Phenomenology with Massive Neutrinos in 2022

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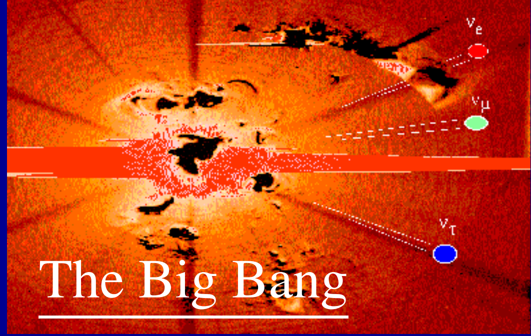
OUTLINE

The confirmed picture: 3ν Lepton Flavour Parameters

Some Q&A and some open avenues

http://www.nu-fit.org

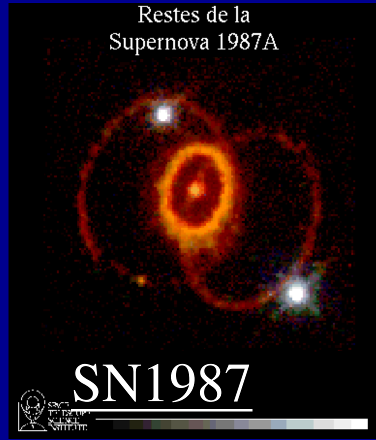
Sources of ν's



The Big Bang

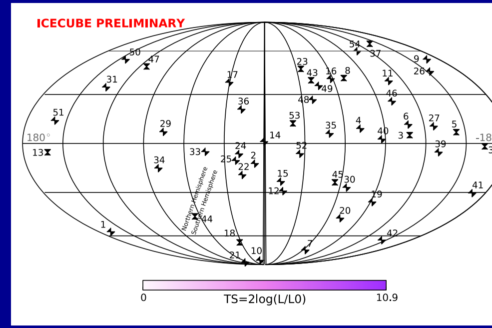
$\rho_\nu = 330/\text{cm}^3$

$p_\nu = 0.0004$ eV



SN1987

$E_\nu \sim$ MeV



ExtraGalactic

$E_\nu \gtrsim 30$ TeV

The Sun

ν_e

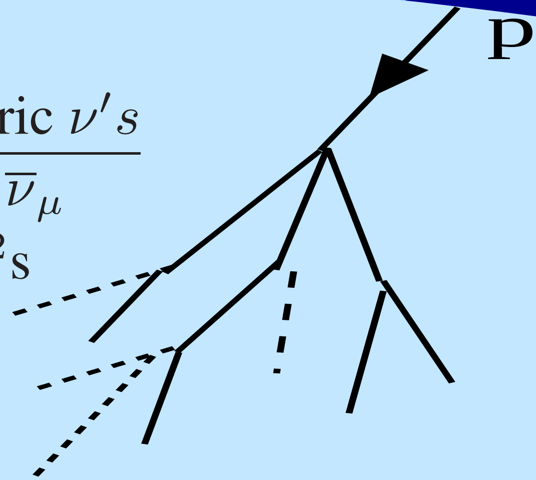
$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\text{cm}^2\text{s}$

$E_\nu \sim 0.1$–20 MeV

Atmospheric $\nu' s$

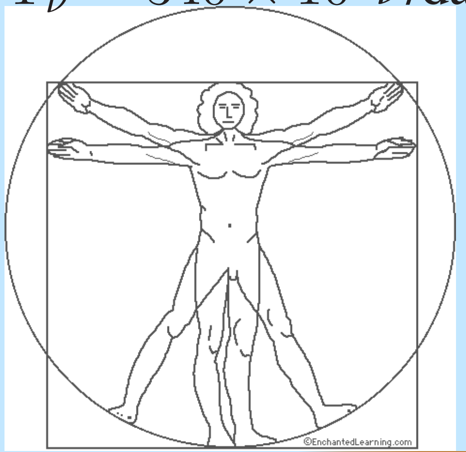
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$

$\Phi_\nu \sim 1 \nu/\text{cm}^2\text{s}$



Human Body

$\Phi_\nu = 340 \times 10^6 \nu/\text{day}$



Nuclear Reactors

$E_\nu \sim$ few MeV

$\overline{\nu}_e$

Earth's radioactivity

$\Phi_\nu \sim 6 \times 10^6 \nu/\text{cm}^2\text{s}$

Accelerators

$E_\nu \simeq 0.3$–30 GeV

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

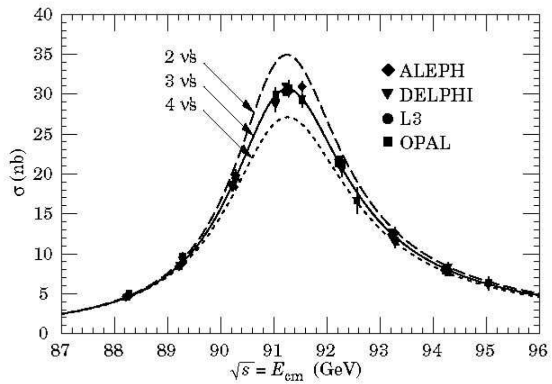
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

With three generation of fermions

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

There is no ν_R

Three and only three



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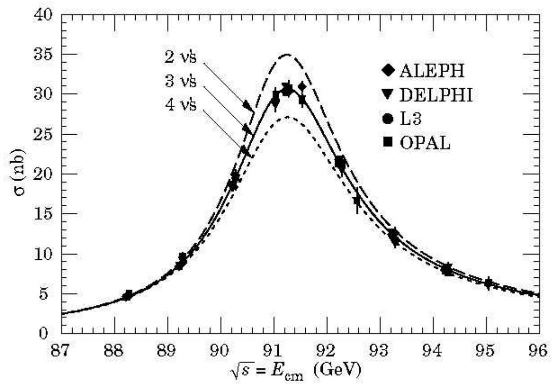

There is no ν_R

$\Downarrow$

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$ (hence $L = L_e + L_\mu + L_\tau$)

$\Downarrow$

ν *strictly* massless

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

  * Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, **ICECUBE**)
  * Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**)
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What BSM?

- Today 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

  $*$ Introduce ν_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 $\nu = \nu^c$

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

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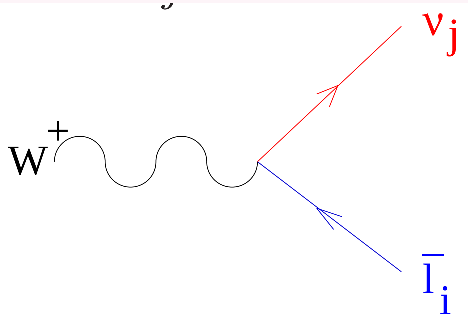
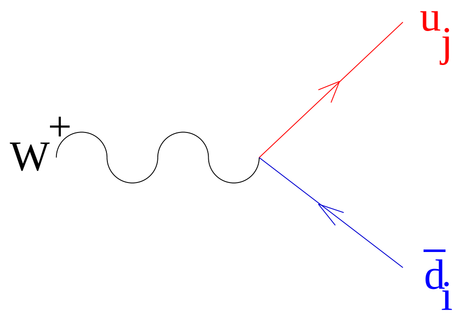
- The charged current interactions of leptons are not diagonal (similar to quarks)

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





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- In general for $N = 3 + s$ massive neutrinos $U_{\rm LEP}$ is $3 \times N$ matrix

$$U_{\rm LEP} U_{\rm LEP}^\dagger = I_{3\times 3} \qquad \text{but in general} \qquad U_{\rm LEP}^\dagger U_{\rm LEP} \neq I_{N\times N}$$

- $U_{\rm LEP}$: $3 + 3s$ angles + $2s + 1$ Dirac phases + $s + 2$ Majorana phases

ν Mass Oscillations in Vacuum

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$

  is a linear combination of the mass eigenstates ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i} |\nu_i\rangle$

- After a distance L it can be detected with flavour β with probability

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

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

No information on ν mass scale nor Majorana versus Dirac

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- When osc between 2-ν dominates:

$$P_{\alpha\alpha} = 1 - P_{osc} \quad \text{Disappear}$$

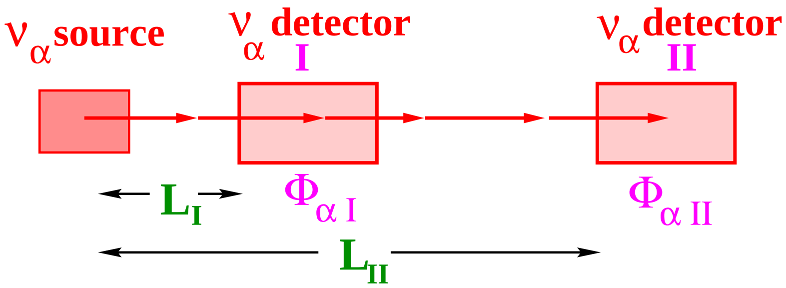
$$P_{osc} = \sin^2(2\theta)\, \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right) \quad \text{Appear}$$

$\Rightarrow$ No info on sign of Δm^2 and θ octant

ν Oscillations: Experimental Probes

- Generically there are two types of experiments to search for ν oscillations :

Disappearance Experiment



Compares $\Phi_{\alpha\, I}$ and $\Phi_{\alpha\, II}$ to look for loss

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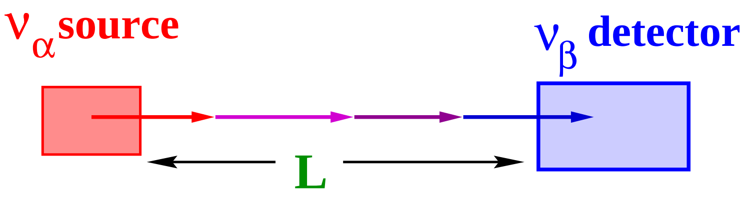

Searches for
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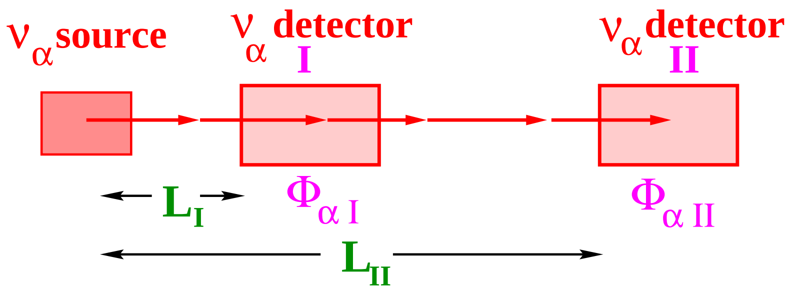

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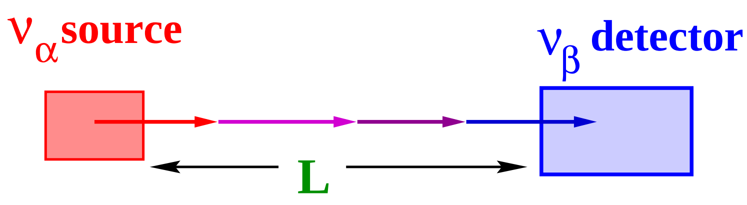
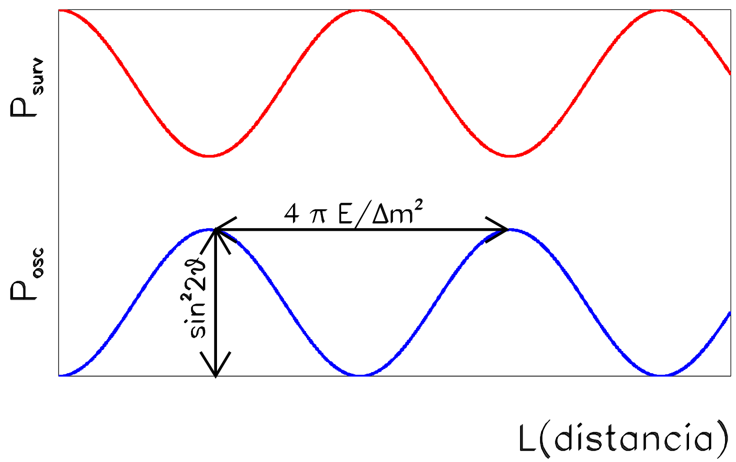


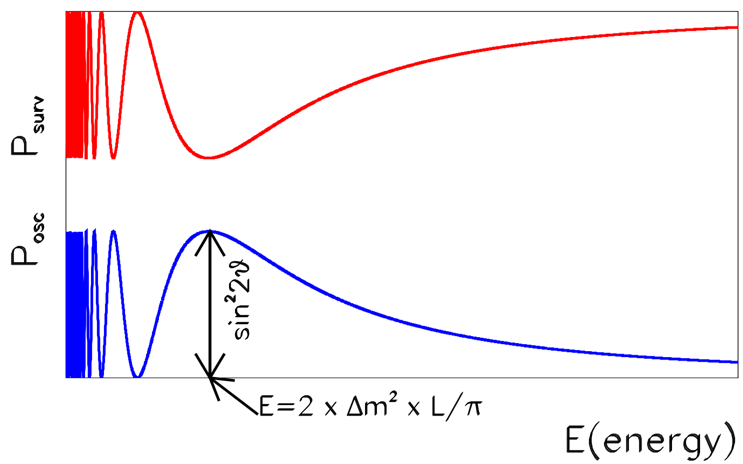
Searches for β diff α

- To detect oscillations we can study the neutrino flavour

as function of the Distance to the source

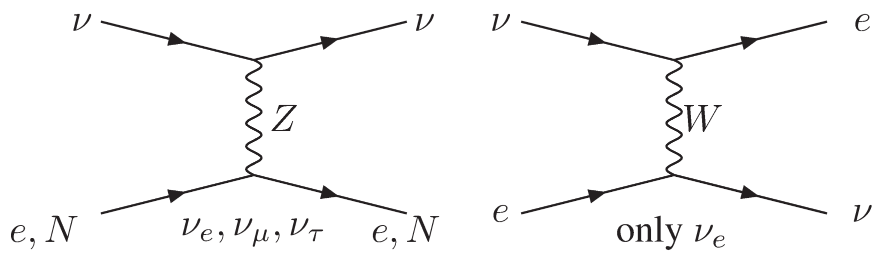


As function of the neutrino Energy



Matter Effects

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



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

$$-i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix} = \left[\Big[- \begin{pmatrix} V_e - V_X - \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix}$$

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

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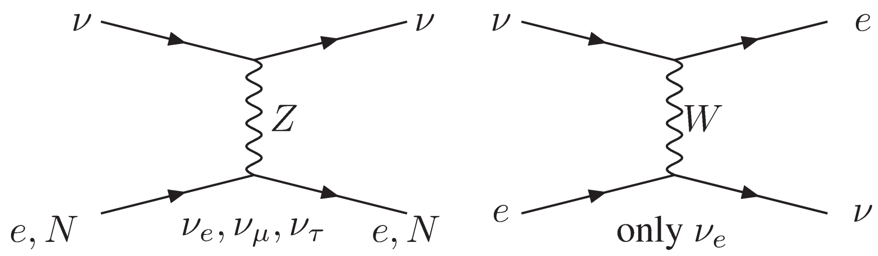

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- Mass difference and mixing in matter:

$$\Delta m^2_m = \sqrt{(\Delta m^2 \cos 2\theta - 2E\Delta V)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m^2_{mat}}$$

$\Rightarrow$ For solar $\nu' s$ in adiabatic regime

$P_{ee} = \frac{1}{2}\left[1 + \cos(2\theta_m)\cos(2\theta)\right]$

Dependence on θ octant

$\Rightarrow$ In LBL terrestrial experiments

Dependence on sign of Δm^2

and θ octant

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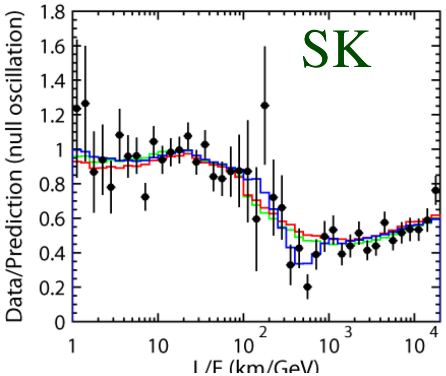
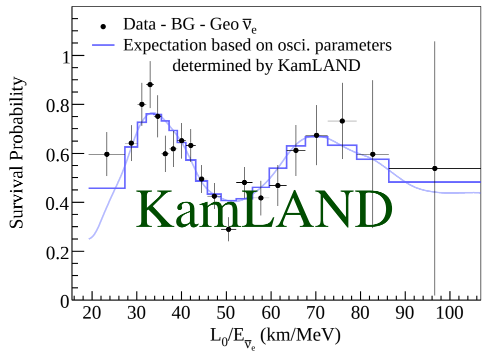
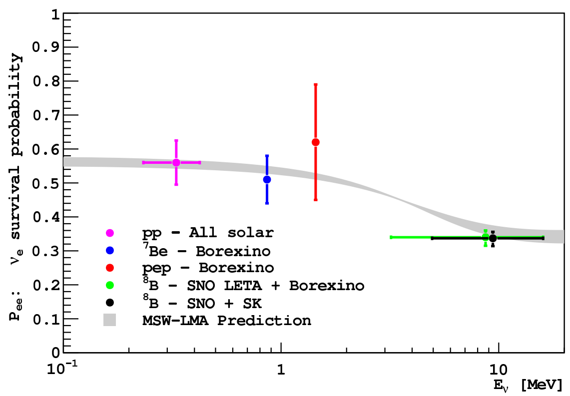
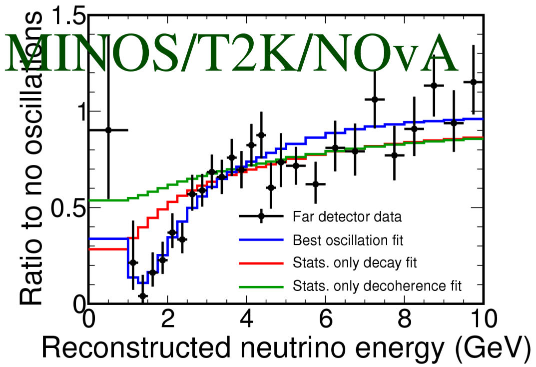
Vacuum oscillation L/E pattern with 2 frequencies

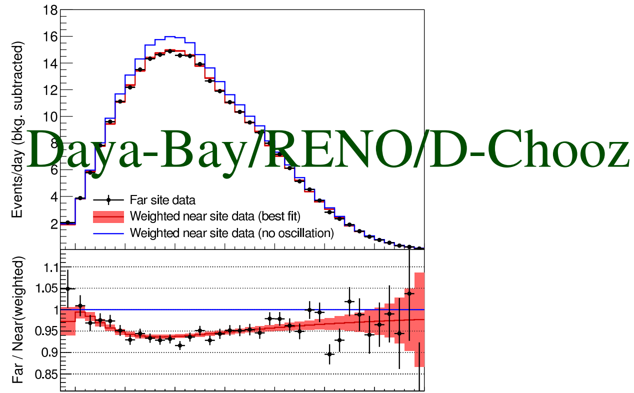




MSW conversion in Sun







3ν Flavour Parameters

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

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

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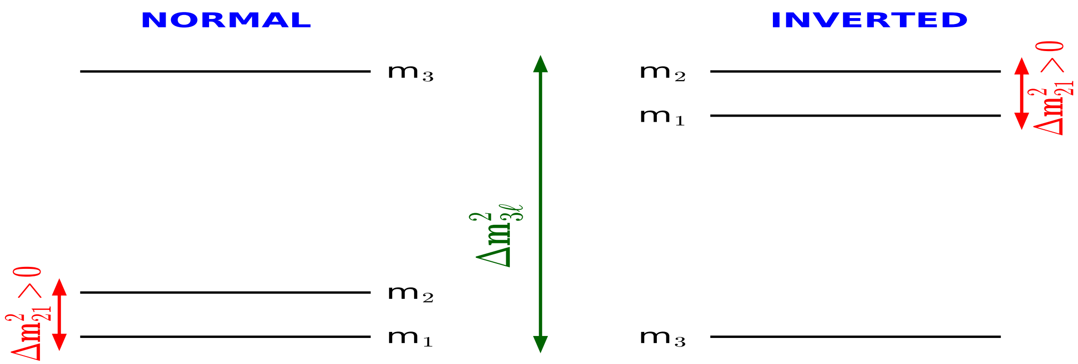
- Convention: $0 \leq \theta_{ij} \leq 90°$ $\quad 0 \leq \delta \leq 360°$ $\quad \Rightarrow$ 2 Orderings



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

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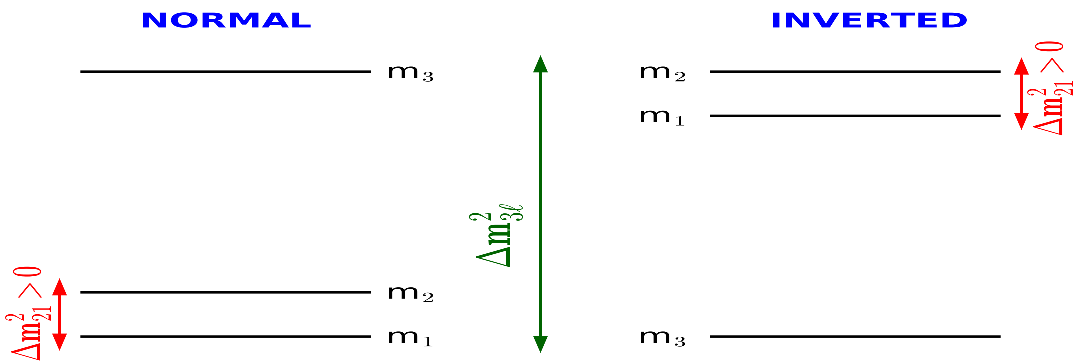

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Experiment	Dominant Dependence	Important Dependence
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13} $\Delta m^2_{3\ell}$	
Atmospheric Experiments (SK,IC)		θ_{23}, $\Delta m^2_{3\ell}$, 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}

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, 24 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 408-day low-E spect, 42 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 1958-day EH2/EH1 & EH3/EH1 ratios,52 points. Missing new 3158 day spectra.
- 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 (χ^2 table provided by SK).* Missing SK-V (not table avalable yet).

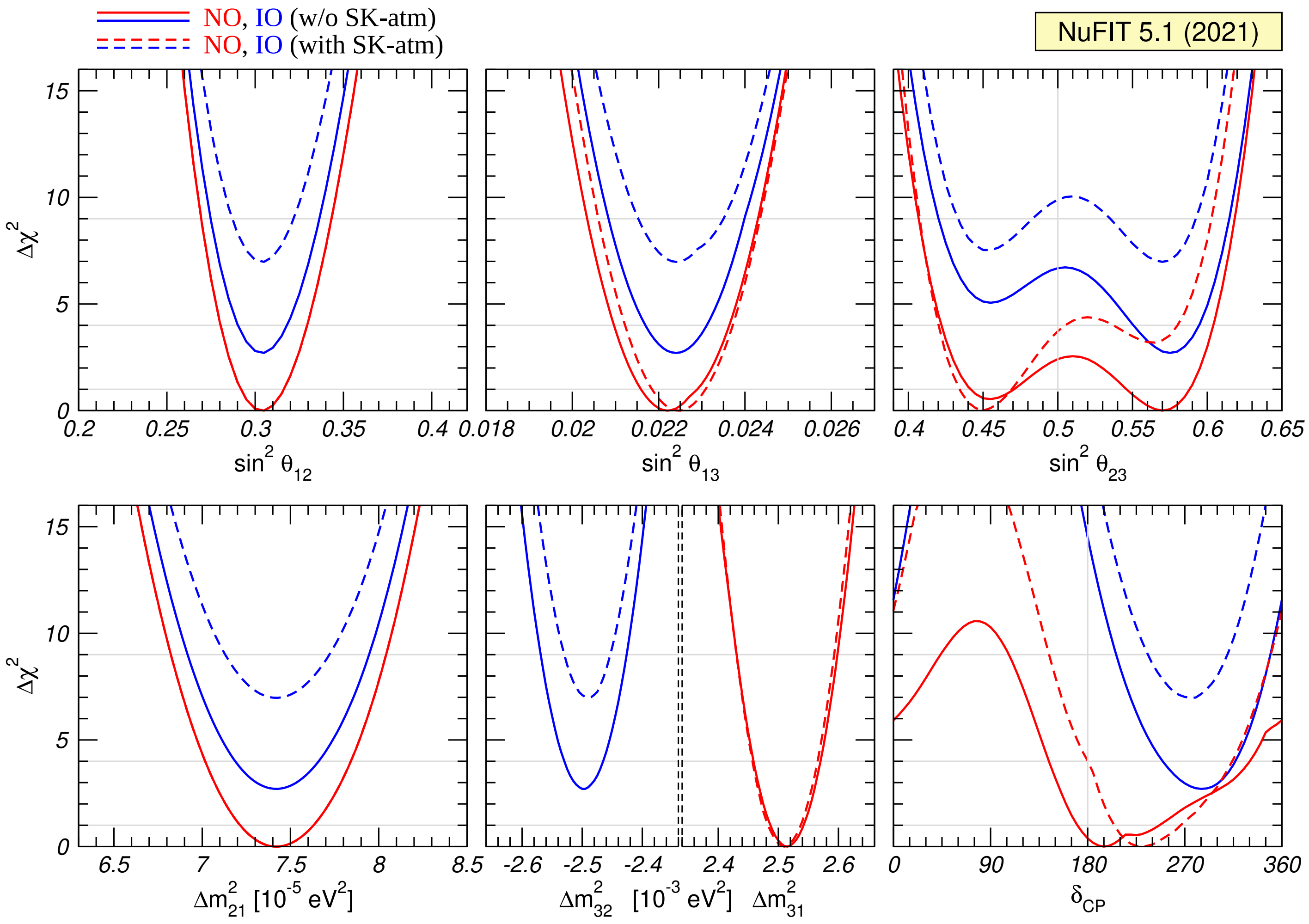
Accelerator experiments

- MINOS 10.71×10^{20} pot ν_μ-disapp data, 39 poins.
- MINOS 3.36×10^{20} pot $\bar{\nu}_\mu$-disapp data , 14 points.
- MINOS 10.6×10^{20} pot ν_e-app data , 5 points.
- MINOS 3.3×10^{20} pot $\bar{\nu}_e$-app data , 5 points.
- T2K 19.7×10^{20} pot ν_μ-disapp data, 35 points.
- T2K 19.7×10^{20} pot ν_e-app data, 23 points CCQE and 16 points CC1π.
- T2K 16.3×10^{20} pot $\bar{\nu}_\mu$-disapp, 35 points.
- T2K 16.3×10^{20} pot $\bar{\nu}_e$-app, 23 points.
- NOνA 13.6×10^{20} pot ν_μ-disapp data , 76 points.
- NOνA 13.6×10^{20} pot ν_e-app data , 13 points.
- NOνA 12.5×10^{20} pot $\bar{\nu}_\mu$-disapp, 76 points.
- NOνA 12.5×10^{20} pot $\bar{\nu}_e$-app, 13 points.

Summary: Global 3 ν Flavour Parameters

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

Esteban, G-G, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792], G-G, Maltoni, Schwetz, 2111.03086



SK-atm $\equiv$ χ^2 table from SK1-4 for 372 kton-years

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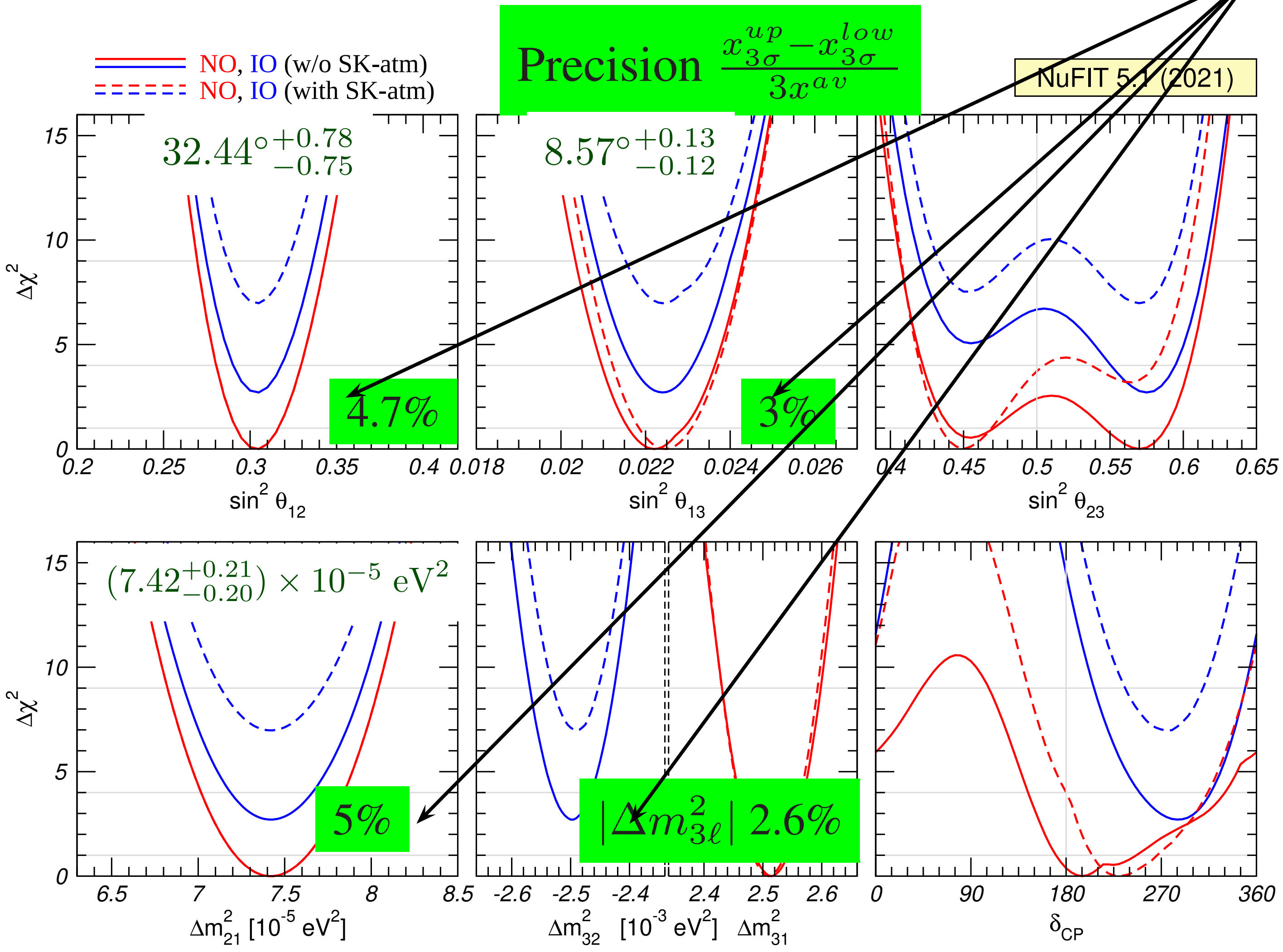
Esteban, G-G, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792], G-G, Maltoni, Schwetz, 2111.03086

- 4 well-known parameters:

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



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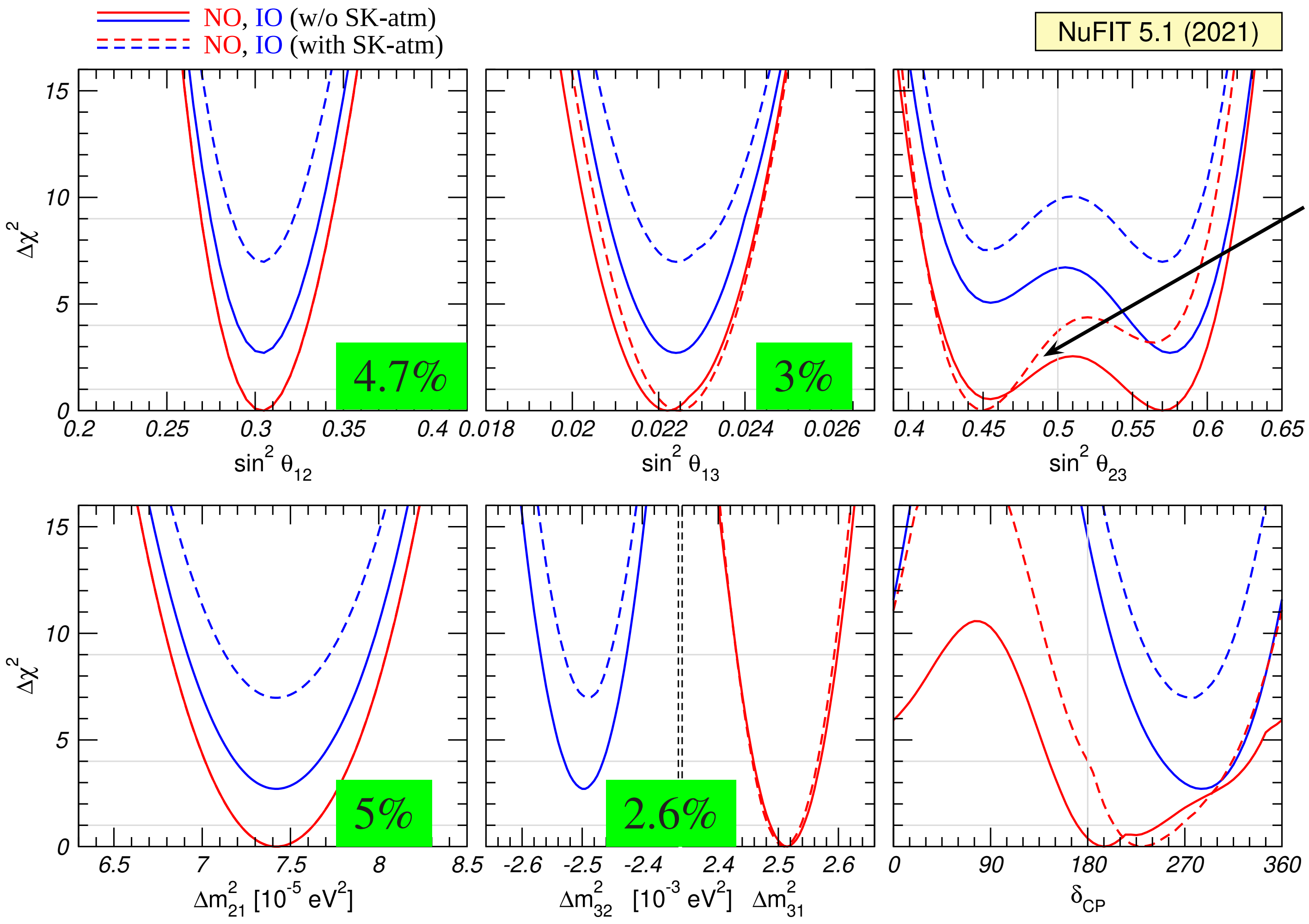

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  Δm^2_{21} Solar vs KLAND

  Tension Resolved

- θ_{23}: Least known angle

  Maximal? Octant?

  non-robust wrt ATM

Summary: Global 3 ν Flavour Parameters

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

Esteban, G-G, Maltoni, Schwetz, Zhou, JHEF … 2111.03086

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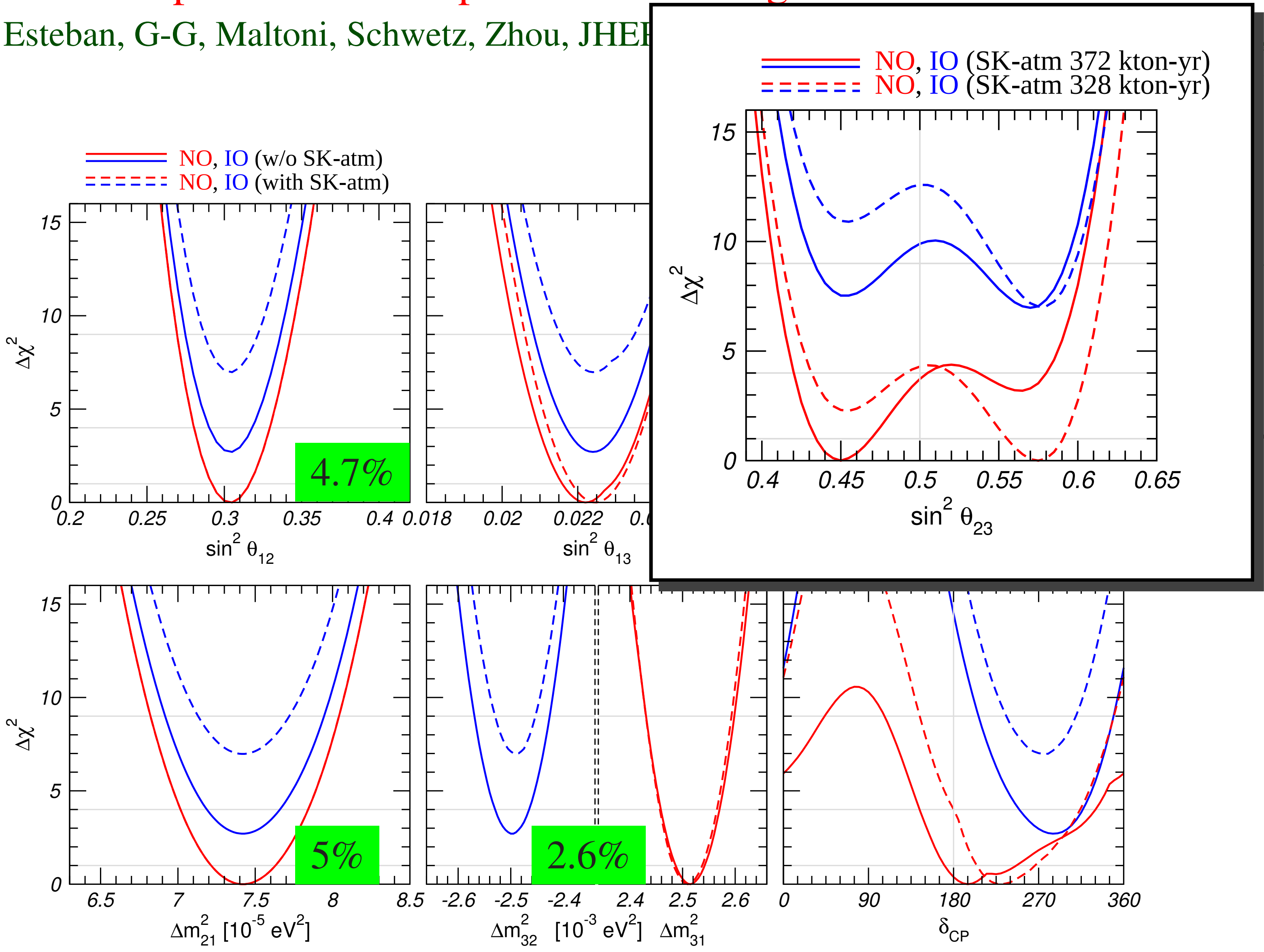

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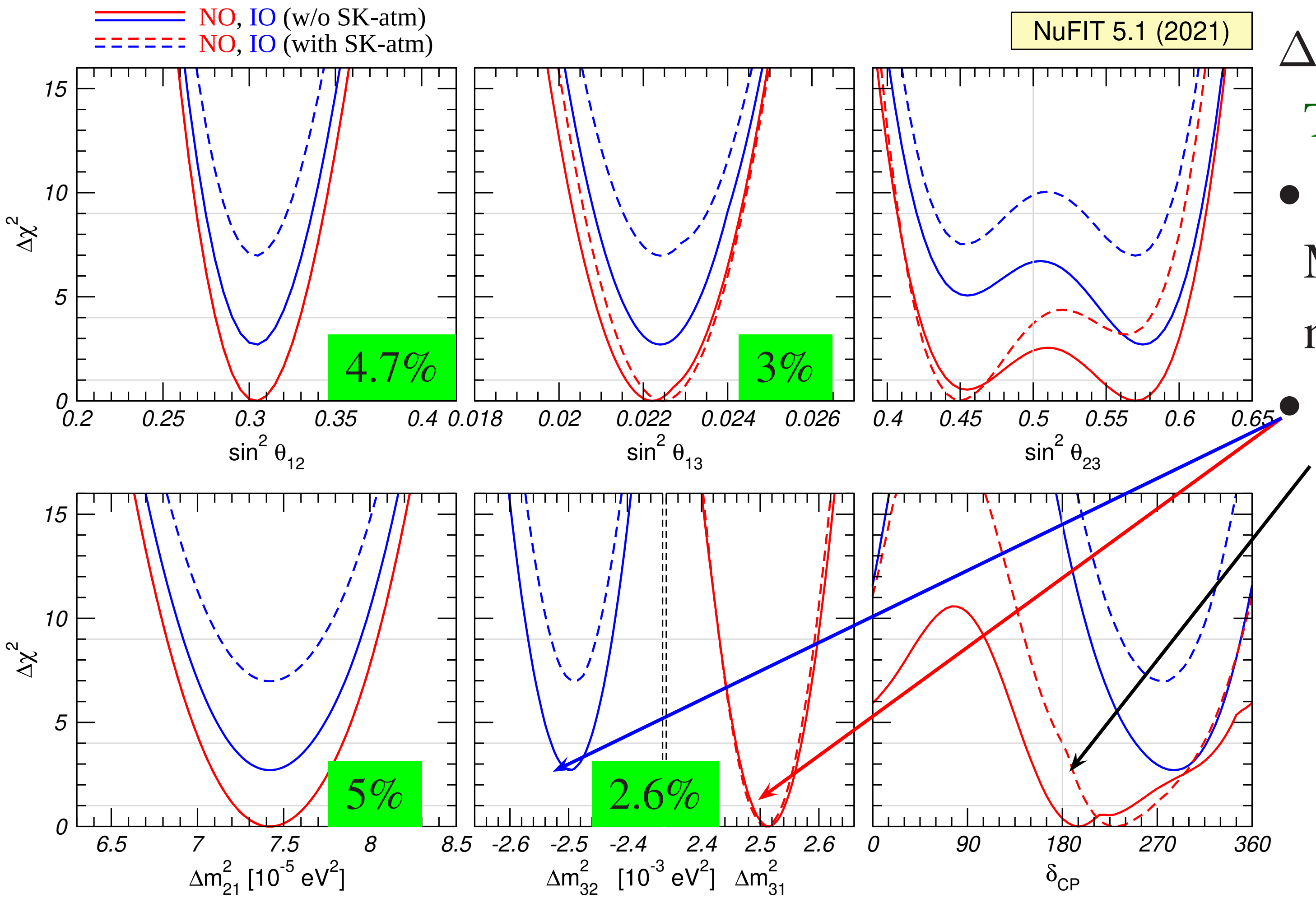

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  Maximal? Octant?

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- Ordering NO or IO?

  CPV?:

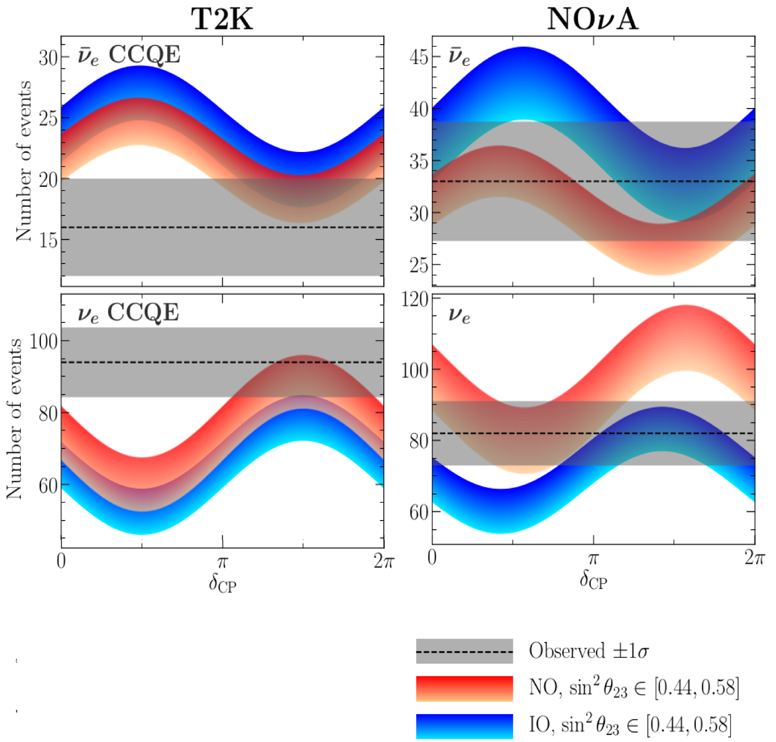
CPV and Ordering in LBL: ν_e appearace

lez-Garcia 17

- Dominant information from ν_e apperance 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

CPV and Ordering in LBL: ν_e appearace

z-Garcia 17-a

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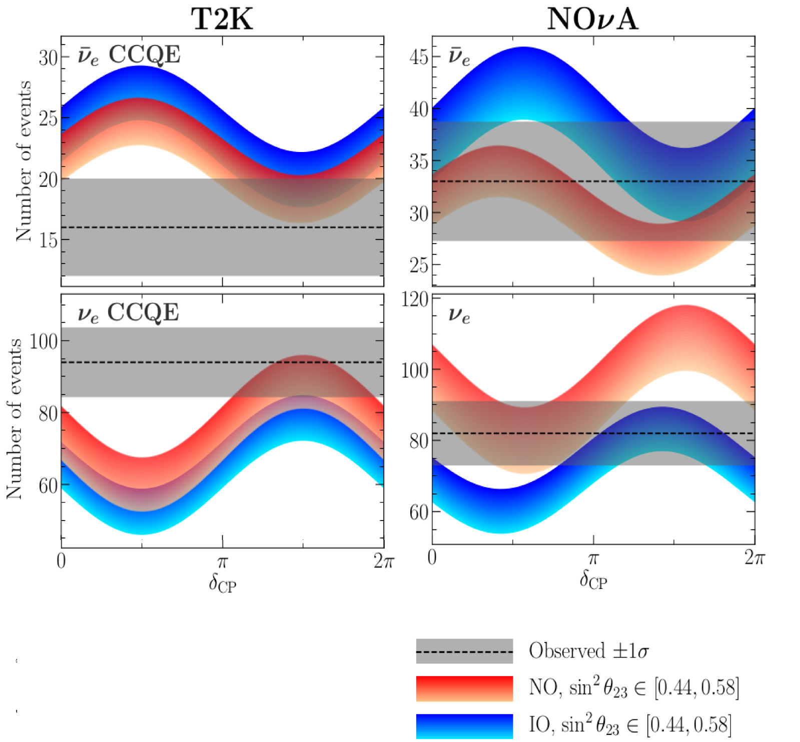
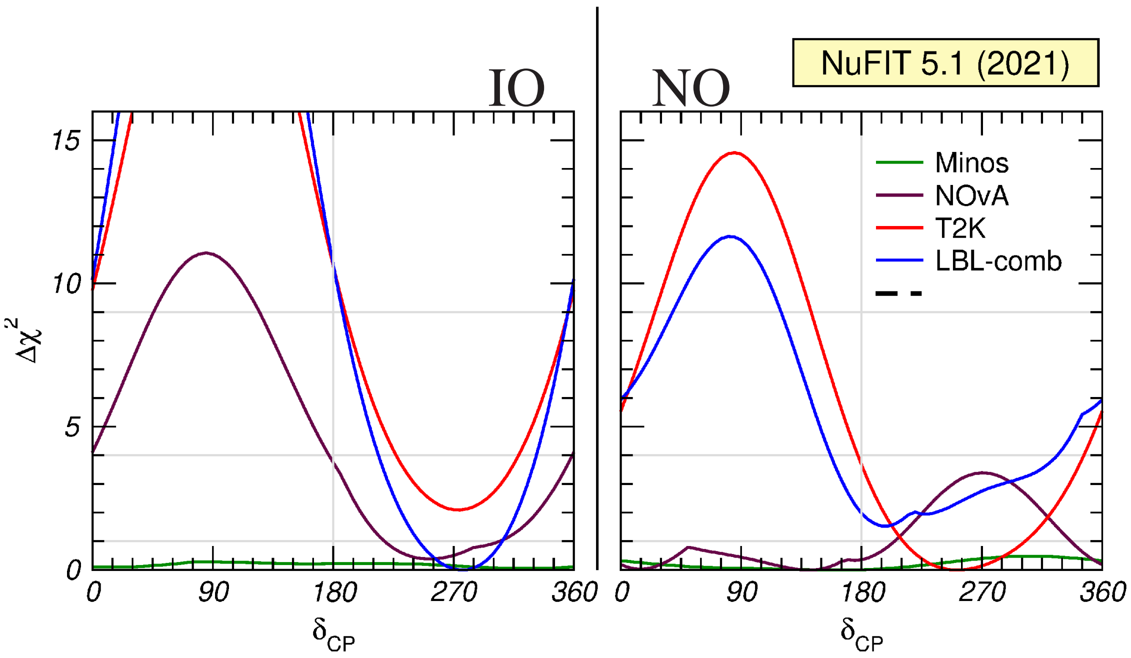


⇒ Each T2K and NOνA favour NO

But tension in favoured values of δ_{CP} in NO



⇒ IO best fit in LBL combination

Δm^2_{3l} in LBL & Reactors

- At LBL determined in ν_μ and $\bar{\nu}_\mu$ disapperance 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

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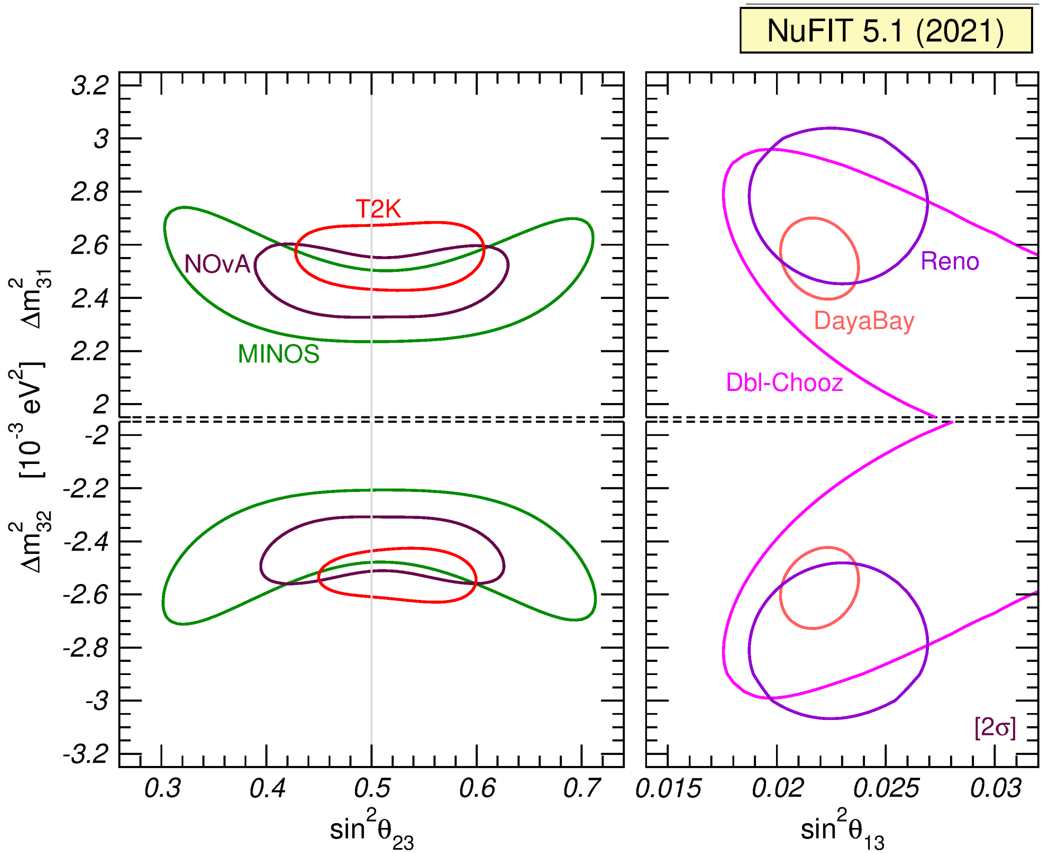

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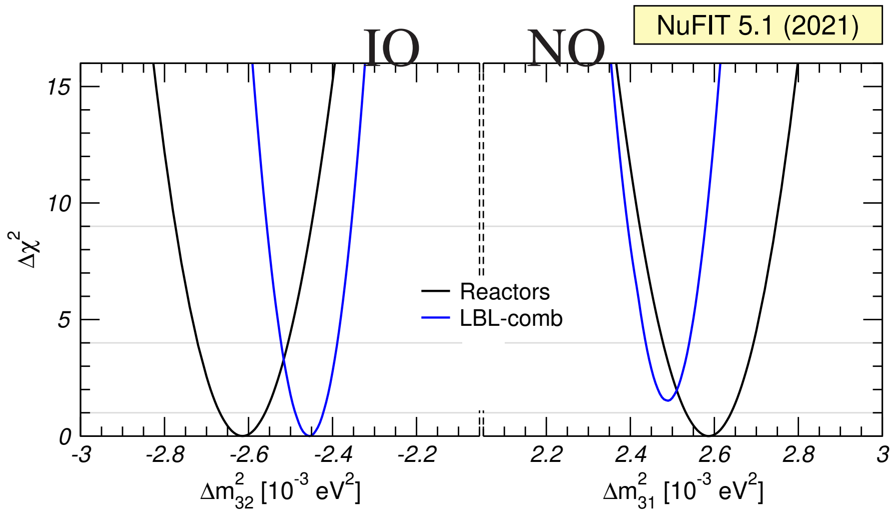

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- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors

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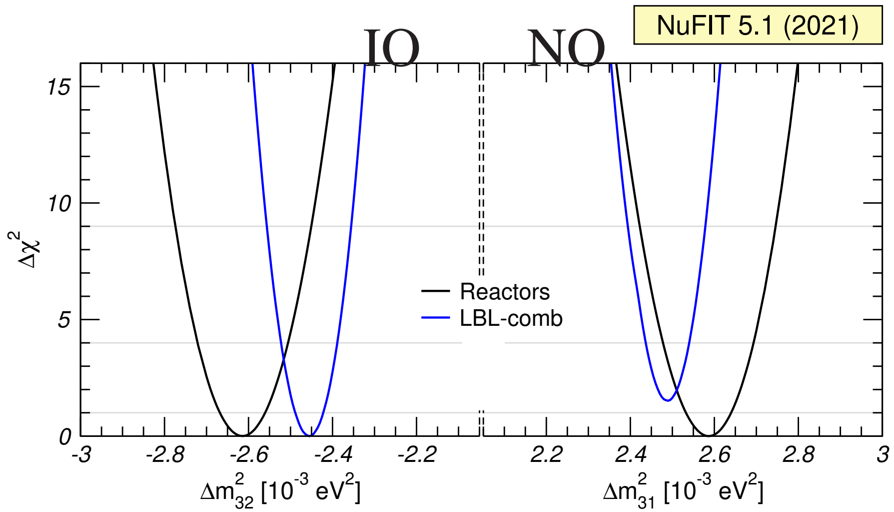

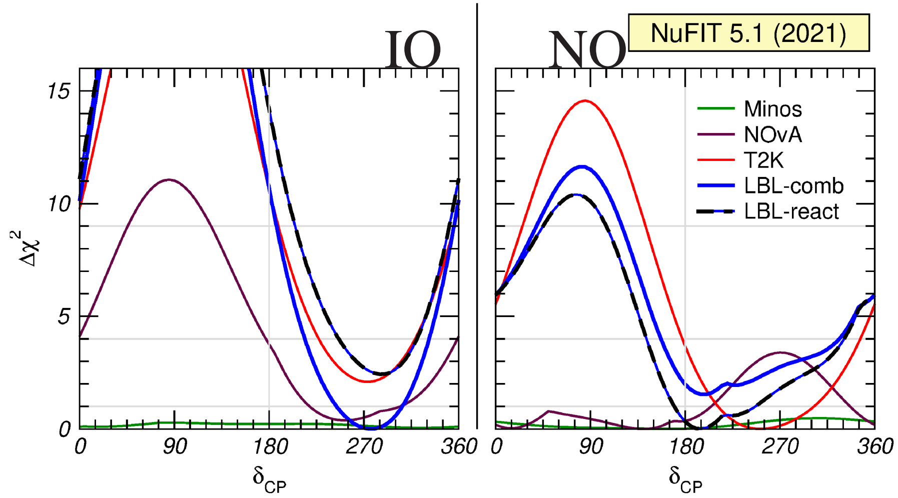

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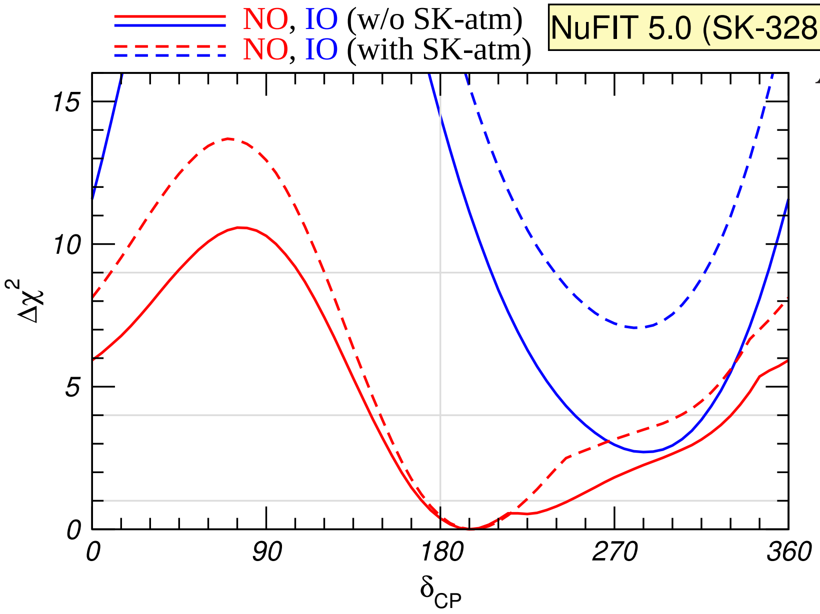
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors
- in NO: b.f $\delta_{\rm CP} = 195°$ $\Rightarrow$ <u>CPC allowed at 0.6 σ</u>
- in IO: b.f $\delta_{\rm CP} \sim 270°$ $\Rightarrow$ <u>CPC disfavoured at 3 σ</u>

Ordering and CPV including ATM

ATM results added to global fit using SK χ^2 tables

- NUFIT 5.0: included SK I-IV 328 kton-years table

- NUFIT 5.1: include SK I-IV 372.8 kton-years table



Add SK-atm table⇒ favouring of NO:

$$\Delta\chi^2_{\rm NO-IO,w/o\,SK-atm} = 2.7$$
$$\Delta\chi^2_{\rm NO-IO,with\,SK-atm} = 7.1$$

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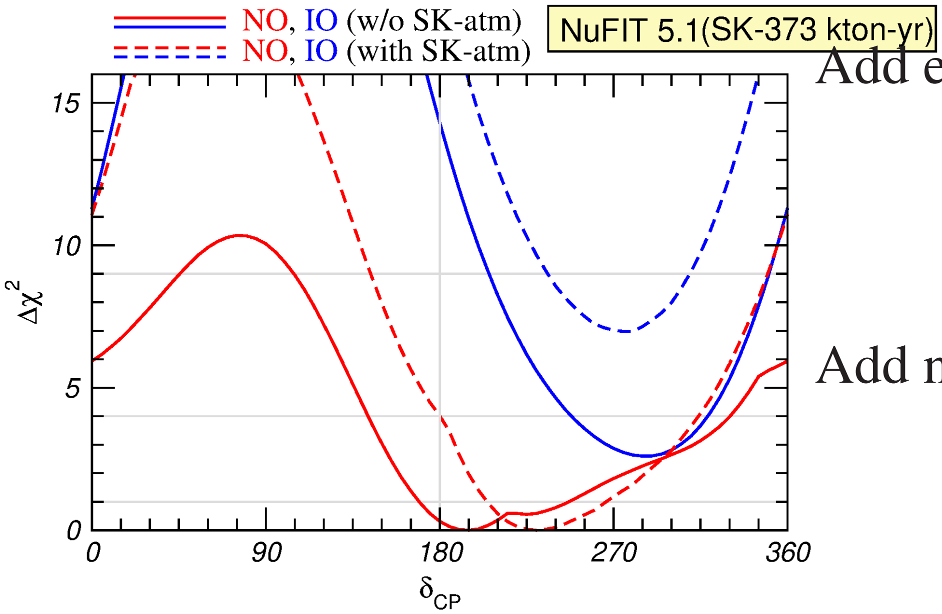

Add either SK-atm table⇒ favouring of NO:

$$\Delta\chi^2_{\rm NO-IO,w/o\ SK-atm} = 2.7$$
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Add new table ⇒ slight increase of significance of CPV in NO

w/o SK-Atm b.f $\delta_{\rm CP} = 195^\circ$ CPC at 0.6σ

with SK-Atm: b.f $\delta_{\rm CP} = 230^\circ$ CPC at 2σ

Flavour Parameters: Mixing Matrix

- We have the three leptonic mixing angles determined (at $\pm\, 3\sigma/6$)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.844 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.639 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}$$

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- Good progress but still precision very far from:

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

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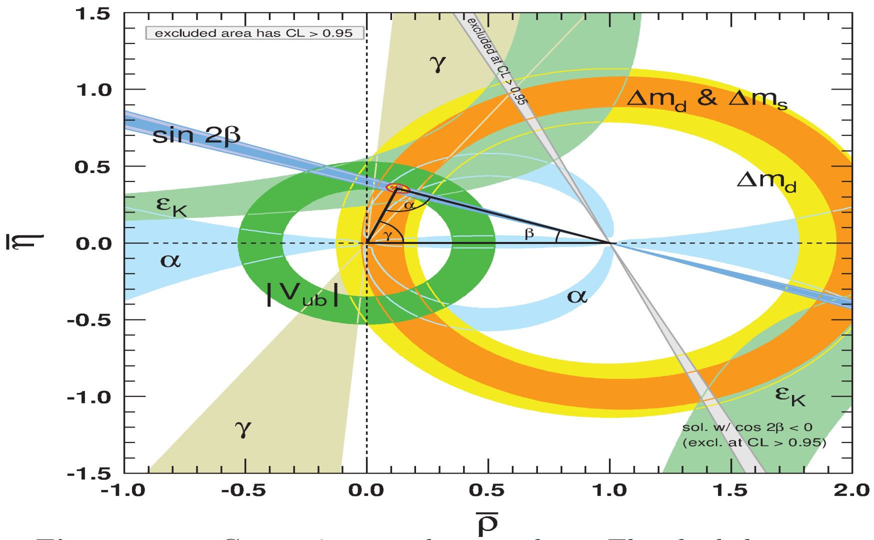
- Also very different flavour mixing of leptons vs quarks

3ν Mixing: Leptonic Unitarity Triangle

Unitarity triangle in quark sector



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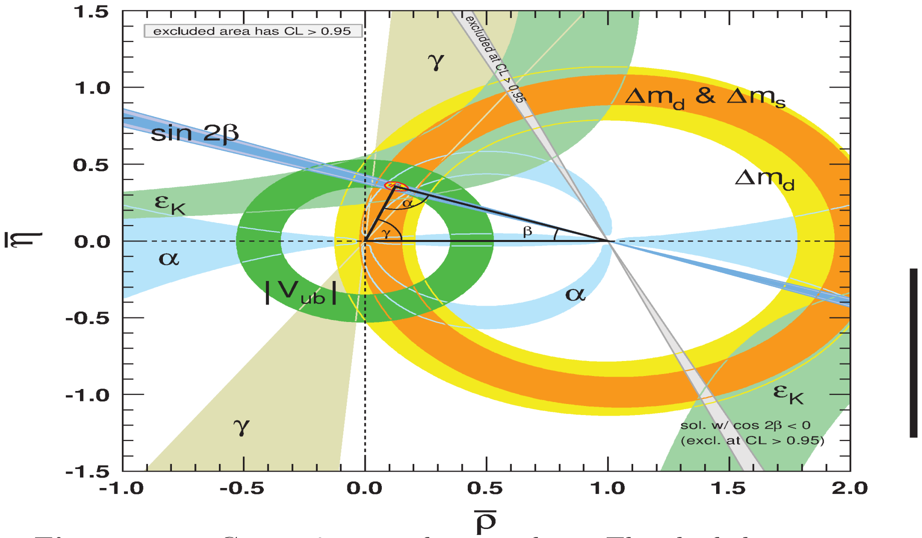
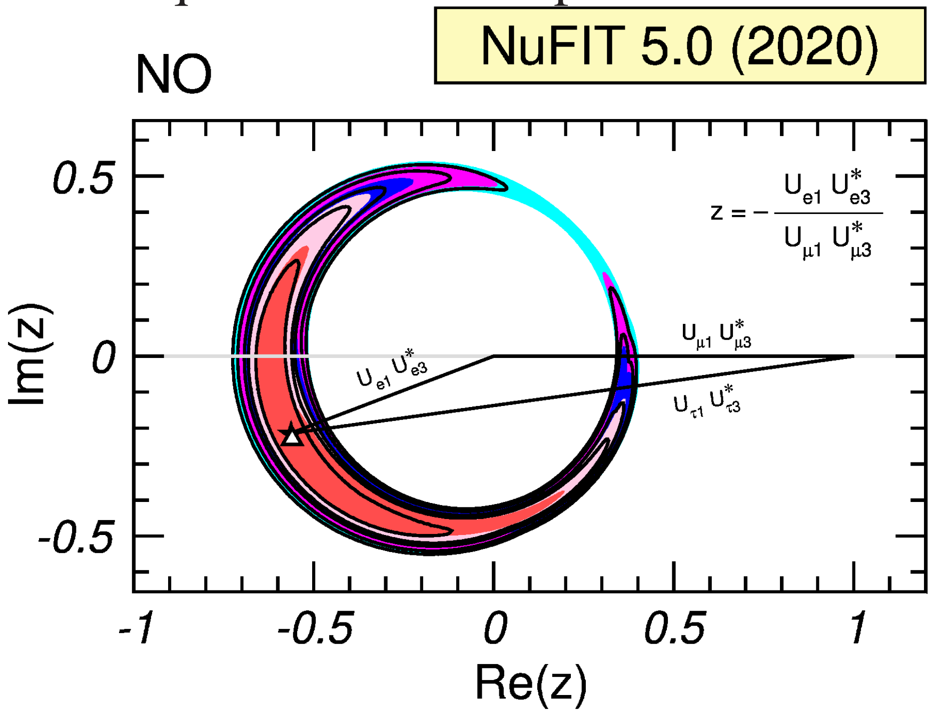


The equivalent in the leptonic sector



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_ν reconstruction

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

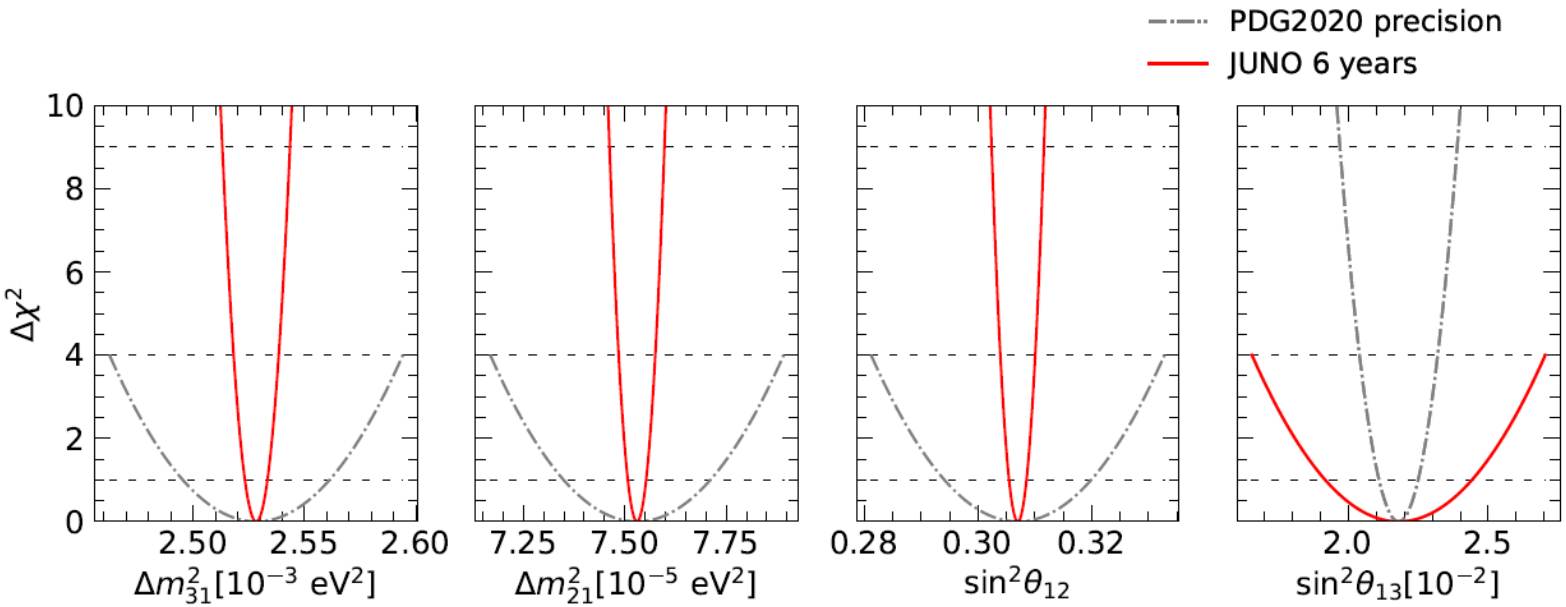
- Reactor experiment at $L \sim 60$ km (vacuum) able to observe the difference between oscillations with Δm^2_{31} and Δm^2_{32}: JUNO, RENO-50

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

  – Challenge: Energy resolution

JUNO: Sensitivity to Oscillation Parameters

	Central Value	PDG2020	100 days	6 years	20 years
Δm^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$0.0029 (0.1%)
Δm^2_{21} ($\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%)



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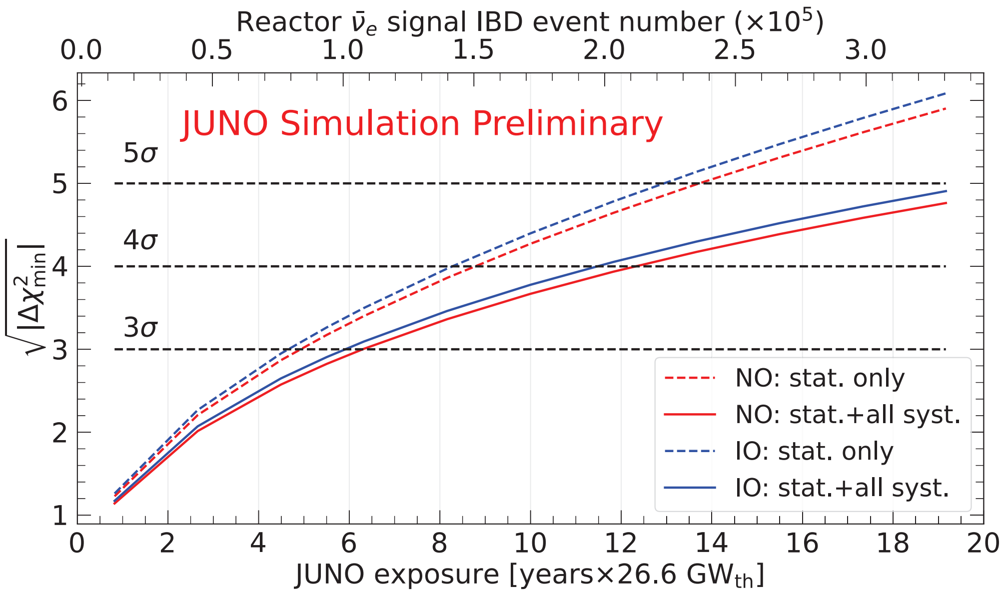
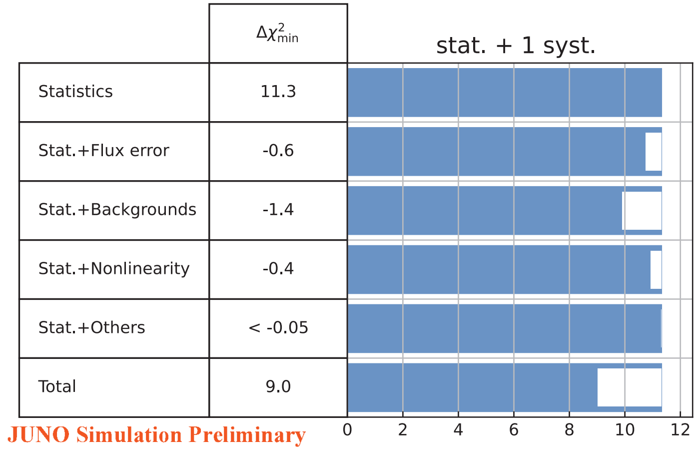
Sensitivity to Neutrino Mass Ordering



Impact of systematics:



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

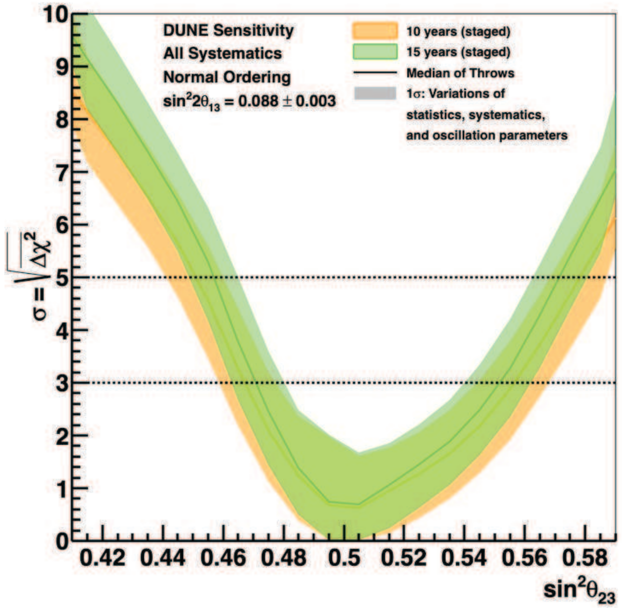
- ✓ JUNO+TAO, 6 years×26.6 GW exposure: $\sim 3\sigma$
- ✓ +1% external constrain on Δm^2_{32}: $> 4\sigma$
- ✓ combined with accelerator/atmospheric experiment: $> 5\sigma$
  ↪ sensitivity boost due to tension for wrong ordering

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

▸ Extra [2008.11280], JUNO+IceCube [1911.06745]

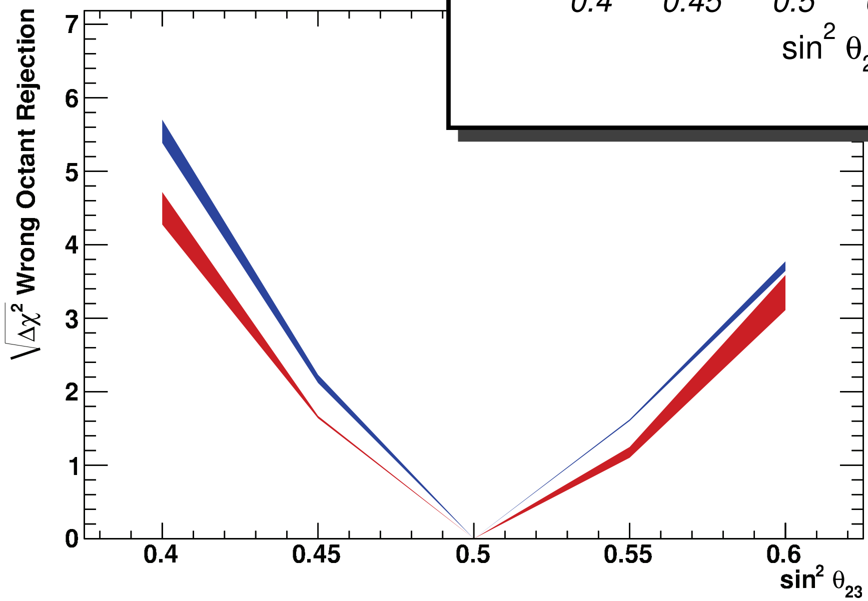
DUNE & Hyper-Kamiokande: θ_{23}

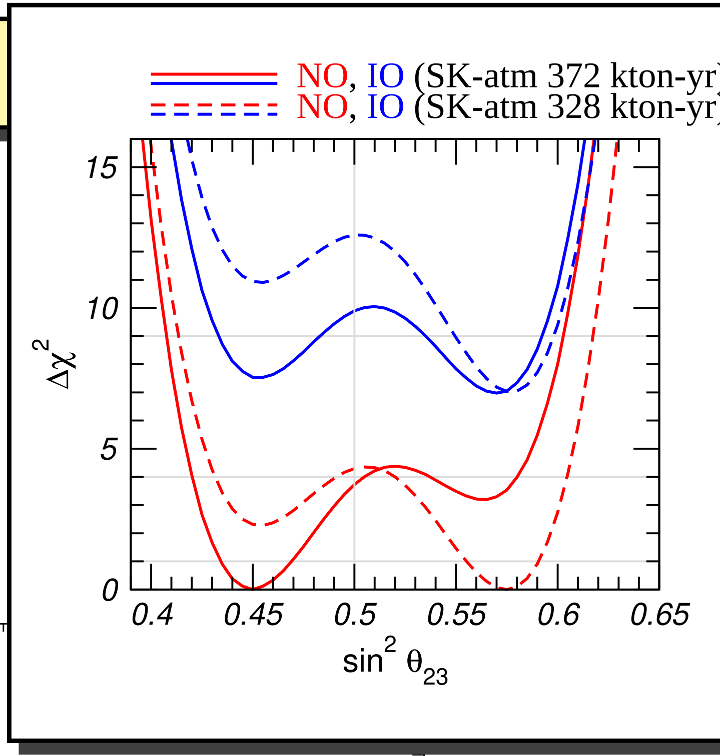
θ_{23} octant: future sensitivities



$\sim 3 - 5\sigma$

DUNE 2002.03005





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

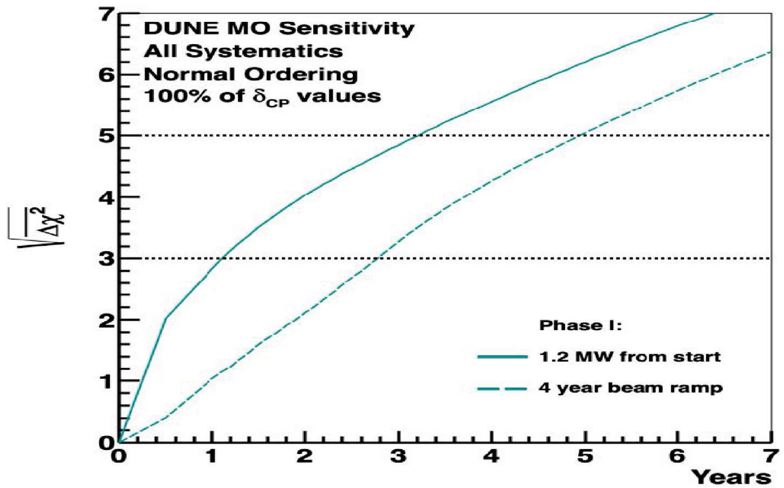
HK 1805.04163

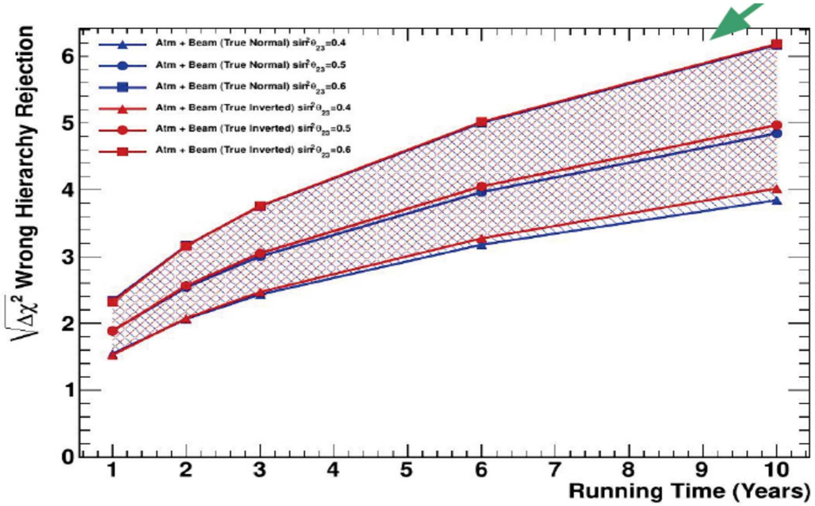
DUNE & Hyper-Kamiokande: CPV and MO

Mass Ordering

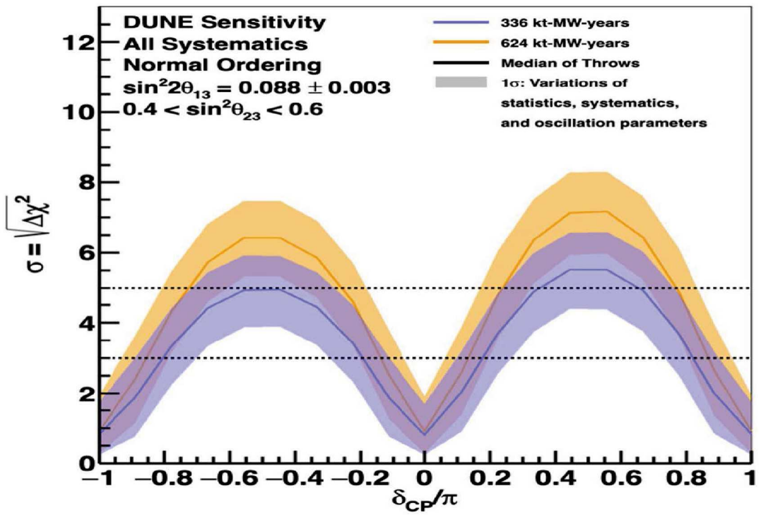
DUNE

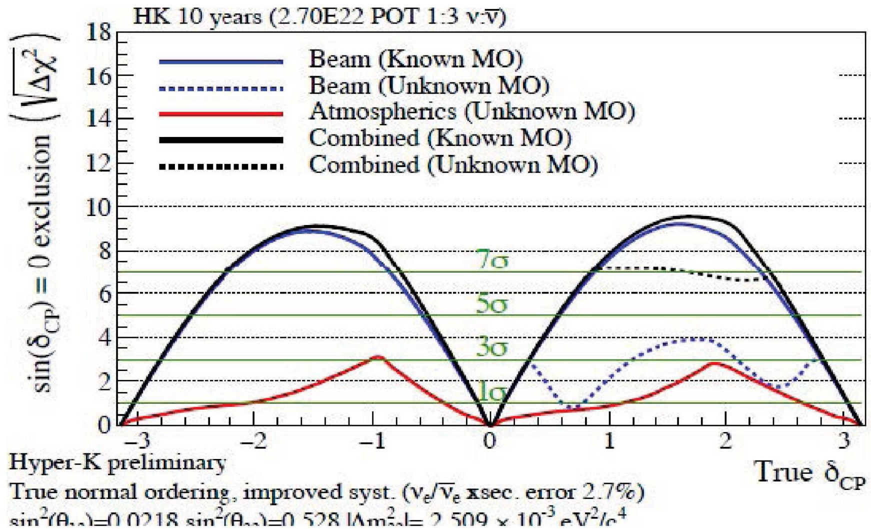
Hyper-Kamiokande





CPV





Confirmed LE Picture and today's List of Q&A

- At least two neutrinos are massive ⇒ There is NP
- Updated 3ν fit
  - 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

    ⇒ interplay of LBL/reactor/ATM results

	best fit MO	$\Delta\chi^2$(MO)	best fit $\delta_{\rm CP}$	$\Delta\chi^2$(CPC)	oct.θ_{23}	$\Delta\chi^2$(oct)
LBL	IO	1.5	275°	2.0	2nd	2.2
+reactors	NO	2.7	195°	0.4	2nd	0.5
+ SK-Atm 328 kt-y (NuFIT 5.0)	NO	7.1	197°	0.5	2nd	2.5
or + SK-Atm 373 kt-y (NuFIT 5.1)	NO	7.0	230°	4.0	1st	3.2

    ⇒ not statistically significant yet

    ⇒ definitive answer will likely require new experiments

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- Only three light states?

Beyond 3ν's: Light Sterile Neutrinos

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

LSND &MiniBoone

LSND 2001:

Signal $\nu_\mu \to \nu_e$ (3.8 σ)

MiniBooNE 2020:

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

(639 $\pm$ 132.8 events)

Gallium Anomaly

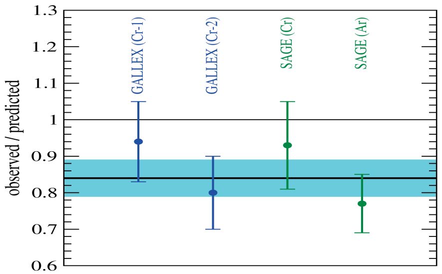
Acero, Giunti, Laveder, 0711.4222
Giunti, Laveder,1006.3244

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



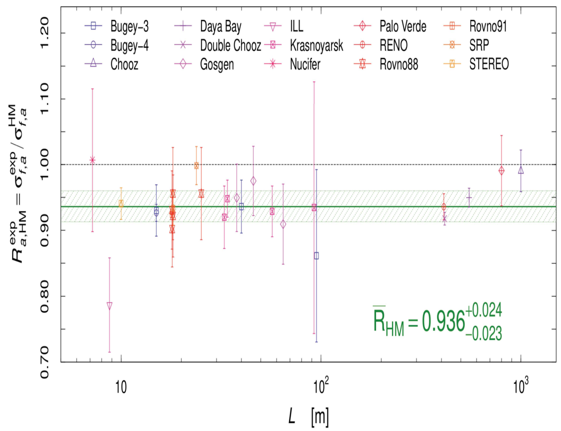
Explained as ν_e disappearance

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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MiniBooNE 20

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ & ν_μ

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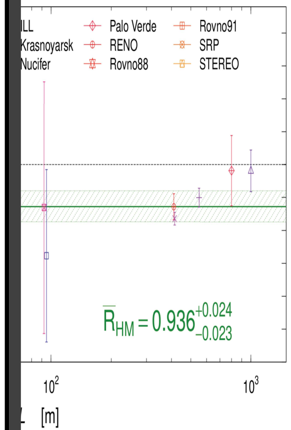
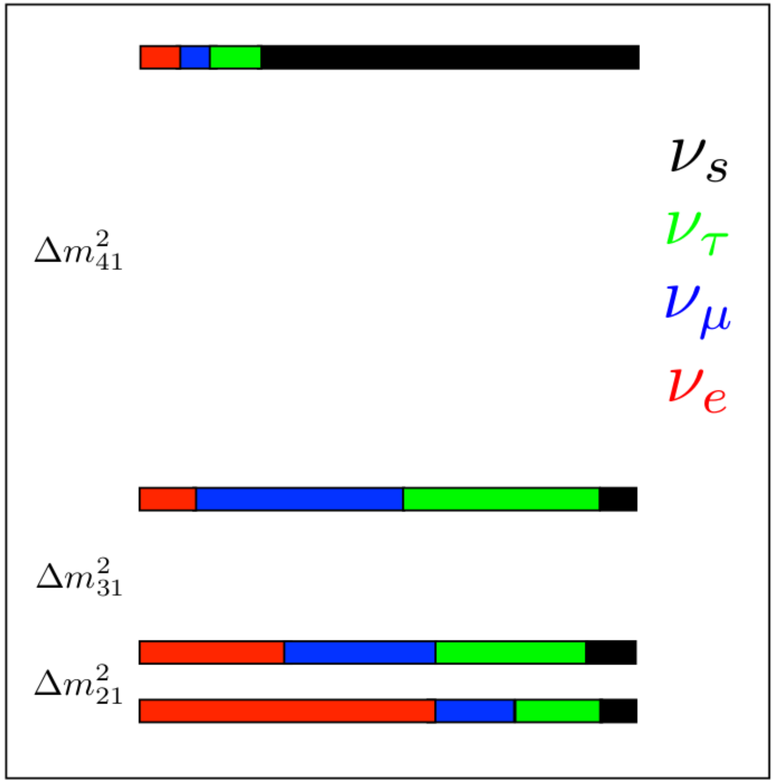


disappearance

Oscillation Interpretation Requires new (sterile) ν's



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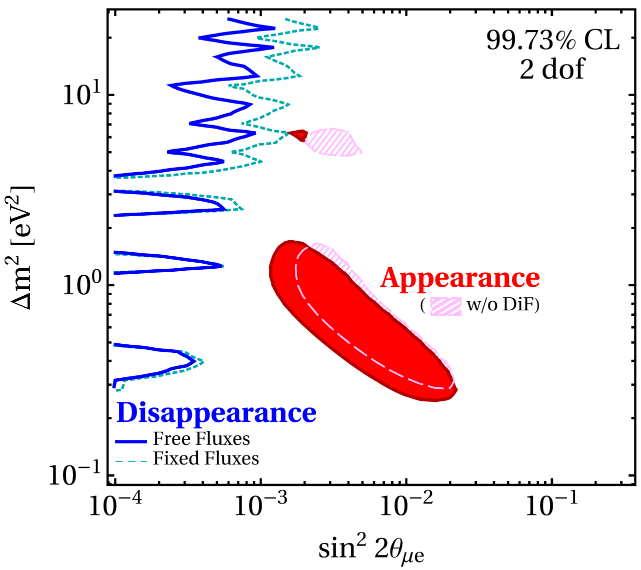
$\bar{\nu}_\mu \to \bar{\nu}_e$ & $\nu_\mu \to \nu_e$

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

Strong tension with
non-obervation of ν_μ dissap



Dentler etal, 1803.10661

Purely sterile oscillation
robustly disfavoured
additional SM or NP effects?

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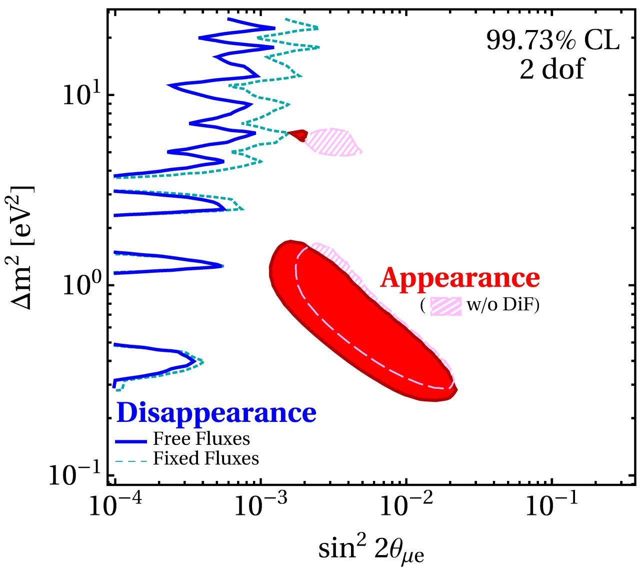

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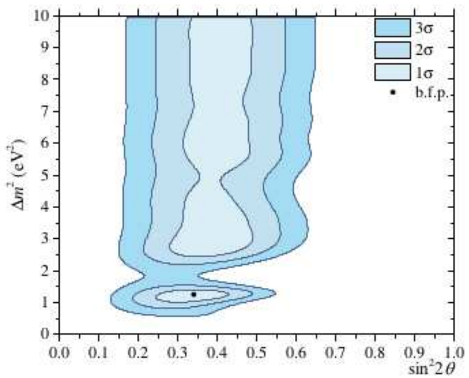
Confirming results from BEST

2109.11482



Requires large mixings

Ruled out/tension by solar $\nu' s$

Goldhagen etal 2109.14898

Berryman etal 2111.12530

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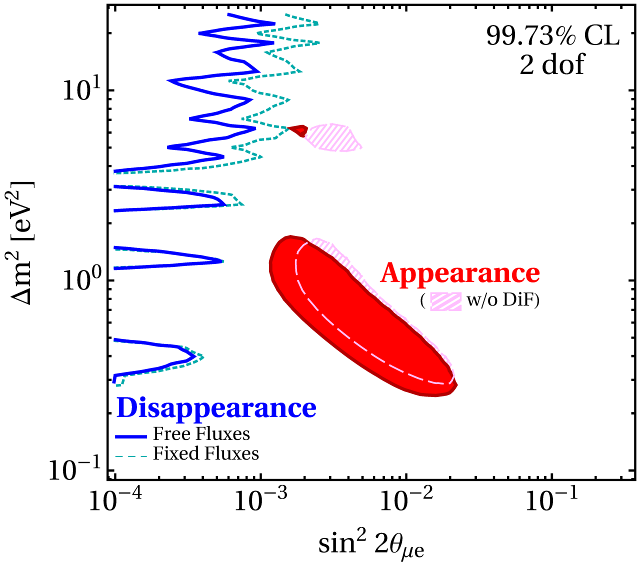

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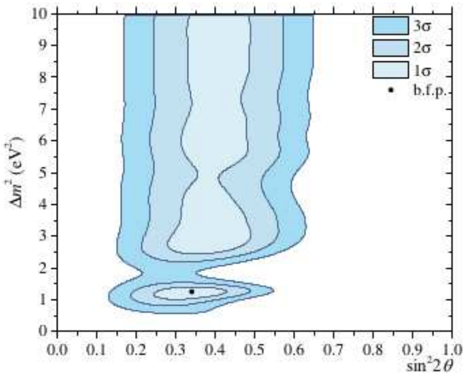

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Huber, 1106.068,Mention *etal* ,1101.2755

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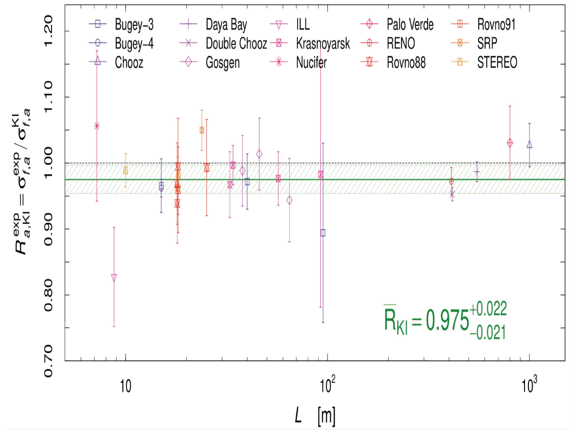
Deficit in $R = \frac{\text{data}}{\text{predict}}$ at $L \lesssim 100$ m

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

2022 with updated inputs (^{235}U)

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

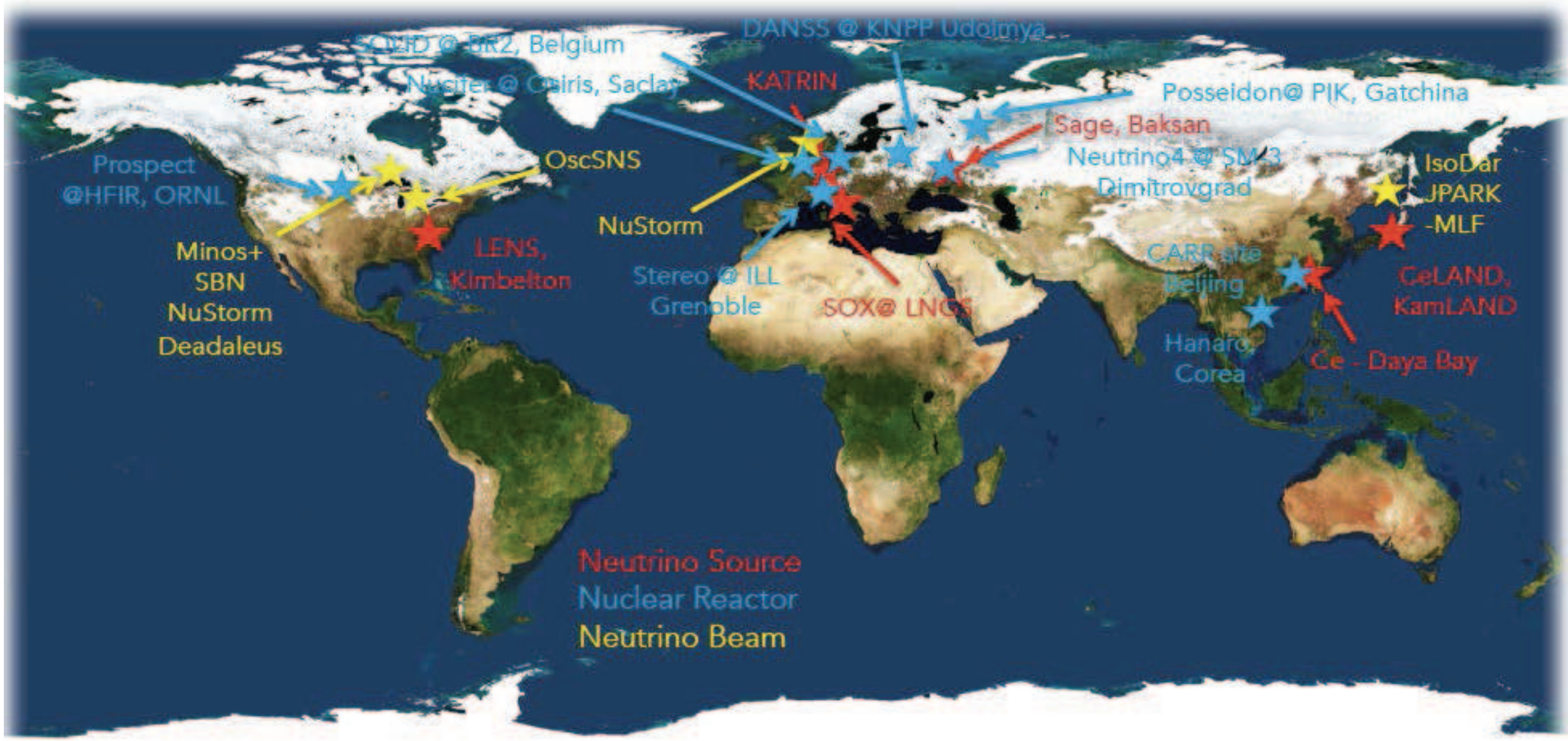


(Fig from Giunti etal, 2110.06820)

Anomaly $\sim 1\,\sigma$

with new fluxes

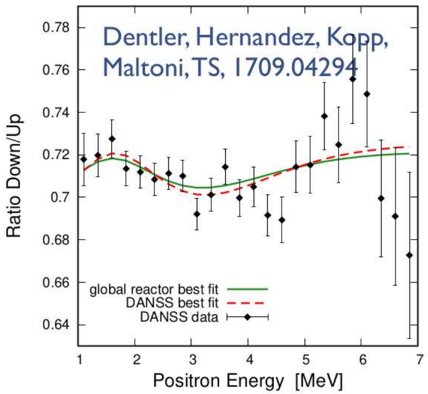
Searches for eV sterile neutrinos



This talk: (anti-) ν_e disapearance only

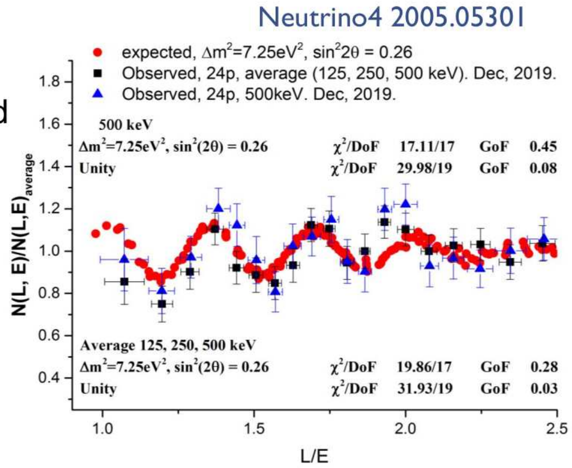
$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

Recent relative spectral measurments

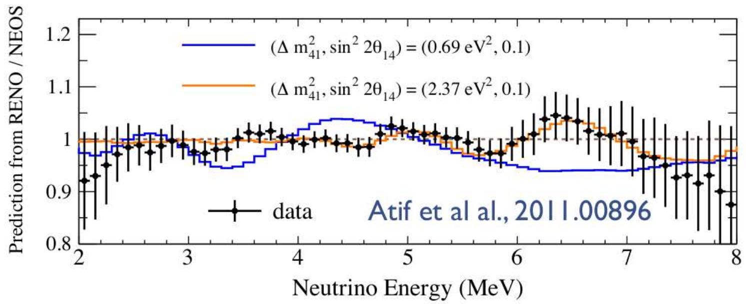


DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20 (update at EPS-HEP21)

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



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 ν_s oscillations

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- Other NP at play?

Non Standard ν Interactions (NSI)

At dimension-6 new 4-fermion interactions involving ν's.

Some can afffect CC process in production and detection

$$(\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta)(\bar{f}' \gamma^\mu P f)$$

and can be strongly constrained with charged lepton processes

Some affect only NC ν interactions

$$(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f)$$

and are more poorely constrained

NC-Non Standard ν Interactions in ν-OSC

Including non-standard neutrino NC interactions with fermion f

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

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$$H_{\rm mat} = \sqrt{2}G_F N_e(r)\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2}G_F N_e(r)\begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

$\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=ued}\frac{N_f(r)}{N_e(r)}\varepsilon_{\alpha\beta}^{fV}$ $\Rightarrow$ 3ν evolution depends on 6 (vac) + 8 per f (mat)

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$\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=ued} \frac{N_f(r)}{N_e(r)} \varepsilon^{fV}_{\alpha\beta}$ $\Rightarrow$ 3ν evolution depends on 6 (vac) + 8 per f (mat)

$\Rightarrow$ Parameters degeneracies

In particular $H \to -H^*$ $\Rightarrow$ same Probabilities $\Rightarrow$ invariance under simultaneously:

$$\theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12}\,, \qquad (\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2\,,$$

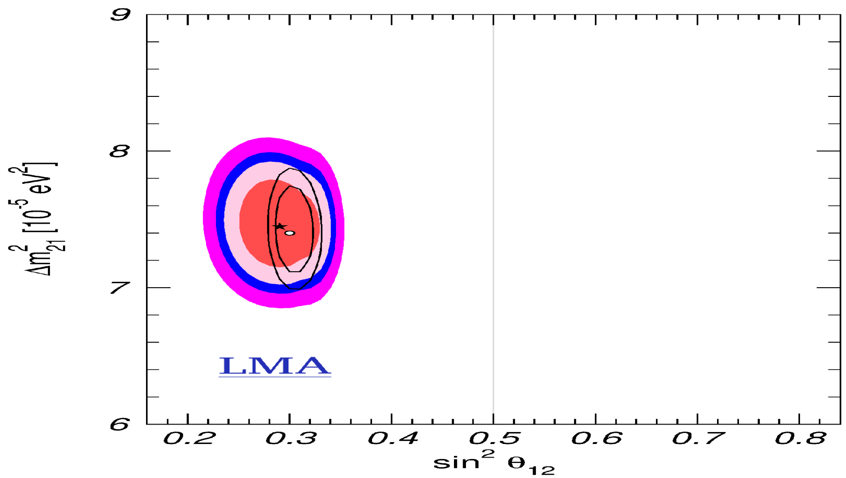
$$\Delta m^2_{31} \to -\Delta m^2_{32}\,, \qquad (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu})\,,$$

$$\delta \to \pi - \delta\,, \qquad \varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,,$$

$\Rightarrow$ Degeneracies in θ_{12} octant and mass ordering

NSI: Bounds/Degeneracies from/in Oscillation data

Esteban *etal* JHEP'18[1805.04530] Coloma, Esteban, MCGG, Maltoni, JHEP'19[1911.09109] (updated 2020)

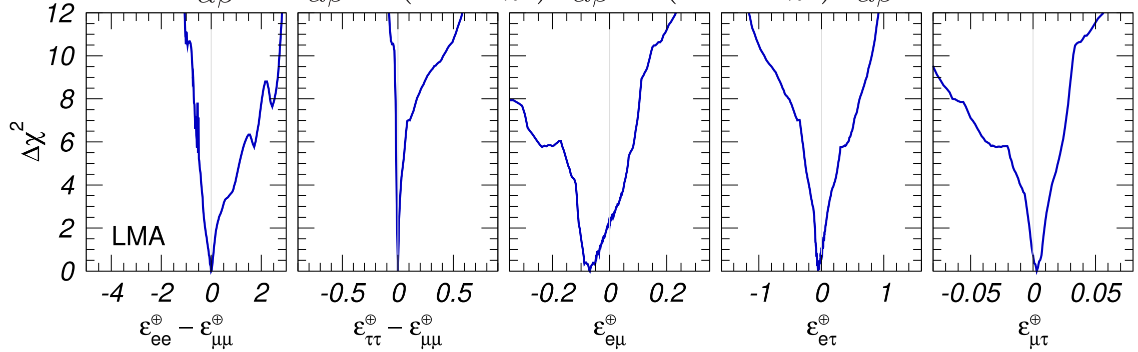


	LMA
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$

- Standard Fit $\equiv$ LMA $\Rightarrow$ Bounds $\mathcal{O}(1\% - 10\%)$

  $\Rightarrow$ Maximum effect at LBL experiments:

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



$\Rightarrow$ To be considered in effects/sensitivity studies at DUNE, HK… (tables available)

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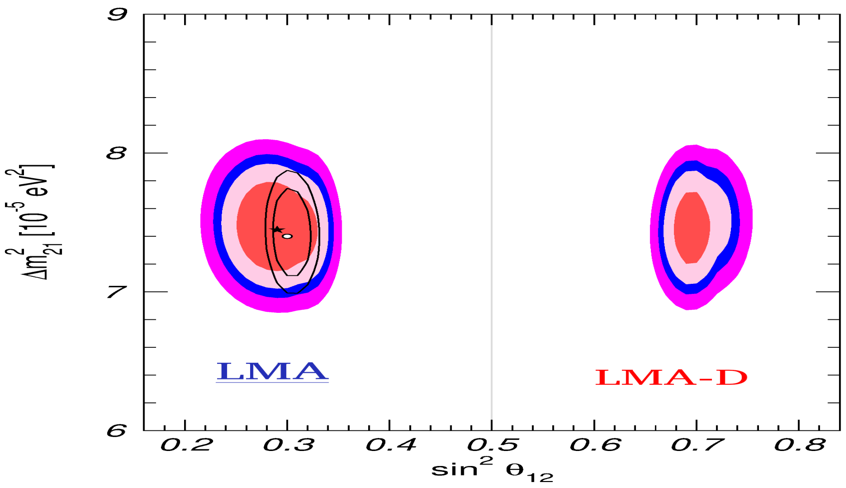

	LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$	$\oplus[-1.042, -0.743]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.016, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$	$[-0.050, +0.059]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$	$[-0.111, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$

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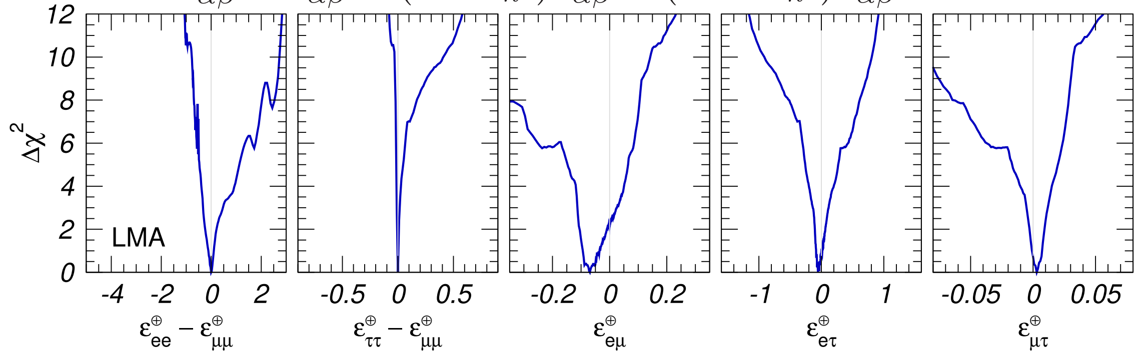

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- Degenerate solution $\equiv$LMA-D

  Miranda,Tortola, Valle, hep-ph/0406280

  $\Rightarrow \theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12}$ & $(\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2$

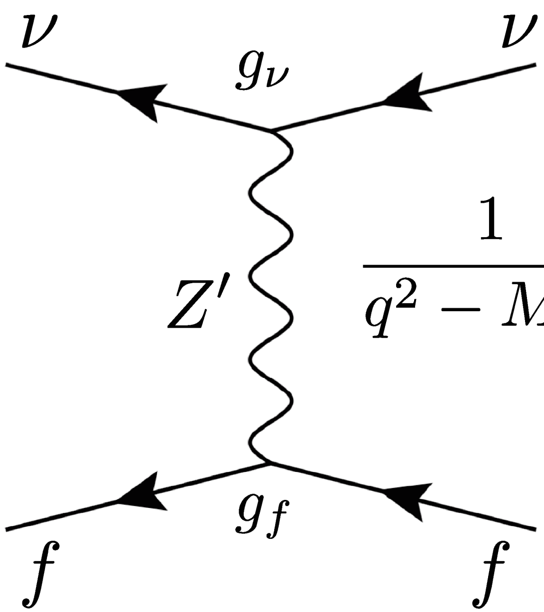
  $\Rightarrow$ Requires NSI $\sim G_F$ (light mediators?)

  Farzan 1505.06906, and Shoemaker 1512.09147

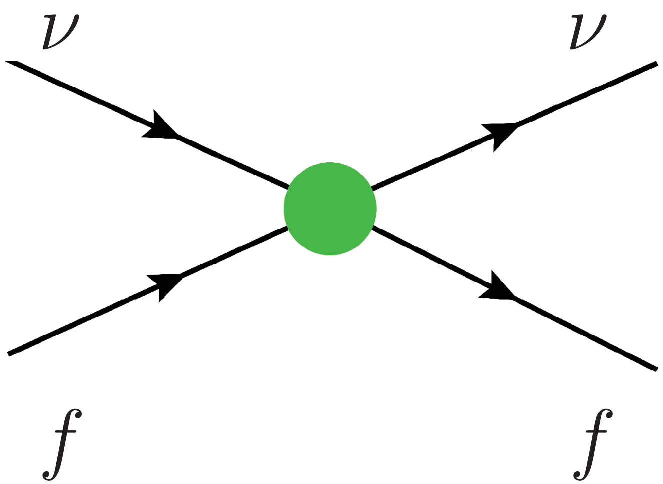
Oscillation bounds on Z'/Dark Photons

Coloma, MCGG, Maltoni, JHEP'21 [2009.14220]

Interpreting



$$\frac{1}{q^2 - M_{Z'}^2} \quad \Longleftarrow_{q^2 \to 0}$$

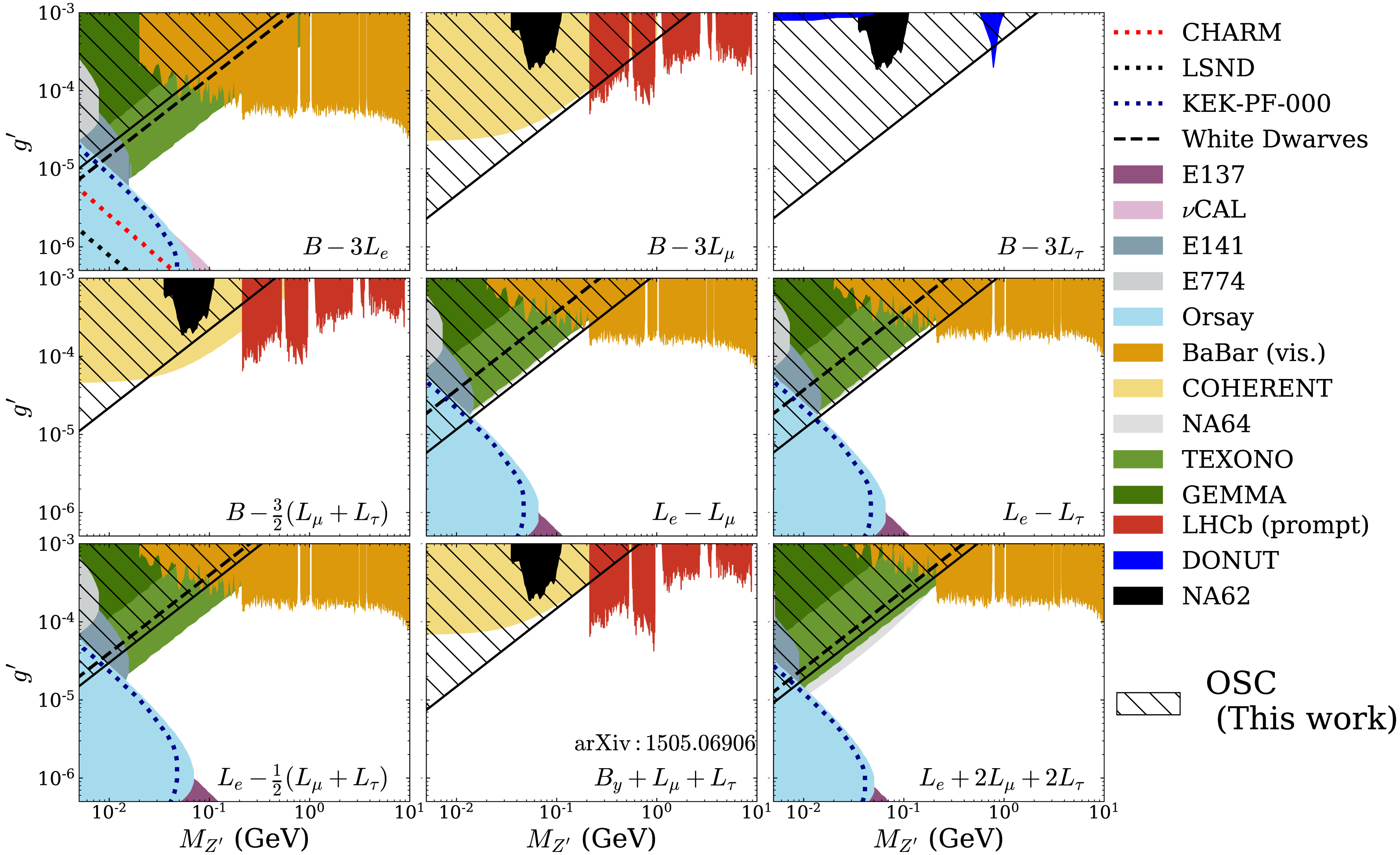


$$\frac{g'^2}{M_{Z'}^2} \, q'_f \, q'_\nu \qquad \Leftarrow \qquad \epsilon^f_{\alpha\beta}$$

Z' Models: ν Oscillations Bounds

Coloma, MCGG, Maltoni ArXiv:2009.14220

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



$\Rightarrow$ Bounds from Oscillations stronger than scattering bounds on some models

Z' Models: Long Range Regime

For extremely light Z' the potential encountered by ν at $\vec{x}$ depends on the integral of the source density within a radius $\sim 1/M_{Z'}$ around it

We can still formally write $H_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1+\varepsilon_{ee}(\vec{x}) & 0 & 0 \\ 0 & \varepsilon_{\mu\mu}(\vec{x}) & 0 \\ 0 & 0 & \varepsilon_{\tau\tau}(\vec{x}) \end{pmatrix}$

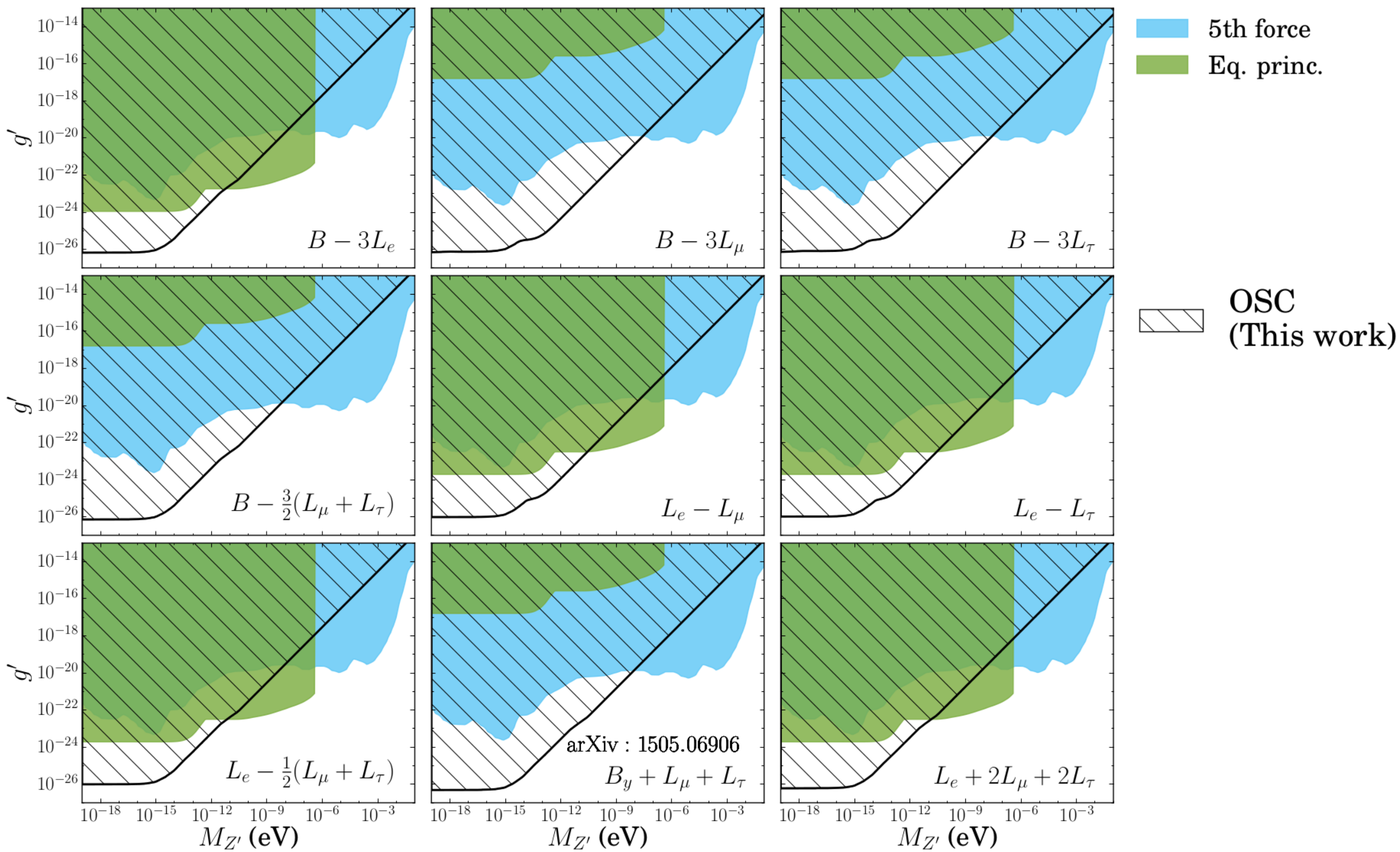
$$\varepsilon_{\alpha\beta}(\vec{x}) \equiv \sum_f \frac{\hat{N}_f(\vec{x}, M_{Z'})}{N_e(r)} \varepsilon^f_{\alpha\beta} \qquad \hat{N}_f(\vec{x}, M_{Z'}) \equiv \frac{4\pi}{M^2_{Z'}} \int N_f(\vec{\rho}) \, \frac{e^{-M_{Z'}|\vec{\rho}-\vec{x}|}}{|\vec{\rho}-\vec{x}|} \, d^3\vec{\rho}$$

de Holanda, MCGG, Masso,Zukanovich hep-ph/0609094

Z'/Dark-photon: Bounds from ν Oscillations

Coloma, MCGG, Maltoni, JHEP'21 [2009.14220]

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

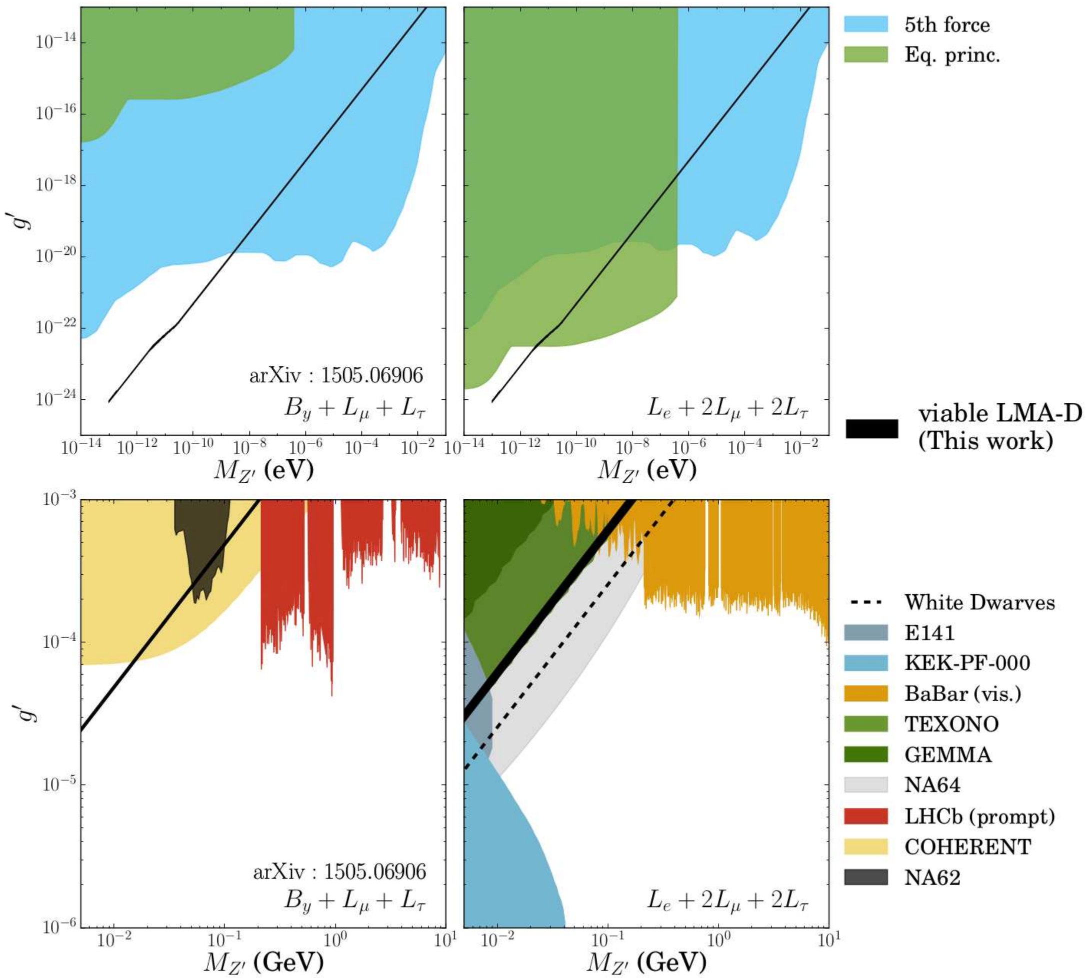


$\Rightarrow$ Bounds from Oscillations stronger than 5th force and VEP experiments

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. Two examples



Coloma, MCGG, Maltoni ArXiv:2009.14220

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Bottom-up: Light ν from *Generic* New Physics

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

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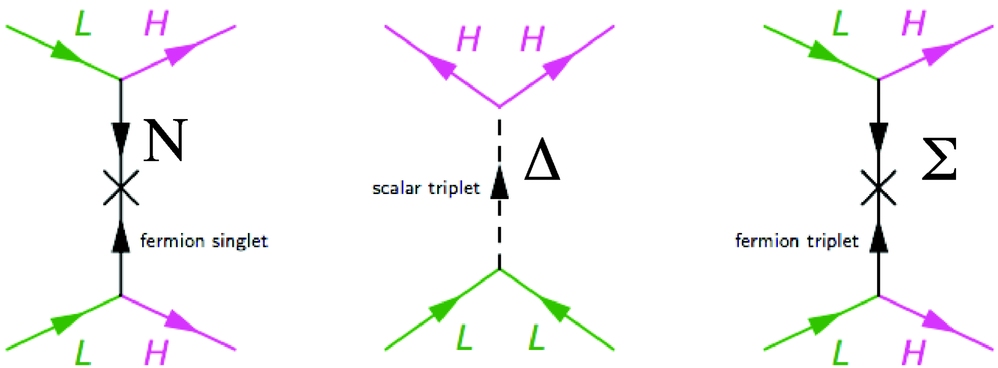
– $m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV for $Z^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}{\rm GeV} \Longrightarrow$ $\Lambda_{\rm NP} \sim$ GUT scale

$\Rightarrow$ Leptogenesis possible

[But if $Z^\nu \sim (Y_e)^2 \Rightarrow \Lambda_{\rm NP} \sim$ TeV scale]

Model Degeneracy at Low Energy

$\mathcal{O}_5$ is generated for example by tree-level exchange of singlet ($N_i \equiv (1,1)_0$) (Type-I) or triplet fermions ($N_i \equiv \Sigma_i \equiv (1,3)_0$) (Type-III) or a scalar triplet $\Delta \equiv (1,3)_1$ (Type-II)



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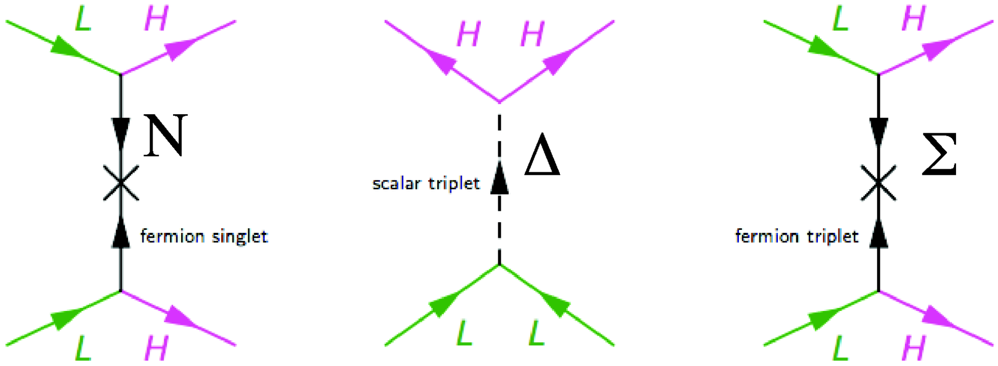

• For fermionic see-saw $-\mathcal{L}_{\rm NP} = -i\overline{N_i}\not{D}N_i + \frac{1}{2}M_{N\,ij}\overline{N_i^c}N_j + \lambda^\nu_{\alpha j}\overline{L_\alpha}\tilde{\phi}N_j[.\tau]$

$$\Rightarrow \mathcal{O}_5 = \frac{(\lambda^{\nu T}\lambda^\nu)_{\alpha\beta}}{\Lambda_{\rm NP}}\left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) \quad \text{with} \quad \Lambda_{\rm NP} = M_N$$

• For scalar see-saw $-\mathcal{L}_{\rm NP} = f_{\Delta\,\alpha\beta}\overline{L_\alpha}\,\Delta\,L^C_\beta + M^2_\Delta\,|\Delta|^2 + \kappa\,\phi^T\,\Delta^\dagger\,\phi\,\ldots$

$$\Rightarrow \mathcal{O}_5 = \frac{f_{\Delta\,\alpha\beta}}{\Lambda_{NP}}\left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) \quad \text{with} \quad \Lambda_{\rm NP} = \frac{M^2_\Delta}{\kappa}$$

Very different physics, but same ν parameters: How to proceed?

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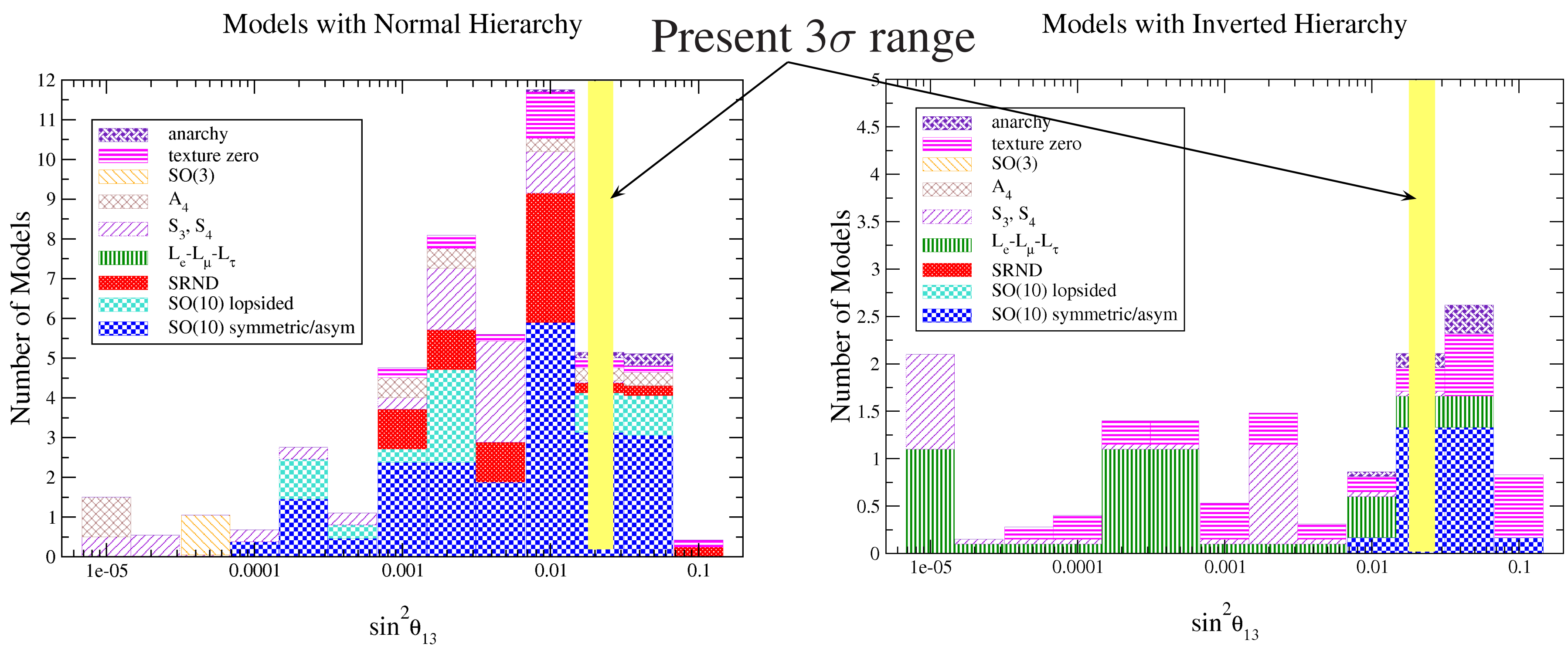
Same $\mathcal{O}_5$ can be generated by very different High Energy physics

Very different physics, but same ν parameters: How to proceed?

– Top-down: Assume some specific model and work out the relations

Modeling Lepton Flavour: 2006 to 2022

- Survey of 63 ν mass models in 2006 (Albright, M-C Chen,hep-ph/0608136)



– Determination of θ_{13} has given us important handle in flavour modeling

– Next *frontier* is the ordering

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– Search for additional information from charged LFV, collider signals . . .

Connection to CLFV & Collider Signatures?

- ν oscillation $\Rightarrow$ Lepton Flavour is not conserved and generically new $\Lambda_{\rm NP}$ scale

  If only $\mathcal{O}_5$ $\Rightarrow Br(\tau \to \mu\gamma) \sim 10^{-41}$ too small and $\Lambda_{\rm NP} \sim v^2/m_\nu$ too high

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- In general to have observable LFV one needs to *decouple* :

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

  New Physics scale Λ_{LF} ($\ll \Lambda_{LN}$) controlling of LFV

  and if heavy state mass $M \sim \Lambda_{LF} \sim$ TeV $\Rightarrow$ Collider signatures

  Furthermore if $c_{6,i} \propto c_5{}^{\text{some power}} \Rightarrow$ LFV and coll signals directly related to M_ν

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Minimal Lepton Flavour Violation

Cirigliano, Grinstein, Isidori, Wise(05); Davidson, Palorini (06); Gavela, Hambye, Hernandez,Hernandez (09)
Alonso, Isidori, Merlo, Munoz, Nardi(11)

MLFV & Collider Signatures

- Minimal Flavour Violation Hypothesis: Chivukula, Georgi (87) Buras, Gambino, Gorbahn, Jager, Silvestrini,(01) d'Ambrosio, Giudice, Isidori, Strumia (02)

  Yukawas are the only source of flavour violation in and beyond SM

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- Scalar (Type-II) see-saw is MLFV

  $c_{5,\alpha\beta} = f_{\Delta\,\alpha\beta}\frac{\kappa}{M_\Delta}$ $\qquad$ $c_{6,\alpha\beta\gamma\rho} = f^\dagger_{\Delta\,\alpha\beta} f_{\Delta\,\gamma\rho}$

- If $M_\Delta \lesssim$ TeV

  $\Rightarrow$ Production of triplet scalars: $H^{\pm\pm}$ $H^\pm$, A_0, H_0

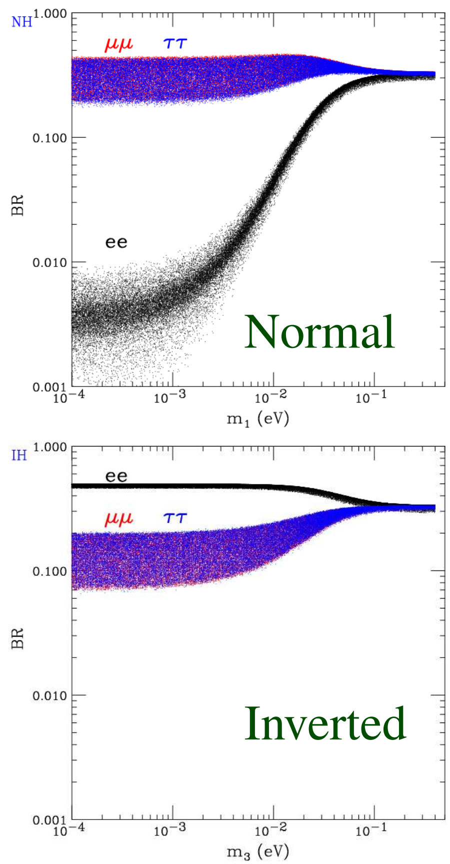
Striking Signatures

$$pp \to H^{++}H^{--}$$

$$pp \to H^{++}H^{-}$$

$\Rightarrow$ $\quad H^{\pm\pm} l_i^\pm l_j^\pm$, $H^\pm \to l_i^\pm \nu_j$

predicted by neutrino parameters



Akeroyd *et al*, Chao *et al*, Fileviez *et al*
Garayoa *et al*, Han *et al*, Kadastik *et al* ...

MLFV & Collider Signatures

- MLFV Fermionic (I or III) Inverse see-saw

  Gavela, Hambye, Hernandez,Hernandez (09)

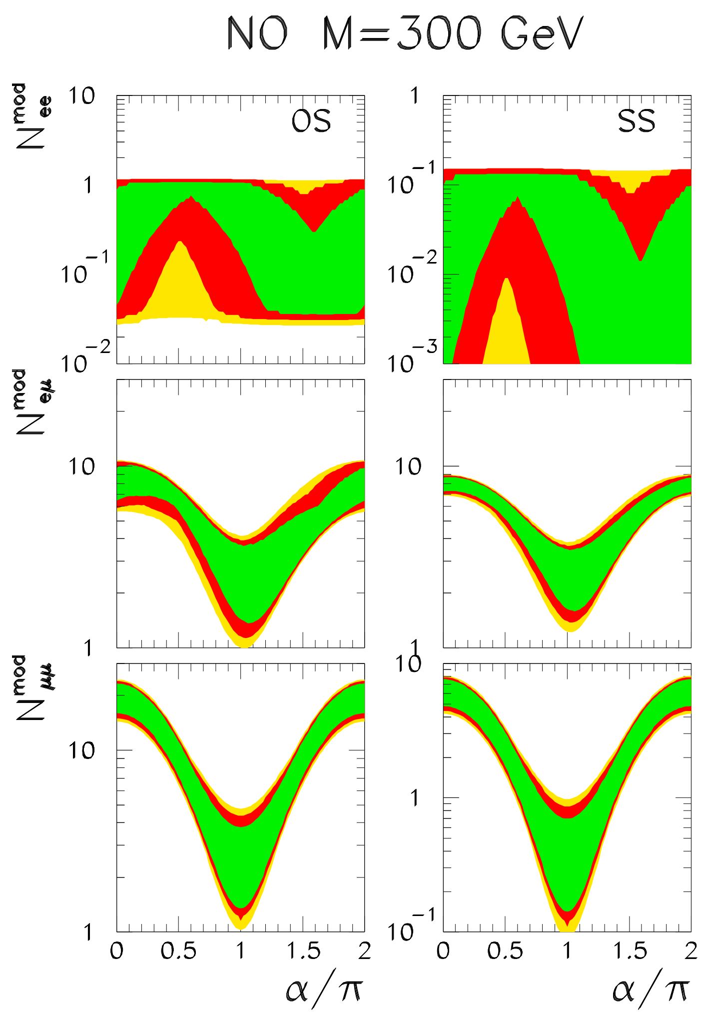
  $\rightarrow$ one massless ν & one CP phase α

  $\rightarrow$ Yukawas $\lambda_{\alpha N}$ determined by ν parameters

- At LHC:
  - Type-I unobservable but Type-III observable

    $$pp \rightarrow F(\rightarrow \ell_\alpha X)F'(\rightarrow \ell_\beta X')$$

  - Rates predictable in terms of ν parameters
  - Unambiguous constraints from existing data
  - Best with final state flavour and charge info



Rosa-Agostinho,Eboli, MCGG 1708.08456

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Answer will require some positive signal in colliders, CLFV . . . experiments

THANK YOU

BACK-UP SLIDES

Summary: Global 3 ν Flavour Parameters

Evolution of global 3 flavour fit

Gonzalez-Garcia, Maltoni, TS [arXiv:2111.03086]

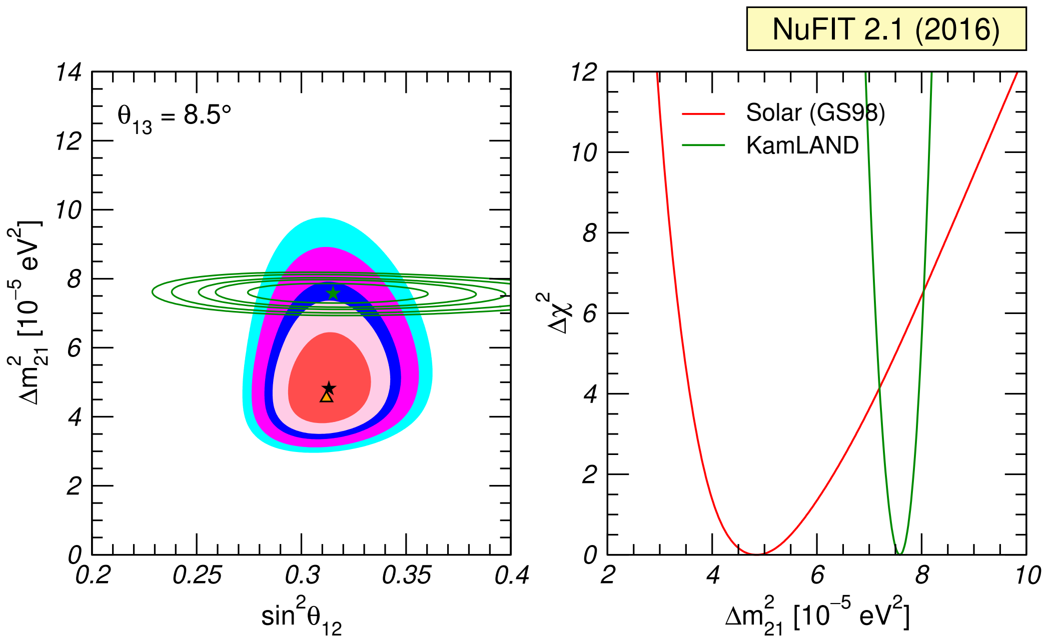
	2012 NuFIT 1.0	2014 NuFIT 2.0	2016 NuFIT 3.0	2018 NuFIT 4.0	2021 NuFIT 5.1	
θ_{12}	15%	14%	14%	14%	14%	**1.07**
θ_{13}	30%	15%	11%	8.9%	9.0%	**3.3**
θ_{23}	43%	32%	32%	27%	27%	**1.6**
Δm^2_{21}	14%	14%	14%	16%	16%	**0.88**
$\|\Delta m^2_{3\ell}\|$	17%	11%	9%	7.8%	6.7% [6.5%]	**2.5**
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]	**1 [1.2]**
$\Delta\chi^2_{\text{IO-NO}}$	± 0.5	-0.97	$+0.83$	$+4.7$ [$+9.3$]	$+2.6$ [$+7.0$]	

w/o [w] SK atm data

relat. precision at 3σ: $\frac{2(x^+ - x^-)}{(x^+ + x^-)}$

improvement factor from 2012 to 2021

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



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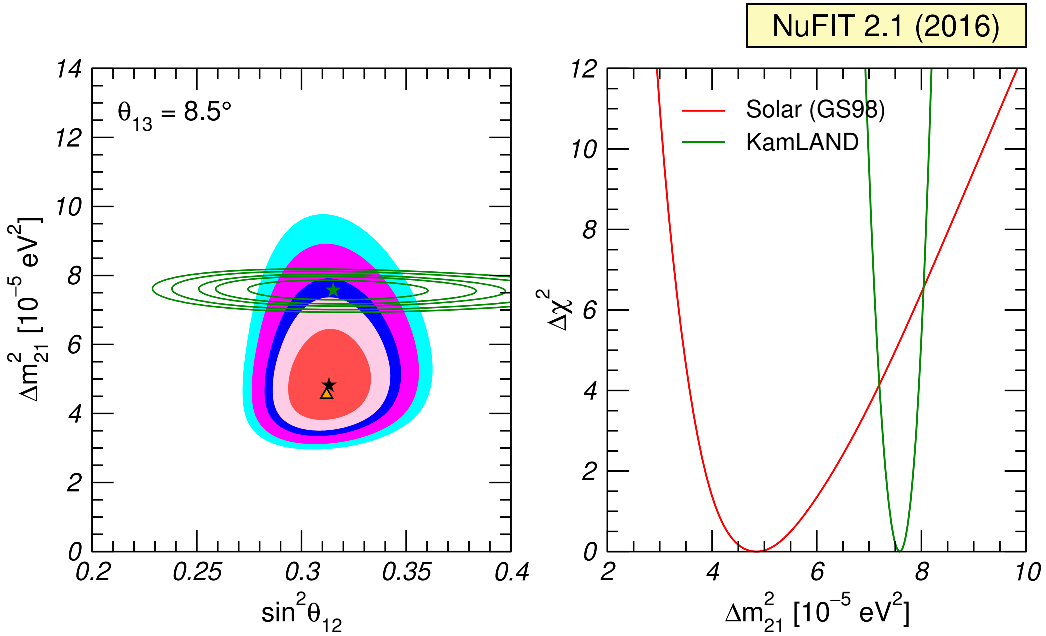

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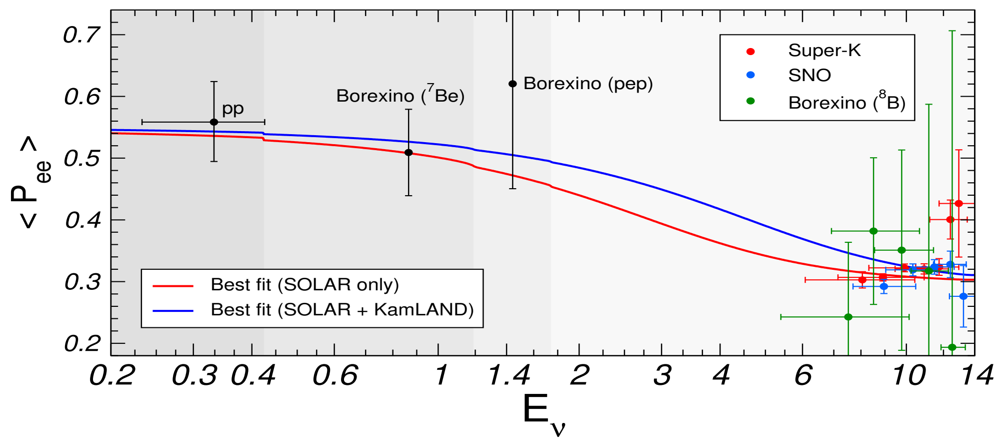
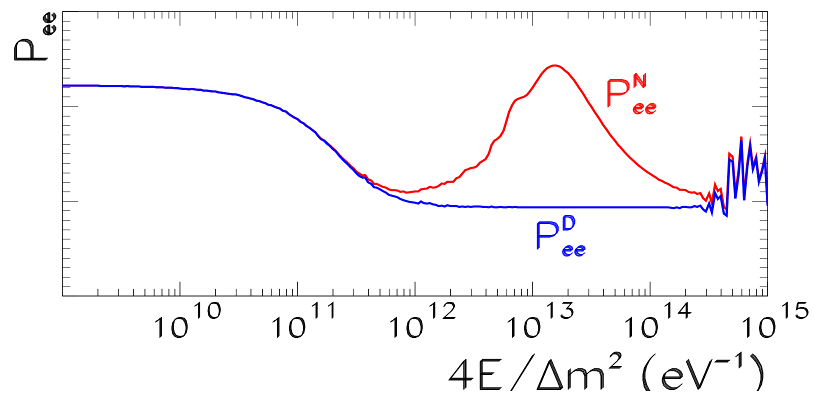


"too large" of Day/Night at SK

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



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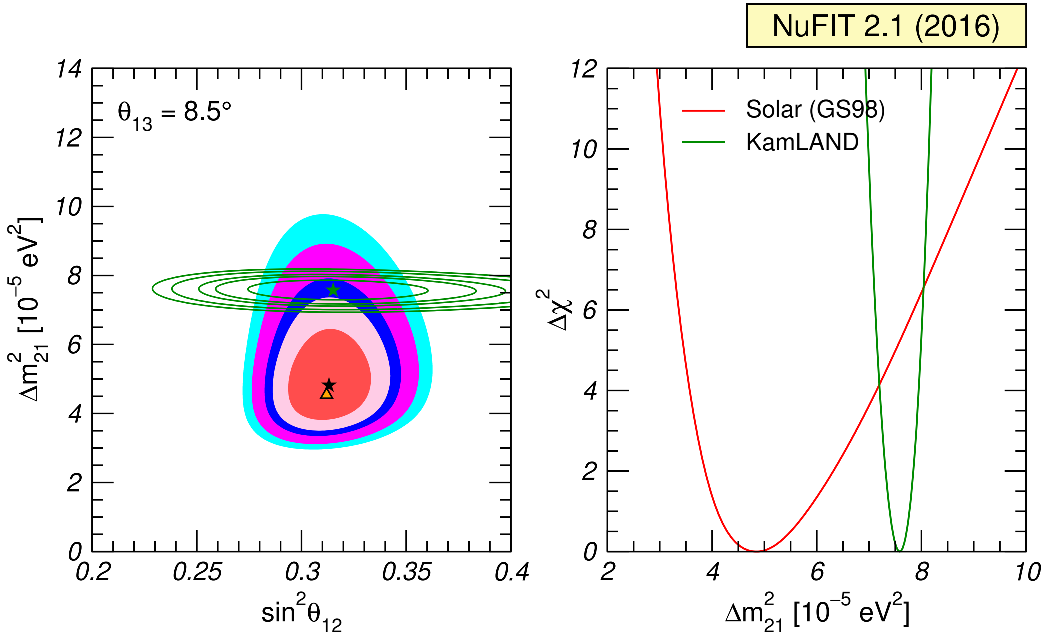

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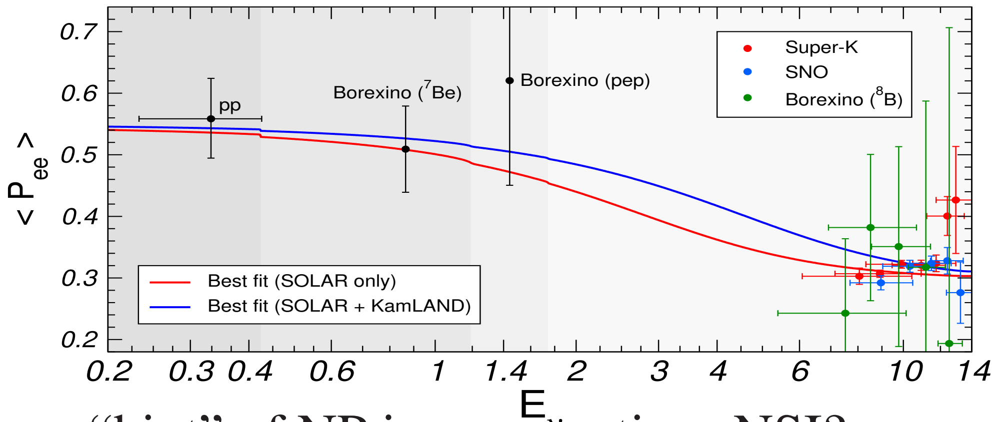

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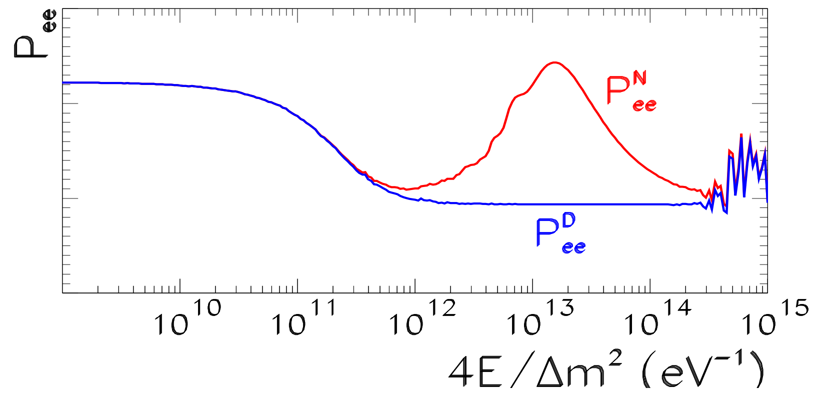
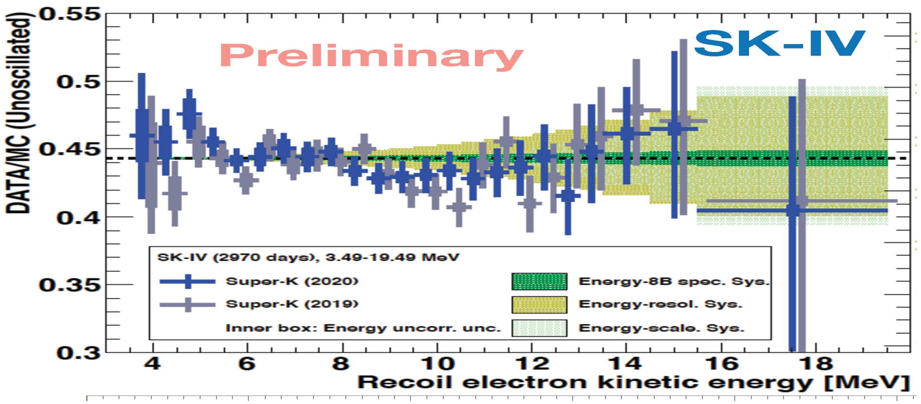


$\Rightarrow$ "hint" of NP in propagation: NSI?

- AFTER NU2020: With SK4 2970 days data

Slightly more pronounced low-E turn-up



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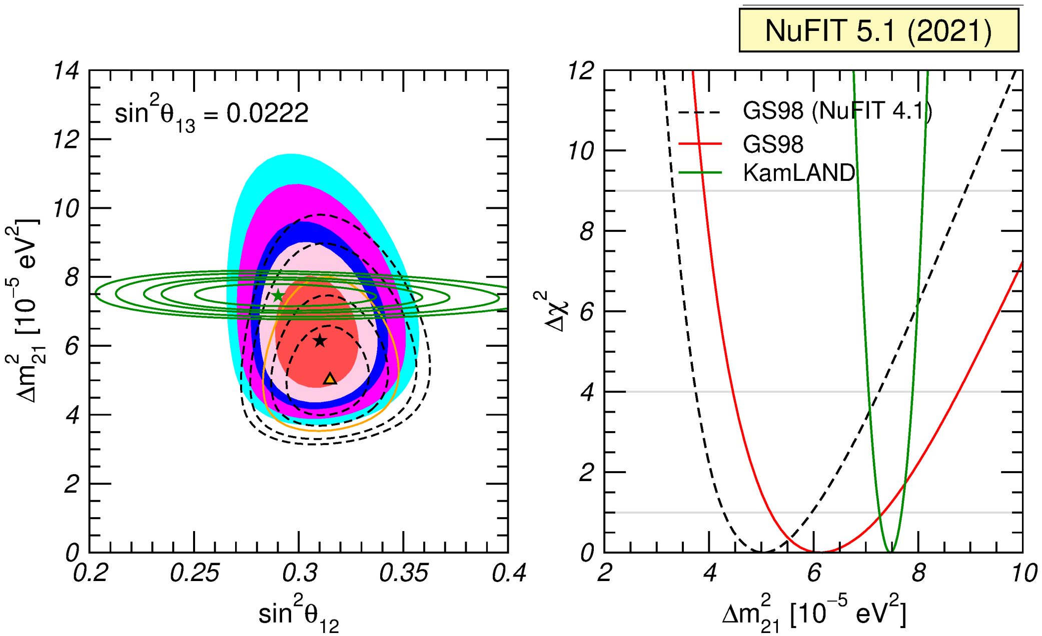
$$A_{\rm D/N,SK4-2970} = [-2.1 \pm 1.1]\%$$

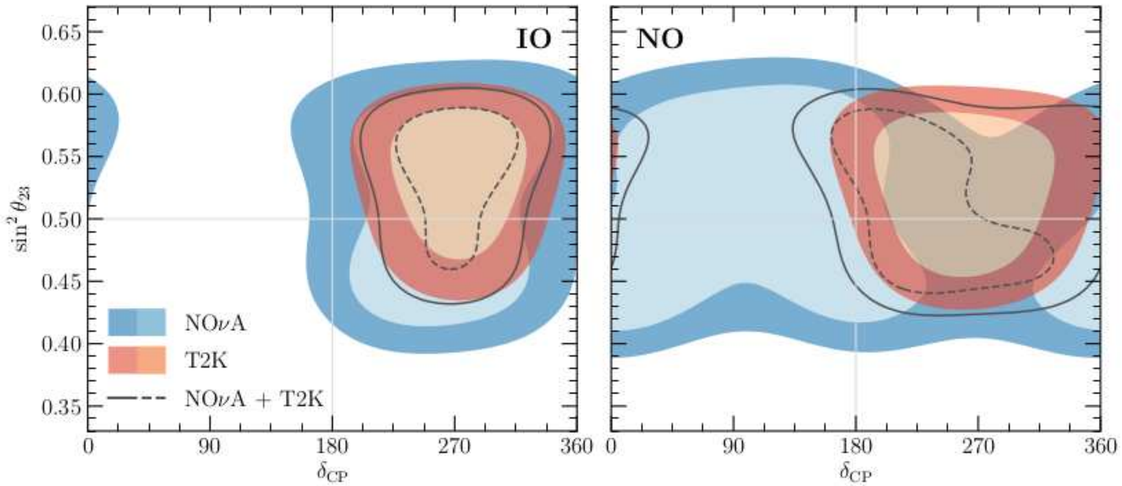
- In NuFIT 5.1



$\Rightarrow$ Agreement of Δm^2_{21} between solar and KamLAND at 1 σ

Compatibility T2K/NOνA

- 1 and 2 σ (2dof) allowed regions (for $s^2_{13} = 0.0224$, marg over $|\Delta m^2_{3\ell}|$)



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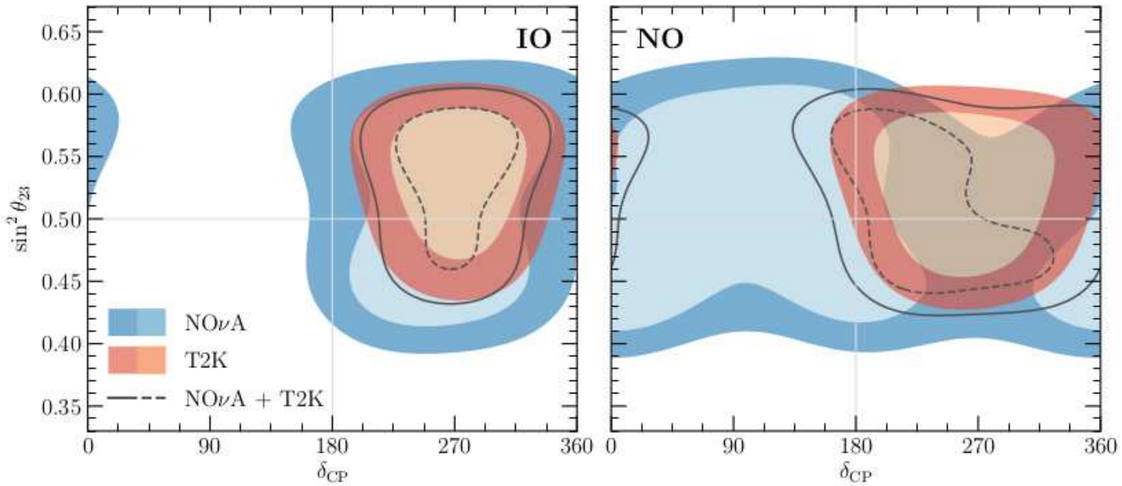

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- Parameter goodness-of-fit (PG) test:

	normal ordering			inverted ordering		
	χ^2_{PG}/n	p-value	$\#\sigma$	χ^2_{PG}/n	p-value	$\#\sigma$
T2K vs NOvA (θ_{13} free)	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs NOvA (θ_{13} fix)	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ

No significant incompatibility

Leptonic CP Violation

- Leptonic $\not{C}$P $\Rightarrow P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$:

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto J \quad \text{with} \quad J = \text{Im}(U_{\alpha 1} U^*_{\alpha_2} U_{\beta 2} U^*_{\beta_1}) = J^{\max}_{\text{LEP,CP}} \sin \delta_{\text{CP}}$$

$$J^{\max}_{\text{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

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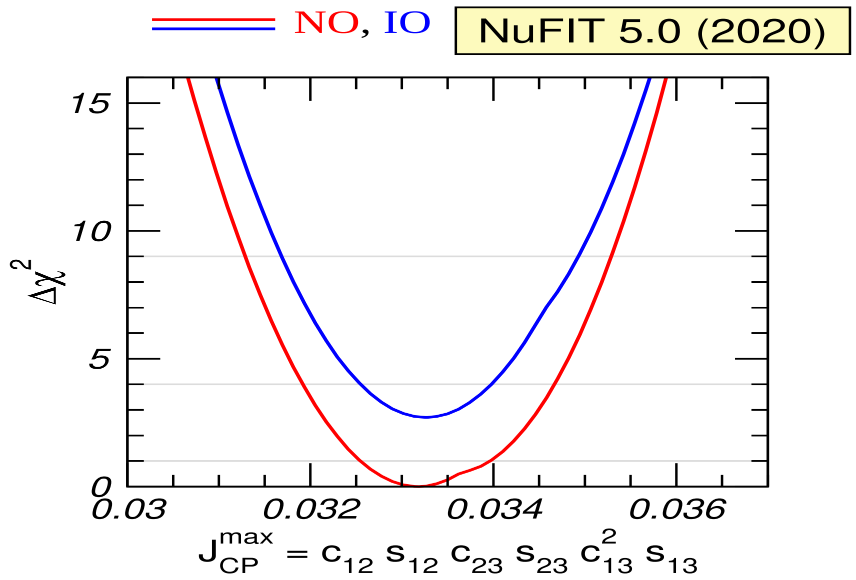
- Maximum Allowed Leptonic CPV:



$$J^{\max}_{\text{LEP,CP}} = (3.29 \pm 0.07) \times 10^{-2}$$

to compare with

$$J_{\text{CKM,CP}} = (3.04 \pm 0.21) \times 10^{-5}$$

$\Rightarrow$ Leptonic CPV may be largest CPV
in New Minimal SM

if $\sin \delta_{\text{CP}}$ not too small

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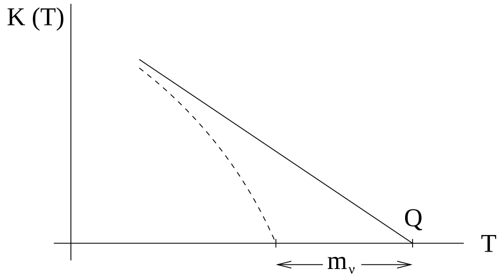
Neutrino Mass Scale: β Decay

Single β decay : Dirac or Majorana ν mass modify spectrum endpoint



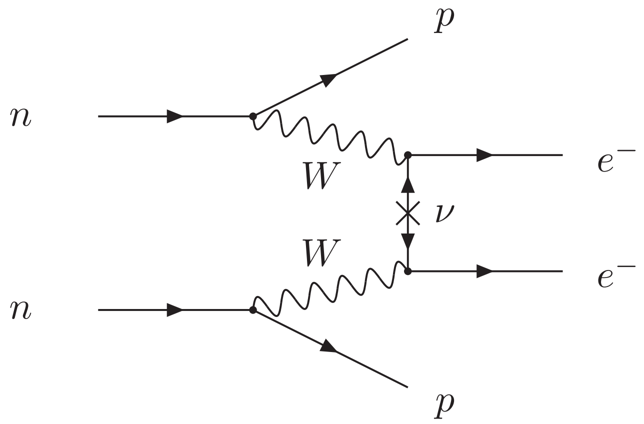
$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2$$

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

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

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

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



If m_ν only source of ΔL

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\, M_{\rm nucl}^2\, m_{ee}^2$$

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

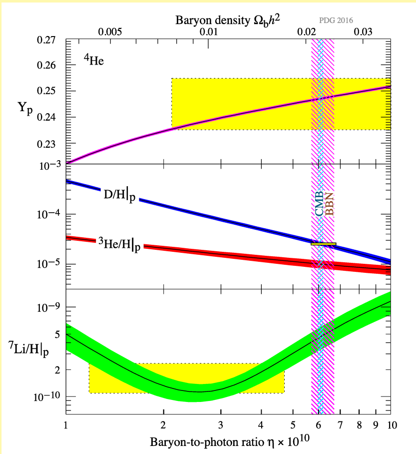
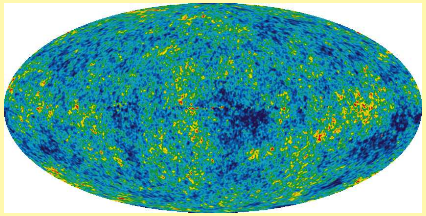
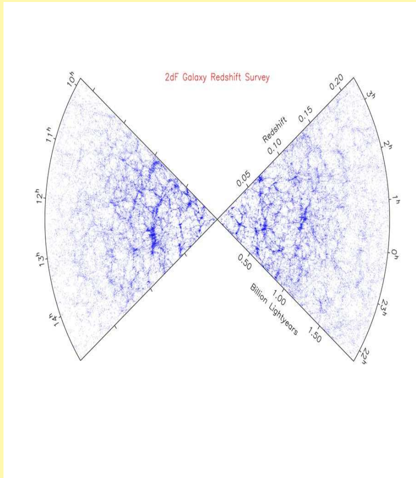
At present only bounds

Isotope	Experiment	year	$T_{1/2}$ limit (yr)	$m_{\beta\beta}$ (meV)
^{76}Ge	GERDA	2020	1.8×10^{26}	79 – 180
^{76}Ge	MAJORANA DEMONSTRATOR	2019	2.7×10^{25}	200 – 433
^{136}Xe	KamLAND-Zen	2022	2.3×10^{26}	36 – 156
^{136}Xe	EXO-200	2019	3.5×10^{25}	93 – 286
^{130}Te	CUORE	2022	2.2×10^{25}	90 – 305

Light massive ν in Cosmology

Relic $\nu' s$: Effects in several cosmological observations at several epochs

Mainly via two effects: $\rho_r = \left[1 + \frac{7}{8} \times \left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right] \rho_\gamma$ and $\sum_i m_{\nu_i}$

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Large Scale Structure Formation LSS
$T \sim$ MeV	$T \lesssim$ eV	
Number of $\nu' s$ ($N_{\rm eff}$)	$N_{\rm eff}$ and $\sum m_\nu$	

BUT: Observables also depend on all other cosmo parameters (and assumptions)

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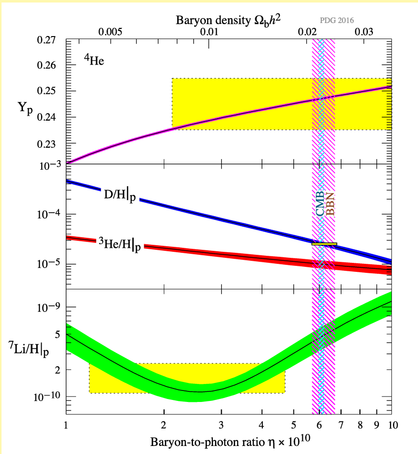	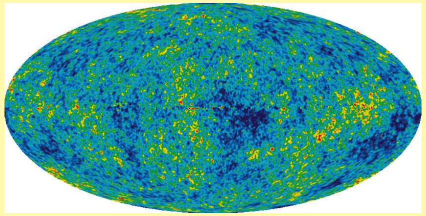	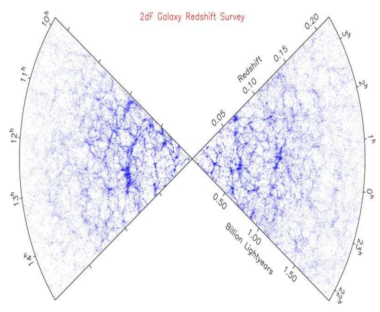
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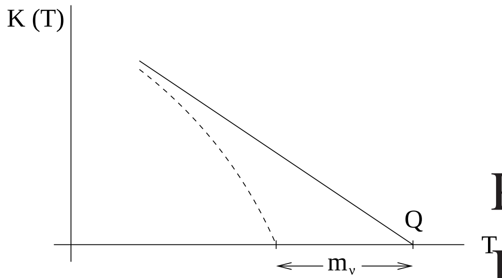
$\sum m_\nu < 0.26\,\text{eV}$ **Planck**
$\sum m_\nu < 0.12\,\text{eV}$ **Planck+BAO**
$\sum m_\nu < 0.86\,\text{eV}$ **BOSS P(k)**
$\sum m_\nu < 0.16\,\text{eV}$ **Planck+BOSS P(k)**
$\sum m_\nu < 0.58\,\text{eV}$ **Lyman-α+H_0prior**
$\sum m_\nu < 0.10\,\text{eV}$ **Planck+Lyman-α**
$\sum m_\nu < 0.08\,\text{eV}$ **Planck+BAO+H_0**
$\sum m_\nu < 0.09\,\text{eV}$ **Planck+BAO+SN+RSD**

BUT: Observables also depend on all other cosmo parameters (and assumptions)

Probes of Mass Scale in 3ν-mixing

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

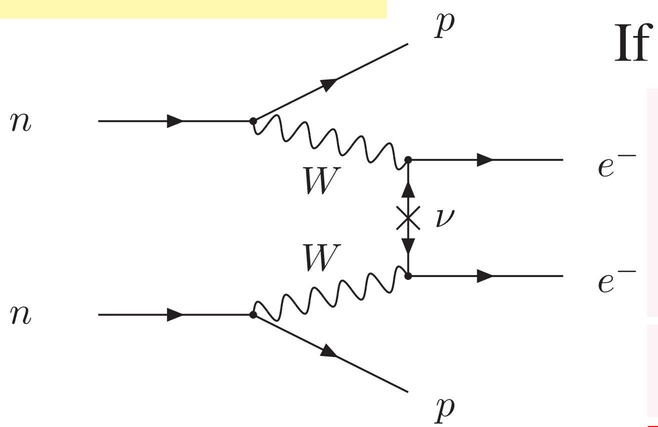


$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = \begin{cases} \text{NO}: \; m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: \; m^2_\ell + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

Present bound: $m_{\nu_e} \leq 0.8$ eV (90% CL KATRIN 2022)

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

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



If m_ν only source of ΔL: $(T^{0\nu}_{1/2})^{-1} = G^{0\nu} M^2_{\text{nucl}} m^2_{ee}$

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

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

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

Present Bounds: $m_{ee} < 0.04$–0.5 eV

COSMO for Dirac or Majorana

m_ν affect growth of structures

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

Neutrino Mass Scale: The Cosmo-Lab Connection

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

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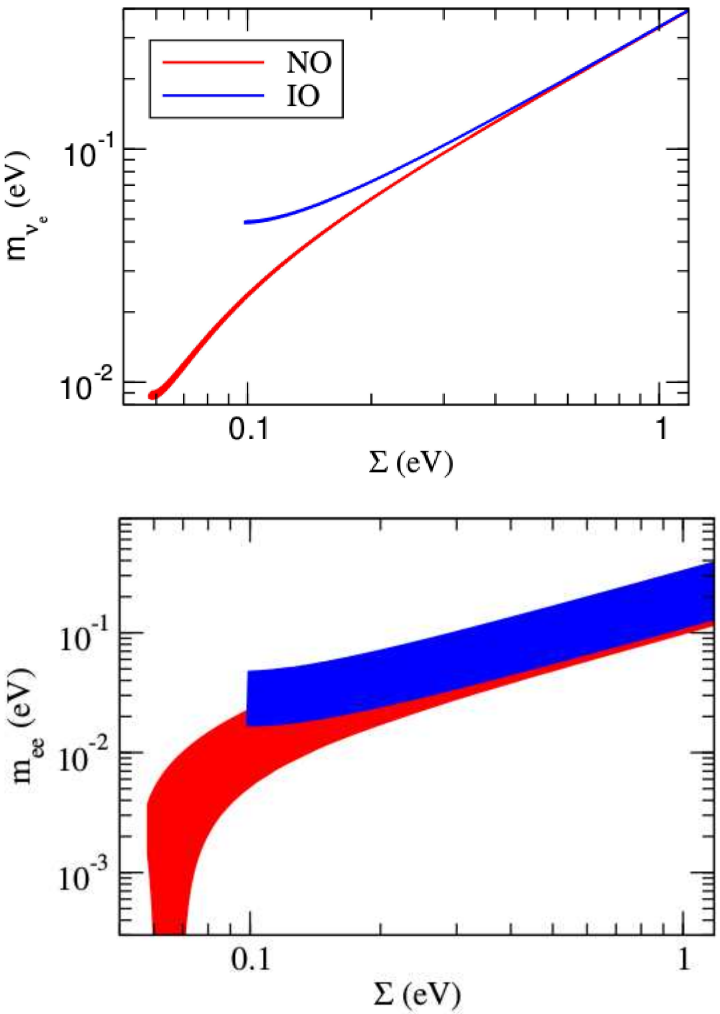
NuFIT 4.1 (2019)



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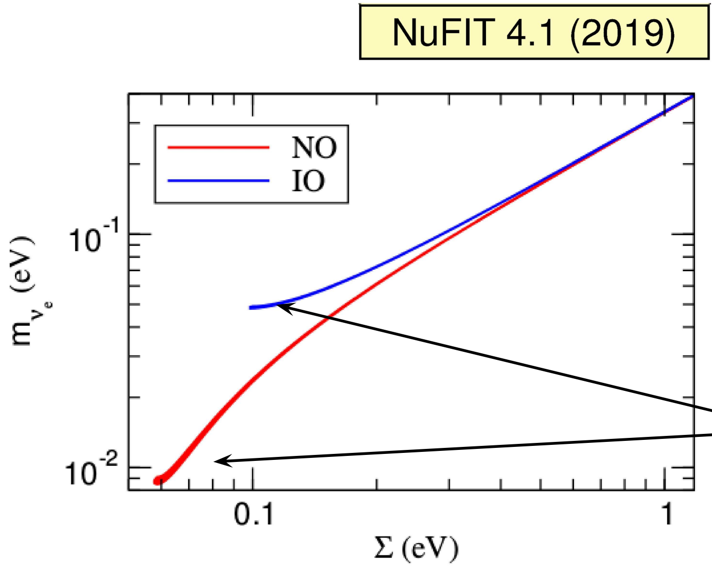
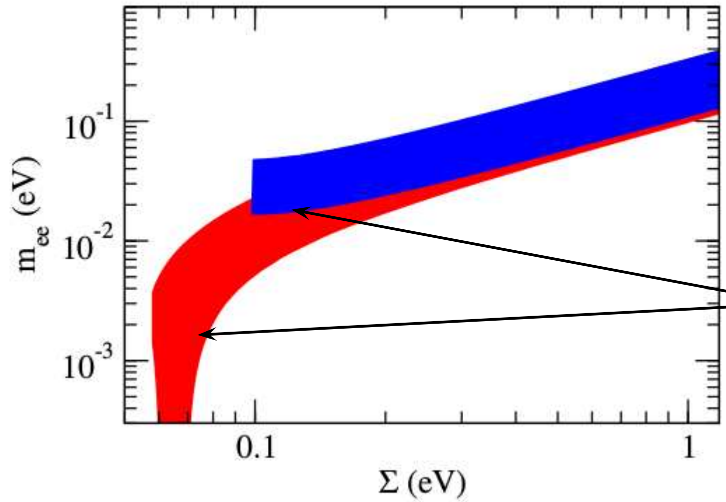


Width due to range in oscillation parameters very narrow

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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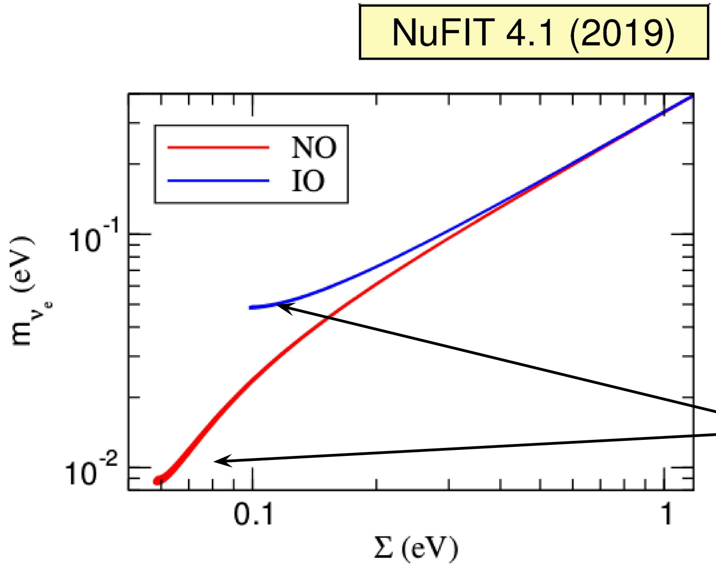

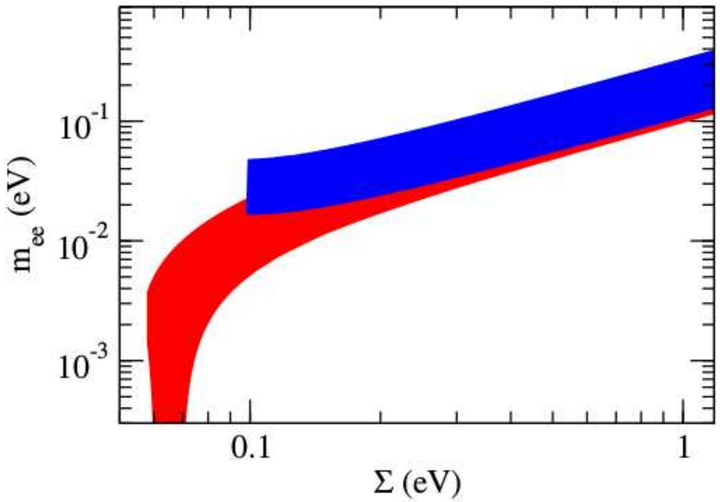

Lower bound on $\sum m_i$ depends on ordering

Precision determination/bound of $\sum m_i$ can give information on ordering ?

Hannestad, Schwetz 1606.04691, Simpson etal 1703.03425, Capozzi etal 1703.04471 …

Cosmo data will only add to N/I likelihood
when accuracy on Σm_ν better than 0.02 eV
(to see a 2σ N/I difference between 0.06 and 0.1)

Hannestad, Schwetz 1606.04691

Alternative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

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- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to gravitational potential* ϕ

$$\lambda = \frac{\pi}{E|\phi|\delta\gamma}$$

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97

Non universal asymptotic velocity of neutrinos $c_1 \neq c_2 \Rightarrow E_i = \frac{m_i^2}{2p} + c_i p$

$$\lambda = \frac{2\pi}{E\Delta c}$$

Interactions with space-time torsion: Sabbata, Gasperini 81

Non universal couplings of neutrinos $k_1 \neq k_2$ *to torsion strength* Q

$$\lambda = \frac{2\pi}{Q\Delta k}$$

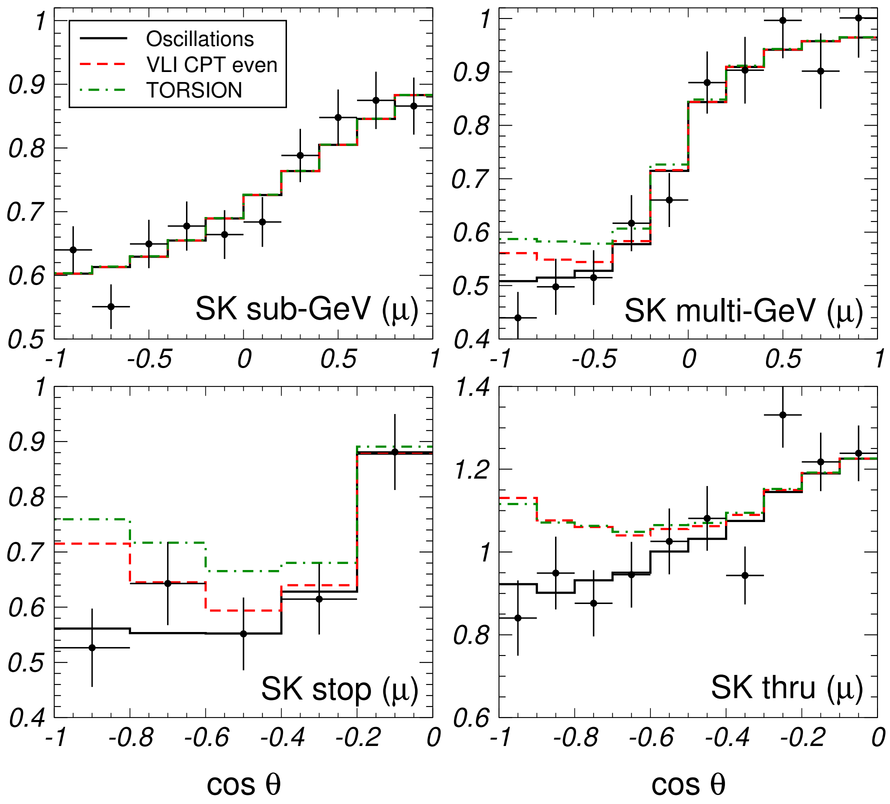
Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

due to CPT violating terms: $\bar{\nu}_L^\alpha b_\mu^{\alpha\beta} \gamma_\mu \nu_L^\beta \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

$$\lambda = \pm\frac{2\pi}{\Delta b}$$

Alternative Mechanisms vs ATM ν's

Severly constrained (MCG-G, M. Maltoni PRD 04,07)



At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

$$|\phi\,\Delta\gamma| \leq 5.9 \times 10^{-25}$$

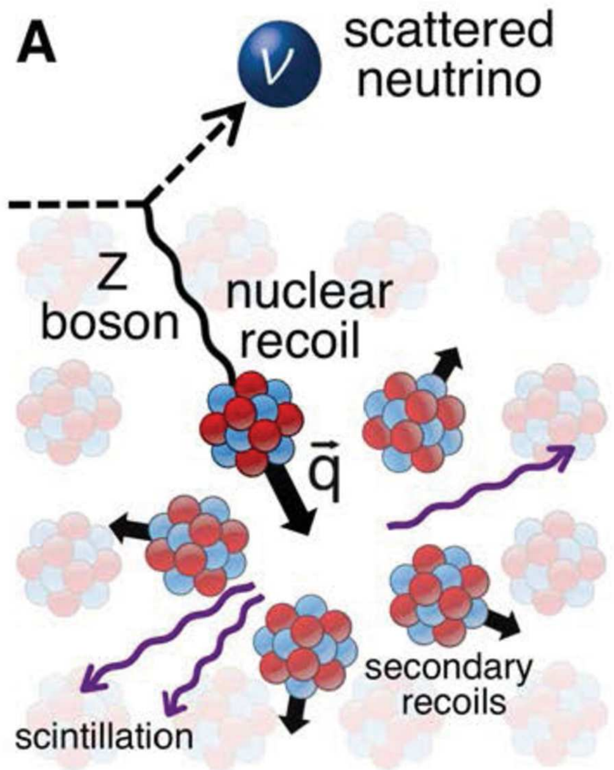
$$|Q\,\Delta k| \leq 4.8 \times 10^{-23}\ \text{GeV}$$

$$|\Delta b| \leq 3.0 \times 10^{-23}\ \text{GeV}$$

COHERENT EXPERIMENT

Science 2017 [ArXiv:1708.01294]

- observation of coherent neutrino-nucleus scattering at 6.7σ at CsI[Na] detector
- neutrinos from stopped pion source at Oak Ridge NL
- 142 events observed, in agreement with Standard Model



NSI: Combination with COHERENT data

Coloma, MCGG, Maltoni,Schwetz ArXiv:1708.02899

- COHERENT has detected for first time Coherent νN scattering 1708.01294:

  142(1± 0.28(sys)) observed events over a steady bck of 405

  136(SM) + 6(1± 0.25(sys) beam-on bck) expected

- In presence of NSI: $N_{\rm NSI}(\varepsilon) = \gamma \left[f_{\nu_e} Q^2_{we}(\varepsilon) + (f_{\nu_\mu} + f_{\bar{\nu}_\mu}) Q^2_{w\mu}(\varepsilon) \right]$

$$Q^2_{w\alpha} \propto \left[Z(g_p^V + 2\varepsilon_{\alpha\alpha}^{u,V} + \varepsilon_{\alpha\alpha}^{d,V}) + N(g_n^V + \varepsilon_{\alpha\alpha}^{u,V} + 2\varepsilon_{\alpha\alpha}^{d,V}) \right]^2 + \sum_{\beta\neq\alpha} \left[Z(2\varepsilon_{\alpha\beta}^{u,V} + \varepsilon_{\alpha\beta}^{d,V}) + N(\varepsilon_{\alpha\beta}^{u,V} + 2\varepsilon_{\alpha\beta}^{d,V}) \right]^2$$

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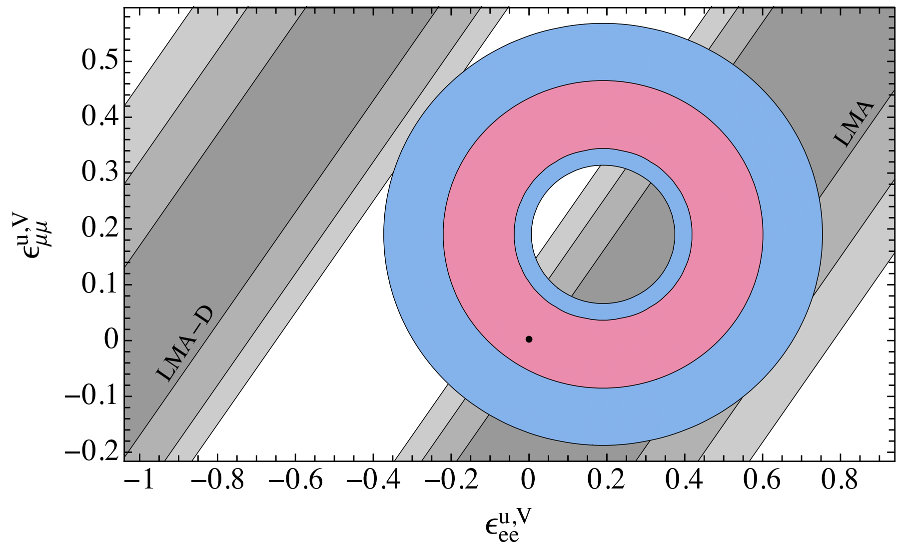
- Impact on LMA-D: Allowed COHERENT region vs LMA-D required range



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- OSCILLATION + COHERENT $\Rightarrow$ LMA-D excluded at more than 3.1 σ

All NSI's constrained

	$f=u$	$f=d$
$\epsilon^{f,V}_{ee}$	$[0.028, 0.60]$	$[0.030, 0.55]$
$\epsilon^{f,V}_{\mu\mu}$	$[-0.088, 0.37]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{\tau\tau}$	$[-0.090, 0.38]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{e\mu}$	$[-0.073, 0.044]$	$[-0.07, 0.04]$
$\epsilon^{f,V}_{e\tau}$	$[-0.15, 0.13]$	$[-0.13, 0.12]$
$\epsilon^{f,V}_{\mu\tau}$	$[-0.01, 0.009]$	$[-0.009, 0.008]$