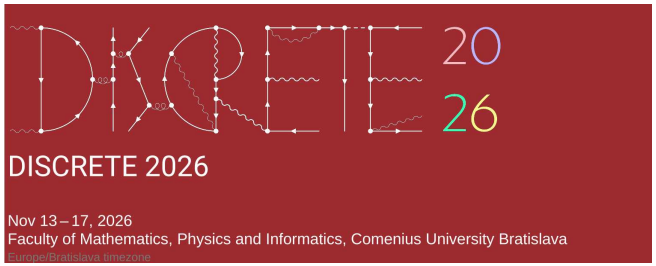
LESSONS FROM GLOBAL ANALYSIS OF NEUTRINO OSCILLATIONS

Concha Gonzalez-Garcia
(ICREA-University of Barcelona & YITP-Stony Brook)



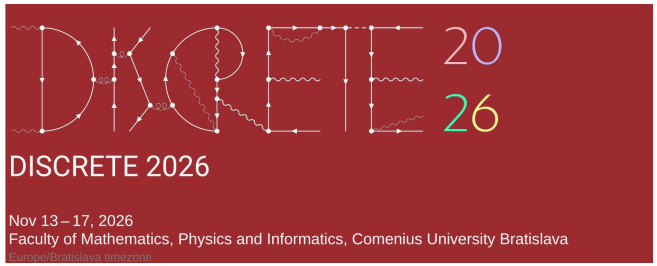






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Outline

Status of the 3ν global description

What we know and what we do not know (yet?)

Some implications & explorations







The ν evidence & path to BSM

- In the SM only $\nu_{L,\alpha}$, $\alpha = e, \mu, \tau$:

  Gauge Invariance $\Rightarrow$ Each Lepton Flavour α conserved $\Rightarrow$ Total Lepton # Conserved

  $\Leftrightarrow$ ν strictly massless

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- We have observed with high (or good) precision:
  - $*$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear likely to ν_τ (SK, MINOS, IceCube, KM3NeT)
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, T2K, MINOS, NOνA)
  - $*$ Some accel ν_μ & $\bar{\nu}_\mu$ appear as ν_e & $\bar{\nu}_e$ at $L \sim 300/800$ Km (T2K, MINOS, NOνA)
  - $*$ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
  - $*$ Reactor $\overline{\nu}_e$ disappear at $L \sim 200/60$ Km (KamLAND. JUNO)
  - $*$ Reactor $\overline{\nu}_e$ disappear at $L \sim 1$ Km (D-Chooz, Daya Bay, Reno)

  $\Rightarrow$ L_α are violated $\Rightarrow$ There is BSM Physics

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  $\Rightarrow$ L_α are violated $\Rightarrow$ There is BSM Physics

- The *important* question: What BSM? Not in this talk

  Talks by A. Teixeira, C. Hagedorn, M-C. Chen, F. Feruglio...

- The global analysis path:

  Precise consistent determination of the low energy effective Lagrangian of such BSM

The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

  $*$ With SM fields: Use ν_L^c is right-handed

$$\mathcal{L} - \mathcal{L}_{SM} = -\tfrac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c. \Rightarrow \begin{cases} L \text{ is violated} \Rightarrow \text{Majorana } \nu = \nu^c \\ SU(2)_L \text{ is violated} \Rightarrow \text{Effective LE} \end{cases}$$

  $*$ Introduce ν_R AND impose L conservation

$$\mathcal{L} - \mathcal{L}_{SM} = -M_D \overline{\nu_L} \nu_R - \tfrac{1}{2} M_R \cancel{\overline{\nu_R}} \nu_R^C + h.c. \Rightarrow \text{Dirac } \nu \neq \nu^c\text{:}$$

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- Either way $\Rightarrow$ Charged current interactions of massive leptons are not diagonal

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{\rm LEP}^{ij} \, \overline{\ell^i} \, \gamma^\mu \, L \, \nu^j \; + \; U_{\rm CKM}^{ij} \, \overline{U^i} \, \gamma^\mu \, L \, D^j \right) \; + \; h.c.$$

  For $N = 3 + s$ $\nu' s$: $U_{\rm LEP}$= $3 \times N$ $U_{\rm LEP} U_{\rm LEP}^\dagger = I_{3\times 3}$ $U_{\rm LEP}^\dagger U_{\rm LEP} \neq I_{N\times N}$

- Either way $\Rightarrow$ Lepton flavours not conserved in ν propagation

The New Minimal Standard Model: ν flavour oscillations

- In vacuum:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j<i}^{n} \mathrm{Re}[U^{\star}_{\alpha i}U_{\beta i}U_{\alpha j}U^{\star}_{\beta j}]\sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j<i}\mathrm{Im}[U^{\star}_{\alpha i}U_{\beta i}U_{\alpha j}U^{\star}_{\beta j}]\sin\left(\Delta_{ij}\right)$$

$\frac{\Delta_{ij}}{2} = (m_i^2 - m_j^2)\frac{L}{4E} \Rightarrow$ No information on ν mass scale nor Majorana/Dirac

- When osc between 2-ν dominates: $P_{\alpha\neq\beta} = \sin^2(2\theta)\ \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$

  $\Rightarrow$ No information on Mass Ordering ($\equiv \mathrm{sign}(\Delta m^2)$) nor octant of θ nor CPV

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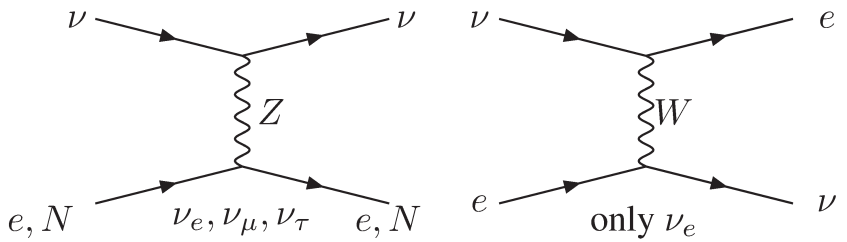
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j<i}^{n} \mathrm{Re}[U^{\star}_{\alpha i}U_{\beta i}U_{\alpha j}U^{\star}_{\beta j}]\sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j<i}\mathrm{Im}[U^{\star}_{\alpha i}U_{\beta i}U_{\alpha j}U^{\star}_{\beta j}]\sin\left(\Delta_{ij}\right)$$

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- If ν cross matter regions (Sun, Earth...)
  it interacts *coherently*
  Different flavours have different interactior



  $\Rightarrow$ Effective potential in ν_e evolution: $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^{\nu_e} = -\Delta V^{\bar{\nu}_e} = \sqrt{2}G_F N_e$

  $\Rightarrow$ Modification of mixing angle and oscillation wavelength (MSW)

    $\Rightarrow$ Solar $\nu_e' s$: 2ν-dominant dependence on θ octant

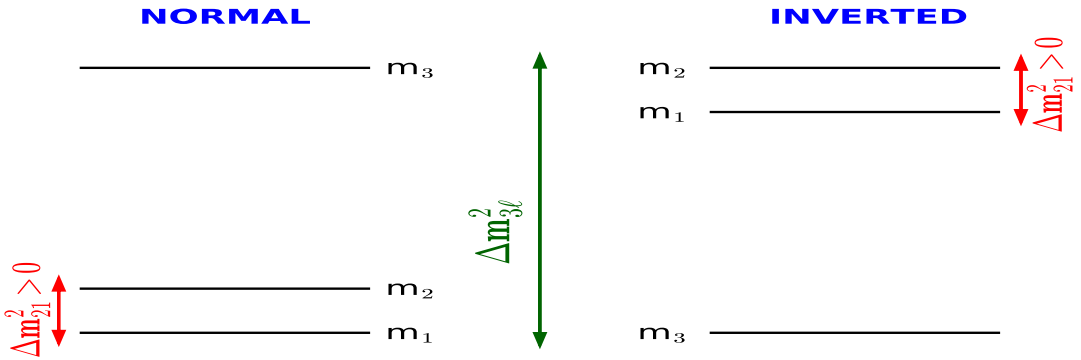
    $\Rightarrow$ LBL & ATM $\nu_{\mu(e)}, \overline{\nu}_{\mu(e)}$: Dependence on sign($\Delta m^2$)

3 ν Flavour Parameters

- For **for 3 ν's** : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Convention: $0 \leq \theta_{ij} \leq 90^\circ \quad 0 \leq \delta \leq 360^\circ \quad \Rightarrow$ 2 Mass Orderings (MO)



$\Delta m^2_{21} > 0$ by convention

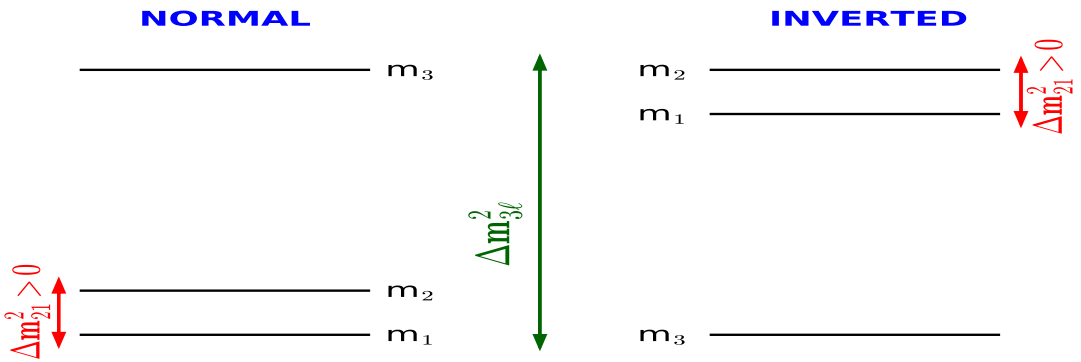
$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

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Experiment	2ν dominant	3ν effects	3ν synergies
Solar Experiments	θ_{12}, Δm^2_{21}	θ_{13}	
Reactor LBL (KamLAND/JUNO)	θ_{12}, Δm^2_{21}	θ_{13}, $\lvert\Delta m^2_{3\ell}\rvert$, MO	
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{3\ell}\rvert$	θ_{12}, Δm^2_{21}	
Atmospheric Experiments (SK,IC)	θ_{23}, $\lvert\Delta m^2_{3\ell}\rvert$	θ_{13}, $\delta_{\rm cp}$, MO	MO
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	θ_{23} , $\lvert\Delta m^2_{3\ell}\rvert$	θ_{12}, Δm^2_{21}	
Acc LBL ν_e App (Minos,T2K,NOvA)	θ_{13}, $\lvert\Delta m^2_{3\ell}\rvert$	$\delta_{\rm cp}$, MO, θ_{23}	

3 ν Global Analysis

Bari

PHYSICAL REVIEW D **111,** 093006 (2025)

Neutrino masses and mixing: Entering the era of subpercent precision

Francesco Capozzi,[1,2] William Giarè,[3] Eligio Lisi,[4] Antonio Marrone,[5,4] Alessandro Melchiorri,[6,7] and Antonio Palazzo[5,4]

[1]*Dipartimento di Scienze Fisiche e Chimiche, Università degli Studi dell'Aquila, 67100 L'Aquila, Italy*
[2]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali del Gran Sasso, 67100 Assergi (L'Aquila), Italy*
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[7]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma I, Piazzale Aldo Moro 2, 00185 Rome, Italy*

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We perform an updated global analysis of the known and unknown parameters of the standard three-neutrino (3ν) framework, using data available at the beginning of 2025. The known oscillation parameters include three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and two squared mass gaps, chosen as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)$, where the discrete parameter $\alpha = \mathrm{sign}(\Delta m^2)$ distinguishes normal ordering (NO, $\alpha = +1$) from inverted ordering (IO, $\alpha = -1$). With respect to our previous 2021 update, the combination of accelerator, reactor, and atmospheric neutrino data leads to appreciably reduced uncertainties for θ_{23}, θ_{13}, and $|\Delta m^2|$. In particular, $|\Delta m^2|$ is the first 3ν parameter to enter the domain of subpercent precision (0.8% at 1σ). We underline some issues about common systematics in combined fits that might affect (and possibly weaken) this error estimate. Concerning oscillation unknowns, we find a relatively weak preference for NO versus IO (at 2.2σ), for *CP* violation versus conservation in NO (1.3σ), and for the first θ_{23} octant versus the second in NO (1.1σ). We discuss the current status and qualitative prospects of the mass ordering hint in the plane charted by the mass parameters $(\delta m^2, \Delta m^2_{ee})$, where $\Delta m^2_{ee} = |\Delta m^2| + \frac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$, to be jointly measured by the JUNO experiment with subpercent precision. We also discuss upper bounds on nonoscillation observables, including the effective ν_e mass m_β in β decay, the effective Majorana mass $m_{\beta\beta}$ in $0\nu\beta\beta$ decay, and the sum of neutrino masses Σ in cosmology. We adopt $m_\beta < 0.50$ eV (2σ) from current ^{3}H data and report $m_{\beta\beta} < 0.086$ eV (2σ) from a combined ^{76}Ge, ^{130}Te, and ^{136}Xe data analysis, accounting for parametrized nuclear matrix element covariances. Concerning Σ, current results show tensions within the standard Λ cold dark matter (ΛCDM) cosmological model, pulling Σ toward unphysical values and suggesting possible model extensions. We discuss representative combinations of data, with or without augmenting the ΛCDM model with extra parameters accounting for possible systematics (lensing anomaly) or new physics (dynamical dark energy). The resulting 2σ upper limits are roughly spread around the bound $\Sigma < 0.2$ eV within a factor of 3 (both up- and downward), with different implications for NO and IO scenarios. Bounds from oscillation and nonoscillation data are also discussed in the planes charted by pairs of $(m_\beta, m_{\beta\beta}, \Sigma)$ parameters.

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I. INTRODUCTION

Results from solar, atmospheric, accelerator, and reactor neutrino oscillation experiments have established the standard three-neutrino (3ν) framework, where the neutrino states $(\nu_e, \nu_\mu, \nu_\tau)$ with definite flavor are mixed with neutrino states (ν_1, ν_2, ν_3) with definite masses (m_1, m_2, m_3) via a unitary mixing matrix U_{ai} [1,2]. The current pillars of the 3ν framework are represented by multiple measurements of five parameters: three mixing angles θ_{ij} $(\theta_{12}, \theta_{13}, \theta_{23})$ governing oscillation amplitudes and two independent squared mass differences governing oscillation frequencies, which we choose as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)$. Each of these

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2020 global reassessment of the neutrino oscillation picture

P.F. de Salas,[a] **D.V. Forero,**[b] **S. Gariazzo,**[c,d] **P. Martínez-Miravé,**[c,e] **O. Mena,**[c] **C.A. Ternes,**[c,d] **M. Tórtola**[c,e] **and J.W.F. Valle**[c]

[a] *The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, 10691 Stockholm, Sweden*
[b] *Universidad de Medellín, Carrera 87 N° 30-65, Medellín, Colombia*
[c] *Instituto de Física Corpuscular, CSIC-Universitat de València, 46980 Paterna, Spain*
[d] *INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*
[e] *Departament de Física Teòrica, Universitat de València, 46100 Burjassot, Spain*

E-mail: pablo.fernandez@fysik.su.se, dvanegas@udem.edu.co, gariazzo@to.infn.it, pamarmi@ific.uv.es, omena@ific.uv.es, chternes@ific.uv.es, mariam@ific.uv.es, valle@ific.uv.es

Abstract: We present an updated global fit of neutrino oscillation data in the simplest three-neutrino framework. In the present study we include up-to-date analyses from a number of experiments. Concerning the atmospheric and solar sectors, besides the data considered previously, we give updated analyses of IceCube DeepCore and Sudbury Neutrino Observatory data, respectively. We have also included the latest electron antineutrino data collected by the Daya Bay and RENO reactor experiments, and the long-baseline T2K and NOνA measurements, as reported in the Neutrino 2020 conference. All in all, these new analyses result in more accurate measurements of θ_{13}, θ_{12}, Δm^2_{21} and $|\Delta m^2_{31}|$. The best fit value for the atmospheric angle θ_{23} lies in the second octant, but first octant solutions remain allowed at $\sim 2.4\sigma$. Regarding CP violation measurements, the preferred value of δ we obtain is 1.08π (1.58π) for normal (inverted) neutrino mass ordering. The global analysis still prefers normal neutrino mass ordering with 2.5σ statistical significance. This preference is milder than the one found in previous global analyses. These new results should be regarded as robust due to the agreement found between our Bayesian and frequentist approaches. Taking into account only oscillation data, there is a weak/moderate

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NuFit-6.0: updated global analysis of three-flavor neutrino oscillations

Ivan Esteban,[a,b] **M.C. Gonzalez-Garcia,**[c,d,e] **Michele Maltoni,**[f] **Ivan Martinez-Soler,**[g] **João Paulo Pinheiro**[c] **and Thomas Schwetz**[h]

[a] *Department of Physics, University of the Basque Country UPV/EHU, PO Box 644, 48080 Bilbao, Spain*
[b] *EHU Quantum Center, University of the Basque Country UPV/EHU, PO Box 644, 48080 Bilbao, Spain*
[c] *Departament de Física Quàntica i Astrofísica and Institut de Ciencies del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain*
[d] *Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluis Companys 23, 08010 Barcelona, Spain*
[e] *C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, NY 11794-3840, U.S.A.*
[f] *Instituto de Física Teórica UAM/CSIC, Calle de Nicolás Cabrera 13–15, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[g] *Institute for Particle Physics Phenomenology, Durham University, South Road, DH1 3LE, Durham, U.K.*
[h] *Institut für Astroteilchenphysik, Karlsruher Institut für Technologie (KIT), 76021 Karlsruhe, Germany*

E-mail: ivan.esteban@ehu.eus, concha.gonzalez-garcia@stonybrook.edu, michele.maltoni@csic.es, ivan.j.martinez-soler@durham.ac.uk, joaopaulo.pinheiro@fqa.ub.edu, schwetz@kit.edu

Abstract: We present an updated global analysis of neutrino oscillation data as of September 2024. The parameters θ_{12}, θ_{13}, Δm^2_{21}, and $|\Delta m^2_{3\ell}|$ $(\ell = 1, 2)$ are well-determined with relative precision at 3σ of about 13%, 8%, 15%, and 6%, respectively. The third mixing angle θ_{23} still suffers from the octant ambiguity, with no clear indication of whether it is larger or smaller than 45°. The determination of the leptonic CP phase $\delta_{\rm CP}$ depends on the neutrino mass ordering: for normal ordering the global fit is consistent with CP conservation within 1σ, whereas for inverted ordering CP-violating values of $\delta_{\rm CP}$ around 270° are favored against CP conservation at more than 3.6σ. While the present data has in principle 2.5–3σ sensitivity to the neutrino mass ordering, there are different tendencies in the global data that reduce the discrimination power: T2K and NOvA appearance data individually favor normal ordering, but they are more consistent with each other for inverted ordering. Conversely, the joint determination of $|\Delta m^2_{3\ell}|$ from global disappearance data prefers normal ordering. Altogether,

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Talk by A. Marrone

3 ν Global Analysis

Bari

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2020 global reassessment of the neutrino oscillation picture

P.F. de Salas,[a] D.V. Forero,[b] S. Gariazzo,[c,d] P. Martínez-Miravé,[c,e] O. Mena,[c] C.A. Ternes,[c,d] M. Tórtola[c,e] and J.W.F. Valle[c]

[a]*Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*
[b]*Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, VA 24061, U.S.A.*
[c]*Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[d]*Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*
[e]*Departament de Física Teòrica, Universitat de València, 46100 Burjassot, Spain*

E-mail: pablo.fernandez@fysik.su.se, dvanegas@udem.edu.co, gariazzo@to.infn.it, pamarmi@ific.uv.es, omena@ific.uv.es, chternes@ific.uv.es, mariam@ific.uv.es, valle@ific.uv.es

Abstract: We present an updated global fit of neutrino oscillation data in the simplest three-neutrino framework. In the present study we include up-to-date analyses from a number of experiments. Concerning the atmospheric and solar sectors, besides the data considered previously, we give updated analyses of IceCube DeepCore and Sudbury Neutrino Observatory data, respectively. We have also included the latest electron antineutrino data collected by the Daya Bay and RENO reactor experiments, and the long-baseline T2K and NOνA measurements, as reported in the Neutrino 2020 conference. All in all, these new analyses result in more accurate measurements of θ_{13}, θ_{12}, Δm^2_{21} and $|\Delta m^2_{31}|$. The best fit value for the atmospheric angle θ_{23} lies in the second octant, but first octant solutions remain allowed at $\sim 2.4\sigma$. Regarding CP violation measurements, the preferred value of δ we obtain is 1.08π (1.58π) for normal (inverted) neutrino mass ordering. The global analysis still prefers normal neutrino mass ordering with 2.5σ statistical significance. This preference is milder than the one found in previous global analyses. These new results should be regarded as robust due to the agreement found between our Bayesian and frequentist approaches. Taking into account only oscillation data, there is a weak/moderate

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NuFIT (www.nu-fit.org)

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NuFit-6.0: updated global analysis of three-flavor neutrino oscillations

Ivan Esteban,[a,b] M.C. Gonzalez-Garcia,[c,d,e] Michele Maltoni,[f] Ivan Martinez-Soler,[g] João Paulo Pinheiro[c] and Thomas Schwetz[h]

[a]*Department of Physics, University of the Basque Country UPV/EHU, PO Box 644, 48080 Bilbao, Spain*
[b]*Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706, USA*
[c]*Institute for Nuclear Theory, 31 West 43rd Street, New York, NY 10036, USA*
[d]*Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA*
[e]*Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[f]*Institute for Particle Physics Phenomenology, Durham University, South Road, DH1 3LE, Durham, U.K.*
[g]*Institut für Astroteilchenphysik, Karlsruher Institut für Technologie (KIT), 76021 Karlsruhe, Germany*

E-mail: ivan.esteban@ehu.eus, concha.gonzalez-garcia@stonybrook.edu, michele.maltoni@csic.es, ivan.j.martinez-soler@durham.ac.uk, joaopaulo.pinheiro@fqa.ub.edu, schwetz@kit.edu

Abstract: We present an updated global analysis of neutrino oscillation data as of September 2024. The parameters θ_{12}, θ_{13}, Δm^2_{21}, and $|\Delta m^2_{3\ell}|$ $(\ell = 1, 2)$ are well-determined with relative precision at 3σ of about 13%, 8%, 15%, and 6%, respectively. The third mixing angle θ_{23} still suffers from the octant ambiguity, with no clear indication of whether it is larger or smaller than 45°. The determination of the leptonic CP phase $\delta_{\rm CP}$ depends on the neutrino mass ordering: for normal ordering the global fit is consistent with CP conservation within 1σ, whereas for inverted ordering CP-violating values of $\delta_{\rm CP}$ around 270° are favored against CP conservation at more than 3.6σ. While the present data has in principle 2.5–3σ sensitivity to the neutrino mass ordering, there are different tendencies in the global data that reduce the discrimination power: T2K and NOvA appearance data individually favor normal ordering, but they are more consistent with each other for inverted ordering. Conversely, the joint determination of $|\Delta m^2_{3\ell}|$ from global disappearance data prefers normal ordering. Altogether,

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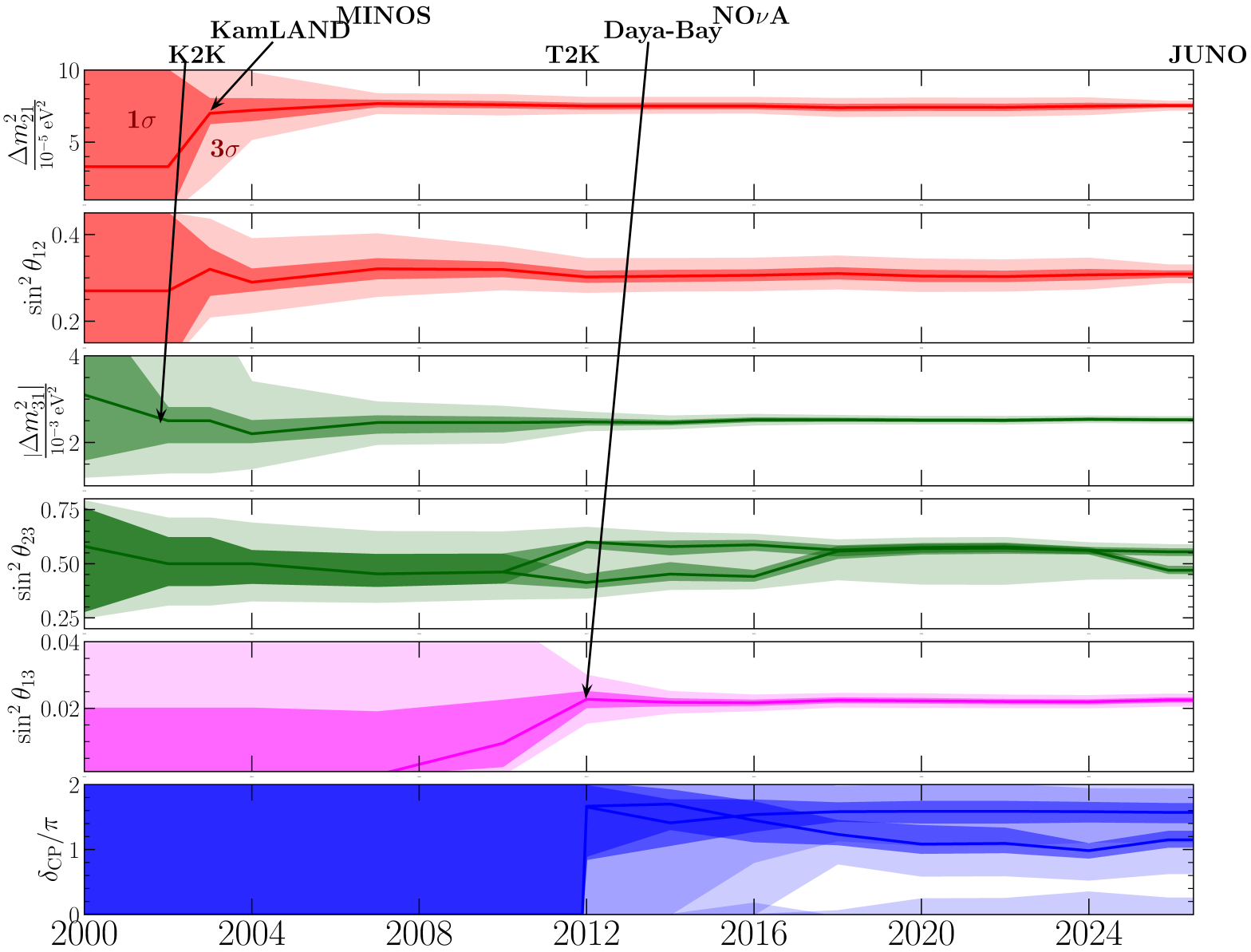
https://doi.org/10.1007/JHEP12(2024)216

Special Thanks you my NuFIT Collaborators:

Ivan Esteban, Michele Maltoni, Ivan Martinez-Solar, Joao P Pinheiro, Thomas Schwetz

Talk by A. Marrone

3 ν Flavour Parameters: Time Perspective



Data to be Described

Solar experiments

- Chlorine total rate, 1 data point.
- Gallex & GNO total rates, 2 points.
- SAGE total rate, 1 data point.
- SK1 E and zenith spect, 44 poins.
- SK2 E and D/N spect, 33 points.
- SK3 E and D/N spect, 42 points.
- SK4 2970-day E spectrum and D/N asym, 46 points.
- SNO combined analysis, 7 points.
- Borexino Ph-I 740.7-day low-E spect 33 points.
- Borexino Ph-I 246-day high-E spect ,6 points.
- Borexino Ph-II 1292-day low-E spect, 192 points.
- Borexino Ph-III 1433-day low-E spect, 120 points.

Reactor experiments

- KamLAND DS1,DS2&DS3 spectra with Daya-Bay fluxes 69 points
- DChooz FD/ND ratios with 1276-day (FD) and 587-day (ND) exposures , 26 points.
- Daya-Bay 158-day EH1,2,3 spectra ,78 points.
- Reno 300-day FD/ND ratios 45 points.
- SNO+ 1.45 Kt-ur spectrum DSI & II, 46 points
- JUNO 207.2-day spectrum, 156 data points
- NOT INCLUDED: SK-reactor 411.5 days hep-ex/2610.03143

Atmospheric experiments

- IceCube/DeepCore 2023 8-years,200 points.
- IceCube/DeepCore 2024 9.3-years (χ^2 map).
- SK I-V(2024) 484 kton-years(χ^2 map).
- NOT INCLUDED: { IceCube/DeepCore 11.2-years; KM3NeT/ORCA 510 days; SK-VI ν-2026 }

Accelerator experiments

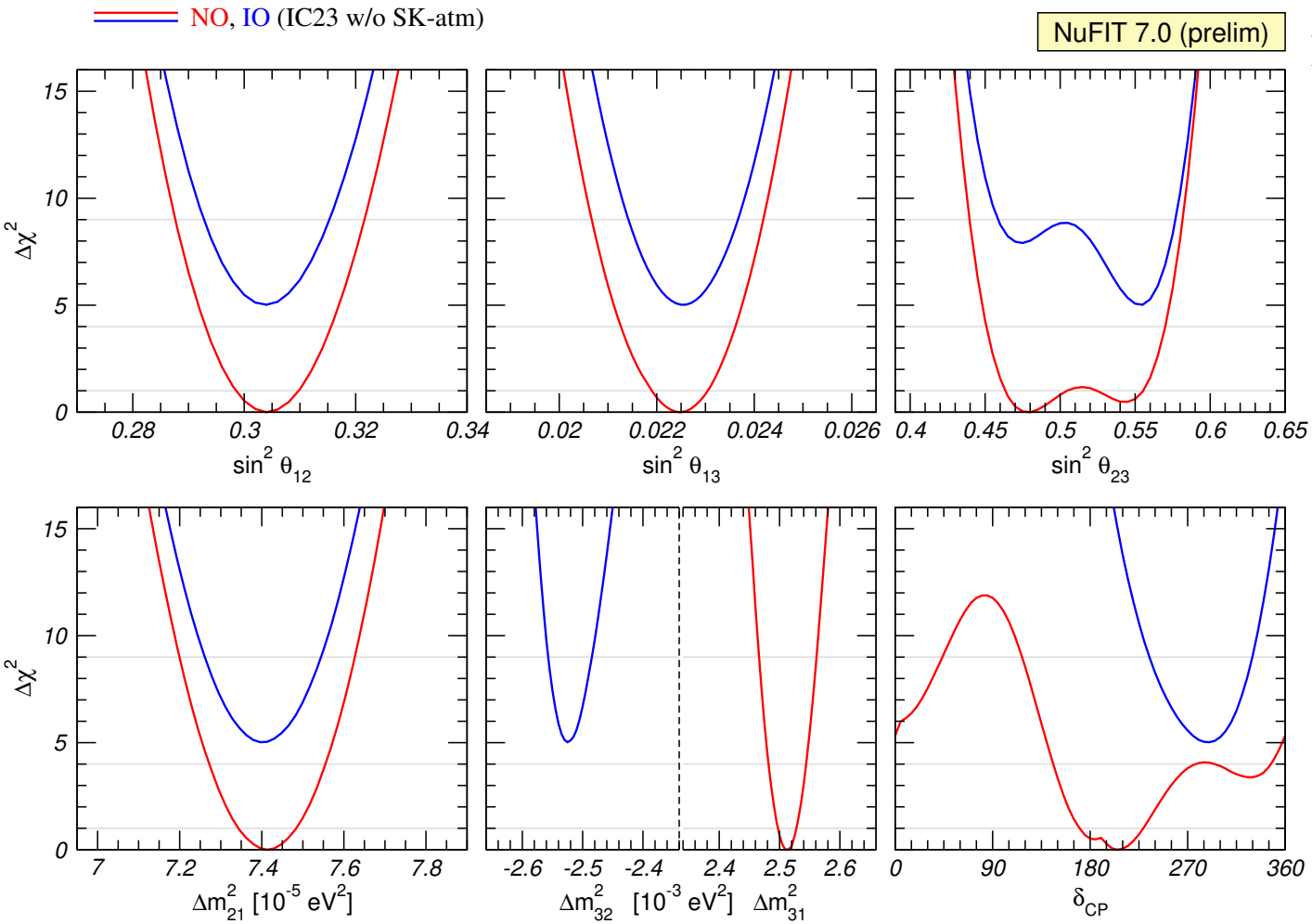
- MINOS 10.71×10^{20} pot ν_μ-disapp data, 39 poins.
- MINOS 3.36×10^{20} pot $\bar{\nu}_\mu$-disapp data , 14 points.
- MINOS 10.6×10^{20} pot ν_e-app data , 5 points.
- MINOS 3.3×10^{20} pot $\bar{\nu}_e$-app data , 5 points.
- T2K 21.4×10^{20} pot ν_μ-disapp data, 28 points.
- T2K 21.4×10^{20} pot ν_e-app data, 9 points CCQE and 7 points CC1π.
- T2K 16.3×10^{20} pot $\bar{\nu}_\mu$-disapp, 19 points.
- T2K 16.3×10^{20} pot $\bar{\nu}_e$-app, 9 points.
- NOνA 26.6×10^{20} pot ν_μ-disapp data , 21 points.
- NOνA 26.6×10^{20} pot ν_e-app data , 15 points.
- NOνA 12.5×10^{20} pot $\bar{\nu}_\mu$-disapp, 18 points.
- NOνA 12.5×10^{20} pot $\bar{\nu}_e$-app, 13 points.

Global 3 ν Flavour Parameters: Fall 2026

Global 6-parameter fit http://www.nu-fit.org

Esteban, MCGG, Maltoni, Martinez, Pinheiro,Schwetz, 2410.05480,2601.09791

(In last years good agreement with results from Bari and Valencia groups)



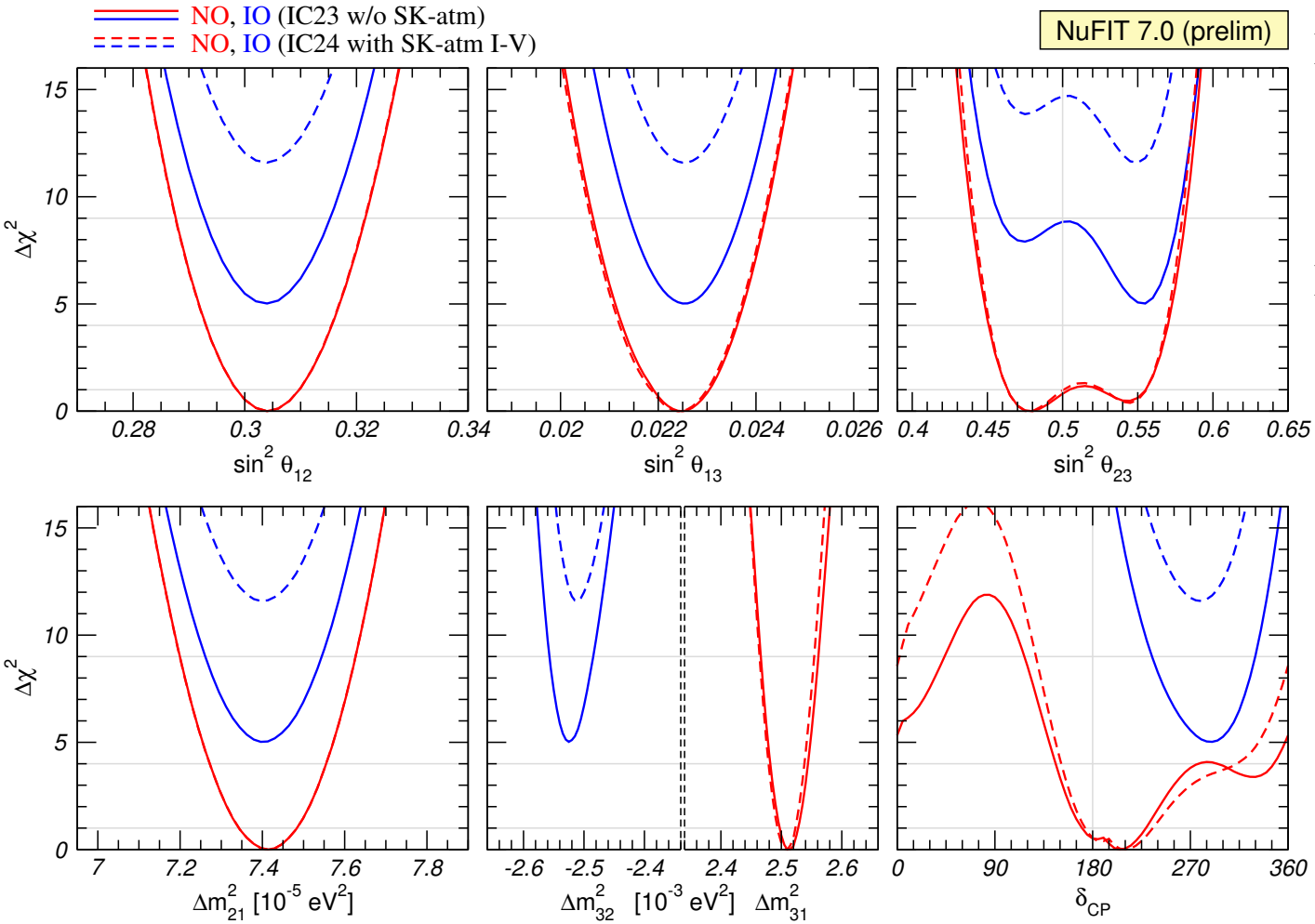
IC23 $\equiv$ Our analysis of Icecube data from 2304.12236

Global 3 ν Flavour Parameters: Fall 2026

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IC23 $\equiv$ Our analysis of Icecube data from 2304.12236

SK-atm $\equiv \chi^2$ table from SK1-5

IC24 $\equiv \chi^2$ table from Icecube data from 2405.02163

Global 3 ν Flavour Parameters: Fall 2026

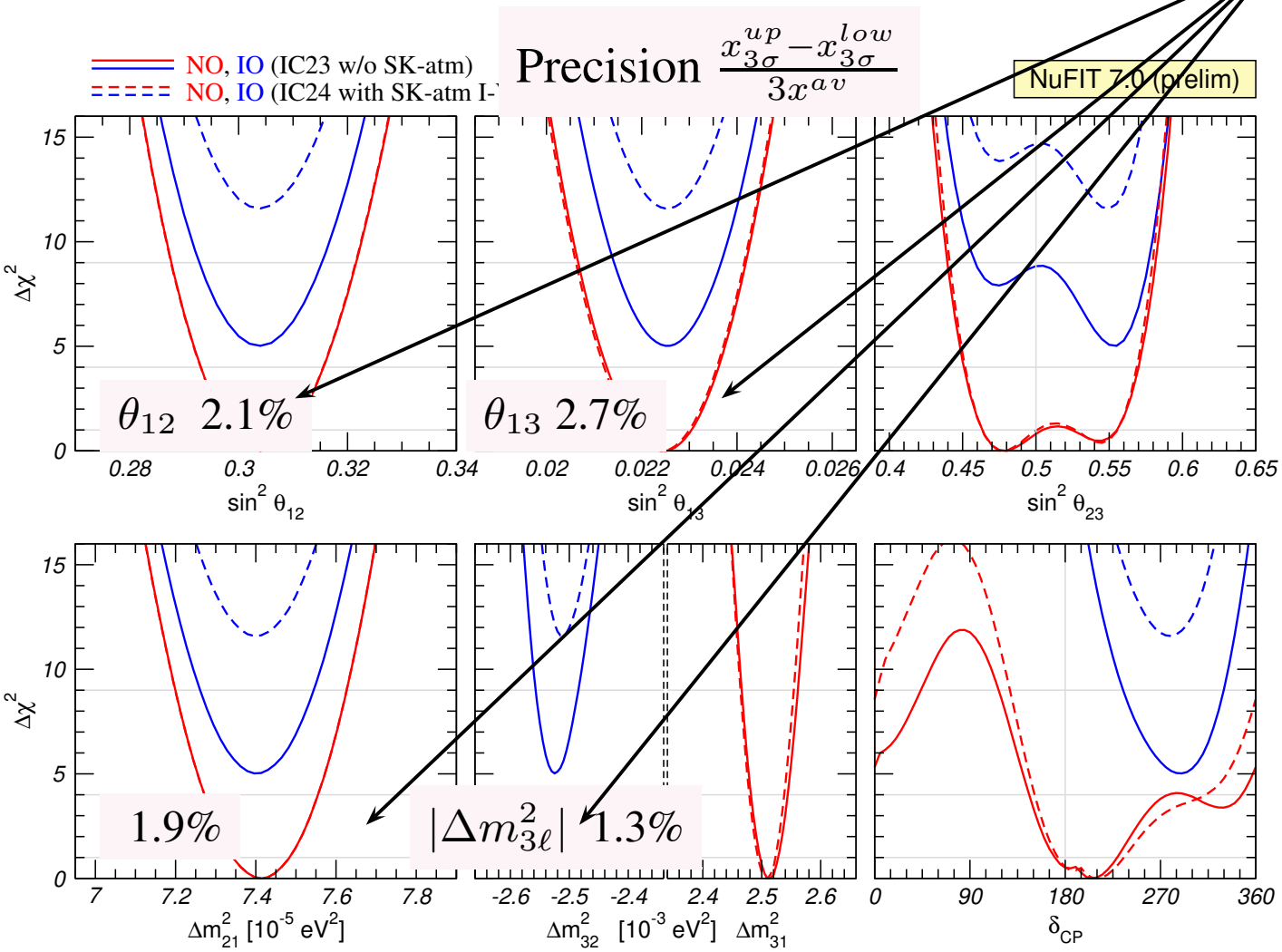
Global 6-parameter fit http://www.nu-fit.org

Esteban, MCGG, Maltoni, Martinez, Pinheiro,Schwetz, 2410.05480,2601.09791

4 well-known parameters:

$\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$

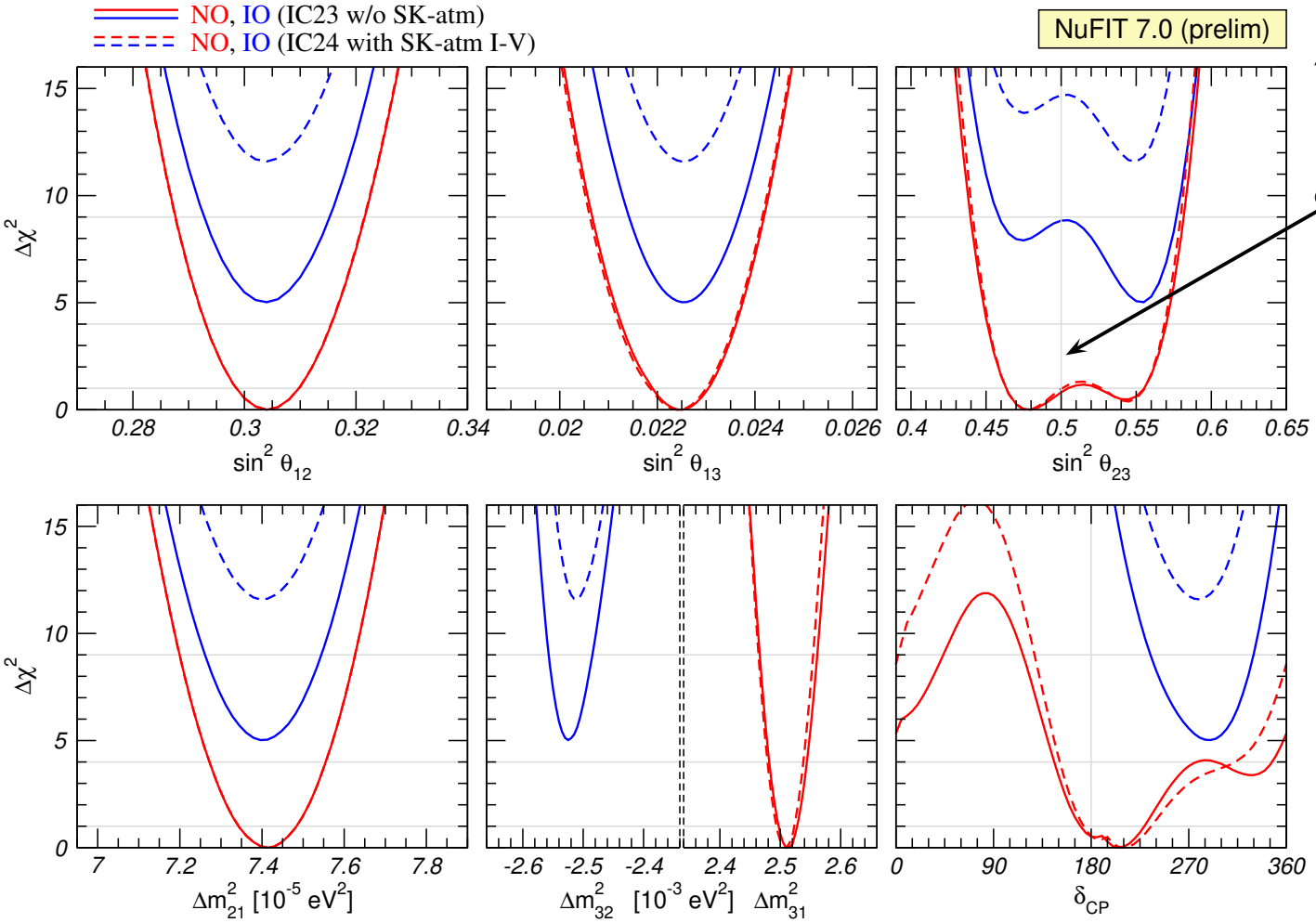
Δm^2_{21} Solar vs Reactors



Global 3 ν Flavour Parameters: Fall 2026

Global 6-parameter fit http://www.nu-fit.org

Esteban, MCGG, Maltoni, Martinez, Pinheiro,Schwetz, 2410.05480,2601.09791

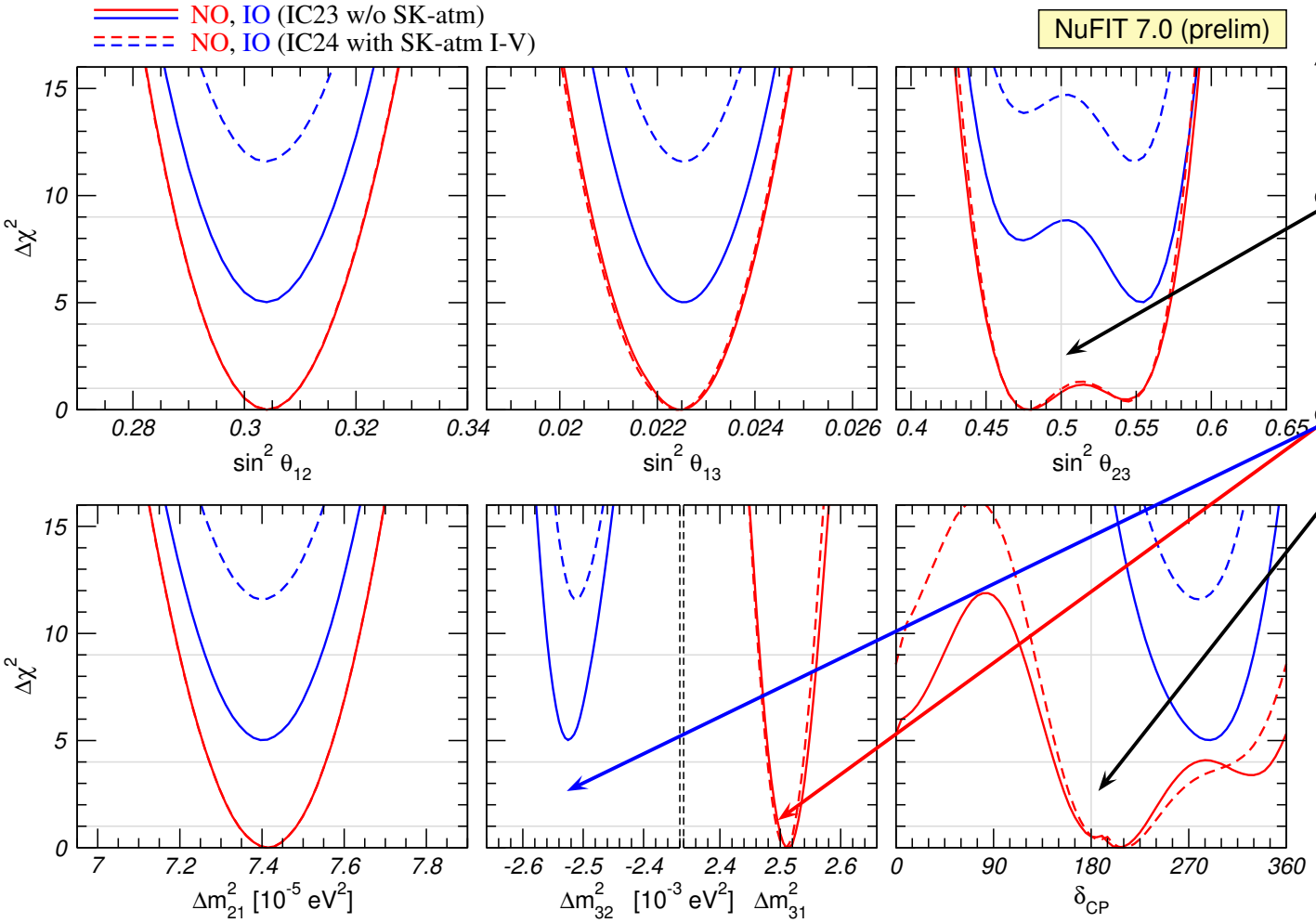


- 4 well-known parameters:
  $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$
  Δm^2_{21} Solar vs Reactors
- θ_{23}: Least known angle
  Maximal? Octant?
  non-robust yet

Global 3 ν Flavour Parameters: Fall 2026

Global 6-parameter fit http://www.nu-fit.org

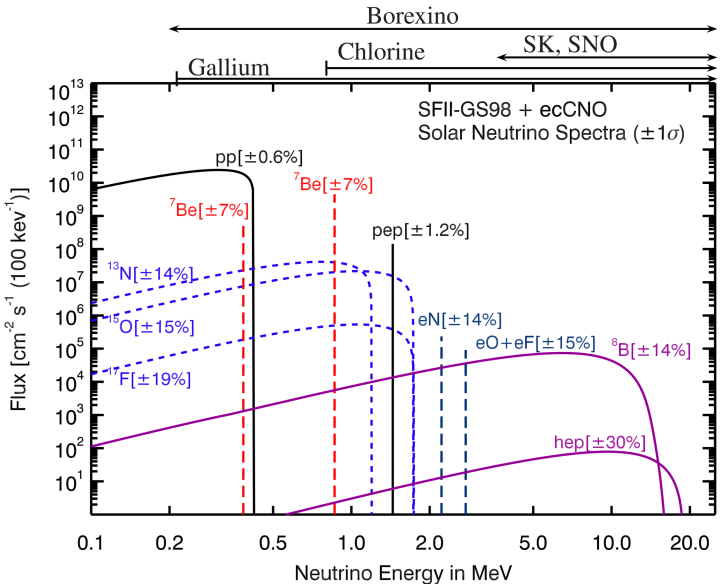
Esteban, MCGG, Maltoni, Martinez, Pinheiro,Schwetz, 2410.05480,2601.09791

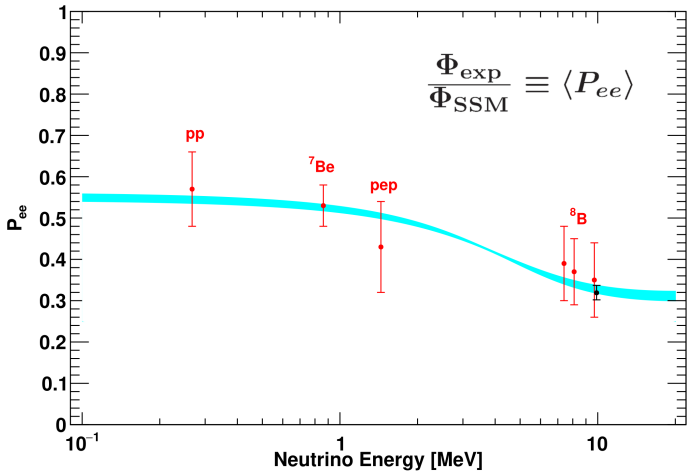


- 4 well-known parameters:
  $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$
  Δm^2_{21} Solar vs Reactors
- θ_{23}: Least known angle
  Maximal? Octant?
  non-robust yet
- Ordering NO or IO?
  CPV?:

3 ν Analysis: Dominant Δm^2_{21} Osc.

Solar

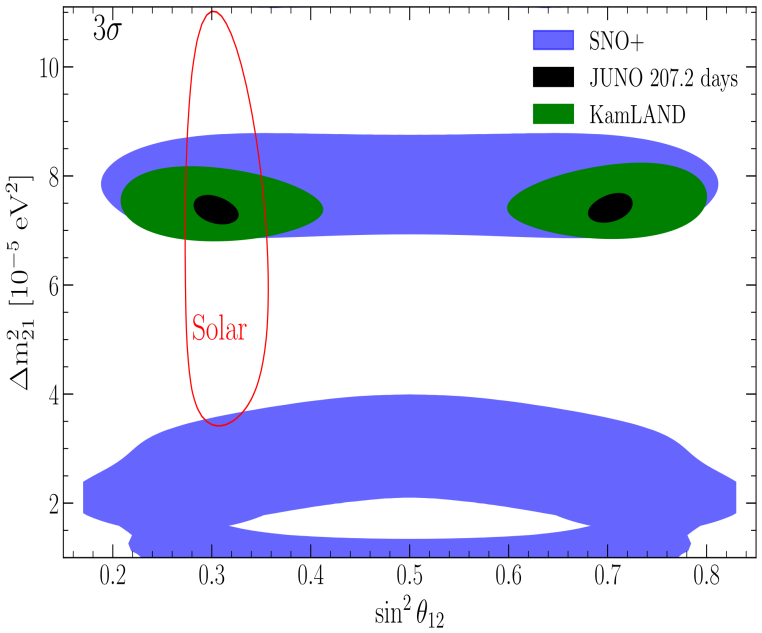




- From average vac. osc. ($E \lesssim 1$ MeV)
  to adiabatic matter transitions ($E \gtrsim 4$ MeV)
  $\Rightarrow \theta_{12} \leq 45^\circ$

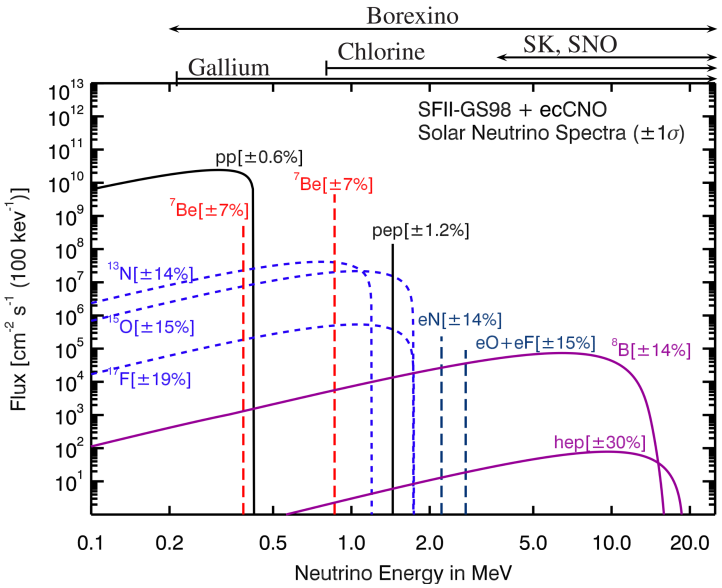
Reactors LBL

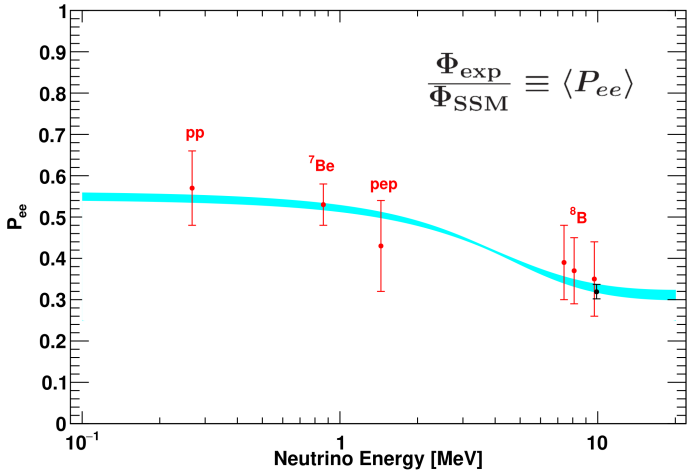
- Effectively vacuum oscillations



3 ν Analysis: Dominant Δm^2_{21} Osc.

Solar

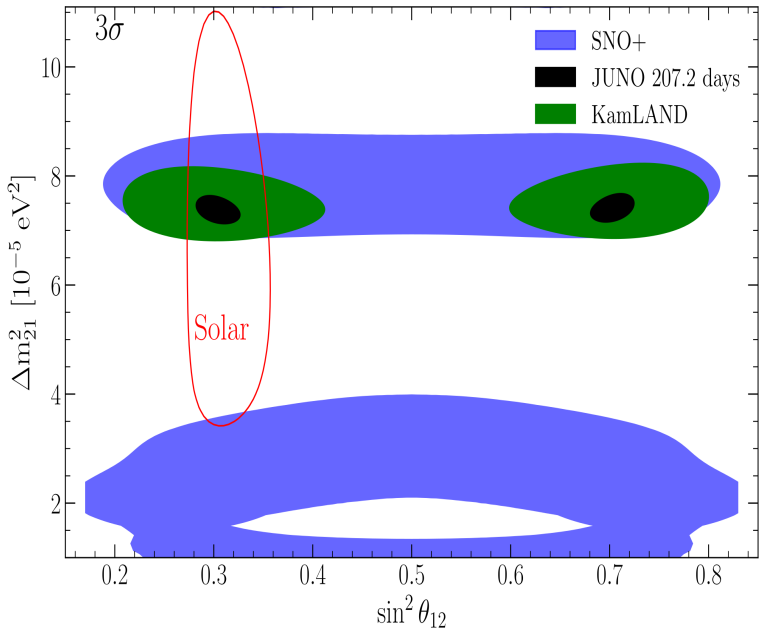




- From average vac. osc. ($E \lesssim 1$ MeV)
  to adiabatic matter transitions ($E \gtrsim 4$ MeV)
  $\Rightarrow \theta_{12} \leq 45^\circ$

Reactors LBL

- Effectively vacuum oscillations



- 2003-2015:

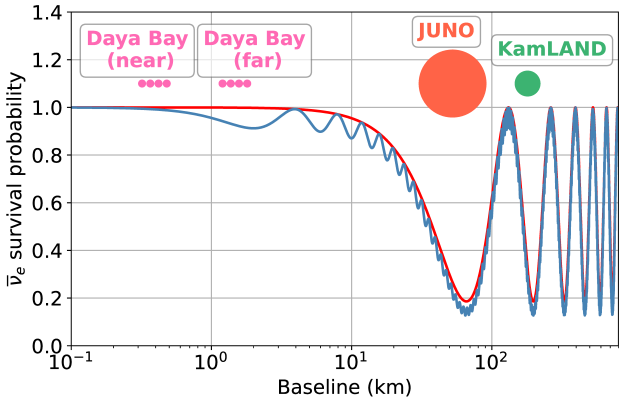
  KamLAND dominant Δm^2_{12} precision
  Solar dominant θ_{12} precision

- After Dec 2025:

  JUNO leads Δm^2_{21} and θ_{12} precision
  (with solar prior $\theta_{12} \leq 45^\circ$)

Results from JUNO:

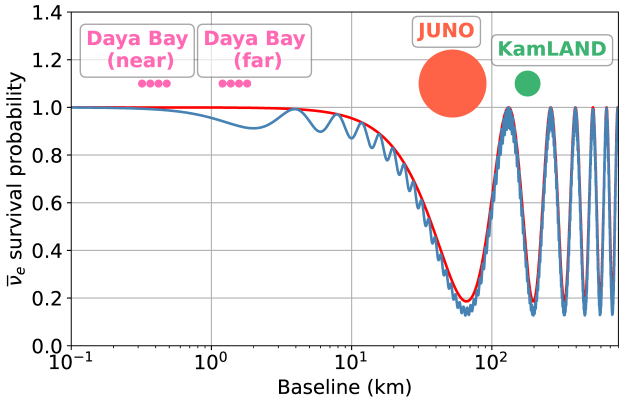
$$P_{\nu_e,\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)\right]$$



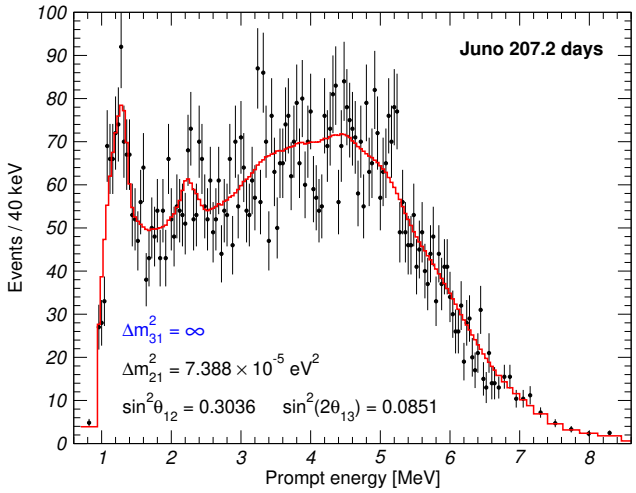
Talks by V. Vorobel, T. Tmej

Results from JUNO: Dominant Δm^2_{12} Osc.

$$P_{\nu_e,\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \left\langle \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)\right\rangle + s_{12}^2 \left\langle \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right\rangle\right]$$



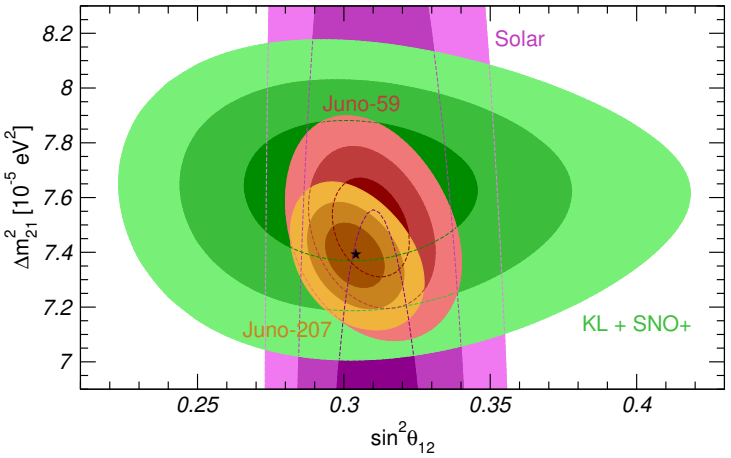
207.2 Day data :



M. Maltoni PIC2026 Talk

Talks by V. Vorobel, T. Tmej

- Leading precision in θ_{12} and Δm^2_{12}



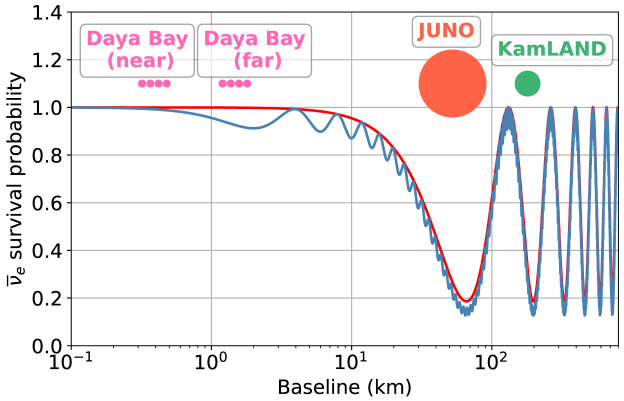
M. Maltoni PIC2026 Talk

- rel precision at 3σ/3:

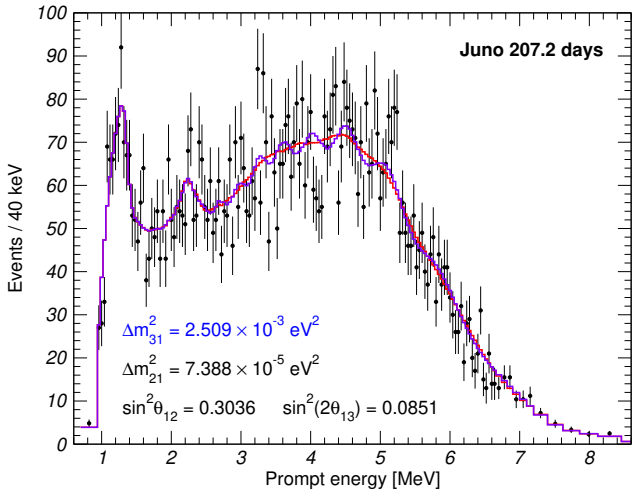
	Before JUNO	w JUNO 90d	w JUNO 207.2 d
	Nufit 6.0 $\rightarrow$	NuFit 6.1 $\rightarrow$	NuFit 7.0 (prel)
θ_{12}	4.3% $\rightarrow$	2.5% $\rightarrow$	2.1%
Δm^2_{21}	5% $\rightarrow$	2.6% $\rightarrow$	1.9%

Results from JUNO: *Subdominant* $\Delta m^2_{3\ell}$ Osc.

$$P_{\nu_e,\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]$$

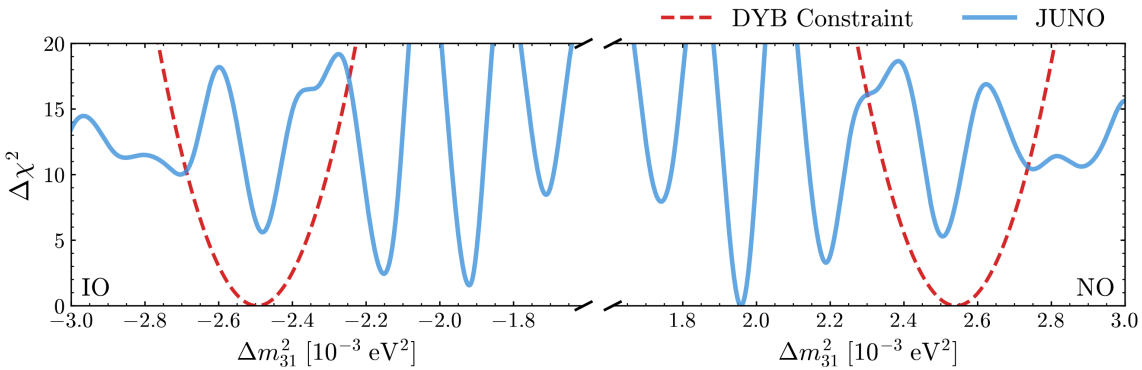


207.2 Day data :



M. Maltoni PIC2026 Talk

- Still several quasi-degenerated minima



arXiv:2609.37895

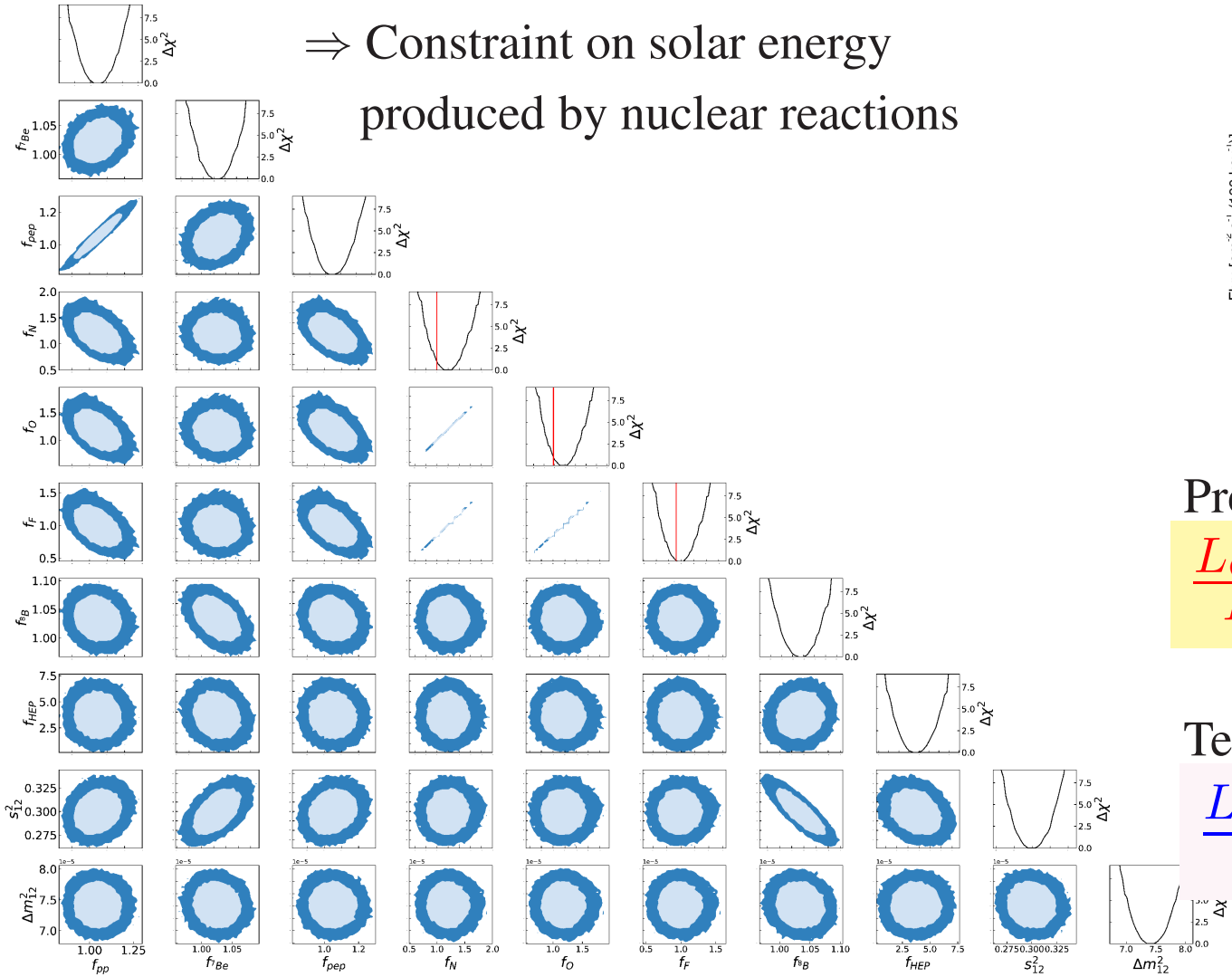
- But precision once minima selected with Daya-Bay

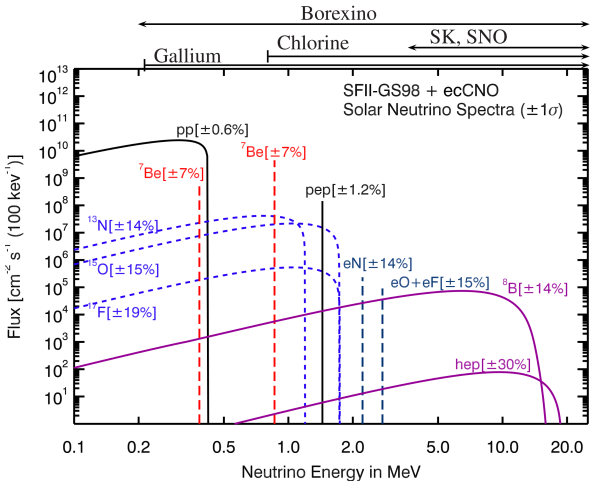
$\Rightarrow$ Relevant info for MO (in 4 slides)

Spin-off: Testing How the Sun Shines with $\nu's$

Fitting together oscillations and normalization of ν-producing reactions: $f_i = \frac{\Phi_i}{\Phi_i^{SSM}}$

$\Rightarrow$ Constraint on solar energy produced by nuclear reactions





Present limit on CNO:

$$\frac{L_{\rm CNO}}{L_\odot} < (0.75 \pm 0.3)\,\%\ (3\sigma)$$

Test of Lum Constraint:

$$\frac{L_\odot(\nu - \text{inferred})}{L_\odot} = 1.04 \pm 0.06$$

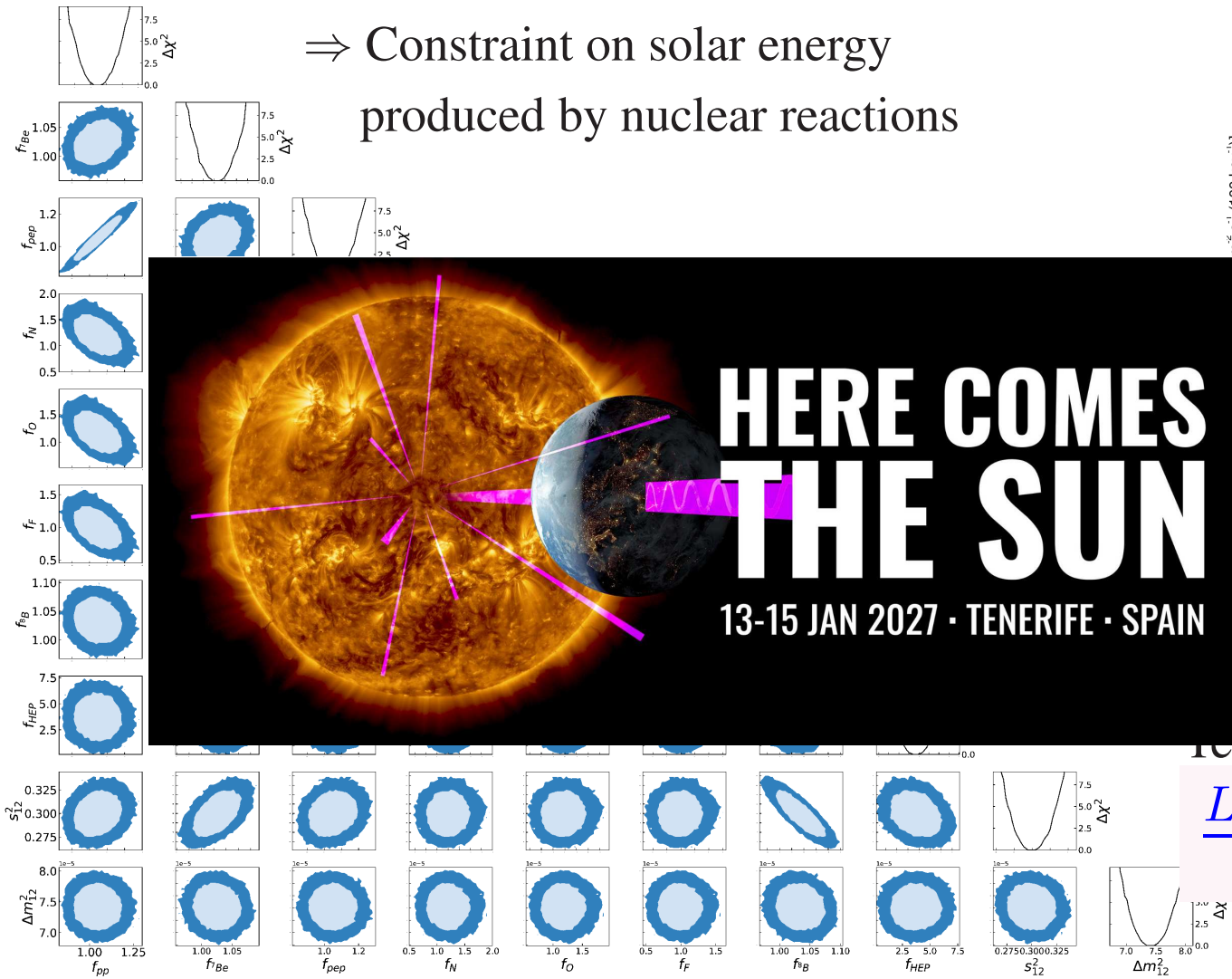
MCGG, Maltoni, Pinheiro, Serenelli 2311.16226

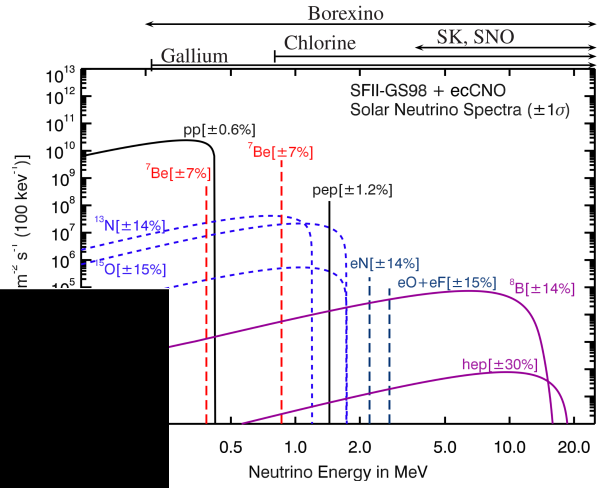
$\Rightarrow$ Bounds on other sources of solar energy loss: sterile $\nu's$, ALP's...

Spin-off: Testing How the Sun Shines with $\nu's$

Fitting together oscillations and normalization of ν-producing reactions: $f_i = \frac{\Phi_i}{\Phi_i^{SSM}}$

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MCGG, Maltoni, Pinheiro, Serenelli 2311.16226

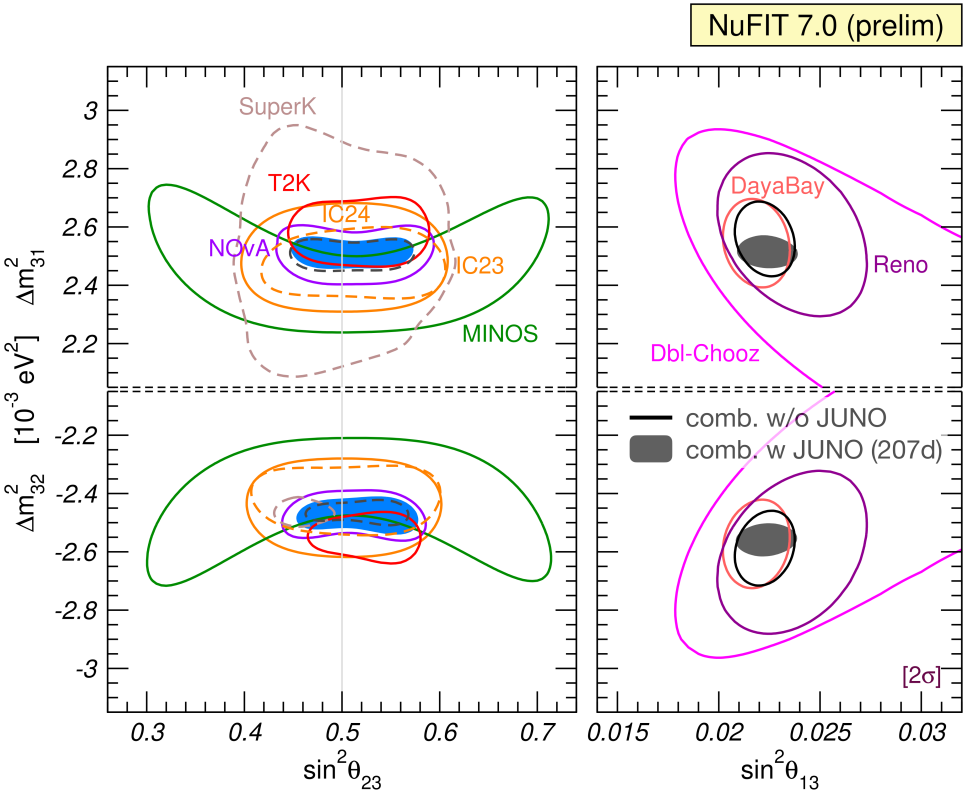
$\Rightarrow$ Bounds on other sources of solar energy loss: sterile $\nu's$, ALP's...

3 ν Analysis: Dominant $\Delta m^2_{3\ell}$ Osc.

- Dominant in ν_μ osc in LBL accel exper and ν_e MBL reactor exper
  $\Rightarrow$ complementarity
- Non-trivial check of 3ν framework
- Relat. Precision at 3σ/3

  Nufit 6.0 $\rightarrow$ NuFit 7.0 (prel)

  $|\Delta m^2_{3\ell}|$ 1.7% $\rightarrow$ 1.3%

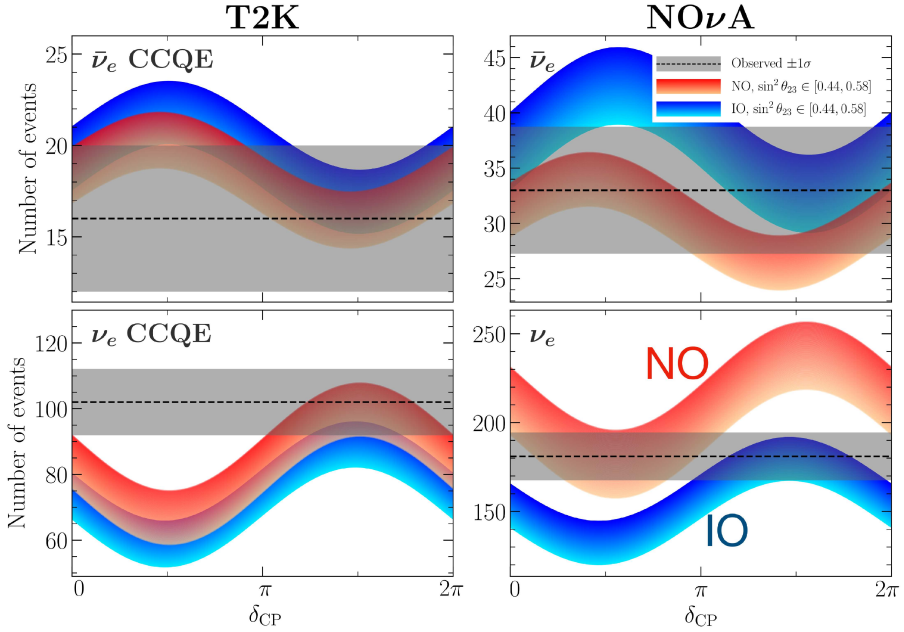


MO, CPV, Octant θ_{23}: $\nu_\mu \to \nu_e$ at LBL

- Dominant info from ν_e vs $\overline{\nu}_e$ appearance in LBL T2K (285 km) and NOνA (810) Km

$$P_{\mu e} \simeq s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + \tilde{J} \frac{\Delta_{21}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{4E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$



- Each T2K and NOνA favour NO
- But tension in δ_{CP} in NO

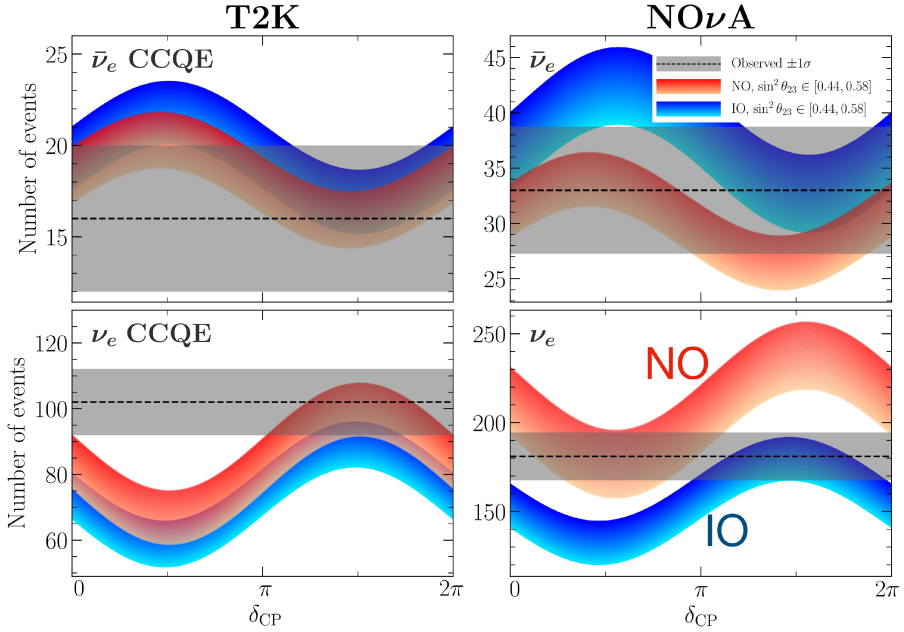
Talk by T. Nosek

MO, CPV, Octant θ_{23}: $\nu_\mu \to \nu_e$ at LBL

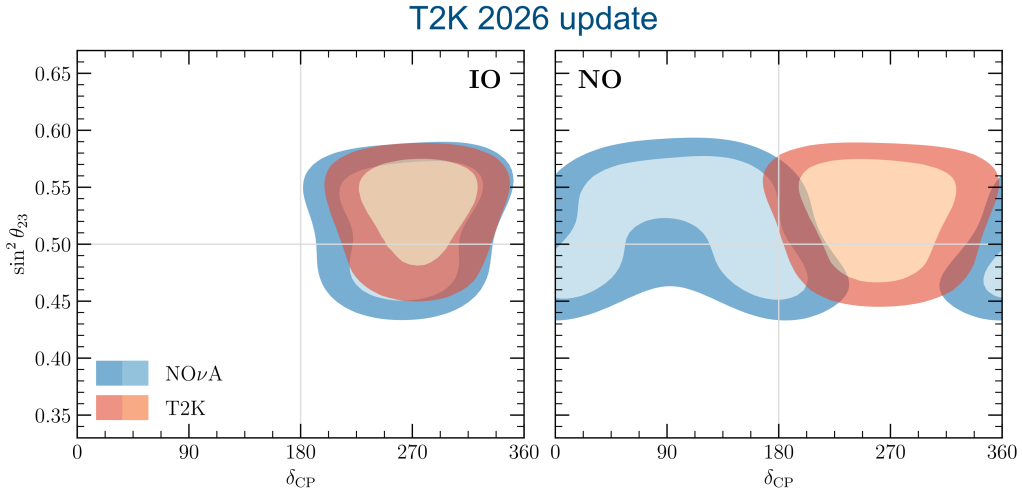
- Dominant info from ν_e vs $\overline{\nu}_e$ appearance in LBL T2K (285 km) and NOνA (810) Km

$$P_{\mu e} \simeq s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + \tilde{J} \frac{\Delta_{21}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{4E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$



- Each T2K and NOνA favour NO
- But tension in δ_{CP} in NO



- Better consistency in IO $\Rightarrow \chi^2_{\rm IO} - \chi^2_{\rm NO} = -3.2$

Talk by T. Nosek

IO
- b.f. $\delta_{\rm CP}$ close to $270° \equiv$ Max CPV
- CPC excluded at $\gtrsim 3\ \sigma$
- $\theta_{23} > 45°$ favoured

NO
- b.f. $\delta_{\rm CP}$ close to $180° \equiv$ CPC
- both θ_{23} octant at $1\ \sigma$

MO: MBL reactors vs LBL/ATM

- MO info from ν_μ disapp (LBL/ATM): $\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$

  vs ν_e disapp (BL React): $\Delta m^2_{ee} = \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$

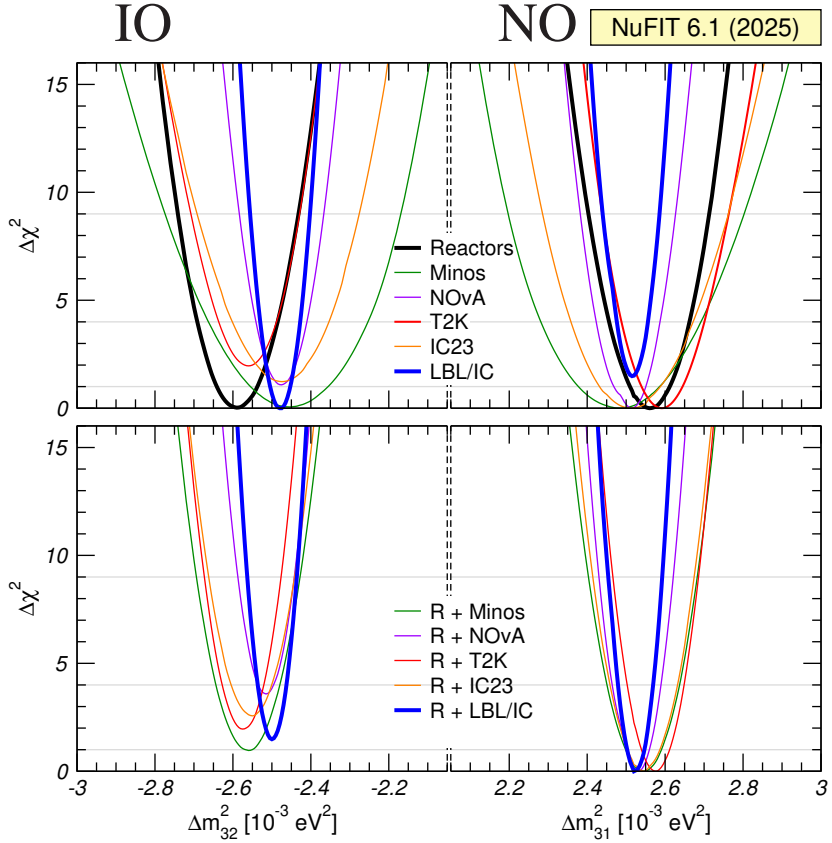
Nunokawa,Parke,Zukanovich hep-ph/0503283

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Before JUNO:



- Better compatibility in NO

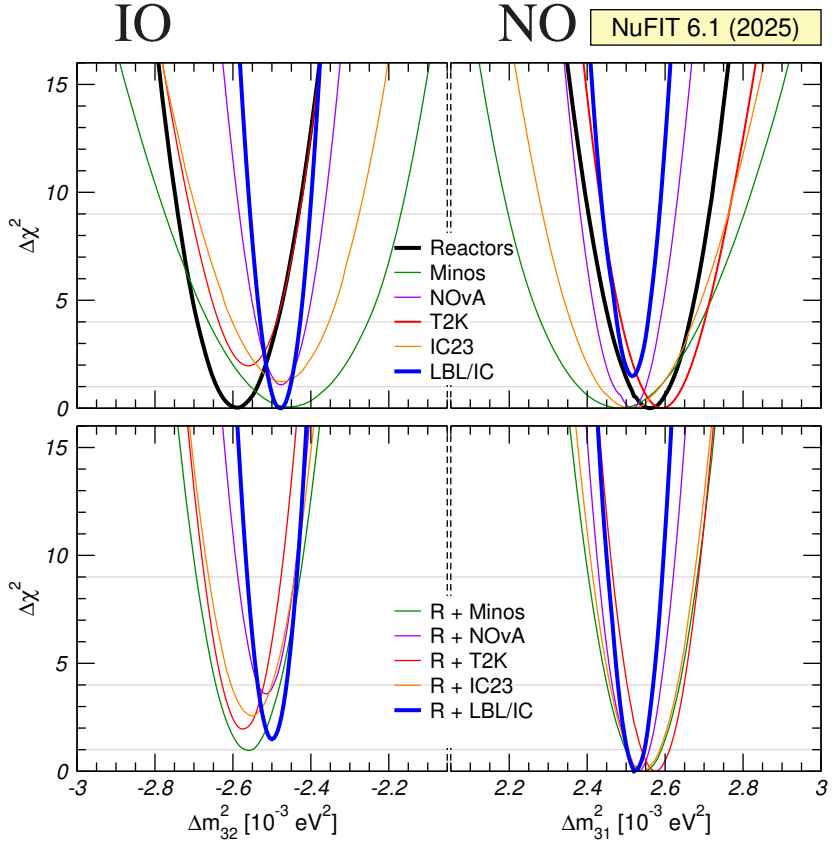
$\Rightarrow$ compensates for IO favour in NoVA+T2K

MO: MBL reactors vs LBL/ATM

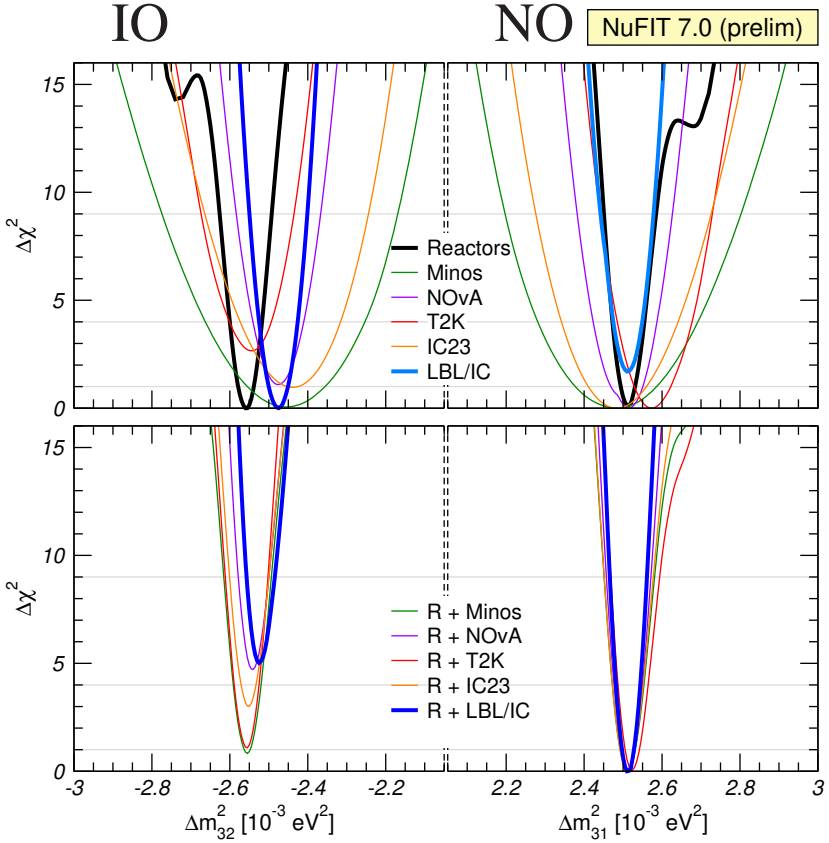
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Before JUNO:



With JUNO 207.2 days:



- Better compatibility in NO

$\Rightarrow$ compensates for IO favour in NoVA+T2K

- Increased favouring of NO

$$\Rightarrow \chi^2_{\text{IO}} - \chi^2_{\text{NO}} = 5.0$$

- But dependence on subtleties in combination

MO: MBL reactors vs LBL/ATM

- MO info from ν_μ disapp (LBL/ATM): $\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$

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  Nunokawa,Parke,Zukanovich hep-ph/0503283

- MO preference from this effect is fragile under details on combinations

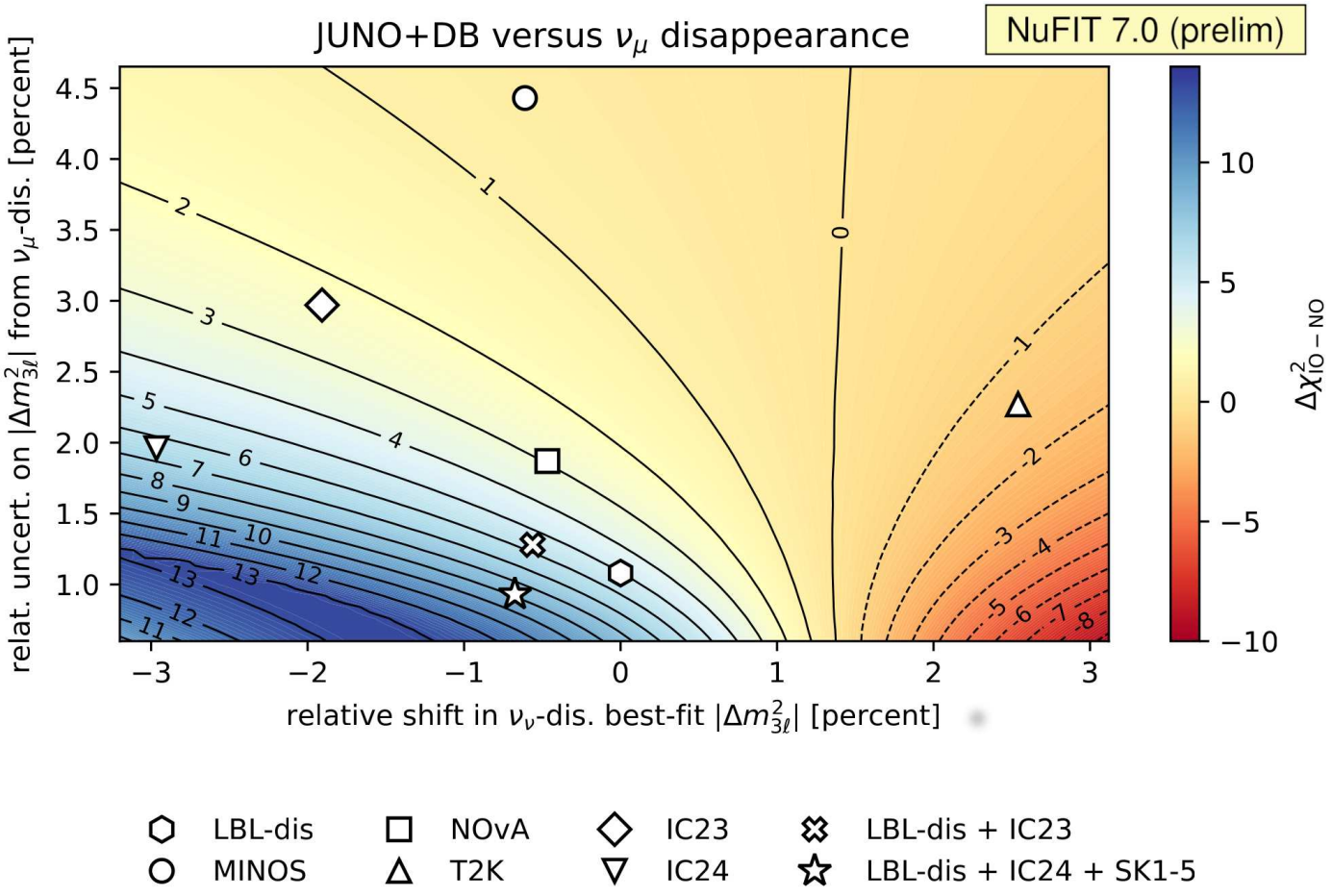
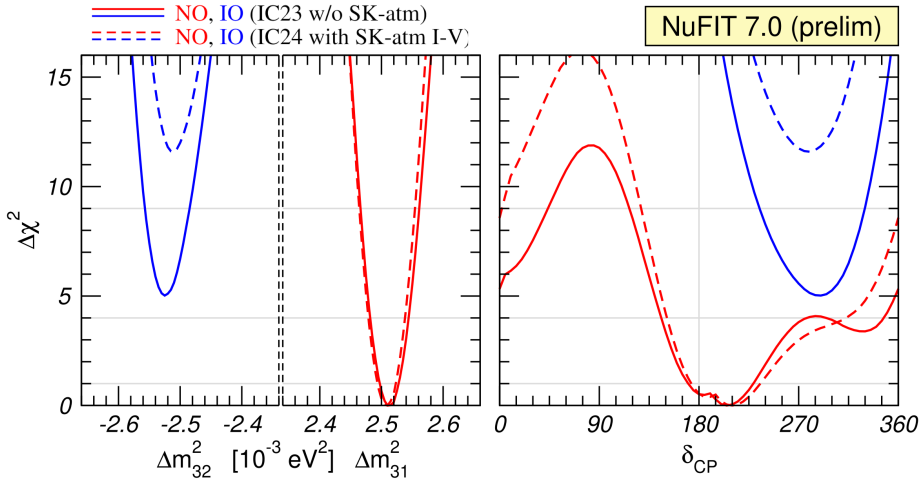


Figure courtesy of T. Schwetz

MO and ATM neutrinos

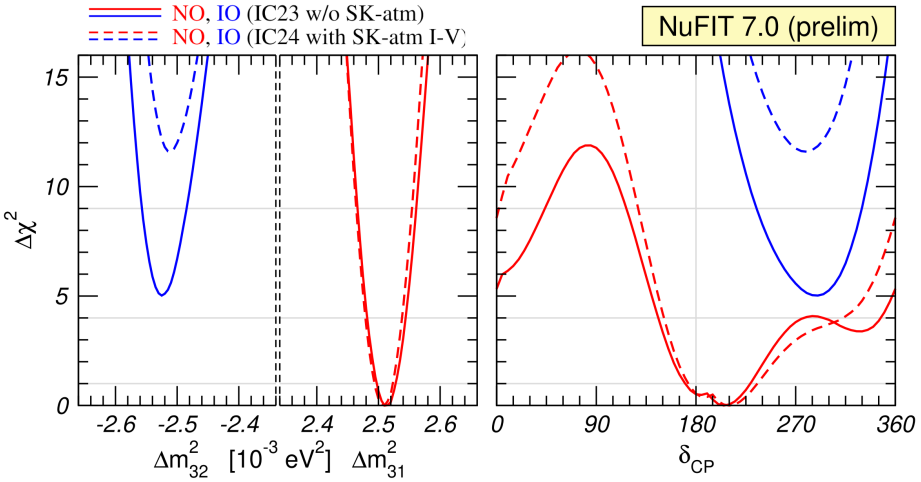
- In addition to synergies with reactors via ν_μ disappearance, ATM ν_e's provide further sensitivity to MO via MSW effect in the Earth (and also CPV)
- Difficult to simulate outside collab. $\Rightarrow$ Add χ^2 map provided by experiment
- Adding the χ^2 map of SK I-V (and IC24)



$$\Rightarrow \chi^2_{\rm IO} - \chi^2_{\rm NO} : 5.0 \to 11.6$$

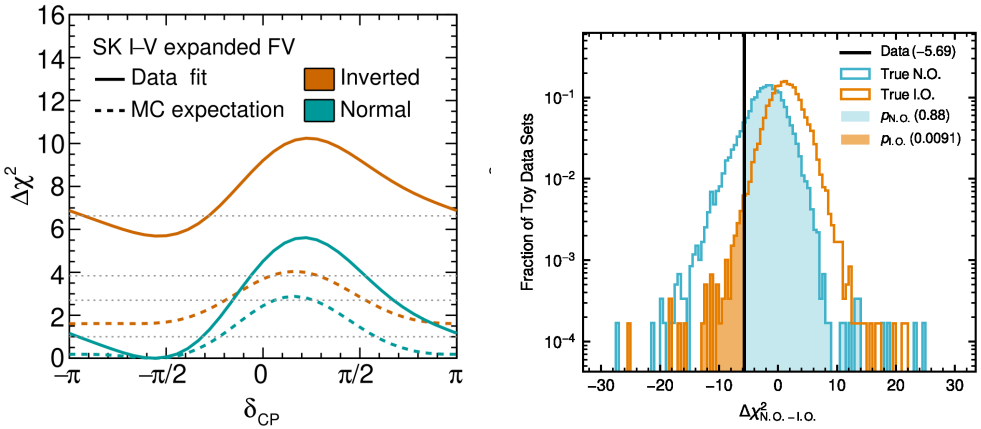
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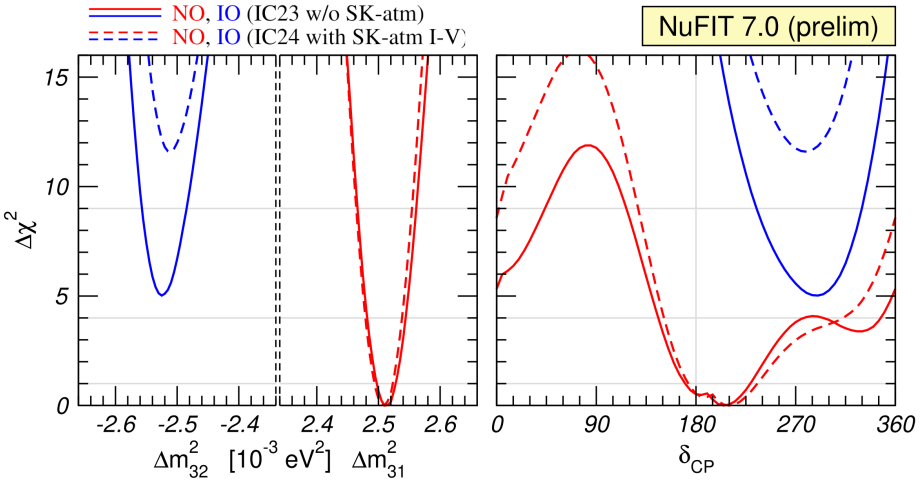
But beyond expectation



SK Coll. arXiv:2311.05105

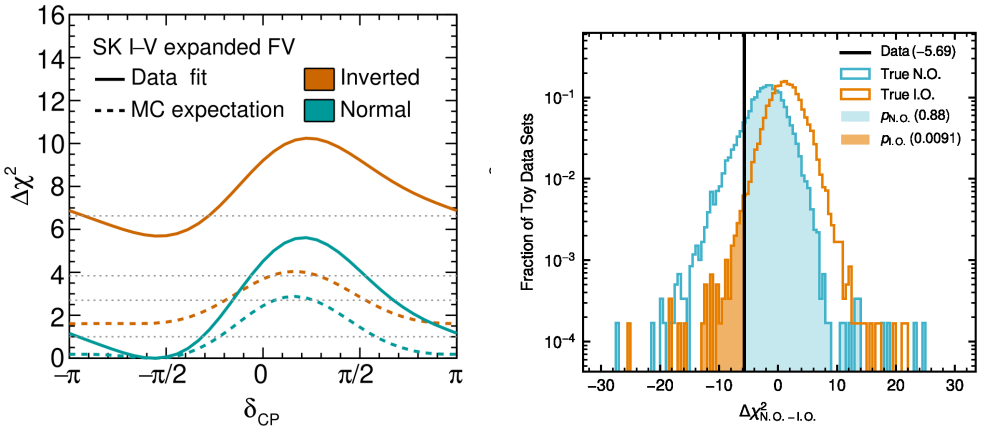
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$$\Rightarrow \chi^2_{\rm IO} - \chi^2_{\rm NO} : 5.0 \rightarrow 11.6$$

But beyond expectation



SK Coll. arXiv:2311.05105

- Results presented in Neutrino26 conf

  Including SK-VI: 8.8% more statistics

  analysis improvements

	Previous study (SK I-V)	This study (SK I-VI)
$\Delta\chi^2_{IO-NO}$	5.69	**3.69**

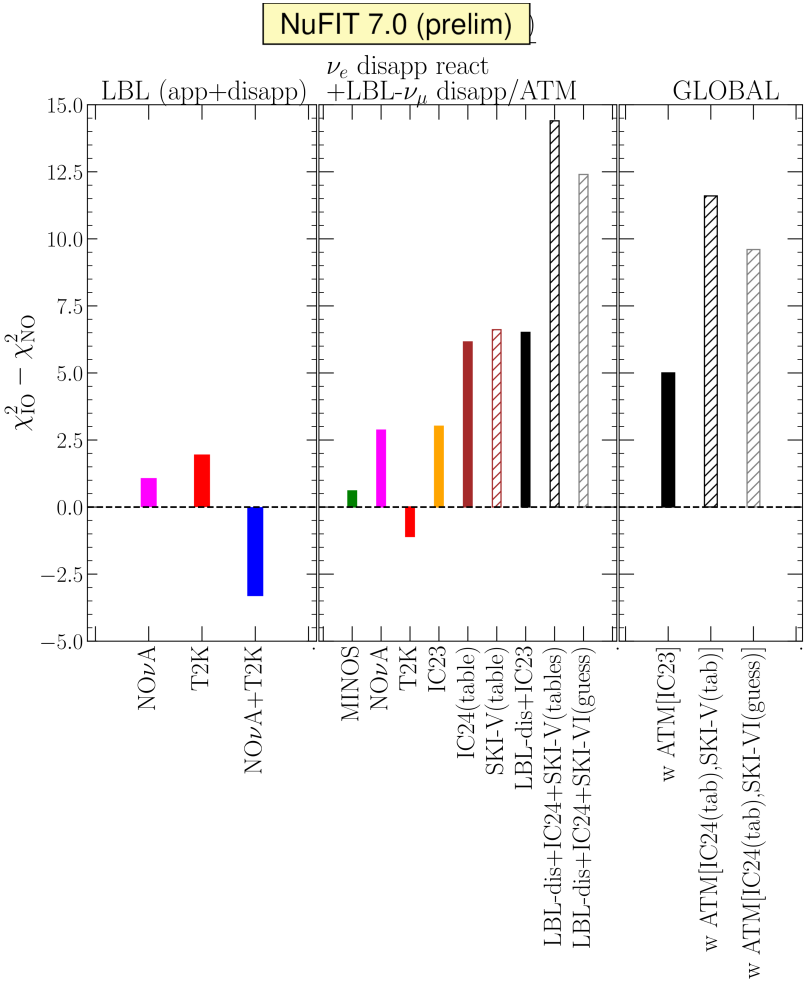
Toy experiments show a rejection of inverted ordering at 86% ≃ 1.08σ (CL$_s$ method)

Talk by Zhuojun Hu at Neutrino26

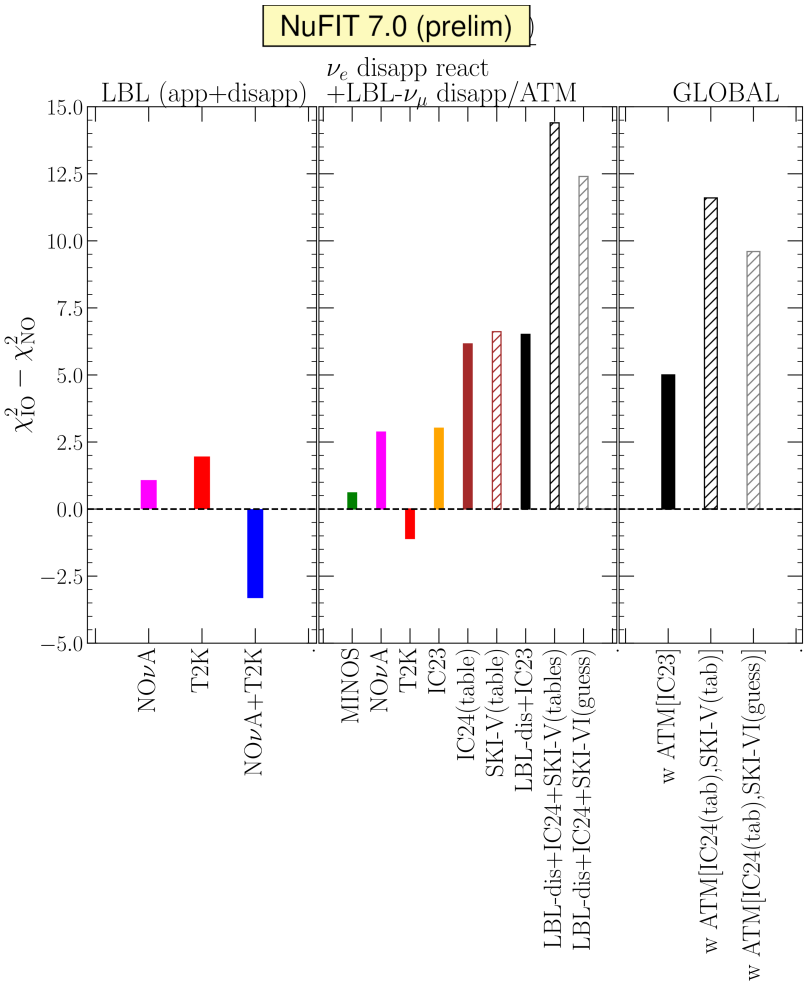
- Naive estimate for global fit:

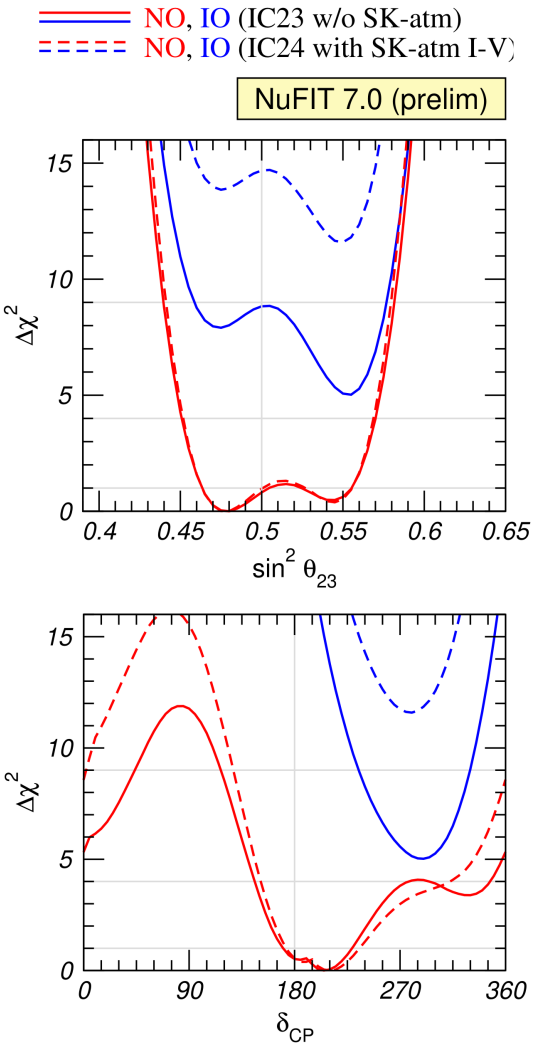
$$\chi^2_{\rm IO} - \chi^2_{\rm NO} : 11.6 \rightarrow\sim 9.6$$

MO, CPV, θ_{23}: Global Status



MO, CPV, θ_{23}: Global Status





NO:

– CPC ($\delta_{\rm CP} = 180^\circ$) at 1 σ

– Excluded at 3σ

$45^\circ < \delta_{\rm CP} < 115^\circ$ w/o SK-ATM
$(3^\circ < \delta_{\rm CP} < 127^\circ)$(w SKI-V)

– θ_{23}: b.f. 1st octant but both at 1 σ

IO:

– b.f. $\delta_{\rm CP} \sim 270^\circ \equiv$ Max CPV

– CPC excluded at 4.2 (5.5) σ

– θ_{23}: b.f. 2nd octant

$\chi^2_{{\rm min},\theta_{23}<45^\circ} - \chi^2_{{\rm min},\theta_{23}>45^\circ} = 3\ (2.3)$

Flavour Parameters: leptons vs quarks

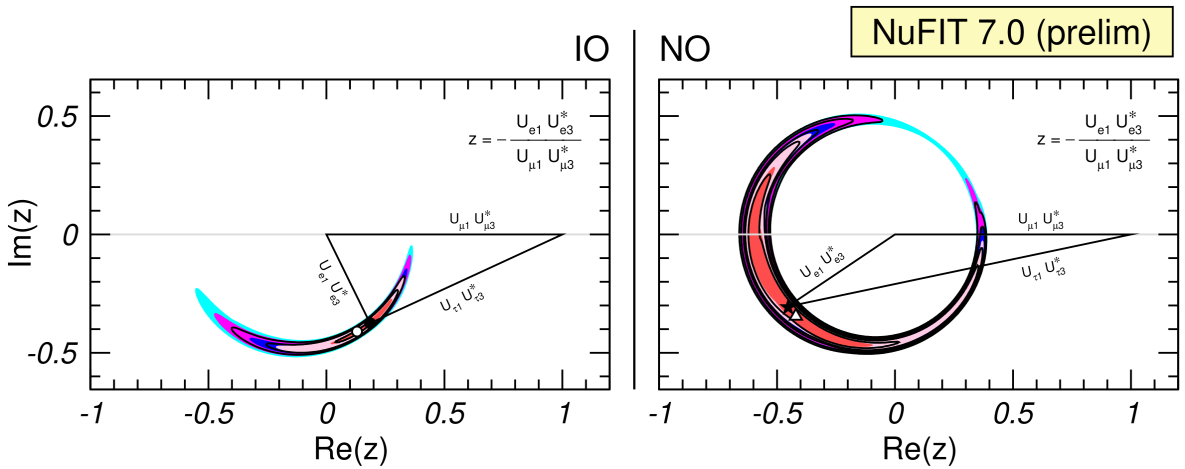
- Leptonic mixing matrix

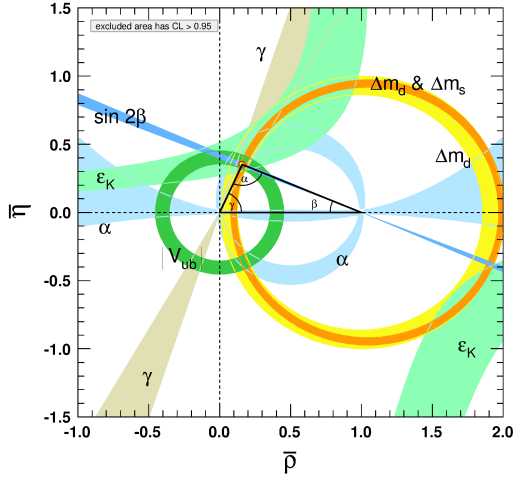
$$|U|_{3\sigma} = \begin{pmatrix} 0.810 \to 0.834 & 0.532 \to 0.568 & 0.144 \to 0.156 \\ 0.258 \to 0.502 & 0.479 \to 0.680 & 0.650 \to 0.758 \\ 0.274 \to 0.512 & 0.486 \to 0.684 & 0.635 \to 0.745 \end{pmatrix}$$

- Very different and precision very far from:

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

- CP violation



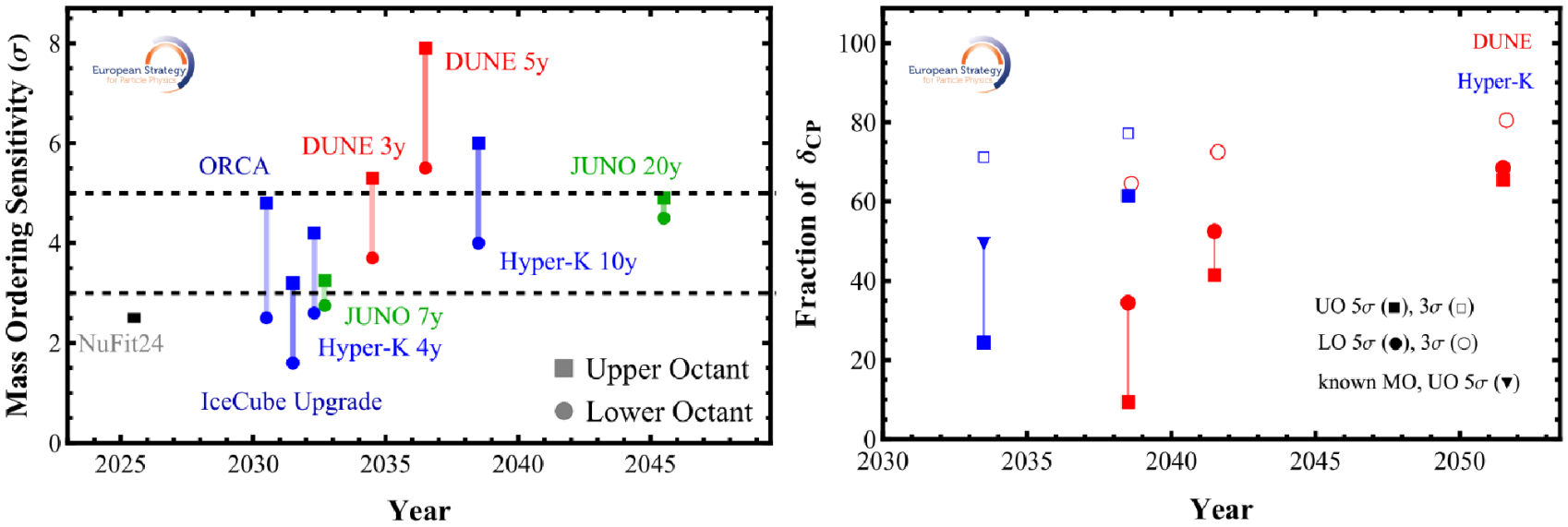


Future for CP and Ordering: Strategies

- Reactor experiment at $L \sim 60$ km (vacuum) able to observe
  the difference between oscillations with Δm^2_{31} and Δm^2_{32}: JUNO
  – Challenge: Energy resolution

- $\nu/\bar{\nu}$ comparison with or without Earth matter effects in $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ at LBL:
  DUNE (wide band beam, L=1300 km), HK (narrow band beam, L=300 km)
  – Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

- Earth matter effects in large statistics ATM : HK,IC/DC,ORCA ...
  – Challenge: ATM flux uncertainties



Physics Briefbook for European Strategy of Particle Physics 2511.03883

ν OSC and New Physics w/o new states in OSC

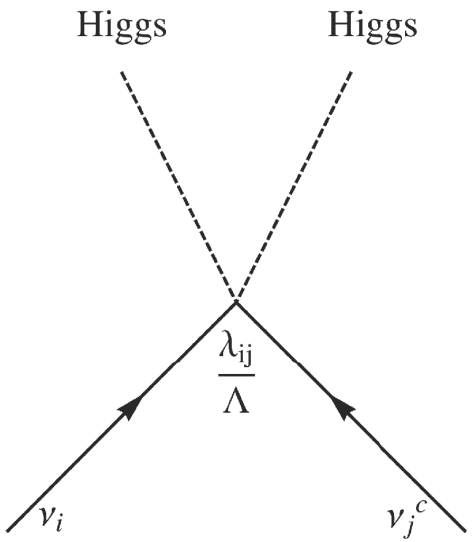
If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_n \frac{1}{\Lambda_{\rm NP}^{n-4}} \mathcal{O}_n$$

– At dim=5 only 1 operator:

$O_5 = \frac{\lambda^\nu_{ij}}{\Lambda_{\rm NP}} \left(\overline{L_{L,i}}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_{L,j}\right) \Rightarrow \frac{1}{2}\overline{\nu}_L M_\nu \nu^C_L \equiv$ Majorana Mass $\Rightarrow \nu$-less $\beta\beta$ decay



$m_\nu \sim \frac{\lambda^\nu v^2}{\Lambda_{\rm NP}} > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV:

For $\lambda^\nu \sim 1 \Rightarrow \Lambda_{\rm NP} \sim 10^{15}$GeV $\sim$ GUT scale

$\Rightarrow$ Leptogenesis but no signatures in lab

For $\lambda^\nu \sim (Y_e)^2 \Rightarrow \Lambda_{\rm NP} \sim$ EW scale

ν OSC and New Physics w/o new states in OSC

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– At dim=6 $\mathcal{O}_6 \sim \bar{L}\bar{L}LL$, $\bar{Q}Q\bar{L}L$ are LN conserving but can be LFV so in general

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_{5\alpha\beta}}{\Lambda_{LN}}\left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) + \sum_i \frac{c_{6,i}}{\Lambda^2_{LF}}\mathcal{O}_{6,i}$$

$\Rightarrow$ possible to *decouple* :

New Physics scale Λ_{LN} responsible for the small m_ν from

New Physics scale Λ_{LF} ($\ll \Lambda_{LN}$) controlling signals at Lab experiments.

$\Rightarrow$ possible signals in ν experiments: Non-standard ν int. (NSI), non-unitarity ...

NSI in ν Oscillations : Degeneracies

- Effective parametrization: $\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{f} \gamma_\mu P f)\,, \qquad P = L, R$

NSI in ν Oscillations : Degeneracies

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- In matter with NSI: $\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=p,n,e} \frac{N_f(r)}{N_e(r)}\varepsilon^f_{\alpha\beta}$

$$H^\nu = U_{\rm vac}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E_\nu} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E_\nu}\end{pmatrix} U^\dagger_{\rm vac} + \sqrt{2}G_F N_e(r)\begin{pmatrix} 1+\varepsilon_{ee}-\varepsilon_{\mu\mu} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & 0 & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}\end{pmatrix}$$

- So $H \to -H^*$ ($\equiv$ Probabilities are Invariant) if simultaneously:

$\theta_{12} \to \frac{\pi}{2} - \theta_{12}$ and $(\varepsilon_{ee}-\varepsilon_{\mu\mu}) \to -(\varepsilon_{ee}-\varepsilon_{\mu\mu}) - 2$ New "Dark" ($\theta_{12} > \frac{\pi}{4}$) region (solar)

$\Delta m^2_{31} \to -\Delta m^2_{32}$ and $(\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu})$ Lost order info (ATM&LBL)

$\delta \to \pi - \delta$ and $\varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta}$ $(\alpha \neq \beta)$ CPV confusion (ATM&LBL)

Miranda,Tortola, Valle, hep-ph/0406280
MCGG,Maltoni,Salvado 1103.4265
Coloma, Schwetz, 1604.05772

for $N_f(r)/N_e(r) \neq$ constant $\Rightarrow \varepsilon_{\alpha\beta}$ are not constant $\Rightarrow$ degeneracy only approximate

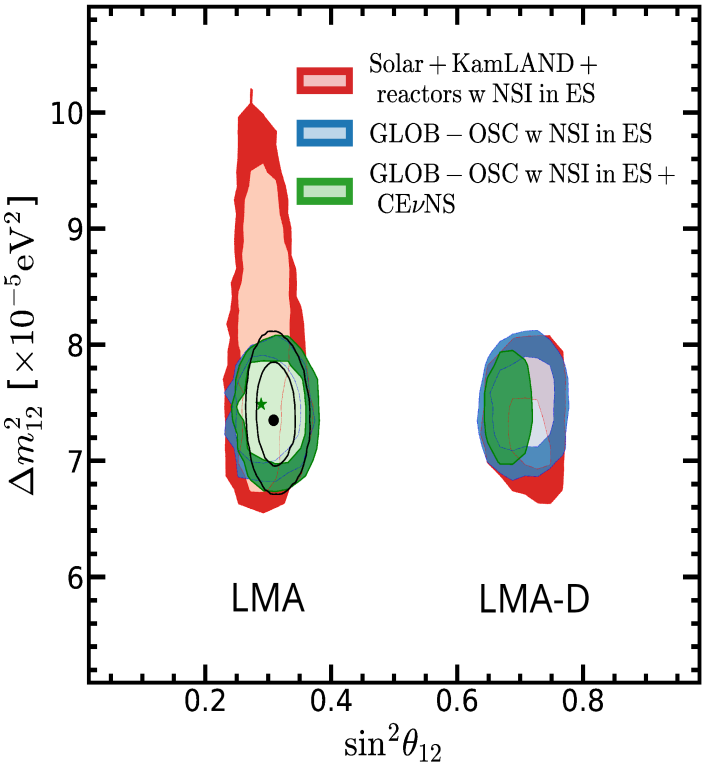
NSI in ν OSC (and CEνNs): Global Analysis

With NSI with up,down and/or e: Coloma, MCGG, Maltoni, Pinheiro, Urrea 2305.07698

LMA-D allowed by oscillations

Adding CEνNs ($M_{\rm med} \gtrsim 50$ MeV)

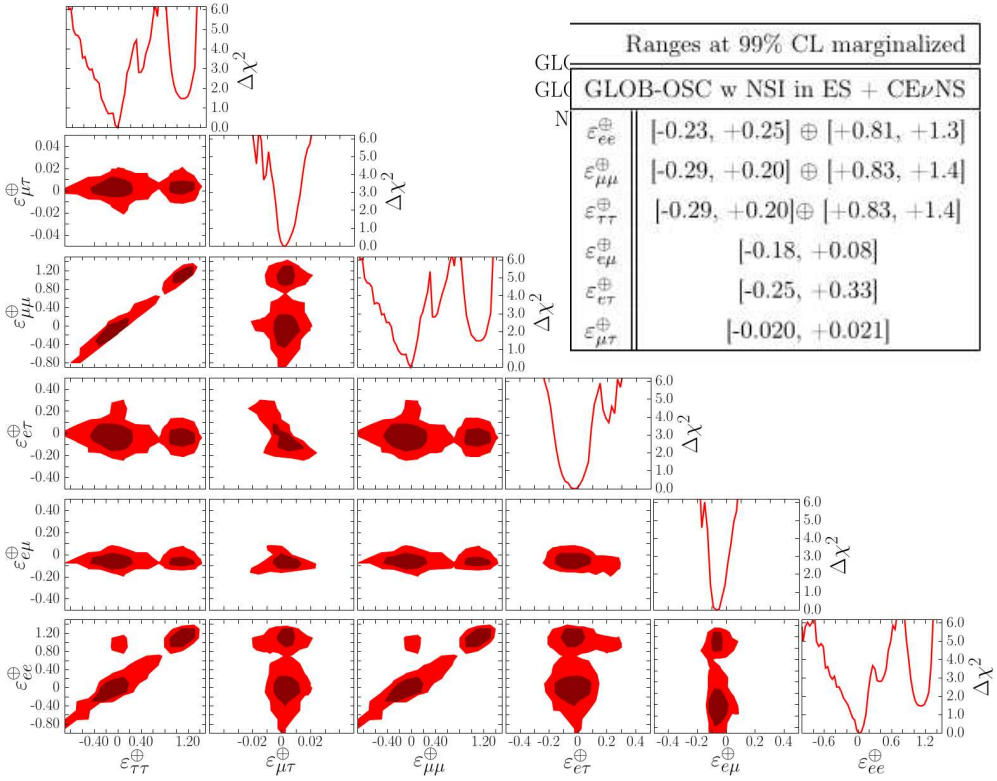
$\Rightarrow$ LMA-D only above 2σ



No evidence of CP conserving NSI's

$\Rightarrow$ Maximum effect at future LBL experiments

$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + (2 + Y^{\oplus}_{n})\varepsilon^{u}_{\alpha\beta} + (1 + 2Y^{\oplus}_{n})\varepsilon^{d}_{\alpha\beta}$$



Ranges at 99% CL marginalized	GLOB-OSC w NSI in ES + CEνNS
$\varepsilon^{\oplus}_{ee}$	[-0.23, +0.25] $\oplus$ [+0.81, +1.3]
$\varepsilon^{\oplus}_{\mu\mu}$	[-0.29, +0.20] $\oplus$ [+0.83, +1.4]
$\varepsilon^{\oplus}_{\tau\tau}$	[-0.29, +0.20] $\oplus$ [+0.83, +1.4]
$\varepsilon^{\oplus}_{e\mu}$	[-0.18, +0.08]
$\varepsilon^{\oplus}_{e\tau}$	[-0.25, +0.33]
$\varepsilon^{\oplus}_{\mu\tau}$	[-0.020, +0.021]

Blanco,Coloma, Esteban,MCGG, Maltoni, Martinez, Pinheiro, 26XX.XXXX

ν OSC bounds in SMEFT

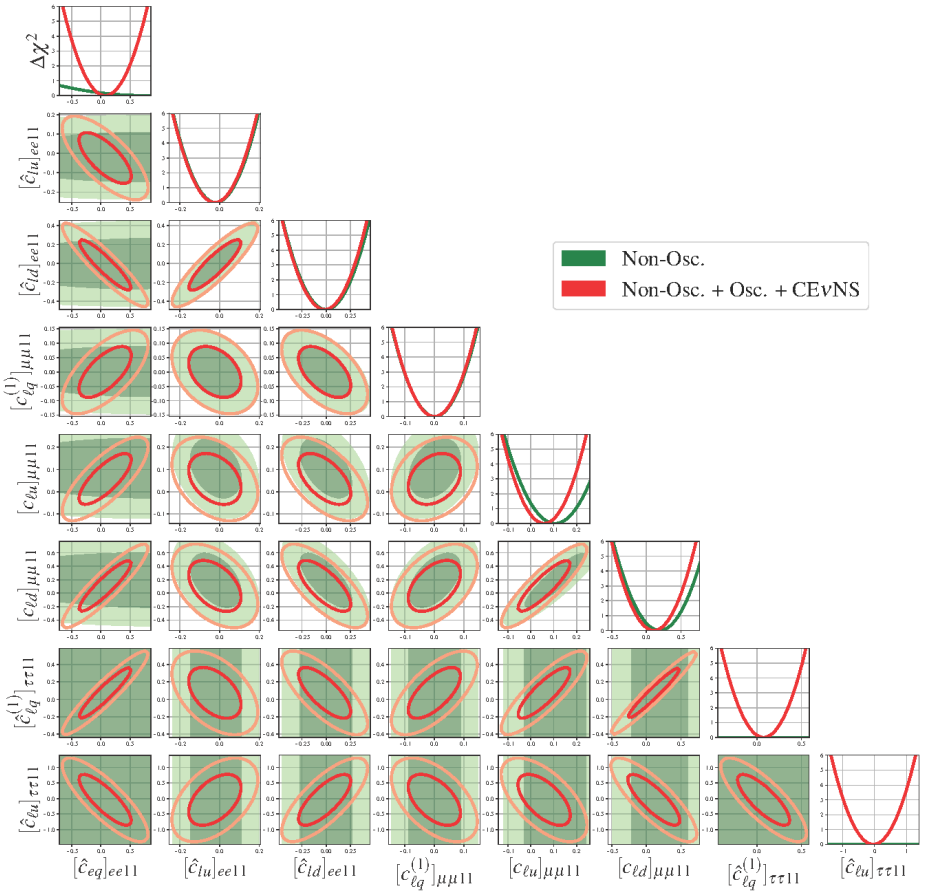
SMEFT $\Rightarrow$ NC-NSI for ν_ℓ and ℓ & CC-NSI all related. Are ν-osc bounds still relevant?

Recent efforts on consistently embedding NSI constraints in SMEFT framework show the relevance of the constraints from oscillations

ν OSC bounds in SMEFT

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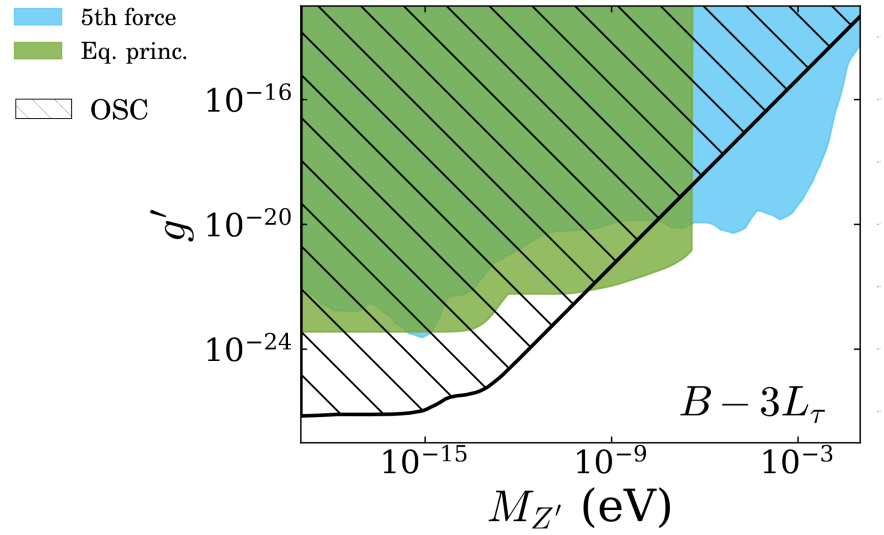
Coloma *etal* 2411.00090

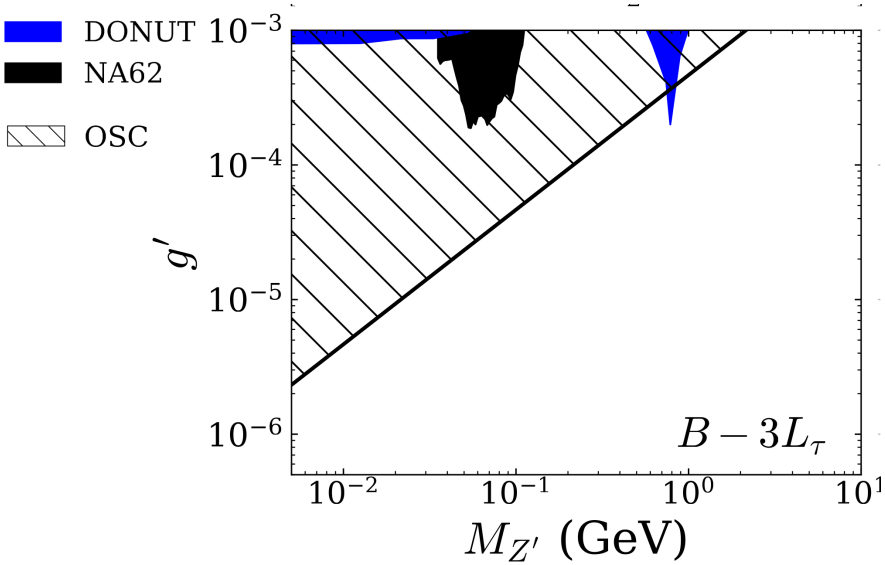
Operators	1σ interval	
	Non-Osc.	Non-Osc. + Osc. + CEνNS
$[\hat{c}_{eq}]_{ee11}$	0.76 ± 1.80	0.07 ± 0.30
$[c_{\ell u}]_{\mu\mu 11}$	0.110 ± 0.091	0.058 ± 0.076
$[c_{\ell d}]_{\mu\mu 11}$	0.19 ± 0.27	0.11 ± 0.25
$[\hat{c}^{(1)}_{\ell q}]_{\tau\tau 11}$	Unconstrained	0.07 ± 0.19
$[\hat{c}_{\ell u}]_{\tau\tau 11}$	Unconstrained	-0.04 ± 0.54

$$
\begin{aligned}
[O_{\ell q}]_{IIJJ} &= (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{q}_J \bar{\sigma}^\mu q_J) \\
[O^{(3)}_{\ell q}]_{IIJJ} &= (\bar{\ell}_I \bar{\sigma}_\mu \sigma^i \ell_I)(\bar{q}_J \bar{\sigma}^\mu \sigma^i q_J) \\
[O_{\ell u}]_{IIJJ} &= (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(u^c_J \sigma^\mu \bar{u}^c_J) \\
[O_{\ell d}]_{IIJJ} &= (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(d^c_J \sigma^\mu \bar{d}^c_J) \\
[O_{eq}]_{IIJJ} &= (e^c_I \sigma_\mu \bar{e}^c_I)(\bar{q}_J \bar{\sigma}^\mu q_J) \\
[O_{eu}]_{IIJJ} &= (e^c_I \sigma_\mu \bar{e}^c_I)(u^c_J \sigma^\mu \bar{u}^c_J) \\
[O_{ed}]_{IIJJ} &= (e^c_I \sigma_\mu \bar{e}^c_I)(d^c_J \sigma^\mu \bar{d}^c_J)
\end{aligned}
$$

From NSI to Light Mediator Models

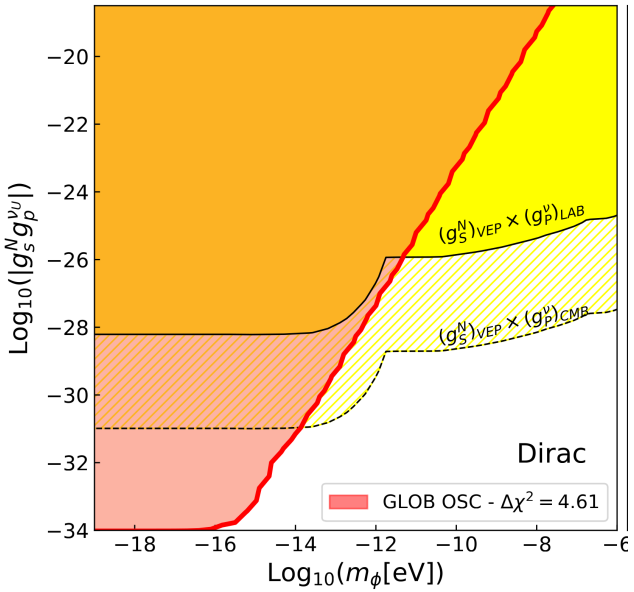
Vector Mediator





Coloma, MCGG, Maltoni, 2009.14220

Scalar-pseudoscalar Mediator



Ansarifard, MCGG, Maltoni, Pinheiro,2405.05340

Summary

- 3ν paradigm is robustly established:

  – Flavour parameters Fall 2026

		best fit $\pm 1\sigma$		3σ rel prec
		IC23 w/o SK-ATM	w IC24 & SKI-V	
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$		$7.414^{+0.070}_{-0.070}$	$7.414^{+0.070}_{-0.070}$	**5.7%**
$\sin^2\theta_{12}$		$0.3041^{+0.0057}_{-0.0055}$	$0.3088^{+0.0057}_{-0.0055}$	**11 %**
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	(NO)	$+2.512^{+0.016}_{-0.014}$	$+2.508^{+0.015}_{-0.014}$	**3.6–3.8%**
	(IO)	$-2.525^{+0.019}_{-0.016}$	$-2.512^{+0.019}_{-0.017}$	**4.5–4.7%**
$\sin^2\theta_{23}$	(NO)	$0.479^{+0.025}_{-0.015}$	$0.478^{+0.022}_{-0.014}$	30–29%
	(IO)	$0.554^{+0.012}_{-0.016}$	$0.549^{+0.013}_{-0.016}$	29–28%
$\sin^2\theta_{13}$	(NO)	$0.02248^{+0.00056}_{-0.00057}$	$0.02242^{+0.00057}_{-0.00056}$	**15%**
	(IO)	$0.02254^{+0.00055}_{-0.00056}$	$0.02253^{+0.00056}_{-0.00056}$	
$\delta_{\mathrm{CP}}/^\circ$	(NO)	205^{+24}_{-35}	210^{+35}_{-37}	100–98%
	(IO)	289^{+22}_{-26}	279^{+21}_{-22}	54–55%
$\chi^2_{\mathrm{IO}} - \chi^2_{\mathrm{NO}}$		5.0	11.6	

  – Status of **MO**, CPV, and θ_{23} octant correlated & obscured by the slight tension in ν_e appearance between T2K and NOνA in NO

  – Complementarity in $|\Delta m^2_{3\ell}|$ determination with ν_μ disappearance at LBL & ATM and ν_e disappearance at reactors becoming more relevant in **MO** determination but size of effect not robust against small changes in combinations/NP

- Robustness of the 3ν-osc picture $\Rightarrow$ relevant constraints in extended scenarios

  Talks by M. Beccaria, A. Palazzo

  * Constraints on NSI relevant to future LBL and present tensions
  * Relevant information in the context of the SMEFT, light mediator models...

Thank you!!

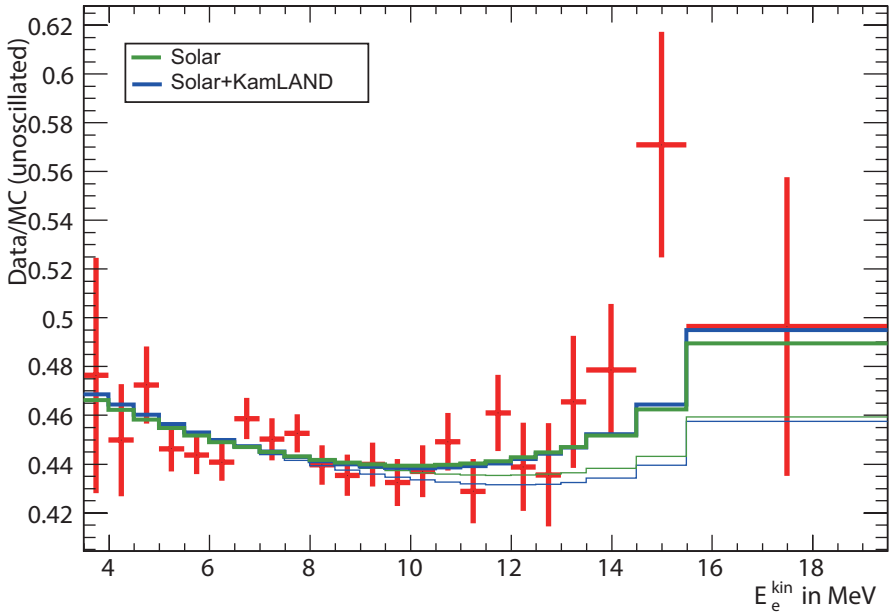
Special thanks to my Collaborators:
Ivan Esteban, Michele Maltoni, Ivan Martinez-Solar,
Joao P Pinheiro, Thomas Schwetz
Pilar Coloma, Pablo Blanco-Mas, Salvador Urrea

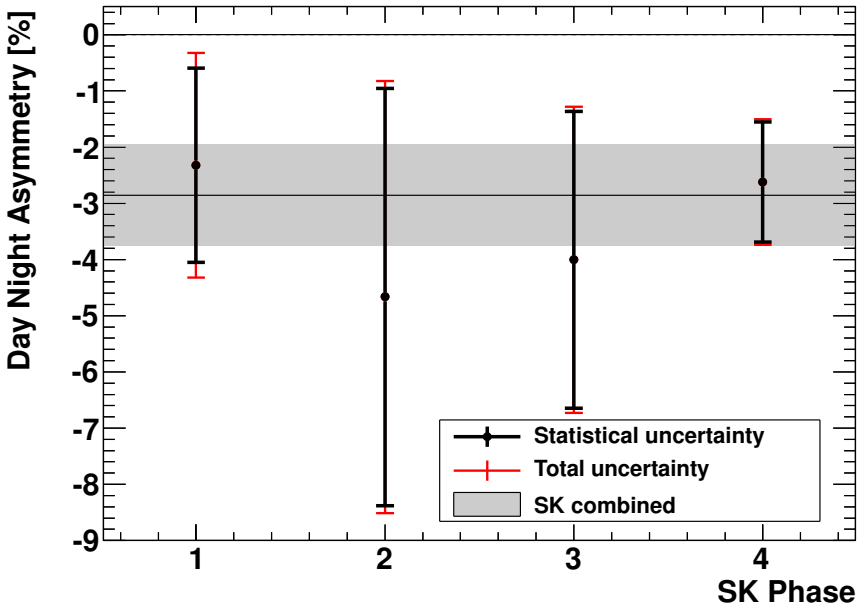
Backup Slides

3 ν Analysis: status of Δm^2_{21} tension

- Long-standing weak tension on preferred Δm^2_{21} from solar and reactor LBL
- Choice of the assumed solar model (GS, AGSS, MB22,...) has little impact
- Cause
  - Too much Day-Night asymmetry (D/N) in SK
  - No indication of low-E MSW turn-up
- With SK IV
  - D/N: 3.6% $\rightarrow$ 2.6%
  - "Hints" of turn-up

$\Rightarrow$ Tension reduced



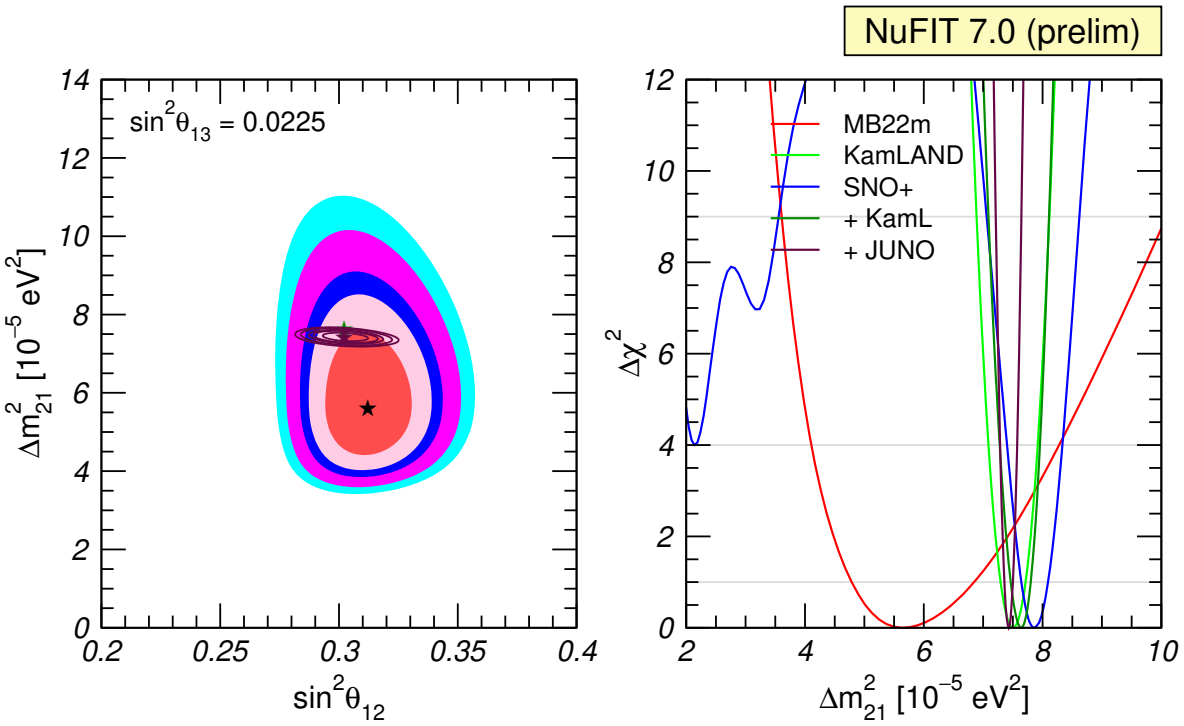


SK Collab. 2312.12907

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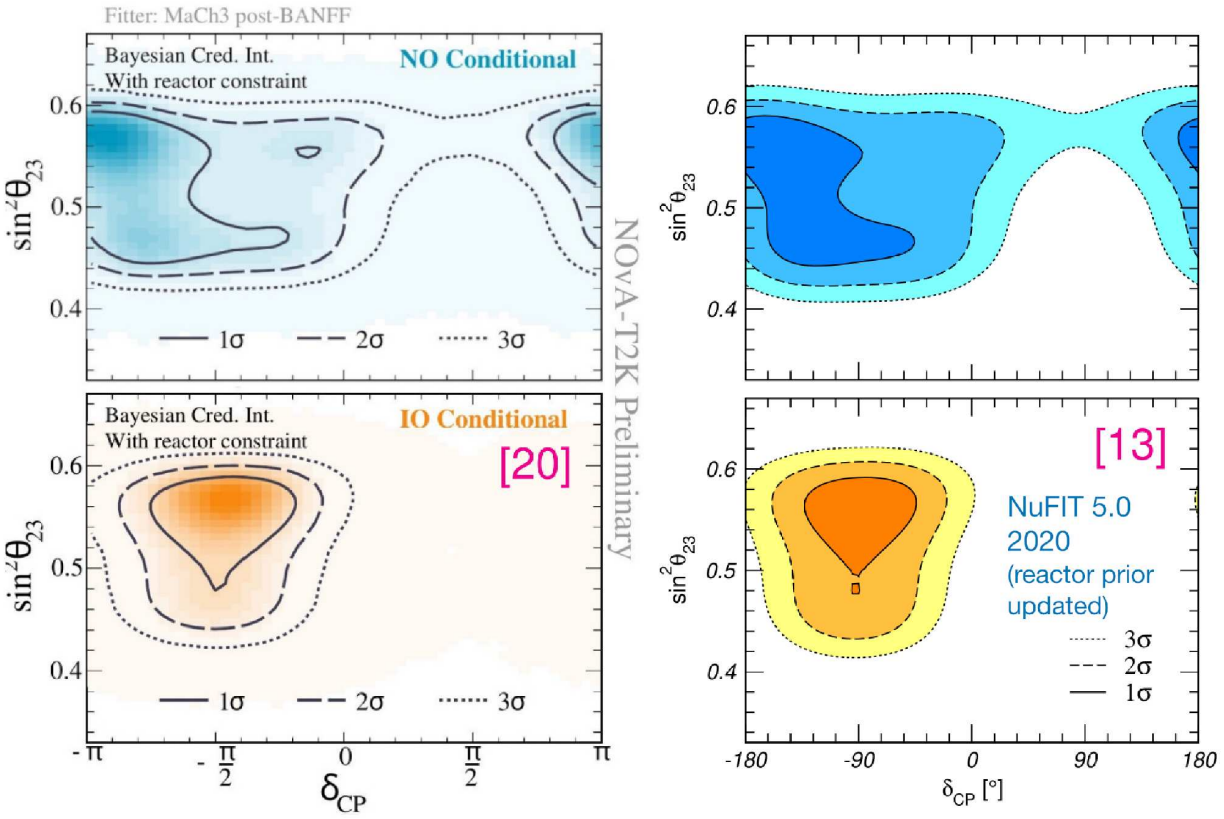
$\Rightarrow$ Tension reduced : $\chi^2_{\mathrm{PG,Sol\,vs\,reac}}/n = 2.3/2$ (#σ=1)



Should we trust the global fits by phenomenologists?

Collaborations start performing (partial) combined analysis, e.g.:

Joint NOvA + T2K analysis of 2020 data became available in 2024 [20]



[20] M. Sanchez [NOvA], talk at Moriond-EW 2024, La Thuile, Italy, March 24–31, 2024.

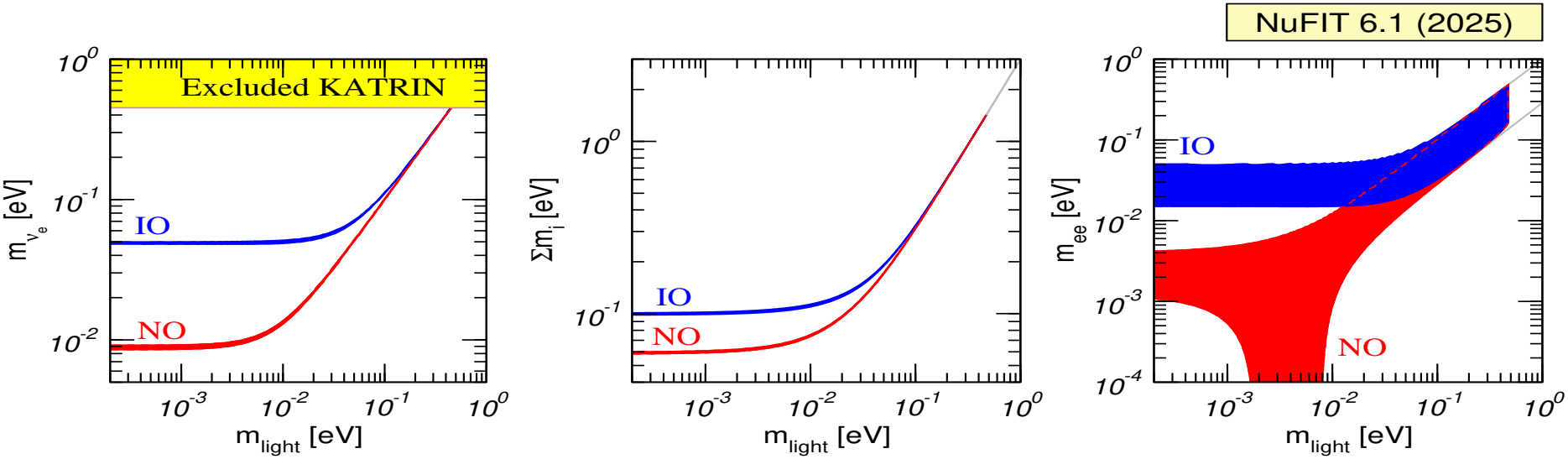
[13] I. Esteban *et al.*, JHEP **09** (2020) 178 [arXiv:2007.14792] & NuFIT 5.2 [http://www.nu-fit.org].

Mass Scale & Dirac vs Majorana in 3ν-mixing

β decay: Dirac or Majorana $\quad m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = \begin{cases} \text{NO}: & m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: & m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$

ν-less β-β decay: $\Leftrightarrow$ Majorana $\quad m_{ee} = |\sum U^2_{ej} m_j| = f(m_\ell, \text{osc param}, \text{maj phases})$

Cosmology: Dirac or Majorana $\quad \sum m_i = \begin{cases} \text{NO}: & \sqrt{m^2_\ell} + \sqrt{\Delta m^2_{21} + m^2_\ell} + \sqrt{\Delta m^2_{31} + m^2_\ell} \\ \text{IO} & \sqrt{m^2_\ell} + \sqrt{-\Delta m^2_{31} - \Delta m^2_{21} - m^2_\ell} + \sqrt{-\Delta m^2_{31} - m^2_\ell} \end{cases}$



95% CL

NO : $\quad 0.0085\ \text{eV} \leq m_{\nu_e} \leq 0.4\ \text{eV} \qquad 0.058\ \text{eV} \leq \sum m_\nu \leq 1.2\ \text{eV} \qquad 0 \leq m_{ee} \leq 0.41\ \text{eV}$

IO : $\quad 0.048\ \text{eV} \leq m_{\nu_e} \leq 0.4\ \text{eV} \qquad 0.098\ \text{eV} \leq \sum m_\nu \leq 1.2\ \text{eV} \qquad 0.015\ \text{eV} \leq m_{ee} \leq 0.41\ \text{eV}$

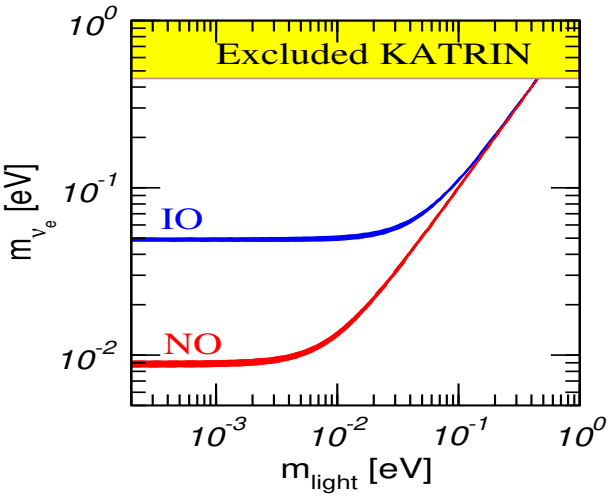
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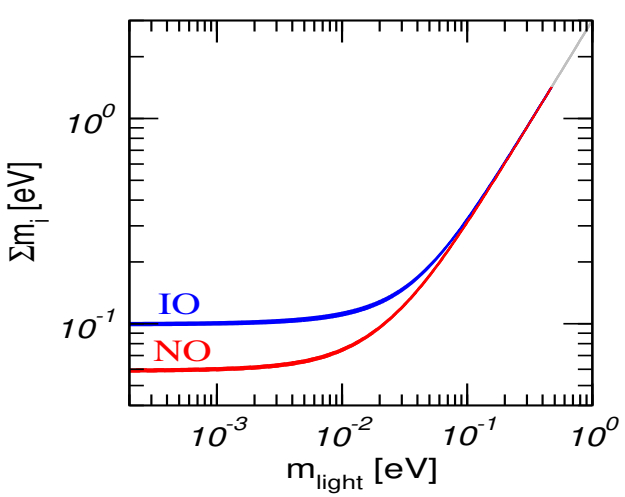
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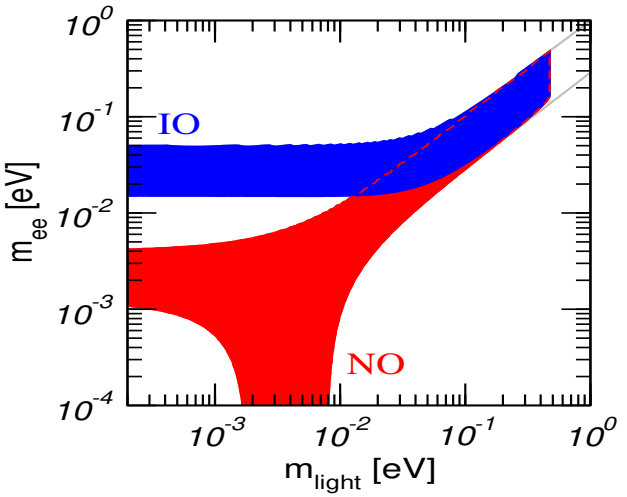
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NuFIT 6.1 (2025)







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Lepton Mixing Unitarity

- If ν_L mixed with n extra states $U_{\rm LEP} = (K_{l,3\times 3}\,, K_{h,3\times n})$ Schechter, Valle (1980)

$$K_{l,3\times 3} = \left[I_{3\times 3} - \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{e\mu} & \alpha_{\mu\mu} & 0 \\ \alpha_{e\tau} & \alpha_{\mu\tau} & \alpha_{\tau\tau} \end{pmatrix} \right] \times U_{3\times 3}(\theta_{ij}, \delta)$$

Xing arXiv:1110.0083; Escrihuela *etal* arXiv:1503.08879, Blennow *etal* arXiv:1609.08637

- For extra states with $M \gtrsim 10$ eV oscillation experiments depend on $K_{l,3\times 3}$

  $\Rightarrow$ effects in production, propagation and detection
  (not always consistently accounted for in literature) *Blennov et al 2502.14980*

- Unitarity violation $\Rightarrow$ effects in charge lepton flavour observables (CLFO)

  $\Rightarrow$ for $M \gtrsim$ EW scale stronger bounds from CLFO

90% CL	Averaged ν Oscillations m > 10 eV		Flavour & EWPO [53] m > M_Z	
	Direct	Schwarz	Direct	Schwarz
α_{ee}	8.4×10^{-3} [108]	-	1.2×10^{-3}	-
$\alpha_{\mu\mu}$	1.2×10^{-2} [117]	-	8.6×10^{-5}	-
$\alpha_{\tau\tau}$	2.9×10^{-2} [110]	-	6.0×10^{-4}	-
$\lvert\alpha_{\mu e}\rvert$	1.8×10^{-2} [105]	1.4×10^{-2}	1.9×10^{-5}	5.4×10^{-4}
$\lvert\alpha_{\tau e}\rvert$	6.1×10^{-2} [104]	2.2×10^{-2}	6.2×10^{-3}	1.5×10^{-3}
$\lvert\alpha_{\tau\mu}\rvert$	9.1×10^{-3} [104]	2.6×10^{-2}	6.9×10^{-3}	1.5×10^{-4}

Blennow et al arxiv: 2502.14980

NSI: Effect in Coherent Elastic ν-Nucleus Scattering (CEνNS)

- Predicted by Freedman etal in 1974. First observed by COHERENT experiment 2017.

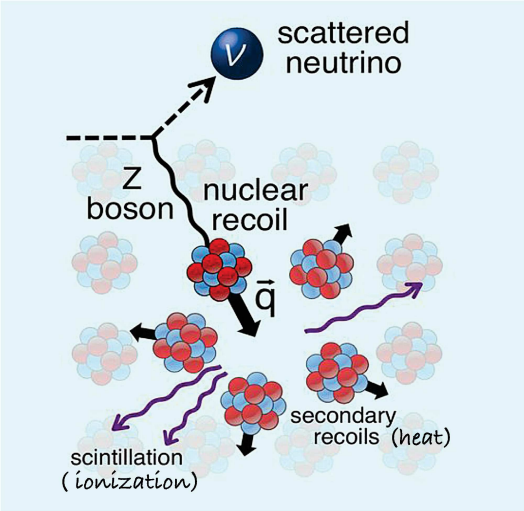
$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{2\pi}\frac{\mathcal{Q}^2}{4}F^2(2ME_r)M\left(2-\frac{ME_r}{E_\nu^2}\right)$$

$$\frac{\mathcal{Q}^2}{4} = \left[Zg_p^V + Ng_n^V\right]^2$$

For neutrinos at/below 50 MeV, coherence condition(q < 1/R) satisfied for a medium size nucleus (Ar, Ge, ... Cs, Xe)

Although predicted in 1974, it has not been observed until 2017!

Freedman et al, PRD9 (1974) 1389



- By 2025: Observed in CsI 1708.01294, Ar 2006.12659, Ge 2202.09672,2406.13806,2501.05206 and Xe 2407.10892,2408.02877
- For $M_{\rm Med} \gtrsim 50$ MeV and NSI with quarks $\Rightarrow$ effect in CEνNS

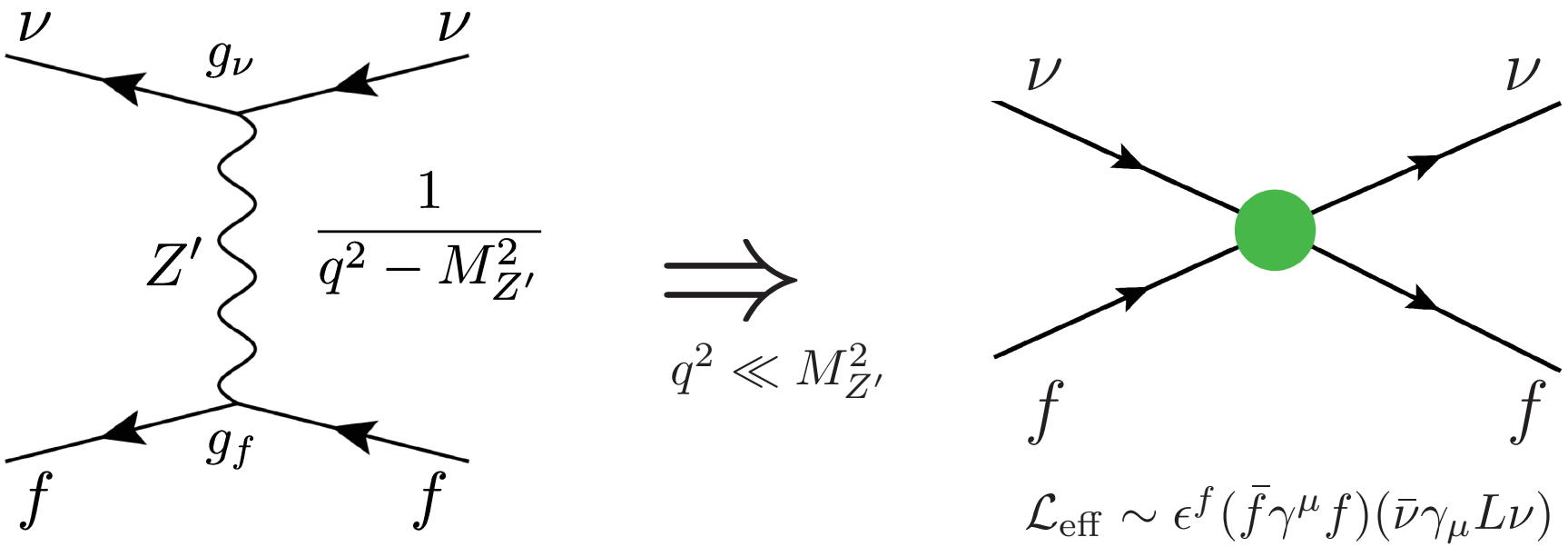
$$\mathcal{Q}_{\alpha\beta} \propto Z\left(g_p^V\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{p,V}\right) + N\left(g_n^V\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{n,V}\right)$$

Neutral Current Non Standard ν Interactions

- Effective Lagrangian

$$\mathcal{L}^{\rm NC}_{\rm NSI} = -2\sqrt{2}G_F \varepsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{f}\gamma_\mu P f)\,, \qquad P = L, R$$

- Generically understood as:



Beyond 3ν's: $\mathcal{O}$(eV) Sterile Neutrinos

LSND &MiniBoone

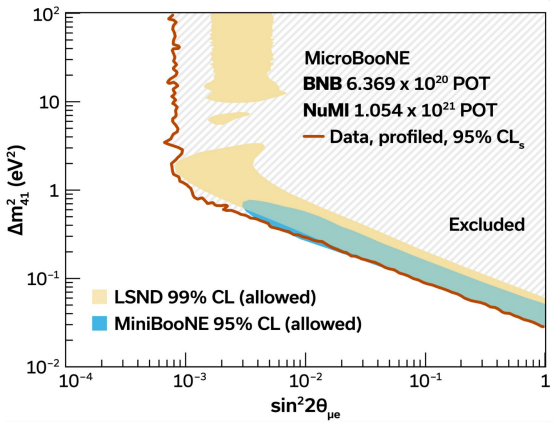
$$\bar{\nu}_\mu \to \bar{\nu}_e \;\&\; \nu_\mu \to \nu_e$$

$$\sin^2 2\theta_{\mu e} \sim \tfrac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

No confirmed in MicroBoone

Strong tension with

non-observation of ν_μ disapp



Purely sterile oscillation

robustly disfavoured

additional SM or NP effects?

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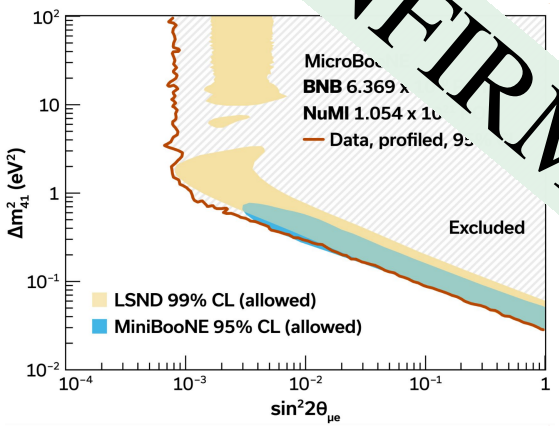
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UNCONFIRMED

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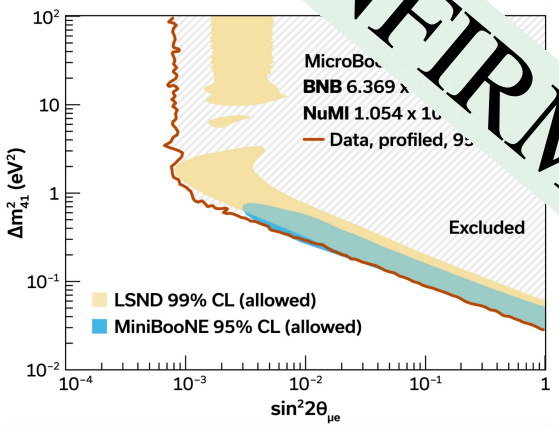
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Reactor Anomaly

Huber, 1106.068,Mention *etal* ,1101.2755

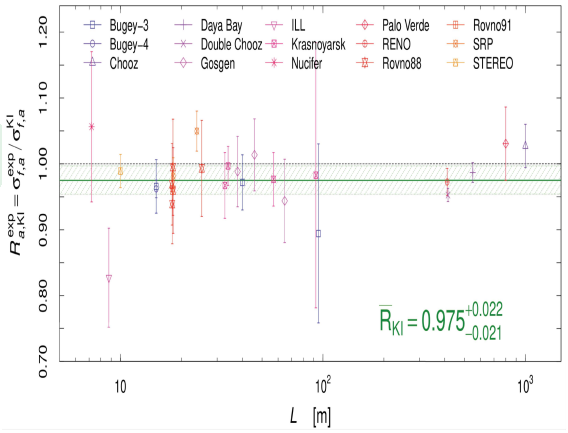
2011 reactor flux calculation $\Rightarrow$

Deficit in $R = \frac{\text{data}}{\text{predict}}$ at $L \lesssim 100$ m

Explained as $\bar{\nu}_e$ disappearance

2022 with updated inputs (^{235}U)

Berryman Huber, 2005.01756
Kipeikin etal, 2103.01486
Giunti etal, 2110.06820



(Fig from Giunti etal, 2110.06820)

Anomaly $\sim 1\,\sigma$

with new fluxes

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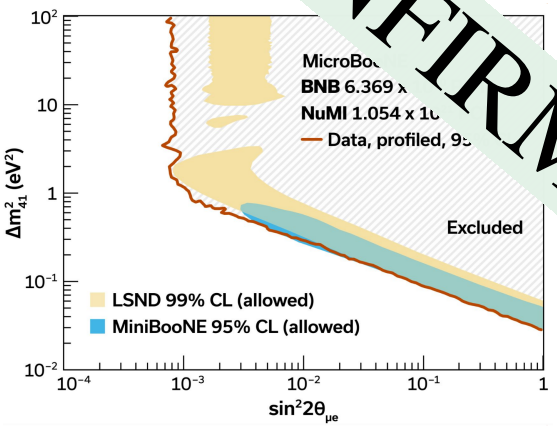
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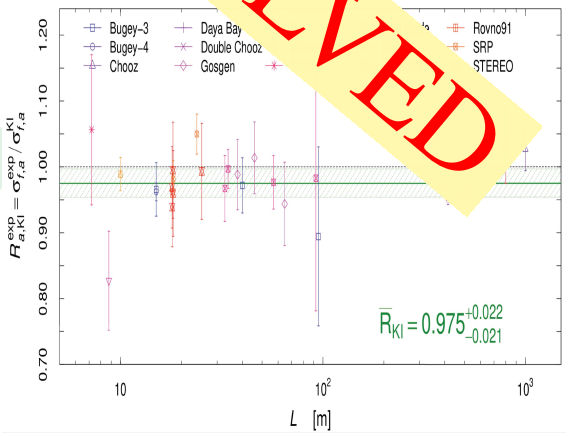
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Be... Huber, 2005.01756

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RESOLVED



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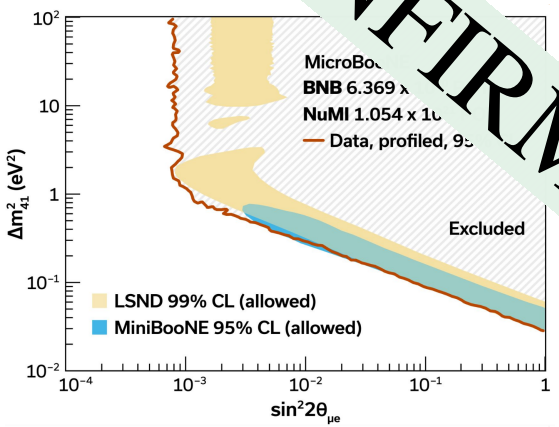
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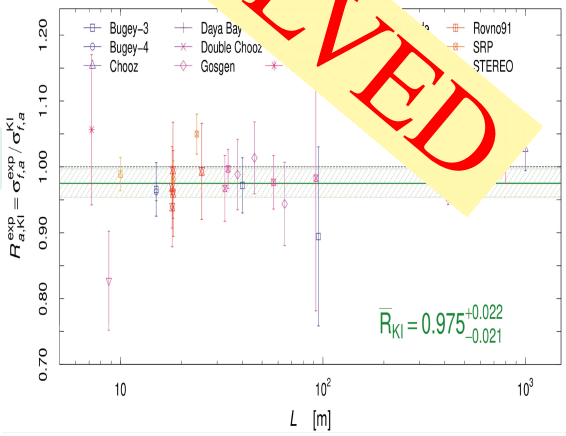
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Gallium Anomaly

Acero etal, 0711.4222;Giunti, Laveder,1006.3244

$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

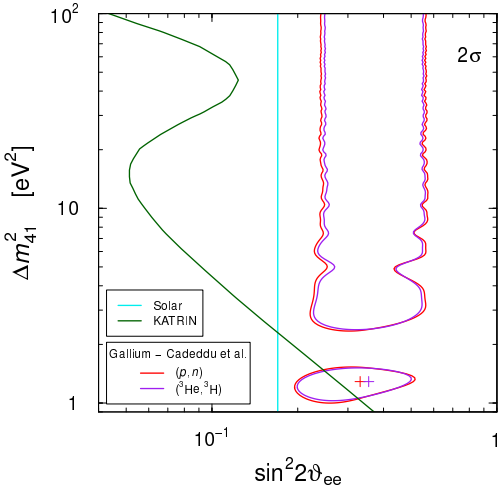
Rate lower than expected

Explained as ν_e disappearance

Confirming results from BEST

But oscillation solution

Requires large mixings



Caddedu etal, 2507.13013

Ruled out/tension with solar+ reactor+KATRIN

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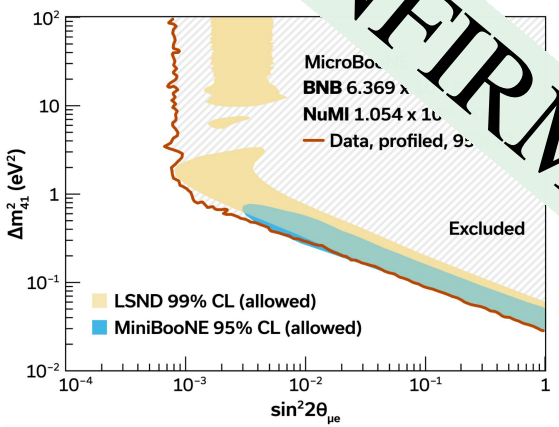
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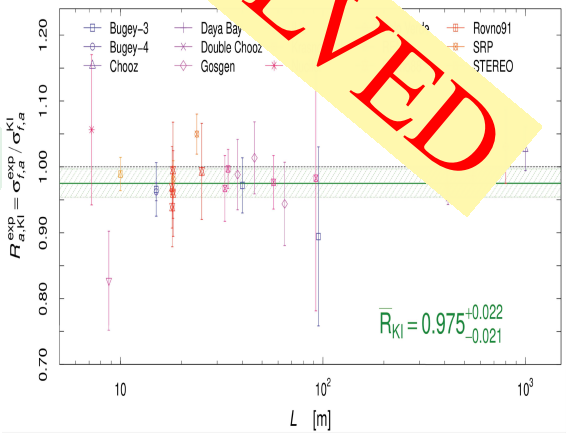
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Gallium Anomaly

Acero etal, 0711.4222;Giunti, Laveder,1006.3244

$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

Rate lower than expected

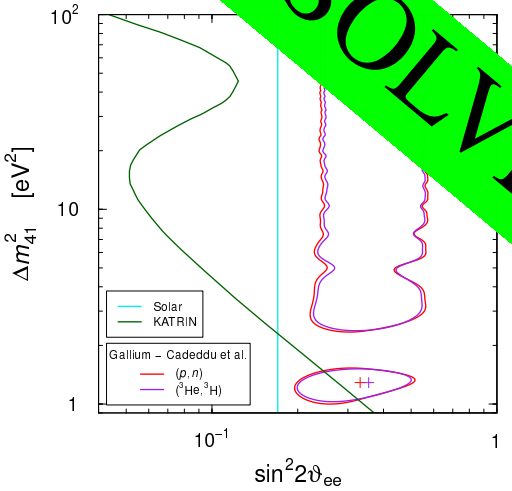
Exp ined as ν_e disappearance

UNRESOLVED (?)

g results from BEST

But o lution

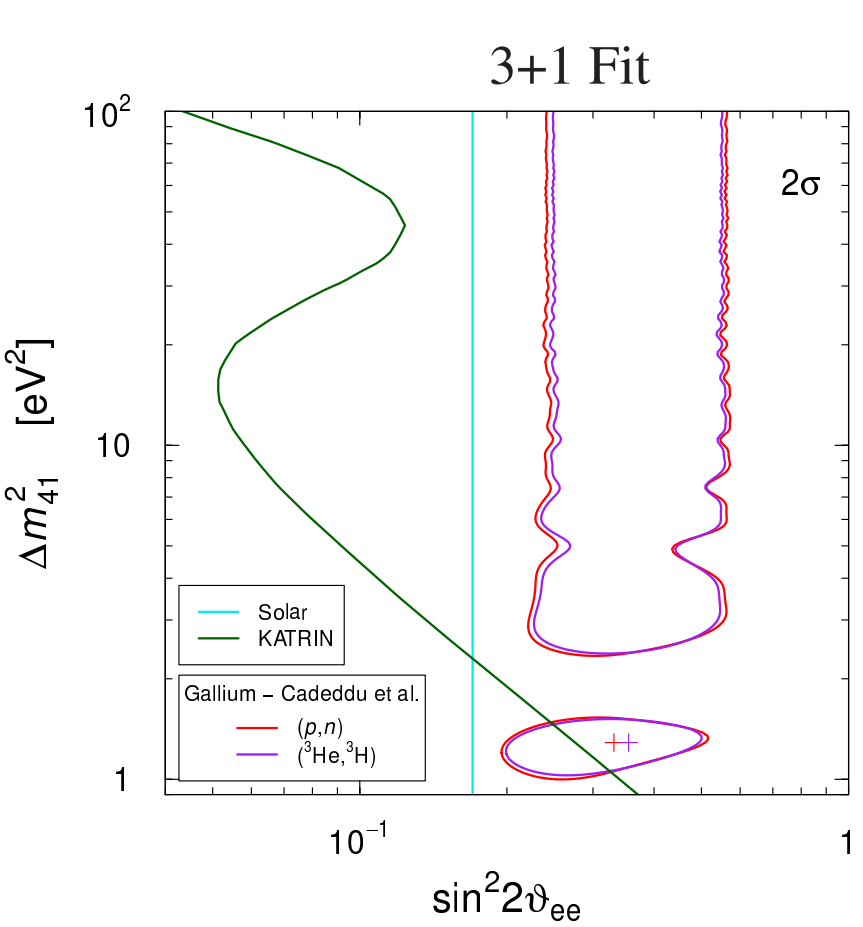
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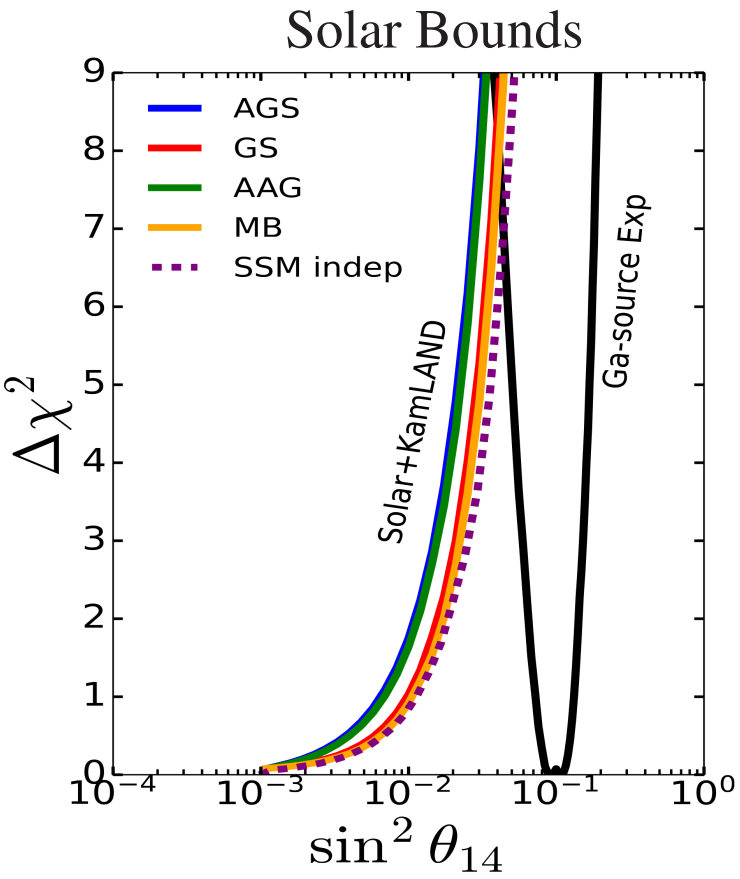
Caddedu etal, 2507.13013

Ruled out/tension with solar+ reactor+KATRIN

Solar modeling and the Gallium anomaly



Caddedu etal, 2507.13013



In all cases $\chi^2_{\rm PG}/n > 13.5$ ($\#\sigma > 3.7$)

$\Rightarrow$ Incompatiblity is SSM independent

MCGG, M.Maltoni, J. Pinheiro, 2411.16840