Axion-Photon Conversion and Effects on 21cm Line

Yong Tang

中国科学院大学
University of Chinese Academy of Sciences

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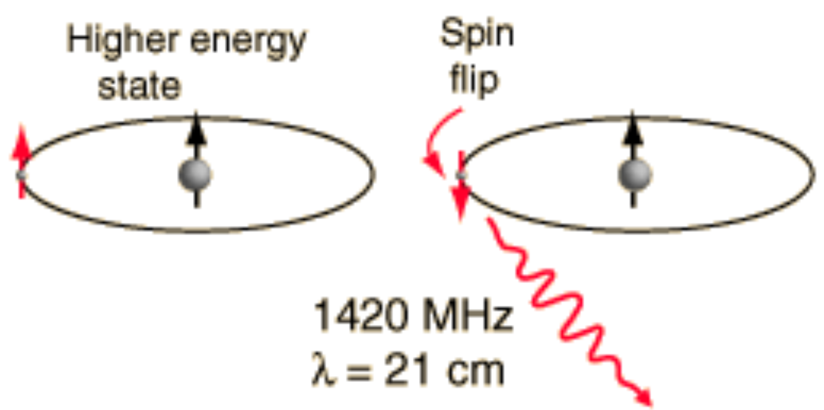
Takeo Moroi, Kazunori Nakayama & *YT,* **1804.10379**
Phys.Lett. B 783 (2018) 301

Outline

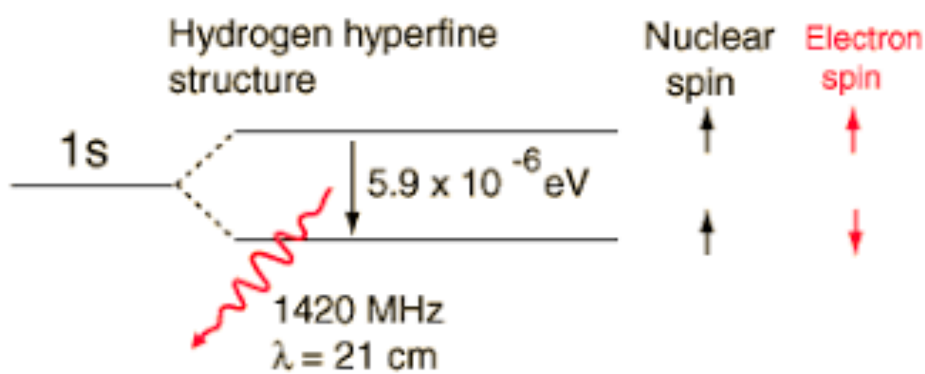
- 21cm Line
  - Physical picture
  - EDGES excess
- Axion-Photon Conversion
  - Formalism
  - Application to EDGES
- Summary

21cm Line

- 21cm line or H I line is emitted when a triplet neutral hydrogen atom changes to the singlet.



- frequency ~ 1420MHz
  wavelength ~ 21cm



- photon's energy
  $\Delta E = 5.9 * 10^{-6}$ eV
  $T_* = 0.068K$

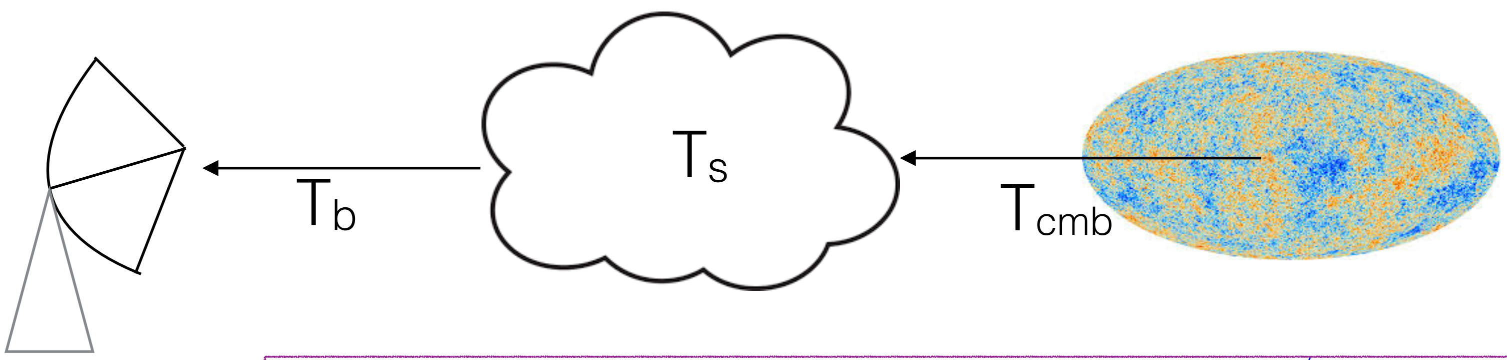
21cm Cosmology

- The number ratio for hydrogens in the excited and ground states is

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left[-\frac{\Delta E}{k_B T_s}\right] = 3 \exp\left[-\frac{T_*}{T_s}\right]$$

- T_s is the defined effective spin temperature, and T_* =0.068K is the equivalent temperature for the energy difference

- absorption or emission



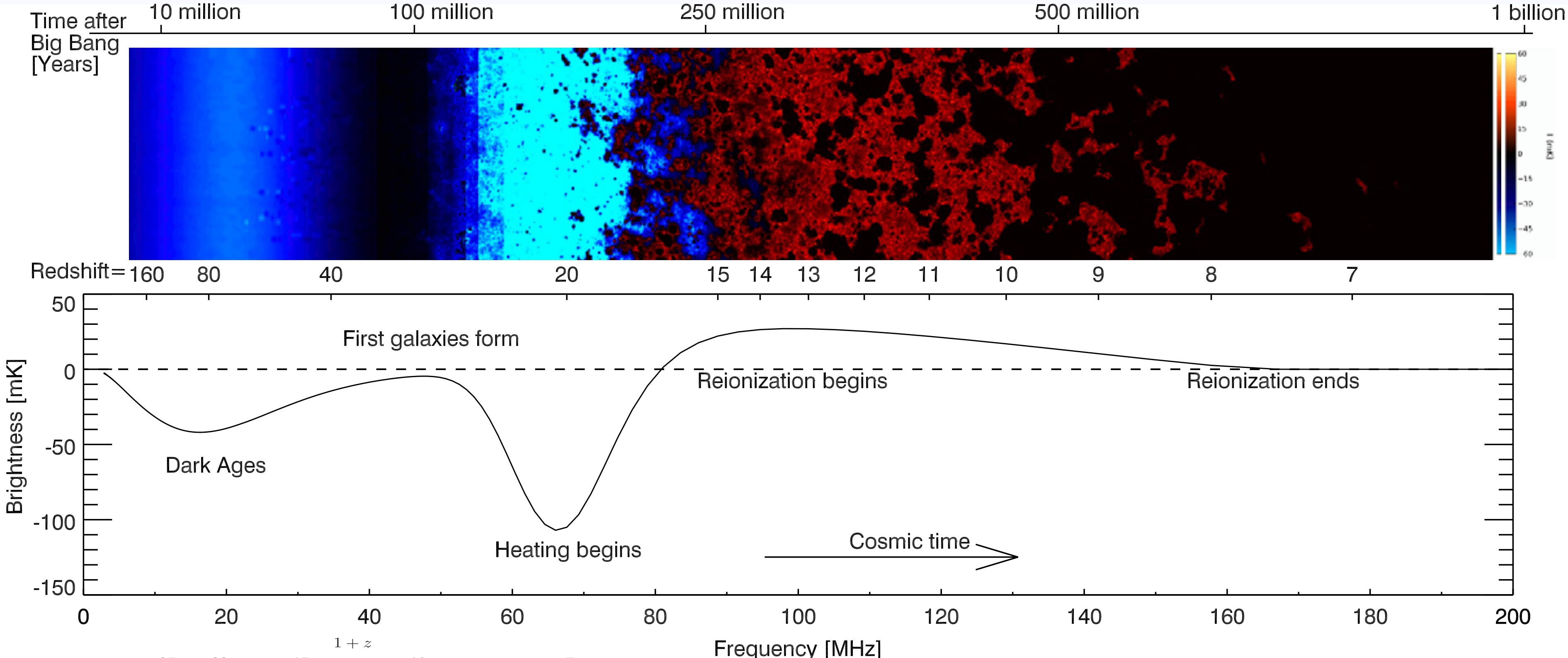
- $\delta T_b = T_b - T_{\rm cmb}$

$$T_{21}(z) \equiv \delta T_b \simeq 23\,{\rm mK} \times x_{\rm HI}(z) \left(\frac{\Omega_{\rm b} h^2}{0.02}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_{\rm m} h^2}\right)^{1/2} \left(1 - \frac{T_\gamma(z)}{T_{\rm S}(z)}\right),$$

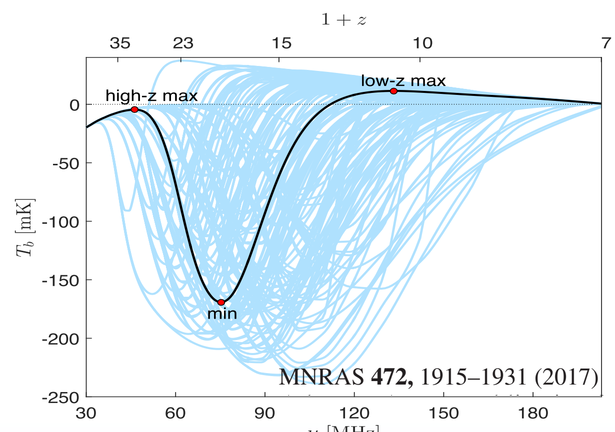
$x_{\rm HI}$: neutral fraction of the hydrogen atom

Furlanetto+,2006

21cm Cosmology



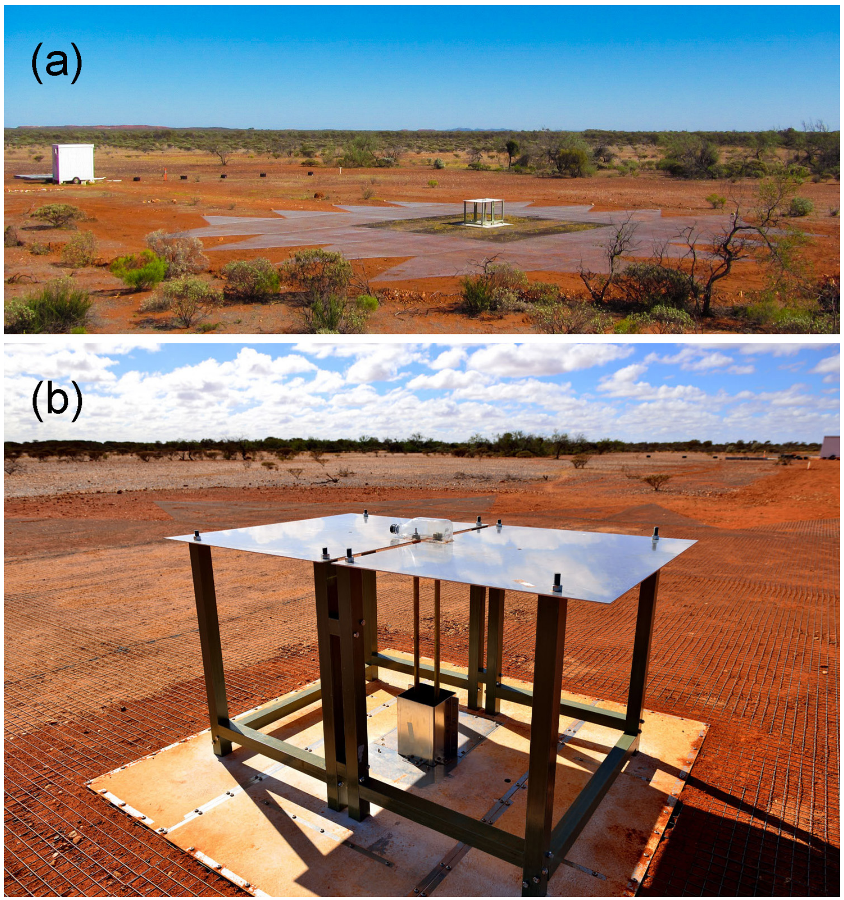
Pritchard and Loeb, arXiv:1109.6012



Factors: star formation efficiency, X-ray efficiency, spectral energy distribution of X-ray sources, feedback mechanism

EDGES

- **E**xperiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature(**EDGES**), located at Murchison Radio-astronomy Observatory in Western Australia;



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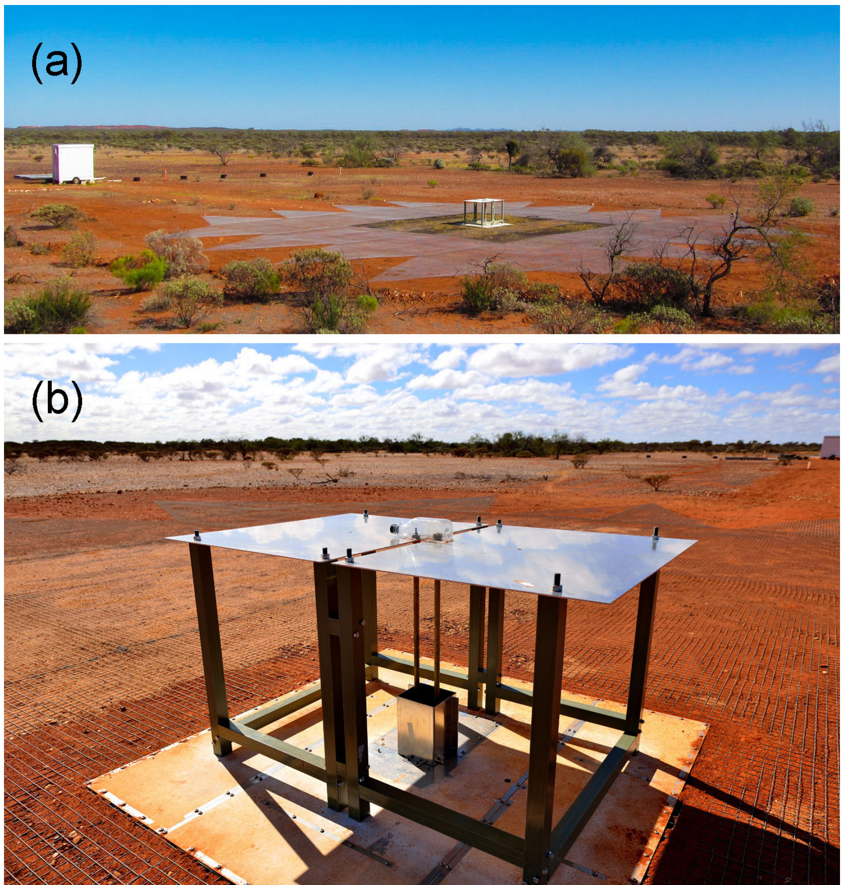
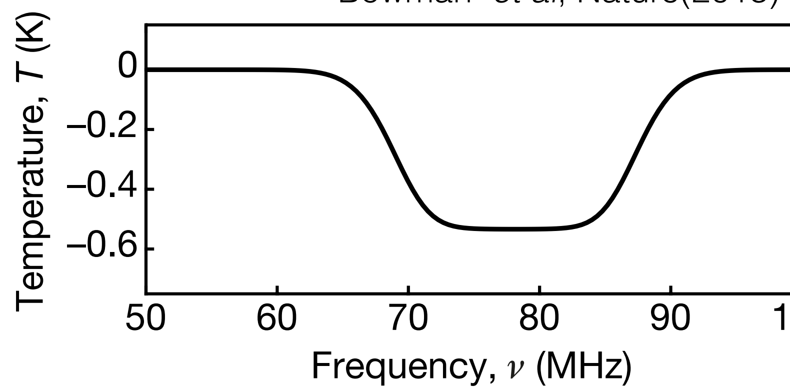


- excess signal the low-band for 50-100MHz (27>z>13), centered at 78MHz(z=17.z)

Bowman *et al*, Nature(2018)



- The absorption is about factor 2 larger than the largest expected value from theory.

Possible Explanations

$$T_{21}(z) \equiv \delta T_b \simeq 23\,\mathrm{mK} \times x_{\rm HI}(z) \left(\frac{\Omega_{\rm b} h^2}{0.02}\right) \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_{\rm m} h^2}\right)^{1/2} \left(1 - \frac{T_\gamma(z)}{T_{\rm S}(z)}\right),$$

- Colder Gas
  - DM-baryon scattering ($\Omega h^2 < 1\%$)

    [Barkana (2018); Berlin, Hooper, Krnjaic&McDermott (2018) …….]

- Hotter Radiation
  - New contributions to CMB at low frequency
    - Dark Photon [Pospelov, Pradler, Ruderman & Urbano (2018)]
    - Axion [Moroi, Nakayama & Tang (2018)]

Axion-Photon Mixing

- axion-photon coupling [axion-like-particle (ALP), a]

$$\mathcal{L}_{\text{int}} = -\frac{1}{4} g_a a F_{\mu\nu} \widetilde{F}^{\mu\nu} = g_a a \mathbf{E} \cdot \mathbf{B},$$

$F_{\mu\nu}$: EM field strength tensor, $\widetilde{F}^{\mu\nu}$ is its dual

g_a: the strength of the ALP-photon coupling.

- In the presence of background magnetic field B, an effective mixing rises between a and photon

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

E Energy

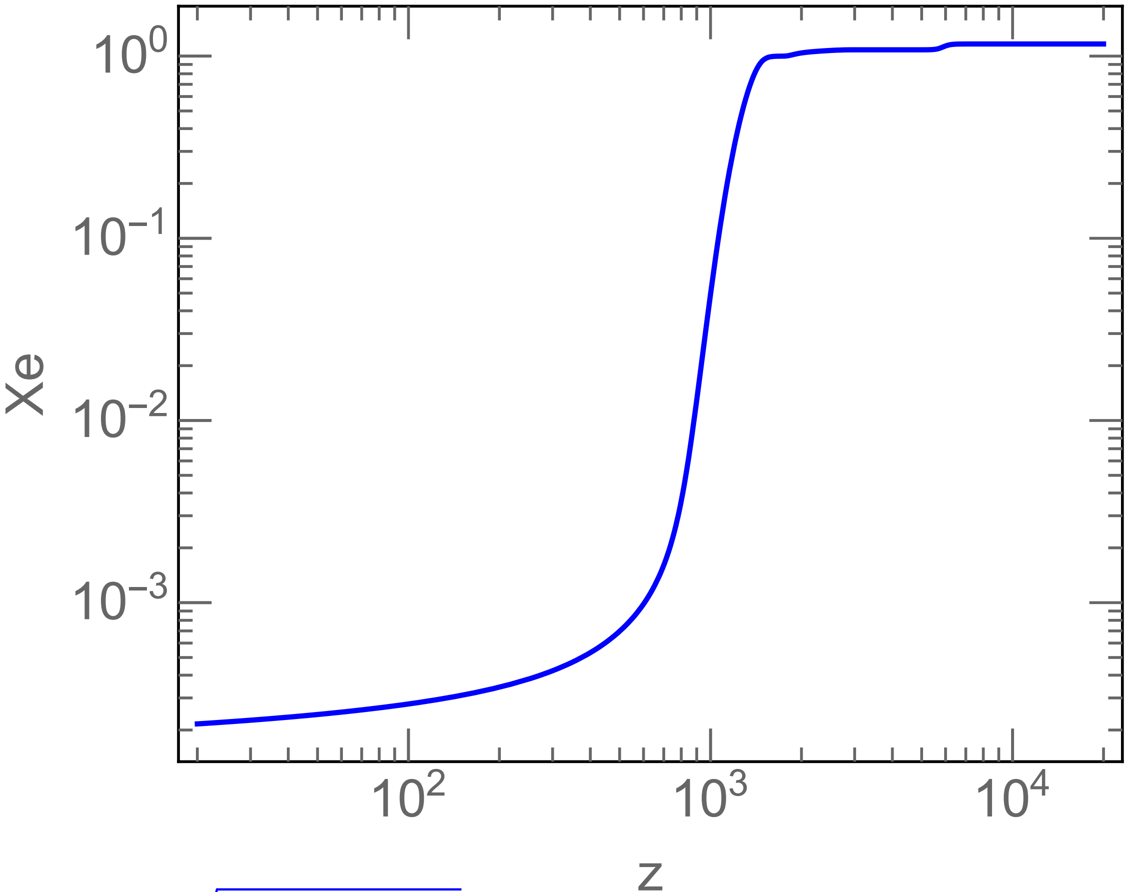
$B_\perp$ perpendicular

- Plasma frequency

$$\omega_p(z) = \sqrt{\frac{4\pi\alpha n_e(z)}{m_e}} \simeq 1.6 \times 10^{-14}\,\text{eV}\,(1+z)^{3/2} X_e^{1/2}.$$

Plasma Frequency

- Free electron fraction



$$\omega_p(z) = \sqrt{\frac{4\pi\alpha n_e(z)}{m_e}} \simeq 1.6 \times 10^{-14}\,\mathrm{eV}\,(1+z)^{3/2} X_e^{1/2}.$$

Axion-Photon Mixing

- ALP-photon system evolves as

$$i\frac{d}{dt}\left[\begin{array}{c}|a\rangle\\|\gamma\rangle\end{array}\right]=\frac{1}{2E}\mathcal{M}^2\left[\begin{array}{c}|a\rangle\\|\gamma\rangle\end{array}\right]$$

- Two mass eigenstates

$$\left[\begin{array}{c}|a\rangle\\|\gamma\rangle\end{array}\right]=\begin{pmatrix}\cos\theta_m & \sin\theta_m\\-\sin\theta_m & \cos\theta_m\end{pmatrix}\left[\begin{array}{c}|1\rangle\\|2\rangle\end{array}\right]$$

- Masses and mixing angle

$$M_{1,2}^2=\frac{m_a^2+\omega_p^2}{2}\pm\frac{1}{2}\sqrt{\left(m_a^2-\omega_p^2\right)^2+4\left(Eg_aB_\perp\right)^2}$$

$$\sin^2(2\theta_m)=\frac{(2Eg_aB_\perp)^2}{(2Eg_aB_\perp)^2+(\omega_p^2-m_a^2)^2}.\quad \omega_p^2=m_a^2:\ \text{resonance}\rightarrow z_{\text{res}}$$

Conversion Probability

- If propagate adiabatically from A to B

$$\frac{d\theta}{dt} \ll \frac{M_1^2 - M_2^2}{2E}$$

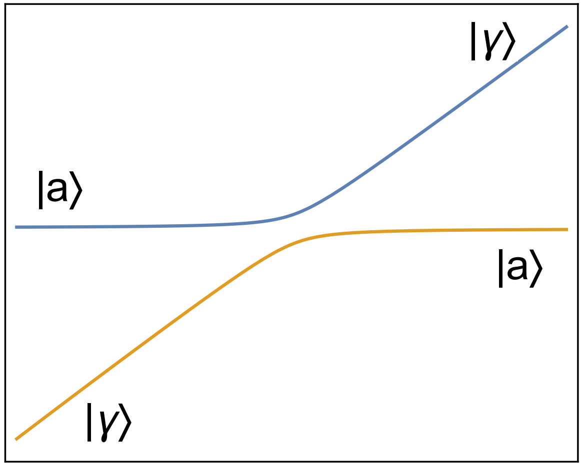
- In this case, conversion probability is given by

$$P_{a\to\gamma} = 1 - \frac{1}{2}\left(1 + \cos 2\theta_A \cos 2\theta_B\right)$$

$$\theta_A \simeq \frac{\pi}{2}, \theta_B \simeq 0 \Rightarrow P_{a\to\gamma} \simeq 1$$

CMB spectral distortion

$$P_{a\to\gamma} \lesssim 10^{-4}$$



- Adiabatic approximation is not valid in our setup, mostly-violated around the resonance regime

Conversion Probability

- Generally

[Mirizzi, Redondo & Sigl(2009)]

$$P_{a\to\gamma} \simeq \frac{1}{2} + \left(\mathcal{P} - \frac{1}{2}\right)\cos 2\theta_A \cos 2\theta_B\,,\ 0 \le \mathcal{P} \le 1$$

$$\mathcal{P} = 0 \text{ adiabatic}$$

- Landau-Zener transition

Level-crossing Probability

$$\mathcal{H} \equiv \frac{\mathcal{M}^2}{2E} = \frac{1}{2E}\begin{pmatrix} m_a^2 & E g_a B_\perp \\ E g_a B_\perp & \omega_p^2 \end{pmatrix} \Rightarrow \mathcal{P} = \exp\left[-\frac{2\pi \mathcal{H}_{12}^2}{|d(\mathcal{H}_{11} - \mathcal{H}_{22})/dt|}\right]$$

- Our case

$$P_{a\to\gamma} = 1 - \exp\left(-\frac{2\pi r \sin^2\theta}{2E/m_a^2}\right) \simeq \frac{\pi r g_a^2 B_\perp^2 E}{m_a^2},$$

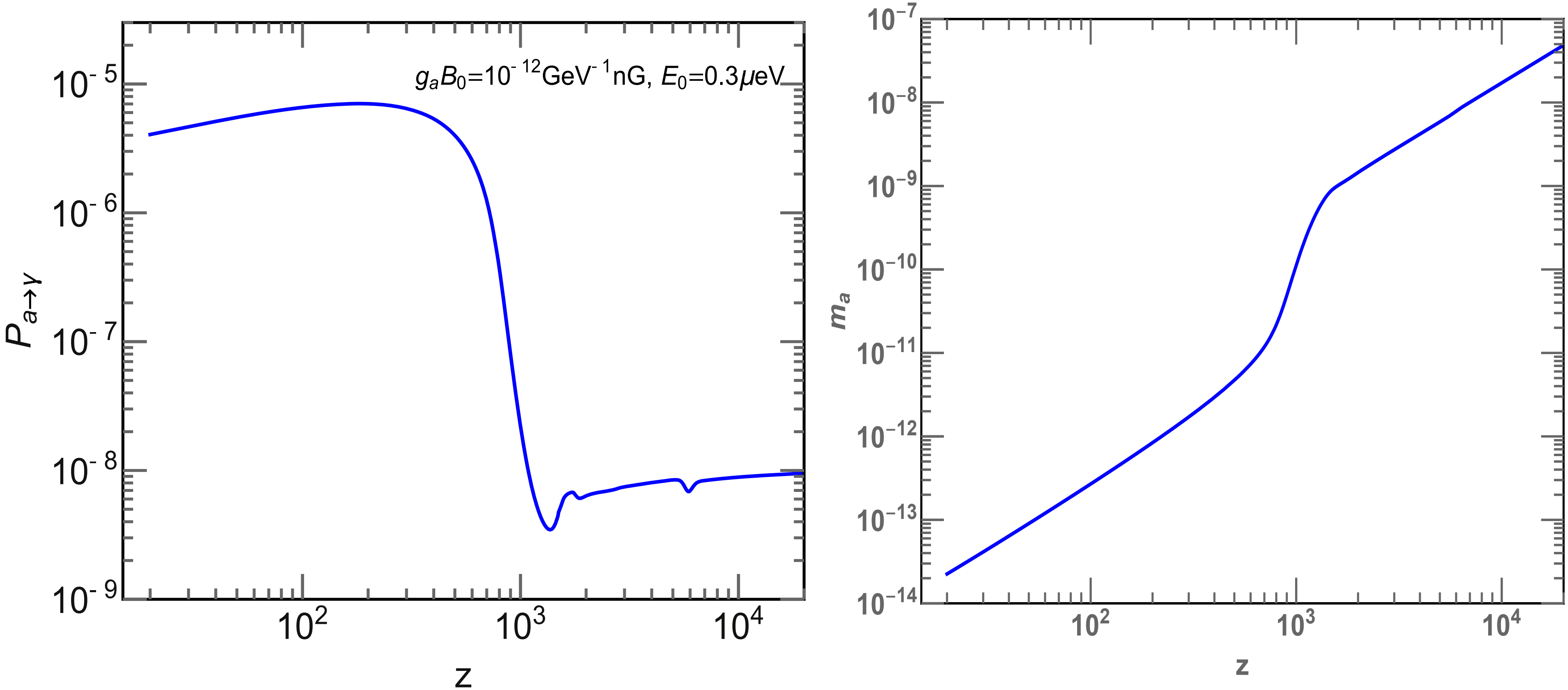
$$\sin\theta = \frac{E g_a B_\perp}{\sqrt{(2E g_a B_\perp)^2 + (m_a^2)^2}} \simeq \frac{E g_a B_\perp}{m_a^2}$$

$$r^{-1} \equiv \frac{d\ln\omega_p^2}{dt} = 3H + \frac{d\ln X_e}{dt},$$

$$E g_a B_\perp \ll m_a^2$$

$$H:\ \text{Hubble parameter}$$

Conversion Probability



$$P_{a\to\gamma} \sim 1.7\times 10^{-7}\left(\frac{E_0}{1\,\mu\mathrm{eV}}\right)\left(\frac{g_a}{10^{-11}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{B_0}{1\,\mathrm{nG}}\right)^2\left(\frac{10^{-14}\,\mathrm{eV}}{m_a}\right)^2(1+z_{\mathrm{res}})^{7/2}.$$

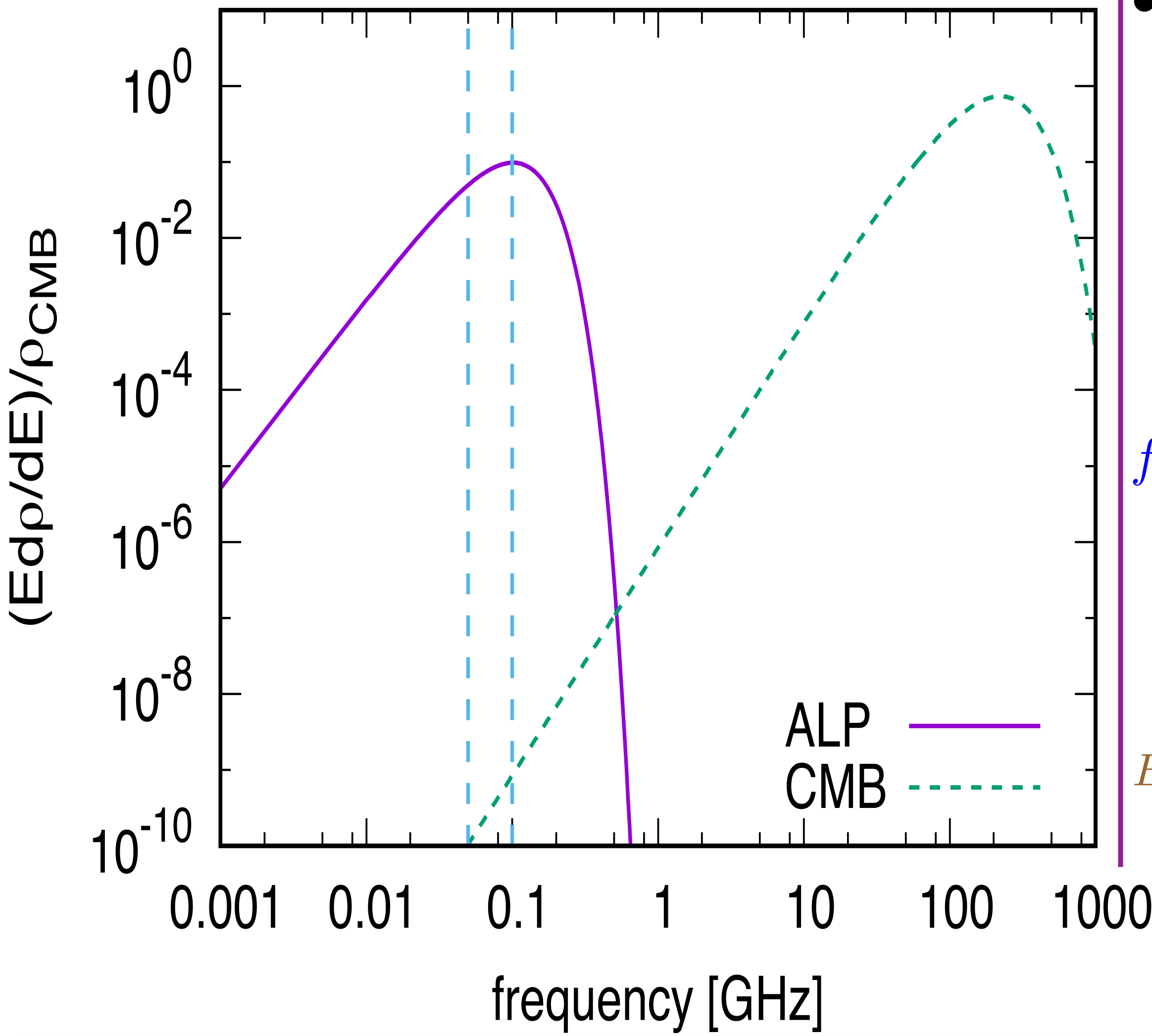
EDGES: 50–100 MHz

$\rightarrow E_0 \simeq (0.2-0.4)\,\mu\mathrm{eV}.$

recombination effects at $z \simeq 1100$

Application to EDGES

- Differential energy fraction



- Moduli decay

$$\phi \to aa$$

$$\tau_\phi^{-1} = \Gamma_{\phi\to 2a} = \frac{1}{64\pi}\frac{m_\phi^3}{f^2},$$

$$\Delta N_{\rm eff} \sim \mathcal{O}(0.1)$$

$$f \sim 10^8\,\mathrm{GeV}, m_\phi \sim 10^3\,\mathrm{GeV} \sim T_R$$

$$E_0 \frac{dn_\gamma}{dE_0} = E_0 \frac{dn_\gamma}{dE_0} + E_0 \frac{dn_{a\to\gamma}}{dE_0}$$

$$E_0 \frac{dn_{a\to\gamma}}{dE_0} = \left(E \frac{dn_a}{dE}\right)_{z=0} P_{a\to\gamma}(z_{\rm res}).$$

Estimations

- Energy fraction of photon in EDGES frequency range

$$f_\gamma^{(\text{EDGES})} \equiv \frac{\pi^{-2}\int T_0 E^2 dE}{\pi^2 T_0^4/15} \simeq 2.5\times 10^{-10},$$

- Energy fraction of ALP

$$f_a^{(\text{EDGES})} \equiv \frac{\int dE E dn_a/dE}{\rho_a},$$

Moduli decay

$$\phi \to aa$$

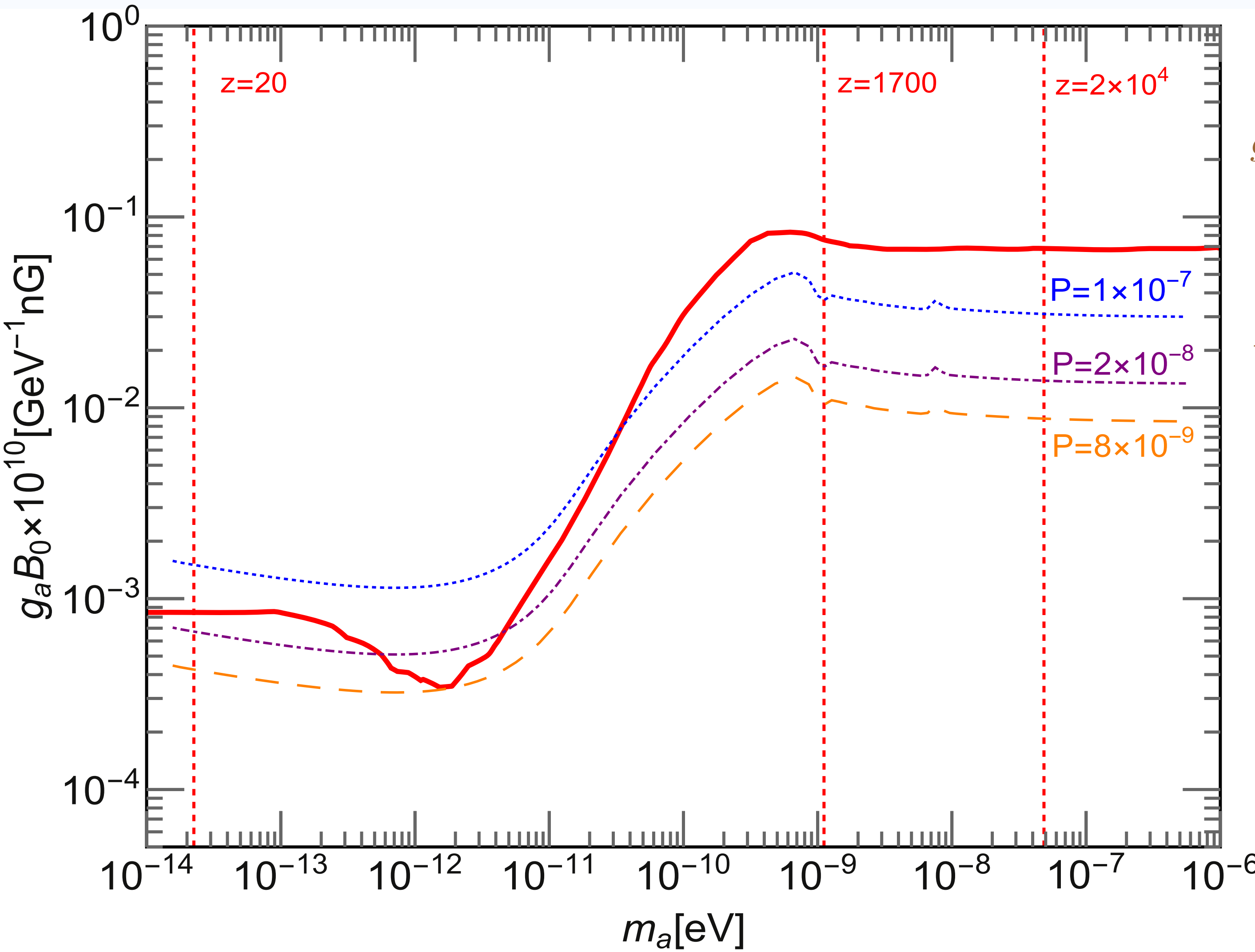
$$f_a \sim 0.4$$

- To increase ρ_γ in the EDGES range by an amount

$$\rho_a f_a^{(\text{EDGES})} P_{a\to\gamma}(E_0) \sim \rho_\gamma f_\gamma^{(\text{EDGES})},$$

$$P_{a\to\gamma}(E_0) \sim 1.1\times 10^{-9}\left(f_a^{(\text{EDGES})}\Delta N_{\text{eff}}\right)^{-1}, \quad \Delta N_{\text{eff}} \simeq \frac{\rho_a}{0.23\rho_\gamma},$$

Parameter Space



CAST

$g_a \lesssim 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$

$B_0 \lesssim$ a few nG

- Above the solid red curve, excluded by CMB distortion [Mirizzi, Redondo & Sigl(2009)]

Future Tests

- Axion experiments
    - IAXO,…

$$g_a < (\text{a few}) \times 10^{-12}\,\text{GeV}^{-1}$$

- CMB measurements
    - PIXIE or PRISM
    - N_{eff}
- 21cm observations
    - SKA, HERA, …

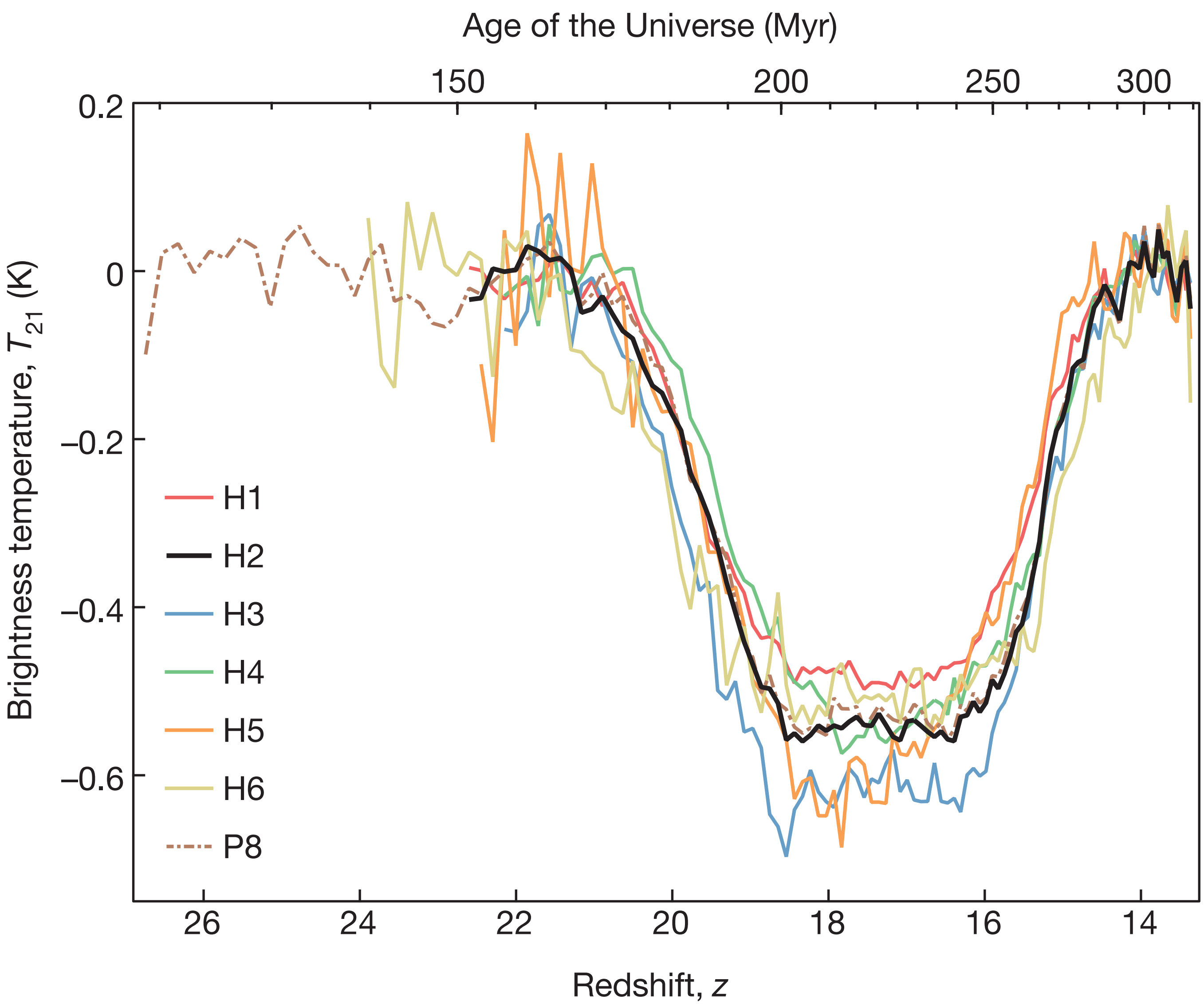
Summary

- We discuss a scenario that the recent observed excess of 21cm signal at EDGES is explained by increasing the radiation temperature at the low frequency range.
- Especially, we present a scenario where axion is converted to photon resonantly.
- Future experiments on Axion, CMB N_{eff}, and 21cm can provide further tests.

Thank you!

Backup

EDGES



Age of the Universe (Myr)
150
200
250
300
0.2
0
−0.2
−0.4
−0.6
Brightness temperature, T_{21} (K)
H1
H2
H3
H4
H5
H6
P8
26
24
22
20
18
16
14
Redshift, z

Conversion Probability

- Adiabatic

$$P_{\alpha\to\beta} = \sum_i P^A_{\alpha\to i} P^B_{i\to\beta}$$

$$= \begin{pmatrix} \cos^2\theta_A & \sin^2\theta_A \\ \sin^2\theta_A & \cos^2\theta_A \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos^2\theta_B & \sin^2\theta_B \\ \sin^2\theta_B & \cos^2\theta_B \end{pmatrix}$$

- Generally

$$P_{\alpha\to\beta} = \sum_{i,j} P^A_{\alpha\to i} P^B_{i\to j} P^B_{j\to\beta}$$

$$= \begin{pmatrix} \cos^2\theta_A & \sin^2\theta_A \\ \sin^2\theta_A & \cos^2\theta_A \end{pmatrix} \begin{pmatrix} 1-\mathcal{P} & \mathcal{P} \\ \mathcal{P} & 1-\mathcal{P} \end{pmatrix} \begin{pmatrix} \cos^2\theta_B & \sin^2\theta_B \\ \sin^2\theta_B & \cos^2\theta_B \end{pmatrix}$$

$$\mathcal{P} = |\langle 1|2\rangle|^2$$

Decay

- Moduli Decay

$$\tau_\phi^{-1} = \Gamma_{\phi\to 2a} = \frac{1}{64\pi}\frac{m_\phi^3}{f^2},$$

$$\Gamma \sim H$$

$$m_\phi \sim \begin{cases} 4\times 10^3\,\text{GeV}\left(\frac{f}{10^8\,\text{GeV}}\right)^2\left(\frac{1\,\mu\text{eV}}{E_\text{peak}}\right)^2 \\ \quad \text{if} \quad \Gamma_{\phi\to 2a} < H_{T=T_\text{R}} \\ 2\times 10^4\,\text{GeV}\left(\frac{f}{10^9\,\text{GeV}}\right)^{4/3}\left(\frac{1\,\mu\text{eV}}{E_\text{peak}}\right)\left(\frac{T_\text{R}}{10^3\,\text{GeV}}\right) \\ \quad \text{if} \quad \Gamma_{\phi\to 2a} > H_{T=T_\text{R}} \end{cases},$$

- Abundance

$$m_\phi Y_\phi = \frac{1}{8}T_\text{R}\left(\frac{\phi_i}{M_\text{P}}\right)^2 \simeq 1.3\times 10^2\,\text{GeV}\left(\frac{T_\text{R}}{10^3\,\text{GeV}}\right)\left(\frac{\phi_i}{M_\text{P}}\right)^2,$$