# PHENOMENOLOGY WITH MASSIVE NEUTRINOS IN 2024

Concha Gonzalez-Garcia

*(YITP-Stony Brook & ICREA-University of Barcelona )*

**SUSY24: The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions**

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## OUTLINE

Status of the $3\nu$ global description

Explorations beyond $3\nu$'s: steriles, NSI's, Z's . . .

Global fit to neutrino oscillation data
HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos
AGENCIA ESTATAL DE INVESTIGACIÓN
NSF

# Introduction: The Evidence of BSM

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

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  - ∗ Atmospheric $\nu_\mu$ & $\bar{\nu}_\mu$ disappear most likely to $\nu_\tau$ (**SK**,MINOS, **ICECUBE**)
  - ∗ Accel. $\nu_\mu$ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K**, MINOS, **NO$\nu$A**)
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- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino $\equiv \nu$SM

  - $*$ Introduce $\nu_R$ AND impose $L$ conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  - $*$ NOT impose $L$ conservation $\Rightarrow$ Majorana $\nu = \nu^c$

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

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  $\Rightarrow$ CC interactions of leptons are not diagonal (same as quarks)

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

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

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  $\Rightarrow$ Flavour Oscillations:

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

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

No information on $\nu$ mass scale nor Majorana versus Dirac

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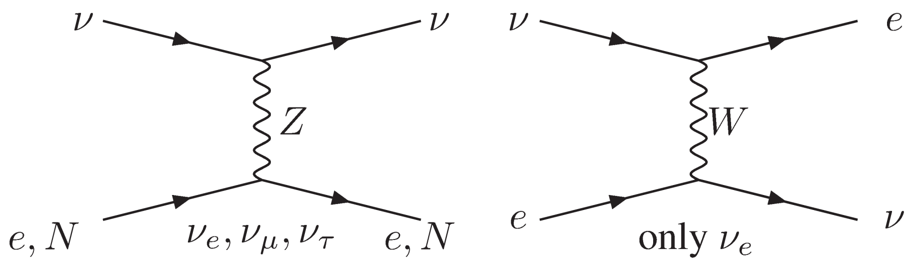
- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino $\equiv \nu$SM

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




$\Rightarrow$ Effective potential in $\nu$ evolution : $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^{\nu_e} = -\Delta V^{\bar{\nu}_s} = \sqrt{2} G_F N_e$
$\Rightarrow$ Modification of mixing angle and oscillation wavelength (MSW)

# 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 3-year data, 64 points.
- *SK I-IV 328 and 372 kton-years& SK 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 $19.7 \times 10^{20}$ pot $\nu_\mu$-disapp data, 35 points.
- T2K $19.7 \times 10^{20}$ pot $\nu_e$-app data, 23 points CCQE and 16 points CC$1\pi$.
- T2K $16.3 \times 10^{20}$ pot $\bar{\nu}_\mu$-disapp, 35 points.
- T2K $16.3 \times 10^{20}$ pot $\bar{\nu}_e$-app, 23 points.
- NO$\nu$A $13.6 \times 10^{20}$ pot $\nu_\mu$-disapp data , 76 points.
- NO$\nu$A $13.6 \times 10^{20}$ pot $\nu_e$-app data , 13 points.
- NO$\nu$A $12.5 \times 10^{20}$ pot $\bar{\nu}_\mu$-disapp, 76 points.
- NO$\nu$A $12.5 \times 10^{20}$ pot $\bar{\nu}_e$-app, 13 points.

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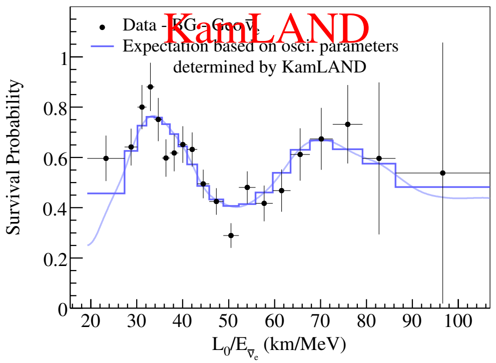
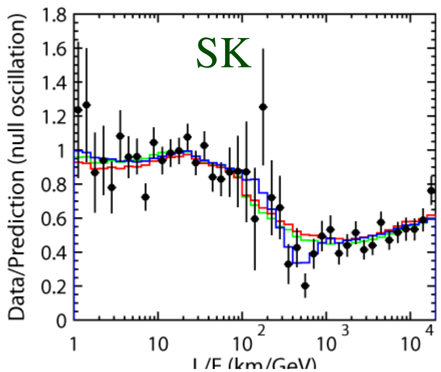
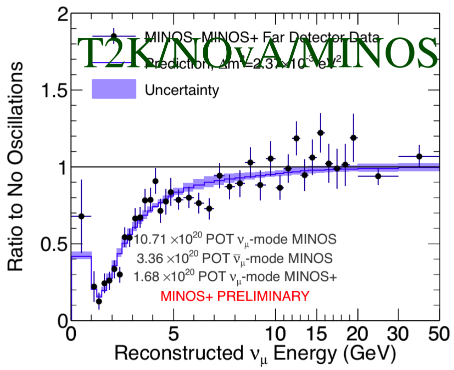
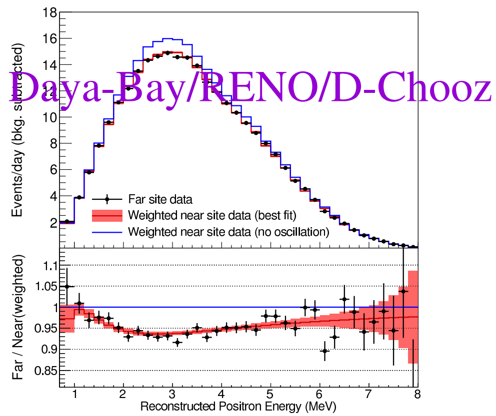
  - $*$ Accel. $\nu_\mu$ & $\bar\nu_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K**, MINOS, **NO$\nu$A**) $\theta \sim 45^\circ$
  - $*$ Some accel $\nu_\mu$ & $\bar\nu_\mu$ appear as $\nu_e$ & $\bar\nu_e$ at $L \sim 300/800$ Km ( **T2K**, MINOS,**NO$\nu$A**) $\theta \sim 8^\circ$
  - $*$ Solar $\nu_e$ convert to $\nu_\mu/\nu_\tau$ (Cl, Ga, **SK, SNO, Borexino**) $\frac{\Delta m^2}{\mathrm{eV}^2} \sim 10^{-5}, \theta \sim 30^\circ$
  - $*$ 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) $\frac{\Delta m^2}{\mathrm{eV}^2} \sim 2\,10^{-3}, \theta \sim 8^\circ$
- Confirmed: – Vacuum oscillation $L/E$ pattern with 2 frequencies

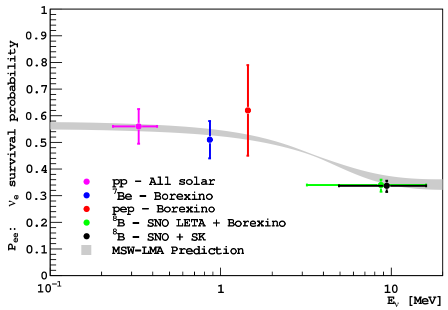



– MSW conversion in Sun



# $3\nu$ Flavour Parameters

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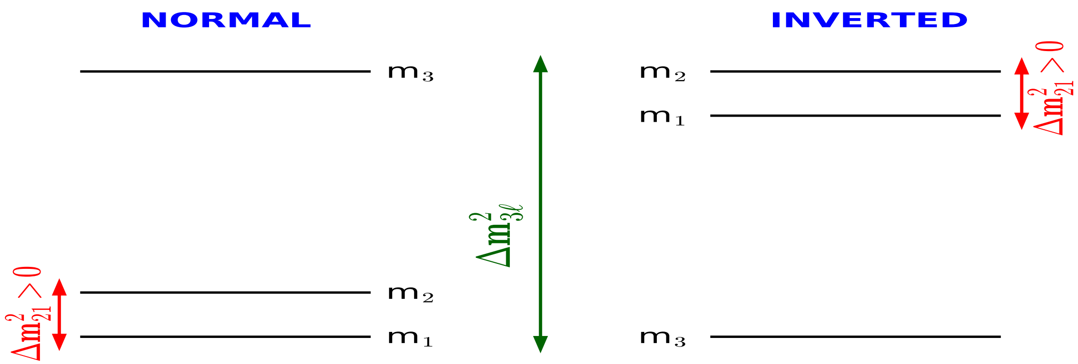
- For **for 3 $\nu$'s** : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

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

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




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

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

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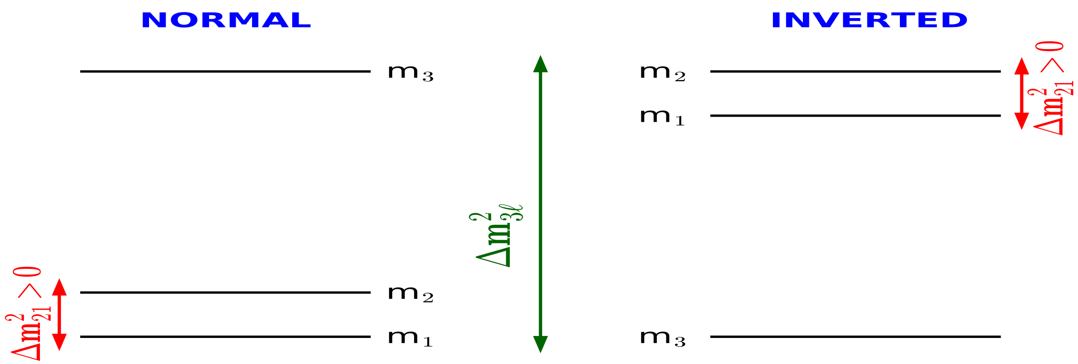


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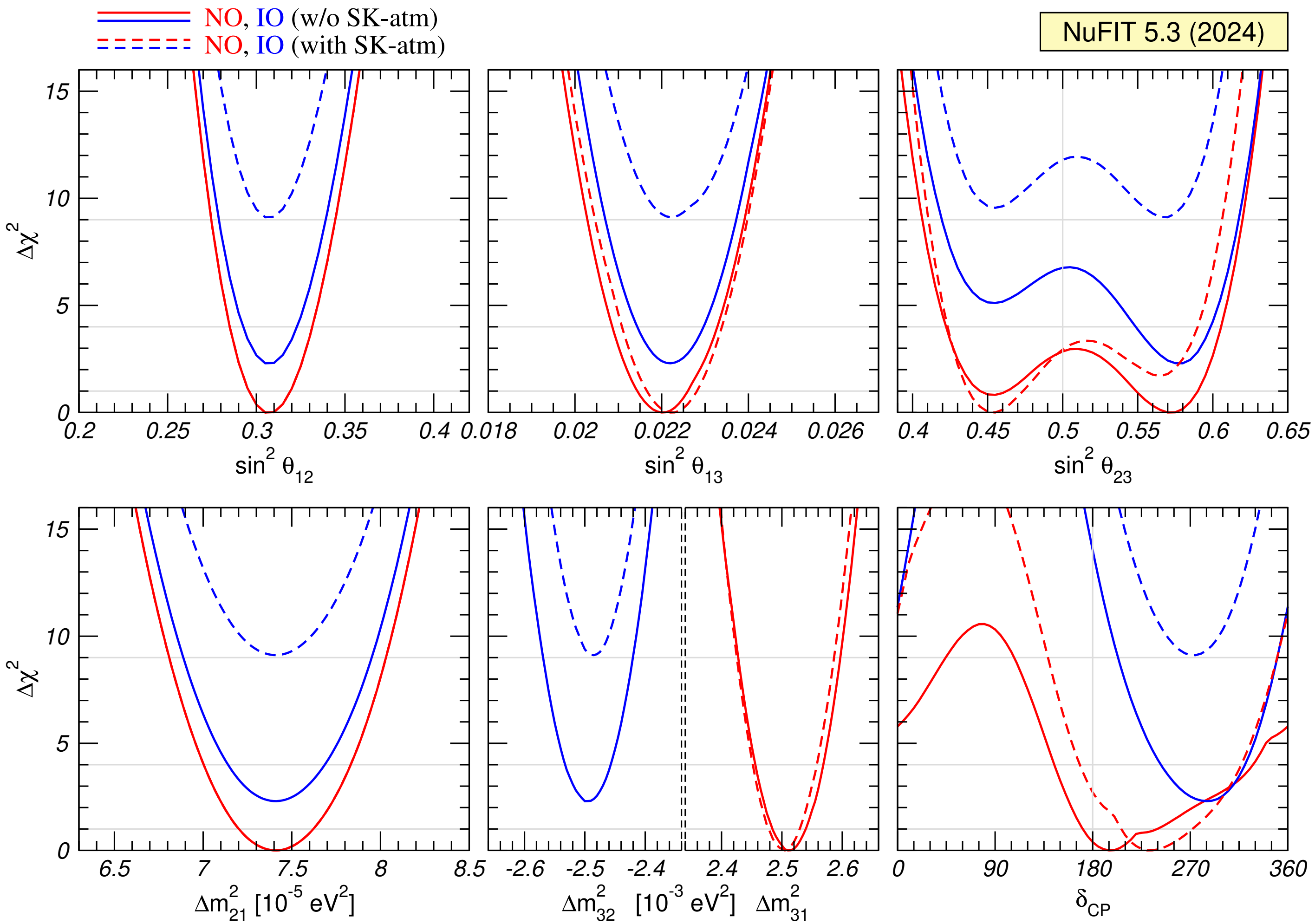
| Experiment | Dominant | Important | Additional |
|---|---|---|---|
| Solar Experiments | $\theta_{12}$ | $\Delta m^2_{21}$ | $\theta_{13}$ |
| Reactor LBL (KamLAND) | $\Delta m^2_{21}$ | $\theta_{12}$ | $\theta_{13}$ |
| Reactor MBL (Daya Bay, Reno, D-Chooz) | $\theta_{13}$, $\Delta m^2_{3\ell}$ | | |
| 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) | $\delta_{\rm cp}$ | | $\theta_{13}$ |

# Summary: Global 3 $\nu$ Flavour Parameters

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

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

(Good agreement with other groups': Capozzi,et al, 2107.00532; Salas etal 2006.11237)




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

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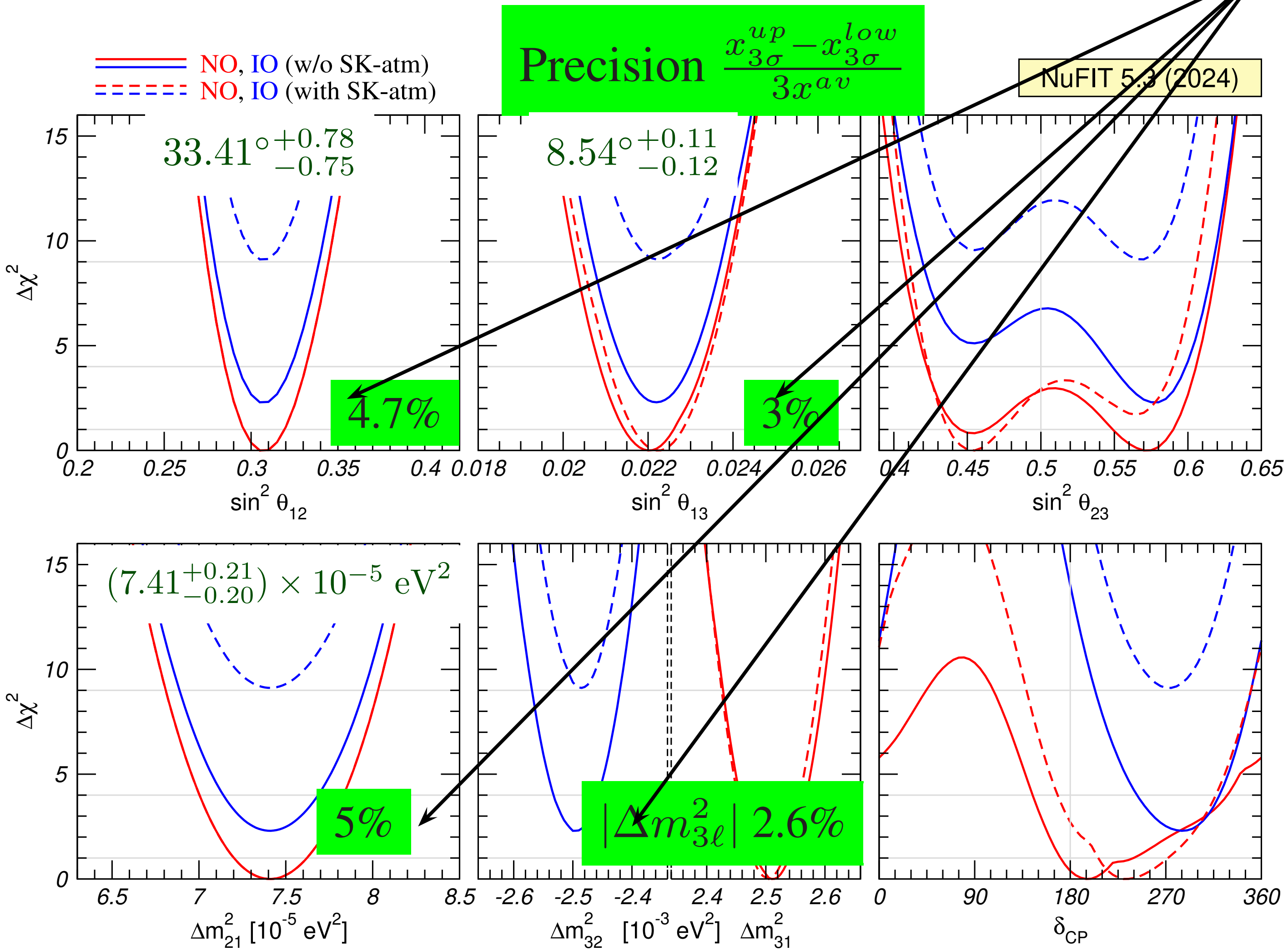

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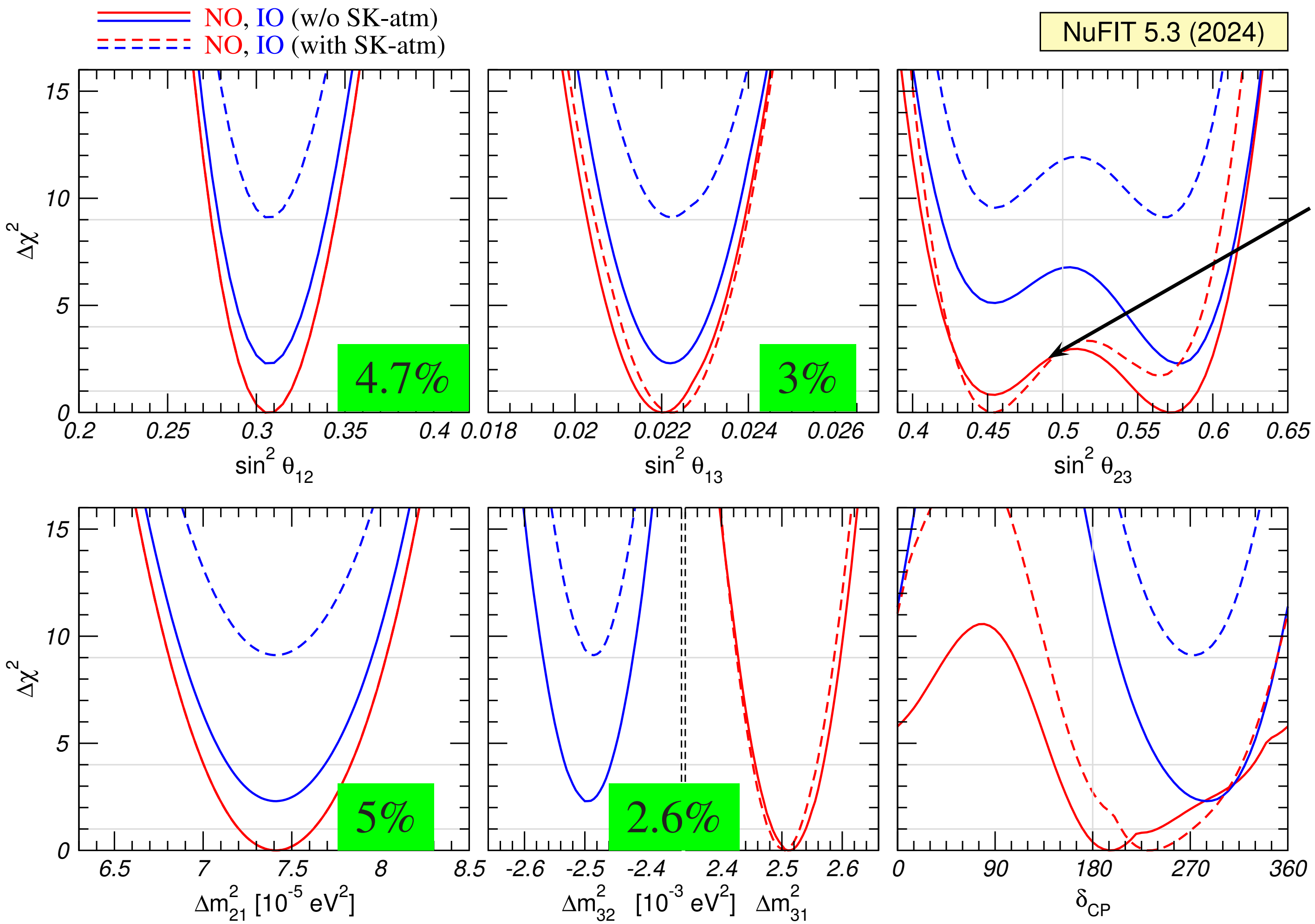


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  Tension Resolved
- $\theta_{23}$: Least known angle

  Maximal? Octant?

  non-robust wrt ATM

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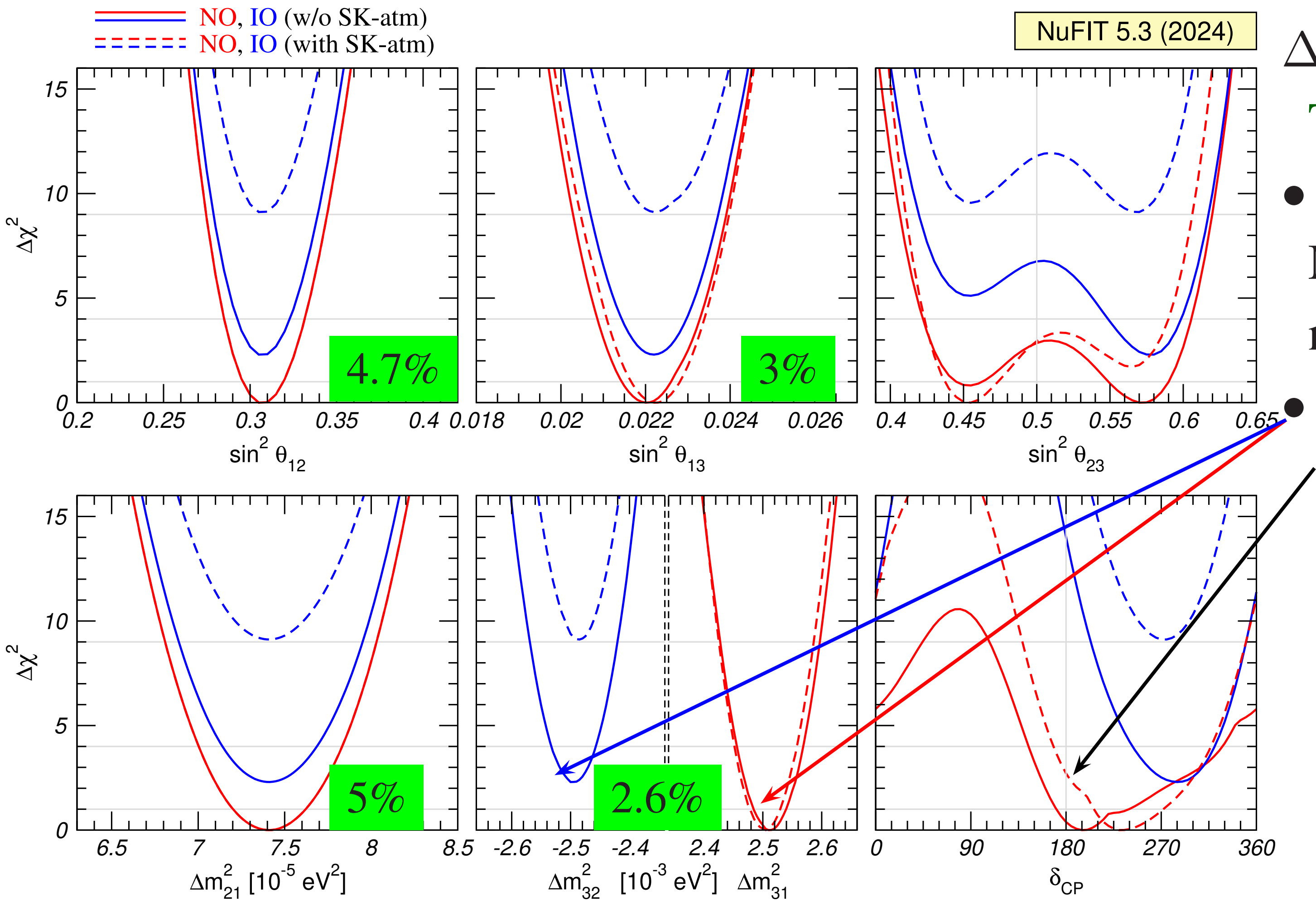


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- Ordering NO or IO?

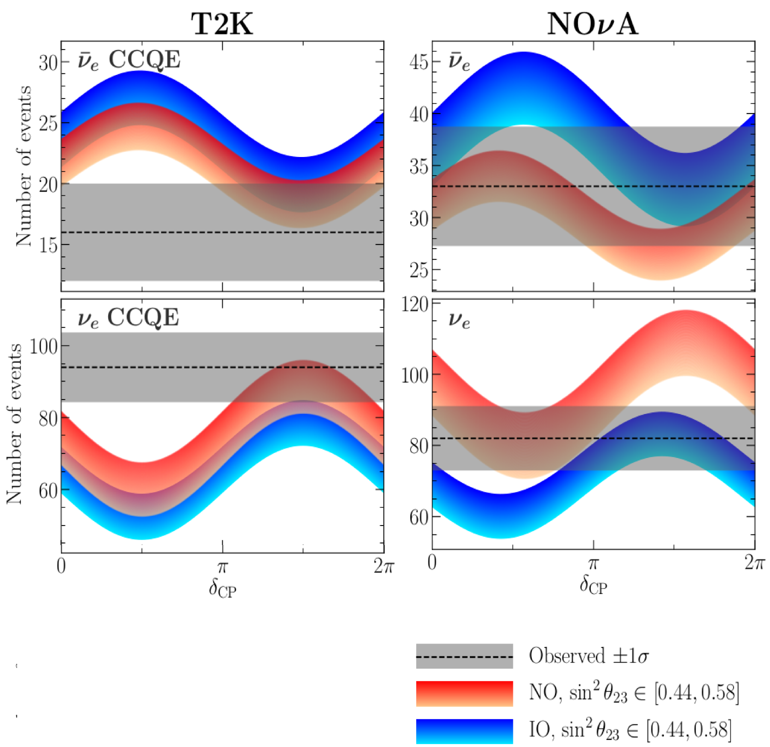
  CPV?:

# Ordering and CPV in LBL: $\nu_e$ appearace

- Dominant information from $\nu_e$ appearance in LBL

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

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

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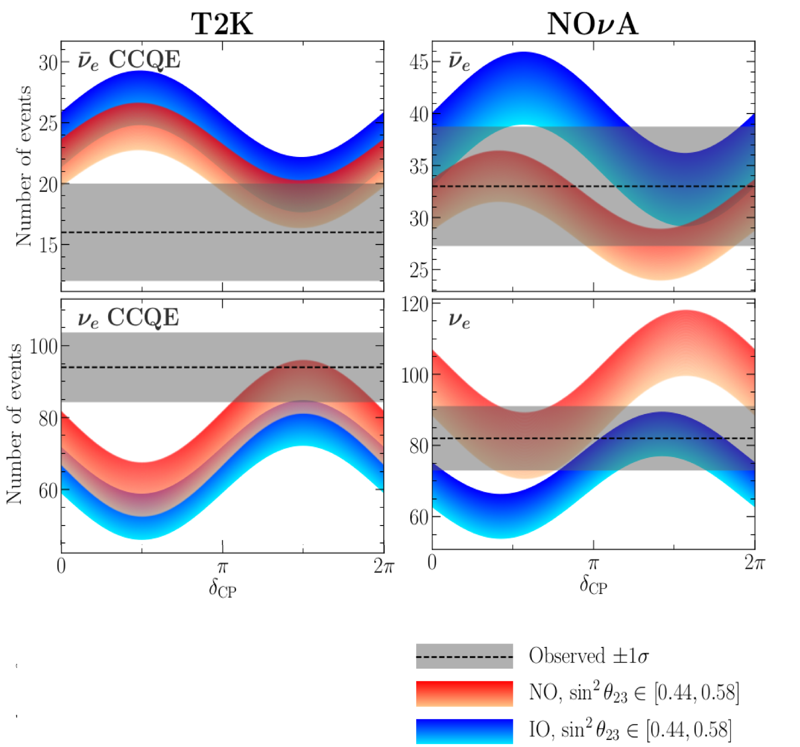
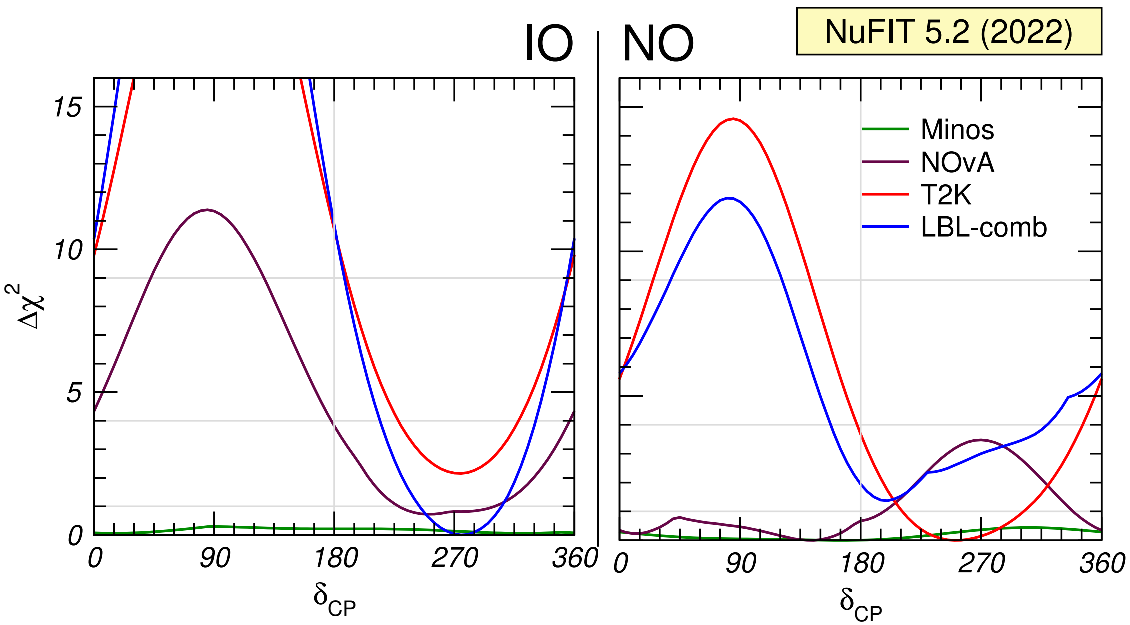



$\Rightarrow$ Each T2K and NO$\nu$A favour NO

But tension in favoured values of $\delta_{CP}$ in NO




$\Rightarrow$ IO best fit in LBL combination

# $\Delta m^2_{3l}$ in LBL & Reactors

- At LBL determined in $\nu_\mu$ and $\bar\nu_\mu$ disappearance spectrum

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

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar\nu_e$ disapp spectrum

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

Nunokawa,Parke,Zukanovich (2005)

$\Rightarrow$ Contribution to NO/IO from combination of LBL with reactor data

# $\Delta m^2_{3l}$ in LBL & Reactors

- At LBL determined in $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance spectrum

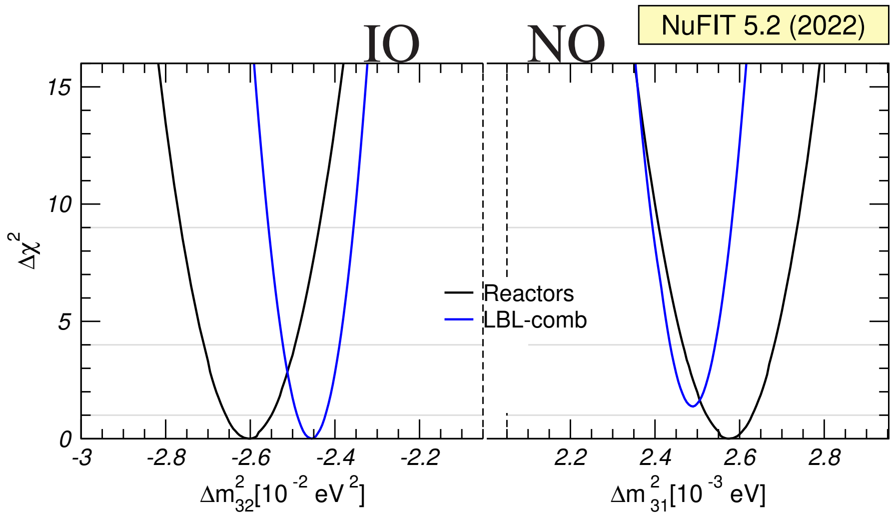
$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$$

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar{\nu}_e$ disapp spectrum

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

Nunokawa,Parke,Zukanovich (2005)

$\Rightarrow$ Contribution to NO/IO from combination of LBL with reactor data




- T2K and NO$\nu$A more compatible in IO $\Rightarrow$IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors

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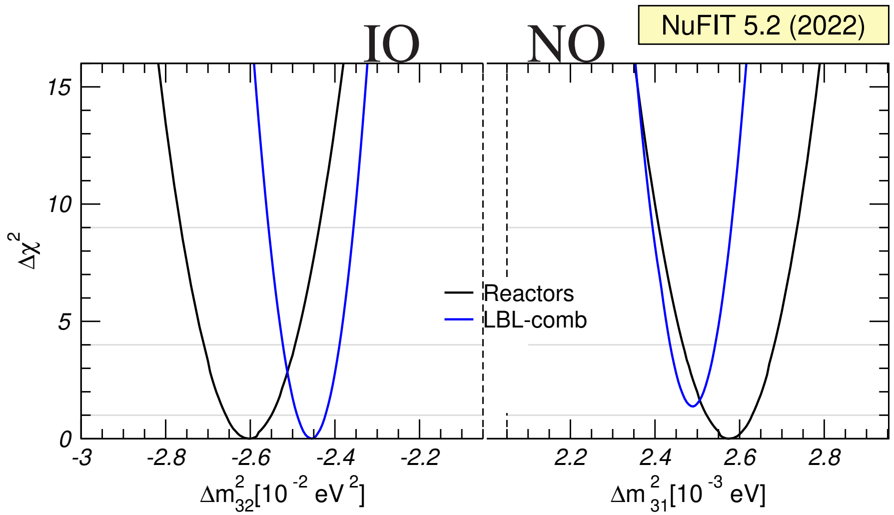
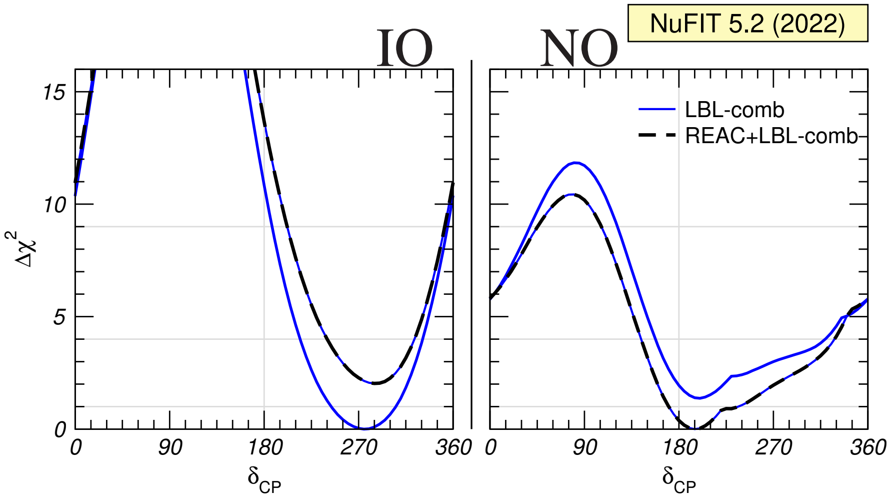


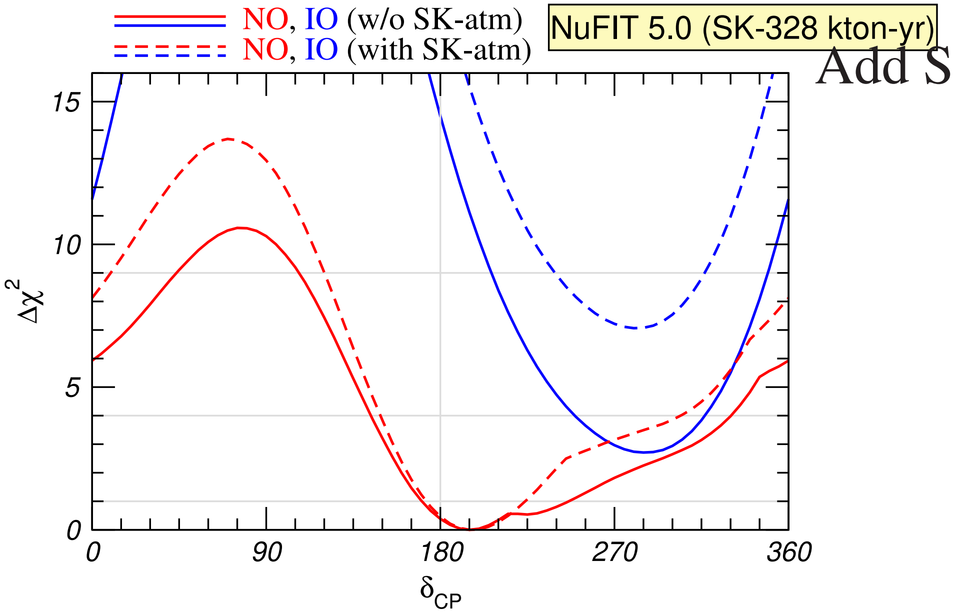




- T2K and NO$\nu$A more compatible in IO $\Rightarrow$ IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors
- in NO: b.f $\delta_{\rm CP} \sim 195^\circ$ $\Rightarrow$ CPC allowed at 0.6 $\sigma$
- in IO: b.f $\delta_{\rm CP} \sim 270^\circ$ $\Rightarrow$ CPC disfavoured at 3 $\sigma$

# Ordering and CPV including SK-ATM

ATM results added to global fit using SK $\chi^2$ tables

- NUFIT 5.0: included SK I-IV 328 kton-years table
- NUFIT 5.1 and 5.2: include SK I-IV 372.8 kton-years table
- NUFIT 5.3: include SK I-V 484 kton-years table




Add SK-atm table $\Rightarrow$ favouring of NO:

$$\Delta\chi^2_{\mathrm{NO-IO,w/o\ SK-atm}} = 2.3$$
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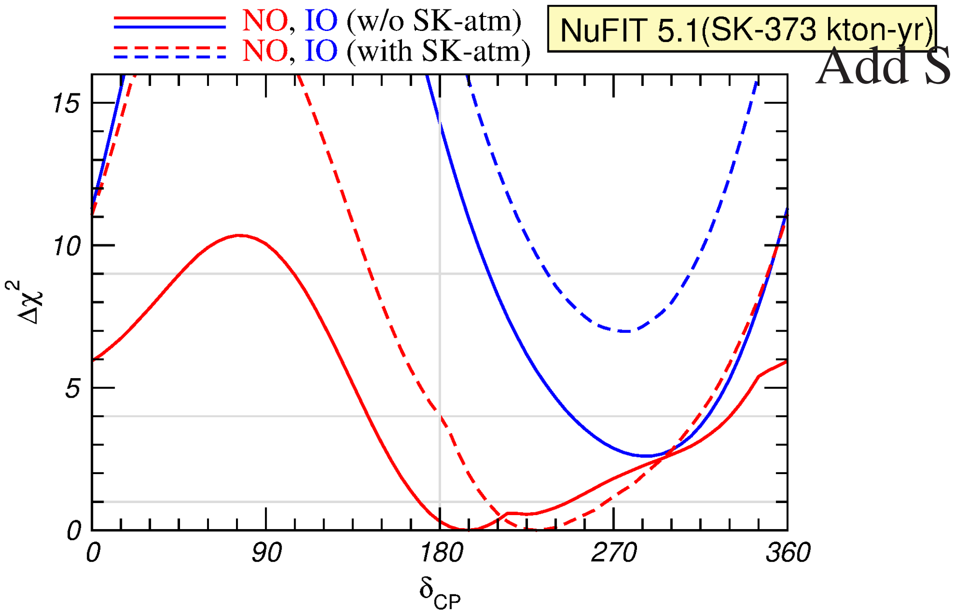


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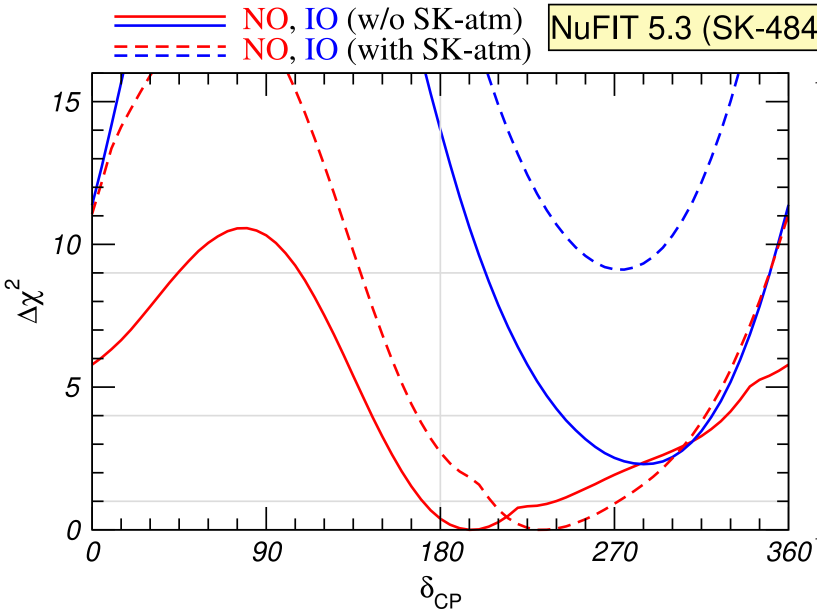


Add any SK-atm table⇒ favouring of NO:

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$$\Delta\chi^2_{\rm NO-IO,with\ SK-atm328} = 6.4$$
$$\Delta\chi^2_{\rm NO-IO,with\ SK-atm373} = 6.4$$
$$\Delta\chi^2_{\rm NO-IO,with\ SK-atm484} = 9.0$$

Add 373 (484) table ⇒ slight increase of signif of CPV in NO:

w/o SK-Atm b.f $\delta_{\rm CP} = 197°$ CPC at $0.6\sigma$

with SK-Atm: b.f $\delta_{\rm CP} = 232°$ CPC at $\sim 2\ (1.5)\sigma$

# *Confirmed* Low Energy Picture and MY List of Q&A

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    $\Rightarrow$ interplay of LBL/reactor/ATM results

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    – T2K and NO$\nu$A will run till $\sim$ 2027
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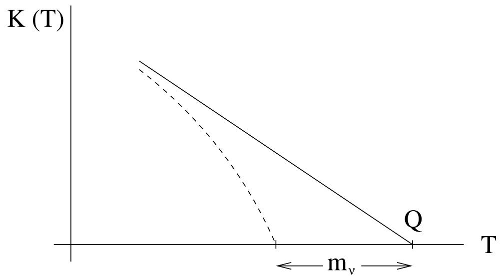
- Oscillations DO NOT determine the lightest mass

- Oscillations DO NOT distinguish Dirac/Majorana

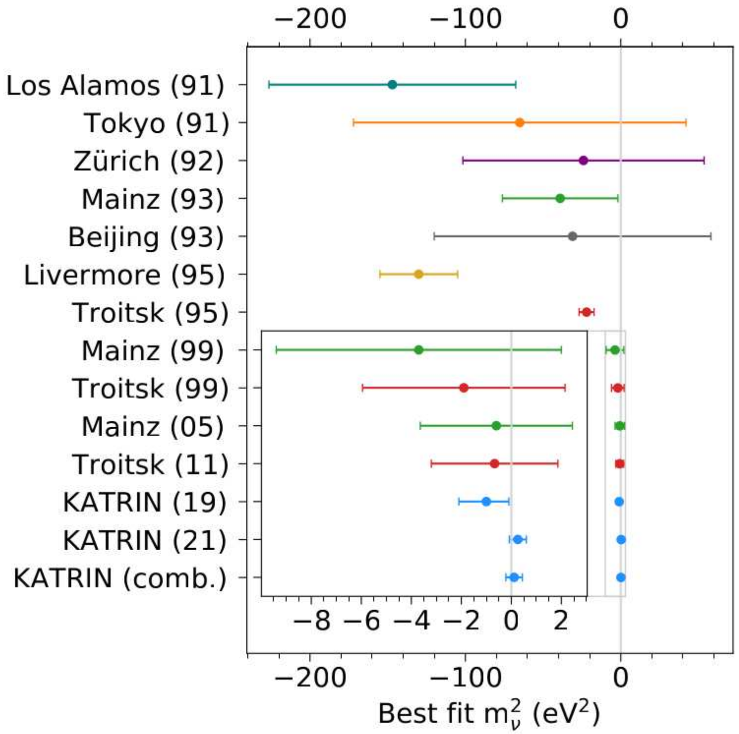
# Neutrino Mass Scale: $\beta$ Decay

Single $\beta$ decay : Dirac or Majorana $\nu$ mass modify spectrum endpoint




$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = c^2_{13} c^2_{12} m^2_1 + c^2_{13} s^2_{12} m^2_2 + s^2_{13} m^2_3$$

Purely kinematics $\Rightarrow$ Only model independent probe $\nu$-mass scale



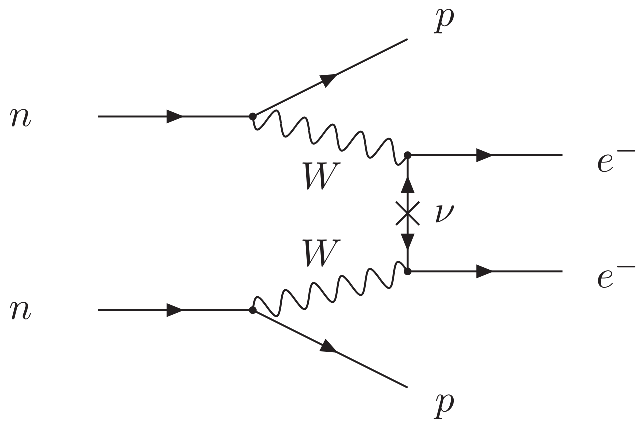

**KATRIN :** $m_{\nu_e} \leq 0.8$ eV **(at 90 % CL)**

arXiv:2105.08533

Future Katrin Sensitivity to $m_{\nu_e} \sim 0.2\,\text{eV}$

# Majorana or Dirac: $0\nu\beta\beta$ Decay

$0\nu\beta\beta \Rightarrow$ L violation $\Leftrightarrow$ Majorana $\nu$




Best bounds from

$^{136}$Xe (KamLAND-ZEN):

$$T_{1/2}^{0\nu,\mathrm{Xe}} > 2.3 \times 10^{26} \text{ yr at 90\%CL}$$

$^{76}$Ge (Gerda):

$$T_{1/2}^{0\nu,\mathrm{Ge}} > 1.8 \times 10^{26} \text{ yr at 90\%CL}$$

$^{130}$Te (Cuore):

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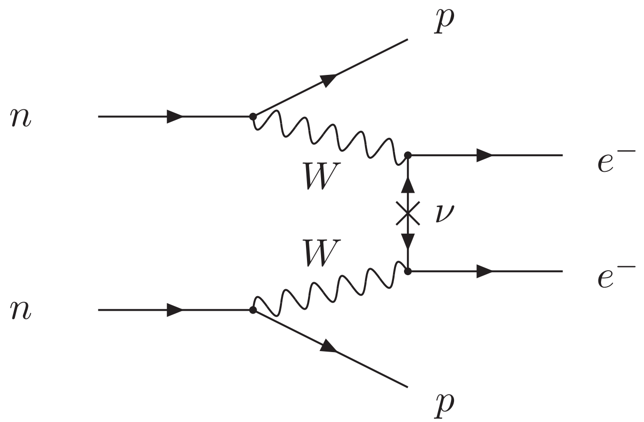


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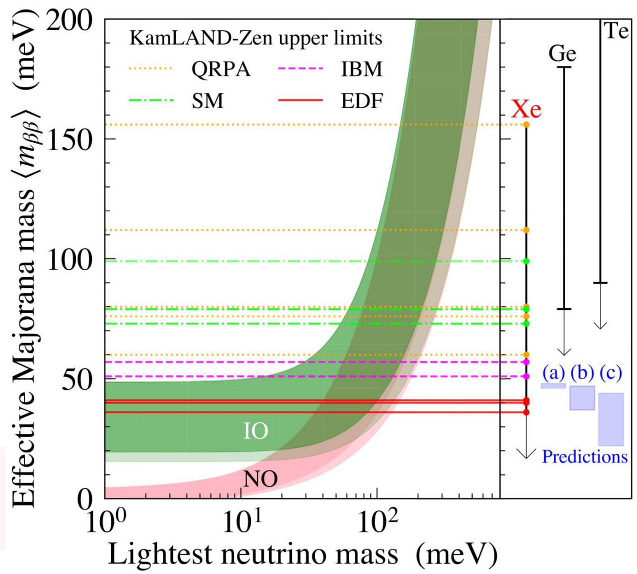
If $m_\nu$ only source of $\Delta L$

$$T_{1/2}^{0\nu} = \frac{m_e}{G_{0\nu}\, M_{\mathrm{nucl}}^2\, m_{ee}^2}$$

$$m_{ee} = |\sum U_{ej}^2 m_j|$$

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

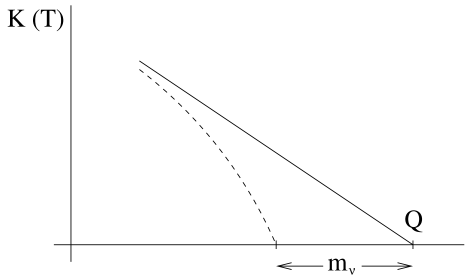
$= f(m_\ell$, order, maj phases$)$




KamLAND-Zen Coll. ArXiv:2203.02139

# Probes of Mass Scale in 3$\nu$-mixing

**Single $\beta$ decay** : Pure kinematics, Dirac or Majorana $\nu$'s, only model independent

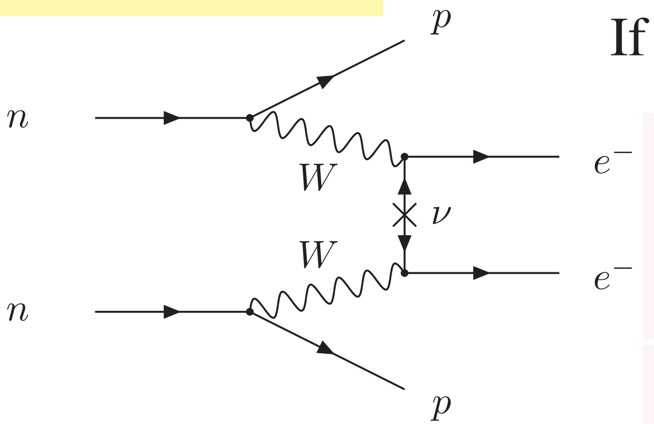



$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

Present bound: $m_{\nu_e} \leq 0.8$ eV (90% CL KATRIN 2021)

Katrin (20XX) Sensitivity to $m_{\nu_e} \sim 0.2$ eV

**$\nu$-less Double-$\beta$ decay:** $\Leftrightarrow$ Majorana $\nu' s$




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

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

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

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

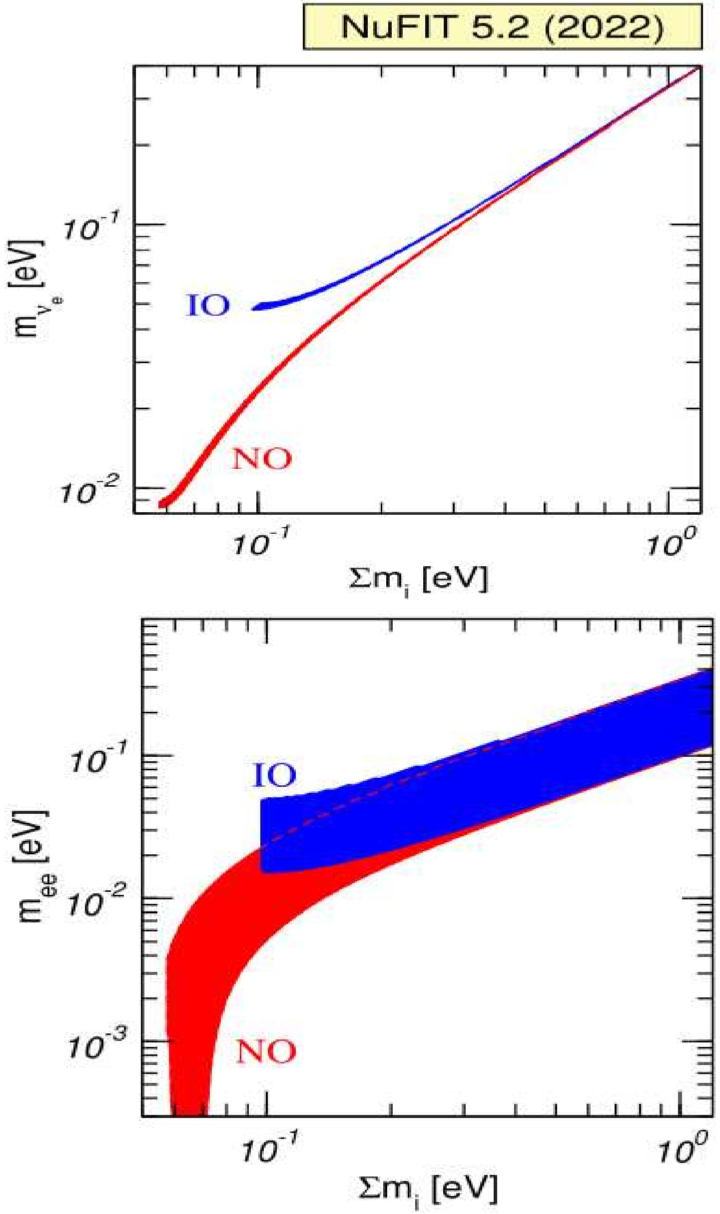
Present Bounds: $m_{ee} < 0.04$–$0.2$ eV

**COSMO** for Dirac or Majorana
$m_\nu$ affect growth of structures

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

# Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis$\Rightarrow$ Correlations $m_{\nu_e}$, $m_{ee}$ and $\sum m_\nu$( Fogli *et al* (04))



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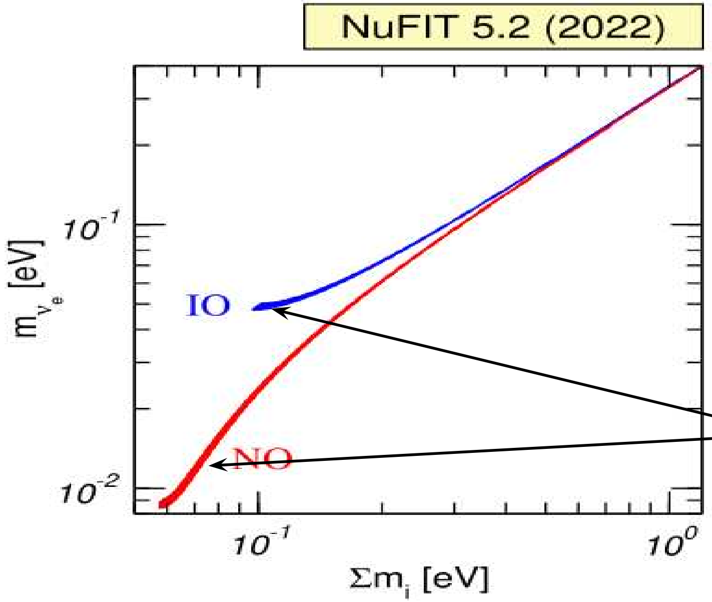
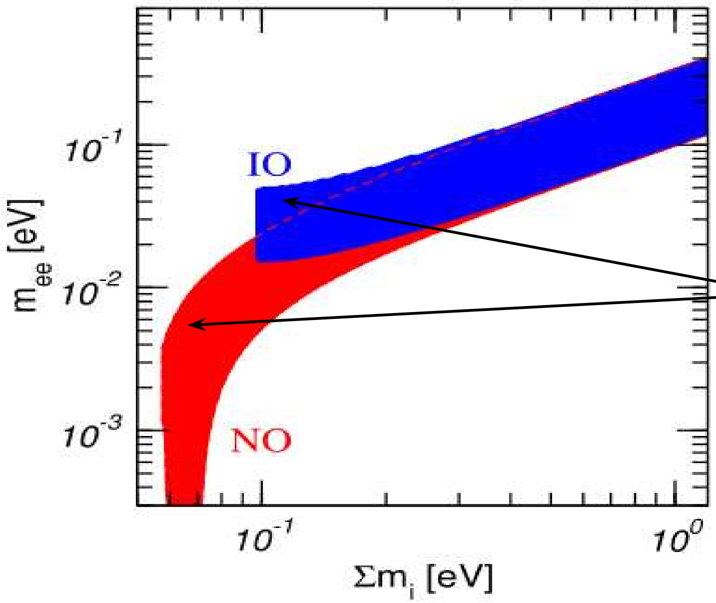



Width due to range in oscillation parameters very narrow

Lower bound on $\sum m_i$ depends on ordering




Wide band due to unknown Majorana phases ⇒

Possible Det of Maj phases?

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    $\Rightarrow$ definitive answer will likely require new experiments

- What about mass scale and Dirac vs Majorana?
  - Only model independent probe of $m_\nu$ $\beta$ decay: $\sum m_i^2 |U_{ei}|^2 \leq (0.8\text{ eV})^2$
  - Dirac or Majorana?: We do not know, *anxiously* waiting for $\nu$-less $\beta\beta$ decay
  - Cosmological effects?: Steadily improving bounds

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- Only three light states?

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

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

## LSND &MiniBoone

LSND 2001:

Signal $\nu_\mu \to \nu_e$ (3.8 $\sigma$)

MiniBooNE 2020:

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

(639 $\pm$ 132.8 events)

## Gallium Anomaly

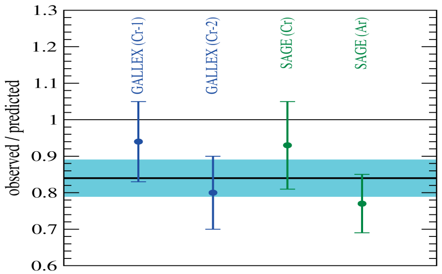
Acero, Giunti, Laveder, 0711.4222
Giunti, Laveder,1006.3244

Radioactive Sources ($^{51}$Cr, $^{37}$Ar)

in calibration of Ga Solar Exp;

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

Give a rate lower than expected



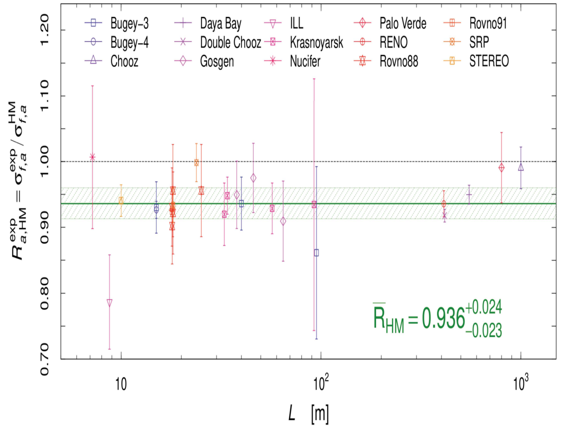

Explained as $\nu_e$ disappearance

## Reactor Anomaly (2011)

Huber, 1106.0687
Mention *etal* ,1101.2755

New reactor flux calculation

$\Rightarrow$ Deficit in data at $L \lesssim 100$ m

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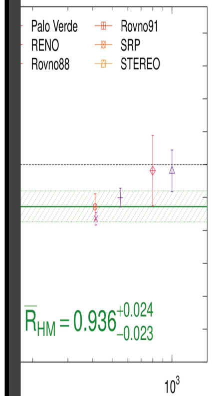
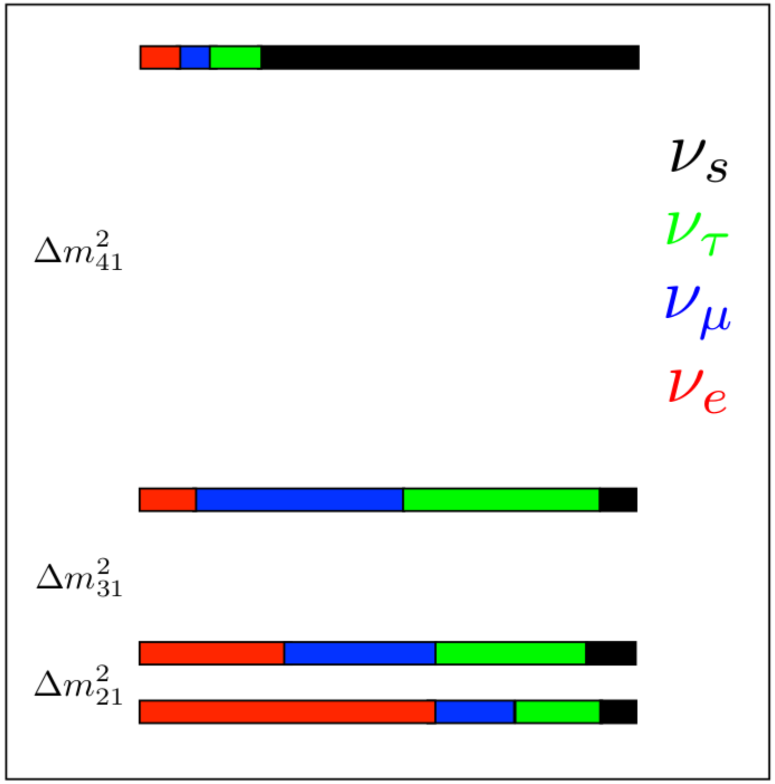



ppearance

Oscillation Interpretation Requires $\mathcal{O}$(eV) sterile $\nu$'s



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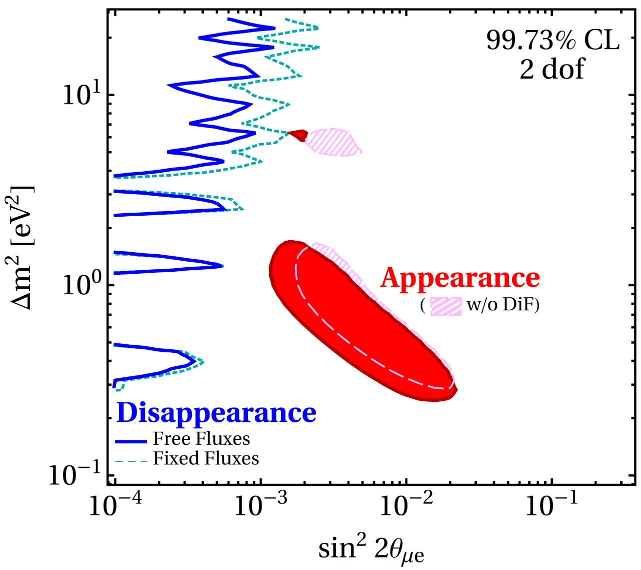
Strong tension with
non-obervation of $\nu_\mu$ dissap




Dentler etal, 1803.10661

Purely sterile oscillation
robustly disfavoured
additional SM or NP effects?

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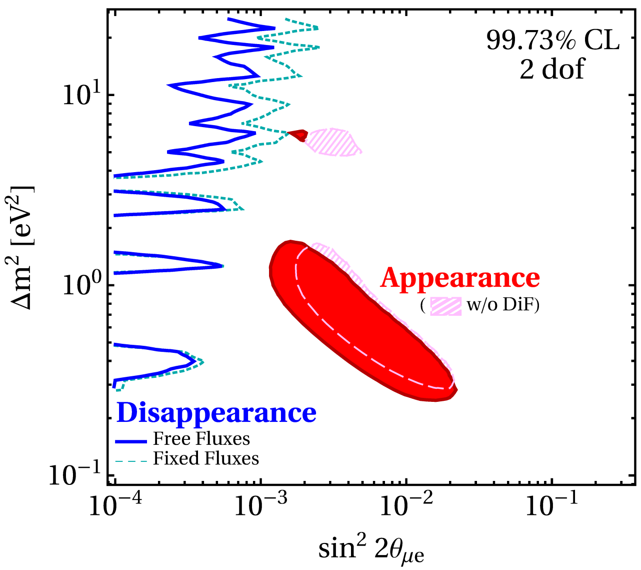


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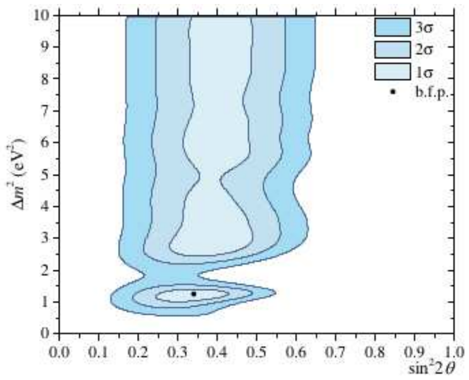
Rate lower than expected

Explained as $\nu_e$ disappearance

Confirming results from BEST

2109.11482




Requires large mixings

Ruled out/tension by solar and reactor

$\nu' s$

Goldhagen etal 2109.14898

Berryman etal 2111.12530

Giunti etal, 2209.00916

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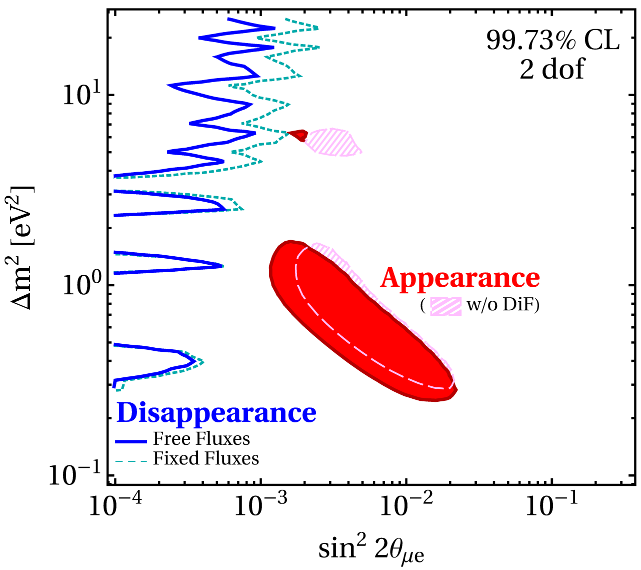


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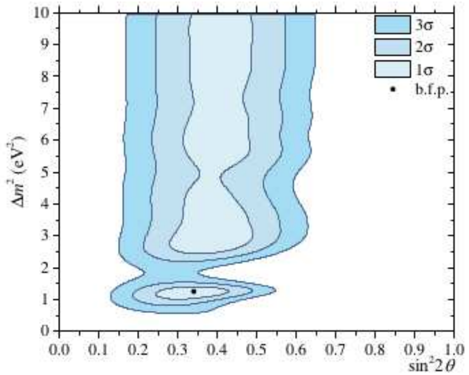


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Huber, 1106.068,Mention *etal* ,1101.2755

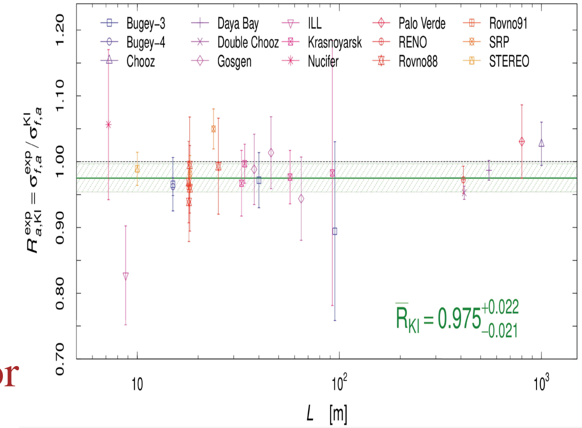
2011 reactor flux calculation $\Rightarrow$

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

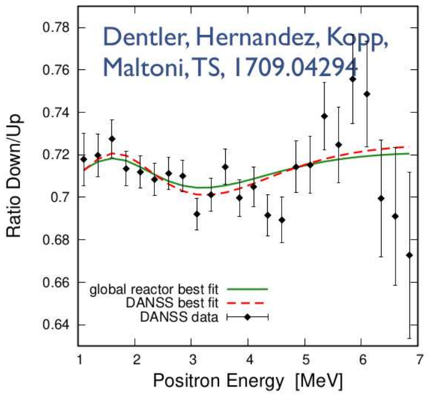



(Fig from Giunti etal, 2110.06820)

Anomaly $\sim 1\,\sigma$

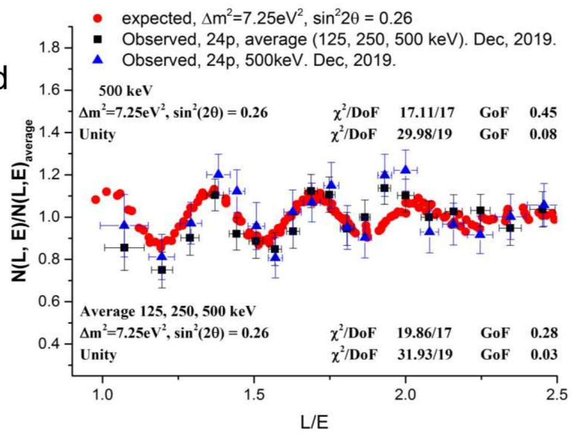
with new fluxes

# Recent relative spectral measurments

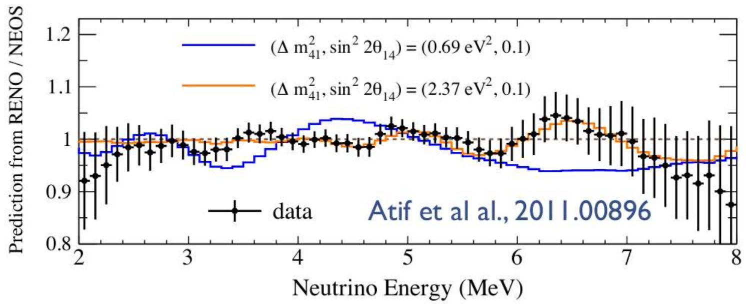



Neutrino4: segmented detector, L = 6.25 to 11.9 m, 216 bins in L/E „3σ“ indication

Neutrino4 2005.05301




DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20 (update at EPS-HEP21)




segmented detectors:
STEREO [arXiv:1912.06582]
L = 9 to 11 m $\Delta\chi^2$(no osc) ≈ 9
PROSPECT [arXiv:2006.11210]
L = 6.7 to 9.2 m

NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7



Spectral ratios at different baselines ⇒ Independent of flux normalizations.

But low statistical significance (Wilk's theorem fails) Berryman, etal 2111.12530
MC estimation of prob distribution ⇒ no significant indication of $\nu_s$ oscillations

# *Confirmed* Low Energy Picture and MY List of Q&A

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  Expected relevant result from:
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# Neutral Current Non Standard $\nu$ Interactions

- Effective Lagrangian

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

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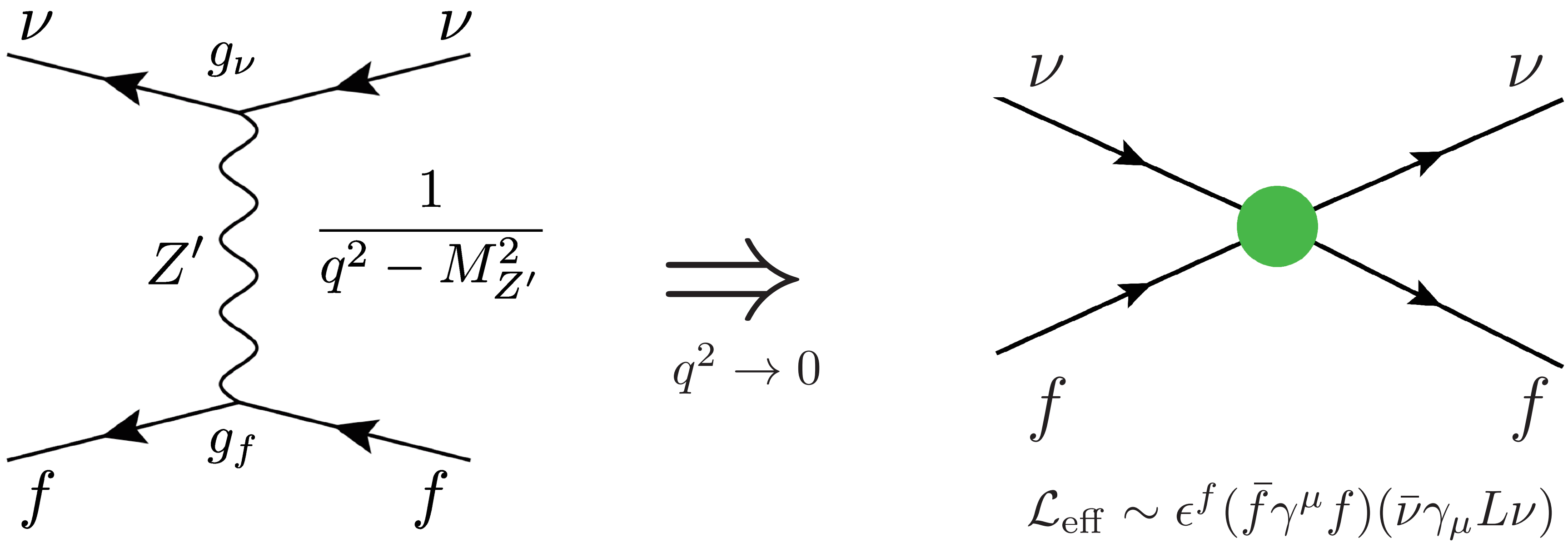
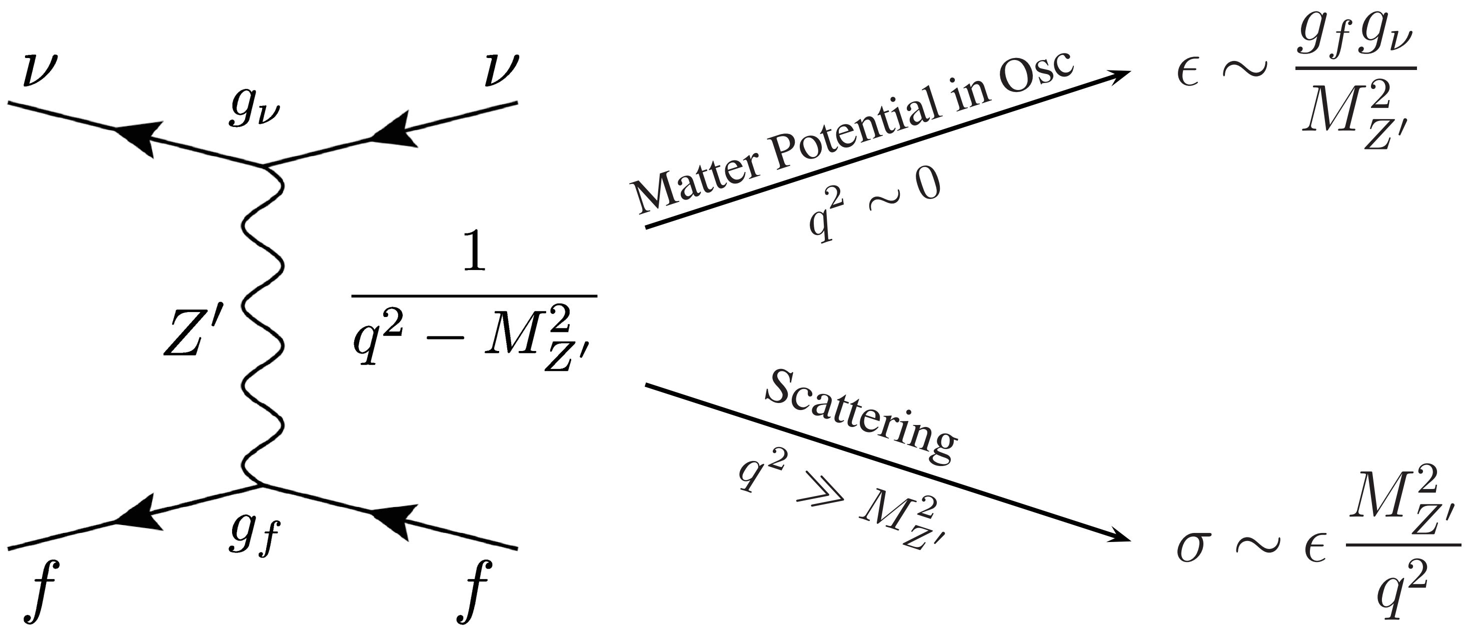
- Generically understood as:



# Neutral Current Non Standard $\nu$ Interactions

- Depending on $Z'$ (Mediator) Mass:




$\Rightarrow$ For mediator mass $\lesssim \mathcal{O}(10)'s$ MeV– GeV effects in scattering suppressed

# NSI in $\nu$ Oscillations : Degeneracies

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

Convention $U_{\rm vac} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\delta_{\rm CP}} & s_{13} \\ -s_{12}c_{23}e^{-i\delta_{\rm CP}} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23}e^{-i\delta_{\rm CP}} - c_{12}s_{13}c_{23} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix}$

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

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

| | | | |
|---|---|---|---|
| $\theta_{12} \to \frac{\pi}{2} - \theta_{12}$ | | $(\varepsilon_{ee}-\varepsilon_{\mu\mu}) \to -(\varepsilon_{ee}-\varepsilon_{\mu\mu}) - 2$ | 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) |
| $\delta \to \pi - \delta$ | | $\varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \quad (\alpha \neq \beta)$ | CPV confusion (ATM&LBL) |

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

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

# NSI in $\nu$-OSC: Global Analysis

- In matter with NSI: $i\frac{d}{dx}\vec{\nu} = H^\nu \vec{\nu}$ with $H^\nu = H_{\text{vac}} + H_{\text{mat}}^{\text{SM}} + H_{\text{mat}}^{\text{NSI}}$

$$H_{\text{mat}}^{\text{SM}} + H_{\text{mat}}^{\text{NSI}} \equiv \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 + \varepsilon_{ee} - \varepsilon_{\mu\mu} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & 0 & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} \end{pmatrix} \text{ with } \varepsilon_{\alpha\beta}(r) \equiv \sum_f \frac{N_f(r)}{N_e(r)} \varepsilon_{\alpha\beta}^f$$

$\Rightarrow$ $3\nu$ evolution depends on 6 (vac) + 8 [5 if real] per $f$ (mat) parameters $\Rightarrow$ Too many!!

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$\Rightarrow$ $3\nu$ evolution depends on 6 (vac) + 8 [5 if real] per $f$ (mat) parameters $\Rightarrow$ Too many!!

– Start assuming NSI with $f = u$ OR $f = d$

$\Rightarrow$ NSI only affect matter effects MCGG M.Maltoni, J. Salvado 1103.4265;MCG-G M.Maltoni, 1307.3092

– Introduce couplings to general combination of u and d quarks

$$\varepsilon^f_{\alpha\beta} = \xi^f(\eta)\varepsilon_{\alpha\beta} \quad \text{with} \quad \xi^p = \sqrt{5}\cos\eta \qquad \xi^n = \sqrt{5}\sin\eta$$

$\Rightarrow$ NSI still only affect matter effects Esteban etal 1805.04530, Coloma eta 1911.09109

– Introduce couplings to general combinatins of u and d quarks and electrons

$$\varepsilon^f_{\alpha\beta} = \xi^f(\eta,\zeta)\varepsilon_{\alpha\beta} \quad \text{with} \quad \xi^e = \sqrt{5}\cos\eta\sin\zeta \qquad \xi^p = \sqrt{5}\cos\eta\cos\zeta \qquad \xi^n = \sqrt{5}\sin\eta$$

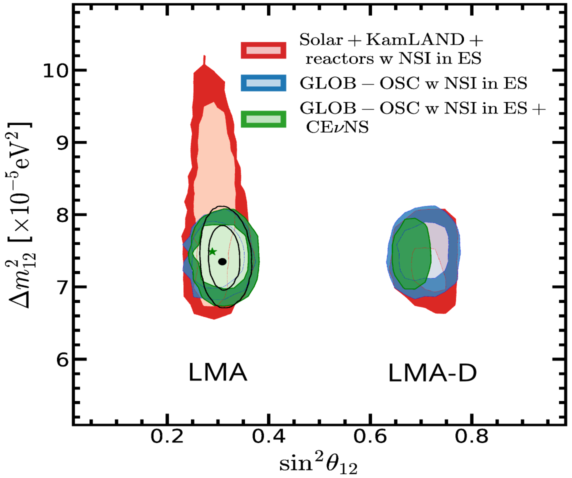
$\Rightarrow$ If $M_{\rm med} \gtrsim 0.5$ MeV NSI with $e^-$ can also affect ES (SK, SNO, Borexino)

Coloma eta 2305.07698

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

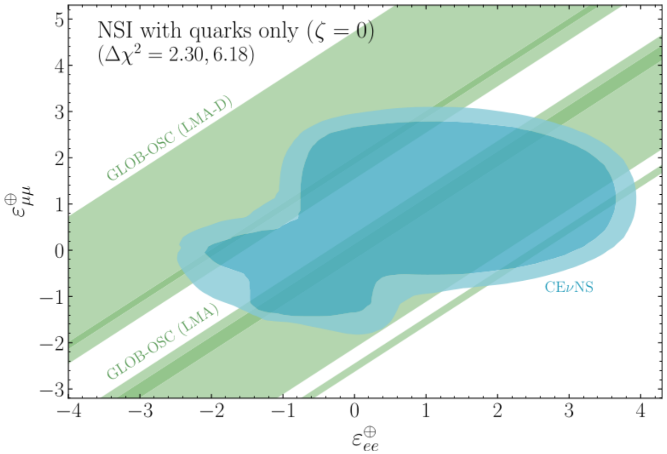
With most general couplings:

– LMA-D allowed by oscillations




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

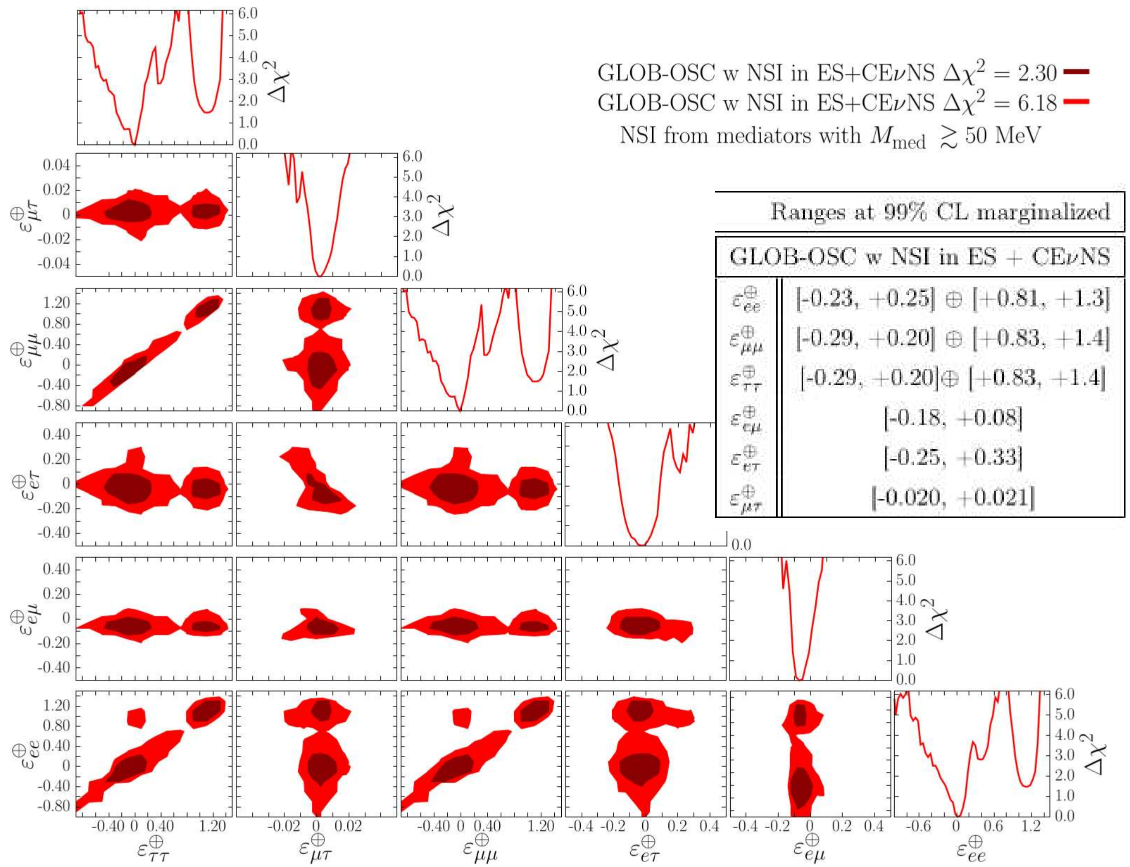
$\Rightarrow$ LMA-D only above $2\sigma$




Still important bounds on the NSI's

$\Rightarrow$ Maximum effect at future LBL experiments

$$\varepsilon^\oplus_{\alpha\beta} = \varepsilon^e_{\alpha\beta} + (2 + Y^\oplus_n)\varepsilon^u_{\alpha\beta} + (1 + 2Y^\oplus_n)\varepsilon^d_{\alpha\beta}$$




| Ranges at 99% CL marginalized | |
|---|---|
| | GLOB-OSC w NSI in ES + CE$\nu$NS |
| $\varepsilon^\oplus_{ee}$ | [-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

# Bounds on $Z'$ Models

Coloma, MCGG, Maltoni ArXiv:2009.14220

$$\mathcal{L}_{\nu\text{prop}}^{Z'} = -g' \left( a_u \, \bar{u}\gamma^\alpha u + a_d \, \bar{d}\gamma^\alpha d + a_e \, \bar{e}\gamma^\alpha e + b_e \, \bar{\nu}_e \gamma^\alpha P_L \nu_e + b_\mu \, \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu + b_\tau \, \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau \right) Z'_\alpha$$

We can map $\mathcal{L}_{\nu\text{prop}}^{Z'}$ to

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

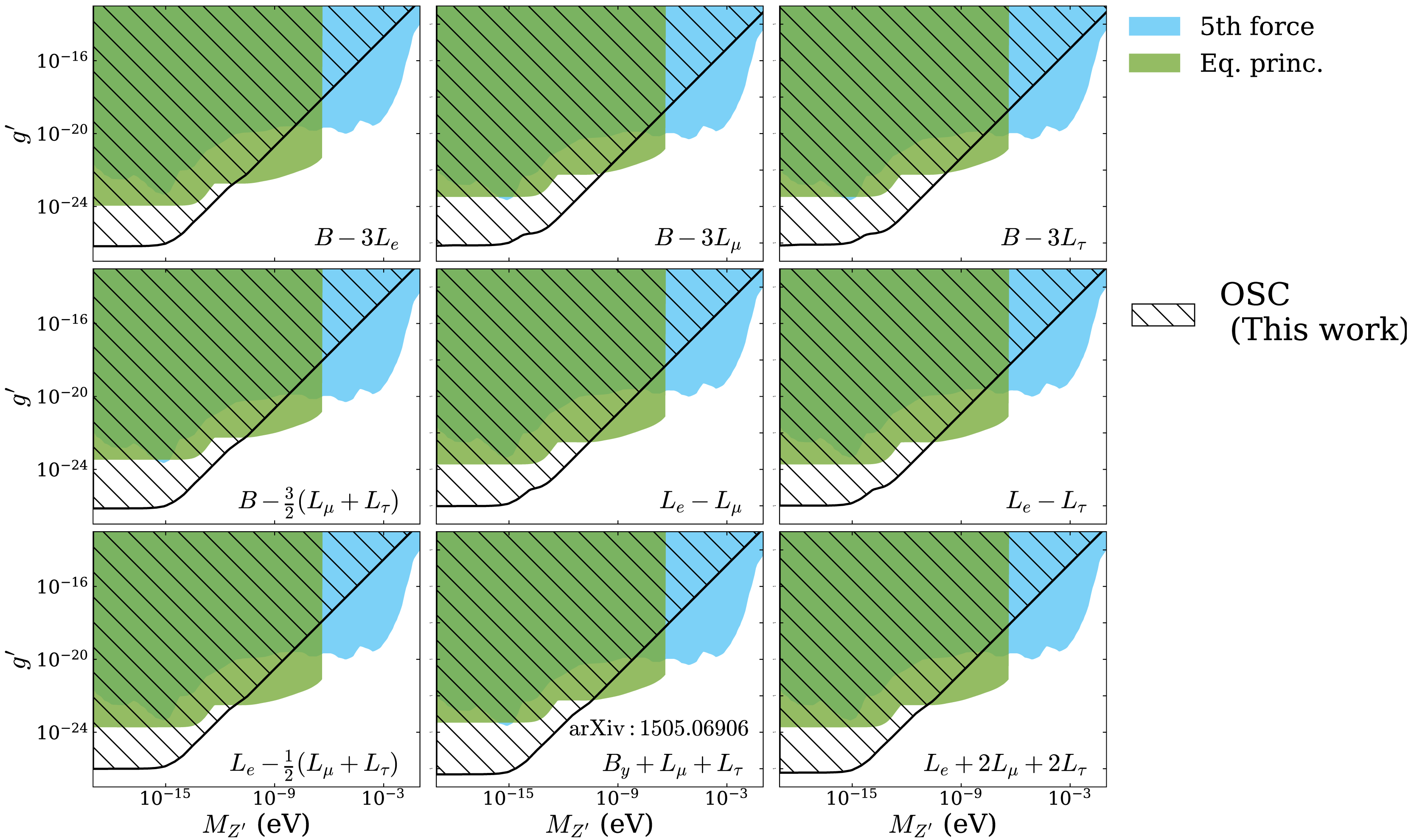
with

$$\varepsilon_{\alpha\beta}^f = \delta_{\alpha\beta} \, a_f \, b_\alpha \, \varepsilon^0 \quad \text{with} \quad \varepsilon^0 = \frac{1}{\sqrt{2} G_F} \frac{g'^2}{M_{Z'}^2}$$

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

# $Z'$/Dark-photon: Bounds from $\nu$ Oscillations

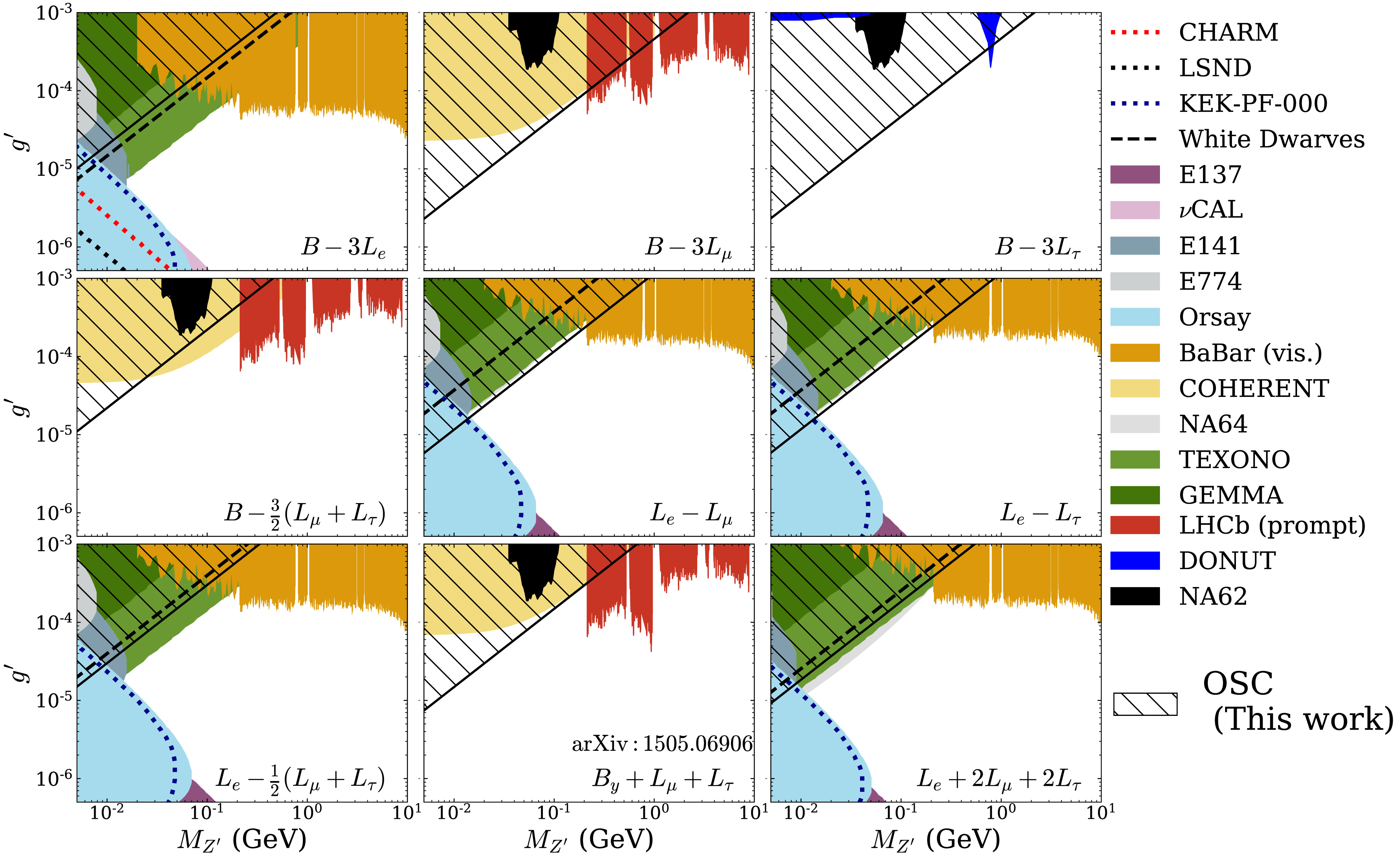
Very light ($M' \lesssim \mathcal{O}(\mathrm{eV})$) mediator $\Rightarrow$ Contact Interaction to Long Range Force




Coloma, MCGG, Maltoni ArXiv:2009.14220

# $Z'$ Models: $\nu$ Oscillations Bounds

$M_{Z'} \gtrsim \mathcal{O}(\text{MeV}) \Rightarrow$ Contact Interaction in $H_{\text{mat}}$




Coloma, MCGG, Maltoni ArXiv:2009.14220

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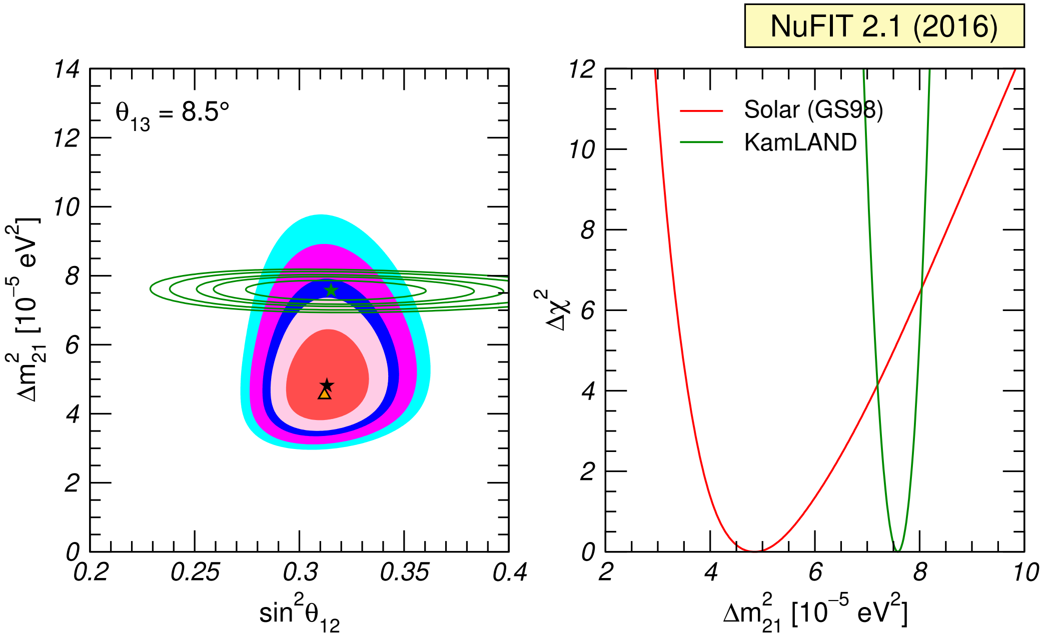
- Other NP at play?
  - L$\alpha$-dependent or $\nu$-helicity-flipping NP$\Rightarrow$ modified matter potential $\Rightarrow$ Bounds
  - Most relevant bounds for scenarios with extra-light mediators

MCG-G work funded by USA-NSF grant PHY-2210533 and by the European Union's through the Horizon 2020 research and innovation program (Marie Skłodowska-Curie grant agreement 860881-HIDDeN) and the Horizon Europe research and innovation programme (Marie Skłodowska-Curie Staff Exchange grant agreement 101086085-ASYMMETRY), and by MCIN/AEI/10.13039/501100011033 grant PID2022-126224NB-C21 and Excellence Maria de Maeztu 2020-2023" award to the ICC-UB CEX2019-000918-M, as well as from grant 2021-SGR-249 (Generalitat de Catalunya).

# Backup Slides

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

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

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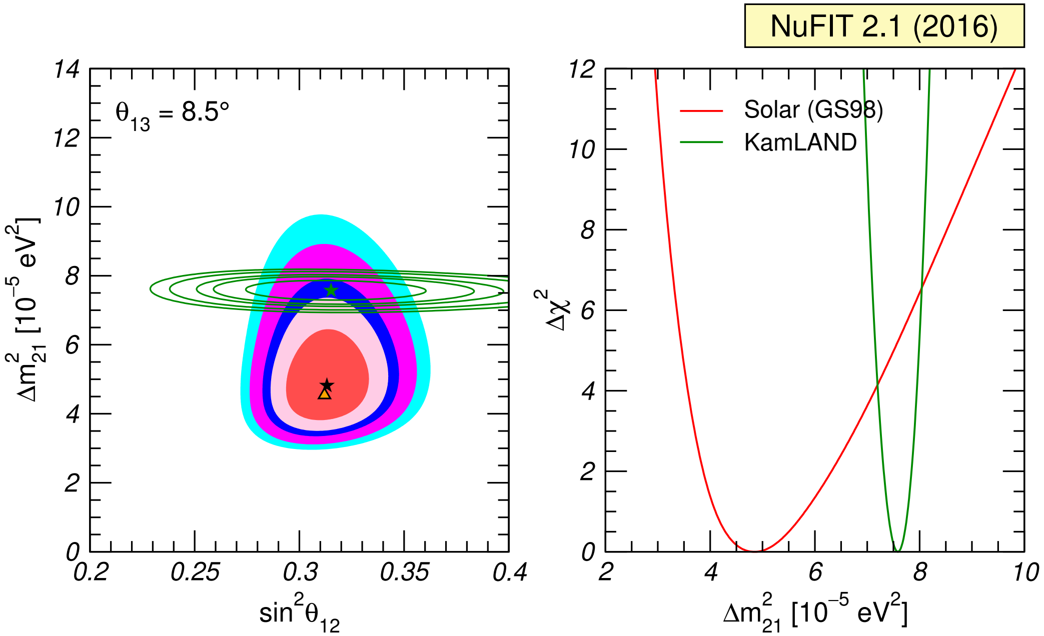


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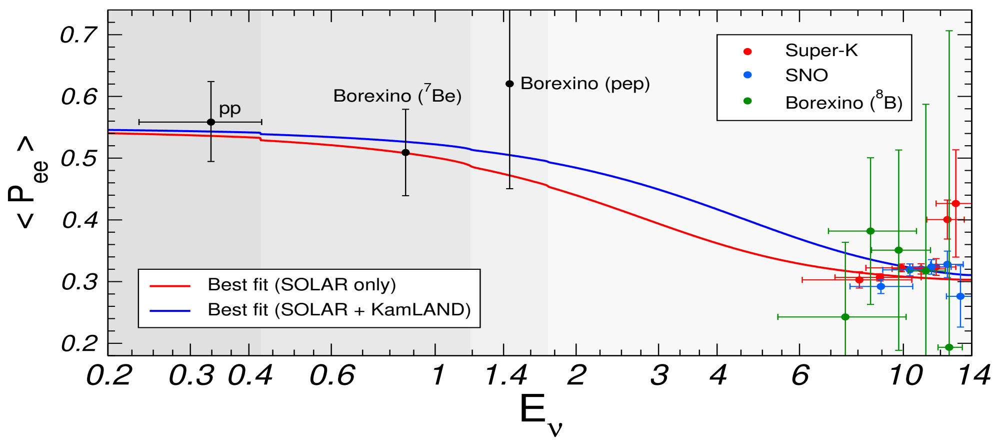
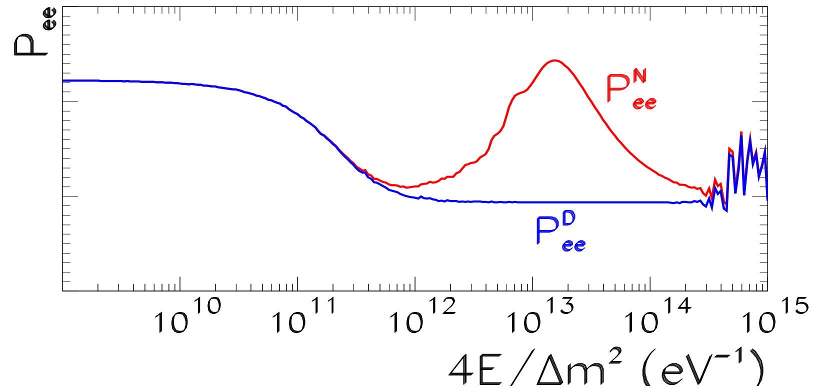
Smaller-than-expected MSW low-E turn-up in SK/SNO spectrum at global b.f.

"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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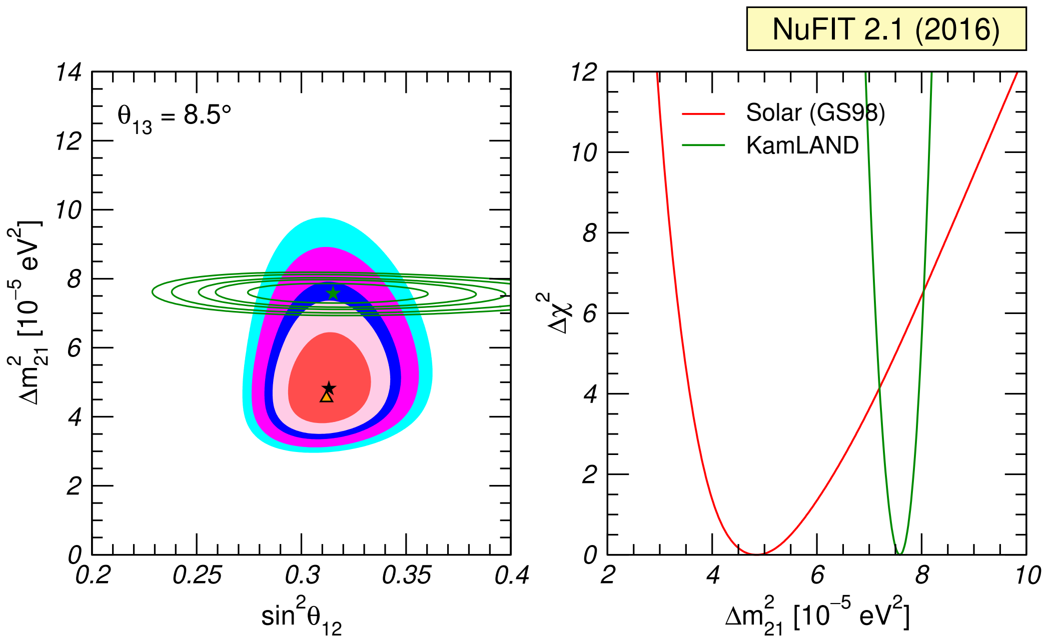


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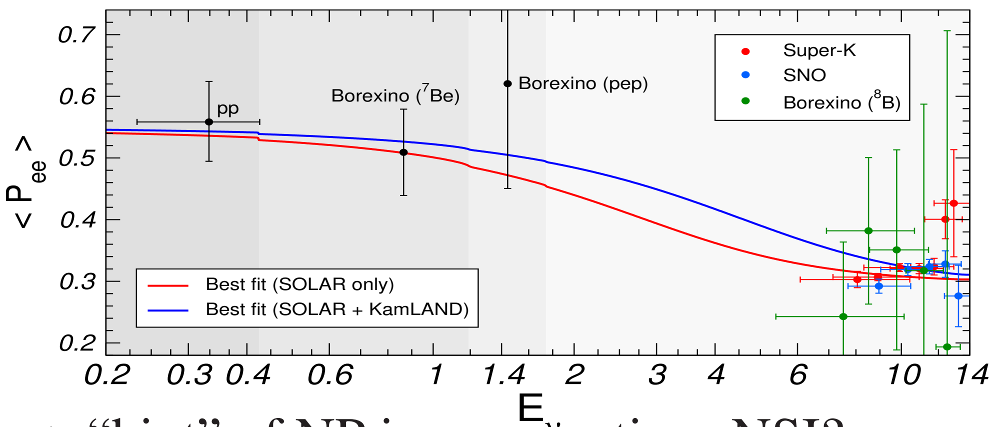
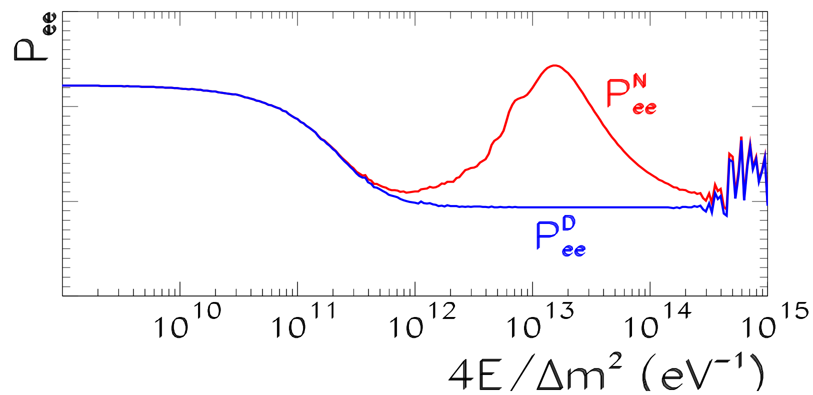
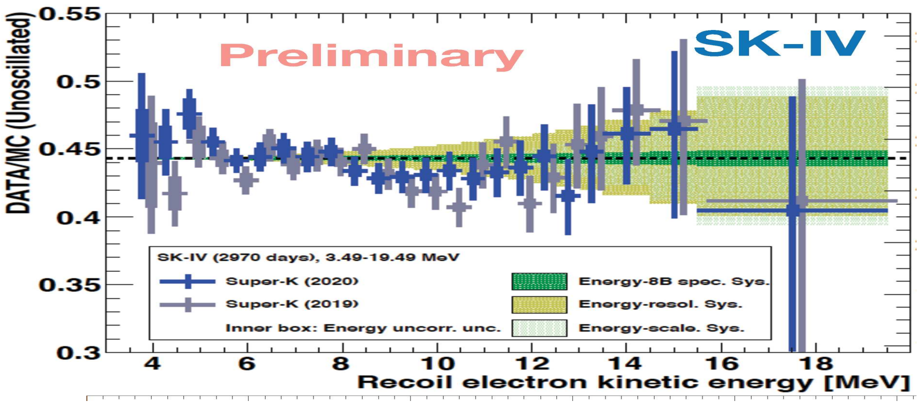



$\Rightarrow$ "hint" of NP in propagation: NSI?

• AFTER NU2020: With SK4 2970 days data

Slightly more pronounced low-E turn-up

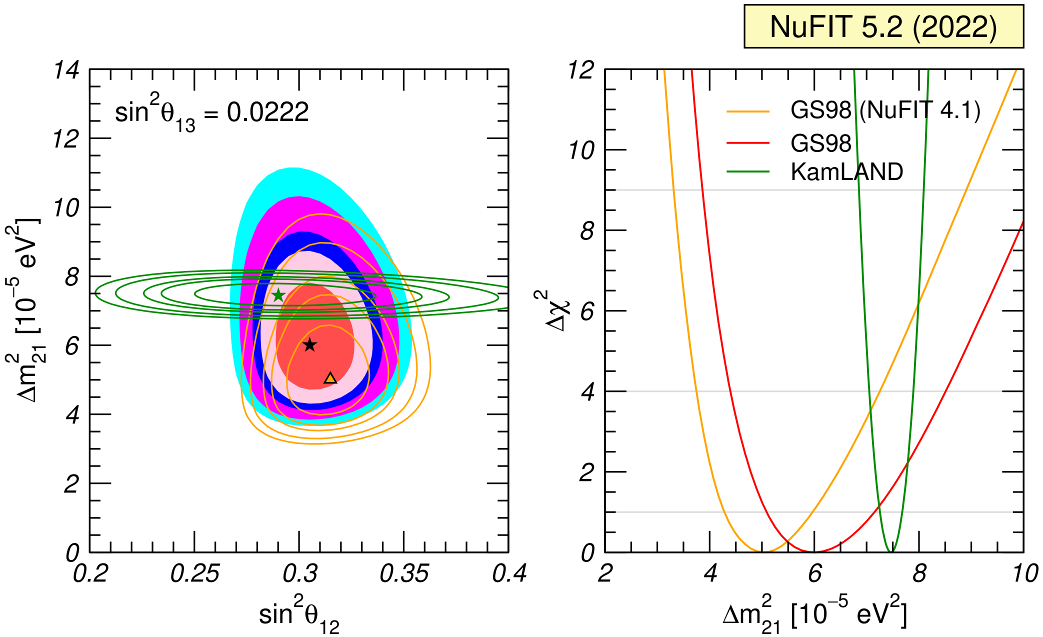



Smaller of Day/Night at

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

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

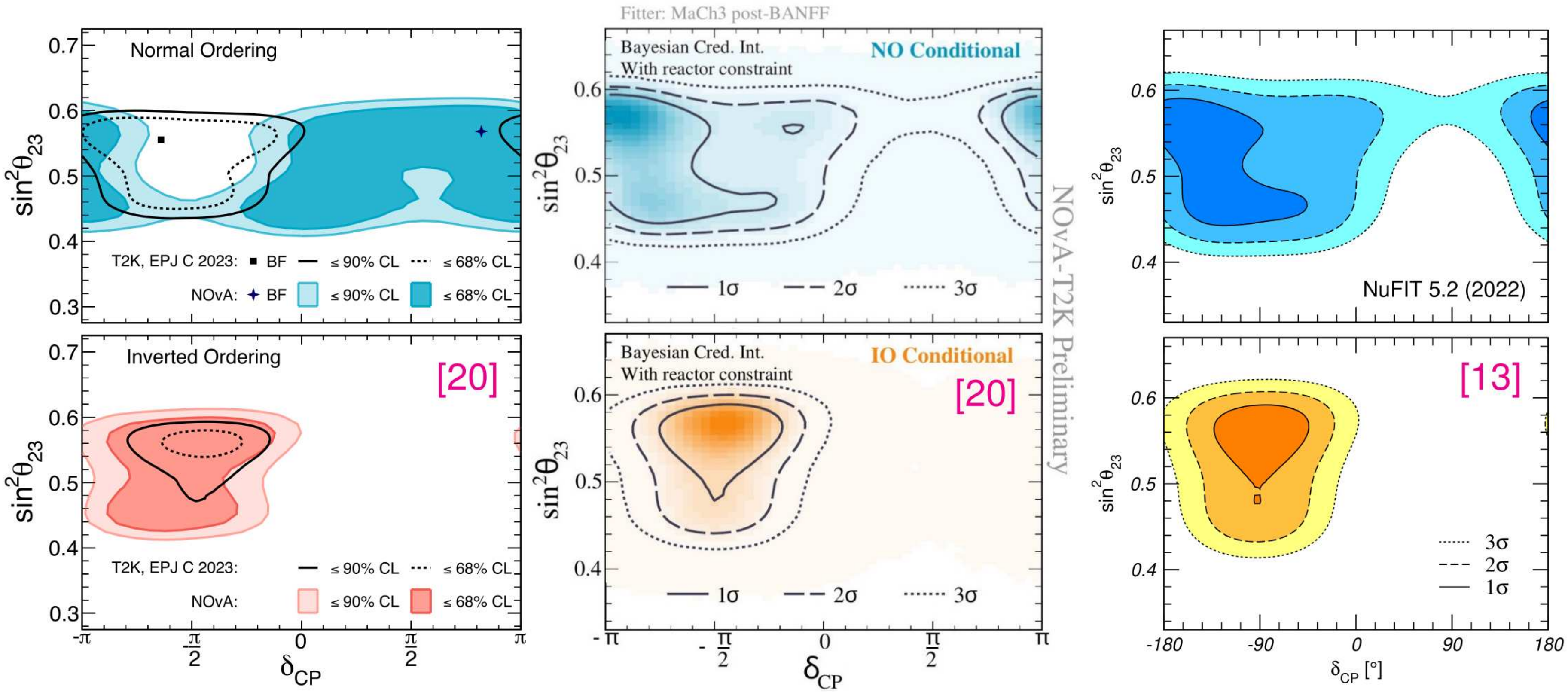
• In NuFIT 5.2




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

# Tension between NOvA and T2K data

- Neutrino 2020: tension on $\delta_{CP}$ between T2K and NOvA for **NO** (no problem for **IO**);
- official joint T2K/NOvA analysis finally presented [20], results very similar to estimates [13].





[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].

# $\Delta m^2_{3l}$ in LBL & Reactors

- At LBL determined in $\nu_\mu$ and $\bar\nu_\mu$ disappearance spectrum

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

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar\nu_e$ disapp spectrum

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

Nunokawa,Parke,Zukanovich (2005)

$\Rightarrow$ Contribution to NO/IO from combination of LBL with reactor data

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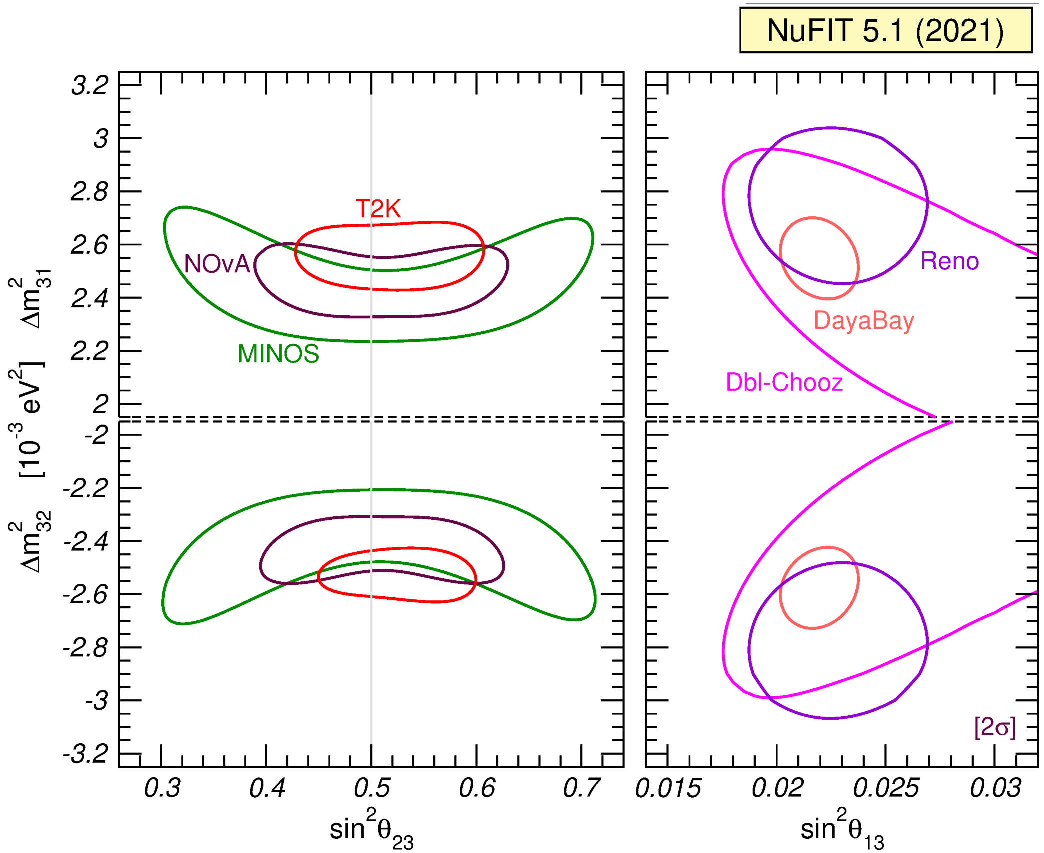


# Beyond 3$\nu$'s: Light Sterile Neutrinos



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

LSND &MiniBoone

LSND 2001:

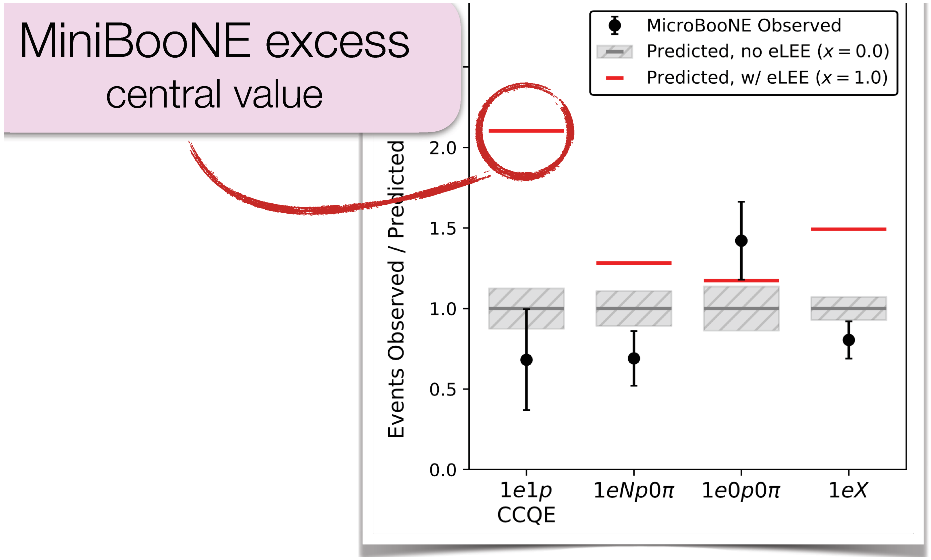
Signal $\nu_\mu \to \nu_e$ (3.8 $\sigma$)

MiniBooNE 2020:

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

($639 \pm 132.8$ events)

MicroBooNE 2021/2022:




No support for excess $\nu_e$ interpretation in MiniBooNE

(Fig from Kopp's $\nu$2022 talk)

MicroBooNE Coll.

2110.14054

# *Near* Future for CP and Ordering: Strategies

- $\nu/\bar\nu$ 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)

$$P_{\mu e} \simeq s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\Delta_{31} \pm V}\right)^2 \sin^2\left(\frac{\Delta_{31} \pm V\, L}{2}\right)$$
$$+8\, J_{\rm CP}^{\rm max}\, \frac{\Delta_{12}}{V}\, \frac{\Delta_{31}}{\Delta_{31} \pm V} \sin\left(\frac{V L}{2}\right) \sin\left(\frac{\Delta_{31} \pm V L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$J_{\rm CP}^{\rm max} = c^2_{13} s_{13} c_{23} s_{23} c_{12} s_{12}$$

– Challenge: Parameter degeneracies, Normalization uncertainty, $E_\nu$ reconstruction

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- Reactor experiment at $L \sim 60$ km (vacuum) able to observe the difference between oscillations with $\Delta m^2_{31}$ and $\Delta m^2_{32}$: JUNO, RENO-50

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

  – Challenge: Energy resolution

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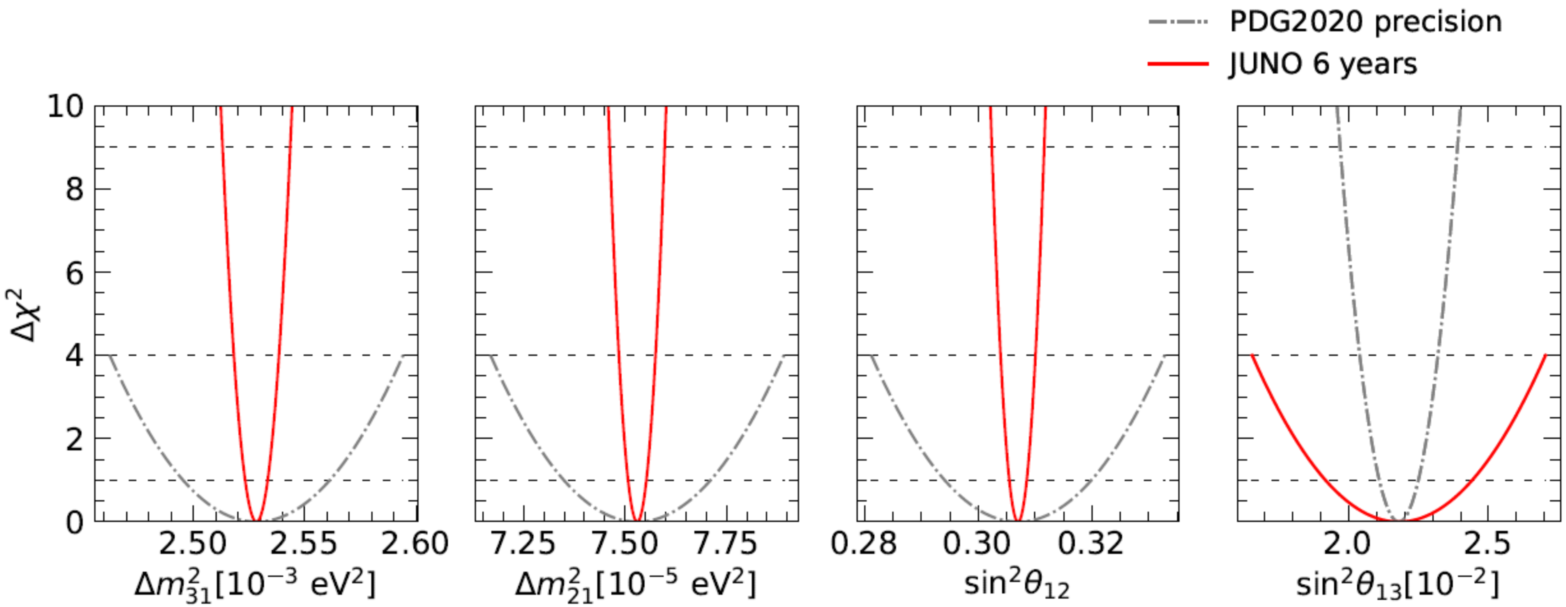
- Earth matter effects in large statistics ATM $\nu_\mu$ disapp : HK,INO, PINGU,ORCA ...
  – Challenge: ATM flux contains both $\nu_\mu$ and $\bar\nu_\mu$, ATM flux uncertainties

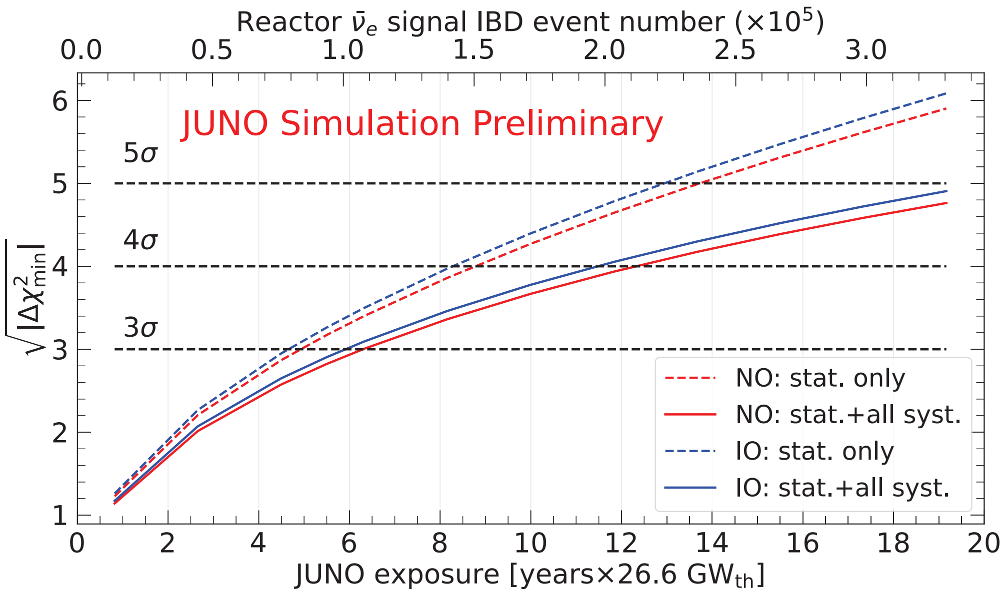
# JUNO: Sensitivity to Oscillation Parameters

| | Central Value | PDG2020 | 100 days | 6 years | 20 years |
|---|---|---|---|---|---|
| $\Delta m^2_{31}$ ($\times 10^{-3}$ eV$^2$) | 2.5283 | $\pm$0.034 (1.3%) | $\pm$0.021 (0.8%) | $\pm$0.0047 (0.2%) | $\pm$0.0029 (0.1%) |
| $\Delta m^2_{21}$ ($\times 10^{-5}$ eV$^2$) | 7.53 | $\pm$0.18 (2.4%) | $\pm$0.074 (1.0%) | $\pm$0.024 (0.3%) | $\pm$0.017 (0.2%) |
| $\sin^2\theta_{12}$ | 0.307 | $\pm$0.013 (4.2%) | $\pm$0.0058 (1.9%) | $\pm$0.0016 (0.5%) | $\pm$0.0010 (0.3%) |
| $\sin^2\theta_{13}$ | 0.0218 | $\pm$0.0007 (3.2%) | $\pm$0.010 (47.9%) | $\pm$0.0026 (12.1%) | $\pm$0.0016 (7.3%) |



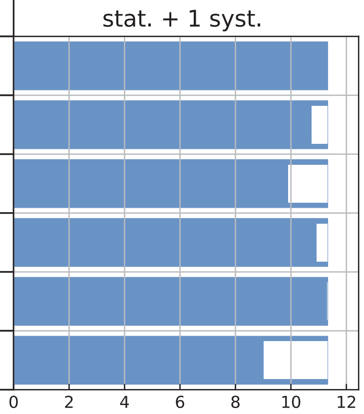

2204.13249

# Sensitivity to Neutrino Mass Ordering




Impact of systematics:

| | $\Delta\chi^2_{\rm min}$ |
|---|---|
| Statistics | 11.3 |
| Stat.+Flux error | -0.6 |
| Stat.+Backgrounds | -1.4 |
| Stat.+Nonlinearity | -0.4 |
| Stat.+Others | < -0.05 |
| Total | 9.0 |




JUNO Simulation Preliminary

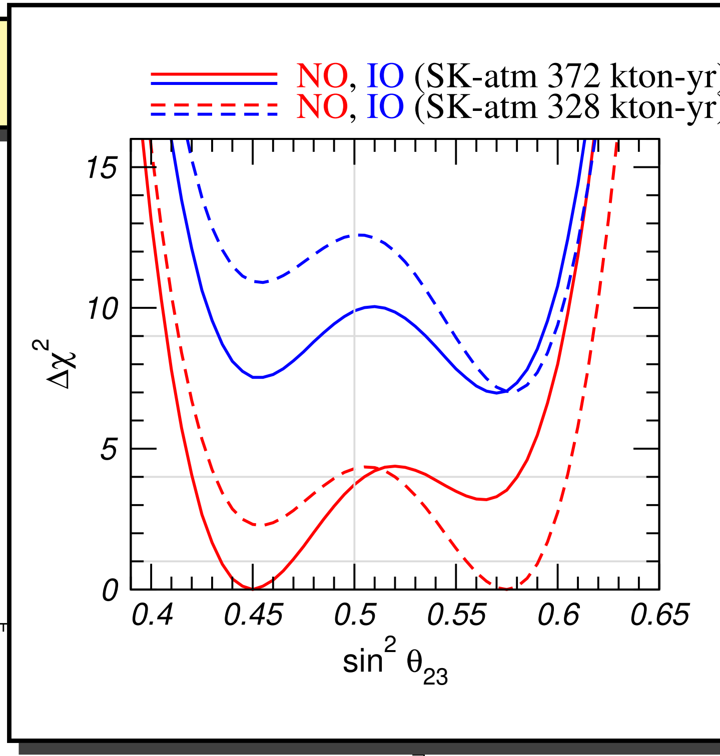
- ✓ JUNO+TAO, 6 years×26.6 GW exposure: $\sim 3\sigma$
- ✓ +1% external constrain on $\Delta m^2_{32}$: $> 4\sigma$
- ✓ combined with accelerator/atmospheric experiment: $> 5\sigma$

  $\hookrightarrow$ sensitivity boost due to tension for wrong ordering

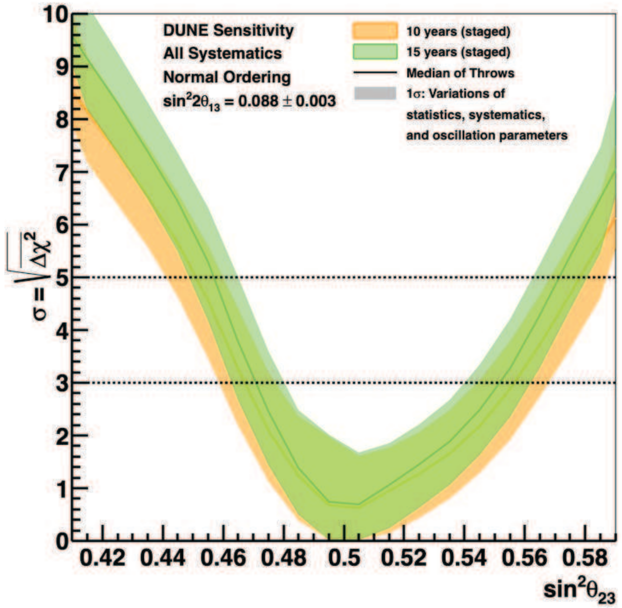
- Paper under preparation.
- Combination of reactor and atmospheric channels within JUNO is investigated.

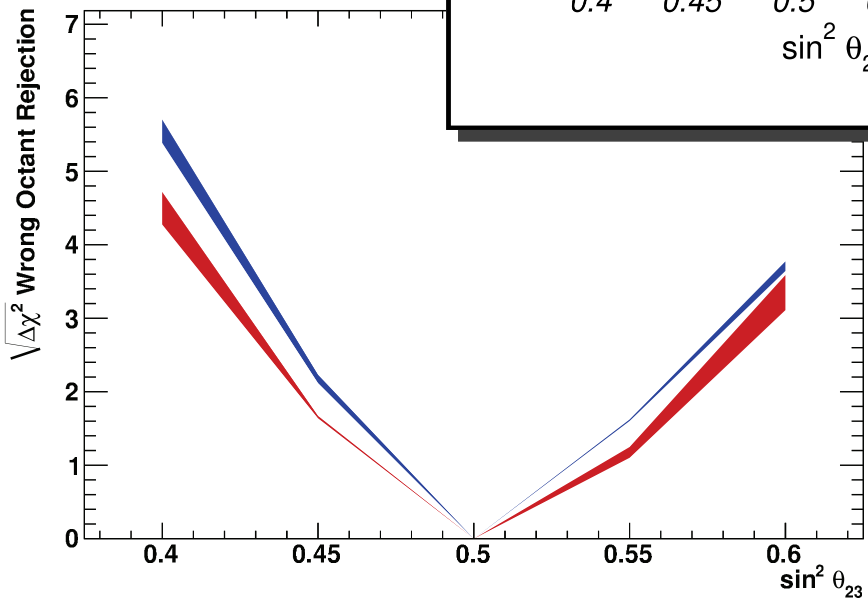
Extra [2008.11280], JUNO+IceCube [1911.06745]

# DUNE & Hyper-Kamiokande: $\theta_{23}$




$\theta_{23}$ octant: future sensitivities




$\sim 3-5\sigma$

DUNE 2002.03005

Beam+Atm$\Rightarrow\sim 3-6\sigma$

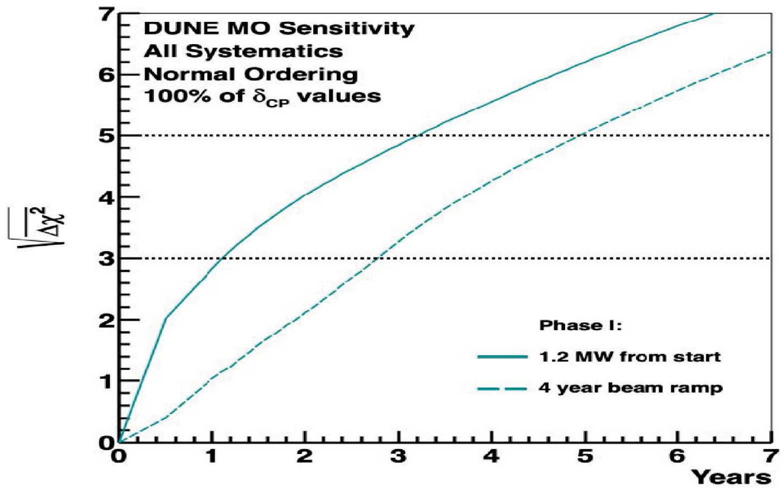
HK 1805.04163

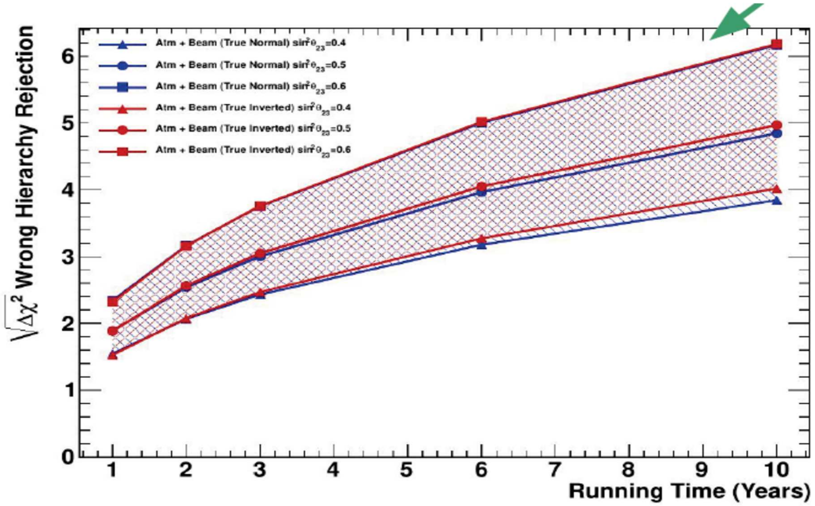
# DUNE & Hyper-Kamiokande: CPV and MO

## Mass Ordering

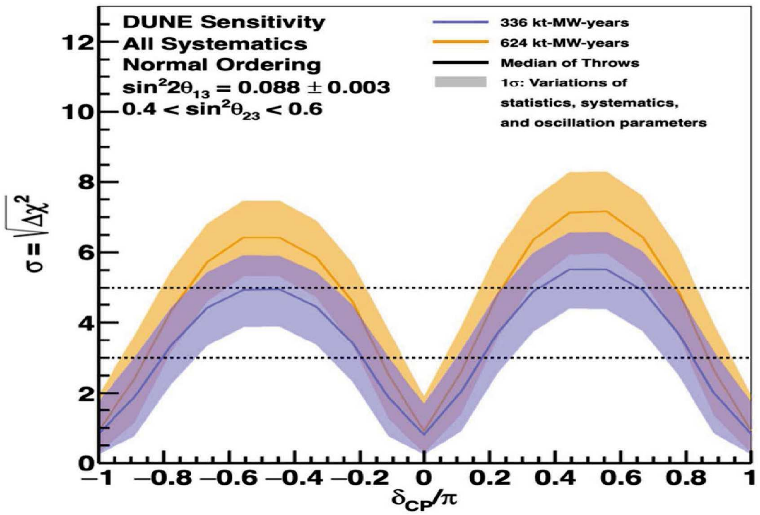
DUNE

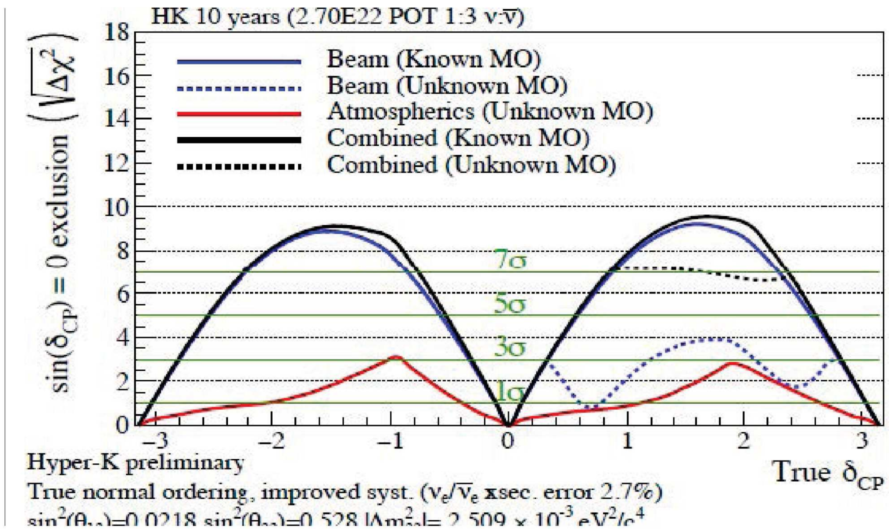
Hyper-Kamiokande




## CPV



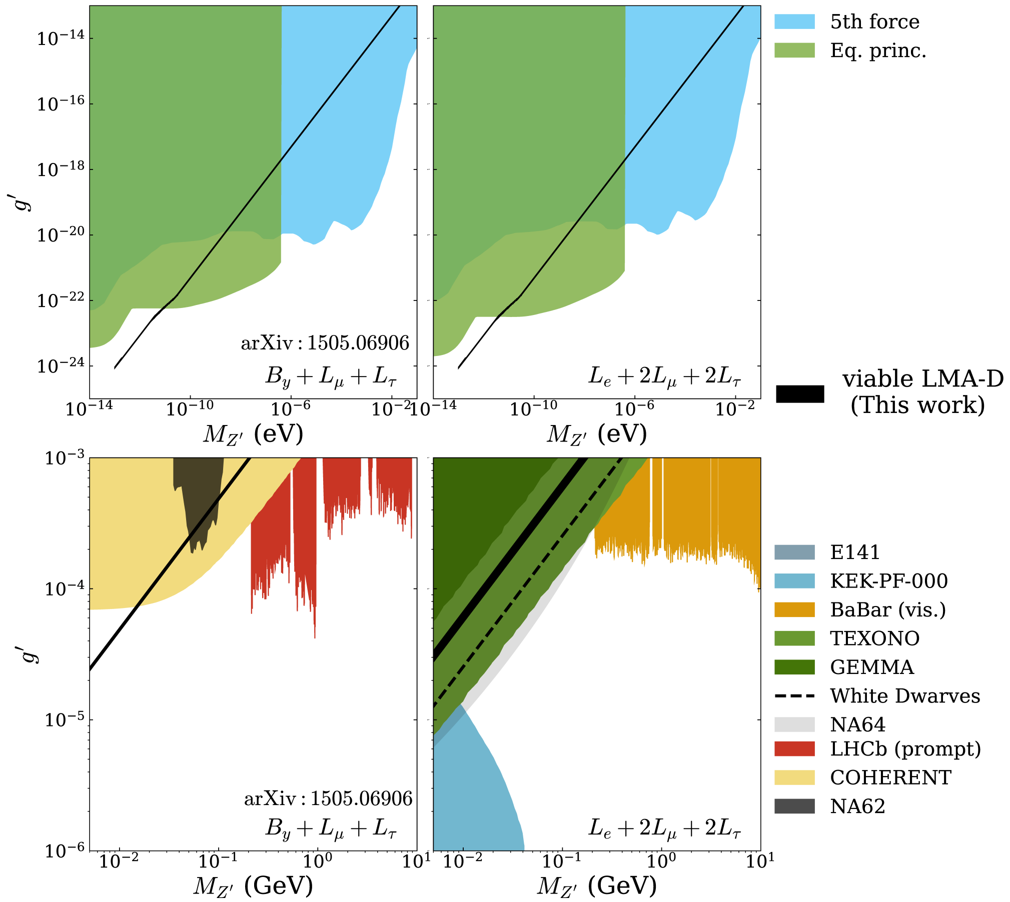
# $Z'$ Models: Viable models for LMA-D

Survey 10000 set of models characterized by the six relevant fermion $U(1)$ charges

About 5% lead to a viable LMA-D solution.

None was anomaly-free with SM$\nu_R$ states only

Two examples




Coloma, MCGG, Maltoni ArXiv:2009.14220