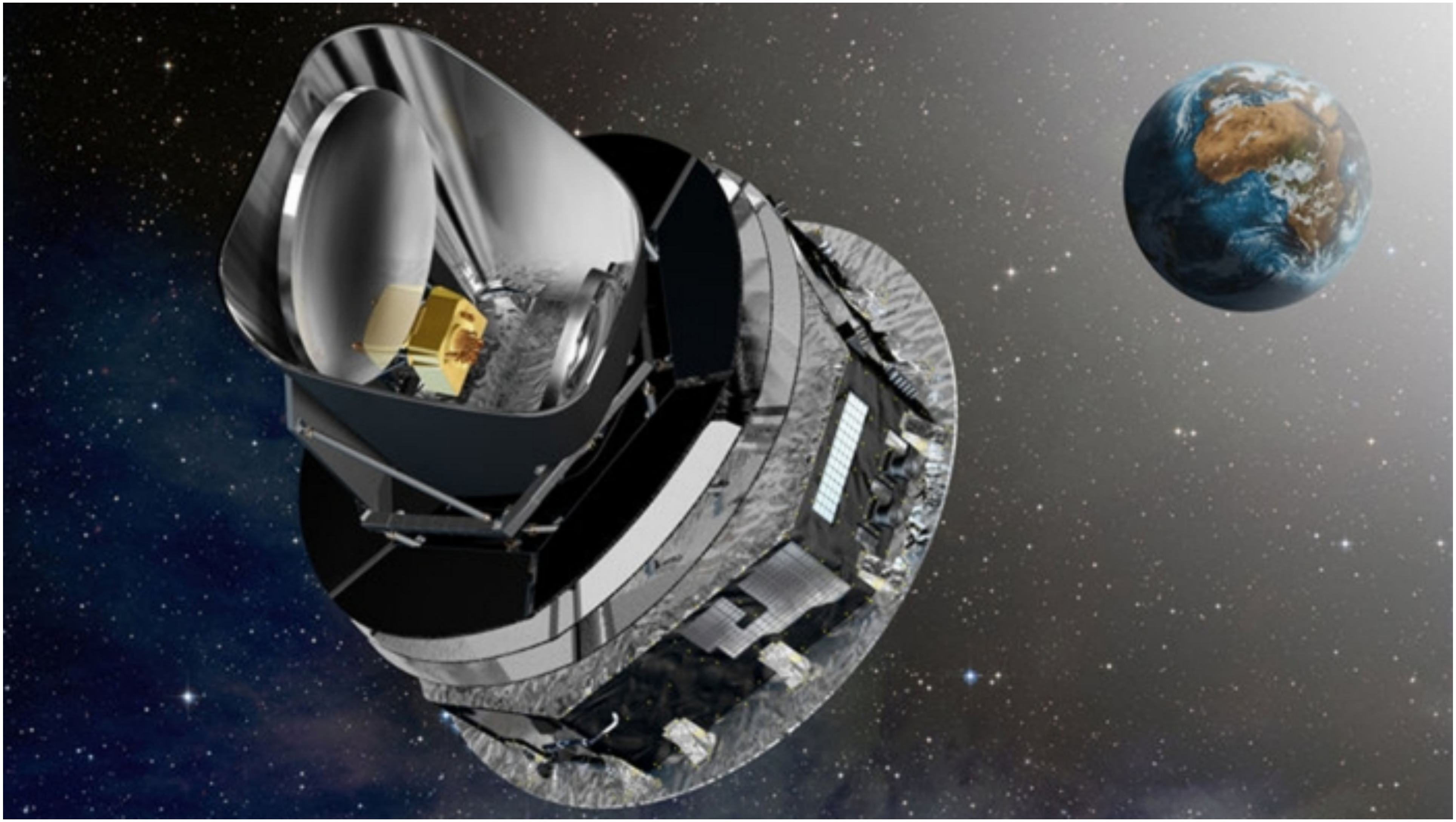
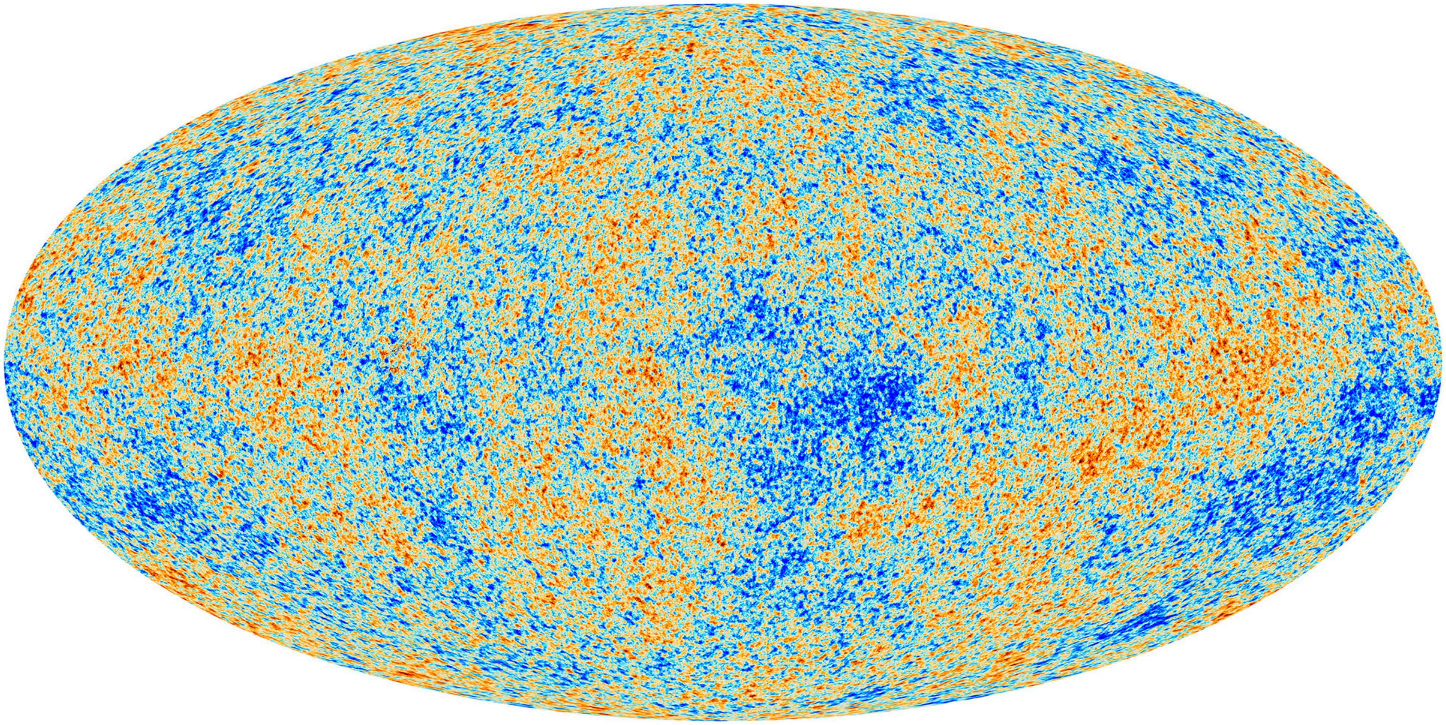


Precision cosmology from modern CMB experiments: Planck data and plans for future missions

Soumen Basak
SISSA, Trieste, Italy

CMB map from Planck



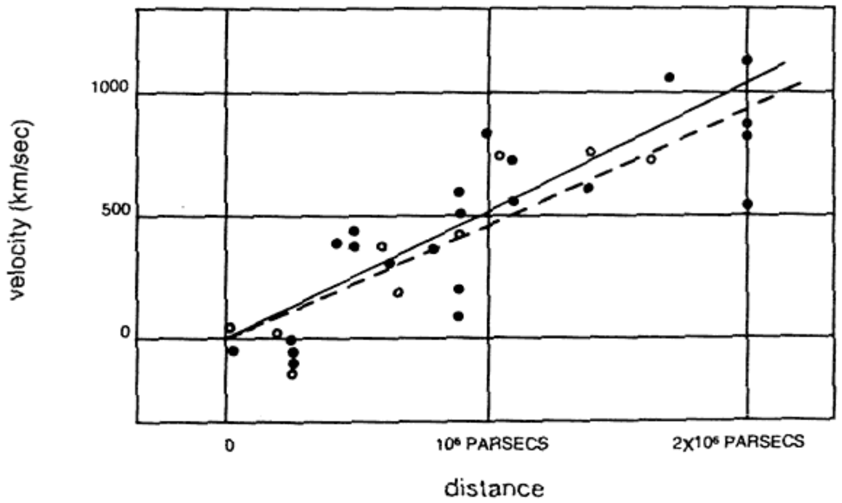
High temperature 🟥 🟦 Low temperature

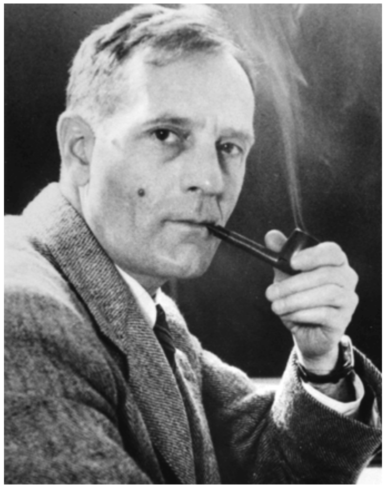
An accurate snapshot of oldest light of our Universe

Based on the mission's first 15.5 months of observations

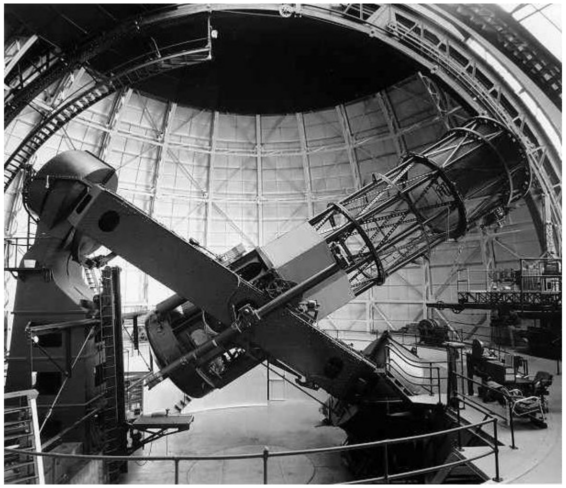
Originated around 380,000 years after Universe came into existence

Universe is expanding





Edwin Hubble



100-inch Hooker Telescope

Hubble's observations (1929)

- Distant galaxies in every direction are moving away from us.
- Galaxies that are further away are moving at faster rate.

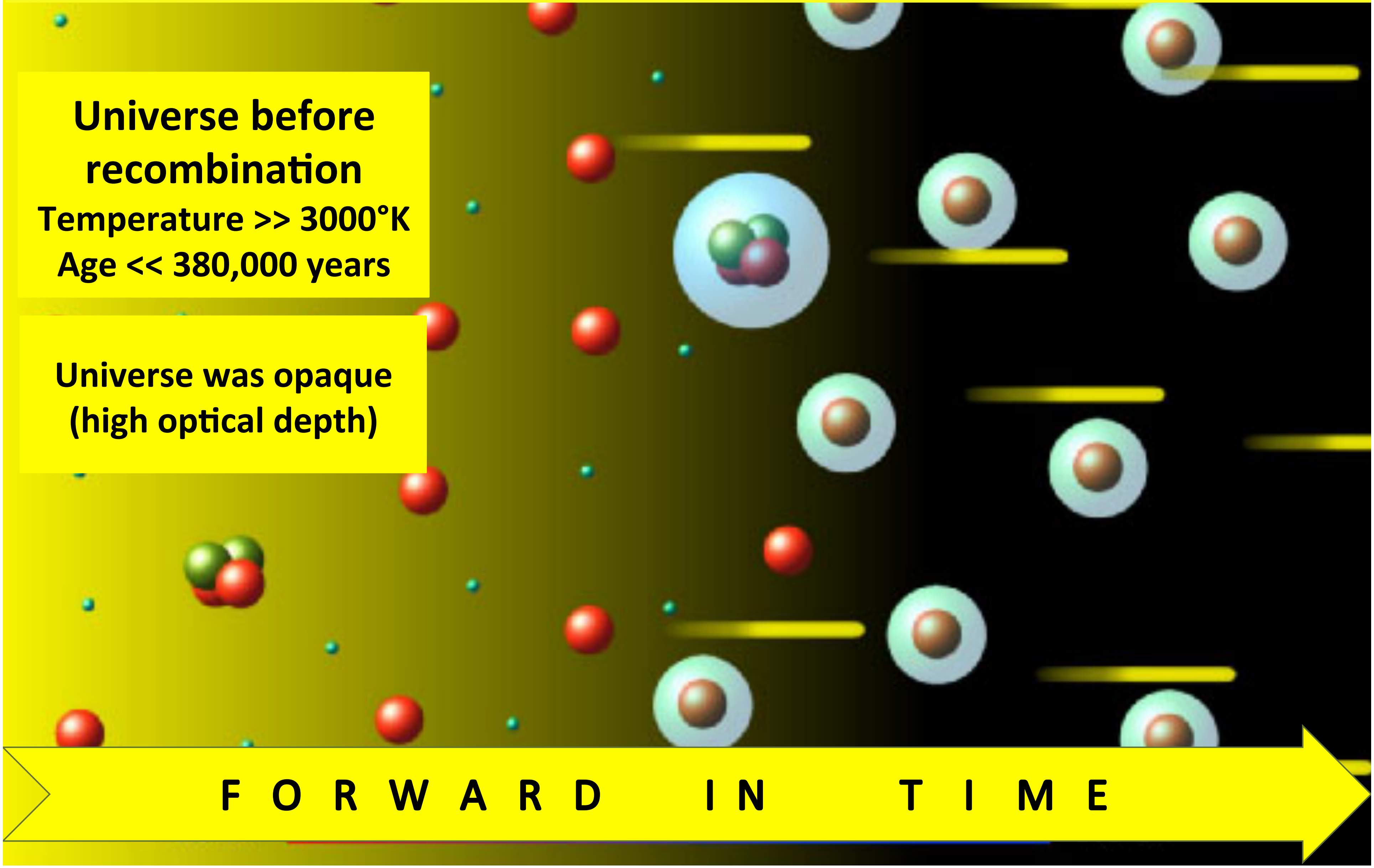
Hubble's law: $v = H_0 d$

- v = Relative velocity of galaxy
- H_0 = Hubble's constant
- d = Distance from earth

Cosmological principle

There is no preferred location or direction in our Universe as, on the largest cosmological scales, Universe is homogeneous and isotropic.

Origin of CMB



Universe before recombination

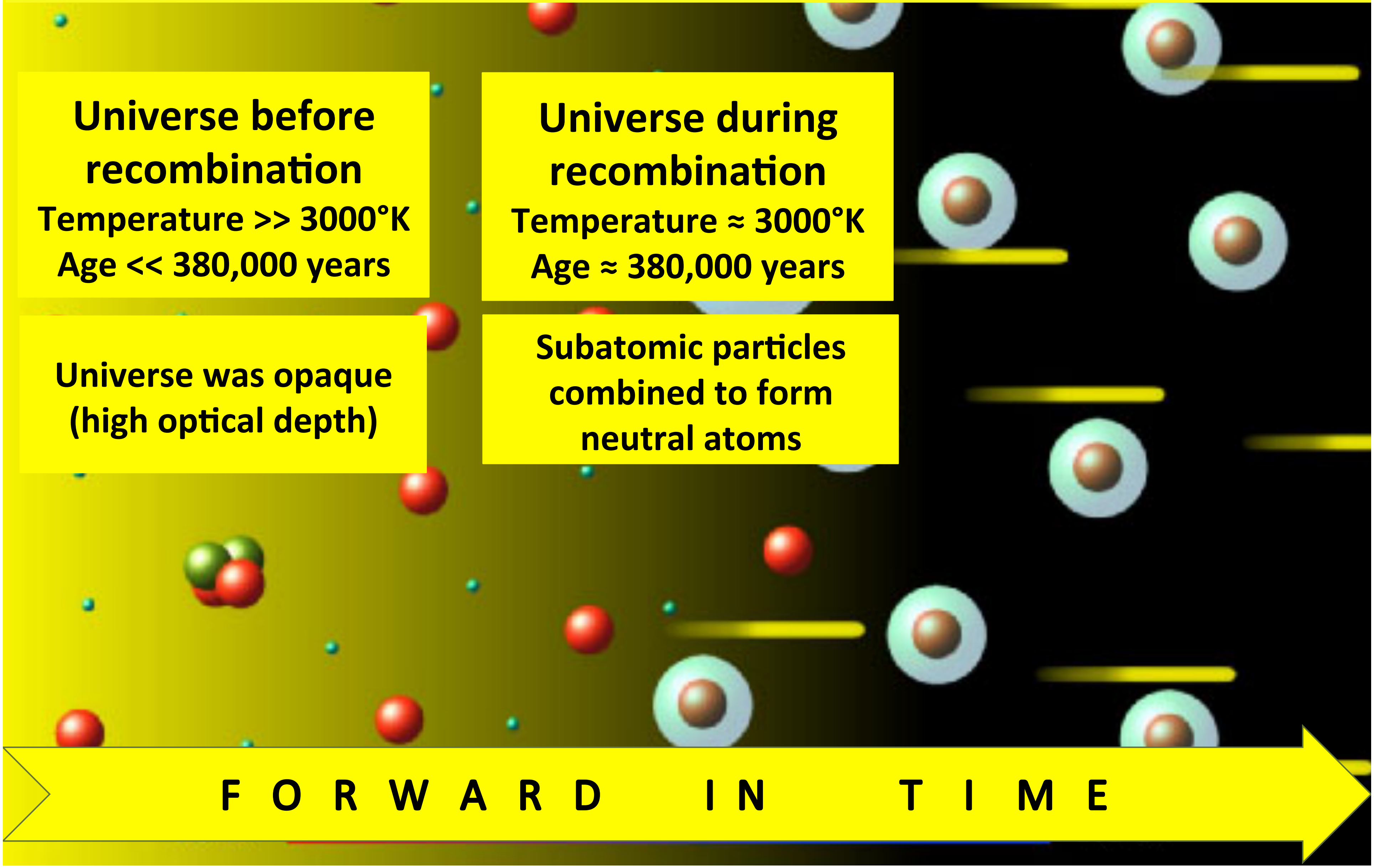
Temperature >> 3000°K

Age << 380,000 years

Universe was opaque (high optical depth)

FORWARD IN TIME

Origin of CMB



Universe before recombination

Temperature >> 3000°K

Age << 380,000 years

Universe during recombination

Temperature ≈ 3000°K

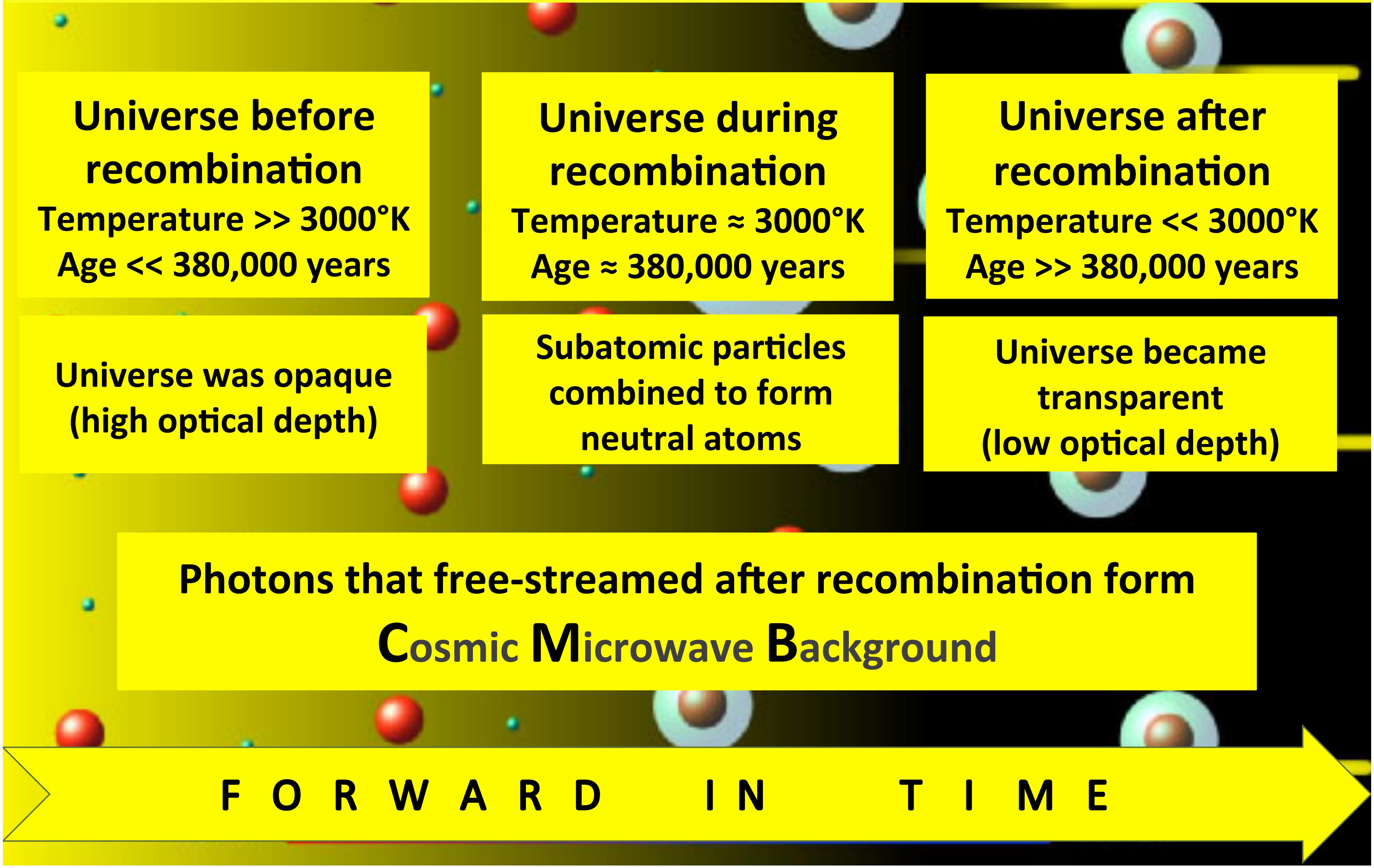
Age ≈ 380,000 years

Universe was opaque (high optical depth)

Subatomic particles combined to form neutral atoms

FORWARD IN TIME

Origin of CMB



Universe before recombination
Temperature >> 3000°K
Age << 380,000 years

Universe during recombination
Temperature ≈ 3000°K
Age ≈ 380,000 years

Universe after recombination
Temperature << 3000°K
Age >> 380,000 years

Universe was opaque
(high optical depth)

Subatomic particles combined to form neutral atoms

Universe became transparent
(low optical depth)

Photons that free-streamed after recombination form
Cosmic **M**icrowave **B**ackground

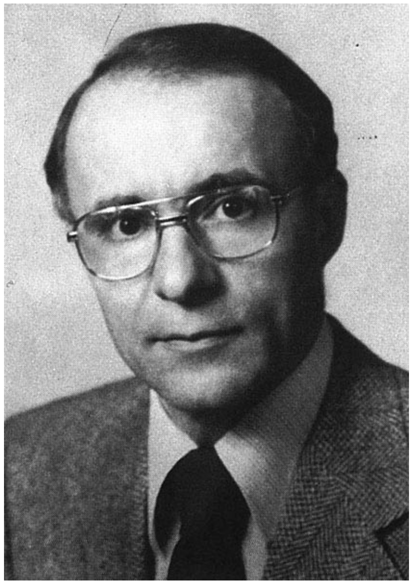
FORWARD IN TIME

Prediction

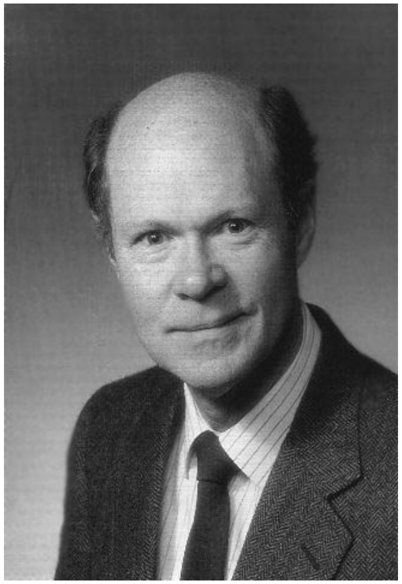
CMB was predicted by George Gamow in 1948 as a part of his work on Nucleosynthesis in early Universe

Predicted Temperature of CMB
5° - 10° K

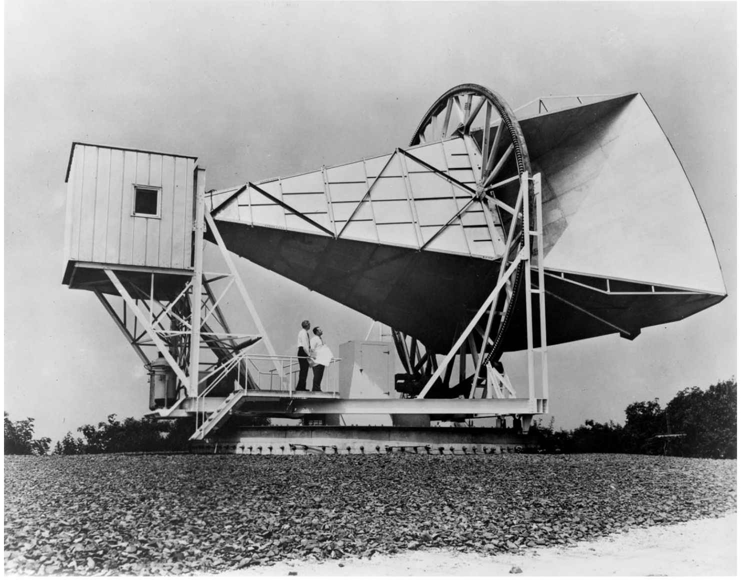
Discovery



Arno Penzias



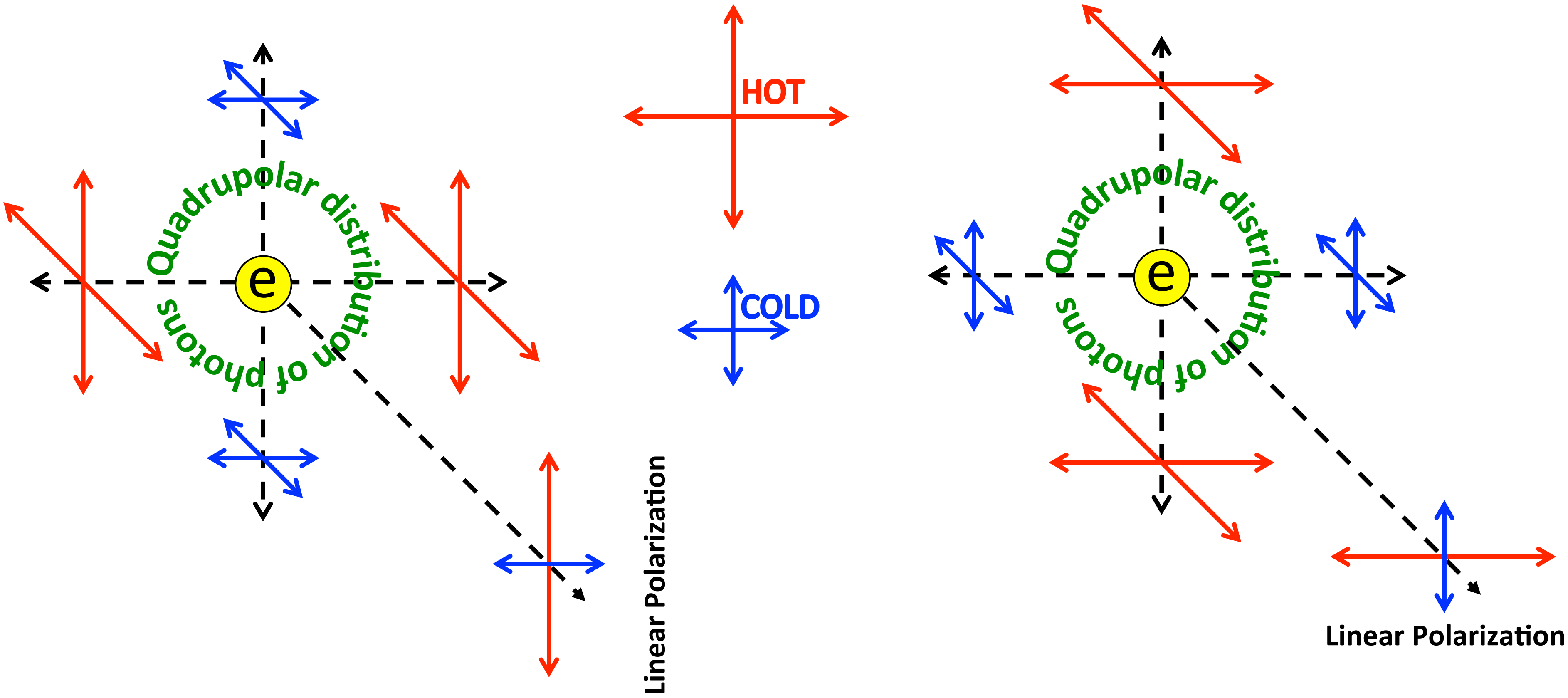
Robert Wilson



CMB was accidentally discovered by Arno Penzias and Robert Wilson at Bell Lab, New Jersey in 1965

Nobel Prize
1978

Origin of CMB polarization



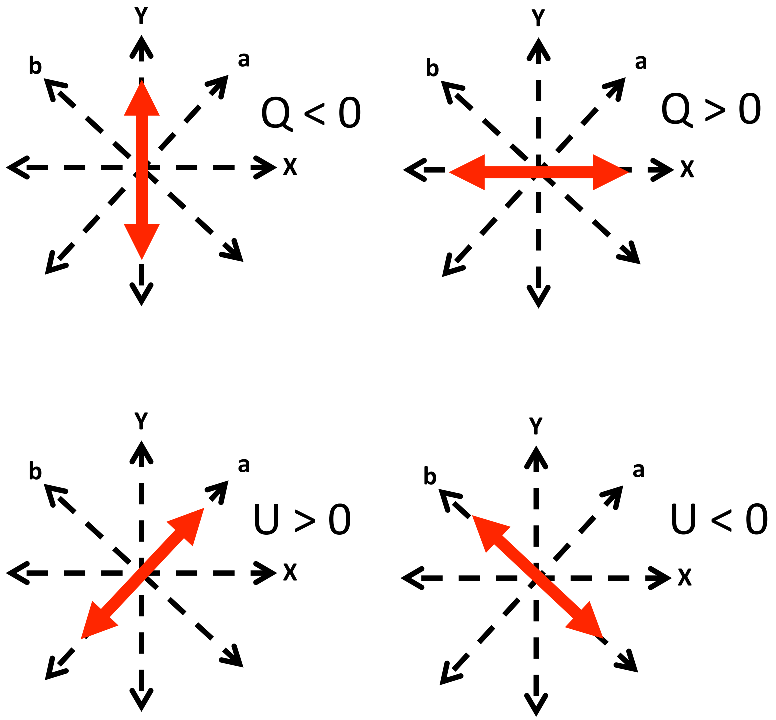
Cross-section of Thomson scattering:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{\mathrm{e}^2}{4\pi \mathrm{m}\mathrm{c}^2}\right)^2 |\hat{\epsilon}_{\mathrm{I}}.\hat{\epsilon}_{\mathrm{S}}|^2$$

CMB is partially polarized due to Thomson scattering of quadrupolar distribution of photons with free electrons at the time of recombination and reionization.

Characterization of CMB polarization

Linear polarization of CMB is fully characterized by Stokes parameters Q and U



Electric field of scattered radiation :

$$\overrightarrow{\mathrm{E}} = \mathrm{E_x}\,\widehat{\mathrm{x}} + \mathrm{E_y}\,\widehat{\mathrm{y}} = \mathrm{E_a}\,\widehat{\mathrm{a}} + \mathrm{E_b}\,\widehat{\mathrm{b}}$$

Stokes Q : $\mathrm{Q} = |\mathrm{E_x}|^2 - |\mathrm{E_y}|^2$

Stokes U : $\mathrm{U} = |\mathrm{E_a}|^2 - |\mathrm{E_b}|^2$

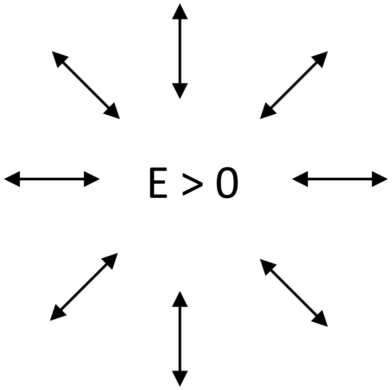
Stokes parameters are coordinate dependent

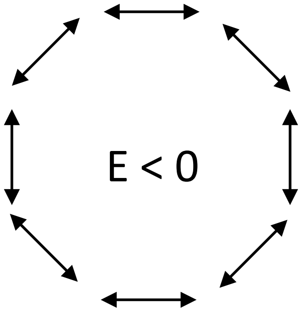
E-mode and B-mode of CMB polarization

CMB polarization fields can be decomposed into two scalar components

E-modes (curl-free):

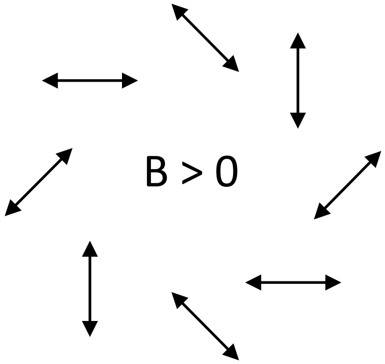
- Generated both by density perturbations and gravity waves
- Scalar under rotation on sphere
- An order of magnitude weaker than temperature anisotropy

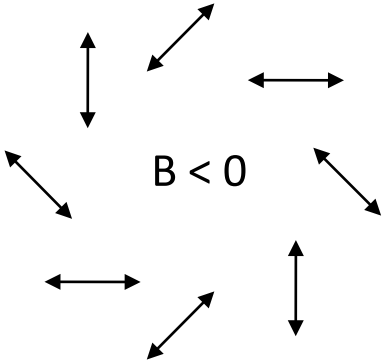




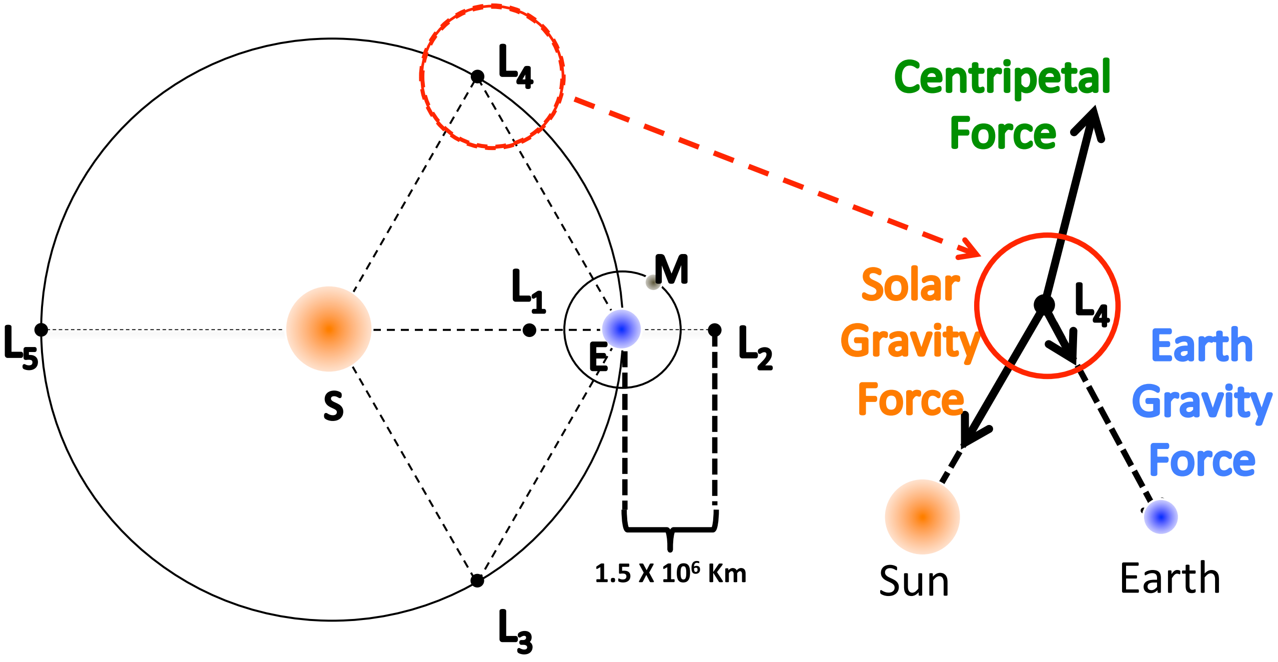
B-modes (divergence-free):

- Generated only by gravity waves
- Pseudo-scalar under rotation on sphere (changes sign under parity)
- Weaker (strength unknown) than even E-mode





Launch and operation of Planck



At Lagrange ($L_{1,2,3,4,5}$) points of Sun-Earth system, a satellite requires very little fuel to main its position

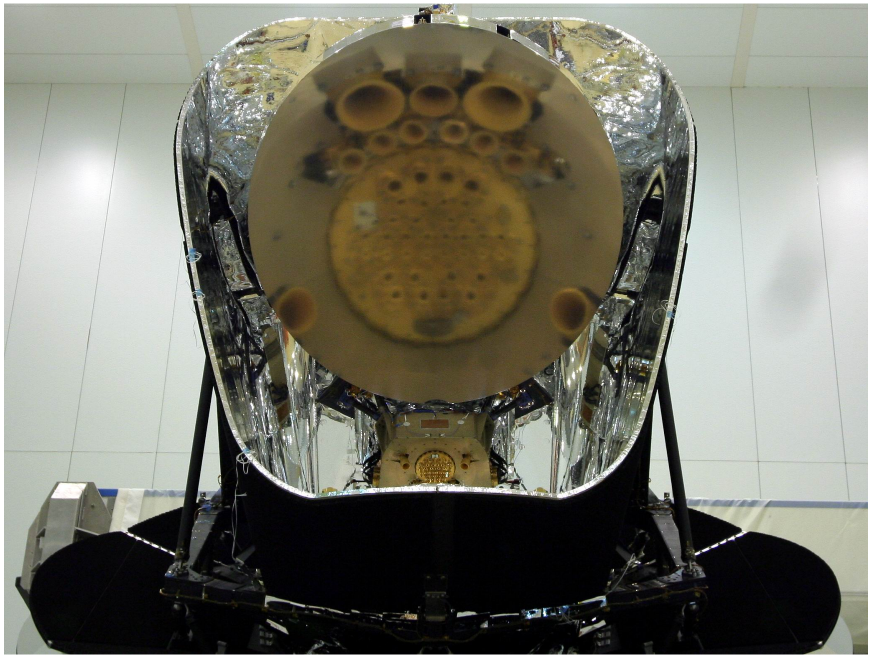
- Planck was launched on 14th May 2009 at Kurur in French Guiana
- Planck operated from 2nd Lagrange point (L_2) of Sun-Earth system

The L_2 point is the most suitable for Planck

- Close enough for quick communication
- Exceptionally stable environment
- Unobstructed view of deep space

Planck Satellite

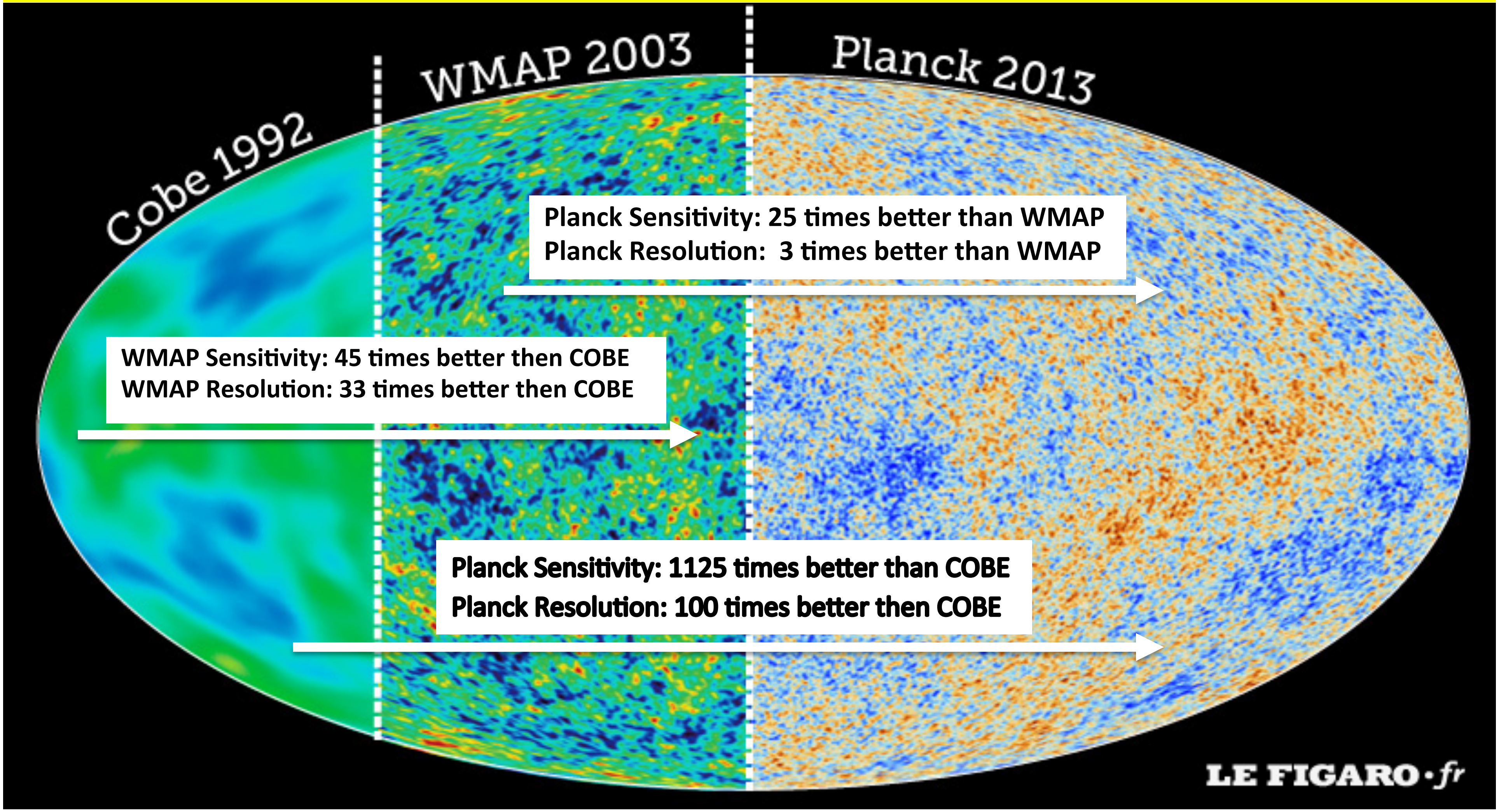
- Instruments:
  - Telescope
  - Detectors
    - Low Frequency Instrument (LFI)
    - High Frequency Instrument (HFI)
- Frequency coverage (in GHz):
  - LFI: 30, 40 and 70
  - HFI: 100, 143, 217, 353, 545 and 857
- Angular resolution:
  - Up to 5 arc minutes (approximately)
- Sensitivity:
  - Off the order of one millionth of °K
- Operational temperatures: 20°K for LFI and 0.1°K for HFI
  - Planck satellite is the coldest know object in space



Planck Satellite

It is as difficult (or easy) as measuring from earth the heat of a rabbit sitting on the surface of our Moon

Comparison of CMB map from three satellite missions



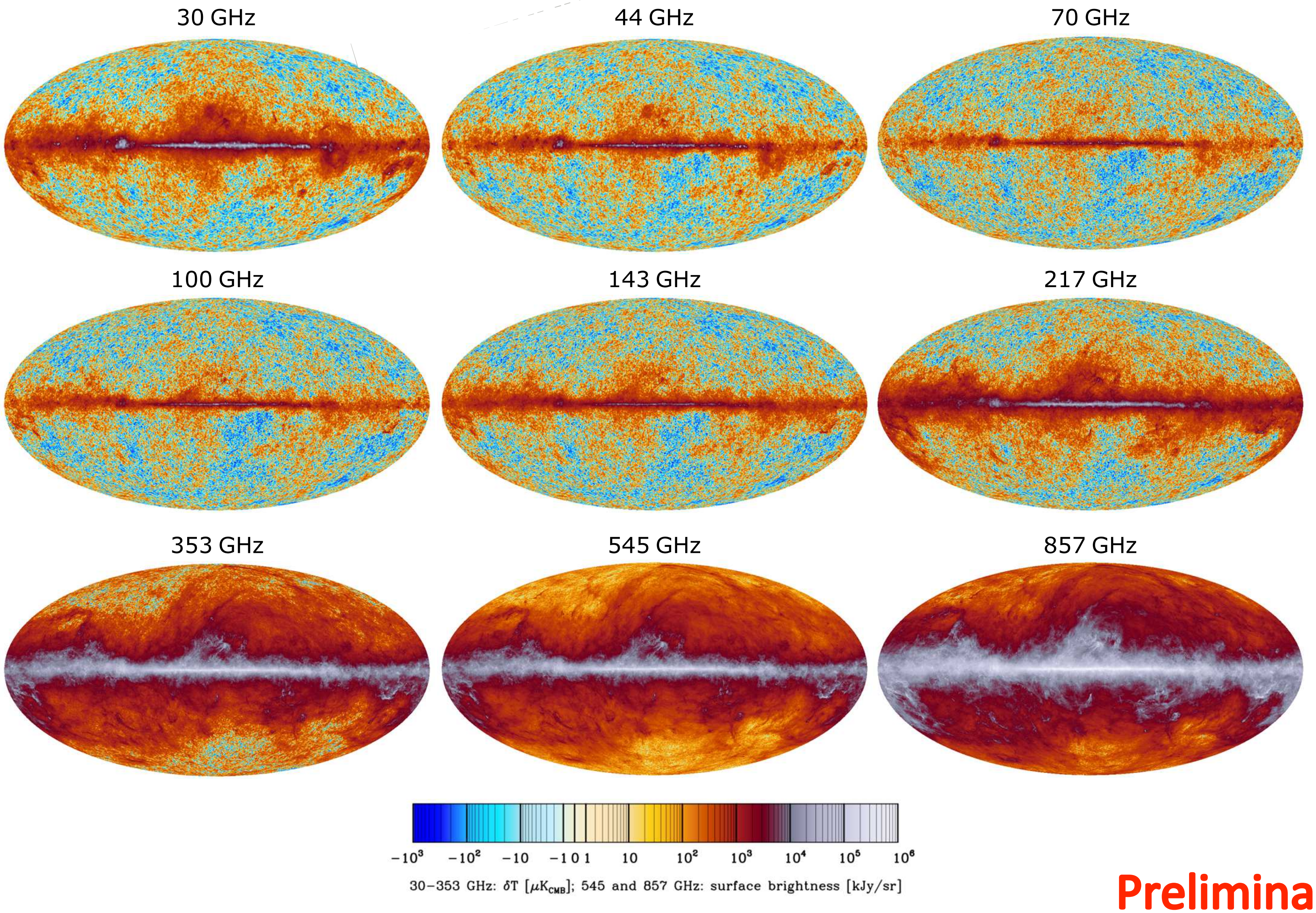
Planck Sensitivity: 25 times better than WMAP
Planck Resolution: 3 times better than WMAP

WMAP Sensitivity: 45 times better then COBE
WMAP Resolution: 33 times better then COBE

Planck Sensitivity: 1125 times better than COBE
Planck Resolution: 100 times better then COBE

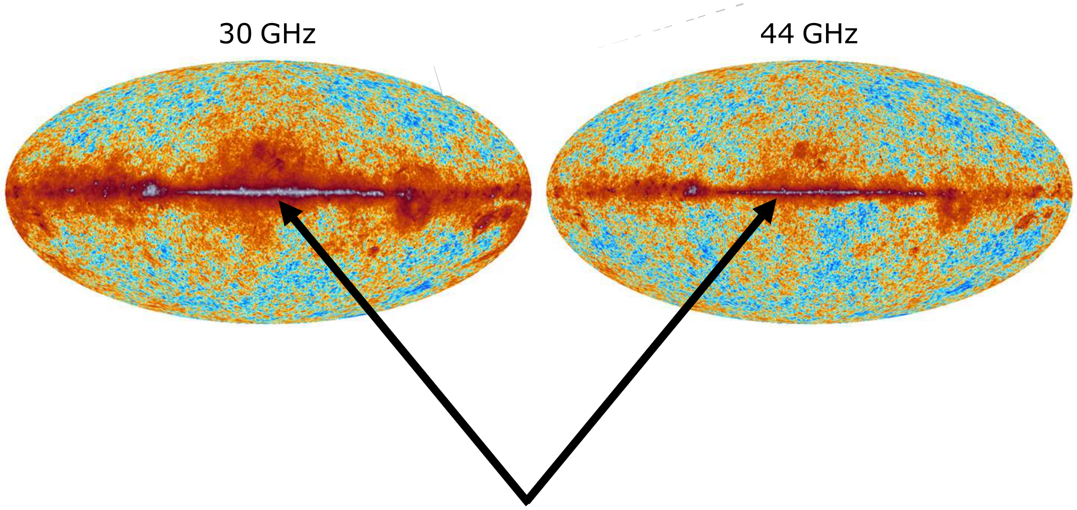
Planck is far superior than previous two satellite in terms of angular resolution and sensitivity

Temperature sky maps from Planck



Preliminary

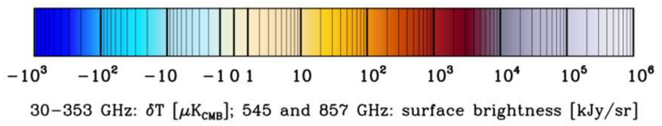
Temperature sky maps from Planck



Synchrotron emission

+

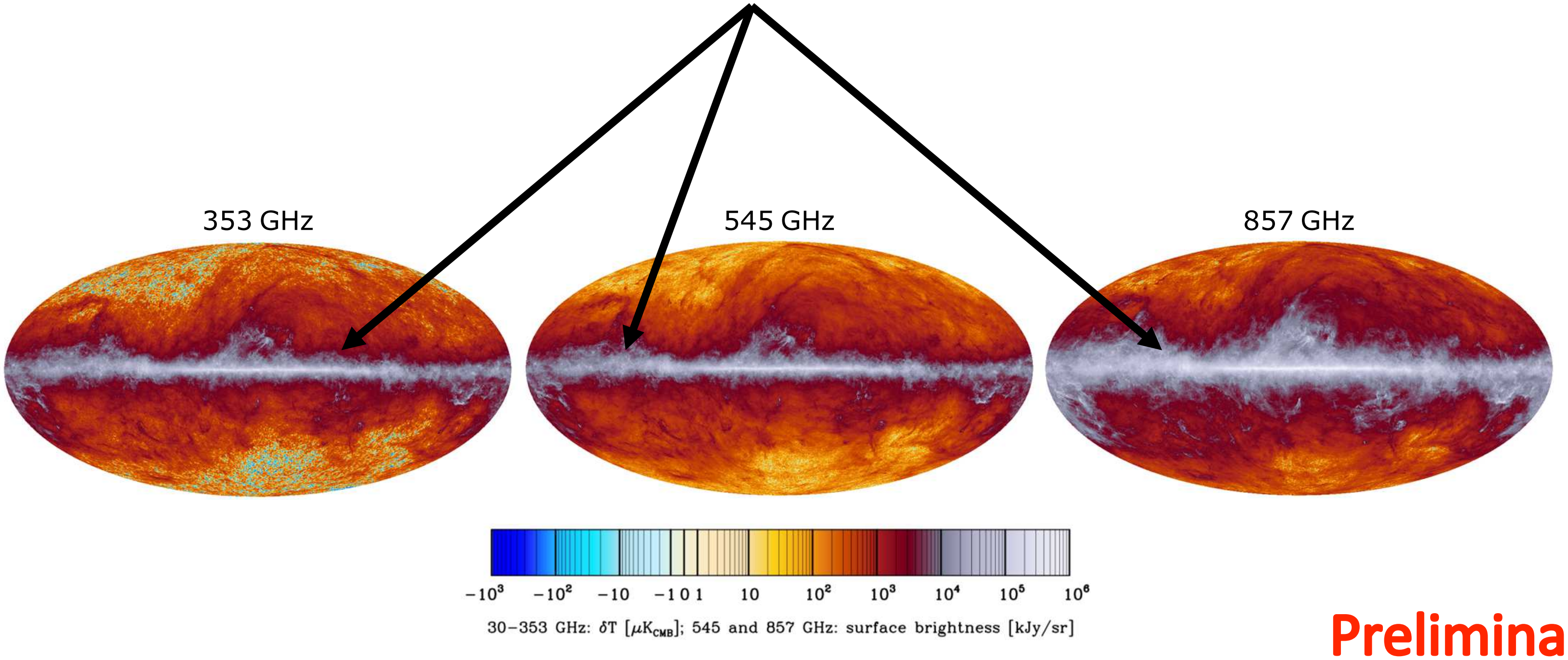
Bremsstrahlung emission



Preliminary

Temperature sky maps from Planck

Dust emission

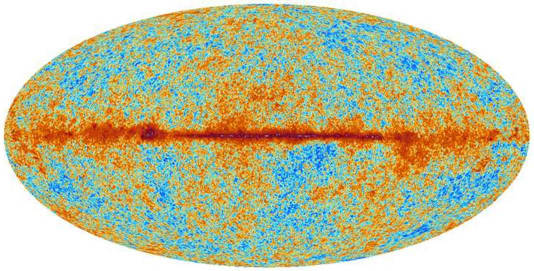


Preliminary

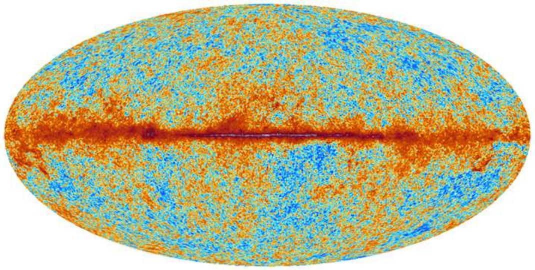
Temperature sky maps from Planck

CMB is most evident in the intermediate frequency bands between 70 and 217 GHz.

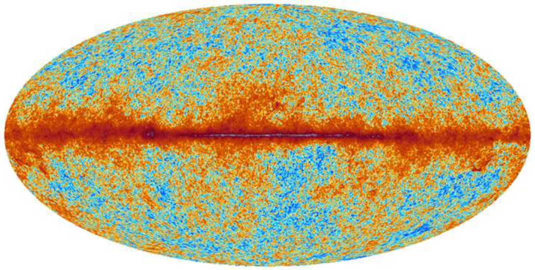
70 GHz



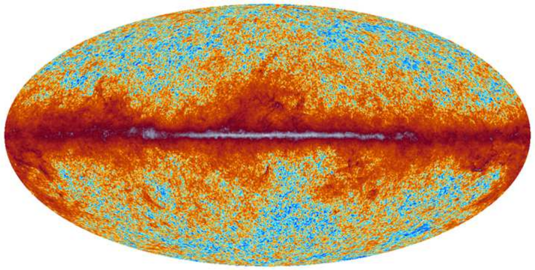
100 GHz

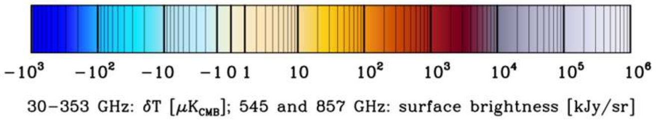


143 GHz



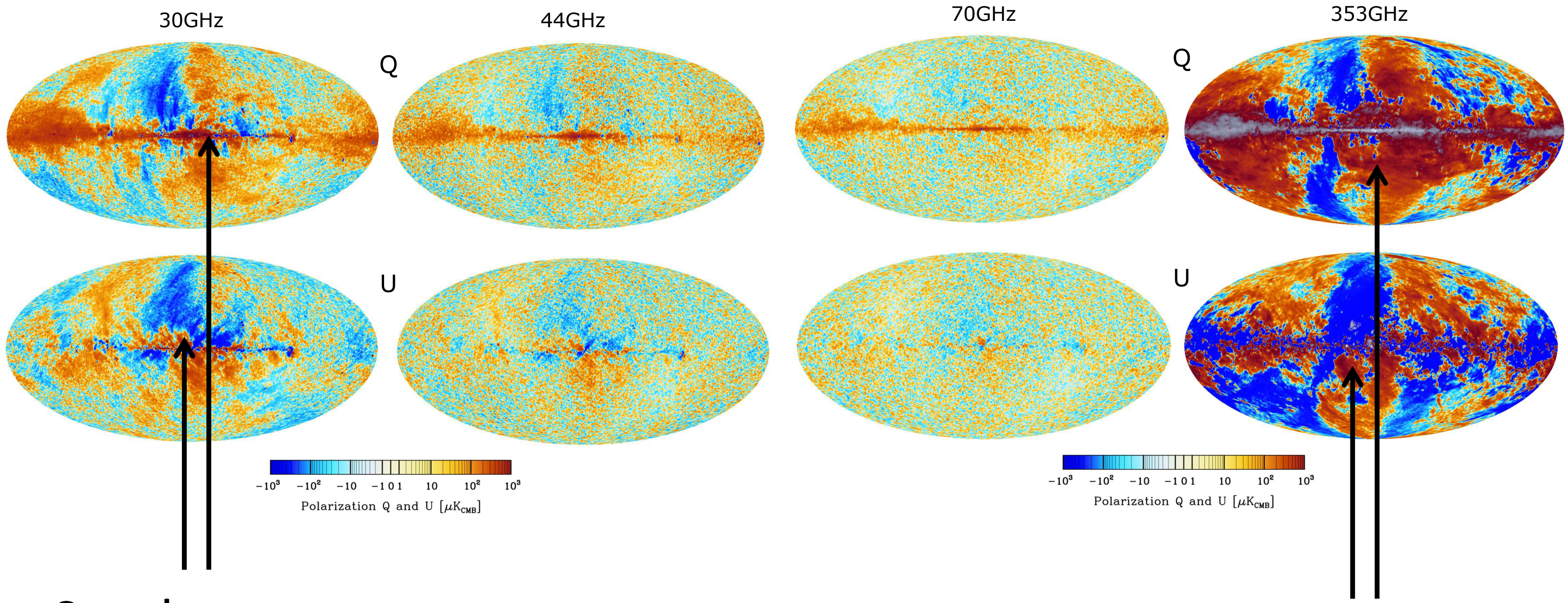
217 GHz





Preliminary

Polarization sky maps from Planck



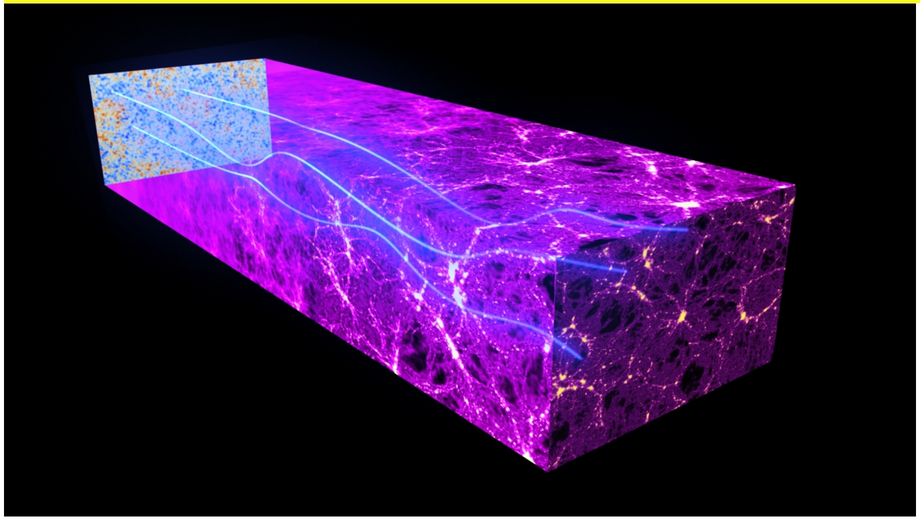
Synchrotron
emission

Dust emission

Images of polarization sky maps for 100, 143 and 217 GHz are yet to be made public

Preliminary

CMB Lensing



CMB lensing:

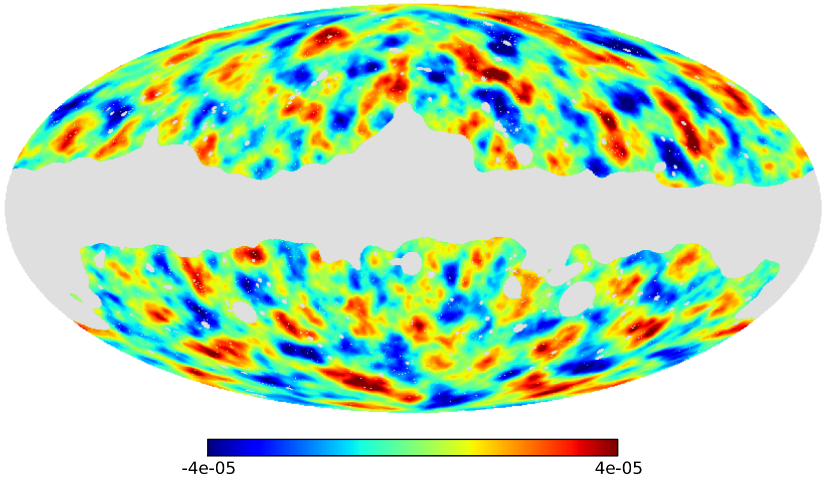
- Remaps the CMB field without changing surface brightness

$$\Delta \mathrm{T}(\hat{\mathrm{n}}) \longrightarrow \Delta \mathrm{T}\left(\hat{\mathrm{n}} + \vec{d}\,(\hat{\mathrm{n}})\right)$$

$$\vec{d}\,(\hat{\mathrm{n}}) = \vec{\nabla}\Phi(\hat{\mathrm{n}})$$

Typical RMS value of d: ~ 2.5 arcmin

- Induces correlation between CMB field on the sky and its gradient, hence, leaves a distinct non-Gaussian signature on CMB.



🟥 High mass density

⬜ Mask

🟦 Low mass density

Measurement of higher order non-Gaussian correlation helps to reconstruct lensing signal, which is related to total mass along the line of sight

Planck is the first experiment to provide a full-sky reconstruction of the projected mass, along every line of sight back to the surface of last scattering. **Preliminary**

Statistics of CMB temperature anisotropy

CMB temperature anisotropy fields on sphere

$$\Delta \mathrm{T}(\hat{\mathrm{n}}) = \sum_{\mathrm{l}=2}^{\infty} \sum_{\mathrm{m}=-\mathrm{l}}^{\mathrm{l}} \Delta \mathrm{T}_{\mathrm{lm}}\, \mathrm{Y}_{\mathrm{lm}}(\hat{\mathrm{n}})$$

$$\Delta \mathrm{T}_{\mathrm{lm}} = \int_{\Omega_{\mathrm{n}}} \mathrm{d}\Omega_{\hat{\mathrm{n}}}\, \Delta \mathrm{T}\left(\widehat{\mathrm{n}}\right) \mathrm{Y}^{*}_{\mathrm{lm}}\left(\widehat{\mathrm{n}}\right)$$

CMB temperature anisotropy is Gaussian up to a very good accuracy, hence, two-point correlation contains most of its information

CMB angular power spectrum (two-point correlation)

$$\mathrm{C}_{\mathrm{l}} = 4\pi \int_{0}^{\infty} \frac{\mathrm{dk}}{\mathrm{k}} \Delta_{\mathrm{l}}^{2}(\mathrm{k})\, \mathrm{P}(\mathrm{k})$$

$$\langle \Delta \mathrm{T}_{\mathrm{lm}} \Delta \mathrm{T}^{*}_{\mathrm{l}'\mathrm{m}'} \rangle = \delta_{\mathrm{l}\,\mathrm{l}'}\, \delta_{\mathrm{m}\,\mathrm{m}'}\, \mathrm{C}_{\mathrm{l}}$$

Transfer function

Evolution of Universe

Primordial spectrum

Initial conditions of Universe

CMB angular power spectrum is sensitive to both Initial conditions and evaluation of Universe

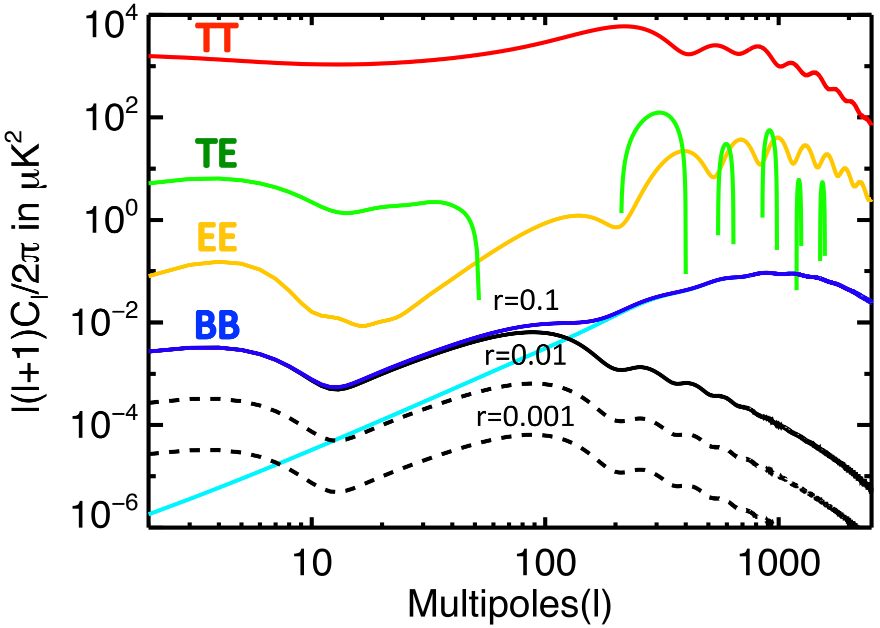
Statistics of CMB temperature anisotropy and Polarization

CMB anisotropy (X={ΔT, E and B) fields on sphere

$$X(\hat{n}) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} X_{lm}\, Y_{lm}(\hat{n})$$

$$X_{lm} = \int_{\Omega_n} d\Omega_{\hat{n}}\, X\left(\widehat{n}\right) Y^*_{lm}\left(\widehat{n}\right)$$

X = ΔT, E and B



CMB angular power spectra

$$C_l^{TT} \xrightarrow{\text{Parity}} C_l^{TT}$$

$$C_l^{EE} \xrightarrow{\text{Parity}} C_l^{EE}$$

$$C_l^{BB} \xrightarrow{\text{Parity}} C_l^{BB}$$

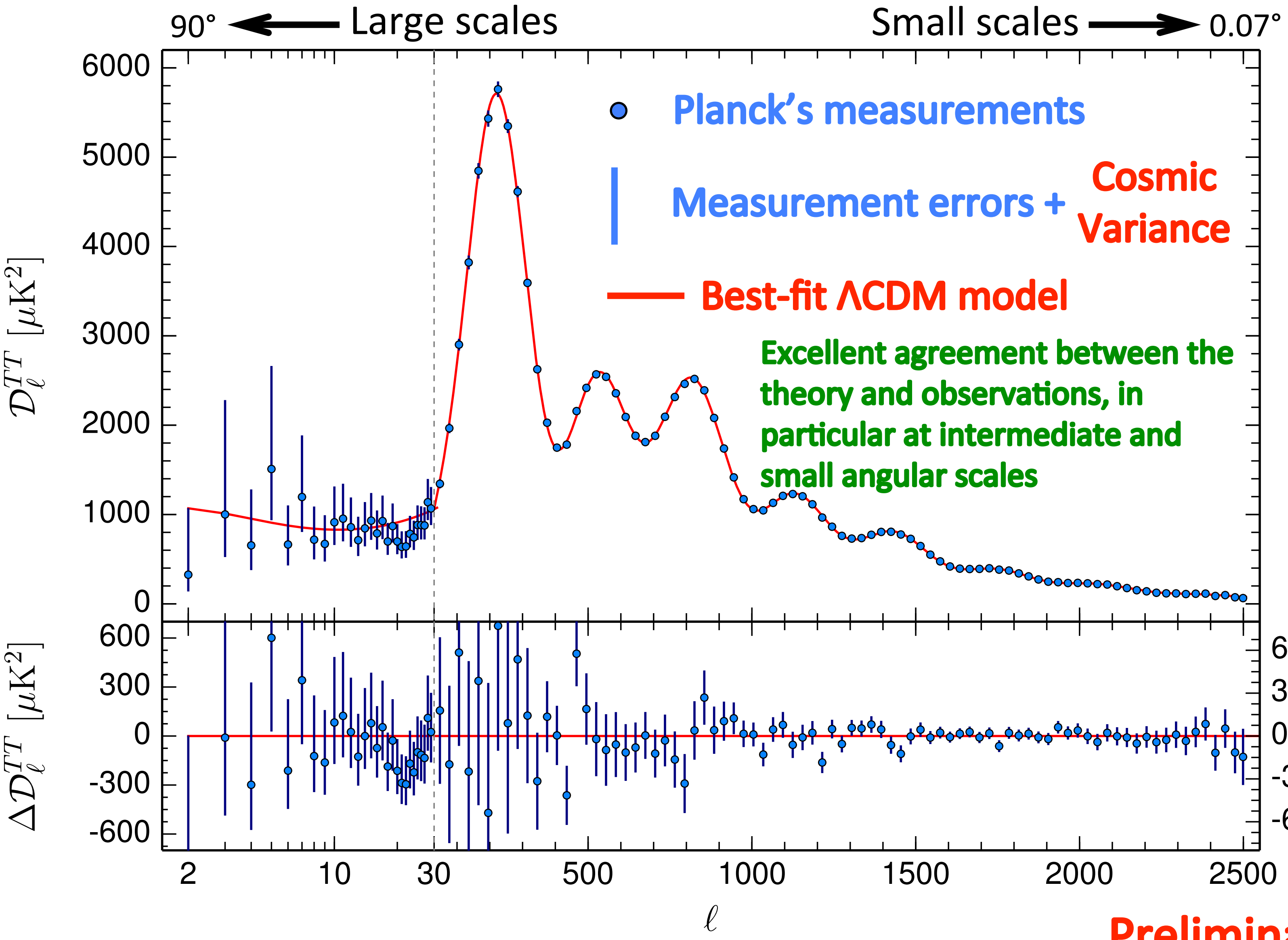
$$C_l^{TE} \xrightarrow{\text{Parity}} C_l^{TE}$$

$$\langle X_{lm} Z^*_{l'm'} \rangle = \delta_{l\,l'}\, \delta_{m\,m'}\, C_l^{XZ}$$

$$\left.\begin{array}{l} C_l^{TB} \xrightarrow{\text{Parity}} -\,C_l^{TB} \\ C_l^{EB} \xrightarrow{\text{Parity}} -\,C_l^{EB} \end{array}\right\}$$

Vanishes to preserve parity

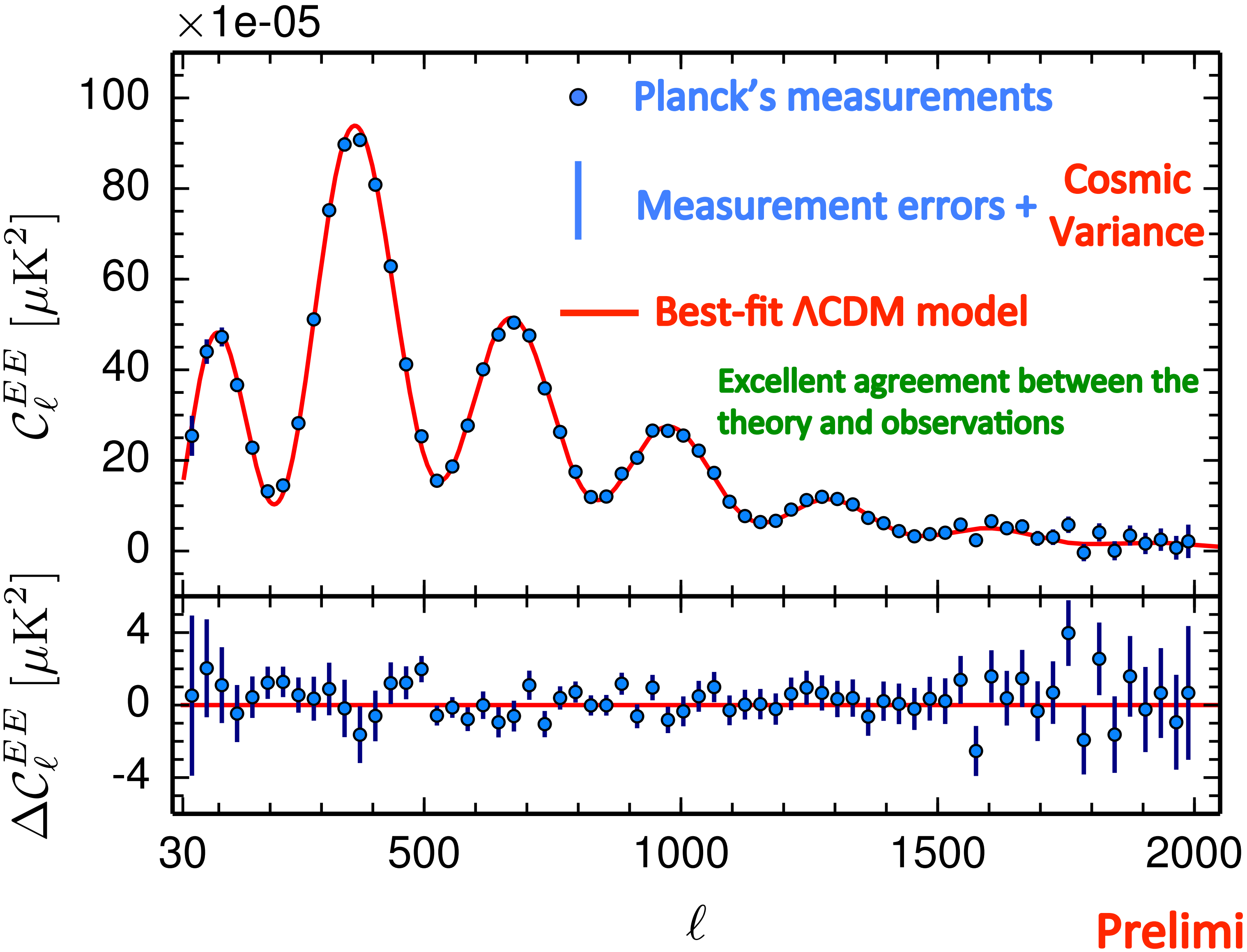
Angular Power Spectrum



Excellent agreement between the theory and observations, in particular at intermediate and small angular scales

Preliminary

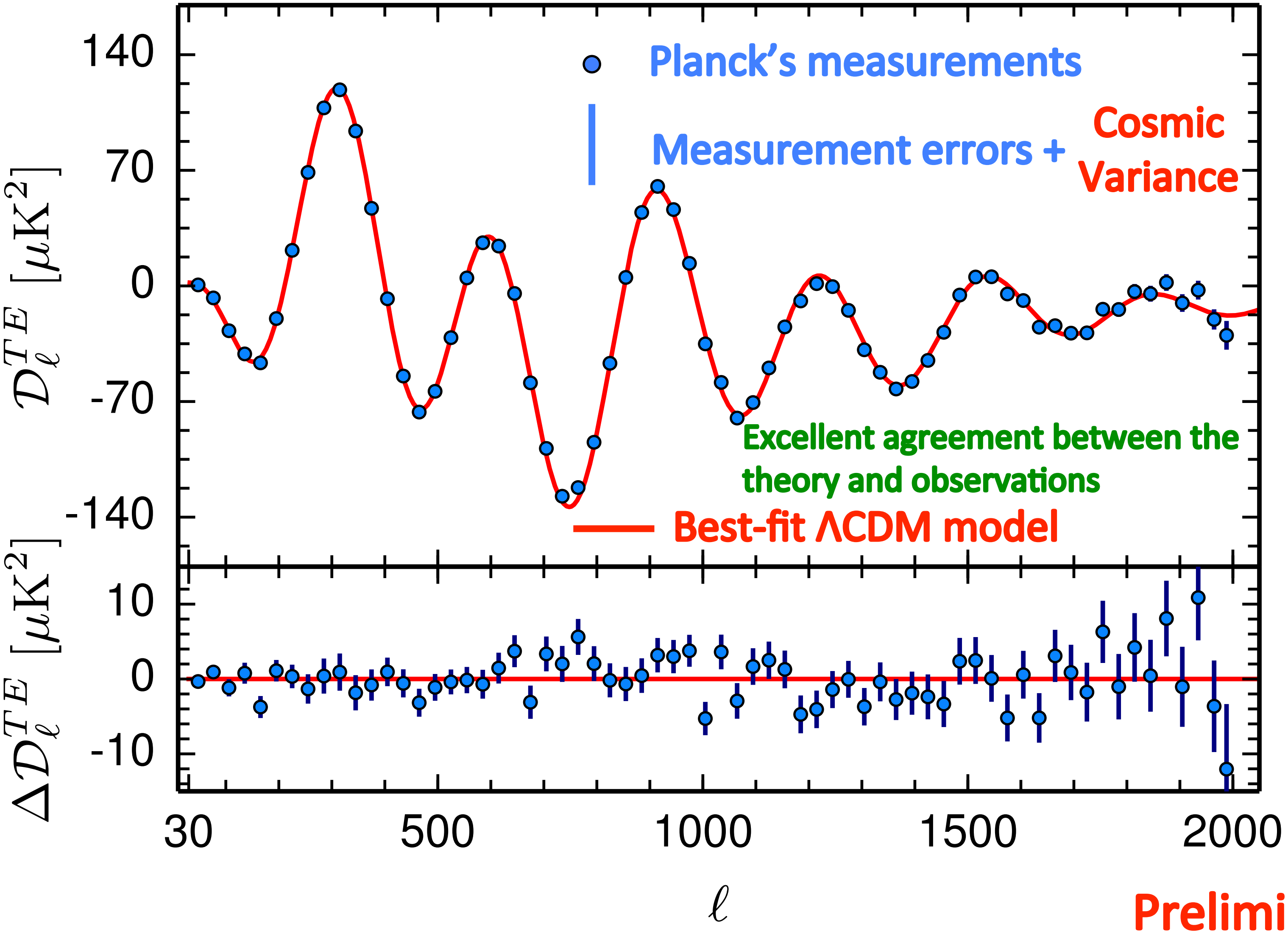
Angular Power Spectrum



Excellent agreement between the theory and observations

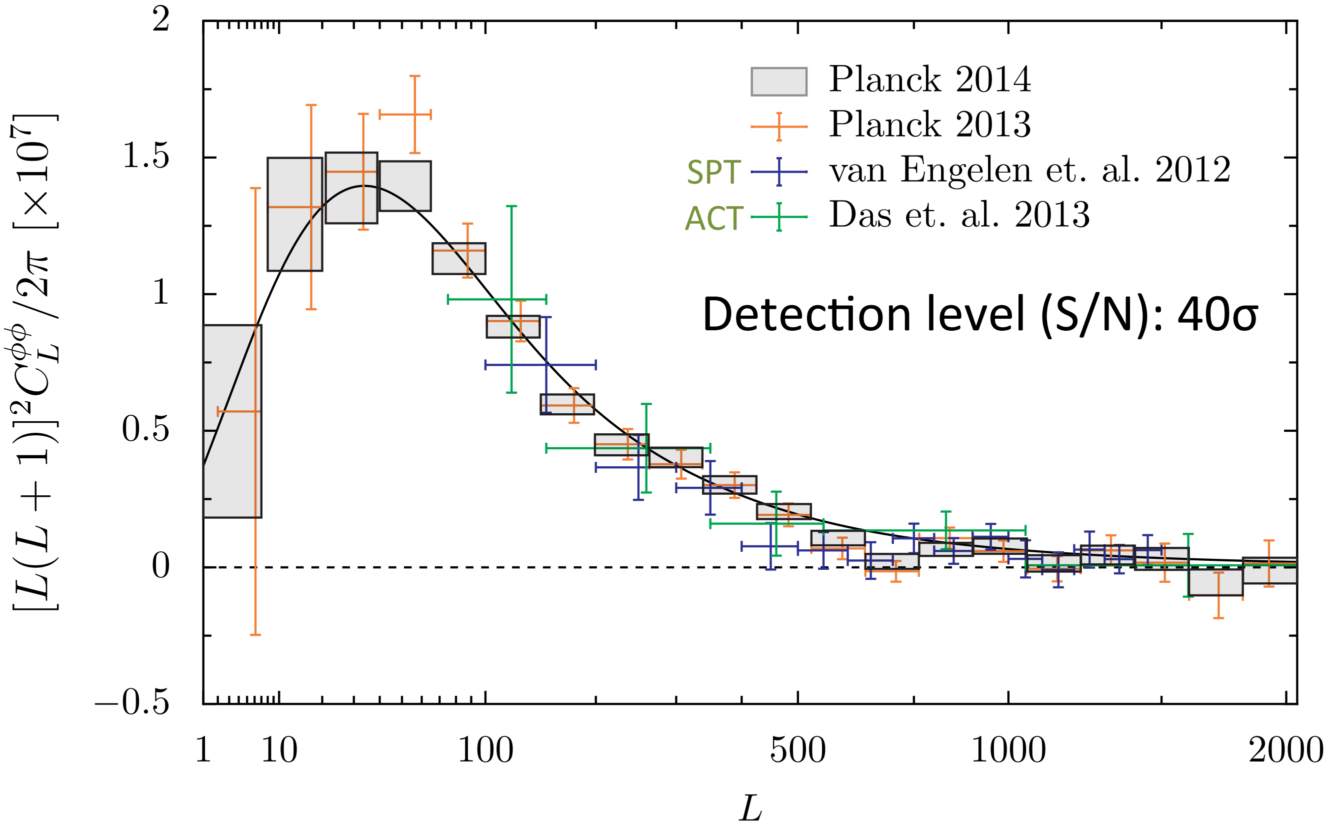
Preliminary

Angular Power Spectrum



Preliminary

Lensing power spectrum



Angular power spectrum of lensing potential is sensitive to the growth of structure between the surface of last scattering and the present, hence, allows us to measure cosmological parameters by breaking parameter degeneracies.

Preliminary

Six-parameter ΛCDM model

Model:

A spatially flat universe with radiation, baryons, cold dark matter (CDM) and cosmological constant (Λ), and a power-law power spectrum of adiabatic Gaussian primordial fluctuations.

Cosmological Parameters:

Acoustic scale: θ_s

- Characteristic scale of acoustic oscillations

Physical baryon density: $\Omega_b h^2$

- Fraction of Universe’s density is in the form of baryonic matter

Physical Cold Dark Matter density: $\Omega_c h^2$

- Fraction of Universe’s density is in the form of cold dark matter

Amplitude of primordial spectrum: A_s

- Strength of the primordial density perturbations

Spectral index of primordial spectrum: n_s

- Variation of primordial spectrum with scale

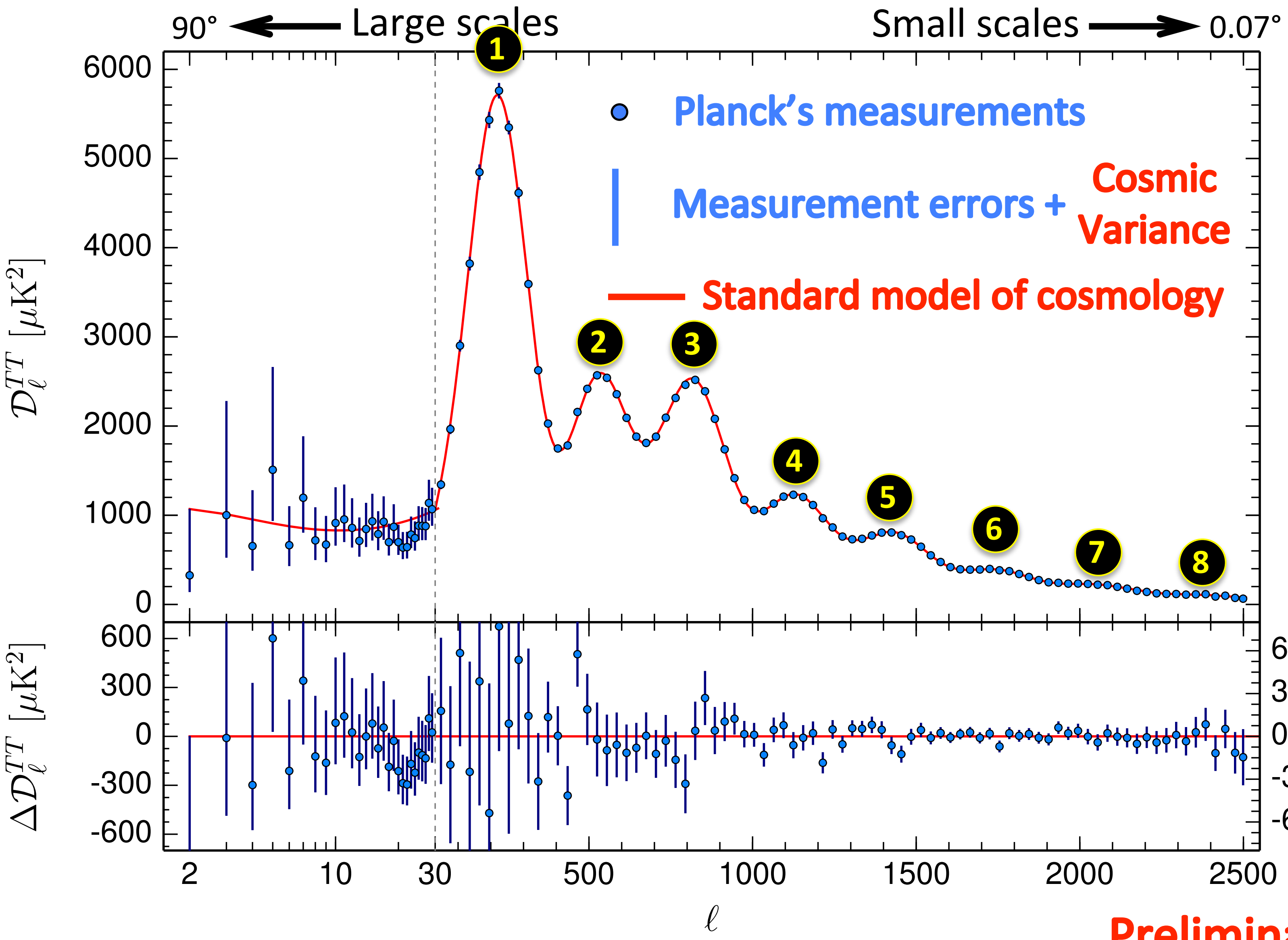
Optical depth of reionization: τ

- Fraction of photons lost due to reionization

$$\Omega_X = \frac{\rho_X}{\rho_c} \qquad \rho_c = \frac{3H_0^2}{4\pi G}$$

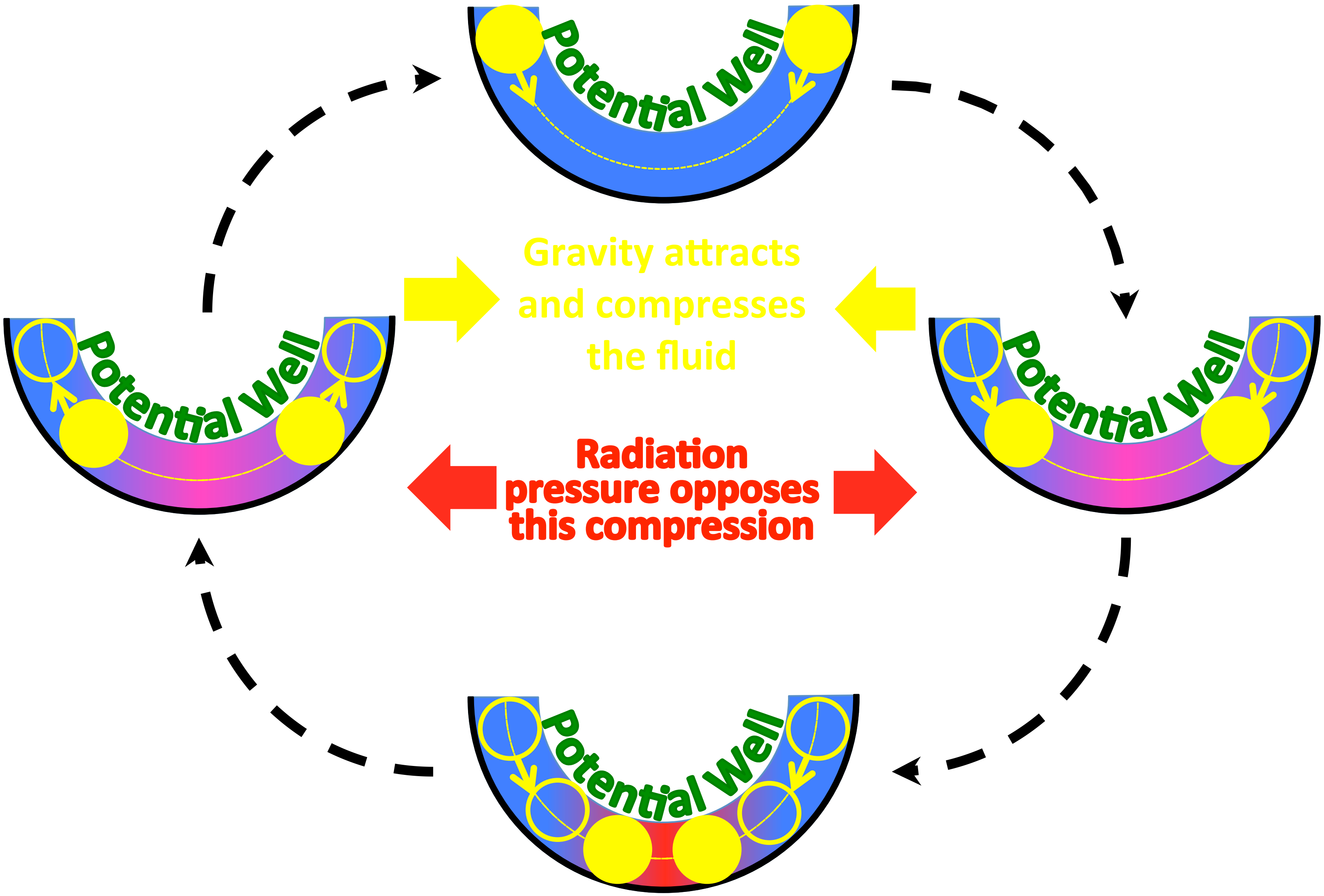
$$h = \frac{\text{Hubble constant } (H_0)}{100 \text{ Km s}^{-1} \text{ Mpc}^{-1}}$$

Angular Power Spectrum



Preliminary

Acoustic oscillations in photon-baryon fluid

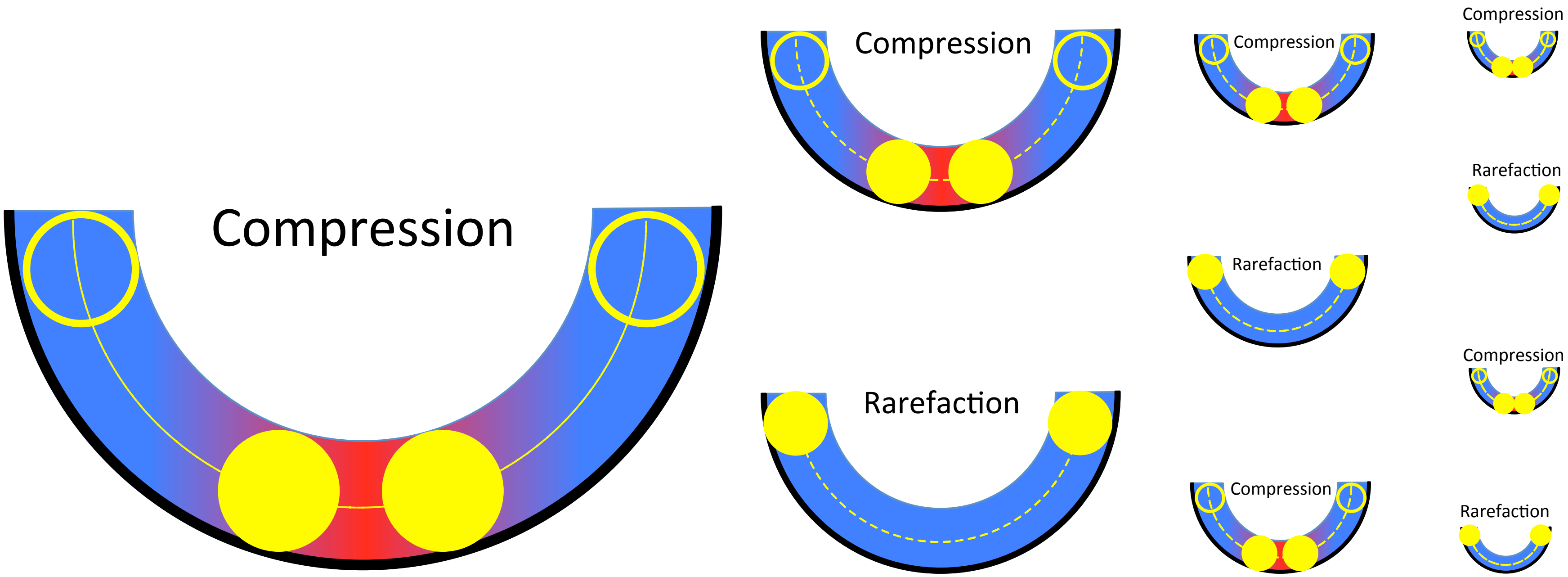


Gravity attracts
and compresses
the fluid

**Radiation
pressure opposes
this compression**

Acoustic oscillations in photon-baryon fluid

Different modes of acoustic oscillations of photon-baryon fluid froze into CMB at the time of decoupling



DECOUPLING

1st peak

2nd peak

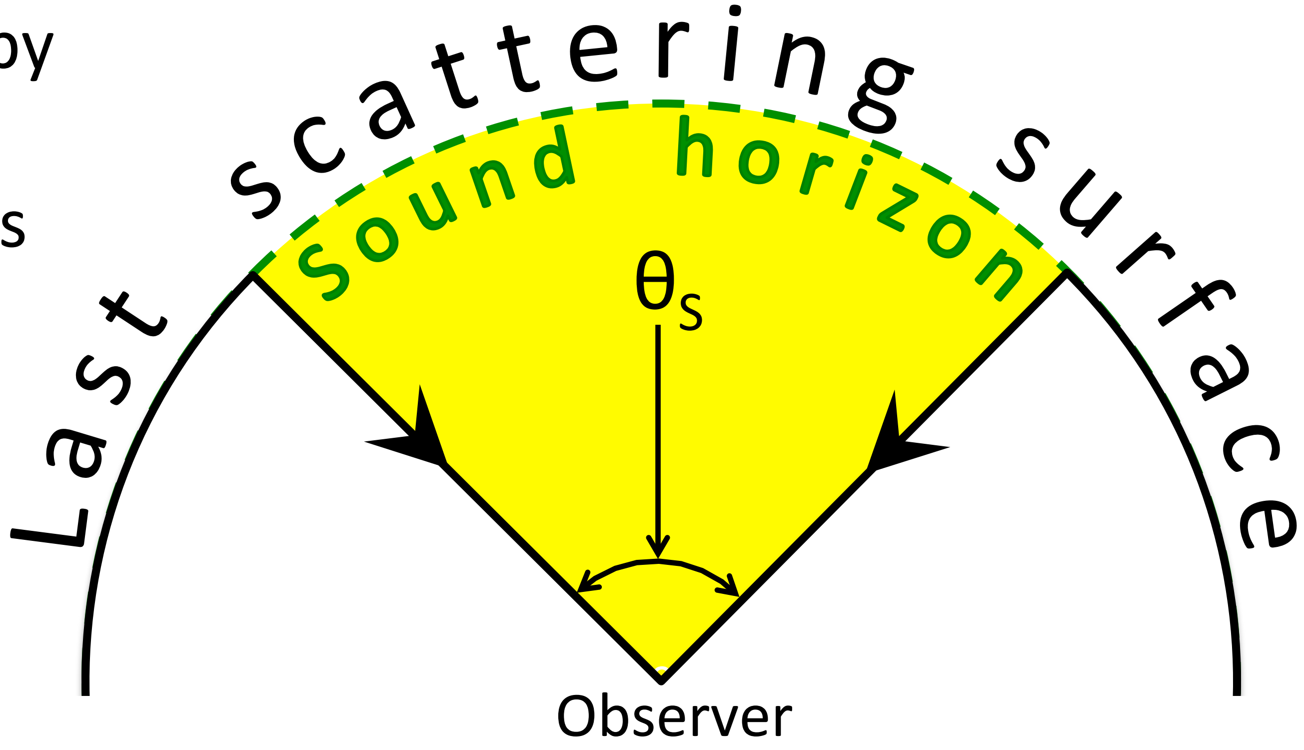
3rd peak

4th peak

Acoustic scale(θ_S)

θ_S is constrained by the positions of the acoustic peaks but not by their amplitudes

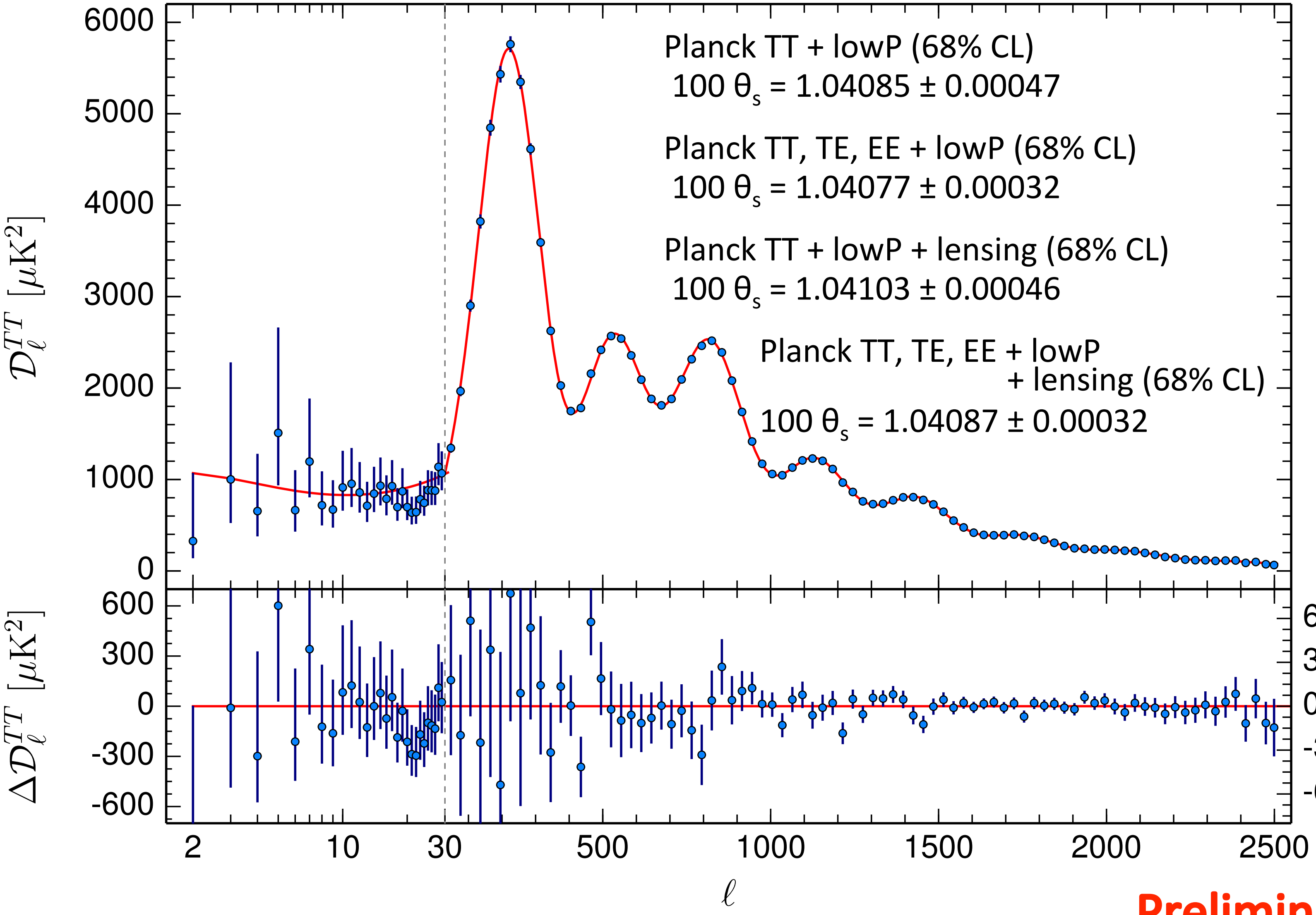
$$\theta_S = r_S / d_A$$



r_S = Size of sound horizon at the time of decoupling

d_A = Angular diameter distance to last scattering surface

Acoustic scale(θ_s)



Planck TT + lowP (68% CL)
100 θ_s = 1.04085 ± 0.00047

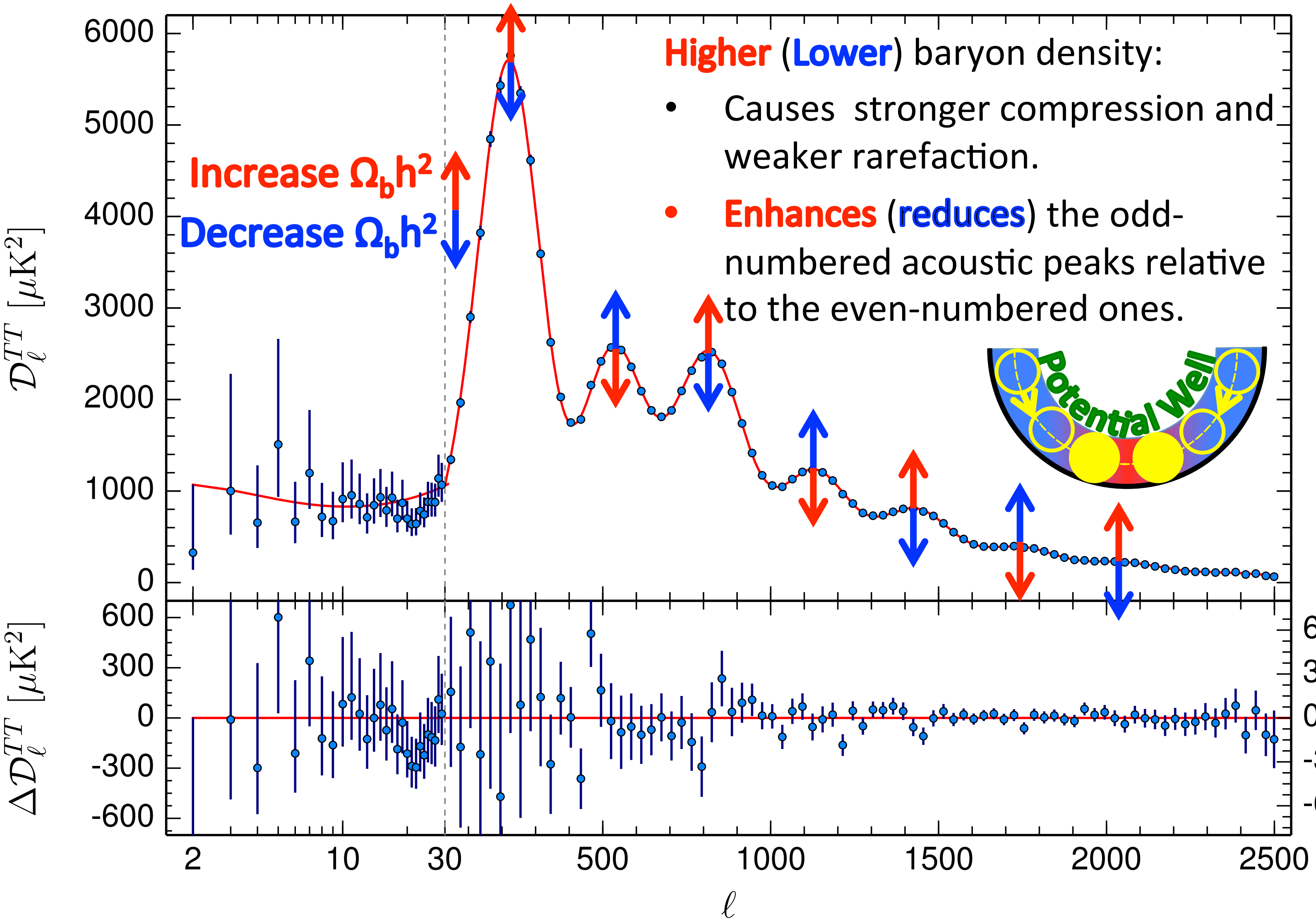
Planck TT, TE, EE + lowP (68% CL)
100 θ_s = 1.04077 ± 0.00032

Planck TT + lowP + lensing (68% CL)
100 θ_s = 1.04103 ± 0.00046

Planck TT, TE, EE + lowP
+ lensing (68% CL)
100 θ_s = 1.04087 ± 0.00032

Preliminary

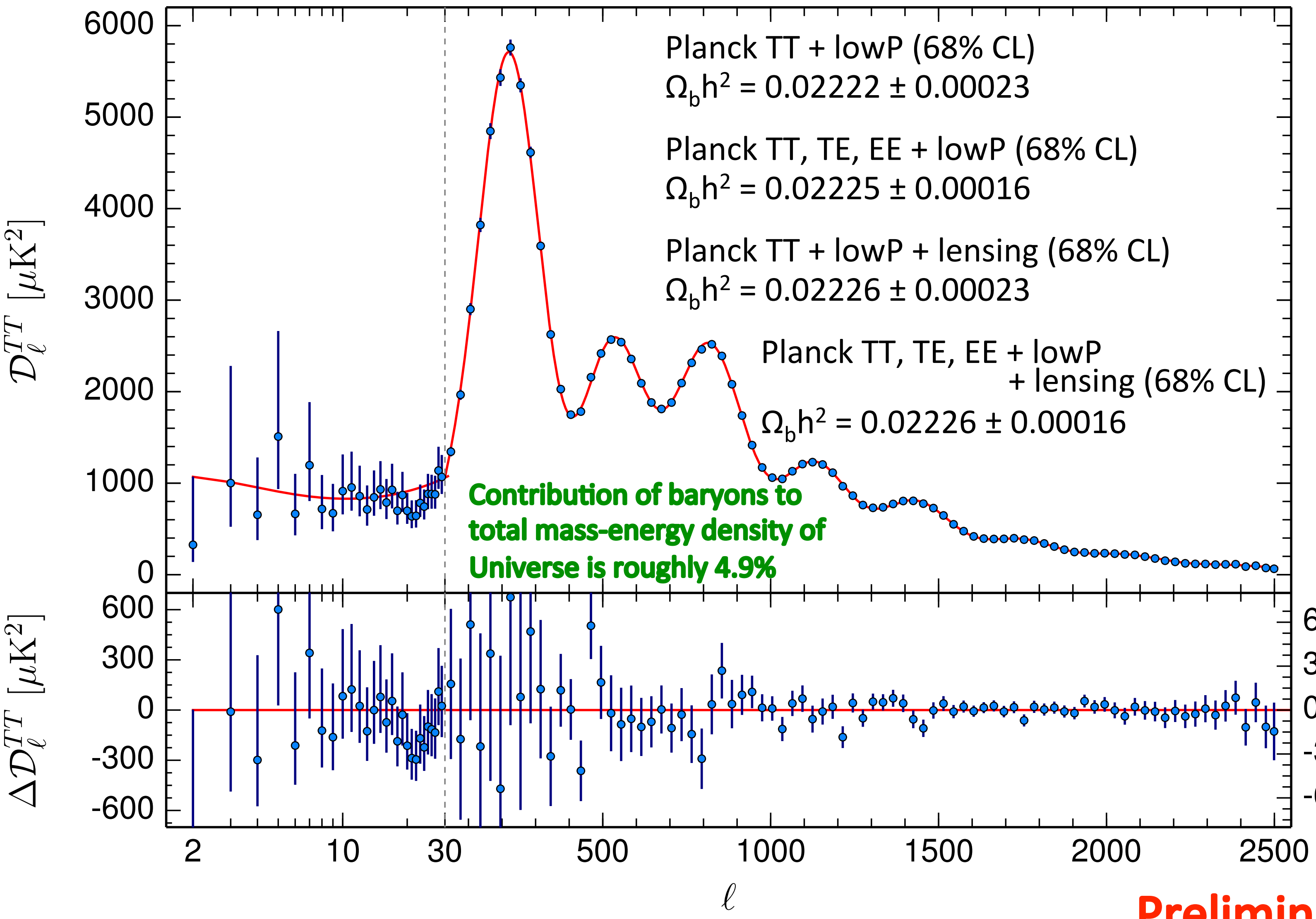
Baryon density ($\Omega_b h^2$)



Higher (**Lower**) baryon density:

- Causes stronger compression and weaker rarefaction.
- **Enhances** (**reduces**) the odd-numbered acoustic peaks relative to the even-numbered ones.

Baryon density ($\Omega_b h^2$)



Planck TT + lowP (68% CL)
$\Omega_b h^2 = 0.02222 \pm 0.00023$

Planck TT, TE, EE + lowP (68% CL)
$\Omega_b h^2 = 0.02225 \pm 0.00016$

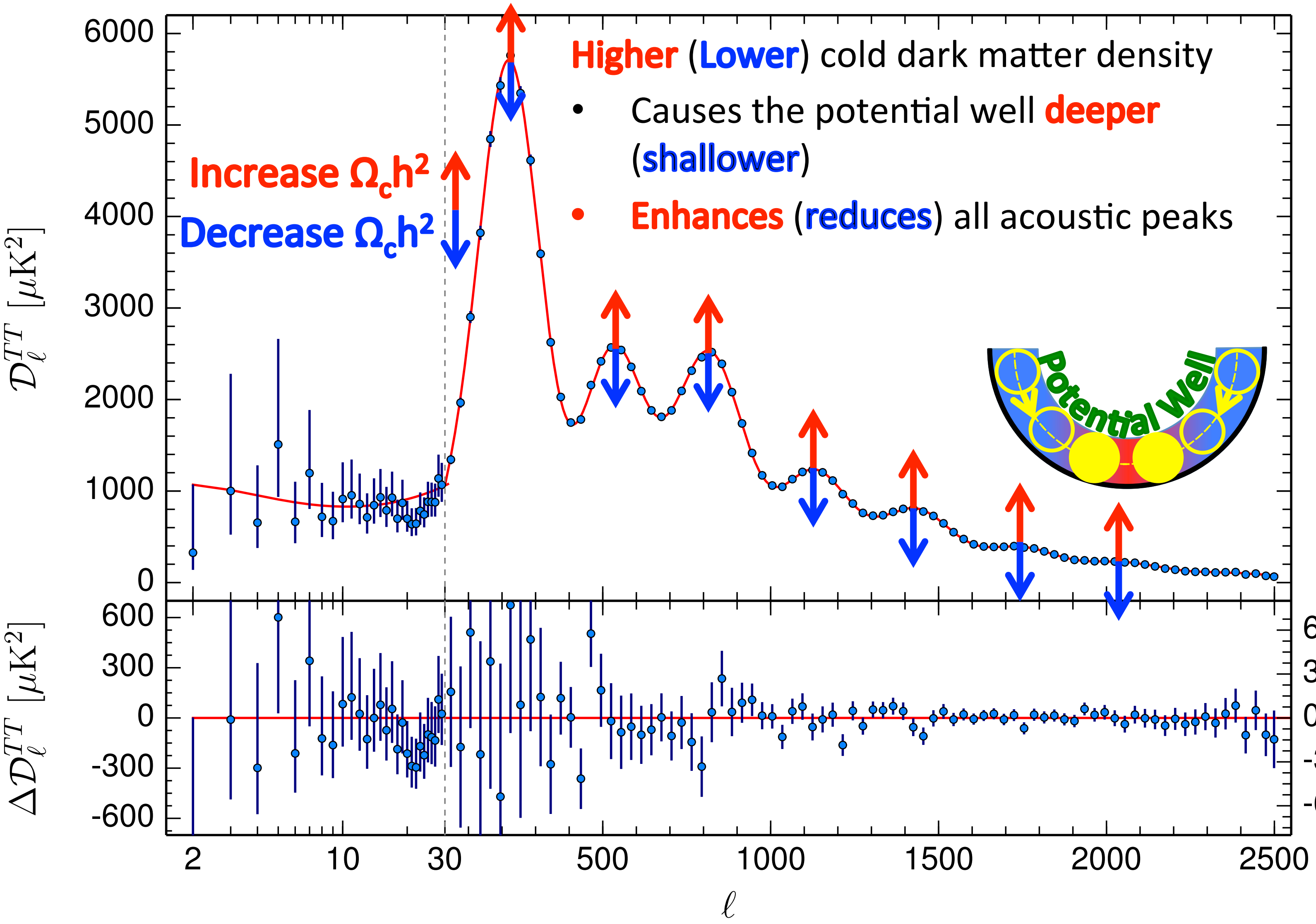
Planck TT + lowP + lensing (68% CL)
$\Omega_b h^2 = 0.02226 \pm 0.00023$

Planck TT, TE, EE + lowP
+ lensing (68% CL)
$\Omega_b h^2 = 0.02226 \pm 0.00016$

Contribution of baryons to total mass-energy density of Universe is roughly 4.9%

Preliminary

Cold Dark Matter density($\Omega_c h^2$)



Higher (**Lower**) cold dark matter density

- Causes the potential well **deeper** (**shallower**)
- **Enhances** (**reduces**) all acoustic peaks

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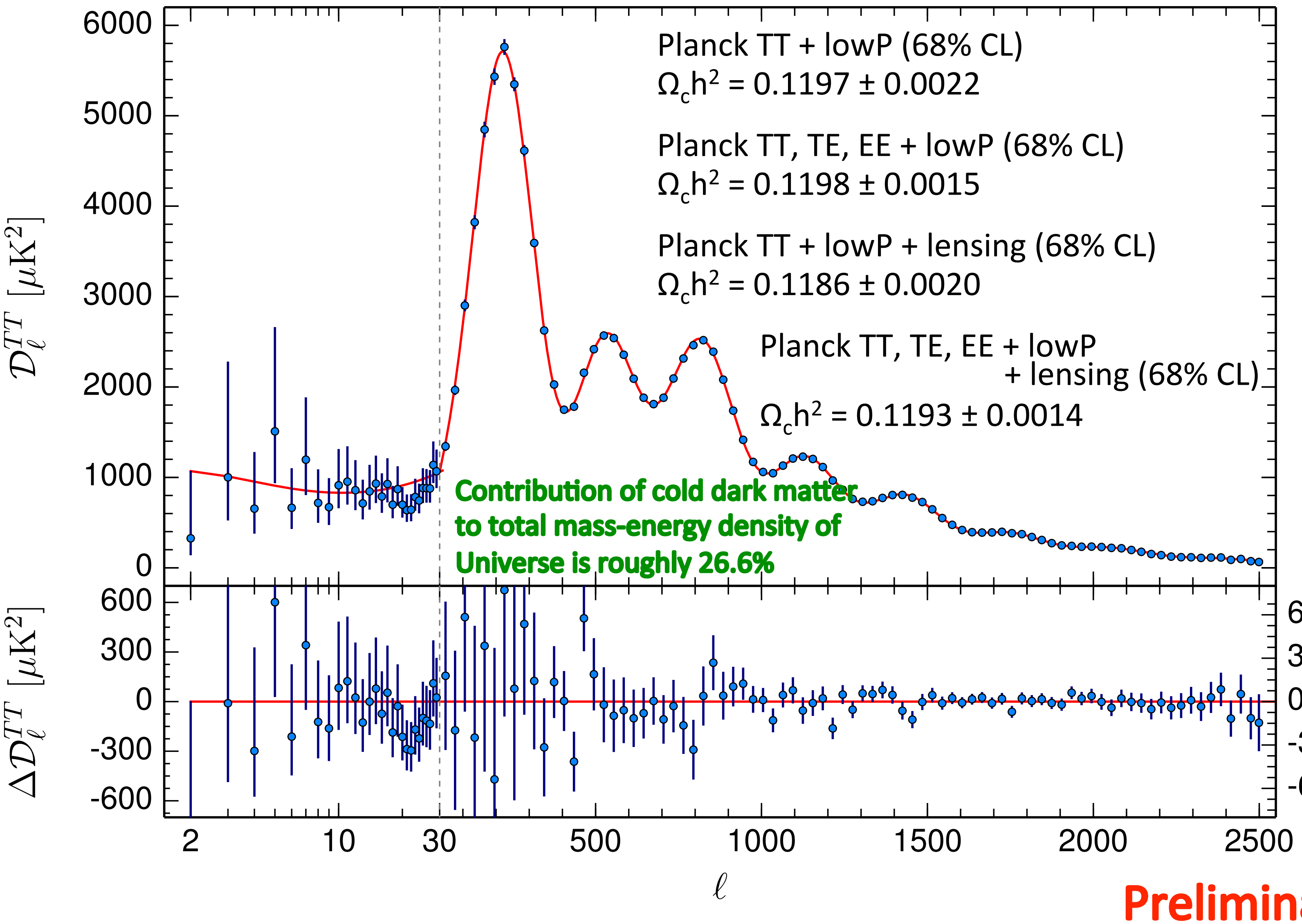


Planck TT + lowP (68% CL)
$\Omega_c h^2 = 0.1197 \pm 0.0022$

Planck TT, TE, EE + lowP (68% CL)
$\Omega_c h^2 = 0.1198 \pm 0.0015$

Planck TT + lowP + lensing (68% CL)
$\Omega_c h^2 = 0.1186 \pm 0.0020$

Planck TT, TE, EE + lowP
+ lensing (68% CL)

$\Omega_c h^2 = 0.1193 \pm 0.0014$

Contribution of cold dark matter to total mass-energy density of Universe is roughly 26.6%

Preliminary

Geometry

$$\text{Density parameter } (\Omega_0) = \frac{\text{Actual mass Density } (\rho)}{\text{Critical mass density } (\rho_c)} \qquad \rho_c = \frac{3H_0^2}{4\pi G}$$

$\Omega_0 > 1$ Closed and Finite

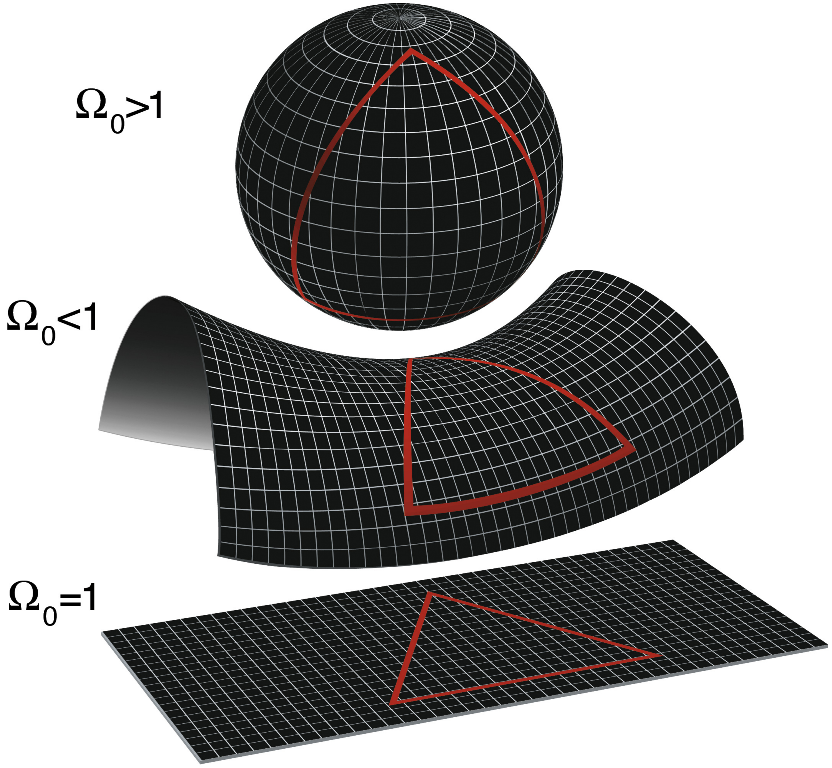
Universe contains sufficient matter to reverse the observed expansion through its gravitational contraction.

$\Omega_0 < 1$ Open and infinite

Universe does no contain enough mass to counteract the expansion by Gravity.

$\Omega_0 = 1$ Flat and infinite

Universe contains just enough mass to counteract the expansion by Gravity in an infinitely long time



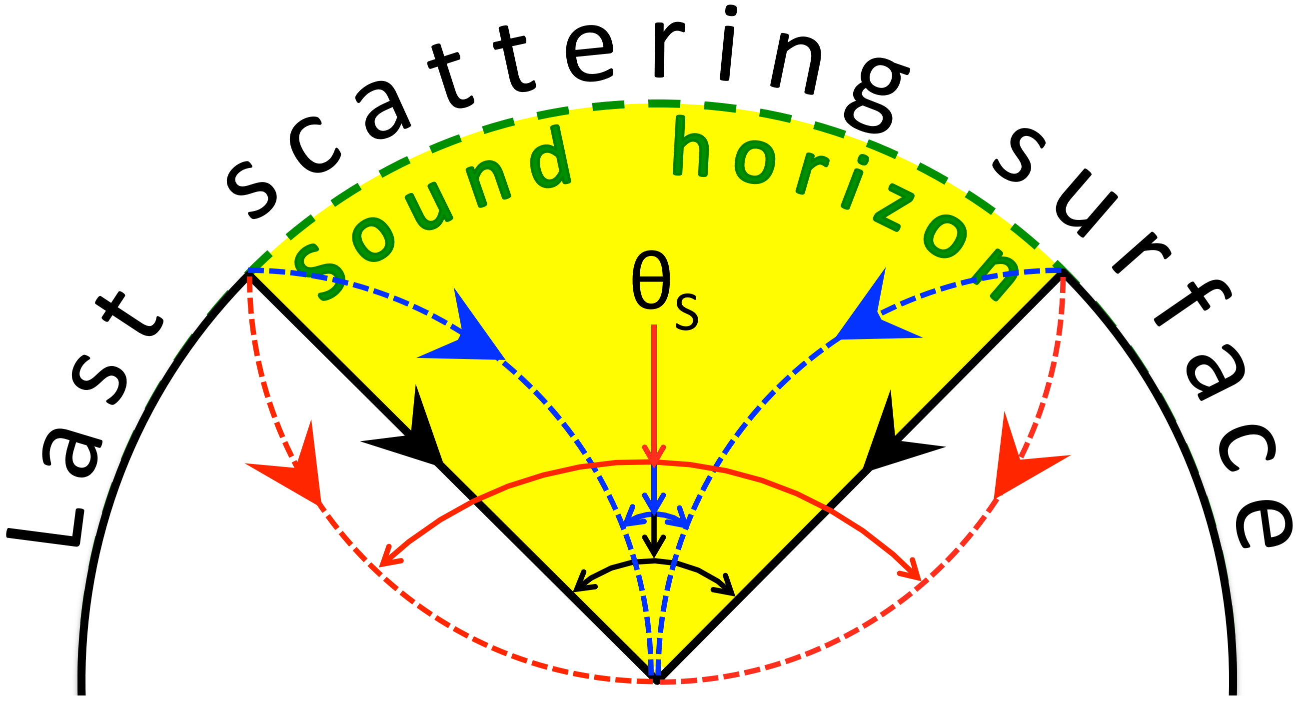
Angular size of sound horizon

- - - - - - θ_s

—— θ_s

- - - - - - θ_s

$$\theta_s = r_s / d_A$$

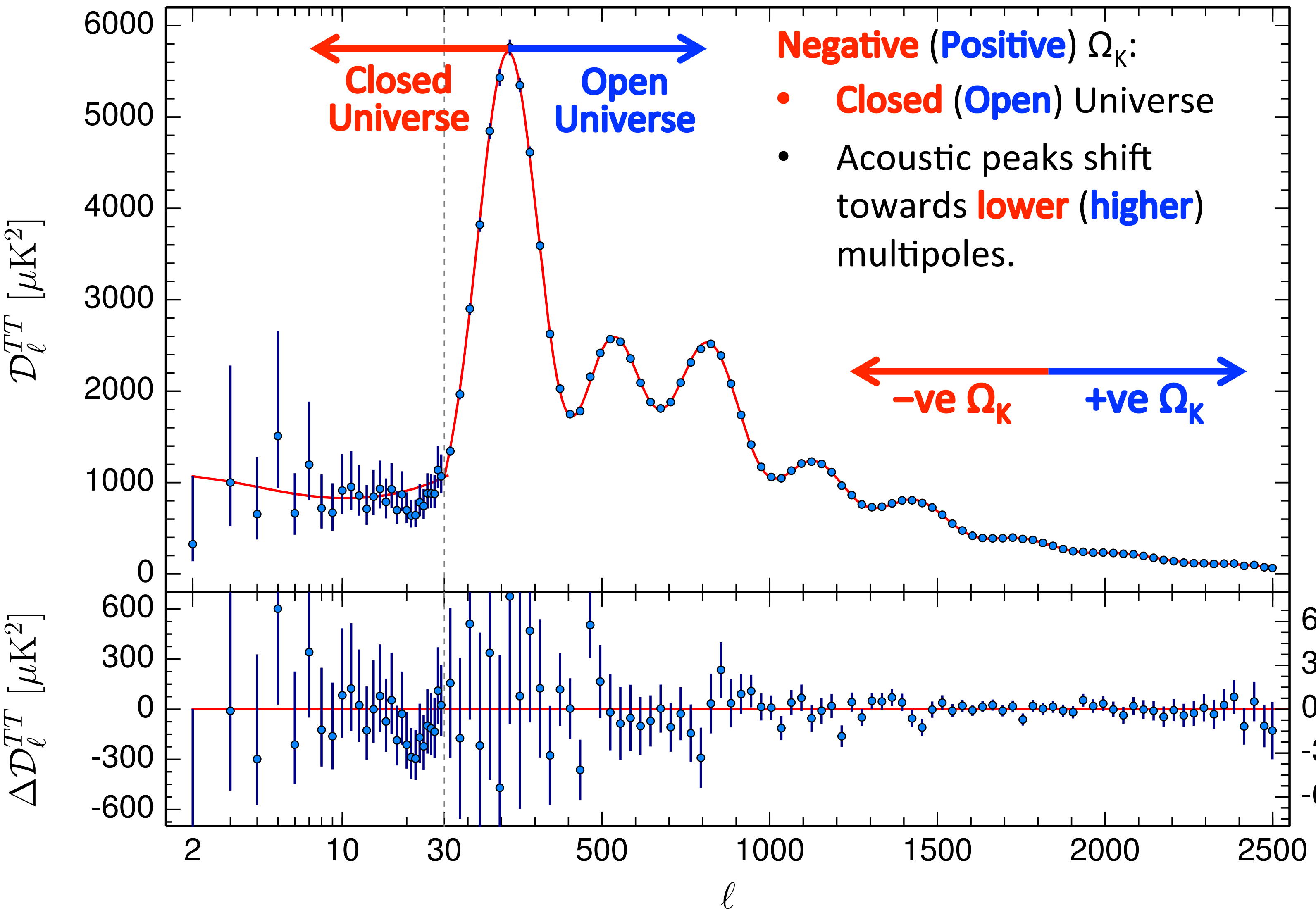


Closed: Sound horizon appears to us to be larger than its true size

Open: Sound horizon appears to us to be smaller than its true size

Flat: Sound horizon appears to us with its true size

Curvature parameter ($\Omega_K = 1 - \Omega_0$)



Negative (**Positive**) Ω_K:

- **Closed** (**Open**) Universe
- Acoustic peaks shift towards **lower** (**higher**) multipoles.

Curvature parameter ($\Omega_K = 1 - \Omega_0$)

Lensing breaks the geometric degeneracy between Ω_m and Ω_Λ

Planck TT + lowP (95% CL)

$$\Omega_K = -0.052^{+0.049}_{-0.055}$$

Planck TT, TE, EE + lowP (95% CL)

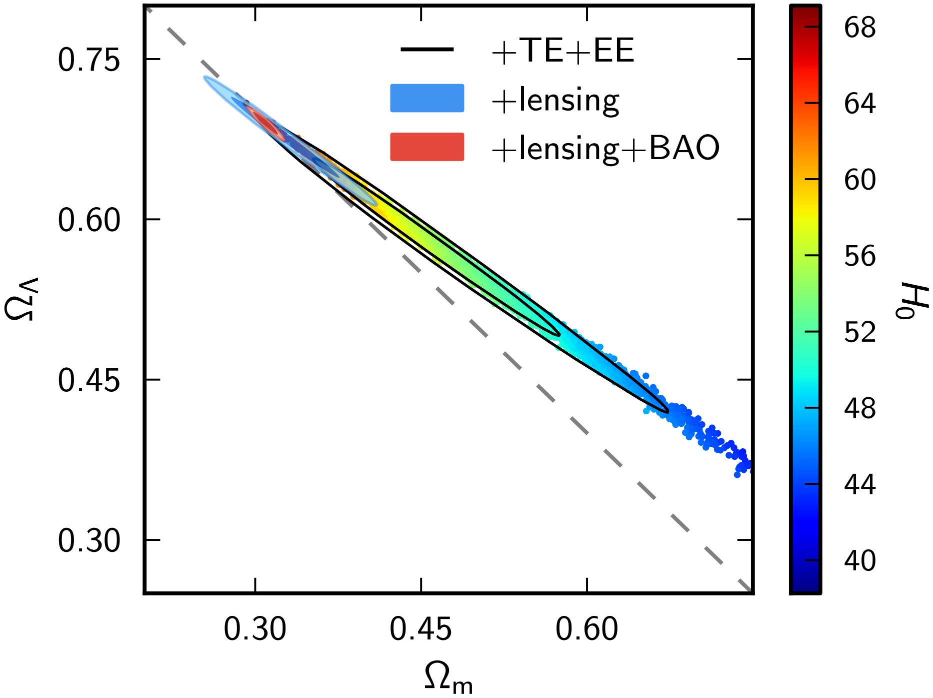
$$\Omega_K = -0.040^{+0.038}_{-0.041}$$

Planck TT + lowP + lensing (95% CL)

$$\Omega_K = -0.005^{+0.016}_{-0.017}$$

Planck TT + lowP + lensing + BAO (95% CL)

$$\Omega_K = 0.000 \pm 0.005$$



Planck data are consistent with a nearly flat universe

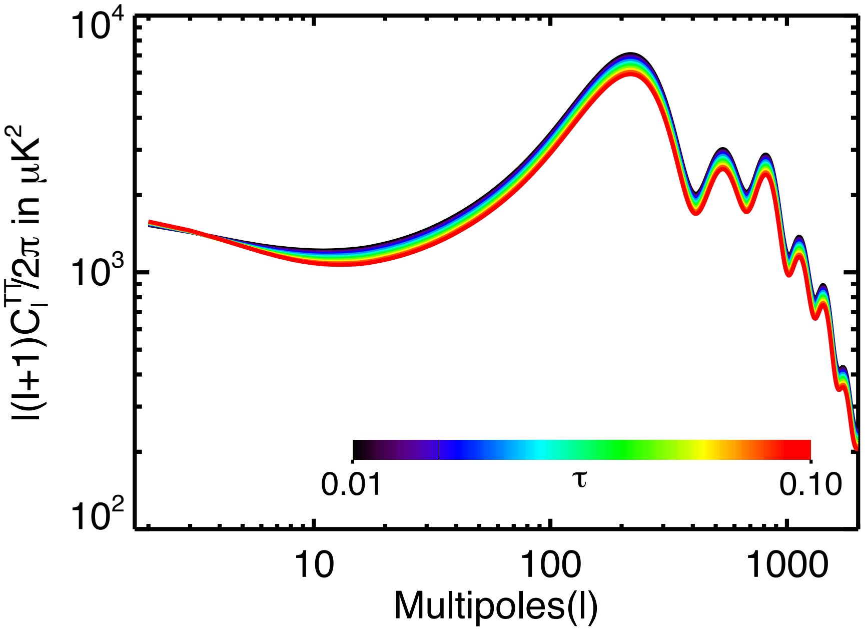
Reionization

Recombination 0.3 Myr	Dark ages 0.3 – 500 Myr	Star and Galaxy Formation 500 Myr	Reionization 0.5 – 1 Gyr

Optical depth to reionization

$$\tau\left(\mathrm{t} : \mathrm{t}_0\right) = \int_{\mathrm{t}}^{\mathrm{t}_0} \sigma_{\mathrm{T}}\, \mathrm{n}_{\mathrm{e}}\, \mathrm{dt}$$

Probability that a CMB photon, now (at time t_0) observed, has travelled freely since time t is $\mathrm{e}^{-\tau(\mathrm{t}:\mathrm{t}_0)}$



Impacts of reionization on CMB:

- Damping of Temperature fluctuations at almost all angular scales
- Generation of Polarization at large angular scales

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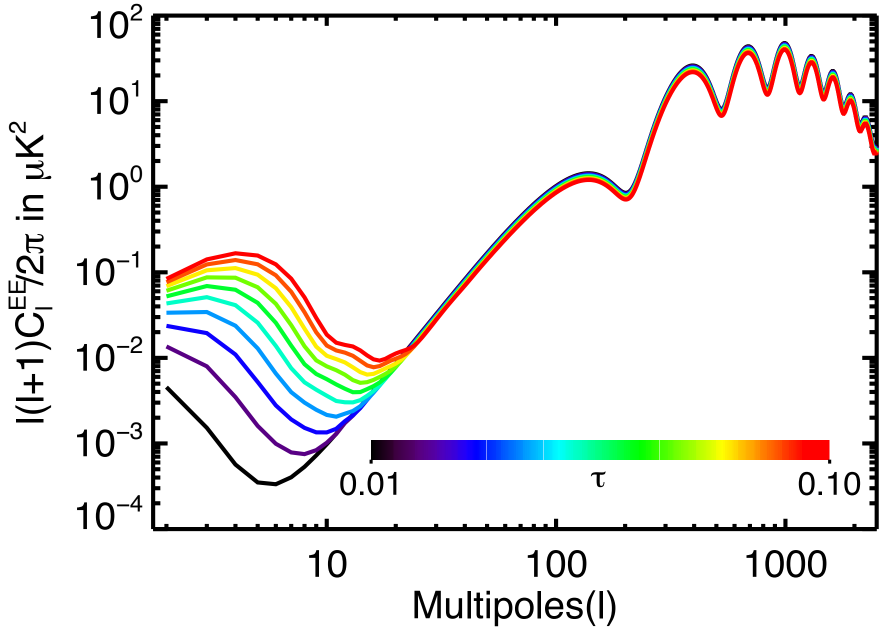


Impacts of reionization on CMB:

- Damping of Temperature fluctuations at almost all angular scales
- Generation of Polarization at large angular scales

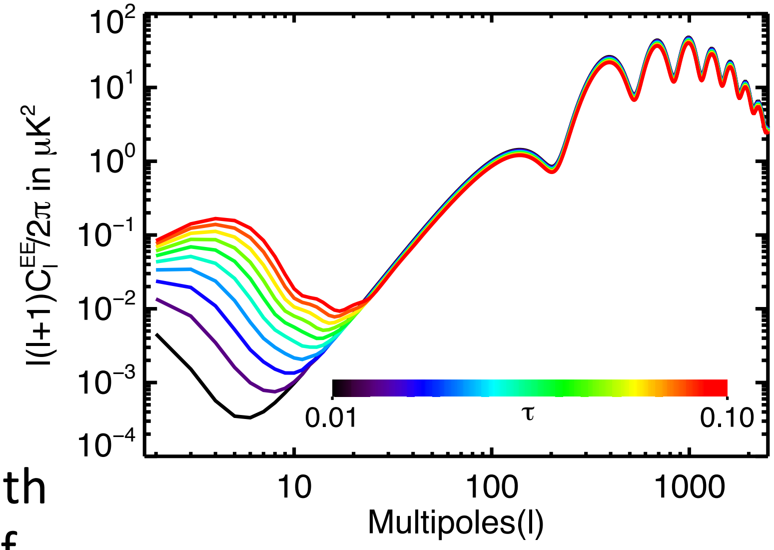
Reionization

CMB polarization is more sensitive to reionization epoch than its temperature fluctuations

The height and location of reionization peak are sensitive to optical depth and redshift of reionization respectively

CMB lensing breaks degeneracy between A_s and τ

The preference of lensing for a smaller optical depth is driven by the preference for lower amplitudes of the primordial spectrum



Planck TT + lowP (68% CL)

$\tau = -\,0.078 \pm 0.019$

$\ln(10^{10}A_s) = 3.089 \pm 0.036$

Planck TT, TE, EE + lowP (68% CL)

$\tau = -\,0.079 \pm 0.017$

$\ln(10^{10}A_s) = 3.094 \pm 0.034$

Planck TT + lowP + lensing (68% CL)

$\tau = -\,0.066 \pm 0.016$

$\ln(10^{10}A_s) = 3.062 \pm 0.029$

Planck TT, TE, EE + lowP + lensing (68% CL)

$\tau = -\,0.063 \pm 0.014$

$\ln(10^{10}A_s) = 3.059 \pm 0.025$

Preliminary

Inflation

Inflation is an epoch of accelerated expansion in the early Universe ($\sim 10^{-34}$ sec after our Universe came into existence) which allows to solve two major inconsistencies of expanding Universe model

Basic Idea:

- This scenario is based upon the idea that the vacuum energy of a scalar quantum field, dubbed the inflaton, dominates over other forms of energy, hence giving rise to a quasi-exponential (de Sitter) expansion

Solves:

- Horizon problem:
  Why is the Universe so homogeneous and isotropic on average ?
- Flatness problem:
  Why is the Universe spatial curvature so small ?
- Cosmic fluctuations problem:
  How did all inhomogeneties come from ?

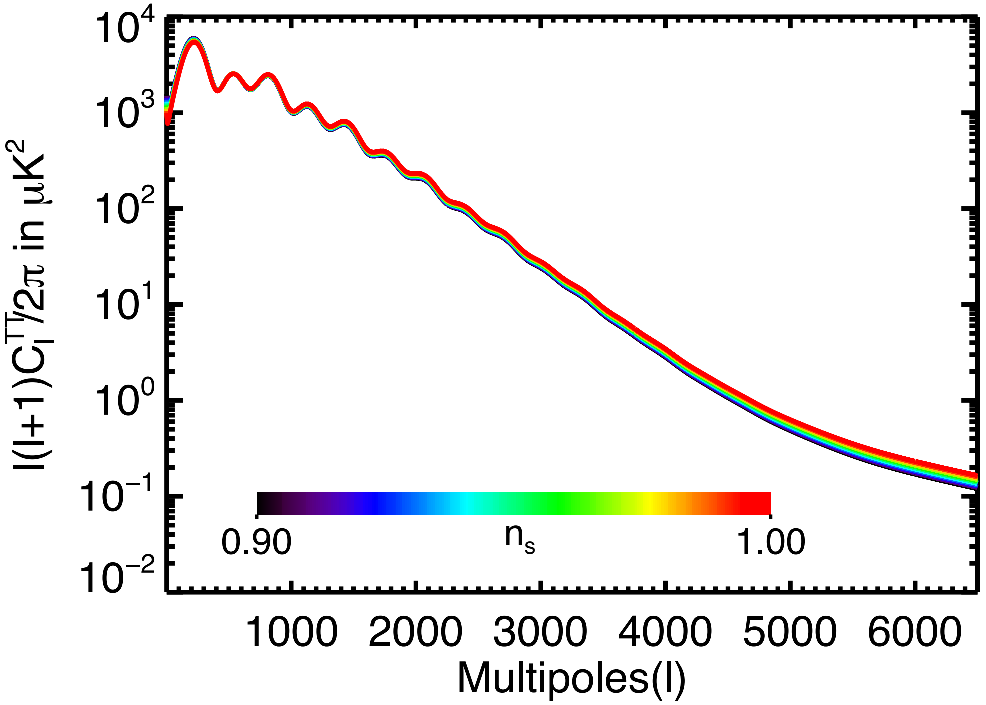
Spectral index (n_s) of primordial spectrum

Inflation predicts a (nearly) scale invariant spectrum (P_R) of primordial density fluctuations

$$P_R(k) = A_S \left(\frac{k}{k_0}\right)^{n_s - 1}$$

$$k_0 = 0.05\,(\mathrm{Mpc})^{-1}$$

Harrison-Zeldovich spectra($n_s = 1$) is excluded by Planck at more than 5σ



Planck TT + lowP (68% CL)
$n_s = 0.9562 \pm 0.0062$

Planck TT, TE, EE + lowP (68% CL)
$n_s = 0.9639 \pm 0.0047$

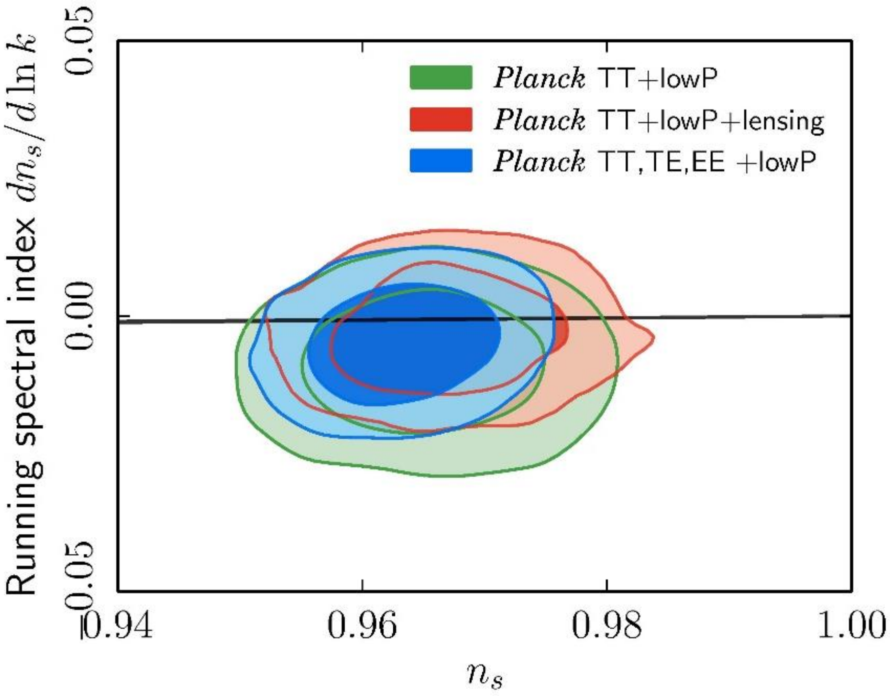
Planck TT, TE, EE + lowP (68% CL)
$n_s = 0.9672 \pm 0.0045$

Planck TT, TE, EE + lowP (68% CL)
$n_s = 0.9675 \pm 0.0059$

Preliminary

Running of spectral index ($dn_s/dlnk$)

$$P_R(k) = A_S \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\left(\frac{dn_s}{dlnk}\right)\ln\left(\frac{k}{k_0}\right)} \qquad k_0 = 0.05\,(\mathrm{Mpc})^{-1}$$



Planck TT + lowP (68% CL)

$$\frac{dn_s}{dlnk} = -\,0.0087 \pm 0.0082$$

Planck TT, TE, EE + lowP (68% CL)

$$\frac{dn_s}{dlnk} = -\,0.0049 \pm 0.0070$$

Planck TT+ lowP + lensing (68% CL)

$$\frac{dn_s}{dlnk} = -\,0.0031 \pm 0.0074$$

Preliminary

Planck data are consistent with zero running of the scalar spectral index.

Tensor to Scalar ratio (r)

The relative contribution of tensor perturbations (gravity waves) to density perturbations:

$$\mathrm{r} = \frac{\mathrm{A_T}}{\mathrm{A_s}} \approx -8\mathrm{n_T}$$

Power spectrum of primordial tensor perturbations:

$$\mathrm{P_T(k)} = \mathrm{A_T}\left(\frac{\mathrm{k}}{\mathrm{k_0}}\right)^{\mathrm{n_T}}$$

A measurement of r is a direct measurement of the energy scale of Inflation

$$\mathrm{V}^{1/4} = (2 \times 10^{16}\mathrm{GeV})\left(\frac{\mathrm{r}}{0.1}\right)^{1/4}$$

Planck TT + lowP (95% CL)

$r_{0.002} < 0.10$

Planck TT, TE, EE + lowP (95% CL)

$r_{0.002} < 0.10$

Planck TT + lowP + lensing (95% CL)

$r_{0.002} < 0.11$

Planck TT + lowP + lensing + BAO (95% CL)

$r_{0.002} < 0.11$

Planck havn't found any evidence for gravitational waves

Preliminary

Effective number relativistic degrees of freedom (N_{eff})

Radiation energy density of the Universe:

$$\rho_{\rm r} = \rho_\gamma + \rho_\nu \;= \left[1 + \frac{7}{8}\left(\frac{\rm T_\nu}{\rm T_\gamma}\right)^4 {\rm N_{eff}}\right]\rho_\gamma \qquad \frac{\rm T_\nu}{\rm T_\gamma} = \left(\frac{4}{11}\right)^{1/3}$$

Standard model of cosmology: N_{eff} = 3.046 (3 neutrino species)

WMAP 7yr + external
N_{eff} = 4.34 ± 0.87 (68% CL)

WMAP 9yr + external
N_{eff} = 3.84 ± 0.40 (68% CL)

N_{eff} = 4 is excluded by Planck at more than 3σ

Planck TT + lowP (95% CL)
N_{eff} = 3.13 ± 0.32

Planck TT + lowP + BAO (95% CL)
N_{eff} = 3.15 ± 0.23

Planck TT, TE, EE + lowP (95% CL)
N_{eff} = 2.99 ± 0.20

Planck TT, TE, EE + lowP + BAO (95% CL)
N_{eff} = 3.04 ± 0.18

Preliminary

Sum of light neutrino species (Σm_ν)

Neutrino oscillation experiments

– Sensitive to the square mass difference between different neutrino mass eigenstates.

Planck TT + lowP (95% CL)
$\Sigma m_\nu < 0.72$ eV

Planck TT, TE, EE + lowP (95% CL)
$\Sigma m_\nu < 0.49$ eV

Planck TT + lowP + BAO (95% CL)
$\Sigma m_\nu < 0.21$ eV

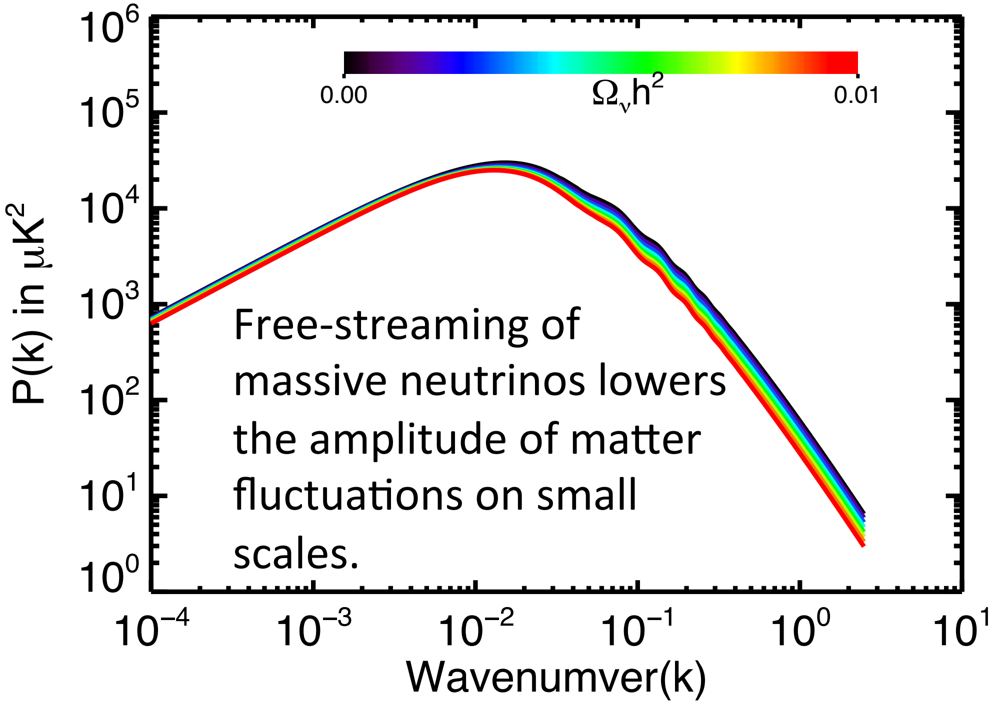
Planck TT, TE, EE + lowP + BAO (95% CL)
$\Sigma m_\nu < 0.17$ eV

Cosmological measurements

– Sensitive to the sum of light neutrino species

– Energy density of neutrino:

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94\,\mathrm{eV}}$$

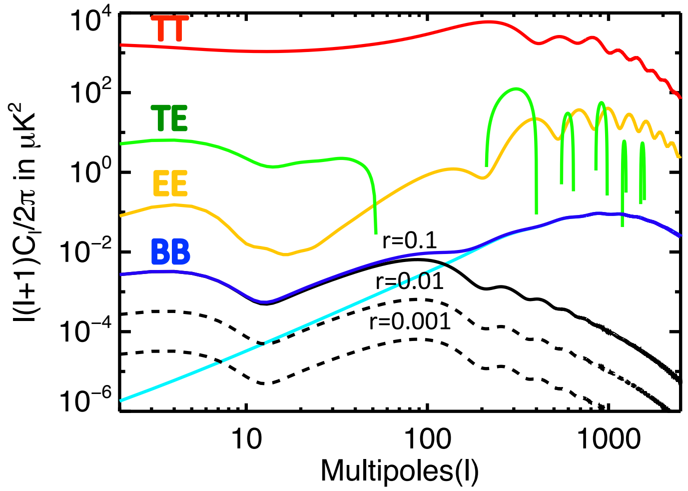


Free-streaming of massive neutrinos lowers the amplitude of matter fluctuations on small scales.

Cosmic Origin Explorer + (COrE+)

COrE+ will be the nearly-ultimate mission for CMB polarization

Prime objective of this mission is to measure signature of primordial gravity waves with tensor to scalar ratio $r \sim 10^{-3}$



COrE+light

- Number of detectors: 2100
  (roughly 75% in CMB channels)
- Number of frequency channels: > 15
- CMB polarization sensitivity:
  ~ 2.2 μK.arcmin
- Budget 550 M€

COrE+extended

- Number of detectors: 5800
  (roughly 65% in CMB channels)
- Number of frequency channels: > 18
- CMB polarization sensitivity:
  ~ 1.3 μK.arcmin
- Budget 700 M€

Summary

- Planck has produced high-quality maps of sky based on 48/29 months of LFI/HFI observations in nine widely separated frequency bands.
- Planck has demonstrated the ability to measure the CMB temperature anisotropy and polarization from multi-frequency observations by subtracting Galactic and extragalactic foregrounds.
- Planck has demonstrated the ability to measure the CMB lensing signal with high signal to noise ratio.
- Planck has measured the angular power spectra of the CMB temperature anisotropy and polarization with unprecedented accuracy.
- Planck has fitted cosmological parameters to the data and has found results that are consistent with 6 parameter ΛCDM model.
- Despite trying a wide range of extensions (Ω_K, $dn_s/d\ln k$, N_{eff}, r, w etc.) to the 6-parameter ΛCDM model Planck hasn't found any evidence for a failure of the model.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Thank you