NSI and more (beyond 3-ν)

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European Neutrino Town meeting (CERN)

ICCUB

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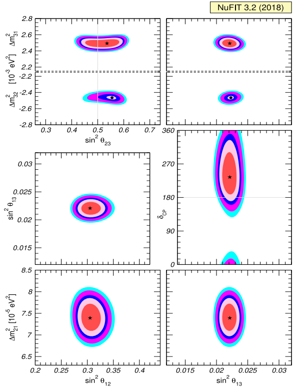
Neutrino Oscillations Quantum Evolution

Current knowledge

Talk by M. Concepcion Gonzalez-Garcia



- Neutrinos propagate in a non trivial way.
- Well described by 3D quantum mechanics coherent evolution.

$$H = U \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC}+V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}$$

Using the dispersion relation $\varepsilon_i^2 = p^2 + m_i^2$

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC}+V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}$$

- Quantum interference is very sensible to small parameters $\Delta m_{21}^2 = 7.4 \times 10^{-5} \mathrm{eV}^2$ and $\Delta m_{31}^2 = 2.49 \times 10^{-3} \mathrm{eV}^2$
- Can we use that?

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \rightarrow 0.844 & 0.516 \rightarrow 0.582 & 0.141 \rightarrow 0.156 \\ 0.242 \rightarrow 0.494 & 0.467 \rightarrow 0.678 & 0.639 \rightarrow 0.774 \\ 0.284 \rightarrow 0.521 & 0.490 \rightarrow 0.695 & 0.615 \rightarrow 0.754 \end{pmatrix}$$

JHEP 01 (2017) 087 Ivan Esteban et al.
Prog.Part.Nucl.Phys. 102 (2018) 48-72 F. Capozzi et al.
Phys.Lett. B782 (2018) 633-640 P.F. de Salas et al.

www.nu-fit.org

Neutrino Oscillations Quantum Evolution

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Sterile Neutrinos

- LSND, MiniBooNE
- Reactor anomaly
- Galium anomaly

Talk by Thomas Schwetz

- Seesaw neutrinos

Talk by Enrique Fernandez-Martinez

NOT in this talk

Neutrino Oscillations Quantum Evolution

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Non-standard interactions with matter

NSI

Neutrino Oscillations Quantum Evolution

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Using the dispersion relation $\varepsilon_i^2 = p^2 + m_i^2 + \Lambda_{ij}$

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC}+V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix} + \left(\frac{E}{\Lambda}\right)^n \mathcal{O}$$

- CPT (odd, even) Lorentz Violation
- Coupling with Torsion
- Equivalence Principle

- Quantum interference is very sensible to small parameters $\Delta m_{21}^2 = 7.4 \times 10^{-5}\text{eV}^2$ and $\Delta m_{31}^2 = 2.49 \times 10^{-3}\text{eV}^2$
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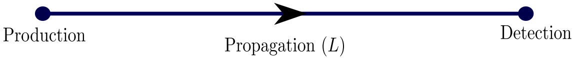
Neutrino Oscillations Quantum Evolution



- Neutrinos propagate in a non trivial way.
- Well described by 3D quantum mechanics ~~coherent~~ evolution.

Non-unitary Evolution

$$H = U \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC} + V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix} + i\Gamma$$

Using the dispersion relation $\varepsilon_i^2 = p^2 + m_i^2$

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC} + V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix} + i\Gamma$$

- U is not unitar
- Decoherence
- Neutrino Decay

- Quantum interference is very sensible to small parameters
  $\Delta m_{21}^2 = 7.4 \times 10^{-5} \mathrm{eV}^2$ and $\Delta m_{31}^2 = 2.49 \times 10^{-3} \mathrm{eV}^2$
- Can we use that?

Non-Standard interactions

- We can test non-standard interactions with ordinary matter.

$(\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta)(\bar{f}' \gamma^\mu P f)$ CC-NSI ✗ Better constrained by scattering measurements

$(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f)$ NC-NSI ✓ Oscillations

Models: Phys.Lett. B724 (2013) 84-87. Yasaman Farzan

Non-Standard interactions

- We can test non-standard interactions with ordinary matter.

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\left[\sum_{\alpha,\beta}\varepsilon^{\eta}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\right]\left[\sum_{f,P}\xi^{f,P}(\bar{f}\gamma_\mu P f)\right]$$

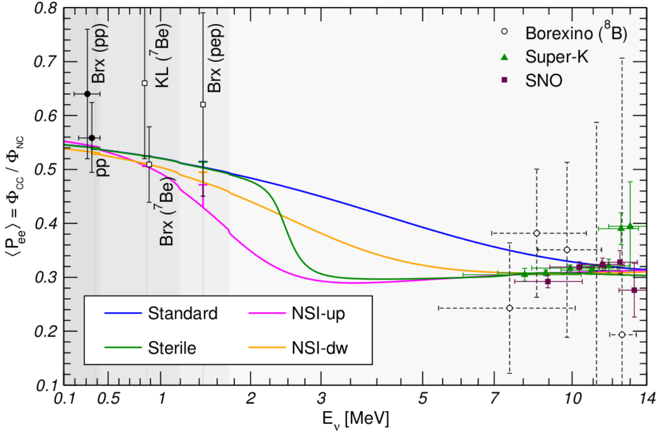
- This induces a modification in the matter potential.

$$H = \frac{1}{2E}U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + \sqrt{2}G_F N_e(x)\begin{pmatrix} 1+\varepsilon_{ee}(x) & \varepsilon_{e\mu}(x) & \varepsilon_{e\tau}(x) \\ \varepsilon^*_{e\mu}(x) & \varepsilon_{\mu\mu}(x) & \varepsilon_{\mu\tau}(x) \\ \varepsilon^*_{e\tau}(x) & \varepsilon^*_{\mu\tau}(x) & \varepsilon_{\tau\tau}(x)\end{pmatrix}$$

$$\varepsilon_{\alpha\beta}(x) = \varepsilon^{\eta}_{\alpha\beta}\left[\xi^p + Y_n(x)\xi^n\right] \quad \text{with} \quad \xi^p = \sqrt{5}\cos\eta \quad \xi^n = \sqrt{5}\sin\eta$$

Non-Standard interactions Motivation

- NSI may solve the Solar vs KamLAND tension.



Eur.Phys.J. A52 (2016) no.4, 87 M.Maltoni, et al.

Non-Standard interactions (DATA)

- Atm-LBL-MBL
  - Super-Kamiokande SK1-4, 3 years of DeepCore, ν_μ induced up-going μ
  - MINOS, T2K, NOvA to be consistent with CP conserving we don't include T2K and NOvA appearance channels
  - Double-Chooz, Daya-Bay, Reno
- Solar and KamLAND
  - KamLAND.
  - Chlorine, Gallex/GNO, SAGE, Super-Kamiokande, SNO, Borexino
- COHERENT

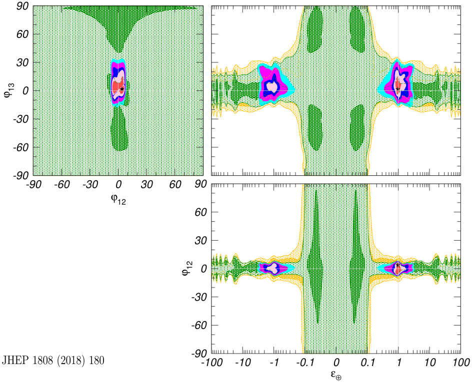
For details:

JHEP 1808 (2018) 180. arXiv:1805.04530

Non-Standard interactions (LBL-Reactor-IceCube)

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + \varepsilon_{ee}(x) & \varepsilon_{e\mu}(x) & \varepsilon_{e\tau}(x) \\ \varepsilon^*_{e\mu}(x) & \varepsilon_{\mu\mu}(x) & \varepsilon_{\mu\tau}(x) \\ \varepsilon^*_{e\tau}(x) & \varepsilon^*_{\mu\tau}(x) & \varepsilon_{\tau\tau}(x) \end{pmatrix}$$

$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{\eta}_{\alpha\beta}\left(\xi^p + Y^{\oplus}_n \xi^n\right) = \sqrt{5}\left(\cos\eta + Y^{\oplus}_n \sin\eta\right) \varepsilon^{\eta}_{\alpha\beta}$$



JHEP 1808 (2018) 180

- Constant n/p
- No bound on the physical ε^{η}

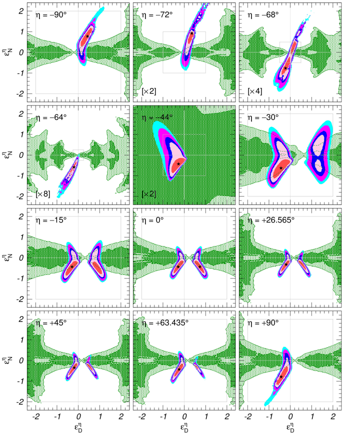
$$\begin{aligned}
\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu} &= \varepsilon_{\oplus}\left(\cos^2\varphi_{12} - \sin^2\varphi_{12}\right)\cos^2\varphi_{13} - 1 \\
\varepsilon^{\oplus}_{\tau\tau} - \varepsilon^{\oplus}_{\mu\mu} &= \varepsilon_{\oplus}\left(\sin^2\varphi_{13} - \sin^2\varphi_{12}\cos^2\varphi_{13}\right) \\
\varepsilon^{\oplus}_{e\mu} &= -\varepsilon_{\oplus}\cos\varphi_{12}\sin\varphi_{12}\cos^2\varphi_{13} \\
\varepsilon^{\oplus}_{e\tau} &= -\varepsilon_{\oplus}\cos\varphi_{12}\cos\varphi_{13}\sin\varphi_{13} \\
\varepsilon^{\oplus}_{\mu\tau} &= \varepsilon_{\oplus}\sin\varphi_{12}\cos\varphi_{13}\sin\varphi_{13}
\end{aligned}$$

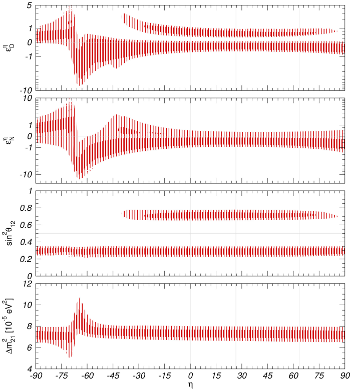
Non-Standard interactions (Solar and KamLAND)

$$H = \frac{1}{2E}\tilde{U}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}\tilde{U}^\dagger + \sqrt{2}G_F N_e(x)\left[\begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix} + \left[\xi^p + Y_n(x)\xi^n\right]\begin{pmatrix} -\varepsilon^\eta_D & \varepsilon^\eta_N \\ \varepsilon^{\eta *}_N & \varepsilon^\eta_D \end{pmatrix}\right]$$

$$\varepsilon^\eta_D = c_{13}s_{13}\ \mathrm{Re}\left(s_{23}\,\varepsilon^\eta_{e\mu} + c_{23}\,\varepsilon^\eta_{e\tau}\right) - \left(1 + s^2_{13}\right) c_{23}s_{23}\ \mathrm{Re}\left(\varepsilon^\eta_{\mu\tau}\right) - \frac{c^2_{13}}{2}\left(\varepsilon^\eta_{ee} - \varepsilon^\eta_{\mu\mu}\right) + \frac{s^2_{23} - s^2_{13}c^2_{23}}{2}\left(\varepsilon^\eta_{\tau\tau} - \varepsilon^\eta_{\mu\mu}\right)$$

$$\varepsilon^\eta_N = c_{13}\left(c_{23}\,\varepsilon^\eta_{e\mu} - s_{23}\,\varepsilon^\eta_{e\tau}\right) + s_{13}\left[s^2_{23}\,\varepsilon^\eta_{\mu\tau} - c^2_{23}\,\varepsilon^{f,V*}_{\mu\tau} + c_{23}s_{23}\left(\varepsilon^\eta_{\tau\tau} - \varepsilon^\eta_{\mu\mu}\right)\right]$$





JHEP 1808 (2018) 180

Non-Standard interactions (Solar and KamLAND)

$$H = \frac{1}{2E}\tilde{U}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}\tilde{U}^\dagger + \sqrt{2}G_F N_e(x)\left[\begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix} + \left[\xi^p + Y_n(x)\xi^n\right]\begin{pmatrix} -\varepsilon^\eta_D & \varepsilon^\eta_N \\ \varepsilon^{\eta*}_N & \varepsilon^\eta_D \end{pmatrix}\right]$$

$$\varepsilon^\eta_D = c_{13}s_{13}\ \mathrm{Re}\left(s_{23}\,\varepsilon^\eta_{e\mu} + c_{23}\,\varepsilon^\eta_{e\tau}\right) - \left(1 + s^2_{13}\right)c_{23}s_{23}\ \mathrm{Re}\left(\varepsilon^\eta_{\mu\tau}\right) - \frac{c^2_{13}}{2}\left(\varepsilon^\eta_{ee} - \varepsilon^\eta_{\mu\mu}\right) + \frac{s^2_{23} - s^2_{13}c^2_{23}}{2}\left(\varepsilon^\eta_{\tau\tau} - \varepsilon^\eta_{\mu\mu}\right)$$

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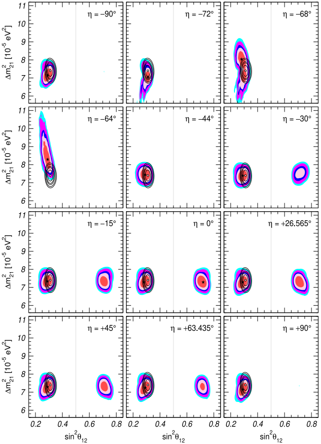

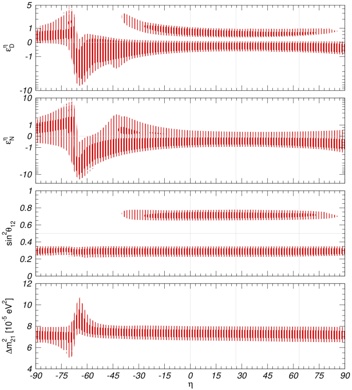

Non-Standard interactions (Solar and KamLAND)

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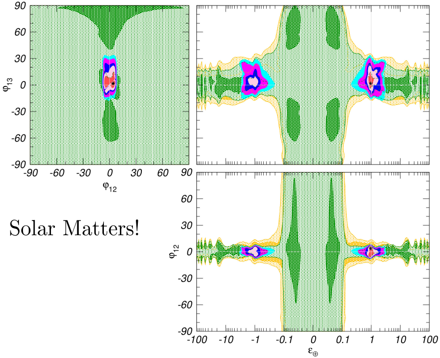
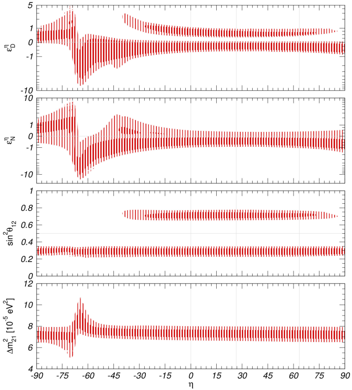


Solar Matters!



JHEP 1808 (2018) 180

Non-Standard interactions (All + COHERENT)

Production

Propagation (L)

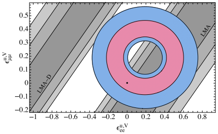
✓ Detection

$$N_{\rm NSI} = \gamma\left[f_{\nu_e} Q^2_{we} + (f_{\nu_\mu} + f_{\bar{\nu}_\mu}) Q^2_{w\mu}\right] \qquad f_{\nu_e} = 0.31,\ f_{\nu_\mu} = 0.19, \text{ and } f_{\bar{\nu}_\mu} = 0.50$$

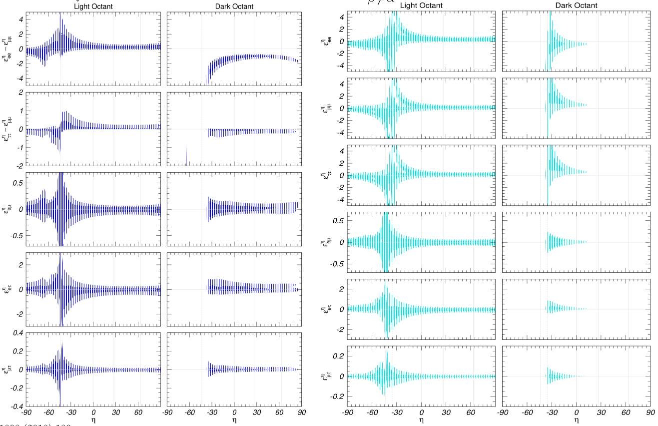
$$Q^2_{w\alpha} \propto \sum_i \left\{\left[Z_i(g_p^V + \varepsilon^p_{\alpha\alpha}) + N_i(g_n^V + \varepsilon^n_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha}\left[Z_i\varepsilon^p_{\alpha\beta} + N_i\varepsilon^n_{\alpha\beta}\right]^2\right\}$$

Without and With COHERENT

Discriminates LMA & LMA-D



Phys. Rev. D 96, 115007 (2017)

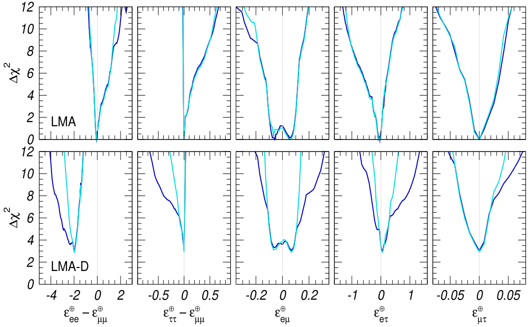


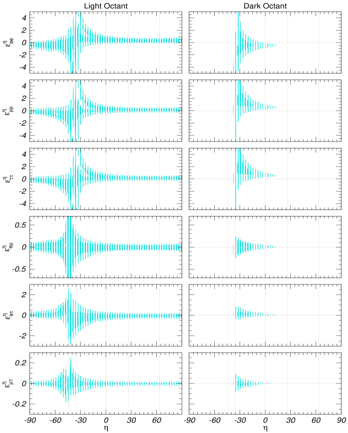
JHEP 1808 (2018) 180

Non-Standard interactions (All + COHERENT)

$$N_{\text{NSI}} = \gamma \left[f_{\nu_e} Q^2_{we} + (f_{\nu_\mu} + f_{\bar{\nu}_\mu}) Q^2_{w\mu} \right] \qquad f_{\nu_e} = 0.31,\ f_{\nu_\mu} = 0.19, \text{ and } f_{\bar{\nu}_\mu} = 0.50$$

$$Q^2_{w\alpha} \propto \sum_i \left\{ \left[Z_i (g_p^V + \varepsilon^p_{\alpha\alpha}) + N_i (g_n^V + \varepsilon^n_{\alpha\alpha}) \right]^2 + \sum_{\beta \neq \alpha} \left[Z_i \varepsilon^p_{\alpha\beta} + N_i \varepsilon^n_{\alpha\beta} \right]^2 \right\}$$





Lorentz Violation

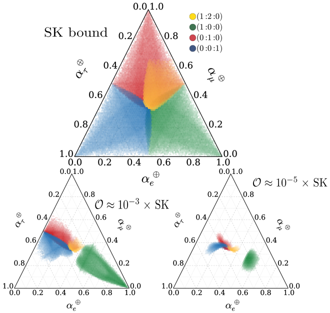
$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC} + V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix} + \left(\frac{E}{\Lambda}\right)^n \tilde{U} \mathcal{O} \tilde{U}^\dagger$$

Neutrinos propagating very long distances at very high energies may be the best

Phys. Rev. D 91, 052003 (2015) SK
Nature Physics 2018 s41567-018-0172-2 IC

dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[5]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$ $< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[6]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[7]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[8]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped Ca^+ ion	tabletop	electron	$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$ $< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$ $< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV^{-3}	[6]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$ $< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

Flavor content of Astrophysical neutrinos



Phys.Rev.Lett. 115 (2015) 161303

Decoherence

$$\frac{d\rho}{dt} = -i\,[H,\rho] - \mathcal{D}\,[\rho]$$

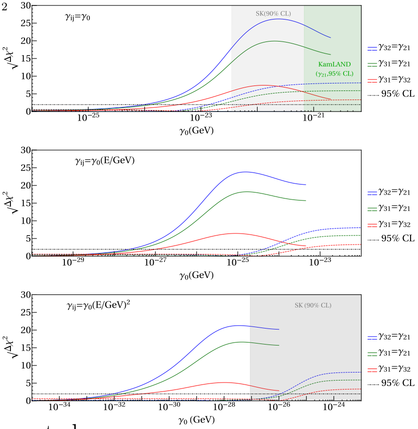
High Energy ATM-ν are important

$$D_m = \tilde{U}\,\mathrm{diag}\left\{d_m^1, d_m^2, d_m^3\right\}\tilde{U}^\dagger \qquad \gamma_{ij} \equiv \sum_m \left(d_m^i - d_m^j\right)^2$$

$$\mathcal{D}\,[\rho] = \sum_m \left[\left\{\rho, D_m D_m^\dagger\right\} - 2 D_m \rho D_m^\dagger\right]$$

		$n=-2$	$n=-1$	$n=0$	$n=1$	$n=2$
Normal Ordering	**IceCube (this work)**					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$2.8\cdot10^{-18}$	$4.2\cdot10^{-21}$	$\mathbf{4.0\cdot10^{-24}}$	$\mathbf{1.0\cdot10^{-27}}$	$\mathbf{1.0\cdot10^{-31}}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$6.8\cdot10^{-19}$	$1.2\cdot10^{-21}$	$\mathbf{1.3\cdot10^{-24}}$	$\mathbf{3.5\cdot10^{-28}}$	$\mathbf{1.9\cdot10^{-32}}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$5.2\cdot10^{-19}$	$9.2\cdot10^{-22}$	$9.7\cdot10^{-25}$	$2.4\cdot10^{-28}$	$9.0\cdot10^{-33}$
	DeepCore (this work)					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$\mathbf{4.3\cdot10^{-20}}$	$2.0\cdot10^{-21}$	$8.2\cdot10^{-23}$	$3.0\cdot10^{-24}$	$1.1\cdot10^{-25}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$\mathbf{1.2\cdot10^{-20}}$	$5.4\cdot10^{-22}$	$2.1\cdot10^{-23}$	$6.6\cdot10^{-25}$	$2.0\cdot10^{-26}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$7.5\cdot10^{-21}$	$3.5\cdot10^{-22}$	$1.4\cdot10^{-23}$	$4.2\cdot10^{-25}$	$1.1\cdot10^{-26}$
Inverted Ordering	**IceCube (this work)**					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$6.8\cdot10^{-19}$	$1.2\cdot10^{-21}$	$\mathbf{1.3\cdot10^{-24}}$	$\mathbf{3.5\cdot10^{-28}}$	$\mathbf{1.9\cdot10^{-32}}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$5.2\cdot10^{-19}$	$9.2\cdot10^{-22}$	$9.8\cdot10^{-25}$	$2.4\cdot10^{-28}$	$9.0\cdot10^{-33}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$2.8\cdot10^{-18}$	$4.2\cdot10^{-21}$	$\mathbf{4.1\cdot10^{-24}}$	$\mathbf{1.0\cdot10^{-27}}$	$\mathbf{1.0\cdot10^{-31}}$
	DeepCore (this work)					
	Atmospheric ($\gamma_{31}=\gamma_{32}$)	$\mathbf{1.4\cdot10^{-20}}$	$5.8\cdot10^{-22}$	$2.2\cdot10^{-23}$	$7.5\cdot10^{-25}$	$2.3\cdot10^{-26}$
	Solar I ($\gamma_{31}=\gamma_{21}$)	$8.3\cdot10^{-21}$	$3.6\cdot10^{-22}$	$1.4\cdot10^{-23}$	$4.7\cdot10^{-25}$	$1.3\cdot10^{-26}$
	Solar II ($\gamma_{32}=\gamma_{21}$)	$\mathbf{5.0\cdot10^{-20}}$	$2.3\cdot10^{-21}$	$9.4\cdot10^{-23}$	$3.3\cdot10^{-24}$	$1.2\cdot10^{-25}$
	Previous Bounds					
	SK (two families)		$2.4\cdot10^{-21}$	$4.2\cdot10^{-23}$		$1.1\cdot10^{-27}$
	MINOS (γ_{31},γ_{32})		$\mathbf{2.5\cdot10^{-22}}$	$1.1\cdot10^{-22}$	$2\cdot10^{-24}$	
	KamLAND (γ_{21})		$\mathbf{3.7\cdot10^{-24}}$	$6.8\cdot10^{-22}$	$1.5\cdot10^{-19}$	

DeepCore/IceCube bounds on γ_{ij}^0 in GeV ($\gamma_{ij} = \gamma_{ij}^0 (E/\mathrm{GeV})^n$)



Eur.Phys.J. C78 (2018) no.8, 614 Pilar Coloma, et al.

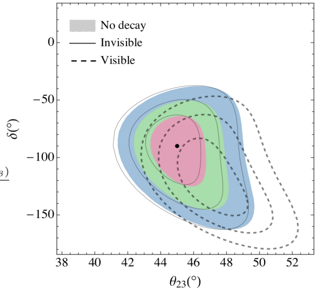
Neutrino Decay

$$\mathcal{L}_{\text{int}} = \sum_{i=1,2} \frac{g_{3i}}{2} \bar{\nu}_i \nu_3 \phi + \frac{g'_{3i}}{2} \bar{\nu}_i i\gamma_5 \nu_3 \phi + \text{h.c.}$$

$$\mathcal{A}_{\nu_\alpha^r \to \nu_\beta^s}(E_\alpha, E_\beta) = \sum_{j=1,2} (U^r_{\alpha 3})^* U^s_{\beta j} e^{-iE_\beta(L-L')} e^{-iE_\alpha L'} e^{-\Gamma^{rs}_{3j} L'/2} \sqrt{\Gamma^{rs}_{3j}} \sqrt{W^{rs}_{3j}}$$

$$W^{rs}_{3j} \equiv \frac{1}{\Gamma^{rs}_{3j}} \frac{d\Gamma^{rs}_{3j}(E_\alpha, E_\beta)}{dE_\beta}$$

$$\Delta P^{\text{vis}}_{\nu_\alpha^r \to \nu_\beta^s}(E_\alpha, E_\beta) = \int_0^L \mid \mathcal{A}_{\nu_\alpha^r \to \nu_\beta^s}(E_\alpha, E_\beta) \mid^2 dL'$$



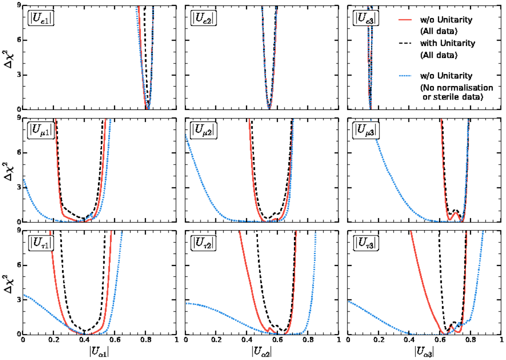
Analysis	Decaying particle	Decay mode	Limit
Solar data [15]	ν_2	Invisible	$\tau_2/m_2 > 7.2 \times 10^{-4}$ s/eV (99% C.L.)
Solar data [14]	ν_2	Invisible	$\tau_2/m_2 > 7.1 \times 10^{-4}$ s/eV (2σ C.L.)
Atmospheric and long-baseline data [19]	ν_3	Invisible	$\tau_3/m_3 > 2.9 \times 10^{-10}$ s/eV (90% C.L)
MINOS and T2K data [20]	ν_3	Invisible	$\tau_3/m_3 > 2.8 \times 10^{-12}$ s/eV (90% C.L.)
MINOS and T2K data [54]	ν_3	Visible	$\tau_3/m_3 > 1.5 \times 10^{-11}$ s/eV (90% C.L.)
JUNO expected sensitivity [31]	ν_3	Invisible	$\tau_3/m_3 > 7.5 \times 10^{-11}$ s/eV (95% C.L.)
DUNE expected sensitivity (this work)	ν_3	Visible	$\tau_3/m_3 > 1.95 - 2.6 \times 10^{-10}$s/eV (90% C.L.)

arXiv:1705.03599 P.Coloma, et al.
JHEP 1711 (2017) 022 Alberto M. Gago, et al.
Phys.Lett. B740 (2015) 345-352 R.A. Gomes, et al.
Phys.Lett. B663 (2008) 405-409 M.C. Gonzalez-Garcia, et al.

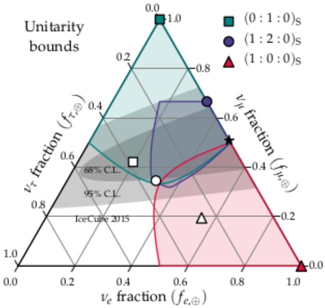
Neutrino Decay

arXiv:1810.00893 M.Ahlers, et al.

From Oscillations



Phys.Rev. D93 (2016) no.11, 113009 S. Parke, et al.



Implications for

Astrophysical Neutrinos

Conclusions

- NSI
  - We include *p* vs *n* in the NSI fit.
  - For Solar+KamLAND and Atm+LBL+MBL separated η reduce the bounds for both, the NSI parameters and the oscillations ones.
  - The combination solve the problem: global fit is important.
- LV, Decoherence, ...
  - Neutrino oscillations is competitive.
  - High energy helps! IceCube, Antares, Km^3.
  - Some extension have the equivalent phenomenology. Sterile neutrinos may look like NSI and or Non-unitarity depending on the setup JHEP 1704 (2017) 153 Mattias Blennow, et al.
  - In most of this cases a full general parametrization of the new physics may need a global picture.