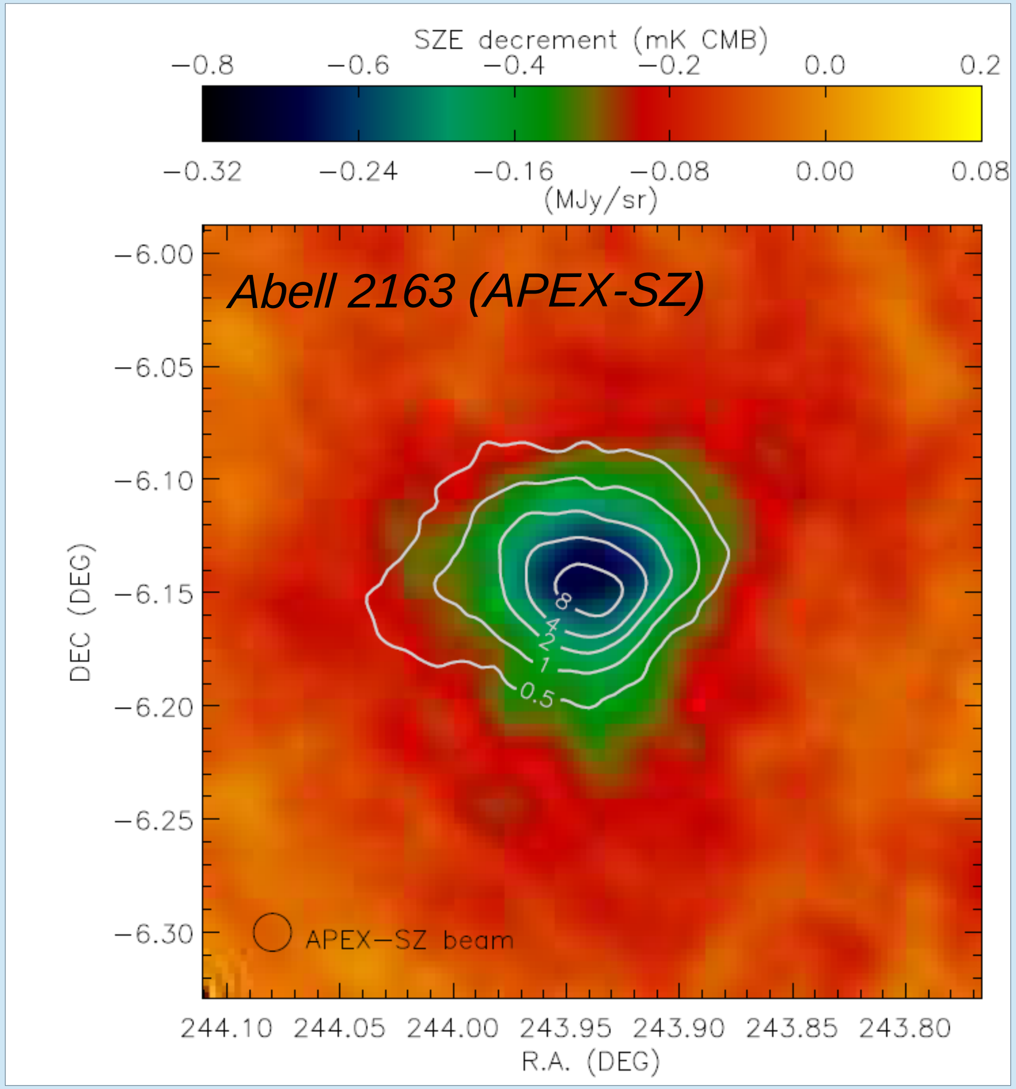
Spectral distortions of cosmic radiobackground and fast radiobursts' low frequency radiation due to Compton scattering



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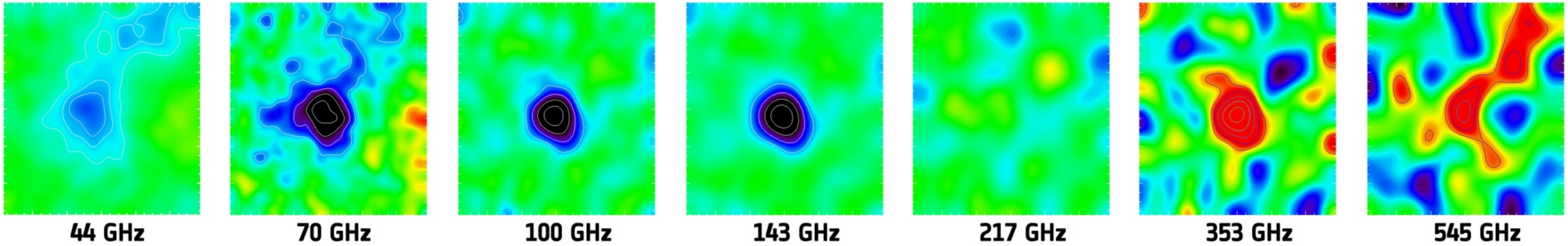
Sunyaev-Zeldovich or SZ effect (SZE):

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-centimeter) 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 the radio (meter-decimeter) frequency band.



Abell 2319 from Planck

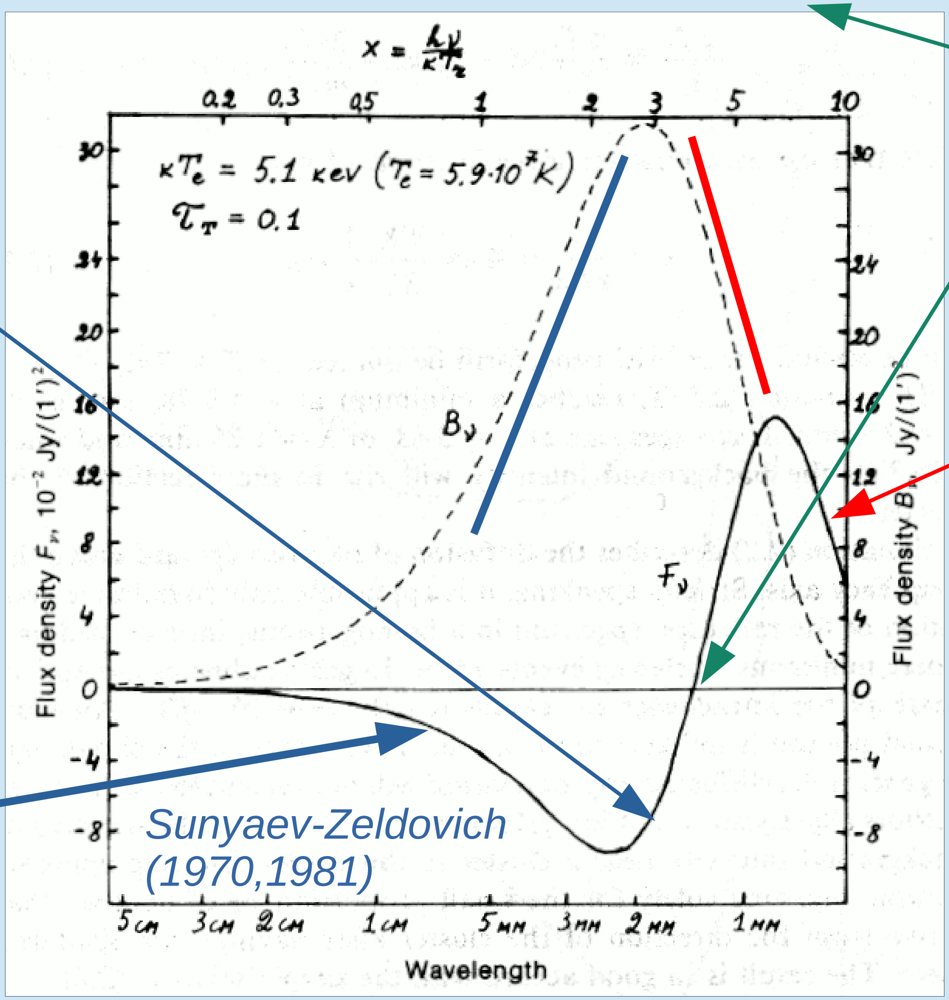
A negative source on the map of CMB fluctuations in the millimeter (radio) band.

Compton scattering leads to a Doppler shift of photons towards higher frequencies, for $kT_e \sim 5$ keV:
$\Delta\nu / \nu = kT_e / m_e c^2 \sim 0.01$.

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)

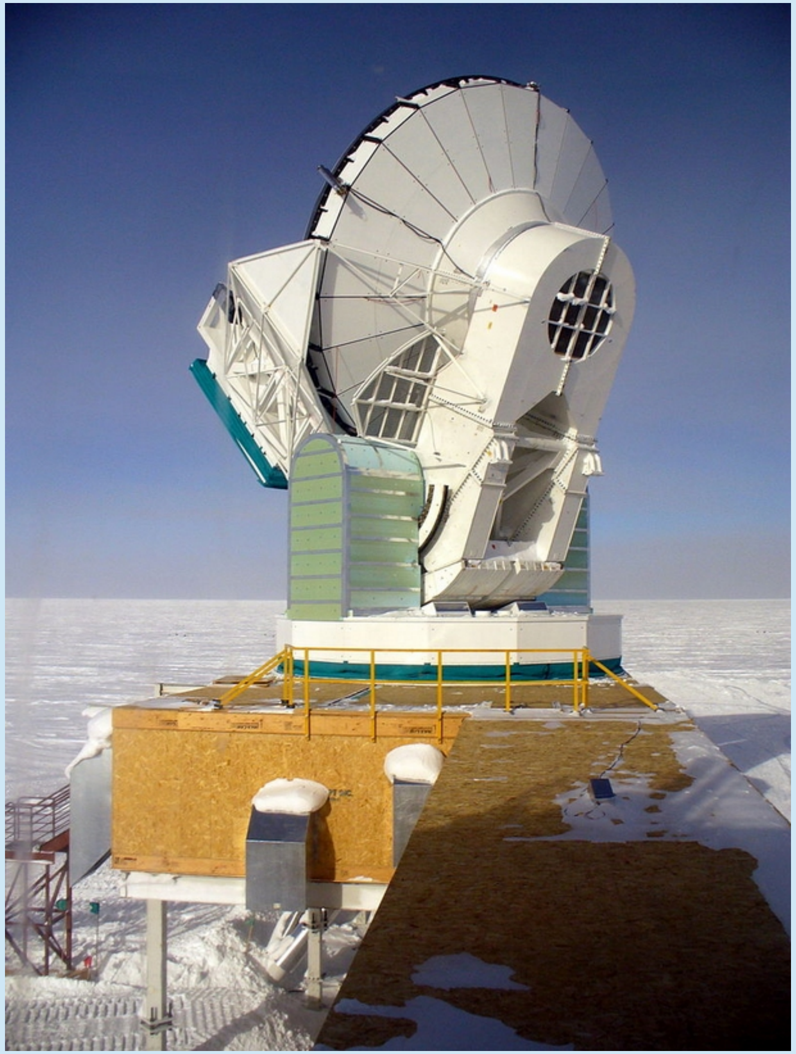
A positive source on the map of CMB fluctuations in the submillimeter (microwave) band.

In the limit $h\nu \ll kT_m$

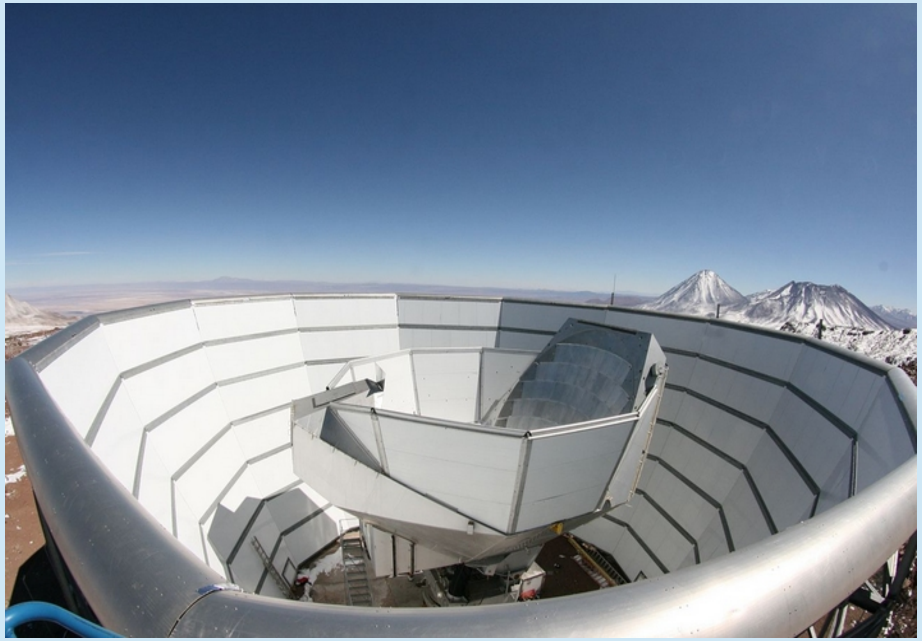
$$\Delta B_\nu / B_\nu \simeq -2 y_{\rm C}$$

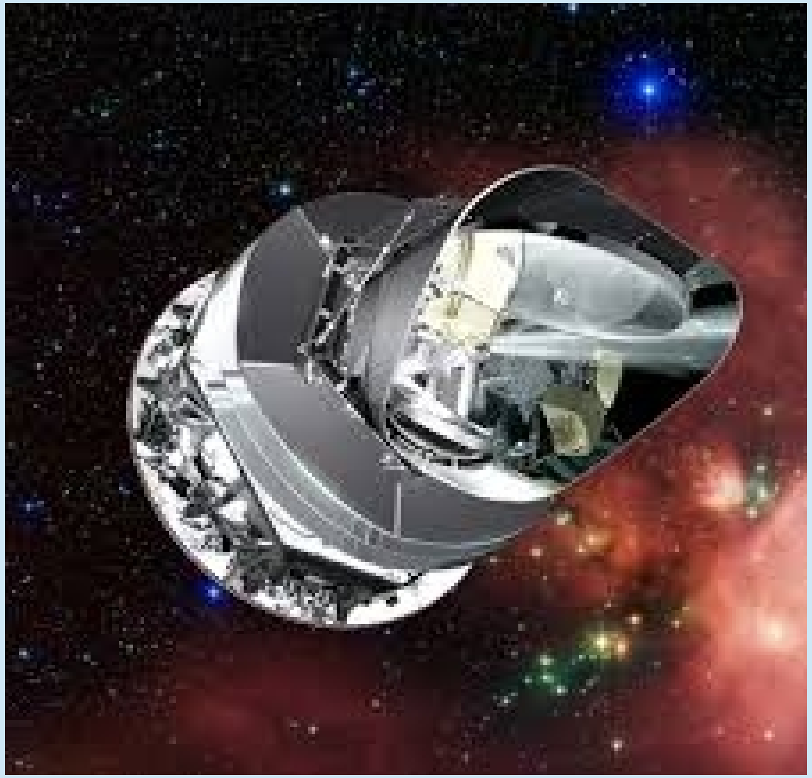
or $\Delta T / T_m = -2\,(kT_e / m_e c^2)\tau_T$, where $\tau_T \sim 10^{-3}$ is the Thomson optical depth toward the cluster center.

SZ-effect



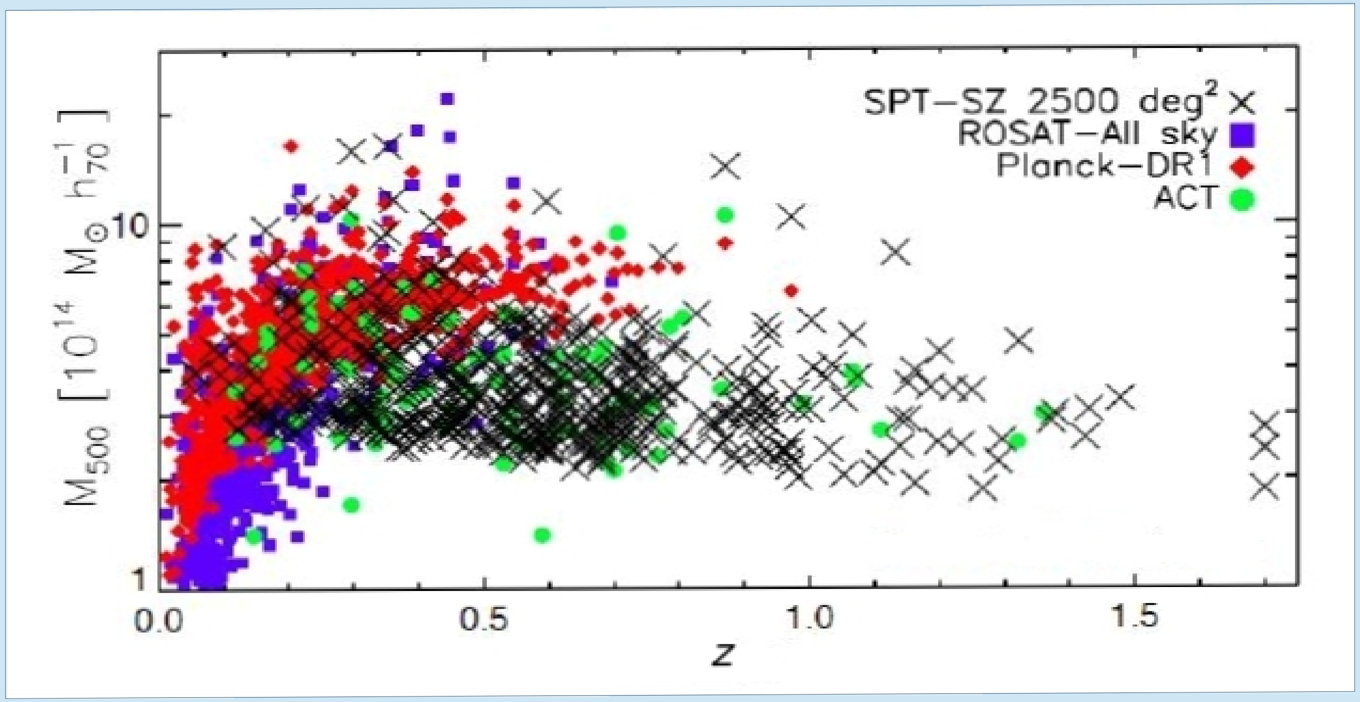
SPT, ACT, Planck, ALMA/ACA

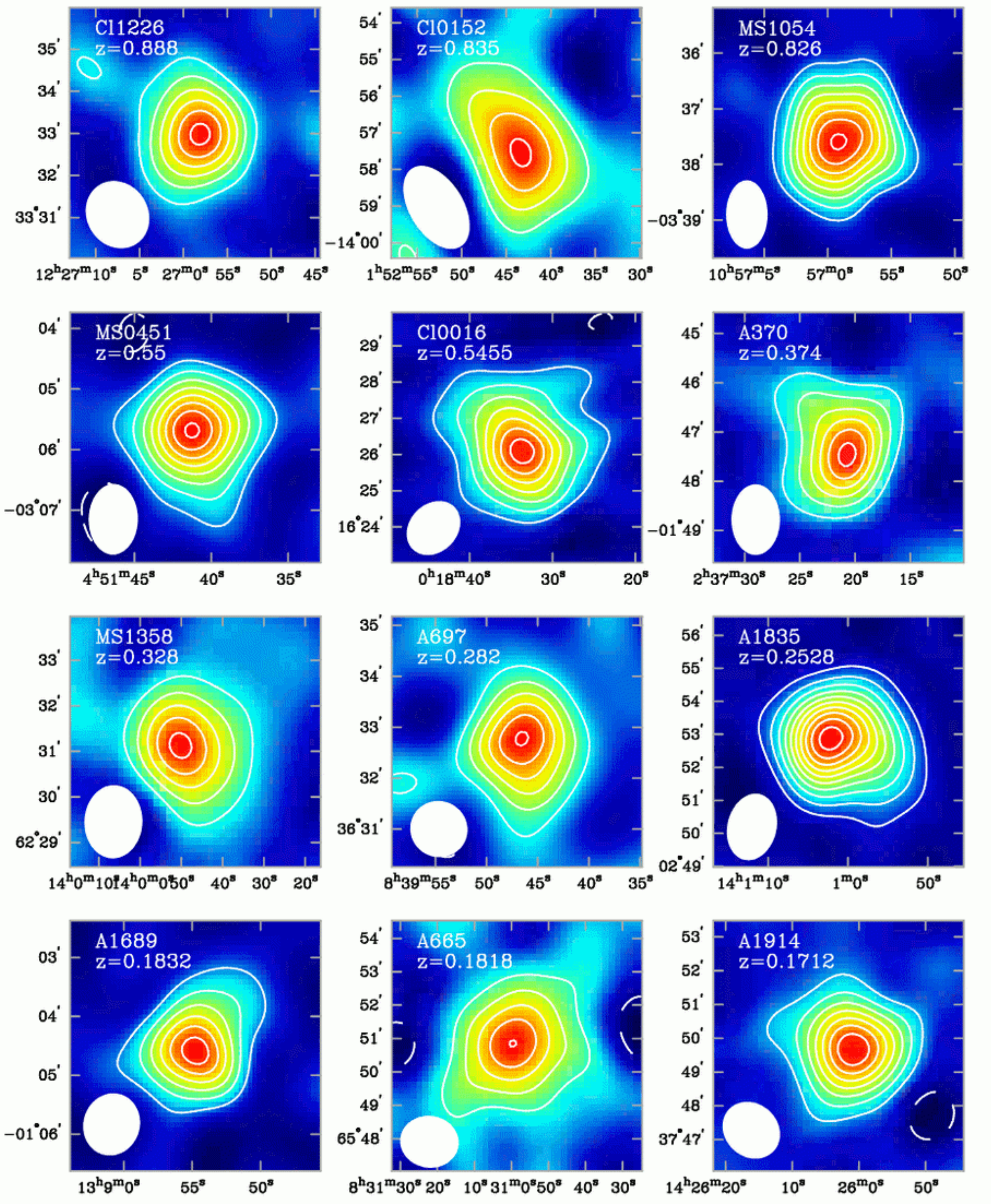




Why the SZ-effect is important?

- *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)*

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

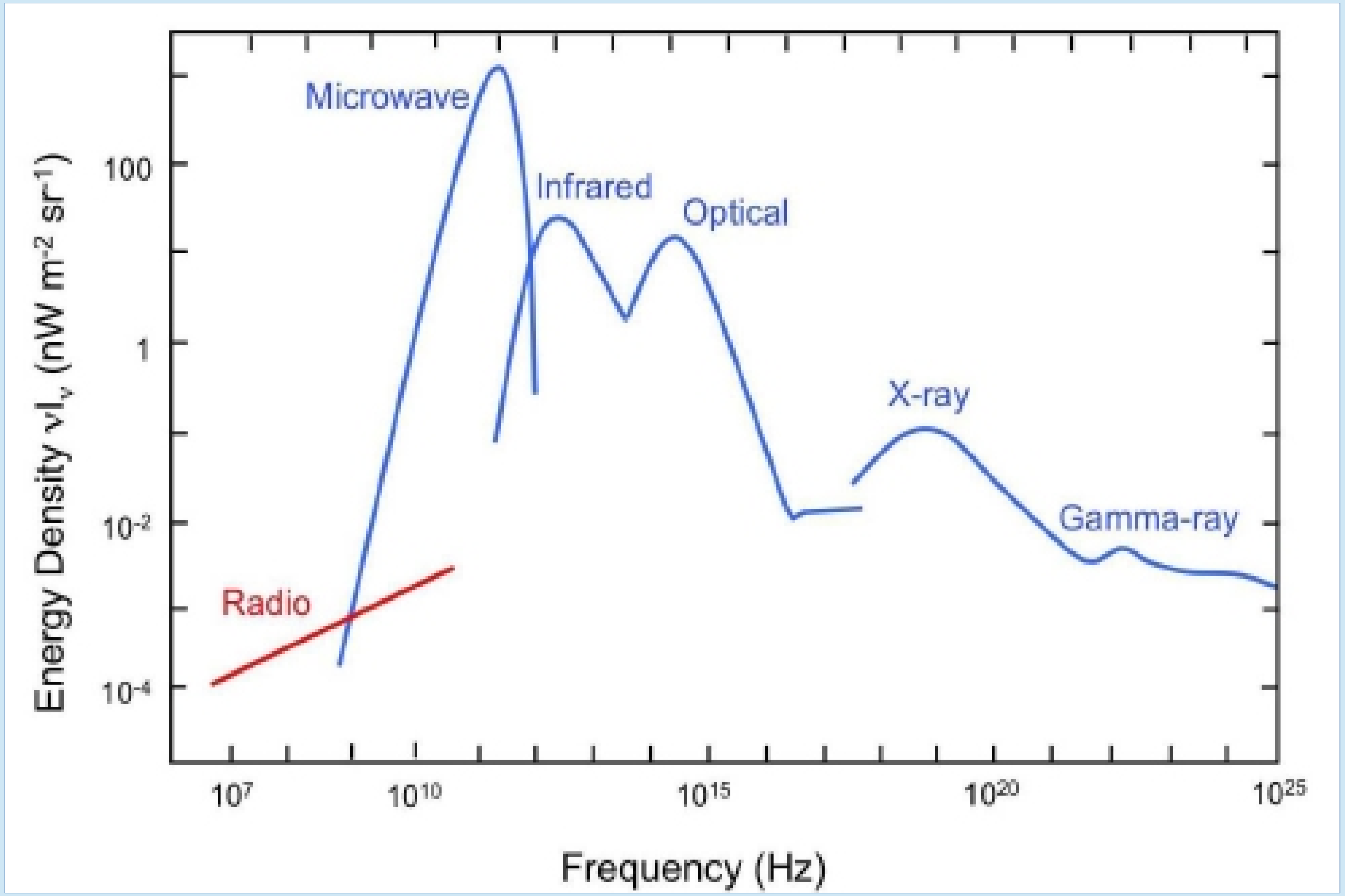
$$\nu_* = 310\ \text{МГц},\ T_* = (30.4 \pm 2.1)\,\mathrm{K}$$

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

or $F_{\mathrm{R}}(\nu) = F_*\nu^{-\alpha}$, где $\alpha = 0.58 \pm 0.05$

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

- *But it is isotropic like CMB*



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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.

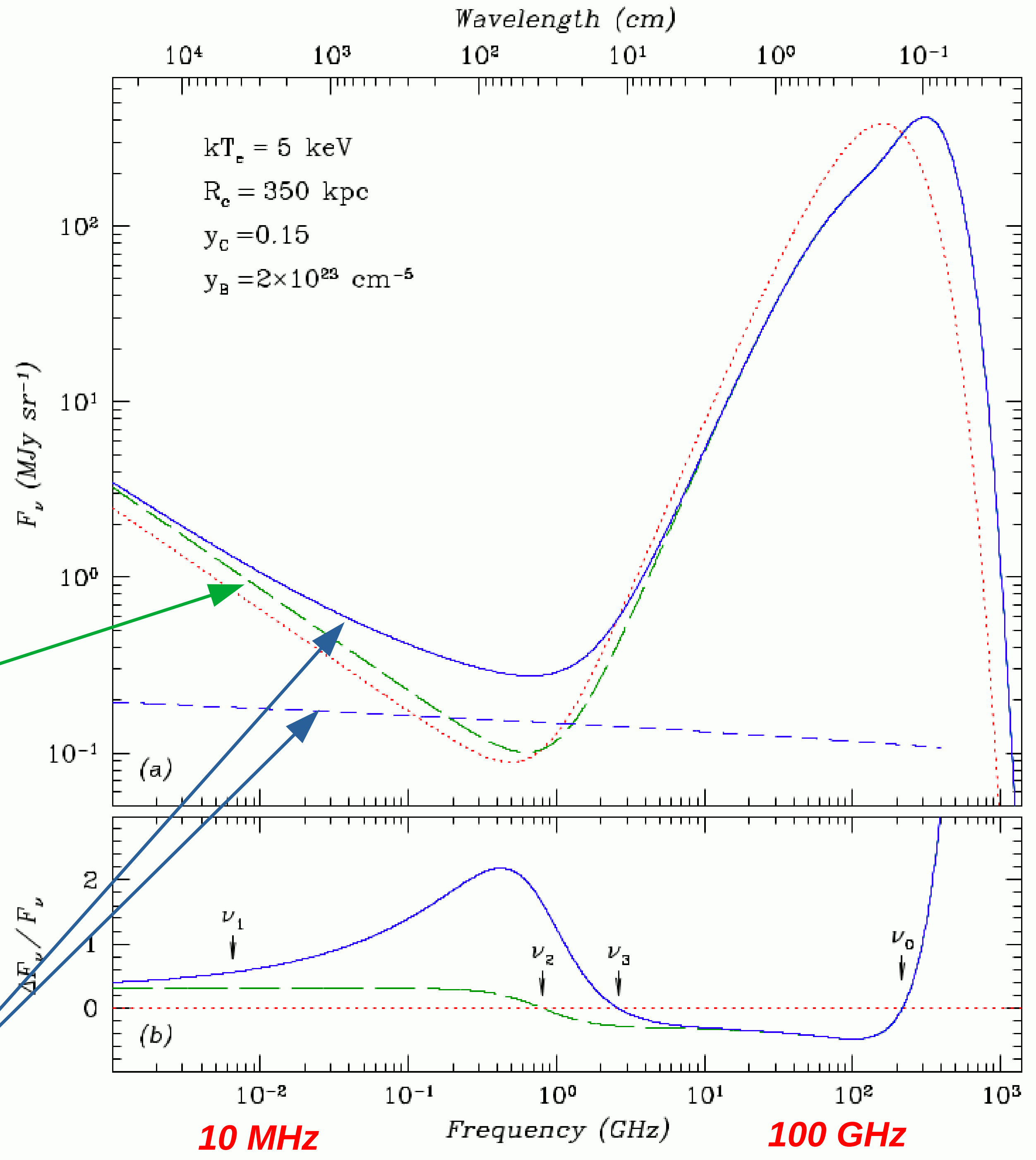
Substituting the radio background spectrum $F_R(\nu)$ in the Kompaneets equation we obtain its relative distortions:

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

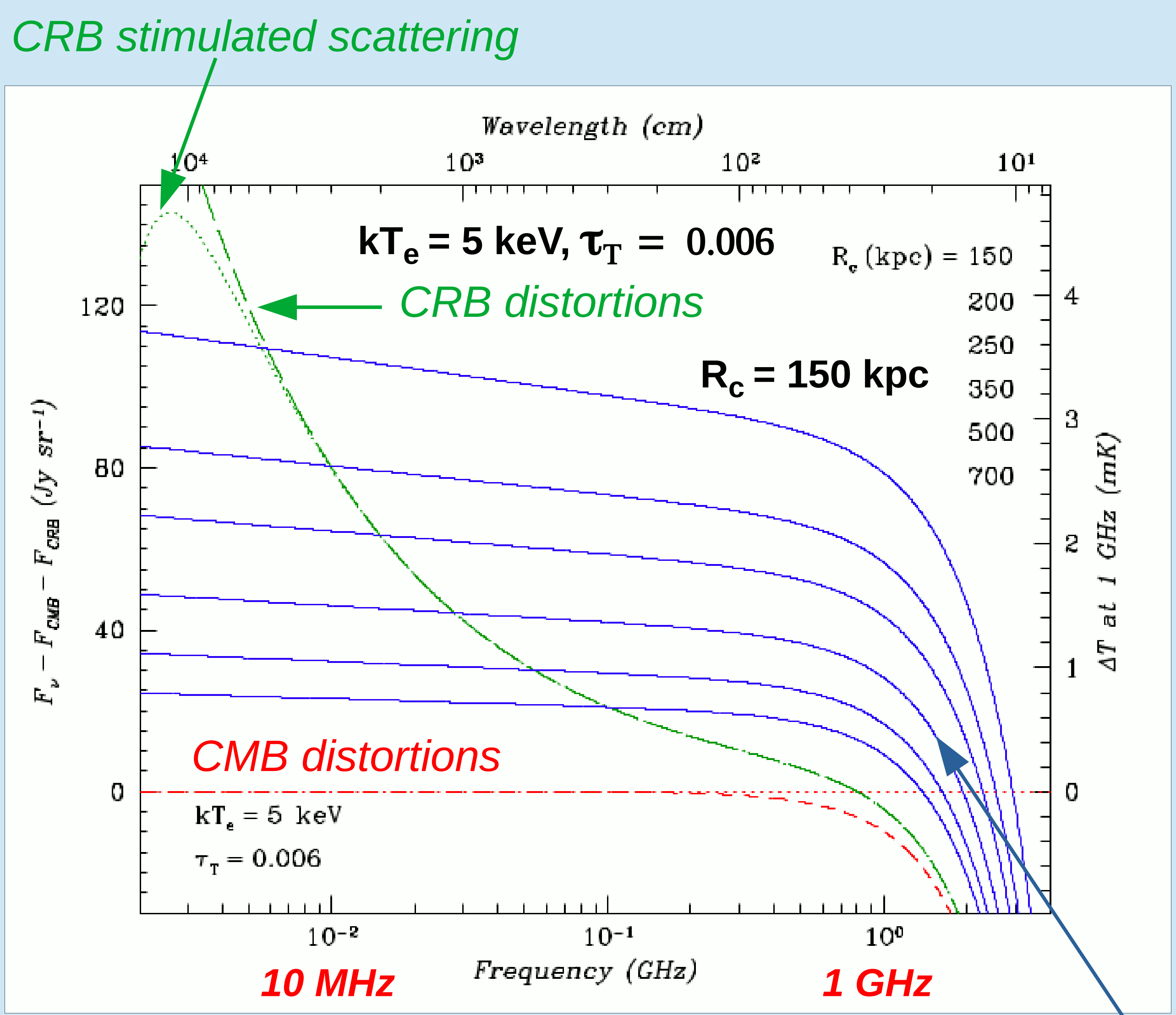
It is similar to SZ distortions of the CMB spectrum but positive. These distortions completely compensate each other at frequency $\nu_2 = 810$ MHz (Holder, Chluba 2021).

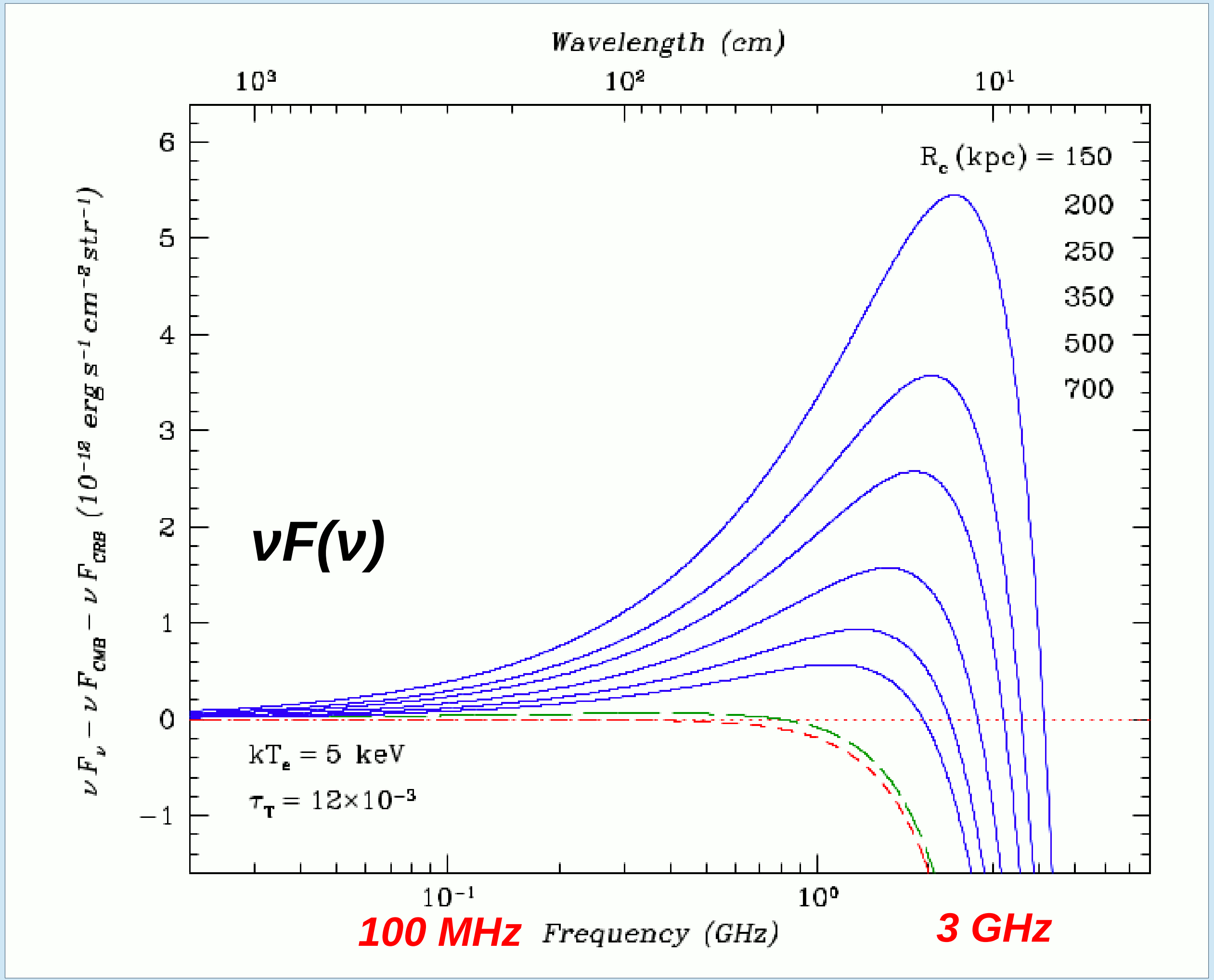
But there is thermal bremsstrahlung from the hot gas which is important in this case:

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



Radiobackground (CRB) distortions in the cluster gas

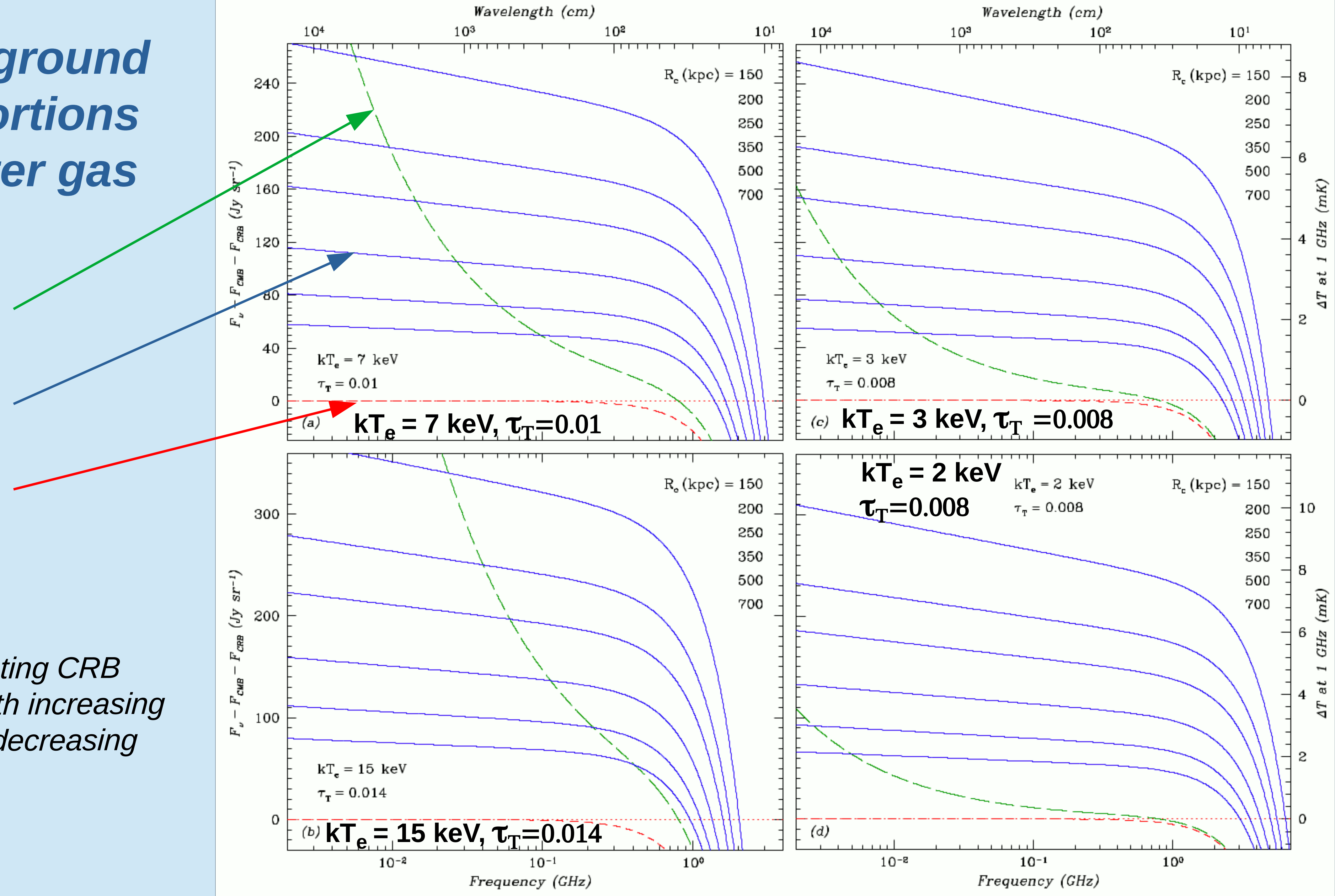




Simplest model (sphere of constant density).

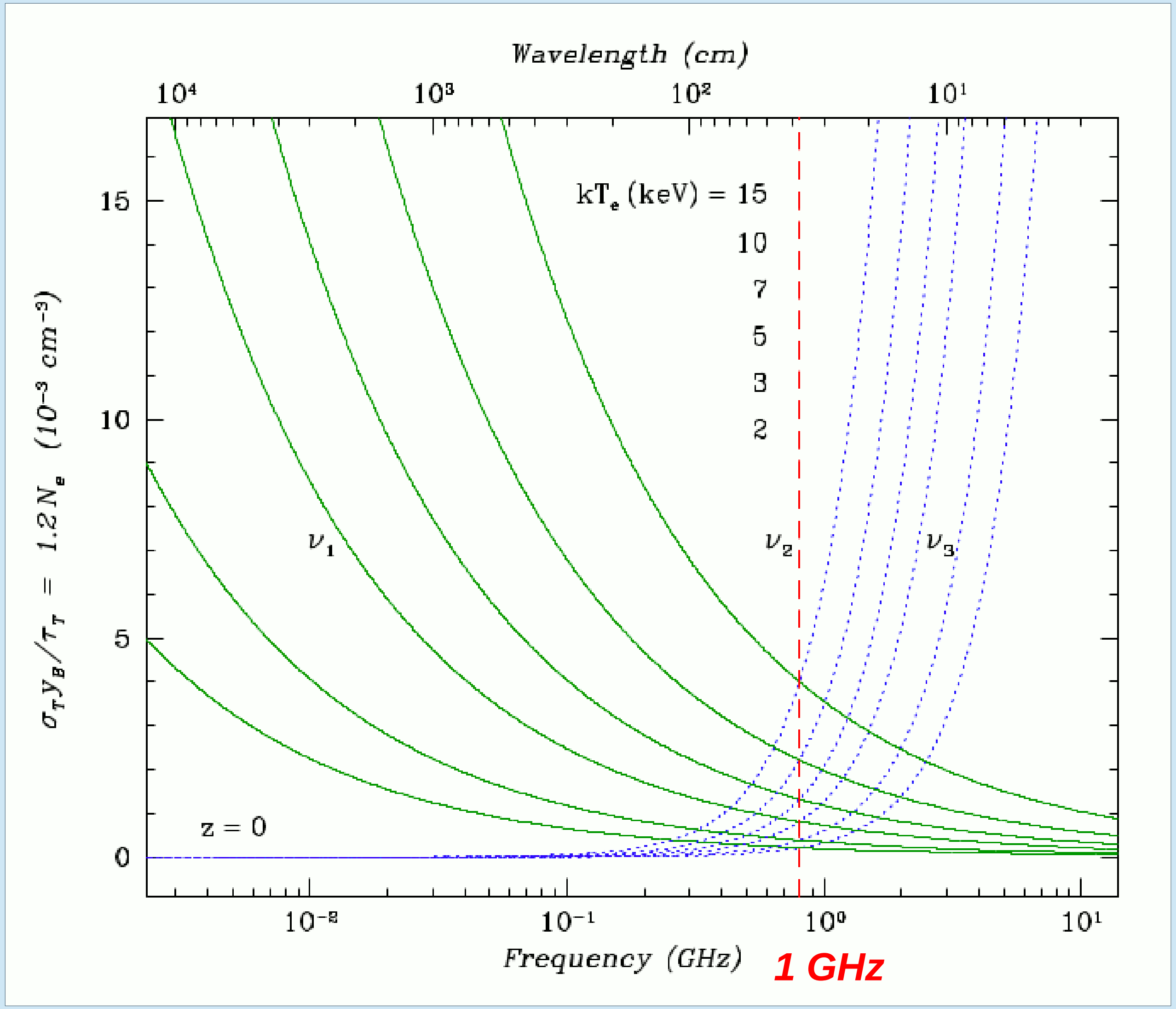
Bremsstrahlung

Radiobackground (CRB) distortions in the cluster gas



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



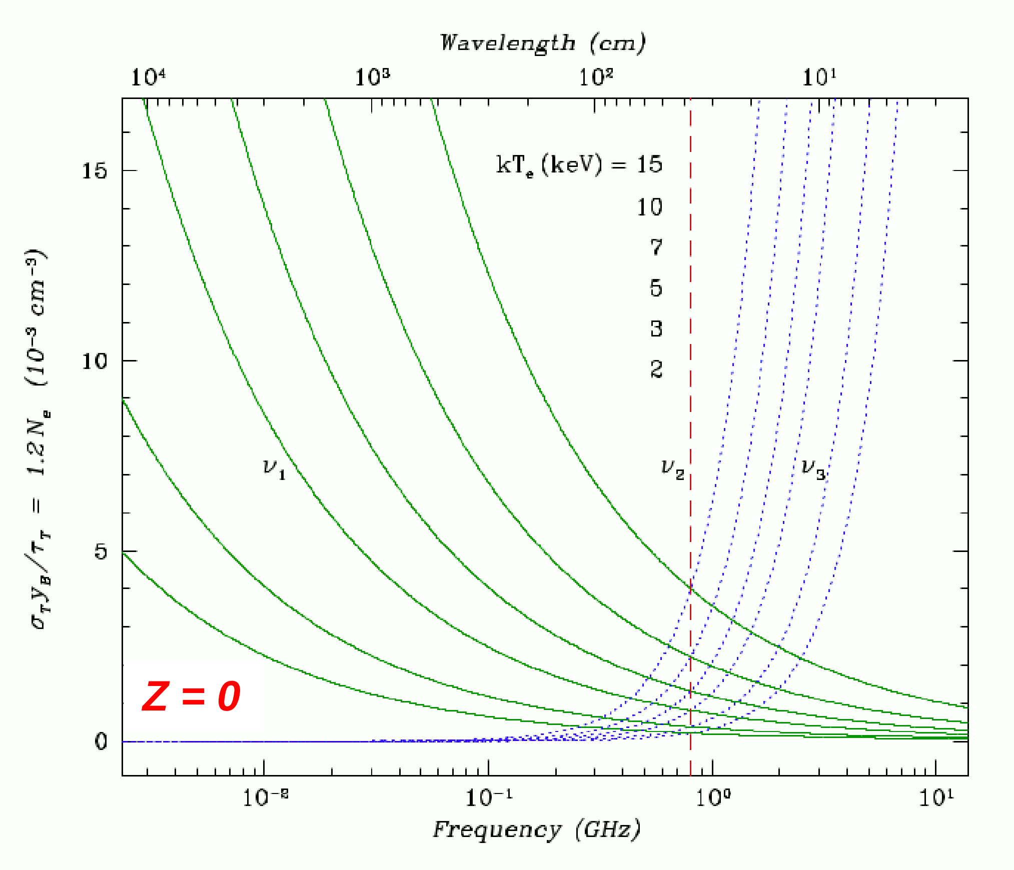
Frequency range with dominant bremsstrahlung contribution vs the interstellar gas temperature and density (for close cluster (z ~ 0).

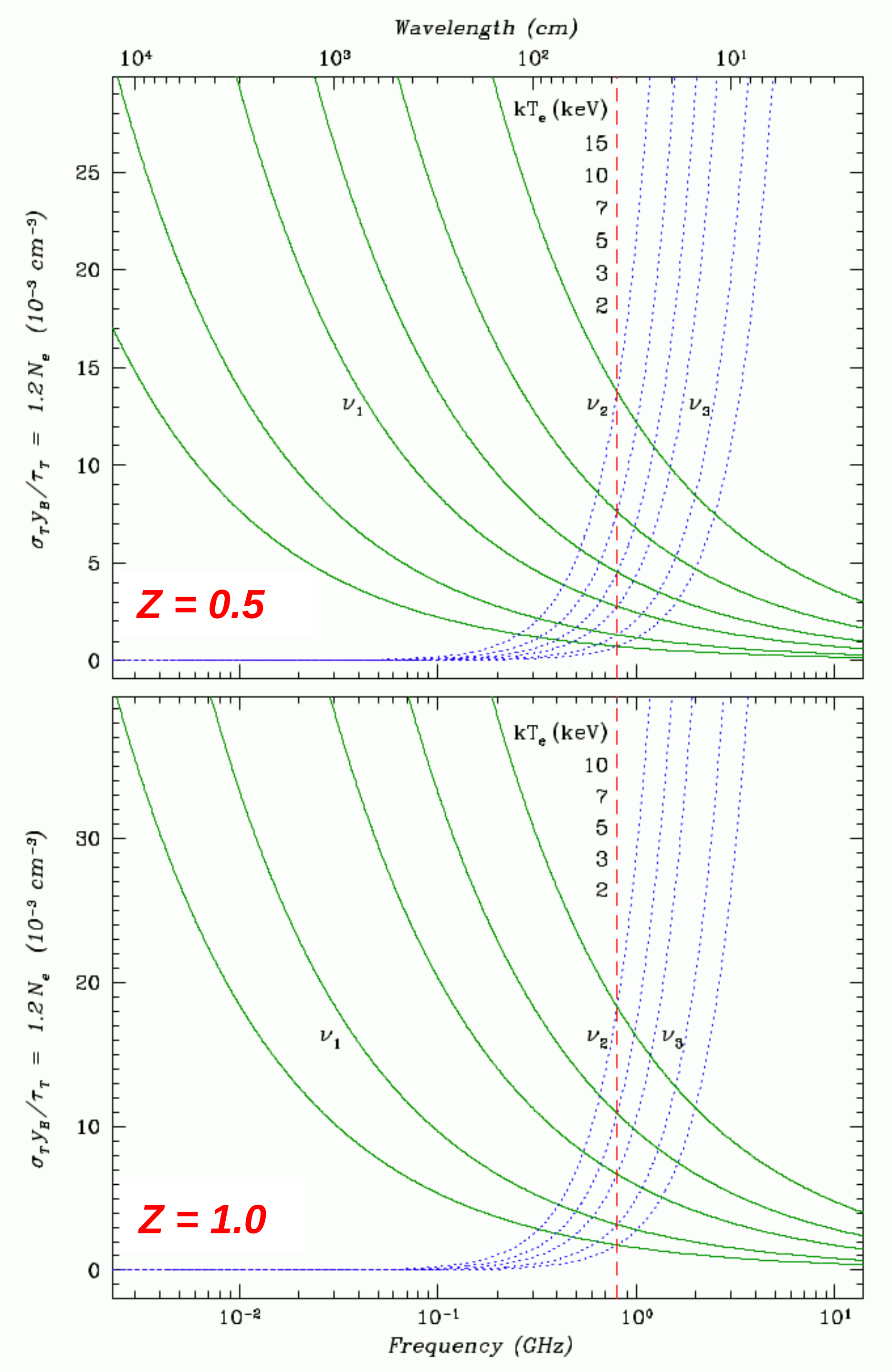
This range is narrowest at high temperatures and large densities of the interstellar gas.

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 bremsstrahlung.

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:

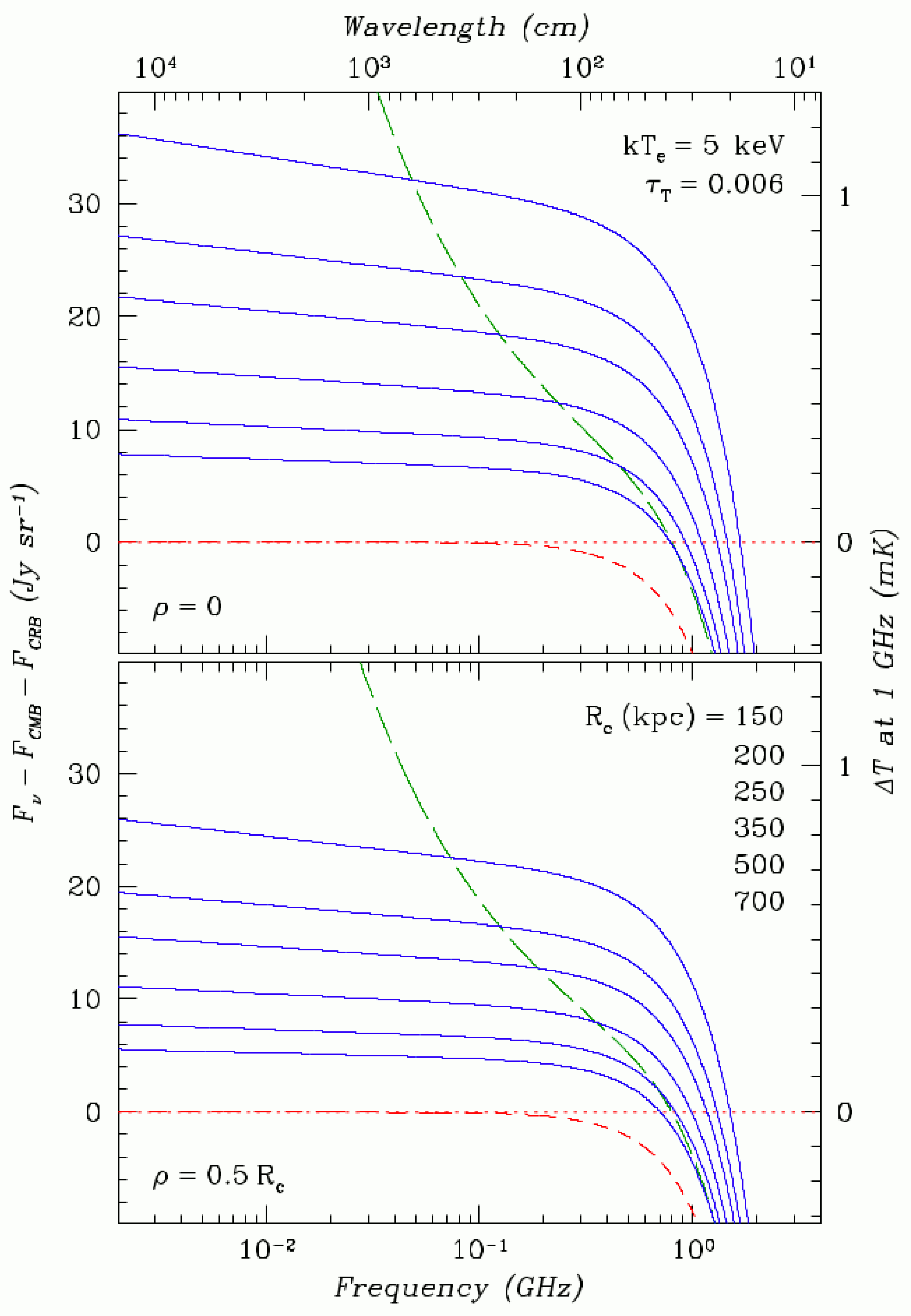
$$N_{\rm e} = N_{\rm c}\left(1+\frac{R^2}{R_{\rm c}^2}\right)^{-3\beta/2}$$

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

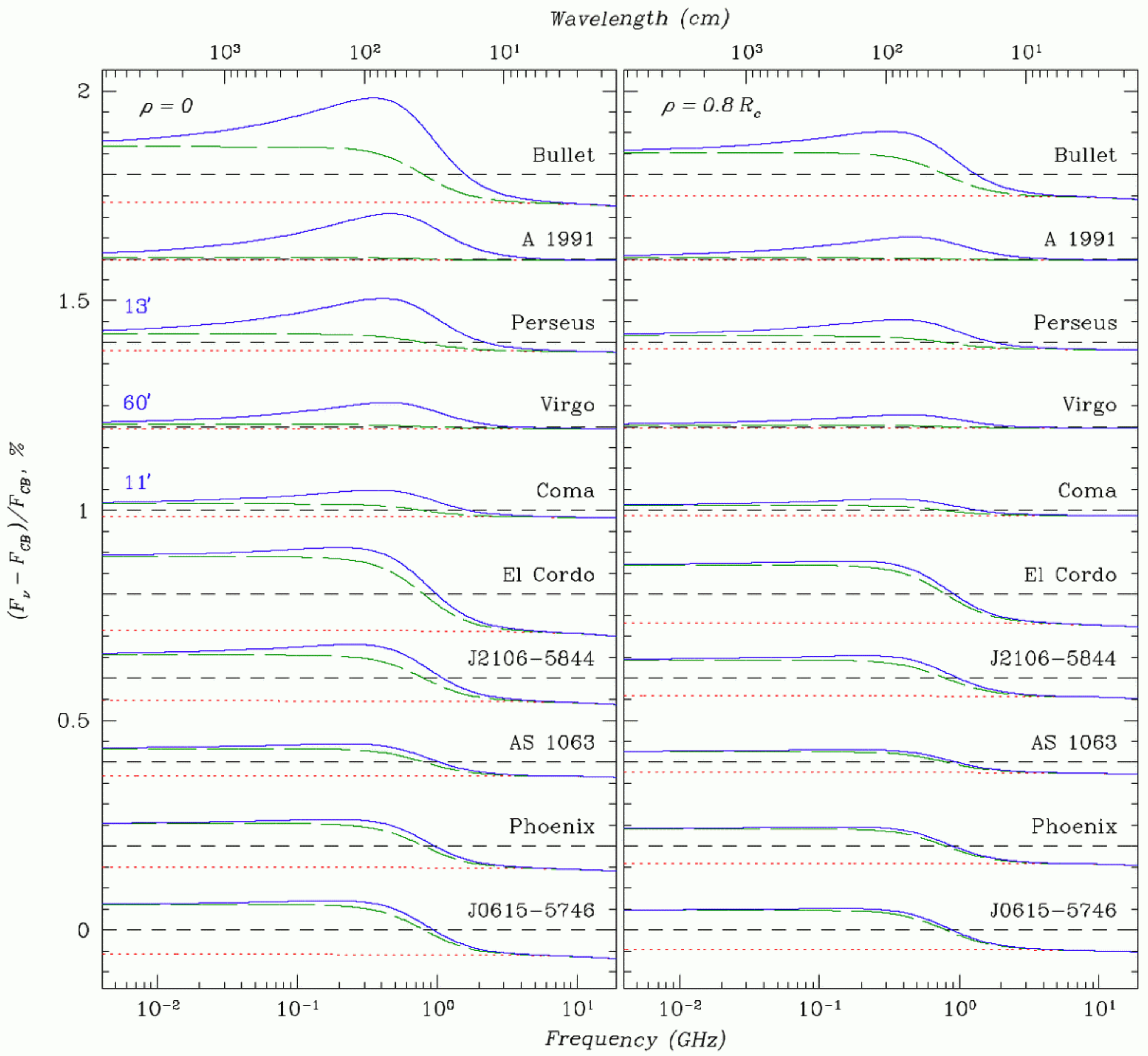
β-model of the gas density distribution.

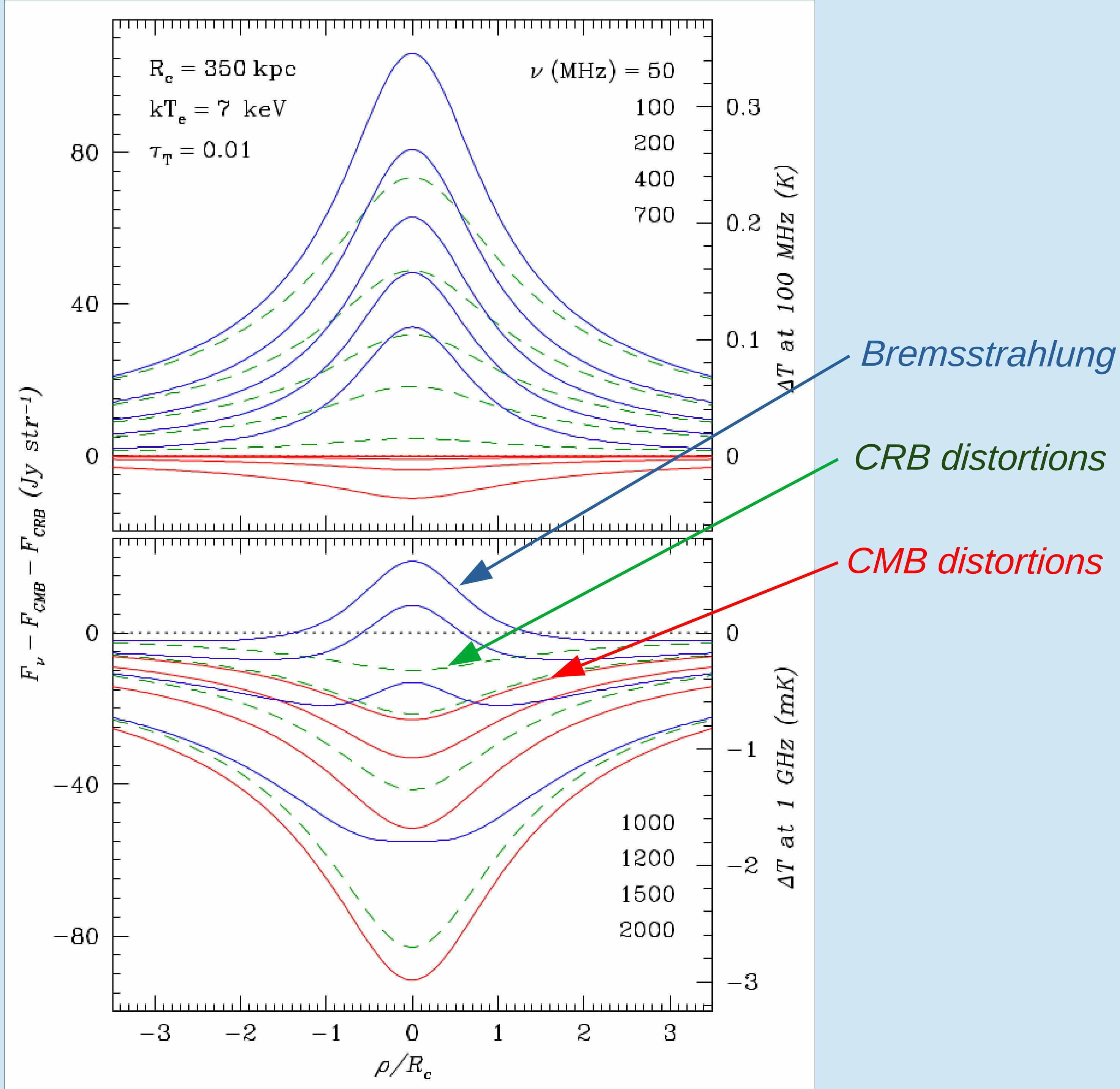
Predictions for 10 real clusters and two impact parameters ρ=0 (left) and ρ=0.8 R_c (right).

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

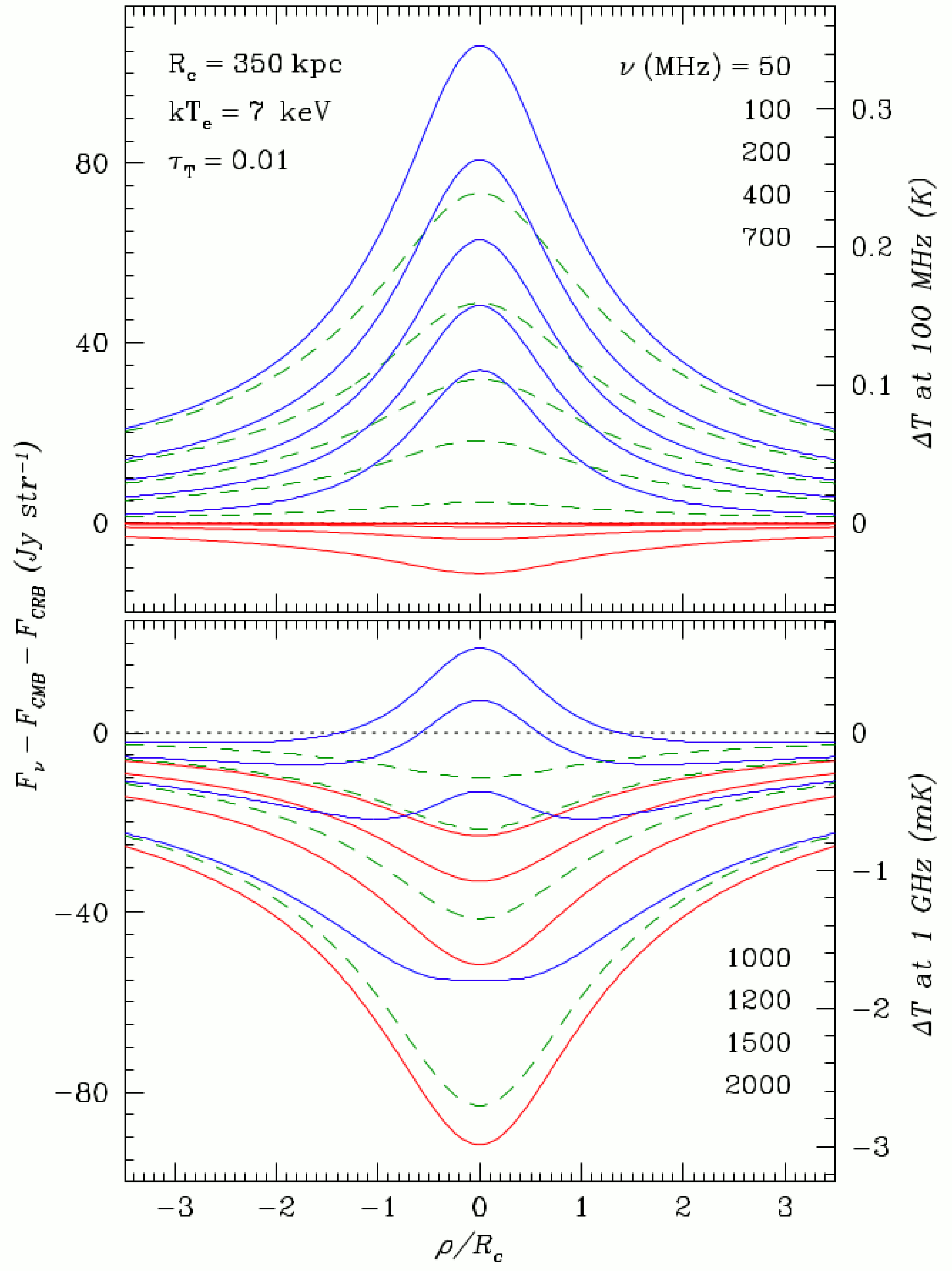
β-model for the gas density distribution

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

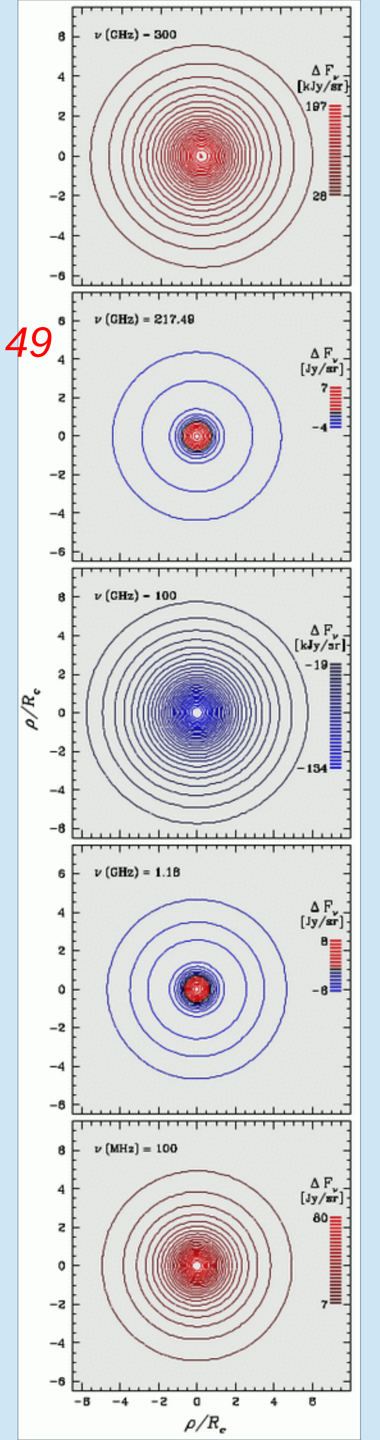
300

217.49

100

1.18

100 MHz

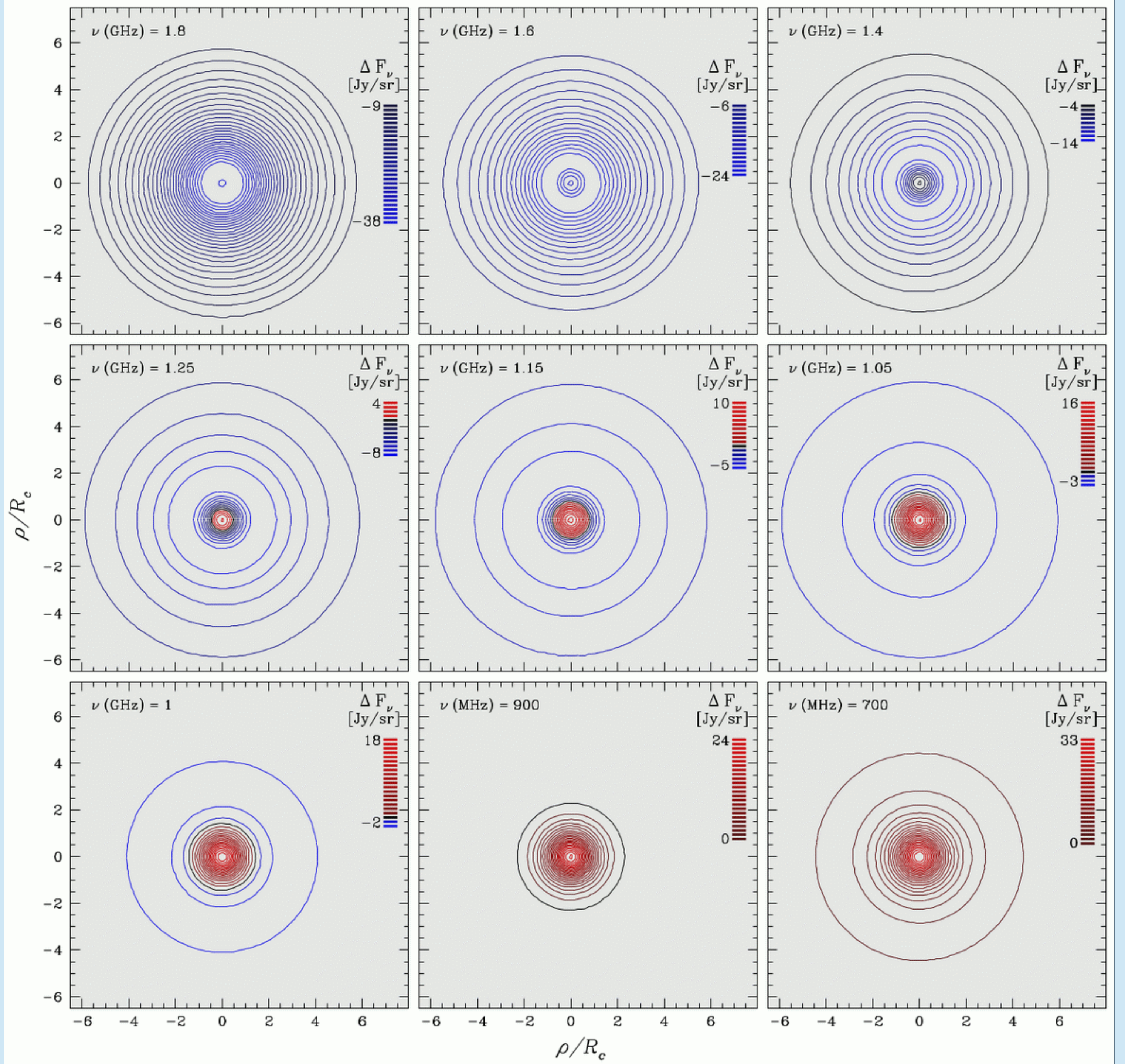


Evolution of the source shape at the map of radio-background fluctuations

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

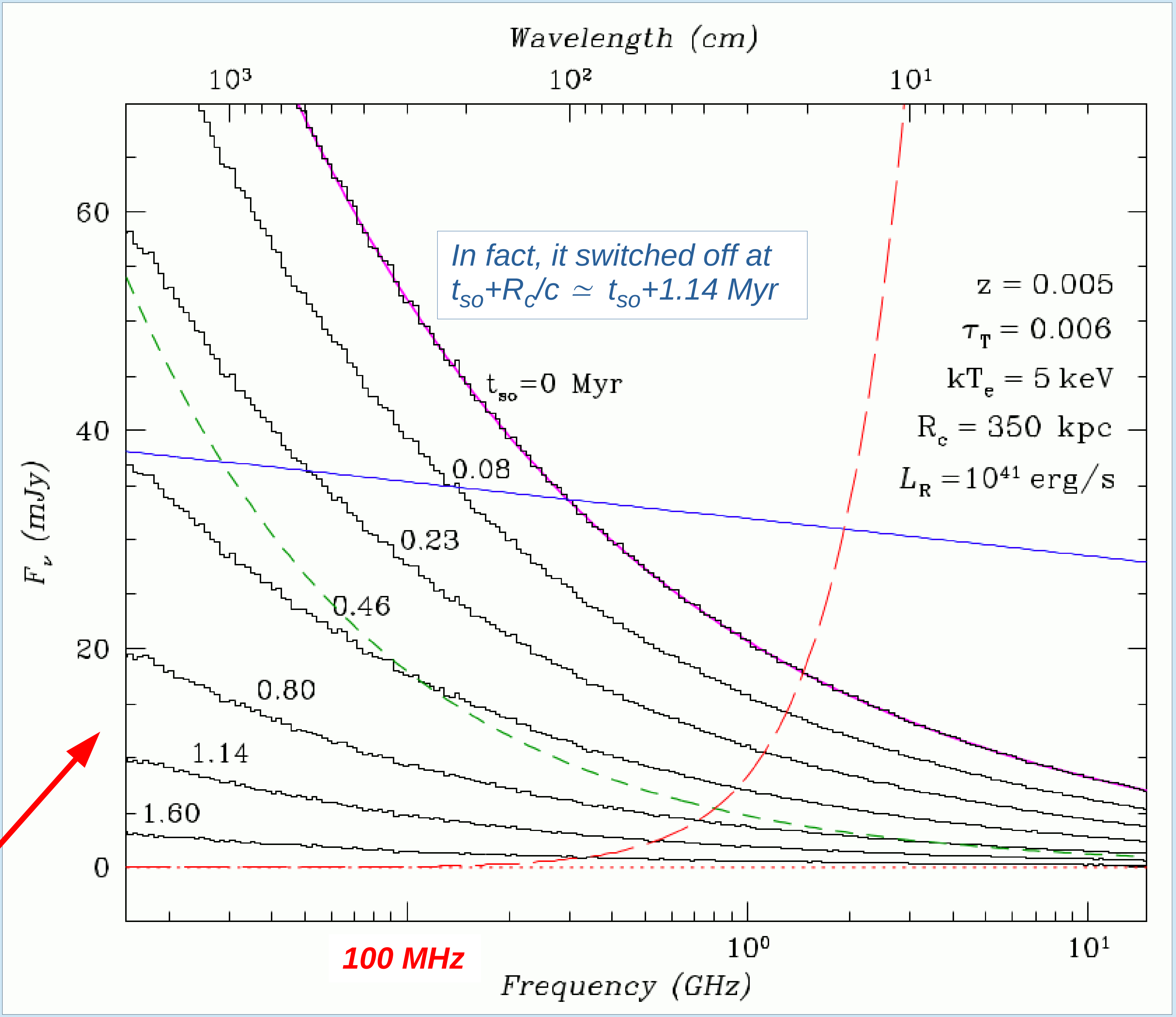
We showed that in many cases thermal bremsstrahlung may prevent (or make it complex) direct detection of increment of the radio background.

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

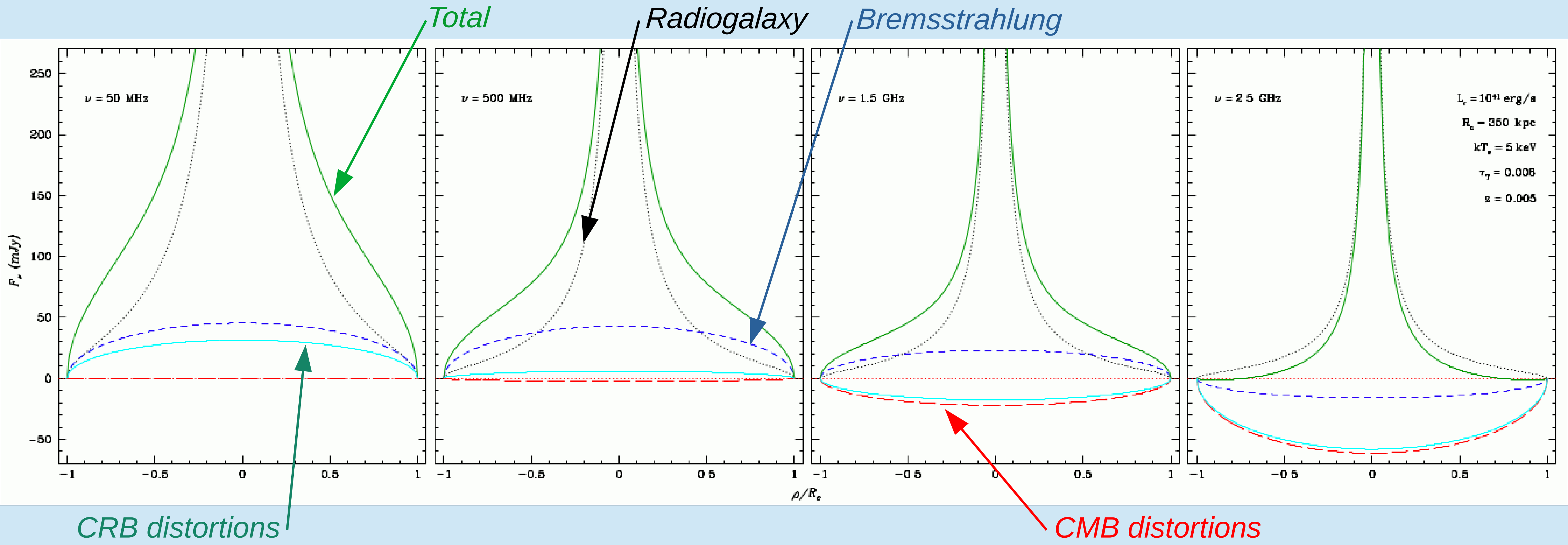
1). The cluster may have a radio halo connected with relativistic electrons accelerated at shocks during cluster mergers or collisions. About 30% clusters have such a halo. They can not be used.

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.



Contribution of diffuse radiation from an extinct active galaxy



Radial distribution of the diffuse emission from the recently switched off bright radiogalaxy (at different different frequences). Simple model (sphere with constant density).

Stimulated Compton scattering

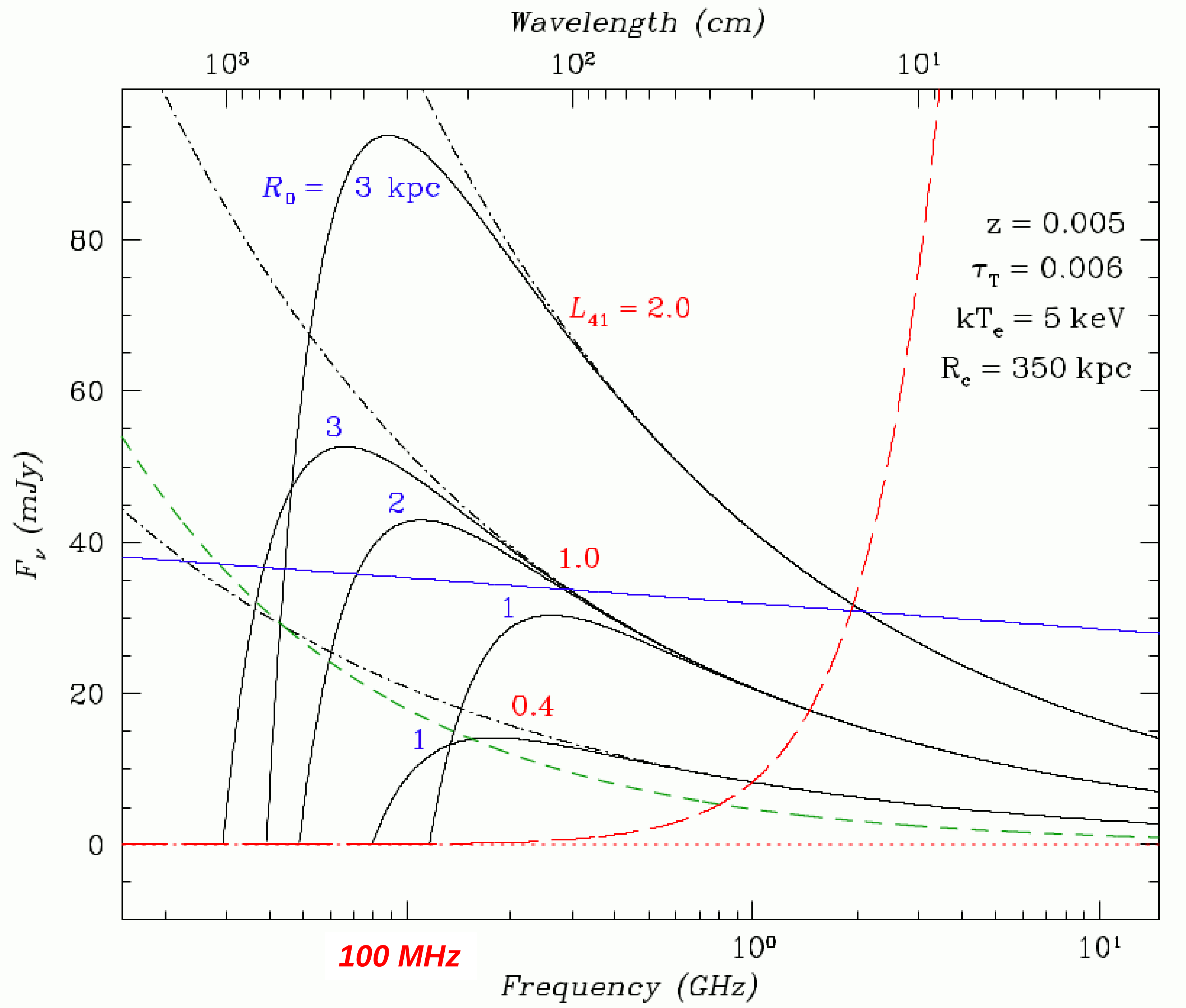
For bright radiogalaxies of the clusters the stimulated Compton scattering of their emission in the intergalactic gas is important.

It leads to the shift of their radio emission towards low frequencies and flattening their spectrum.

Chances to detect scattered radio background increase !

Simple model (sphere of constant density). L_{41} is in 10^{41} for the frequency range 10 MHz - 100 GHz.

R_0 is radius of the cavern surrounding the galaxy which contains no gas.



Stimulated Compton scattering

It was taken into account here by substituting the radiogalaxy power law spectrum into the Kompaneets equation having the stimulated term.

$$\frac{\partial F_\nu}{\partial \tau_{\rm T}} = \frac{\nu}{2m_{\rm e}} \frac{\partial}{\partial \nu} \left(\frac{F_\nu^2}{\nu^2} \right).$$

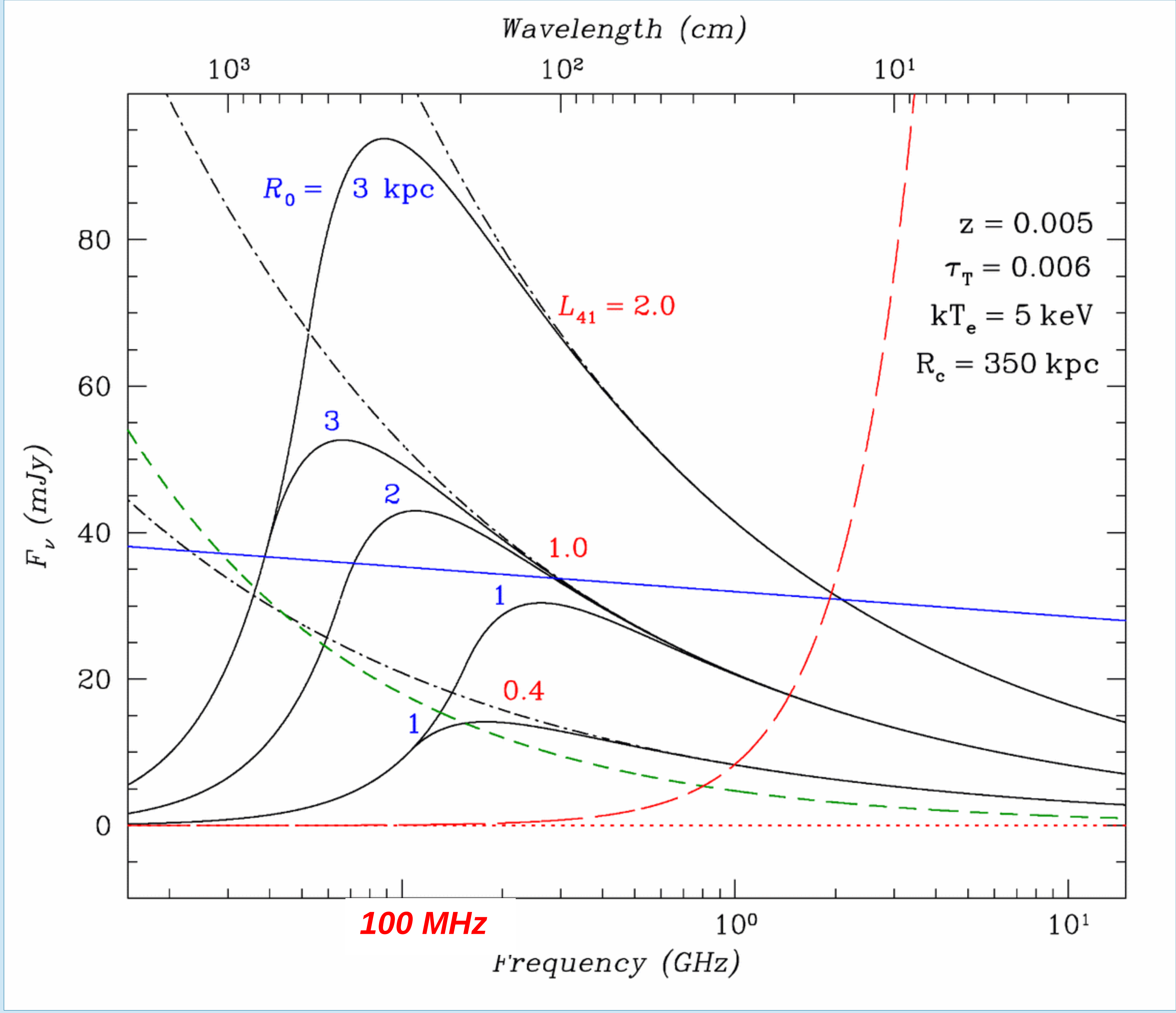
We obtain

$$F_{\rm A}(\nu) = \frac{L_{\rm R}}{4\pi R_{\rm c}^2} \left(\frac{(1-\gamma)\, 10^{14}}{10^{(2-2\gamma)} - 10^{(2\gamma-2)}} \right) \nu_9^{-\gamma} \text{ Ян.}$$

$$F_\nu(\nu) = F_{\rm A} \tau_{\rm c} \frac{R_{\rm c}^2}{d_L^2} \left[1 - \frac{F_{\rm A}}{10^{23}} \frac{(1+\gamma)}{3\, m_{\rm e} \nu^2} \left(\frac{R_{\rm c}^3}{R_0^3} - 1 \right) \right]$$

The steep cutoff at low frequencies indicates that this approach is too rough.

It seems the spectrum should follow the Rayleigh-Jeans law 1 ν^{2} at the frequencies



Stimulated Compton scattering

Astrophysical Letters, 1970, Vol. 7, pp. 19–21

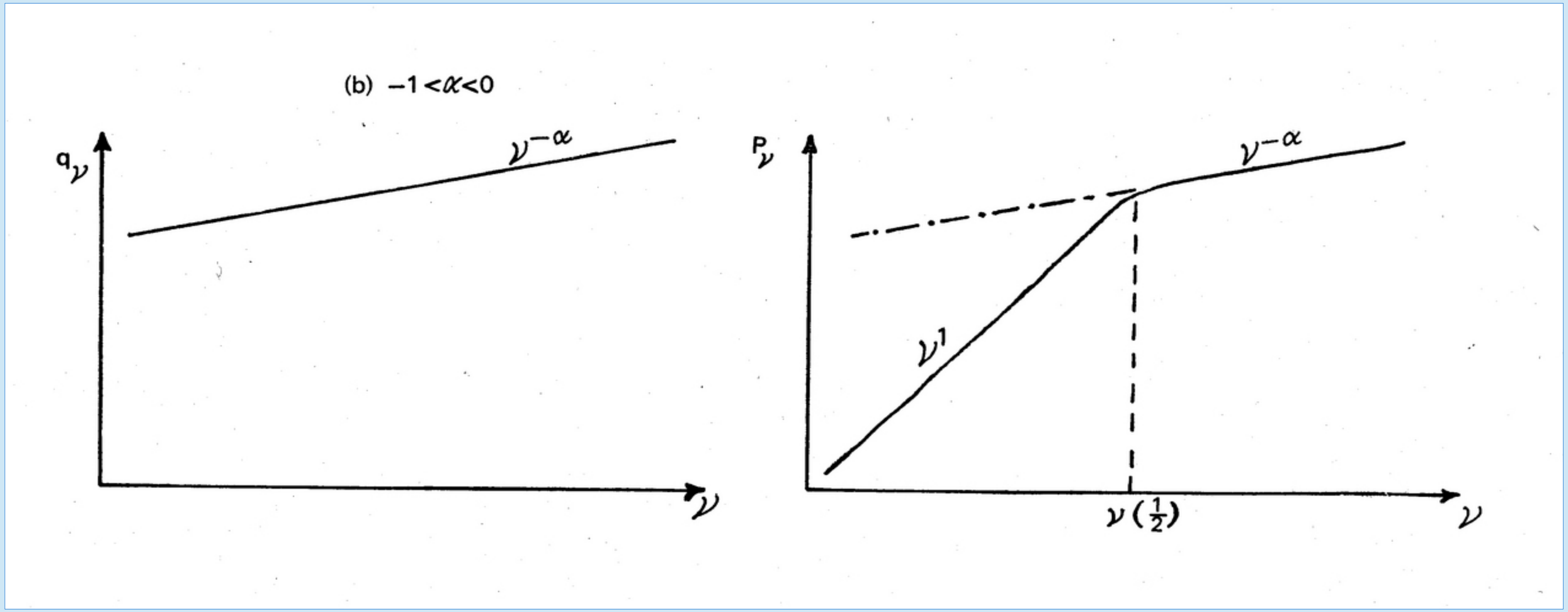
Distortions in the Low-Frequency Spectra of Radio Sources due to Induced Compton Effect

R. A. SUNYAEV *Institute of Applied Mathematics, Moscow, U.S.S.R.*

It is directly seen from the Kompaneets equation that the law ν^{2} is its only power law solution.

$$\frac{\partial F_\nu}{\partial \tau_{\mathrm{T}}} = \frac{\nu}{2m_{\mathrm{e}}} \frac{\partial}{\partial \nu} \left(\frac{F_\nu^2}{\nu^2} \right).$$

It was sugessted that the stimulated Compton scattering leads to precisely this spectrum in the low frequency range (Levich, Zeldovich 1968; Sunyaev 1970)

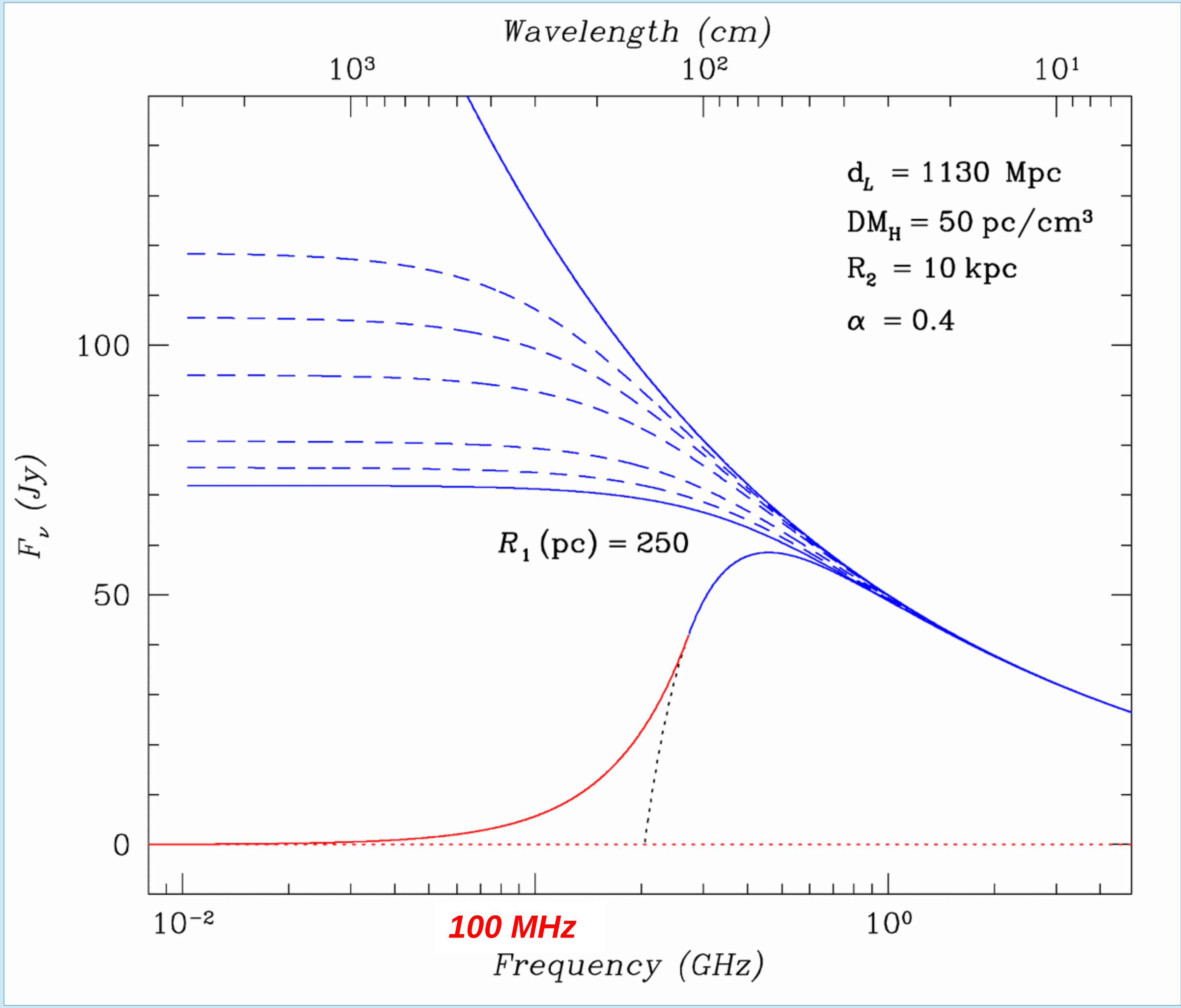


Stimulated Compton scattering

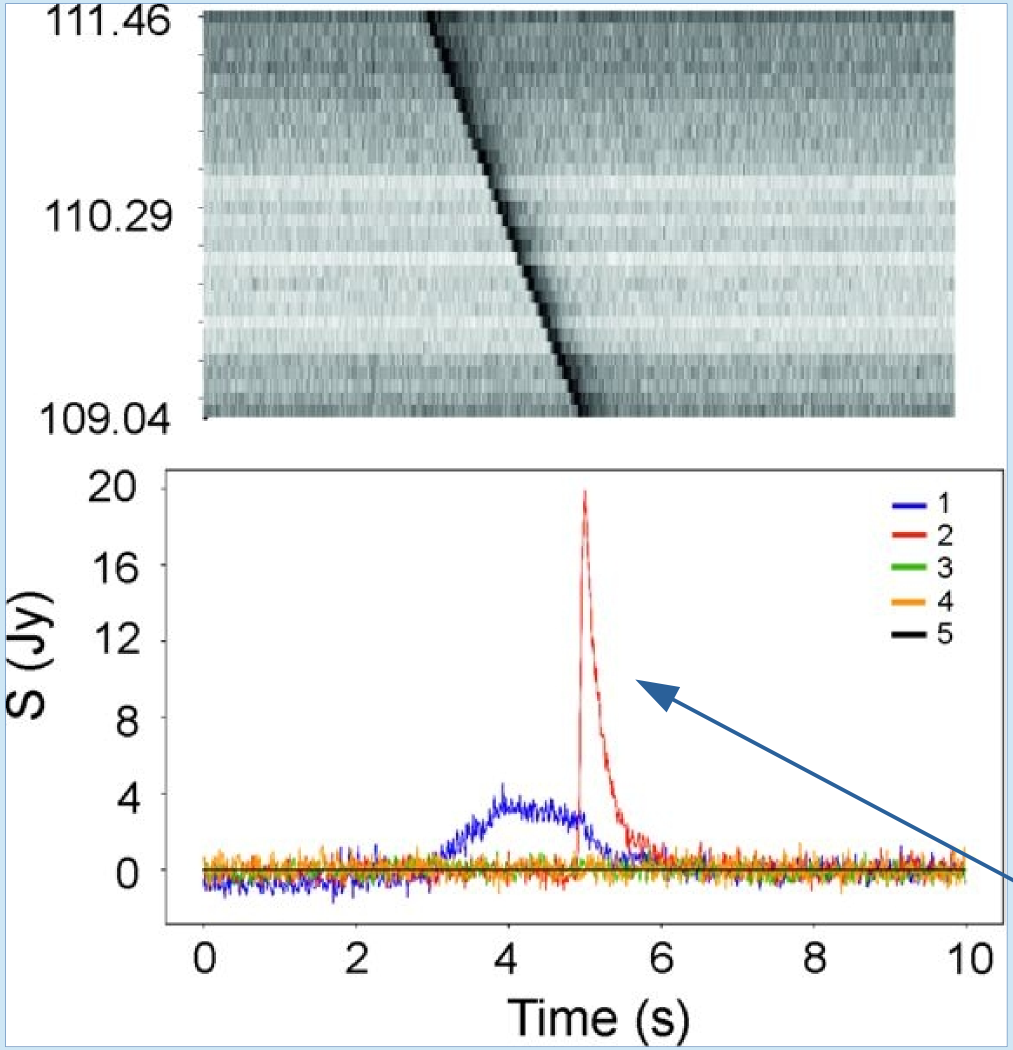
When we computed the spectral evolution numerically we have found the completely different picture. The spectrum of the galaxy is flattening below some frequency due to stimulated scattering.

And this is natural because such a flat spectrum is also the precise solution of the Kompaneets equation.

$$\frac{\partial F_\nu}{\partial \tau_T} = \frac{\nu}{2m_e}\frac{\partial}{\partial \nu}\left(\frac{F_\nu^2}{\nu^2}\right).$$

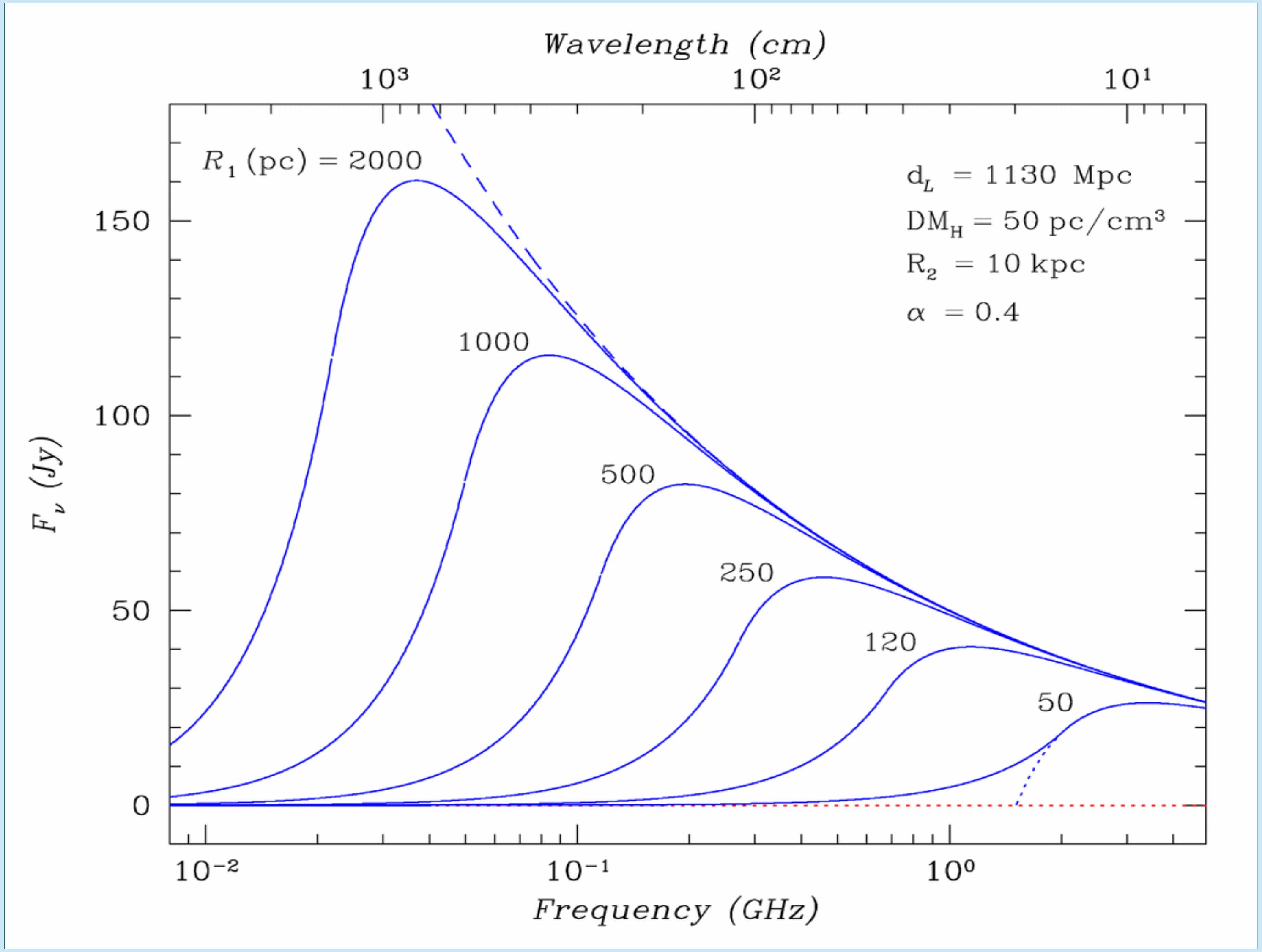


Fast Radio Bursts (FRBs)



- First FRB was found in 2007 by Lorimer et al. in the data of Parkes.
- Currently ASKAP (CRAFT), CHIME, LOFAR, UTMOST detected thousands FRBs + archival FRBs have been found in the Arecibo data.
- Rate a few bursts per day at the whole sky.
- Extremely bright (10-50 Jy), brightness temperature exceeds 10^{36} K, suggesting coherent nonthermal mechanism.
- Very short (0.1-100 ms).
- Strongly dispersed DM ~500 pc cm^{-3} thus extragalactic (Gpc)
- Mainly in the 1.2-2.4 GHz and 600-800 MHz ranges, but a few low frequency events at 111-180 MHz and a number of high frequency events at ~8 GHz were detected.
- FRB 20190203 at 111 MHz (Tyul'bashev et al. 2024)

Fast Radio Bursts (FRBs)

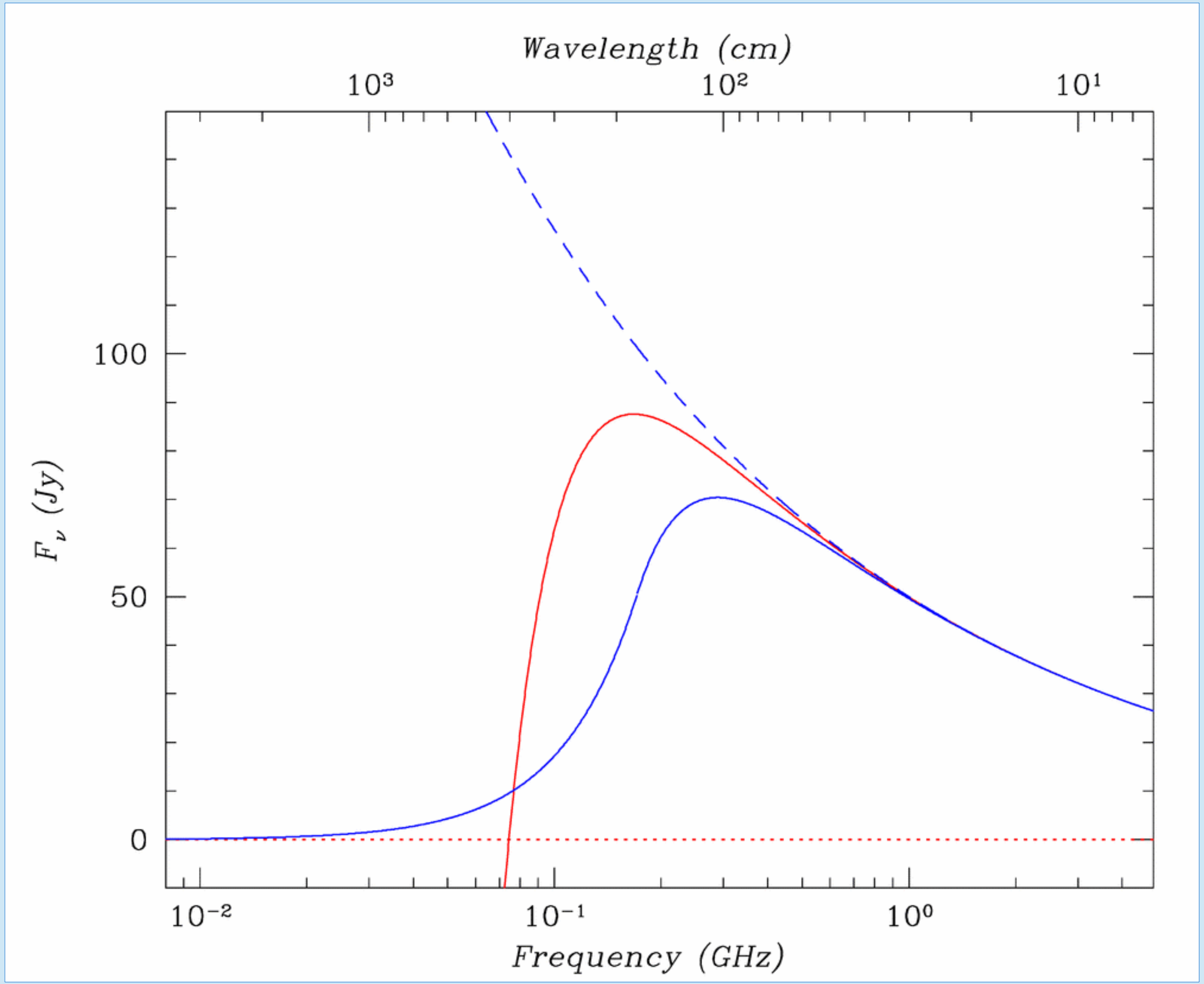


- *Could be affected by stimulated scattering in the ionized gas of the host galaxy (normal Compton scattering is negligible because of the small optical depth – $\sigma_T DM_{host}$~10^{-4})*
- *In fact short duration of FRBs changes the conditions of its appearance. The Thomson depth in the equation should be replaced by $\sigma_T N_e c\Delta t$ (Lybarsky 2008).*

$$F_\nu(\nu) = F_A \tau_c \frac{R_c^2}{d_L^2}\left[1 - \frac{F_A}{10^{23}}\frac{(1+\gamma)}{3\, m_e \nu^2}\left(\frac{R_c^3}{R_0^3} - 1\right)\right]$$

- *Nevertheless stimulated scattering may be important to suppress the low frequency emission of FRBs and explain why such LF FRBs are so rare.*

Fast Radio Bursts (FRBs)



- *Could be affected by stimulated scattering in the ionized gas of the host galaxy (normal Compton scattering is not important because of the small optical depth – $\sigma_T DM_{host}$~10^{-4})*
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- *Nevertheless stimulated scattering may be important to suppress the low frequency emission of FRBs and explain why such LF FRBs are so rare.*

Conclusions

- *The distortions in the cosmic radio 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.*
- *Stimulated scattering can suppress the low frequency radio emission of the cluster galaxies and the low frequency radio emission from Fast Radio Bursts.*

Thank you