Observational Cosmology

The Cosmic Microwave Background

Part I: CMB history & thermal spectrum

Kaustuv Basu

Course website:
https://www.astro.uni-bonn.de/~kbasu/ObsCosmo

Disclaimer: Questions at any time!

Outline of the CMB Lectures

CMB theory

➡ Discovery of the CMB

➡ Thermal spectrum of the CMB

➡ Temperature anisotropies and the angular power spectrum

➡ CMB polarization – its origin and power spectra

➡ CMB secondary anisotropies

CMB experiments

➡ Cosmological parameter estimation

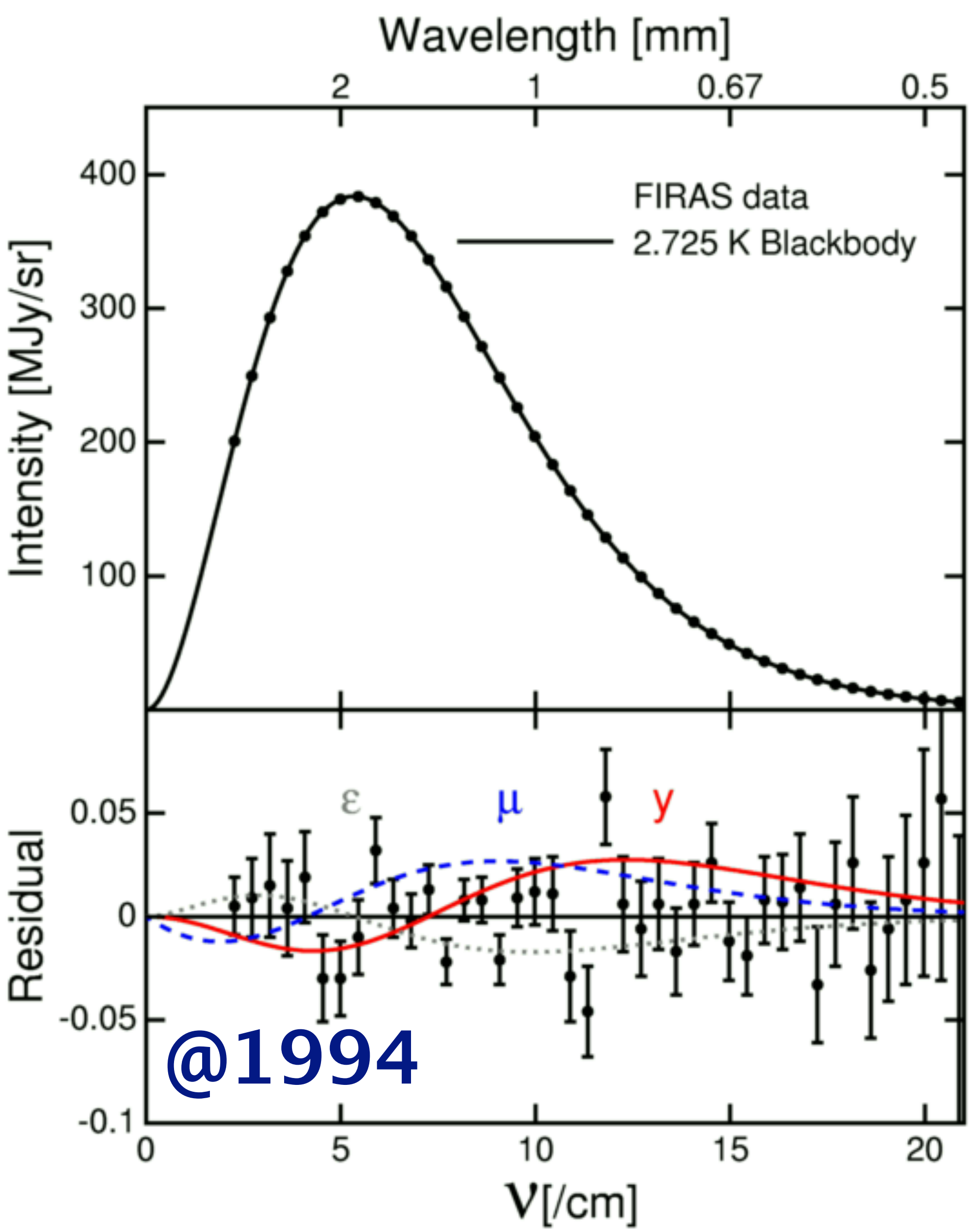
➡ Planck results – what’s next?

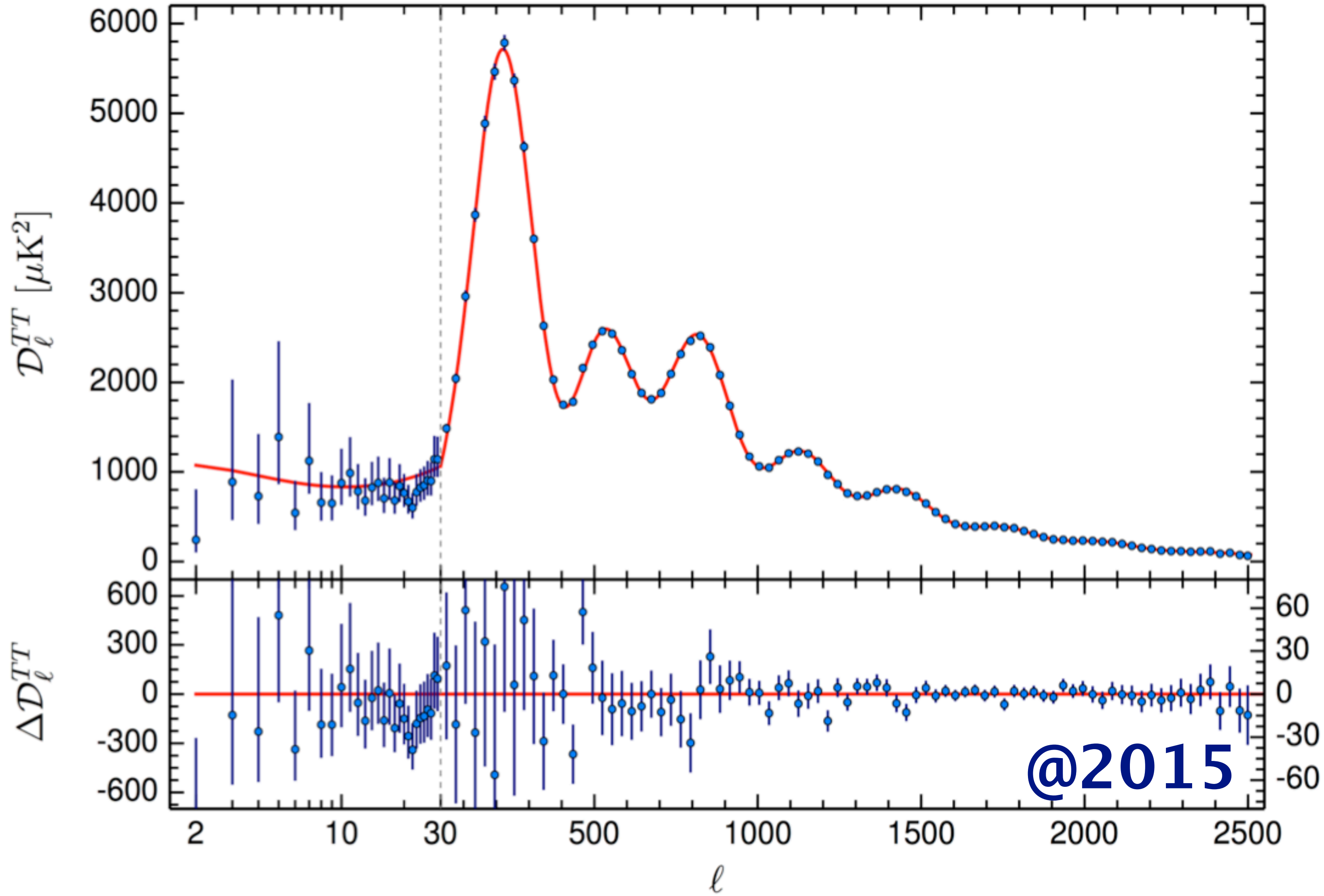
➡ CMB polarization in the coming decade, CMB@HD

➡ CMB data analysis: map making and foreground subtraction basics

Is CMB science dead?

There is now widespread belief among non-cosmologists that CMB science is practically over. Indeed, CMB research has been victim of its own success!





6-parameter ΛCDM cosmology is excellent fit to data!

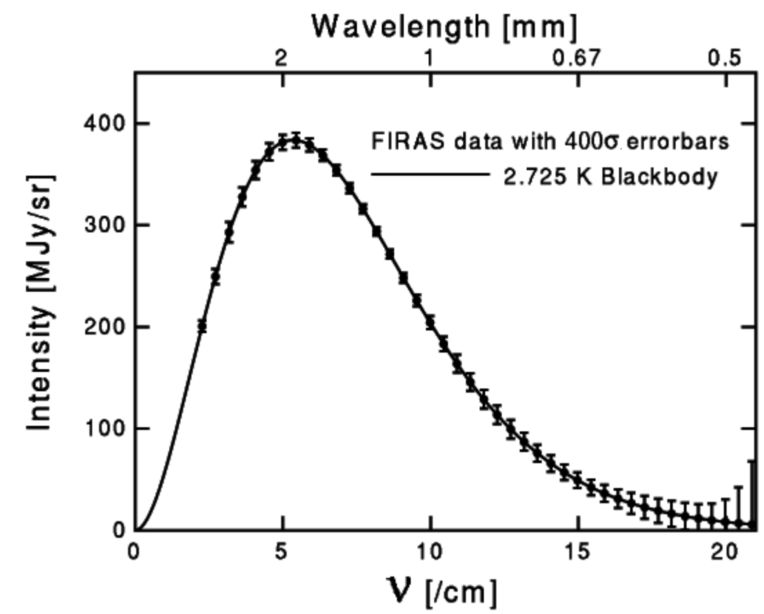
ΛCDM. Want more?

- Thanks to the CMB and other observations (large-scale structure of the Universe, supernovae, …), We now have the standard model of cosmology (ΛCDM), which can describe what we see from the early Universe to the present epoch
- What more do we want from the CMB?
- We have entered the new era: we ask deeper questions
  - **Has inflation really happened?** Did we really originate from quantum fluctuations in the early Universe?
  - **Is ΛCDM really right?** We don't understand the physical nature of Λ or CDM!

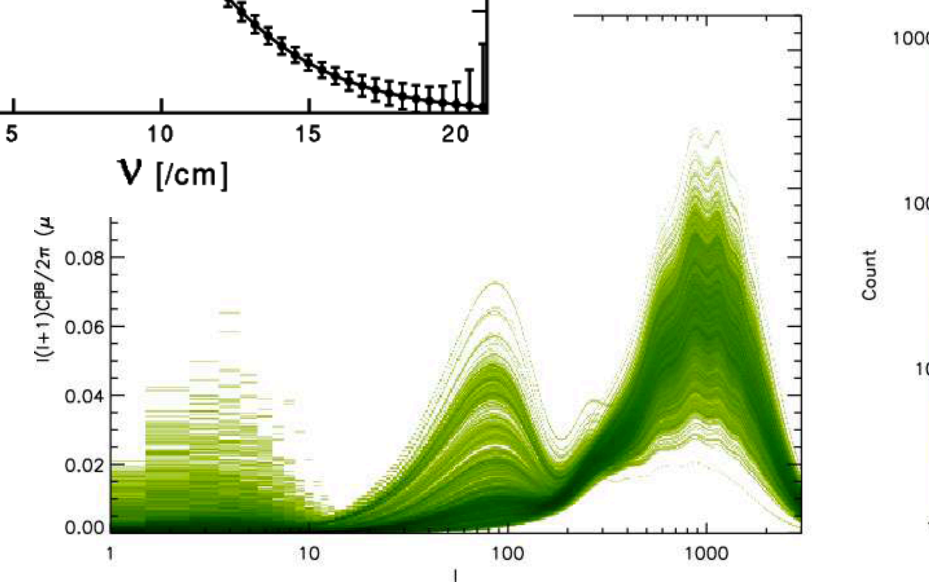
Many tests! Were there new light particles? Do DM particles annihilate? What is the mass of neutrinos? Is DE a cosmological constant? Is the distribution of hot gas and velocities consistent with ΛCDM? Etc, etc…

CMB today: Main focus of our lecture

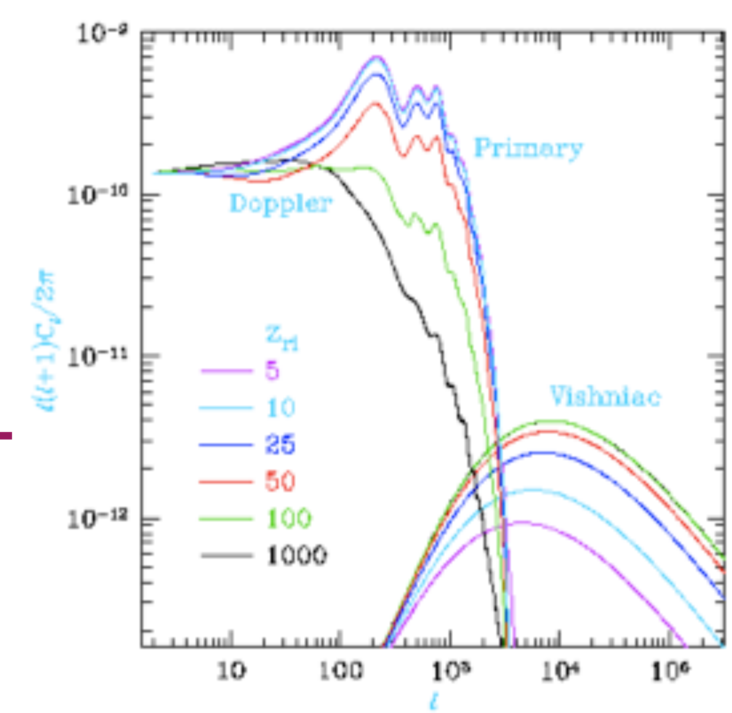
1. The thermal (blackbody) spectrum and its distortions as cosmological probe



2. Polarization anisotropies and the search for the primordial gravitational waves



3. Secondary anisotropies and the study of the growth of large-scale structure



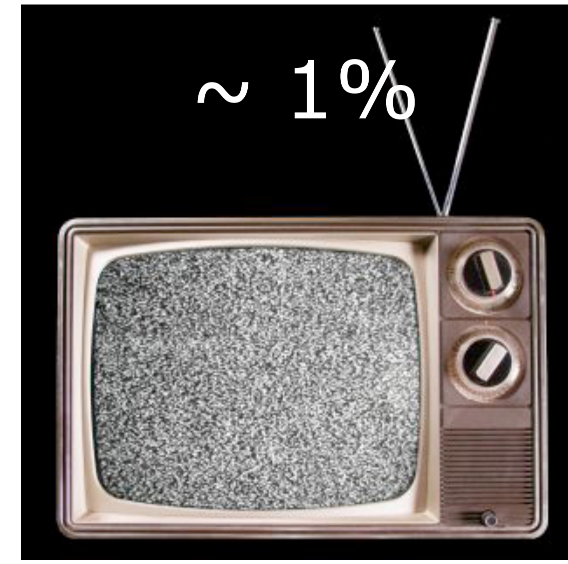
Part 1:

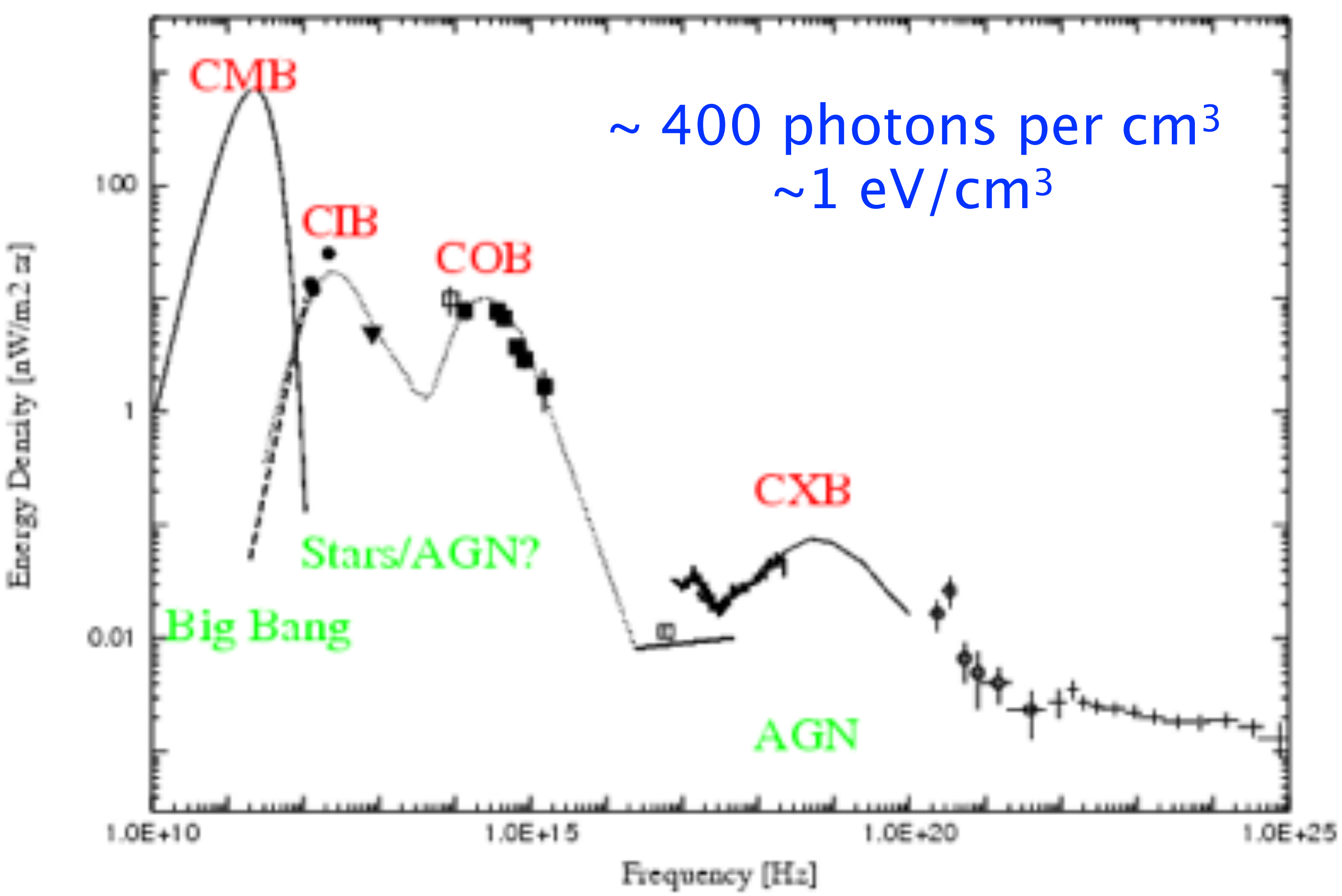
A Brief History of CMB Measurements

Where is the CMB?

- CMB dominates the radiation content of the universe

- It contains nearly 93% of the radiation energy density and 99% of all the photons (and the reason for the high photon-to-baryon ratio!)



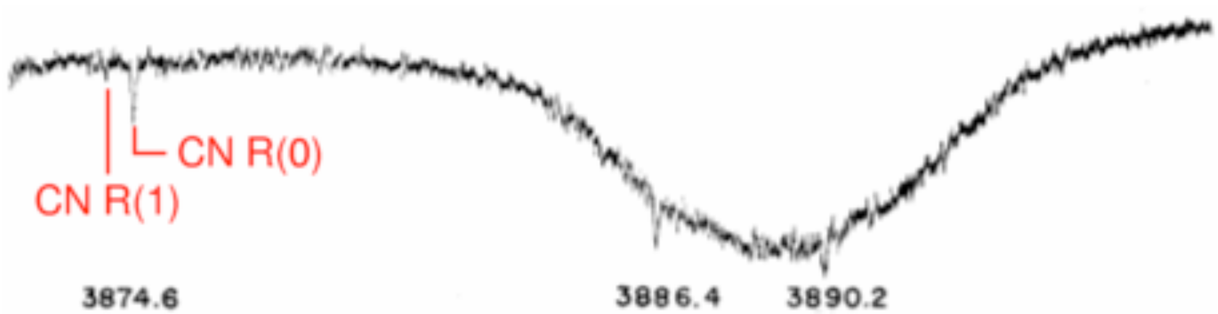


- The spectrum of CMB has a peak at 1.1mm.
- Let's compare it with…
  - Microwave oven: 12cm
  - Cellular phone: 20cm
  - UHF Television: 39-64cm
  - FM radio: 3m
  - AM radio: 300m

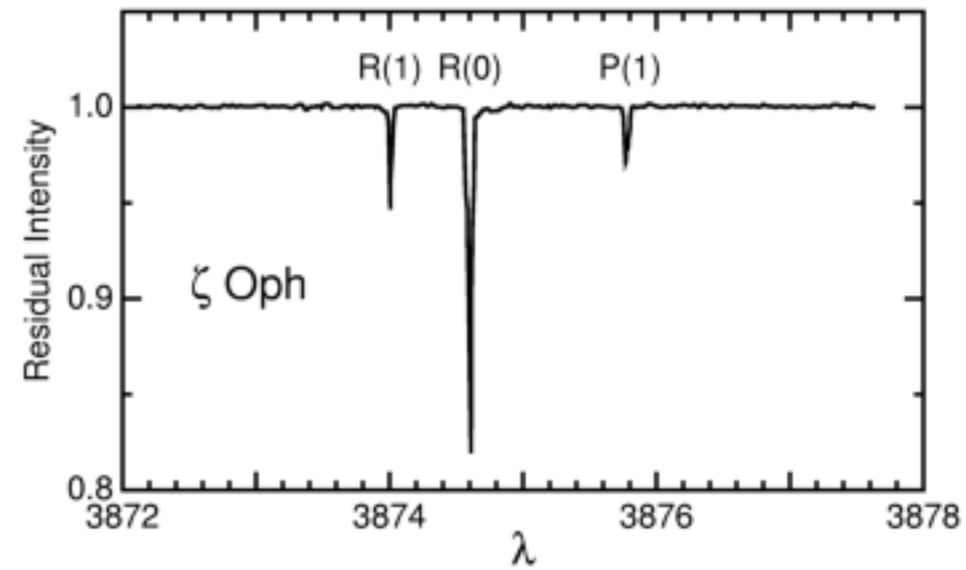
You can "see" CMB by TV (not by a cable TV of course!).

Perhaps you can "hear" CMB by a cell phone?

Discovery of the CMB



McKellar (1940)



- In 1940, McKellar discovers CN molecules in interstellar space from their absorption spectra (one of the first IS-molecules)

- From the excitation ratios, he infers the “rotational temperature of interstellar space” to be 2° K (1941, PASP 53, 233)

- In his 1950 book, the Nobel prize winning spectroscopist Herzberg remarks: “From the intensity ratio of the lines with K=0 and K=1 a rotational **temperature of 2.3° K follows, which has of course only a very restricted meaning**.”

Discovery of the CMB

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. Bethe
Cornell University, Ithaca, New York

AND

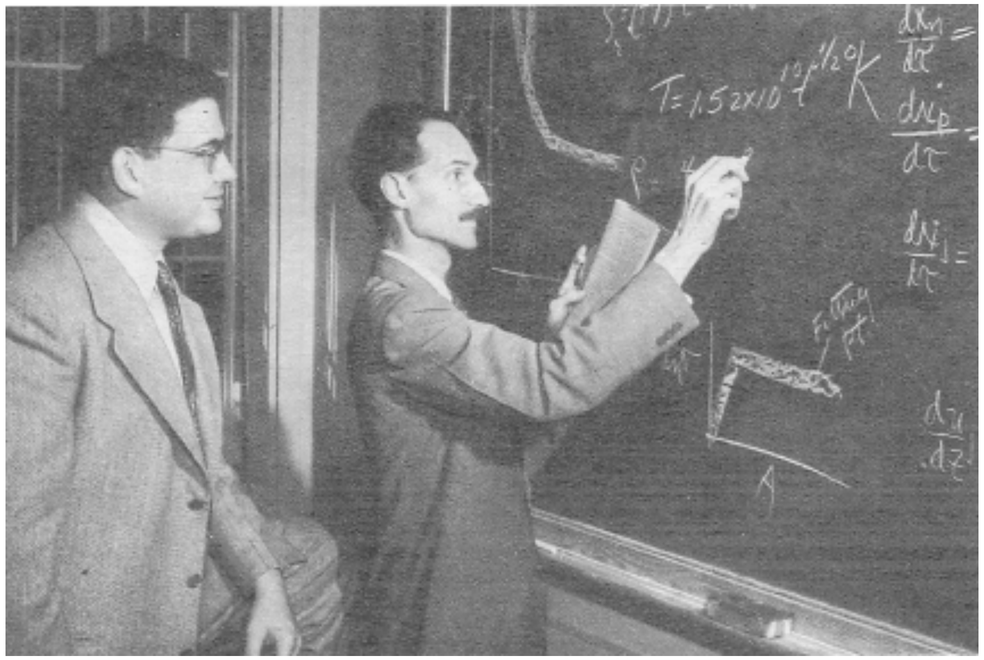
G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

• Alpher, Bethe & Gamow, in their 1948 paper, first proposed the very hot and dense early phase of the Universe (later termed derisively as "Big Bang" by Fred Hoyle). They mistakenly concluded that all elements were produced in this hot early phase.

The results of these calculations were first announced in a letter to The Physical Review, April 1, 1948. This was signed Alpher, Bethe, and Gamow, and is often referred to as the 'alphabetical article'. It seemed unfair to the Greek alphabet to have the article signed by Alpher and Gamow only, and so the name of Dr. Hans A. Bethe (in absentia) was inserted in preparing the manuscript for print. Dr. Bethe, who received a copy of the manuscript, did not object, and, as a matter of fact, was quite helpful in subsequent discussions. There was, however, a rumor that later, when the alpha, beta, gamma theory went temporarily on the rocks, Dr. Bethe seriously considered changing his name to Zacharias.

George Gamow, "The Creation of The Universe"

Discovery of the CMB



- After the "α-β-γ paper", Alpher & Herman (1948) predict 5 K radiation background as by-product of their theory of the nucleosynthesis in the early universe (with no suggestion of its detectability).

- Shmaonov (1957) measures an uniform noise temperature of 4±3 K at λ=3.2 cm.

- Doroshkevich & Novikov (1964) emphasize the detectability of this radiation, predict that the spectrum of the relict radiation will be a blackbody, and also mention that the twenty-foot horn reflector at the Bell Laboratories will be the best instrument for detecting it!

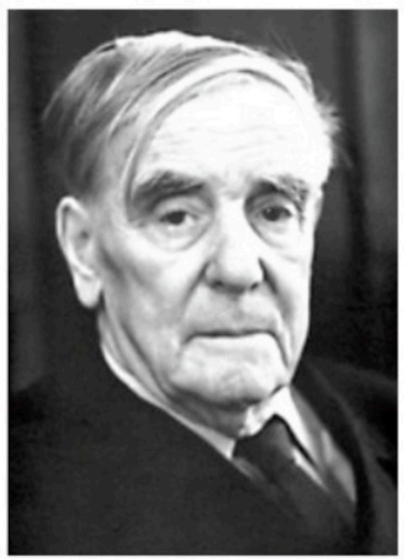
No Nobel prize for these guys ..

Discovery of the CMB

The Nobel Prize in Physics 1978

"for his basic inventions and discoveries in the area of low-temperature physics"

"For their discovery of cosmic microwave background radiation"



Pyotr Leonidovich Kapitsa

1/2 of the prize

USSR

Academy of Sciences
Moscow, USSR

b. 1894
d. 1984

Arno Allan Penzias

1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

b. 1933
(in Munich, Germany)

Robert Woodrow Wilson

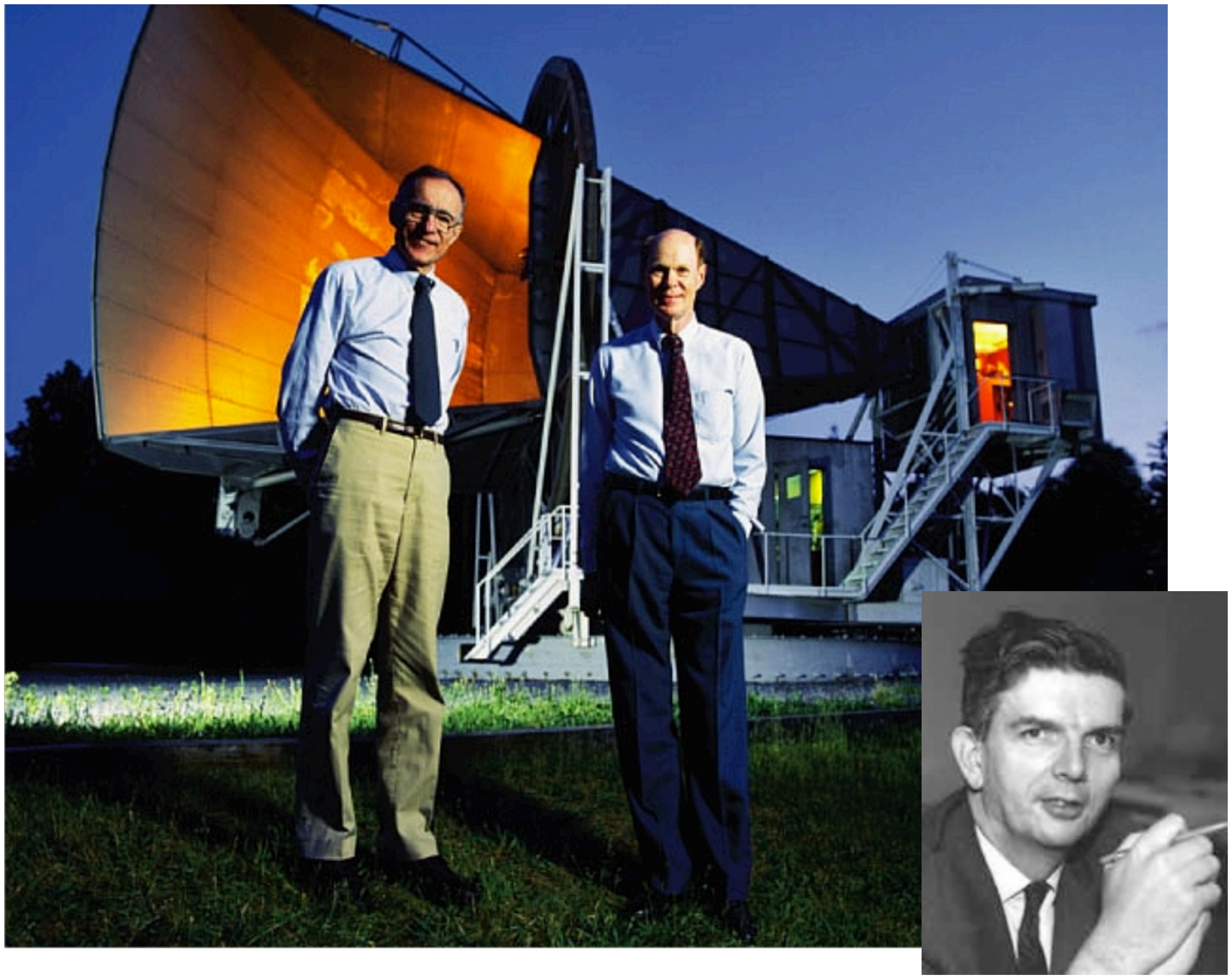
1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

b. 1936

Discovery of the CMB



- Originally wanted to measure Galactic emission at λ=7.3 cm (1964-65)

- Found a direction-independent noise (3.5±1.0 K) that they could not get rid of, despite drastic measures

- So they talked with colleagues..

- Explanation of this "excess noise" was given in a companion paper by Robert Dicke and collaborators

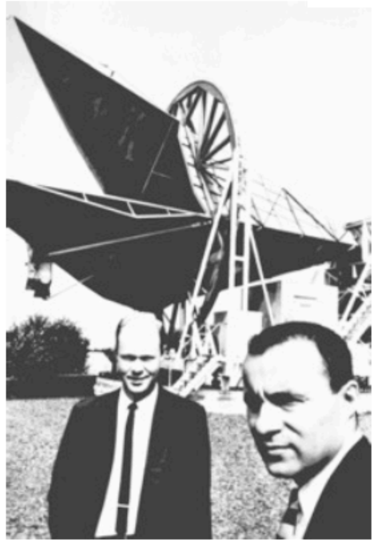
(no Nobel prize for Dicke either, not to mention Gamow!)

Arno Penzias & Robert Wilson, 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY



A. A. PENZIAS
R. W. WILSON

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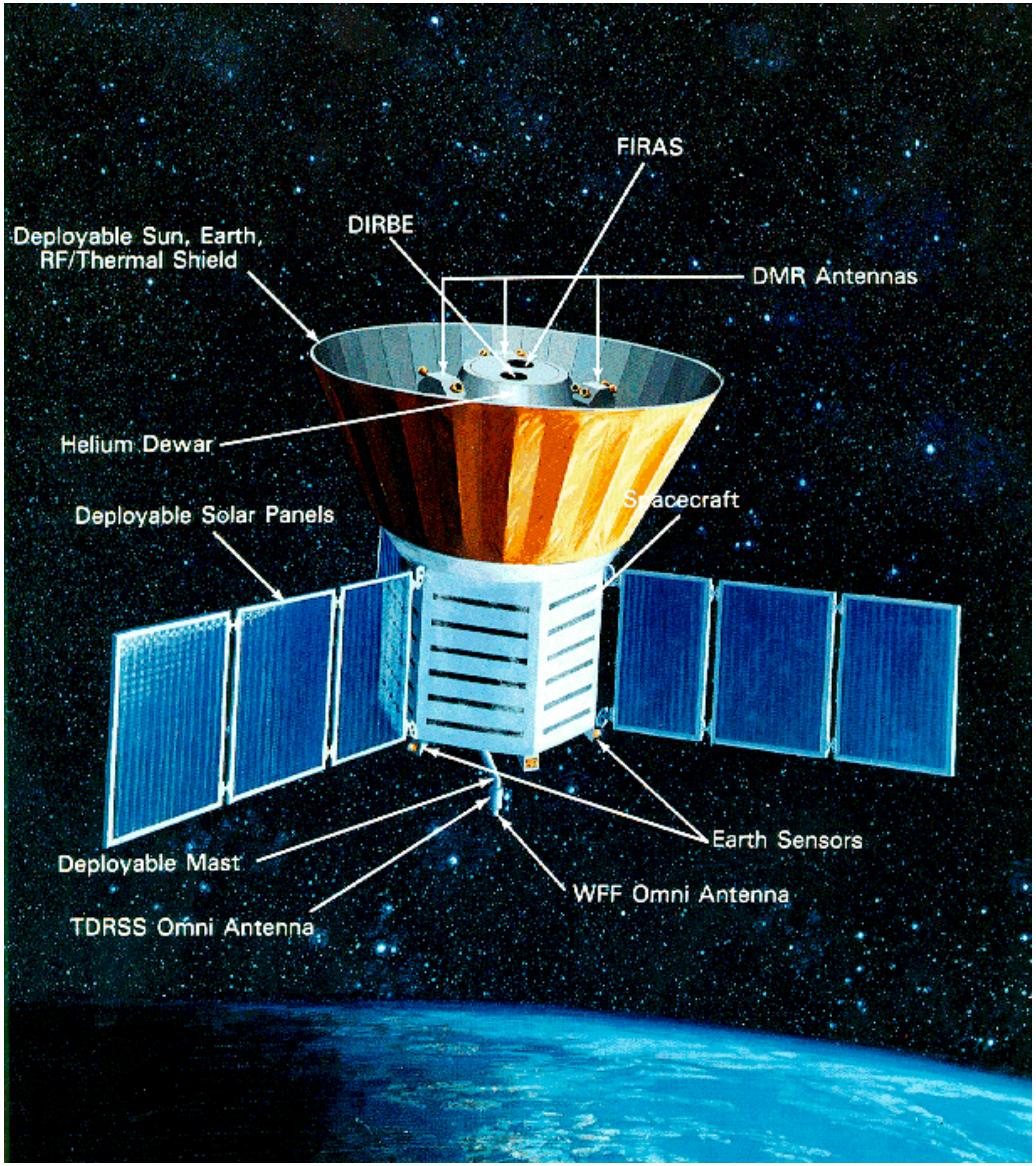
COBE satellite



Credit: NASA

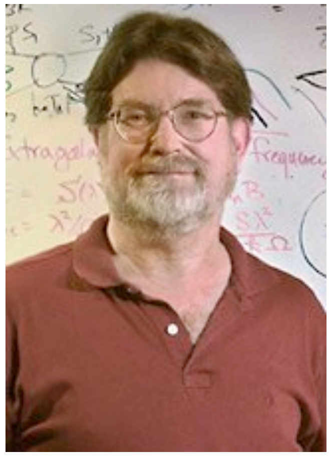
Launched on Nov. 1989 on a Delta rocket.

DIRBE: Measured the absolute sky brightness in the 1–240 μm wavelength range, to search for the Infrared Background

FIRAS: Measured the spectrum of the CMB, finding it to be an almost perfect blackbody with $T_0 = 2.725 \pm 0.002$ K

DMR: Found "anisotropies" in the CMB for the first time, at a level of 1 part in 10^5

2006 Nobel prize in physics



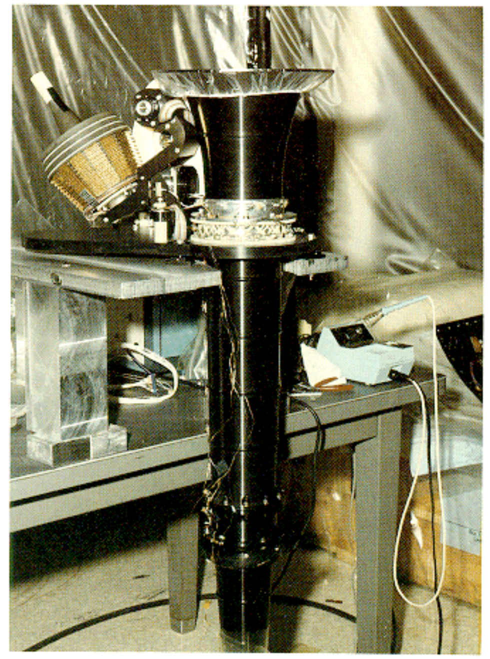
FIRAS on COBE

Far Infra-Red Absolute Spectrophotometer

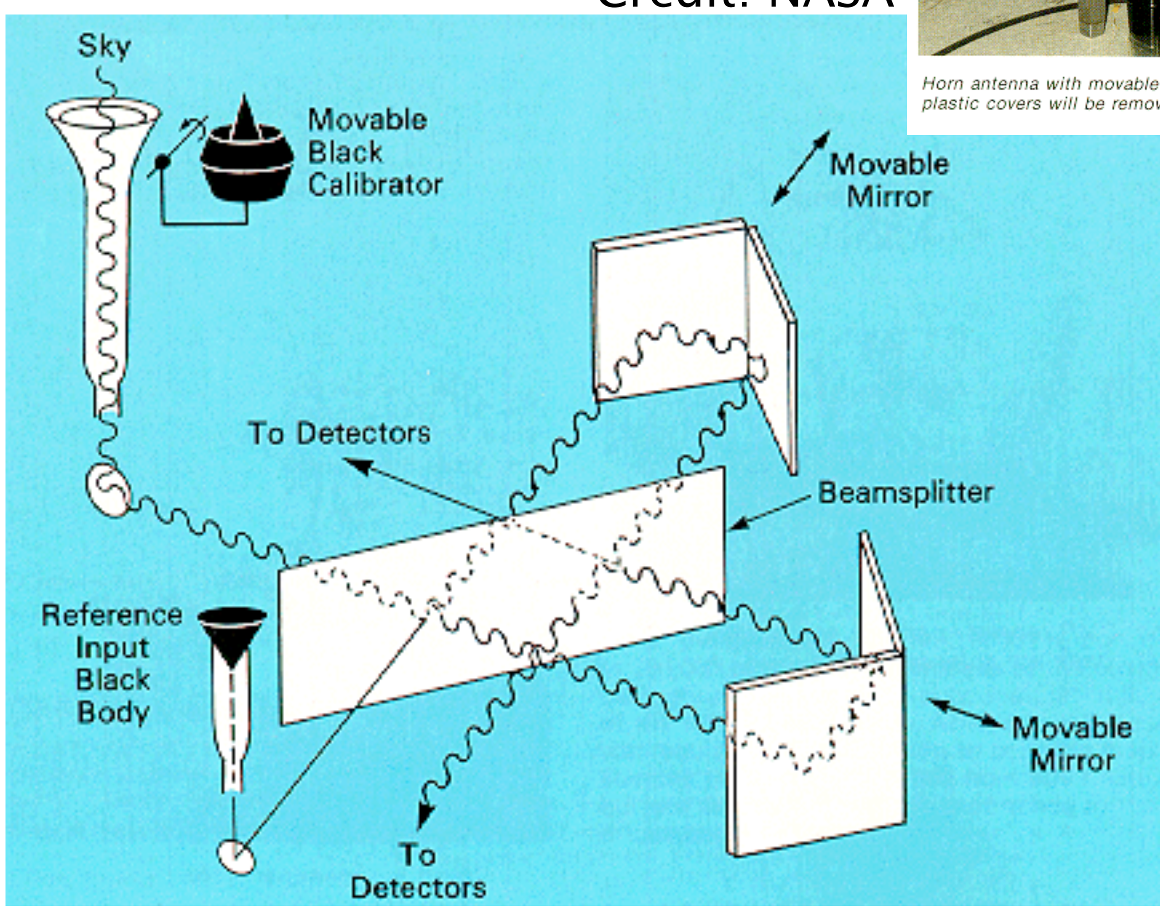
A differential polarizing Michelson interferometer

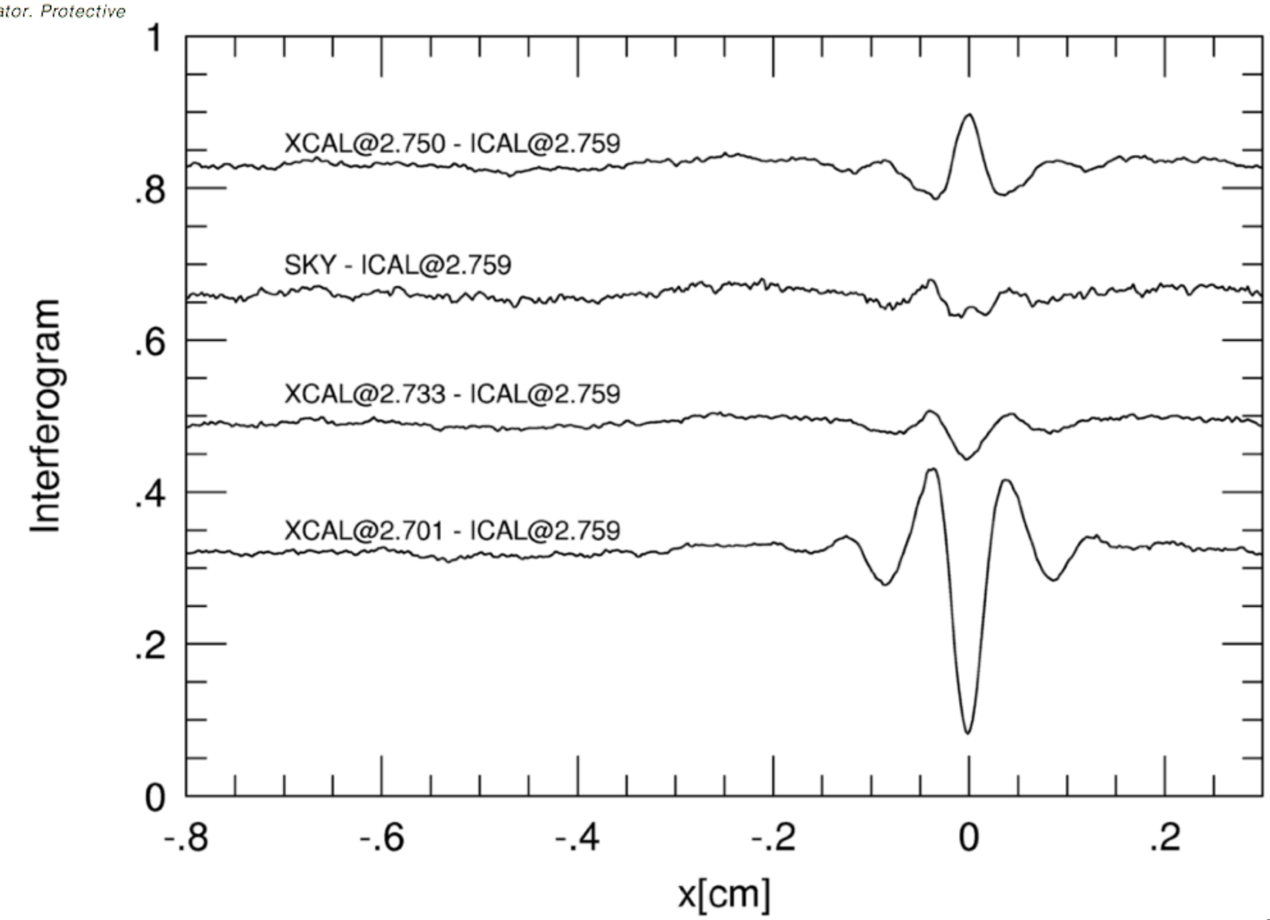
- One input is either the sky or a blackbody, other is a pretty good blackbody
- Zero output when the two inputs are equal
- Internal reference kept at T_0 ("cold load"), to minimize non-linear response of the detectors
- Residual is the measurement!

Credit: NASA

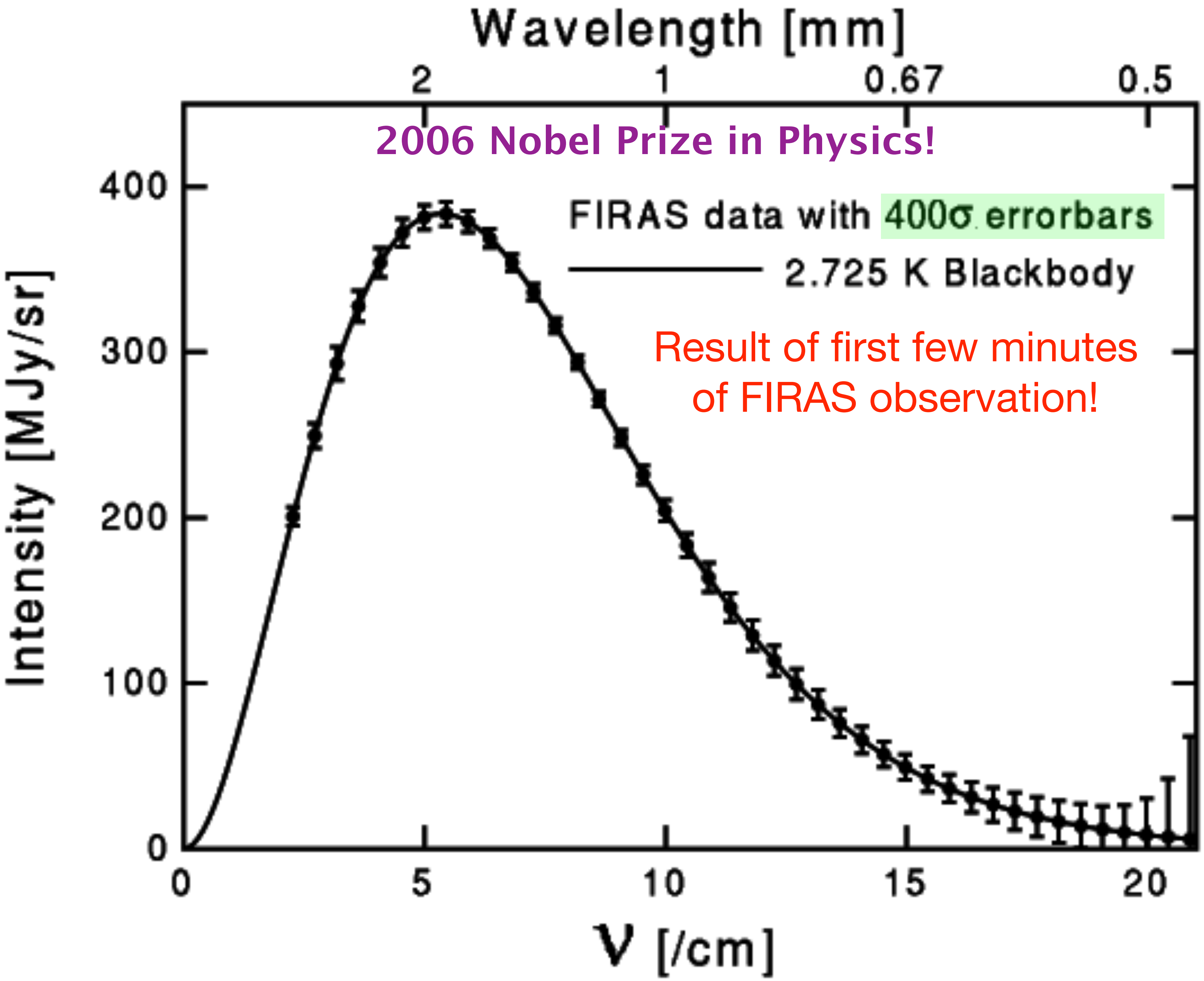


Horn antenna with movable calibrator. Protective plastic covers will be removed.





The CMB blackbody



The CMB blackbody

MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COBE*[1] FIRAS INSTRUMENT

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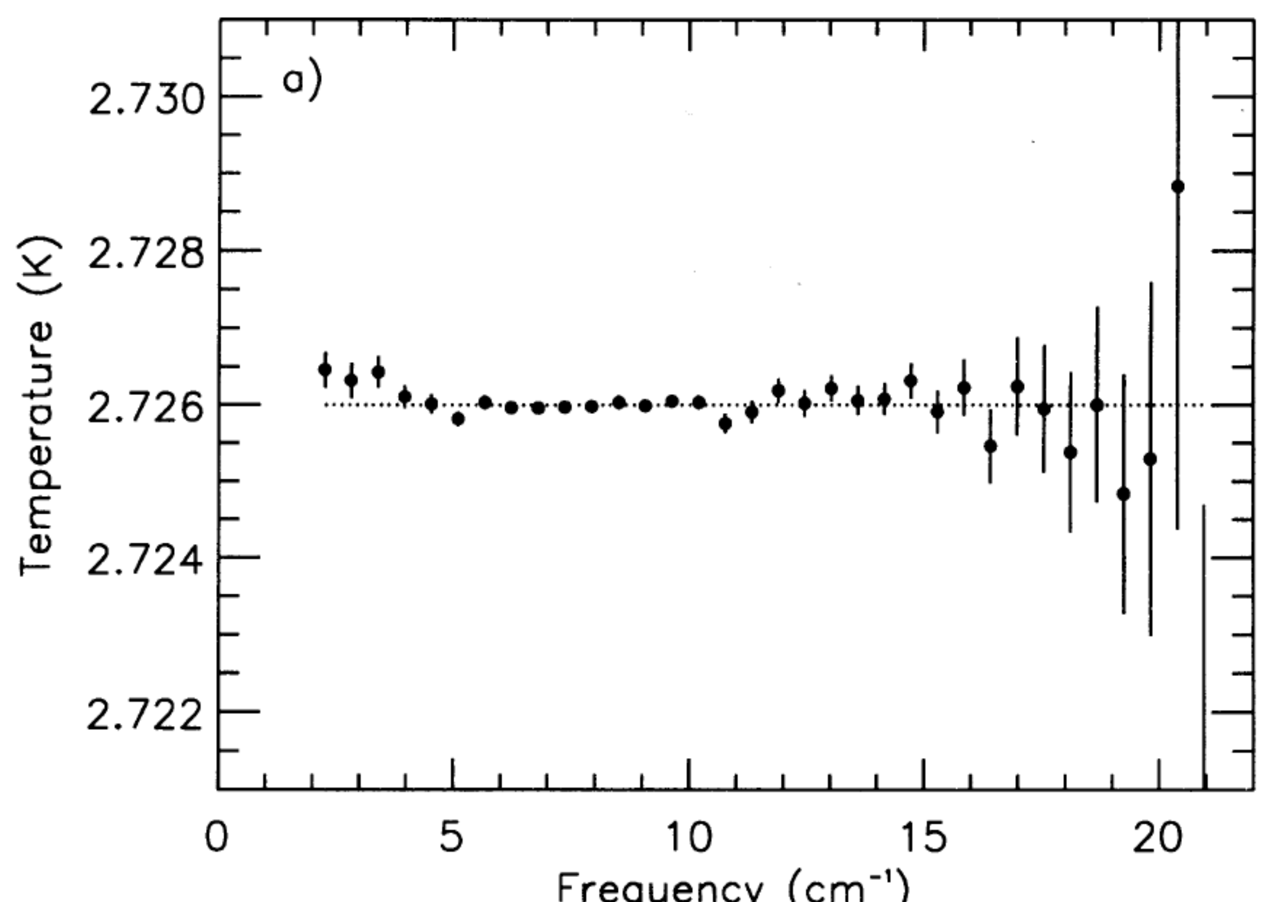
ABSTRACT

The cosmic microwave background radiation (CMBR) has a blackbody spectrum within 3.4×10^{-8} ergs cm^{-2} s^{-1} sr^{-1} cm over the frequency range from 2 to 20 cm^{-1} (5–0.5 mm). These measurements, derived from the FIRAS instrument on the *COBE* satellite, imply stringent limits on energy release in the early universe after $t \sim 1$ year and redshift $z \sim 3 \times 10^6$. The deviations are less than 0.03% of the peak brightness, with an rms value of 0.01%, and the dimensionless cosmological distortion parameters are limited to $|y| < 2.5 \times 10^{-5}$ and $|\mu| < 3.3 \times 10^{-4}$ (95% confidence level). The temperature of the CMBR is 2.726 ± 0.010 K (95% confidence level systematic).

Subject headings: cosmic microwave background — cosmology: observations — early universe

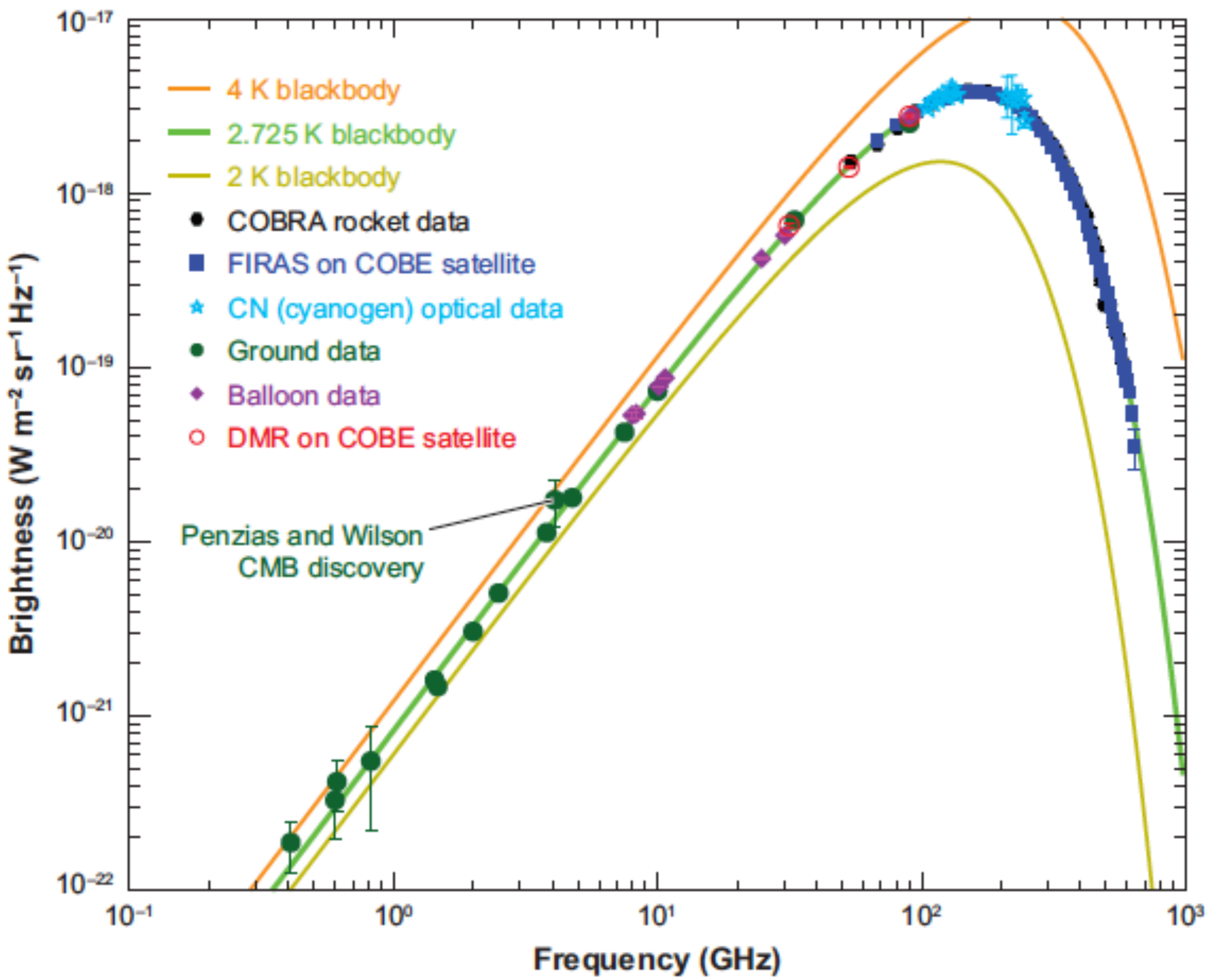
Mather et al. (1994)
Fixsen et al. (1996)



$T_0 = 2.7255 \pm 0.0006$ K

Measurement of T_{CMB}

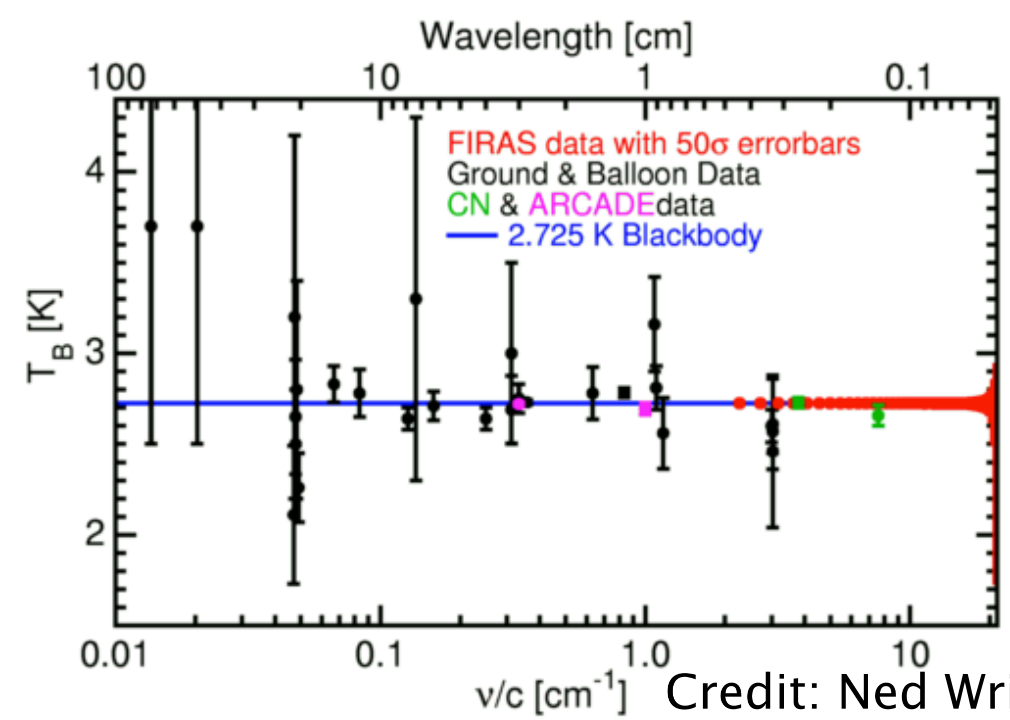
Credit: D. Samtleben



Measured blackbody spectrum of the CMB, with fit to various data

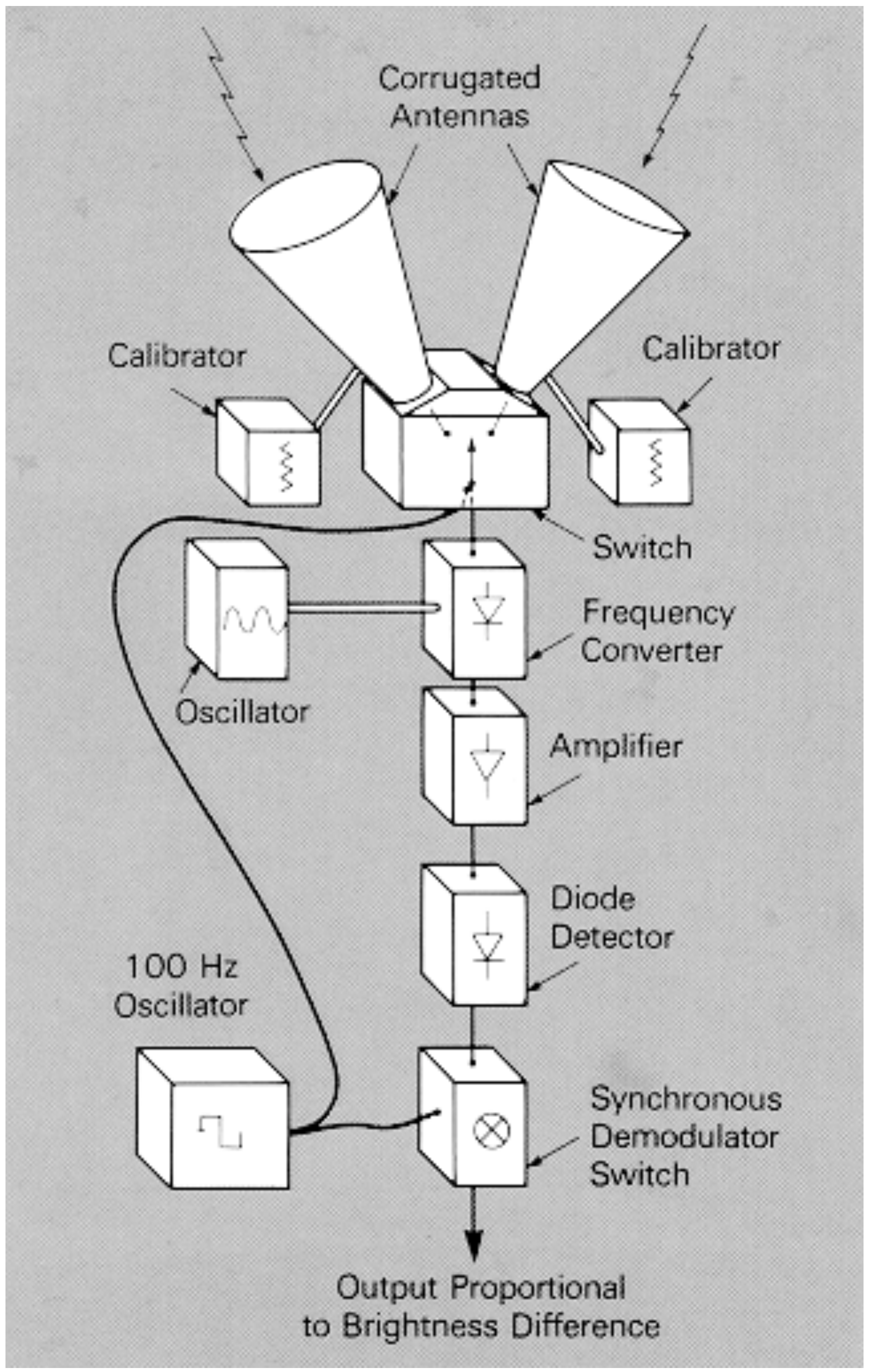
Ground and balloon based experiments have been measuring CMB temperature for decades with increasing precision

but it was realized that one has to go to the stable thermal environment of outer space to get a really accurate measurement (and observe in the Wien part).



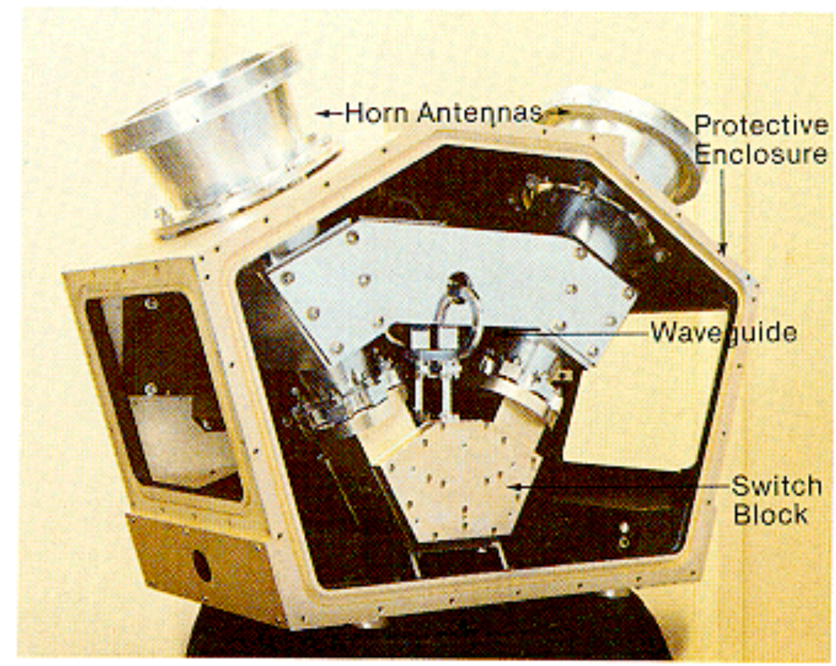
Credit: Ned Wright

DMR on COBE



Credit: NASA

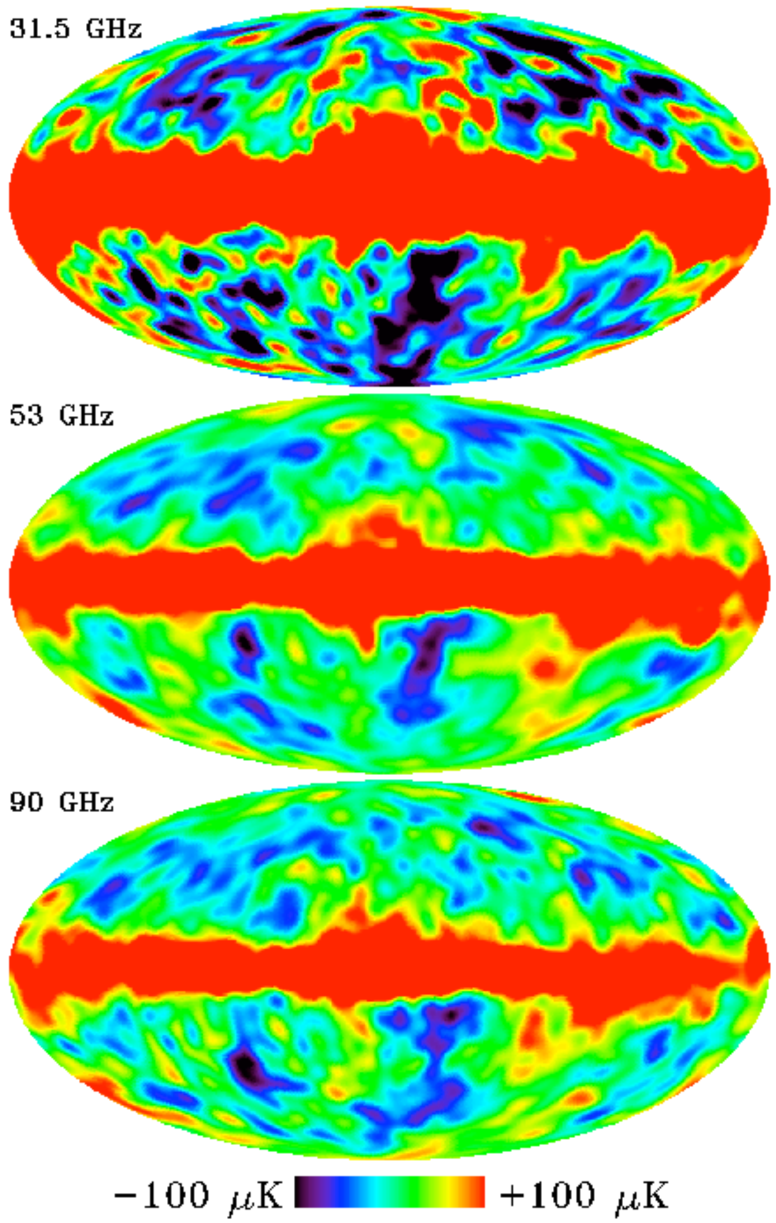
Differential Microwave Radiometer

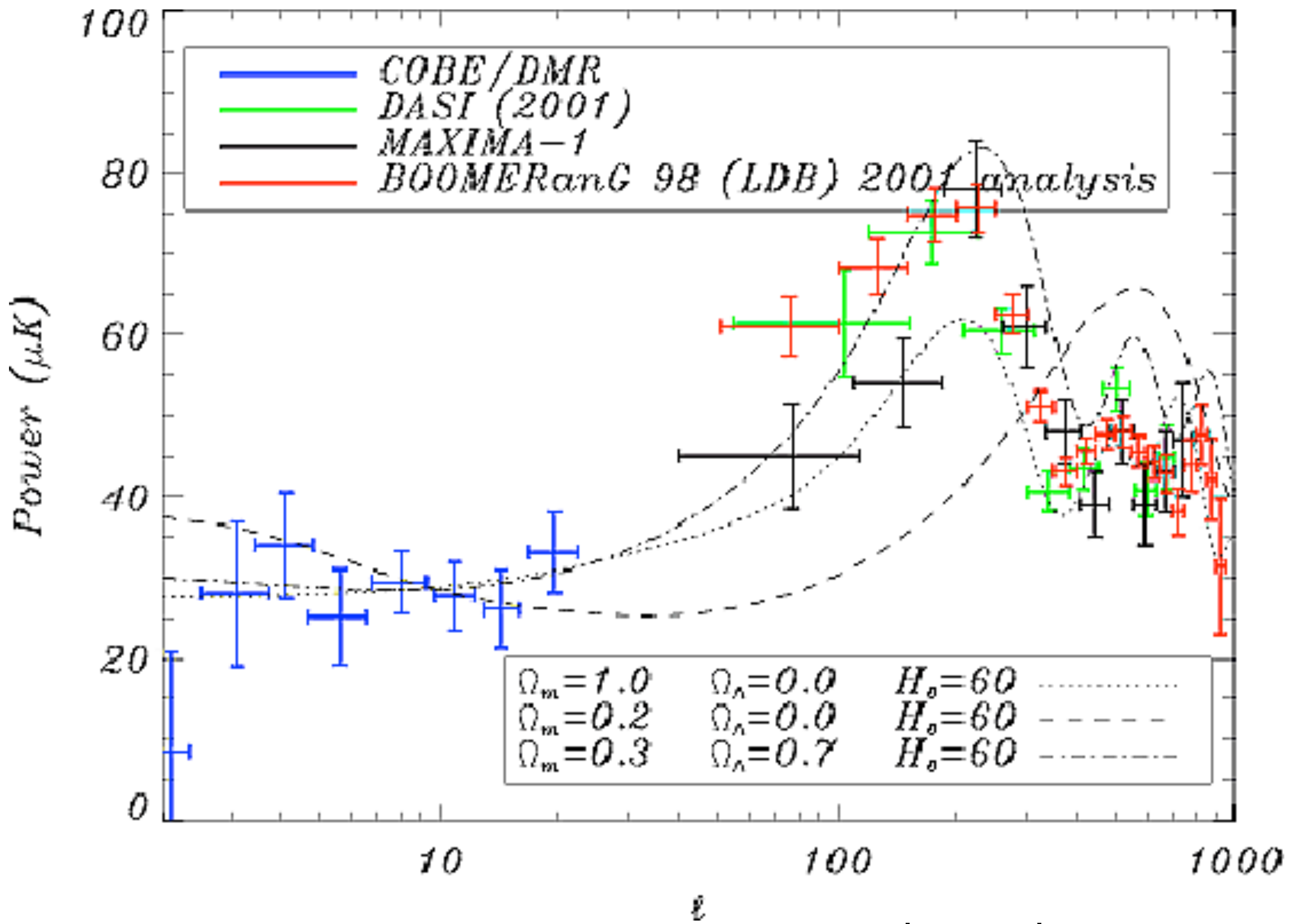


The 9.6 mm DMR receiver partially assembled. Corrugated cones are antennas.

- Differential radiometers measured at frequencies 31.5, 53 and 90 GHz, over a 4-year period
- Comparative measurements of the sky offer far greater sensitivity than absolute measurements

COBE DMR Measurements



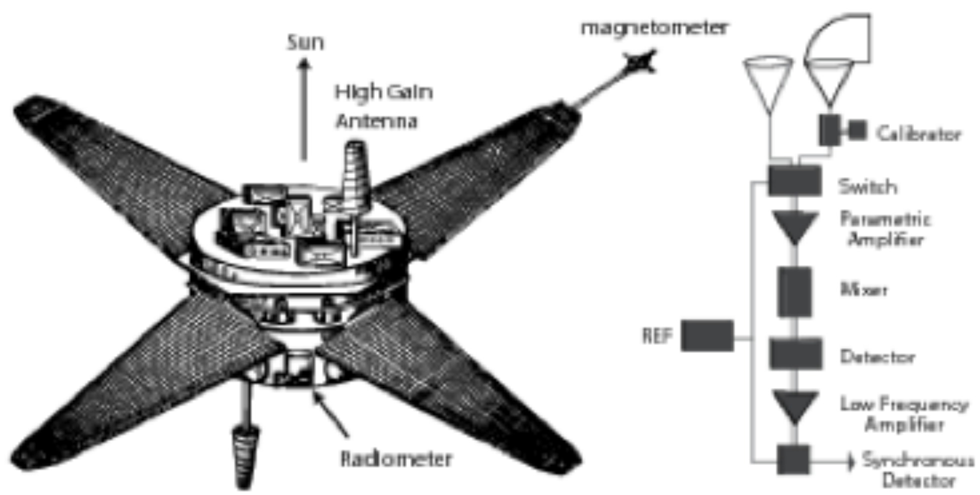


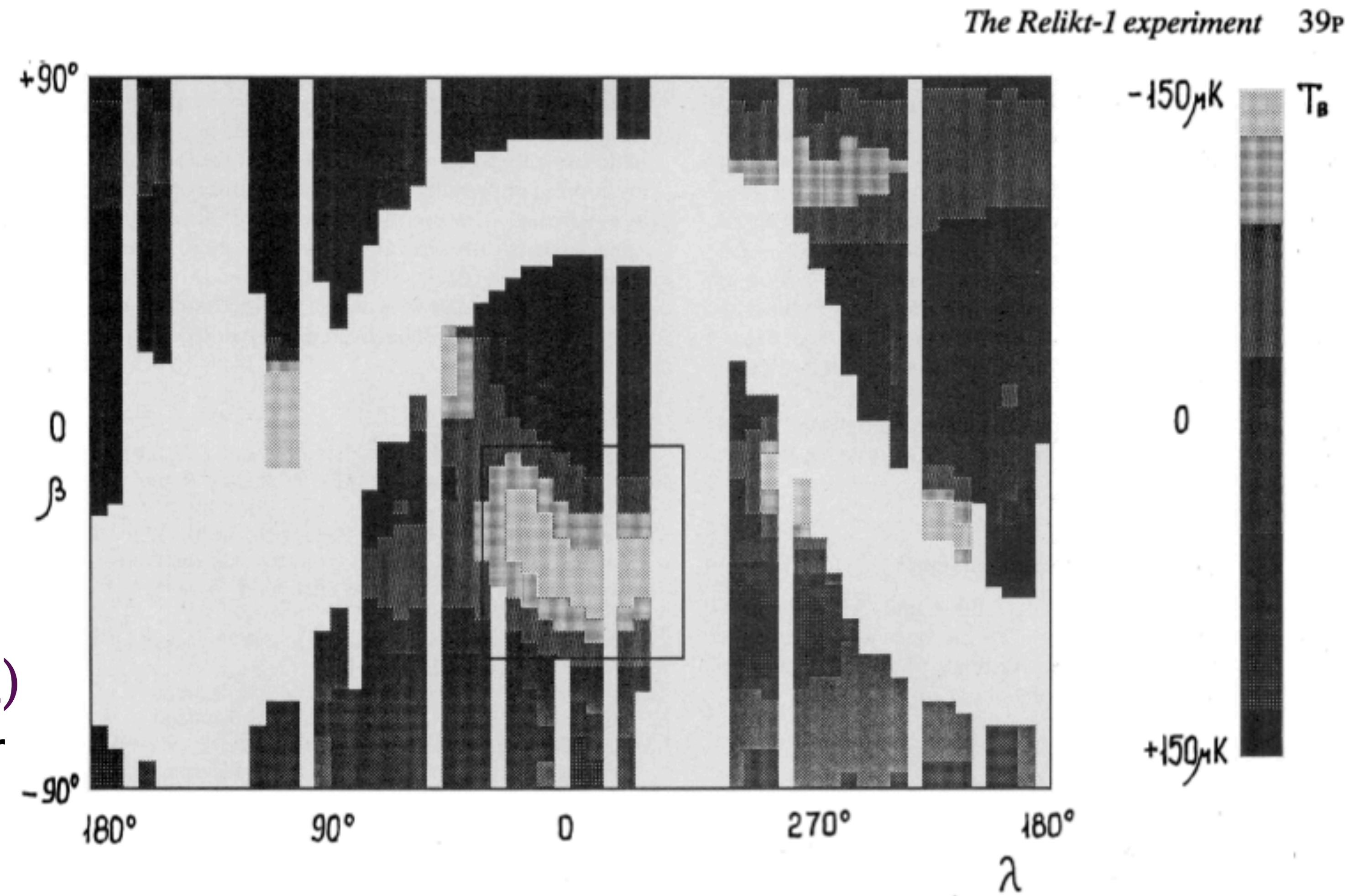
Credit: Archeops team

COBE DMR results
First announced in Smoot et al. (1992)

2006 Nobel Prize in Physics for George Smoot

Relikt-1





Launched July 1983 (6 yr before COBE)
Single frequency (37 GHz) radiometer

Strukov et al. (1992)

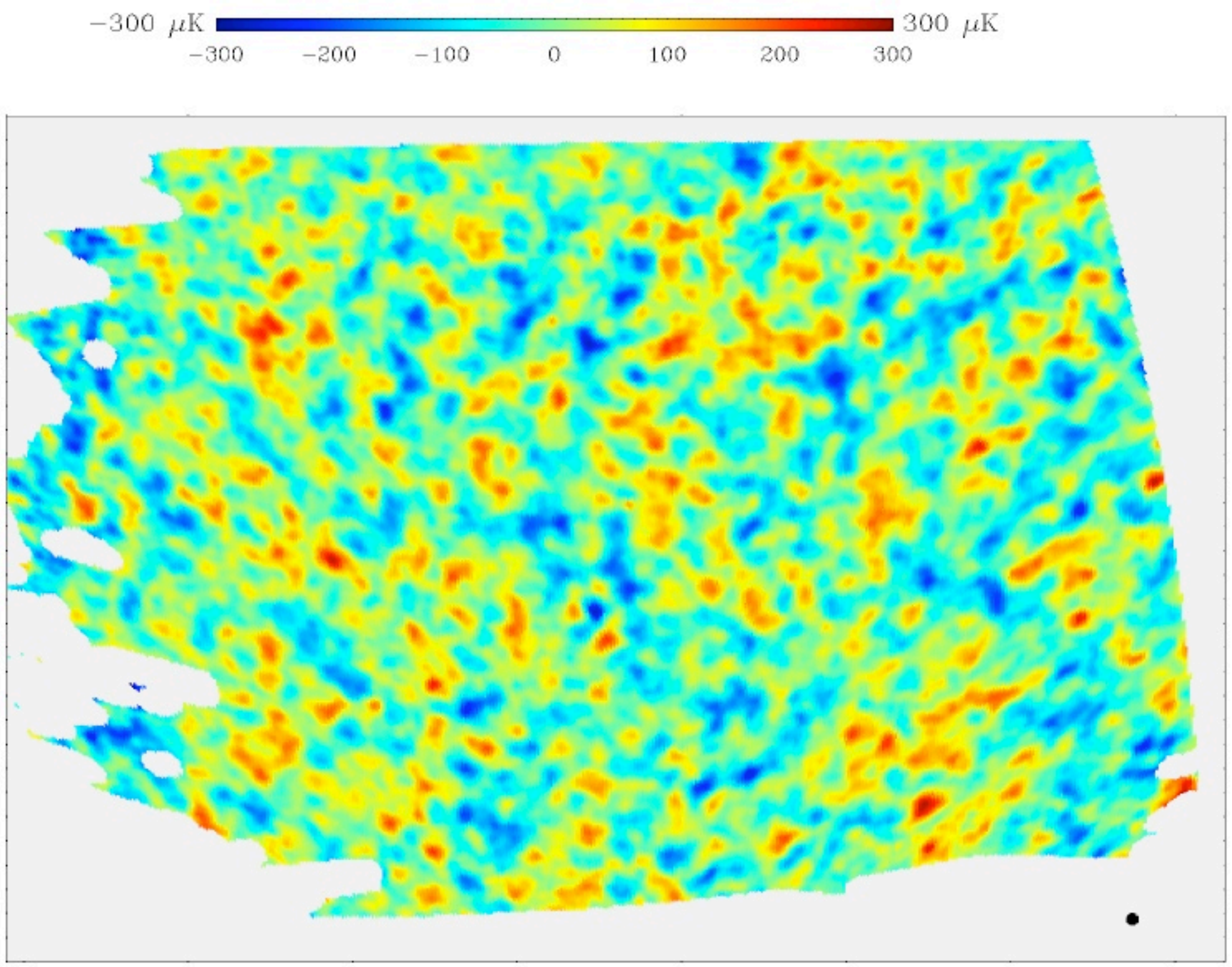
Analysis seriously delayed by the breakup of the USSR..

A 1992 paper reported a temperature decrement of
−71 ± 43 μK at large angles at 90% confidence,
including systematics.

Anisotropies seen by BOOMERANG

Boomerang launch Dec 1998

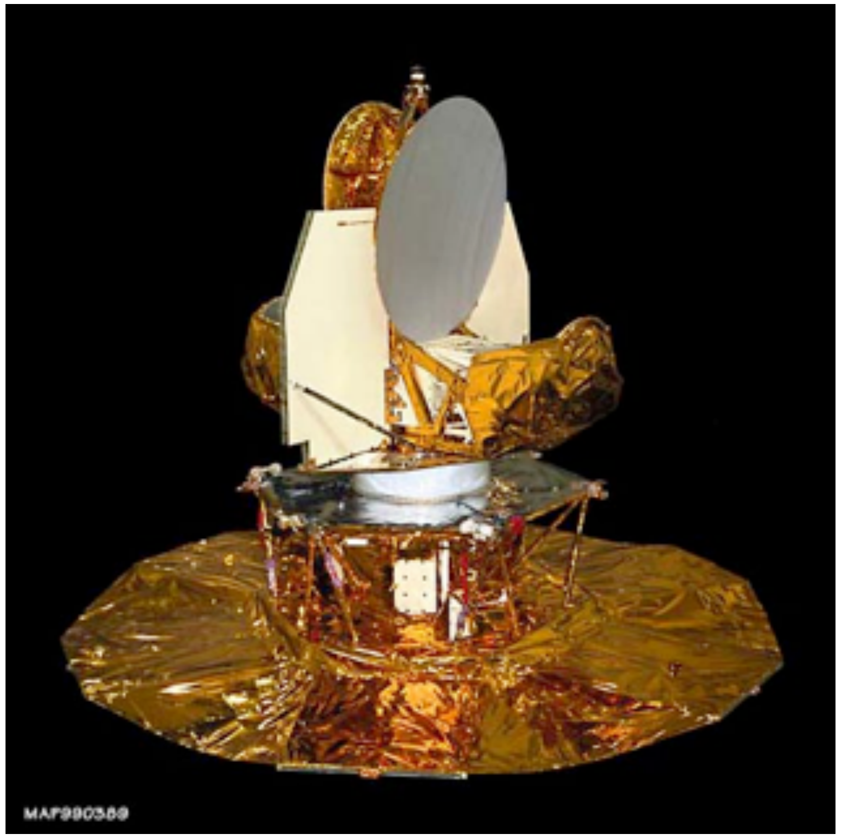
(Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics)



Flight: 10 days
1800 deg^2
3 % of the Sky
Resolution 0.2°

WMAP: 2001–2010

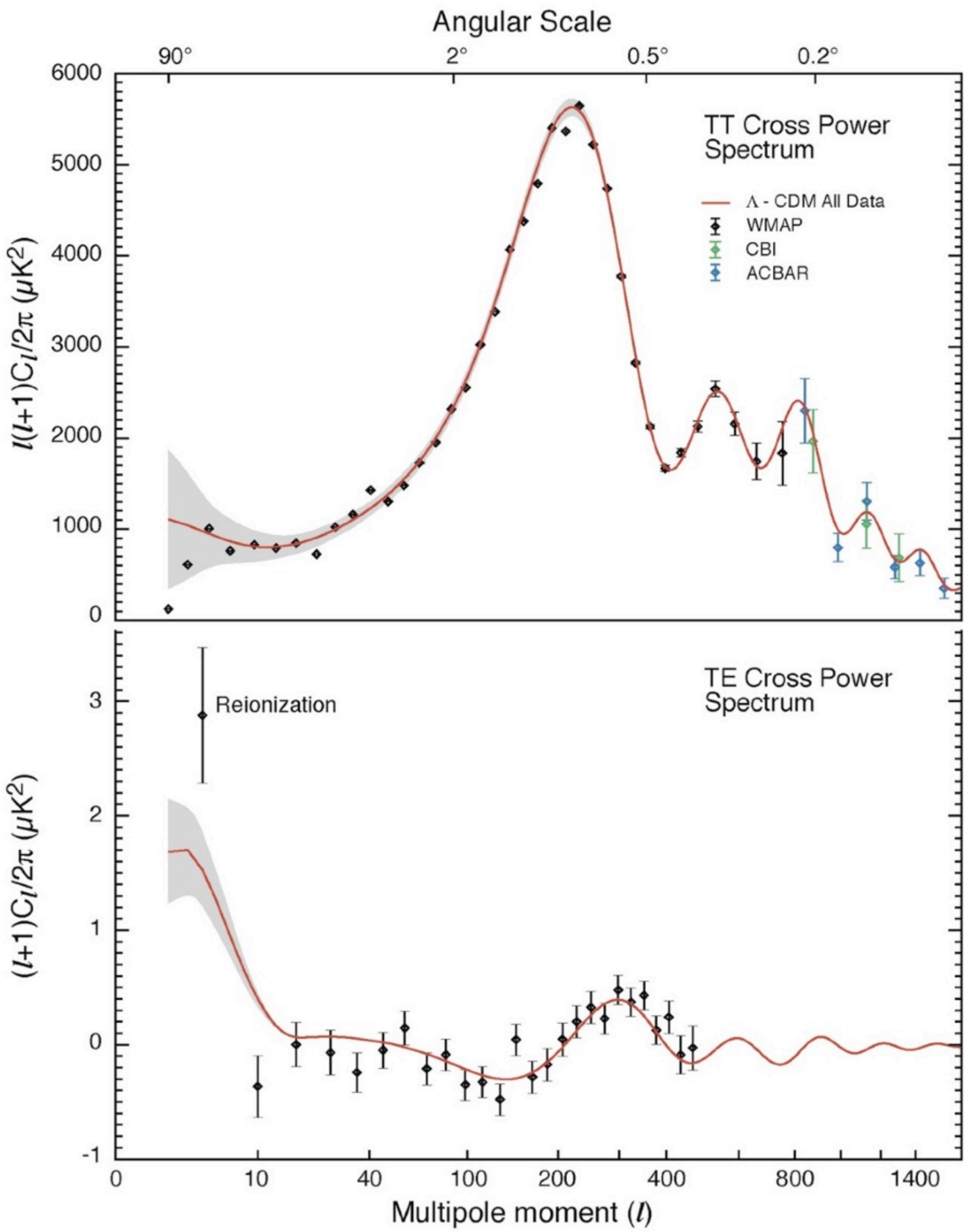
Credit: NASA



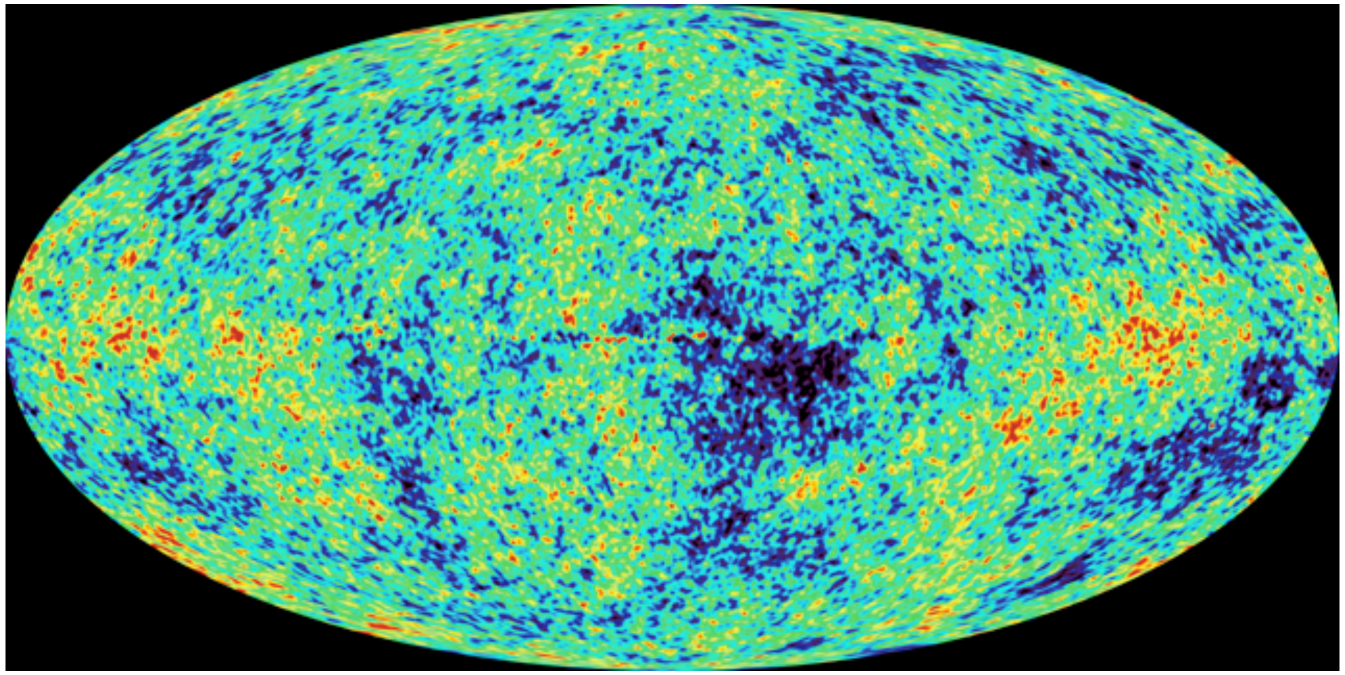
Note the same dual receivers as COBE. This design, plus the very stable conditions at the L2, minimizes the "1/f noise" in amplifiers and receivers.

Thus after 7 years, the data could still be added and noise lowered (of course, the improvement gradually diminishes).

WMAP results after 1st year



(Credit: WMAP Science Team)



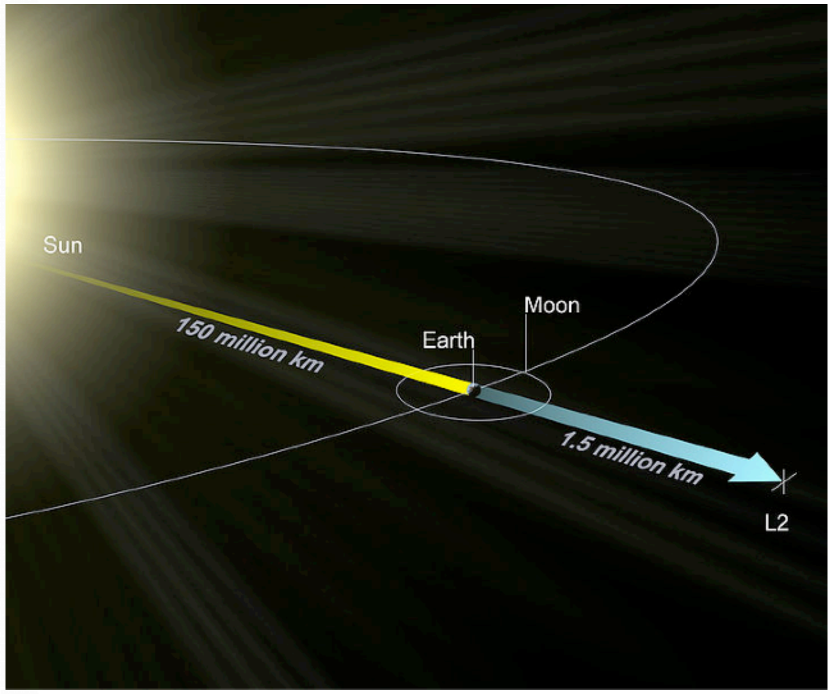
Internal Linear Combination map

Planck satellite (2009–2013)

Credit: ESA

PLANCK launch: May 2009

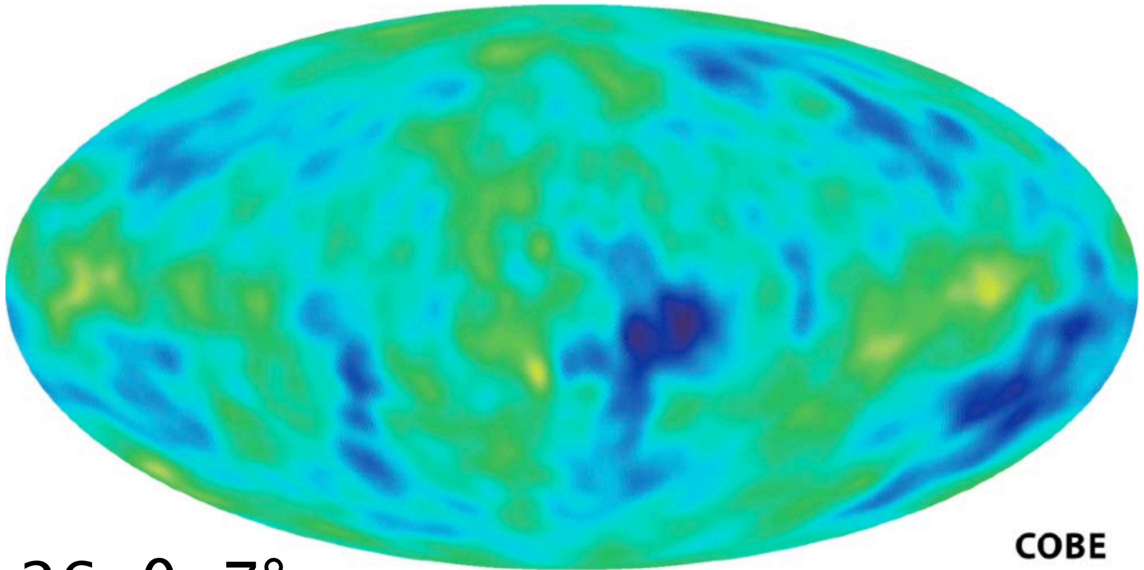
Credit: ESA



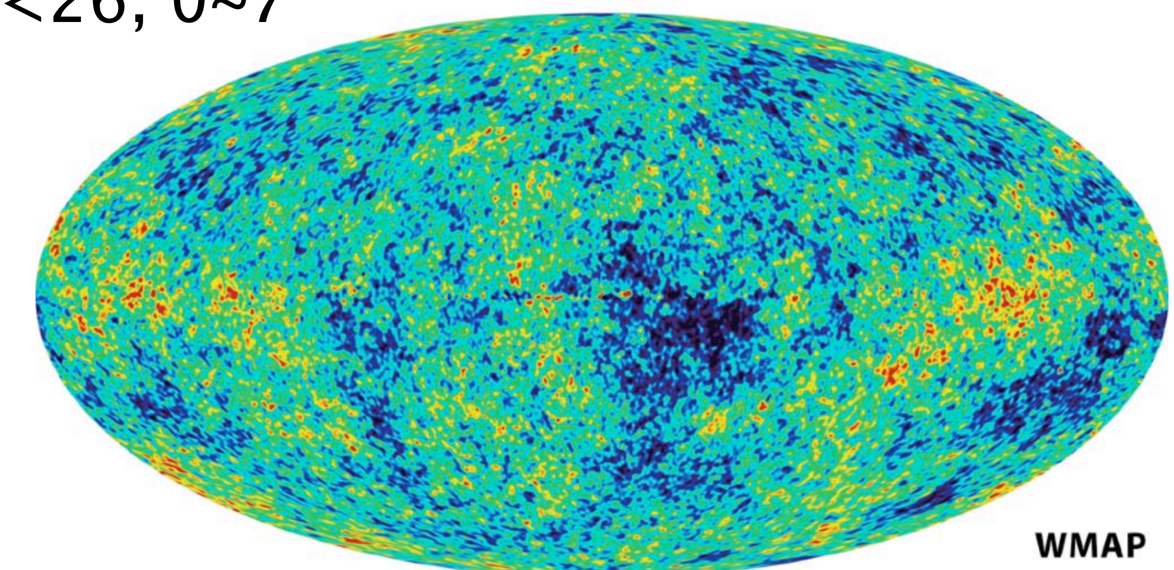
Destination L2: the second Lagrangian point

(getting crowded there!)

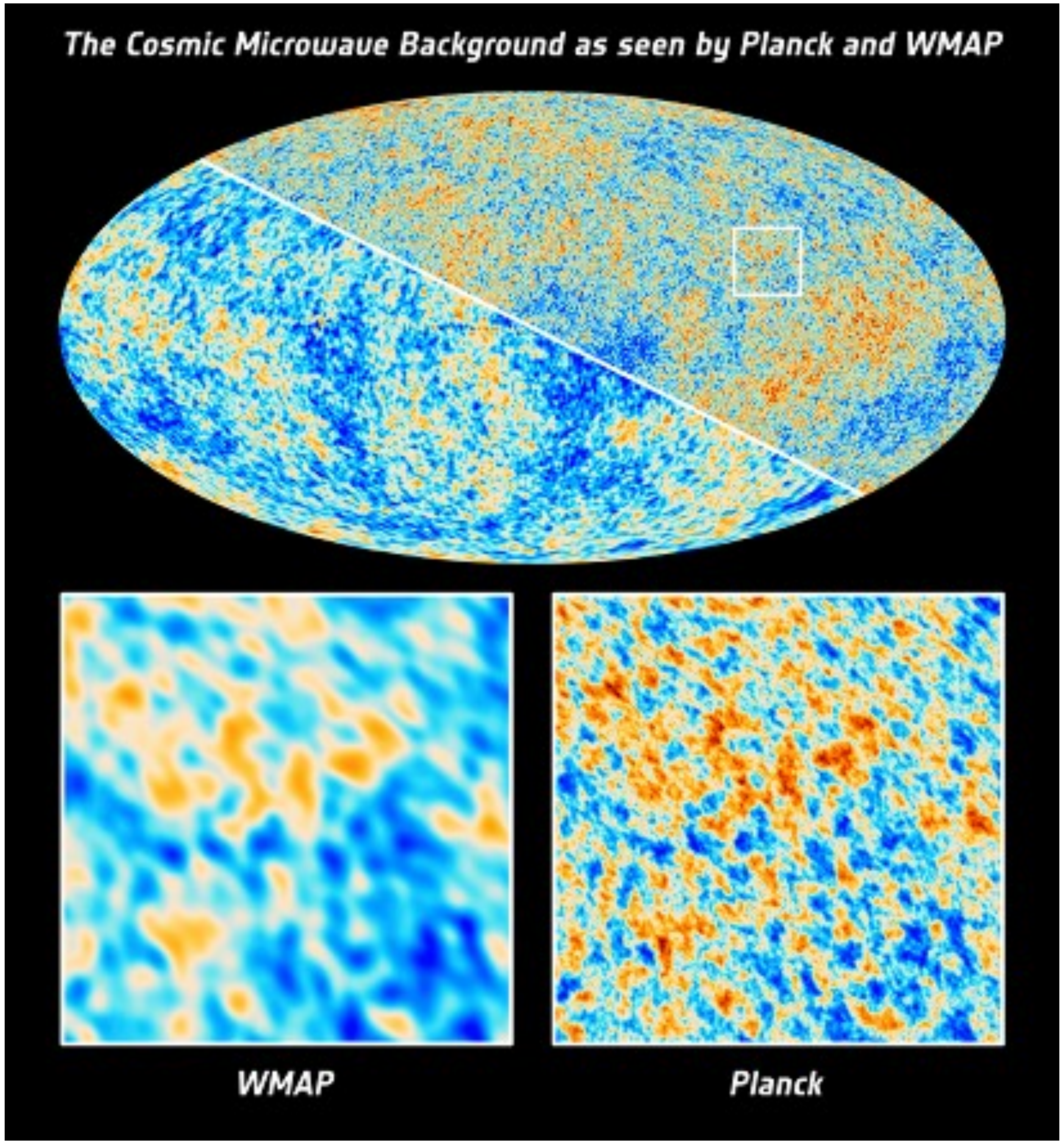
Planck transforming the CMB science



l<26, θ~7°

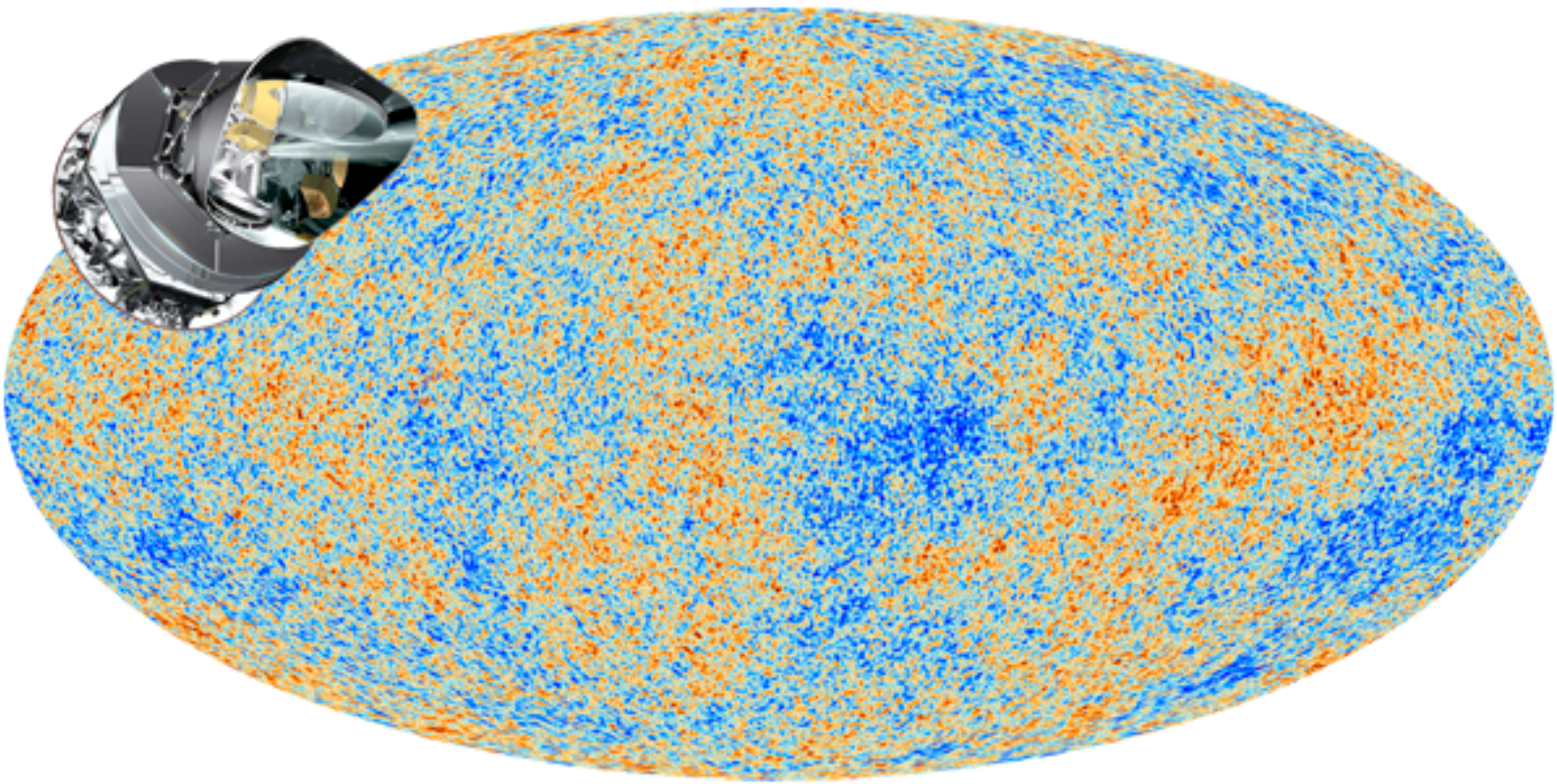


l<780, θ~0.2°



l<2160, θ~0.1°

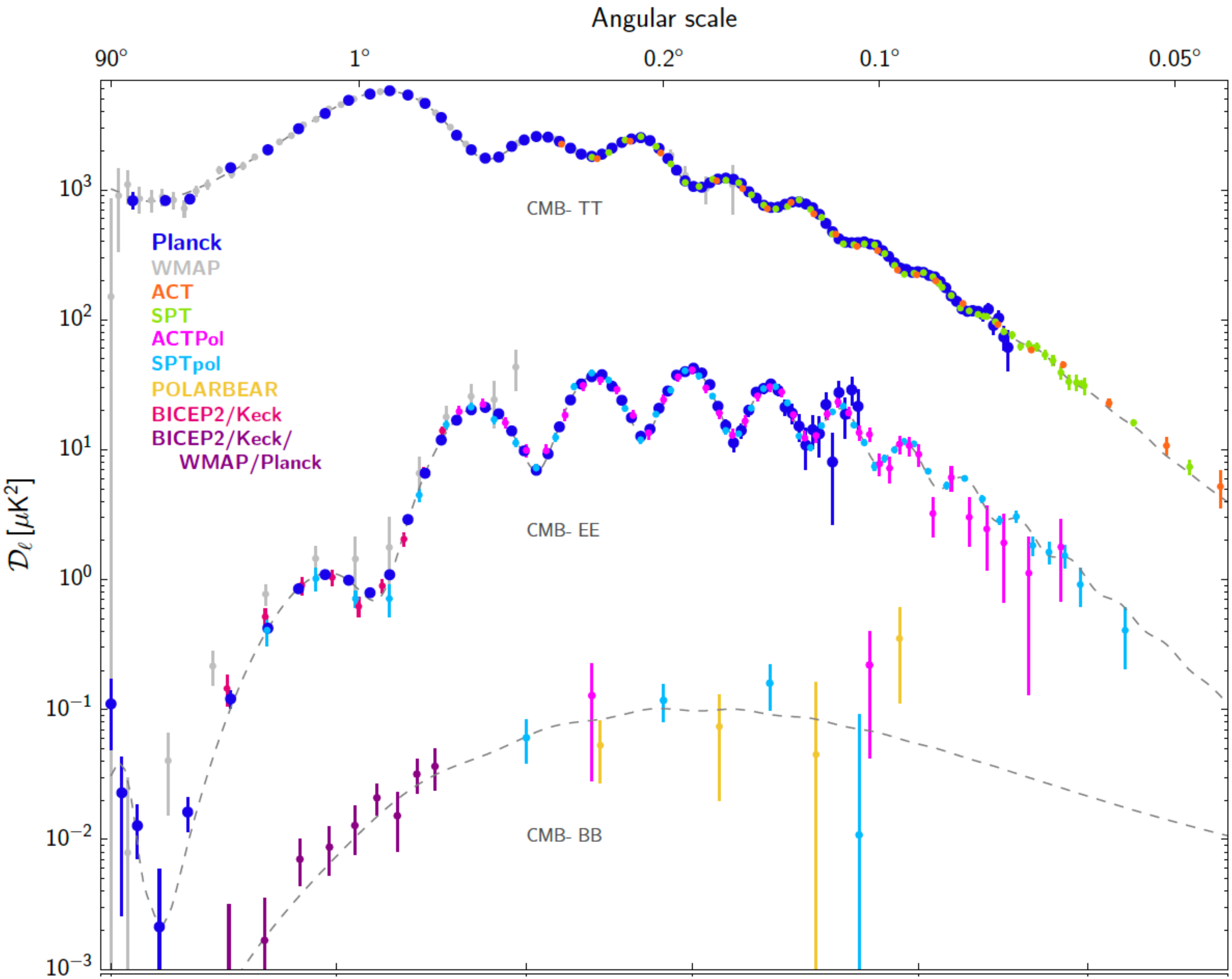
CMB sky seen from Planck

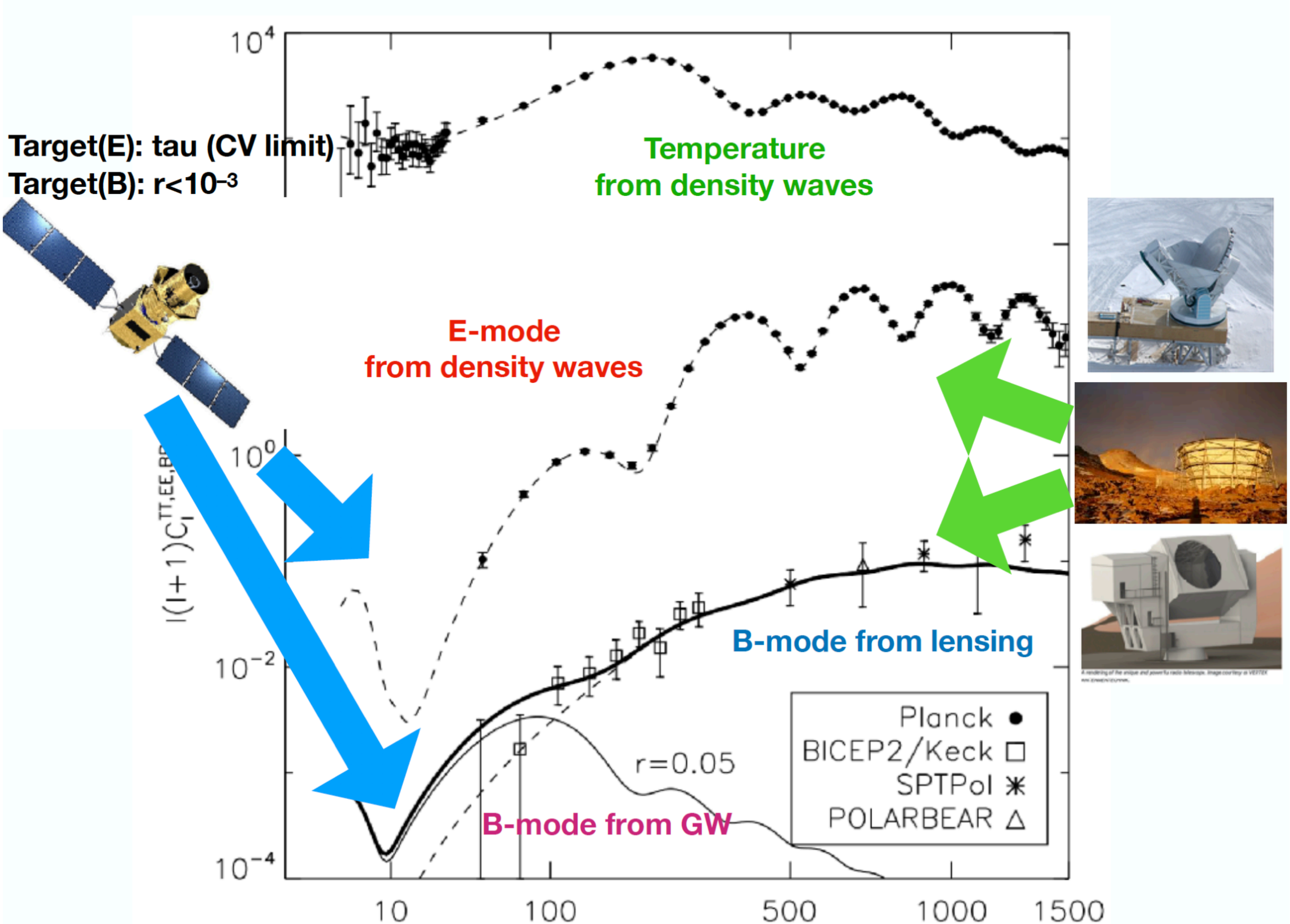


Measurement from Planck, dipole and Galaxy subtracted.

We learned in the last lecture how to do science from this 2D map.

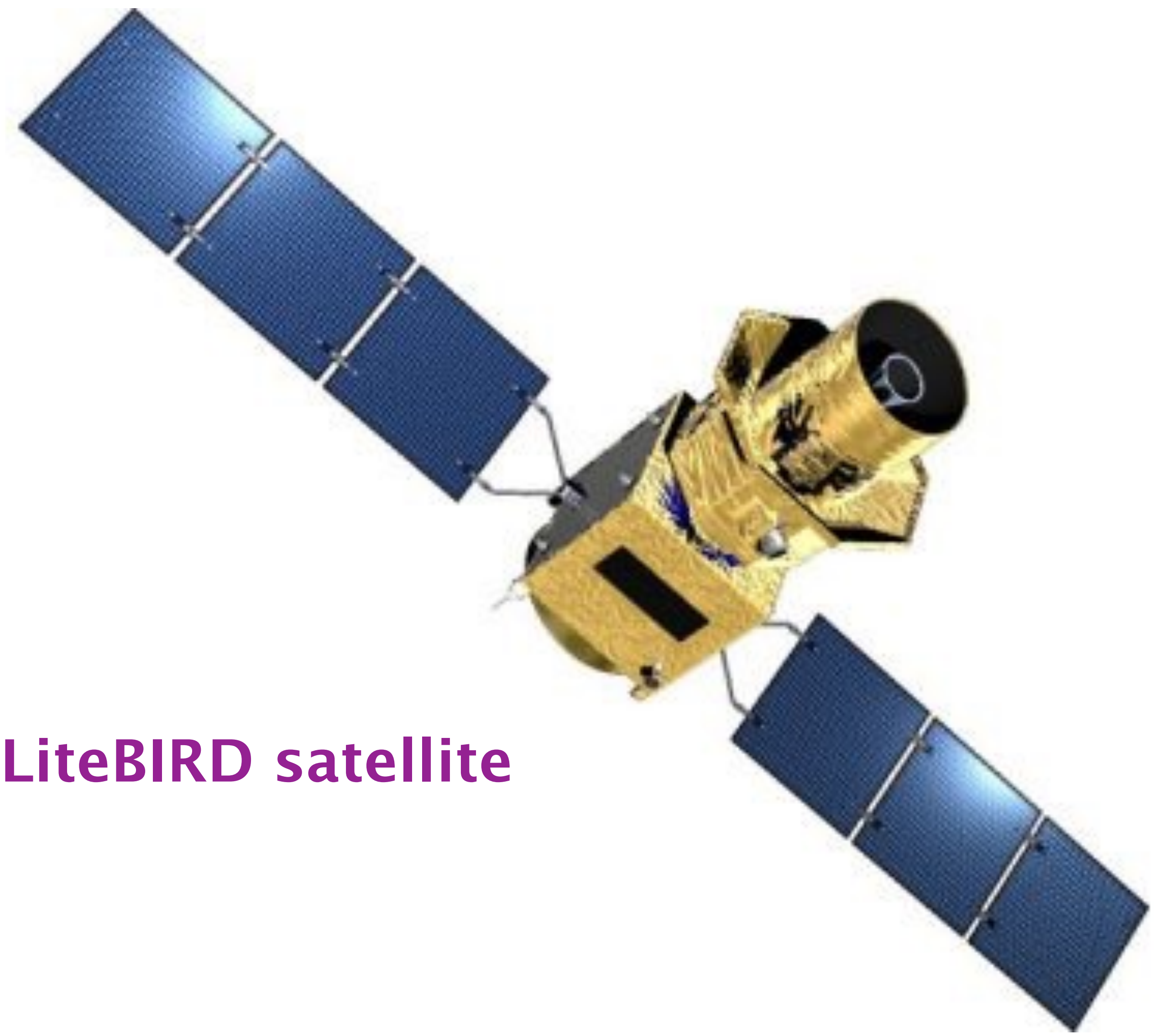
CMB state-of-the-art, mid-2018



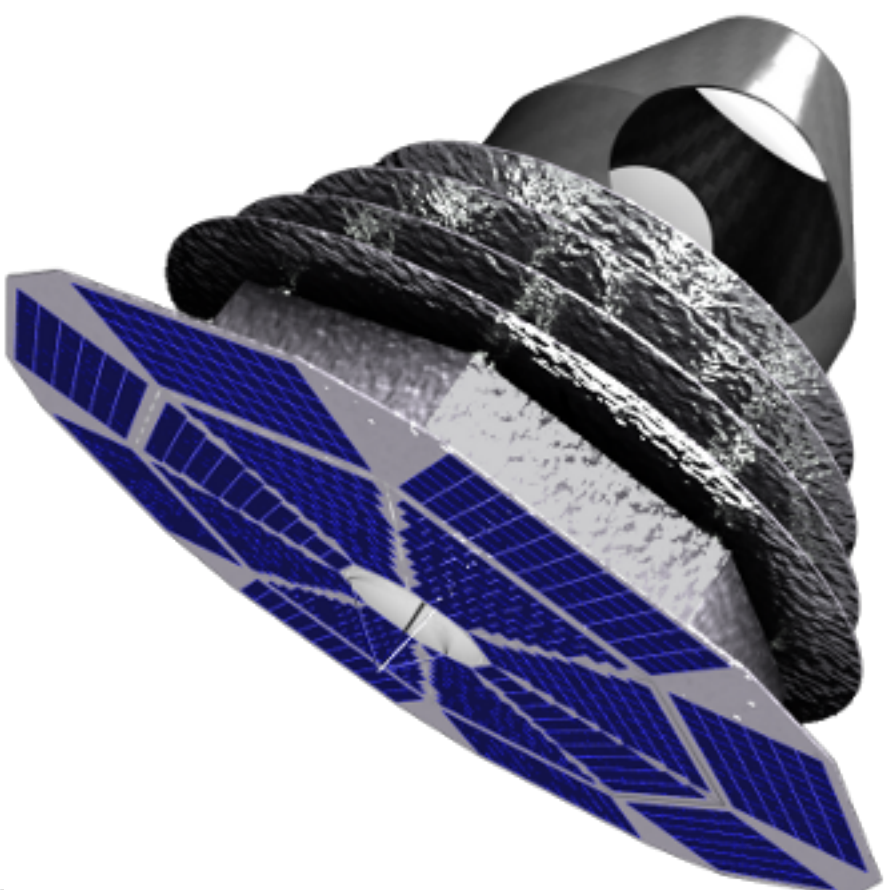


Slide courtesy: E. Komatsu

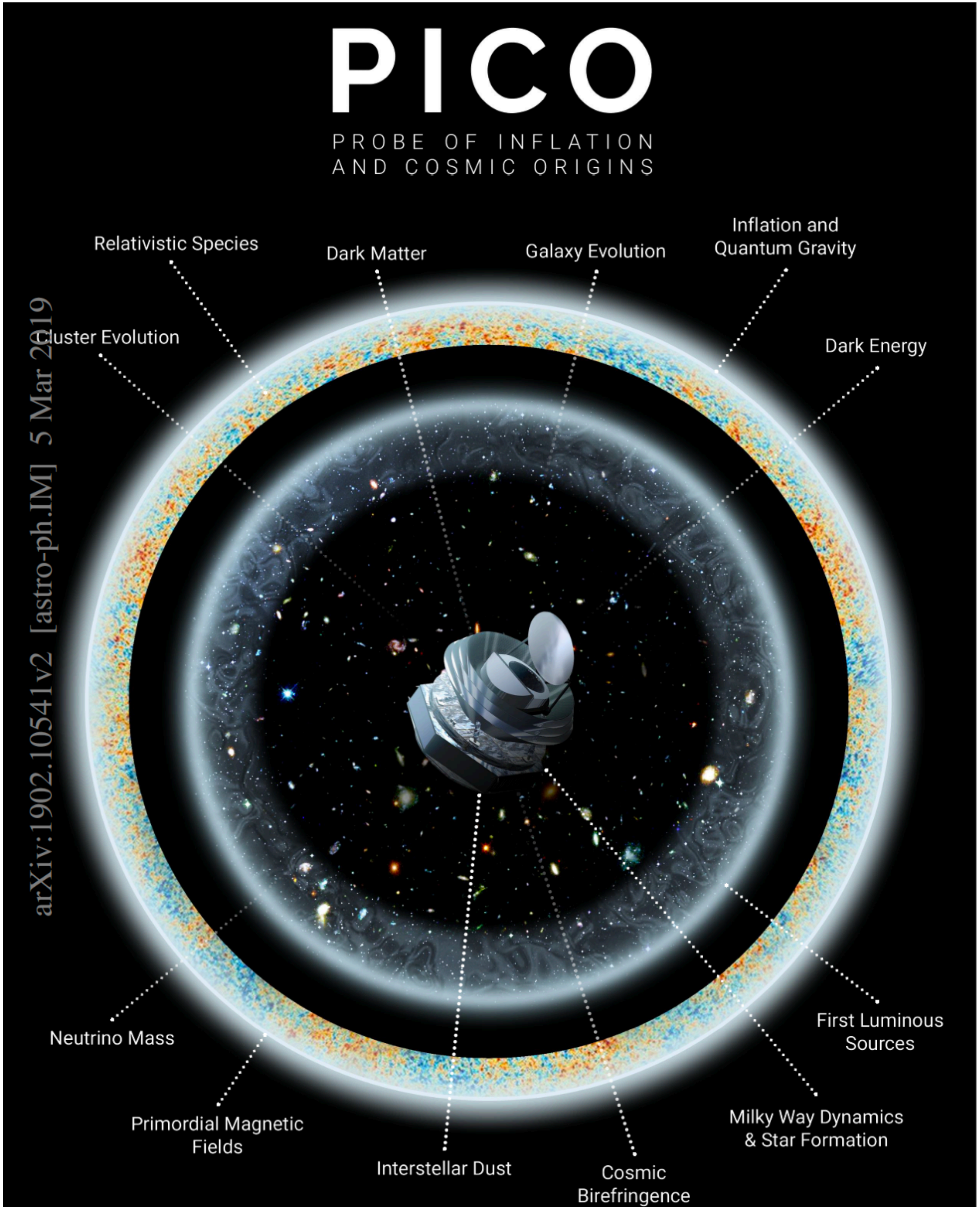
Future space-missions/concepts



LiteBIRD satellite



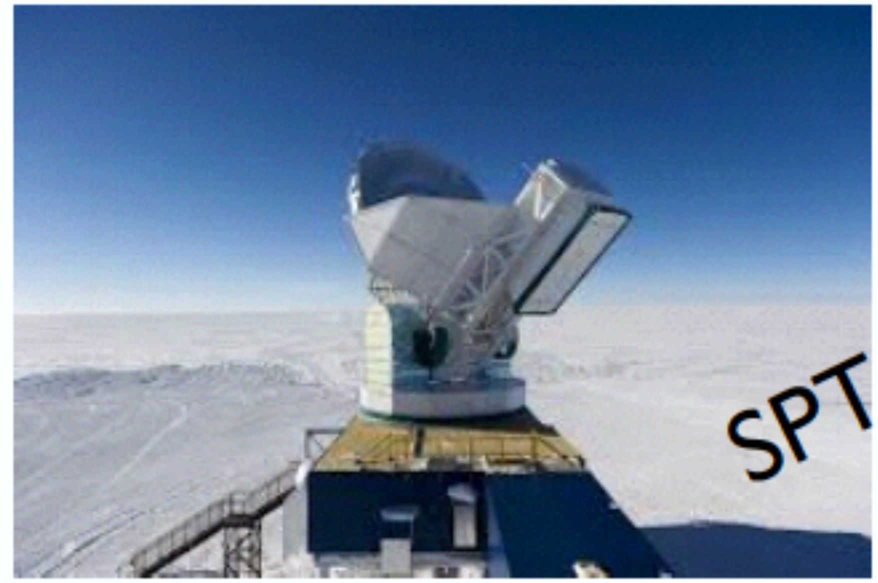
Cosmic Origins Explorer (COrE)



Science Goals (from NASA Science Plan)	Science Objectives
Explore how the Universe began: Inflation	**SO1**. Probe the physics of the big bang by detecting the energy scale at which inflation occurred if it is above 5×10^{15} GeV, or place an upper limit if it is below (§ 2.2.1, Fig. 2.1)
	SO2. Probe the physics of the big bang by excluding classes of potentials as the driving force of inflation (§ 2.2.1, Fig. 2.2)
Discover how the Universe works: neutrino mass and N_{eff}	**SO3**. Determine the sum of neutrino masses. (§ 2.2.2, Fig. 2.5)
	SO4. Tightly constrain the thermalized fundamental particle content of the early Universe (§ 2.2.2, Fig. 2.4)
Explore how the Universe evolved: reionization	**SO5**. Distinguish between models that describe the formation of the earliest luminous sources in the Universe (§ 2.3, Fig. 2.6)
Explore how the Universe evolved: Galactic structure and dynamics	**SO6**. Test models of the composition of Galactic interstellar dust (§ 2.5.1)
	SO7. Determine if magnetic fields are the dominant cause of low Galactic star-formation efficiency (§ 2.5.2)

Several new experiments

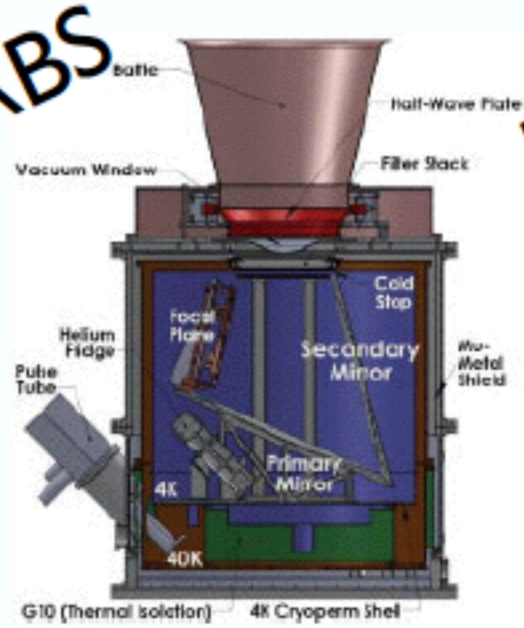
ACTpol



SPTpol

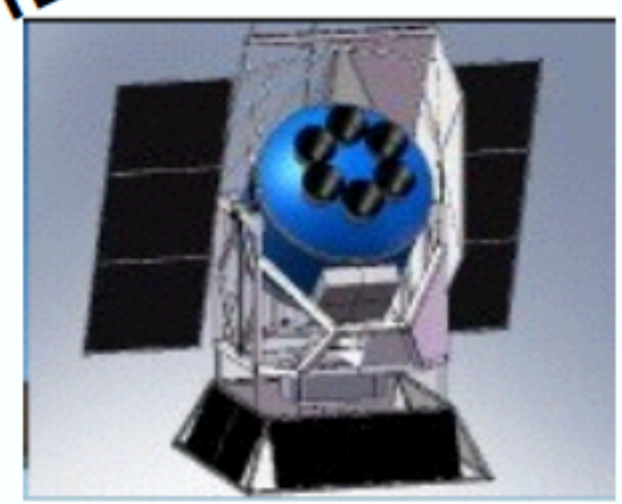
Have broad science range

ABS



Polarbear

SPIDER



Dedicated to r

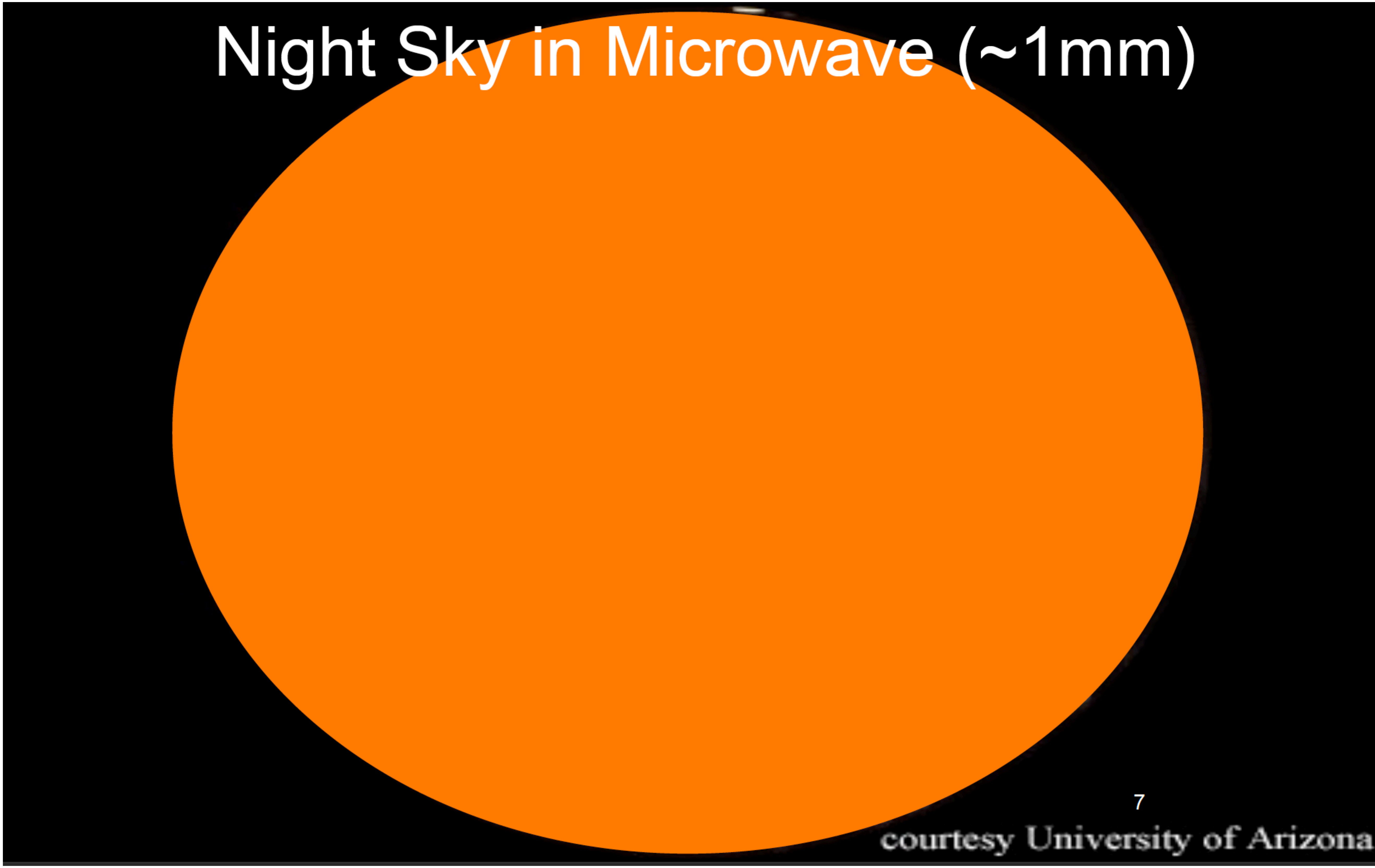
Several new experiments

Goal is to constrain the value of r < 0.1 %

https://www.simonsfoundation.org/series/the-eternal-sky/

Part 2:

The Blackbody (Thermal) Spectrum of the CMB


Night Sky in Microwave (~1mm)
7
courtesy University of Arizona

First evidence of blackbody spectrum

COSMIC BACKGROUND RADIATION AT 3.2 cm – SUPPORT FOR COSMIC BLACK-BODY RADIATION*

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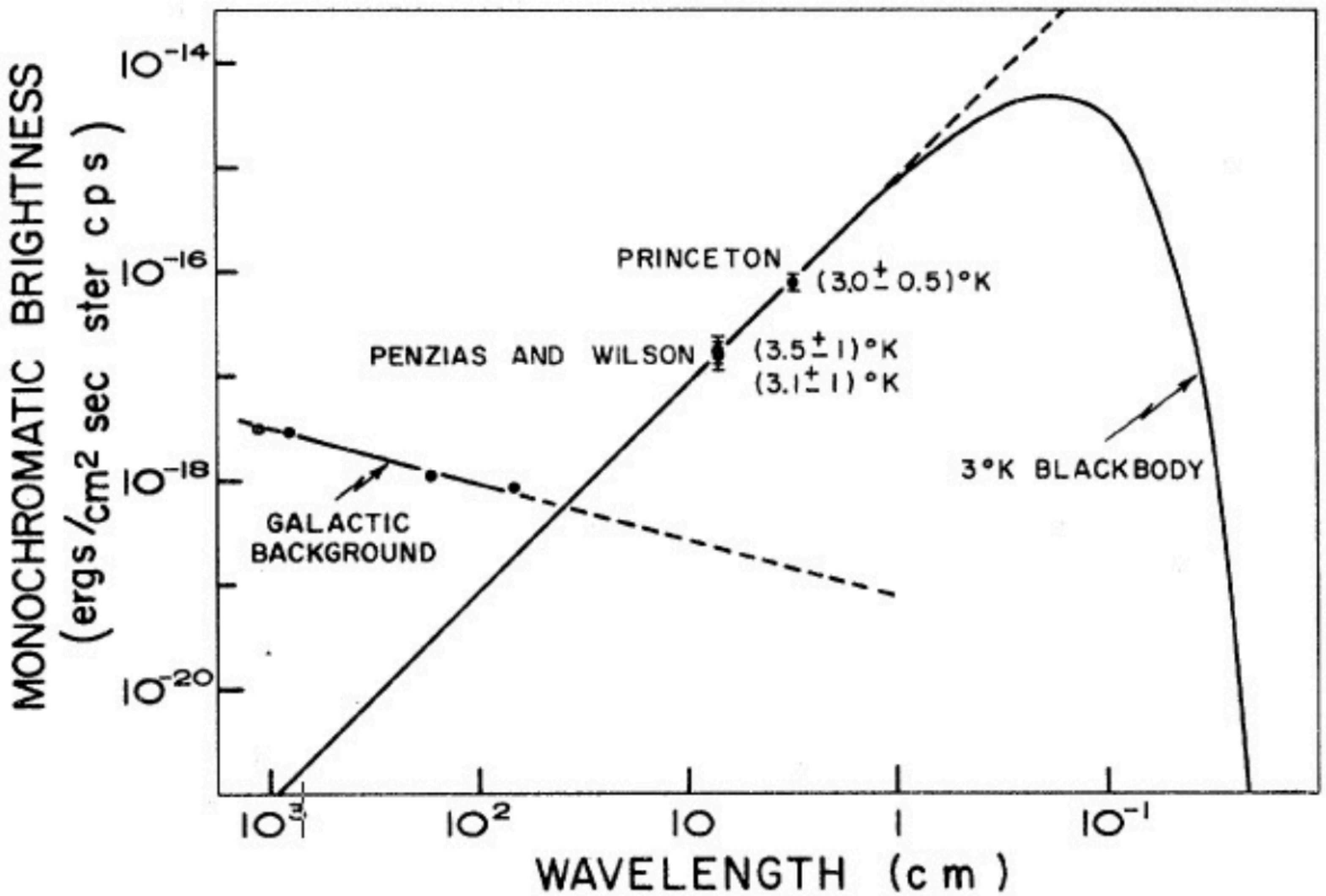
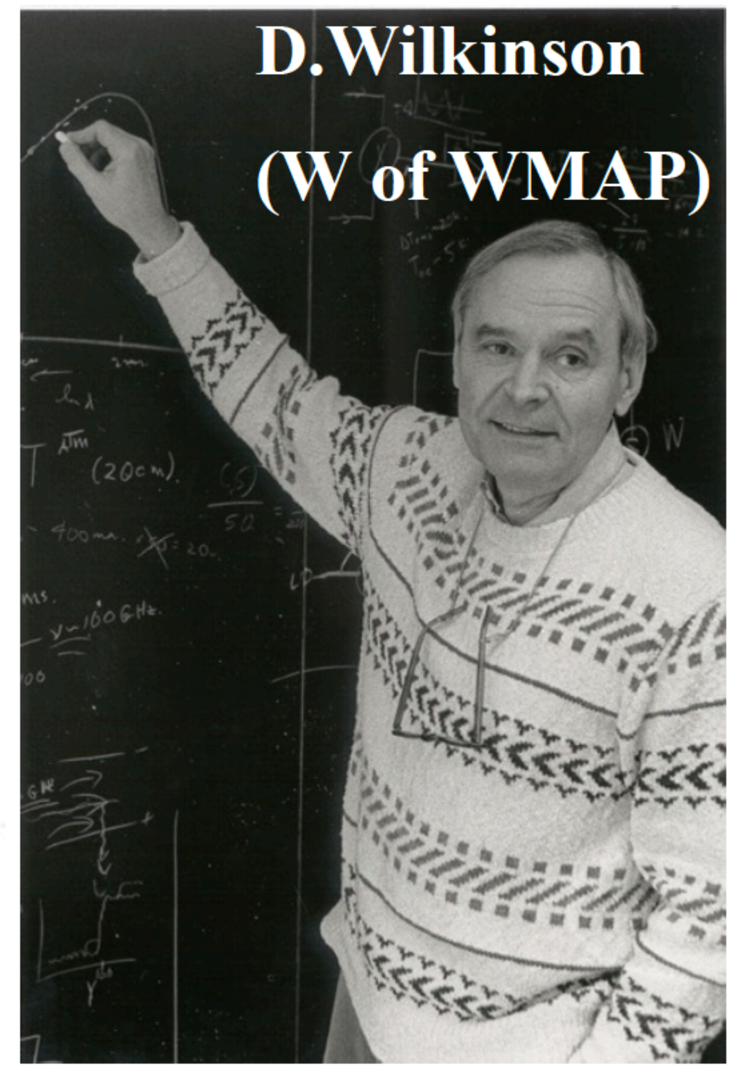
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received 27 January 1966)





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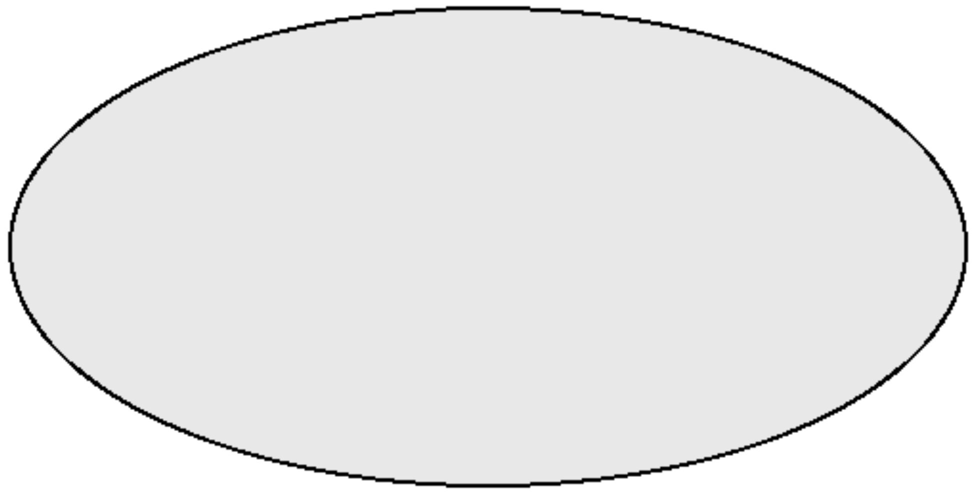
Recombination temperature & redshift



CMB temperature map on a scale of 0 K (black) to 3 K (white), made by Ned Wright

The temperature of last scattering depends very weakly on the cosmological parameters (weaker than logarithmically).

It is mainly determined by the ionization potential of hydrogen and the baryon-to-photon ratio.

$n_e \sim 500\ \mathrm{cm}^{-3}$ (roughly same as Galactic HII regions)

$$T_e = T_r = 2970\ \mathrm{K} = 0.26\ \mathrm{eV}$$

$$z_r = T_r/T_{CMB} - 1 = 1090$$

Why is it so low compared to the ionization potential of hydrogen, 13.6 eV?

Recombination temperature & redshift

›the CMB number density dominates over that of baryons by ~10^9. (valid for all times).

$$\eta \equiv n_b/n_\gamma = 5.4 \times 10^{-10} \left(\frac{\Omega_b h^2}{0.02}\right)$$

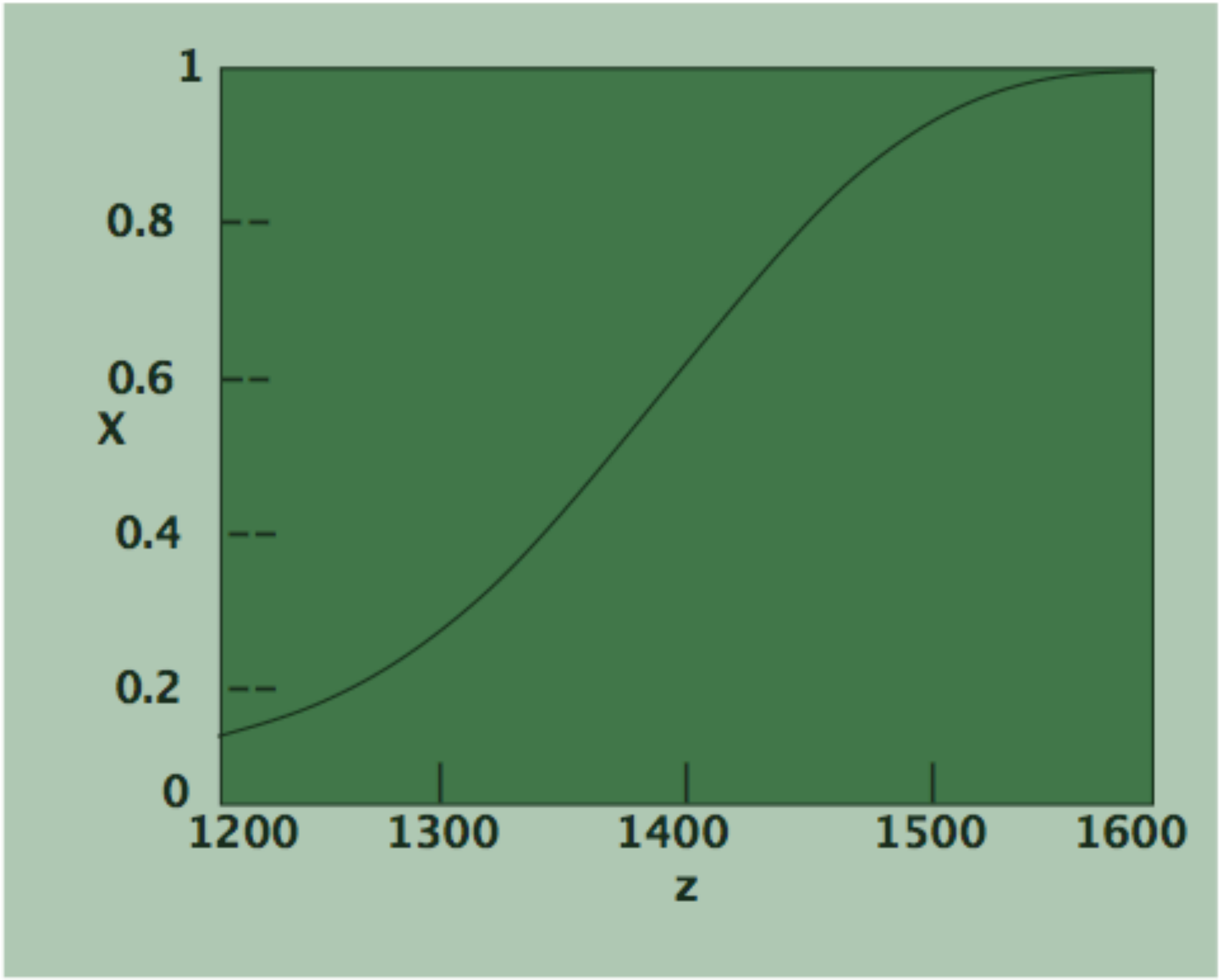
This ratio implies that recombination occurs at substantially lower temperature than the binding energy **B = 13.6 eV** of the Hydrogen atom, at **T ≈ 0.3 eV** only, or at a redshift of $z_* \approx 10^3$.

This follows from Saha's ionization equilibrium equation, which in terms of ionization fraction X (since $n_e = n_p$) and photon-to-baryon ratio η reads as

$$\boxed{\frac{1-X}{X^2} = 3.84\eta\left(\frac{kT}{m_e c^2}\right)^{3/2} \exp\left(\frac{Q}{kT}\right) = S, \quad X = \frac{-1+\sqrt{1+4S}}{2S}}$$

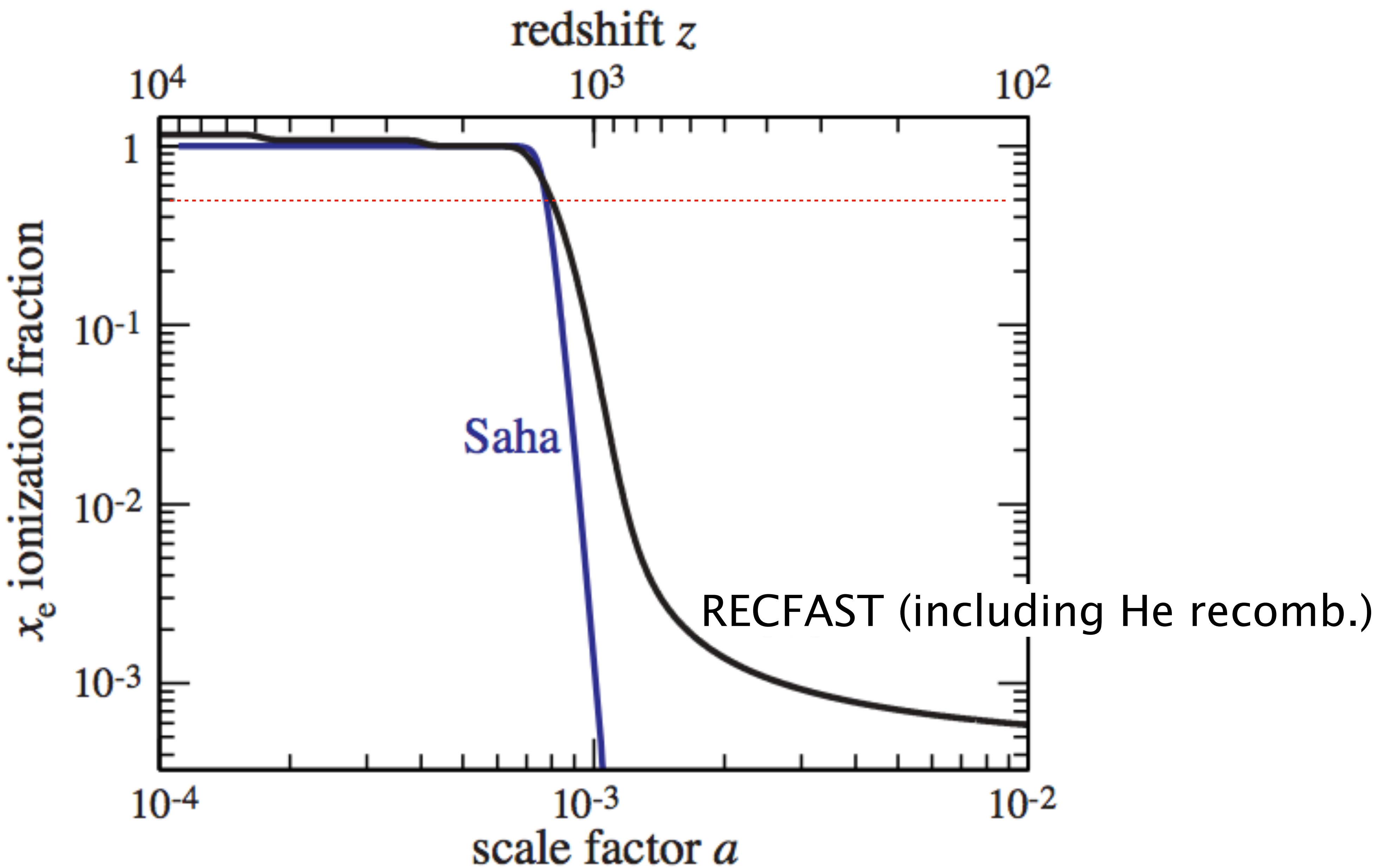
Recombination temperature & redshift

$$\boxed{\frac{1-X}{X^2} = 3.84\eta\left(\frac{kT}{m_e c^2}\right)^{3/2} \exp\left(\frac{Q}{kT}\right)}$$



Once $Q_{13.6\ eV}/T_b$ reaches a certain level, recombination proceeds rapidly.
If we define the moment of recombination when $\chi = 1/2$, we get

$$\boxed{kT_{rec} = 0.323\, eV \Rightarrow T_{rec} = 3740\,K, \quad 1 + z_{rec} = \frac{1}{a_{rec}} = \frac{T_{rec}}{T_{CMB,0}} = \frac{3740\,K}{2.73\,K} \approx 1371}$$



In the above plot, hydrogen recombination in Saha equilibrium is shown against more precise numerical calculation with RECFAST (recombination is aided by the H-atom 2s→1s two-photon decay). The features seen before hydrogen recombination are due to helium recombination.

Recombination is not an instantaneous process, but nevertheless proceeds rapidly (χ=0.9 to χ=0.1 in a time interval Δt=70,000 y). Its redshift is practically independent of the standard cosmological parameters.

Epoch of decoupling

The photon Thomson scattering rate is controlled by how many electrons are available. The scattering rate Γ is thus a function of ionization fraction:

$$\Gamma = \frac{c}{\lambda} = n_e(z)\sigma_e c = X(z) n_{B,0}(1+z)^3 \sigma_e c = 4.4 \times 10^{-21} X(z)(1+z)^3 s^{-1}$$

For free streaming of electrons, this scattering rate should at least be of the order of Hubble time, H(z). Now recombination and photon decoupling takes place in the matter dominated era, so from Friedmann equation:

$$\frac{H^2}{H_0^2} = \frac{\Omega_{m,0}}{a^3} = \Omega_{m,0}(1+z)^3 \Rightarrow H = 1.24 \times 10^{-18}(1+z)^{3/2}$$

Setting $\Gamma \sim H$ (condition for photon free streaming), we get

$$1 + z_{dec} = \frac{43.0}{X(z_{dec})^{2/3}} \Rightarrow z_{dec} = 1130$$

Actually, when $\Gamma \sim H$, the system is not in equilibrium (Saha equation not valid). A more precise calculation yields

$z_{dec} \approx 1100$, $T_{dec} \approx 3000$K, $t_{dec} \approx 380{,}000$ yrs

Epoch of decoupling: Summary

$z_{dec} \approx 1100$

$t_{dec} \approx 380{,}000$ yrs

$T_{dec} = 0.27$ eV

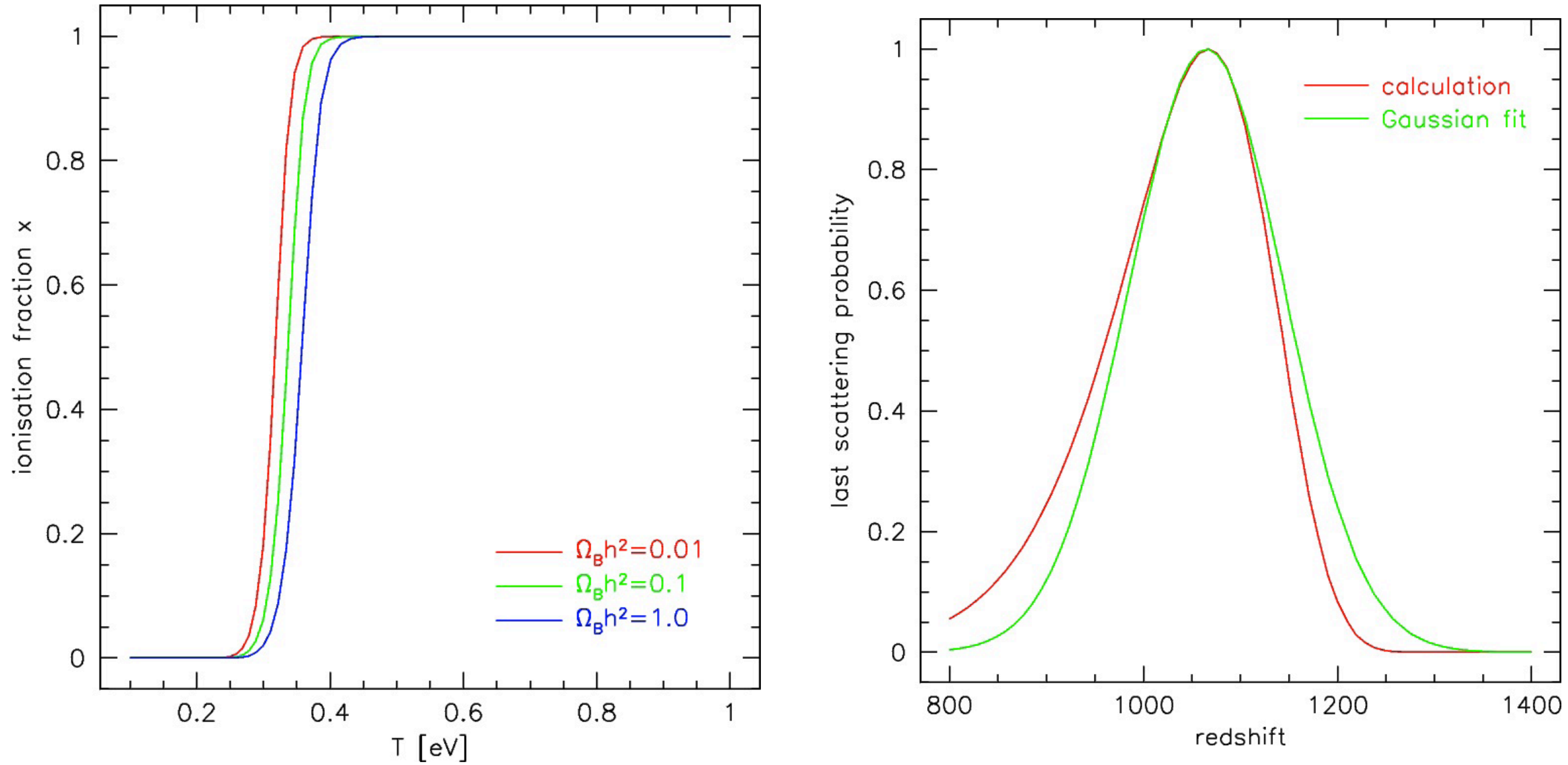
Although z_{dec} isn't far from z_{rec} (roughly $z \approx 1300$), the ionization fraction decreases significantly between recombination and decoupling:

$\chi_e(z_{rec}) \approx 0.5 \rightarrow \chi_e(z_{dec}) \approx 0.1.$

This shows that a large degree of neutrality is necessary for the universe to become transparent to photon propagation.

After decoupling the photons stream freely.

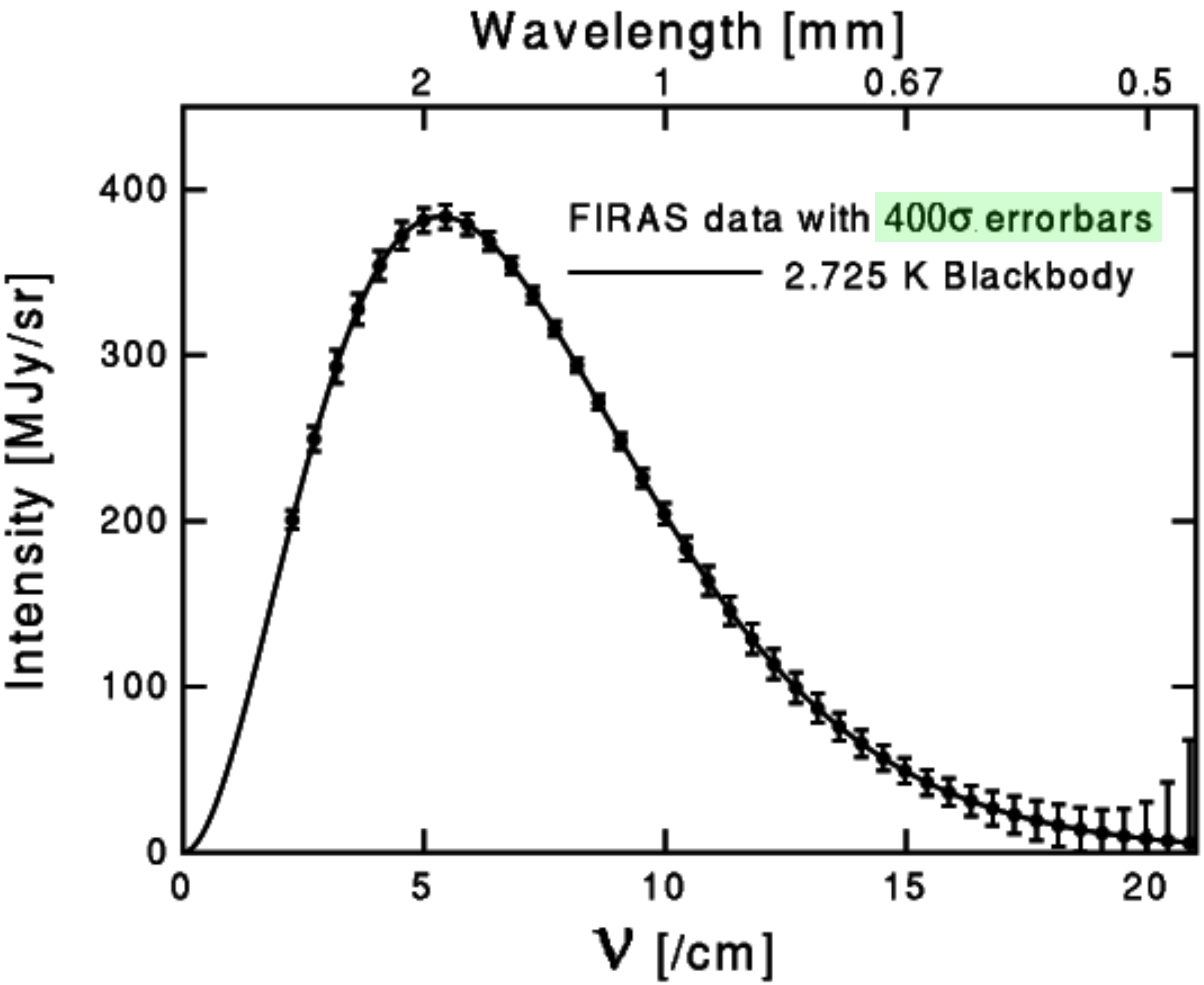
Thickness of the last scattering surface

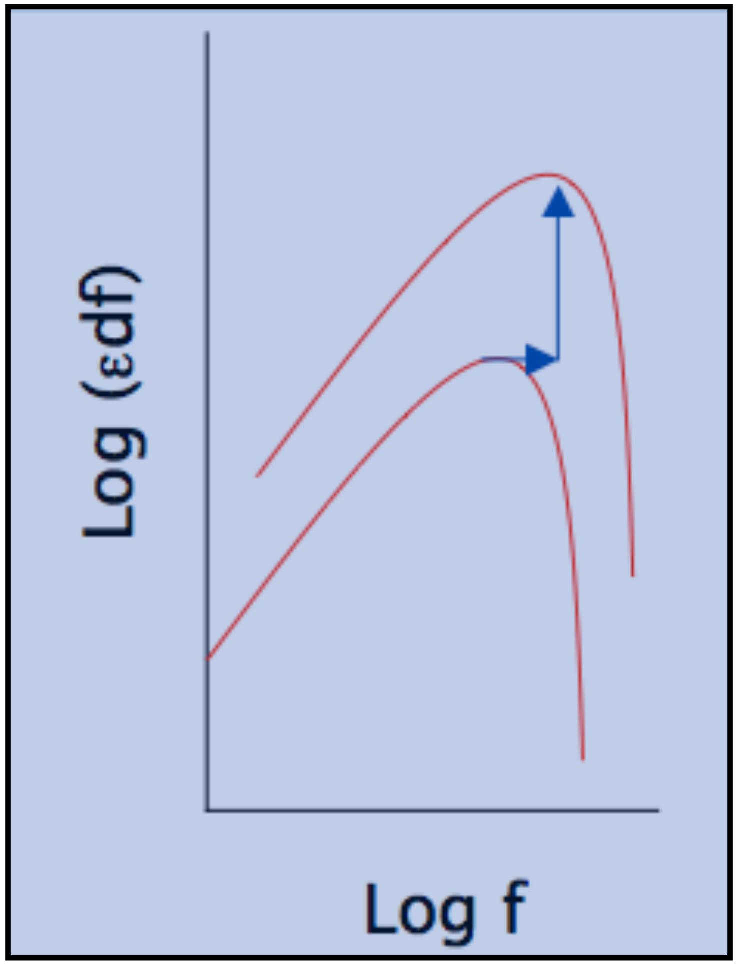


The visibility function is defined as the probability density that a photon is last scattered at redshift z: $g(z) \sim \exp(-\tau)\, d\tau/dz$

Probability distribution is well described by Gaussian with mean $z \sim 1100$ and standard deviation $\delta z \sim 80$.

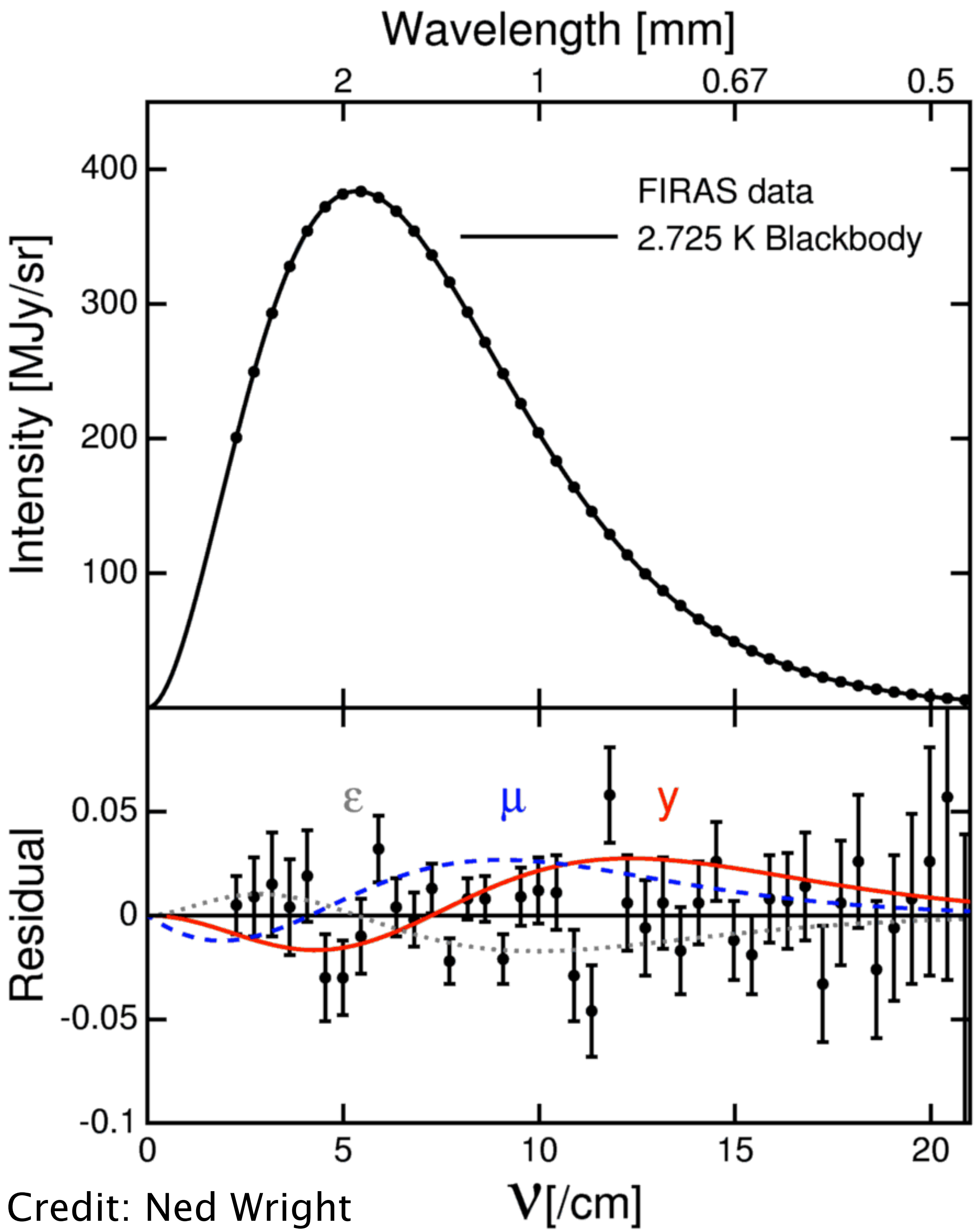
The CMB blackbody





The blackbody shape is preserved at all redshifts if expansion is purely adiabatic. The frequency shifts by $1/a$, and energy density by $1/a^4$.

FIRAS Measurements



Credit: Ned Wright

Fundamental FIRAS measurement is the plot at the bottom: the difference between the CMB and the best-fitting blackbody. The top plot shows this residual added to the theoretical blackbody spectrum at the best fitting cold load temperature.

The three curves in the lower panel represents three likely non-blackbody spectra:

Red and blue curves show effect of hot electrons adding energy before and after recombination (roughly), the grey curve shows effect of a non-perfect blackbody as calibrator (less than 10^{-4})

Thermalization of the CMB

Process that changes photon energy, not number:

Compton scattering: $e + \gamma = e + \gamma$

Processes that creates photons:

Radiative (double) Compton scattering: $e + \gamma = e + \gamma + \gamma$

Bremsstrahlung: $e + Z = e + Z + \gamma$

At an early enough epoch, timescale of the radiative Compton scattering rate must be shorter than the expansion timescale. They are equal at $\mathbf{z \sim 2x10^6}$, or roughly two months after the big bang.

The universe reaches thermal equilibrium by this time through scattering and photon-generating processes. Thermal equilibrium generates a blackbody radiation field. Any energy injection before this time cannot leave any spectral signature on the CMB blackbody.

For pure adiabatic expansion of the universe afterwards, a blackbody spectrum — once established — should be maintained.

Thermalization of the CMB

True thermal equilibrium requires the creation and destruction of photons as well as energy redistribution by scattering (see, for instance, Kompaneets, 1957). In the early Universe, radiative Compton scattering permits the generation of photons needed to ensure true thermal equilibrium. The bremsstrahlung process is less important, due to the high photon-to-baryon ratio.

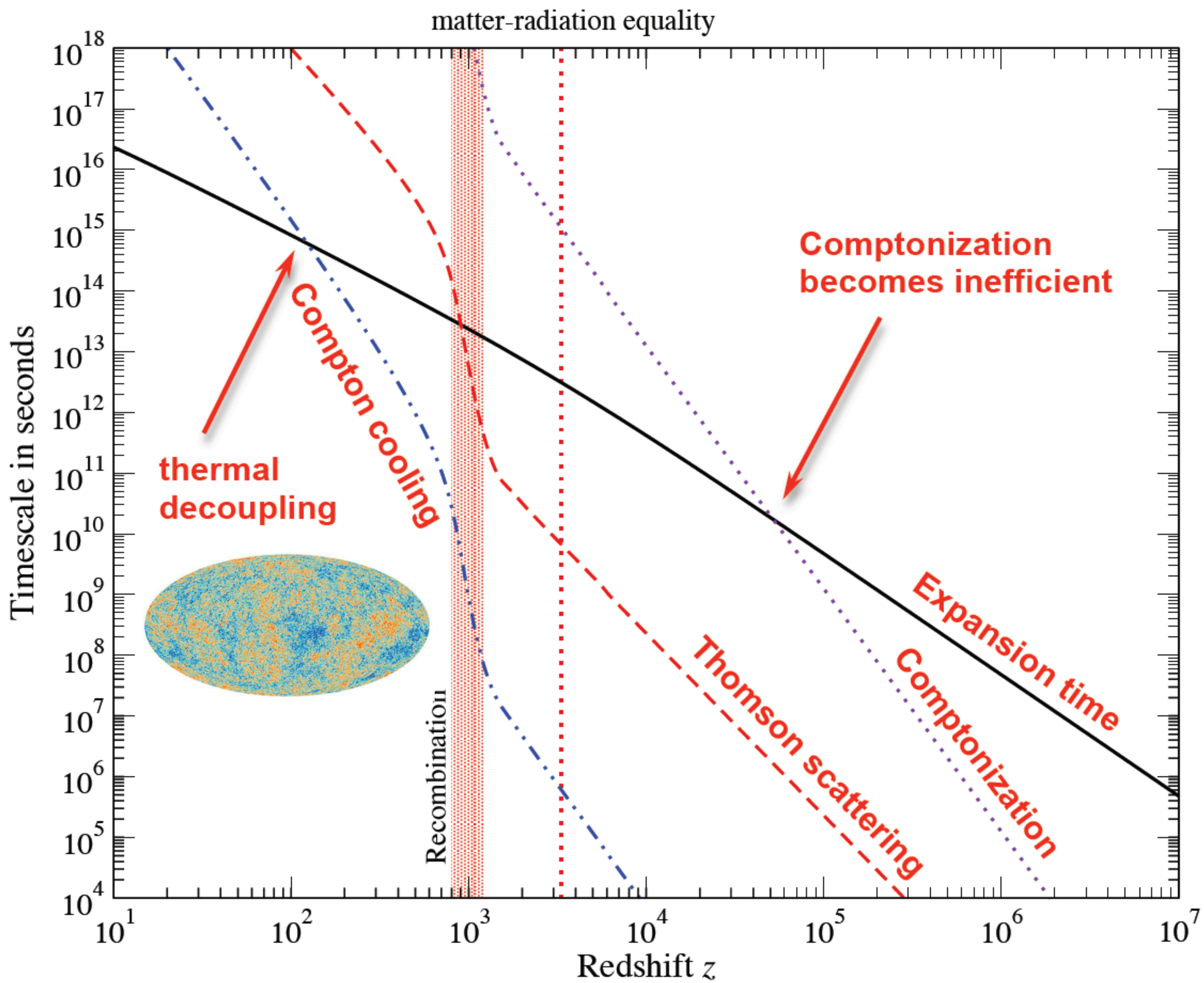
The efficiency of these two processes keep on dropping with time, and after about $z \sim 2 \times 10^6$ they cannot keep the universe in thermal equilibrium anymore.

Kinetic Equilibrium can be established by any process with a timescale less than H^{-1}

Under KE, as opposed to thermal equilibrium, the spectrum is Bose-Einstein: $n = [\exp(h\nu/kT + \mu) - 1]^{-1}$

Clearly, μ leaves a only small imprint at high frequencies, but the discrepancy becomes larger as the frequency drops (μ can also be either positive or negative).

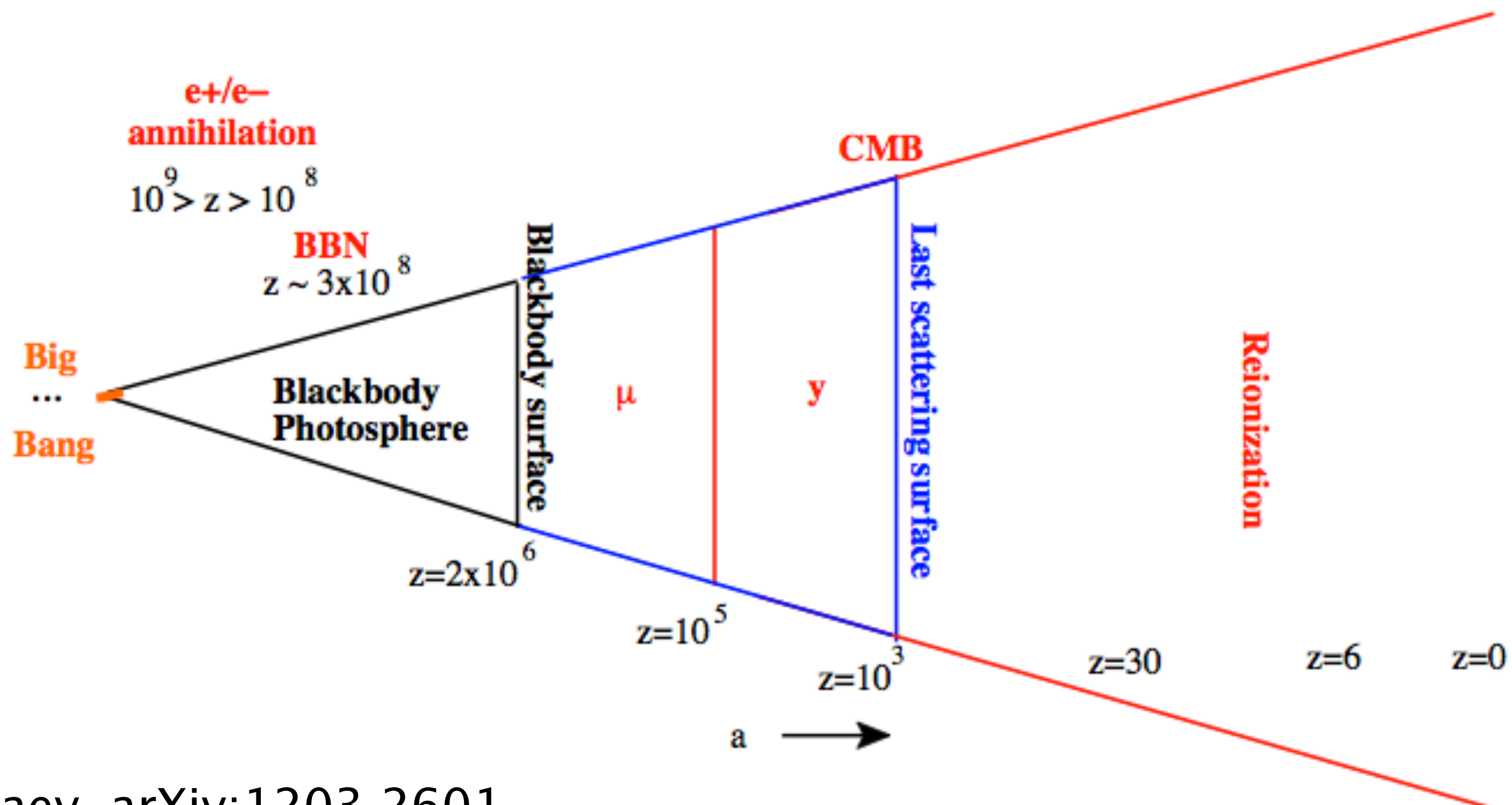
Compton scattering efficiency



From Chluba (2018), arXiv:1806.02915

Bose–Einstein spectrum

The claim that thermal equilibrium is established at the high redshift of ~2×10^6 is equivalent to the claim that μ is driven essentially to zero by that redshift. However, if energy is added to the CMB radiation field after redshift of ~2×10^6, there may still be time to reintroduce kinetic equilibrium, but not full thermal equilibrium. In that case, the spectrum would be a Bose-Einstein spectrum ($y > 1$). This phase is generally termed as the epoch of μ–distortion (~$2\times10^6 < z <$ ~10^5) - here Comptonization is efficient!



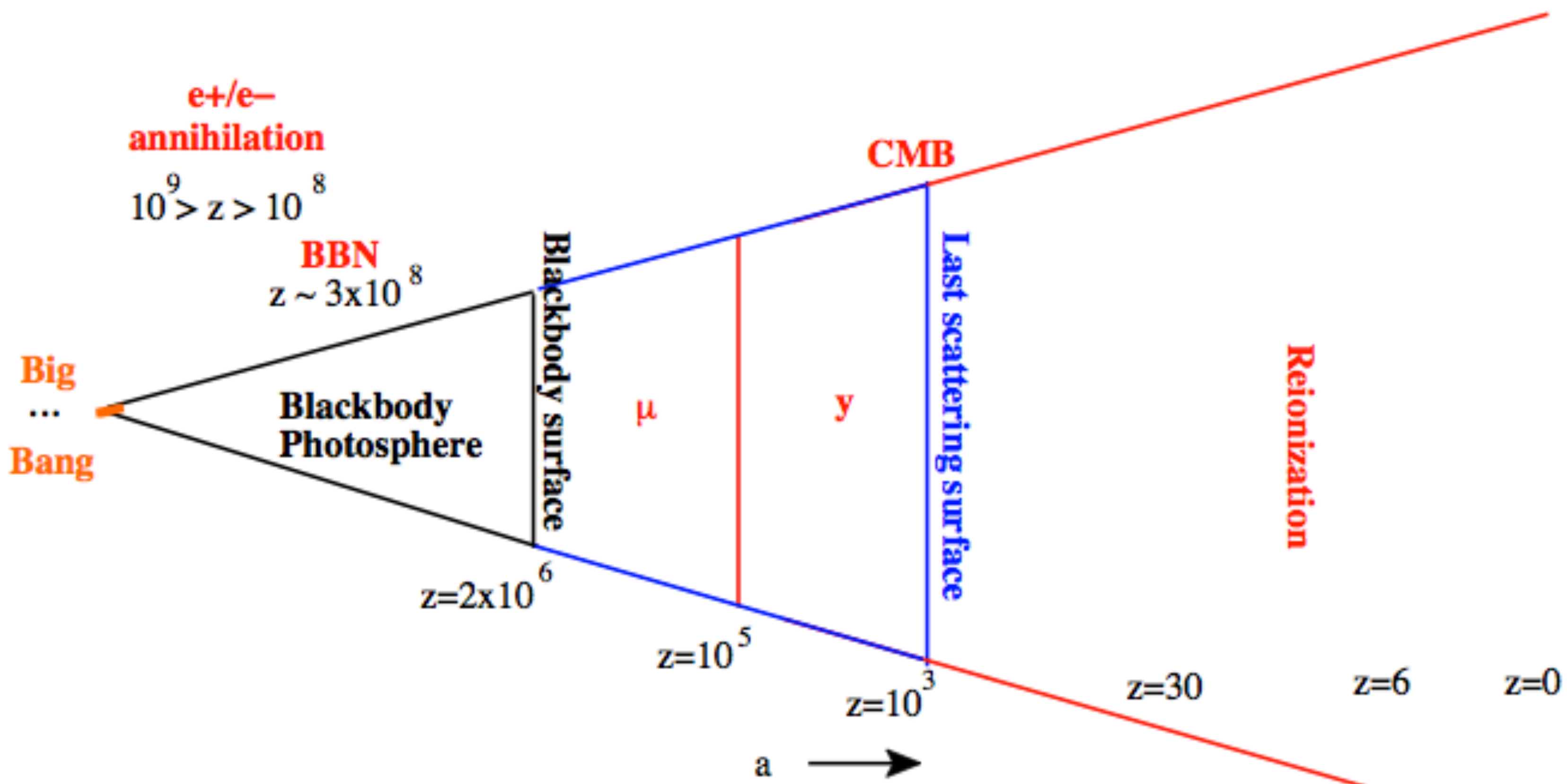
Ref: Khatri & Sunyaev, arXiv:1203.2601

Figure 1. Important events in the history of the CMB spectrum and anisotropy formation in big bang cosmology. Redshift range ($2 \times 10^6 \gtrsim z \gtrsim 10^5$), where the energy injection would give rise to a Bose-Einstein spectrum (μ-type distortion), is marked as μ. At much smaller redshifts ($z \lesssim 10^4$), any heating of CMB through Compton scattering would create a y-type distortion. The spectrum in the intermediate redshift range would not be a pure μ or y type but in between the two types.

μ– and y–type distortions

A μ–type distortion can not be generated at recent epochs and thus directly probe the physics of the pre–recombination era.

At later epochs (up to recombination and during reionization) any energy input will generally create a y-type distortion. Here Comptonization is inefficient ($\Gamma > H^{-1}$), so we get $y \ll 1$. This can be created at any redshift after z_{rec} , down to z = 0.



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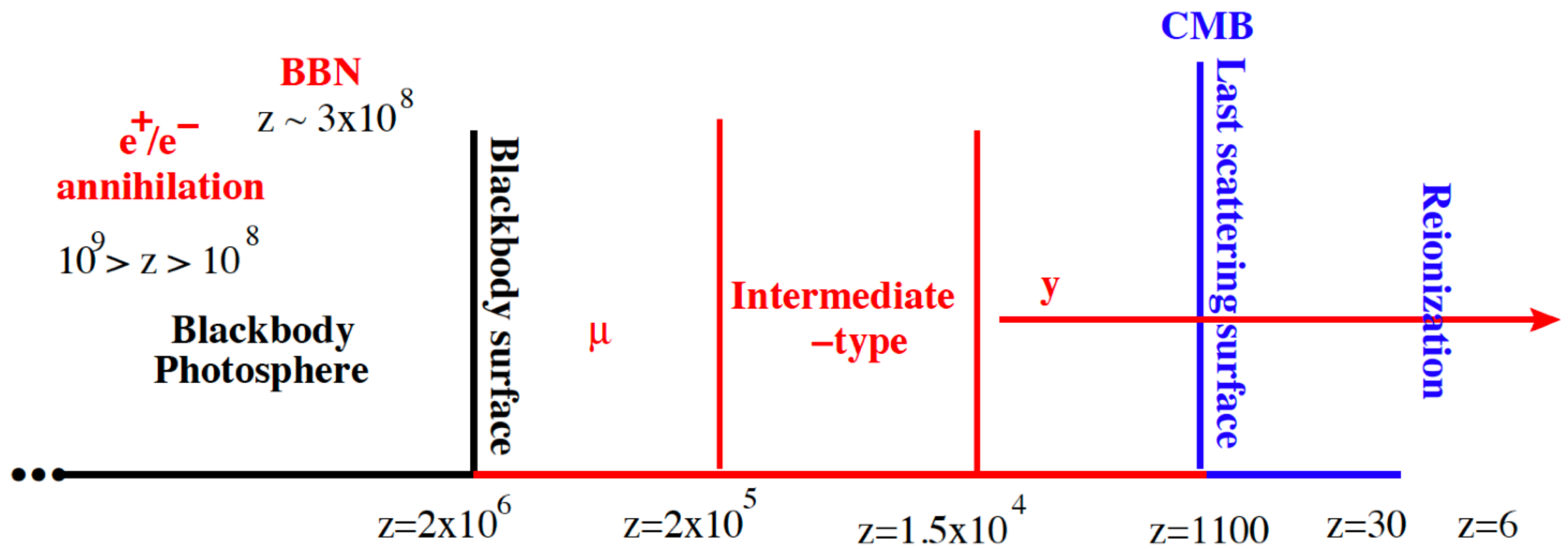
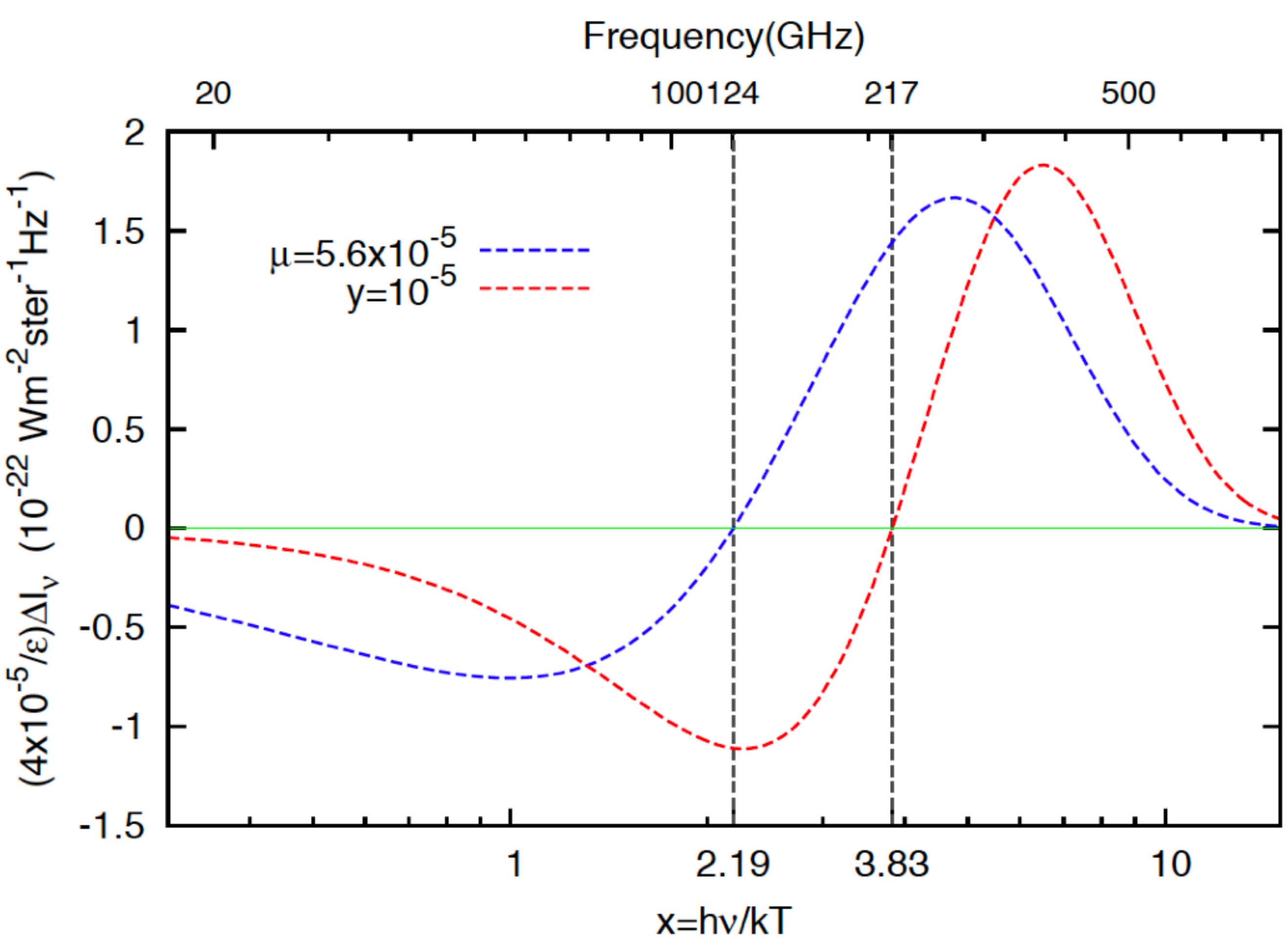
μ and y distortions: Summary





Example: μ- and y-type distortions for a fixed addition of energy $\varepsilon=\Delta E/E=4\times10^{-5}$ to a blackbody at temperature *T*.

Shown here is the intensity difference w.r.t the reference blackbody.

(From Khatri & Sunyaev 2012)

μ- and y-type distortions

Table 1. Census of μ distortions in standard cosmology. The adiabatic cooling of matter results in negative distortions shown in red. Table is taken from Ref. 63.

Process	μ
electron-positron annihilation	10^{-178}
BBN tritium decay	2×10^{-15}
BBN ^{7}Be decay	10^{-16}
WIMP dark matter annihilation	$3 \times 10^{-9} f_\gamma \frac{10\mathrm{GeV}}{m_{\mathrm{WIMP}}}$
Silk damping	$10^{-8} - 10^{-9}$
Adiabatic cooling of matter and Bose-Einstein condensation	-2.7×10^{-9}

Table 2. Census of y-type distortions in standard cosmology. y-type distortion from the mixing of blackbodies in our CMB sky[31] are also shown. Adiabatic cooling of matter creates negative distortions shown in red. Reionization/WHIM contributions after recombination dominate. Table is taken from Ref. 63.

Process	y
WIMP dark matter annihilation	$6 \times 10^{-10} f_\gamma \frac{10\mathrm{GeV}}{m_{\mathrm{WIMP}}}$
Silk damping	$10^{-8} - 10^{-9}$
Adiabatic cooling of matter and Bose-Einstein condensation	-6×10^{-10}
Reionization/WHIM	$10^{-6} - 10^{-7}$
Mixing of blackbodies: CMB $\ell \geq 2$ multipoles	8×10^{-10}

Ref: Khatri & Sunyaev, arXiv:1203.2601

Current limits on Spectral Distortions

- Energy added after $z \sim 2 \times 10^6$ will show up as spectral distortions. Departure from a Planck spectrum at fixed T is known as "μ distortion" (B-E distribution). μ distortion is easier to detect at wavelengths $\lambda > 10$ cm.

  COBE measurement: $|\mu| < 9 \times 10^{-5}$ (95% CL)

- The amount of inverse Compton scattering at later epochs ($z < 10^5$) show up as "y distortion", where $y \sim \sigma_T n_e kT_e$ (e.g. the Sunyaev-Zel'dovich effect). This rules out a uniform intergalactic plasma as the source for X-ray background.

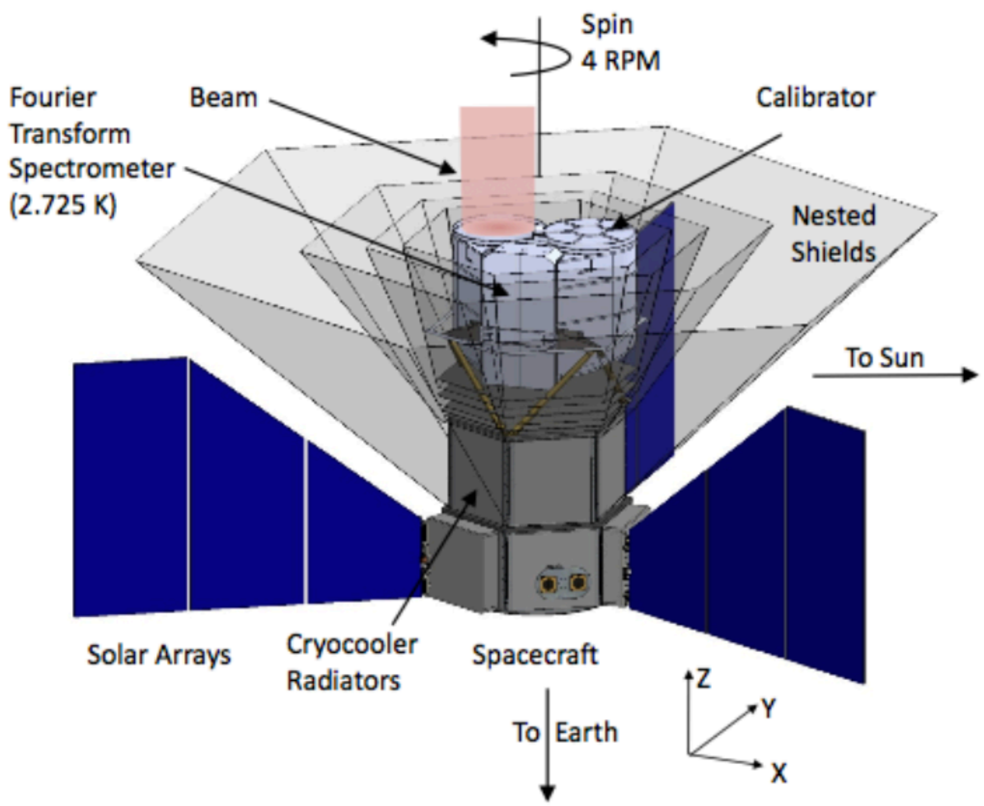
  COBE measurement: $y < 1.2 \times 10^{-5}$ (95% CL)

- Energy injection at much later epochs ($z << 10^5$), e.g. free-free distortions, are also tightly constrained.

  COBE measurement: $Y_{ff} < 1.9 \times 10^{-5}$ (95% CL)

μ & y distortions with current technology

Sensitivity of the proposed Pixie satellite
Kogut et al. (2011), arXiv:1105.2044



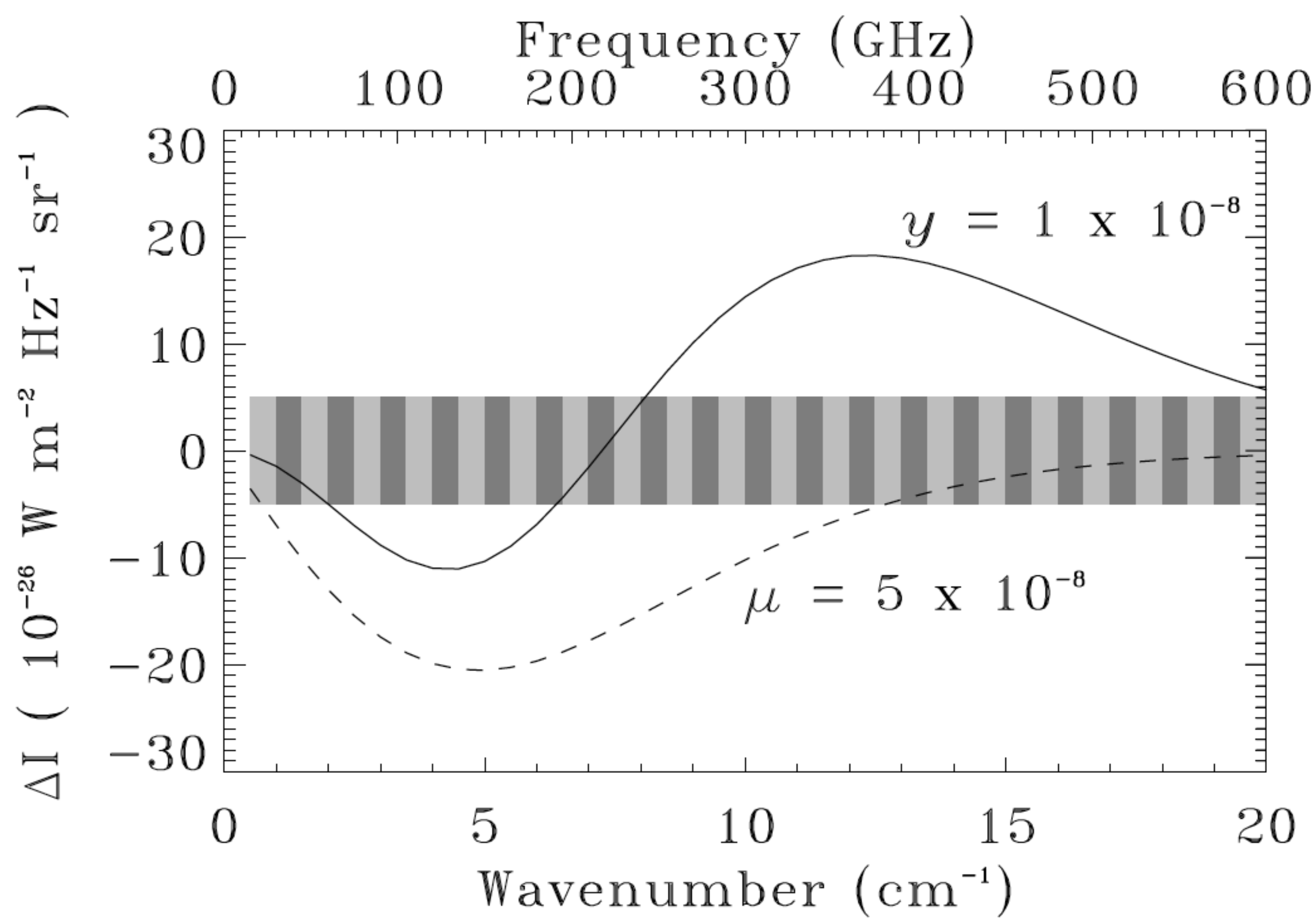
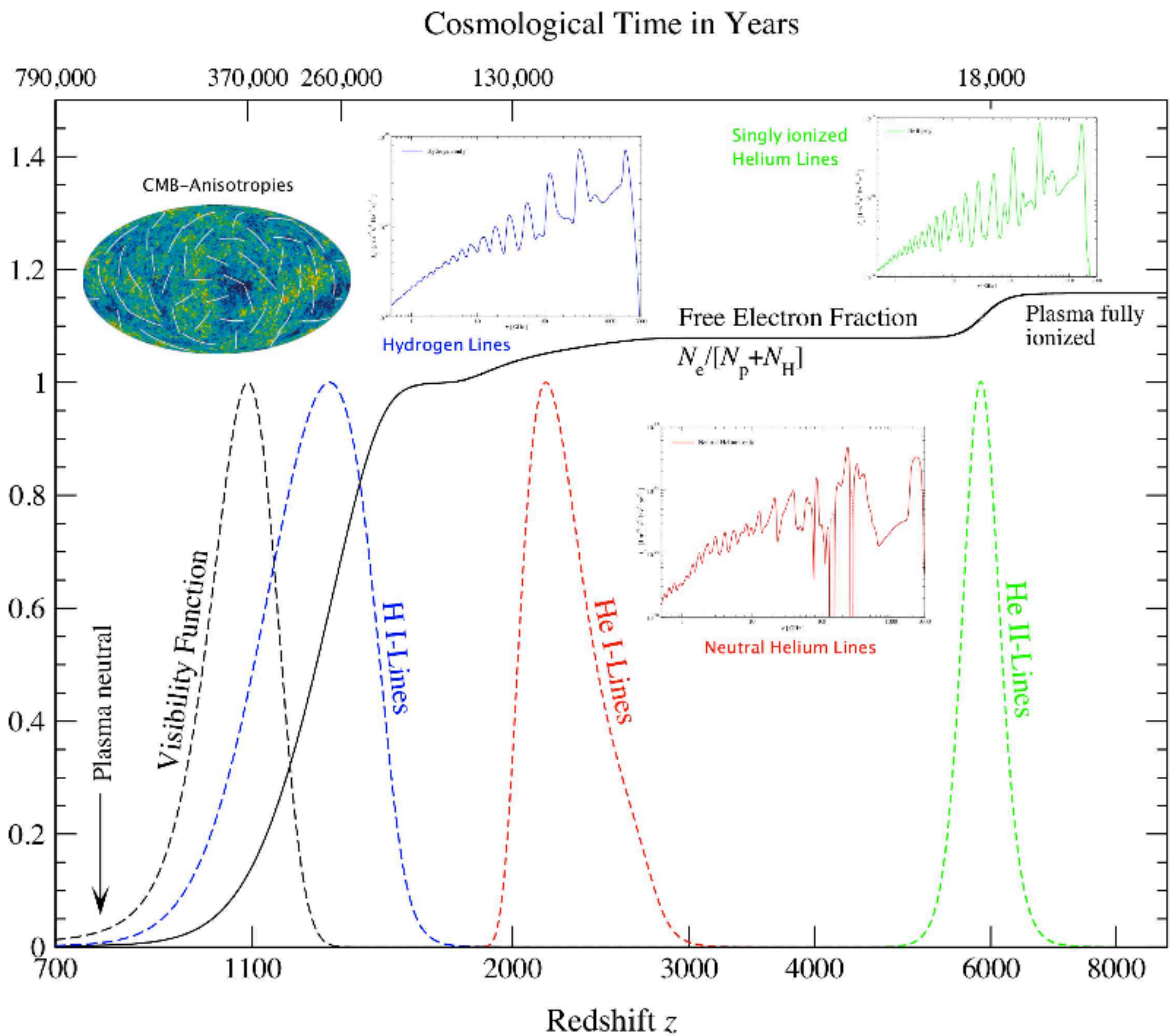


Figure 12. Distortions to the CMB blackbody spectrum compared to the PIXIE instrument noise in each synthesized frequency channel. The curves show 5σ detections of Compton (y) and chemical potential (μ) distortions. PIXIE measurements of the y distortion determine the temperature of the intergalactic medium at reionization, while the μ distortion probes early energy release from dark matter annihilation or Silk damping of primordial density perturbations.

See Spectral Distortion White Paper for the Astro2020 Decadal Review, Chluba et al. (2019), arXiv:1903.04218

The known physics of recombination predicts several other spectral features on the CMB, and failure to detect those will create big theoretical challenge!



Sunyaev & Chluba (2009)

Spectral features from recombination

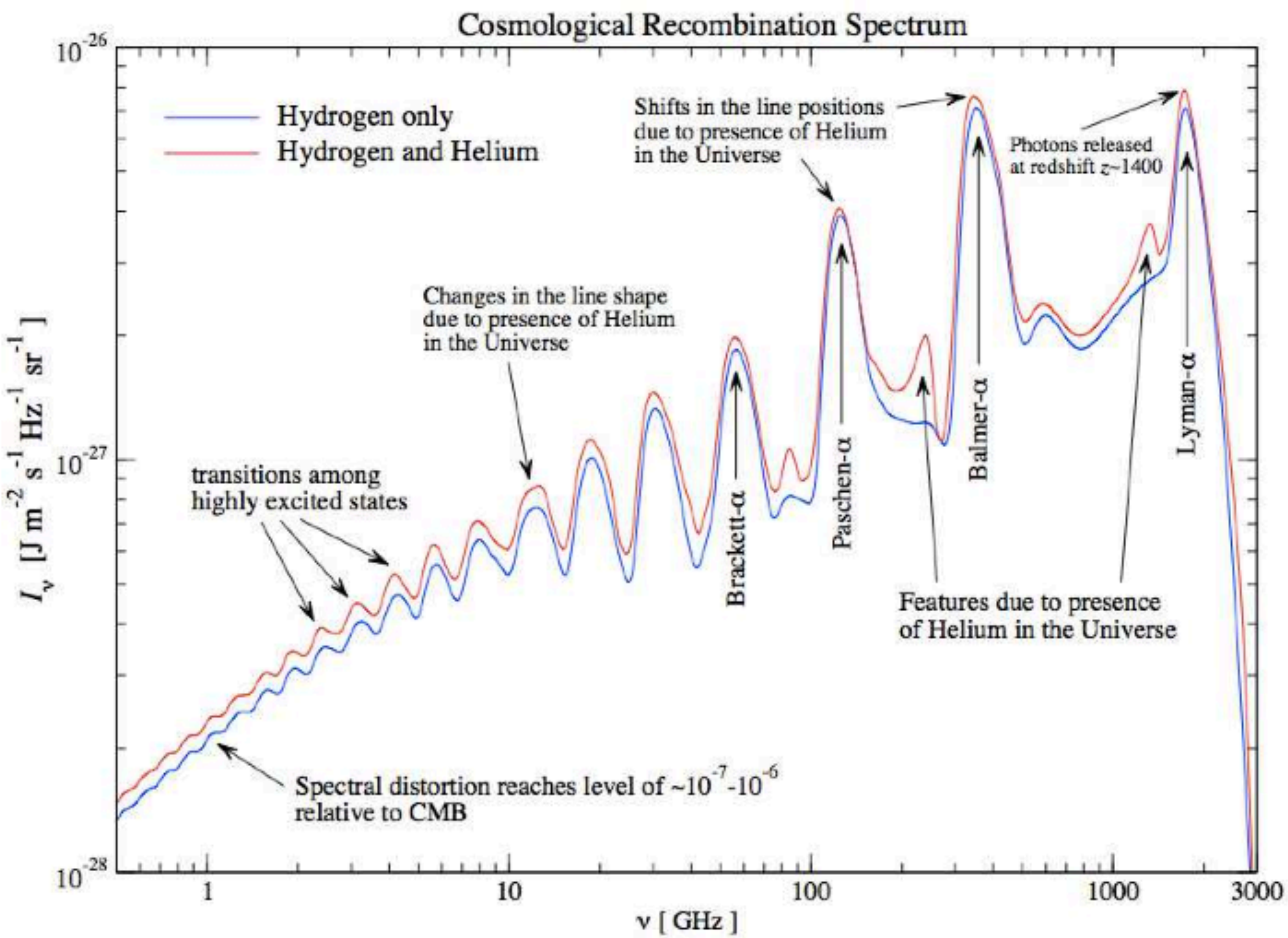
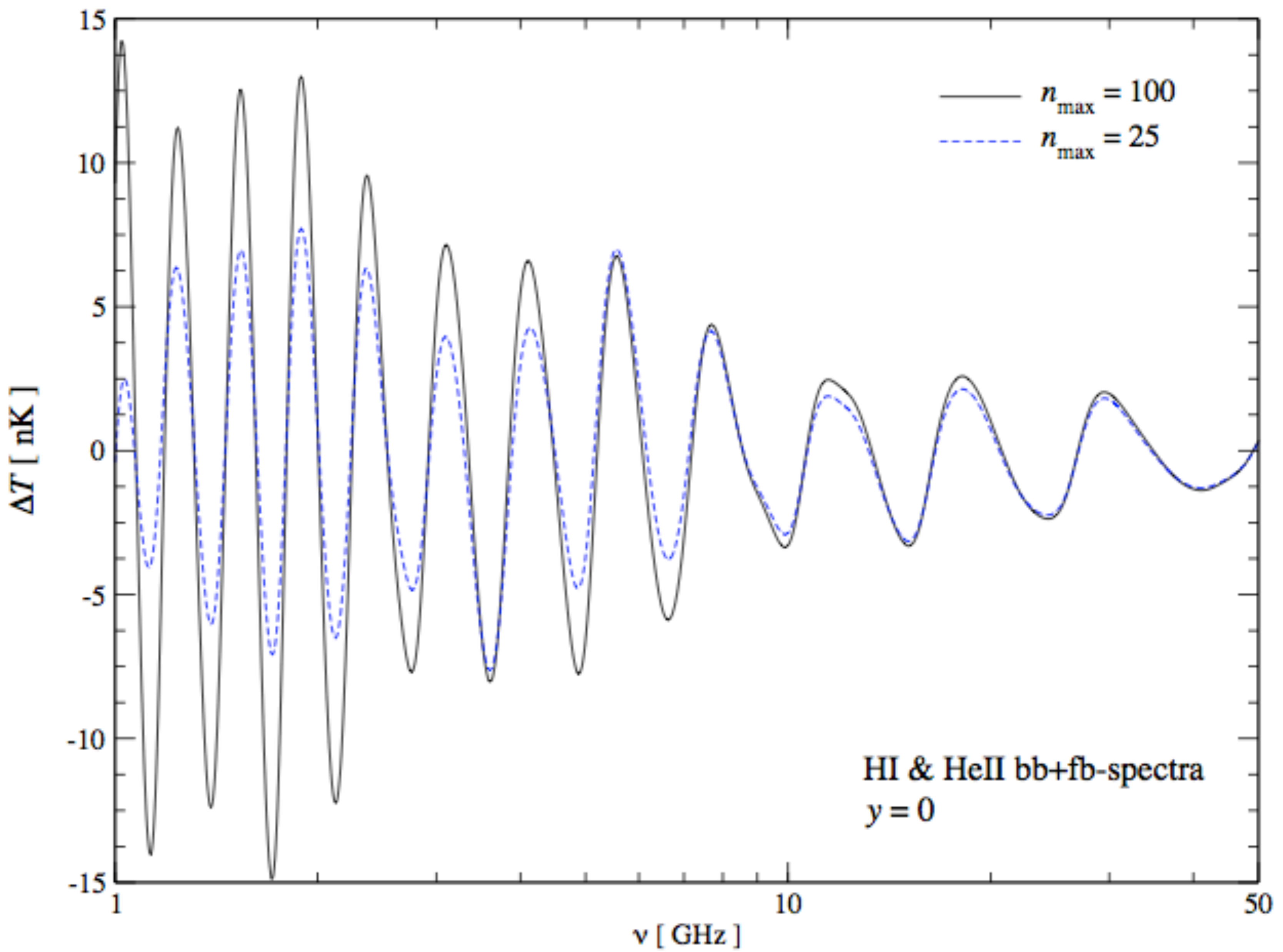


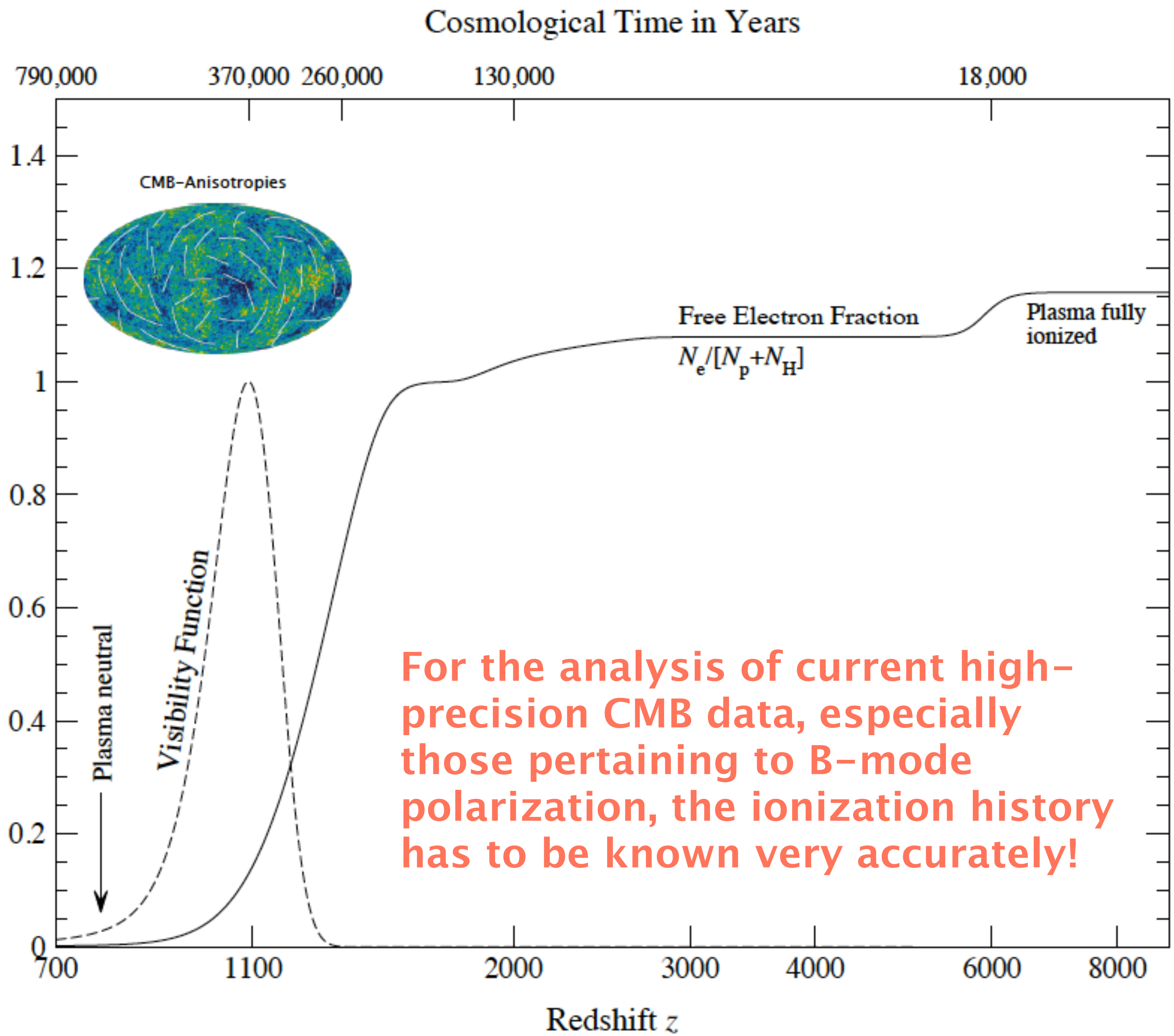
Fig. 3. Intensity of the recombination lines from the epoch of helium and hydrogen recombination. Figure courtesy of Chluba, Rubino-Martin and Sunyaev based on calculations in Ref. [11].

Spectral features from recombination



From Chluba & Sunyaev (2006)

Frequency dependent modulation in the CMB temperature from the H I and He II recombination epoch, after subtracting the mean recombination spectrum. This signal is unpolarized and **same in all directions on the sky**.

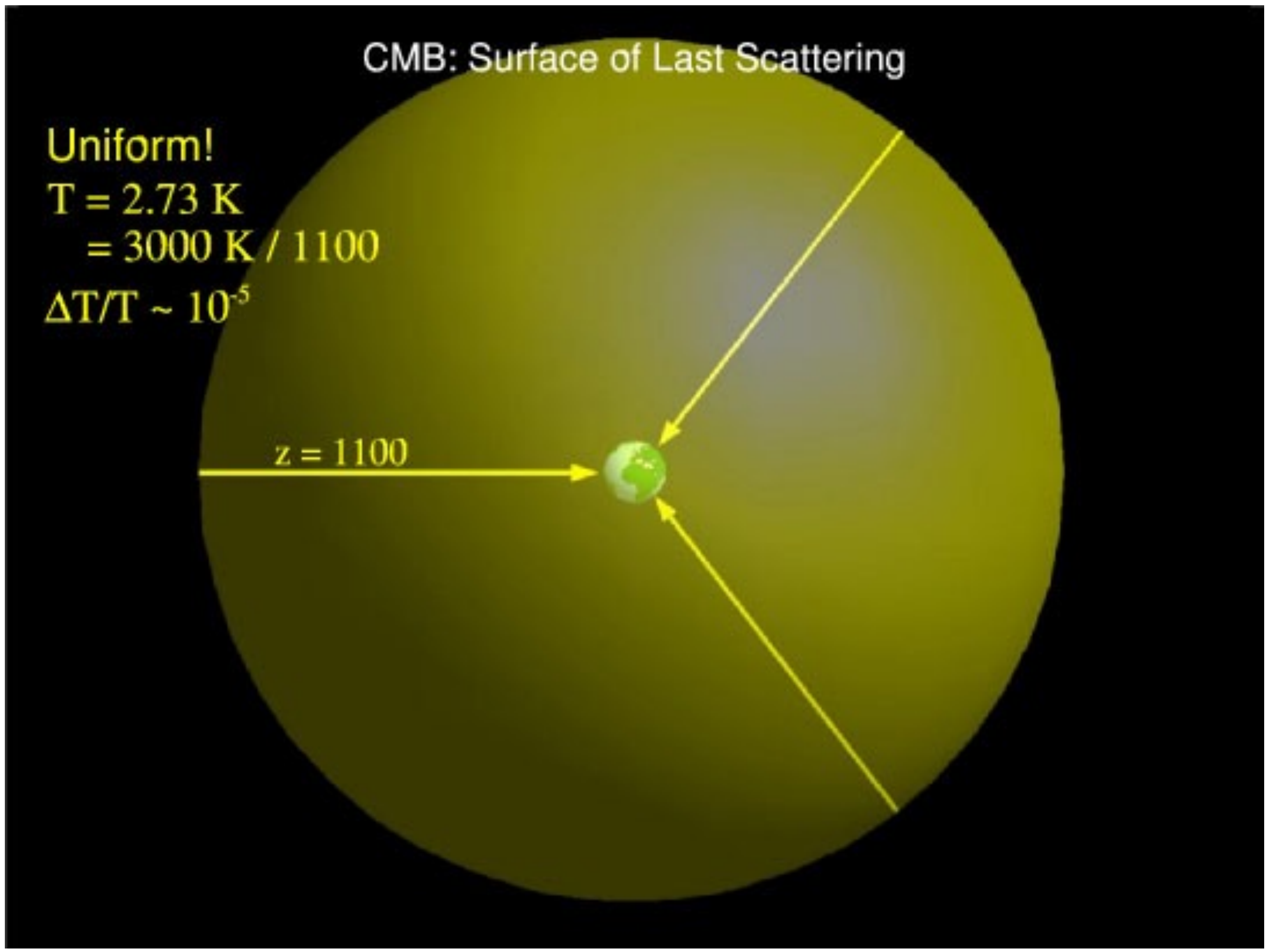


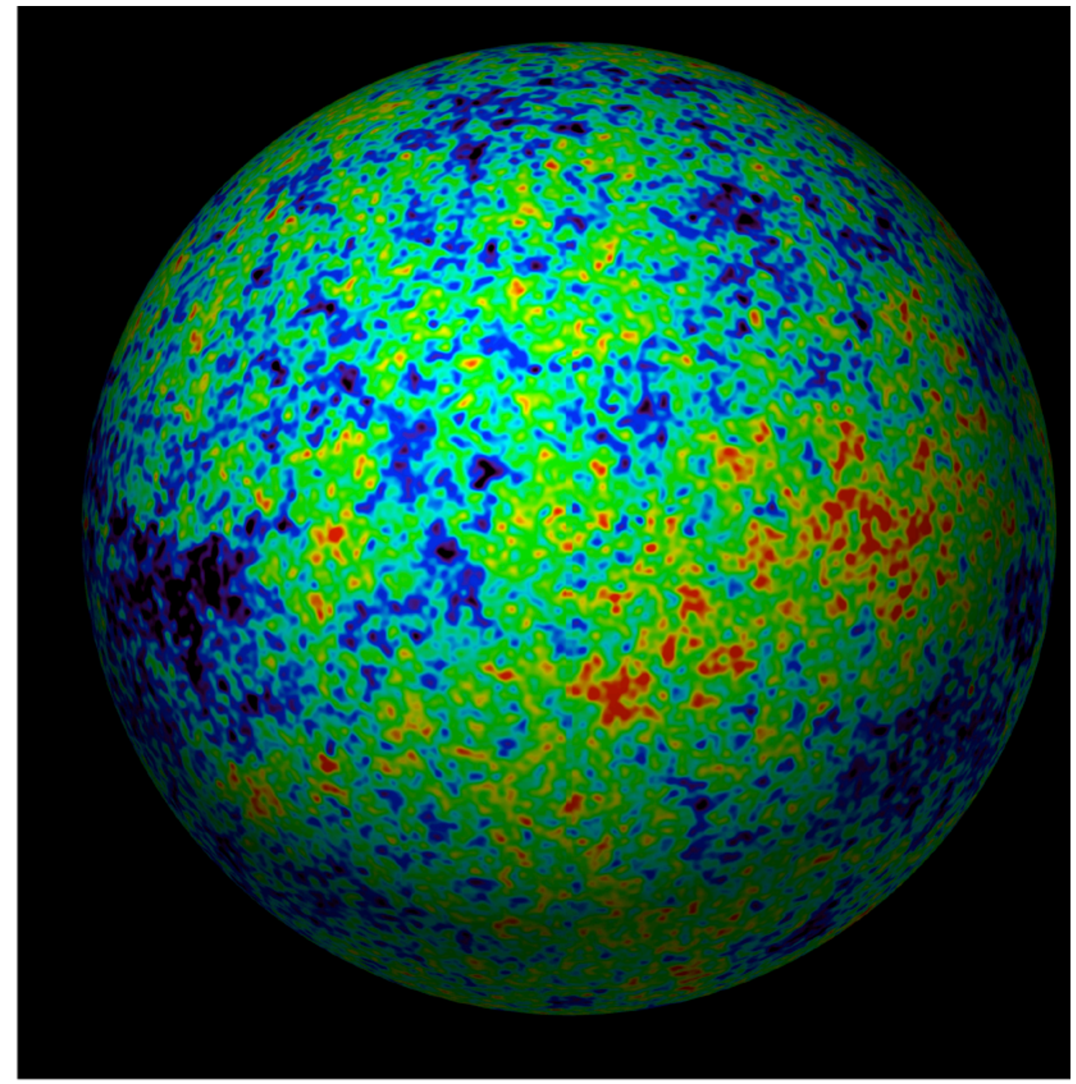
See Spectral Distortion White Paper for the Astro2020 Decadal Review, Chluba et al. (2019), arXiv:1903.04218

Part 2:

The Temperature Anisotropies in the CMB

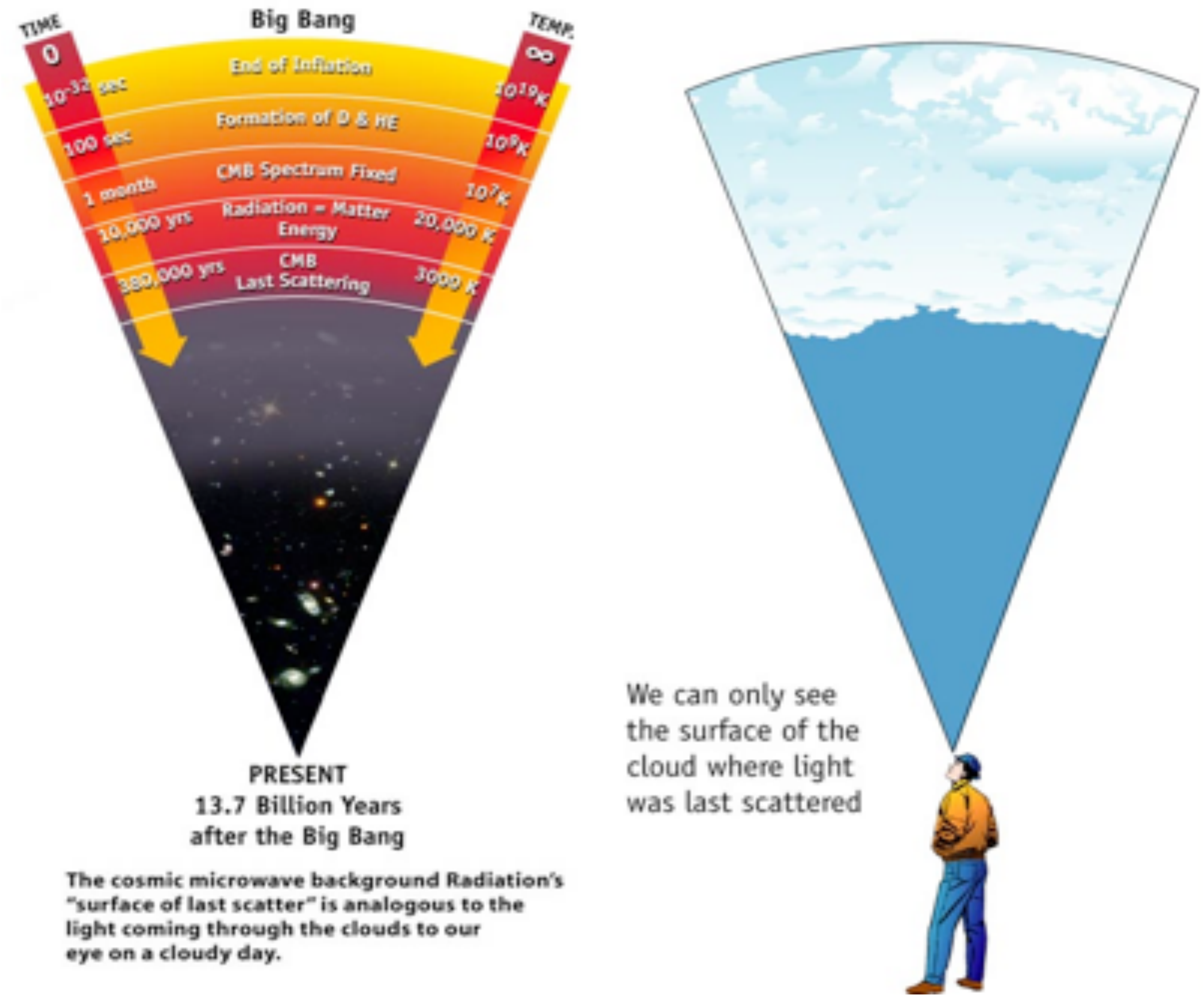
The last scattering "sphere"





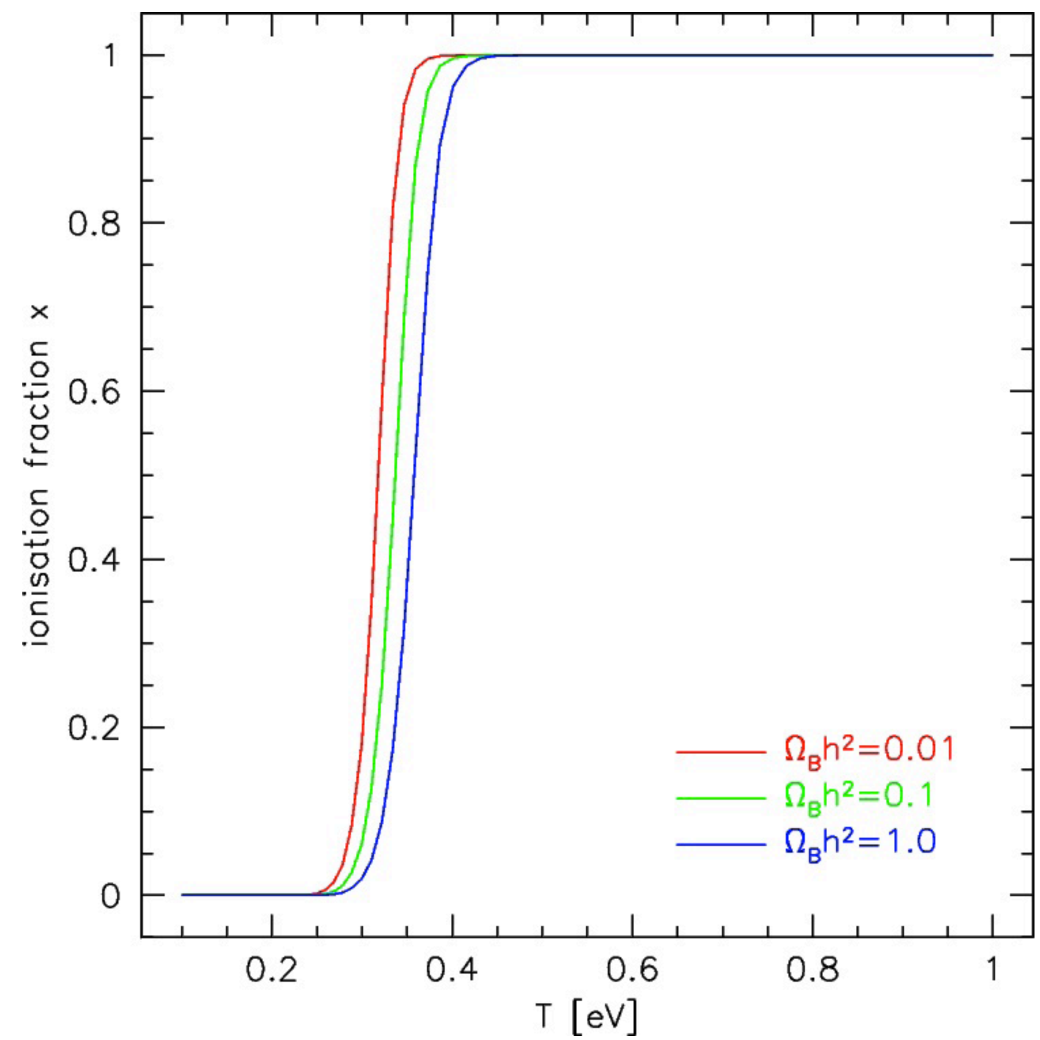
anisotropy amplitude $\Delta T/T \sim 10^{-5}$

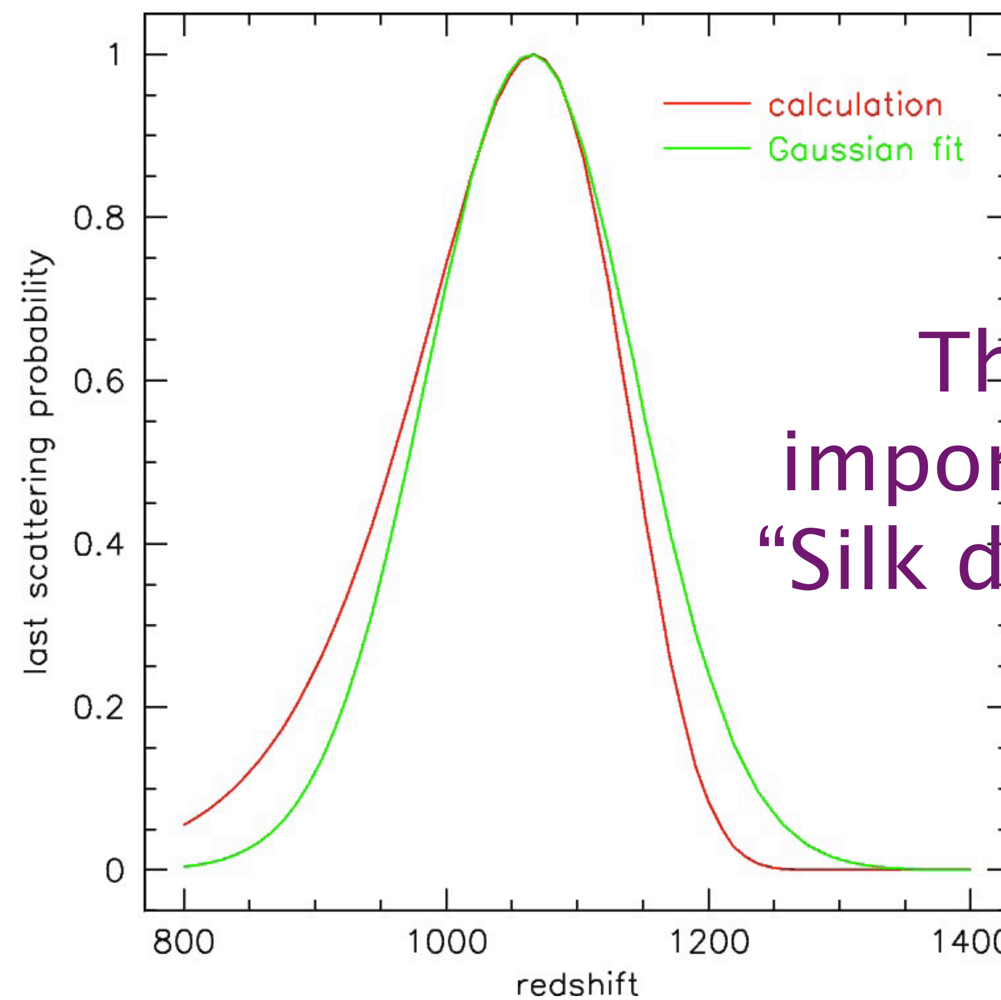
The Last Scattering Surface



All photons have travelled roughly the same distance since recombination. We can think of the CMB being emitted from inside of a spherical surface, we're at the center. (This surface has a thickness)

Thickness of the last scattering surface



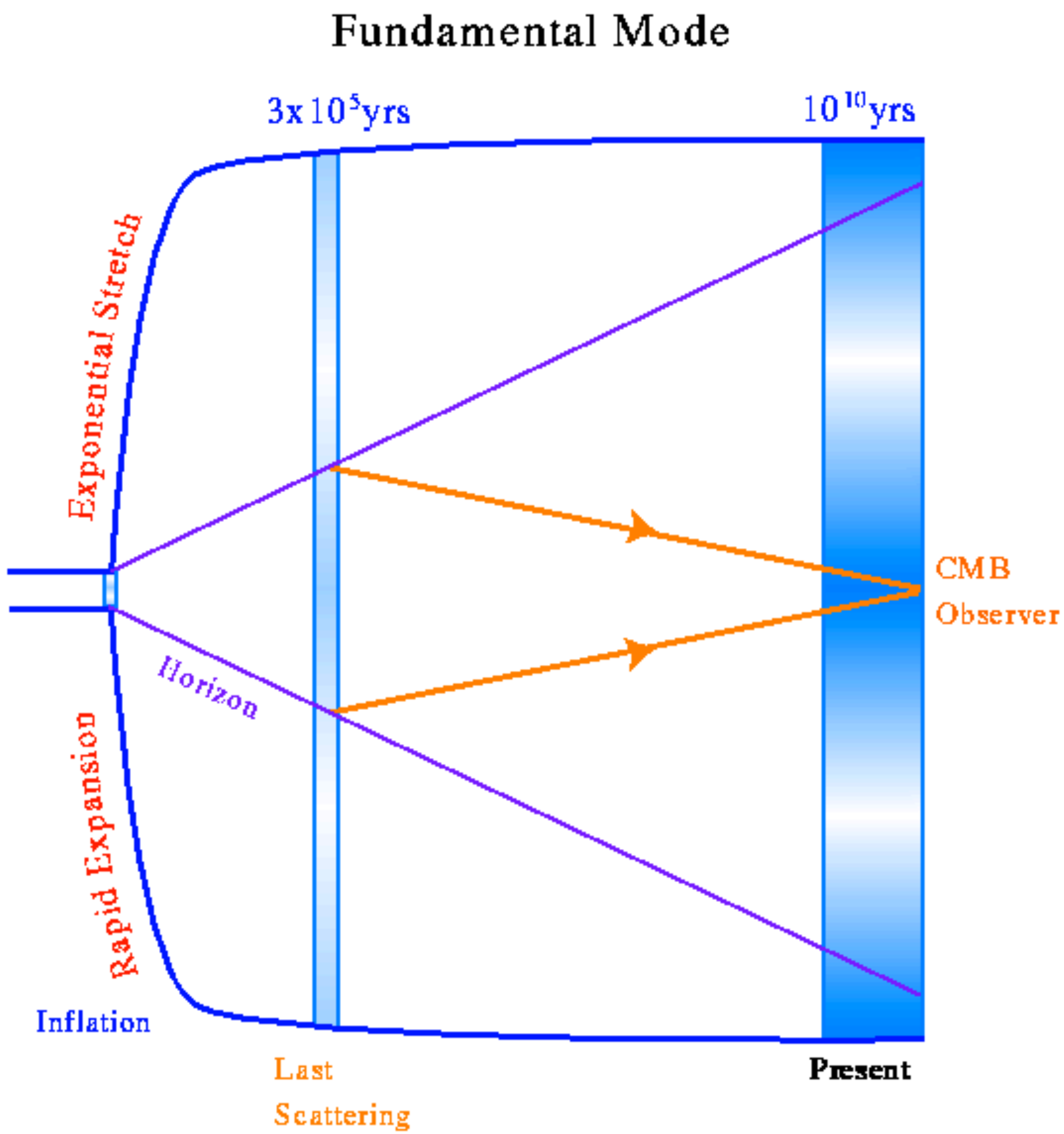


This is important for "Silk damping"

The visibility function is defined as the probability density that a photon is last scattered at redshift z: $g(z) \sim \exp(-\tau)\, d\tau/dz$

Probability distribution is well described by Gaussian with mean $z \sim 1100$ and standard deviation $\delta z \sim 80$.

Horizon scale at Last Scattering



Distance to the last scattering surface (assume Ω_m=1 EdS universe)

$$r_{LS} = \frac{c}{H_0} \int_0^{z_{LS}} (1+z)^{-3/2} dz$$
$$= \frac{2c}{H_0} (1 - (1+z_{LS})^{-1/2})$$

Thus, the factor $2c/H_0$ is approximately the comoving distance to the LSS ($z_{LS}>>1$).

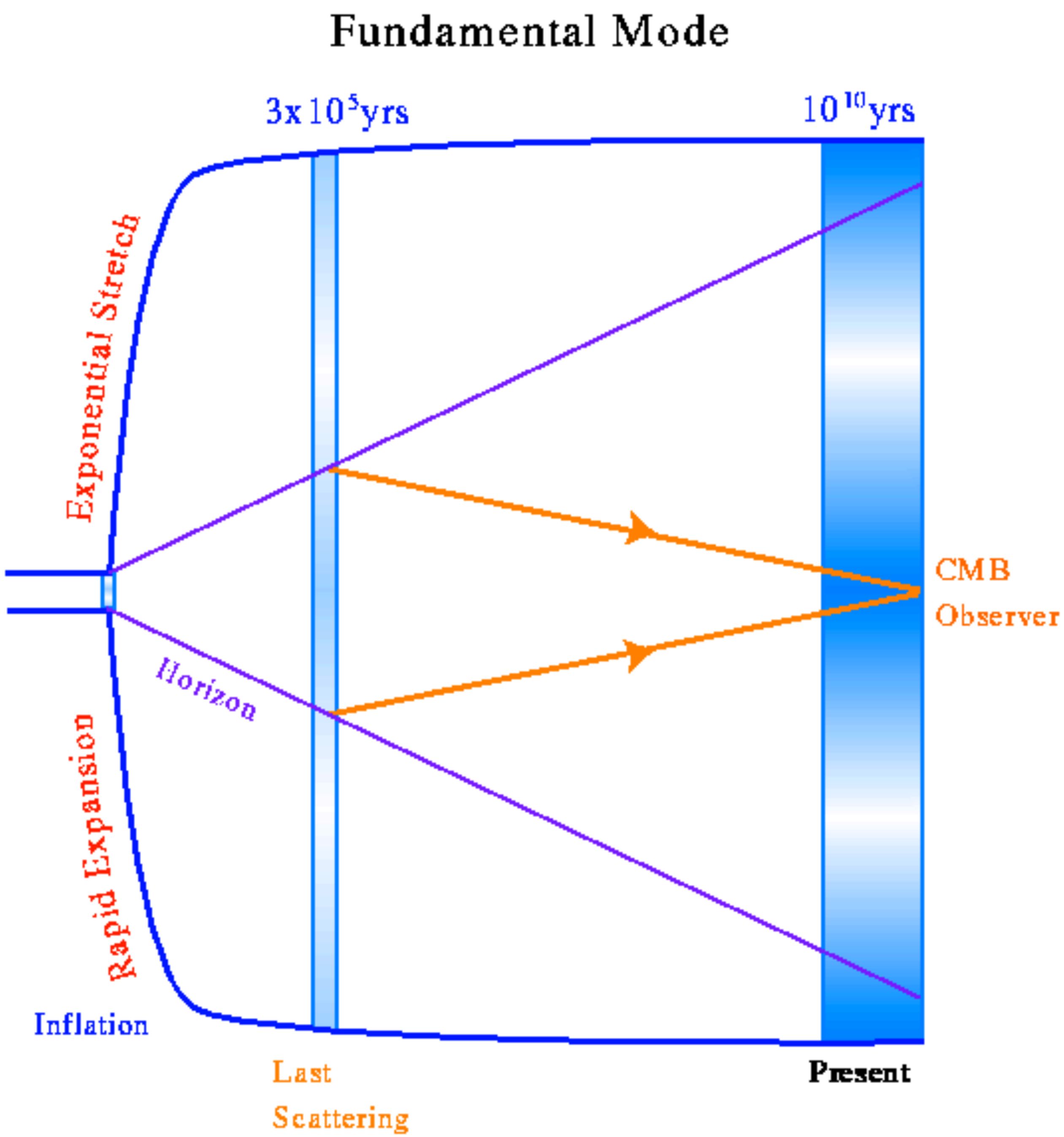
The particle horizon length at the time of last scattering (i.e. the distance light could travel since big bang) is give by

$$d_H(z=z_{LS}) = \int_{z_{LS}}^{\infty} \frac{dz}{H(z)} = \frac{2c}{H_0} (1+z_{LS})^{-1/2}$$

for $z_{LS} \approx 1100$, means that

$$\theta_H^{LS} = (1+z_{LS})^{-1/2} \approx 1.7^\circ$$

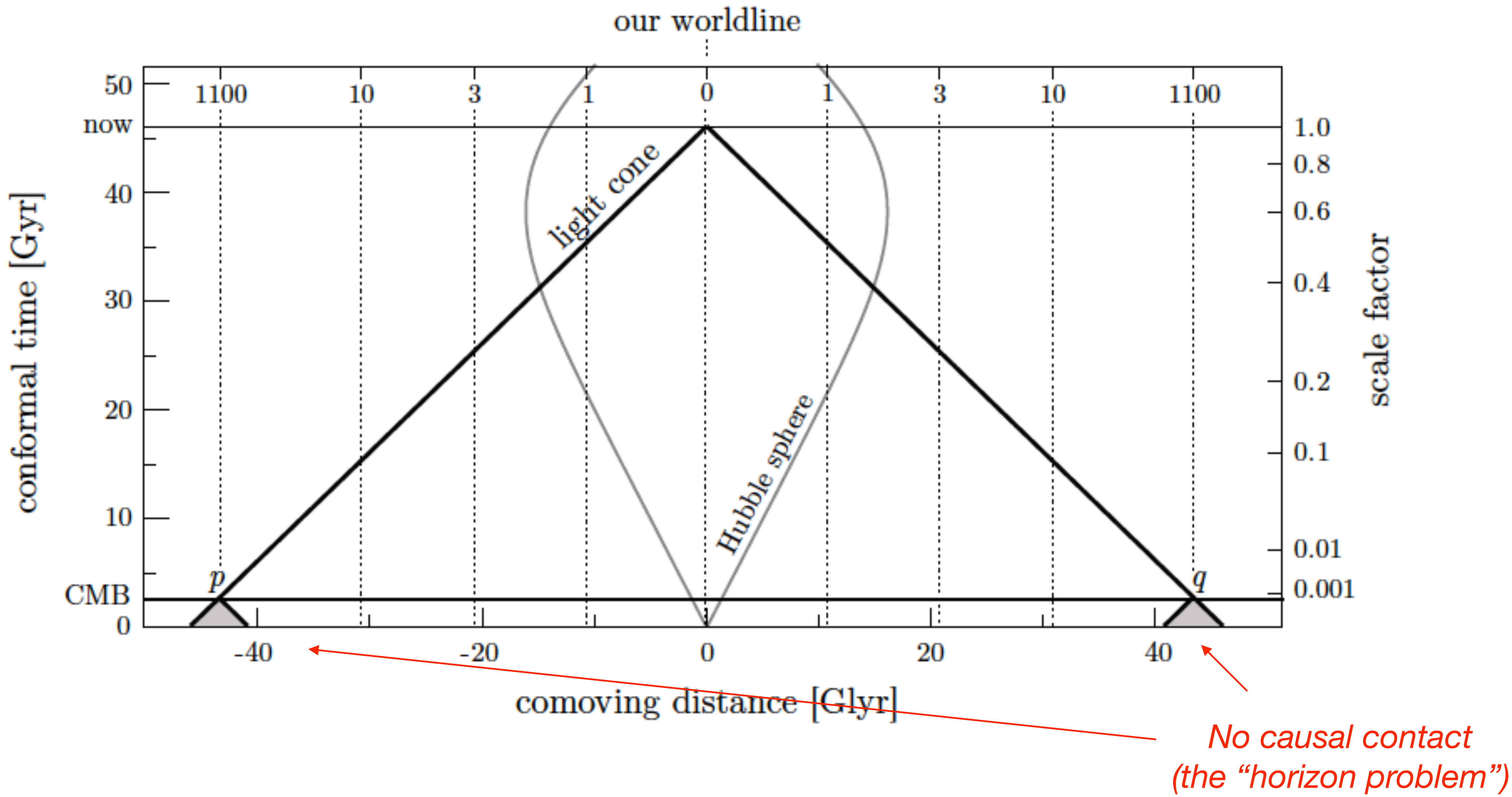
Horizon scale at Last Scattering



This tells us that scales larger than ~1.7° in the sky were not in causal contact at the time of last scattering. However, the fact that we measure the same mean temperature across the entire sky suggests that all scales were once in causal contact – this led to the idea of Inflation.

Inflationary theories suggests that the Universe went through a period of very fast expansion, which would have stretched a small, causally connected patch of the Universe into a region of size comparable to the size of the observable Universe today.

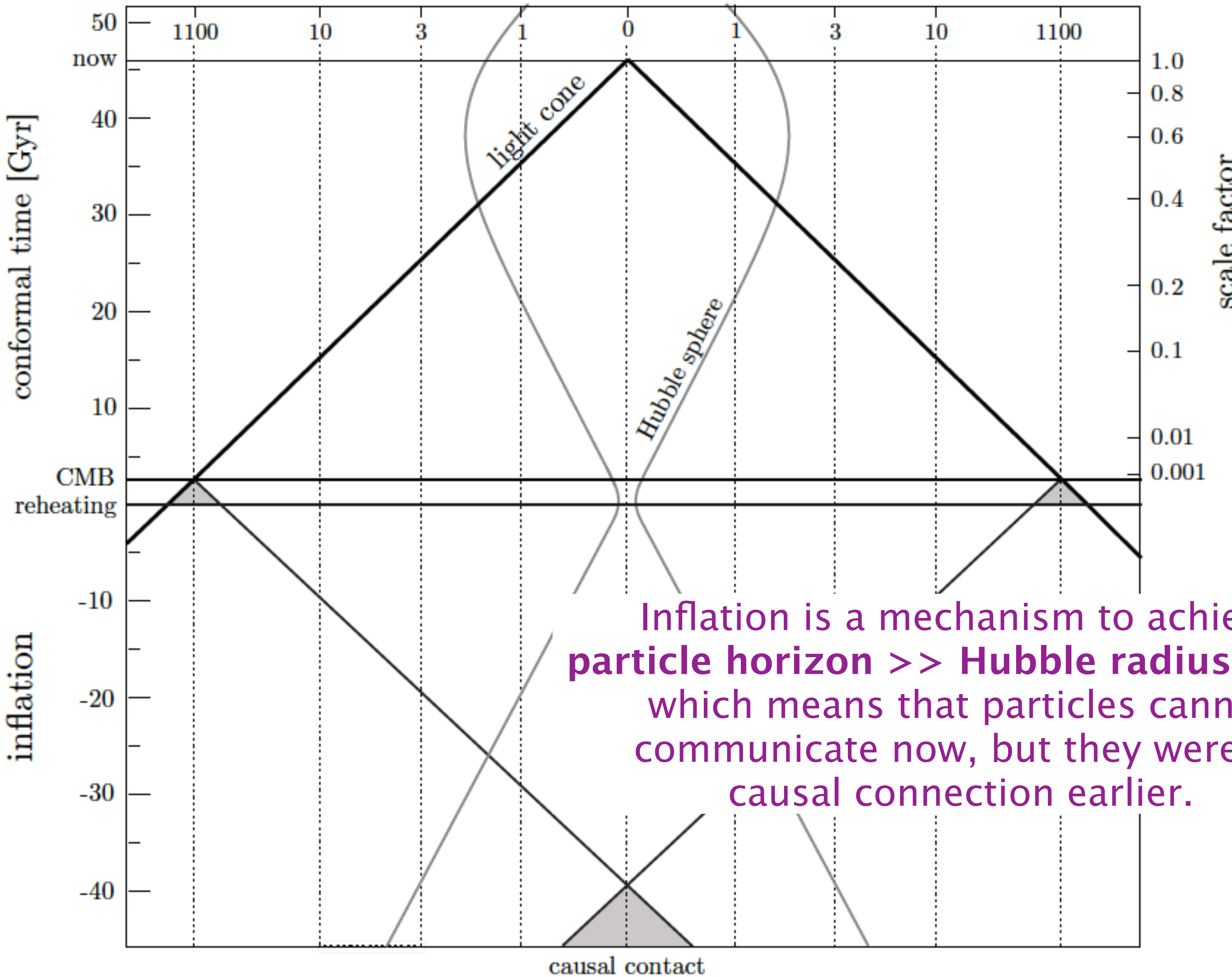
Inflation & the horizon problem



Inflationary solution to the horizon problem: The comoving Hubble sphere shrinks during inflation and expands during the conventional Big Bang evolution (at least until dark energy takes over at a≈0.5). **Conformal time during inflation is negative (i.e. there is time before and after τ=0).** The spacelike singularity of the standard Big Bang (τ=0) is replaced by the reheating surface. All points in the CMB have overlapping past light cones and therefore originated from a causally connected region of space.

Image credit: Daniel Baumann
(see www.damtp.cam.ac.uk/user/db275/Cosmology/Lectures.pdf)

Inflation & the horizon problem



Inflation is a mechanism to achieve **particle horizon >> Hubble radius $(aH)^{-1}$** which means that particles cannot communicate now, but they were in causal connection earlier.

Image credit: Daniel Baumann
(see www.damtp.cam.ac.uk/user/db275/Cosmology/Lectures.pdf)

Predictions of inflation

Inflationary models make **specific set of predictions that can be verified with CMB data:**

- Small spacial curvature
- Nearly scale-invariant spectrum of density perturbations
- CMB temperature anisotropies from large to small angular scales (Sachs-Wolfe effect and acoustic peaks)
- Gaussian perturbations
- Existence of primordial gravity waves!

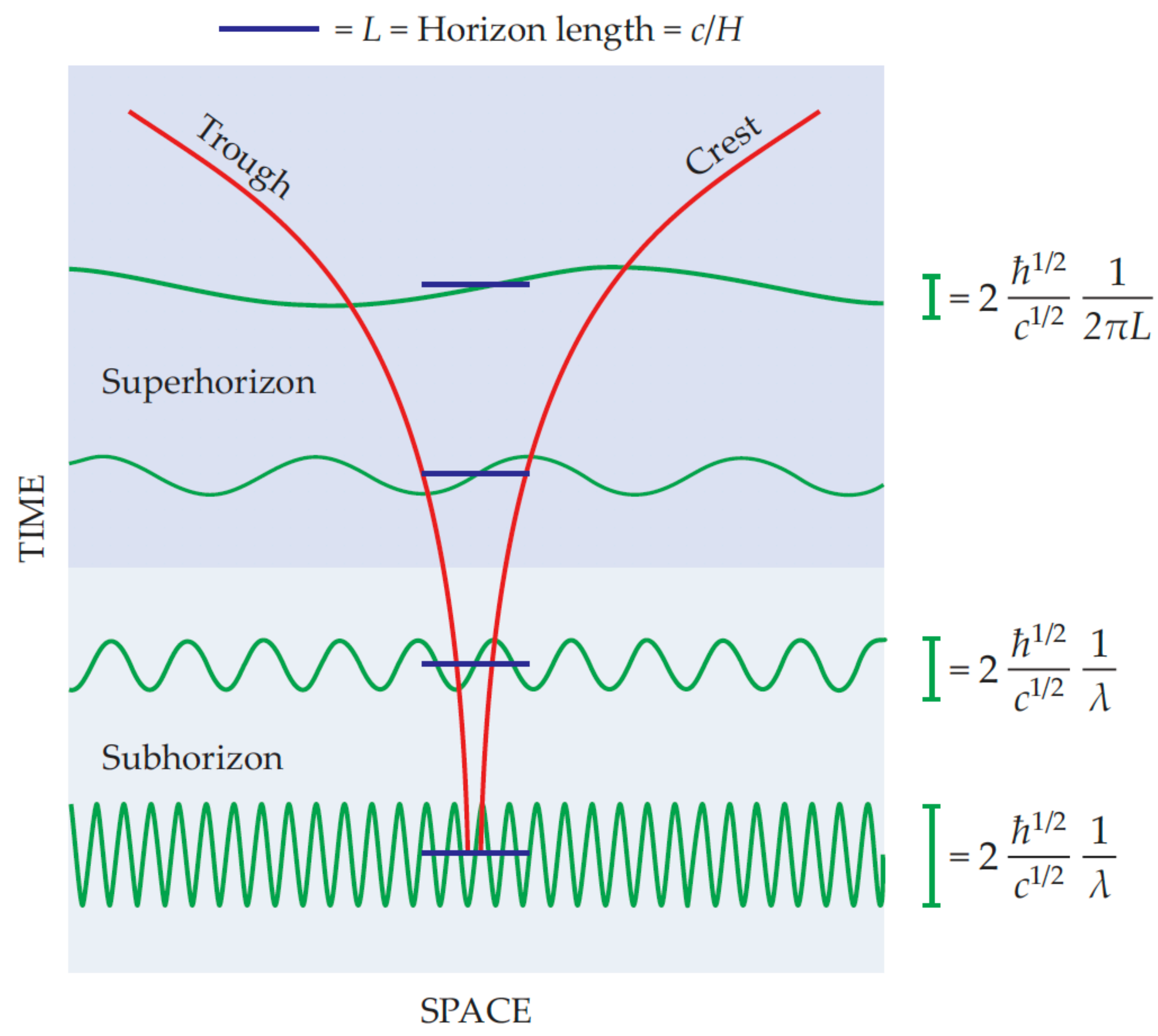


Figure from Carlstrom, Crawford & Knox (2015), Physics Today