Implications of the Dark Age Consistency Ratio for models beyond ΛCDM

Phys. Rev. Lett. 133 (2024) 13, 131001

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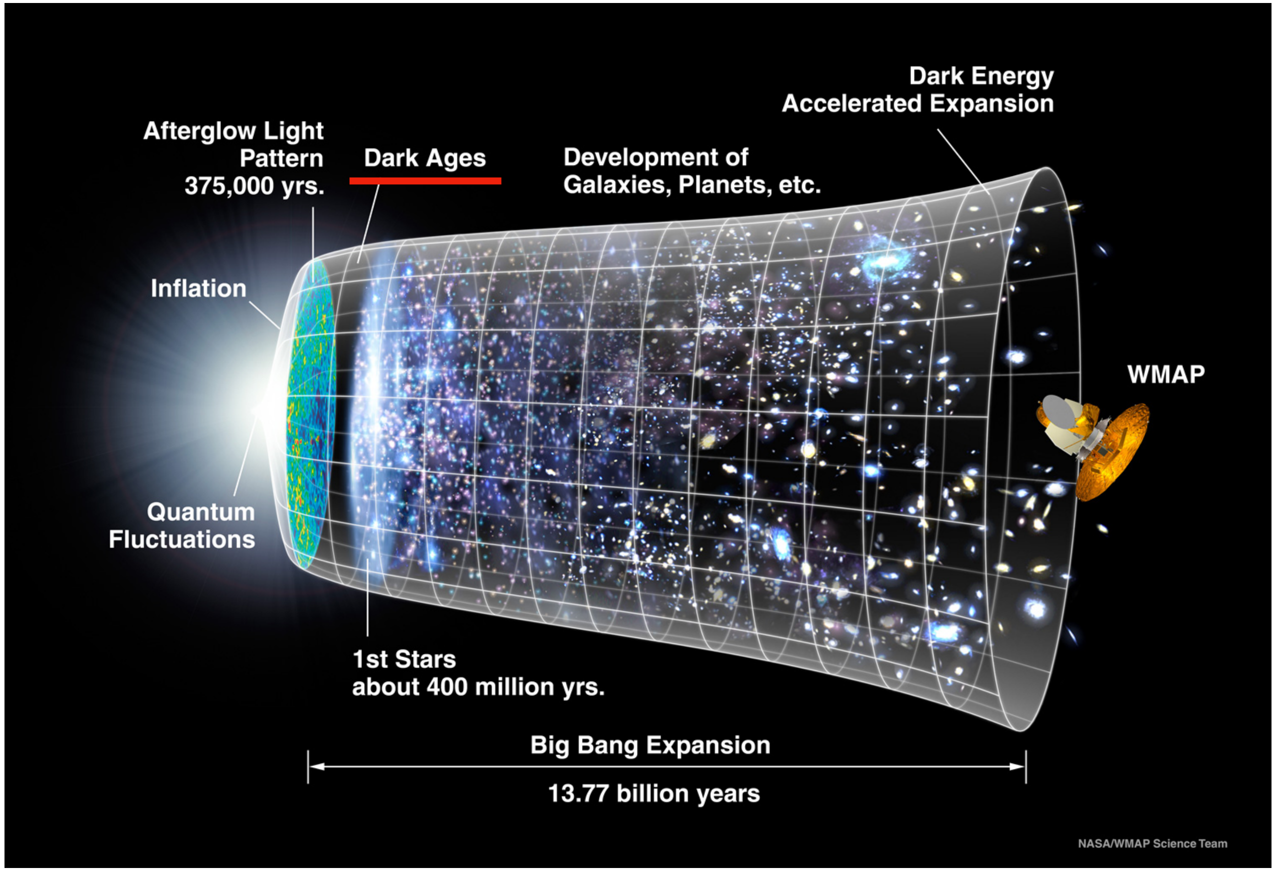
2023/11/ 7Saga-Yonsei partnership program

Purpose

- The frequency of the dark age 21cm signal is very low and difficult to observe from the ground due to the Earth's ionosphere.
- Various observations are now being planned to probe the dark age 21cm signal from a telescope on the moon or a satellite orbiting around the moon.
- We would like to investigate what kind of information can be obtained from the dark age 21cm signal.
- We propose new observables for the dark age 21cm line global signal and show that the new observables can probe models beyond the standard model.
- We also discuss the possibility of constraining model parameters using new observables.

• Dark ages



https://map.gsfc.nasa.gov/media/060915/index.html

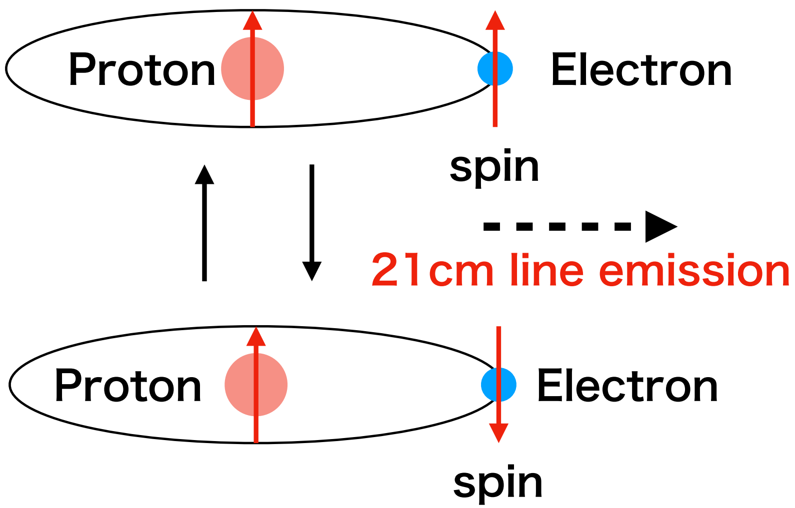
The Dark Ages is the period
When there are only neutral hydrogen gas
and a small amount of helium gas,
and no astrophysical objects.

The redshift corresponding to
the dark ages is from 30 to 300.

During this period,
we can ignore the astrophysical effects.

• 21cm line signal

The neutral hydrogen H_I



The 21cm line radiation :
a spectral line emitted by transitions between two different levels, depending on the relative orientation of the proton and electron spins.

$$\nu_{21\mathrm{cm}} \simeq 1420.40\ \mathrm{MHz}$$

$$\lambda_{21\mathrm{cm}} \simeq 21.10\ \mathrm{cm}$$

• The spin temperature

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{T_*}{T_s}\right)$$

n_0 : the number density of 1S singlet state,

n_1 : the number density of 1S triplet state

$$T_* \equiv \frac{h_p c}{k_B \lambda_{21}} \simeq 0.068\ \mathrm{K}$$

h_p : Planck constant, k_B : Boltzmann constant, c : speed of light

• 21cm line signal

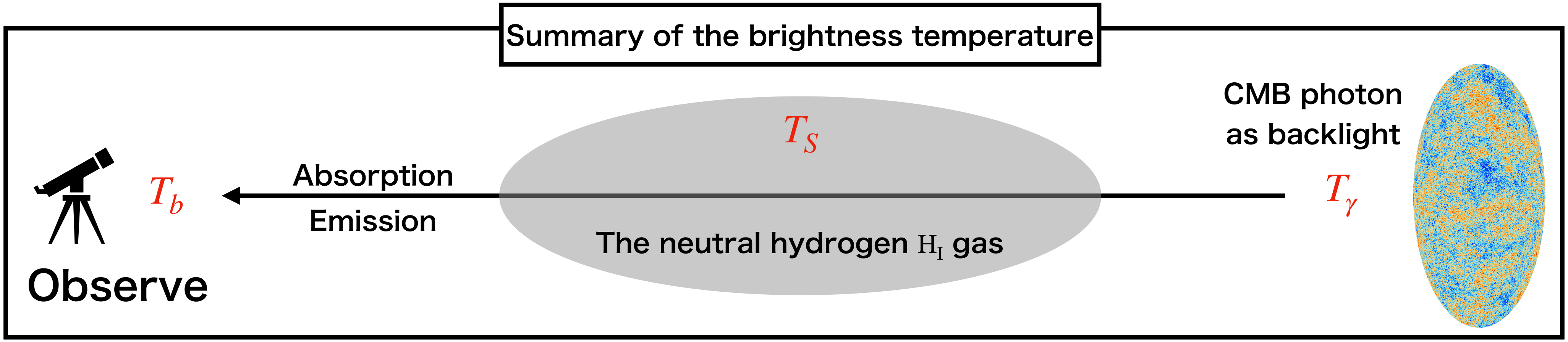
- The 21 cm signal is charactered by the brightness temperature.

$$T_b = \frac{T_s - T_\gamma}{1+z}\left(1 - \exp(-\tau_{21})\right) \qquad \tau_{21} = \frac{3ch_p\lambda_{21}^2 A_{10} x_{\rm HI}(1-Y_p)n_b}{32\pi k_B T_s H(z)}$$

A_{10} : Einstein cofficient, $x_{\rm HI}$: the fraction of the neutral hydrogen,

Y_p :the abundance of Helium, n_b : the number density of baryon,

$H(z)$: Hubble parameter, τ_{21} : the optical depth for the 21 cm line



• 21cm line signal

• Three processes affect the evolution of spin temperature.

1. Spin-flip effect due to collisions between atoms : x_c

   Collisions between hydrogens, hydrogen and electron, proton and hydrogen

2. Transition effects due to absorption and emission of background photons(CMB photons).

3. Effects of transitions occurring via other energy levels due to Lyman-α effects (Wouthuysen-Field effect) : x_α

• The evolution of the spin temperature

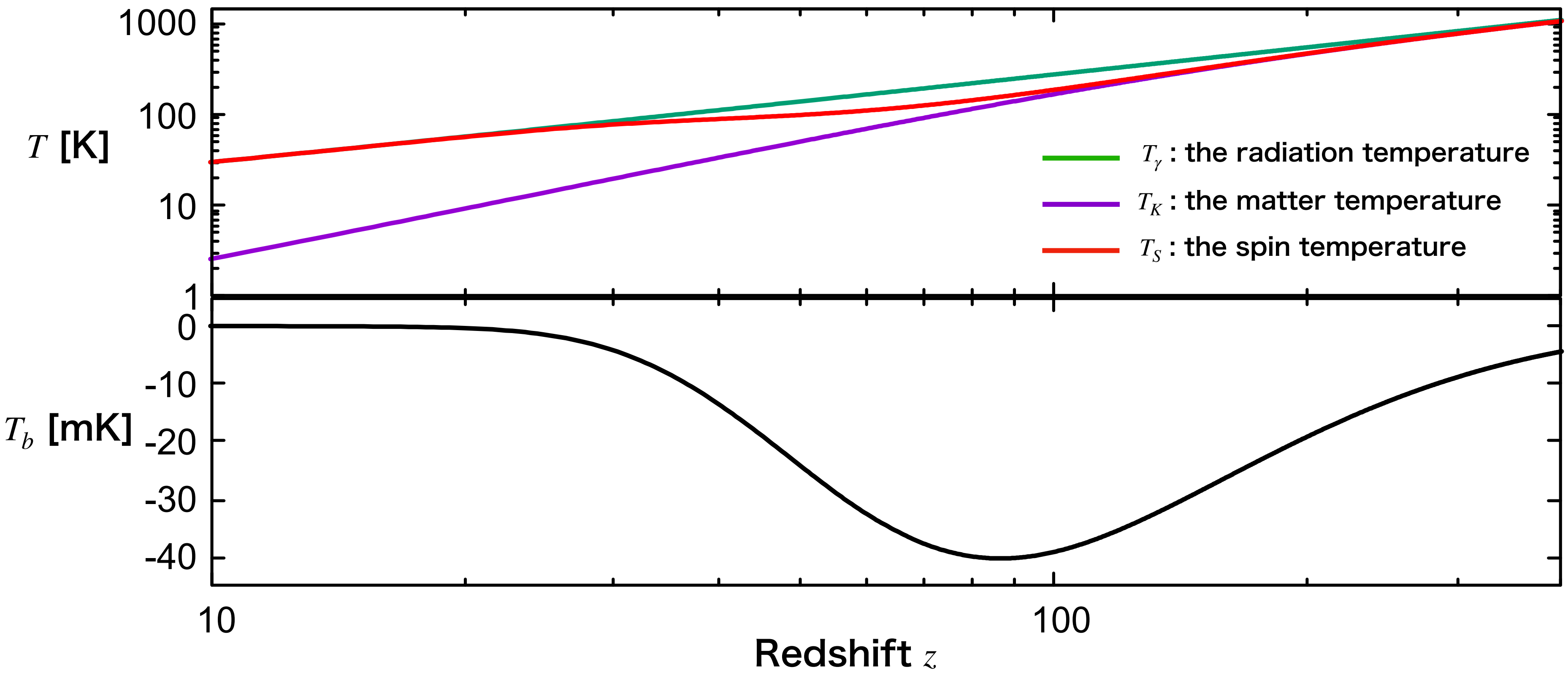
$$T_s^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_K^{-1}}{1 + x_c + x_\alpha}$$

x_c :the atomic collision coefficient, x_α : Wouthuysen–Field effect,

T_K : the matter temperature, T_γ : the photon temperature

• 21cm line signal

• The evolution of the spin temperature in the ΛCDM model at the dark ages



※In the dark age, we can ignore x_α when we consider ΛCDM model.

When cosidering non-standard models, it is possible that x_α cannot be ignored.

Cosmological parameter dependence

• For the standard ΛCDM model

- We investigated the Dark ages 21 cm global signal in flat-ΛCDM model.

- To predict the Dark ages 21 cm global signal, we have to specify cosmological parameters.

$\Omega_b h^2$: baryon density, $\Omega_c h^2$: cold dark matter density,

H_0 : Hubble constant, Y_p : the helium abundance

- To indicate how the Dark ages 21 cm global signal depend on cosmological parameters・・・

mean value and 1σ error	Parameters range	
$\Omega_b h^2 = 0.02237 \pm 0.00015$	$[0.02162,\ 0.02312]$	Planck Collaboration., (arXiv:1807.06209)
$\Omega_c h^2 = 0.12 \pm 0.0012$	$[0.114,\ 0.126]$	
$Y_p = 0.2436^{+0.0039}_{-0.0040}$	$[0.22384,\ 0.2633]$	Hsyu et al, (arXiv:2005.12290)

• For the standard ΛCDM model

- T_b has the following cosmological parameter dependence:

$$T_b \propto \frac{(\omega_b)^2(1-Y_p)^2}{(\omega_m)^{1/2}} \qquad \omega_b = \Omega_b h^2,\ \omega_m = \Omega_m h^2$$

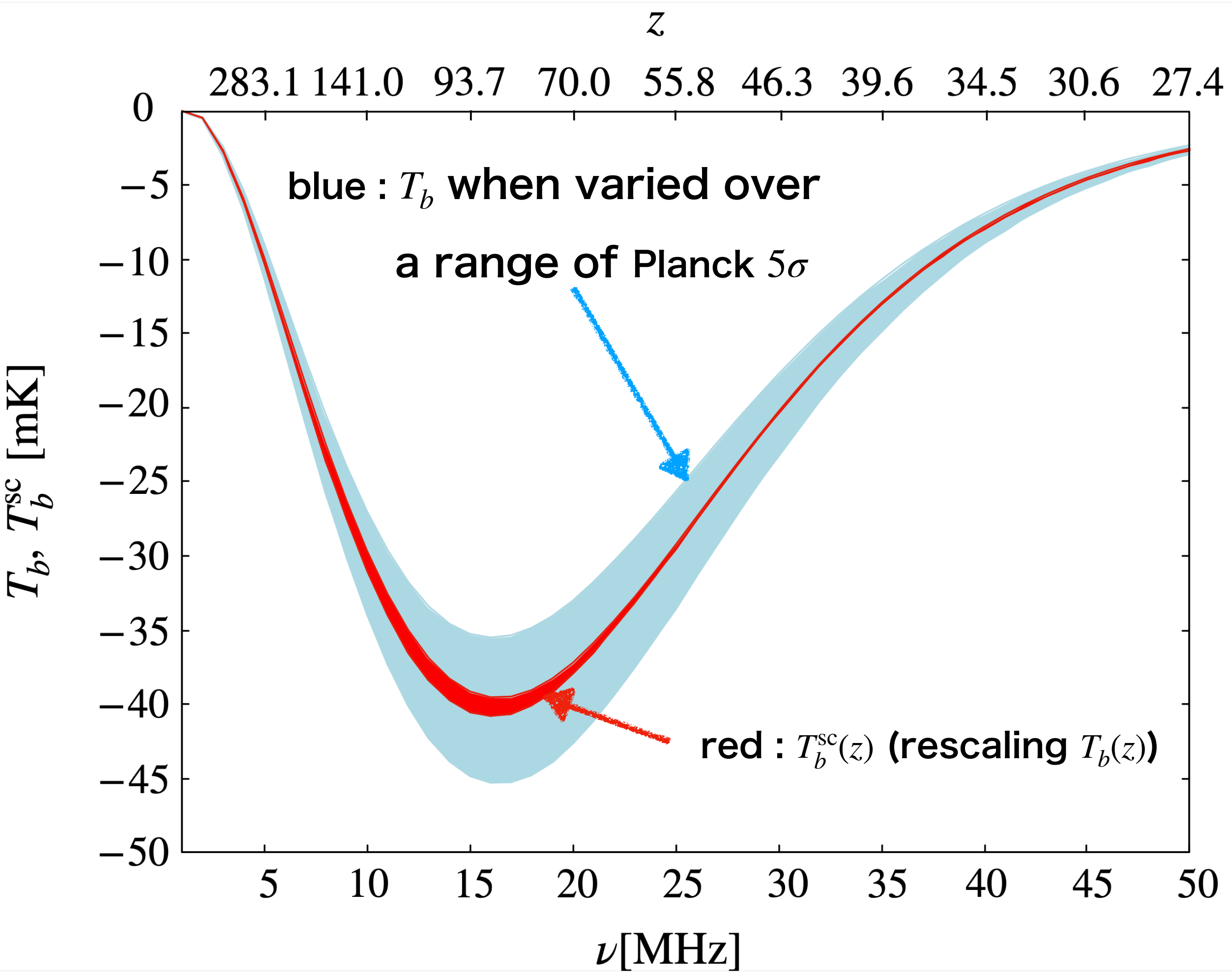
(See also Mondal and Barkana (2305.08593))

- Defining $C(\omega_b, \omega_c, Y_p)$, we obtain the equation rescaling T_b that is derived by different cosmological parameters.

$$T_b^{\rm sc}\left(\nu; \tilde{\boldsymbol{\theta}}, \boldsymbol{\theta}\right) = T_b\left(\nu; \boldsymbol{\theta}\right)\frac{C(\tilde{\boldsymbol{\theta}})}{C(\boldsymbol{\theta})} \qquad C \equiv \frac{(\omega_b)^2(1-Y_p)^2}{(\omega_m)^{1/2}}$$

$\boldsymbol{\theta} = (\omega_b, \omega_m, Y_p)$ $\quad \tilde{}$ represent the reference value($\omega_b = 0.02237,\ \omega_c = 0.12,\ Y_p = 0.2436$)

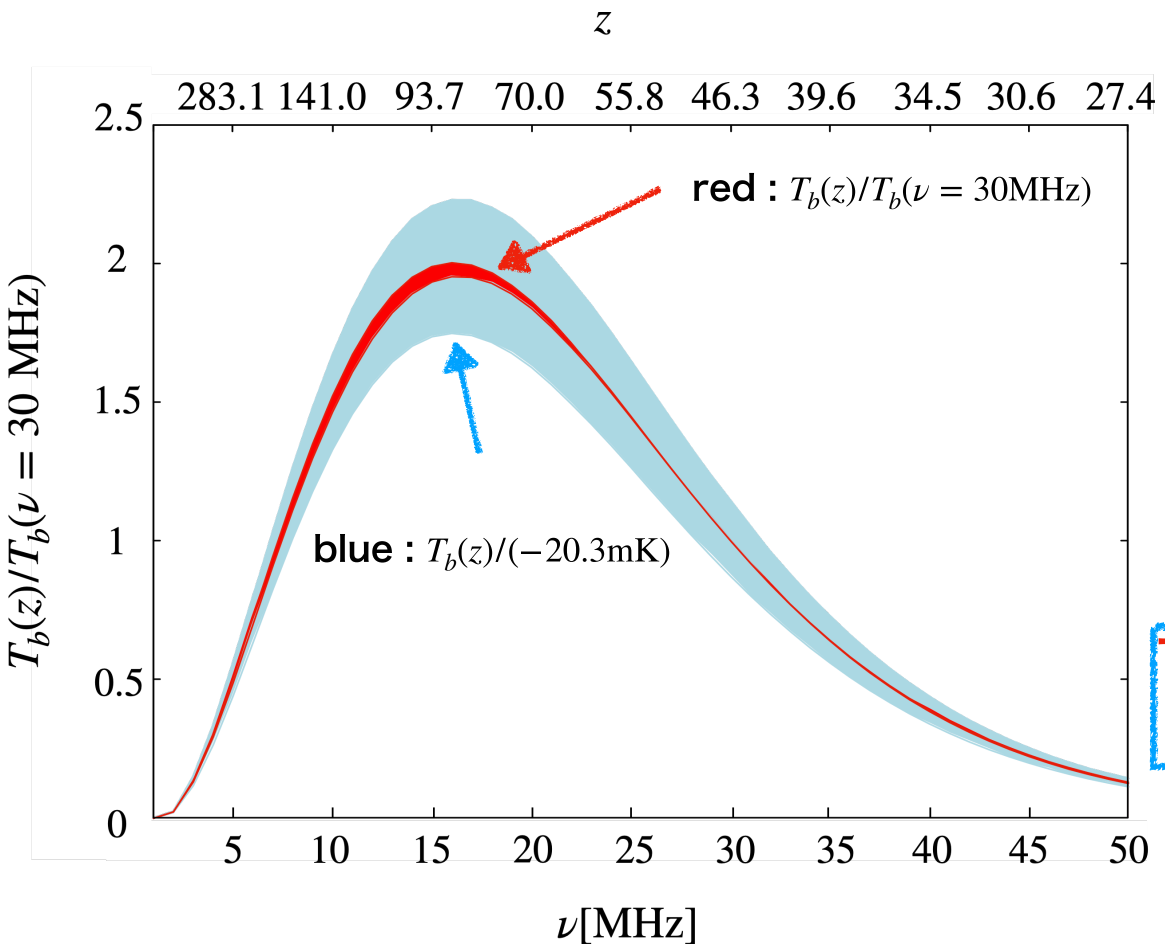
• For the standard ΛCDM model



※Rescaled T_b almost remains the same due to rescaling

Taking the ratios T_b at the different frequency,
We get quantities that are independent of cosmological parameters

• For the standard ΛCDM model



• These quantities are almost constant regardless cosmological parameters

They can be used as a consistency check of the standard ΛCDM model

- **For the standard ΛCDM model**

  - We define the ratio of T_b at different frequencies as:

$$R_{\nu_i\,/\,\nu_j} \equiv \frac{T_b(\nu = \nu_i\ [\mathrm{MHz}])}{T_b(\nu = \nu_j\ [\mathrm{MHz}])}$$

    which we call the "the dark-age consistency ratio".

  - The bottom table shows $R_{\nu_i\,/\,\nu_j}$ for some frequencies ν_i when cosmological parameters are varied.

ν_i	$R_{\nu_i/30}$	$T_b(\nu_i)$ [mK]
40	0.3873 ± 0.0029 (0.76%)	-7.923 ± 1.0107 (12.76%)
35	0.6401 ± 0.0016 (0.24%)	-13.10 ± 1.7301 (13.20%)
25	1.4454 ± 0.0023 (0.16%)	-29.59 ± 3.9133 (13.23%)
20	1.8487 ± 0.0126 (0.68%)	-37.82 ± 4.8074 (12.71%)

- For the standard ΛCDM model

  - If one or more of the following assumptions is violated in the dark ages, The deviation from the value of the ΛCDM model can appear.

(i) The universe is matter-dominated → Early Dark Energy

(ii) Lyman-α sources are negligible

(iii) Matter and photons are coupled via the Compton scattering

} → Dark Matter Decay

(iv) the radiation field is determined by CMB → Excess radio background

$$T_\gamma = T_{\mathrm{CMB},0}(1+z)$$

We investigate the consistency ratio in the above non-standard models.

- For models beyond the standard model
  - Early Dark Energy model
    - It has been proposed to consider a non-negligible EDE component during the dark ages to explain the EDGES signal.(J. C. Hill and E. J. Baxter, (arXiv:1803.07555))

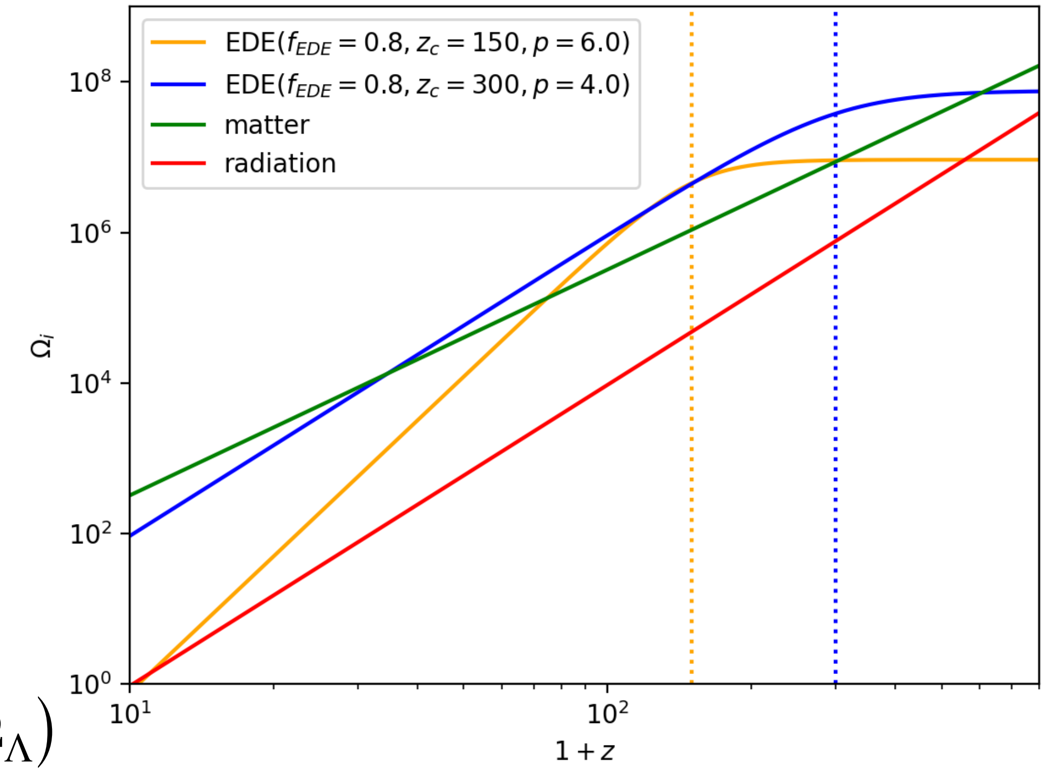
$$\rho_{\rm EDE}(z) = \frac{f_{\rm EDE}}{1-f_{\rm EDE}} \frac{\rho_{\rm r,m,DE}(z_c)}{f(z_c)} f(z)$$

$$f(z) = \frac{1+(1+z_c)^{-p}}{(1+z)^{-p}+(1+z_c)^{-p}}$$

$$f_{\rm EDE} = \frac{\rho_{\rm EDE}(z_c)}{\rho_{\rm r,m,DE}(z_c)+\rho_{\rm EDE}(z_c)}$$

$$\rho_{\rm r,m,DE}(z) = \rho_{\rm crit}\left(\Omega_{\rm r}(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda\right)$$

$z_c = 150 \quad z_c = 300$



• For models beyond the standard model

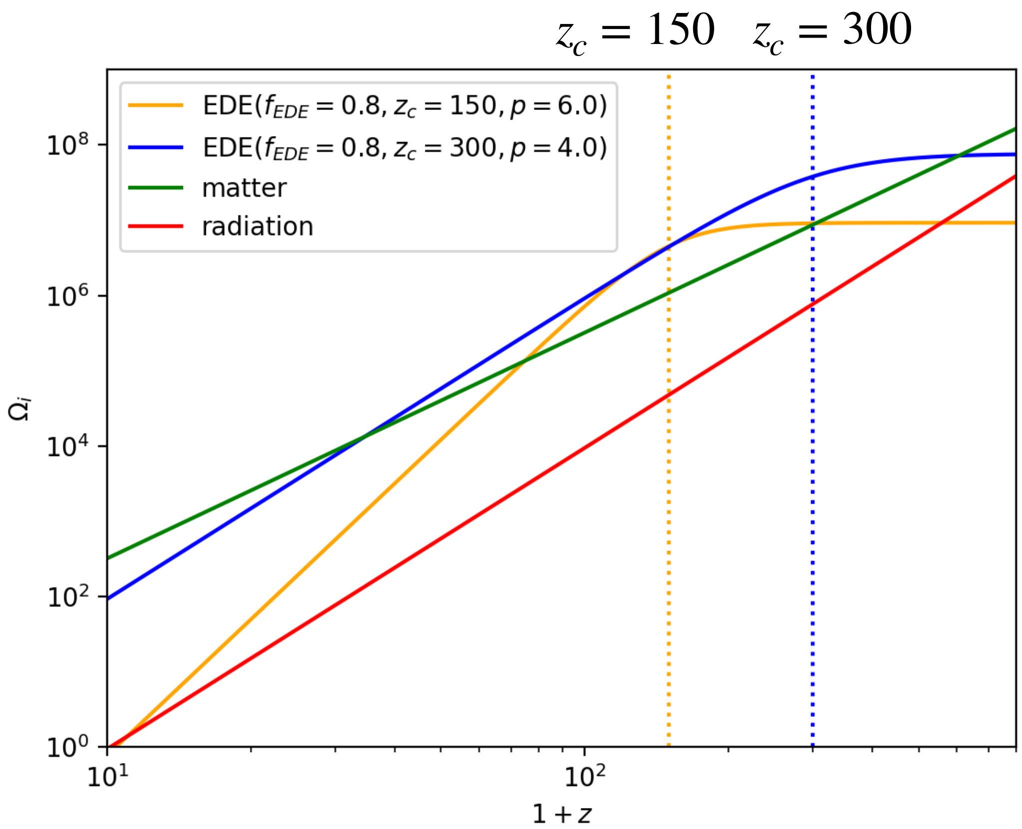
• Early Dark Energy model

- It has been proposed to consider a non-negligible EDE component during the dark ages to explain the EDGES signal.(J. C. Hill and E. J. Baxter, (arXiv:1803.07555))

- The EDE component…

For $z \gg z_c$ → The energy density of EDE component is constant

For $z \ll z_c$ → The energy density of the EDE component decreases.



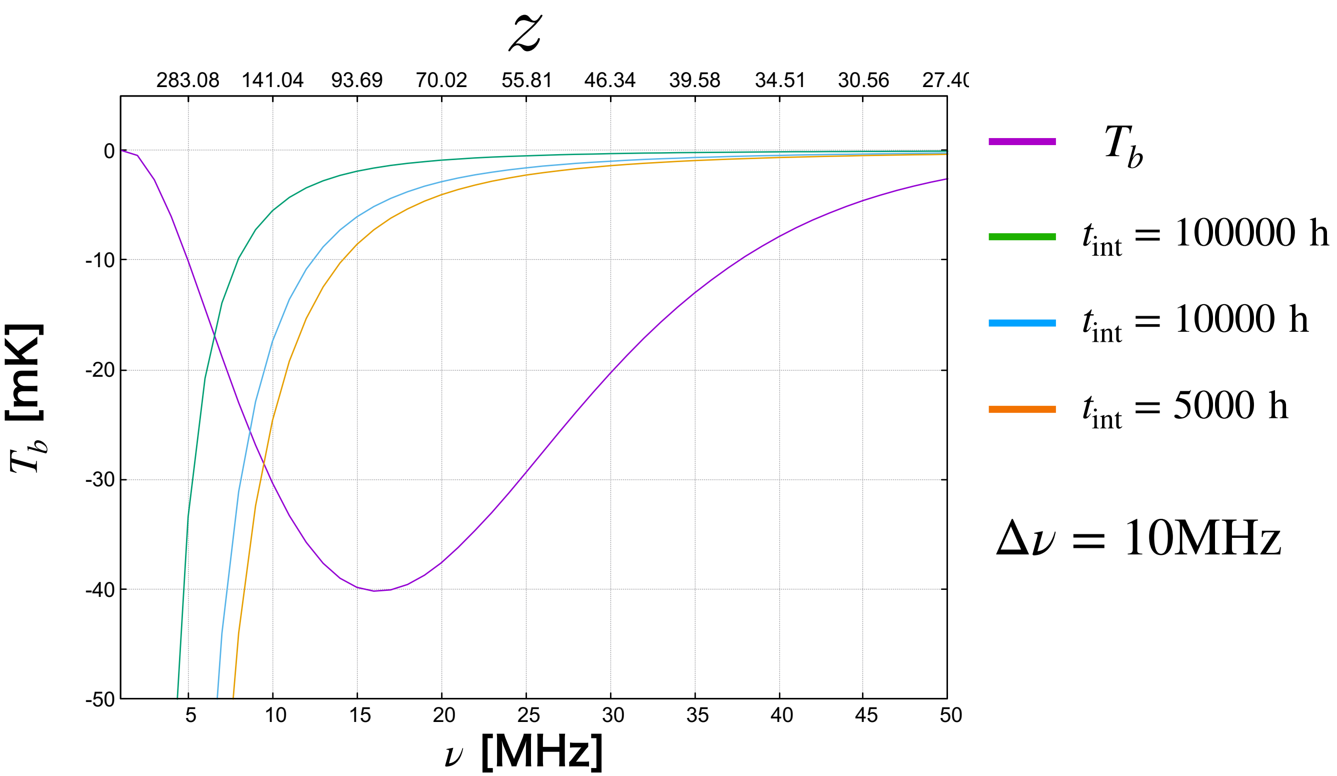
• For models beyond the standard model

- In order to evaluate expected noise for the 21 cm signal…

- thermal noise $$\sigma_\nu = \frac{T_{\rm sys}}{\sqrt{\Delta\nu \ \ t_{\rm int}}}$$

$T_{\rm sys} \simeq T_{\rm sky} = 180 \times (\nu/180{\rm MHz})^{-2.6}$ K

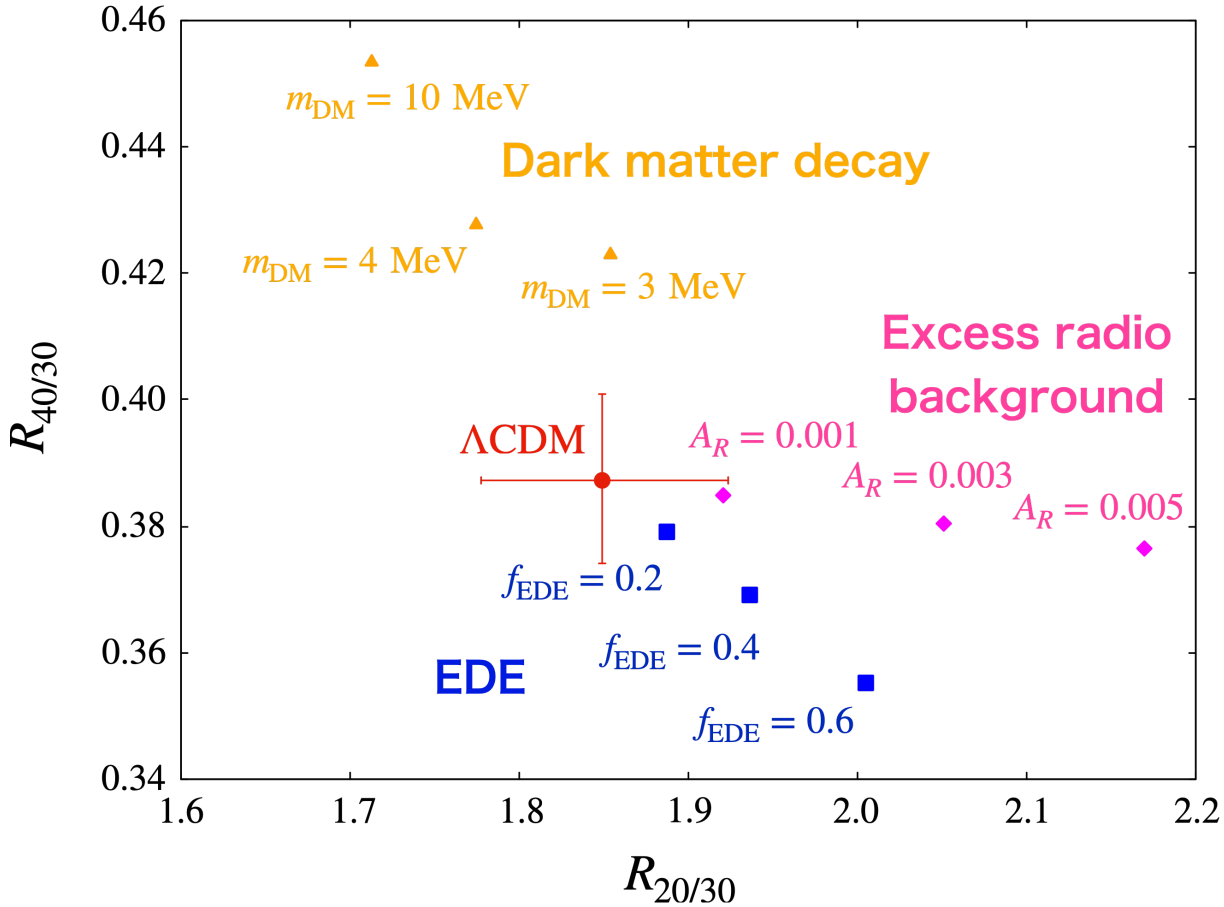
$t_{\rm int}$: integration time



- We used

$t_{\rm int} = 100000$ h and $\Delta\nu = 10$ MHz

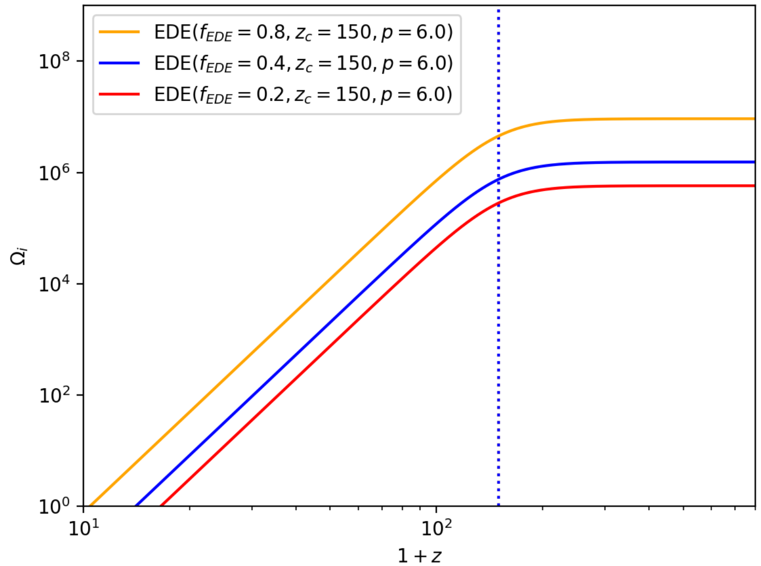
- **For models beyond the standard model**
  - **the consistency ratio $R_{\nu_i\,/\,\nu_j}$**



The dark-age consistency ratio is the useful probe of non-standard models

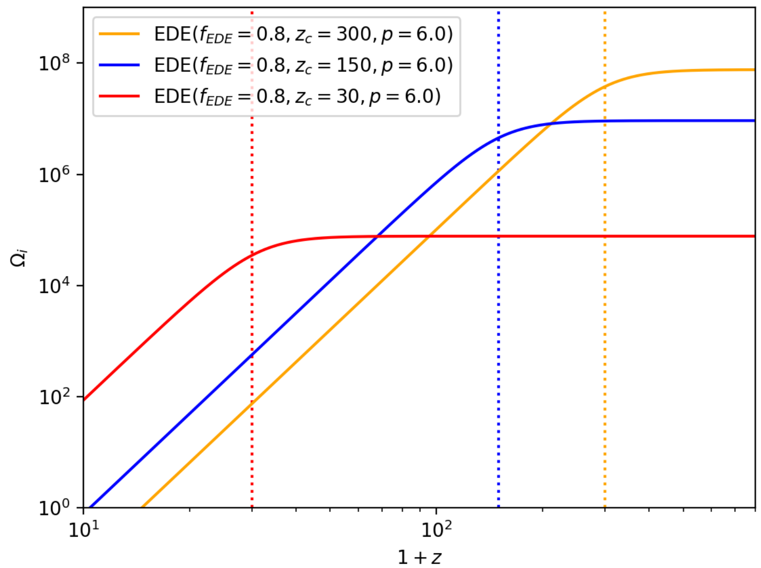
- For models beyond the standard model

  - We check the behavior of the consistency ratio in the EDE model when the model parameters are changed.



- $f_{\rm EDE}$ represents the contribution of the EDE component to the total energy density.

- z_c is the redshift at which the energy density of the EDE begins to decrease.



- We show the result when the model parameters are varied within the following ranges.

$$0.1 \leq f_{\rm EDE} \leq 1.0 \qquad 30 \leq z_c \leq 200$$

• For models beyond the standard model

- We check the behavior of the consistency ratio in the EDE model when the model parameters are changed.
- For EDE model…
  - f_{EDE} represents the contribution of the EDE component to the total energy density.

$$0.1 \leq f_{\mathrm{EDE}} \leq 1.0$$

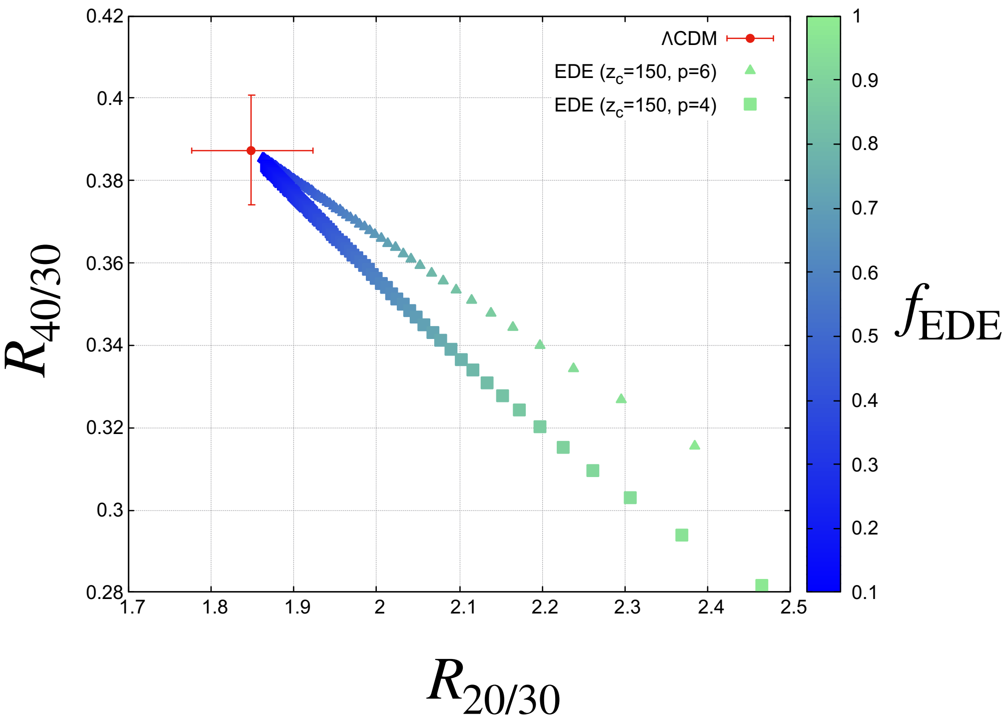
  - z_c is the redshift at which the energy density of the EDE begins to decrease.

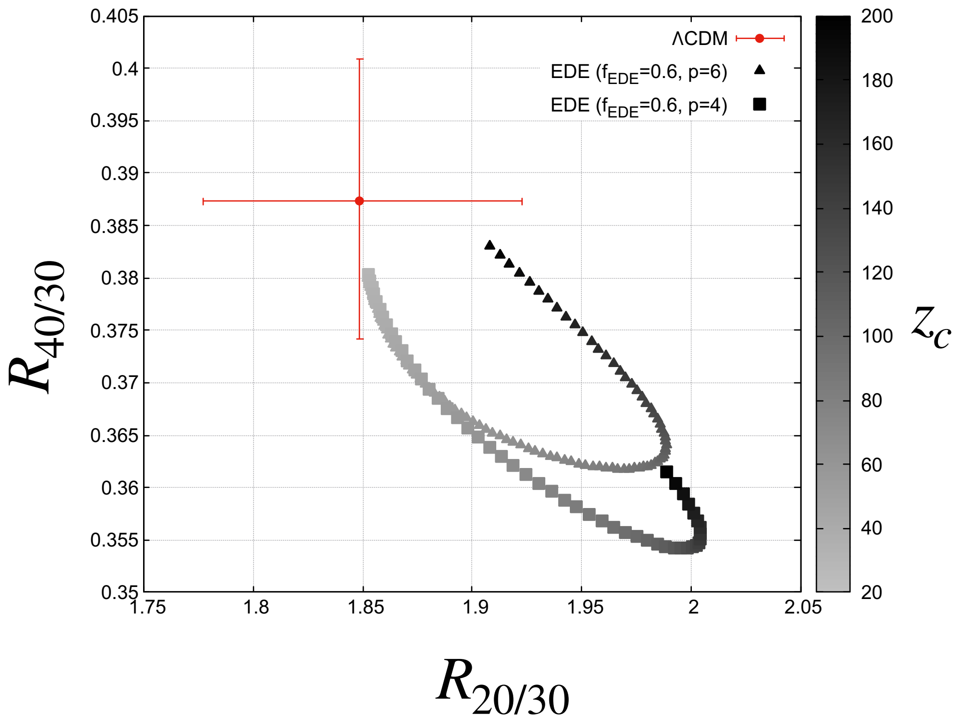
$$30 \leq z_c \leq 200$$

- Using the ΛCDM model's consistency ratios $R_{40/30}$ and $R_{20/30}$ as mock data, we perform a χ^2 analysis to constrain f_{EDE} and z_c.

• For models beyond the standard model

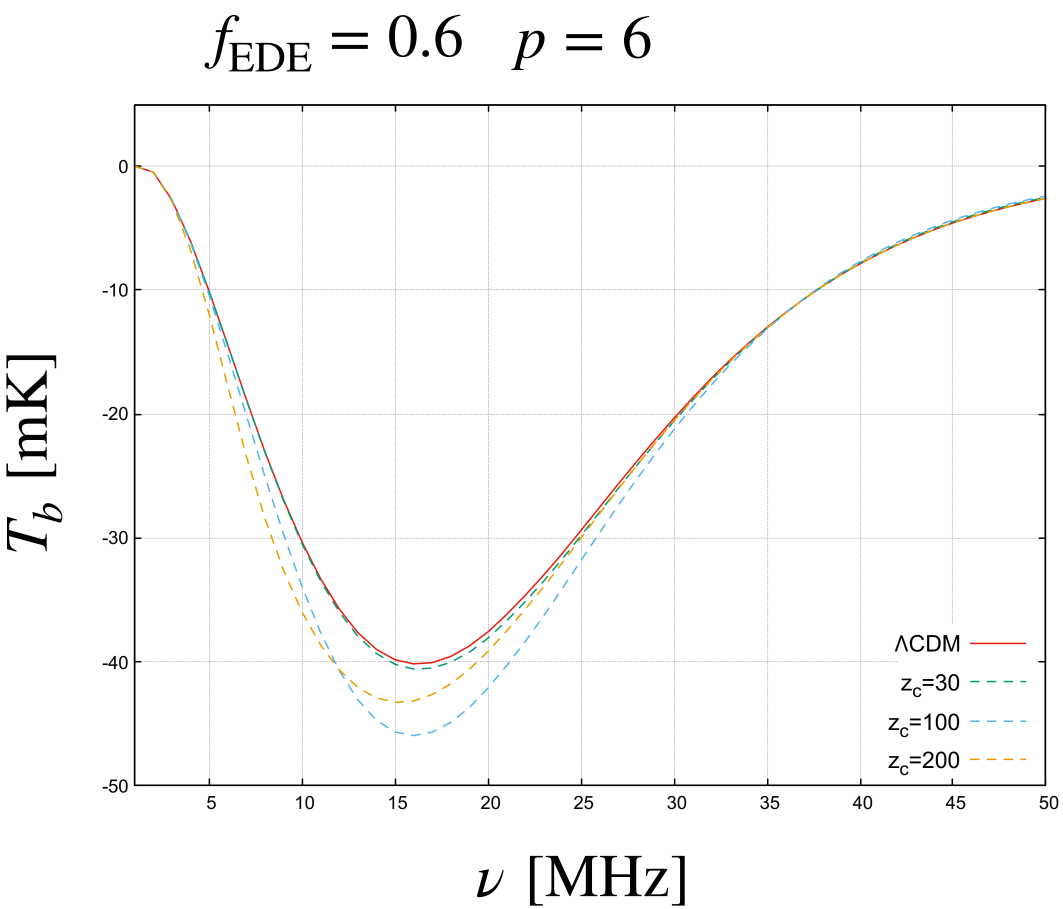
• For EDE model…

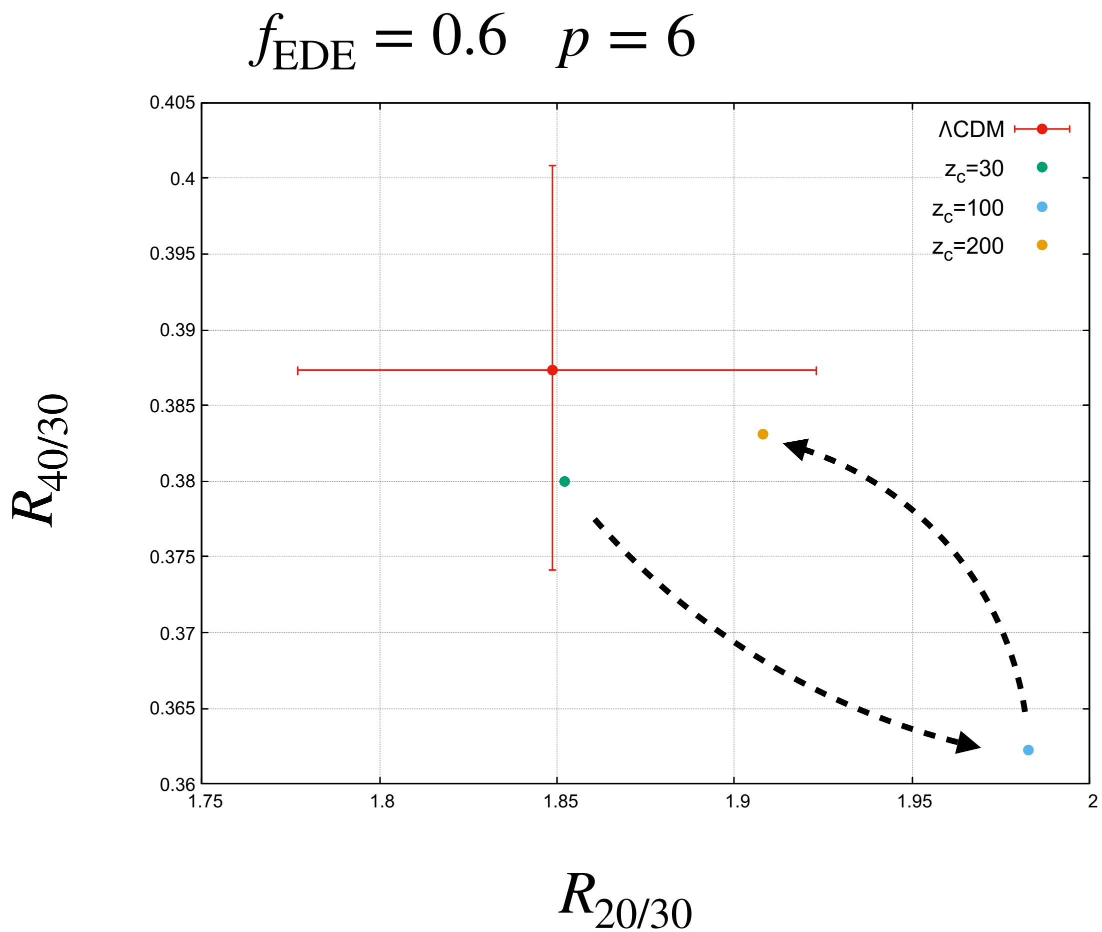




• For models beyond the standard model

- **For EDE model…**

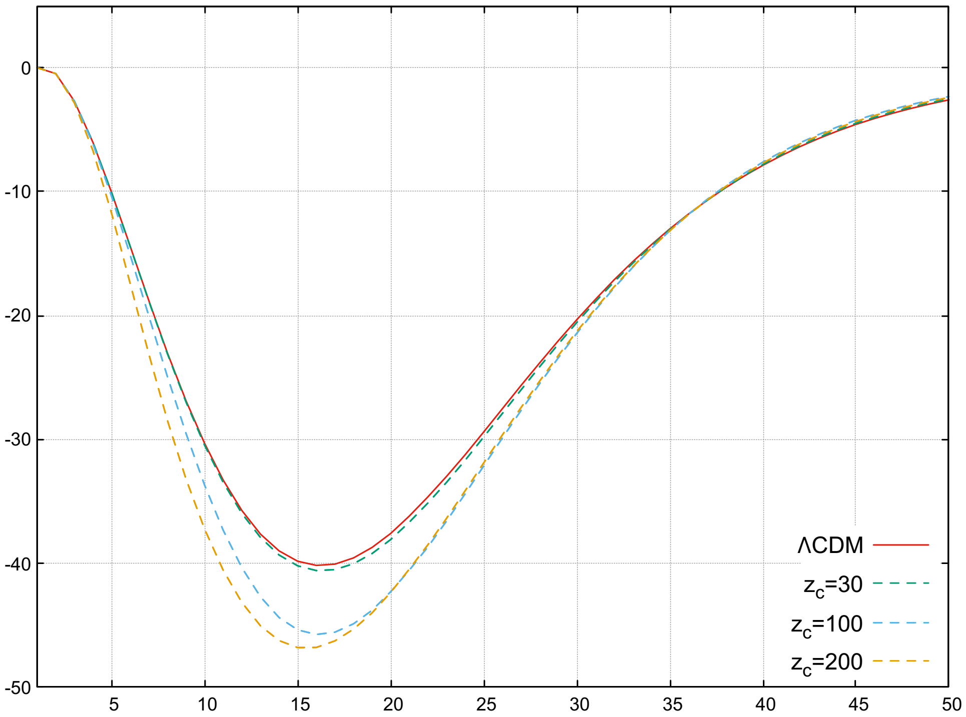




• For models beyond the standard model

- For EDE model…

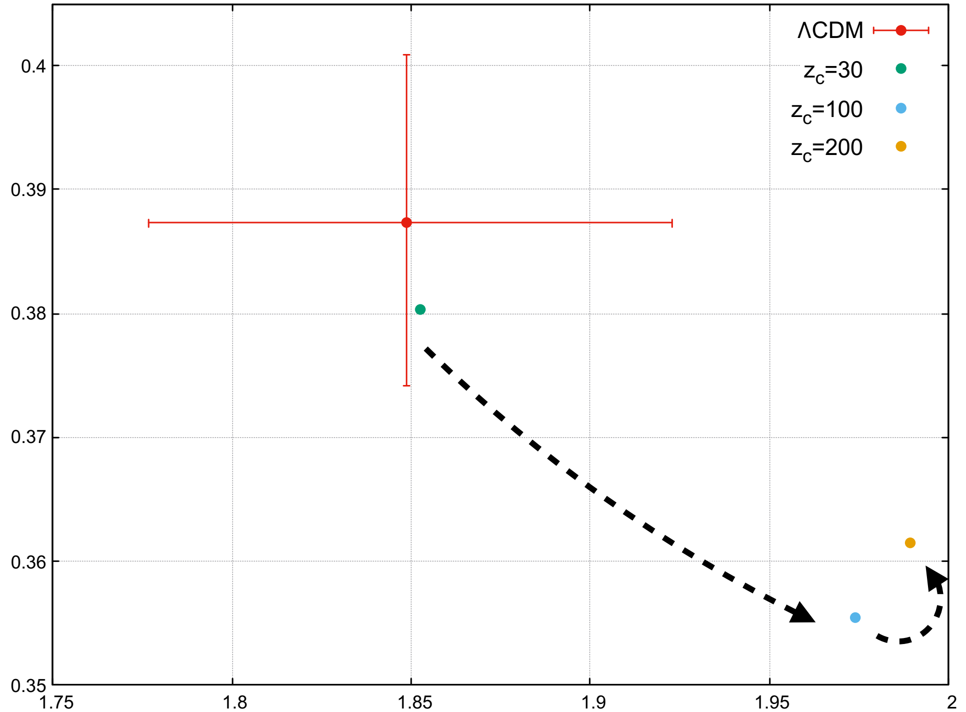
$f_{\mathrm{EDE}} = 0.6 \quad p = 4$



T_b [mK]

ν [MHz]

$f_{\mathrm{EDE}} = 0.6 \quad p = 4$

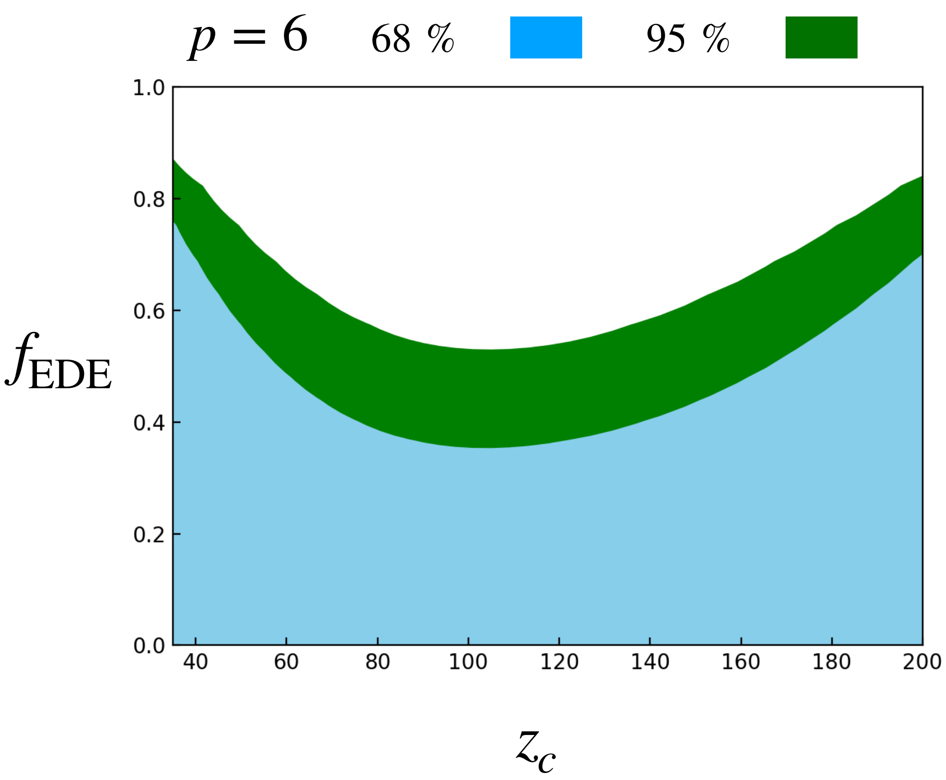


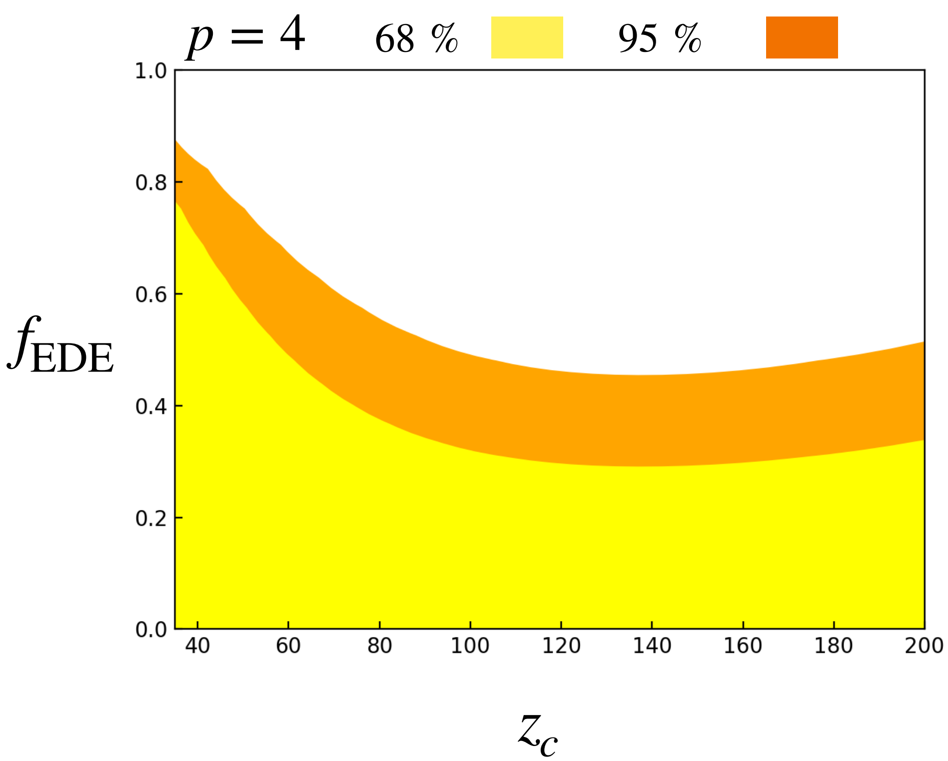
$R_{40/30}$

$R_{20/30}$

• For models beyond the standard model

- For EDE model…





- The parameter space of each area is allowed.
- For $z \geq 80$, the constraints for the $p = 4$ case are more stringent than for the $p = 6$ case.

Conclusion

- We proposed the new observable R_{ν_i/ν_j} , so-called "the dark-age consistency ratio",
  for the dark age 21 cm global signal.

  → It is based on the fact the shape of the functional form of the brightness temperature against the frequency is cosmological-parameter independent in the standard ΛCDM model

- The consistency ratio value of the ΛCDM model is almost constant and could be used as an important test of cosmological models.

- The new observable only needs measurement at some frequency bands so that the useful information on cosmology can be obtained even at the early stage of 21cm observations of the dark ages

- Using the dark age consistency ratio, we investigated the possibility of constraining model parameters for the EDE model.

Backup

質問

・Why is the reference frequency 30MHz?

・consistency ratioが宇宙論パラメータに依存しない理由は？

・Dark matter decay modelにおいて、massが３MeVから10MeVになるだけで、
Tbやratioが大きく変わる理由は？

・EDEでEDGESが説明できる理由は？

• 21cm line signal

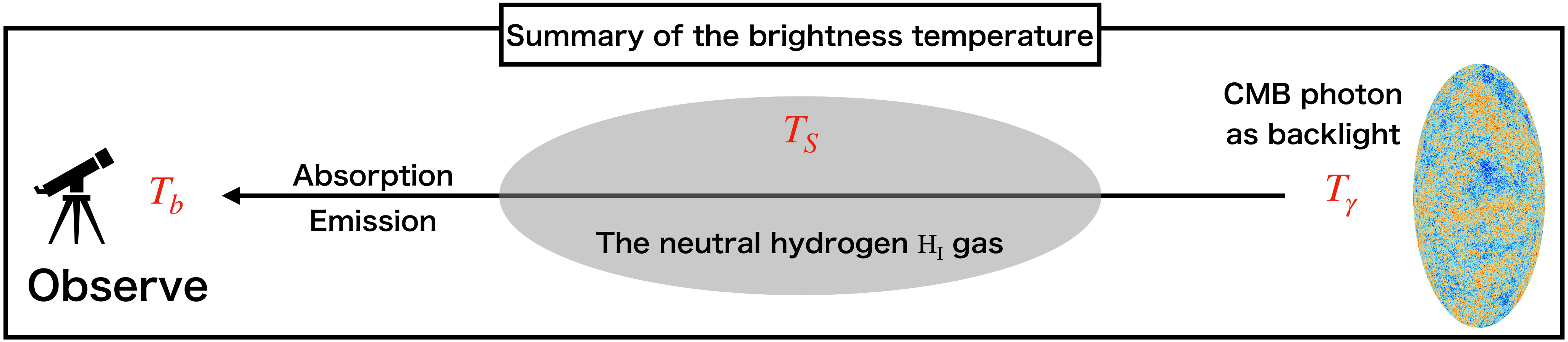
- The 21 cm signal is charactered by the brightness temperature.

$$T_b = \frac{T_s - T_\gamma}{1+z}\left(1 - \exp(-\tau_{21})\right)$$

$T_b > 0$: The 21 cm line is the emission for CMB.

$T_b < 0$: The 21 cm line is the absorption for CMB.

τ_{21} : the optical depth for the 21 cm line



• 21cm line signal

• The evolution of the spin temperature

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_K^{-1}}{1 + x_c + x_\alpha}$$

x_c :the atomic collision coefficient, x_α : Wouthuysen–Field effect,

T_K : the matter temperature, T_γ : the photon temperature

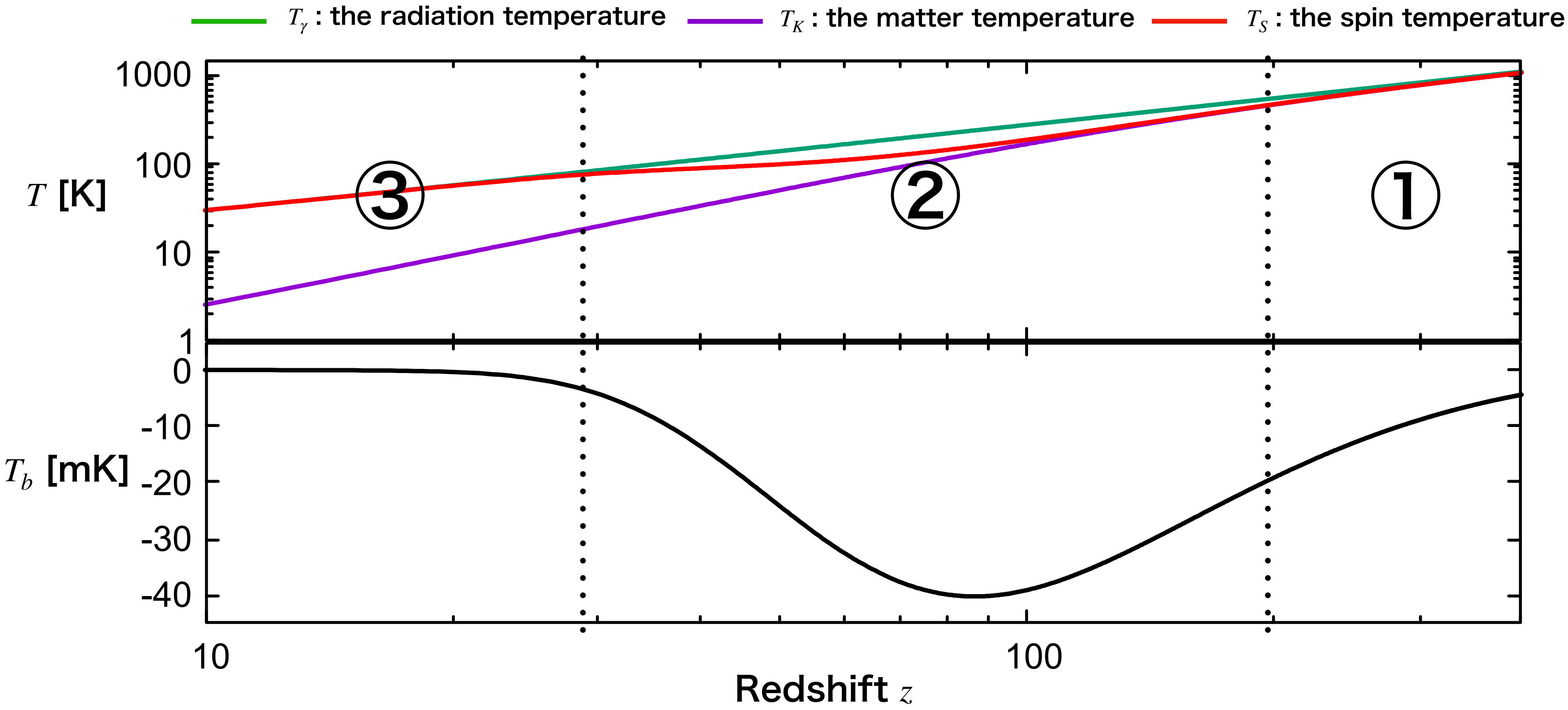
$$x_c = \frac{T_*}{A_{10} T_\gamma} \left(\kappa_{10}^{\mathrm{HH}}(T_K) n_{\mathrm{H}} + \kappa_{10}^{\mathrm{eH}}(T_K) n_{\mathrm{e}} + \kappa_{10}^{\mathrm{pH}}(T_K) n_{\mathrm{p}} \right)$$

$\kappa_{10}^{i\mathrm{H}}$: Scattering rates for HH (hydrogen-hydrogen), eH (electron-hydrogen), and pH (proton-hydrogen) collisions,

n_i : the number density of H,e,p

• 21cm line signal

- The evolution of the spin temperature in the ΛCDM model at the dark ages

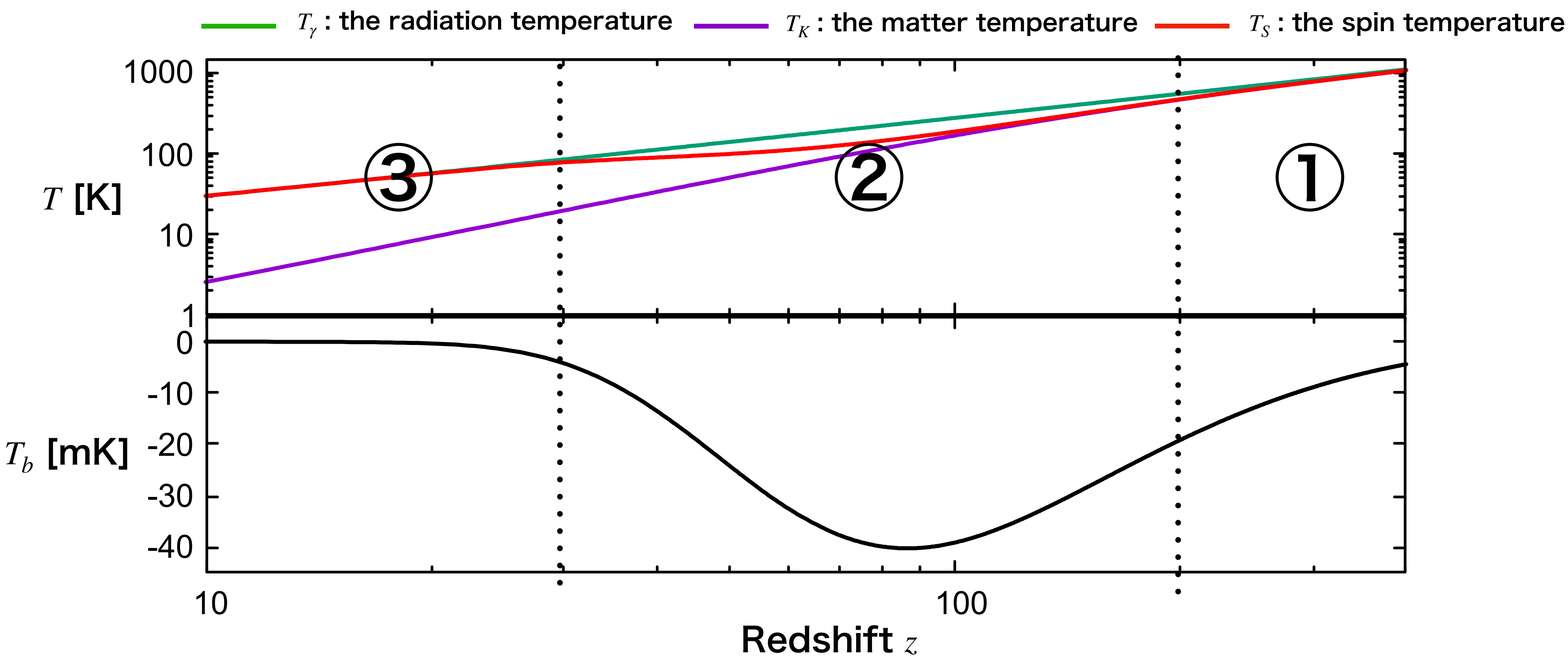


①After recombination, there remains free electrons to keep T_γ and T_K via Compton scattering.

$$T_\gamma = T_K = T_S \text{ , } T_b = 0$$

• 21cm line signal

- The evolution of the spin temperature in the ΛCDM model at the dark ages



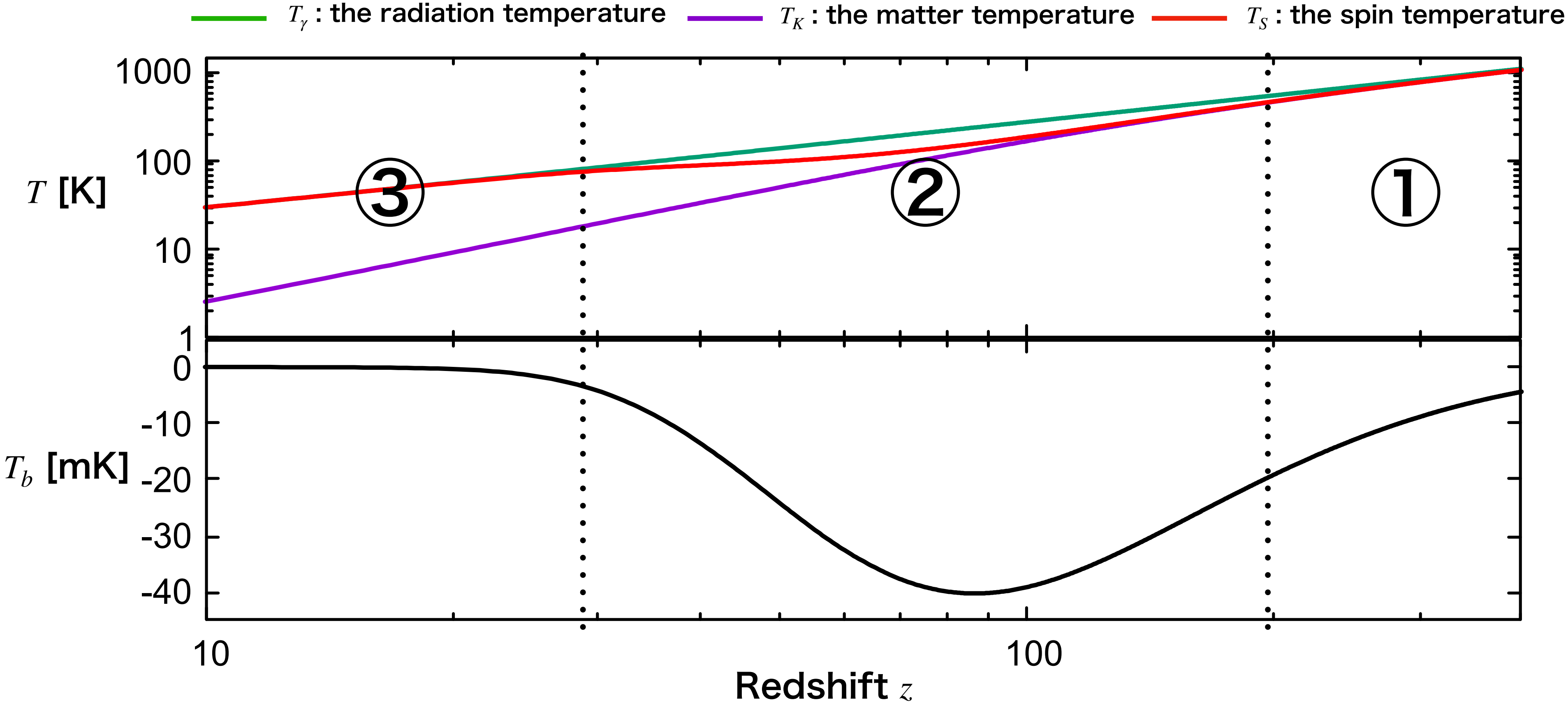
②Compton scattering becomes ineffective. $T_K \propto \frac{1}{(1+z)^2}$.

$T_K = T_S,\ T_\gamma > T_S\ ,\ T_b < 0$

In this time, effects of collisions is larger than transition effects due to CMB photons.

• 21cm line signal

- The evolution of the spin temperature in the ΛCDM model at the dark ages



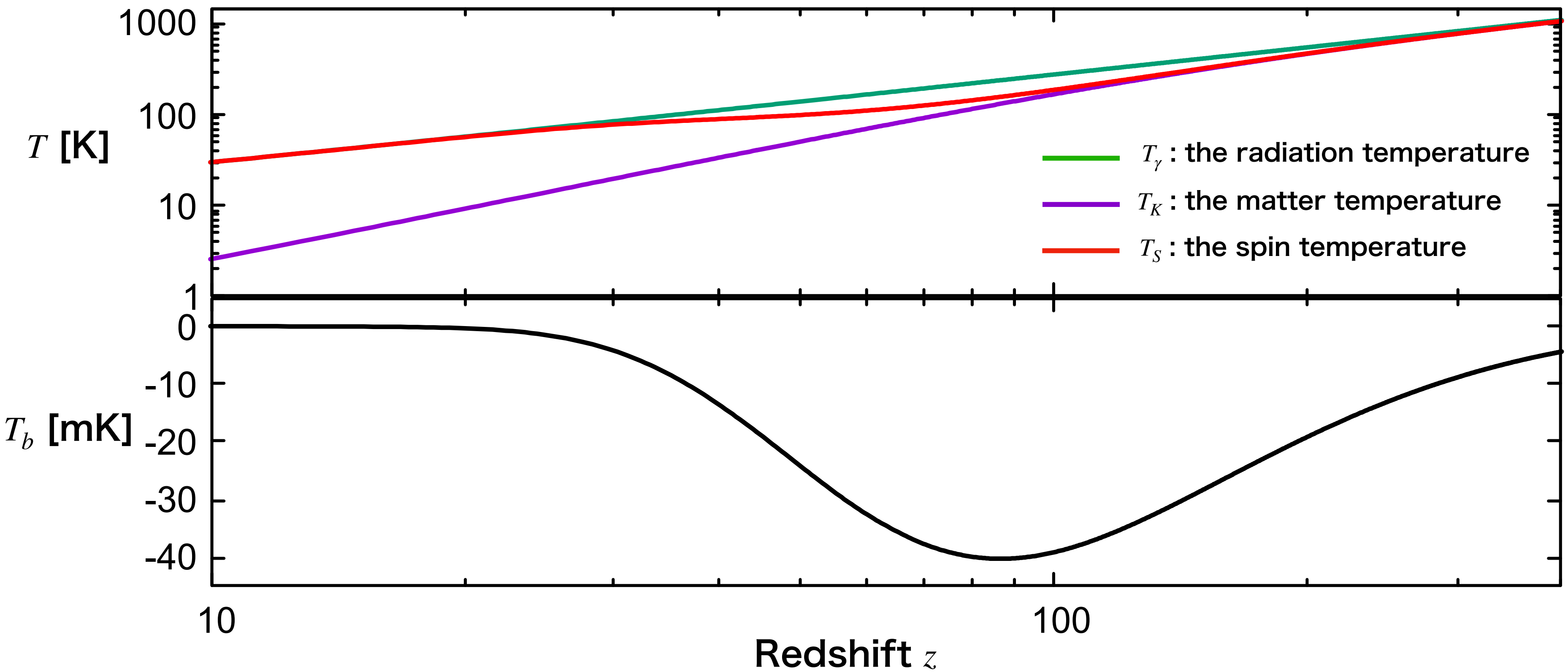
③The collisional coupling between T_K and T_S becomes ineffective.

In this time, transition effects due to CMB photons is larger than effects of collisions.

$$T_\gamma = T_S,\ T_b = 0$$

• 21cm line signal

• The evolution of the spin temperature in the ΛCDM model at the dark ages

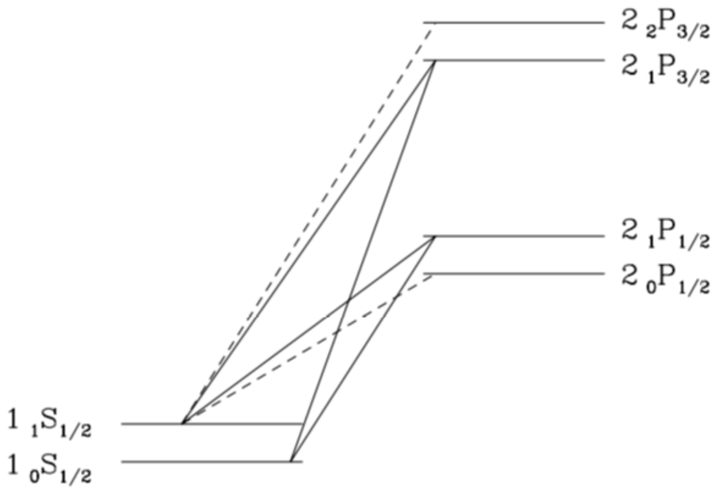


※In the dark age, we can ignore x_α when we consider ΛCDM model.

Cosidering non-standard models, it is possible that x_α cannot be ignored.

• The Wouthuysen-Field effect

Jonathan R. Pritchard and Abraham Loeb,(arXiv:1109.6012)



Hyperfine structure of the hydrogen atom and transitions relevant for the Wouthuysen-Field effect

• Lyman-α photons absorb or emit when transitions between 1s orbital and 2p orbital occur.

$$1_0S_{\frac{1}{2}} \underbrace{\rightarrow}_{\text{Ly}\alpha \text{ absorption}} (2P) \underbrace{\rightarrow}_{\text{Ly}\alpha \text{ emission}} 1_1S_{\frac{1}{2}}$$

• When the above process occurs, it is a spin flip.

➡ These process are the Wouthuysen-Field effect

• For the standard ΛCDM model

$$T_b = \frac{T_s - T_\gamma}{1+z}\left(1 - \exp(-\tau_{21})\right)$$

• $\tau_{21} \ll 1$, we assume the universe is the matter dominant so that obtain as follows:

$$T_b \simeq 85\mathrm{mK}\left(\frac{T_s - T_\gamma}{T_s}\right)\left(\frac{\Omega_b h^2}{0.02237}\right)\left(\frac{0.144}{\Omega_m h^2}\right)^{1/2}\left(\frac{1-Y_p}{1-0.24}\right)\left(\frac{1+z}{100}\right)^{1/2} x_{\mathrm{HI}}$$

$$\Omega_b h^2 + \Omega_c h^2 = \Omega_m h^2$$

• T_s is written as:

$$\frac{T_s - T_\gamma}{T_s} = \frac{x_c}{1+x_c}\left(1 - \frac{T_\gamma}{T_K}\right)$$

which $x_\alpha = 0$

• For the standard ΛCDM model

- Since x_c is mainly determined by HH collision, x_c has the cosmological parameter dependence as follows:

$$x_c \propto \Omega_b h^2 (1 - Y_p)$$

- In addition, $x_c \ll 1$ in $30 \leq z \leq 80$ so that T_b is proportion relation as:

$$T_b \propto \frac{(\omega_b)^2 (1 - Y_p)^2}{(\omega_m)^{1/2}} \qquad \omega_b = \Omega_b h^2,\ \omega_m = \Omega_m h^2$$

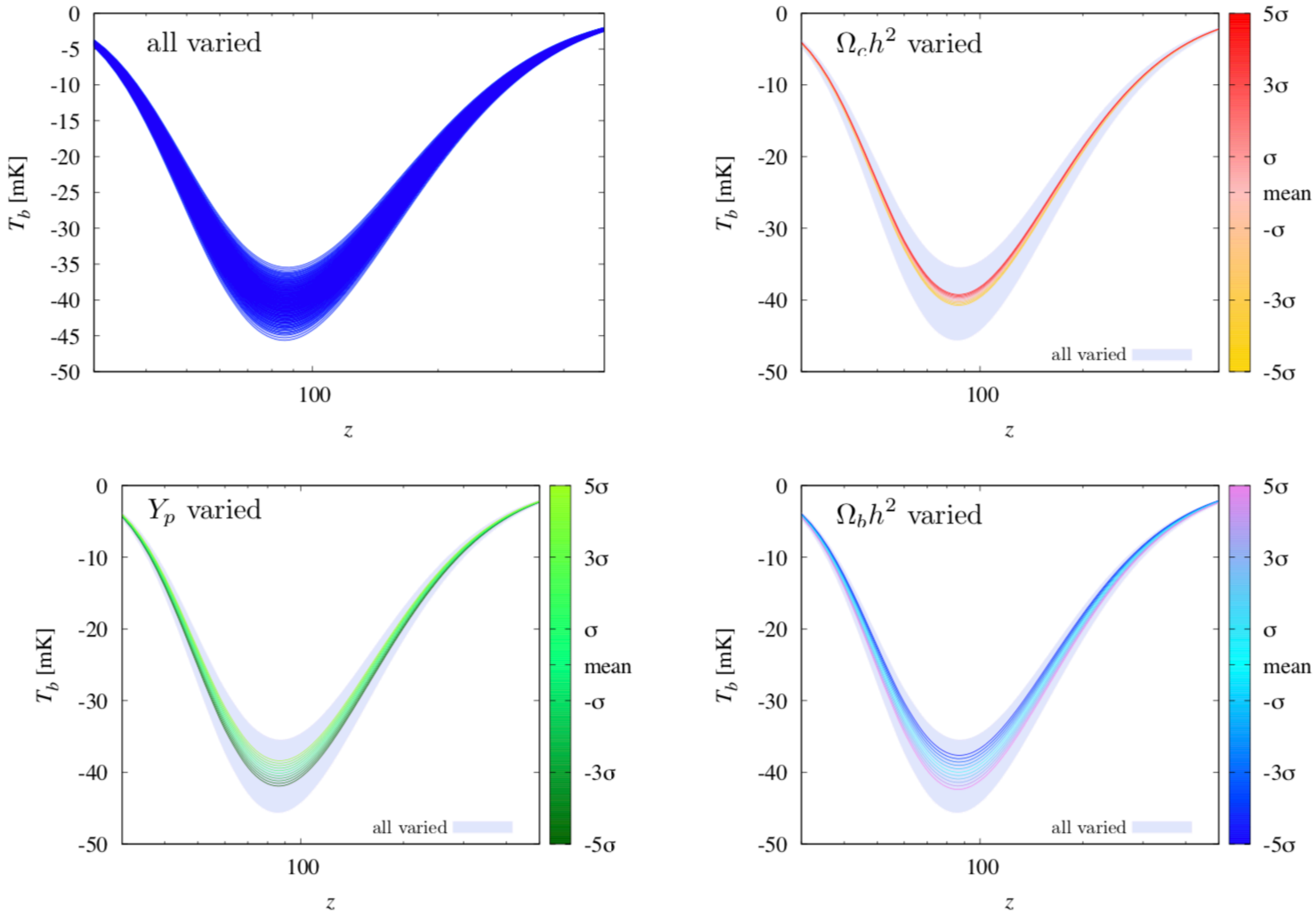
(See also Mondal and Barkana (2305.08593))

- Defining $C(\omega_b, \omega_c, Y_p)$, we obtain the equation rescaling T_b that is derived by different cosmological parameters.

$$T_b^{\mathrm{sc}}\left(\nu; \tilde{\boldsymbol{\theta}}, \boldsymbol{\theta}\right) = T_b\left(\nu; \boldsymbol{\theta}\right) \frac{C(\tilde{\boldsymbol{\theta}})}{C(\boldsymbol{\theta})} \qquad C \equiv \frac{(\omega_b)^2 (1 - Y_p)^2}{(\omega_m)^{1/2}}$$

$\boldsymbol{\theta} = (\omega_b, \omega_m, Y_p)$ $\quad \sim$ represent the reference value($\omega_b = 0.02237,\ \omega_c = 0.12,\ Y_p = 0.2436$)

• For the standard ΛCDM model



• The redshift of the global signal peak is little changed.

$$z_{\rm peak} \sim 86.5$$

$$\nu_{\rm peak} \sim 16.2{\rm MHz}$$

• The amplitude of the global signal peak is affected

In the ΛCDM model,
We derive the cosmological parameter dependence of global signal.

- For the standard ΛCDM model

  - If one or more of the following assumption is violated in the dark ages, there are possible to deviate from the value of the ΛCDM model.

(i)The universe is matter-dominated

(ii) Lyman-α sources are negligible

(iii) Matter and photons are coupled via the Compton scattering

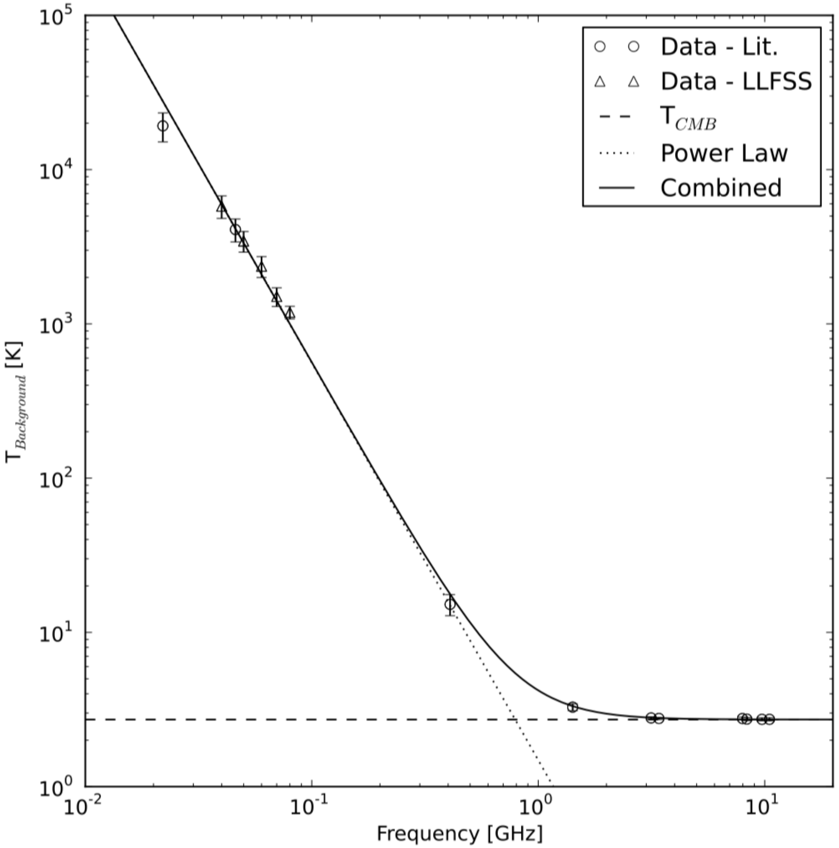
(iv) The radiation field is determined by CMB

$$T_\gamma = T_{\mathrm{CMB},0}(1+z)$$

• For models beyond the standard model

• Excess radio background model

- This model has been proposed by ARCADE2(D. J. Fixsen et al ,(arXiv:0901.0555)) and LWA1 (D. Dowell and G. B. Taylor,(arXiv:1804.08581)) etc…



(D. Dowell and G. B. Taylor,(arXiv:1804.08581))

- The existence of excess radio background has been suggested by Bridle MNRAS, 136, 219 (1967).

- The left-figure shows the modeled background temperature using observed the extragalactic temperature data.

$$T_\gamma = T_{\rm CMB}(1+z)\left[1 + A_R\left(\frac{\nu}{\nu_{\rm ref}}\right)^\beta\right]$$

A_R : the relative size of the extra source to the CMB temperature

$\beta = -2.6,\ \nu_{\rm ref} = 78\ \rm MHz$

- For models beyond the standard model

  - Dark matter decay model

    - Dark matter decay/annihilation may generate photons in the Lyman-α energy range, providing an additional heat source to the gas temperature.

  - In this work, we use a method similar to (M. Valdes et al ,(astro-ph/0701301)) and present results for a DM decay model in which light-dark matter with some mass decays.

    - The rate of the energy transfer due to dark matter decays

$$\dot{E}_\chi(z) = f_{\rm abs}(z)\dot{n}_{\rm DM}(z)m_{\rm DM} \simeq f_{\rm abs}(z)\frac{n_{\rm DM,0}}{\tau_{\rm DM}}m_{\rm DM}$$

$f_{\rm abs}$: the fraction of the DM particle rest mass that is absorbed by the gas at a given redshift z

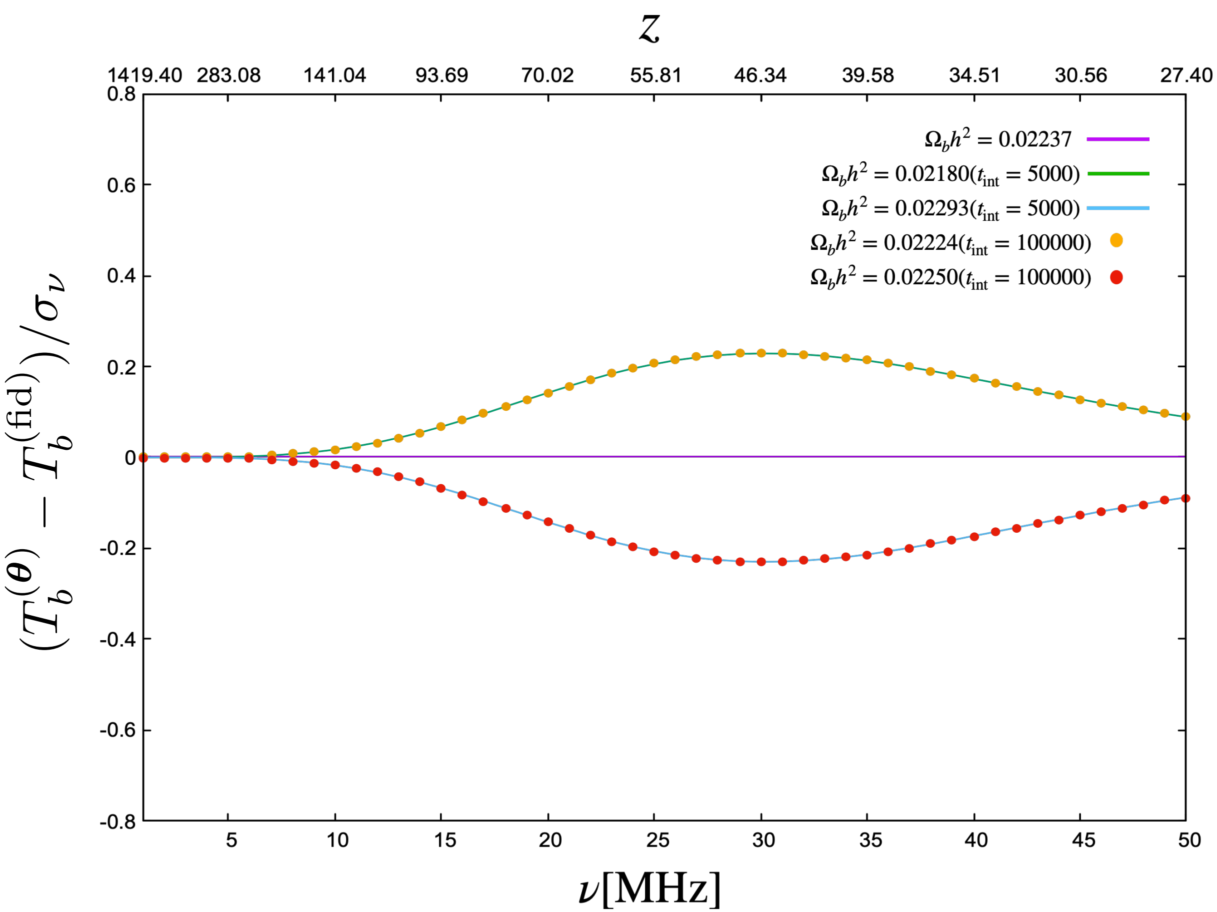
$\dot{n}_{\rm DM}$: the decrease rate of the number of DM particle per baryon,

$n_{\rm DM,0}$: the current number of DM particle per baryon,

$m_{\rm DM}$: the mass of DM particle

$\tau_{\rm DM}$: the lifetime of DM particle

• For the standard ΛCDM model



- Why is the reference frequency 30 MHz?
  - thermal noise

$$\sigma_\nu = \frac{T_{\rm sys}}{\sqrt{\Delta\nu \, t_{\rm int}}}$$

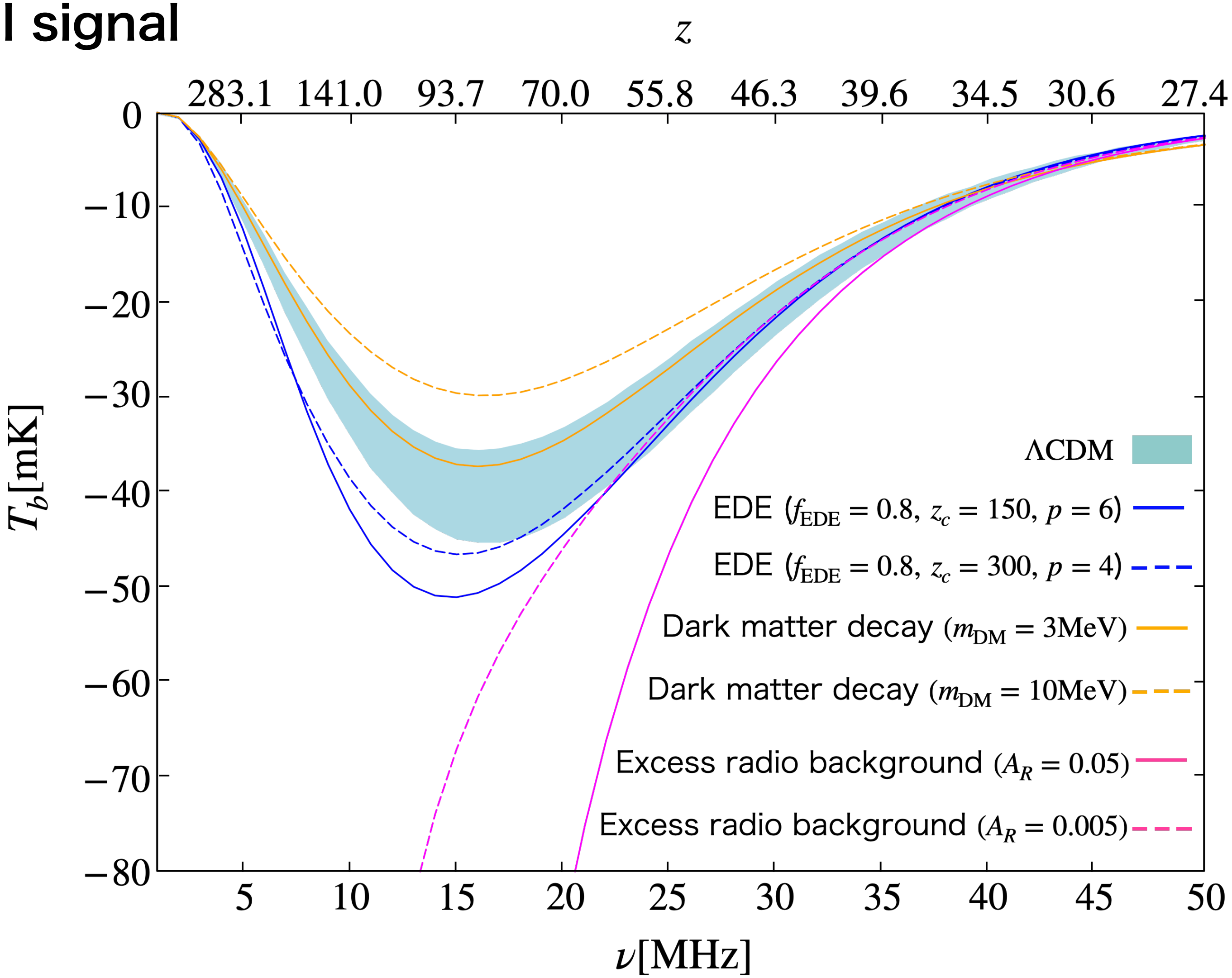
$\Delta\nu = 1{\rm MHz}$ $\quad t_{\rm int} = 5000$ or 100000 **hour**

$T_{\rm sys} \simeq T_{\rm sky} = 180 \times (\nu/180{\rm MHz})^{-2.6}$ **K**

Signal to Noise reaches its maximum at around 30 MHz.

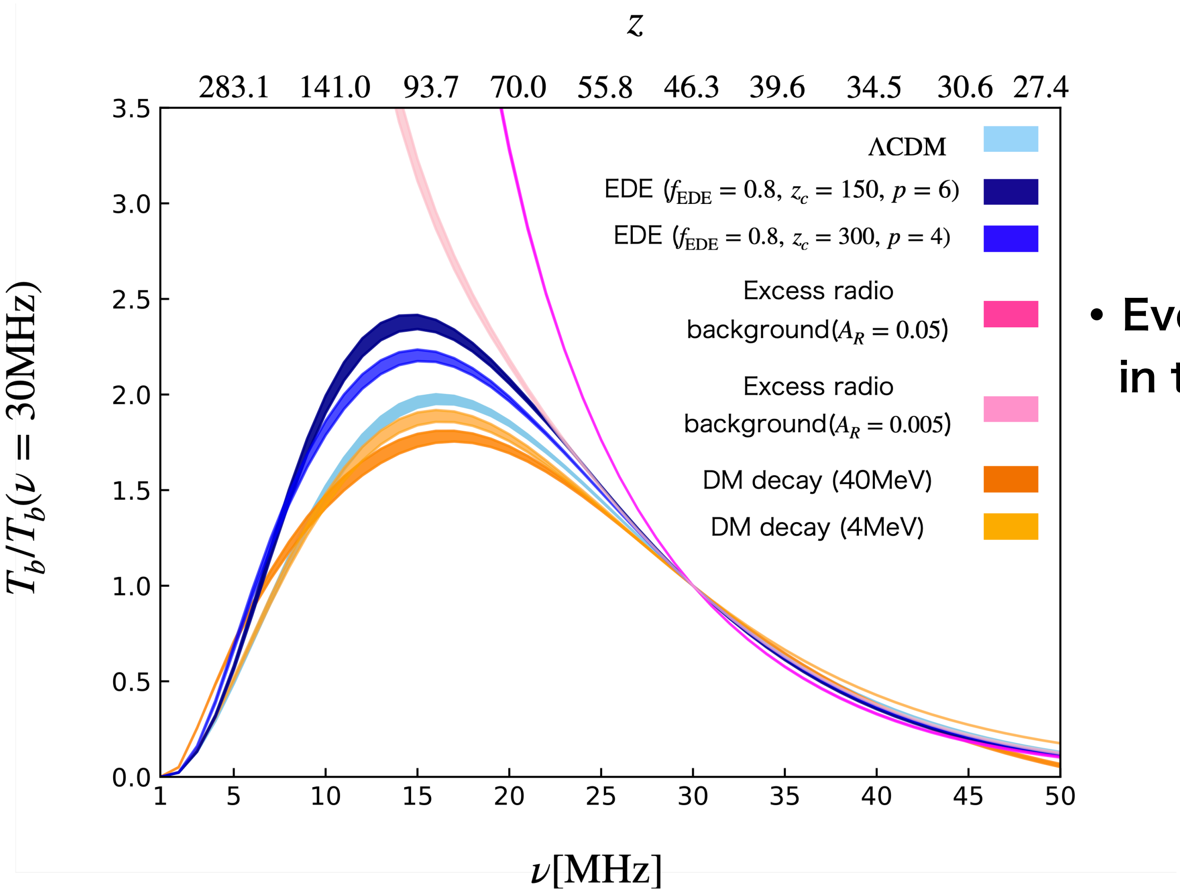
We treat T_b at 30 MHz as the reference frequency.

- For models beyond the standard model
  - 21 cm global signal



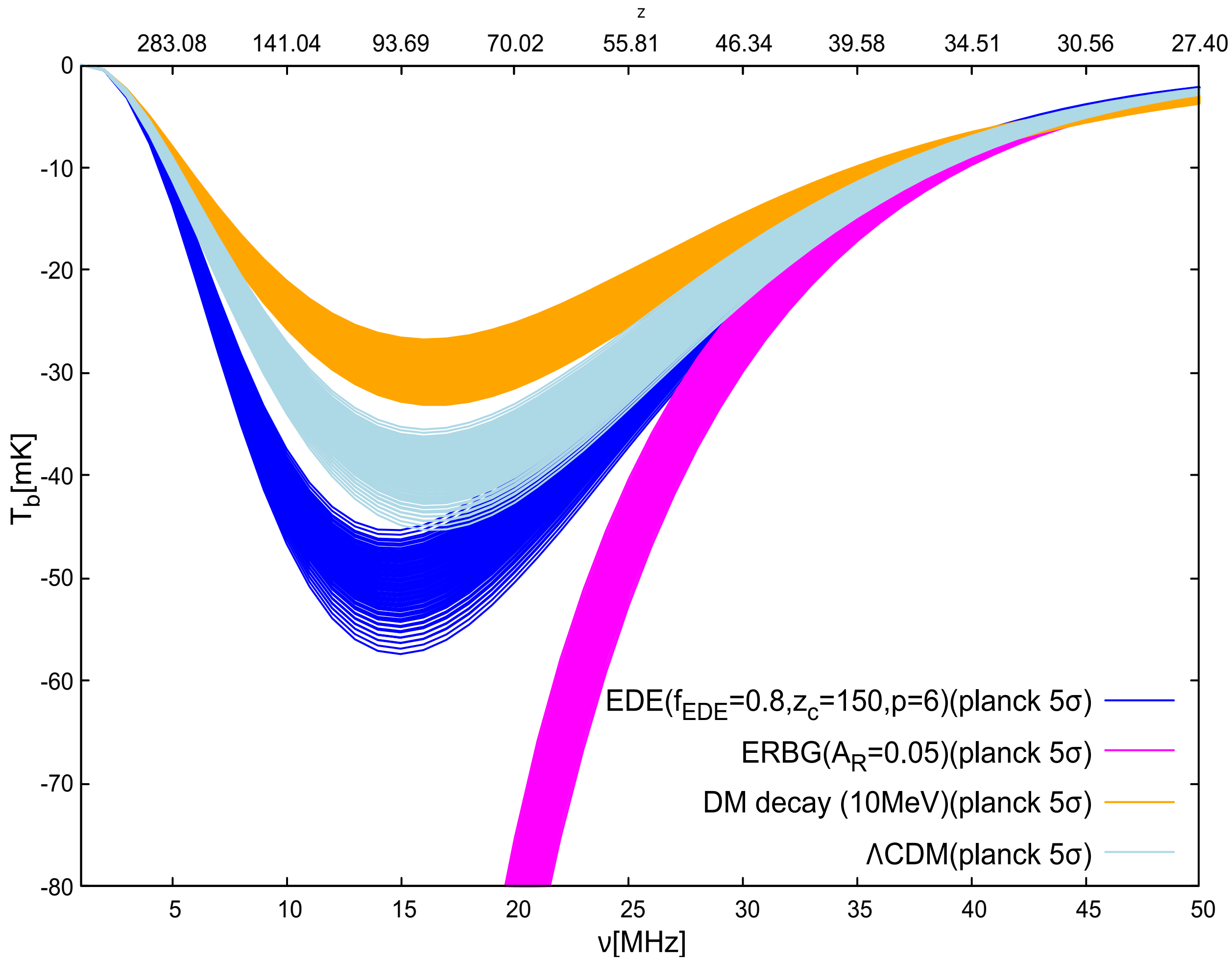
• For models beyond the standard model

- This figure shows the ratio of T_b at each frequency to T_b at 30 MHz for several models with varying cosmological parameters.



- Even in the non-standard models considered in this study, the ratio is determined by about 1%.

• **For non-standard models when cosmological parameters are varied**



• **For non-standard models when cosmological parameters are varied**