

The Oldest Light We Can See

QTC-011 · From Quarks to Consciousness

The Universe, Life, and How We Found Out

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Article Abstract

The cosmic microwave background is the oldest electromagnetic light we can observe across the whole sky, but it is not light from the beginning. Its photons last scattered when the Universe was about 380,000 years old, after cooling plasma became transparent. A prediction preceded the celebrated 1965 detection; the detection itself was a single-frequency excess, not yet a measured blackbody spectrum. COBE later established an extraordinarily precise thermal spectrum, while COBE, WMAP and Planck mapped fluctuations and polarization that encode earlier physics. Those maps are calibrated reconstructions shaped by beams, foreground removal and statistical inference. The CMB is therefore both an observational horizon and an archive: a real field of ancient photons whose meaning depends on a carefully tested physical model.

In 60 Seconds

The oldest light visible across the sky did not emerge at time zero. Before roughly 380,000 years, free electrons scattered photons so often that the Universe was opaque to ordinary electromagnetic observation. As atoms formed, scattering became rare and most photons began to travel freely. Expansion then stretched their wavelengths from a roughly 3000 K radiation field into today's microwave background. Hot-Universe calculations predicted such relic radiation before Penzias and Wilson reported an unexplained 3.5 ± 1.0 K antenna excess in 1965. That one-frequency result needed independent wavelengths and, eventually, COBE/FIRAS to establish an almost perfect blackbody spectrum. Tiny departures across the sky—about one part in 100,000—carry information about the early photon-baryon fluid. Polarization and gravitational lensing add further structure. Yet a published CMB map is not a raw photograph: instruments, calibration, masks and component-separation methods intervene. The CMB lets us infer conditions earlier than last scattering, but it does not directly image the beginning or remove model dependence.

Why This Question Matters

Calling the CMB the oldest light can create two opposite mistakes: treating it as a photograph of the beginning, or dismissing everything inferred about earlier epochs as speculation. The real achievement lies between them. Physicists identified an observational boundary, measured the radiation's spectrum and minute structure, and learned how indirect signatures can carry information from an era no telescope can image directly. That middle position matters because it shows how a boundary can become a tool: the last-scattering surface blocks an ordinary photograph

of earlier times, yet its spectrum, anisotropy and polarization preserve testable consequences of the plasma that preceded it. The article is therefore about disciplined inference, not about replacing observation with a story.

1. Oldest Does Not Mean First

The Question

If these are the oldest photons we can see across the sky, are we looking at the beginning of the Universe? No: we are looking at the epoch when an opaque plasma became transparent enough for light to travel freely.

The cosmic microwave background, or CMB, is the oldest electromagnetic light directly observable across the whole sky. Most of its photons last scattered when the Universe was about 380,000 years old, near redshift 1100.[8,27,31] Those numbers are approximate and model-linked, and last scattering occurred across a finite interval rather than at one mathematical instant.

Photons existed earlier. The obstacle was not the absence of light but the abundance of free electrons in the hot plasma. Repeated scattering continually redirected the radiation, preventing ordinary electromagnetic observations from producing a direct image through that opaque era.[7,8] Earlier physics can still leave later traces, but a trace is not a photograph.

The phrase last-scattering surface is useful only if surface is not mistaken for a material shell centred on Earth. It is a finite-thickness probability layer: for every direction, there is a distribution of places and times at which arriving photons most likely scattered for the last time. Every comoving observer has an analogous observable boundary.[8]

Matter and radiation were near 3000 K when the photons decoupled. The radiation was therefore not emitted as microwaves. Cosmic expansion stretched its wavelengths and reduced its temperature until the relic field reached today's microwave band.[7,8,31] The colour of the oldest light is a history of expansion, not a label attached at emission.

Oldest directly observable light also does not mean oldest recoverable information. Processes before photon decoupling could alter the spectrum, phases, polarization or statistical pattern later carried by the CMB.[8,33,34] Such inferences depend on theory and alternatives, but they reach behind the electromagnetic horizon without pretending to see through it.

Where That Leaves Us

The CMB marks an observational horizon, not the birth of the Universe. Its photons existed in a scattering plasma, escaped across a finite probability layer and were redshifted into microwaves. Earlier events can survive only through imprints on that later light. To understand why anyone searched for such a relic, the story must begin with a prediction made before the famous detection.

2. A Prediction Before a Detection

A hot expanding Universe predicts that radiation once in thermal equilibrium should cool as space expands while preserving its blackbody form, unless later processes distort it.[1,2,19] The essential idea is simple but powerful: expansion changes the temperature scale without erasing the characteristic spectral relationship among frequencies.

In 1948 Ralph Alpher and Robert Herman published a Nature letter explicitly correcting parts of George Gamow's recent calculation. Within that developing programme they estimated that the relic radiation should now be of order 5 K.[2] The number depended on the cosmological and nuclear assumptions then available; it was a prediction of scale, not today's precision value.

The prediction did not remain continuously central to cosmology. By the early 1960s, a Princeton group led by Robert Dicke was preparing an independent microwave search, motivated by renewed calculations of a hot early Universe.[3,5] Independent here does not mean untouched by the wider history of cosmology; it means their programme was not built to explain a signal already reported by Bell Labs.

The two lines met rapidly in 1965. Arno Penzias and Robert Wilson reported an unexplained excess antenna temperature; Dicke, Peebles, Roll and Wilkinson supplied the cosmological interpretation in a companion paper.[3,4] The roles were complementary but different: one paper described an instrument result, while the other argued that cosmic blackbody radiation was the natural meaning.

That sequence resists both the lone-genius story and the pure-accident story. Prediction, instrument building, elimination of mundane causes, independent interpretation and later confirmation each mattered.[2–4] Contingency brought the groups together, but only a chain of reasoning and measurement turned an unexplained noise temperature into evidence about the early Universe.

Where That Leaves Us

The relic radiation was predicted before it was recognized, then rediscovered through two independent programmes with different evidential roles. The Princeton group supplied a cosmological interpretation; Bell Labs supplied the unexplained antenna excess. Neither alone established the modern CMB. The next question is therefore narrower and more revealing: what exactly did Penzias and Wilson measure, and what still remained to be proved?

3. The Noise That Would Not Go Away

The Question

Why was an unexplained hiss at one radio frequency taken seriously as evidence about the early Universe? Because careful elimination made it hard to assign locally, while an independent cosmological calculation predicted radiation of the right order.

Penzias and Wilson reported an excess antenna temperature of 3.5 ± 1.0 K at 4080 MHz, corresponding to a wavelength of about 7.35 centimetres.[4] Within their uncertainties it appeared approximately isotropic. This was a precise statement about one observing band, not yet a precision thermodynamic temperature for the entire background.

A measurement at one frequency cannot establish a blackbody spectrum. Many different spectral shapes can pass through one point.[4] The isotropy, magnitude and failure of ordinary explanations made the excess important, but the thermal interpretation required measurements at other frequencies and far better control of calibration and foregrounds.

The famous pigeons belong inside that diagnostic work, not at its centre. Penzias and Wilson investigated instrumental and environmental causes, including removing pigeon-related dielectric material from the antenna, yet the excess remained.[4] The episode is memorable because a mundane cause was tested and rejected; the birds neither produced the cosmic signal nor explain the discovery.

The companion Princeton paper interpreted the excess as cosmic blackbody radiation expected in an evolutionary Universe.[3,5] That interpretation had explanatory reach, but it did not retroactively turn the Bell Labs receiver into a spectrometer. The evidence acquired its force by joining a bounded measurement to a theory that made further tests possible.

Observations at other wavelengths strengthened the cosmic case, including a 3.2-centimetre measurement by Roll and Wilkinson.[6] Decades later COBE/FIRAS measured the spectrum across a broad range, first preliminarily and then with the full data set.[11,12] Confirmation was cumulative: the 1965 anomaly opened the door, but the blackbody spectrum made the thermal interpretation exceptionally difficult to imitate.

Where That Leaves Us

The 1965 result was persuasive because the excess survived sustained diagnosis and matched an independent prediction, not because one frequency revealed an entire spectrum. Multi-frequency measurements and FIRAS completed the thermal case later. But the background could reach us only after the Universe changed its optical behaviour. The story therefore moves from receivers on Earth to the physics that released the photons.

4. When the Universe Became Transparent

Near redshift 1100, roughly 380,000 years after the hot early phase, the plasma cooled to around 3000 K. Electrons combined with nuclei and hydrogen became predominantly neutral, sharply reducing the supply of free electrons that scattered radiation.[7,8,31] The traditional word recombination survives even though these electrons and nuclei had not previously formed stable atoms.

As the free-electron abundance fell, Thomson scattering became much less frequent and most CMB photons began to free-stream across the expanding Universe.[7,8] Recombination describes the changing ionization state; photon decoupling describes the transport transition. They are tightly related, but treating them as exact synonyms hides useful physics.

Neither process was an instantaneous switch. Precision calculations describe non-equilibrium atomic kinetics and a visibility function of finite width: the probability that an observed photon last scattered at a given time or redshift.[8] The apparent surface on a CMB map is therefore a blurred statistical layer built into the physics itself, not merely an imperfection of our telescopes.

Much later, the first luminous sources reionized intergalactic gas and caused a fraction of CMB photons to scatter again. In the baseline Planck 2018 analysis, the integrated optical depth was $\tau = 0.054 \pm 0.007$. [21,31,37] The value depends on model and data combination, while the timing and patchiness of reionization remain less certain than the existence of rescattering.

Before decoupling, photons also diffused out of small-scale hot and cold regions, erasing some fine angular structure. This high-multipole suppression is called Silk damping.[9,19] Its observed shape

depends not only on diffusion but also on recombination history, geometry and other parameters, so it is a physical effect embedded in a wider inference rather than a ruler read in isolation.

Where That Leaves Us

Transparency emerged gradually as the free-electron population collapsed, leaving a finite last-scattering layer rather than a sharp wall. Reionization later rescattered some photons, while earlier diffusion erased fine structure. The CMB we receive has therefore been filtered by a sequence of physical processes. Its strongest historical credential is not merely that it exists, but the exact form of its spectrum.

5. A Blackbody Beyond Imitation

The Question

Diffuse microwave radiation could have many origins. What made the CMB a decisive relic of a hot early Universe was not one temperature reading, but a spectrum whose entire frequency dependence follows a blackbody with extraordinary precision.

COBE's Far Infrared Absolute Spectrophotometer compared the sky with a precise internal blackbody. Analysis of the full FIRAS data found root-mean-square deviations below 50 parts per million of the spectrum's peak brightness.[11,12,35] The limit applies to the instrument and frequency range; it does not declare mathematically perfect blackness at every possible frequency.

Temperature estimates also have a provenance that numbers alone can hide. In 2009 Dale Fixsen independently recalibrated FIRAS against WMAP and obtained 2.7260 ± 0.0013 K. He then combined that result with other measurements from the literature to obtain 2.72548 ± 0.00057 K. [13] The recalibration is one input to the combined value, not an independent confirmation of it.

A blackbody is the spectral signature of radiation once driven toward thermal equilibrium. Cosmic expansion can cool such a field while preserving the form of the spectrum.[12,35] That makes the shape a fossil of thermal history and stronger evidence for a hot early phase than the mere presence of diffuse microwaves, even though the inference still uses radiative-transfer theory.

FIRAS also turned non-detections into constraints. Departures described by parameters such as Compton y or chemical potential μ would reveal particular kinds and epochs of energy release. [10,12,35,38] No distortion at FIRAS sensitivity does not mean no distortion exists. Future instruments could measure signals below its limits and convert an upper bound into a new history.

The mean intensity is overwhelmingly uniform, but most of the CMB's cosmological information appears in tiny angular, frequency and polarization differences after foregrounds and systematics are controlled.[12,15] The mean spectrum establishes the thermal relic. The variations turn that relic into a map of dynamics.

Where That Leaves Us

FIRAS transformed a plausible background into an extraordinarily precise thermal fossil: not an exactly perfect blackbody by decree, but a measured spectrum with deviations bounded at tens of parts per million. Its temperature estimates share calibration ancestry and must be described accordingly. Once the mean spectrum was secure, attention shifted to the tiny departures from uniformity that carry most of the structural information.

6. The Wrinkles Carry the Message

COBE's Differential Microwave Radiometers detected intrinsic temperature anisotropies at the level of roughly one part in 100,000.[14,16,19,36] The shorthand 10^{-5} describes an order of magnitude, not one universal pixel value. Amplitude depends on angular scale, statistic, mask and foreground treatment.

The largest pattern is the dipole, produced mainly by our motion relative to the local CMB rest frame—the frame in which that dipole vanishes.[16,28,36] Defining such a frame does not violate relativity or make the laws of physics prefer it. The kinematic dipole is modelled or removed before the much smaller primordial anisotropies are interpreted.

Across smaller angular scales, the acoustic peaks record oscillations in the coupled photon-baryon fluid before decoupling.[17–19,25] They are genuine sound-like waves in that early plasma, not pressure waves travelling through today's Universe. Gravity, baryon loading, diffusion and projection all help shape the observed sequence.

The positions, spacings and relative heights of those peaks constrain geometry and the densities and dynamics of matter and radiation within an explicit cosmological model.[17–20,30,31] No peak is a direct gauge for one quantity in isolation. Parameters are correlated, and their reported precision depends on the model, likelihood and data combination.

WMAP and Planck converted calibrated time-ordered measurements into sky maps and angular power spectra.[20,22,27,31] These products represent real observations, but they are statistical reconstructions rather than raw colour photographs. Beams, scanning strategy, noise models, masks, calibration and component separation all stand between detector output and the familiar mottled image.

Where That Leaves Us

The CMB's faint wrinkles transformed a thermal relic into a quantitative probe of geometry and cosmic contents. Their interpretation requires removing the motion-induced dipole and fitting a correlated pattern, not reading physical quantities directly from coloured spots. Because the signal is so small, the reliability of the conclusion depends on how maps are reconstructed, foregrounds are separated and independent pipelines agree.

7. A Map Must Be Reconstructed

The Question

When a satellite publishes a full-sky CMB image, which parts came directly from the sky and which were produced by analysis? The answer is both: real measurements become usable only through calibration, foreground modelling and statistical reconstruction.

Thomson scattering generates linear polarization when electrons see a local quadrupole in the incoming radiation. In 2002 DASI reported the first detection of CMB polarization.[21,23–26] That milestone did not detect every later polarization signal; it established that the background carried an additional orientation-dependent record beyond temperature anisotropy.

Intervening structure then gravitationally lenses the CMB, slightly remapping directions and mixing polarization patterns. Planck reported lensing detections at about 9 sigma from

polarization alone and 40 sigma in its combined reconstruction.[32] These are statistical detections whose significance depends on estimators and data combinations, not direct photographs of a mass screen.

The cosmological signal shares the sky with Galactic dust, synchrotron, free-free and line emission, unresolved radio and infrared sources, and instrument-specific systematics.[15,27–29] Frequency dependence, spatial morphology, detector tests and masks help separate them. No foreground cleaning is assumption-free, and residuals vary with scale, frequency and target signal.

Planck therefore produced CMB solutions with four major component-separation methods: Commander, NILC, SEVEM and SMICA.[27,29] Agreement among pipelines is valuable because their assumptions and operations differ. It is not proof that every pixel or multipole is uncontaminated; simulations still reveal different residuals, noise properties and biases.

Where That Leaves Us

A CMB map is a disciplined reconstruction: genuine sky data filtered through calibration, beam modelling, masking and several foreground-separation strategies. Polarization and lensing add information, while pipeline agreement tests robustness without guaranteeing perfection. The final interpretive step is therefore unavoidable. We must ask which conclusions are close to direct observations, which depend on a cosmological model and which limits no better instrument can remove.

8. What This Light Can and Cannot Tell Us

Within base Lambda-CDM and specified extensions, the CMB constrains baryon density, dark-matter density, the acoustic scale, spectral parameters and optical depth.[20,22,30,31] These are model-mediated inferences, not model-free meter readings. Expanding the parameter space, changing likelihoods or adding external data can broaden or shift the results even when the sky measurements remain unchanged.

The reach behind last scattering can be remarkable. Free-streaming particles such as neutrinos alter the phase of acoustic oscillations, and a characteristic phase shift has been detected in CMB data.[33,34] This is indirect evidence for pre-recombination physics: a later pattern carries the effect. It is not a photograph of neutrinos, and alternative mechanisms must be judged against the full structure.

One limitation is irreducible. We observe only one sky, so the largest-scale modes provide only a finite sample of the underlying statistical process. Cosmic variance remains even with a perfect detector.[19,22,31] Cross-correlations and new tracers can add information, but they cannot create another independent realization of the same primordial sky.

The article boundary follows the evidence. QTC-011 owns the observational anchor: what the oldest light is, how it was measured and how maps become claims. QTC-012 asks what scientists mean by the Big Bang, and QTC-013 reconstructs the earlier pre-atomic Universe. Observation comes first here because those later arguments inherit its calibrations, limits and distinctions.

Where That Leaves Us

The oldest visible light is neither a direct view of the beginning nor a mute wall. Its spectrum, anisotropy and polarization support powerful but model-mediated inferences about earlier physics. Some limits yield to better instruments; cosmic variance does not. The scientific achievement is the chain itself: prediction, detection, calibration, reconstruction and explicit boundaries on what the evidence can carry.

What We Know, and How

- The CMB is the oldest electromagnetic light directly observable across the whole sky, released across a finite last-scattering interval roughly 380,000 years after the hot early phase.[7,8,27,31]
- Prediction preceded detection: Alpher and Herman estimated a relic temperature of order 5 K, while the two 1965 papers separated the Bell Labs measurement from the Princeton interpretation.[2–4]
- COBE/FIRAS measured an exceptionally close blackbody spectrum, with full-data root-mean-square deviations below 50 parts per million of peak brightness.[11,12,35]
- Temperature anisotropy and acoustic structure are extracted through calibrated maps, foreground control and likelihood-based power-spectrum reconstruction.[16,18,19,27,30]
- Polarization and gravitational lensing add distinct observables whose maps are likewise reconstructed rather than raw photographs.[21,23,27,32]
- CMB-derived cosmological parameters are precise within stated models and likelihoods, while cosmic variance irreducibly limits the largest-scale modes.[19,20,22,30,31]

What We Still Don't Know

- Whether primordial spectral distortions lie below FIRAS limits and which energy-release histories future measurements may recover.
- The detailed timing, duration and patchiness of reionization beyond its established integrated effect on CMB photons.
- How far extensions or alternatives to base Lambda-CDM can change parameter meanings while still fitting the full temperature, polarization and lensing data.
- Which pre-recombination signatures are uniquely diagnostic and which could be mimicked by different physical mechanisms.

What Could Change Our Minds

- A reproducible calibration or foreground correction revealing a significant non-cosmic contribution to signals now treated as primordial.
- A confirmed spectral distortion that replaces FIRAS-era upper limits with a measured departure and a specific thermal history.
- A cosmological framework that fits the complete CMB data better while assigning materially different meanings to the inferred parameters.
- Evidence that the dominant dipole or acoustic peak sequence has a different physical origin from the kinematic and photon-baryon interpretations now supported.

If You Remember Only One Thing

The CMB is not a photograph of the beginning: it is ancient light released when the Universe became transparent, then calibrated and reconstructed into evidence about still earlier physics.

Related Articles

- QTC-001 — Everything You See Is the Past
- QTC-002 — Why Is the Night Sky Dark?
- QTC-012 — What Do We Really Mean by the Big Bang?
- QTC-013 — Before Atoms

References

- [1] G. Gamow. The Evolution of the Universe. *Nature* 162, 680–682 (1948). DOI 10.1038/162680a0. <https://doi.org/10.1038/162680a0>
- [2] Ralph A. Alpher and Robert Herman. Evolution of the Universe. *Nature* 162, 774–775 (1948). DOI 10.1038/162774b0. <https://doi.org/10.1038/162774b0>
- [3] R. H. Dicke, P. J. E. Peebles, P. G. Roll and D. T. Wilkinson. Cosmic Black-Body Radiation. *The Astrophysical Journal* 142, 414–419 (1965). DOI 10.1086/148306. <https://doi.org/10.1086/148306>
- [4] A. A. Penzias and R. W. Wilson. A Measurement of Excess Antenna Temperature at 4080 Mc/s. *The Astrophysical Journal* 142, 419–421 (1965). DOI 10.1086/148307. <https://doi.org/10.1086/148307>
- [5] P. J. E. Peebles. The Black-Body Radiation Content of the Universe and the Formation of Galaxies. *The Astrophysical Journal* 142, 1317–1326 (1965). DOI 10.1086/148417. <https://doi.org/10.1086/148417>
- [6] P. G. Roll and David T. Wilkinson. Cosmic Background Radiation at 3.2 cm—Support for Cosmic Black-Body Radiation. *Physical Review Letters* 16, 405–407 (1966). DOI 10.1103/PhysRevLett.16.405. <https://doi.org/10.1103/PhysRevLett.16.405>
- [7] P. J. E. Peebles. Recombination of the Primeval Plasma. *The Astrophysical Journal* 153, 1–11 (1968). DOI 10.1086/149628. <https://doi.org/10.1086/149628>
- [8] Sara Seager, Dimitar D. Sasselov and Douglas Scott. How Exactly Did the Universe Become Neutral? *The Astrophysical Journal Supplement Series* 128, 407–430 (2000). DOI 10.1086/313388. <https://doi.org/10.1086/313388>
- [9] Joseph Silk. Cosmic Black-Body Radiation and Galaxy Formation. *The Astrophysical Journal* 151, 459–471 (1968). DOI 10.1086/149449. <https://doi.org/10.1086/149449>
- [10] R. A. Sunyaev and Ya. B. Zeldovich. The interaction of matter and radiation in the hot model of the Universe, II. *Astrophysics and Space Science* 7, 20–30 (1970). DOI 10.1007/BF00653472. <https://doi.org/10.1007/BF00653472>
- [11] J. C. Mather, E. S. Cheng, R. E. Eplee, Jr., R. B. Isaacman, S. S. Meyer, R. A. Shafer, R. Weiss, E. L. Wright, C. L. Bennett, N. W. Boggess, E. Dwek, S. Gulkis, M. G. Hauser, M. Janssen, T. Kelsall, P. M. Lubin, S. H. Moseley, Jr., T. L. Murdock, R. F. Silverberg, G. F. Smoot and D. T. Wilkinson. A Preliminary Measurement of the Cosmic Microwave Background Spectrum by the Cosmic Background Explorer (COBE) Satellite. *The Astrophysical Journal Letters* 354, L37–L40 (1990). DOI 10.1086/185717. <https://doi.org/10.1086/185717>
- [12] D. J. Fixsen, E. S. Cheng, J. M. Gales, J. C. Mather, R. A. Shafer and E. L. Wright. The Cosmic Microwave Background Spectrum from the Full COBE FIRAS Data Set. *The Astrophysical Journal* 473, 576–587 (1996). DOI 10.1086/178173. <https://doi.org/10.1086/178173>
- [13] D. J. Fixsen. The Temperature of the Cosmic Microwave Background. *The Astrophysical Journal* 707, 916–920 (2009). DOI 10.1088/0004-637X/707/2/916. <https://doi.org/10.1088/0004-637X/707/2/916>
- [14] G. F. Smoot, C. L. Bennett, A. Kogut, E. L. Wright, J. Aymon, N. W. Boggess, E. S. Cheng, G. de Amici, S. Gulkis, M. G. Hauser, G. Hinshaw, P. D. Jackson, M. Janssen, E. Kaita, T. Kelsall, P. Keegstra, C. Lineweaver, K. Loewenstein, P. Lubin, J. Mather, S. S. Meyer, S. H. Moseley, T. Murdock, L. Rokke, R. F. Silverberg, L. Tenorio, R. Weiss and D. T. Wilkinson. Structure in the COBE Differential Microwave Radiometer First-Year Maps. *The Astrophysical Journal Letters* 396, L1–L5 (1992). DOI 10.1086/186504. <https://doi.org/10.1086/186504>
- [15] C. L. Bennett, G. F. Smoot, G. Hinshaw, E. L. Wright, A. Kogut, G. de Amici, S. S. Meyer, R. Weiss, D. T. Wilkinson, S. Gulkis, M. Janssen, N. W. Boggess, E. S. Cheng, M. G. Hauser, T. Kelsall, J. C. Mather, S. H. Moseley, Jr., T. L. Murdock and R. F. Silverberg. Preliminary Separation of Galactic and Cosmic Microwave Emission for the COBE Differential Microwave Radiometer. *The Astrophysical Journal Letters* 396, L7–L12 (1992). DOI 10.1086/186505. <https://doi.org/10.1086/186505>
- [16] C. L. Bennett, A. J. Banday, K. M. Górski, G. Hinshaw, P. Jackson, P. Keegstra, A. Kogut, G. F. Smoot, D. T. Wilkinson and E. L. Wright. Four-Year COBE DMR Cosmic Microwave Background Observations: Maps and Basic Results. *The Astrophysical Journal Letters* 464, L1–L4 (1996). DOI 10.1086/310075. <https://doi.org/10.1086/310075>
- [17] P. de Bernardis, P. A. R. Ade, J. J. Bock, J. R. Bond, J. Borrill, A. Boscaleri, K. Coble, B. P. Crill, G. De Gasperis, P. C. Farese, P. G. Ferreira, K. Ganga, M. Giacometti, E. Hivon, V. V. Hristov, A. Iacoangeli, A. H. Jaffe, A. E. Lange, L. Martinis, S. Masi, P. V. Mason, P. D. Mauskopf, A. Melchiorri, L. Miglio, T. Montroy, C. B. Netterfield, E. Pascale, F. Piacentini, D. Pogossyan, S. Prunet, S. Rao, G. Romeo, J. E. Ruhl, F. Scaramuzzi, D. Sforna and N. Vittorio. A Flat Universe from High-Resolution Maps of the Cosmic Microwave Background Radiation. *Nature* 404, 955–959 (2000). DOI 10.1038/35010035. <https://doi.org/10.1038/35010035>
- [18] C. B. Netterfield, P. A. R. Ade, J. J. Bock, J. R. Bond, J. Borrill, A. Boscaleri, K. Coble, C. R. Contaldi, B. P. Crill, P. de Bernardis, P. Farese, K. Ganga, M. Giacometti, E. Hivon, V. V. Hristov, A. Iacoangeli, A. H. Jaffe, W. C. Jones, A. E. Lange, L. Martinis, S. Masi, P. Mason, P. D. Mauskopf, A. Melchiorri, T. Montroy, E. Pascale, F. Piacentini, D. Pogossyan, F. Pongetti, S. Prunet, G. Romeo, J. E. Ruhl and F. Scaramuzzi. A Measurement by BOOMERANG of Multiple Peaks in the Angular Power Spectrum of the Cosmic Microwave Background. *The Astrophysical Journal* 571, 604–614 (2002). DOI 10.1086/340118. <https://doi.org/10.1086/340118>
- [19] Wayne Hu and Scott Dodelson. Cosmic Microwave Background Anisotropies. *Annual Review of Astronomy and Astrophysics* 40, 171–216 (2002). DOI 10.1146/annurev.astro.40.060401.093926. <https://doi.org/10.1146/annurev.astro.40.060401.093926>
- [20] D. N. Spergel, L. Verde, H. V. Peiris, E. Komatsu, M. R. Nolte, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, J. L. Weiland, E. Wollack and E. L. Wright. First-Year Wilkinson Microwave Anisotropy Probe (WMAP)

Observations: Determination of Cosmological Parameters. The Astrophysical Journal Supplement Series 148, 175–194 (2003). DOI 10.1086/377226. <https://doi.org/10.1086/377226>

[21] A. Kogut, D. N. Spergel, C. Barnes, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, E. Wollack and E. L. Wright. First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Temperature-Polarization Correlation. The Astrophysical Journal Supplement Series 148, 161–173 (2003). DOI 10.1086/377219. <https://doi.org/10.1086/377219>

[22] G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolte, M. Halpern, R. S. Hill, N. Odegard, L. Page, K. M. Smith, J. L. Weiland, B. Gold, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, E. Wollack and E. L. Wright. Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results. The Astrophysical Journal Supplement Series 208, article 19 (2013). DOI 10.1088/0067-0049/208/2/19. <https://doi.org/10.1088/0067-0049/208/2/19>

[23] J. M. Kovac, E. M. Leitch, C. Pryke, J. E. Carlstrom, N. W. Halverson and W. L. Holzapfel. Detection of Polarization in the Cosmic Microwave Background Using DASI. Nature 420, 772–787 (2002). DOI 10.1038/nature01269. <https://doi.org/10.1038/nature01269>

[24] Arthur Kosowsky. Cosmic Microwave Background Polarization. Annals of Physics 246, 49–85 (1996). DOI 10.1006/aphy.1996.0020. <https://doi.org/10.1006/aphy.1996.0020>

[25] Wayne Hu and Martin White. A CMB Polarization Primer. New Astronomy 2, 323–344 (1997). DOI 10.1016/S1384-1076(97)00022-5. [https://doi.org/10.1016/S1384-1076\(97\)00022-5](https://doi.org/10.1016/S1384-1076(97)00022-5)

[26] Matias Zaldarriaga and Uroš Seljak. All-Sky Analysis of Polarization in the Microwave Background. Physical Review D 55, 1830–1840 (1997). DOI 10.1103/PhysRevD.55.1830. <https://doi.org/10.1103/PhysRevD.55.1830>

[27] Planck Collaboration. Planck 2018 Results. I. Overview and the Cosmological Legacy of Planck. Astronomy & Astrophysics 641, A1 (2020). DOI 10.1051/0004-6361/201833880. <https://doi.org/10.1051/0004-6361/201833880>

[28] Planck Collaboration. Planck 2018 Results. III. High Frequency Instrument Data Processing and Frequency Maps. Astronomy & Astrophysics 641, A3 (2020). DOI 10.1051/0004-6361/201832909. <https://doi.org/10.1051/0004-6361/201832909>

[29] Planck Collaboration. Planck 2018 Results. IV. Diffuse Component Separation. Astronomy & Astrophysics 641, A4 (2020). DOI 10.1051/0004-6361/201833881. <https://doi.org/10.1051/0004-6361/201833881>

[30] Planck Collaboration. Planck 2018 Results. V. CMB Power Spectra and Likelihoods. Astronomy & Astrophysics 641, A5 (2020). DOI 10.1051/0004-6361/201936386. <https://doi.org/10.1051/0004-6361/201936386>

[31] Planck Collaboration. Planck 2018 Results. VI. Cosmological Parameters. Astronomy & Astrophysics 641, A6 (2020). DOI 10.1051/0004-6361/201833910. <https://doi.org/10.1051/0004-6361/201833910>

[32] Planck Collaboration. Planck 2018 Results. VIII. Gravitational Lensing. Astronomy & Astrophysics 641, A8 (2020). DOI 10.1051/0004-6361/201833886. <https://doi.org/10.1051/0004-6361/201833886>

[33] Brent Follin, Lloyd Knox, Marius Millea and Zhen Pan. First Detection of the Acoustic Oscillation Phase Shift Expected from the Cosmic Neutrino Background. Physical Review Letters 115, 091301 (2015). DOI 10.1103/PhysRevLett.115.091301. <https://doi.org/10.1103/PhysRevLett.115.091301>

[34] Sergei Bashinsky and Uroš Seljak. Signatures of relativistic neutrinos in CMB anisotropy and matter clustering. Physical Review D 69, 083002 (2004). DOI 10.1103/PhysRevD.69.083002. <https://doi.org/10.1103/PhysRevD.69.083002>

[35] NASA Legacy Archive for Microwave Background Data Analysis. COBE FIRAS Overview. Current. https://lambda.gsfc.nasa.gov/product/cobe/firas_overview.html

[36] NASA Legacy Archive for Microwave Background Data Analysis. COBE DMR Overview. Current. https://lambda.gsfc.nasa.gov/product/cobe/dmr_overview.html

[37] Planck Collaboration. Planck Intermediate Results. XLVII. Planck Constraints on Reionization History. Astronomy & Astrophysics 596, A108 (2016). DOI 10.1051/0004-6361/201628897. <https://doi.org/10.1051/0004-6361/201628897>

[38] J. Chluba and R. A. Sunyaev. The Evolution of CMB Spectral Distortions in the Early Universe. Monthly Notices of the Royal Astronomical Society 419, 1294–1314 (2012). DOI 10.1111/j.1365-2966.2011.19786.x. <https://doi.org/10.1111/j.1365-2966.2011.19786.x>