Global Fit Constraints on NSI

Iván Martínez Soler

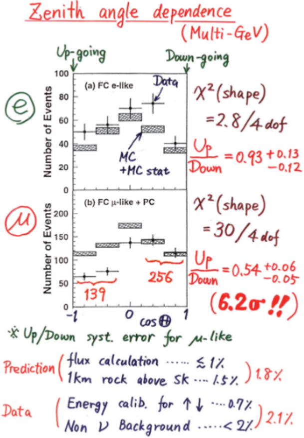
Based on paper: I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler,
J. Salvado, JHEP 1808 (2018) 180, arXiv:1805.04530.

NTN Workshop on Neutrino Non-Standard Interactions

May 29th, 2019

Motivation: 3ν mixing

- In SM, neutrinos are massless.



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

- The experiments established that neutrinos are massive particles.

Motivation: Neutrino Non-Standard Interactions

SM can be considered as a low energy effective model.

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

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

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

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

Motivation: Neutrino Non-Standard Interactions

SM can be considered as a low energy effective model.

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

- For $d = 5$. Weinberg operator.
- For $d = 6$. NSI
- We will focus

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

Motivation: NSI-NC

Described by effective four-fermion operators

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- 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

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- Not gauge invariant
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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]

Motivation: NSI-NC

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

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

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

Motivation: NSI-NC

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

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

$$\epsilon_{\alpha\beta}(x) = \epsilon^p_{\alpha\beta} + Y_n(x)\epsilon^n_{\alpha\beta} \qquad Y_n = N_n(x)/N_e(x)$$

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

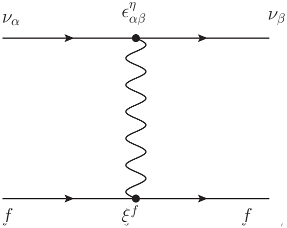
Motivation: NSI-NC

The results are obtained under the approximation

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

- $\epsilon^{\eta}_{\alpha\beta}$ 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

$$\epsilon^{p}_{\alpha\beta} = \sqrt{5}\epsilon^{\eta}_{\alpha\beta} \cos\eta \qquad \epsilon^{n}_{\alpha\beta} = \sqrt{5}\epsilon^{\eta}_{\alpha\beta} \sin\eta$$



Neutrino evolution in the presence of NSI

Neutrino evolution is described by the Schrödinger equation

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

Evolution in vacuum

Evolution throught the matter

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

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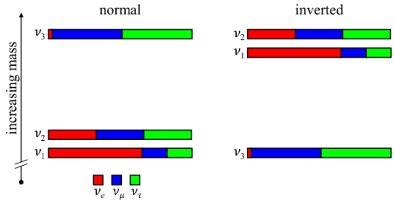
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\imath\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{\imath\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Depends on:
  - **three mixing angles** (θ_{12}, θ_{13}, θ_{23}) and a **complex phase** (δ_{cp});
  - **two mass splittings** ($\Delta m^2_{21} \sim 10^{-5} eV^2$ and $\Delta m^2_{31} \sim 10^{-3} eV^2$)
  - $\epsilon_{\alpha\beta}$: five real parameters and three phases.

Two possible mass hierarchies



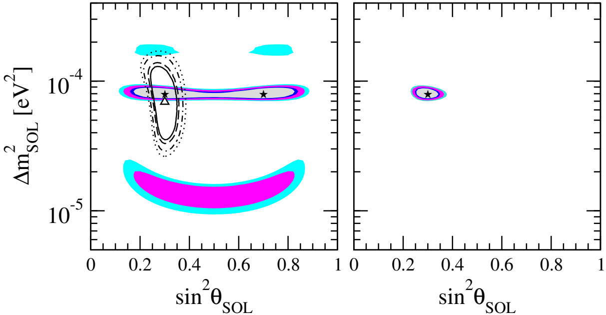
CPT symmetry

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

$$\begin{array}{rcl} \Delta m^2_{31} & \rightarrow & -\Delta m^2_{32} \\ \theta_{12} & \rightarrow & \pi/2 - \theta_{12} \\ \delta_{cp} & \rightarrow & \pi - \delta_{cp} \end{array}$$

- The degeneracy is broken in matter.

JHEP 0610 (2006) 008



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 $\epsilon_{\alpha\beta}$ indenpendent of x
- LMA-D solution.

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

Backup:Solar neutrinos and KamLAND in the presence of NSI

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

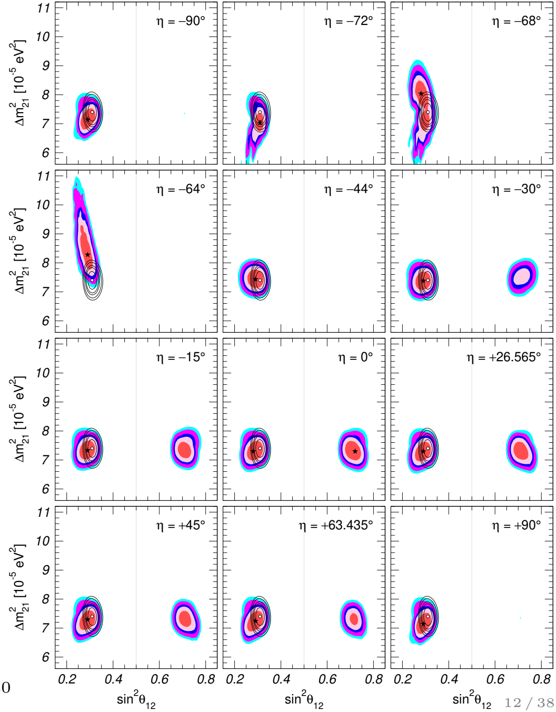
$$H^{eff}_{vac} = \frac{\Delta m^2_{21}}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} e^{i\delta_{cp}} \\ -\sin 2\theta_{12} e^{-i\delta_{cp}} & \cos 2\theta_{12} \end{pmatrix}$$

$$H^{eff}_{mat} = \sqrt{2} G_F N_e(x) \left[\begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix} + [\xi^p + Y_n(x)\xi^n] \begin{pmatrix} -\epsilon^\eta_D & \epsilon^\eta_N \\ \epsilon^{\eta *}_N & \epsilon^\eta_D \end{pmatrix} \right]$$

- NSI effects are described by the effective parameters ϵ^η_D and ϵ^η_N
- Shows a high dependence of η.
- We assume real NSI

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.



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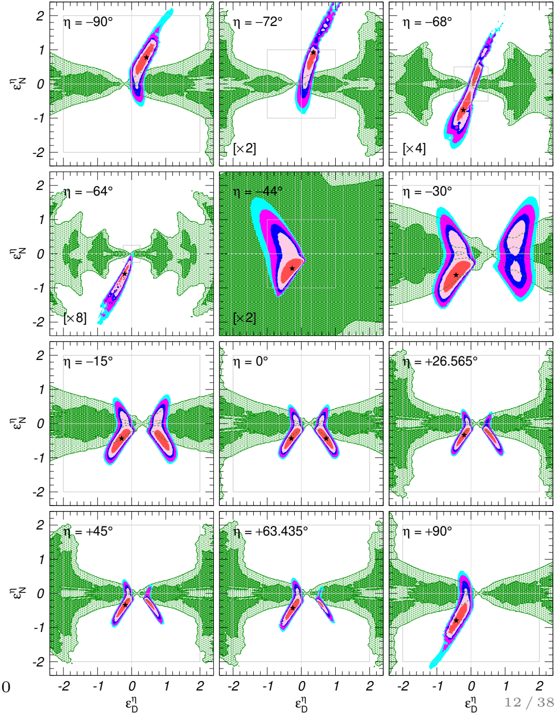
Solar and KamLAND

- 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 $\eta = \pm 90^\circ \rightarrow \epsilon_{\alpha\beta}^p = 0$
- $\epsilon_{\alpha\beta}^f \geq 1$



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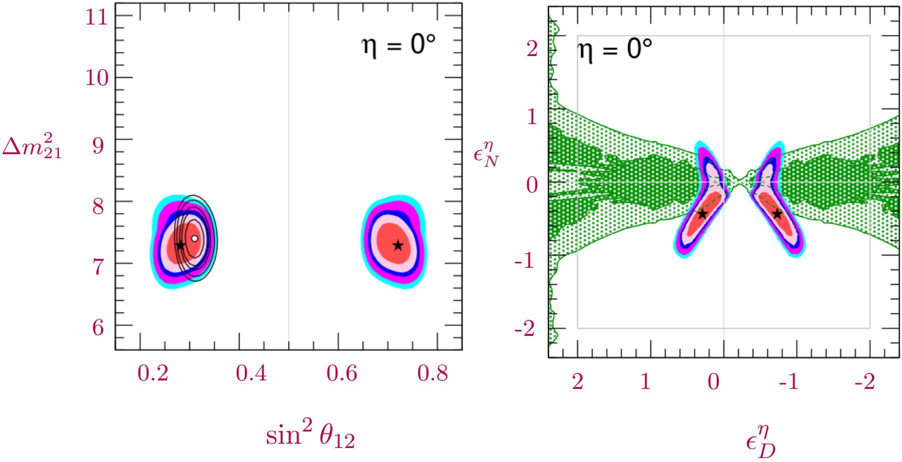
Solar and KamLAND

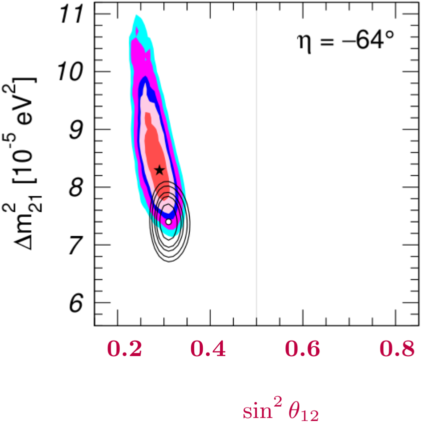
- For $\eta = 0 \to \epsilon^n_{\alpha\beta} = 0$
- The degeneracy is exact.

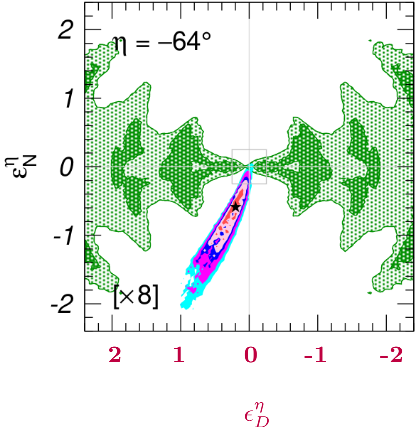


Solar and KamLAND

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

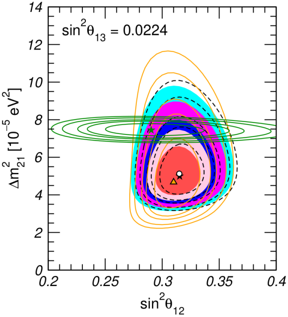
$$\epsilon_{\alpha\beta}(x) = \epsilon^p_{\alpha\beta}(x) + Y_n \epsilon^n_{\alpha\beta}(x) \to 0$$

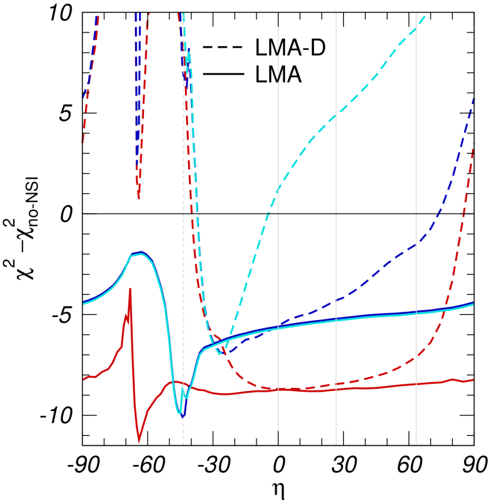




Solar and KamLAND

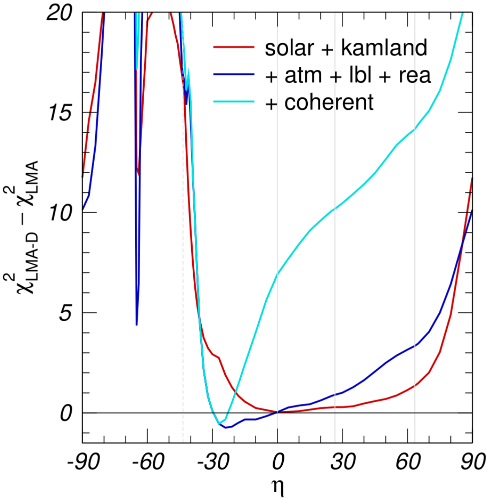
- NSI improves the agreement berween solar and KamLAND.
  - The tension in Δm^2_{21} is reduced in the whole η range ($\sim 2.5\sigma$).





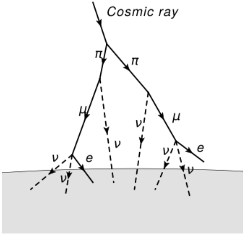
Solar and KamLAND

- 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

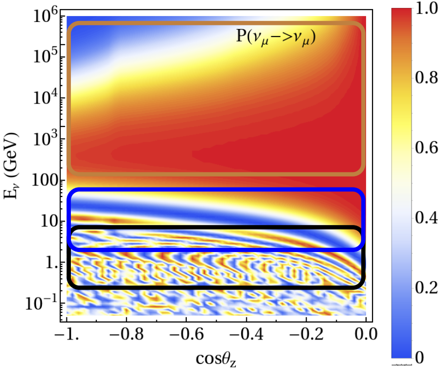
Atmospheric neutrinos.



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

$$\begin{aligned}\pi^{\pm} &\rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}})\\ K^{\pm} &\rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}})\\ \mu^{\pm} &\rightarrow e^{\pm} + \nu_{e}(\overline{\nu_{e}}) + \nu_{\mu}(\overline{\nu_{\mu}})\end{aligned}$$

- 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)



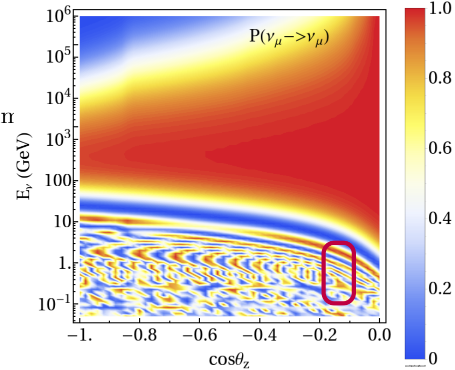
Terrestrial experiments

Long-baseline accelerators

- $\nu_e/\overline{\nu}_e$ and $\nu_\mu/\overline{\nu}_\mu$ with $E_\nu \in [0.6 - 7]$ GeV (T2K:~ 0.6 GeV, NOνA: ~ 2 GeV, MINOS: ~ 3 GeV)

- The baseline is ~ 100 km (T2K:~ 295 km, NOνA: ~ 810 km
MINOS: ~ 735 km)

- $\nu_\mu \to \nu_\mu$ (T2K, NOνA, MINOS), $\nu_\mu \to \nu_e$ (MINOS)

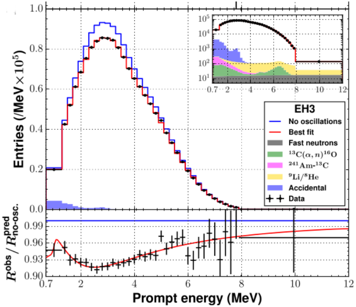


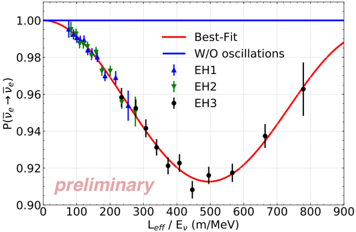
Terrestrial experiments

Reactor experiments

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

Phys. Rev. D95, 072006 (2017)





NSI formalism in the Earth

We parametrize the matter potential as

$$V_{mat} = \sqrt{2} G_F N_e(x) \left(\begin{array}{ccc} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\tau\mu} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{array} \right) = Q_{rel} U_{mat} D_{mat} U^\dagger_{mat} Q^\dagger_{rel}$$

- $D_{mat} = \sqrt{2} G_F N_e(x) diag(\epsilon_\oplus, \epsilon'_\oplus, 0)$.
- $U_{mat} = R(\psi_{12}) R(\psi_{13}) R(\psi_{23}, \delta_{NS})$.
- $Q_{rel} = diag(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i(\alpha_1+\alpha_2)})$.

NSI formalism in the Earth

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In order to simplify the analysis:

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

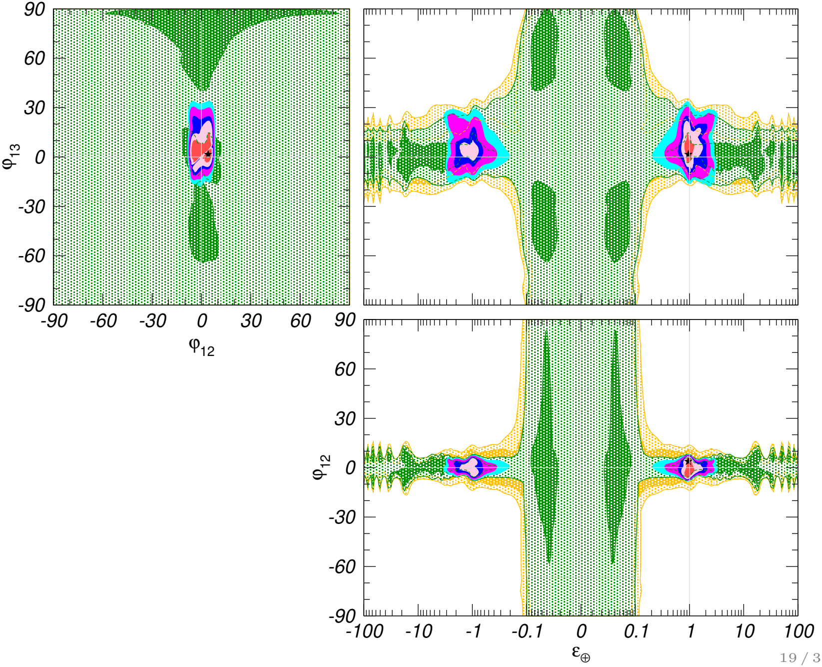
$$D_{mat} = \sqrt{2} G_F N_e(x) diag(\epsilon_\oplus, 0, 0)$$

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

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

- We assume real NSI, $\alpha_1 = \alpha_2 = 0$

Results from the global analysis

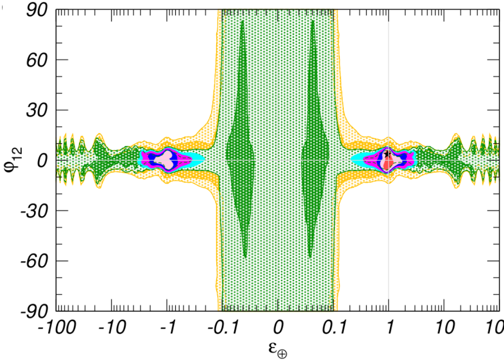


Results from the global analysis

- No bounds over $\epsilon_\oplus$ due to the lack of matter effect on the ν_e sector.
- No bounds on the $(\varphi_{12}, \varphi_{13})$ plane.
- The main sensitivity for $|\epsilon_\oplus| \sim 0.1 - 1$ comes from IceCube data

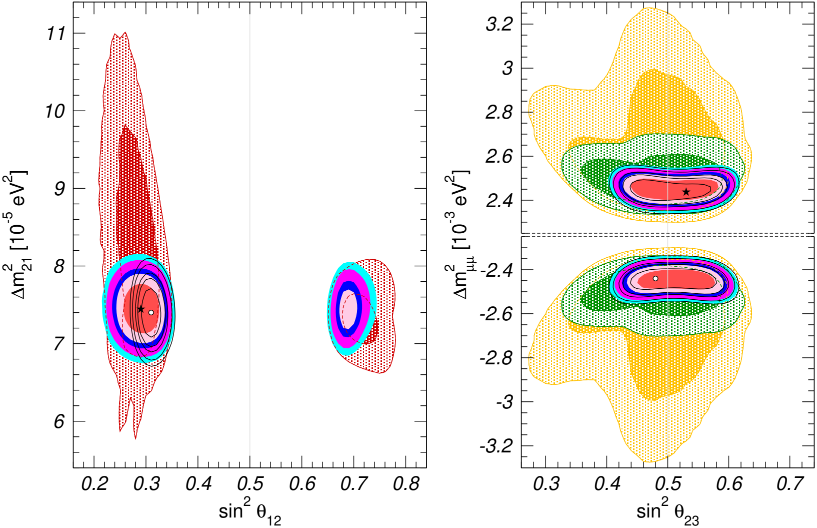
$$P_{\mu\mu} \simeq 1 - \sin^2 2\varphi_{\mu\mu} \sin^2\left(\frac{d_e(\Omega_\nu)\epsilon_\oplus}{2}\right)$$

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



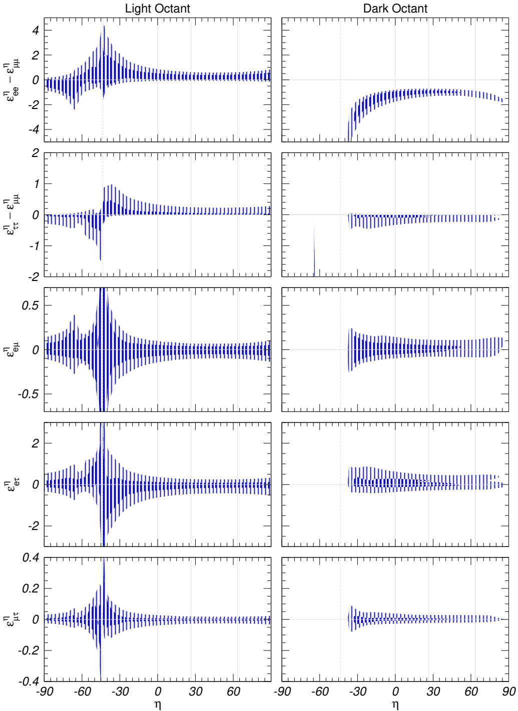
Results from the global analysis

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



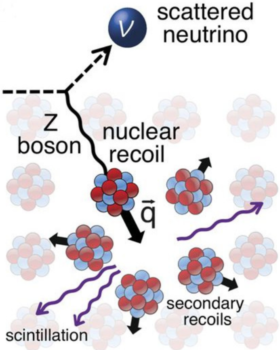
Results from the global analysis

$$\epsilon^p_{ee} - \epsilon^p_{\mu\mu} \in [-3.3, -1.9]$$
$$\epsilon^p_{\tau\tau} - \epsilon^p_{\mu\mu} \in [-0.4, 0.4]$$
$$\epsilon^p_{e\mu} \in [-0.18, 0.18]$$
$$\epsilon^p_{e\tau} \in [-0.95, 0.95]$$
$$\epsilon^p_{\mu\tau} \in [-0.035, 0.035]$$



Coherent Elastic Scattering

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



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

COHERENT data analysis

- The number of events

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

- $Q^2_{w\alpha}$ encode the coupling with NSI

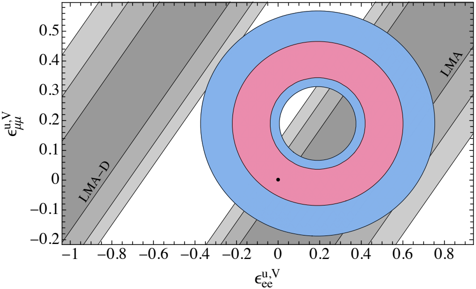
$$Q^2_{w\alpha} \sim \left[(g_p^V + Y_n^{coh} g_n^V) + \epsilon^{coh}_{\alpha\alpha} \right]^2 + \sum_{\beta \neq \alpha} (\epsilon^{coh}_{\alpha\beta})^2$$

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

COHERENT curtail the LMA-D solution

- Oscillation experiments shows a degeneracy in the $\epsilon_{\mu\mu} - \epsilon_{ee}$ plane;

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

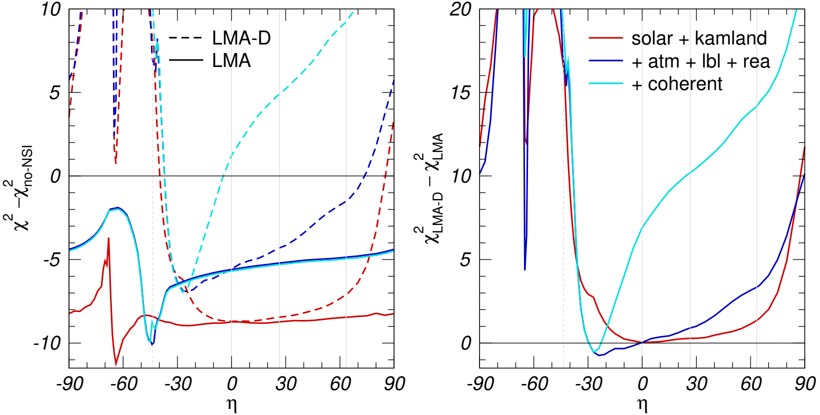


- COHERENT constraints the NSI couplings accordings to

$$Q^2_{w\alpha} \sim \left[(g^V_p + Y^{coh}_n g^V_n) + \epsilon^{coh}_{\alpha\alpha}\right]^2 + \sum_{\beta\neq\alpha} (\epsilon^{coh}_{\alpha\beta})^2$$

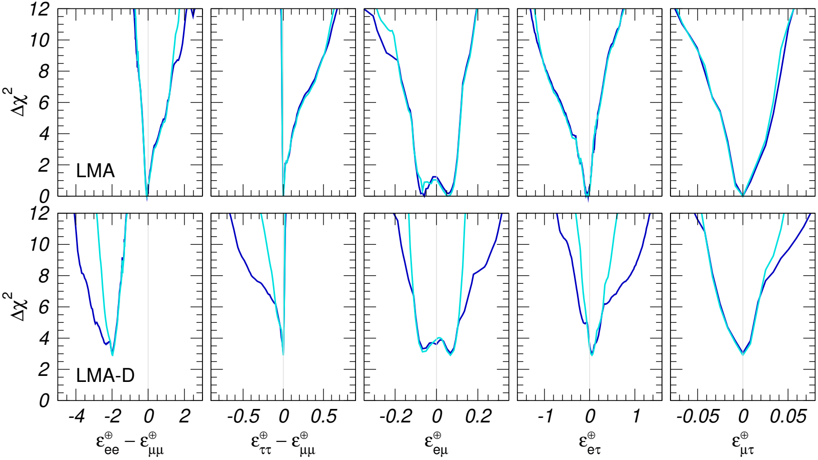
Combined analysis of oscillation and COHERENT

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



Combined analysis of oscillation and COHERENT

- Non-diagonal couplings are also reduced.



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 $-38^\circ \leq \eta \leq 14^\circ$.
- $|\epsilon^p_{\alpha\alpha}| \sim 2$ and $|\epsilon^p_{\alpha\beta}| \sim 0.8$

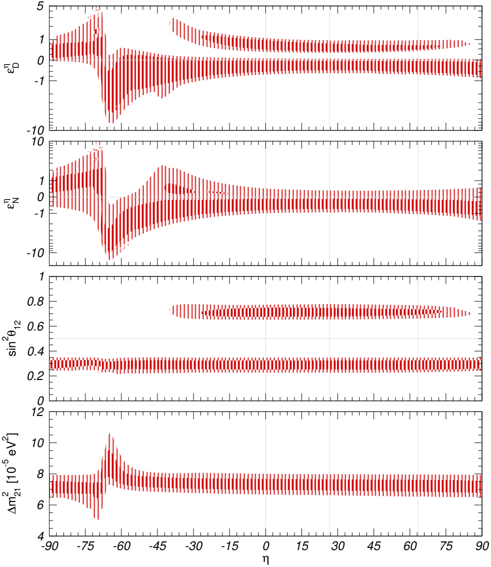
Thank you!

Backup: matter potential in the Sun and for KamLAND

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

$$\begin{aligned}
\varepsilon^{\eta}_{D} &= c_{13}s_{13}\ \mathrm{Re}\big(s_{23}\,\varepsilon^{\eta}_{e\mu} + c_{23}\,\varepsilon^{\eta}_{e\tau}\big) - \big(1 + s^{2}_{13}\big)\,c_{23}s_{23}\ \mathrm{Re}\big(\varepsilon^{\eta}_{\mu\tau}\big) \\
&\qquad - \frac{c^{2}_{13}}{2}\big(\varepsilon^{\eta}_{ee} - \varepsilon^{\eta}_{\mu\mu}\big) + \frac{s^{2}_{23} - s^{2}_{13}c^{2}_{23}}{2}\big(\varepsilon^{\eta}_{\tau\tau} - \varepsilon^{\eta}_{\mu\mu}\big)\,, \\
\varepsilon^{\eta}_{N} &= c_{13}\big(c_{23}\,\varepsilon^{\eta}_{e\mu} - s_{23}\,\varepsilon^{\eta}_{e\tau}\big) + s_{13}\left[s^{2}_{23}\,\varepsilon^{\eta}_{\mu\tau} - c^{2}_{23}\,\varepsilon^{f,V*}_{\mu\tau} + c_{23}s_{23}\big(\varepsilon^{\eta}_{\tau\tau} - \varepsilon^{\eta}_{\mu\mu}\big)\right].
\end{aligned}$$

Backup: solar and KamLAND

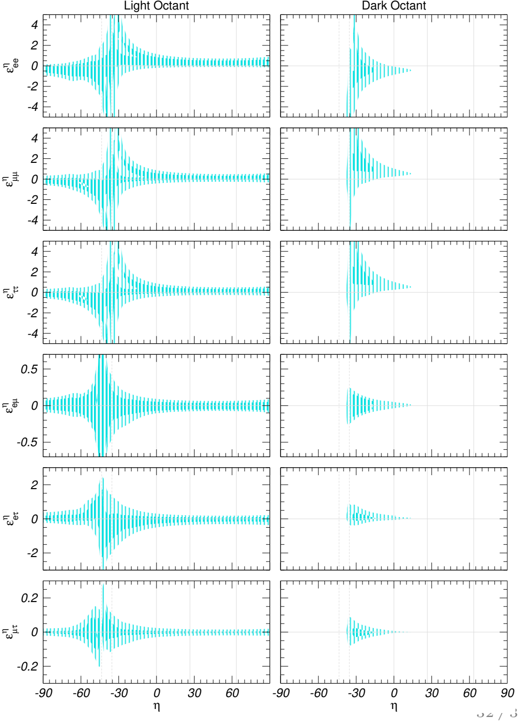


- For $-70^\circ \leq \eta \leq -60^\circ$ NSI contribution to the matter potential in the Sun almost vanish.
  - Small constraint from solar data to NSI in that η range.
  - NSI parameters can take higher values.
- NSI can modify the neutrino propagation in KamLAND and so the determination of Δm^2_{21}.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

OSC			+COHERENT		
	LMA	LMA $\oplus$ LMA-D		LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$	ε^u_{ee}	$[-0.008, +0.618]$	$[-0.008, +0.618]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$	$\varepsilon^u_{\mu\mu}$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
			$\varepsilon^u_{\tau\tau}$	$[-0.110, +0.404]$	$[-0.110, +0.404]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$	$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.049]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$	$\varepsilon^u_{e\tau}$	$[-0.248, +0.116]$	$[-0.248, +0.116]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$	$\varepsilon^u_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$	ε^d_{ee}	$[-0.012, +0.565]$	$[-0.012, +0.565]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$	$\varepsilon^d_{\mu\mu}$	$[-0.103, +0.361]$	$[-0.103, +0.361]$
			$\varepsilon^d_{\tau\tau}$	$[-0.102, +0.361]$	$[-0.102, +0.361]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$	$\varepsilon^d_{e\mu}$	$[-0.058, +0.049]$	$[-0.058, +0.049]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$	$\varepsilon^d_{e\tau}$	$[-0.206, +0.110]$	$[-0.206, +0.110]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$	$\varepsilon^d_{\mu\tau}$	$[-0.011, +0.009]$	$[-0.011, +0.009]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.041, +1.312]$	$\oplus[-3.327, -1.958]$	ε^p_{ee}	$[-0.010, +2.039]$	$[-0.010, +2.039]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$	$\varepsilon^p_{\mu\mu}$	$[-0.364, +1.387]$	$[-0.364, +1.387]$
			$\varepsilon^p_{\tau\tau}$	$[-0.350, +1.400]$	$[-0.350, +1.400]$
$\varepsilon^p_{e\mu}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$	$\varepsilon^p_{e\mu}$	$[-0.179, +0.146]$	$[-0.179, +0.146]$
$\varepsilon^p_{e\tau}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$	$\varepsilon^p_{e\tau}$	$[-0.860, +0.350]$	$[-0.860, +0.350]$
$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$	$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.028]$	$[-0.035, +0.028]$

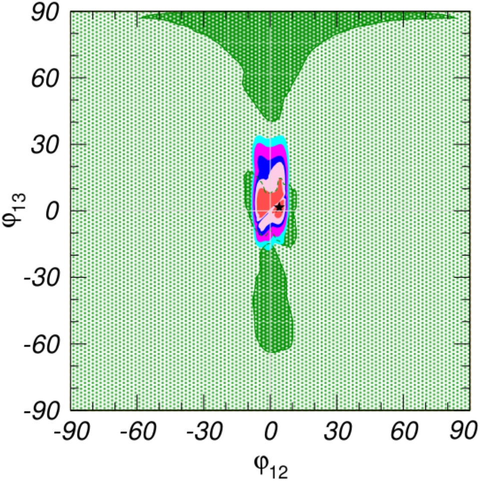
Backup: Combined analysis of oscillation and COHERENT

$$\epsilon^p_{ee} \in [-0.01, 2.0]$$
$$\epsilon^p_{\mu\mu} \in [-0.4, 1.4]$$
$$\epsilon^p_{\mu\mu} \in [-0.35, 1.4]$$
$$\epsilon^p_{e\mu} \in [-0.18, 0.14]$$
$$\epsilon^p_{e\tau} \in [-0.86, 0.35]$$
$$\epsilon^p_{\mu\tau} \in [-0.035, 0.028]$$



Backup: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

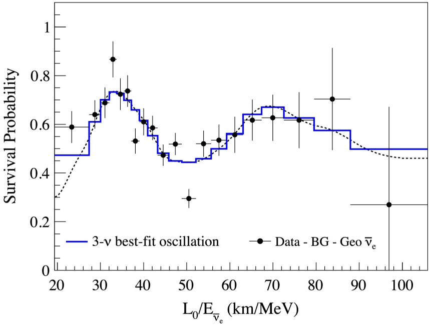


Backup: Tension in Δm^2_{21}

KamLAND

- Long-baseline reactor experiment;
- $\overline{\nu}_e$ are emited with energies between 1.8 and 8 MeV;
- baseline $\sim$ 180 km;
- matter effects are very tiny.

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



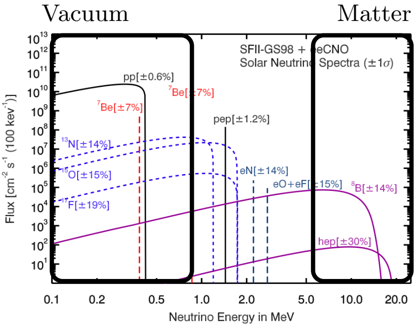
Backup: Tension in Δm^2_{21}

Solar neutrinos

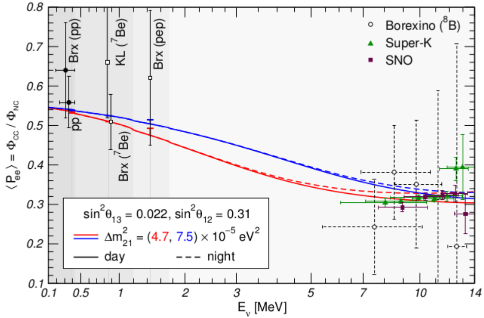
Measurement of the low-energy ^8B neutrino spectrum.

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)

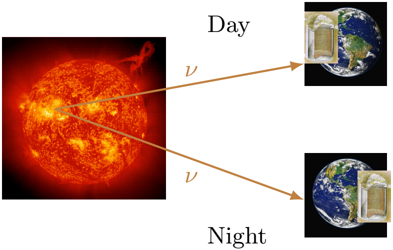


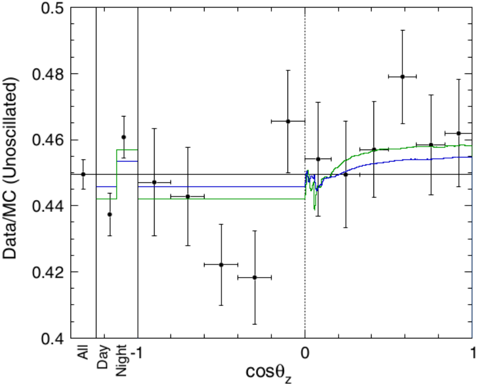
Eur.Phys.J. A52 (2016) no.4, 87

Backup: Tension in Δm^2_{21}

Solar neutrinos

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





Phys. Rev. D94, 052010 (2016)

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.

Backup: COHERENT data analysis

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 $\eta = \arctan(-1/Y_n^{coh}) \approx -35.4^\circ$