Searching for new physics with neutrino experiments

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Why do we study neutrinos?

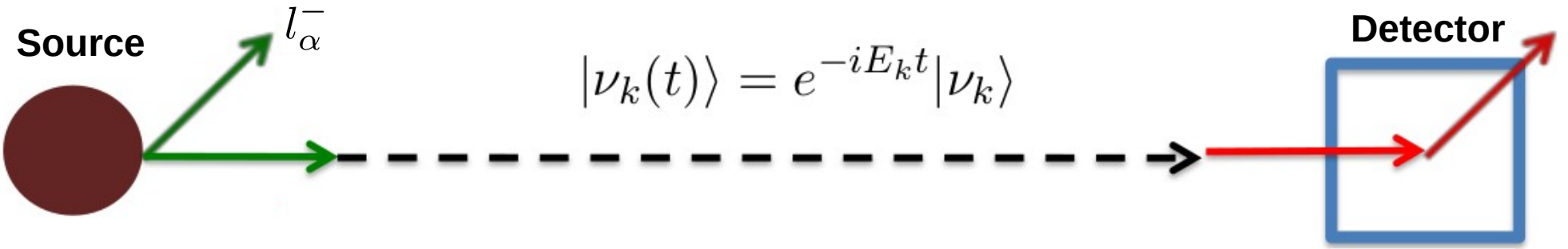
Due to the small interaction rate neutrinos can be used to study the interior of the Sun or also Supernova explosions

Neutrinos play a role in the evolution of the universe, in the formation of large scale structures, big bang nucleosynthesis, etc.

Neutrinos might help to understand the matter-antimatter asymmetry of the Universe

Neutrinos are our only clear hint for physics beyond the standard model! Note that there is no particle detection of dark matter so far :(

Neutrino oscillations



$$P(\alpha \to \beta; E, L) = \sum_{k,j} U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}e^{i\frac{\Delta m^2_{kj}}{2E}L}$$

Three-neutrino oscillations

Neutrino mixing matrix

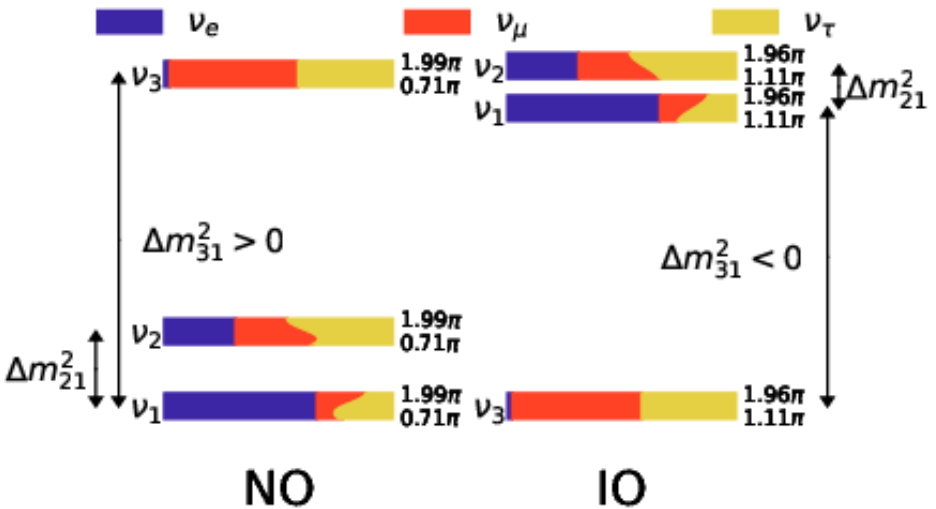
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$

1 Dirac + 2 Majorana CP-phases

Three masses m_1, m_2, m_3 for which two orderings are possible

Oscillations are only sensitive to mass splittings



Three-neutrino oscillations

Parameter	Main contribution from	Other contributions from
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	-
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

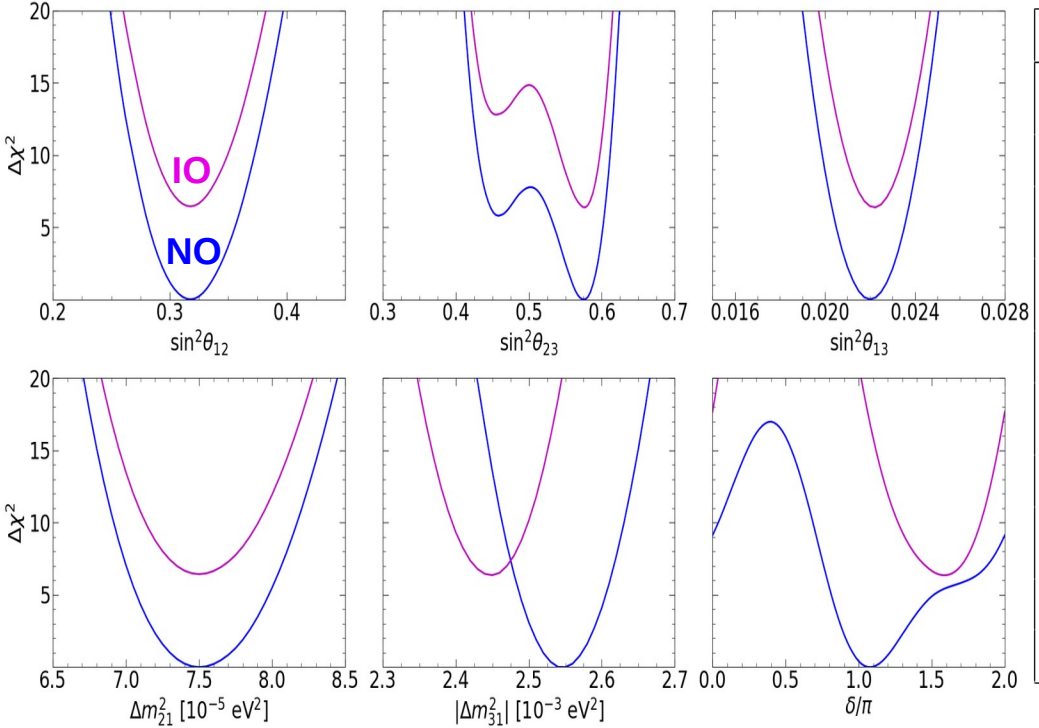
Common sensitivities from different types of experiments

Combination of data sets can enhance sensitivities to oscillation parameters

=> Perform a global fit to neutrino oscillation data!

Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



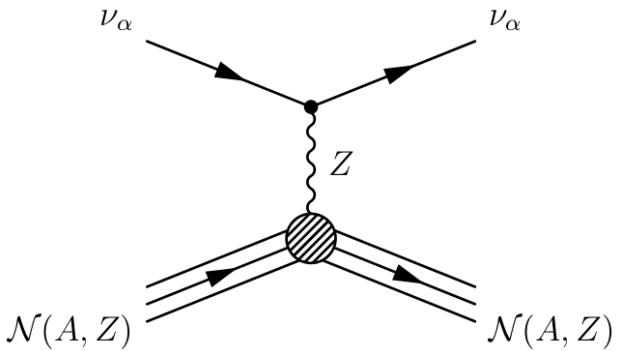
parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

See also:
Bari - 2107.00532, PRD 2021

See also:
NuFit - 2111.03086, Universe 2021

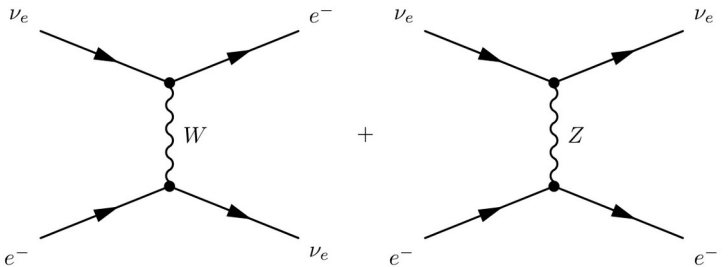
(Two selected) detection channels

Coherent elastic neutrino nucleus scattering



$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\rm nr}}(E,T_{\rm nr}) = \frac{G_{\rm F}^2 M}{\pi}\left(1-\frac{MT_{\rm nr}}{2E^2}\right)(Q^V_{\ell,\rm SM})^2$$

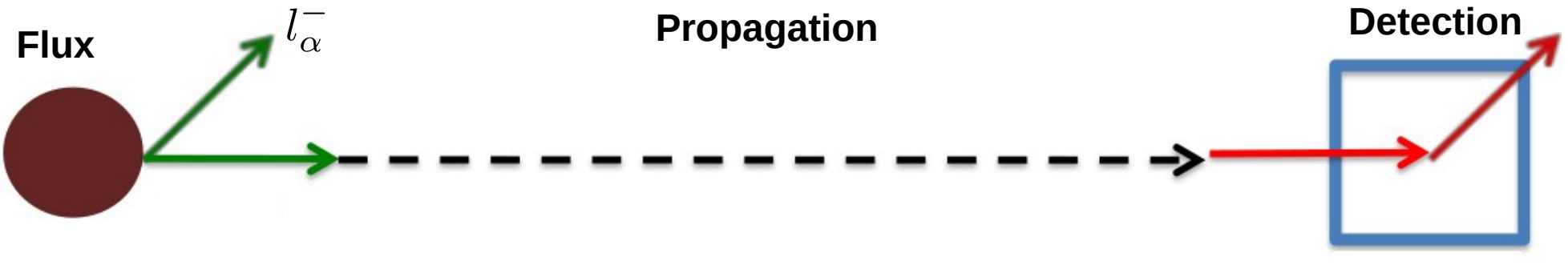
Elastic neutrino electron scattering



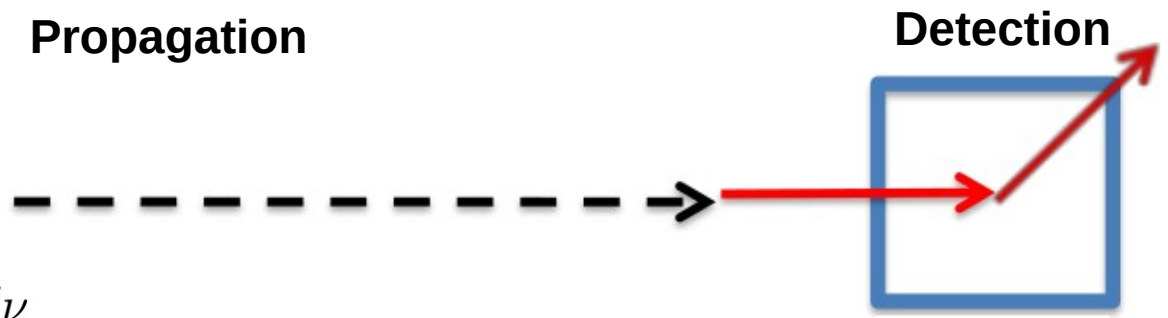
$$\frac{d\sigma^{\rm SM}_{\nu_\ell-{\rm Xe}}}{dT_{\rm e}}(E_\nu,T_{\rm e}) = Z^{\rm Xe}_{\rm eff}(T_e)\frac{G_{\rm F}^2 m_e}{2\pi}\left[(g_V^{\nu_\ell}+g_A^{\nu_\ell})^2 + \right.$$

$$\left. + (g_V^{\nu_\ell}-g_A^{\nu_\ell})^2\left(1-\frac{T_e}{E_\nu}\right)^2 - ((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2)\frac{m_e T_e}{E_\nu^2}\right]$$

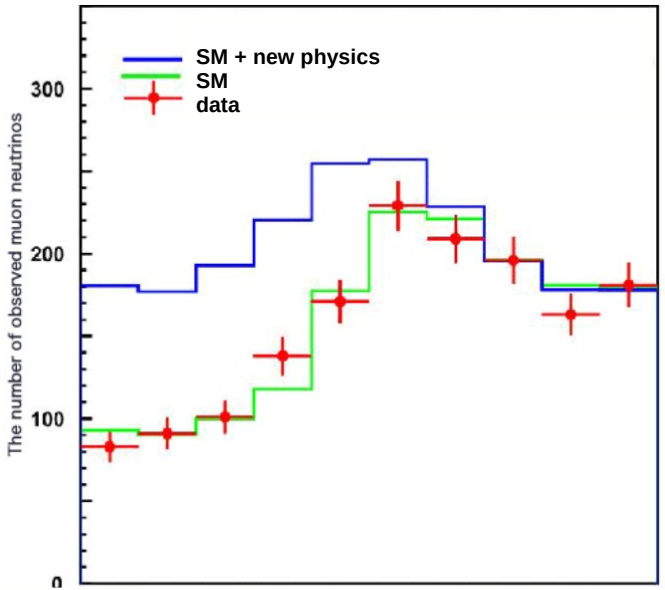
A neutrino experiment



A neutrino experiment

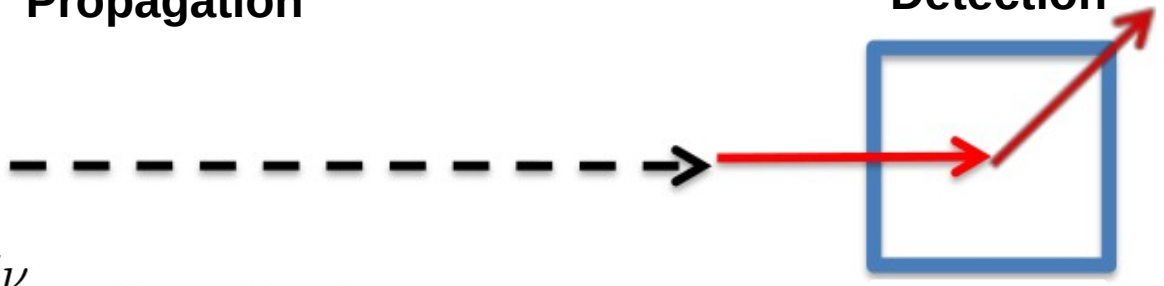


A neutrino experiment



Propagation

Detection



$$i\frac{d\nu}{dt} = (\mathcal{H} + \mathcal{H}_{\rm NP})\nu$$

$$\sigma(\nu\mathcal{X}) = \sigma(\nu\mathcal{X})_{\rm SM} + \sigma(\nu\mathcal{X})_{\rm NP}$$

New physics searches at neutrino experiment

CPT violation

Altered dispersion relations

Quantum gravity effects

NSI

Neutrino decay

Neutrino wavepackets

Lorentz violation

active sterile transitions

Quasi-Dirac neutrinos

Light sterile neutrinos

New vector bosons

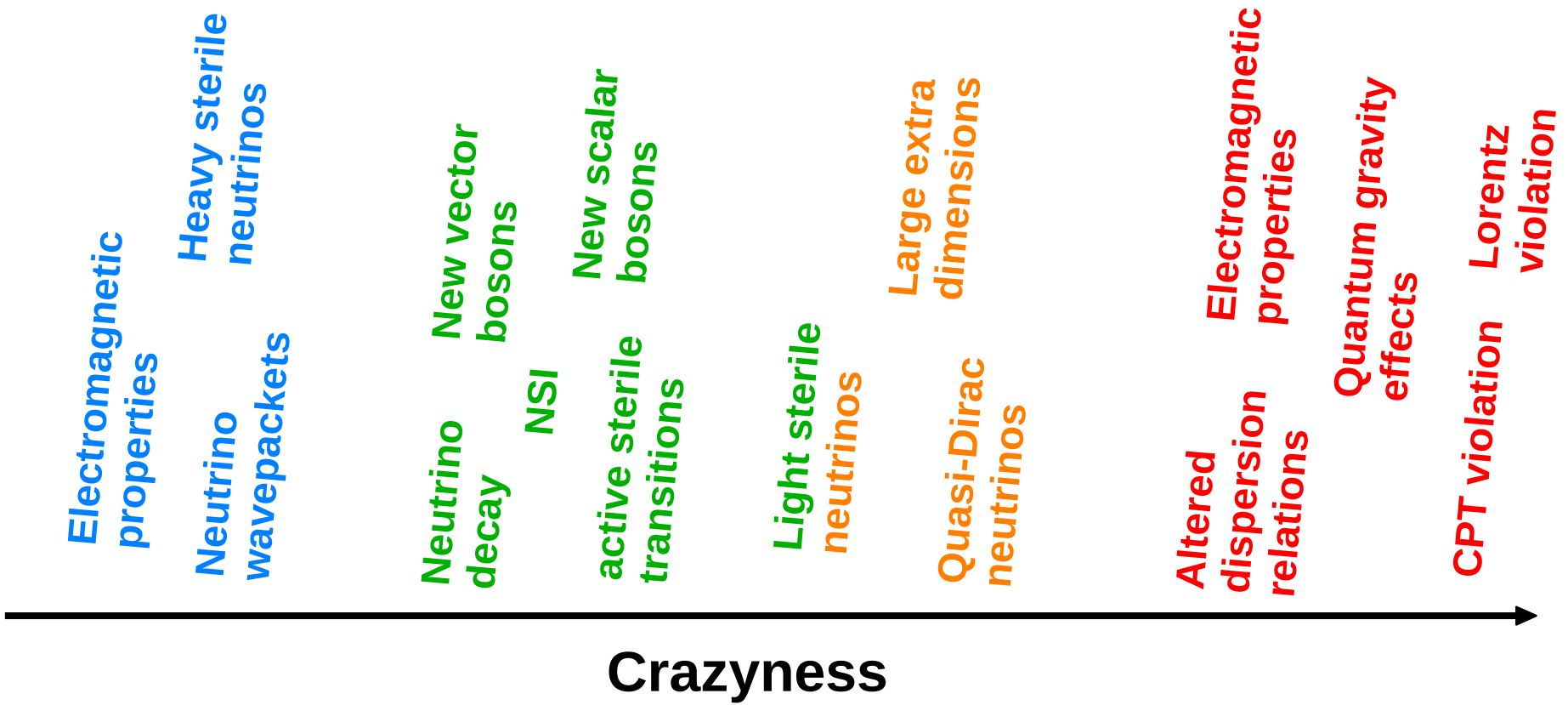
New scalar bosons

Large extra dimensions

Electromagnetic properties

Heavy sterile neutrinos

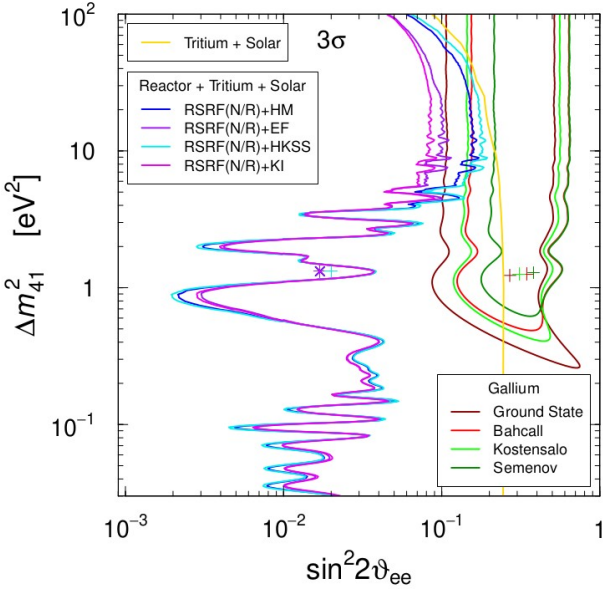
New physics searches at neutrino experiment



Examples

Investigation of neutrino anomalies

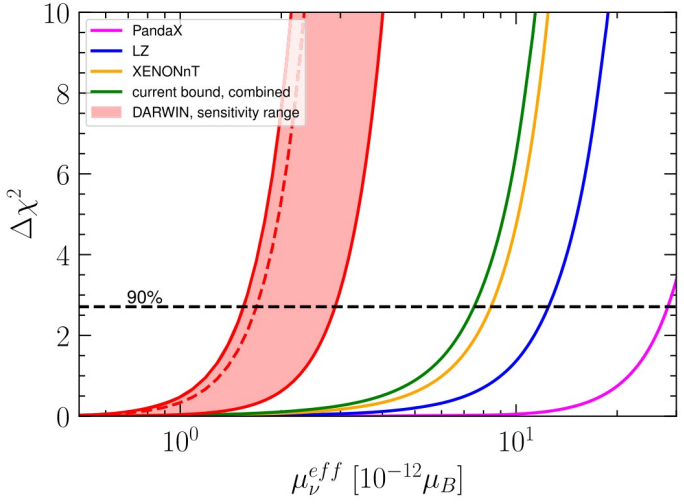
E.g.: tension among Gallium and reactor experiments



Giunti, Li, Ternes, Tyagi, Xin
2209.00916, JHEP 2022

New physics searches using neutrino interactions

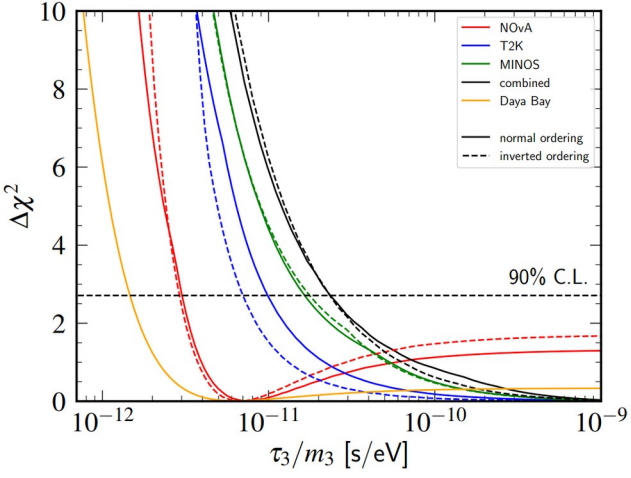
E.g.: Bounding effective neutrino magnetic moments with direct detection data



Giunti, Ternes
2309.17380, PRD 2023

Neutrino oscillation phenomenology

E.g.: Invisible neutrino decay at accelerator experiments



Ternes, Pagliaroli
2401.14316, PRD 2024


Grazie!
electron-
neutrino
muon
neutrino
tau-
neutrino