Illuminating LMA-Dark solution and superlight sterile neutrinos by intermediate baseline reactor neutrino experiments

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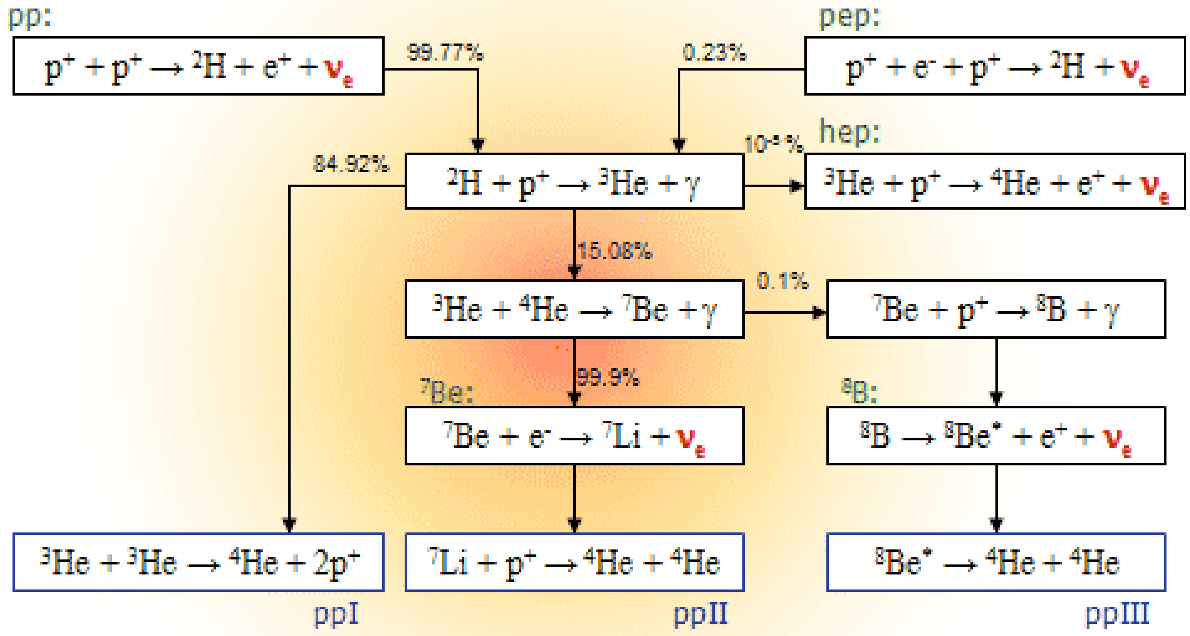
IPM

Outline of my talk

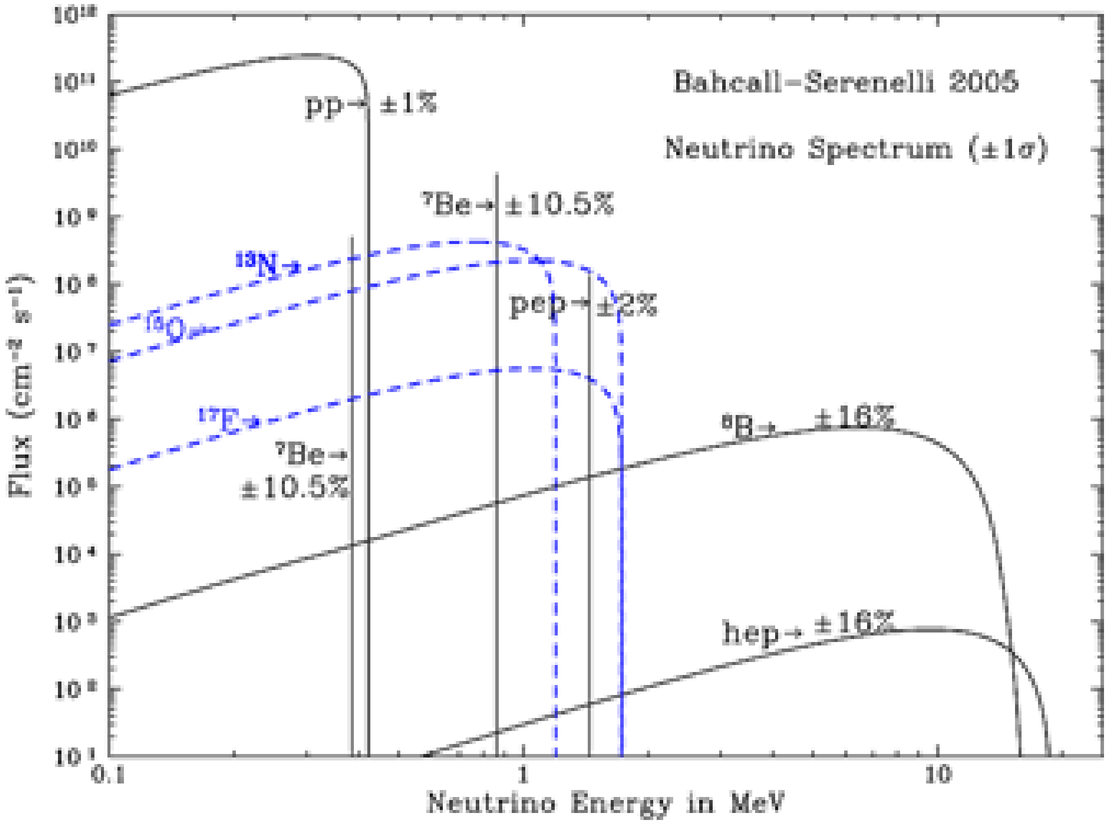
- Review: Solar Neutrino anomaly and MSW effect
- Some tension: suppression of low energy upturn
- Superlight Sterile Neutrino Scenario (SSNS)
- Testing SSNS via intermediate baseline reactor experiments: JUNO and RENO-50
- Summary
- Non-Standard Neutrino Interactions (NSI)
- LMA-Dark solution
- Testing LMA-Dark solution via intermediate baseline reactor experiments: JUNO and RENO-50
- Summary

Solar neutrinos

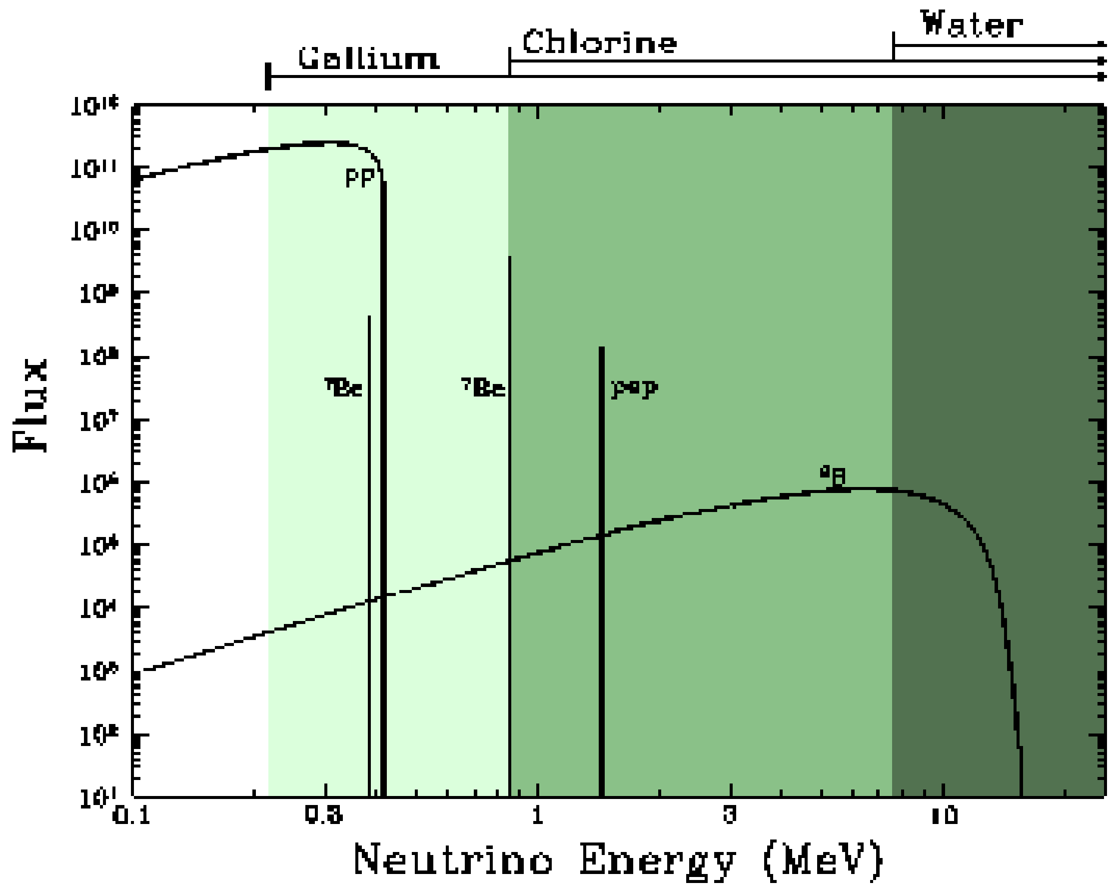
- Proton fusion: $4p \rightarrow He + 2e^{+} + 2\nu_e$



Solar Neutrino spectrum



Detection thresholds



Borexino threshold=0.25 MeV

Started data taking in 2007

Liquid scintillator

Homestake

- Gold mine in South Dakota-1960s-1994
- Raymond Davis and John Bahcall

$$\nu_e + \mathrm{Cl} \rightarrow e + \mathrm{Ar}$$

- Observed/predicted=1/3

Davis, Harmer and Hoffman, PRL (1968)

- Confirmed by Kamiokande, SAGE, GALLEX, Super-kamiokande and SNO

Solar Neutrino Anomaly

- SM: Lepton flavor conservation

Solar neutrino anomaly

- Solution: Lepton flavor violation

PMNS mixing matrix

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

$U_{\alpha i}$ is a unitary matrix.

$$\sum_i U_{\alpha i} U^*_{\beta i} = \delta_{\alpha\beta} \qquad \sum_\alpha U_{\alpha i} U^*_{\alpha j} = \delta_{ij}$$

Propagation in matter

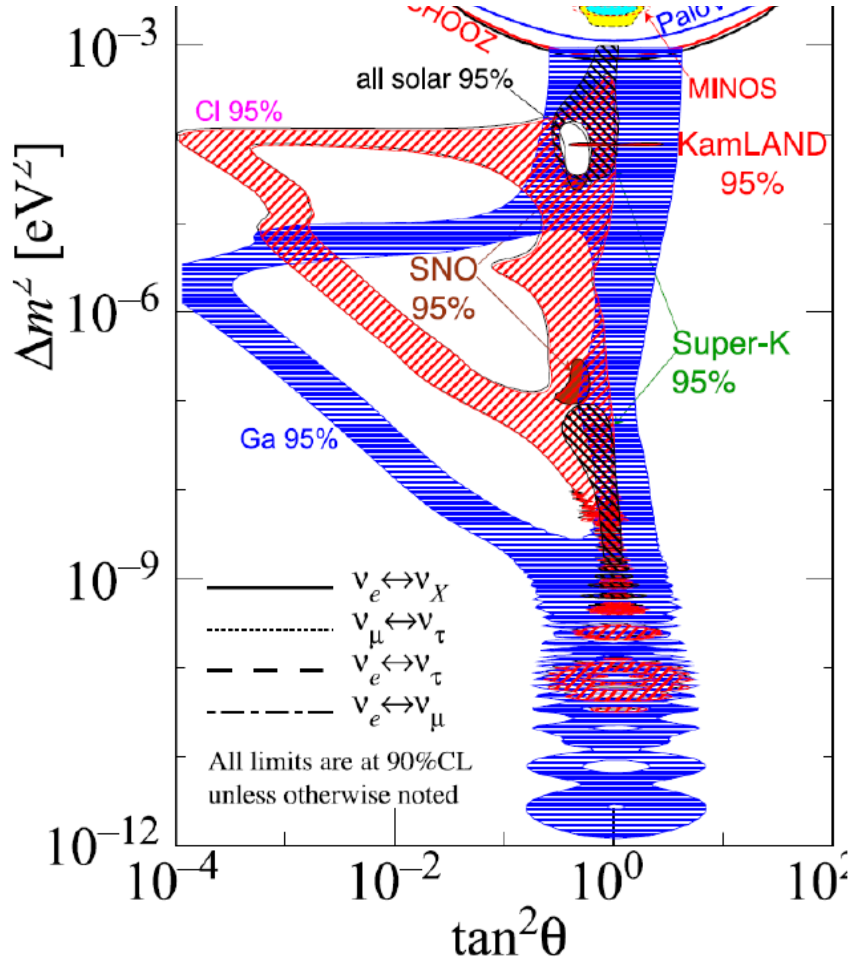
$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix}=\mathcal{H}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix}$$

$$\mathcal{H}=\underbrace{\begin{pmatrix}\cos\theta & \sin\theta\\-\sin\theta & \cos\theta\end{pmatrix}\cdot\begin{pmatrix}0 & 0\\0 & \frac{\Delta m^2_{21}}{2E}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta & -\sin\theta\\\sin\theta & \cos\theta\end{pmatrix}}+\underbrace{\begin{pmatrix}V_e & 0\\0 & V_a\end{pmatrix}}_{\text{Matter effect}}$$

$$\boxed{V_e=\sqrt{2}G_F(n_e-n_n/2)\qquad V_a=-G_Fn_n/\sqrt{2}}$$

KamLAND massacre!

~~Magnetic transition moment solution~~



LMA-solution

$$\theta_{12} = (33.48^{+0.78}_{-0.75})^\circ \qquad \Delta m^2_{21} = 7.50^{+0.19}_{-0.17} \times 10^{-5}\ eV^2$$

- M.C. Gonzalez-Garcia, Michele Maltoni, Thomas Schwetz, arXiv:1409.5439

NuFIT 2.0 (2014)

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

http://www.nu-fit.org

Propagation in matter

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix}$$

$$\mathcal{H} = \underbrace{\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\cdot\begin{pmatrix}0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}}_{} + \begin{pmatrix}V_e & 0\\ 0 & V_a\end{pmatrix}$$

Matter effect

$$\boxed{V_e = \sqrt{2}G_F(n_e - n_n/2) \quad V_a = -G_F n_n/\sqrt{2}}$$

MSW effect

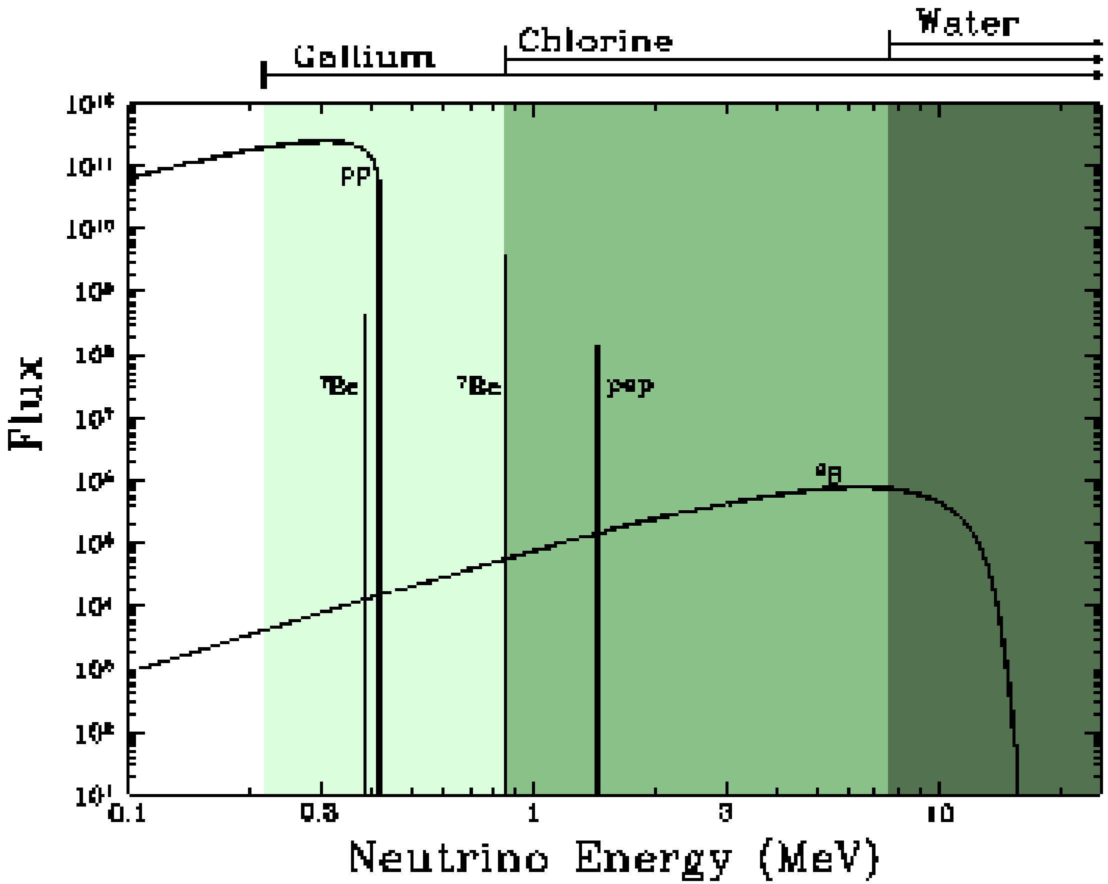
- Mikheyev Smirnov Wolfenstein effect

$$E \to 0 : \quad \frac{\Delta m_{21}^2}{2E} \gg V_e - V_a \quad \text{vacuum oscillation limit}$$

$$E \to \infty : \quad \frac{\Delta m_{21}^2}{2E} \ll V_e - V_a \quad \text{matter effects limit}$$

For solar neutrinos transition takes place in 0.5-7 MeV.

Detection thresholds



Borexino threshold=0.25 MeV

Started data taking in 2007

Liquid scintillator

Does the Low energy solar data fit the MSW prediction?

- Be line measured by Borexino is in complete agreement.

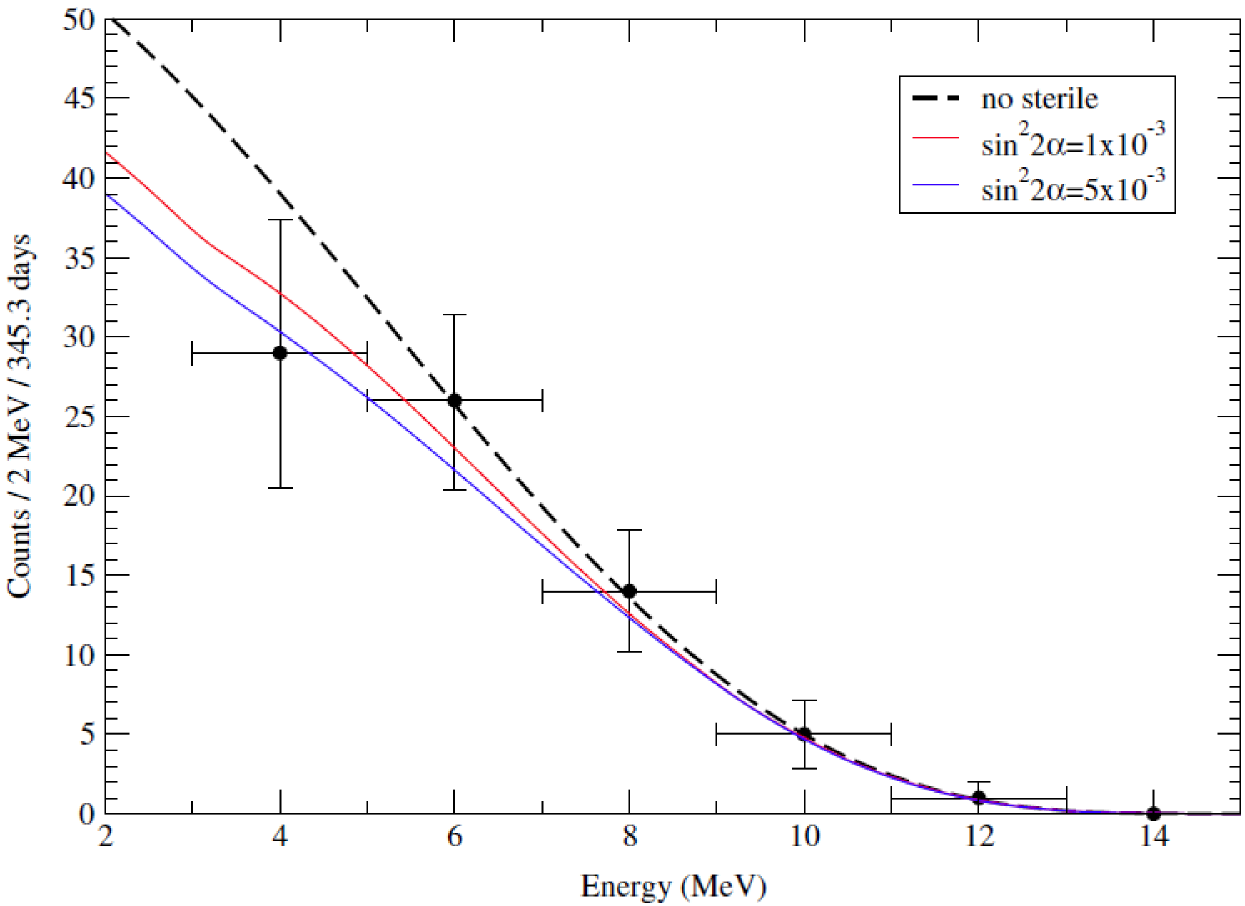
- But there is about 1-2 sigma deviation in data found by Homestake, Borexino (Boron spectrum), SNO-LETA, Super-Kamiokande I and III.

(For a review *see,* de Holanda and Smirnov, PRD83 (2011) 113011)

Boron Spectrum prediction has a 15 % uncertainty.

Absence of low energy upturn of the spectrum

PHYSICAL REVIEW D **83,** 113011 (2011)



^{8}B-neutrinos at Borexino

REDUCING UPTURN

- Superlight Sterile Neutrinos Scenario (SSNS):

De Holanda and Smirnov, PRD 83 (2011) 113611; PRD69 (2004) 113002.

- Non-standard interaction:

Miranda et al, JHEP 0610 (2006) 008; PRD 80 (2009) 105009.

SSNS

- Superlight sterile neutrinos Scenario (SSNS):
- Not to be confused with warm dark matter candidate or 1 eV sterile neutrino of LSND and MiniBooNE
- De Holanda and Smirnov, PRD 83 (2011) 113611:

$$\Delta m^2_{01} = (0.7 - 2) \times 10^{-5}\ \mathrm{eV}^2 \quad \sin^2 2\alpha \sim 10^{-3}$$

SSNS formalism

$$\begin{pmatrix}\nu_s\\ \nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\cdot\begin{pmatrix}\nu_0\\ \nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U \equiv \begin{pmatrix}1 & 0\\ 0 & U_{PMNS}\end{pmatrix}\cdot U_S$$

$$U_S = \begin{pmatrix}\cos\alpha & \sin\alpha e^{i\delta_1} & 0 & 0\\ -\sin\alpha e^{-i\delta_1} & \cos\alpha & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}\cos\gamma & 0 & \sin\gamma & 0\\ 0 & 1 & 0 & 0\\ -\sin\gamma & 0 & \cos\gamma & 0\\ 0 & 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}\cos\beta & 0 & 0 & \sin\beta e^{i\delta_2}\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ -\sin\beta e^{-i\delta_2} & 0 & 0 & \cos\beta\end{pmatrix}$$

Atmospheric neutrinos for $\Delta m^2_{01} \sim 10^{-5}\ \mathrm{eV}^2$: $\boxed{\sin^2\beta < 0.2.}$

Cirelli et al, Nucl Phys B708 (2005) 215

Minos bound

$$\sin^2\beta \leq 0.2, \qquad (90\%\ \text{C.L.}).$$

Adomson et al, PRD81 (210) 82004
arXiv:1104.3922

SSNS formalism

$$\begin{pmatrix} \nu_s \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad U \equiv \begin{pmatrix} 1 & 0 \\ 0 & U_{PMNS} \end{pmatrix} \cdot U_S$$

$$U_S = \begin{pmatrix} \cos\alpha & \sin\alpha e^{i\delta_1} & 0 & 0 \\ -\sin\alpha e^{-i\delta_1} & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos\gamma & 0 & \sin\gamma & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\gamma & 0 & \cos\gamma & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos\beta & 0 & 0 & \sin\beta e^{i\delta_2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\beta e^{-i\delta_2} & 0 & 0 & \cos\beta \end{pmatrix}$$

KamLAND and Solar data by 2005 for $\Delta m^2_{01} \sim 10^{-5}\ \mathrm{eV}^2$:

$$\boxed{\sin^2\alpha < 0.1}$$

Cirelli et al, Nucl Phys B708 (2005) 215

Extra relativistic degrees of freedom

$$\Delta N_{eff} \ll 1$$

- Mirizzi et al, PLB726 (2013) 8-14

$$\boxed{\sin^2\alpha,\ \sin^2\beta,\ \sin^2\gamma < \text{few} \times 10^{-2}}$$

- However, ...

Wyman et al, arXiv:1307.7715, Archidiacono et al, arXiv:1307.0637

Effect on solar data

- For $\Delta m_{01}^2 = (0.7 - 2) \times 10^{-5}\ \mathrm{eV}^2 \quad \sin^2 2\alpha \sim 10^{-3}$
- Electron neutrino to sterile neutrino conversion
- Dip in survival probability for E=0.5-7 MeV
- Suppression of upturn at lower range energies

Testing SSN

- KamLAND solar, SNO+, … (De Holanda and Smirnov, PRD 83 (2011) 113611).

- Can we test via reactor experiments?

Pouya Bakhti and Y.F., JHEP 10 (2013) 200.

Medium Baseline reactor experiments

- DAYA BAY in CHINA → JUNO
- RENO in South Korea → RENO-50

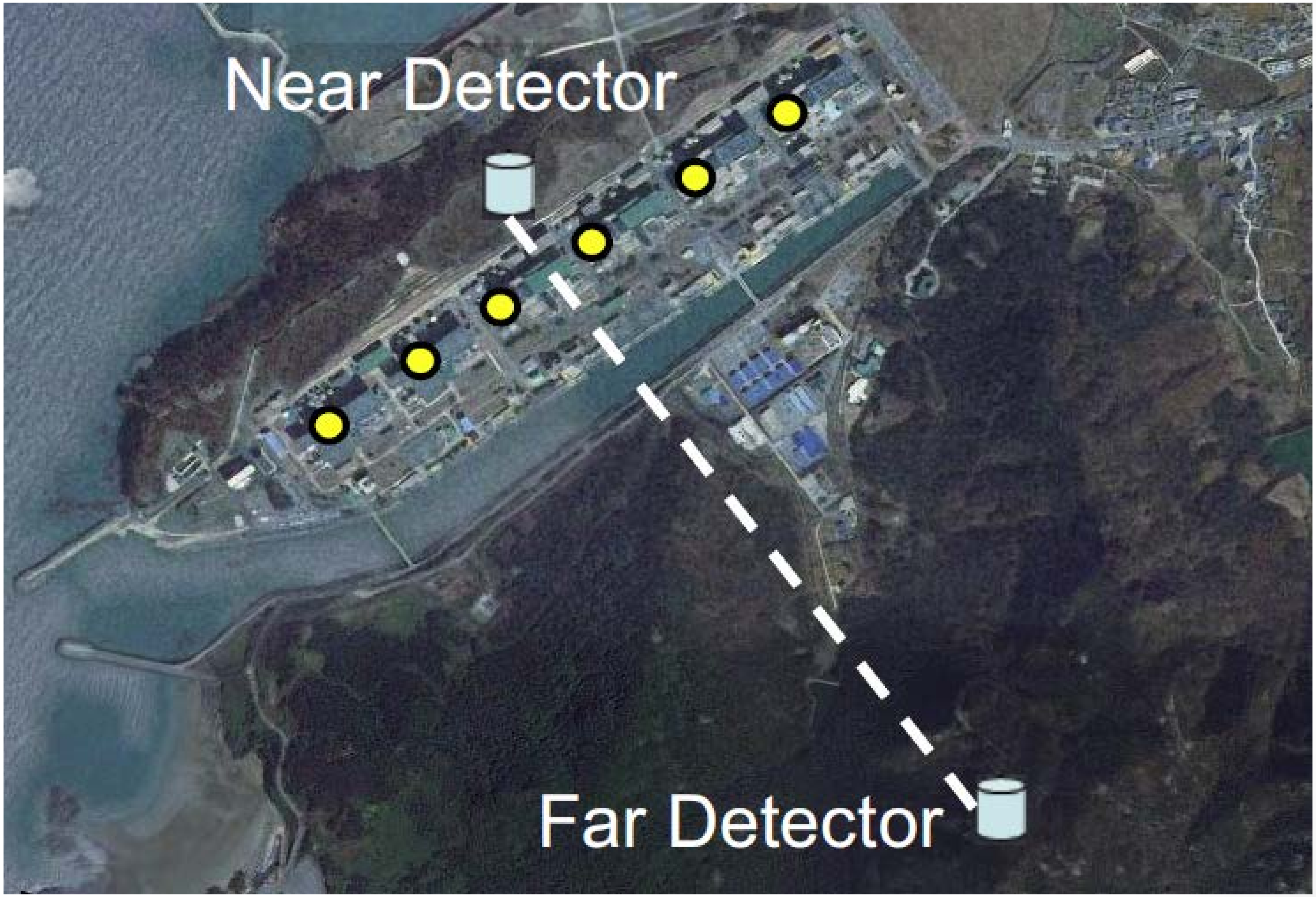
Ready for data taking in 2020.

- Baseline ~ 50 km

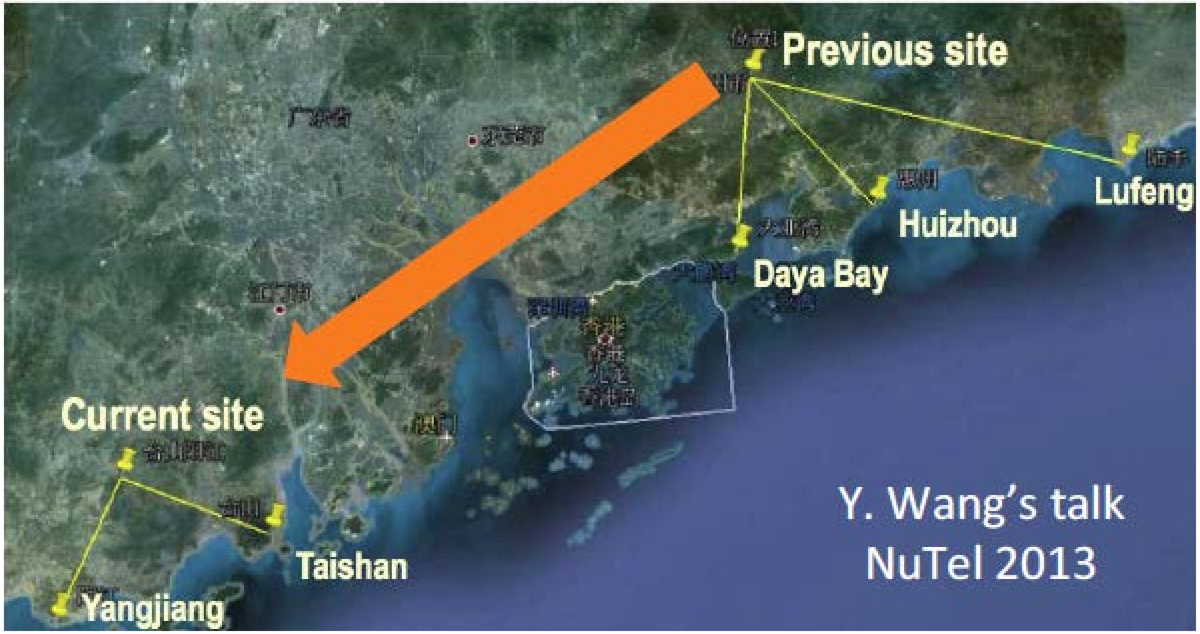
$$\frac{\Delta m^2_{01} L}{2E_\nu} \sim 0.4 \frac{\Delta m^2_{01}}{10^{-5}\ \mathrm{eV}^2} \frac{L}{50\ \mathrm{km}} \frac{3\ \mathrm{MeV}}{E_\nu}$$

- Main goal determination of $\mathrm{sgn}(\Delta m^2_{31})$

RENO-50 in South Korea



Daya Bay and Juno



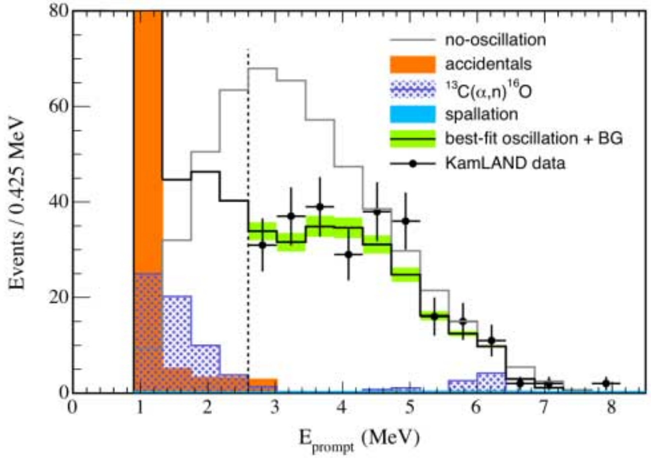
Detector characteristics

Liquid Scintillator

- Reno-50: 18 kton, 16.4 GW
- JUNO: 20 kton, 36 GW

$$\text{Energy resolution} \sim 3\% \sqrt{\frac{E_\nu}{\text{MeV}}}$$

- 62 energy bins between 1.8-8MeV
-
-



Oscillation in SSNS

- For reactor neutrinos

$$V_{eff} \sim G_F n_e \sim G_F n_n \ll \Delta m_{01}^2/E_\nu < \Delta m_{21}^2/E_\nu \ll |\Delta m_{31}^2/E_\nu|.$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left| M_0 e^{i\Delta_0} + M_1 e^{i\Delta_1} + M_2 e^{i\Delta_2} + M_3 e^{i\Delta_3} \right|^2$$

$$\Delta_i = m_i^2 L/2E_\nu$$

$$\begin{aligned}
M_0 &= |\cos\beta(-e^{-i\delta_1}\cos\gamma\cos\theta_{12}\cos\theta_{13}\sin\alpha - \cos\theta_{13}\sin\gamma\sin\theta_{12}) - e^{-i(\delta_D+\delta_2)}\sin\beta\sin\theta_{13}|^2,\\
M_1 &= |\cos\alpha\cos\theta_{12}\cos\theta_{13}|^2\\
M_2 &= |-e^{-i\delta_1}\cos\theta_{12}\cos\theta_{13}\sin\alpha\sin\gamma + \cos\gamma\cos\theta_{13}\sin\theta_{12}|^2\\
M_3 &= |\sin\beta(-e^{-i\delta_1}\cos\gamma\cos\theta_{12}\cos\theta_{13}\sin\alpha - \cos\theta_{13}\sin\gamma\sin\theta_{12}) + e^{-i(\delta_D+\delta_2)}\cos\beta\sin\theta_{13}|^2.
\end{aligned}$$

GloBES

Authors:
GLoBES is maintained by Patrick Huber
Joachim Kopp
Manfred Lindner
Walter Winter

http://www.mpi-hd.mpg.de/personalhomes/globes/index.html

Huber, Lindner and Winter, **Comput.Phys.Commun. 167 (2005) 195**

Huber et al, **Comput.Phys.Commun. 177 (2007) 432-438**

Kopp et al, PRD 77

Backgrounds

(i) accidental background;

(ii) $^{13}C(\alpha, n)^{16}O$ background

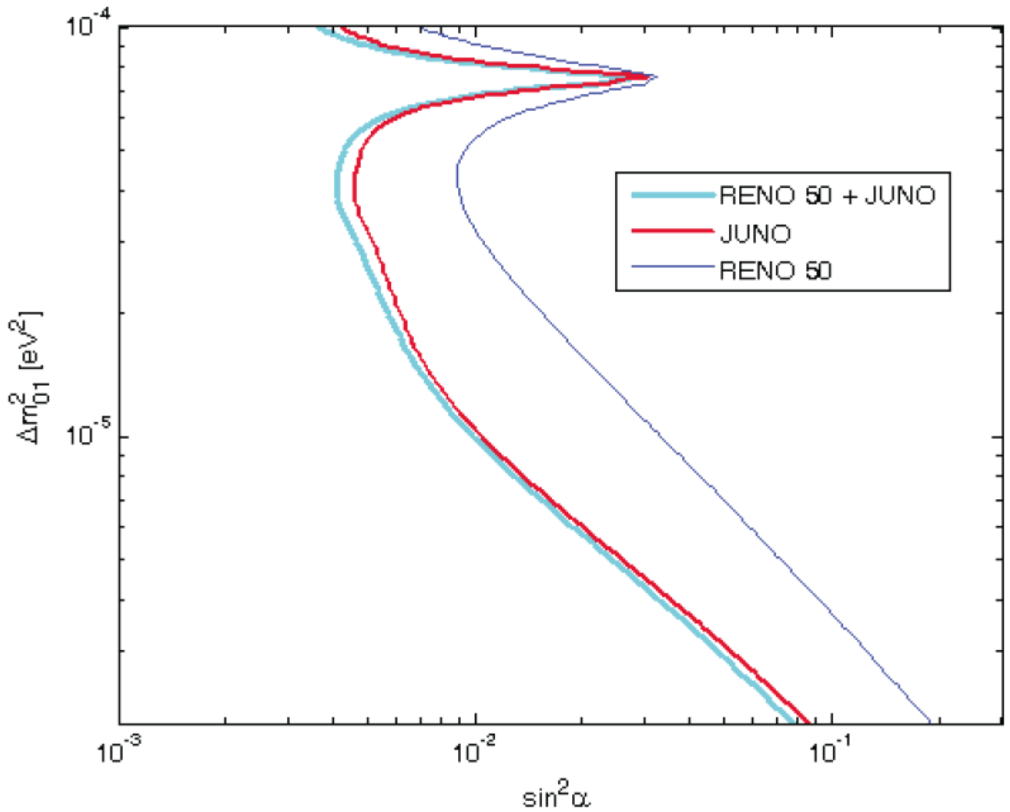
(iii) Geoneutrino background.

- Kettell et al, arXiv:1307.7419; Ciuffoli et al., arXiv:1302.0624.

Uncertainties

- We use pull-method to treat uncertainties in neutrino parameters and flux.
- 3 % flux uncertainty for JUNO
- 0.3 % flux uncertainty for RENO-50
- Gonzalez-Garcia et al, JHEP 12 (2012) 123 (nu-fit.org)

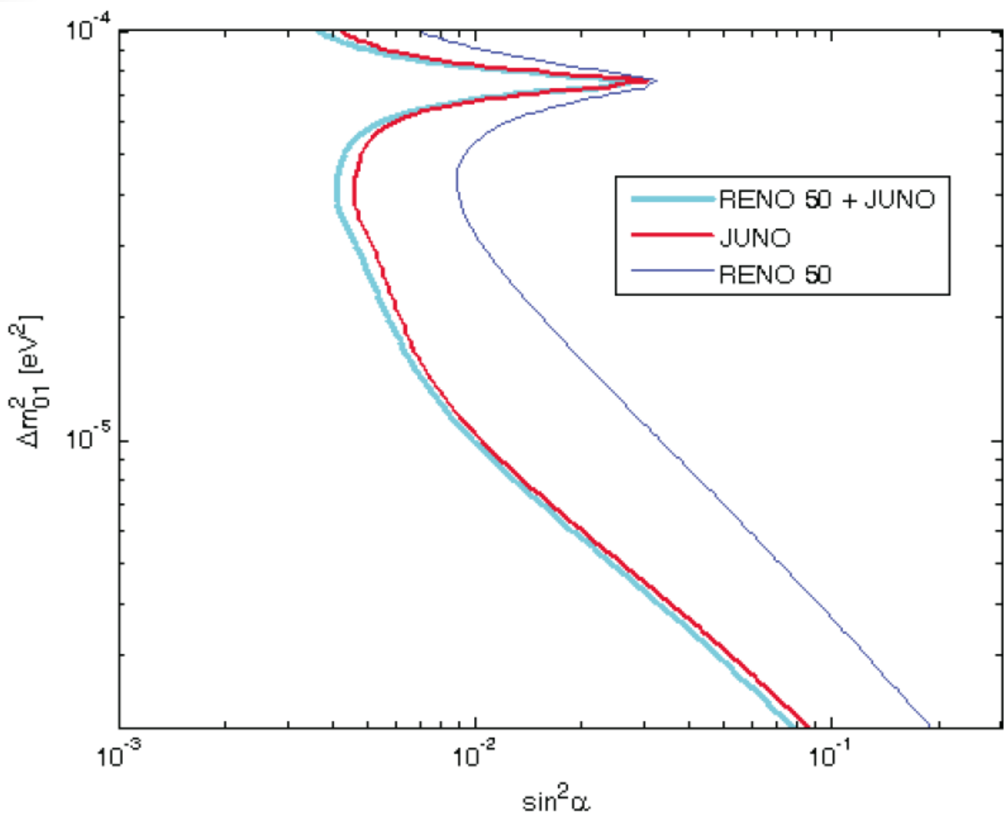
$$\theta_{12}\ ,\theta_{23}\ ,\Delta m^2_{31}\ ,\Delta m^2_{21}$$



The 95% C.L. upper bound on $\sin^2\alpha$ versus Δm^2_{01}.

$$\alpha = \beta = \gamma = 0$$

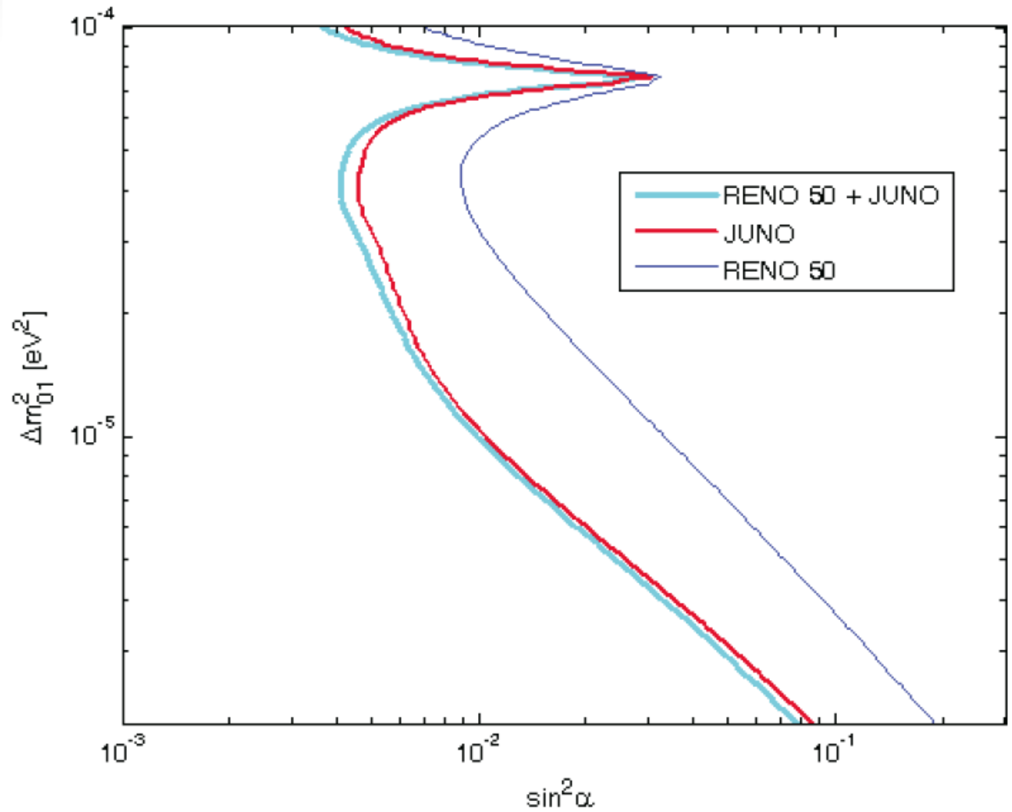
- Five years of data taking



Case I, $\sin\beta = \sin\gamma = 0$ *and* $\alpha \neq 0$:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\cos^2\theta_{13}\cos^2\theta_{12}\sin^2\alpha e^{i\Delta_0} + \cos^2\alpha\cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}e^{i\Delta_2} + \sin^2\theta_{13}e^{i\Delta_3}\right|^2$$

As expected in the $\Delta m^2_{01} \to 0$ limit, the sensitivity to α is lost.



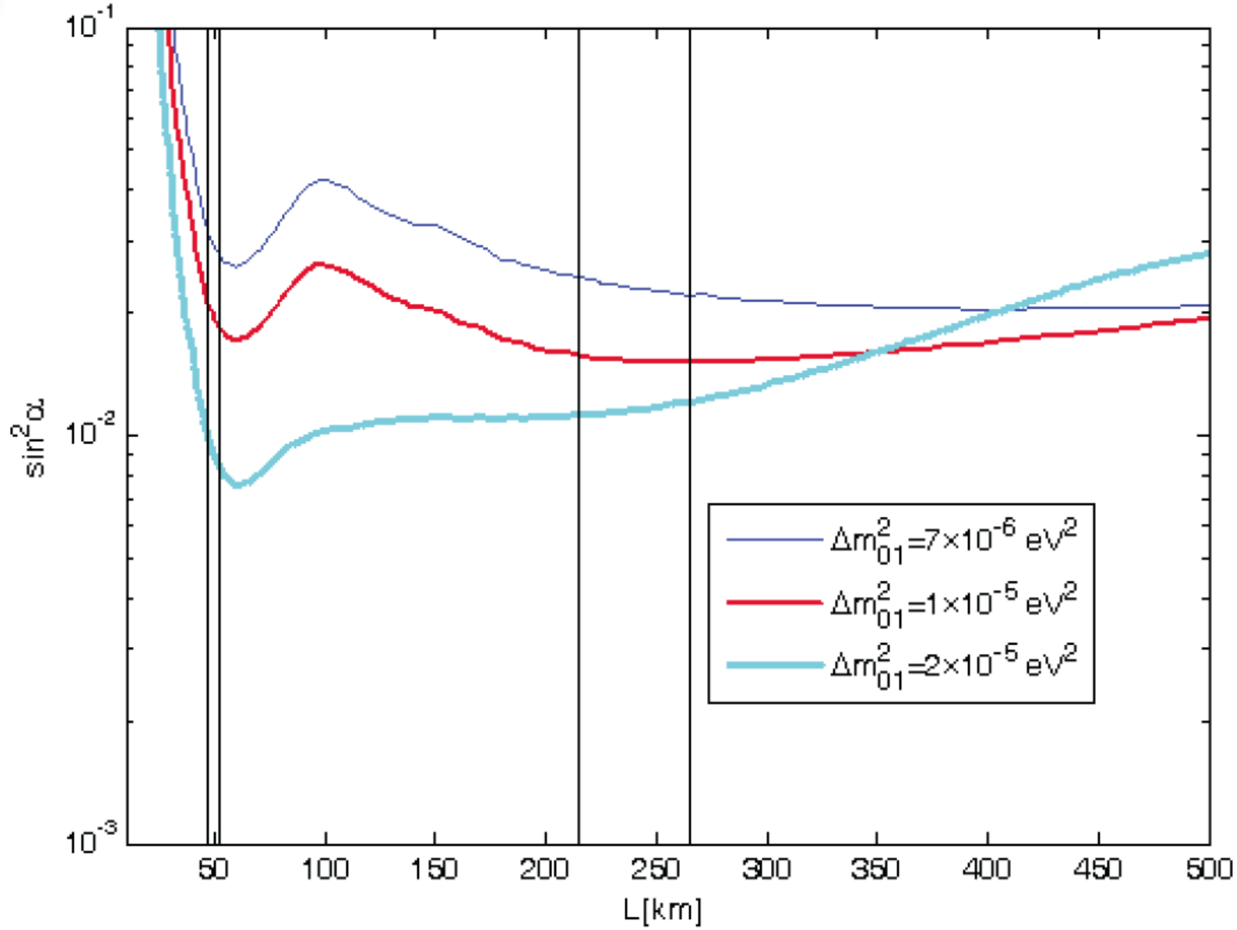
$$\Delta_0 \to \Delta_2$$

$$\Delta m^2_{01} \to \Delta m^2_{21}$$

$$Case\ I,\ \sin\beta = \sin\gamma = 0\ \ and\ \alpha \neq 0:$$

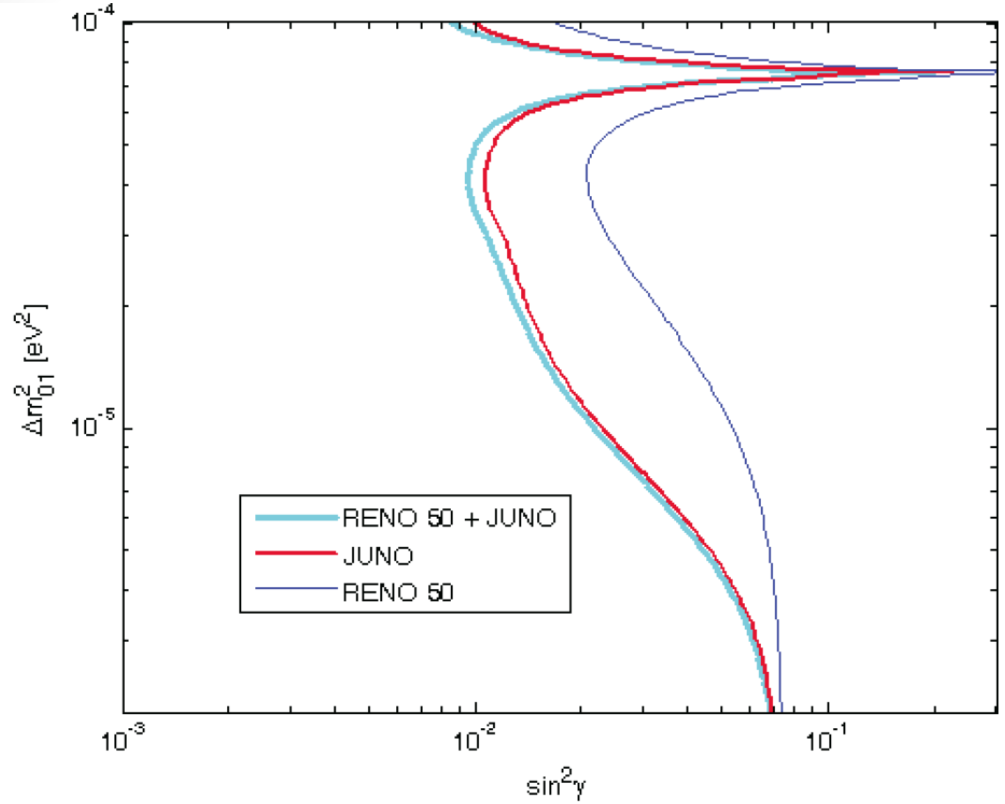
$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\cos^2\theta_{13}\cos^2\theta_{12}\sin^2\alpha e^{i\Delta_0} + \cos^2\alpha\cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}e^{i\Delta_2} + \sin^2\theta_{13}e^{i\Delta_3}\right|^2$$

- Uncertainty in θ_{12}: $\sin^2\alpha < \delta\sin^2\theta_{12}/\cos^2\theta_{12}$.

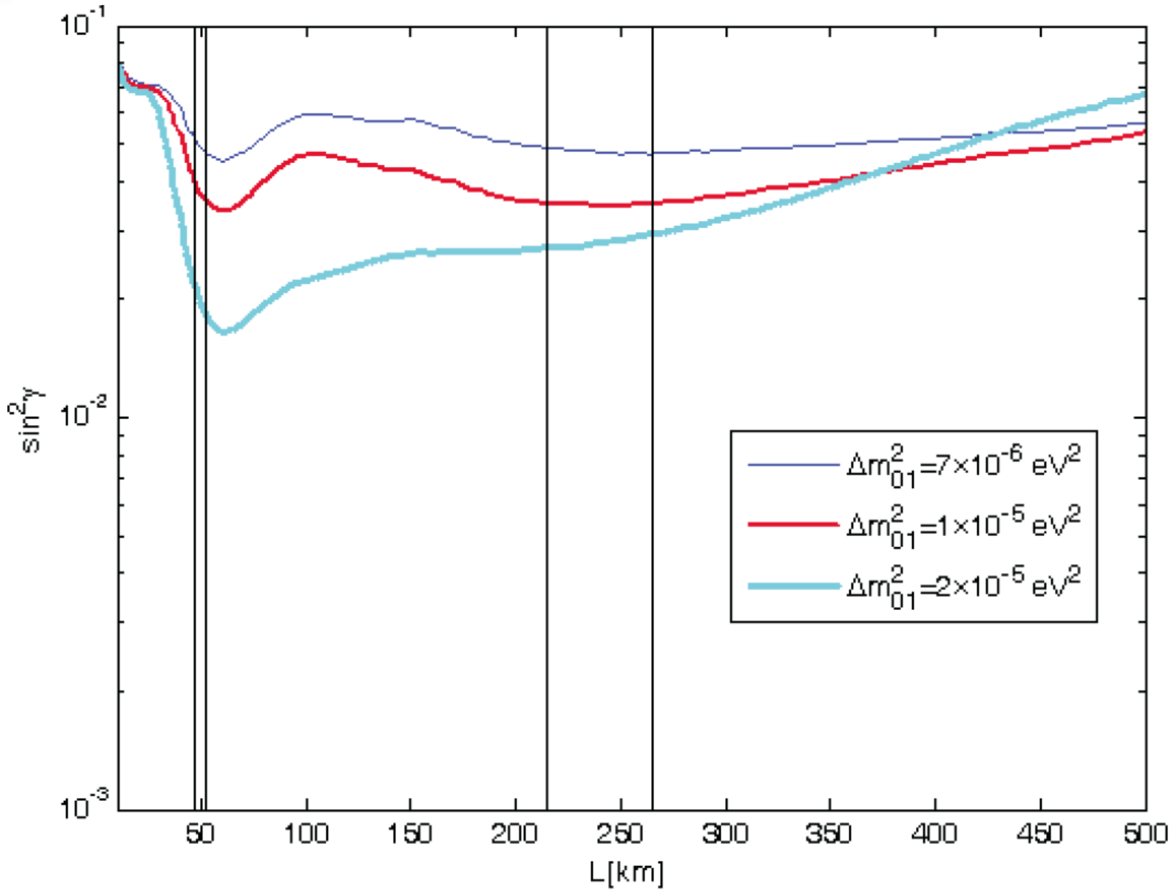


The 95% C.L. upper bound on $\sin^2\alpha$ versus the baseline.

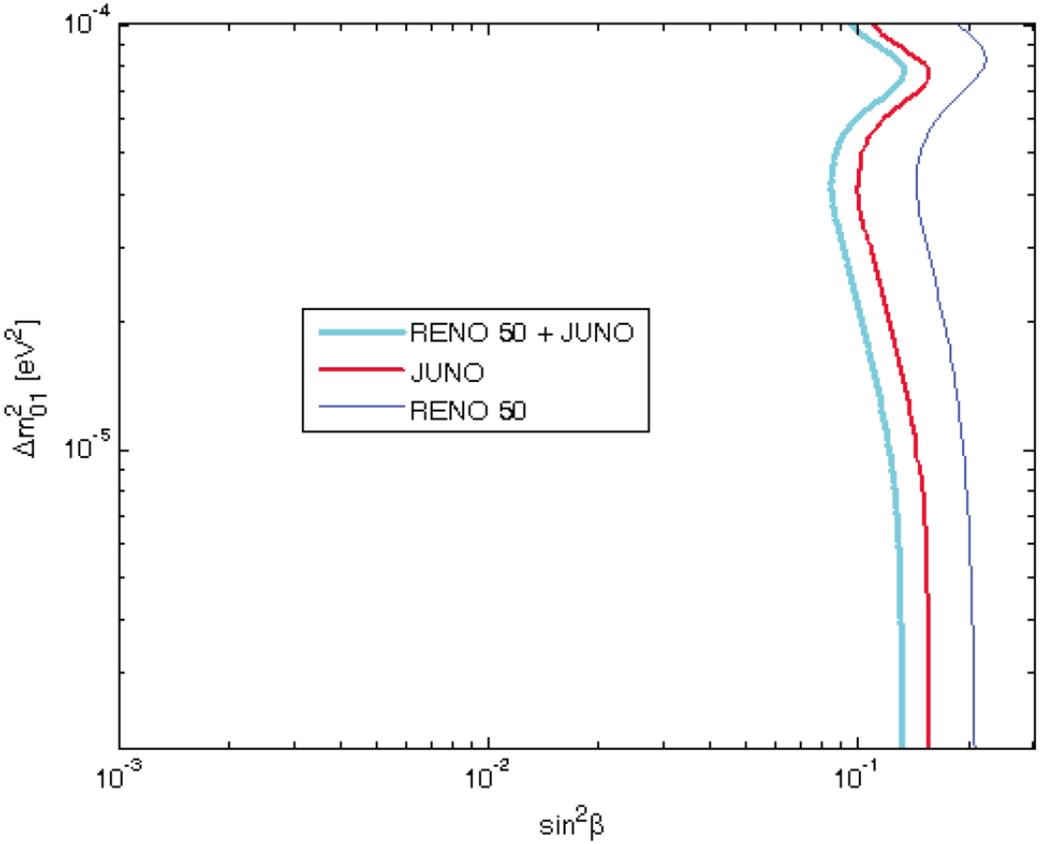
Five years of data taking with a 20 kton detector and 36 GW reactor source



$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\cos^2\theta_{13}\sin^2\theta_{12}\sin^2\gamma e^{i\Delta_0} + \cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}\cos^2\gamma e^{i\Delta_2} + \sin^2\theta_{13}e^{i\Delta_3}\right|^2$$



The 95% C.L. upper bound on $\sin^2\gamma$ versus the baseline.



Case III, $\sin\alpha = \sin\gamma = 0$ *and* $\beta \neq 0$: In this limit,

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\sin^2\theta_{13}\sin^2\beta e^{i\Delta_0} + \cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}e^{i\Delta_2} + \sin^2\theta_{13}\cos^2\beta e^{i\Delta_3}\right|^2$$

$$\sin^2\theta_{13} \ll 1$$

SSNS

- Superlight sterile neutrinos Scenario (SSNS):
- De Holanda and Smirnov, PRD 83 (2011) 113611.

- Parameter range to cure upturn of low energy solar neutrinos:

$$\Delta m^2_{01} = (0.7 - 2) \times 10^{-5}\ \mathrm{eV}^2 \quad \sin^2 2\alpha \sim 10^{-3}$$

To probe such small values of mixing about 20 years of data taking is required.

How to improve

- The results are not too sensitive to background, energy resolution, normalization uncertainty of flux and etc
- Accumulation of flux from various reactors are useful
- Main limitation: statistics
- Going to Bigger detector and longer data collecting time smaller values of mixing can be probed.

Conclusion

- The medium baseline reactor experiments can (in principle) probe SSNS

Non-standard Interaction

- Within SM, neutral current interaction are flavor-diagonal and universal.

- But, going to beyond SM

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma_\mu P\ f)$$

Examples: Grand unification, various seesaw models, extra U(1), left-right symmetric models, etc

T.Ohlsson, Rept. Prog. Phys 76 (2013) 044201

NSI

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma_\mu P\ f)$$

f is the matter field ($u,\ d$ or e).

P is the chirality projection matrix

$\epsilon_{\alpha\beta}^{fP}$ is a dimensionless matrix

Relevant for neutrino oscillation

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{f}\gamma_\mu P\ f)$$

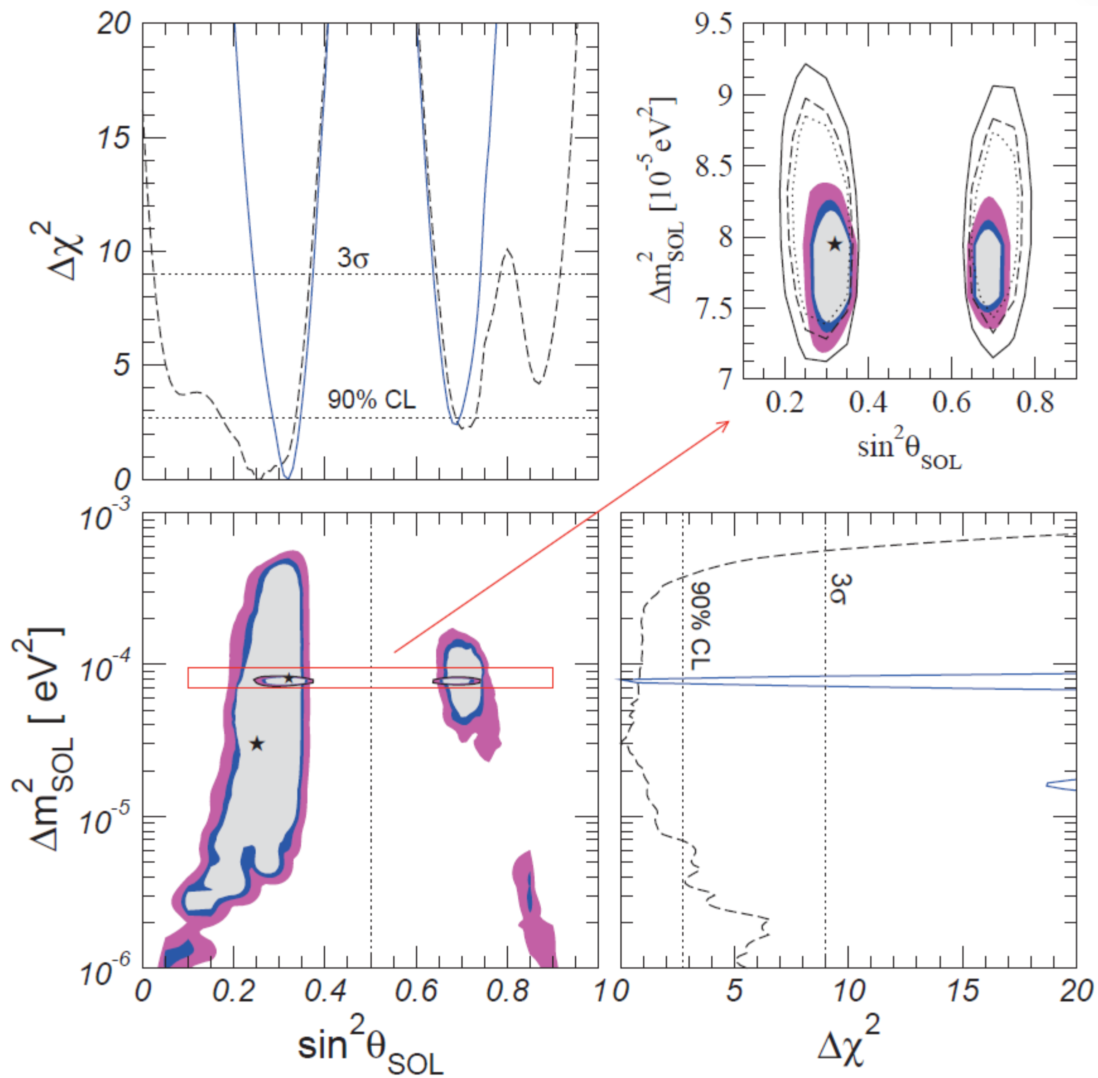
$$\epsilon^{f}_{\alpha\beta} \equiv \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}.$$

LMA-Dark solution

- For $$|\epsilon^f_{ee} - \epsilon^f_{\mu\mu}|, |\epsilon^f_{ee} - \epsilon^f_{\tau\tau}| \neq 0$$

- Another solution with $\cos(2\theta_{12}) < 0$

O. G. Miranda, M. A. Tortola and J. W. F. Valle, JHEP **0610** (2006) 008 [hep-ph/0406280]; O. G. Miranda, M. A. Tortola and J. W. F. Valle, AIP Conf. Proc. **917** (2007) 100; F. J. Escrihuela, O. G. Miranda, M. A. Tortola and J. W. F. Valle, Phys. Rev. D **80** (2009) 105009 [Erratum-ibid. D **80** (2009) 129908] [arXiv:0907.2630 [hep-ph]]; *see also*, A. Friedland and I. M. Shoemaker, arXiv:1207.6642 [hep-ph].



- Miranda et al., JHEP 0610 (2006) 008

Has LMA-dark solution survives?

- Solution survives the test of all the neutrino

Gonzalez-Garcia and Maltoni, JHEP 1309 (2013) 152

3 sigma range

Standard Matter Potential

$$\sin^2\theta_{12} \in [0.27, 0.35]\,,$$
$$\sin^2\theta_{23} \in [0.36, 0.67]\,,$$
$$\sin^2\theta_{13} \in [0.016, 0.030]\,,$$
$$\Delta m^2_{21} \in [6.87, 8.03] \times 10^{-5}\ \mathrm{eV}^2,$$
$$|\Delta m^2_{31}| \in [2.20, 2.58] \times 10^{-3}\ \mathrm{eV}^2,$$

Generalized Matter Potential

$$\sin^2\theta_{12} \in [0.26, 0.35] \oplus [0.65, 0.75]\,,$$
$$\sin^2\theta_{23} \in [0.34, 0.67]\,,$$
$$\sin^2\theta_{13} \in [0.016, 0.030]\,,$$
$$\Delta m^2_{21} \in [6.86, 8.10] \times 10^{-5}\ \mathrm{eV}^2,$$
$$|\Delta m^2_{31}| \in [2.20, 2.65] \times 10^{-3}\ \mathrm{eV}^2.$$

		90% CL		3σ	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$	$[-0.09, +0.71]$	$\oplus\ [-1.40, -0.68]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$	$[-0.03, +0.20]$	$[-0.19, +0.20]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$	$[-0.40, +0.30]$	$[-0.40, +0.40]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^u_{D}	-0.140	$[-0.24, -0.01]$	$\oplus\ [+0.40, +0.58]$	$[-0.34, +0.04]$	$\oplus\ [+0.34, +0.67]$
ε^u_{N}	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$	$[-0.29, +0.21]$	$[-0.29, +0.21]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$	$[-0.10, +0.71]$	$\oplus\ [-1.44, -0.87]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$	$[-0.03, +0.19]$	$[-0.16, +0.19]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$	$[-0.38, +0.29]$	$[-0.38, +0.35]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^d_{D}	-0.145	$[-0.25, -0.02]$	$\oplus\ [+0.49, +0.57]$	$[-0.34, +0.05]$	$\oplus\ [+0.42, +0.70]$
ε^d_{N}	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$	$[-0.28, +0.21]$	$[-0.28, +0.21]$

LMA-Dark

- LMA-Dark solution fits the solar data slightly better as it suppresses the upturn of the spectrum at low energy

Other bounds

- Invisible Z-decay (loop level)
- Neutrino scattering off matter
- Ohlsson, Rept Prog Phys 76 (2013) 44201

Other bounds

- Invisible Z-decay (loop level)
- Neutrino scattering off matter
- Ohlsson, Rept Prog Phys 76 (2013) 44201
- The bound from CHARM scattering experiment combined with NuTeV rules out a part of parameter space for LMA-Dark.

$$(i.e.,\ 0.9 < |\epsilon_{ee}^{d} - \epsilon_{\mu\mu}^{d}| < 0.8 \text{ at } 90\ \%\ \text{C.L.})$$

Davidson, Pena-Garay, Rius and Santamaria, JHEP 0303 (2003) 011.

Medium Baseline reactor experiments

- DAYA BAY in CHINA → JUNO
- RENO in South Korea → RENO-50

Ready for data taking in 2020.

- Baseline ~ 50 km

$$\frac{\Delta m^2_{01} L}{2E_\nu} \sim 0.4 \frac{\Delta m^2_{01}}{10^{-5}\ \mathrm{eV}^2} \frac{L}{50\ \mathrm{km}} \frac{3\ \mathrm{MeV}}{E_\nu}$$

- Main goal determination of $\mathrm{sgn}(\Delta m^2_{31})$

Charged current NSI

- Charged current NSI

$$(\bar{d}\gamma^{\mu} P \ u)(\bar{e}\gamma_{\mu} L \nu_{\mu(\tau)})$$

Affects neutrino production and detection

- Neutral current NSI

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

Affects neutrino propagation through matter effects

Charged current NSI at JUNO

$$|\hat{\nu}^{\mathrm{s}}_{\alpha}\rangle = \frac{1}{N^{\mathrm{s}}_{\alpha}}\left(|\nu_{\alpha}\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^{\mathrm{s}}_{\alpha\beta}|\nu_{\beta}\rangle\right)$$

$$\langle\hat{\nu}^{\mathrm{d}}_{\beta}| = \frac{1}{N^{\mathrm{d}}_{\beta}}\left(\langle\nu_{\beta}| + \sum_{\alpha=e,\mu,\tau} \varepsilon^{\mathrm{d}}_{\alpha\beta}\langle\nu_{\alpha}|\right)$$

Khan et al, PRD 88 (2013) 113006
Ohlsson, Zhang and Zhou, PLB 728 (2014) 148

Neutral current NSI at reactor neutrino experiments

$$\Delta m^2_{21}/E_\nu \gg \sqrt{2}G_F N_e$$

- Small matter effects

- Little sensitivity to neutral current NSI

Our suggestion to test LMA-Dark

- Pouya Bakhti and Y.F., 1403.0744

- Determining $\cos 2\theta_{12}$

Survival probability without matter effects

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left||U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}}\right|^2 = \left|c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}}\right|^2 =$$

$$c_{13}^4(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta_{21}}{2}) + s_{13}^4 + 2s_{13}^2 c_{13}^2[\cos\Delta_{31}(c_{12}^2 + s_{12}^2 \cos\Delta_{21}) + s_{12}^2 \sin\Delta_{31} \sin\Delta_{21}]$$

where $\Delta_{ij} = \Delta m_{ij}^2 L/(2E_\nu)$ in which L is the baseline.

Observation

- A reactor neutrino set-up that is sensitive to hierarchy should also distinguish between solution

$$\text{with } \theta_{12} > \pi/4 \text{ and } \theta_{12} < \pi/4$$

GloBES

Authors:
GLoBES is maintained by Patrick Huber
Joachim Kopp
Manfred Lindner
Walter Winter

http://www.mpi-hd.mpg.de/personalhomes/globes/index.html

Huber, Lindner and Winter, **Comput.Phys.Commun. 167 (2005) 195**

Huber et al, **Comput.Phys.Commun. 177 (2007) 432-438**

Characteristics of JUNO and RENO-50

- The same as before except that we added

background caused by ^{9}Li from cosmic muon interaction

- Grassi, Evslin Giuffoli and Zhang, 1401.7796

- 10000 and 5000 fake neutrinos from Li at JUNO and RENO-50

Energy bins

- Energy range between 1.8 to 8 MeV to 350 bins 0f 17.7 keV

- Good energy resolution is required

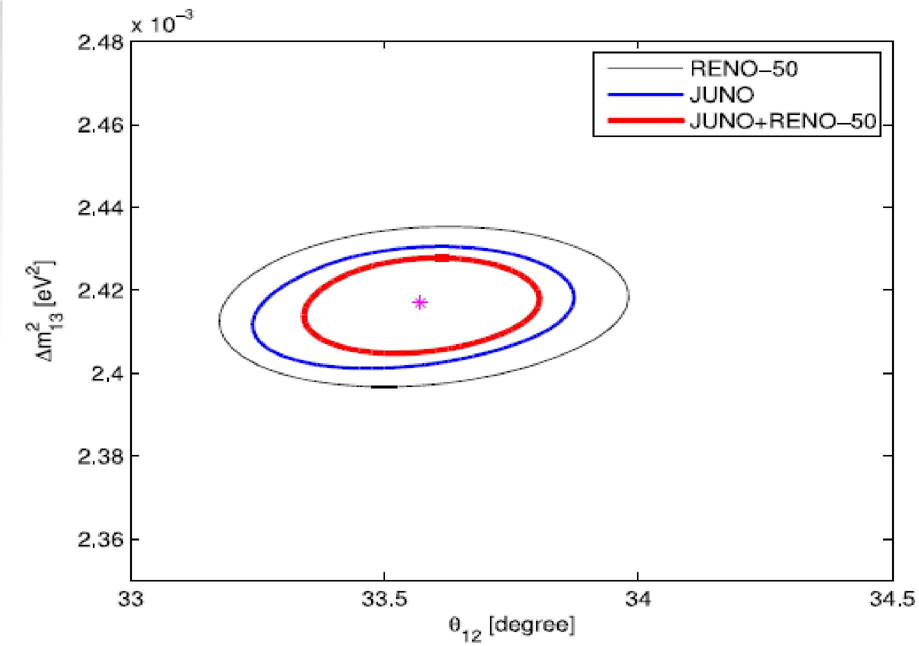
$$\frac{\delta E_\nu}{E_\nu} \simeq 3\% \times (\frac{E_\nu}{\text{MeV}})^{1/2}.$$

Results

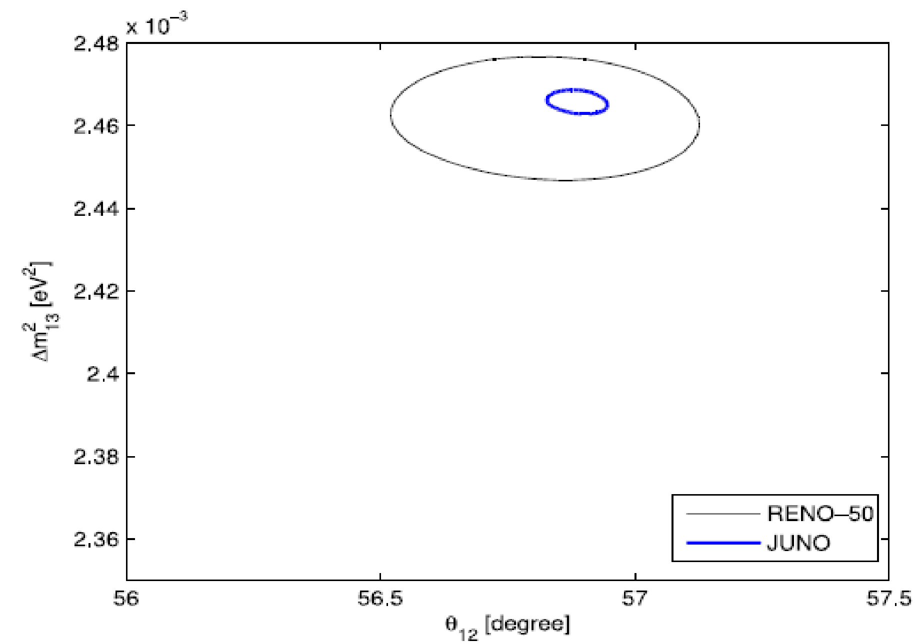
- After 5 years of data taking by JUNO and RENO-50

$$\Delta m^2_{21} = (7.45 \pm 0.45) \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{13} = (8.75 \pm 0.5)^\circ$$


x 10^-3
2.48
2.46
2.44
2.42
2.4
2.38
2.36
Δm²13 [eV²]
33
33.5
34
34.5
θ12 [degree]
RENO–50
JUNO
JUNO+RENO–50

(a)


x 10^-3
2.48
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2.4
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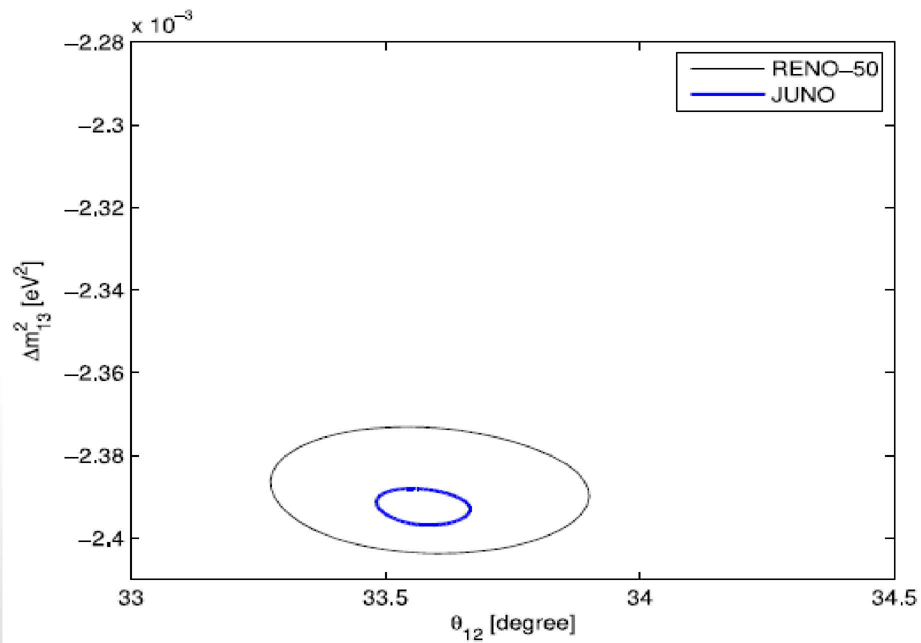
Δm²13 [eV²]
56
56.5
57
57.5
θ12 [degree]
RENO–50
JUNO

(b)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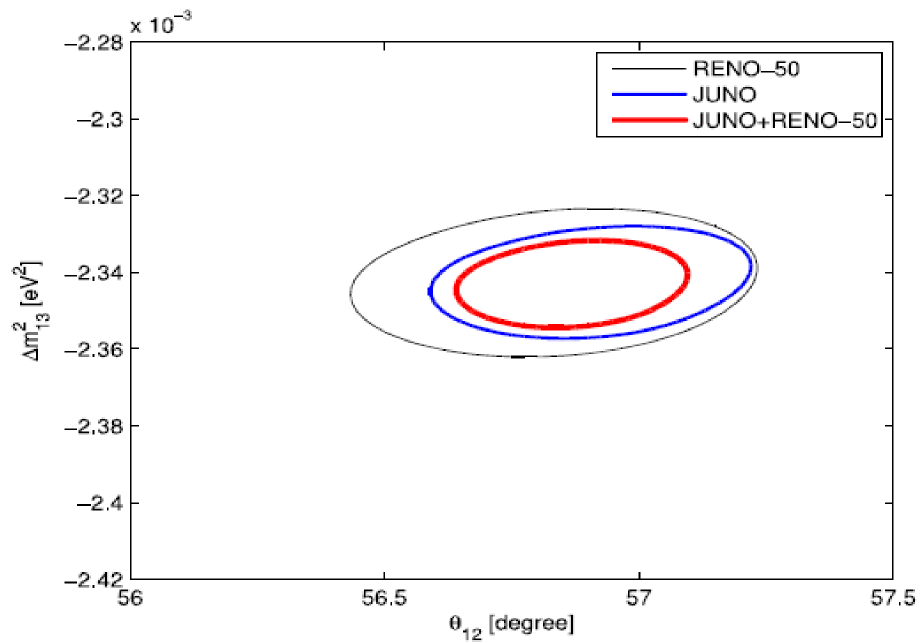
(c)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56
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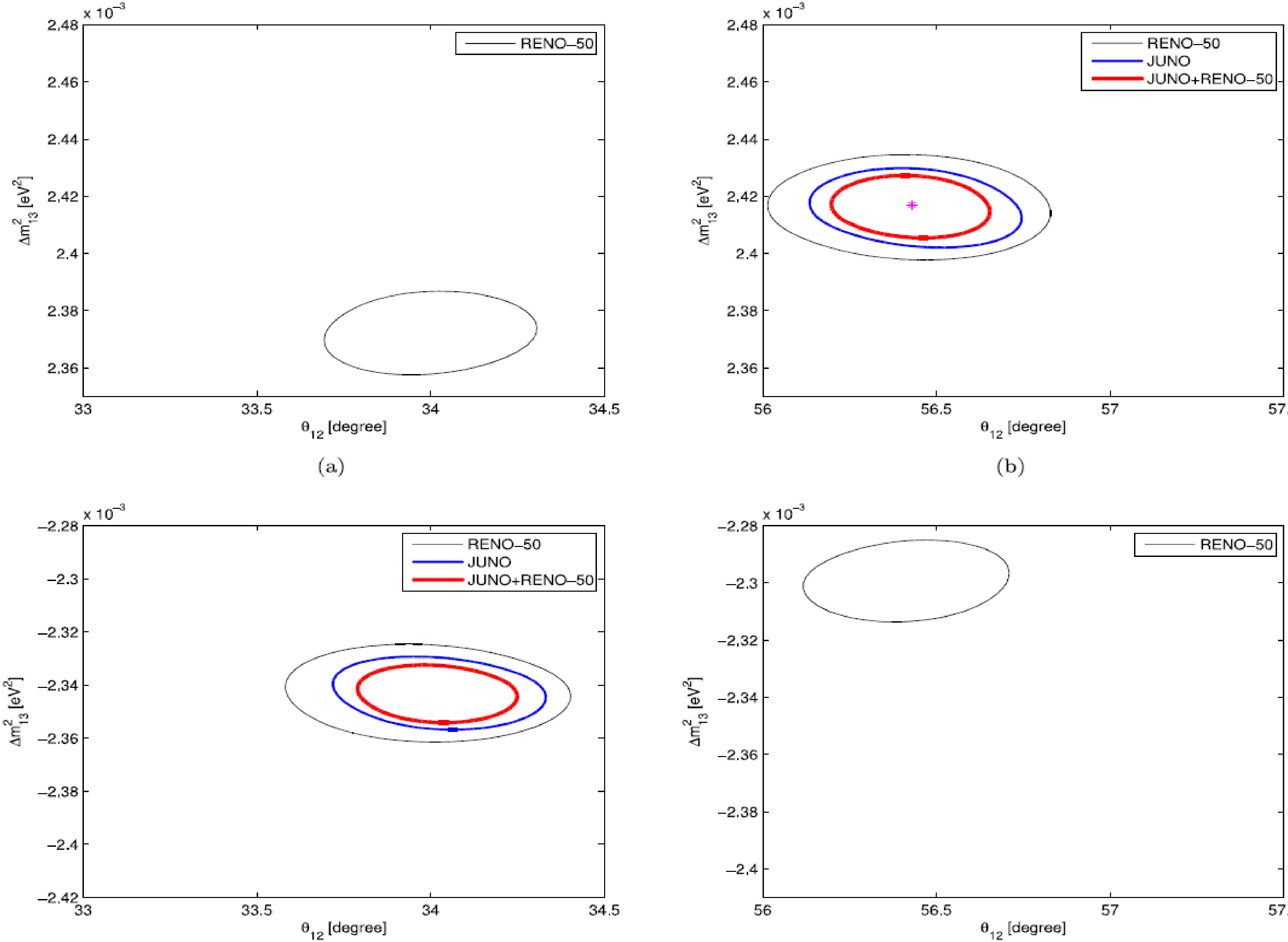
JUNO
JUNO+RENO–50

(d)



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(a) (b) (c) (d)

Degeneracy

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left| |U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}} \right|^2 = \left| c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}} \right|^2$$

$$s_{12} \leftrightarrow c_{12} \ (i.e., \ \theta_{12} \to \frac{\pi}{2} - \theta_{12}) \quad \text{and} \quad \Delta_{31} \to -\Delta_{31} + \Delta_{21}$$

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$$s_{12} \leftrightarrow c_{12}$$

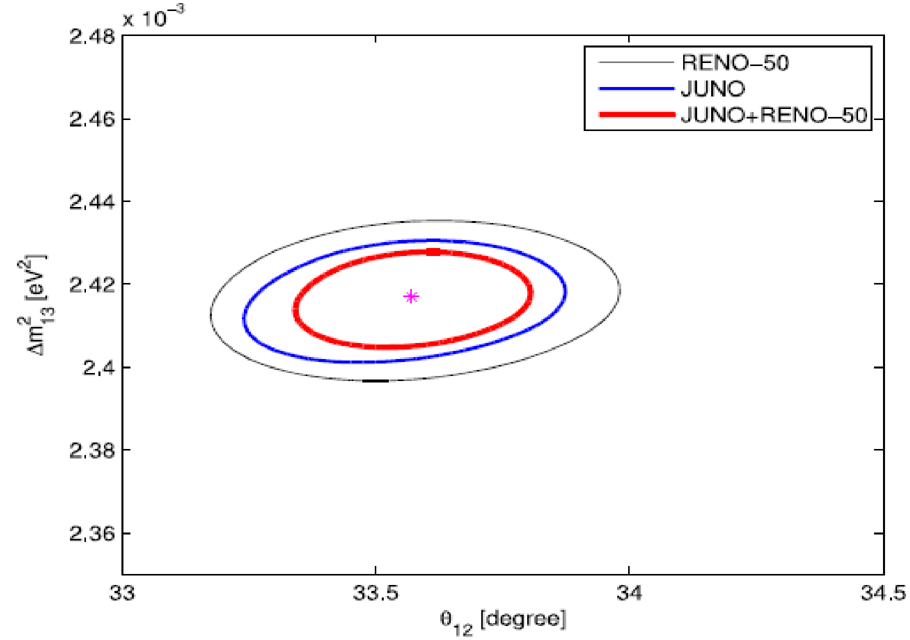
$$|s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}}| =$$

$$|s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{-i\Delta_{21}} + s_{13}^2 e^{-i\Delta_{31}}| =$$

$$|e^{i\Delta_{21}}(s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{-i\Delta_{21}} + s_{13}^2 e^{-i\Delta_{31}})|$$

- As long as we neglect matter effects

$$s_{12} \leftrightarrow c_{12} \ (i.e., \ \theta_{12} \rightarrow \frac{\pi}{2} - \theta_{12}) \quad \text{and} \quad \Delta_{31} \rightarrow -\Delta_{31} + \Delta_{21}$$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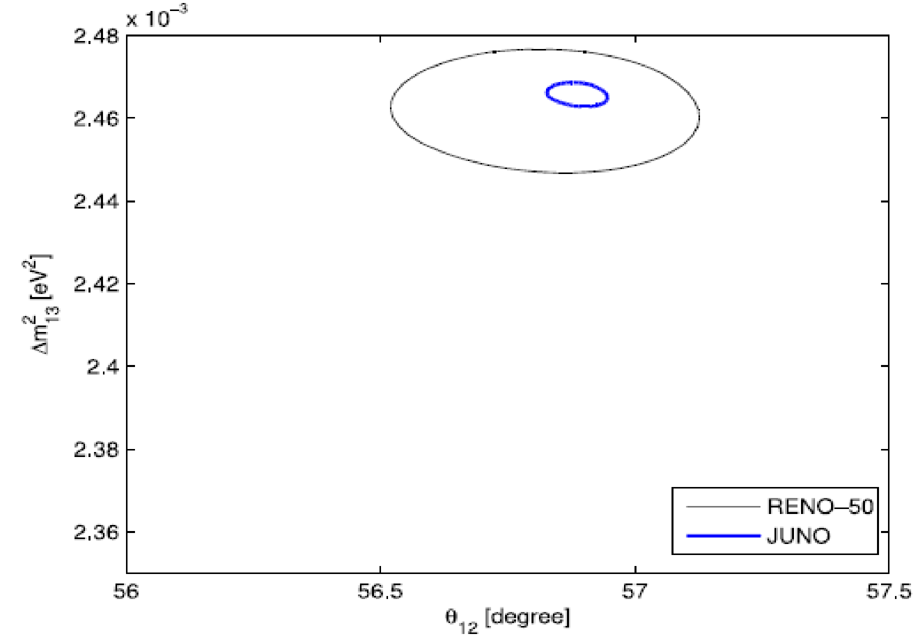
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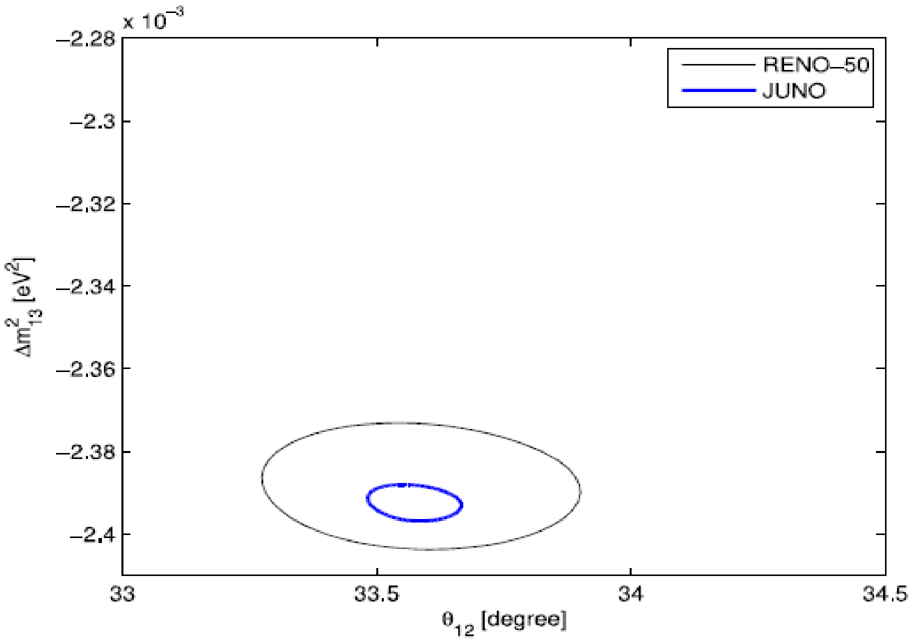
RENO–50
JUNO

(b)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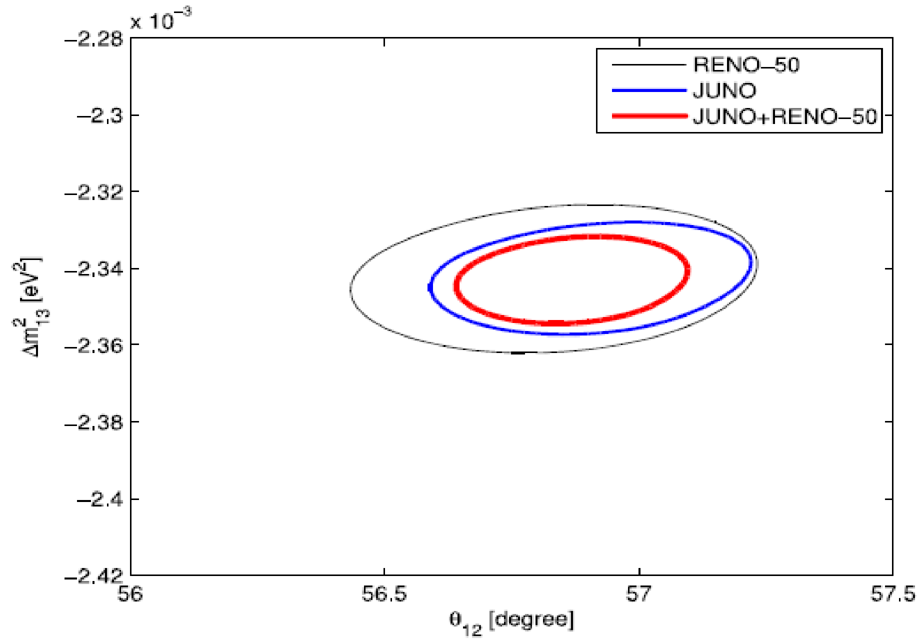
(c)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(d)

Summary of results

- RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution

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- RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution
  - Increasing energy resolution from 3% to 3.5% makes the wrong solution acceptable at 3 sigma!
  - Removing the background, JUNO alone can rule the wrong solution at more than 3 sigma.
  - There is a degeneracy that can be solved by scattering experiments sensitive to NSI.

Backup

- Gadolinium-doped Liquid scintillator
- AD=anti-neutrino detector:
- Accidental background: correlation of two unrelated events

- Beta-neutron decay of Li/He produced by muons inside AD

- Neutron spallation

$$H = V_{vacc} + V_{eff} \quad \text{where} \quad V_{vacc} = U_{PMNS} \cdot Diag(\Delta_1, \Delta_2, \Delta_3) \cdot U_{PMNS}^T,$$

$$\Delta_i = m_i^2/(2E_\nu)$$

Replacing $\theta_{12} \to \pi/2 - \theta_{12}$, $\delta \to \delta + \pi$ and $\Delta_1 \leftrightarrow \Delta_2$,

$$\Downarrow$$

V_{vacc} will transform into $S \cdot V_{vacc} \cdot S$

$$S = Diag(1, -1, -1)$$

Since we have the freedom of rephasing ν_α

- The oscillation probability will remain the same if

$$V_{eff} \to S \cdot V_{eff} \cdot S;$$

$\Delta_1 \leftrightarrow \Delta_2$ is equivalent to $\Delta_{21} \to -\Delta_{21}$ and $\Delta_{31} \to \Delta_{31} - \Delta_{21}$

Invariance of probabilities under

$$\theta_{12} \to \frac{\pi}{2} - \theta_{12}, \;\; \delta \to \pi - \delta, \;\; \Delta_{31} \to -\Delta_{13} + \Delta_{21} \;\text{ and }\; V_{eff} \to -S \cdot V_{eff} \cdot S.$$

$$V_{eff} \to -S \cdot V_{eff} \cdot S$$

$$\Updownarrow$$

$$\epsilon_{ee} + 1 \to -(1 + \epsilon_{ee}).$$

$$\epsilon_{\alpha\beta} = Y_u \epsilon^u_{\alpha\beta} + Y_d \epsilon^d_{\alpha\beta}$$

$$Y_u = 2 + Y_n \text{ and } Y_d = 1 + 2Y_n$$

- Composition of the sun and the earth are different so degeneracy can be partially solved.

We examined the possibility of solving degeneracy by using the NOvA experiment. Sensitivity of NOvA to NSI had also been discussed in [34]. We used the GLoBES software to carry out the analysis. Details of the simulation of NOvA experiment is based on [35, 36]. For true values we have taken $\theta_{12} = 33.57$ and set all the NSI parameters to zero; $\epsilon = 0$. We have assumed normal hierarchical scheme. We have found that after six years of data taking (*i.e.*, 3 years in neutrino mode and 3 years in antineutrino mode), NOvA can rule out the other solution with opposite sign of $\cos 2\theta_{12}$ and Δ_{31} with $\chi^2 = 3.9$ which for 2 dof corresponds to about 85% C.L.

Solution of the puzzle

- Neutrino oscillation

- Potecorvo proposed in 1957 in analogy of

$$K^0 \leftrightarrows \bar{K}^0$$

Even before solar neutrinos were discovered!!!

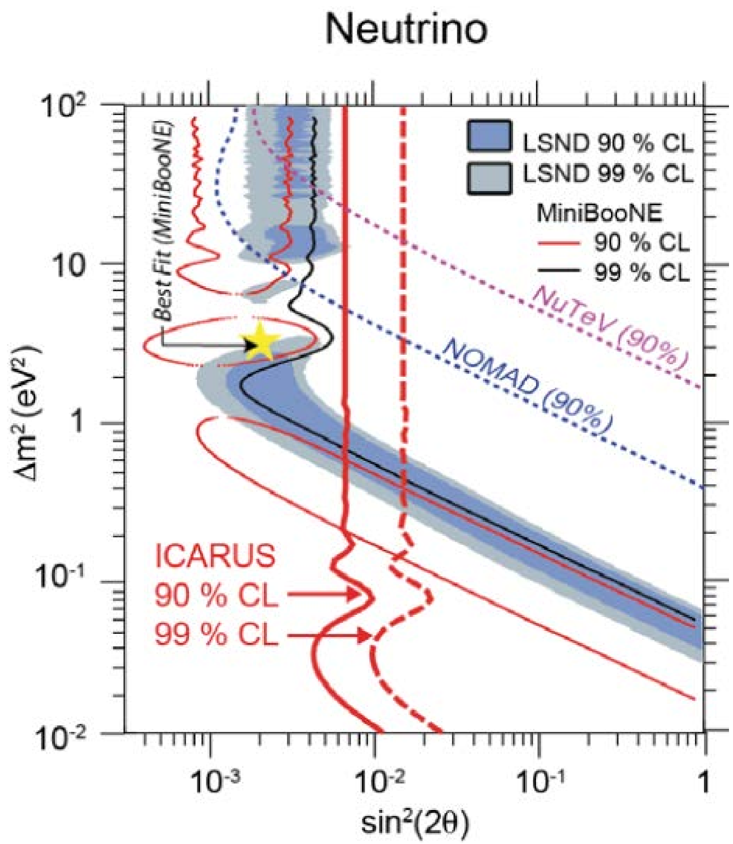
Invisible Z decay width

$$Z \rightarrow e^- e^+ \quad Z \rightarrow \mu^- \mu^+$$

$$Z \rightarrow \nu_e \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$$

Fourth Neutrino ?!

Icarus



A better bound from electron neutrino appearance at ICARUS, Eur. Phys. J. C73 (2013) 2599

arXiv:1307.3922