Future Perspective of Particle Physics (& Astrophysics)

3rd KNO Workshop

(November 2, 2018, KNU)

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This is only my personal perspective

in year 2018 !!!

Maybe ??

Maybe ??

- Supersymmetry → ……… → String

Maybe ??

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- Extra Dimensions (ADD, UED, RS, ….)
- Extended Higgs

Maybe ??

- Supersymmetry ⟹ ……… ⟹ String
- Extra Dimensions (ADD, UED, RS, ….)
- Extended Higgs
- Strong CP, Axion
- GUT, guts, extra U(1)’s, …..
- Naturalness, Hierarchy, Fine tuning, …..
- ……
- ……
- Unparticles
- Clockworks

Could be ?

Could be ?

- Dark energy → modified GR
- Quark-gluon plasma

Could be ?

- Dark energy → modified GR
- Quark-gluon plasma
- Baryogenesis → Leptogenesis
- Inflation → Multiverse

Must be !

Must be !

- Gravitational wave → Graviton

Must be !

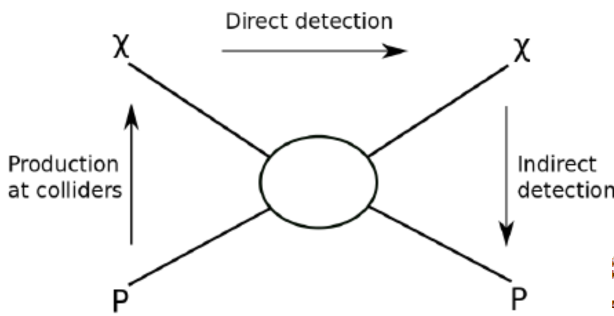
- Gravitational wave → Graviton
- Dark Matter

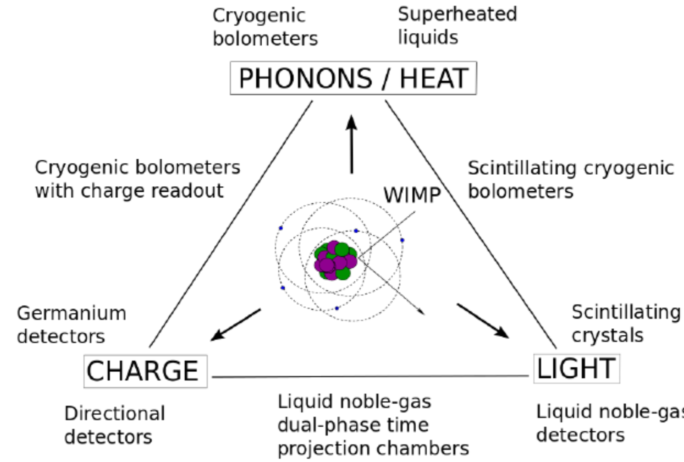
Must be !

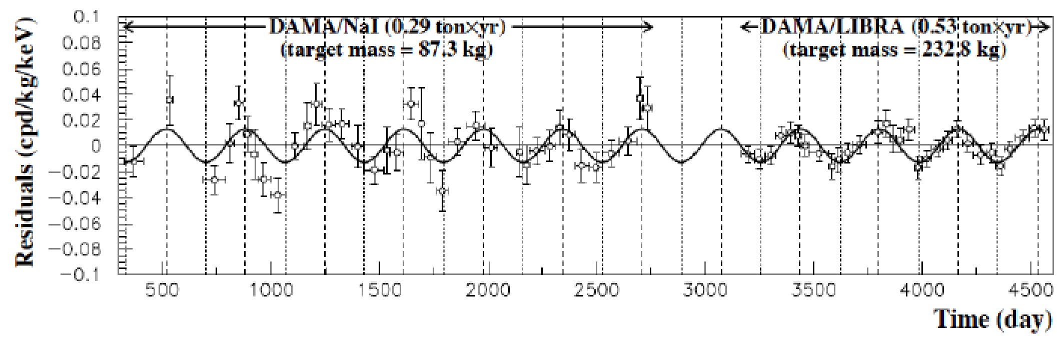
- Gravitational wave → Graviton
- Dark Matter
- Neutrino

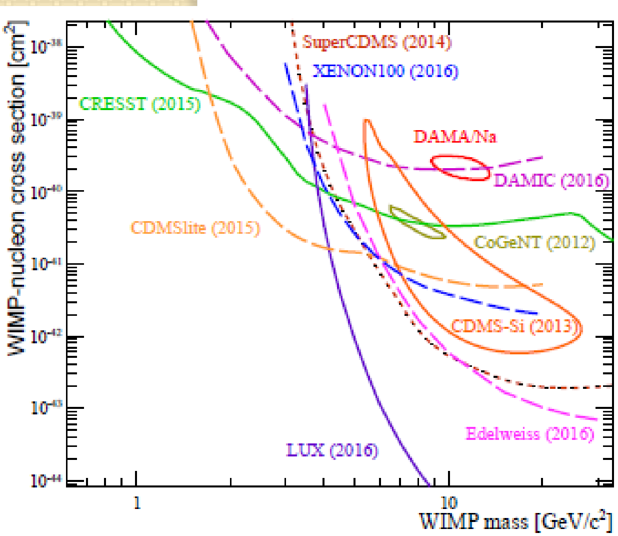
Dark Matter

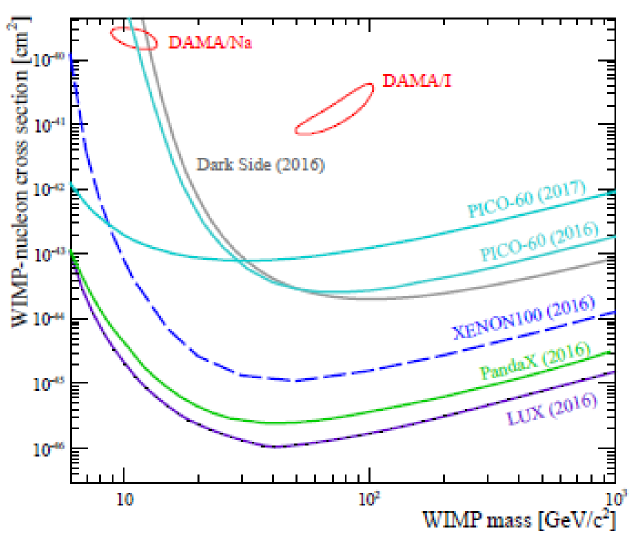
- (arXiv:1509.08762v2)

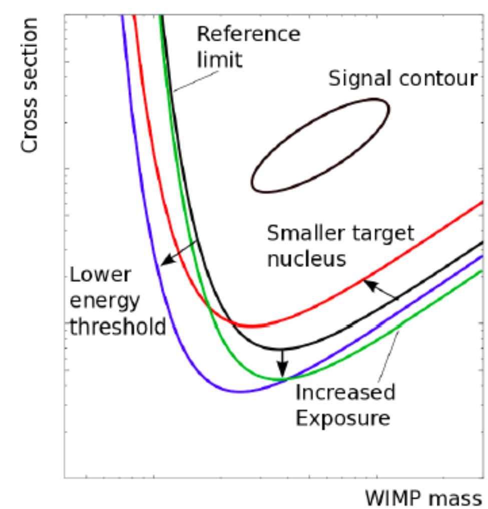












Neutrinos (mass, PMNS, CP)

- In the SM, neutrinos are
  - massless ($m_\nu = 0$) and
  - only left-handed (ν_L). No right-handed neutrinos (ν_R) observed yet.
- Giving neutrinos mass in the SM is possible iff we introduce ν_R,

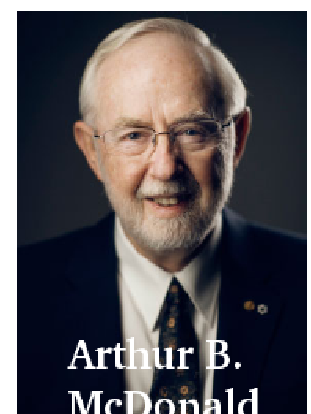
$$\mathscr{L}_{\text{SM}} \supset -m_\nu \left(\overline{\nu_R}\,\nu_L + \overline{\nu_L}\,\nu_R\right), \quad \text{where} \quad m_\nu = \frac{Y_\nu \, \mathrm{v}}{\sqrt{2}},$$

$Y_\nu =$ Higgs-neutrino Yukawa coupling constant,

$\mathrm{v} =$ Higgs VEV.

- neutrino oscillation $\Longrightarrow$ $m_\nu \neq 0$.
- **Nobel Prize in Physics 2015**

"for the discovery of neutrino oscillations, which shows that neutrinos have mass".



There are various suggestions as to how neutrinos can get mass.

- **Dirac mass:**
  - *Assumption:* ν_R exists.
  - *Lagrangian:*

$$\mathscr{L}^{D}_{\text{mass}} = -m^{D}_{\nu}\left(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R\right).$$

  - *Disadvantage:* No reason for m^{D}_{ν} to be small.
  - *Challenge:* Finding ν_R.

- **Majorana mass:**
  - *Assumption:* neutrino $\equiv$ anti-neutrino.
  - *Lagrangian:*

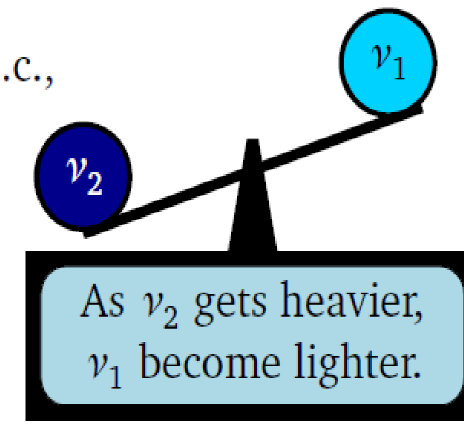
$$\mathscr{L}^{M}_{\text{mass}} = \frac{1}{2}m^{M}_{\nu}\left(\overline{\nu^{C}_{L}}\nu_L + \overline{\nu_L}\nu^{C}_{L}\right).$$

  - *Disadvantage:* $\mathscr{L}^{M}_{\text{mass}}$ is not invariant under $SU(2)_L \times U(1)_Y$ gauge group $\therefore \mathscr{L}^{M}_{\text{mass}}$ is not allowed by SM.
  - *Challenge:* To ascertain the Majorana nature of light neutrino.

- **See-saw mechanism:** A simpler version of Dirac-Majorana mass, with a nice twist.
  - *Assumptions:* $m_\nu^L = 0$ and $m_\nu^D \ll m_\nu^R$.
  - *Lagrangian:*

$$\mathscr{L}_{\text{mass}}^{D+M} = \tfrac{1}{2} m_\nu^R \left(\overline{\nu_R^C} \nu_R \right) - m_\nu^D \left(\overline{\nu_R} \nu_L \right) + \text{H.c.}$$
$$= \tfrac{1}{2} \left(m_1 \overline{\nu_1^C} \nu_1 + m_2 \overline{\nu_2^C} \nu_2 \right) + \text{H.c.},$$

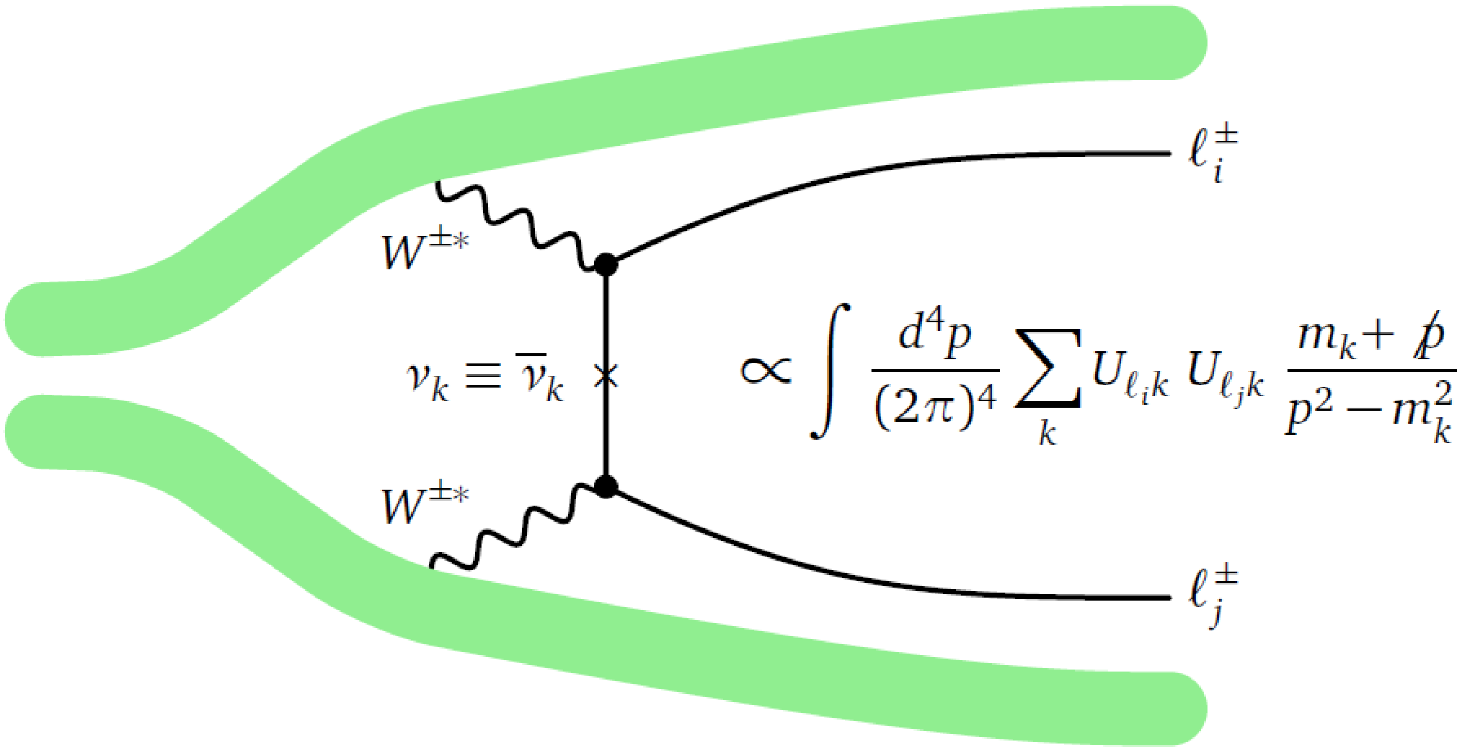
where $m_1 \approx -\dfrac{\left(m_\nu^D\right)^2}{m_\nu^R}$ and $m_2 \approx m_\nu^R$.



  - *Advantage:* $m_1 \ll m_2 \implies \nu_1$ is a light neutrino
  - *Challenges:*
    - To find the heavy ν_2 experimentally.
    - To prove that both the light ν_1 and heavy ν_2 are Majorana neutrinos.

Looking for Majorana neutrinos via $\Delta L = 2$ processes

- Neutrinos: the only known *elementary fermions* that *can* have Majorana nature ($\nu \equiv \overline{\nu}$).
- Majorana neutrino: very unique phenomenology (lepton number non-conservation), they mediate $\Delta L = 2$ processes.



- $\Delta L = 2$ processes play crucial role to probe Majorana nature of ν's.
  - neutrinoless double-beta ($0\nu\beta\beta$) decay
  - Rare meson decays with $\Delta L = 2$
  - Collider searches at LHC

- **Decay rate of any $\Delta L = 2$ process with final leptons $\ell_1^+ \ell_2^+$:**

$$\Gamma_{\Delta L=2} \propto \left| \sum_k U_{\ell_1 k} U_{\ell_2 k} \frac{m_k}{p^2 - m_k^2 + i m_k \Gamma_k} \right|^2,$$

where we have used the fact that $(1-\gamma^5)\, \not{p} (1-\gamma^5) = 0$.

- Light ν:

$$\Gamma_{\Delta L=2} \propto \left| \sum_k U_{\ell_1 k} U_{\ell_2 k} m_k \right|^2 = \left| m_{\ell_1 \ell_2} \right|^2.$$

- Heavy ν:

$$\Gamma_{\Delta L=2} \propto \left| \sum_k \frac{U_{\ell_1 k} U_{\ell_2 k}}{m_k} \right|^2.$$

- Resonant ν:

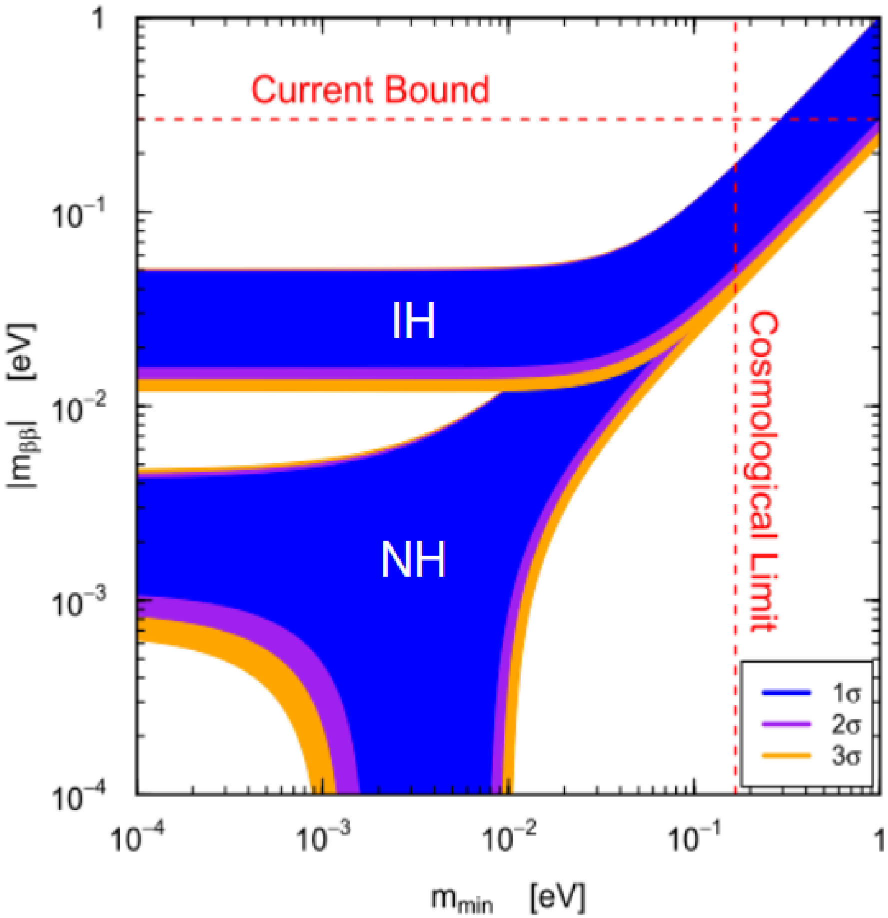
$$\Gamma_{\Delta L=2} \propto \frac{\Gamma(N \to i)\, \Gamma(N \to f)}{m_N \Gamma_N}.$$

- The half-life of a nucleus decaying via $0\nu\beta\beta$ is,

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} \; |M_{0\nu}| \; \left|m_{\beta\beta}\right|^{2},$$

where

- $G_{0\nu}$ is phase space factor,
- $M_{0\nu}$ is the *nuclear matrix element*, (large theoretical uncertainty)
- $m_{\beta\beta}$ is *effective Majorana mass*. $m_{\beta\beta} = \sum_{k=1}^{3} U_{ek}^{2} m_k$ is complex, in general, and can be zero due to possible cancellations arising from phases in U_{ek}.

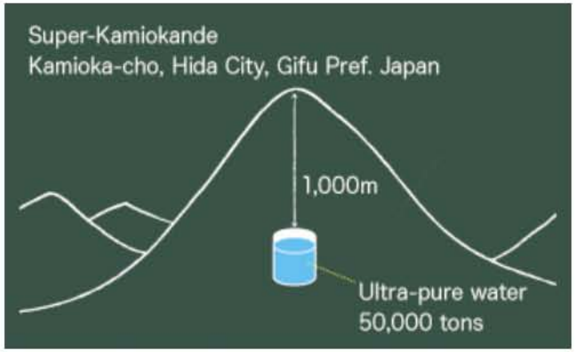


NH: Normal hierarchy
IH: Inverted hierarchy

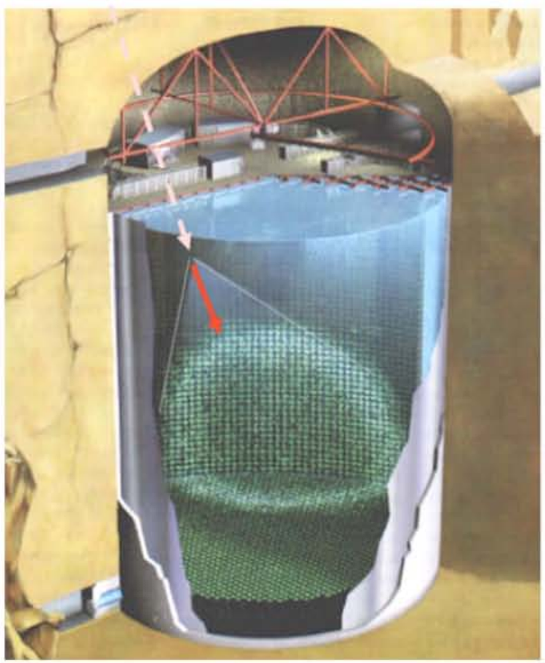
S. M. Bilenky and C. Giunti
Mod. Phys. Lett. A **27**, 1230015 (2012),
arXiv:1203.5250

- **If $m_{\beta\beta} < 10^{-2}$, only NH is viable and the $T^{0\nu}_{1/2}$ will be much larger than the current experimental lower bound.**

Neutrinos (mass, PMNS, CP)

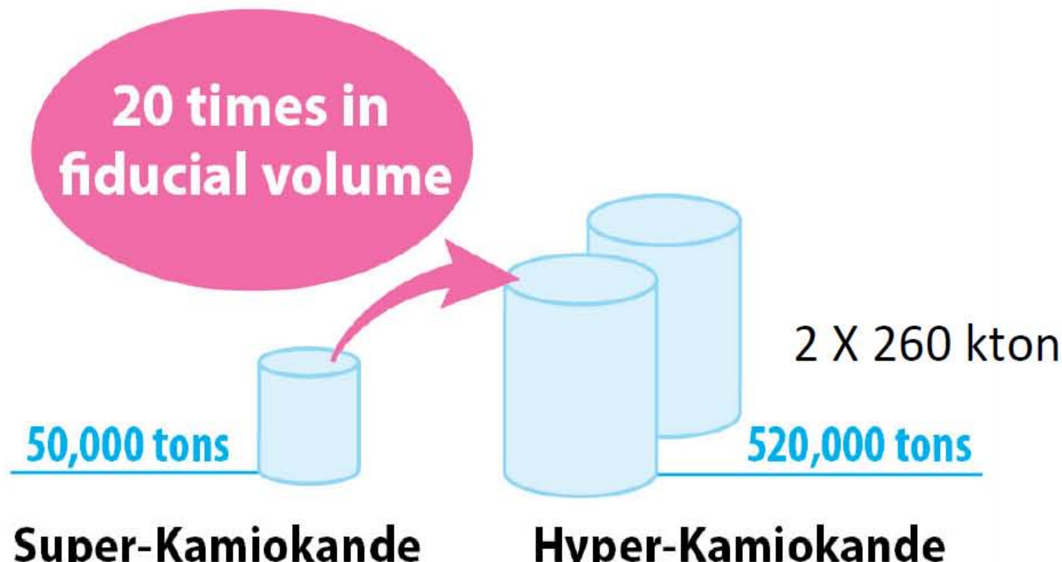


Super-K

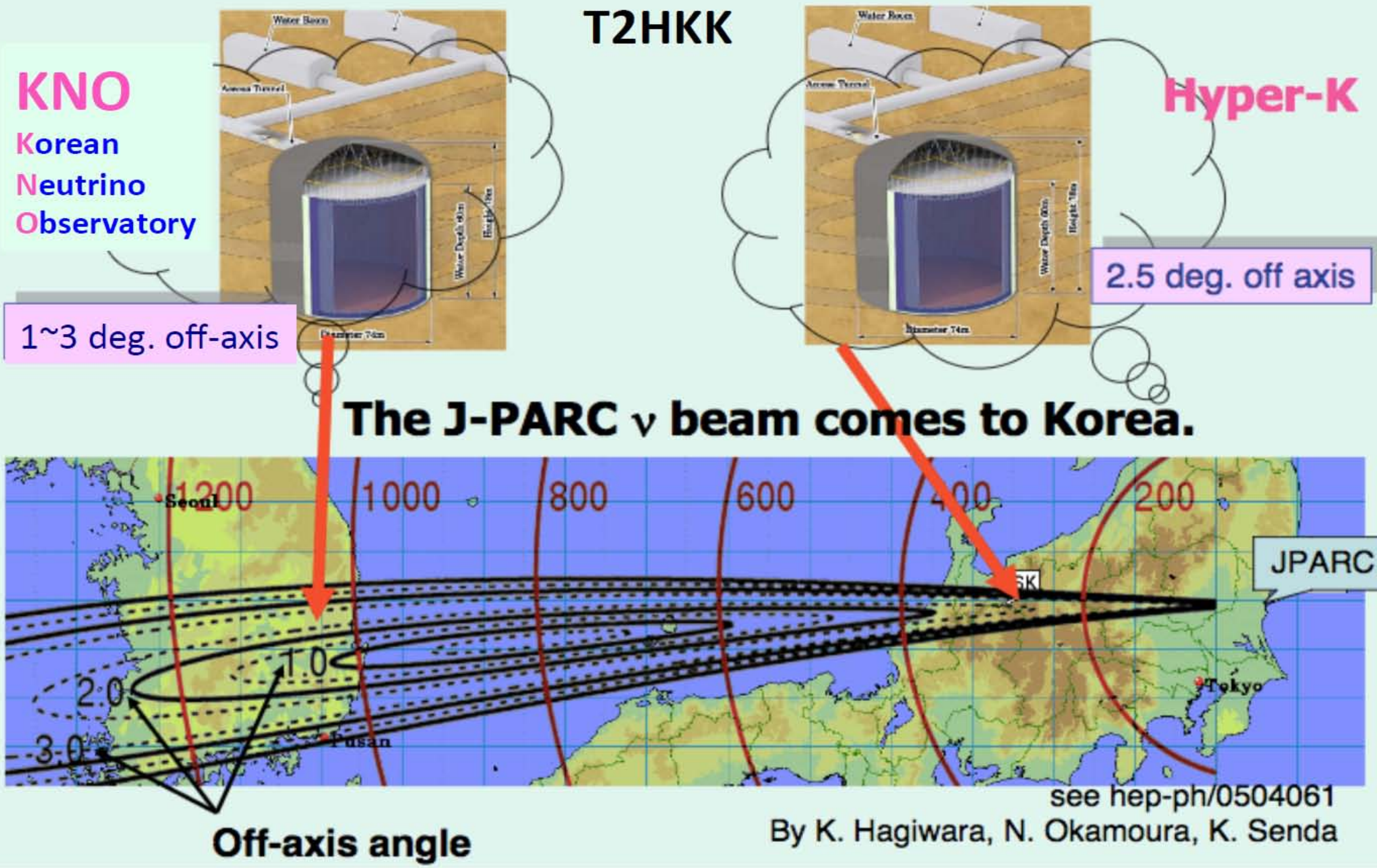


Super-K → Hyper-K

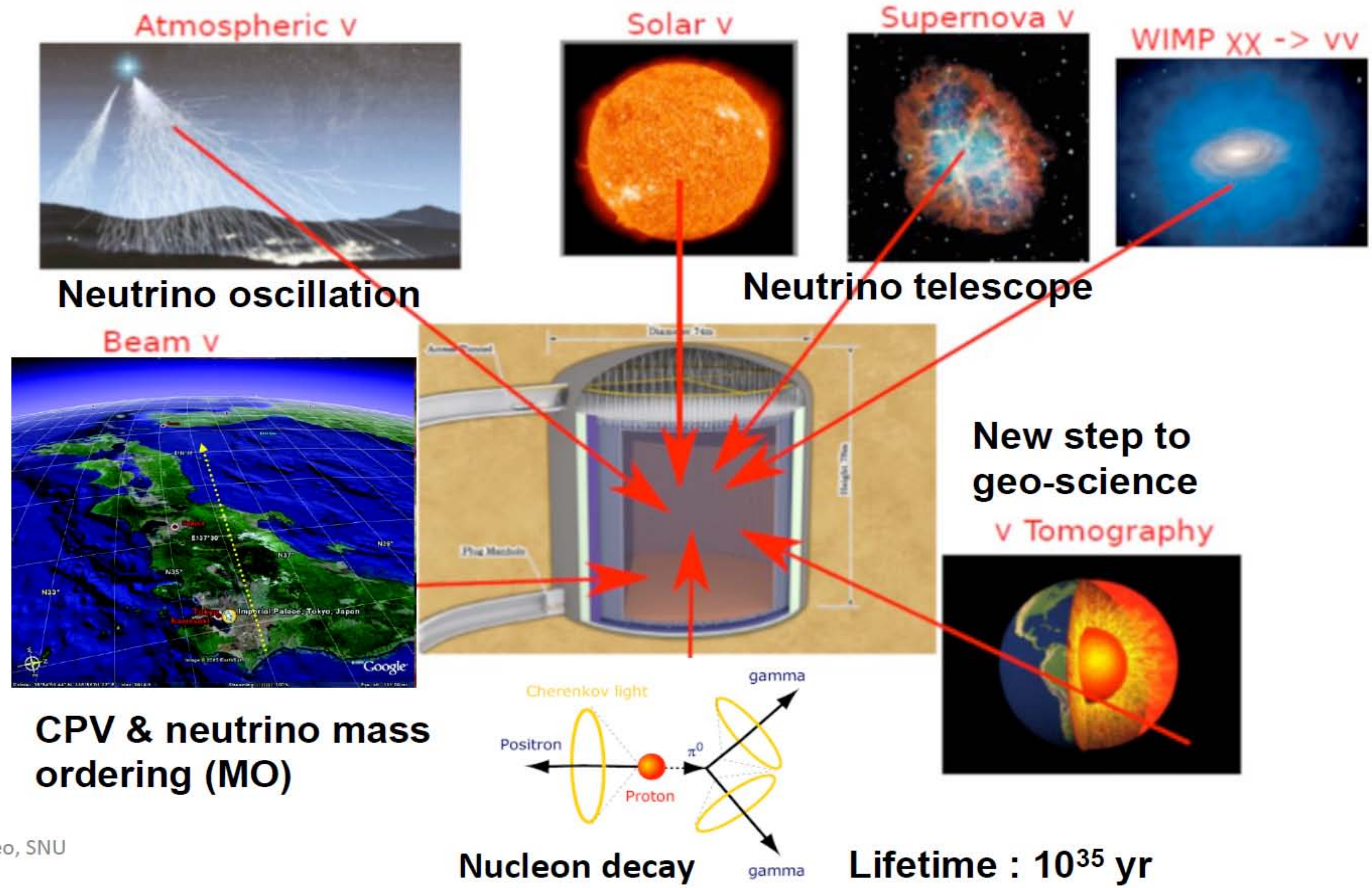
Currently running exp. Future exp.



2nd Hyper-K Detector in Korea



Broad Physics Program with KNO



Proton Decay

Baryogenesis ➔ Baryon number violation ➔ Proton decay

Super-K (p -> e^+ pi^0 : 2015) T_p > 1.67 X 10^34 years

SU(5) GUT predicted < 10^31 years !!

Theory class	Proton lifetime (years)[11]
Minimal SU(5) (Georgi–Glashow)	$10^{30}...10^{31}$
Minimal SUSY SU(5)	$10^{28}...10^{32}$
SUGRA SU(5)	$10^{32}...10^{34}$
SUSY SU(5)(MSSM)	$\sim 10^{34}$
Minimal (Basic) SO(10) – Non SUSY	$< \sim 10^{35}$ (maximum range)
SUSY SO(10)	$10^{32}...10^{35}$
SUSY SO(10) MSSM G(224)	$2 \cdot 10^{34}$
Flipped SU(5) (MSSM)	$10^{35}...10^{36}$
SUSY SU(5) – 5 dimensions	$10^{34}...10^{35}$

T2HKK would possibly kill (almost) all, or confirm one of GUT

miniBooNE and light sterile neutrino?

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

A. A. Aguilar-Arevalo[13], B. C. Brown[6], L. Bugel[12], G. Cheng[5], J. M. Conrad[12], R. L. Cooper[10,15], R. Dharmapalan[1,2], A. Diaz[12], Z. Djurcic[2], D. A. Finley[6], R. Ford[6], F. G. Garcia[6], G. T. Garvey[10], J. Grange[7], E.-C. Huang[10], W. Huelsnitz[10], C. Ignarra[12], R. A. Johnson[3], G. Karagiorgi[5], T. Katori[12,16], T. Kobilarcik[6], W. C. Louis[10], C. Mariani[19], W. Marsh[6], G. B. Mills[10,†], J. Mirabal[10], J. Monroe[18], C. D. Moore[6], J. Mousseau[14], P. Nienaber[17], J. Nowak[9], B. Osmanov[7], Z. Pavlovic[6], D. Perevalov[6], H. Ray[7], B. P. Roe[14], A. D. Russell[6], M. H. Shaevitz[5], J. Spitz[14], I. Stancu[1], R. Tayloe[8], R. T. Thornton[10], M. Tzanov[4,11], R. G. Van de Water[10], D. H. White[10], D. A. Wickremasinghe[3], E. D. Zimmerman[4]

(The MiniBooNE Collaboration)

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[†] *Deceased*

(Dated: May 31, 2018)

arXiv:1805.12028

	No sterile neutrino	One sterile neutrino ν_s
Decay mode	$\tau^- \to \mu^- \overline{\nu_\mu} \nu_\tau$	$\tau^- \to \mu^- \overline{\nu_\mu} \nu_\tau, \mu^- \overline{\nu_\mu} \nu_s, \mu^- \overline{\nu_s} \nu_\tau, \mu^- \overline{\nu_s} \nu_s$
Decay rate	$\Gamma_\tau = \frac{\left(G_F^0\right)^2 m_\tau^5}{192\pi^3} \times f\left(m_\mu^2/m_\tau^2\right)$	$\Gamma_\tau = \frac{\left(G_F^0\right)^2 m_\tau^5}{192\pi^3} \times \rho_{\mu\tau} \times f\left(m_\mu^2/m_\tau^2\right)$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x,$$

$$\rho_{\mu\tau} = 1 + |V_{\mu s}|^2 + |V_{\tau s}|^2 + |V_{\mu s}|^2 |V_{\tau s}|^2 .$$

$$\frac{\Gamma_\tau}{\Gamma_\mu} = \begin{cases} \left(\frac{m_\tau}{m_\mu}\right)^5 \frac{f\left(m_\mu^2/m_\tau^2\right)}{f\left(m_e^2/m_\mu^2\right)} & \text{(No sterile neutrino)} \\ \left(\frac{m_\tau}{m_\mu}\right)^5 \frac{f\left(m_\mu^2/m_\tau^2\right)}{f\left(m_e^2/m_\mu^2\right)} \frac{\rho_{\mu\tau}}{\rho_{e\mu}} & \text{(One sterile neutrino } \nu_s\text{)} \end{cases}$$

$$\rho_{e\mu} = 1 + |V_{es}|^2 + |V_{\mu s}|^2 + |V_{es}|^2 |V_{\mu s}|^2$$

$$\frac{\Gamma_\tau}{\Gamma_\mu} = \begin{cases} \left(\frac{m_\tau}{m_\mu}\right)^5 \left(\frac{f\left(m_\mu^2/m_\tau^2\right)}{f\left(m_e^2/m_\mu^2\right)}\right) \frac{\left(1 + \frac{3}{5}\left(m_\tau^2/m_W^2\right)\right)\left(1 + \left(\frac{\alpha(m_\tau^2)}{2\pi}\right)\left(\frac{25}{4} - \pi^2\right)\right)}{\left(1 + \frac{3}{5}\left(m_\mu^2/m_W^2\right)\right)\left(1 + \left(\frac{\alpha(m_\mu^2)}{2\pi}\right)\left(\frac{25}{4} - \pi^2\right)\right)} & \text{(No sterile neutrino)} \\ \left(\frac{m_\tau}{m_\mu}\right)^5 \left(\frac{f\left(m_\mu^2/m_\tau^2\right)}{f\left(m_e^2/m_\mu^2\right)}\right) \frac{\left(1 + \frac{3}{5}\left(m_\tau^2/m_W^2\right)\right)\left(1 + \left(\frac{\alpha(m_\tau^2)}{2\pi}\right)\left(\frac{25}{4} - \pi^2\right)\right)}{\left(1 + \frac{3}{5}\left(m_\mu^2/m_W^2\right)\right)\left(1 + \left(\frac{\alpha(m_\mu^2)}{2\pi}\right)\left(\frac{25}{4} - \pi^2\right)\right)} \times \frac{\rho_{\mu\tau}}{\rho_{e\mu}} & \text{(One sterile neutrino } \nu_s\text{)} \end{cases},$$

$$\frac{1}{2} \leqslant \frac{\rho_{\mu\tau}}{\rho_{e\mu}} \leqslant 2.$$

	No sterile neutrino	One sterile neutrino ν_s
Process	$\tau^- \to P^- \nu_\tau$	$\tau^- \to P^- \nu_\tau, P^- \nu_s$
Decay rate	$\Gamma_{\tau\to P\nu} = \frac{(G_F^0)^2 \|V_{UD}^0\|^2}{16\pi} f_P^2 m_\tau^3 \left(1 - \frac{m_P^2}{m_\tau^2}\right)^2$	$\Gamma_{\tau\to P\nu} = \frac{(G_F^0)^2 \|V_{UD}^0\|^2}{16\pi} f_P^2 m_\tau^3 \left(1 - \frac{m_P^2}{m_\tau^2}\right)^2 \left(1 + \|V_{\tau s}\|^2\right)$
Process	$P^- \to \mu^- \overline{\nu_\mu}$	$P^- \to \mu^- \overline{\nu_\mu}, \mu^- \overline{\nu_s}$
Decay rate	$\Gamma_{P\to\mu\nu} = \frac{(G_F^0)^2 \|V_{UD}^0\|^2}{8\pi} f_P^2 m_\mu^2 m_P \left(1 - \frac{m_\mu^2}{m_P^2}\right)^2$	$\Gamma_{P\to\mu\nu} = \frac{(G_F^0)^2 \|V_{UD}^0\|^2}{8\pi} f_P^2 m_\mu^2 m_P \left(1 - \frac{m_\mu^2}{m_P^2}\right)^2 \left(1 + \|V_{\mu s}\|^2\right)$

$$\frac{\Gamma_{\tau\to P\nu}}{\Gamma_{P\to\mu\nu}} = \begin{cases} \frac{1}{2}\frac{m_P^3}{m_\mu^2 m_\tau}\left(\frac{m_\tau^2 - m_P^2}{m_P^2 - m_\mu^2}\right)^2 & \text{(No sterile neutrino)} \\ \frac{1}{2}\frac{m_P^3}{m_\mu^2 m_\tau}\left(\frac{m_\tau^2 - m_P^2}{m_P^2 - m_\mu^2}\right)^2 \left(\frac{1+|V_{\tau s}|^2}{1+|V_{\mu s}|^2}\right) & \text{(One sterile neutrino } \nu_s\text{)} \end{cases}$$

$$\frac{\Gamma_{\tau\to P\nu}}{\Gamma_{P\to\mu\nu}} = \begin{cases} \frac{1}{2}\frac{m_P^3}{m_\mu^2 m_\tau}\left(\frac{m_\tau^2 - m_P^2}{m_P^2 - m_\mu^2}\right)^2 \frac{1+(2\alpha/\pi)\ln(m_Z/m_\tau)}{1+\frac{3}{2}(\alpha/\pi)ln(m_Z/m_P)+\frac{1}{2}(\alpha/\pi)ln(m_Z/m_{P^*})} & \text{(No sterile neutrino)} \\ \frac{1}{2}\frac{m_P^3}{m_\mu^2 m_\tau}\left(\frac{m_\tau^2 - m_P^2}{m_P^2 - m_\mu^2}\right)^2 \frac{1+(2\alpha/\pi)\ln(m_Z/m_\tau)}{1+\frac{3}{2}(\alpha/\pi)ln(m_Z/m_P)+\frac{1}{2}(\alpha/\pi)ln(m_Z/m_{P^*})} \left(\frac{1+|V_{\tau s}|^2}{1+|V_{\mu s}|^2}\right) & \text{(One sterile neutrino } \nu_s\text{)} \end{cases}$$

	No sterile neutrino	One sterile neutrino ν_s
Decay mode	$Z \to \nu_\ell \overline{\nu_\ell}$	$Z \to \nu_\ell \overline{\nu_\ell}, \nu_s \overline{\nu_\ell}, \nu_\ell \overline{\nu_s}, \nu_s \overline{\nu_s}$
Decay rate	$\Gamma_{inv} = \frac{G_F^0 m_Z^3}{4\pi\sqrt{2}}$	$\Gamma_{inv} = \frac{G_F^0 m_Z^3}{4\pi\sqrt{2}} \left(1 + \sum_{\ell=e,\mu,\tau} \left(\|V_{\ell s}\|^2 + \|V_{\ell s}\|^4\right)\right)$

$$\Gamma_{inv} = \begin{cases} m_Z^3 \sqrt{\frac{14\pi}{T_\mu m_\mu^5} f\left(m_e^2/m_\mu^2\right)} & \text{(No sterile neutrino)} \\ m_Z^3 \sqrt{\frac{14\pi}{T_\mu m_\mu^5} f\left(m_e^2/m_\mu^2\right)} \left(\frac{1 + \sum_{\ell=e,\mu,\tau} \left(|V_{\ell s}|^2 + |V_{\ell s}|^4\right)}{\sqrt{1 + |V_{es}|^2 + |V_{\mu s}|^2 + |V_{es}|^2 |V_{\mu s}|^2}}\right) & \text{(One sterile neutrino } \nu_s) \end{cases}$$

$$T_\mu = \frac{1}{\Gamma_\mu}$$

$$\frac{N_\nu}{3} = \frac{\Gamma_{inv}^{exp}}{\Gamma_{inv}^{SM}}, \qquad N_\nu = 3\left(\frac{1 + \sum_{\ell=e,\mu,\tau} \left(|V_{\ell s}|^2 + |V_{\ell s}|^4\right)}{\sqrt{1 + |V_{es}|^2 + |V_{\mu s}|^2 + |V_{es}|^2 |V_{\mu s}|^2}}\right)$$

According to PDG the number of light active neutrinos is $N_\nu = 2.9840 \pm 0.0082$, which gives us

$$\boxed{\frac{1 + |V_{es}|^2 + |V_{\mu s}|^2 + |V_{\tau s}|^2}{\sqrt{1 + |V_{es}|^2 + |V_{\mu s}|^2}} \approx \frac{N_\nu}{3} = 0.9947 \pm 0.0027.}$$

$$\frac{d\Gamma\left(\tau^- \to \mu^- + \text{“missing”}\right)}{dE_\mu} = \begin{cases} \frac{\left(G_F^0\right)^2}{12\pi^3}\left(3E_\mu\left(m_\tau^2+m_\mu^2\right)-2m_\tau\left(m_\mu^2+2E_\mu^2\right)\right)\sqrt{E_\mu^2-m_\mu^2} \\ \text{(No sterile neutrino)} \\ \frac{\left(G_F^0\right)^2\rho_{\mu\tau}}{12\pi^3}\left(3E_\mu\left(m_\tau^2+m_\mu^2\right)-2m_\tau\left(m_\mu^2+2E_\mu^2\right)\right)\sqrt{E_\mu^2-m_\mu^2} \\ \text{(One sterile neutrino } \nu_s\text{)} \end{cases}$$

$$\begin{aligned} T_\mu &= (2.1969811 \pm 0.0000022) \times 10^{-6}\ \text{s} = (2.1969811 \pm 0.0000022) \times 1.52 \times 10^{18}\ \text{GeV}^{-1} \\ &= (3.3394113 \pm 0.0000033) \times 10^{18}\ \text{GeV}^{-1}, \\ m_\mu &= 105.6583715 \pm 0.0000035\ \text{MeV} = 0.1056583715 \pm 0.0000000035\ \text{GeV}, \\ m_\tau &= 1776.82 \pm 0.16\ \text{MeV} = 1.77682 \pm 0.00016\ \text{GeV}. \end{aligned}$$