Neutrinos in Cosmology and the Cosmic Microwave Background

Bradford Benson
Fermilab/UChicago
August 6, 2025

Outline

1) Introduction to Cosmology and the CMB
2) How we constrain cosmology from the CMB
3) Cosmological constraints on neutrinos:
   (a) The number of neutrino species and the abundance of neutrinos.
   (b) The sum of the neutrino masses
4) Current and future constraints

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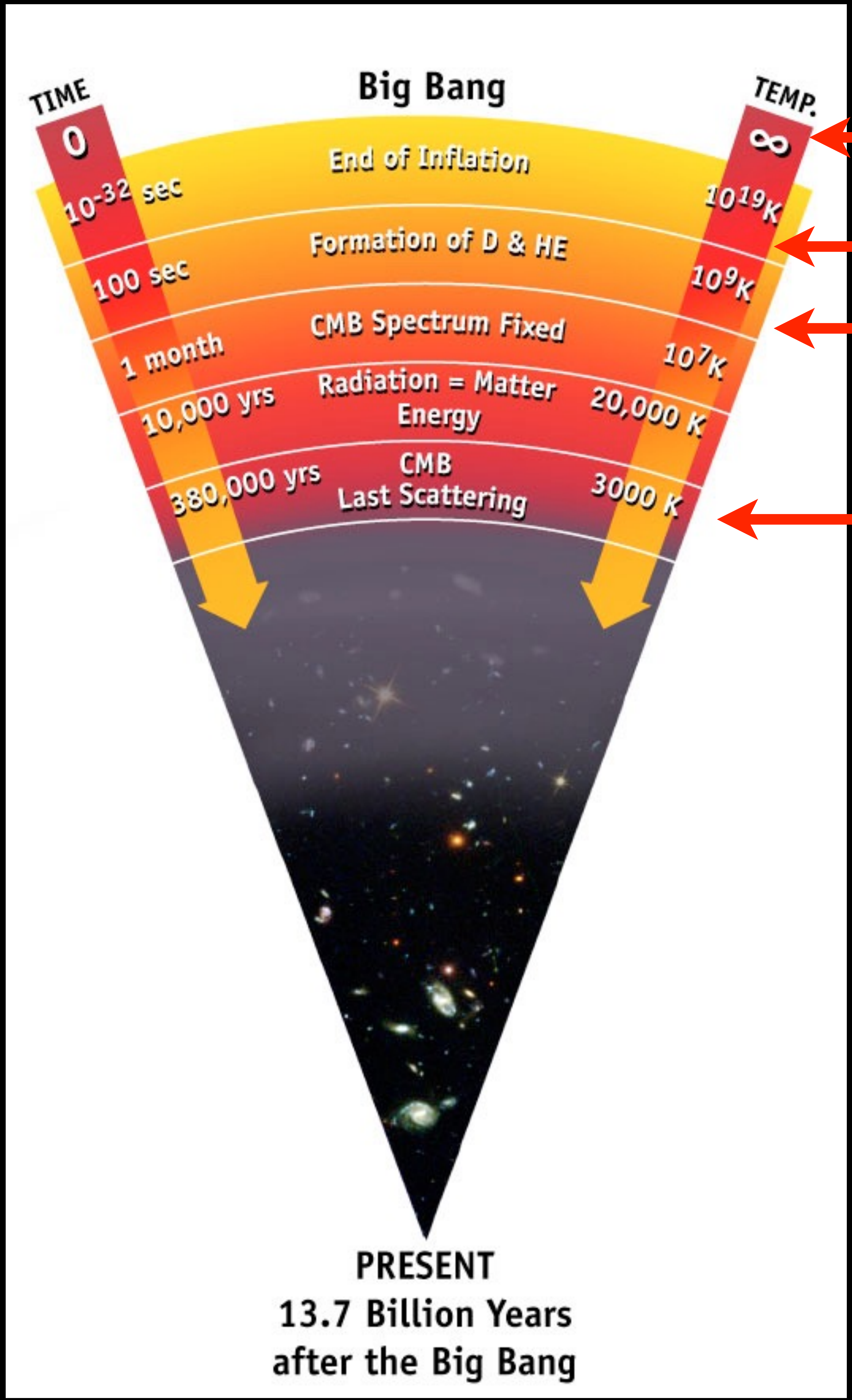
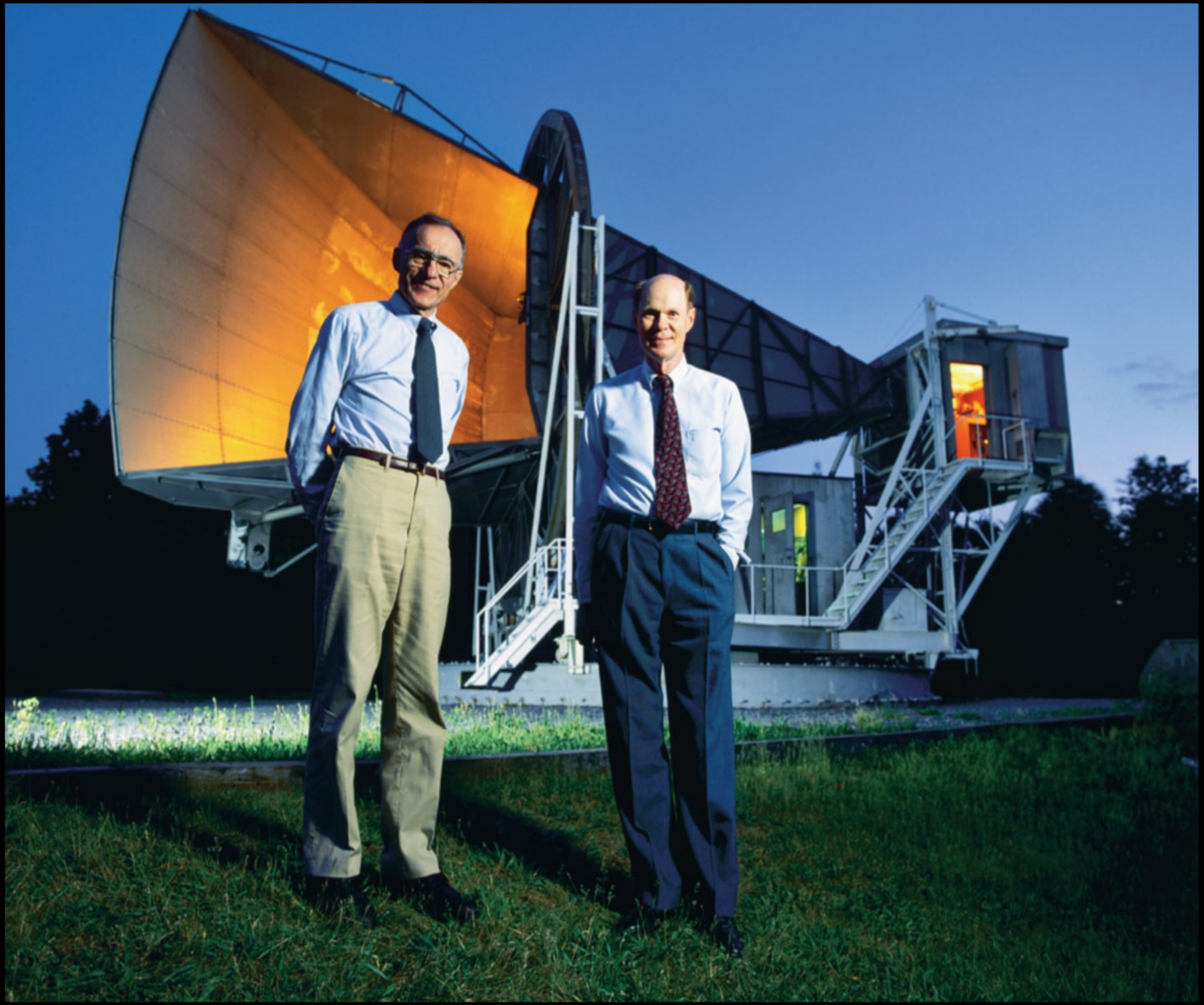


Inflation	**10^{-34} s**	**(~10^{16} GeV)**
Cosmic Neutrino Background	**1 s**	**(~2 MeV)**
BBN - Big Bang Nucleosynthesis (Helium, Deuterium)	**100 s**	**(~0.1 MeV)**
Cosmic Microwave Background	**$3.8\text{x}10^5$ yrs**	**(~1 eV)**

The Universe is the Ultimate High-Energy Physics Laboratory!

1965: Discovery of the Cosmic Microwave Background (CMB)

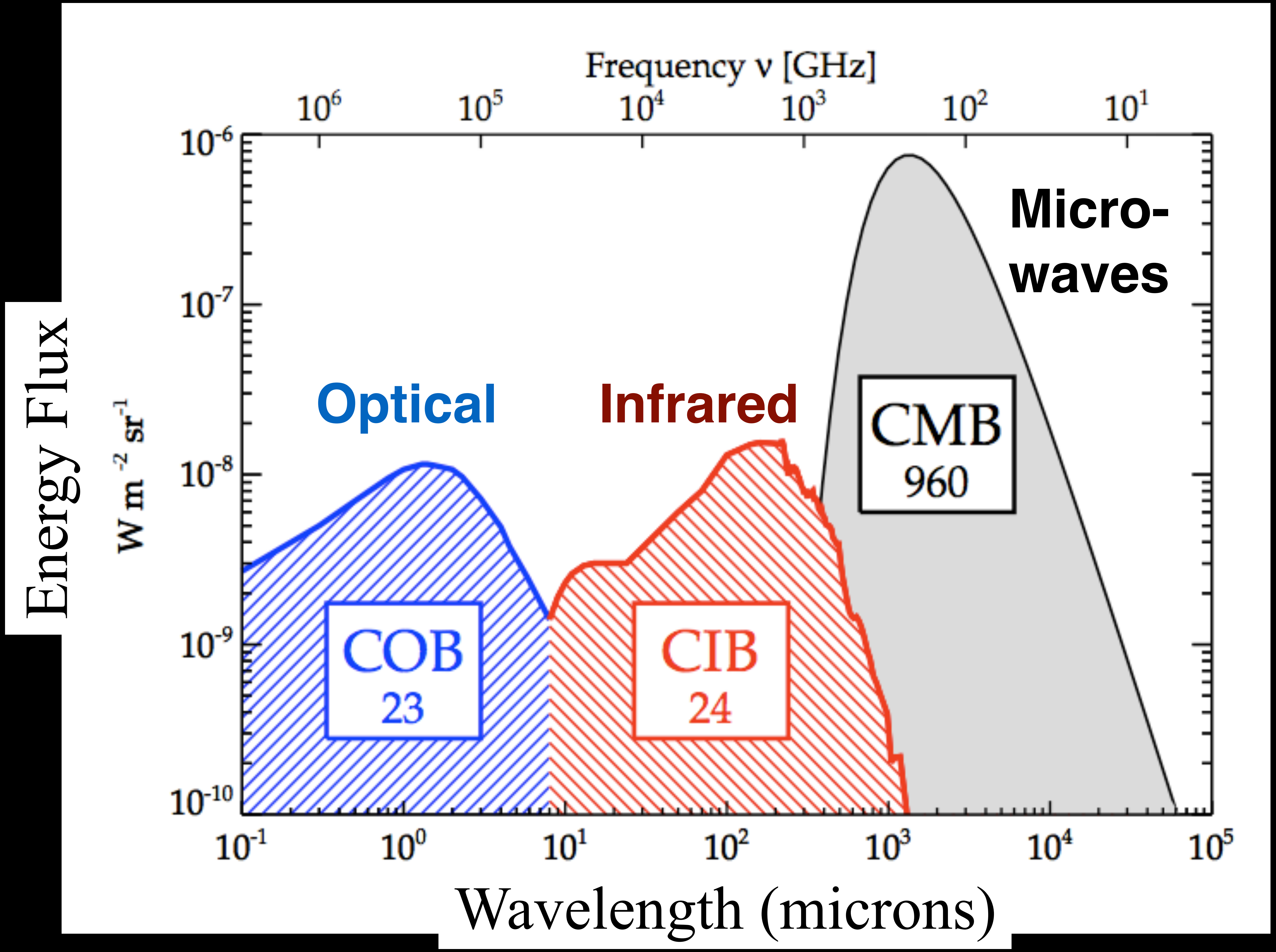


Received 1978 Nobel Prize

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

“Smoking Gun” evidence for the Big Bang

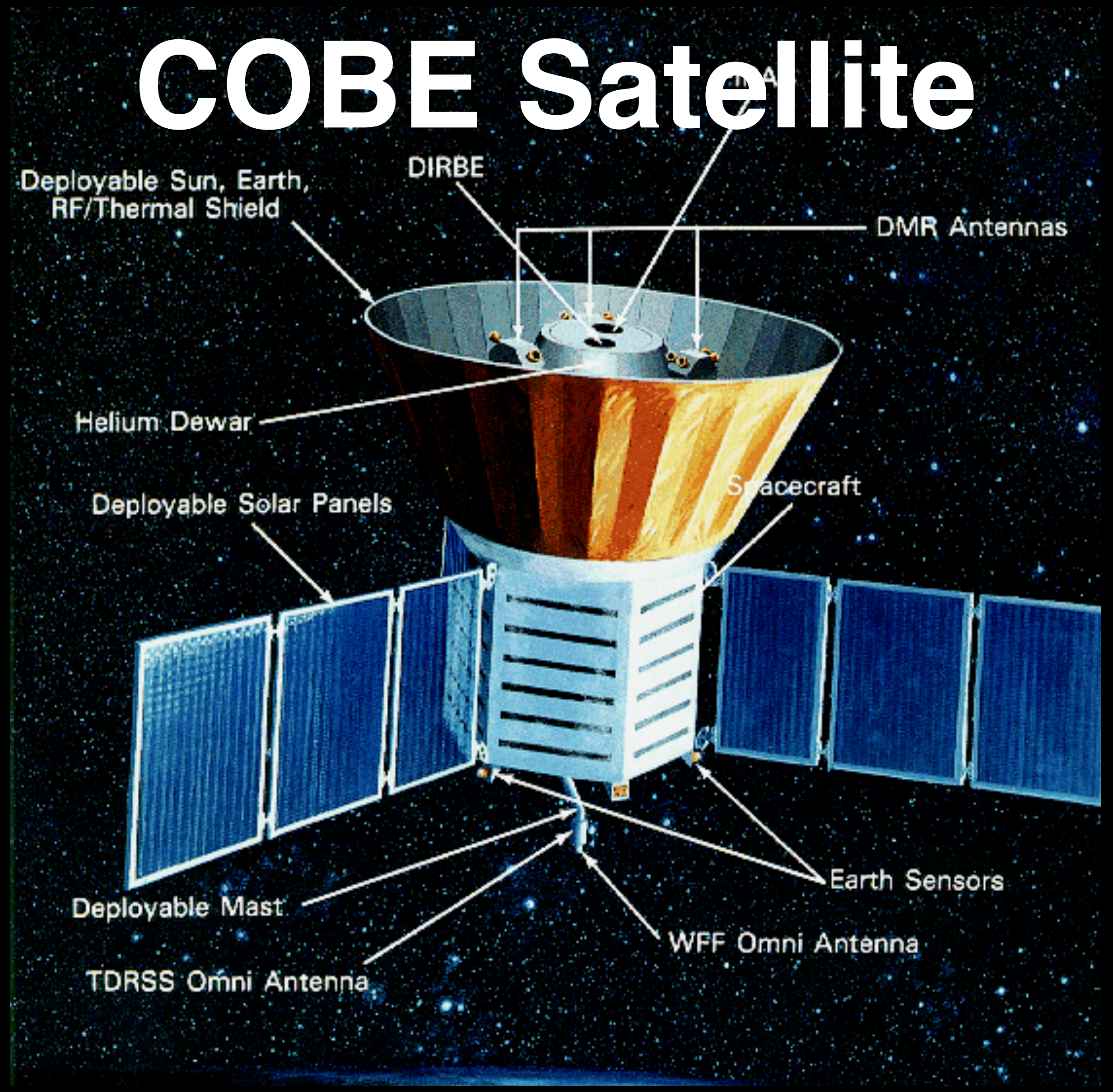
The CMB is really bright!

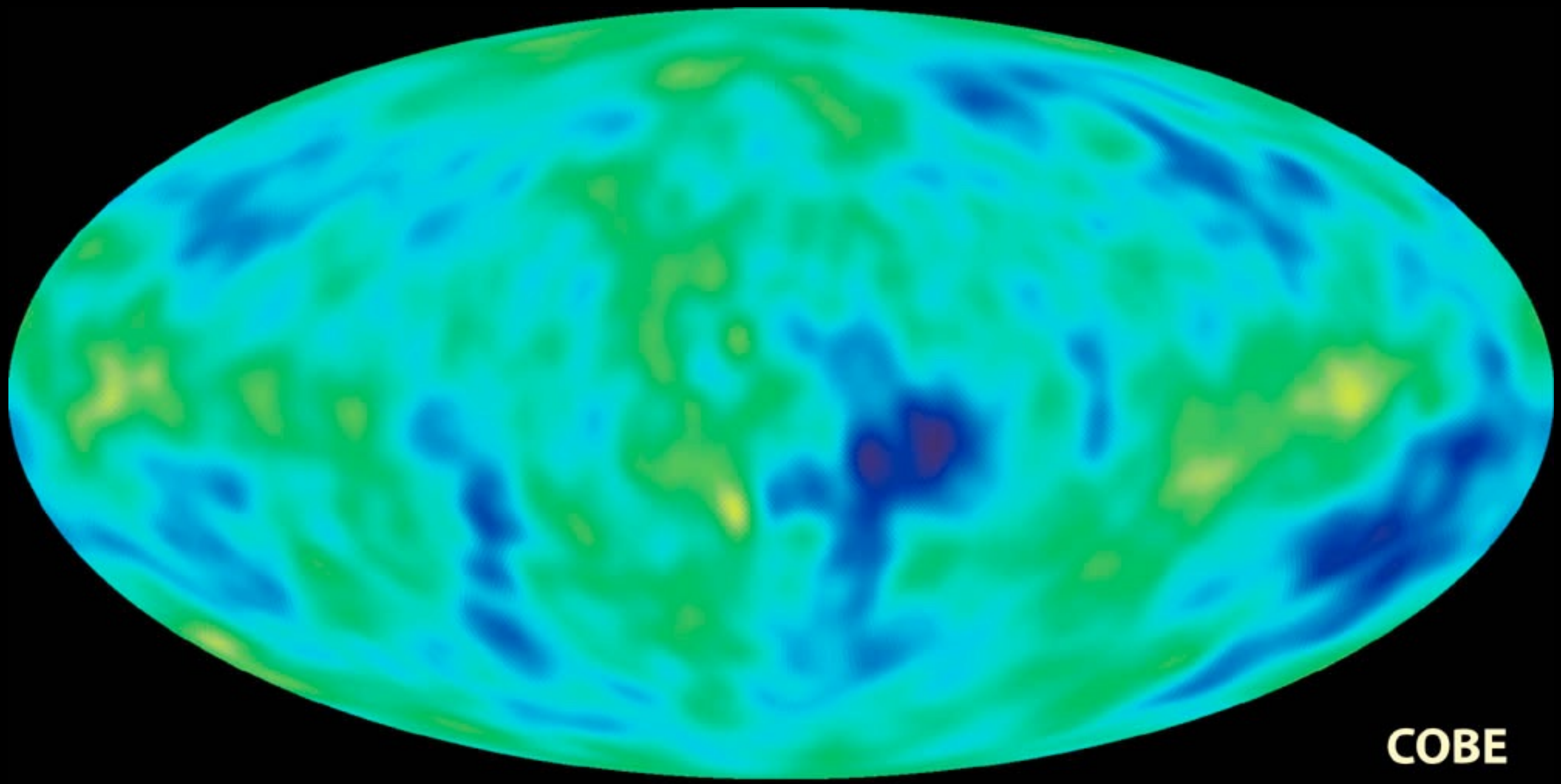


If you took a census of energy in the form of light in the Universe, more than 90% is from the CMB

The CMB is 10x brighter than every star that's shone in the history of the Universe!

1992: Structure in CMB Discovered by COBE

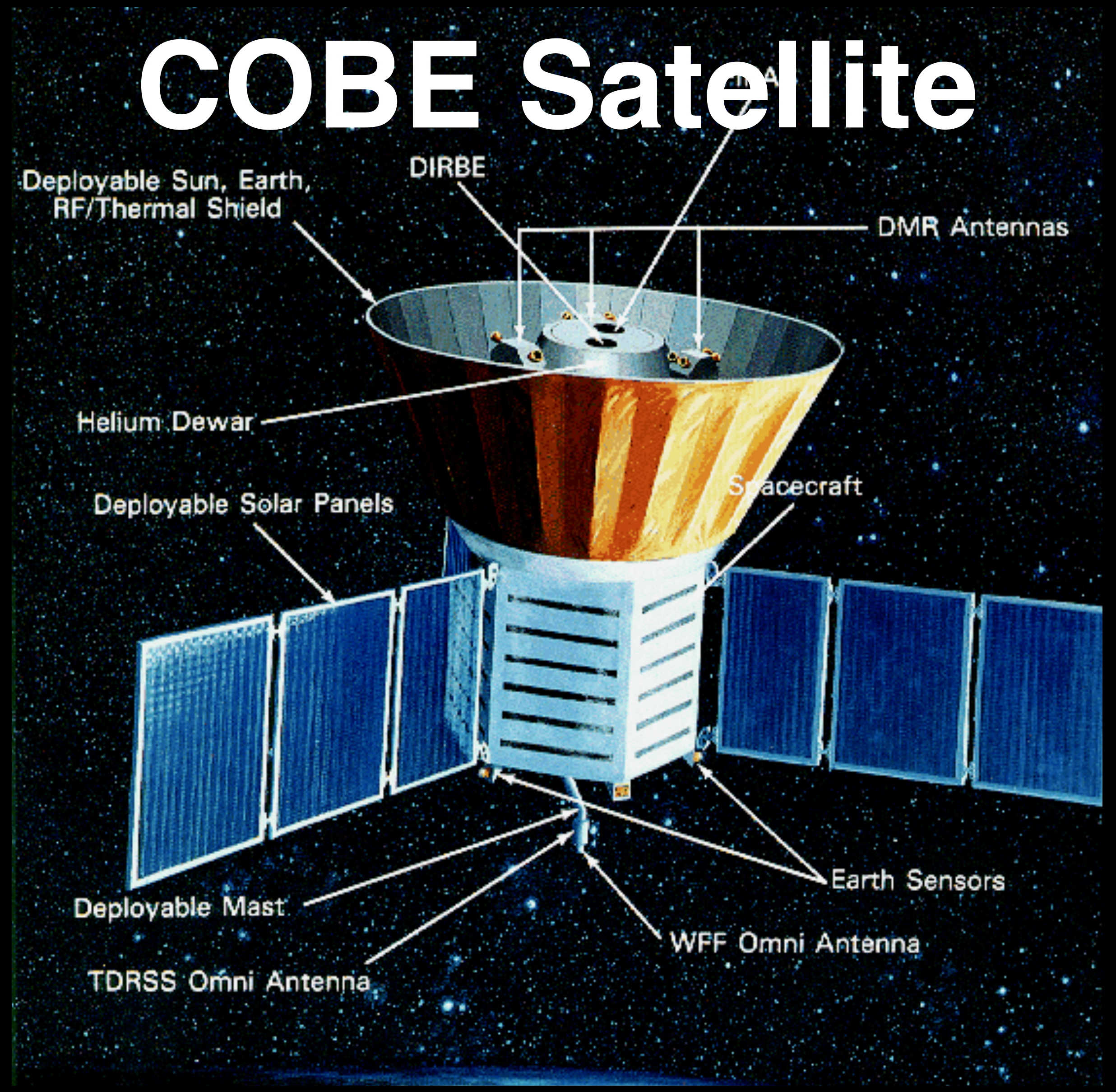


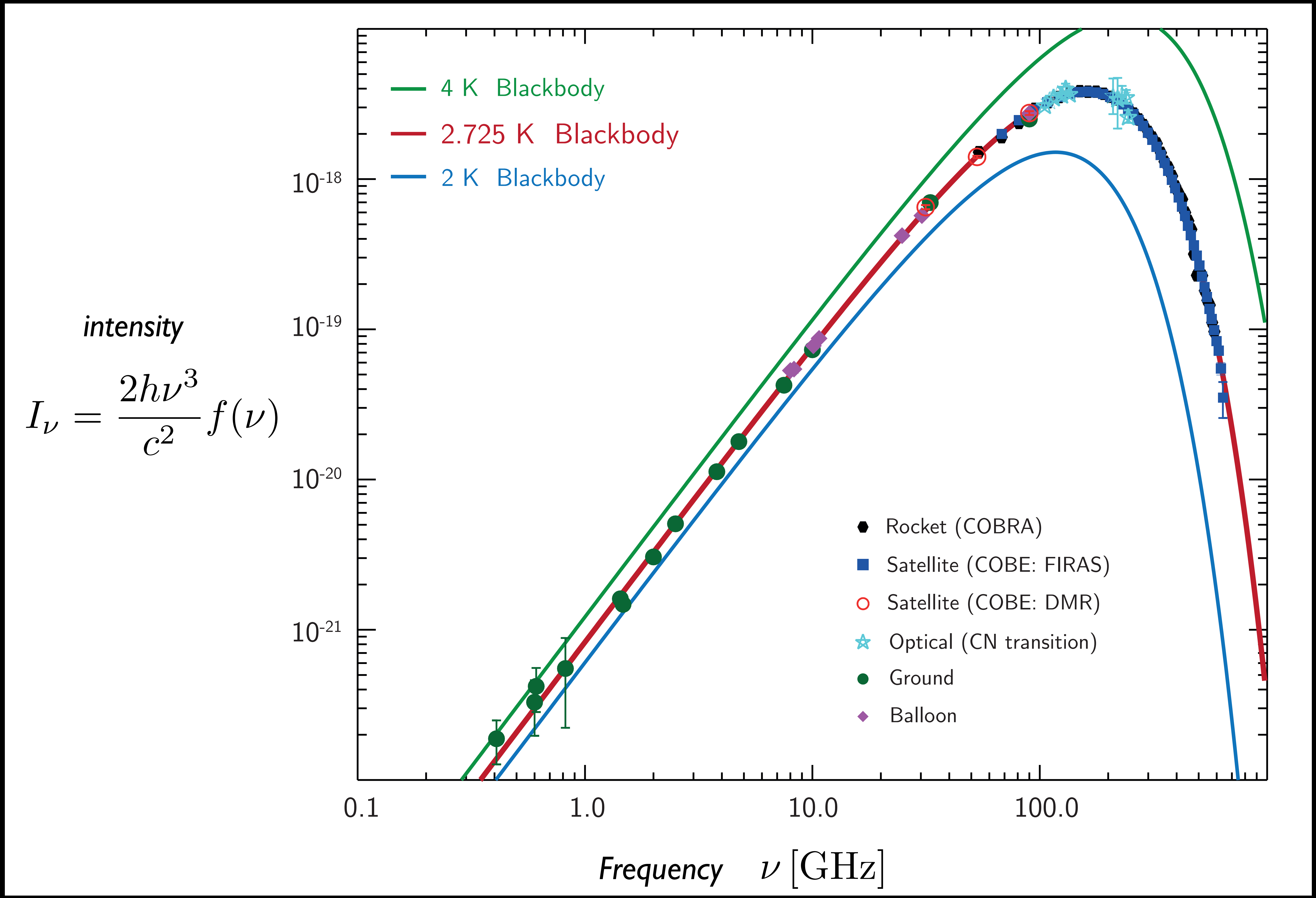


COBE team leaders
John Mather & George Smoot
Received 2006 Nobel Prize

1) Smooth to 1 part in 100,000
2) Near-perfect 2.7 K blackbody

1992: The CMB is measured to be the most perfect black body in the Universe





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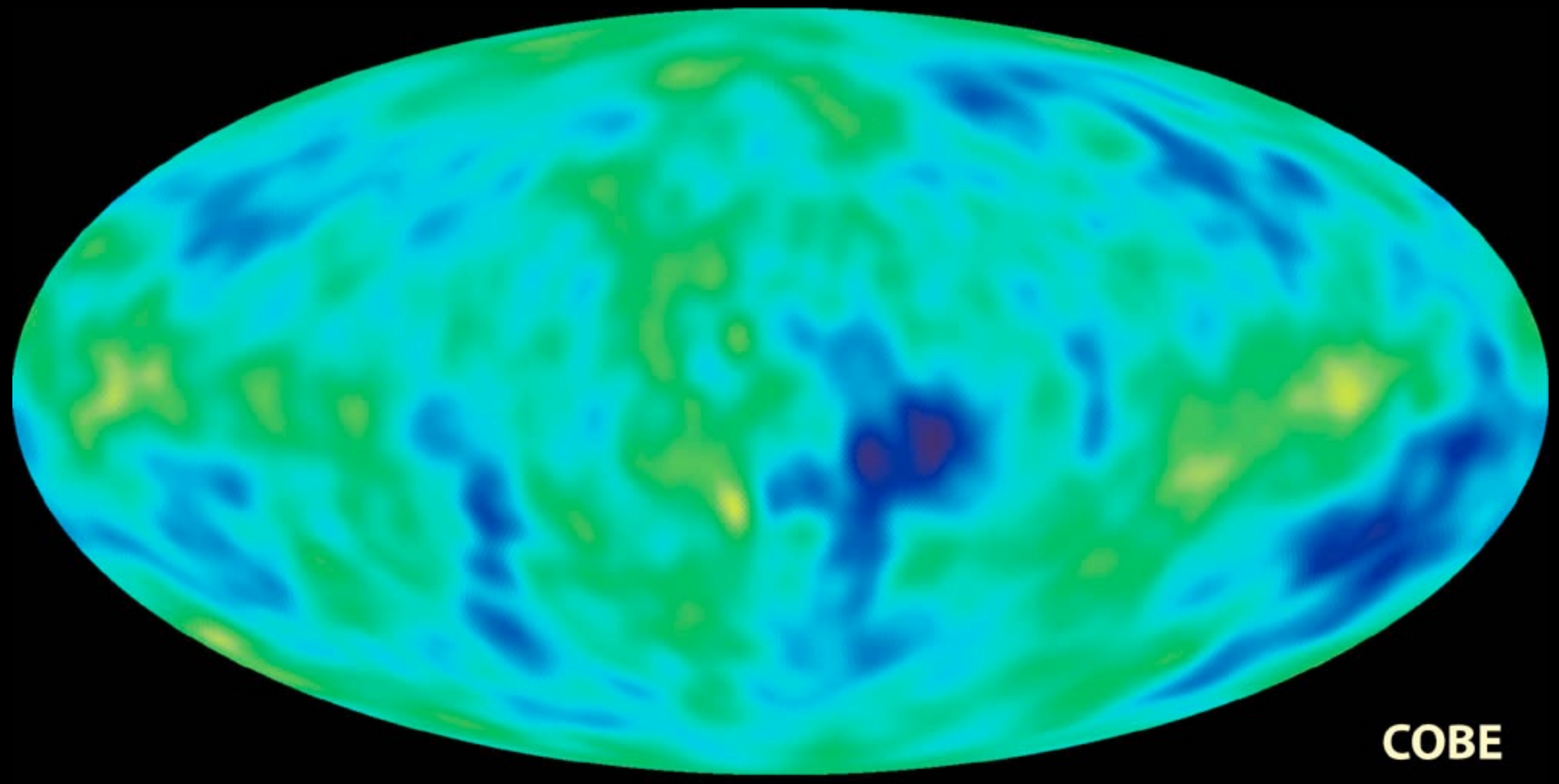
The CMB is a “Baby” Picture of the Universe

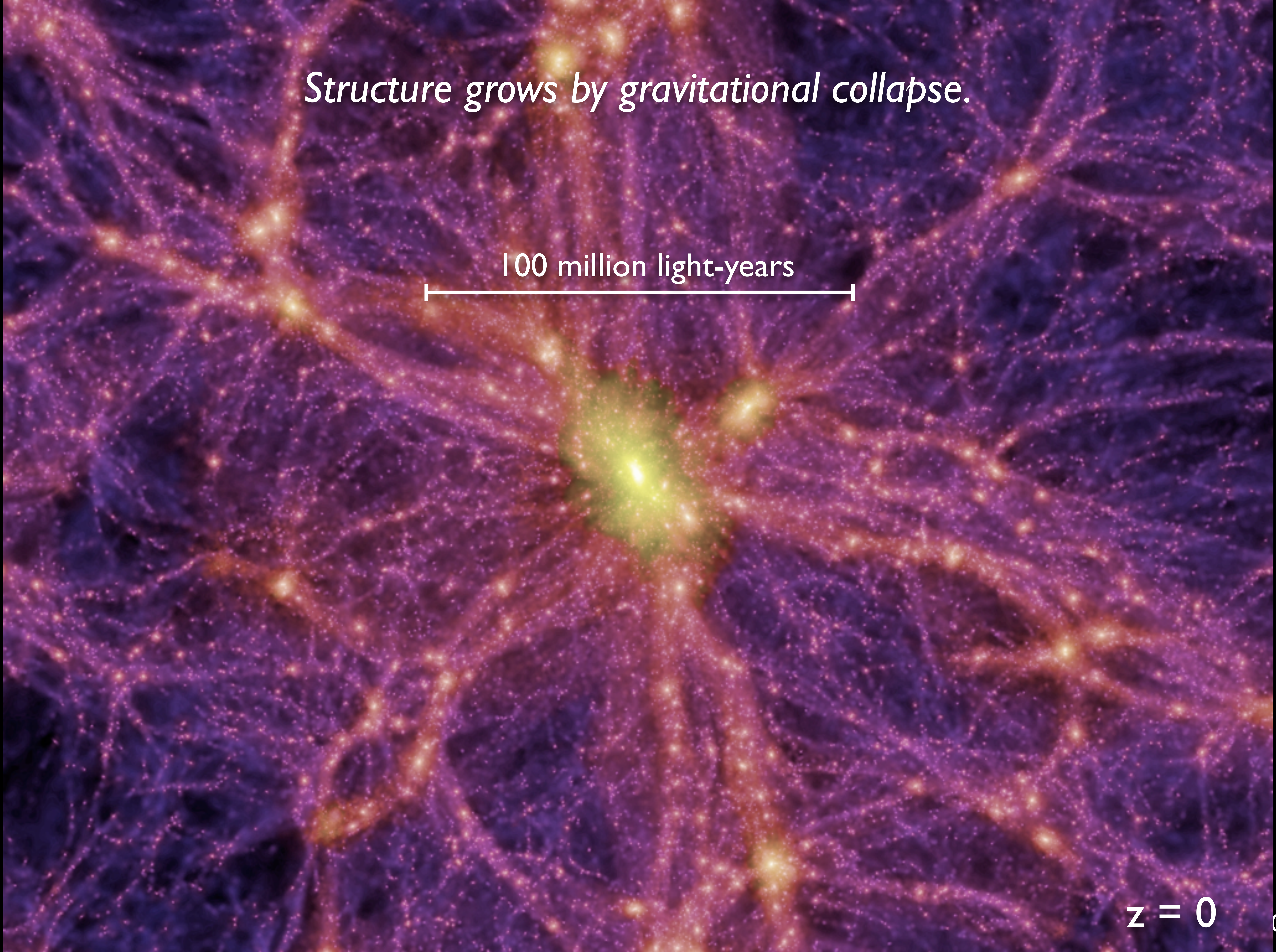
THE TIMES

25 April 1992

Stephen Hawking said of the COBE measurement:

“It is the discovery of the century, if not of all time.”



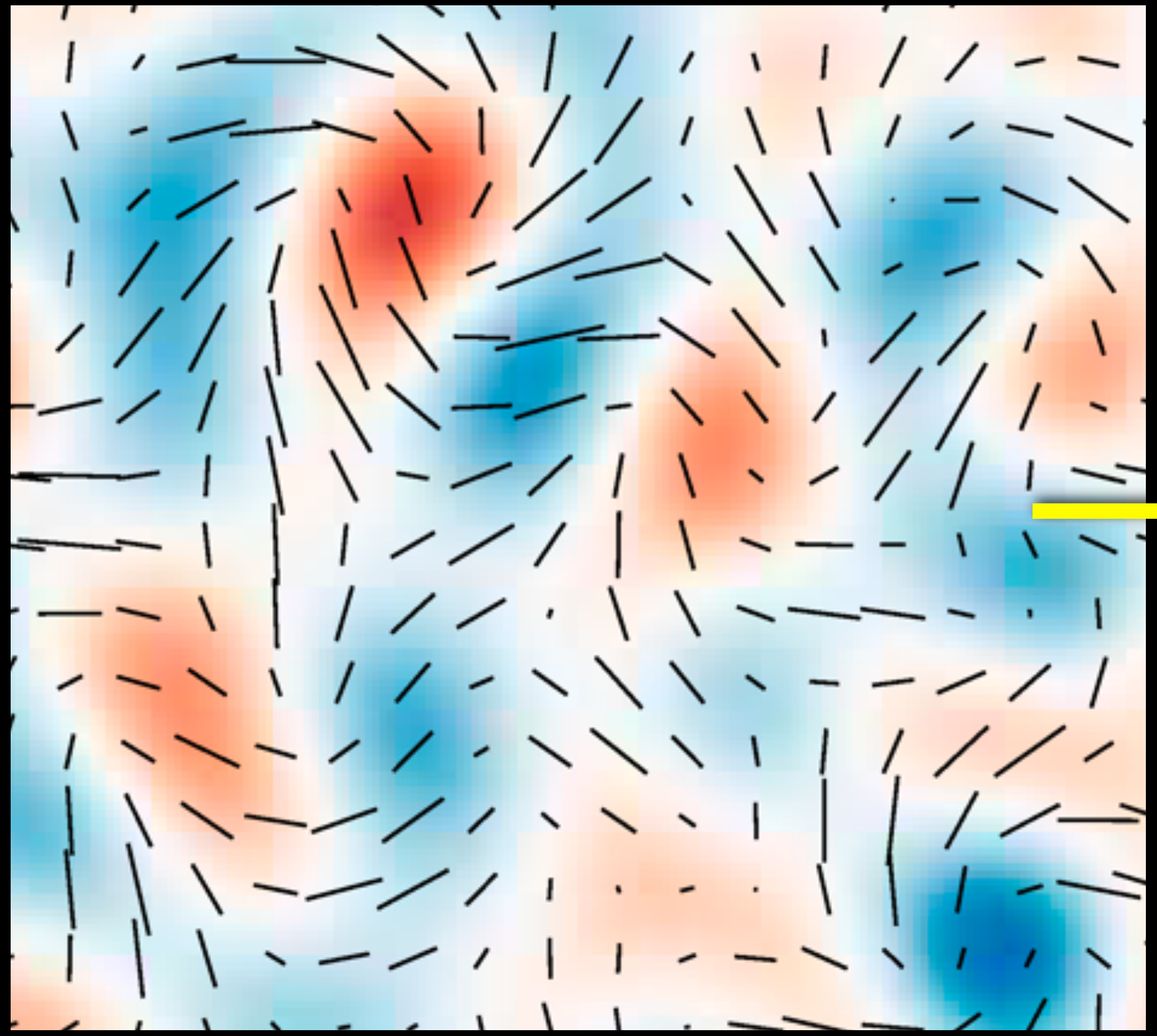

Structure grows by gravitational collapse.
100 million light-years
z = 0

Hubble Deep Field

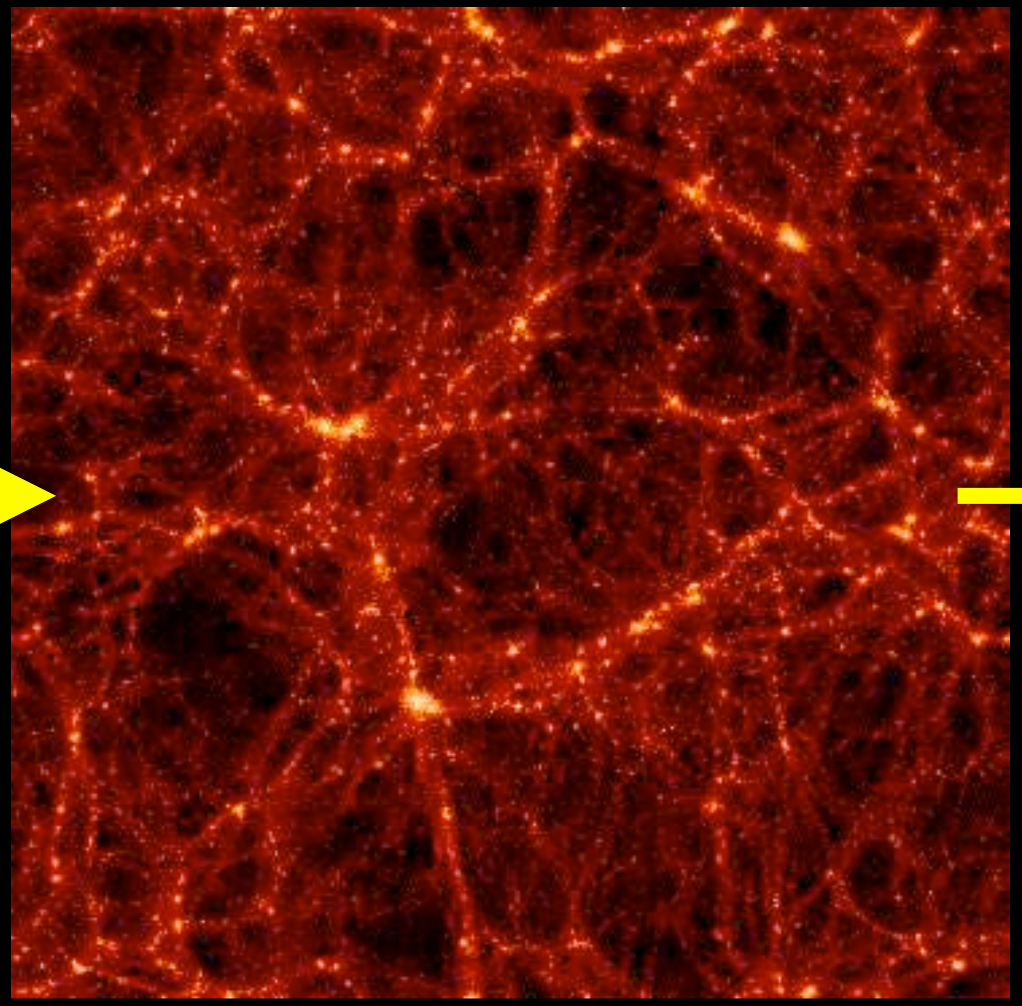
The CMB is a "Baby" Picture of the Universe

Cosmic Observables

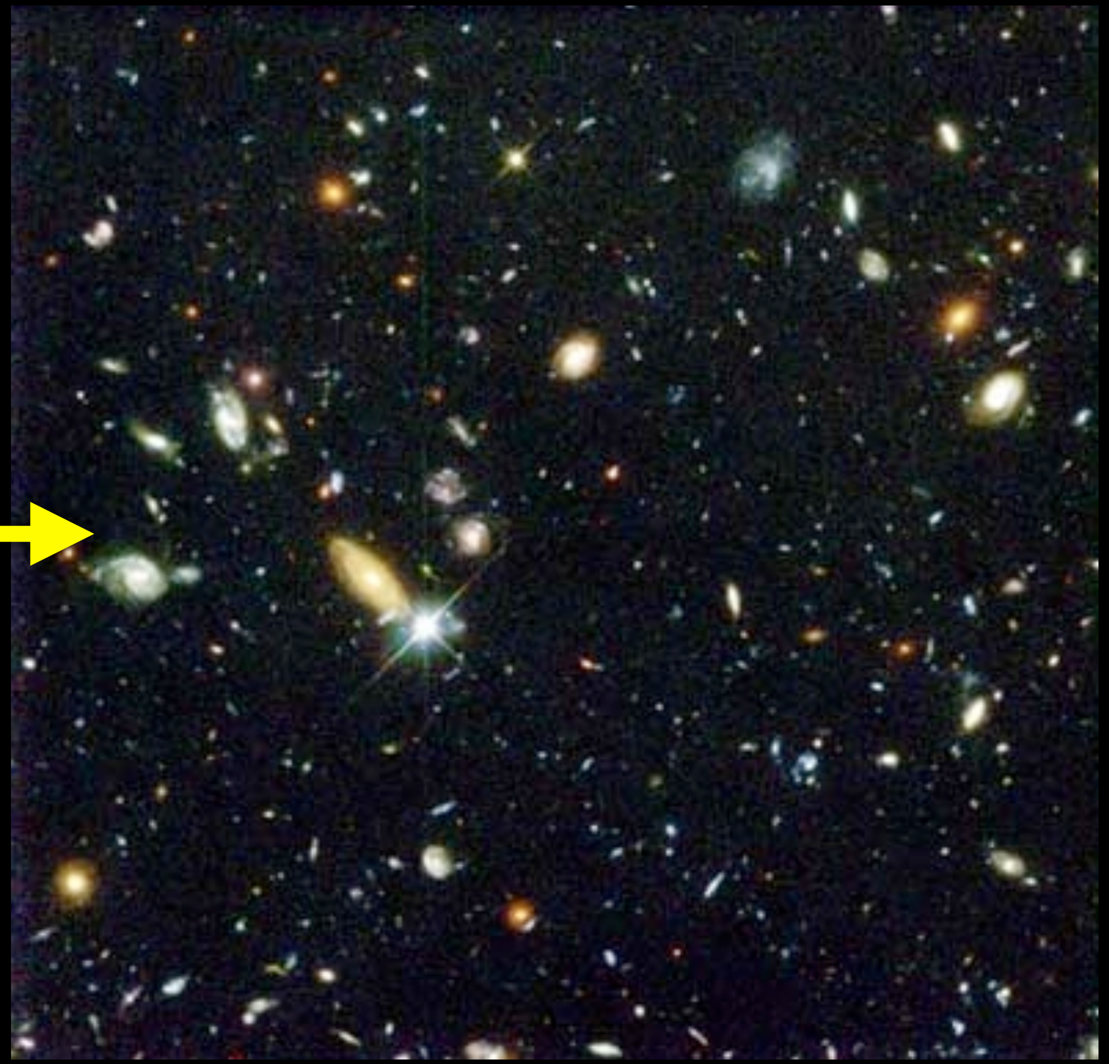
Cosmic Microwave Background



Structure Formation



Galaxies and Clusters of Galaxies



Human Equivalent Ages

First Several Minutes

First Few Years

Near Retirement

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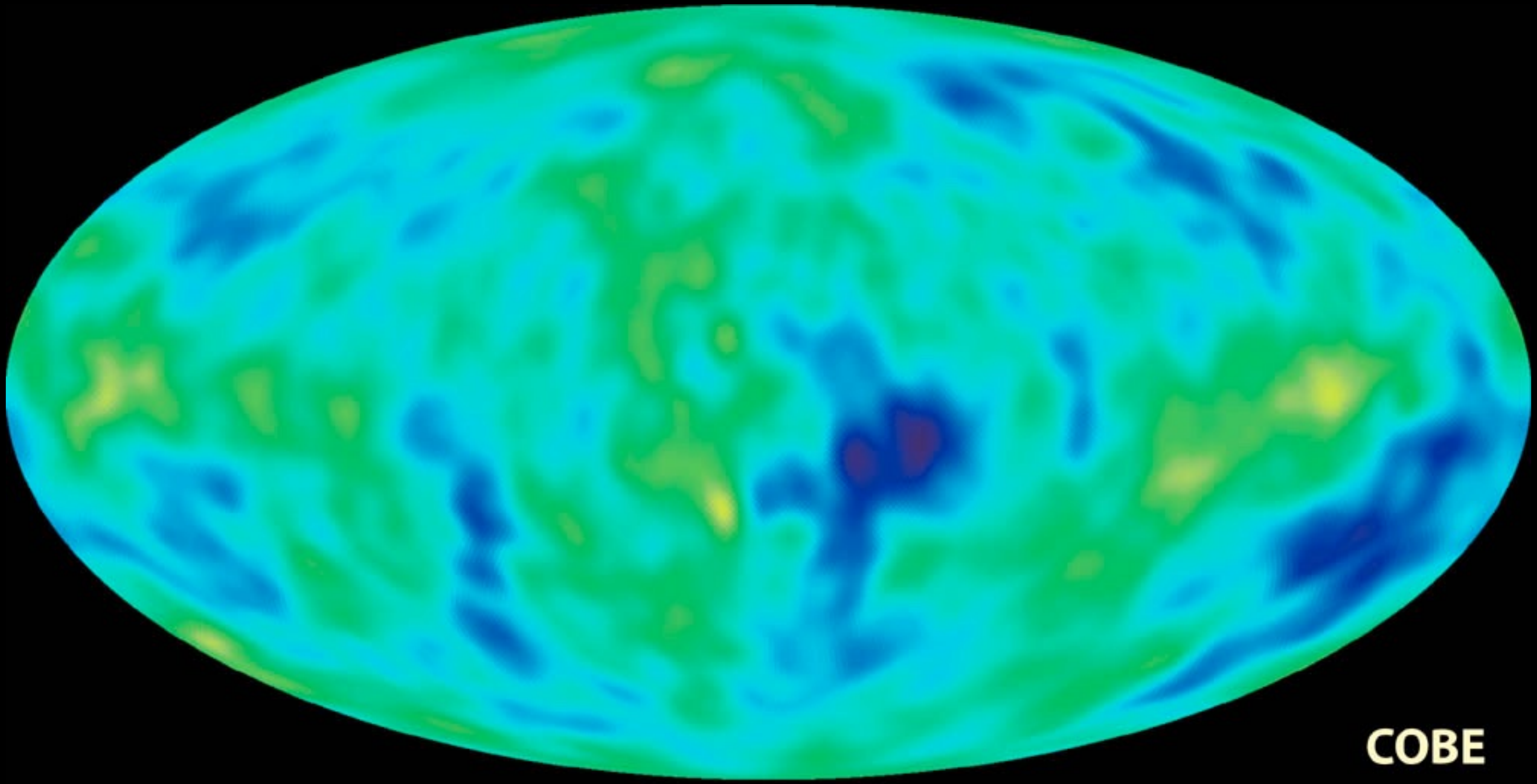
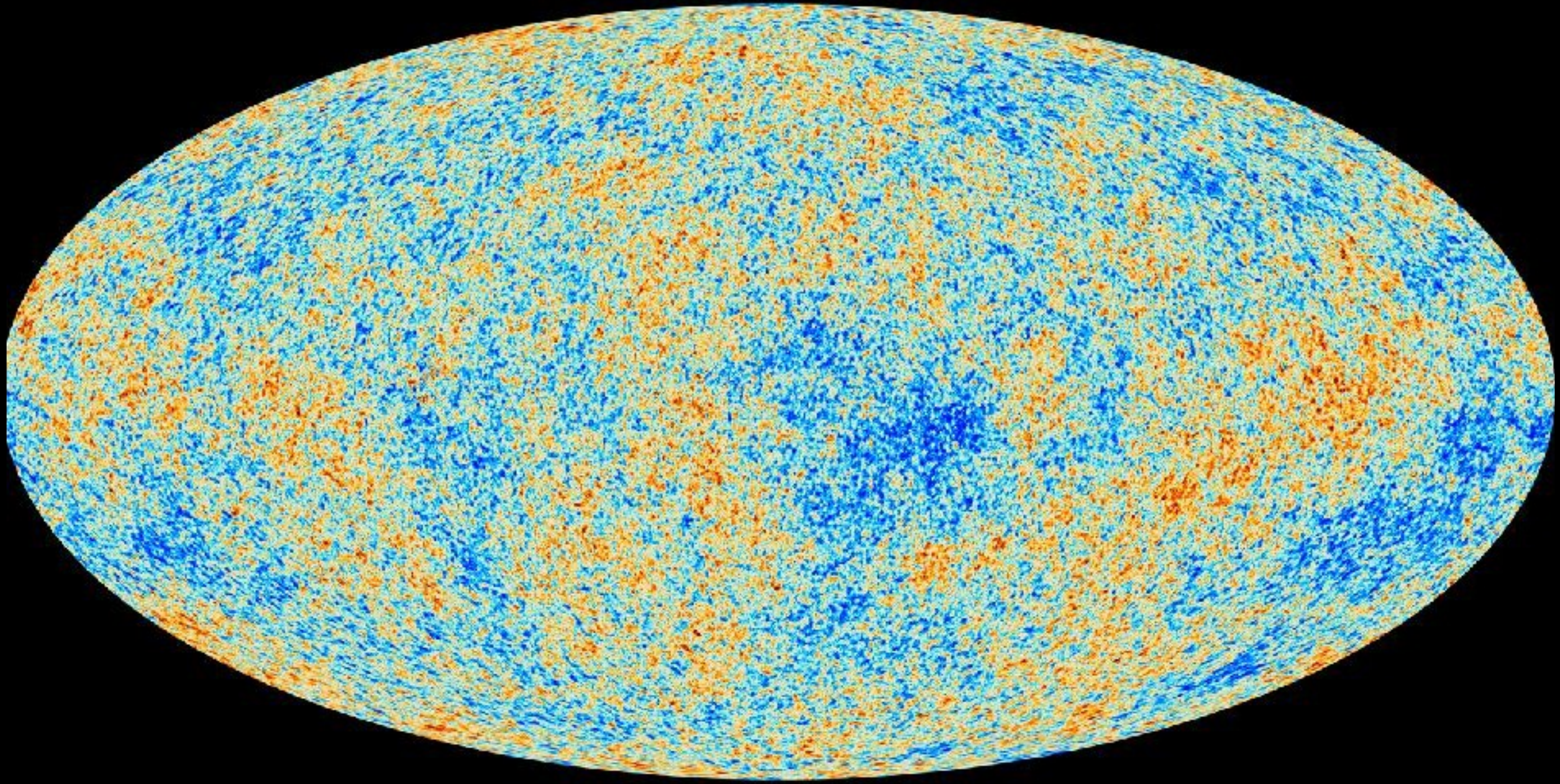
1992: COBE

1/100,000 fluctuations on 3 Kelvin background



2013: Planck

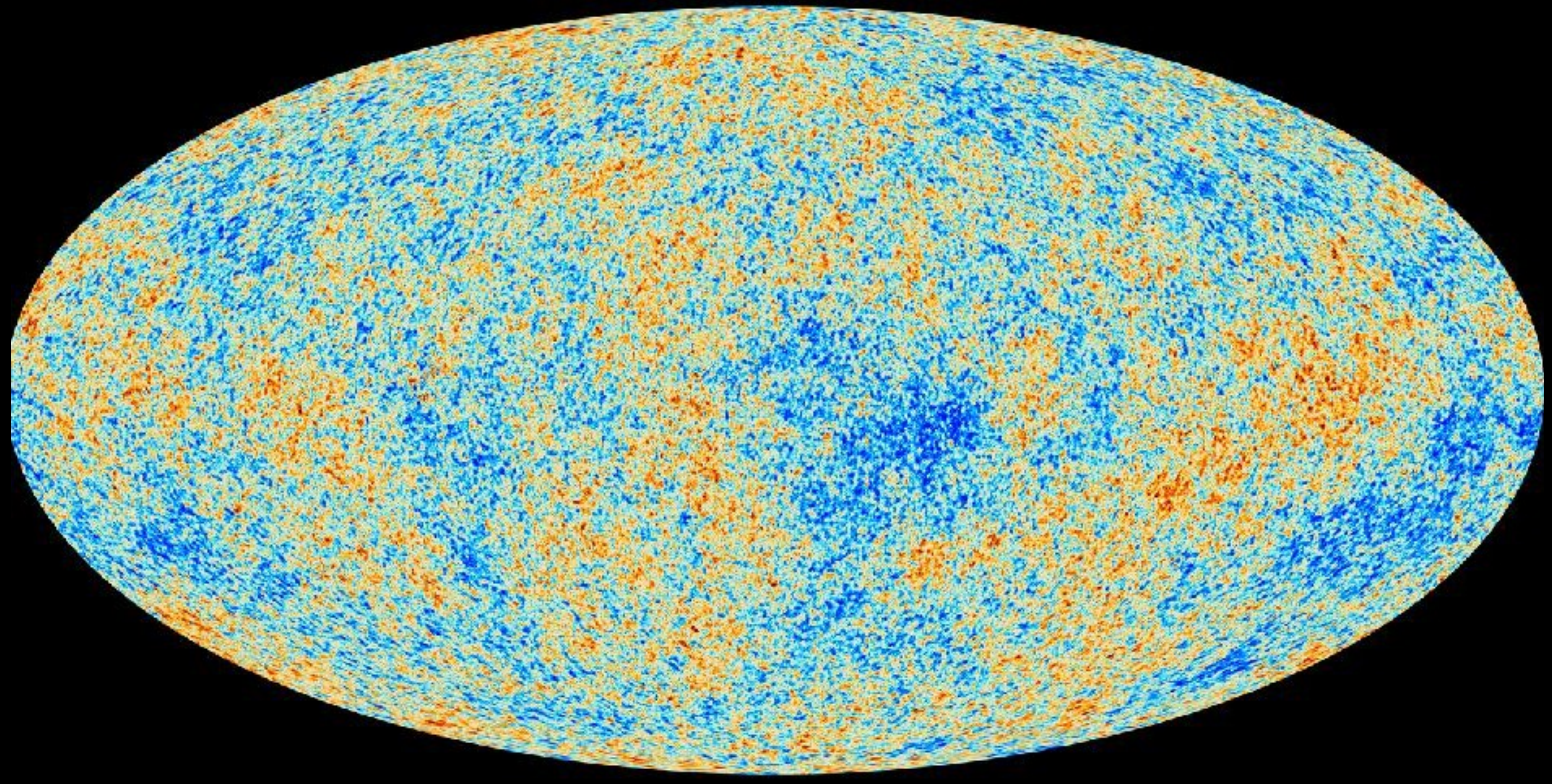
1/100,000 fluctuations on 3 Kelvin background



Credit: ESA (Planck)

What have we learned?

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



Bass **Treble**

Like a stereo equalizer characterizes the spectrum of sound, the **"angular power spectrum"** characterizes the signal in the CMB maps as a function of spatial scale.

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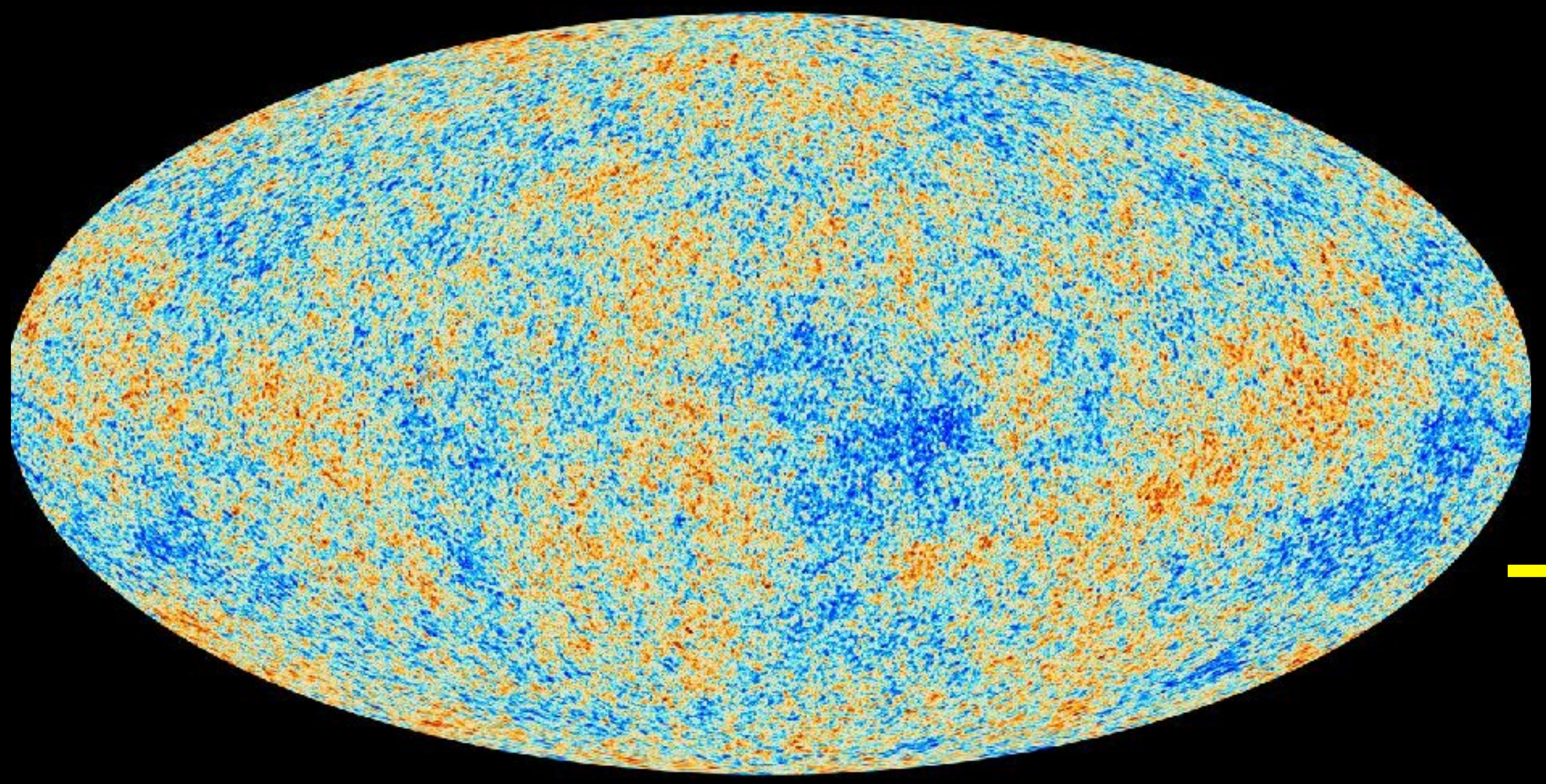
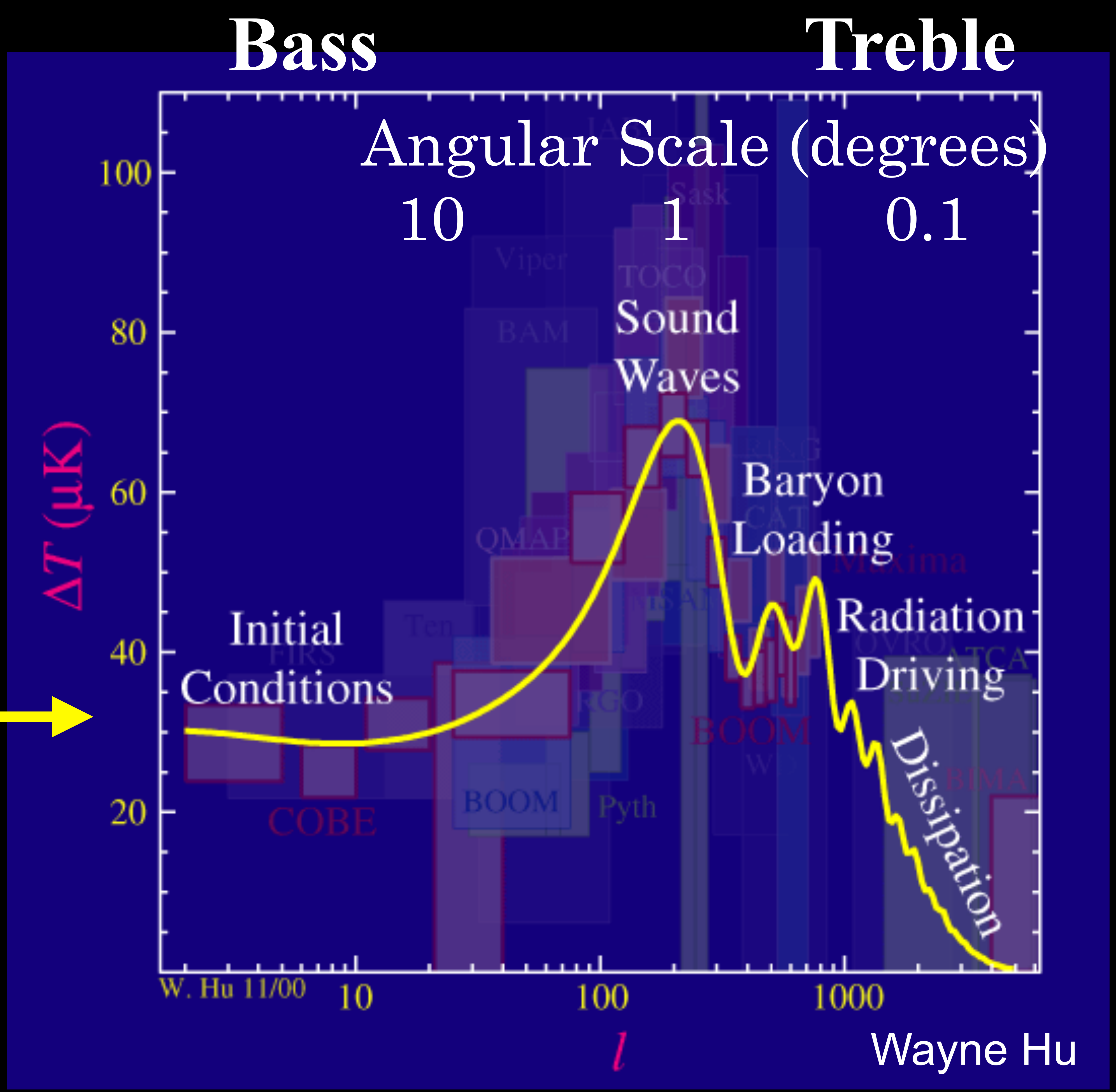
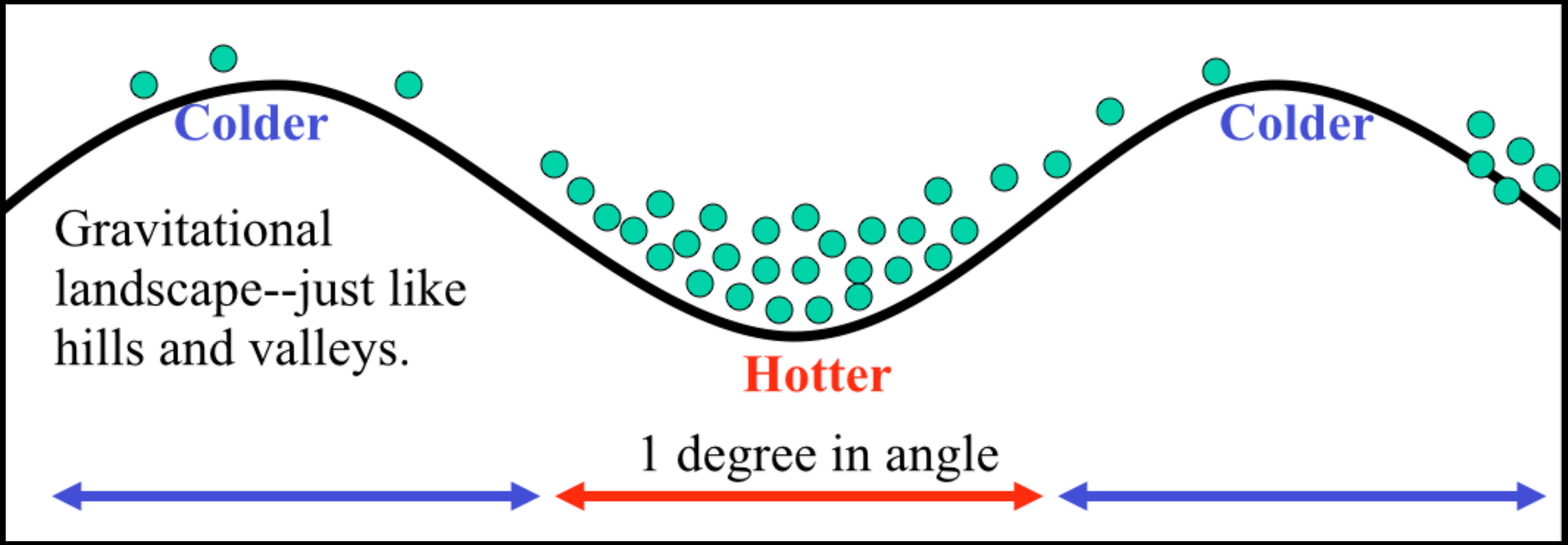
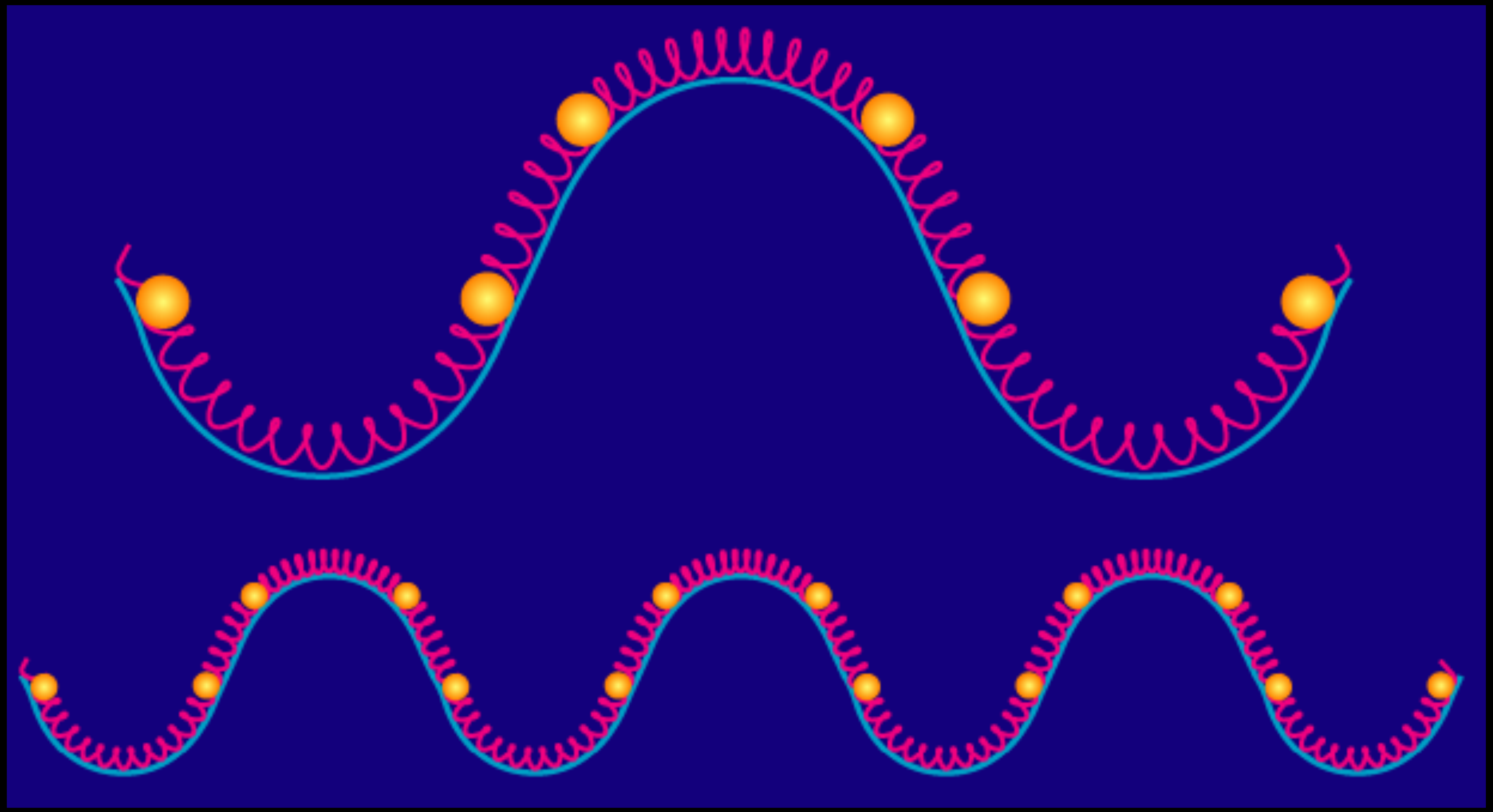


Cosmology predicts a distinct "spectrum" to the CMB with well-defined "harmonics"



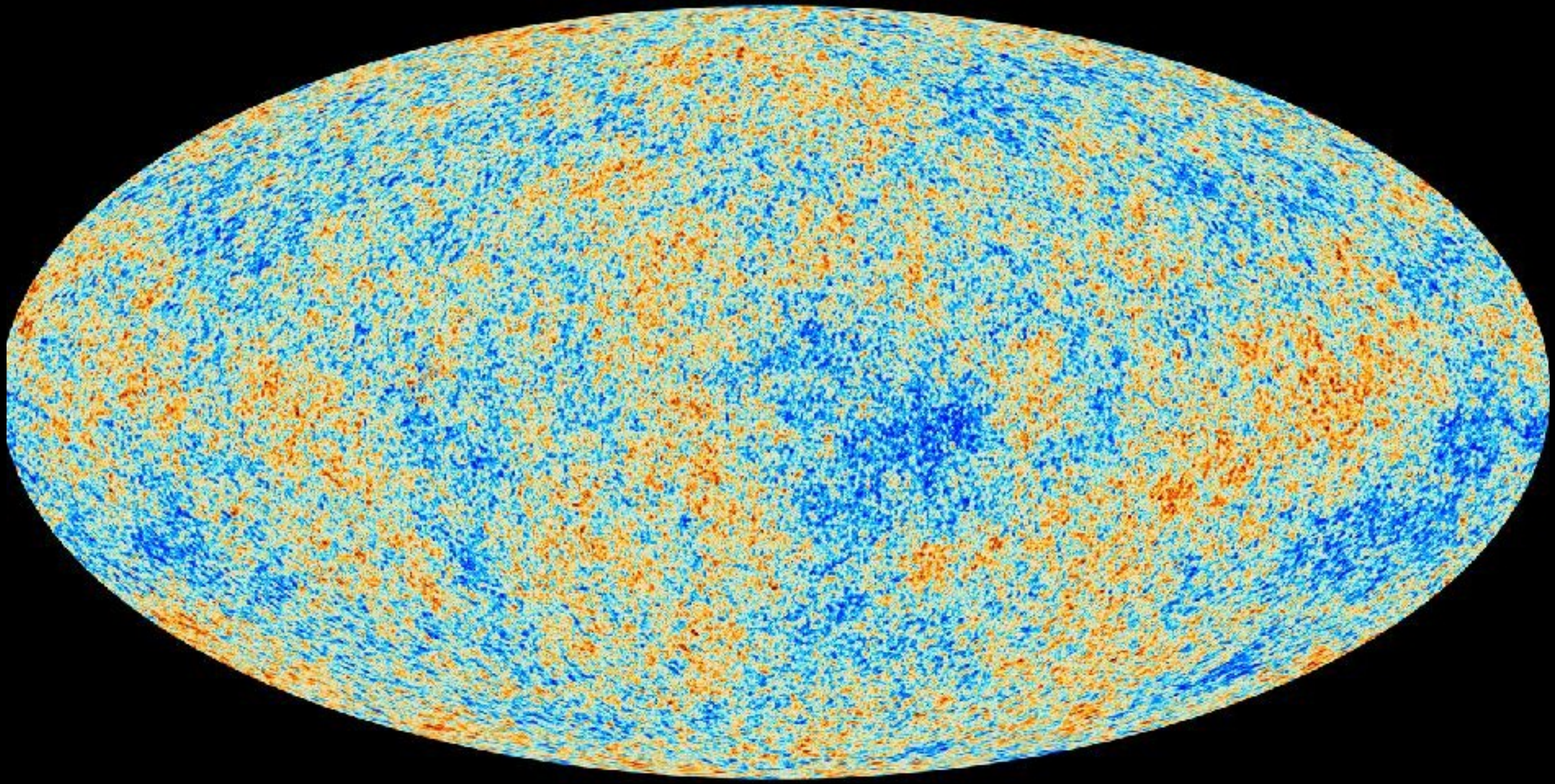
A Cosmic Symphony!





2013: Planck

1/100,000 fluctuations on 3 Kelvin background



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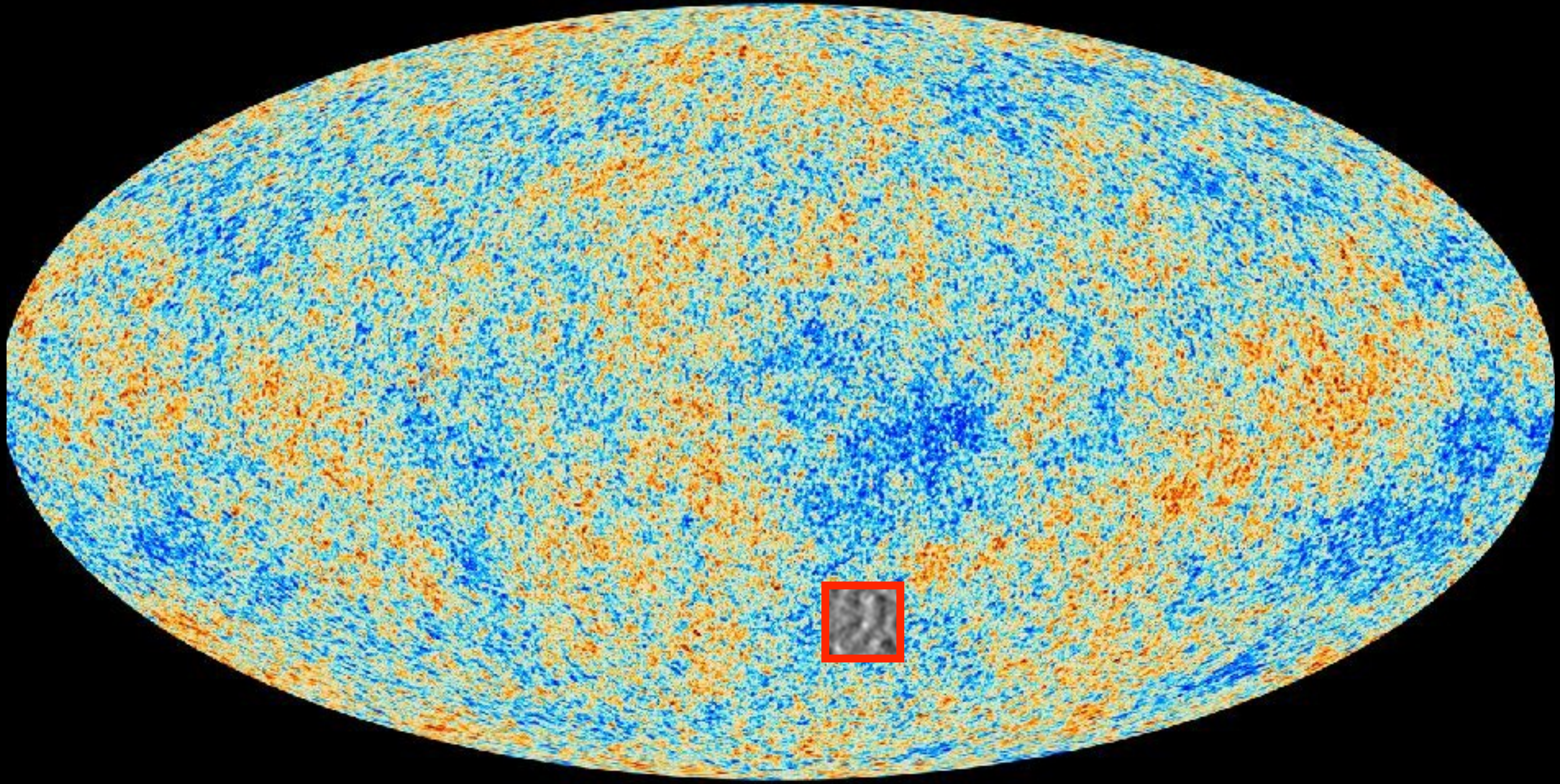


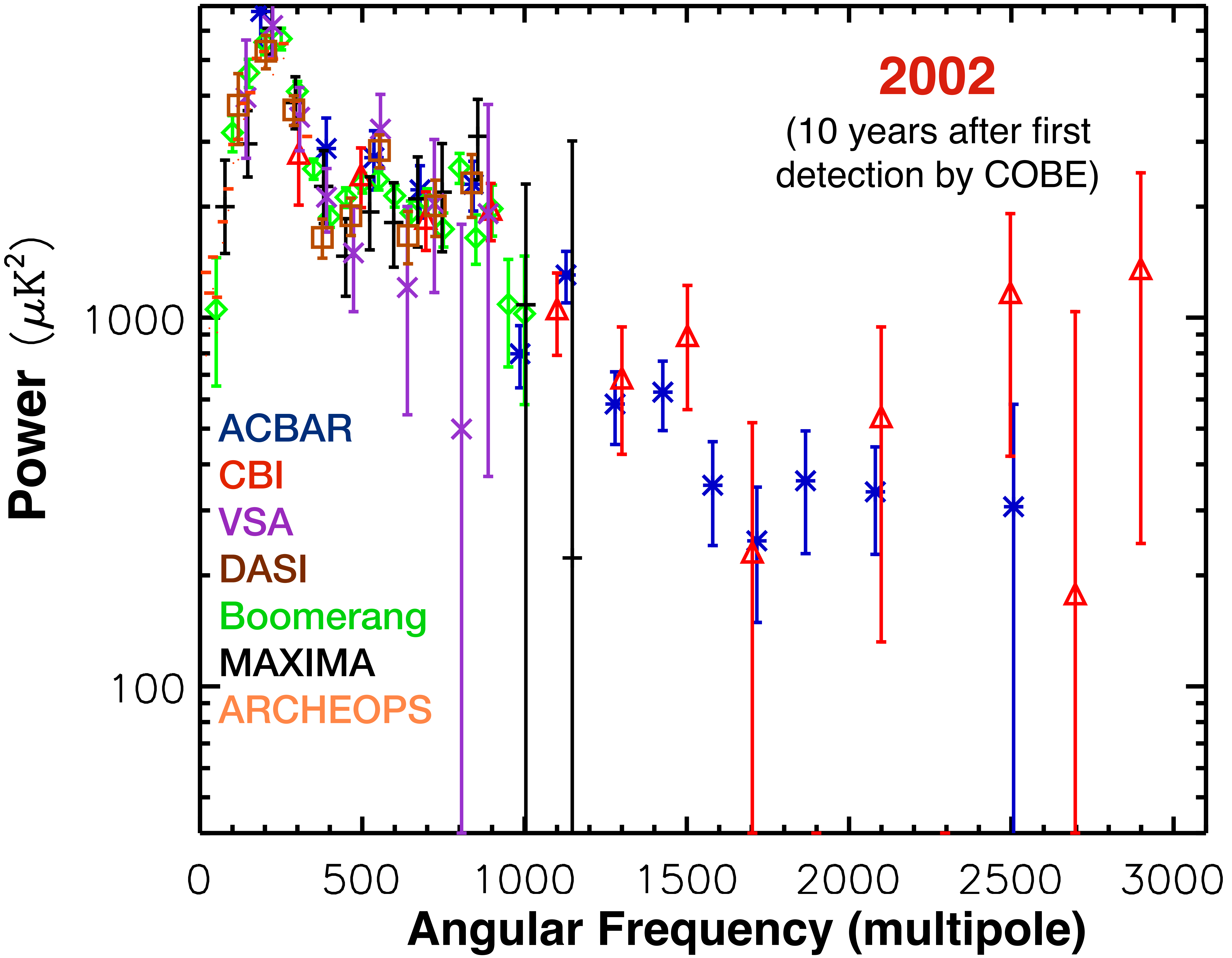
Credit: ESA (Planck)


Planck
50 deg²
The moon
(for scale)

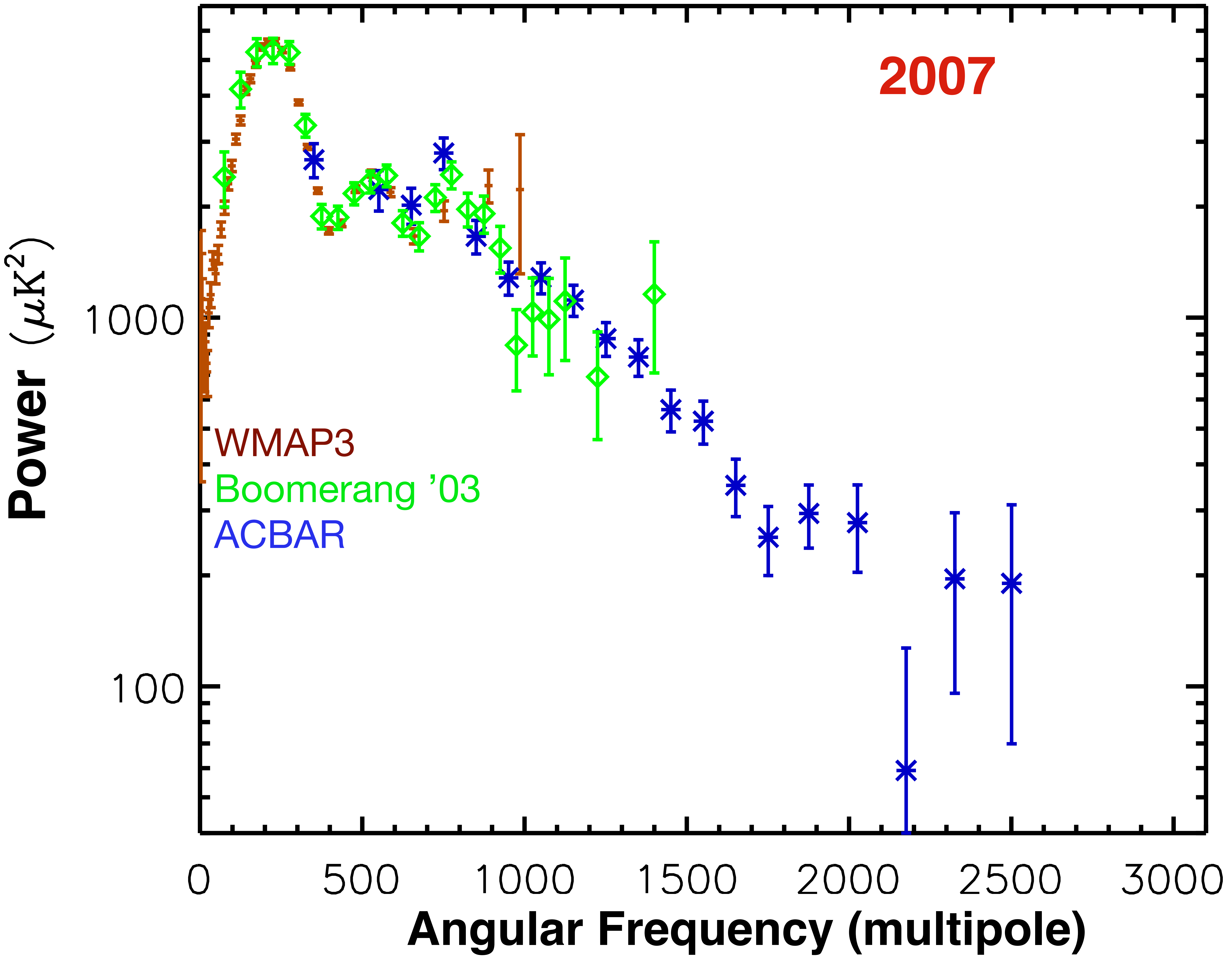

SPT
50 deg^2
6x deeper
6x finer angular resolution
The moon (for scale)


SPT
150 GHz
50 deg²
The moon
(for scale)
CMB Anisotropy
Variations in the
Matter Distribution in
the Early Universe

Evolution of CMB Power Spectrum Measurements



Evolution of CMB Power Spectrum Measurements



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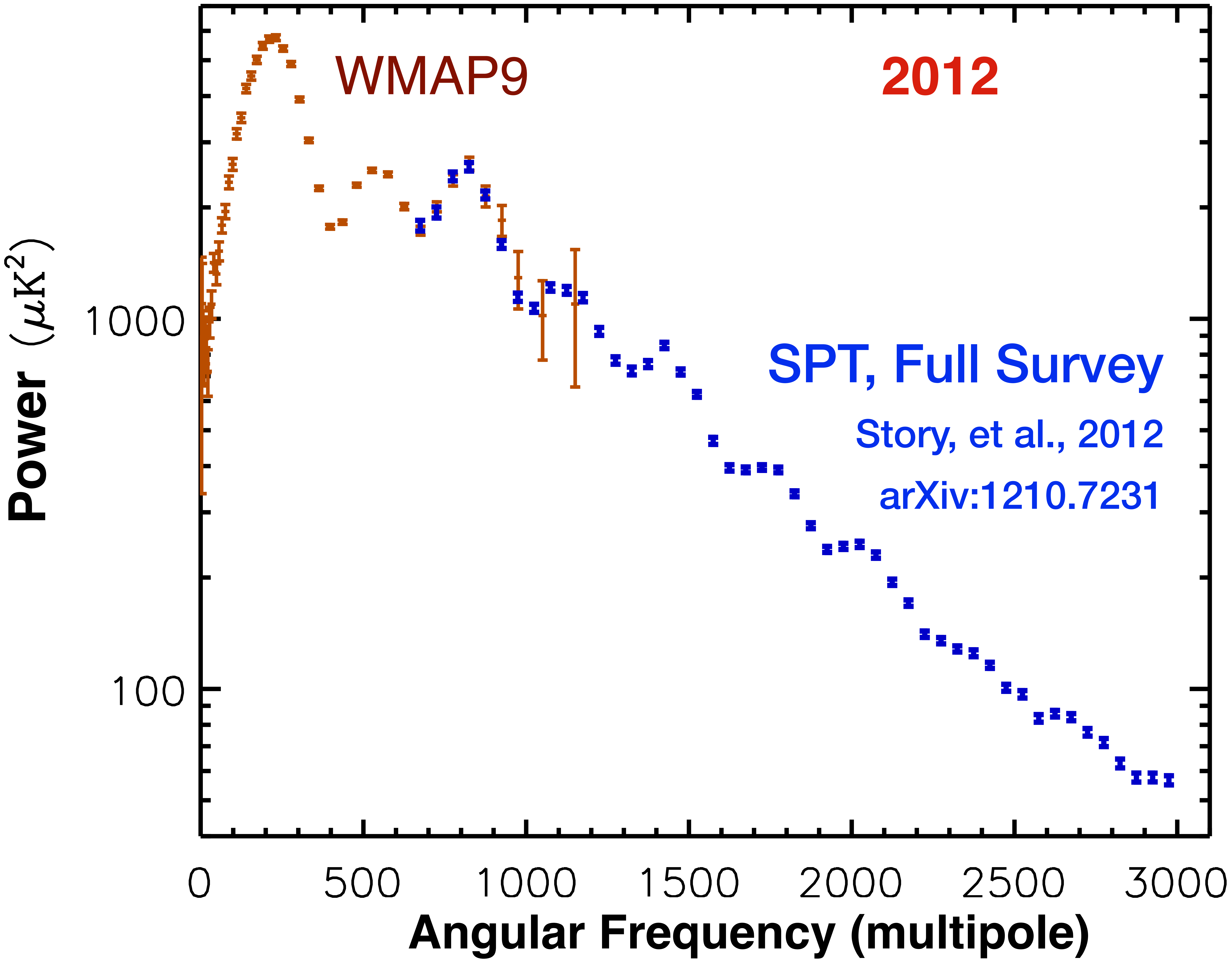

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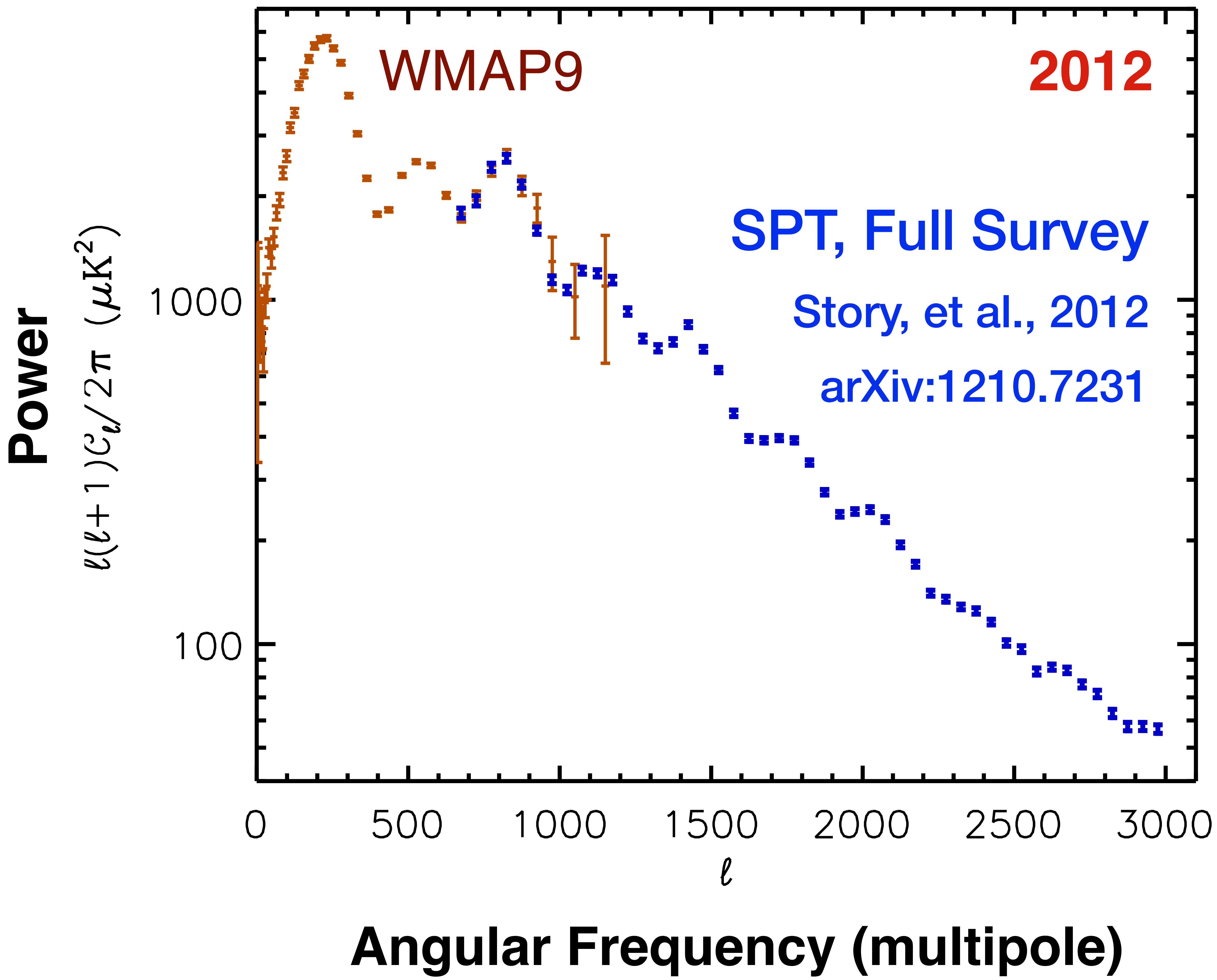
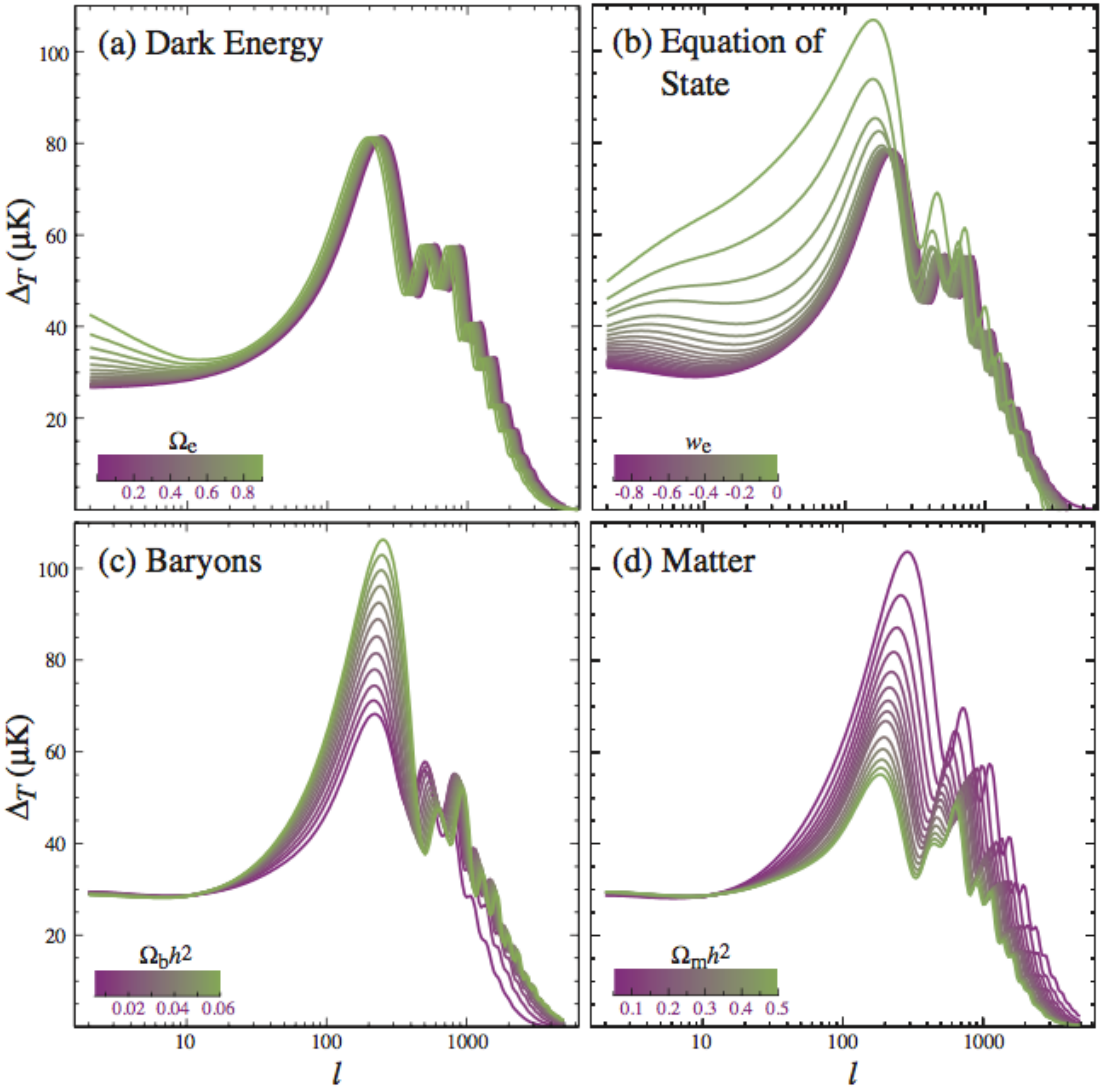
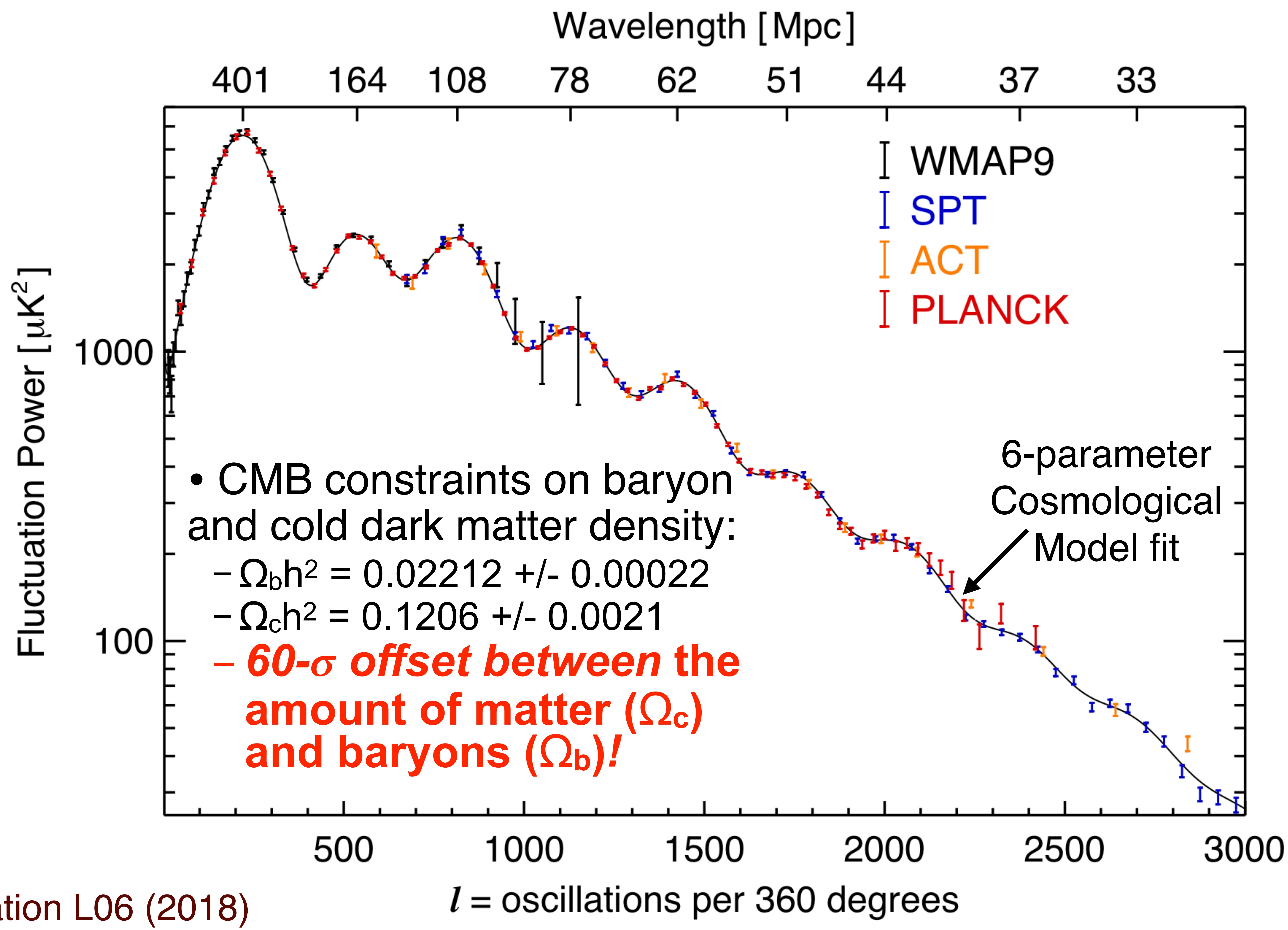




Hu 2008, arXiv: 0802.3688

The CMB Today: implies a Universe dominated by dark matter and dark energy (ΛCDM model)



- CMB constraints on baryon and cold dark matter density:
  - $\Omega_b h^2$ = 0.02212 +/- 0.00022
  - $\Omega_c h^2$ = 0.1206 +/- 0.0021
  - ***60-σ offset between*** **the amount of matter (Ω_c) and baryons (Ω_b)*!***

Planck Collaboration L06 (2018)

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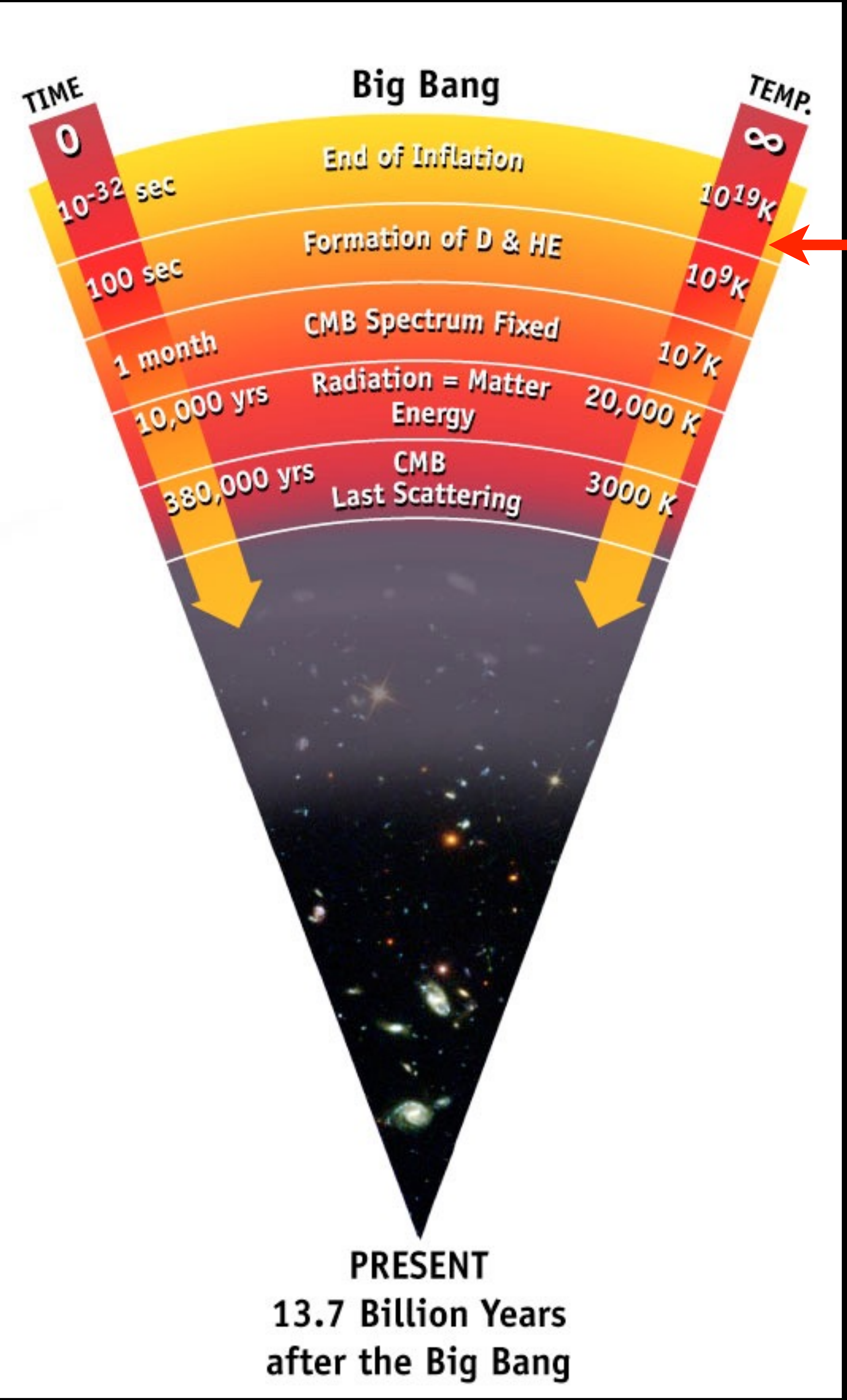
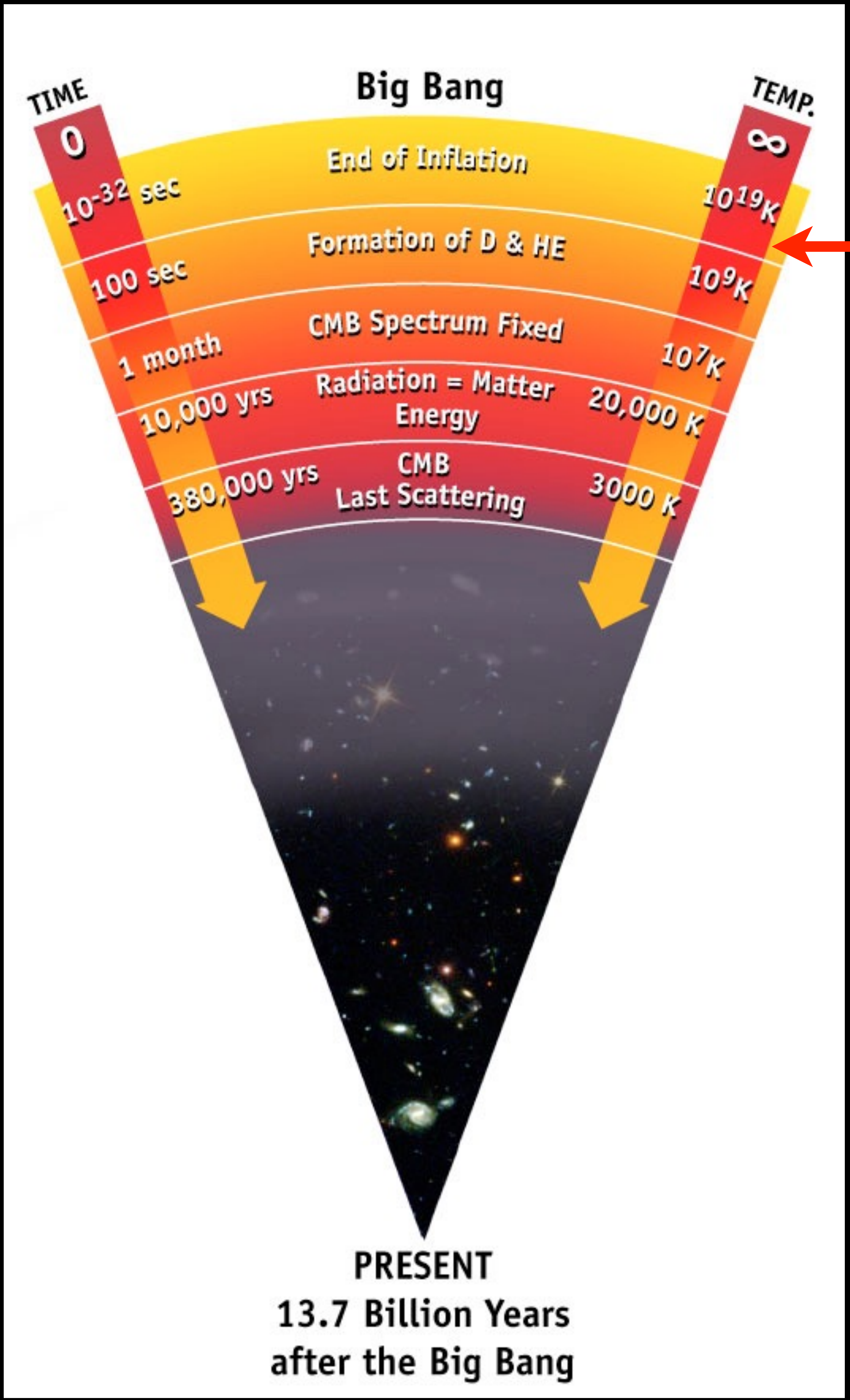


The Cosmic Neutrino Background

Cosmic Neutrino Background **1 s (~2 MeV)**

- Neutrinos were thermally generated in the very early universe (first ~second), coupled to regular matter via weak interactions.
- After ~1-sec (temperatures <~2MeV), neutrinos decoupled from regular matter, and these relic neutrinos today are called the **Cosmic Neutrino Background** (or CvB)



The Cosmic Neutrino Background

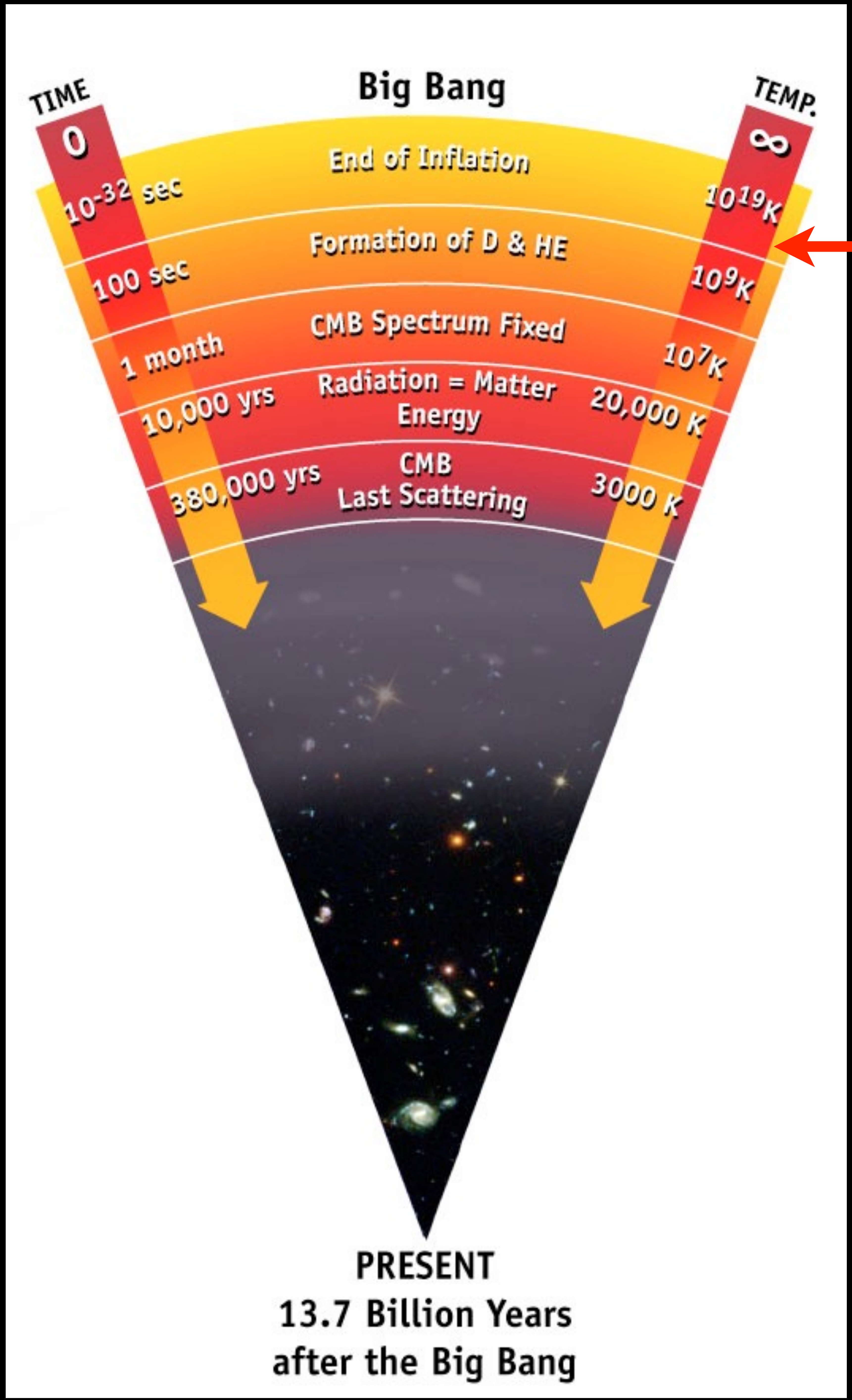
Cosmic Neutrino Background **1 s (~2 MeV)**

- Since neutrinos are in thermal equilibrium with photons, the density of neutrinos in the Universe only depends on the photon density and the **number of neutrino species**

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

- **Neff** is the effective number of relativistic species.
- Standard model prediction is **Neff = 3.044**
  - 3 from 3 neutrino species. And 0.044 for energy injected by electron/positron annihilation.
- Neff > 3.044 could correspond additional relativistic density, e.g., due to a new relativistic particle species generated thermally during recombination

The Cosmic Neutrino Background



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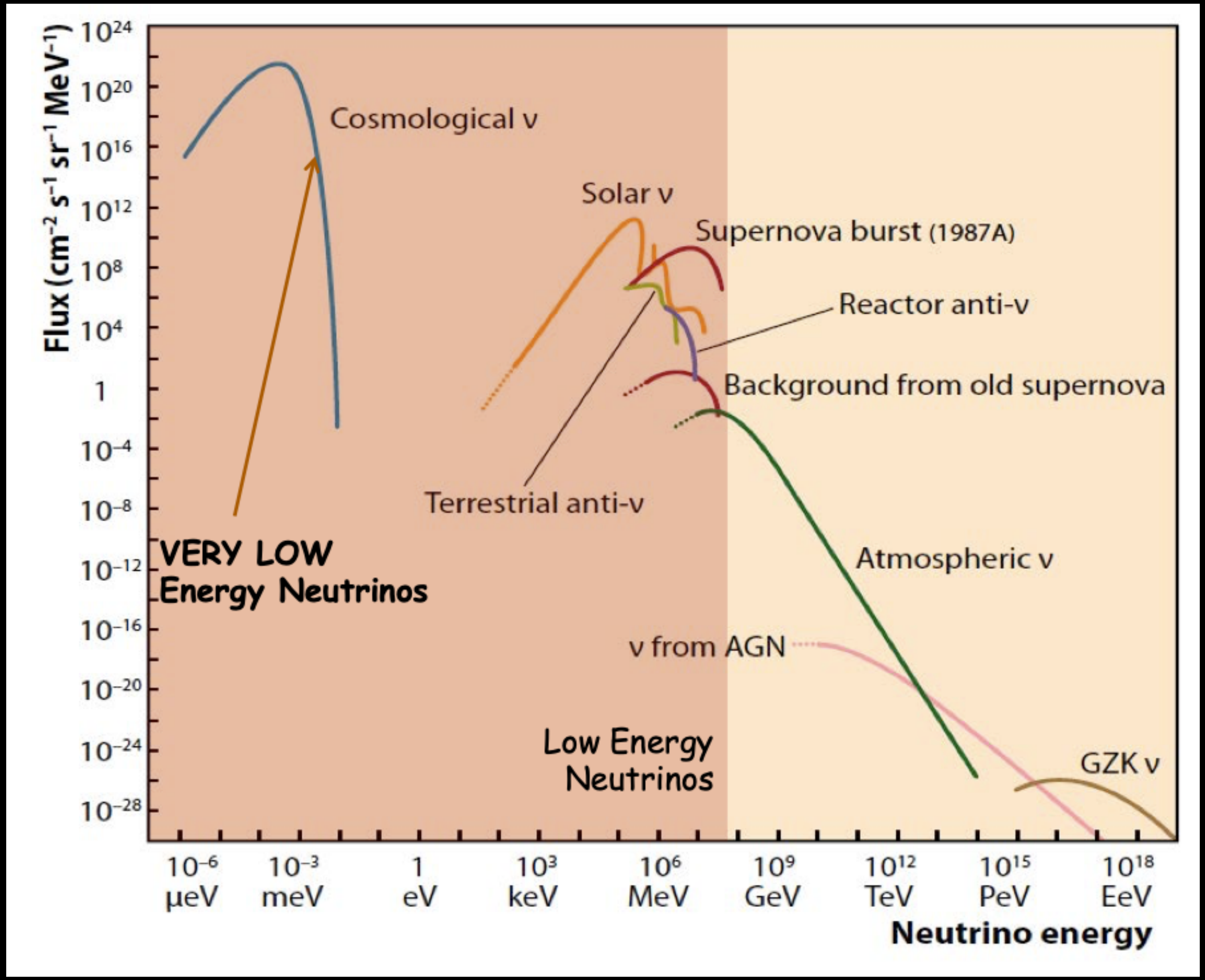
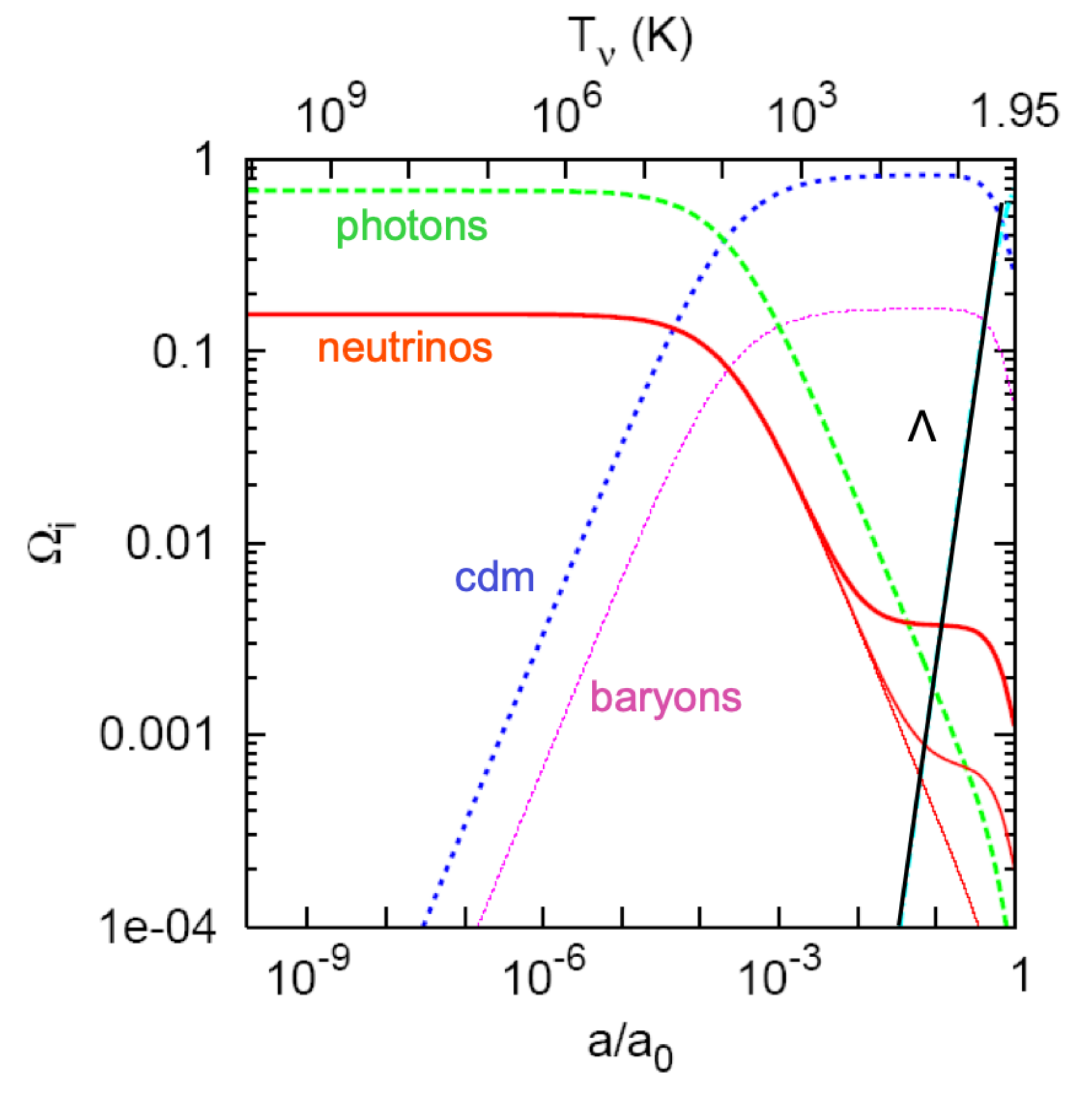
1 s (~2 MeV)



Number Density of Neutrinos over Cosmic Time

Density of Components (Ω_i)



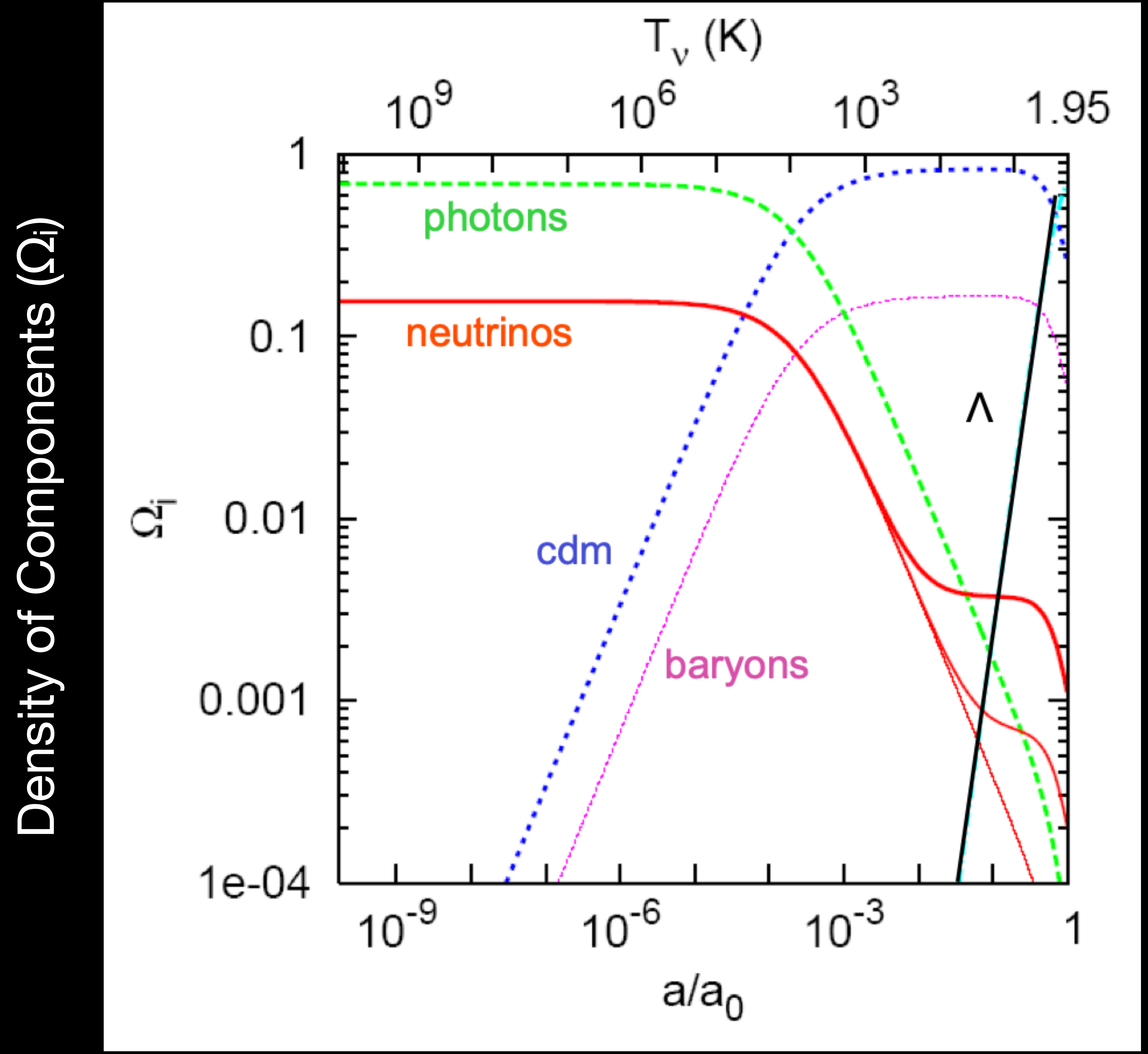
Scale Factor (of Universe) = a

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

- Universe began in **photon dominated** state
- Components dilute differently as Universe expands, based on scale factor (a), or the size of Universe, e.g.,
  - Dark Energy is modeled as a "cosmological constant", density independent of scale factor
  - Radiation energy density dilutes faster because wavelength also scales with scale factor
- Radiation component includes photons and relativistic neutrinos
- Matter component includes baryons, dark matter, and non-relativistic neutrinos.

Lesourges & Pastor (2014), arXiv: 1404.1740

Number Density of Neutrinos over Cosmic Time



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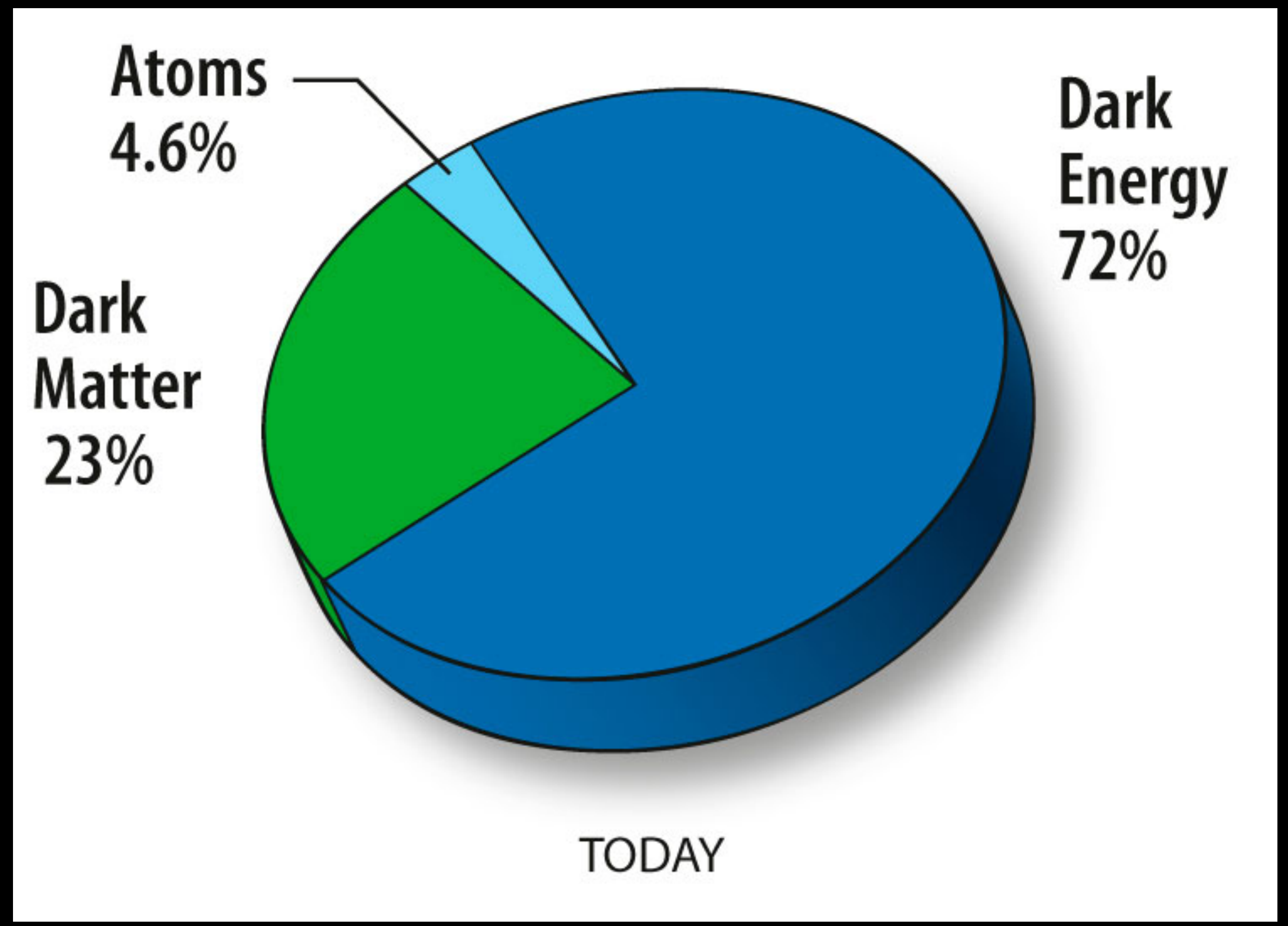
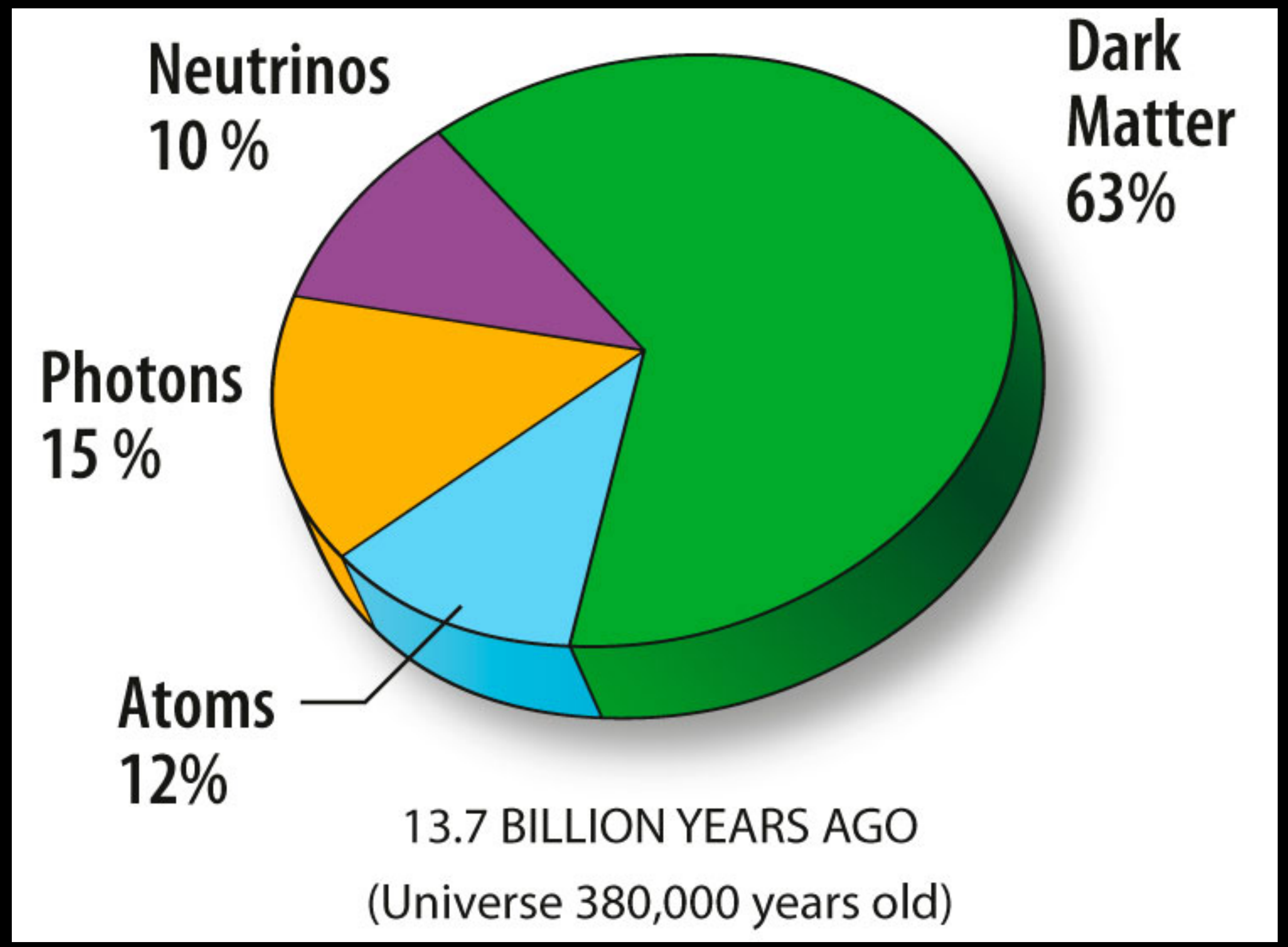
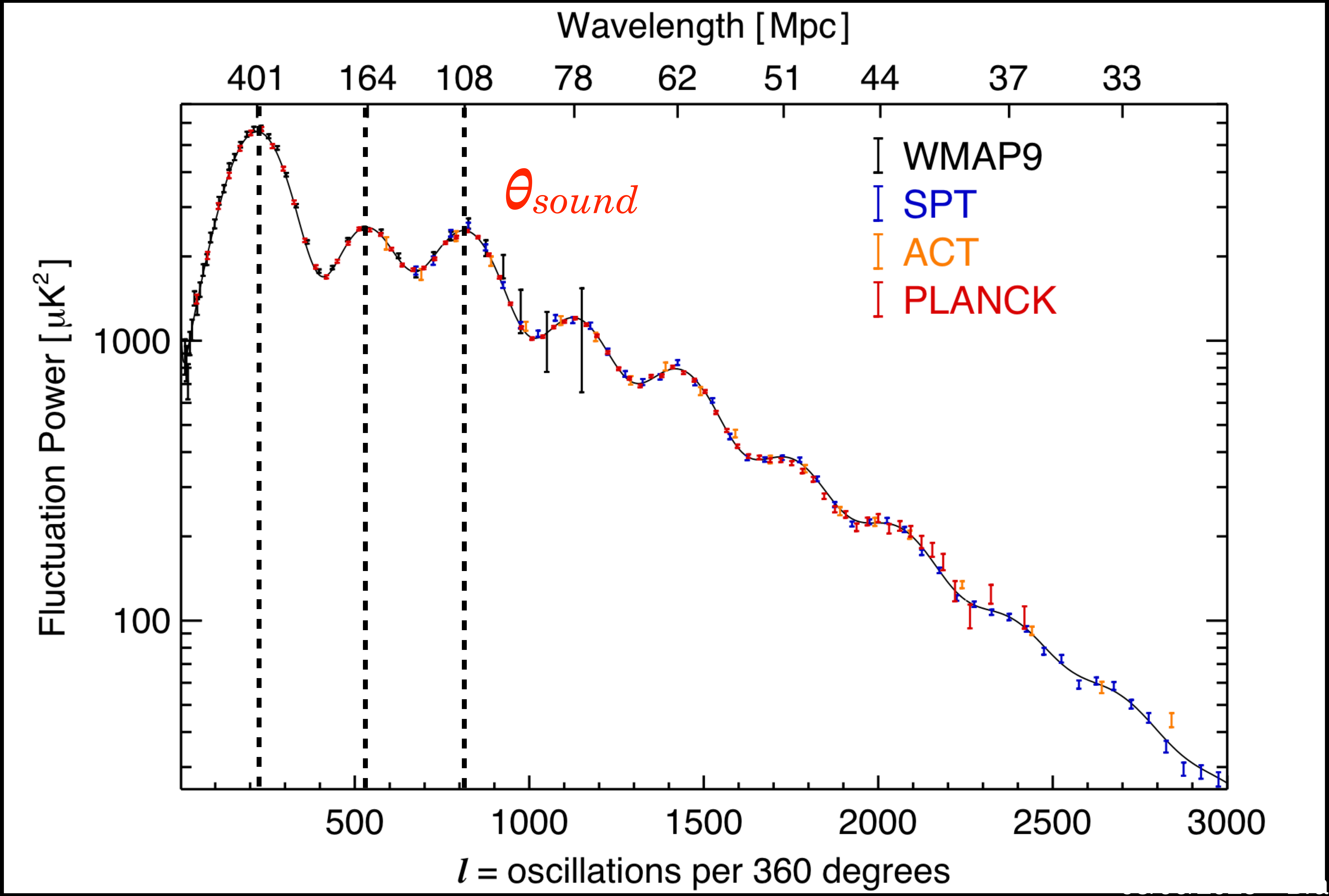




When the CMB was emitted 13.7 Billion Years ago, neutrinos made up ~10% of the energy density of the Universe

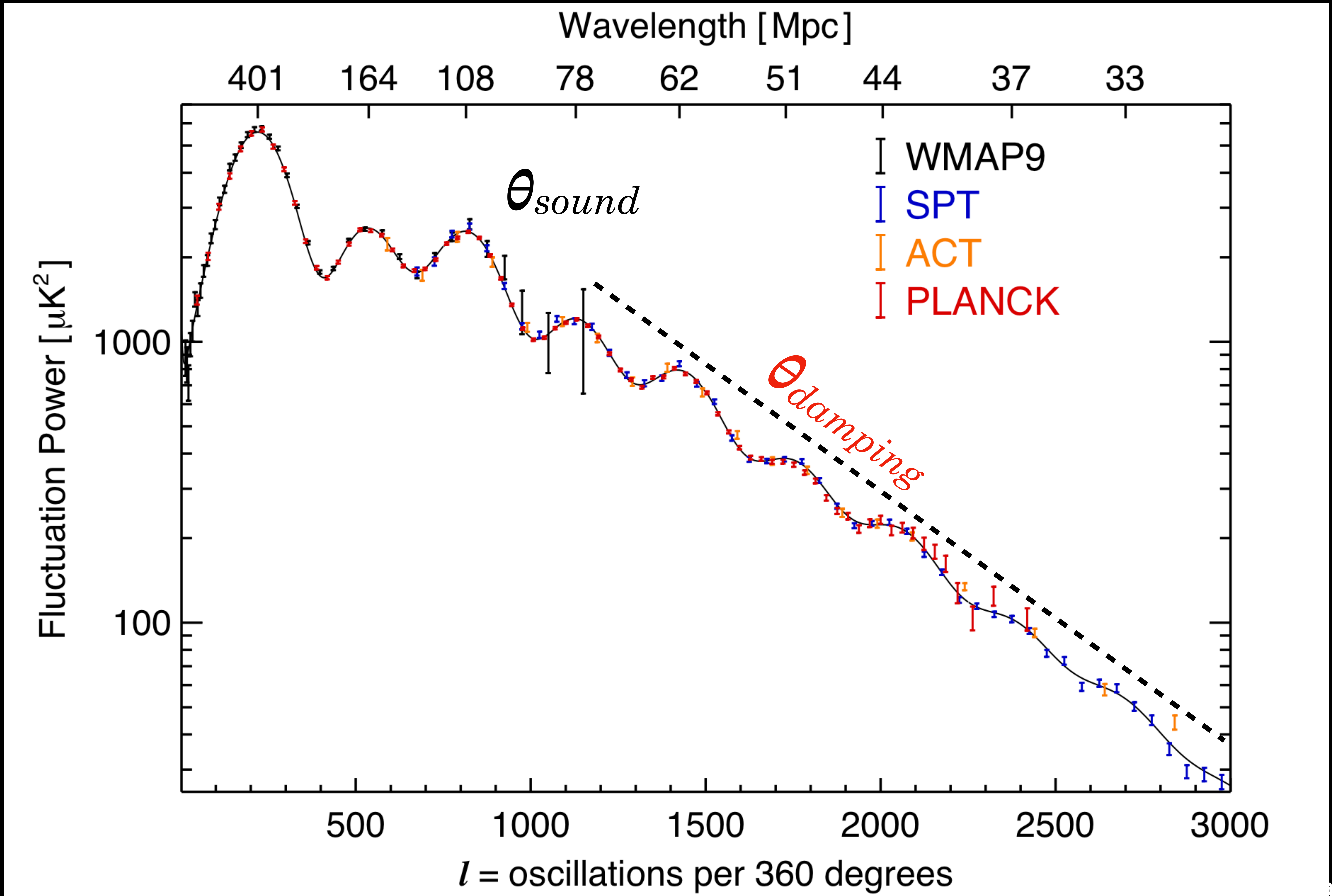
Lesourges & Pastor (2014), arXiv: 1404.1740

CMB Angular Scales



θ_{sound}, is the angular distance a sound wave could have travelled at recombination

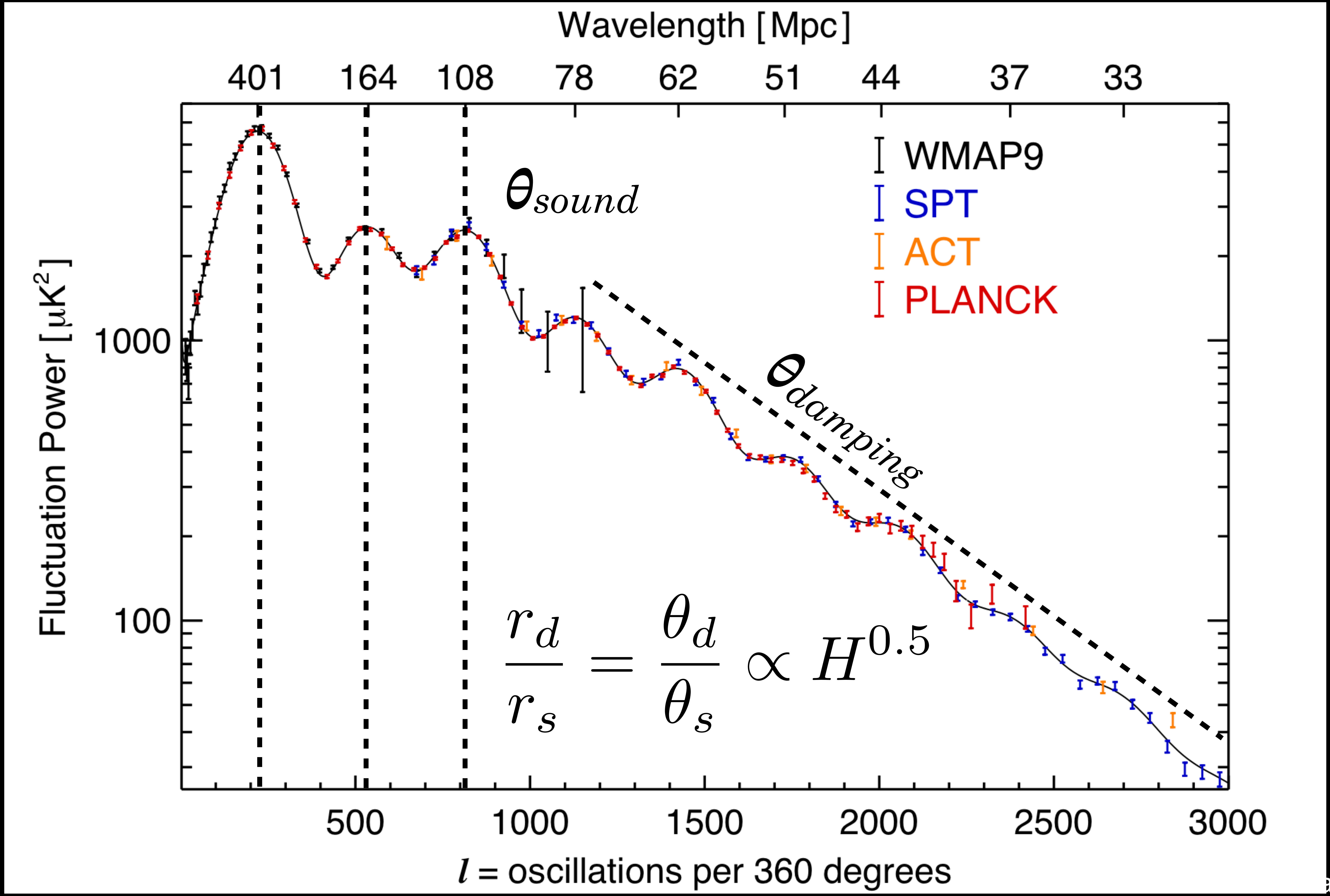
CMB Angular Scales



Photons have a mean free path and diffuse in hot plasma, causing exponential damping in CMB power spectrum.

$\theta_{damping}$, CMB photon diffusion length at recombination

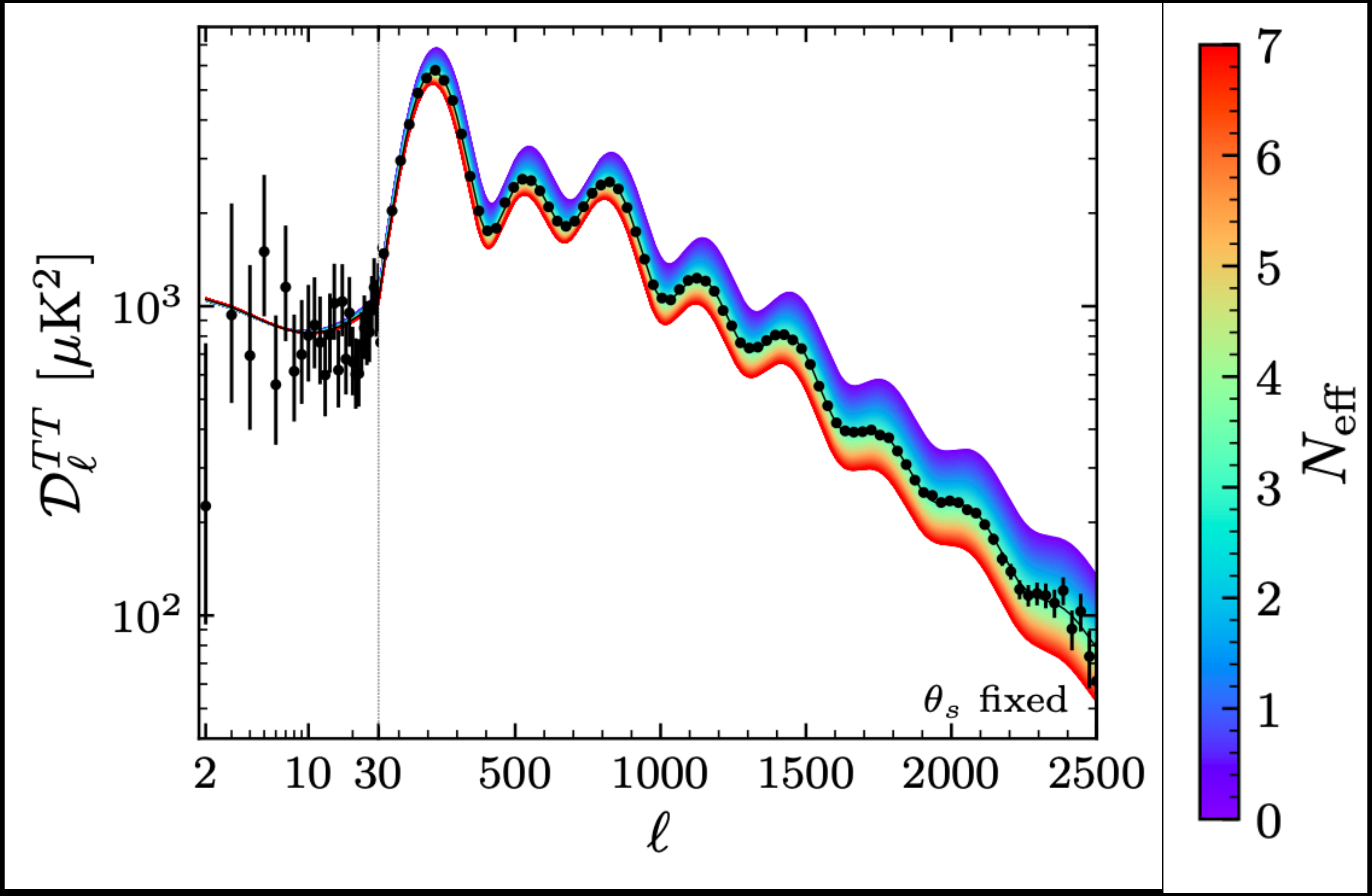
CMB Angular Scales



A measurement of both the sound and damping scale allows a measurement of the expansion rate (H) at recombination (z ~ 1100).

The expansion rate depends on the density / total number of neutrinos.

CMB Power Spectrum variation with Neff



Gerbino et al. (2022), arXiv: 2203.07377

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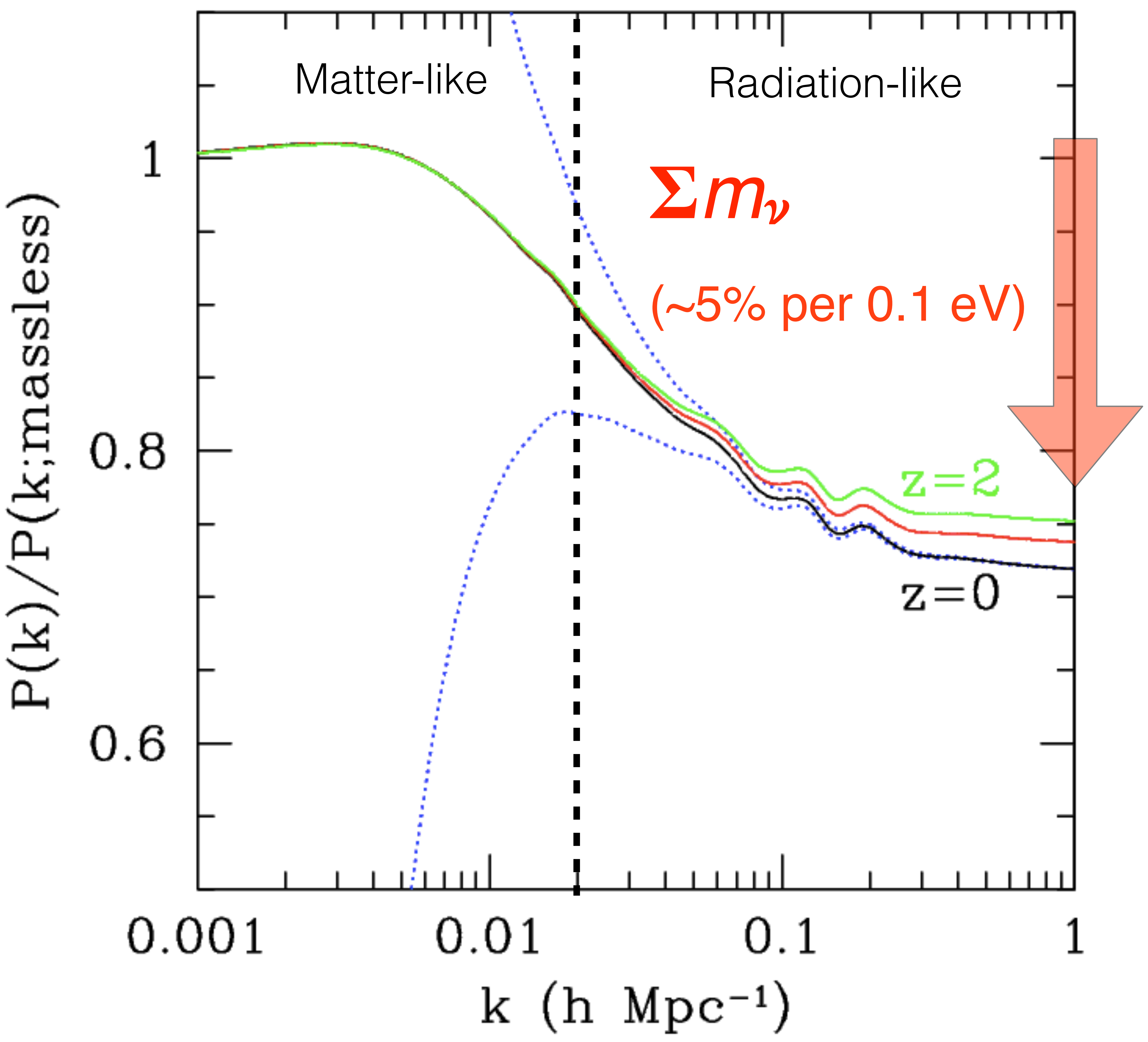
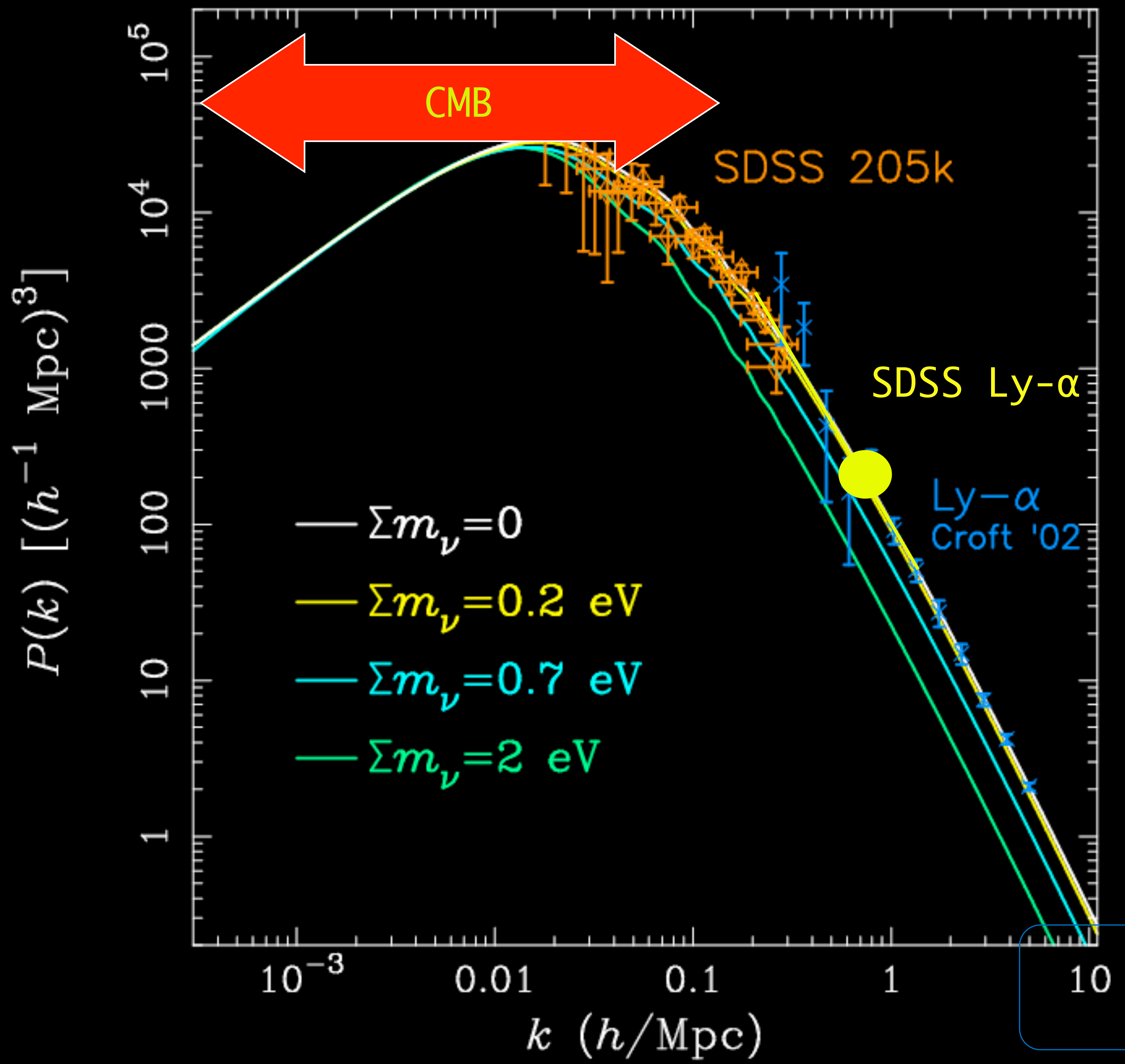
Neutrino Mass Affects Structure Growth



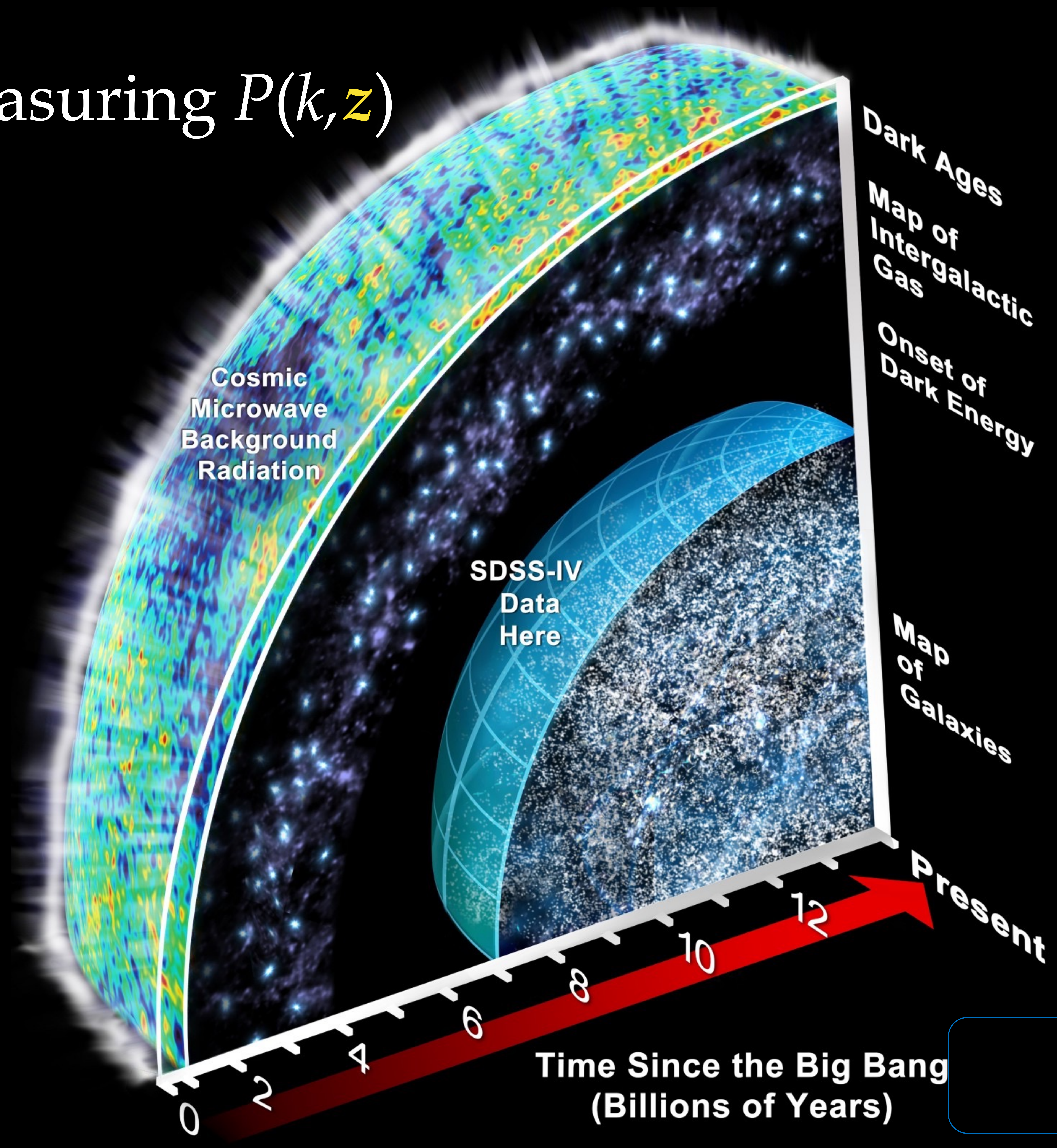
- Neutrinos affect growth of large-scale structure in the Universe
- Sum of the neutrino mass species (Σm_ν) > 0.06 eV from oscillation experiments
  - ***Neutrinos ~> mass of all the stars in the Universe***
- Above free-streaming scale, neutrinos act like **matter**
- Below free-streaming scale, neutrinos act like **radiation**

Measuring Large Scale Structure $P(k)$ & Σm_ν



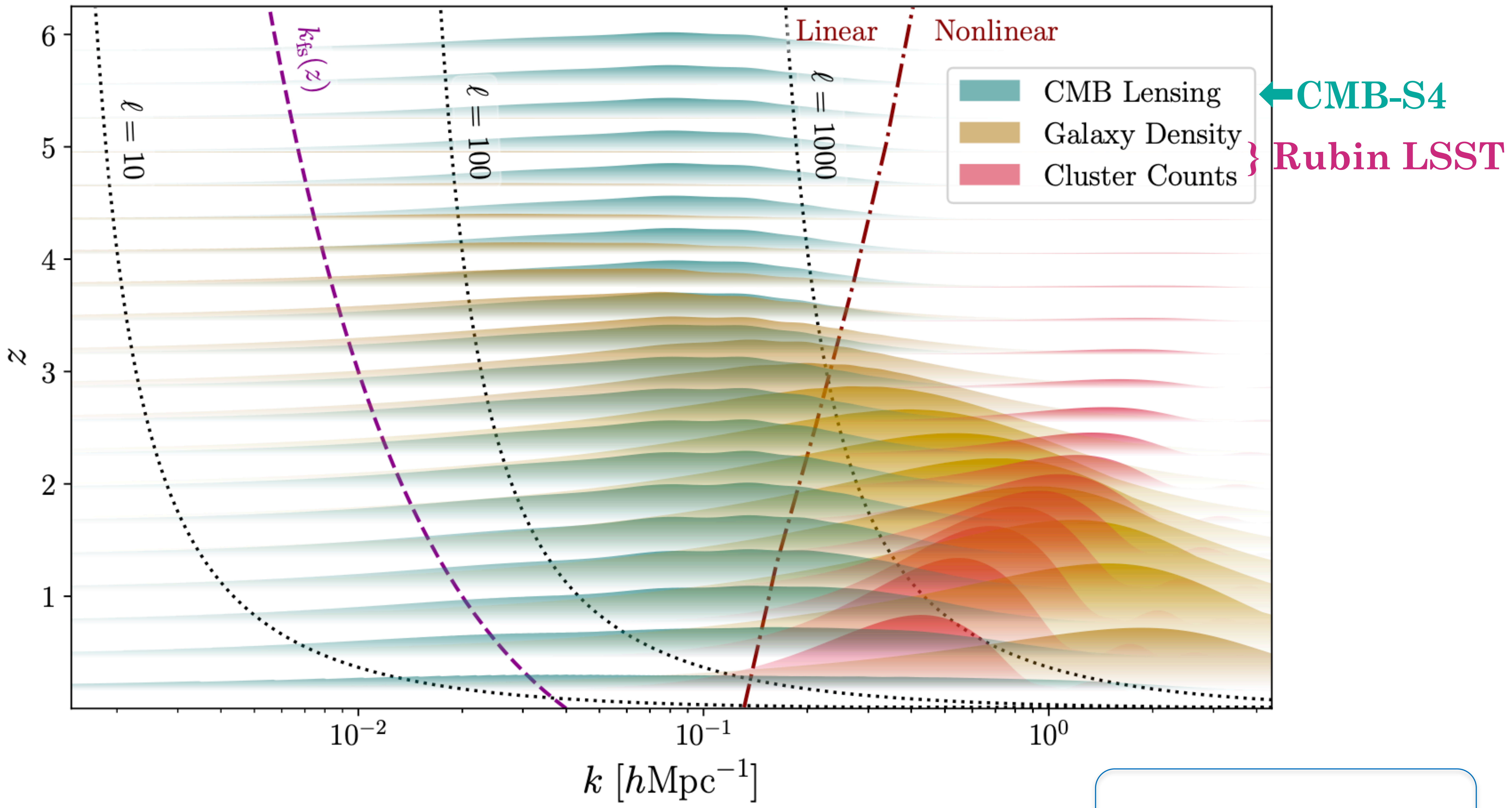
Abazajian (2022)

Measuring $P(k,z)$



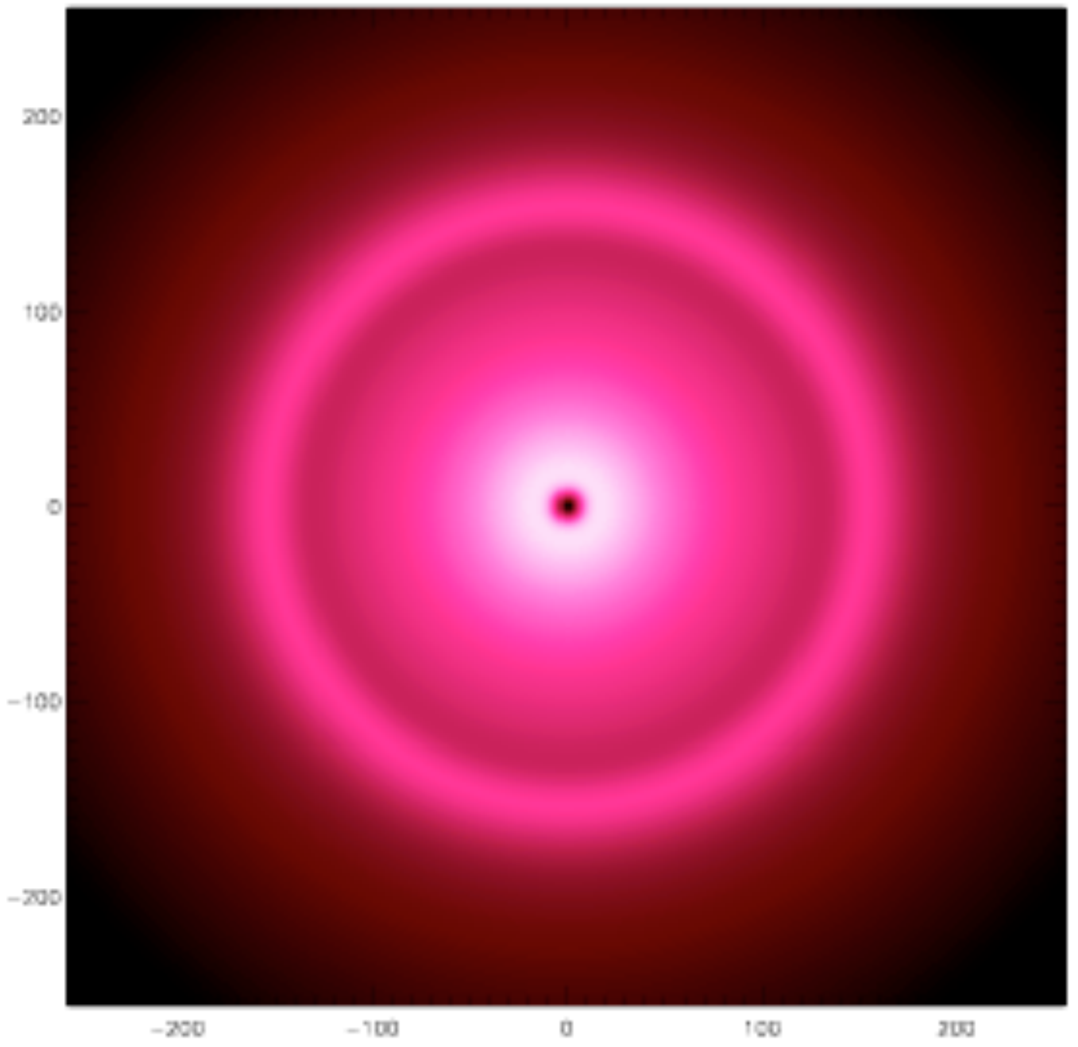
Abazajian (2022)

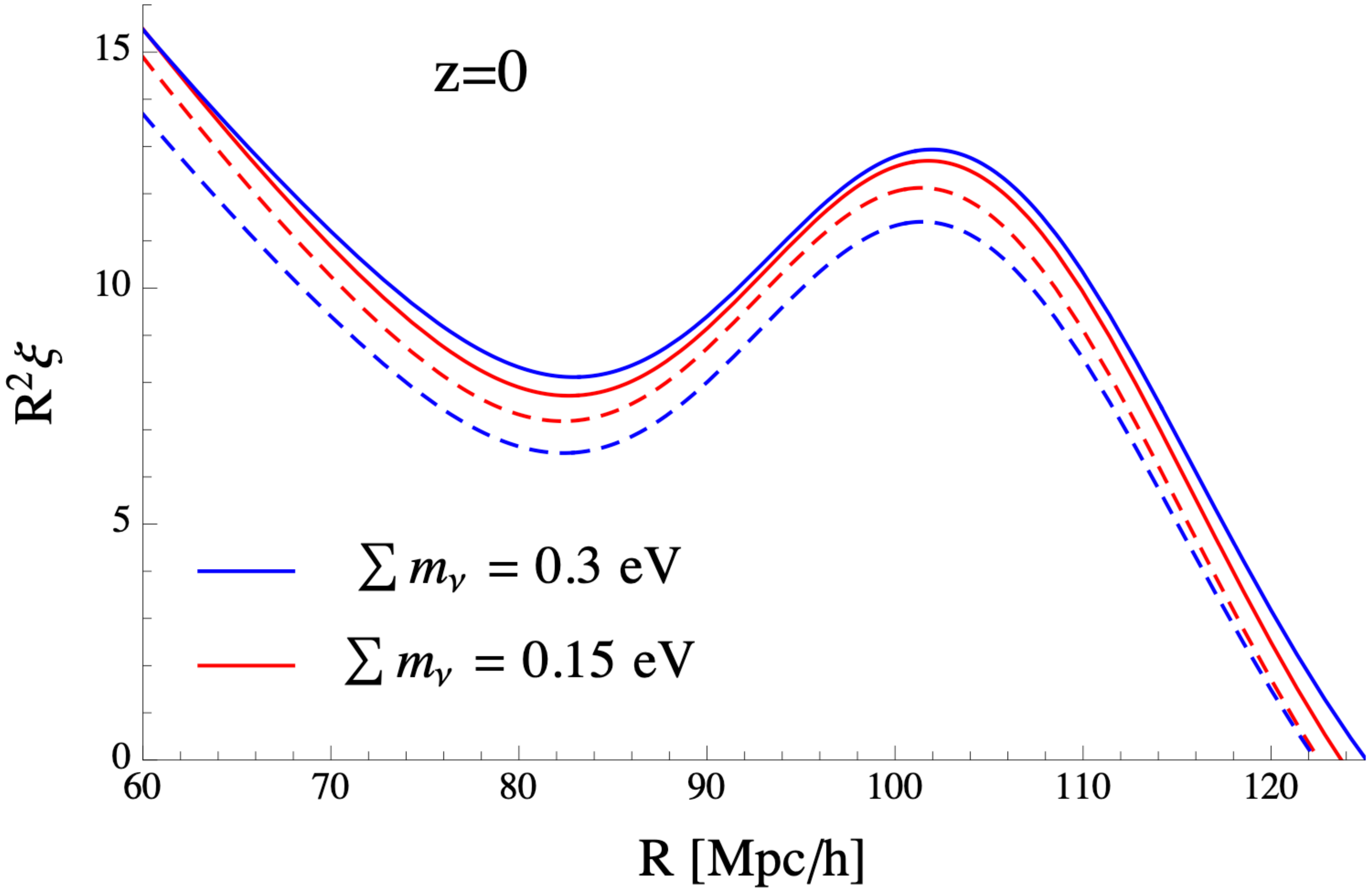
Observations' Sensitivity to LSS $P(k,z)$



Abazajian et al. arXiv:2203.07377

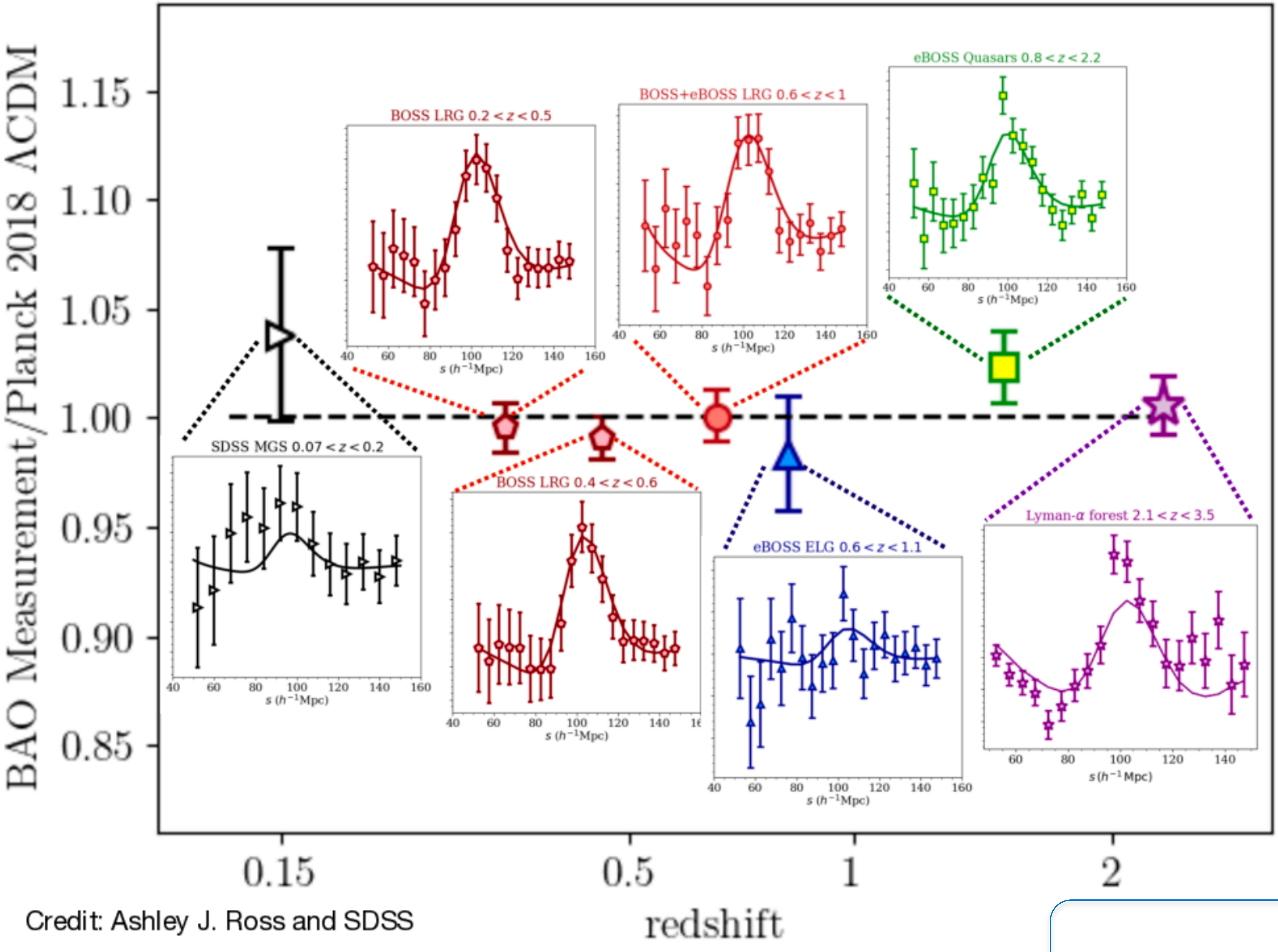
Baryon Acoustic Oscillations





Peloso et al., arXiv:1505.07477

Baryon Acoustic Oscillations: SDSS Distance Ladder



Credit: Ashley J. Ross and SDSS

via Di Valentino

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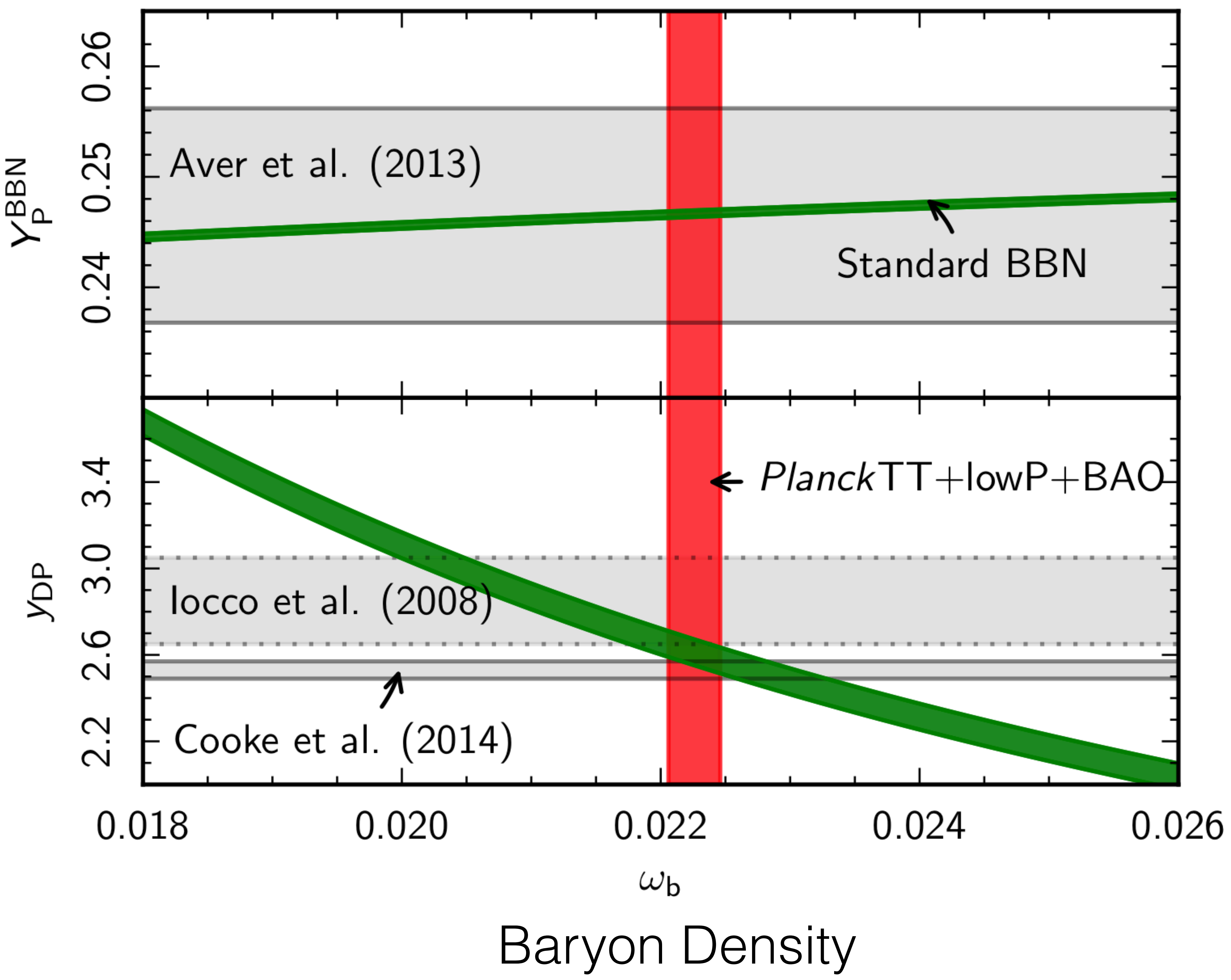
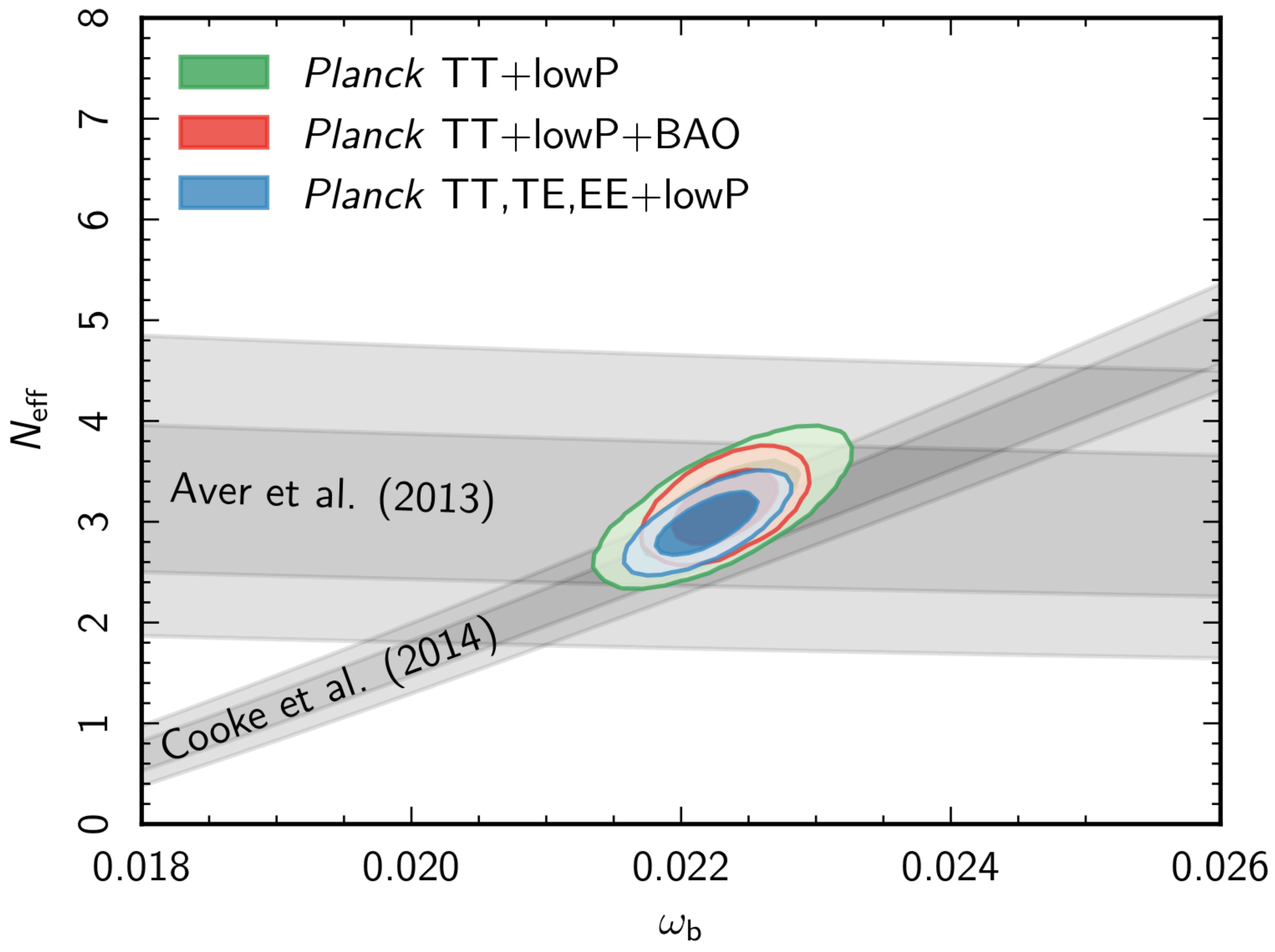
Big Bang Nucleosynthesis (BBN):
The Abundance of Light Elements



- BBN predicts the abundance of light elements created ~3 minutes after the Big Bang
- We can measure abundance of Helium (Y_P) and Deuterium (Y_{DP}) in old (just forming) galaxies
- Compare to prediction given BBN theory and baryon density measured from Planck

Planck Collaboration XIII (2015)

Neff Constraints from the CMB & BBN



- Use Helium, Deuterium abundance measurements, to also constrain "N_{eff}"
- Excellent agreement with CMB measurements
- Connects physics at three very different epochs in Universe:
  1) Cosmic neutrino background at ~1 sec
  2) Light element production at ~3 min.
  3) CMB emitted at ~380,000 years

Planck Collaboration XIII (2015)

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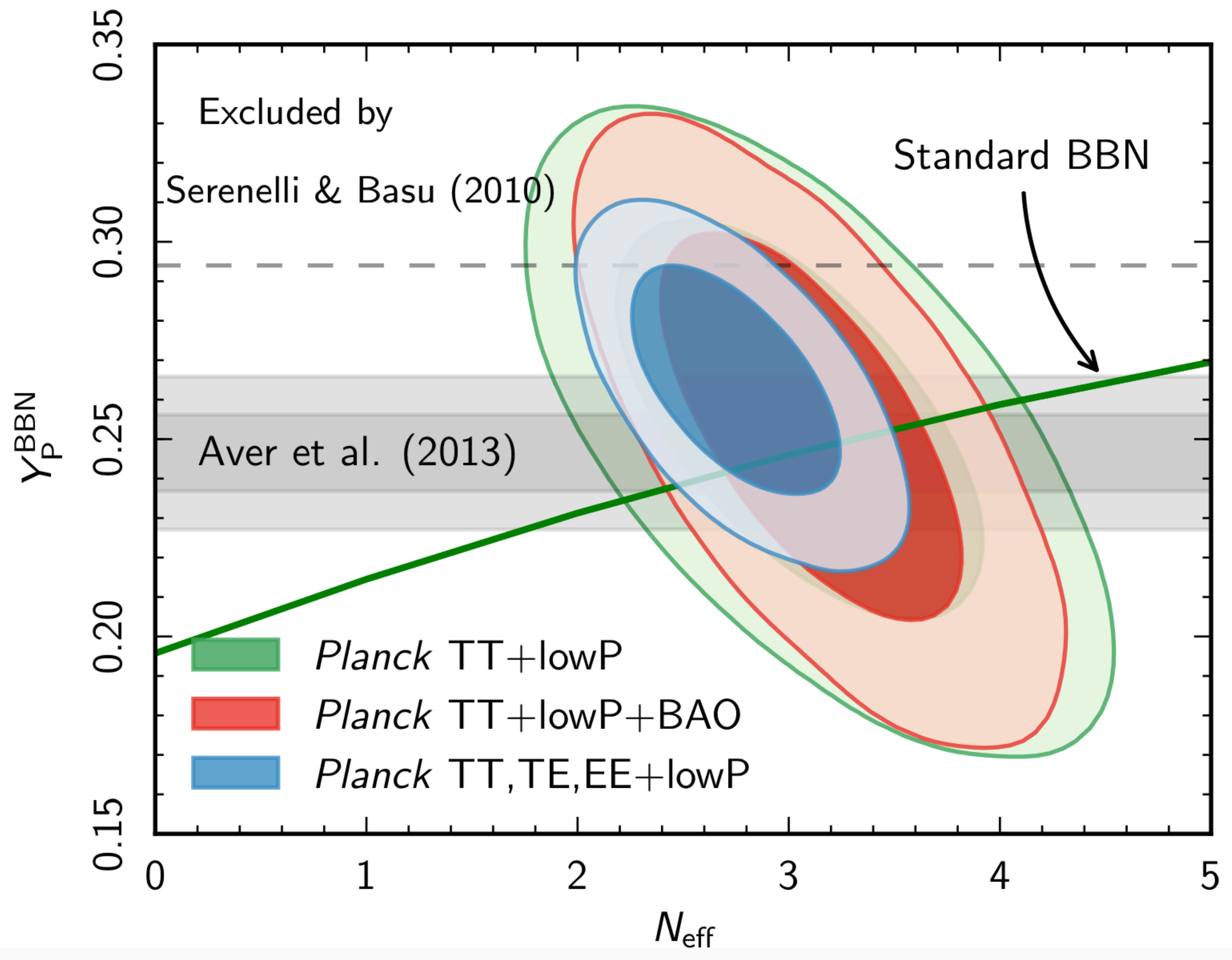

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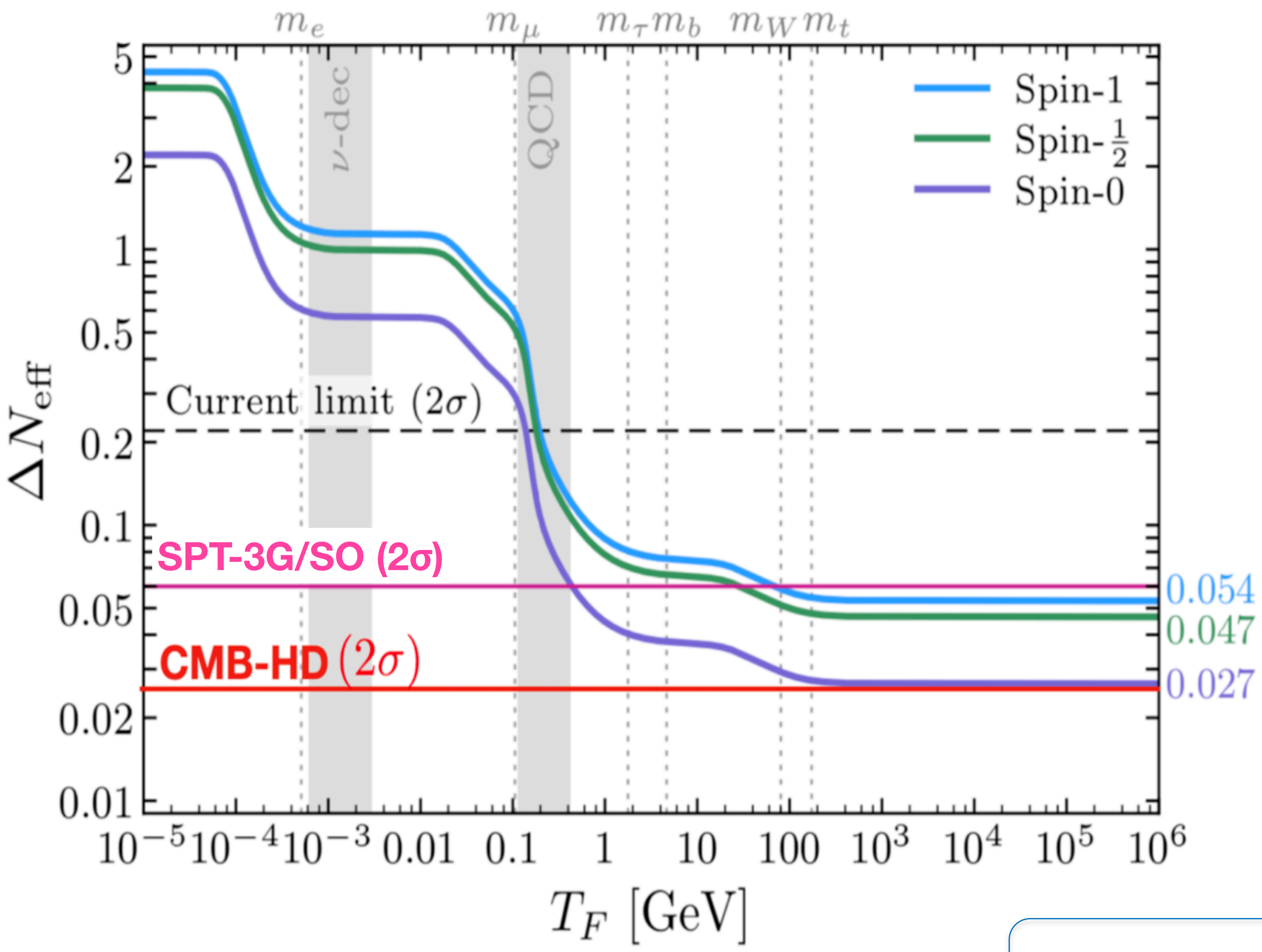
Planck Collaboration XIII (2015)

N_{eff}: Not just Light Relics



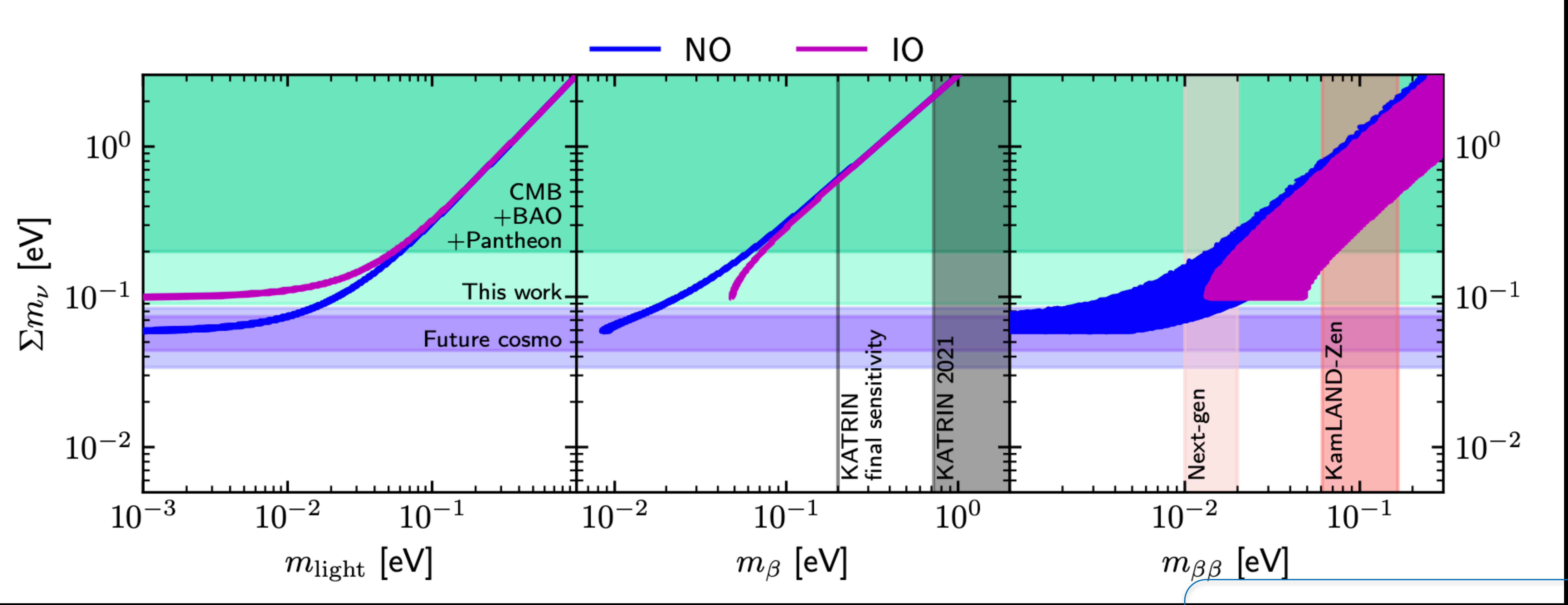
C. Chang et al., arXiv:2203.07638 [Snowmass]

Current Σm_ν Limits

Neutrino mass is degenerate with other cosmological parameters (Ω_m especially), so all cosmological data useful in improving constraints:

CMB + CMB Lensing (Planck 2018)
+ Type Ia SNe (Pantheon)
+ BAO + RSD (SDSS DR12+DR16)

$\Sigma m_\nu < 0.09$ eV (95% CL)



Di Valentino, Gariazzo & Mena, arXiv:2106.15267

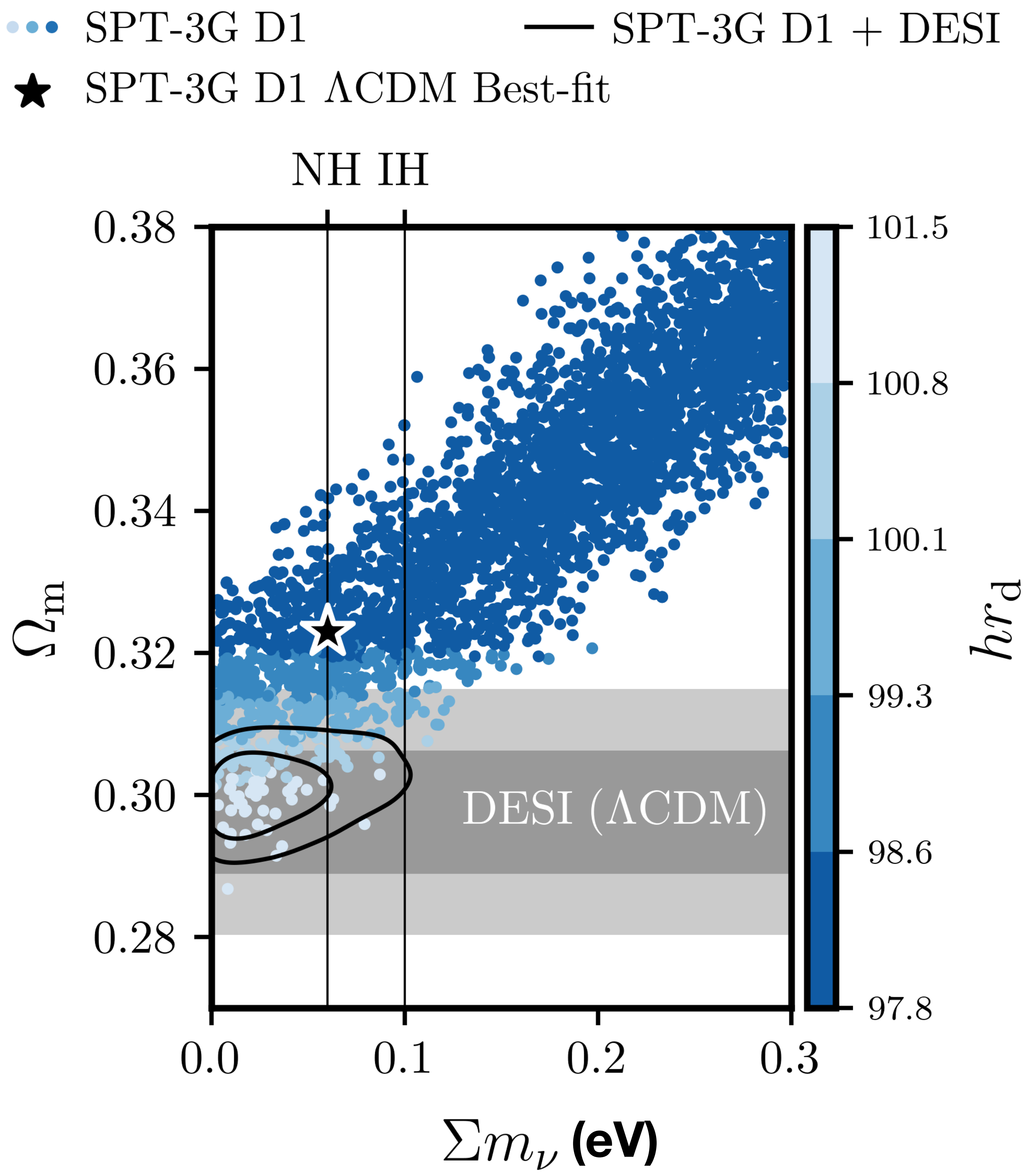
Cosmic Complementarity with HEP Neutrino Experiments

Scenario	$m_{\beta\beta}$ (ββ)	m_β (β)	$\sum m_\nu$ (Cosmo)	$\Delta N_{\rm eff}$	Conclusion
Normal hierarchy	$< 2\sigma$	$< 2\sigma$	60 meV	0	Normal neutrino physics; no evidence for BSM
Dirac Neutrinos	$< 2\sigma$	$< 2\sigma$	350 meV	0	Neutrino is a Dirac particle
Sterile Neutrino	$< 2\sigma$	$< 2\sigma$	350 meV	> 0	Detection of sterile neutrino consistent with short-baseline
Diluted Neutrinos	0.25 eV	0.25 eV	< 150 meV	< 0	Modified thermal history (e.g. late decay)
Exotic Neutrinos	0.25 eV	0.25 eV	< 150 meV	0	e.g. Modified thermal history; (e.g. neutrino decay to new particle)
Excluded	0.25 eV	0.25 eV	500 meV	0	Already excluded by cosmology
Dark Radiation	$< 2\sigma$	$< 2\sigma$	60 meV	> 0	Evidence for new light particles; normal hierarchy for neutrinos
Late Decay	$< 2\sigma$	$< 2\sigma$	60 meV	< 0	Energy-injection into photons at temperature $T \lesssim 1$ MeV

Table 3-2. *Relation between neutrino experiments and cosmology. We include the measurement of the Majorona mass via NLDBD ($m_{\beta\beta}$) or a kinematic endpoint (m_β) compared to the cosmological measurement of the sum of the masses $\sum m_\nu$ and the CMB measurement of $N_{\rm eff}$. Here $< 2\sigma$ indicates an upper limit from future observations. For Section 3.4, one can use $\sigma(m_{\beta\beta}) \approx 0.075$ eV and $\sigma(m_\beta) \approx 0.1$ eV for observations on the timescale of CMB-Stage IV. For $\Delta N_{\rm eff}$ the use of $\gtrless 0$ indicates a significant deviation from the Standard Model value.*

CMB-S4 Science Book (arXiv:1610.02743)

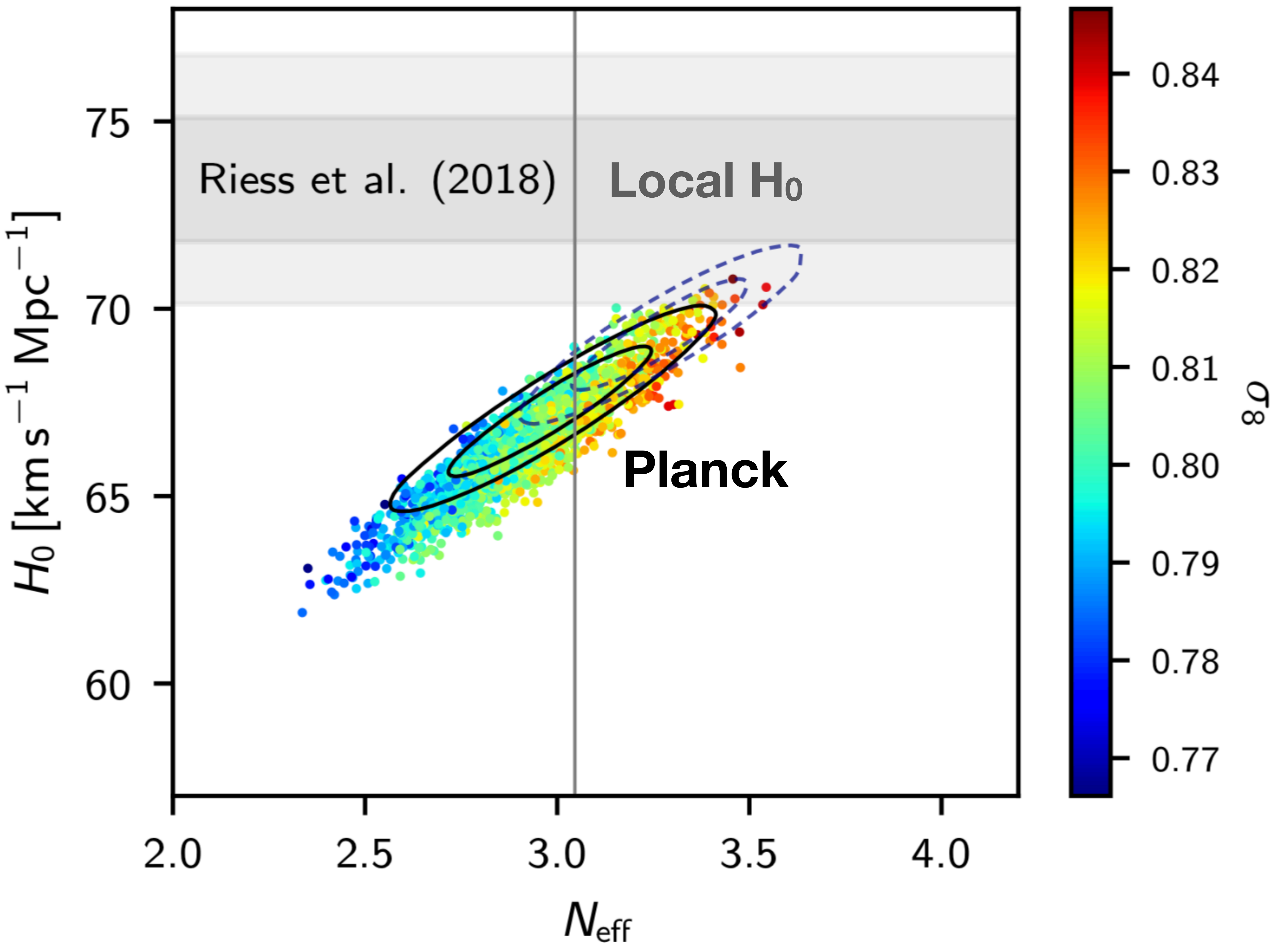
Cosmological Tensions: CMB & BAO



- Cosmology data are nearing the sensitivity to require an additional model parameter to fit the data: ***Neutrino mass***
- Current CMB & BAO measurements currently give best constraints, however they are in weak (~3-sigma) tension, giving a possibly artificially low lower limit.
- Could also be an exciting indication of other new physics in early Universe (e.g., early Dark energy)

(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

Cosmological Tensions: Hubble Constant



- Tension between Hubble constant measured from local probes and CMB could also be an indication of new early Universe physics, e.g.,
- Additional relativistic energy density (i.e., Neff > 3.04) could help relive this.
  - Standard model predicts $Neff = 3.044$, defined to be roughly equal to number of neutrinos species

Planck Collaboration VI (2018)

Summary: Neutrinos in Cosmology

- *Near a cosmological detection of neutrino mass*
- *Significant detection of cosmic neutrino background (CvB), soon will make precision test standard model prediction of relativistic particles*
- *Amazing consistency between physics at 1 sec (CNB) - 3 min (BBN) - 380,000 years (CMB) after the Big Bang*
- *Next-generation cosmology experiments will further hone in on neutrino properties, i.e., the sum of the neutrino masses, sterile neutrinos, and other relativistic light relic particles*

Extras

CMB Sensitivity to Neutrino Density

- The neutrino density increases the expansion rate during this early radiation-dominated era

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 \propto (\rho_\gamma + \rho_\nu + \rho_{\mathrm{matter}} + \ldots)$$

$$\frac{\theta_d}{\theta_s} \propto (\rho_\gamma + \rho_\nu + \rho_m + \ldots)^{0.25}$$

More neutrinos -> higher density -> faster expansion

- The ratio $\frac{\theta_d}{\theta_s}$ is measured well using the CMB.

- The photon density ρ_γ is well known from 3K temperature of CMB.

- The ratio $\frac{\rho_m}{\rho_\gamma + \rho_\nu} = 1 + z_{\mathrm{EQ}}$ is also well measured using CMB.

-> We can solve for the neutrino density ρ_ν

Cosmic Complementarity with HEP Neutrino Experiments

Lower limits for ββ Exp.

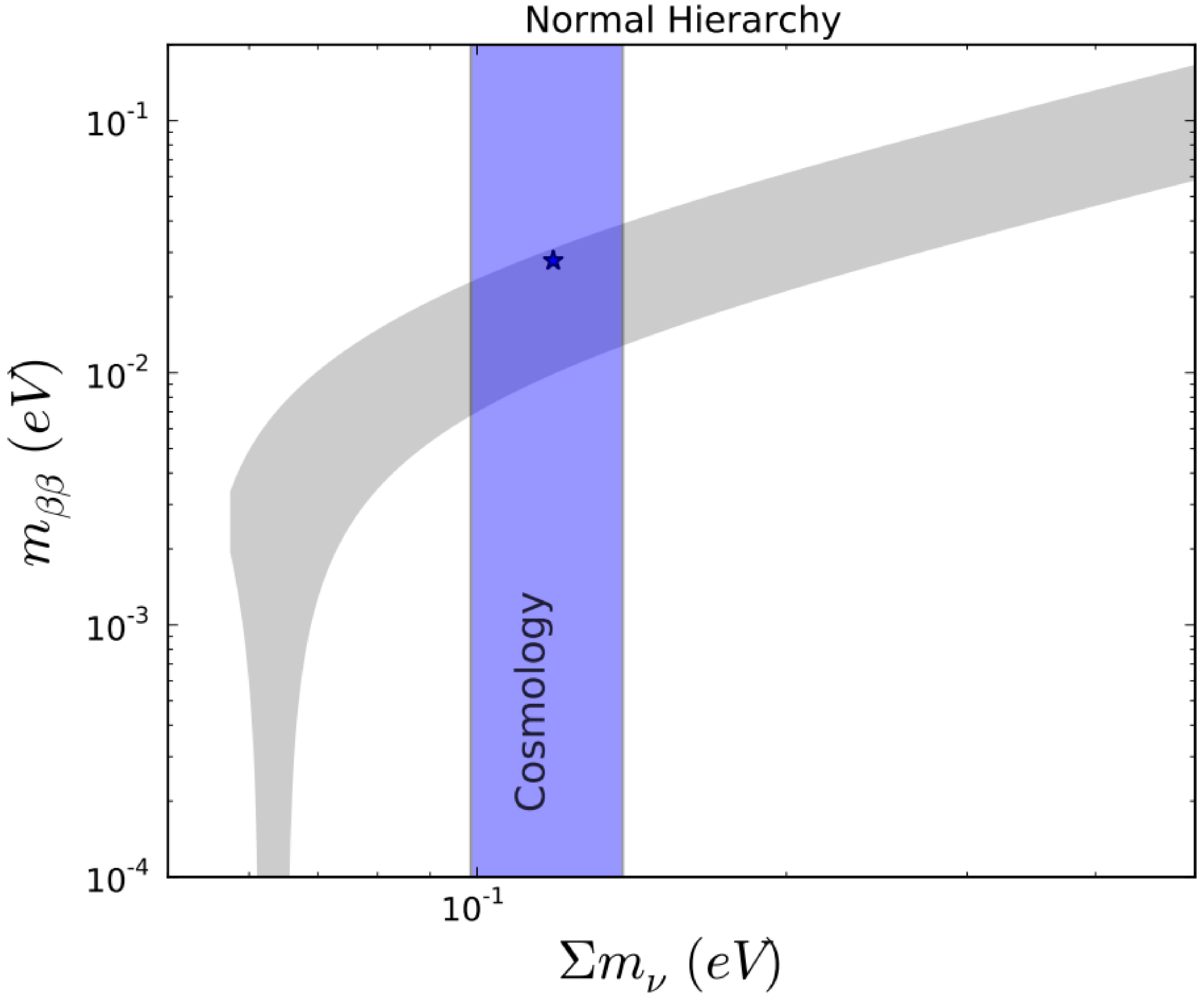
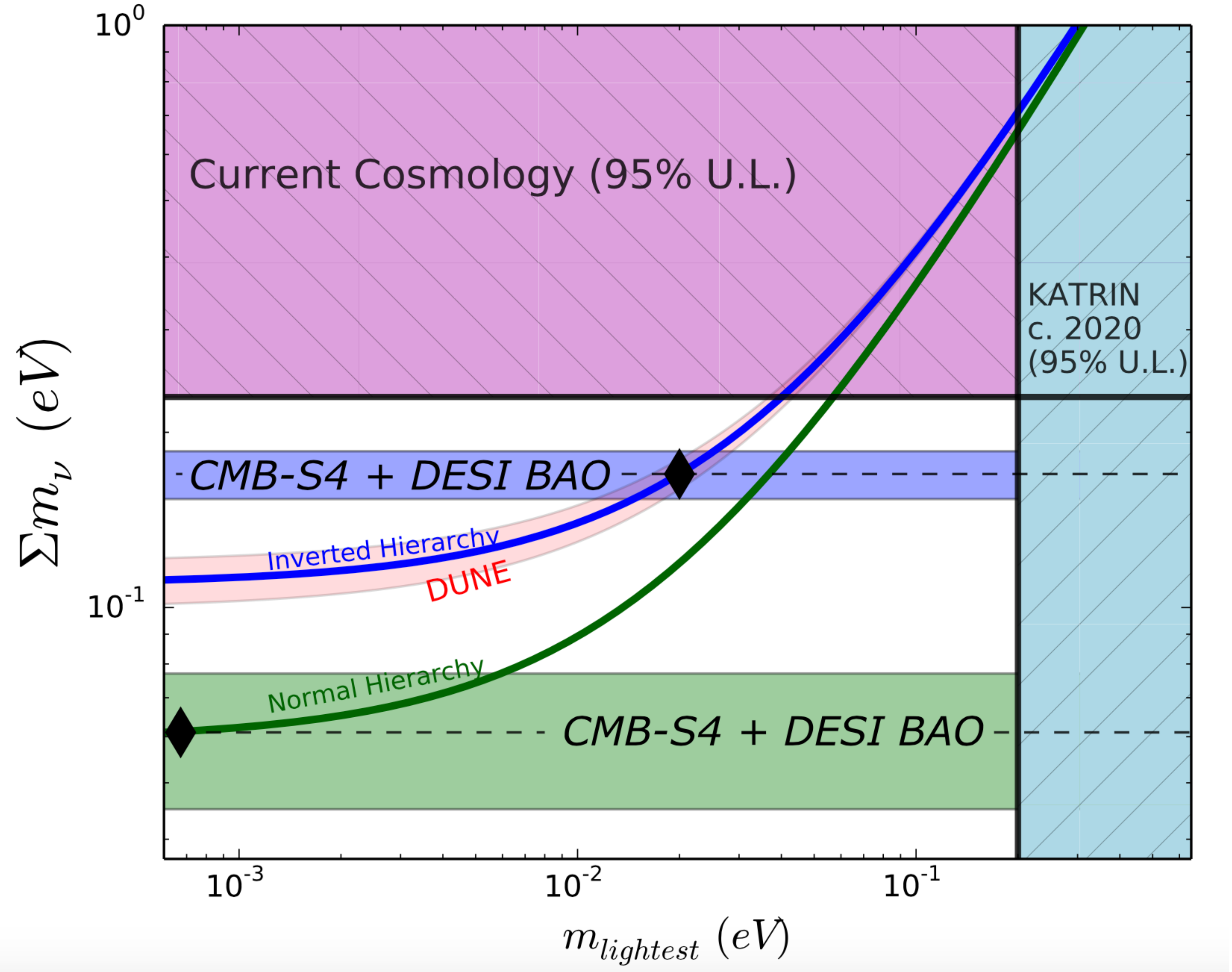


FIG. 3: If the mass hierarchy is normal but the sum of the masses is still relatively large, for example at the value indicated by the star, then there will be a lower limit on $m_{\beta\beta}$, a target for ambitious future double beta decay experiments.

Dodelson & Lykken (arXiv:1403.5173)

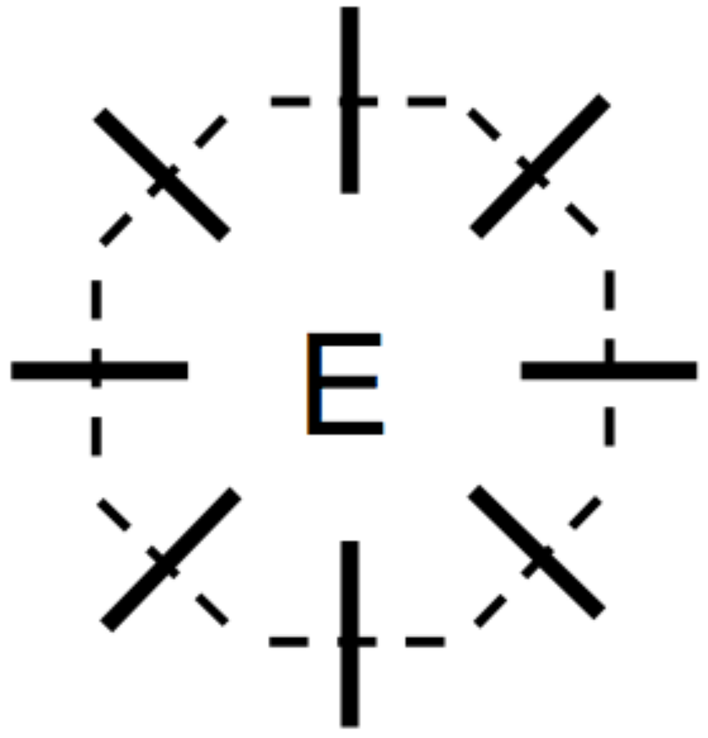
CMB-S4 Science Book (arXiv:1610.02743)

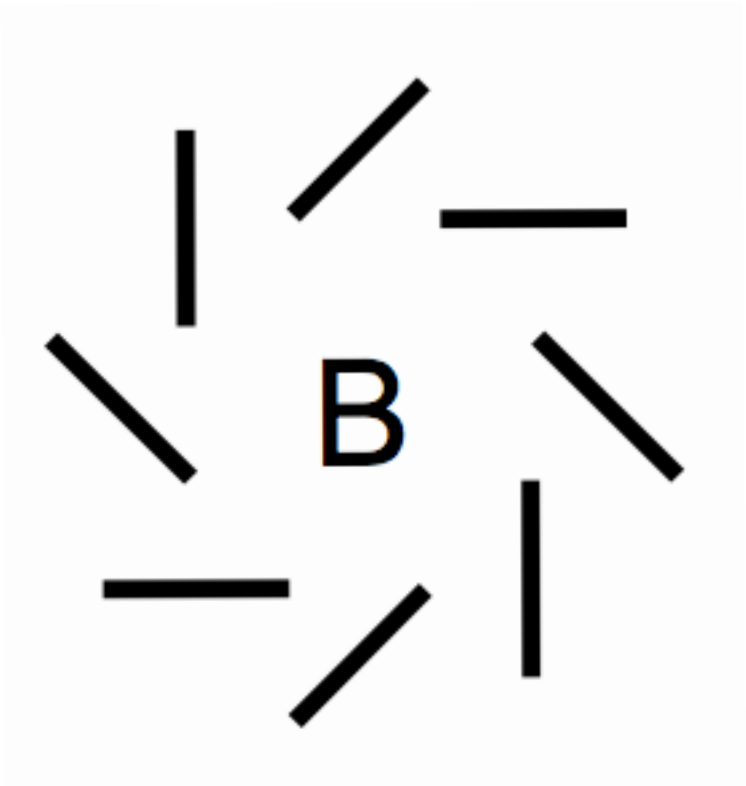
Synergy with DUNE

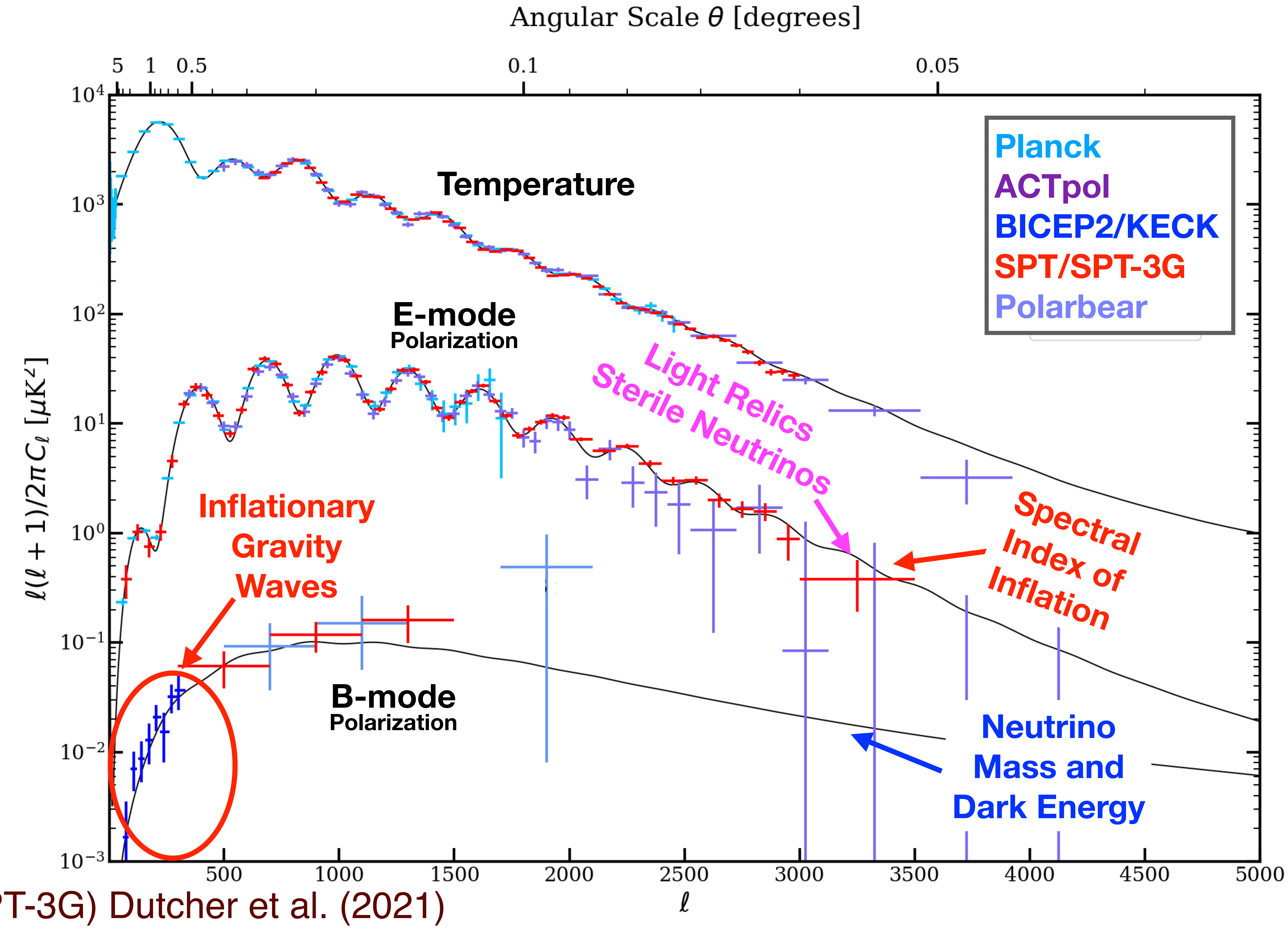


"In the case of a normal neutrino mass ordering with an example case marked as diamond on the lower curve, CMB-S4 would detect the lowest ?Σm_ν at ?>3σ. Also shown is the sensitivity from the long baseline neutrino experiment (DUNE) as the pink shaded band, which should be sensitive to the neutrino hierarchy. "

The Next Frontier: CMB Polarization



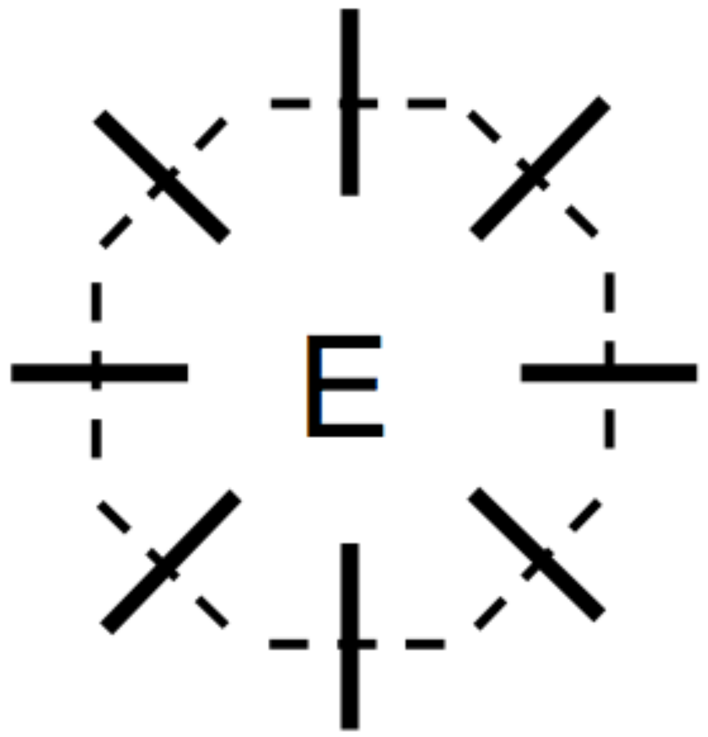


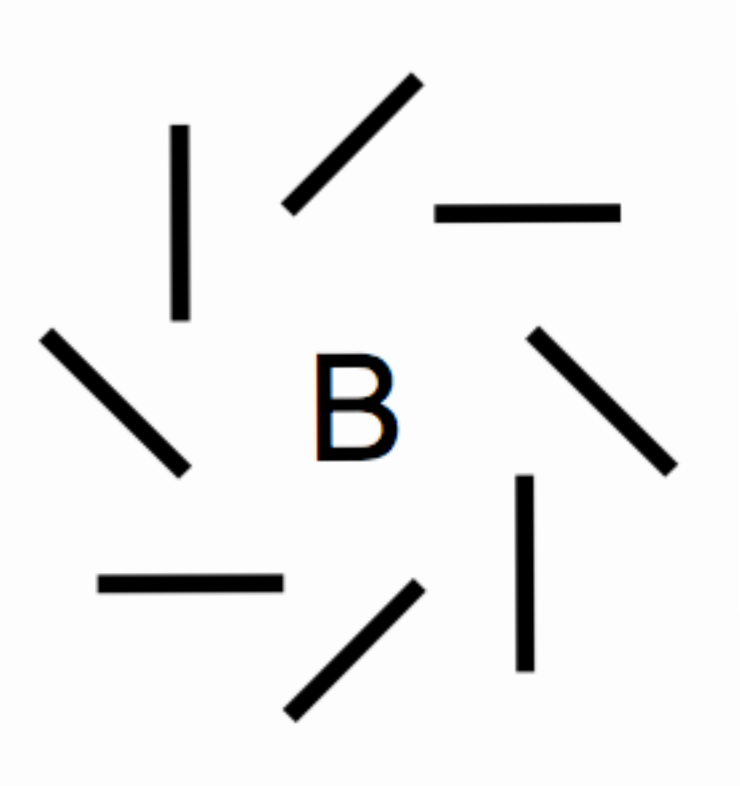


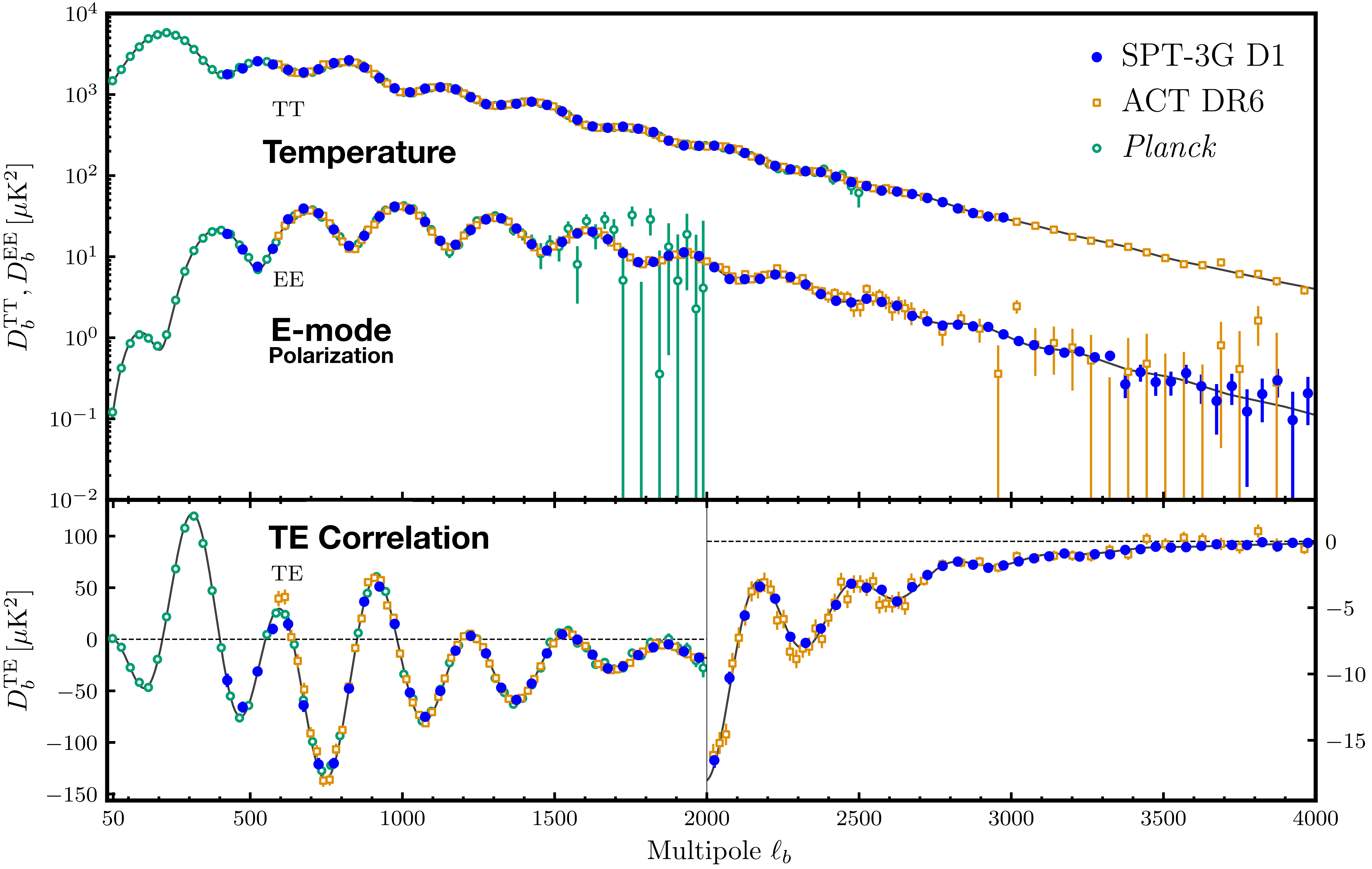
(SPT-3G) Dutcher et al. (2021)

(SPTpol) Henning et al. (2018), ApJ

The Next Frontier: CMB Polarization

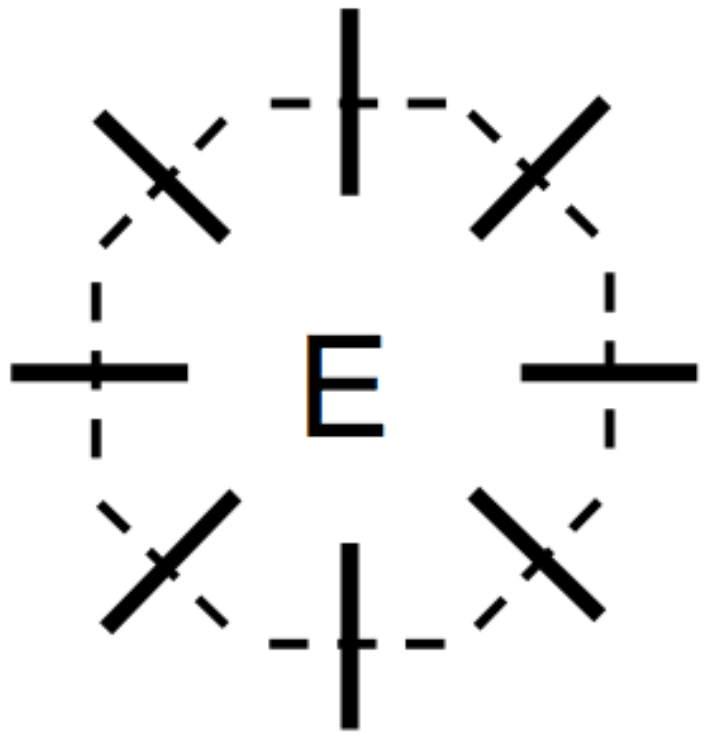


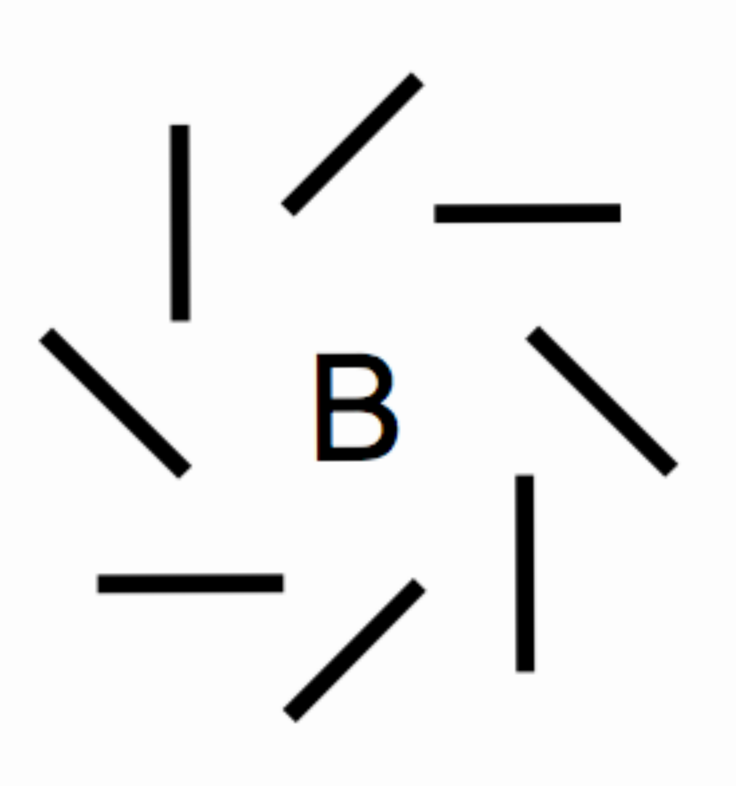


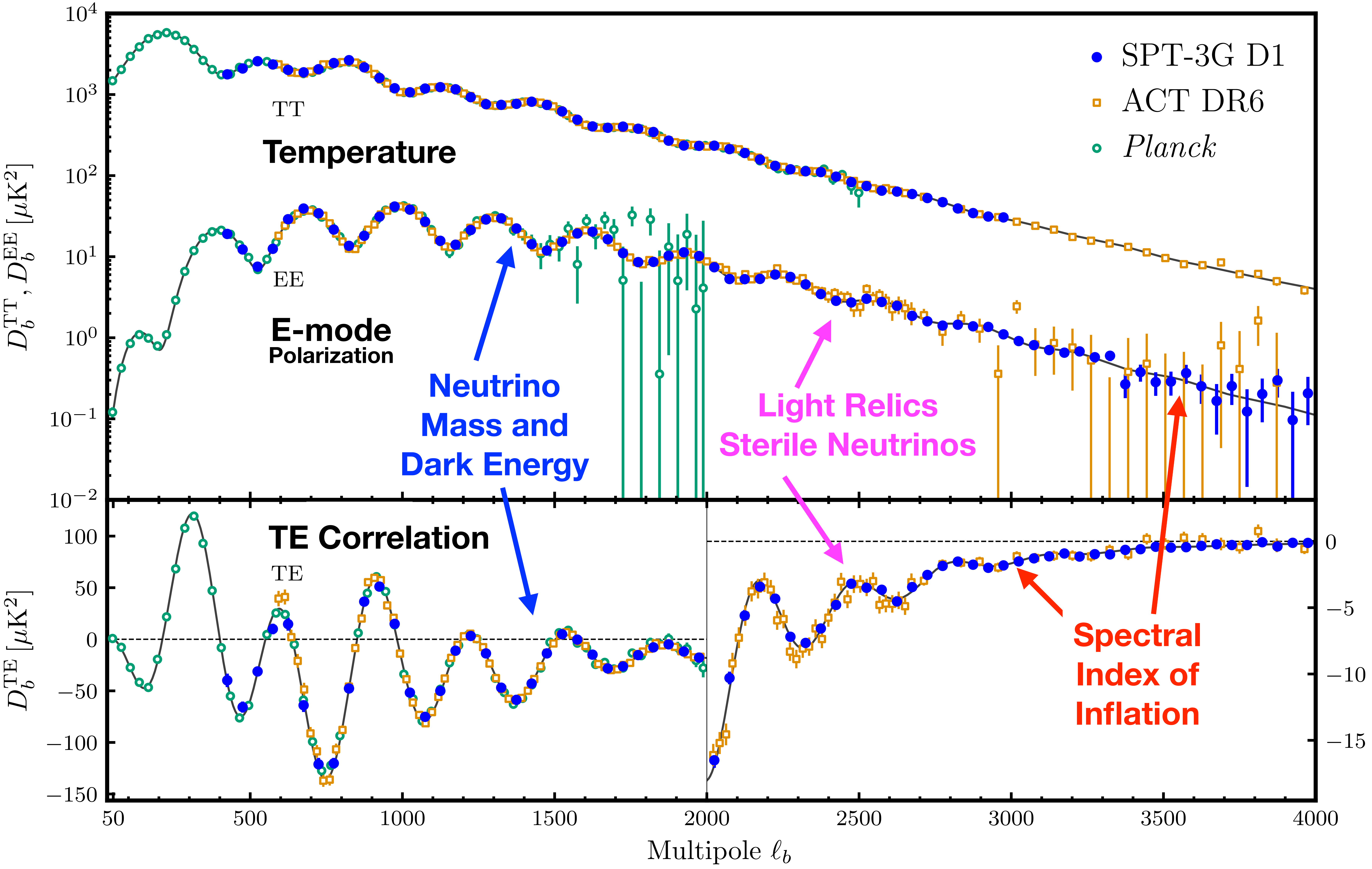


(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

The Next Frontier: CMB Polarization

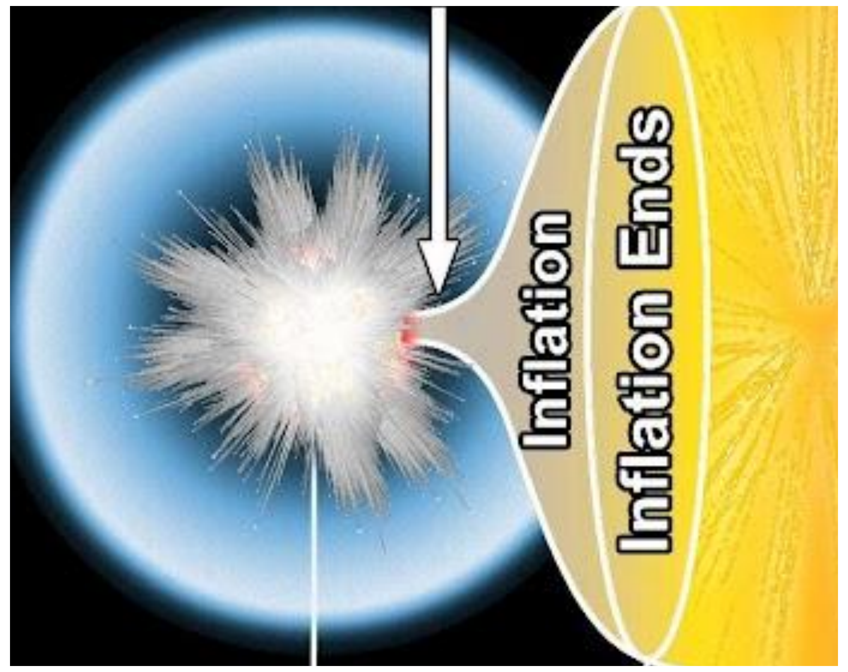


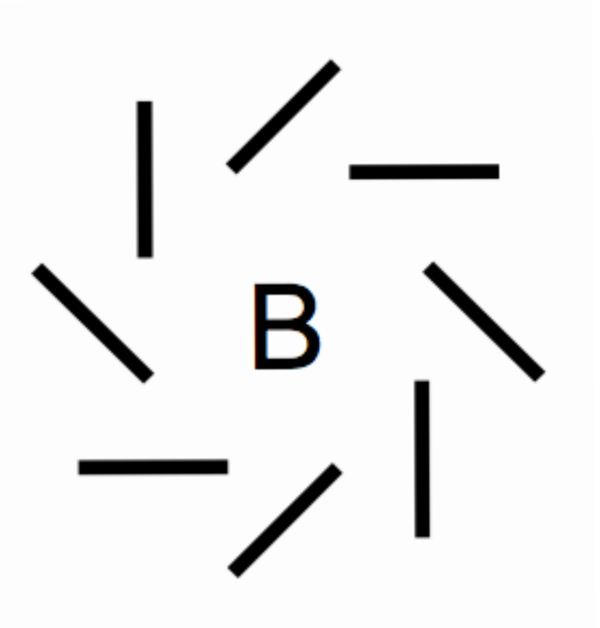




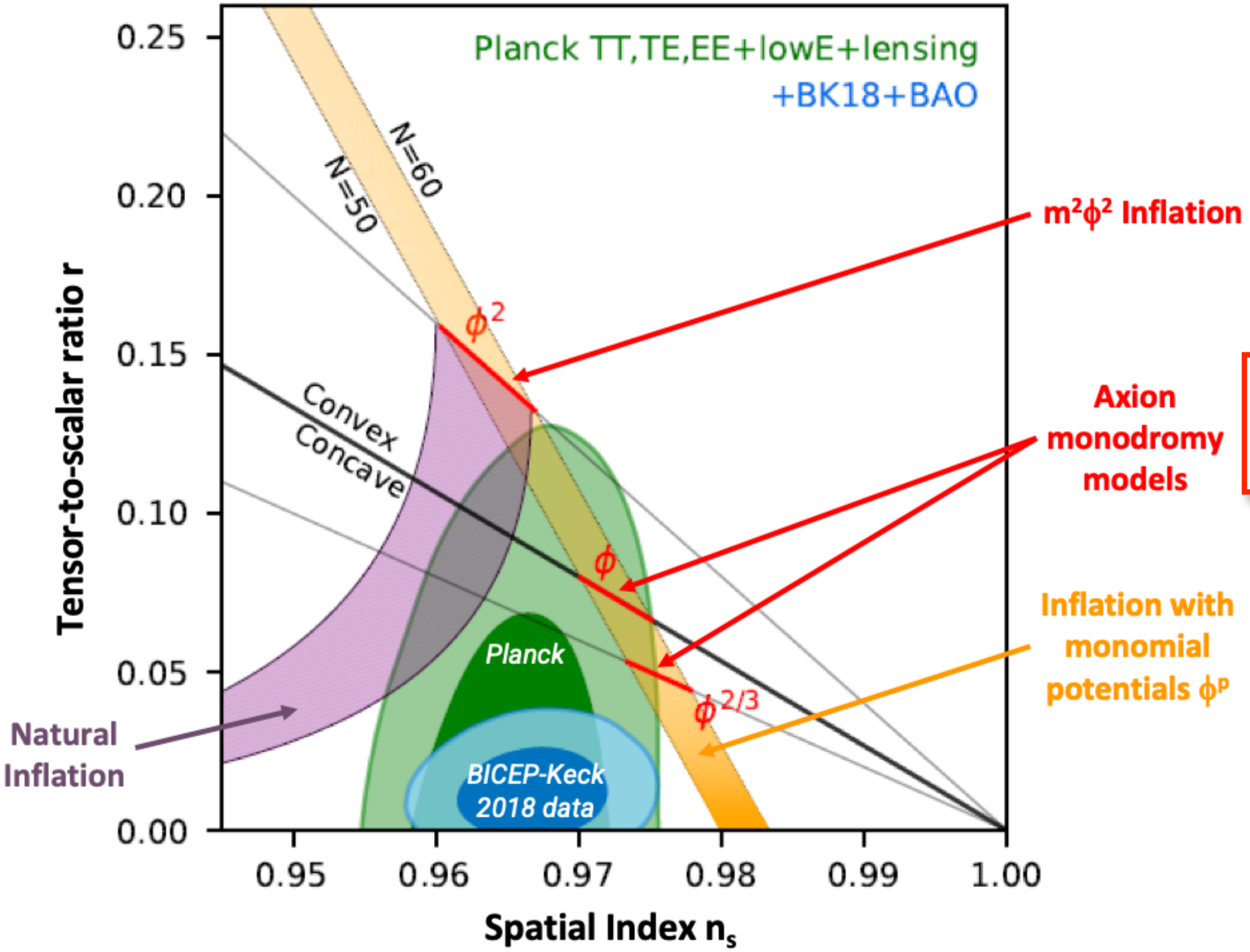
(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

Probing Cosmic Inflation:
Testing physics at energies 1-trillion times beyond the Large Hadron Collider (LHC)





South Pole Observatory (SPO)



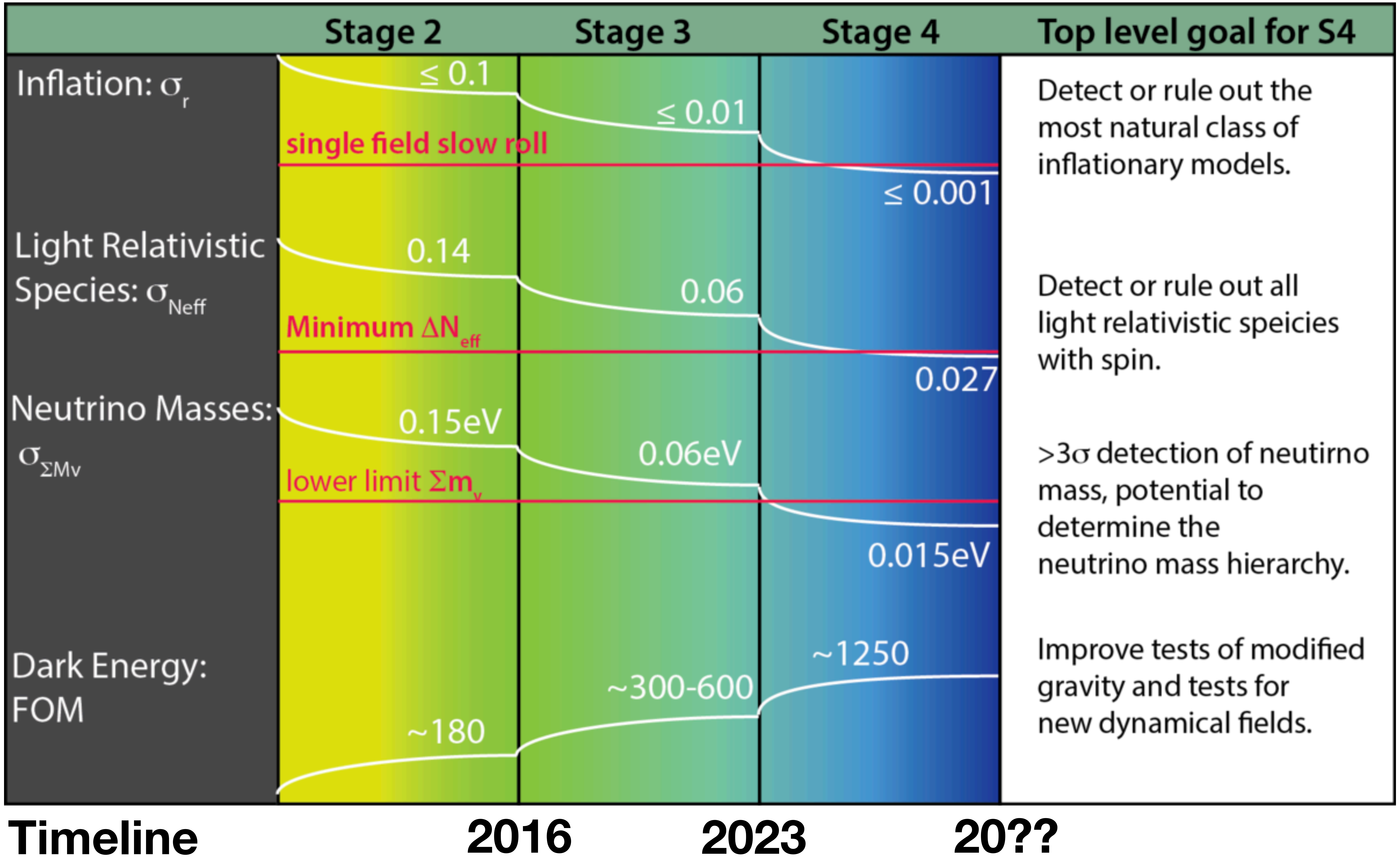
CMB measurements of the B-mode polarization constrain "r", the tensor-to-scalar ratio.
Testing physics at 10^{16} GeV!

$$\text{energy} = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}}\ \text{GeV}$$

BICEP/ Keck (BK) and South Pole Observatory (SPO) program is providing world leading constraints on Inflation

(BICEP/Keck, BK18) arXiv: 2203.16556

CMB Science Thresholds



CMB-S4 Science Book: arxiv:1610.02743