Large Extra Dimensions and Neutrino Experiments

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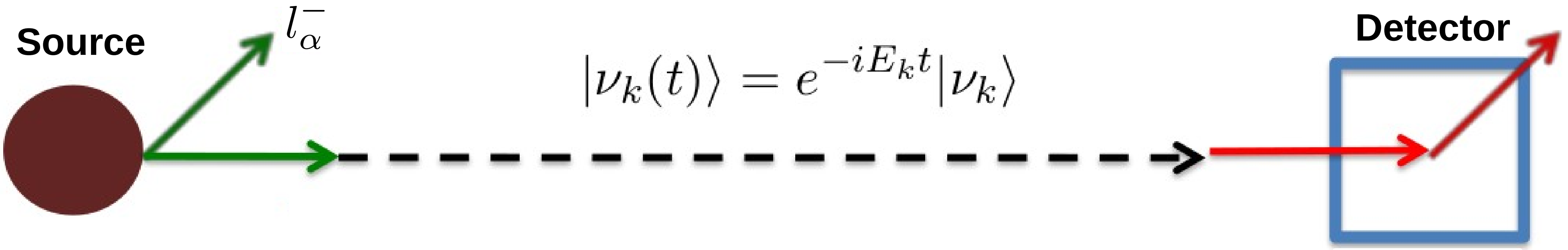
Neutrino oscillations



$$|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$$

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle$$

$$\langle\nu_\beta|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k}U_{\beta k}e^{-iE_k t}$$

$$P_{\nu_\alpha\to\nu_\beta}(t) = \left|A_{\nu_\alpha\to\nu_\beta}(t)\right|^2 = \sum_{k,j} U^*_{\alpha k}\,U_{\beta k}\,U_{\alpha j}\,U^*_{\beta j}\,e^{-i(E_k-E_j)t}$$

Three-neutrino oscillations

Neutrino mixing matrix

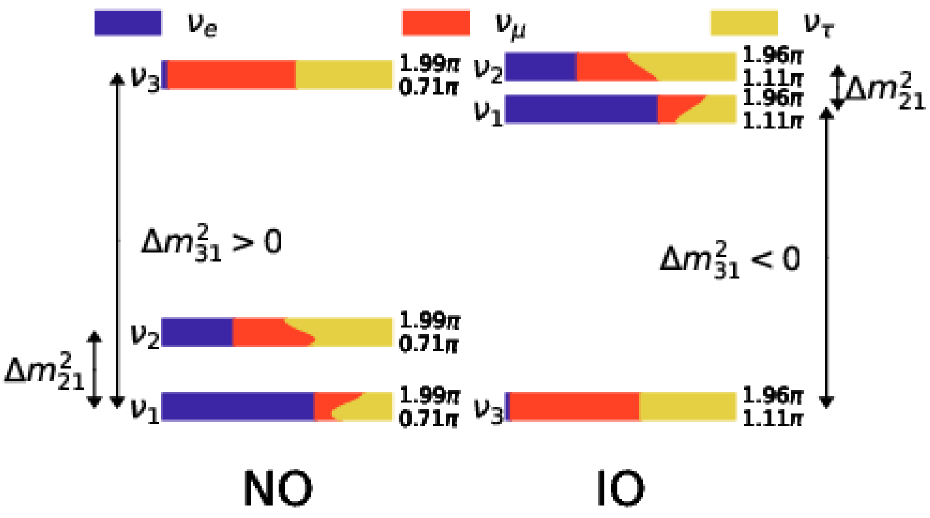
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

1 Dirac + 2 Majorana CP-phases

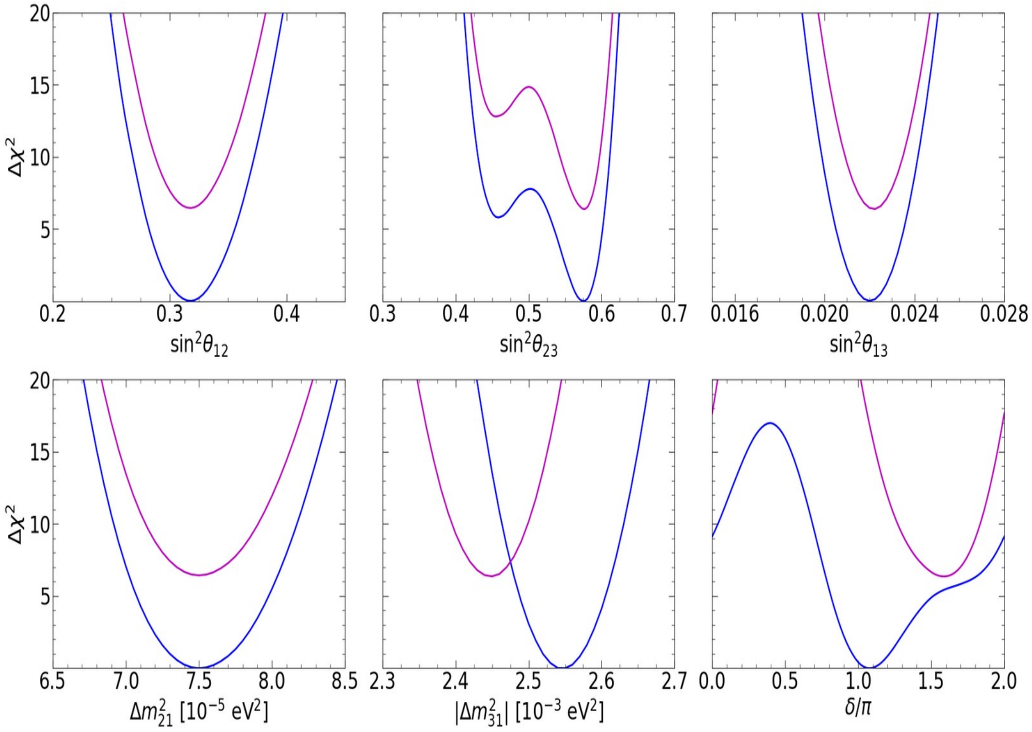
Three masses m_1, m_2, m_3 for which two orderings are possible

Oscillations are only sensitive to mass splittings



Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



parameter	best fit $\pm$ 1σ	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
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (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

Large Extra Dimensions

Motivation

Theories with Large Extra Dimensions (LED) originally constructed to solve the Standard Models hierarchy problem

New particles moving in standard and new dimensions can generate neutrino masses

The Kaluza-Klein excitations of the higher-dimensional right-handed neutrinos behave like an infinite tower of sterile neutrinos

The standard neutrino oscillation probability is affected by the parameters describing the Large Extra Dimension

Neutrino oscillations with LED

Diagonalization is performed in two steps. Neutrino mixing is given by

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \sum_{n=0}^{\infty} V_{in} \nu_{iL}^{(n)} \qquad (V_{in})^2 = \frac{2}{1 + \pi^2 \left(m_i^{\mathrm{D}} R_{\mathrm{ED}}\right)^2 + (m_i^{(n)}/m_i^{\mathrm{D}})^2} \qquad m_i^{(n)} = \lambda_i^{(n)}/R_{\mathrm{ED}}$$

$$\lambda_i^{(n)} - \pi \left(m_i^{\mathrm{D}} R_{\mathrm{ED}}\right)^2 \cot\left(\pi \lambda_i^{(n)}\right) = 0 \qquad \lambda_i^{(n)} \in [n, n+1/2]$$

Dienes, Dudas, Gherghetta, hep-ph/9811428, NPB 1999

Arkani-Hamed, Dimopoulos, Dvali, March-Russell, hep-ph/9811448, PRD 2001

Neutrino oscillations with LED

Caution!

$$\Delta m_{ij}^2 \neq \left(m_i^D\right)^2 - \left(m_j^D\right)^2$$

$$\Delta m_{kj}^2 = (m_k^{(0)})^2 - (m_j^{(0)})^2$$

Strategy:

- Using m_1^{D} calculate $\left(\lambda_1^{(0)}\right)^2$.
- Calculate

$$\left(\lambda_3^{(0)}\right)^2 = \left(\lambda_1^{(0)}\right)^2 + R_{\mathrm{ED}}^2 \Delta m_{\mathrm{atm}}^2 \qquad \left(\lambda_2^{(0)}\right)^2 = \left(\lambda_1^{(0)}\right)^2 + R_{\mathrm{ED}}^2 \Delta m_{\mathrm{sol}}^2$$

- Now obtain remaining Dirac masses from

$$\lambda_i^{(n)} - \pi \left(m_i^D R_{\mathrm{ED}}\right)^2 \cot\left(\pi \lambda_i^{(n)}\right) = 0$$

- Next solve for all modes of interest

Basto-Gonzales, Esmaili, Peres
1205.6212, PLB 2013

Neutrino oscillations with LED

LED effect the oscillations of neutrinos

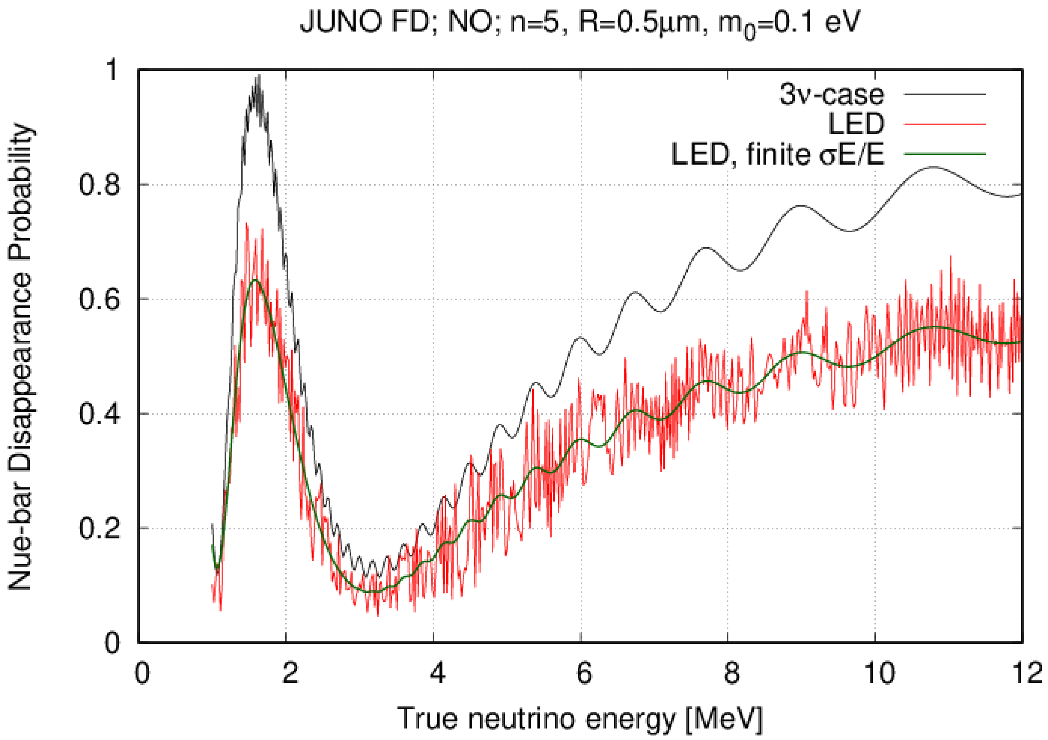
$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_{k=1}^{3} U_{\alpha k} U_{\beta k}^* \exp\left(-\frac{m_k^2 L}{2E_\nu}\right) \right|^2$$

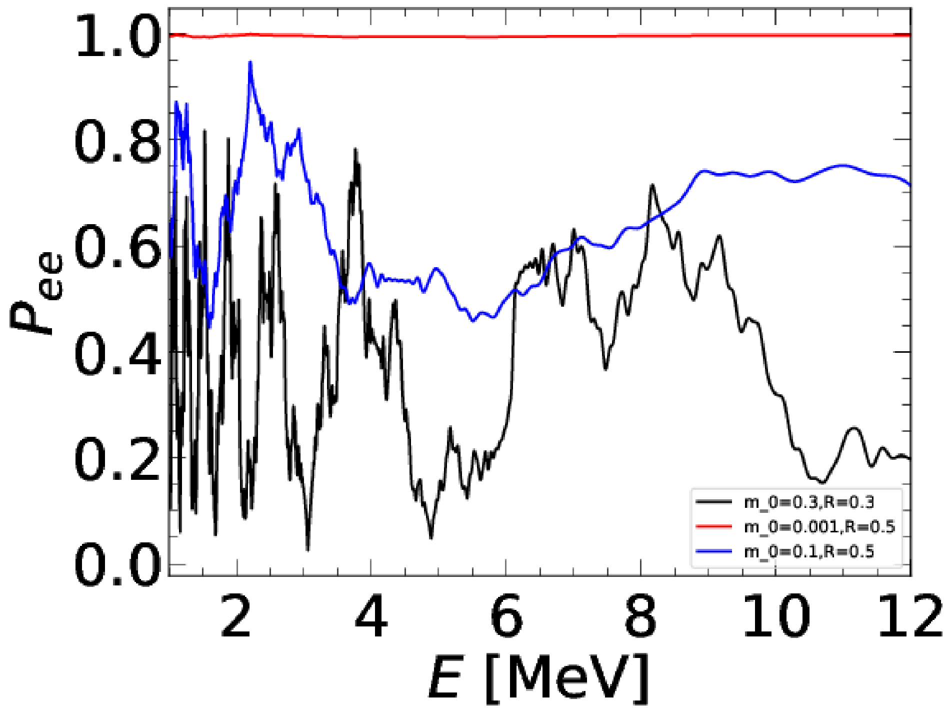
$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{i=1}^{3} \sum_{n=0}^{\infty} U_{\alpha i}^* U_{\beta i} V_{in}^2 \exp\left(-i \frac{(m_i^{(n)})^2 L}{2E}\right) \right|^2$$

Christoph Ternes

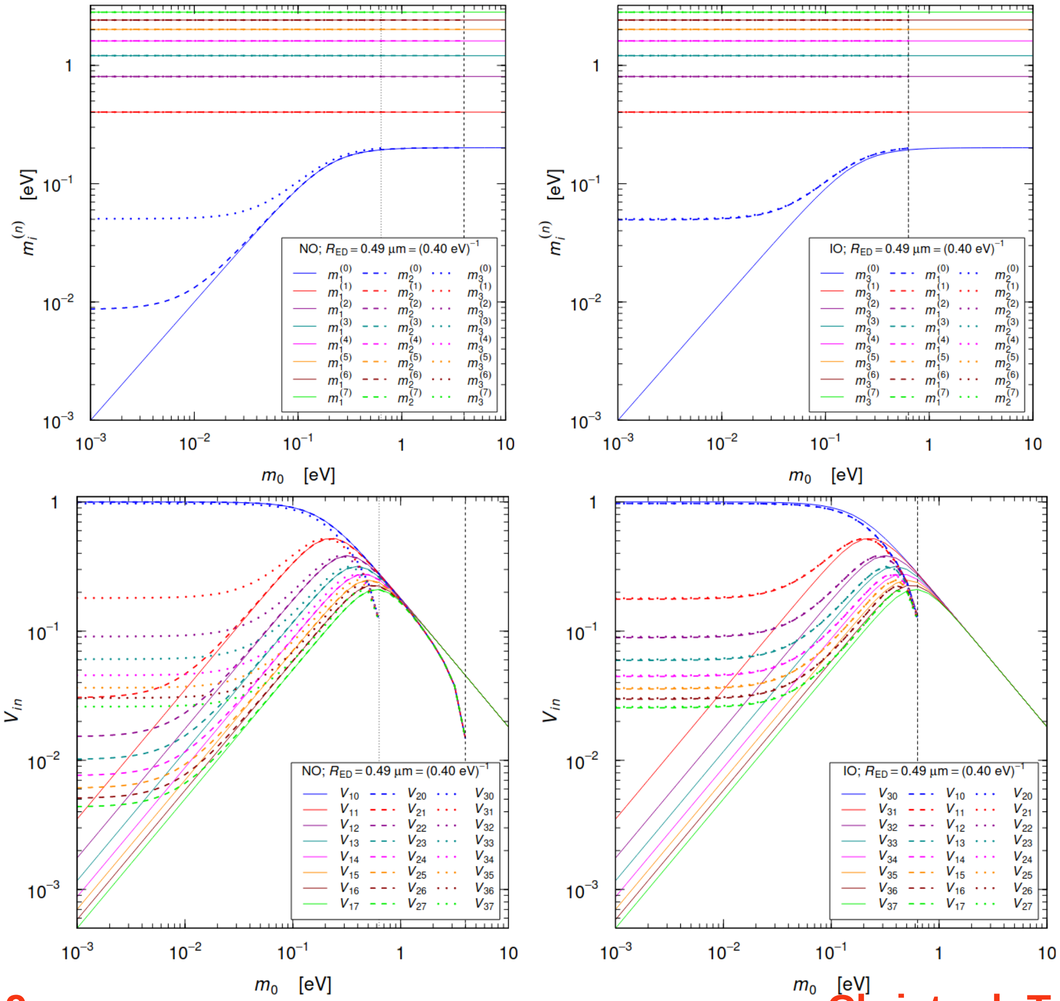
Neutrino oscillations with LED

LED effect the oscillations of neutrinos in far and near detectors





Neutrino oscillations with LED



LED effect the oscillations of neutrinos

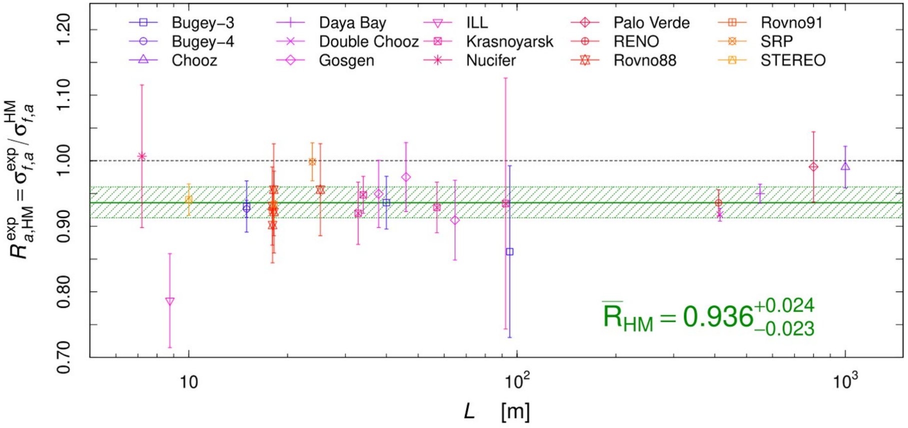
Different entrees of the mixing matrix are relevant for NO and IO

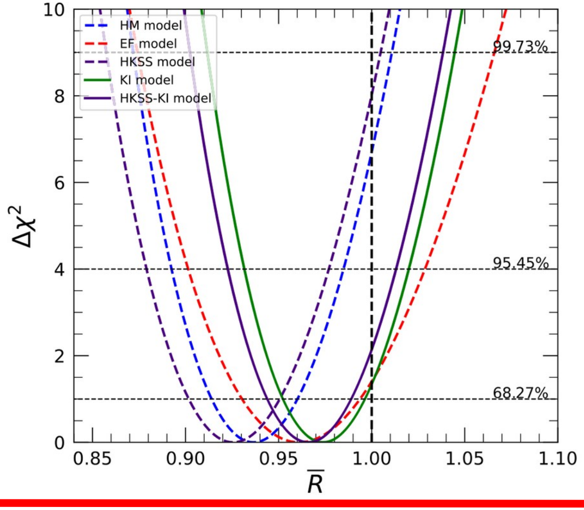
This leads to an enhanced sensitivity in IO when considering electron neutrino experiments

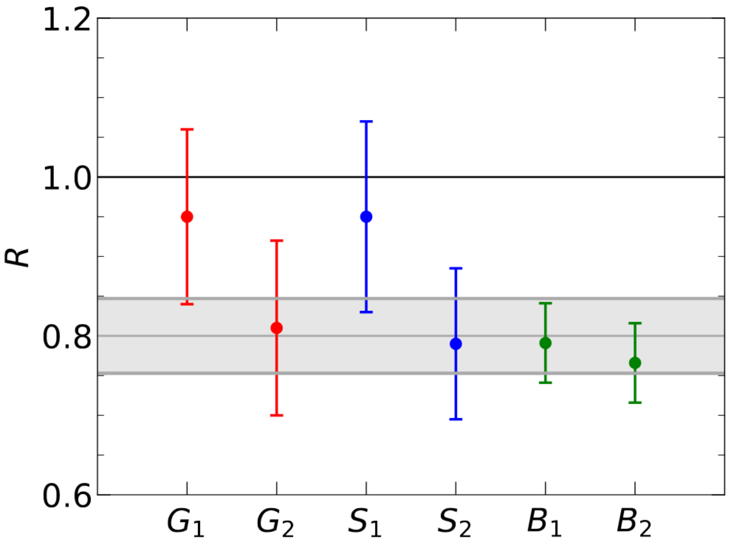
Forero, Giunti, Ternes, Tyagi, 2207.02790

SBN anomalies

Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

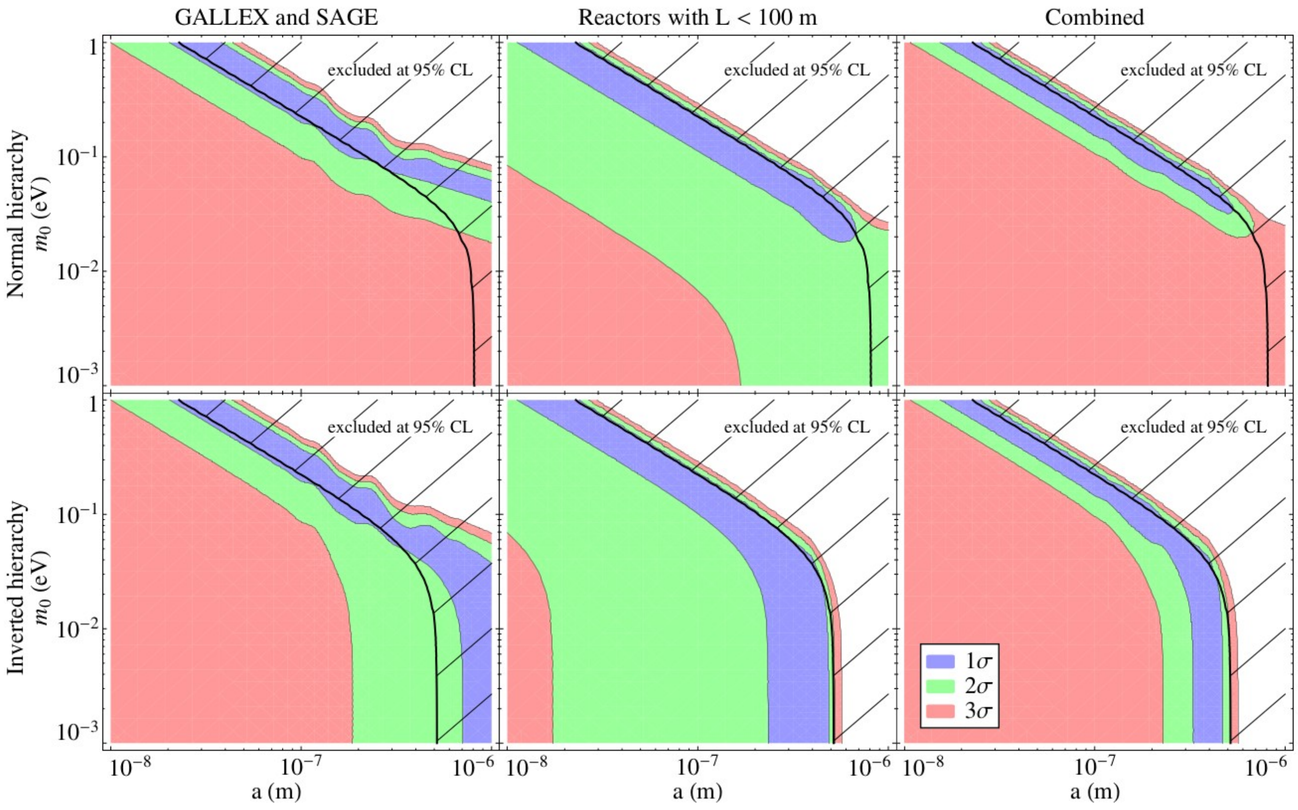






Reactor rate and Gallium experiments measure a deficit in the flux with respect to expectation

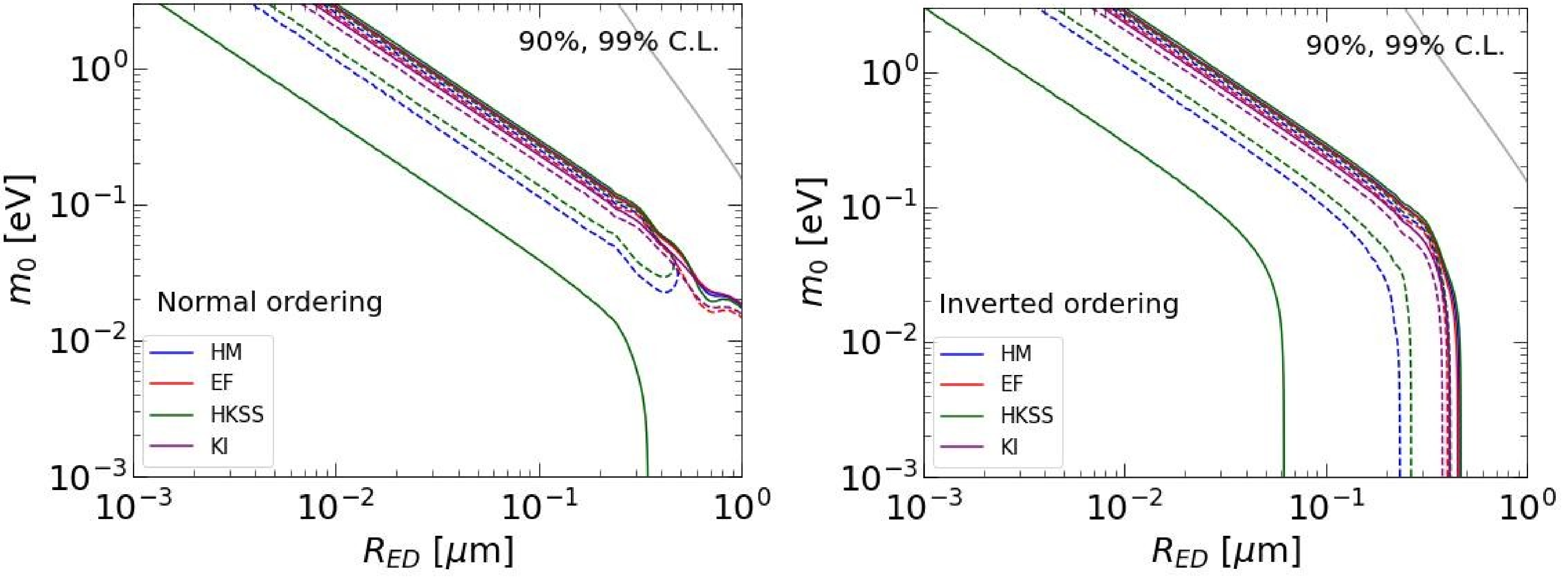
LED at short baselines



LED oscillations provided an alternative explanation of the Reactor and Gallium anomalies

Machado, Nunokawa, dos Santos, Zukanovich Funchal
1107.2400, PRD 2012

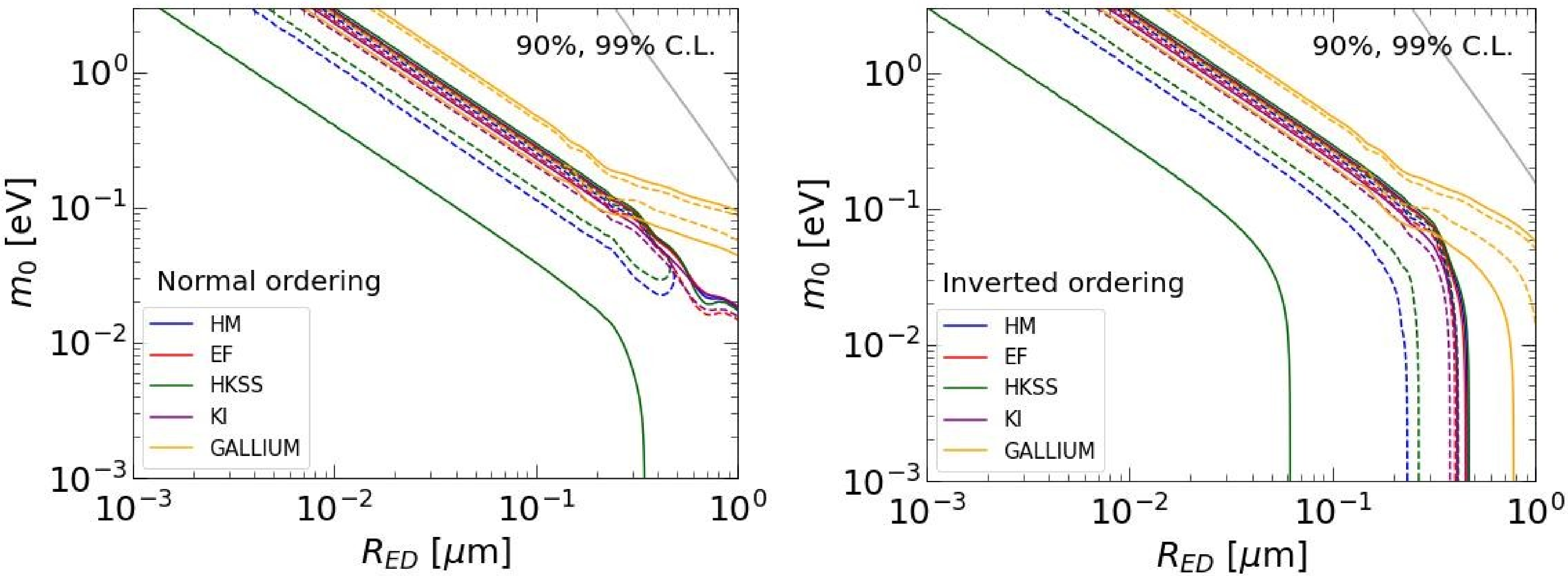
LED at short baselines



We perform an up-to-date analysis of reactor rate data...

Forero, Giunti, Ternes, Tyagi, 2207.02790

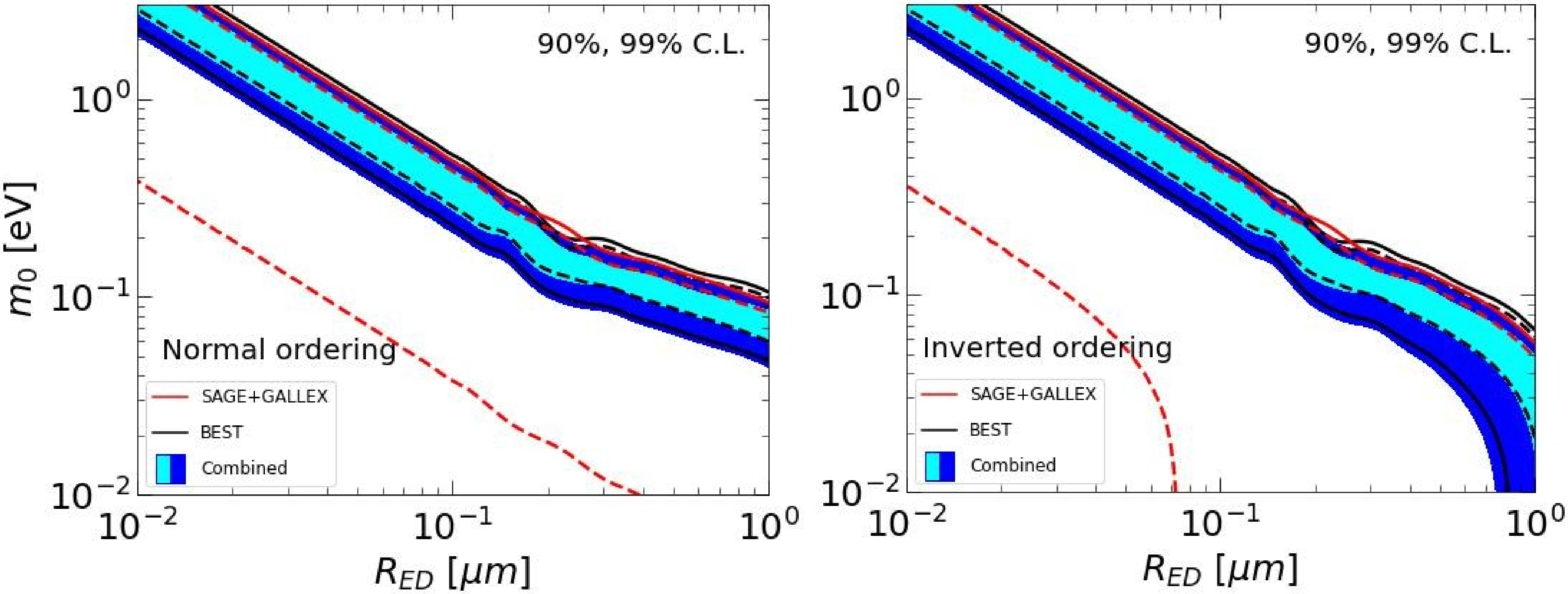
LED at short baselines



...and the GALLIUM data

Forero, Giunti, Ternes, Tyagi, 2207.02790

LED at short baselines



BEST data is pushing the preferred region away from the RAA region

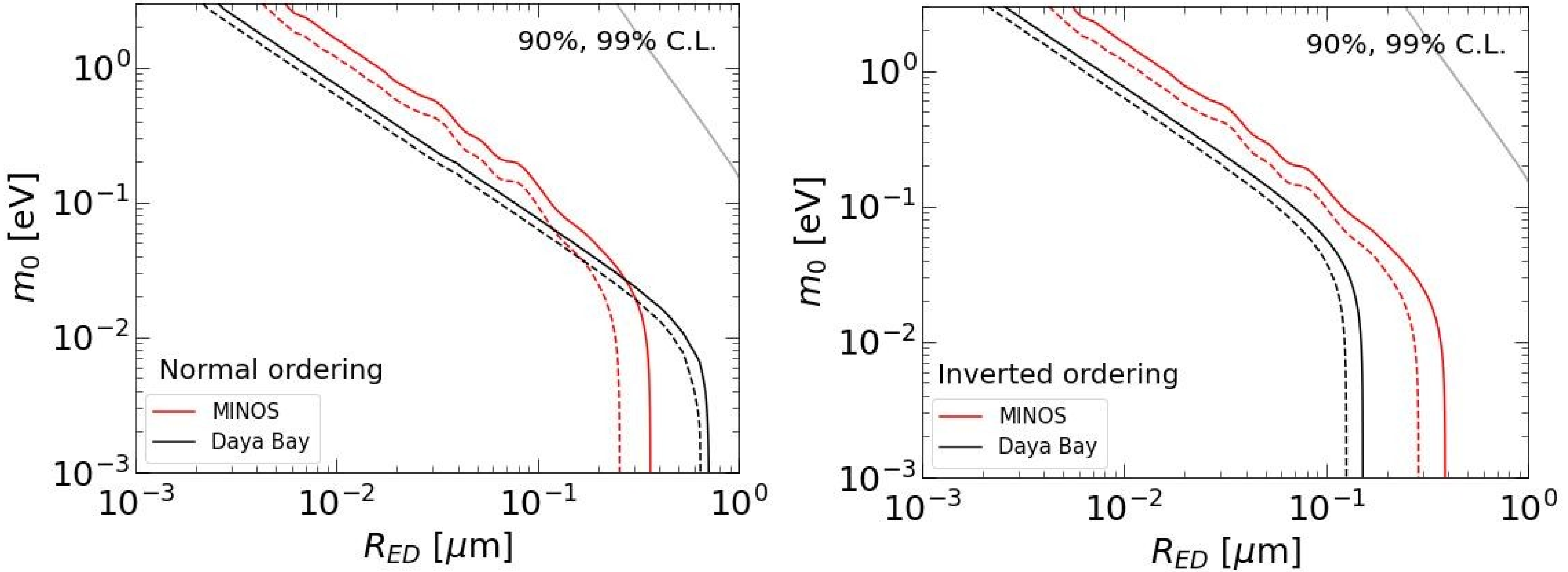
LED at long(ish) baselines

We also use data from Daya Bay and MINOS/MINOS+ to bound LED

Daya Bay uses 6 reactor cores (electron neutrinos) and measures the neutrino spectra at 3 experimental sites

MINOS/MINOS+ used the NUMI beam (muon neutrinos) from Fermilab to measure the neutrino flux at a near and a far detector

LED at long(ish) baselines



Daya Bay is most dominant for IO, while both experiments contribute to the region for NO

Forero, Giunti, Ternes, Tyagi, 2207.02790

LED at KATRIN

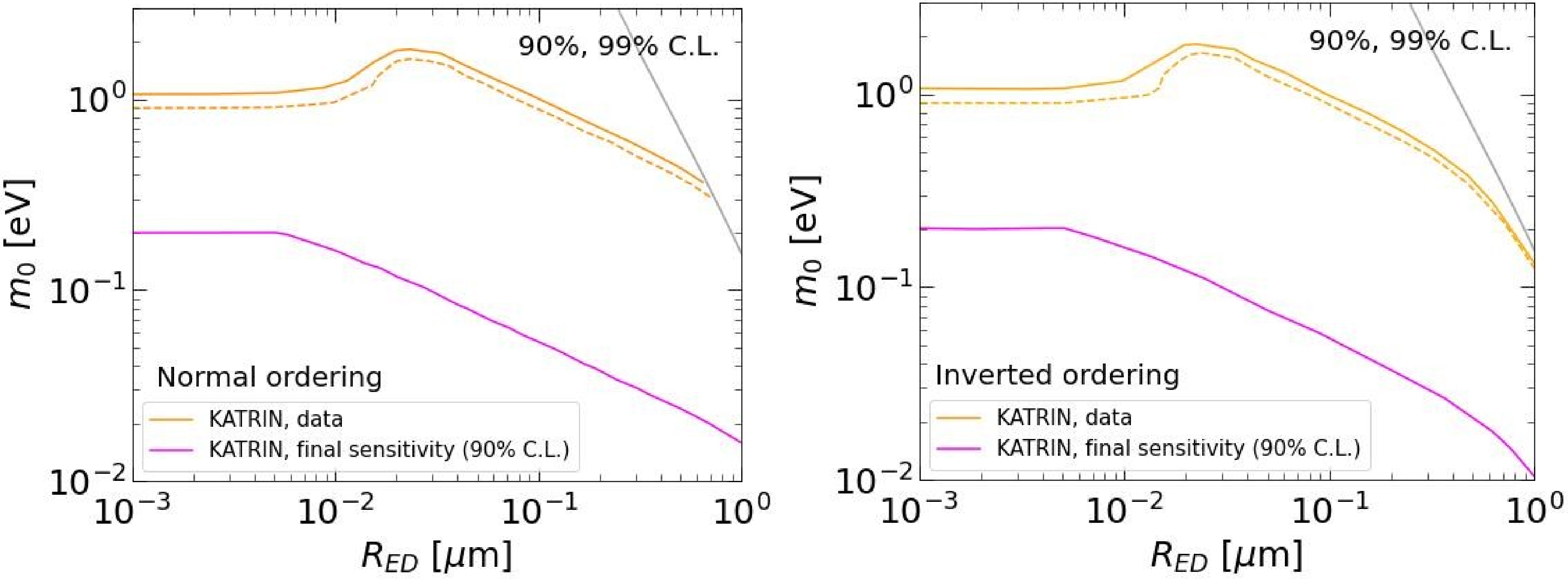
KATRIN measures the spectrum

$$R_\beta(E) \simeq \frac{G_F^2 \cos^2\theta_C}{2\pi^3} |\mathcal{M}|^2 F(E, Z+1)$$
$$\times (E + m_e)\sqrt{(E+m_e)^2 - m_e^2}$$
$$\times \sum_j \zeta_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_\beta^2}\,\Theta(\varepsilon_j - m_\beta)$$

where the last part gets modified to

$$K(E, m_0, R_{ED}) = \sum_j p_j \epsilon_j \sum_{i=1}^{3} |U_{ei}|^2 \sum_{n=0}^{\infty} (V_{in})^2 \sqrt{\epsilon_j^2 - \left(\frac{\lambda_i^{(n)}}{R_{\mathrm{ED}}}\right)^2}\,\Theta\left(\epsilon_j - \frac{\lambda_i^{(n)}}{R_{\mathrm{ED}}}\right)$$

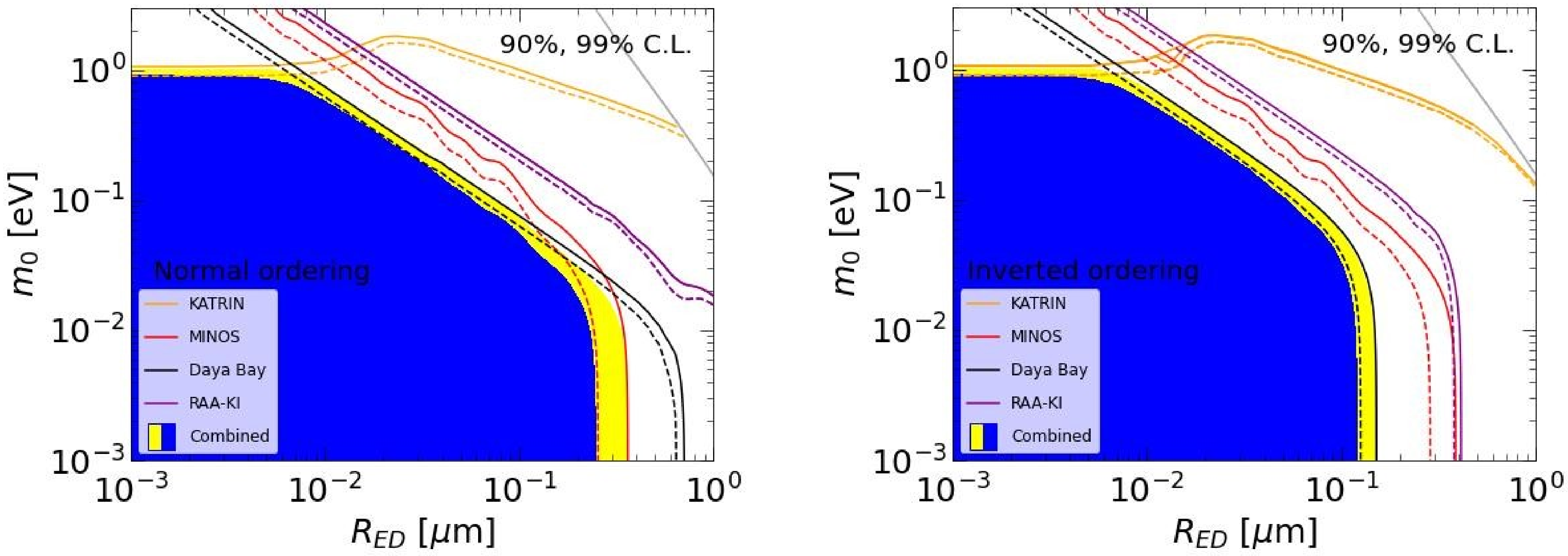
LED at KATRIN



KATRIN bounds the allowed regions for arbitrary small values of the compactification radius

Forero, Giunti, Ternes, Tyagi, 2207.02790

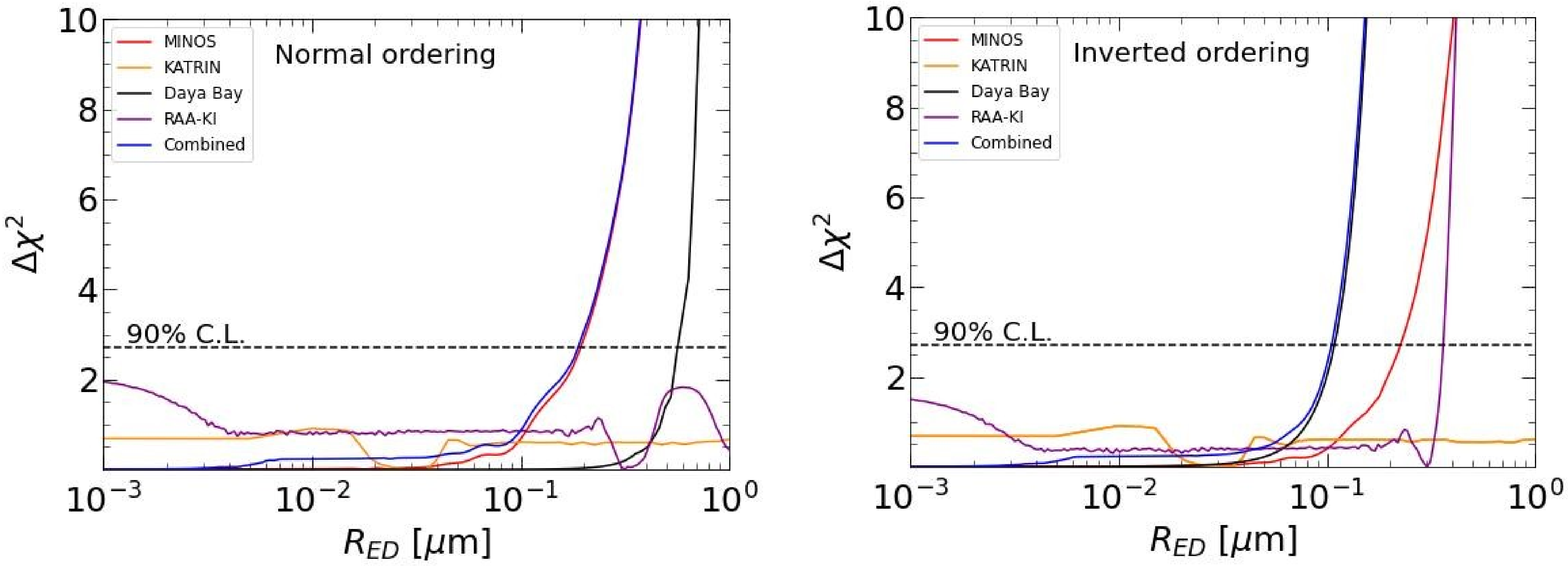
Combined bound on LED



Daya Bay, MINOS and KATRIN contribution particularly important to the allowed regions

Forero, Giunti, Ternes, Tyagi, 2207.02790

Combined bound on LED



We can set quite strong bounds on the compactification radius

Forero, Giunti, Ternes, Tyagi, 2207.02790

Bounds on LED

Neutrino experiments:

$$R_{\rm ED} < 0.20\ \mu{\rm m}\ \text{at}\ 90\%\ \text{C.L. for NO}$$
$$R_{\rm ED} < 0.10\ \mu{\rm m}\ \text{at}\ 90\%\ \text{C.L. for IO}\,.$$

CMS:

$$R_{\rm ED} < 4.8\ \mu{\rm m}\ \text{at}\ 95\%\ \text{C.L.}$$

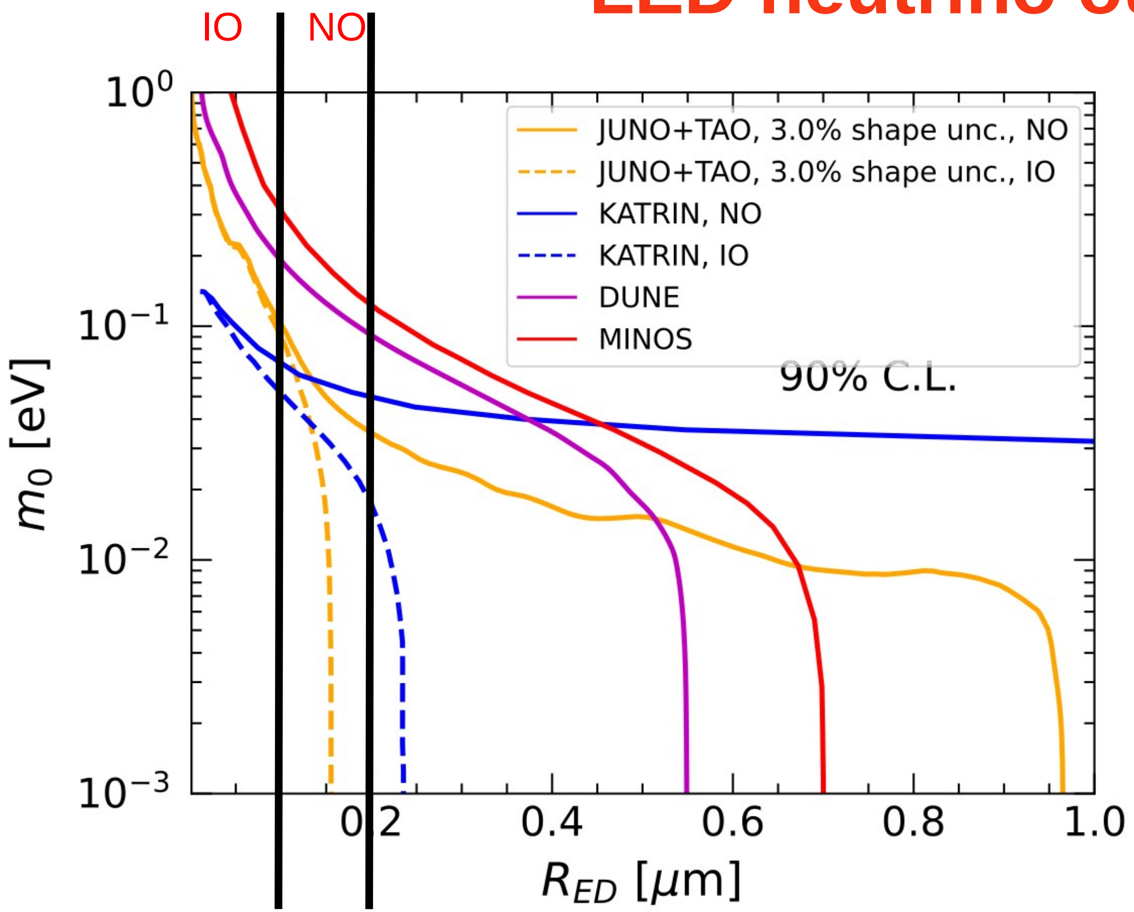
Table top gravitational experiments:

$$R_{\rm ED} < 37\ \mu{\rm m}\ \text{at}\ 95\%\ \text{C.L.}$$

Astrophysical tests:

$$R_{\rm ED} < 0.16 - 916\ {\rm nm}\ \text{at}\ 95\%\ \text{C.L.}$$

LED neutrino outlook



Current bounds are stronger than the expectations from next generation experiments

KATRIN data will become more constraining in the near future

Basto-Gonzalez, Forero, Giunti, Quiroga, Ternes, 2112.00379, PRD 2022

Conclusions

Neutrino oscillation experiments can be used to bound models with new states like models with Large Extra Dimensions

A LED explanation of the Gallium and reactor anomaly is excluded

Strong bounds on LED parameters can be set from the combined analysis of MINOS, Daya Bay and KATRIN data

The bound on the compactification radius of the largest LED from neutrino experiments is about two orders of magnitude stronger than from table top experiments


Grazie!
electron-neutrino
muon neutrino
tau-neutrino

LED model

Add 5-dim Fermion fields to SM $\Psi^\alpha = (\psi_L^\alpha, \psi_R^\alpha)$

They appear as Kaluza Klein exitations in our 4-dim brane

$$\nu_R^{\alpha(0)} = \psi_R^{\alpha(0)},$$

$$\nu_{L,R}^{\alpha(n)} = \frac{1}{\sqrt{2}}(\psi_{L,R}^{\alpha(n)} + \psi_{L,R}^{\alpha(-n)}), \quad \text{for } n = 1, \dots, \infty,$$

One obtains

$$\mathcal{L} = m_{\alpha\beta}^D \left(\bar{\nu}_R^{\alpha(0)} \nu_L^\beta + \sqrt{2} \sum_{n=0}^{\infty} \bar{\nu}_R^{\alpha(n)} \nu_L^\beta \right) + \sum_{n=1}^{\infty} \frac{n}{R_{\text{ED}}} \bar{\nu}_R^{\alpha(n)} \nu_L^{\alpha(n)} + \text{H.c.},$$

LED model

First step of diagonalization:

$$\mathrm{diag}(m_1^D, m_2^D, m_3^D) = R'^{\dagger} m^D U$$

with

$$\nu_L^\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_L^{i(0)},$$

$$\nu_R^{\alpha(0)} = \sum_{i=1}^{3} R'_{\alpha i} \nu_R^{i(0)},$$

$$\nu_{L,R}^{\alpha(n)} = \sum_{i=1}^{3} R'_{\alpha i} \nu_{L,R}^{i(n)}, \quad n = 1, 2, \ldots, \infty.$$

LED model

This leads to

$$\mathcal{L} = \sum_{i=1}^{3} \bar{\nu}_R^i M_i \nu_L^i + \text{H.c.}$$

with

$$\nu_{L,R}^i = (\nu_{L,R}^{i(0)}, \nu_{L,R}^{i(1)}, \ldots)^T,$$

$$M_i = \begin{pmatrix} m_i^D & 0 & 0 & \ldots \\ \sqrt{2} m_i^D & 1/R_{\text{ED}} & 0 & \ldots \\ \sqrt{2} m_i^D & 0 & 2/R_{\text{ED}} & \ldots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$