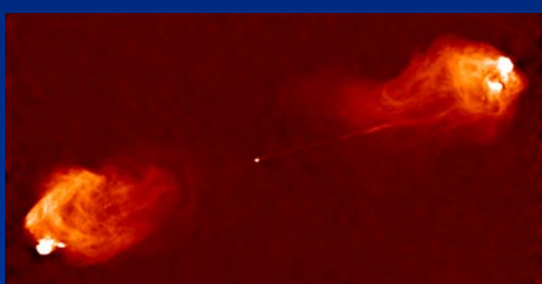
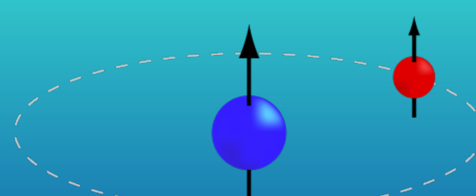
Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg





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23.10. Emission mechanisms, physics of radiation (HB)
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27.11. Continuous radiation (free-free, synchrotron, dust) (HL)
04.12. Radiation transfer & CMB (HL)
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18.12. Buffer ...
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
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05.02. Exam week

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Topics for today:

- radiative transfer (very basic, on the blackboard)

- frequency dependence of the optical depth

- Cosmic Microwave background

Opacities and intensities as a function of frequency

In the next few slides, I will show three curves that show the frequency dependence of different quantities for the examples of free-free radiation and dust emission.

(a) Always, the black dashed curve shows the full Planck function $B_\nu(T)$ (not only the Rayleigh-Jeans approximation) over frequency.

(b) The red dotted curve shows the behaviour of the optical depth τ_ν as a function of frequency.

(c) Finally, the black continuous curve always shows the full expression of the intensity: $I_\nu = B_\nu(T) \cdot (1 - \exp(-\tau_\nu))$.

Although I always plot the full expression for I_ν, the limiting cases:

$I_\nu \sim B_\nu(T)$ for $\tau_\nu >> 1$ and $I_\nu \sim \tau_\nu \cdot B_\nu(T)$ for $\tau_\nu << 1$

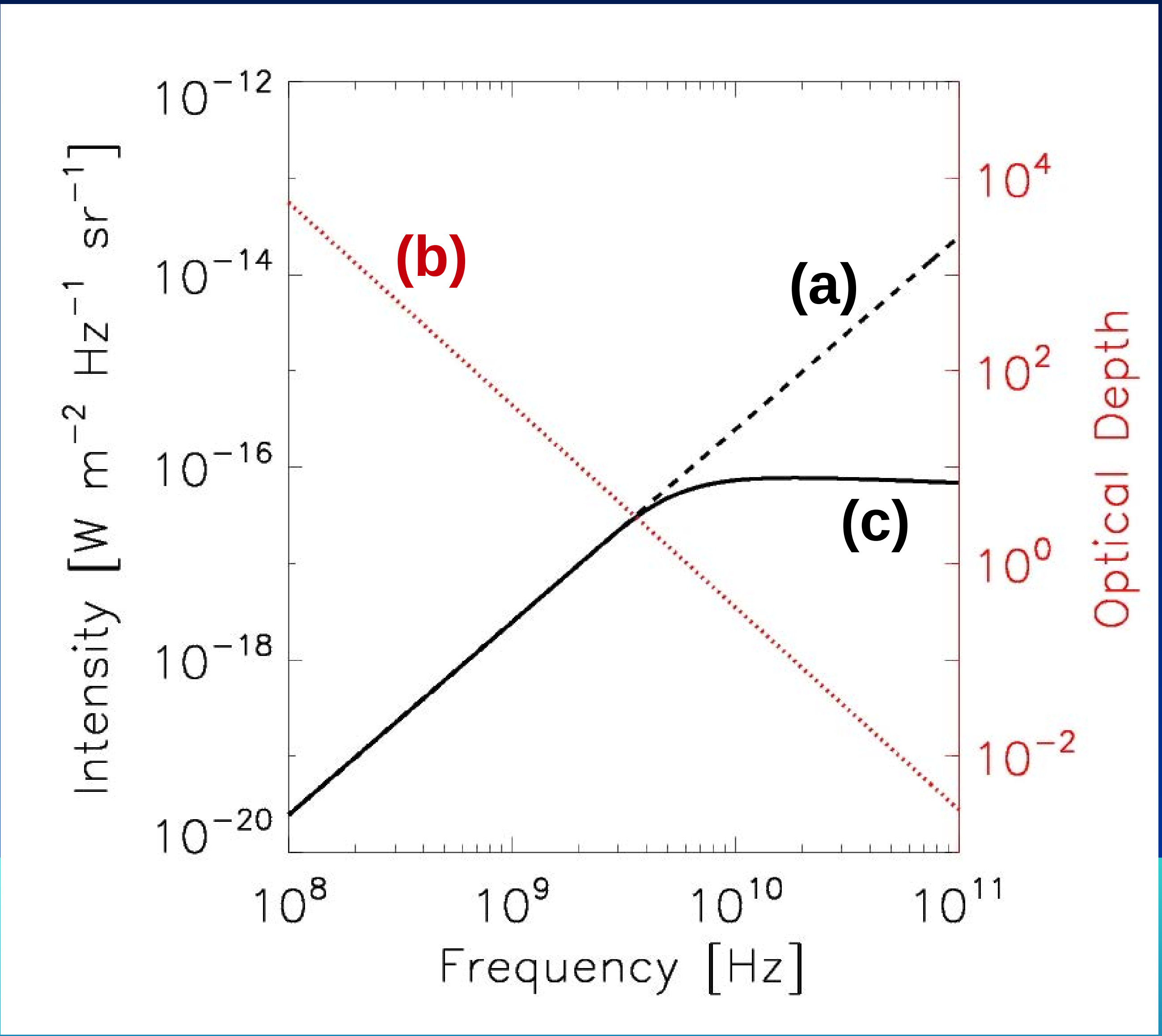
naturally occur in the plots !

Remember from the previous lecture, we eventually obtain the classic expression for the optical depth of free-free emission:

$$\tau_\nu \approx 3.28 \times 10^{-7} \left(\frac{T_\mathrm{e}}{10^4\ \mathrm{K}}\right)^{-1.35} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.1} \left(\frac{EM}{\mathrm{pc\ cm}^{-6}}\right)$$

The radio spectrum of our idealized HII region. It is a black body $B_\nu(T_e)$ at low frequencies, with slope 2 (if assuming a uniform cylinder) and < 2 otherwise. At some frequency the optical depth $\tau_\nu \sim 1$, and at much higher frequencies the spectral slope becomes ~ -0.1,because the opacity coefficient $\kappa_\nu \sim \nu^{-2.1}$.

Optical depth and intensity – Case 1: free – free emission



The radio spectrum of a typical ultracompact HII region.
$EM = 10^8$ pc cm^{-6}
$T_{e-} = 8{,}000$ K

(a) The Planck function $B_\nu(T_e)$:
In the classic Rayleigh-Jeans limit, its frequency dependence is $B_\nu \sim \nu^{2}$

(b) frequency dependence of the ff-optical depth $\sim \nu^{-2.1}$ (see the right scale for this curve)

(c) At low optical depth, the intensity is a product of B_ν and τ_ν, the resulting frequency slope is -0.1 !

Remember from the previous lecture, we eventually obtain an expression for the dust emission optical depth:

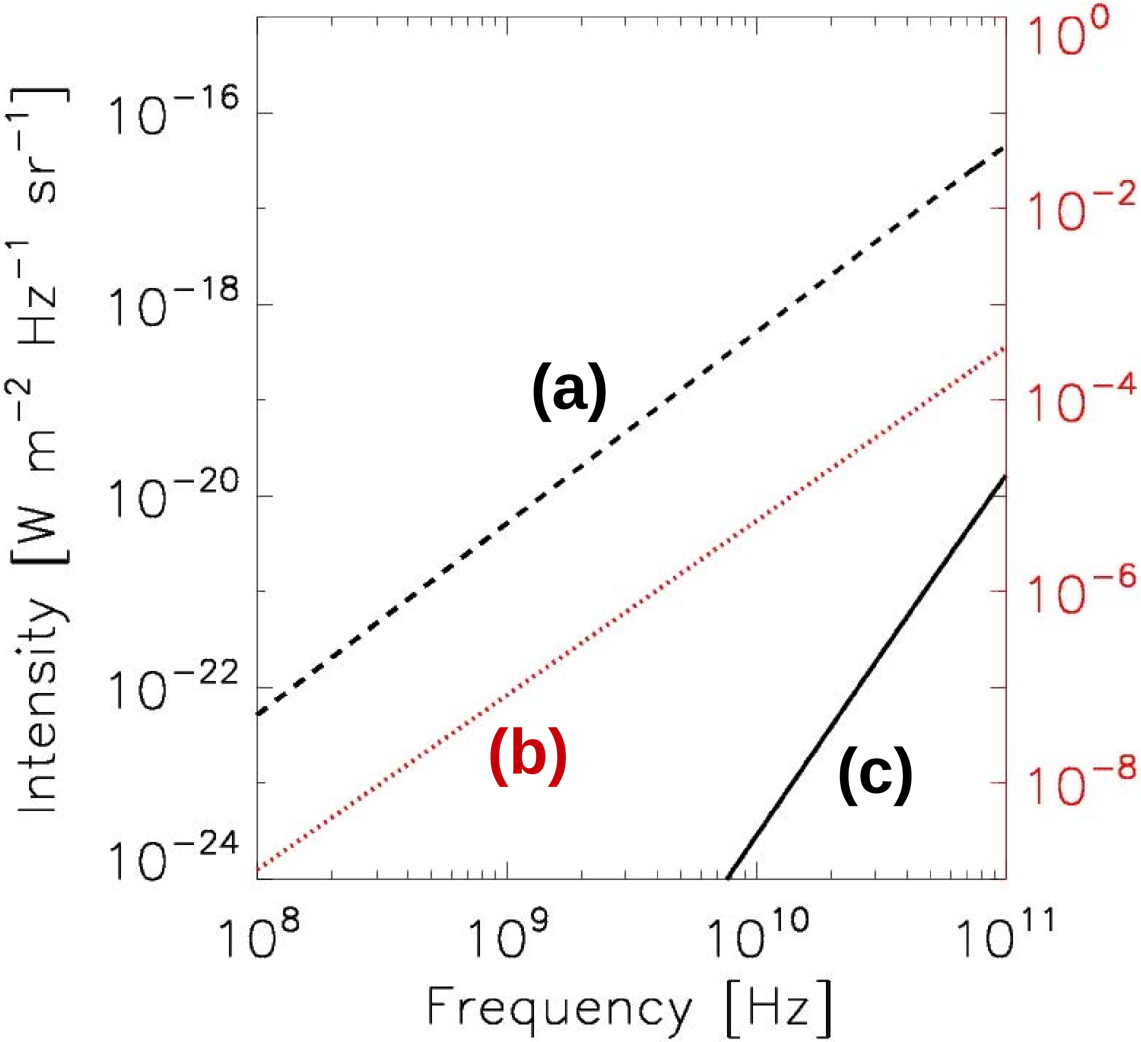
Optical depth τ_ν = dust opacity κ_ν [cm^2 / g] · dust column density [g / cm^2]

$$\tau_\nu = \kappa_\nu \int_{\mathrm{visual}} \rho \, dl,$$

$$\left[\frac{\kappa_\nu}{\mathrm{cm}^2\ \mathrm{g}^{-1}}\right] = \kappa_0 \left[\frac{\nu}{1000\ \mathrm{GHz}}\right]^\beta,$$

The benchmark opacity κ_0 (here given at 1000 GHz) and the power law slope β are debated in the literature and are different for different environments ...

Optical depth and intensity – Case 2a: dust emission emission (low frequencies)



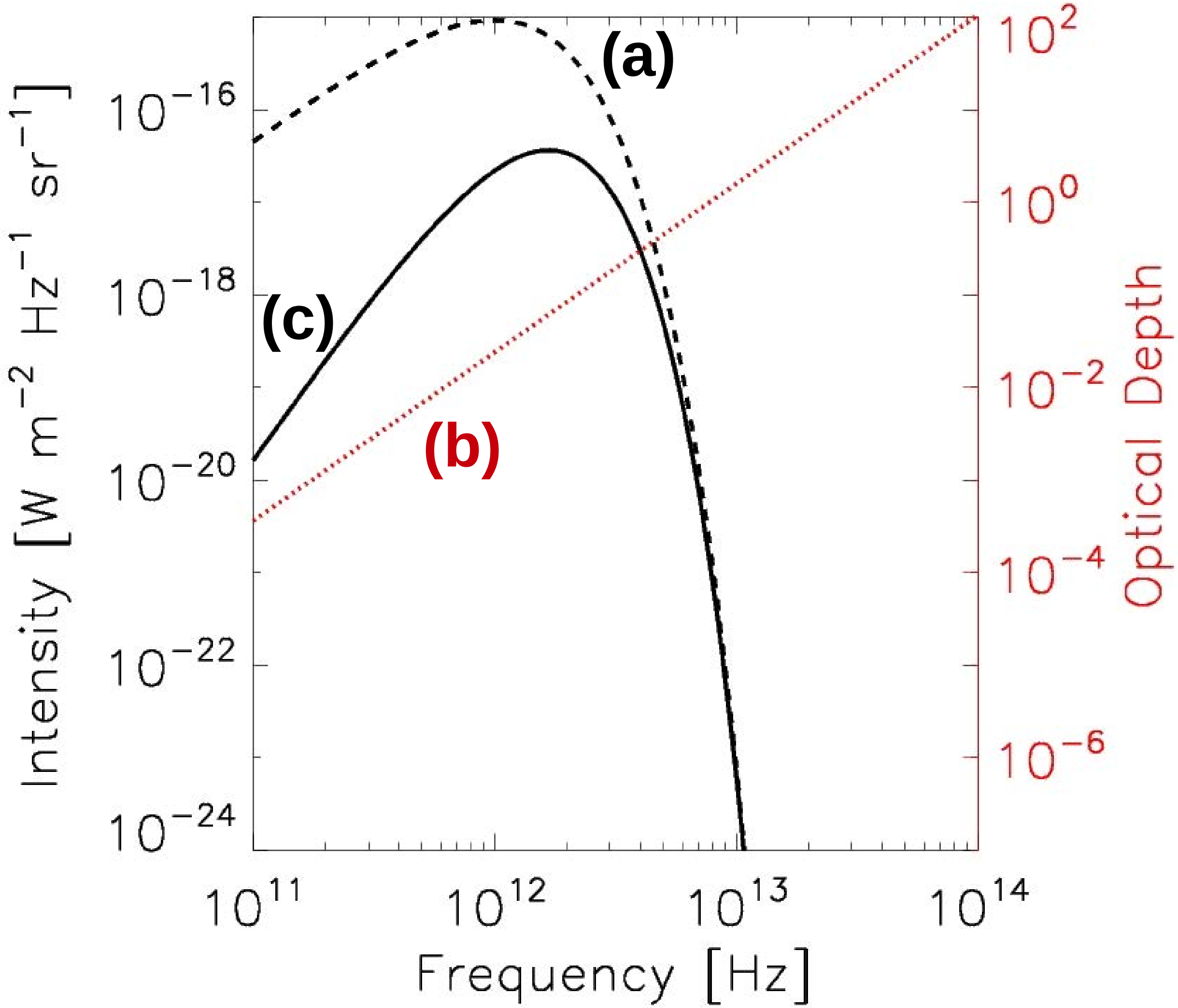
Dense interstellar medium dust.
β = 1.82 (dust opacity slope in standard non-coagulated dust)
T_d = 17 K (typical for ISM dust)
κ_0 = 4.8 cm^2 / g (at 1000 GHz)
Dust column density = 0.005g/cm^2

(a) The Planck function $B_\nu(T_d)$:
In the classic Rayleigh-Jeans limit, its frequency dependence is $B_\nu \sim \nu^{2}$

(b) frequency dependence of the dust-optical depth $\sim \nu^{1.82}$ (see the right scale for this curve)

(c) At low optical depth, the intensity is a product of B_ν and τ_ν ,the resulting frequency slope is +3.82 !

Optical depth and intensity – Case 2b: dust emission emission (high frequencies)



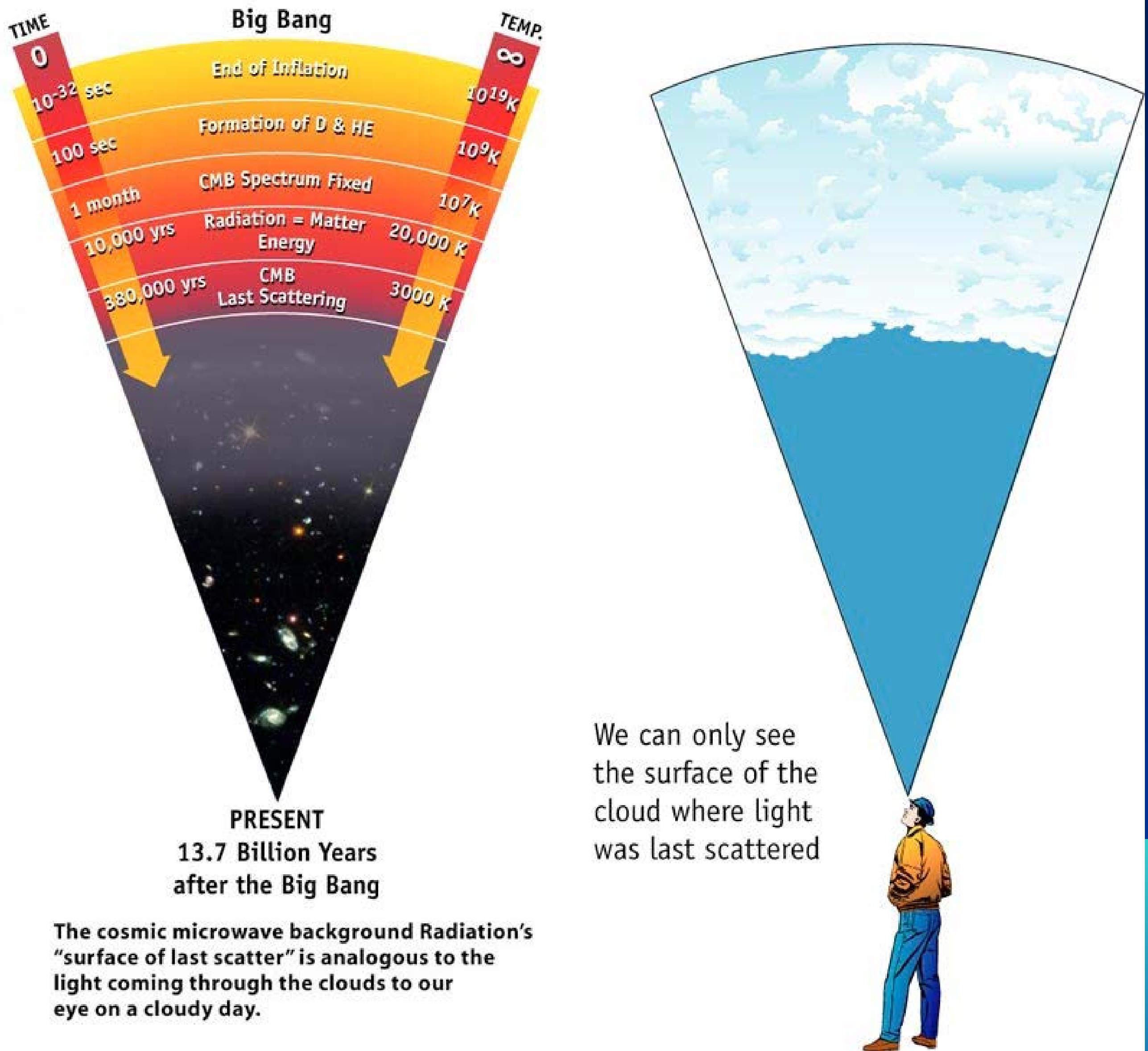
Dense interstellar medium dust.
β = 1.82 (dust opacity slope)
T_d = 17 K (typical for ISM dust)
κ_0 = 4.8 cm^2 / g (at 1000 GHz)
Dust column density = 0.005g/cm^2

(a) The Planck function $B_\nu(T_d)$:
At high frequencies, it turns from the Rayleigh-Jeans limit to the full Planck function.

(b) frequency dependence of the dust-optical depth ~ $\nu^{1.82}$ (see the right scale for this curve)

(c) At high optical depth, the real intensity eventually aligns with the Planck function B_ν !

The Cosmic Microwave Background : a few introductory remarks



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

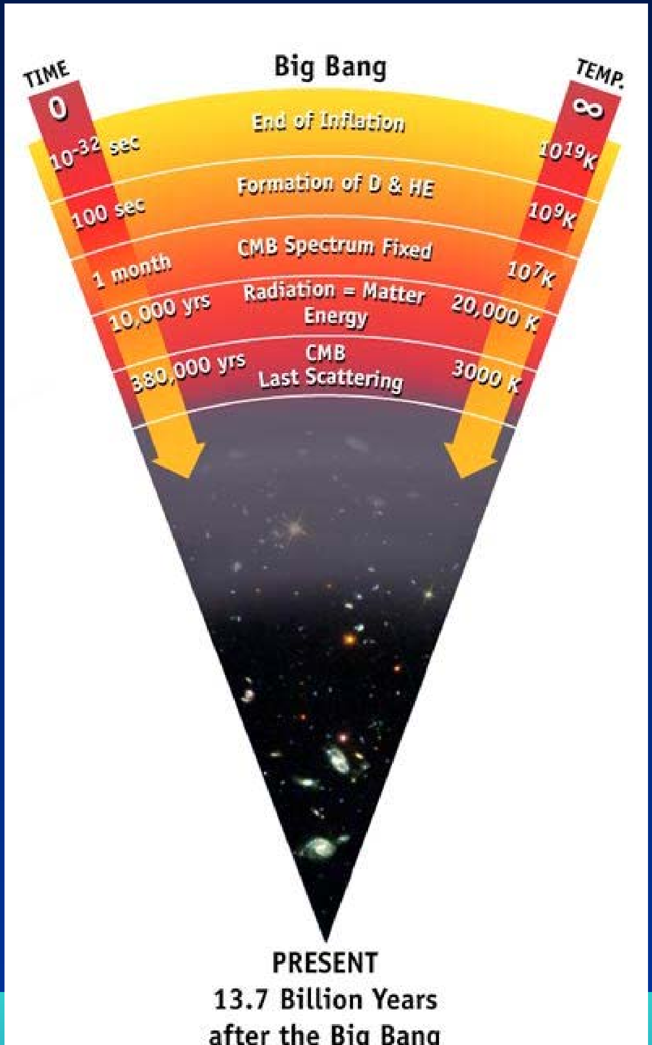
The Big-Bang scenario predicts the existence of a remnant photon radiation field.

Energy of the CMB stems from annihilation of particle/anti-particle pairs in a very early phase of baryogenesis (first few seconds after the BB).

Universe expansion lowers the temperature of the photon field. Eventually, E too low to ionise hydrogen → final recombination

Photon field and atom decouple: "Surface of last scatter" at ~ 380,000 yrs after the BB ... at a redshift z ~ 1100.

The Cosmic Microwave Background : a few introductory remarks



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

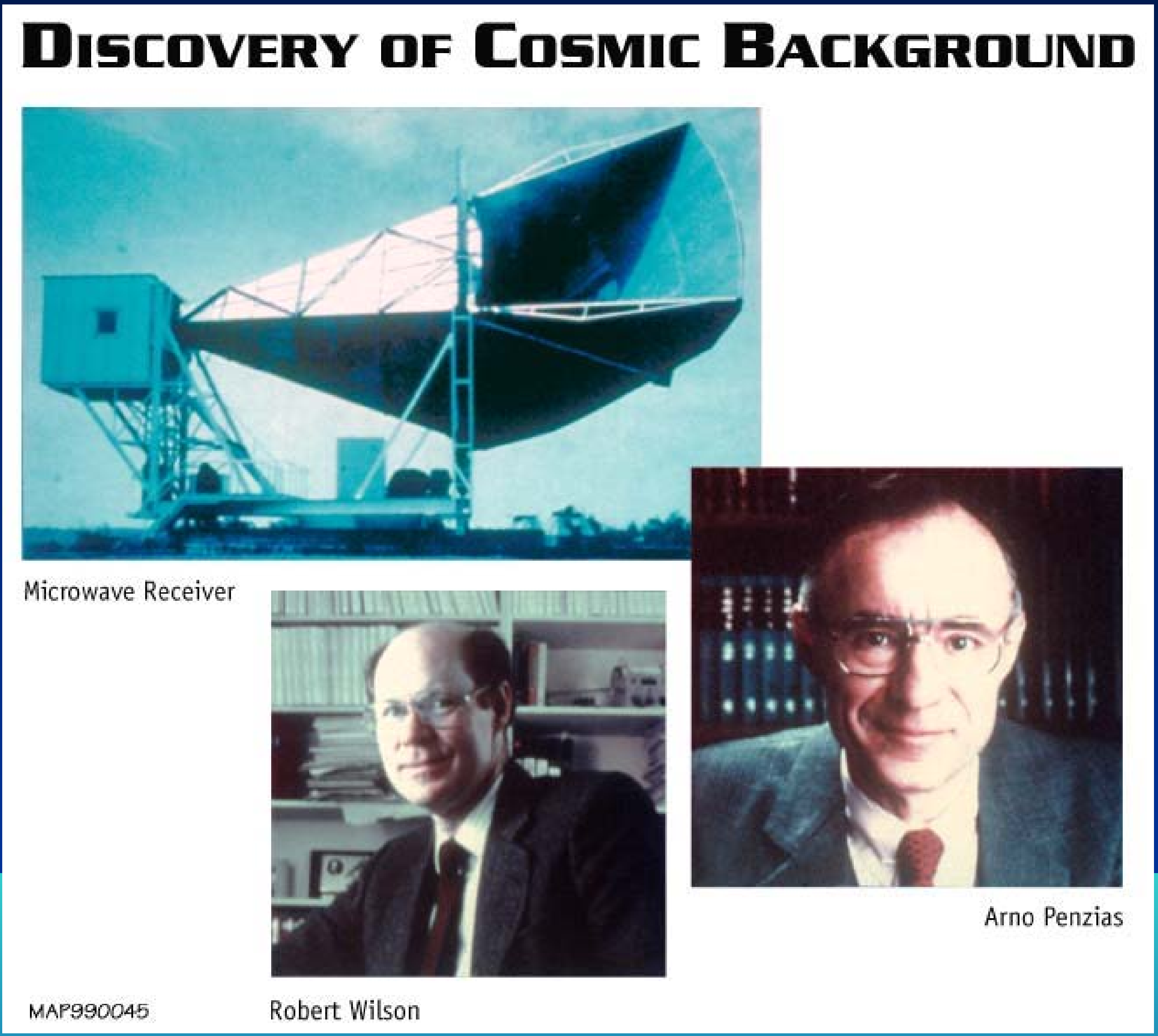
Interestingly, the final recombination happens at T ~3,000 K, while the ionisation of hydrogen (~ 13.6 eV) would call for T ~10^5 K.

A conundrum? Not necessarily!

Keep in mind:
(a) There are a billion CMB photons for every proton in the Universe.
(b) Due to previous 380,000 yrs of continuous interaction with the matter in the optically thick regime, the photon field is thermalised and a very good approximation for a "black body".

→ high energy tail of the Planck distribution of the photons allows them to keep the comparatively small number of hydrogen atoms ionised until temperatures and energies << 13.6 eV !

The Cosmic Microwave Background finally found observationally:



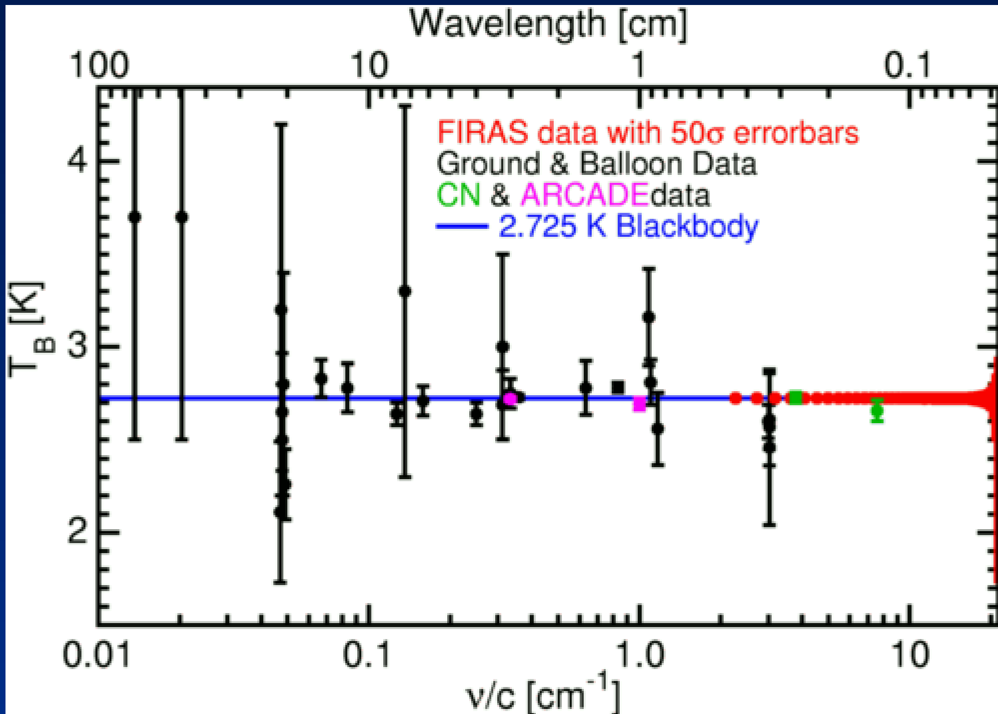
Penzias & Wilson 1965: investigations of noise characteristics of a high-sensitive antenna with very low beam side-lobes at λ = 7.35 cm (a horn antenna as shown here)

Found excess signal, after all other sources of noise had been explained or removed …

One man's noise is an other man's signal! Detection seems to agree with prediction from BB Theory, T ~ 3 K, basically isotropic (which prevents a standard on-source/off-source differential measurement)

Nobel price for Penzias & Wilson in 1978

The next step for CMB measurements: precision measurements



COBE satellite (1992): FIRAS instrument precisely measured the CMB temperature

Pinpointed at $T_0 = 2.725$ K, better than ever before …

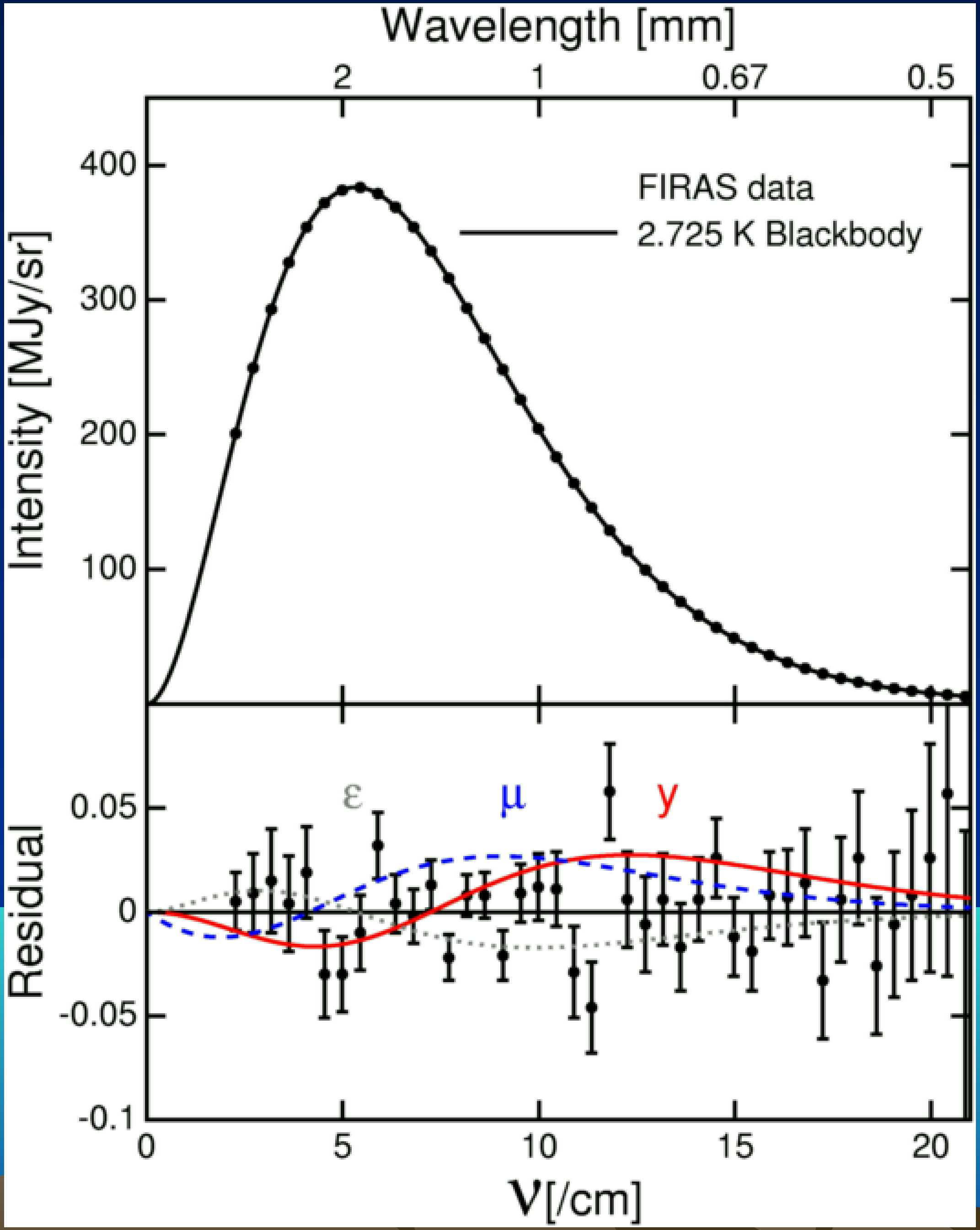
Interesting: earlier periods in the evolution after the recombination had seen a warmer CMB
$T_{CMB}(z) = T_0\,(1 + z)$

But: "earlier" means also more redshifted for us observers!
$\lambda = \lambda_0\,(1 + z)$

→ *redshift makes the warmer (but redshifted) distant universe appear to have the same temperature as today*

The universe on the CMB level looks isothermal to us!

The next step for CMB measurements: characterising temperature anisotropies



COBE satellite (1992): FIRAS

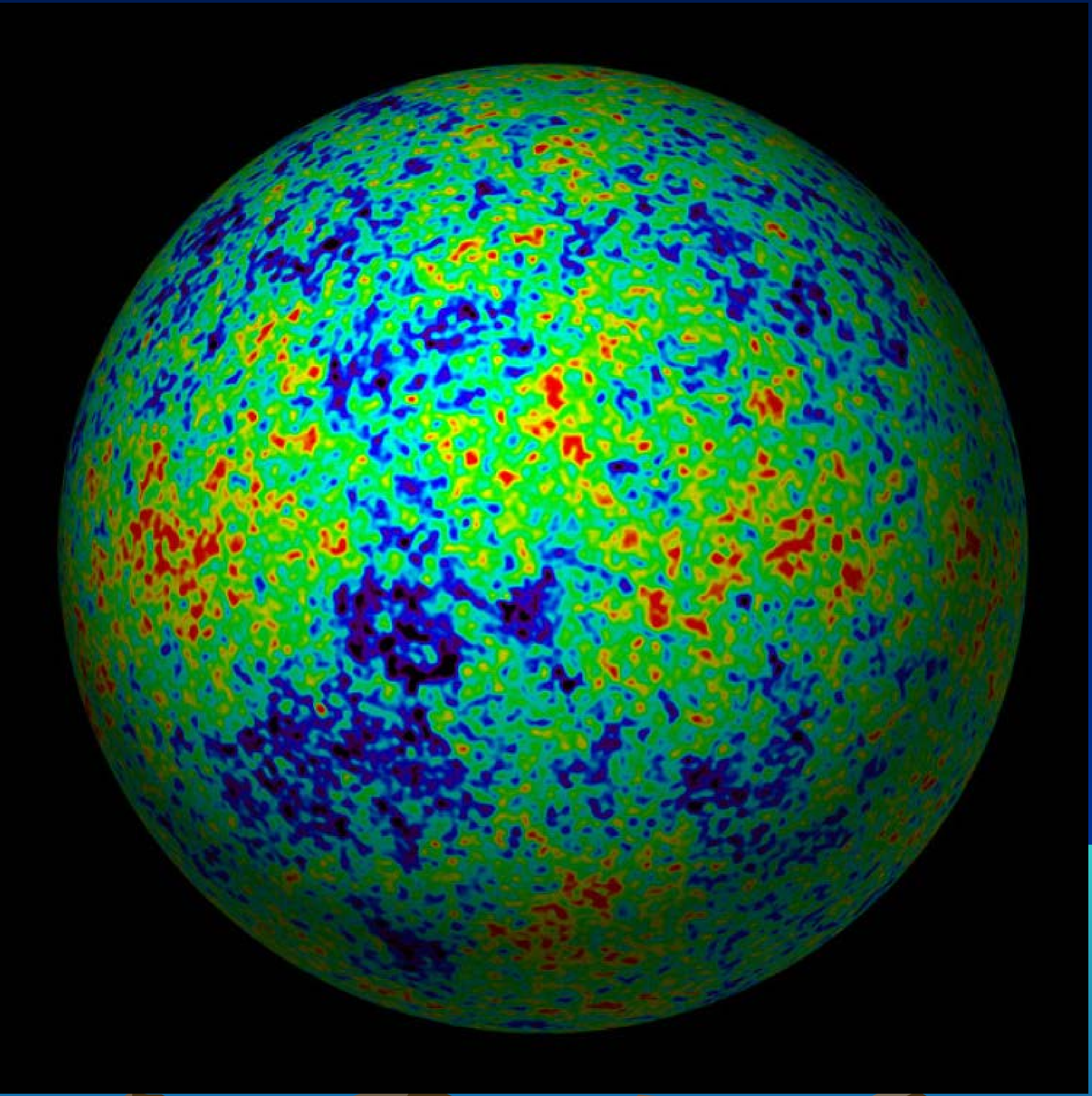
The spectral energy distribution shows very good approximation to a black body … peak in the 2-mm band!

But real temperature anisotropies on sub-milli-Kelvin level have been revealed!

The fundamental FIRAS measurement is the residual plot at the bottom. This is what FIRAS actually measured: the difference between the CMB and the best fitting blackbody.

***ε**, μ and y as 3 different physical anisotropy models*

Enormous refinement of the CMB measurements: WMAP (2001 – 2010)



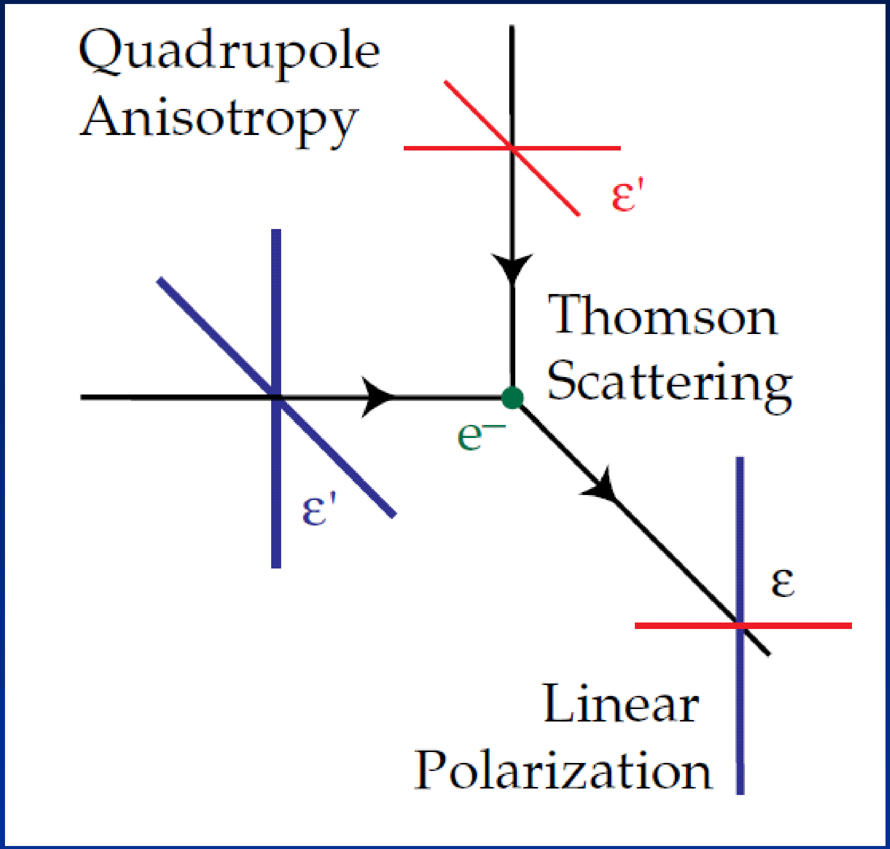
Results of the recent satellite mission WMAP (Wilkinson Microwave Anisotropy Probe):

Small fluctuations in the brightness of the CMB ($\Delta T \sim 0.0002$ K), greatly accentuated in this false-color image.

WMAP: NASA satellite with two ~ 1.5 m main mirrors.
5 passbands from 22 to 90 GHz

Differential experiment: WMAP measures the temperature difference between two points in the sky rather than measuring absolute temperatures.

One interesting quantity to get from the CMB: Polarisation mapping



Taken from Hu & White 1997,
New Astronomy 2, 323-344

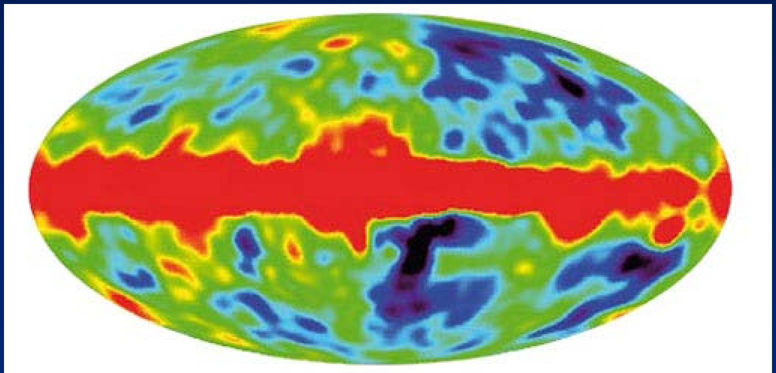
Possible with the Planck satellite of ESA (launched May 2009):

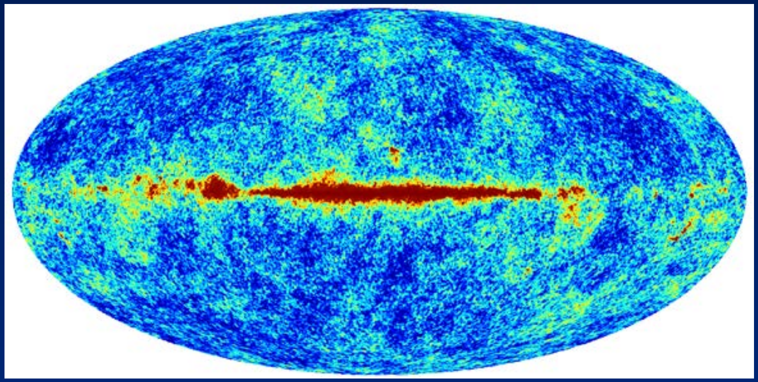
Linear polarisation maps to reveal imprints of quadrupole temperature variations

Thomson scattering of radiation with a quadrupole anisotropy generates linear polarization. Blue colors (thick lines) represent hot and red colors (thin lines) cold radiation.

Keep in mind: warmer patches give slightly higher intensities.
And: EM waves are transversal waves. After scattering, original wave components in the new longitudinal direction cannot be propagated.

CMB temperature anisotropy studies: from COBE to Planck





COBE satellite (measured) Planck satellite (a priori simulation)

Both maps in Aitoff projection

The real COBE measurements, compared to an ESA simulation of what to expect with Planck: Much better spatial resolution to trace temperature variations on higher spatial frequencies

→ better constraints for cosmological models ...

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Scripts at : http://www.mpia.de/homes/beuther/lecture_ws1213.html

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