NEUTRINO THEORY (MASSIVE NEUTRINOS IN 2025)

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RENATA (Red Nacional de Astroparticulas) 2025

OUTLINE

Status of the 3ν global description

Explorations/Implications beyond 3ν's

The ν evidence of BSM

- In the SM $\nexists \nu_R \Rightarrow \underline{L_\alpha \text{ conserved}} \Leftrightarrow m_\nu = 0$

- 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 $L \sim 200$ Km (**KamLAND**)

  $*$ Reactor $\overline{\nu}_e$ disappear at $L \sim 1$ Km (D-Chooz, **Daya Bay**, Reno)

  $\Rightarrow L_\alpha$ are violated $\Rightarrow$ There is Physics Beyond SM

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- The *important* question:

  What BSM?

- The *starting* path:

  Precise determination of the low energy parametrization

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

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

  * Introduce ν_R

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  $*$ Introduce ν_R AND impose L conservation

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

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- Either way $\Rightarrow$ CC Int interactions of massive leptons are not diagonal$\Rightarrow U_{\rm LEP}$

  $\Rightarrow$ Lepton flavours not conserved in ν propagation $\equiv$ Flavour Oscillations:

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

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\text{eV}^2} \frac{L/E}{\text{Km/GeV}}$$

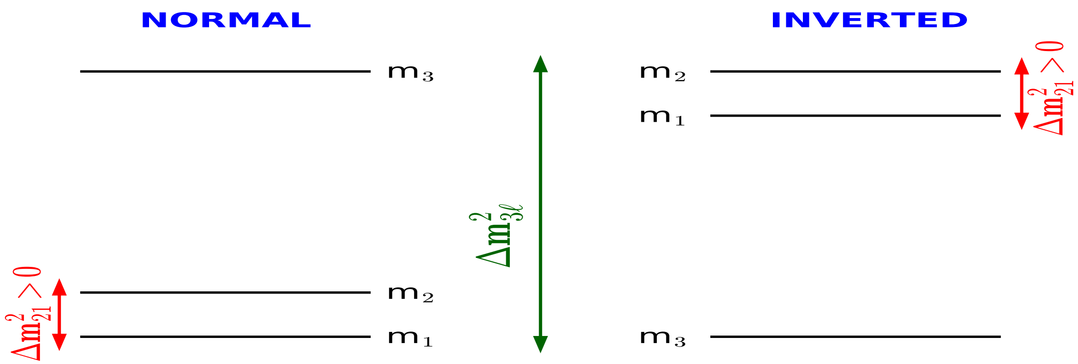
No information on ν mass scale nor Majorana versus Dirac

3ν Flavour Parameters

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

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \xcancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

- Convention: $0 \le \theta_{ij} \le 90°$ $\quad 0 \le \delta \le 360°$ $\quad \Rightarrow$ 2 Orderings



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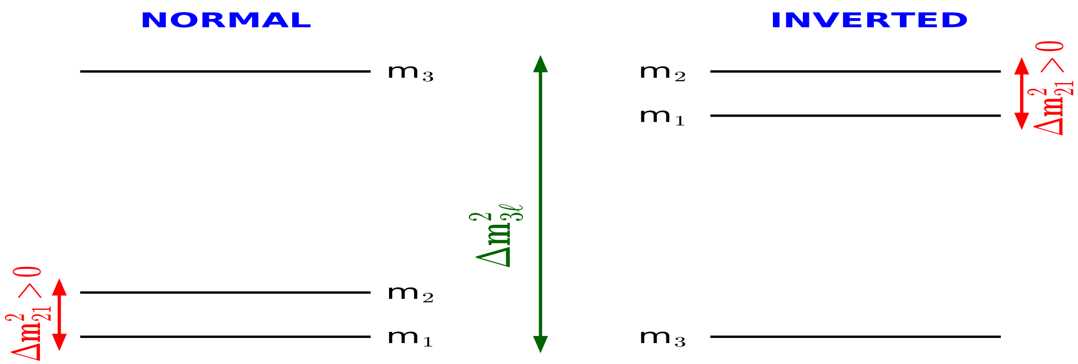

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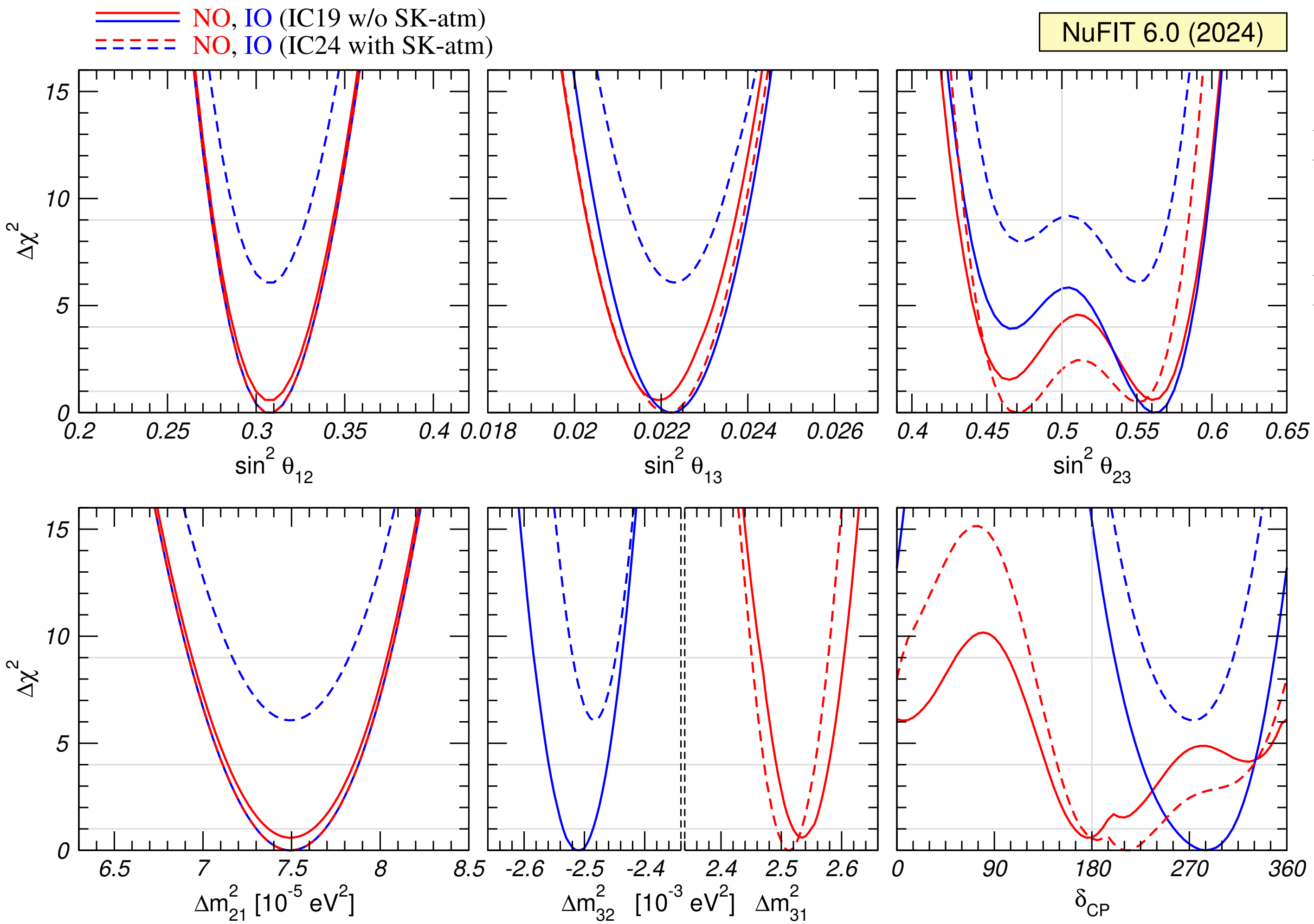
Experiment	Dominant	Important	Additional
Solar Experiments	θ_{12}	Δm^2_{21}	θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12}	θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13}, $\Delta m^2_{3\ell}$		
Atmospheric Experiments (SK,IC)	θ_{23}	$\Delta m^2_{3\ell}$	θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\Delta m^2_{3\ell}$. θ_{23}		
Acc LBL ν_e App (Minos,T2K,NOvA)	$\delta_{\rm cp}$	θ_{13}	θ_{23}, $\Delta m^2_{3\ell}$,$\Delta m^2_{3\ell}$

Global 3 ν Flavour Parameters: Spring 2025

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

Esteban, G-G, Maltoni, Martinez, Pinheiro,Schwetz, 2410.05380

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



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

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

IC19 $\equiv$ Our analysis of Icecube data from 1902.07771

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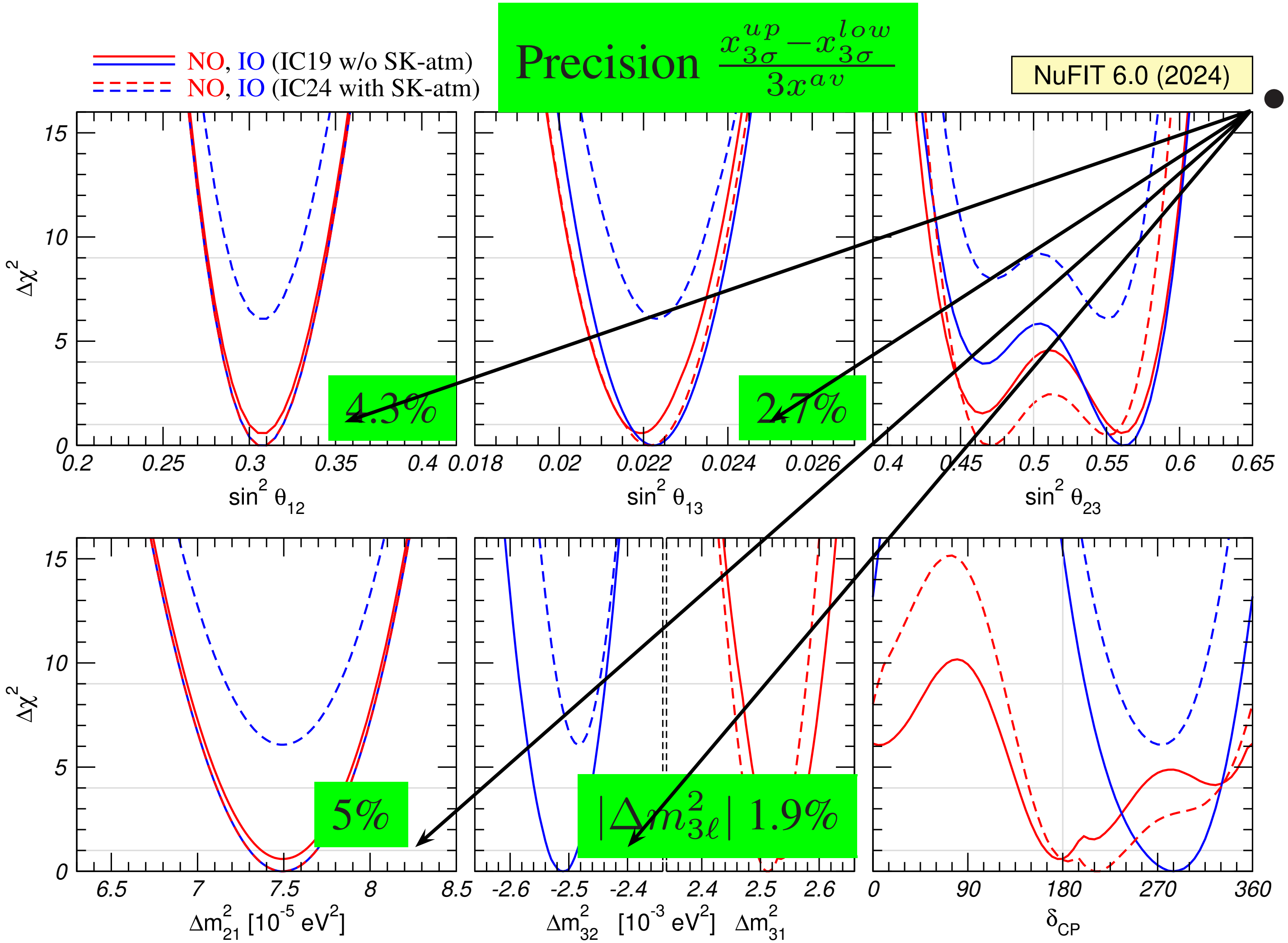

- 4 well-known parameters: $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$

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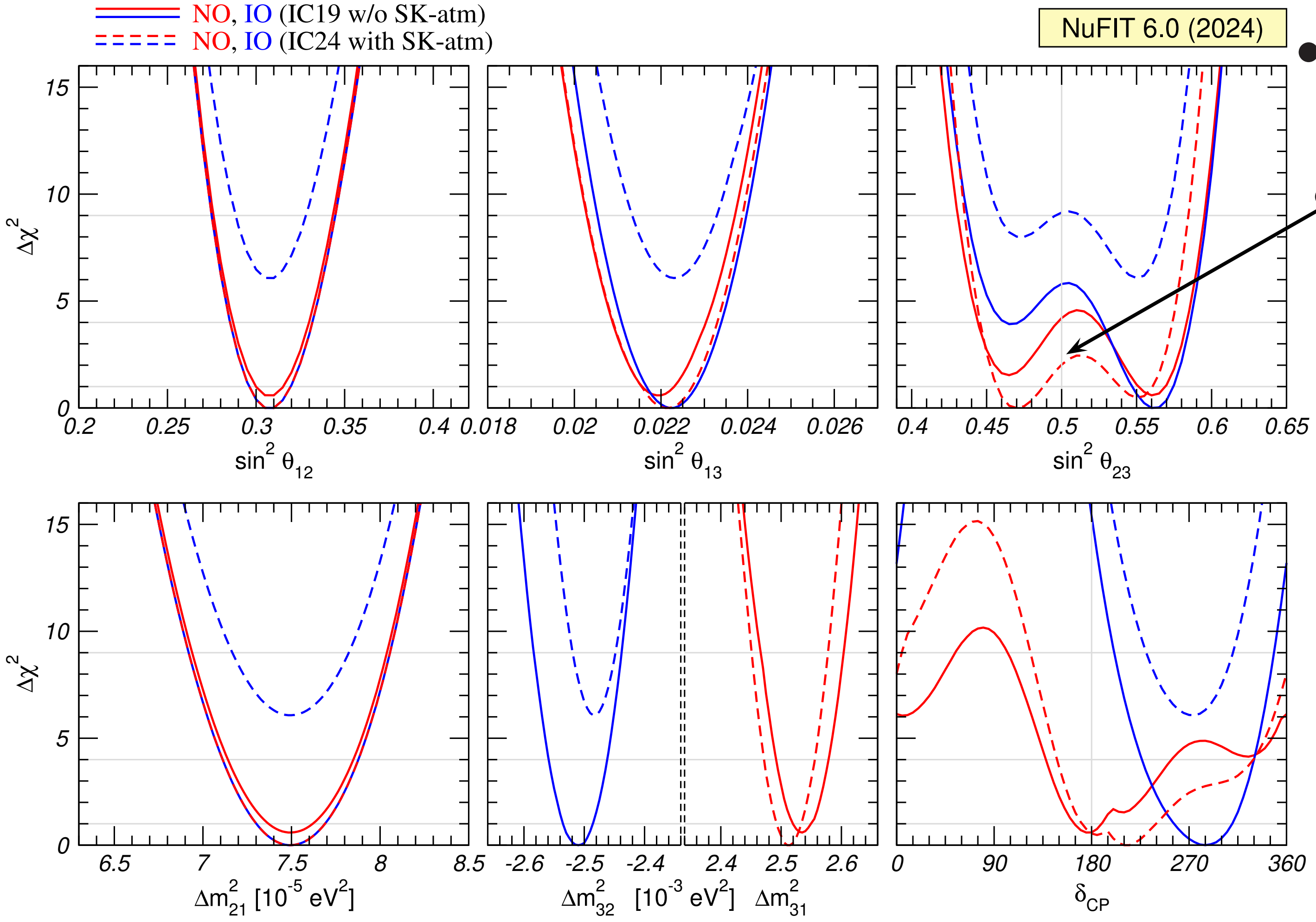

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  Maximal? Octant?

  non-robust yet

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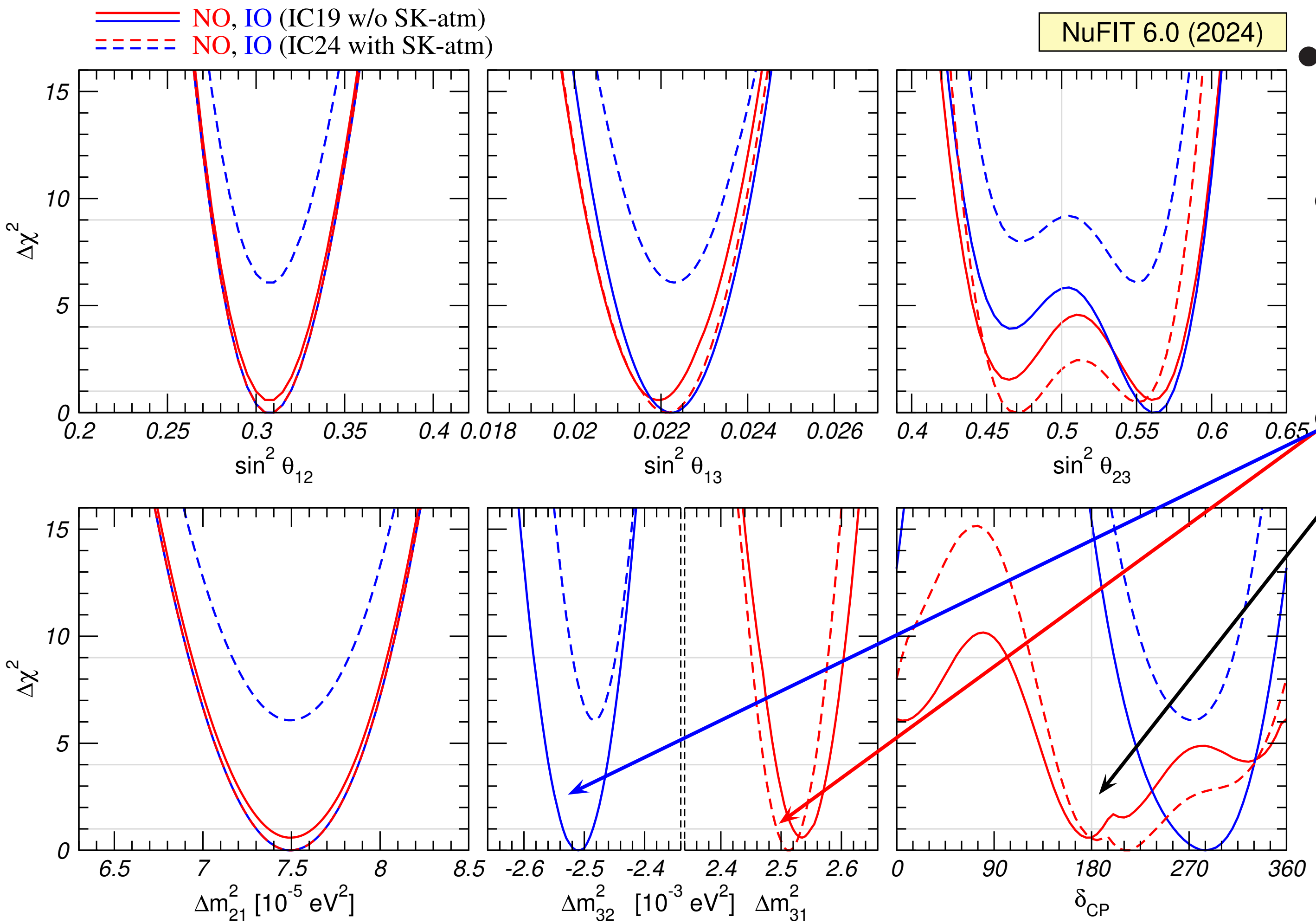

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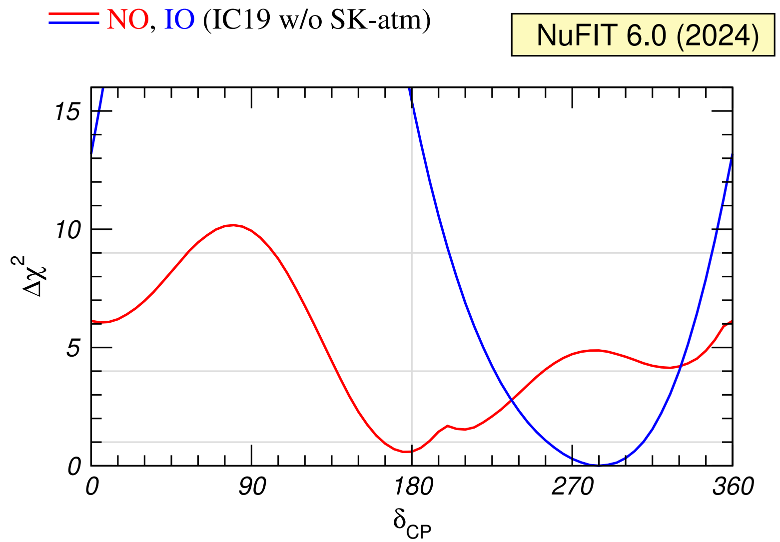
- Ordering NO or IO?
- CPV?:

Mass Ordering (and CPV)



- Dominant information in ν_e vs $\overline{\nu}_e$ appearance in LBL:

  Each T2K and NOνA favour NO but tension in value of δ_{CP} in NO

  $\Rightarrow$ IO best fit in LBL combination $\Rightarrow$ b.f. $\delta_{\rm CP} \sim 290°$, CPC disfavoured at $\gtrsim 3.5\sigma$

- Additional information from ν_μ in LBL vs ν_e disapperance in MBL Reactors:

  Slightly better in NO $\Rightarrow$ LBL+Reac: NO and IO equally good $\Rightarrow$ CPC OK

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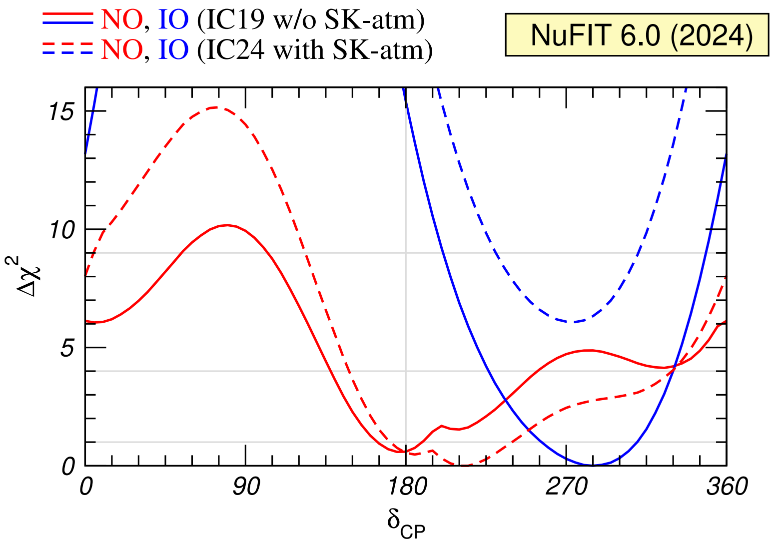

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- Adding SK-ATM χ^2 Table:

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  $\Delta\chi^2_{\rm IO-NO, with\ SK-atm} \simeq 6$

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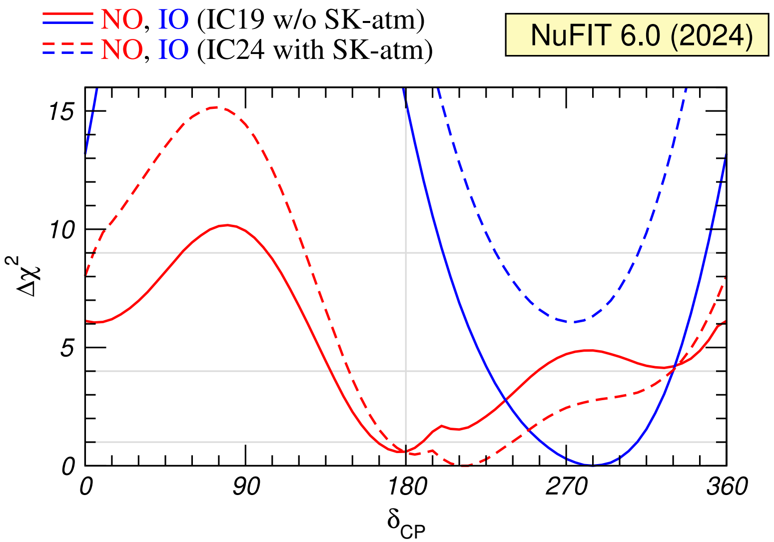

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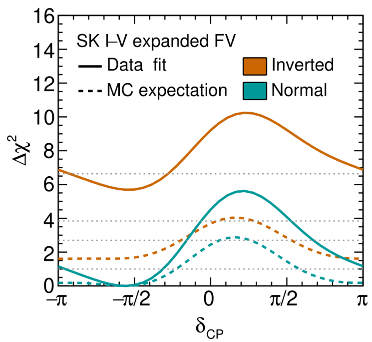
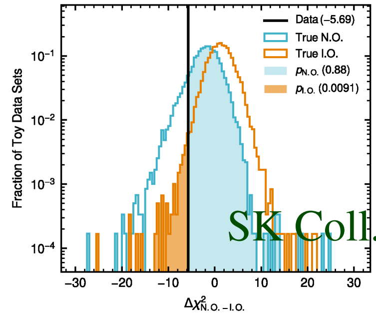
SK-atm beyond expectation and not clearly compatible





SK Coll. arXiv:2311.05105

Confirmed Low Energy Picture

- 3ν scenario:
  - Robust determination of θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  - Mass ordering, θ_{23} Octant, CPV depend on subdominant 3ν-effects

    $\Rightarrow$ interplay of LBL/reactor/ATM results. Not statistically significant yet

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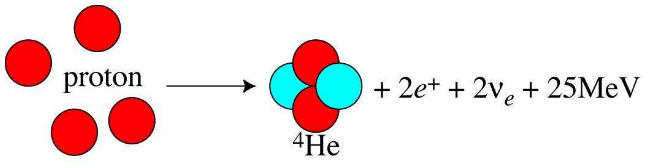
    – T2K and NOνA will run till $\sim$ 2027

    – JUNO taking data $\Rightarrow$ Ordering (alone and/or comb with ν-telescopes)

    – Hyper-K and DUNE expected within a decade $\Rightarrow$ Ordering, $\delta_{\rm CP}$ & θ_{23}

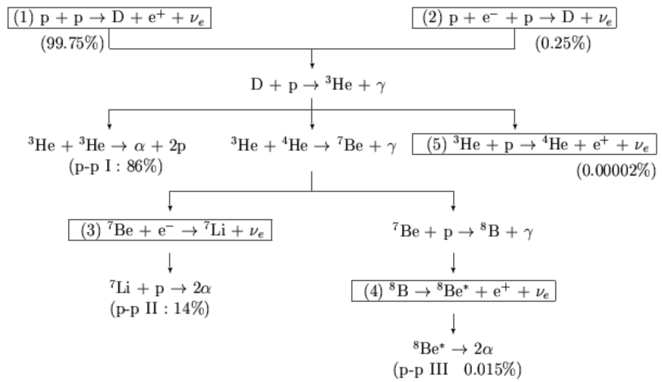
Byproduct: Testing How the Sun Shines with $\nu's$

- Sun shines by nuclear fusion

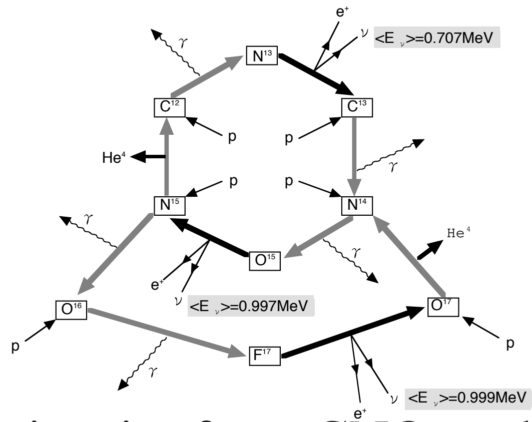


- Two main chains of nuclear reactions:

pp Chain :

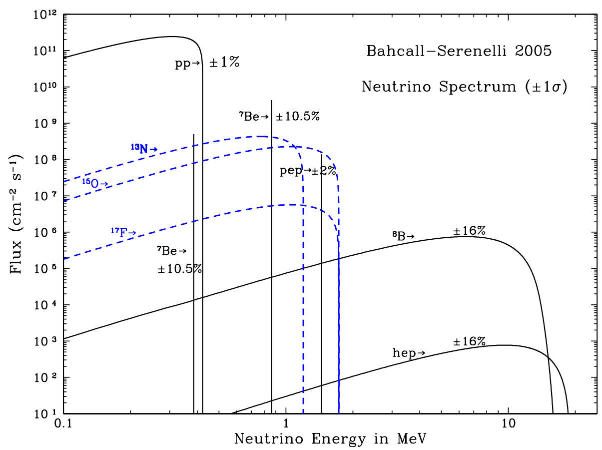


CNO cycle:



- Standard Solar Models predict $< 1\%$ of solar luminosity from CNO cycle.

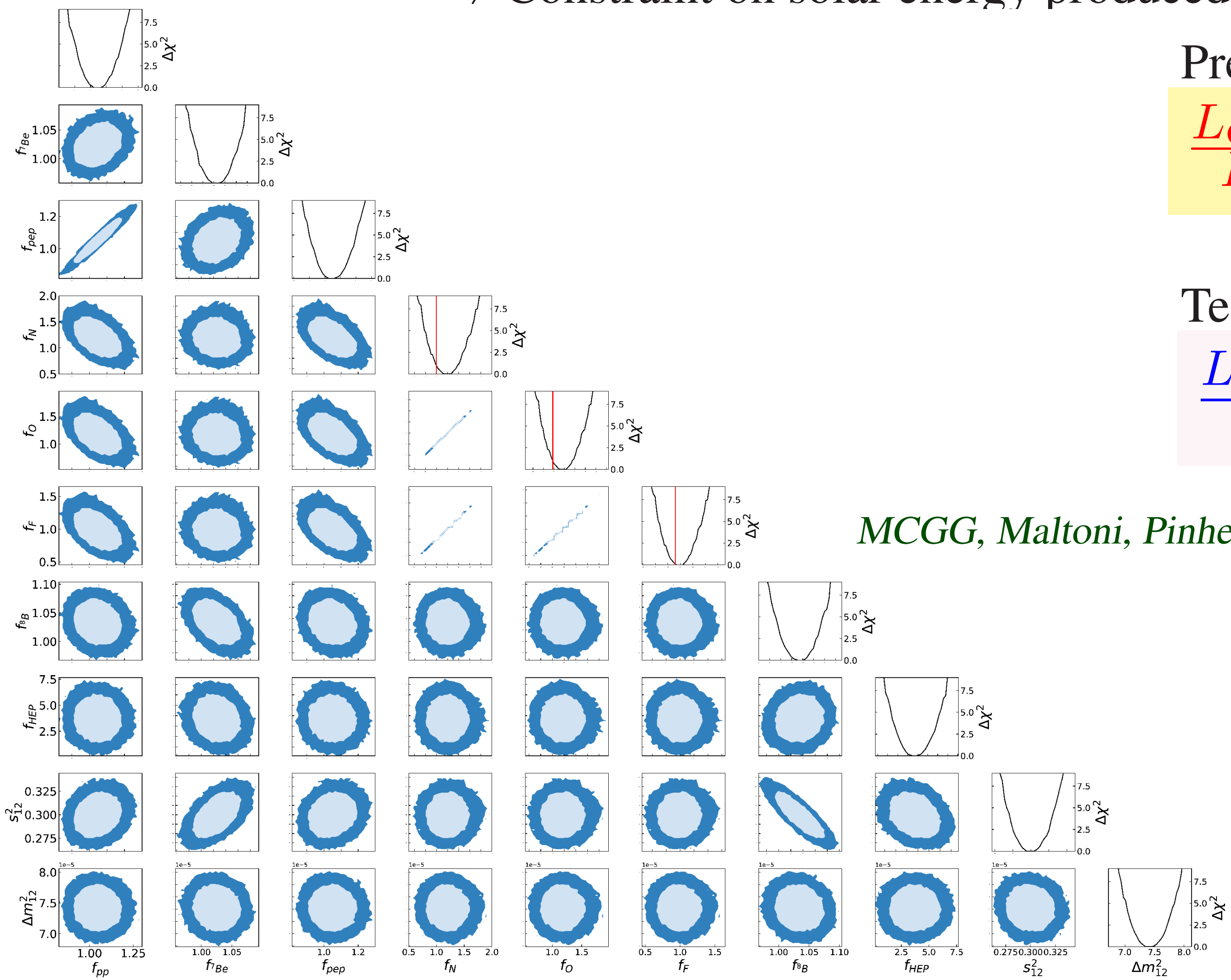
They also predict the corresponding neutrino fluxes



Byproduct: Testing How the Sun Shines with $\nu' s$

Fitting together Δm^2, θ 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:

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

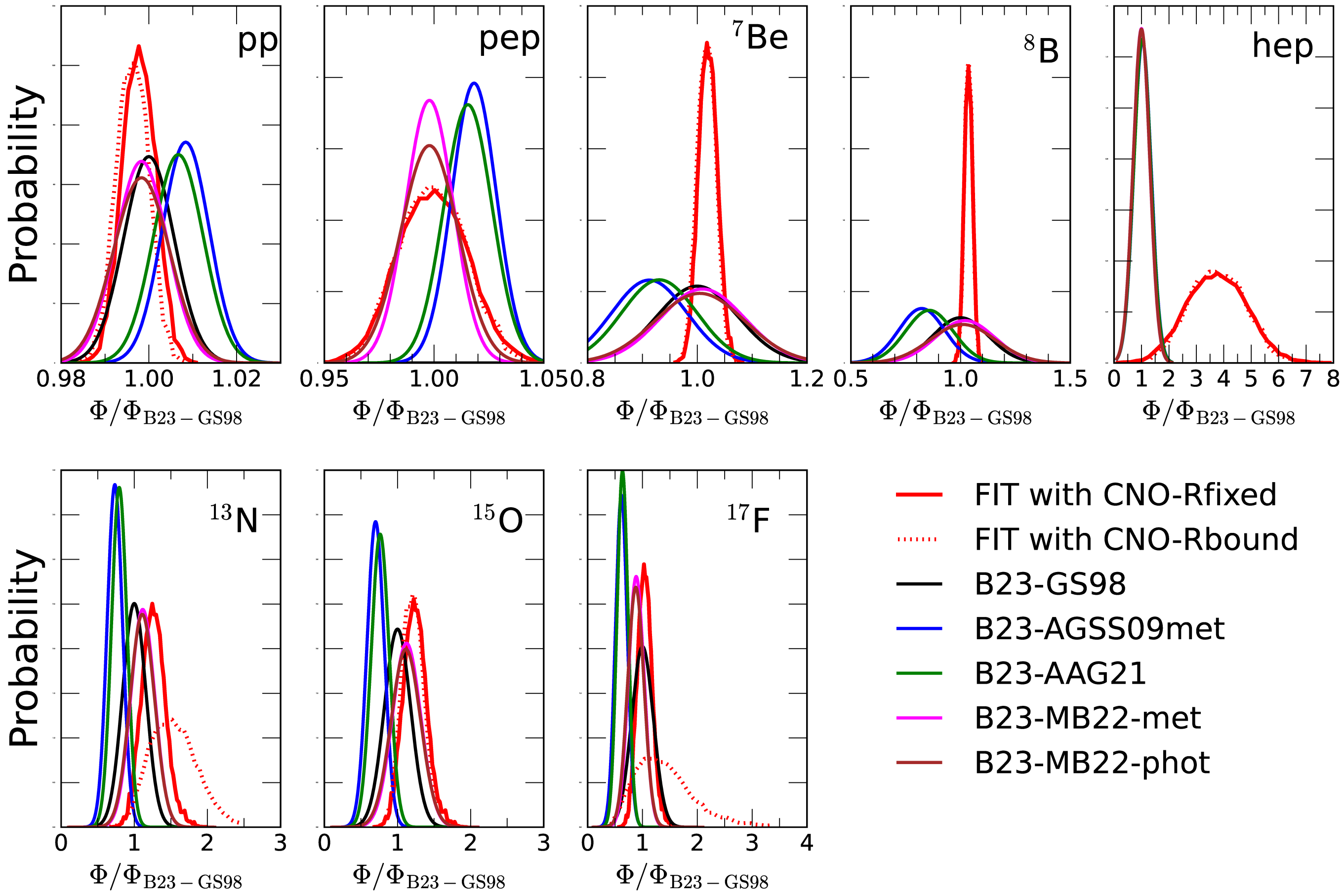
Test of Lum Constraint:

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

MCGG, Maltoni, Pinheiro, Serenelli 2311.16226

Byproduct: Testing How the Sun Shines with $\nu's$

SSM independent fluxes can be used to improve modeling



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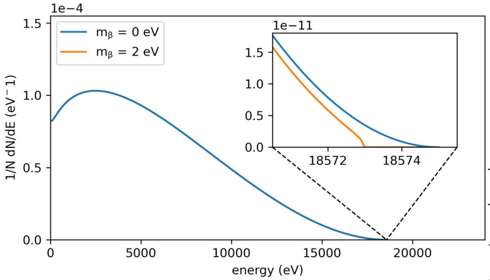
    – Hyper-K and DUNE expected within a decade $\Rightarrow$ Ordering, $\delta_{\rm CP}$ & θ_{23}
- Oscillations DO NOT determine the lightest mass nor distinguish Dirac/Majorana

Probes of Mass Scale in 3ν-mixing

Single β decay : Pure kinematics, Dirac or Majorana ν's, only model independent

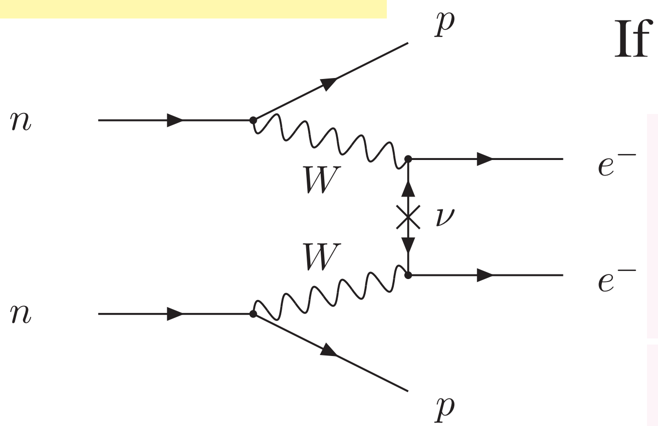


$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: & m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: & m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

Present bound: $m_{\nu_e} \leq 0.45$ eV (90% CL KATRIN 2406.13516)

Katrin sensitivity to $m_{\nu_e} \sim 0.3$ eV

ν-less Double-β decay: $\Leftrightarrow$ Majorana $\nu' s$



If m_ν only source of ΔL $\quad T^{0\nu}_{1/2} = \dfrac{m_e}{G_{0\nu}\, M^2_{\rm nucl}\, m^2_{ee}}$

$$m_{ee} = \left|\sum U^2_{ej} m_j\right|$$

$$= \left|c^2_{13} c^2_{12} m_1\, e^{i\eta_1} + c^2_{13} s^2_{12} m_2\, e^{i\eta_2} + s^2_{13} m_3\, e^{-i\delta_{CP}}\right|$$

$$= f(m_\ell, \text{order}, \text{maj phases})$$

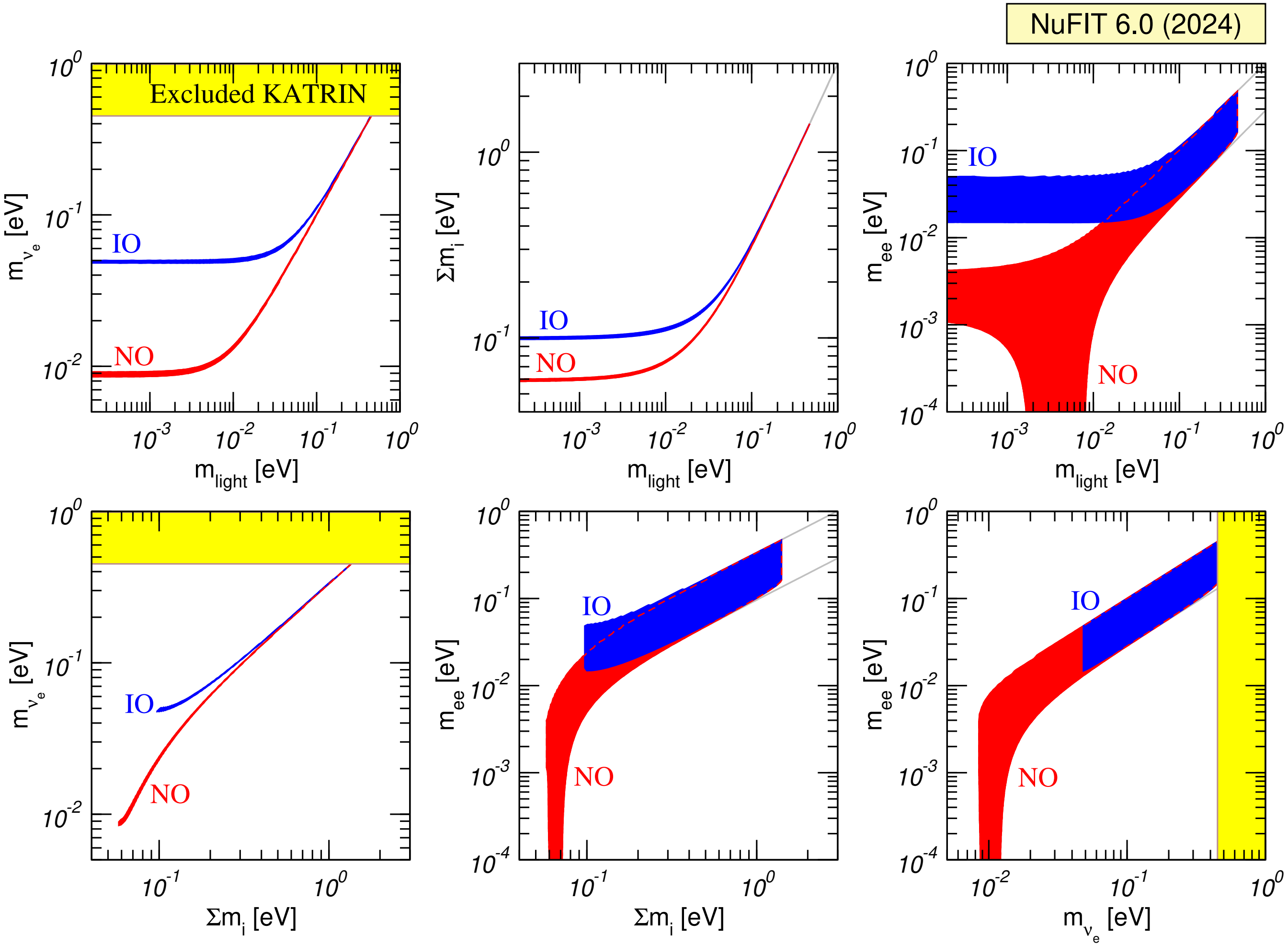
Present Bounds: $m_{ee} < 0.04\text{–}0.2$ eV

COSMO for Dirac or Majorana
m_ν affect growth of structures

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

Probes of Mass Scale in 3ν-mixing: Correlations

In 3ν-mixing the expectations for these probes are correlated: Fogli *etal* hep-ph:0408045



Combination global Osc+KATRIN

In NO at 95% CL:

$$0.0085 \text{ eV} \leq m_{\nu_e} \leq 0.4 \text{ eV}$$
$$0.058 \text{ eV} \leq \sum m_\nu \leq 1.2 \text{ eV}$$
$$0 \leq m_{ee} \leq 0.41 \text{ eV}$$

In IO at 95% CL:

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

Confirmed Low Energy Picture and MY List of Q&A

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- What about mass scale and Dirac vs Majorana?
  - Only model indep probe of m_ν β decay: $\sqrt{\sum m_i^2 |U_{ei}|^2} \leq 0.45$ eV *(KATRIN 24)*
  - Dirac or Majorana?: ν-less $\beta\beta$ decay (*Talk M. Sorel*)
  - Cosmological effects?:Steadily improving bounds (*Talk E. Sanchez ...*)

- Only three light states?

Beyond 3ν's: Light Sterile Neutrinos

- Several Observations which can be Interpreted as Oscillations with $\Delta m^2 \sim \text{eV}^2$

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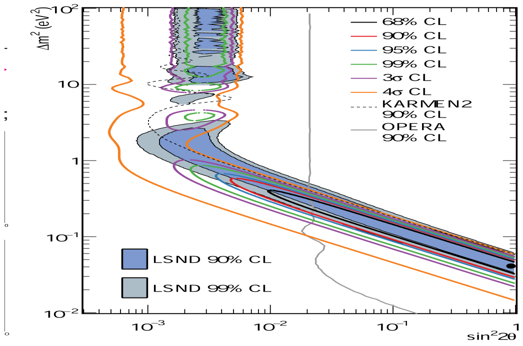
LSND &MiniBooNe

$\nu_\mu \to \nu_e$



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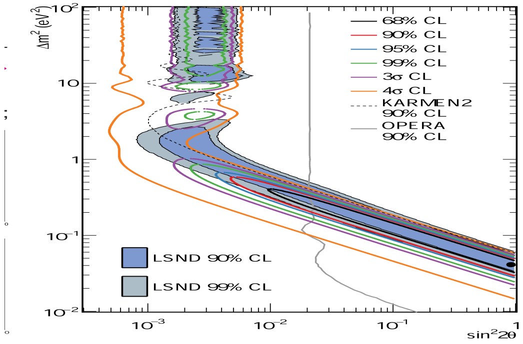
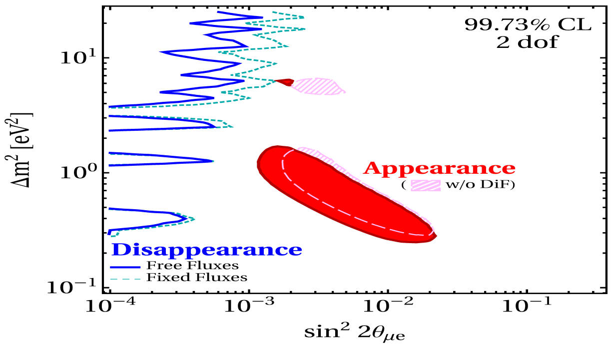


Strong tension with ν disapp

Dentler etal, 1803.10661



MicroBooNE

ArXiv:2412.14407:

No Confirmation (99% CL)

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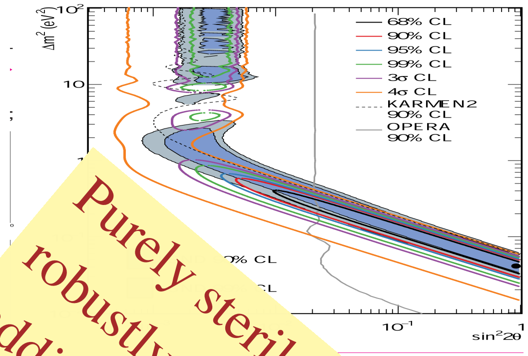
LSND &MiniBooNe

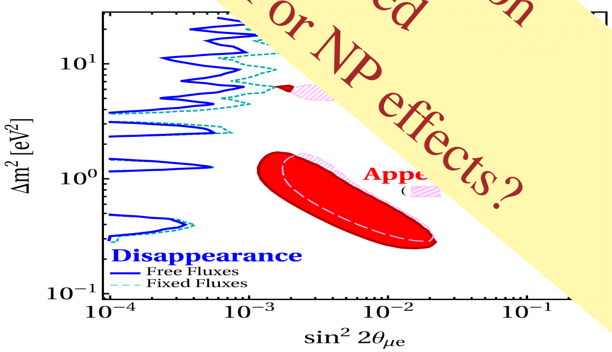
$\nu_\mu \to \nu_e$



Purely sterile oscillation
robustly disfavoured
additional SM or NP effects?

St... ...th ν disapp

D... ...661



MicroBooNE
ArXiv:2412.14407:
No Confirmation (99% CL)

Beyond 3ν's: Light Sterile Neutrinos

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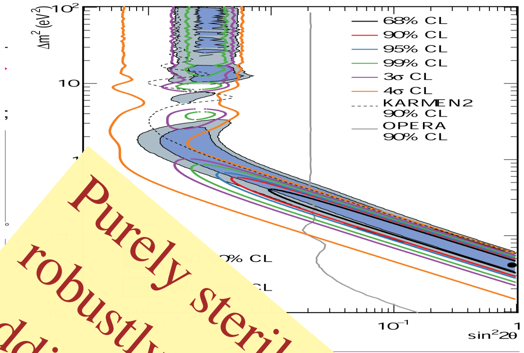

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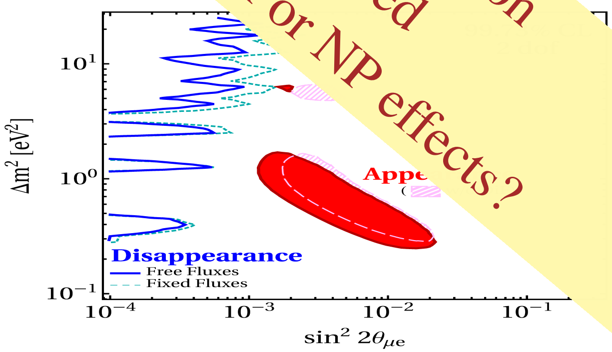

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Reactor Anomaly

Huber, 1106.068,Mention *etal* ,1101.2755

2011 reactor flux calculation:

$\overline{R}_{\text{Reac}} = \frac{\text{data}}{\text{predict}} = 0.936^{+0.024}_{-0.023}$ at $L \lesssim 100$ m

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

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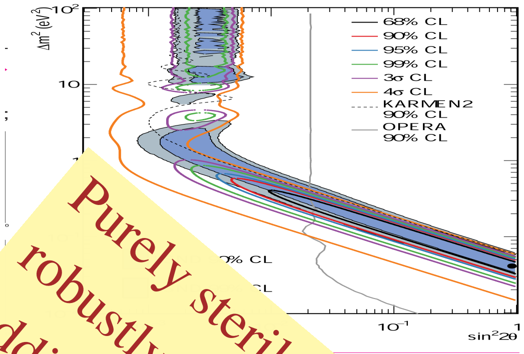

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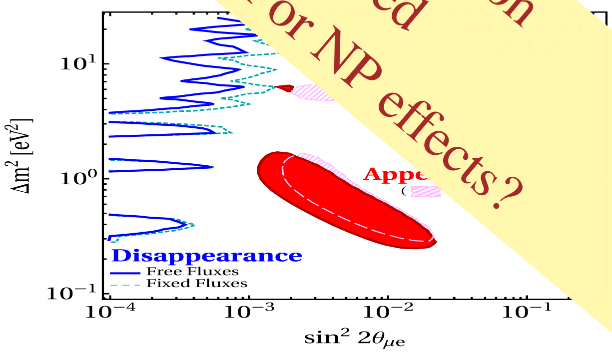

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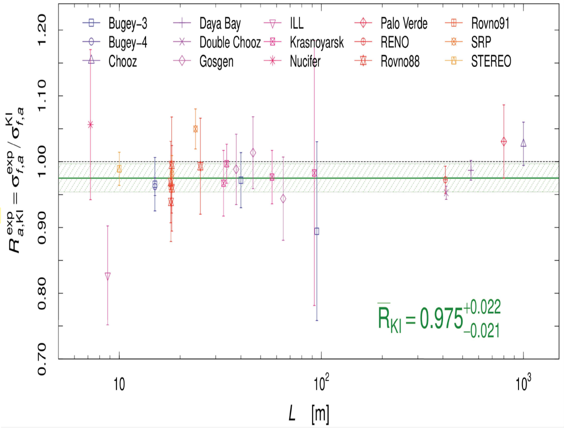
2022 with updated inputs (^{235}U)

Berryman Huber, 2005.01756
Kipeikin etal, 2103.01486



Deficit $\lesssim 1\,\sigma$

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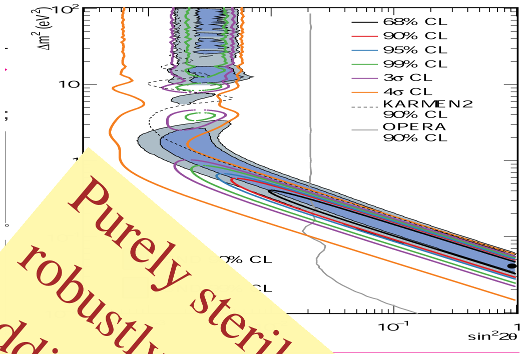

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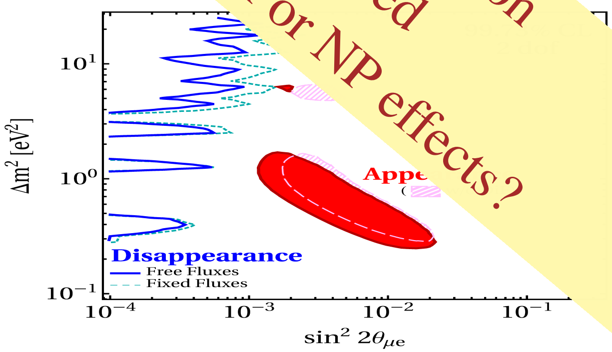

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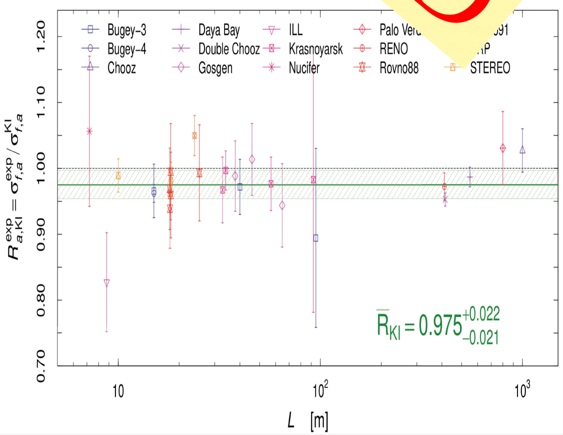
2022 with ... inputs (^{235}U)

Berryman Huber, ...756
Kipeikin etal, 2103...

RESOLVED



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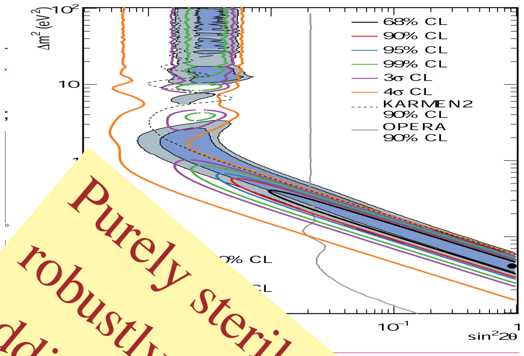

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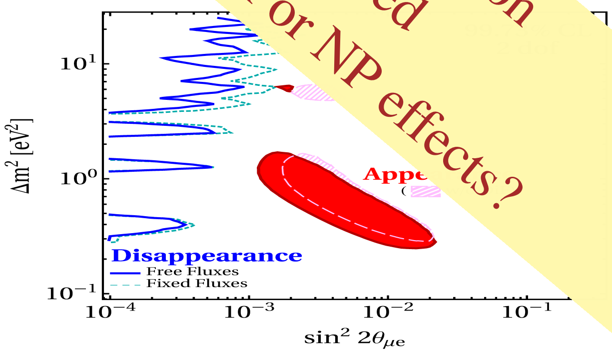

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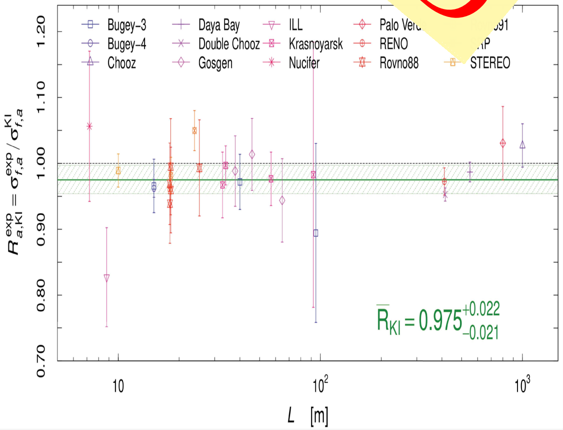

Deficit $\lesssim 1\,\sigma$

Gallium Anomaly

Acero etal, 0711.4222;Giunti, Laveder,1006.3244

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

$\overline{R_{\text{Ga}}} = \frac{\text{data}}{\text{predict}} = 0.8 \pm 0.04$ at $L \sim$0.5-1.1 m

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

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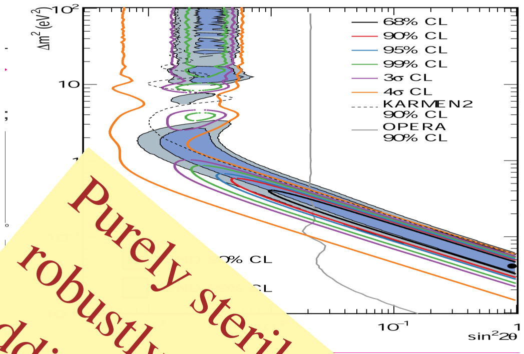
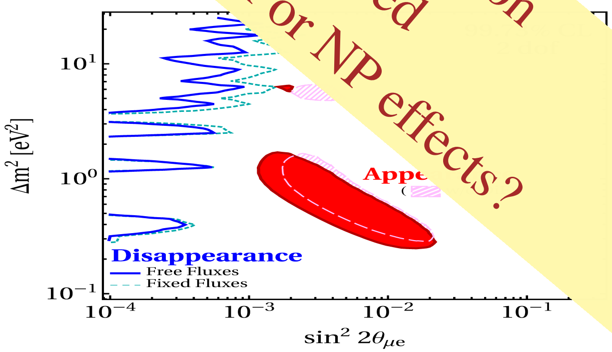


Str... ...th ν disapp

D... ...661



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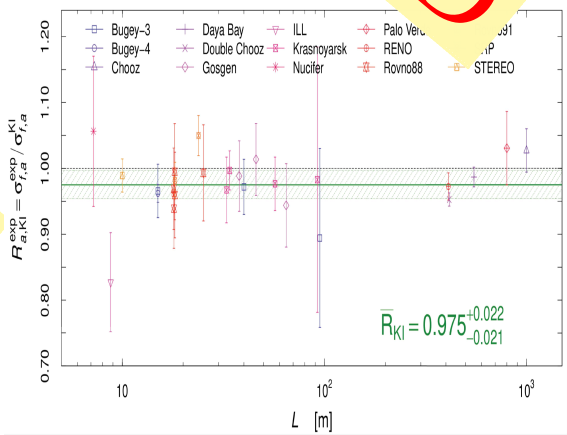
Ex... ...s $\bar\nu_e$ disappearance

2022 wit... ...l inputs (^{235}U)

Berryman Huber, ...1756

Kipeikin etal, 2103....

RESOLVED



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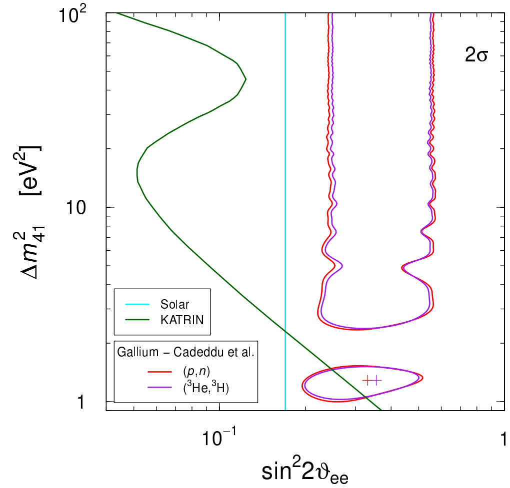
Explained as $\bar\nu_e$ disappearance

Confirmed by BEST (4σ)

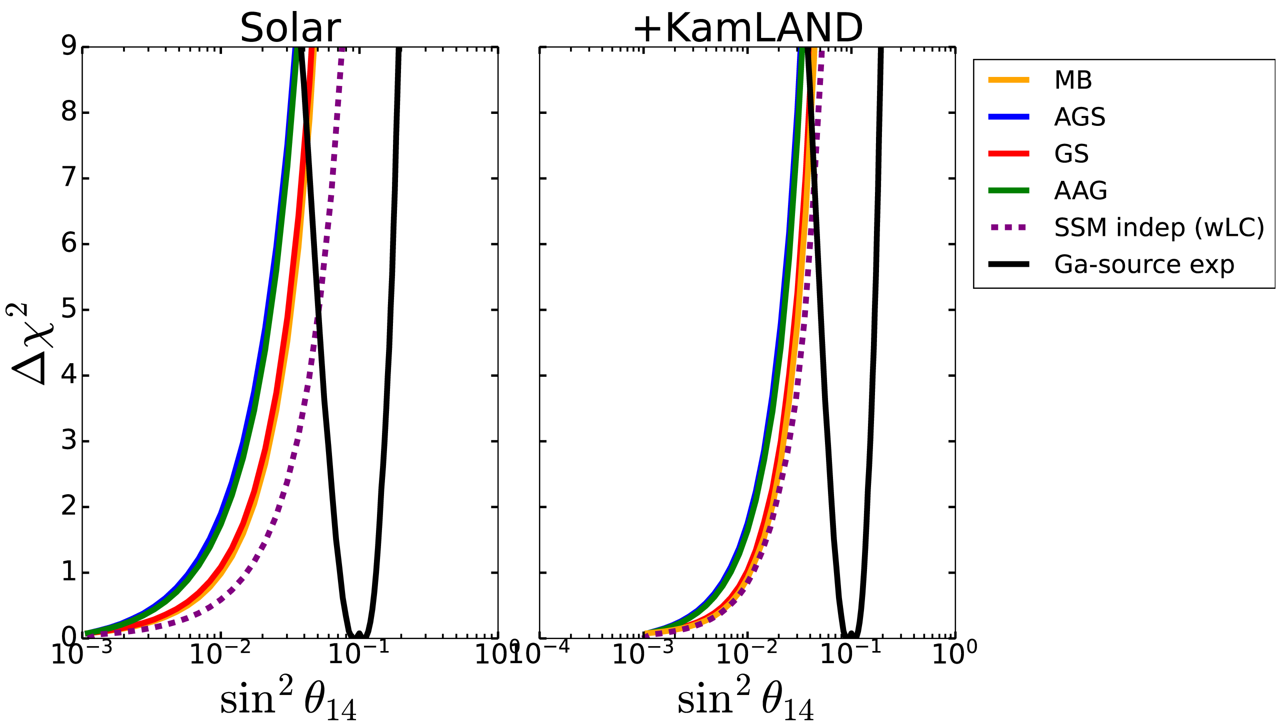
But oscillation solution



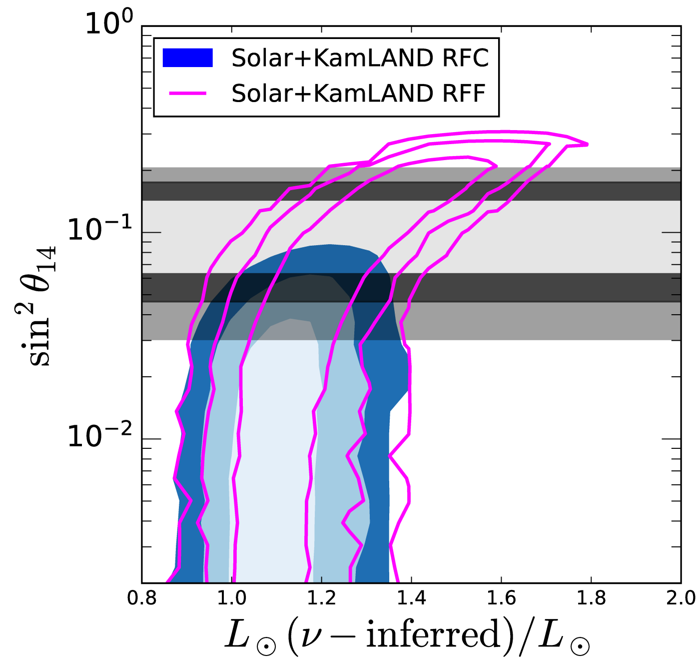
Caddedu etal, 2507.13013

Ruled out/tension with solar+ reactor+KATRIN

Solar modeling and the Gallium anomaly



Incompatiblity is SSM independent



Compatibility $\Rightarrow$
$\gtrsim 10\%$ of solar energy
not in radiation

MCGG, M.Maltoni, J. Pinheiro arXiv:2411.16840

Confirmed Low Energy Picture and MY List of Q&A

- 3ν scenario: Robust determination of θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  - Mass ordering, θ_{23} Octant, CPV depend on subdominant 3ν-effects

    $\Rightarrow$ interplay of LBL/reactor/ATM results. Not statistically significant yet

    $\Rightarrow$ definitive answer will require new experiments *(Talk M. Sorel)*

- What about mass scale and Dirac vs Majorana?
  - Only model indep probe of m_ν β decay: $\sqrt{\sum m_i^2 |U_{ei}|^2} \leq 0.45$ eV *(KATRIN 24)*
  - Dirac or Majorana?: ν-less $\beta\beta$ decay *(Talk. M. Sorel)*
  - Cosmological effects?: Steadily improving bounds (*Talks E. Sanchez,...*)

- Only three light states? No consistent/stable description/status of SBL anomalies

- Additional information on NP?

Bottom-up: Light ν and New Physics

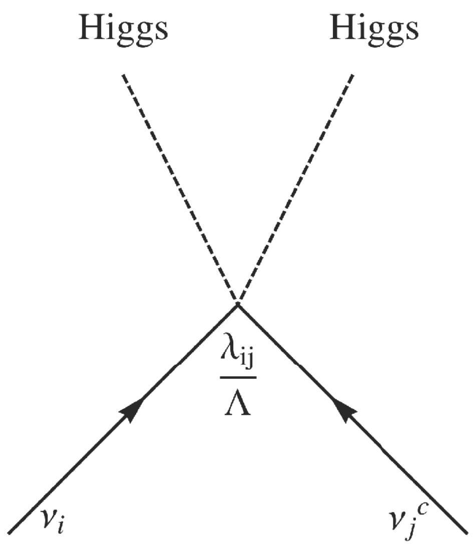
If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– 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:

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



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

For $\lambda^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}$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

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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 interactions (NSI), non-unitarity

$\ldots$

Lepton Mixing Unitarity

- If ν_L mixed with n extra states $U_{\rm LEP} = (K_{l,3\times3}\,, K_{h,3\times n})$ Schechter, Valle (1980)

$$K_{l,3\times3} = \left[I_{3\times3} - \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{e\mu} & \alpha_{\mu\mu} & 0 \\ \alpha_{e\tau} & \alpha_{\mu\tau} & \alpha_{\tau\tau} \end{pmatrix} \right] \times U_{3\times3}(\theta_{ij}, \delta)$$

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 $K_{l,3\times3}$
  $\Rightarrow$ 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 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}	-
$\|\alpha_{\mu e}\|$	1.8×10^{-2} [105]	1.4×10^{-2}	1.9×10^{-5}	5.4×10^{-4}
$\|\alpha_{\tau e}\|$	6.1×10^{-2} [104]	2.2×10^{-2}	6.2×10^{-3}	1.5×10^{-3}
$\|\alpha_{\tau\mu}\|$	9.1×10^{-3} [104]	2.6×10^{-2}	6.9×10^{-3}	1.5×10^{-4}

Blennow et al arxiv: 2502.14980

NSI

- 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

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

- In matter with NSI: $i\dfrac{d}{dx}\vec\nu = H^\nu \vec\nu \quad H^\nu = U_{\rm vac}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E_\nu} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E_\nu}\end{pmatrix} U^\dagger_{\rm vac} + H^{\rm SM}_{\rm mat} + H^{\rm NSI}_{\rm mat}$

$$H^{\rm SM}_{\rm mat} + H^{\rm NSI}_{\rm mat} \equiv \sqrt{2}G_F N_e(r)\begin{pmatrix} 1+\varepsilon_{ee}-\varepsilon_{\mu\mu} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & 0 & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}\end{pmatrix} \text{ with } \varepsilon_{\alpha\beta}(r) \equiv \sum_{f=p,n,e}\frac{N_f(r)}{N_e(r)}\varepsilon^f_{\alpha\beta}$$

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

$$\begin{array}{lcl} \theta_{12} \to \frac{\pi}{2} - \theta_{12} & & (\varepsilon_{ee}-\varepsilon_{\mu\mu}) \to -(\varepsilon_{ee}-\varepsilon_{\mu\mu}) - 2 \\ \Delta m^2_{31} \to -\Delta m^2_{32} & \text{and} & (\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}) \\ \delta \to \pi - \delta & & \varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta) \end{array}$$

New “Dark” ($\theta_{12} > \frac{\pi}{4}$) region (solar)
Lost order info (ATM&LBL)
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 $\varepsilon_{\alpha\beta}$ are not constants $\Rightarrow$ degeneracy only approximate

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

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

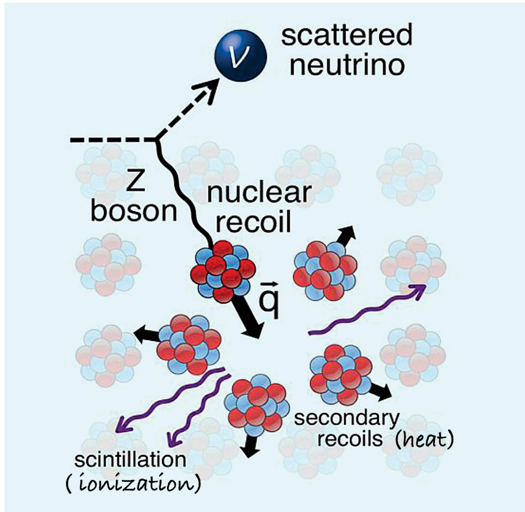
$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{2\pi}\frac{\mathcal{Q}^2}{4}F^2(2ME_r)M\left(2-\frac{ME_r}{E_\nu^2}\right)$$

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

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

Rich physics program: precision EW tests, Nuclear physics, ν-charge radius, μ_ν sterile neutrinos, light-mediators, NSI...

Explored by spanish pheno groups: Rossi+ 2311.17168, de Romeri+ 2211.11905, Miranda+ 2109.09545, 2106.11660,2008.02759,2003.12050,2002.01482; Alonso-Gonzalez+ 2307.05176, Amaral+ 2302.12846; Coloma+ 2305.07698, 2202.10829, 2009.14220,2006.08624,1911.09109; Baxter+ 1911.00762...

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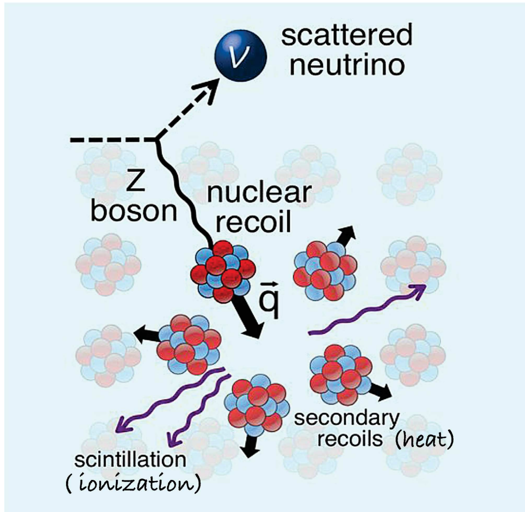


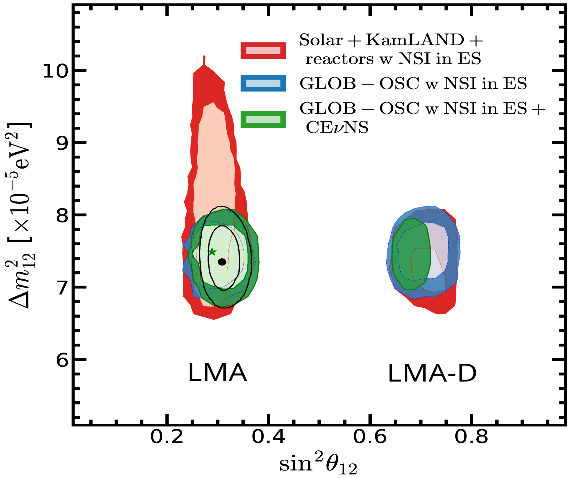
- By 2025: Observed in CsI 1708.01294, Ar 2006.12659, Ge 2202.09672,2406.13806,2501.05206 and Xe 2407.10892,2408.02877
- For $M_{\rm Med} \gtrsim 50$ MeV and NSI with quarks $\Rightarrow$ effect in CEνNS

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

NSI in ν-OSC (and CEνNs): Global Analysis

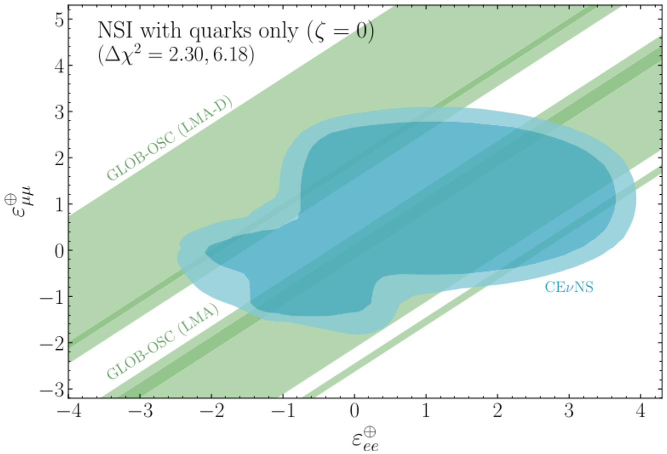
With most general couplings to up, down and/or e:

– LMA-D allowed by oscillations



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

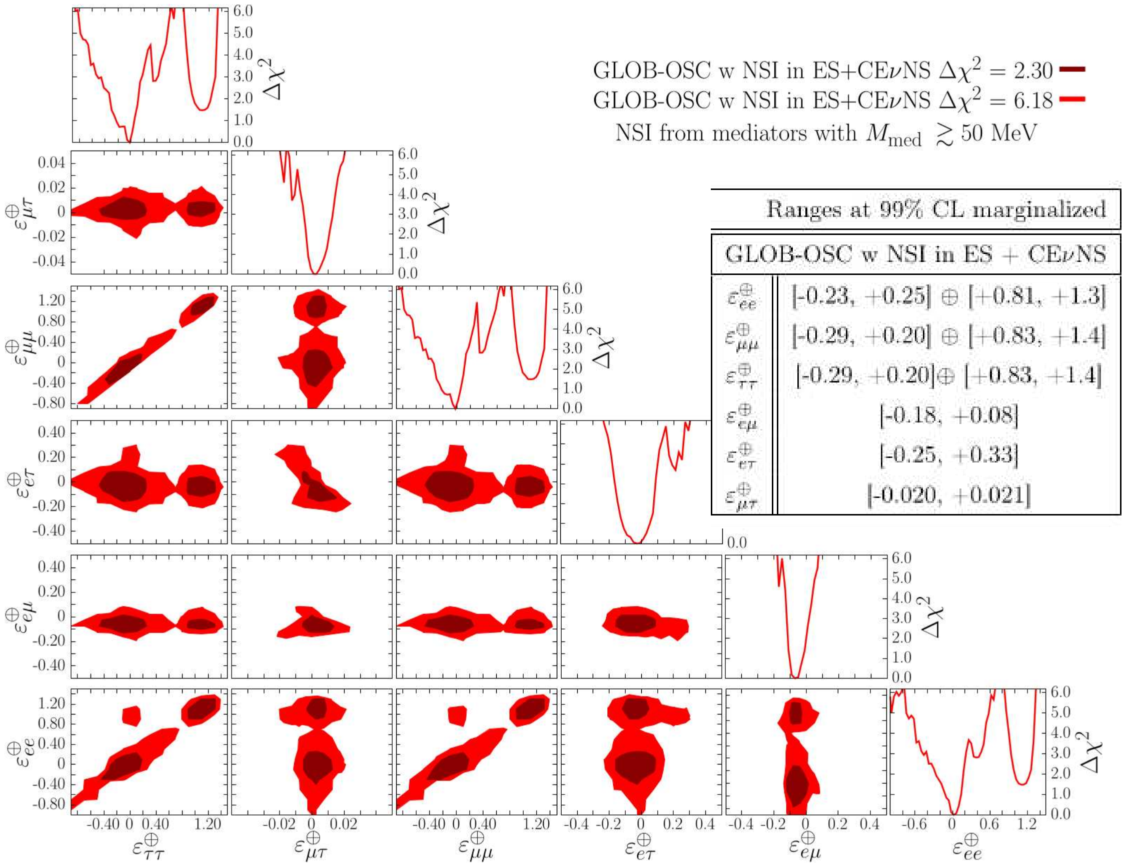
$\Rightarrow$ LMA-D only above 2σ



Still important bounds on the NSI's

$\Rightarrow$ Maximum effect at future LBL experiments

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



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

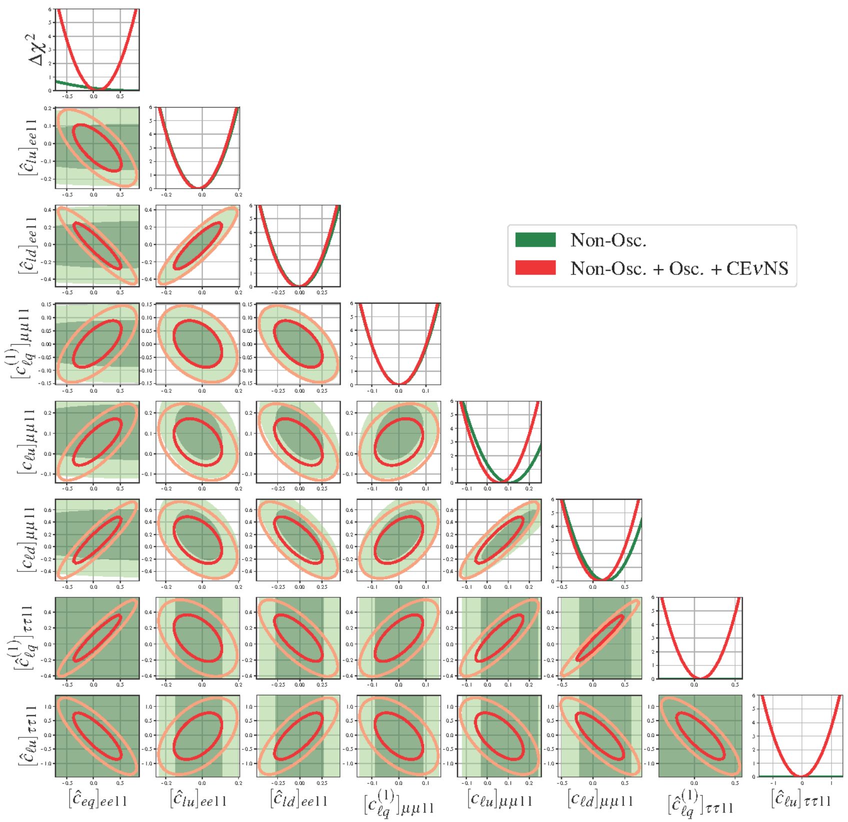
Coloma, MCGG, Maltoni, Pinheiro, Urrea 2305.07698

From NSI to SMEFT

In SMEFT NC-NSI for ν_ℓ and ℓ as well as CC-NSI are related.

Are ν-osc bounds still be relevant?

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



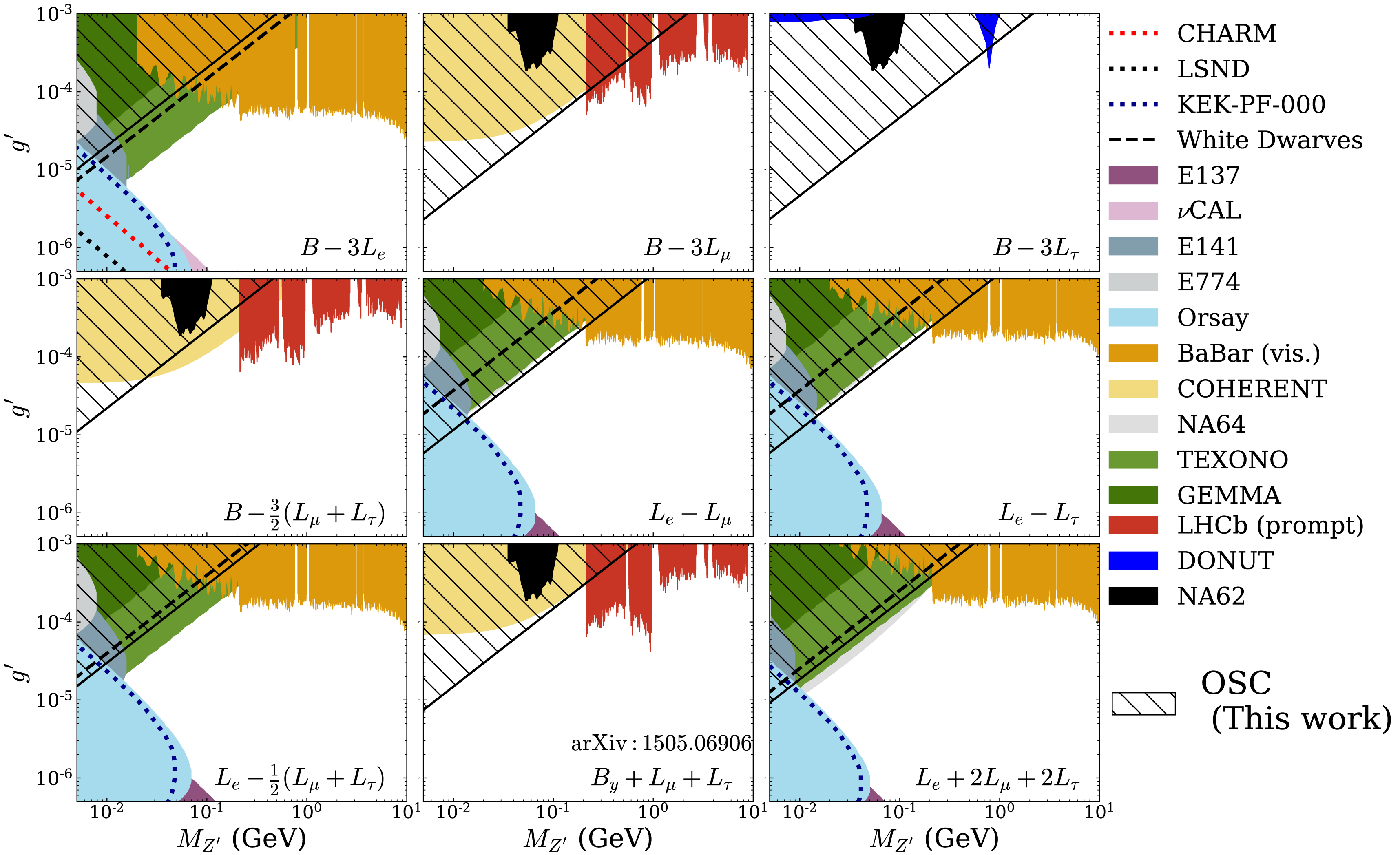
Coloma *etal* 2411.00090

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

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

From NSI to light mediator models

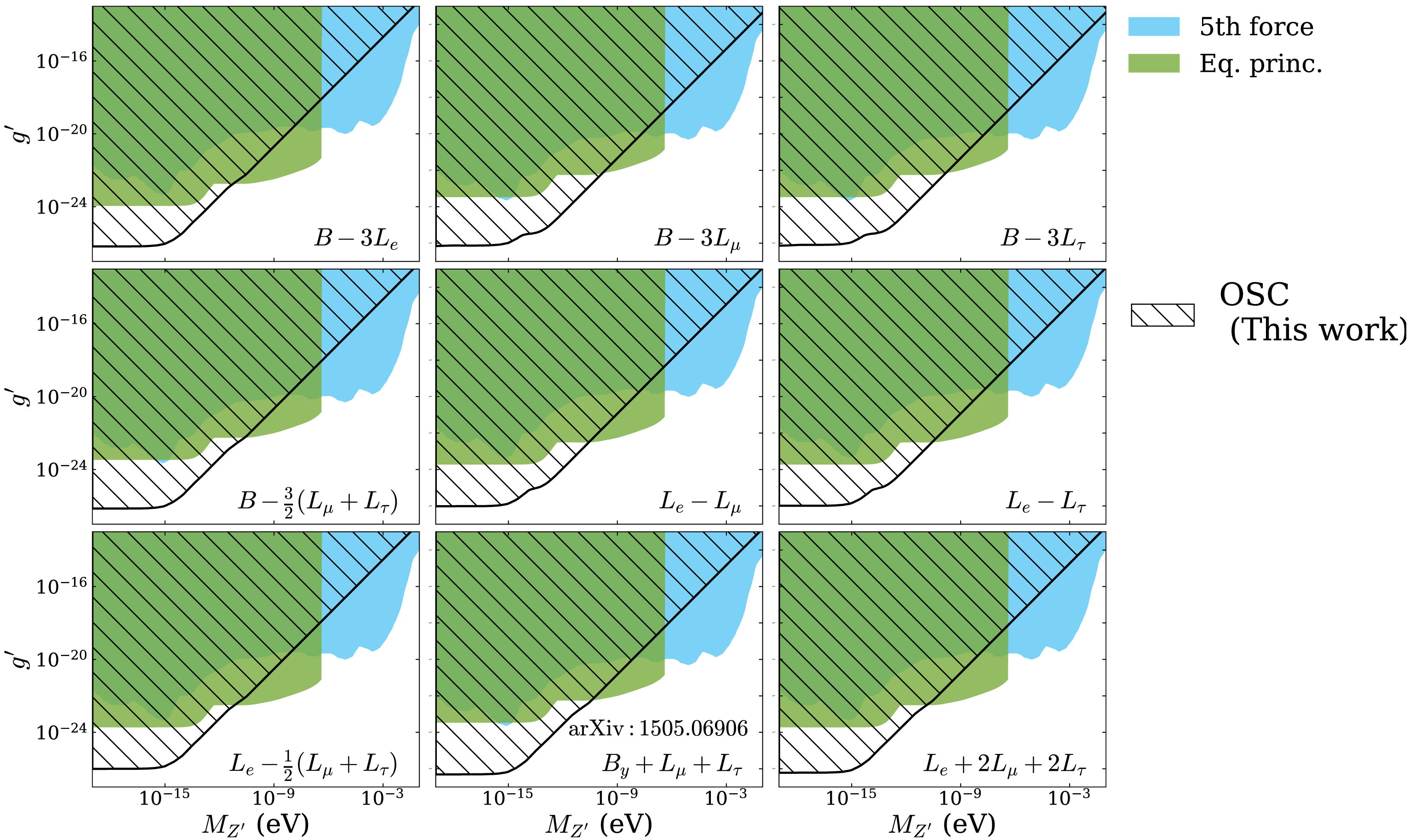
For $M_{Z'} \gtrsim \mathcal{O}(\mathrm{MeV}) \Rightarrow$ Contact Interaction in H_{mat}: $\varepsilon^{f}_{\alpha\alpha} = q_{\nu_\alpha} q_f \frac{1}{\sqrt{G_F}} \frac{g'^2}{M^2_{Z'}}$



Coloma, MCGG, Maltoni ArXiv:2009.14220

From NSI to ultralight mediator models

For ultralight ($M' \lesssim \mathcal{O}(\text{eV})$) mediator $\Rightarrow$ Contact Interaction to Long Range Force



Coloma, MCGG, Maltoni ArXiv:2009.14220

Confirmed Low Energy Picture and MY List of Q&A

- 3ν scenario: Robust determination of θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  - Mass ordering, θ_{23} Octant, CPV depend on subdominant 3ν-effects

    $\Rightarrow$ interplay of LBL/reactor/ATM results. Not statistically significant yet

    $\Rightarrow$ definitive answer will require new experiments *(Talk M. Sorel)*

- What about mass scale and Dirac vs Majorana?
  - Only model indep probe of m_ν β decay: $\sqrt{\sum m_i^2 |U_{ei}|^2} \leq 0.45$ eV *(KATRIN 24)*
  - Dirac or Majorana?: ν-less $\beta\beta$ decay *(Talk M. Sorel)*
  - Cosmological effects?: Steadily improving bounds *(Talks E. Sanchez,...)*

- Only three light states? No consistent/stable description/status of SBL anomalies

- Additional information on NP?
  - Lα-dependent NP$\Rightarrow$ NSI $\Rightarrow$ modified matter potential $\Rightarrow$ Bounds
  - Relevant information in the context of the SMEFT
  - Relevant information for scenarios with light to ultralight mediators

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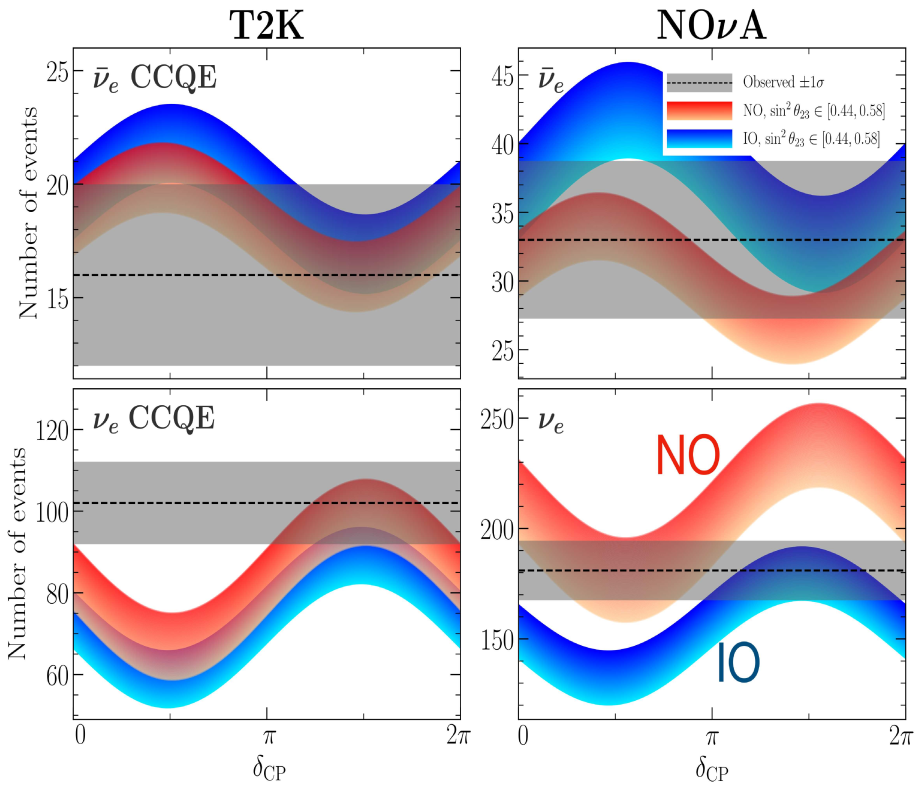
Backup Slides

Mass Ordering (and CPV)

- Dominant information in ν_e vs $\overline{\nu}_e$ appearance in LBL

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

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



$\Rightarrow$ Each T2K and NOνA favour NO

But some tension in value of δ_{CP} in NO

Mass Ordering (and CPV)

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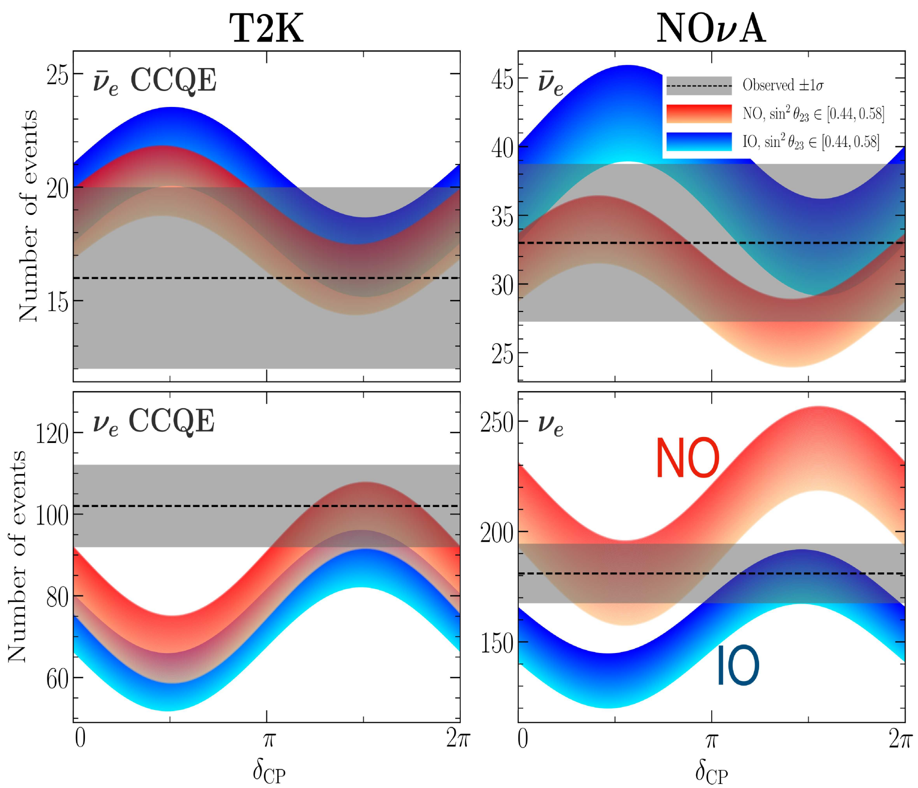
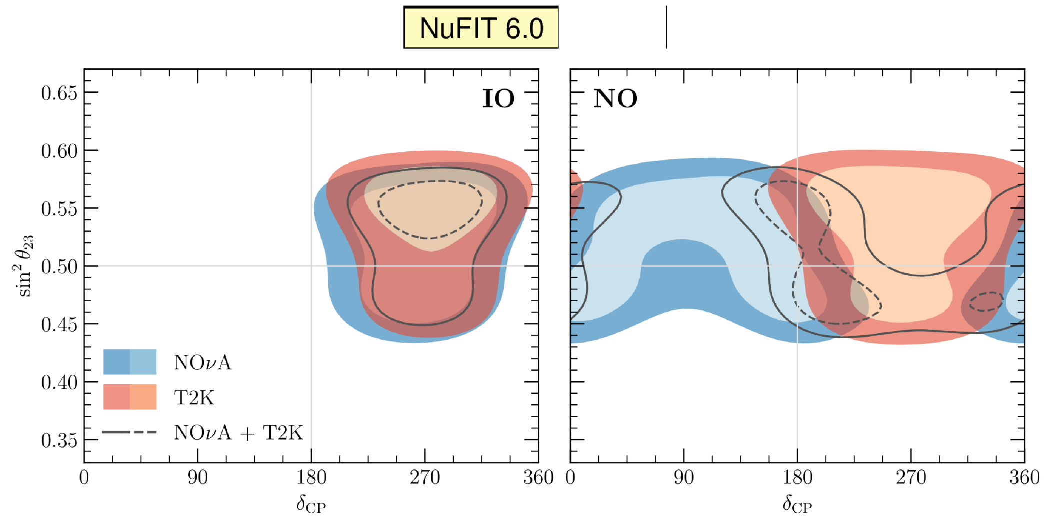
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{4E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13}\, \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$



$\Rightarrow$ Each T2K and NOνA favour NO

But some tension in value of δ_{CP} in NO

$\Rightarrow$ IO best fit in LBL combination



Parameter goodness-of-fit (PG) test:

	normal ordering			inverted ordering		
	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$
T2K vs NOvA	7.9/3	0.047	2.0σ	1.8/3	0.61	0.5σ

No statistically significant incompatibility yet

Mass Ordering (and CPV)

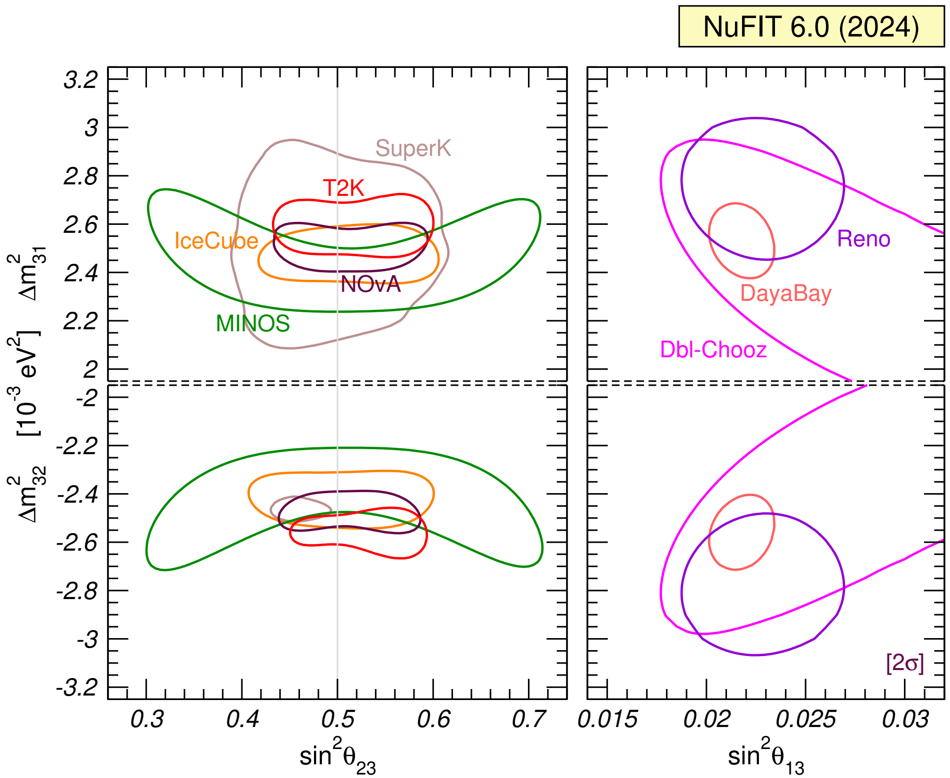
- Dominant information in ν_e vs $\overline{\nu}_e$ appearance in LBL:
  Each T2K and NOνA favour NO but tension in value of δ_{CP} in NO
  $\Rightarrow$ IO best fit in LBL combination $\Rightarrow$ b.f. $\delta_{\rm CP} \sim 290°$, CPC disfavoured at $\gtrsim 3.5\sigma$

- Additional information from ν_μ in LBL vs ν_e disapperance in MBL Reactors:

$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$$

$$\Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$$

Nunokawa,Parke,Zukanovich hep-ph/0503283

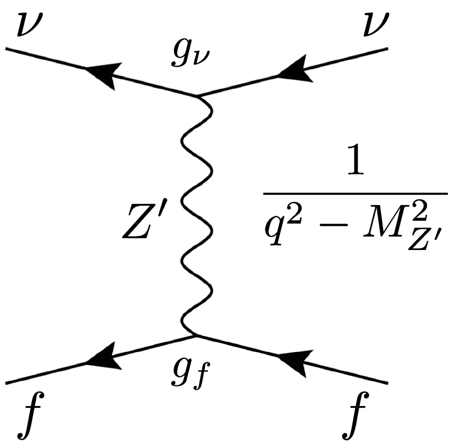


$\Rightarrow$ Slightly better agreement in NO

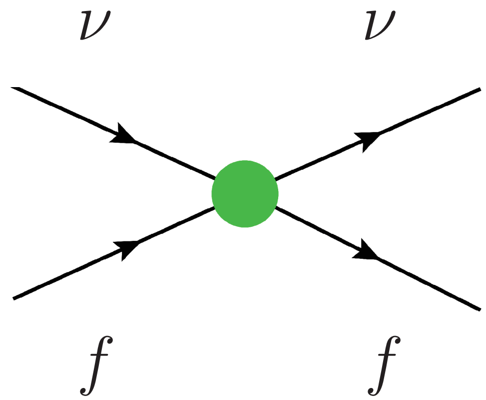
$\Rightarrow$ LBL+Reac: NO and IO equally good

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

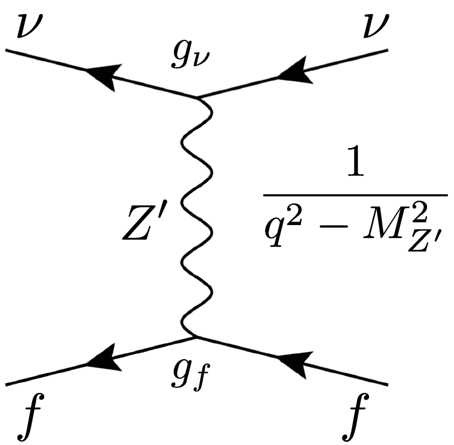
- Generically understood as:

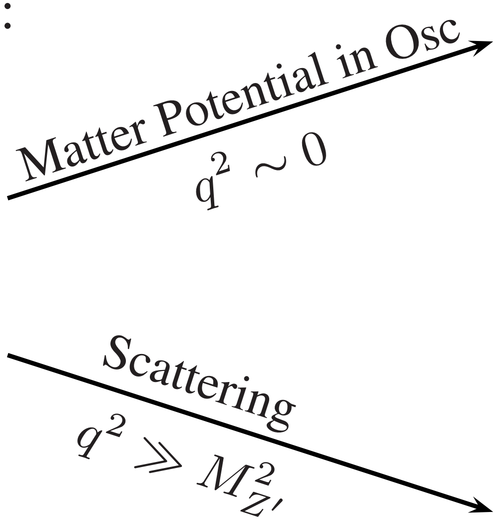


$\Longrightarrow$
$q^2 \ll M_{Z'}^2$



- Depending on Mediator Mass:





$\epsilon \sim \frac{g_f g_\nu}{M_{Z'}^2}$

$\sigma \sim \epsilon\,\frac{M_{Z'}^2}{q^2}$

Flavour Parameters: leptons vs quarks

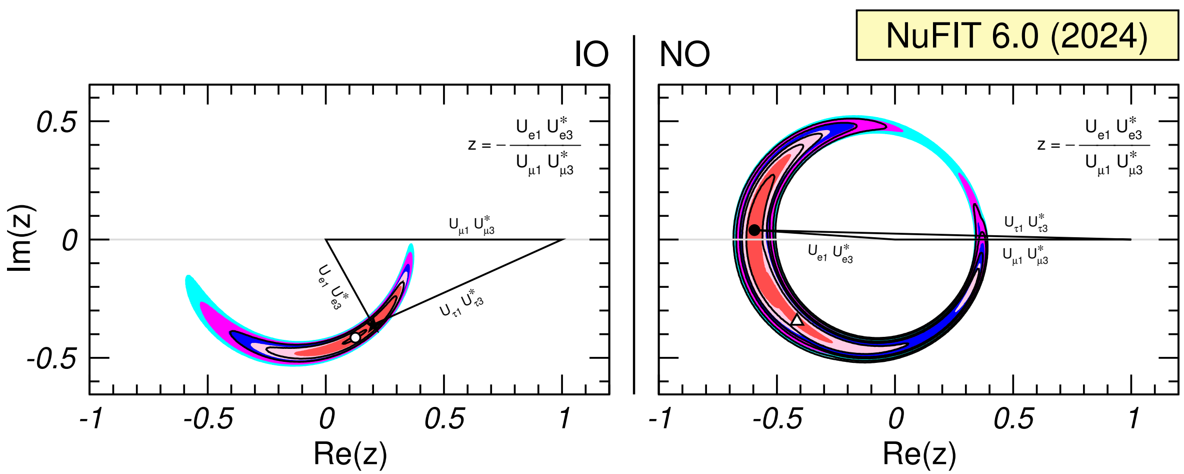
- Leptonic mixing matrix

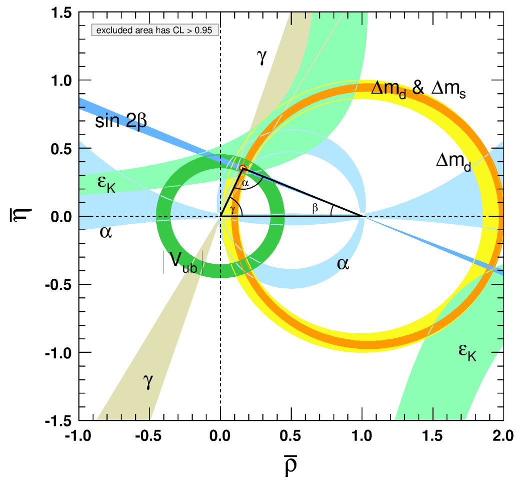
$$|U|_{3\sigma} = \begin{pmatrix} 0.80 \to 0.85 & 0.51 \to 0.56 & 0.14 \to 0.16 \\ 0.23 \to 0.51 & 0.46 \to 0.69 & 0.63 \to 0.78 \\ 0.26 \to 0.53 & 0.47 \to 0.70 & 0.61 \to 0.76 \end{pmatrix}$$

- Very different and precision very far from:

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

- CP violation





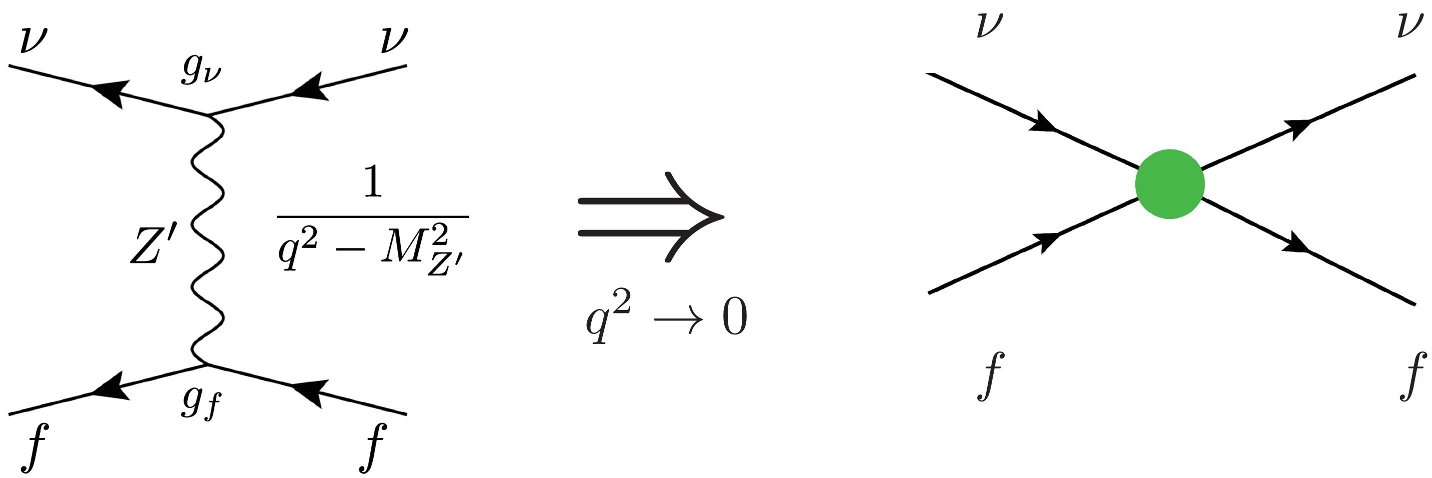
From NSI to light mediator models

Coloma, MCGG, Maltoni ArXiv:2009.14220

- Effective Lagrangian

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

- If understood as:



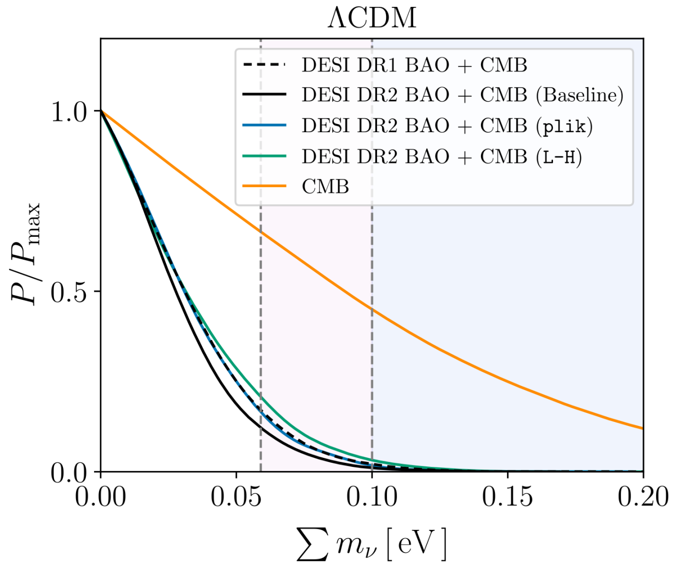
$$\varepsilon_{\alpha\beta}^{f} = \delta_{\alpha\beta}\, q'_f\, q'_\nu \frac{1}{\sqrt{2}G_F} \frac{g'^2}{M_{Z'}^2}$$

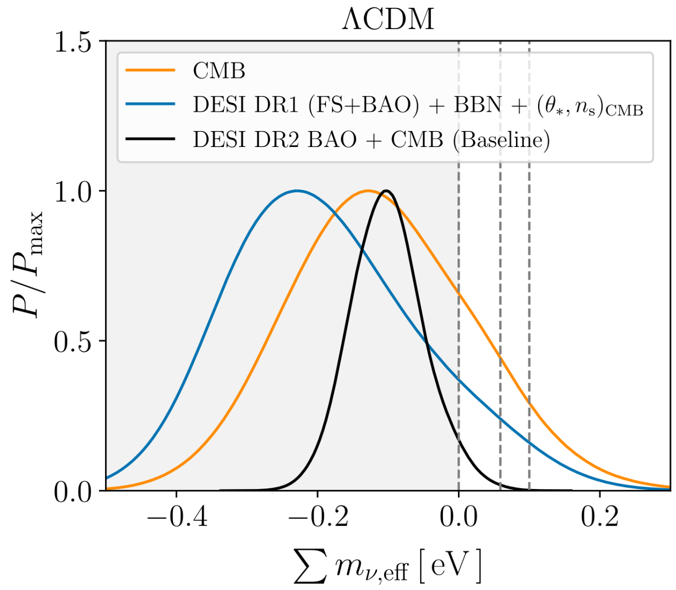
$\Rightarrow$ adapt the OSC+NSI fit BUT performed in subspace of flavour diagonal NSI

Cosmological Bounds:DESI

- ΛCDM : $\sum m_{\nu_i} < 0.064$ eV (95% CL)

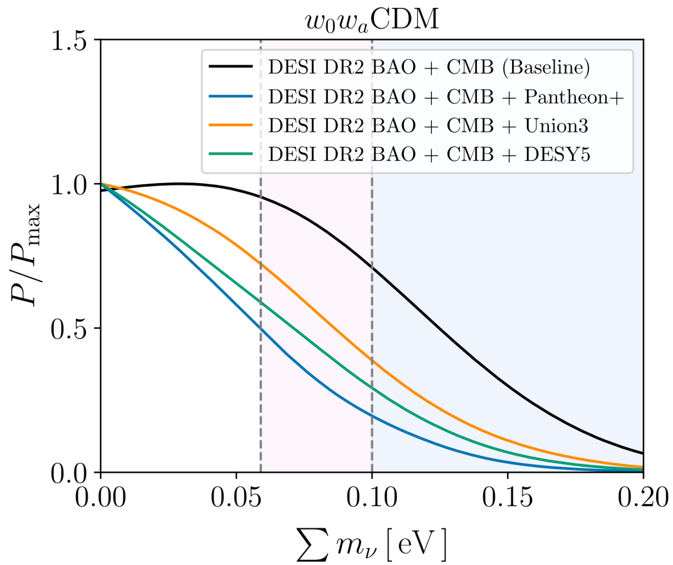
But 3σ tension with physical m_ν

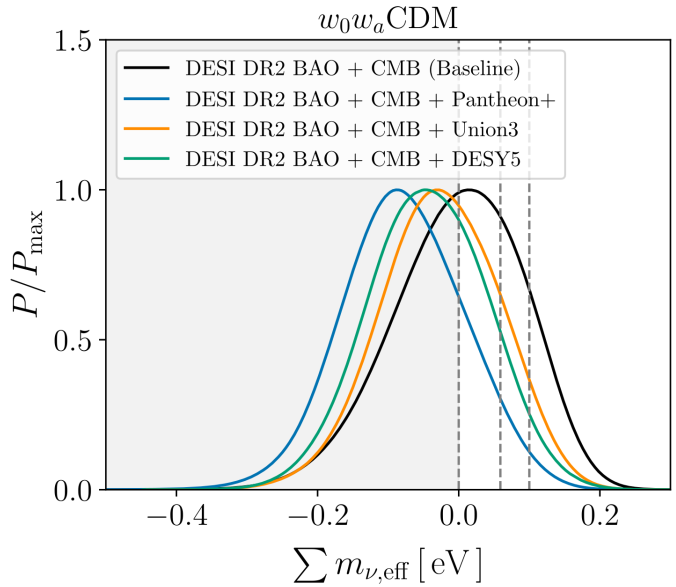




- With evolving DE: $\sum m_{\nu_i} < 0.163$ eV

No tension with physical m_ν





DESI arXiv:2503.15744