CURRENT AND FUTURE CONTRAINTS ON STERILE NEUTRINOS FROM CEVNS

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- This presentation is based on the following papers:
- **Coherent elastic neutrino-nucleus scattering as a precision test for the Standard Model and beyond: the COHERENT proposal case**, O. G. Miranda , G. Sanchez Garcia , OS
- **Implications of the first detection of coherent elastic neutrino-nucleus scattering (CEvNS) with Liquid Argon,** O. G. Miranda, D. K. Papoulias, G. Sanchez Garcia, M. Tórtola, J. W. F. Valle, OS
- O. G. Miranda, D. K. Papoulias, M. Tórtola, J. W. F. Valle, OS in progress.

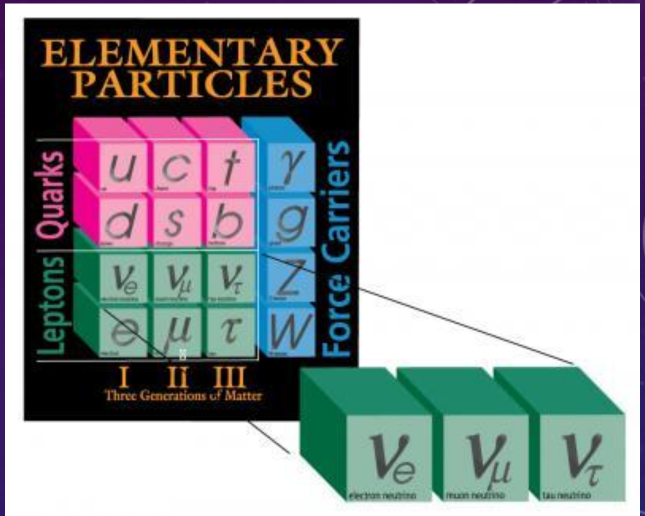
- This work was supported by CONACYT-Mexico.

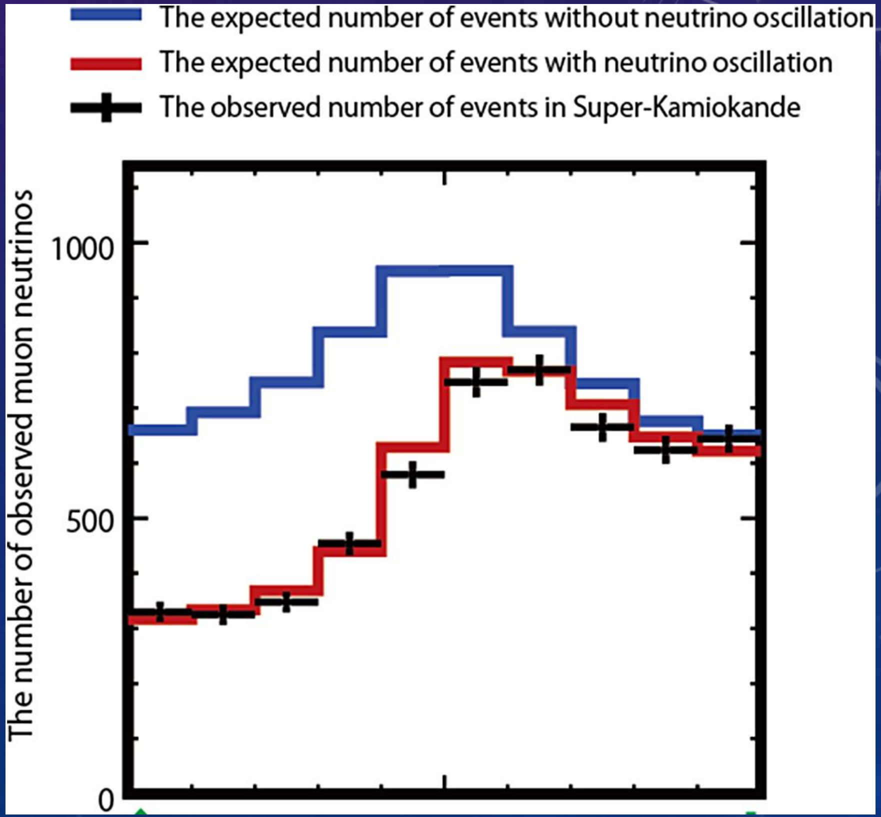
OUTLINE

- **Introduction**
  - Neutrino oscillations
  - Sterile neutrinos
  - CEvNS
- **Future perspectives**
  - COHERENT
  - ESS
  - CAPTAIN-MILLS
- **OTHER STUDIES**
  - Weak mixing angle
  - Non-unitarity neutrino mixing
- **Summary**

NEUTRINO OSCILLATIONS

- The Standard Model describes neutrinos as massless and chargeless particles that come in three different flavors.
- Recent experiments suggested that neutrinos have multiple mass eigenstates, indicating mixing.
- Neutrino oscillations were first proposed by Bruno Pontecorvo on 1957 as an analogy to Kaons oscillations.
- On 1998 the SUPER-KAMIOKANDE detector observed an anomaly in the atmospheric neutrinos flux.
- This was the **first evidence** of neutrino oscillations.





- Neutrino oscillations in vacuum are a quantum-mechanical phenomenon possible by the existence of non-degenerate neutrino masses and lepton flavor mixing.
- The flavor eigenstates are related to the mass eigenstates by an unitary transformation.

$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix}_L = U \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \end{pmatrix}_L .$$

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \, .$$

- The matrix can be parametrized using three mixing angles and one Dirac phase which accounts for CP violation.

- Majorana phases are not taken into account because they do not contribute to neutrino oscillations.

$$\begin{aligned} U &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P \\ &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix} P\,. \end{aligned}$$

- The propagation of the neutrinos causes the mass eigenstates to evolve with its own phase factor, modifying the superposition:

$$|\nu(t)\rangle = \sum_i U_{\alpha i}^* e^{-iE_i t} |\nu_i\rangle = \sum_i U_{\alpha i}^* e^{-iE_i t} \sum_\beta U_{\beta i} |\nu_\beta\rangle .$$

- So the probability amplitude of the oscillation to a different flavor is given by:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \left| \sum_i U_{\beta i} U_{\alpha i}^* e^{-iE_i t} \right|^2$$

- Finally, by considering neutrinos as ultra-relativistic particles, we get:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right) + 2\sum_{i<j} \mathrm{Im}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ji} L}{2E}\right),$$

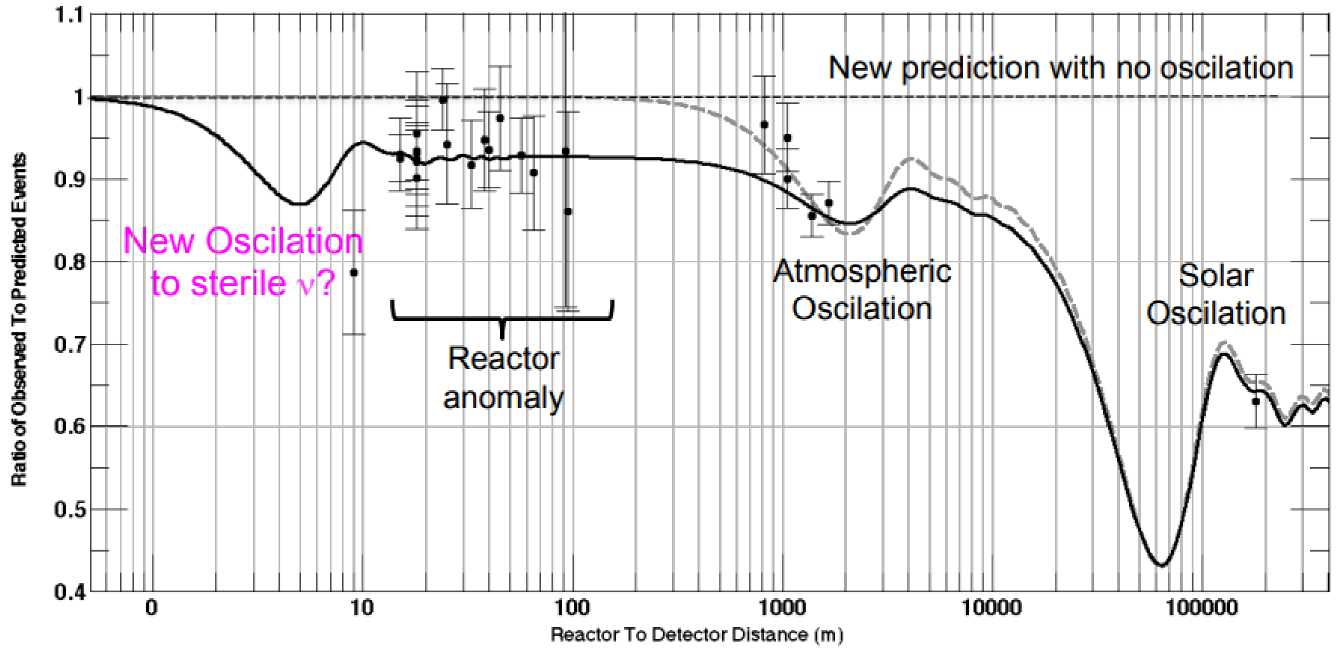
- It is a good approximation for many experimental situations to work only with **two neutrino flavors**, in this case we have a probability given by:

$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad (\beta \neq \alpha),$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2 2\vartheta \sin^2\left(1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{m}]}{E[\mathrm{MeV}]}\right) = \sin^2 2\vartheta \sin^2\left(1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E[\mathrm{GeV}]}\right).$$

STERILE NEUTRINOS

- There are some anomalies that cannot be described by a 3-neutrino model.
- There are some extra anomalies such as:
  - LSND observed an excess of electron antineutrino
  - MiniBooNE observed an excess of electron neutrino and antineutrino
  - The gallium anomaly, in which it is observed a deficit of electron antineutrinos from calibration sources.



Observed/predicted averaged event ratio: R=0.936±0.024 (2.7 σ)

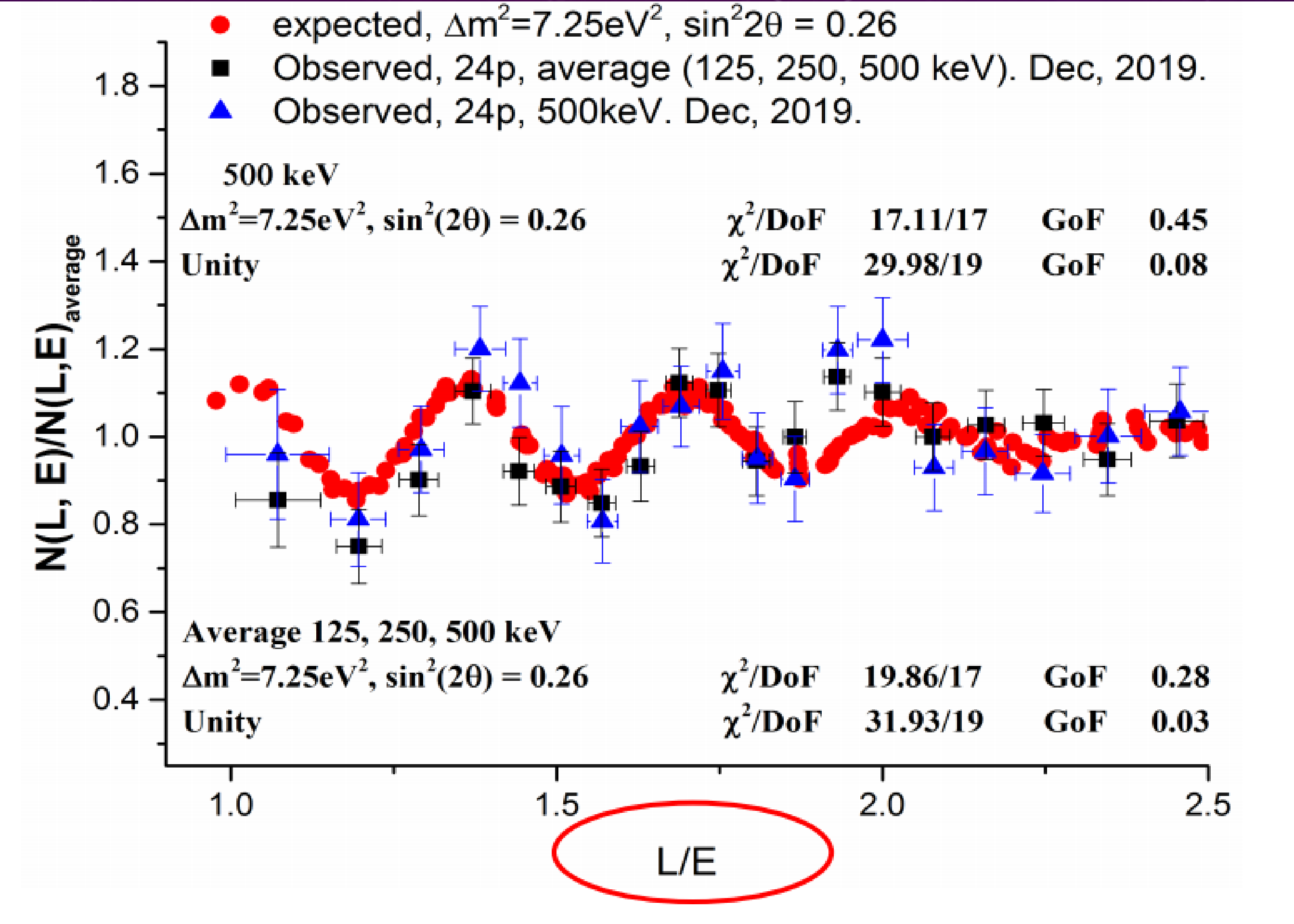
D. Lhuillier, 16th Lomonosov conference

- If these anomalies are interpreted as a consequence of neutrino oscillations, then we get values of
  - $\Delta m^2 \approx 1 - 2\ Ev^2$ and
  - $\sin^2(2\theta) \approx 0.1 - 0.2$

- Since the number of active neutrinos is established by the invisible decay of the Z boson

$$N_\nu \equiv \frac{\Gamma_Z^{\text{invisible}}}{\Gamma(Z \to \nu\bar{\nu})_{\text{SM}}} = 2.9840 \pm 0.0082\,,$$

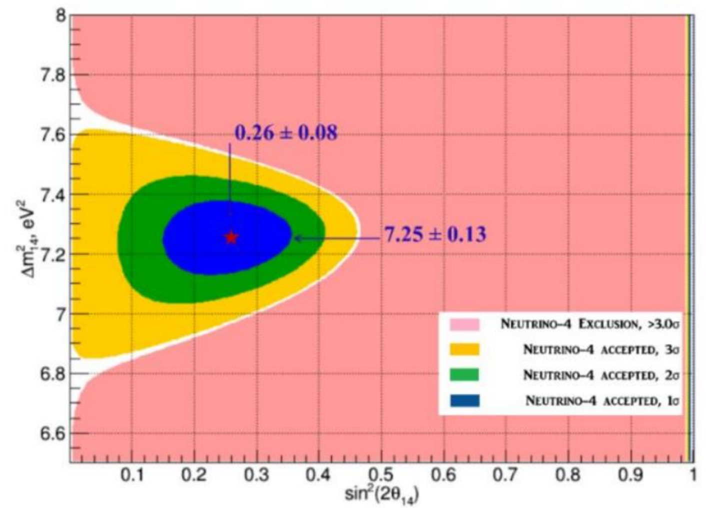
- In this scenario it is necessary to include the existance of neutrinos that do not interact via weak interaction, this neutrinos are called sterile neutrinos.



A.P.Serebrov, et al. JETP Letters, Volume 109, 2019 Issue 4, pp 213–221

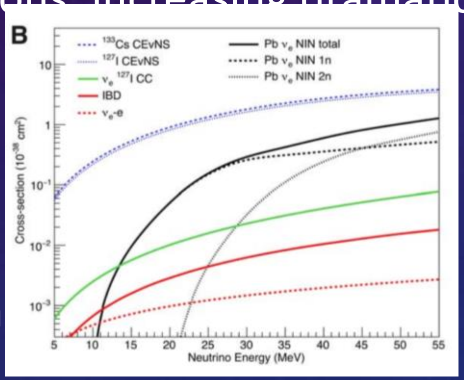
- Neutrino-4 experiment observed the effect of oscillation reporting at a C.L. 2.8 σ of:
  - $\Delta m^2 = 7.25 \pm 1\ eV^2$
  - $\sin^2(2\theta) = 0.26 \pm 0.09$

- CEvNS can give another channel to study neutrino oscillations in order to confirm or neglect the existence of sterile neutrinos.



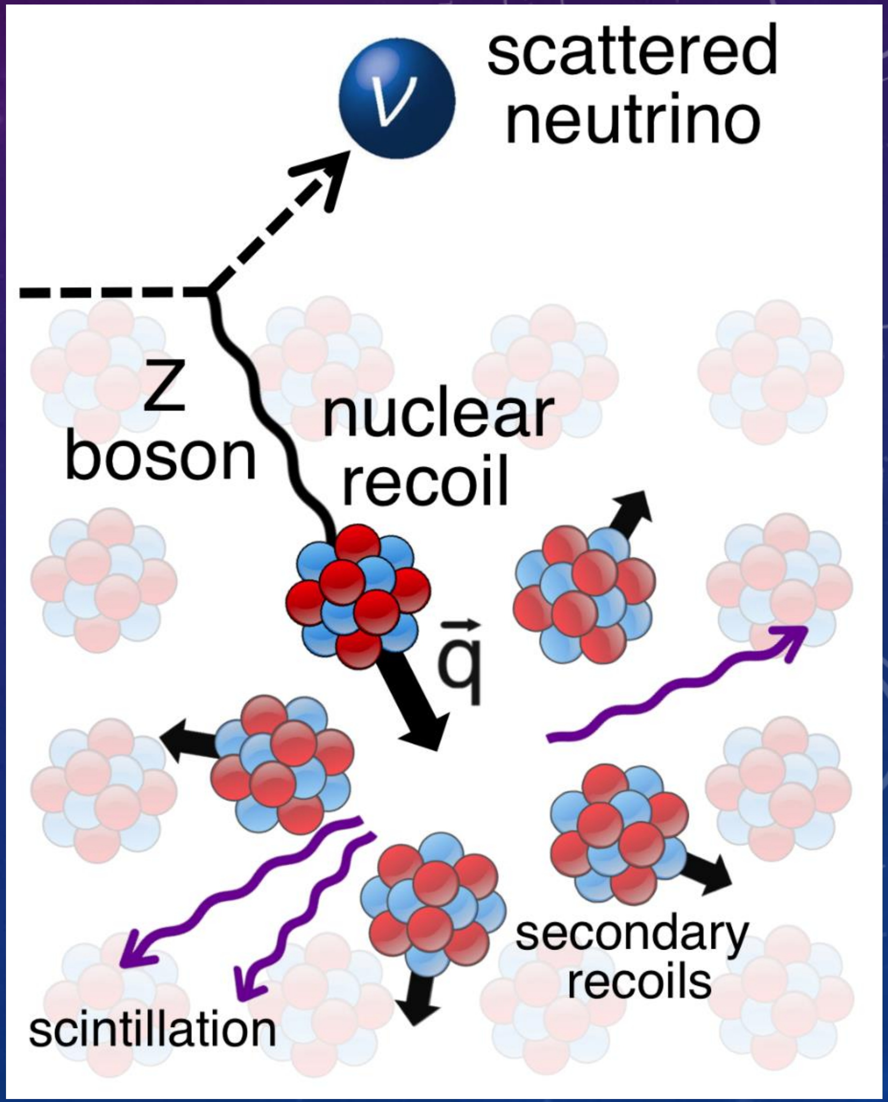
COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING(CEVNS)

- In this process, a neutrino scatters from a nucleus by exchanging an electrically neutral Z boson.
- **The scattering process is coherent:** the neutrino interacts with the nucleus as a whole, rather than with individual nucleons or groups of nucleons, increasing dramatically the cross section.



COHERENT COLLABORATION
10.1126/science.aao0990

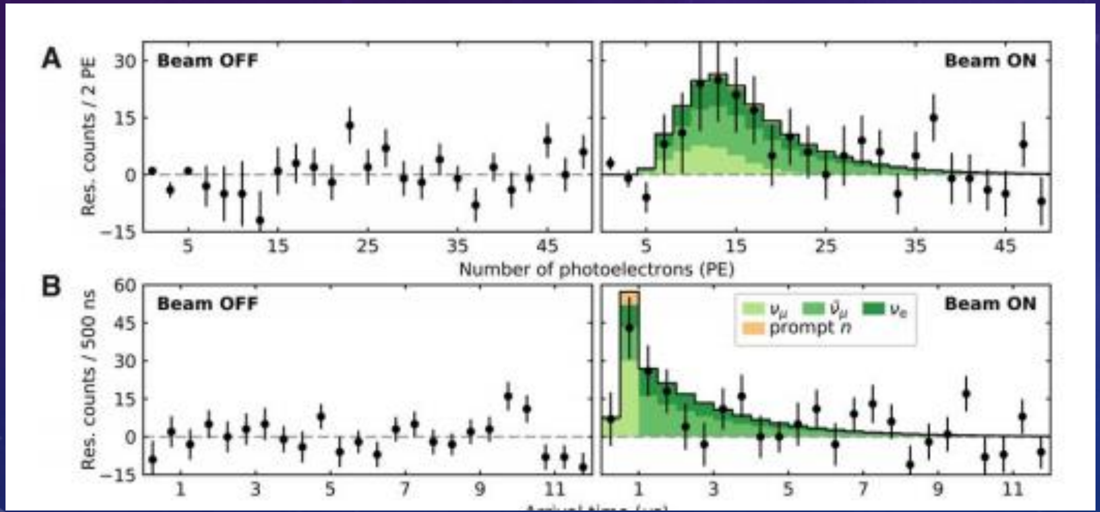
- **It is elastic:** the neutrino and the nucleus are the same at the initial and final states, conserving the total kinetic energy.



- The lightest nucleus is literally hundreds of millions of times more massive than a neutrino. The nuclear recoil is quite small, from hundreds of eV to few KeV. This makes the detection of this process quite complicated even when the neutrino is carrying a fair amount of energy, approx. 50 MeV.

- Coherent elastic neutrino-nucleus scattering was first proposed more than forty years ago and was recently detected by the **COHERENT collaboration** using CsI and LAr detectors.

CsI Detector



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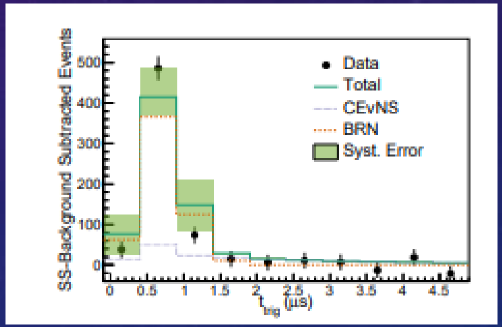
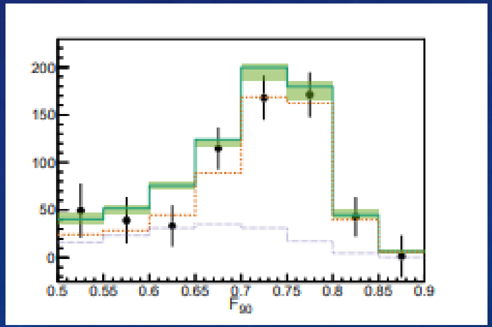
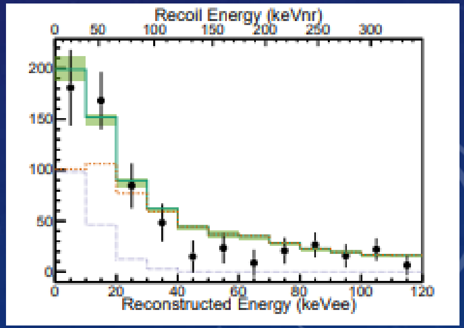
LAr Detector







COHERENT COLLABORATION
arXiv:2003.10630

χ^2 ANALYSIS

- In order to study the possible sensitivity for different CEvNS experiments, we use a χ^2 análisis.

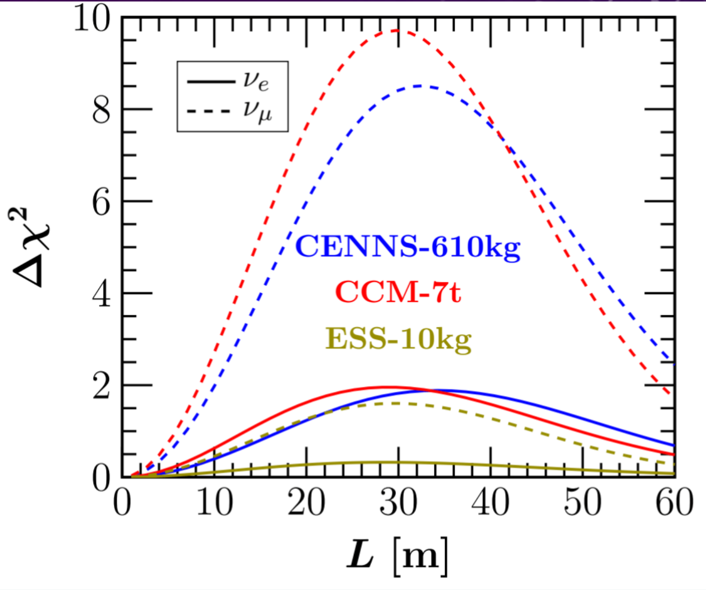
$$\chi^2 = \left(\frac{N^{exp} - (1+\alpha)N^{th}(X) - (1+\beta)N^{bg}}{\sigma}\right)^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2,$$

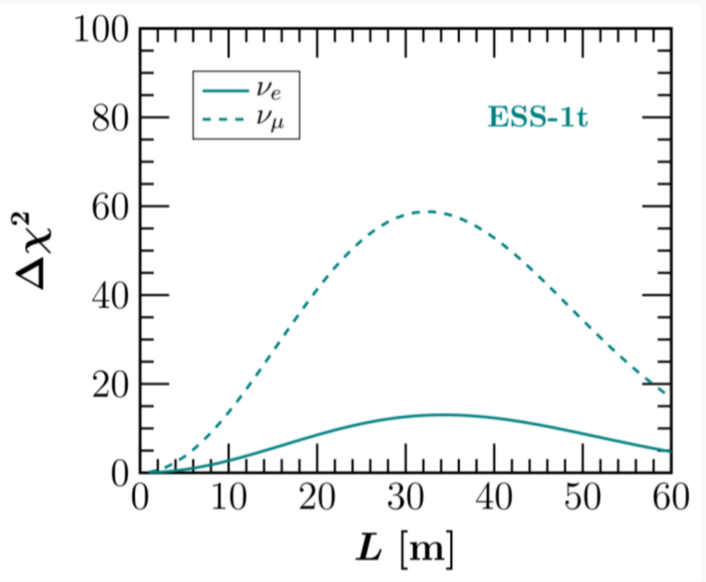
$$N^{th} = N_D \int_T A(T)dT \int_{E_{min}}^{52.8MeV} dE\lambda(E_\nu, T)\frac{\mathrm{d}\sigma}{\mathrm{d}T},$$

- There are different experiments planned to measure CEvNS such as:

- COHERENT
- ESS
- CAPTAIN-MILLS

- For the experiments that are still under construction, it is possible to propose an ideal baseline to study sterile neutrino oscillations





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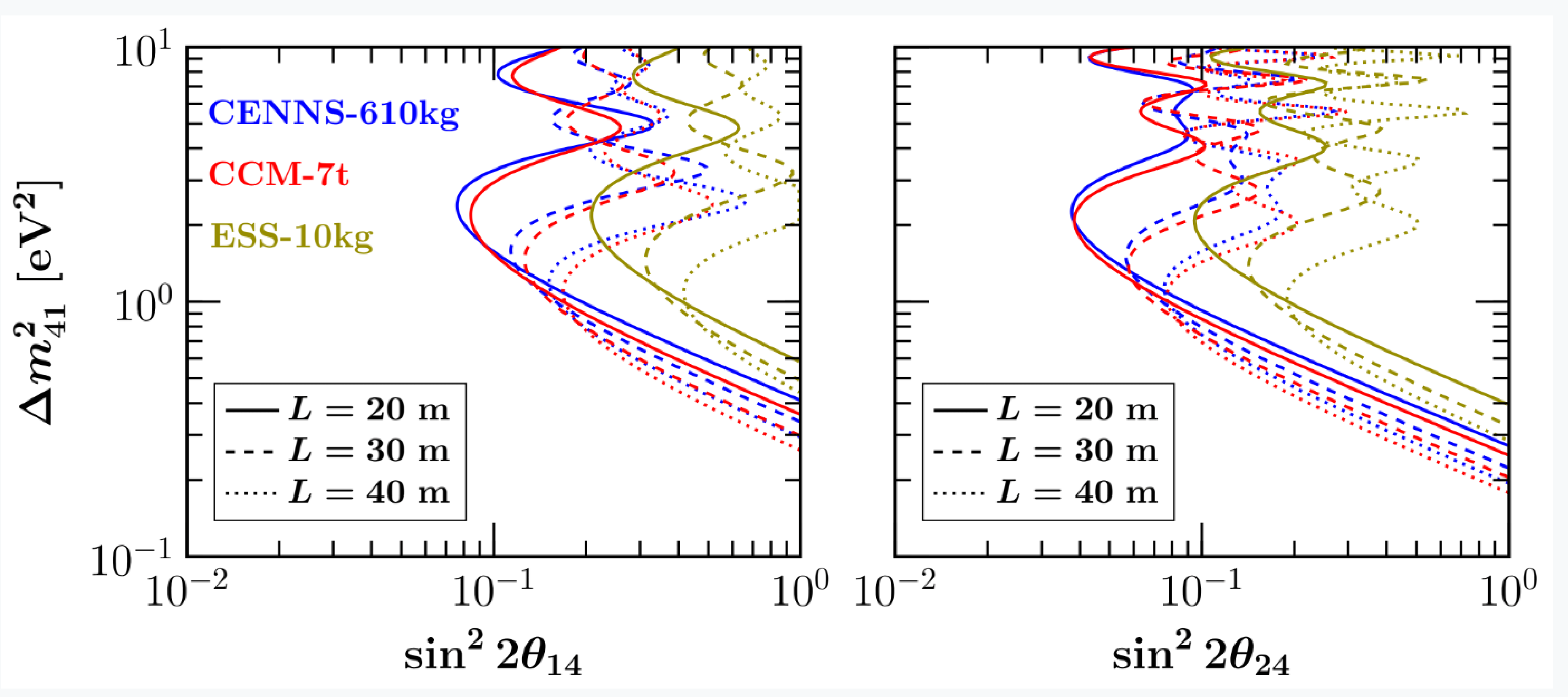
SENSITIVITY TO STERILE NEUTRINOS



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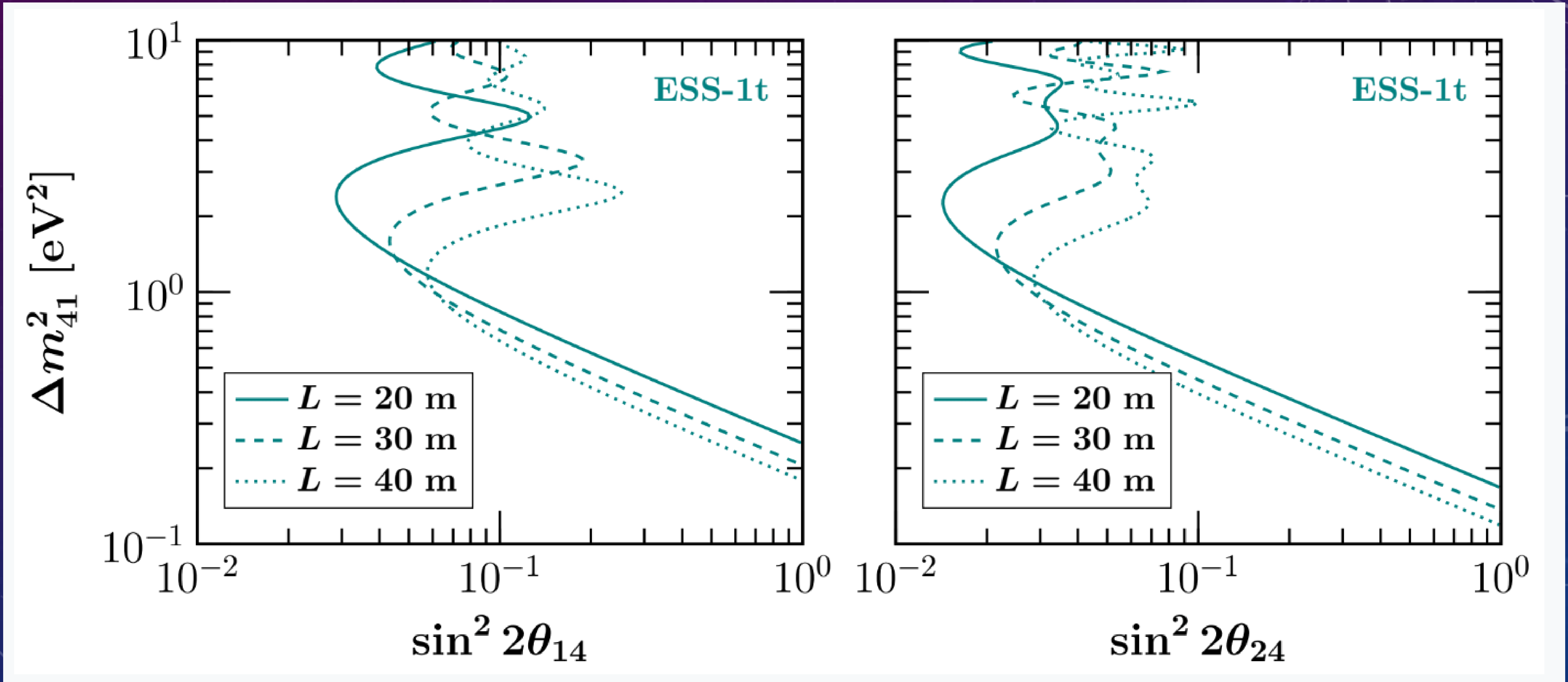
SENSITIVITY TO STERILE NEUTRINOS



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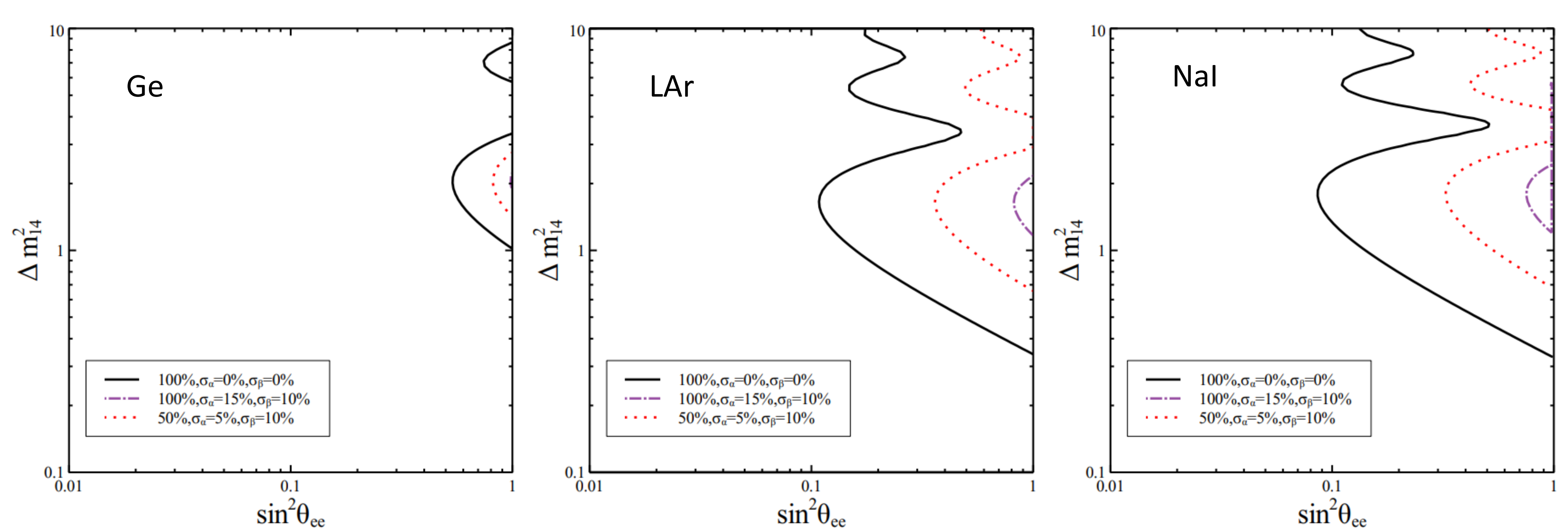
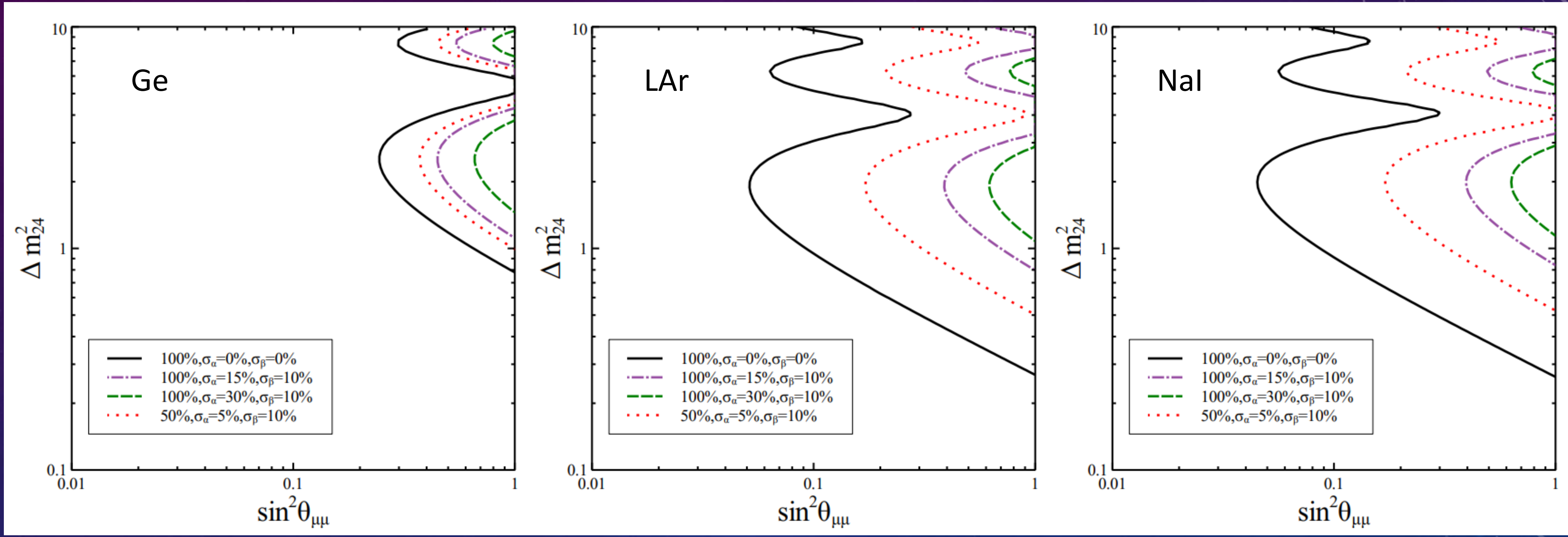
COHERENT COLLABORATION



O. G. Miranda, G. Sanchez Garcia, OS 10.1155/2019/3902819

COHERENT COLLABORATION

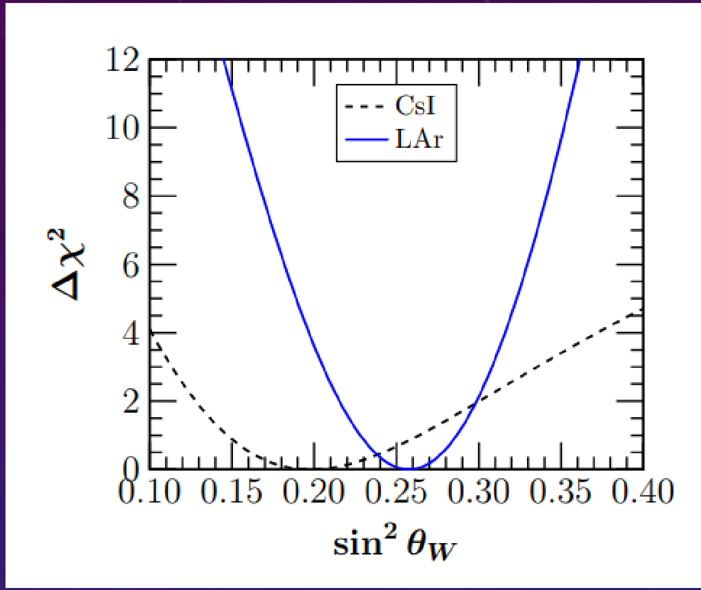


O. G. Miranda, G. Sanchez Garcia, OS [10.1155/2019/3902819](https://doi.org/10.1155/2019/3902819)

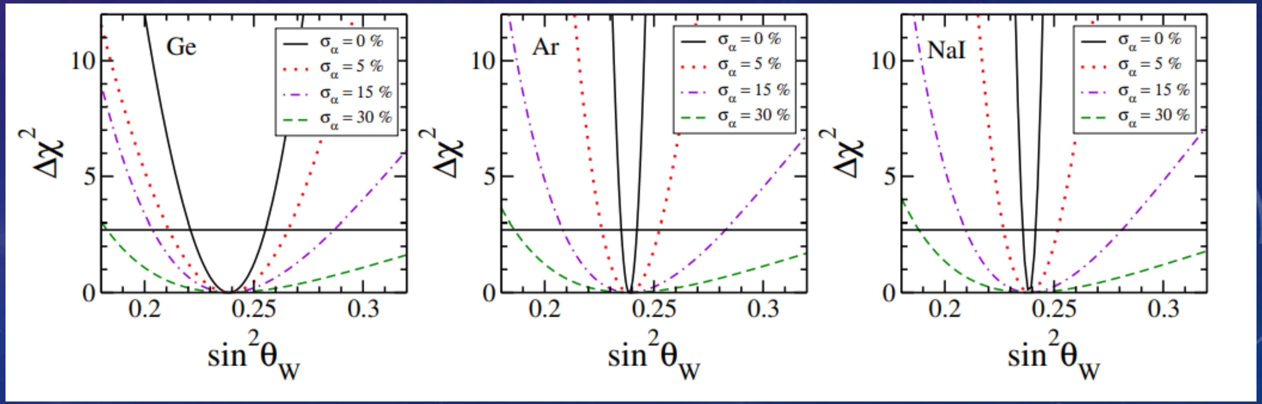
WEAK MIXING ANGLE

- The weak mixing angle is a fundamental parameter of the Standard model, and any deviation from its predicted value may be due to new physics.

$$\sin^2 \theta_W = 0.258^{+0.048}_{-0.050}$$



O. G. Miranda, D. K. Papoulias, G. Sanchez Garcia, M. Tórtola, J. W. F. Valle, OS 10.1007/JHEP05(2020)130



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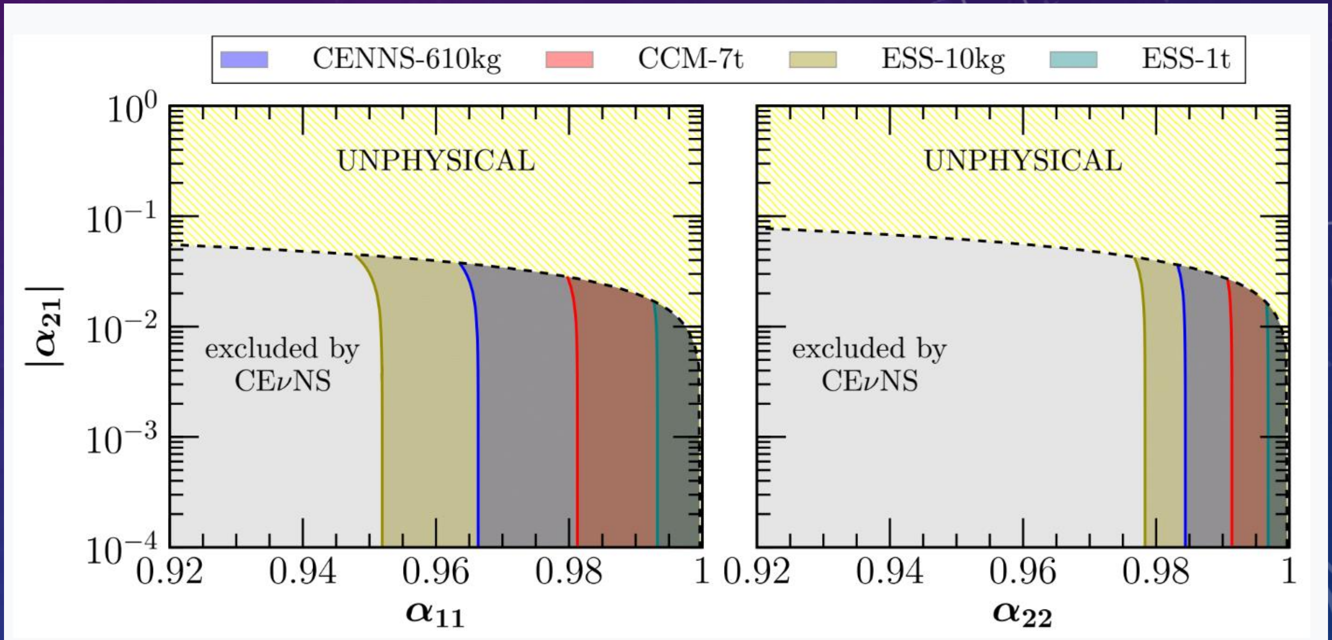
NON-UNITARITY NEUTRINO MIXING

- Neutral heavy leptons(NHL) arise naturally in some extensions of the SM, and have a posible role as messengers of neutrino masses.
- The presence of extra heavy fermions imply the non-unitarity of the 3x3 light neutrino mixing matrix.
- This produces an oscillation probability at zero distance

$$P_{ee} = \alpha_{11}^4,$$
$$P_{\mu\mu} = (|\alpha_{21}|^2 + \alpha_{22}^2)^2,$$
$$P_{\mu e} = \alpha_{11}^2 |\alpha_{21}|^2,$$
$$P_{e\tau} = \alpha_{11}^2 |\alpha_{31}|^2,$$
$$P_{\mu\tau} \simeq \alpha_{22}^2 |\alpha_{32}|^2,$$

$$|\alpha_{21}| \leq \sqrt{(1-\alpha_{11}^2)(1-\alpha_{22}^2)}\,,$$
$$|\alpha_{31}| \leq \sqrt{(1-\alpha_{11}^2)(1-\alpha_{33}^2)}\,,$$
$$|\alpha_{32}| \leq \sqrt{(1-\alpha_{22}^2)(1-\alpha_{33}^2)}\,.$$



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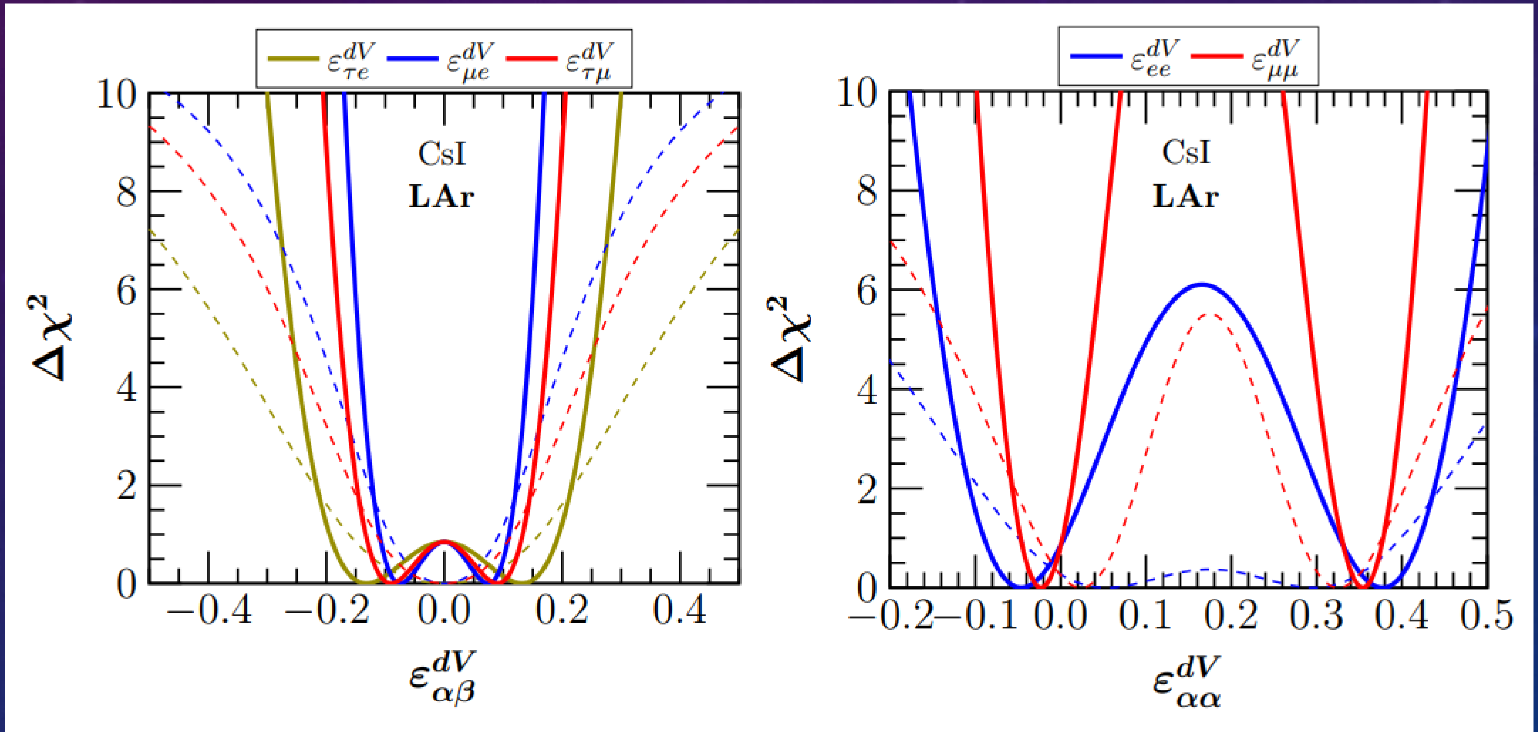
SUMMARY

- CEvNS has a great potential in the study of physics beyond the standard model
- There are different future experiments aiming to measure this interaction.
- There is still a lot of work to do in this future perspective by considering more realistic characteristics such as quenching factors, distances, masses and uncertainties.

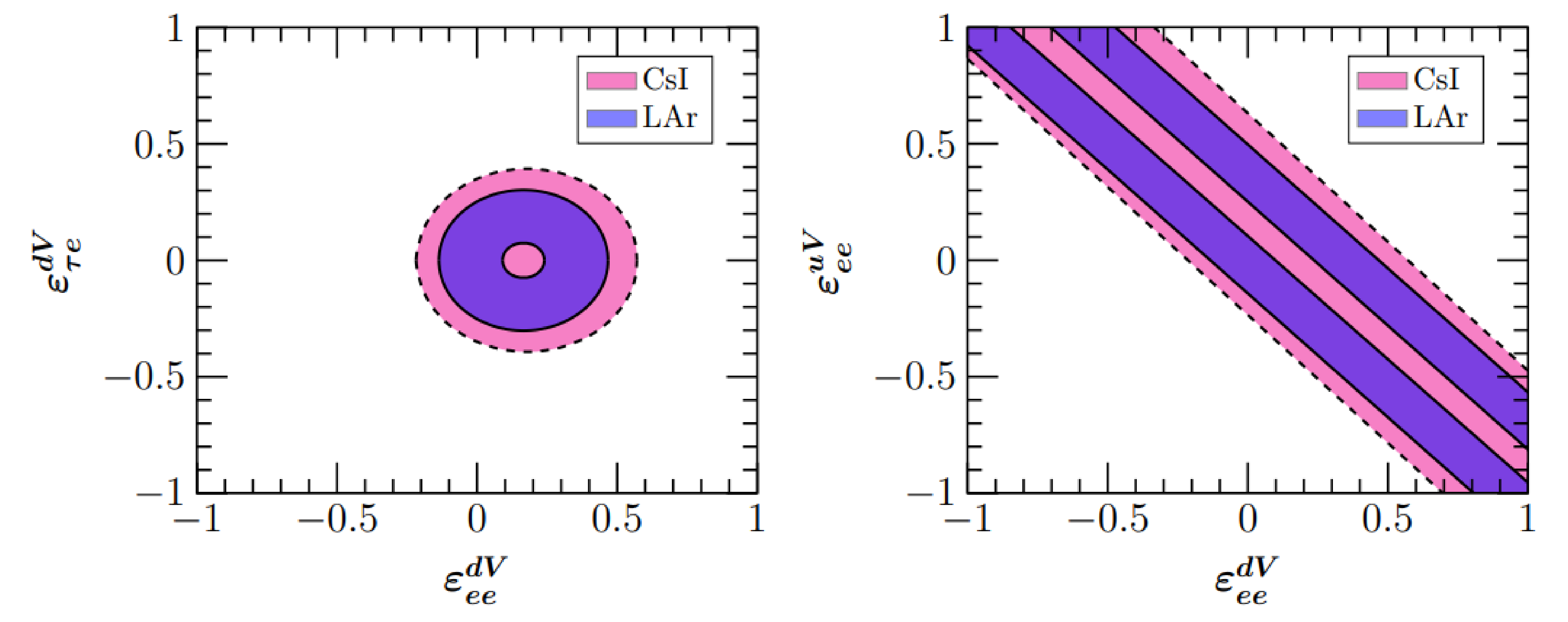
THANKS FOR YOUR ATTENTION

NSI PRESENT

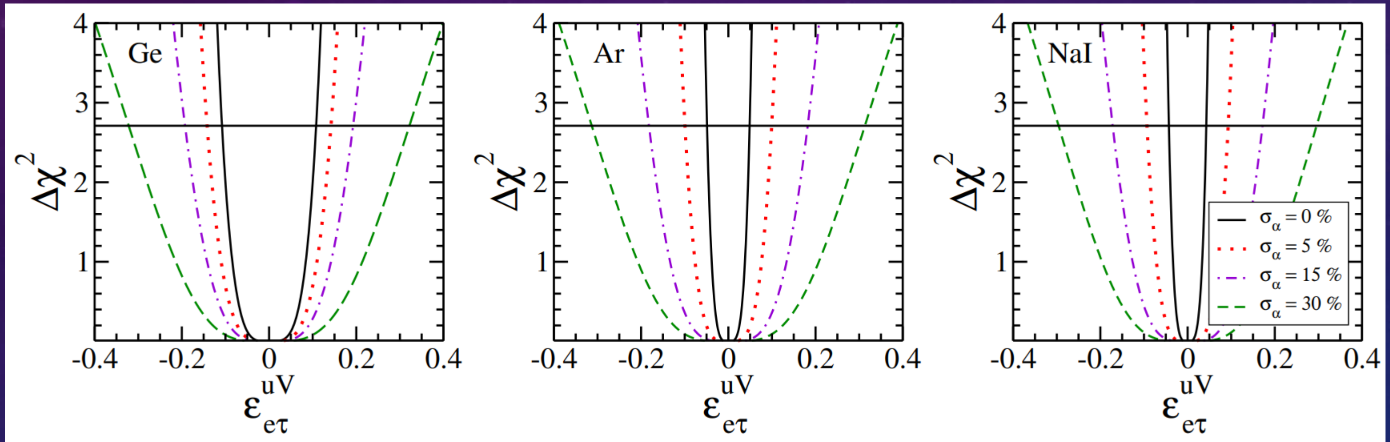


$\varepsilon_{\tau e}^{dV}$ $\varepsilon_{\mu e}^{dV}$ $\varepsilon_{\tau\mu}^{dV}$
CsI
LAr
$\Delta\chi^2$
$\varepsilon_{\alpha\beta}^{dV}$
ε_{ee}^{dV} $\varepsilon_{\mu\mu}^{dV}$
CsI
LAr
$\Delta\chi^2$
$\varepsilon_{\alpha\alpha}^{dV}$

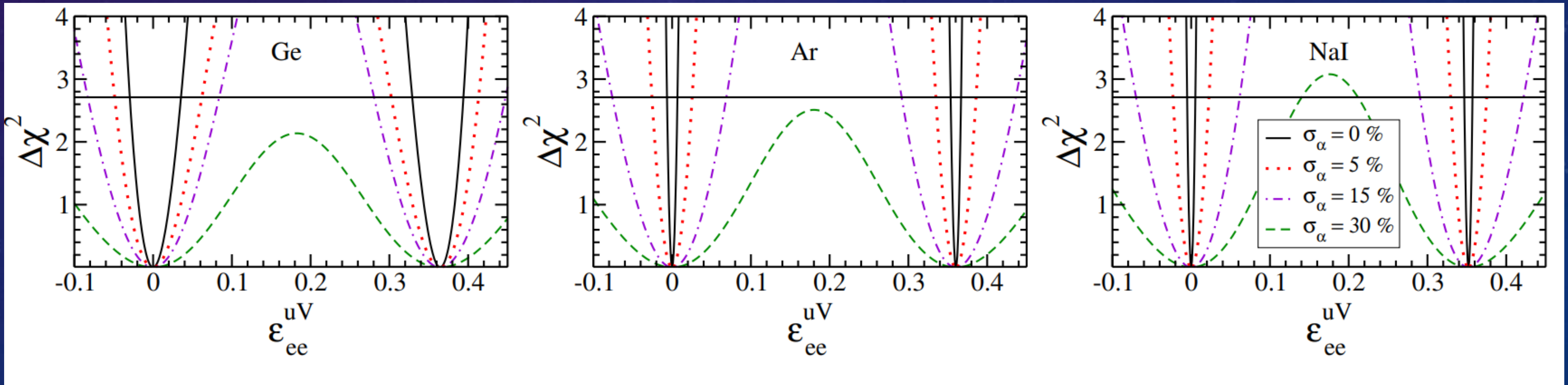
NSI PRESENT


CsI
LAr
$\varepsilon_{\tau e}^{dV}$
ε_{ee}^{dV}
CsI
LAr
ε_{ee}^{uV}
ε_{ee}^{dV}
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1

NSI FUTURE

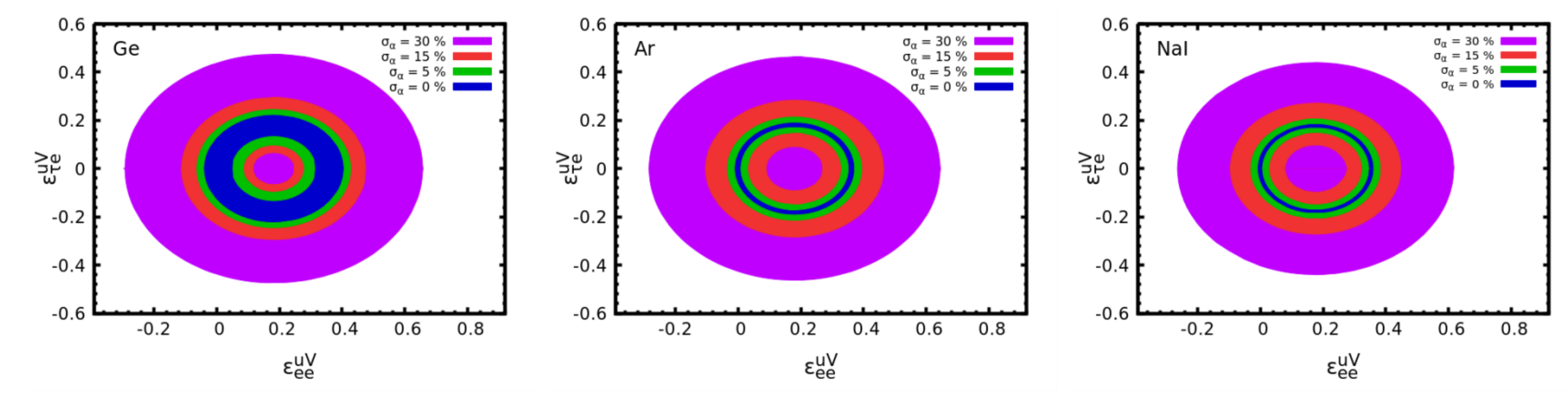


Ge
Ar
NaI
$\Delta\chi^2$
$\varepsilon_{e\tau}^{uV}$
$\sigma_\alpha = 0$ %
$\sigma_\alpha = 5$ %
$\sigma_\alpha = 15$ %
$\sigma_\alpha = 30$ %



Ge
Ar
NaI
$\Delta\chi^2$
ε_{ee}^{uV}
$\sigma_\alpha = 0$ %
$\sigma_\alpha = 5$ %
$\sigma_\alpha = 15$ %
$\sigma_\alpha = 30$ %

NSI FUTURE



Ge
Ar
NaI
σα = 30 %
σα = 15 %
σα = 5 %
σα = 0 %
$\varepsilon^{uV}_{\tau e}$
ε^{uV}_{ee}
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.2
0
0.2
0.4
0.6
0.8

NEUTRON MEAN RADIUS