CMB@60

Turin, May 28th, 2025

From the CMB discovery to the launch of the COBE spacecraft (Nov. 1989)

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One of the first theoretical predictions made after the discovery of the CMB was
Silk Damping (J.Silk, ApJ, 1968). It was discovered by the South Pole Telescope
and several other instruments, more than 40 years later of the theoretical prediction.

Preface

March 1965, I (a 5th year student who before had studied physics and elementary particle theory) became a diploma student of Yakov Zeldovich

I got to study a copy of my mentor's review of the comparison between the predictions **of the hot model of the Universe** proposed by George Gamov and the **cold model** proposed by Zeldovich himself.

June 1965: Great news about ***the discovery of the 3 K radiation by Penzias and Wilson*** reached Moscow.

A week later, Zeldovich made a long report at the All-Moscow Astrophysical Seminar and spoke about the ***significance of this discovery*** and the ***most important stages of the evolution of the Universe*** and mentioned ***the primary density perturbations,*** leading to the formation of inhomogeneities of matter in the Universe.

He talked about the ***dipole anisotropy*** of the CMB, the possibility of an ***initial anisotropy*** of the Universe that should have left traces on the CMB angular distribution.

I knew from his 1965 review of the importance of helium abundance and the results of calculations of light element fusion by Hayashi (1950), Fermi and Turkevich in the USA, and Smirnov (1964) in Zeldovich's group at the secret (at that time) nuclear center in Sarov. The practically final result was found by Wagoner et al (1967)

I also knew about the work done under Zeldovich's supervision in Moscow by Doroshkevich and Novikov (1964), where the importance of the of the background radiation measurements in radio waves was demonstrated.

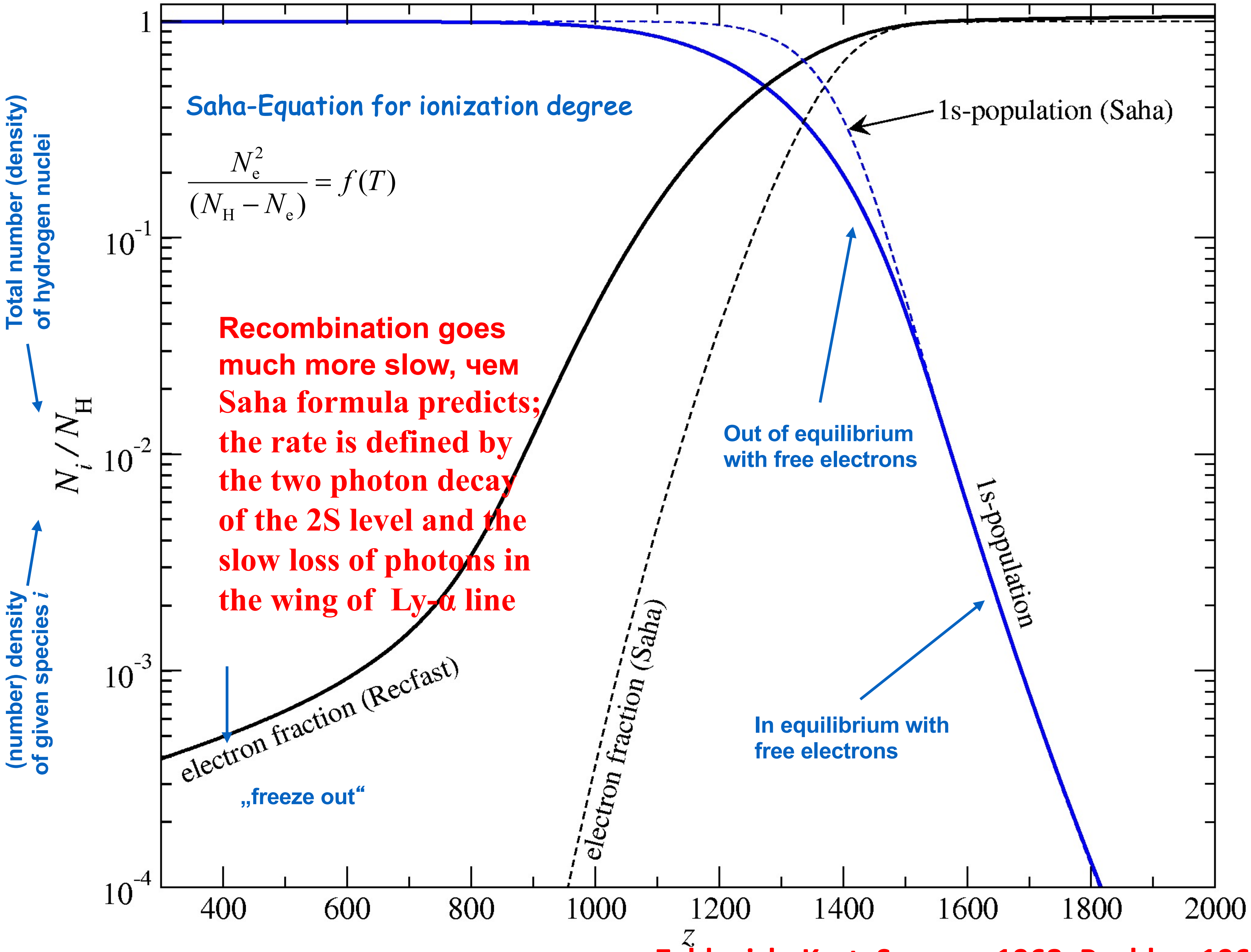
I also read about the stage of dominance of electron-positron pairs before the period of nuclear reactions and even about the recombination of the primary plasma in equilibrium with the black body radiation.

The written version of this talk was then published by Zeldovich in Russian in the Soviet Physics Uspekhi (1966), and six months later, an English translation appeared.

Zeldovich told me at that time that since I knew quite a lot about elementary physical processes, the search for traces of intergalactic gas and physical processes in the early Universe would be my main occupation in the preparation of my diploma thesis.

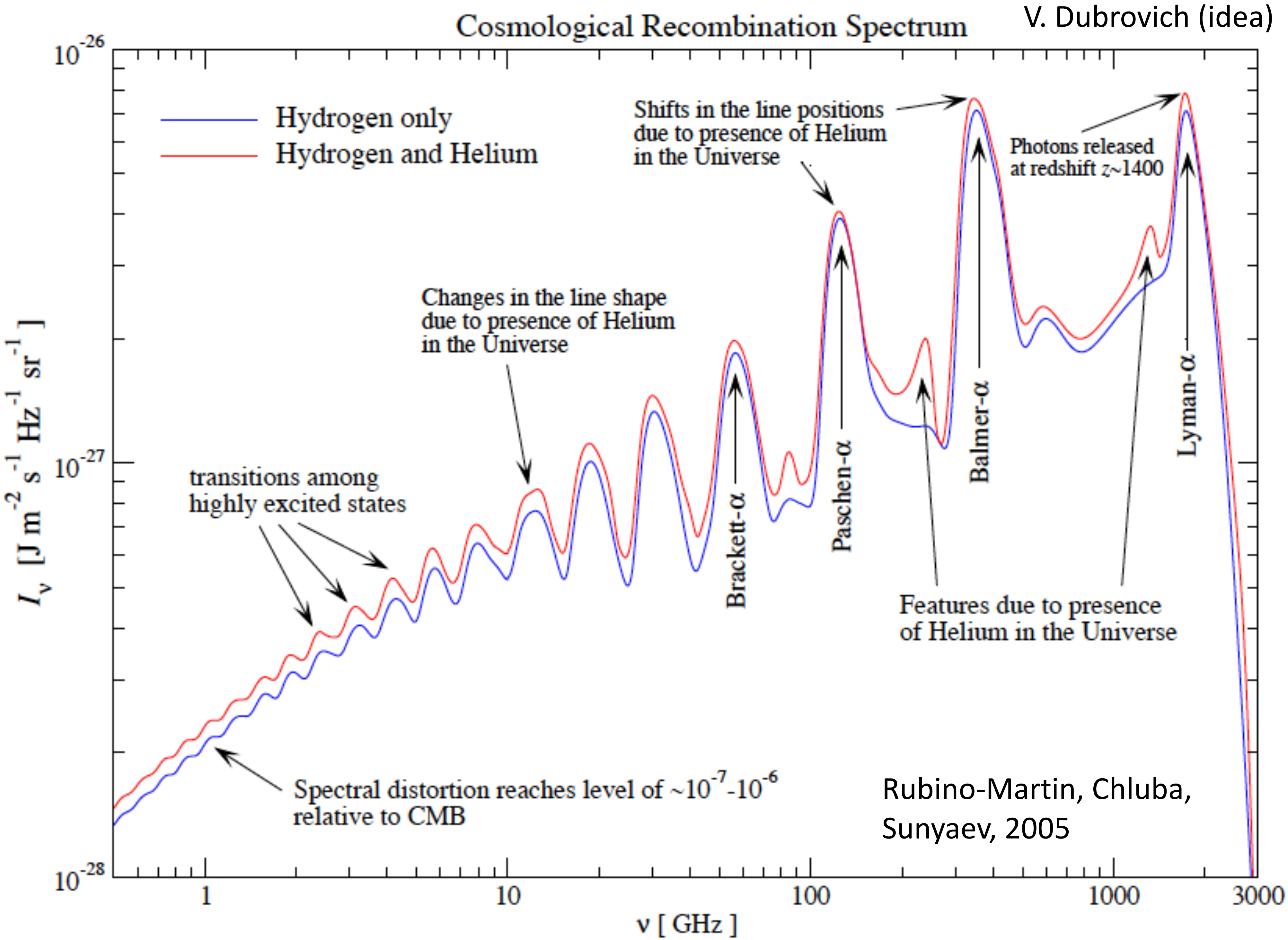
Recombination of the primordial plasma

1. Strong deviations from simple Saha ionization equilibrium
2. Reason: slow escape of the Ly-alpha photons due to the Hubble expansion
3. The role of the 2s level decay (lifetime 1/8 sec)
4. Transitions between high levels of hydrogen atoms (idea of Dubrovich)
5. Visibility function and CMB angular fluctuations



from Chluba, Sunyaev, 2009

Zeldovich, Kurt, Sunyaev,1968; Peebles, 1968



V. Dubrovich (idea)
Cosmological Recombination Spectrum
Hydrogen only
Hydrogen and Helium
Shifts in the line positions due to presence of Helium in the Universe
Photons released at redshift z~1400
Changes in the line shape due to presence of Helium in the Universe
transitions among highly excited states
Brackett-α
Paschen-α
Balmer-α
Lyman-α
Features due to presence of Helium in the Universe
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
Rubino-Martin, Chluba, Sunyaev, 2005
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
ν [GHz]
10^-26
10^-27
10^-28
1
10
100
1000
3000

Visibility function

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

R. A. SUNYAEV and YA. B. ZELDOVICH

(Received 11 September, 1969)

Astrophysics and Space Science **7** (1970) 3

Last scattering surface

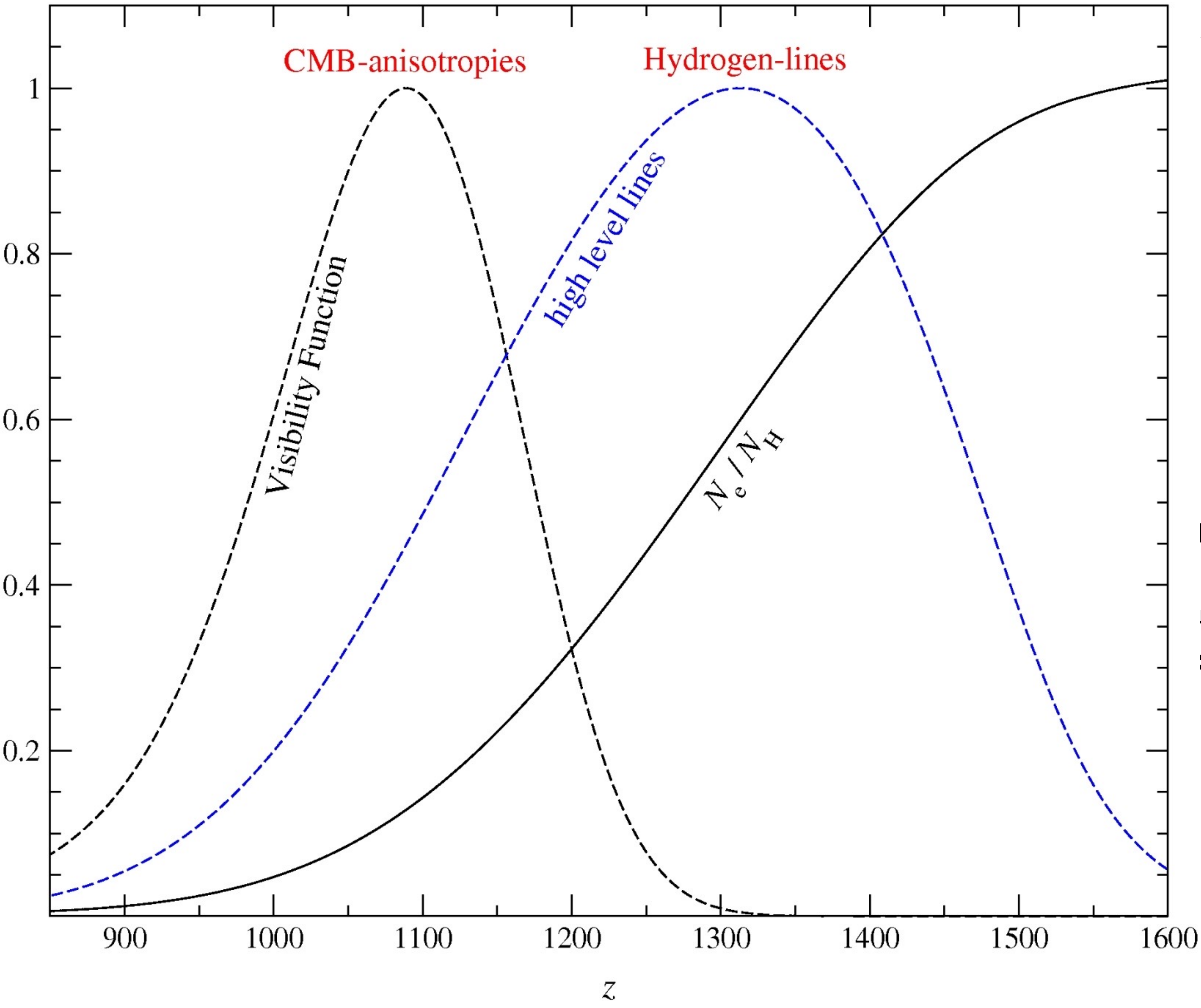
Below we will need the function

$$e^{-\tau}\frac{\mathrm{d}\tau}{\mathrm{d}z} = \sigma_T n_c c H_0^{-1} A z^{-1/2} \exp\left\{-az^{3/2}e^{-B/z} - \frac{B}{z} - \tau_0\right\}, \tag{6}$$

which in agreement with (3) has a sharp maximum for $z_{\max} = 1055$ ($\mathrm{e}^{-\tau}(\mathrm{d}\tau/\mathrm{d}z)_{z=z[\max]} = 3.32 \times 10^{-3}$) and exponentially decreases in both directions, the value of the function decreasing to half its maximum value for $z_3 = 960$ and $z_4 = 1135$. It will be convenient in what follows to approximate this function by a Gaussian function with dispersion $\sigma_z = 75$ whose integral equals 1.

The redshift and the width of this function were very well confirmed by WMAP and then PLANCK spacecraft.

ION*



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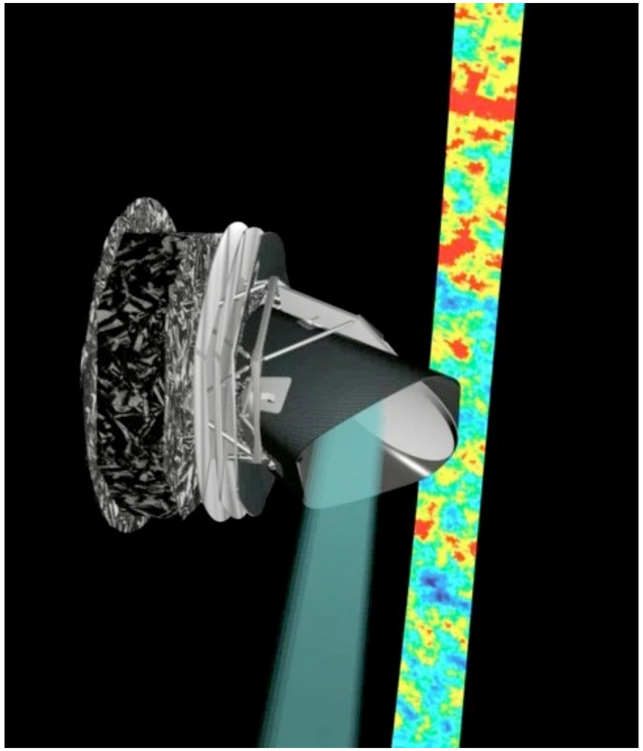


PLANCK spacecraft scans the sky

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION 9

standing sound waves (Lifshits, 1946)

From paper Sunyaev, Zeldovich 1970

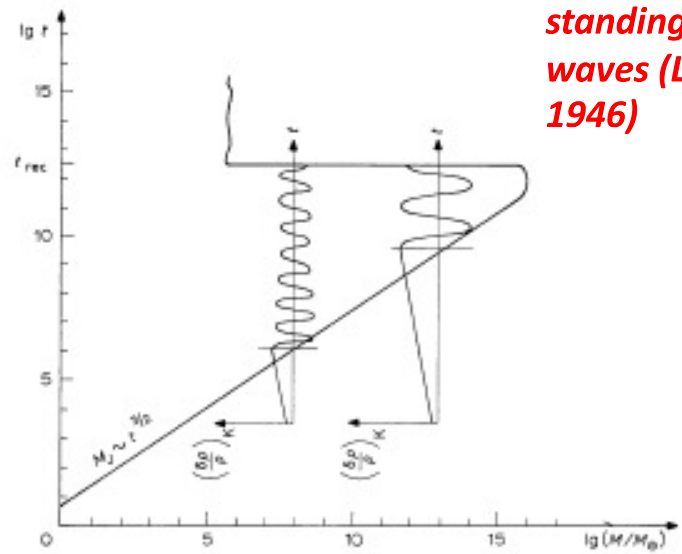
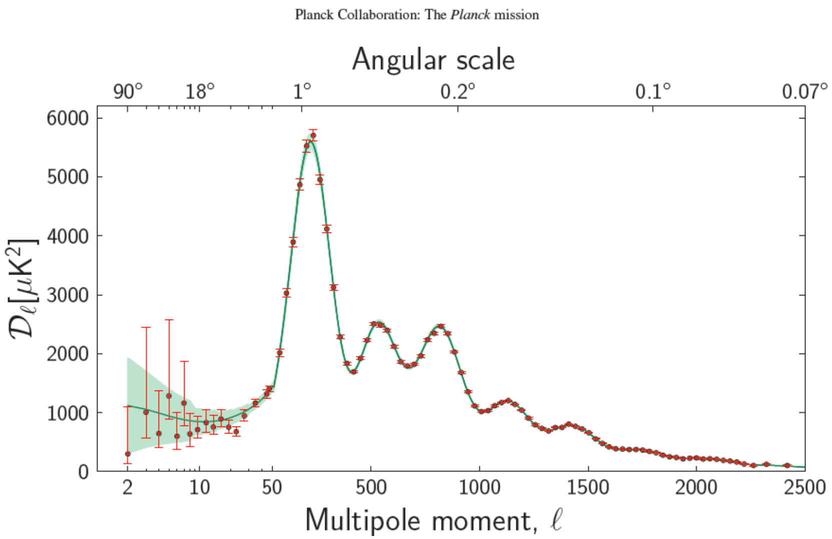


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.



Prediction of acoustic peaks and barionic acoustic oscillations

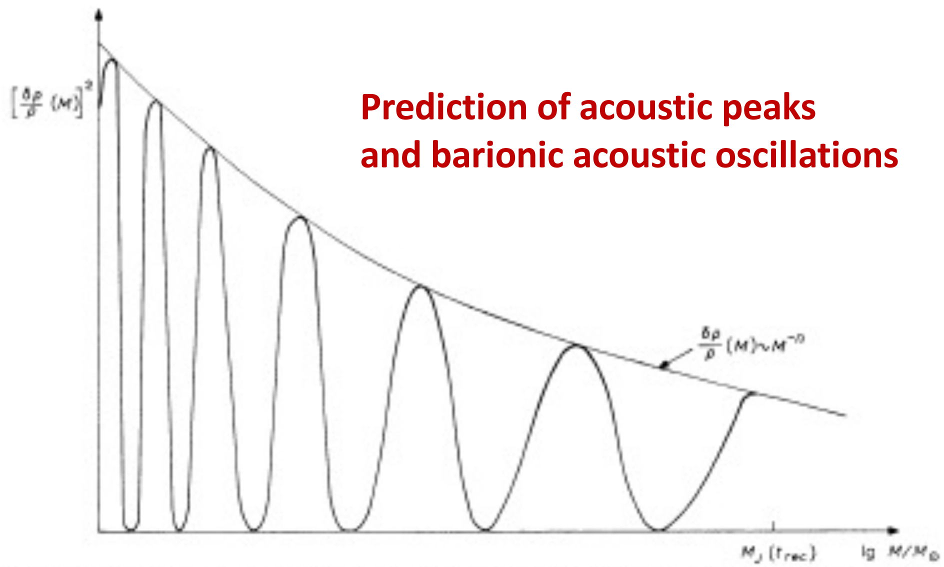


Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

CMB spectral distortions

In the spring of 1966 Yakov Zeldovich asked me to review on the group seminar the preprints of Layzer and Burbidges stating that CMB spectrum is just the stellar light thermalized by the dust.

I decided to check in addition the usual mechanism responsible for black body spectrum production inside hot stars: **the Rosseland free-free optical depth of the Universe for CMB – it was negligibly small up to the time of positron-electron annihilation.**

$$\tau_{\text{free-free}} \sim \int_0^{t(z)} \mathrm{d}t\, n_{\mathrm{e}}{}^2 \sigma_{\mathrm{T}} c \frac{\alpha_{\mathrm{fs}}}{(24\pi^3)^{1/2}} \left(\frac{k_{\mathrm{B}} T_{\mathrm{e}}}{m_{\mathrm{e}} c^2}\right)^{-7/2} \left(\frac{h}{m_{\mathrm{e}} c x_{\mathrm{e}}}\right)^3 (1 - e^{-x_{\mathrm{e}}})$$
$$\sim 4 \times 10^{-5} \left(\frac{1+z}{10^8}\right)^{1/2},$$

but Thomson optical depth was huge.

$$\tau_{\text{Thomson}} = \int_0^{t(z)} n_{\mathrm{e}} \sigma_{\mathrm{T}} c \mathrm{d}t \overset{z \gg z_{\mathrm{eq}}}{\approx} 0.21(1+z)$$ ~ 2 10^7 (z/10^8)

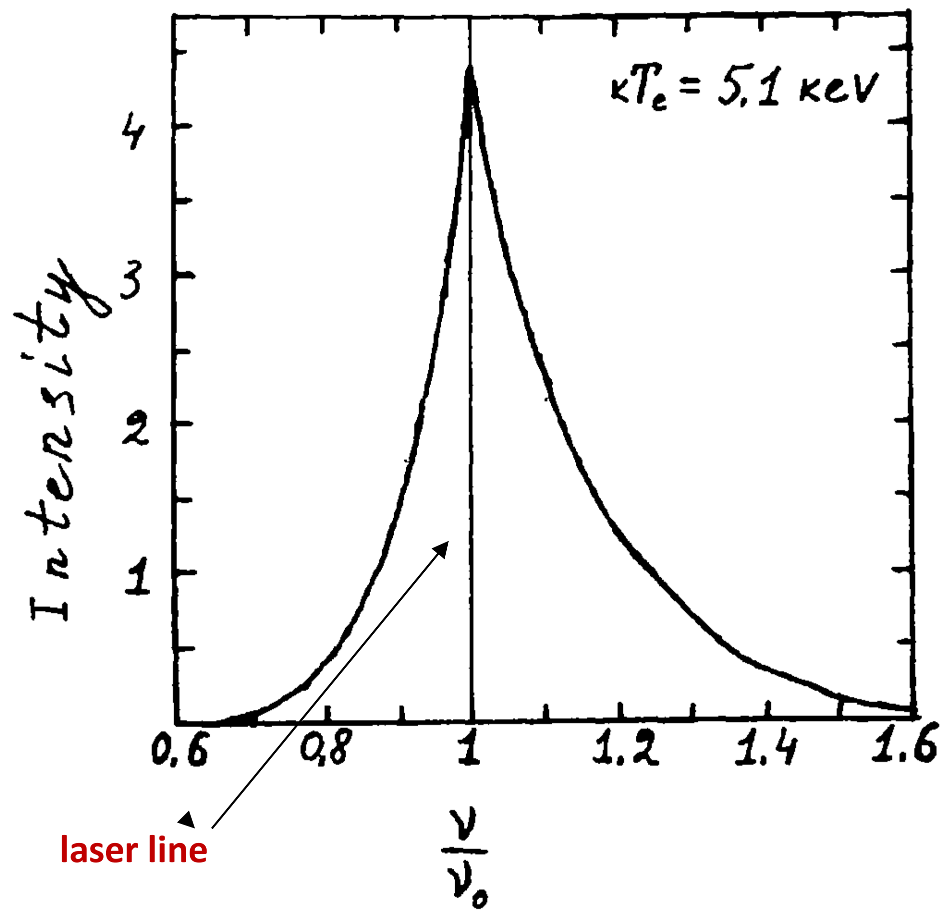
Optical depth – probability for the photon to be absorbed or scattered

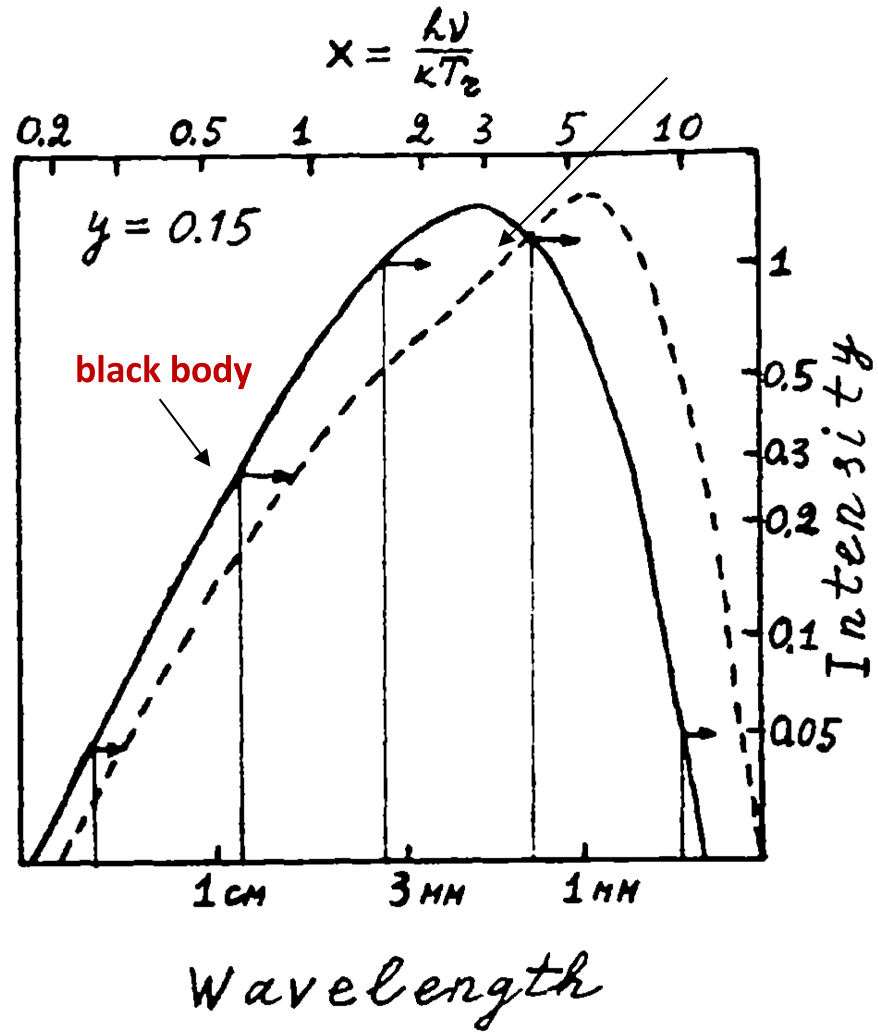
SCATTERING OF RADIATION BY HOT MAXWELLIAN ELECTRONS

y-type spectral distortions (Zeldovich, Sunyaev, 1969)

spectral changes due to doppler-effect on moving electrons

with kTe~ 5 KeV and average velocity of the order of 1/7 c



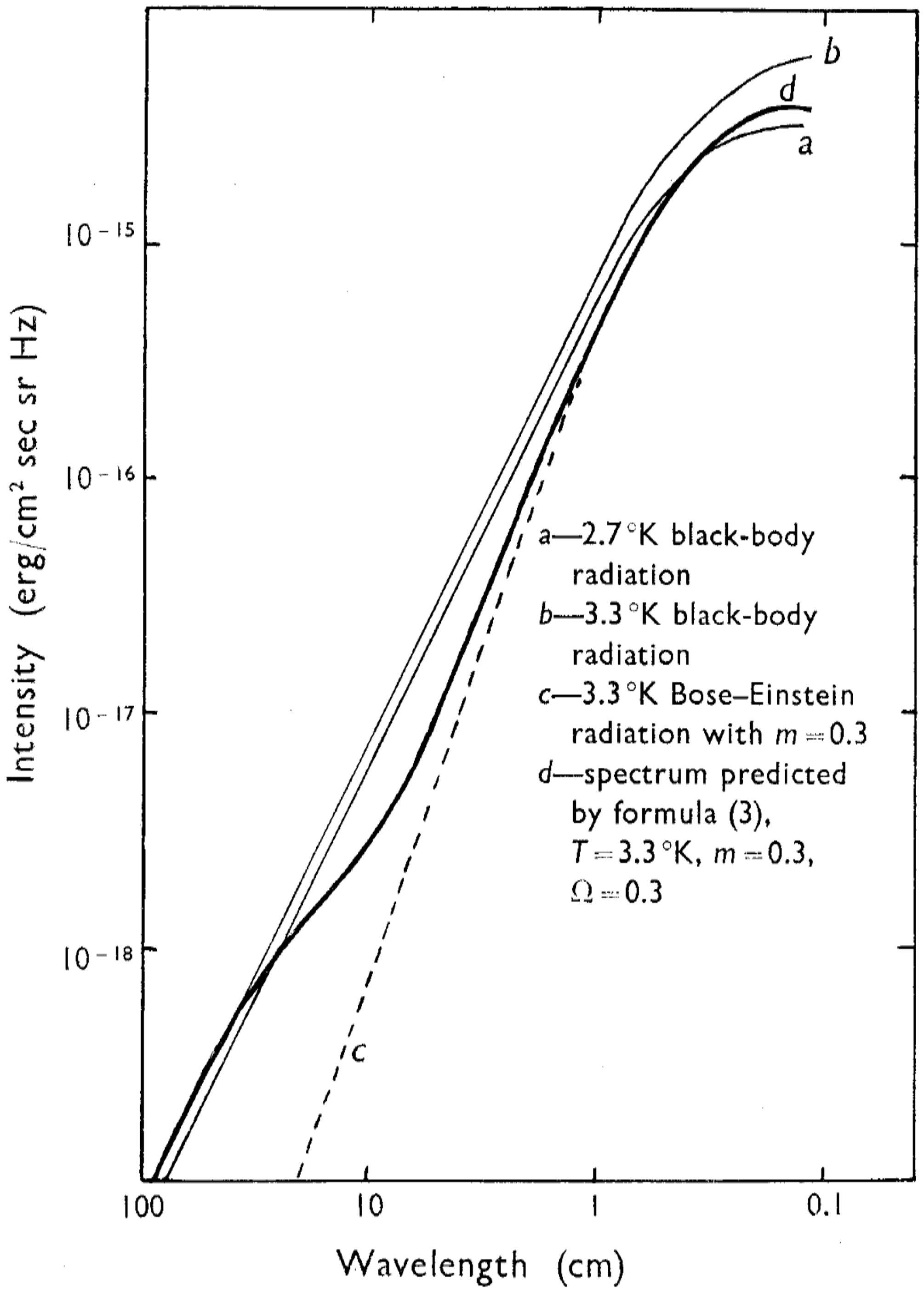


Line is broadened and effectively shifted toward higher frequencies due to second order effects in v/c

Bose-Einstein spectrum- Chemical potential (μ)

$$n(x) = \frac{1}{e^{x+\mu} - 1}$$

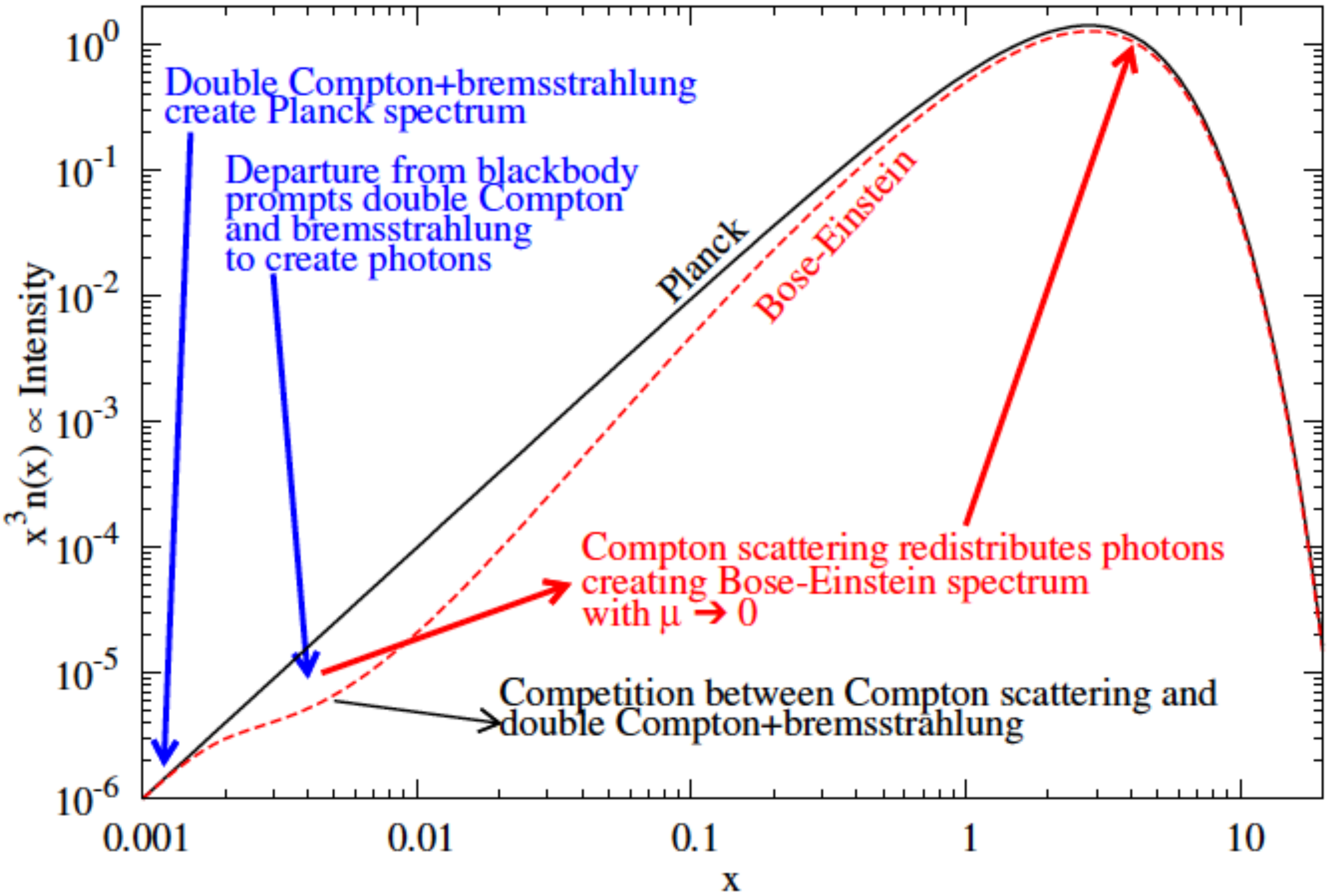
Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.



myu-type CMB distortions due to energy release in the early Universe 10^5 < z < 210^6

Sunyaev, Zeldovich, 1970

Creation of CMB Planck spectrum



Analitical solution(Sunyaev, Zeldovich, 1970

$$\mu = \mu(t_0)\, e^{-2\sqrt{(ak)}\,(t-t_0)}$$

Where a and k are scattering (Comptonisation) and real absorption coefficients correspondently

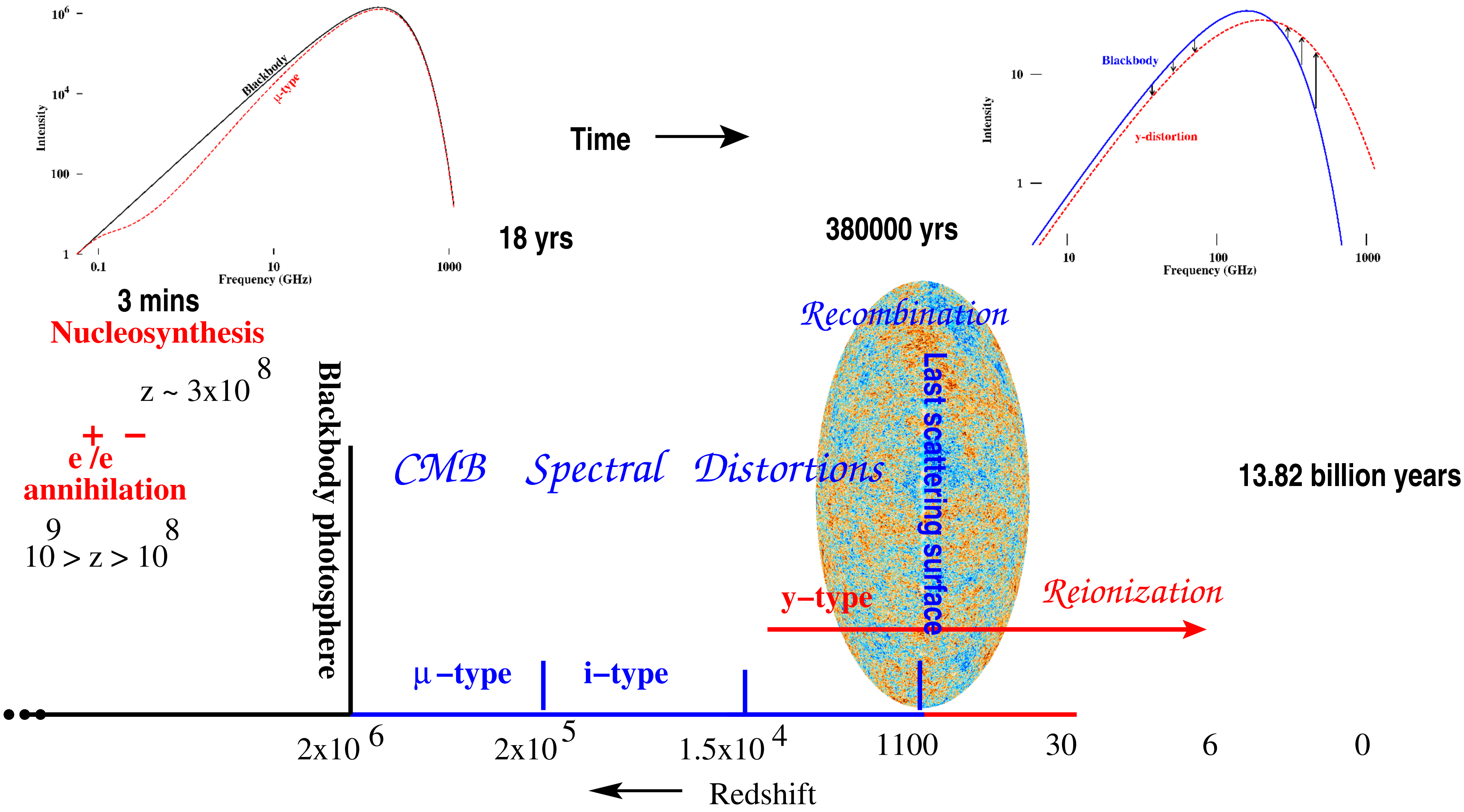
In the case of Double Compton (emission of second photon during scattering) spectral deviations decrease with time

$$\frac{\mu^{\mathrm{final}}}{\mu^{\mathrm{initial}}} \approx e^{-(z_{\mathrm{i}}/z_{\mathrm{dc}})^{5/2}}$$

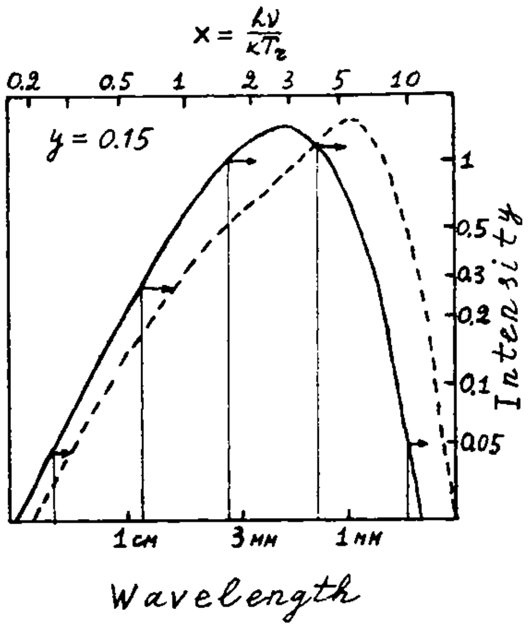
Danese, de Zotti, 1984

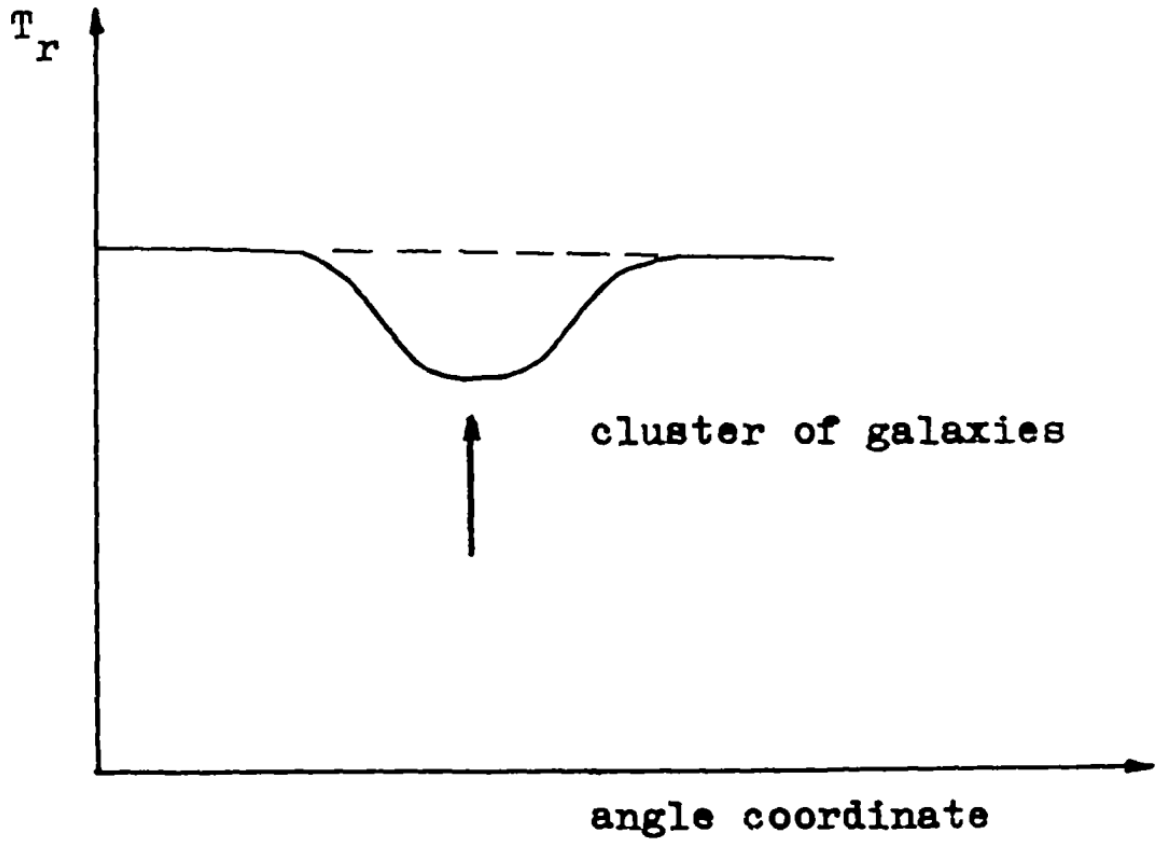
Two milestones in the life of the Universe:

Last Scattering Surface and
Black Body Photosphere



with Rishi Khatri and Jens Chluba





$$y = \int \frac{\sigma_T}{m_e c^2} P_e dl$$

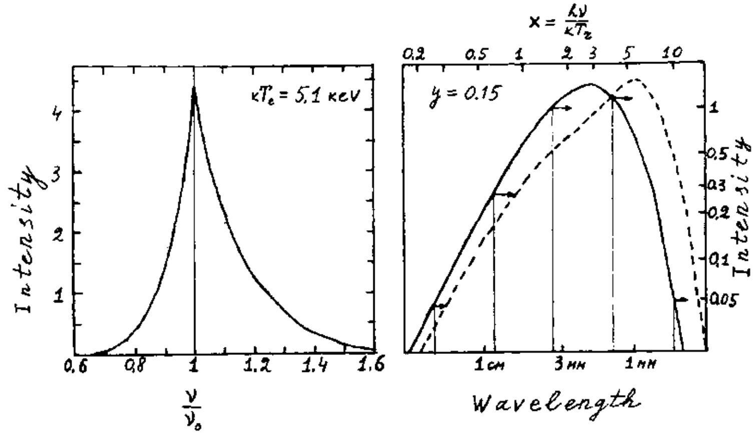
Pe = Ne kTe – electron thermal pressure

*In centimeter and mm spectral bands cluster should be observed as a **shadow** in the sky average brightness defined by CMB intensity*

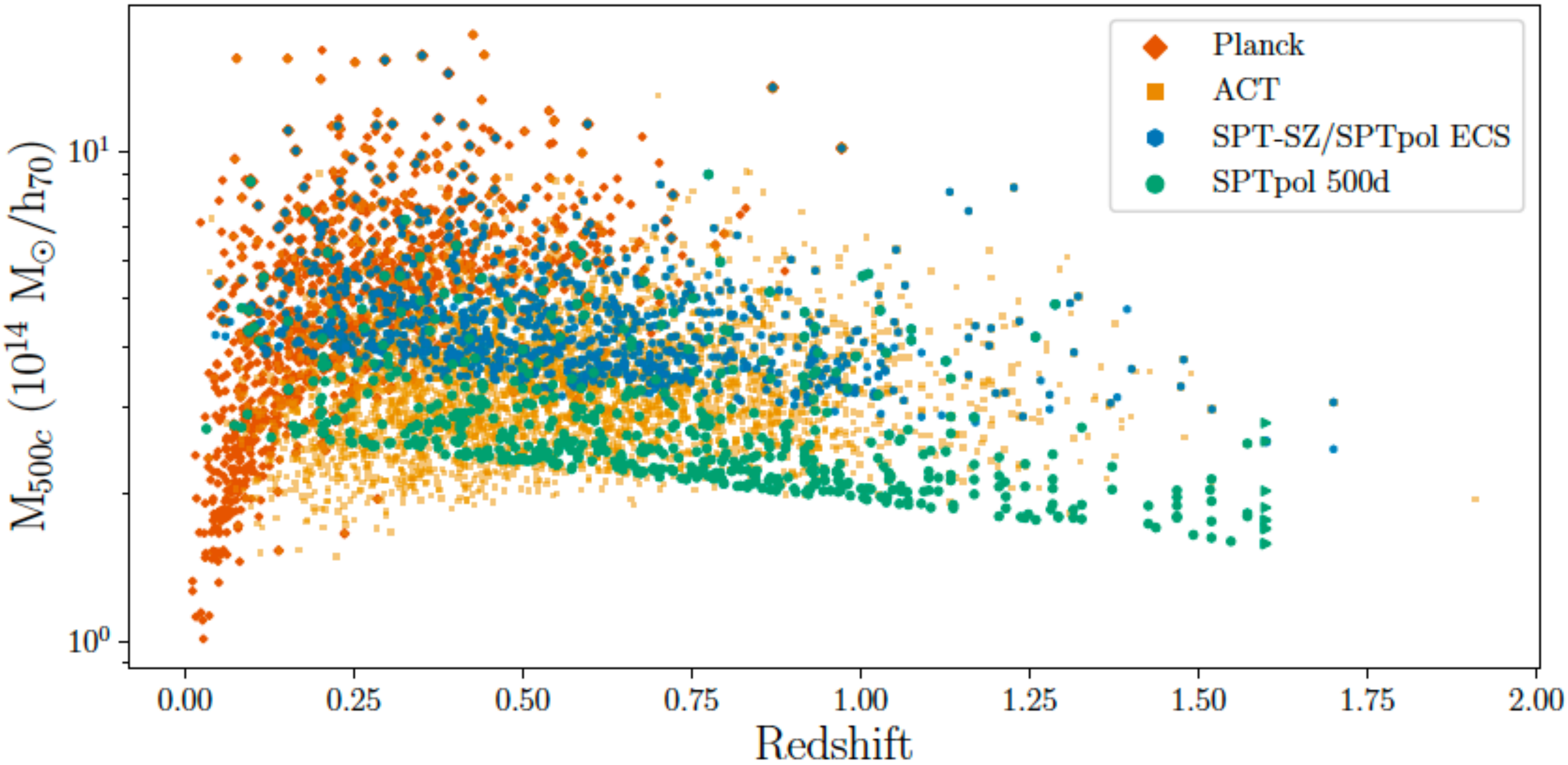
the depth of this hole does not depend on the redshift of the cluster of galaxies

It depends only on temperature of the electrons and optical depth of the cluster

Thermal SZ effect (change of the CMB spectrum in the direction to the cloud with hot gas)



689 Galaxy Clusters Discovered in the SPTpol 500d Survey 1



At small y << 1, tau << 1

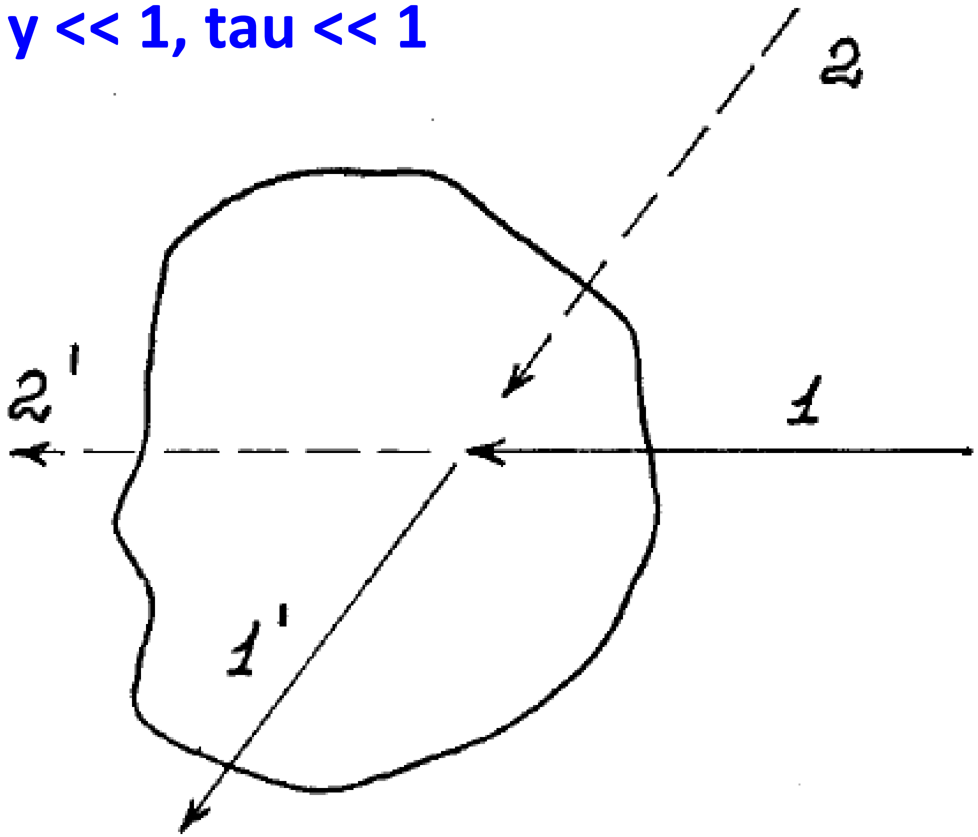
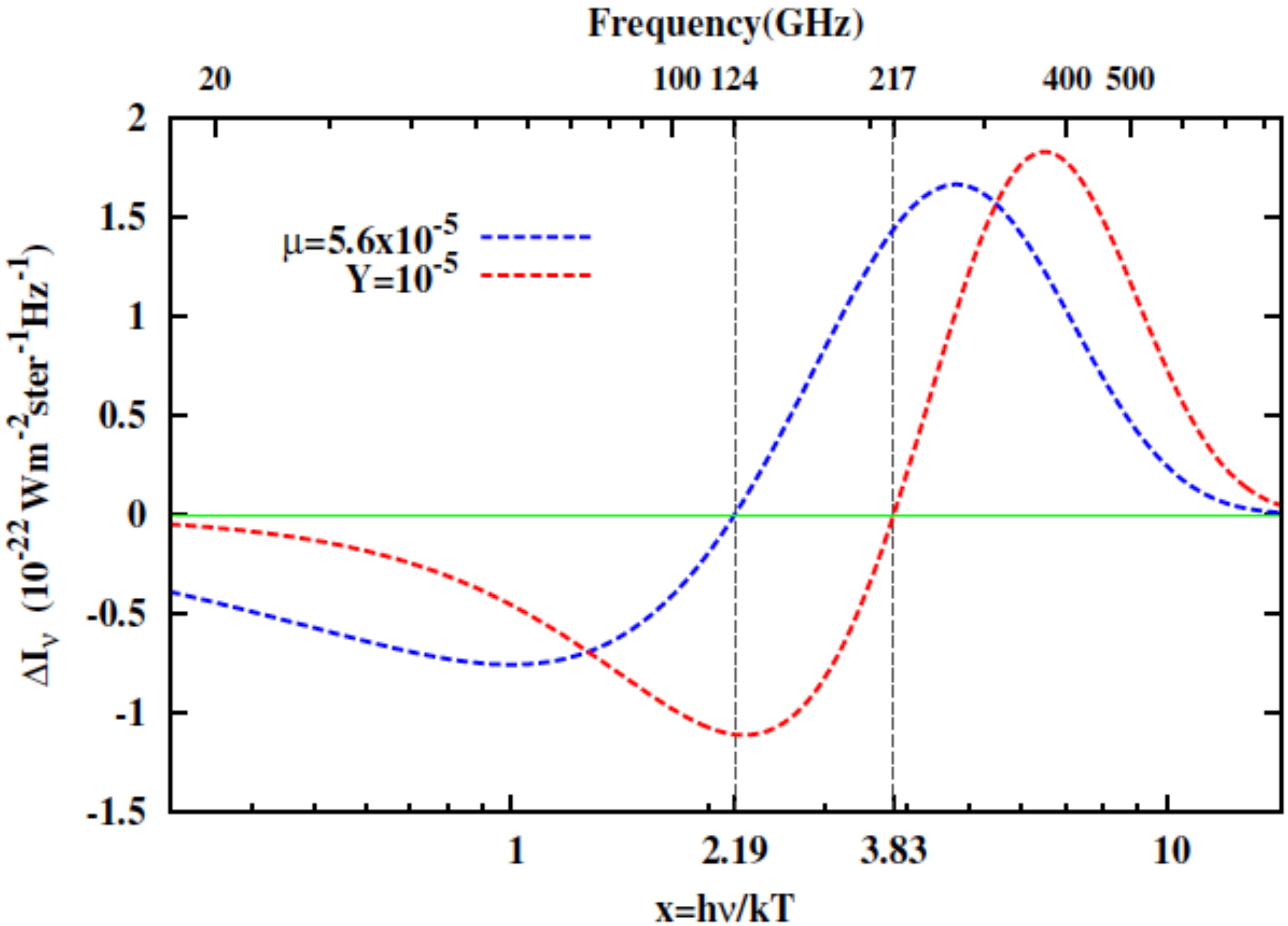


FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

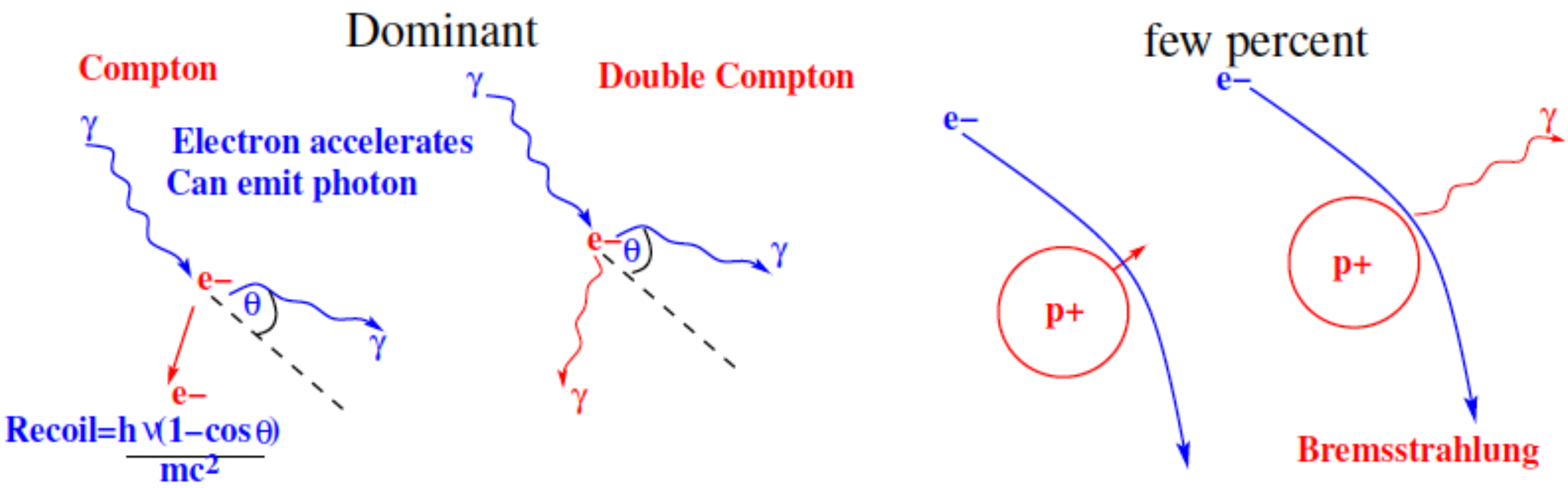
Cloud is invisible
in CMB radiation field

μ-distortion: Bose-Einstein spectrum, $y_\gamma \gg 1$

COBE-FIRAS limit (95%): $\mu \lesssim 9 \times 10^{-5}$ *(Fixsen et al. 1996)*



Processes responsible for creation of CMB spectrum



- Double Compton and bremsstrahlung create/absorb photons ($\propto 1/x^2$)
- Compton scattering distributes them over the whole spectrum