Reactor Anti-neutrino Data and Global Analyses

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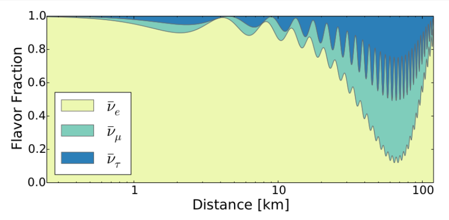
Reactor Anti-neutrinos

3ν Oscillation framework

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - 4\sum_{i=1}^{2}\sum_{j>i}^{3}|U_{ei}|^2\left|U_{ej}\right|^2\sin^2\left(\Delta m_{ij}^2\frac{L}{4E}\right)$$

NuFIT 4.0 (2018), www.nu-fit.org I. Esteban, C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, T. Schwetz



P.Vogel et.al. [arXiv:1503.01059]

3ν Oscillation framework

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - 4 \sum_{i=1}^{2} \sum_{j>i}^{3} |U_{ei}|^2 \left|U_{ej}\right|^2 \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

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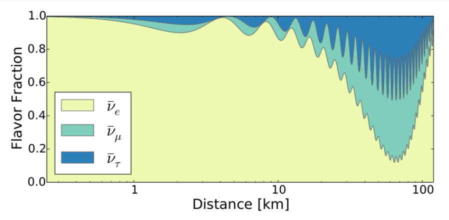


P.Vogel et.al. [arXiv:1503.01059]

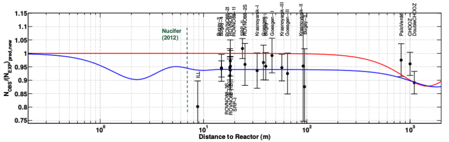
Sterile neutrino framework

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - 4 \sum_{i=1}^{3} \sum_{j>i}^{4} |U_{ei}|^2 \left|U_{ej}\right|^2 \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

$$P_{\overline{\nu}_e \to \overline{\nu}_e} \underset{\text{SBL}}{\simeq} 1 - \sin^2 2\theta_{14} \sin^2\left(\Delta m_{41}^2 \frac{L}{4E}\right)$$

M.Dentler et.al. [arXiv:1803.10661]

M.Dentler, A.Hernandez-Cabezudo, J.Kopp, P.A.N.Machado, M.Maltoni, I.Martinez-Soler, T.Schwetz



K. N. Abazajian et.al. [arXiv:1204.5379]

Outline

Reactor Anti-neutrino Data in Global Analyses

- Reactor Anti-neutrino
  - Event predictions
  - Data analysis and systematics treatment
- Statistical applications in global analysis
  - 3ν global analysis
  - Parameter goodness-of-fit test in the sterile neutrino scenario

Event predictions

Number of events

$$N_i^d = \mathcal{N} \sum_r \sum_{\text{iso}} \frac{\epsilon^d}{L_{rd}^2} \int_{E_i^{rec}}^{E_{i+1}^{rec}} dE^{\text{rec}} \int_0^\infty dE_\nu \, \sigma(E_\nu) f^{\text{iso}} \phi^{\text{iso}}(E_\nu) P^{rd}_{\bar{\nu}_e \to \bar{\nu}_e}(E_\nu) R(E^{\text{rec}}, E_\nu)$$

- Oscillation probability

$$P^{rd}_{\bar{\nu}_e \to \bar{\nu}_e}(\theta_{13}, \Delta m^2_{\text{atm}}(, \theta_{14}, \Delta m^2_{41})) \;\to\; N_i^d(\theta_{13}, \Delta m^2_{\text{atm}}(, \theta_{14}, \Delta m^2_{41}))$$

- Fluxes

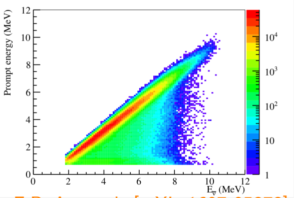
  Huber-Mueller neutrino flux predictions from the decay of the isotopes: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U

  T.Mueller et.al. [arXiv:1101.2663], P.Huber [arXiv:1106.0687]

- Response function

  Simplified version: *gaussian energy resolution*.

  More experimental effects as *non-linearity* and *IAV effect* should be also taken into account.



F.P. An et.al. [arXiv:1607-05378]

Data analysis

$$\chi^2(\boldsymbol{\theta}) = \sum_{i,j} \left(Obs_i - Pred_i(\boldsymbol{\theta})\right) V_{ij}^{-1} \left(Obs_j - Pred_j(\boldsymbol{\theta})\right)$$

Pull approach

$$\chi^2(\boldsymbol{\theta}, \boldsymbol{\eta}) = \sum_{i,j} \frac{\left(Obs_i - Pred_i(\boldsymbol{\theta}, \boldsymbol{\eta})\right)^2}{(\sigma_i^{\mathrm{stat}})^2} + \boldsymbol{\eta}_k V_{kl}^{-1} \boldsymbol{\eta}_l$$

$\boldsymbol{\eta}$: pull parameters accounting for the **systematics**. We include as much information from the collaborations as it is given.

Data anlysis: systematics treatment

- Main systematics to take into account (when there is enough information):
  - Relative efficiency among detectors

$$N_i \to N_i(\epsilon) = \epsilon N_i$$

  - Relative energy scale

$$N_i \to N_i(\eta) = \sum \int_0^\infty \mathrm{d}E_\nu \cdots \int_{\eta E_i^{\mathrm{rec}}}^{\eta E_{i+1}^{\mathrm{rec}}} \mathrm{d}E^{\mathrm{rec}} R(E^{\mathrm{rec}}, E_\nu)$$

  - Background uncertainty

$$B \to B(b_\alpha) = B + \sum_\alpha (b_\alpha - 1) B_\alpha$$

- Linearize $N(\boldsymbol{\theta}, \boldsymbol{\eta})$ with respect to the pull parameters $\boldsymbol{\eta}$
- Minimize $\chi^2(\boldsymbol{\theta}, \boldsymbol{\eta})$ with respect to $\boldsymbol{\eta}$ for every $\boldsymbol{\theta}$

3ν NuFit combined analysis

$$\chi^2(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{\mathrm{sol}}, \Delta m^2_{\mathrm{atm}}) =$$

3ν NuFit combined analysis

$$P_{\rm KLAND} = \sin^4\theta_{13} + \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta_{\rm sol}L}{4E}\right)$$

$\chi^2(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{\rm sol}, \Delta m^2_{\rm atm}) =$
$\chi^2_{\rm sol+KLAND}(\theta_{12}, \Delta m^2_{\rm sol}, \theta_{13})$

3ν NuFit combined analysis

$$\begin{aligned} P_{\mathrm{KLAND}} &= \sin^4\theta_{13} + \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta_{\mathrm{sol}}L}{4E}\right) \\ P_{\mathrm{reactor}} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta_{\mathrm{sol}}L}{4E} - \\ &\quad \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta_{32}L}{4E}\right) \end{aligned}$$

$$\begin{aligned} &\chi^2(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{\mathrm{sol}}, \Delta m^2_{\mathrm{atm}}) = \\ &\chi^2_{\mathrm{sol+KLAND}}(\theta_{12}, \Delta m^2_{\mathrm{sol}}, \theta_{13}) \\ + \quad &\chi^2_{\mathrm{reactor}}(\theta_{12}, \Delta m^2_{\mathrm{sol}}, \theta_{13}, \Delta m^2_{\mathrm{atm}}) \end{aligned}$$

3ν NuFit combined analysis

$$\begin{aligned}
P_{\mathrm{KLAND}} &= \sin^4\theta_{13} + \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta_{\mathrm{sol}}L}{4E}\right) \\
P_{\mathrm{reactor}} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta_{\mathrm{sol}}L}{4E} - \\
&\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta_{32}L}{4E}\right)
\end{aligned}$$

$$\begin{aligned}
&\chi^2(\theta_{12},\theta_{23},\theta_{13},\delta_{CP},\Delta m^2_{\mathrm{sol}},\Delta m^2_{\mathrm{atm}}) = \\
&\chi^2_{\mathrm{sol+KLAND}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13}) \\
+\quad&\chi^2_{\mathrm{reactor}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}}) \\
+\quad&\chi^2_{\mathrm{LBL}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}},\theta_{23},\delta_{CP})
\end{aligned}$$

3ν NuFit combined analysis

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P_{\rm KLAND} &= \sin^4\theta_{13} + \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta_{\rm sol}L}{4E}\right) \\
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+\quad &\chi^2_{\rm LBL}(\theta_{12},\Delta m^2_{\rm sol},\theta_{13},\Delta m^2_{\rm atm},\theta_{23},\delta_{CP}) \\
+\quad &\chi^2_{\rm atm}(\theta_{12},\Delta m^2_{\rm sol},\theta_{13},\Delta m^2_{\rm atm},\theta_{23},\delta_{CP})
\end{aligned}
$$

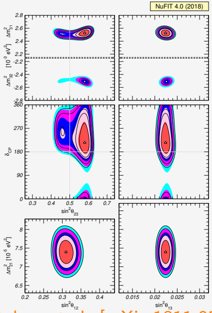
3ν NuFit combined analysis

$$P_{\rm KLAND} = \sin^4\theta_{13} + \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta_{\rm sol}L}{4E}\right)$$

$$P_{\rm reactor} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta_{\rm sol}L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta_{32}L}{4E}\right)$$

Combined analysis

$$\begin{aligned}
&\chi^2(\theta_{12},\theta_{23},\theta_{13},\delta_{CP},\Delta m^2_{\rm sol},\Delta m^2_{\rm atm}) = \\
&\chi^2_{\rm sol+KLAND}(\theta_{12},\Delta m^2_{\rm sol},\theta_{13}) \\
+\;&\chi^2_{\rm reactor}(\theta_{12},\Delta m^2_{\rm sol},\theta_{13},\Delta m^2_{\rm atm}) \\
+\;&\chi^2_{\rm LBL}(\theta_{12},\Delta m^2_{\rm sol},\theta_{13},\Delta m^2_{\rm atm},\theta_{23},\delta_{CP}) \\
+\;&\chi^2_{\rm atm}(\theta_{12},\Delta m^2_{\rm sol},\theta_{13},\Delta m^2_{\rm atm},\theta_{23},\delta_{CP})
\end{aligned}$$



I.Esteban et.al. [arXiv:1811.05487]

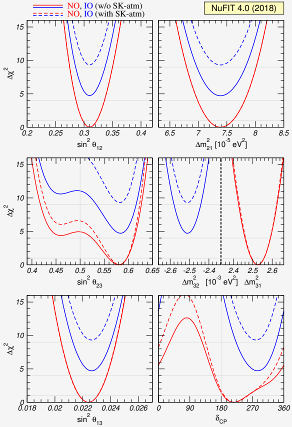
3ν NuFit combined analysis: C.L.

We assume that our statistics follows a χ^2 distribution with 1 degree of freedom.

NuFIT 4.0 (2018)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

I.Esteban et.al. [arXiv:1811.05487]



I.Esteban et.al. [arXiv:1811.05487]

For $\sin^2\theta_{23}$, δ_{CP} and mass ordering, the 1 dof χ^2 distribution could be a bad approximation.
Montecalo studies $\to$ I.Esteban et.al. [arXiv:1611.01514]

3ν NuFit combined analysis: non-gaussianity deviations

Montecalo studies to test the non-gaussianity deviations of $\sin^2\theta_{23}$, $\delta_{CP}$and mass ordering $\rightarrow$ I.Esteban et.al. [arXiv:1611.01514]

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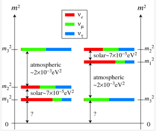
- Sensitivity of current data to δ_{CP} is still limited.
- The mass ordering is a discrete parameter.



S.King et.al. [arXiv:1301.1340]

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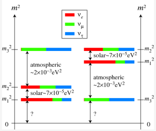
- Sensitivity of current data to δ_{CP} is still limited.
- The mass ordering is a discrete parameter.
- Correlations between $\sin^2\theta_{23}$, δ_{CP} and mass ordering.



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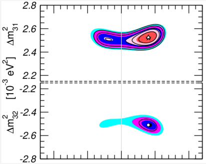

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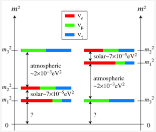
- Sensitivity of current data to δ_{CP} is still limited.
- The mass ordering is a discrete parameter.
- Correlations between $\sin^2\theta_{23}$, δ_{CP} and mass ordering.
- Physical boundaries for the parameters ($\sin^2 2\theta_{23} \leq 1$).



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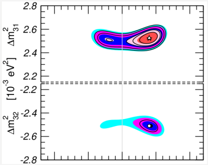

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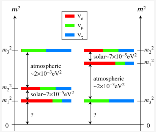

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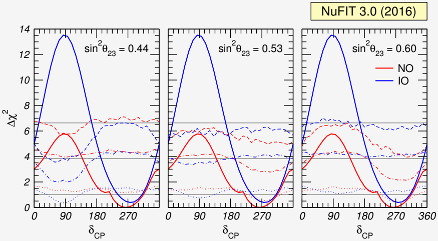

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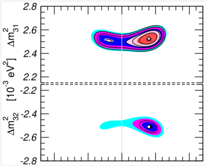


I.Esteban et.al. [arXiv:1811.05487]

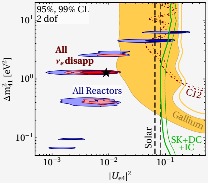
The gaussian limit is a good approximation and can be assumed that $\Delta\chi^2$ follows a 1 dof χ^2 distribution.

Sterile neutrino oscillations

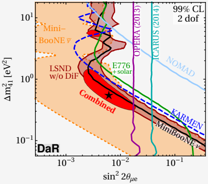
Short Baseline Anomalies:

- LSND/MiniBooNE anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (appearance)
- Reactor anti-neutrino anomaly: $\overline{\nu_e} \to \overline{\nu_e}$ (disappearance)
- Gallium Anomaly: $\nu_e \to \nu_e$ (disappearance)

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ (disappearance)



M.Dentler et.al. [arXiv:1803.10661]



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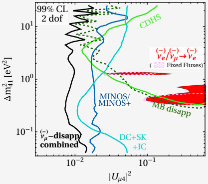

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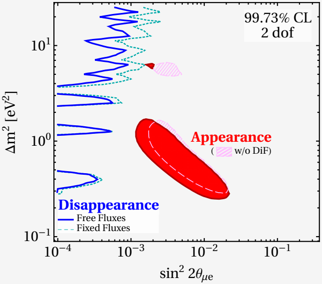
Parameter goodness-of-fit test in the sterile neutrino scenario

There is tension between the disappearance and appearance data!



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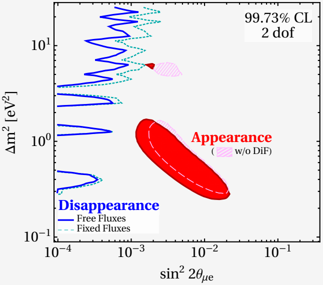
Parameter goodness-of-fit test in the sterile neutrino scenario

There is tension between the disappearance and appearance data!
⇒ PG test

$$\chi^2_{\rm PG} \equiv \chi^2_{\rm min,global} - \chi^2_{\rm min,A} - \chi^2_{\rm min,B} = \Delta\chi^2_A + \Delta\chi^2_B$$
$$({\rm dof})\ N_{\rm PG} \equiv P_A + P_B - P\ ({\rm parameters})$$

M.Maltoni et.al. [hep-ph/0304176]



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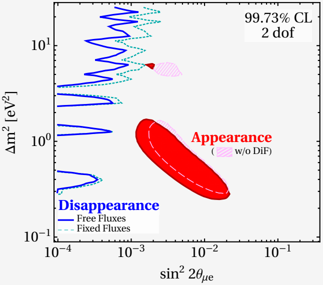

Subset A: $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ disappearance
Subset B: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance

Global data analysis GOF: $68 - 64\%$

PG test: p-value $\sim 10^{-6} - 10^{-7}$
⇒ Incompatibility $\sim 5\sigma$

M.Dentler et.al. [arXiv:1803.10661]

The Goodness of fit is meaningless, since **data is totally incompatible**

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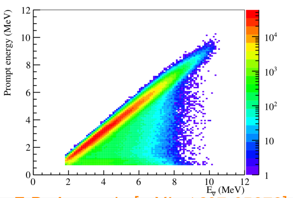

F.P. An et.al. [arXiv:1607-05378]

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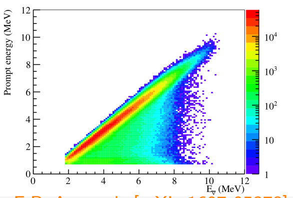

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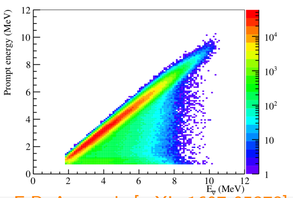

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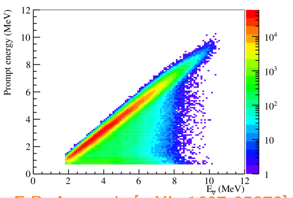

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- Proper statistical analysis have to be performed in order to understand the data. e.g.:
  - 3ν scenario: 1dof χ^2 distribution approximation.
  - Sterile neutrino scenario: studies of data compatibility via PG test.