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SUNG KYUN KWAN UNIVERSITY(SKKU)

Sterile Neutrino Dark Matter with PTOLEMY-like experiment

Workshop on the physics of Dark Cosmos

Erdenebulgan Lkhagvadorj
Collaboration with prof. Ki-Young Choi and Seong Moon Yoo
(Sungkyunkwan University)

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PTOLEMY-like experiment

Cosmic neutrino capture on tritium: $\boldsymbol{\nu_i + {}^3H \to {}^3He + e^-}$

1. Find evidence for CNB
2. Light DM detection
3. Accurate measurement of neutrino mass

Capture rate of STERILE NEUTRINO (subdominant contribution)

$$\boxed{\Gamma_s = \frac{M_T}{m_T}|U_{e4}|^2 \int dE_{\nu_4} \sigma v_{\nu_4} \frac{dn_{\nu_4}}{dE_{\nu_4}} \simeq \frac{M_T}{m_T}|U_{e4}|^2 (\sigma v)_0 n_{s,\mathrm{loc}}.}$$

PTOLEMY with
100 g of tritium
Δ = 150 meV:

$$E_{\min} = E_0 - 5\ \mathrm{eV},$$
$$E_{\max} = E_0 + 10\ \mathrm{eV},$$
$$\Gamma_b \lesssim 10^{-5}\ \mathrm{Hz}$$

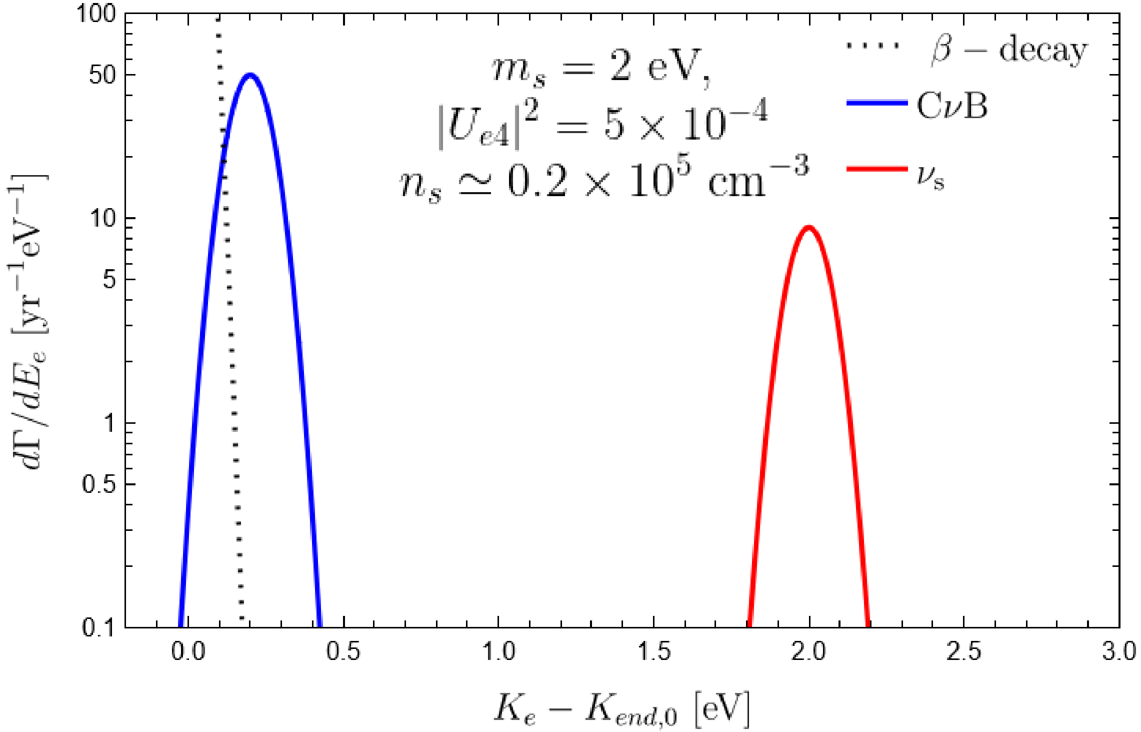
Electron energy from CNB:

$$E_e^i \simeq K_{\mathrm{end}}^0 + m_e + E_{\nu_i}$$

Maximal electron energy from β-decay:

$$E_{\mathrm{end}} \simeq K_{\mathrm{end}}^0 + m_e - m_{\mathrm{lightest}}$$

[Boyarsky, JCAP, 03:089, 2021]

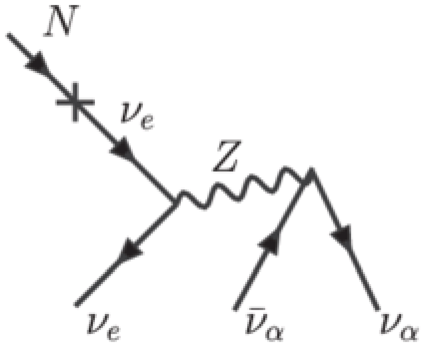


Sterile neutrino as dark matter

Sterile neutrino with keV mass scale is a good candidate for DM.

[Dodelson, Widrow, 1994] [Dolgov, Hansen, 2002] [Asaka, Blanchet, Shaposhnikov, 2005]

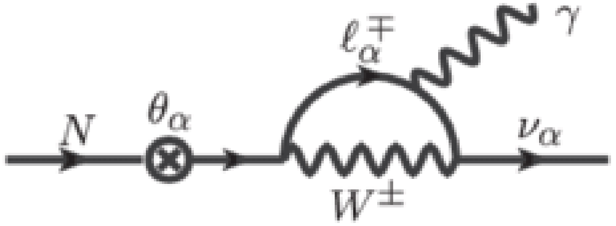
- ✓ Stable within the age of the Universe
- ✓ Relic abundance should be $\Omega_{dm}h^2$
- ✓ Provide cosmological constraints



$$\tau \simeq 1.44 \times 10^{27}\,\mathrm{s} \left(\frac{1\mathrm{kev}}{m_s}\right)^5 \frac{10^{-8}}{\sum |U_{\alpha s}|^2}$$

but greater than the age of the Universe if

$$\frac{|U_{\alpha s}|^2}{3 \times 10^{-3}} < \left(\frac{10\ \mathrm{keV}}{M_s}\right)^5$$



DM sterile neutrinos can be searched at X-ray telescopes

$$\frac{|U_{\alpha s}|^2}{3 \times 10^{-11}} \lesssim \left(\frac{10\ \mathrm{keV}}{M_s}\right)^4$$

Dodelson-Widrow (DW) scenario

Production by thermal scatterings induced via active-sterile neutrino oscillation

[Dodelson, Widrow 1994 hep-ph/9303287]

Evolution of number density of sterile neutrino: $\nu_e \leftrightarrow \nu_s$

(Neutrinos are kept in thermal equilibrium by electroweak processes)

$$\frac{dn_s}{dt} + 3Hn_s = P(\nu \to \nu_s)\Gamma_\nu n_\nu$$

$$\sin^2(2\theta_m)\sin^2(\omega_m t)$$

$$n_\nu = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_* T_\nu^3 .$$

$$\Gamma_\nu \sim G_F^2 T_\nu^2$$

⇒

$$n_s(T) \approx 10^{-5}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right) n_\nu(T)$$

Dominant production occurs at QCD phase transition epoch

$$T_{\max} \simeq 133\ \mathrm{MeV}\,(m_s/\mathrm{keV})^{1/3}.$$

$$\boxed{\Omega_s \approx 0.2\left(\frac{\sin^2\theta}{3\times 10^{-9}}\right)\left(\frac{m_s}{3\ \mathrm{keV}}\right)^{1.8}}$$

[Dasgupta, Kopp, 2021]

- **Clustering in the Milky Way:**

$$n_s^{\mathrm{loc}} = (1+f_c)n_s$$

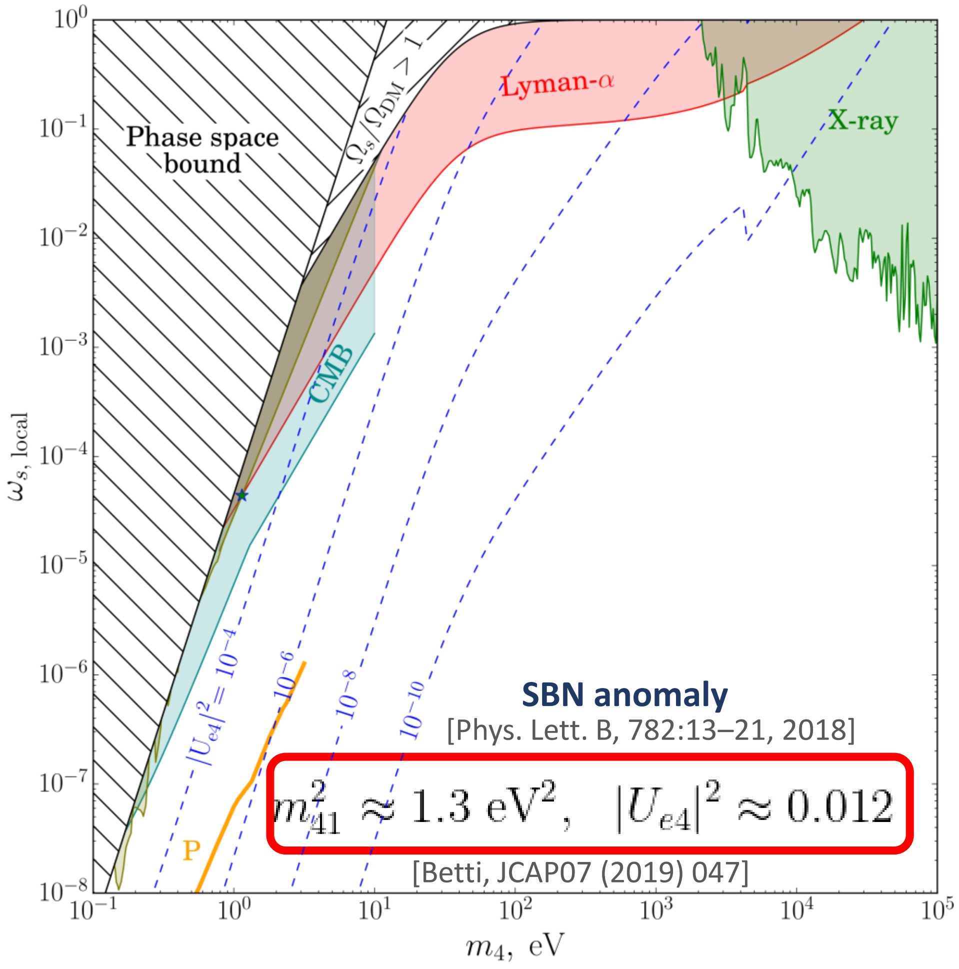
$$f_c(m_s) = f_{c,\mathrm{DM}}\left[1+\left(a\,\frac{\mathrm{kev}}{m}\right)^b\right]^{-2.21/b}$$

$$f_{c,\mathrm{DM}} = 2.4\times 10^5,\ a = 0.038,\ b = 2.45$$

Donnino Anderhalden, JCAP, 10:047, 2012.

- **The local number density of the sterile neutrino from DW mechanism**

$$\boxed{n_{s,\mathrm{loc}} = \frac{\Omega_s}{\Omega_{\mathrm{DM}}}\frac{1+f_c(m_s)}{f_{c,\mathrm{DM}}}\frac{\rho_{\mathrm{DM,\ local}}}{m_s}}$$

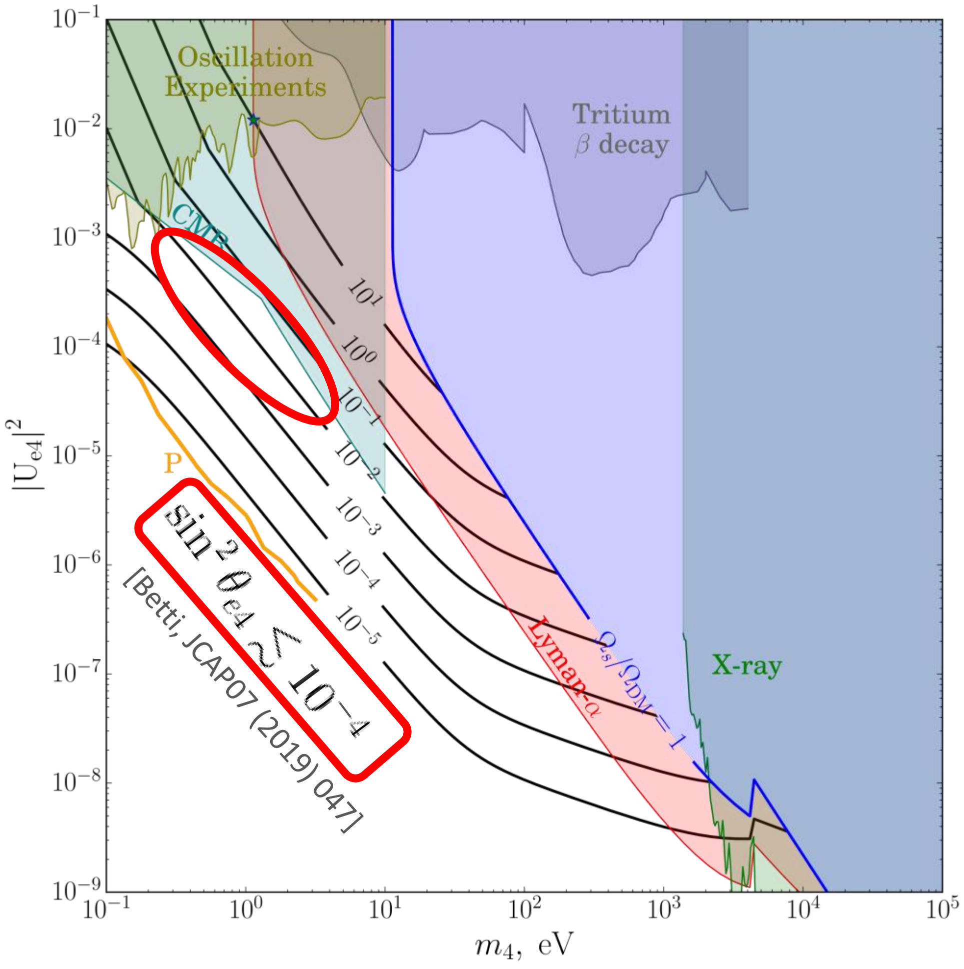


SBN anomaly

[Phys. Lett. B, 782:13–21, 2018]

$$\boxed{m_{41}^2 \approx 1.3\ \mathrm{eV}^2, \quad |U_{e4}|^2 \approx 0.012}$$

[Betti, JCAP07 (2019) 047]



$$\boxed{\sin^2\theta_{e4} \lesssim 10^{-4}}$$

[Betti, JCAP07 (2019) 047]

- **Phase space bound**

$$n_{s,\mathrm{loc}} \leq g_s \frac{(m_s v_{esc})^3}{6\pi^2}$$

[Tremaine, Gunn, Phys. Rev. Lett., 42:407–410, 1979]

- **CMB: PLANCK-2018**

$$N_{\mathrm{eff}} < 3.29, \;\; m_{\nu_s}^{eff} < 0.65\ \mathrm{eV}$$

[Astron.Astrophys. 652, C4 (2021)]

- **Lyman-α:**

$$\omega_{s,\mathrm{lim}}(m_{\mathrm{WDM}}) = \frac{m_{\mathrm{WDM}}}{7.2\ \mathrm{kev}} + 0.1$$

[Hooper 2022, arXiv.2206.08188]

$$\boxed{\omega_{s,\mathrm{local}}(m_{\mathrm{WDM}}) = f_c(m_s)\, \omega_{s,\mathrm{lim}}(m_{\mathrm{WDW}})}$$

- **Cosmic X-ray:**

(Chandra + NuStar M31)

[Phys. Rev. D, 89(2):025017, 2014. Phys. Rev.D, 101(10):103011, 2020.]

$$\boxed{\sin^4\theta_{\mathrm{DW,lim}} = \sin^2\theta_0 \sin^2\theta_{1,\mathrm{lim}}}$$

Low temperature scenario

- ✓ The production of sterile neutrinos through the oscillation of active neutrinos starts at the Universe becomes dominated by a radiation bath with a low temperature

$$\boxed{T_c < T_{\rm max} \simeq 133\ {\rm MeV}\left(\frac{m_s}{\rm keV}\right)^{1/3}}$$

[Gelmini, 2004], [Hasegawa, JCAP, 08:015, 2020], [Gelmini, JCAP 10, A01 (2020)]

- ✓ Relic abundance of sterile neutrinos does not impose that their mixing to active neutrinos to be as small as usually considered.

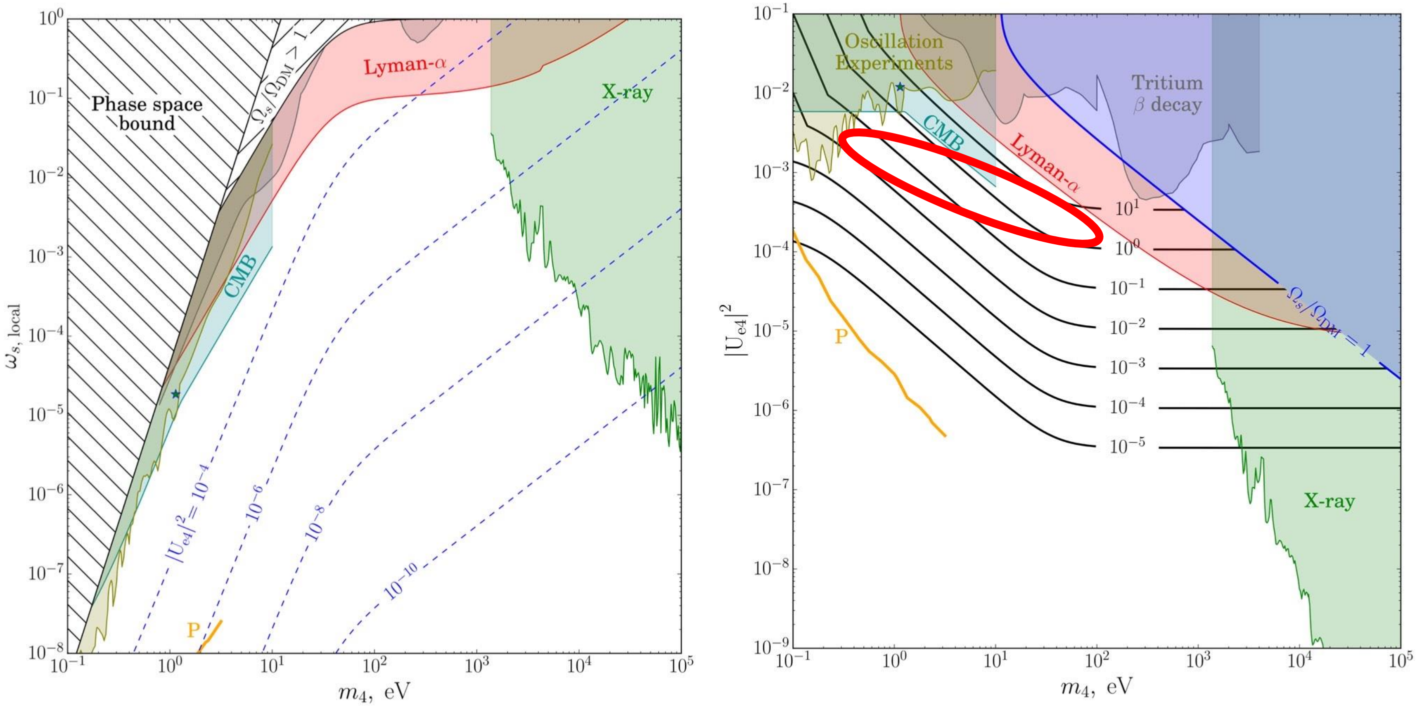
$$\left(\frac{\partial f_s(E,T)}{\partial T}\right)_{E/T} \simeq \frac{1}{2}\sin^2(2\theta_M)\frac{\Gamma(E,T)}{HT}f_\alpha(E,T)$$

$$\nu_e \leftrightarrow \nu_s \qquad \boxed{f_s(E,T) \simeq 0.13|U_{e4}|^2\left(\frac{10.75}{g_*}\right)^{-1/2}\left(\frac{T_c}{\rm MeV}\right)^3\left(\frac{E}{T}\right)f_\alpha(E,T).}$$

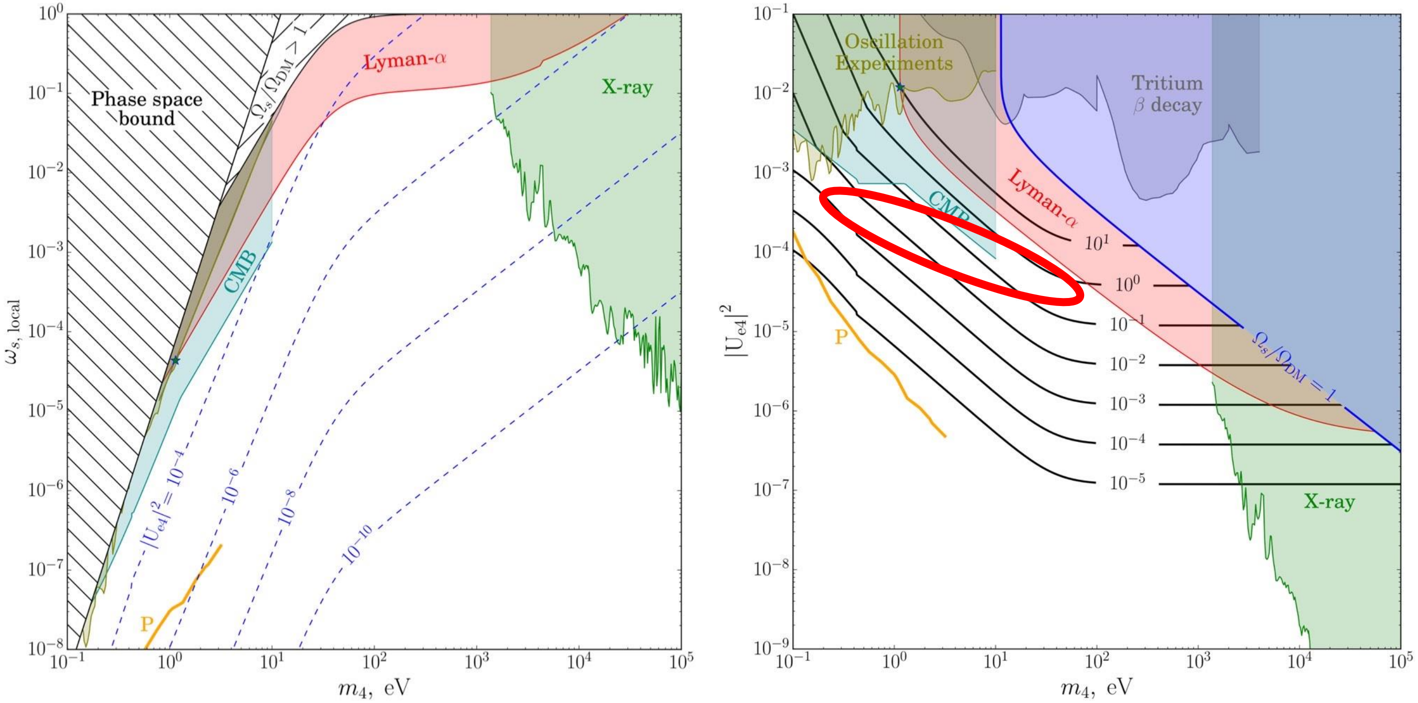
$T_c = 5$ MeV – **low reheating temperature**: $n_s \simeq 51.2\,|U_{e4}|^2\left(\frac{10.75}{g_*}\right)^{1/2}\left(\frac{T_c}{5\ {\rm MeV}}\right)^3 n_\nu$

$$\boxed{\Omega_s h^2 \simeq 0.5\left(\frac{|U_{e4}|^2}{10^{-3}}\right)\left(\frac{10.75}{g_*}\right)^{1/2}\left(\frac{m_s}{\rm keV}\right)\left(\frac{T_c}{5\ {\rm MeV}}\right)^3.}$$

$T_c = 5$ **MeV**



$T_c = 10$ **MeV**



Conclusion

- We consider the capture rate of sterile neutrino in the PTOLEMY-like experiment depending on two different cosmological models.
- In both cases, we can obtain that the sterile neutrino mass range in eV scale and large mixing are satisfied with other experimental and cosmological bounds.
  - DW: up to $\sim\vartheta(10^{-1})$ events per year from $\mathrm{C}\nu_s\mathrm{B}$ interaction
  - LRT: up to $\sim\vartheta(10)$ events per year from $\mathrm{C}\nu_s\mathrm{B}$ interaction
- If sterile neutrino would be detected in PTOLEMY, it will give us fruitful information of $\mathrm{C}\nu_s\mathrm{B}$ and light dark matter candidate.
- If not, PTOLEMY would give some limits on Lyman-α and CMB bounds in the LRT model.

Thank you for your attention.