Flavor effects on captures of sub-eV and keV dark matter neutrinos

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【IHEP Beijing】

★ **DM from active and sterile neutrinos?**

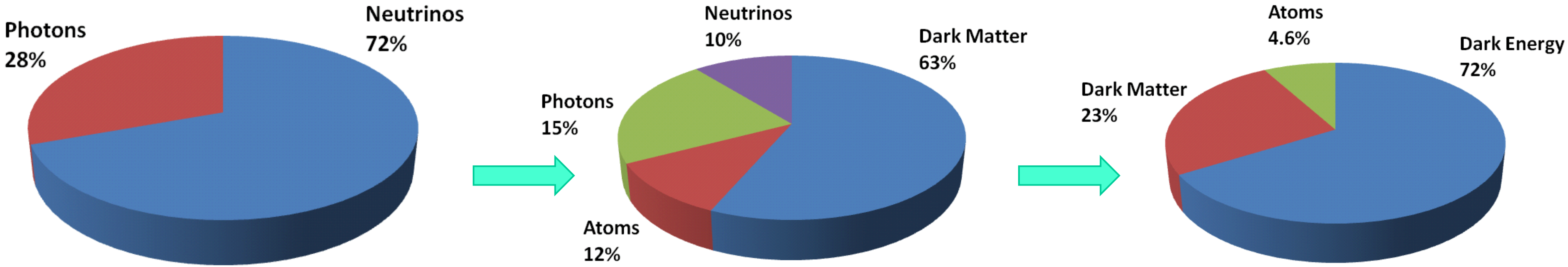
★ **Flavor effects on captures of the CνB**

★ **Flavor effects on captures of keV νDM**

Topical Workshop on Dark Matter and Neutrinos, Institut Henri Poincare, Paris, 12~23—5—2025

Dark matter is a big deal

♦ The Universe has undergone the radiation- and dark matter-dominant epochs. Today the invisible dark energy and dark matter play crucial roles behind the visible matter world.



neutrino decoupling
t = 1 second

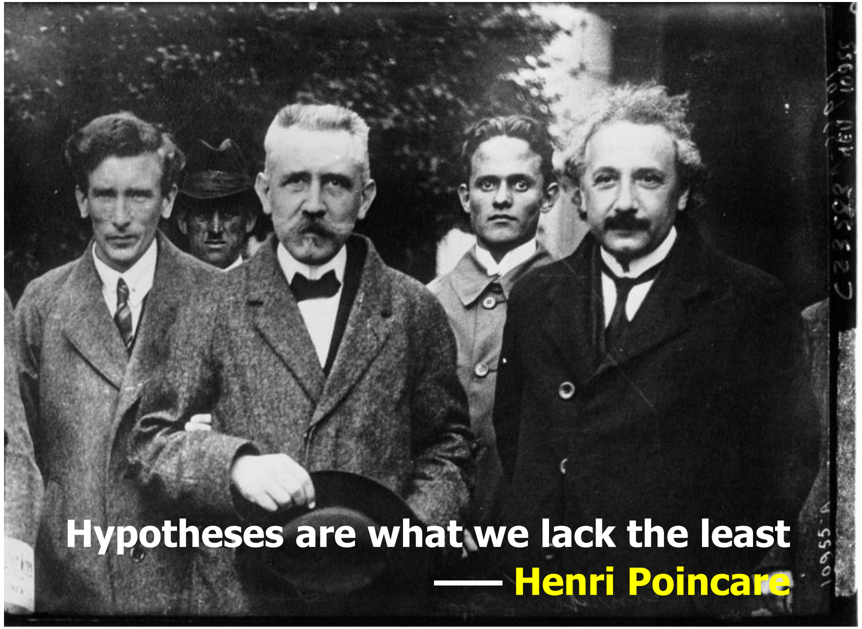
photon decoupling
t = 380 000 years

Today
t = 13.7 billion years

♦ Three categories of dark matter in the observable Universe, classified by the mass of a candidate dark matter particle at onset of the galaxy formation with temperature ~ keV:

Part A

DM from real and hypothetical neutrinos



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Markets of real and hypothetical neutrinos

sub-eV
active ν's

SM weak interaction

flavor oscillation

cosmic messenger

anomalies

sub-eV
sterile ν's

warm DM
talks by
Bringmann, Sil, Rosauro-Alcaraz, Tangarife, ...

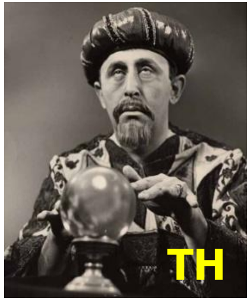
keV
sterile ν's

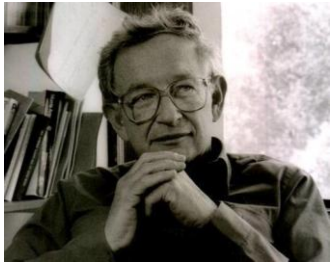
LHC

TeV
Majorana ν's

seesaw

$\geq$ EeV
Majorana ν's



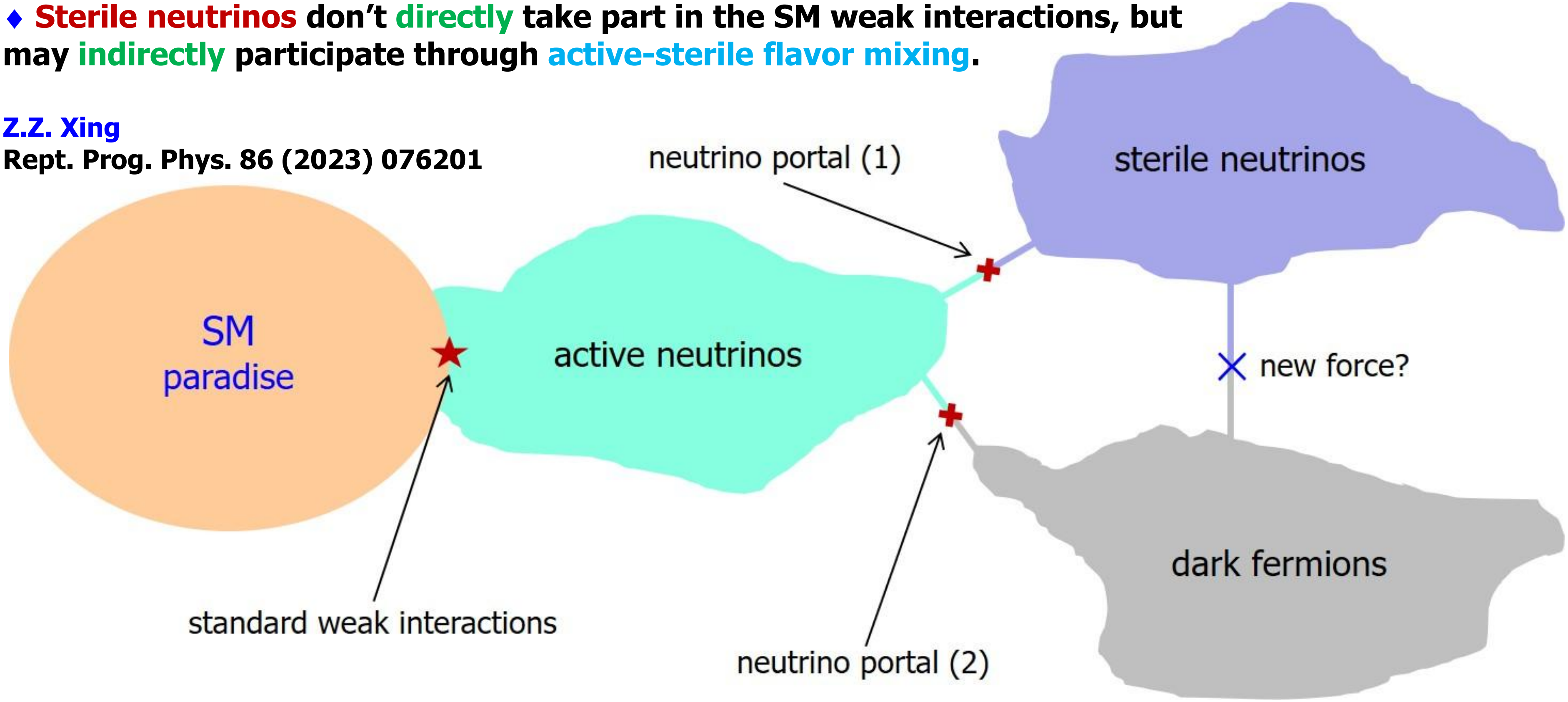


More is (dynamically) different
—— P. Anderson (1972)

How sterile, how dark, how many species?

♦ Sterile neutrinos don't directly take part in the SM weak interactions, but may indirectly participate through active-sterile flavor mixing.

Z.Z. Xing
Rept. Prog. Phys. 86 (2023) 076201



♦ Dark matter doesn't appear to interact with observable EM radiation, and is therefore invisible to the entire EM spectrum. But it might weakly interact with normal matter.

HOT, WARM, COLD dark matter?

HOT

COLD

WARM (keV)

relativistic

$$\Omega_\nu = \frac{21}{8}\left(\frac{4}{11}\right)^{4/3}\Omega_\gamma \approx 1.68 \times 10^{-5} h^{-2}$$

CνB = guaranteed hot DM

non-relativistic

$$\Omega_\nu = \frac{8\pi G_N}{3H^2}\sum_i m_i \left(n_{\nu_i} + n_{\overline{\nu}_i}\right) \approx \frac{1}{94\ h^2\ \mathrm{eV}}\sum_i m_i$$

keV sterile neutrinos?

axions?

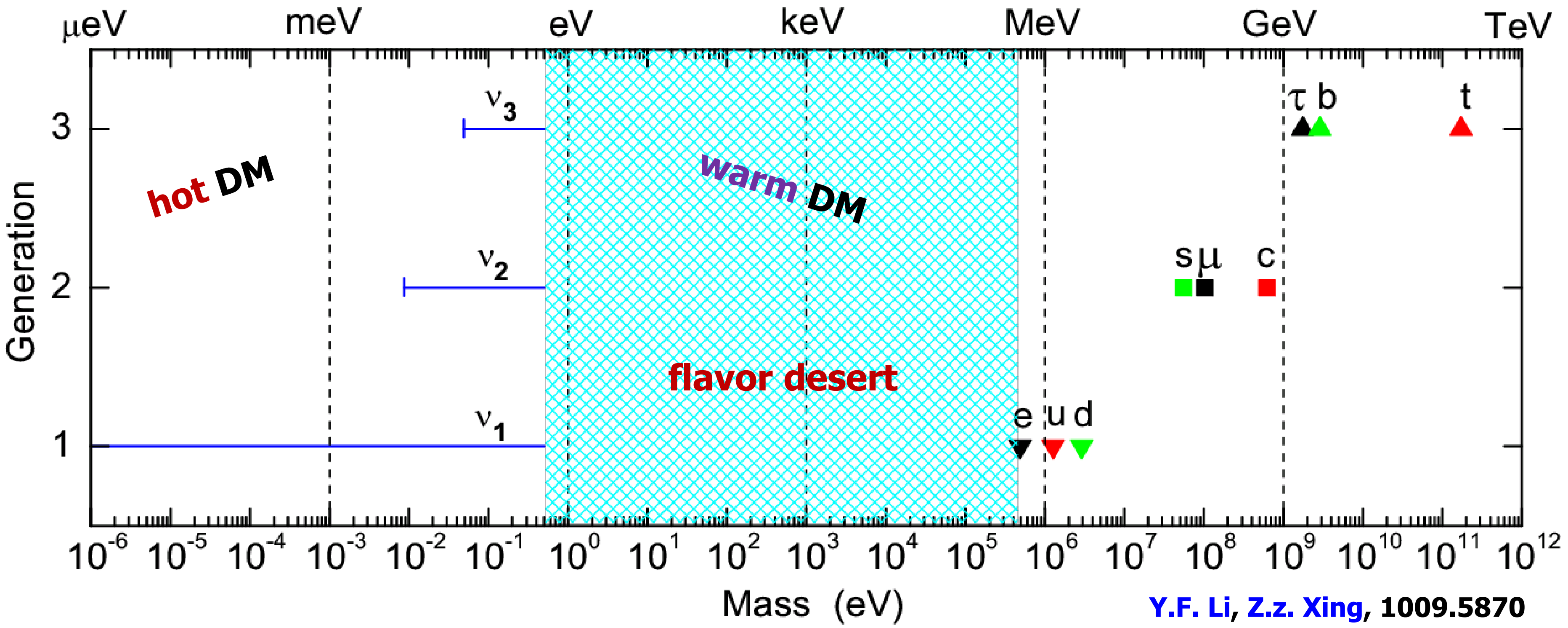
WIMPs?

neutralinos?

something exotic or unexpected?

The sub-eV and keV neutrino DM

- ♦ **Possible existence of keV sterile neutrinos would help soften the flavor desert problem of the SM?**



Y.F. Li, Z.z. Xing, 1009.5870

- ♦ **If today's Universe originated from the Big Bang, one has to explain a) how primordial antimatter has disappeared; b) what is dark matter and how it has functioned.**

How many —— a (3+3) flavor mixing scheme

- Picture (1): well-motivated seesaw + leptogenesis with 3 light and 3 heavy Majorana neutrinos.
- Picture (2): phenomenological hot + warm νDM with 3 sub-eV and 3 keV neutrinos.

3+3

active flavor / sterile flavor / mass state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_x \\ \nu_y \\ \nu_z \end{pmatrix} = \mathcal{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{pmatrix}$$

$$\mathcal{U} = \underbrace{\begin{pmatrix} I & \mathbf{0} \\ \mathbf{0} & U_0' \end{pmatrix}}_{\text{sterile}} \underbrace{\begin{pmatrix} A & R \\ S & B \end{pmatrix}}_{\text{interplay}} \underbrace{\begin{pmatrix} U_0 & \mathbf{0} \\ \mathbf{0} & I \end{pmatrix}}_{\text{active}}$$

An advertisement:

A parametrization of (3+3+3) flavor mixing, H.c. Han, Z.z. Xing 2110.12705

PMNS =

$$\begin{pmatrix} U_0 & 0 \\ 0 & I \end{pmatrix} = O_{23}O_{13}O_{12} \; ,$$

$$\begin{pmatrix} I & 0 \\ 0 & U_0' \end{pmatrix} = O_{56}O_{46}O_{45} \; ,$$

$$\begin{pmatrix} A & R \\ S & B \end{pmatrix} = O_{36}O_{26}O_{16}O_{35}O_{25}O_{15}O_{34}O_{24}O_{14}$$

Z.z. Xing 0709.2220 1110.0083

- A specific model to kill three birds with only one stone: the split seesaw (A. Kusenko, F. Takahashi, T. Yanagida, 2010): two heavy and one keV-scale Majorana neutrinos.

Dark matter
Neutrino mass
Antimatter

Weak charged-current interactions

♦ **The weak leptonic charged-current interactions turn out to be ($U = AU_0$ is the PMNS matrix):**

$$-\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}}\,\overline{(e\ \ \mu\ \ \tau)_{\rm L}}\,\gamma^\mu \left[U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}_{\rm L} + R\begin{pmatrix}\nu_4\\ \nu_5\\ \nu_6\end{pmatrix}_{\rm L}\right] W^-_\mu + {\rm h.c.}$$

active sterile

$$\begin{cases} c_{ij} \equiv \cos\theta_{ij} \\ \hat{s}_{ij} \equiv e^{{\rm i}\delta_{ij}}\sin\theta_{ij}\ \ (\text{for}\ \ 1 \le i < j \le 6)\end{cases}$$

$$U_0 = \begin{pmatrix} c_{12}c_{13} & \hat{s}^*_{12}c_{13} & \hat{s}^*_{13} \\ -\hat{s}_{12}c_{23} - c_{12}\hat{s}_{13}\hat{s}^*_{23} & c_{12}c_{23} - \hat{s}^*_{12}\hat{s}_{13}\hat{s}^*_{23} & c_{13}\hat{s}^*_{23} \\ \hat{s}_{12}\hat{s}_{23} - c_{12}\hat{s}_{13}c_{23} & -c_{12}\hat{s}_{23} - \hat{s}^*_{12}\hat{s}_{13}c_{23} & c_{13}c_{23}\end{pmatrix}$$

$$A = \begin{pmatrix} c_{14}c_{15}c_{16} & 0 & 0 \\ \begin{array}{l} -c_{14}c_{15}\hat{s}_{16}\hat{s}^*_{26} - c_{14}\hat{s}_{15}\hat{s}^*_{25}c_{26} \\ -\hat{s}_{14}\hat{s}^*_{24}c_{25}c_{26}\end{array} & c_{24}c_{25}c_{26} & 0 \\ \begin{array}{l} -c_{14}c_{15}\hat{s}_{16}c_{26}\hat{s}^*_{36} + c_{14}\hat{s}_{15}\hat{s}^*_{25}\hat{s}_{26}\hat{s}^*_{36} \\ -c_{14}\hat{s}_{15}c_{25}\hat{s}^*_{35}c_{36} + \hat{s}_{14}\hat{s}^*_{24}c_{25}\hat{s}_{26}\hat{s}^*_{36} \\ +\hat{s}_{14}\hat{s}^*_{24}\hat{s}_{25}\hat{s}^*_{35}c_{36} - \hat{s}_{14}c_{24}\hat{s}^*_{34}c_{35}c_{36}\end{array} & \begin{array}{l} -c_{24}c_{25}\hat{s}_{26}\hat{s}^*_{36} - c_{24}\hat{s}_{25}\hat{s}^*_{35}c_{36} \\ -\hat{s}_{24}\hat{s}^*_{34}c_{35}c_{36}\end{array} & c_{34}c_{35}c_{36}\end{pmatrix}$$

$$R = \begin{pmatrix} \hat{s}^*_{14}c_{15}c_{16} & \hat{s}^*_{15}c_{16} & \hat{s}^*_{16} \\ \begin{array}{l} -\hat{s}^*_{14}c_{15}\hat{s}_{16}\hat{s}^*_{26} - \hat{s}^*_{14}\hat{s}_{15}\hat{s}^*_{25}c_{26} \\ +c_{14}\hat{s}^*_{24}c_{25}c_{26}\end{array} & -\hat{s}^*_{15}\hat{s}_{16}\hat{s}^*_{26} + c_{15}\hat{s}^*_{25}c_{26} & c_{16}\hat{s}^*_{26} \\ \begin{array}{l} -\hat{s}^*_{14}c_{15}\hat{s}_{16}c_{26}\hat{s}^*_{36} + \hat{s}^*_{14}\hat{s}_{15}\hat{s}^*_{25}\hat{s}_{26}\hat{s}^*_{36} \\ -\hat{s}^*_{14}\hat{s}_{15}c_{25}\hat{s}^*_{35}c_{36} - c_{14}\hat{s}^*_{24}c_{25}\hat{s}_{26}\hat{s}^*_{36} \\ -c_{14}\hat{s}^*_{24}\hat{s}_{25}\hat{s}^*_{35}c_{36} + c_{14}c_{24}\hat{s}^*_{34}c_{35}c_{36}\end{array} & \begin{array}{l} -\hat{s}^*_{15}\hat{s}_{16}c_{26}\hat{s}^*_{36} - c_{15}\hat{s}^*_{25}\hat{s}_{26}\hat{s}^*_{36} \\ +c_{15}c_{25}\hat{s}^*_{35}c_{36}\end{array} & c_{16}c_{26}\hat{s}^*_{36}\end{pmatrix}$$

My parametrization
Z.z. Xing
0709.2220/1110.0083

THE SEESAW CASE:

The latest stringent *bounds* on possible PMNS nonunitarity.
M. Blennow et al. 2023

$$\begin{cases} \theta_{1j} < 2.92^\circ \\ \theta_{2j} < 0.27^\circ \\ \theta_{3j} < 2.56^\circ \\ [j = 4, 5, 6]\end{cases}$$

Xing, Zhu, 2412.17698

Components of the electron neutrino

♦ The active and sterile components of the electron neutrino flavor in this regard:

e-flavor

$$\nu_e = \underbrace{c_{14}c_{15}c_{16}}_{} \underbrace{\left[c_{12}c_{13}\nu_1 + \hat{s}^*_{12}c_{13}\nu_2 + \hat{s}^*_{13}\nu_3\right]}_{\text{the active component}} + \underbrace{\hat{s}^*_{14}c_{15}c_{16}\nu_4 + \hat{s}^*_{15}c_{16}\nu_5 + \hat{s}^*_{16}\nu_6}_{\text{the sterile component}}$$

non-unitarity of the PMNS matrix

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = c^2_{14}c^2_{15}c^2_{16} \simeq 1 - \left(s^2_{14} + s^2_{15} + s^2_{16}\right)$$

- **Indirect unitarity violation**: the sterile neutrinos are heavy enough and kinematically forbidden

The β-decay effective mass: $$\langle m \rangle_\beta \equiv \left[\sum_{i=1}^{3} m_i^2 |U_{ei}|^2\right]^{1/2} = c_{14}c_{15}c_{16}\sqrt{m_1^2 c_{12}^2 c_{13}^2 + m_2^2 s_{12}^2 c_{13}^2 + m_3^2 s_{13}^2}$$

- **Direct unitarity violation**: the sterile neutrinos can appear in the processes under consideration

The β-decay effective mass: $$\langle m \rangle'_\beta \equiv \left[\sum_{i=1}^{6} m_i^2 |U_{ei}|^2\right]^{1/2} = \sqrt{\langle m \rangle_\beta^2 + m_4^2 s_{14}^2 c_{15}^2 c_{16}^2 + m_5^2 s_{15}^2 c_{16}^2 + m_6^2 s_{16}^2}$$

♦ To reduce the number of free parameters, one may simplify the (3+3) picture to the (3+1) case.

Flavor effects on effective neutrino masses

♦ **In the standard 3-active flavor case with the PMNS matrix being unitary.**

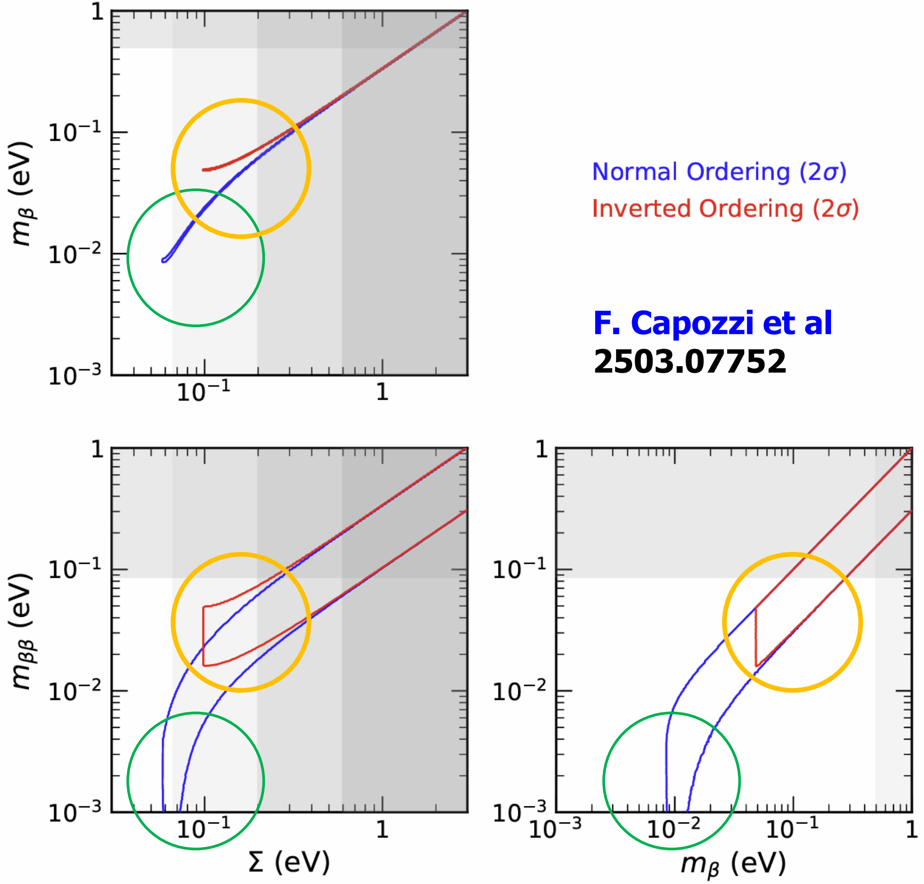
Flavor effects:

- ♦ **The absolute mass**
- ♦ **The mass ordering**
- ♦ **Flavor mixing angles**
- ♦ **CP-violating phases**
- ♦ **Extra flavor species**

= unlucky region

= lucky region

from a kind of intelligent design?

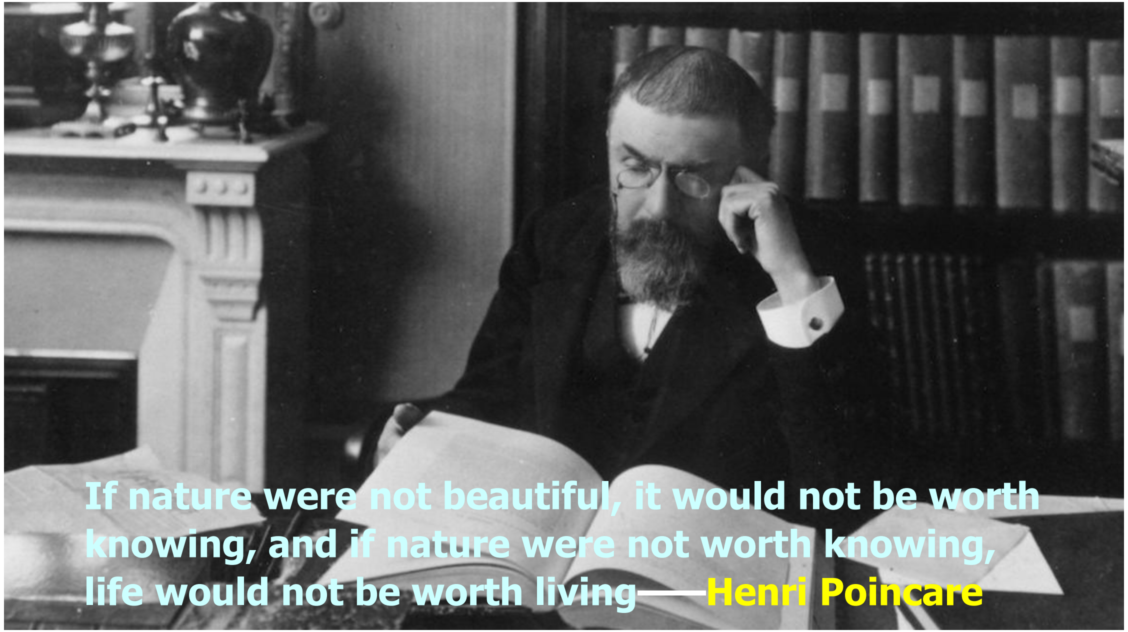


F. Capozzi et al 2503.07752

♦ **The situation will be more complicated if the extra (sterile) species of neutrinos are included.**

Part B

Flavor effects on captures of CνB and keV νDM



The formation of CνB

When $T \sim$ a few MeV after Big Bang, the survival particles: photons, electrons, positrons, neutrinos and antineutrinos

$$\begin{cases} \gamma + \gamma \rightleftharpoons e^+ + e^- \rightleftharpoons \nu_\alpha + \overline{\nu}_\alpha \\ \overline{\nu}_e + e^- + p \rightleftharpoons n \\ \nu_e + n \rightleftharpoons e^- + p \\ \overline{\nu}_e + p \rightleftharpoons e^+ + n \end{cases}$$

Neutrinos decoupled from matter in the early Universe as follows:

Weak interactions $\Gamma \sim G_F^2 T^5$

Hubble expansion $H \sim \dfrac{\sqrt{g_*}T^2}{M_{Pl}}$

Number density of 6 relic ν's:

$$n_\nu = \frac{9}{11} n_\gamma \approx 336 \left(\frac{T_\gamma}{2.725\ \mathrm{K}}\right)^3 \mathrm{cm}^{-3}$$

$\boxed{\Gamma > H}$ $\boxed{\Gamma \sim H}$ $\boxed{\Gamma < H}$

talk by Ovchynnikov

ν's in thermal contact with plasma

ν's not in interaction with matter

arrow of time

neutrino and photon temperatures:

$\boxed{T_\nu = T_\gamma}$

neutrino decoupling

$$T_{fr} \sim \left(\frac{\sqrt{g_*}}{G_F^2 M_{Pl}}\right)^{1/3} \sim 1\ \mathrm{MeV}$$

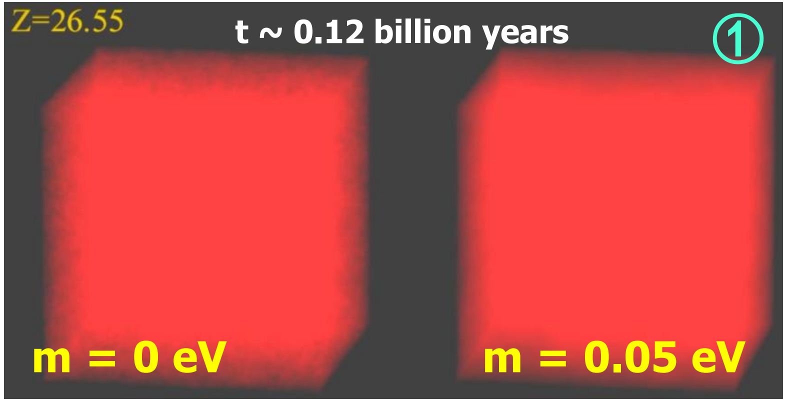
$\boxed{T < m_e}$ $e^+ + e^- \to \gamma + \gamma$

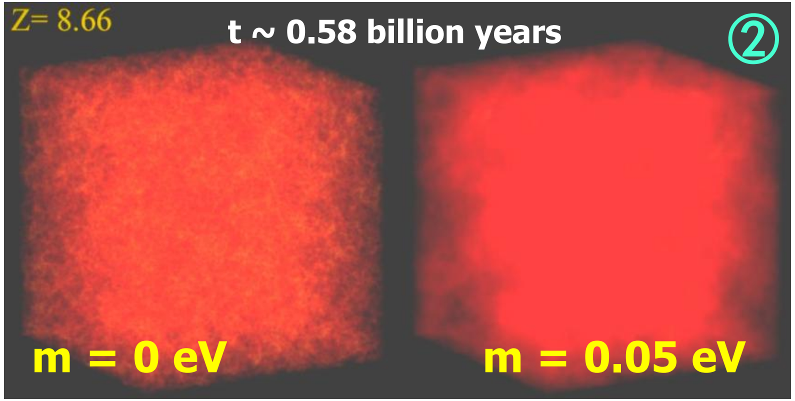
$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

Neutrinos decoupled from thermal bath, traveled freely in space, formed cosmic ν background (CνB)

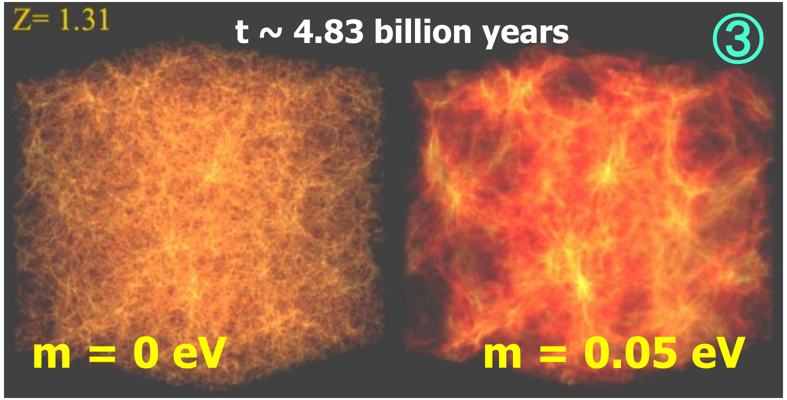
A simulation of the CνB on the LSS

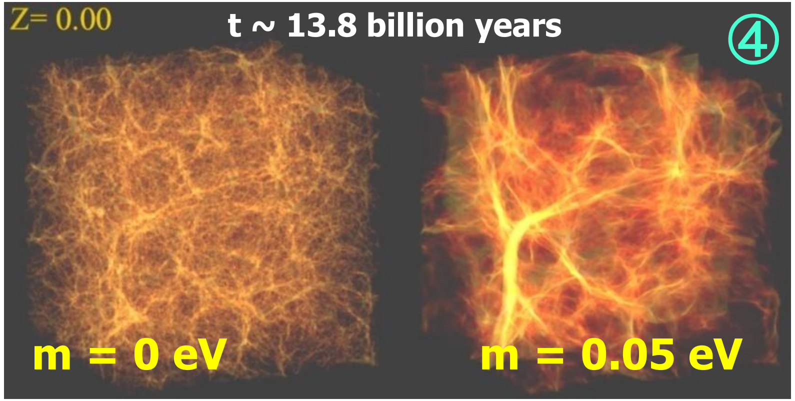
♦ In the matter-dominant epoch, the cosmic neutrino background may leave an indelible imprint on the anisotropy of cosmic microwave background and the large scale structure of the Universe.





H. Yu, …
Z.z. Xing, ….
Nature Astronomy 2017

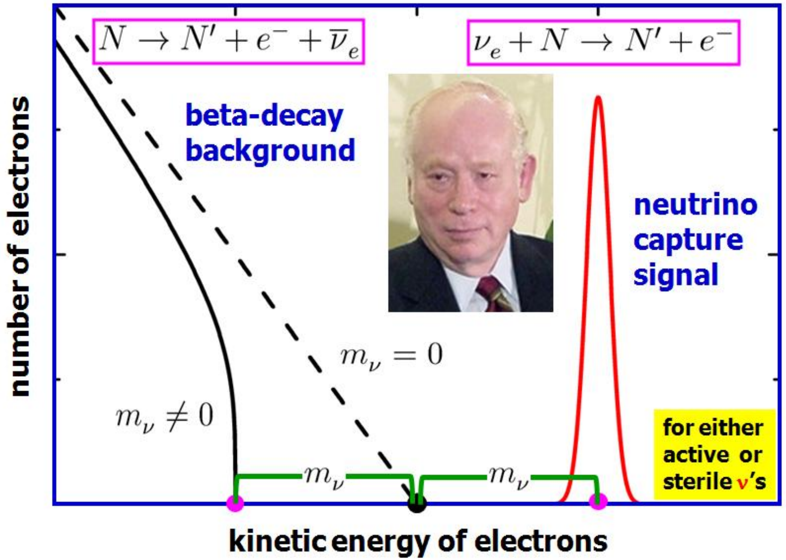




A possibility to directly detect the CνB

♦ Captures of slow relic ν's on radioactive β-decaying nuclei (S. Weinberg 1962; J. Irvine, R. Humphreys 1983; A. Cocco, G. Mangano, M. Messina 2007).

♣ no energy threshold on incident ν's;
♣ mono-energetic outgoing electrons as a signal;
♣ Reasonable cross section with tiny ν velocities.



• The CνB temperature today:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945 \text{ K}$$

• The mean momentum of relic ν's today:

$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4} \text{ eV}$$

• Given the neutrino oscillation data, at least two kinds of relic ν's are cold (i.e., non-relativistic) today.

The cross section of this capture process scales with c/v_ν , so the number of events converges to a constant for $v_\nu \to 0$:

$$\boxed{\nu_e + {}^3\text{H} \to {}^3\text{He} + e^-}$$

$$\sigma(\nu_e {}^3\text{H}) \cdot \frac{v_\nu}{c}\bigg|_{v_\nu \to 0} \simeq (7.84 \pm 0.03) \times 10^{-45} \text{cm}^2$$

The capture rate and background

♦ **Taking 100 g of tritium as the sample target mass, for example, one may estimate the differential rates of the CνB signal and its background from the β-decay:**

♣ **The Capture rate (1 MCi = 100 g : $N_{\rm T} \approx 2.1 \times 10^{25}$ tritium atoms):** $\boxed{T_e^i = Q_\beta + E_{\nu_i}}$

$$\frac{{\rm d}N_{{\rm C}\nu{\rm B}}}{{\rm d}T_e} \approx 6.5 \sum_i |U_{ei}|^2 \frac{n_{\nu_i}}{\langle n_{\nu_i}\rangle} \cdot \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T_e - T_e^i)^2}{2\sigma^2}\right] {\rm yr}^{-1}\,{\rm MCi}^{-1}$$

♣ **The Background (the tritium β-decay):** $E_e = T_e' + m_e$, $\langle n_{\nu_i}\rangle \approx \langle n_{\overline{\nu}_i}\rangle \approx 56~{\rm cm}^{-3}$

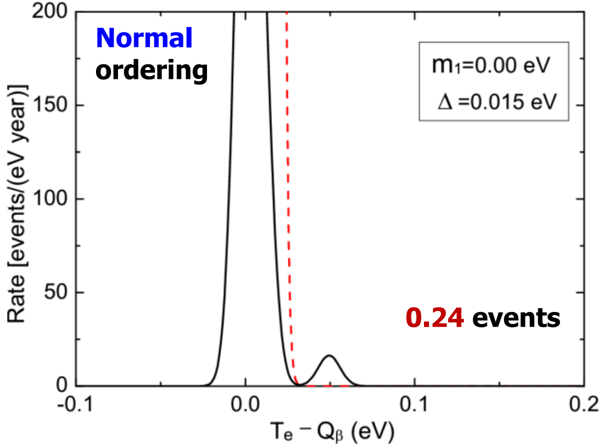
$$\frac{{\rm d}N_\beta}{{\rm d}T_e} \approx 5.55 \int_0^{Q_\beta - \min(m_i)} {\rm d}T_e' \left\{ N_{\rm T} \frac{G_{\rm F}^2 \cos^2\theta_{\rm C}}{2\pi^3} F(Z,\,E_e) \sqrt{E_e^2 - m_e^2}\, E_e (Q_\beta - T_e') \right.$$
$$\left. \times \sum_i \left[|U_{ei}|^2 \sqrt{\left(Q_\beta - T_e'\right)^2 - m_i^2}\; \Theta(Q_\beta - T_e' - m_i)\right] \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T_e - T_e')^2}{2\sigma^2}\right] \right\}$$

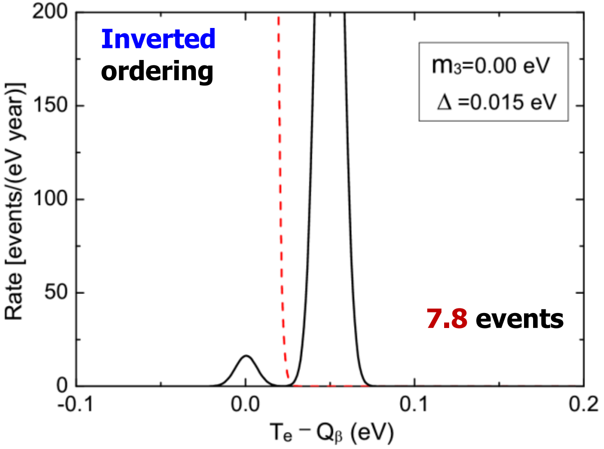
♣ **The Energy resolution (the Gaussian function) :** $\Delta = 2\sqrt{2\ln 2}\,\sigma \approx 2.35482\,\sigma$

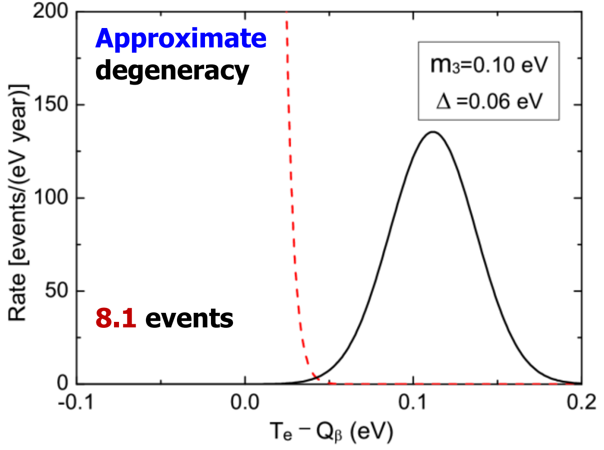
♦ **More detailed analyses can be found from the Ptolemy collaboration (M. Betti et al, 1902. 05508).**

A numerical illustration

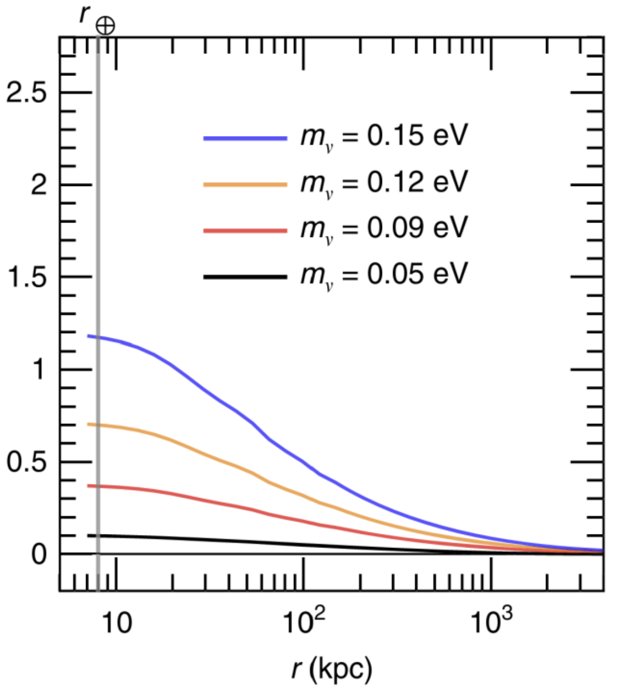
♦ Target: 100 g tritium (Y.F. Li, Z.z. Xing, S. Luo) for (3+0) case.







♦ Gravitational clustering effect on Big Bang relic neutrinos may help enhance the signal rate to some extent, but not promising (e.g., J. Zhang, X. Zhang 2018).



The neutrino contrast as a function of the distance to the galactic center of MW. (The location of the Earth r⊕=8 kpc is shown by the gray vertical line).

A capture of the keV WDM neutrinos?

♦ The keV sterile neutrinos could be produced via tiny active-sterile flavor mixing in the early epoch of the Universe. The warm DM in the form of keV sterile neutrinos may help suppress the formation of dwarf galaxies and other small-scale structures.

♦ Occam's razor: let's consider one sterile species: $\nu_e = c_{14}\left[c_{12}c_{13}\nu_1 + \hat{s}^*_{12}c_{13}\nu_2 + \hat{s}^*_{13}\nu_3\right] + \hat{s}^*_{14}\nu_4$

$$\boxed{\nu_e + N \to N' + e^-}$$

$$\boxed{Q_\beta = m_N - m_{N'} - m_e}$$

$$\boxed{N \to N' + e^- + \overline{\nu}_e}$$

- The capture rate with a Gaussian energy resolution:

$$\frac{\mathrm{d}\mathcal{N}_\nu}{\mathrm{d}T_e} = \sum_{i=1}^{4} N_\mathrm{T}|U_{ei}|^2\sigma_{\nu_i}v_{\nu_i}n_{\nu_i}\,\frac{1}{\sqrt{2\pi}\,\sigma}\exp\left[-\frac{(T_e - T_e^i)^2}{2\sigma^2}\right]$$

- Assumption: the number density of sterile neutrinos is equivalent to the total amount of DM in our galactic neighborhood.

$$\boxed{\begin{aligned}&\rho_\mathrm{DM}^\mathrm{local} \simeq 0.3\ \mathrm{GeV\ cm^{-3}}\\ &n_{\nu_4} \simeq 10^5\ (3\ \mathrm{keV}/m_4)\ \mathrm{cm^{-3}}\end{aligned}}$$

- Half-life effect of target nuclei (Y.F. Li, Z.z. Xing, 2011): $N_\mathrm{T} = \dfrac{N(0)}{\lambda t}\left(1 - e^{-\lambda t}\right)\ , \quad \lambda = \dfrac{\ln 2}{t_{1/2}}$

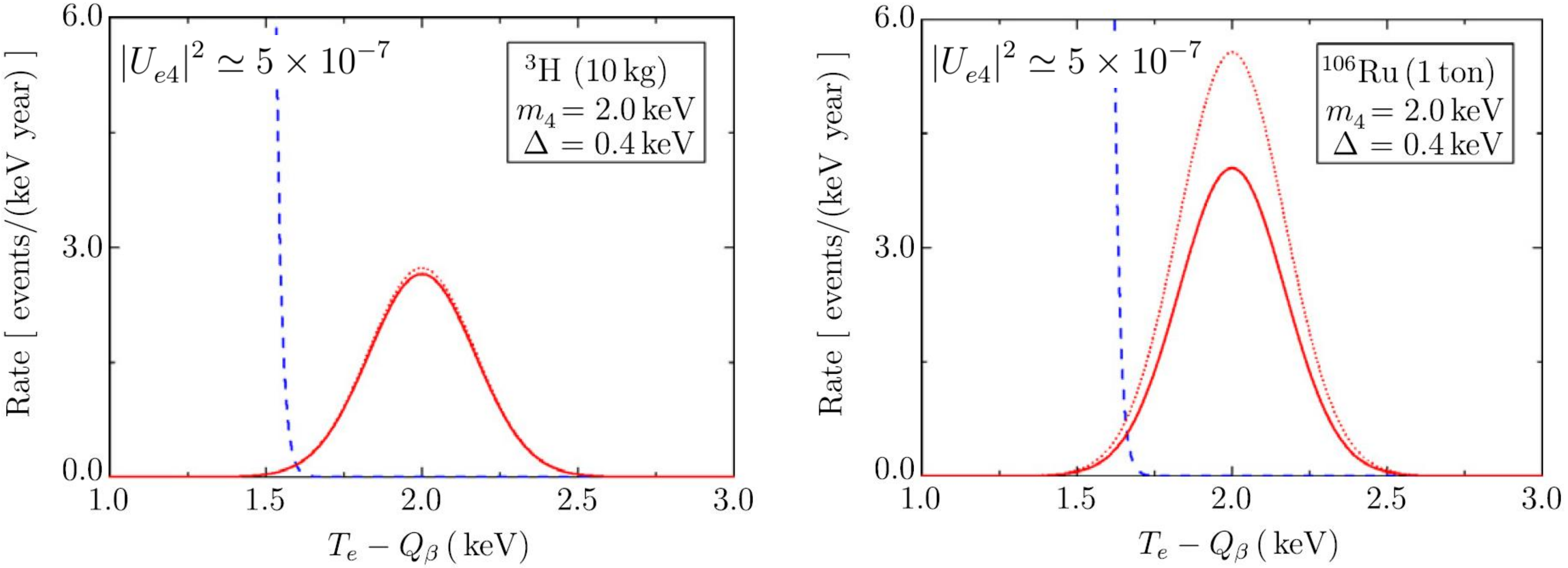
$$^{3}\mathrm{H}\ :\ Q_\beta = 18.6\ \mathrm{keV}\ ,\quad t_{1/2} = 3.888\times10^{8}\ \mathrm{s}\ ,\quad \sigma_{\nu_i}v_{\nu_i}/c = 7.84\times10^{-45}\ \mathrm{cm}^2$$

$$^{106}\mathrm{Ru}\ :\ Q_\beta = 39.4\ \mathrm{keV}\ ,\quad t_{1/2} = 3.228\times10^{7}\ \mathrm{s}\ ,\quad \sigma_{\nu_i}v_{\nu_i}/c = 5.88\times10^{-45}\ \mathrm{cm}^2$$

(Ru = ruthenium)

An out-of-date numerical illustration

♦ **Illustration of the number of events per year: solid (dotted) curves with (without) half-life effect.**



♦ **The observability of keV sterile neutrino DM in this way turns out to be rather dim and remote:**

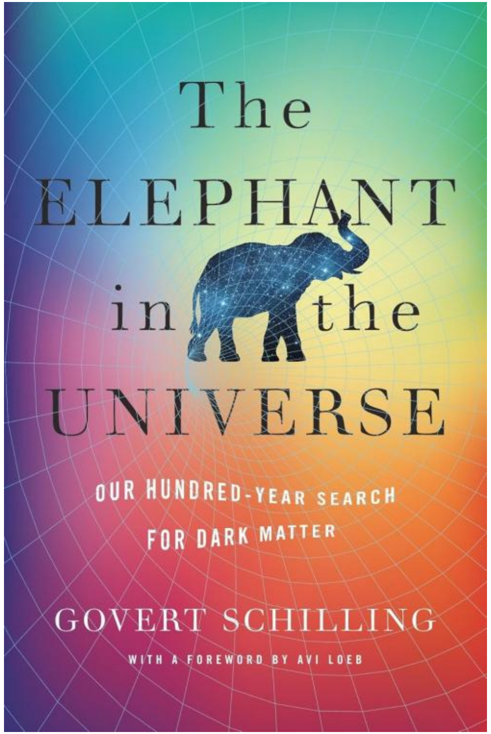
- **The main problem arises from the too suppressed active-sterile flavor mixing;**
- **The background may include the keV solar neutrinos and $\nu_4 + e^- \to \nu_i + e^-$ scattering.**

Concluding remarks

♦ To understand the nature of dark matter, including those elusive neutrinos, one has to go beyond the SM and introduce some new degrees of freedom.

♦ A new idea often appeared as a guiding principle, but turned out to be a misguiding principle. Let us remember Weinberg's remarks in 1983:

> You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you will be sorry.



♦ Let us see who in this room will be sorry 5/10/20 years later.

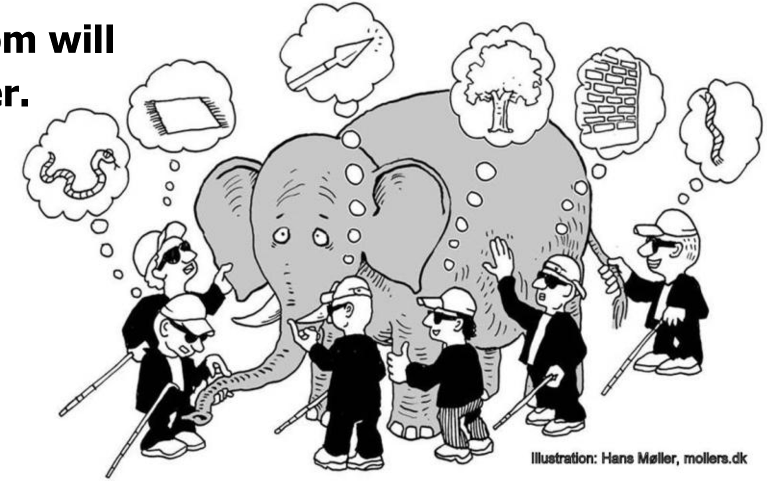


Illustration: Hans Møller, mollers.dk

THANK YOU