성균관대학교
SUNG KYUN KWAN UNIVERSITY(SKKU)

Probing Sterile Neutrino Dark Matter In The PTOLEMY-like Experiment

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Ki-Young Choi, Erdenebulgan Lkhagvadorj and **Seong Moon Yoo**
Sungkyunkwan University

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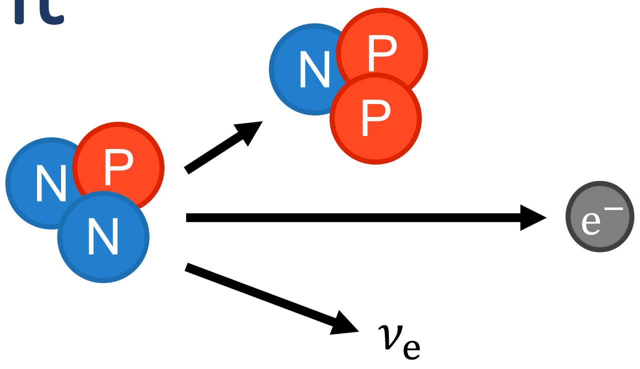
Contents

PTOLEMY Experiment

1. Accurate measurement of neutrino mass

Tritium beta decay: $^{3}H \rightarrow\ ^{3}He + e^{-} + \overline{\nu_e}$



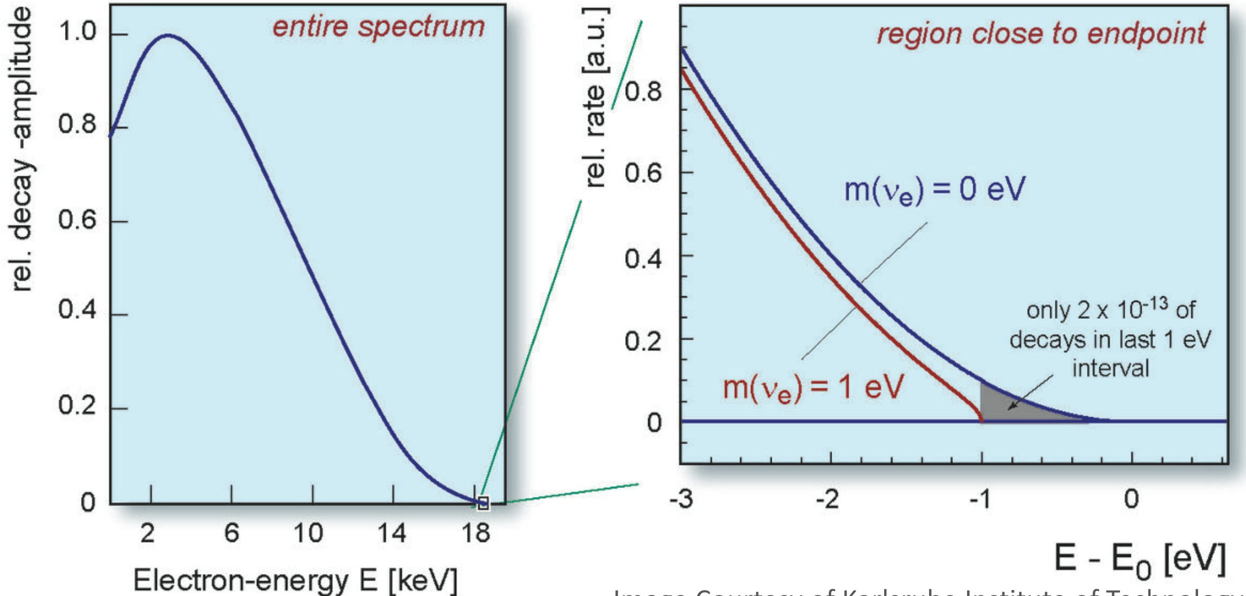
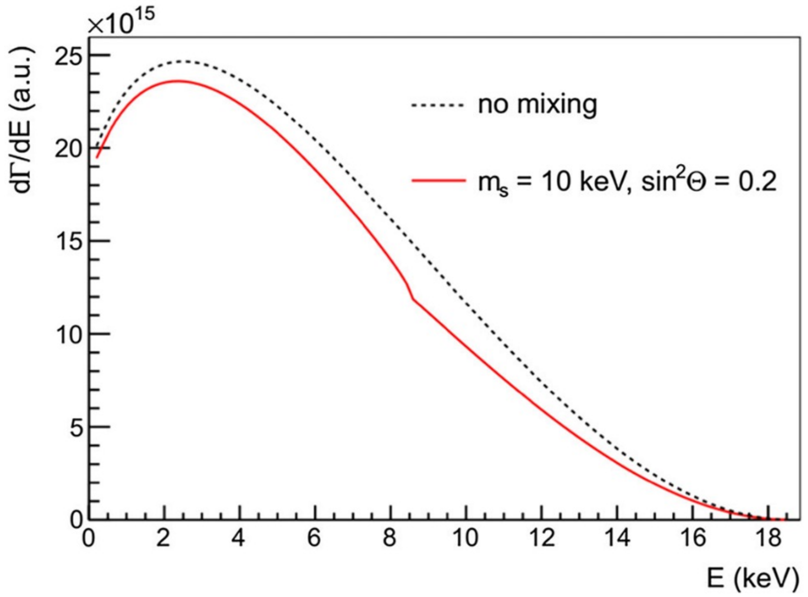


Image Courtesy of Karlsruhe Institute of Technology

Maximal electron energy from β-decay:

$$E_{\text{end}} \simeq K^{0}_{\text{end}} + m_e - m_{\text{lightest}}$$



N. M. N. Steinbrink et. al. (2018)

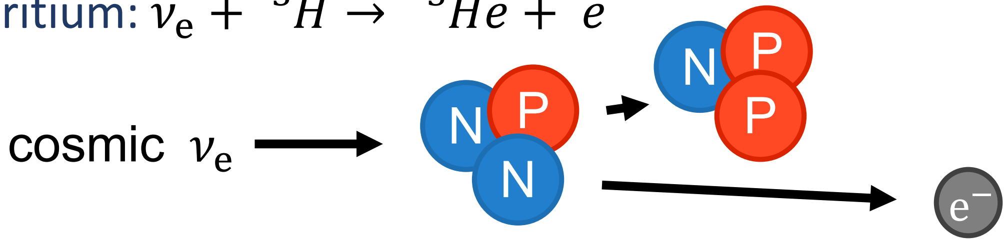
Distortion and kink of beta spectrum

PTOLEMY Experiment

1. Accurate measurement of neutrino mass
2. Find evidence for relic neutrinos

Capture event of sterile neutrino (subdominant contribution)

Cosmic neutrino capture on tritium: $\nu_e + {}^3H \rightarrow {}^3He + e^-$



CνB

$$\Gamma_{C\nu B} = 2(\sigma v) N_T \sum_{i=1}^{3} n_{\nu_i} |U_{ei}|^2 \quad \text{(Majorana)}$$

$$\Gamma_{C\nu B} = (\sigma v) N_T \sum_{i=1}^{3} n_{\nu_i} |U_{ei}|^2 \quad \text{(Dirac)}$$

σ: cross-section of $\nu_e + {}^3H \rightarrow {}^3He + e^-$
v: velocity of ν_i

Relic sterile neutrino

$$\Gamma_s = 2(\sigma v) N_T n_{\nu_s} |U_{e4}|^2 \quad \text{(Majorana)}$$

$$\Gamma_s = (\sigma v) N_T n_{\nu_s} |U_{e4}|^2 \quad \text{(Dirac)}$$

N_T: Total number of tritium
n_{ν_i}: number density of ν_i

PTOLEMY Experiment

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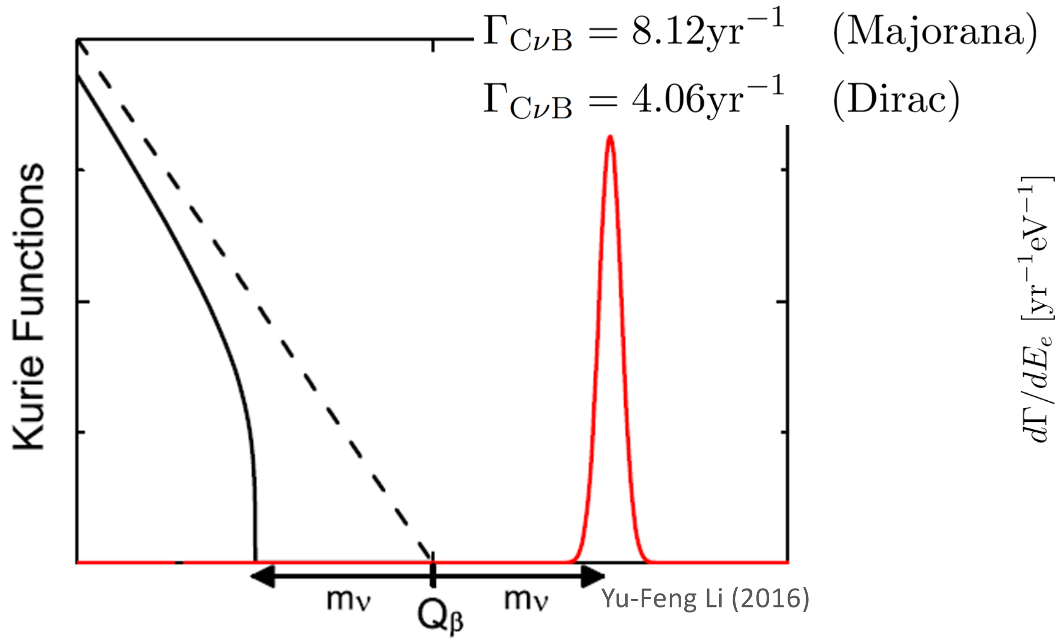
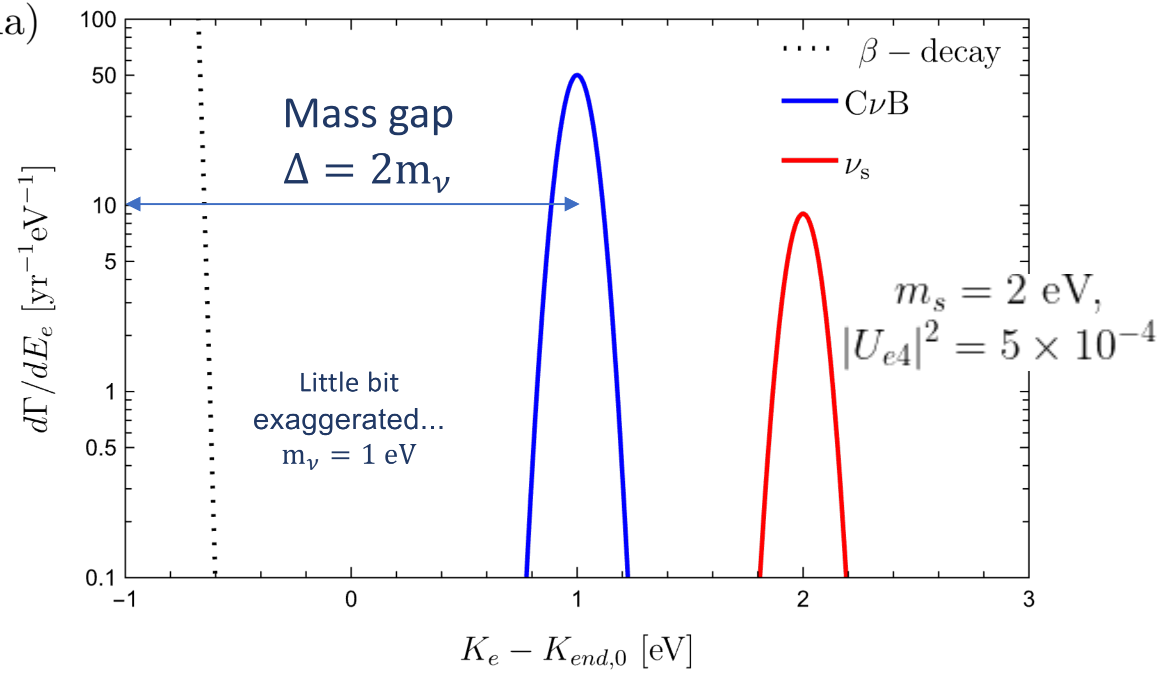
Cosmic neutrino capture on tritium: $\nu_e + {}^3H \rightarrow {}^3He + e^-$

What CνB would looks like

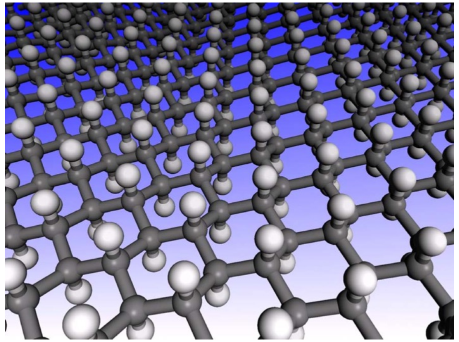


With sterile neutrino



Electron energy from CNB: $E_e^i \simeq K_{\text{end}}^0 + m_e + E_{\nu_i}$

PTOLEMY Experiment



Sofo, Chaudhari, Barber (2007)

KATRIN

Use T_2 gas
→ Rapid change of molecular state after decay($^3He^+T$)
→ Lower energy resolution(~1 eV)

PTOLEMY

Use Hydrogenated graphene
→ Binding energy is much lower
→ Better energy resolution(~0.15 eV)

$$E_{\rm min} = E_0 - 5\ {\rm eV},$$
$$E_{\rm max} = E_0 + 10\ {\rm eV}$$

Total 100 energy bin.
$\Gamma_b \lesssim 10^{-5}$ Hz is required to detect CνB.

Can we detect the relic sterile neutrino with PTOLEMY?

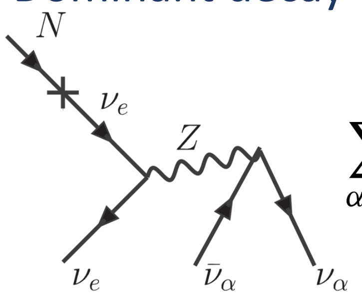
Sterile Neutrino as Dark Matter

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 can be up to $\Omega_{\rm DM} h^2$
- ✓ Provide cosmological constraints

Dominant decay channel:



Boyarsky, et. al. (2012)

$$\sum_{\alpha=e}^{\tau}\sum_{\beta=e}^{\tau} \Gamma(\nu_4 \to \nu_\alpha + \nu_\beta + \bar{\nu}_\beta) = \frac{C_\nu G_{\rm F}^2 m_4^5}{192\pi^3}\sum_{\alpha=e}^{\tau}|V_{\alpha 4}|^2$$

Li, Xing (2011)

$$\Gamma_s < t_{\rm universe} \Leftrightarrow \frac{|U_{\alpha s}|^2}{3\times 10^{-3}} < \left(\frac{10\ \rm keV}{M_s}\right)^5$$

Sterile Neutrino as Dark Matter

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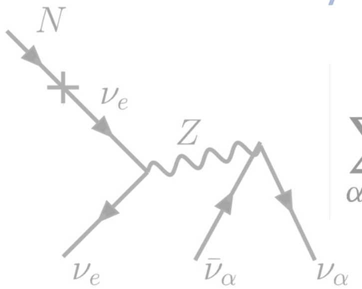

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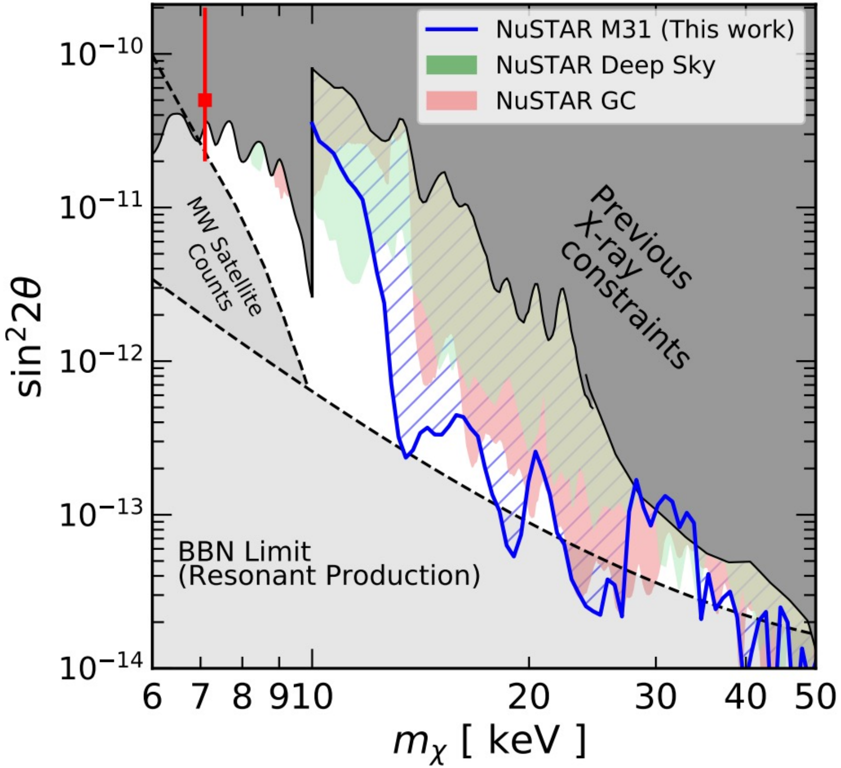
Or… is it?

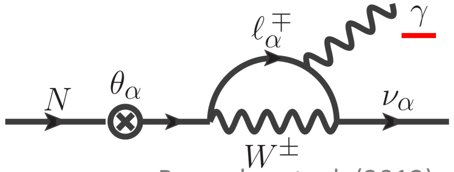
K. C .Y. Ng et. al. (2020)



We consider the sterile neutrino as a sub-component dark matter.

Constraints on Sterile Neutrino

- X-ray constraints



Boyarsky, et. al. (2012)

$$\sum_{i=1}^{3} \Gamma(\nu_4 \to \nu_i + \gamma) \simeq \frac{9\alpha_{\rm em} C_\nu G_F^2 m_4^5}{512\pi^4} \sum_{i=1}^{3} \left| \sum_{\alpha=e}^{\tau} V_{\alpha 4} V_{\alpha i}^* \right|^2$$

Li, Xing (2011)

Ordinary X-ray constraints assumed $\Omega_{\rm DM} = \Omega_s$.

For $\Omega_s \propto \sin^2\theta_{a4}$ cases, we can change the constraints according to the model.

$$|U_{e4}|^2_{\omega_s<1} = \left(\frac{\Omega_{\rm DM,local}}{\Omega_{\rm s,local}}\right) |U_{e4}|^2_{\omega_s=1}$$

M31 observations made by Chandra + NuStar are used.

S. Horiuchi et. al. (2014), K. C .Y. Ng et. al. (2020)

- Tritium β-decay constraints

Found from the distortion and the kink of the beta spectrum.

Troitsk and KATRIN experiment dominates for now. K. H. Hiddemann et. al. (1995), C. Kraus et. al. (2013), A. I. Belesev et. al. (2014) J. N. Abdurashitov et. al. (2017), M. Aker et. al. PRD (2022), M. Aker et. al. (2022) arxiv: 2207.06337

PTOLEMY also has an estimated sensitivity.

E. Baracchini et. al. (2018) arxiv: 1808.01892

Constraints on Sterile Neutrino

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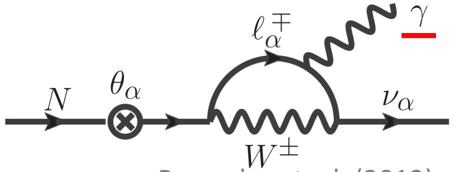

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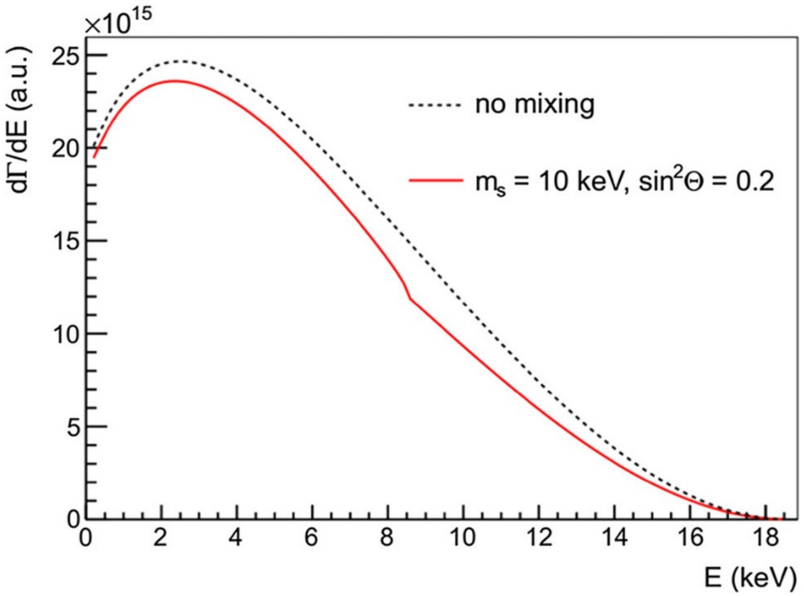


Constraints on Sterile Neutrino

- **CMB constraints**

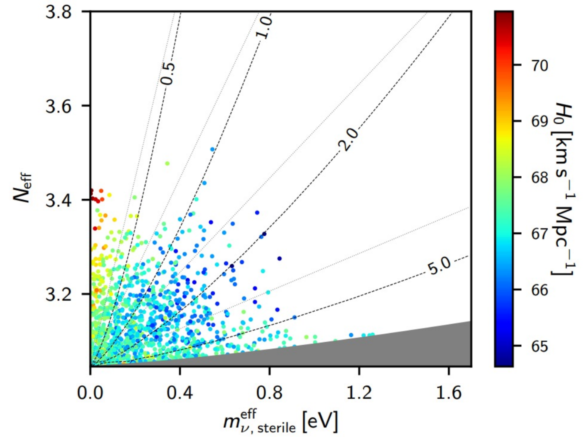
Compare $\triangle N_{\rm eff}$ and $m_s^{\rm eff}$ from the power spectrum.

$$m_s^{\rm eff} = \Omega_s h^2 (94.1{\rm eV}),\ m_s \Delta N_{\rm eff} = m_s^{\rm eff}$$

$N_{\rm eff} < 3.29,\ m_{\nu_s}^{\rm eff} < 0.65\ {\rm eV}$ in a condition of $m_s \leq 10\ {\rm eV}$

Planck 2018 Collaboration IV(2020)

Planck 2018 Collaboration IV(2020)



- **Lyman-α forest constraints**

Connection between WDM and sterile neutrino from free streaming scale

Relation between sterile neutrino & WDM:

$$m_s = 4.46{\rm keV}\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{\frac{4}{3}}\left(\frac{10.75}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.12}{\Omega_{\nu_s}h^2}\right)^{\frac{1}{3}}$$

G. Gelmini et. al. (2018)
Viel et. al. (2005)

Current limit:

$$\frac{\Omega_{s,\rm lim}(m_{\rm WDM})h^2}{\Omega_{\rm DM}h^2} = \frac{m_{\rm WDM}}{7.2\ {\rm keV}} + 0.1$$

D. C. Hooper et. al., arXiv:2206.08188

- **Phase space bound**

Phase space density of Fermion gas is limited.

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

Tremaine, Gunn (1979)

- **Neutrino oscillation experiments**

Daya Bay & MINOS+ collaboration

P. Adamson et al. (Daya Bay Collaboration, MINOS+ Collaboration) (2020)

Dodelson-Widrow (DW) Scenario

Production by thermal scatterings induced via active-sterile neutrino mixing

Dodelson, Widrow(1994)
Abazajian, Fuller, Patel(2001)
Abazajian(2005)
Rehagen, Gelmini(2014)

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

$$\frac{\partial f_s(E,t)}{\partial t} - HE\frac{\partial f_s(E,t)}{\partial E} = \frac{1}{4}\sin^2(2\theta_M)\Gamma_\alpha(f_\alpha - f_s)$$

where

$$\Gamma_\alpha \approx 1.27 \times G_F^2 T^4 E$$

$$\sin^2(2\theta_M) = \frac{\sin^2(2\theta)}{\sin^2(2\theta) + [\cos(2\theta) - 2E\, V_T(T)/m_s^2]^2}$$

$$V_T(T) = -\frac{8\sqrt{2}G_F E}{3}\left(\frac{\rho_\alpha}{m_W^2} + \frac{\rho_{\nu_\alpha}}{m_Z^2}\right)$$

&

H: Hubble rate
E: Energy of ν_s
T: Photon temperature
f_i: Phase density of ν_i
θ: Mixing angle between ν_e & ν_s
ρ_i: Energy density of the particle i.

Dominant production occurs near QCD phase transition epoch.

$$T_{\rm max} \simeq 108\ {\rm MeV}(m_s/{\rm keV})^{1/3}$$

The temperature where $\frac{\partial(n_s/n_\alpha)}{\partial \log T}$ is the max. under the constant g_*.

Dodelson, Widrow(1994)

Dodelson-Widrow (DW) Scenario

y and Hubble rate are as follows:

$$y \equiv E/T, \;\; H = \sqrt{\frac{\pi^2 g_*}{30}} \frac{T^2}{M_{\rm Pl}}.$$

By using relations,

$$\frac{\partial f_s(E,t)}{\partial t} - HE\frac{\partial f_s(E,t)}{\partial E} \simeq -HT\left(\frac{\partial f_s(y,T)}{\partial T}\right)_y$$

(assuming g_* as a constant).

Again, by changing f_s into $f_s = f_\alpha[1 - e^{-f_{s,0}/f_\alpha}]$,

$$-HT\left(\frac{\partial f_{s,0}(y,T)}{\partial T}\right)_y \simeq \frac{1}{4}\sin^2(2\theta_M)\Gamma_\alpha(y,T)f_\alpha(y)$$

($f_s(y,T)$ in the RHS is omitted).

$$\Rightarrow \;\; f_s \simeq -\int_\infty^{T_0} \frac{1}{4HT}\sin^2(2\theta_M)\Gamma_\alpha(y,T)f_\alpha(y)dT$$

Number density and energy density of ν_s are

$$n_s(T) = \frac{2}{(2\pi)^3}\int_0^\infty f_s(E/T,T)4\pi E^2 dE = \frac{2}{(2\pi)^3}T^3\int_0^\infty f_s(y,T)4\pi y^2 dy, \quad \rho_s(T_0) \simeq m_s n_s(T_0).$$

Gravitational Clustering

- The local number density of the sterile neutrino

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

- Fitting formulae

$$f_c(m_s) = \left[1 + 0.008 \left(\frac{\mathrm{keV}}{m_s}\right)^2 \left(\frac{\mathrm{kpc}}{r_\odot}\right)\right]^{-1}, \quad m_s \in [0.05, 1]\ \mathrm{keV}$$

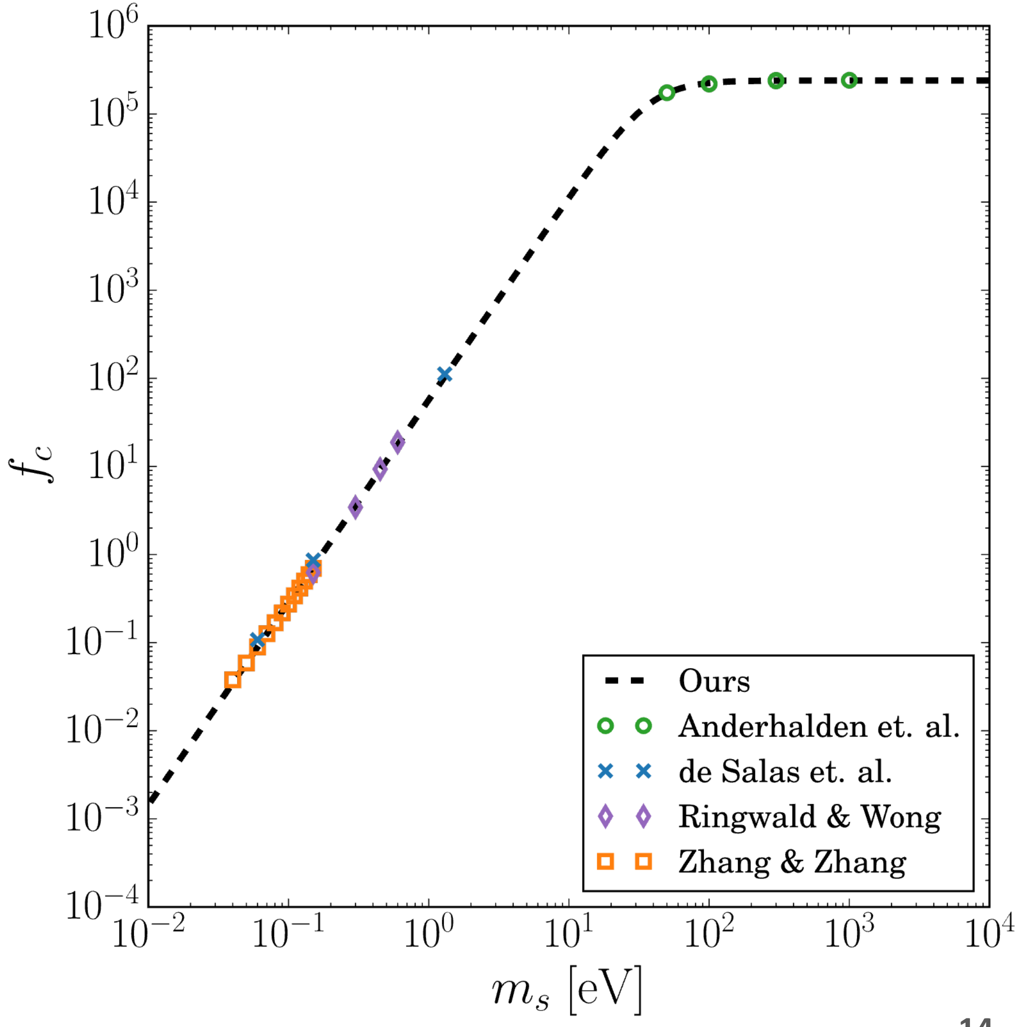
D. Anderhalden et. al. (2012)

$$f_c(m_s) = 76.5 \left(\frac{m_s}{\mathrm{eV}}\right)^{2.21}, \quad m_s \in [0.04, 0.15]\ \mathrm{eV}$$

Zhang, Zhang (2018)

The lower formula is consistent until ~1 eV.

P. F. de Salas et. al. (2018)



Gravitational Clustering

- New Fitting formula

$$f_c(m_s) = f_{c,\mathrm{DM}}\left[1+\left(a\frac{\mathrm{keV}}{m_s}\right)^b\right]^{-c/b}, \quad f_{c.\mathrm{DM}} = 2.4\times 10^5$$

Fitting values for a, b, c are as follows:

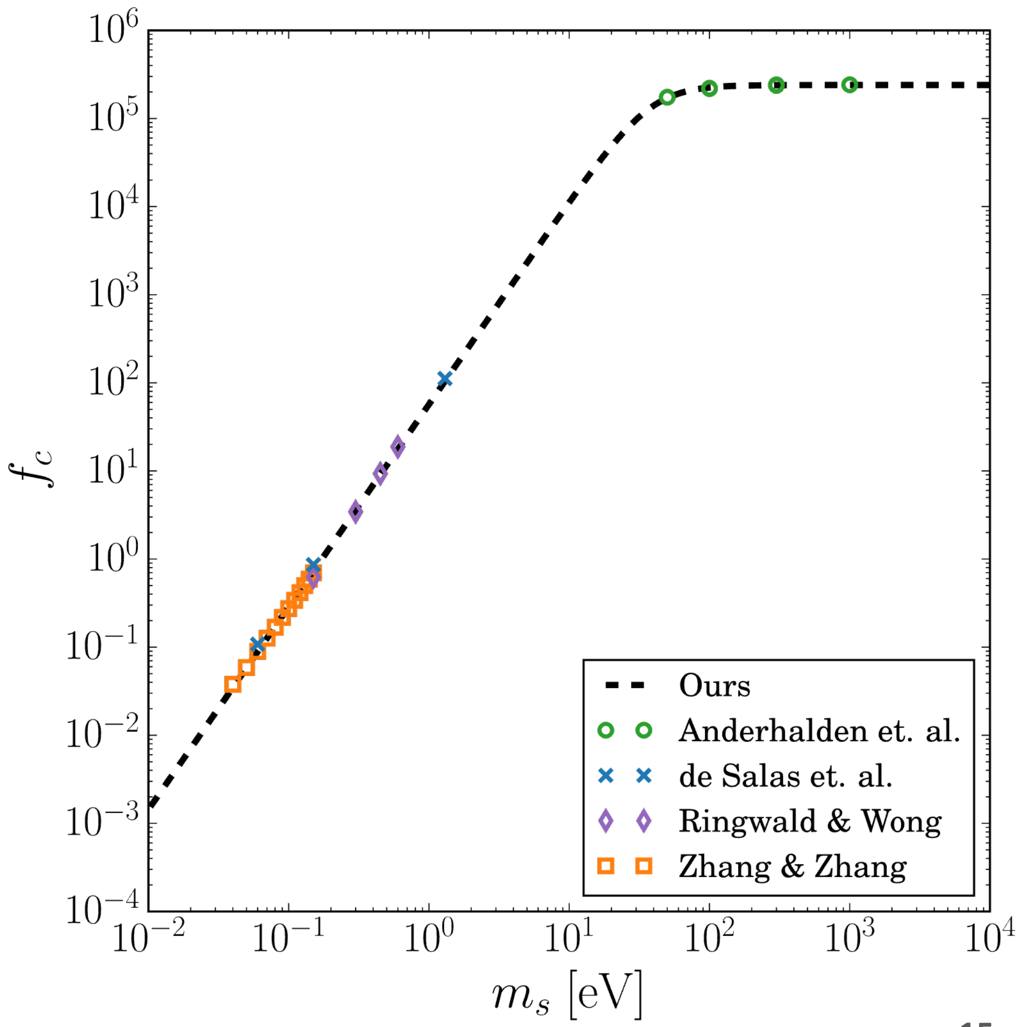
$$a = 0.37, b = 2.61, c = 2.3.$$

This works for any WDM as a sub-component DM.

Full N-body simulation is not yet done.

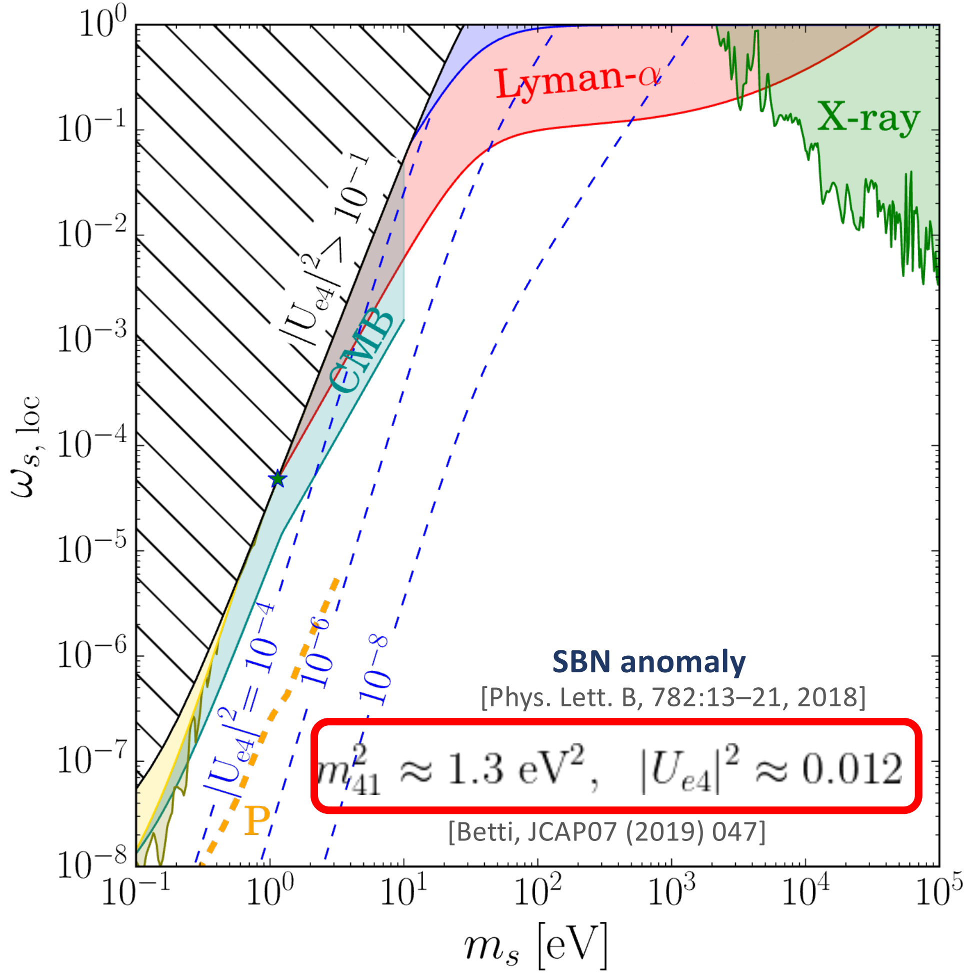
→ Uncertainty remains.

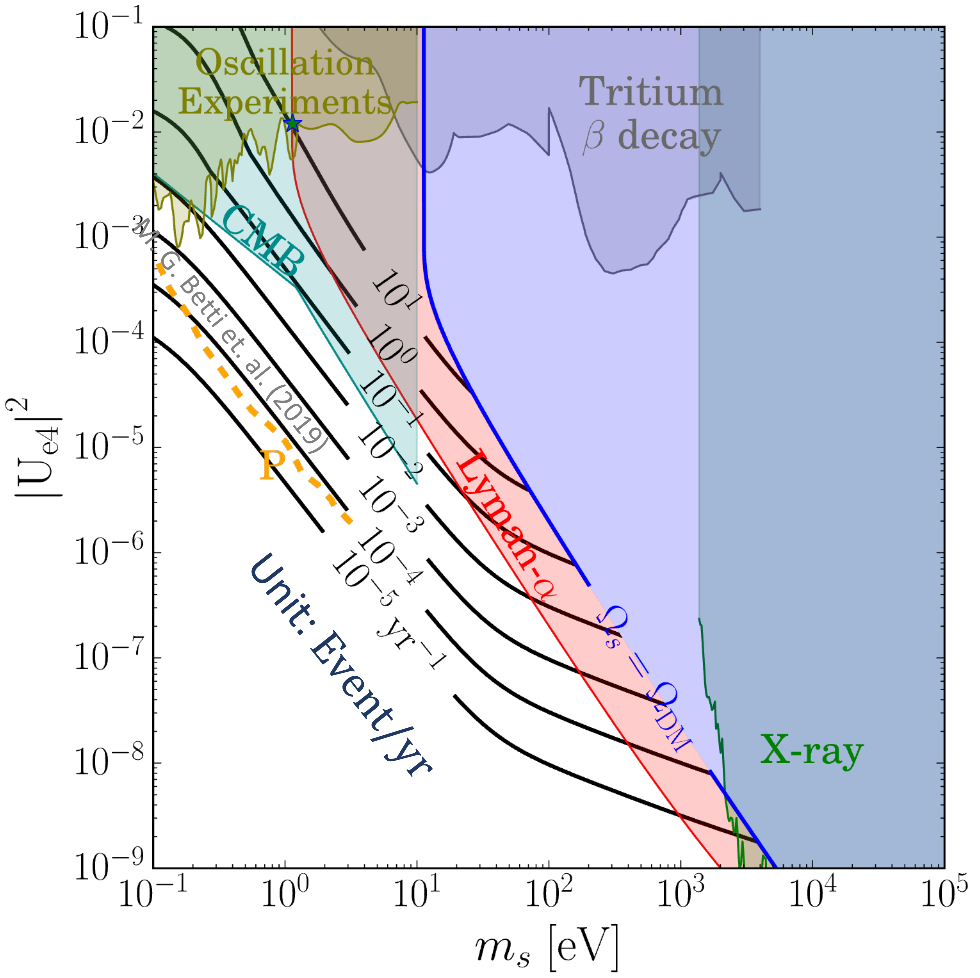
Calculation is done!



Results on DW Scenario

$\omega_{s,\mathrm{loc}}$: Local density ratio of ν_s / DM





$$\Gamma_s \lesssim 0.1\ \mathrm{yr}^{-1}$$

Low Reheating Temperature Scenario

✓ If reheating of the universe ends early enough that could satisfies the inequality below.

Gelmini et. al. (2004), Hasegawa, JCAP, 08:015, (2020)

$$T_{\rm RH} \lesssim T_{\max} \simeq 108~\mathrm{MeV}\left(\frac{m_s}{\mathrm{keV}}\right)^{1/3}$$

✓ Sterile neutrino production suppressed!

→ Large mixing sterile neutrino can constitute the dark matter.

→ The lowest bound of reheating temperature from BBN is $T_{\rm RH} \gtrsim 2~\mathrm{MeV} \sim 5~\mathrm{MeV}$.

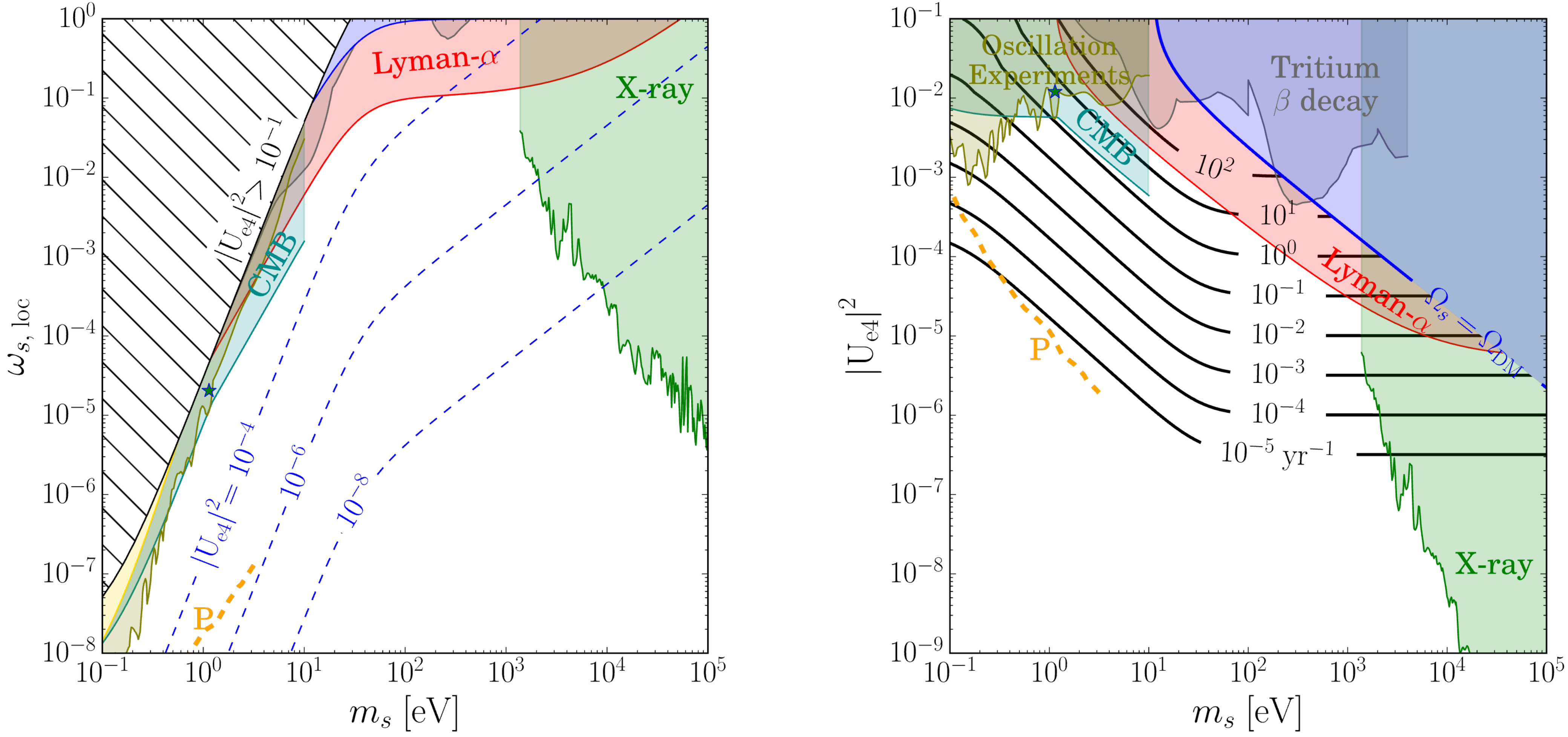
Hasegawa, JCAP, 08:015, (2020)

$$-HT\left(\frac{\partial f_{s,0}(y,T)}{\partial T}\right)_y \simeq \frac{1}{4}\sin^2(2\theta_M)\Gamma_\alpha(y,T)f_\alpha(y)$$

$$f_s \simeq -\int_{\infty}^{T_0}\frac{1}{4HT}\sin^2(2\theta_M)\Gamma_\alpha(y,T)f_\alpha(y)dT \quad \Rightarrow \quad f_s \simeq -\int_{T_{\rm RH}}^{T_0}\frac{1}{4HT}\sin^2(2\theta_M)\Gamma_\alpha(y,T)f_\alpha(y)dT$$

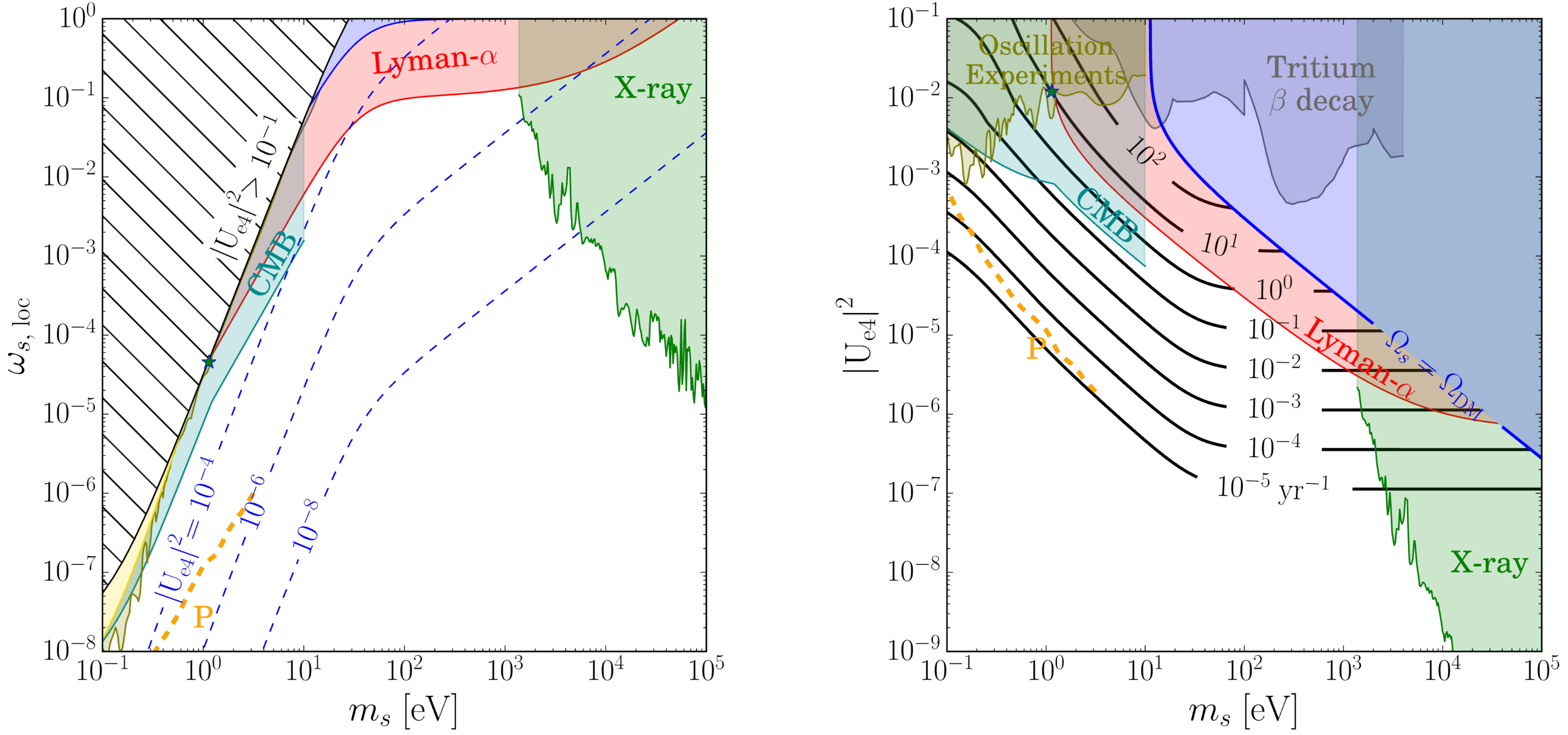
DW Scenario ⇒ RH Scenario

Results on LRT Scenario, $T_{\mathrm{RH}} = 5\ \mathrm{MeV}$



$\Gamma_s \lesssim 10\ \mathrm{yr}^{-1}$

Results on LRT Scenario, $T_{\mathrm{RH}} = 10\ \mathrm{MeV}$



$\Gamma_s \lesssim 1\ \mathrm{yr}^{-1}$

Late-Time Phase Transition Scenario

✓ Right-handed neutrino N have a Yukawa interaction with unknown scalar particle ϕ, which doesn't interact (much) with standard particles, and have a VEV after T_C.

$$\mathcal{L} = i\bar{N}\not{\partial}N + Y_\nu H\bar{\nu_\alpha}N + \frac{\lambda}{2}\phi\bar{N}^c N + h.c.$$

1. Before the phase transition of ϕ:
   - From the mass insertion approximation,

$$\left(\frac{\partial f_s(y,T)}{\partial T}\right)_y \simeq -\frac{1}{2}\frac{M_D^2}{E^2}\frac{\Gamma_\alpha}{HT}f_\alpha \qquad \Rightarrow \qquad f_s \approx \frac{8\times 10^{-7}|U_{e4}|^2}{y}\left(\frac{10.75}{g_*(T_{\mathrm{RH}})}\right)\left(\frac{m_s}{\mathrm{keV}}\right)\left(\frac{T_{\mathrm{RH}}}{5\ \mathrm{MeV}}\right)f_\alpha.$$

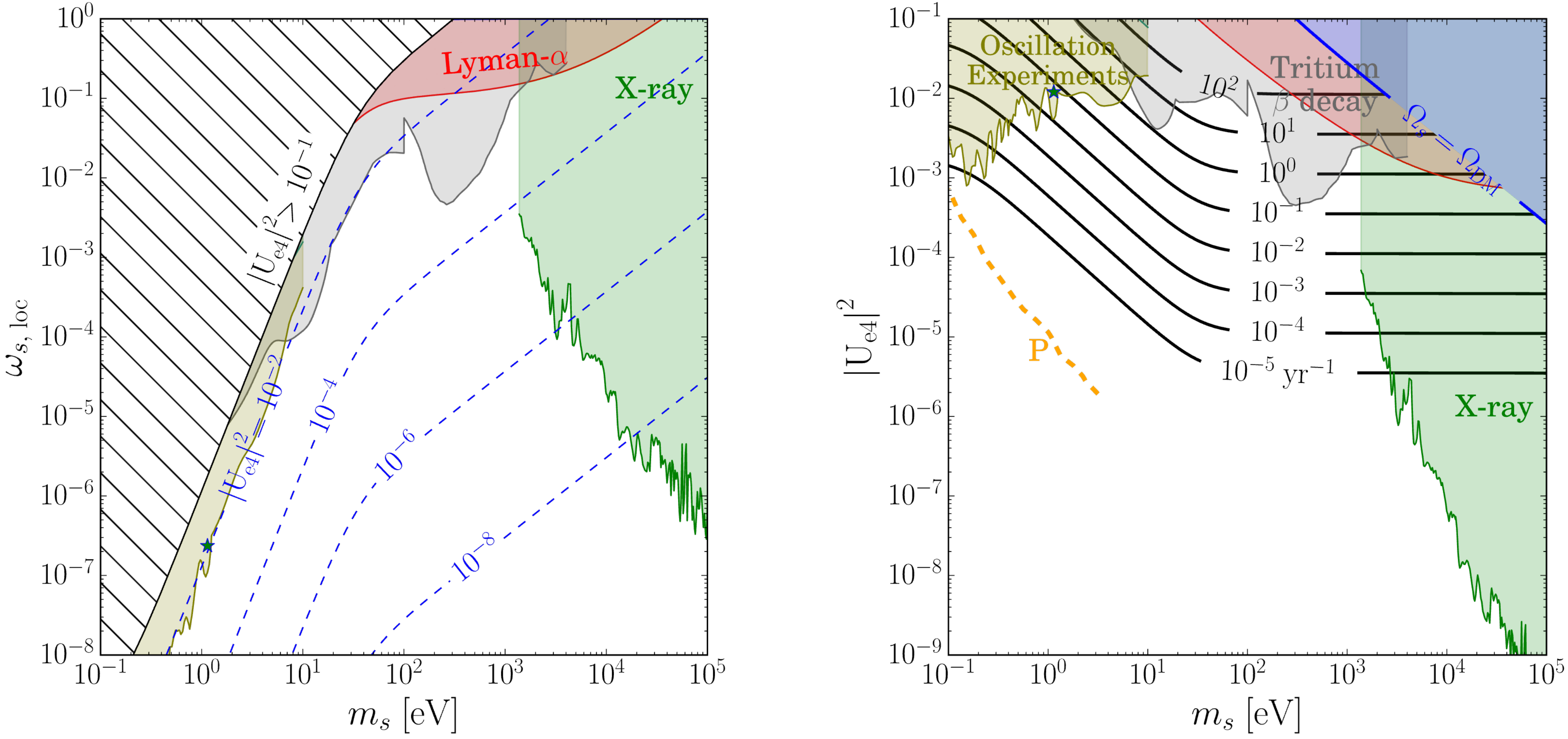
   - Note that f_s diverges if $T_{\mathrm{RH}} = \infty$, but if $T_{\mathrm{RH}} \sim \mathrm{MeV}$, $f_s \ll 1$.

2. After the phase transition of ϕ:

$$f_s \simeq -\int_{T_c}^{T_0}\frac{1}{4HT}\sin^2(2\theta_M)\Gamma_\alpha(y,T)f_\alpha(y)dT$$

By combining, we get total f_s.
The contribution from <T_C won't matters for low reheating temperature.

Results on PT Scenario, $T_C = 1$ MeV



$\Gamma_s \lesssim 10\ \mathrm{yr}^{-1}$

Conclusion

- We consider the capture rate of sterile neutrino in the PTOLEMY-like experiment depending on two different cosmological models.
- We 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
  - LRT & PT: up to$\sim\vartheta(10)$ events per year
- If sterile neutrino would be detected in PTOLEMY, it will give us fruitful information of $C\nu_s B$ and light dark matter candidate.
  - 10 events per year → reheating temperature can be low? or other interesting scenarios?
- If not, PTOLEMY would give a direct constraints on sterile neutrino, unlike CMB & Lyman-α forest.

Thank you for your attention.