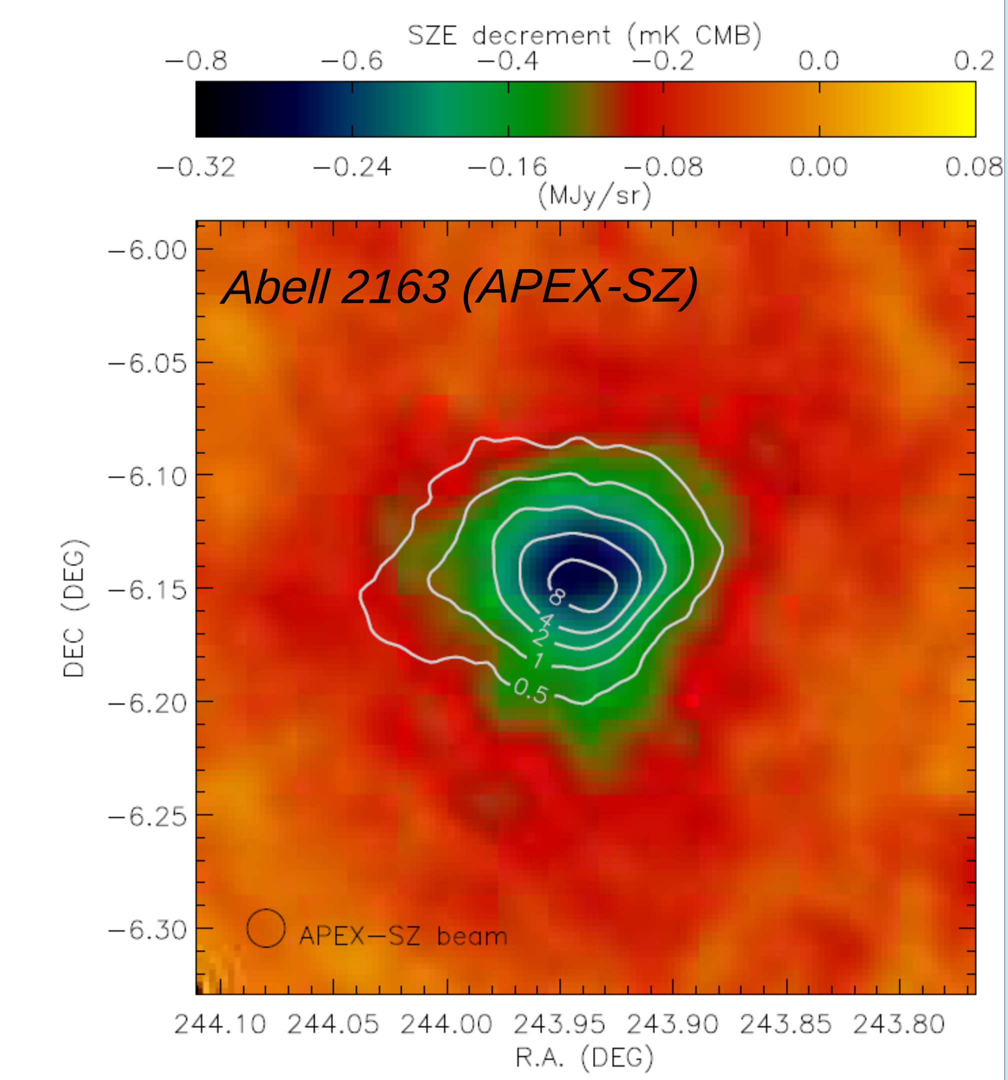
Change in the brightness of the cosmic X-ray, soft gamma-ray and radio background toward clusters of galaxies



S.A. Grebenev, R.A. Sunyaev

Space Research Institute, Moscow

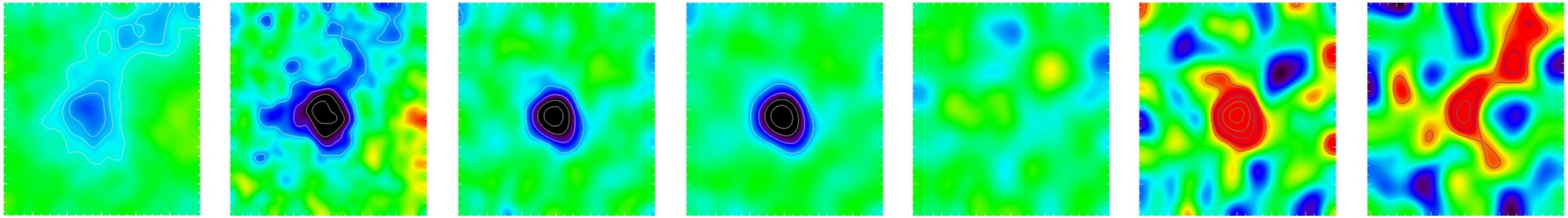
Sunyaev-Zeldovich or SZ effect (SZE):

Appearance of a negative source (brightness decrement) on the map of cosmic background fluctuations in the direction to clusters of galaxies (due to its inverse Compton scattering by electrons of the hot intergalactic gas).

Background is CMB (relic emission) but observed in radio (millimeter-decimeter) wavelength bands.

This effect is weak (fractions of mK or ~$3\times10^{-4}\,T_m$ where $T_m = 2.7255\pm0.0006\ K$ is the CMB temperature) but now well measured. And it is very important !

We extend this effect into other (radio and X- /soft gamma-ray) energy bands.



Abell 2319 from Planck

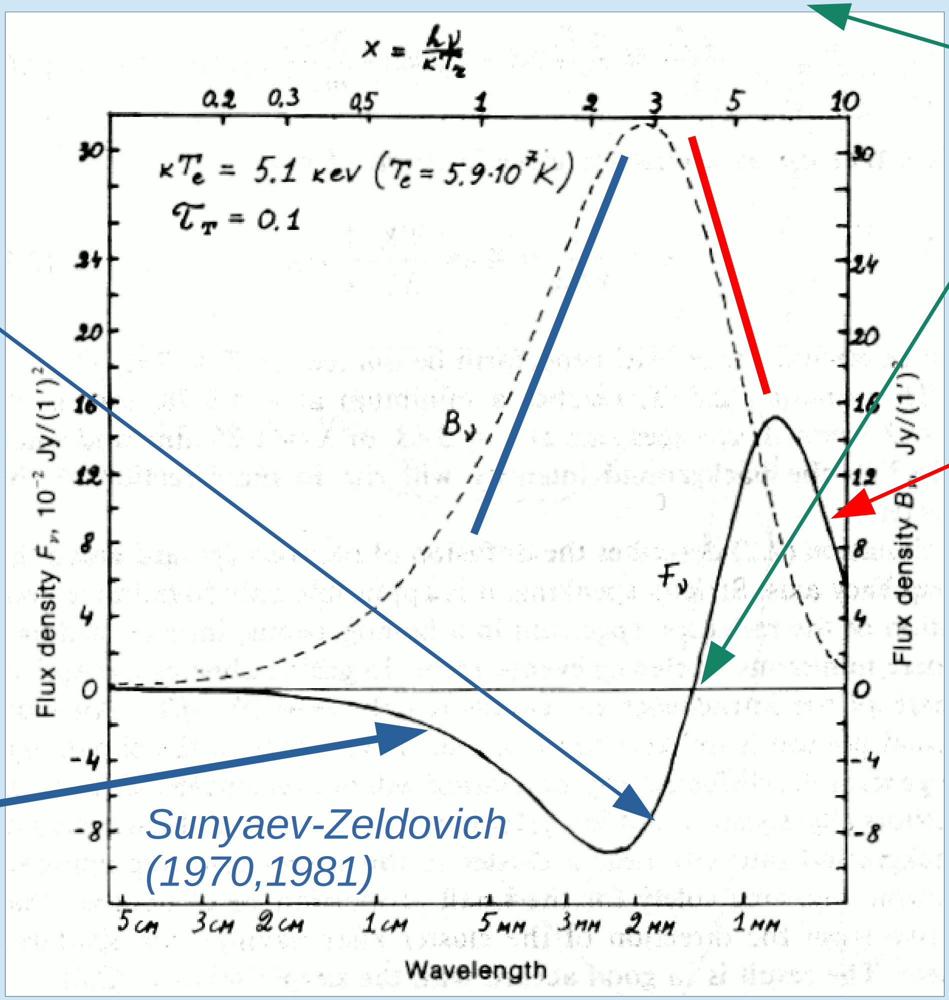
A negative source on the map of CMB fluctuations in the millimeter (radio) band.

Compton scattering leads to a Doppler shift of photons towards higher frequencies, for $kT_e \sim 5$ keV:
$\Delta\nu / \nu = (kT_e / m_e c^2)^{1/2} \sim 0.1$.

Substituting the CMB Planck spectrum into the Kompaneets equation we come to more accurate formula for distortions

$$\frac{\Delta B_\nu}{B_\nu} = y_{\rm C}\, \frac{x e^x}{e^x - 1} \left[x \left(\frac{e^x + 1}{e^x - 1} \right) - 4 \right]$$

Here $x = h\nu / kT_{\rm m}$, a $y_{\rm C} = \tau_{\rm T}\,(kT_{\rm e}/m_{\rm e}c^2)$



Sunyaev-Zeldovich (1970,1981)

Distortions disappear at 217.5 GHz (λ 1.37 mm)

A positive source on the map of CMB fluctuations in the submillimeter (microwave) band.

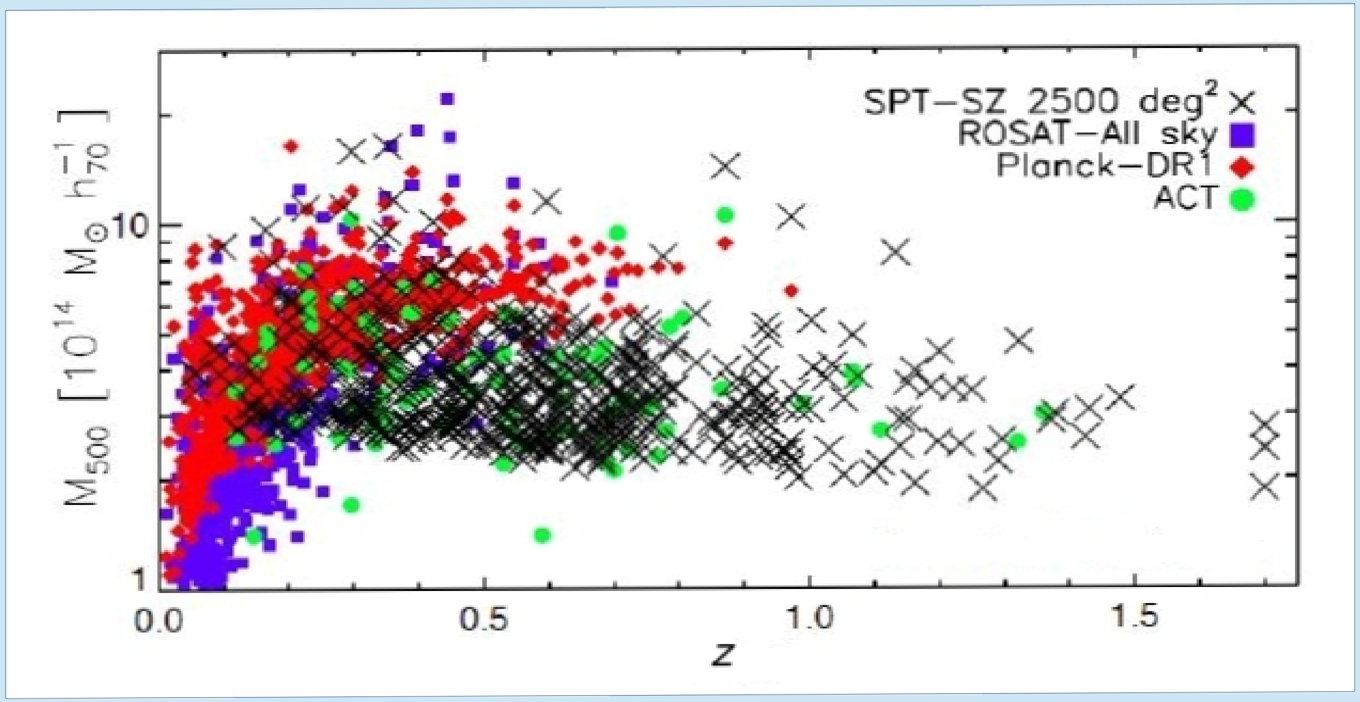
In the limit $h\nu \ll kT_m$

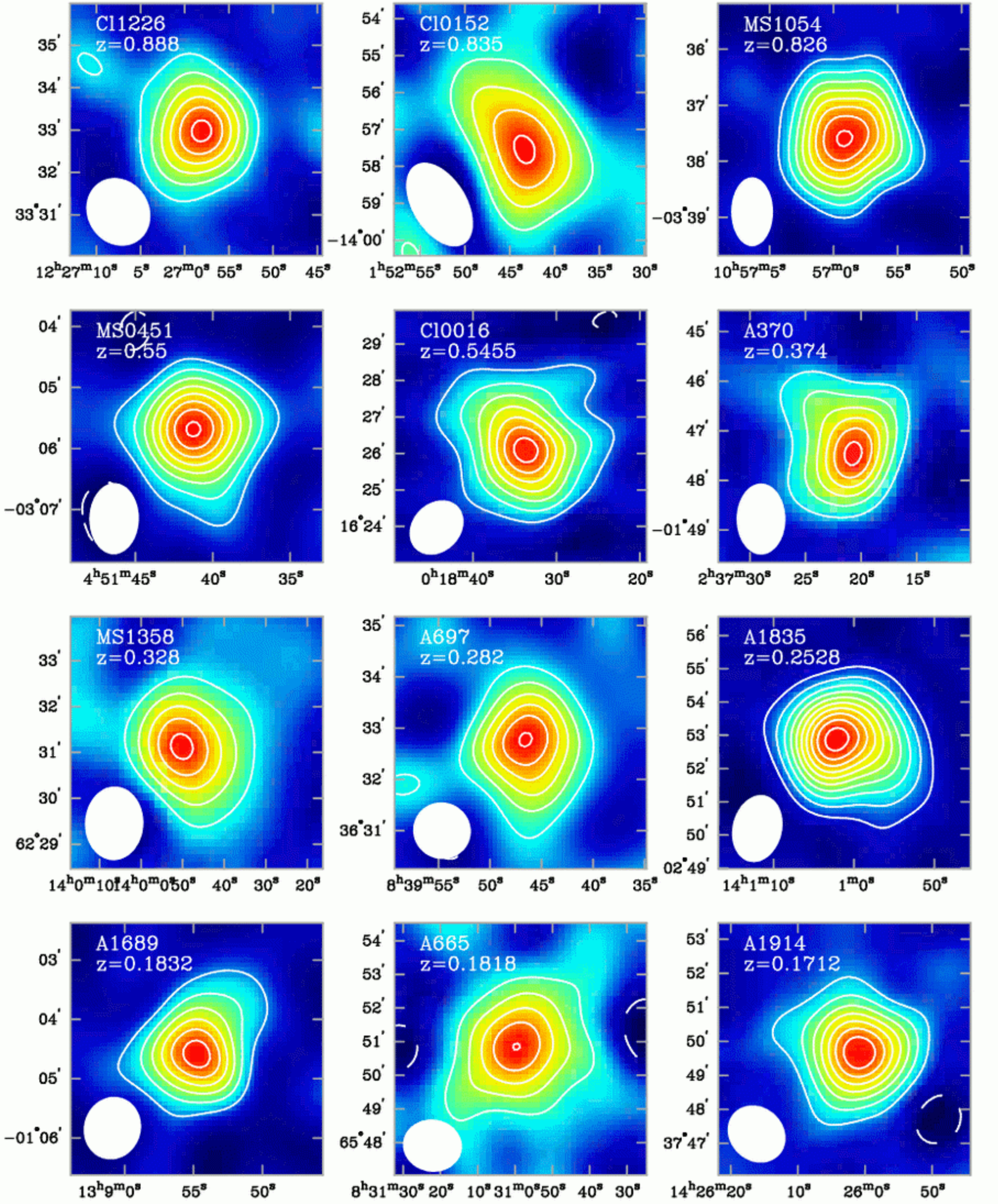
$$\Delta B_\nu / B_\nu \simeq -2 y_{\rm C}$$

or $\Delta T / T_m = -2\,(kT_e / m_e c^2)\tau_T$, where $\tau_T \sim 10^{-3}$ is the Thomson optical depth toward the cluster center.

Why the SZ-effect is important?

- *Amplitude of the effect $\Delta T/T \sim N_e T_e$, in contrast to the intensity of X-ray thermal bremsstrahlung ($\sim N_e^2 T_e^{1/2}$).*
- *Amplitude (intensity) and the shape of the distortion spectrum does not depend on redshift z (see clusters detected by BIMA at z=0.1-0.9).*
- *Exellent for discovering and studying most distant clusters.*





Background radiation in other spectral bands
Cosmic Radio-Background (CRB)

- *In the radio-band the spectrum is power-law (synchrotron)*

$$T_{\rm R}(\nu) = T_* \left(\nu/\nu_*\right)^{-2.58\pm0.05}\,{\rm K},$$

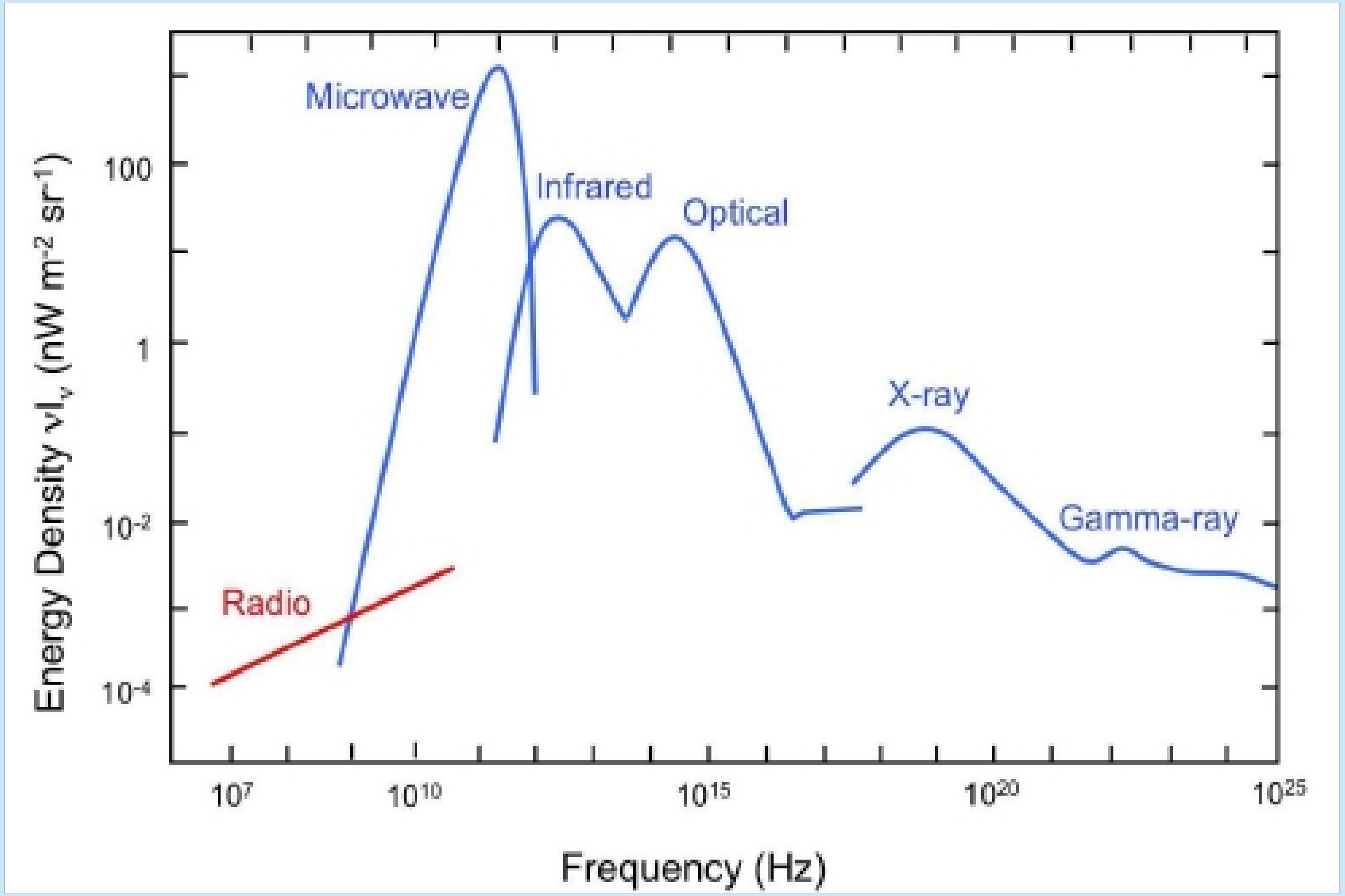
$$\nu_* = 310\ \text{МГц},\ T_* = (30.4\pm2.1)\,{\rm K}$$

(Fixsen et al. 2011; Dowell, Taylor 2018)

or $F_{\rm R}(\nu) = F_*\nu^{-\alpha}$, где $\alpha = 0.58\pm0.05$

- *The origin is unknown. Only ~25% may be attributed to radiogalaxies and other radiosources.*

- *But it is isotropic like CMB*



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Astronomy Letters, v. 50, pp. 159-185 (2024)

Increase in the Brightness of the Cosmic Radio Background toward Galaxy Clusters

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Doppler effect is again the main process of Compton scattering. It shifts photons to higher frequencies.

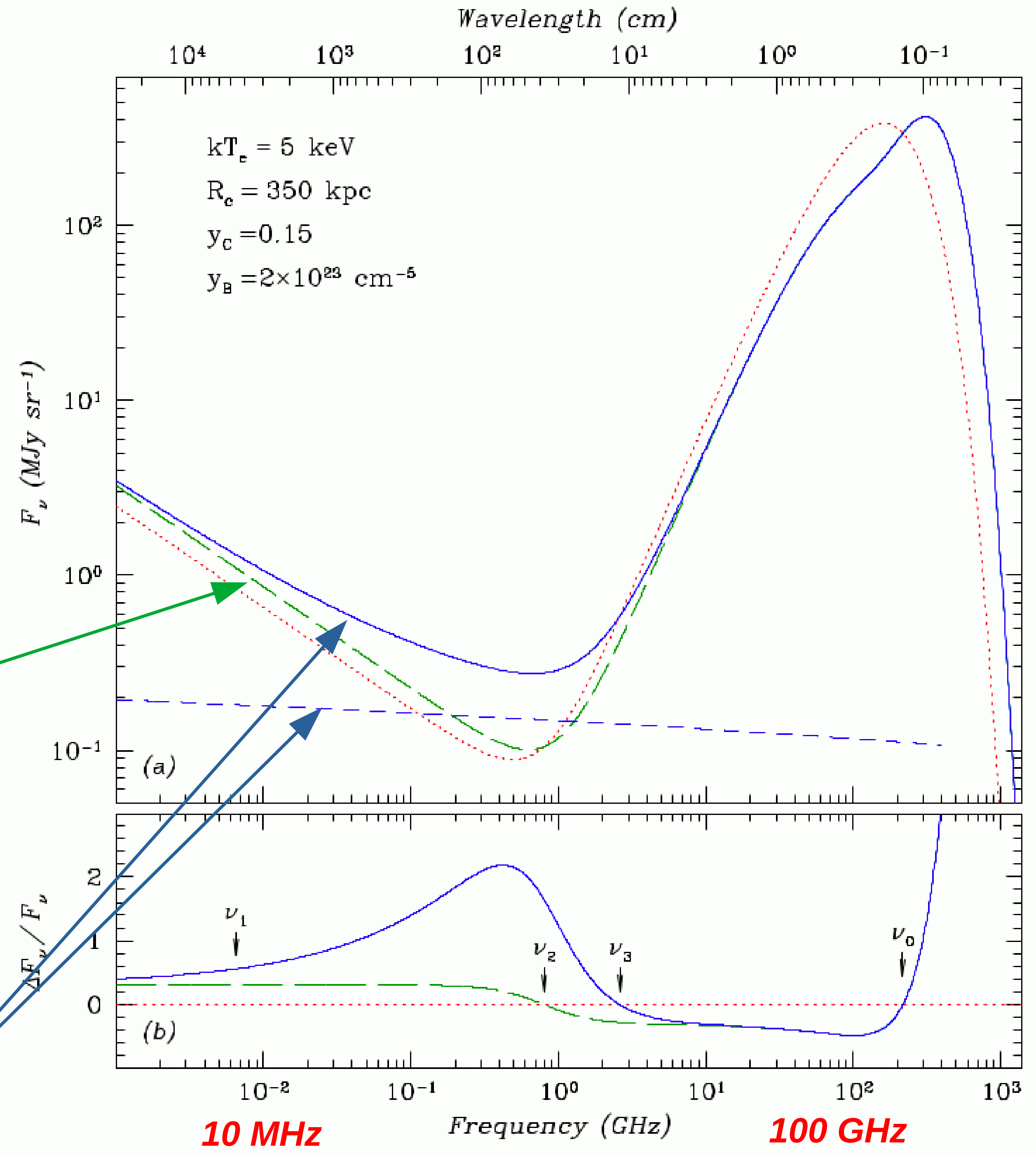
Substituting the radio background spectrum $F_R(\nu)$ in the Kompaneets equation we obtain its relative distortions:

$$\Delta F_R / F_R = y_C\, \alpha(3+\alpha) \simeq 2.08\, y_C$$

It is similar to SZ distortions of the CMB spectrum but positive. These distortions completely compensate each other at frequency $\nu_2 = 810$ MHz (Holder, Chluba 2021).

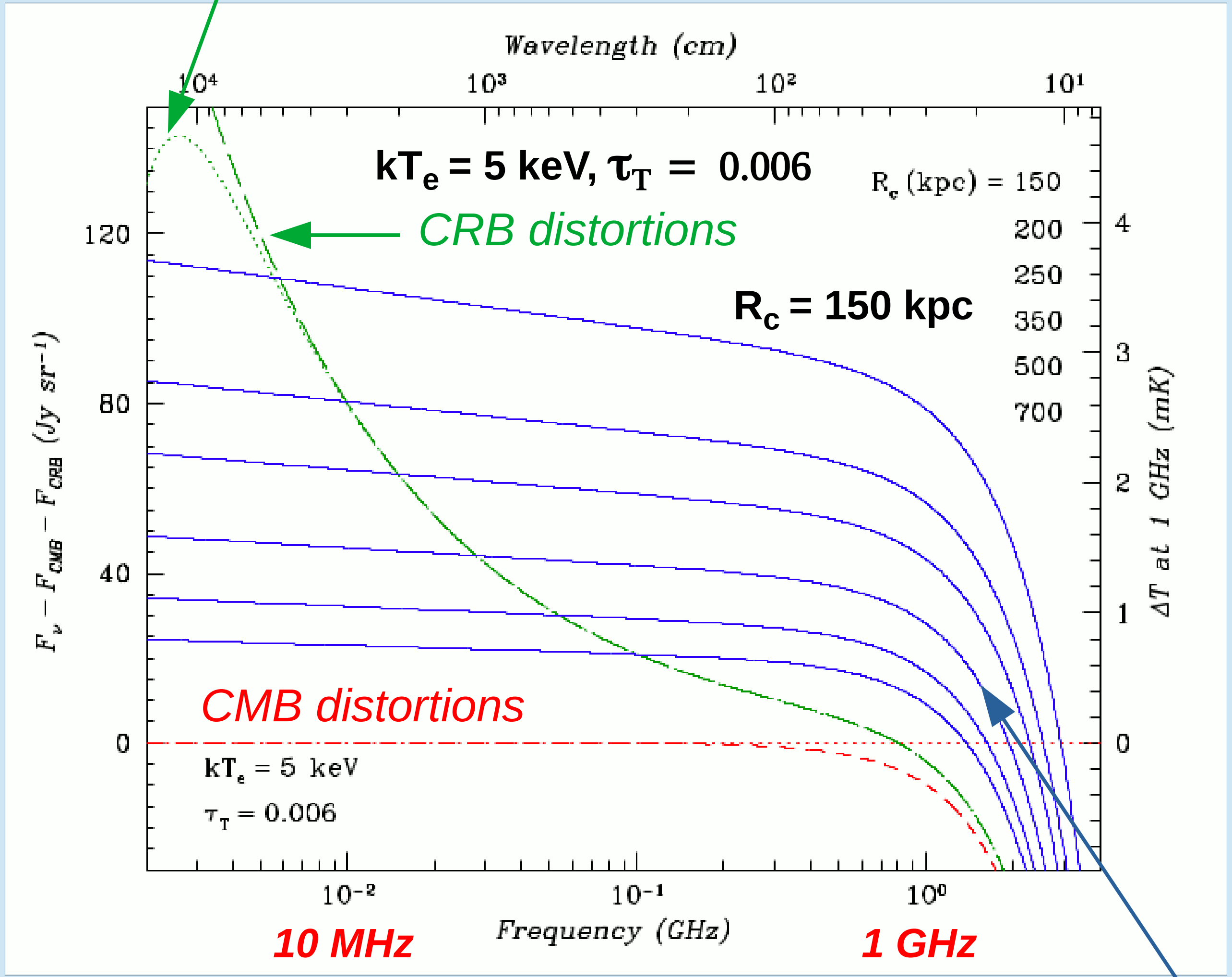
But there is thermal bremsstrahlung from the hot gas which is important in this case:

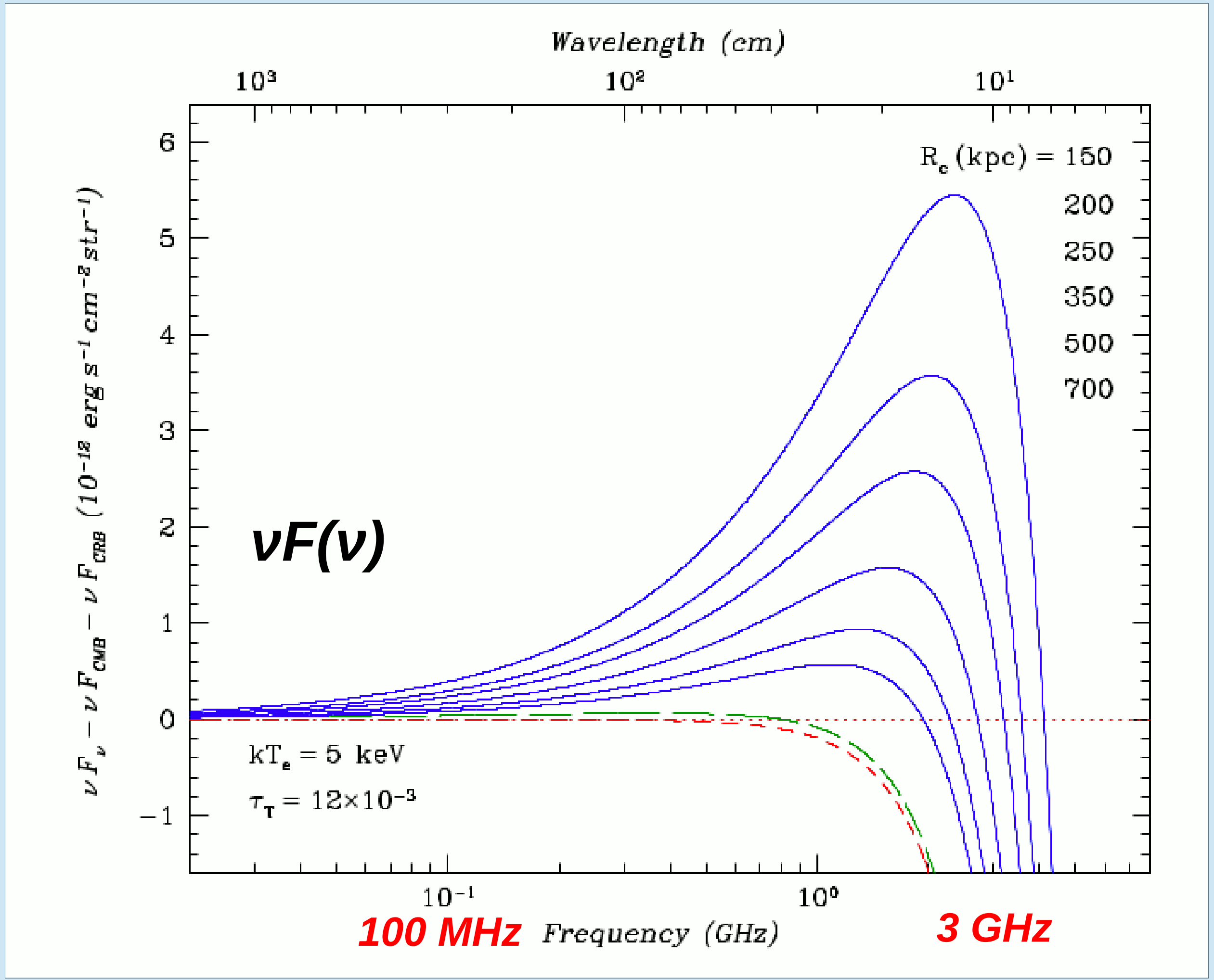
$$F_B(\nu) = y_B A T_e^{-1/2} g(\nu, T_e) \exp(-h\nu/kT_e)$$



Radiobackground (CRB) distortions in the cluster gas

CRB stimulated scattering





Simplest model (sphere of constant density).

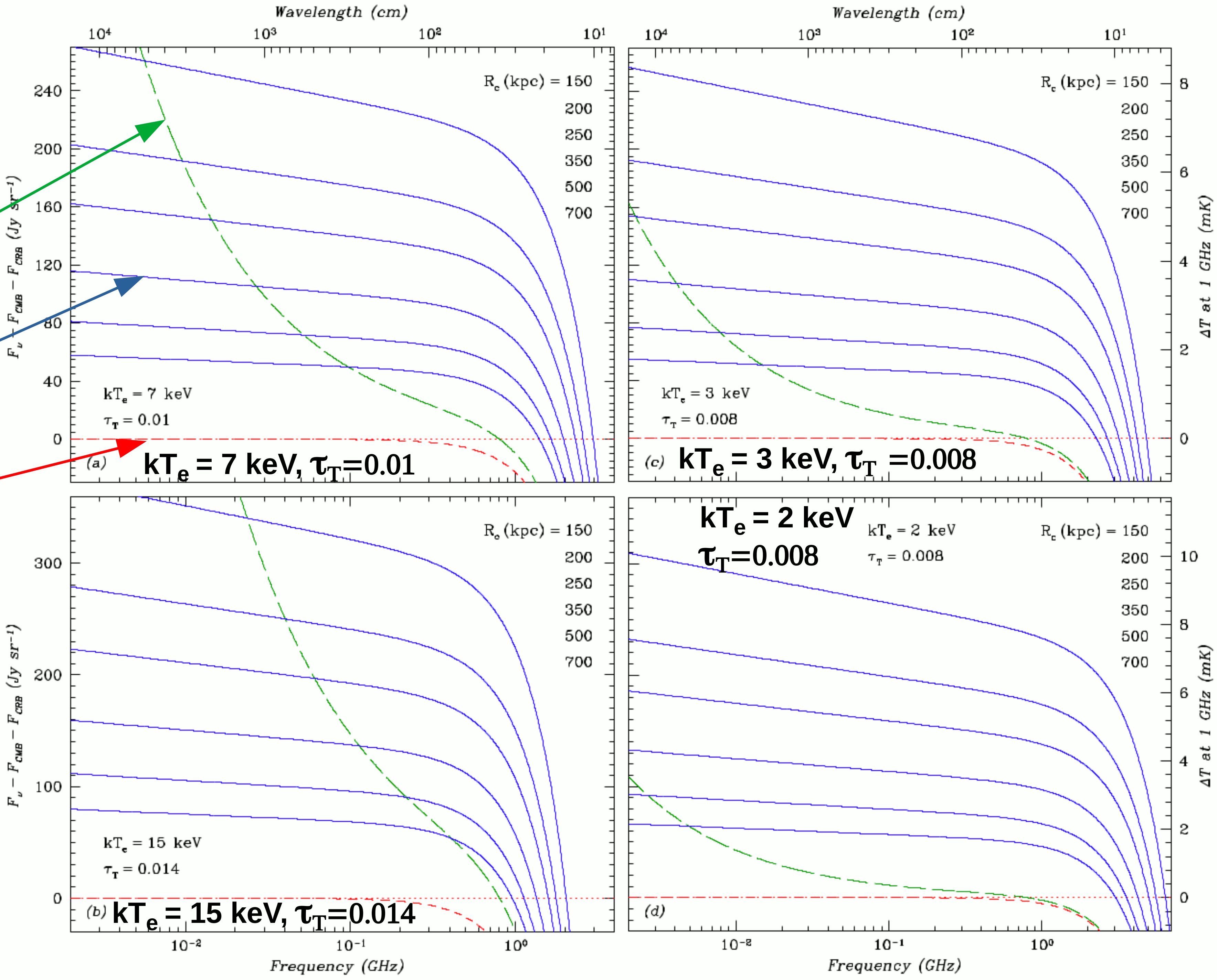
Bremsstrahlung

Radiobackground (CRB) distortions in the cluster gas

CRB distortions

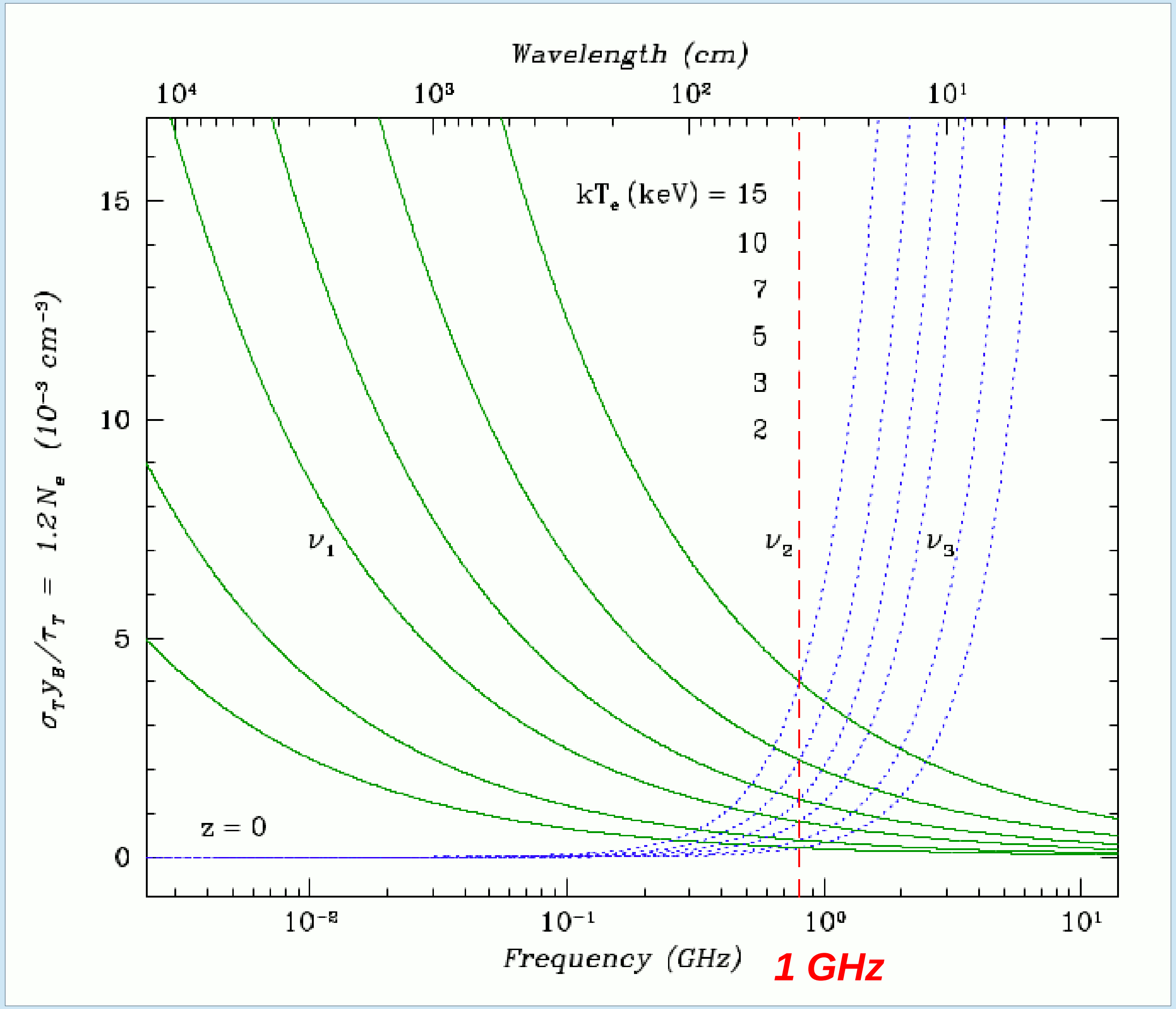
Bremsstrahlung

CMB distortions



Chances of detecting CRB distortions rise with increasing temperature and decreasing density of the gas.

Cosmic Radio-Background (CRB) distortions in the hot cluster gas



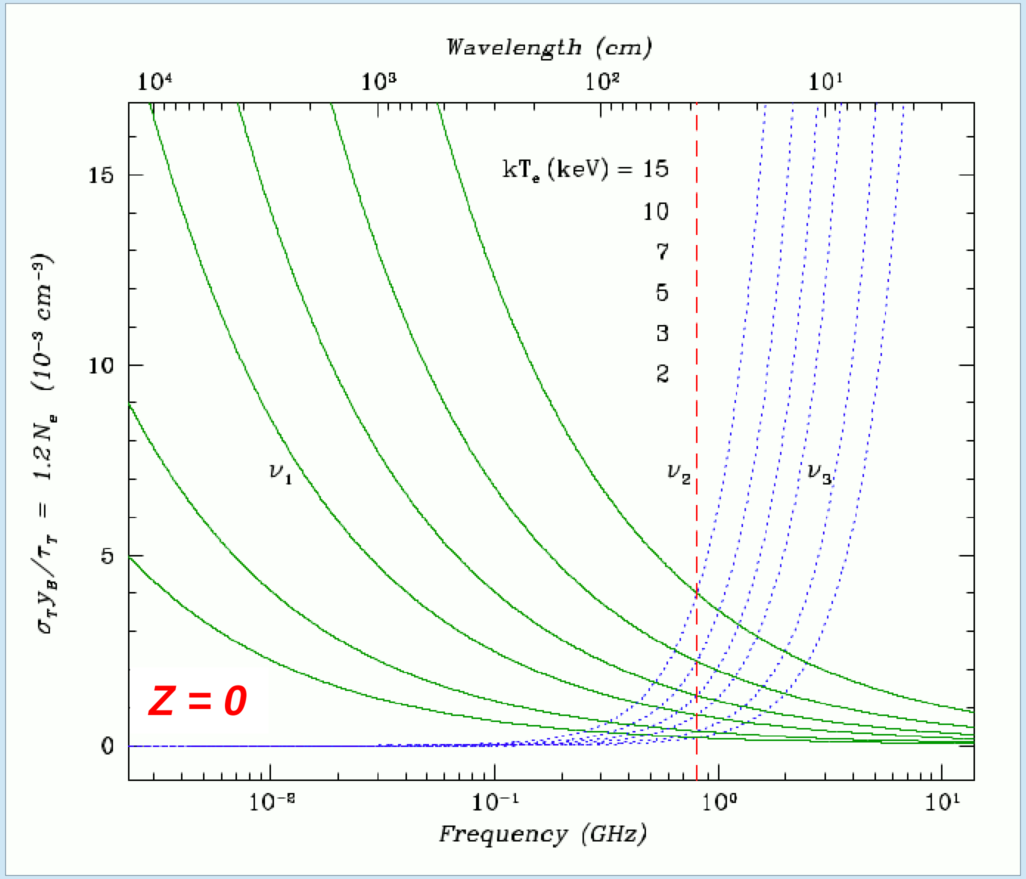
Frequency range with dominant bremsstrahlung contribution vs the interstellar gas temperature and density (for close cluster (z ~ 0).

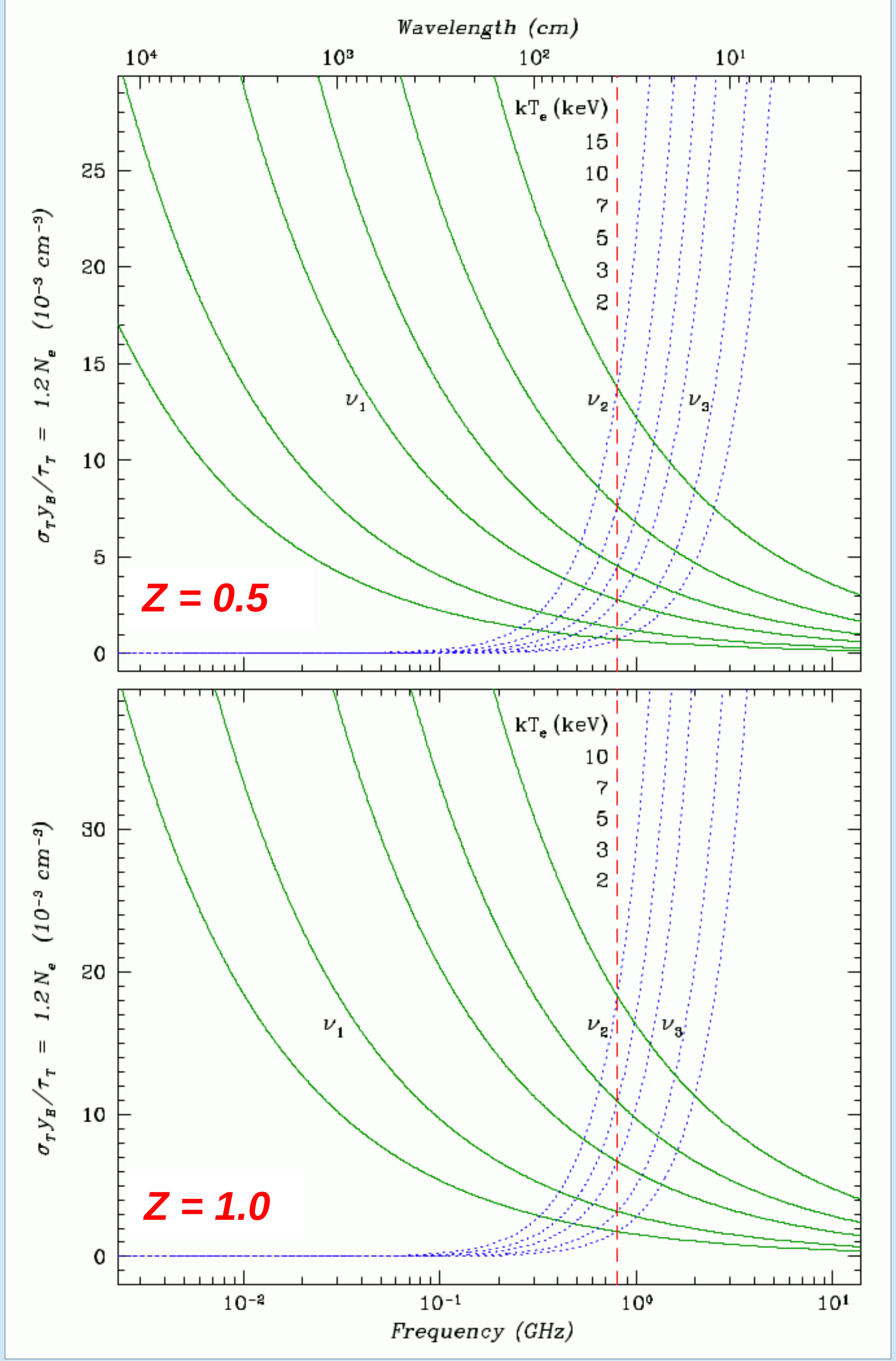
This range is narrowest at high temperatures and large densities of the interstellar gas.

ν_1 is the frequency where CRB distortions become equal to the bremsstrahlung contribution.

ν_3 is the frequency where CMB distortions are completely compensated by the bremstrahlung.

Cosmic Radio-Background (CRB) distortions in the hot cluster gas





The frequency range with dominant bremsstrahlung contribution narrows with increasing redshift z (it is narrower for the distant clusters).

It is advantageous to observe more distant clusters !

Real distribution of the gas

β-model for the gas density distribution:

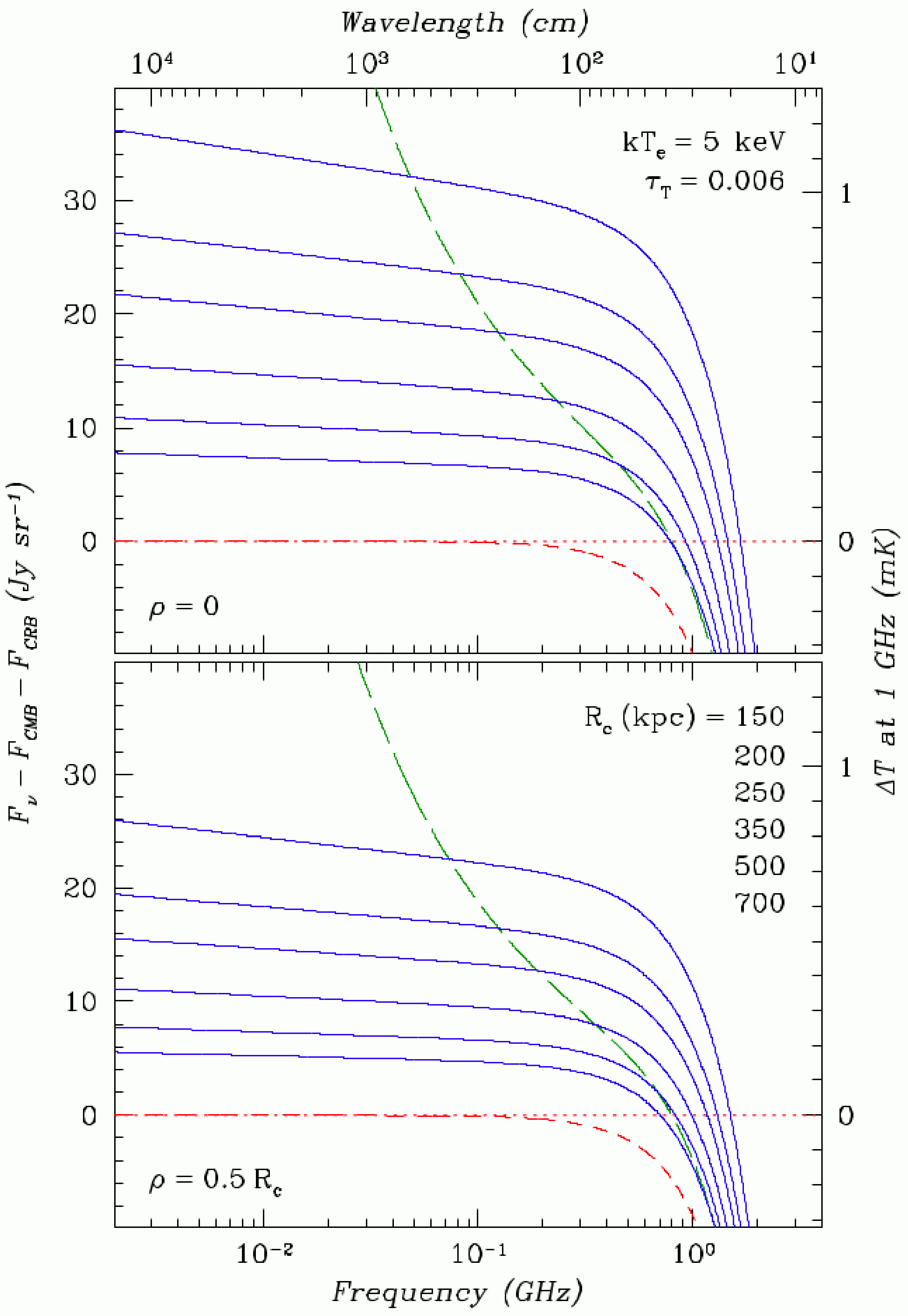
$$N_{\rm e} = N_{\rm c} \left(1 + \frac{R^2}{R_{\rm c}^2}\right)^{-3\beta/2}$$

Bremsstrahlung and scattering parameters:

$$y_{\rm B}(\rho) = 0.59\,\pi \left(1 + \frac{\rho^2}{R_{\rm c}^2}\right)^{-3/2} N_{\rm c}^2\, R_{\rm c}$$

$$\tau_{\rm T}(\rho) = \pi \left(1 + \frac{\rho^2}{R_{\rm c}^2}\right)^{-1/2} \sigma_{\rm T}\, N_{\rm c}\, R_{\rm c}$$

Results of computations for two different impact parameters



Cosmic Radio-Background (CRB) distortions in the hot cluster gas

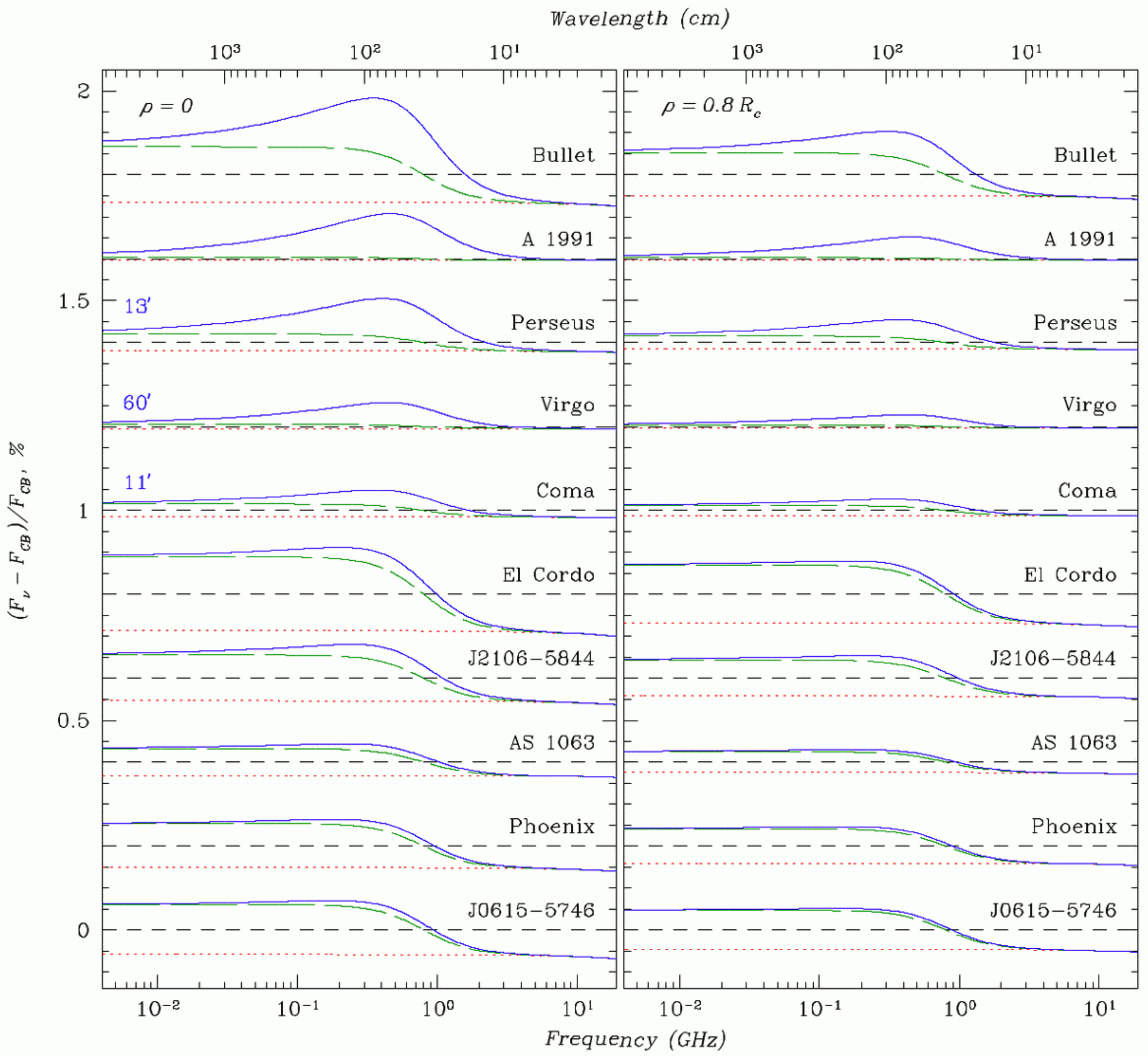
β-model of the gas density distribution.

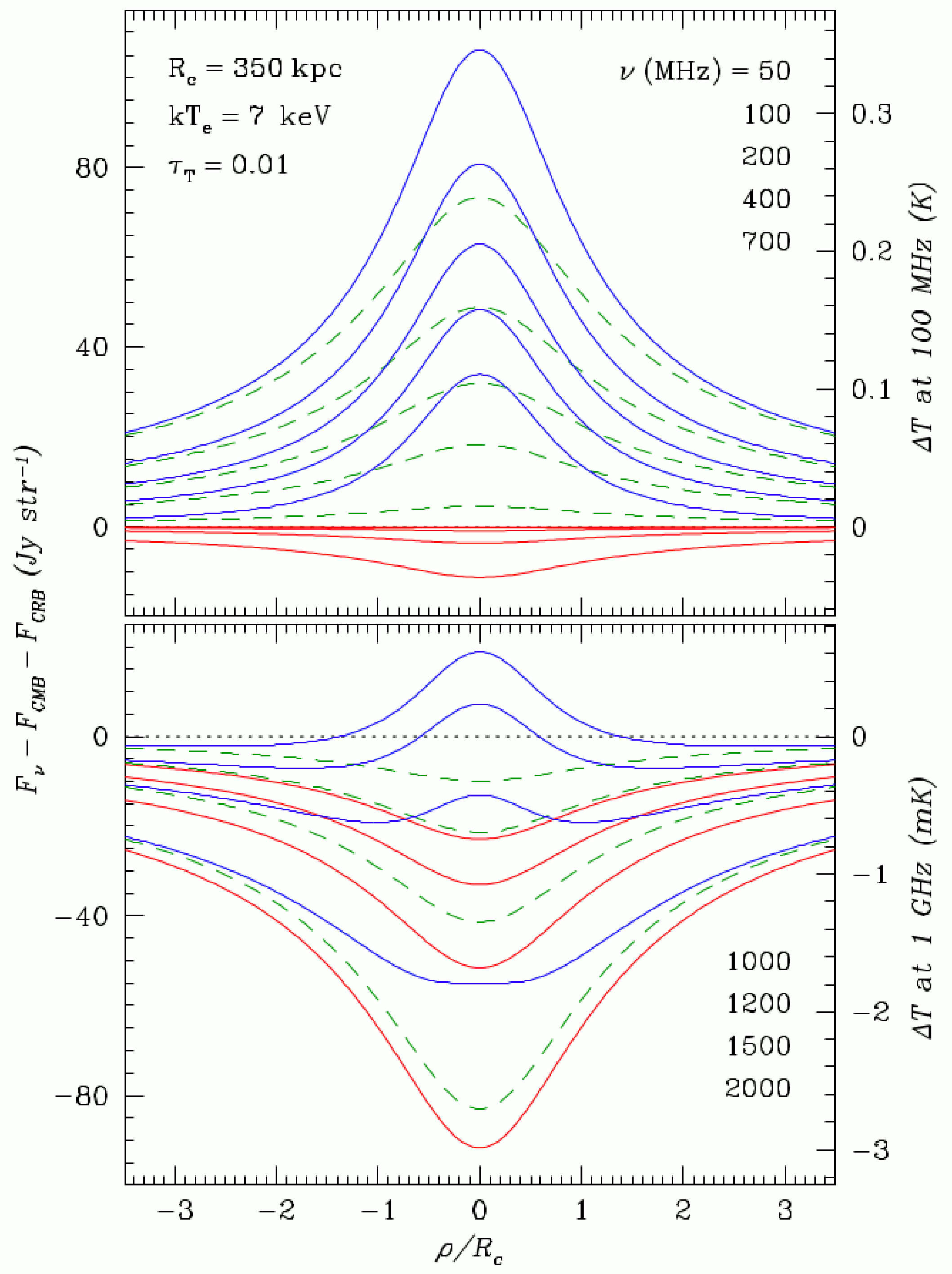
Predictions for 10 real clusters and two impact parameters ρ=0 (left) and ρ=0.8 R_c (right).

It is advantageous to observe the effect of scattering

1). for the hot distant clusters and

2). it is desirable - on their periphery.





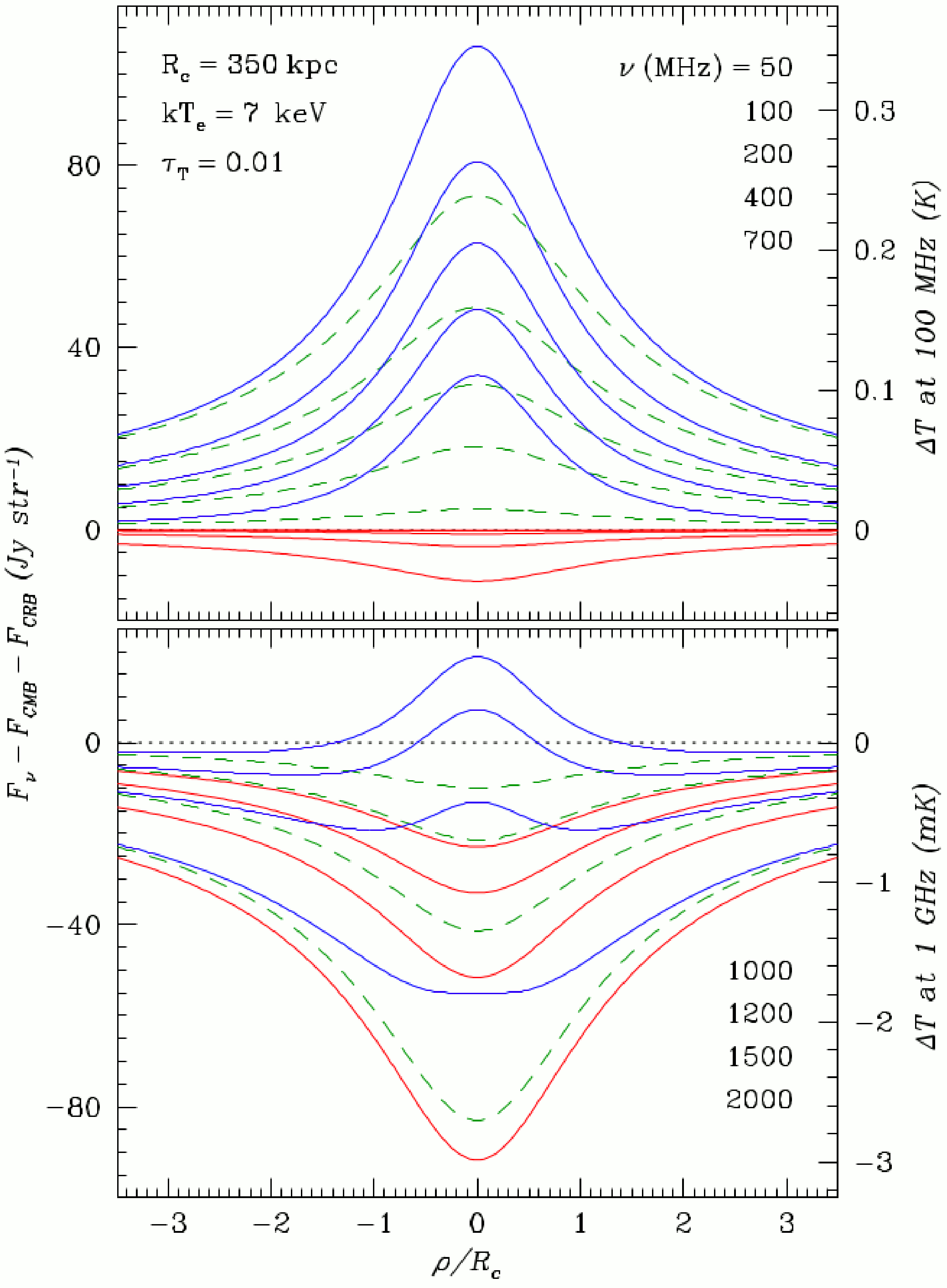
Cosmic Radio-Background (CRB) distortions in the hot cluster gas

β-model for the gas density distribution

Dependence on impact parameter ρ at different frequencies.

Only positive source at ν < 700 MHz (due to general decay of CMB).

Very unusual shape of the source at 800 MHz < ν < 1500 MHz
A hybrid source – a bright narrow positive source surrounded by a dark (negative) ring.



Cosmic CRB distortions in the hot cluster gas

β-model for the gas density distribution.

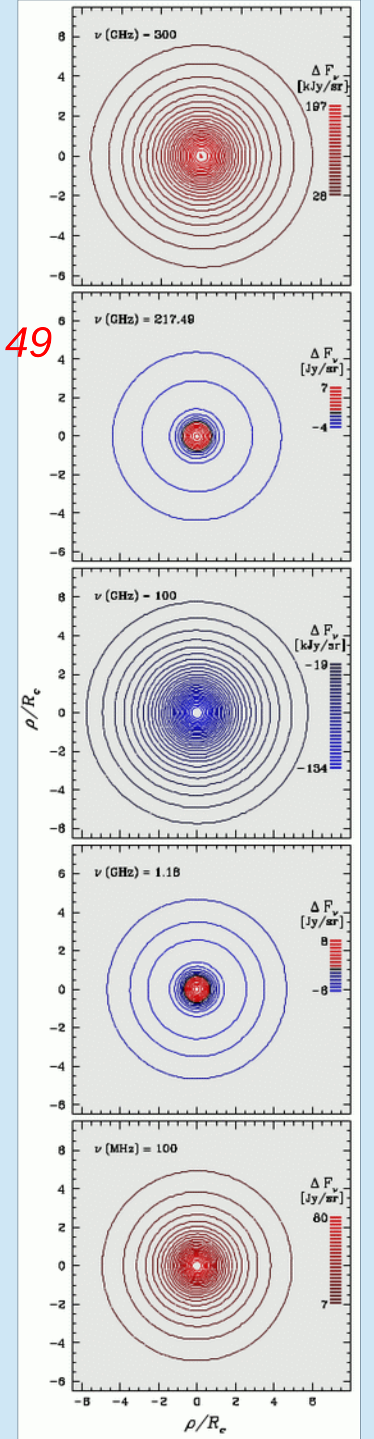
Dependence on impact parameter ρ at different frequencies.

Transition from the brightness decrement to its increment occurs through the appearance of a very unusual (hybrid) source – a bright narrow positive spot surrounded by a dark (negative) ring.

SZ-source does not dissapear at ν ~ 217.5 ГГц but also turns into such a hybrid source.

<u>This is because</u>
1). scattered emission has extremely wide spatial distribution,
2). thermal bremsstrahlung strongly concentrates toward the center.

GHz
300
217.49
100
1.18
100 MHz

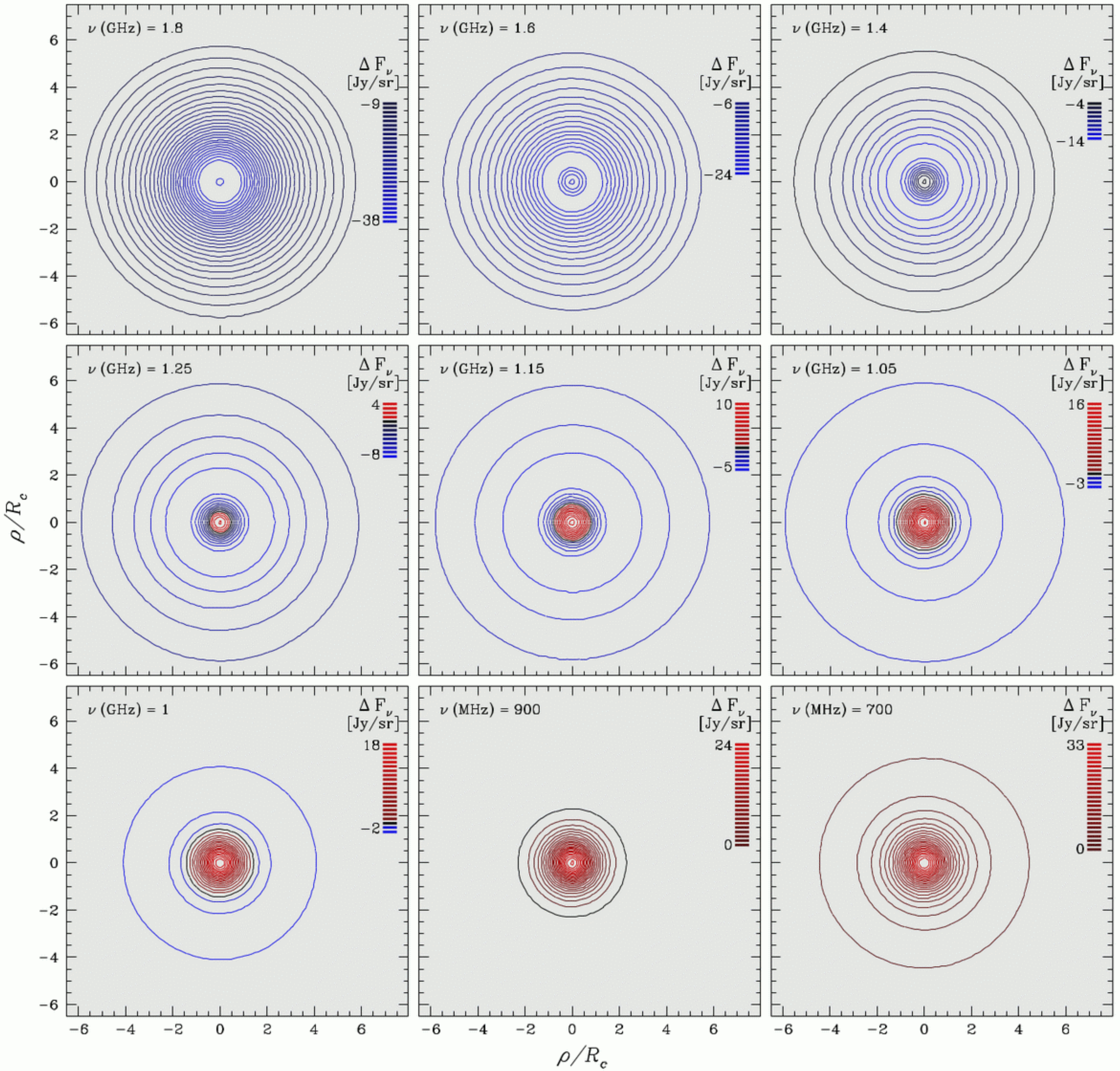


Evolution of the source shape at the map of radio-background fluctuations

Appearance and decay of a hybrid source in the direction to the cluster while the frequency decreases from ν = 1.8 GHz to ν = 700 MHz.

Hybrid source is in the latent shape in the frequency range 1.4 GHz < ν < 1.8 GHz

Only thermal bremsstrahlung is observed at ν = 900 MHz



Diffuse radiation

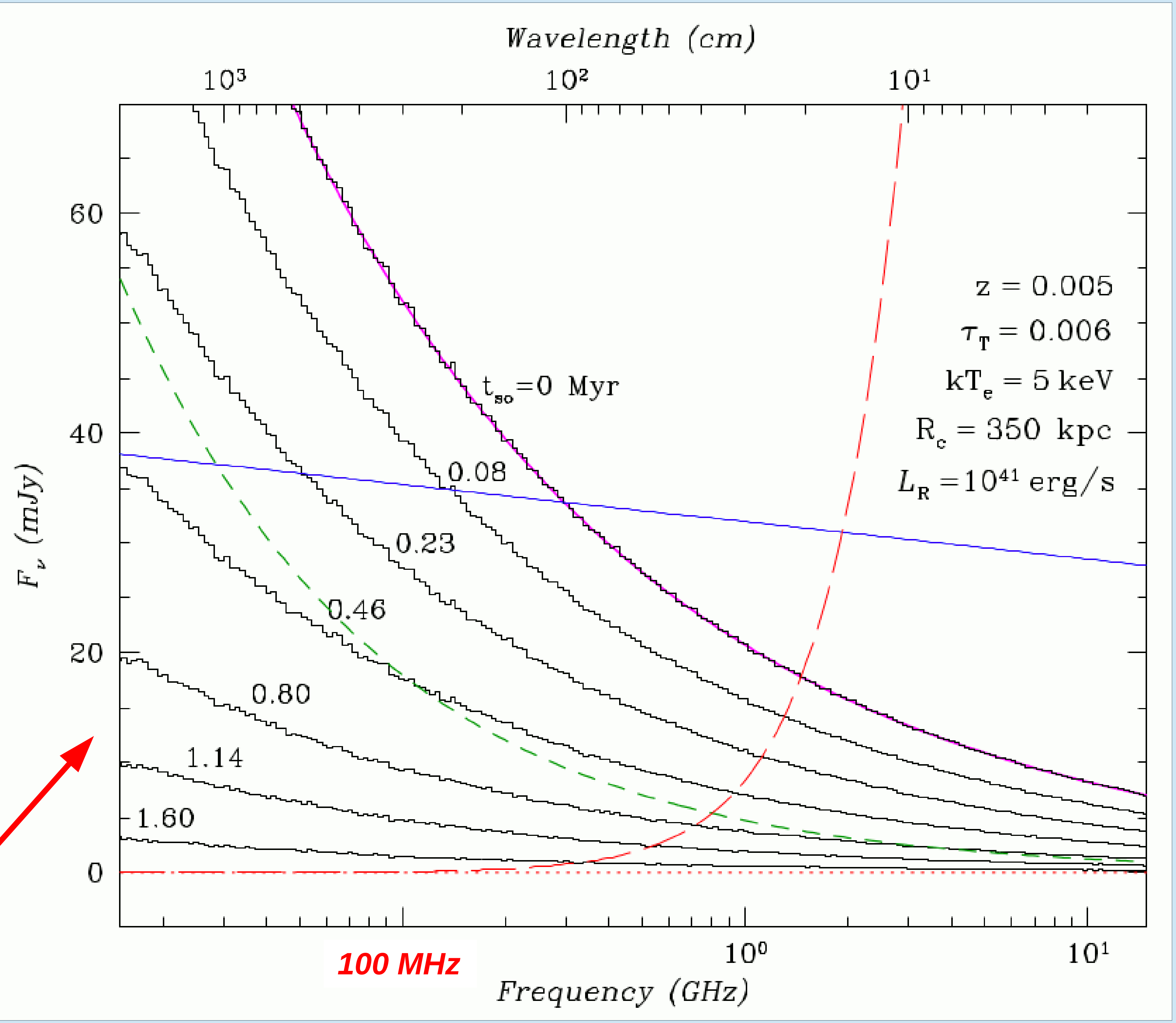
We showed that in many cases thermal bremsstrahlung may prevent (or make it complex) direct detection of increment of the radio background.

Synchrotron radiation can be also a serious obstacle for such detection:

1). The cluster may have a radio halo connected with relativistic electrons accelerated at shocks during cluster mergers or collisions. About 30% clusters have such a halo. They can not be used.

2). Diffuse emission from an extinct bright radiogalaxy inside the cluster (emission from the currently active galaxy can be still accounted).

Simple model (sphere with constant density), Monte Carlo simulations. L_R is in the 10 MHz - 100 GHz range.



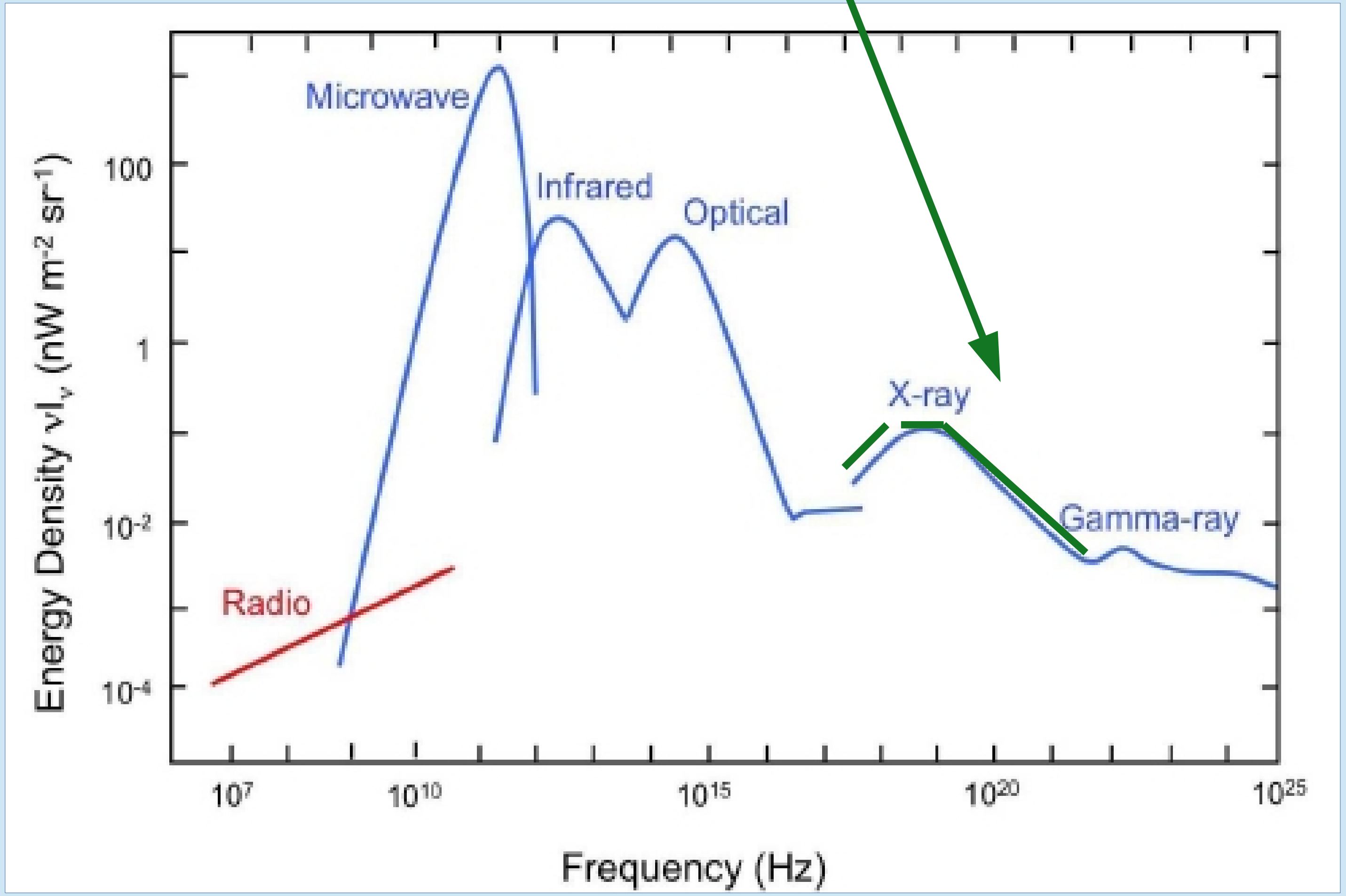
Background radiation in other spectral bands

Cosmic X-ray and soft Gamma-ray Background (CXB)

- *In the X-ray (> 3 keV) and soft gamma-ray band the spectrum was measured by HEAO-1 (Gruber et al. 1991). Here E is in keV, S_0 is in keV cm $^{-2}$ s $^{-1}$ keV $^{-1}$ stem $^{-1}$.*

$$S_0(E) \simeq \begin{cases} 7.877\ E^{-0.29} e^{-E/41.13}, & \text{at } E < 60 \\ 0.0259\ (E/60)^{-5.5} + \\ 0.504\ (E/60)^{-1.58} + & , \quad \text{at } E > 60. \\ 0.0288\ (E/60)^{-1.05} \end{cases}$$

- *The fit agrees well with the COMPTEL-EGRET measurements in the 1 MeV – 100 GeV band*
- *It is formed by AGNs at z > 1 but saves its shape at higher redshifts. It is isotropic like CMB and CRB.*
- *Monte Carlo computations, code described by Pozdnyakov et al. (1983).*
- *Ionization structure computed (Raymond-Smith code).*
- *Photoabsorption cross-sections by ions of heavy elements from Verner et al. (1995-96).*



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Decrease in the Brightness of the Cosmic X-ray and Soft Gamma-ray Background toward Clusters of Galaxies

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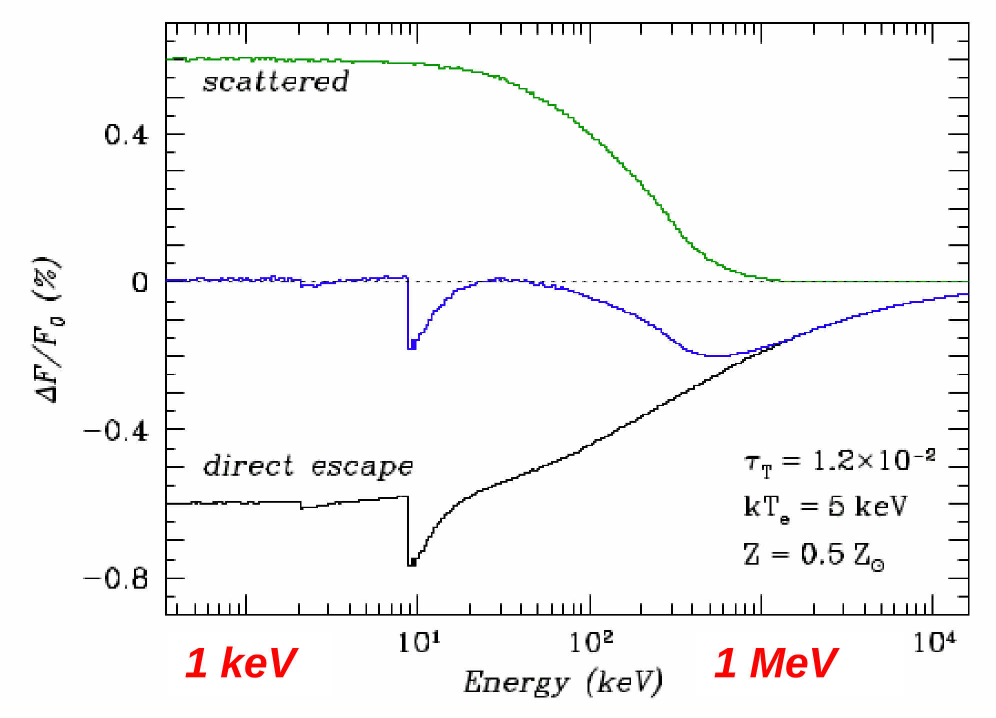
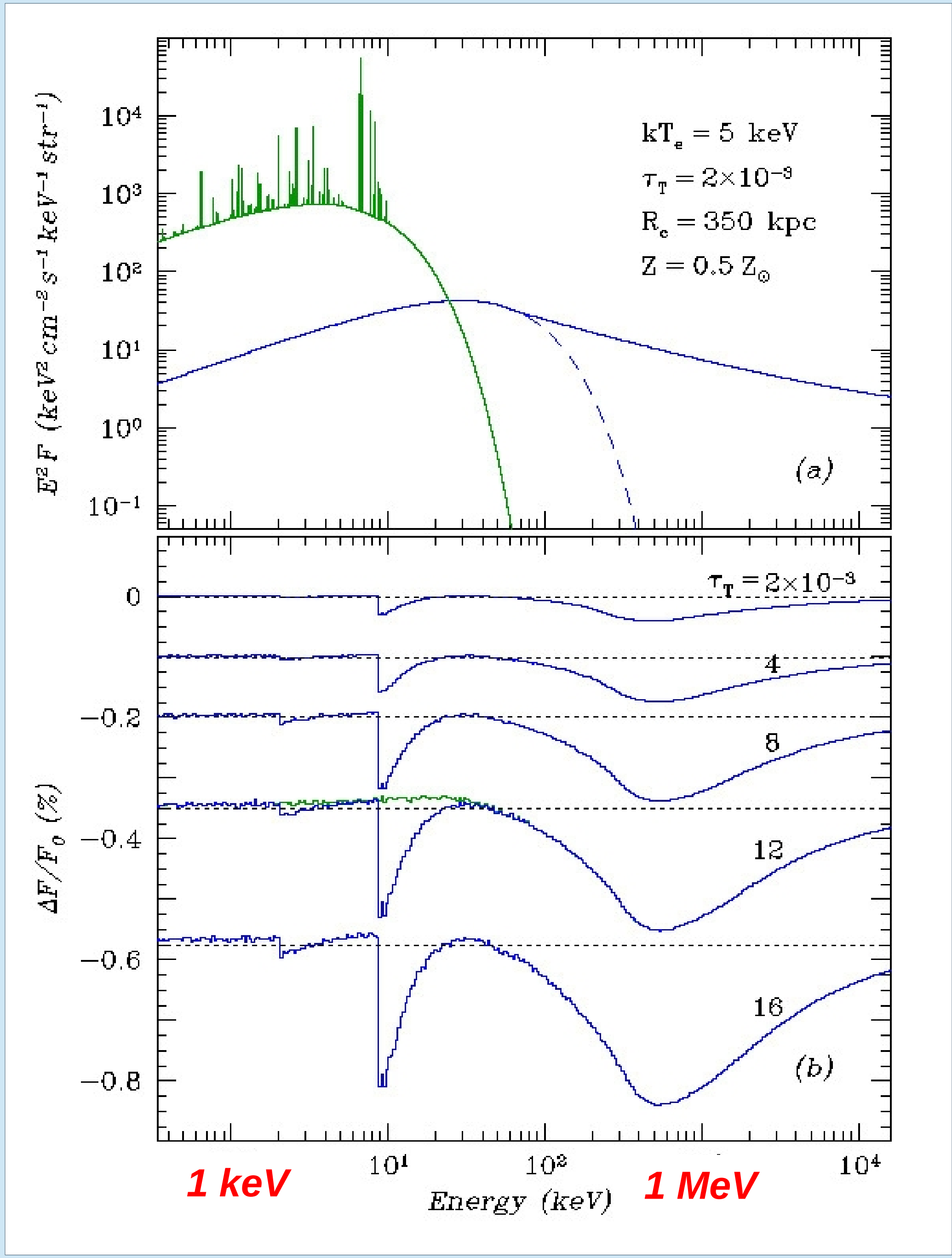
Scattered emission responsible for the positive distortions of CXB is connected with the emission incident on the cluster from all sides (thus, these distortions are not sensitive to the background fluctuations).





All negative distortions occur in the CXB emission coming to us through the cluster (they are sensitive to CXB inhomogeneities).

Dependence on τ_T

CXB distortions in the hot gas

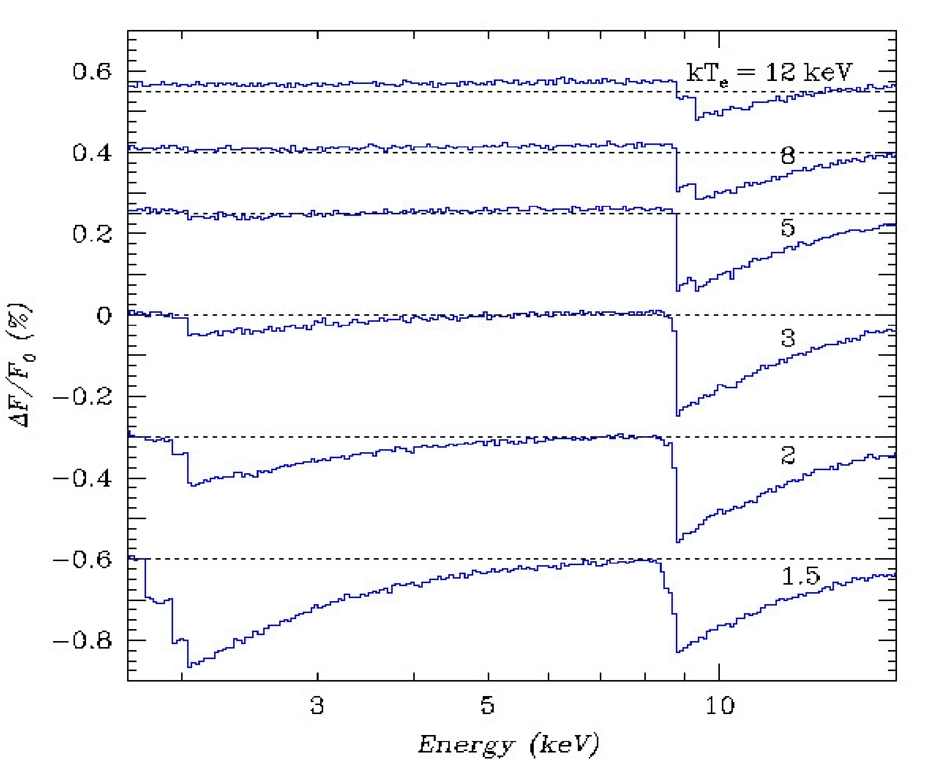
In the classical SZ-effect (scattering of CMB) hν « kTe, therefore the Doppler effect is working.

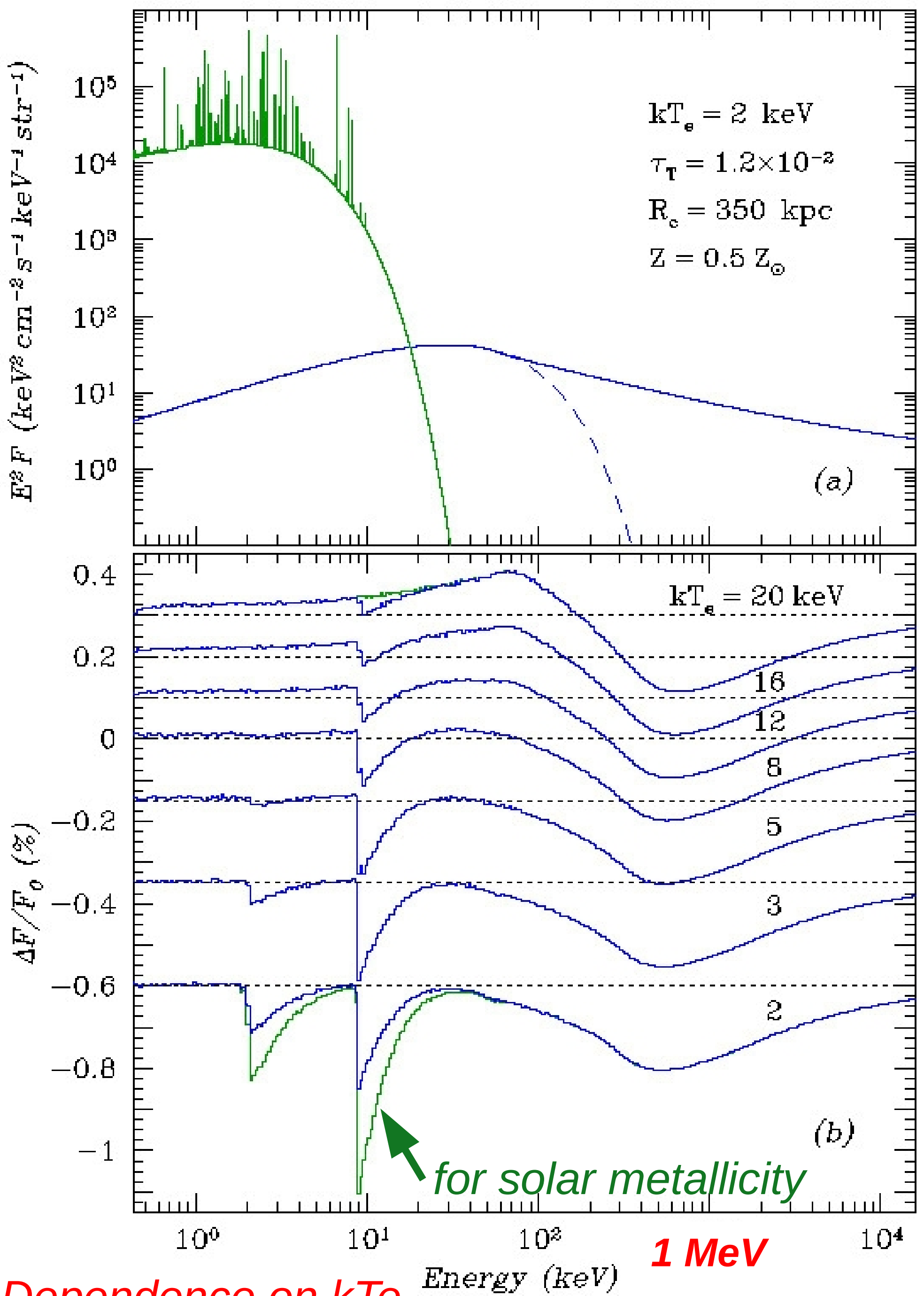
When scattering of X-ray and soft gamma-ray photons is considered hν > kTe, thus both the Doppler effect and recoil effect are important.

The broad feature in absorption is formed in the background near 500-600 keV.

Photoabsorption by highly (but not completely) ionized iron, nickel and other elements is very important producing absorption features near ~9 and ~2 keV.

Thresholds are consist of the steps corresponding to various ions.





Dependence on kTe

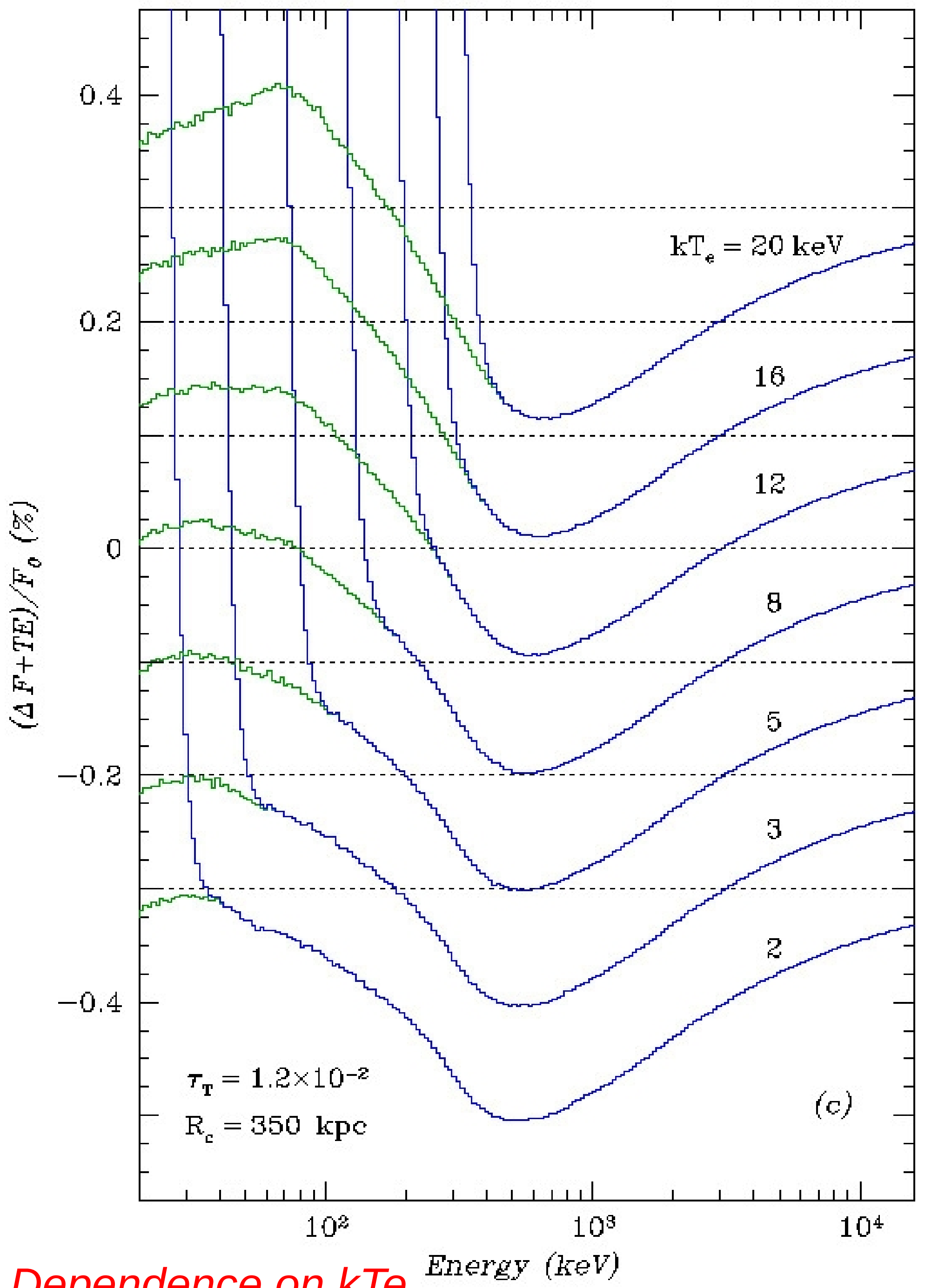
CXB distortions in the hot gas

Again the main obstacle for observation of the CXB scattering is thermal bremsstrahlung from the hot gas.

Green curves – net CXB distortions relatively the incident spectrum.

Blue curves – took also into account thermal bremsstrahlung from the hot gas.

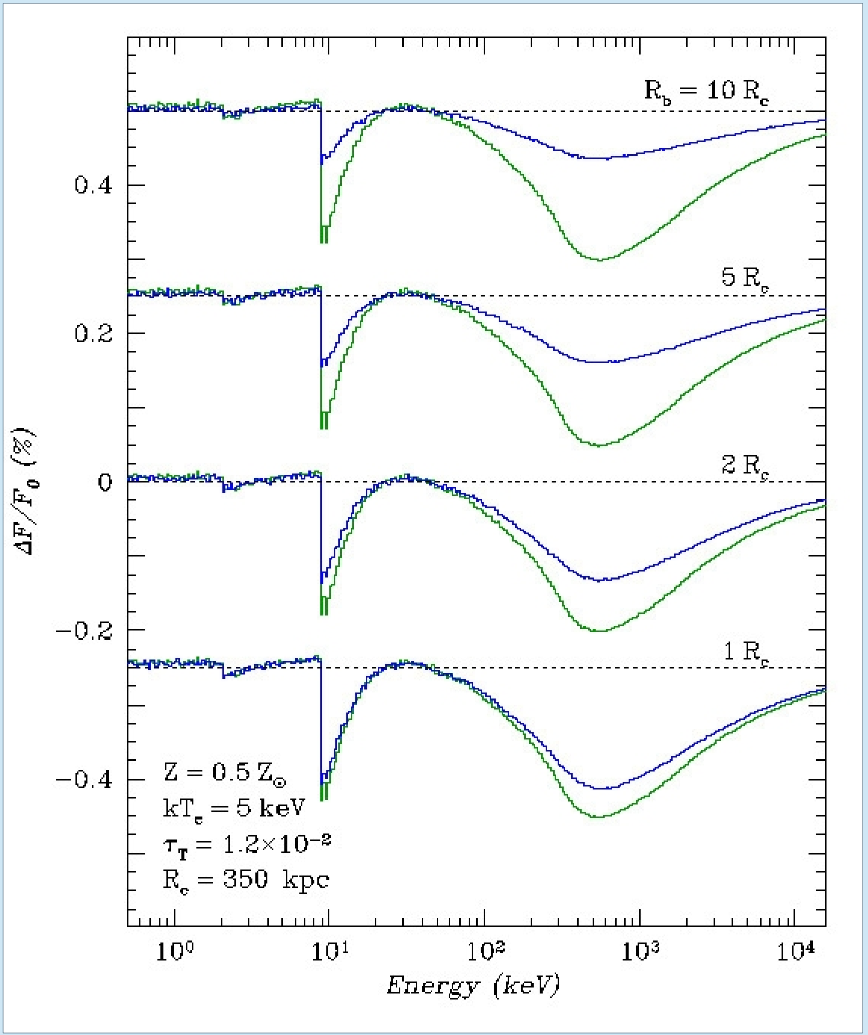
"MeV-feature in absorption" is not distorted by thermal emission of the gas even in the case of highest temperatures.



Dependence on kTe

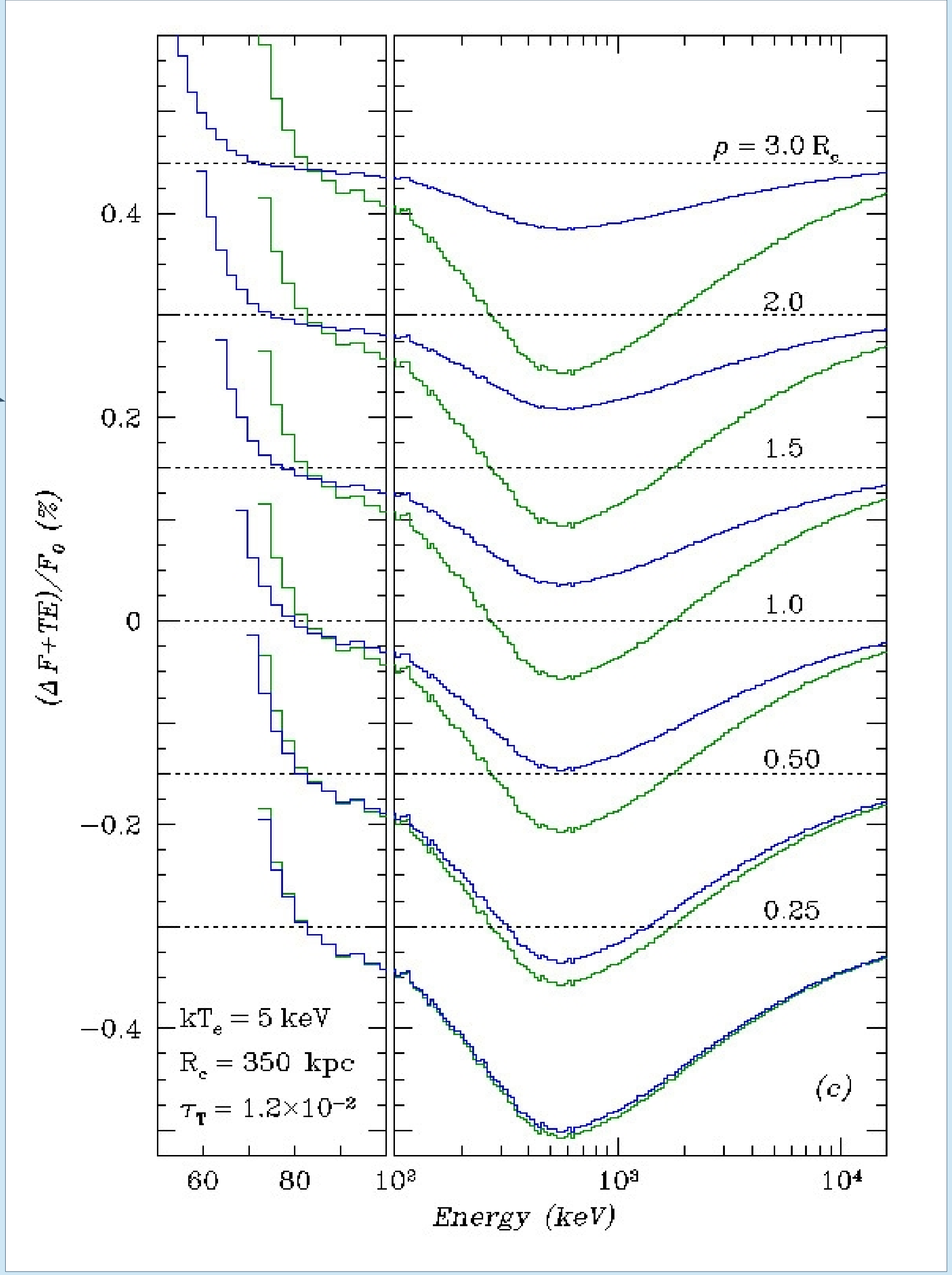
CXB distortions in the hot gas

We then considered the model with some realistic density distribution (i.e. β-model) and modelled observations of the CXB distortions with different impact parameters ρ



The contribution of thermal emission decreases with ρ, but the effect itself also decreases.

Green line shows the result for the sphere with constant density.



Here the green line shows the case of ρ = 0.

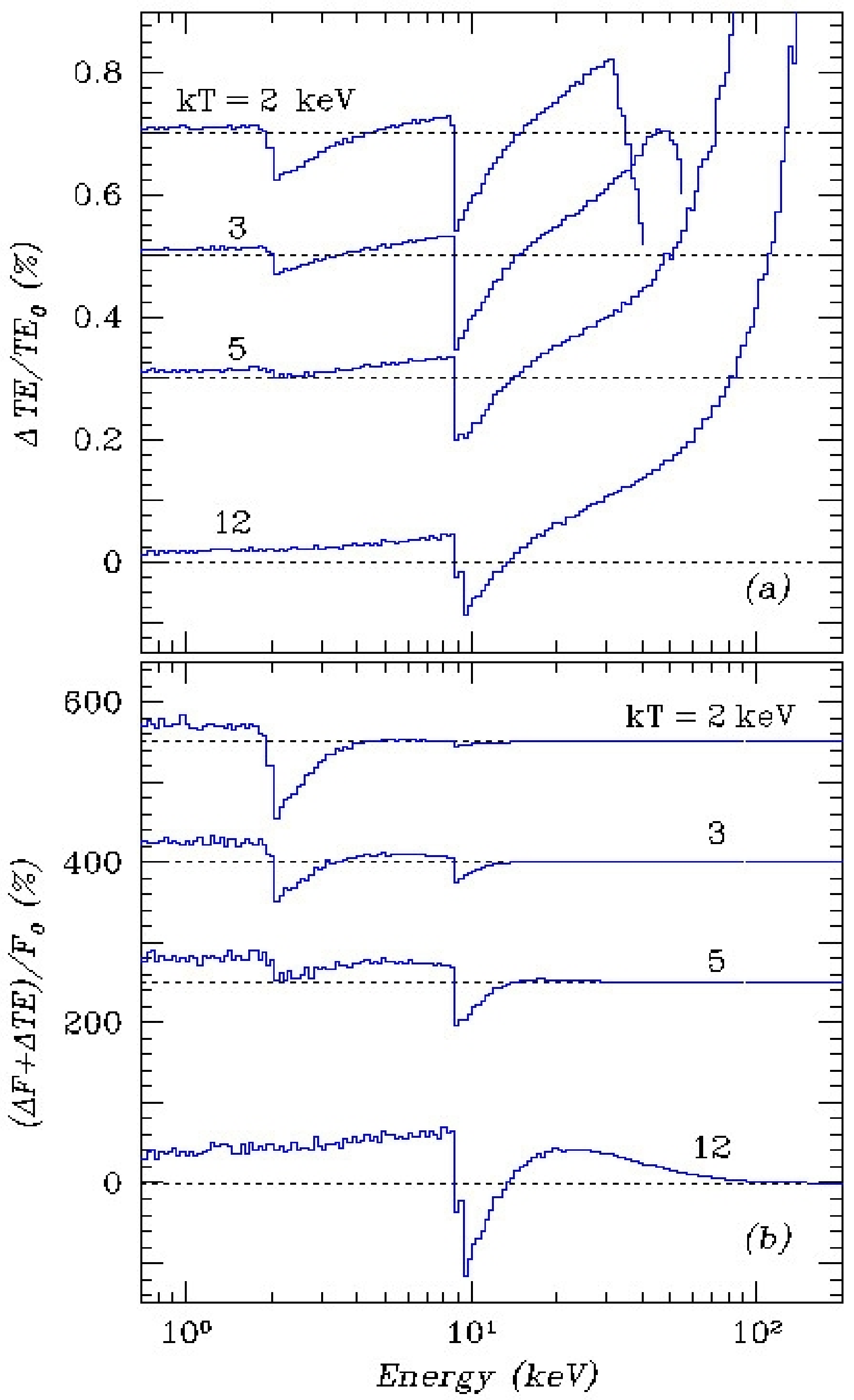
Distortions in the spectrum of the thermal emission of the hot gas

Due to finit optical depth of the cluster gas distortions similar to those predicted for the background spectrum arise in its thermal emission and accounted as the distortions in CXB. The amplitude of these distortions reaches 100% and more relatively the background spectrum.

Top panel – distortions in the thermal emission of the cluster gas relatively the bremsstrahlung spectrum itself. Rise in the amplitude of distortions at high energies is connected with the Doppler effect (inverse Compton scattering).

Bottom spectrum – distortions relatively the background spectrum (when the theoretical spectrum of optically thin plasma is subtracted from the measured spectrum).

The absorption line at 8 keV is not formed in the case kTe = 2 keV, because the thermal spectrum quickly cuts off.

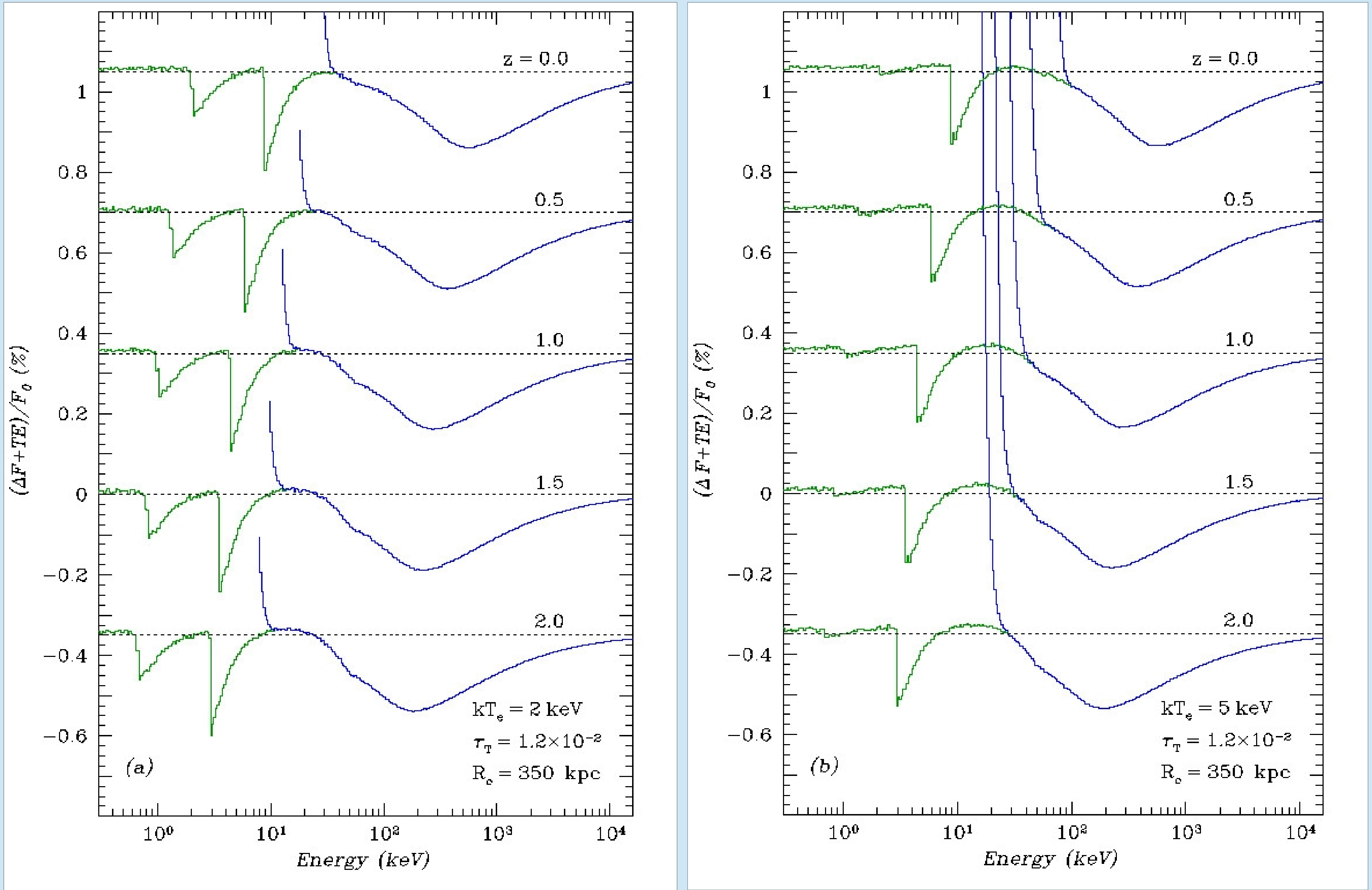


Dependence of CXB distortions on redshidt (z)

In contrast with the classical SZ-effect distortions in CXB depend on z, because the photoabsorption lines and MeV-feature are associated with well-defined energies.

Spectrum of thermal bremsstrahlung also changes with z.

Figures correspond different temperatures kTe = 2 and 5 keV.

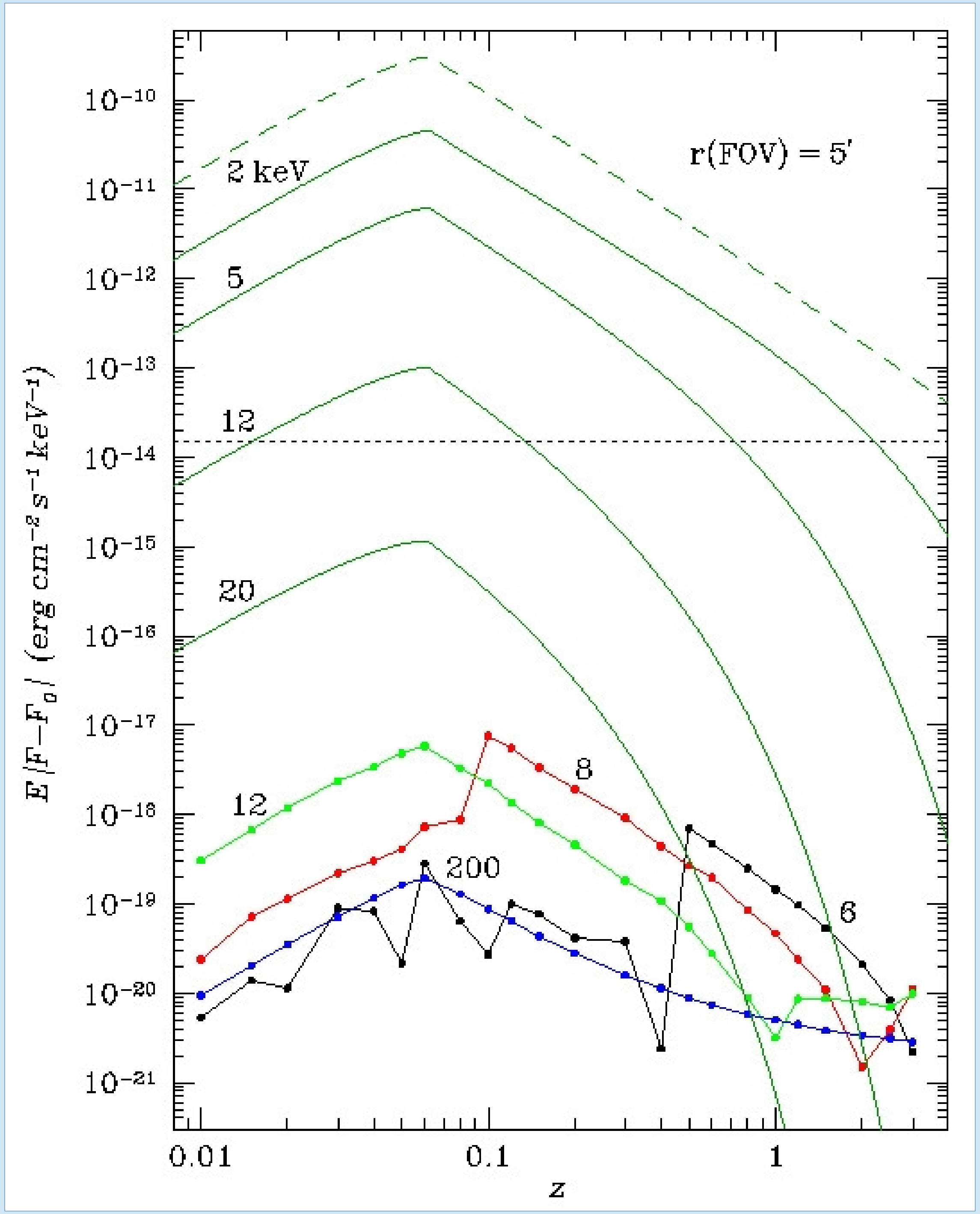


Dependence of CXB distortions on z

Absolute changes of the spectral flux within telescope's aperture (FOV = 5 arcmin) at different energies recorded from the thermal spectrum with kTe = 2 keV (green lines) and CXB (lines with dots) vs redshift (z).

Flux in the incident background spectrum at 5 keV is shown by a dotted line.

Integrated flux of the thermal bremsstrahlung is shown by a dashed line.

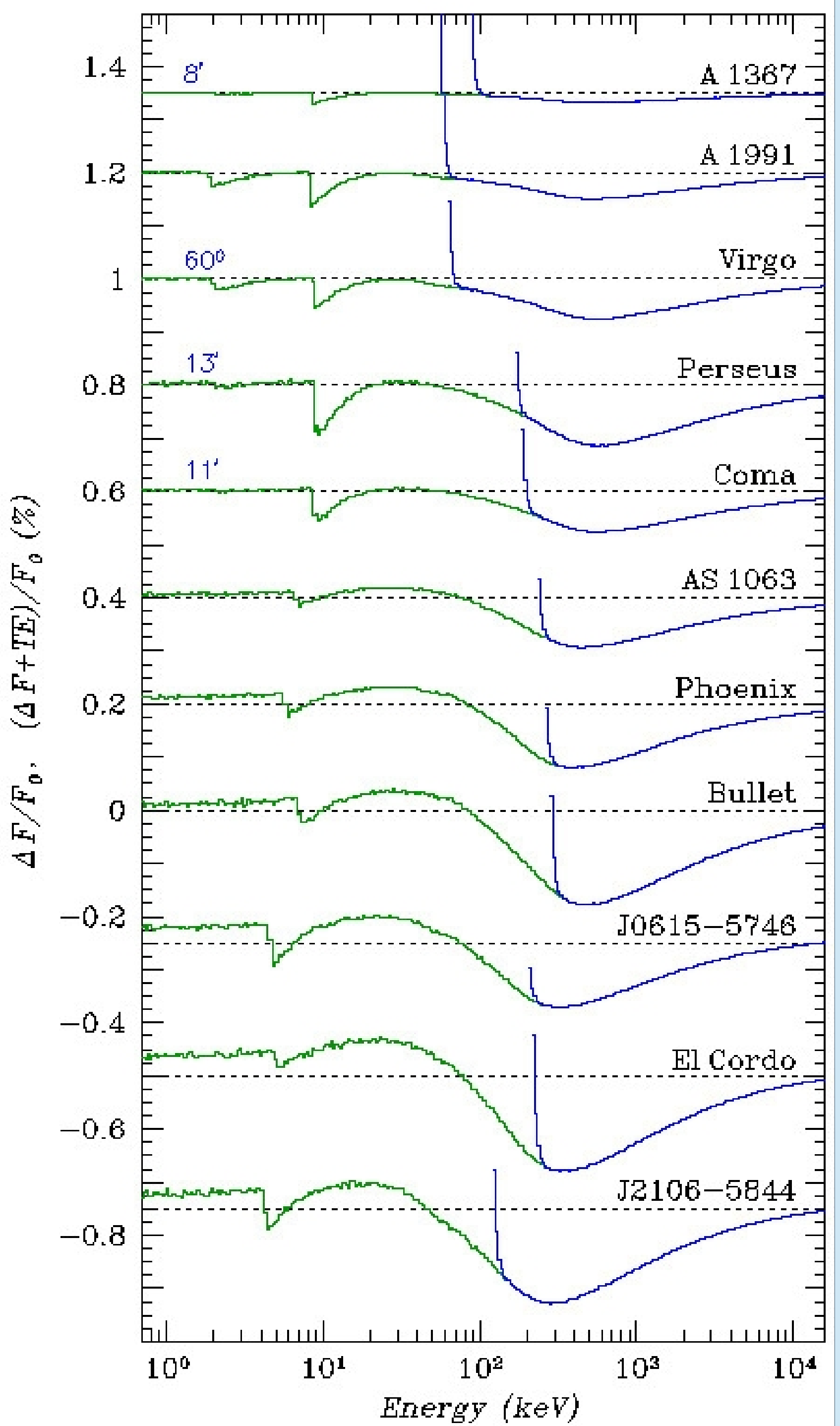


Distortions in the CXB spectrum towards several real clusters

We consider several nearby clusters or very massive ones with measured large SZE decrements. These are the same clusters used for reconstructing the CRB distortions.

The dip at about 500 keV is present in all the spectra, even in those belonging to low-massive cold clusters.

Perhaps, it may be even more promising to observe such cold but nearby and extended clusters than the hot supermassive ones discovered with the classical SZ-effect (because the latter are characterized by intense thermal emission).



Distortions in the CXB spectrum connected with past activity of AGN

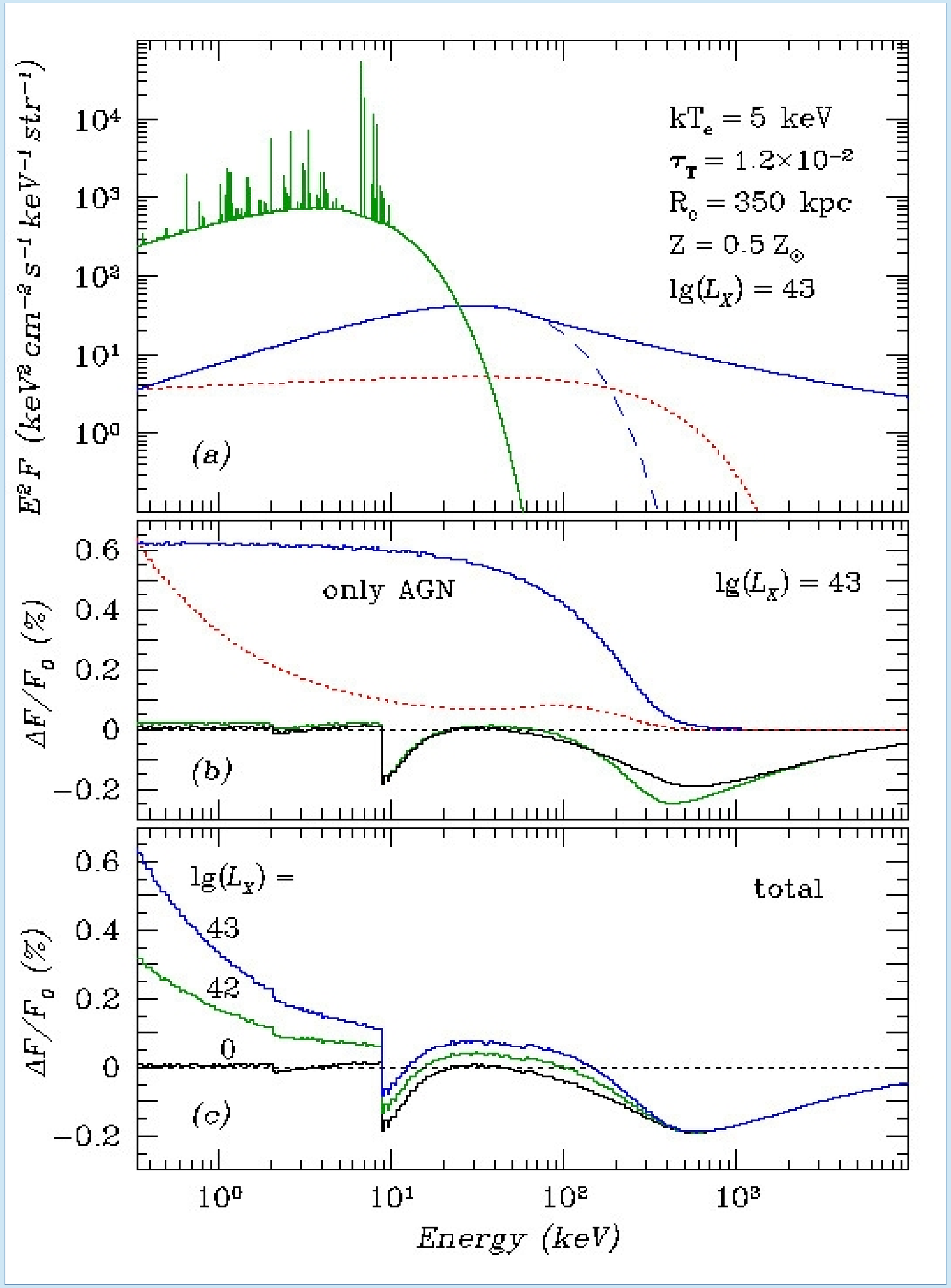
Outburst of AGN within the cluster several hundred years ago will leave behind diffuse radiation scattered in the hot cluster gas which will provide positive background distortions in CXB.

Maximum distortions arise in the soft X-ray band but depend on the intrinsic absorption in the AGN spectrum.

Panel (a) – the AGN radiation spectrum (red dotted line) in comparison with the background and cluster gas spectra.

Panel (b) – the distortions of the AGN (green) and background (black curves) spectra, the scattered AGN radiation relative to its initial spectrum (blue curve) and relative to the initial background spectrum (red dotted line)

Panel (c) – the background distortions including the scattered AGN radiation. The dip at ~500 keV was not affected.



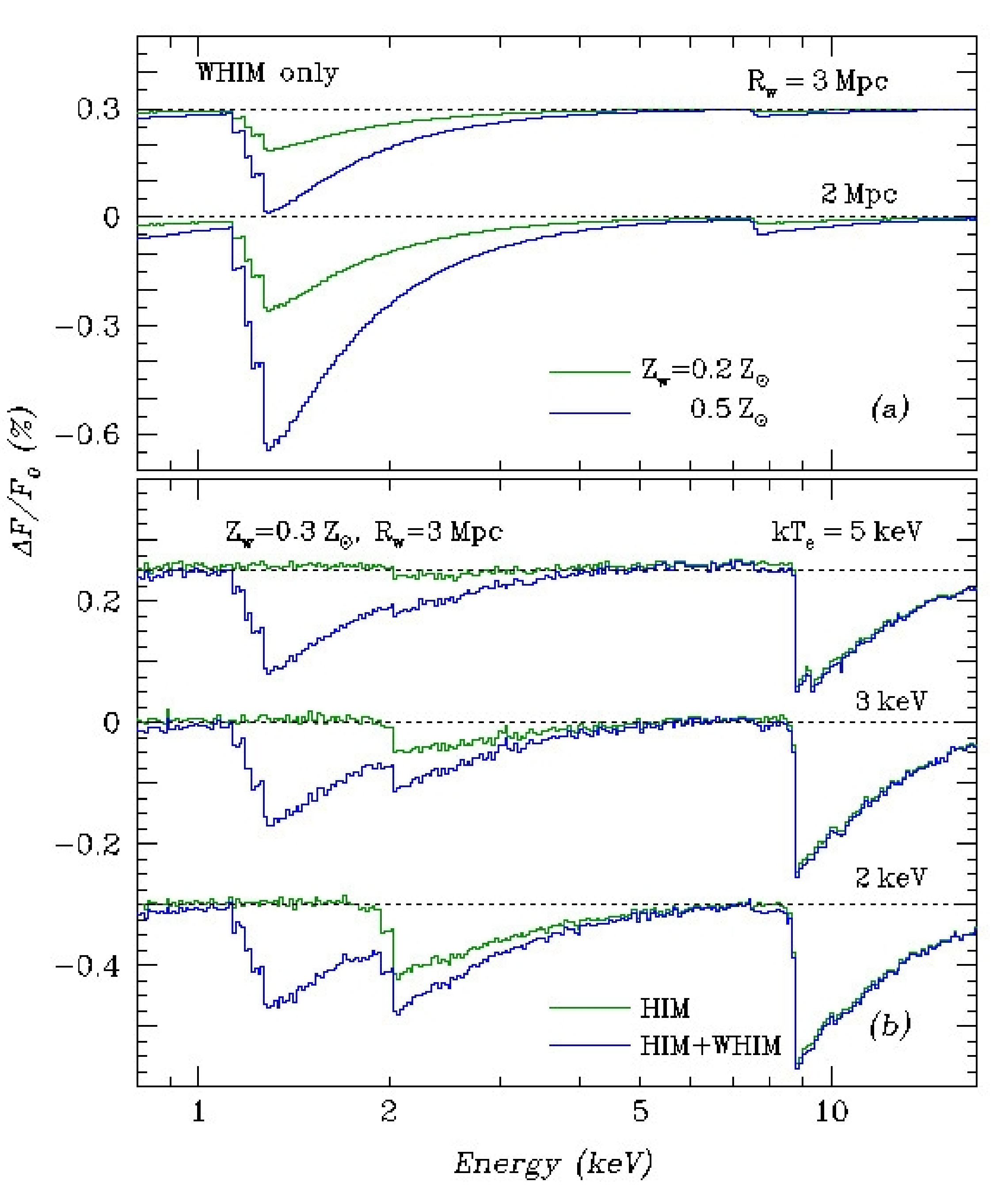
Distortions in the CXB spectrum connected with warm plasma (WHIM) on the periphery of clusters

It is believed (Cen, Ostriker 1999) that 2/3 of all baryons at z<1 are contained in the Warm-Hot Intergalactic Medium (WHIM) which is the moderately hot plasma with a temperature ~10^6 K located in filaments and other similar structures on the far periphery of galaxy clusters. This plasma has eluded observation.

Then the mass of WHIM surrounding a cluster Mw = 4 Mg, where Mg is the mass of its intergalactic gas. Assuming the outer radius of the WHIM envelope Rw = 3 Mpc, we considered how the WHIM envelope may affect the background.

Top panel – *relative distortions in the CXB due to WHIM.*

Bottom panel – *distortions from both the WHIM envelope and hot intergalactic gas of the cluster.*

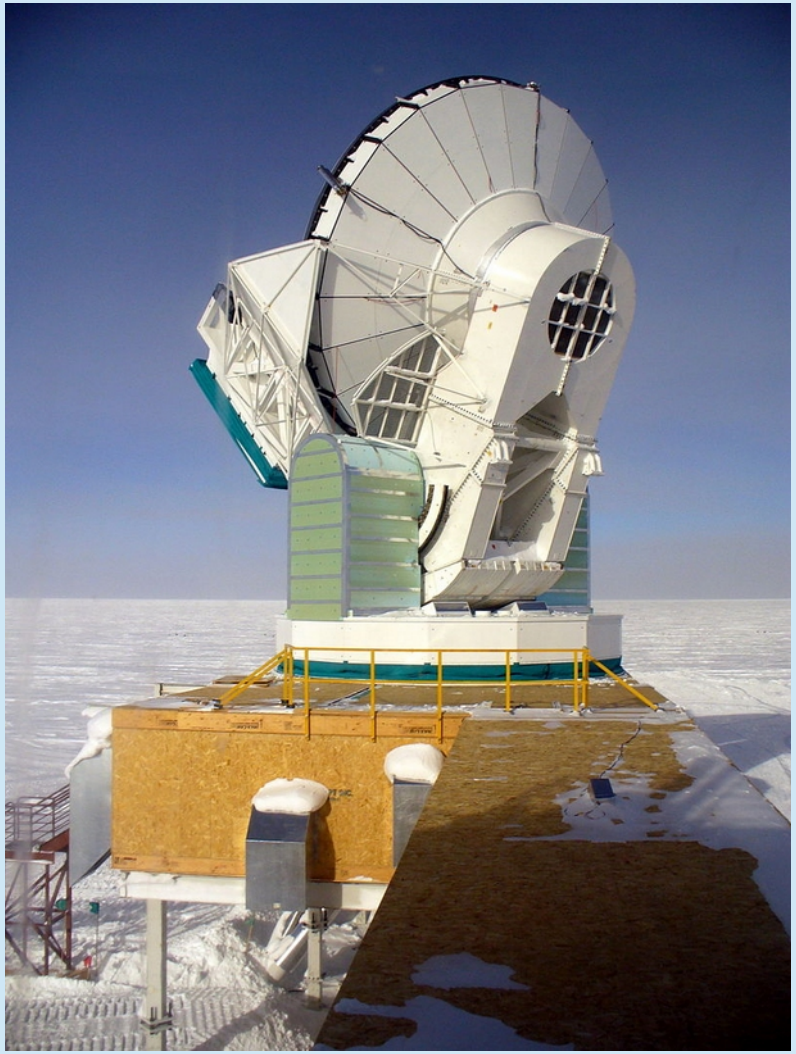


Conclusions

- *The distortions in the cosmic radio, X-ray and soft gamma-ray background arising in the direction of clusters of galaxies due to Compton scattering in the hot intergalactic gas are diverse, very interesting and quite measurable in near future.*
- *They are at the level of fractions of percent which is similar to amplitudes of the CMB distortions in the classical SZ-effect.*
- *Thermal bremsstrahlung and synchrotron emission may be a serious obstacle for direct measurement of these distortions but there are ways to minimize them.*
- *The unusual hybrid source (bright narrow spot surrounded by a dark ring) must be observed on the map of background fluctuations in several specific radio bands.*
- *The broad absorption feature must arise near 500 keV in the hard X-ray - soft gamma-ray cosmic background spectrum.*

Thank you

SZ-effect



SPT, ACT, Planck, ALMA/ACA