# GLOBAL ANALYSIS OF $\nu$ OSCILLATIONS

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

**XXI Workshop on Neutrino Telescopes**

## OUTLINE

Status/Implications of the $3\nu$ global description

Explorations/Implications beyond $3\nu$'s

# The $\nu$ evidence of BSM

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

  Gauge Invariance $\Rightarrow$ Lepton Flavour $\alpha$ conserved $\Rightarrow$ Total Lepton # Conserved

  $\Leftrightarrow$ $\nu$ strictly massless

- We have observed with high (or good) precision:

  * Atmospheric $\nu_\mu$ & $\bar\nu_\mu$ disappear likely to $\nu_\tau$ (**SK**,MINOS, **ICECUBE**, KM3NeT)
  * Accel. $\nu_\mu$ & $\bar\nu_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K**, MINOS, **NO$\nu$A**)
  * Some accel $\nu_\mu$ & $\bar\nu_\mu$ appear as $\nu_e$ & $\bar\nu_e$ at $L \sim 300/800$ Km ( **T2K**, MINOS,**NO$\nu$A**)
  * Solar $\nu_e$ convert to $\nu_\mu/\nu_\tau$ (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)

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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 $\nu_L^c$ is right-handed

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

  * Introduce $\nu_R$

$$\mathcal{L}-\mathcal{L}_{SM} = -M_D \overline{\nu_L}\nu_R - \frac{1}{2}M_R \overline{\nu_R}\nu_R^C + h.c.$$

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  $*$ Introduce $\nu_R$ AND impose $L$ conservation

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

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

# The New Minimal Standard Model: $\nu$ flavour oscillations

- In vacuum:

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

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

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

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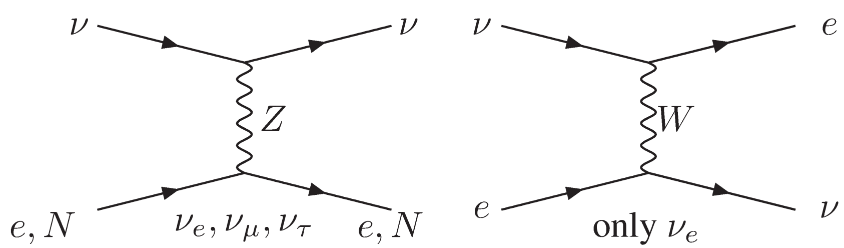
- If $\nu$ cross matter regions (Sun, Earth...)
  it interacts *coherently*
  Different flavours have different interactio[n]




$\Rightarrow$ Effective potential in $\nu$ 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)

$\Rightarrow$ For solar $\nu' s$: Dependence on $\theta$ octant

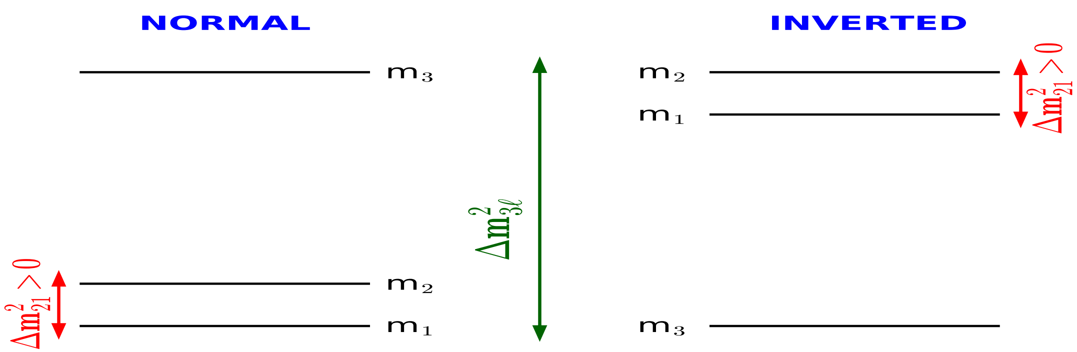
$\Rightarrow$ In LBL terrestrial experiment: Dependence on sign of $\Delta m^2$ and $\theta$ octant

# $3\nu$ Flavour Parameters

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

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

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




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

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

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

# 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 3158-day EH1,EH2, EH3 spectra ,78 points.
- Reno 2908-day FD/ND ratios 45 points.

## Atmospheric experiments

- IceCube/DeepCore 2019 3-year data.
- IceCube/DeepCore 2014 9,3-year data ($\chi^2$ table provided
- K I-V 484 kton-years( $\chi^2$ table provided by SK)

## Accelerator experiments

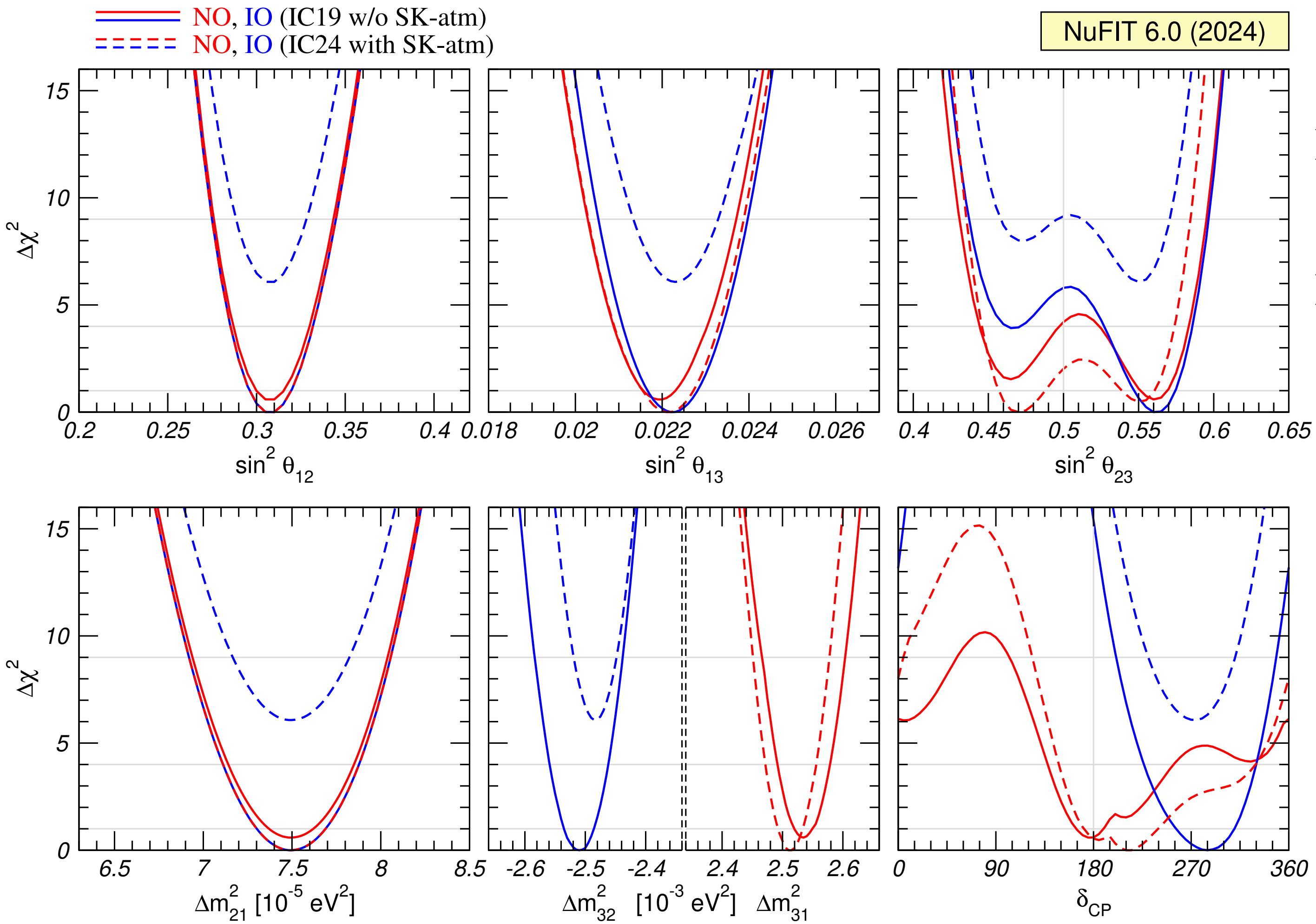
- MINOS 10.71 $\times$ $10^{20}$ pot $\nu_\mu$-disapp data, 39 poins.
- MINOS 3.36 $\times$ $10^{20}$ pot $\bar{\nu}_\mu$-disapp data , 14 points.
- MINOS 10.6 $\times$ $10^{20}$ pot $\nu_e$-app data , 5 points.
- MINOS 3.3 $\times$ $10^{20}$ pot $\bar{\nu}_e$-app data , 5 points.
- T2K 21.4 $\times$ $10^{20}$ pot $\nu_\mu$-disapp data, 28 points.
- T2K 21.4 $\times$ $10^{20}$ pot $\nu_e$-app data, 9 points CCQE and 7 p
- T2K 16.3 $\times$ $10^{20}$ pot $\bar{\nu}_\mu$-disapp, 19 points.
- T2K 16.3 $\times$ $10^{20}$ pot $\bar{\nu}_e$-app, 9 points.
- NO$\nu$A 26.6 $\times$ $10^{20}$ pot $\nu_\mu$-disapp data , 21 points.
- NO$\nu$A 26.6 $\times$ $10^{20}$ pot $\nu_e$-app data , 15 points.
- NO$\nu$A 12.5 $\times$ $10^{20}$ pot $\bar{\nu}_\mu$-disapp, 18 points.
- NO$\nu$A 12.5 $\times$ $10^{20}$ pot $\bar{\nu}_e$-app, 13 points.

# Global 3 $\nu$ Flavour Parameters: Fall 2025

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

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

Good agreement with results from Bari (2503.07752, *Talk by A. Marrone*) 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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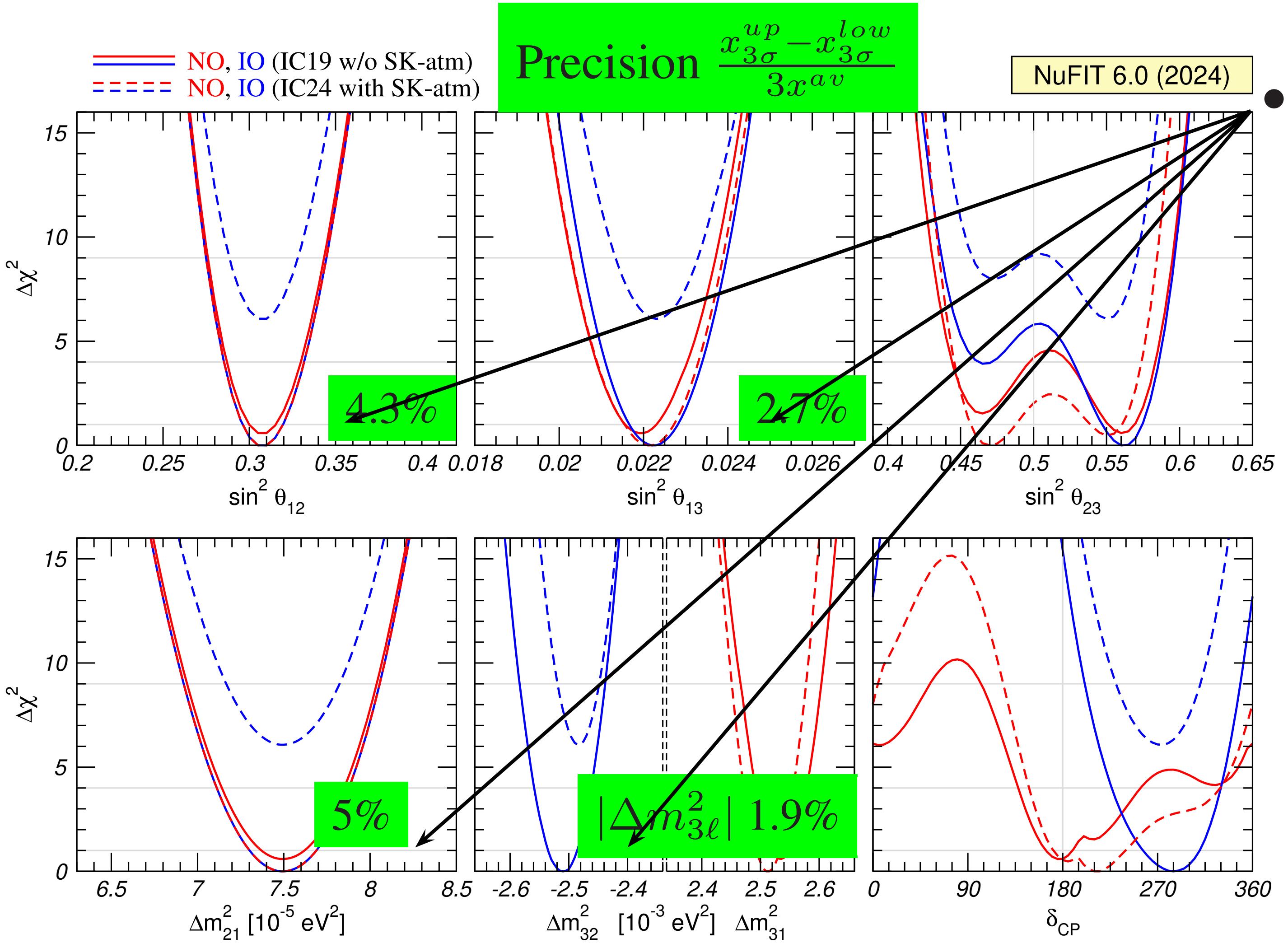


- 4 well-known parameters:

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

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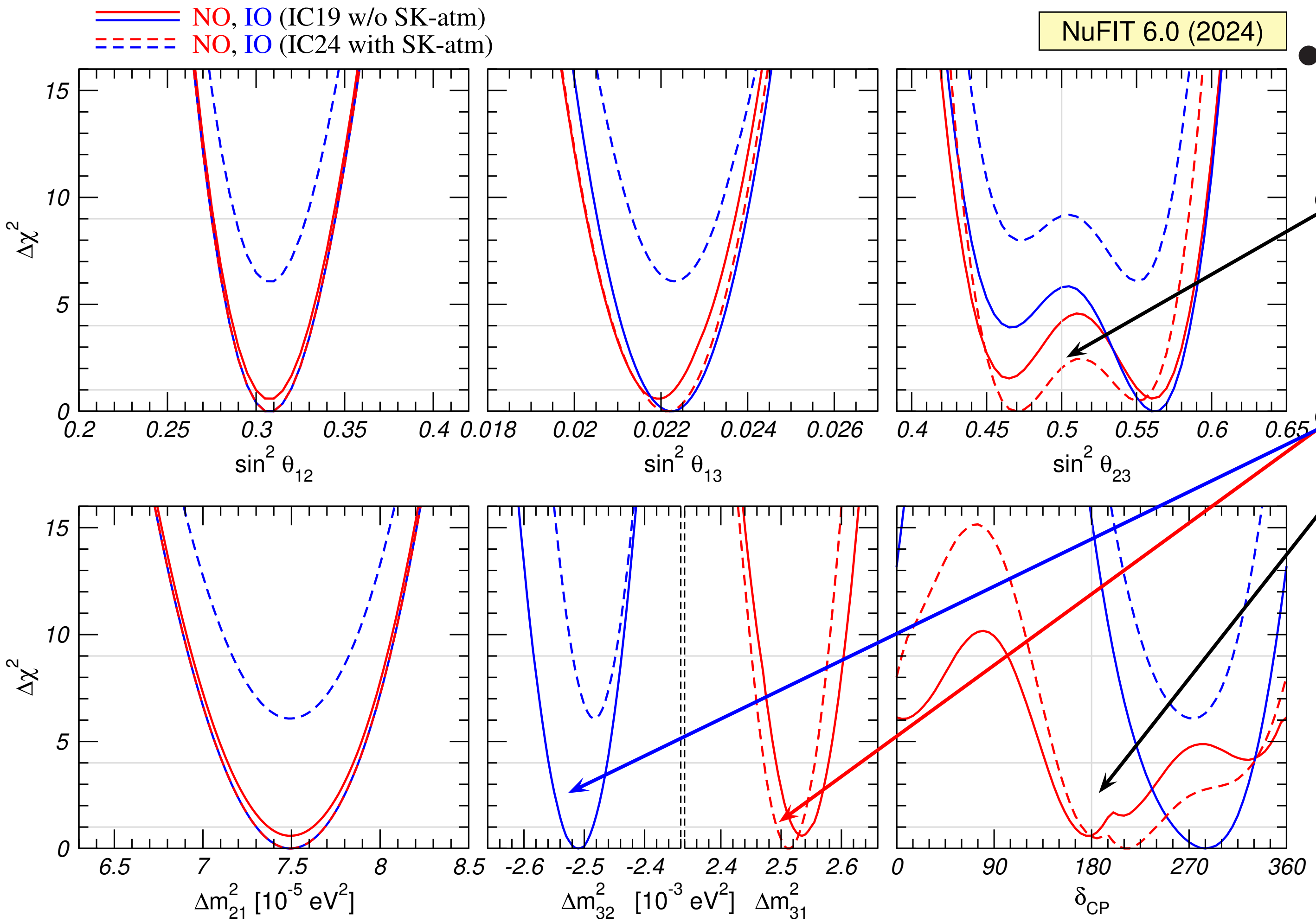



- 4 well-known parameters: $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$
- $\theta_{23}$: Least known angle
  Maximal? Octant?
  non-robust yet
- Ordering NO or IO?
  CPV?:

# Summary: Global 3 $\nu$ Flavour Parameters

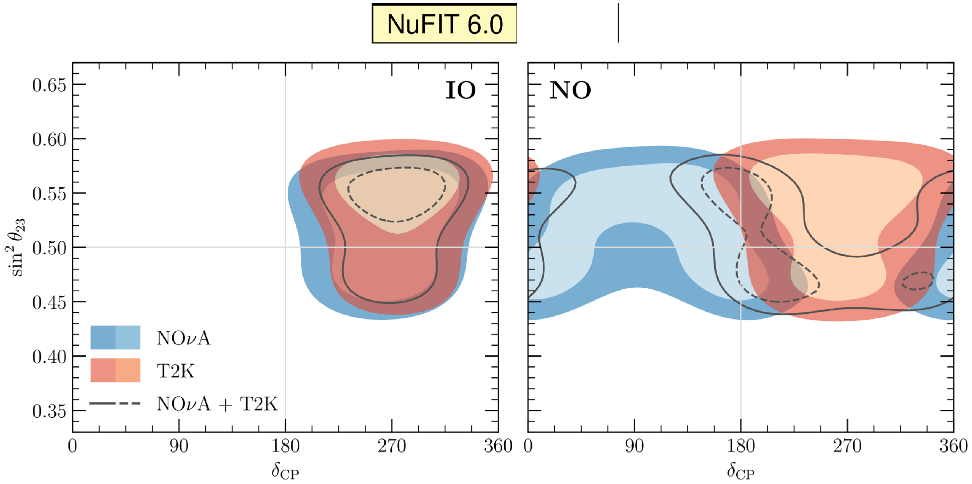
Evolution of relative precision at 3 $\sigma$:

| | 2012 | 2014 | 2016 | 2018 | 2021 | 2024 | |
|---|---|---|---|---|---|---|---|
| | NuFIT 1.0 | NuFIT 2.0 | NuFIT 3.0 | NuFIT 4.0 | NuFIT 5.1 | NuFIT 6.0 | Improv |
| $\theta_{12}$ | 15% | 14% | 14% | 14% | 14% | 13% | 1.15 |
| $\theta_{13}$ | 30% | 15% | 11% | 8.9% | 9.0% | 8.1% | 3.7 |
| $\theta_{23}$ | 43% | 32% | 32% | 27% | 27% | 21% | 2 |
| $\Delta m^2_{21}$ | 14% | 14% | 14% | 16% | 16% | 15% | 0.93 |
| $\|\Delta m^2_{3\ell}\|$ | 17% | 11% | 9% | 7.8% | 6.7% [6.5%] | 5.8% [5.1%] | 2.9[3.3] |
| $\delta_{\rm CP}$ | 100% | 100% | 100% | 100% [92%] | 100% [83%] | 100% [98%] | |
| $\Delta\chi^2_{\rm IO-NO}$ | $\pm 0.5$ | $-0.97$ | $+0.83$ | $+4.7$ [$+9.3$] | $+2.6$ [$+7.0$] | $-0.6$ [$+6.1$] | |

w/o [w] SK atm data

# Mass Ordering and CPV

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




Parameter goodness-of-fit (PG) test:

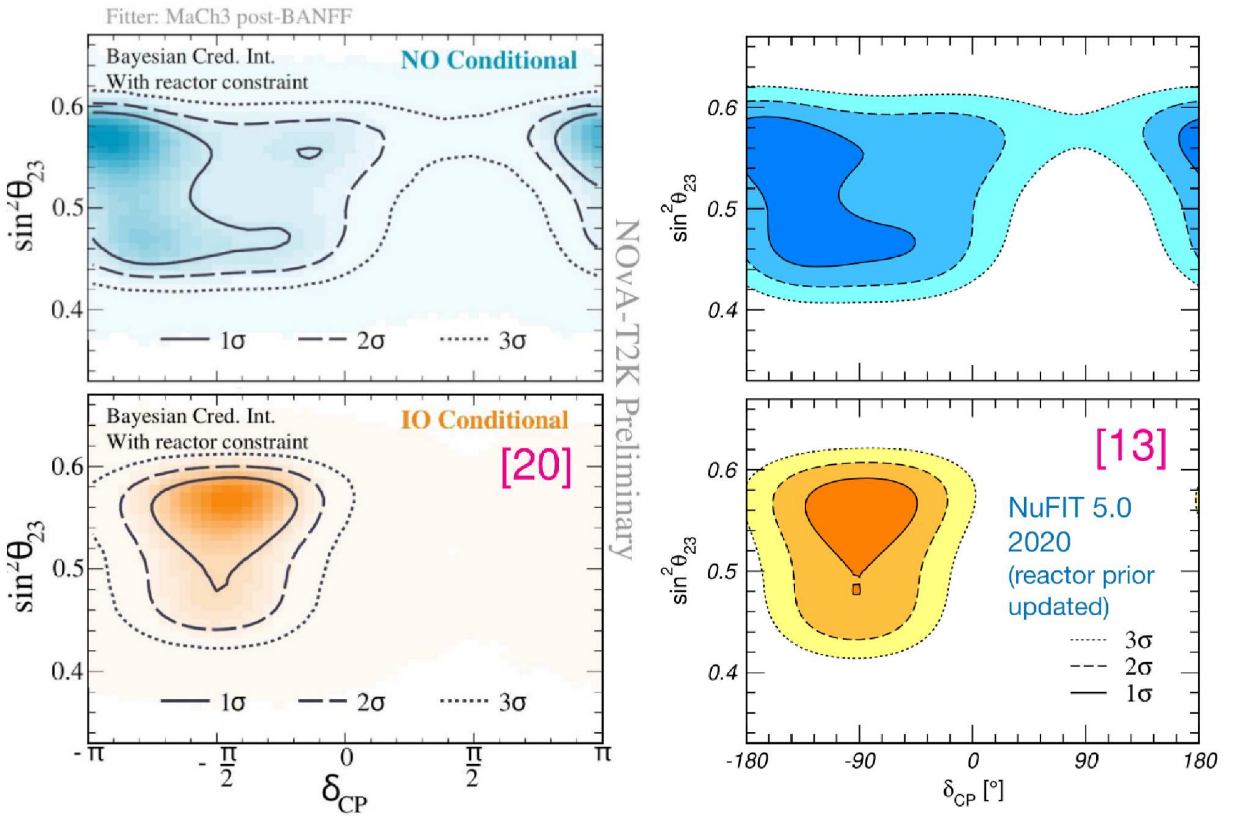
| | normal ordering | | | inverted ordering | | |
|---|---|---|---|---|---|---|
| | $\chi^2_{\rm PG}/n$ | $p$-value | $\#\sigma$ | $\chi^2_{\rm PG}/n$ | $p$-value | $\#\sigma$ |
| T2K vs NOvA | 7.9/3 | 0.047 | $2.0\sigma$ | 1.8/3 | 0.61 | $0.5\sigma$ |

No statistically significant incompatibility yet

# 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].

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- Dominant information in $\nu_e$ vs $\overline{\nu}_e$ appearance in LBL:
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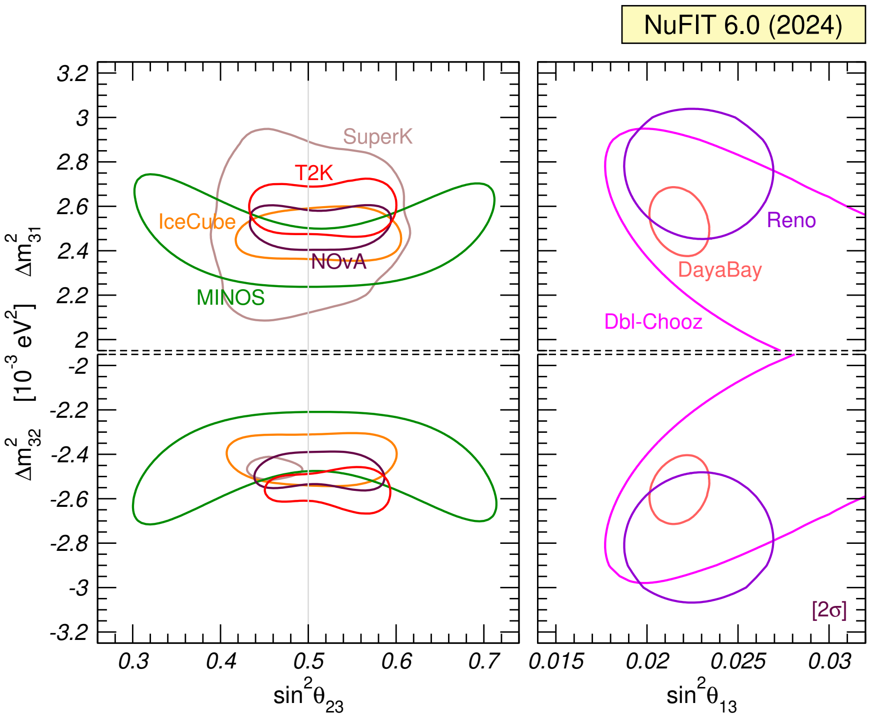
- Additional information from $\nu_\mu$ in LBL vs $\nu_e$ disapperance in MBL Reactors:

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

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

Nunokawa,Parke,Zukanovich hep-ph/0503283




$\Rightarrow$ Slightly better agreement in NO

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

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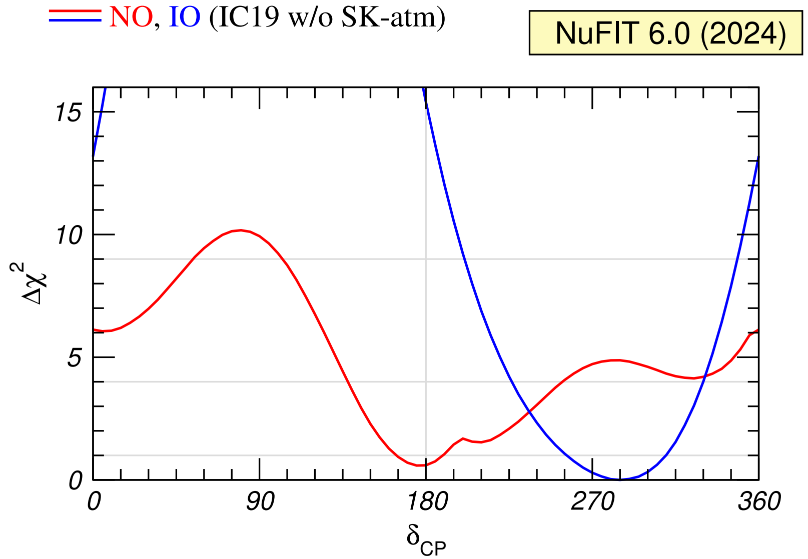

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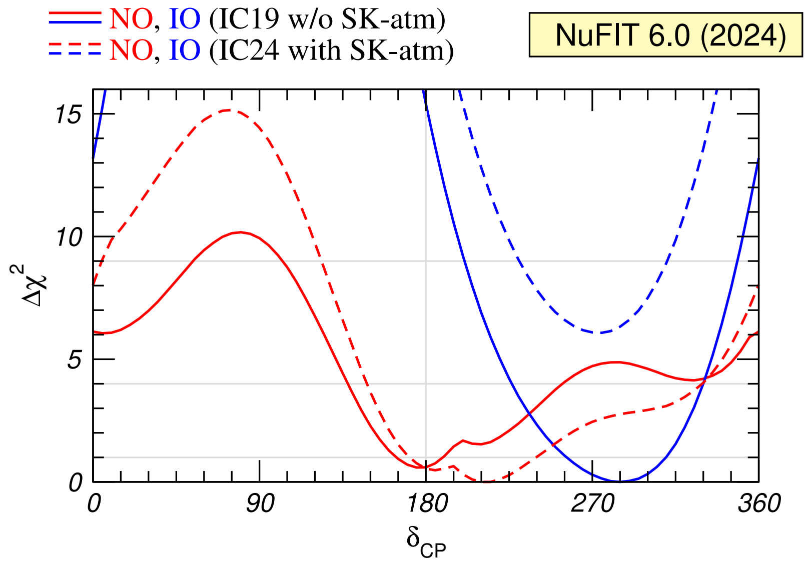

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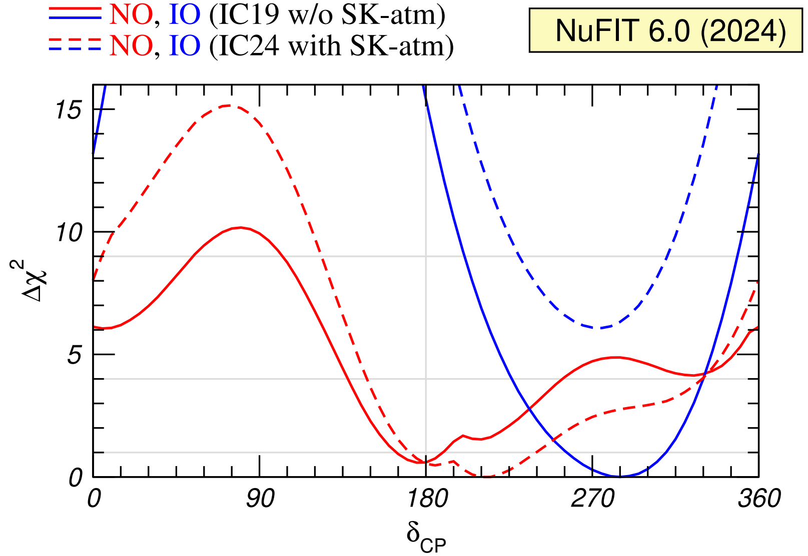
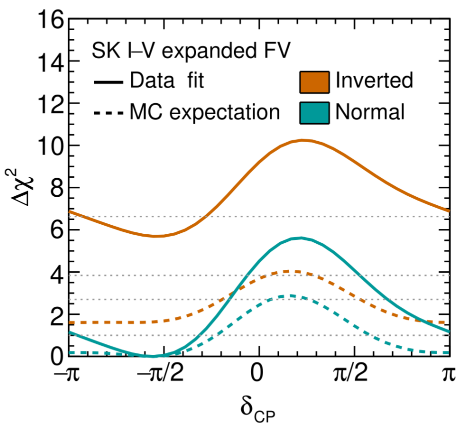
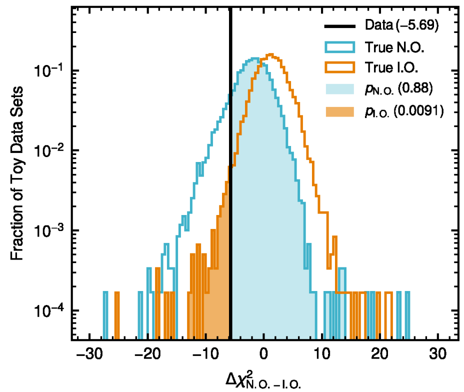
  But SK-atm beyond expectation

  and not fully compatible with either ordering?




SK Coll. arXiv:2311.05105

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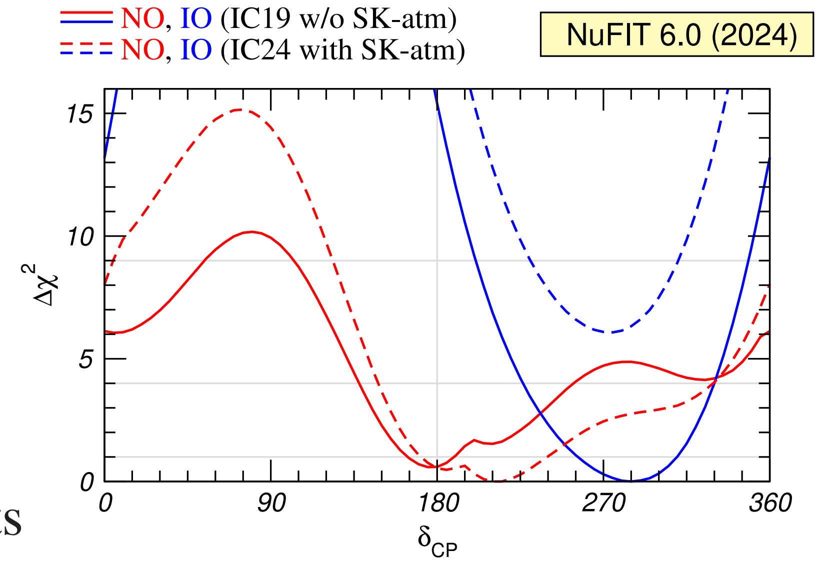



**My Conclusion:**

MO, $\theta_{23}$ Octant, CPV depend on subdominant $3\nu$-effects

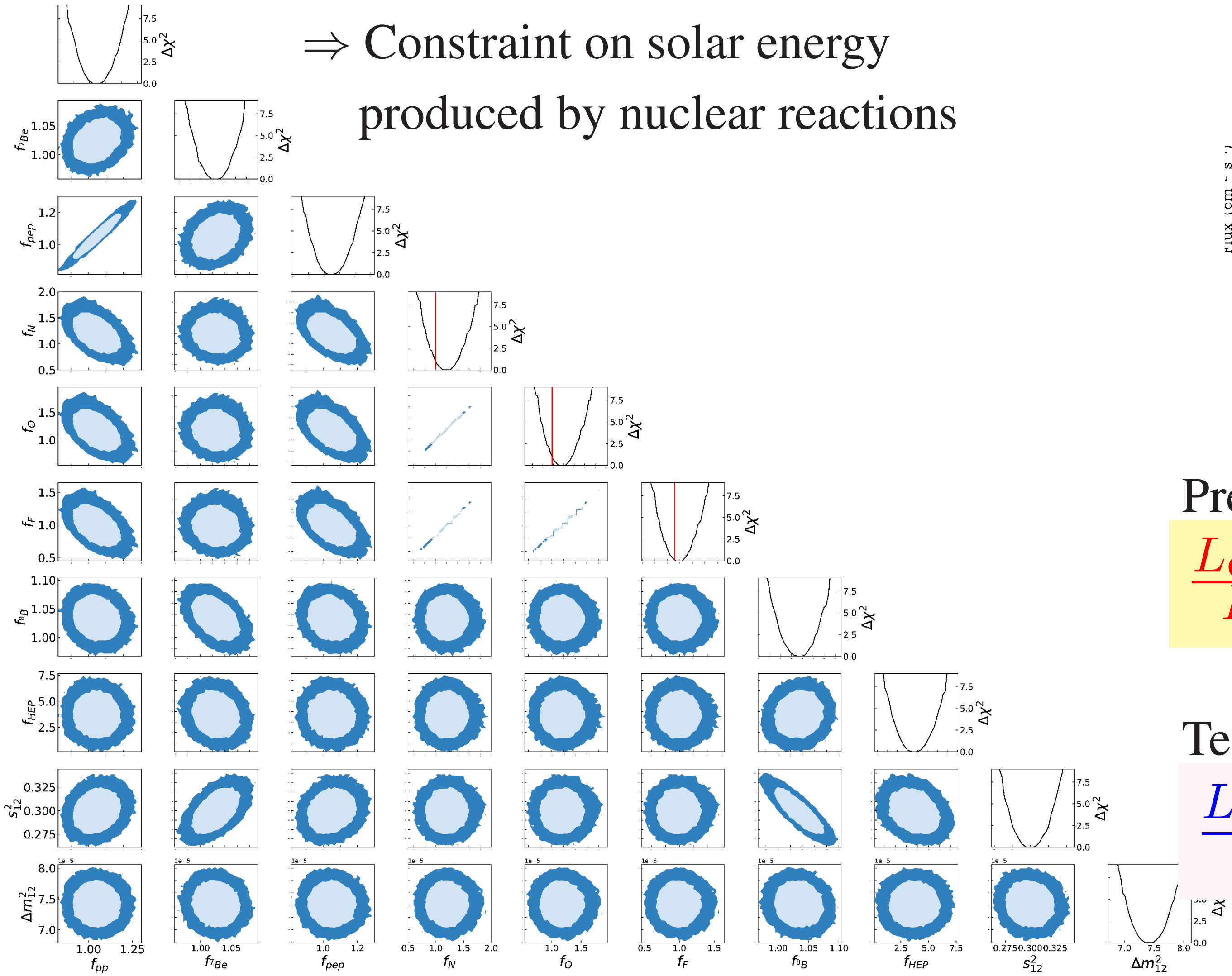
$\Rightarrow$ definitive answer will require new experiments:

- T2K and NO$\nu$A will run till $\sim$ 2027
- JUNO taking data $\Rightarrow$ Ordering (alone or comb with $\nu$-telescopes)
- Hyper-K and DUNE expected within a decade $\Rightarrow$ Ordering, $\delta_{\rm CP}$ & $\theta_{23}$

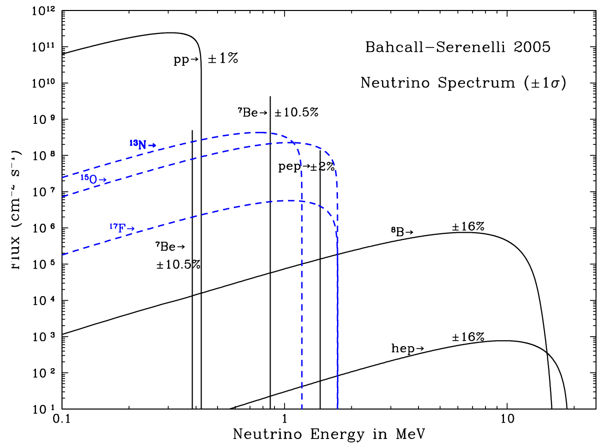
*Talks by Frank, King, Machado, Blot, Valder, Rivera, Sisti, Perrin-Terin, Martinez-Soler, Cerrone, Zhang*

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

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



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




Present limit on CNO:

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

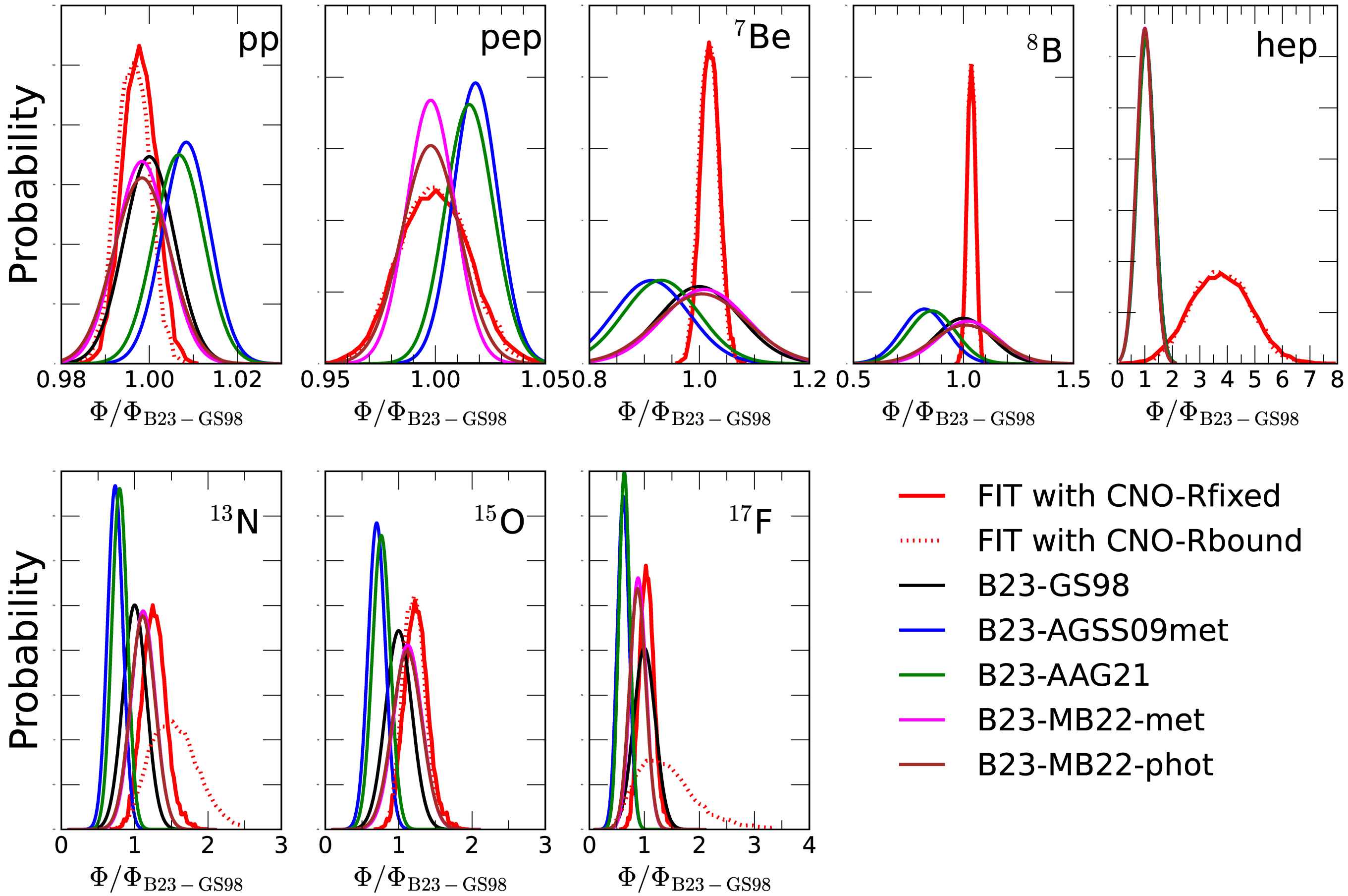
Test of Lum Constraint:

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

*MCGG, Maltoni, Pinheiro, Serenelli 2311.16226*

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

SSM independently determined fluxes can be used to improve SSM's




*MCGG, Maltoni, Pinheiro, Serenelli 2311.16226*

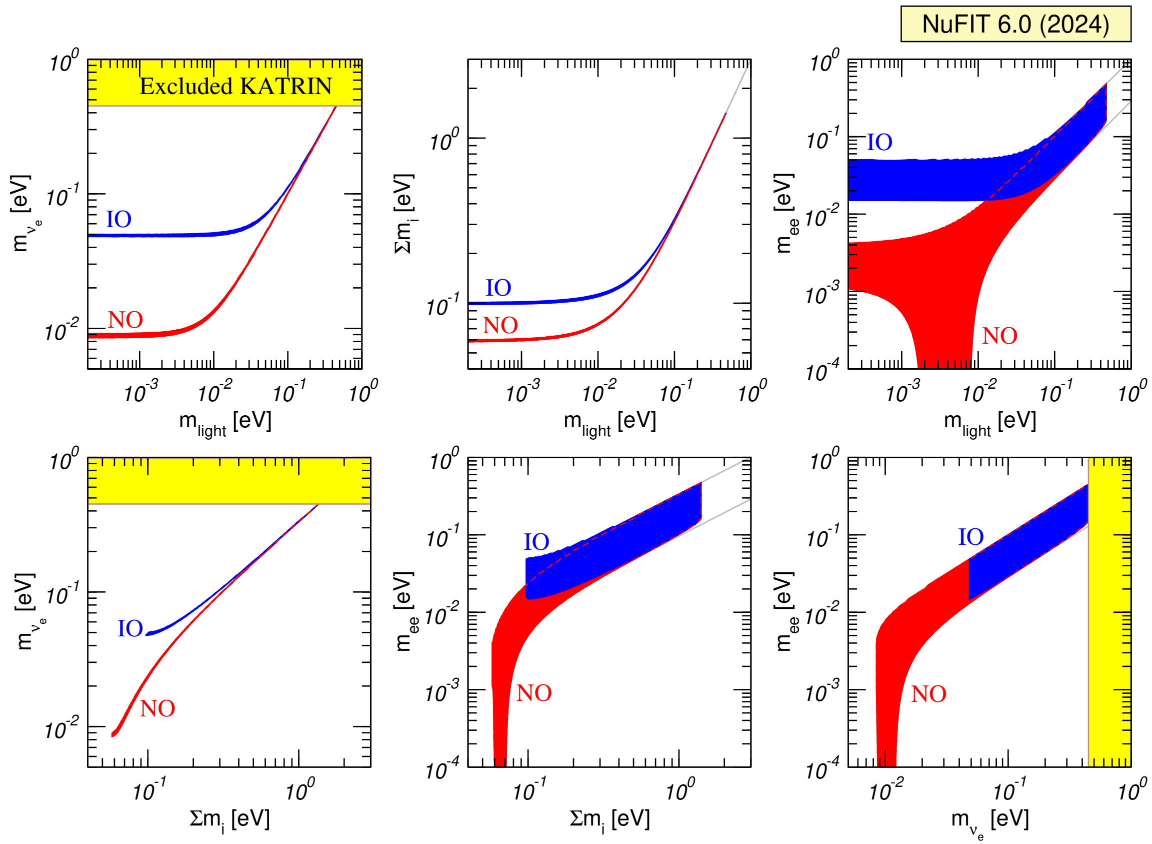
# Mass Scale & Dirac vs Majorana in 3$\nu$-mixing

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

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

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

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




Combination global Osc+KATRIN

In NO at 95% CL:

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

In IO at 95% CL:

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

*Talks by Pavan, Gastaldo, Rossi, Di. Valentino; Fu, Goria, Gusev, Petro, Palmeiro, Volta Ferrari-Baruso, Pofi*

# *Confirmed* Low Energy Picture

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

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

    $\Rightarrow$ definitive answer will require new experiments
  - Correlated information on neutrino mass-scale probes $\Rightarrow$ MO
  - Independent determination of solar $\nu$ fluxes $\Rightarrow$ relevant for SSM
- More Information on BSM?
  - No new states in $\nu$ osc experiments
  - New states in $\nu$ osc experiments

# Bottom-up: Light $\nu$ and New Physics

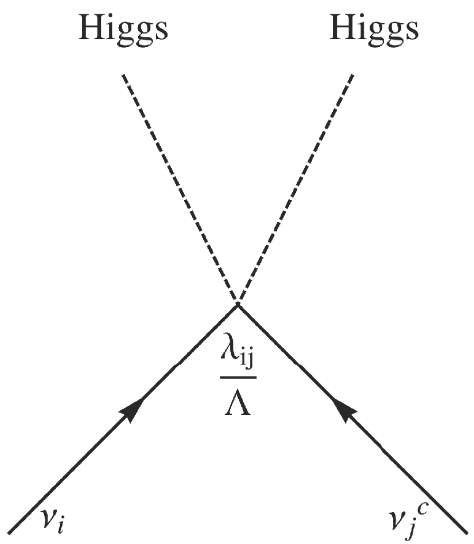
If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– 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:

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




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

For $\lambda^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}\text{GeV} \sim$ 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 $\Lambda_{LN}$ responsible for the small $m_\nu$ from

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

$\Rightarrow$ possible signals in $\nu$ exper: Non-standard $\nu$ interactions (NSI), non-unitarity . . .

# Lepton Mixing Unitarity

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

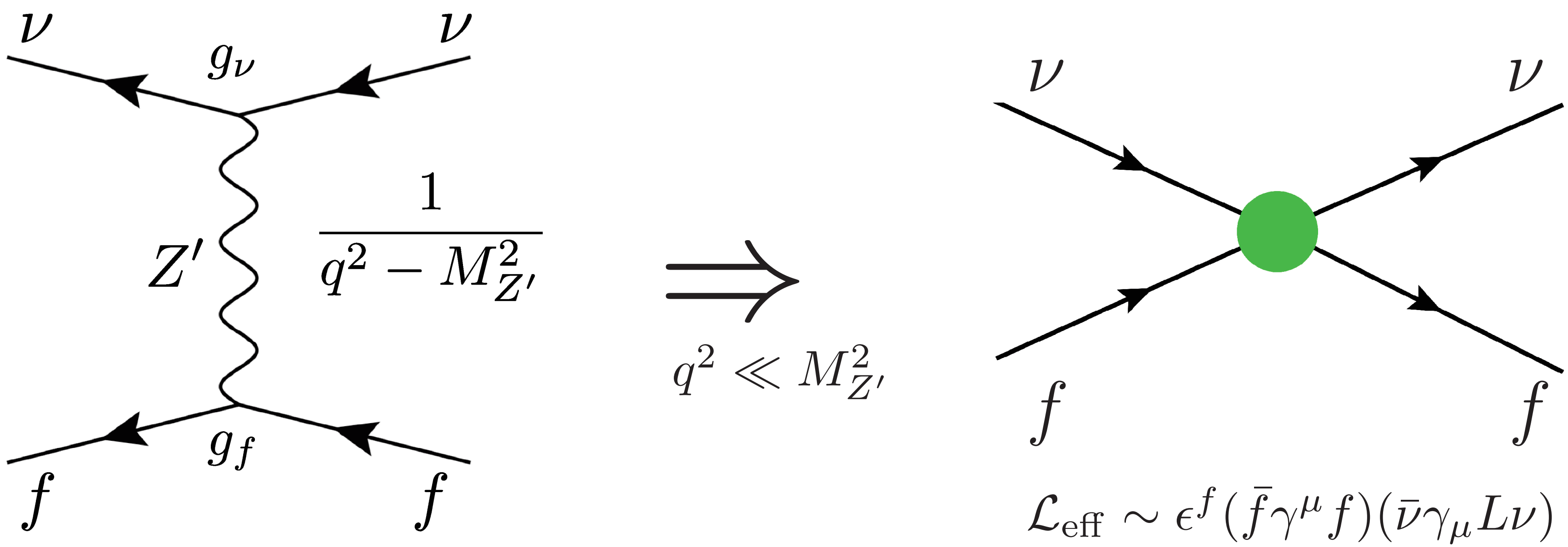
Blennow et al arxiv: 2502.14980

# Neutral Current Non Standard $\nu$ Interactions

- Effective Lagrangian

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

- Generically understood as:




$$\mathcal{L}_{\rm eff} \sim \epsilon^f (\bar{f}\gamma^\mu f)(\bar{\nu}\gamma_\mu L \nu)$$

# NSI in $\nu$ Oscillations : Degeneracies

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

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

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

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

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 $\nu$-Nucleus Scattering (CE$\nu$NS)

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

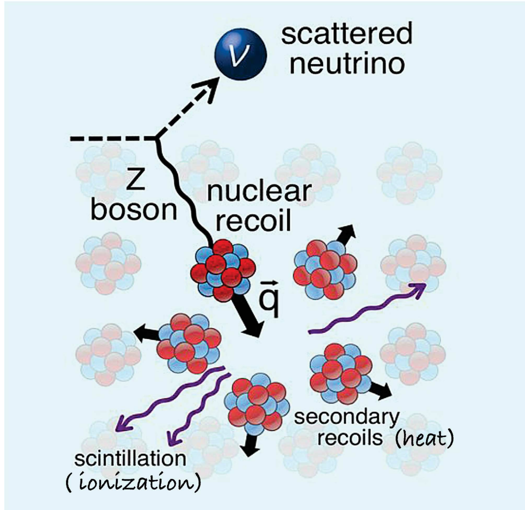
$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{2\pi}\frac{\mathcal{Q}^2}{4}F^2(2ME_r)M\left(2 - \frac{ME_r}{E_\nu^2}\right)$$

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

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, $\nu$-charge radius, $\mu_\nu$...

*Talks by Atzori Corona, Buck, Cargioli, Cadeddu, Blanco*

- For $M_{\rm Med} \gtrsim 50$ MeV and NSI with quarks $\Rightarrow$ effect in CE$\nu$NS

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

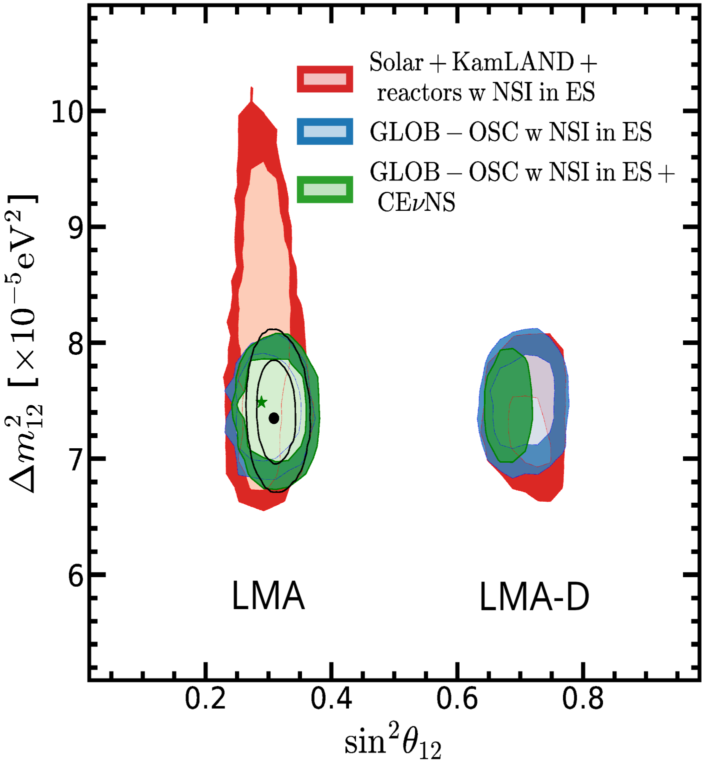
# NSI in $\nu$-OSC (and CE$\nu$Ns): Global Analysis

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

LMA-D allowed by oscillations

Adding CE$\nu$Ns ($M_{\rm med} \gtrsim 50$ MeV)

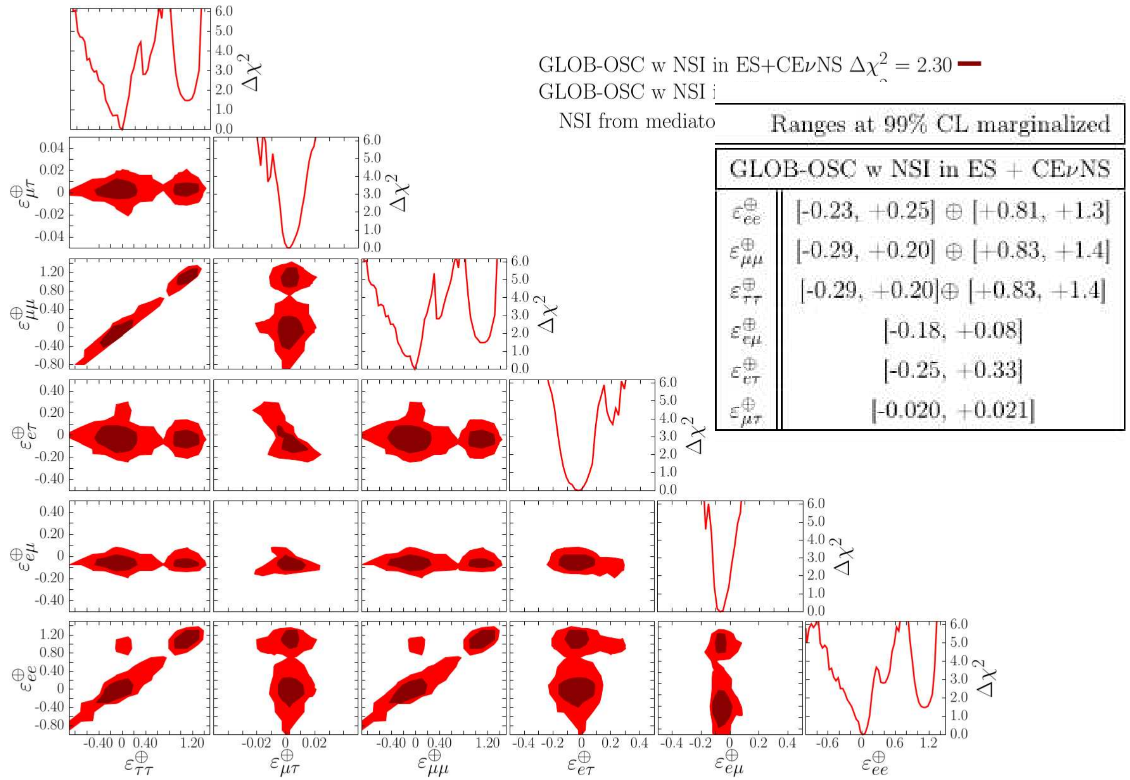
$\Rightarrow$ LMA-D only above $2\sigma$




Important bounds on the NSI's

$\Rightarrow$ Maximum effect at future LBL experiments

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



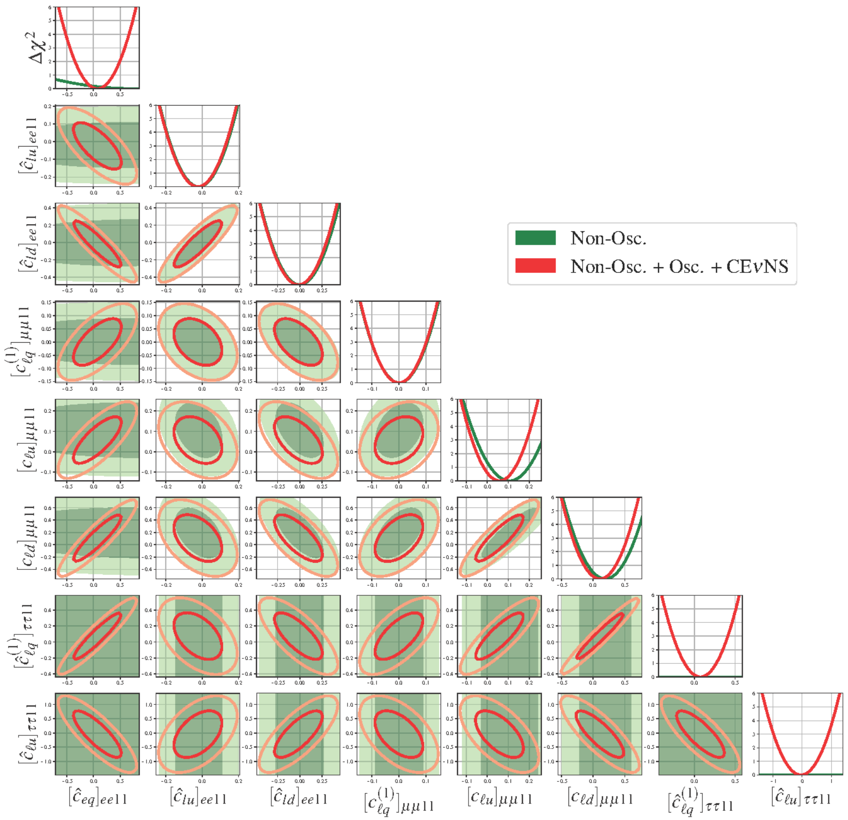

Coloma, MCGG, Maltoni, Pinheiro, Urrea 2305.07698

# From NSI to SMEFT

In SMEFT NC-NSI for $\nu_\ell$ and $\ell$ as well as CC-NSI are related.

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

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

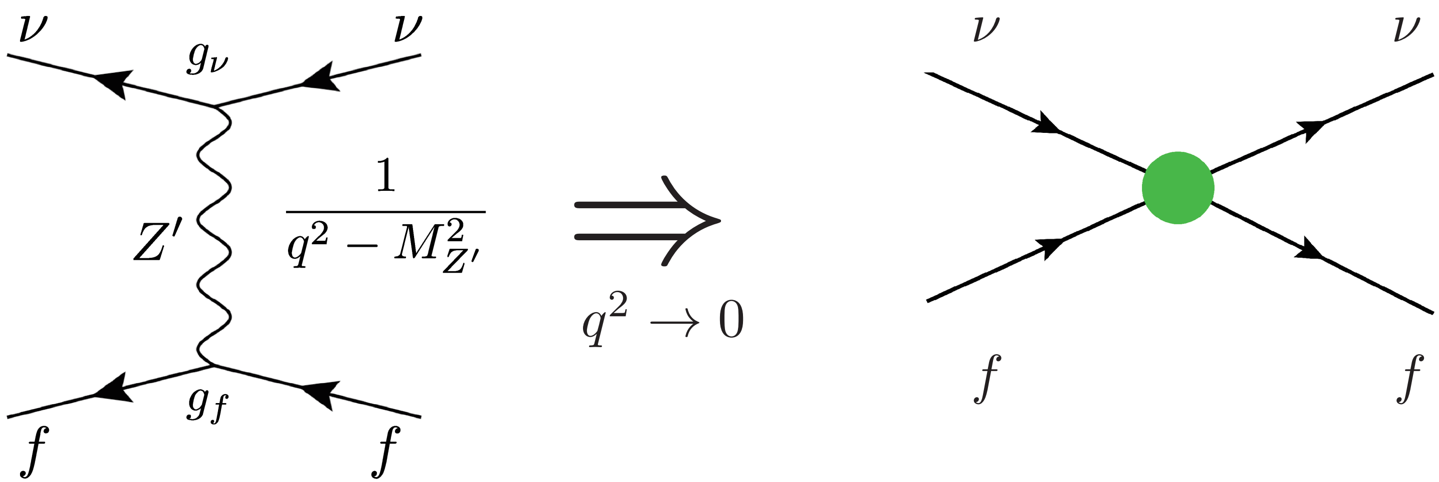
# From NSI to $U(1)'$ models with (ultra)light mediators

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:

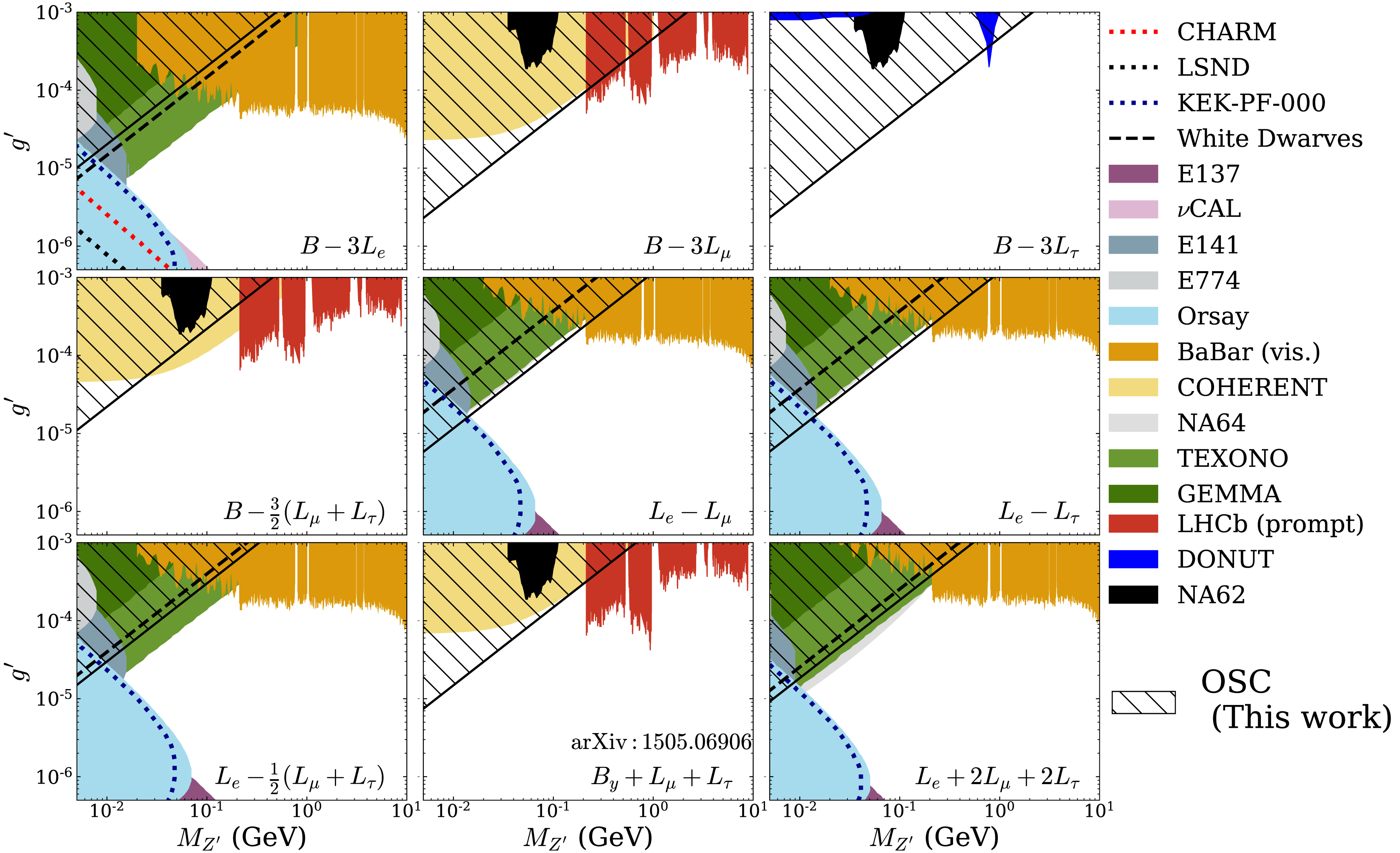



$$\varepsilon_{\alpha\beta}^{f} = \delta_{\alpha\beta}\, q'_f\, q'_\nu \frac{1}{\sqrt{2}G_F}\frac{g'^2}{M_{Z'}^2}$$

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

# From NSI to light mediator models

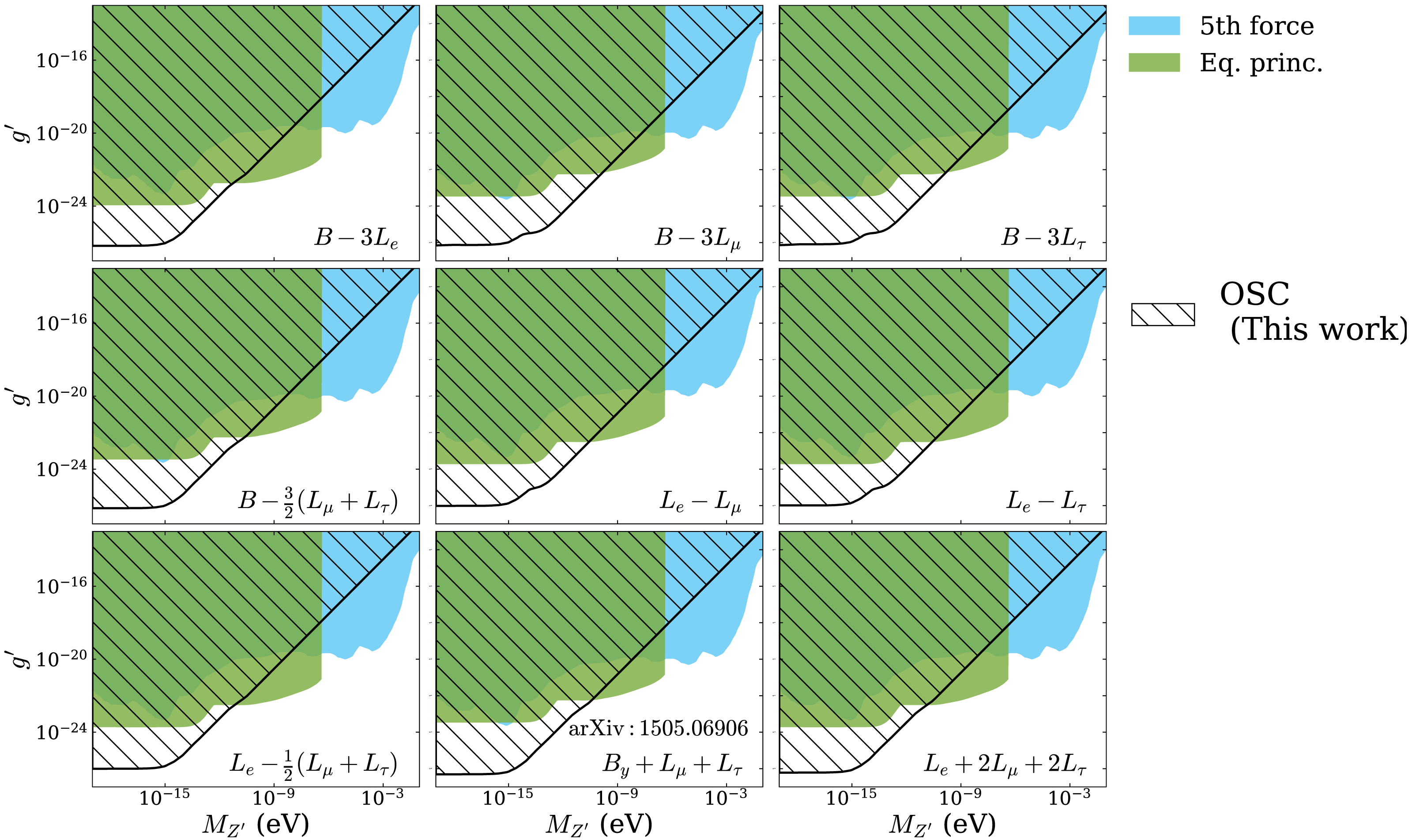
For $M_{Z'} \gtrsim \mathcal{O}(\mathrm{MeV}) \Rightarrow$ Contact Interaction in $H_{\mathrm{mat}}$: $\varepsilon^{f}_{\alpha\alpha} = q_{\nu_\alpha} q_f \frac{1}{\sqrt{G_F}} \frac{g'^2}{M^2_{Z'}}$




Coloma, MCGG, Maltoni ArXiv:2009.14220

# From NSI to ultralight mediator models

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



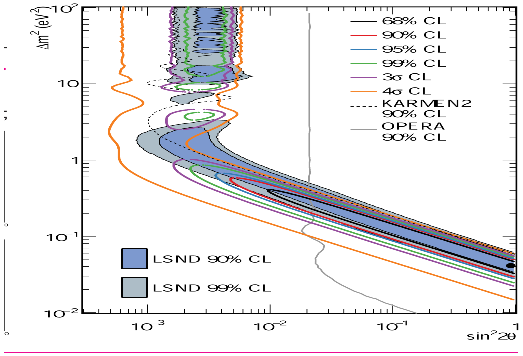

Coloma, MCGG, Maltoni ArXiv:2009.14220

# Beyond 3$\nu$'s: Light Sterile Neutrinos

- Several observations which can be interpreted as Oscillations with $\Delta m^2 \sim \mathrm{eV}^2$

## LSND &MiniBooNe

$\nu_\mu \to \nu_e$




## Reactor Anomaly

Huber, 1106.068,Mention *etal* ,1101.2755

2011 reactor flux calculation:

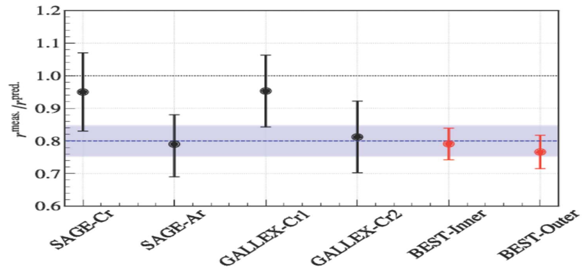
$$\overline{R}_{\mathrm{Reac}} = \frac{\mathrm{data}}{\mathrm{predict}} = 0.936^{+0.024}_{-0.023} \text{ at } L \lesssim 100 \text{ m}$$

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

## Gallium Anomaly

Acero etal, 0711.4222;Giunti, Laveder,1006.3244

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




Explained as $\nu_e$ disappearance

Confirmed by BEST ($4\sigma$)

2201.07364

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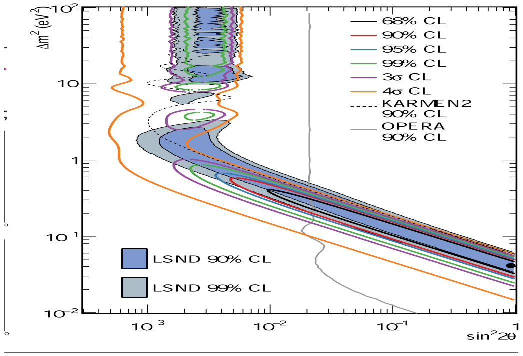
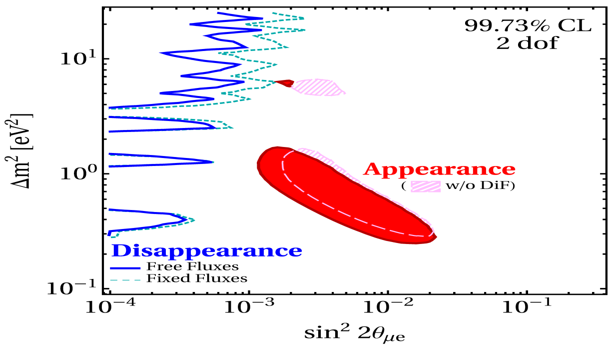



Strong tension with $\nu$ disapp

Dentler etal, 1803.10661




MicroBooNE 2412.14407:
No Confirmation (99% CL)

*Talk by F.Gao*

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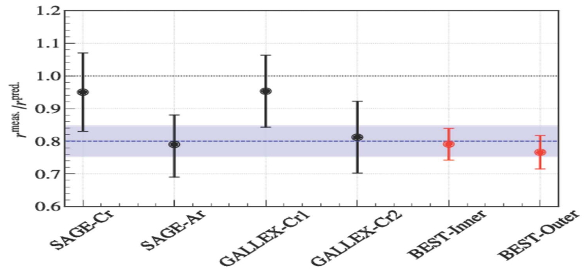


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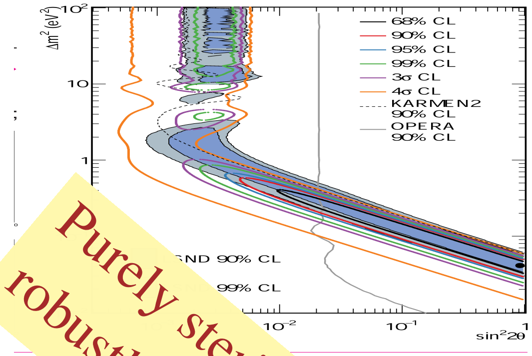
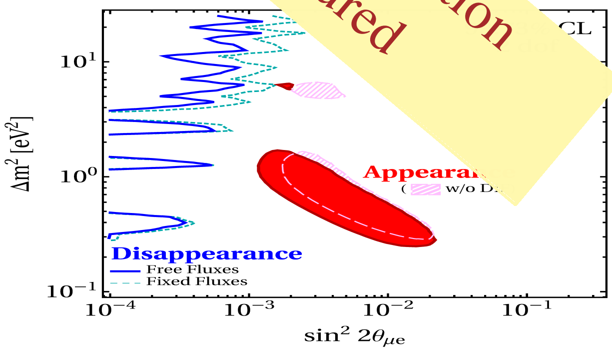



Purely sterile oscillation robustly disfavoured

Stron... with $\nu$ disapp

Dent... 10661

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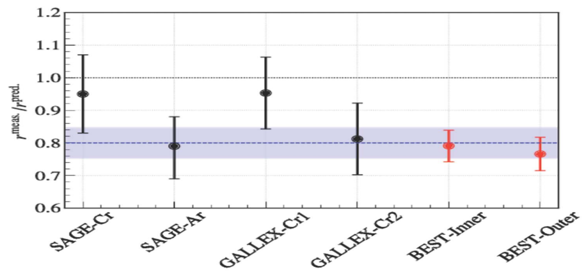


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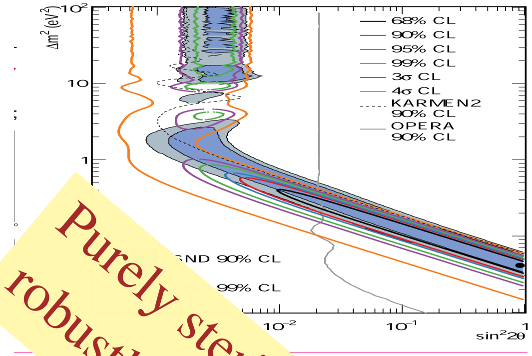


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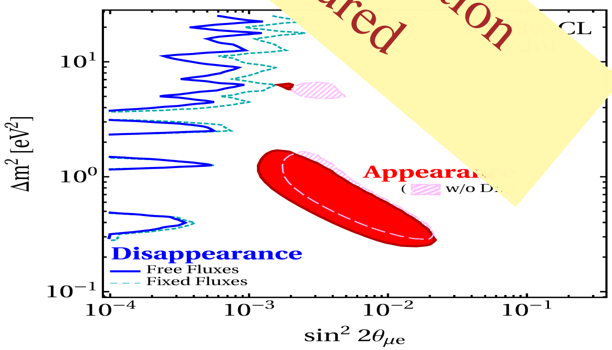



MicroBooNE 2412.14407:
No Confirmation (99% CL)

*Talk by F.Gao*

## Reactor Anomaly

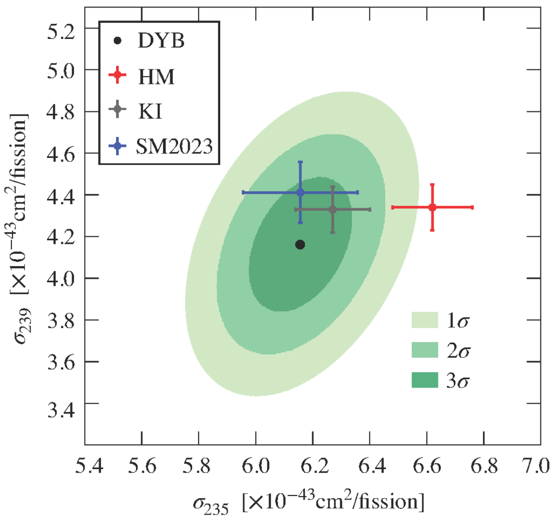
Huber, 1106.068,Mention *etal* ,1101.2755

2011 reactor flux calculation:

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

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

2022 with updated inputs ($^{235}$U)



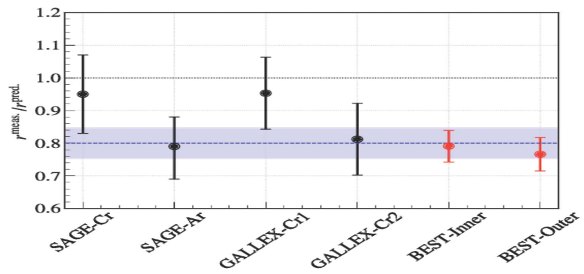

10% $^{235}$U flux reduction

Daya-Bay 2501.00746

## Gallium Anomaly

Acero etal, 0711.4222;Giunti, Laveder,1006.3244

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




Explained as $\nu_e$ disappearance

Confirmed by BEST ($4\sigma$)

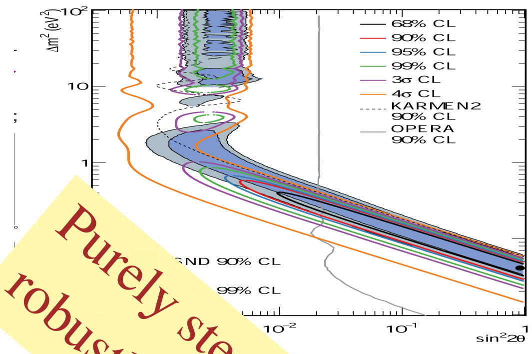
2201.07364

# Beyond 3$\nu$'s: Light Sterile Neutrinos

- Several observations which can be interpreted as Oscillations with $\Delta m^2 \sim$ eV$^2$

## LSND &MiniBooNe

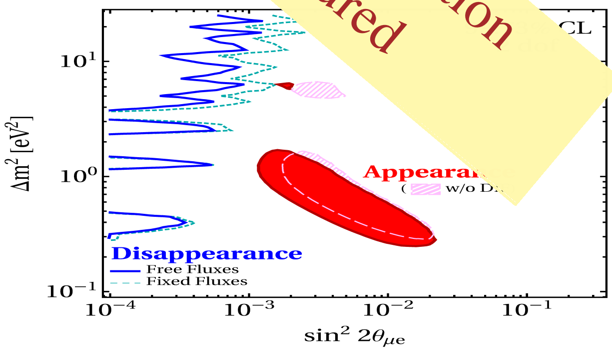
$\nu_\mu \to \nu_e$




Purely sterile oscillation robustly disfavoured

Stro... with $\nu$ disapp

Den... 10661

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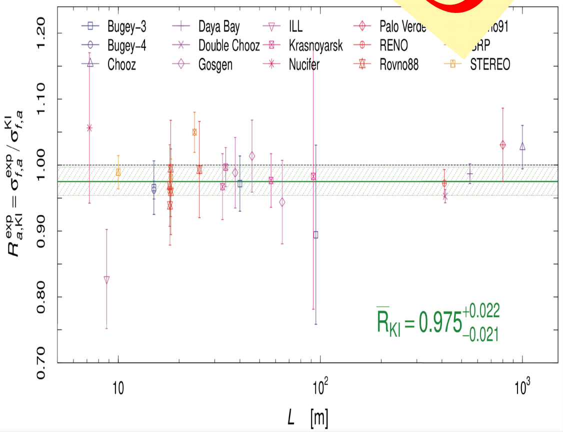
Ex... as $\bar{\nu}_e$ disappearance

2022 wi... d inputs ($^{235}$U)

Berryman Hu... 01756
Kipeikin etal, 21...
Giunti etal, 2110.068...

RESOLVED




Deficit $\lesssim 1\,\sigma$

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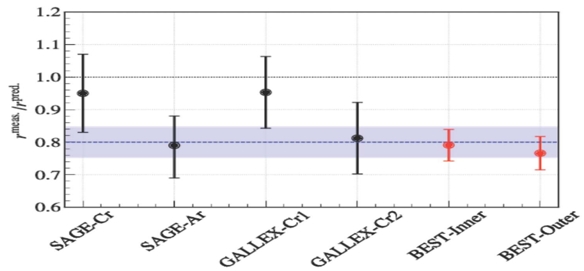


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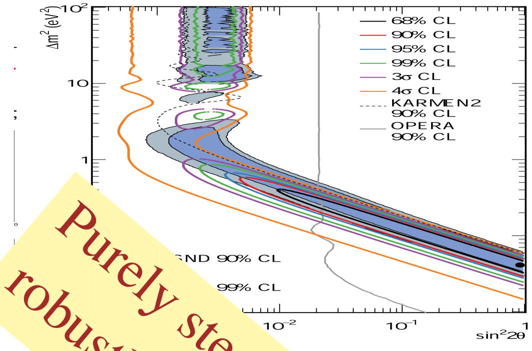


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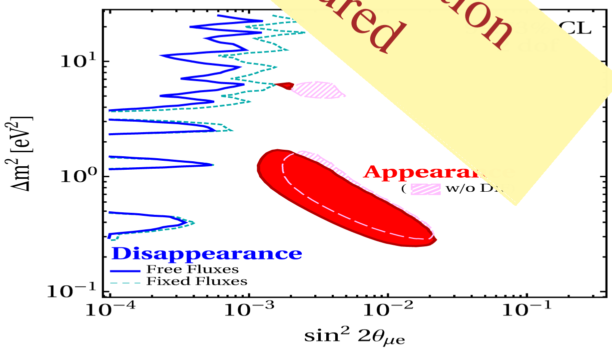


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RESOLVED

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Kipeikin etal, 21...
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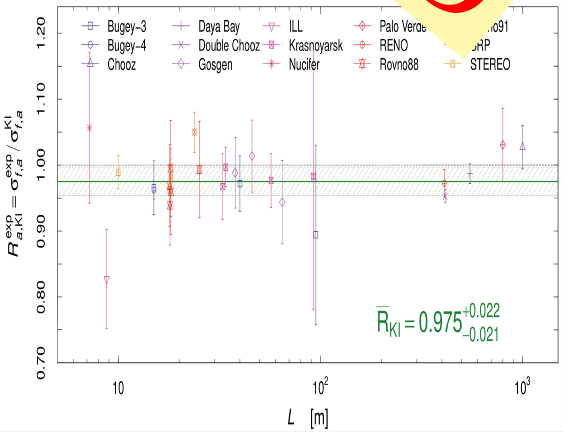


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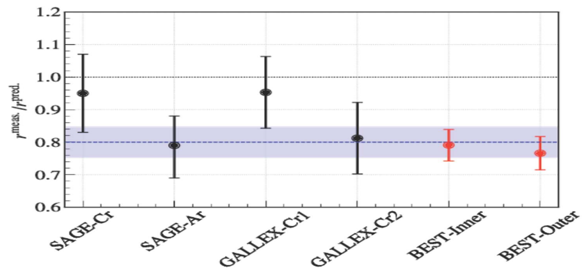
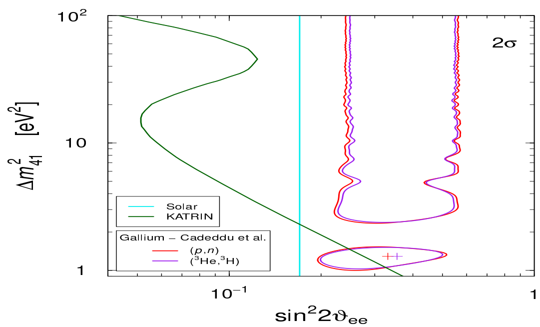



Explained as $\nu_e$ disappearance

Confirmed by BEST ($4\sigma$)
2201.07364

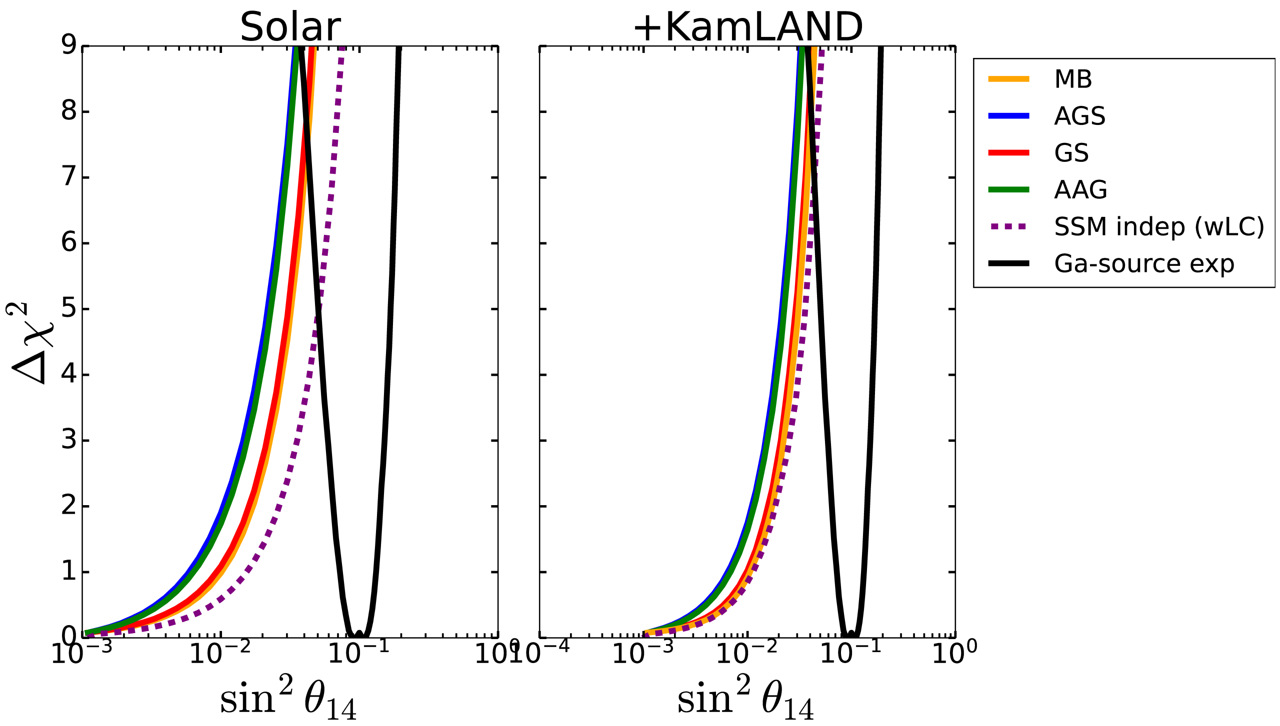
But oscillation solution

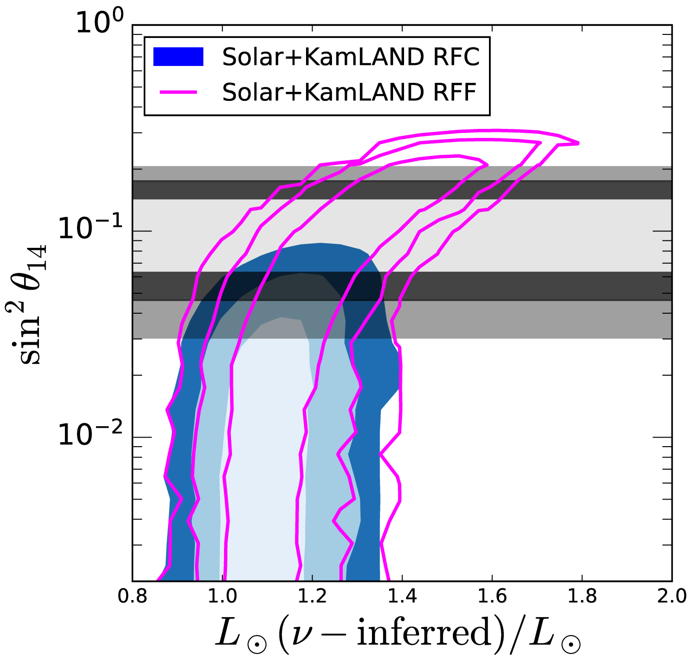



Cadeddu etal, 2507.13013

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*

# Summary

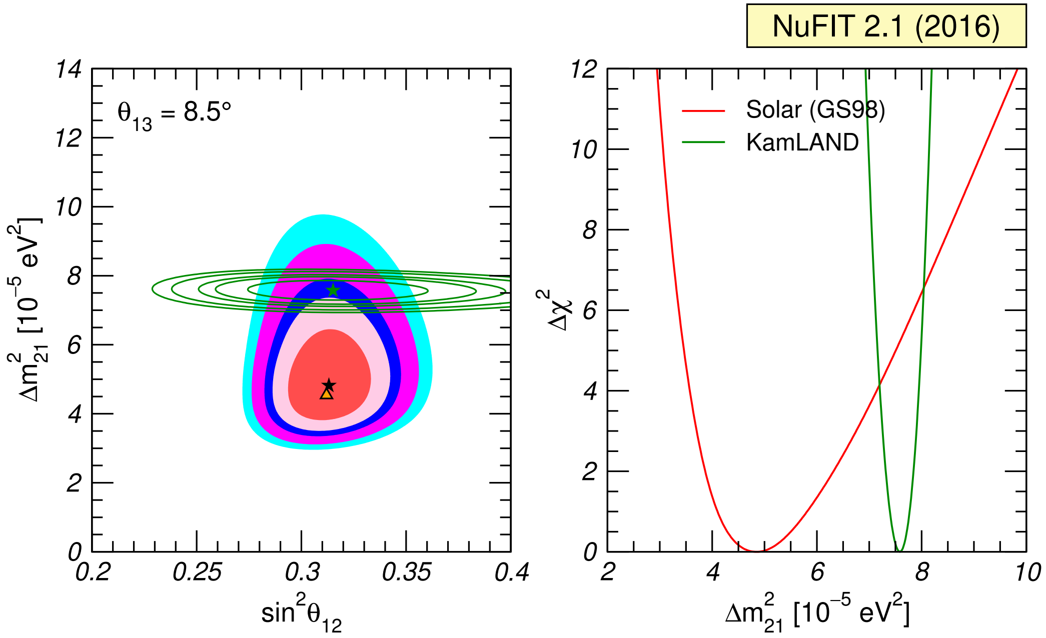
- $3\nu$ scenario:
  - Robust determination of $\theta_{12}$, $\theta_{13}$, $\Delta m^2_{21}$, $|\Delta m^2_{3\ell}|$
  - Mass ordering, $\theta_{23}$ Octant, CPV depend on subdominant $3\nu$-effects

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

    $\Rightarrow$ definitive answer will require new experiments
  - Correlated information on neutrino mass-scale probes $\Rightarrow$ MO
  - Independent determination of solar $\nu$ fluxes $\Rightarrow$ relevant for SSM
- Extended Scenarios *Talks by Palazzo,Nebot-Guinot, Gao, Cadeddu*
  - No new states in $\nu$ osc experiments
    - $L\alpha$-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
  - Light-sterile ($\mathcal{O}(eV)$) in $\nu$ osc experiments:
    - No consistent description of *surviving* SBL anomalies
    - Relevant upcoming results SBND, JNS2

# Backup Slides

• Last decade: after including $\theta_{13} \simeq 9^\circ$ the comparison of KamLAND vs Solar




$\theta_{12}$ better than $1\sigma$ agreement

But $\sim 2\sigma$ tension on $\Delta m^2_{12}$

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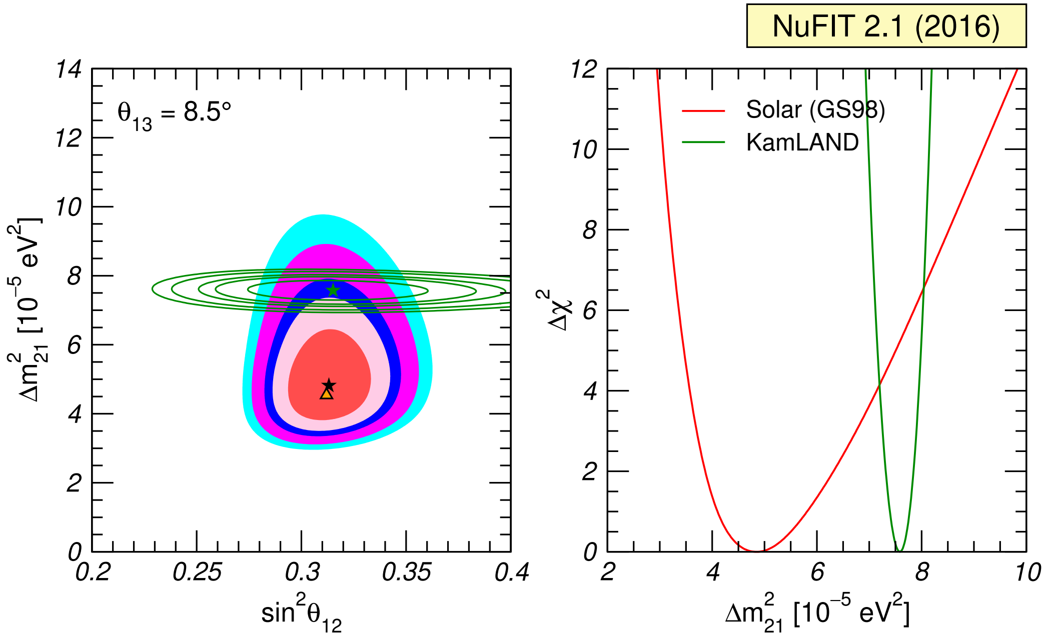


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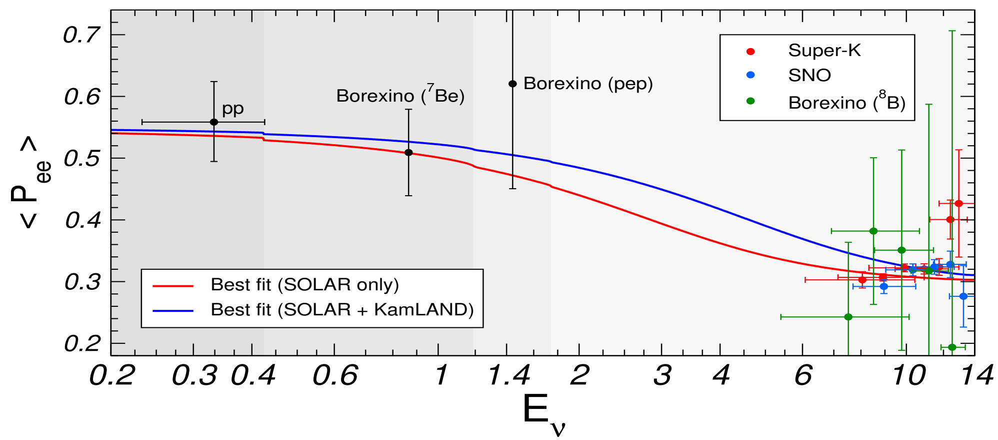
But $\sim 2\sigma$ tension on $\Delta m^2_{12}$

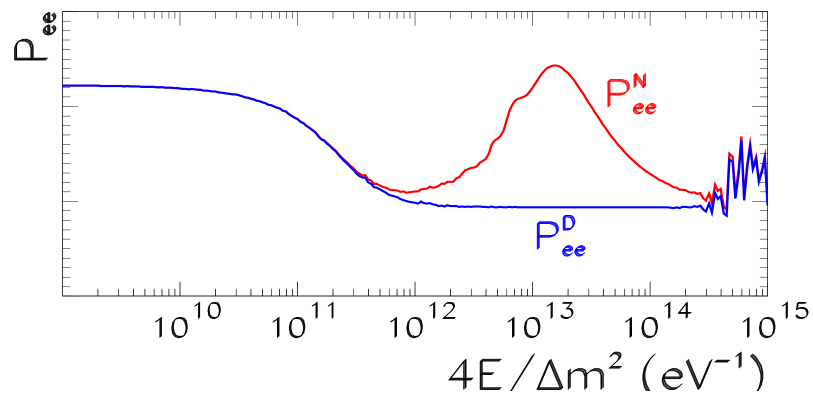
• Tension arising from:

Smaller-than-expected MSW low-E turn-up in SK/SNO spectrum at global b.f.




"too large" of Day/Night at SK

$A_{\mathrm{D/N,SK4-2055}} = [-3.1 \pm 1.6(\mathrm{stat.}) \pm 1.4(\mathrm{sys.})]\%$



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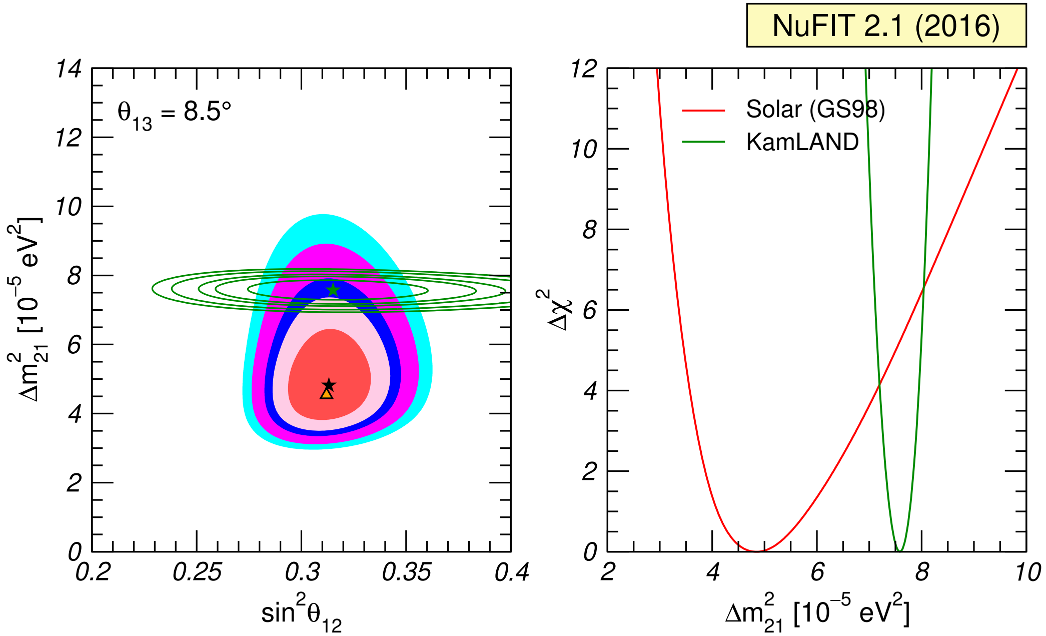


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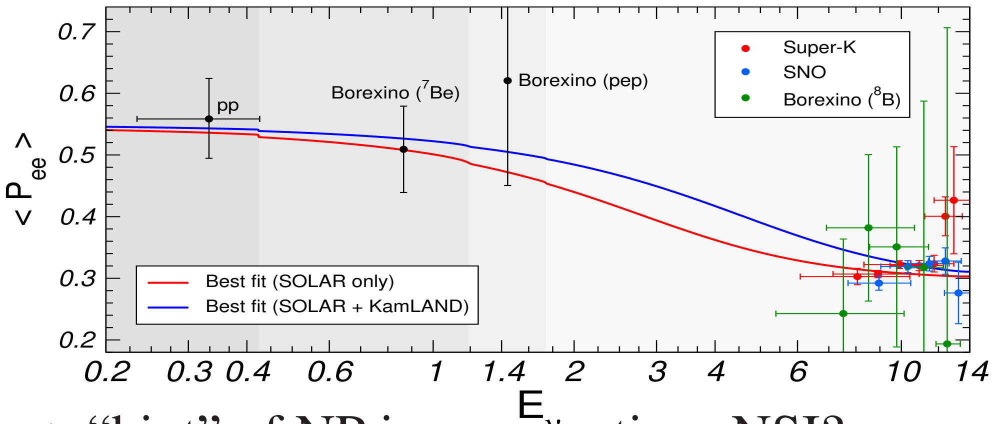
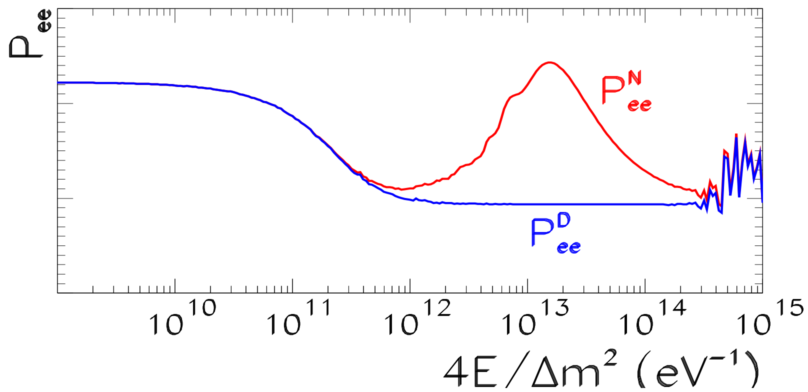
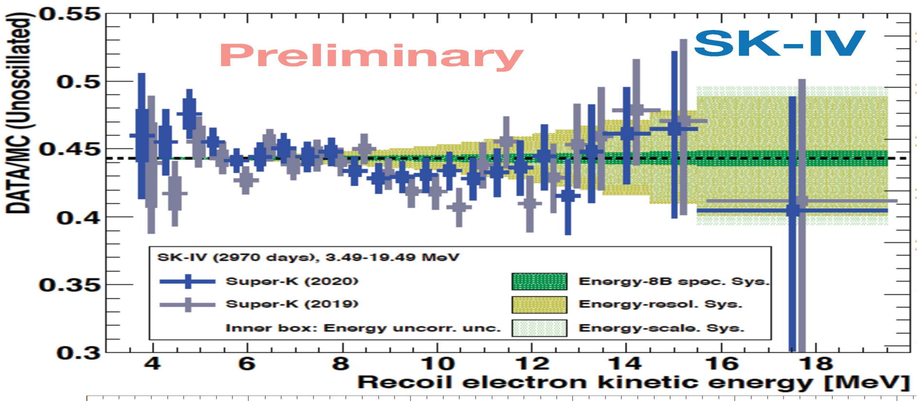



$\Rightarrow$ "hint" of NP in propagation: NSI?

• AFTER NU2020: With SK4 2970 days data

Slightly more pronounced low-E turn-up




Smaller of Day/Night at

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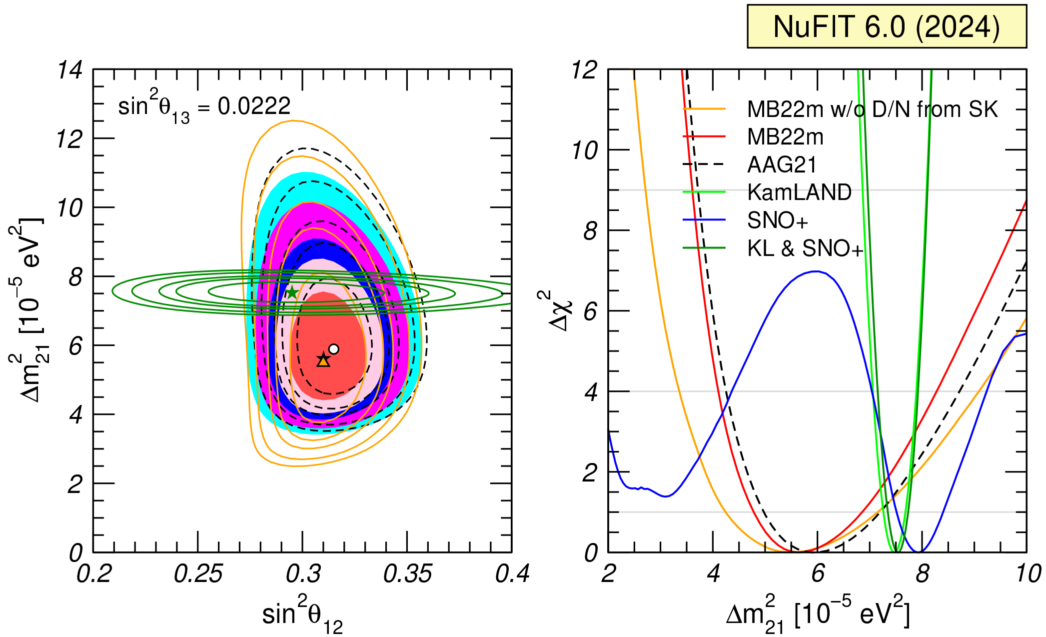
$$A_{\mathrm{D/N,SK4-2970}} = [-2.1 \pm 1.1]\%$$

• In NuFIT 6.0




$\Rightarrow$ Agreement of $\Delta m^2_{21}$ between solar and KamLAND at $\sim 1\sigma$