September 11th 2024

Physics Concerto Seminar Series
Supported by the Weinberg Institute for Theoretical Physics,
Department of Physics, University of Texas

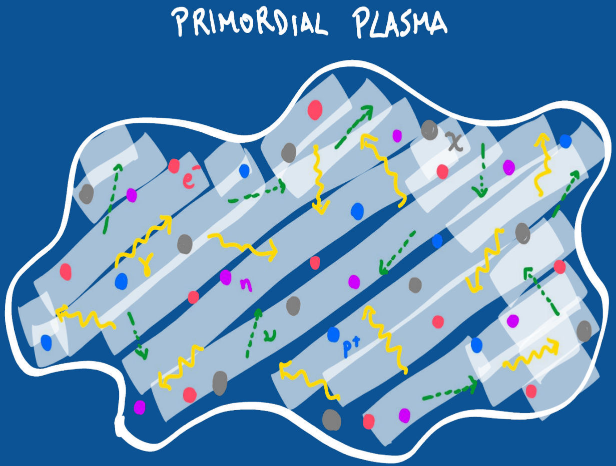
What every Physicist should know about the Cosmic Microwave Background

Gabriele Montefalcone
Weinberg Institute for Theoretical Physics, University of Texas at Austin

PHYSICS CONCERTO
BRIDGING PHYSICS SPECIALTIES THROUGH PEER TO PEER SEMINARS

The Big Picture

The Hot Big Bang



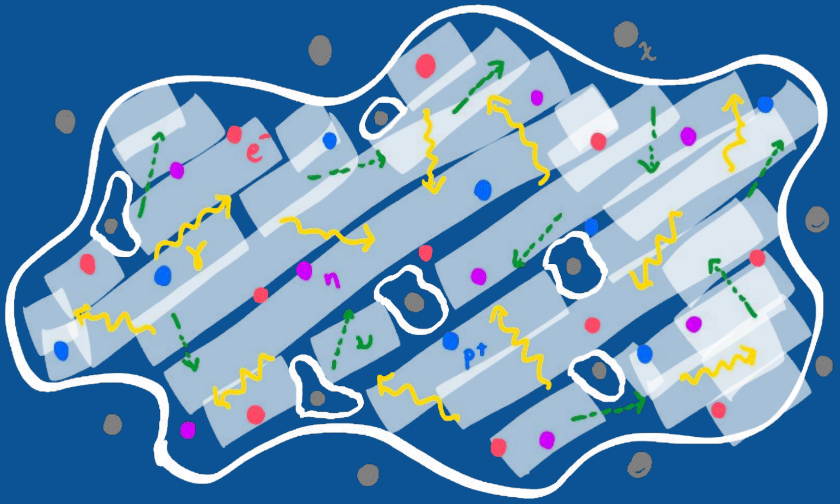
All SM particles species* are in thermal equilibrium at a temperature **T**

*possibly even dark matter

The Big Picture

$$(T_{\mathrm{dec}}) \approx H\,(T_{\mathrm{dec}})$$

interaction rate   expansion rate



EXPANSION

As the Universe expands, it cools and different species decouple from the primordial plasma

- The first one to go is dark matter

The Big Picture

$$(T_{\text{dec}}) \approx H\,(T_{\text{dec}})$$

interaction rate   expansion rate

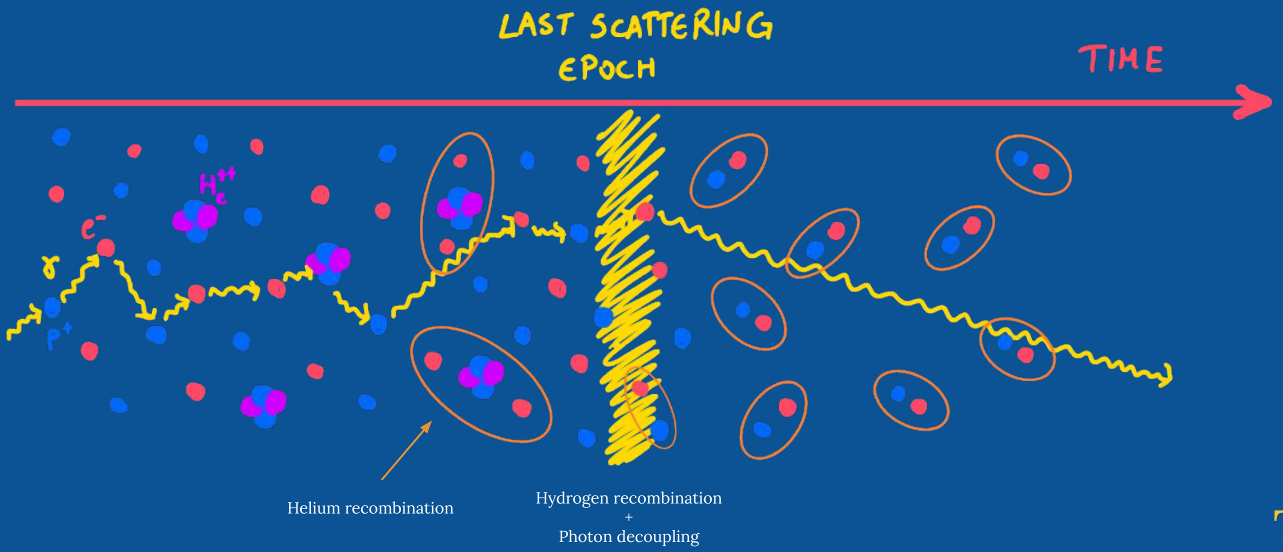
EXPANSION

Then neutrinos decouple, and shortly after nuclei form in the process known as Big Bang Nucleosynthesis

- Mainly ^{4}He
- Also ^{3}He, ^{2}H, ^{7}Li

T~ MeV

The Big Picture



T~ eV

Once the universe is cool enough for neutral Hydrogen to form, photons are finally free to travel across the universe, reaching us today

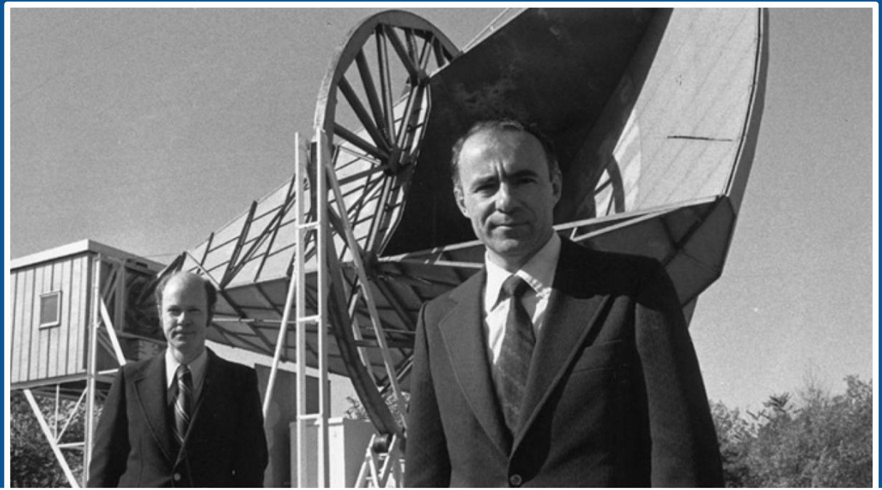
EXPANSION

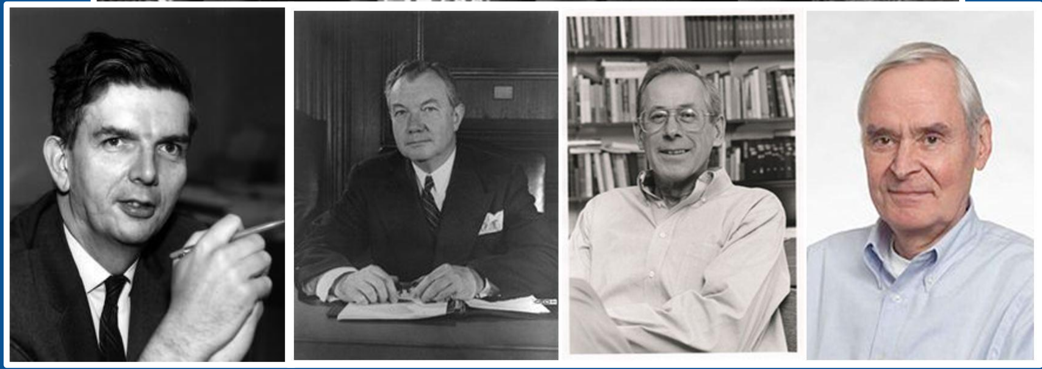
If the Big Bang picture is correct, we expect the universe
to be filled by a Cosmic Background of photons,
all roughly at the same temperature.

The Discovery of the Cosmic Microwave background (CMB)
1965

- Penzias & Wilson detect *excess radiation* in their radio antenna at ν = 4 GHz, corresponding to a **T ≈ 3 K radiation**

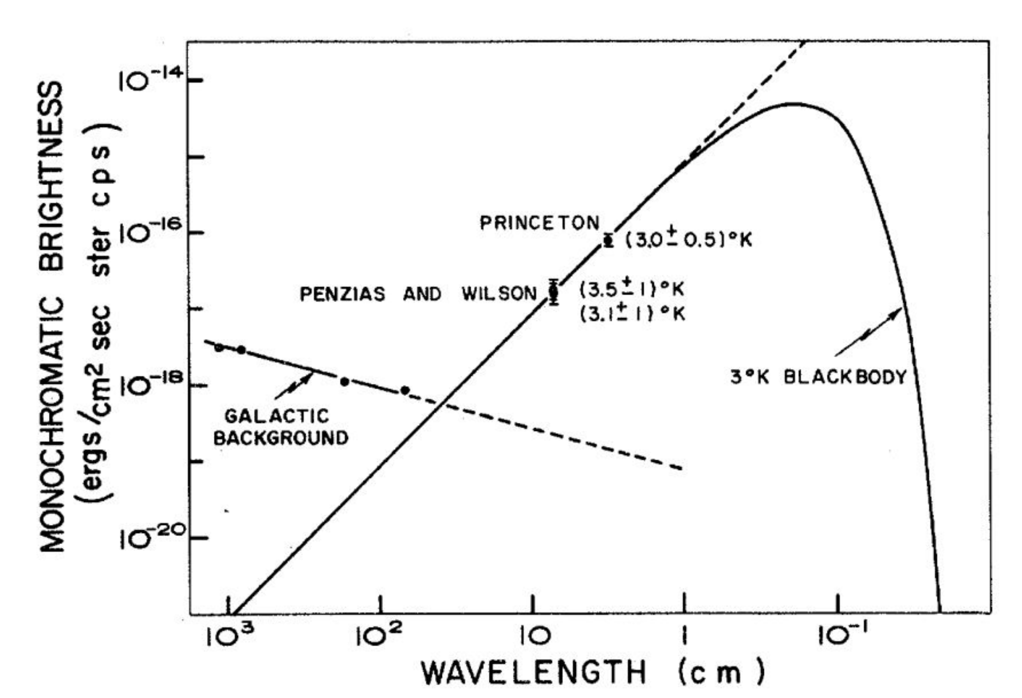
- Dicke, Peebles, Roll & Wilkinson interpret this signal as the Cosmic Microwave Background (CMB)





The Discovery of the Cosmic Microwave background (CMB) 1965

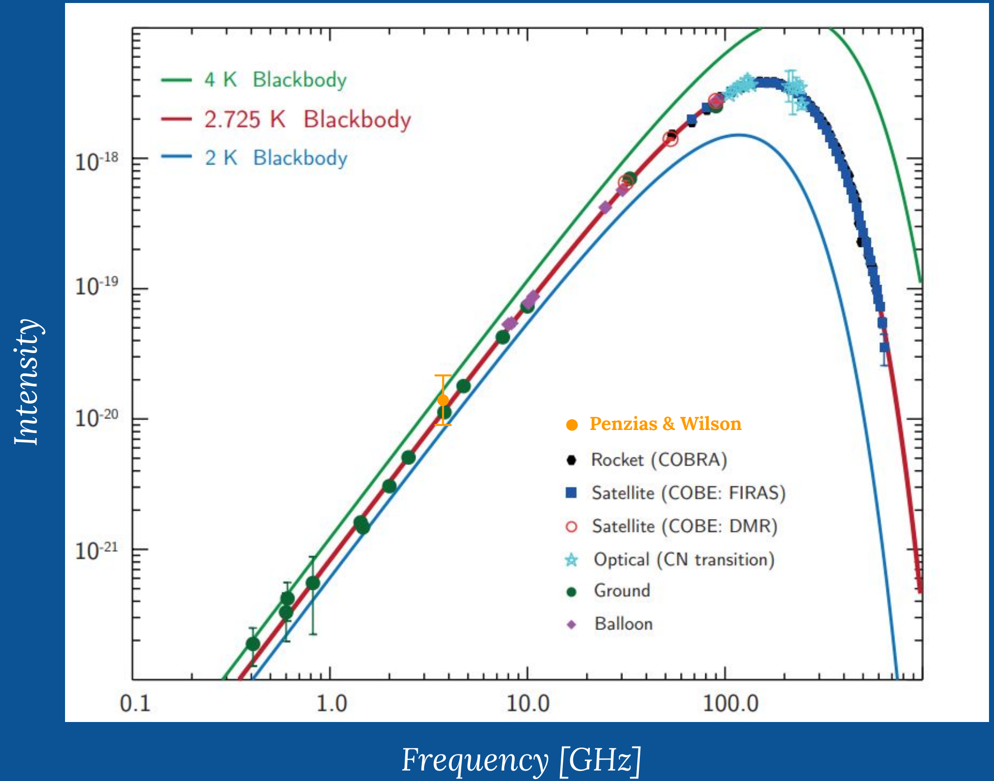
- Penzias & Wilson detect *excess radiation* in their radio antenna at ν = 4 GHz, corresponding to a **T ≈ 3 K radiation**
- Dicke, Peebles, Roll & Wilkinson interpret this signal as the Cosmic Microwave Background (CMB)



The CMB Frequency Spectrum

The CMB is consistent with a black-body spectrum at a temperature of 2.7255 K

- First measurement by the **COBE FIRAS** instrument (1990)

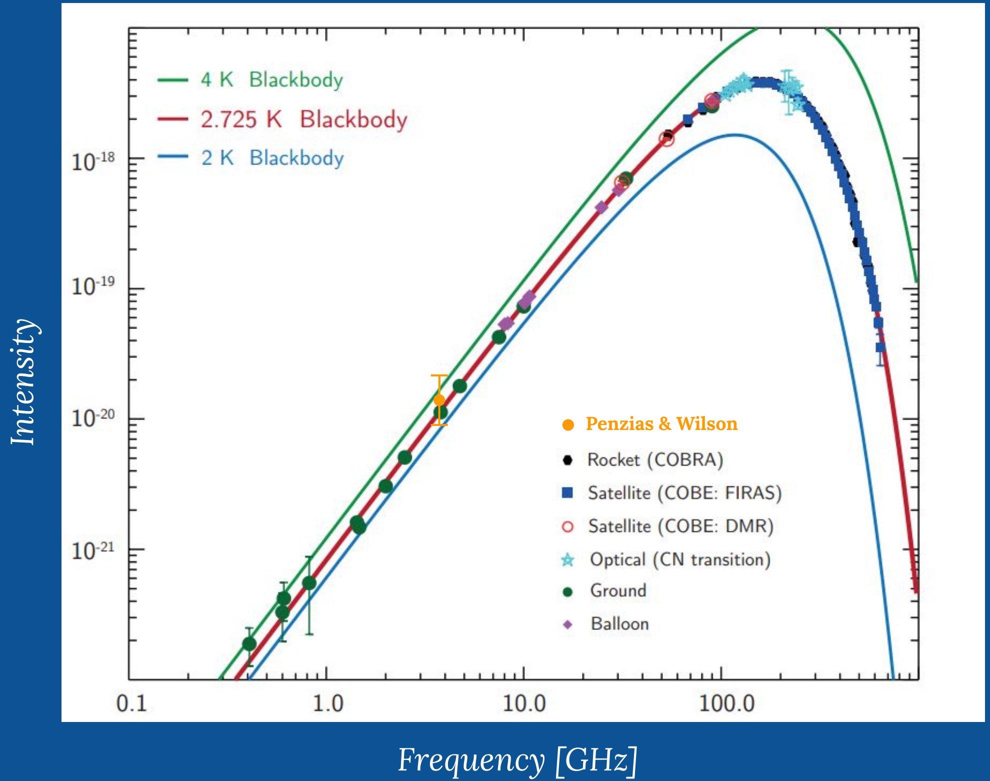


The CMB Frequency Spectrum

The CMB is consistent with a black-body spectrum at a temperature of 2.7255 K

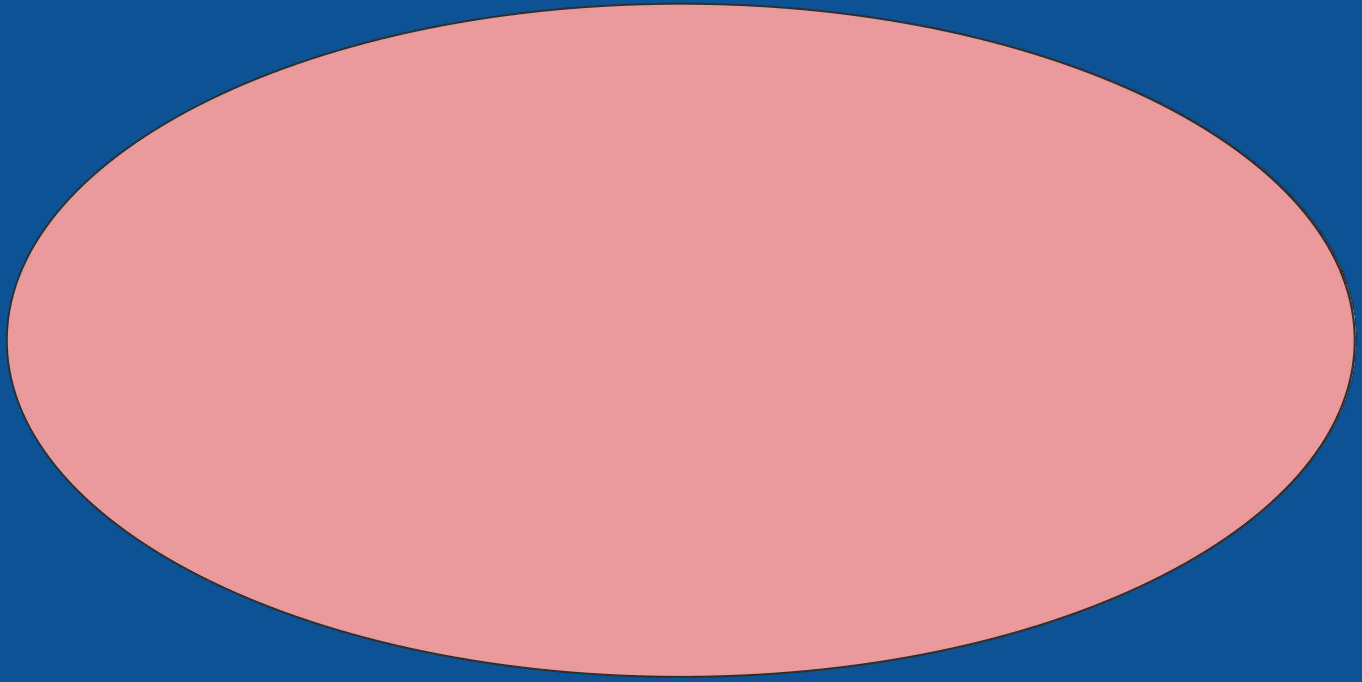
- First measurement by the **COBE FIRAS** instrument (1990)

This precise measurement is a pillar of the Big Bang model,
proving the early universe was in
near-perfect thermal equilibrium



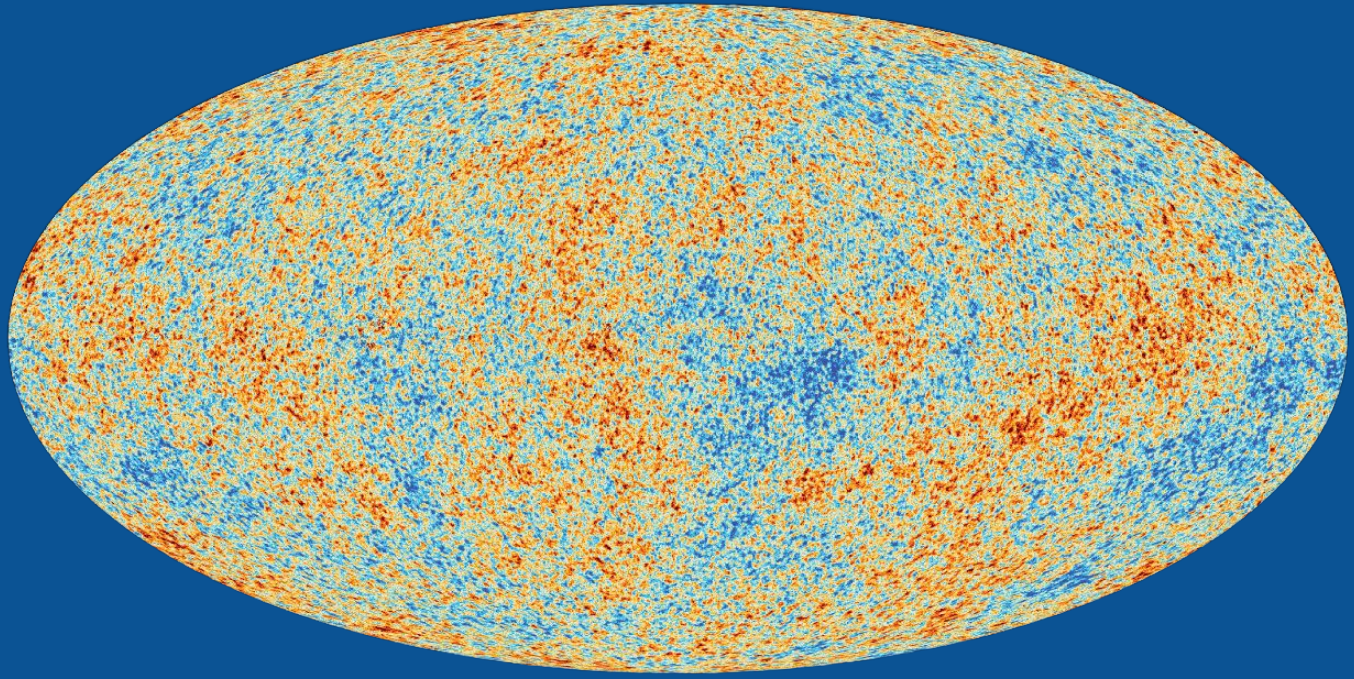
CMB anisotropies

An almost perfect black-body spectrum at a temperature of $T_0 = 2.7255$ K today



CMB anisotropies

Small temperature anisotropies in the order of $\Delta T/T \sim 10^{-5}$



Planck Collaboration

Cosmic Sound Waves

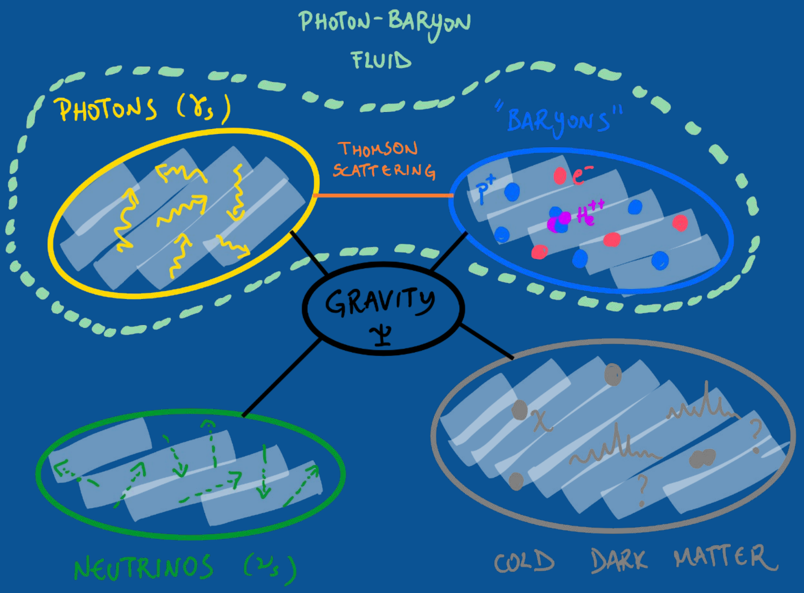
- Photons and baryons are strongly coupled

  Ideal fluid: $\begin{cases} \text{Photons} \rightarrow \text{pressure} \\ \text{Baryons} \rightarrow \text{containment} \end{cases}$

- Initial fluctuations excited sound waves in the primordial plasma

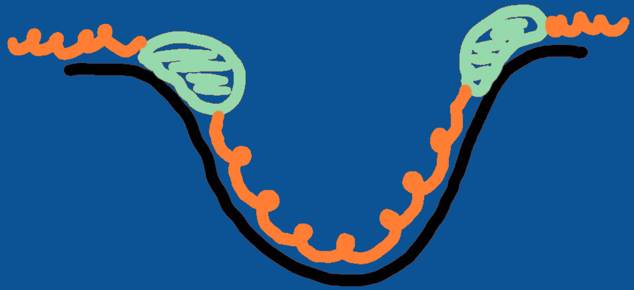
- Gravity sources the fluctuations in the photon-baryon fluid

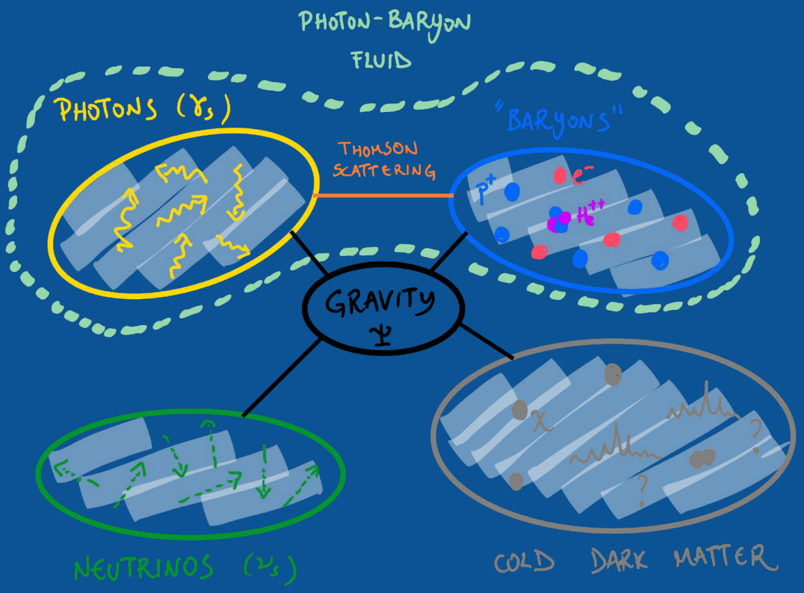
$$\ddot{\delta}_\gamma - \underbrace{c_\gamma^2}_{\text{Photon Pressure}} \nabla^2 \delta_\gamma = \underbrace{\nabla^2 \Phi_+}_{\text{Gravity}}$$



Cosmic Sound Waves

$$\ddot{\delta}_\gamma - \underbrace{c_\gamma^2}_{\text{Photon Pressure}} \nabla^2 \delta_\gamma = \underbrace{\nabla^2 \Phi_+}_{\text{Gravity}}$$





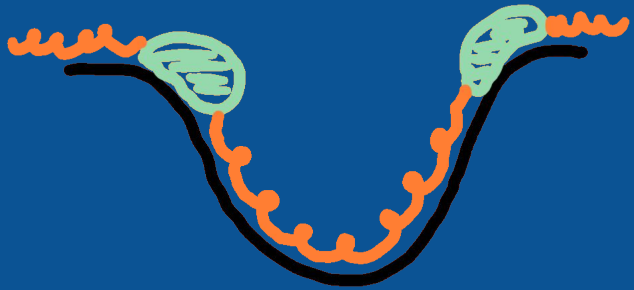
$$\delta_\gamma \sim \underbrace{A_{\vec{k}}}_{\substack{\text{Initial condition} \\ \text{(inflation)}}} \cos\left(c_s k \tau\right),$$

$$c_s^2 \sim \frac{c}{3\left(1 + \underbrace{R_b}_{R_b \equiv 3\bar{\rho}_b / \left(4\bar{\rho}_\gamma\right)}\right)}$$

Baryons add inertia to the fluid

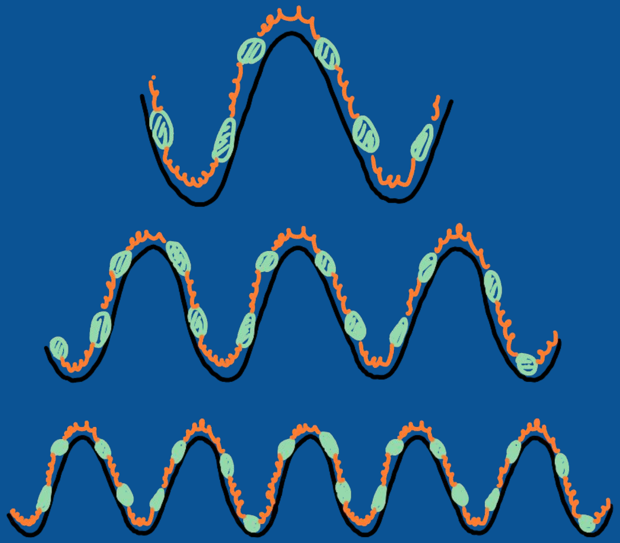
Cosmic Sound Waves

$$\ddot{\delta}_\gamma - \underbrace{c_\gamma^2 \nabla^2}_{\text{Photon Pressure}} \delta_\gamma = \underbrace{\nabla^2 \Phi_+}_{\text{Gravity}}$$



$$\delta_\gamma \sim \underbrace{A_{\vec{k}}}_{\substack{\text{Initial condition} \\ \text{(inflation)}}} \cos\left(c_s k \tau\right),$$

Initial fluctuations generate curvature perturbations at all scales!



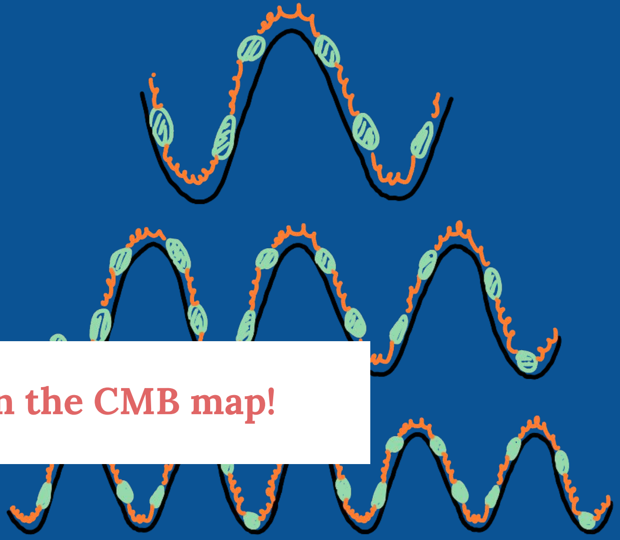
$$c_s^2 \sim \frac{c}{3\left(1 + \underbrace{R_b}_{R_b \equiv 3\bar{\rho}_b / \left(4\bar{\rho}_\gamma\right)}\right)}$$

Baryons add inertia to the fluid

Cosmic Sound Waves

$$\ddot{\delta}_\gamma - \underbrace{c_\gamma^2 \nabla^2}_{\text{Photon Pressure}} \delta_\gamma = \underbrace{\nabla^2 \Phi_+}_{\text{Gravity}}$$

Initial fluctuations generate curvature perturbations at all scales!



We observe these acoustic oscillations in the CMB map!

$$\delta_\gamma \sim \underbrace{A_{\vec{k}}}_{\substack{\text{Initial condition} \\ \text{(inflation)}}} \cos\left(c_s k \tau\right),$$

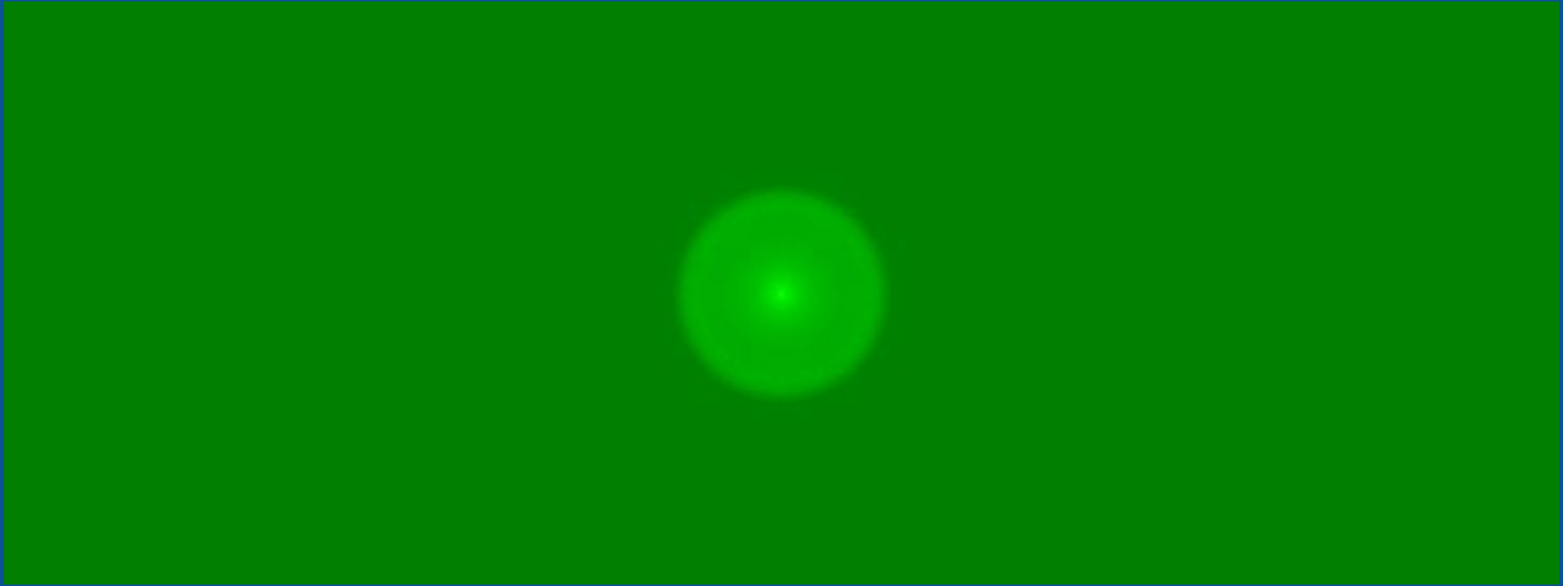
$$c_s^2 \sim \frac{c}{3\left(1 + \underbrace{R_b}\right)}$$

$$R_b \equiv 3\bar{\rho}_b / \left(4\bar{\rho}_\gamma\right)$$

Baryons add inertia to the fluid

Cosmic Sound Waves

The CMB is the final snapshot of the superposition of many incoherent sound waves, that have been oscillating for ~400,000 years



The state of these oscillations is **frozen** at recombination when the baryons release the photons.

The CMB Power Spectrum

The CMB angular power spectrum represents the variance of temperature fluctuations as a function of angular scale

A spherical harmonic expansion of the temperature field

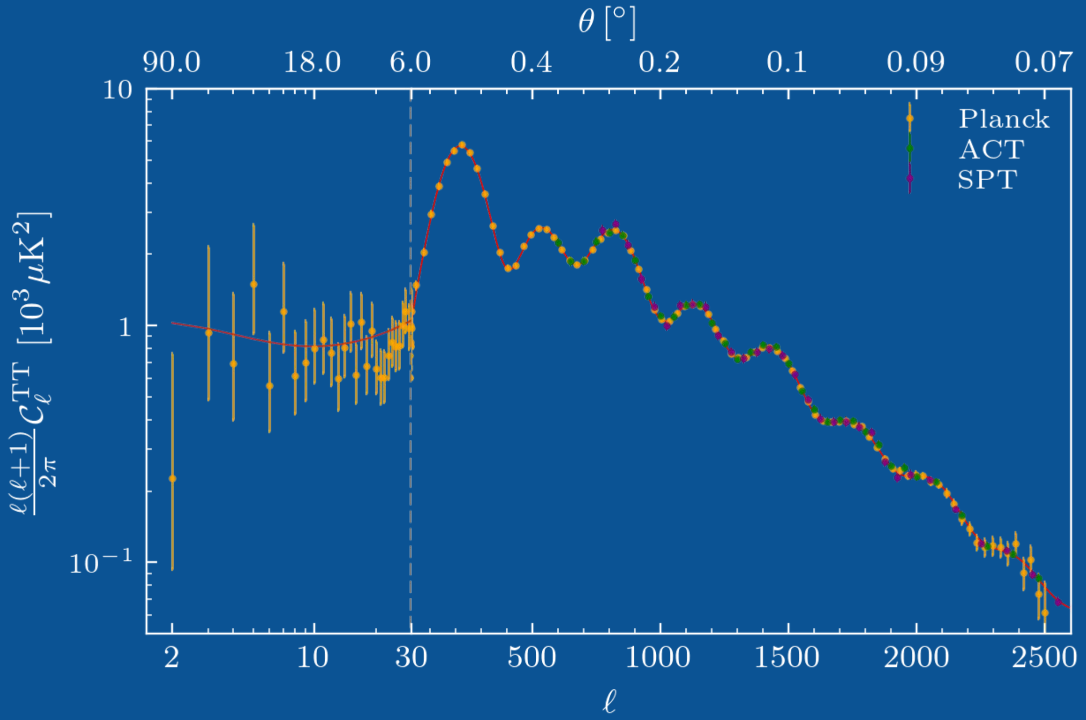
$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{\bar{T}} = \sum_{\ell m} \Theta_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

$$\boxed{\mathcal{C}_\ell \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\Theta_{\ell m}|^2}$$

This compresses 10^7 pixels of the CMB map into 10^3 multipole moments

The CMB Power Spectrum

The CMB angular power spectrum represents the variance of temperature fluctuations as a function of angular scale

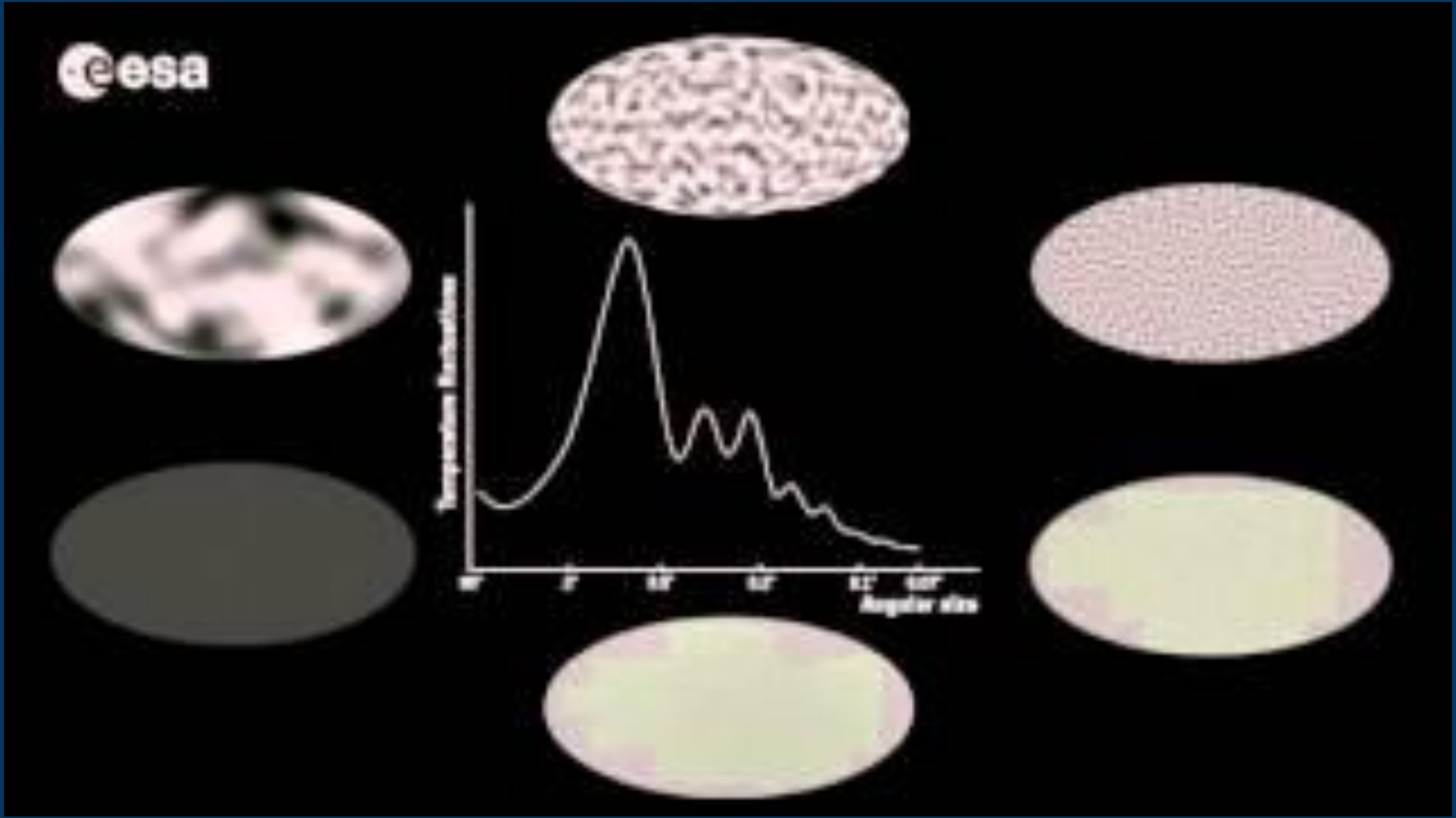


$$\delta_\gamma \sim A_{\vec{k}} \cos\left(c_s k \tau\right),$$

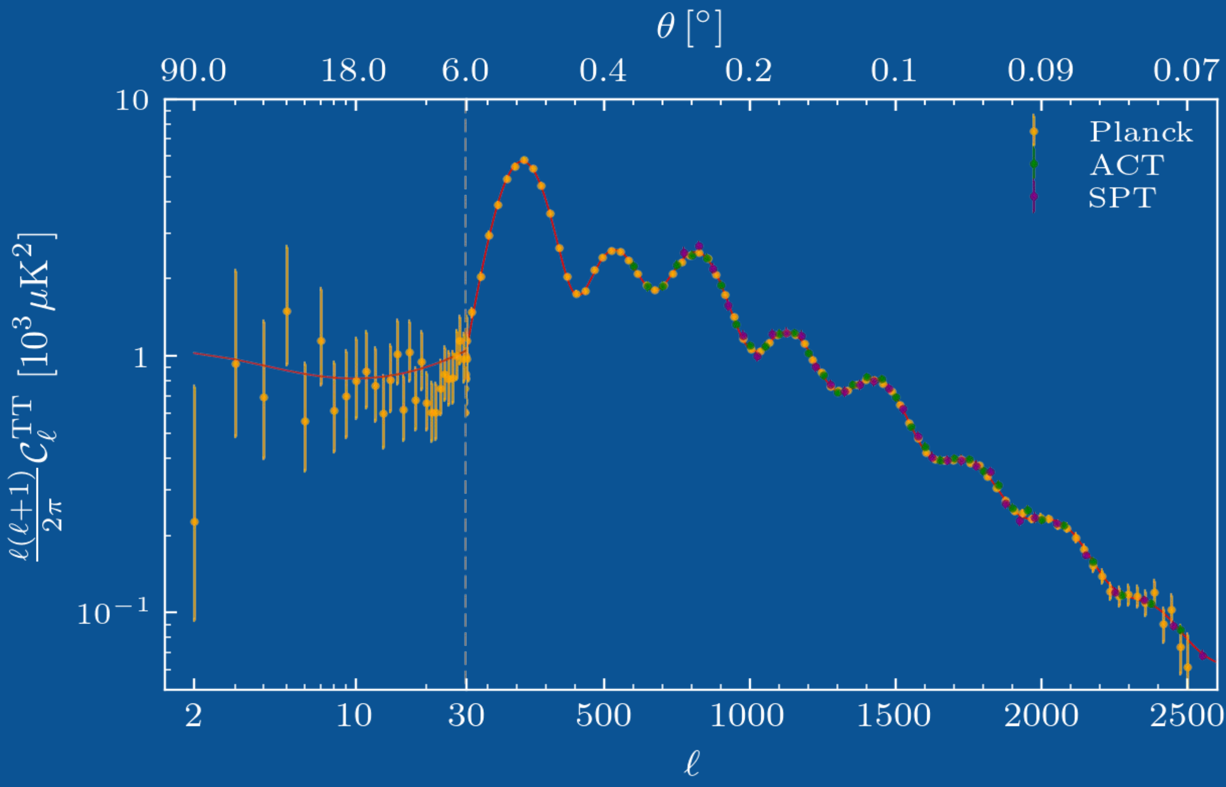
$$\downarrow$$

$$\mathcal{C}_\ell^{TT} \propto \cos^2(\theta_s \ell)$$

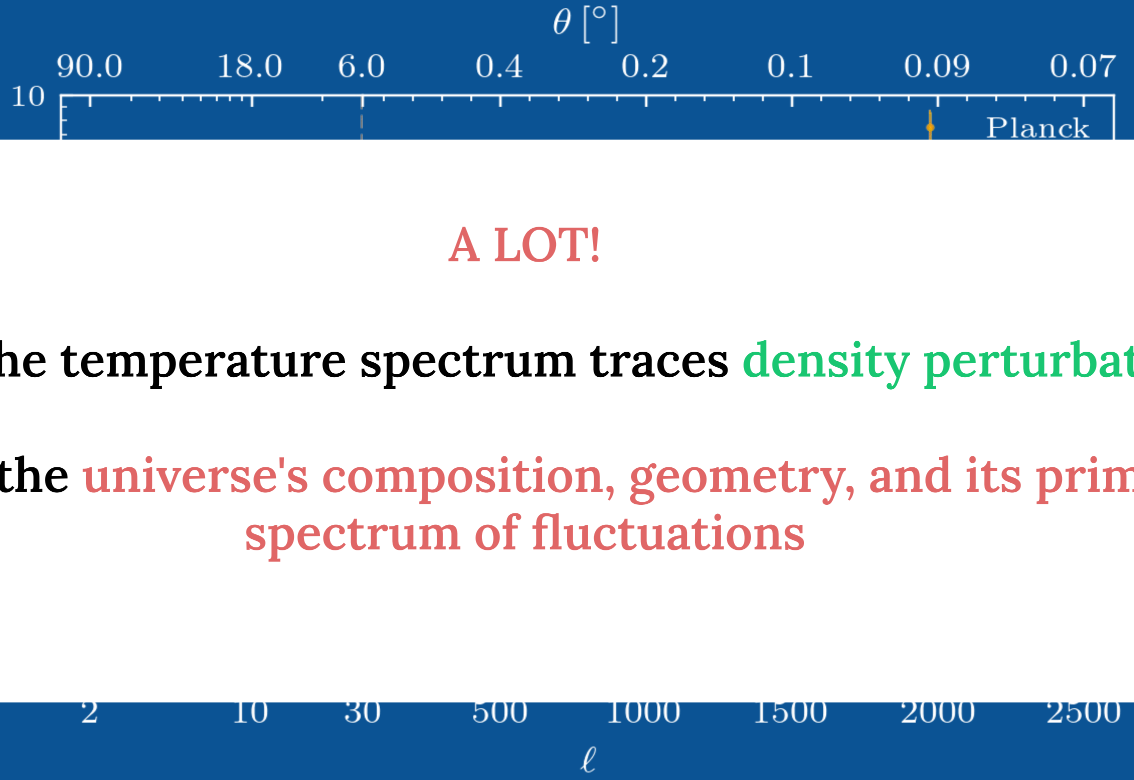
CMB Power Spectrum



What can we learn from the CMB Power Spectrum?



What can we learn from the CMB Power Spectrum?

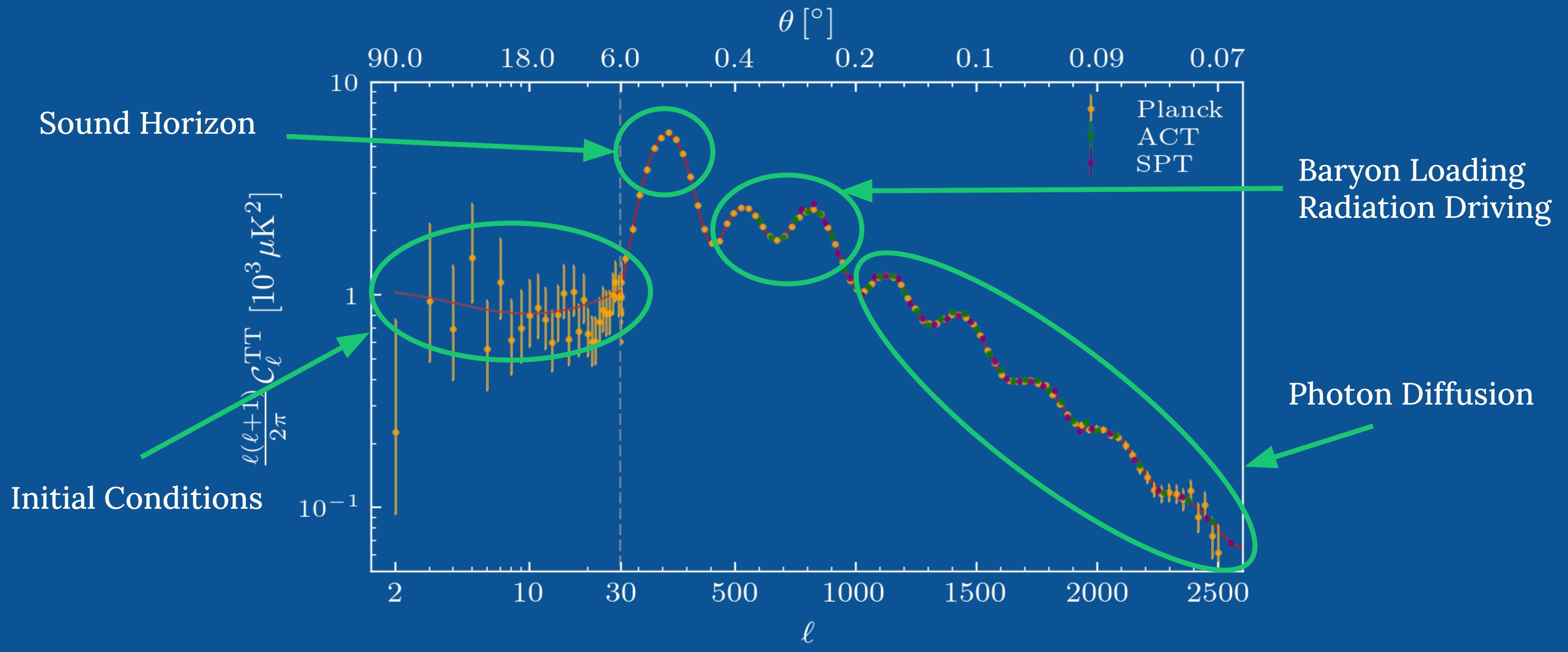


A LOT!

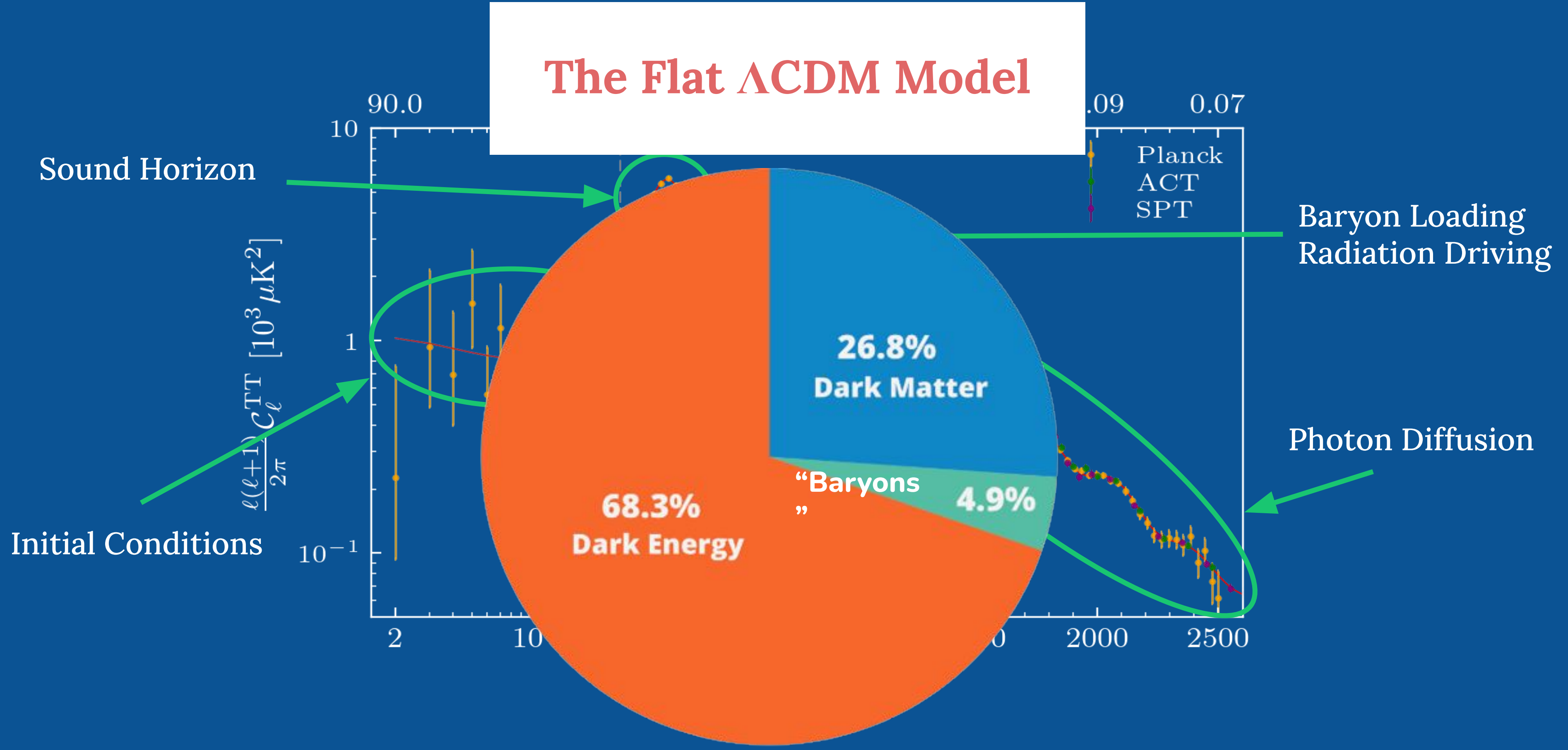
Recall: the temperature spectrum traces density perturbations

revealing the universe's composition, geometry, and its primordial spectrum of fluctuations

What can we learn from the CMB Power Spectrum?



What can we learn from the CMB Power Spectrum?

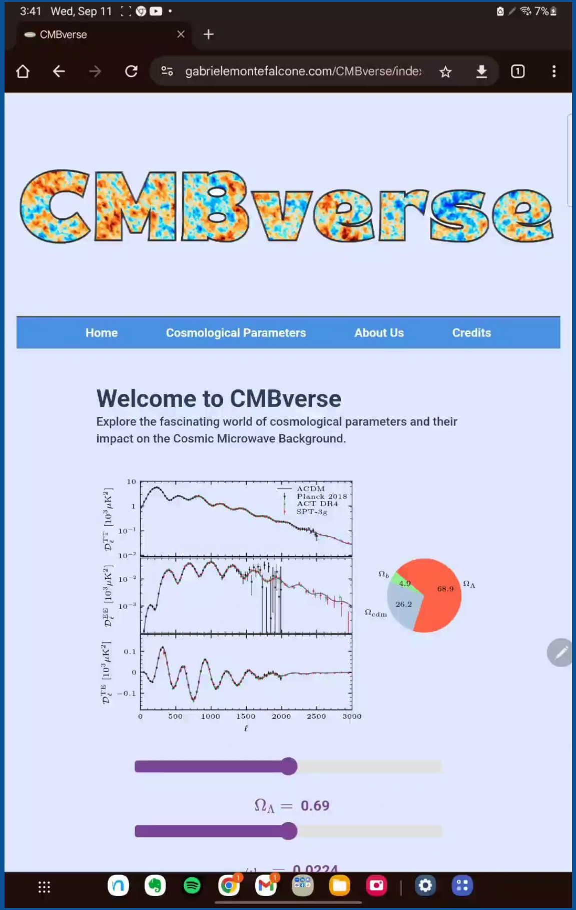


What Else?

- The CMB is **polarized**
  - Generated by a non-vanishing quadrupole of the temperature anisotropy
  - Less power than temperature spectrum but a clear probe of the physics at the very last scattering surface.
- The CMB is **lensed**
  - Gravitational lensing by large-scale structures distorts the CMB, slightly altering its path on its way to us
  - Provides a unique way to map the matter distribution and trace the growth of structure over time

CMBverse

A New Website to Learn about the CMB



Jack

Sofia

Chase

SCAN ME

Preliminary

Main Takeaways

- The CMB is the relic radiation associated with the formation of the first hydrogen atoms and the consequent decoupling of photons from the plasma.
- The CMB is consistent with a black-body spectrum at a temperature of **2.7255 K**, providing strong evidence that the early universe was in near-perfect thermal equilibrium, thereby confirming the Big Bang Theory.
- The patterns in the spectrum of the fluctuations in the CMB encode information about the physical processes in the early universe and it subsequent expansion, revealing the Universe's composition, geometry, and the growth of cosmic structures.