Bounds on sterile neutrino lifetime and mixing angle with active neutrinos by global 21 cm signal

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Based on Phys.Lett.B 827 (2022) 136955

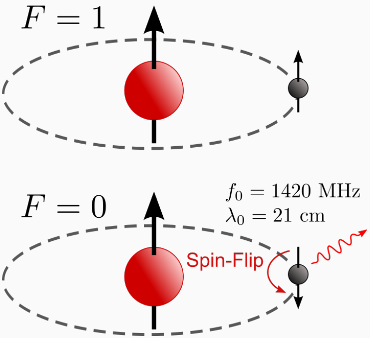
Plan of the talk

1. 21 cm line
2. Constraints on Sterile Neutrino
3. Conclusion

21 cm line

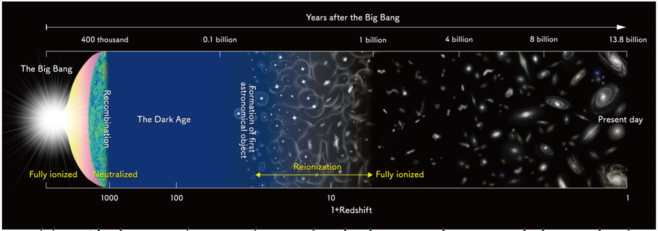
21 cm line

- 21cm signal arises from hyperfine splitting of hydrogen atom due to the interaction of magnetic moment of electron and proton.



$$\mathbf{F} = \mathbf{I} + \mathbf{S}$$

Motivation



Ref: https://earthsky.org/space/cosmic-dark-ages-lyman-alpha-galaxies-lager

- Information about Universe's first structure.
- Hints of baryon dark matter interaction.

Transition rate of 21 signal

- This transition is highly forbidden because transition rate is $3 \times 10^{-15}\, s^{-1}$ (equivalent to Einstein's coefficient A_{10}).
- Characteristic time scale $= 1/$ transition rate $= 10^7$years.

Spin temperature

- Relative number density of triplet(n_1) and singlet states (n_0) of HI is

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{E_{21}}{T_s}}$$

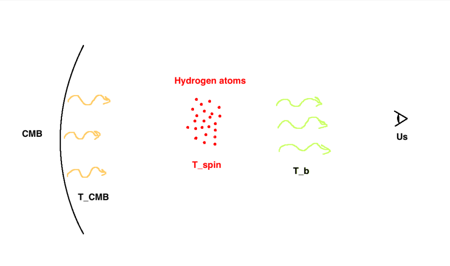
where $E_{21} = 5.9 \times 10^{-6}\, eV = \frac{2\pi}{21\text{cm}}$=0.068 K and $\frac{g_1}{g_0} = 3$.

T_s is the spin temperature.

Brightness temperature

- Under Rayleigh–Jeans limit, the specific intensity for a blackbody can be written
  $$I_\nu = \frac{2K_B T_B \nu^2}{c^2}$$
  T_B quantity is the Brightness Temperature.

Differential brightness temperature



- The intensity of the signal is quantify in differential brightness temperature:

$$T_{21} = T_B - T_{CMB} = \frac{1}{1+z}(T_S - T_{CMB})(1 - \exp^{-\tau})$$

Here τ is the optical depth, which is given by

$$\tau \approx \frac{3\lambda_{21}^2 A_{10} n_H}{16 T_S H(z)} \ ,$$

Spin Temperature dependence

- Detectability of T_{21} depends upon the T_S.
- $T_S > T_{CMB}$, we observe 21 cm emission signal.
  $T_S < T_{CMB}$, we observe 21 cm absorption signal.
  $T_S = T_{CMB}$, there is no signal
- Deviation of spin temperature from background temperature can be expressed as

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c},$$

  where x_c and x_α are coupling coefficient due to atomic collision and scattering of Lyα respectively.
- $T_{CMB} = 2.72K(1 + z)$

Collisional coupling coefficient

- Collisional coupling coefficient is given as

$$x_c = x_c^{HH} + x_c^{eH} + x_c^{pH}$$

  where $x_c^{HH} = k^{HH} n_H$, $x_c^{eH} = k^{eH} n_e$, $x_c^{pH} = k^{pH} n_p$
  k's are scattering rate.
- x_c^{HH} gives dominant contribution.

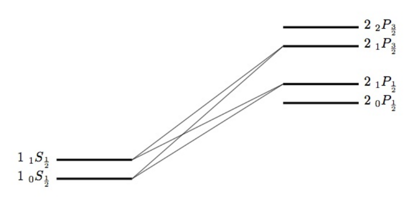
Lyα coefficient and Wouthuysen-Field effect

- Lyα coupling coefficient is given as

$$x_\alpha = \frac{4P_\alpha}{27A_{10}}\frac{0.068K}{T_{CMB}}$$

where P_α is the scattering rate of Lyα photons.

- Indirect spin flip due to Lyα radiation



Selection rule: $\Delta S = 0$, $\Delta L = \pm 1$,
$\Delta L = 0, \pm 1$ (except 0 to 0)
$\Delta F = 0, \pm 1$ (except 0 to 0)

Evolution of 21cm Signal: Phase-I

$\underline{\mathbf{200 < z < 1010}}$

- Residual free electron undergoes Thomson scattering to maintain thermal coupling of the gas to the CMB $\implies T_K = T_{CMB}$.
- Collisions drive $T_{CMB} = T_S$
- In this case, $x_\alpha = 0$ and $x_c >> 1$, so

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_c T_K^{-1}}{1 + x_c},$$

$\implies T_S = T_{CMB}$

- No 21 cm signal

Evolution of 21cm Signal: Phase-II

$\underline{\mathbf{40 < z < 200}}$

- Gas cools adiabatically: $T_K \propto (1+z)^2$ and $T_{CMB} \propto (1+z)$, $\implies T_K < T_{CMB}$.
- Collisions drive $T_K = T_S$, here $x_\alpha = 0$ and $x_c >> 1$, so

$$T_S^{-1} = \frac{T_{CMB}^{-1}}{1+x_c} + T_K^{-1},$$

$\implies T_S = T_K$

- Early 21 cm absorption signal.

Evolution of 21cm Signal: Phase-III

$\underline{\mathbf{z_\star < z < 40}}$

- Due to expansion, gas density decrease and collisional coupling becomes very less.
- Here $x_\alpha = 0$ and $x_c << 1$, so

$$T_S^{-1} = \frac{T_{CMB}^{-1}}{1 + x_c} + x_c T_K^{-1},$$

$\implies T_S = T_{CMB}$

- No 21 cm signal.

Evolution of 21cm Signal: Phase-IV

$\underline{\mathbf{15 < z < z_\star}}$

- Universe's first star is formed.
- Lyα photons via Wouthuysen-Field effect drive T_S to T_K: $T_S = T_K$ and $T_K < T_{CMB}$
- Here $x_\alpha >> 1$ and $T_\alpha = T_K$

$$T_S^{-1} = \frac{T_{CMB}^{-1}}{1 + x_c + x_\alpha} + T_K^{-1},$$

$\implies T_S = T_K$

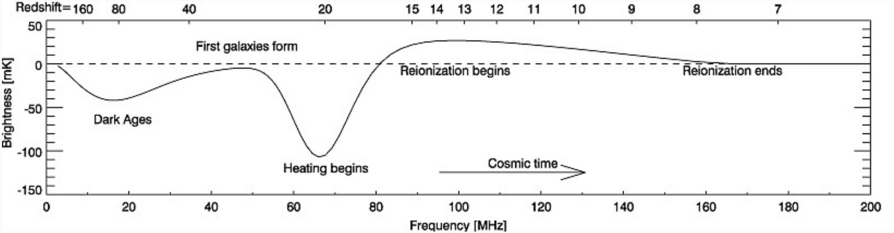
- We observe 21 cm absorption signal.

Evolution of 21cm Signal: Phase-V

$\underline{\mathbf{8 < z < 15}}$

- X-rays from active galactic nuclei heat the IGM : $T_K > T_{CMB}$.
- $T_\alpha = T_K$ due to Wouthuysen-Field effect.
- We observe 21 cm emission signal.
- Finally reionization happens, all the neutral hydrogen becomes ionized and signal disappears.

Evolution of 21cm Signal

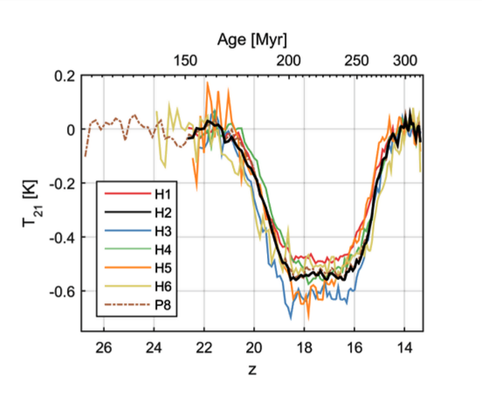


- The standard astrophysics prediction for brightness temperature

$$T_{21}(z = 17) \geq -220\ mK$$

This correspond to gas temperature 6.8 K at z=17.

EDGES Signal



- Brightness measurement with 99% confidence interval is

$$T_{21}^{EDGES}(z = 17) \approx -500^{+200}_{-300}\ mK$$

This correspond to gas temperature : $3.26^{+1.94}_{-1.58}\ K$ (Bowman 2018)

- Either decrease T_S or increase T_{CMB} during Cosmic Dawn era.

Constraints on Sterile Neutrino

Decay of sterile neutrino

- Deacy of sterile neutrino into photon:

$$\Gamma_{\nu_s} = \Gamma_{\nu_s \to \nu_a \gamma} = \frac{9\ \alpha\ G_F^2}{1024\,\pi^4}\ \sin^2(2\,\theta)\, m_{\nu_s}^5$$
$$\simeq 5.52 \times 10^{-22}\ \sin^2(\theta)\ \left[\frac{m_{\nu_s}}{\mathrm{KeV}}\right]^5\ \left[\frac{1}{\mathrm{sec}}\right],$$

- The decay of sterile neutrino dark matter to active neutrino via the radiative process can inject the photon energy into IGM.
- This process can modify the absorption amplitude of the 21 cm signal

Evolution of gas temperature

- Evolution gas temperature is given by

$$\frac{dT_{gas}}{dz} = \frac{2T_{gas}}{(1+z)} - \frac{\Gamma_C}{(1+z)H}(T_{CMB} - T_{gas})$$

  Γ_C is the Thomson scattering rate.

- Electron fractions evolve as

$$\frac{dx_e}{dz} = \frac{\mathcal{P}}{H\,(1+z)} \times \left[n_H x_e^2 \alpha_B(T_{gas}) - (1-x_e)\beta_B(T_{gas})\, e^{-E_\alpha/T_{gas}}\right]$$

- $\mathcal{P}$ is the Peebles coefficient

Gas evolution in presence of sterile neutrino decay

- Gas evolution in presence of of sterile neutrino decay:

$$\frac{dT_{gas}}{dz} = \frac{2T_{gas}}{(1+z)} - \frac{\Gamma_C}{(1+z)H}(T_{CMB} - T_{gas}) - \frac{2}{3H(1+z)} \times \frac{(1+2x_e)\epsilon}{3N_{tot}}$$

  where $N_{tot} = n_H(1 + f_{He} + x_e)$ is the total number density of gas

- Electron fraction evolution becomes

$$\frac{dx_e}{dz} = \frac{\mathcal{P}}{H\,(1+z)} \times \left[n_H x_e^2 \alpha_B(T_{gas}) - (1-x_e)\beta_B(T_{gas})\, e^{-E_\alpha/T_{gas}} \right] - \frac{1}{H(1+z)}\left(\frac{1}{E_0} - \frac{1-\mathcal{P}}{E_\alpha}\right)\frac{(1-x_e)\epsilon}{3\,n_H} \qquad (1)$$

- $E_\alpha = (3/4)E_0$, where E_0 is the ground state energy
- We have also included VDKZ18 effect.

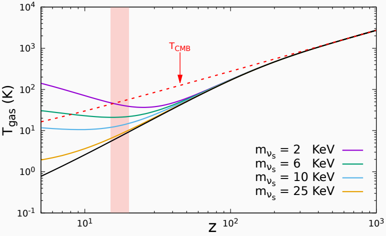
Energy deposition rate

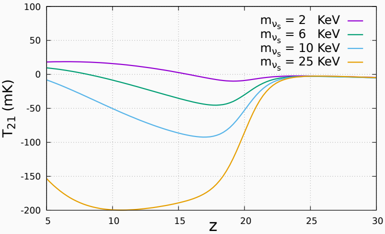
- The energy desposition rate is given by :

$$\epsilon(z, m_{\nu_s}) = \mathcal{F}_S f_{abs}(z, m_{\nu_s})\ \rho_{\nu_s,\mathrm{o}}\ \tau_{\nu_s}^{-1}\ (1+z)^3$$

- τ_{ν_s} is the lifetime of sterile neutrino .
- $\mathcal{F}_S$ is the fraction of the sterile neutrinos that are decaying, we take $\mathcal{F}_S = 1$.
- $\rho_{\nu_s,0} = m_{\nu_s}\, n_{\nu_s,0}$ is the present day energy density of sterile neutrino.
- $f_{\mathrm{abs}}(z, m_{\nu_s})$ is the energy deposition efficiency into IGM by decaying sterile neutrinos.
- $f_{\mathrm{abs}}(z, m_{\nu_s})$ depends on the redshift, mass of sterile neutrino and decay channel.

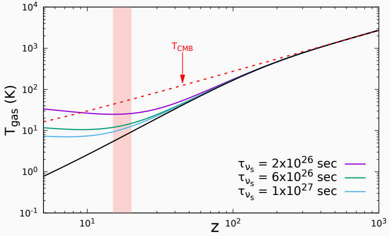
Temperatature variation for different sterile neutrino mass

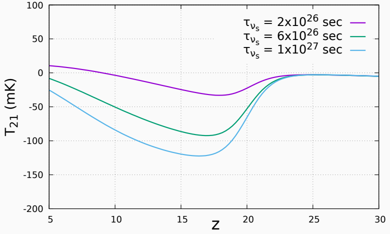




Here, Life time τ_{ν_s} constant to 6×10^{26} sec

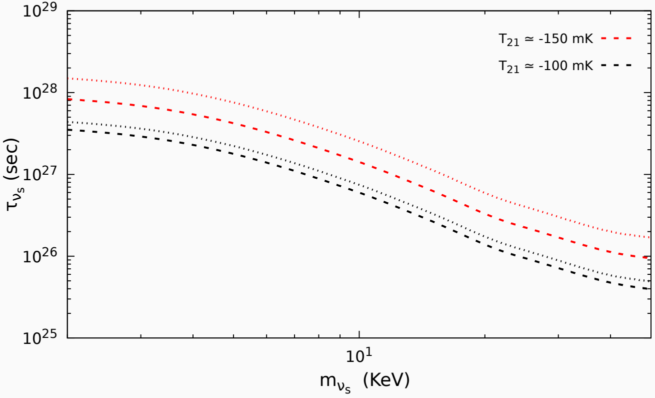
Temperatature variation for different sterile neutrino life time



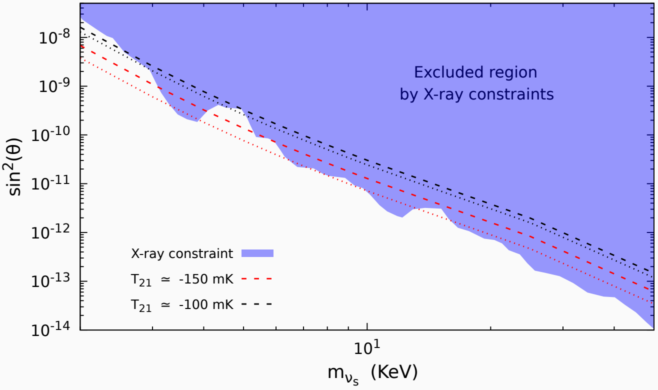


Here, we keep mass of sterile neutrino fix to 10 KeV.

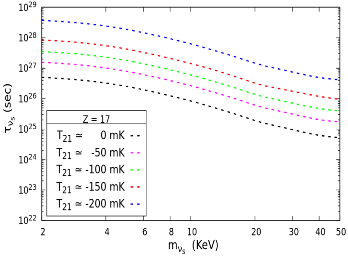
Constraint on Sterile neutrino mass and life time

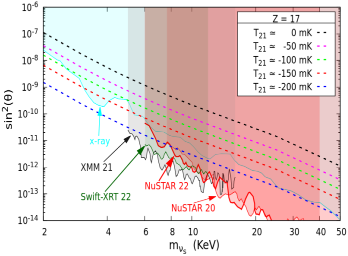


Constraint on Sterile neutrino mass and life time



Constraint on Sterile neutrino mass and life time





Conclusion

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- The lifetime of sterile neutrino decrease when one increases the mass of the sterile neutrino
- We get more window to increase the gas temperature, i.e. we can decrease the lifetime of sterile neutrinos.
- The upper bound on the mixing angle ($\sin^2\theta$) varies from 6.8×10^{-9} to 6.1×10^{-14} by varying sterile neutrino mass from 2 KeV to 50 KeV.