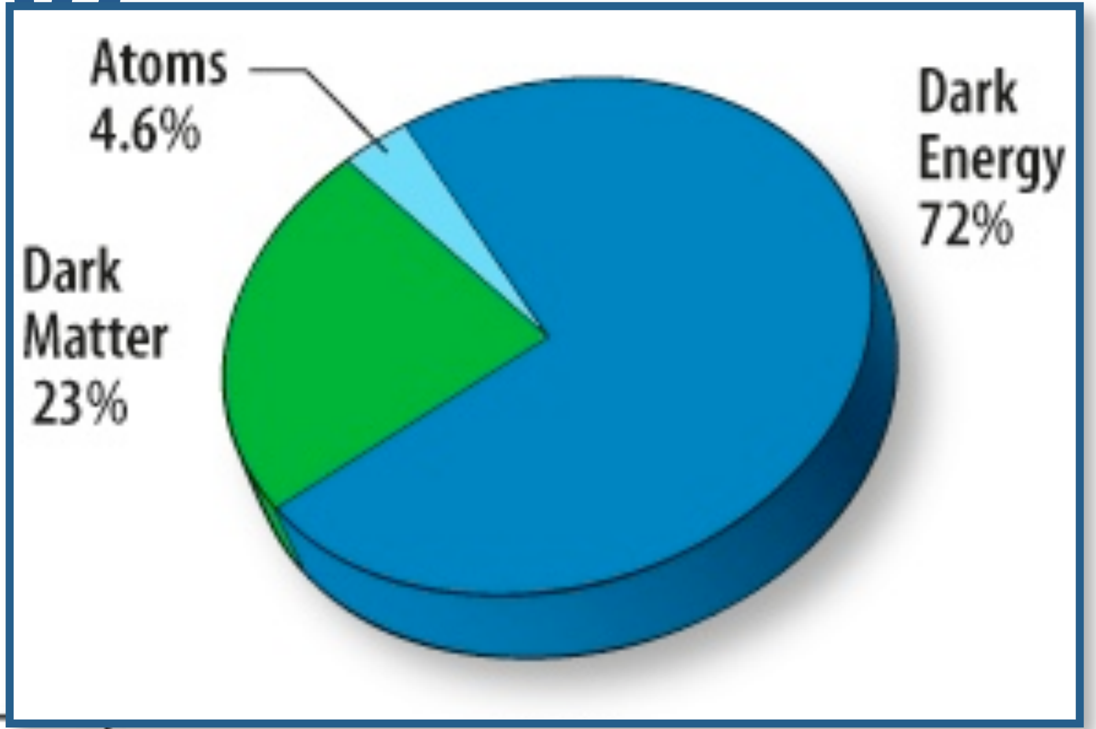
$\Omega_b h^2$, $\Omega_m h^2$, A_s, τ, n_s, Ω_Λ

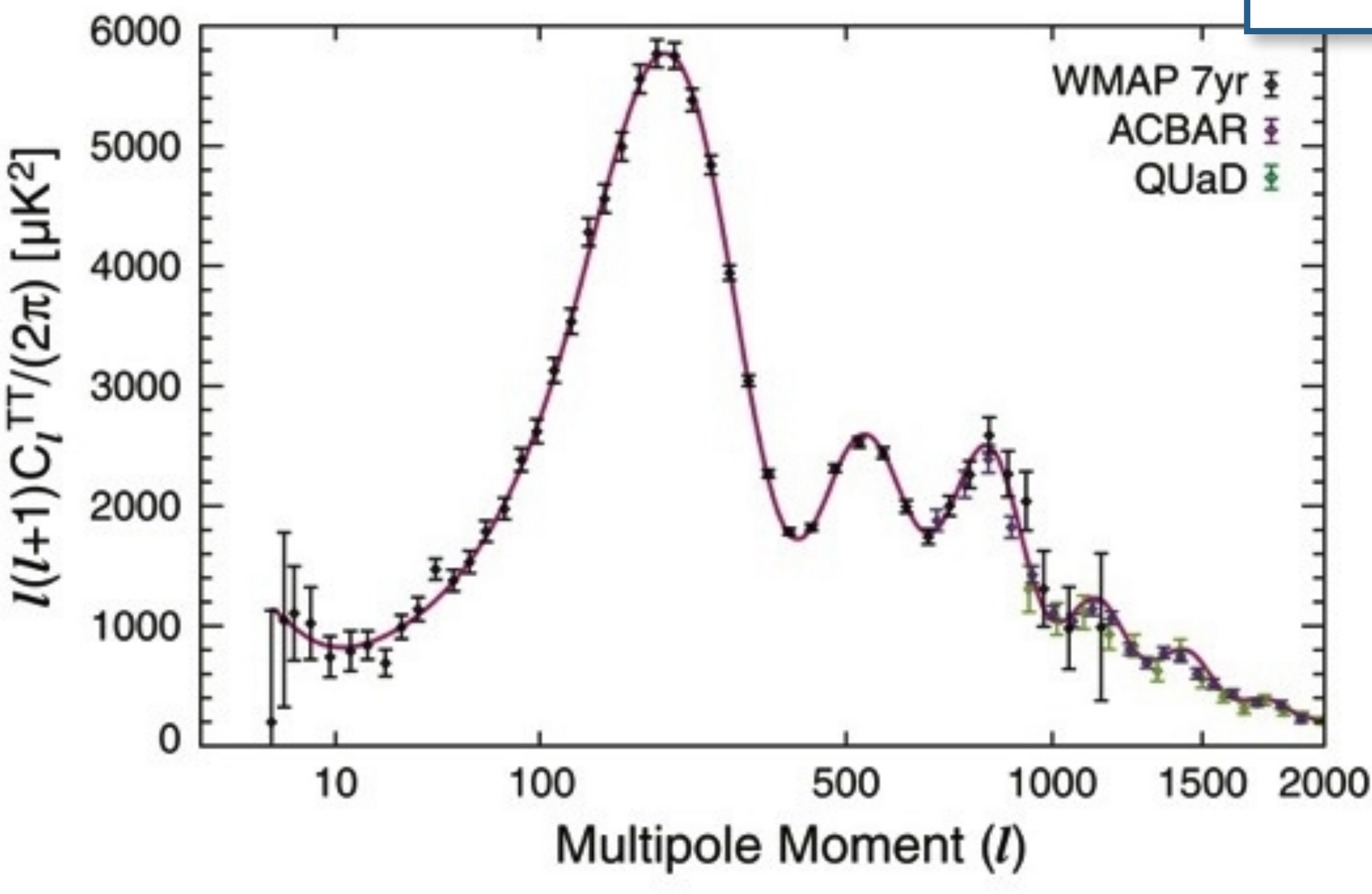
- ***Inflation (flat, n_s)***
- ***Non-baryonic dark matter (3rd peak)***
- ***Dark Energy***

Komatsu et al., arXiv:1001:4538; Larson et al., arXiv:1001.4635

Incredible progress with CMB







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Push to higher resolution
ACT and SPT

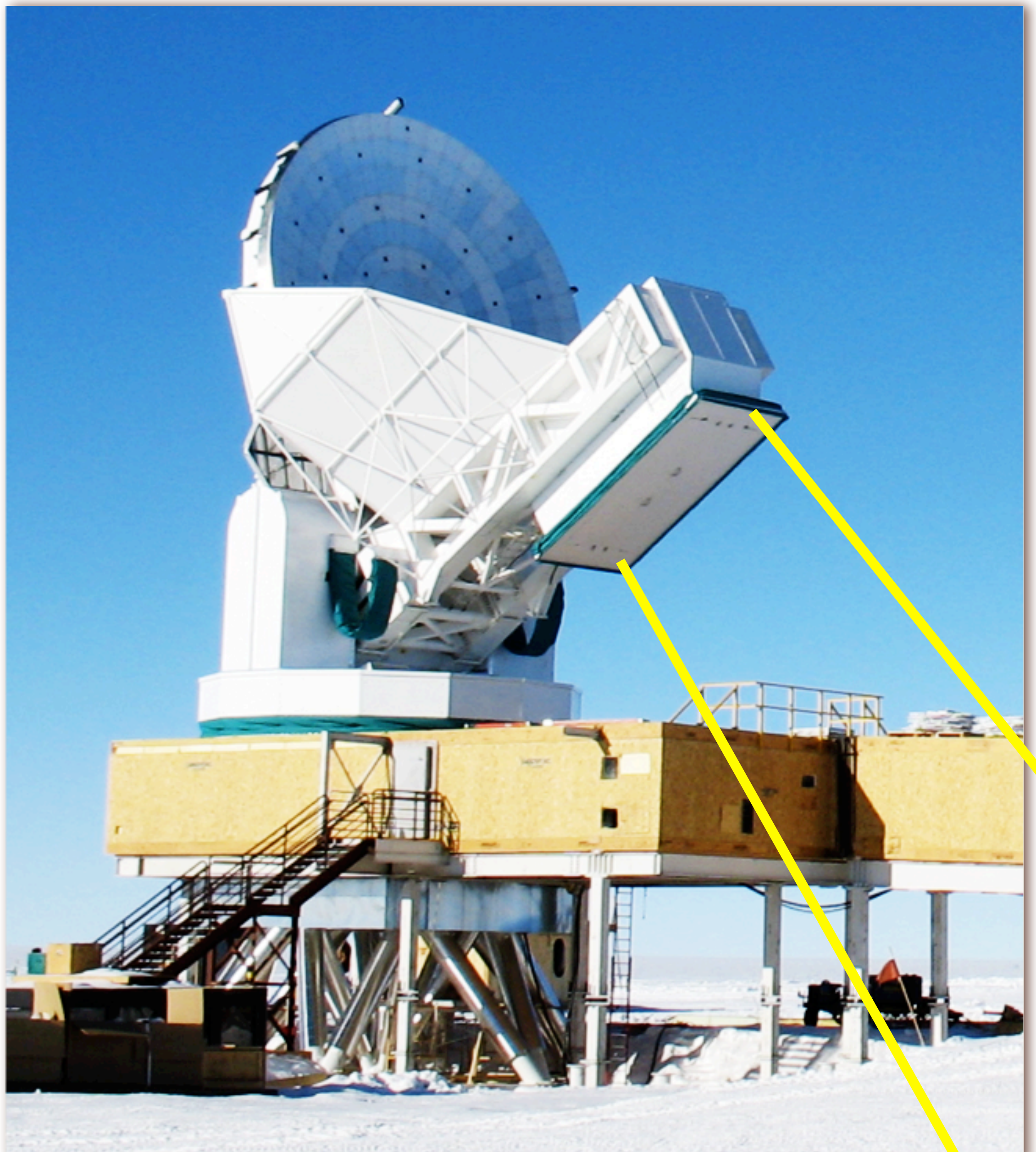
Cameras with ~1000 detectors

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

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

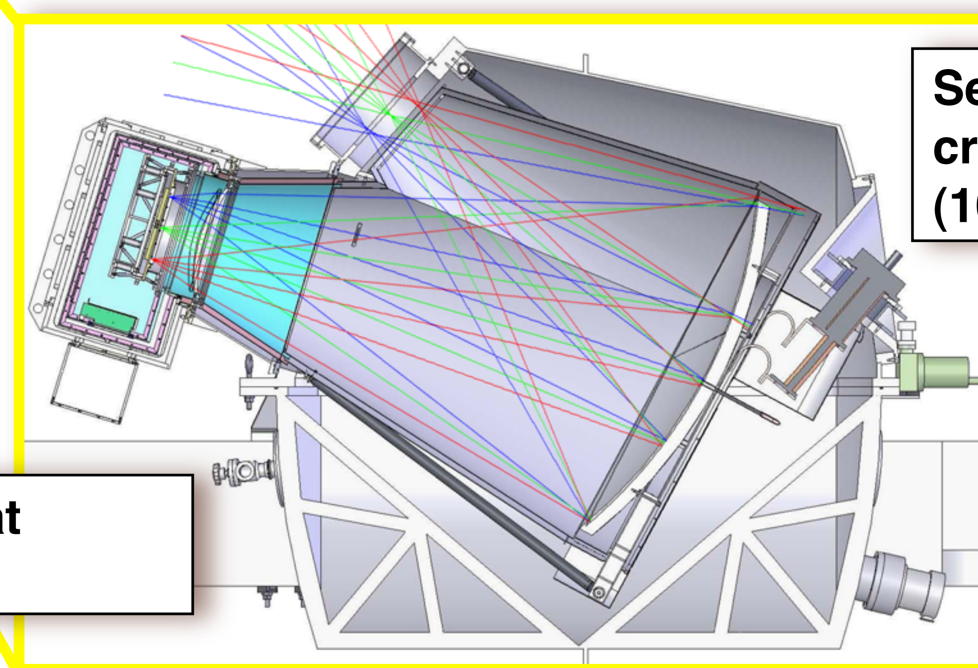
- High, dry sites for dedicated CMB observations.
- Exploiting ongoing revolution in low-noise bolometer cameras

The 10 meter South Pole Telescope



Some Key Features:

- 1 arcmin resolution at 150 GHz
- 1 deg FOV, unblocked optics
- 960 feedhorn coupled detectors
- Observe in 3+ bands 90, 150 & 220 GHz simultaneously with a modular focal plane
- Site: fantastic atmospheric transparency and stability, 24/7/52 observing

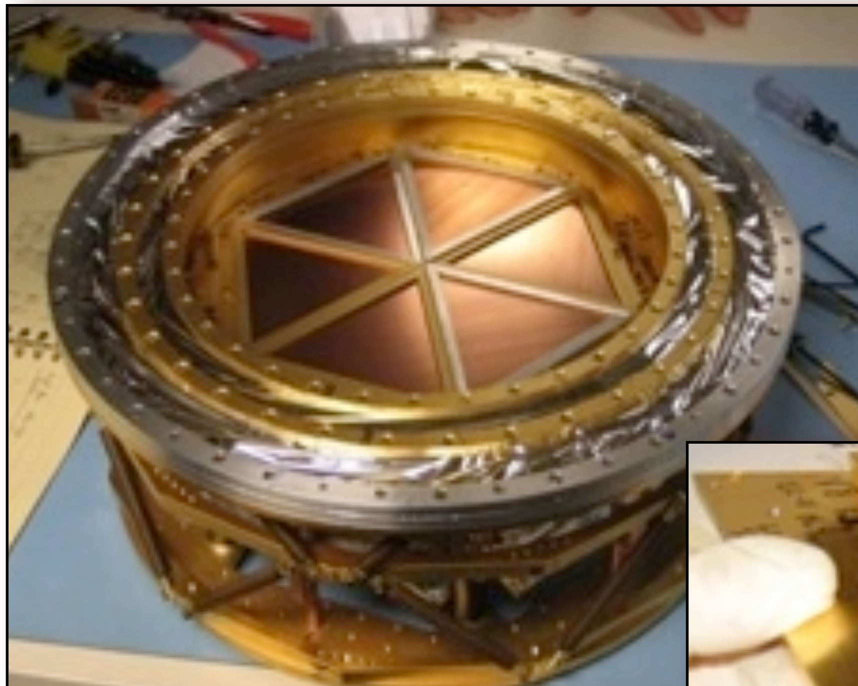


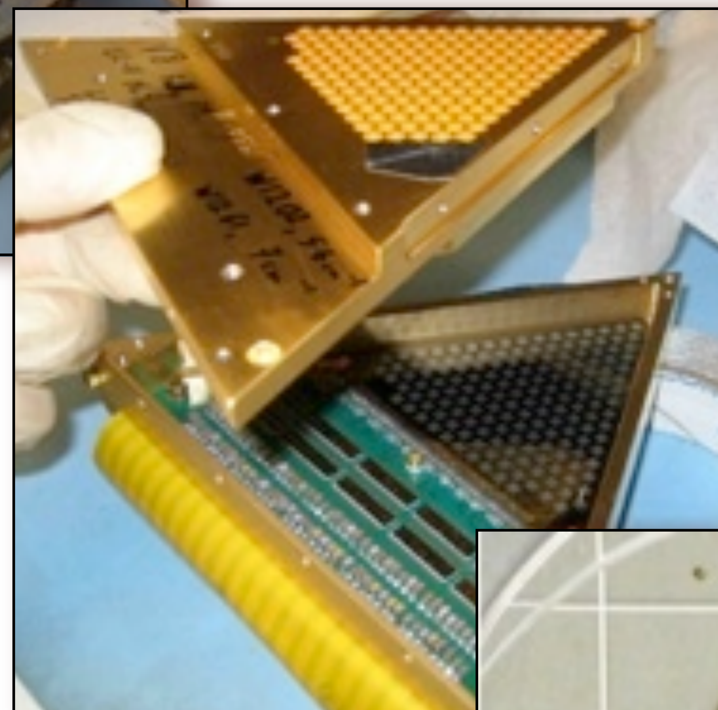
Secondary Mirror cryostat (10 K)

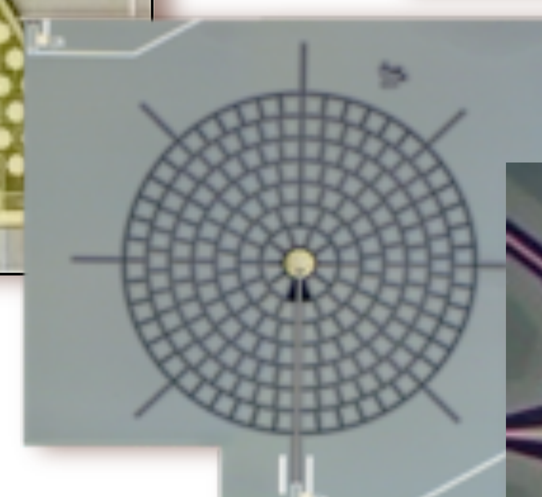
Receiver cryostat (250mK)

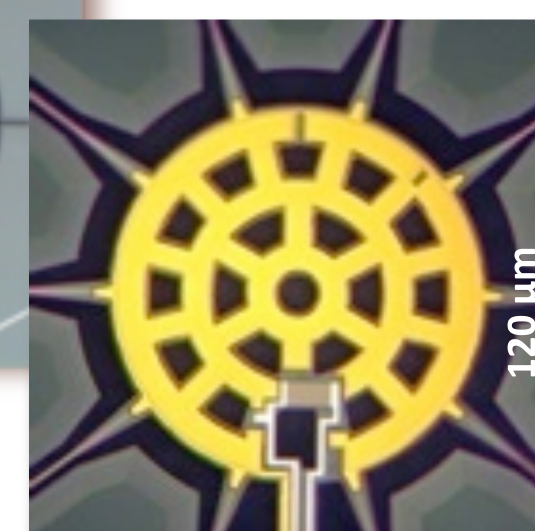
South Pole Telescope Camera

developed and built at U.C. Berkeley



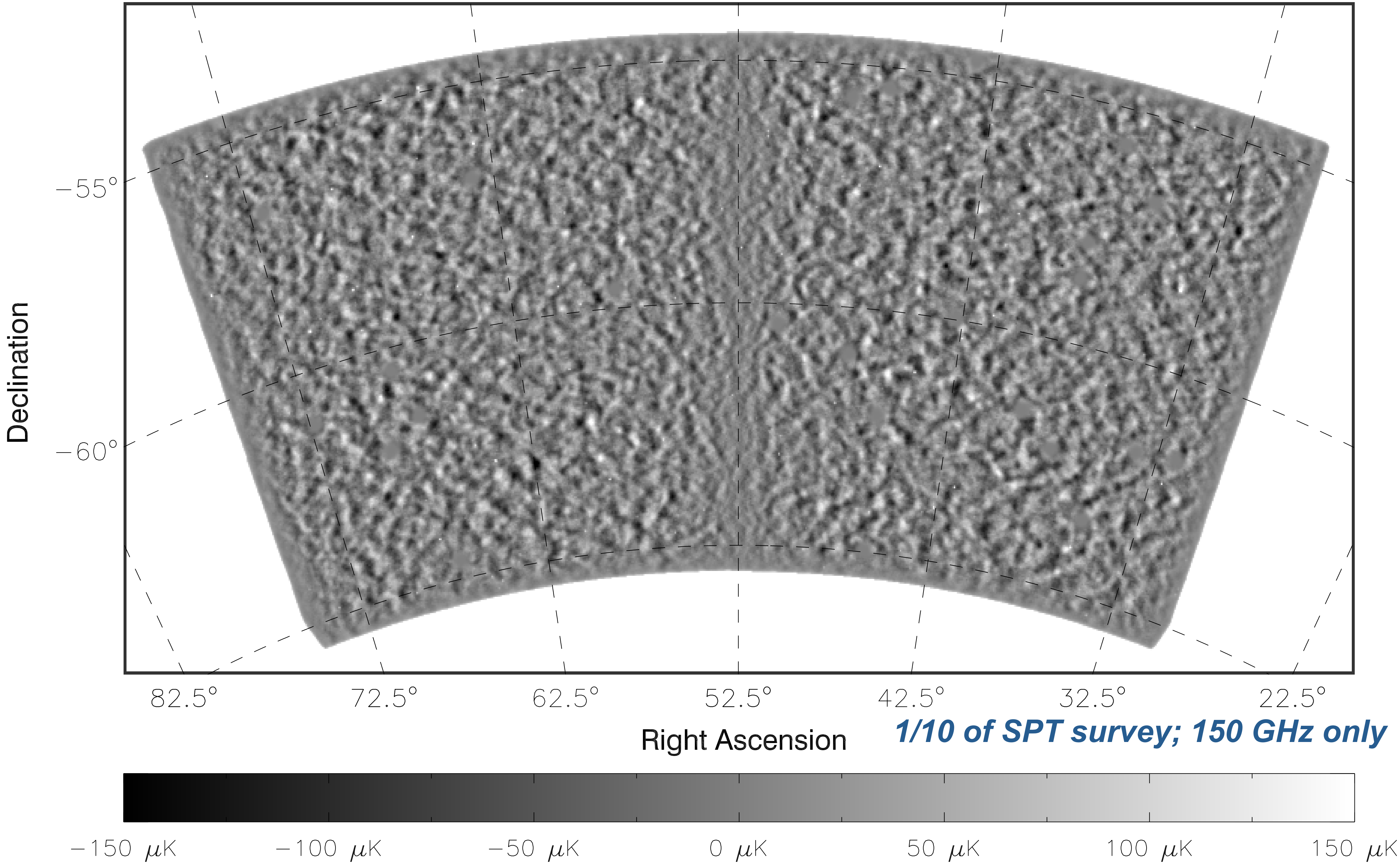






Ongoing revolution of mm & submm arrays. Soon it will be possible to field tens to hundreds of thousands of detector focal plane arrays.

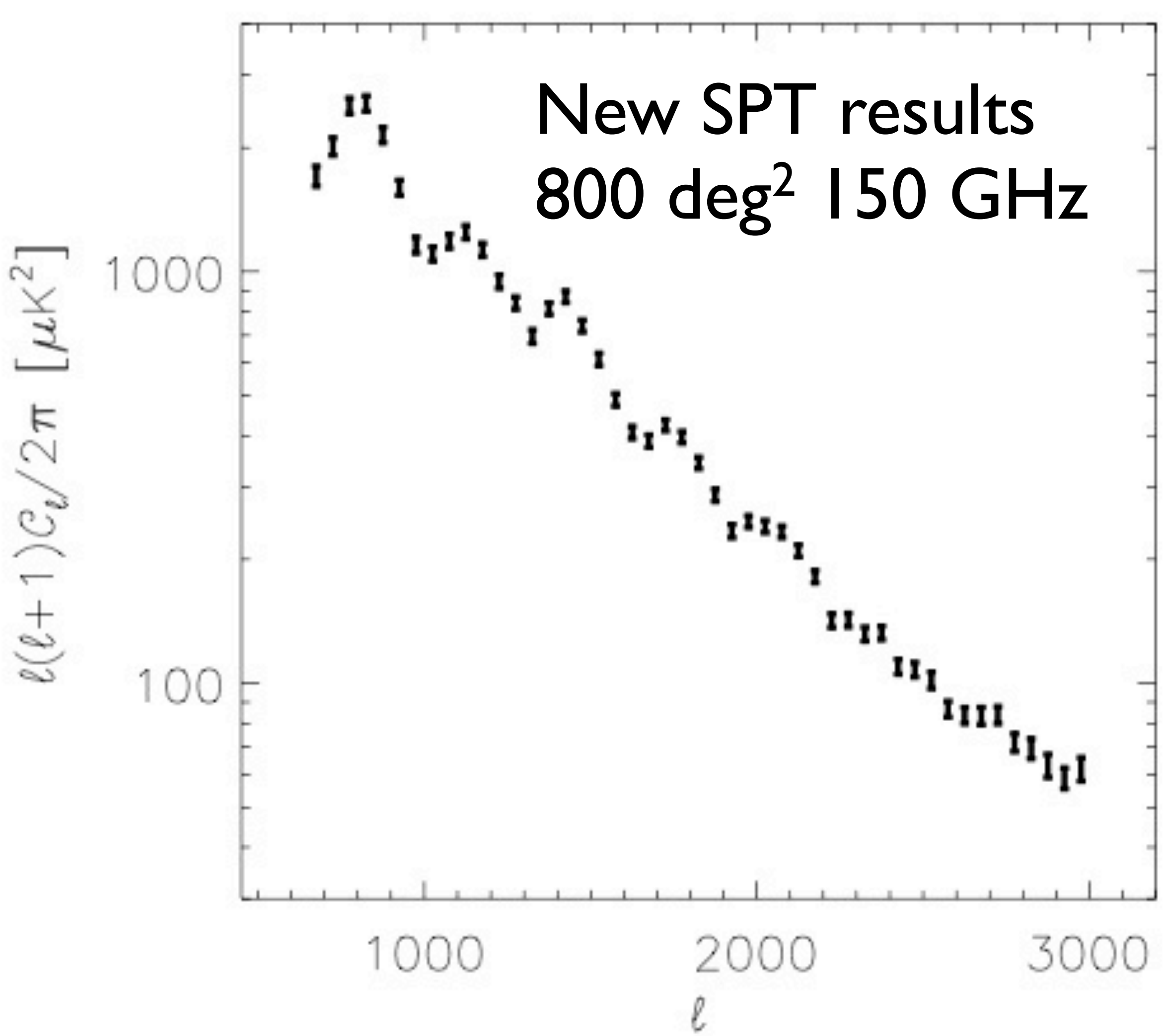
Sample SPT map of CMB anisotropy

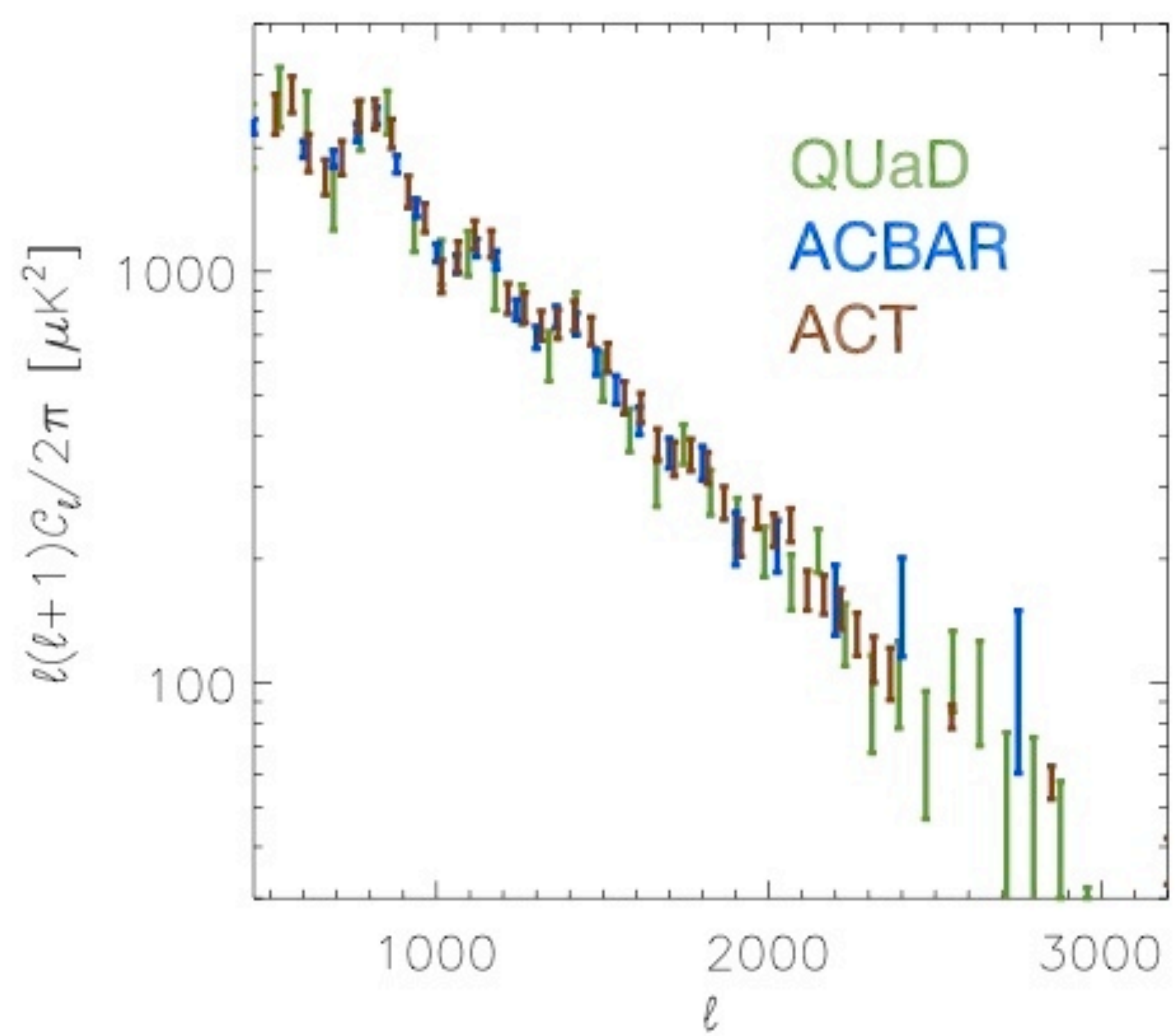


1/10 of SPT survey; 150 GHz only

Keisler et al., arXiv:1105.3182

CMB anisotropy damping tail measurements





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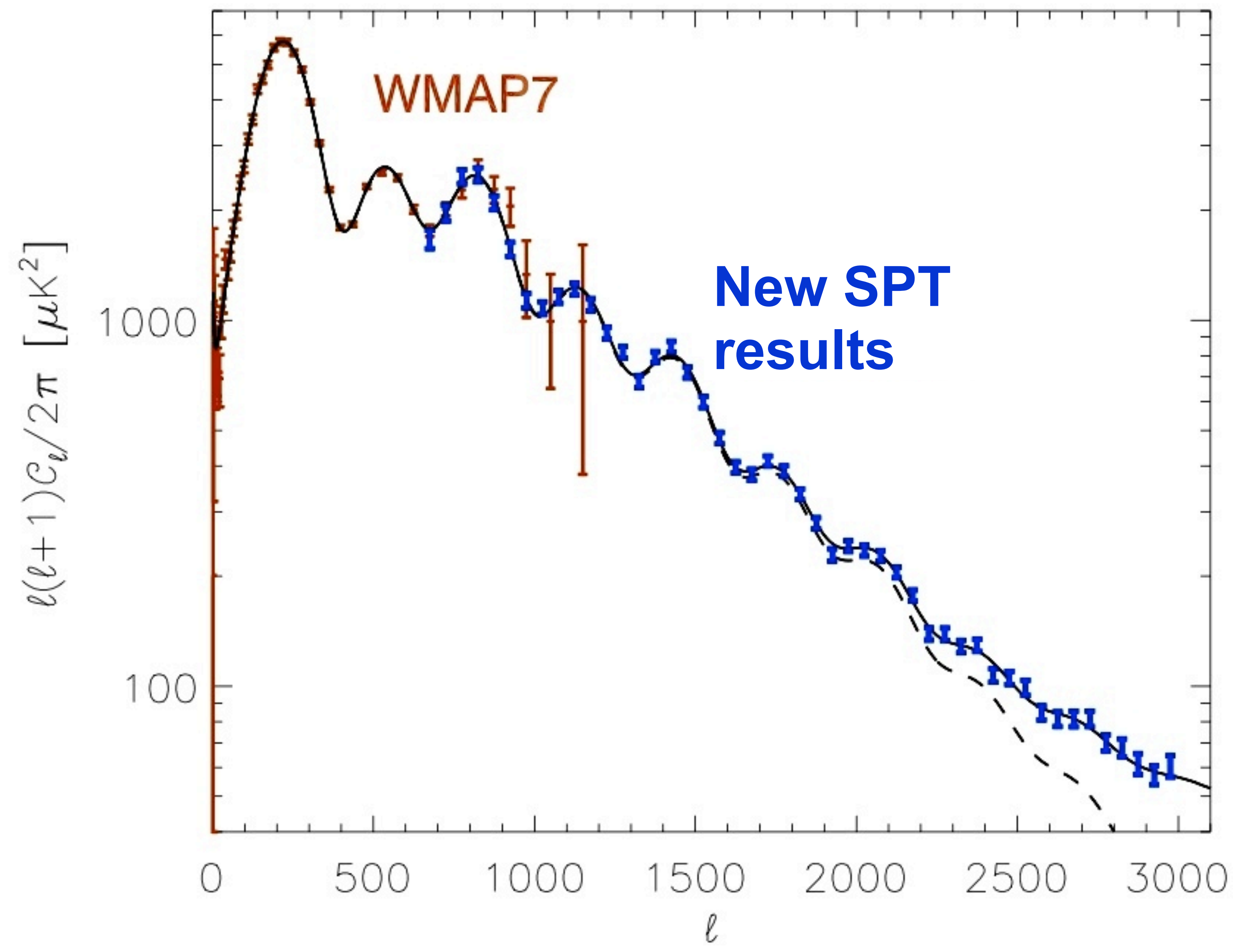

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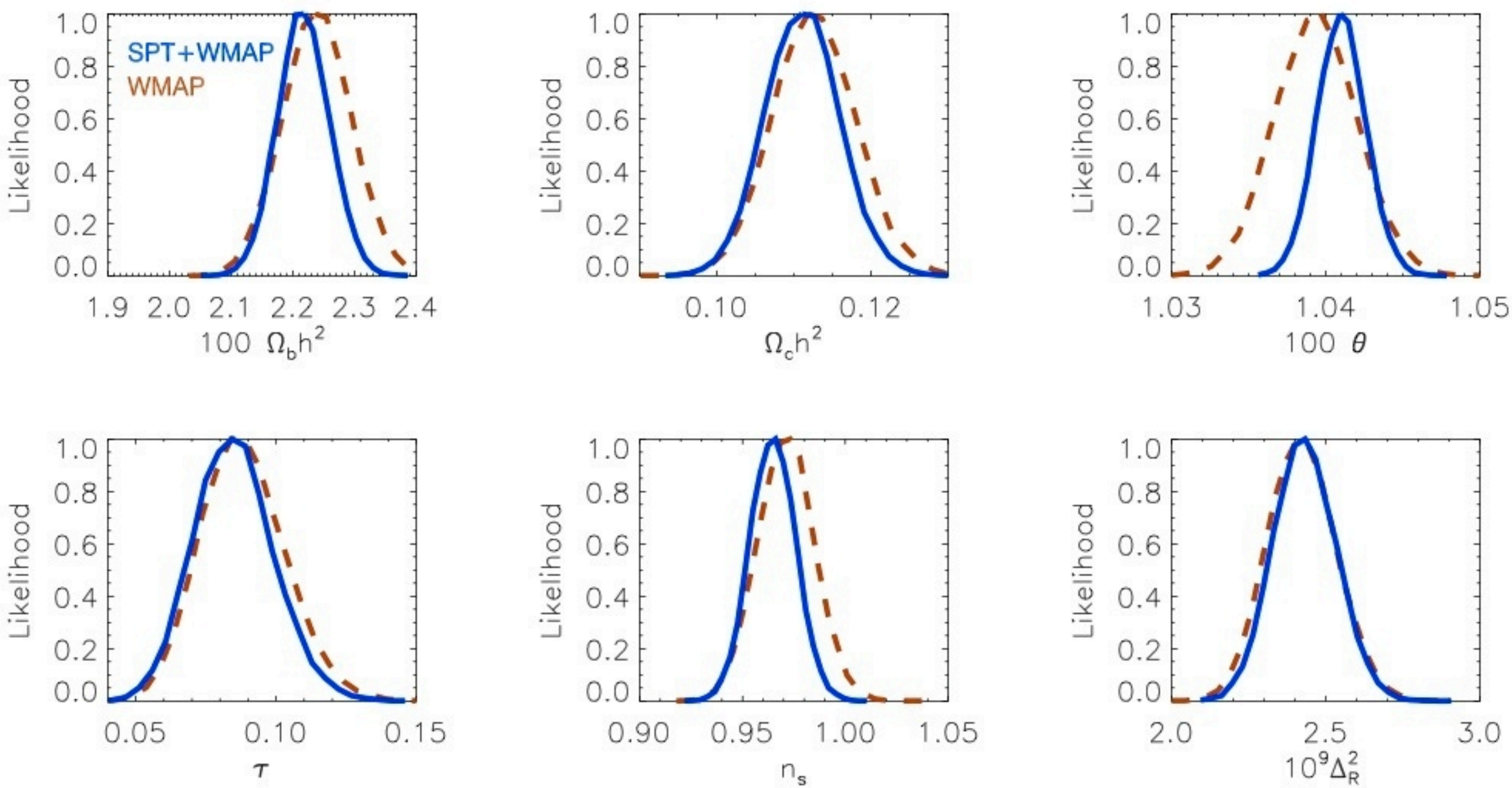
SPT and WMAP give consistent values for standard ΛCDM 6-parameters, so we fit jointly.



SPT: Keisler et al., arXiv:1105.3182; for ACT results see Dunkley et al arXiv:1009.0866

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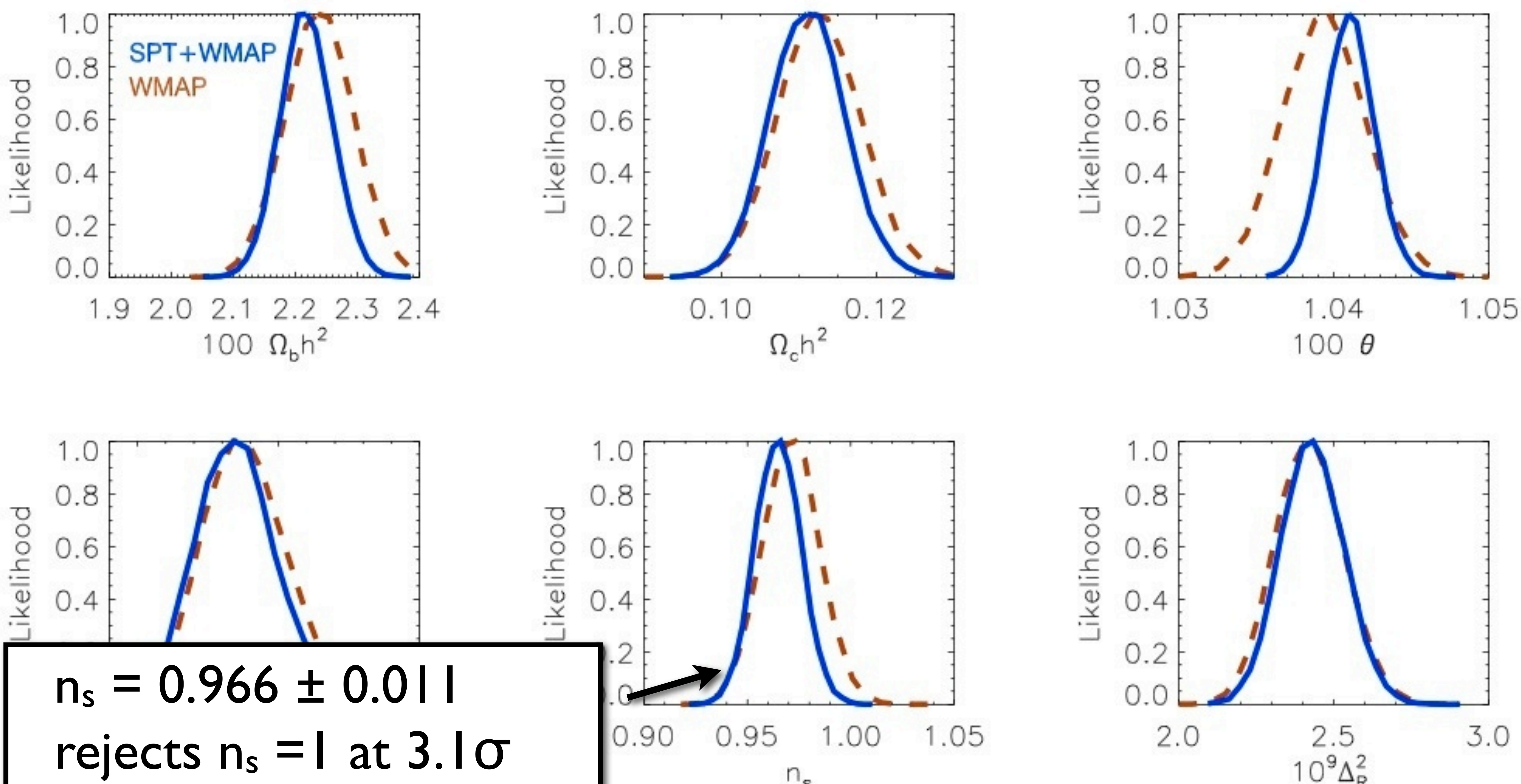


$n_s = 0.966 \pm 0.011$

rejects $n_s = 1$ at 3.1σ

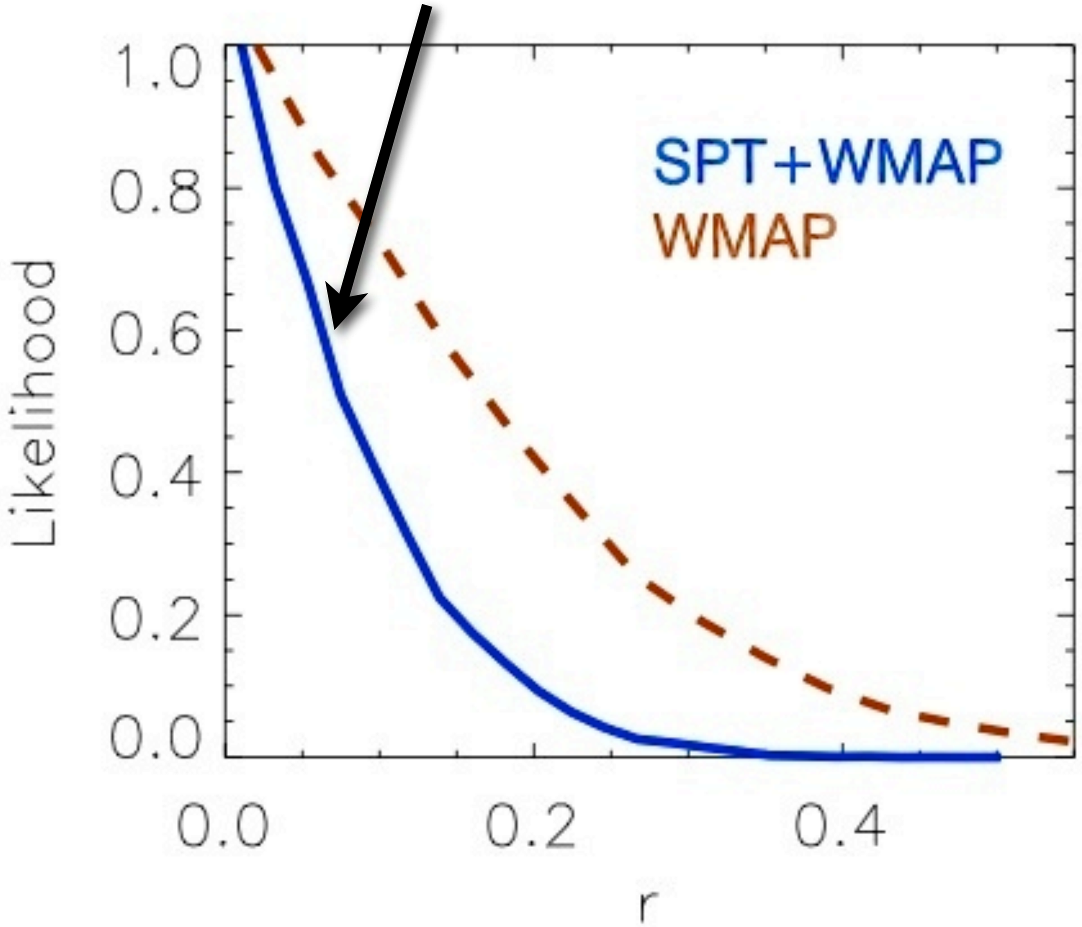
(at 3.6 σ with Ho and BAO included)

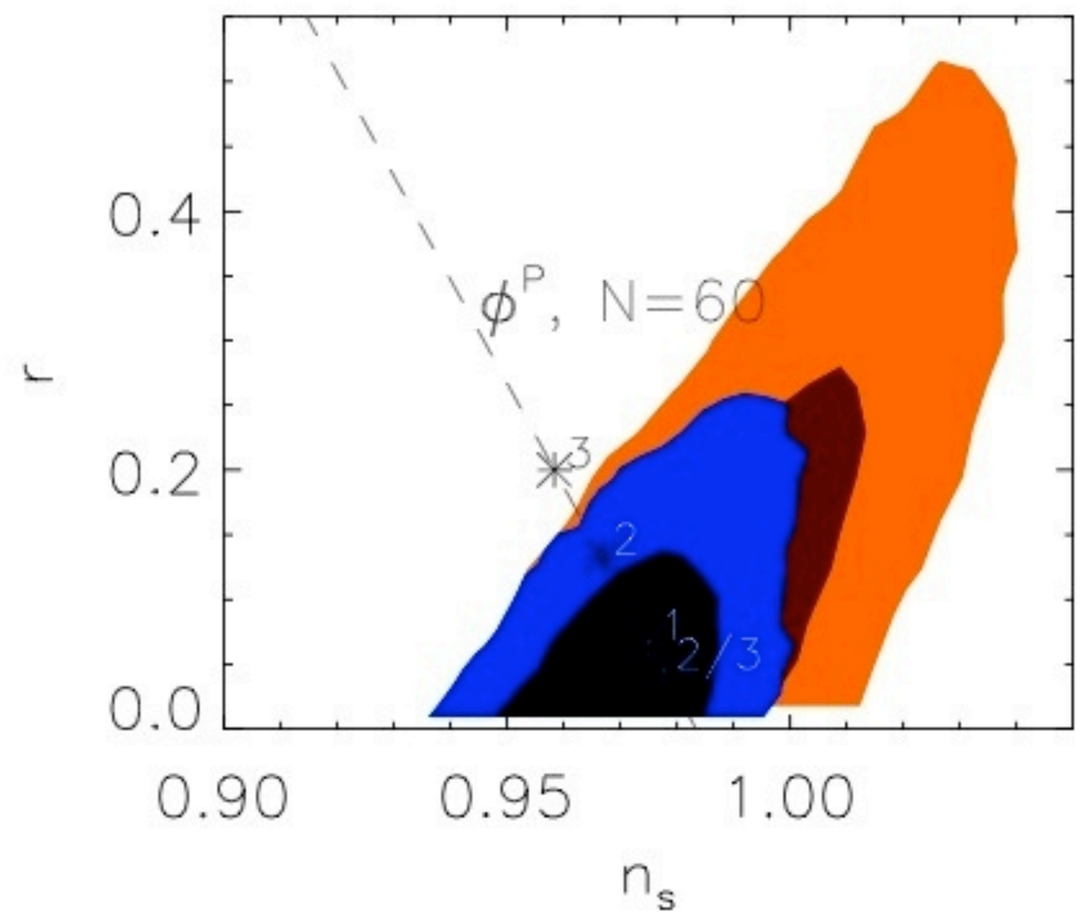
SPT: Keisler et al., arXiv:1105.3182; for ACT results see Dunkley et al arXiv:1009.0866

Going beyond the 6 ΛCDM parameters: fitting an additional parameter

Improved limit to tensor perturbations

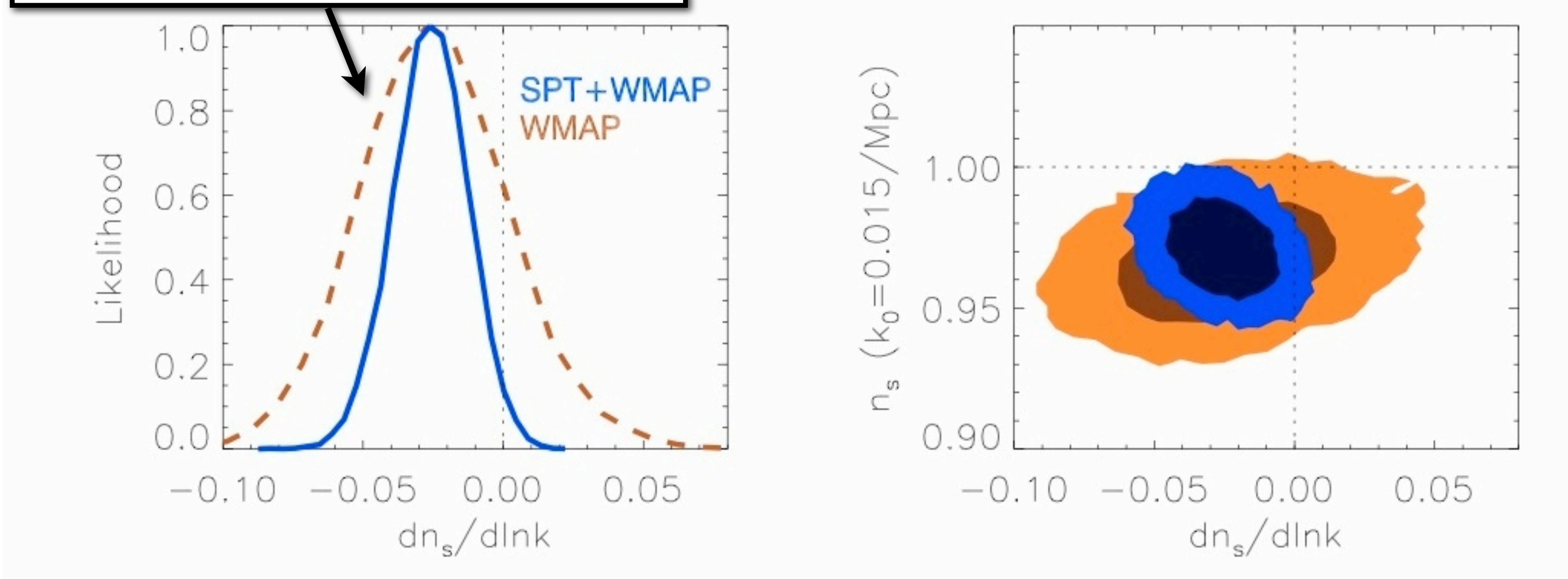
r < 0.21 at 95% CL
(r < 0.17 with Ho and BAO included)





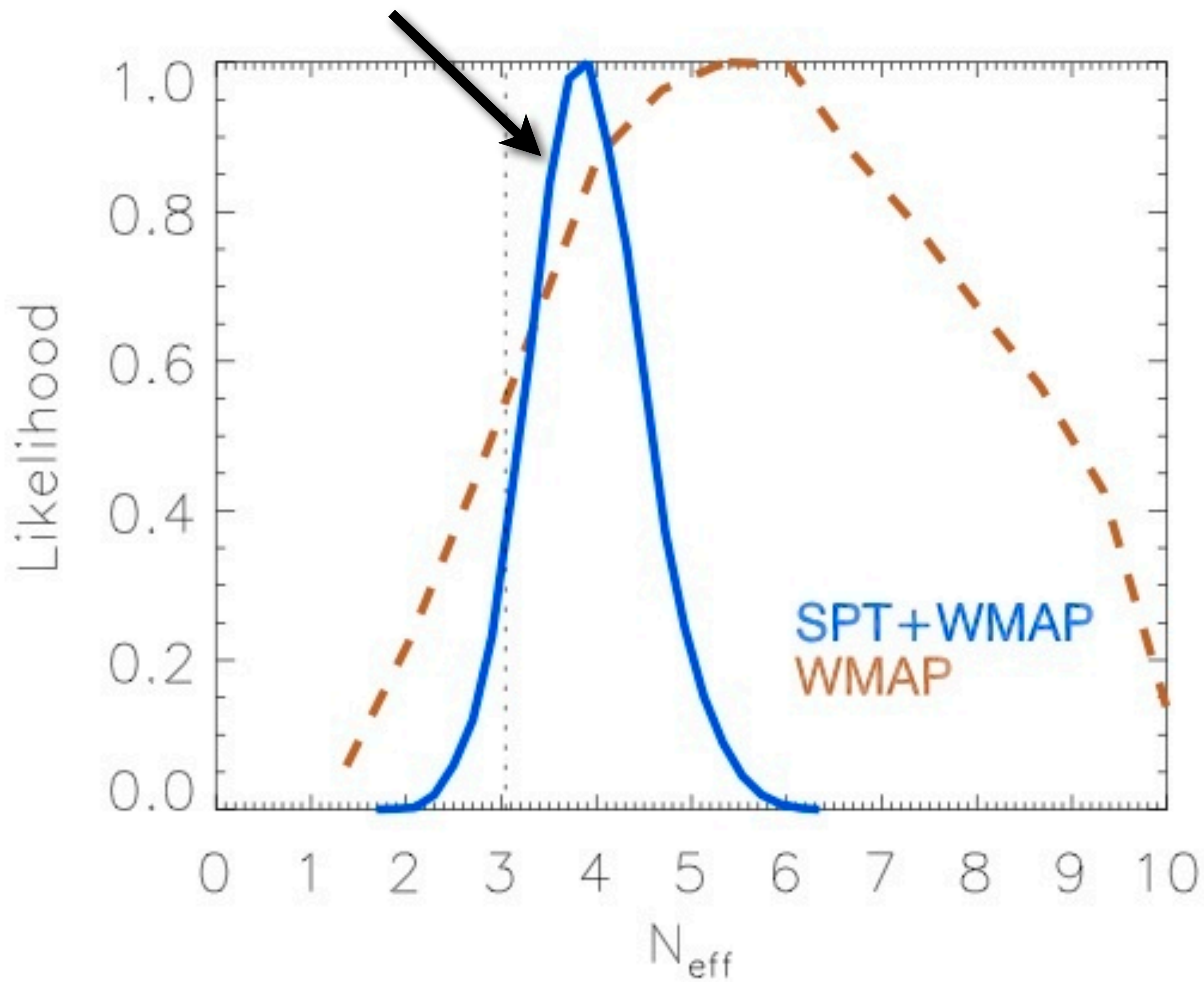
Running of the spectral index?

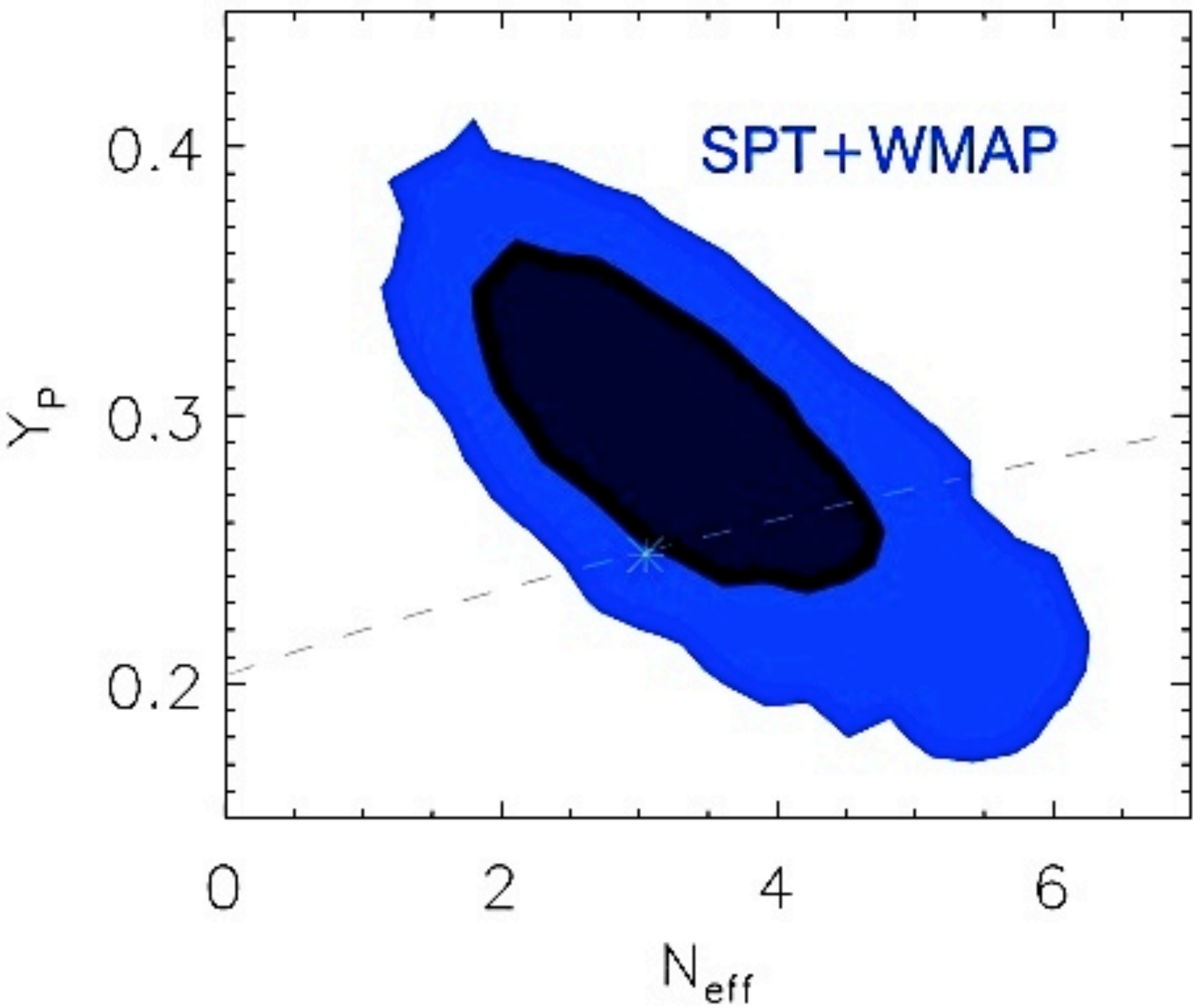
$dn_s/dlnk = -0.024 \pm 0.013$



Number of relativistic species, N_{eff}

N_{eff} = 3.87 ± 0.61
rejects N_{eff} = 0 at 7.5σ
(N_{eff} = 3.85 ± 0.44 with H_o and BAO)

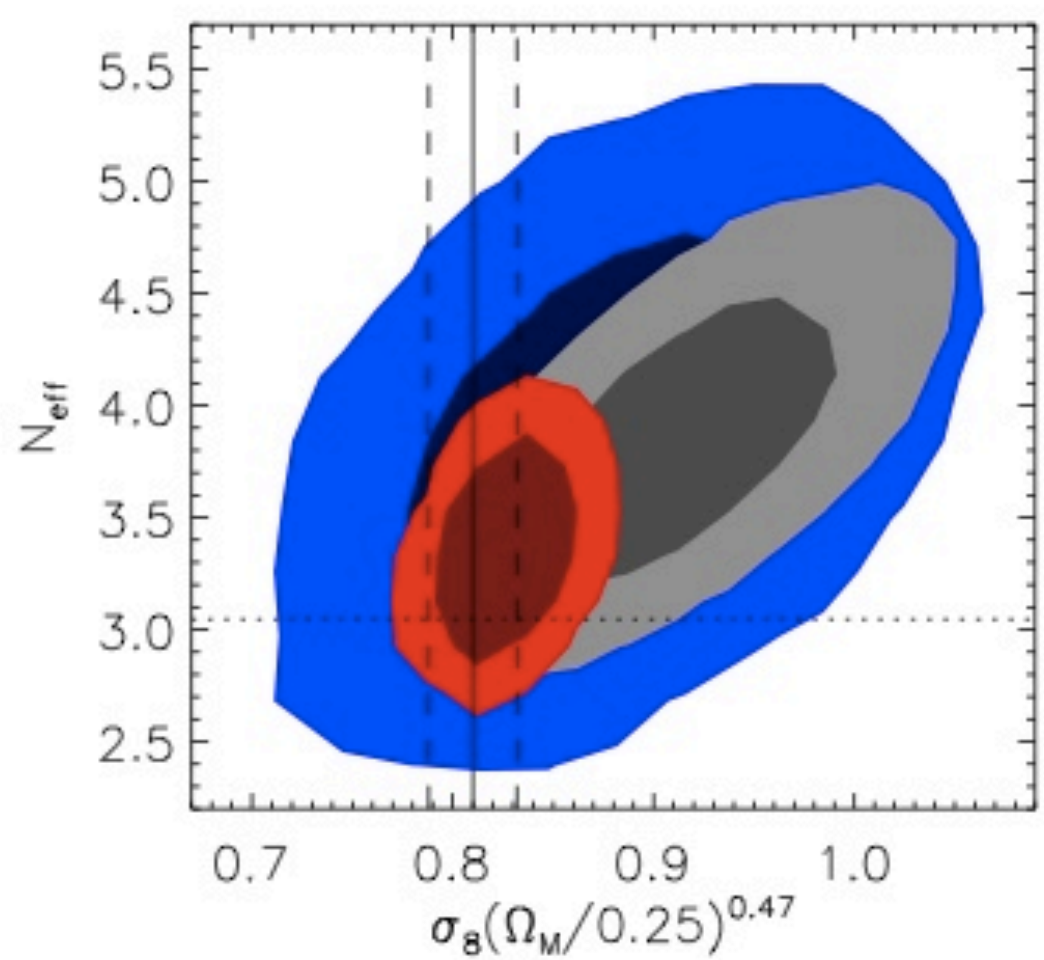




To understand CMB sensitivity to N_{eff}, see Hou et al., arXiv: 1104.2333

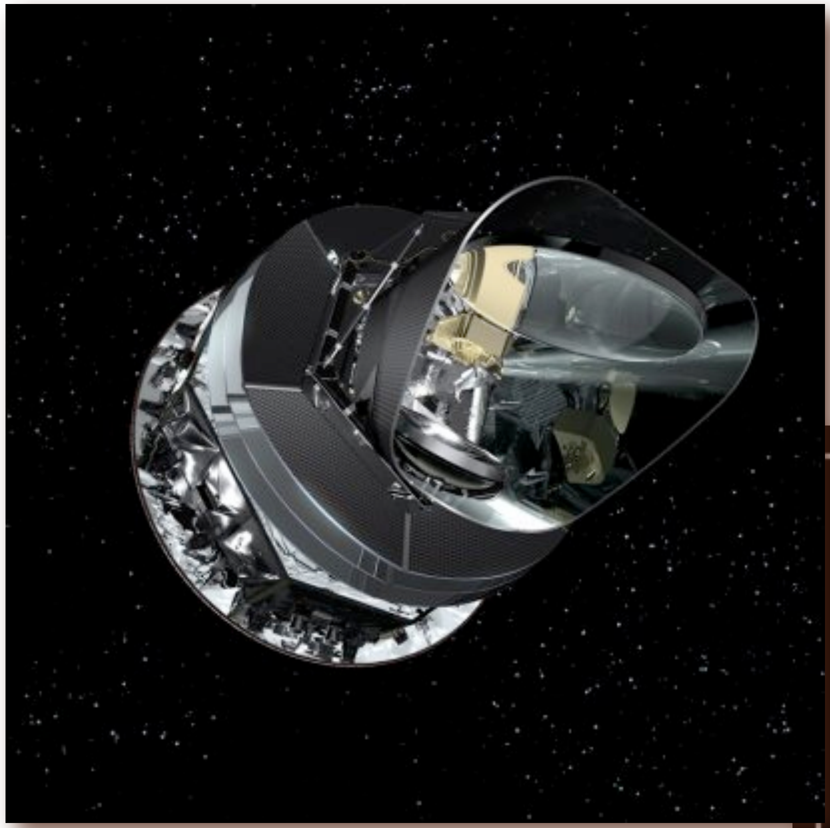
Additional neutrinos?

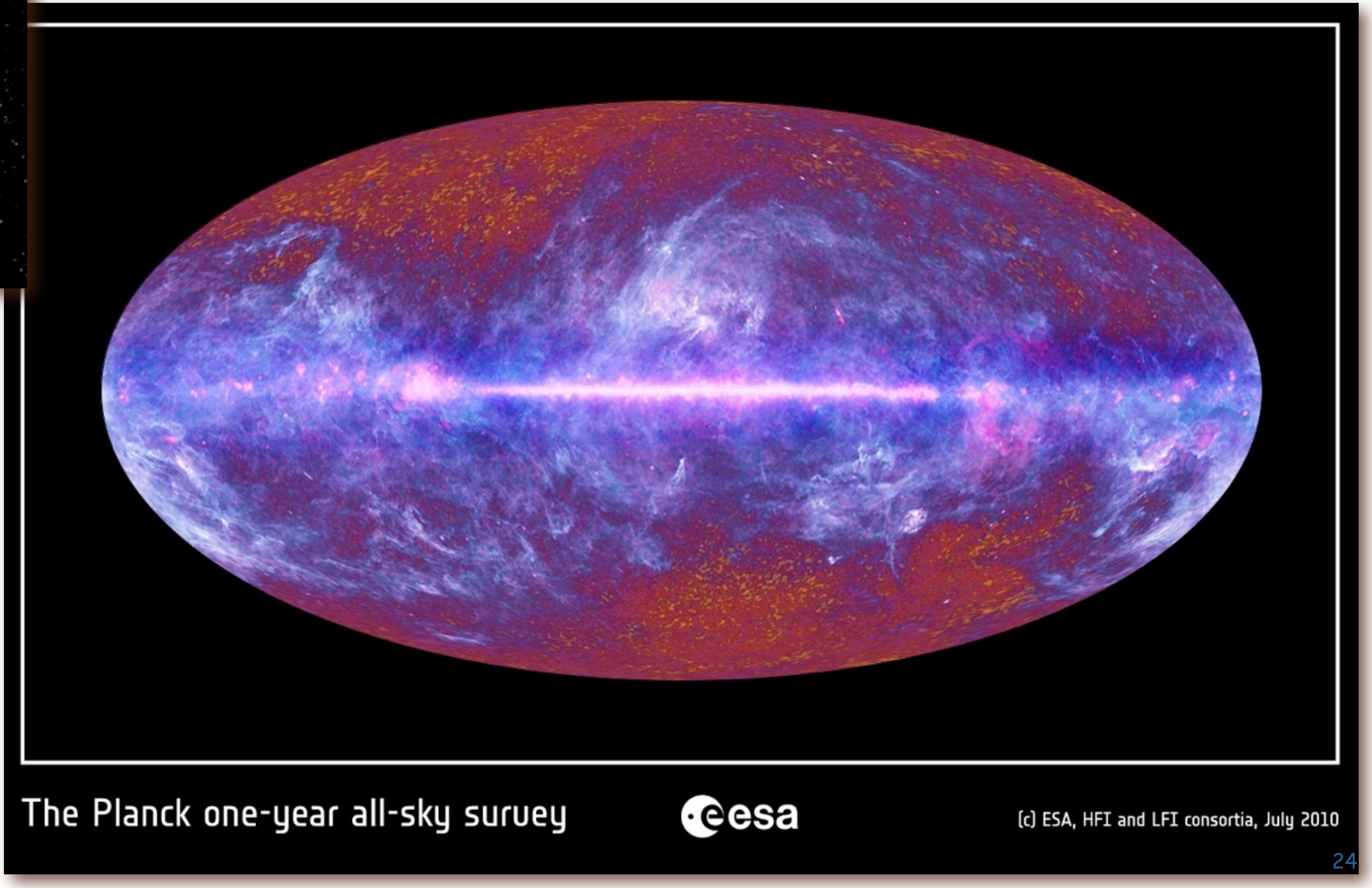
Adding cluster abundance constraint on σ_8 pushes N_{eff} closer to 3



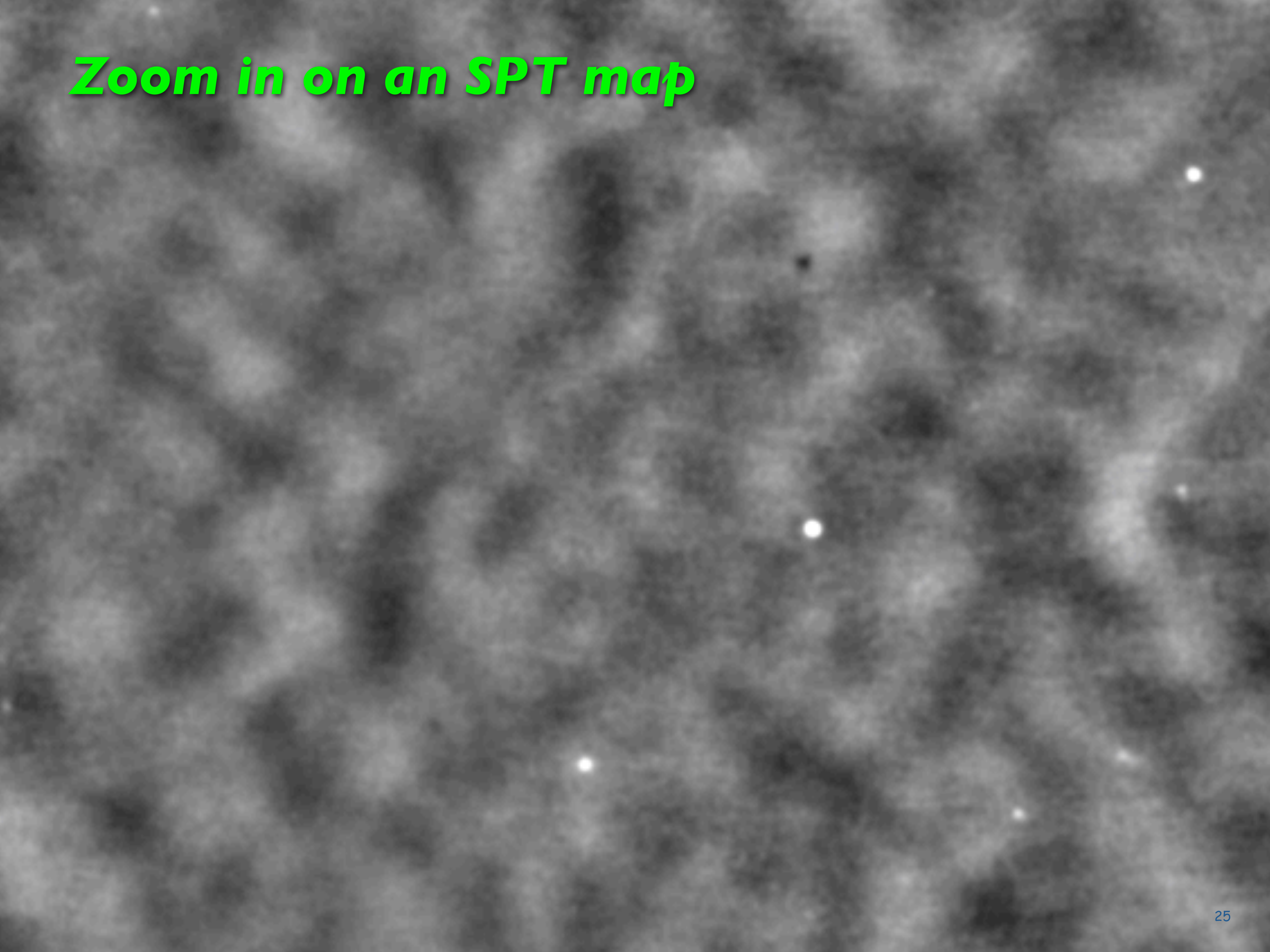
Using σ_8 constraints from local abundance of galaxy clusters (Vikhlinin et al., 2009).

Stay tuned for more results from SPT, ACT & Planck





Zoom in on an SPT map



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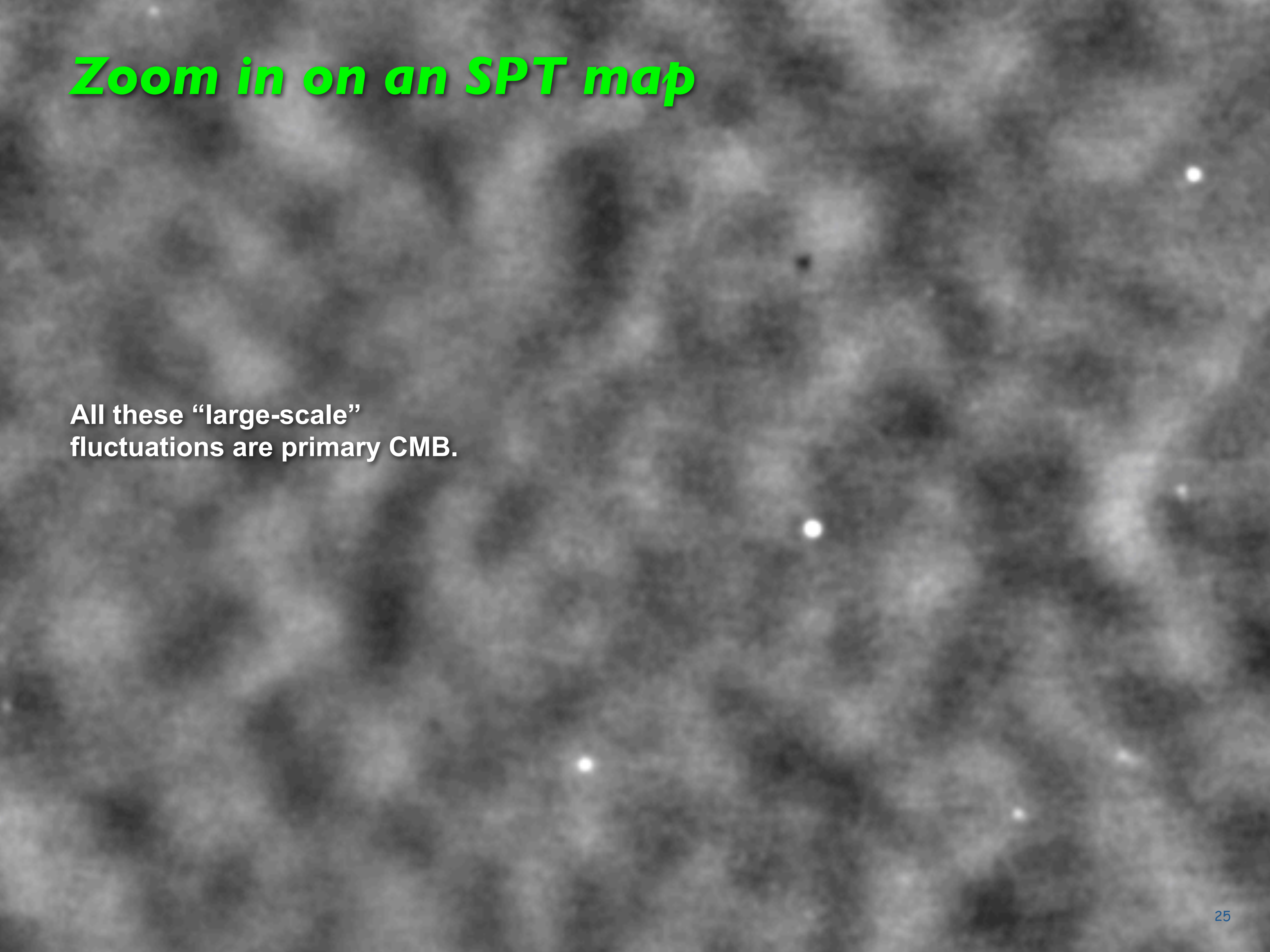

All these “large-scale” fluctuations are primary CMB.

Zoom in on an SPT map

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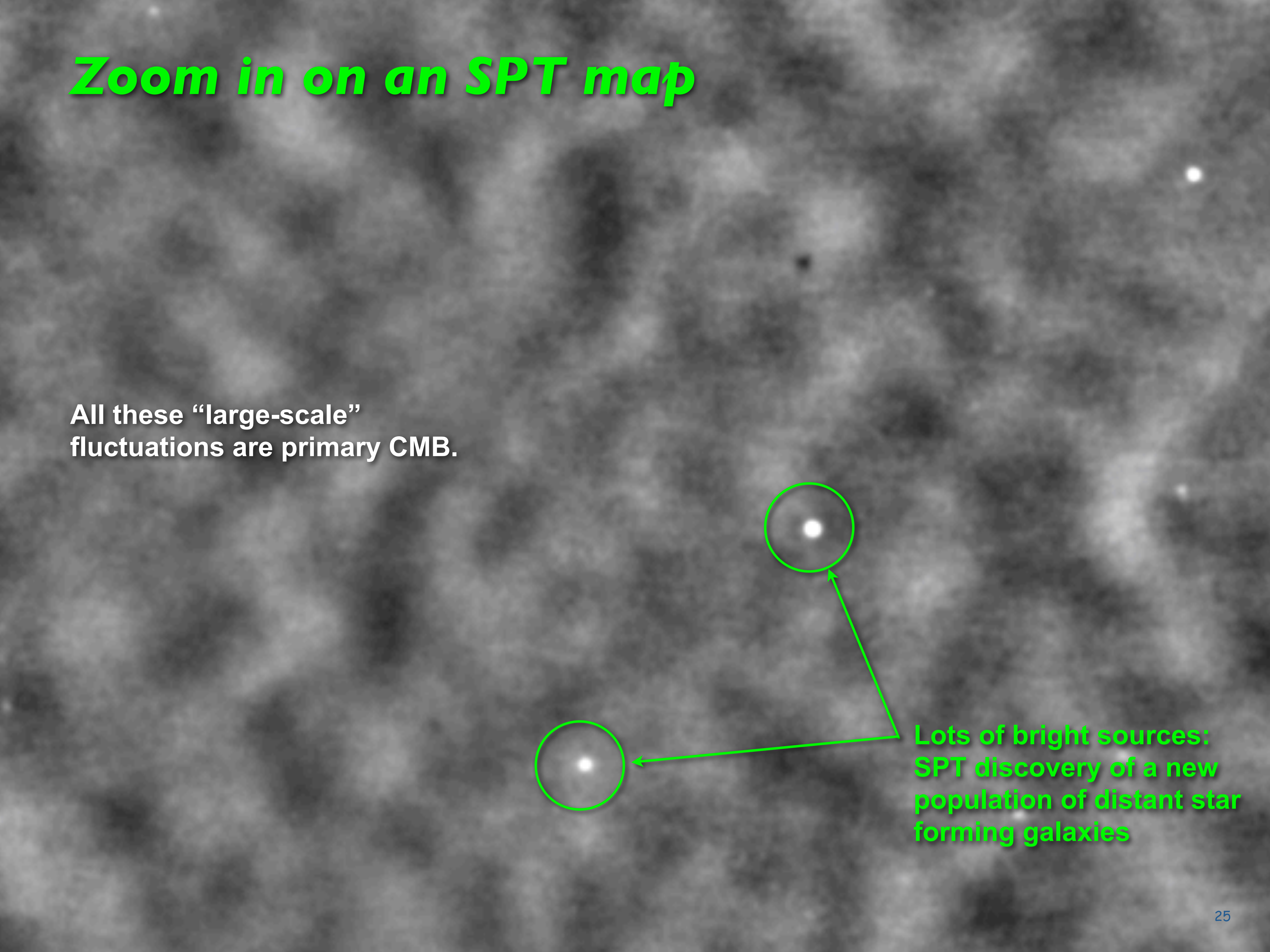

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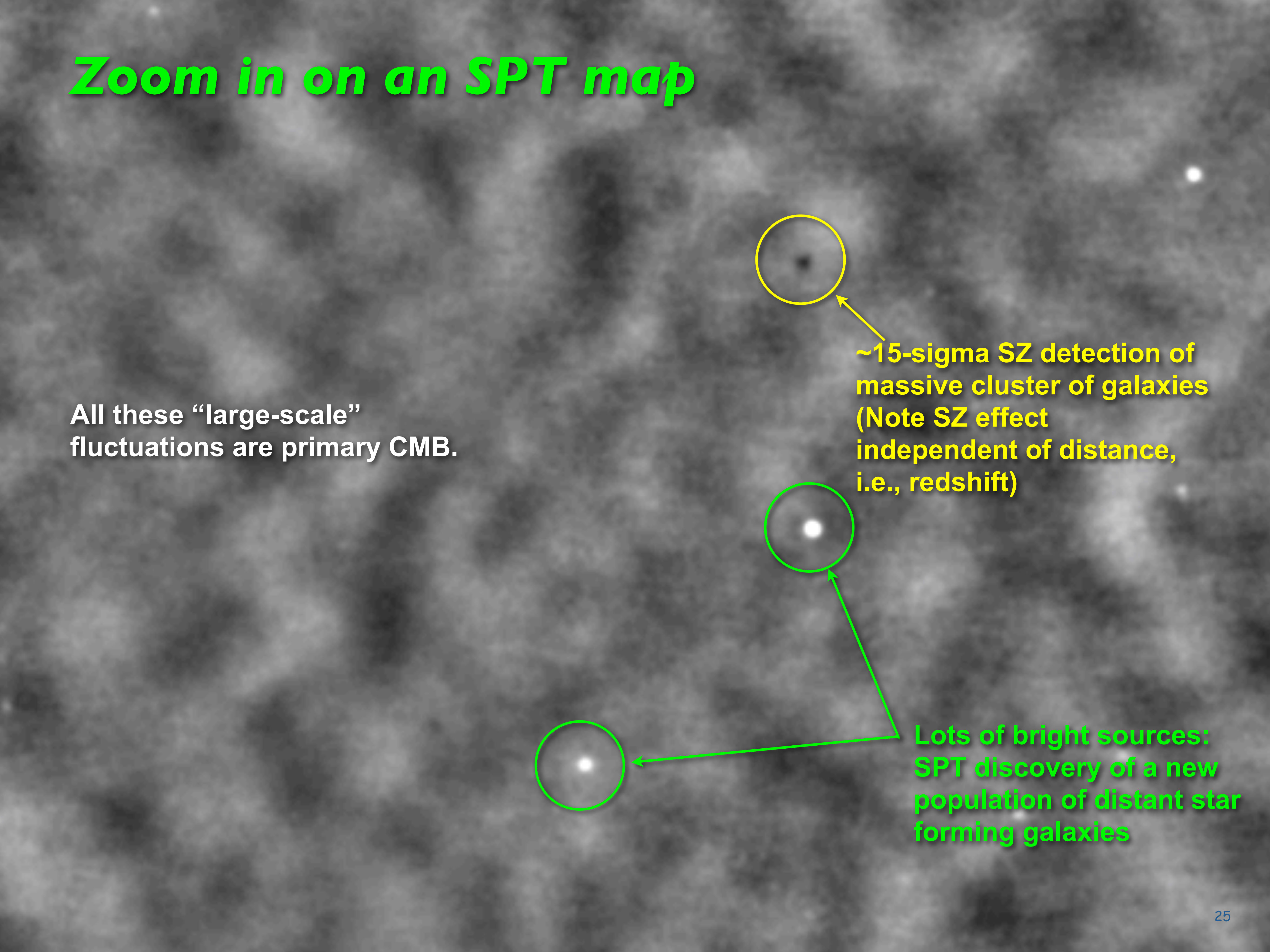
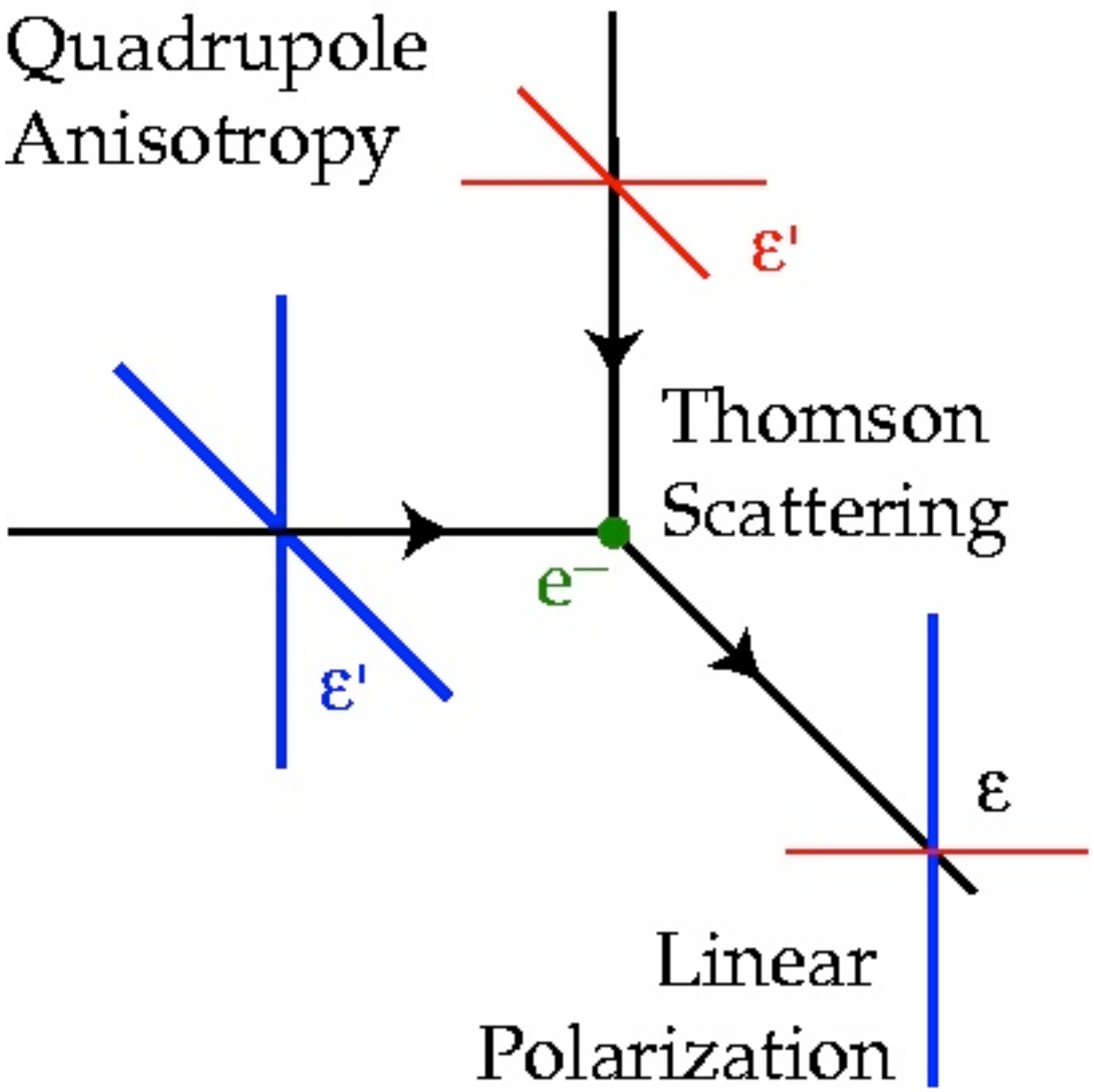


Polarization of the CMB

The *CMB must be polarized* due to Thomson scattering



from W. Hu's web page

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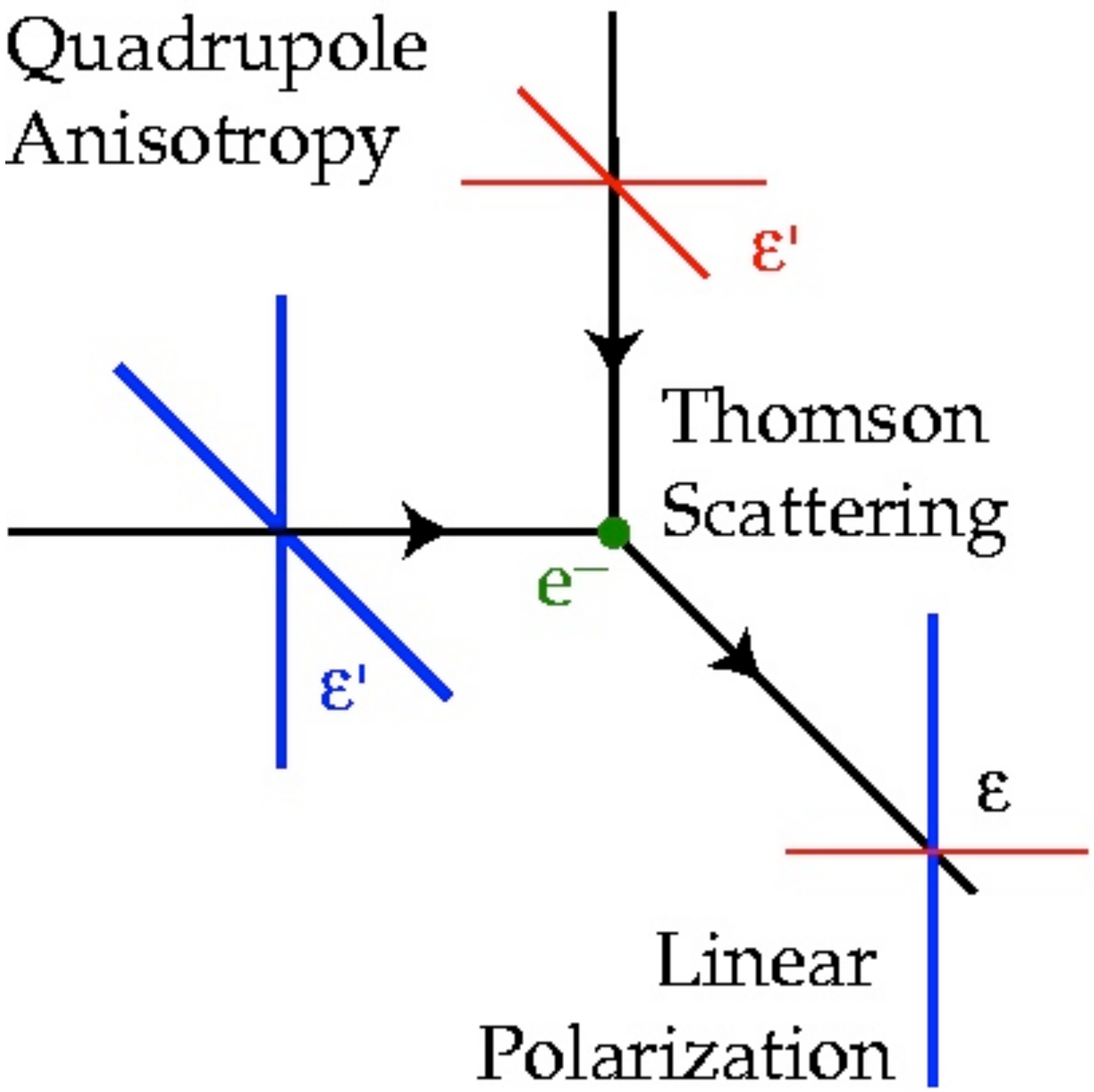

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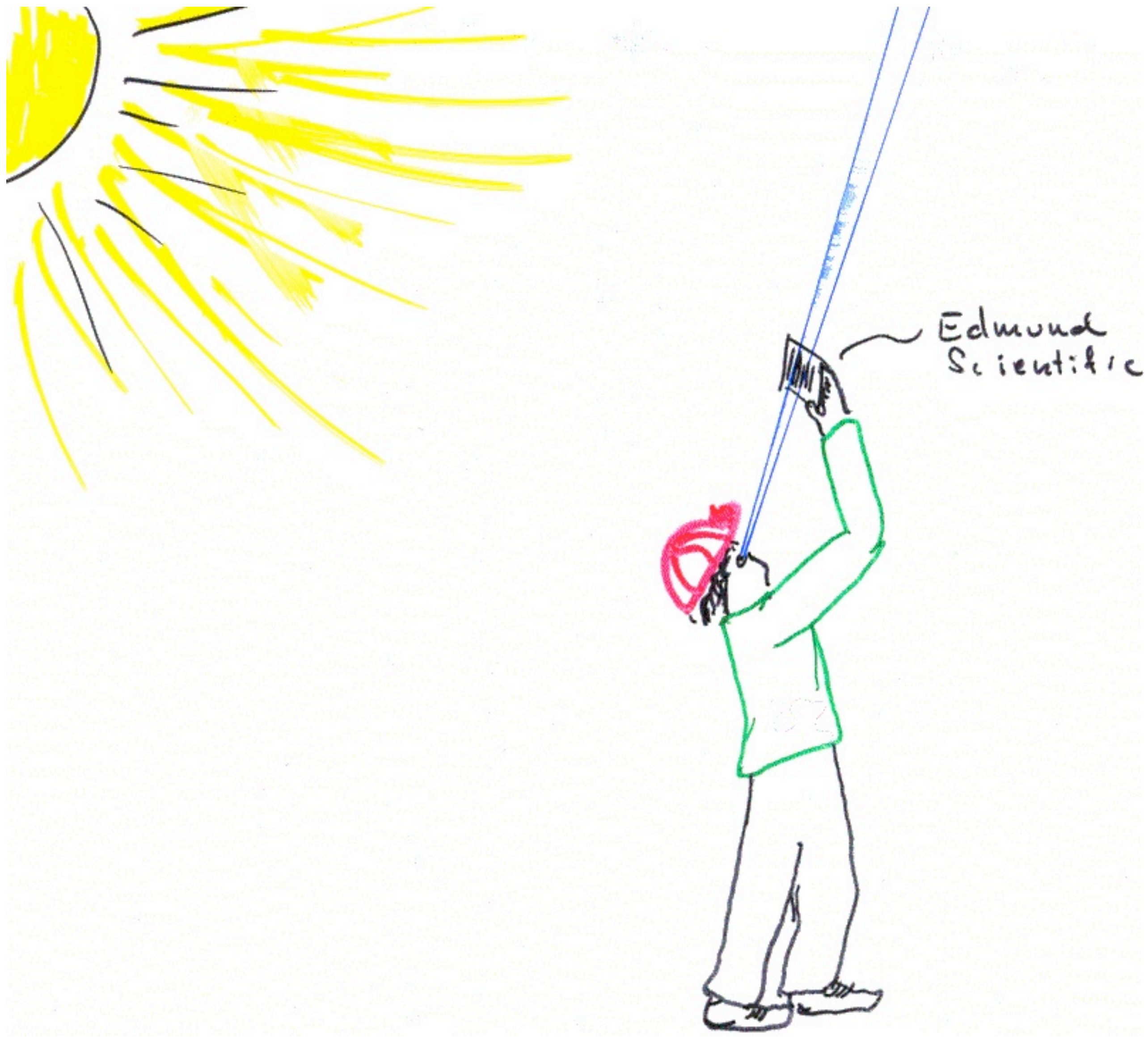
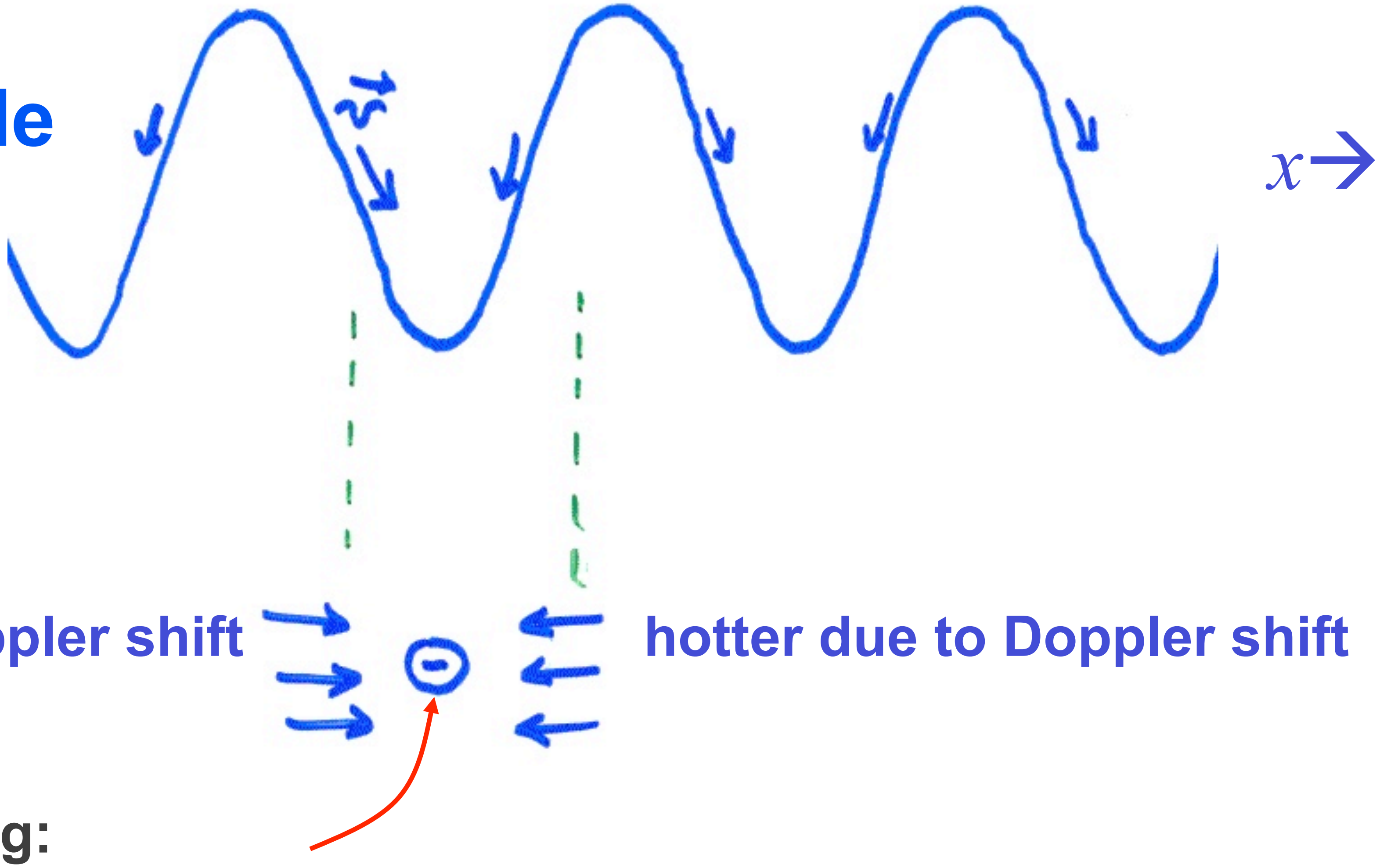


Generating CMB polarization

Density mode



hotter due to Doppler shift

hotter due to Doppler shift

Before decoupling:

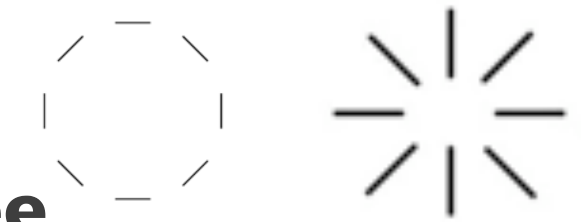
- electron 'sees' only a local monopole

During decoupling:

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

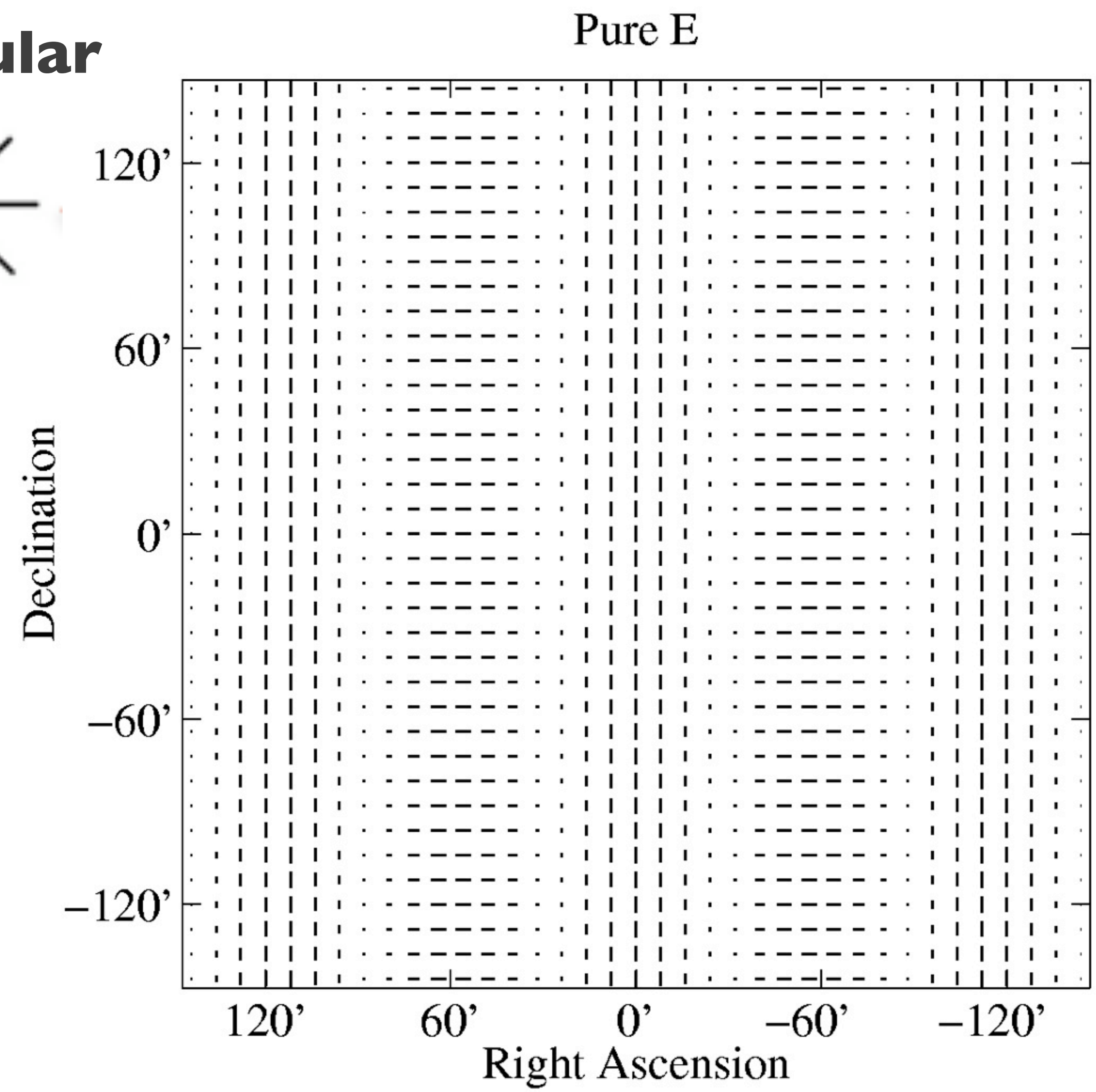
E-mode Polarization (even parity)

Polarization parallel & perpendicular to wave vector



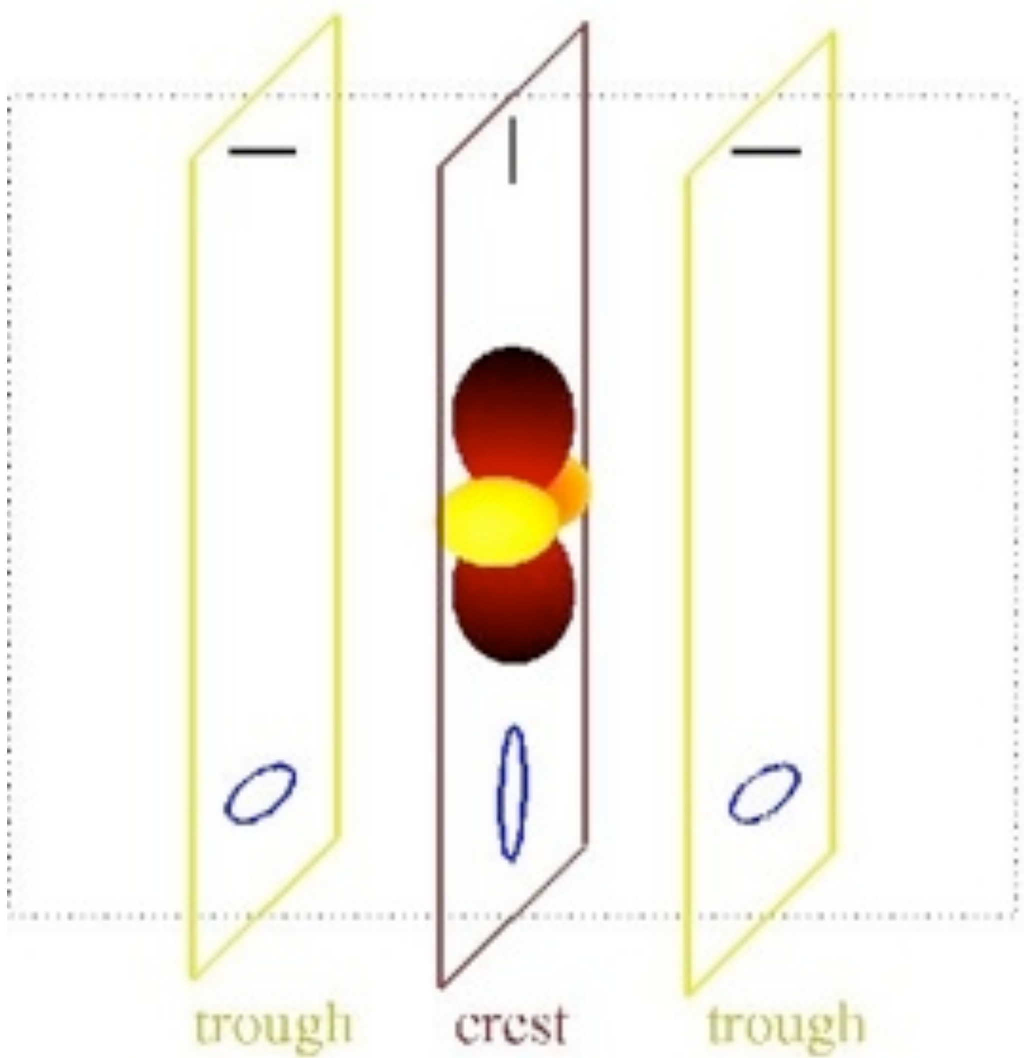
Even parity, curl-free

Density (scalar) fluctuations generate only E-Polarization



Gravitational wave induced CMB polarization

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



E-mode

Figure from John Kovac's thesis

Gravitational wave induced CMB polarization

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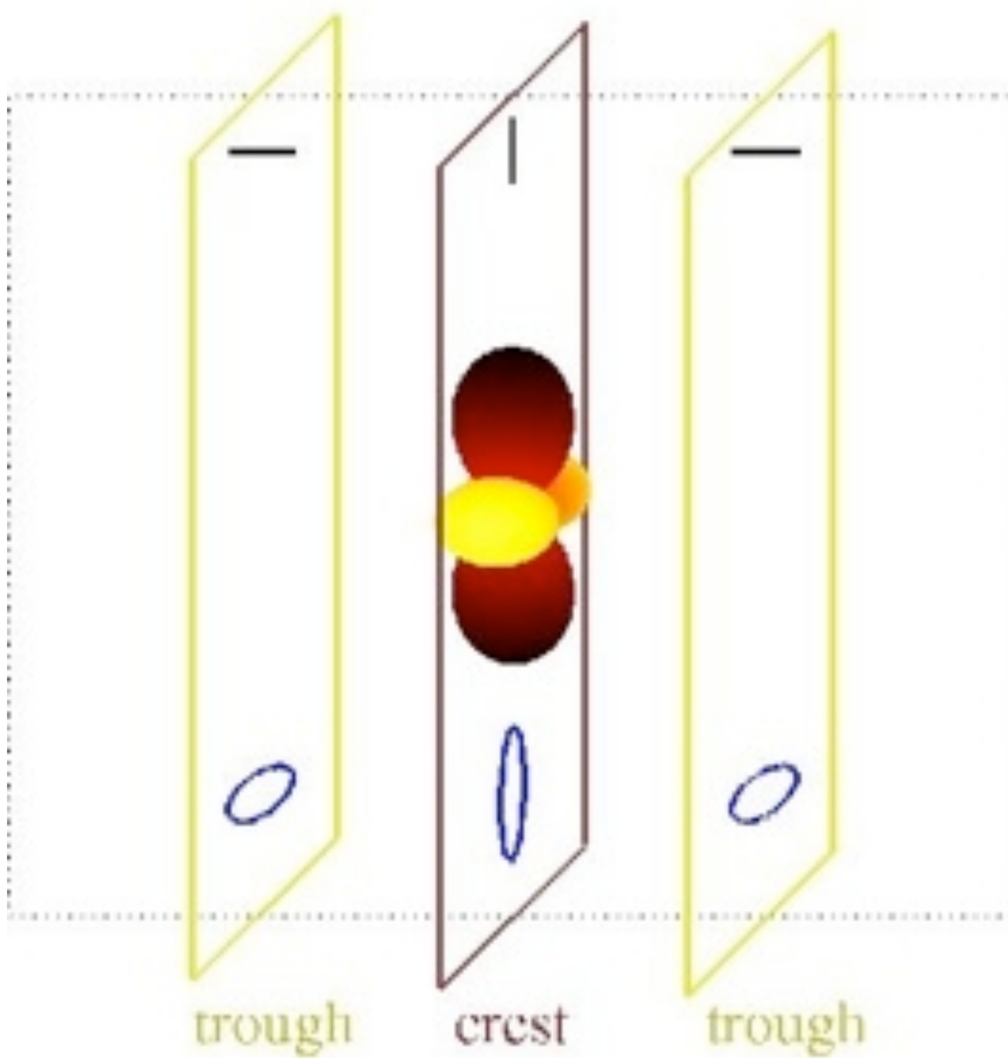
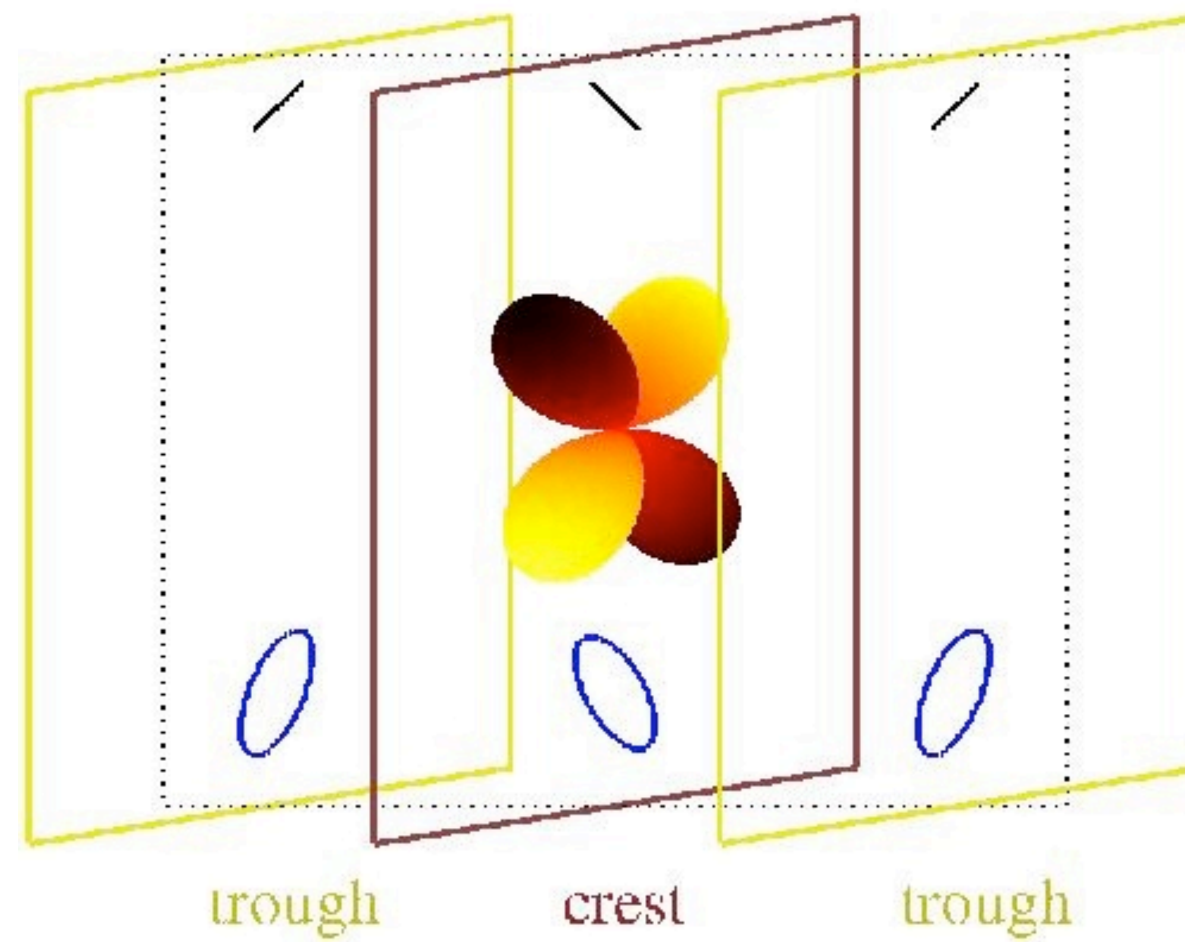


E-mode

'×' mode, $\vec{k}$ not parallel



B-mode

(Inflationary GW B-modes)

Figure from John Kovac's thesis

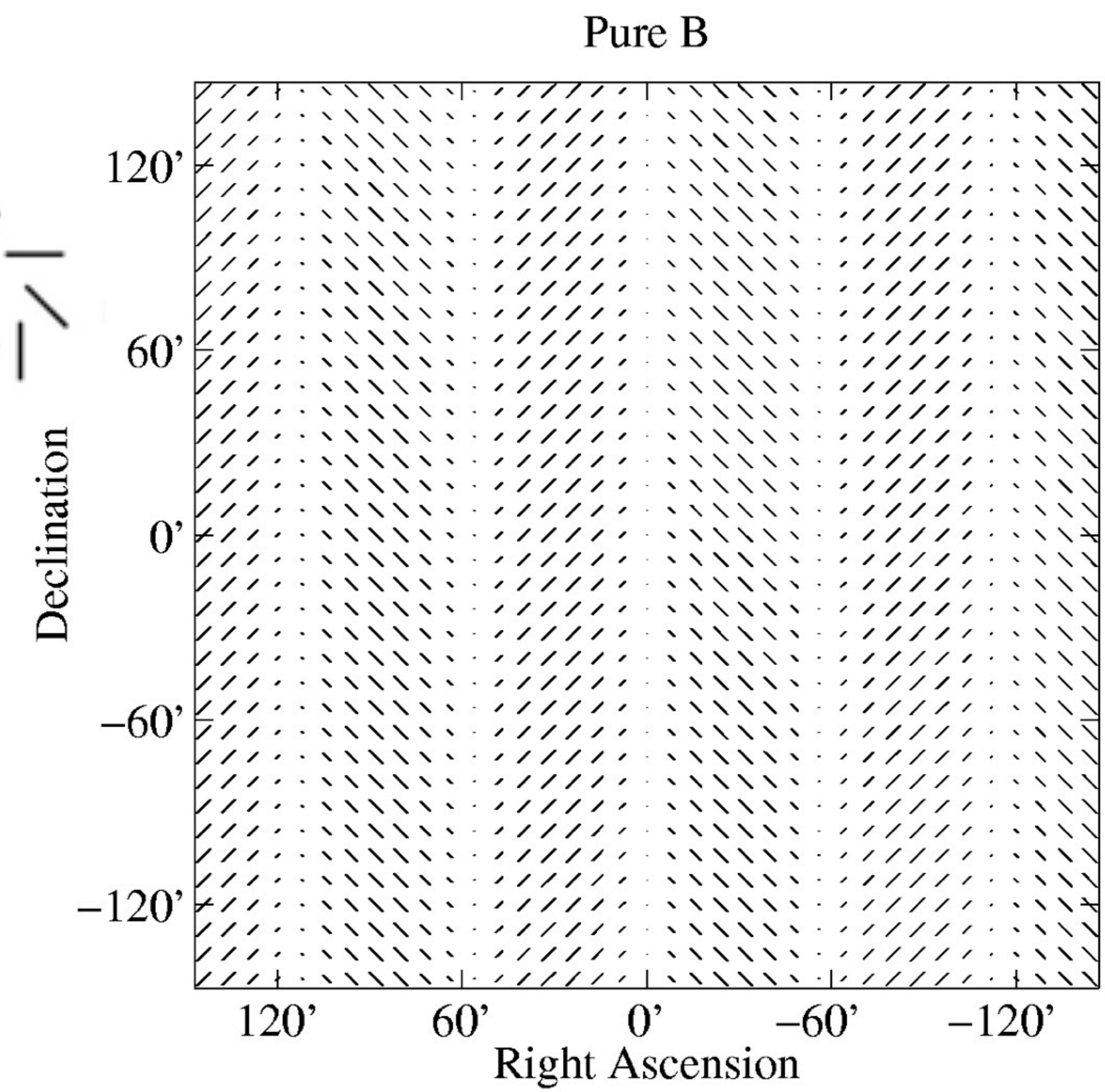
B-mode Polarization (odd parity)

Polarization oriented ±45 degrees to wave vector

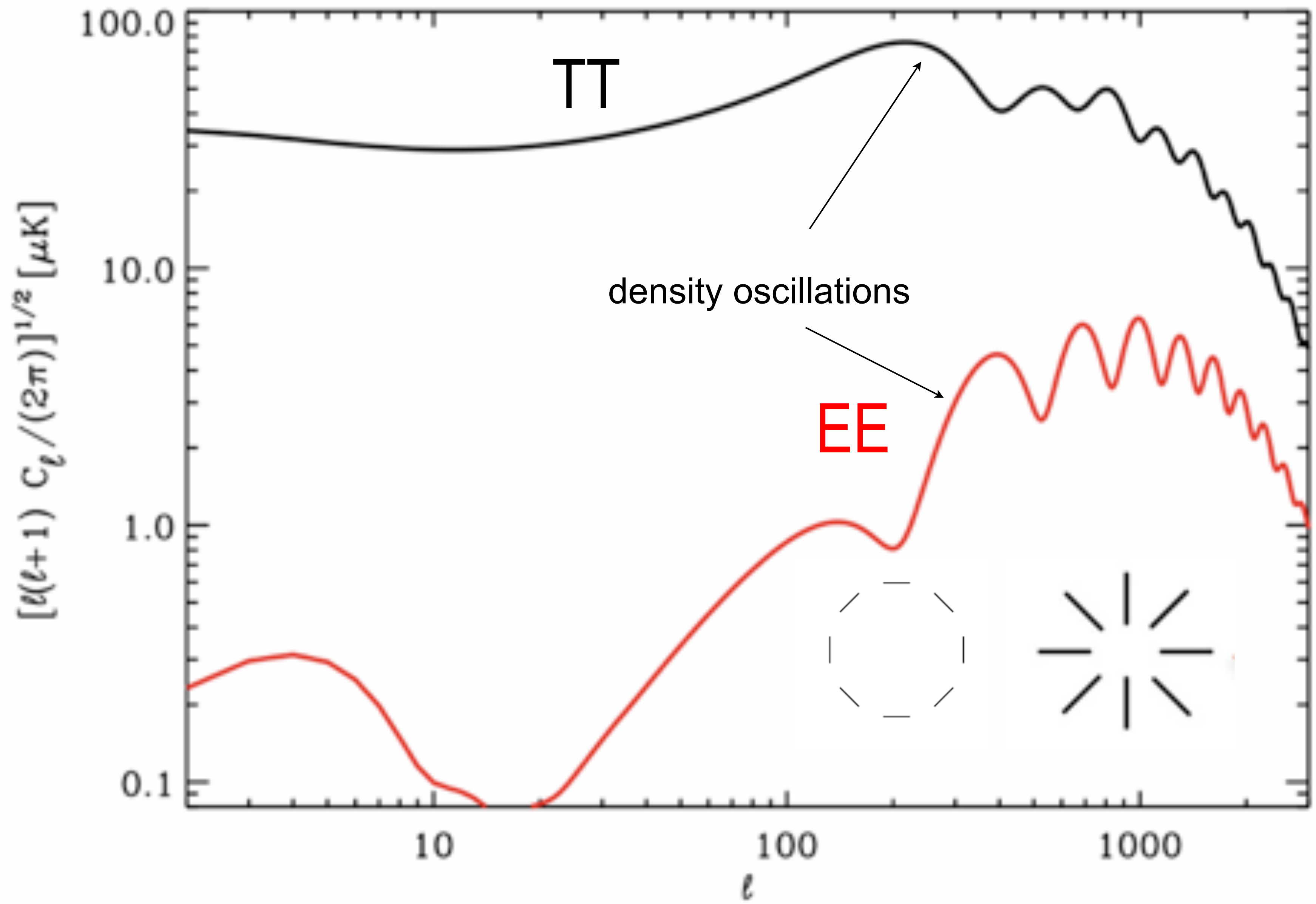
Odd parity, div free

Can NOT be generated by the density fluctuations, but can be 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

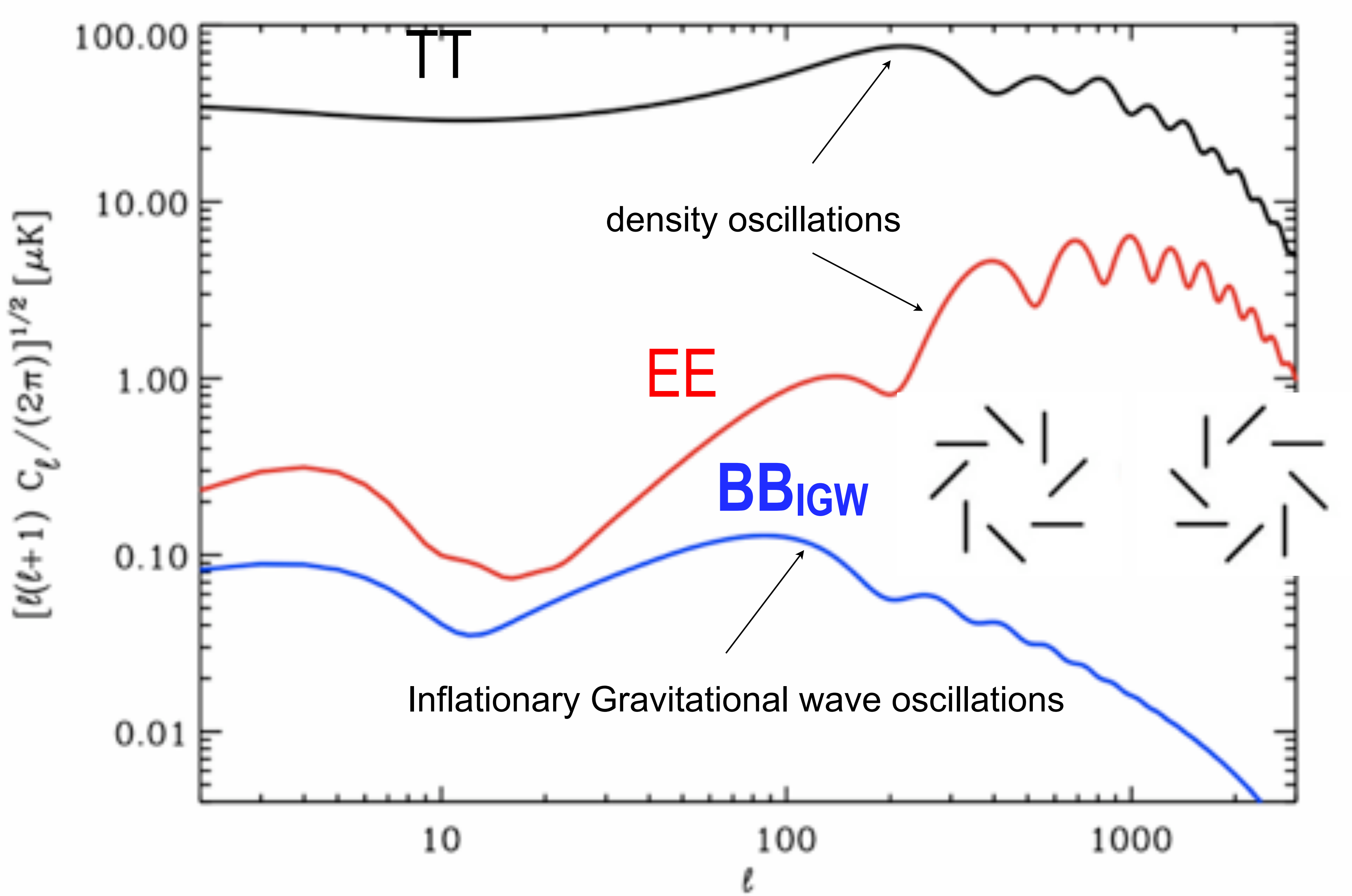


CMB polarization

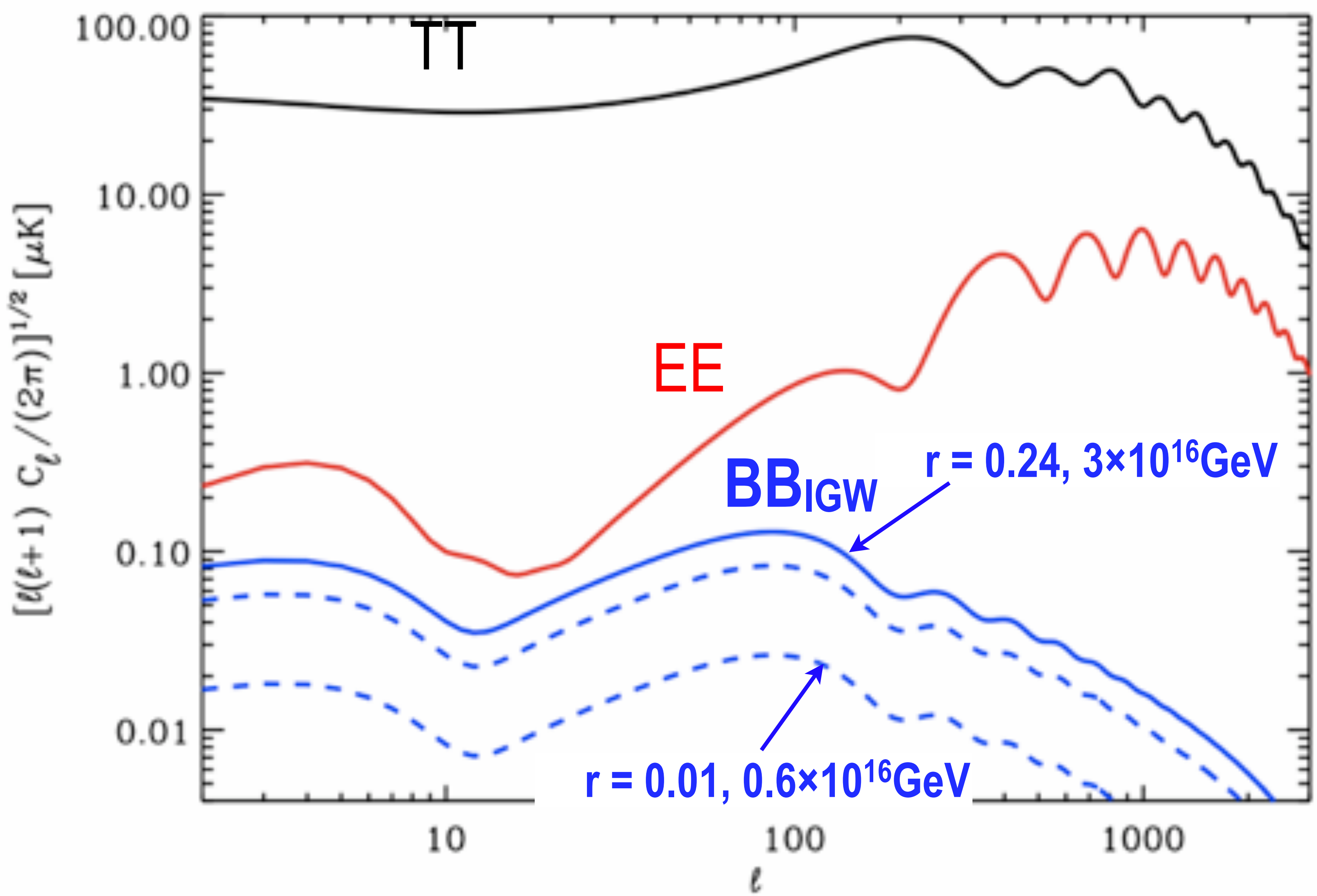


Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

CMB polarization

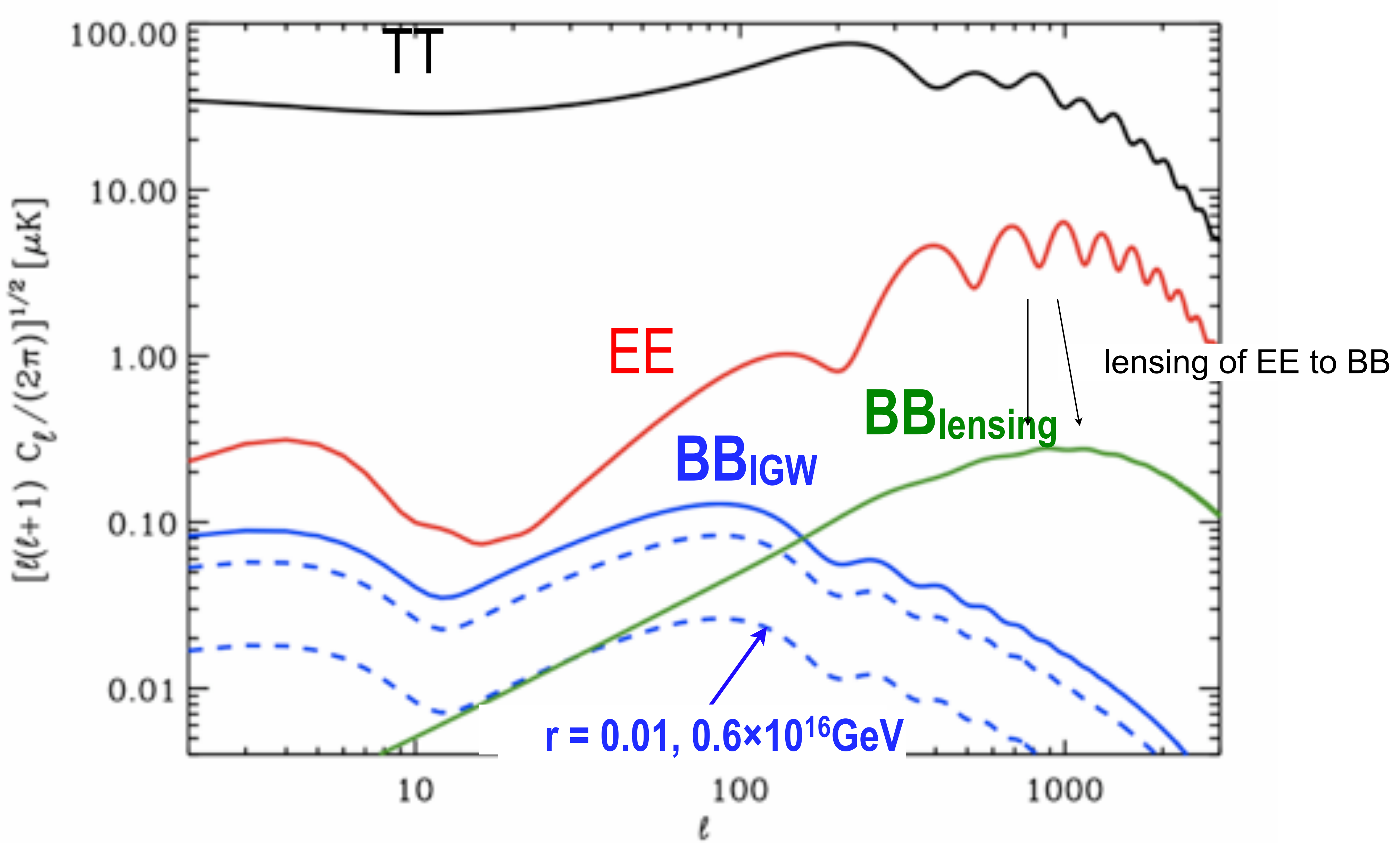


CMB polarization

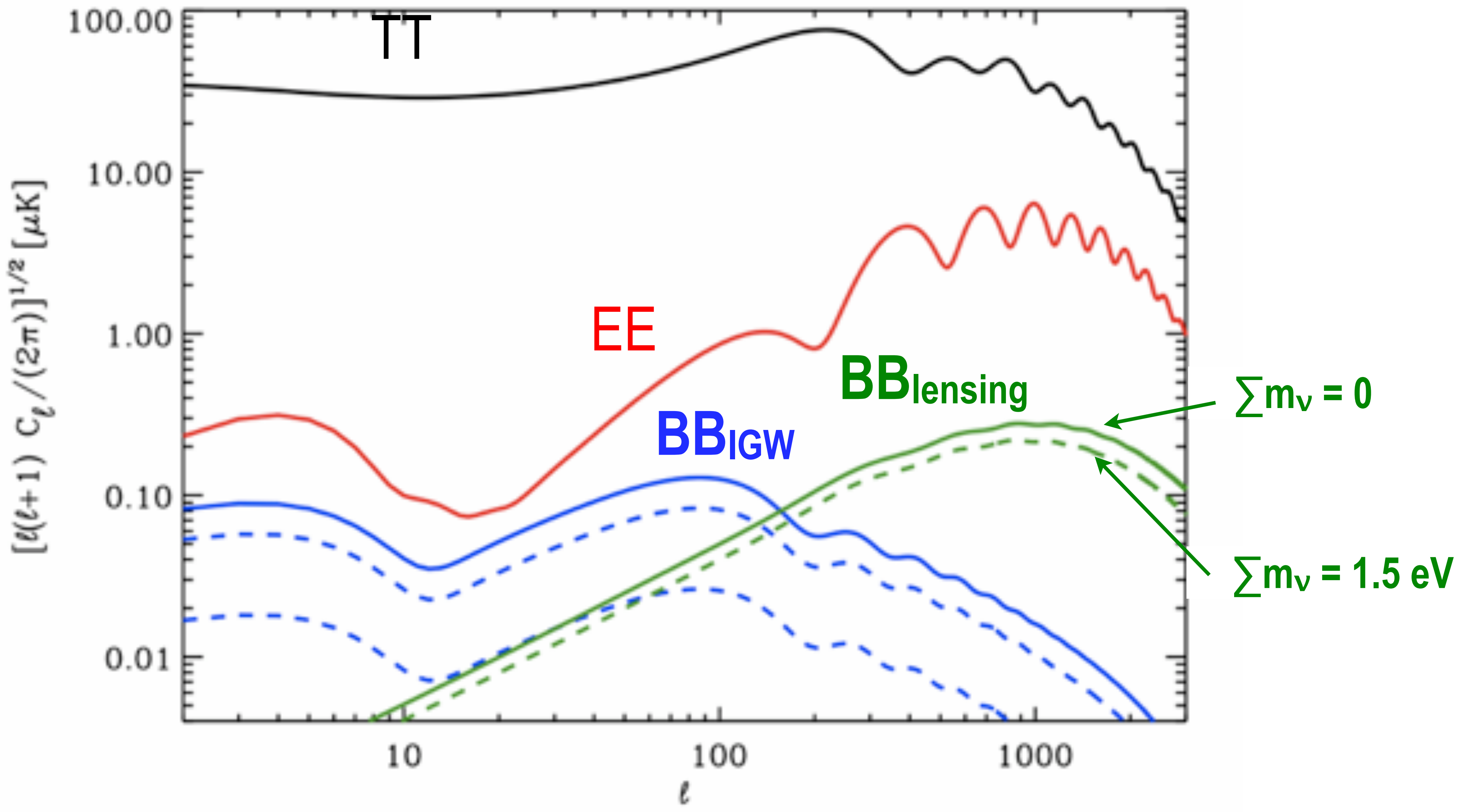


r is the tensor to scalar ratio of the primordial fluctuations

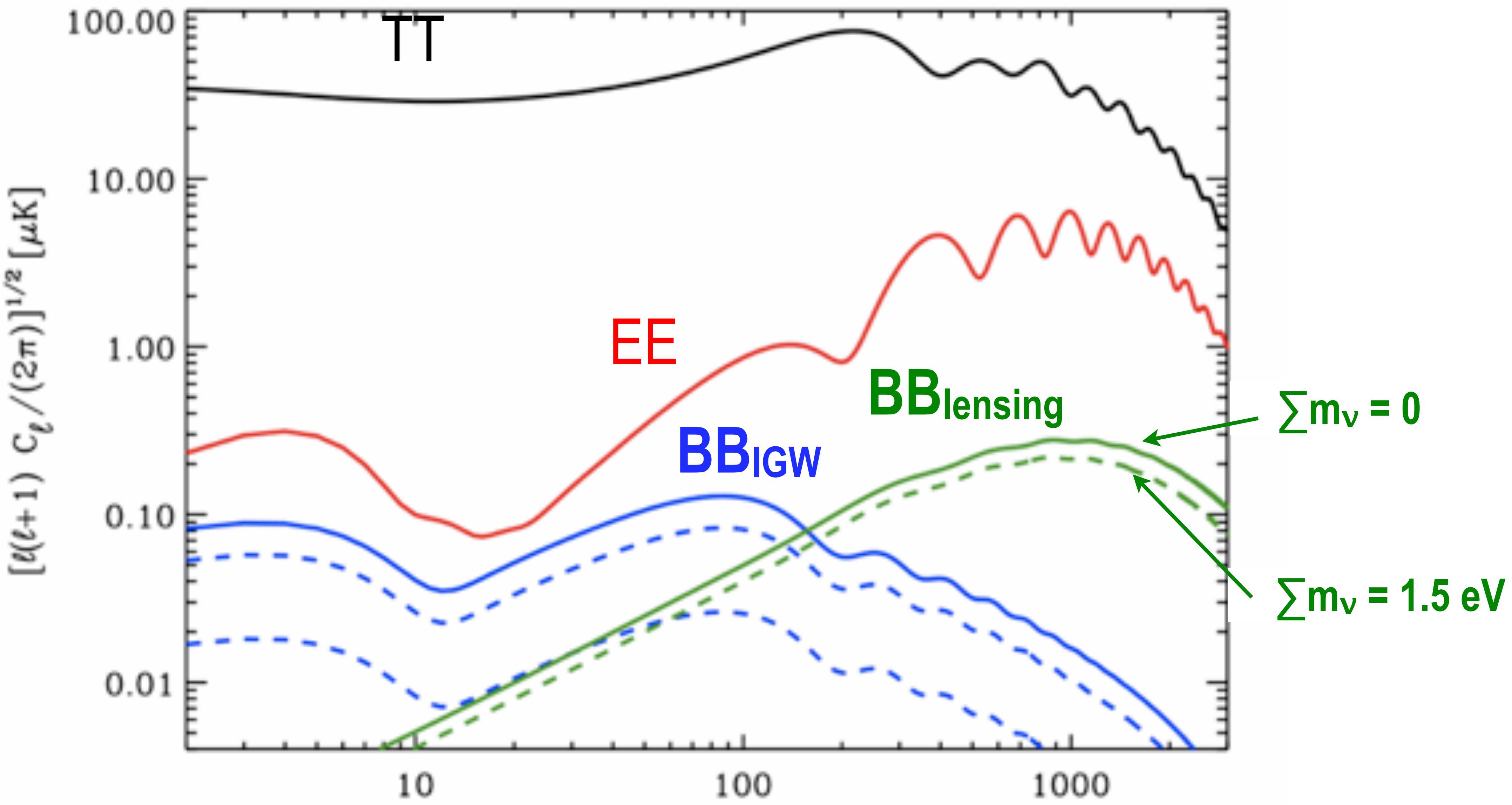
CMB polarization



CMB polarization

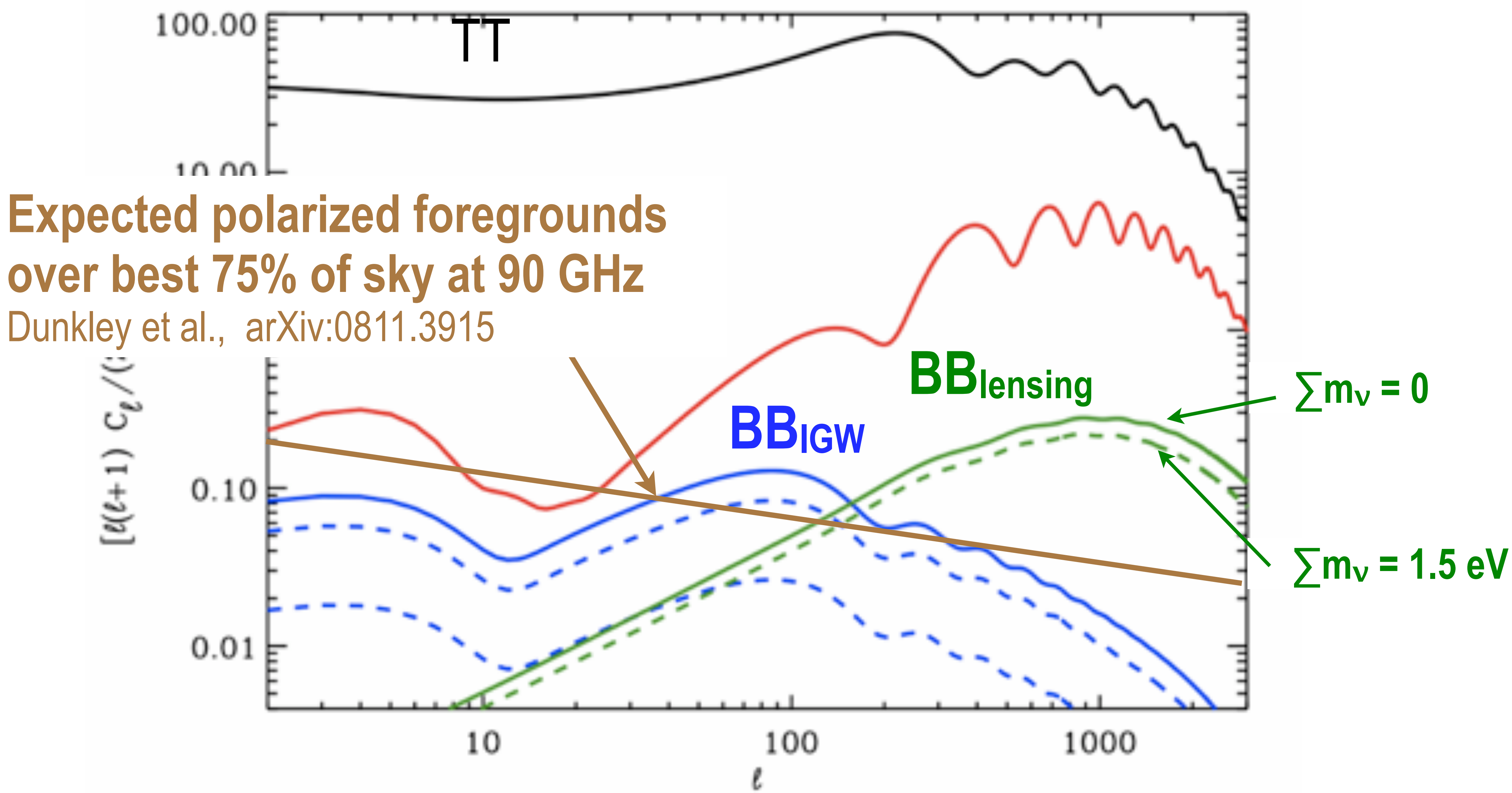


CMB polarization

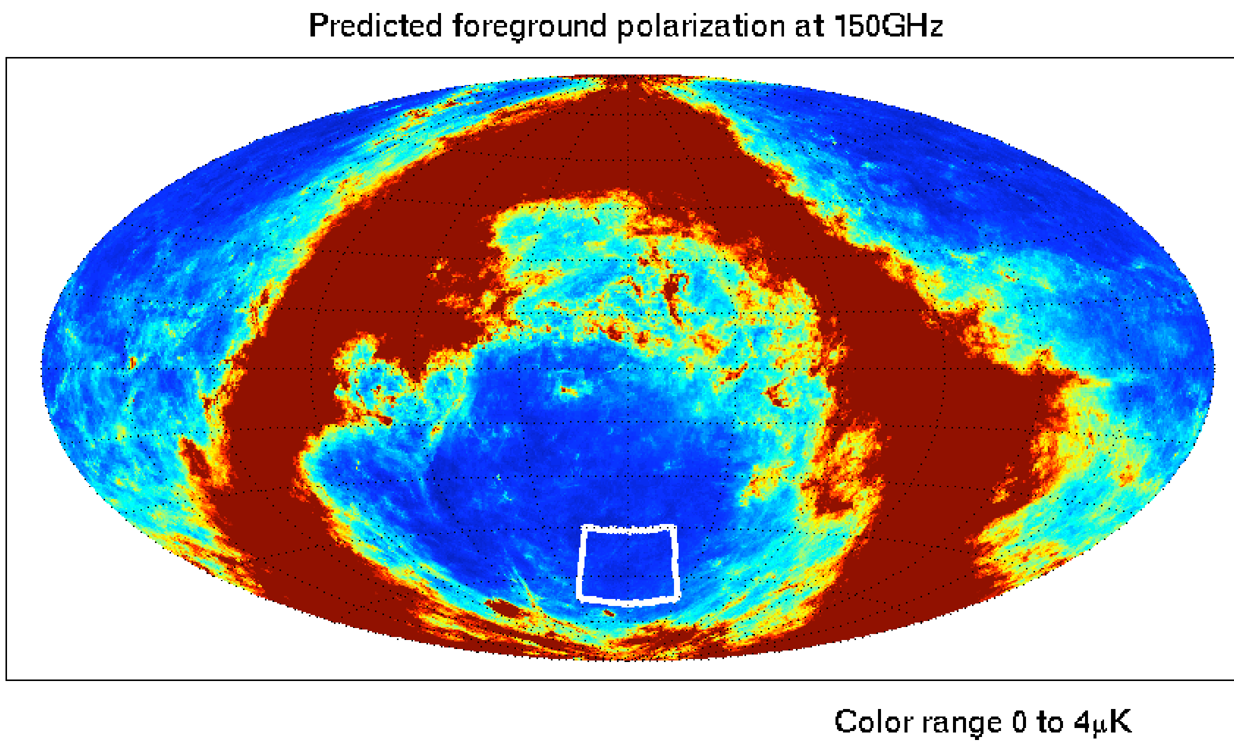


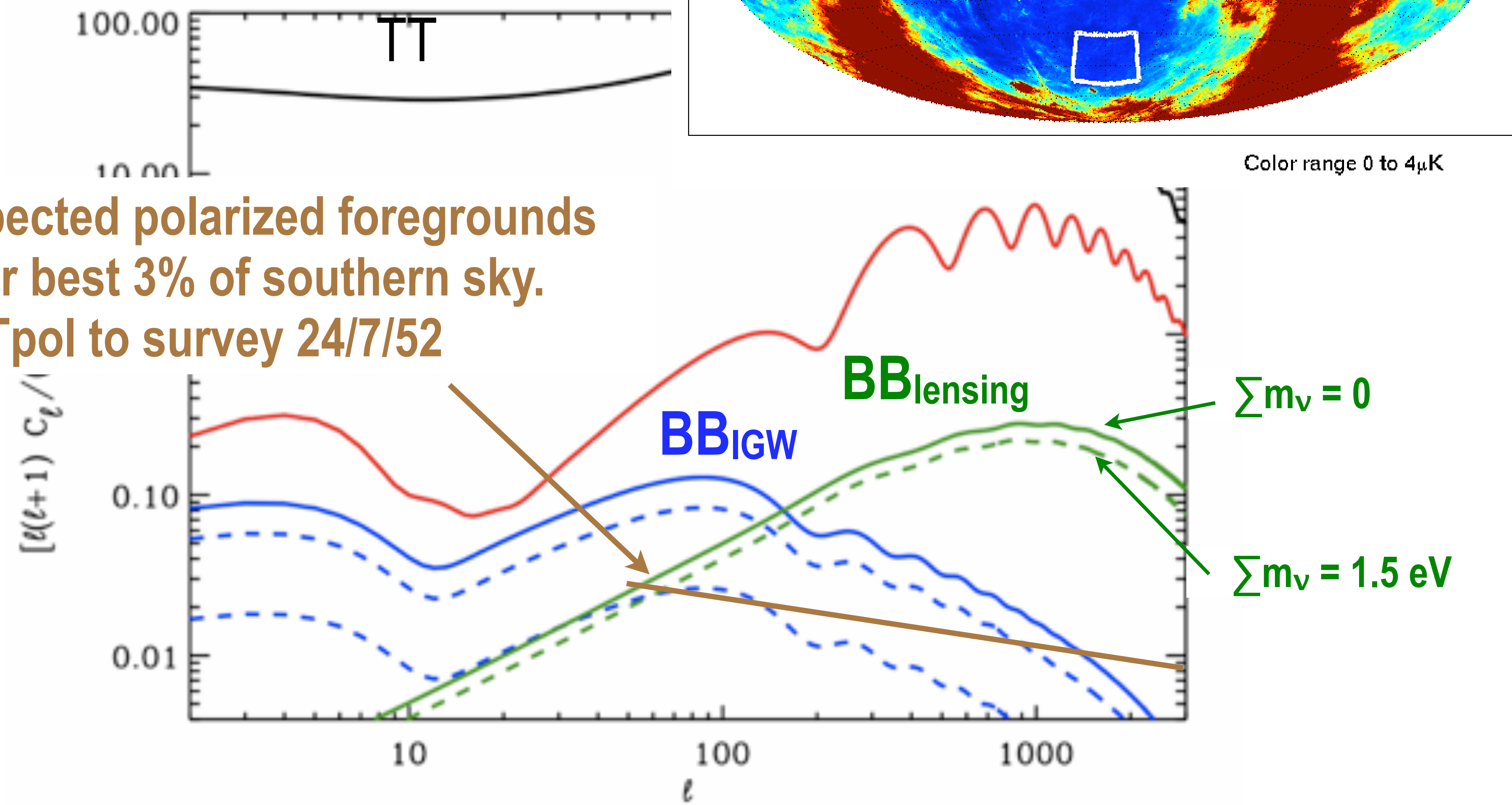
CMB measurements should be able to achieve σ(∑mν) = 0.05eV, comparable to Δm measured by neutrino oscillations.

CMB polarization



CMB polarization

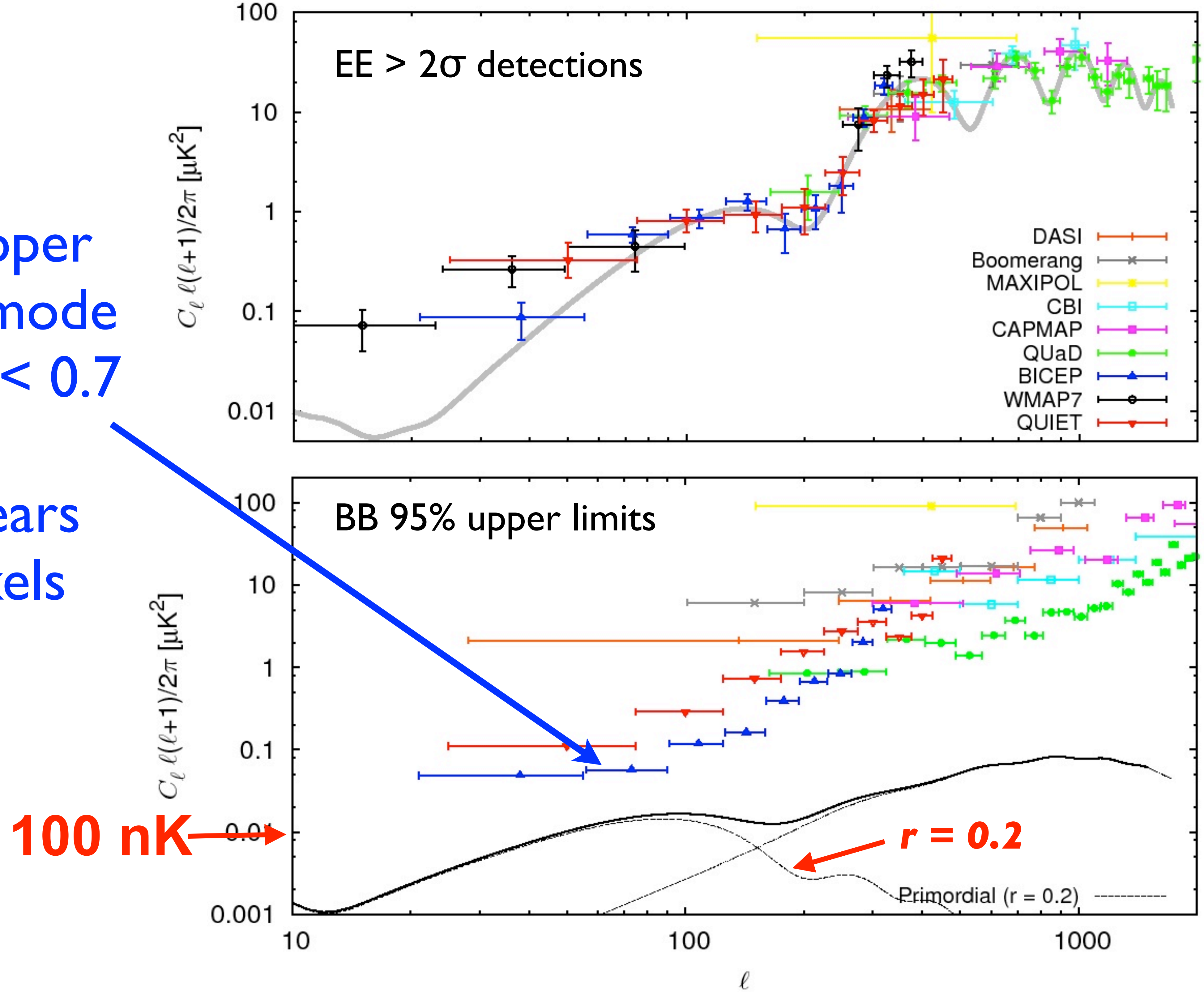




Closing in on inflation

BICEP's upper limit on B-mode level sets r < 0.7

From 2 years w/ 50 pixels



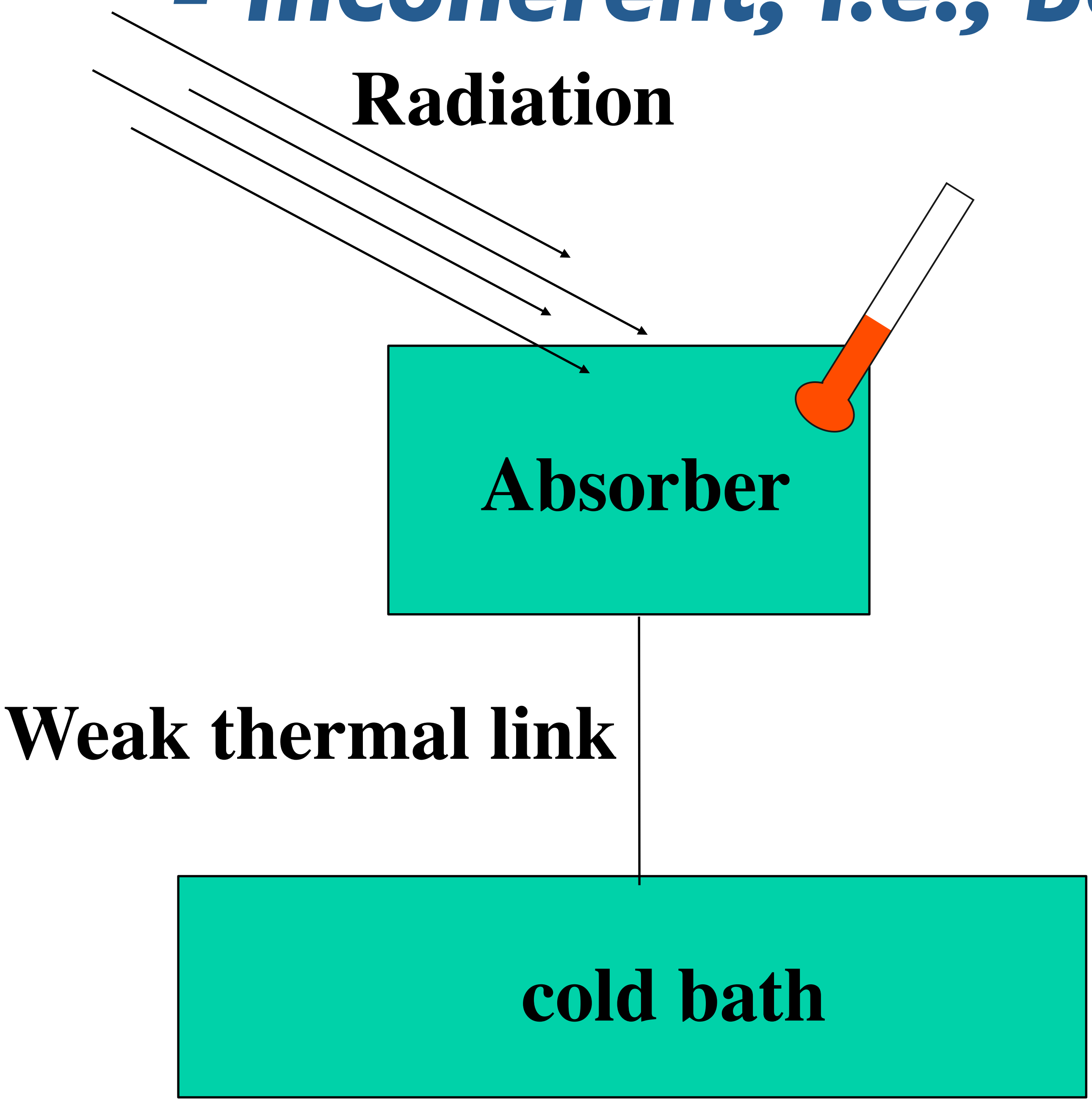
Leitch et al (2005), Montroy et al (2006), Piacentini et al (2006), Sievers et al (2007), Wu et al (2007), Bischoff et al (2008), Brown et al (2009), Chiang et al (2010), QUIET (2010)

Compilation from A. Kusaka

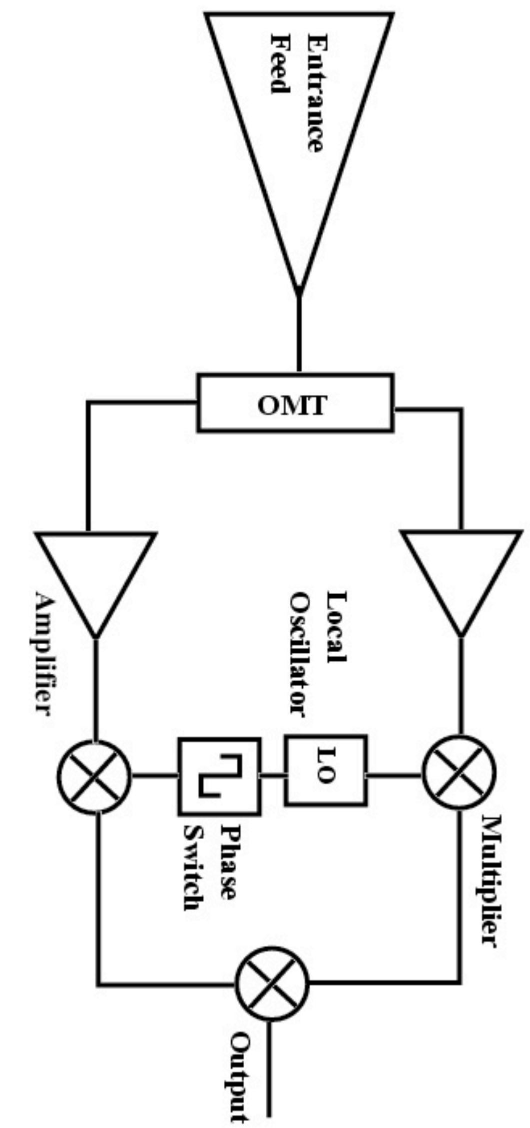
Need more sensitivity!

Achieved with more throughput with large focal planes of background limited detectors.

Two general approaches for detectors:
- coherent, i.e., direct amplification
- incoherent, i.e., bolometers (IR)

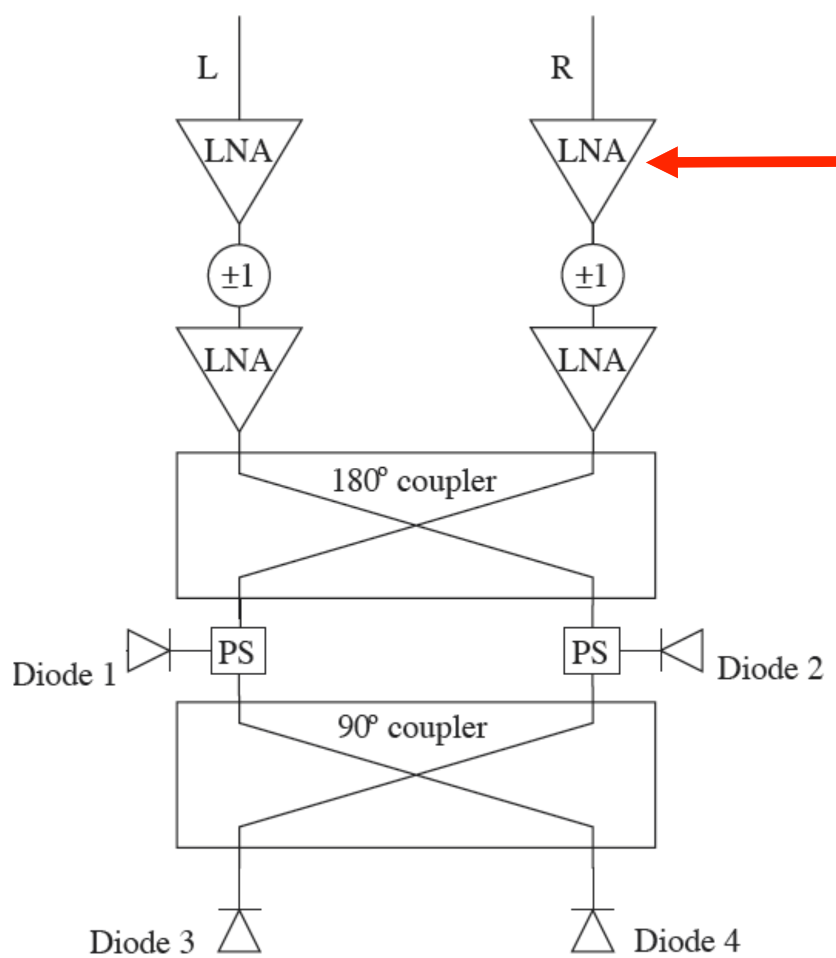


e.g., BOOMERANG, Maxima, ACBAR, QUaD, SPT, ACT, BICEP, Planck HFI, ...
Background limited performance (BLIP) from the ground, balloon and space.

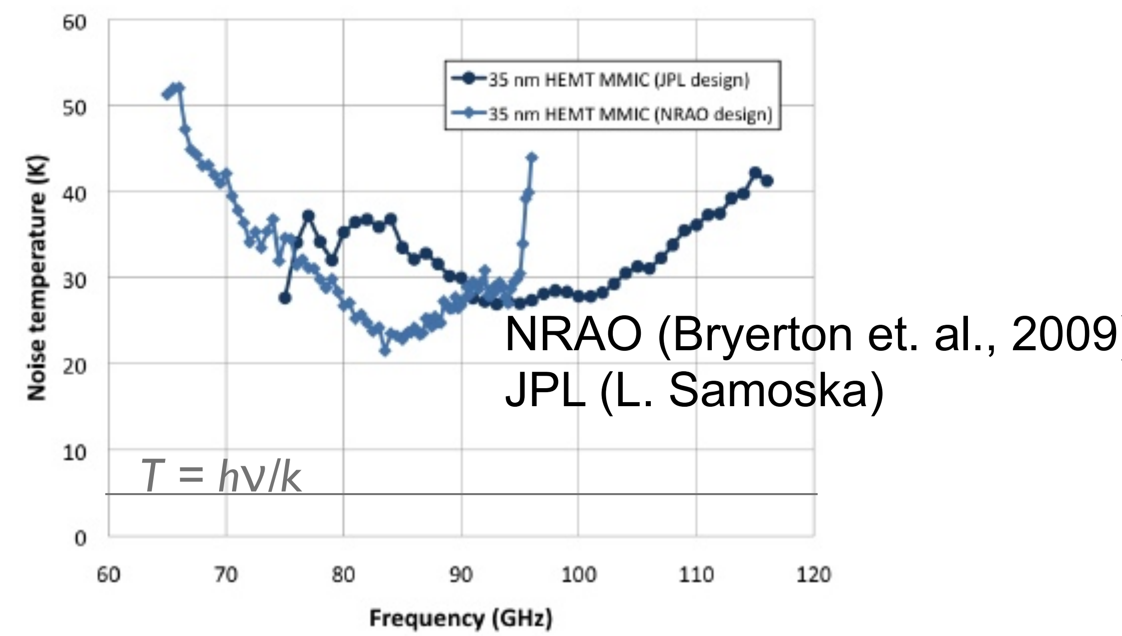


e.g., COBE, WMAP, CBI, DASI, CapMap, QUIET, Planck LFI,...
Several times quantum noise limit performance. Competive sensitivity at low frequencies from the ground.

Coherent detectors
- cooled HEMT amplifiers



State of the art MMICs (35nm gate)



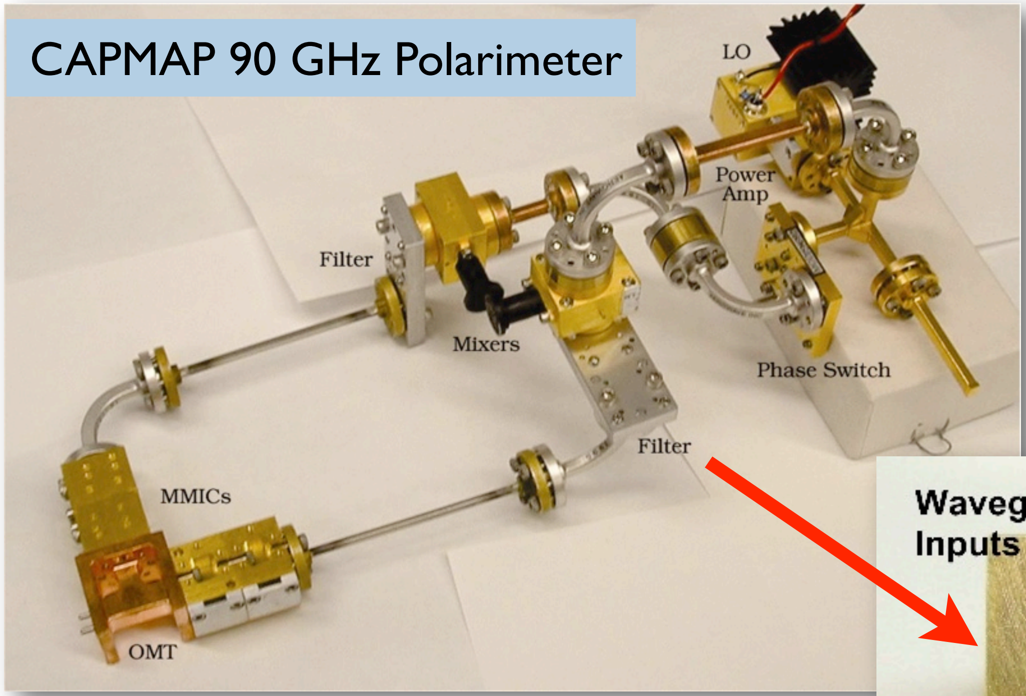
Once amplified and quantum noise penalty taken, signal is easily manipulated, cryogenics simple

Several times quantum limited performance achieved, competitive at ν ≤ 90 GHz on ground.

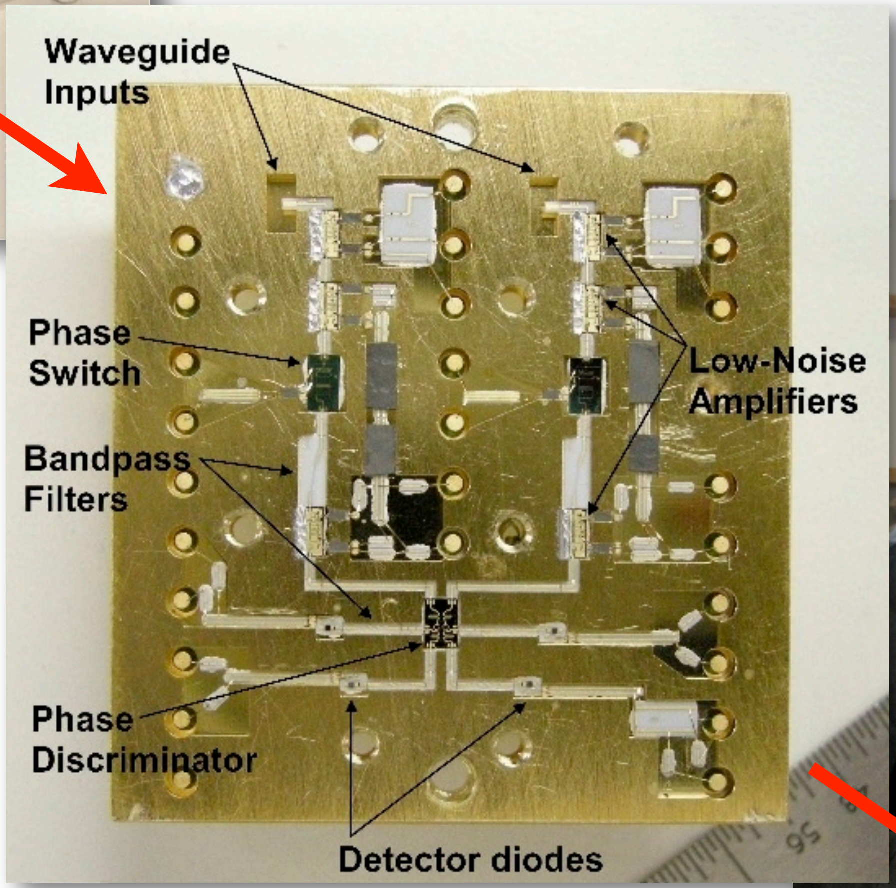
Technology of choice at lower frequencies.

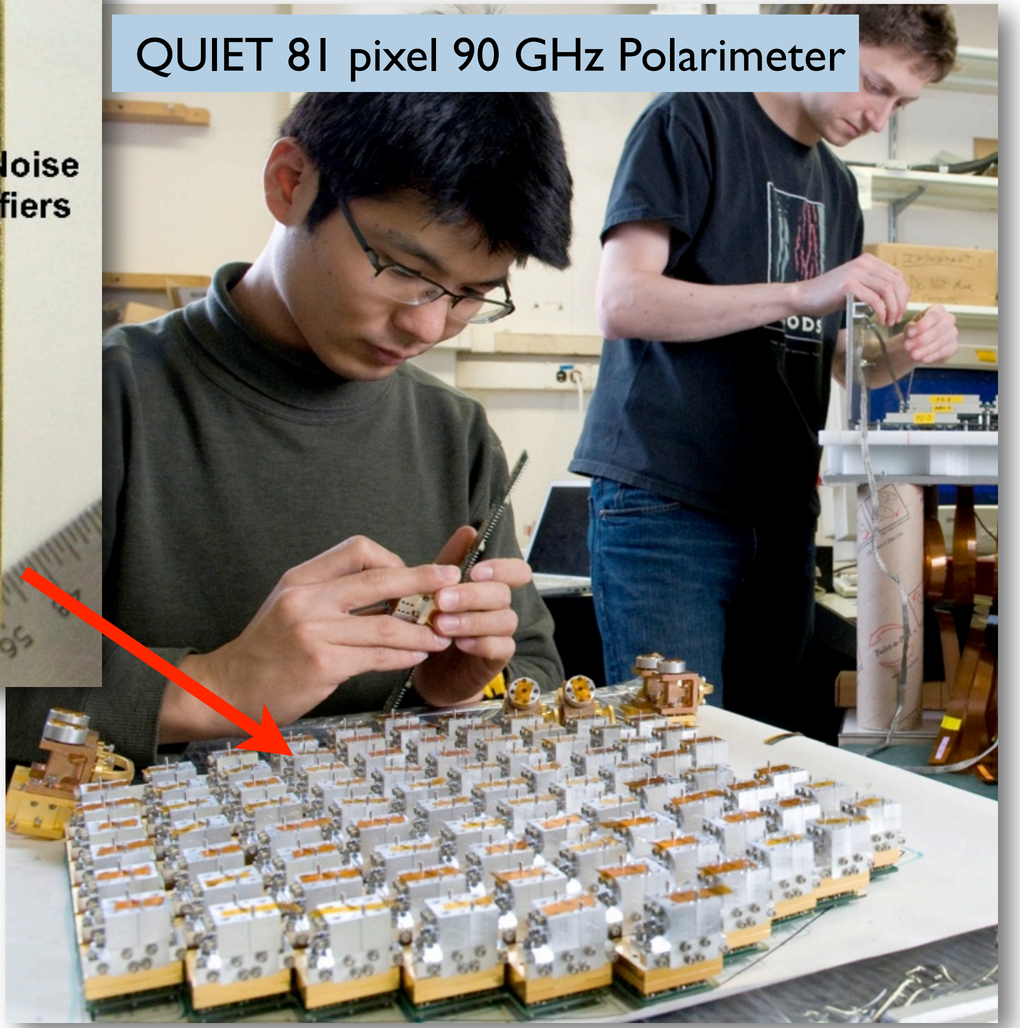
Future CMB requires improvement in noise and scalability

Coherent detectors
- cooled HEMT amplifiers



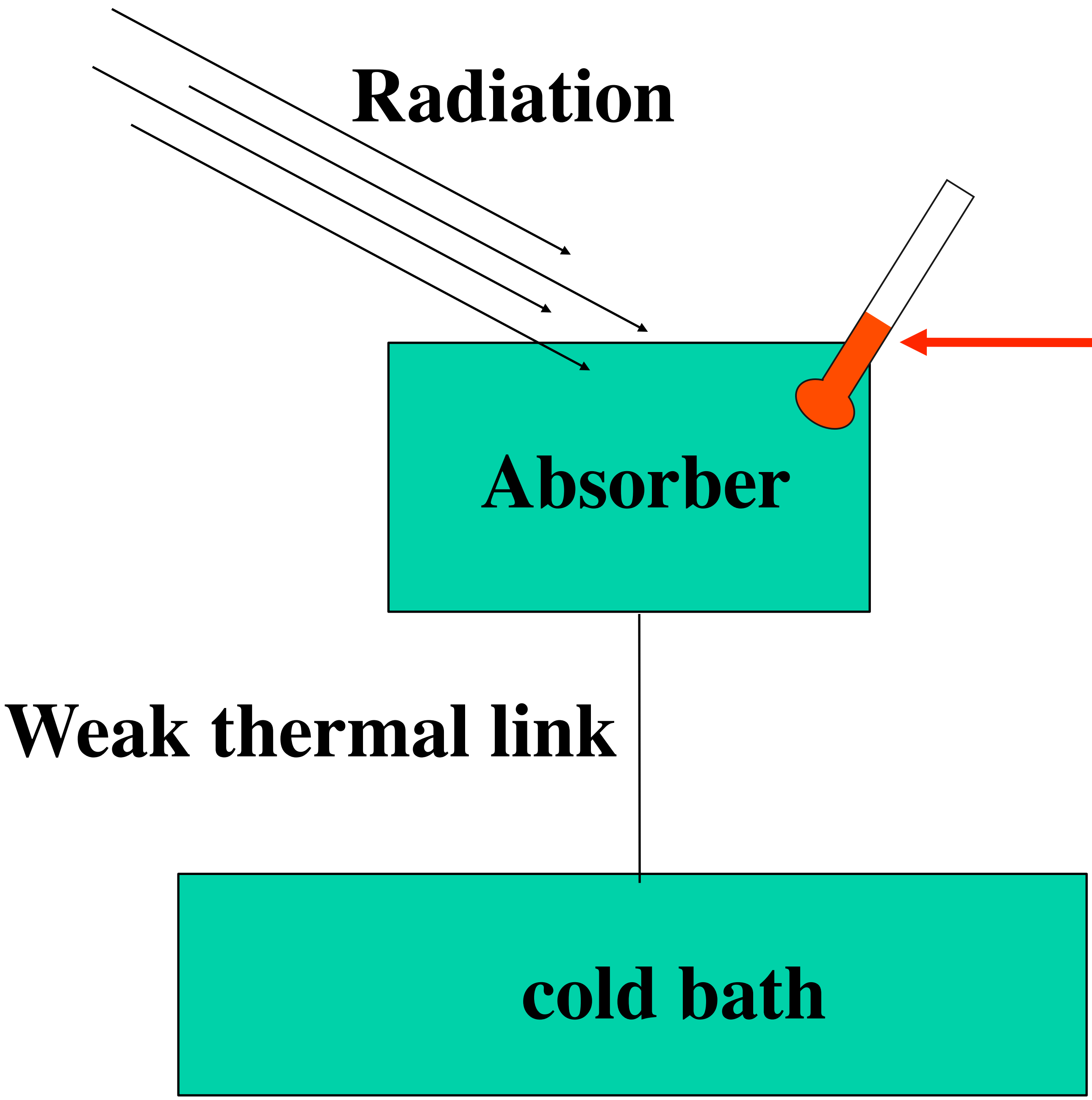
1st step in scalability: polarimeter on a chip...



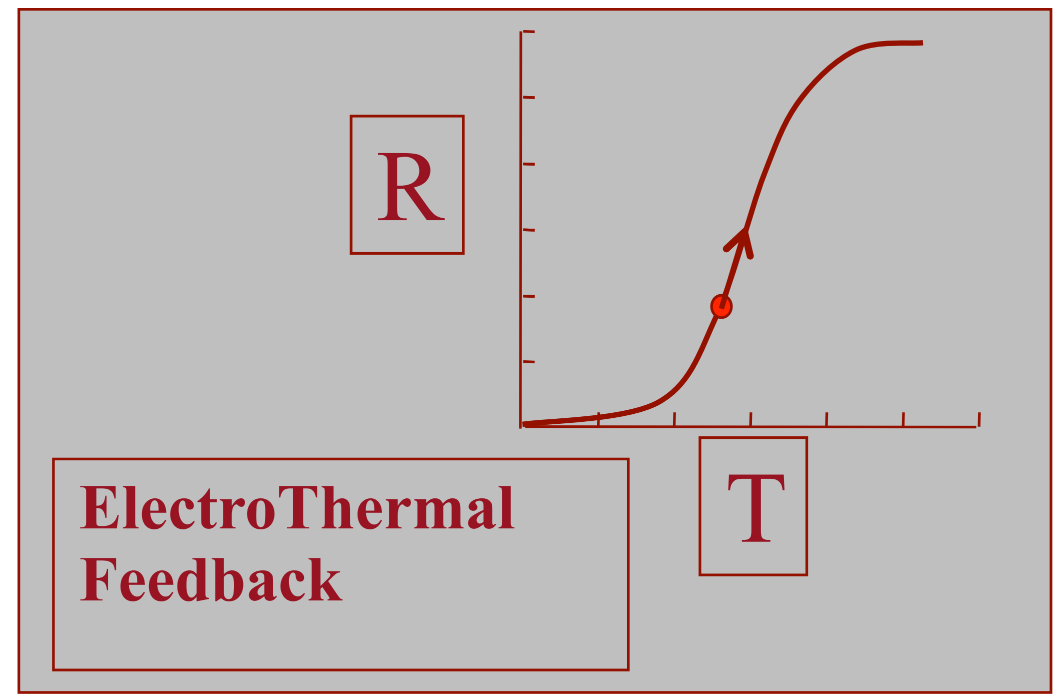


See talk on QUIET by Hogan Nguyen

Bolometers
- TES sensors



TES - Transition-Edge-Sensor

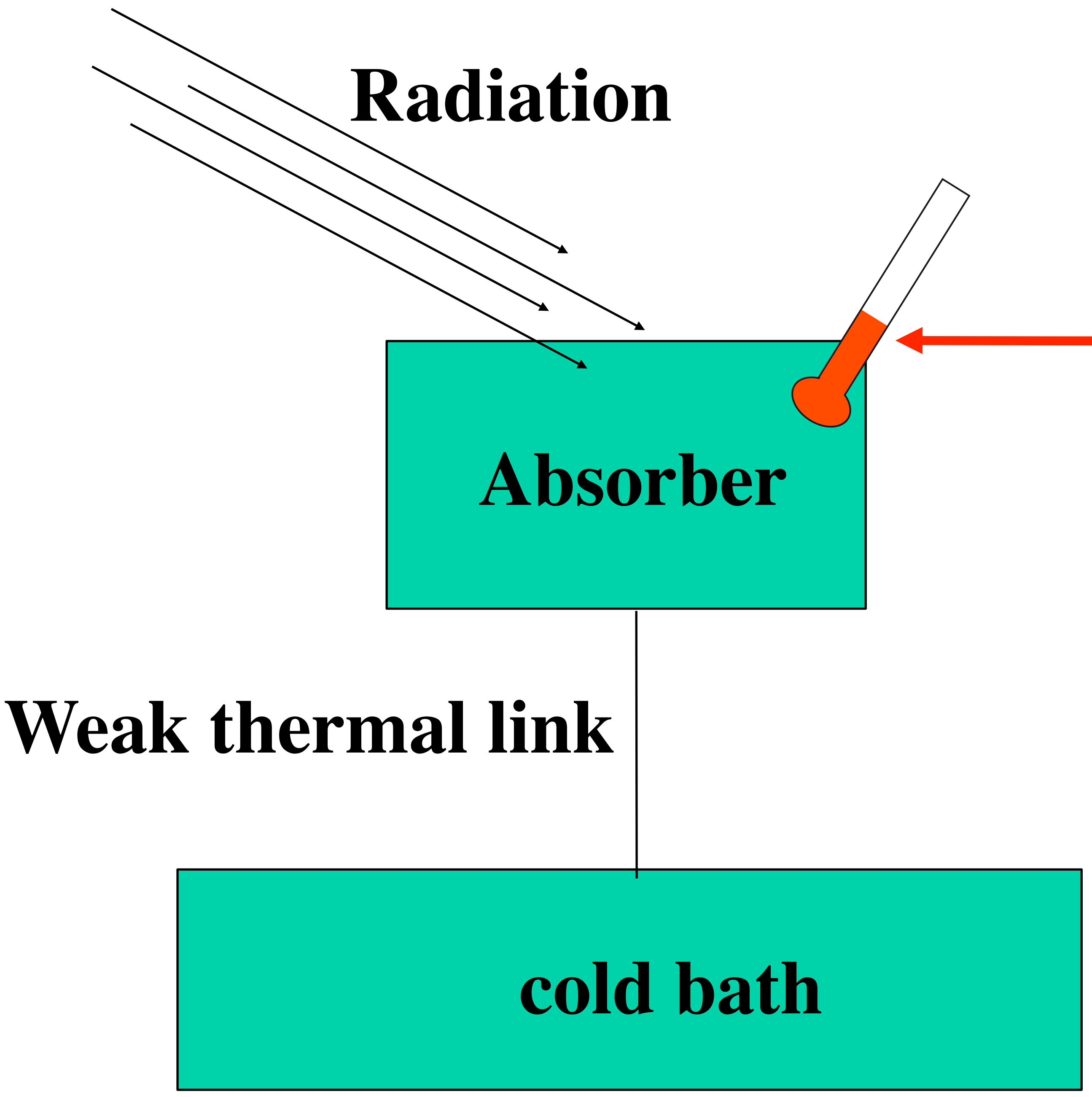


Voltage biased transition edge sensor (TES).

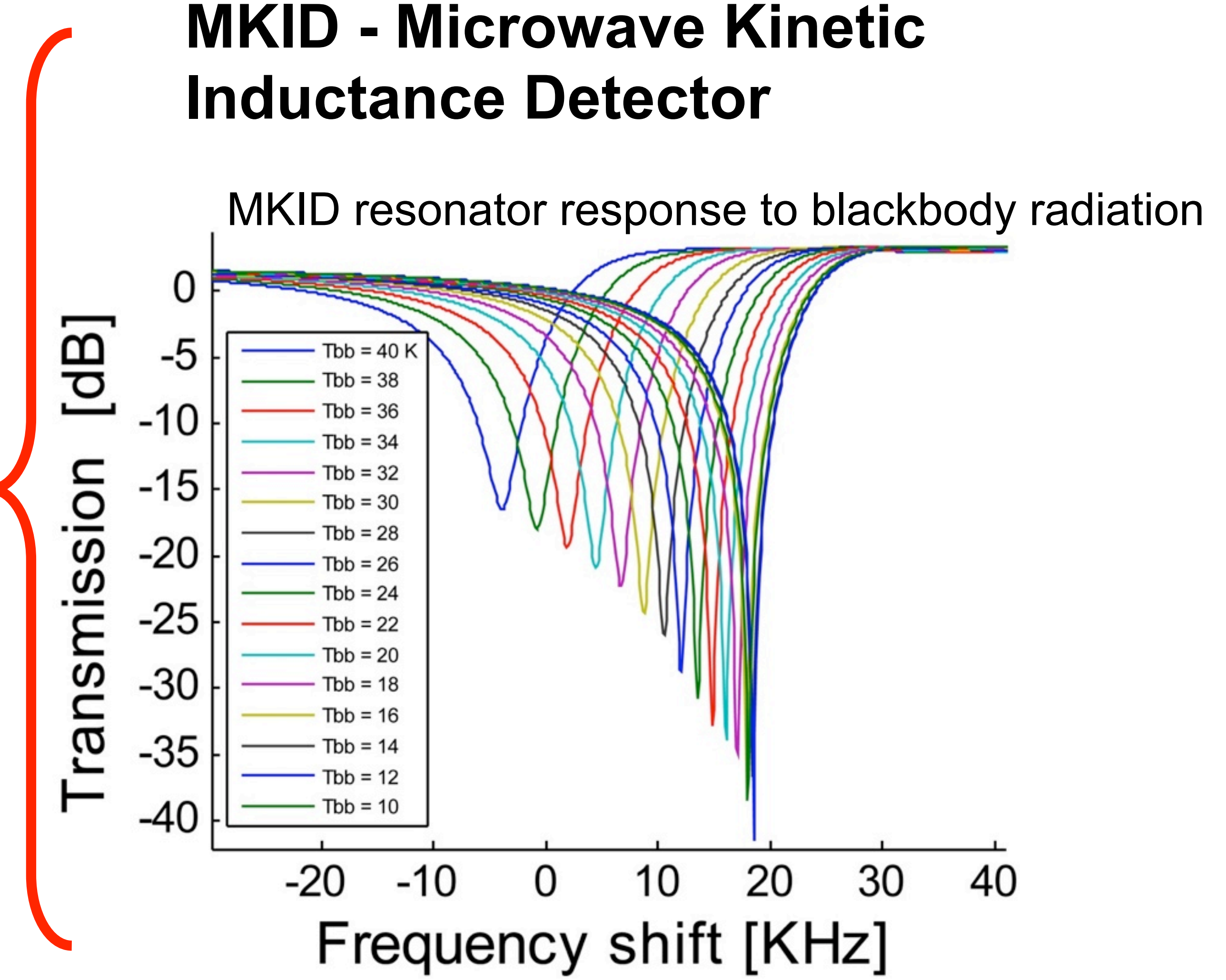
Measure incident power (pW) by change in bias current using SQUIDS.

Multiplexed in frequency or time.

Bolometers
- MKID sensors



MKID - Microwave Kinetic Inductance Detector

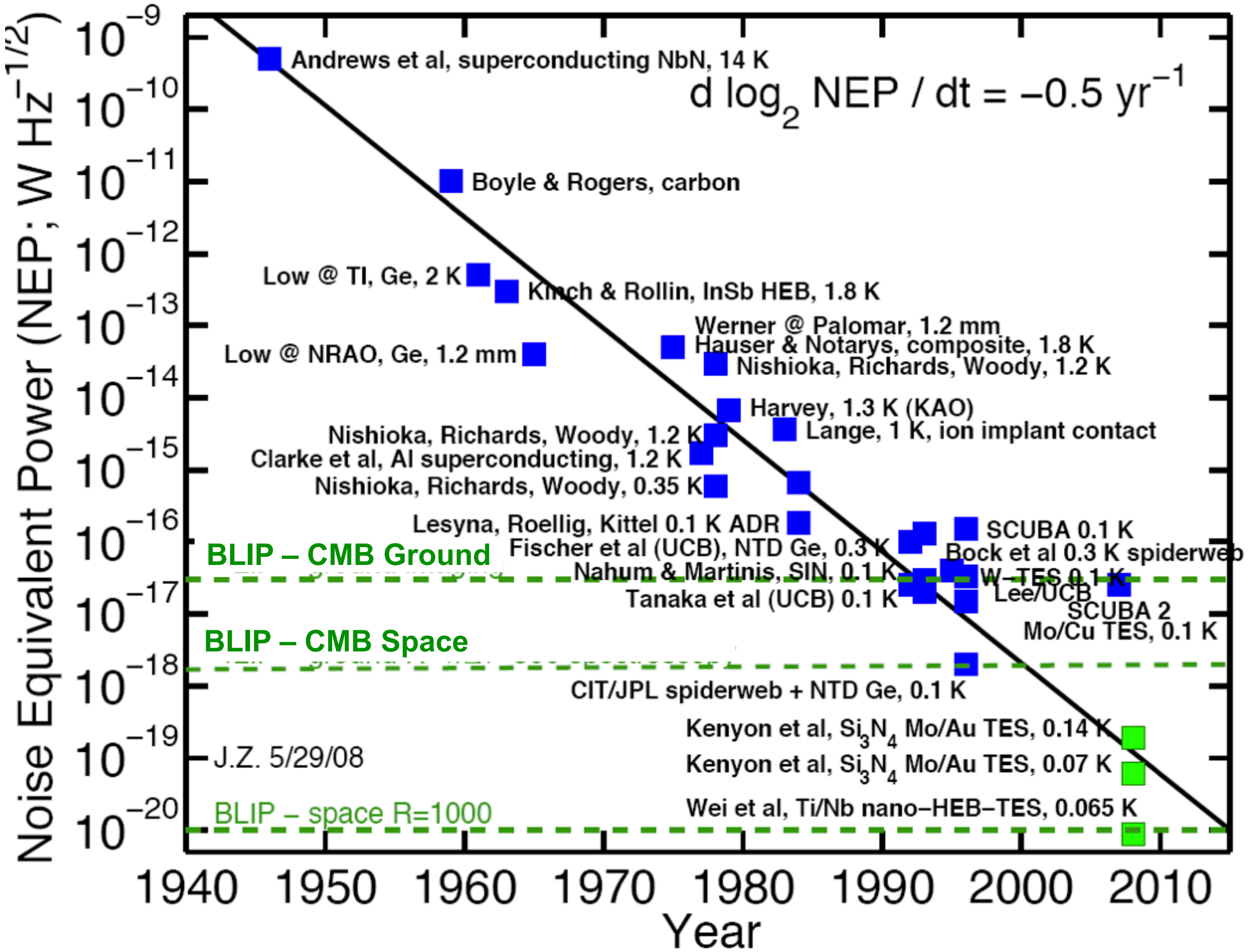


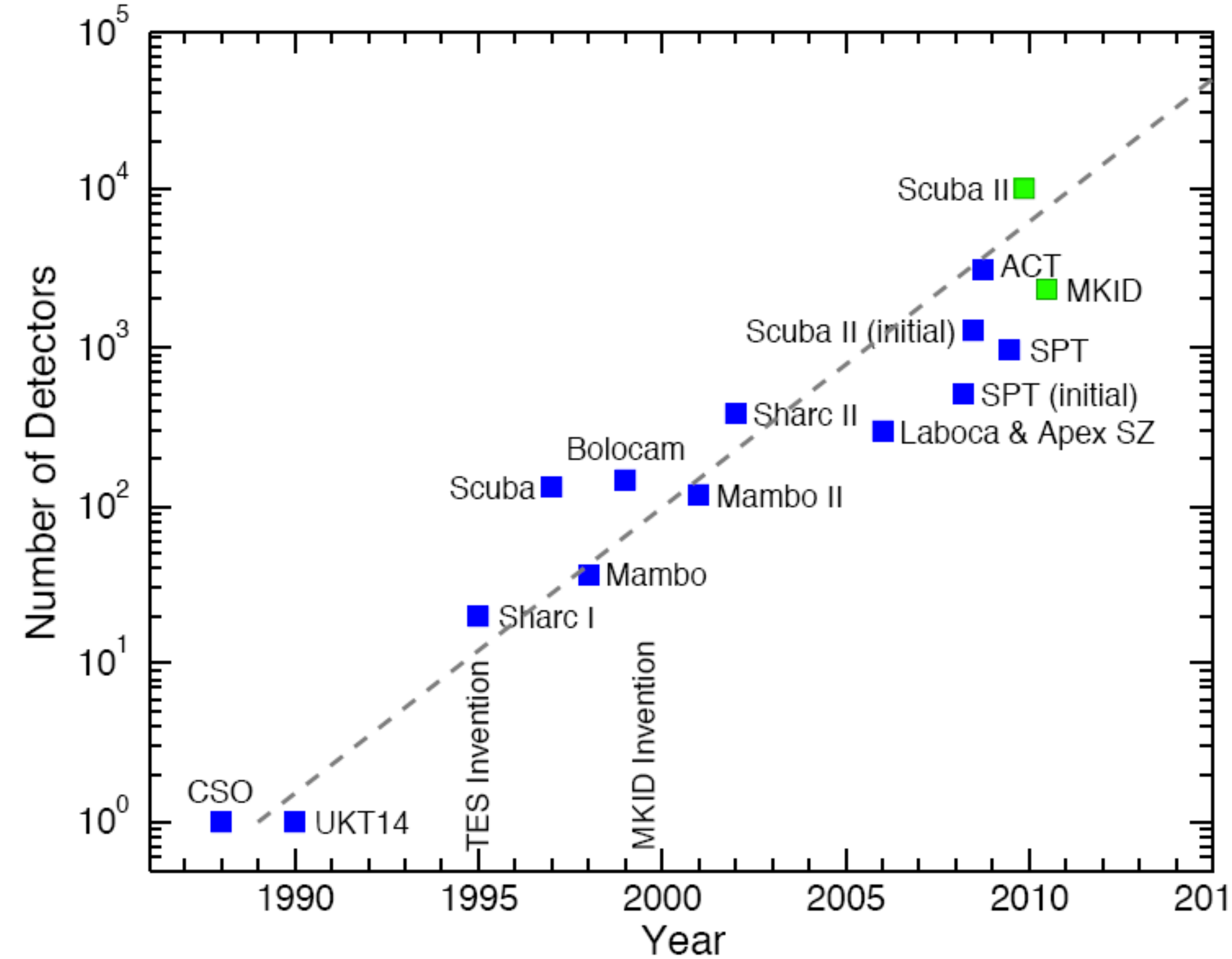
Measure incident power (pW) by change resonator frequency and quality factor (Q)

Potentially simple multiplexing.

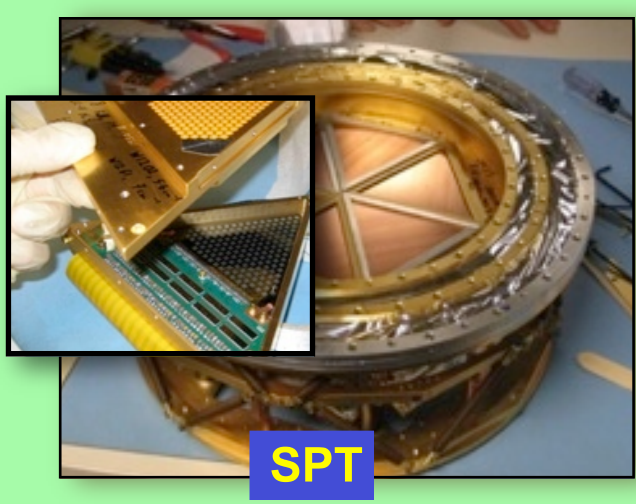
Rapid Progress in Superconducting Bolometer Detectors

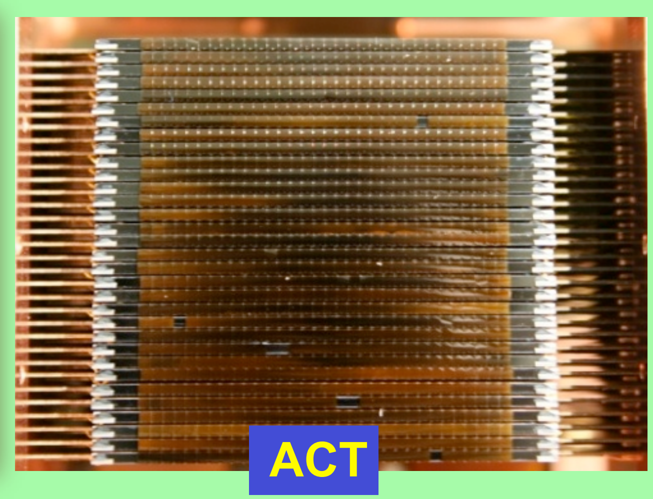
Slide adapted from Jamie Bock

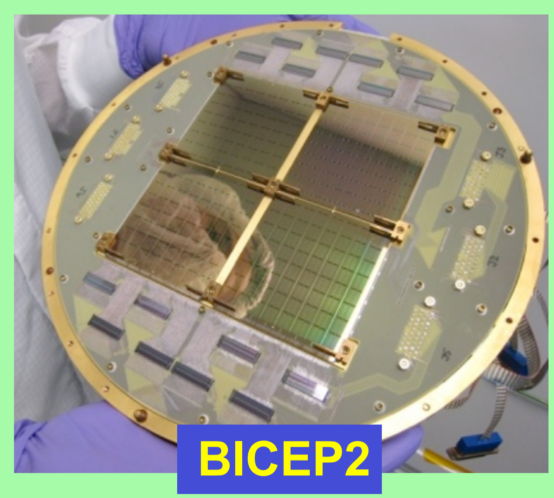


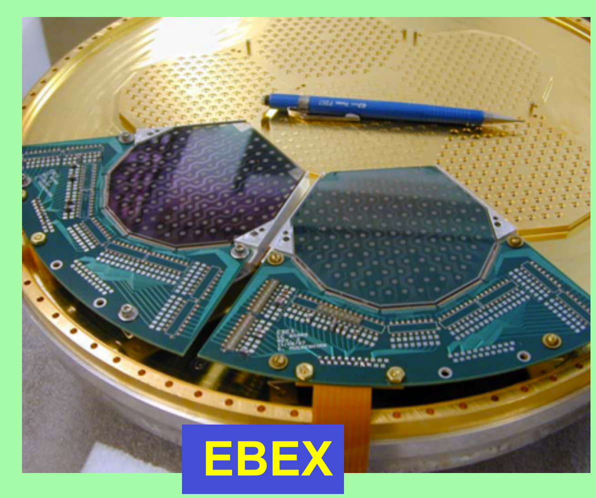


State of the Art Bolometer Arrays





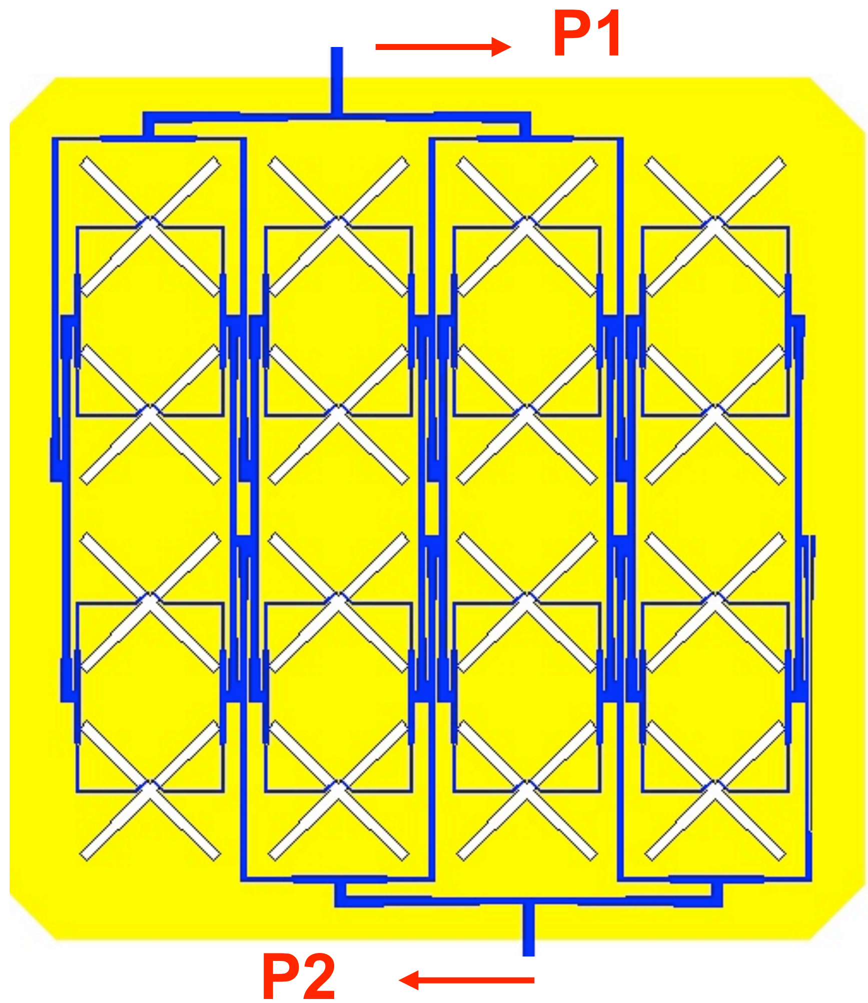


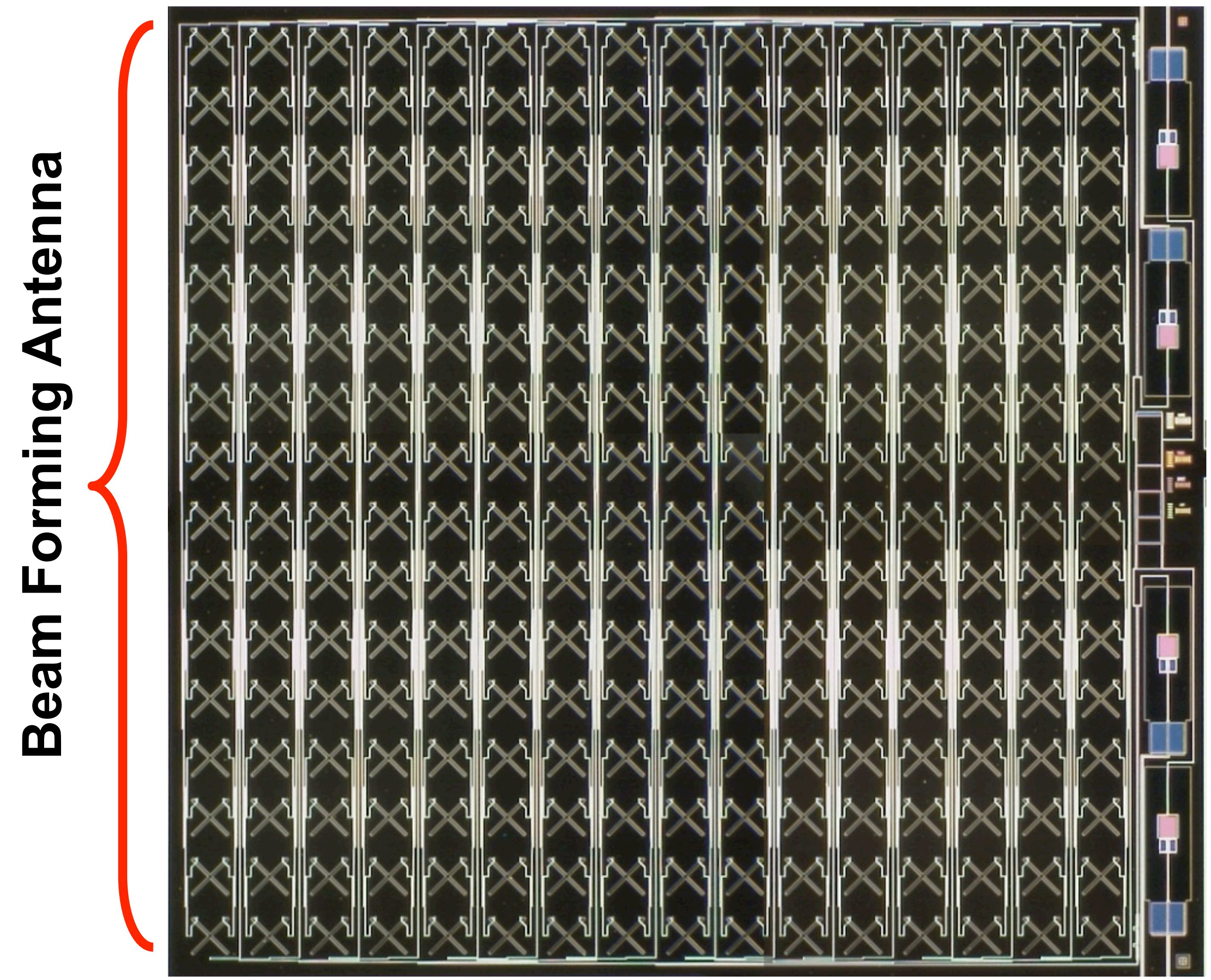


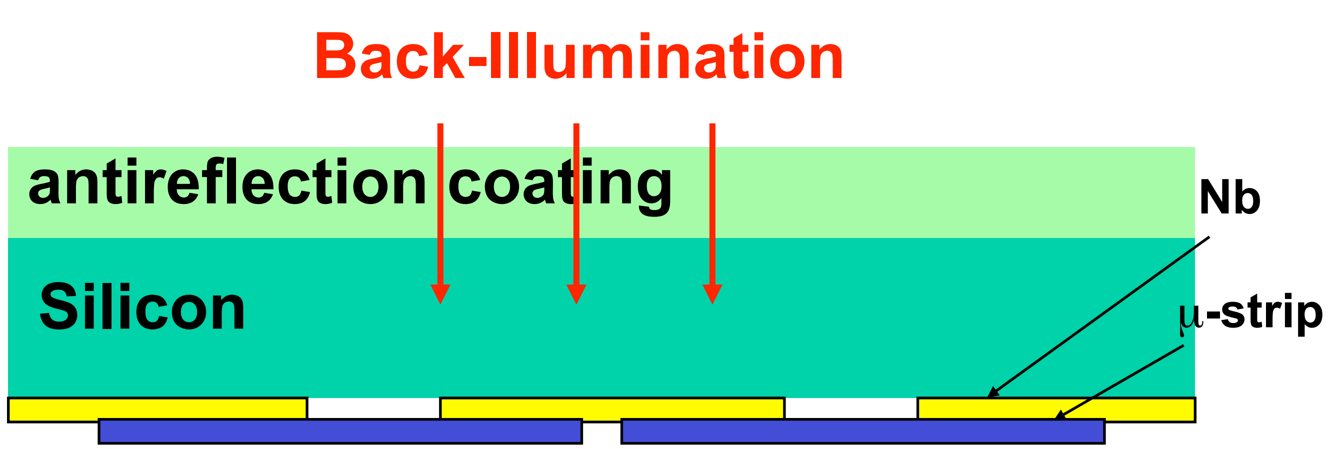
JPL: Planar Antenna-Coupled Polarimeters

Slide adapted from Jamie Bock

Dual Polarization, Single Band





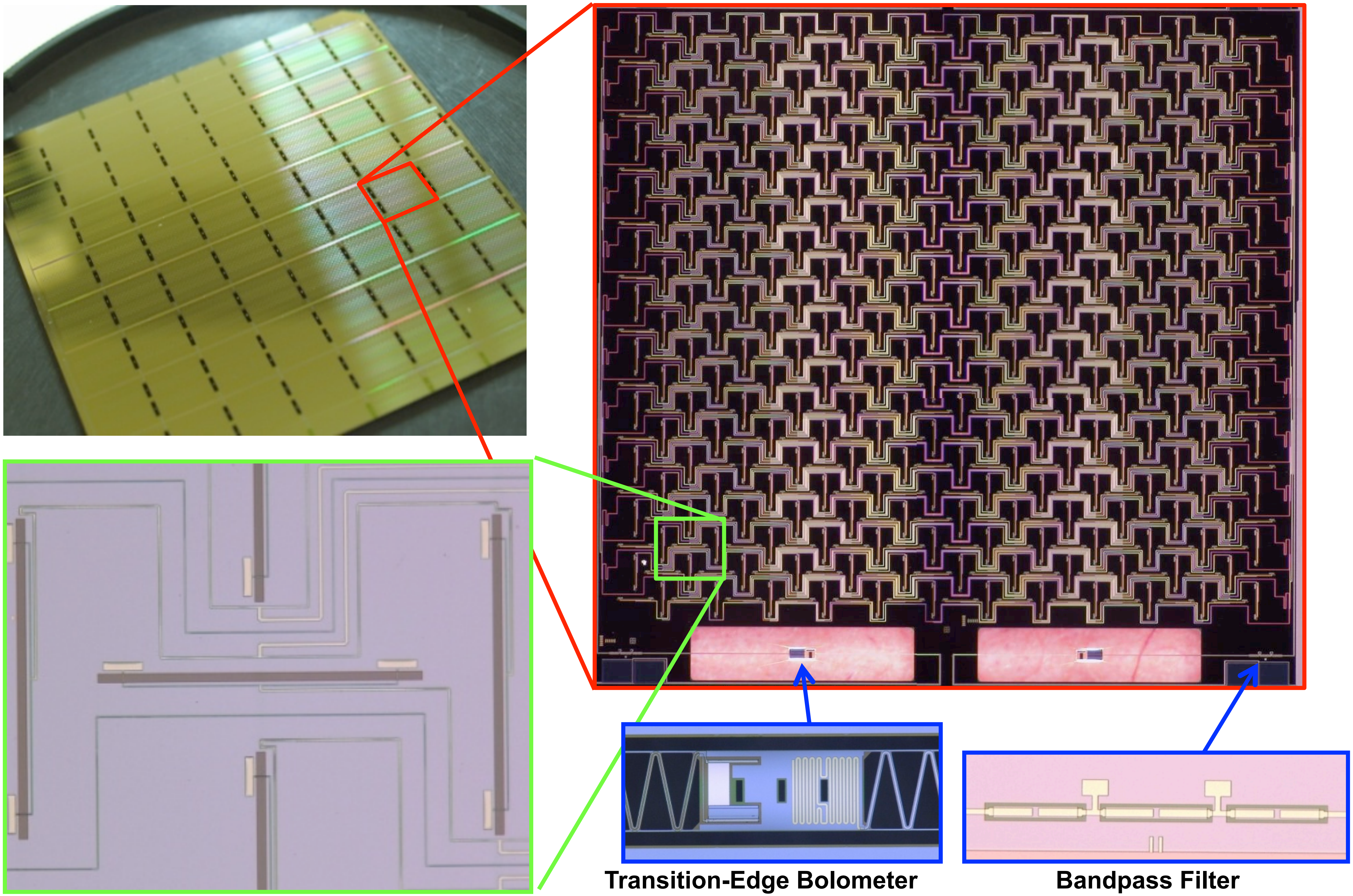


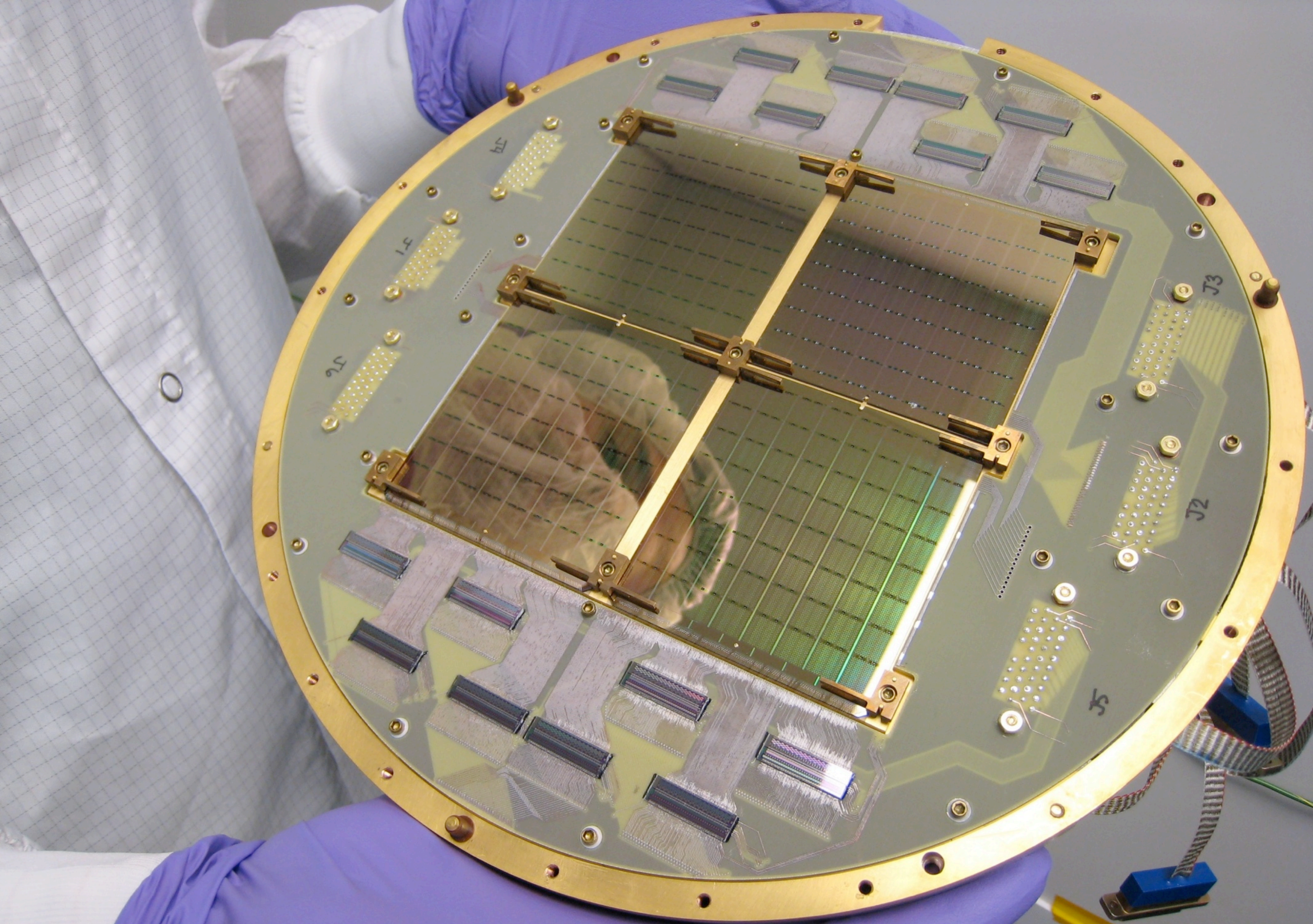
<u>Advantages</u>

- Photon-limited sensitivity
- Multiplexed readout for arrays
- Planar architecture for arrays
- No coupling optics
- Easily scaled in frequency

JPL: Planar Antenna-Coupled Polarimeters

Slide adapted from Jamie Bock



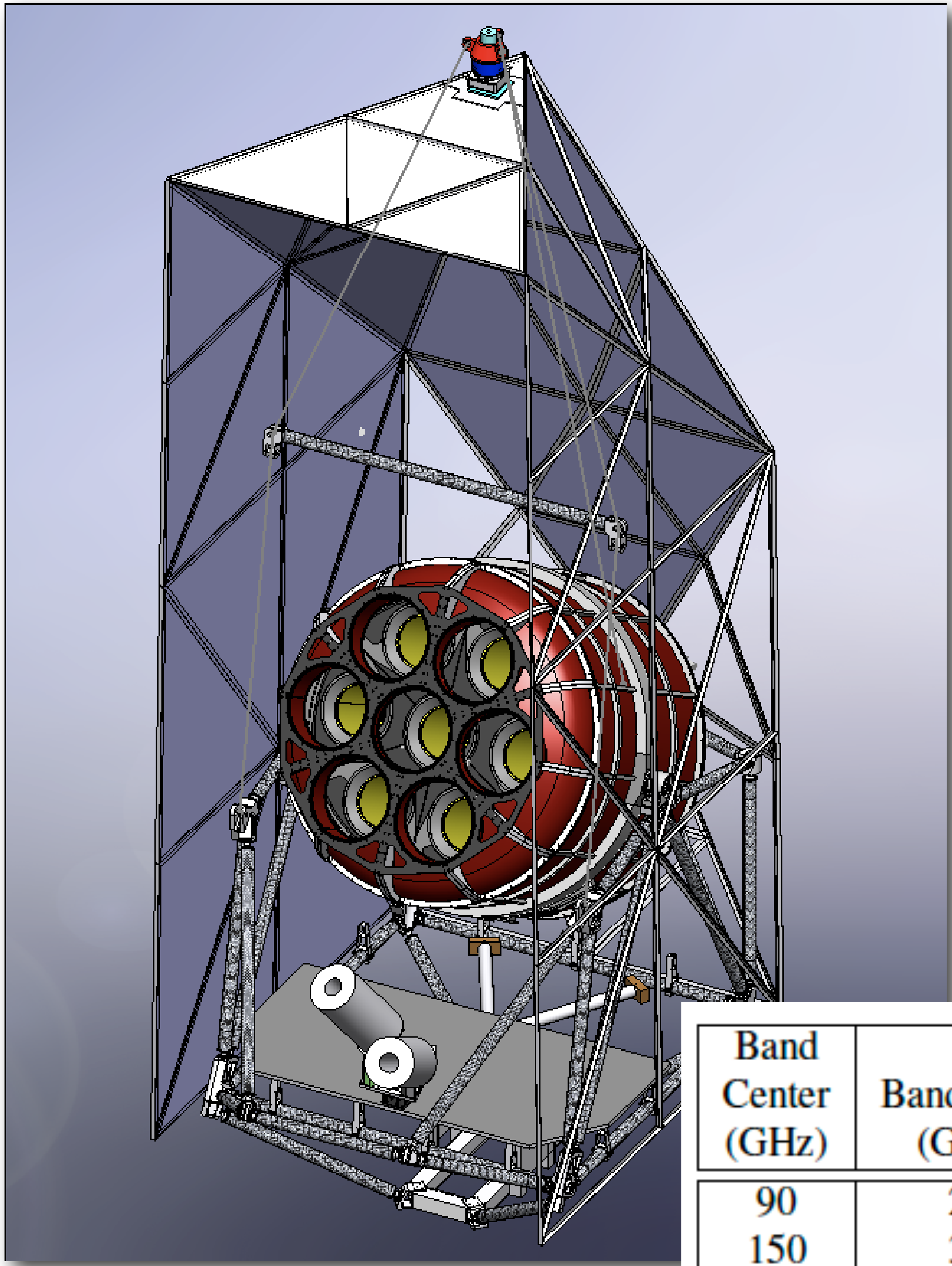


BICEP2, Keck Array, Spider focal plane: 256 planar feed pixels, 512 TES bolometers

on degree scale CMB experiments at the South Pole

Slide adapted from John Ruhl

And soon on a balloon …
"Spider"

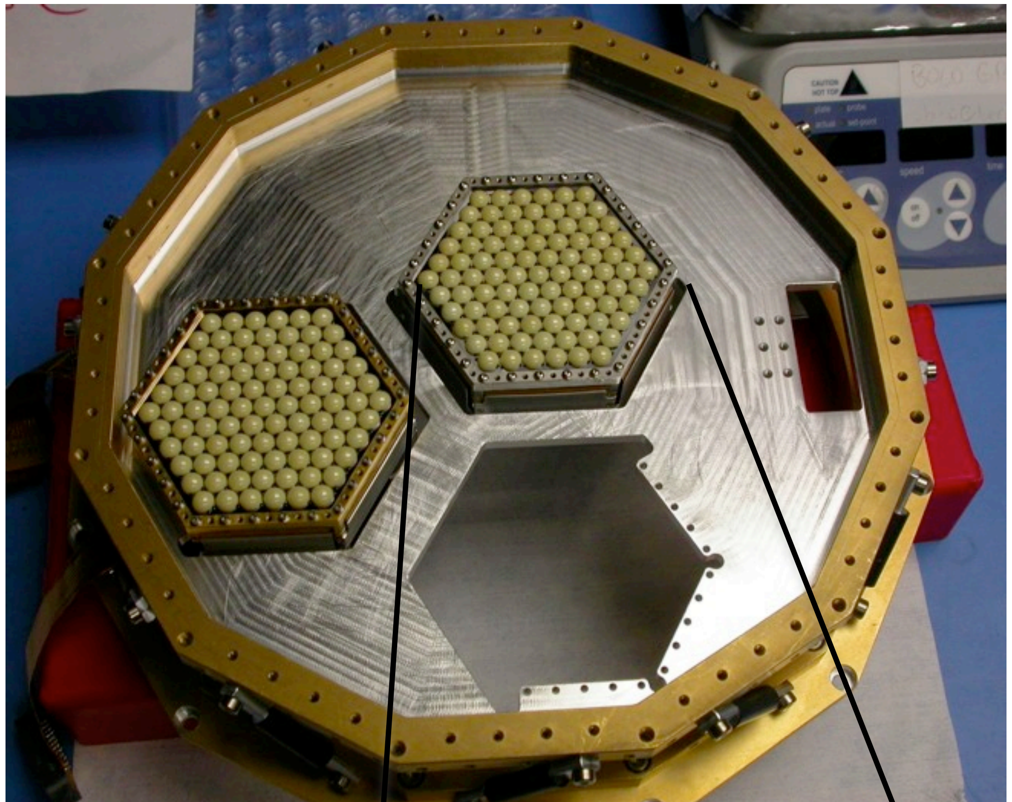


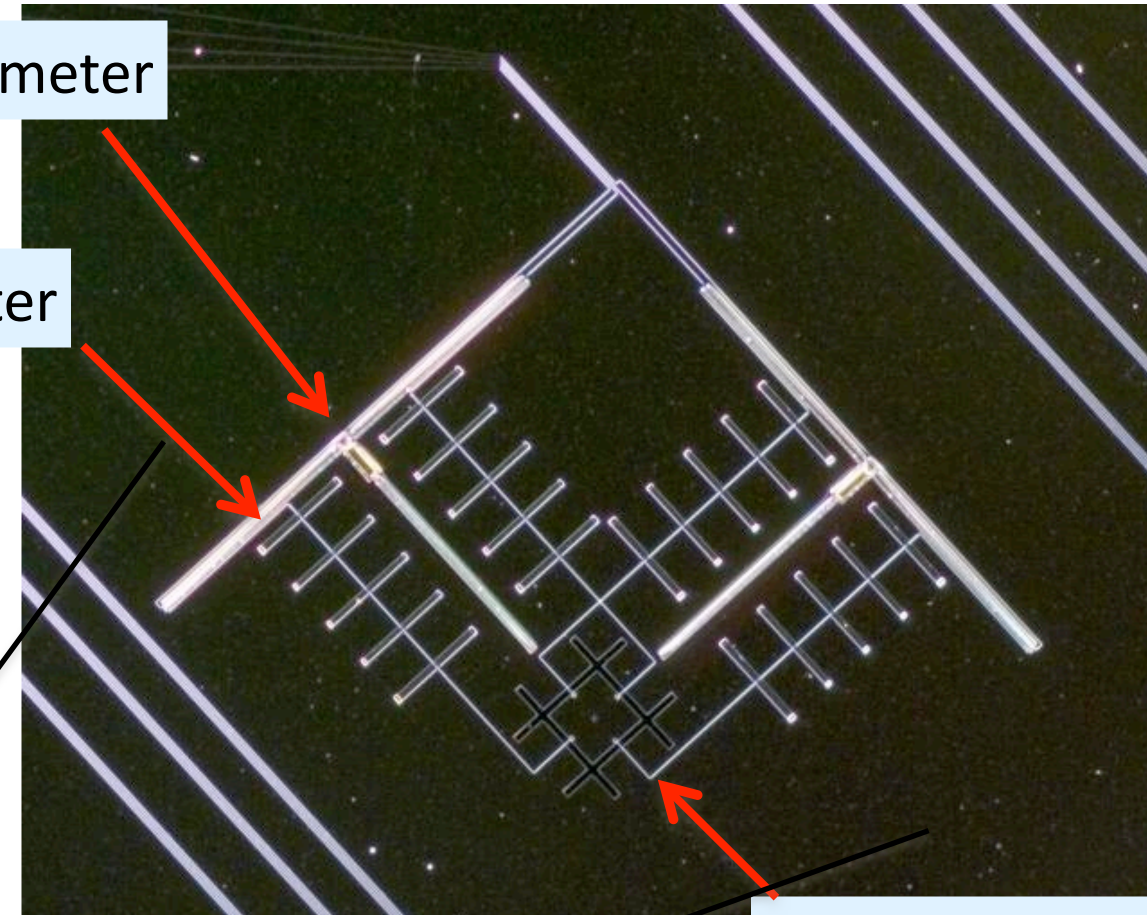
The 1284 liter, 6-telescope flight cryostat

Band Center (GHz)	Bandwidth (GHz)	Beam FWHM (arcmin)	Number of Spatial Pixels	Number of Detectors per FPU	Detector Sensitivity ($\mu K_{CMB}\sqrt{s}$)	FPU Sensitivity ($\mu K_{CMB}\sqrt{s}$)
90	22	49	144	288	150	10
150	36	30	256	512	150	7
280	67	17	256	512	380	18

Berkeley: "Polarbear" Lensed coupled arrays

Slide adapted from Adrian Lee

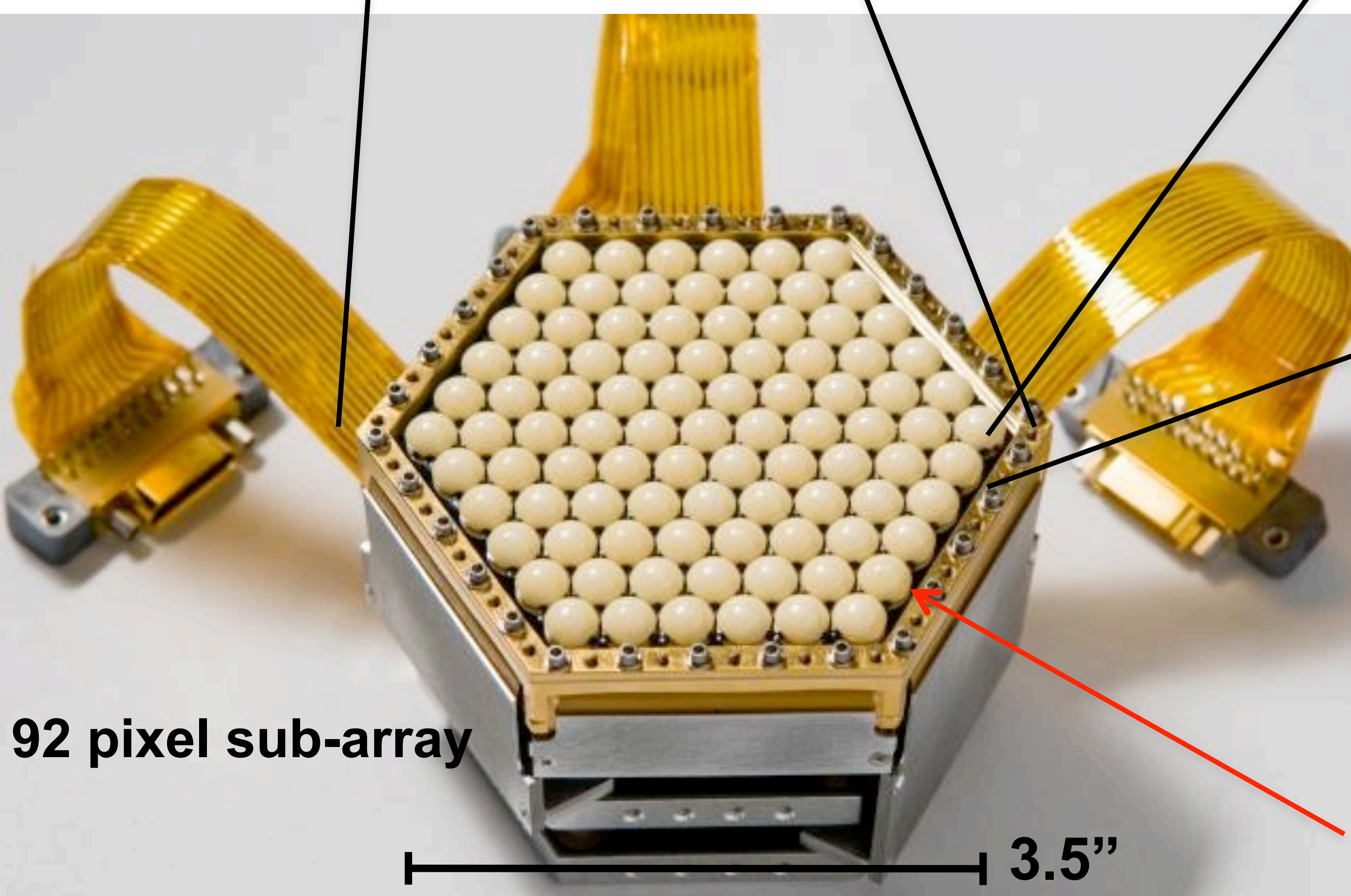




TES Bolometer

Filter

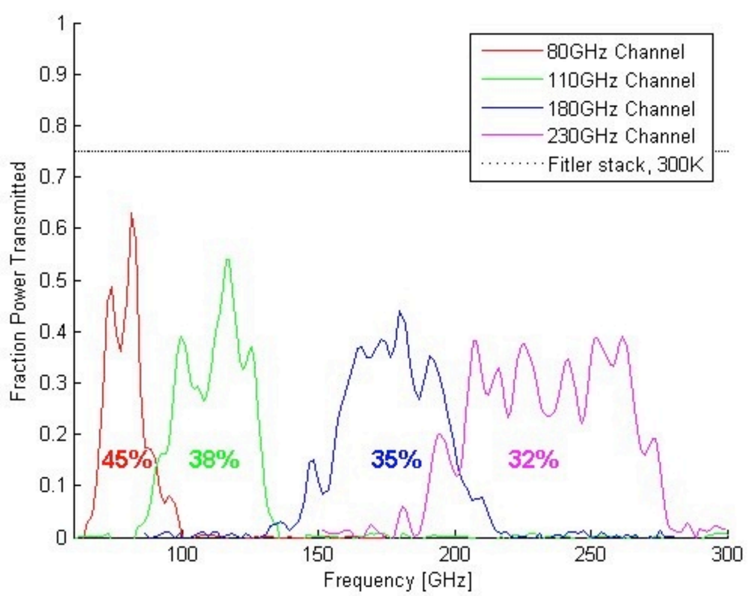
Planar antenna



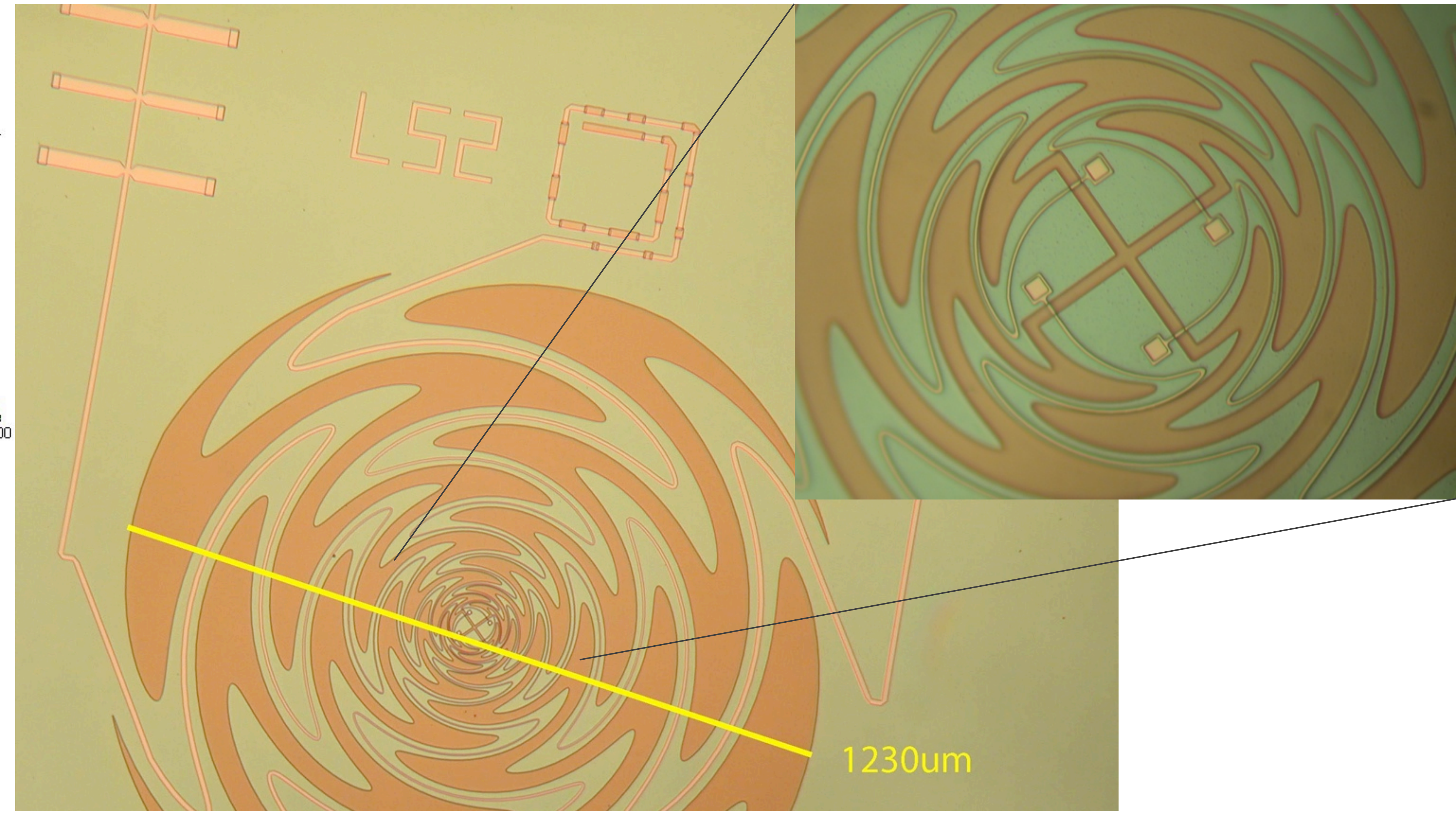
Lenslet

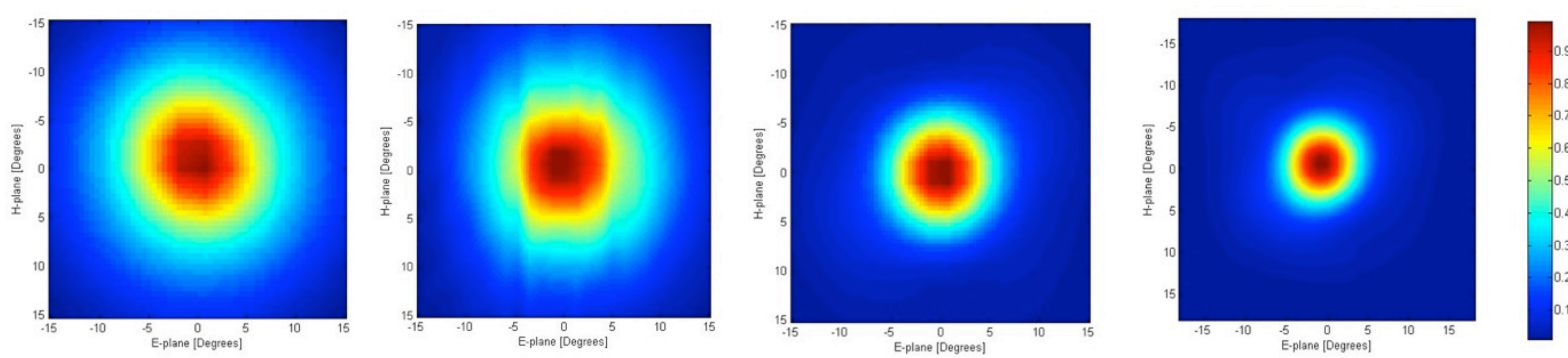
Multichroic pixel focal planes
- UC Berkeley sinuous planar antenna

Slide adapted from Adrian Lee



Receiver *end-to-end* efficiency



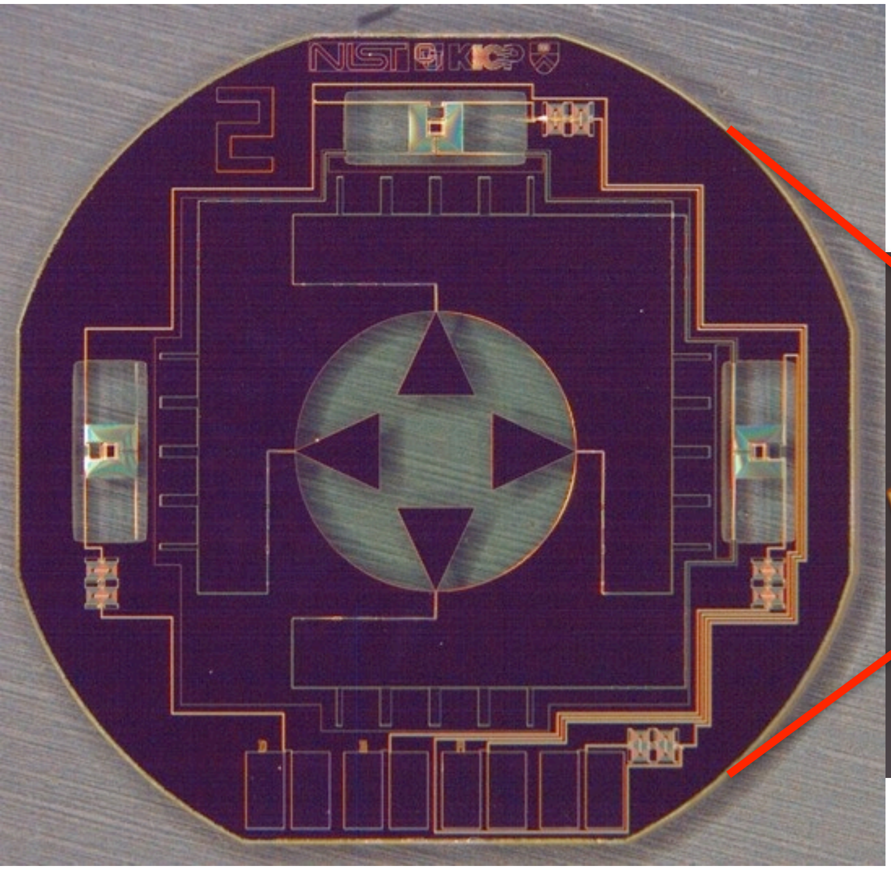


4:1 Bandwidth, Symmetric beams, low cross-pol

NIST Polarimeter Arrays

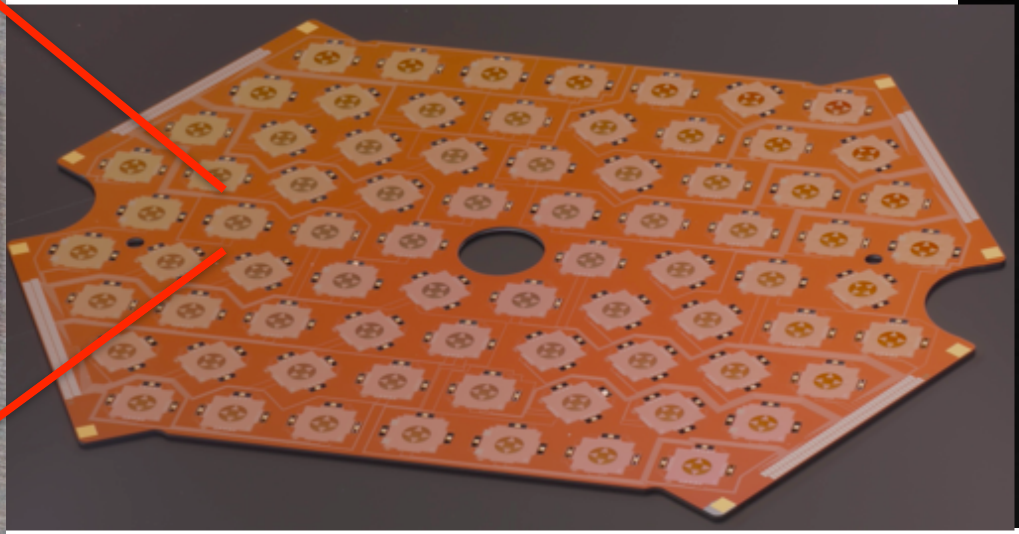
- Truce Collaboration: NIST, UC Berkeley, CU Boulder, U Chicago, U Michigan, U Penn., Princeton, NASA GSFC, Stanford
- Superconducting transition-edge-sensor polarimeters (TES)
- Monolithic corrugated silicon feedhorn arrays
- For ABS (Atacama B-mode Search), ACTpol, SPTpol

Single Truce 150 GHz polarimeter

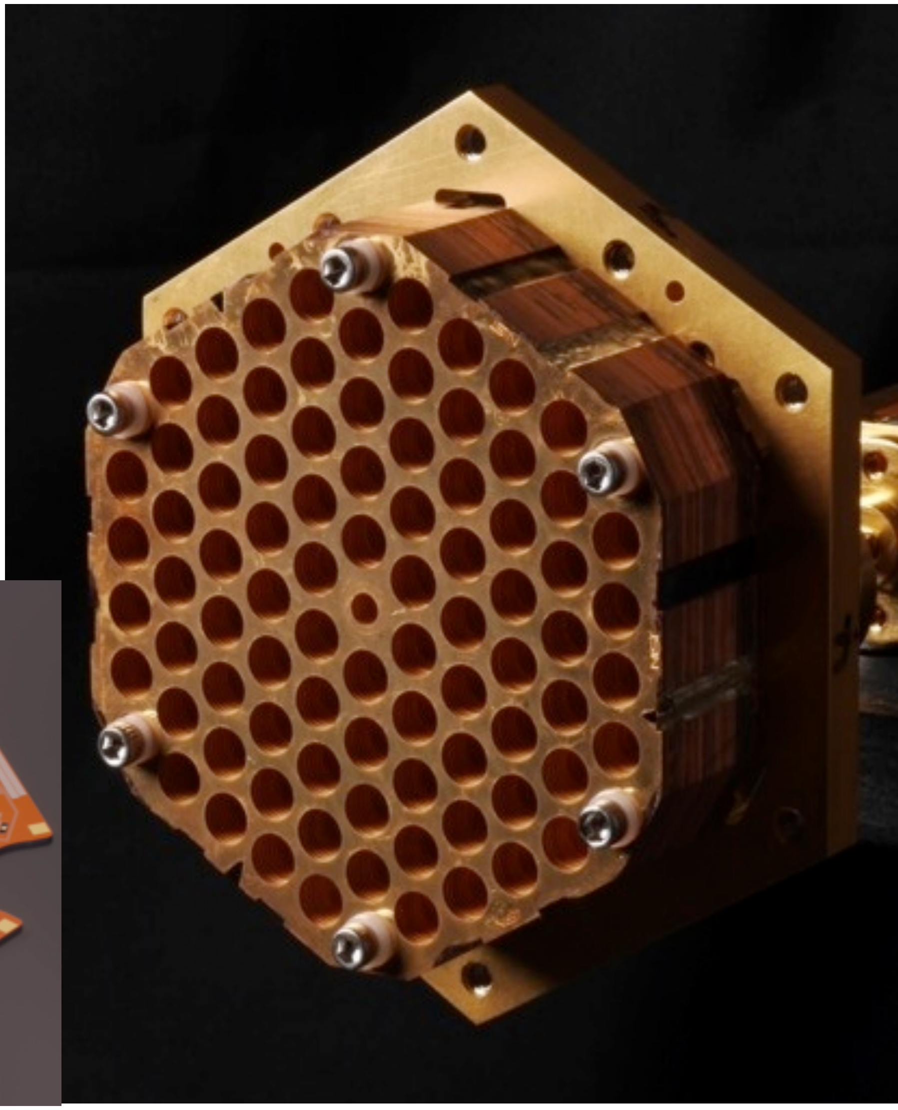


5 mm

Polarimeter array



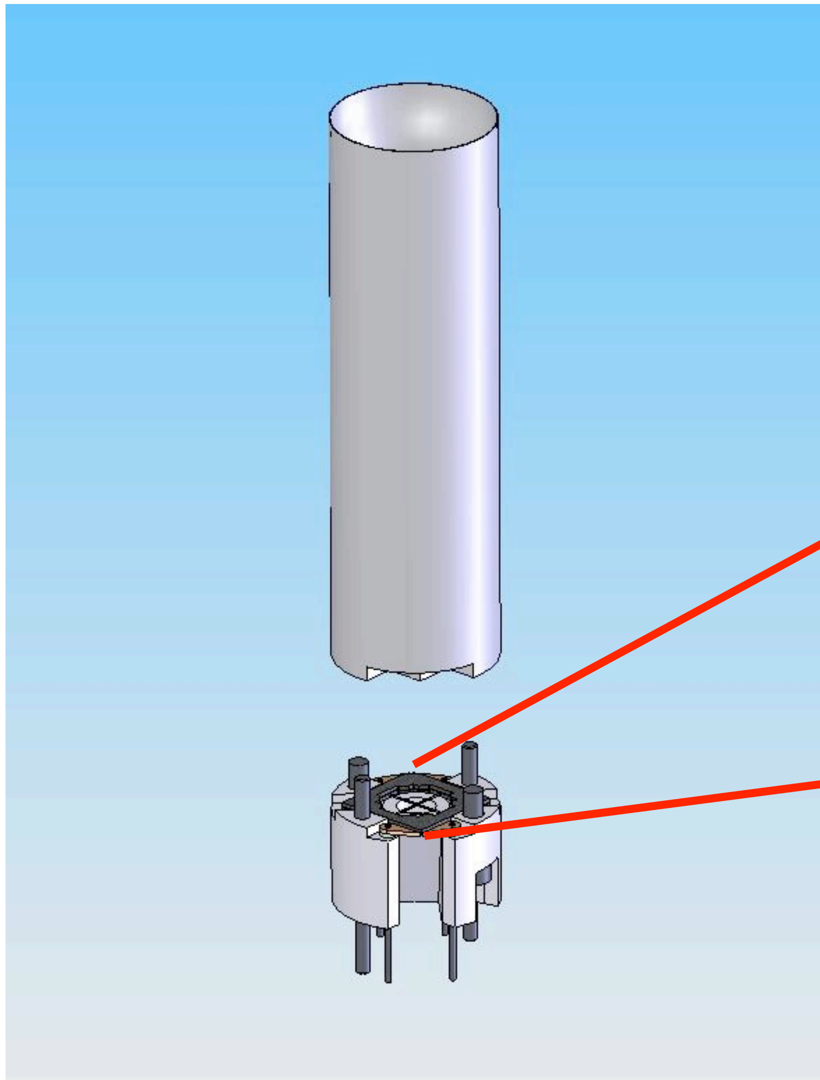
Gold-plated silicon feed array

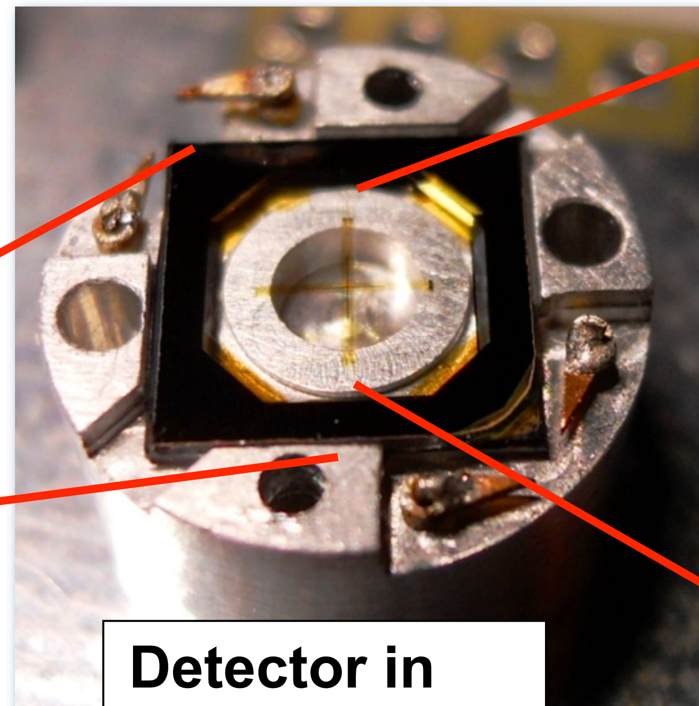


5 cm

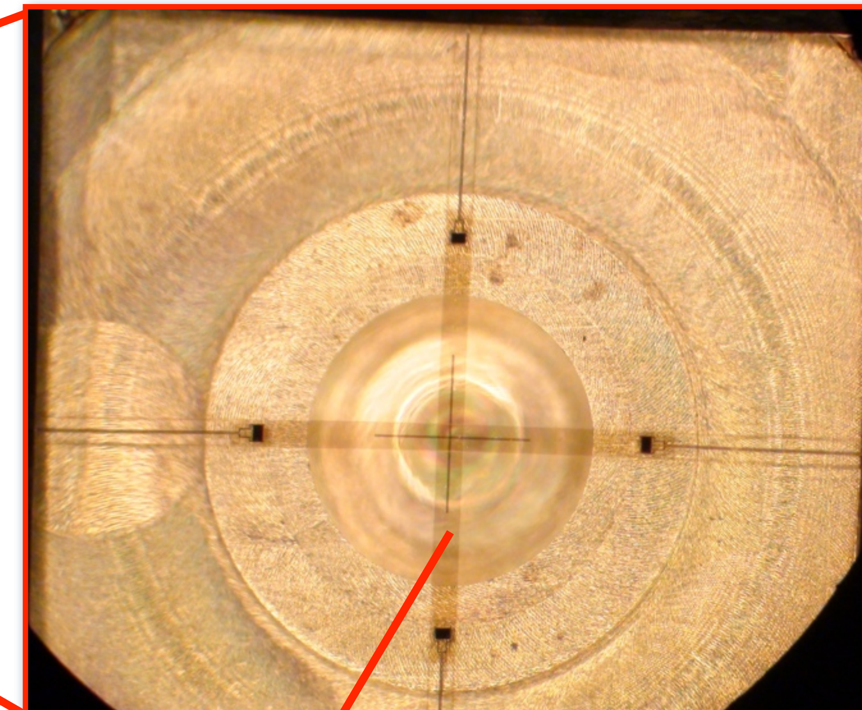
See talk by Michael Niemack and more info at
http://casa.colorado.edu/~henninjw/TRUCE/

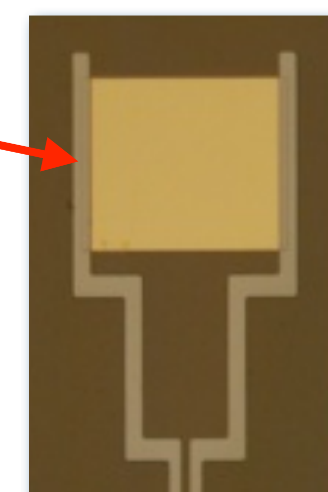
First Argonne Labs TES pixels (90 GHz)





Detector in 2.5 mm waveguide mount

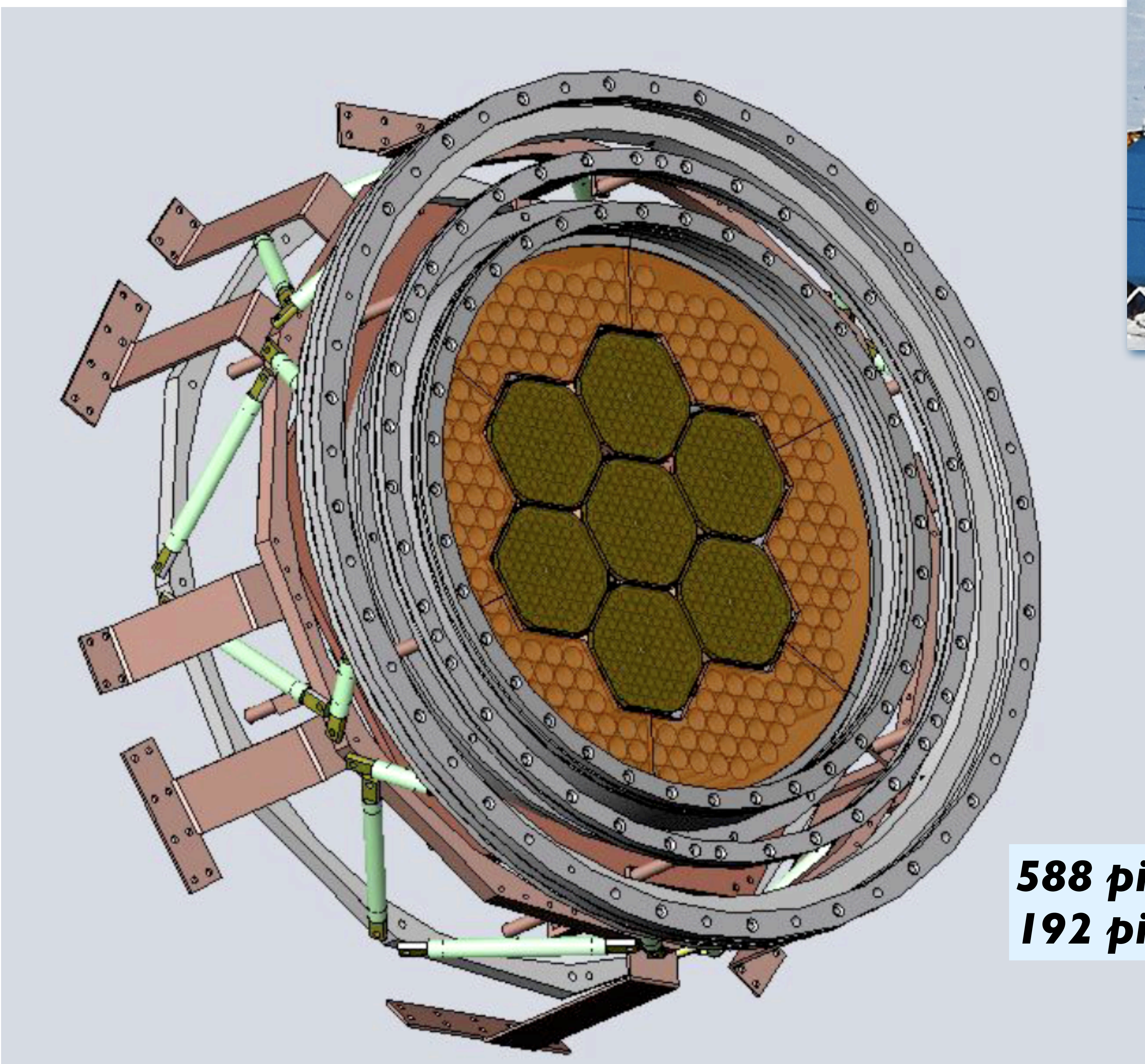




Mo/Au proximity effect 500mK T_C bilayer TES

See talk on Argonne efforts and SPTpol by Clarence Chang

South Pole Telescope initial polarimeter "SPTpol"



588 pixels at 150GHz from NIST
192 pixels at 95GHz from Argonne

last words

Driven by advances in detectors, we expect the next ten years of CMB research to be as exciting as the last ten.

- Put ΛCDM to the test & constrain extensions
  More surprises?
- Tests of dark energy. Is it just Λ or...
- Neutrino masses from CMB polarization
- Test inflation with CMB polarization