Conversion of dark radiation (DR) to photon in early universe and 21cm signal

Takeo Moroi (Tokyo)

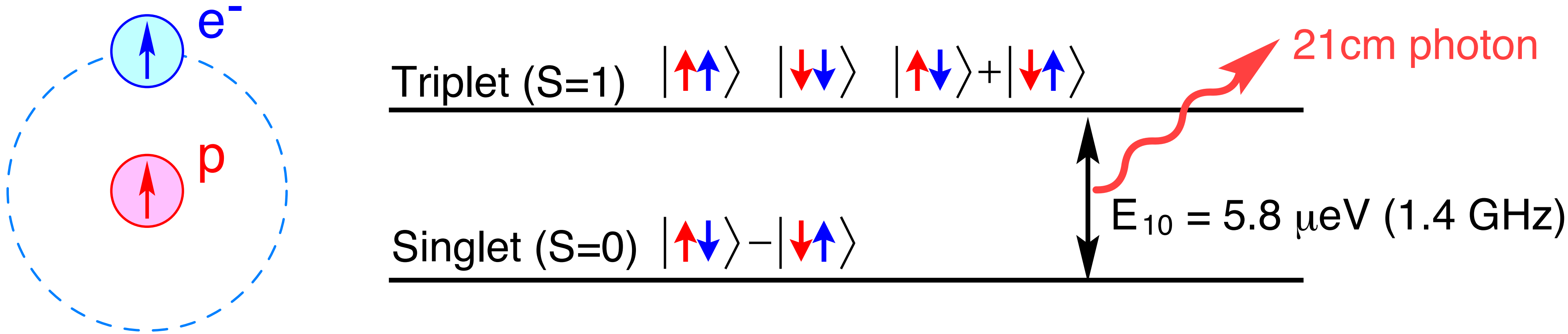
Ref:

TM, Nakayama, Tang, PLB 783 ('18) 301 [1804.10378]

1. Introduction

21cm photon:

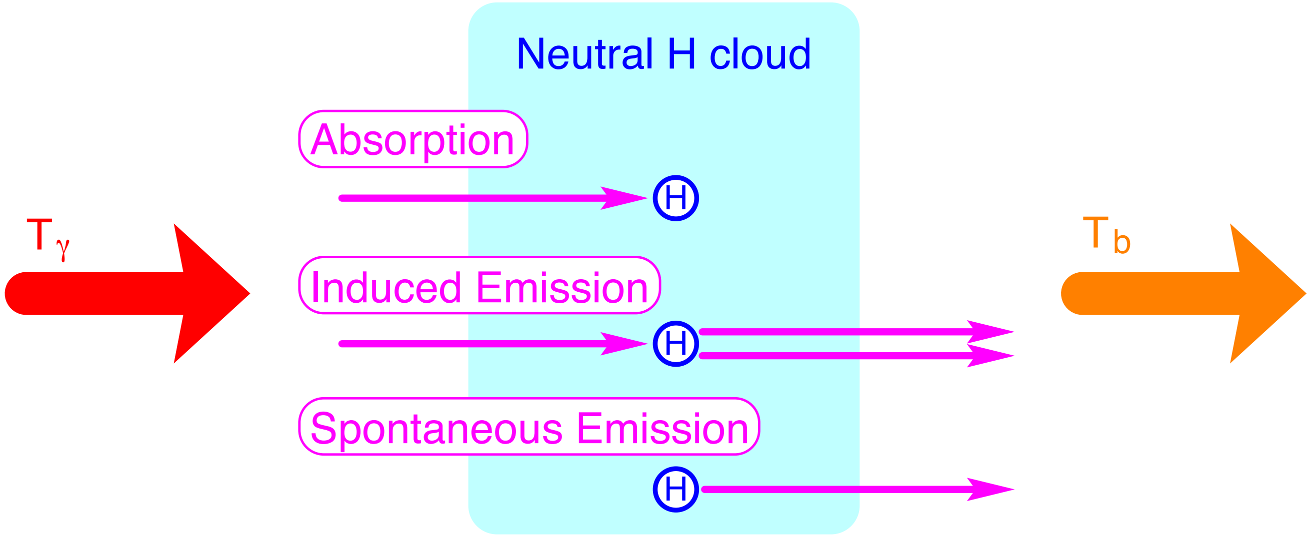
Transition between spin singlet and triplet of 1s hydrogen



Rich information is imprinted in cosmic 21cm spectrum

- EDGES collaboration announced their result
- There are up-coming experiments

21cm photons are absorbed / emitted in the early universe



$$\frac{dn_\gamma^{(\mathrm{RJ})}}{dE} \equiv \frac{1}{\pi^2} E T^{(\mathrm{RJ})}(E)$$

Differential brightness temperature against CMB

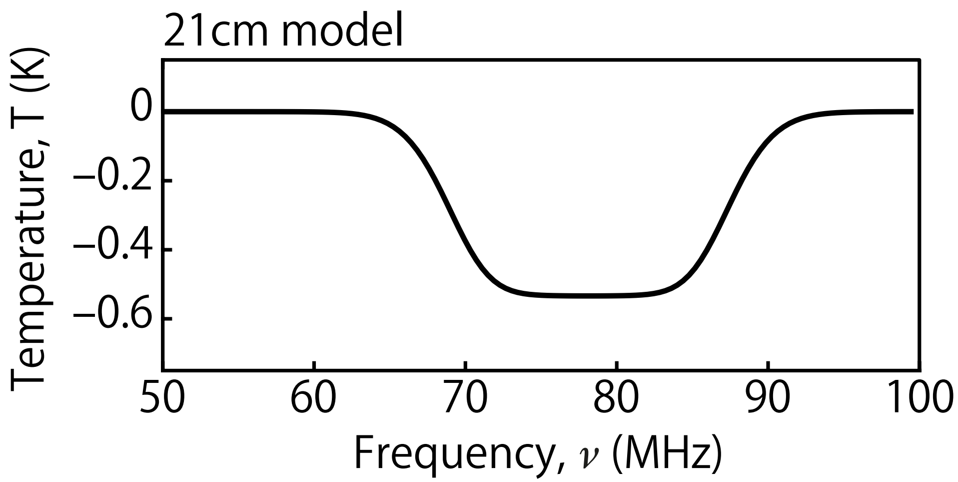
$$\delta T_b(z) = \frac{T_b(z) - T_\gamma(z)}{1+z} \simeq 23\,\mathrm{mK} \times x_{\mathrm{HI}}(z) \left[\frac{1+z}{10}\right]^{1/2} \left[1 - \frac{T_\gamma(z)}{T_S(z)}\right]$$

T_S: spin temperature $\Leftrightarrow$ $\dfrac{n_{S=1}(z)}{n_{S=0}(z)} \equiv 3e^{-E_{10}/T_S(z)}$

EDGES result on δT_b (for $50 \lesssim \nu \lesssim 100$ MHz)

[EDGES Collaboration ('18)]

$\Leftrightarrow$ 21cm hyperfine line produced at $14 \lesssim 1+z \lesssim 28$



- The absorption at $\nu \sim 78$ MHz is consistent with the 21cm signal due to early star formation
- The absorption is factor of ~ 2 larger than the largest prediction

Possible explanations

[EDGES Collaboration ('18)]

- The primordial gas was cooler than expected
- The CMB flux at the Rayleigh-Jeans (RJ) tail was larger than expected

Here, I discuss the possibility to heat up the RJ tail

Outline

1. Introduction
2. DR-Photon Conversion
3. Implications to EDGES Anomaly
4. Summary

2. DR-Photon Conversion

Comment on a naive scenario:

Radiative decay of a scalar field φ to heat up the RJ tail

For example:

$$\mathcal{L}_{\text{int}} = -\frac{1}{4} g_\varphi \varphi F^{\mu\nu} \widetilde{F}_{\mu\nu} \;\Rightarrow\; \Gamma_{\varphi\to\gamma\gamma} = \frac{1}{32\pi} g_\varphi^2 m_\varphi^3$$

To heat up the photons in the EDGES frequency range:

$$E_{\text{now}} \sim m_\varphi (1+z_d)^{-1}$$

z_d = redshift at the decay $\Leftrightarrow H(z_d) \sim \Gamma_\varphi$

Enormously large g_a is required:

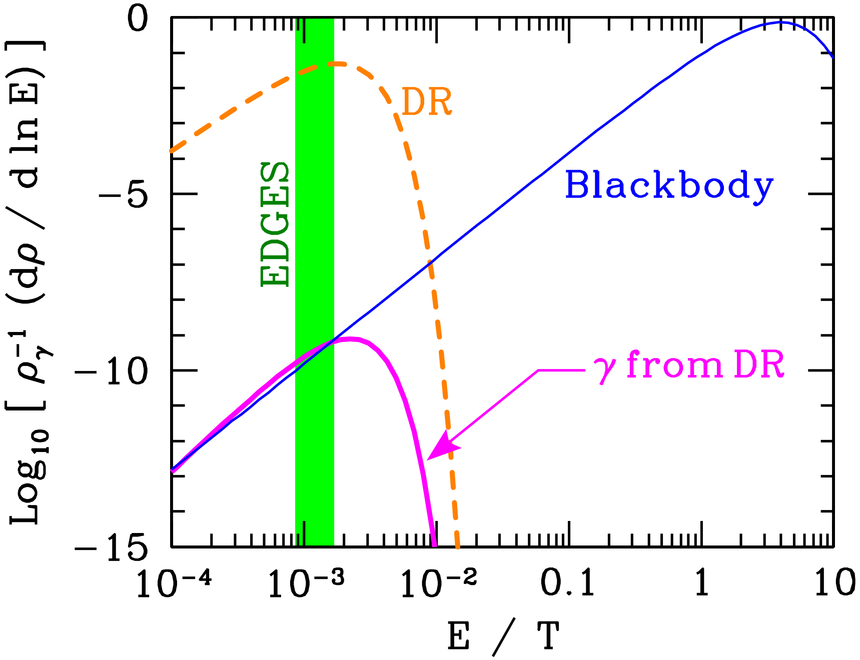
$$g_\varphi^{-1} \sim 10\ \text{GeV} \times \left(\frac{E_{\text{now}}}{\omega_{\text{EDGES}}}\right)^{3/2} \left(\frac{1+z_{\text{d}}}{1000}\right)^{3/4}$$

We consider conversion of DR to photon in early epoch

1. DR production (maybe by the decay of heavier particle)

2. DR is converted to photon (before $z \sim 20$)

$$\frac{dn_\gamma}{dE} = \left[\frac{dn_\gamma}{dE}\right]_{\text{Black Body}} + \frac{dn_{\text{DR}}}{dE} \times (\text{Conversion Probability})$$



The case of dark photon γ'

[Pospelov, Pradler, Ruderman & Urbano ('18)]

$$\mathcal{L}_{\gamma'} = -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu$$

Effective mass matrix (for $k^2 = m_{\gamma'}^2$)

$$\mathcal{M}^2 = \begin{pmatrix} m_{\gamma'}^2 & \epsilon\, m_{\gamma'}^2 \\ \epsilon\, m_{\gamma'}^2 & \omega_p^2 \end{pmatrix}$$

ω_p: Plasma frequency

$$\omega_p(z) = \sqrt{\frac{4\pi\alpha n_e(z)}{m_e}} \simeq 1.9 \times 10^{-14}\ \text{eV} \times (1+z)^{3/2} X_e^{1/2}$$

X_e: Ionization fraction

The case of axion-like particle (ALP)

[TM, Nakayama & Tang ('18)]

$$\mathcal{L}_{\mathsf{int}} = -\frac{1}{4} g_a a F^{\mu\nu} \widetilde{F}_{\mu\nu} \to g_a \epsilon_{ijk} k_i B_j A_k a$$

g_a: ALP-photon coupling constant

$g_a \lesssim 6.6 \times 10^{-11}$ GeV^{-1} (CAST / HB stars)

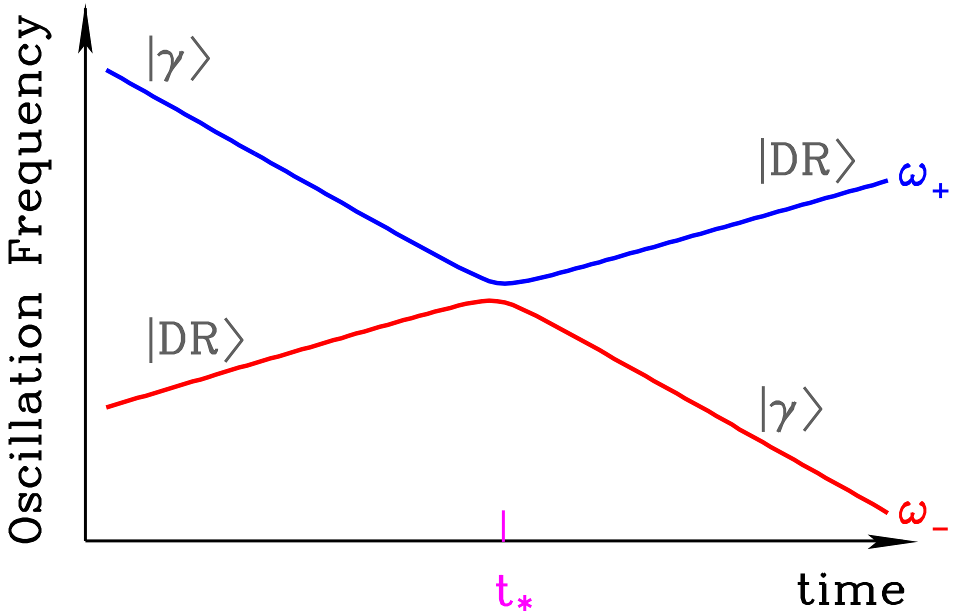
Effective mass matrix with magnetic field:

$$\mathcal{M}^2 = \begin{pmatrix} m_a^2 & E g_a B_\perp \\ E g_a B_\perp & \omega_p^2 \end{pmatrix}$$

E: energy of photon (or ALP)

Equation for DR $\leftrightarrow \gamma$ oscillation

$$i\frac{d}{dt}\begin{pmatrix}|\mathrm{DR}\rangle \\ |\gamma\rangle\end{pmatrix} = \frac{1}{2E}\begin{pmatrix} m_{\mathrm{DR}}^2 & \Delta_{\mathrm{DR}} \\ \Delta_{\mathrm{DR}} & \omega_p^2 \end{pmatrix}\begin{pmatrix}|\mathrm{DR}\rangle \\ |\gamma\rangle\end{pmatrix} \quad \text{with} \quad \begin{cases}\Delta_{\gamma'} = \epsilon m_{\gamma'}^2 \\ \Delta_a = E g_a B_\perp\end{cases}$$



In the case of our interest, adiabaticity does not hold

$\Rightarrow P_{\mathrm{DR}\leftrightarrow\gamma} \ll 1$

We expand ω_p^2 around $\omega_p^2 \simeq m_{\mathsf{DR}}^2$ as:

$$\omega_p^2 \simeq m_{\mathsf{DR}}^2 \left[1 + r^{-1}(t - t_*) + \cdots\right]$$

$$r^{-1} \equiv \frac{d \ln \omega_p^2}{dt} \text{ and } \omega_p^2(t_*) = m_{\mathsf{DR}}^2$$

Approximated oscillation equation:

$$i\frac{d}{dt}\begin{pmatrix} |\mathsf{DR}\rangle \\ |\gamma\rangle \end{pmatrix} \simeq \frac{1}{2E}\begin{pmatrix} m_{\mathsf{DR}}^2 & \Delta_{\mathsf{DR}} \\ \Delta_{\mathsf{DR}} & m_{\mathsf{DR}}^2\left[1 + r^{-1}(t - t_*)\right] \end{pmatrix}\begin{pmatrix} |\mathsf{DR}\rangle \\ |\gamma\rangle \end{pmatrix}$$

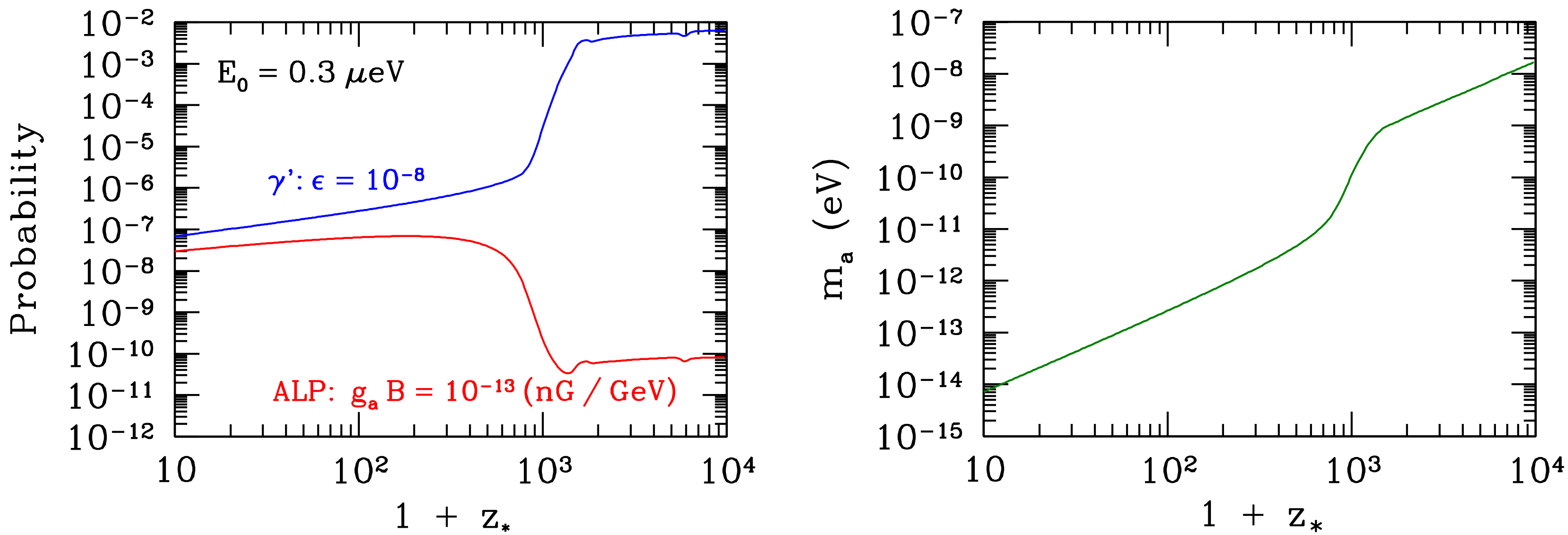
Treating the off-diagonal element as perturbation:

[Parke ('86); Mirizzi, Redondo & Sigl ('09)]

$$P_{\mathsf{DR}\leftrightarrow\gamma}(E) \simeq \frac{\pi \Delta_{\mathsf{DR}}^2}{m_{\mathsf{DR}}^2 E}\left(\frac{d \ln \omega_p^2}{dt}\right)^{-1}\Bigg|_{t=t_*}$$

Conversion probability (for $E_{\text{now}} = 0.3\ \mu\text{eV}$) and DR mass

$\Leftrightarrow$ Our formula of the conversion is valid when $P_{\text{DR}\leftrightarrow\gamma} \ll 1$



- $1 + z_* \gtrsim 20$
- $1 + z_* \lesssim 1700$ in order not to thermalize the converted γ

  [Chluba ('15)]

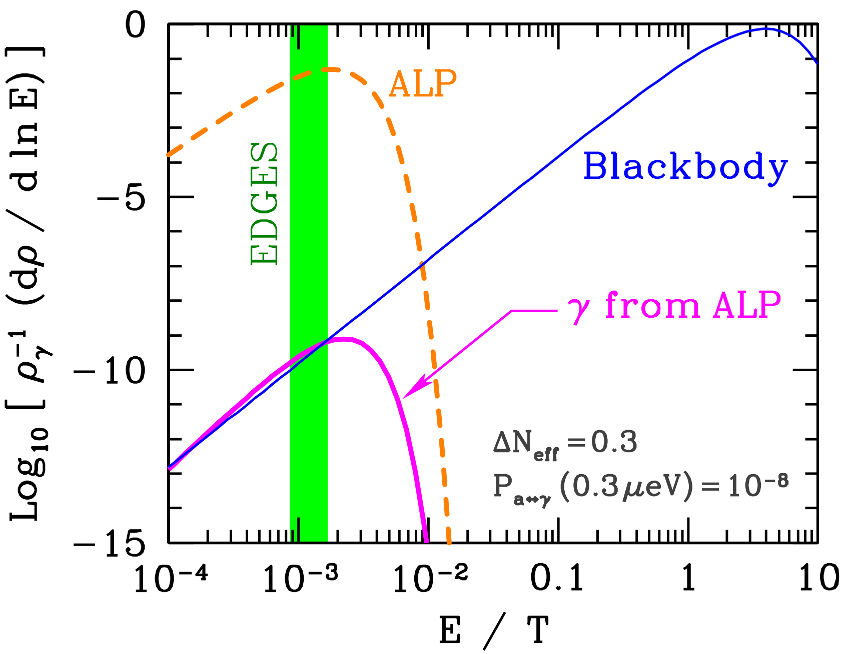
  $\Rightarrow 10^{-14}$ eV $\lesssim m_{\text{DR}} \lesssim 10^{-9}$ eV

3. ALP to photon conversion for EDGES anomaly

For $m_a \sim \omega^{(\mathrm{EDGES})}(1+z_{\mathrm{d}})$

$$\frac{\Delta\rho_\gamma^{(\mathrm{DR})}}{\Delta\rho_\gamma^{(\mathrm{Black\,Body})}} \simeq 1 \times \left(\frac{P_{a\leftrightarrow\gamma}(\omega^{(\mathrm{EDGES})})}{10^{-8}}\right)\left(\frac{\Delta N_{\mathrm{eff}}^{(\mathrm{DR})}}{0.3}\right)$$

$$\Delta\rho_\gamma = \int_{E_\gamma\sim\omega^{(\mathrm{EDGES})}} dE_\gamma \frac{d\rho_\gamma}{dE_\gamma}$$



- $\Delta N_{\mathrm{eff}}^{(\mathrm{ALP})} = 0.3$
- $P_{a\leftrightarrow\gamma}(0.3\,\mu\mathrm{eV}) = 10^{-8}$

$P_{\mathsf{DR}\leftrightarrow\gamma}$ depends on energy of photon

- Dark photon: $P_{\gamma'\leftrightarrow\gamma} \propto E^{-1}$ (because $\Delta_{\gamma'}$ is constant)
- ALP: $P_{a\leftrightarrow\gamma} \propto E$ (because $\Delta_{\mathsf{ALP}} \propto E$)

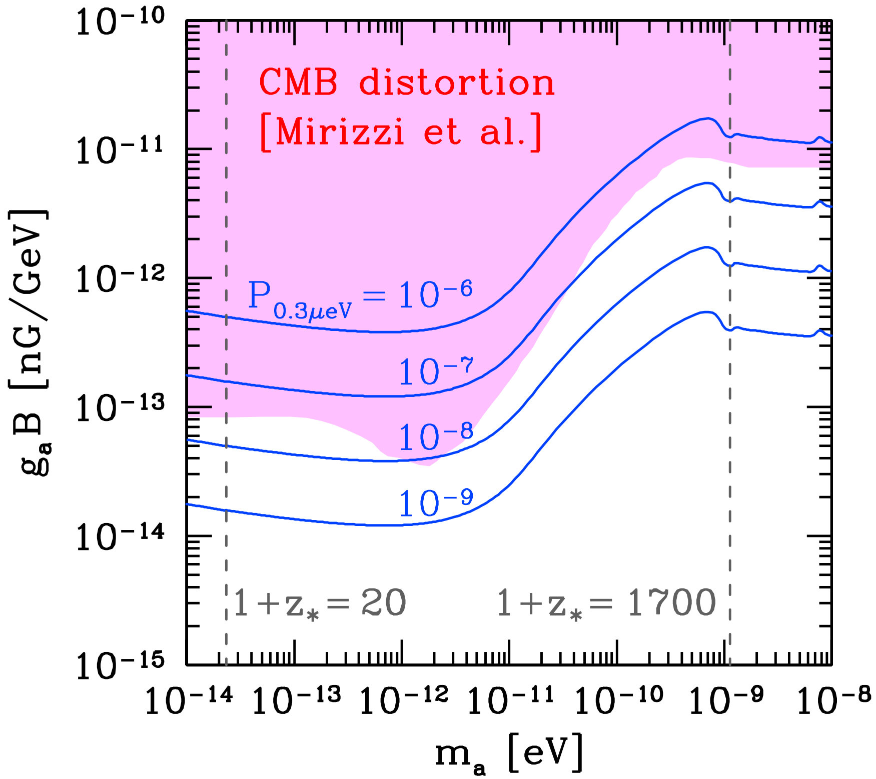
ALP scenario is severely constrained by CMB distortion

[Mirizzi, Redondo & Sigl ('09)]

- $P_{a\leftrightarrow\gamma} \propto E \;\;\Rightarrow\;\; P_{a\leftrightarrow\gamma}(E^{(\mathsf{3K})}) \sim 10^3 P_{a\leftrightarrow\gamma}(E^{(\mathsf{EDGES})})$
- $P_{a\leftrightarrow\gamma}(E^{(\mathsf{EDGES})}) \lesssim 10^{-6} - 10^{-8}$
- For the case with γ', the constraint is much weaker

To enhance the photon flux by the factor of ~ 2:

$\Rightarrow P_{a\leftrightarrow\gamma}(E^{(\mathrm{EDGES})}) \gtrsim 10^{-8}$, if $\Delta N_{\mathrm{eff}} \lesssim 0.3$



The constraint from the CMB distortion may be improved

PIXIE, PRISM

Primordial magnetic field?

- Origin is an open question

  $\Leftrightarrow B_0 \gtrsim 10^{-3}\,$nG is suggested (or $10^{-4}\,$nG, if $\Delta N_{\rm eff} \gg 0.3$)

- Here, I assume it was somehow generated

Primordial magnetic field may heat up the gas if $B_0 \sim$ sub nG

[Sethi & Subramanian; Schleicher et al.]

- Ambipolar diffusion

- Decay of turbulence

  $\Rightarrow$ In order not heat up the gas so much, $B_0 \ll$ sub nG

4. Summary

I discussed a scenario to explain the EDGES anomaly

- Heating up the RJ tail by converting DR to photon

Candidates of the DR:

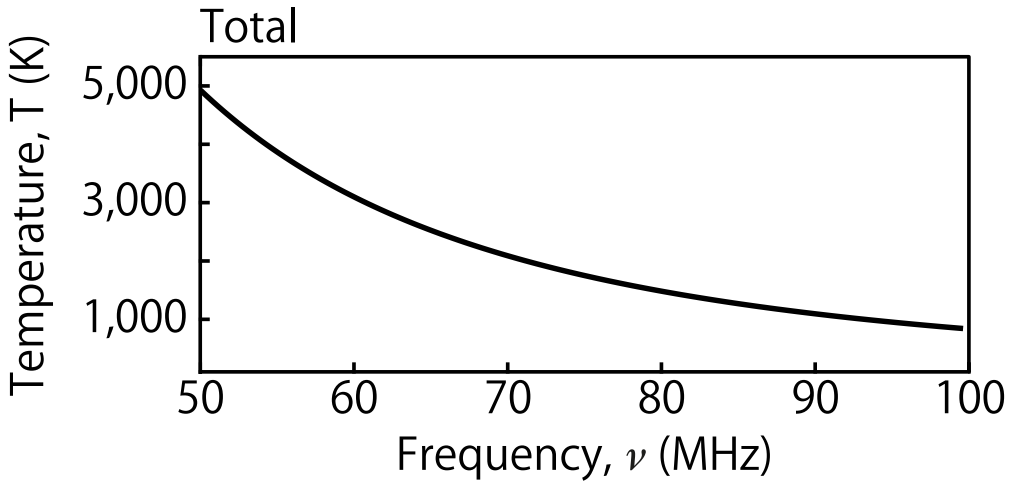
- Dark photon
- ALP

The scenario may be tested by

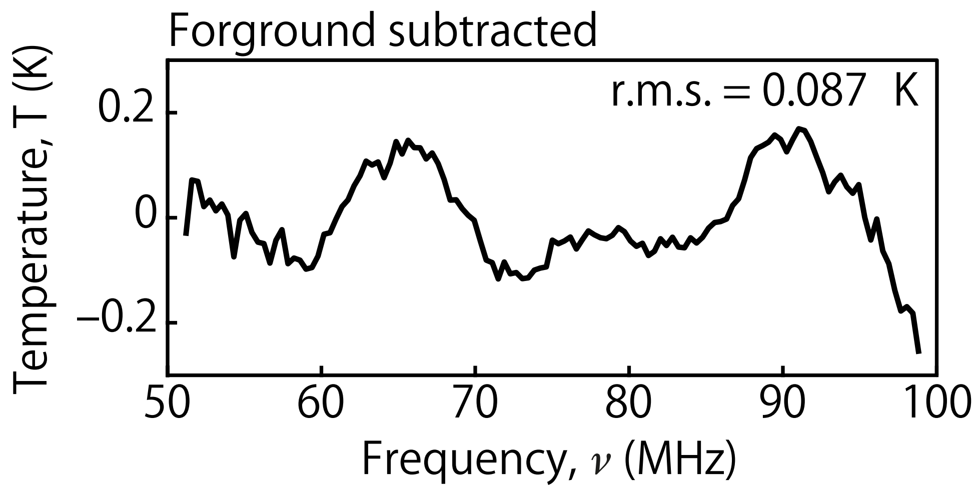
- CMB spectral distortion (PIXIE, PRISM)
- ΔN_{eff}
- For the case of ALP, future axion helioscope (IAXO)

Backup

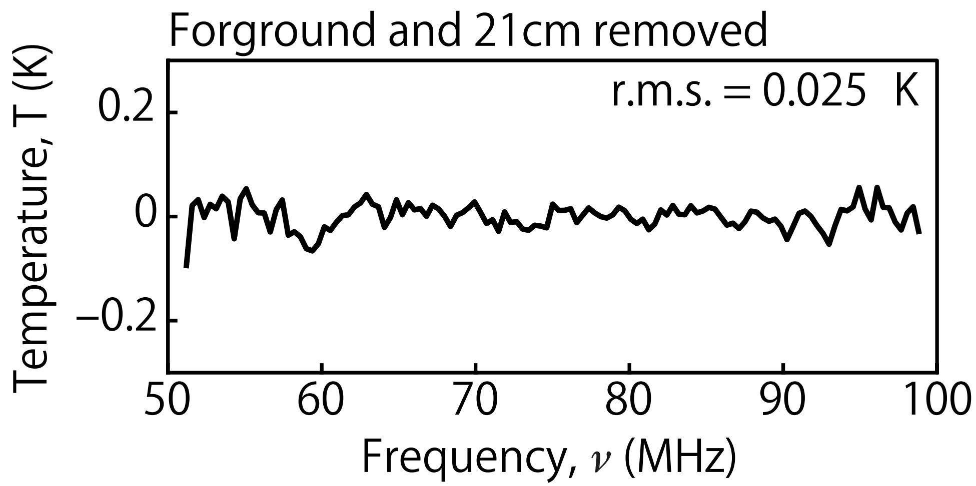
Spectrum observed by EDGES experiment



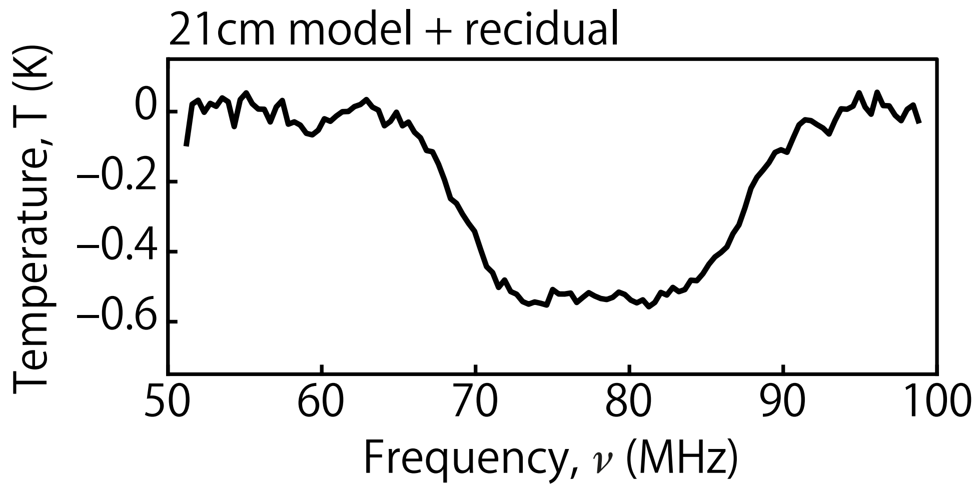
Spectrum after removing the foreground



Spectrum (after removing the foreground and 21cm models)

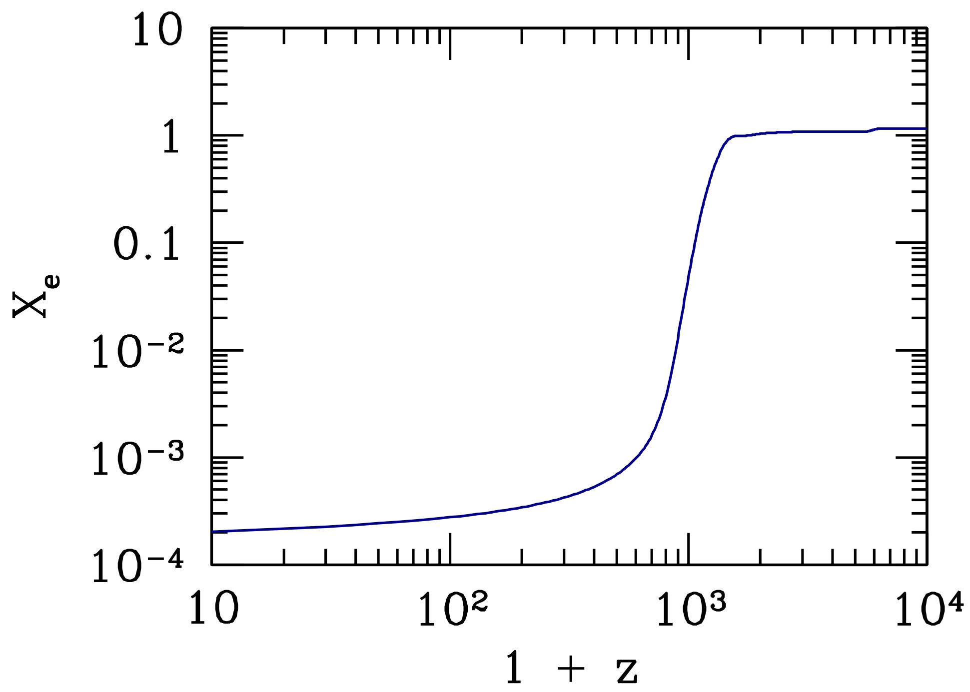


Above + 21cm model



Free electron in the early universe:

Ionization fraction X_e

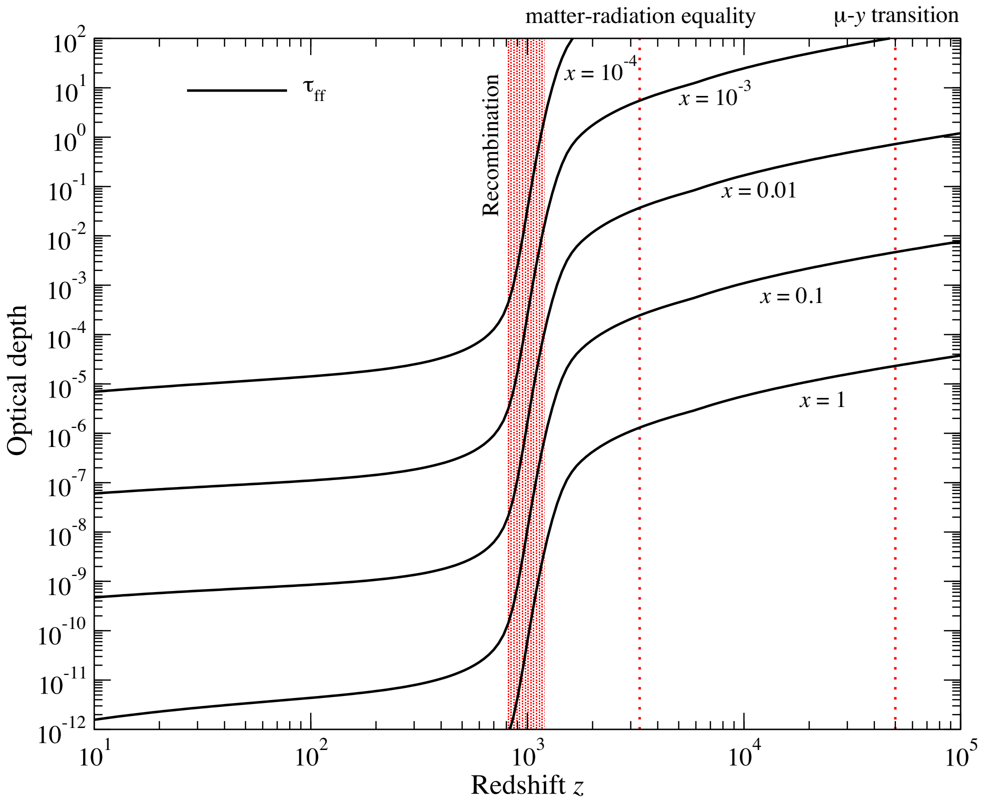


Plasma frequency

$$\omega_p(z) = \sqrt{\frac{4\pi\alpha n_e(z)}{m_e}} \simeq 1.9 \times 10^{-14}\ \text{eV} \times (1+z)^{3/2} X_e^{1/2}$$

Photons in the RJ tail should not be thermalized

$\Leftrightarrow$ Optical depth of the photon in the early universe



$$x = \frac{E_\gamma}{T}\Big|_i$$

[Chluba ('15)]

$\Rightarrow$ For $x \sim 10^{-3}$, $z \lesssim 1700$ is needed to realize $\tau \lesssim 1$

$\Rightarrow$ $m_{\rm DR} \lesssim 10^{-9}$ eV

Oscillation length

$$\ell_{\mathsf{osc}} \sim \frac{\sqrt{Er}}{m_a} \sim 10^{28}\,\mathsf{eV}^{-1}\left(\frac{10^{-14}\,\mathsf{eV}}{m_a}\right)^{-1}\left(\frac{E_0}{1\,\mu\mathsf{eV}}\right)^{1/2}(1+z_*)^{-1/4}$$

Coherent length of the magnetic field

[Durrer & Neronov ('13)]

$$\ell_B \sim 1\,\mathsf{Mpc}\,(1+z)^{-1} \sim 10^{29}\,\mathsf{eV}^{-1}(1+z)^{-1}$$

Mean free path of the photon

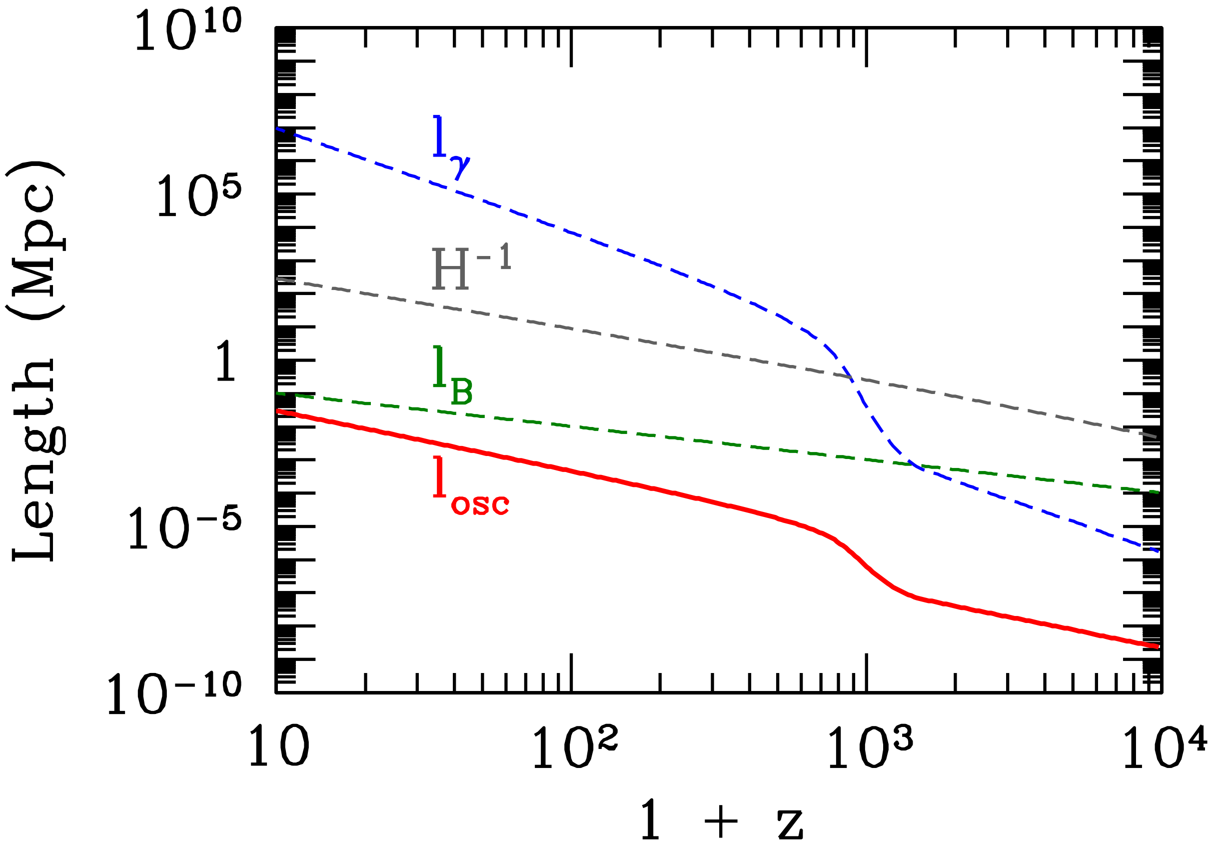
$$\ell_\gamma \sim (\sigma_{\mathsf{T}} n_e)^{-1} \sim 10^{35}\,\mathsf{eV}^{-1}(1+z)^{-3}X_e^{-1}$$

Oscillation length for adiabatic conversion

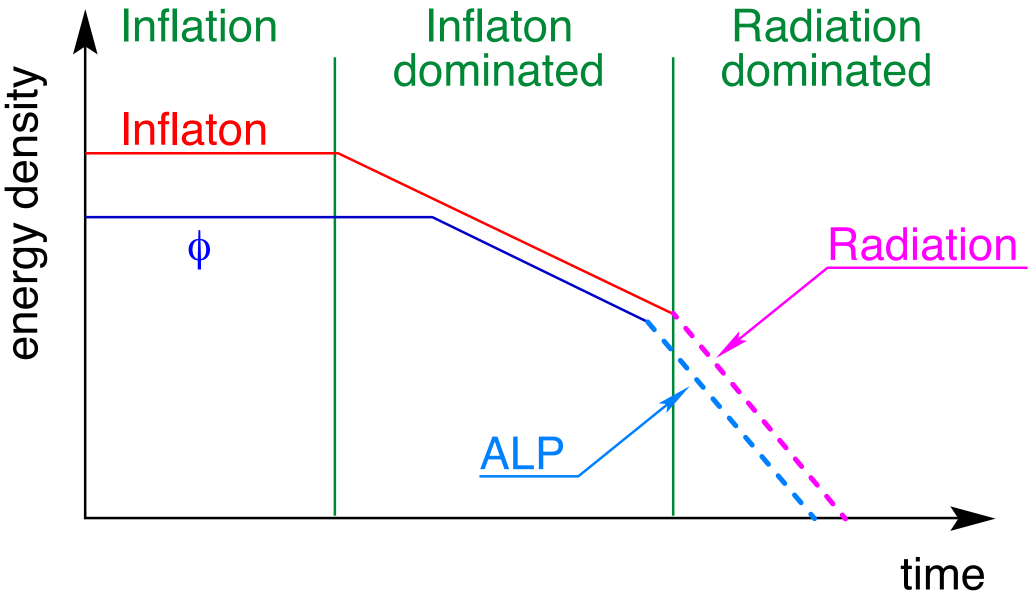
$$\ell_{\mathsf{adi}} \sim (g_a B_\perp)^{-1} \quad \Leftrightarrow \quad P_{a\leftrightarrow\gamma} \sim \frac{\ell_{\mathsf{osc}}^2}{\ell_{\mathsf{adi}}^2}$$

For the validity of our calculation, we need

- $\ell_{\text{osc}} \ll \ell_\gamma$ ($\ell_\gamma =$ mean free path of photon)
- $\ell_{\text{osc}} \ll \ell_B$ ($\ell_B =$ coherent length of magnetic field)



Production of ALP (via the decay of a scalar field ϕ)



We may consider a scenario in which

- a: NG boson in supersymmetric model
- ϕ: Real part of the complex scalar field containing a

  f: breaking scale of the $U(1)$ symmetry

For the case of where ϕ decays before the inflaton decay

$$H(T_{\mathsf{R}}) \lesssim \Gamma_{\phi\to 2a} \sim \frac{1}{64\pi}\frac{m_\phi^3}{f^2}$$

Relation between m_ϕ and the present energy of ALP

$$m_\phi \sim 4\times 10^3\,\mathsf{GeV} \times \left(\frac{f}{10^8\,\mathsf{GeV}}\right)^2 \left(\frac{1\,\mu\mathsf{eV}}{E_{\mathsf{now}}}\right)^2$$

Energy density of ALP (DR)

$$\Delta N_{\mathsf{eff}}^{(\mathsf{ALP})} \sim 0.1 \times \left(\frac{T_{\mathsf{R}}}{10^3\,\mathsf{GeV}}\right)^{4/3} \left(\frac{f}{10^8\,\mathsf{GeV}}\right)^{4/3} \left(\frac{m_\phi}{10^3\,\mathsf{GeV}}\right)^{-2} \left(\frac{\phi_i}{M_{\mathsf{Pl}}}\right)^2$$

One choice to realize $N_{\mathsf{eff}}^{(\mathsf{ALP})} \sim 0.1$:

$$m_\phi \sim 10^3\,\mathsf{GeV},\ f \sim 10^8\,\mathsf{GeV},\ \phi_i \sim M_{\mathsf{Pl}},\ T_{\mathsf{R}} \sim 10^3\,\mathsf{GeV}$$