Sterile neutrino phenomenology

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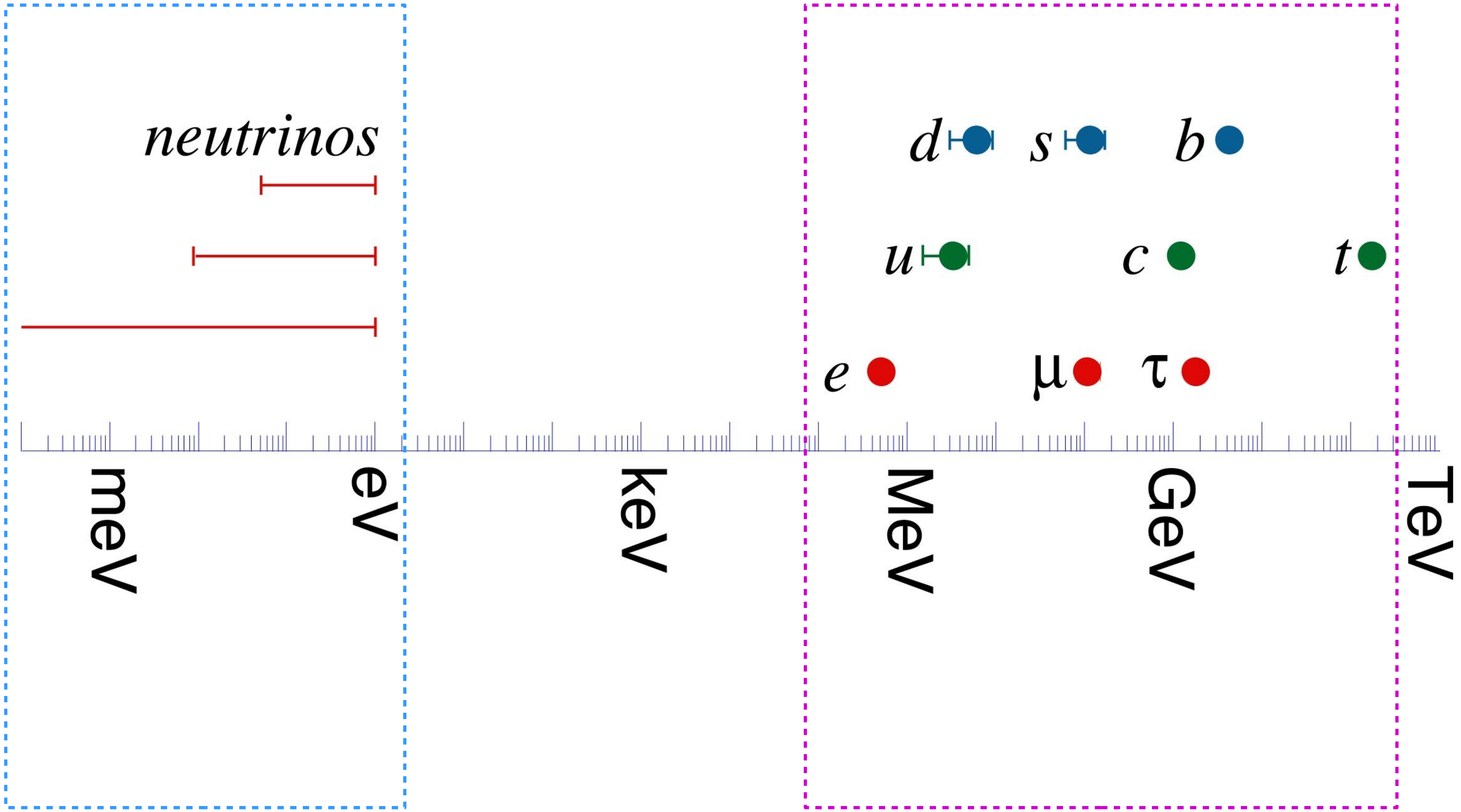
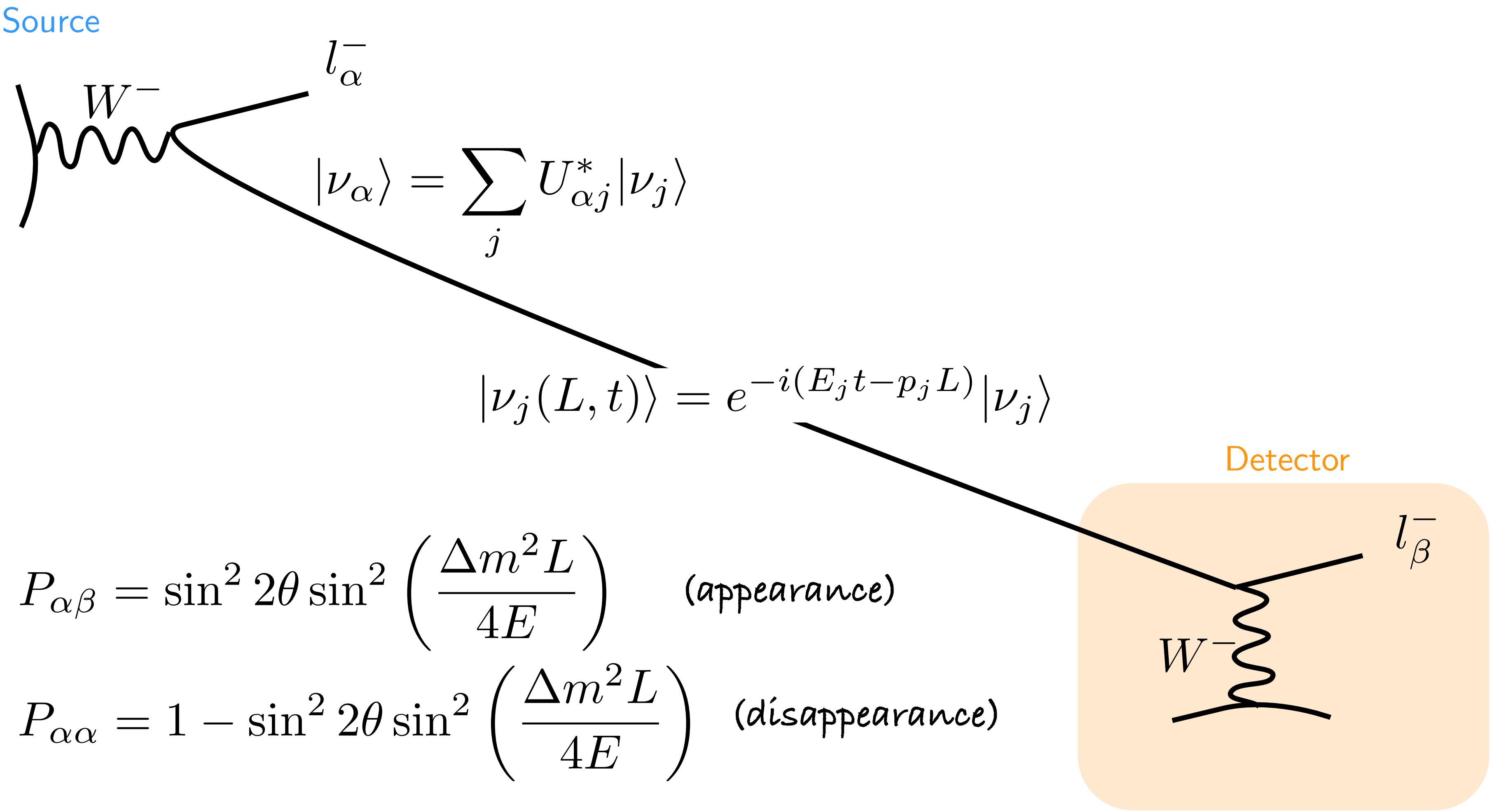
Neutrinos have mass!



Oscillations at long-baseline exps

Neutrino oscillations



$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

$$|\nu_j(L,t)\rangle = e^{-i(E_j t - p_j L)} |\nu_j\rangle$$

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$ (appearance)

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$ (disappearance)

$$\langle \nu_\beta | \nu_\alpha(L)\rangle \simeq \sum_j U_{\beta j} e^{\frac{-i m_j^2 L}{2E}} U^*_{\alpha j}$$

Non-Unitarity

$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M_R \overline{\nu}^c_R \nu_R \quad \longrightarrow \quad m_D \bar{\nu}_L \nu_R + \frac{1}{2} M_R \overline{\nu}^c_R \nu_R$$

$$\mathcal{M}_\nu = U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_R \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

Non-Unitarity

$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M_R \overline{\nu}^c_R \nu_R \longrightarrow m_D \bar{\nu}_L \nu_R + \frac{1}{2} M_R \overline{\nu}^c_R \nu_R$$

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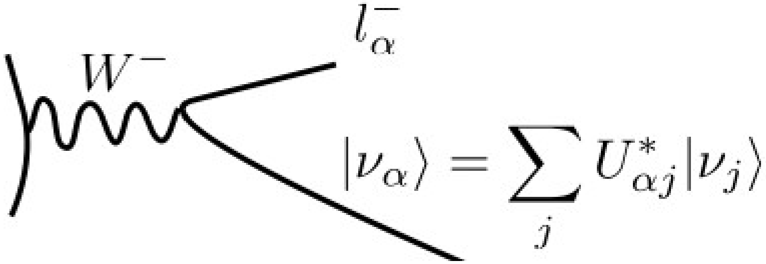
The full matrix is unitary,
but the 3x3 block is not:

$$U = \begin{pmatrix} \boxed{N} & \Theta \\ R & S \end{pmatrix} \longleftarrow \mathcal{O}\left(\frac{m_D}{M_R}\right)$$

Non-unitarity in oscillations

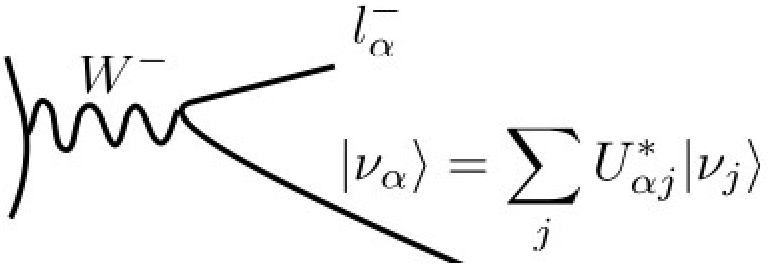


$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle$$

Heavy steriles
(not kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

Non-unitarity in oscillations



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Heavy steriles
(<u>not</u> kinematically accessible)

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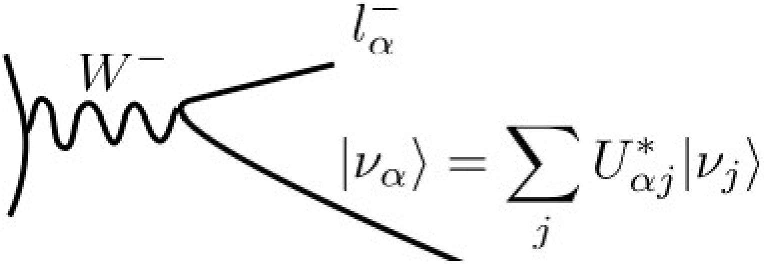
Light steriles
(kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{IJ} L}{2E}}$$

$$+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{iJ} L}{2E}}$$

Non-unitarity in oscillations



Heavy steriles
(<u>not</u> kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

Light steriles
(kinematically accessible)

$$P_{\alpha\beta} \simeq \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}} + \mathcal{O}(\Theta^4)$$

→ Equal <u>at leading order</u>

Blennow, PC, Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, 1609.08637
(see also Fong, Minakata, Nunokawa, 1609.08623)

Non-unitarity in oscillations

A triangular parametrization is most convenient:

$$N = (I - \alpha)U \qquad \alpha = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{e\mu} & \alpha_{\mu\mu} & 0 \\ \alpha_{e\tau} & \alpha_{\mu\tau} & \alpha_{\tau\tau} \end{pmatrix}$$

In a 3+1 scenario (light sterile), one can further identify:

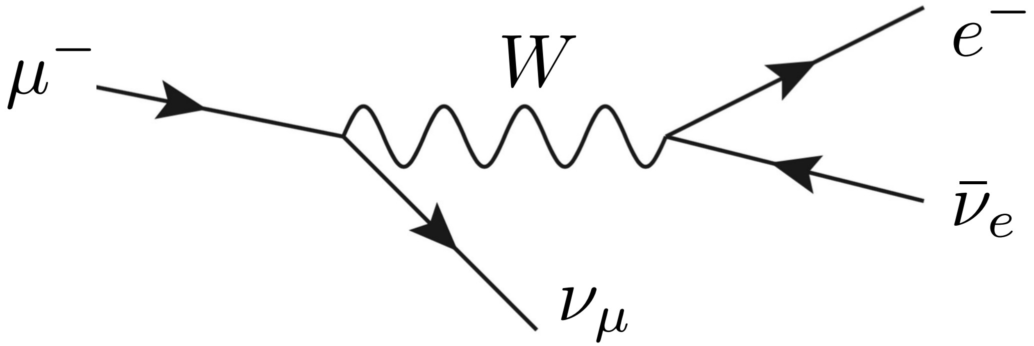
$$N = \left(\hat{O}_{34}\hat{O}_{24}O_{14}O_{23}\hat{O}_{13}O_{12}\right)_{3\times3} \quad \alpha \simeq \begin{pmatrix} \frac{1}{2}s_{14}^2 & 0 & 0 \\ s_{14}\hat{s}_{24}^* & \frac{1}{2}s_{24}^2 & 0 \\ s_{14}\hat{s}_{34}^* & \hat{s}_{24}\hat{s}_{34}^* & \frac{1}{2}s_{34}^2 \end{pmatrix}$$

$$\hat{s}_{ij} \equiv s_{ij}e^{i\phi_{ij}}$$

Xing, 0709.2220 and 0902.2469
Escrihuela, Forero, Miranda, Tortola, Valle, 1503.08879

Current bounds

If the new states are above EW scale, weak processes get affected right away:



$$G_\mu = G_{SM}(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}$$

With

$$G_{\rm SM} = \frac{\alpha\pi M_Z^2}{\sqrt{2}M_W^2(M_Z^2 - M_W^2)}$$

$\Big\}$ They agree at the 0.1% level!

See e.g., Fernandez-Martinez, Hernandez-Garcia and Lopez-Pavon, 1605.08774, Antusch and Fischer, 1407.6607

Current bounds

If the heavy neutrinos are above the EW scale, the bounds are really strong:

$$|\alpha_{\beta\gamma}| \leq \begin{pmatrix} 1.3\cdot 10^{-3} & 0 & 0 \\ 6.8\cdot 10^{-4\,*} & 2.2\cdot 10^{-4} & 0 \\ 2.7\cdot 10^{-3} & 1.2\cdot 10^{-3} & 2.8\cdot 10^{-3} \end{pmatrix} \quad (\text{at } 2\sigma)$$

Bounds adapted from Fernandez-Martinez, Hernandez-Garcia and Lopez-Pavon, 1605.08774
(see also Antusch and Fischer, 1407.6607)

The bounds are relaxed if they are below EW scale

$$|\alpha_{\beta\gamma}| \leq \begin{pmatrix} 2.4\cdot 10^{-3} & 0 & 0 \\ 2.5\cdot 10^{-2} & 2.2\cdot 10^{-2} & 0 \\ 6.9\cdot 10^{-2} & 1.2\cdot 10^{-2} & 1\cdot 10^{-1} \end{pmatrix}$$

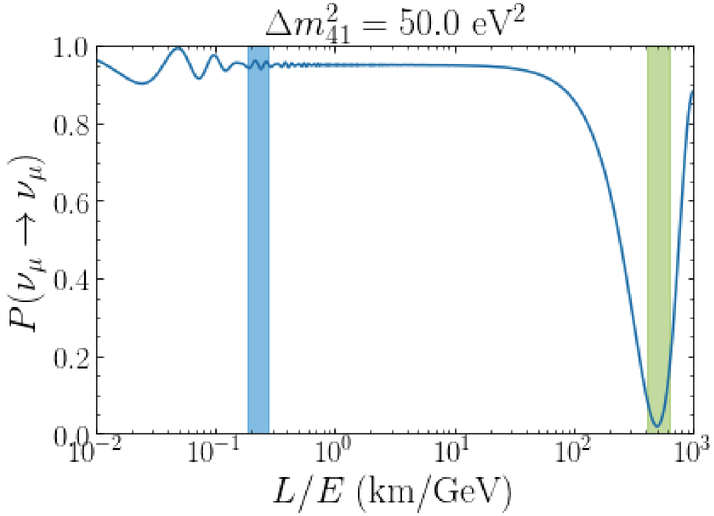
$$(\text{at } 95\%, \ \text{for } \Delta m^2 > 100 \text{ eV}^2)$$

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, 1609.08637

* this bound becomes stronger if we consider $\mu \to e\gamma$ ($< 2.4 * 10^{-5}$)

Role of near detectors

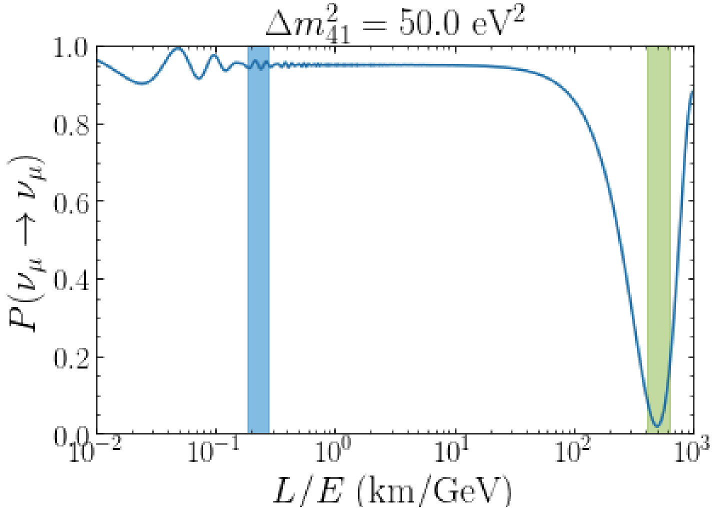
Long-baseline experiments measure a “ratio” of event rates:



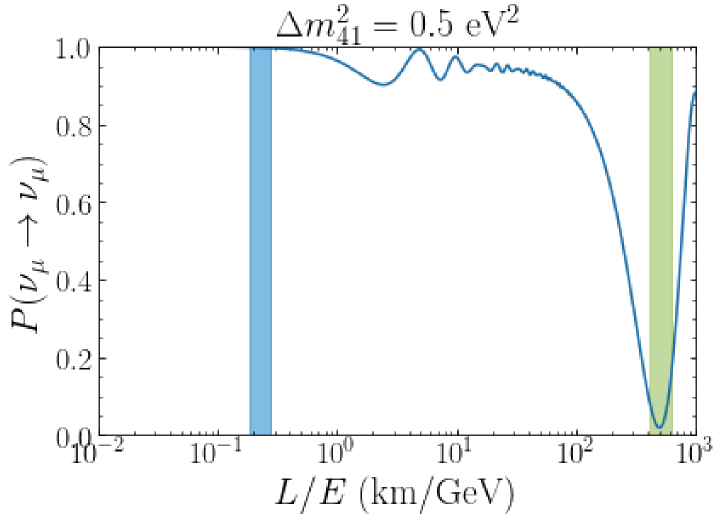
$$\Rightarrow \quad \mathcal{P}^{FD}_{\alpha\beta} = \frac{\mid (N S^0 N^\dagger)_{\beta\alpha} \mid^2}{((N N^\dagger)_{\alpha\alpha})^2}$$

Role of near detectors

Long-baseline experiments measure a “ratio” of event rates:



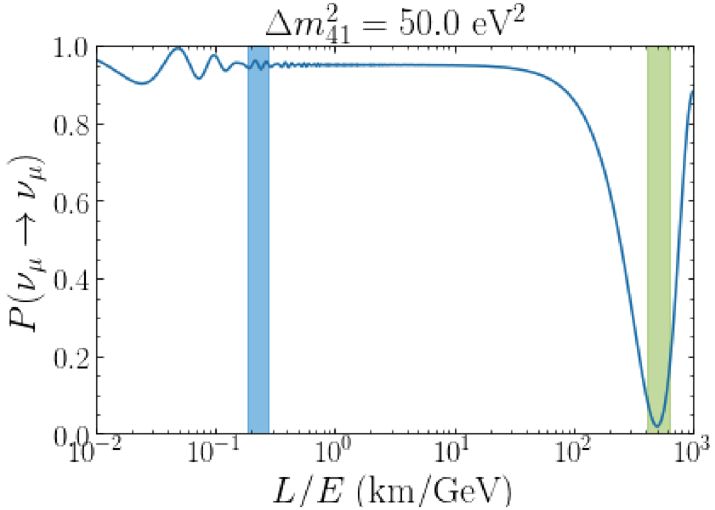
$$\mathcal{P}^{FD}_{\alpha\beta} = \frac{\mid (NS^0N^\dagger)_{\beta\alpha} \mid^2}{((NN^\dagger)_{\alpha\alpha})^2}$$



$$\mathcal{P}^{FD}_{\alpha\beta} \simeq \mid (NS^0N^\dagger)_{\beta\alpha} \mid^2$$

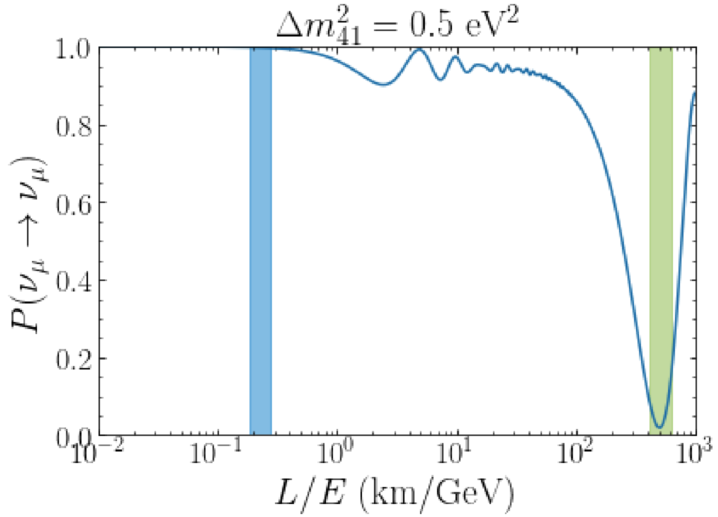
Role of near detectors

Long-baseline experiments measure a “ratio” of event rates:



⇨

$$\mathcal{P}^{FD}_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} + \mathcal{O}(\alpha^2)$$



⇨

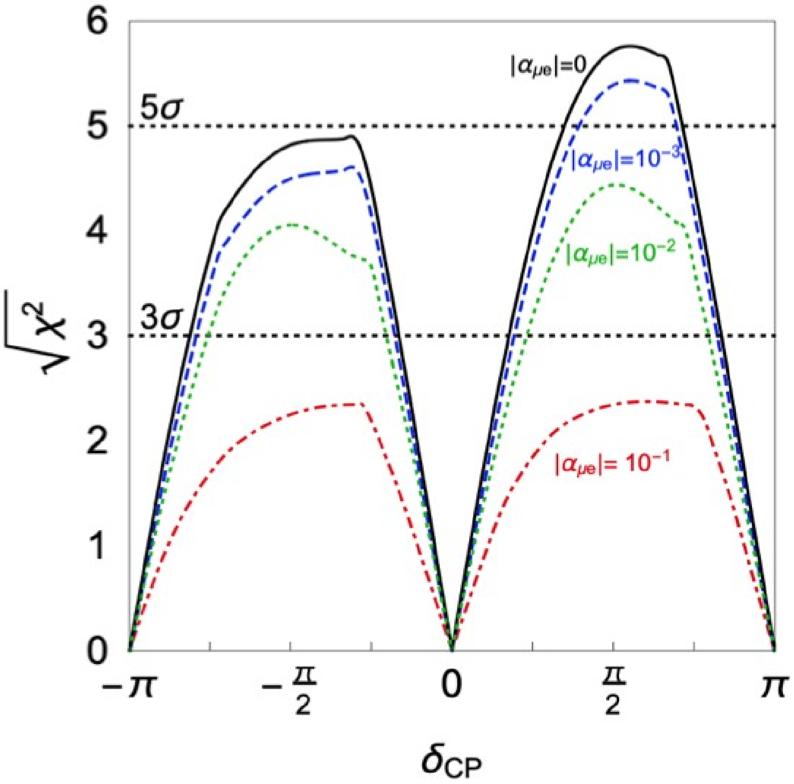
$$\mathcal{P}^{FD}_{\mu\mu} = (1 - 4\alpha_{\mu\mu})(1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31}) + \mathcal{O}(\alpha^2)$$

Impact at long-baseline experiments

$$\mathcal{P}_{\mu e} = (1 - 2\alpha_{ee} + 2\alpha_{\mu\mu}) P_{\mu e}^{3\times 3} + \alpha_{\mu e} P_{\mu e}^{I} + \mathcal{O}(\alpha^2)$$

Escrihuela, Forero, Miranda, Tortola, Valle, 1503.08879
(see also 1612.07377)

DUNE coll., 2008.12769

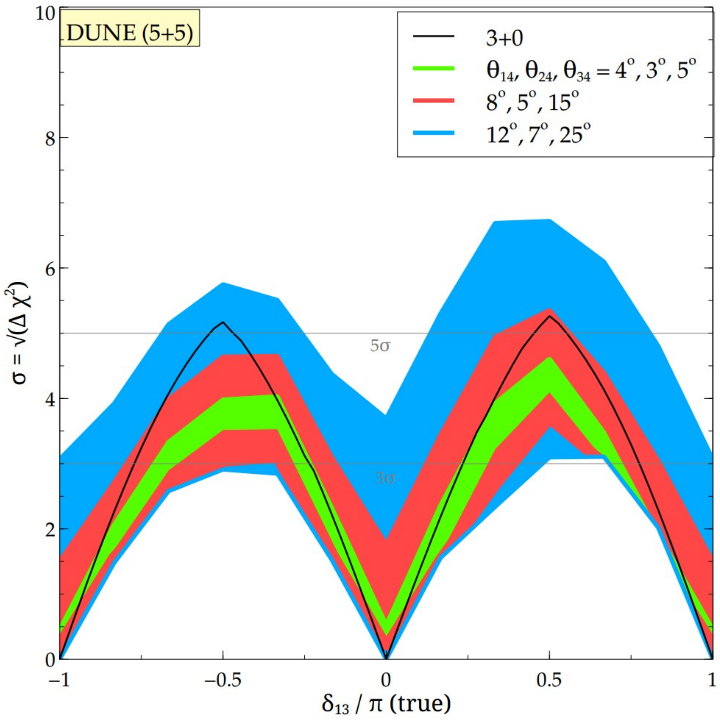


Impact at long-baseline experiments

$$\mathcal{P}_{\mu e} = (1 - 2\alpha_{ee} + 2\alpha_{\mu\mu}) P^{3\times 3}_{\mu e} + \alpha_{\mu e} P^{I}_{\mu e} + \mathcal{O}(\alpha^2)$$

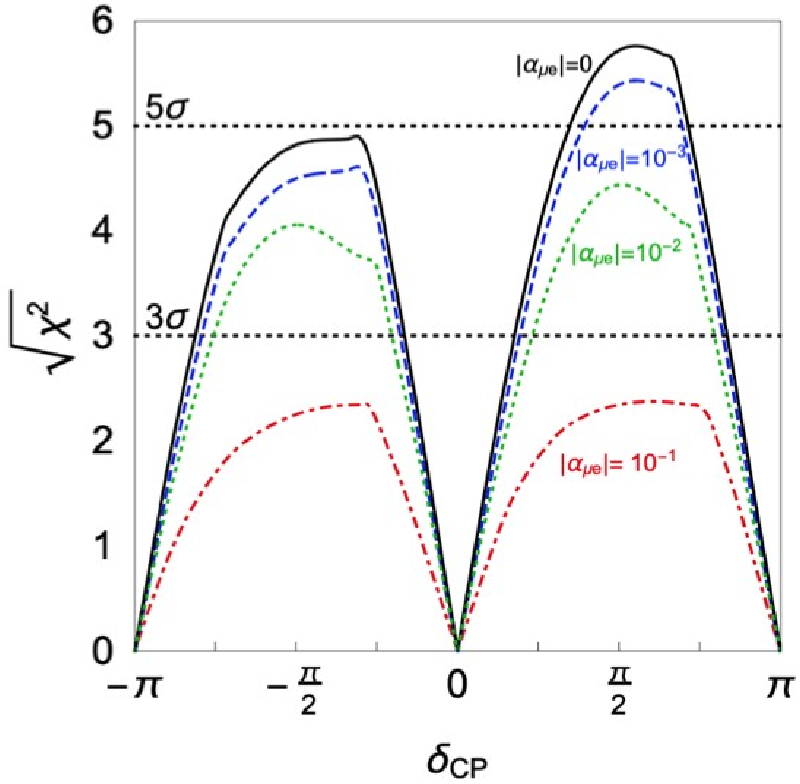
Escrihuela, Forero, Miranda, Tortola, Valle, 1503.08879
(see also 1612.07377)

In a 3+1 scenario, we can identify
$|\alpha_{\mu e}| = s_{14} s_{24}$

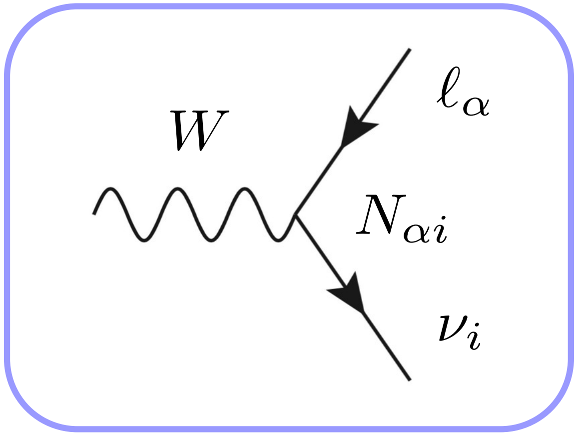


Dutta, Gandhi, Kayser, Masud, Prakash, 1607.02152
See also Agarwalla, Chatterjee, Palazzo, 1605.04299

DUNE coll., 2008.12769



NSI from non-unitarity



$$P_{\alpha\beta} = \left| (NSN^\dagger)_{\beta\alpha} \right|^2$$
$$= \left| \left[(1-\alpha)USU^\dagger(1-\alpha)^\dagger\right]_{\beta\alpha} \right|^2$$

Effects in production, propagation and detection are <u>correlated</u> and <u>simultaneously</u> generated:

$$\epsilon^{s*}_{\alpha\beta} = \epsilon^{d}_{\alpha\beta} = -\alpha_{\alpha\beta}$$

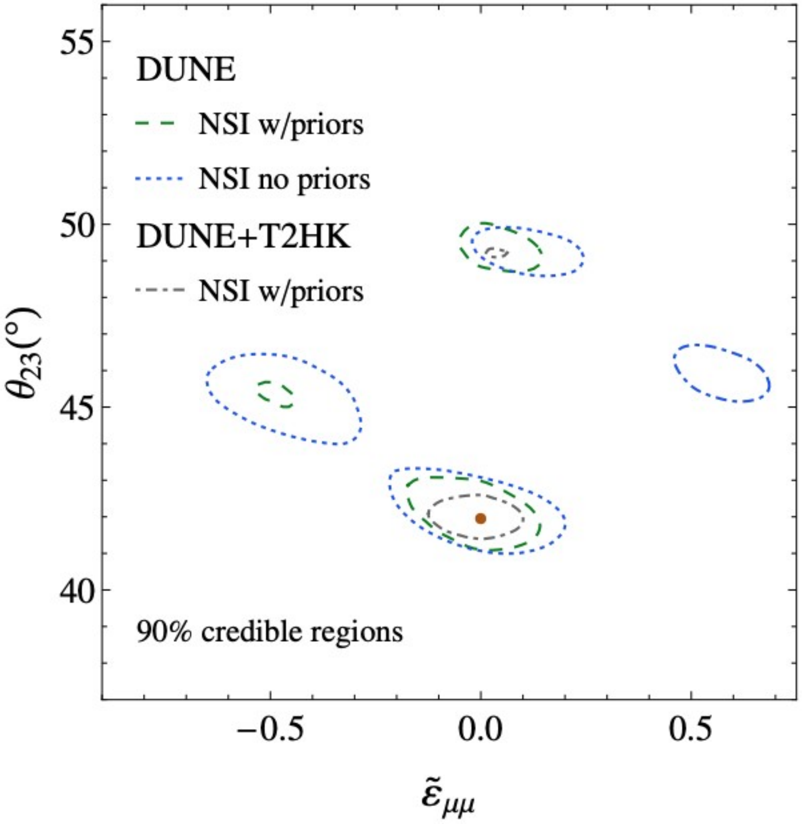
$$\epsilon^m_{ee} = -\alpha_{ee}$$
$$\epsilon^m_{\mu\mu} = \alpha_{\mu\mu}$$
$$\epsilon^m_{\tau\tau} = \alpha_{\tau\tau}$$

$$\epsilon^m_{\alpha\beta} = \frac{1}{2}\alpha^*_{\beta\alpha}$$

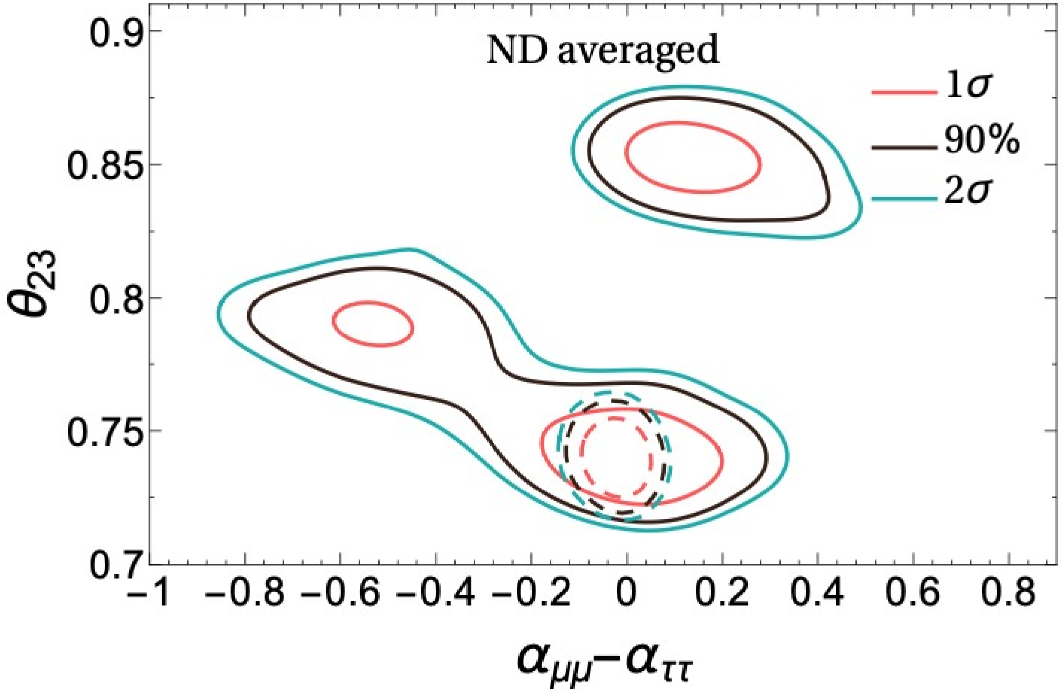
Pilar Coloma - IFT

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, 1609.08637

NSI from non-unitarity



Coloma,1511.06357

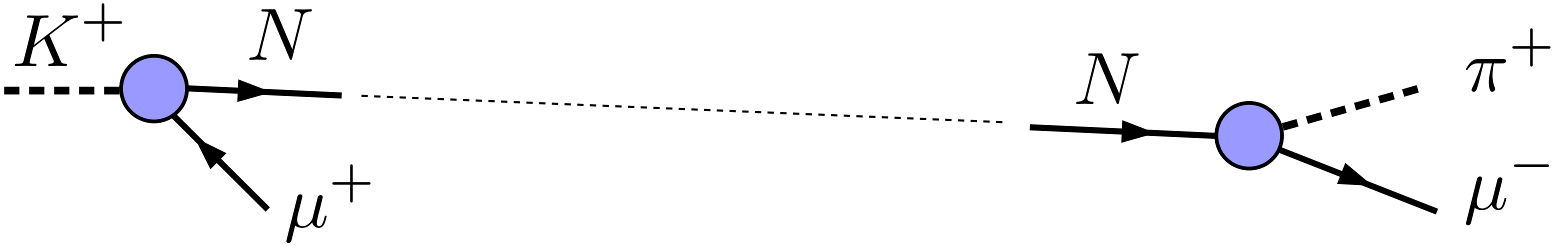


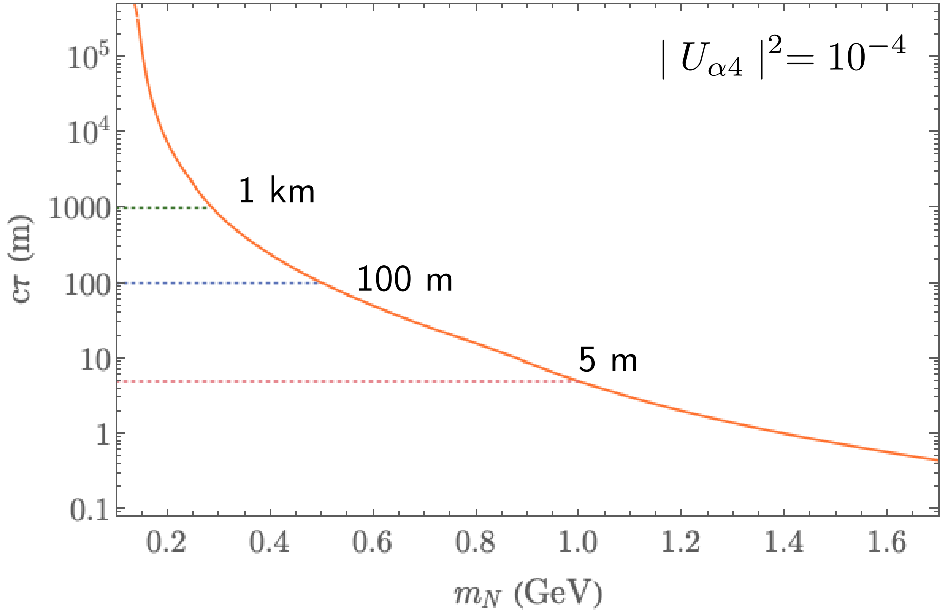
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, Lopez-Pavon, 1609.08637

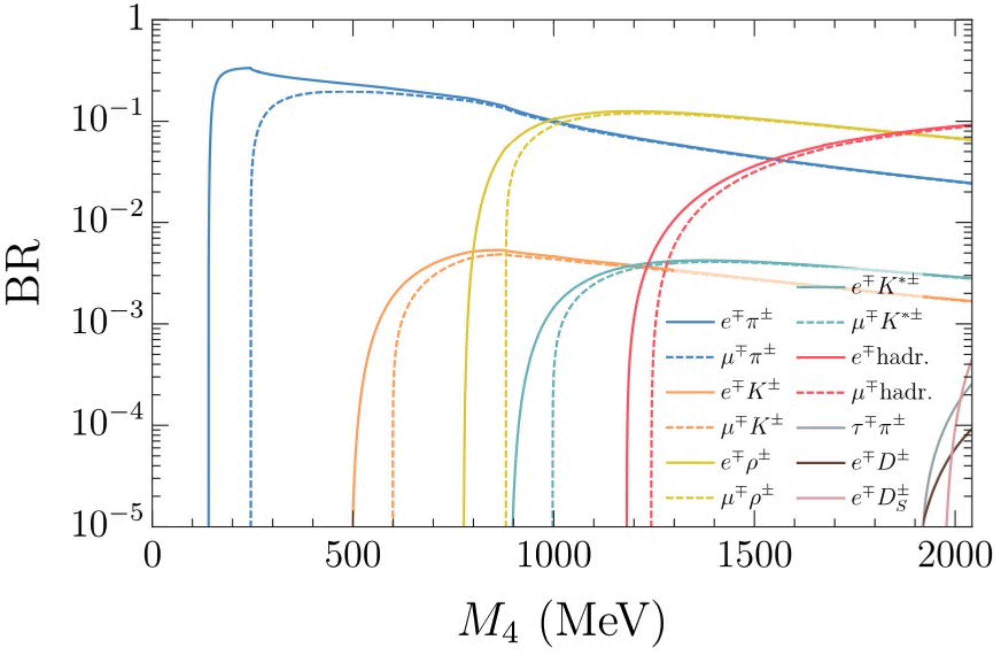
→ see also Agarwalla, Chatterjee and Palazzo, 1605.04299 for a similar effect with averaged-out sterile

Displaced HNL decays

Displaced decays







Coloma, Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia, Pavlovic, 2007.03701

See also works by Ballett, Boschi & Pascoli, Berryman et al, Bondarenko et al, Breitbach et al, Shrock, Drewes & Garbrecht, Krasnov, ...

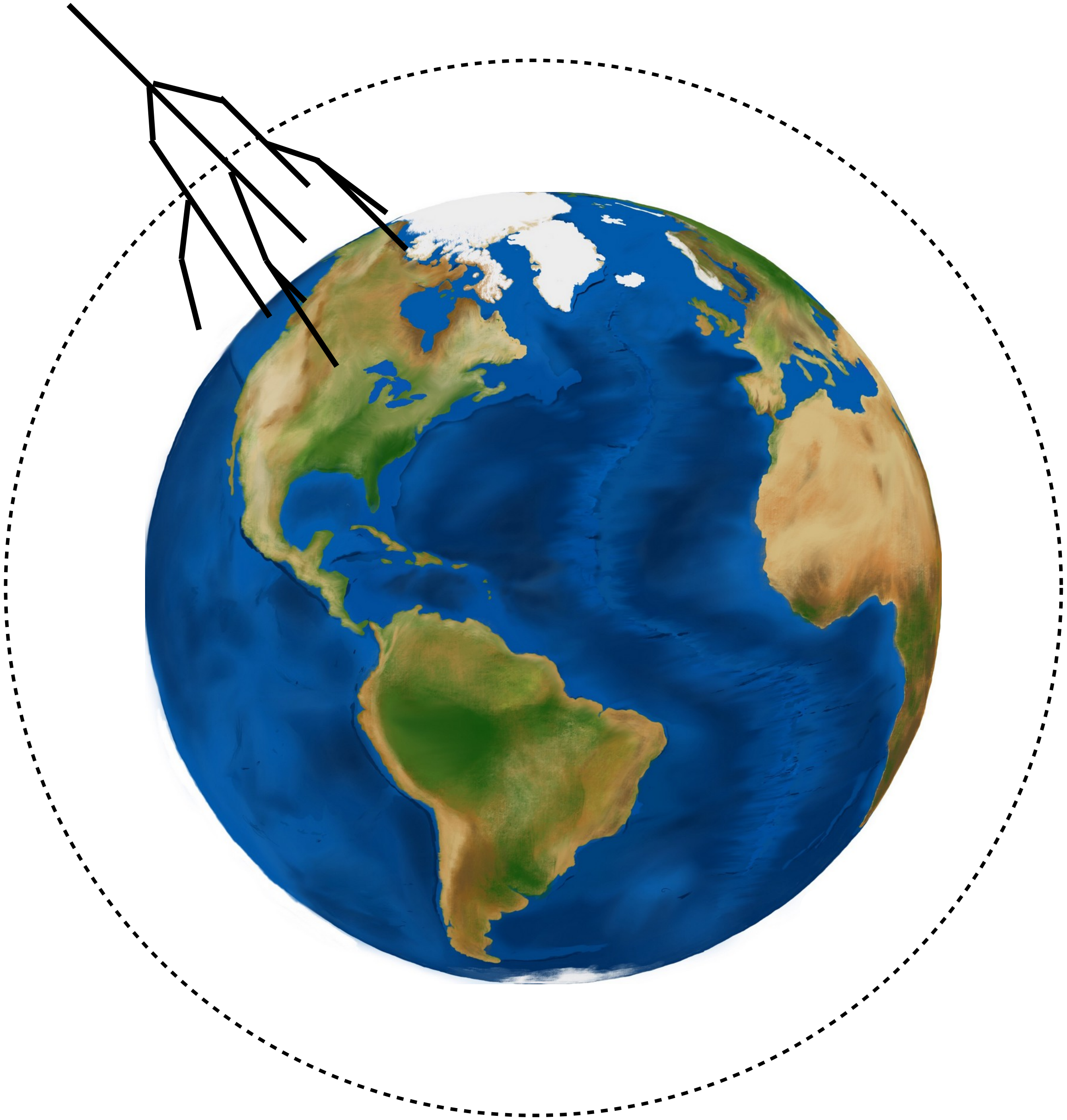


Image credit: https://mingtang.me/

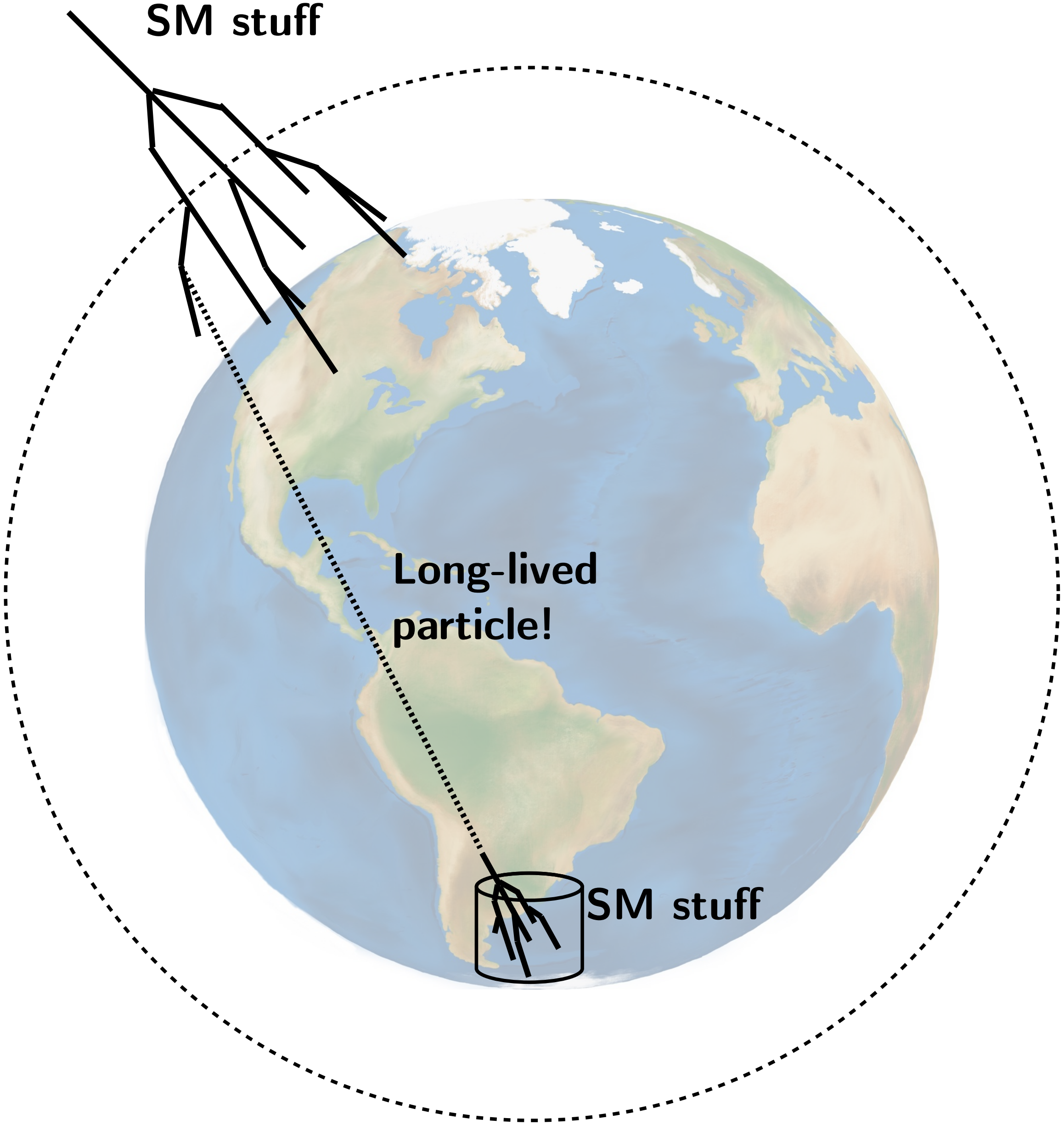
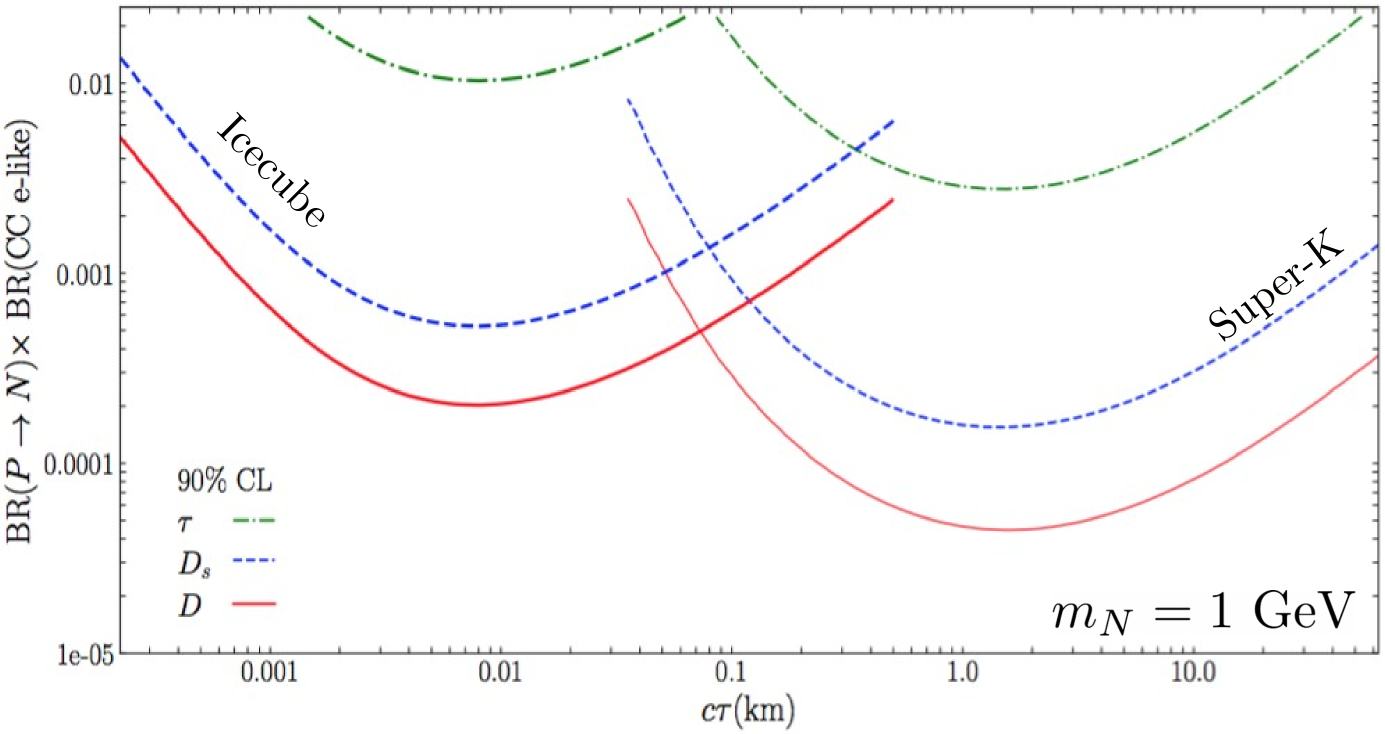


Image credit: https://mingtang.me/

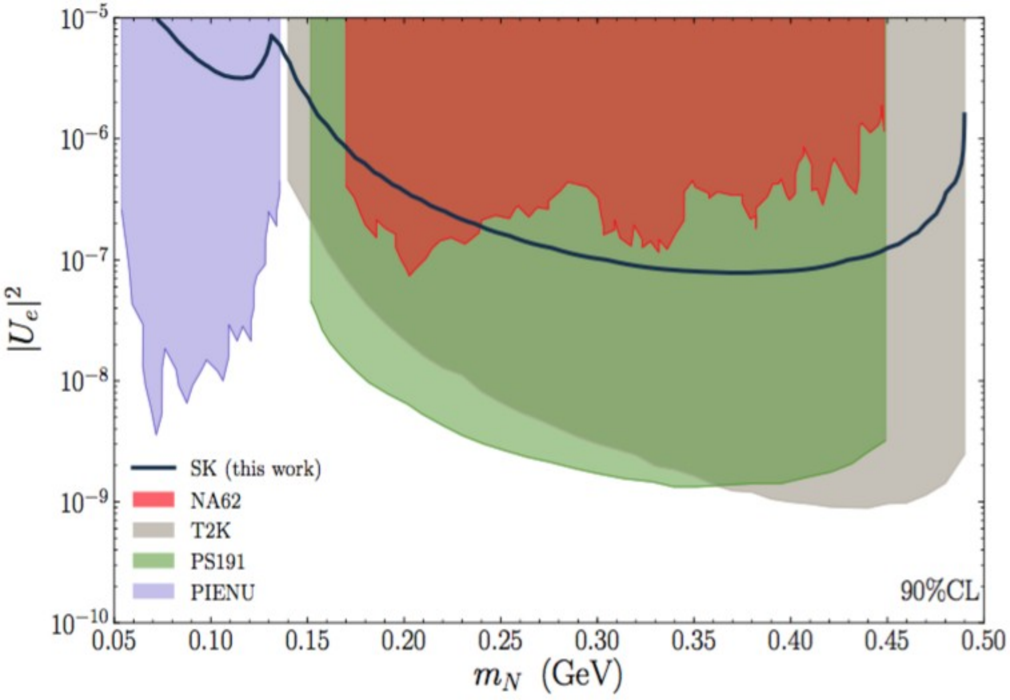
HNL above the kaon mass

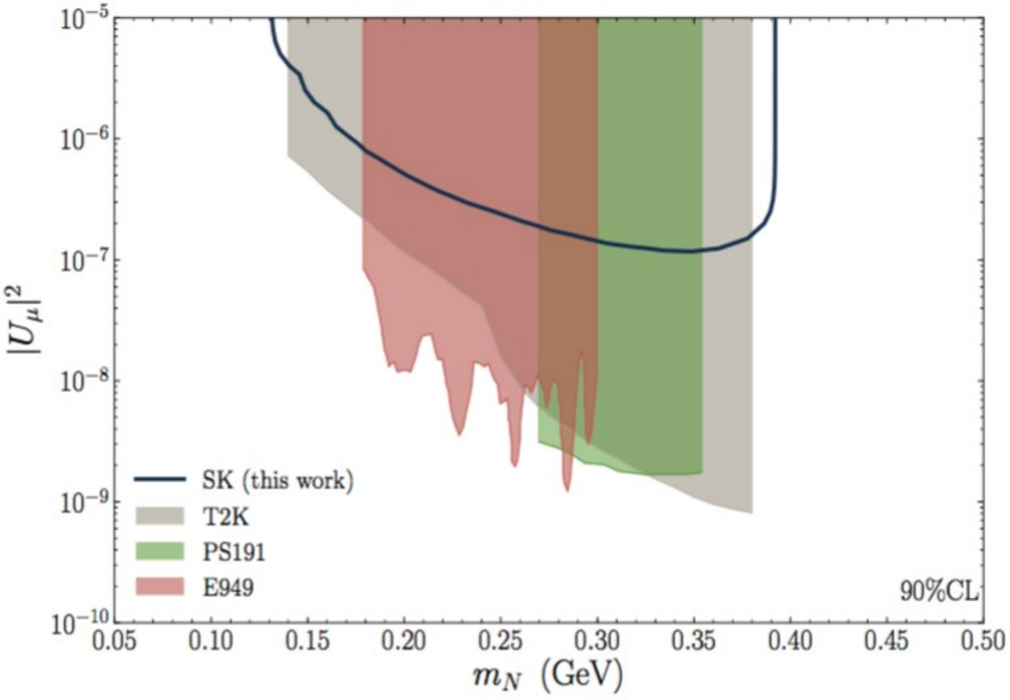


Argüelles, Coloma, Hernandez, Muñoz, 1910.12839

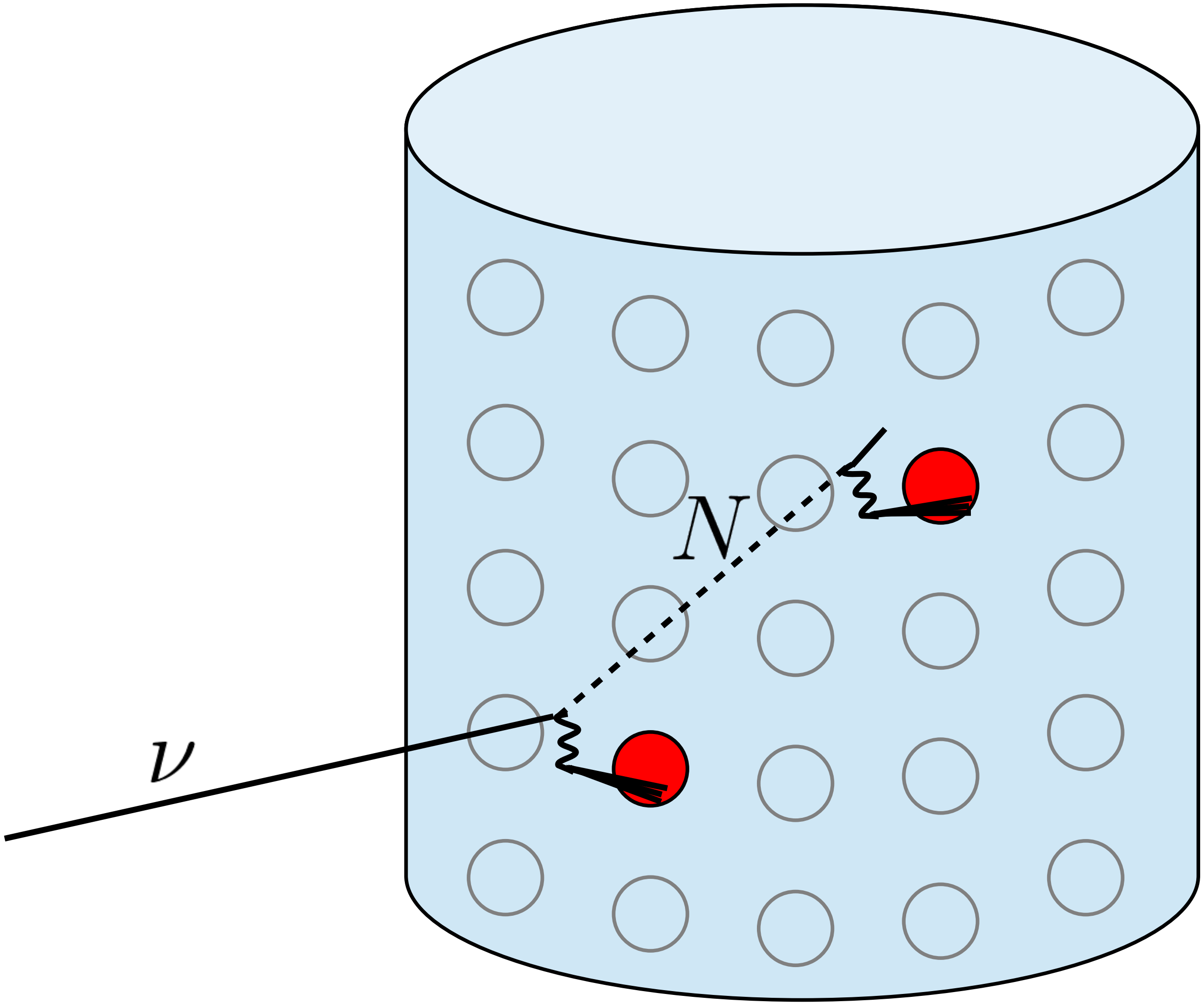
HNL below the kaon mass

→ See talk by Víctor Muñoz on Feb 25th!





Coloma, Hernandez, Muñoz, Shoemaker, 1911.09129
(see also Asaka and Watanabe, 1202.0725, Kusenko, Pascoli and Semikoz, hep-ph/0405198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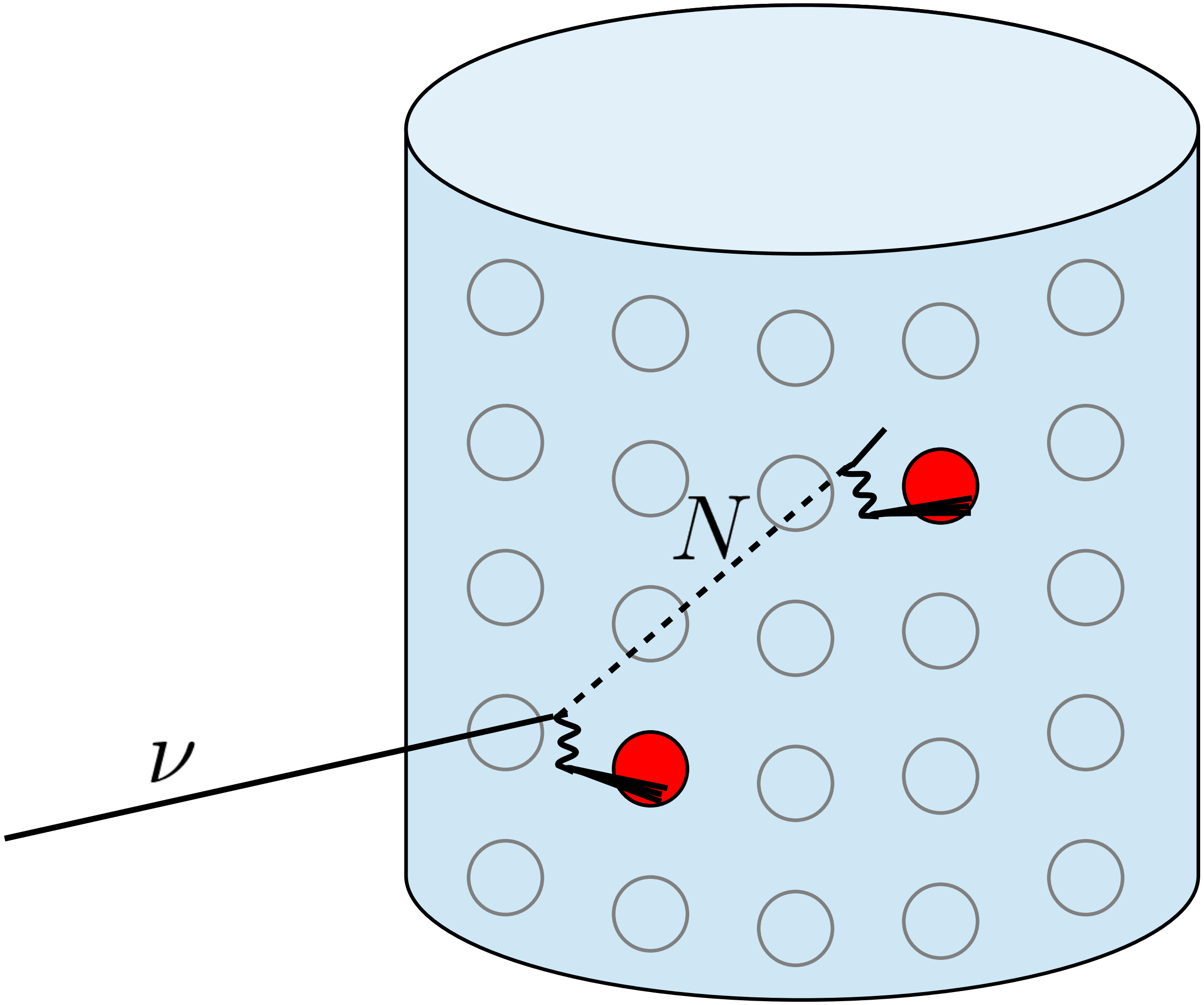
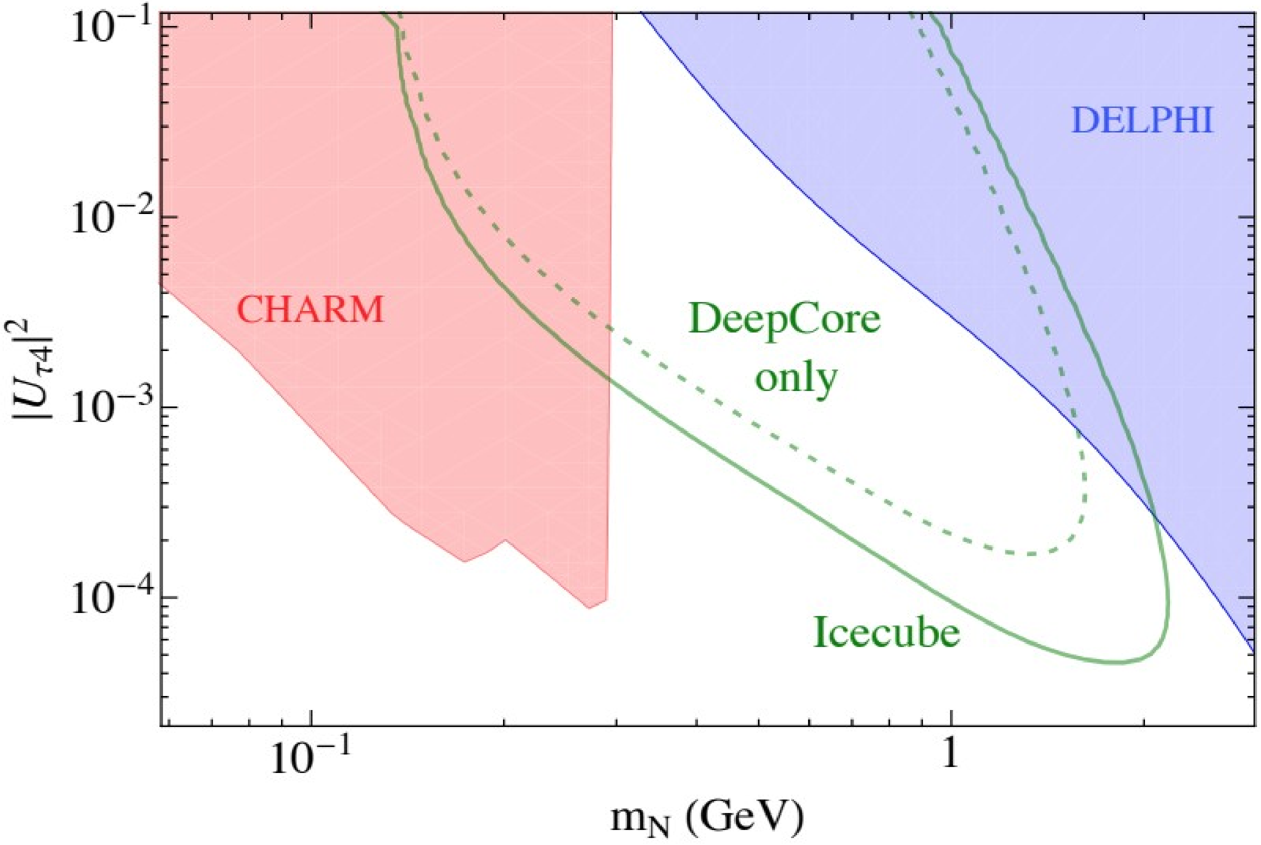


→ see talk by Daria Pankova on Feb 25th

Double-bangs at low energies

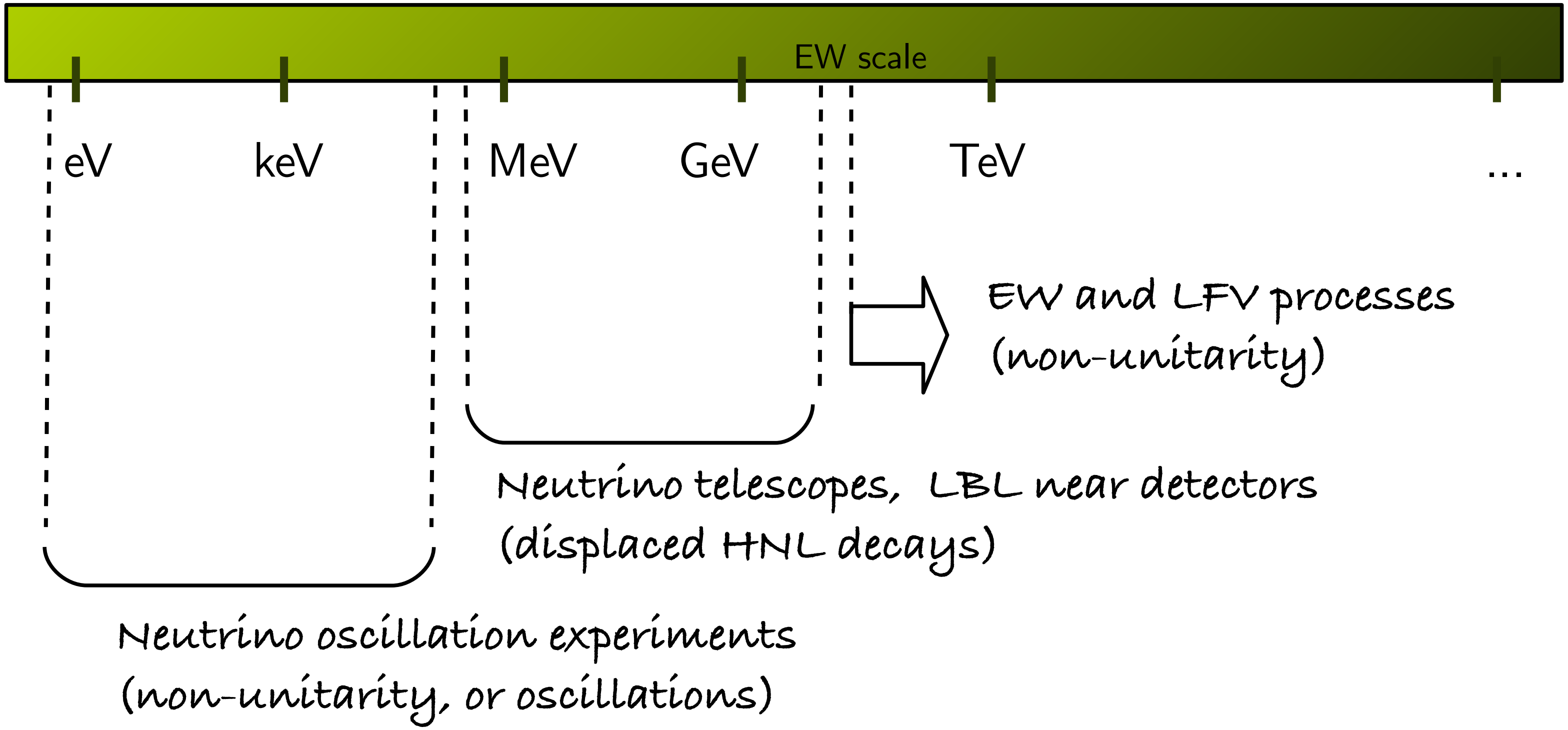
6 years considered



Coloma, Machado, Martinez-Soler and Shoemaker, 1707.08573

Summary and conclusions

Many ways to probe the existence of sterile neutrinos in neutrino experiments at very different scales:



EW scale

eV keV MeV GeV TeV …

EW and LFV processes
(non-unitarity)

Neutrino telescopes, LBL near detectors
(displaced HNL decays)

Neutrino oscillation experiments
(non-unitarity, or oscillations)

Thank you!!