CMB spectral distortions

(Two milestones in the life of the Universe
Last Scattering Surface and
Black Body Photosphere)

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Adiabatic expansion of the Universe preserves the blackbody spectrum established at early times (for example during electron-positron annihilation) (In general $x = \nu / T$ is invariant w.r.t. expansion of the Universe.)

Cosmic Microwave Background (CMB): The most precise black body known: $T = 2.725K \pm 1mK$

No spectral deviations are detected by COBE/FIRAS!

This was 25 years ago

**Now:**

Great progress in the technology of experiments and especially of detectors and cryogenics

PIXIE proposal: up to 100 or even thousand times more sensitive!

There are many theoretical models predicting significant energy release in the early Universe and CMB spectral distortions:

I will speak today only about unavoidable spectral features, which are predicted within standard cosmological model.
Black body photosphere of the Universe

In the spring of 1966 Yakov Zeldovich asked me to review on the group seminar the preprints of Layzer (Harvard) and Burbidges (Caltech) 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.

$$\tau_{\text{free-free}} \sim \int_0^{t(z)} dt \, n_e^2 \sigma_T c \frac{\alpha_{fs}}{(24\pi^3)^{1/2}} \left( \frac{k_B T_e}{m_e c^2} \right)^{-7/2} \left( \frac{h}{m_e c x_e} \right)^3 \left( 1 - e^{-x_e} \right)$$

$$\sim 4 \times 10^{-5} \left( \frac{1 + z}{10^8} \right)^{1/2},$$

but Thomson optical depth was huge.

$$\tau_{\text{Thomson}} = \int_0^{t(z)} n_e \sigma_T c dt \approx 0.21 (1 + z) \sim 2 \times 10^7 \left( \frac{z}{10^8} \right)$$

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

\[ \gamma + e^- \rightarrow \gamma + e^- \]

Doppler: \[ \frac{\delta \nu}{\nu} \sim \frac{v_e}{c} \sim \left( \frac{kT_e}{m_e c^2} \right)^{1/2} \]

2ndorderDoppler: \[ \left( \frac{\delta \nu}{\nu} \right)_{\text{rms}} \sim 4 \left( \frac{kT_e}{m_e c^2} \right) \]

Recoil: \[ \frac{\delta \nu}{\nu} = -\frac{h\nu}{m_e c^2} (1 - \cos \theta) \]

\[ y: \text{Amplitude of distortion} \]

\[ y = \int dt c \sigma_T n_e \frac{k_B (T_e - T_\gamma)}{m_e c^2} \]
Fokker-Planck expansion of the kinetic equation with induced scattering term yields

\[
\frac{\partial n}{\partial y} = \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left( n + n^2 + \frac{\partial n}{\partial x} \right)
\]

Kompaneets (1956)

\[
n = \frac{c^2 I_v}{8\pi h \nu^3}
\]

- occupation number, \( I \) – radiation intensity

\[
x = \frac{\hbar \nu}{k T_e}
\]

\[
y = \frac{k T_e}{m_e c^2} \sigma_T N_e c t = \frac{k T_e}{m_e c^2} u
\]

- photon frequency, \( t \) – time and number of scatterings

**Kompaneets equation** describes interaction of a radiation field with free hot maxwellian electrons due to Compton scattering. The energy exchange due to Doppler effect and recoil. Thomson cross-section limit.

Beautiful physics behind the term \(~ n^2\) describing induced Compton scattering
Efficiency of energy exchange between electrons and photons

Recoil:

\[ y_\gamma = \int dt \, c \sigma_T n_e \frac{k_B T_\gamma}{m_e c^2}, \quad T_\gamma = 2.725 (1 + z) \]

Doppler effect:

\[ y_e = \int dt \, c \sigma_T n_e \frac{k_B T_e}{m_e c^2} \]

In early Universe \( y_\gamma \approx y_e \)

\( y \): Amplitude of distortion

\[ y = \int dt \, c \sigma_T n_e \frac{k_B (T_e - T_\gamma)}{m_e c^2} \]
Efficiency of energy exchange between electrons and photons

Recoil:

\[ y_\gamma = \int dq \sigma T_n e \frac{k_B T_\gamma}{m_e c^2}, \quad T_\gamma = 2.725(1 + z) \]

No. of scatterings

Doppler effect:

\[ y_e = \int dq \sigma T_n e \frac{k_B T_e}{m_e c^2} \]

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Fokker-Planck expansion of the kinetic equation with induced scattering term yields

$$\frac{\partial n}{\partial y} = \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left( n + n^2 + \frac{\partial n}{\partial x} \right)$$

\begin{align*}
n &= c^2 I_v / 8\pi h \nu^3 \quad &\text{- occupation number, } I \text{ – radiation intensity} \\
x &= \nu/kT_e \quad &\text{- photon frequency,}
\end{align*}

$$y = \frac{kT_e}{m_e c^2} \sigma_T N_e c t = \frac{kT_e}{m_e c^2} u$$

\begin{align*}
\text{- time and number of scatterings}
\end{align*}

Kompaneets equation describes interaction of a radiation field with free hot maxwellian electrons due to Compton scattering. The energy exchange due to Doppler effect and recoil. Thomson cross-section limit.

Beautiful physics behind the term \( \sim n^2 \) describing induced Compton scattering
Bose-Einstein spectrum- Chemical potential ($\mu$)

Stationary solution of Kompaneets equation at $y \gg 1$

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

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

Thomson scattering does not change amount of photons

(\textit{photon number conservation in Kompaneets equation})
myu-type CMB distortions due to energy release in the early Universe $10^5 < z < 210^6$

Sunyaev, Zeldovich, 1970
Bose-Einstein spectrum

\[ n_{\text{BE}} = \frac{1}{\frac{h\nu}{e^{k_{\text{B}}T_{\text{BE}}} + \mu} - 1} \]
\[ = \frac{1}{e^{x - 0.456\mu x + \mu} - 1} \]
\[ \approx n_{\text{pl}}(x) + \frac{\mu e^x}{(e^x - 1)^2} \left( \frac{x}{2.19} - 1 \right) , \]

We call this type of spectral distortions as a μ distortion.
At small $y \ll 1$, $\tau \ll 1$

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

Cloud is invisible in CMB radiation field
\[ n_{\text{SZ}} = y \frac{T^4}{\partial T} \frac{1}{T^2} \frac{\partial n_p}{\partial T} \]

\[ = y \frac{xe^x}{(e^x - 1)^2} \left( \frac{e^x + 1}{e^x - 1} - 4 \right) \]

\[ \Delta I_{\text{SZ}} = I_{\text{SZ}} - I_{\text{planck}} = \frac{2h \nu^3}{c^2} n_{\text{SZ}} \]
~ 900 clusters confirmed by X-Ray or optical observations

SZ shadow, Coma cluster of galaxies
y-parameter map, based on 100-857 GHz data
ACT and SPT
Dedicated Telescopes for measurement of CMB polarization and fine angular scale temperature anisotropy

6m Atacama Cosmology Telescope
http://www.physics.princeton.edu/act/

10m South Pole Telescope
http://pole.uchicago.edu

• Exceptional high and dry sites for dedicated CMB observations.
• Exploiting ongoing revolution in low-noise bolometer cameras
Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies
Lower limit on $\langle y \rangle$ from Planck and SPT detected clusters

Sum the $\langle y \rangle$ from Planck clusters at $z < 0.3$ and SPT clusters at $z > 0.3$

Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850
Lower limit on $\langle y \rangle$ from Planck and SPT detected clusters

Observed clusters $\Rightarrow$ Minimum average $y$-distortion in the CMB
$\langle y \rangle > 5.4 \times 10^{-8}$ (Khatri & Sunyaev 2015)

Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850
New upper limit on $\langle y \rangle$ from $y$-map created by combining Planck HFI channels

$y$-distortion map, 10 arcmin

$P(y)$ for the Planck $y$-map of the whole sky (Khatri, 2015)
New upper limit on $\langle y \rangle$ from $y$-map created by combining Planck HFI channels

A simple conservative approach:
- Take all the positive pixels in the map (excluding contaminated regions)
- Average the $y$-distortion in the pixels (All pixels have equal area)

Result: $\langle y \rangle < 2.2 \times 10^{-6}$ (Khatri & Sunyaev 2015)

6.8 times stronger compared to the COBE-FIRAS upper limit:
$\langle y \rangle < 15 \times 10^{-6}$ (Fixsen et al. 1996)
$\mu$-distortion: Bose-Einstein spectrum, $y \gamma \gg 1$

COBE-FIRAS limit (95%): $\mu \lesssim 9 \times 10^{-5}$ (Fixsen et al. 1996)
Intermediate-type distortions \textit{(Khatri and Sunyaev 2012b)}

Solve Kompaneets equation with initial condition of $y$–type solution.

\[
\frac{\partial n}{\partial y_\gamma} = \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left( n + n^2 + \frac{T_e}{T} \frac{\partial n}{\partial x} \right), \quad \frac{T_e}{T} = \frac{\int (n + n^2)x^4 dx}{4 \int nx^3 dx}
\]
For $y_\gamma \gg 1$ equilibrium is established.

$T_e$ and $T_\gamma$ converge to common value.

The photon spectrum relaxes to equilibrium Bose-Einstein distribution.
Processes responsible for creation of CMB spectrum

- **Dominant**
  - Compton
    - Photon $(\gamma)$ interacts with electron $(e^-)$
    - Electron accelerates
    - Can emit photon
  - Double Compton
    - Electron $(e^-)$ interacts with photon $(\gamma)$
    - Electron recoils
    - Recoil: $h \sqrt{1 - \cos \theta}$
    - $h$ is Planck's constant
    - $\theta$ is the scattering angle

- **Few percent**
  - Bremsstrahlung
    - Positron $(p^+)$ interacts with electron $(e^-)$
    - Photon $(\gamma)$ is emitted

- **Key Points**
  1. Double Compton and bremsstrahlung create/absorb photons
        $(\propto 1/x^2)$
  2. Compton scattering distributes these photons over the whole spectrum
Creation of CMB Planck spectrum

Double Compton+bremsstrahlung create Planck spectrum

Departure from blackbody prompts double Compton and bremsstrahlung to create photons

\( x^3 n(x) \propto \text{Intensity} \)

Compton scattering redistributes photons creating Bose-Einstein spectrum with \( \mu \to 0 \)

Competition between Compton scattering and double Compton+bremsstrahlung
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.

\[ \frac{\mu_{\text{final}}}{\mu_{\text{initial}}} \approx e^{-\left(\frac{z_i}{z_{dc}}\right)^{5/2}} \]

Danese, de Zotti, 1984
Bose-Einstein spectrum - Chemical potential ($\mu$)

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

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

Idea behind analytic solutions:
If we know rate of production of photons and energy injection rate, we can calculate the evolution/production of $\mu$ (and $T$)
The general picture
We have reached the resolution limit for CMB anisotropies

Silk damping of standing sound waves due to radiative viscosity and thermal conductivity
Going from 7 to 17 e-folds of inflation

- COBE y limit
- COBE μ limit
- y-type
- i-type
- μ-type
- low redshift confusion
- 7 e-folds
- 17.7 e-folds
- CMB best fit + Ly-α
- Pixie
- PRISM
- Blackbody Photosphere
Two milestones in the life of the Universe:
Last Scattering Surface and
Black Body Photosphere

3 mins
Nucleosynthesis

$z \sim 3 \times 10^8$

$e^\pm$annihilation

$9 \quad 8$

$10 > z > 10$

$13.82$ billion years

Recombination

Blackbody photosphere

CMB Spectral Distortions

Reionization

380,000 yrs

18 yrs

$3 \times 10^6$

Redshift

$2 \times 10^6$

$2 \times 10^5$

$1.5 \times 10^4$

$1100$

$30$

$6$

$0$

with Rishi Khatri and Jens Chluba
Recombination goes much more slow, чем Saha formula predicts; the rate is defined by the two photon decay of the 2S level and the slow loss of photons in the wing of Ly-α line.
Visibility function

Last scattering surface

Below we will need the function

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

which in agreement with (3) has a sharp maximum for \( z_{\text{max}} = 1055 \) (\( e^{-\tau}(d\tau/dz)_{z=z_{\text{max}}} = 3.32 \times 10^{-3} \)) 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 recently PLANCK.
Cosmological Recombination Spectrum

- **Hydrogen only**
- **Hydrogen and Helium**

- Shifts in the line positions due to presence of Helium in the Universe at redshift $z \sim 1400$
- Changes in the line shape due to presence of Helium in the Universe
- Photon transitions among highly excited states
- Spectral distortion reaches level of $\sim 10^{-7} - 10^{-6}$ relative to CMB

Rubino-Martin, Chluba, Sunyaev, 2005
the blurring of primordial fluctuations. Thomson tau = 0.85 (WMAP)

full analogy with Gunn-Peterson effect, but Tr inhomogeneities on the sky are playing the role of quasars and submm lines are used instead Ly-alpha.

Hot and cold spots

zero effect for monopole, polarization from quadrupole

Basu, Hernandez-Monteagudo, Sunyaev, 2004
**Figure 47.** Projected constraints on abundance of C, N, O atoms and ions from 50-600 GHz channels of PRISM assuming it will have the inter-channel calibration accuracy of 0.001% to be able to measure the difference in the optical depth (to the last scattering surface) seen by different channels of $\tau_{\text{LSS}} = 10^{-5}$. The highest and lowest redshifts at the endpoints of the each curve correspond to 50 GHz and 600 GHz observed frequency respectively. The constraints as a fraction of solar abundance are plotted, with the reference solar abundances taken to be photosphere abundances in [399].
Frequency dependence – $\Delta \nu / \nu_{\text{obs}} = 10^{-3}$

Righi, Hernandez-Monteagudo, Sunyaev, 2008
Experiments of the type of COBE/FIRAS are possible not much often than once in 25 years

*The goal, theorists are dreaming:*  

A sensitivity necessary to detect  

a) myu-type distortions on the level of $10^{-9}$ (we do not expect signal below few times $10^{-9}$, but who knows?). However any upper limit will be useful.

b) such a sensitivity will permit to study recombinational lines of hydrogen and helium coming from redshifts ~ 1500, 2400 and 6000

c) It will be possible to separate y distortions produced before recombination from generated much later (they will distort the recombinational spectrum)
The shape of the $\mu$ and intermediate type distortions is rich in information.

With spectral distortions we can extend our 'view' of inflation from 6-7 e-folds at present to 17 e-folds.

Spectral distortions take us a little nearer to the end of inflation.

$\mu$-type and intermediate type distortions can be calculated very fast using analytic and pre-calculated cosmology-independent high precision numerical solutions (Green's functions). This allows us to explore the rich multidimensional parameter space.

$i$-type distortions are quite powerful in removing degeneracies between power spectrum parameters. The extra information comes from the shape of the $i$-type distortion.
THANK YOU !!!
$\mu$-type distortions

Compton + double Compton + bremsstrahlung

Analytic solution: $\mu = 1.4 \int \frac{dQ}{dz} e^{-\mathcal{F}(z)} dz$

(Sunyaev and Zeldovich 1970)
PLANCK spacecraft scans the sky

From paper Sunyaev, Zeldovich 1970

standing sound waves (Lifshits, 1946)
Fenix cluster of galaxies discovered by SPT at $z=0.596$ and observed by CHANDRA, GALEX and Magellan: star burst – 800 solar masses a year, luminosity $8 \times 10^{45}$ erg/s, cooling flow $\sim 3000$ Solar masses a year. Black hole in the center accretes 60 solar masses a year.
Summary continued

With intermediate-type distortions we can distinguish between different mechanisms of energy injection which have different redshift dependence
There is more....

- Cosmological recombination spectrum gives measurement of primordial helium
  *Kurt, Zeldovich, Sunyaev, Peebles, Dubrovich, Chluba, Rubino-Martin*

- Resonant scattering on C, N, O and other ions during and after reionization makes the optical depth to the last scattering surface frequency dependent
  *Basu, Hernandez-Monteagudo, and Sunyaev 2004*

- Sunyaev-Zeldovich effect from hot electrons during reionization/WHIM can give a measurement of average electron temperature, find missing baryons

- Primordial non-gaussianity on extremely small scales
  *Pajer and Zaldarriaga 2012, Ganc and Komatsu 2012*
Summary continued

- Silk damping: \( \frac{dQ}{dz} \propto (1 + z)^{(3n_s - 5)/2} \)
  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)

- Adiabatic cooling: Opposite sign to Silk damping with \( n_s = 1 \)
  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)

- Particle decay: \( \frac{dQ}{dz} \propto e^{- \left( \frac{1+z_{\text{decay}}}{1+z} \right)^2 / (1+z)^4 } \)
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)

- Cosmic strings: \( \frac{dQ}{dz} \propto \text{constant} \)
  Tashiro, Sabancilar, Vachaspati 2012

- Primordial magnetic fields: \( \propto (1 + z)^{(3n+7)/2} \), \( n \) is the spectral index of magnetic field power spectrum
  (Jedamzik, Katalinic, and Olinto 2000)

- Black holes: Depends on the mass function
  Tashiro and Sugiyama 2008, Carr et al. 2010

- Quantum wave function collapse: \( \frac{dQ}{dz} \propto (1 + z)^{-4} \)
  Lochan, Das and Bassi 2012
There is still a long road ahead for CMB cosmology

CMB spectrum is very rich in information about the early Universe, late time Universe and fundamental physics
This information is accessible and within reach of experiments in not too far future: Pixie, PRISM

Thank you !!!
clusters/reionization

\[ y_\gamma \ll 1, \ T_e \sim 10^4 \]

\[ y = (\tau_{\text{reionization}}) \frac{k_B T_e}{m_e c^2} \sim (0.1)(1.6 \times 10^{-6}) \sim 10^{-7} \]
Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int dt \, c \sigma_T n_e \frac{k_B T_\gamma}{m_e c^2}, \quad T_\gamma = 2.725(1+z)$$

No. of scatterings Energy transfer per scattering

Doppler effect:

$$y_e = \int dt \, c \sigma_T n_e \frac{k_B T_e}{m_e c^2}$$

In early Universe $y_\gamma \approx y_e$

y: Amplitude of distortion

$$y = \int dt \, c \sigma_T n_e \frac{k_B (T_e - T_\gamma)}{m_e c^2}$$
Pivot point $k_0 = 42 \text{ Mpc}^{-1}$

$P_\zeta = (A_\zeta 2\pi^2 / k^3) (k/k_0)^{n_s-1} + \frac{1}{2} \frac{dn_s}{d\ln k} (\ln k/k_0)$

$\begin{array}{c}
n_{ss} = 0.5 \\
n_{ss} = 0.8 \\
n_{ss} = 0.9 \\
n_{ss} = 1.0 \\
n_{ss} = 1.1 \\
n_{ss} = 1.2 \\
n_{ss} = 1.5 \\
10A_\zeta, n_{ss} = 2
\end{array}$

$\begin{array}{c}
\text{COBE y limit} \\
\text{COBE \(\mu\) limit} \\
\text{Intermediate-type} \\
\text{\(\mu\)-type} \\
\text{Blackbody Photosphere} \\
\text{Pixie} \\
\text{CMB best fit + Ly-\(\alpha\)} \\
\text{y-type} \\
\text{low redshift confusion limited}
\end{array}$
black body spectrum

$Tr = 2.725 \ (1+z)K$

practically isotropic

COBE-Firas:

400 photons/cm$^3$

dark blue - 200 microK

red +200 microK
Cosmic Microwave Background (CMB): The most precise black body known: \( T = 2.725K \pm 1mK \)

No spectral deviations are detected !!!

Energy density of Planck spectrum

\[
E_\nu = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{kT}} - 1}
\]

\[
E = a_R T^4
\]
CMB lensing is taking off

Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5’
- Lensing efficiency peaks at \( z \sim 2 \)
- Coherent on ~degree (~300 Mpc) scales

graphic from ESA Website
\[ n_{SZ} = y \frac{T^4}{\partial T} \frac{1}{T^2} \frac{\partial n_{Pl}}{\partial T} \]

\[ = y \frac{xe^x}{(e^x - 1)^2} \left( \frac{e^x + 1}{xe^x - 1} - 4 \right) \]

\[ \Delta I_{sz} = I_{sz} - I_{planck} = \frac{2h\nu^3}{c^2} n_{sz} \]
Coma, optical image, central part

\[ n_{SZ} = y \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{Pl}}{\partial T} \]

\[ = y \frac{xe^x}{(e^x - 1)^2} \left( \frac{x e^x + 1}{xe^x - 1} - 4 \right) \]

\[ \Delta I_{\text{sz}} = I_{\text{sz}} - I_{\text{planck}} = \frac{2h\nu^3}{c^2} n_{SZ} \]
~ 900 clusters confirmed by X-Ray or optical observations
~ 900 clusters confirmed by X-Ray or optical observations
Planck
143 GHz
50 deg$^2$

2x finer angular resolution
7x deeper
SPT
150 GHz
50 deg$^2$

13x finer angular resolution
50x deeper
SPT
150 GHz
50 deg$^2$

filtered out
large structure
SPT
150 GHz
50 deg$^2$

CMB Anisotropy
Primordial and secondary anisotropy in the CMB
SPT
150 GHz
50 deg$^2$

Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies

SPT 0538-50
z=2.782
HST-WFC3
ALMA
1"
SPT-SZ: Lensed Sources in SPT-SZ Survey

mm-wavelength Source Number Counts

- SPT
- SCUBA
- unlensed SMGs
- lensed SMGs

SPT lensed high-$z$ (2 < $z$ < 6) galaxies resolved by ALMA

SPT 0103-45
- z = 3.080
- HST/WFC3

SPT 0113-46
- z = 4.232
- HST/WFC3

SPT 0529-54
- z = 3.369
- SOAR/OSIRIS

SPT 0538-50
- z = 2.782
- HST/WFC3

Vieira et al. 2013 Nature
Hezewiah et al. 2013

Next use exquisite resolution and sensitive of ALMA
ALMA to image dark matter subhalos of the lens
Brief history

- BBN: $z \sim 3 \times 10^8$
- $e^+e^-$ annihilation: $10^9 > z > 10^8$
- Blackbody Photosphere
- Spectral Distortions: $\mu$-type, $i$-type
- Recombination
- Last scattering surface
- Reionization
- Redshift
Optical follow-up; redshifts, lensing, dynamical masses
Entropy is conserved in thermodynamic equilibrium

Entropy per baryon of radiation + baryons

\[ \sigma = \frac{4a_R T^3}{3n_B} + Nk_B \ln \left( \frac{T^{3/2}}{n_B C} \right) \]

baryon density
\[ n_B \propto (1 + z)^3 \]

Constant entropy

\[ T_{\text{radiation}} \propto 1 + z \]
\[ T_{\text{baryons}} \propto (1 + z)^2 \]
Figure 2. Example of the strong non-Gaussianity of the $P(D)$ function for SZ clusters. We present the $P(D)$ function for a SZ map in the Rayleigh–Jeans region of the spectrum, where clusters are ‘negative’ sources. For comparison, we also show the best Gaussian fit to this $P(D)$ curve ($\sigma = 6.1 \, \mu K$). This curve will be explained in detail in Section 7.

J. A. Rubiño-Martín and R. A. Sunyaev, 2003
Thousands of galaxies with $v \sim 1000$ km/s
Hot intergalactic gas with $T_e \sim 3 - 10$ keV

**Gravitational potential** defined by invisible *dark matter*

*Distant* galaxies are gravitationally *lensed* by A 2218
There are three effects which make cloud visible:

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

2. **Kinetic effect** (moving cloud changes the spectrum of scattered CMB photons due to Doppler effect)

   Full analogy with the origin of the Dipole Component in the CMB angular distribution arising due to our motion relative to the reference frame where CMB is isotropic.

3. **Blurring effect** (CMB in reality is not isotropic. There are angular fluctuations. Scattering in the cloud removes all anisotropies in the direction to the cloud except 10% of quadrupole at the position of a cloud)

   \[
   \frac{\Delta I}{I_0} = \frac{I_1(\mu) - I(\mu)}{I_0} = -\tau_T \\
   \times \left[ a\mu + 0.9b(\mu^2 - \frac{1}{3}) + \sum_{n=3}^{\infty} C_n P_n(\mu) \right]
   \]

   (see Sunyaev, Zeldovich, 1981)
Electron temperature ~ 9 KeV

Electron density ~ 0.03 cm$^{-3}$

Sound velocity of gas is close to velocities of galaxies

Dark matter mass – up to $10^{15}$ Msun

Msun = $2 \times 10^{33}$ g
SOUTH POLE TELESCOPE

PI: J. Carlstrom

10m dish; 95, 150, 220 GHz
1′

Photograph by: Glenn Grant
National Science Foundation
SCATTERING OF RADIATION BY HOT MAXWELLIAN ELECTRONS

spectral changes due to doppler-effect on moving electrons with $kT_e \sim 5$ 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 $v/c$
In centimeter and mm spectral bands clusters should be observed as a holes in the sky average brightness defined by CMB intensity.

\[
y = \int \frac{\sigma T}{m_e c^2} P_e \, dl
\]

Pe = Ne kTe – electron thermal pressure

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
Angular size as a function of $z$

For distant clusters their angular size does not depend on redshift!

It is close to 1 arcmin

This means, that their total flux also does not depend on redshift for $0.5 < z < 2$
(for similar clusters at different redshifts)
because observed surface brightness also does not depend on the redshift
Figure 34. Map of simulated $y$-distortion taken from [207]. The $y$-type signal from the post-reionization epoch is dominated by the collapsed objects and filaments in the large scale structure.