Oscillation phenomenology beyond the standard three-neutrino paradigm

Interplay between Particle and Astroparticle Physics (IPA2016)
LAL, Orsay, France, 5–9 Sept. 2016

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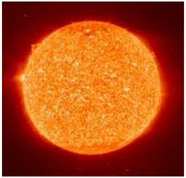
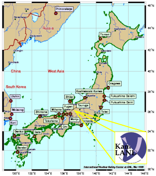
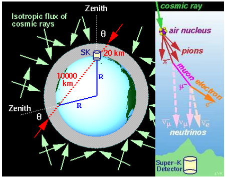
elusives
neutrinos, dark matter & dark energy physics

Orsay, 9 Sept. 2016

Global data on neutrino oscillations

various neutrino sources, vastly different energy and distance scales:

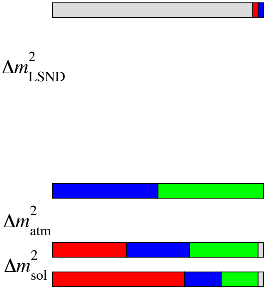
sun	reactors	atmosphere	accelerators
			
Homestake,SAGE,GALLEX SuperK, SNO, Borexino	KamLAND, D-CHOOZ DayaBay, RENO	SuperKamiokande	K2K, MINOS, T2K OPERA, NOvA

- global data fits nicely with the 3 neutrinos from the SM
  www.nu-fit.org, talk by M. Maltoni
- exceptions: "anomalies" at 2-3 σ:
  - short-baseline experiments: $\rightarrow$ **sterile neutrinos?**
  - missing up-turn of solar ν spectrum $\rightarrow$ **non-standard interactions?**

Outline

Sterile neutrinos at the eV scale? talks by D. Lhuillier, A. Hayes

- reactor anomaly ($\bar{\nu}_e$ disappearance)
- Gallium anomaly (ν_e disappearance)
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ appearance)

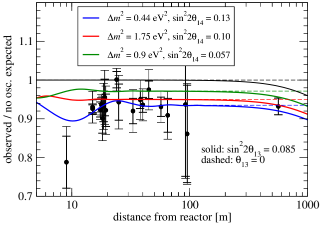


mostly based on Kopp, Machado, Maltoni, Schwetz, 1303.3011

- "phenomenological model": eV scale states are not related to seesaw or the mechanism of neutrino mass generation
- eV scale seesaw e.g.: Blennow, Fernandez-Martinez, 11; Fan, Langacker, 12; Donini, Hernandez, Lopez-Pavon, Maltoni, TS, 12

Hints for SBL $\nu_e \to \nu_e$ disappearance

- **Reactor anomaly:**

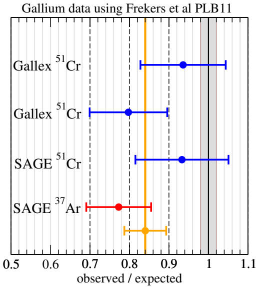


calculation of neutrino flux from nuclear reactors
Mueller et al., 11; P. Huber, 11

$f = 0.935 \pm 0.024$ (different from 1 @ 2.7σ)

talk by A. Hayes

- **Gallium anomaly:**

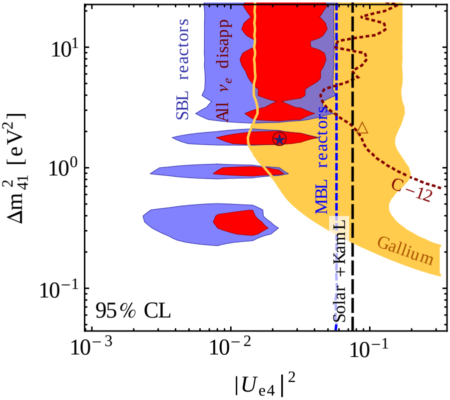


rate from radio-active sources in Gallium solar ν exps compared to cross section calculations
Acero,Giunti,Laveder,07; Giunti,Laveder,10

$$r = 0.84^{+0.054}_{-0.051} \qquad \Delta\chi^2_{r=1} = 8.7\,(2.9\sigma)$$

Global ν_e disappearance data

- reactor and gallium anomalies
- reactors at larger baselines (Chooz, Palo Verde, DoubleChooz, DayaBay, RENO, KamLAND)
- ν_e disappearance constraints from LSND and KARMEN from $\nu_e + ^{12}\mathrm{C} \to ^{12}\mathrm{N} + e^-$
  Reichenbacher, 05; Conrad, Shaevitz, 1106.5552
- solar neutrinos



additional constraints:

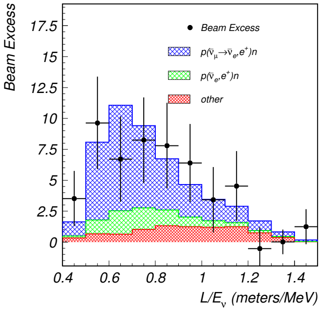
- DayaBay 2016 (important for low Δm^2_{41})
- preliminary results from NEOS
  IHEP16, talk by D. Lhuillier

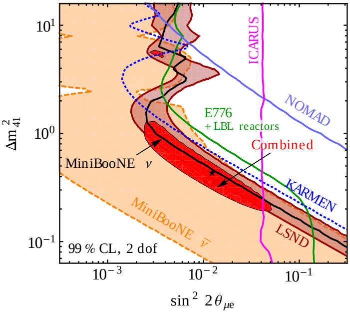
$$\sin^2 2\theta = 0.09\,, \quad \Delta m^2 = 1.78\,\mathrm{eV}^2$$

$$\chi^2_{\text{min}} = 296.8/328\,(64\%)$$

$$\Delta\chi^2_{\text{no-osc}} = 12.9/2 \quad (99.8\%\mathrm{CL}, 3.1\sigma)$$

$\nu_\mu \to \nu_e$ hints from LSND





- LSND signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions at the $E/L \sim 1$ eV^2 scale (3.8σ)
- 2.8σ excess in antineutrinos, consistent with oscillations
- 3.4σ excess in neutrinos, marginally consistent with osc. (p-value 6.1%)
- non-observation of $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance by KARMEN, and others

Can we fit everything together?

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

disappearance ($\alpha = e, \mu$)

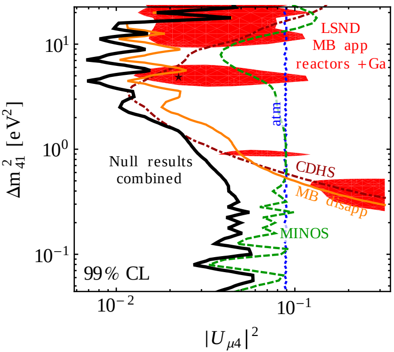
$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

$\nu_\mu \to \nu_e$ app. signal requires also signal in both, ν_e and ν_μ disappearance (appearance mixing angle quadratically suppressed)

Limits on ν_μ disappearance

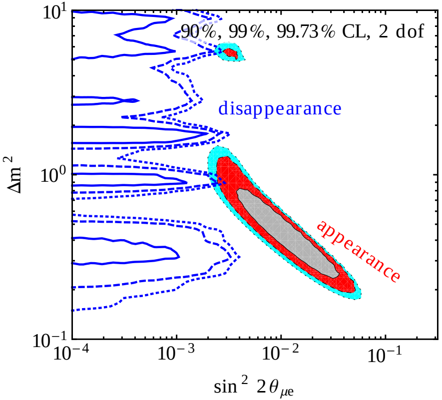
- CDHS PLB 1984
- SuperK atmospherics
  Bilenky, Giunti, Grimus, TS 99;
  Maltoni, TS, Valle 01
- MINOS 1001.0336, 1104.3922
- MiniBooNE $\nu_\mu(\bar{\nu}_\mu)$ disappearance 1106.5685



New results available from MINOS and IceCube

Can we fit everything together?

tension between appearance and disappearance data

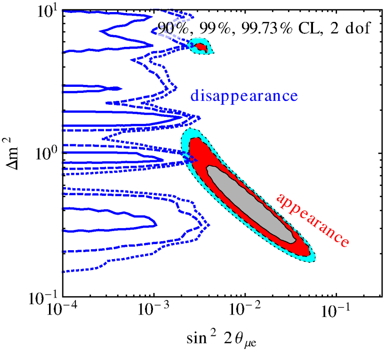


consistency of appearance vs disappearance $\chi^2_{\mathrm{PG}} = 18/2,\ P \approx 10^{-4}$

Kopp, Machado, Maltoni, Schwetz, 1303.3011

Kopp, Machado, Maltoni, Schwetz

[JHEP 1305 (2013) 050]



Best Fit: $\Delta m^2_{41} = 0.93\,\mathrm{eV}^2$

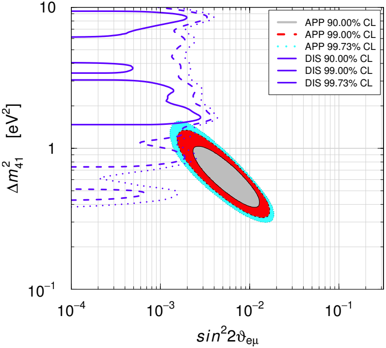
$|U_{e4}|^2 = 0.023 \qquad |U_{\mu4}|^2 = 0.029$

GoF $= 19\%$ (χ^2_{min}/NDF $= 712/680$)

GoF$_{\text{PG}} = 0.01\%$ (χ^2_{PG}/NDF $= 18.0/2$)

Our Fit

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]



Best Fit: $\Delta m^2_{41} = 1.6\,\mathrm{eV}^2$

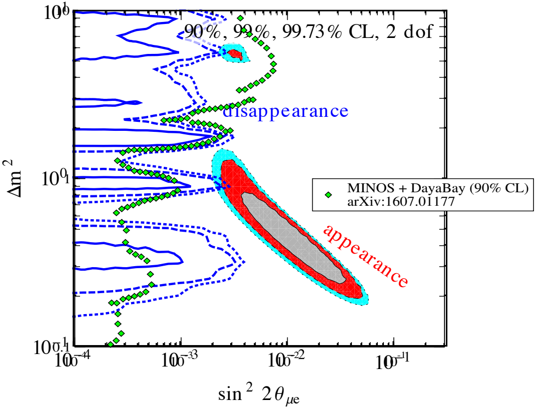
$|U_{e4}|^2 = 0.028 \qquad |U_{\mu4}|^2 = 0.014$

GoF $= 6\%$ (χ^2_{min}/NDF $= 304.0/268$)

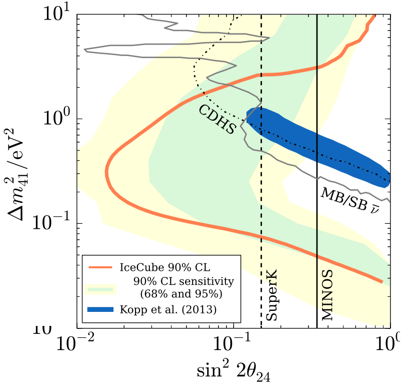
GoF$_{\text{PG}} = 0.06\%$ (χ^2/NDF $= 15.0/2$)

New results from MINOS and Daya Bay

talks @ Neutrino16, 1607.01177

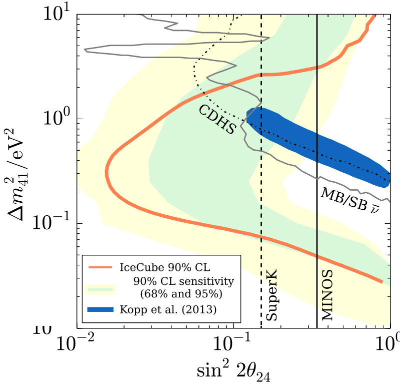


IceCube results PRL 2016

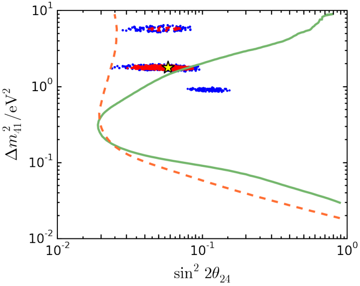


WARNING: maybe not as striking as it looks in this plot?

IceCube results PRL 2016



Collin, Arguelles, Conrad, Shaevitz, 1607.00011

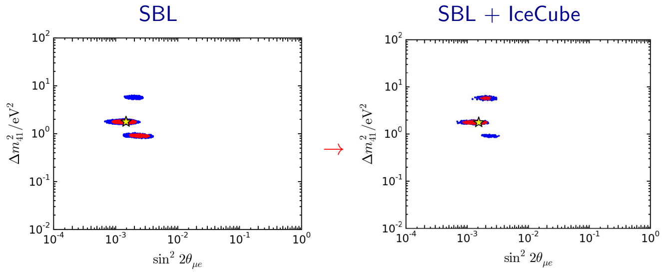


SUPPL. FIG. 1: The solid (dashed) line represents the 90% C.L. IceCube limit when calculated with $\theta_{34} = 0°$ ($\theta_{34} = 15°$). The result of the SBL+IC global fit is overlaid, Red – 90% CL; blue–99% CL.

WARNING: maybe not as striking as it looks in this plot?

SBL + IceCube

[Collin, Arguelles, Conrad, Shaevitz, arXiv:1607.00011]



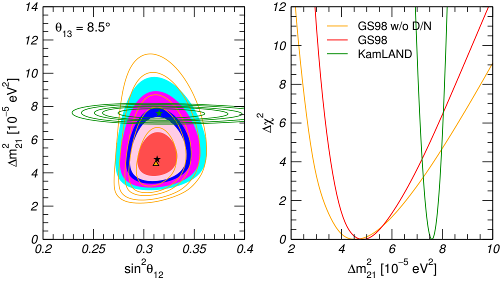
Red: 90% CL Blue: 99% CL

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	N_{bins}	$\chi^2_{\min}$	χ^2_{null}	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.59	568.84	50.26 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

$$\chi^2_{\min}(\mathrm{SBL}+\mathrm{IC}) - \chi^2_{\min}(\mathrm{SBL}) - \chi^2_{\min}(\mathrm{IC}) = 4.67\,(2\,\mathrm{dof})$$

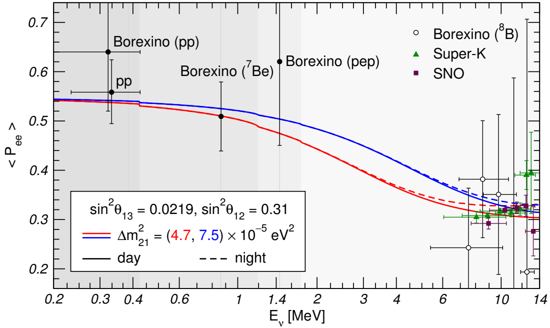
Outline

NuFIT 2.1 (2016)



“Tension” between solar neutrinos and KamLAND ($\sim 2\sigma$)

NuFIT 2.0 (2014)



Non-standard neutrino interactions

Neutrino interactions in the Standard Model:

$$H_{\rm SM}^{\nu_\alpha} = \frac{G_F}{\sqrt{2}}\,\bar\nu_\alpha\gamma_\mu(1-\gamma_5)\nu_\alpha \sum_f \bar f\gamma^\mu(g_V^{\alpha,f} - g_A^{\alpha,f}\gamma_5)f$$

assume presence of new physics inducing NSI:

$$H_{\rm NSI} = \frac{G_F}{\sqrt{2}}\,\bar\nu_\alpha\gamma_\mu(1-\gamma_5)\nu_\beta \sum_f \bar f\gamma^\mu\epsilon^f_{\alpha\beta}f$$

- $\epsilon^f_{\alpha\beta}$ parametrizes strength of NSI relative to G_F
- restrict to vector-type interactions (matter potential)
- NSI can be non-universal ($\alpha = \beta$) or flavour-changing ($\alpha \neq \beta$)
- in general not directly related to neutrino mass (dim-6)
  but generically expected at some level

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Generalized matter potential

$$H = U\text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger + \sqrt{2} G_F N_e(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

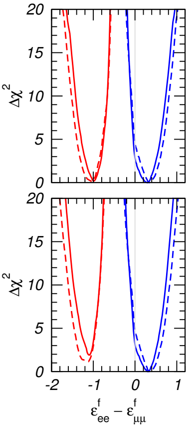
$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} Y_f(x) \epsilon^f_{\alpha\beta}$$

with $Y_f(x) \equiv N_f(x)/N_e(x)$

$N_f(x)$: density of fermion f along the neutrino path

Limits from oscillation data

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$

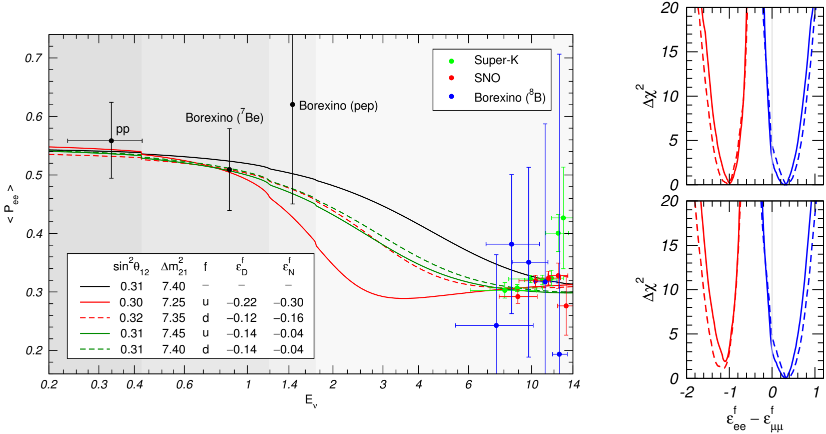


Gonzalez-Garcia, Maltoni, 1307.3092

- limits at the 1% to 10% level
- exception ϵ^q_{ee}: order-one values allowed!

Presence of NSI:

- improved fit to solar neutrino spectrum



Gonzalez-Garcia, Maltoni, 1307.3092

Presence of NSI:

- improved fit to solar neutrino spectrum

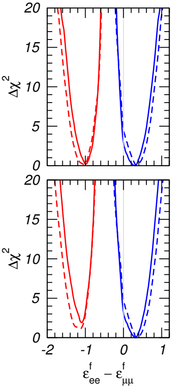
- show up in future experiments (affect CP violation measurments)

  very large literature – few recent examples
  (appologize for ommissions):

  Coloma, 1511.06357; deGouvea, Kelly, 1511.05562; Liao, Marfatia, Whisnant, 1601.00927; Forero, Huber, 1601.03736; Bakhti, Farzan, 1602.07099; Masud, Mehta, 1603.01380; Blennow, Choubey, Ohlsson, Pramanik, Raut, 1606.08851; Agarwalla, Chatterjee, Palazzo, 1607.01745; Ge, Smirnov, 1607.08513

"LMA-dark" solution

Miranda, Tortola, Valle, hep-ph/0406280



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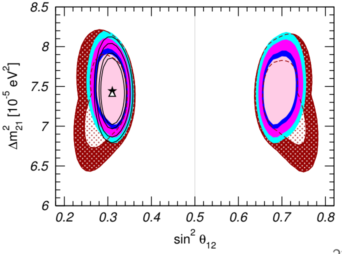
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$

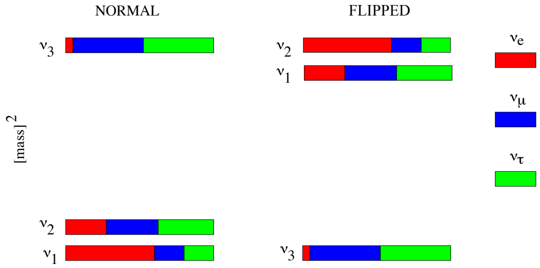


Gonzalez-Garcia, Maltoni, 1307.3092

$$i \frac{d}{dt} \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} = H \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix}$$

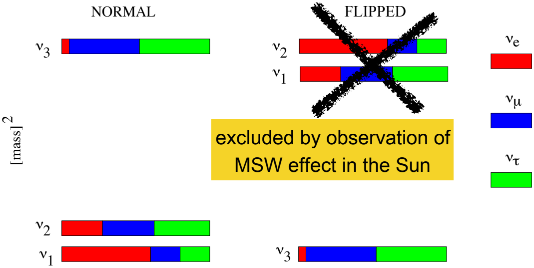
- neutrino evolution is identical under $H \to -H^*$ (CPT invariance)
- in vaccum this can be realised by

$$\Delta m^2_{31} \to -\Delta m^2_{32} \,, \quad \sin\theta_{12} \leftrightarrow \cos\theta_{12} \,, \quad \delta \to \pi - \delta$$



$$H = U\mathrm{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger + \mathrm{diag}(\sqrt{2}G_F N_e, 0, 0)$$

standard matter effect breaks the $H \to -H^*$ symmetry:



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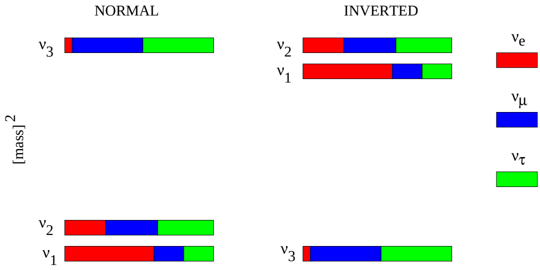


Generalized mass ordering degeneracy

Coloma, Schwetz, 1604.05772

[see also Gonzalez-Garcia, Maltoni, Salvado, 1103.4365;
Gonzalez-Garcia, Maltoni, 1307.3092; Bakhti, Farzan, 1403.0744]

$$H = U\mathrm{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger + \sqrt{2} G_F N_e(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

NSI can restore the $H \to -H^*$ symmetry by

$$\Delta m^2_{31} \to -\Delta m^2_{32}\,, \quad \sin\theta_{12} \leftrightarrow \cos\theta_{12}\,, \quad \delta \to \pi - \delta$$

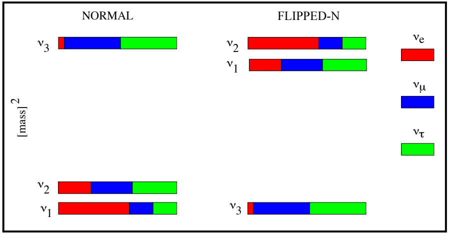
$$\oplus$$

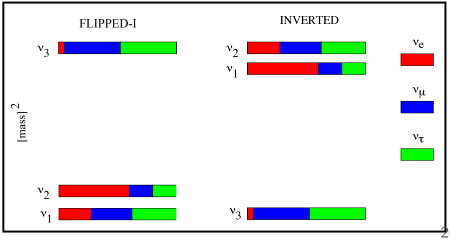
$$\epsilon_{ee} \to -\epsilon_{ee} - 2\,, \quad \epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha\beta \neq ee)$$

Generalized mass ordering degeneracy

$$\epsilon_{ee} \to -\epsilon_{ee} - 2\,, \quad \epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha\beta \neq ee)$$

- in presence of NSI no oscillation experiment can exclude a flipped neutrino mass spectrum
- determination of mass ordering becomes impossible!





Generalized mass ordering degeneracy

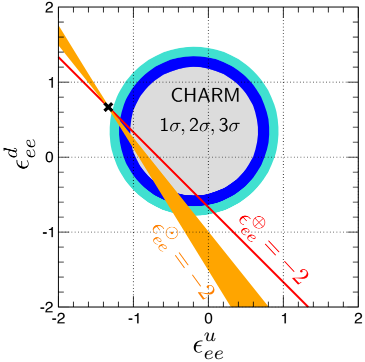
$$\epsilon_{ee} \to -\epsilon_{ee} - 2\,, \quad \epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha\beta \neq ee)$$

- $\epsilon_{\alpha\beta} = \sum_{f=u,d} Y_f(x)\epsilon^f_{\alpha\beta}$ with $Y_f(x) \equiv N_f(x)/N_e(x)$
- for $\epsilon^u_{\alpha\beta} = -2\epsilon^d_{\alpha\beta}$ NSI happen only on protons $\to$ effects become independent of the matter composition
- Ex.: for $\epsilon^u_{ee} = -4/3, \epsilon^d_{ee} = 2/3$ we get $\epsilon_{ee} = -2$ for any matter composition $\to$ degenerate with no NSI

Need data on NC-like ν_e scattering

- need bounds on $\nu_e/\nu_{\tau,\mu}$ neutral-current universality from non-oscillation experiments
- historical data CHARM-II, 1986 constrain part of parameter space
- degeneracy remains approximately
- CHARM constraint is model-dependent
- progress expected from exps looking for coherent neutrino–nucleus scattering talk by K. Scholberg

Coloma, Schwetz, 1604.05772



Generalized mass ordering degeneracy...

- requires ϵ_{ee}^{q} of order one (NSI comparable to weak interaction):

$$\frac{g^2}{\Lambda^2} \sim G_F$$

  - $g \sim 1$, $\Lambda \gtrsim m_W$ strongly constrained (LHC,LFV,...)
  - alternative: $g \ll 1$, MeV $\gtrsim \Lambda \ll m_W$

- consistent gauge models for $\epsilon_{ee}^{q} \sim 1$ exist

  Farzan, 2015; Farzan, Shoemaker, 2015

Outline

Conclusions

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  - no satisfactory fit of global data (app/disapp tension)
  - no signs for steriles in new results $\rightarrow$
    not conclusive yet but hints are getting more and more squeezed ...
- **non-standard neutrino interactions**
  - weak hint (2σ) from solar neutrino spectrum
  - possible manifestation of new physics in the lepton sector
  - LMA-dark: still allowed $\mathcal{O}(1)$ perturbation of neutrino sector
  - requires $\epsilon_{ee} \simeq 1$
  - implies generalized mass ordering degeneracy
    impossible to resolve by oscillations $\rightarrow$ scattering experiments (ν_e NC)

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Thank you for your attention!