

Present Bounds on Non-Standard Interaction from a Global Oscillation Analysis

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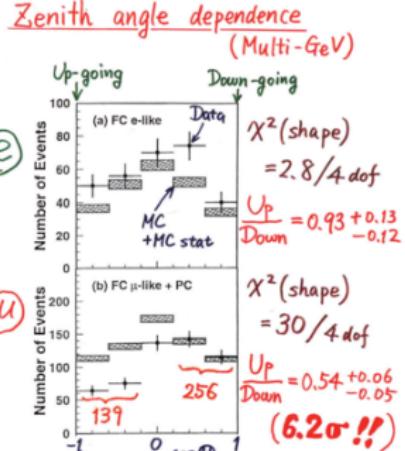
April 3rd, 2019



Northwestern
University

Motivation: 3ν mixing

- In SM, neutrinos are massless.



* Up/Down syst. error for μ -like

Prediction (flux calculation $\lesssim 1\%$,
1km rock above SK 1.5% ,) 1.8%

Data (Energy calib. for $\uparrow \downarrow$ 0.7% ,
Non ν Background $< 2\%$,) 2.1%

Nobel Lecture, Rev. Mod. Phys. 88,
030501

- The experiments established that neutrinos are massive particles.

Motivation: standard 3ν mixing

- ▶ The mass and flavor basis do not have to coincide.
- ▶ U is a mixing matrix that relates flavor and massive states.
 - ▶ The number of independent parameters depends on the neutrino nature.
 - ▶ Special case: 3 Dirac neutrinos or 3 Majorana neutrinos.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$

↑
Majorana phases

Motivation: standard 3ν mixing

In the 3ν scenario, neutrino evolution is described by the Schrödinger equation

$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E} \left[U^\dagger \text{Diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U \pm V_{mat} \right] \vec{\nu} \quad \vec{\nu} = (\nu_e \nu_\mu \nu_\tau)^T$$

Evolution in vacuum

Evolution through the matter

$$V_{mat} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Electron density

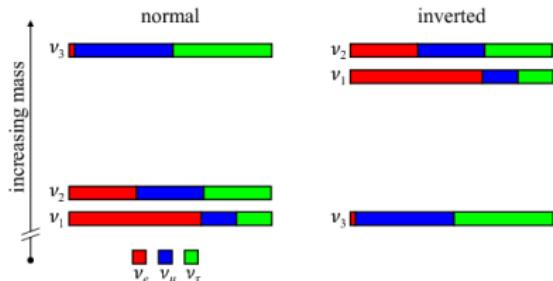
Motivation: standard 3ν mixing

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$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E} \left[U^\dagger \text{Diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U \pm V_{mat} \right] \vec{\nu}$$

- ▶ Depends on:
 - ▶ three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and a complex phase (δ_{cp})
 - ▶ two mass splittings ($\Delta m_{21}^2 \sim 10^{-5} eV^2$ and $\Delta m_{31}^2 \sim 10^{-3} eV^2$)

Two possible mass hierarchies

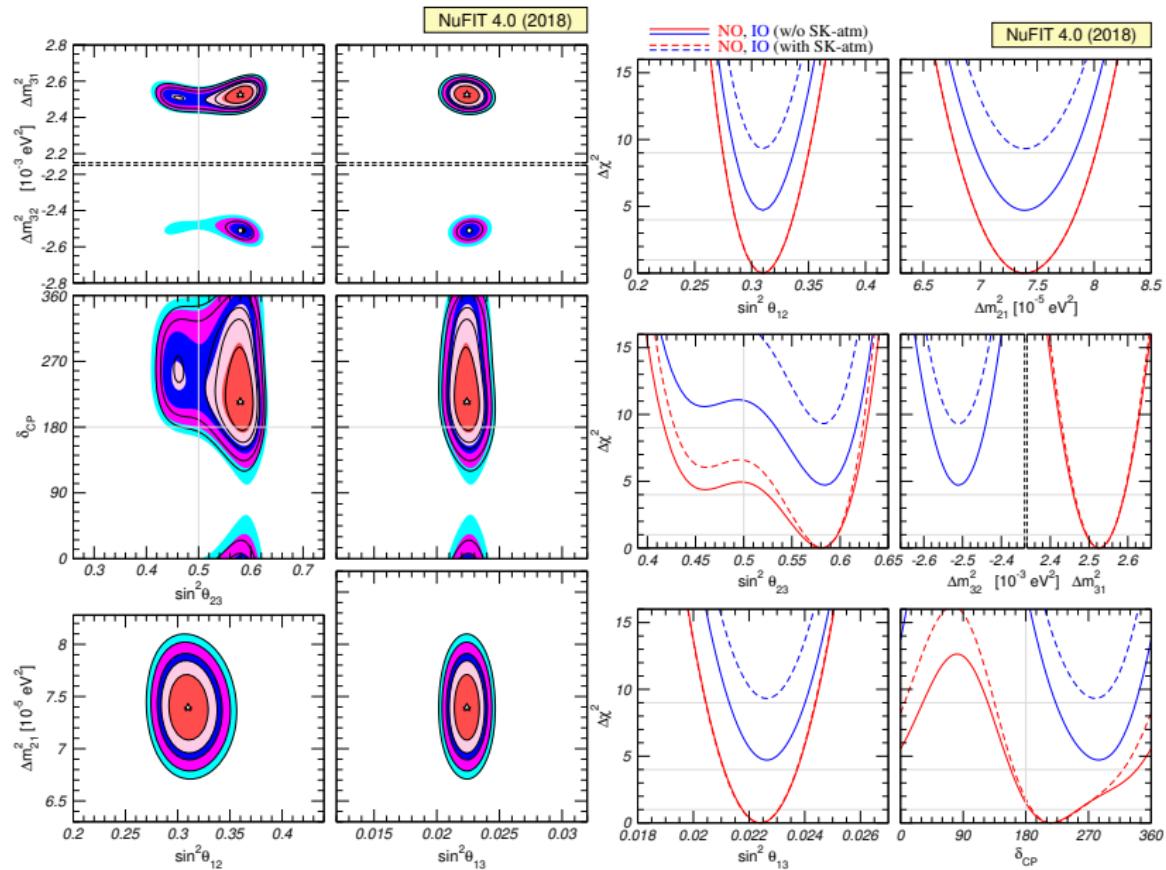


Motivation: standard 3ν mixing

The global fit goal is the determination of the parameters describing the evolution.

Experiment	Dominant	Important
Solar	θ_{12}	$\Delta m_{21}^2, \theta_{13}$
Reactor LBL	Δm_{21}^2	θ_{12}, θ_{13}
Reactor MBL	θ_{13}	$ \Delta m_{3l}^2 $
Atmospheric	θ_{23}	$ \Delta m_{3l}^2 , \theta_{13}, \delta_{CP}$
Accelerator LBL ν_μ Disapp	$ \Delta m_{3l}^2 , \theta_{23}$	
Accelerator LBL ν_e App	δ_{CP}	$\theta_{13}, \theta_{23}, \text{sign}(\Delta m_{3l}^2)$

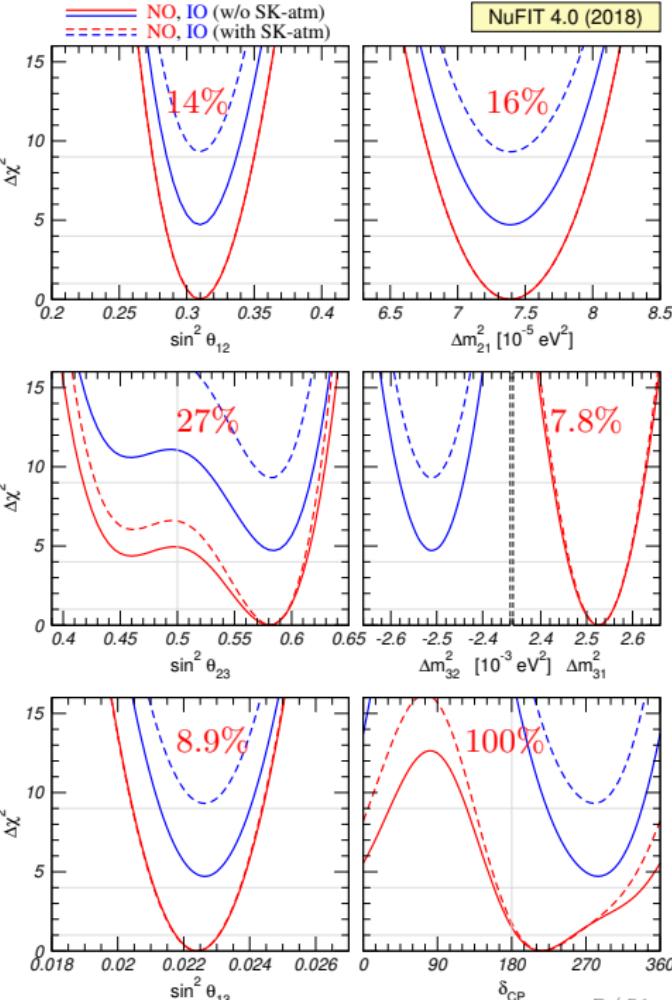
Motivation: standard 3ν mixing



Motivation: standard 3ν mixing

The least known oscillation parameters [1,2,3]:

- ▶ δ_{CP} (Recent result push to non-maximal violation)
- ▶ The octant of θ_{23} (preference for the second octant)
- ▶ The mass hierarchy (preference for NO at more than 3σ)



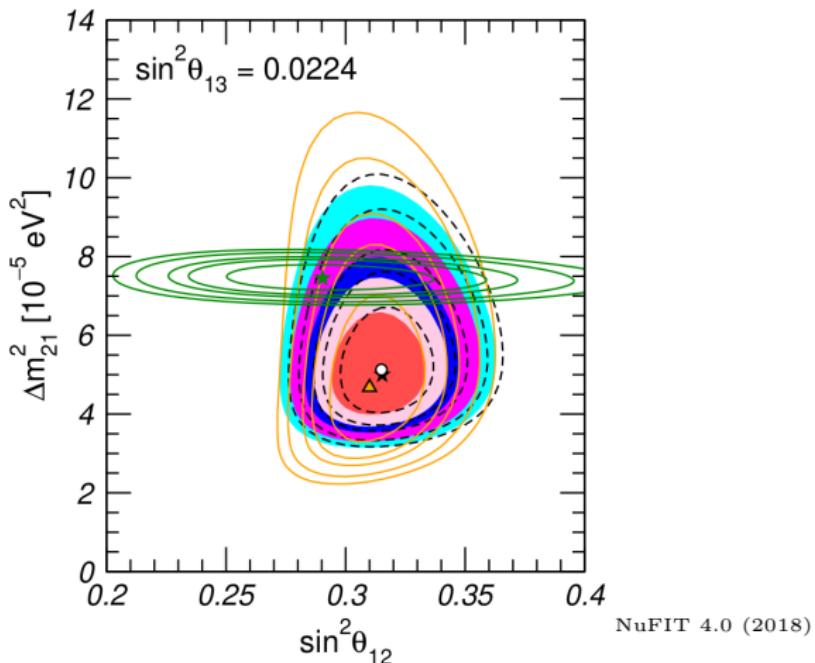
[1] I. Esteban, et al., arXiv:1811.05487, NuFIT 4 (2018), www.nu-fit.org

[2] F. Capozzi, et al., Prog.Part.Nucl.Phys. 102 (2018) 48-72

[3] P.F. de Salas, et al., Phys.Lett. B782 (2018) 633-640

Motivation: Tension in the standard 3ν mixing

Tensions in the determination of Δm_{21}^2

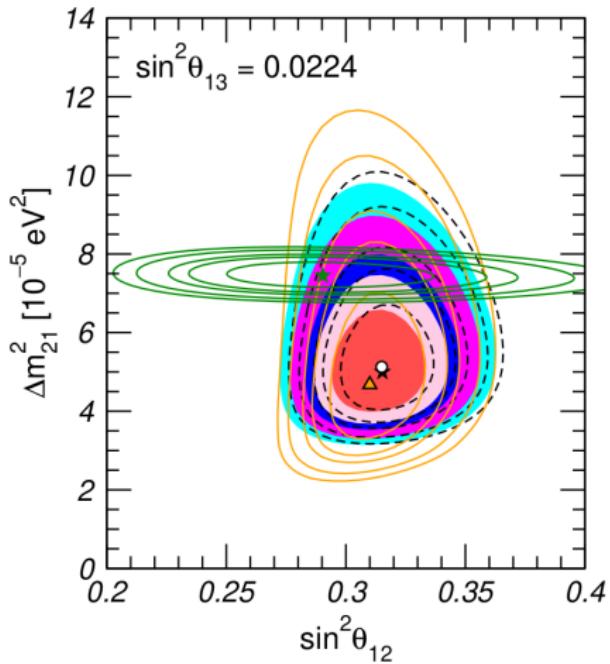


Motivation: Tension in the standard 3ν mixing

NuFIT 4.0 (2018)

Tensions in the determination of Δm_{21}^2

- ▶ KamLAND prefers $\Delta m_{21}^2 \simeq 7.5 \times 10^{-5} \text{ eV}^2$
- ▶ Solar experiments favor $\Delta m_{21}^2 \simeq 5 \times 10^{-5} \text{ eV}^2$

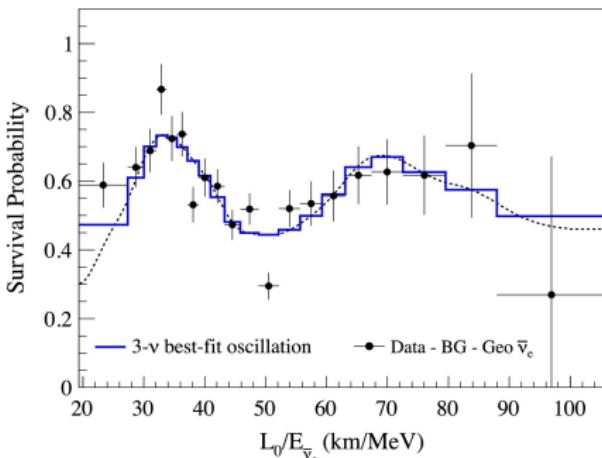


Motivation: Tension in Δm_{21}^2

M.P. Decowski, Nucl.Phys. B908
(2016) 52-61

KamLAND

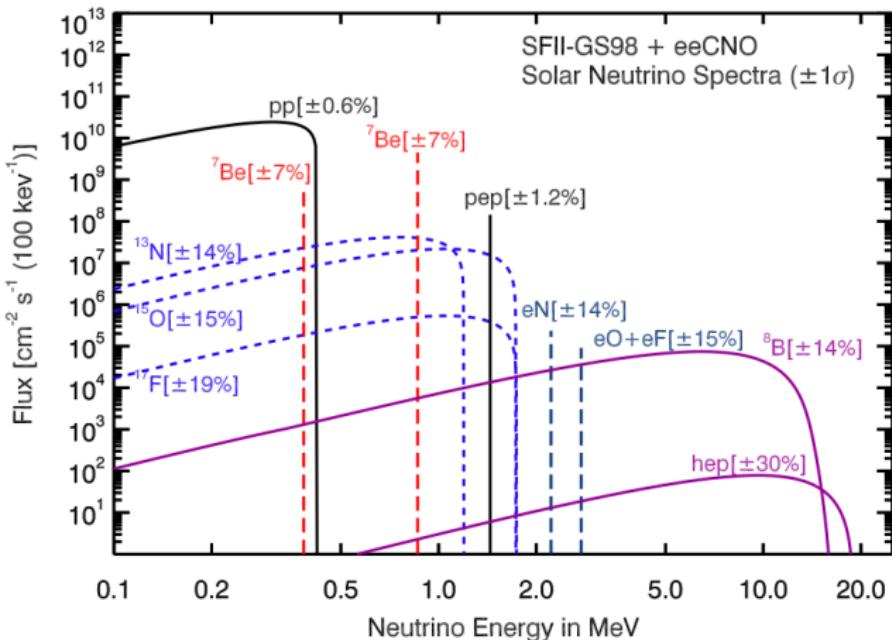
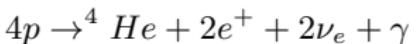
- ▶ Long-baseline reactor experiment;
- ▶ $\bar{\nu}_e$ are emitted with energies between 1.8 and 8 MeV;
- ▶ baseline ~ 180 km;
- ▶ matter effects are very tiny.



Motivation: Tension in Δm_{21}^2

Solar neutrinos

- The flux is composed by ν_e with a characteristic energy (7Be , pep) or spectrum (pp, CNO, 8B , hep).



Phys. Rev. D 98,
030001 (2018)

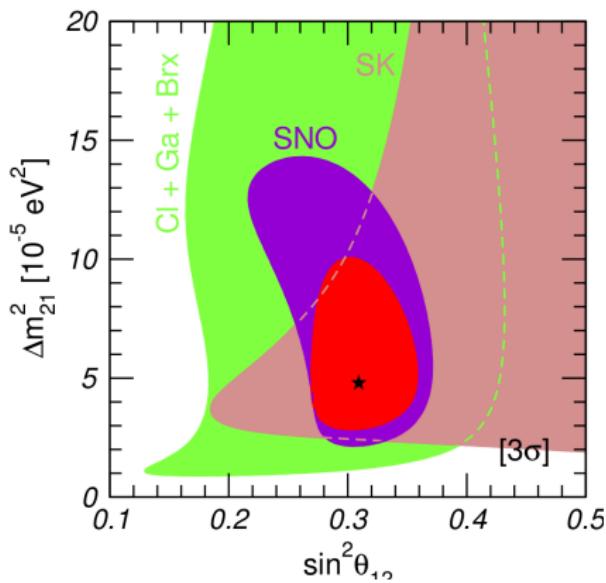
Motivation: Tension in Δm_{21}^2

Solar neutrinos

- ▶ Solar neutrino experiments are mainly sensitive to θ_{12} .
- ▶ The constraints over θ_{12} are mainly driven by SK+SNO.
- ▶ There is a small dependence on Δm_{21}^2 .

$$P_{ee}^{3\nu} = \cos^4 \theta_{13} P_{eff}^{2\nu}(\Delta m_{21}^2, \theta_{12}) + \sin^4 \theta_{13}$$

Where does the tension over Δm_{21}^2 come from?

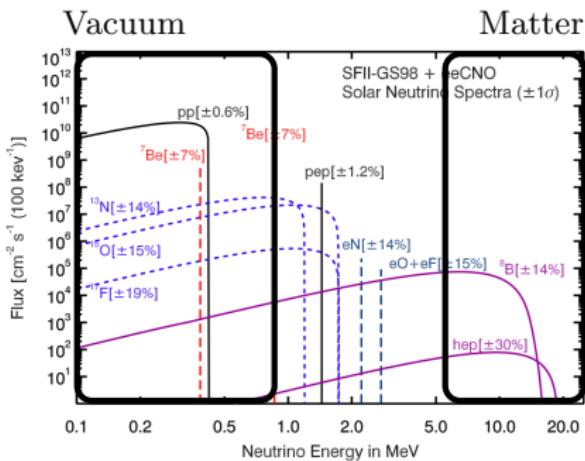


Motivation: Tension in Δm_{21}^2

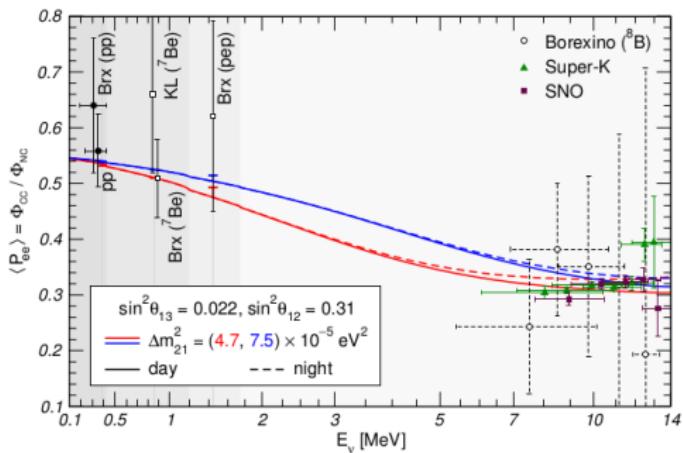
Measurement of the low-energy 8B neutrino spectrum.

Observations indicates:

- ▶ $P_{ee} \sim 30\%$ at high energy (8B , hep).
- ▶ $P_{ee} \sim 60\%$ at low energy (pp, 7Be , CNO and low 8B).



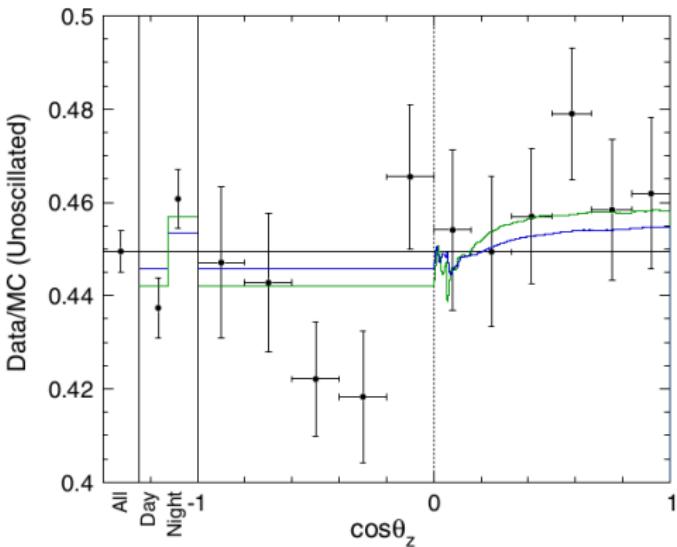
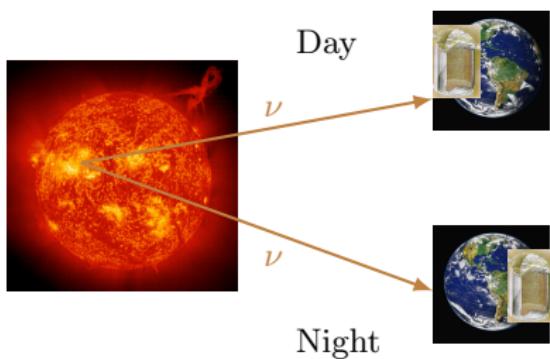
Phys. Rev. D 98, 030001 (2018)



Eur.Phys.J. A52 (2016) no.4, 87

Motivation: Tension in Δm_{21}^2

Observation of a larger day/night asymmetry than predicted by KamLAND.



Phys. Rev. D94, 052010 (2016)

How we can solve the tension in Δm_{21}^2 ?

Motivation: Neutrino Non-Standard Interactions

SM can be considered as a low energy effective model.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{\mathcal{L}_{d=5}}{\Lambda} + \frac{\mathcal{L}_{d=6}}{\Lambda^2} + \dots$$

- ▶ For $d = 5$. Weinberg operator.
- ▶ For $d = 6$. NSI

$$\mathcal{L}_{CC-NSI} = -2\sqrt{2}G_F \sum_{f, f', P, \alpha, \beta} \epsilon_{\alpha\beta}^{ff'P} (\bar{\nu}_\alpha \gamma^\mu P_L l_\beta) (\bar{f}' \gamma_\mu Pf)$$

$$\mathcal{L}_{NC-NSI} = -2\sqrt{2}G_F \sum_{f, P, \alpha, \beta} \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu Pf)$$

Motivation: Neutrino Non-Standard Interactions

SM can be considered as a low energy effective model.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{\mathcal{L}_{d=5}}{\Lambda} + \frac{\mathcal{L}_{d=6}}{\Lambda^2} + \dots$$

- ▶ For $d = 5$. Weinberg operator.
- ▶ For $d = 6$. NSI
- ▶ In this talk we are going to focus in NSI-NC

$$\mathcal{L}_{NC-NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P f)$$

Motivation: NSI-NC

- ▶ Described by effective four-fermion operators

$$\mathcal{L}_{NC-NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P f)$$

- ▶ Not gauge invariant
- ▶ Charged lepton flavour violation (CLFV) processes impose tight constraints

[Phys. Rev. D79 (2009) 013007, Nucl. Phys. B810 (2009) 369-388, Phys. Rev. D90 (2014) 053005]

How we can avoid the constraints?

Motivation: NSI-NC

- ▶ Described by effective four-fermion operators

$$\mathcal{L}_{NC-NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P f)$$

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[Phys. Rev. D79 (2009) 013007, Nucl. Phys. B810 (2009) 369-388, Phys. Rev. D90 (2014) 053005]

How we can avoid the constraints?

- ▶ NSI generated well below the EW scale [Phys.Rev.D70 (2004) 055007, Phys.Lett.B748 (2015) 311-315, JHEP 1712 (2017) 096]

Neutrino evolution: NSI

- ▶ NSI-NC modify the forward -coherent scattering in regions with matter
- ▶ The matter potential can be generalized

$$V_{mat} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\tau\mu} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta}(x) = \sum_{f=e,u,d} \frac{N_f(x)}{N_e(x)} (\epsilon_{\alpha\beta}^{f,L} + \epsilon_{\alpha\beta}^{f,R})$$

Neutrino evolution: NSI

$$V_{mat} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\tau\mu} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

- ▶ Oscillation experiments are sensitive to $\epsilon_{ee}^f - \epsilon_{\mu\mu}^f$ and $\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f$
- ▶ We restrict to NSI with quarks.
- ▶ Assuming neutral matter

$$\epsilon_{\alpha\beta}(x) = \epsilon_{\alpha\beta}^p + Y_n(x)\epsilon_{\alpha\beta}^n \quad Y_n = N_n(x)/N_e(x)$$

- ▶ For the Earth, $Y_n = 1.137$ (core) and $Y_n = 1.012$ (mantle)
- ▶ For the Sun $Y_n \in [1/2, 1/6]$

Neutrino evolution: NSI

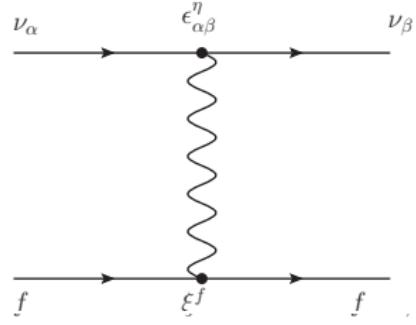
The results are obtained under the approximation

$$\epsilon_{\alpha\beta}(x) = \sum_{f=e,u,d} \frac{N_f(x)}{N_e(x)} \epsilon_{\alpha\beta}^\eta \xi^f$$

- ▶ $\epsilon_{\alpha\beta}^\eta$ is a common factor to all the couplings of all the fermions;
- ▶ the relative value between the different ξ^f is parametrized in term of an angle η ;
- ▶ the couplings with protons and neutrons are given by

$$\epsilon_{\alpha\beta}^p = \sqrt{5} \epsilon_{\alpha\beta}^\eta \cos \eta$$

$$\epsilon_{\alpha\beta}^n = \sqrt{5} \epsilon_{\alpha\beta}^\eta \sin \eta$$

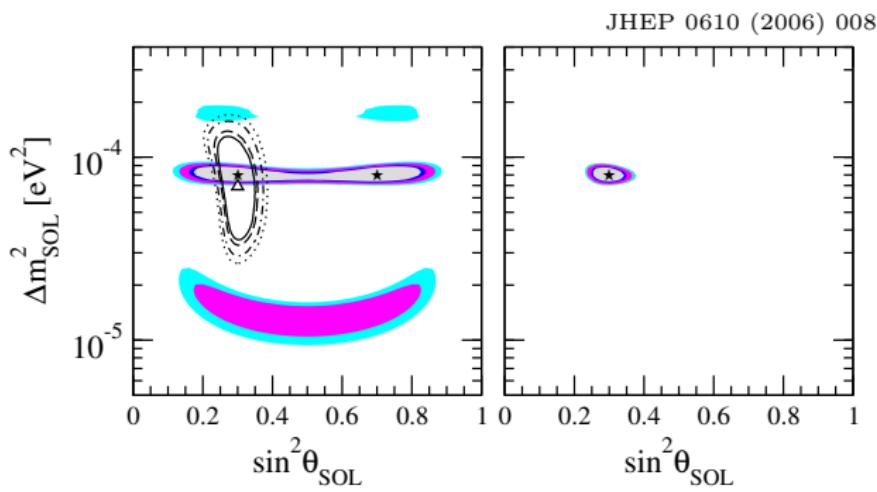


CPT symmetry

- In vacuum the hamiltonian is degenerate under the transformation
 $H_{vac}^\nu \rightarrow -(H_{vac}^\nu)^*$

$$\begin{aligned}\Delta m_{31}^2 &\rightarrow -\Delta m_{32}^2 \\ \theta_{12} &\rightarrow \pi/2 - \theta_{12} \\ \delta_{cp} &\rightarrow \pi - \delta_{cp}\end{aligned}$$

- The degeneracy is broken in matter.



CPT symmetry

- ▶ In the presence of NSI, we can recover the same degeneracy in matter

$$\begin{aligned} [\epsilon_{ee}(x) - \epsilon_{\mu\mu}(x)] &\rightarrow -[\epsilon_{ee}(x) - \epsilon_{\mu\mu}(x)] - 2 \\ [\epsilon_{\tau\tau}(x) - \epsilon_{\mu\mu}(x)] &\rightarrow -[\epsilon_{\tau\tau}(x) - \epsilon_{\mu\mu}(x)] \\ \epsilon_{\alpha\beta}(x) &\rightarrow -\epsilon_{\alpha\beta}^*(x) \quad (\alpha \neq \beta) \end{aligned}$$

- ▶ $H^\nu \rightarrow -(H^\nu)^*$
- ▶ The degeneracy is exact for $\epsilon_{\alpha\beta}$ independent of x
- ▶ LMA-D solution.

What is our current knowledge of $\epsilon_{\alpha\beta}$?

Based on: I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, IMS, J. Salvado, JHEP
1808 (2018) 180

Solar neutrinos and KamLAND in the presence of NSI

- In the presence of NSI, $P_{eff}^{2\nu}$ is obtained by solving the effective hamiltonian

$$H_{vac}^{eff} = \frac{\Delta m_{21}^2}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} e^{i\delta_{cp}} \\ -\sin 2\theta_{12} e^{-i\delta_{cp}} & \cos 2\theta_{12} \end{pmatrix}$$

$$H_{mat}^{eff} = \sqrt{2}G_F N_e(x) \left[\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + [\xi^p + Y_n(x)\xi^n] \begin{pmatrix} -\epsilon_D^\eta & \epsilon_N^\eta \\ \epsilon_N^{\eta*} & \epsilon_D^\eta \end{pmatrix} \right]$$

Standard matter potential

Matter potential by NSI

Solar neutrinos and KamLAND in the presence of NSI

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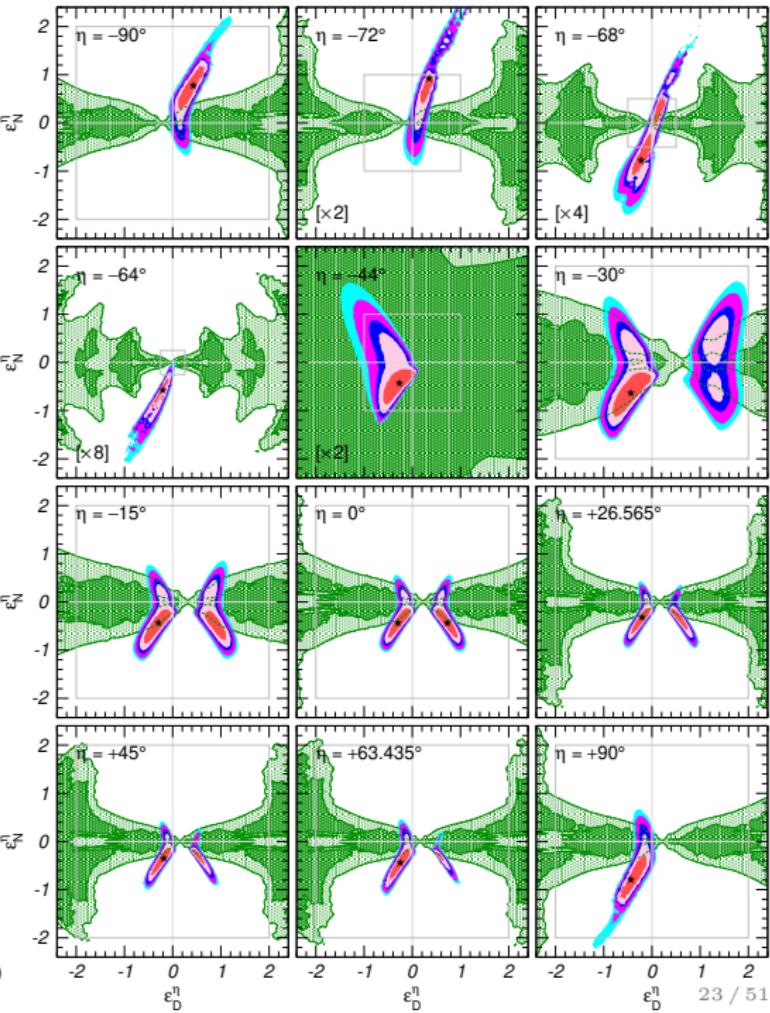
$$H_{vac}^{eff} = \frac{\Delta m_{21}^2}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} e^{i\delta_{cp}} \\ -\sin 2\theta_{12} e^{-i\delta_{cp}} & \cos 2\theta_{12} \end{pmatrix}$$

$$H_{mat}^{eff} = \sqrt{2}G_F N_e(x) \left[\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + [\xi^p + Y_n(x)\xi^n] \begin{pmatrix} -\epsilon_D^\eta & \epsilon_N^\eta \\ \epsilon_N^{\eta*} & \epsilon_D^\eta \end{pmatrix} \right]$$

- ▶ NSI effects are described by the effective parameters ϵ_D^η and ϵ_N^η
- ▶ Shows a high dependence of η .
- ▶ We assume real NSI

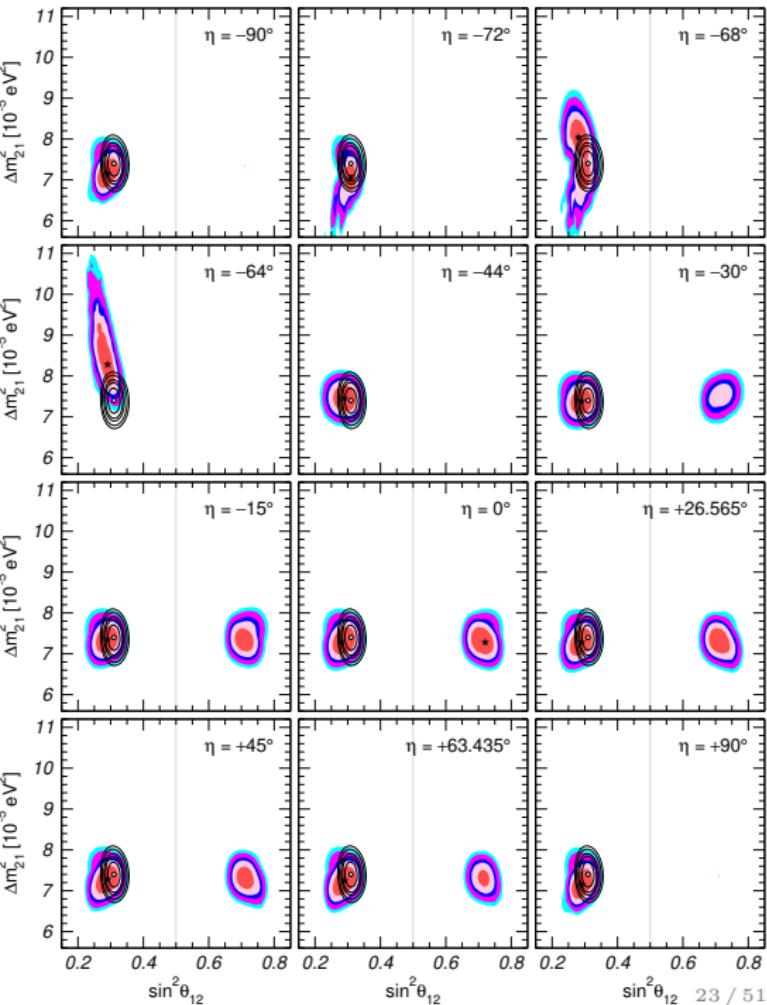
Solar and KamLAND

- ▶ ϵ_N^η and ϵ_D^η are linear combination of $\epsilon_{\alpha\beta}^\eta$.
- ▶ Strong dependence with η .
- ▶ For $\eta = 0 \rightarrow \epsilon_{\alpha\beta}^n = 0$
- ▶ For $\eta = \pm 90^\circ \rightarrow \epsilon_{\alpha\beta}^p = 0$
- ▶ $\epsilon_{\alpha\beta}^f \geq 1$



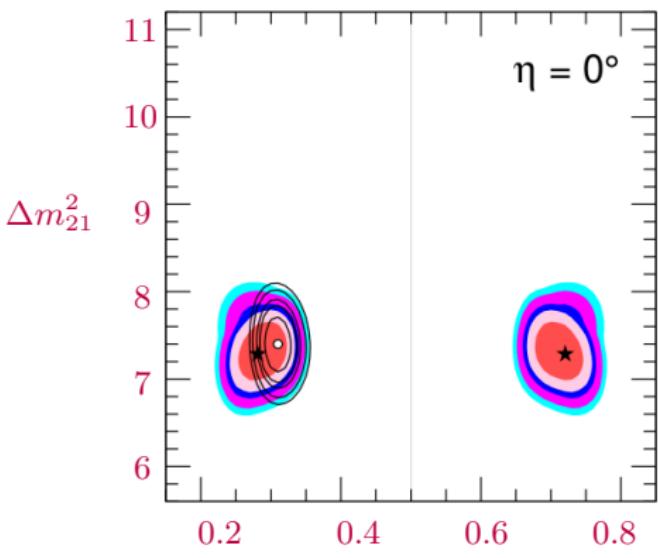
Solar and KamLAND

- ▶ LMA-D exist for $-27^\circ \leq \eta \leq 72^\circ$ at 90% CL
 - ▶ In the ranges $\eta \leq -40^\circ$ and $\eta \geq 86^\circ$ LMA-D solution is not compatible with KamLAND
- ▶ θ_{12} can take smaller values.
 - ▶ A non-zero ϵ_N^η can compensate the flavor transition.
- ▶ The largest values of $\epsilon_{\alpha\beta}^\eta$ modify the determination of Δm_{21}^2 by KamLAND.

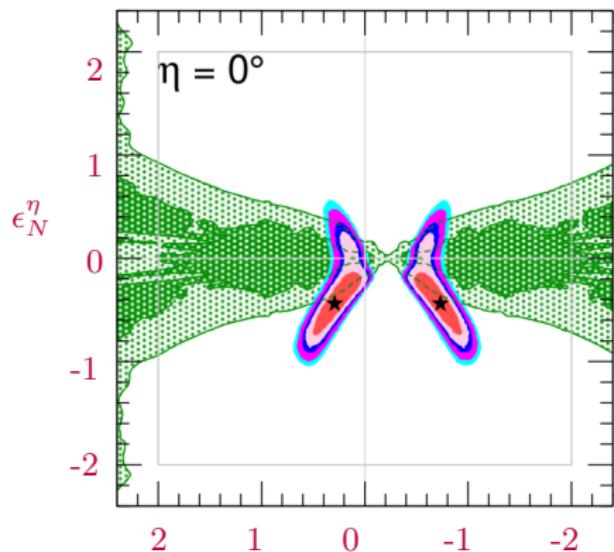


Solar and KamLAND

- ▶ For $\eta = 0 \rightarrow \epsilon_{\alpha\beta}^\eta = 0$
- ▶ The degeneracy is exact.



$$\sin^2 \theta_{12}$$

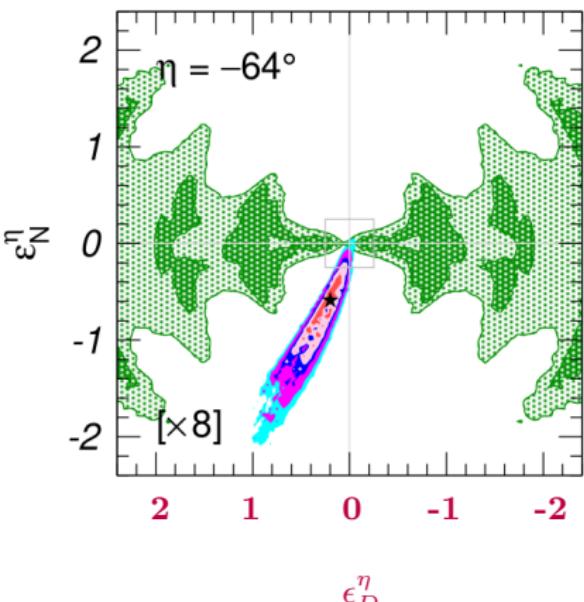
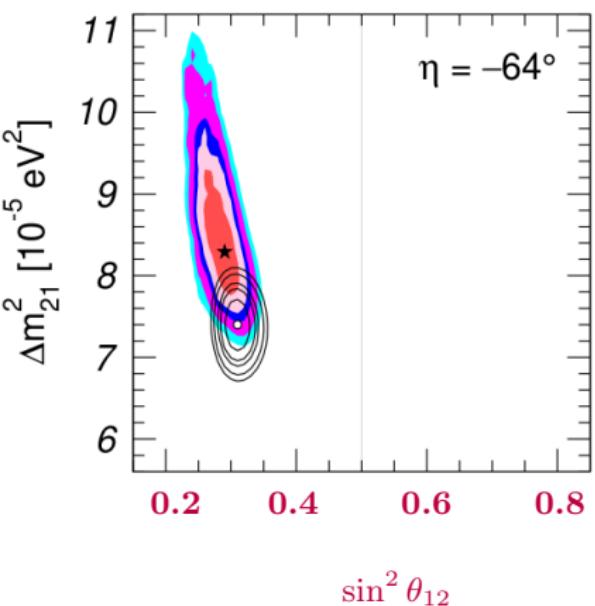


$$\epsilon_D^\eta$$

Solar and KamLAND

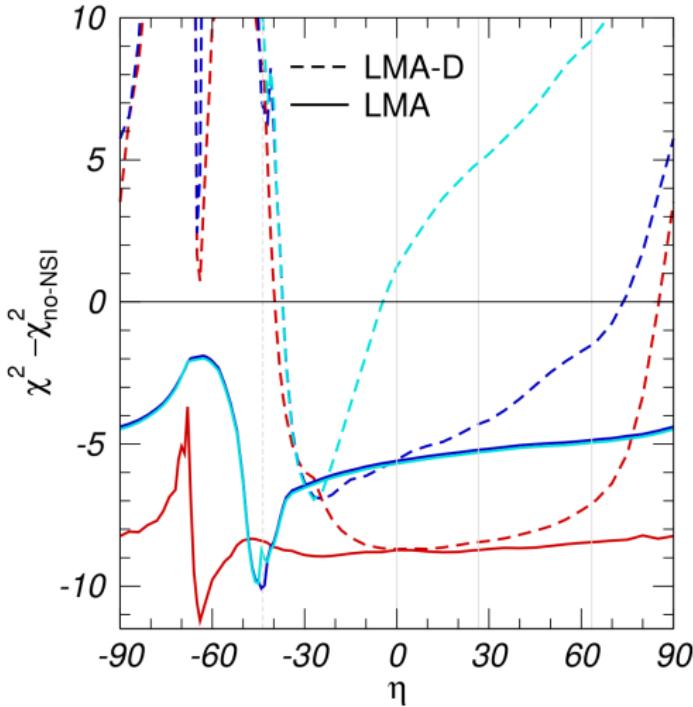
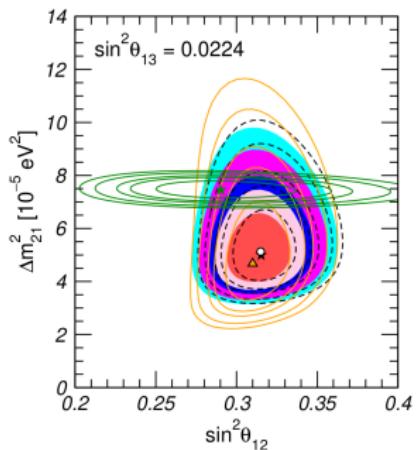
- ▶ For $-70^\circ \leq \eta \leq -60^\circ$ the contribution of the NSI to the solar matter potential cancel.
- ▶ $|\epsilon_{\alpha\beta}^n|/|\epsilon_{\alpha\beta}^p| \sim 2$

$$\epsilon_{\alpha\beta}(x) = \epsilon_{\alpha\beta}^p(x) + Y_n \epsilon_{\alpha\beta}^n(x) \rightarrow 0$$



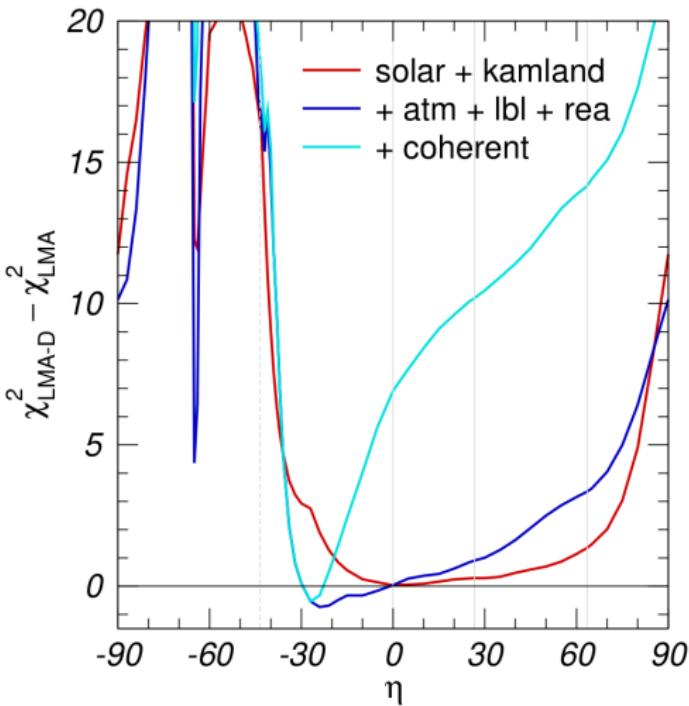
Solar and KamLAND

- ▶ NSI improves the agreement between solar and KamLAND.
 - ▶ The tension in Δm_{21}^2 is reduced in the whole η range ($\sim 2.5\sigma$).



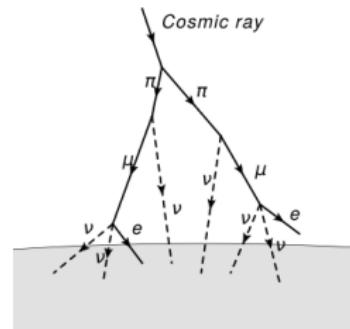
Solar and KamLAND

- ▶ LMA provides a better fit than LMA-D in the whole range of η .
- ▶ LMA-D is disfavored at more than 3σ when $\eta \leq -40^0$ or $\eta \geq 86^0$.



Terrestrial experiments

Atmospheric neutrinos.



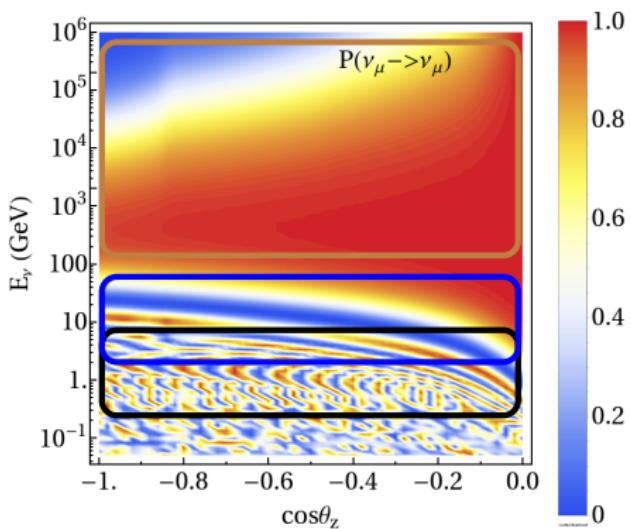
- ▶ Created in the collisions of cosmic rays with the atmosphere.

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$$

$$K^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$$

$$\mu^\pm \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \nu_\mu (\bar{\nu}_\mu)$$

- ▶ Super-K ($E_\nu \in [\sim 0.5, \sim 10]$ GeV)
- ▶ DeepCore ($E_\nu \in [6, 56]$ GeV)
- ▶ IceCube ($E_\nu \in [0.1, 20]$ TeV)



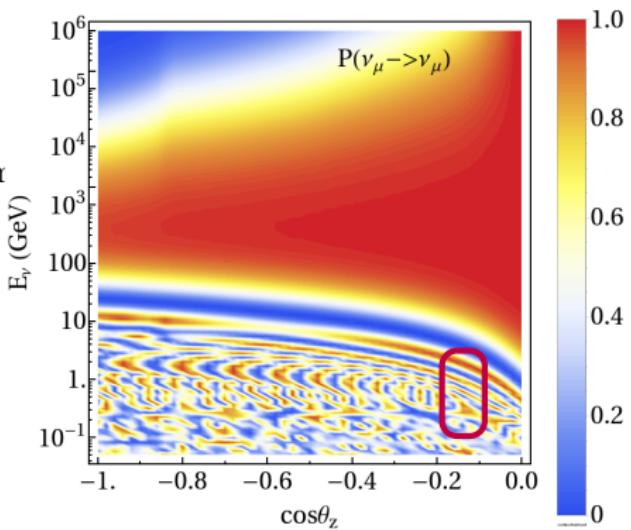
Terrestrial experiments

Long-baseline accelerators

- ▶ $\nu_e/\bar{\nu}_e$ and $\nu_\mu/\bar{\nu}_\mu$ with $E_\nu \in [0.6 - 7]$ GeV
(T2K: ~ 0.6 GeV, NO ν A: ~ 2 GeV,
MINOS: ~ 3 GeV)

- ▶ The baseline is ~ 100 km
(T2K: ~ 295 km, NO ν A: ~ 810 km
MINOS: ~ 735 km)

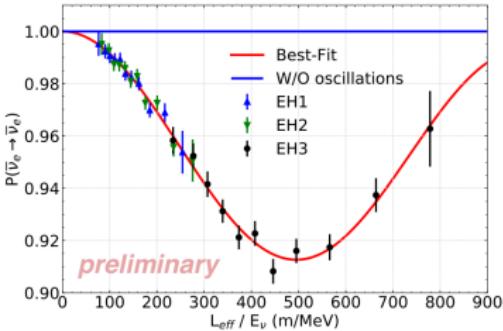
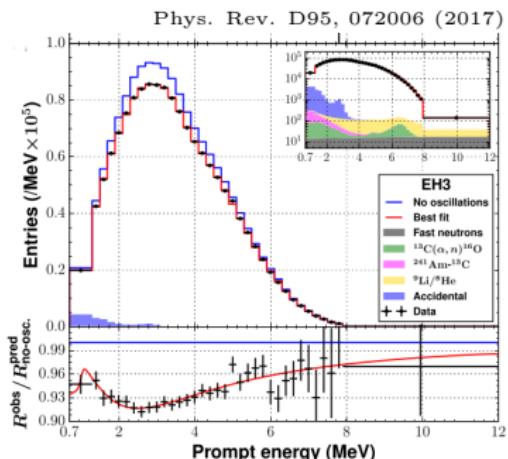
- ▶ $\nu_\mu \rightarrow \nu_\mu$ (T2K, NO ν A, MINOS),
 $\nu_\mu \rightarrow \nu_e$ (MINOS)



Terrestrial experiments

Reactor experiments

- ▶ $\bar{\nu}_e$ emitted from fission reactions;
- ▶ the energy spectrum expand from 1.8 MeV to 8 MeV;
- ▶ baselines ~ 1 Km;
- ▶ insensitive to matter effects;
- ▶ determine with high precision θ_{13} and Δm_{31}^2 .



NSI formalism in the Earth

We parametrize the matter potential as

$$V_{mat} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\tau\mu} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} = U_{mat} D_{mat} U_{mat}^\dagger$$

- ▶ $D_{mat} = \sqrt{2}G_F N_e(x) diag(\epsilon_{\oplus}, \epsilon'_{\oplus}, 0).$
- ▶ $U_{mat} = R(\psi_{12})R(\psi_{13})R(\psi_{23}, \delta_{NS}).$

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In order to simplify the analysis:

- We impose $\epsilon'_\oplus = 0$ (weak constraints)

$$D_{mat} = \sqrt{2}G_F N_e(x) \text{diag}(\epsilon_\oplus, 0, 0)$$

- If $\epsilon'_\oplus \rightarrow 0$, U_{mat} is independent of ψ_{23} and δ_{NS}

$$U_{mat} = R(\psi_{12})R(\psi_{13})$$

NSI formalism in the Earth

We parametrize the matter potential as

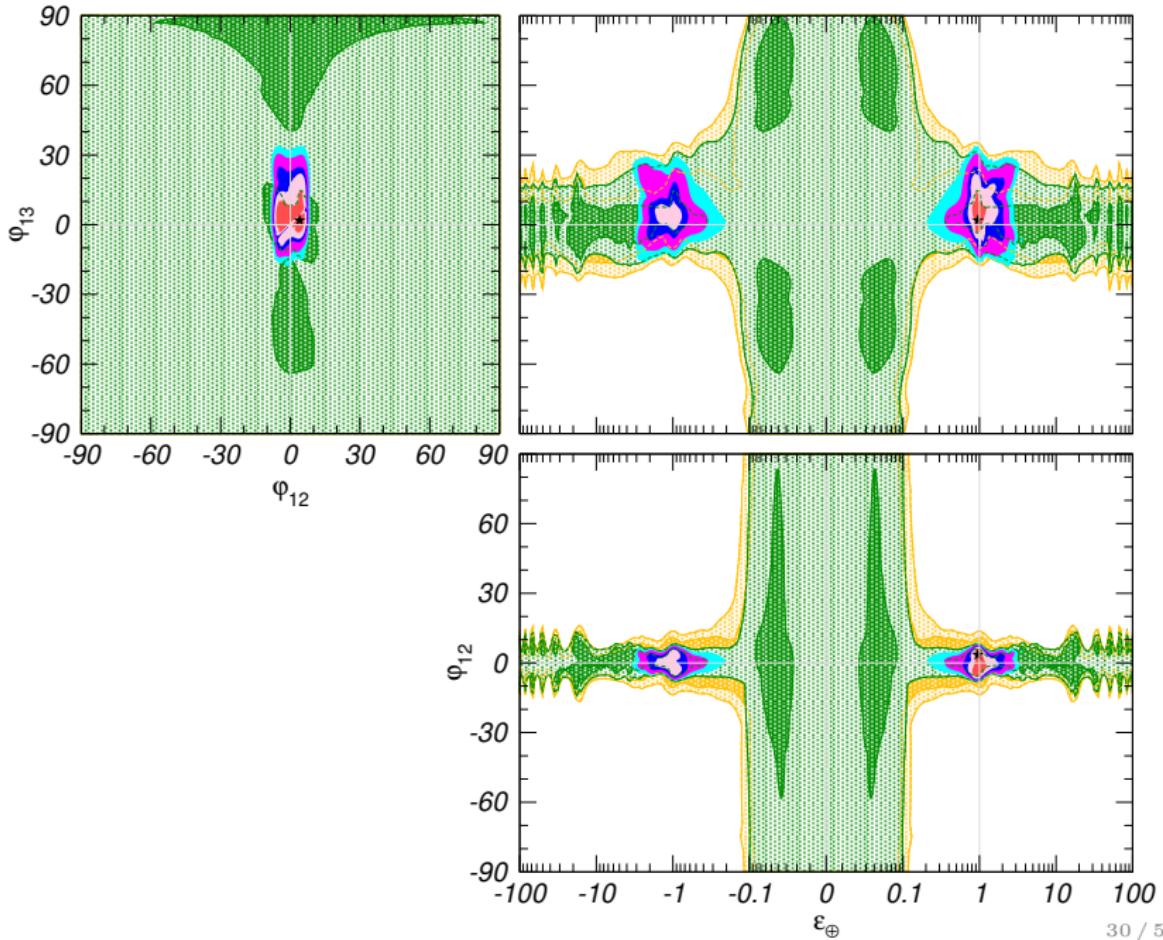
$$V_{mat} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\tau\mu} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} = U_{mat} D_{mat} U_{mat}^\dagger$$

- ▶ Setting $N_n/N_e = Y_n(x) = Y_n^\oplus = 1.051$

$$\epsilon_{\alpha\beta}^\oplus = \sqrt{5}(\cos \eta + Y_n^\oplus \sin \eta) \epsilon_{\alpha\beta}^\eta$$

- ▶ The bounds over $\epsilon_{\alpha\beta}^\oplus$ are independent of η .
- ▶ $\eta = \arctan(-1/Y_n^\oplus)$ the NSI contribution vanish.

Results from the global analysis

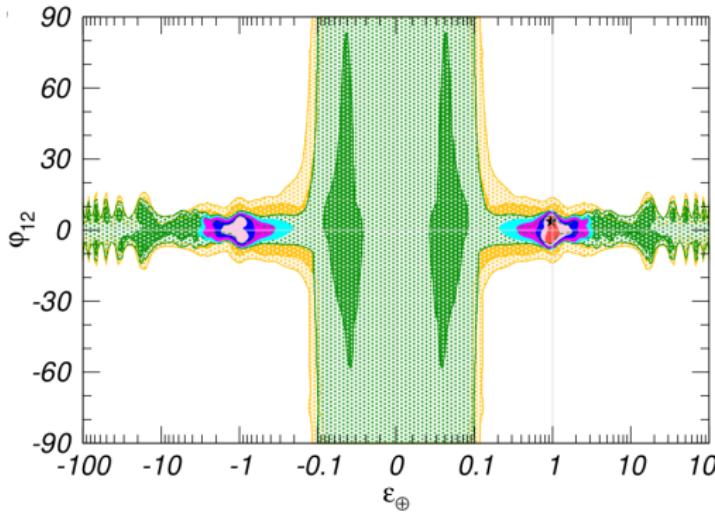


Results from the global analysis

- ▶ No bounds over ϵ_{\oplus} due to the lack of matter effect on the ν_e sector.
- ▶ The main sensitivity for $|\epsilon_{\oplus}| \sim 0.1 - 1$ comes from IceCube data

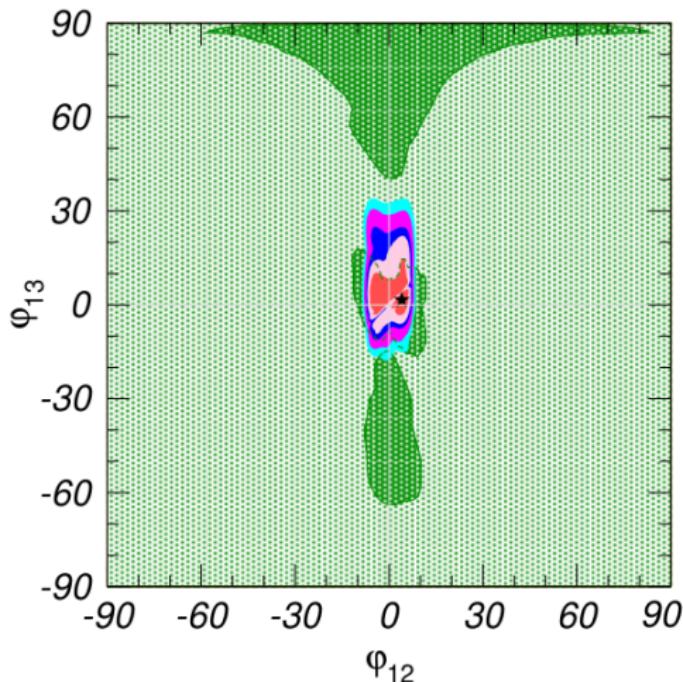
$$P_{\mu\mu} \simeq 1 - \sin^2 2\varphi_{\mu\mu} \sin^2 \left(\frac{d_e(\Omega_\nu) \epsilon_{\oplus}}{2} \right)$$

$$\sin^2 \varphi_{\mu\mu} = \sin^2 \varphi_{12} \cos^2 \varphi_{13}$$



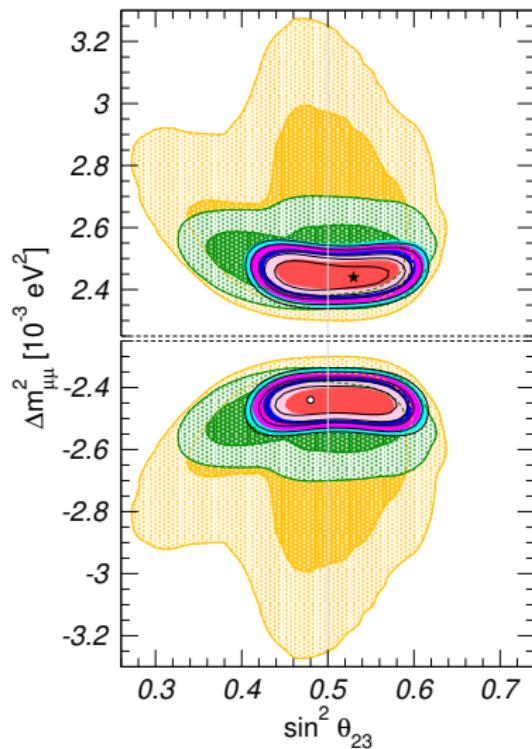
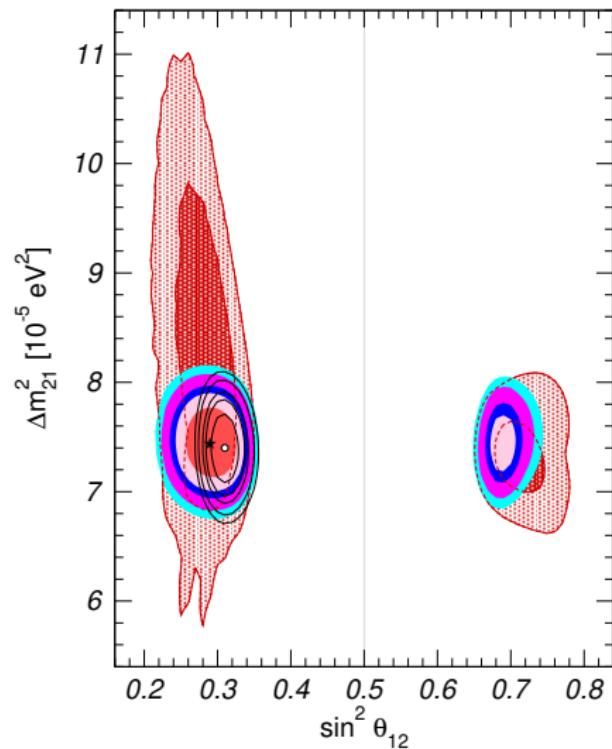
Results from the global analysis

- ▶ No bounds on the $(\varphi_{12}, \varphi_{13})$ plane.
- ▶ Bounds on $(\varphi_{12}, \varphi_{13})$ after considering solar and KamLAND
 - ▶ Introduce sensitivity to ν_e



Results from the global analysis

The results rely on the complementarity and synergies between the different data sets.



Results from the global analysis

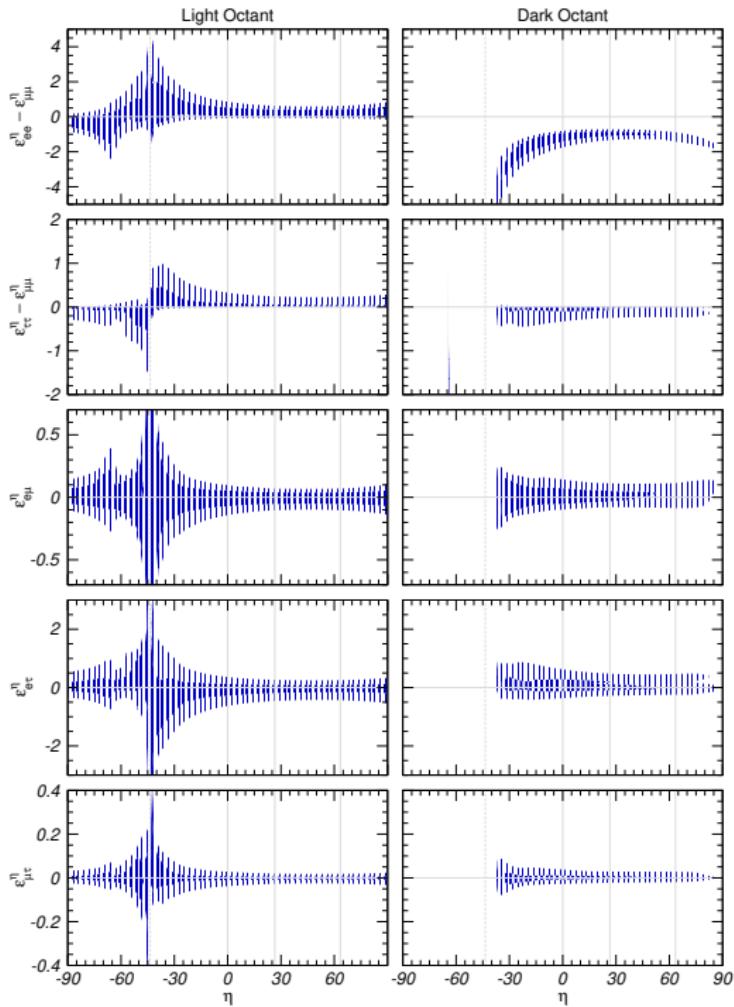
$$\epsilon_{ee}^p - \epsilon_{\mu\mu}^p \in [-3.3, -1.9]$$

$$\epsilon_{\tau\tau}^p - \epsilon_{\mu\mu}^p \in [-0.4, 0.4]$$

$$\epsilon_{e\mu}^p \in [-0.18, 0.18]$$

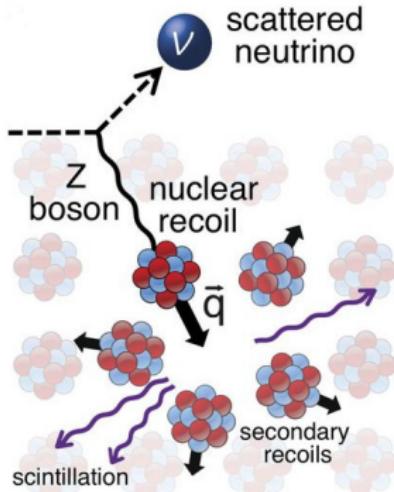
$$\epsilon_{e\tau}^p \in [-0.95, 0.95]$$

$$\epsilon_{\mu\tau}^p \in [-0.035, 0.035]$$



Coherent Elastic Scattering

- ▶ COHERENT report the observation of coherent neutrino-nucleus scattering at 6.7σ [1].
- ▶ Neutrino flux created by pion decay at rest ($\pi^+ \rightarrow \mu^+ \nu_\mu$)
 - ▶ Monocromatic ν_μ flux with $E_\nu \sim 30$
 - ▶ Continuous spectrum of $\bar{\nu}_\mu$ and ν_e from μ^+ decay
- ▶ Establish additional bounds on NSI-NC to oscillation experiments.



[1] Science 357 (2017) no.6356, 1123-1126

COHERENT data analysis

- ▶ The number of events

$$N_{NSI} = \gamma [f_{\nu_e} Q_{we}^2 + (f_{\nu_\mu} + f_{\nu_{\bar{\mu}}}) Q_{w\mu}^2]$$

- ▶ $Q_{w\alpha}^2$ encode the coupling with NSI

$$Q_{w\alpha}^2 \sim \left[(g_p^V + Y_n^{coh} g_n^V) + \epsilon_{\alpha\alpha}^{coh} \right]^2 + \sum_{\beta \neq \alpha} (\epsilon_{\alpha\beta}^{coh})^2$$

- ▶ COHERENT data set independent bounds on the diagonal NSI couplings ($\epsilon_{\alpha\alpha}$).

COHERENT data analysis

- ▶ $Q_{w\alpha}^2$ encode the coupling with NSI

$$Q_{w\alpha}^2 \sim \left[(g_p^V + Y_n^{coh} g_n^V) + \epsilon_{\alpha\alpha}^{coh} \right]^2 + \sum_{\beta \neq \alpha} (\epsilon_{\alpha\beta}^{coh})^2$$

- ▶ The NSI coupling for COHERENT analysis

$$\epsilon_{\alpha\beta}^{coh} = \sqrt{5}(\cos \eta + Y_n^{coh} \sin \eta) \epsilon_{\alpha\beta}^\eta$$

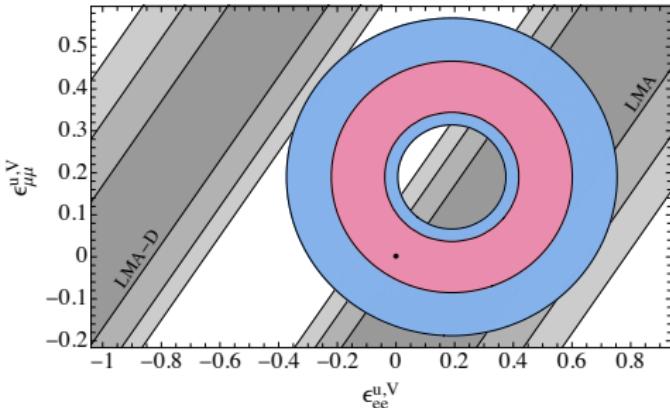
- ▶ Y_n^{coh} is the average between N_{Cs}/Z_{Cs} and N_I/Z_I
- ▶ The bounds on $\epsilon_{\alpha\beta}^{coh}$ are independent of η .
- ▶ For $\eta = \arctan(-1/Y_n^{coh}) \approx -35.4^\circ$

COHERENT curtail the LMA-D solution

Phys.Rev. D96 (2017) no.11, 115007

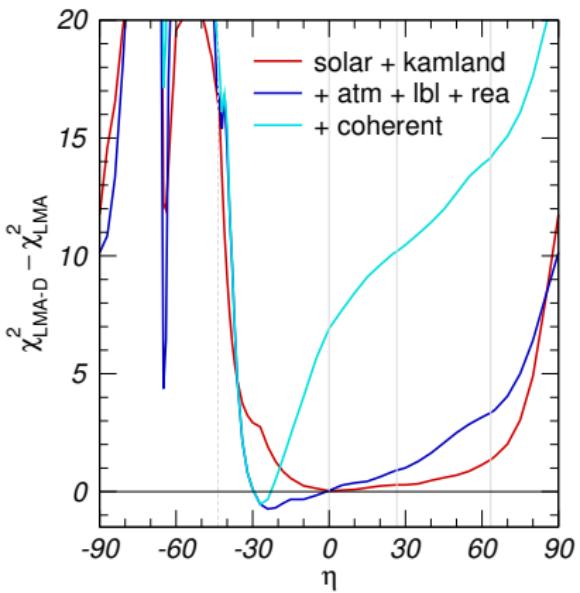
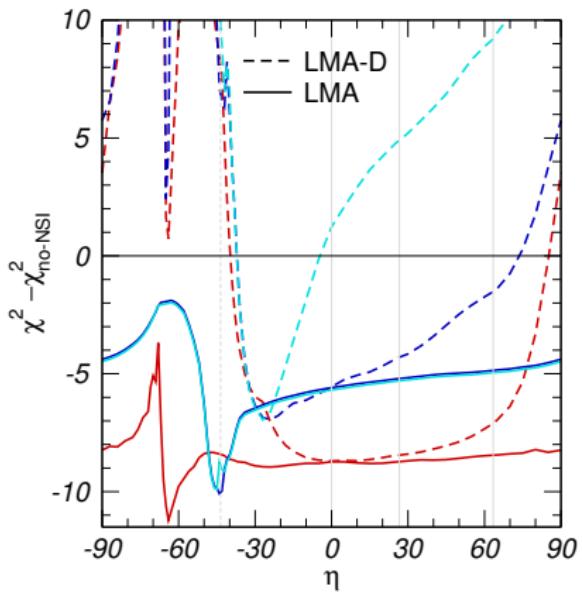
- ▶ Oscillation experiments shows a degeneracy in the $\epsilon_{\mu\mu} - \epsilon_{ee}$ plane;
- ▶ COHERENT constraints the NSI couplings accordings to

$$Q_{w\alpha}^2 \sim \left[(g_p^V + Y_n^{coh} g_n^V) + \epsilon_{\alpha\alpha}^{coh} \right]^2 + \sum_{\beta \neq \alpha} (\epsilon_{\alpha\beta}^{coh})^2$$



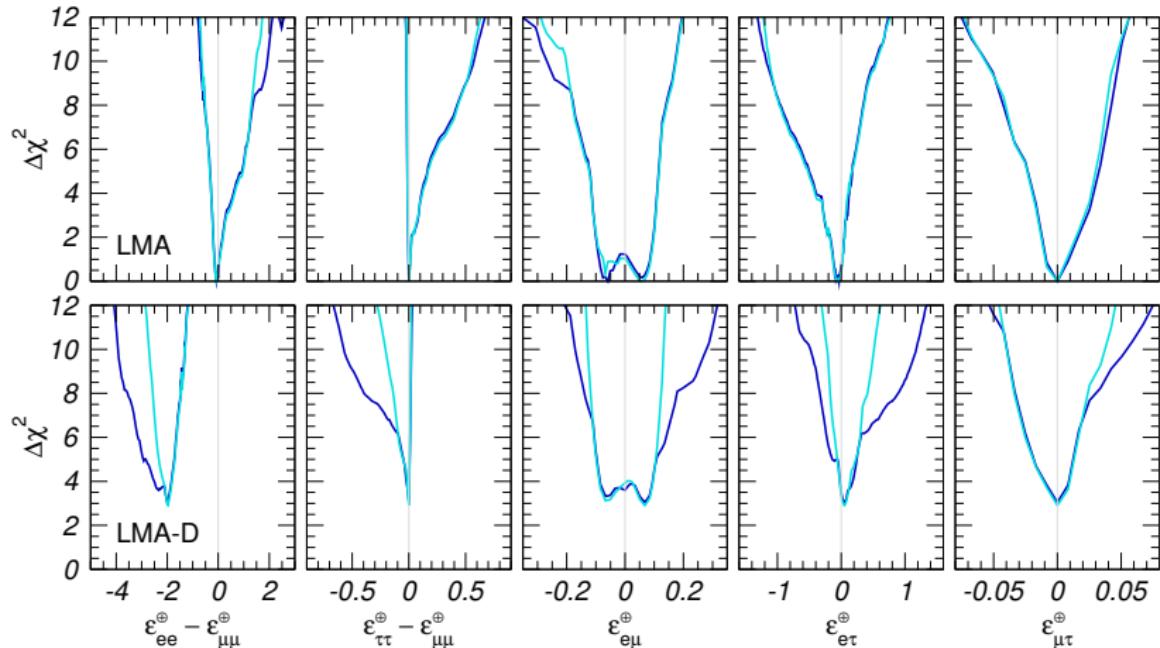
Combined analysis of oscillation and COHERENT

- LMA-D solution is strongly disfavor when COHERENT is included.



Combined analysis of oscillation and COHERENT

- ▶ Non-diagonal couplings are also reduced.

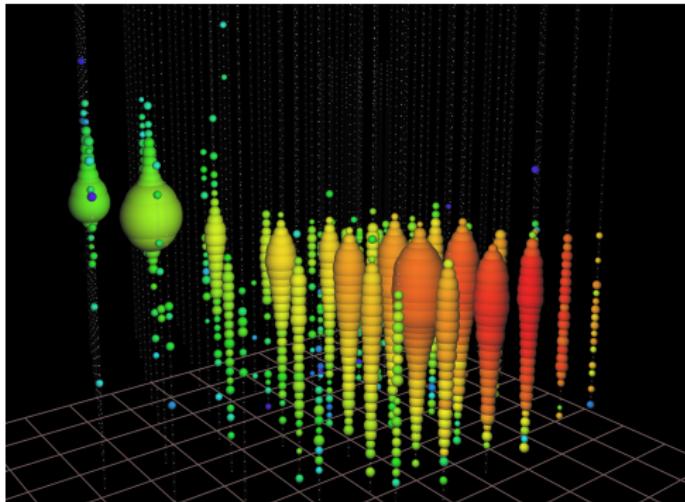


Which other neutrino sources can be used to observe NSI-NC?

Based on: M.C. Gonzalez-Garcia, M. Maltoni, IMS, N. Song, Astropart.Phys. 84 (2016) 15-22 (2016-11)

Astrophysical neutrinos

At very high energies ($E_\nu > 1$ TeV), neutrino evolution through the Earth is dominated by the matter effects.



The flavor of astrophysical neutrinos can be modified in the presence of NSI.

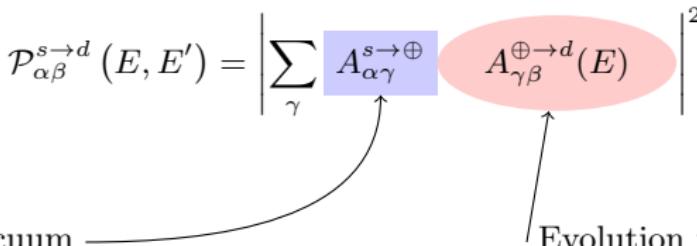
Neutrino fluxes at the detector

$$\phi_{\beta}^d(E) = \sum_{\alpha} \int dE' \mathcal{P}_{\alpha\beta}^{s \rightarrow d}(E, E') \phi_{\alpha}^s(E')$$

$$\mathcal{P}_{\alpha\beta}^{s \rightarrow d}(E, E') = \left| \sum_{\gamma} A_{\alpha\gamma}^{s \rightarrow \oplus} \cdot A_{\gamma\beta}^{\oplus \rightarrow d}(E) \right|^2$$

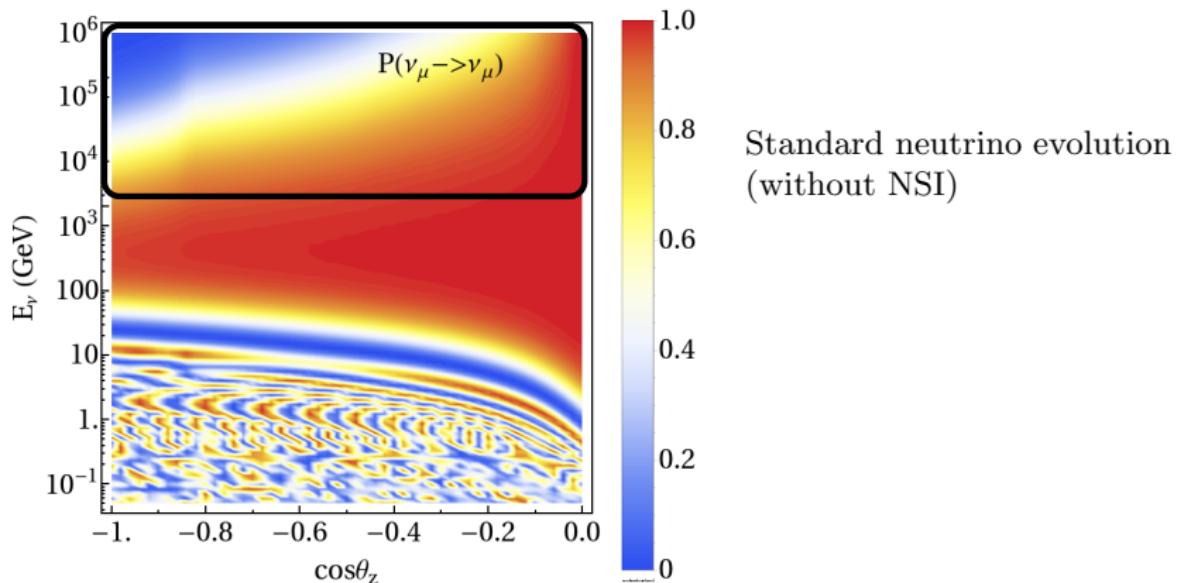
Evolution in vacuum —————

Evolution through the Earth



Neutrino fluxes at the detector

For $E_\nu > 10^5$ GeV neutrino evolution in the Earth is dominated by the inelastic interactions ($F_{\gamma\beta}^{\oplus \rightarrow d}(E, E')$)



Neutrino fluxes at the detector

- ▶ Attenuation is the dominant effect
- ▶ For most energies there is a small dependence with the flavor

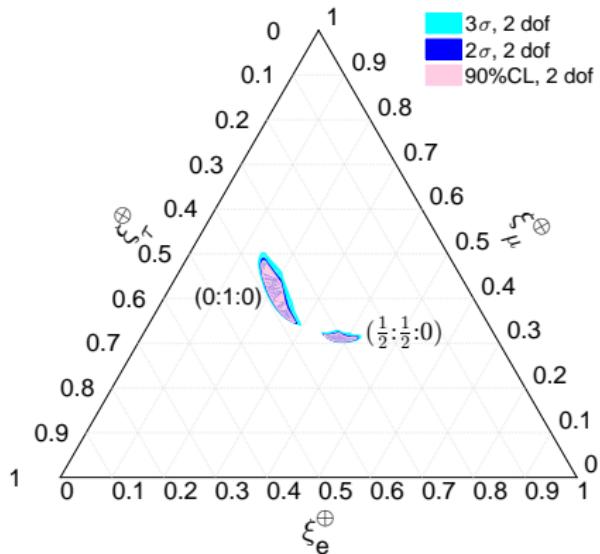
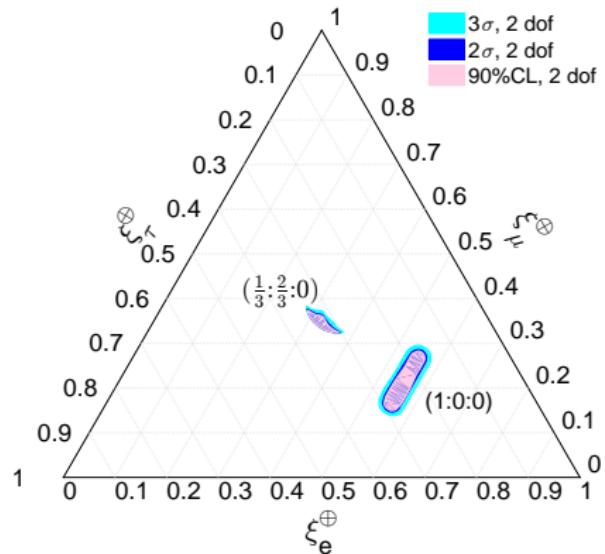
$$F_{\gamma\beta}^{\oplus \rightarrow d}(E, E') \simeq \delta_{\gamma\beta} F_{att}^{\oplus \rightarrow d} \delta(E - E')$$

$$\mathcal{P}_{\alpha\beta}^{s \rightarrow d}(E, E') \simeq \left| \sum_{\gamma} A_{\alpha\gamma}^{s \rightarrow \oplus} A_{\gamma\beta}^{\oplus \rightarrow d}(E) \right|^2 F_{att}^{\oplus \rightarrow d} \delta(E - E')$$

Results: Standard oscillation

Flavor ratio reconstructed at the earth's surface $\xi_{\beta}^{\oplus, rec} = \phi_{\beta}^{\oplus, rec} / \sum_{\gamma} \phi_{\gamma}^{\oplus, rec}$

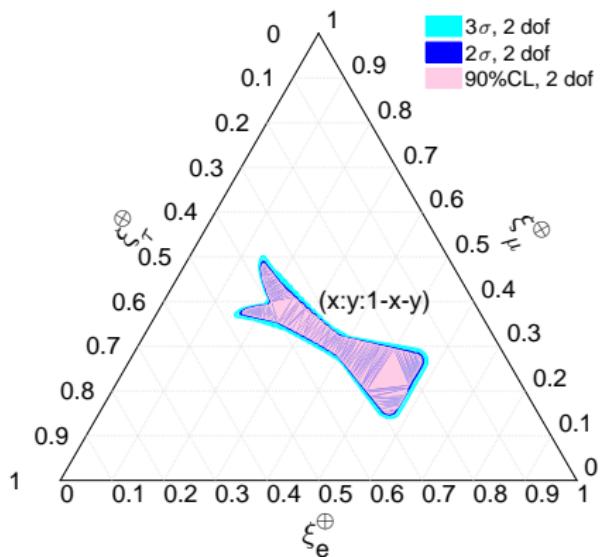
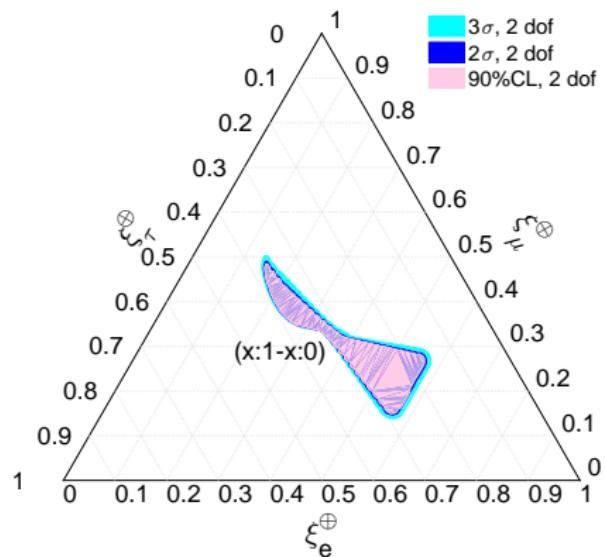
$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2$$



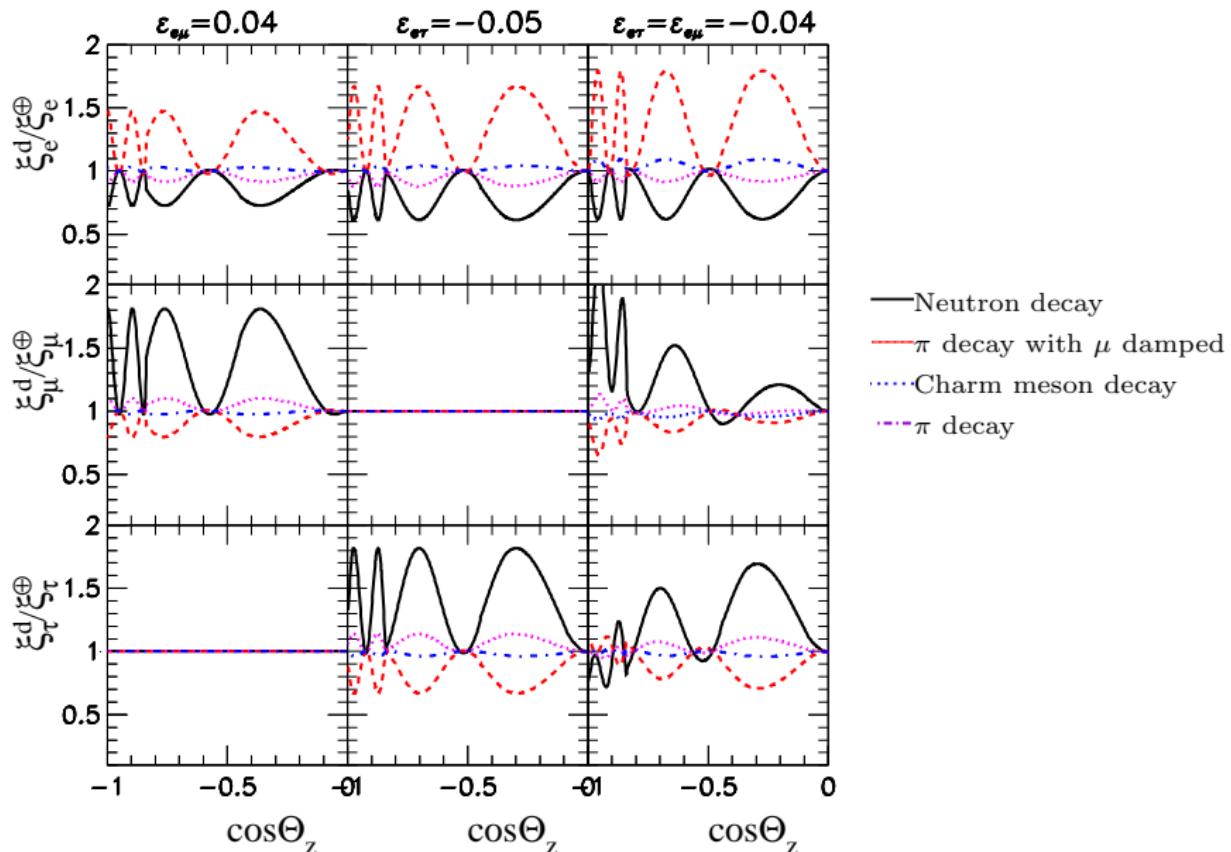
Results: Standard oscillation

Several production processes in the source

$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2$$



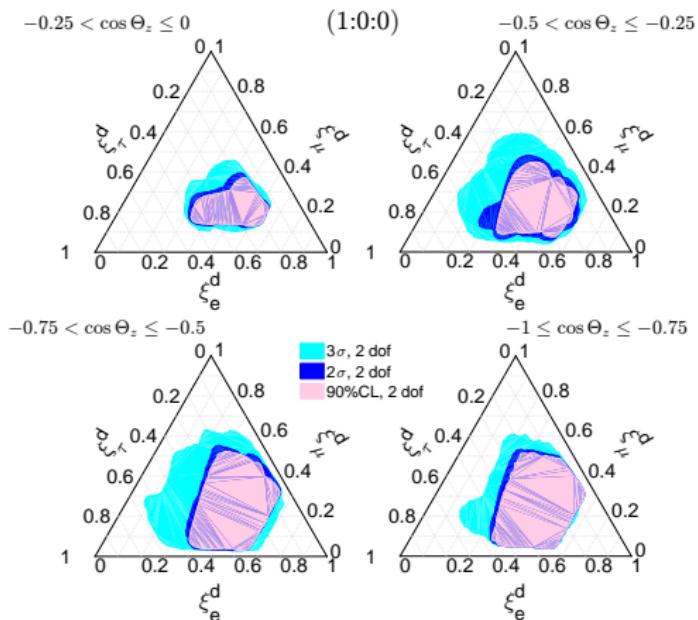
NSI in the earth



Flavor ratios in presence of NSI

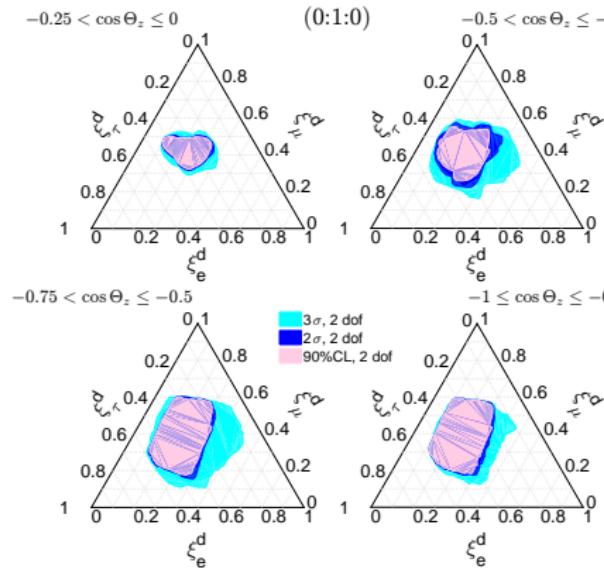
Neutron decay.

- ▶ The range of flavor ratios increase.
- ▶ The largest values of $\epsilon_{\alpha\beta}$ averaged out.

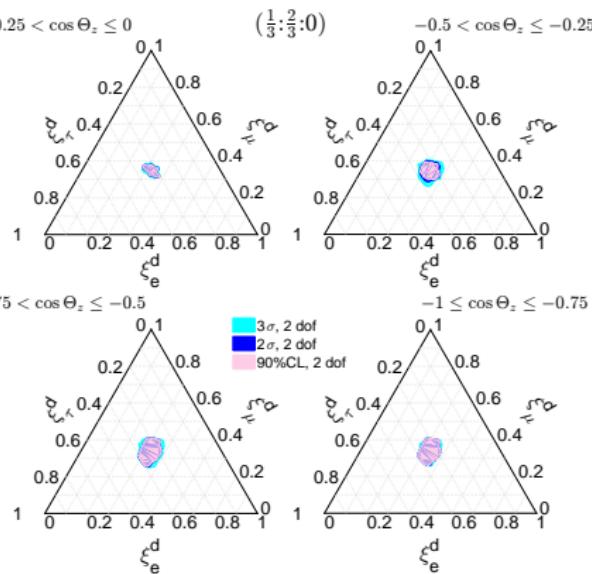


Flavor ratios in presence of NSI

Single μ -flavor flux.



π decay.



Conclusions

- ▶ We present an updated constraints over the size and the flavor structure of NSI-NC.
- ▶ In the analysis we combine the information of a global oscillation analysis with the recent results of COHERENT.
- ▶ LMA-D is allowed at 3σ for $-38^\circ \leq \eta \leq 14^\circ$.
- ▶ $|\epsilon_{\alpha\alpha}^p| \sim 2$ and $|\epsilon_{\alpha\beta}^p| \sim 0.8$
- ▶ Quantification of the astrophysical neutrino flavor modification in the presence of NSI

Thank you!

Backup: matter potential in the Sun and for KamLAND

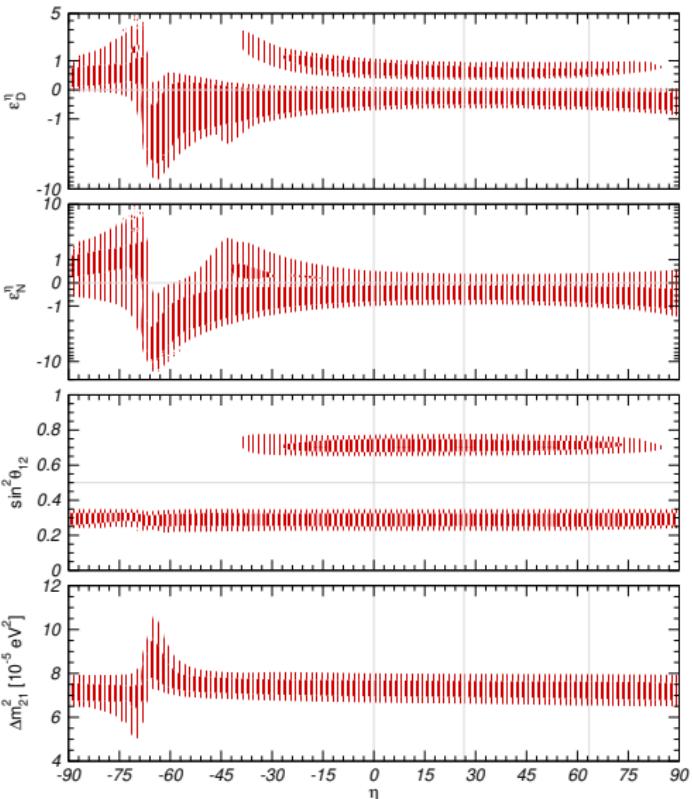
Relation between the solar effective parameters and $\epsilon_{\alpha\beta}^\eta$.

$$\begin{aligned}\varepsilon_D^\eta = & c_{13}s_{13} \operatorname{Re}(s_{23}\varepsilon_{e\mu}^\eta + c_{23}\varepsilon_{e\tau}^\eta) - (1 + s_{13}^2)c_{23}s_{23} \operatorname{Re}(\varepsilon_{\mu\tau}^\eta) \\ & - \frac{c_{13}^2}{2}(\varepsilon_{ee}^\eta - \varepsilon_{\mu\mu}^\eta) + \frac{s_{23}^2 - s_{13}^2c_{23}^2}{2}(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta),\end{aligned}$$

$$\varepsilon_N^\eta = c_{13}(c_{23}\varepsilon_{e\mu}^\eta - s_{23}\varepsilon_{e\tau}^\eta) + s_{13} \left[s_{23}^2\varepsilon_{\mu\tau}^\eta - c_{23}^2\varepsilon_{\mu\tau}^{f,V*} + c_{23}s_{23}(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta) \right].$$

Backup: solar and KamLAND

- ▶ For $-70^\circ \leq \eta \leq -60^\circ$ NSI contribution to the matter potential in the Sun almost vanish.
 - ▶ Small constraint from solar data to NSI in that η range.
 - ▶ NSI parameters can take higher values.
- ▶ NSI can modify the neutrino propagation in KamLAND and so the determination of Δm_{21}^2 .
 - ▶ The best agreement between KamLAND and the solar determination of Δm_{21}^2 is found for $\eta = -64^\circ$



OSC			+COHERENT		
	LMA	LMA \oplus LMA-D		LMA	LMA \oplus LMA-D
$\varepsilon_{ee}^u - \varepsilon_{\mu\mu}^u$	$[-0.020, +0.456]$	$\oplus [-1.192, -0.802]$	ε_{ee}^u	$[-0.008, +0.618]$	$[-0.008, +0.618]$
$\varepsilon_{\tau\tau}^u - \varepsilon_{\mu\mu}^u$	$[-0.005, +0.130]$	$[-0.152, +0.130]$	$\varepsilon_{\mu\mu}^u$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
$\varepsilon_{e\mu}^u$	$[-0.060, +0.049]$	$[-0.060, +0.067]$	$\varepsilon_{\tau\tau}^u$	$[-0.110, +0.404]$	$[-0.110, +0.404]$
$\varepsilon_{e\tau}^u$	$[-0.292, +0.119]$	$[-0.292, +0.336]$	$\varepsilon_{e\mu}^u$	$[-0.060, +0.049]$	$[-0.060, +0.049]$
$\varepsilon_{\mu\tau}^u$	$[-0.013, +0.010]$	$[-0.013, +0.014]$	$\varepsilon_{e\tau}^u$	$[-0.248, +0.116]$	$[-0.248, +0.116]$
$\varepsilon_{ee}^d - \varepsilon_{\mu\mu}^d$	$[-0.027, +0.474]$	$\oplus [-1.232, -1.111]$	$\varepsilon_{\mu\mu}^d$	$[-0.103, +0.361]$	$[-0.103, +0.361]$
$\varepsilon_{\tau\tau}^d - \varepsilon_{\mu\mu}^d$	$[-0.005, +0.095]$	$[-0.013, +0.095]$	$\varepsilon_{\tau\tau}^d$	$[-0.102, +0.361]$	$[-0.102, +0.361]$
$\varepsilon_{e\mu}^d$	$[-0.061, +0.049]$	$[-0.061, +0.073]$	$\varepsilon_{e\mu}^d$	$[-0.058, +0.049]$	$[-0.058, +0.049]$
$\varepsilon_{e\tau}^d$	$[-0.247, +0.119]$	$[-0.247, +0.119]$	$\varepsilon_{e\tau}^d$	$[-0.206, +0.110]$	$[-0.206, +0.110]$
$\varepsilon_{\mu\tau}^d$	$[-0.012, +0.009]$	$[-0.012, +0.009]$	$\varepsilon_{\mu\tau}^d$	$[-0.011, +0.009]$	$[-0.011, +0.009]$
$\varepsilon_{ee}^p - \varepsilon_{\mu\mu}^p$	$[-0.041, +1.312]$	$\oplus [-3.327, -1.958]$	ε_{ee}^p	$[-0.010, +2.039]$	$[-0.010, +2.039]$
$\varepsilon_{\tau\tau}^p - \varepsilon_{\mu\mu}^p$	$[-0.015, +0.426]$	$[-0.424, +0.426]$	$\varepsilon_{\mu\mu}^p$	$[-0.364, +1.387]$	$[-0.364, +1.387]$
$\varepsilon_{e\mu}^p$	$[-0.178, +0.147]$	$[-0.178, +0.178]$	$\varepsilon_{\tau\tau}^p$	$[-0.350, +1.400]$	$[-0.350, +1.400]$
$\varepsilon_{e\tau}^p$	$[-0.954, +0.356]$	$[-0.954, +0.949]$	$\varepsilon_{e\mu}^p$	$[-0.179, +0.146]$	$[-0.179, +0.146]$
$\varepsilon_{\mu\tau}^p$	$[-0.035, +0.027]$	$[-0.035, +0.035]$	$\varepsilon_{e\tau}^p$	$[-0.860, +0.350]$	$[-0.860, +0.350]$
			$\varepsilon_{\mu\tau}^p$	$[-0.035, +0.028]$	$[-0.035, +0.028]$

Backup: Combined analysis of oscillation and COHERENT

$$\epsilon_{ee}^p \in [-0.01, 2.0]$$

$$\epsilon_{\mu\mu}^p \in [-0.4, 1.4]$$

$$\epsilon_{\mu\mu}^p \in [-0.35, 1.4]$$

$$\epsilon_{e\mu}^p \in [-0.18, 0.14]$$

$$\epsilon_{e\tau}^p \in [-0.86, 0.35]$$

$$\epsilon_{\mu\tau}^p \in [-0.035, 0.028]$$

