PHENOMENOLOGY WITH MASSIVE NEUTRINOS IN 2023

Concha Gonzalez-Garcia

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

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OUTLINE

The confirmed picture: 3ν Lepton Flavour Parameters

Some Q&A and some open avenues

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

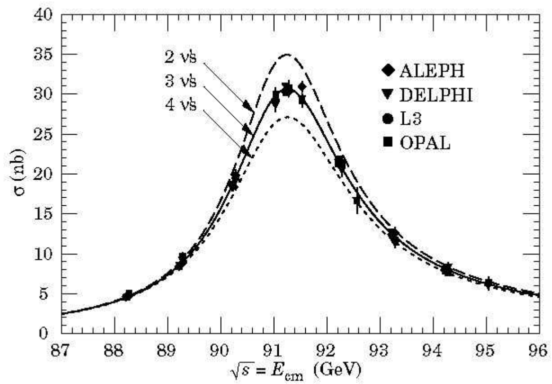
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

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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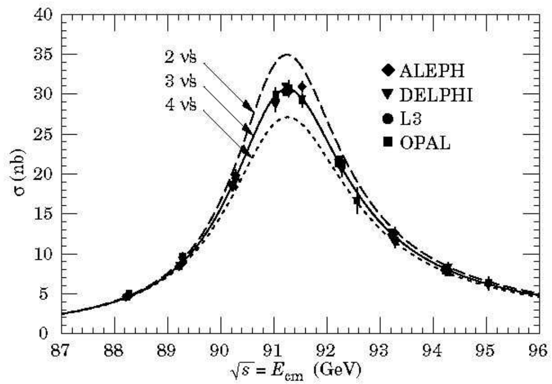


There is no ν_R

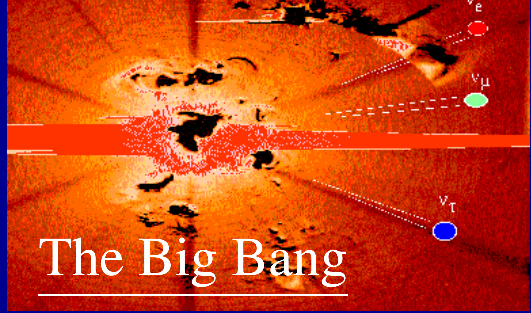
$\Downarrow$

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

$\Downarrow$

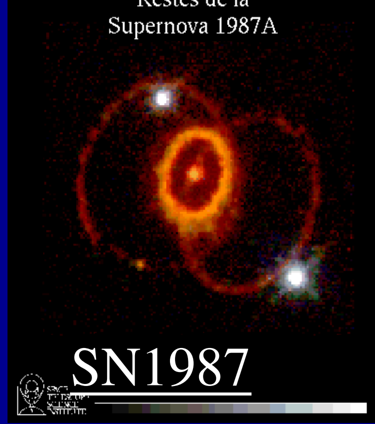
ν *strictly* massless

Sources of ν's

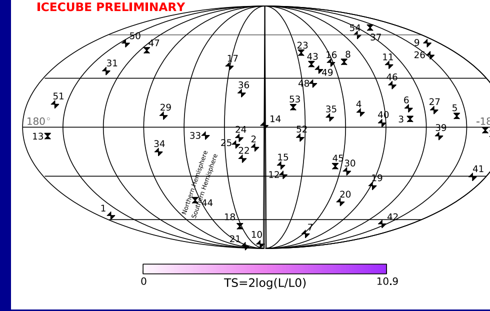


$\rho_\nu = 330/\mathrm{cm}^3$

$p_\nu = 0.0004$ eV



$E_\nu \sim$ MeV



ExtraGalactic

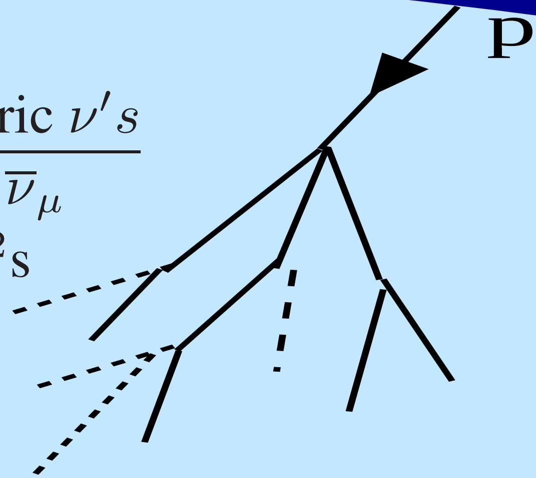
$E_\nu \gtrsim 30$ TeV

The Sun

ν_e

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

$E_\nu \sim 0.1$–20 MeV



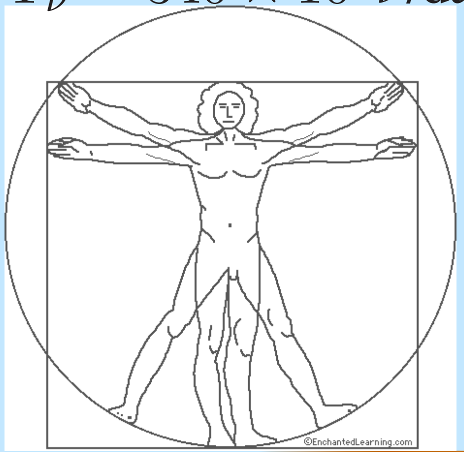
Atmospheric $\nu' s$

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

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

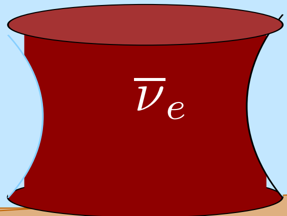
Human Body

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



Nuclear Reactors

$E_\nu \sim$ few MeV



Earth's radioactivity

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

Accelerators

$E_\nu \simeq 0.3$–30 GeV

Fermilab Discovering the Nature of Nature

CERN

KEK

NSS

$E_\nu \sim$ MeV

Oak Ridge National Laboratory

Concha Gonzalez-Garcia

- 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**)
  - ∗ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,NOνA)
  - ∗ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK, SNO, Borexino**)
  - ∗ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
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- 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 $\nu \neq \nu^c$:

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

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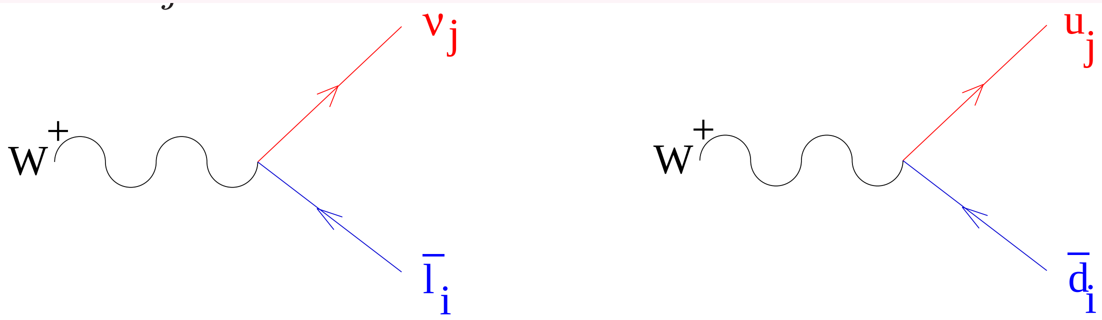
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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

$$U_{\rm LEP} U_{\rm LEP}^\dagger = I_{3\times3} \qquad \text{but in general} \qquad U_{\rm LEP}^\dagger U_{\rm LEP} \neq I_{N\times N}$$

- $U_{\rm LEP}$: $3 + 3s$ 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 ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^{n} U^\star_{\alpha i}\, |\nu_i\rangle$

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

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

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

No information on ν mass scale nor Majorana versus Dirac

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- When osc between 2-ν dominates:

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

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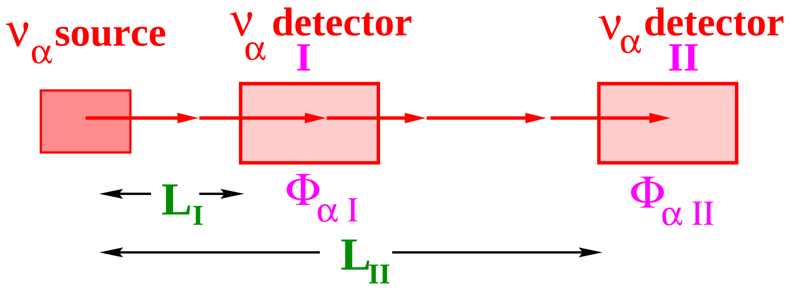
$\Rightarrow$ No info on sign of Δm^2 and θ octant

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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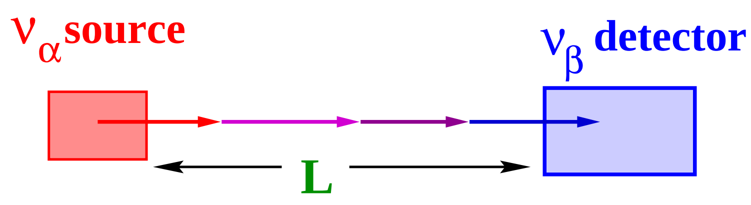

Searches for β diff α

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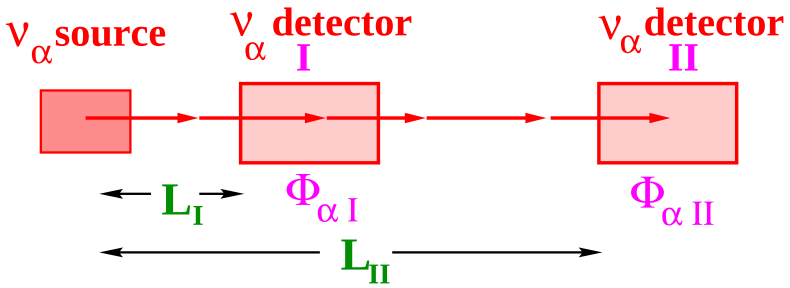

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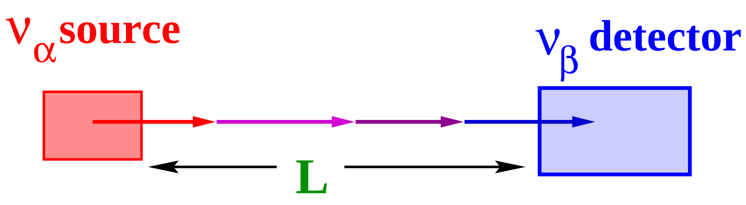
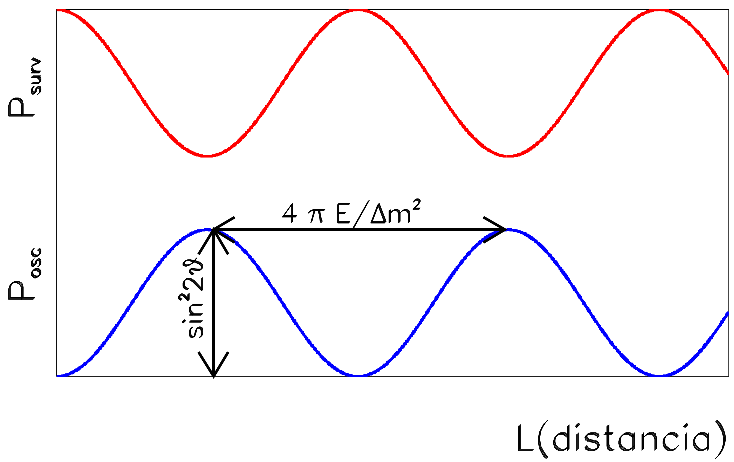


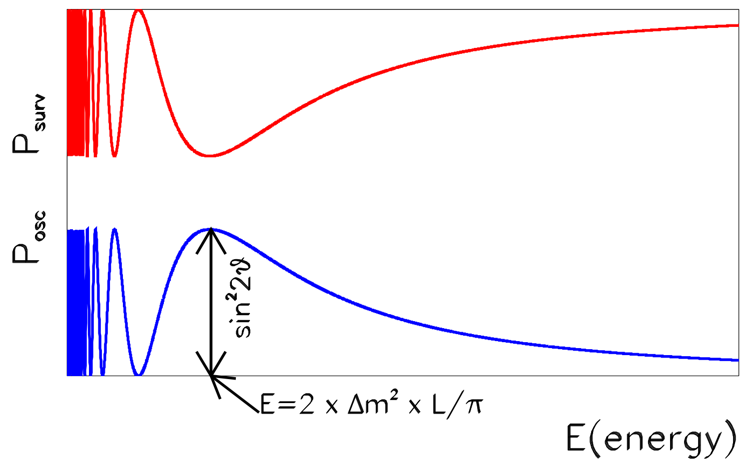
Searches for β diff α

- To detect oscillations we can study the neutrino flavour

as function of the Distance to the source



As function of the neutrino Energy



Flavour Osc in Vacuum vs Transitions in Matter

- In Vacuum
  when osc between 2-ν dominates:

$P_{\alpha\alpha} = 1 - P_{\alpha\neq\beta}$ Disappear

$P_{\alpha\neq\beta} = \sin^2(2\theta)\, \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$ Appear

$\Rightarrow$ No information on Ordering of states (i.e sign(Δm^2)) nor octant of θ

$\Rightarrow$ For $L \gg E/\Delta m^2$, (oscillation averaged) $\Rightarrow P_{\alpha\alpha} > \frac{1}{2}$

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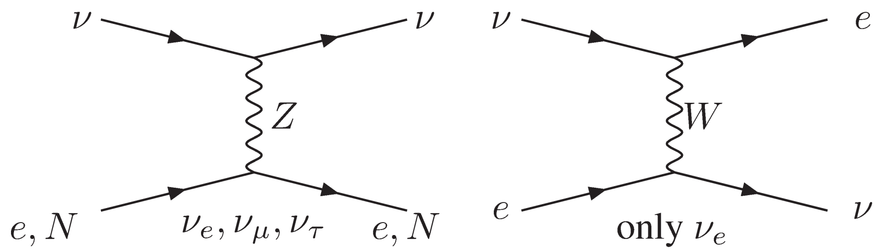
- If ν cross matter regions (Sun, Earth...) it interacts *coherently*

  – And Different flavours
    have different interactions :



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

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

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

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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

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

Dependence on θ octant

$\Rightarrow$ In LBL terrestrial experiments

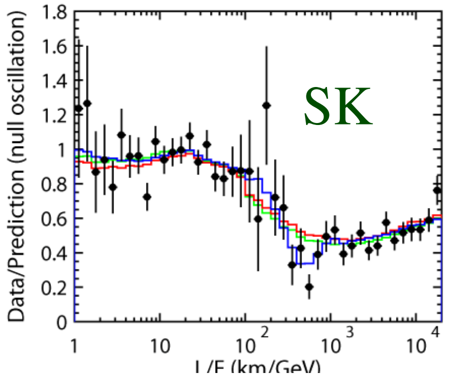
Dependence on sign of Δm^2

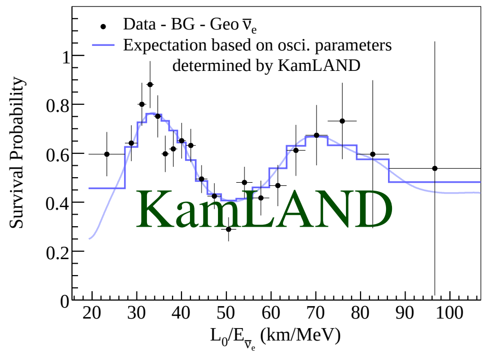
and θ octant

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

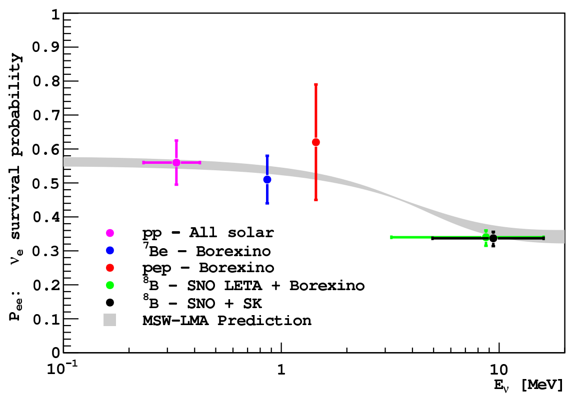
  * Atmospheric ν_μ & $\bar\nu_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE) $\frac{\Delta m^2}{\mathrm{eV}^2} \sim 2\,10^{-3}$
  * Accel. ν_μ & $\bar\nu_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**) $\theta \sim 45^\circ$
  * Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,NOνA) $\theta \sim 8^\circ$
  * Solar ν_e convert to ν_μ/ν_τ (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**) $\frac{\Delta m^2}{\mathrm{eV}^2} \sim 2\,10^{-3}, \theta \sim 8^\circ$

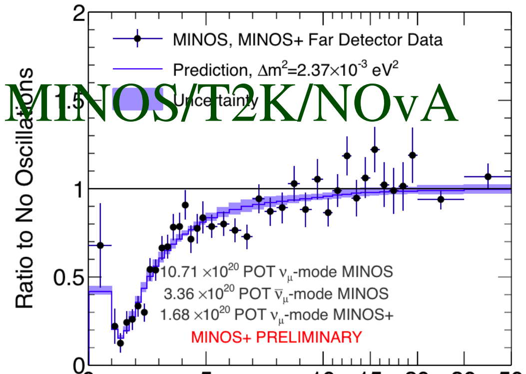
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

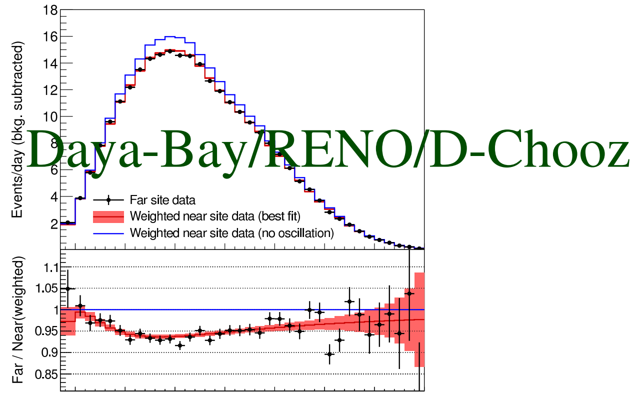




MSW conversion in Sun







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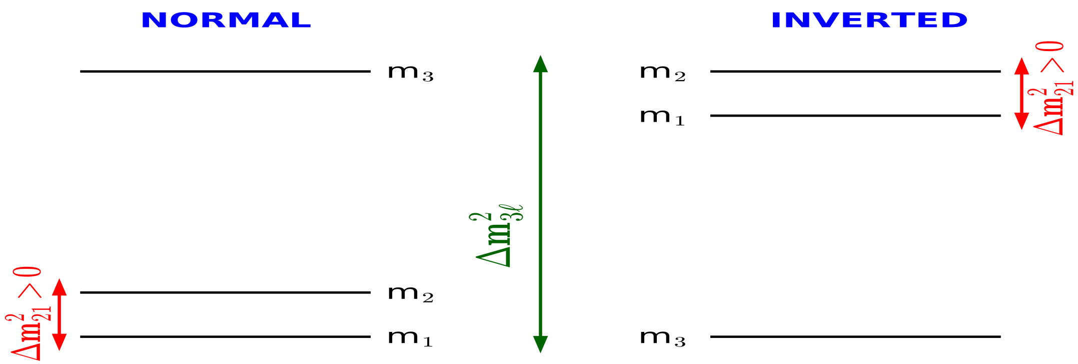
• Convention: $0 \le \theta_{ij} \le 90^\circ$ $\quad 0 \le \delta \le 360^\circ$ $\quad \Rightarrow$ 2 Orderings



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

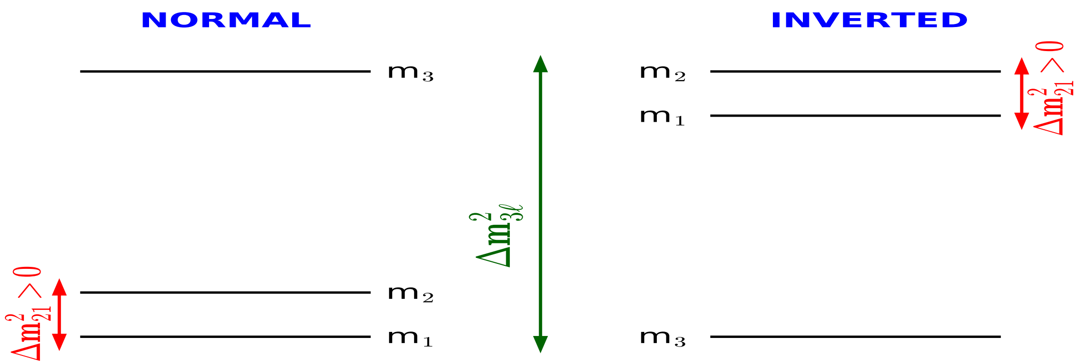
$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

3ν Flavour Parameters

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

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

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



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

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

Experiment	Dominant 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 1292-day low-E spect, 192 points.
- Borexino Ph-III 1433-day low-E spect, 800 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 EH2/EH1 & EH3/EH1 ratios,52 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 (χ^2 table provided by SK).*

Accelerator experiments

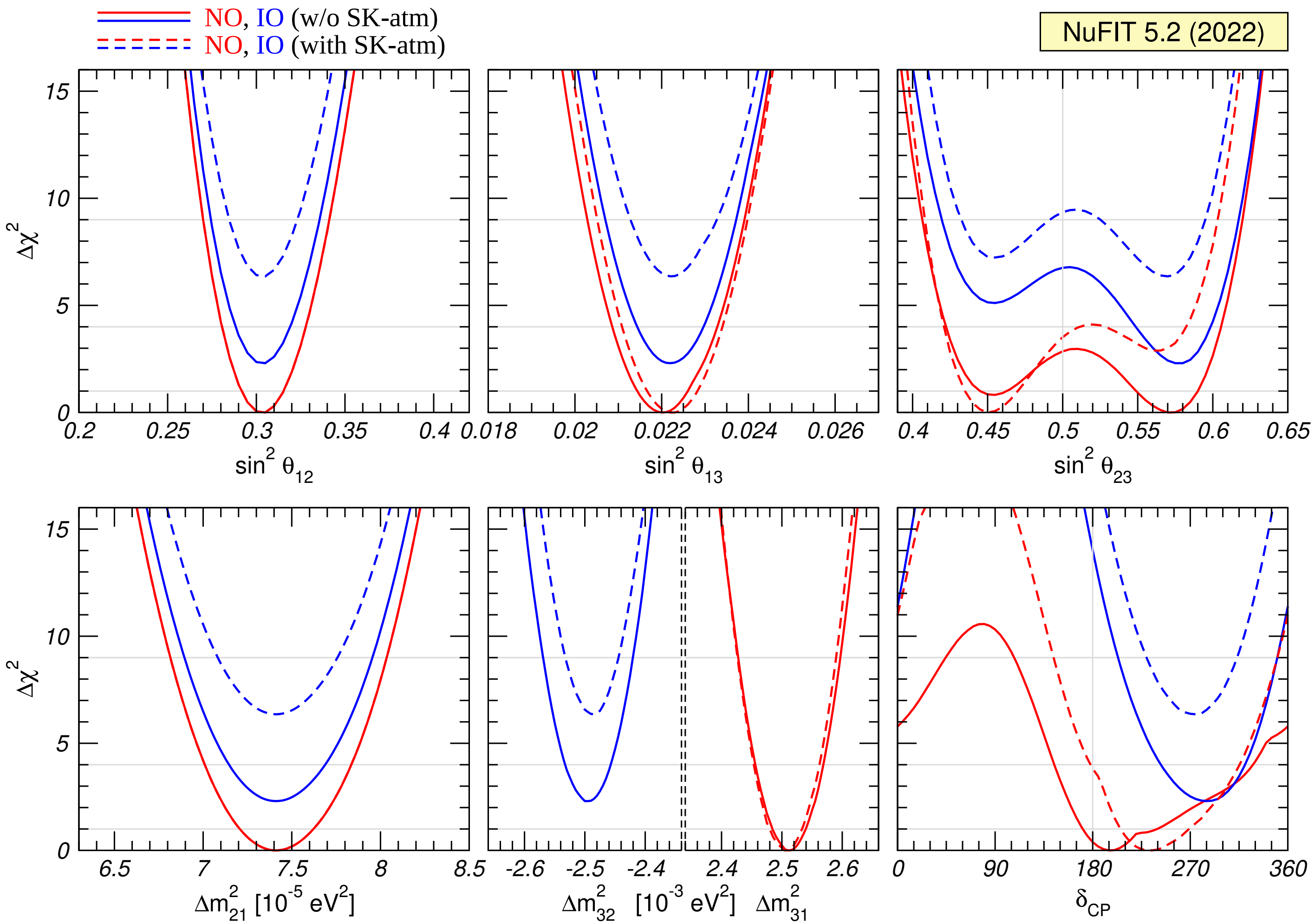
- MINOS 10.71 $\times 10^{20}$ pot ν_μ-disapp data, 39 poins.
- MINOS 3.36 $\times 10^{20}$ pot $\bar{\nu}_\mu$-disapp data , 14 points.
- MINOS 10.6 $\times 10^{20}$ pot ν_e-app data , 5 points.
- MINOS 3.3 $\times 10^{20}$ pot $\bar{\nu}_e$-app data , 5 points.
- T2K 19.7 $\times 10^{20}$ pot ν_μ-disapp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

Summary: Global 3 ν Flavour Parameters

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

Esteban, 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 SK1-4

Summary: Global 3 ν Flavour Parameters

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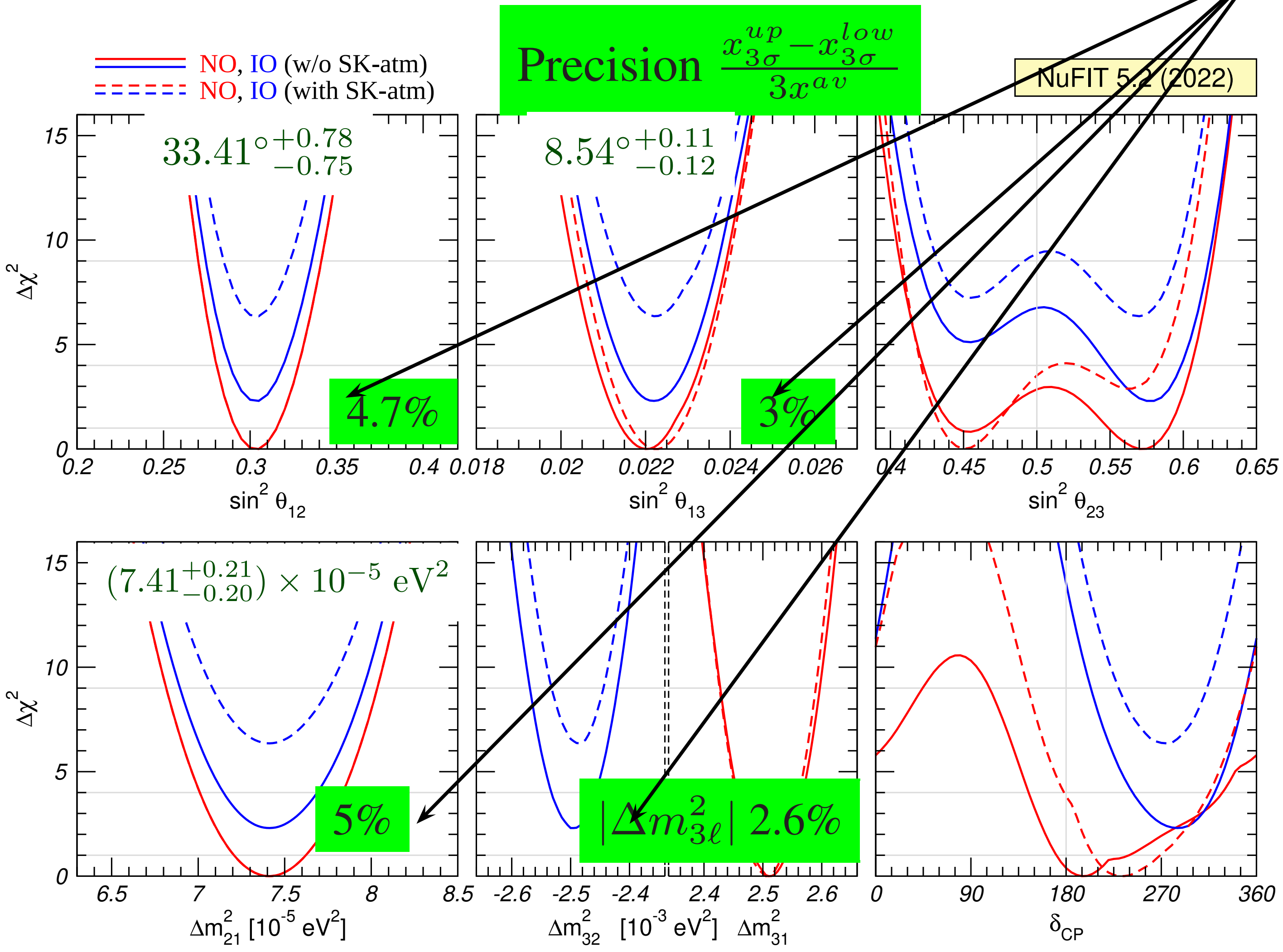
- 4 well-known parameters:

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



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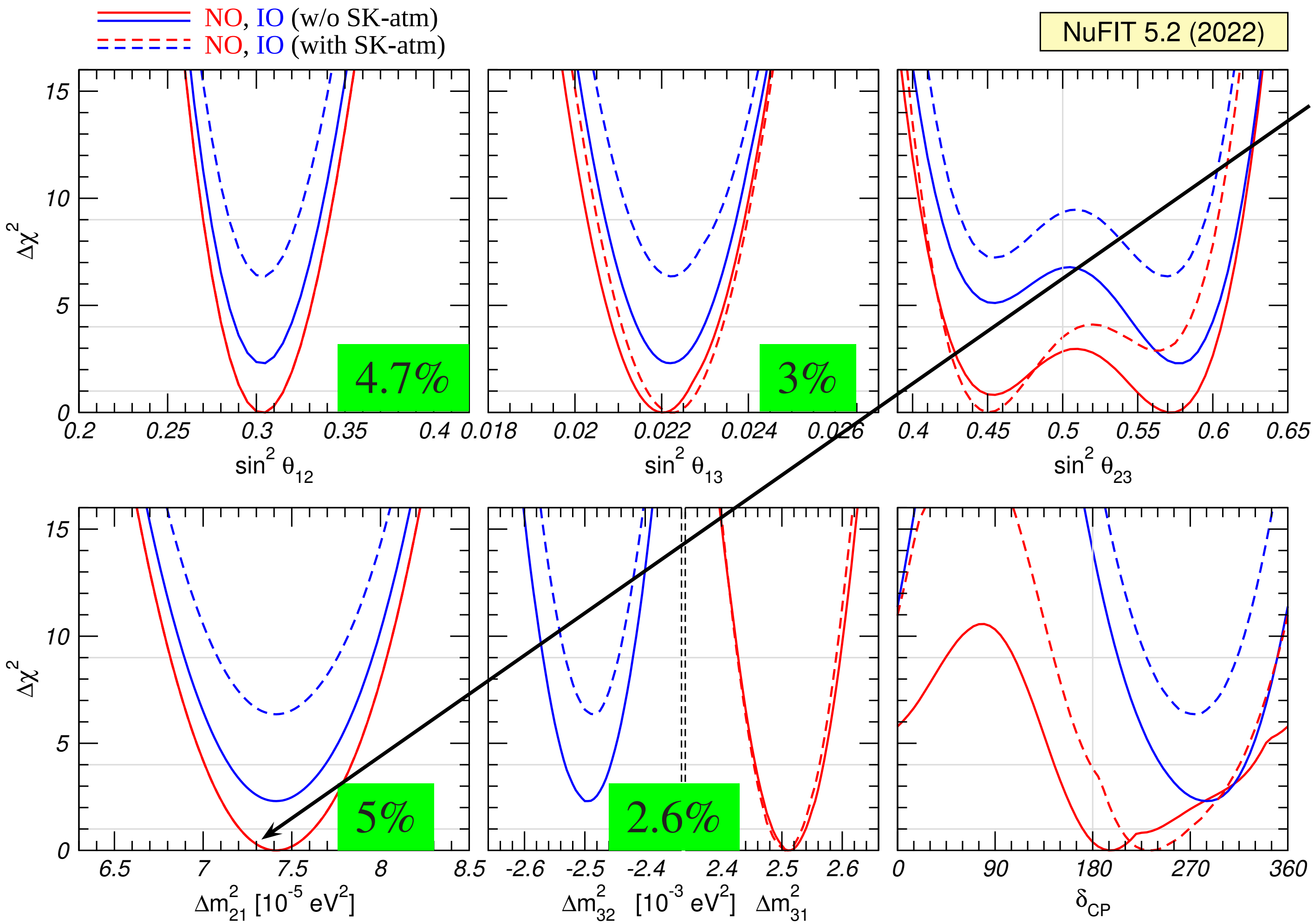

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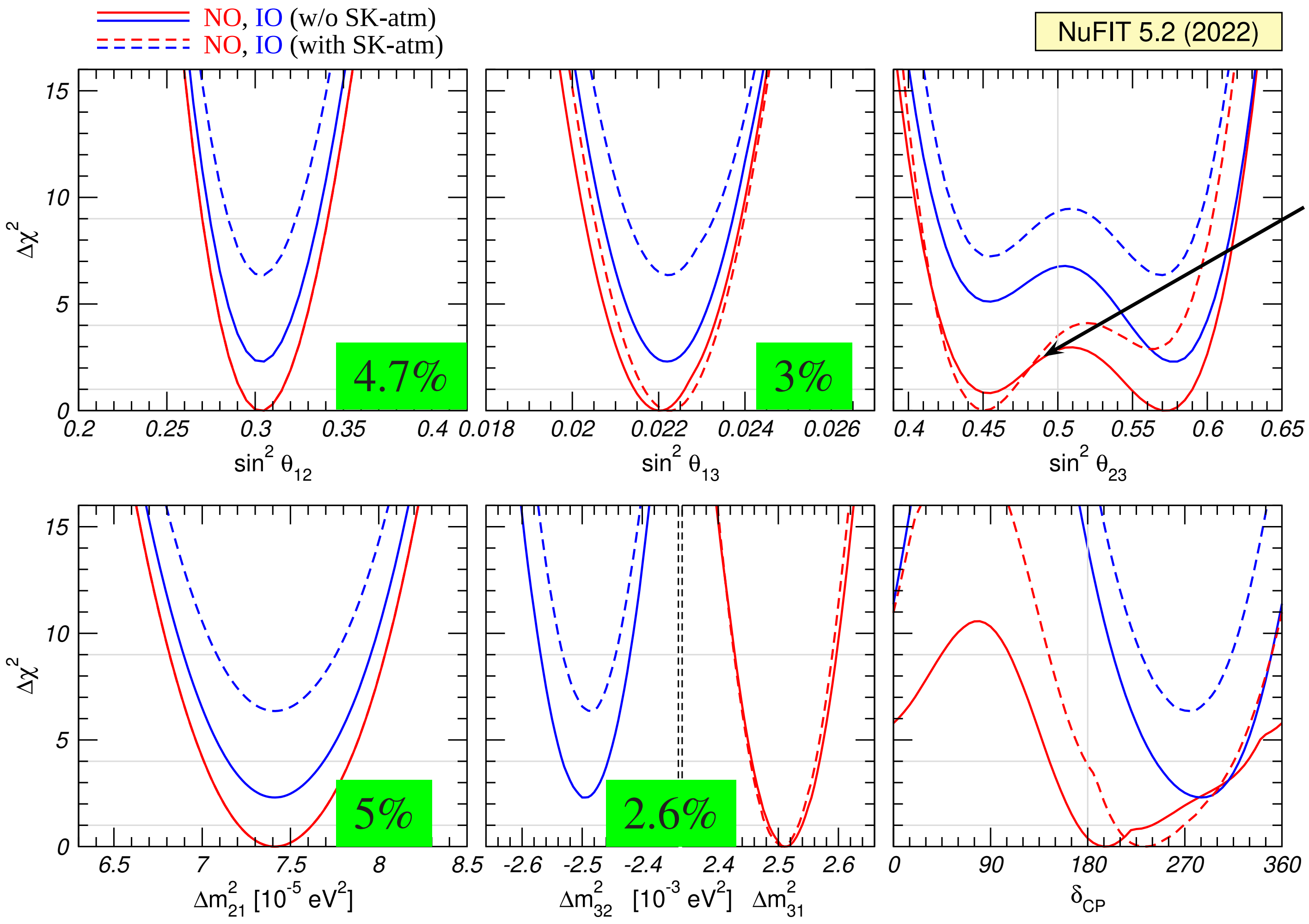

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- θ_{23}: Least known angle

  Maximal? Octant?

  non-robust wrt ATM

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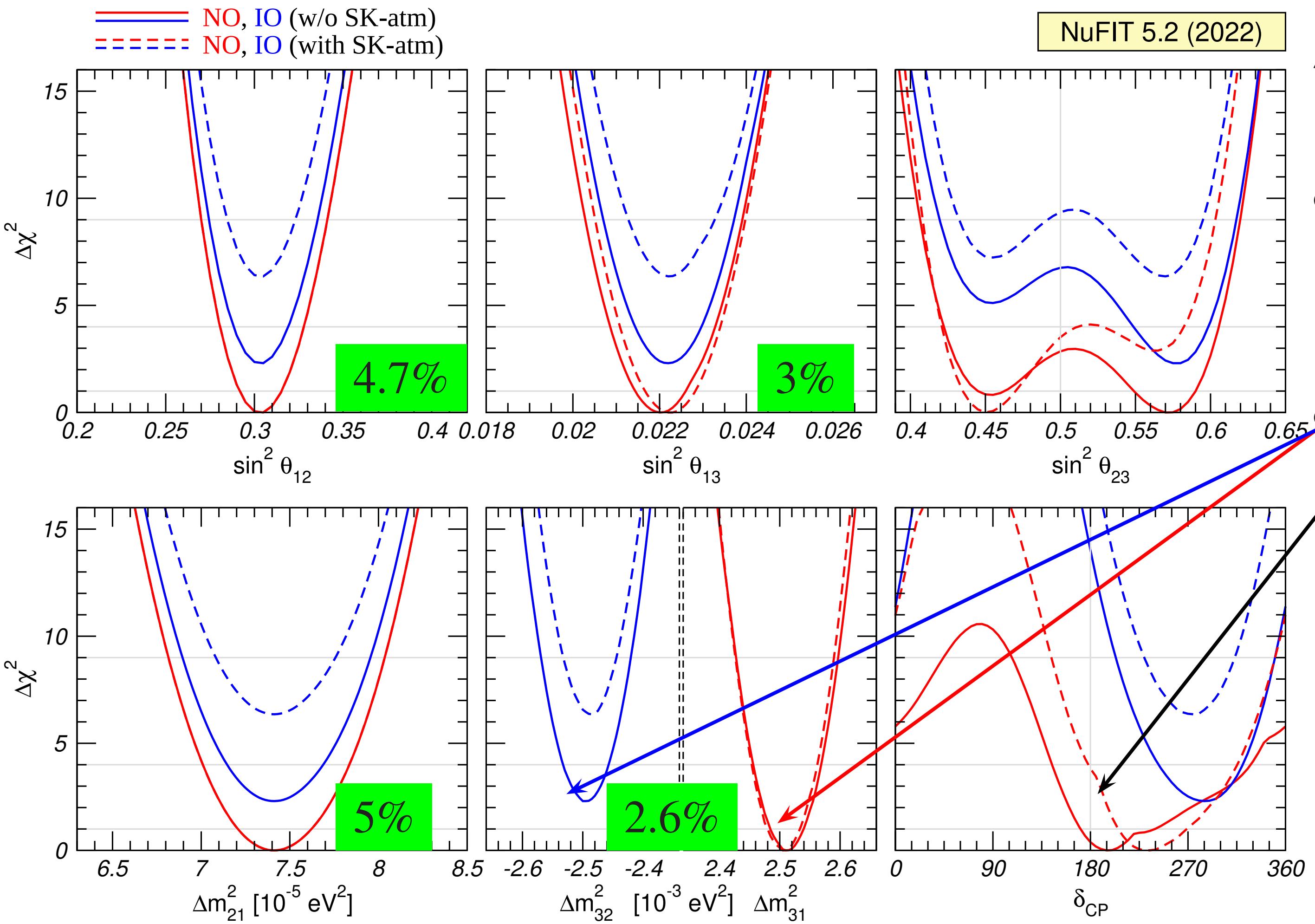

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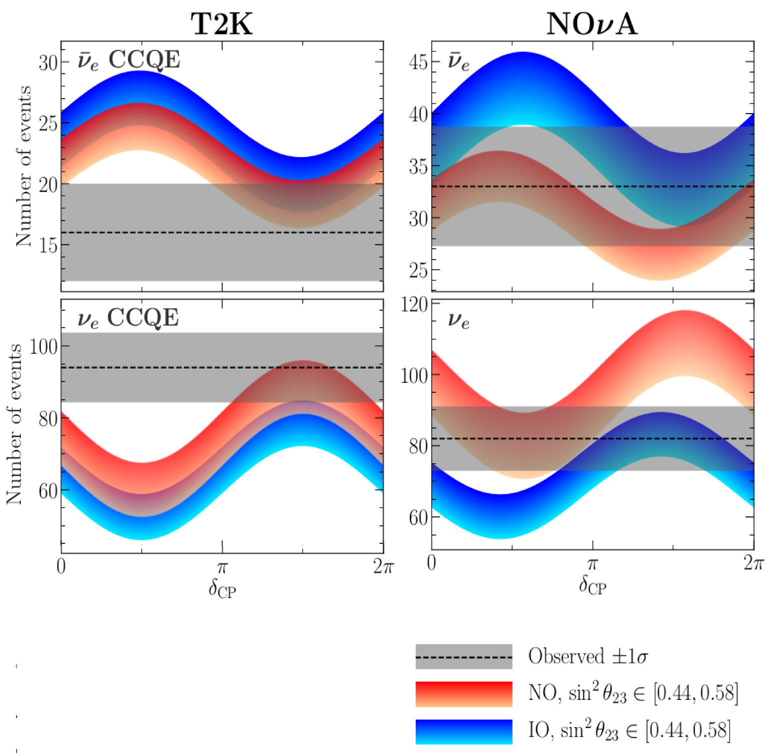
- θ_{23}: Least known angle
  Maximal? Octant?
  non-robust wrt ATM
- Ordering NO or IO?
  CPV?:

CPV and Ordering in LBL: ν_e appearace

- Dominant information from ν_e appearance in LBL

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

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



$\Rightarrow$ Each T2K and NOνA favour NO

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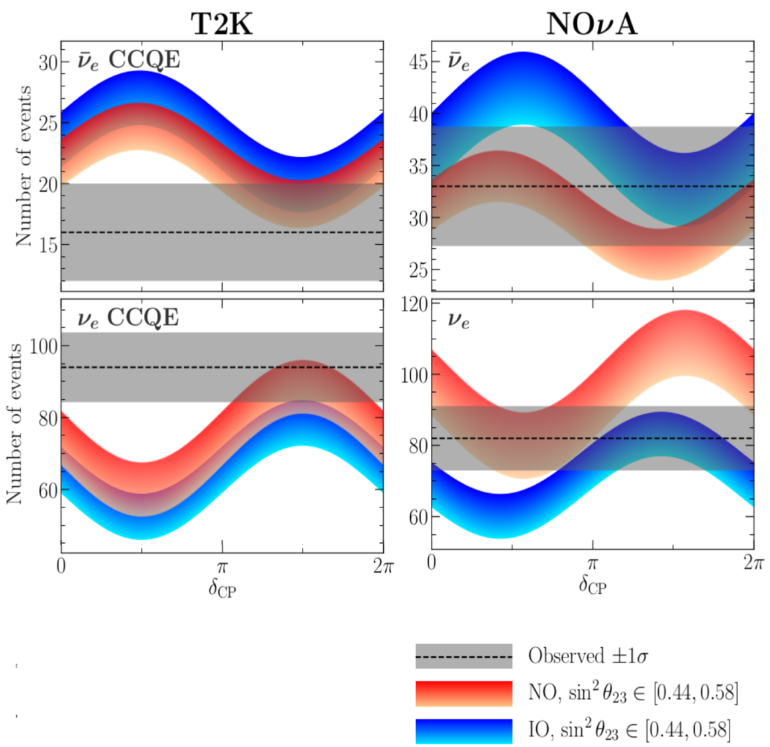
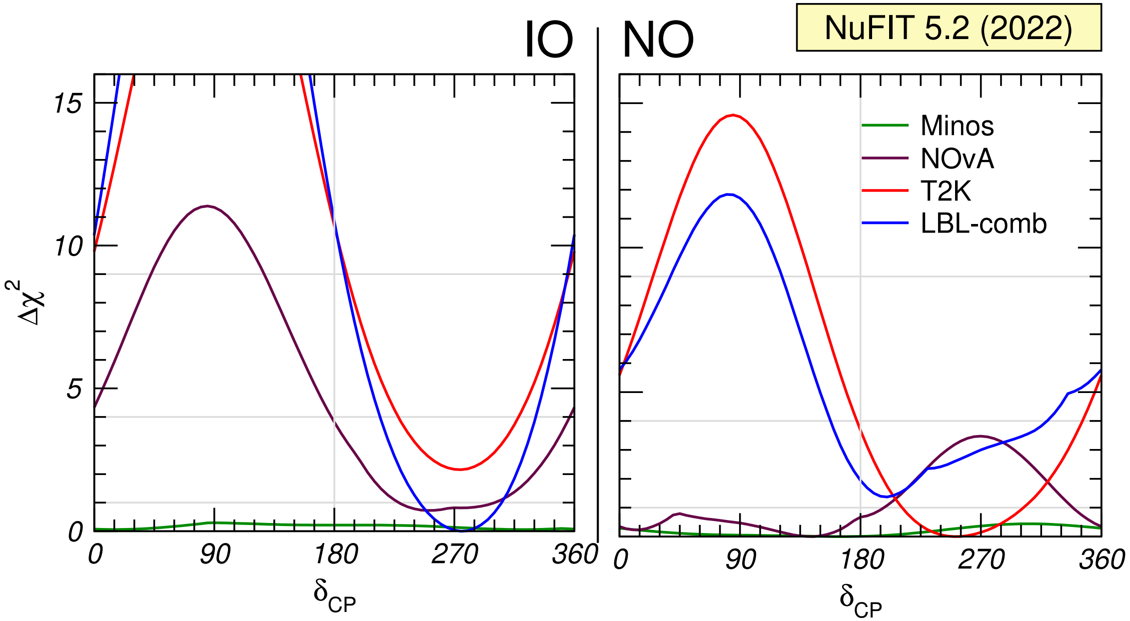


⇒ Each T2K and NOνA favour NO

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 $\bar{\nu}_\mu$ 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

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Nunokawa,Parke,Zukanovich (2005)

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

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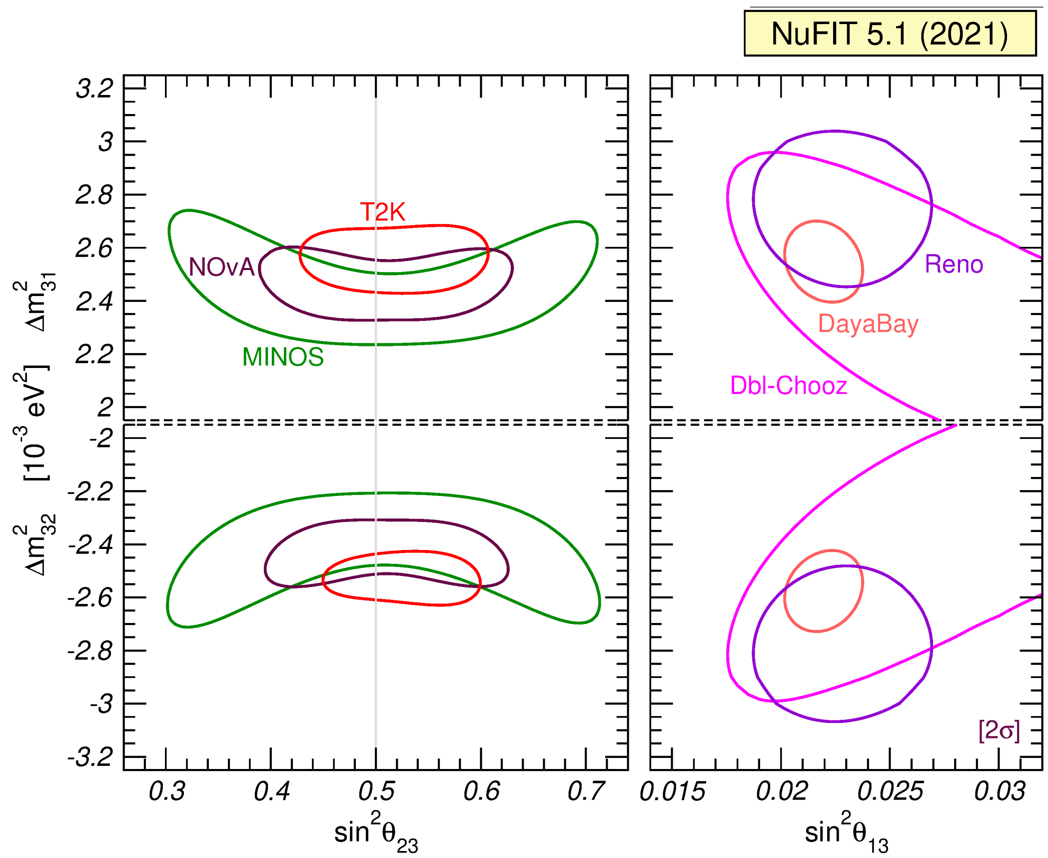

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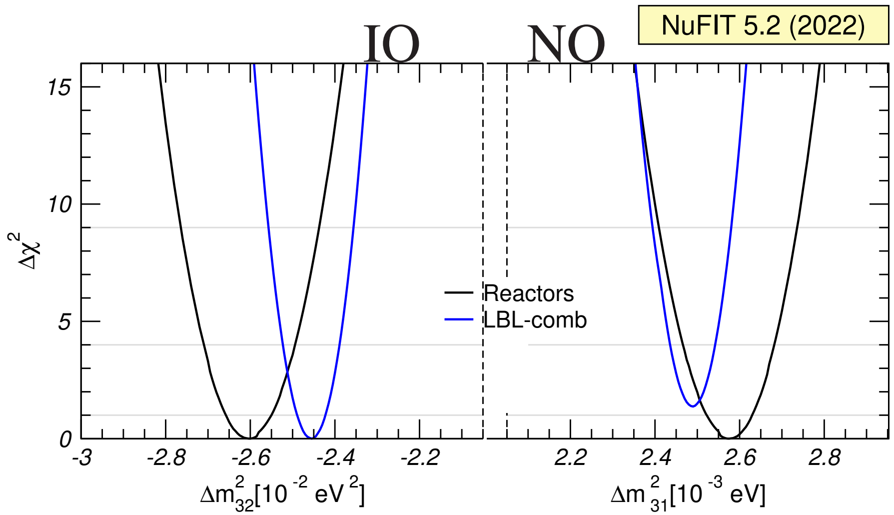

- T2K and NOνA more compatible in IO $\Rightarrow$IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors

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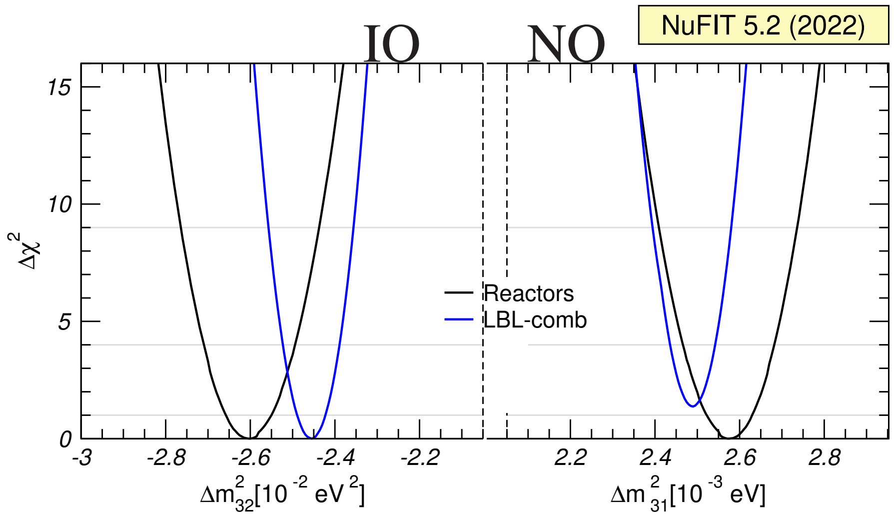
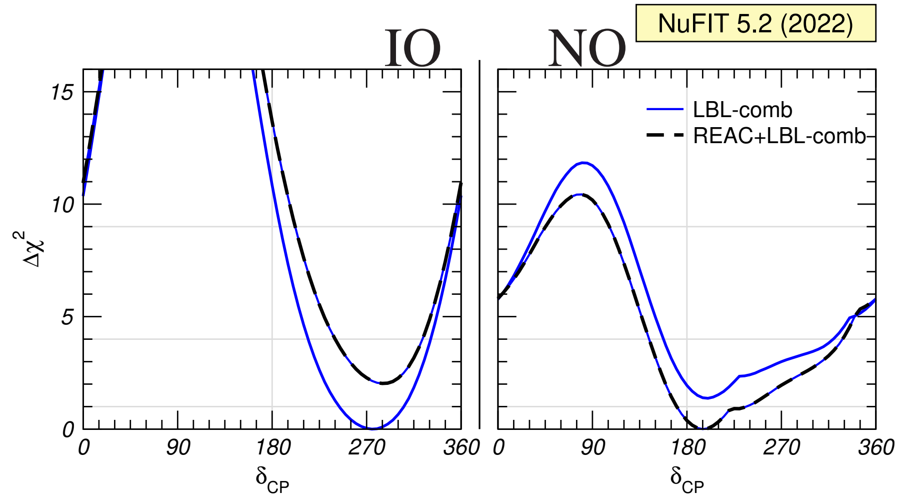




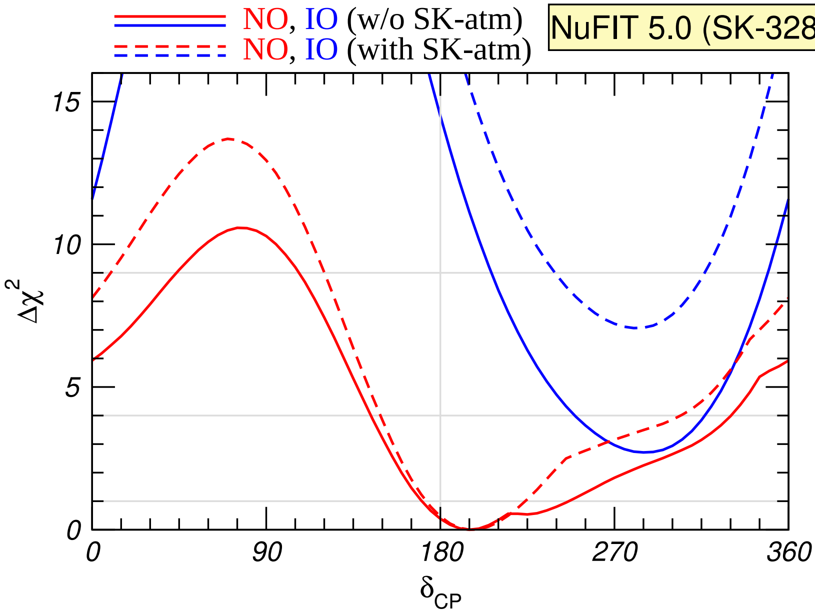
- T2K and NOνA more compatible in IO $\Rightarrow$ IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors
- in NO: b.f $\delta_{\rm CP} \sim 195^\circ$ $\Rightarrow$ CPC allowed at 0.6 σ
- in IO: b.f $\delta_{\rm CP} \sim 270^\circ$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

Ordering and CPV including SK-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 and 5.2: include SK I-IV 372.8 kton-years table



Add either SK-atm table⇒ favouring of NO:

$$\Delta\chi^2_{\rm NO-IO,w/o\ SK-atm} = 2.3$$
$$\Delta\chi^2_{\rm NO-IO,with\ SK-atm} = 6.4$$

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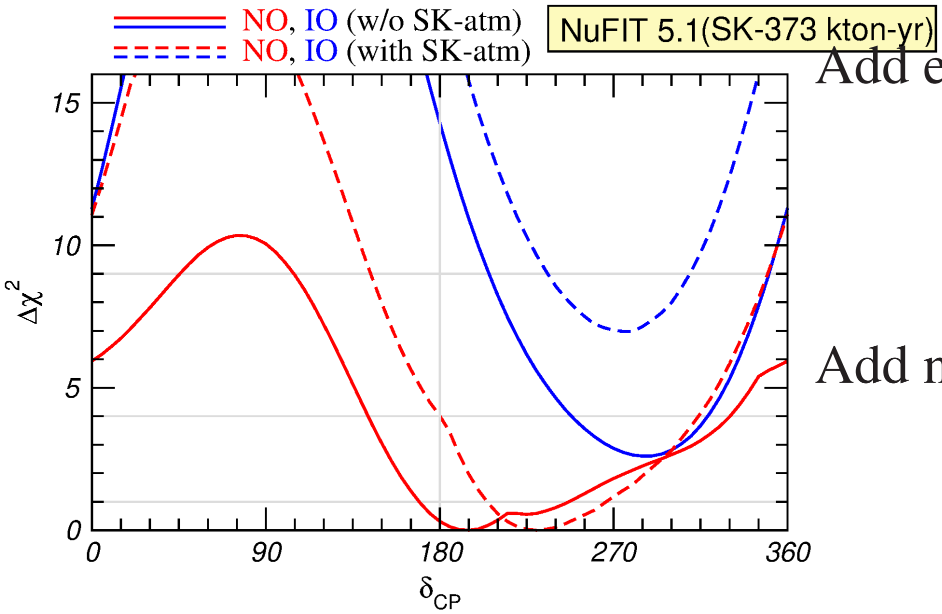

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Add new table ⇒ slight increase of significance of CPV in NO

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

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

Flavour Parameters: Mixing Matrix

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

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

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- Good progress but still precision very far from:

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

- Also very different flavour mixing of leptons vs quarks

Summary so far

- 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

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

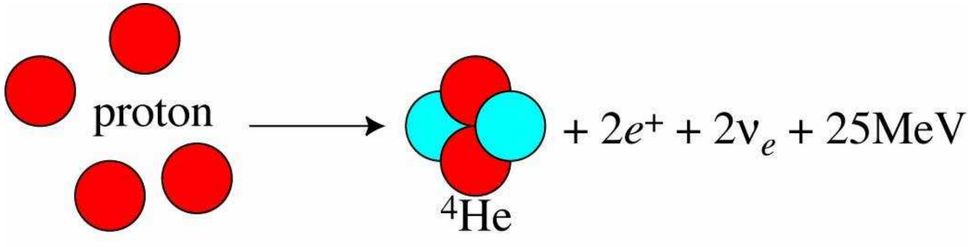
	best fit MO	$\Delta\chi^2$(MO)	best fit δ_{CP}	$\Delta\chi^2$(CPC)	oct.θ_{23}	$\Delta\chi^2$(oct)
LBL	IO	1.5	275°	2.0	2nd	2.2
+reactors	NO	2.3	194°	0.4	2nd	0.5
+ SK-Atm 373 kt-y (NuFIT 5.2)	NO	6.4	232°	4.0	1st	3.2

$\Rightarrow$ not statistically significant yet

$\Rightarrow$ definitive answer will likely require new experiments

A Detour in the Sun

- Sun shines by nuclear fusion of protons into He



And only ν_e are produced

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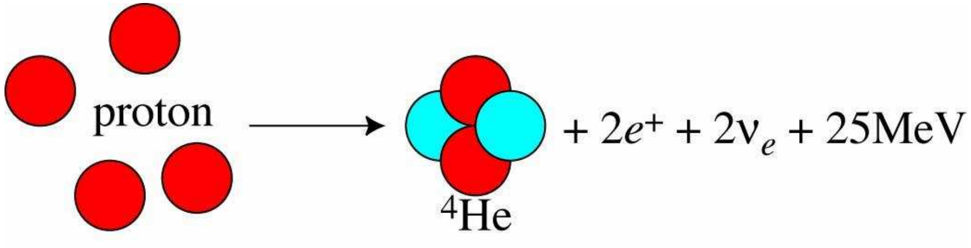
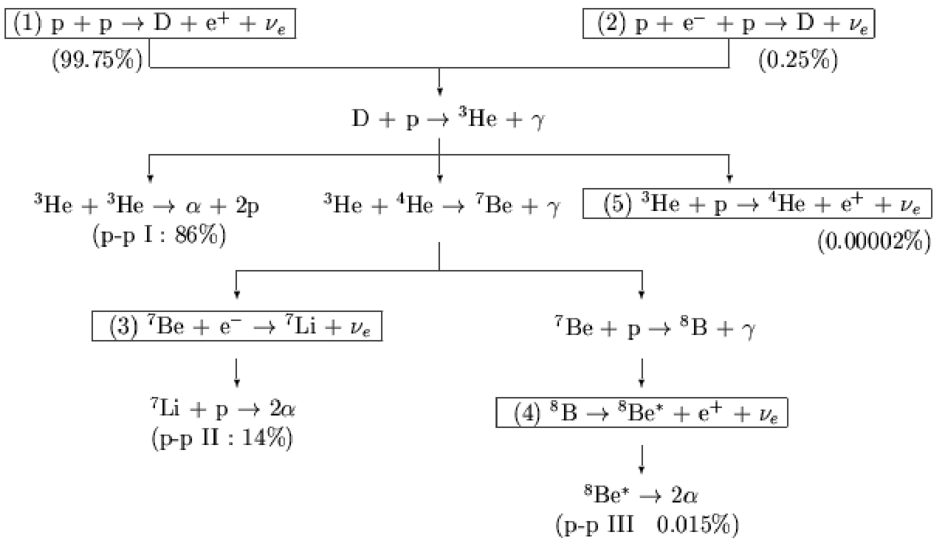


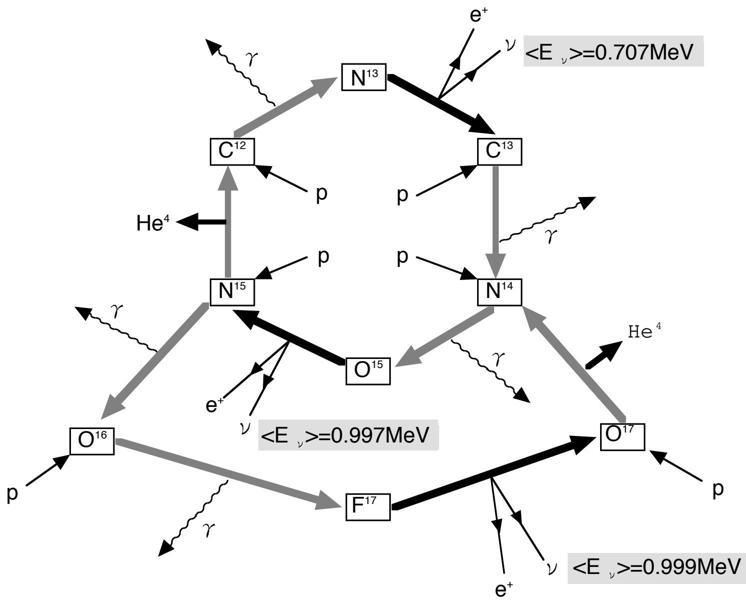
And only ν_e are produced

- Two main chains of nuclear reactions

pp Chain :



CNO cycle:



Modeling the Sun

- Sun=Main sequence star
- Solar Models describes the Sun based on:

Mass:	$M_\odot = 2 \times 10^{33}$ gr
Radius:	$R_\odot = 7 \times 10^5$ km
Surf Lum:	$L_\odot = 3.842 \times 10^{33} (1 \pm 0.004)$ erg/sec
Age:	$\tau_\odot = 4.57 \times 10^9 (1 \pm 0.0044)$ yr

- Basic assumptions:
  - The Sun is spherically symmetric
  - Some Equation of State
- Incorporate:
  - Transport of Energy: Radiative and Convective
  - $\Rightarrow$ Model of opacities
  - Chemical Evolution by Nuclear Reactions
  - $\Rightarrow$ pp-chain and CNO cycles
  - Microscopic Diffusion
- Using inputs from:
  - Lab Measurements of Nuclear Rates
  - Element Abundance Determination By
  - $\Rightarrow$ Spectroscopy of Photosphere: C, N, O
  - $\Rightarrow$ Meteorites: Mg,Si,S,Fe
  - $\Rightarrow$ Other methods: Ne, Ar
- They Predict Observables:
  - Neutrino Flux Spectrum
  - Relevant to Helioseismology :
  - $\Rightarrow$ Surface He Abundance
  - $\Rightarrow$ Inner Radius of Convective Zone
  - $\Rightarrow$ Sound Speed Profile

The Solar Composition Problem

– Newer determination of abundances in solar surface give lower values

$\log \epsilon_i \equiv \log N_i/N_H + 12$

Element	GS98	AGSS09met
C	8.52 ± 0.06	8.43 ± 0.05
N	7.92 ± 0.06	7.83 ± 0.05
O	8.83 ± 0.06	8.69 ± 0.05
Mg	7.58 ± 0.01	7.53 ± 0.01
Si	7.56 ± 0.01	7.51 ± 0.01
S	7.20 ± 0.06	7.15 ± 0.02
Fe	7.50 ± 0.01	7.45 ± 0.01
Ar	6.40 ± 0.06	6.40 ± 0.13
Ne	8.08 ± 0.06	7.93 ± 0.10

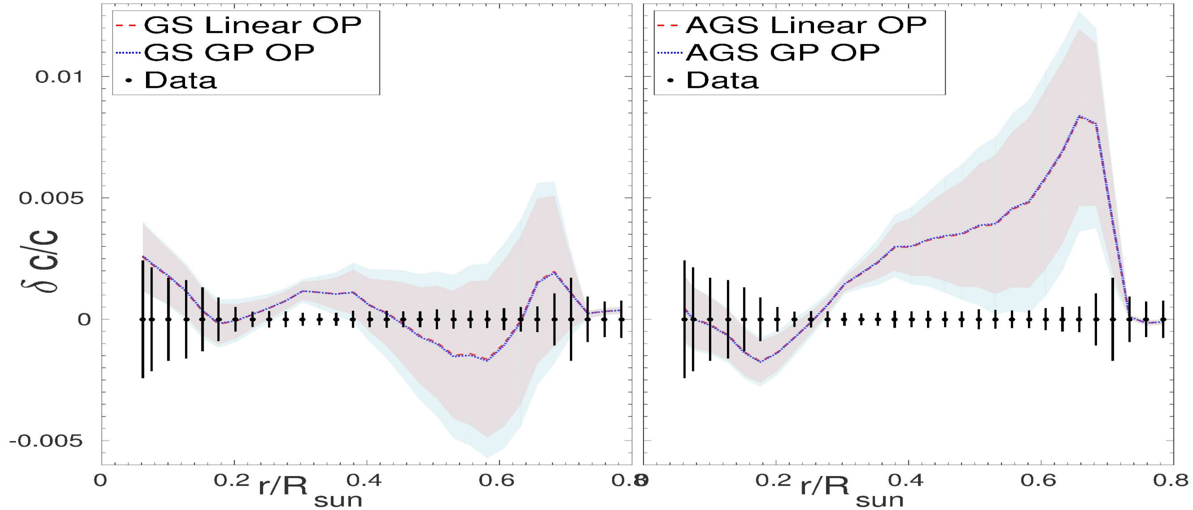
$\Rightarrow$ Two sets of SSM:

Starting from Bahcall *etal* 05, Serenelli *etal* 2016

B16-GS98 with old (high) metalicity

B16-AGSS09met with new (low) metalicity

– Solar Models with lower metalicities fail in reproducing helioseismology data



Predictions very strongly correlated

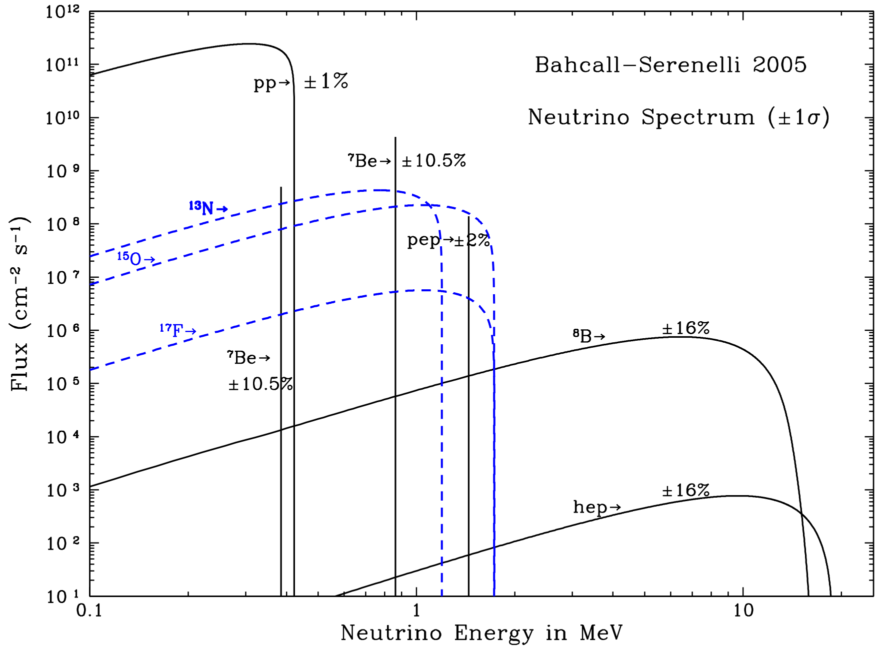
– B16-GS98 at 1.4–3.2 σ

– B16-AGSS09 at 2.7–4.5 σ

– Bayes factor B16-AGSS09/B16-GS98<-4 to -13

$\Rightarrow$ B16-AGSS09 strongly disfavoured to ruled out

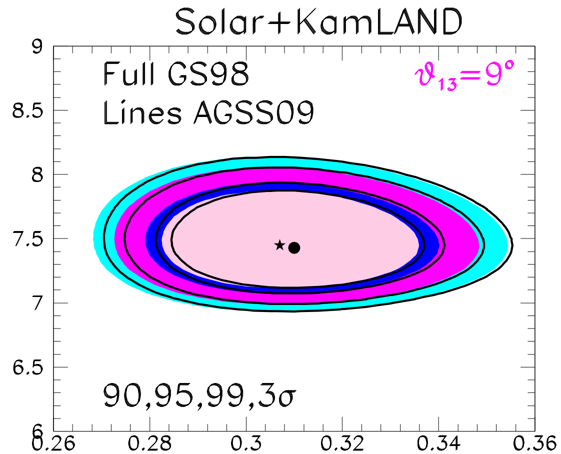
The Neutrino Fluxes



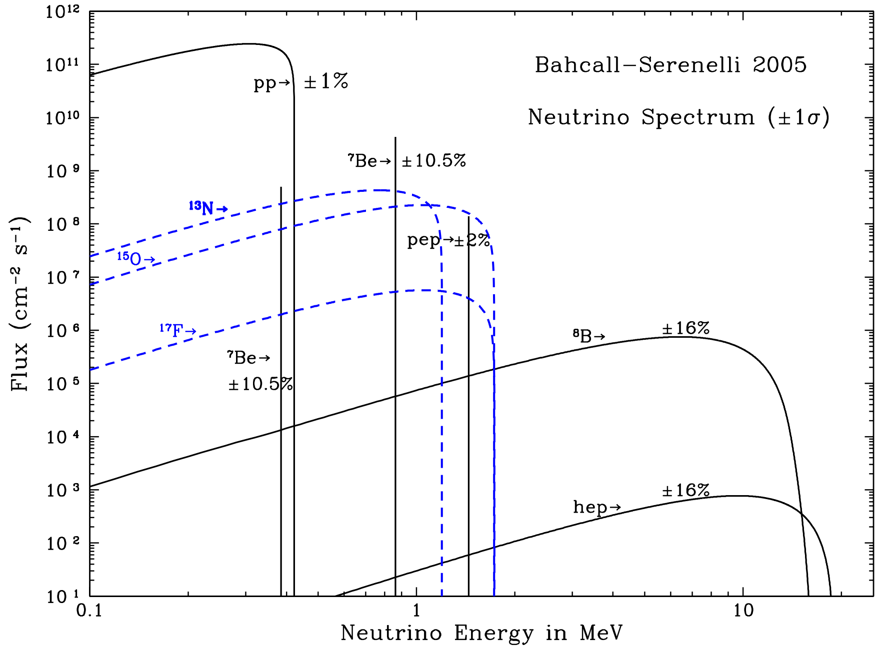
Flux cm^{-2} s^{-1}	B16GS98	B16-AGSS09met	Diff (%)
$pp/10^{10}$	5.98	$6.03\ (1 \pm 0.005)$	0.8
$pep/10^{8}$	1.44	$1.46\ (1 \pm 0.01)$	2.1
$hep/10^{3}$	7.98	$8.25\ (1 \pm 0.30)$	3.4
$^{7}Be/10^{9}$	4.93	$4.40\ (1 \pm 0.06)$	8.8
$^{8}B/10^{6}$	5.46	$4.50\ (1 \pm 0.12)$	17.7
$^{13}N/10^{8}$	2.78	$2.04(1 \pm 0.14)$	**26.7**
$^{15}O/10^{8}$	2.05	$1.44\ (1 \pm 0.16)$	**30.0**
$^{17}F/10^{16}$	5.29	$3.26\ (1 \pm 0.18)$	**38.4**

Most difference in CNO fluxes

– Negligible Impact in Osc Parameter Determination



The Neutrino Fluxes



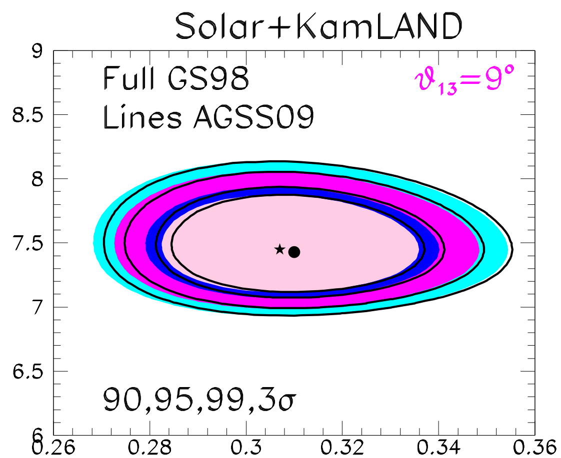
Flux cm^{-2} s^{-1}	B16GS98	B16-AGSS09met	Diff (%)
$pp/10^{10}$	5.98	$6.03\ (1 \pm 0.005)$	0.8
$pep/10^{8}$	1.44	$1.46\ (1 \pm 0.01)$	2.1
$hep/10^{3}$	7.98	$8.25\ (1 \pm 0.30)$	3.4
$^{7}Be/10^{9}$	4.93	$4.40\ (1 \pm 0.06)$	8.8
$^{8}B/10^{6}$	5.46	$4.50\ (1 \pm 0.12)$	17.7
$^{13}N/10^{8}$	2.78	$2.04(1 \pm 0.14)$	**26.7**
$^{15}O/10^{8}$	2.05	$1.44\ (1 \pm 0.16)$	**30.0**
$^{17}F/10^{16}$	5.29	$3.26\ (1 \pm 0.18)$	**38.4**

Most difference in CNO fluxes

– Negligible Impact in Osc Parameter Determination

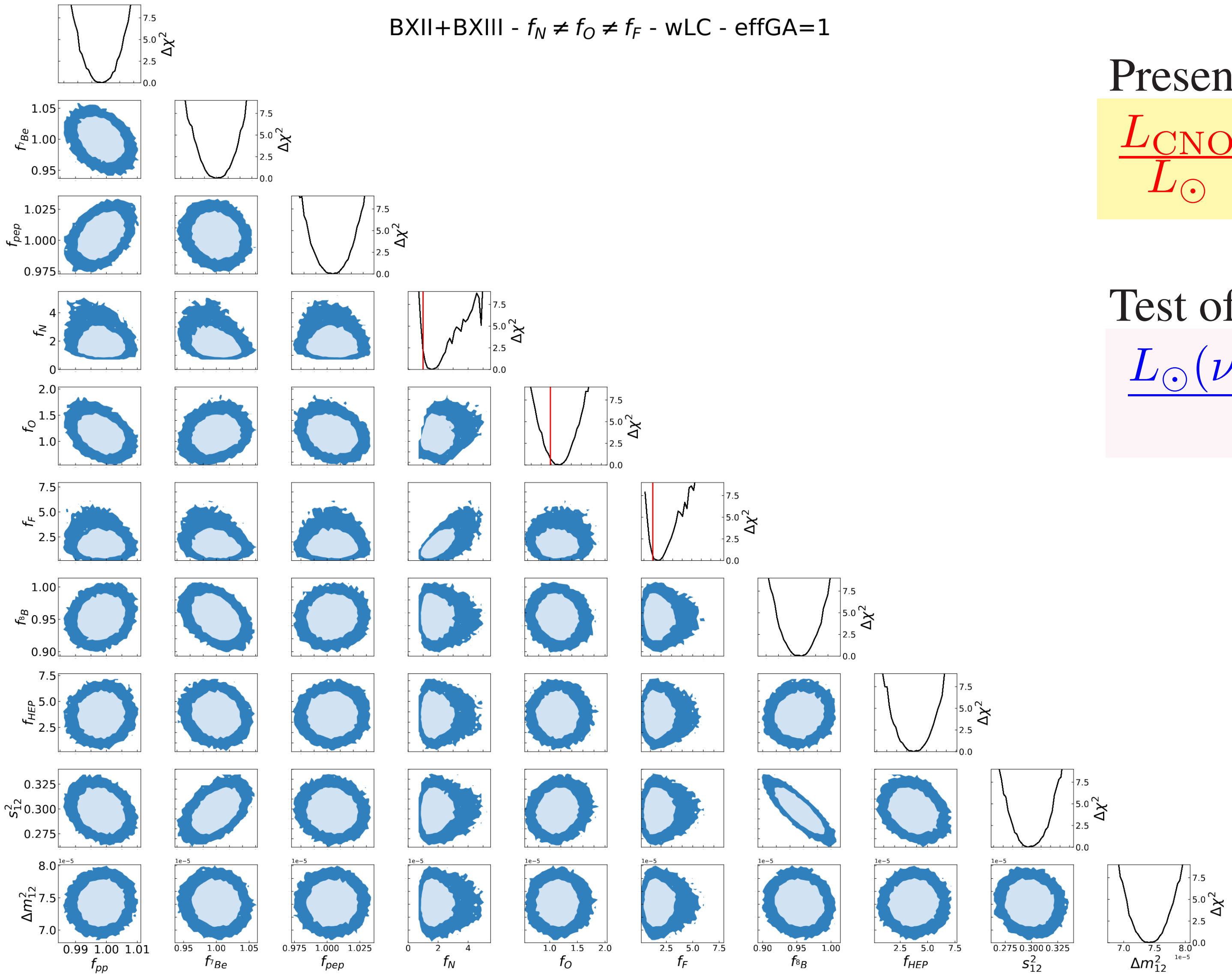
⇒ Possible to extract fluxes for data

⇒ NEW: Inclusion of full Borexino data



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

Results of Oscillation analysis with solar flux normalizations free: $f_i = \frac{\Phi_i}{\Phi_i^{GS98}}$



Present limit on CNO:

$$\frac{L_{\rm CNO}}{L_\odot} < 1.5\,\% \ (99\% CL)$$

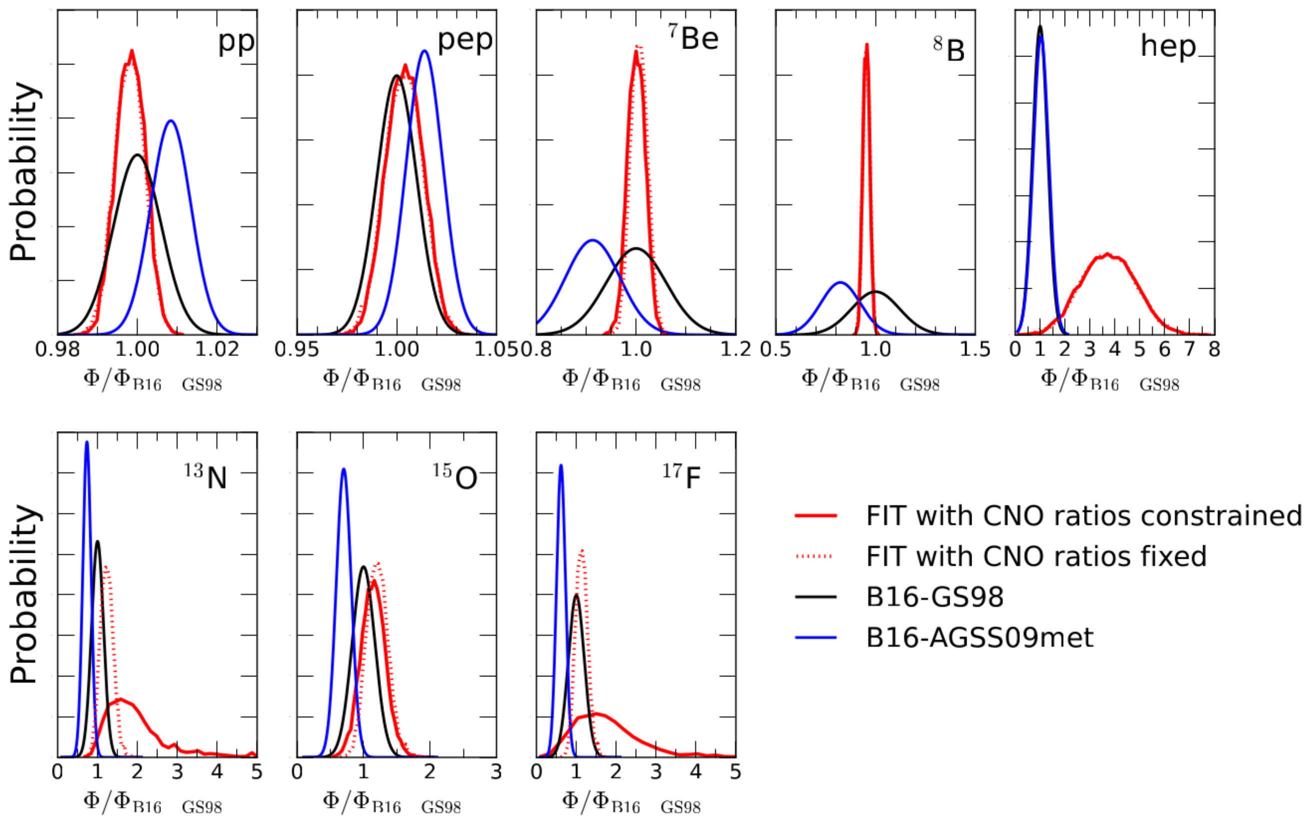
Test of Lum Constraint:

$$\frac{L_\odot(\nu - \text{inferred})}{L_\odot} = 1.024^{+0.078}_{-0.054}$$

J.P Pinheiro,MCG-G, M. Maltoni, in preparation

Fitted Fluxes vs Composition Models

Comparing the extracted fluxes with B16-GS98 and B16-AGSS09 Models



J.P Pinheiro,MCG-G, M. Maltoni, in preparation

Preliminary: $\chi^2_{\nu\ \rm flux}(\rm B16-AGSS09met) - \chi^2_{\nu\ \rm flux}(\rm B16-GS98) = 4.5\text{–}\ 7.5$

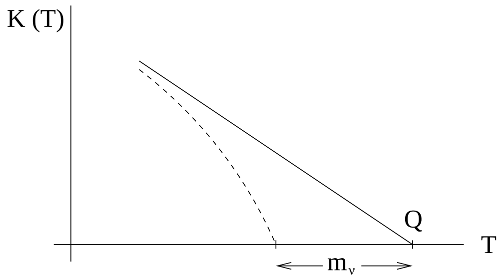
$\Rightarrow$ 2 to 2.7 σ favouring of B16-GS98

Confirmed Low Energy Picture and MY List of Q&A

- At least two neutrinos are massive ⇒ BSM
- 3ν scenario:
  - Robust determination of θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  - Mass ordering, θ_{23} Octant, CPV depend on subdominant 3ν-effects
    ⇒ interplay of LBL/reactor/ATM results
    ⇒ not statistically significant yet
    ⇒ definitive answer will likely require new experiments
- Oscillations DO NOT determine the lightest mass
- Oscillations DO NOT distinguish Dirac/Majorana

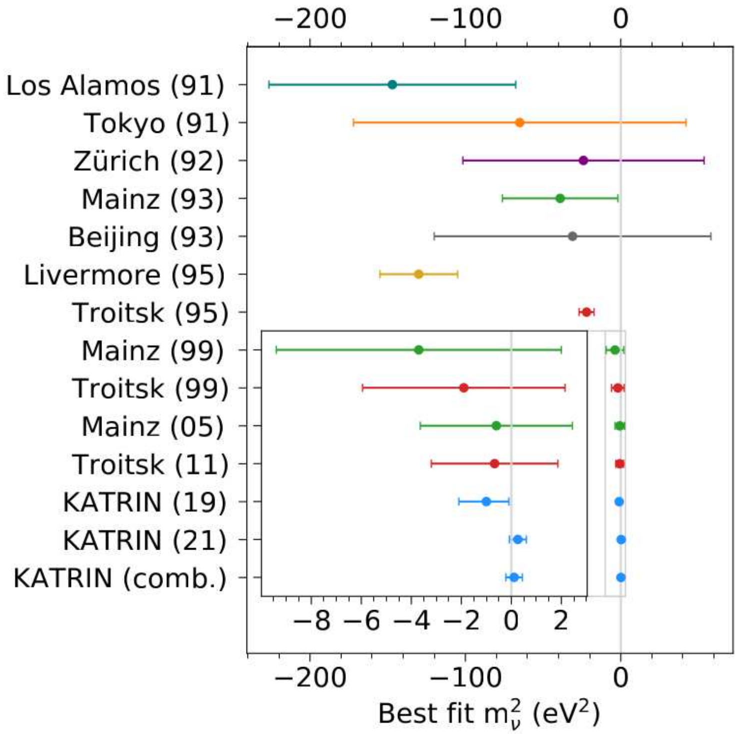
Neutrino Mass Scale: β Decay

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



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

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



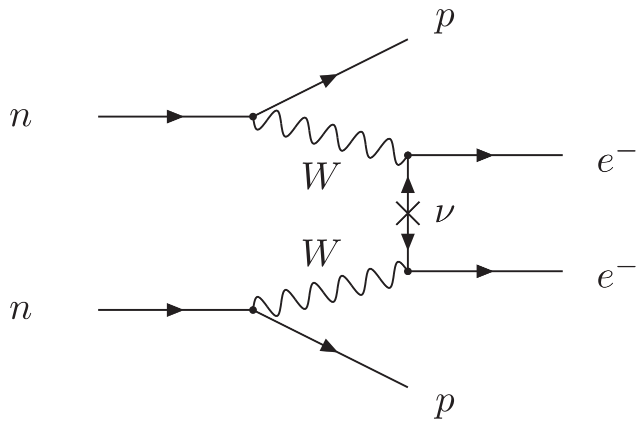
KATRIN : $m_{\nu_e} \leq 0.8$ eV **(at 90 % CL)**

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 ν



Best bounds from

^{136}Xe (KamLAND-ZEN):

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

^{76}Ge (Gerda):

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

^{130}Te (Cuore):

$$T_{1/2}^{0\nu,\mathrm{Te}} > 2.2 \times 10^{25} \text{ yr at } 90\%\mathrm{CL}$$

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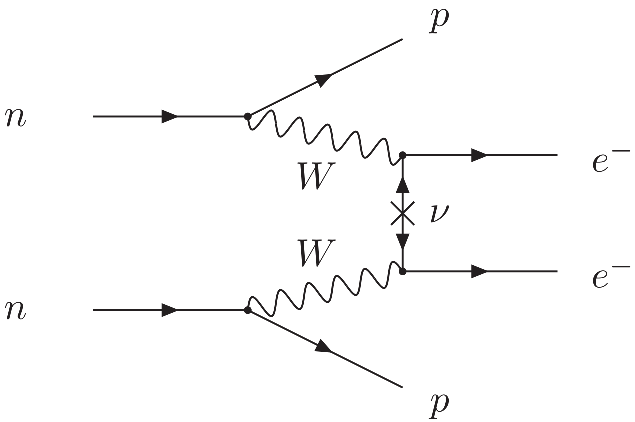

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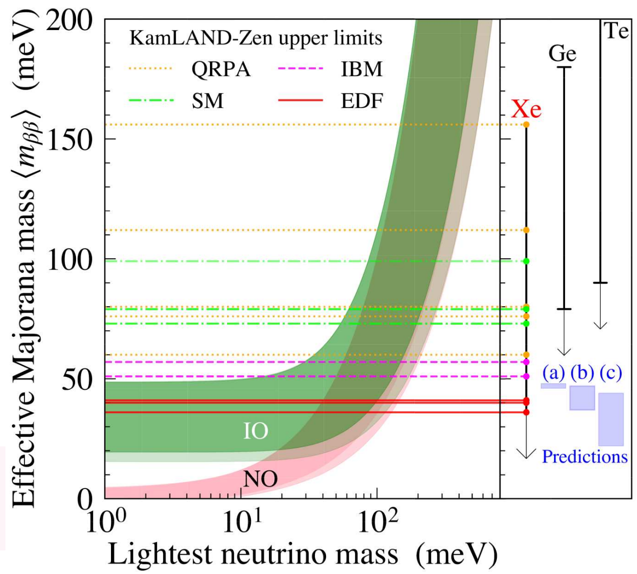
If m_ν only source of ΔL

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

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

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

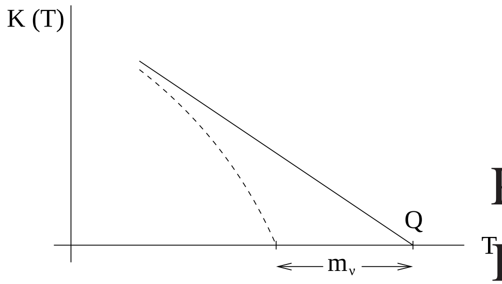
$= f(m_\ell,$ order, maj phases$)$



KamLAND-Zen Coll. ArXiv:2203.02139

Probes of Mass Scale in 3ν-mixing

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

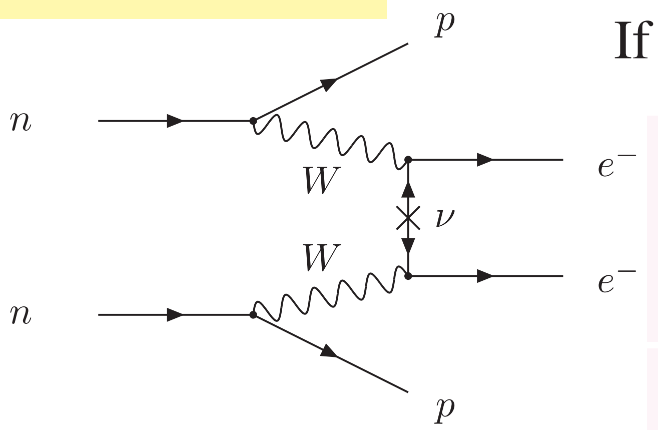


$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

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

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

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



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

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

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

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

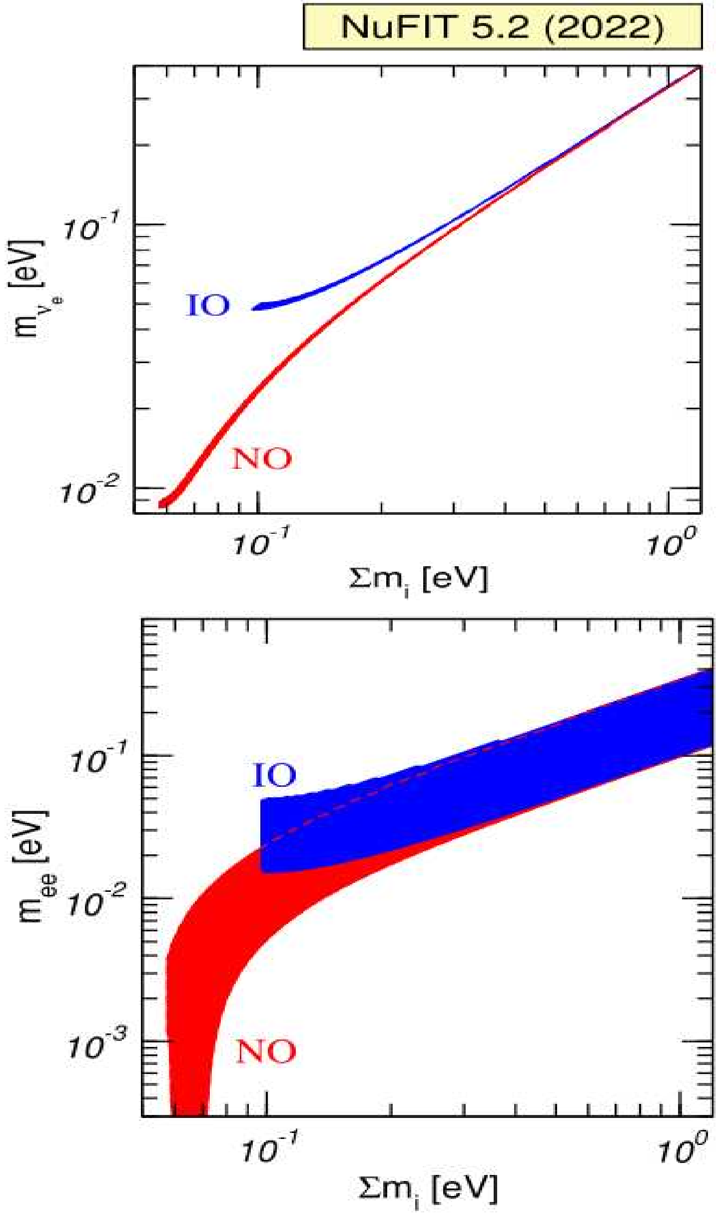
Present Bounds: $m_{ee} < 0.04$–0.2 eV

COSMO for Dirac or Majorana
m_ν 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 ⇒ Correlations m_{ν_e}, m_{ee} and $\sum m_\nu$ (Fogli *et al* (04))



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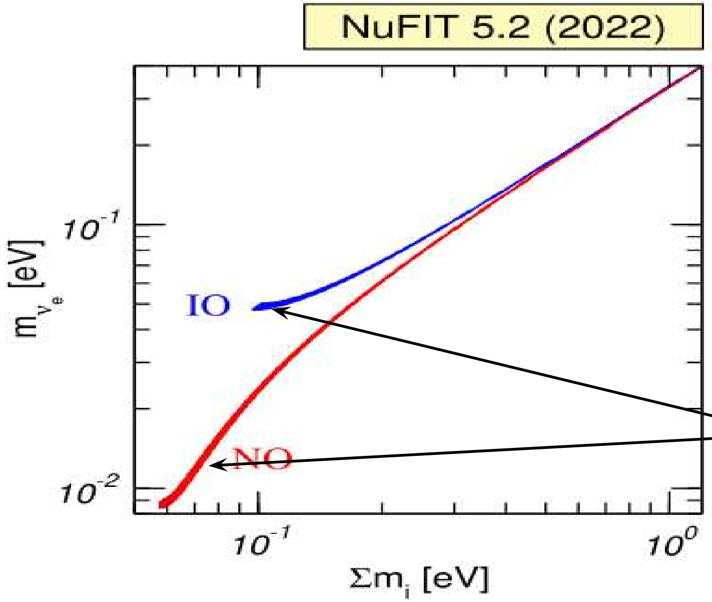
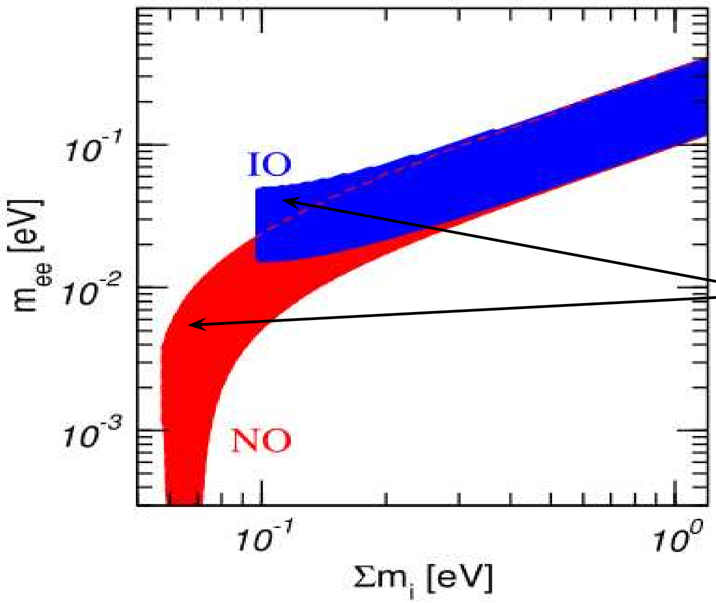


Width due to range in oscillation parameters very narrow
Lower bound on $\sum m_i$ depends on ordering



Wide band due to unknown Majorana phases ⇒
Possible Det of Maj phases?

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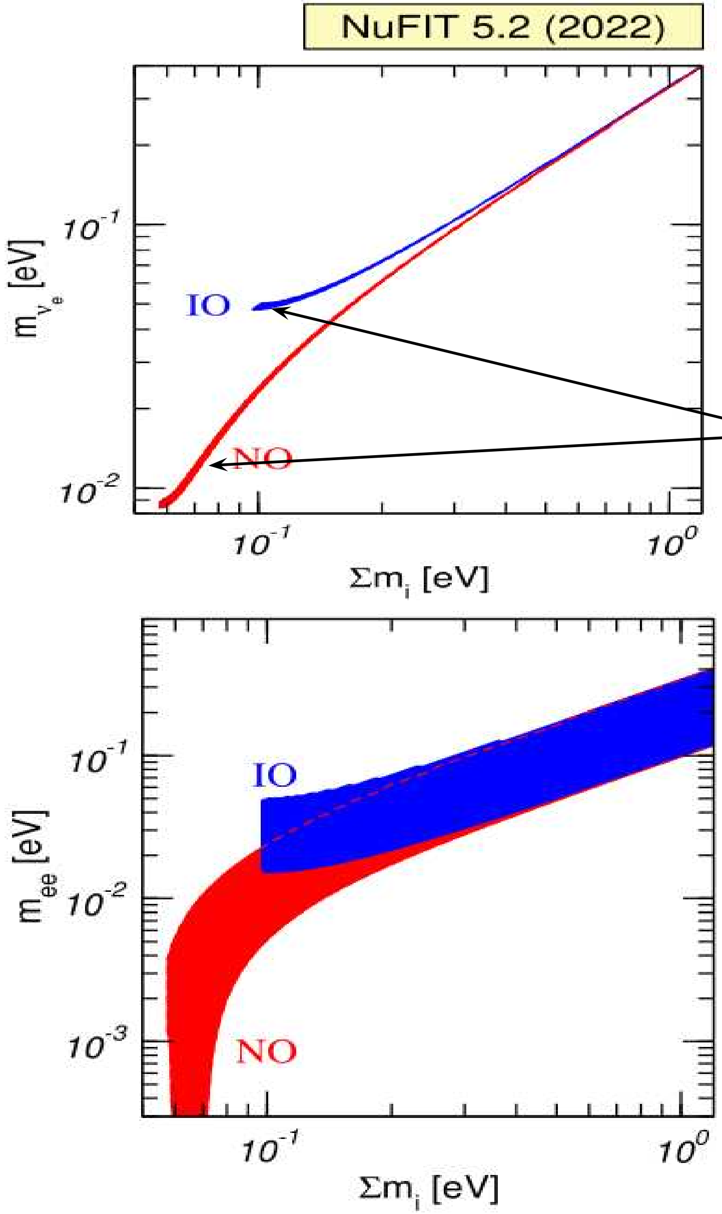

Lower bound on $\sum m_i$ depends on ordering

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

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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)

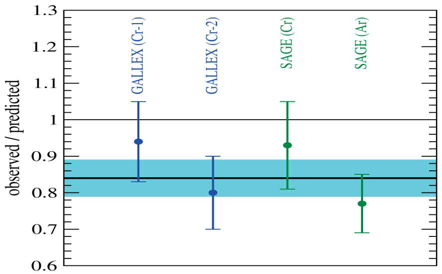
Gallium Anomaly

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



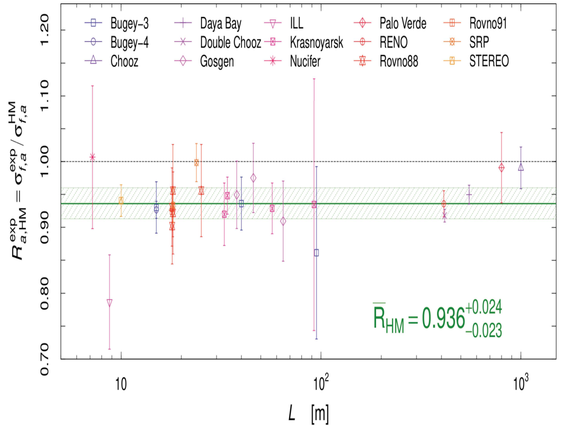
Explained as ν_e disappearance

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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Signal $\nu_\mu \to \nu$...

MiniBooNE 20...

$\bar\nu_\mu \to \bar\nu_e$ & ν_μ...

$(639 \pm 132.8$...

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... calculation

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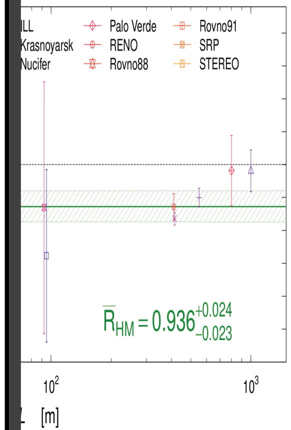
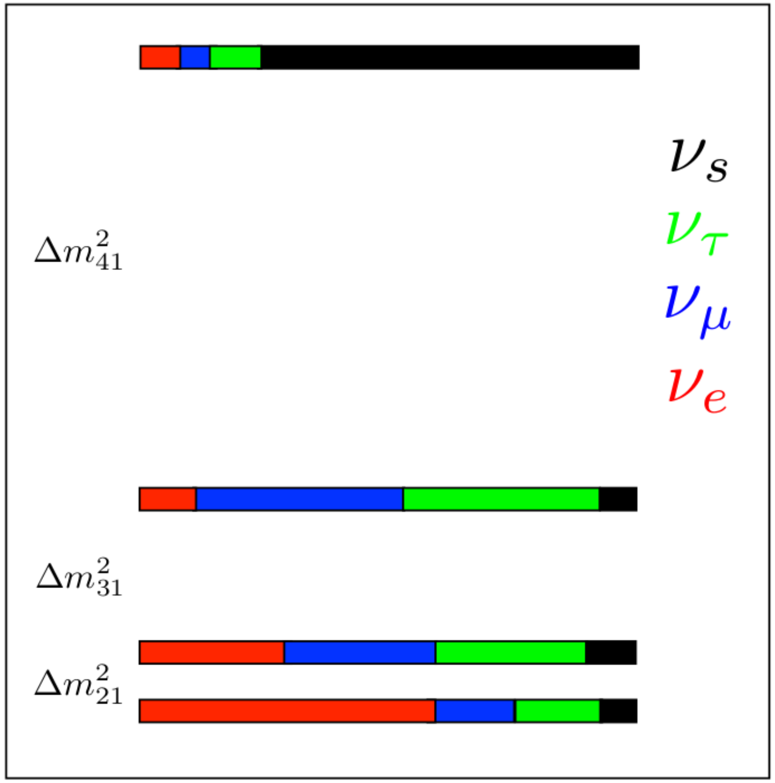


... disappearance

Oscillation Interpretation Requires new (sterile) ν's



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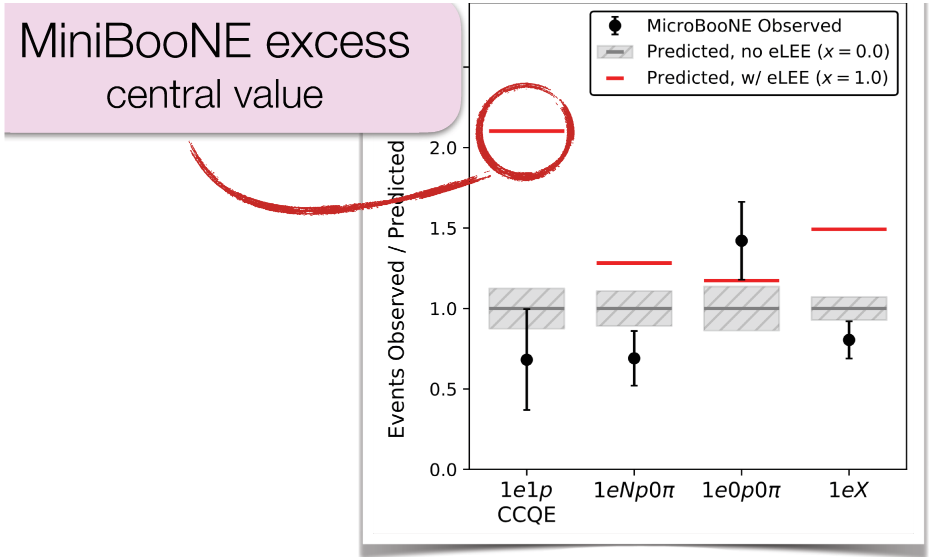
(639 ± 132.8 events)

MicroBooNE 2021/2022:



No support for excess ν_e interpretation in MiniBooNE

(Fig from Kopp's ν2022 talk)

MicroBooNE Coll.

2110.14054

Beyond 3ν's: Light Sterile Neutrinos

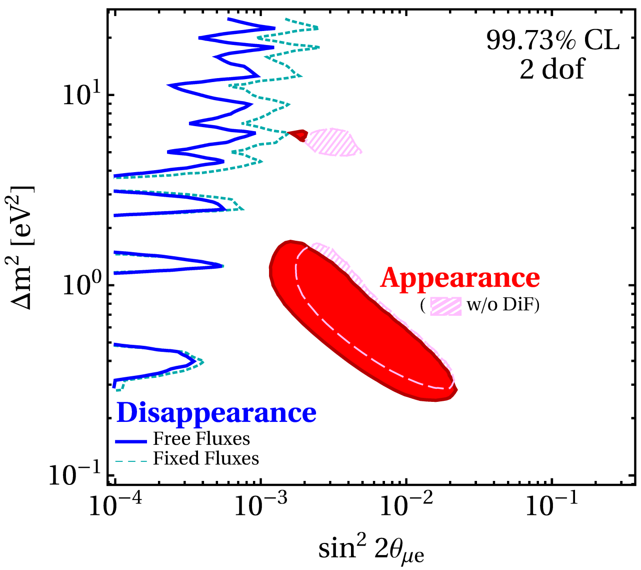
LSND &MiniBoone

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

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

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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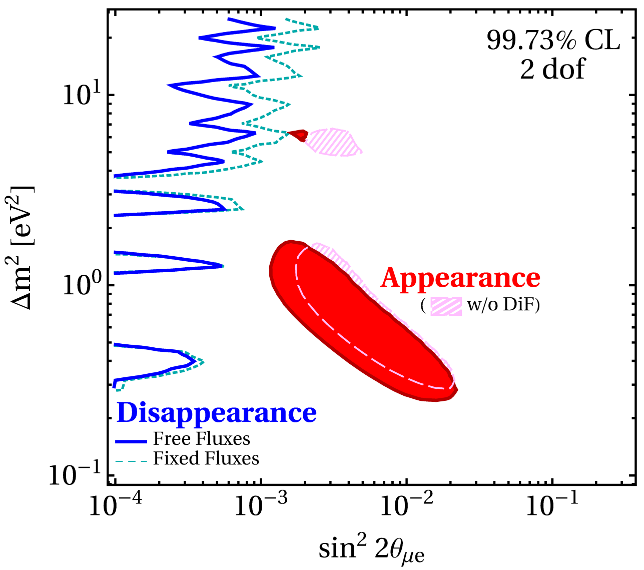

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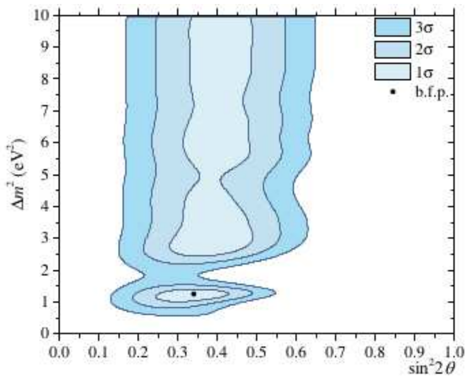
$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

Rate lower than expected

Explained as ν_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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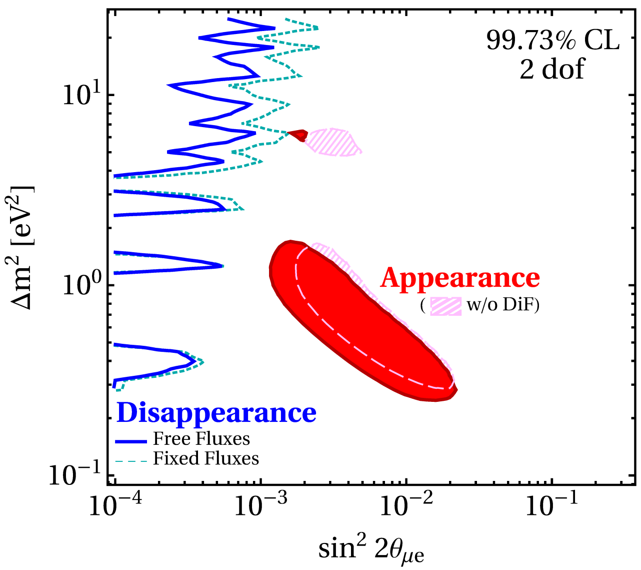

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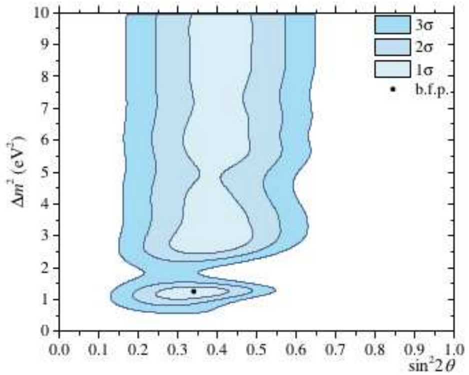

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Goldhagen etal 2109.14898

Berryman etal 2111.12530

Giunti etal, 2209.00916

Reactor Anomaly

Huber, 1106.068,Mention *etal* ,1101.2755

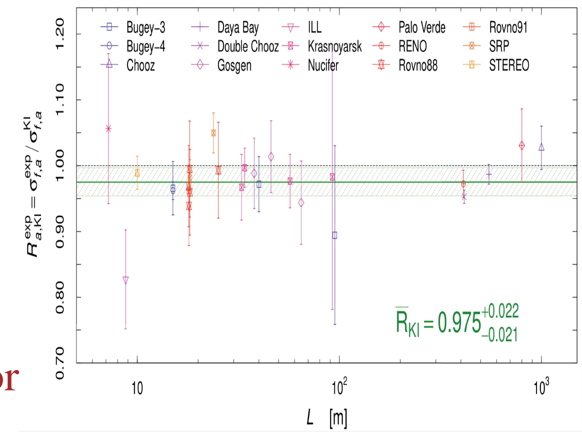
2011 reactor flux calculation $\Rightarrow$

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

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

2022 with updated inputs (^{235}U)

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

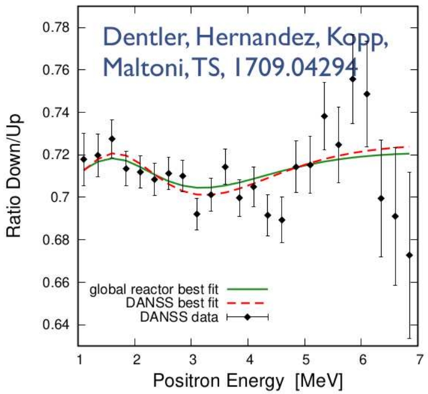


(Fig from Giunti etal, 2110.06820)

Anomaly $\sim 1\,\sigma$

with new fluxes

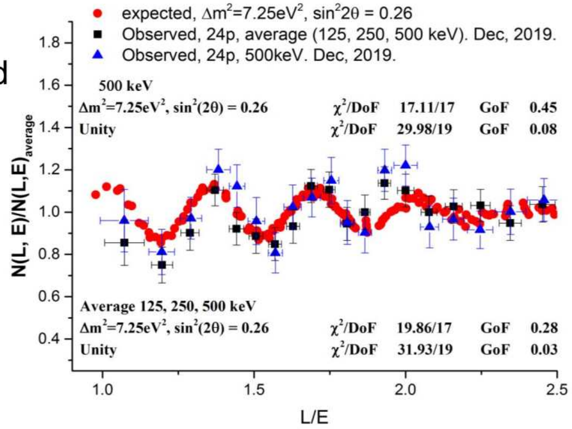
Recent relative spectral measurments

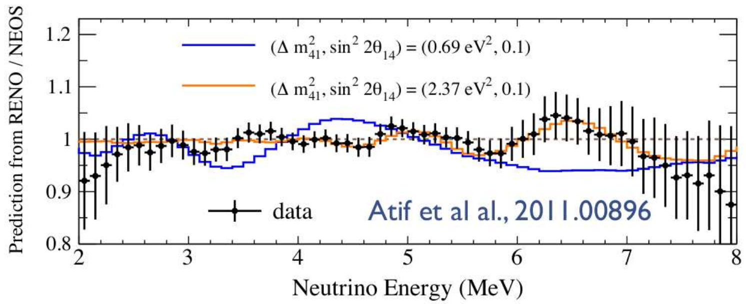


DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20 (update at EPS-HEP21)

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

Neutrino4 2005.05301





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

Confirmed Low Energy Picture and MY List of Q&A

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

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

    $\Rightarrow$ definitive answer will likely require new experiments

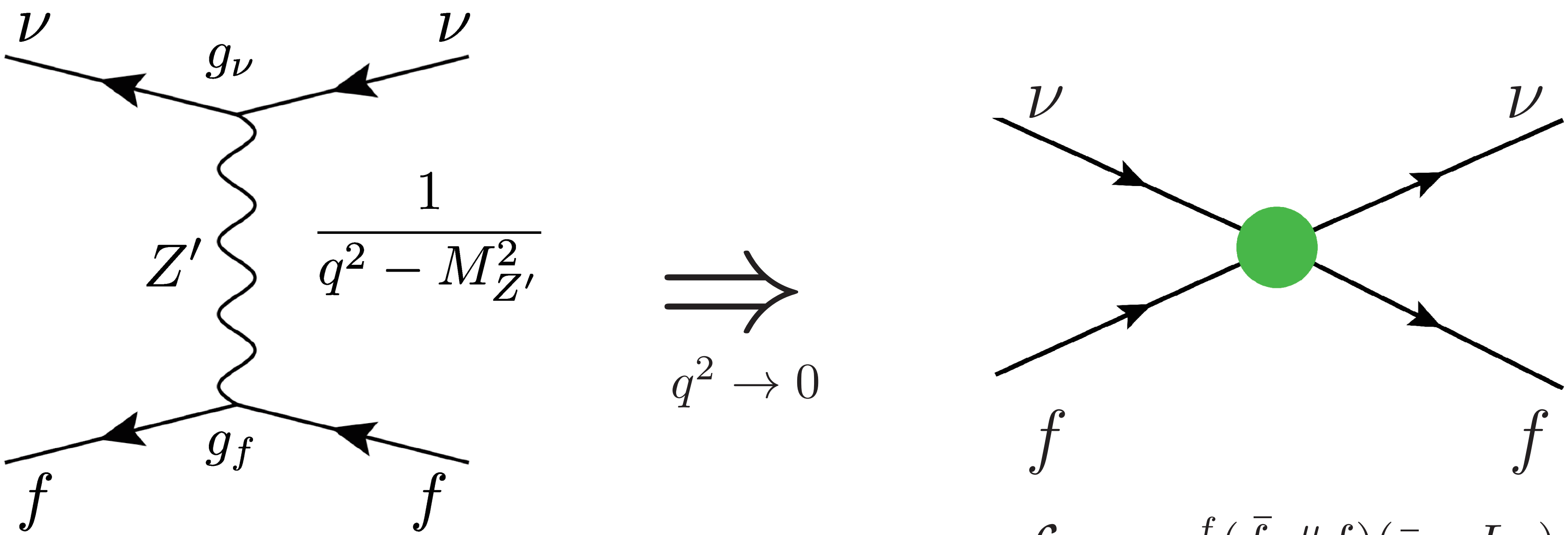
- What about mass scale and Dirac vs Majorana?
  - Only model independent probe of m_ν β decay: $\sum m_i^2 |U_{ei}|^2 \leq (0.8 \text{ eV})^2$
  - Dirac or Majorana?: We do not know, *anxiously* waiting for ν-less $\beta\beta$ decay
  - Cosmological effects?: No signal yet

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

- Other NP at play?

Neutral Current Non Standard ν Interactions

- Generically understood as:



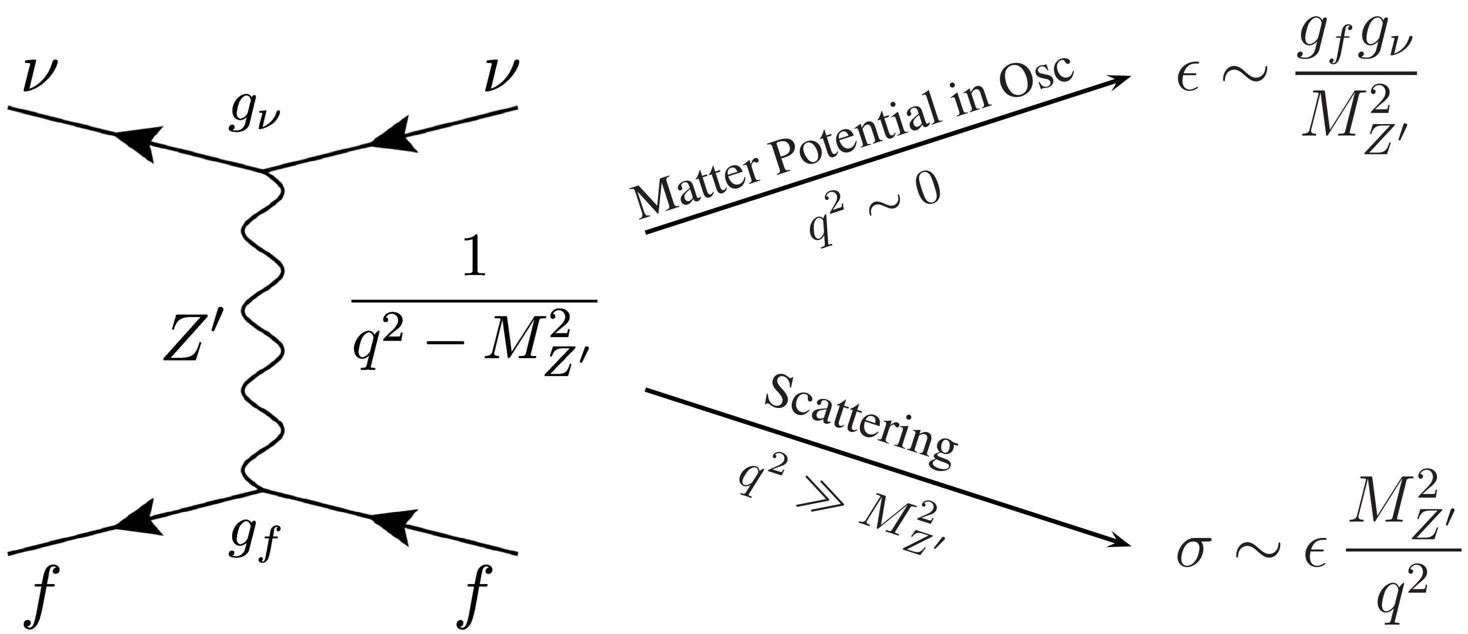
$$\mathcal{L}_{\rm eff} \sim \epsilon^f (\bar{f}\gamma^\mu f)(\bar{\nu}\gamma_\mu L\nu)$$

- More generally

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

Neutral Current Non Standard ν Interactions

- Depending on Z' (Mediator) Mass:



$\Rightarrow$ For mediator mass $\lesssim$ few GeV effects in DIS experiments suppressed

NC-Non Standard ν Interactions in ν-OSC

- Including non-standard neutrino NC interactions with fermion f

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

- In flavour basis $\vec\nu = (\nu_e, \nu_\mu, \mu_\tau)^T$ the neutrino evolution eq.:

$$i\frac{d}{dx}\vec\nu = H^\nu \vec\nu \quad \text{with} \quad H^\nu = H_{\rm vac} + H_{\rm mat} \quad \text{and} \quad H^{\bar\nu} = (H_{\rm vac} - H_{\rm mat})^*$$

$$H_{\rm vac} = U_{\rm vac} D_{\rm vac} U^\dagger_{\rm vac} \quad \text{with} \quad D_{\rm vac} = \frac{1}{2E_\nu}{\rm diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$$

$$H_{\rm mat} = \sqrt{2}G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2}G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} \varepsilon^f_{ee} - \varepsilon^f_{\mu\mu} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f*}_{e\mu} & 0 & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu} \end{pmatrix}$$

$\Rightarrow$ Matter Potential depends on vector NSI $\varepsilon^f_{\alpha\beta} \equiv \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$

NSI in ν Oscillations : Degeneracies

- For $\vec{\nu} = (\nu_e, \nu_\mu, \mu_\tau)^T$ in vaccum: $i\dfrac{d}{dx}\vec{\nu} = H_{\rm vac}\vec{\nu}$

$$H_{\rm vac} = U_{\rm vac} D_{\rm vac} U^\dagger_{\rm vac} \quad \text{with} \quad D_{\rm vac} = \frac{1}{2E_\nu}{\rm diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$$

- Chosing Convention

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

The transformation

$$\begin{aligned} \theta_{12} &\to \tfrac{\pi}{2} - \theta_{12} \\ \Delta m^2_{31} &\to -\Delta m^2_{32} \\ \delta &\to \pi - \delta \end{aligned}$$

$\Rightarrow H_{\rm vac} \to -H^*_{\rm vac} \Rightarrow$ (Evol. Eq) $\to$ (Evol. Eq)*

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The transformation

$$\theta_{12} \to \frac{\pi}{2} - \theta_{12} \Rightarrow \text{No Information of } \theta_{12} \text{ Octant}$$
$$\Delta m^2_{31} \to -\Delta m^2_{32} \Rightarrow \text{No Information of Ordering}$$
$$\delta \to \pi - \delta \Rightarrow \text{No information on sign of CPV}$$

$\Rightarrow H_{\rm vac} \to -H^*_{\rm vac} \Rightarrow$ (Evol. Eq) $\to$ (Evol. Eq)* So leaves Probabilities Invariant

[Notice that for antineutrinos: $H^{\bar{\nu}}_{\rm vac} = H^*_{\rm vac}$ (CPT $\Rightarrow H_{\rm vac} \to -H^{\bar{\nu}}_{\rm vac} = -H^*_{\rm vac}$)]

NSI in ν Oscillations : Degeneracies

• In SM matter: $i\frac{d}{dx}\vec{\nu} = H^\nu \vec{\nu}$ with $H^\nu = H_{\rm vac} + H^{\rm SM}_{\rm mat}$

$$H_{\rm vac} = U_{\rm vac} D_{\rm vac} U^\dagger_{\rm vac} \quad \text{with} \quad D_{\rm vac} = \frac{1}{2E_\nu}{\rm diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$$

$$H^{\rm SM}_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{is real}$$

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Sensitivity to θ_{12} Octant(via MSW Solar)

Sensitivity to Ordering (in LBL&ATM)

Sensitivityto sign of CPV

NSI in ν Oscillations : Degeneracies

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

$$H^{\rm SM}_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad H^{\rm NSI}_{\rm mat} = \sqrt{2} G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} \varepsilon^f_{ee} - \varepsilon^f_{\mu\mu} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f*}_{e\mu} & 0 & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu} \end{pmatrix}$$

Rewriting

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

NSI in ν Oscillations : Degeneracies

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

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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)
$\Delta m_{31}^2 \to -\Delta m_{32}^2$	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 ν-OSC: Global Analysis

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

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

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

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– 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

NSI in ν-OSC: Global Analysis

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– Introduce couplings to general combination of u and d quarks

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

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

NSI in ν-OSC: Global Analysis

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

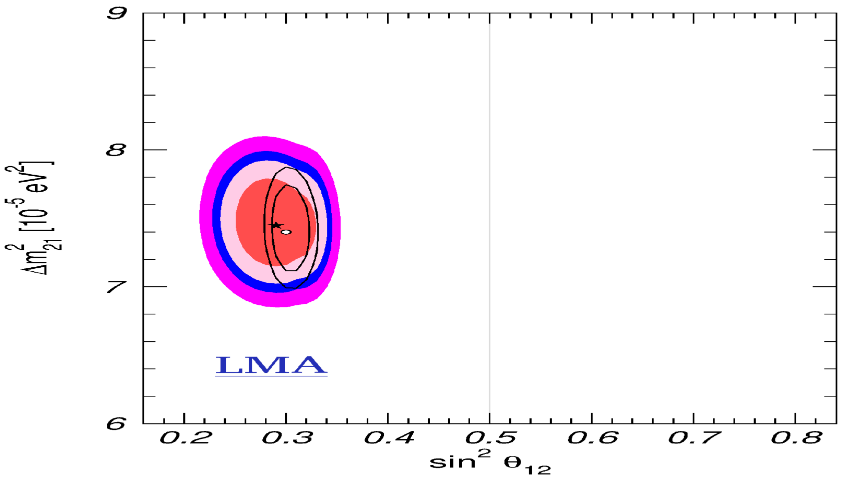
– Introduce couplings to general combinatins of u and d quarks and electrons

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

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

Coloma eta 2305.07698

NSI: Bounds/Degeneracies from Matter Effects



- Standard Solution $\equiv$ LMA $\Rightarrow$ Bounds

Allowed ranges at 99% CL marginalized	
GLOB-OSC w/o NSI in ES	
$\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu}$	[-4.8, -1.6] $\oplus$ [-0.40, +2.6]
$\varepsilon^{\oplus}_{\tau\tau} - \varepsilon^{\oplus}_{\mu\mu}$	[-0.075, +0.080]
$\varepsilon^{\oplus}_{e\mu}$	[-0.32, +0.40]
$\varepsilon^{\oplus}_{\mu\tau}$	[-0.49, +0.45]
$\varepsilon^{\oplus}_{\mu\tau}$	[-0.043, +0.039]

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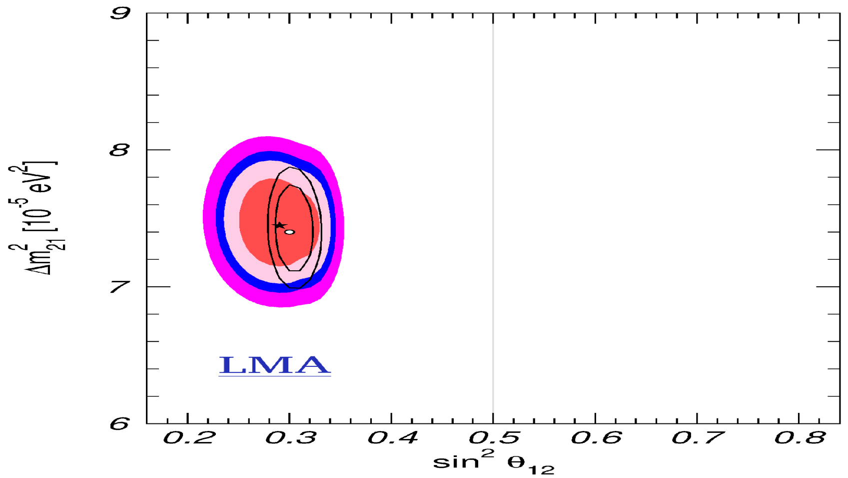
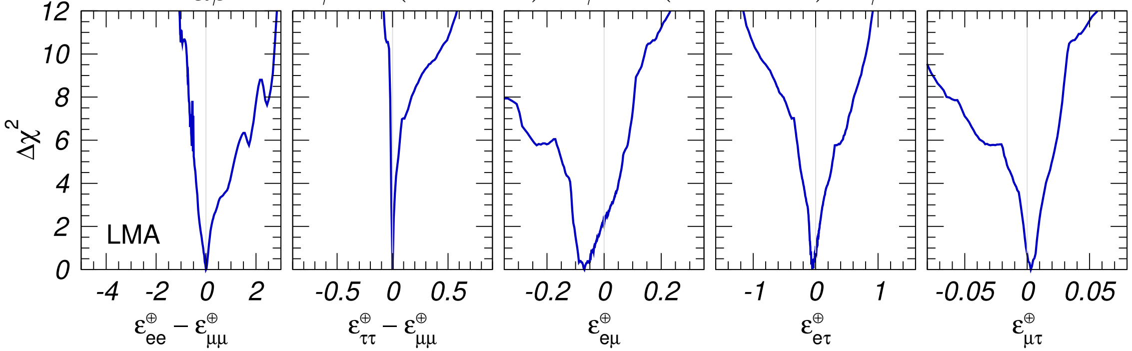


- Standard Solution ≡ LMA ⇒ Bounds

  ⇒ Maximum effect at LBL experiments:

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



⇒ To be considered in effects/sensitivity studies at DUNE, HK…

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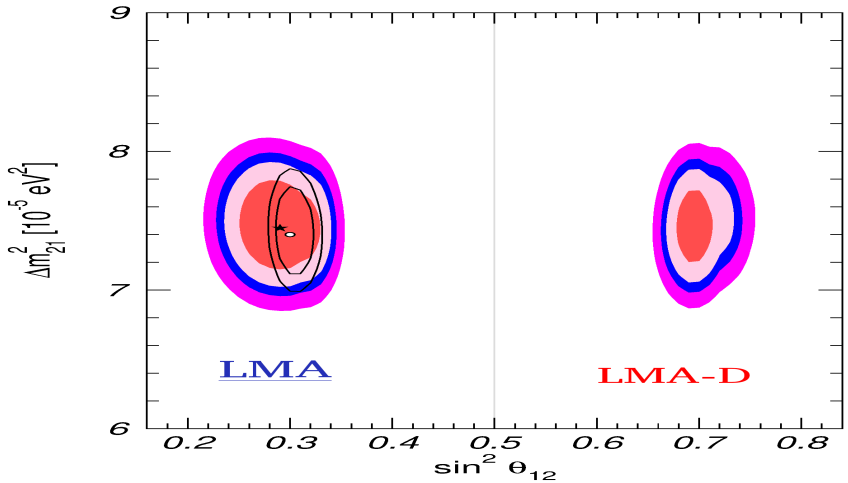

- Standard Solution ≡ LMA ⇒ Bounds

  ⇒ Maximum effect at LBL experiments:

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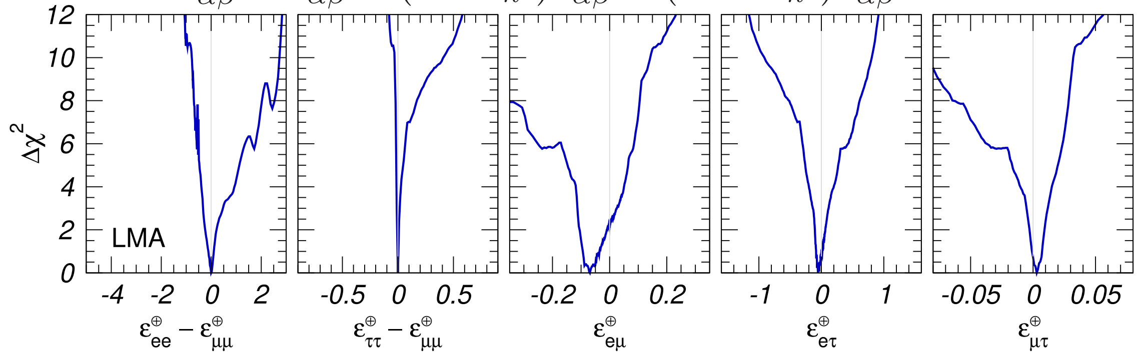

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- Degenerate solution ≡LMA-D

  Miranda,Tortola, Valle, hep-ph/0406280

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

  ⇒ Requires NSI $\sim G_F$

Bounds on Z' Models

Coloma, MCGG, Maltoni ArXiv:2009.14220

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

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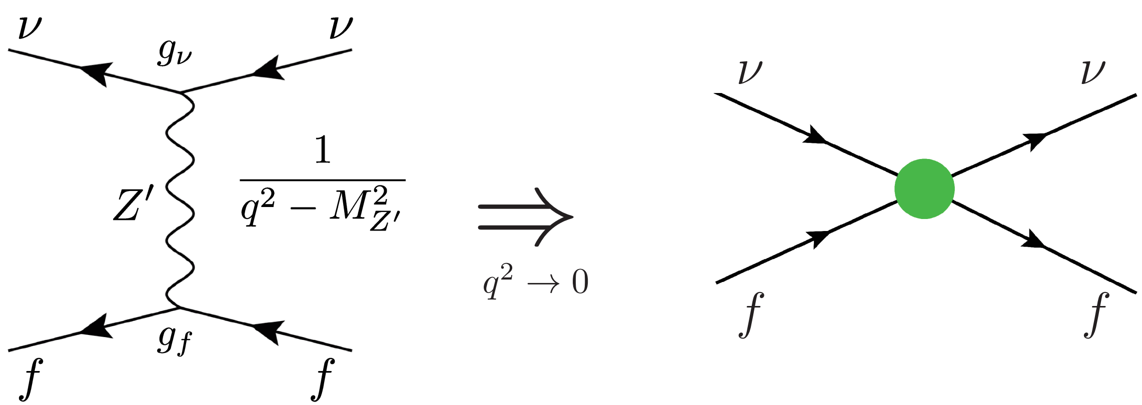
So far we have assumed that ν propagation in matter $\Rightarrow$ contact int approximation



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

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

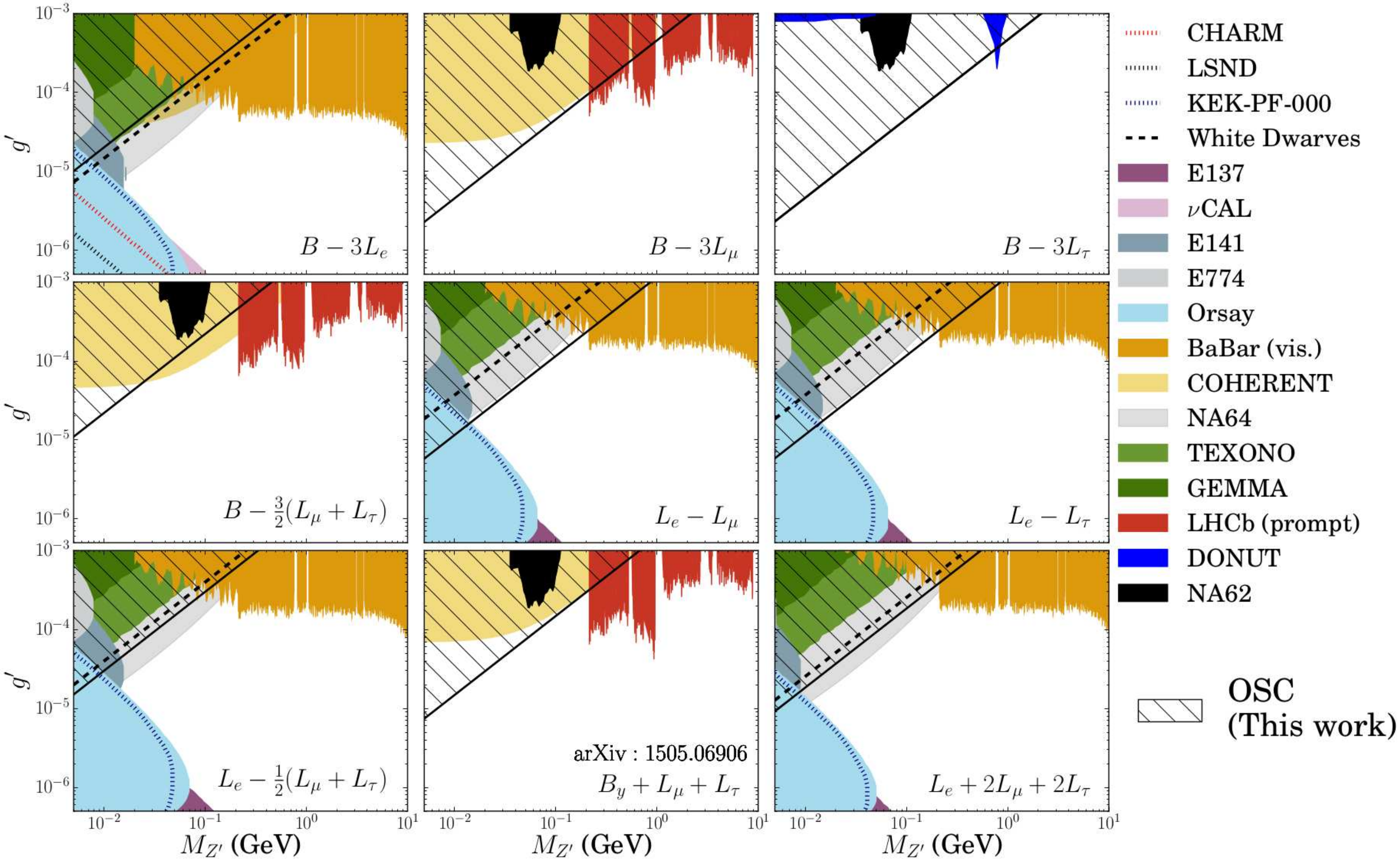
with

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

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

Z' Models: ν Oscillations Bounds

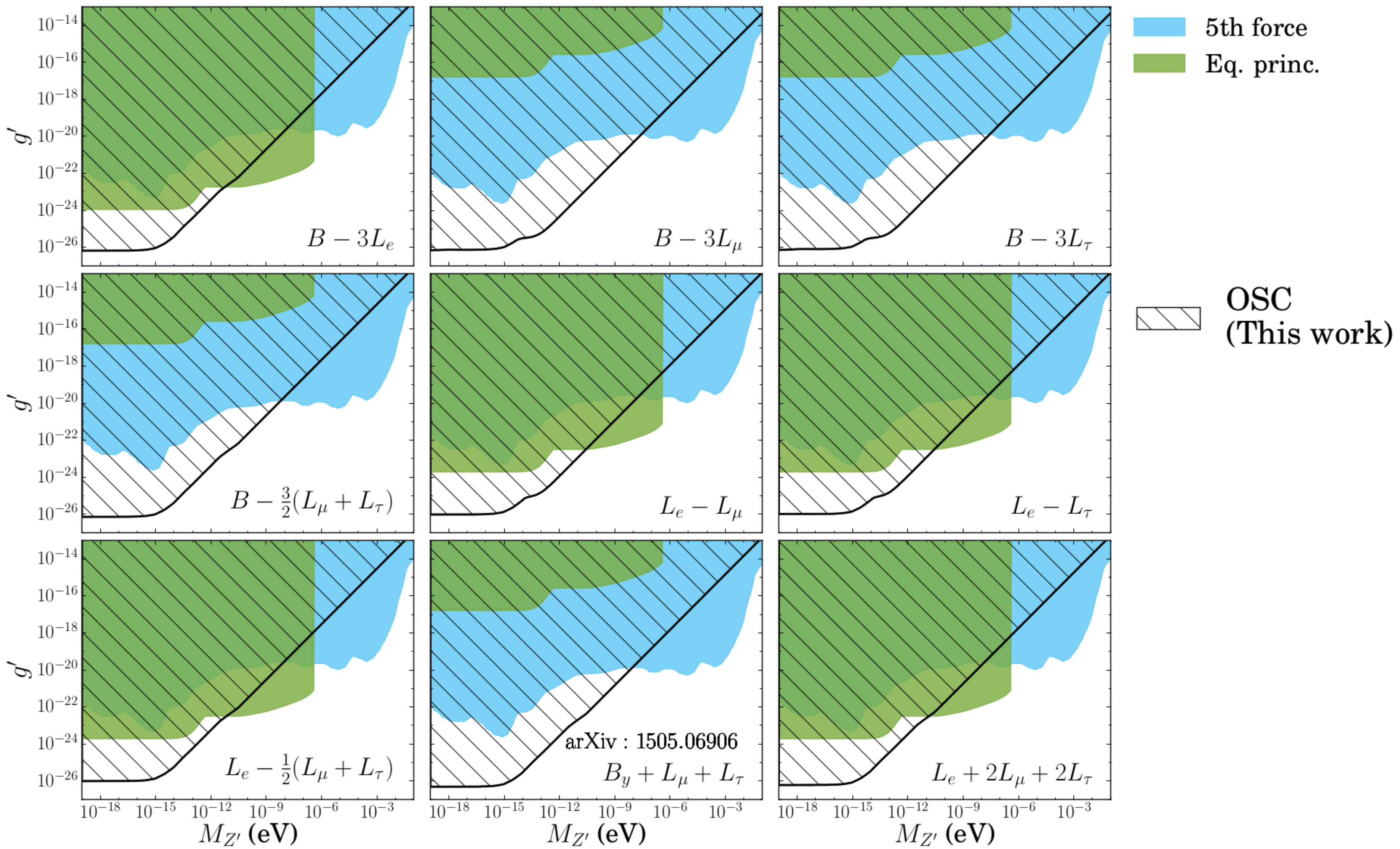
$M_{Z'} \gtrsim \mathcal{O}(\text{MeV}) \Rightarrow$ Contact Interaction in $H_{\rm mat}$



Coloma, MCGG, Maltoni ArXiv:2009.14220

Z'/Dark-photon: Bounds from ν Oscillations

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



Coloma, MCGG, Maltoni ArXiv:2009.14220

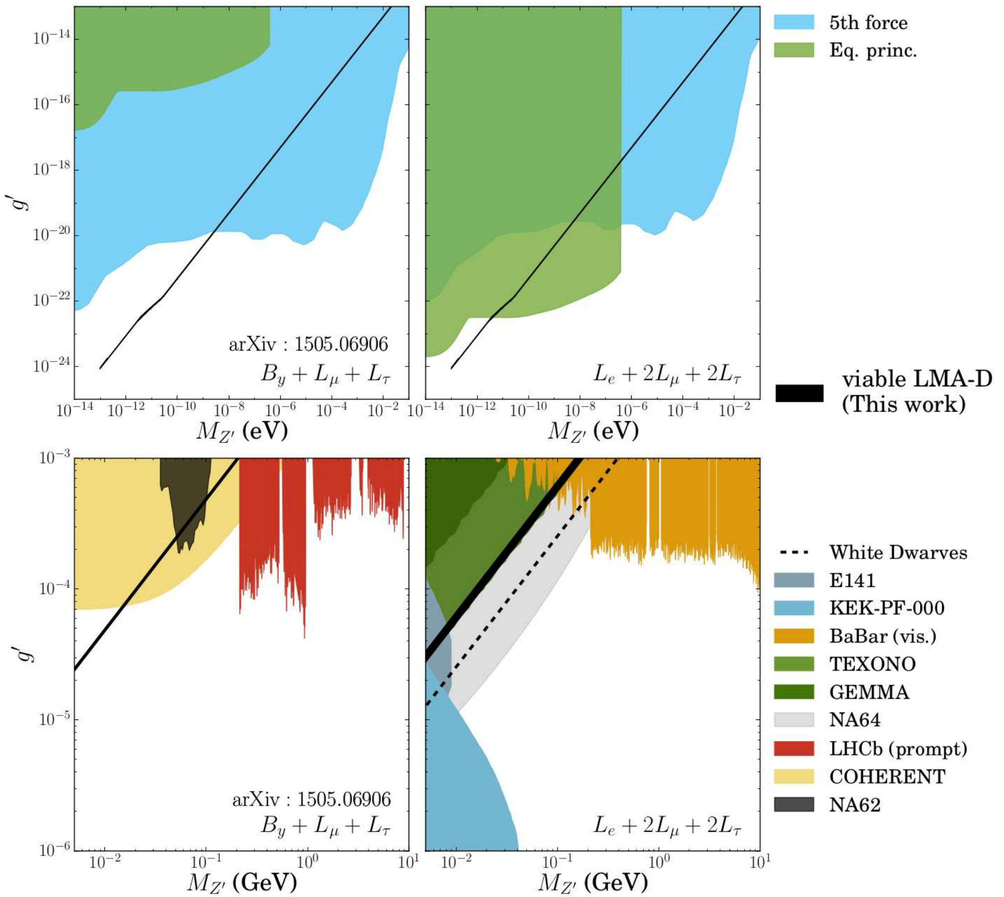
Z' Models: Viable models for LMA-D

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+ν_R states only

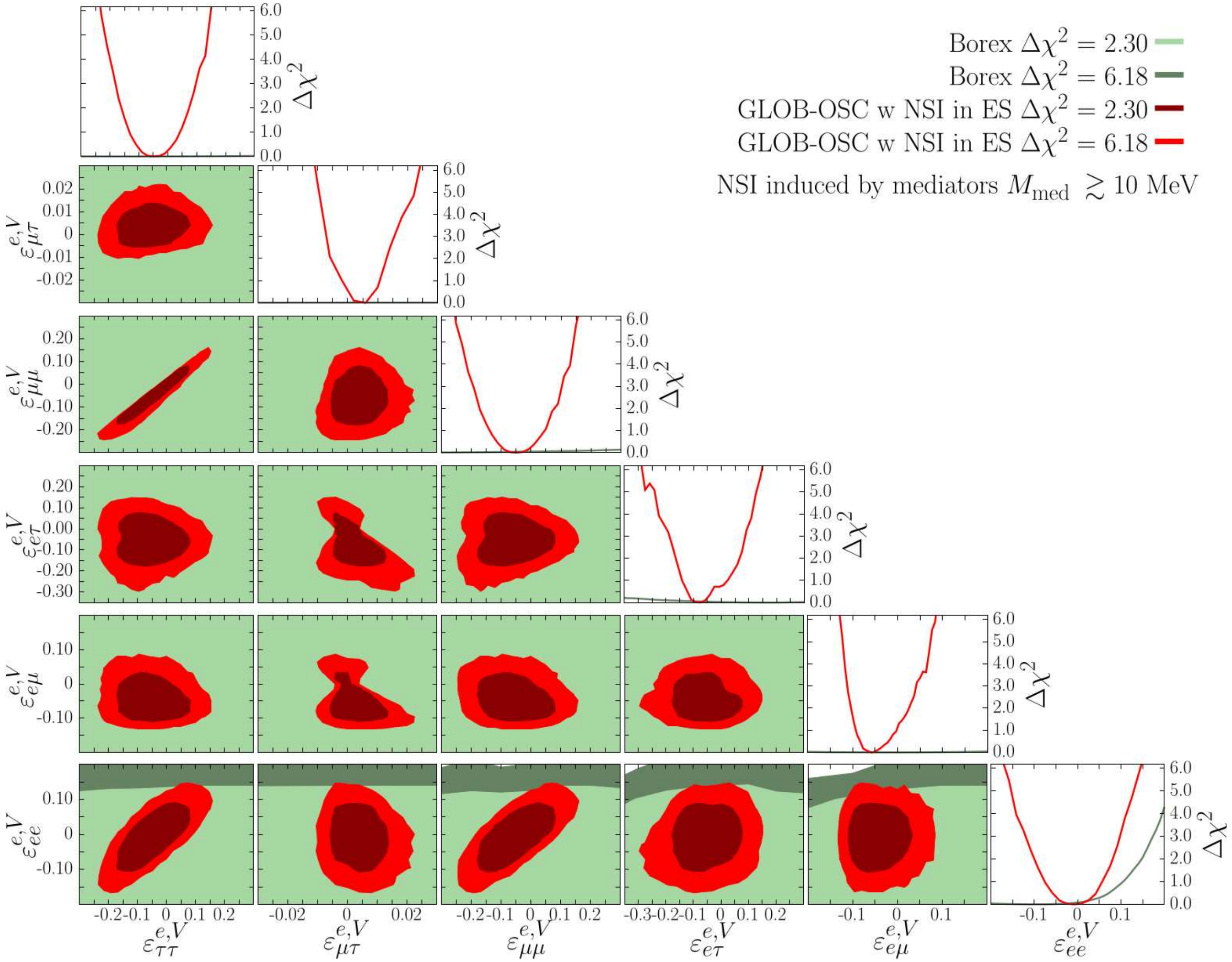
Two examples



Coloma, MCGG, Maltoni ArXiv:2009.14220

NSI: Effect in ES

- For $M_{\rm Med} \gtrsim 10$ MeV and $\zeta \neq 0$ ($\equiv$ NSI with e^-) effect in ES at Borexino, SK, SNO
  - $\Rightarrow$ No LMA-D
  - $\Rightarrow$ Oscillation data analysys can bound all 6 NSI's



Coloma eta 2305.07698

NSI: Effect in CEνNS

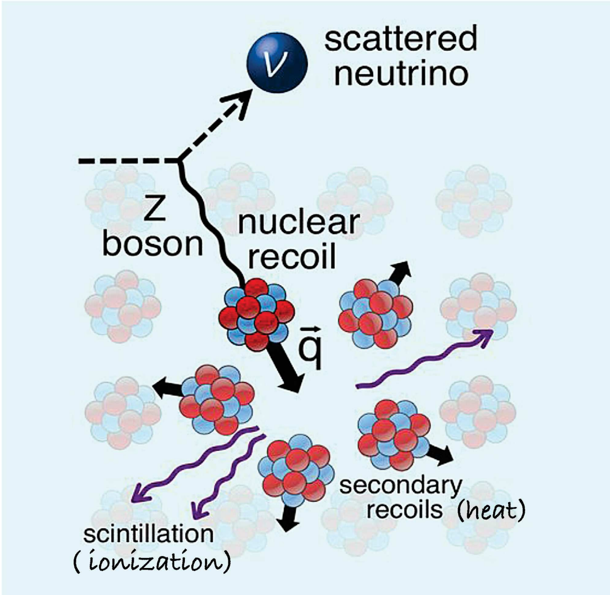
$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{2\pi}\frac{\mathcal{Q}^2}{4}F^2(2ME_r)M\left(2 - \frac{ME_r}{E_\nu^2}\right)$$

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

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

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

Freedman et al, PRD9 (1974) 1389



- For $M_{\rm Med} \gtrsim 50$ MeV and $\eta \neq 0$, $\zeta \neq 90^\circ$ ($\equiv$ NSI with quarks) effect in CEνNS

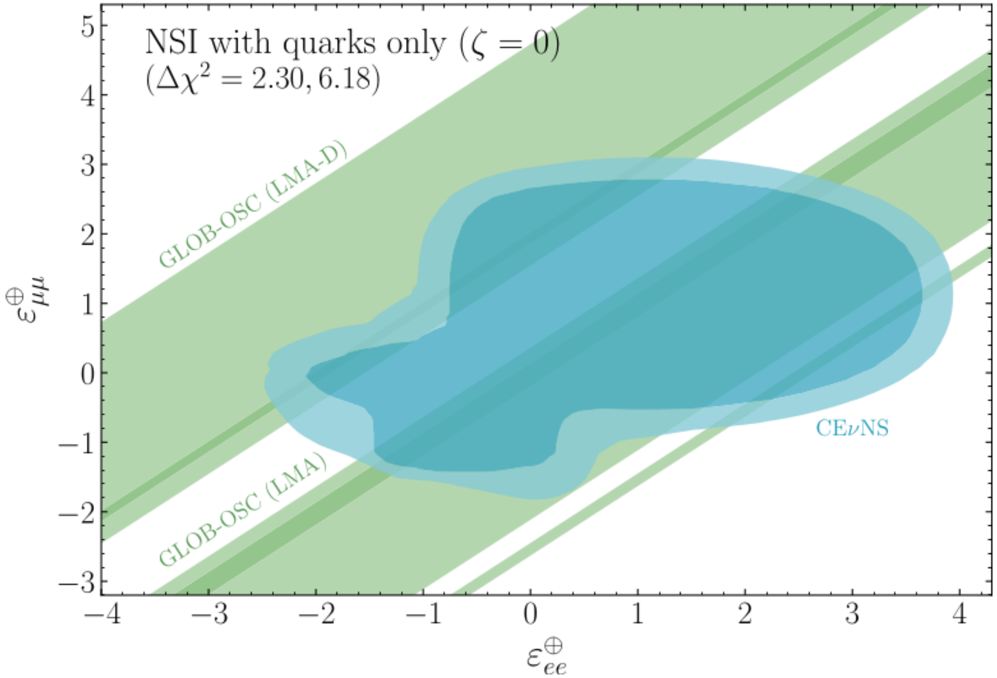
$$\mathcal{Q}_{\alpha\beta} = Z\left(g_p^V\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{p,V}\right) + N\left(g_n^V\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{n,V}\right)$$

$\Rightarrow$ No bounds for arbirary NSI with u and d quarks from CEνNS on a single nucleus

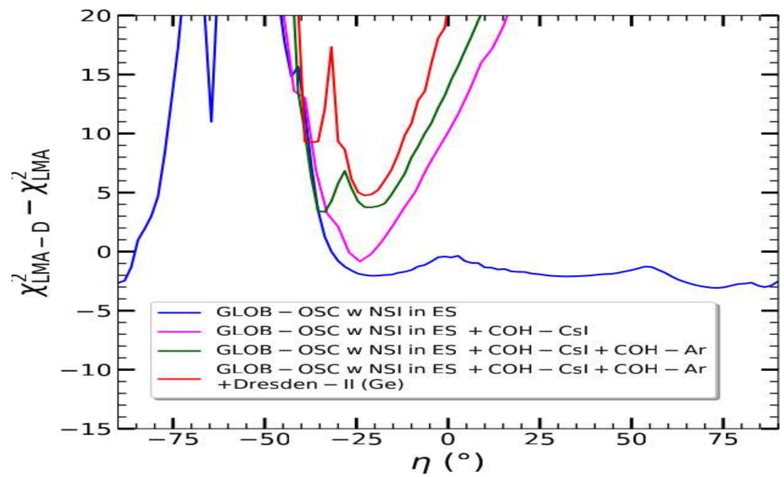
$\Rightarrow$ Complementarity using CEνNS with different nucleus (different Z/N)

NSI: Effect in CEνNS

Bounds from CEνNS on CsI, Ar and Ge



Combination with Oscillations
$\Rightarrow$ LMA-D at more than 2σ
for arbitrary couplings to e, u and d.



$\Rightarrow$ Bounds all 6 effective NSI in Earth:

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

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    ⇒ definitive answer will likely require new experiments

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

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

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

– But there can be non-renormalizable (dim>4) operators

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

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{O}_5 = \frac{Z^{\nu}_{ij}}{\Lambda_{\rm NP}} \left(\overline{L_{L,i}} \tilde{\phi}\right) \left(\tilde{\phi}^T L^C_{L,j}\right)$$

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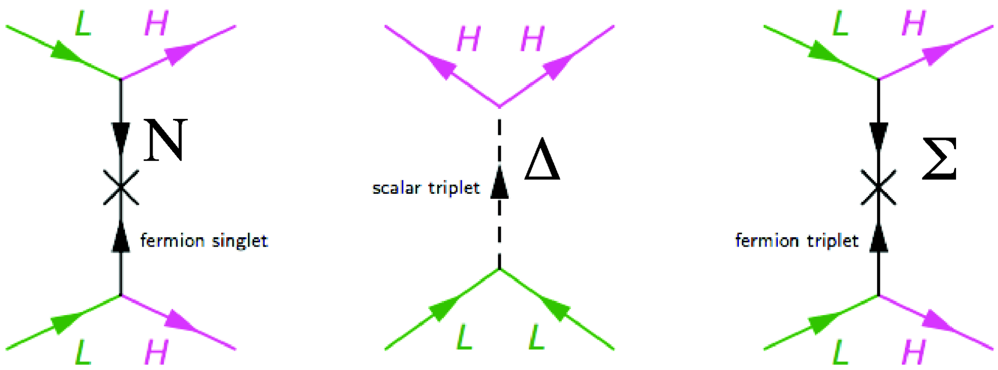
– $m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV for $Z^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}$GeV $\Longrightarrow$ $\Lambda_{\rm NP} \sim$ GUT scale

$\Rightarrow$ 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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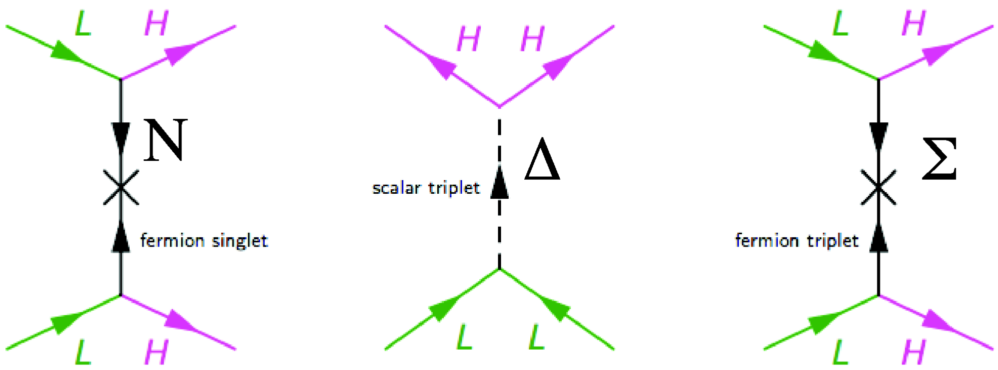

- For fermionic see-saw $\quad -\mathcal{L}_{\rm NP} = -i\overline{N_i}\not{D}N_i + \frac{1}{2}M_{N\,ij}\overline{N_i^c}N_j + \lambda^\nu_{\alpha j}\overline{L_\alpha}\tilde{\phi}N_j[.\tau]$

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

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

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

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

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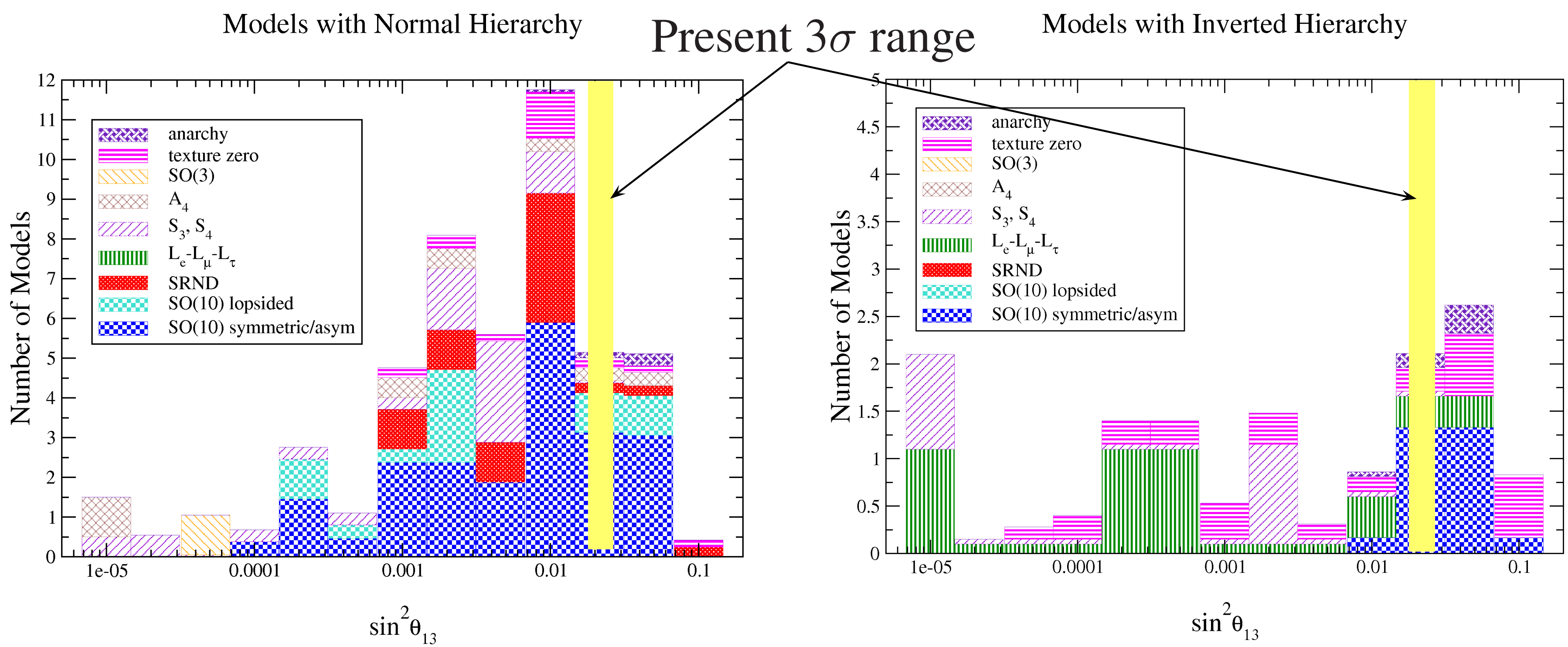
Same $\mathcal{O}_5$ can be generated by very different High Energy physics

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 2023

- 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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– Hope/Wait for additional information from charged LFV, collider signals . . .

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- ν oscillation $\Rightarrow$ Lepton Flavour is not conserved

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

- Collider signatures if heavy state mass $M \sim \Lambda_{LN} \sim$ TeV and/or $M \sim \Lambda_{LF} \sim$ TeV

  If $M \sim \Lambda_{LF} \sim$ TeV ($\ll \Lambda_{LN}$) motivation of light ν OK

  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)

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

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

- If $M_\Delta \lesssim$ TeV

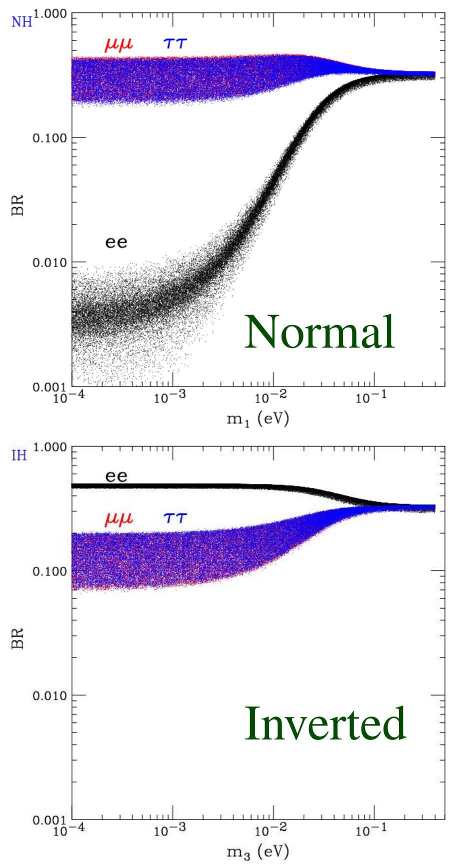
  $\Rightarrow$ Production of triplet scalars: $H^{\pm\pm}\ H^\pm,\ A_0,\ H_0$

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)

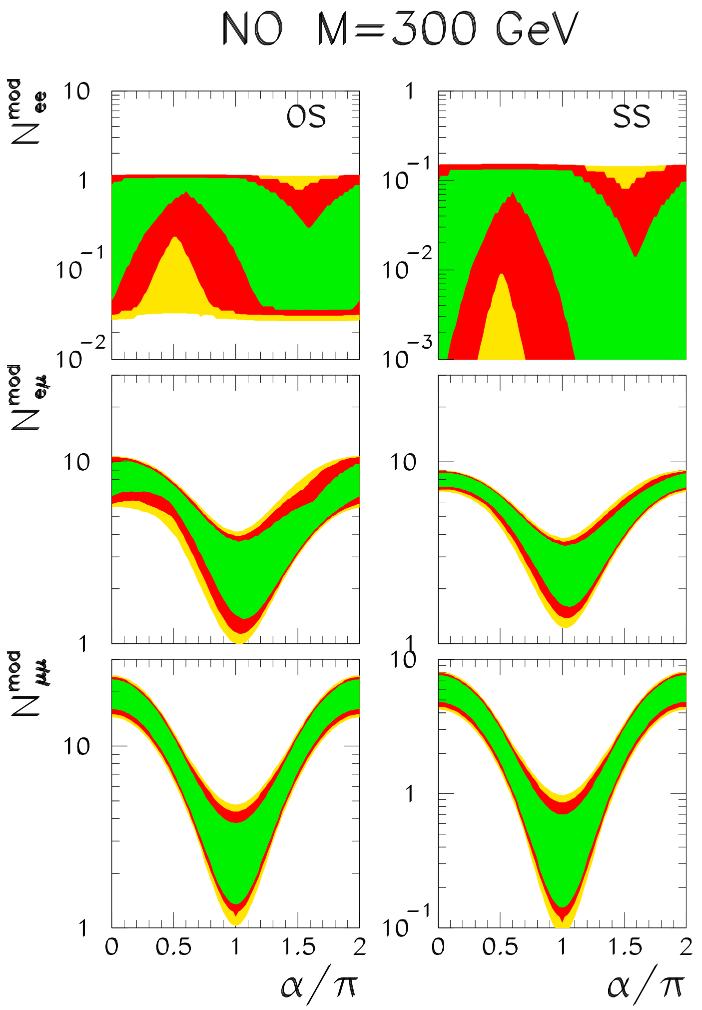
  → one massless ν & one CP phase α

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

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

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

  - 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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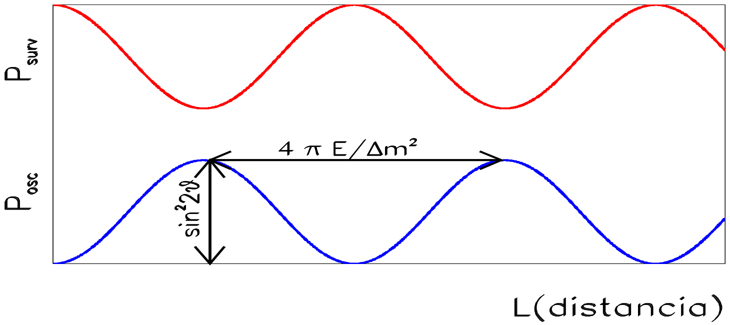
  Answer will require some signal in colliders, CLFV . . . . No lucky break yet

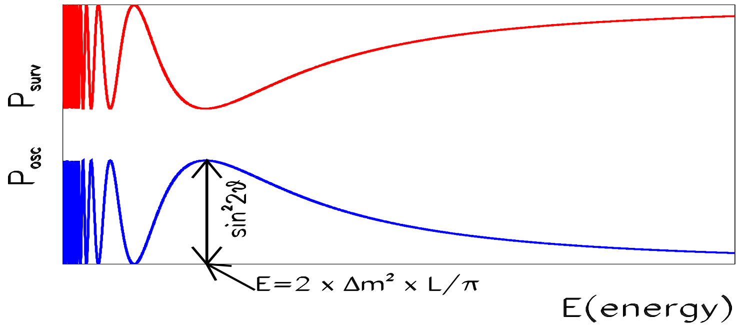
Backup Slides

- To detect oscillations we can study the neutrino flavour

as function of the Distance to the source



As function of the neutrino Energy



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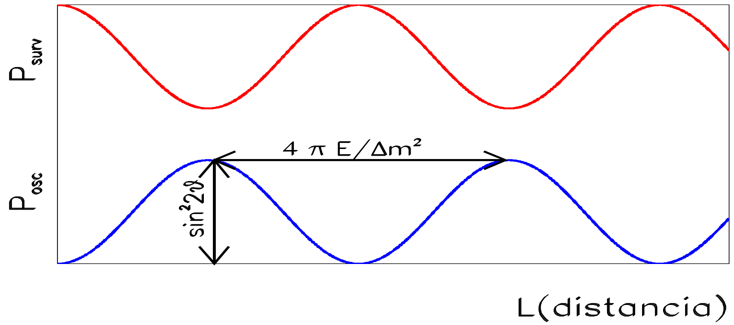

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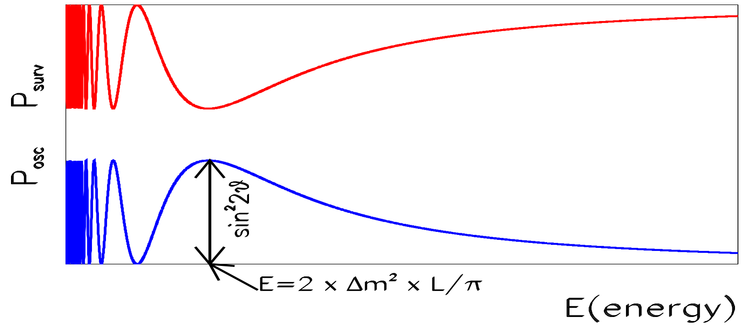
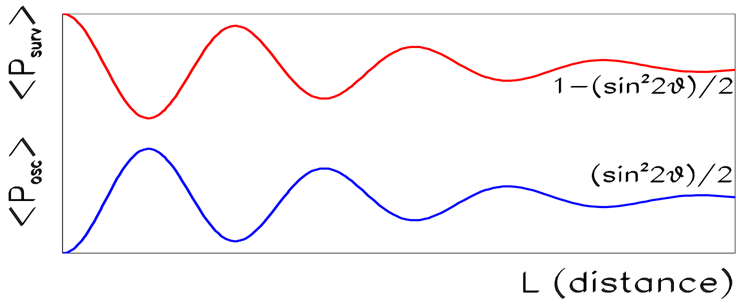
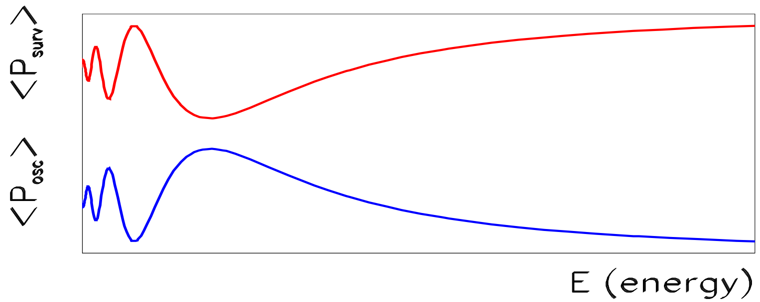


- In real experiments $\Rightarrow$ $\langle P_{\alpha\beta} \rangle = \int dE_\nu \frac{d\Phi}{dE_\nu} \sigma_{CC}(E_\nu) P_{\alpha\beta}(E_\nu)$





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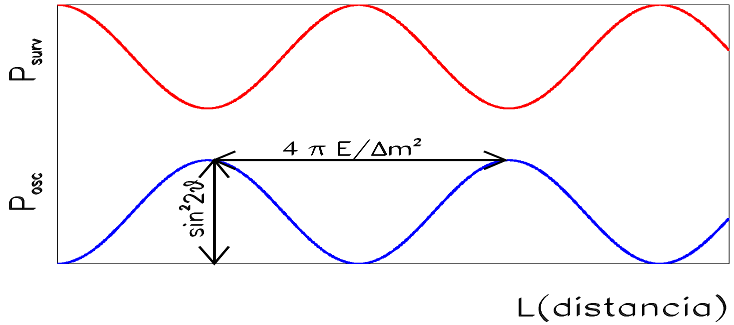

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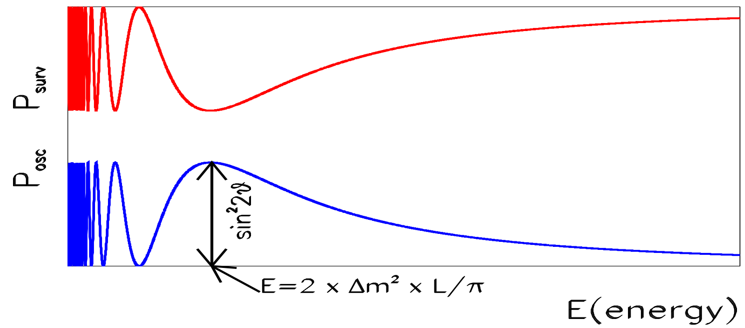

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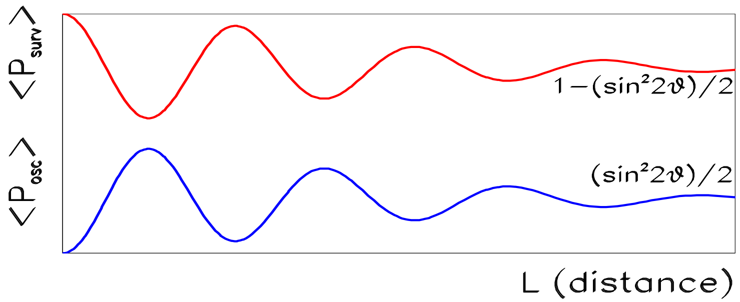
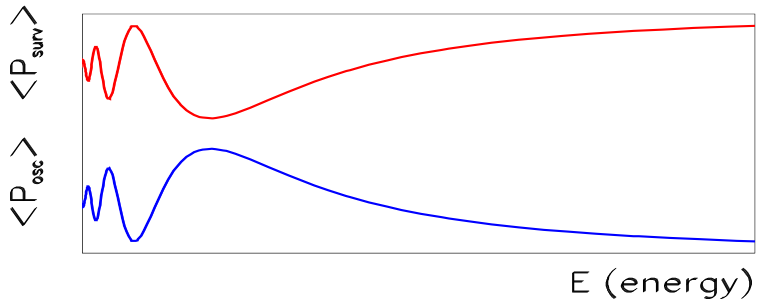


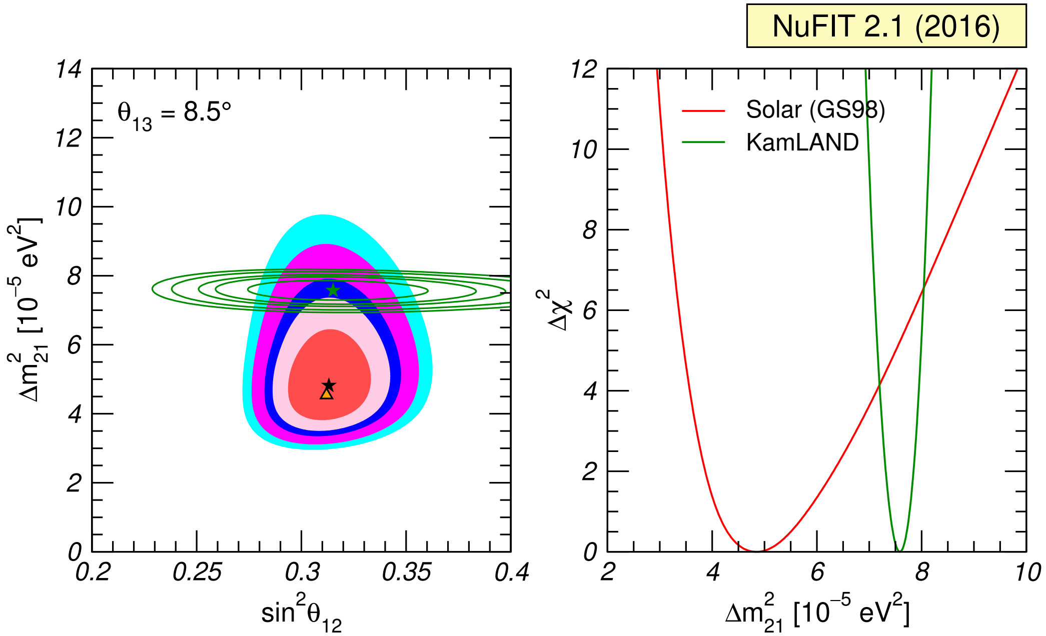


- Maximal sensitivity for $\Delta m^2 \sim E/L$

– $\Delta m^2 \ll E/L \Rightarrow \langle \sin^2(\Delta m^2 L/4E)\rangle \simeq 0 \rightarrow \langle P_{\alpha\neq\beta}\rangle \simeq 0$ & $\langle P_{\alpha\alpha}\rangle \simeq 1$

– $\Delta m^2 \gg E/L \Rightarrow \langle \sin^2(\Delta m^2 L/4E)\rangle \simeq \frac{1}{2} \rightarrow \langle P_{\alpha\neq\beta}\rangle \simeq \frac{\sin^2(2\theta)}{2} \leq \frac{1}{2}$ & $\langle P_{\alpha\alpha}\rangle \geq \frac{1}{2}$

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



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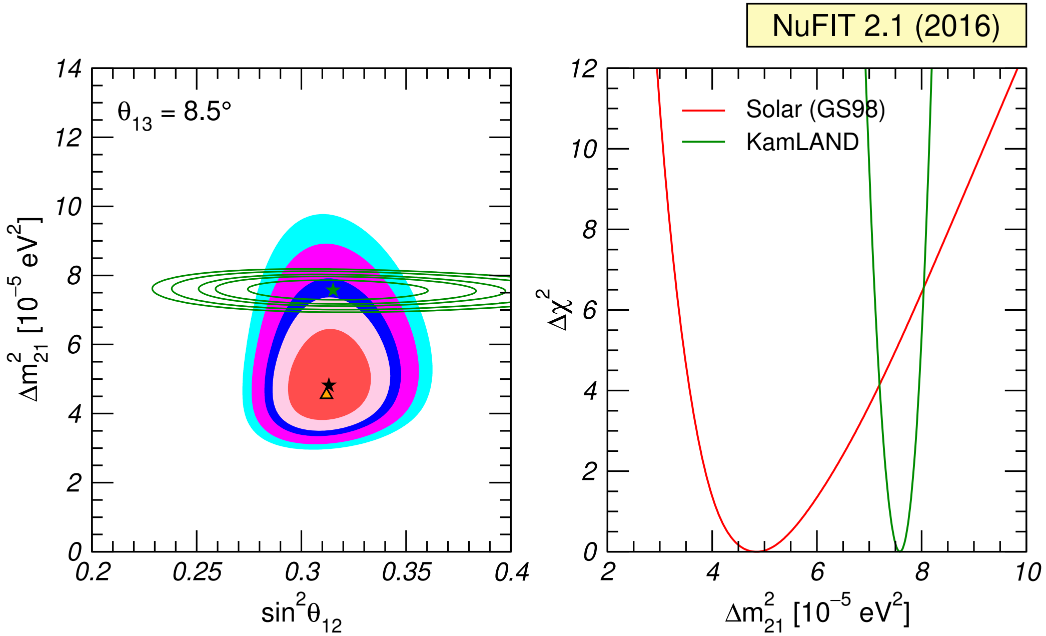

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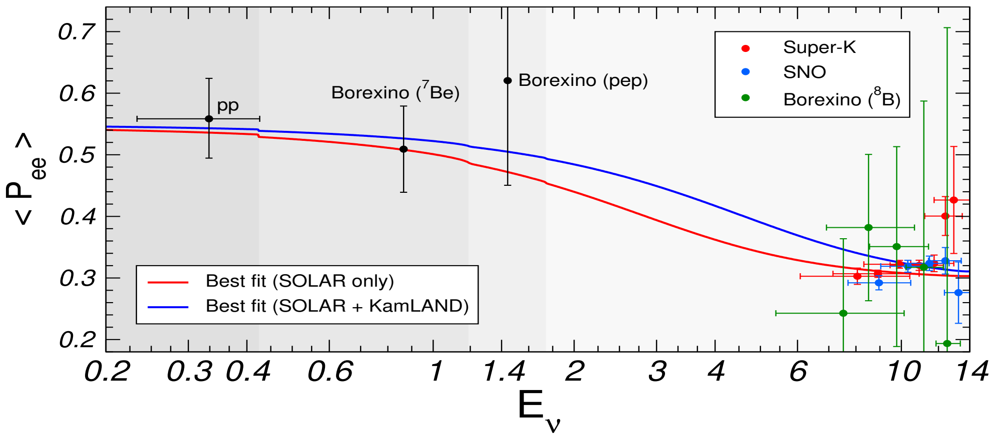
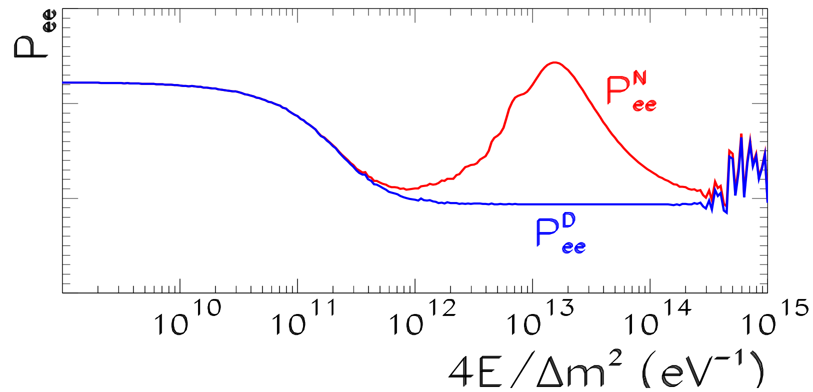
- Tension arising from:

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

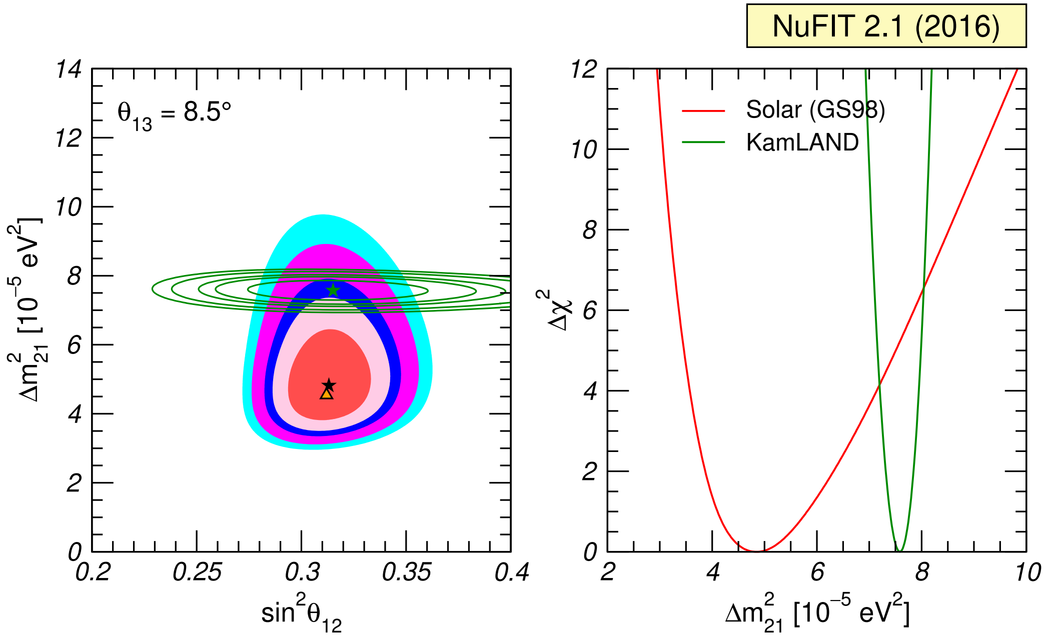
"too large" of Day/Night at SK

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





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

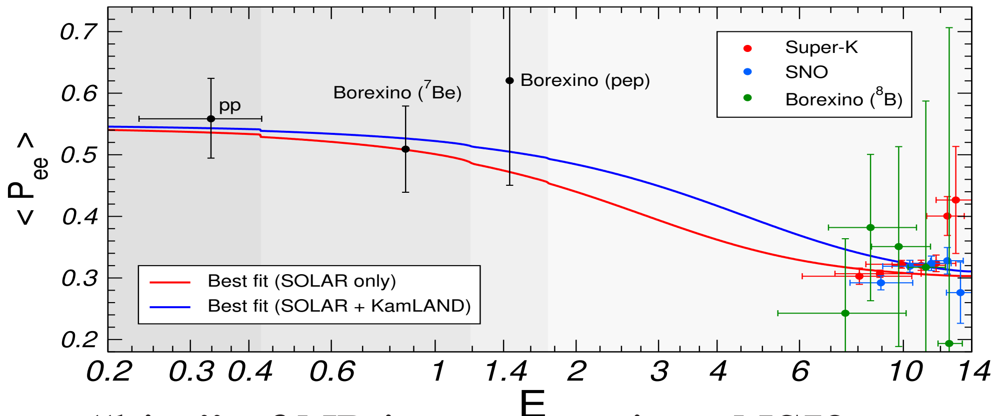


θ_{12} better than 1σ agreement

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

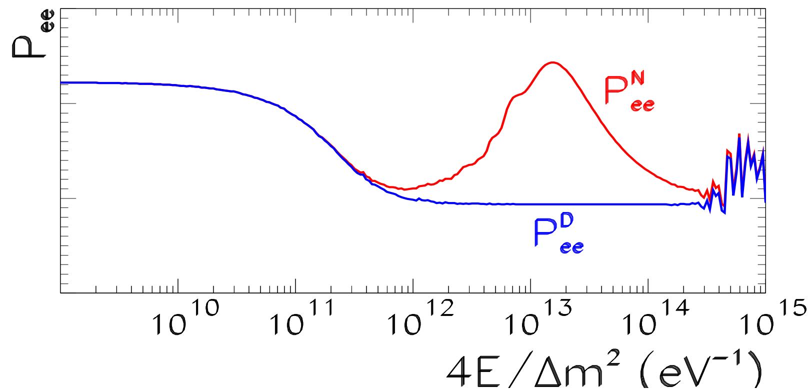
- Tension arising from:

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



"too large" of Day/Night at SK

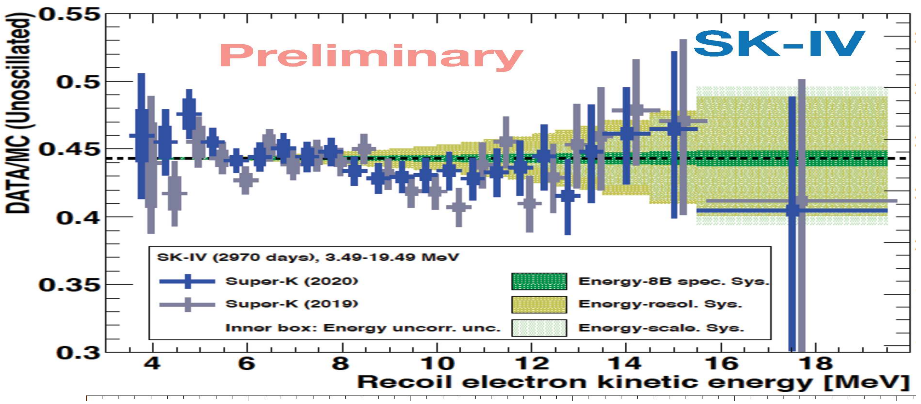
$A_{\rm D/N,SK4-2055} = [-3.1 \pm 1.6({\rm stat.}) \pm 1.4({\rm sys.})]\%$



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

• AFTER NU2020: With SK4 2970 days data

Slightly more pronounced low-E turn-up

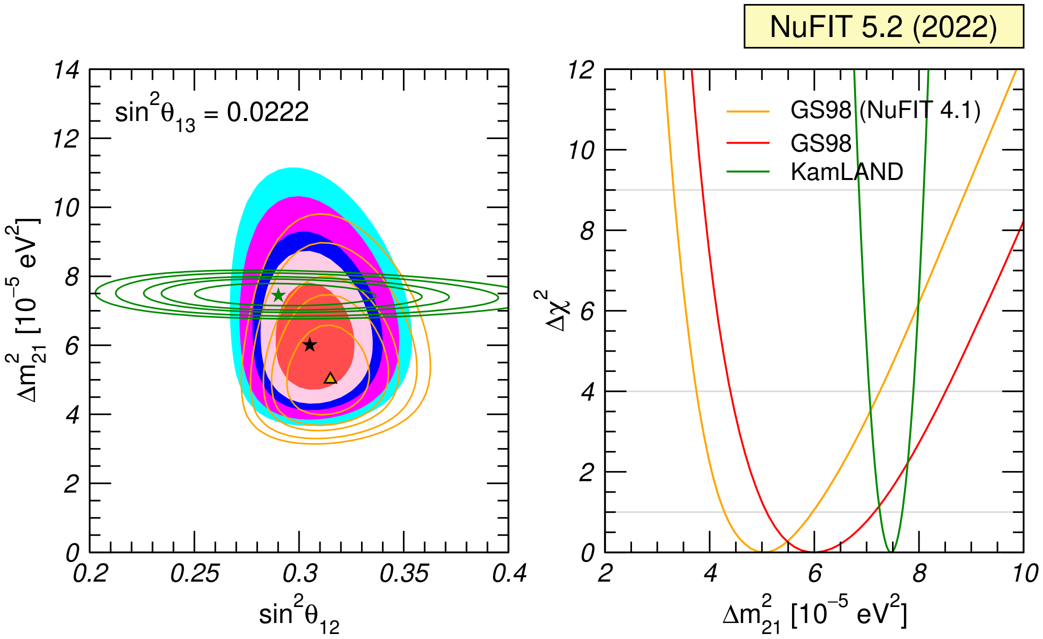


Smaller of Day/Night at

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

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

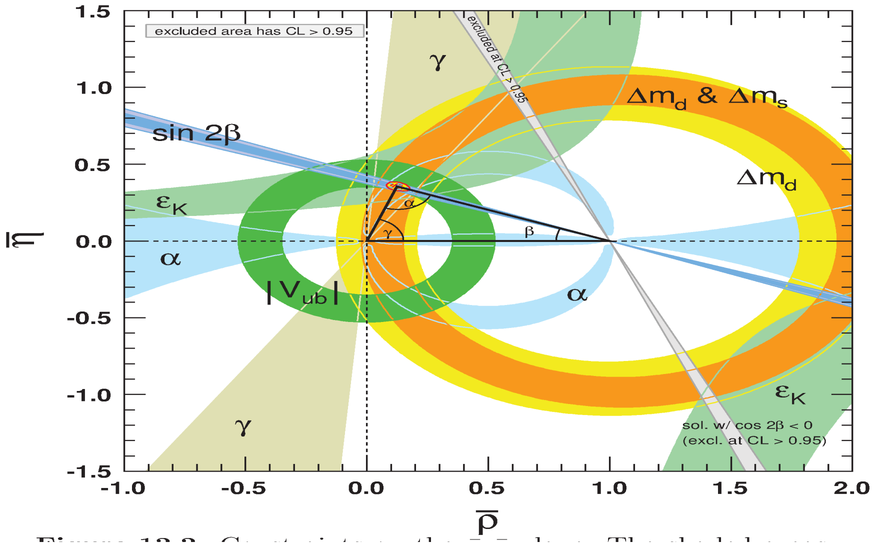
• In NuFIT 5.2



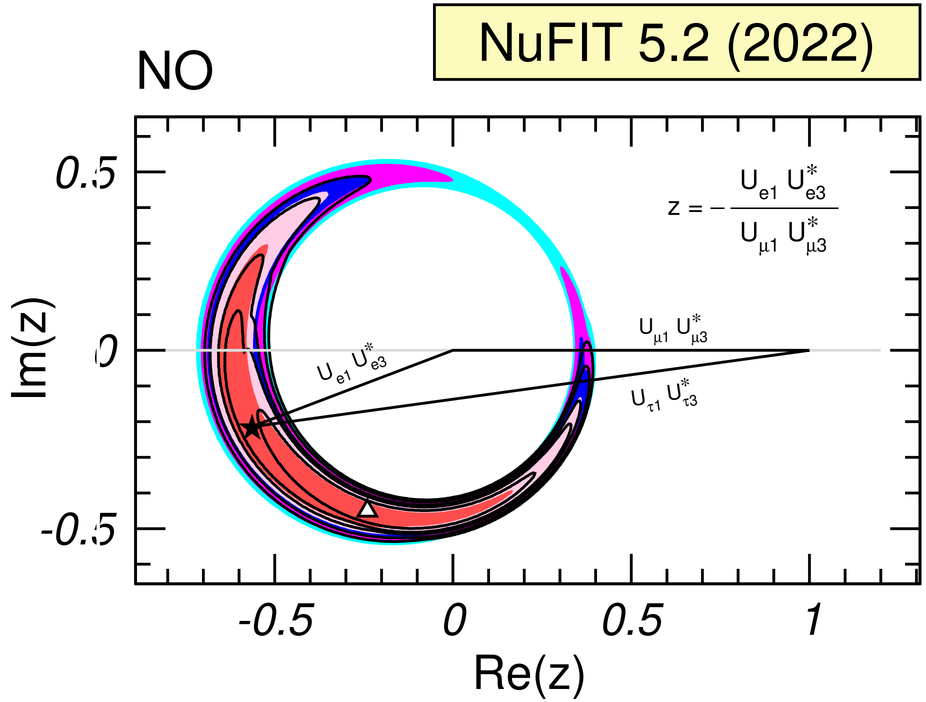
$\Rightarrow$ Agreement of Δm^2_{21} between solar and KamLAND at 1 σ

3ν Mixing: Leptonic Unitarity Triangle

Unitarity triangle in quark sector



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)

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

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

  – Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

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  – Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

- 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

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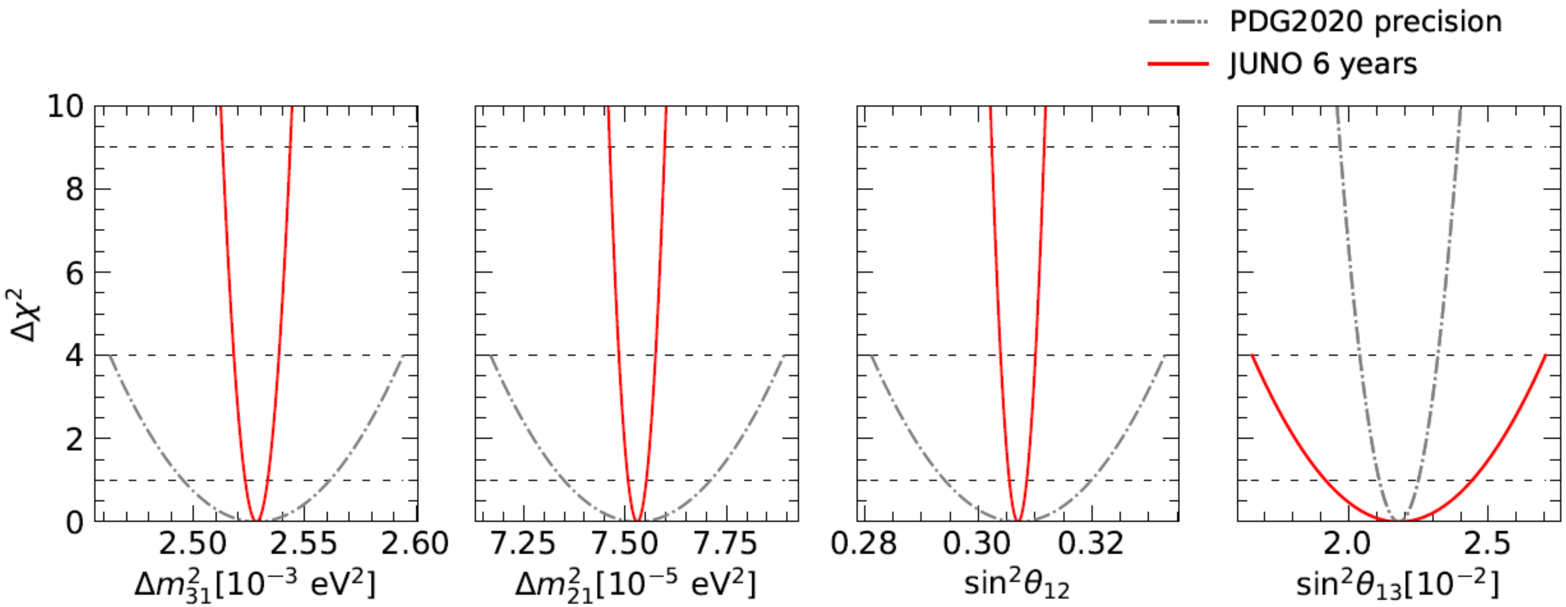
  – Challenge: Energy resolution

- 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

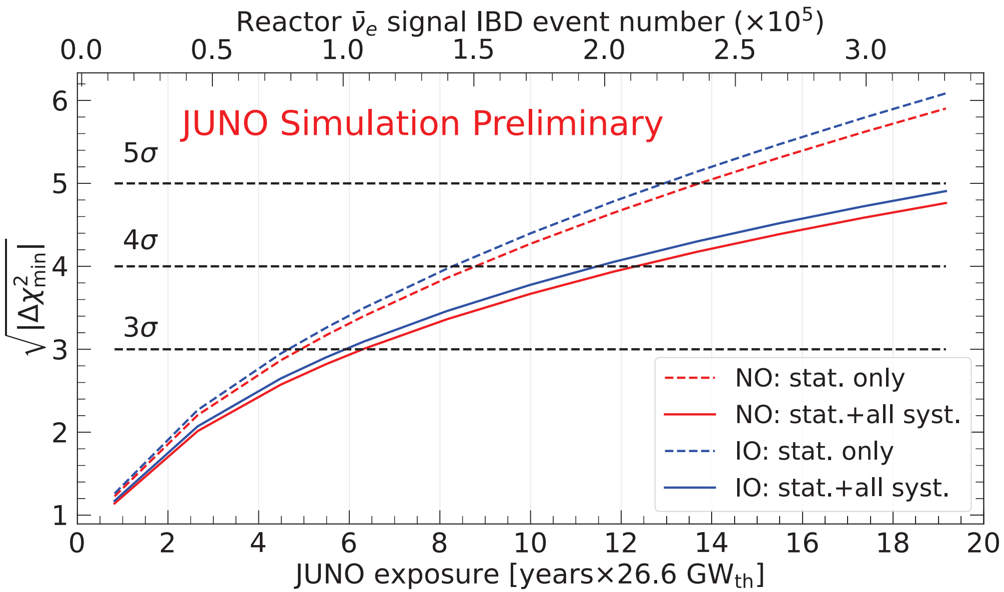
JUNO: Sensitivity to Oscillation Parameters

	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%)



2204.13249

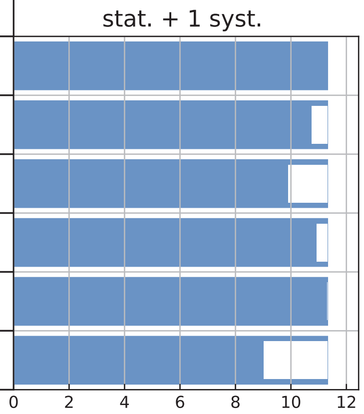
Sensitivity to Neutrino Mass Ordering



- ✓ 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

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

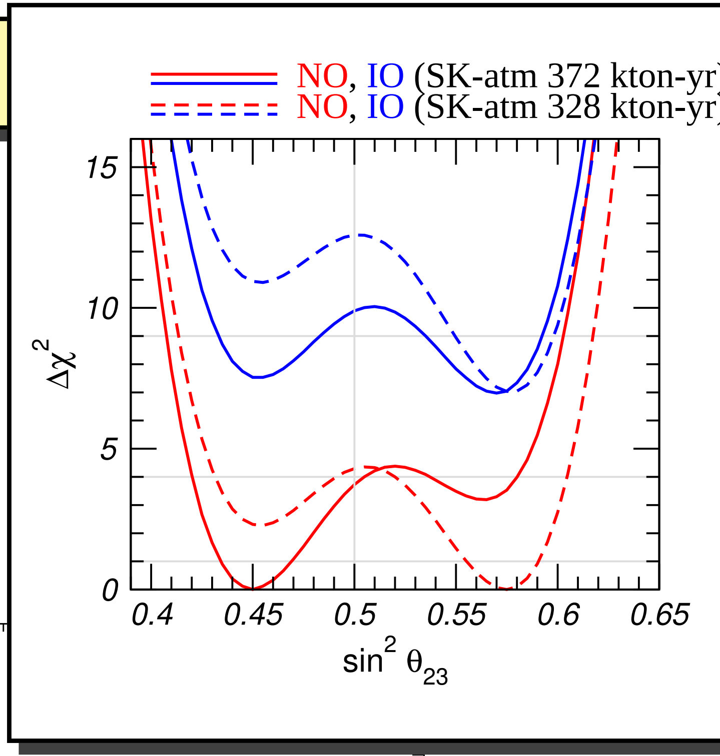


JUNO Simulation Preliminary

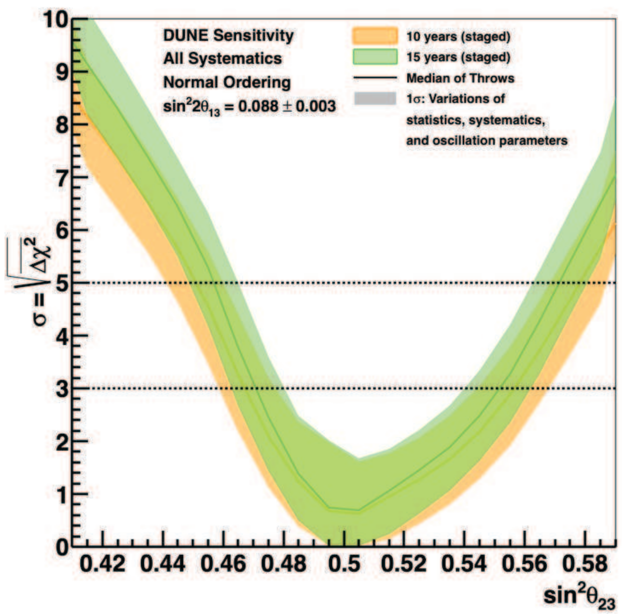
- Paper under preparation.
- Combination of reactor and atmospheric channels within JUNO is investigated.

Extra [2008.11280], JUNO+IceCube [1911.06745]

DUNE & Hyper-Kamiokande: θ_{23}

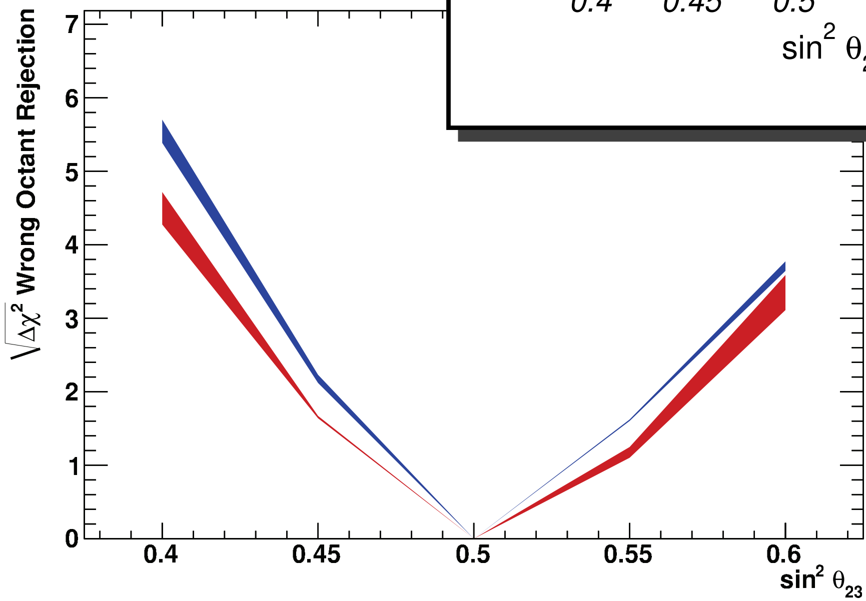


θ_{23} octant: future sensitivities



$\sim 3 - 5\sigma$

DUNE 2002.03005



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

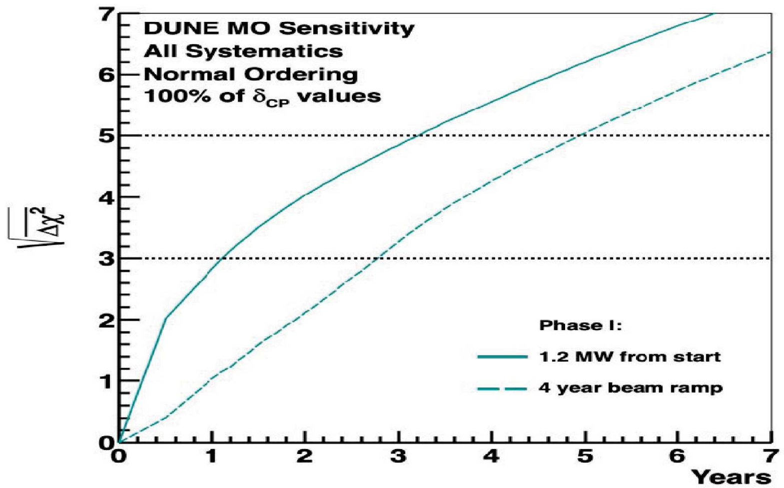
HK 1805.04163

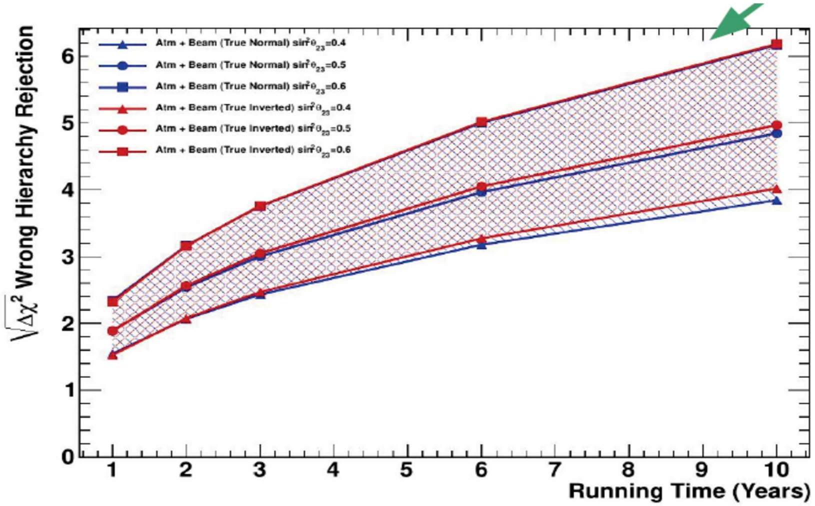
DUNE & Hyper-Kamiokande: CPV and MO

Mass Ordering

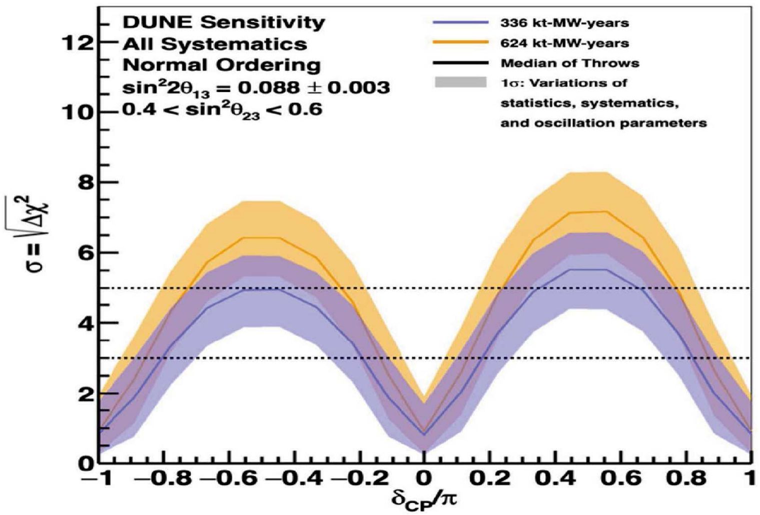
DUNE

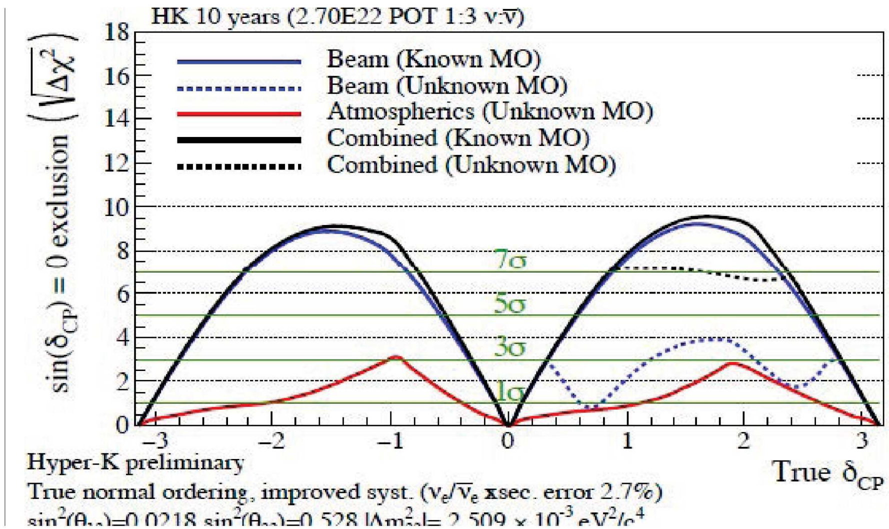
Hyper-Kamiokande





CPV

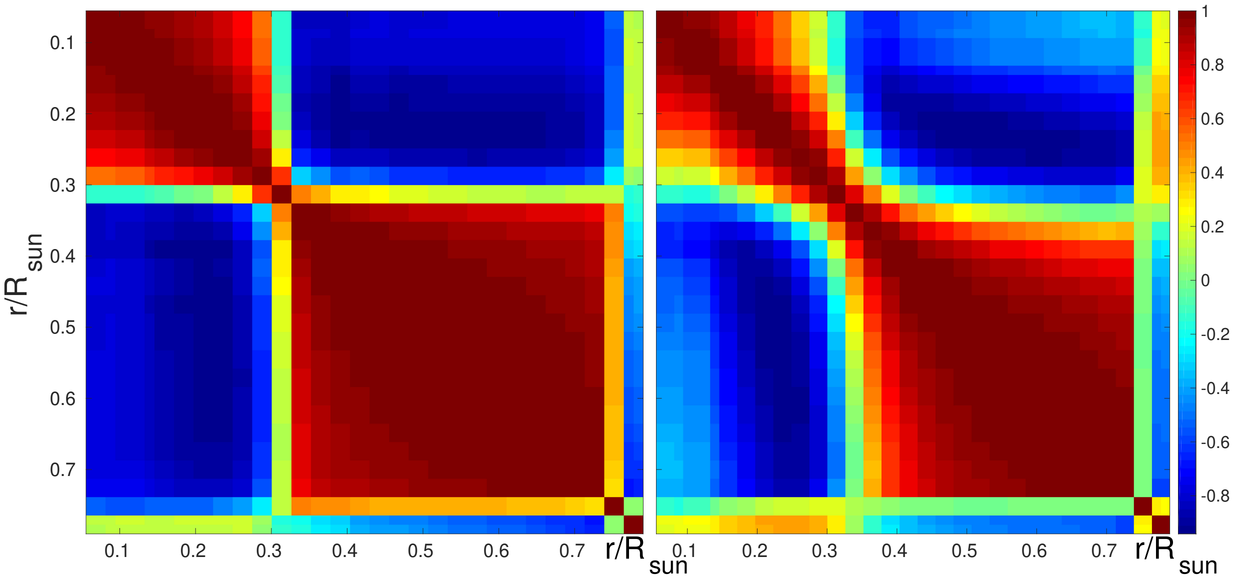




Modeling the uncertainty in the opacity profile

- Opacity is a function $\kappa(T, \rho, X_i = N_i/N_H)$. How to parametrize its uncertainty?
- Generically $(1 + \delta\kappa(T))\langle\kappa(T, \rho, X_i)\rangle$
  $\Rightarrow$ Most studies $\delta\kappa(T) = C$ or $\delta\kappa(T) = a + b\log T$ with prior for σ_C (or σ_a,σ_b)
  $\Rightarrow$ only very rigid variations allowed
- Alternative: Gaussian Process anszat with same $\sigma(T)$ but correlation length $L < 1$

Linear $\delta\kappa$ Gaussian Process $\delta\kappa$



Song, MCG-G, Villante,Vinyoles,Serenelli,1710.0214

Still, even with GP opacity uncertainty Bayes factor B16-AGSS09/B16-GS98=-4.1
(Moderate to strong disfavour)

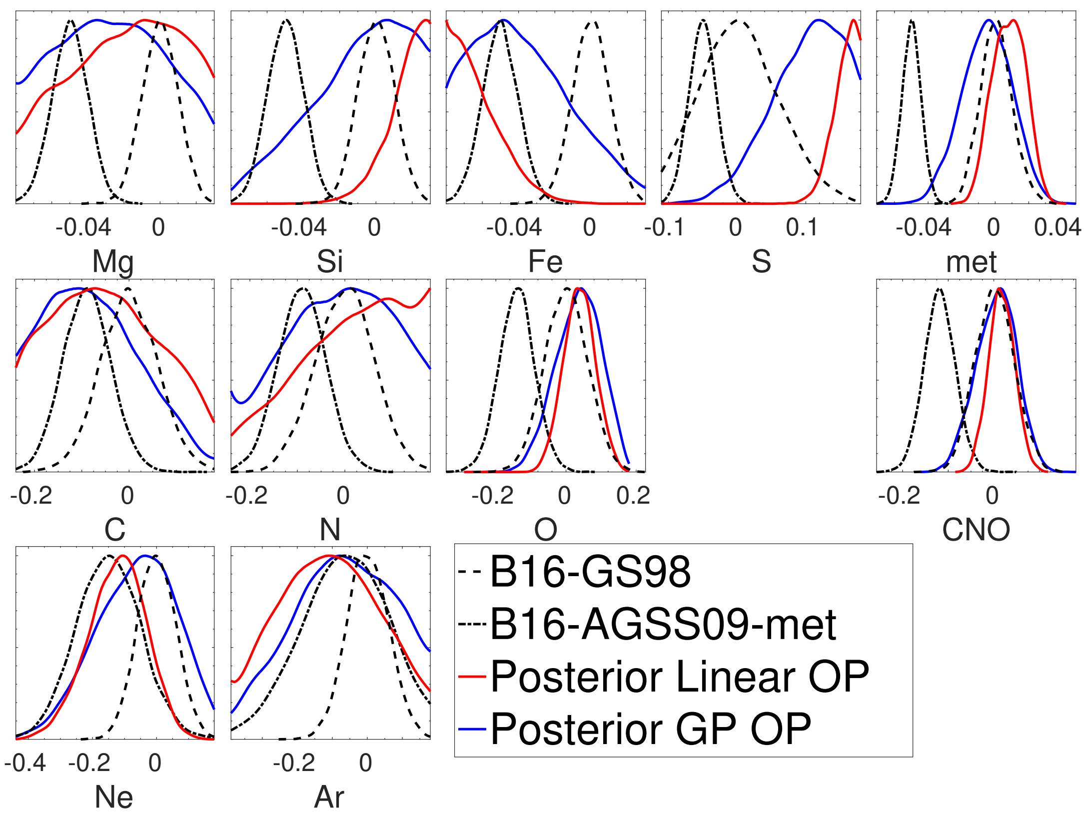
Using ν and Helioseismic Data in Sun Modeling

- Proposal: Invert approach and use the ν and helioseismic data in construction of SSM

– Method: Bayesian Inference of Abundance Posterior Distrib (from Uniform Priors)

– Test effects of effects of other modeling aspects (f.e. opacity uncertainty profiles)

- Results: Helioseismic+ν data reconstructed composition: $x = \ln \frac{N_i}{N_H} - \langle \ln \frac{N_i}{N_H} \rangle_{GS98}$

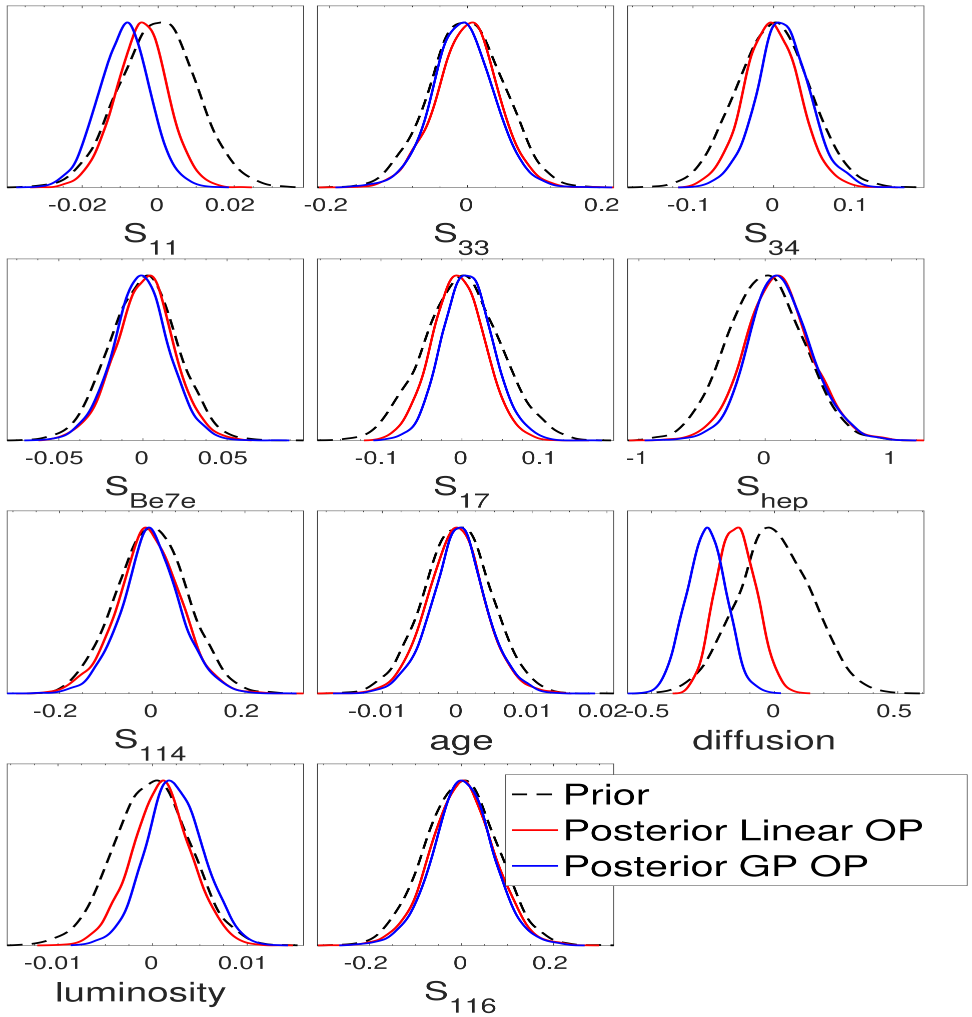


Precision of helioseismic and ν data reconstructed CNO and met abundances comparable to spectroscopic and meteorite determination

Song, MCG-G, Villante,Vinyoles,Serenelli,1710.0214

Using ν and Helioseismic Data in Sun Modeling

- Nuclear rates and other solar model parameters:



S_{11} $\quad p + p \to D\, e^+ \nu$

S_{33} $\quad {}^3He + {}^3He \to \alpha + 2p$

S_{34} $\quad {}^3He + {}^4He \to {}^7Be + \gamma$

S_{Be7e} $\quad {}^7Be + e \to {}^7Li\, \nu$

S_{17} $\quad {}^7Be + p \to {}^8B + \gamma$

Helioseismic and ν data reconstructed:

– S_{11} 1σ lower than nuclear exp extrapolated value used in SSM

– Microscopic diffusion 2σ lower than value assumed in SSM

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

$\Rightarrow$ NSI potential is rescaled w.r.t de MSW by a factor $F_i(\vec{x}, M_{Z'}) \equiv \frac{\hat{N}_i(\vec{x}, M_{Z'})}{N_i(\vec{x})}$

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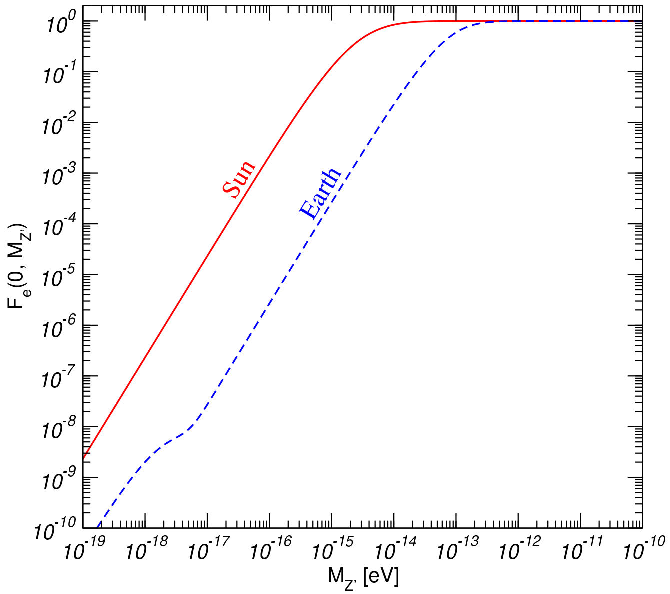

For $M_{Z'} \lesssim 10^{-15}$ eV scaling factor $\propto M_{Z'}$

$\Rightarrow H^{\rm NSI}_{\rm mat}$ independent of $M_{Z'}$

The scaling factors are position dependent

$\Rightarrow H^{\rm SM}_{\rm mat}$ very different " radial profile" than $H^{\rm NSI}_{\rm mat}$

$\Rightarrow$ LMA-D cannot be realized for $M_{Z'} \lesssim 10^{-13}$ eV)