Resolving the LMA-dark NSI degeneracy

with coherent neutrino-nucleus scattering (arXiv:2102.11981)

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Overview

1. Neutrino oscillation, the $\Delta m^2 - \theta_{12}$ solar solutions;
2. The NSI Dark solution;
3. Coherent neutrino nucleon scattering - CEνNS;
4. Status of the LMA-D;
5. Stopped pion source;
6. Reactor source;
7. Conclusions;

Solar neutrinos

Solar neutrinos: Neutrinos are copiously produced inside the sun core through fusion reactions; **Detectors** on earth measure just a fraction of those neutrinos:

$$\frac{\text{measured}}{\text{expected}} \approx 0.3,$$

using inverse beta process.

The solution!?

The neutrino oscillations effect.

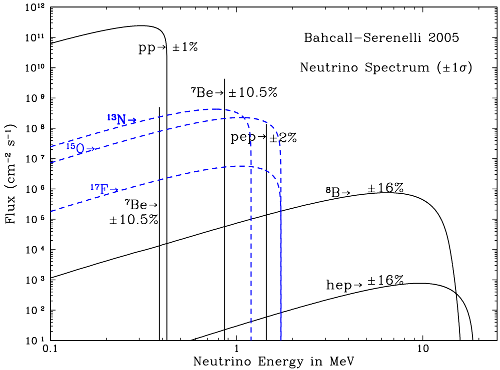


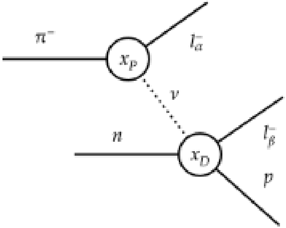
Figure: **The Astrophysical Journal Letters**, v. 621, n. 1, p. L85, 2005.

Neutrino oscillation

Neutrino oscillations predicts that characterized by the production of a lepton flavor α, after travels some distance can rotates in a state of detection that is a mixture of all the lepton flavor. The amplitudes for the detection of a given flavor β will depends on the PMNS matrix:

$$P(\nu_\alpha \to \nu_\beta) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{2E}\right) \quad (1)$$

The PMNS matrix rotates neutrino flavor field into neutrino mass fields.



Neutrino Oscillations

In the present status of neutrinos comes in three families where we know two difference of masses between the neutrinos and the real components of the PMNS matrix:

$$\theta_{12},\ \theta_{13},\ \theta_{23},\ \Delta m^2_{21},\ \Delta m^2_{31}.$$

Remains unknown the mass hierarchy and a possible CP violation phase, δ.

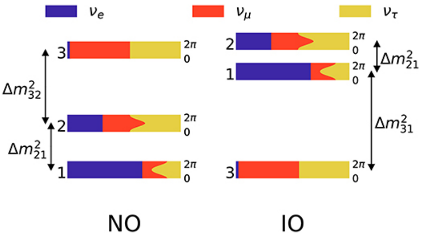


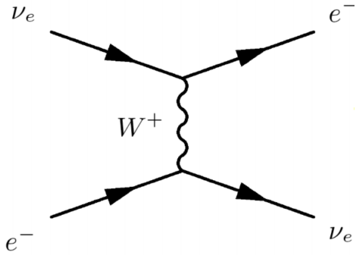
Figure: DE SALAS, Pablo F. et al.Frontiers in Astronomy and Space Sciences, v. 5, p. 36, 2018.

Matter Effects

When travel trough the matter, the neutrino suffer the coherent forward scattering by Z^0 and $W^{\pm}$ exchange[1]. This effect can be translated in a effective potential in a Schröedinger like equation for neutrinos with the inclusion of the following potential:

$$V_{CC} = \sqrt{2} G_F N_e(x), \qquad (2)$$

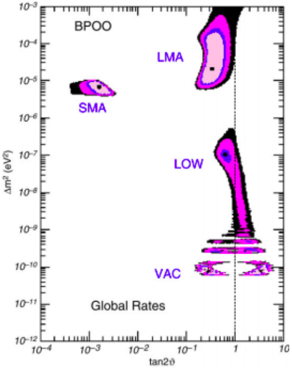
where the V_{CC} appears only in the *ee* component. Here, $N_e(x)$ is the electron number density at the position x.



[1]The only remaining contribution comes from CC $W^{\pm}$

Solar neutrino solutions

In the context of neutrinos coming from the sun. In the early 2000's four solutions exists[2]:



[2]GONZALEZ-GARCIA et. al, Physics Reports, v. 460, n. 1-3, p. 1-129, 2008.

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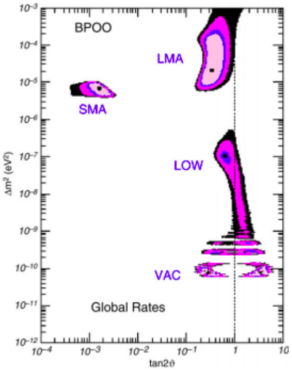
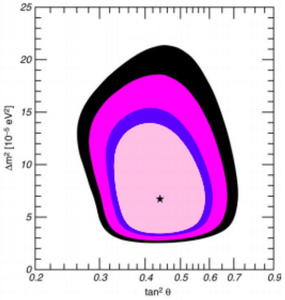


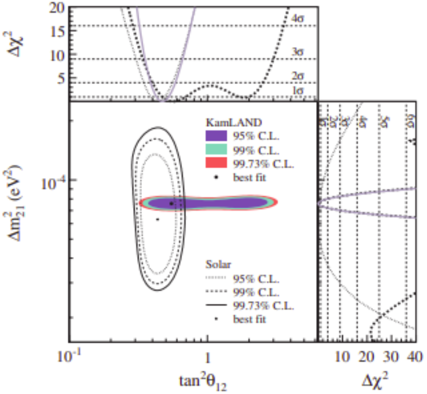


Latter, was found the correct solution was the Large Mixing angle (LMA) solution.

[2]GONZALEZ-GARCIA et. al, Physics Reports, v. 460, n. 1-3, p. 1-129, 2008.

Kamland

A probe for the Δm^2_{21} using reactor neutrino experiment Kamland[3] bring an two angle solutions that were not allowed by the solar scenario:



[3] ABE, S. et al. Physical Review Letters, v. 100, n. 22, p. 221803, 2008.

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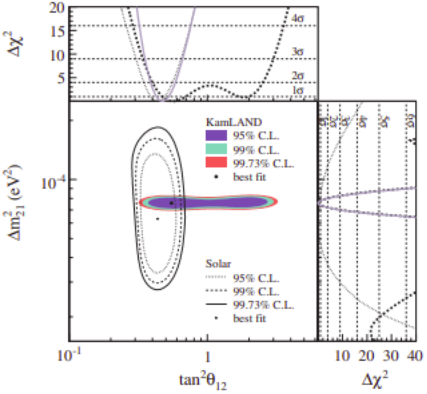

This solution comes from the fact that the vacuum equation of motion is invariant under the following transformation:

$$\Delta m^2_{31} \rightarrow -\Delta m^2_{32}, \quad (3)$$

$$\sin\theta_{12} \rightarrow \cos\theta_{12}, \quad (4)$$

$$\delta \rightarrow \pi - \delta. \quad (5)$$

[3] ABE, S. et al. Physical Review Letters, v. 100, n. 22, p. 221803, 2008.

Non-standard neutrino interactions

Wolfenstein matter effects through non-standard neutrino interactions were first proposed as an alternative to the neutrino oscillation for the solar neutrino problem[4]. In the simplest case they can come in a form of a Fermi interaction:

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2} G_F \varepsilon^f_{\alpha\beta} \left(\overline{\nu}_{\alpha L} \gamma_\mu \nu_{\beta L}\right) \left(\overline{f} \gamma^\mu f\right) \quad (6)$$

whee the underling physics can comes from higher energies.

The effect in the neutrino Hamiltonian is inclusion of more potential terms:

$$V = V_{CC} \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}, \end{pmatrix} \quad (7)$$

where:

$$\epsilon_{\alpha\beta} = \sum_f \frac{N_f(x)}{N_e(x)} \epsilon^f_{\alpha\beta}. \quad (8)$$

[4] GUZZO, M. M. et al., Physics Letters B, v. 260, n. 1-2, p. 154-160, 1991.

LMA-D theory

Given the inclusion of non-standard neutrino interactions it is possible to find a transformation that makes the equation of motion invariant as in the vaccuum case [5]:

$$(\varepsilon_{ee} - \varepsilon_{\mu\mu}) \rightarrow -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2, \tag{9}$$

$$(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \rightarrow -(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}), \tag{10}$$

$$\varepsilon_{\alpha\beta} \rightarrow -\varepsilon^*_{\alpha\beta}, \tag{11}$$

$$\Delta m^2_{31} \rightarrow -\Delta m^2_{32}, \tag{12}$$

$$\sin\theta_{12} \rightarrow \cos\theta_{12}, \tag{13}$$

$$\delta \rightarrow \pi - \delta. \tag{14}$$

[5] COLOMA, Pilar; SCHWETZ, Physical Review D, v. 94, n. 5, p. 055005, 2016.

LMA-D phenomenology

Hence, it is expected this solution for $\varepsilon_{ee} - \varepsilon_{\mu\mu}$ appears for all oscillation experiments. The LMA-D was first discovery for solar experiments for only d quarks interaction [6]:

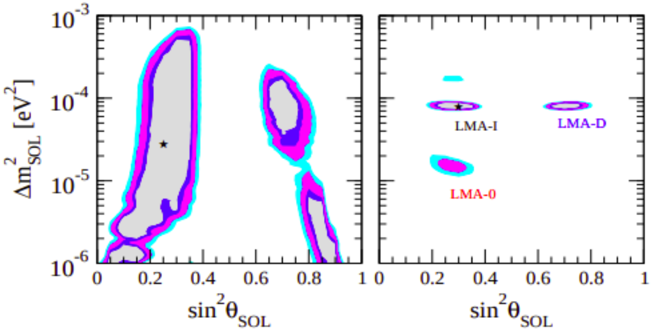

Figure: 90%, 95%, 99% and 99.73% C.L. allowed regions.

[6] MIRANDA, et.al, JHEP, v. 2006, n. 10, p. 008, 2006.

LMA-D phenomenology

The LMA-D solution gives motivation for study this "large" effects on different experimental context, e.g., scattering experiments.

In the most general scenario one can have the combination of three fermions couplings:

$$\varepsilon_{\alpha\beta} = Y_e(x)\varepsilon^{e}_{\alpha\beta} + Y_d(x)\varepsilon^{d}_{\alpha\beta} + Y_u(x)\varepsilon^{u}_{\alpha\beta}, \quad (15)$$

where is is always possible to write in terms of protons and neutrons couplings:

$$\varepsilon^{p}_{\alpha\beta} = 2\epsilon_{\alpha\beta} + \epsilon_{\alpha\beta} \quad (16)$$

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$$\varepsilon^{p}_{\alpha\beta} = 2\epsilon_{\alpha\beta} + \epsilon_{\alpha\beta} \quad (16)$$

$$\varepsilon^{n}_{\alpha\beta} = \epsilon_{\alpha\beta} + 2\epsilon_{\alpha\beta}. \quad (17)$$

The number of protons is always the same as the number of electrons, without loss of generality:

$$\varepsilon_{\alpha\beta} = Y_p(x)\varepsilon^{p}_{\alpha\beta} + Y_n(x)\varepsilon^{n}_{\alpha\beta}, \quad (18)$$

LMA-D phenomenology

With the assumption that the lepton flavor is independent on the quark flavor, the $\varepsilon^{f}_{\alpha\beta}$ can be written as

$$\varepsilon^{f}_{\alpha\beta} = \varepsilon^{\eta}_{\alpha\beta}\xi^{f}(\eta), \tag{19}$$

where

$$\xi^{p}(\eta) = \sqrt{5}\cos\eta, \tag{20}$$

$$\xi^{n}(\eta) = \sqrt{5}\sin\eta. \tag{21}$$

Let, $Y = N_n/N_p$ be the ratio between the number of protons and neutrons.

One can define the **nucleon** effective parameter:

$$\varepsilon^{Y,\eta}_{\alpha\beta} = \sqrt{5}\varepsilon^{\eta}_{\alpha\beta}(\cos\eta + Y\sin\eta) \tag{22}$$

Given that, one can explore different kind of scattering experiments:

- High energy: model dependent as CHARM and NUTEV experiments (only for heavy mediators);
- Low energy, model independent.

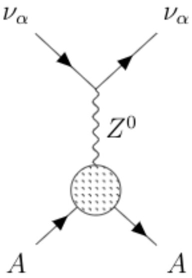
How to get low energy NC data?

Answer: CEνNS!

Theory

The Coherent Neutrino Nucleon Scattering (CEνNS) was first proposed in 1974 [7].

The neutrino "see" the **nucleon** structure as a whole.



[7] D. Z. Freedman, Phys. Rev. D 9, (1974) 1389

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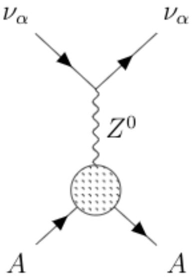

The CEνNS scattering is dominant for:

$$E_\nu < 100 \text{ MeV}, \tag{23}$$

the cross-section at low momentum transfer is

$$\frac{d\sigma}{dT} \approx \frac{G_F^2}{2\pi} Q^2 F^2(q^2) M \left(2 - \frac{MT}{E_\nu^2}\right), \tag{24}$$

in the Standard Model:

$$Q^2 = (Z g_p^V + N g_n^V)^2 \tag{25}$$

[7]D. Z. Freedman, Phys. Rev. D 9, (1974) 1389

Inclusion of non-standard neutrino interactions

If non-standard neutrino interactions are present the weak charge will be modified as

$$Q_\alpha^2 = (Q_{\rm SM} + Z\varepsilon_{\alpha\alpha}^{Y,\eta})^2 + Z^2 \sum_\beta \left(\varepsilon_{\alpha\beta}^{Y,\eta}\right)^2 . \tag{26}$$

remember that

$$\varepsilon_{\alpha\beta}^{Y,\eta} = \sqrt{5}\epsilon_{\alpha\beta}^{\eta}(\cos\eta + Y\sin\eta). \tag{27}$$

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Hence always that:

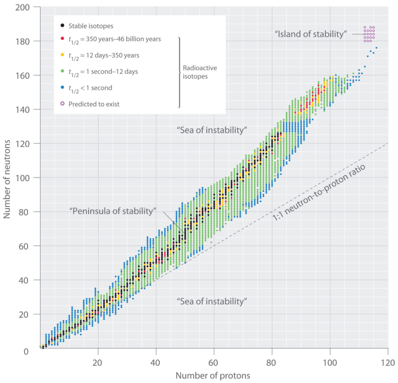
$$\eta_{\rm blind} = -\arctan\left(\frac{1}{Y}\right), \tag{28}$$

the experiment will be blind to the NSI contribution leading to $Q_\alpha^2 = Q_{\rm SM}^2$.

Blinding regions

For the known natural elements Y can vary between[8] ∼1 to ∼1.6 leading to a blinding range of η between -45^o to -32^o.

Target	Z	Y	η_{blind}	$-Q_{\text{SM}}$
C_3F_8	8.2	1.081	-42.8°	4.27
Si	14	1.006	-44.8°	6.72
Ar	18	1.235	-39.0°	10.71
Ge	32	1.270	-38.2°	19.6
CsI	54	1.405	-35.4°	36.7
Xe	54	1.431	-35.0°	37.4



[8] Stable and Unstable Isotopes. (2020, September 9). Retrieved March 16, 2021, from https://chem.libretexts.org/@go/page/278487

The COHERENT Experiment

The COHERENT experiment is the first experiment and the only to measure the CEνNS.[9][10]

- A flux of $\overline{\nu}_\mu$(broad band), ν_μ(wide band) and ν_e(wide band);
- Proportion of neutrino flavor $R_\mu : R_e$ (2:1). The effective measurement: $Q^2_{tot} = 2Q^2_\mu/3 + Q^2_e/3$ and $Q_\mu \times Q_e$ correlation (depending on time binning);

[9] D. Pershey, New CEvNS Results from the COHERENT CsI[Na] Detector, Dec., 2020. seminar talk at Fermilab.

[10] COHERENT, D. Akimov et al., First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon, Phys. Rev. Lett. 126 (2021), no. 1 012002, [2003.10630].

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CsI Last COHERENT measurements:

- Predicted: $Q^2_{SM} = 1346.9$;
- Measured: $Q^2_e = 1200 \pm 602.35$, $Q^2_\mu = 1245.1 \pm 202.3$;
- Q^2_μ and Q^2_e are correlated by $\rho = -0.709$

Ar Argon measurement:

- Predicted: $Q^2_{\mathrm{tot}} = 114.70$
- Measured: $Q^2_{\mathrm{tot}} = 148.9 \pm 12.5$
- Weak time information binning;

[9] D. Pershey, New CEvNS Results from the COHERENT CsI[Na] Detector, Dec., 2020. seminar talk at Fermilab.

[10] COHERENT, D. Akimov et al., First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon, Phys. Rev. Lett. 126 (2021), no. 1 012002, [2003.10630].

LMA-D before this work

What was the status before this work? **LMA-Dark vs. LMA-Light (only CsI)**.

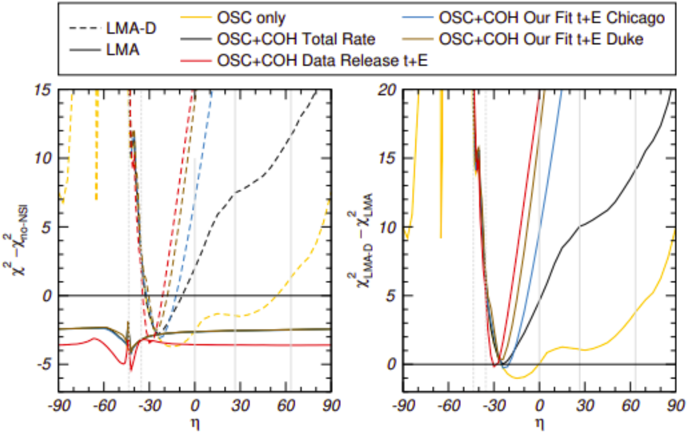


Figure: P. Coloma, I. Esteban, M. C. Gonzalez-Garcia, and M. Maltoni, JHEP 02 (2020) 023, [1911.09109].

Status of the LMA-D

Using present COHERENT data **(CsI+Ar)** together with oscillation we can disfavor the LMA-D by $\sim 2\sigma$.

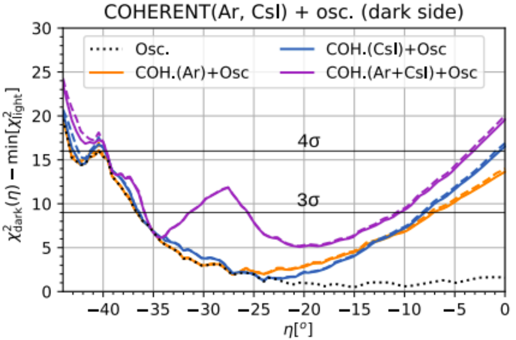
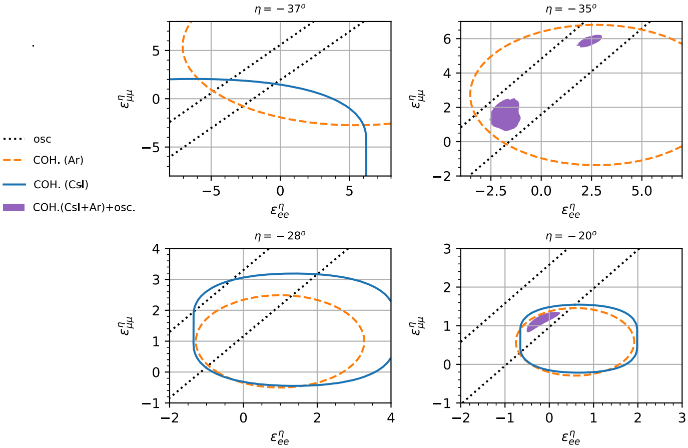


Figure: CHAVES, Mariano; SCHWETZ, Thomas. arXiv preprint arXiv:2102.11981, 2021.

Status of the LMA-D

Why does combining Ar and CsI helps? Contours at 3σ.



Stopped pion source

One possible scenario that can help to exclude the LMA-D is another neutrino beam measurement using a **different target.**

A stopped pion source can measure two quantities the total rate and for some targets also discriminate between ν_μ and ν_e contribution.:

$$\chi^2 = \frac{(Q^2_{\rm SM} - Q^2_e/3 - 2Q^2_\mu/3)^2}{\sigma^2} + \frac{(Q^2_{\rm SM} - Q^2_\mu)^2}{\sigma^2_\mu}\,. \quad (29)$$

There is one recent proposal in this direction: The Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source (ESS).

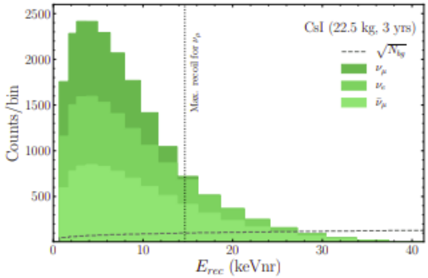


Figure: D. Baxter et al., JHEP 02 (2020) 123, [1911.00762].

ESS targets measurements and properties

We estimate the expected measurements for the ESS using different targets from fig. 12 of **D. Baxter et al., JHEP 02 (2020) 123, [1911.00762]**.

Target	Z	Y	$\eta_{\rm blind}$	$-Q_{\rm SM}$	$\sigma/Q^2_{\rm SM}$	σ_μ/σ
C_3F_8	8.2	1.081	-42.8°	4.27	13.3%	∞
Si	14	1.006	-44.8°	6.72	17.6%	∞
Ar	18	1.235	-39.0°	10.71	12.0%	∞
Ge	32	1.270	-38.2°	19.6	14.2%	4.20
CsI	54	1.405	-35.4°	36.7	12.5%	3.37
Xe	54	1.431	-35.0°	37.4	12.0%	4.01

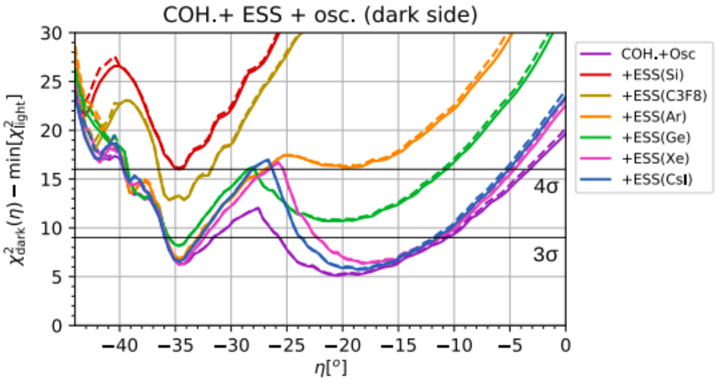
Table: CHAVES, Mariano; SCHWETZ, Thomas. arXiv preprint arXiv:2102.11981, 2021.

Our estimations are in accordance with the expected errors of ESS, around $\sim 12\%$.

Results for ESS

Silicon can exclude with more than 4σ.

- As **lighter** is the element (Si, C3F8), stronger is the bound;
- For the **intermediate** elements (Ar, Ge), constraints do exist at the -20^o valley.
- For the **heavier** elements(Xe, CsI), two local minimum of interest do exists.



Results for ESS

Why does **Si** helps to solve the two local minimums?

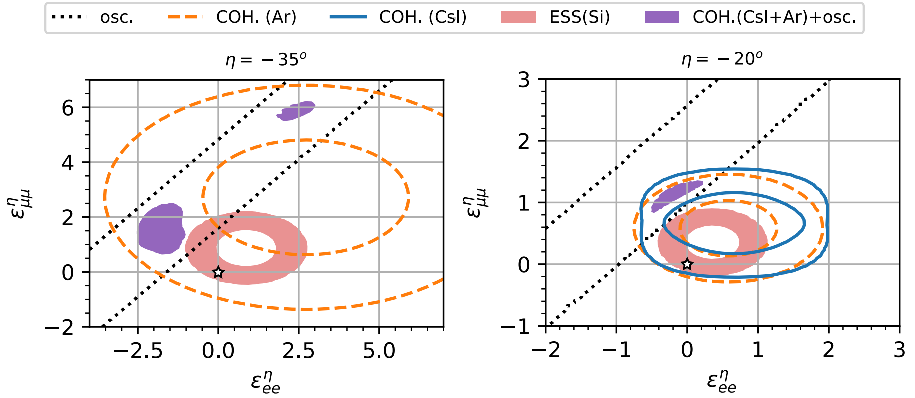
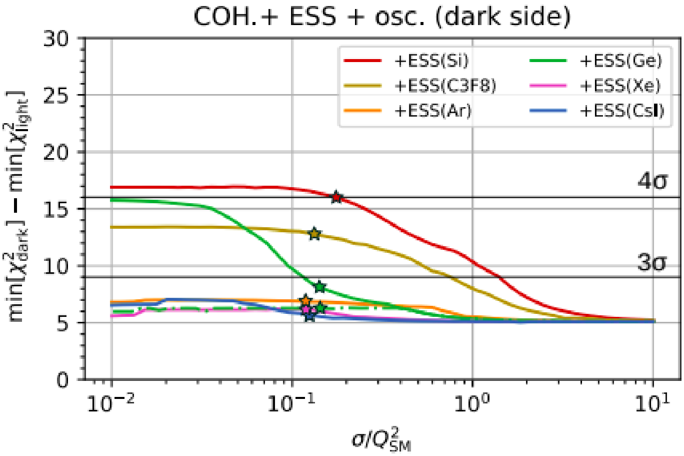


Figure: 3σ (2dof) contours.

Results for ESS

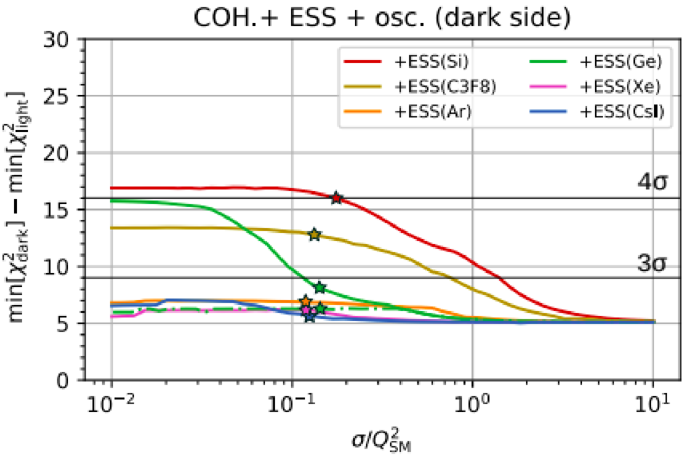
What happens for arbitrary errors?

- As the stronger is experiment precision, the ellipse get tinnier, but not smaller.



Solving ν_μ and ν_e

Why does **Ge** helps?



Solving ν_μ and ν_e

We assume two possibilities. No single Q_μ^2 measurement and including Q_μ^2 measurement.

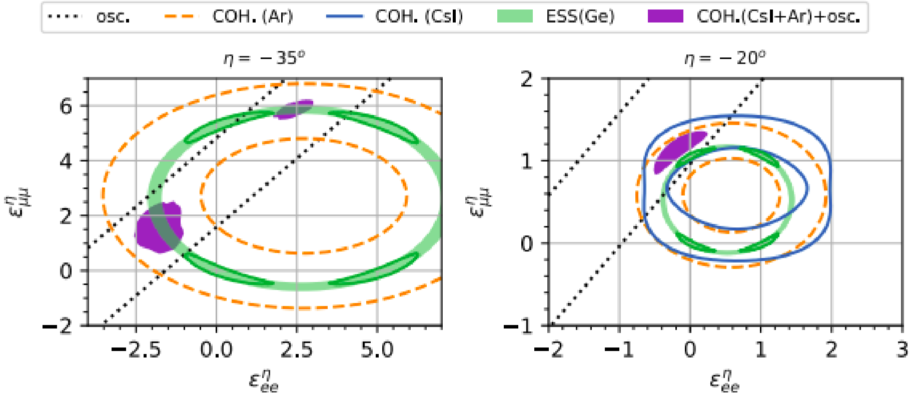


Figure: 3σ contours.

What about rectors?

For reactors the only measured quantity is the Q_e^2, so we can use the following χ^2:

$$\chi^2_{\text{reac}} = \frac{(Q^2_{\rm SM} - Q^2_e)^2}{\sigma^2_{\rm reac}}\,, \tag{30}$$

for reactors, being optimistic, we assume the error $\sigma^2_{\rm reac}$ as 5% of the Q^2_{SM}. We consider two reactor targets, Si and Ge. There are two ongoing reactor experiments using those two targets:

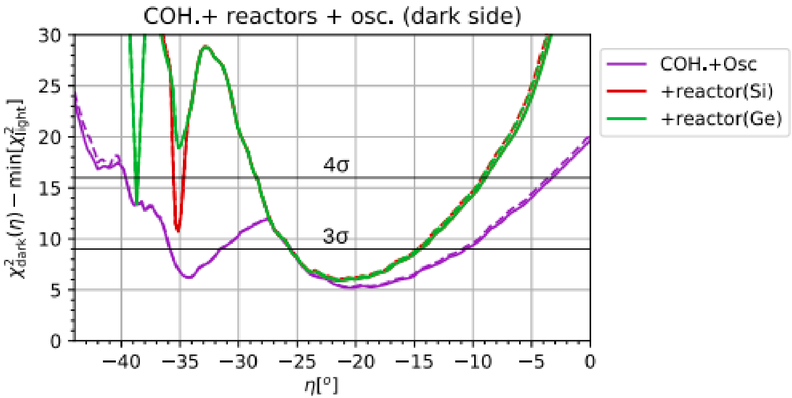
- CONNIE, using Si (in Angra dos Reis, Brazil);
- CONUS, using Ge (in Brokdorf, Germany);

Angra dos Reis, Brazil

Angra dos Reis, Brazil

Reactor results

The results for reactors combined with COHERENT



Why do reactors are not so good?

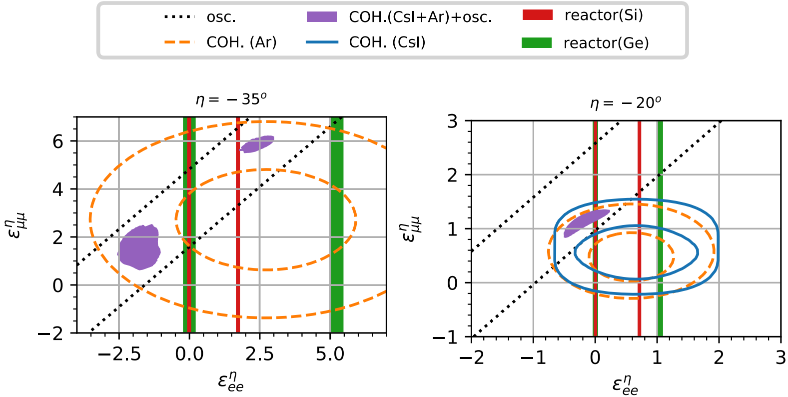
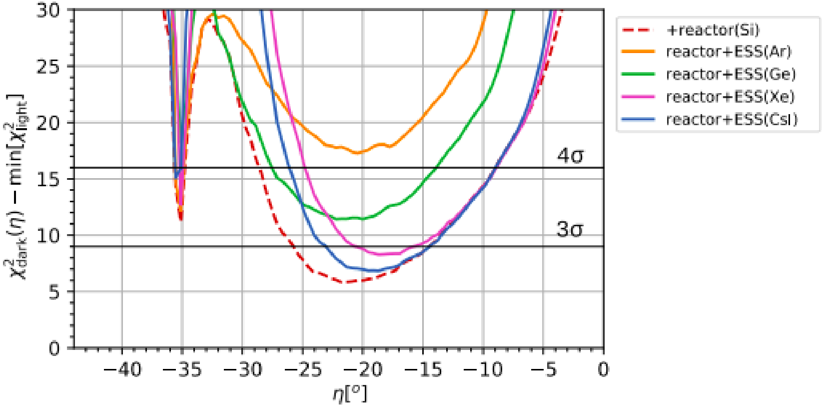


Figure: 3σ contours

Reactor+ESS

Can reactors save the -20^o band for heavier elements using the ESS measurements?



Conclusions

- Resolving the LMA-D is an important issue to enter the neutrino precision age;
- In the present status, the LMA-D is excluded by $\sim 2\sigma$;
- Q_μ^2 and Q_e^2 measurements are necessary to solve the problem;
- The best option in the present proposals is the ESS using Si target;
- Reactors can help some ESS heavier targets to exclude the LMA-D;

The End