Non-Standard ν properties & searches (II)

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International Neutrino Summer School
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Outline

- Non-standard interactions: impact of NSI on oscillations
- Non-standard interactions: scattering (nuclear and electron)

- Non-Unitarity
- Sterile neutrinos in oscillations

Non-unitarity, HNL, N_R, steriles and all that

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

(see Petcov's lectures)

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

Non-unitarity, HNL, N$_R$, steriles and all that

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

(see Petcov's lectures)

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

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

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

Non-unitarity, HNL, N_R, steriles and all that

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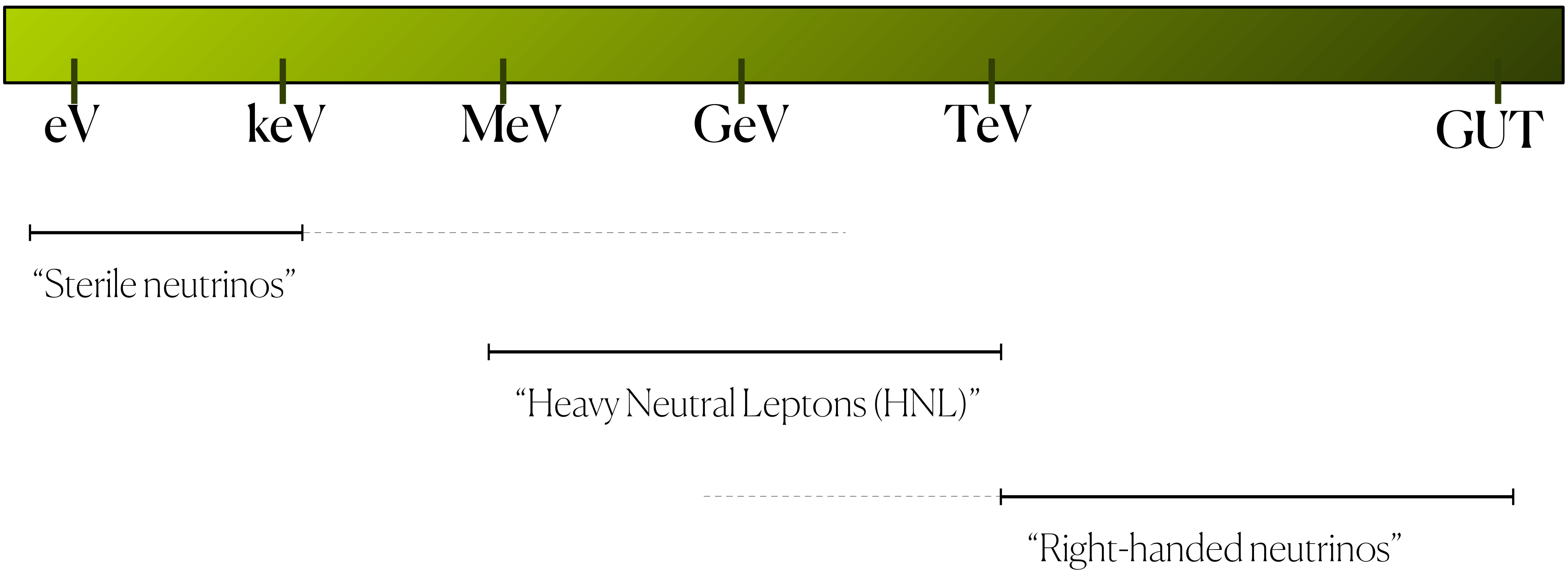
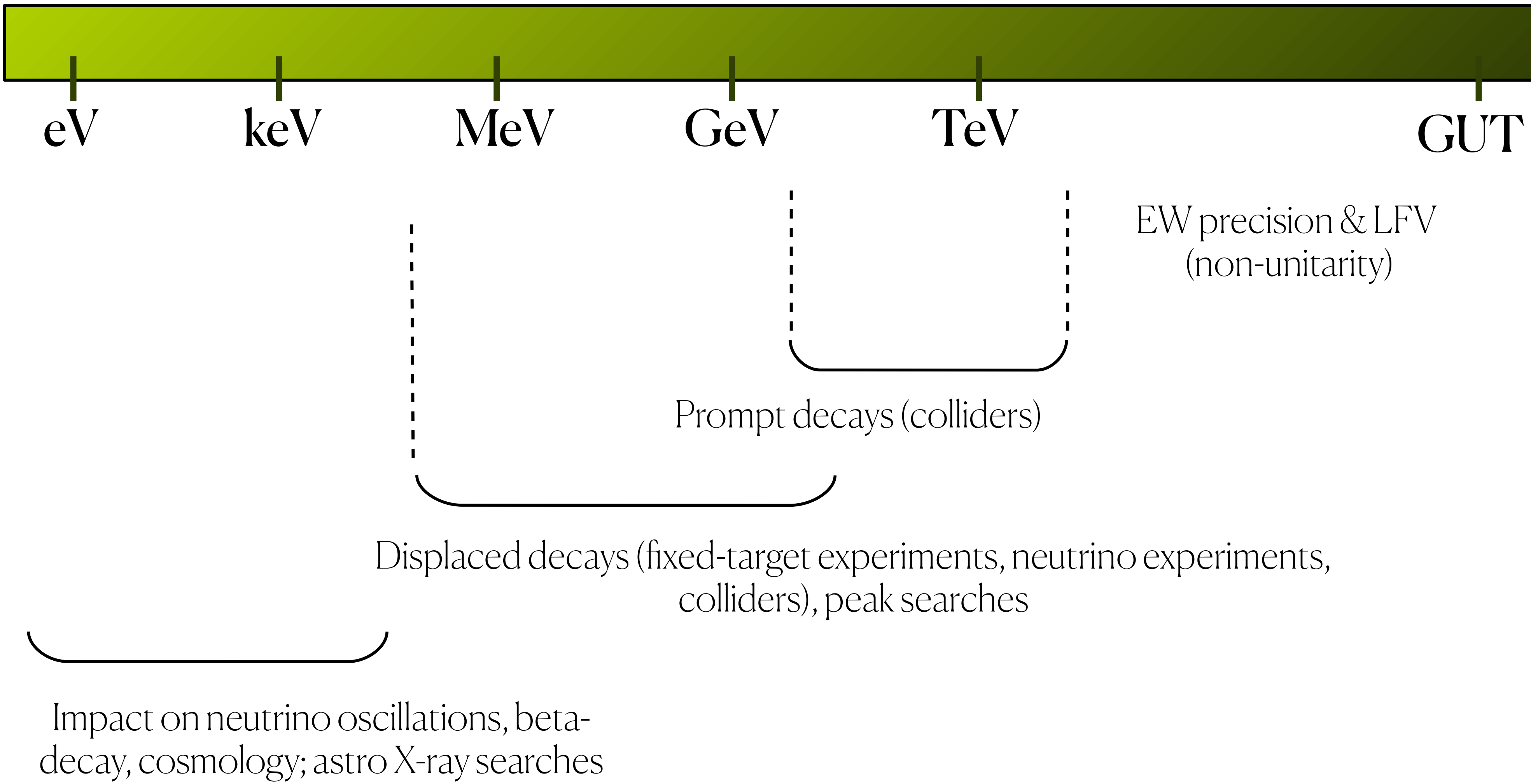
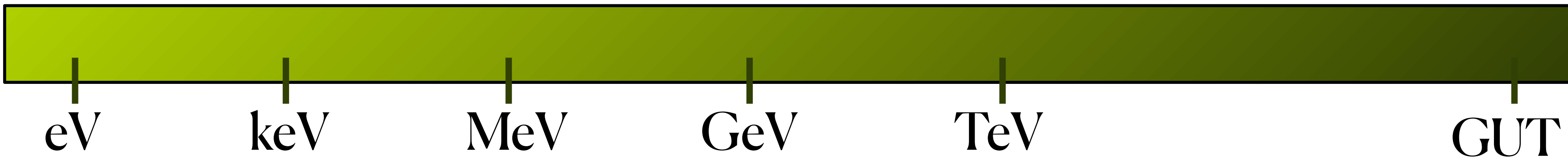


Non-unitarity, HNL, N_R, steriles and all that



Non-unitarity, HNL, N_R, steriles and all that



Directly testable in lab exps;
Indirect tests from cosmology;
Astrophysical tests (e.g. X-ray searches)

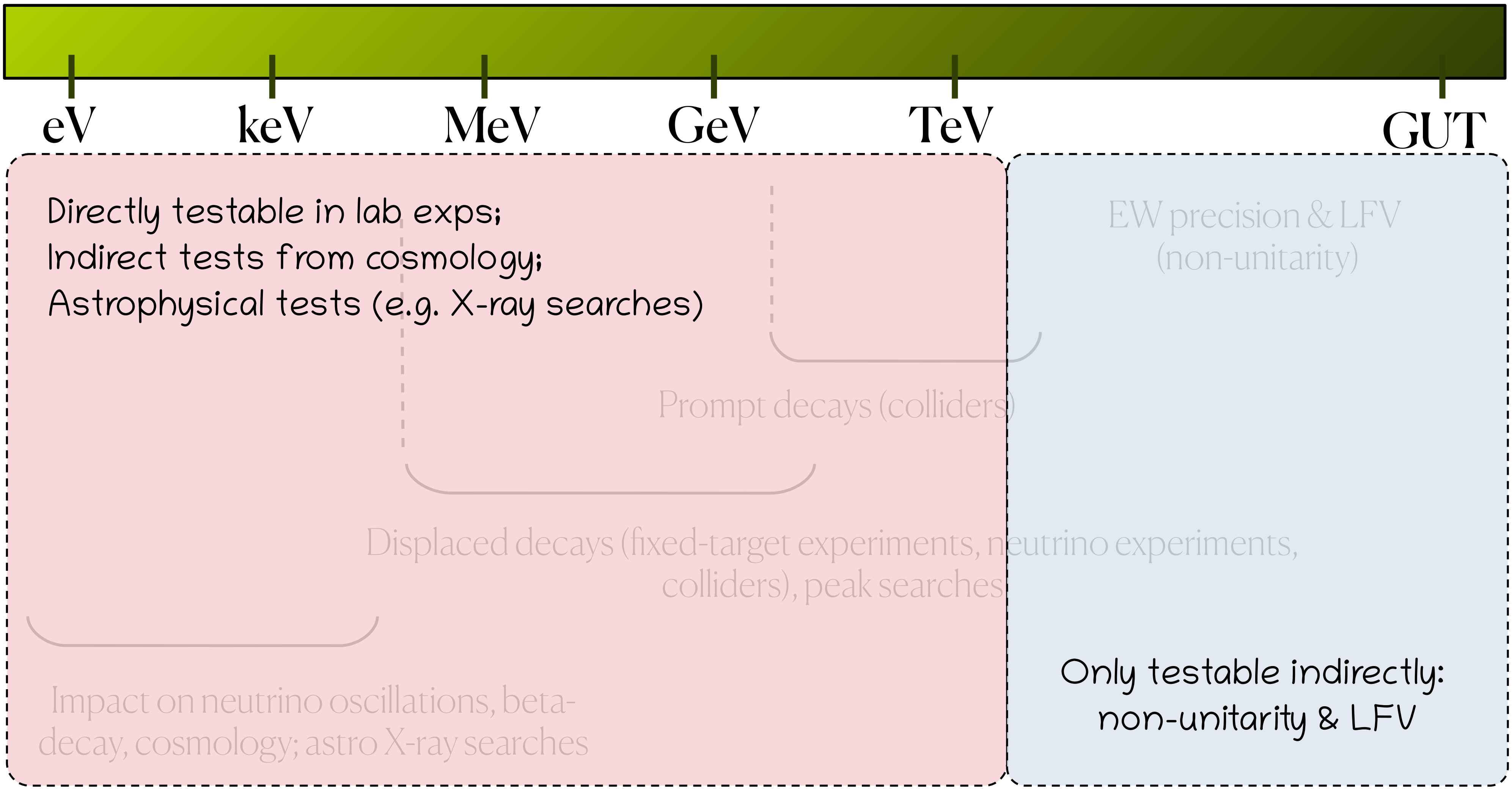
EW precision & LFV (non-unitarity)

Prompt decays (colliders)

Displaced decays (fixed-target experiments, neutrino experiments, colliders), peak searches

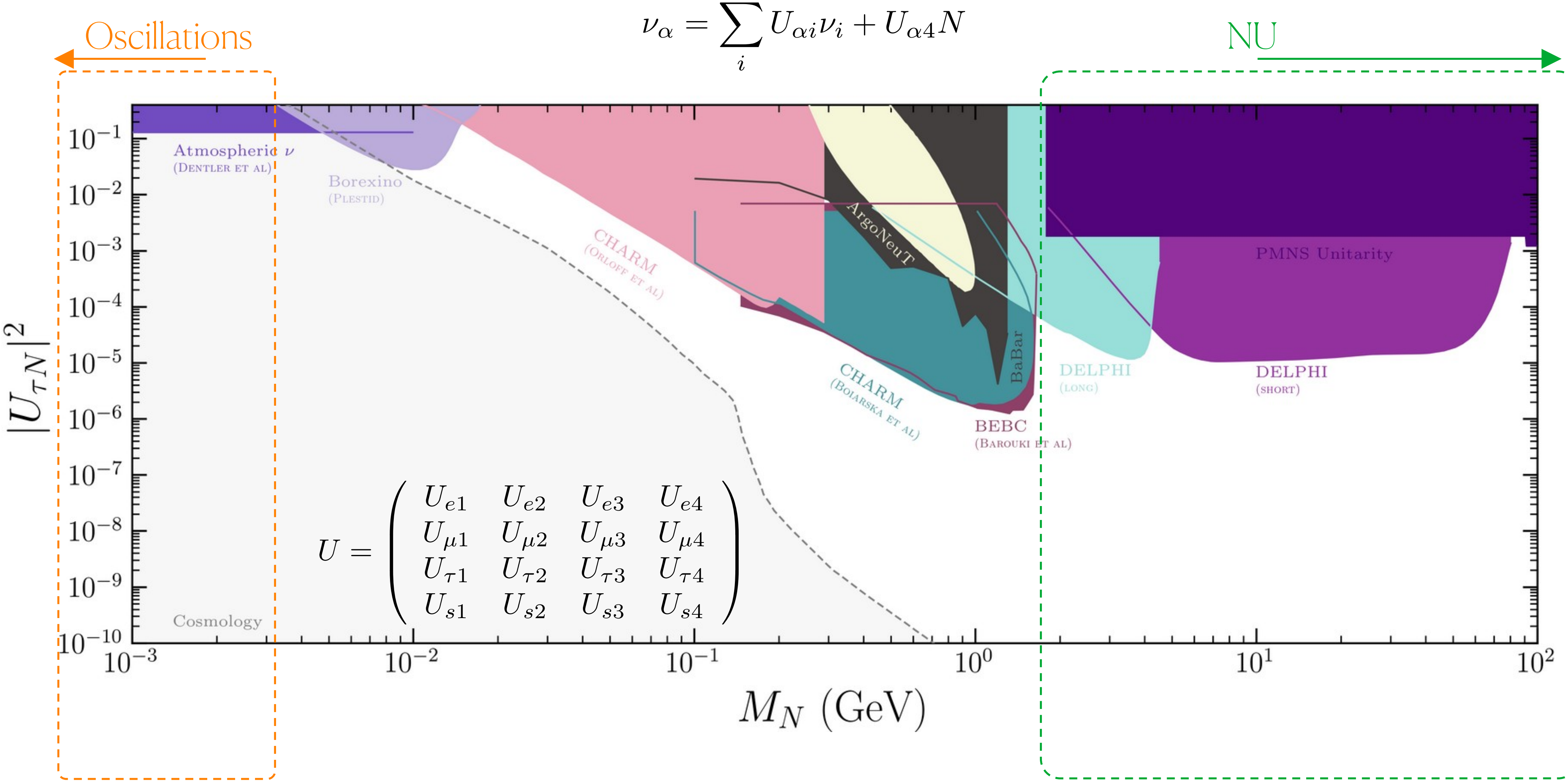
Impact on neutrino oscillations, beta-decay, cosmology; astro X-ray searches

Non-unitarity, HNL, N_R, steriles and all that



Non-unitarity, HNL, N_R, steriles and all that

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$

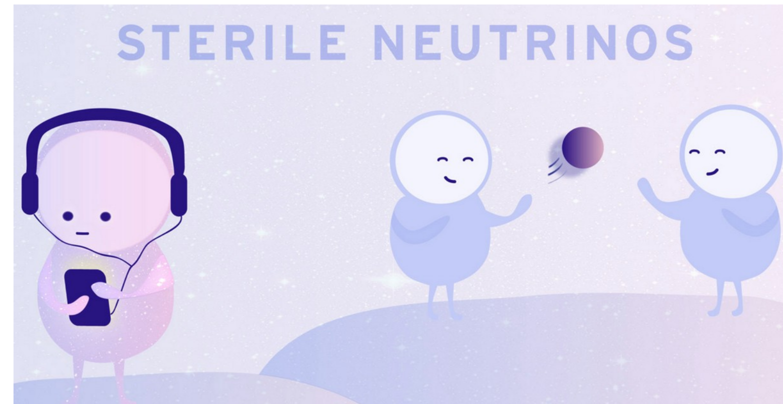


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Figure from Fernandez-Martínez, González-López, Hernández-García, Hostert, López-Pavón, 2304.06772

Sterile neutrinos

eV-scale sterile neutrinos

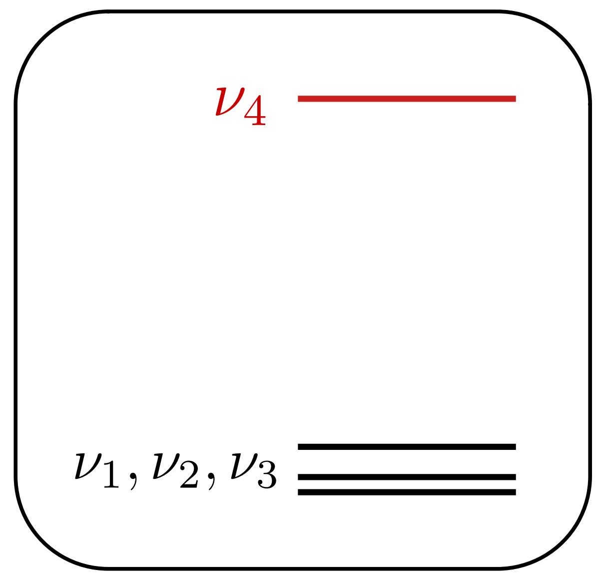


$$i\frac{d}{dt}\Psi_\nu = (UH_0U^\dagger + V)\Psi_\nu$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$P_{ee} \equiv P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$



eV-scale sterile neutrinos

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[U\begin{pmatrix}0 & & & \\ & \Delta_{21} & & \\ & & \Delta_{31} & \\ & & & \Delta_{41}\end{pmatrix}U^\dagger + \begin{pmatrix}V_{CC} & & & \\ & 0 & & \\ & & 0 & \\ & & & -V_{NC}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

$$U = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}$$

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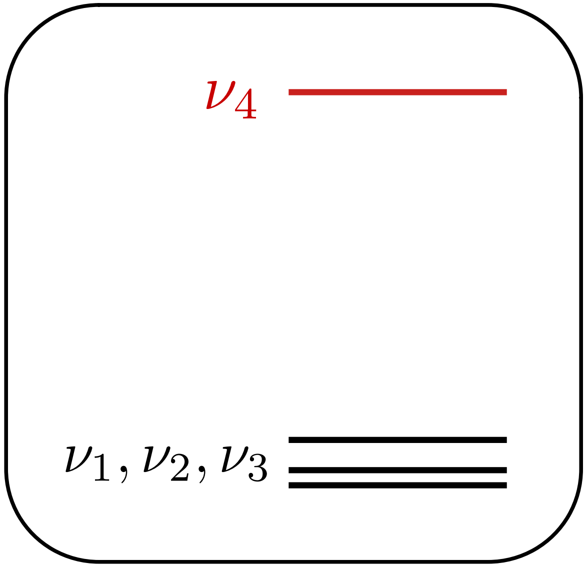

eV-scale sterile neutrinos

Can be searched for in multiple ways:

1) Oscillations:
   - Anomalous appearance
   - ν_e disappearance
   - ν_μ disappearance
   - NC measurements
   - Modified matter potential
2) Beta-decay
3) Cosmology (N_{eff})

~ direct tests

ν_e and $\bar{\nu}_e$ appearance ($P_{\mu e}$)

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\sin^2 2\theta_{\mu e} \rightarrow 4|U_{e4}|^2|U_{\mu 4}|^2$$

→ Will be covered in M. Ross-Lonergan's colloquium next week

LSND
MiniBooNE
MicroBooNE
KARMEN

ν_e and $\bar{\nu}_e$ disappearance (P_{ee})

$$P_{ee} \equiv P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$4|U_{e4}|^2(1-|U_{e4}|^2)$$

Reactors
Gallium experiments

Sterile neutrino oscillations

$$P_{ee} \simeq 1 - \sin^2 2\theta_{14} \sin^2 \Delta_{41} - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - c_{13}^4 \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

Where I have used the usual parametrization:

$$U = V_{34} V_{24} V_{14} V_{23} V_{13} V_{12}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

Sterile neutrino oscillations

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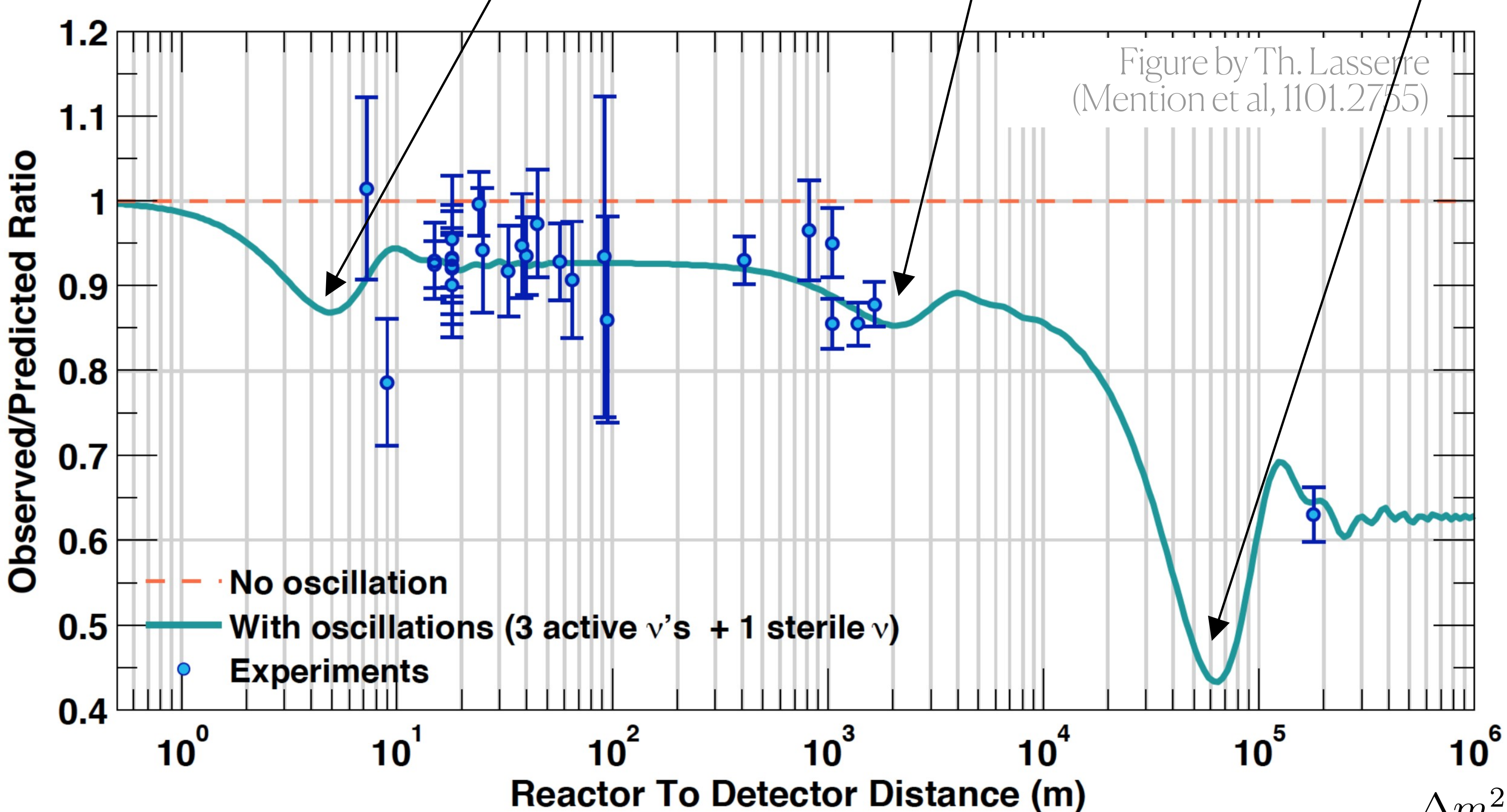
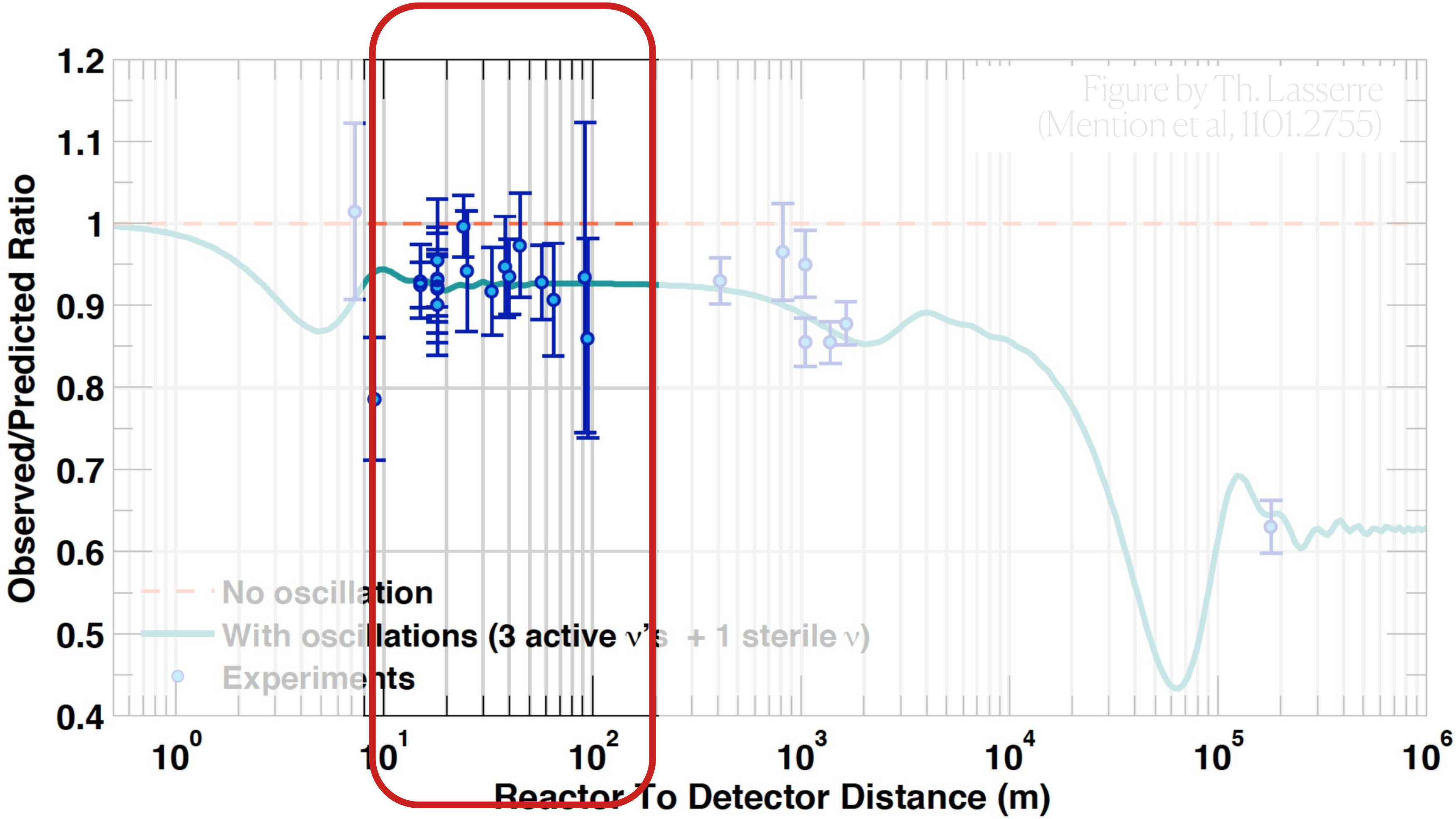


$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

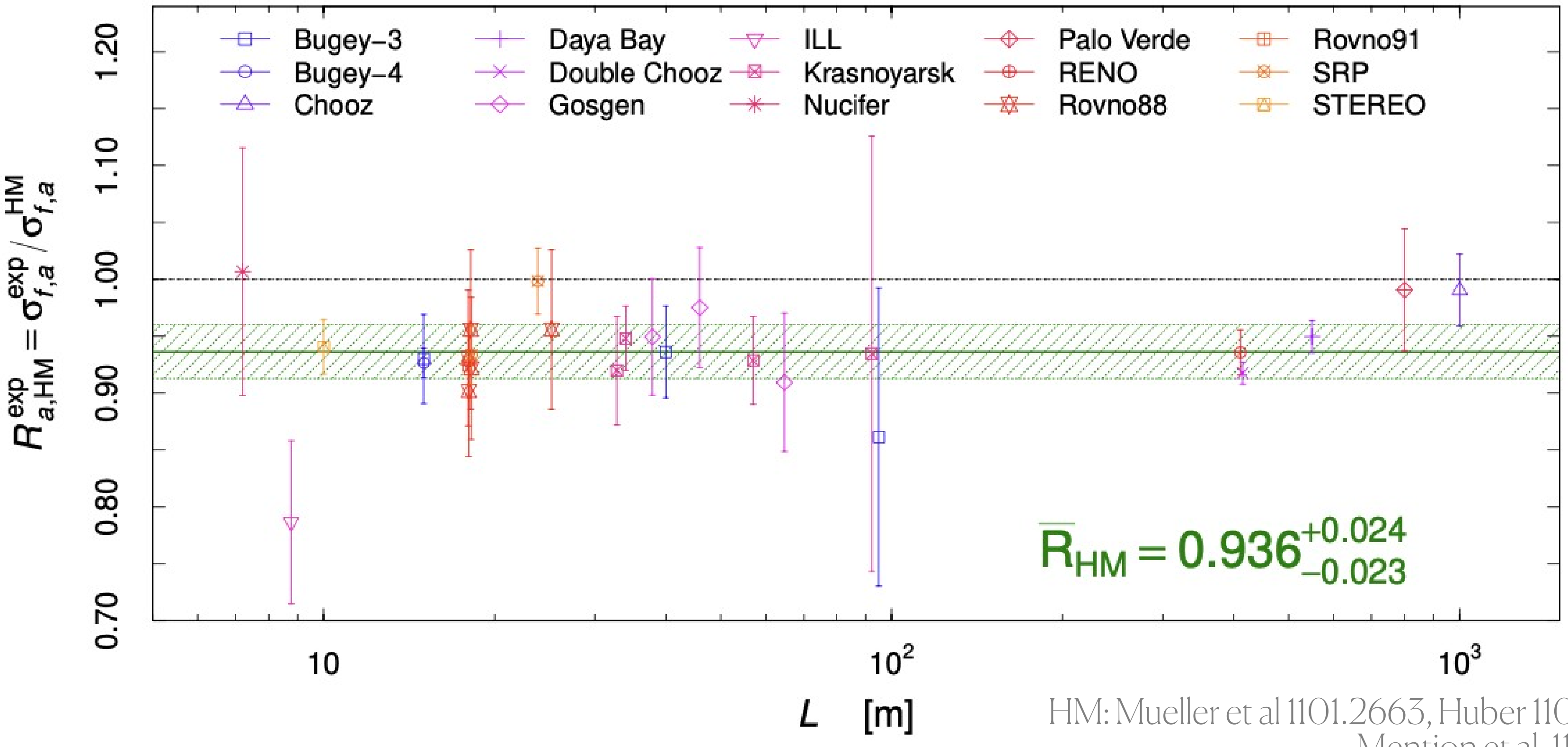
Short-baseline reactors

$$P_{ee} \simeq 1 - \frac{1}{2}\sin^2 2\theta_{14}$$



Short-baseline reactors: the RAA

Situation in 2011:

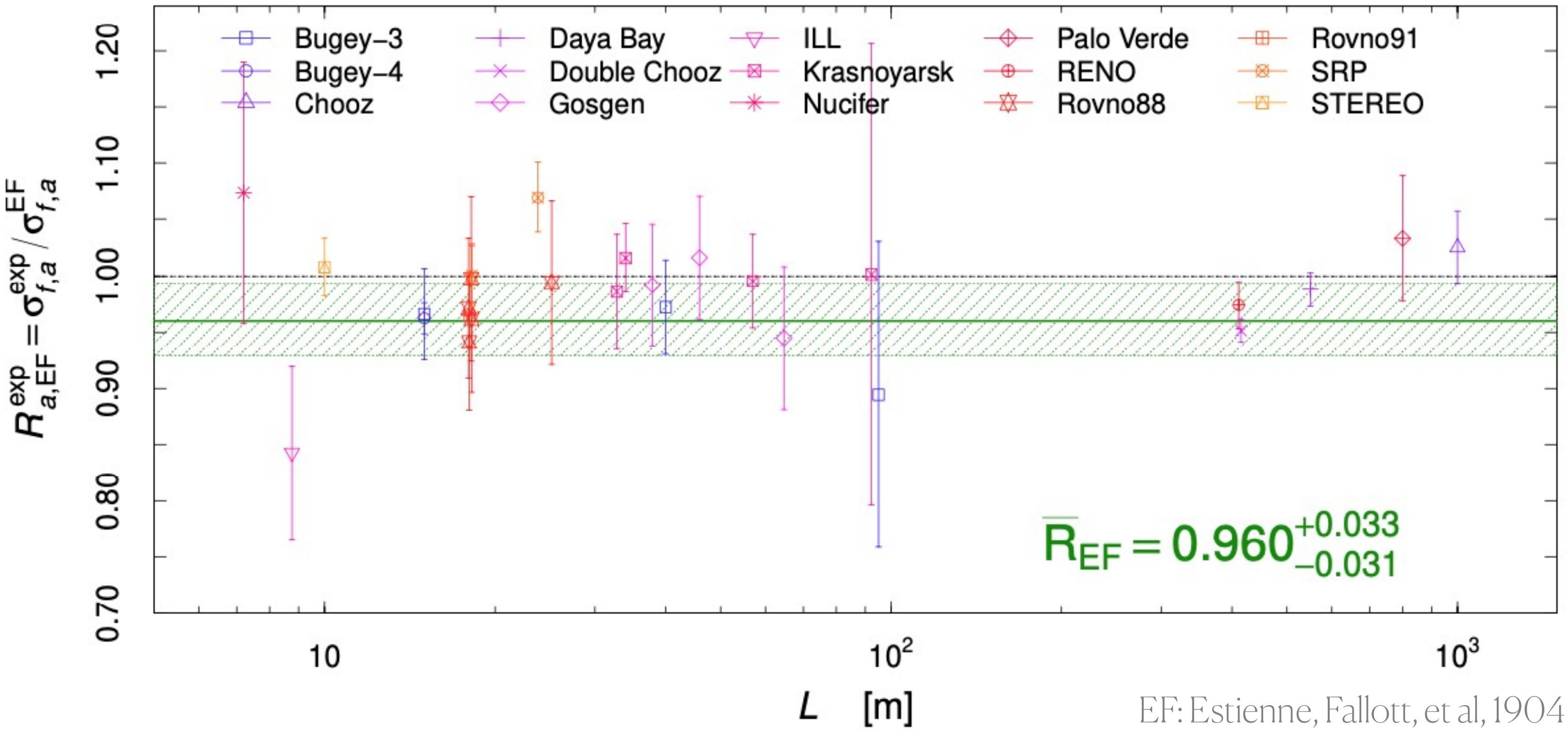


HM: Mueller et al 1101.2663, Huber 1106.0687; Mention et al, 1101.2755

Figure from Giunti, Li, Ternes, Xin, 2110.06820

Short-baseline reactors: the RAA

Situation in 2022:

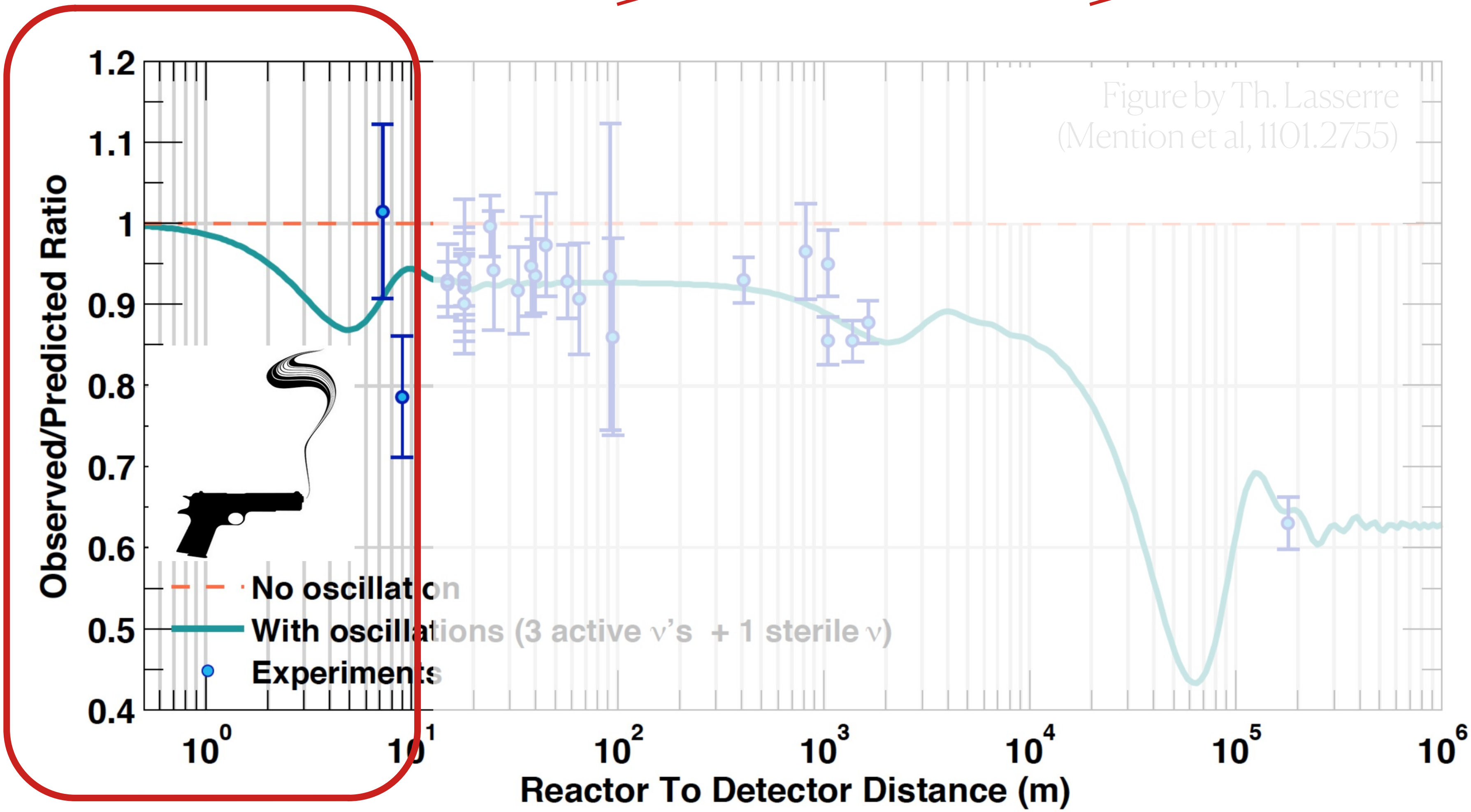


EF: Estienne, Fallott, et al, 1904.09358;

Berryman and Huber, 1909.09267 & 2005.01756
Figure from Giunti, Li, Ternes, Xin, 2110.06820

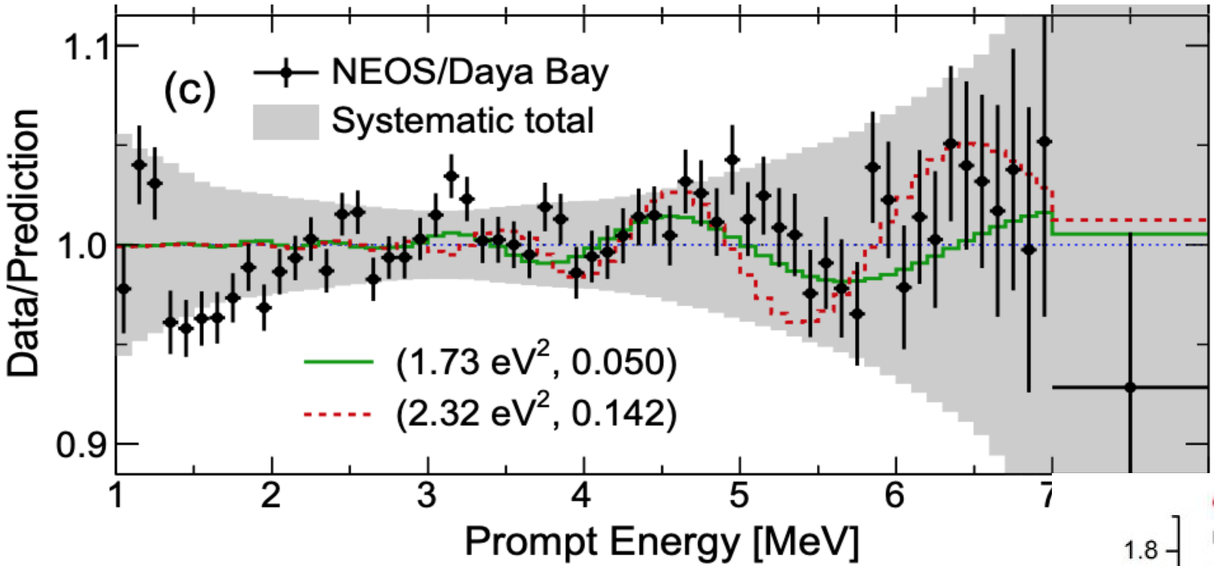
Very-short-baseline reactors

$$P_{ee} \simeq 1 - \sin^2 2\theta_{14} \sin^2 \Delta_{41} - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - c_{13}^4 \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

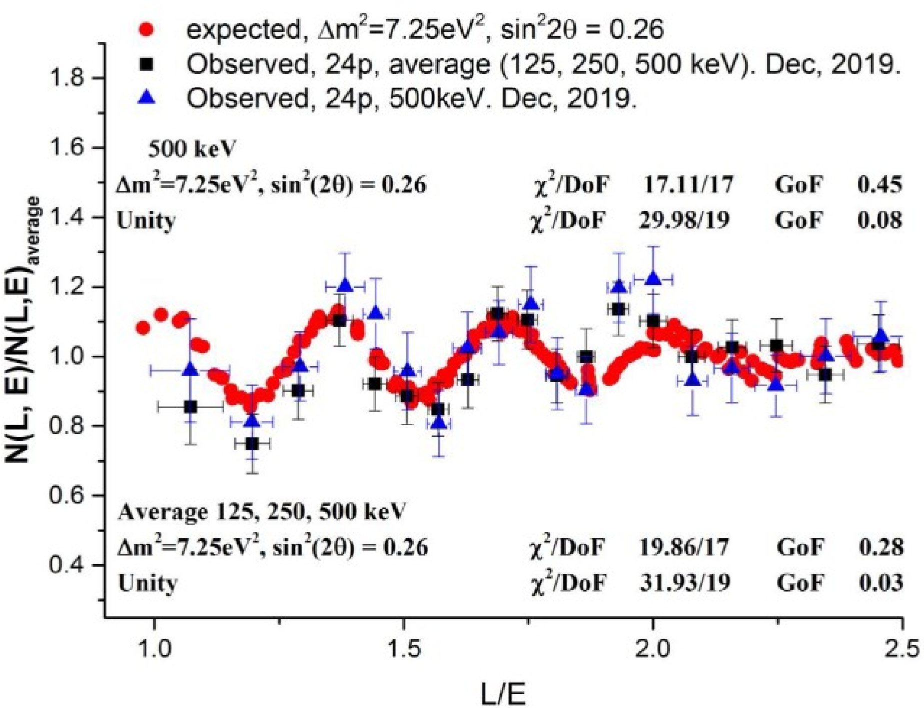


Very-short-baseline reactors

NEOS coll., 1610.05134



Neutrino-4 coll., 2005.05301



<u>**Quick highlights:**</u>

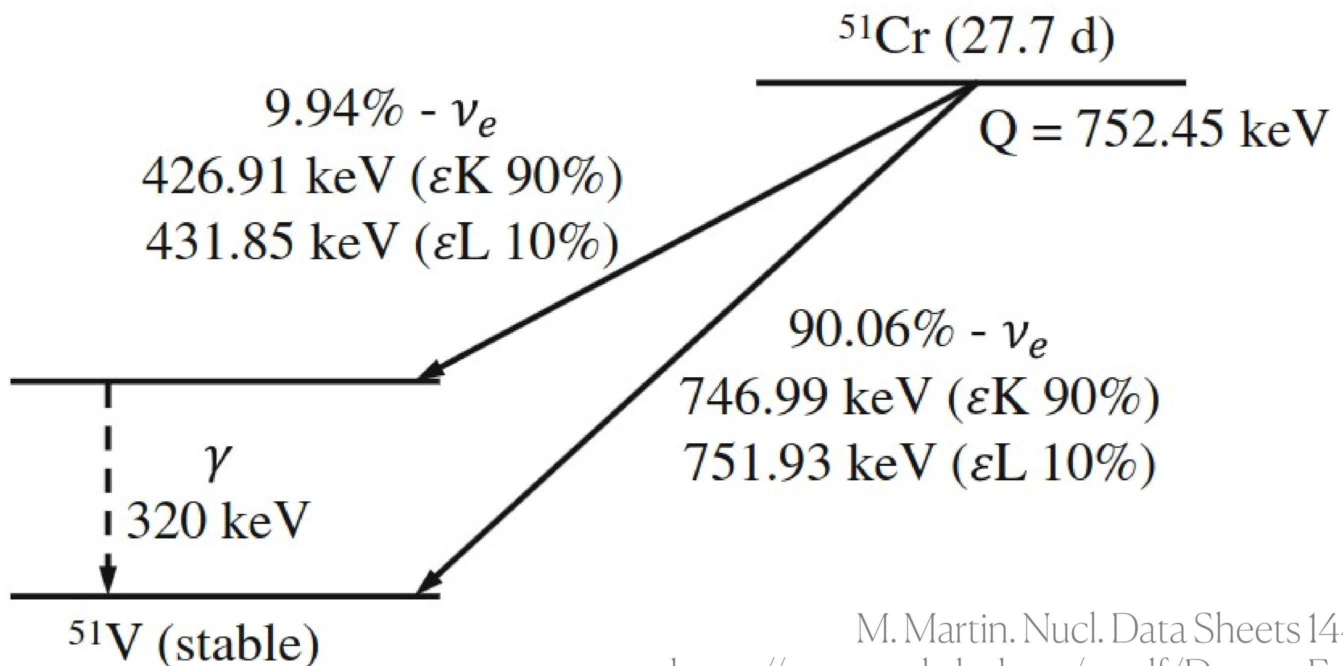
None of the vSBL reactor experiments observed a clear signal at high significance

(exception: Neutrino-4 did report a signal at approx. 3σ)

Gallium experiments

- Electron capture isotopes decay to two bodies, producing a mono-energetic flux of neutrinos at low energies

$$^{51}_{24}\mathrm{Cr} + \text{s-shell } e^- \rightarrow ^{51}_{23}\mathrm{V} + \nu_e \ (+\gamma)$$

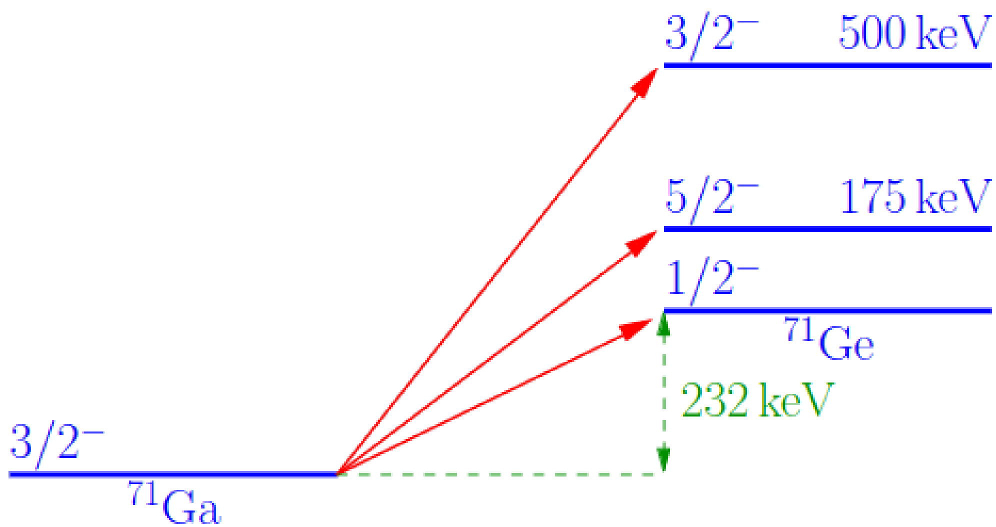


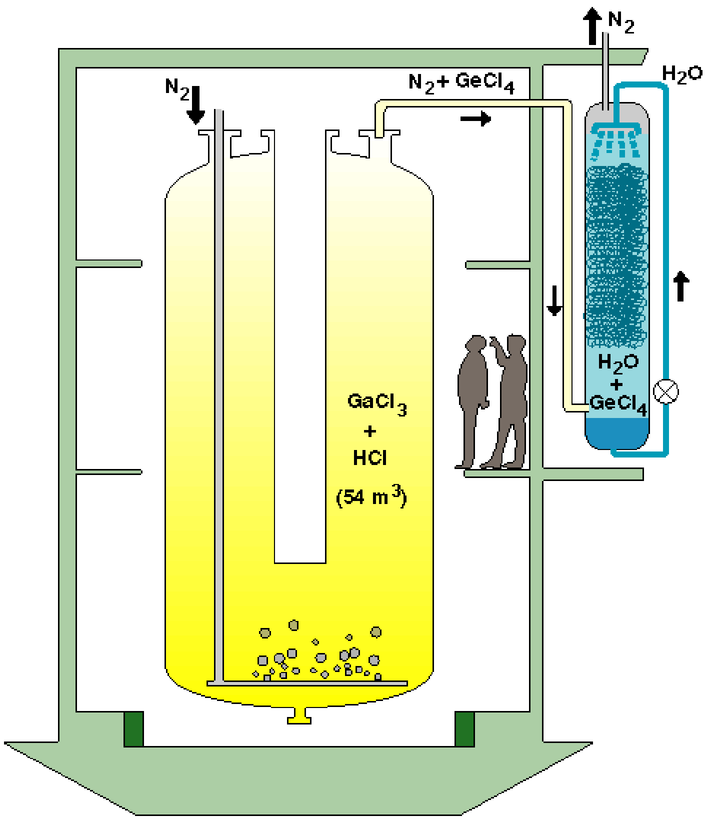
M. Martin. Nucl. Data Sheets 144, 1 (2017).
https://www.nndc.bnl.gov/ensdf/DatasetFetchServlet.

Gallium experiments

Such low energy neutrinos can be detected using their capture on Gallium:

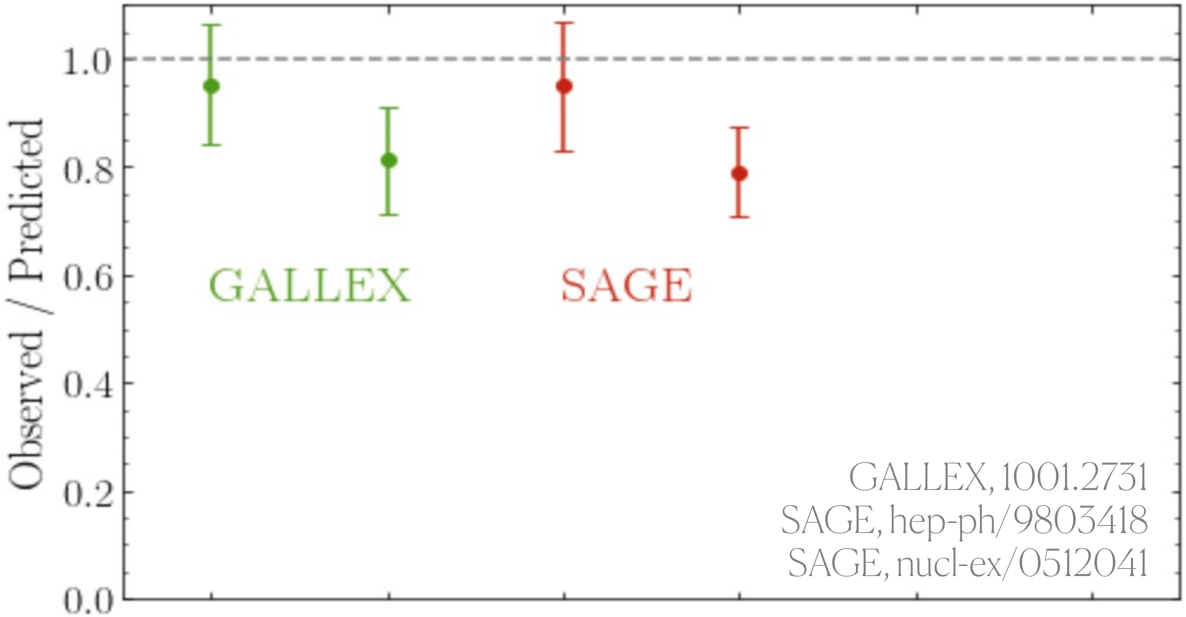
$$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$$

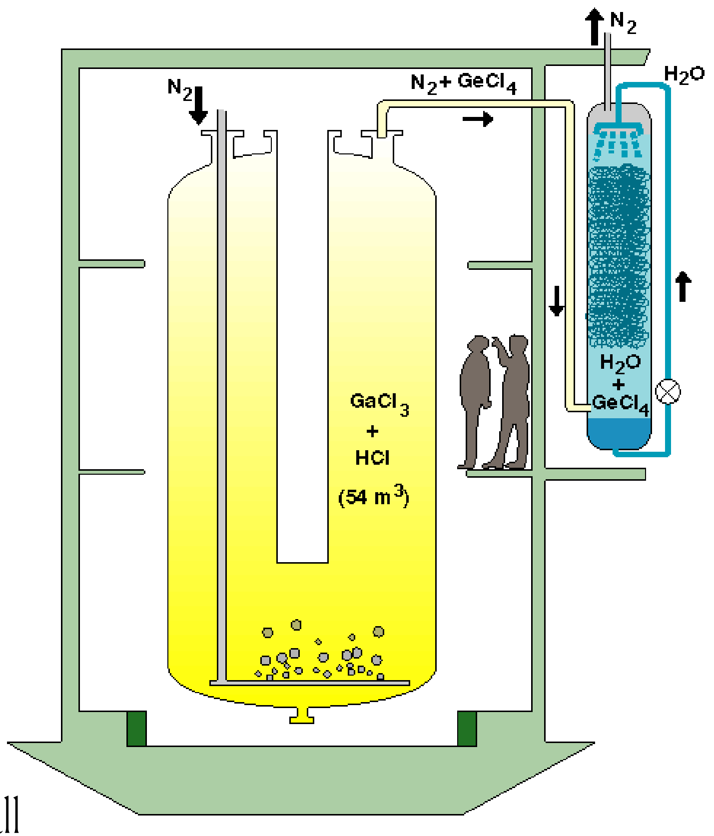




Gallium experiments

Radioactive sources (^{51}Cr, ^{37}Ar) have been used to calibrate solar solar neutrino radiochemical detectors (GALLEX, SAGE)

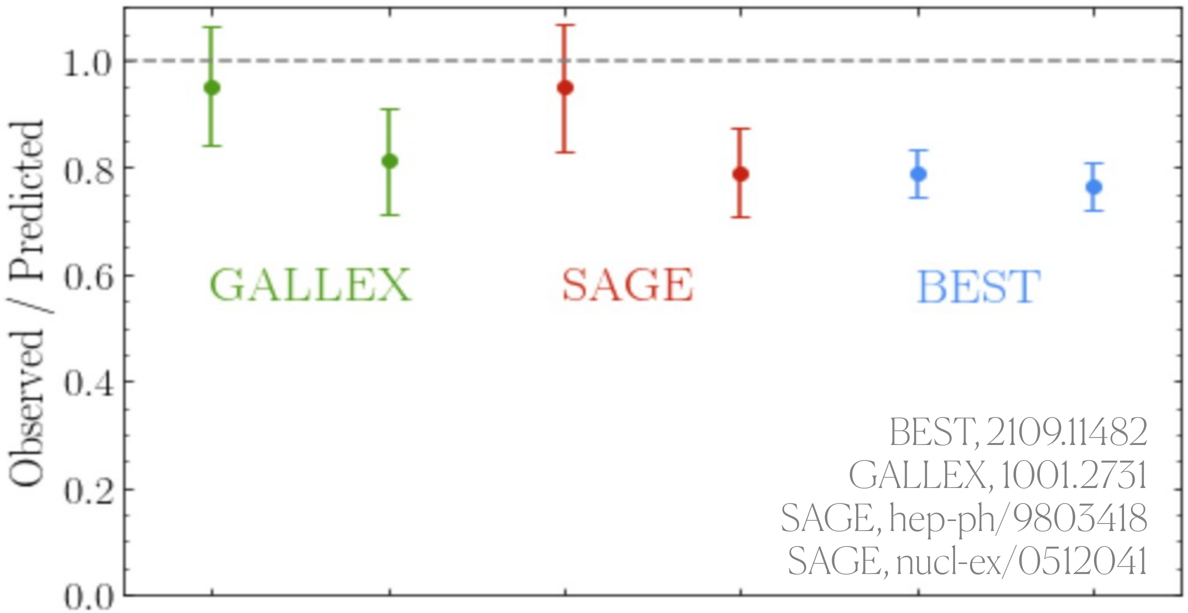




→ No spatial info, though, so no L/E dependence, just an overall deficit would be expected

Gallium experiments

The BEST experiment recently confirmed the reported anomalies, with a much higher significance (above **5σ**)



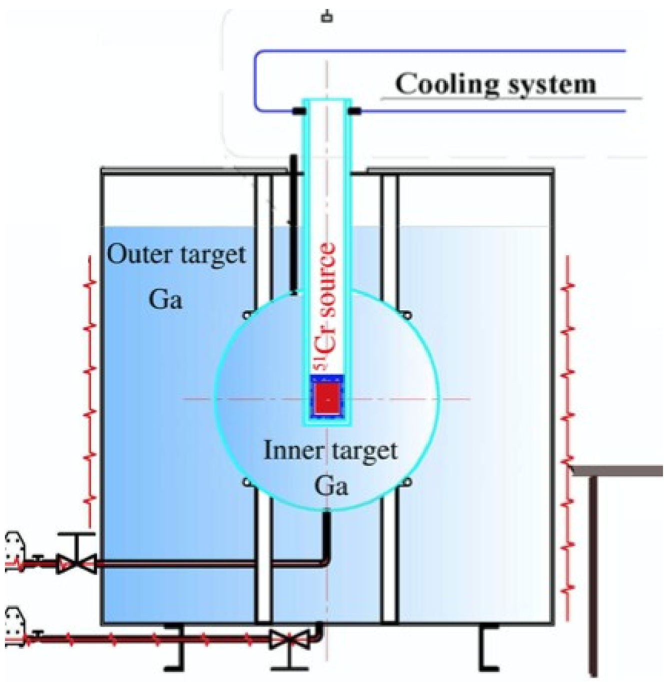


Figure from 2109.11482

→ BEST did use two separate volumes, but they observed the same result in both of them

Solar neutrino experiments (P_{ee})

Super-K
SNO
Borexino
Gallium experiments

Solar neutrinos

- In essence, solar neutrino data is sensitive to P_{ee} and $P_{e\mu} + P_{e\tau}$ at low energies (LE, vacuum) and high energies (HE, strong matter effects):
  - P_{ee} (LE): mainly from Borexino (elastic scattering on electrons) and Gallium data (charged-current)
  - $P_{e\mu} + P_{e\tau}$ (LE): elastic scattering on electrons (Borexino)
  - P_{ee} (HE): SNO charged-current data
  - $P_{ee} + P_{e\mu} + P_{e\tau}$ (HE): SNO neutral-current data (determines the total active neutrino flux)
  - A certain combination of P_{ee} (HE) and $P_{e\mu} + P_{e\tau}$ (HE) is also constrained from elastic scattering on electrons in SK

Solar neutrinos

- Assuming an adiabatic evolution in the Sun, we can write:

$$P_{e\alpha} = \sum_{k=1}^{4} | U_{ek}^{m} |^2 | U_{\alpha k} |^2 \qquad (\alpha \equiv e, \mu, \tau, s)$$

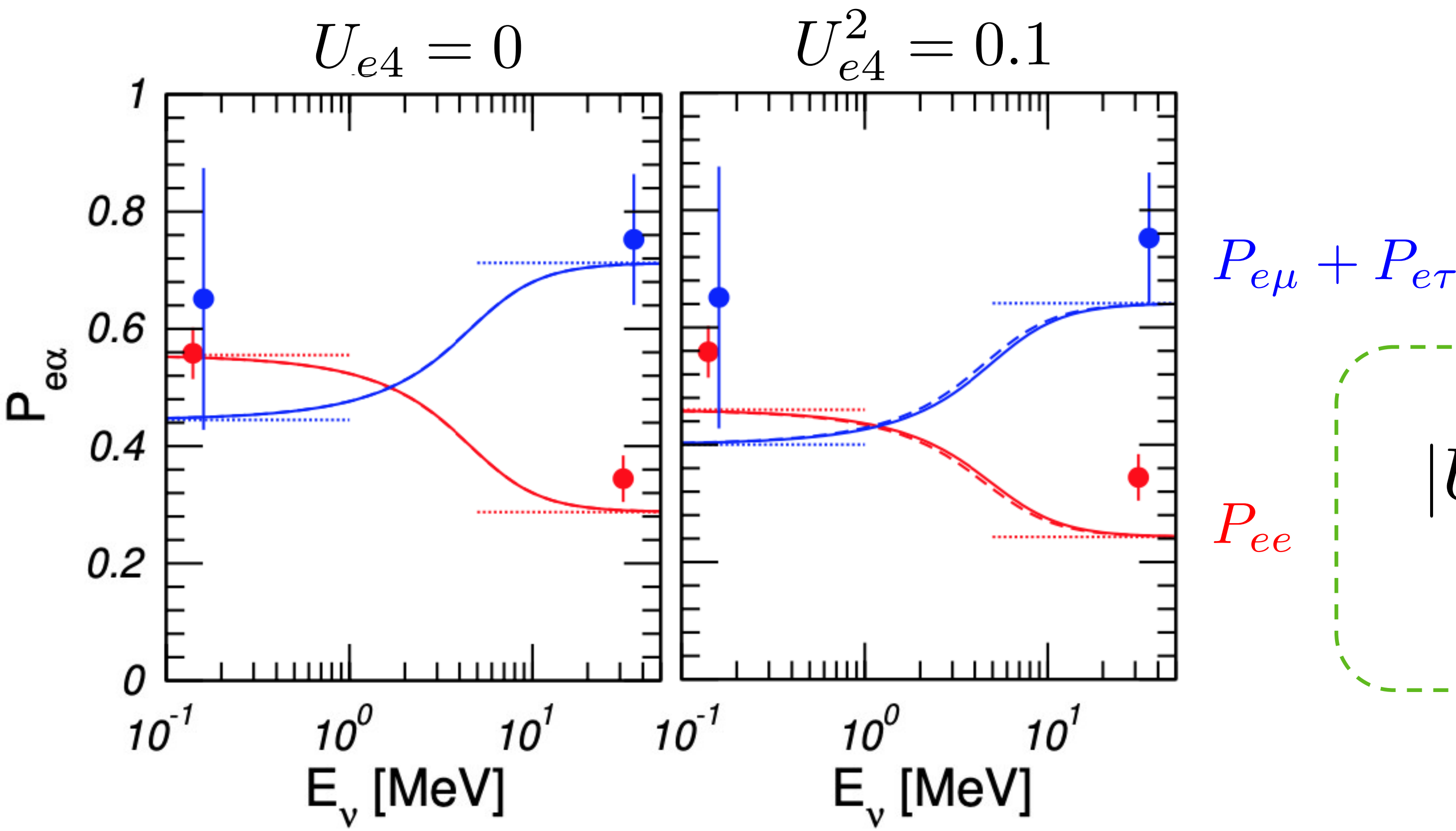
- Taking U_{4x4} to be unitary, we get that these only depend on the first and fourth rows of the mixing matrices in matter and in vacuum:

$$P_{e\mu} + P_{e\tau} = 1 - P_{ee} - P_{es} = 1 - P_{ee} - \sum_{k=1}^{4} | U_{ek}^{m} |^2 | U_{sk} |^2$$

$$P_{ee} = \sum_{k=1}^{4} | U_{ek}^{m} |^2 | U_{ek} |^2$$

- It can be shown (under some approximations) that these oscillation probabilities mainly depend on the values (in vacuum) of θ_{12} and θ_{14}

Solar neutrinos



$$|U_{e4}|^2 < 0.168$$

(90% C.L.)

Figure adapted from Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898

Non-unitarity

Effects due to a non-unitary matrix

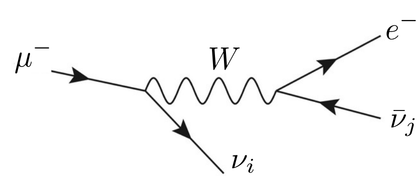
- For a non-unitary matrix N, the weak interaction Lagrangian reads:

$$\mathcal{L}^{\text{weak}} \supset -\frac{g}{\sqrt{2}} W_\mu^- \left(\bar{\ell}_\alpha \gamma^\mu P_L N_{\alpha j} \nu_j + \text{h.c.}\right) - \frac{g}{\cos\theta_w} Z_\mu \left(\bar{\nu}_i \gamma^\mu P_L (N^\dagger N)_{ij} \nu_j + \text{h.c.}\right)$$

- This means that if I want to compute any EW process involving neutrinos I have to be careful…

- Let's do an example: muon decay

$$\mathcal{A}\Big($$



$$\Big) \propto \frac{g^2}{2M_W^2} N_{\mu i} N_{ej}^*$$

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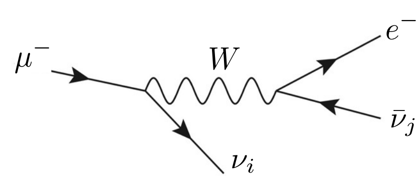
$$\Gamma\Big($$


$$\Big) \propto \left(\frac{g^2}{2M_W^2}\right)^2 N_{\mu i} N^*_{\mu i} N_{ej} N^*_{ej}$$

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- This means that if I want to compute any EW process involving neutrinos I have to be careful…
- Let's do an example: muon decay

$$\Gamma(\mu^- \to e^- \nu \bar{\nu}) = \sum_{i=1}^{3} \sum_{j=1}^{3} \Gamma_{ij} \propto \left(\frac{g^2}{2M_W^2}\right)^2 (NN^\dagger)_{\mu\mu} (NN^\dagger)_{ee}$$

Effects due to a non-unitary matrix

- The muon decay rate is used to determine the value of the Fermi constant with high precision. In the SM, it is defined as

$$G_F^{\text{SM}} \equiv \frac{\sqrt{2}g^2}{8M_W^2}$$

- This means that in practice, however, the experimental measurement determines

$$G_\mu^{\text{exp}} = G_F^{\text{SM}} \sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}$$

- The SM Fermi constant can also be expressed in terms of the EW boson masses, as

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

- Both agree at the 0.1% level! This sets strong constraints $\alpha \lesssim \mathcal{O}(10^{-3})$

See e.g. Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, hep-ph/0607020

Effects due to a non-unitary matrix

Is there a way out of this?

- If the new states are light enough, they could be produced together with the active neutrinos

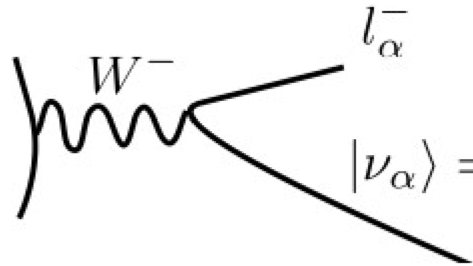
→ Repeating the exercise for muon decay, in this case we get:

$$\Gamma(\mu^- \to e^- \nu \bar{\nu}) = \sum_{i=1}^{n} \sum_{j=1}^{n} \Gamma_{ij} \propto G_F^2 \underbrace{(UU^\dagger)_{\mu\mu}(UU^\dagger)_{ee}}$$

=1, since the full matrix is indeed unitary

→ In this case we recover the SM result, so the bounds from EW observables do not apply

Non-unitarity in oscillations



$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle \qquad U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

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

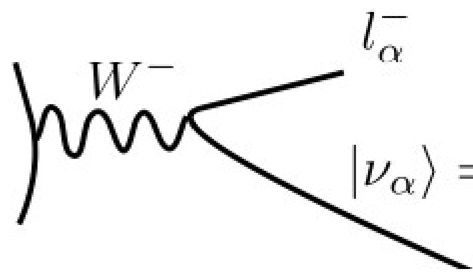
Assuming all states are produced (kinematically accessible), we have:

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

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

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

Non-unitarity in oscillations



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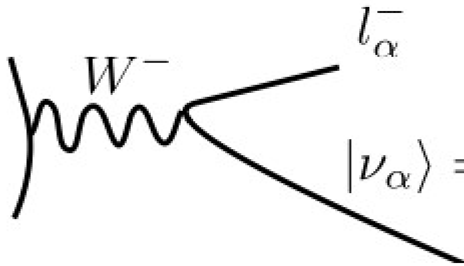
$$+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{iJ} L}{2E}}$$

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

Suppressed
(Θ is small)

Non-unitarity in oscillations



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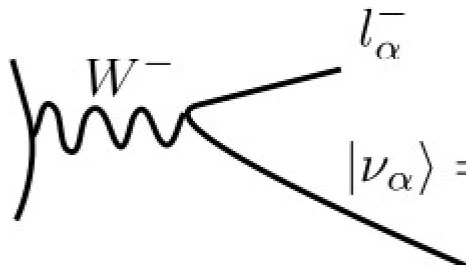
$$+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{iJ} L}{2E}}$$

Averages out
(fast oscillations)

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

Suppressed
(Θ is small)

Non-unitarity in oscillations



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

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

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

Assuming all states are produced (kinematically accessible), we have:

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

Non-unitarity in oscillations: pheno

A triangular parametrization is most convenient:

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

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

A non-unitary 3x3 block has interesting phenomenological implications, e.g.:

→ the so-called zero-distance effect:

$$P_{\beta\gamma}(L=0) = |\alpha_{\beta\gamma}|^2$$
$$P_{\beta\beta}(L=0) = 1 - 4\alpha_{\beta\beta} + \mathcal{O}(\alpha^2)$$

→ allows to set bounds on non-unitarity, recasting sterile neutrino searches

$$\alpha \lesssim \mathcal{O}(10^{-2})$$

Non-unitarity in oscillations: pheno

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→ a modification of the oscillation probabilities, new CP-violating sources, … For example:

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

End of Lecture II

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