Probing cosmic sterile neutrino background with beta-decay experiments

JCAP 06(2023) 021, arXiv:2212.14192

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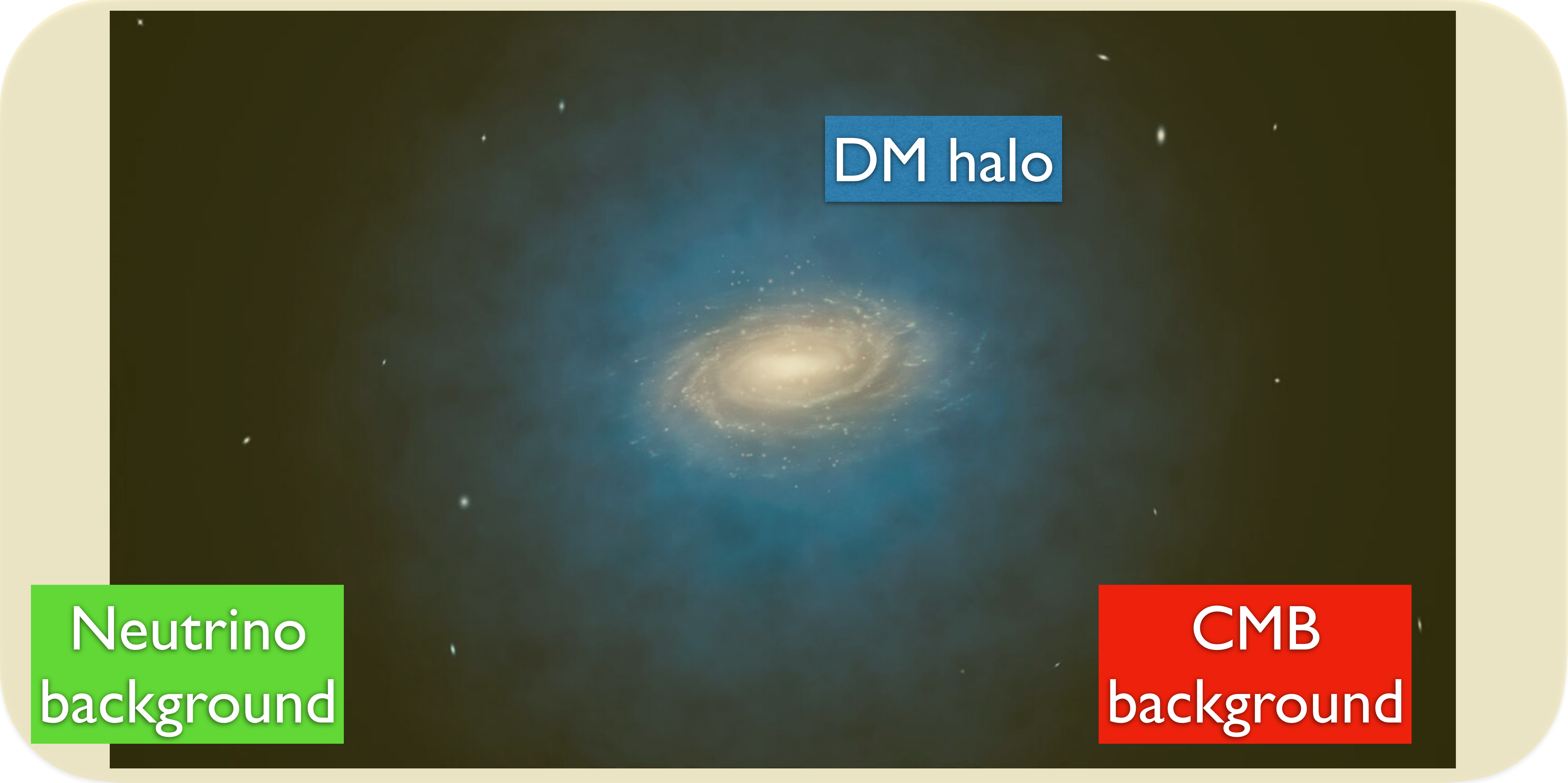
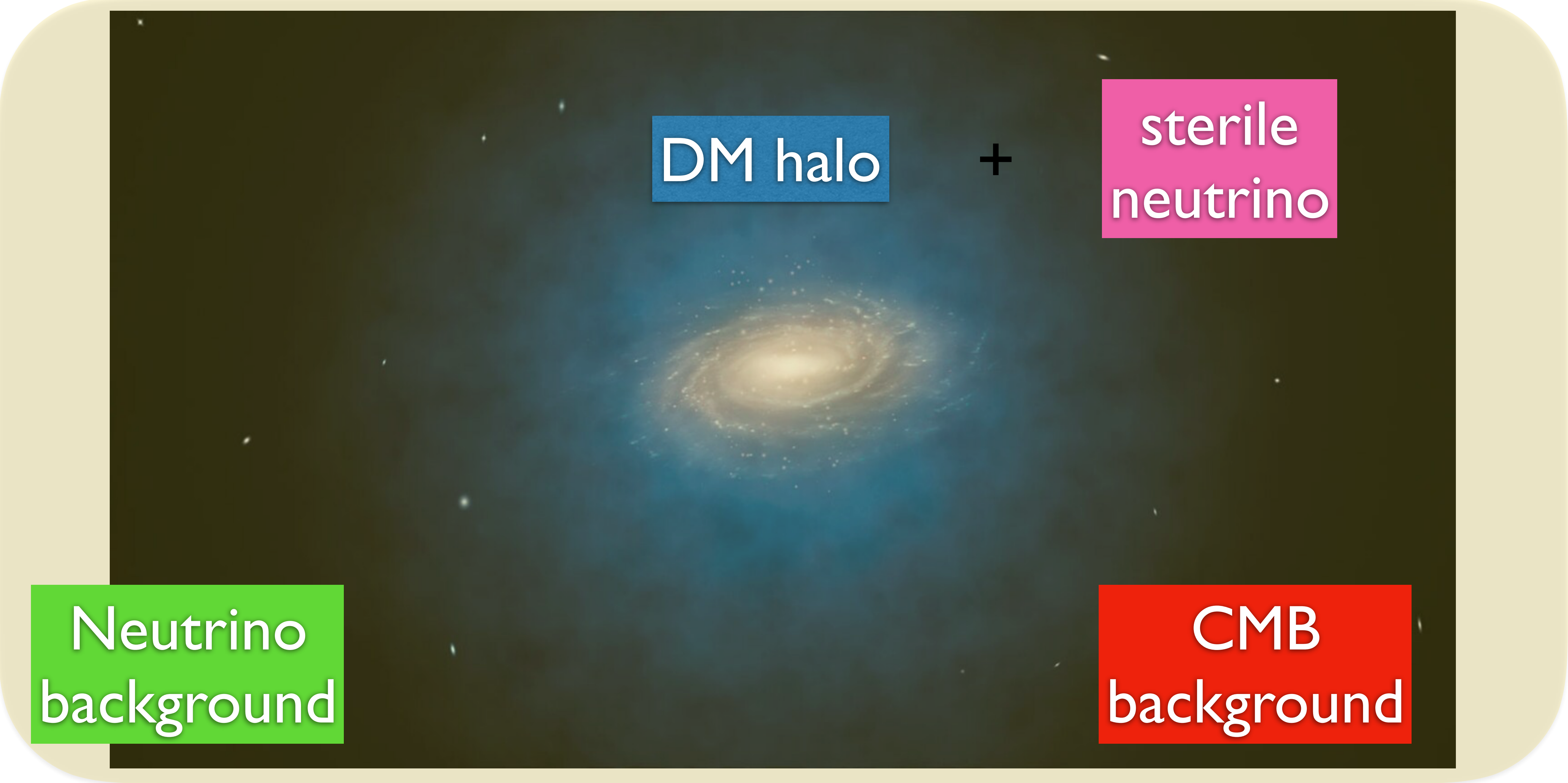
5-9 December, Busan

DM and neutrino around Milky Way



L. Calcada/European Southern Observatory)

DM and neutrino around Milky Way



DM halo

+

sterile neutrino

Neutrino background

CMB background

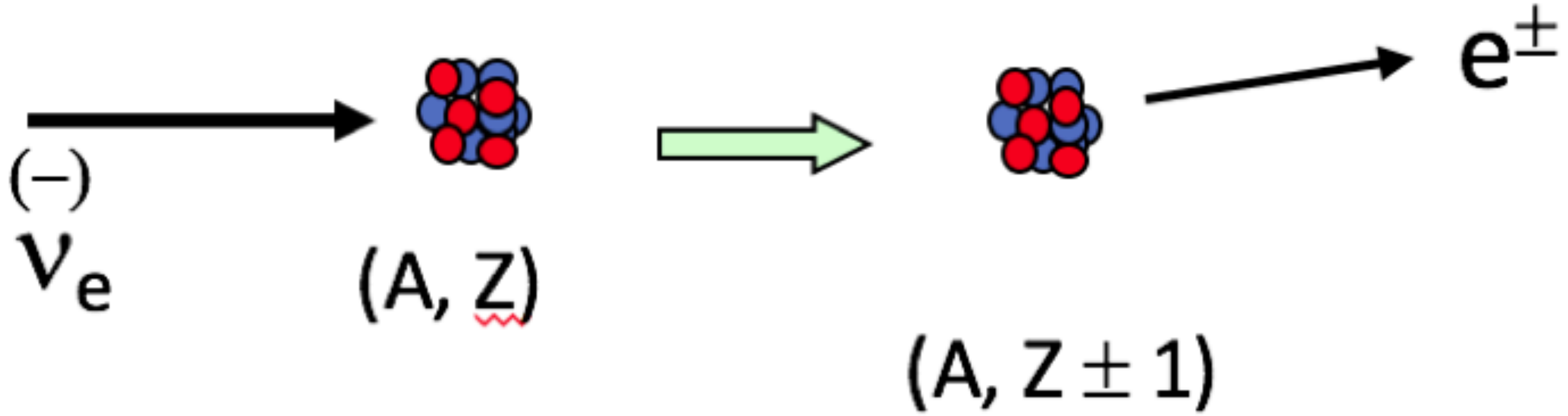
L. Calcada/European Southern Observatory)

Sterile Neutrino

Motivation for sterile neutrino,

- to explain neutrino mass for explaining the oscillation of the active neutrinos
- to explain possible anomalies in the neutrino oscillation in the short baseline experiments
- to explain the asymmetry of matter-antimatter in the Universe through leptogenesis

Neutrino Capture on a Beta Decaying Nucleus (NCB)



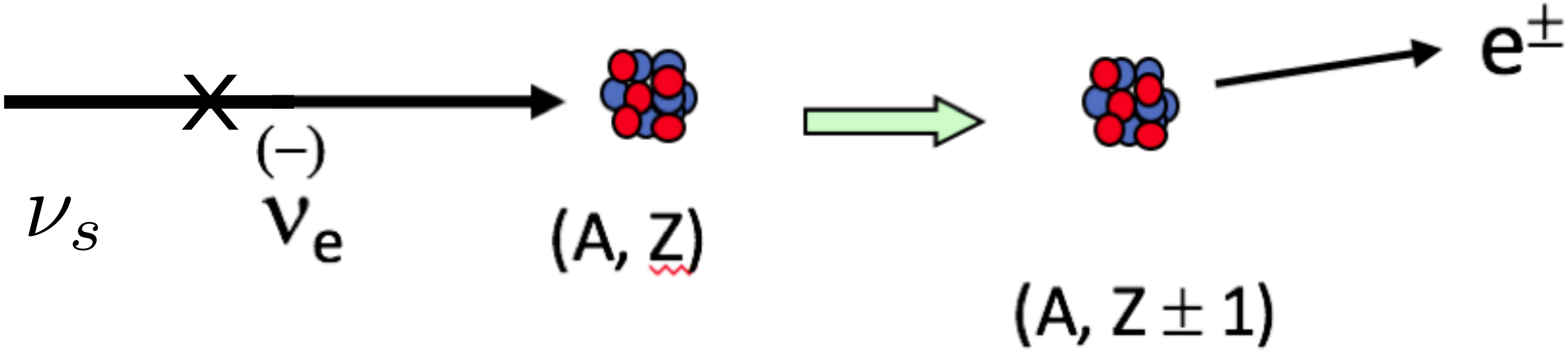
$\overset{(-)}{\nu}_e$

(A, Z)

(A, Z ± 1)

$e^{\pm}$

sterile Neutrino Capture on a Beta Decaying Nucleus (NCB)



Neutrino Mass Measurement

Neutrino in cosmology

The only EM neutral and stable particles in SM, neutrino, is hot dark matter with small fraction.

Neutrinos decouple from a relativistic thermal bath at T~ 1 MeV in the early Universe with a relic density today for non-relativistic ones (at least two)

$$\left(\frac{T_\nu}{T_\gamma}\right)^3 = \frac{4}{11} \qquad \boxed{\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94\mathrm{eV}}} \qquad \ll \Omega_{DM} h^2$$

It is too small amount!

↑

With observational constraints

$$\sum m_\nu < 0.12\,\mathrm{eV} \quad (95\,\%\ \mathrm{CL}).$$

[Planck 2018]

The fluctuations are damped if smaller than the neutrino free streaming scale

$$\lambda_{FS} \sim 20 \left(\frac{30\ \mathrm{eV}}{m_\nu}\right)\ \mathrm{Mpc}$$

It is too hot! top-down structure formation

Tremaine-Gunn bound (1979): minimal mass for fermion DM (if it is 100%) is around 400 eV due to exclusion principle.

It is too light!

Cosmic Neutrino background (CNuB)

The neutrinos decoupled in the early Universe exist around the Universe, which make background today in the same way as the CMB for photon.

Background neutrino number density (for one flavor)

$$n_\nu = n_{\nu,0} + n_{\bar{\nu},0} = 112(1+z)^3 \ \mathrm{cm}^{-3}$$

The mean velocity of non-relativistic neutrino background

$$\langle v_\nu \rangle \simeq 1.6 \times 10^3 (1+z) \left(\frac{0.1\,\mathrm{eV}}{m_\nu} \right) \mathrm{km/s}$$

The average kinetic energy of the neutrinos

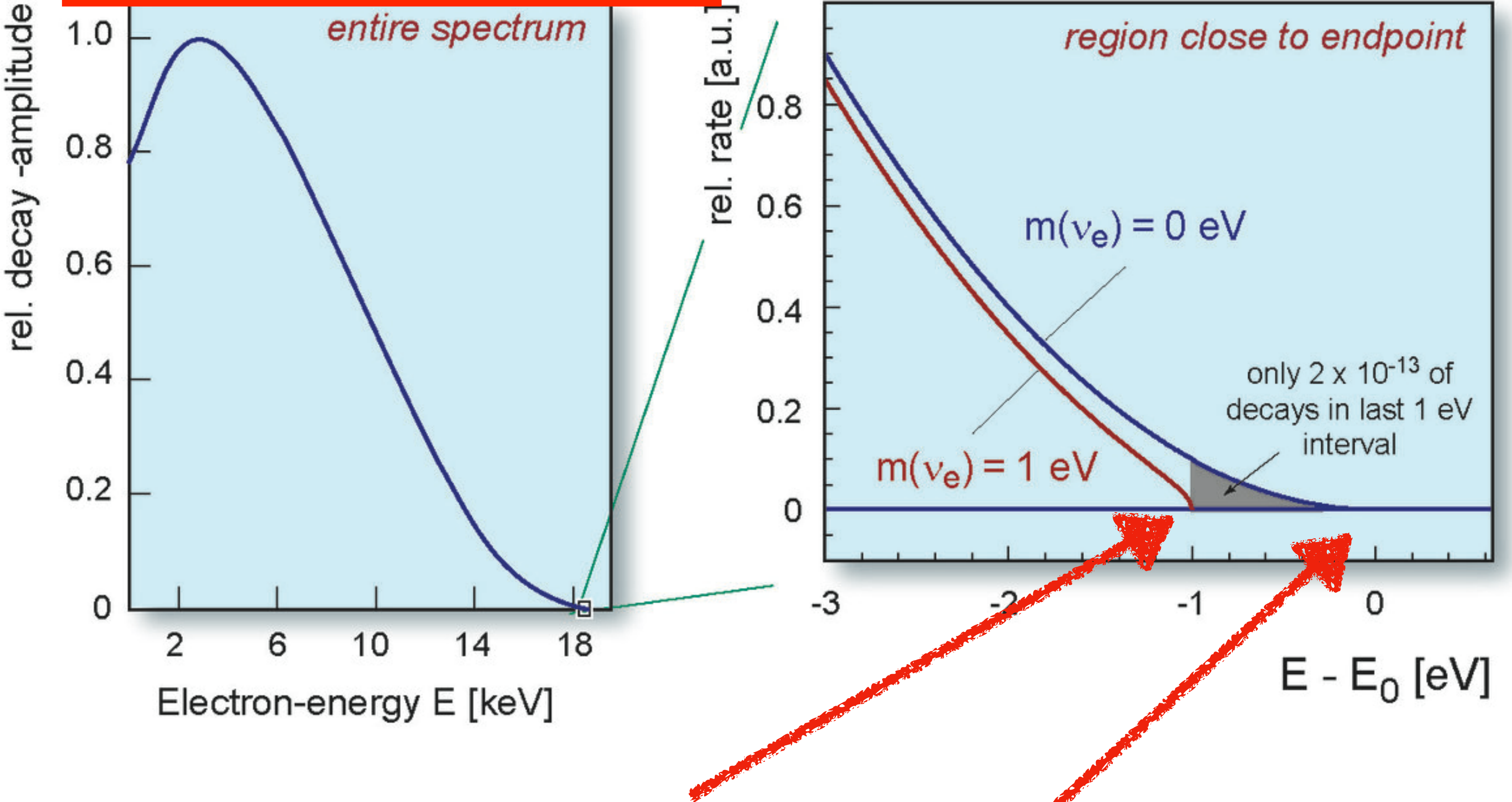
$$T_\nu = \frac{1}{2} m_\nu \langle v_\nu^2 \rangle \simeq 1.4 \times 10^{-9}\,\mathrm{keV} (1+z)^2 \left(\frac{0.1\,\mathrm{eV}}{m_\nu} \right)$$

* $(1+z)^3 = \left(\frac{t_{\mathrm{age}}}{t} \right)^2$ evolution of redshift z in the matter-dominated Universe

Neutrino mass from beta decay

$$\boxed{T_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e}$$

Lifetime 12.3 yrs



$$K_{\mathrm{end}} = \frac{(m_{^3\mathrm{H}} - m_e)^2 - (m_{^3\mathrm{He}} + m_\nu)^2}{2m_{^3\mathrm{H}}}$$

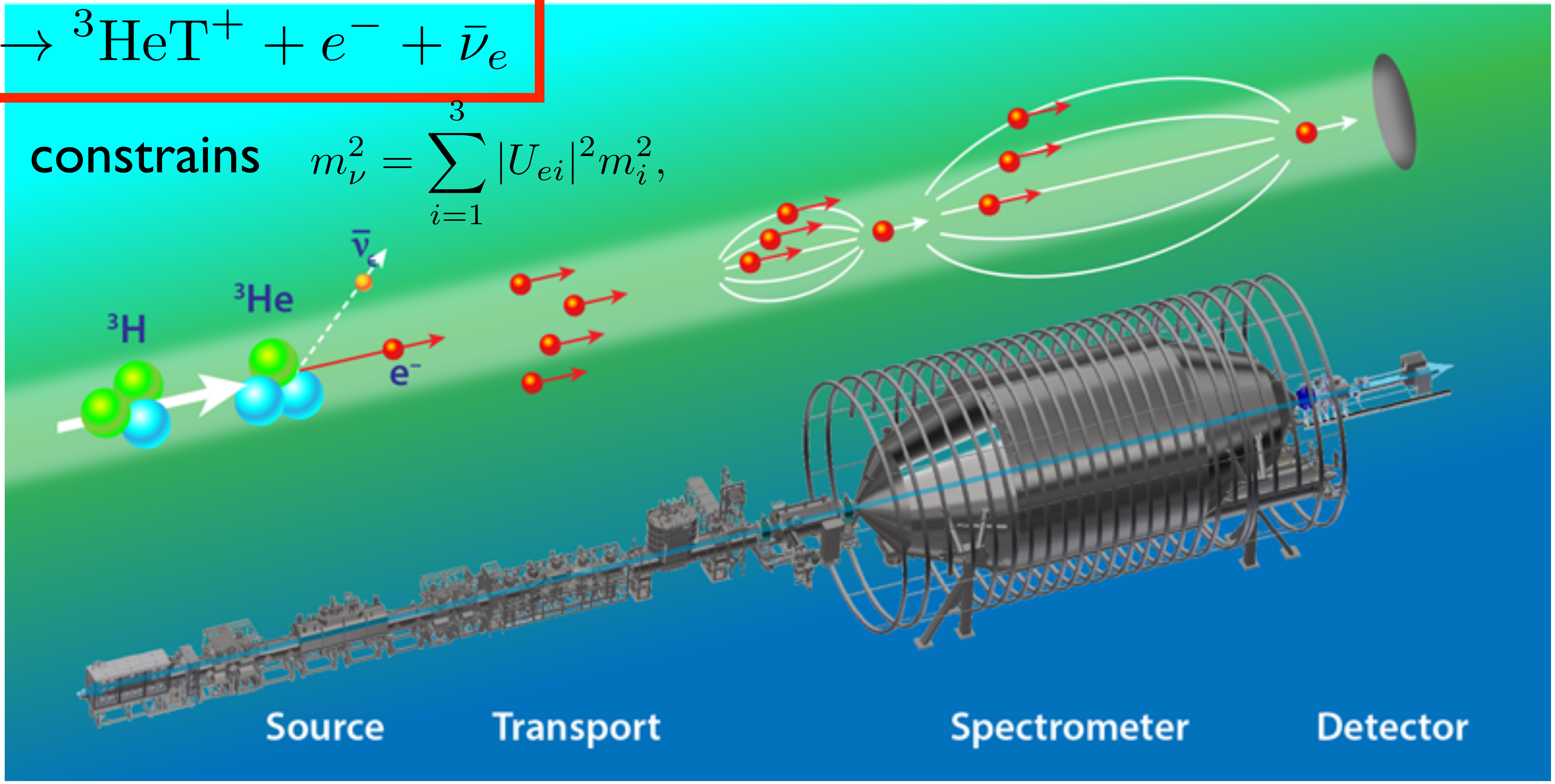
$E_0 = 18.57\,\mathrm{keV}$ for Tritium decay

KATRIN experiment

Karlsruhe **Tri**tium **N**eutrino Experiment

$$\mathrm{T}_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e$$

constrains $m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2,$



KATRIN; adapted by APS/**Alan Stonebraker**

First Measurement campaign (2019) $m_\nu \leq 1.1\,\mathrm{eV}$ $(90\,\%\ \mathrm{C.L.})$ [PRL, 2019 (1909.06048)]

Second Measurement campaign $m_\nu \leq 0.8\,\mathrm{eV}$ $(90\,\%\ \mathrm{C.L.})$ [Nature Physics, 2022 (2105.08533)]

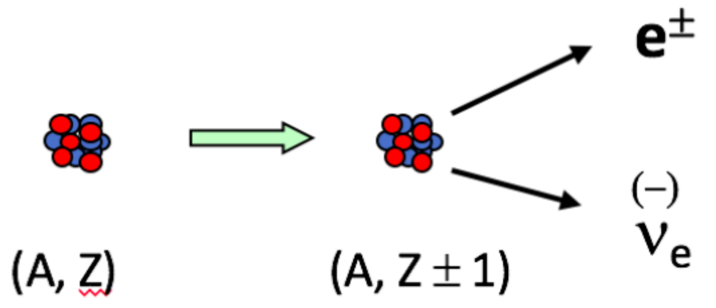
: 40 eV - E0 with 3.76×10^6 tritium β-electrons

Energy resolution $\Delta = 1$ eV

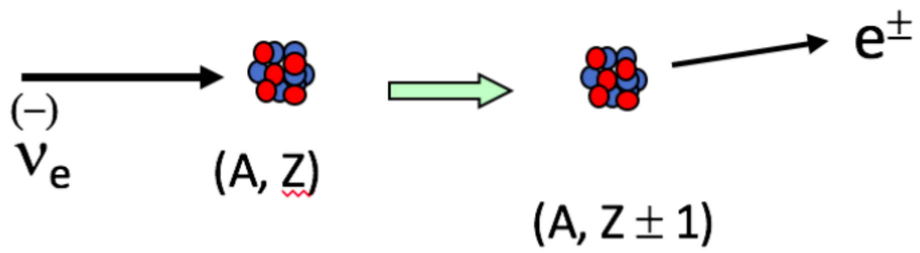
Cosmic Neutrino Background

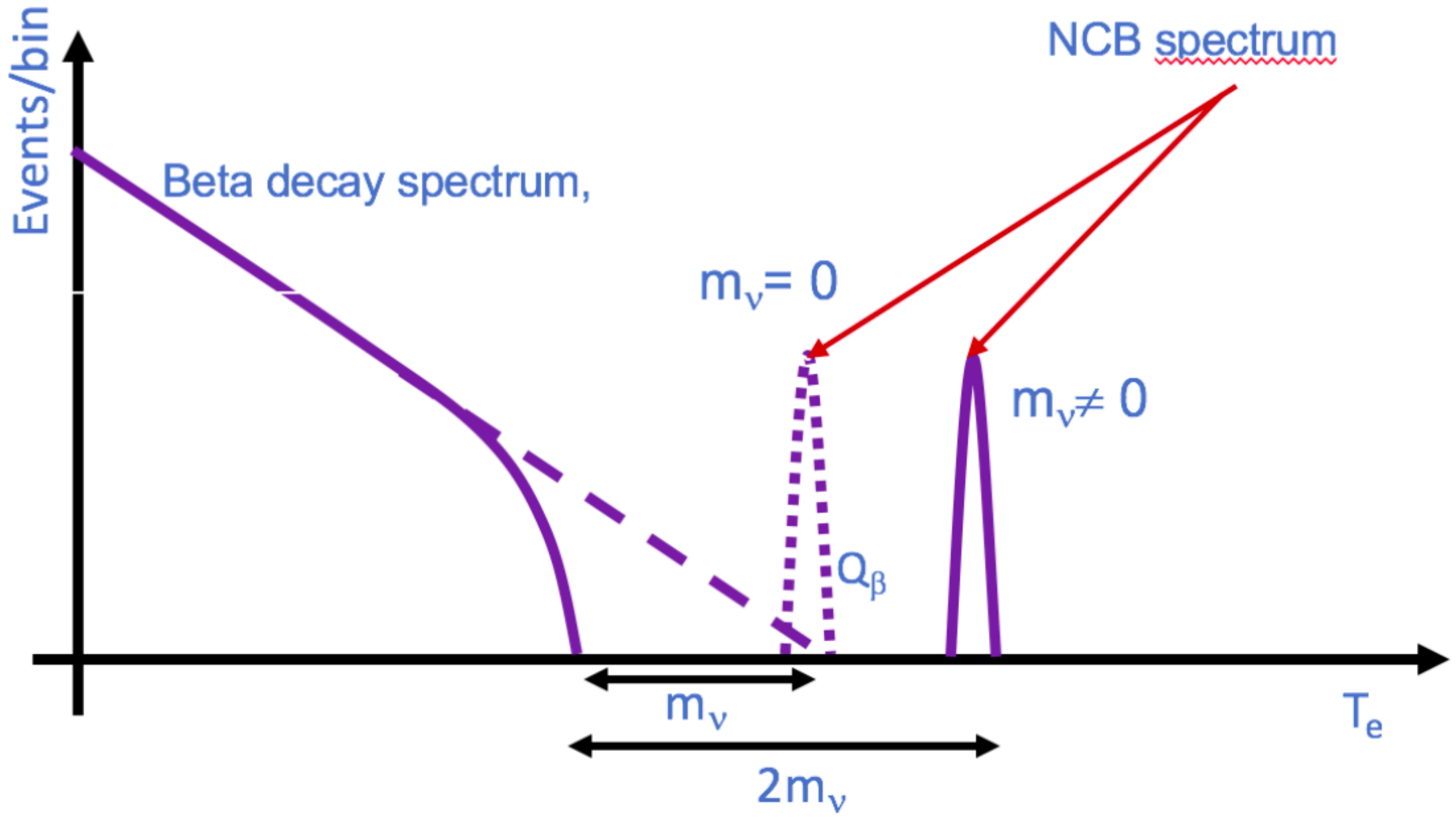
Electron spectrum from Cosmic Neutrino Background (CnuB)

β decay



Neutrino Capture on a
Beta Decaying Nucleus (NCB)





[Figure from Messina at Vulcano Workshop 2018]

Beta decay spectrum

Observed spectrum after convolution with resolution $\Delta = 2\sqrt{2\ln 2}\sigma \simeq 2.35\sigma$

$$\frac{d\tilde{\Gamma}}{dE_e} = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty} dE'_e \frac{d\Gamma}{dE'_e}(E'_e)\exp\left[-\frac{(E'_e - E_e)^2}{2\sigma^2}\right]$$

from the beta decay spectrum

$$\frac{d\Gamma_\beta}{dE_e}(E_e) = \sum_{j=1}^{3} |U_{ej}|^2 \frac{\bar{\sigma}}{\pi^2} H(E_e, m_{\nu_j}) N_T,$$

U_{ej} Pontecorvo-Maki-Nakagawa-Sakata(PMNS) matrix

$$N_T = m_T / m_{^3\mathrm{H}}$$

$$\bar{\sigma} \simeq \sigma_e v_\nu \simeq 3.834 \times 10^{-45}\,\mathrm{cm}^2,$$

$$H\left(E_e, m_{\nu_j}\right) = \frac{1 - m_e^2/\left(E_e m_{^3\mathrm{H}}\right)}{\left(1 - 2E_e/m_{\mathrm{H}} + m_e^2/m_{3_{\mathrm{H}}}^2\right)^2} \sqrt{y\left(y + \frac{2m_{\nu_j} m_{^3\mathrm{He}}}{m_{\mathrm{H}}}\right)} \left[y + \frac{m_{\nu_j}}{m_{^3\mathrm{H}}}\left(m_{^3\mathrm{He}} + m_{\nu_j}\right)\right]$$

$$y = m_e + K_{\mathrm{end}} - E_e$$

Capture rate of CnuB

Spectrum from CnuB capture

$$\frac{d\Gamma_{C\nu B}}{dE_e} = \Gamma_{C\nu B}\,\delta[E_e - (E_{\rm end} + 2m_\nu)],$$

Observed spectrum after convolution energy resolution

$$\boxed{\Delta = 2\sqrt{2\ln 2}\sigma \simeq 2.35\sigma}$$

$$\frac{d\tilde{\Gamma}}{dE_e} = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty} dE_e' \frac{d\Gamma}{dE_e'}(E_e') \exp\left[-\frac{(E_e' - E_e)^2}{2\sigma^2}\right]$$

$\Gamma^{\rm D}_{C\nu B} = \bar{\sigma} n_0 N_T$ for Dirac neutrino

$\Gamma^{\rm M}_{C\nu B} = 2\bar{\sigma} n_0 N_T$ for Majorana neutrino

average neutrino density

$$n_0 = 56\,{\rm cm}^{-3}$$

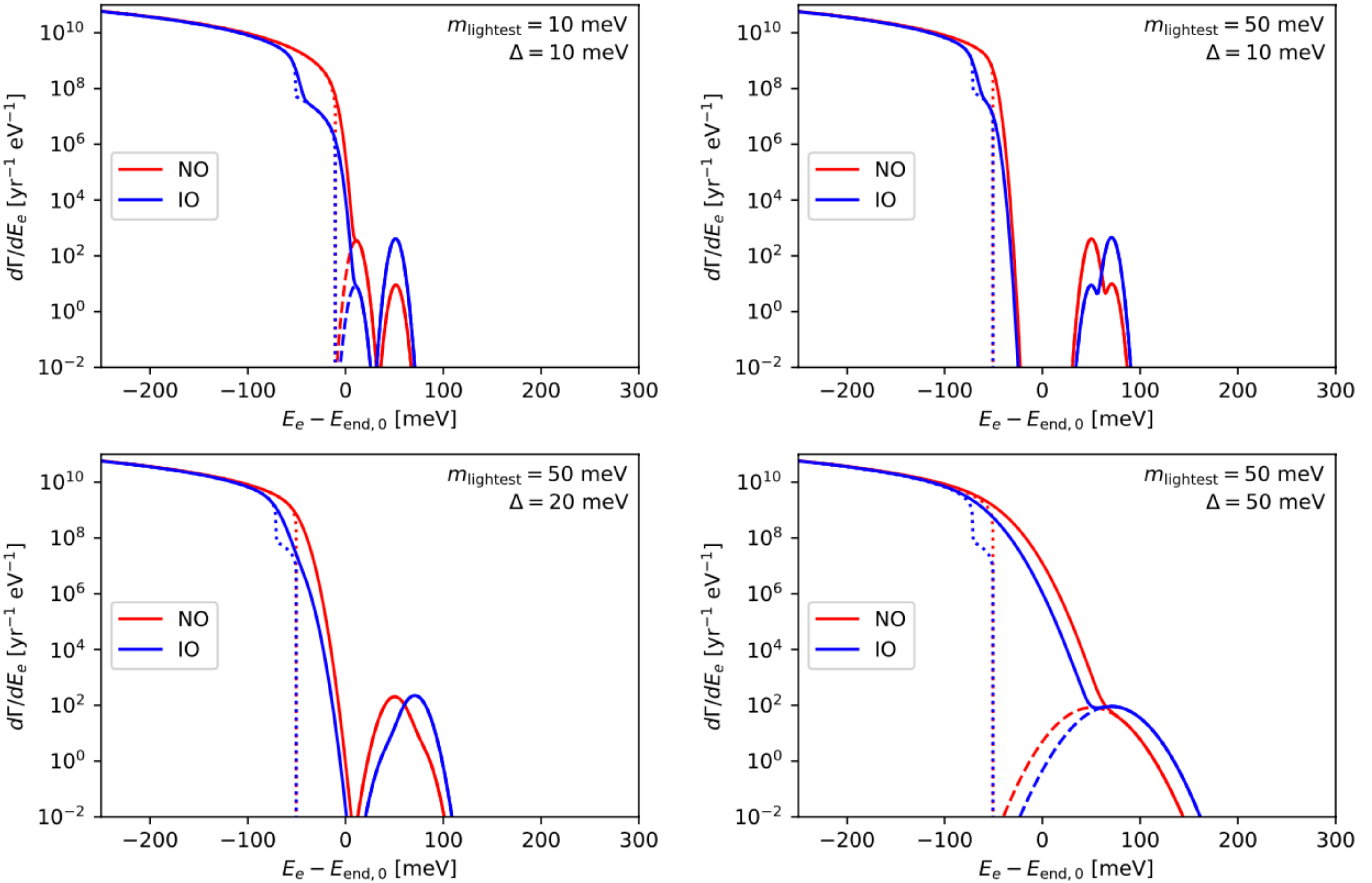
Energy resolution $\Delta \sim 0.15$ eV using hydrogenated graphene

[PTOLEMY, 1808.01892]

with 100 g of Tritium

Expected event rates with PTOLEMY

[PTOLEMY, 2019]
1902.05508



dotted: assuming perfect energy resolution

solid: total with assumed energy resolution

Sterile Neutrino Dark Matter

Neutrino Minimal Standard Model (nuMSM)

[Asaka, Blanchet, Shaposhnikov, 2005]

$$(\nu_R)^c \equiv C\,\overline{\nu_R}^T$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \underbrace{i\overline{\nu_R}\partial\!\!\!/\nu_R}_{\text{singlet RH neutrino}} - \underbrace{\overline{\ell_L}F\nu_R\tilde{\Phi} - \tilde{\Phi}^\dagger\overline{\nu_R}F^\dagger\ell_L}_{\text{Yukawa coupling: Dirac mass with non-zero Higgs VEV}} - \underbrace{\frac{1}{2}(\overline{\nu^c_R}M_M\nu_R + \overline{\nu_R}M_M^\dagger\nu^c_R)}_{\text{Majorana mass}}.$$

$$\ell_L = (\nu_L, e_L)^T$$

$$\tilde{\Phi} = \epsilon\Phi^*$$

Three RH neutrinos with Majorana mass and Yukawa couplings.

After electroweak symmetry breaking, the mass term

$$\frac{1}{2}(\overline{\nu_L}\ \overline{\nu^c_R})\begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix} + h.c.,$$

The hierarchy $m_D \equiv Fv \ll M_M$ gives mass eigenvalues with

three light active neutrinos and three heavy sterile neutrinos.
(See-saw mechanism)

Sterile Neutrinos and mixing

After electroweak symmetry breaking, the mass eigenstates are

interaction eigenstates

$$\boxed{\begin{aligned} B_\mu =& c_W A_\mu - s_W Z_\mu, \\ \nu_{L\alpha} =& U_{\alpha i}\nu_i + \Theta_{\alpha i}\nu^c_{si}, \\ \nu^c_{Ri} =& -(\Theta^\dagger U)_{ij}\nu_j + \nu^c_{si}, \end{aligned}}$$

mass eigenstates

with PMNS matrix U

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

and the mixing parameter

$$\Theta = m_D M_{\nu_R}^{-1} \ll 1,$$

and the light active neutrino mass

$$m_\nu \simeq -m_D \frac{1}{M_{\nu_R}} m_D^T = -\Theta M_{\nu_R} \Theta^T.$$

seesaw mechanism

Interaction of RH Neutrino

RH sterile neutrinos can interact with SM sector through

- Mass mixing after electroweak symmetry breaking

$$\boxed{\Theta = m_D M_{\nu_R}^{-1} \ll 1,}$$

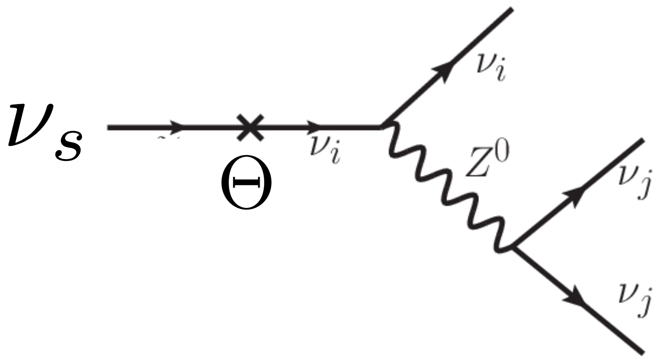
- Yukawa interaction with Higgs and LH neutrino

$$\boxed{y_{\nu\alpha i}\frac{v}{\sqrt{2}} = iU(m_\nu^{\rm diag})^{1/2}\Omega(M_{\nu_R})^{1/2},}$$

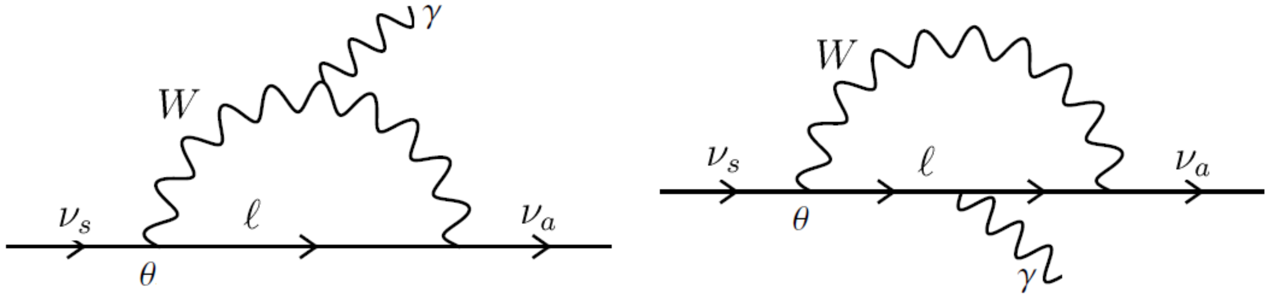
The interaction induces

- Decay of sterile neutrinos into SM neutrino and photon (X-ray)

$$\nu_s \to 3\nu$$



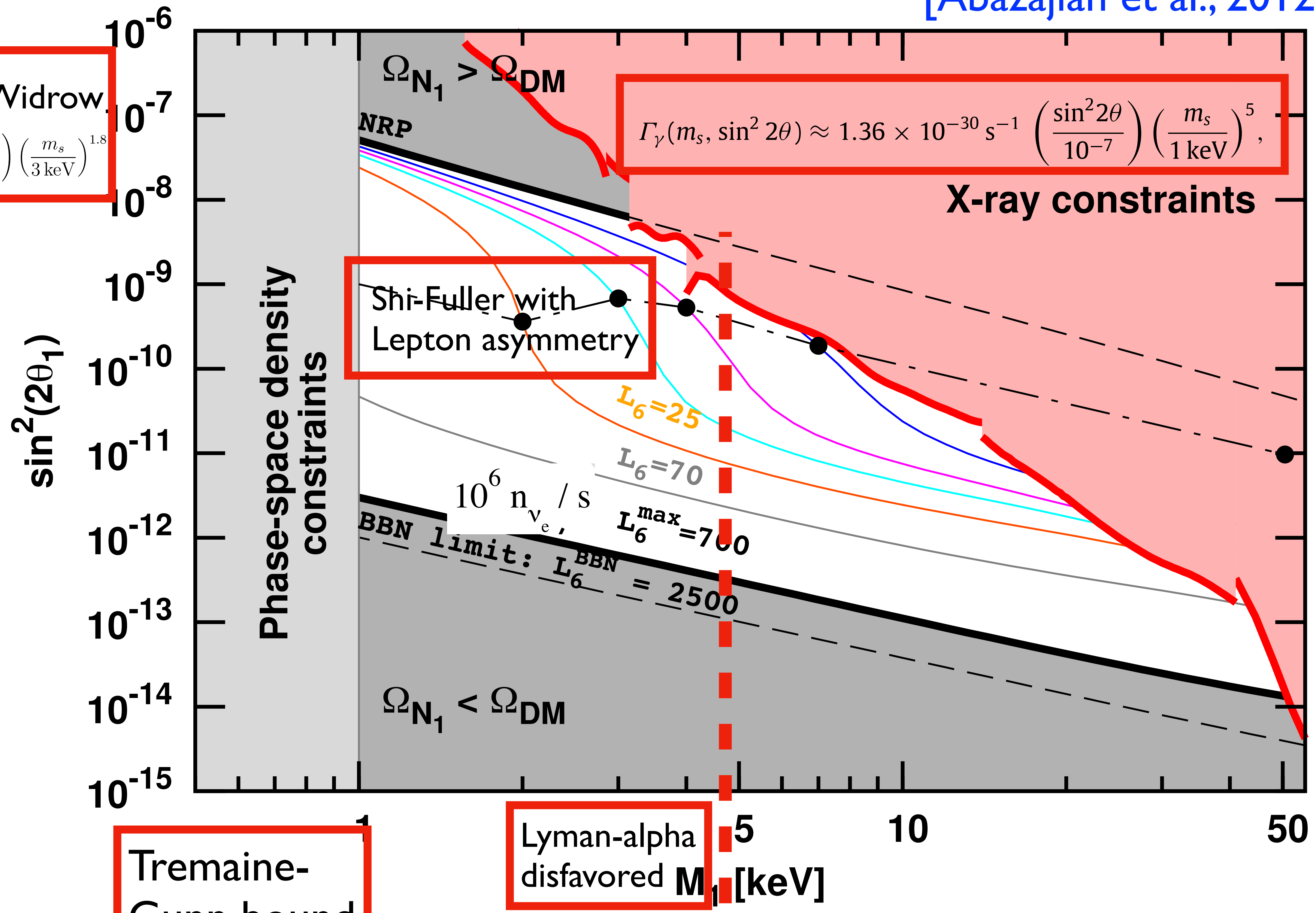
$$\nu_s \to \nu + \gamma$$



Cosmic Sterile Neutrino Background

Sterile Neutrino DM in the nuMSM

[Abazajian et al., 2012]



Dodelson-Widrow

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

$$\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36\times 10^{-30}\,\mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\,\mathrm{keV}}\right)^5,$$

Shi-Fuller with Lepton asymmetry

Lyman-alpha disfavored

Tremaine-Gunn bound

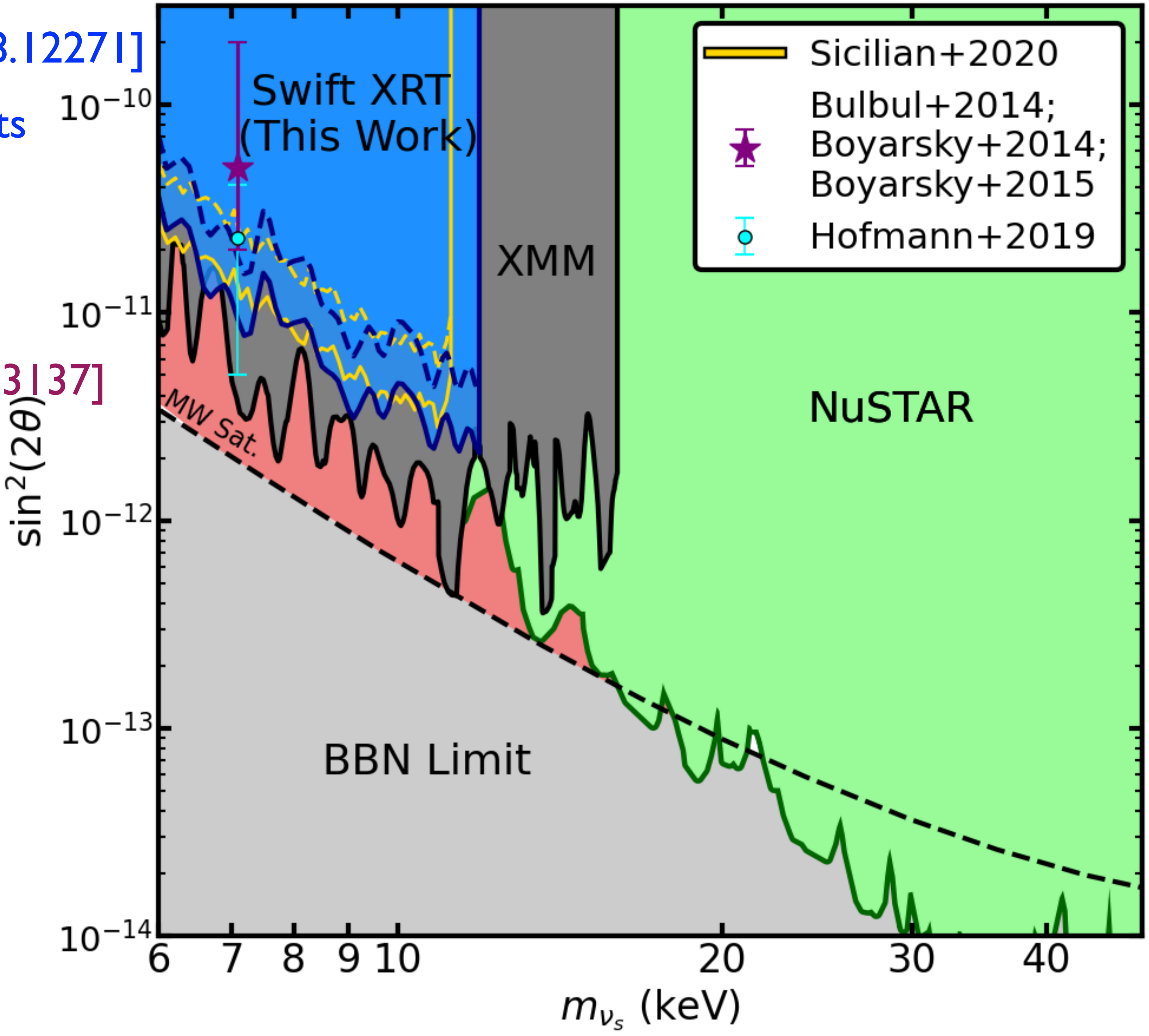
Now, Sterile neutrino 100% DM is ruled out?

[Sicilian etal, 2208.12271]

X-ray constraints

[Dekker etal, 2111.13137]

structure formation of WDM



Sterile neutrino DM in nuMSM

To explain the two mass differences in the neutrino observations, two RH neutrinos are enough. The third RH neutrino, the lightest one around keV, can be DM candidate.

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

Production of DM   oscillation from active neutrinos

- Dodelson-Widrow mechanism (Non-resonant production)

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

- Shi-Fuller (Resonant production) with lepton asymmetry

Decay rate of DM $\nu_s \to 3\nu$

$$\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36\times 10^{-30}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}} \right) \left(\frac{m_s}{1\,\mathrm{keV}} \right)^5,$$

Production of sterile neutrino

Boltzmann equation

[Dodelson, Widrow, 1993]
[Abazajian, Fuller, Pate, 2001]

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

with mixing angle in the matter and the interaction rate with thermal particles

$$\sin^2(2\theta_M) = \frac{\sin^2(2\theta)}{\sin^2(2\theta) + [\cos(2\theta) - 2E\,V_T(T)/m_s^2]^2}, \qquad \Gamma_\alpha \approx 1.27 \times G_F^2 T^4 E,$$

potential in matter $V_T = -BT^4E, \quad \text{and} \quad B \sim \begin{cases} 10.88 \times 10^{-9}\ \mathrm{GeV}^{-4} & T > 2m_e \\ 3.04 \times 10^{-9}\ \mathrm{GeV}^{-4} & T < 2m_e \end{cases}.$

The maximum production rate happens at

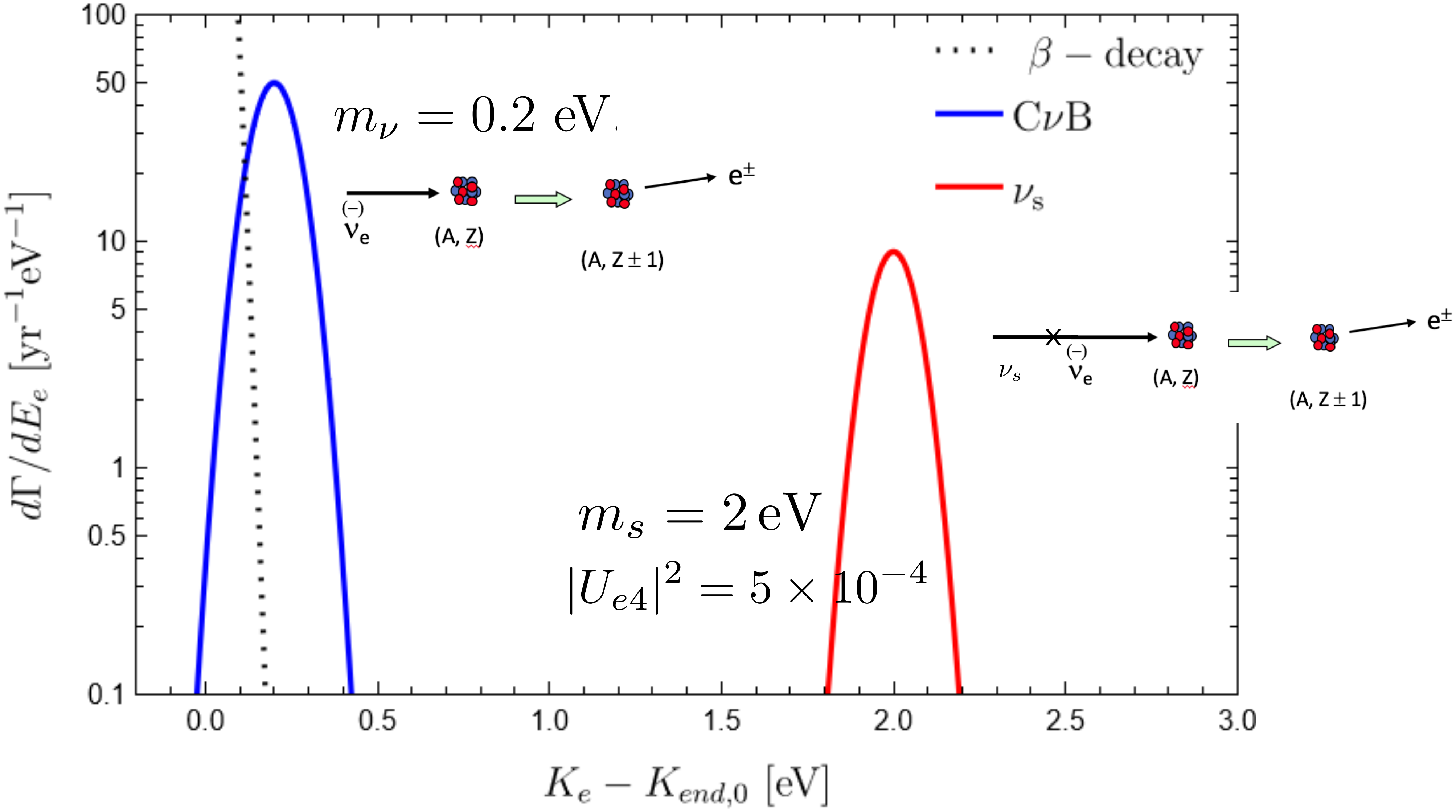
$$T_{\max} \simeq 108\ \mathrm{MeV}\left(\frac{m_s}{\mathrm{keV}}\right)^{1/3}$$

However,
sterile neutrino as small fraction of DM
is still viable!

- Reduced constraints from X-ray observation
- Smaller mass is also viable, safe from the structure formation
- CMB constraints can be reduced

We focus on eV - 100 eV sterile neutrino
with fraction less than 10% of DM energy density

Electron peak spectrum from CSNuB



$m_\nu = 0.2$ eV

$m_s = 2\,$eV

$|U_{e4}|^2 = 5 \times 10^{-4}$

$\Delta \sim 0.15$ eV   with 100 g of Tritium

Local density of sterile neutrinos due to gravitational clustering

$$\boxed{\Gamma_{C\nu_s B} = N_T |U_{e4}|^2 \int dE_{\nu_4} \sigma_e v_{\nu_4} \frac{dn_{\nu_4}}{dE_{\nu_4}} \simeq N_T |U_{e4}|^2 \bar{\sigma} n_{s,\mathrm{loc}}}$$

The local number density of sterile neutrino with clustering

$$n_{s,\mathrm{loc}} = (1 + f_c) n_s = n_s + n_{s,\mathrm{cls}}$$

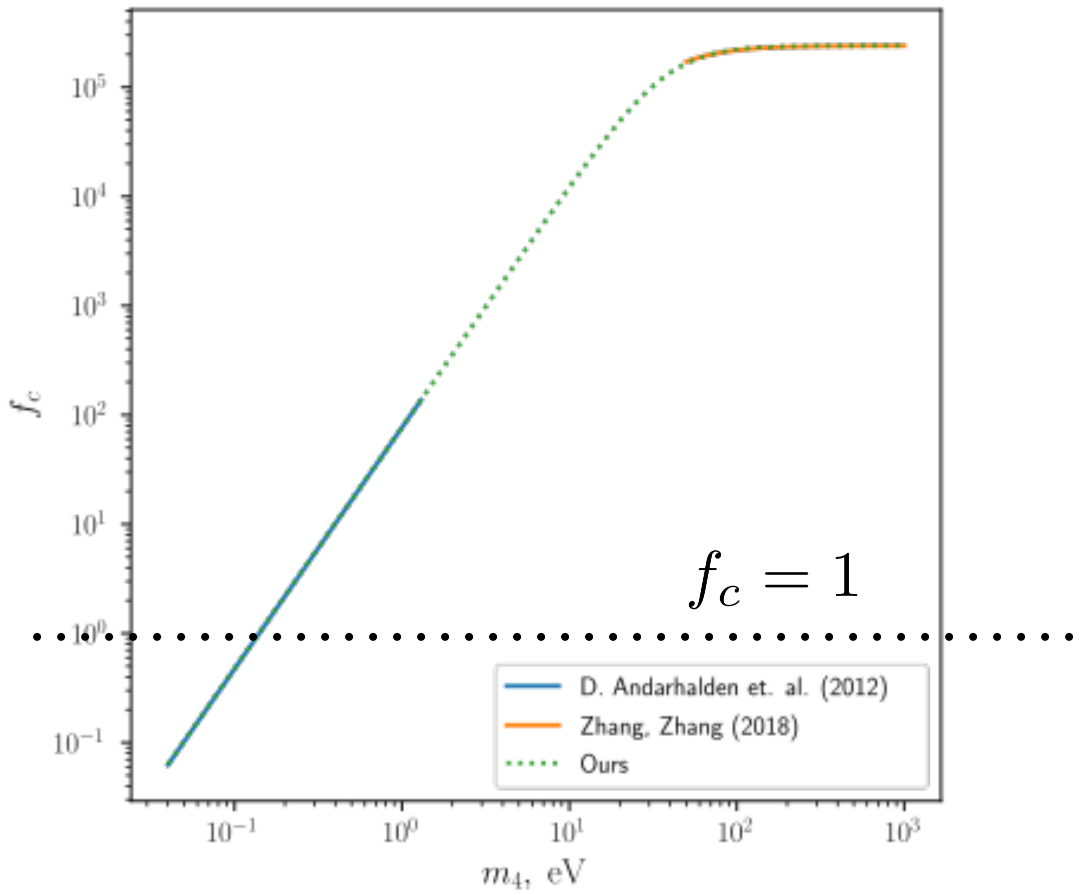
global number density: n_s

clustering effect:

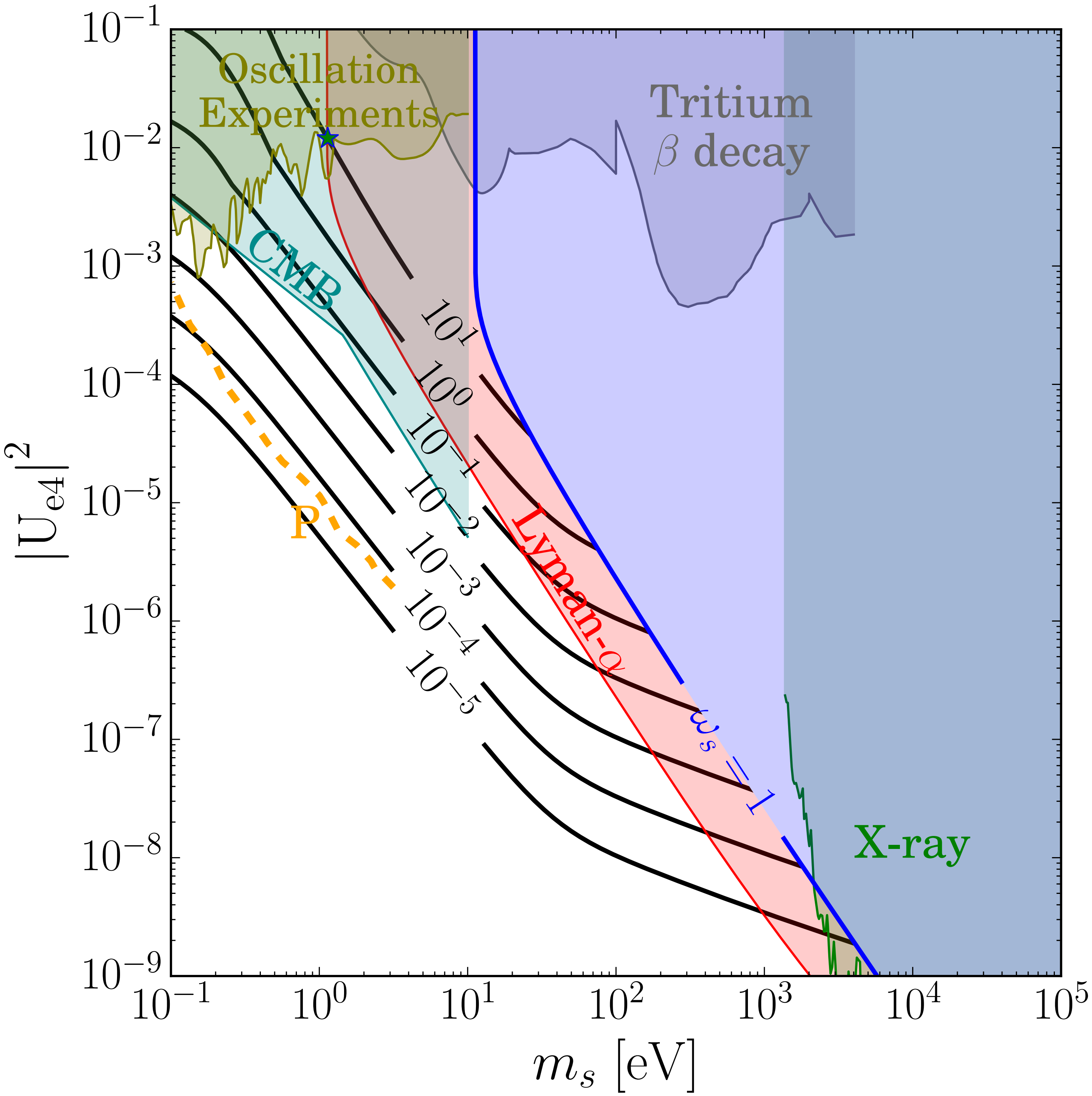
$$f_c(m_s) = f_{c,\mathrm{DM}} \left[1 + \left(a \frac{\mathrm{keV}}{m_s} \right)^b \right]^{-2.21/b}$$

$$f_{c,\mathrm{DM}} = 2.4 \times 10^5$$

$$a = 0.038, \; b = 2.45$$



Capture rate of CSNuB in DW model



Dodelson-Widrow model

less than 0.1 events per year with 100 gram Tritium

Constraints

Oscillation experiments

Beta-decay experiments

X-ray telescope

Phase space bound

CMB, BBN: Neff bound

Lyman-alpha: structure formation

Constraints on $\Delta N_{\rm eff}$

Additional relativistic decoupled particles is parameterized by $\Delta N_{\rm eff}$

$$\rho_s = \Delta N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma,$$

Big Bang Nucleosynthesis (BBN) and cosmic microwave background (CMB) constrains $\Delta N_{\rm eff}$

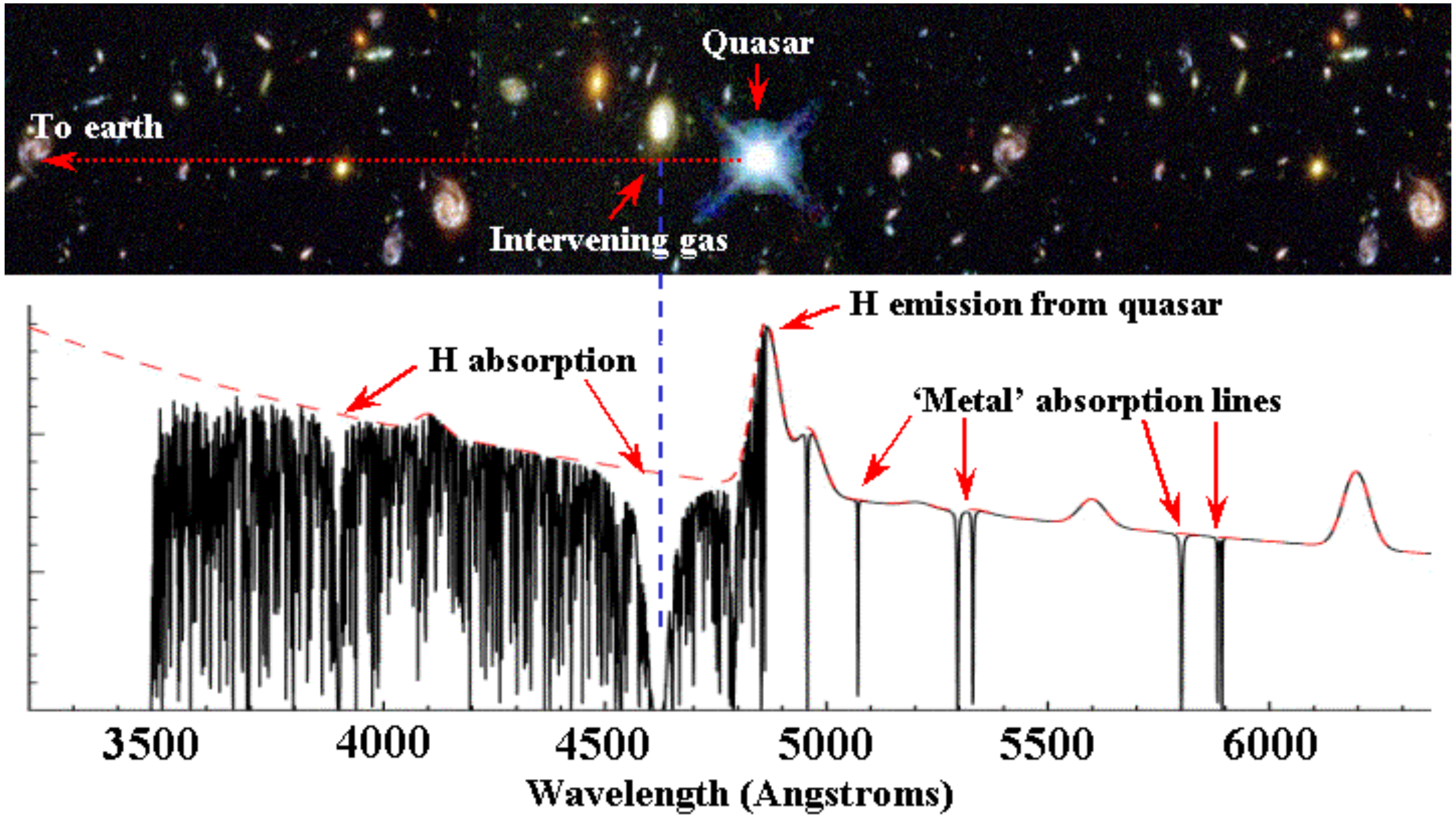
$$\left.\begin{aligned} N_{\rm eff} &< 3.29,\\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.65\ {\rm eV},\end{aligned}\right\}\ \begin{array}{l}\text{95 \%, \textit{Planck} TT,TE,EE+lowE}\\ \text{+lensing+BAO,}\end{array}$$

[Planck 2018]

where $m^{\rm DW}_{\rm sterile} = (\Delta N_{\rm eff})^{-1} m^{\rm eff}_{\nu,\,\rm sterile}$

Constraints on Warm DM from Lyman-alpha

Lyman-alpha forest data constrains the mass of WDM



Constraints on subdominant WDM

For subdominant WDM component, the constraints on the mass is relaxed,

$$m_w \gtrsim m_w^{L-\alpha} \equiv 7.2\,\mathrm{keV}\left(\frac{\Omega_w}{\Omega_{\rm DM}} - 0.1\right)$$ [Hooper etal, 2206.08188]

:mass larger than 7.2 keV or abundance smaller than 10% of DM

Convert the constraints on WDM to the constraints on sterile neutrino DM for the same amount of relic density,

$$m_s^{L-\alpha} = 4.46\ \mathrm{keV}\left(\frac{m_w^{L-\alpha}}{\mathrm{keV}}\right)^{4/3}\left(\frac{10.75}{g_*}\right)^{1/3}\left(\frac{0.12}{\Omega_s h^2}\right)^{1/3}$$ [Viel etal, 2005]

Other scenarios
for the sterile neutrino production

Capture rate of CSNuB in Low-TR model

When the reheating temperature is smaller than $T_{\max} \simeq 108\ \text{MeV} \left(\frac{m_s}{\text{keV}}\right)^{1/3}$

the production is suppressed compared to DW values, and it depends on the reheating temperature.

$$\Omega_s h^2 \simeq 0.5 \left(\frac{|U_{e4}|^2}{10^{-3}}\right) \left(\frac{10.75}{g_*}\right)^{1/2} \left(\frac{m_s}{\text{keV}}\right) \left(\frac{T_R}{5\ \text{MeV}}\right)^3 \qquad T_R \ll T_{\max}$$

Thus, larger mixing angle is required to produce the same amount.

Therefore, the constraints CMB, BBN, Lyman-alpha, which depends on the number density only, change accordingly to larger mixing values.

→ More possibility to capture the CSNuB

which depends on mixing angle as well as number density.

Probing cosmic sterile neutrino in the Low-reheating Temperature

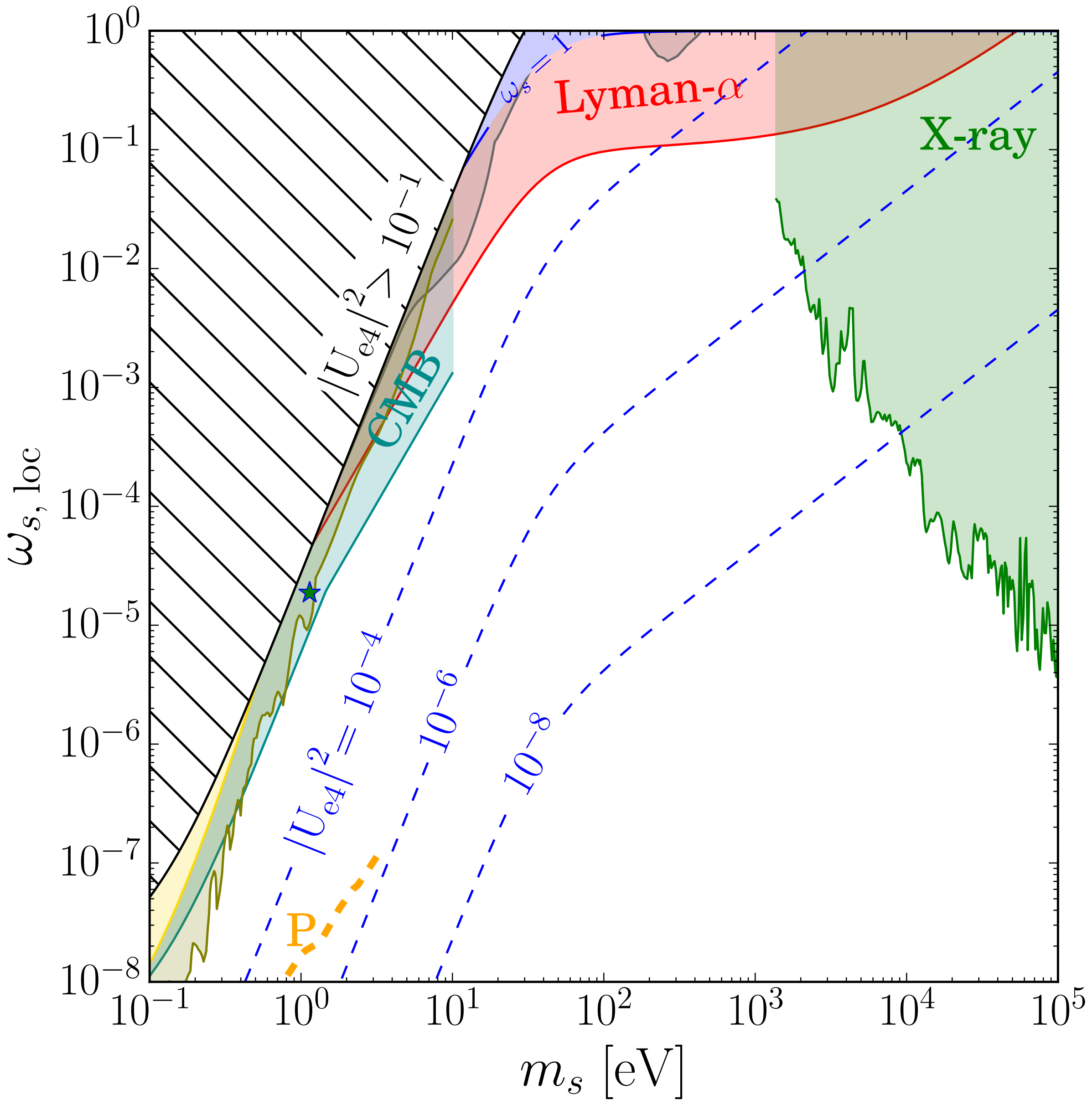
$$\Omega_4 \sim \underset{\nearrow}{\theta^2}\,\underset{\searrow}{\Gamma}$$

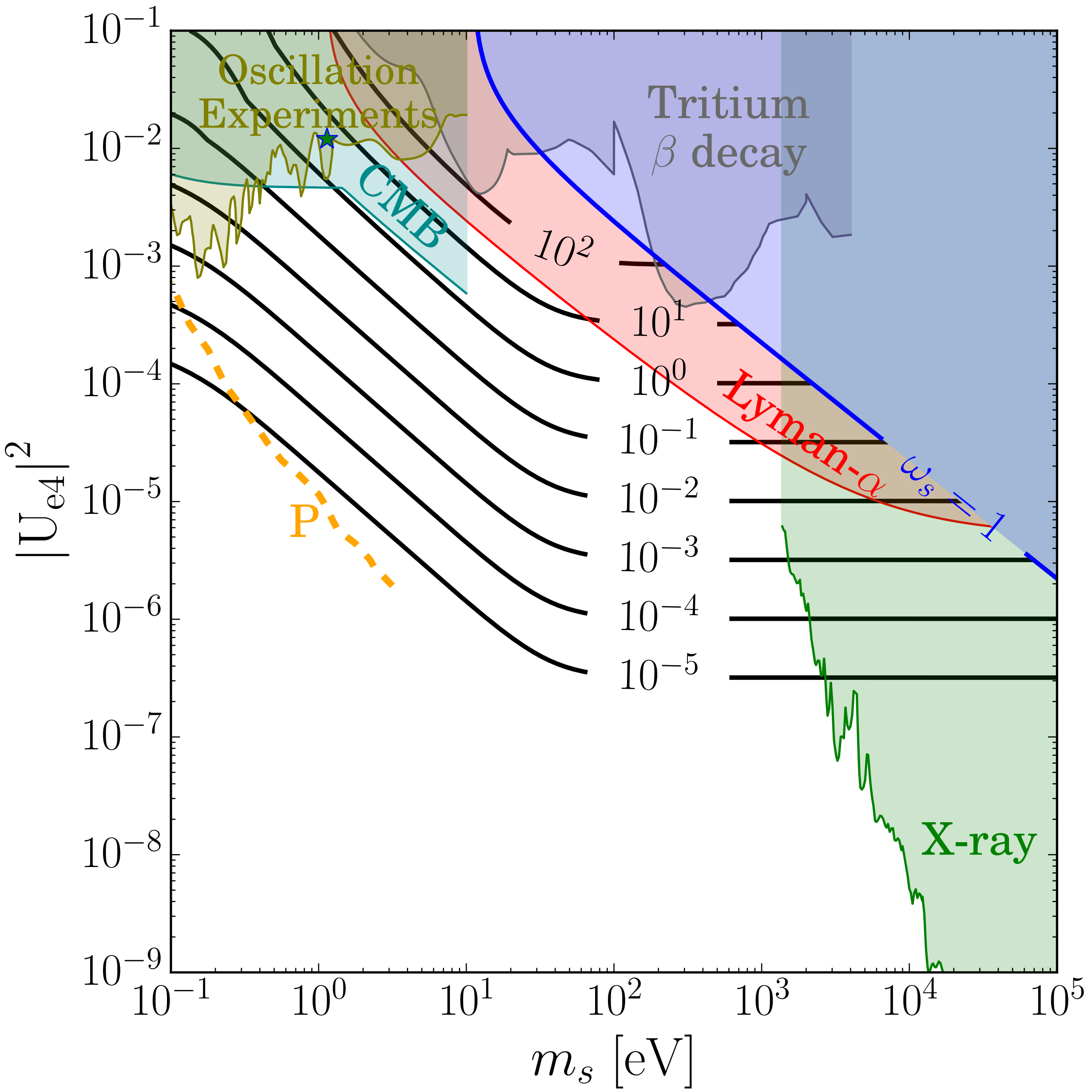
Capture rate of CSNuB in Low-TR model

reheating temperature

$T_R = 5\,\mathrm{MeV}$

up to 10 events per year
with 100 gram Tritium





CSNuB in late time phase transition

$$1\,\mathrm{MeV} \lesssim T_c < T_{EW}$$

The Majorana mass is generated after the non-vanishing VEV of a scalar ϕ

$$\mathcal{L} = i\bar{N}\ \partial\!\!\!/ N + Y_\nu H \bar{\nu}_\alpha N + \frac{\lambda}{2}\phi \bar{N}^c N + h.c.,$$

After the phase transition at T_c, sterile neutrino get Majorana mass.

Above T_c and below EW-symmetry breaking $T_c < T < T_{EW}$

Active neutrino-sterile neutrino make Dirac particles.

$\Omega_{s,R}$ Sterile neutrinos can be produced through its Dirac mass mixing with chirality flip $\propto M_D^2/p^2$

Below phase transition T_c $T < T_c$

$\Omega_{s,c}$ Dirac mass+Majorana mass makes mixing between active and sterile Nu. Sterile neutrinos are produced through the mixing.

CSNuB in low-temperature phase transition

The total relic density is

$$\Omega_s = \Omega_{s,c} + \Omega_{s,R},$$

with

$\boxed{T_0 < T < T_c}$

$$\Omega_{s,c} h^2 \simeq 0.5 \left(\frac{|U_{e4}|^2}{10^{-3}}\right) \left(\frac{10.75}{g_*(T_c)}\right)^{1/2} \left(\frac{m_s}{\text{keV}}\right) \left(\frac{T_c}{5\ \text{MeV}}\right)^3$$

$\boxed{T_c < T < T_R}$

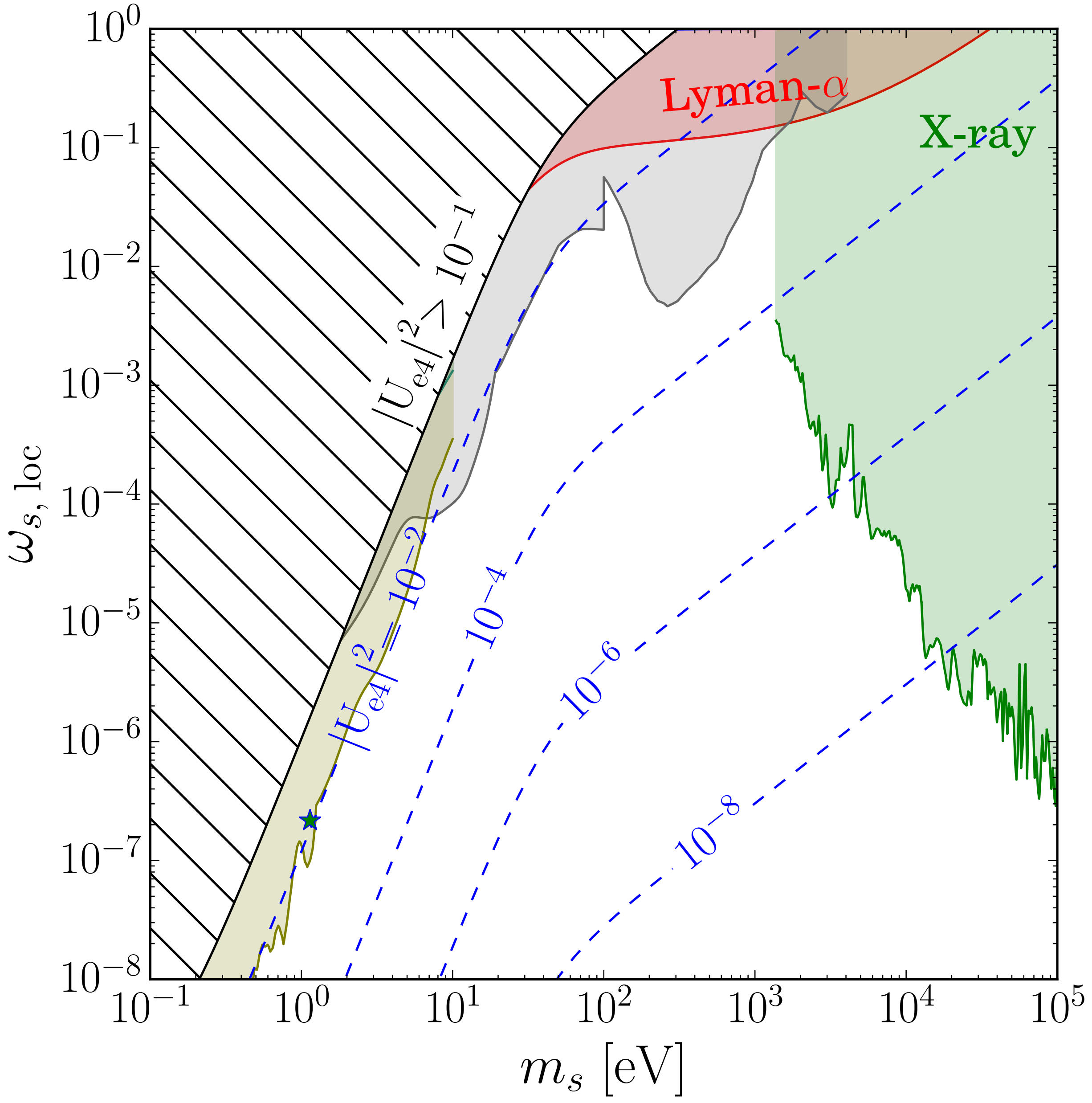
$$\Omega_{s,R} h^2 \approx 2 \times 10^{-9} \left(\frac{|U_{e4}|^2}{10^{-3}}\right) \left(\frac{10.75}{g_*(T_R)}\right)^{1/2} \left(\frac{m_s}{\text{keV}}\right)^3 \left(\frac{T_R}{5\ \text{MeV}}\right)$$

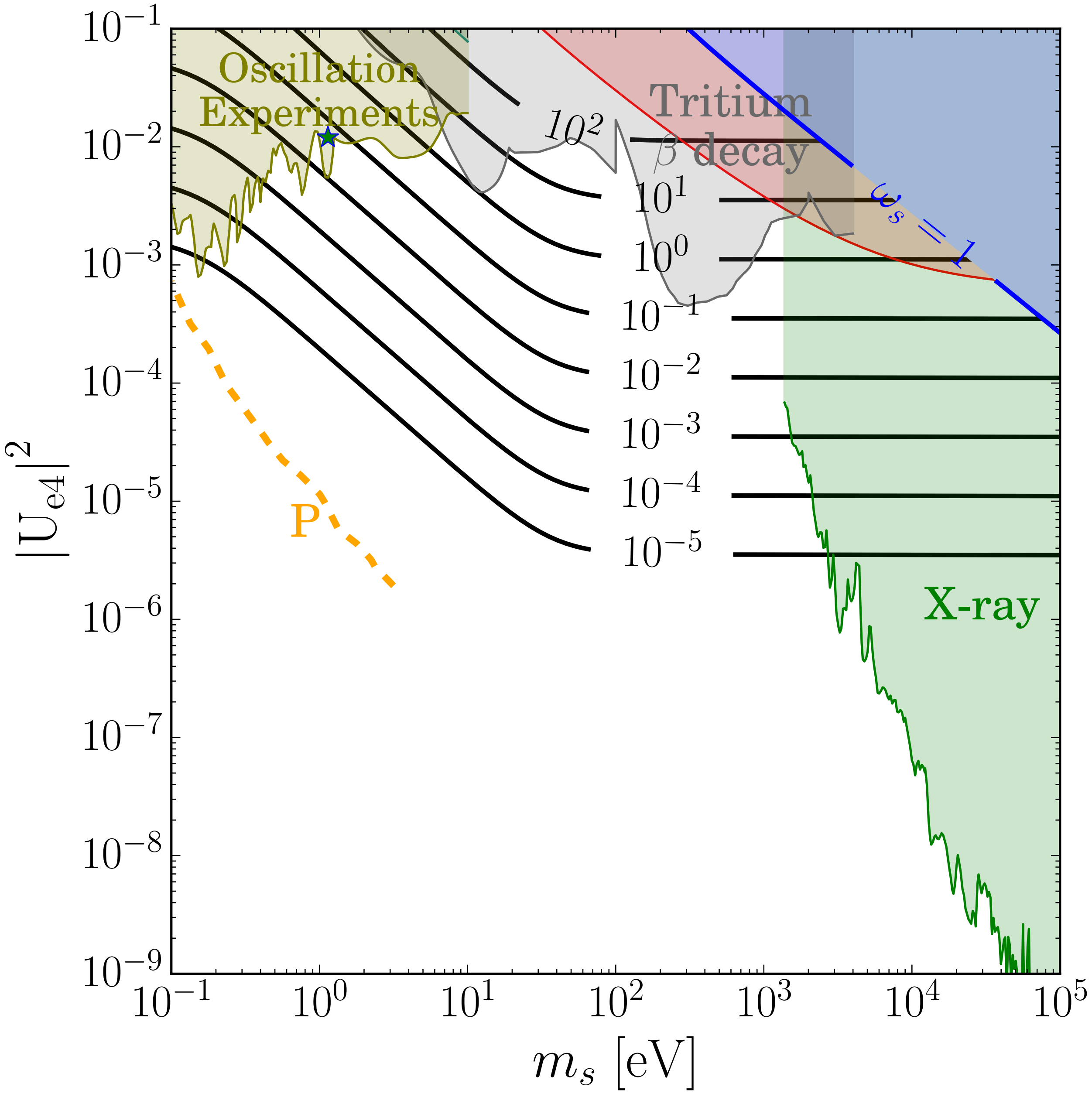
very suppressed

Capture rate of CSNuB in low-temperature phase transition

phase transition at $T_c = 1\,\mathrm{MeV}$

up to 10 events per year with 100 gram Tritium





Discussion

Sterile neutrino may exist as a background around Milky Way, with subdominant component of cold or warm DM.

In standard Dodelson-Widrow, it may not be possible to probe in the near future.

In scenarios with low-reheating temperature or late-phase transition, the suppressed production rate of the sterile neutrinos requires a large mixing and thus enhance the capture rate in the beta decay experiment. Therefore it becomes possible to probe them in the near future.

Thank You!