BSM Physics @ICAL

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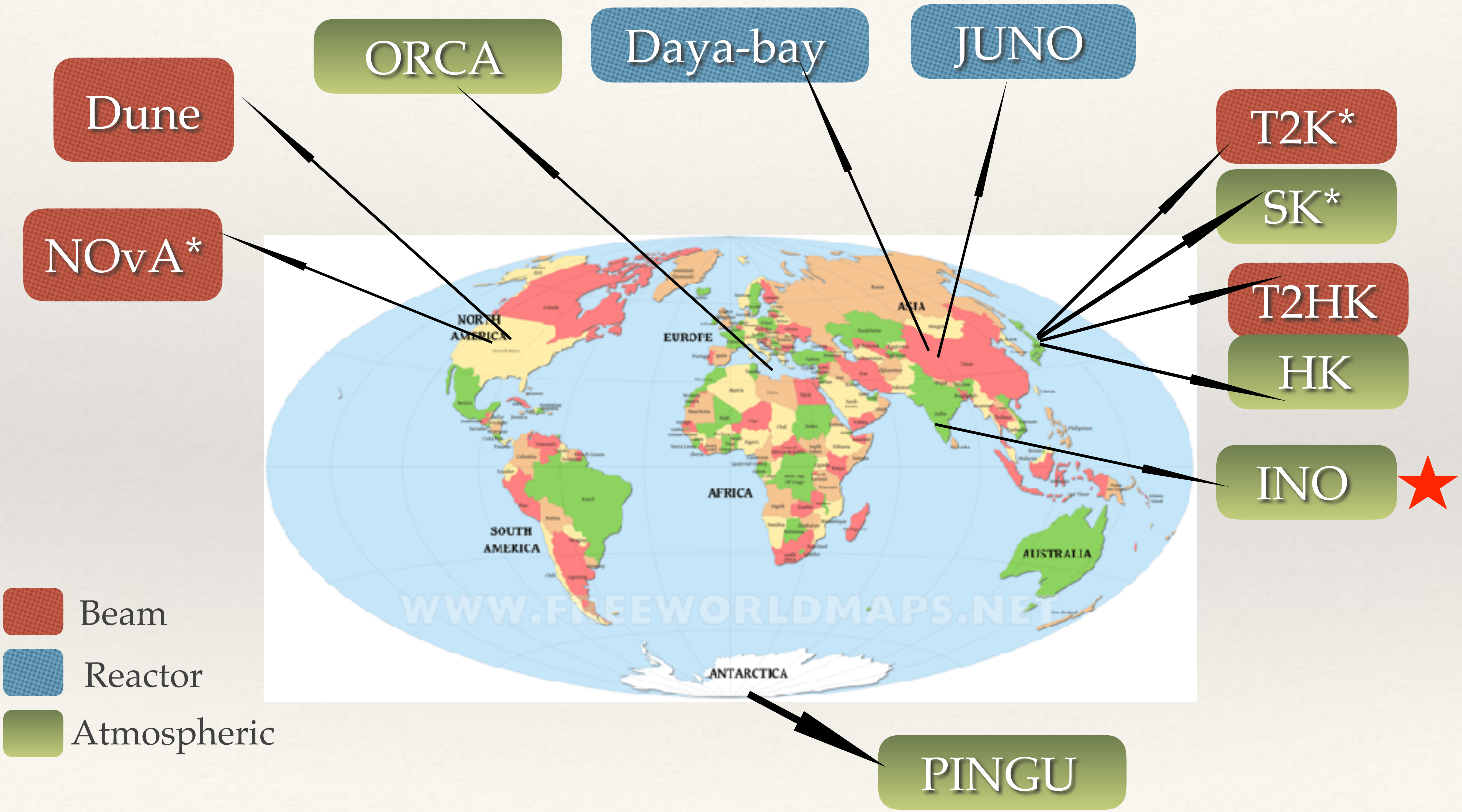
INO Outlook Meeting
19-20th February 2021

Neutrino Oscillation: Current research directions

- Three neutrino oscillation paradigm well established
- Hierarchy, octant and CP phase — immediate goal
- Probing new physics in oscillation experiment ?
- BSM physics sub-leading effect — precise measurements
- Testing models of flavour symmetry — parameter correlations
- Synergy between different experiments

Ongoing and planned experiments



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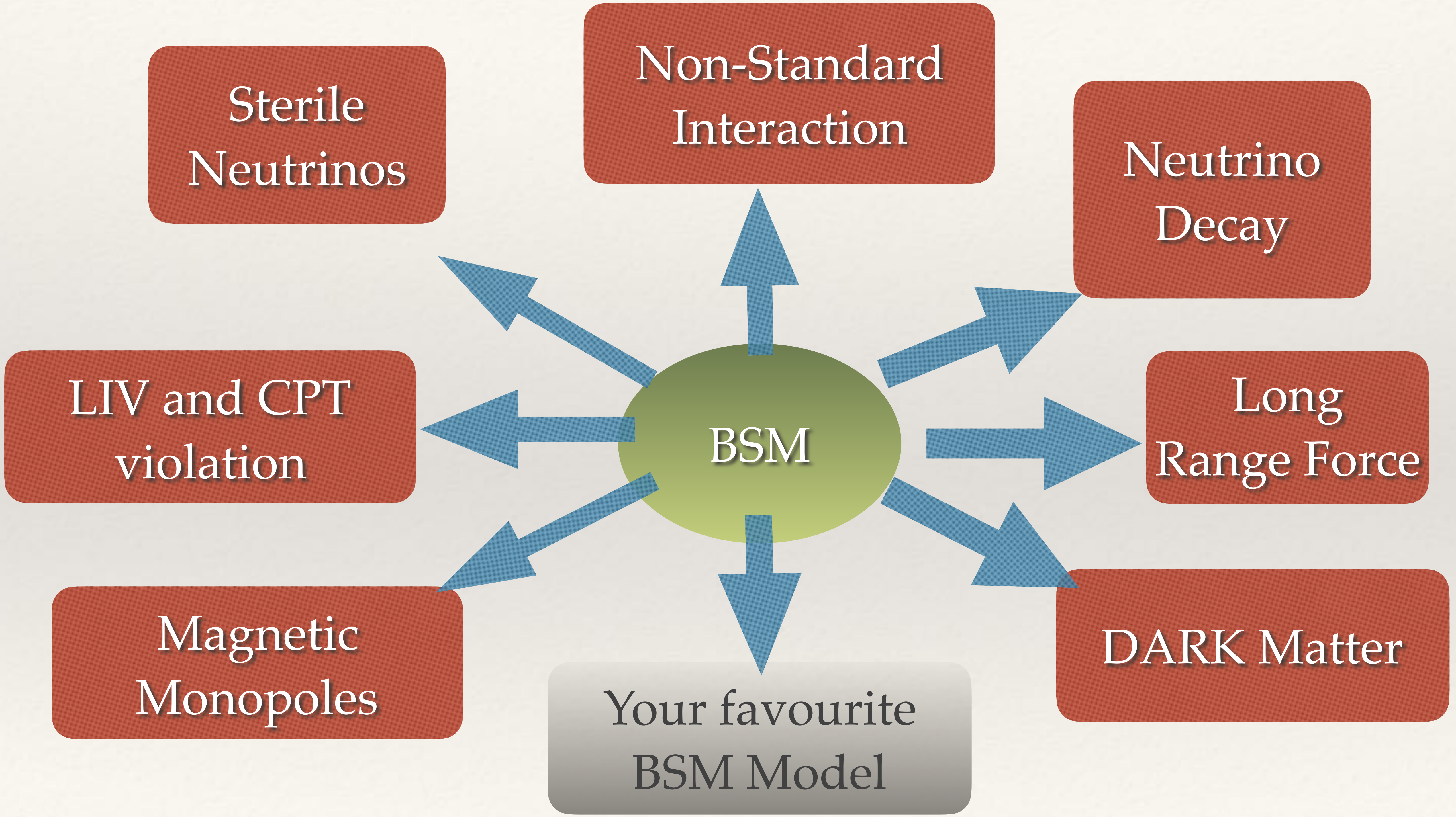


Probing BSM Physics @ICAL

Two Directions

Matter Effect
Charge identification

Impact on the standard Three neutrino picture

Constraining new physics parameters

New Degeneracies → Different parameters giving same probability

Equally good fit to the data → Synergies between Experiments

Latest Results 500 kt yr

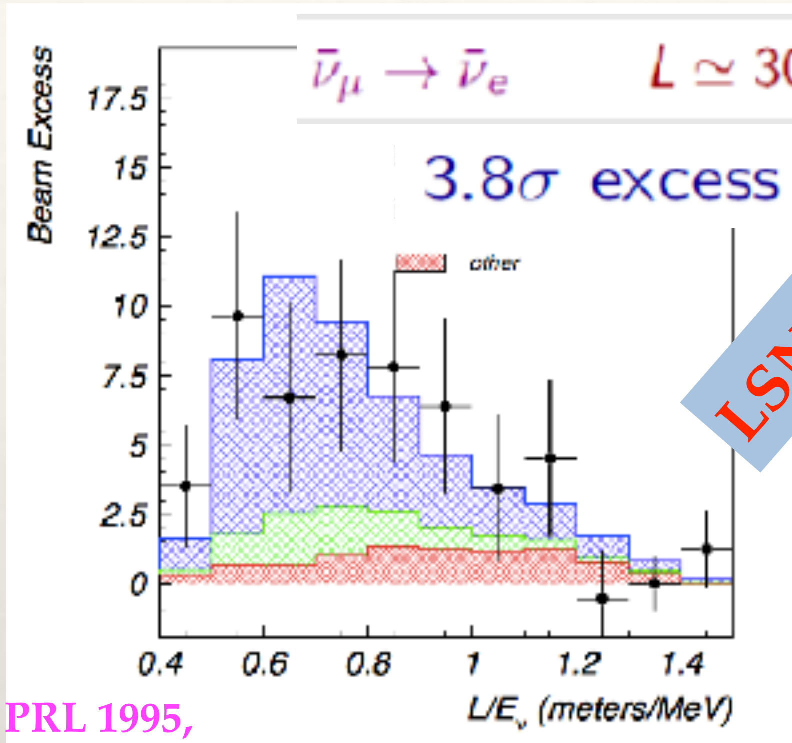
Earlier results : *Pramana* 88 (2017) 5, 79

Sterile Neutrinos

Sterile Neutrinos : indications

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $L \simeq 30\,\mathrm{m}$ $20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$

3.8σ excess $\Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2$



LSND

LSND PRL 1995, PRD 2001

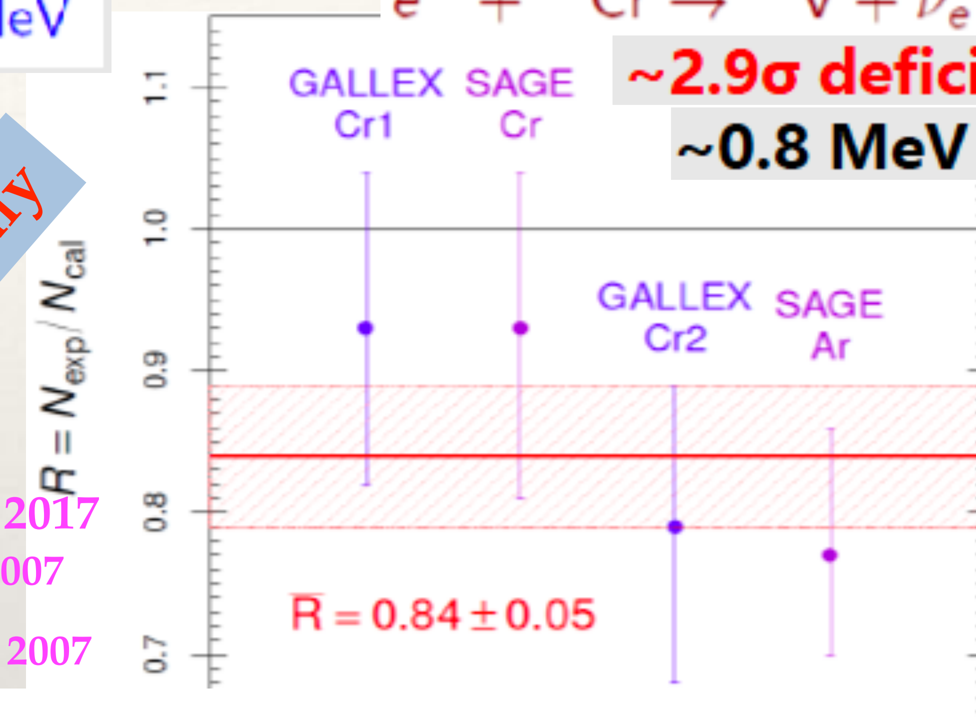
Ga Anomaly

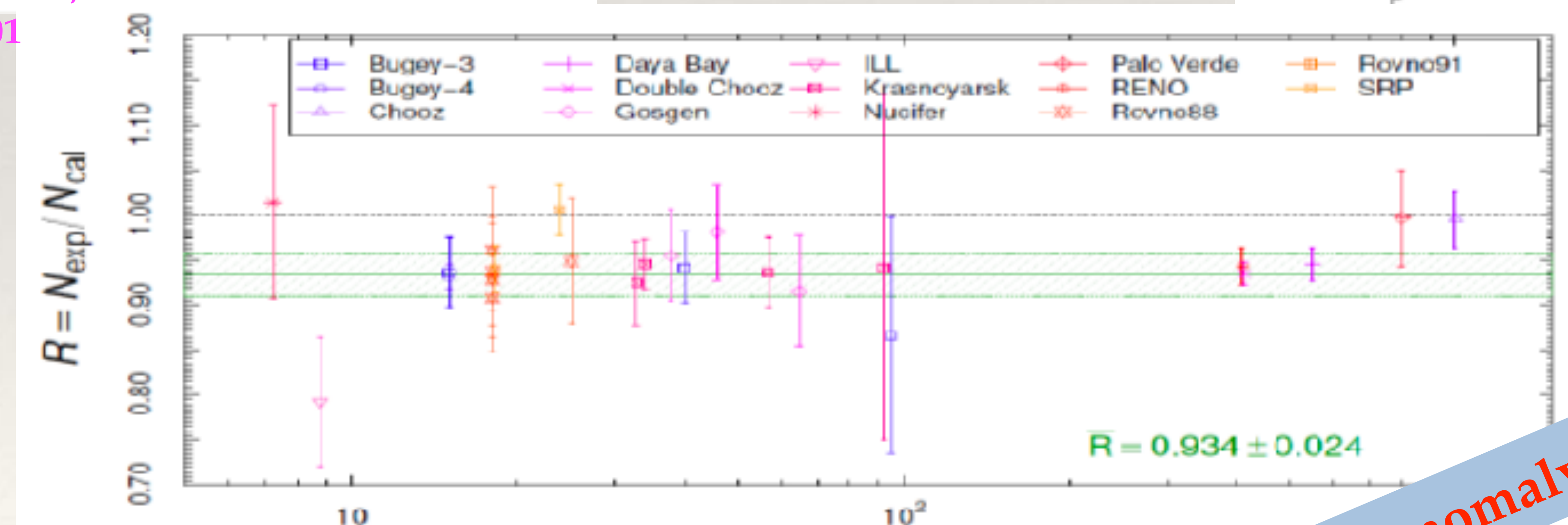
Lavedar et al 2017
SAGE PRC 2007
GALLEX PRC 2007

$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$

~2.9σ deficit

~0.8 MeV





Mueller et al PRC 2011
Huber PRC 2011
Mention et al PRD 2011

$\Delta m^2_{41} = 2.4\ \mathrm{eV}^2$

$\sin^2(2\theta_{14}) = 0.14$

Reactor Anomaly

$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2 \left[1.27 \frac{\Delta m^2_{41} L}{E_\nu} \left(\frac{\mathrm{eV}^2 \cdot \mathrm{m}}{\mathrm{MeV}} \right) \right]$$

NEOS
DANSS
NEUTRINO 4

Disappearance and appearance tension

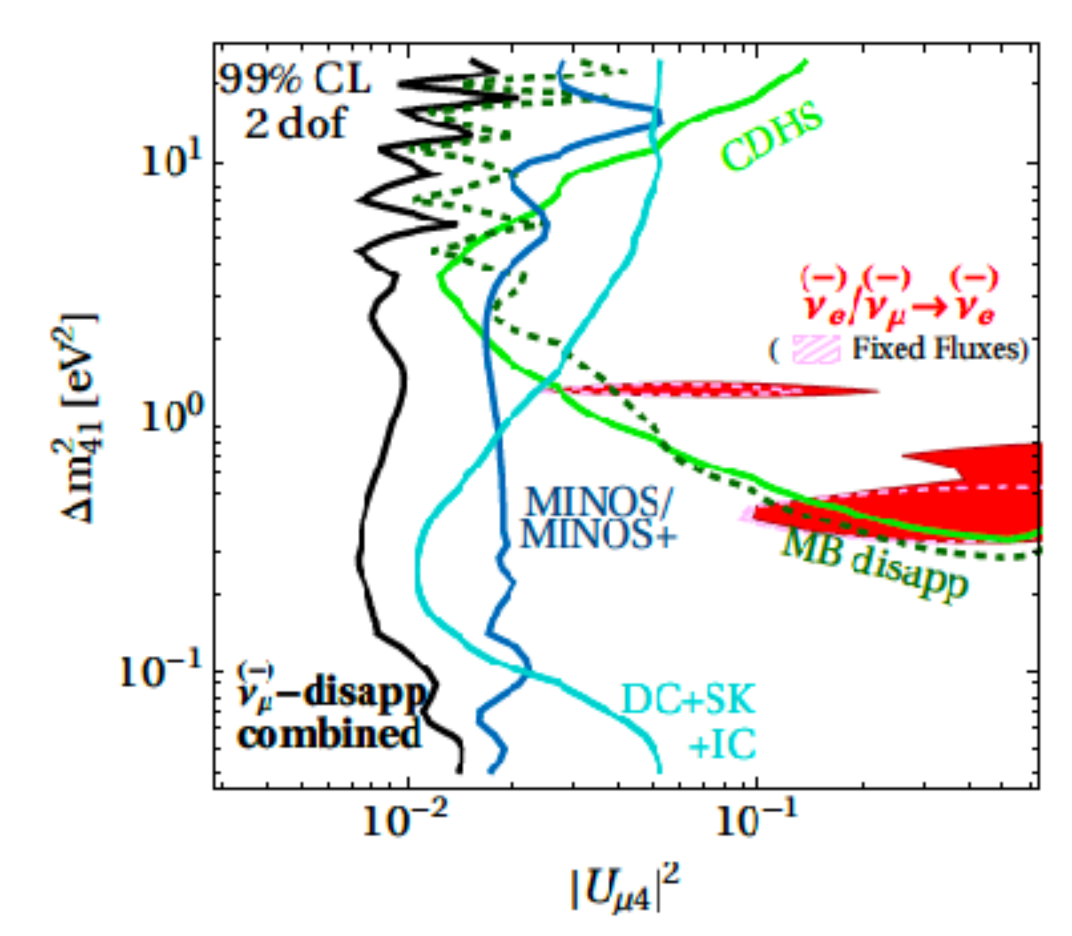
$$P_{\alpha\alpha}^{\mathrm{SBL}} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\alpha\beta}^{\mathrm{SBL}} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right).$$

P_{ee} depends on $|U_{e4}|^2$

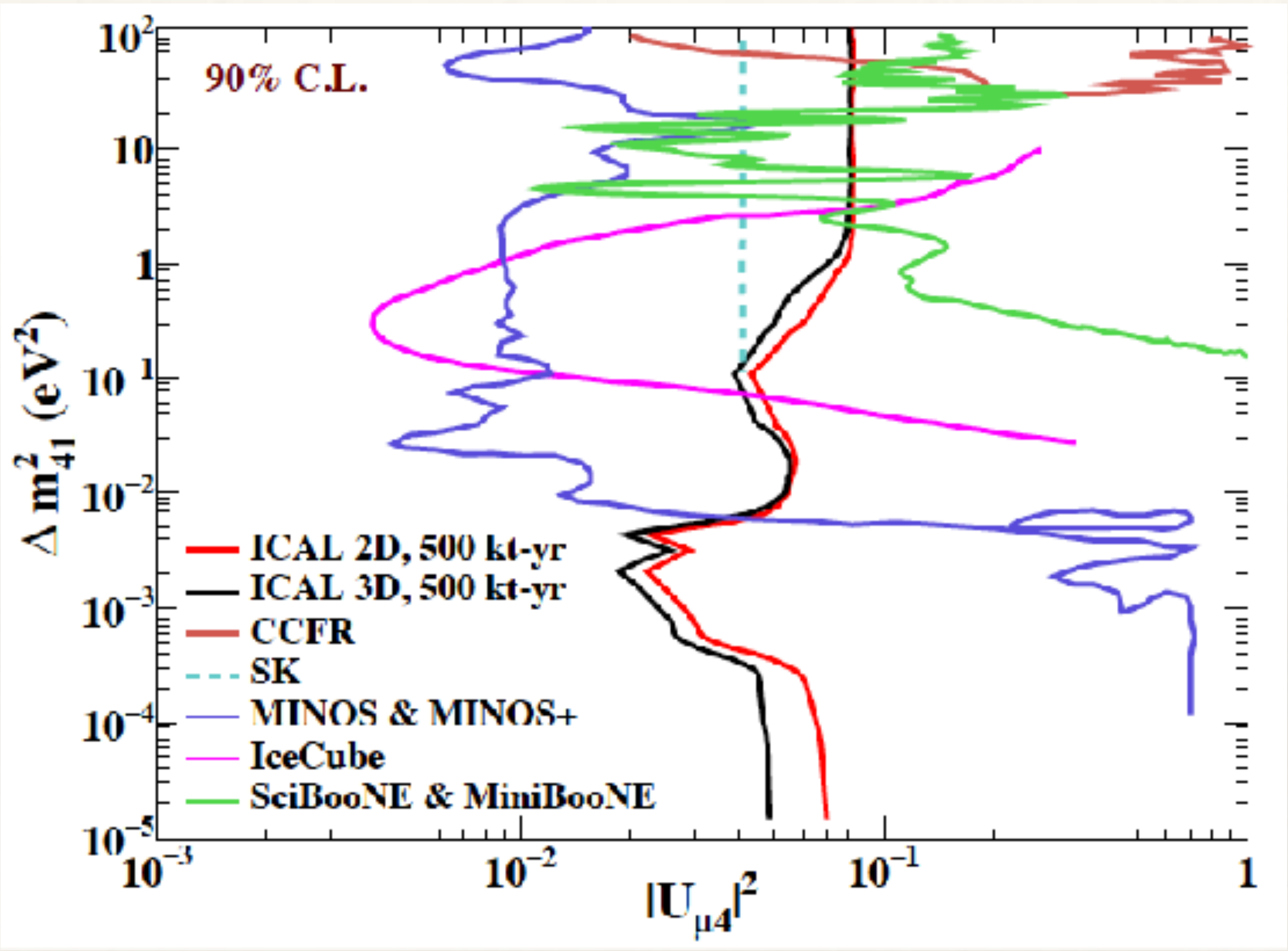
$P_{\mu\mu}$ depends on $|U_{\mu 4}|^2$

$P_{\mu e}$ depends on $|U_{\mu 4}|^2|U_{e4}|^2$



Dentler, Hernandez-Cabezudo,Kopp, Maltoni, Schwetz,JHEP 2017

Sterile Neutrinos@ICAL

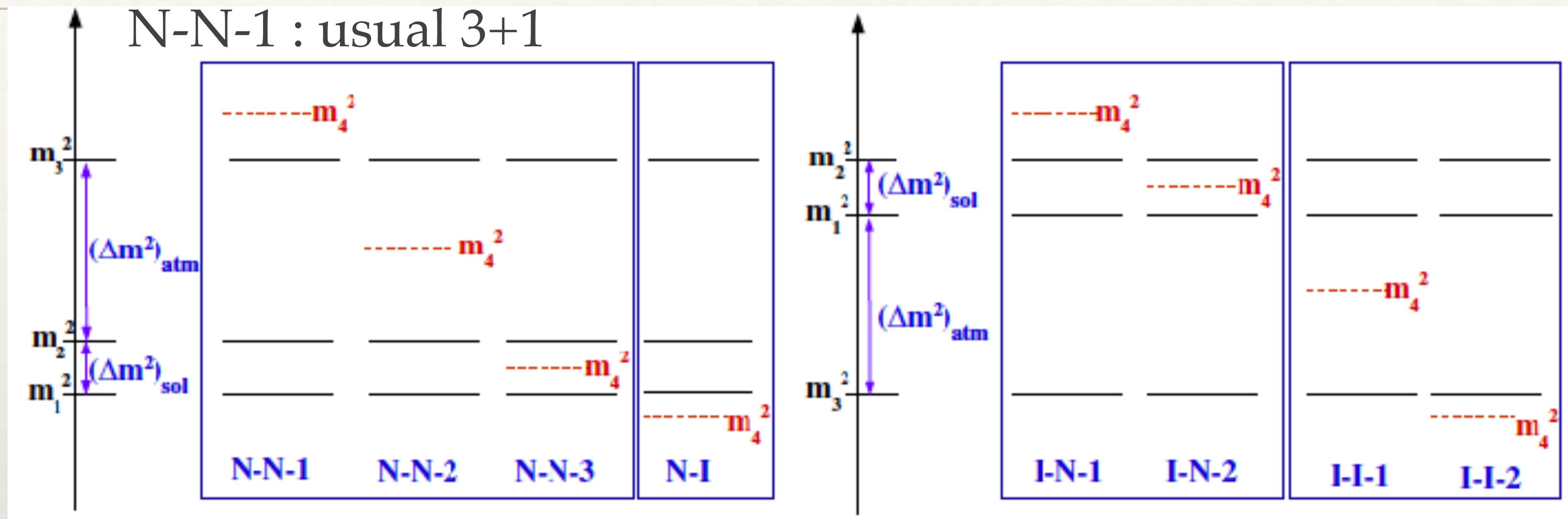


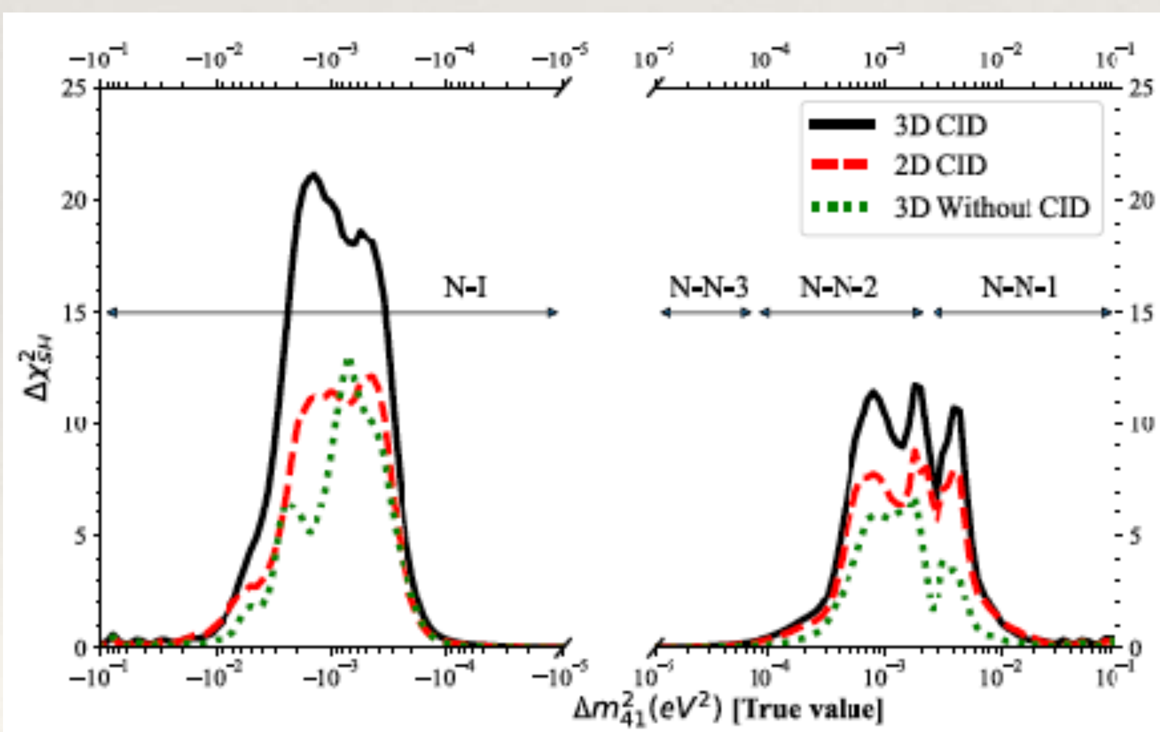
Wide range of baseline and energies available help in probing over a large range of $\Delta m^2{}_{41}$

JHEP 08 (2018) 022, (T. Thakore, M.M. Devi, S.K. Agarwalla, A. Dighe)

Also , Behera, Ghosh, Choubey, Datar et al. EPJC (2017) 5, 307

Mass spectrum of Sterile neutrinos



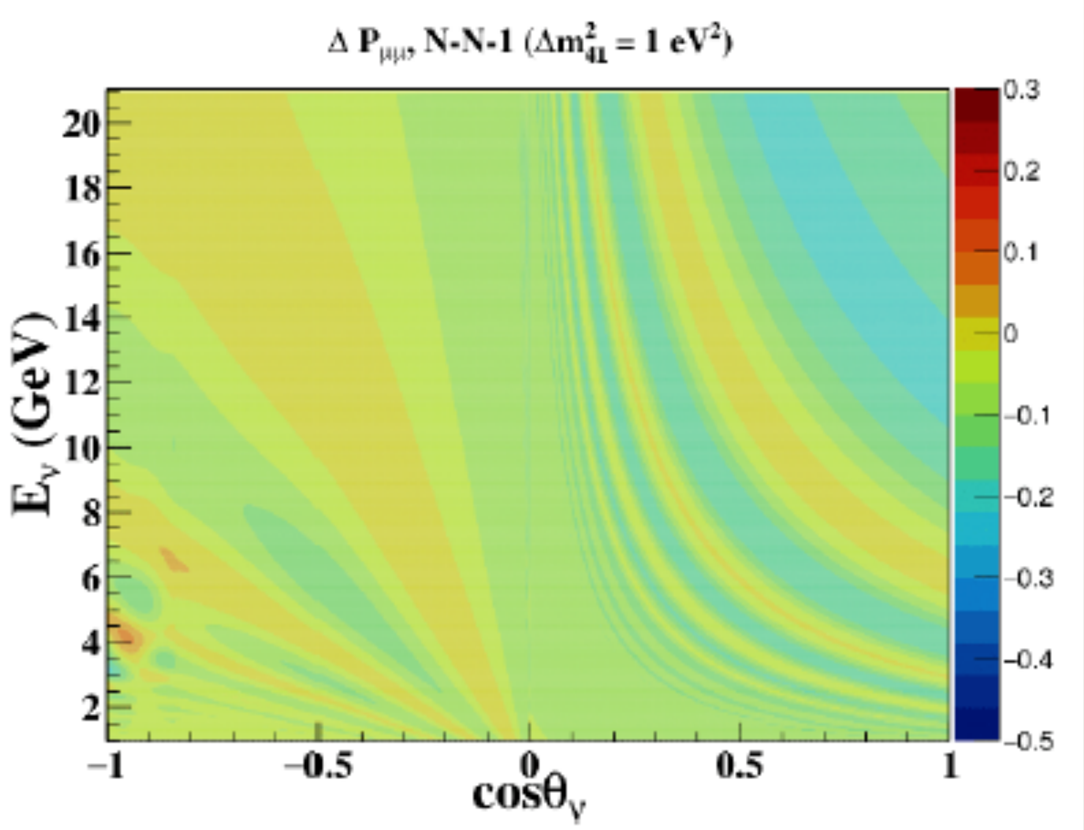


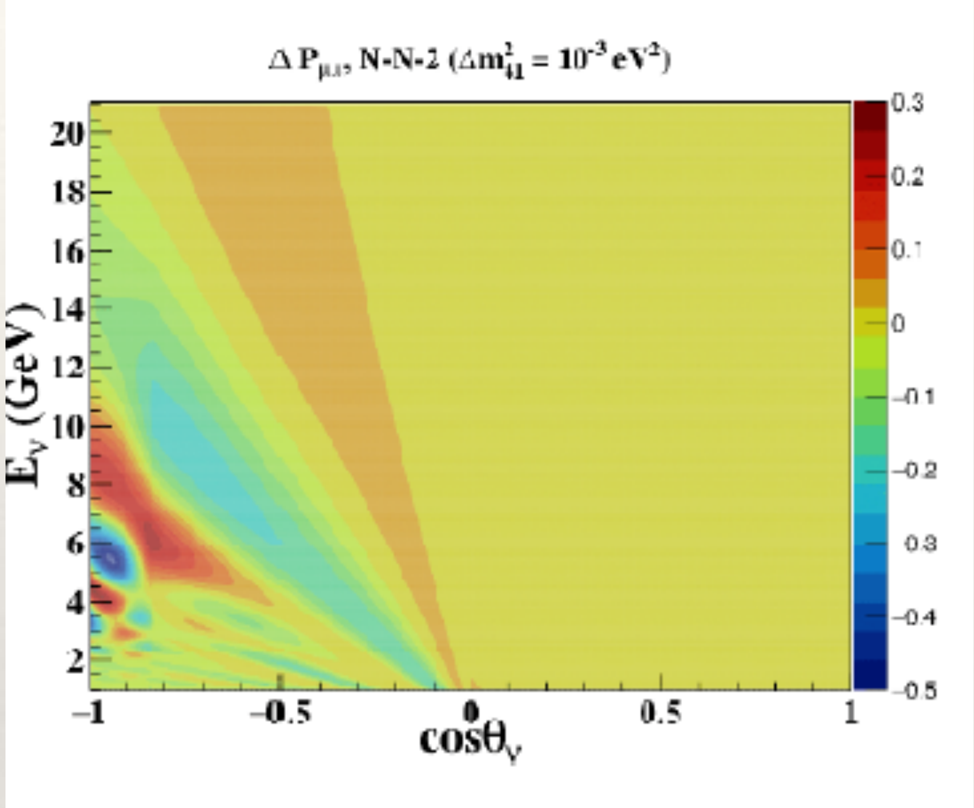
Enhanced sensitivity with Charge-ID

Sensitivity to earth matter effect helps in determination of mass hierarchy presence of sterile neutrino

Thakore, Devi, Agarwalla, Dighe, arXiv:1804.09613 [hep-ph] (INO Collaboration)

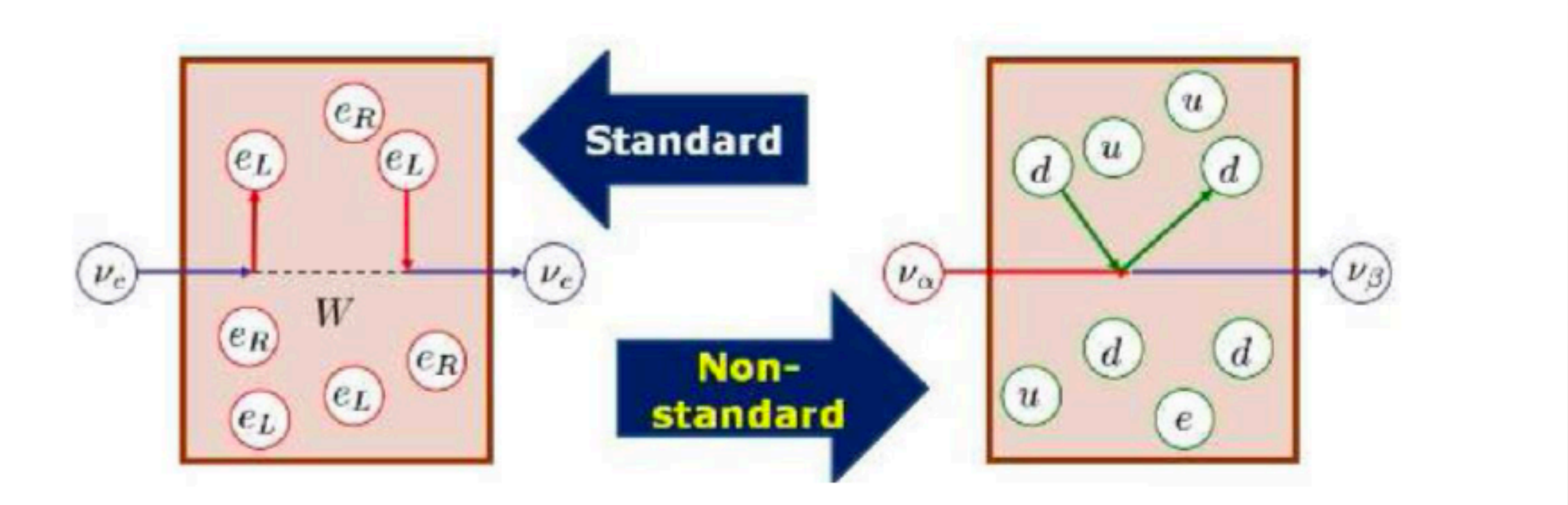
Matter effect





$$\Delta P_{\mu\mu} \equiv P_{\mu\mu}\ (4\mathrm{f})\ - P_{\mu\mu}\ (3\mathrm{f})$$

Non-standard interactions



$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{ff'C} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f'\right)$$

$\varepsilon_{\alpha\beta}^{ff'C}$ are NSI parameters, $\alpha, \beta = e, \mu, \tau$, $f, f' = e, u, d$ and $C = L, R$.

$f \neq f'$ ➡ Charged Current NSI

$f = f'$ ➡ Neutral Current NSI

Non-standard interactions

Standard-NC interaction

$$\nu_\alpha + f \to \nu_\alpha + f$$

Non-Standard NC interaction

$$\nu_\alpha + f \to \nu_\beta + f$$

$$\mathcal{L} = -G^{\alpha\beta}\epsilon^f_{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta\bar{f}\gamma_\mu f$$

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d}\frac{N_f}{N_e}\epsilon^f_{\alpha\beta}$$

$$H = \frac{1}{2E}\left[U\mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U^\dagger + V\right],$$

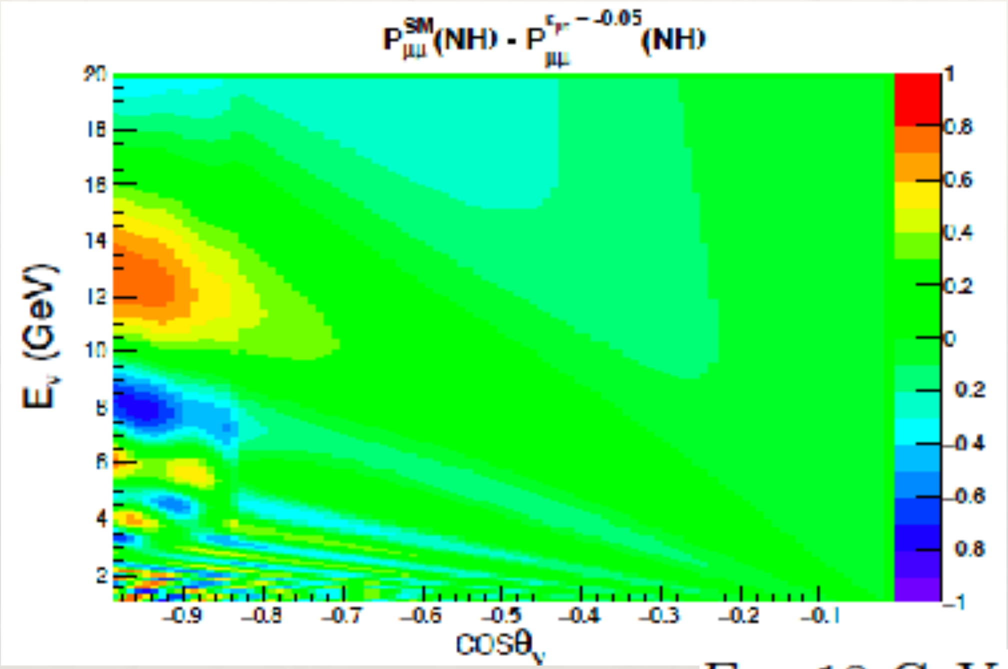
$V \Rightarrow$ matter potential in presence of NSI,

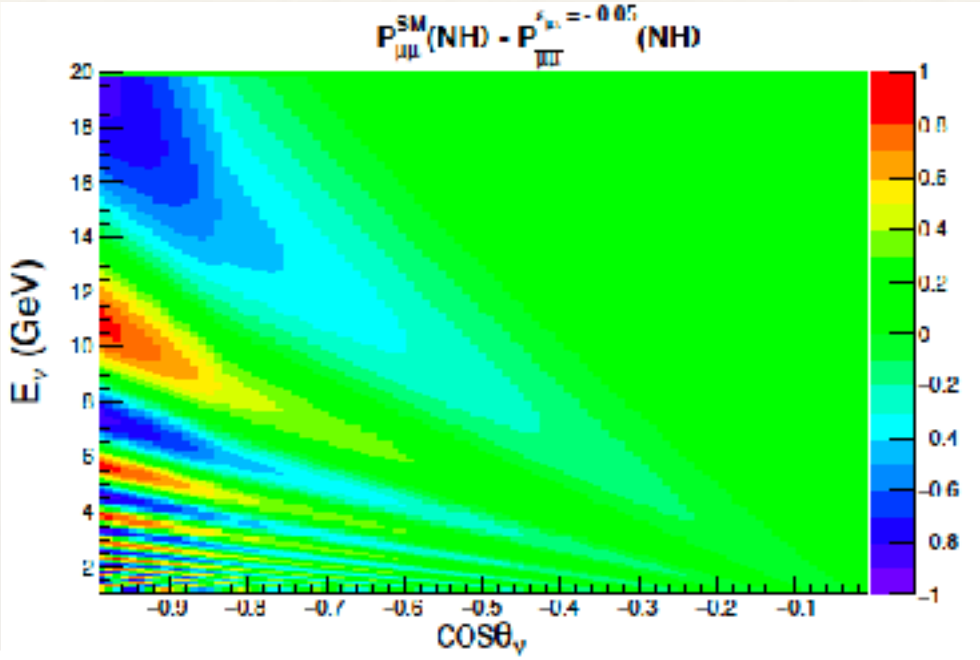
$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}.$$

Here, $A \equiv 2\sqrt{2}G_F N_e E$ and $\epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C}\epsilon^{fC}_{\alpha\beta}\frac{N_f}{N_e}$

Neutrino Propagation in matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\\ \nu_\tau(t)\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + 2\sqrt{2}G_F N_e E\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & \varepsilon_{\mu\tau}\\ 0 & \varepsilon_{\mu\tau} & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$





$E = 18$ GeV and $L = 11500$ km

$P^{\rm diff}_{\mu\mu}(\varepsilon_{\mu\tau} = -0.05) = P^{\rm diff}_{\bar{\mu}\bar{\mu}}(\varepsilon_{\mu\tau} = 0.05)$

~ 0.06

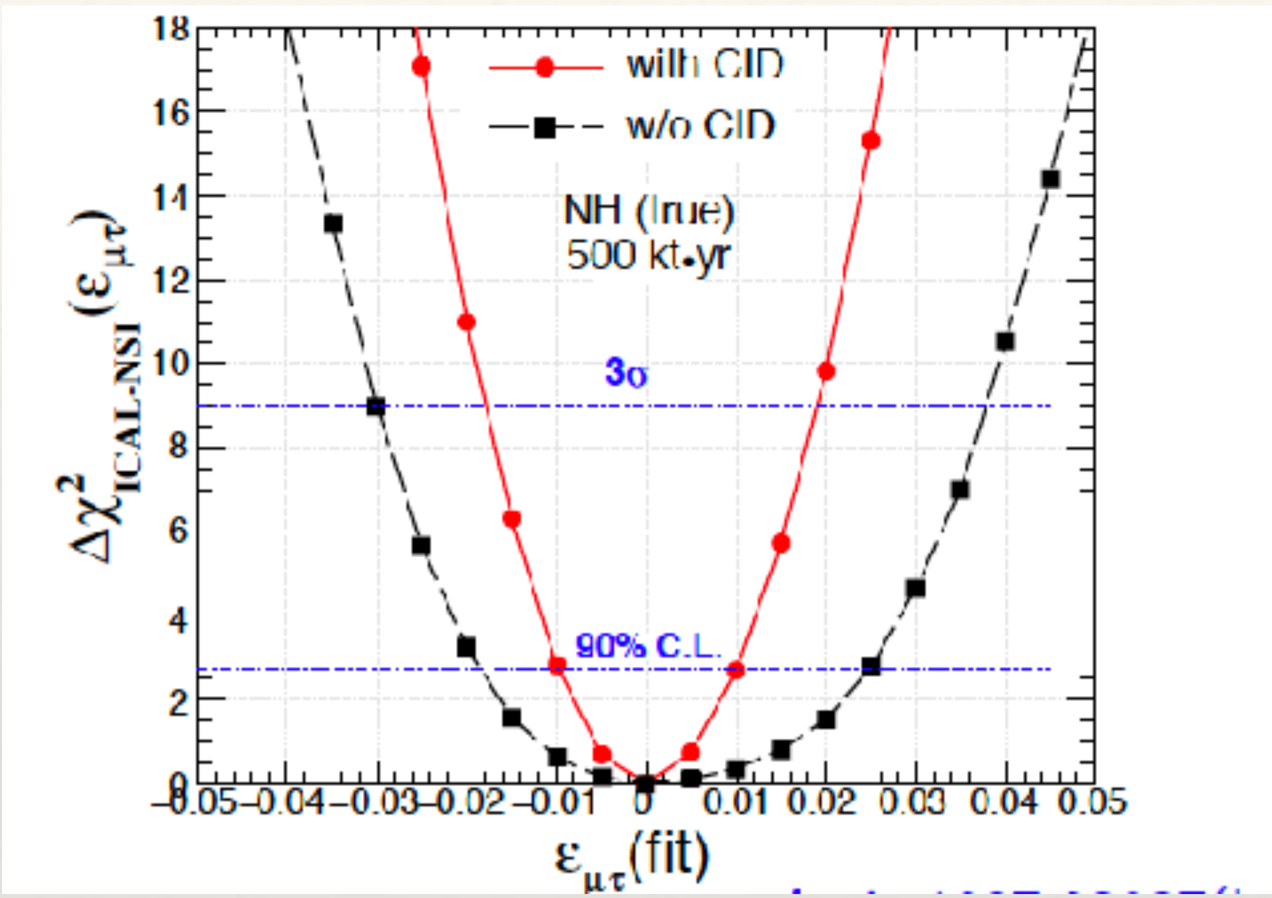
$P^{\rm diff}_{\mu\mu}(\varepsilon_{\mu\tau} = 0.05) = P^{\rm diff}_{\bar{\mu}\bar{\mu}}(\varepsilon_{\mu\tau} = -0.05)$

~ -0.7

Eur.Phys.J.C 80 (2020) 6, 533 (A.Khatun, S.S. Chatterjee, T. Thakore, S.K. Agarwalla)

Charge ID can help in determination of sign of $\varepsilon_{\mu\tau}$

NSI@ICAL



Charge-id improves the sensitivity

Hierarchy Sensitivity worsens in presence of NSI

with CID : $-0.01 < \varepsilon_{\mu\tau} < 0.011$

Eur.Phys.J.C 80 (2020) 6, 533 (A.Khatun, S.S. Chatterjee, T. Thakore, S.K. Agarwalla)

Also S. Choubey, A. Ghosh, T. Ohlsson, and D. Tiwari ,JHEP12(2015) 126 (without Hadrons)

$6.7 \times 10^{3} < \varepsilon_{\mu\tau} < 8.1 \times 10^{3}$

$-0.0201 < \varepsilon_{\mu\tau} < 0.0243$

IceCube Collaboration, M. Aartsen et al

Phys. Rev. **D97** (2018), no. 7 072009

Long-Range Force

Anomaly Free U(1) Symmetry : $Q = a_0(B-L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$

(i) $L_e - L_\mu$ (ii) $(L_e - L_\tau)$ (iii) $(L_\mu - L_\tau)$

Can be gauged in anomaly free way in SM

Very light gauge bosons with range corresponding to Sun-Earth distance

$$V_{e\mu/e\tau}(R_{SE}) = \alpha_{e\mu/e\tau} \frac{N_e^{\odot}}{R_{SE}} \approx 1.3 \times 10^{-14}\,\mathrm{eV} \left(\frac{\alpha_{e\mu/e\tau}}{10^{-53}}\right),$$

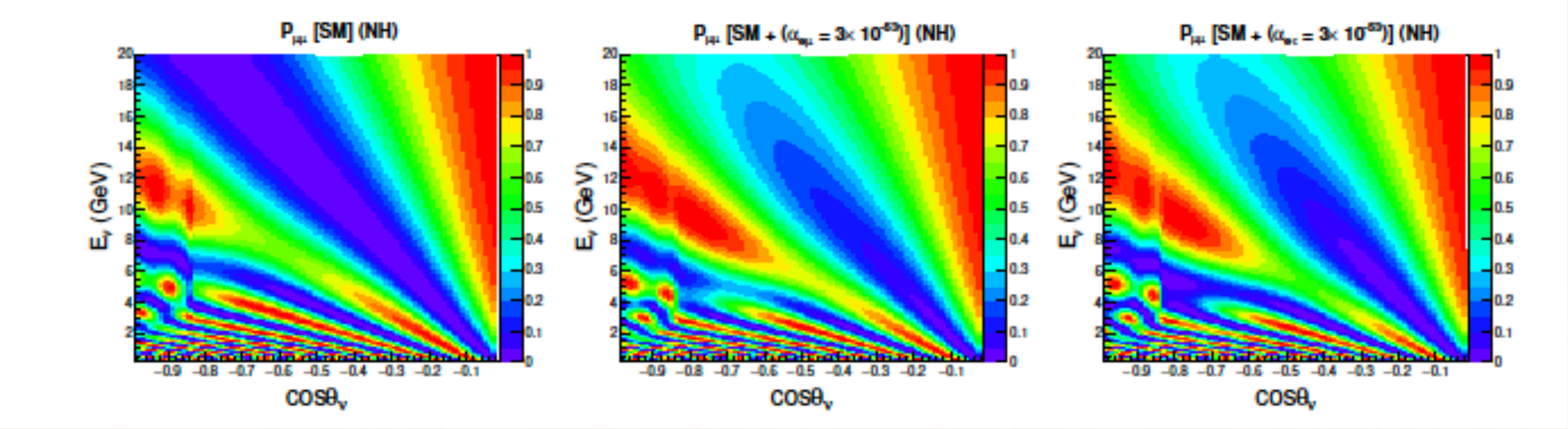
Neutrino propagation in matter

The Effective Hamiltonian in presence matter and of LRF is

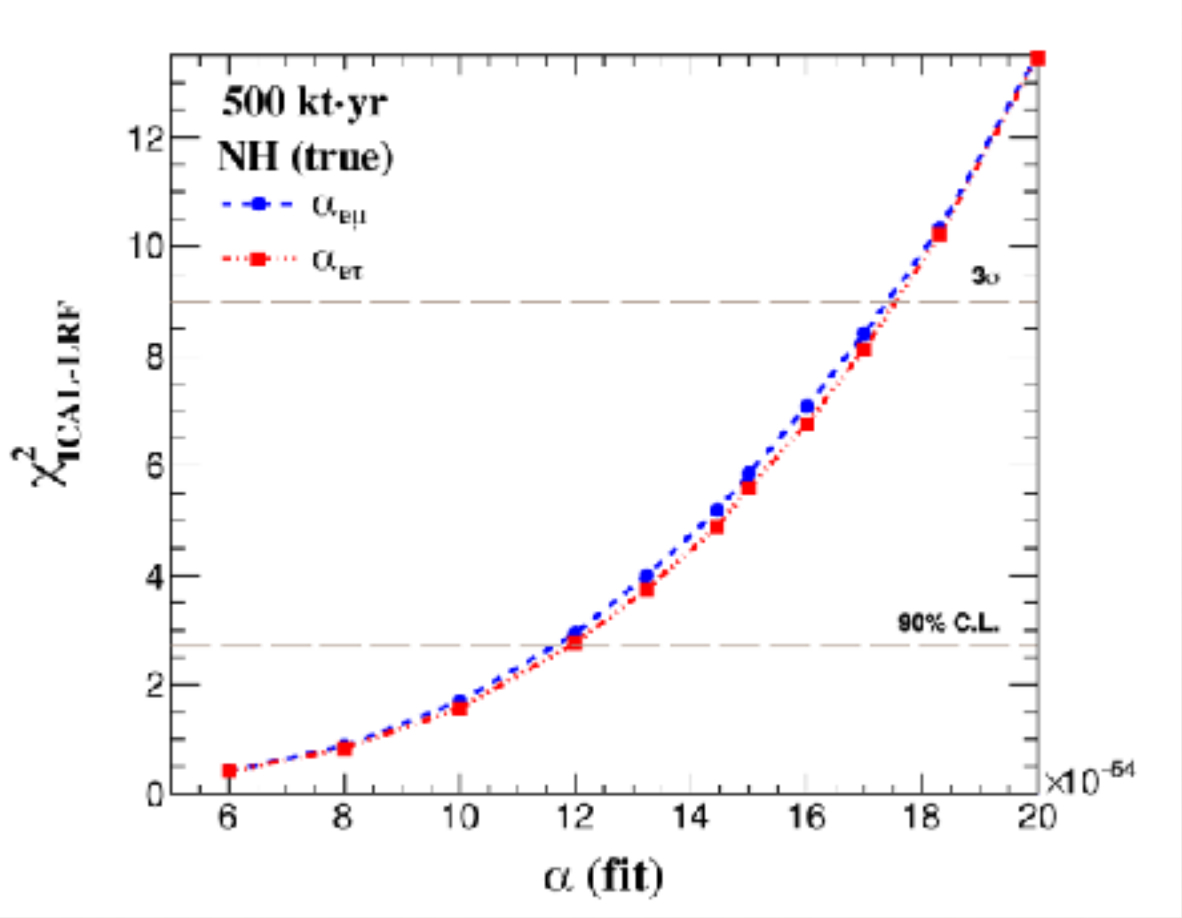
$$H_f = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} U^\dagger + \begin{bmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} \zeta & 0 & 0 \\ 0 & \xi & 0 \\ 0 & 0 & \eta \end{bmatrix} .$$

U : PMNS matrix, $\Delta_{ij} = \Delta m^2_{ij}/2E$, V_{CC} : Matter induced potential

ζ = -ξ = $V_{c\mu}$, η = 0 for $L_e - L_\mu$ case. ζ = -η = $V_{c\tau}$, ξ = 0 for $L_e - L_\tau$ case.



Results



JHEP 04 (2018) 023 (A. Khatun, T. Thakore, S.K. Agarwalla)

From ICAL: $\boldsymbol{\alpha}_{e\mu/e\tau} < 1.2 \times 10^{-53}$ at 90% C.L. using 500 kt.yr exposure

Existing bounds:

1. $\alpha_{e\mu} < 5.5 \times 10^{-52}$ and $\alpha_{e\tau} < 6.4 \times 10^{-52}$ at 90% C.L from SK. arXiv:hep-ph/0310210
2. $\alpha_{e\tau} < 2.5 \times 10^{-53}$ at 3σ C.L. from Solar and KamLAND data. arXiv:hep-ph/0610263

CPT Violation

$$\mathcal{L}_\nu^{\mathrm{CPTV}} = \bar{\nu}_L^\alpha\, b_\mu^{\alpha\beta}\, \gamma^\mu\, \nu_L^\beta$$

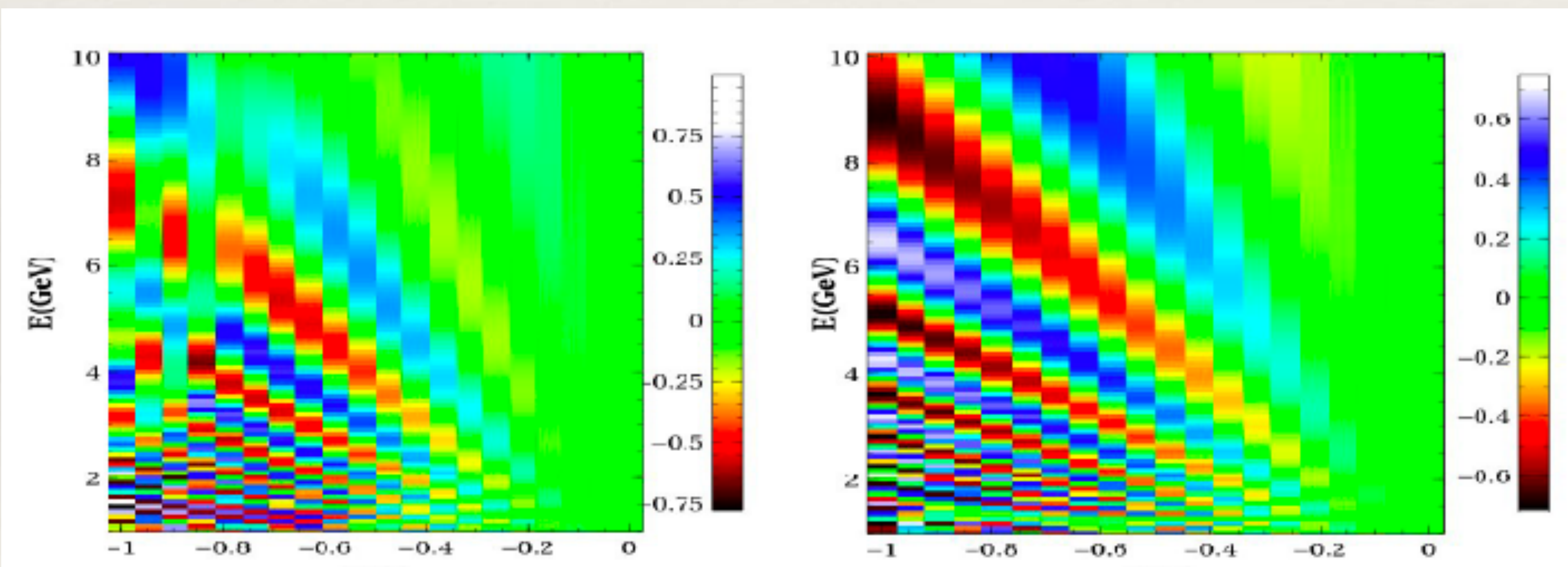
$$H \equiv \frac{MM^\dagger}{2p} + b$$

$$H_f = \frac{1}{2E}.U_0.D(0, \Delta m_{21}^2, \Delta m_{31}^2).U_0^\dagger + U_b.D_b(0, \delta b_{21}, \delta b_{31}).U_b^\dagger + D_m(V_e, 0, 0)$$

$$\Delta P = (P_{\nu_\mu \nu_\mu}^{U_b \neq 0} - P_{\nu_\mu \nu_\mu}^{U_b = 0})$$

$$\delta b_{i1} \equiv b_i - b_1 \text{ for } i = 2, 3,$$

$$\delta b_{31} = 3 \times 10^{-23} \text{ GeV}$$



CPTV

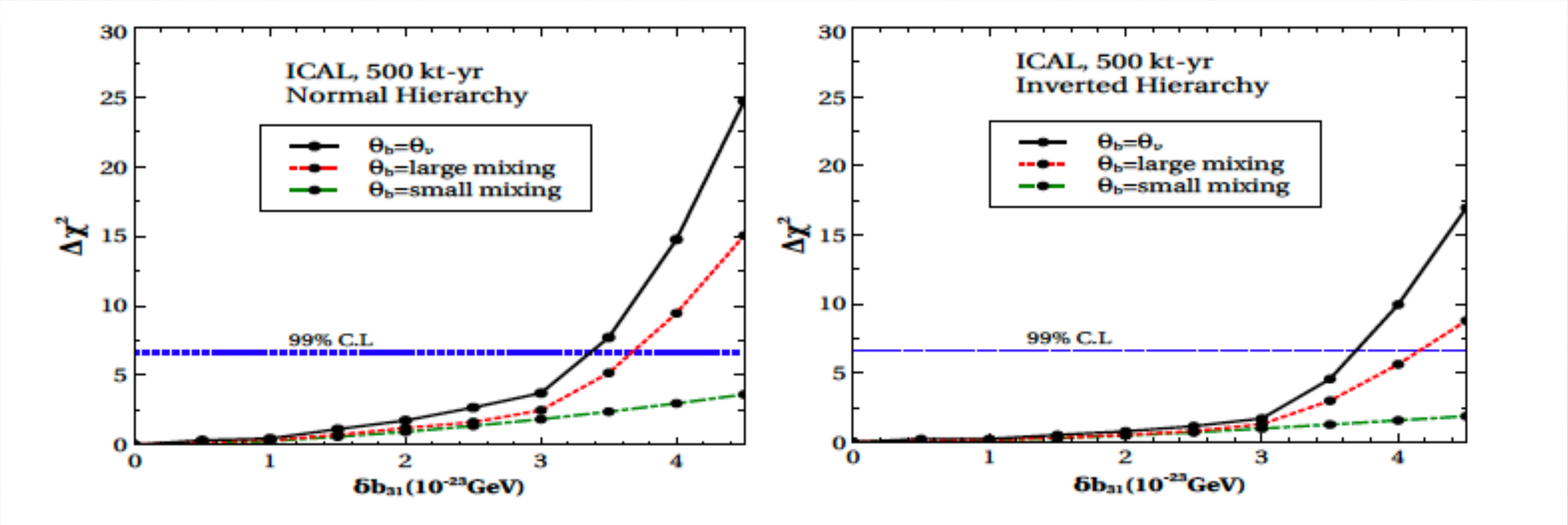
$$\sin\left(\frac{\Delta m^2 L}{2E}\right) \sin(\delta b L)$$

Higher at larger baseline

Intrinsic CPTV sensitivity more for IH for neutrinos

Results

Known Hierarchy

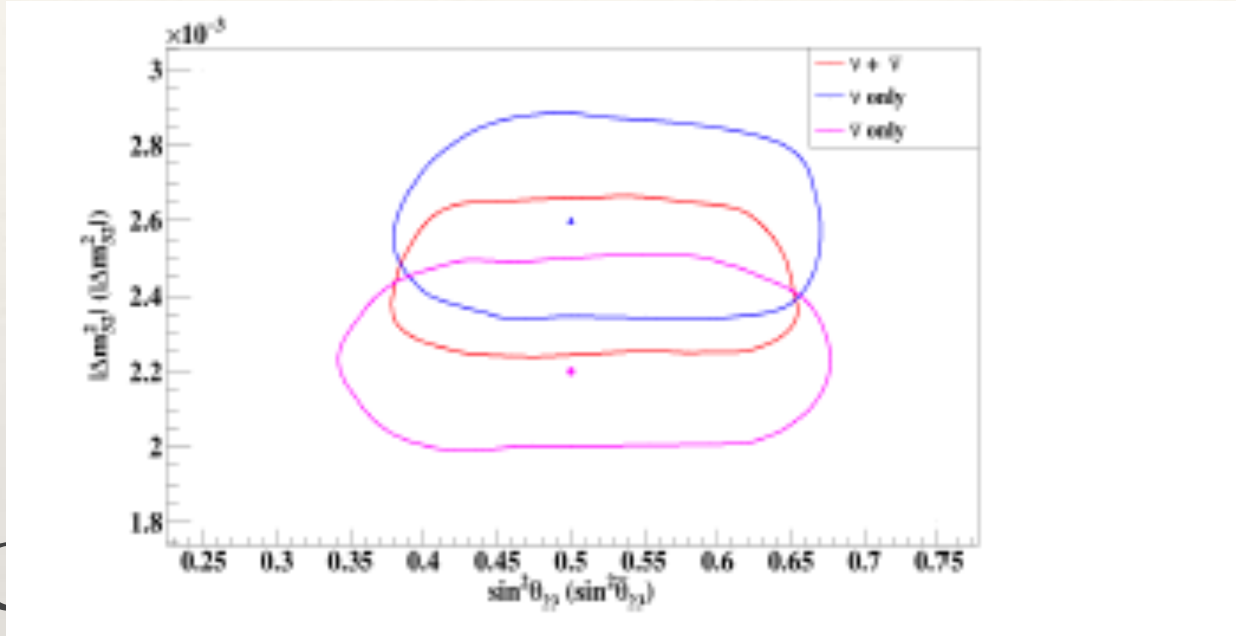


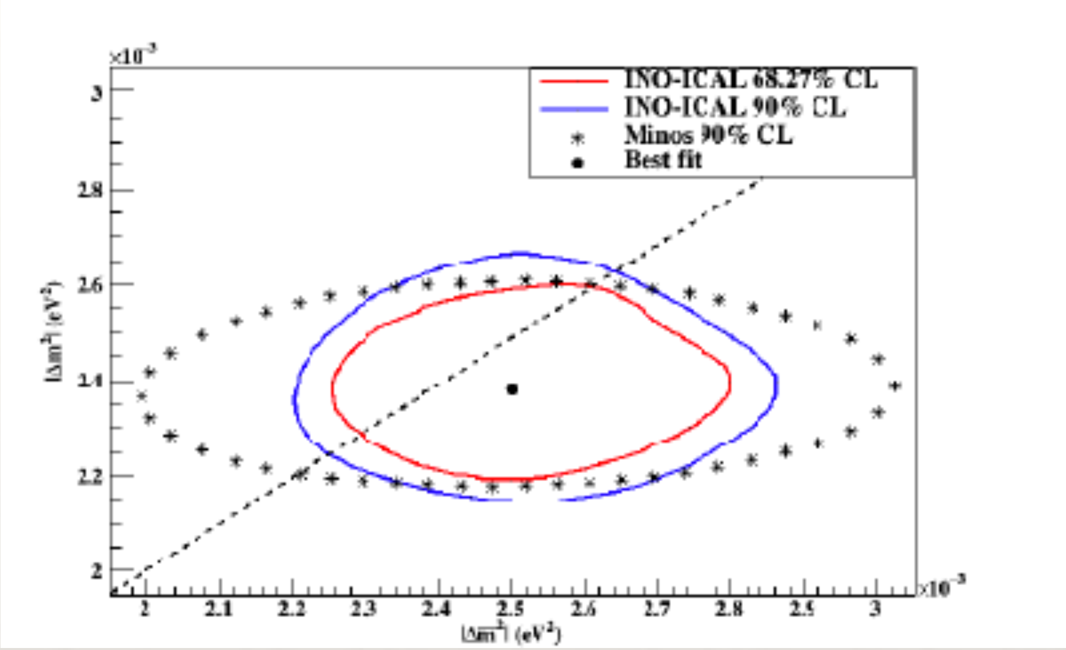
Best bounds are obtained when CPTV angle same as vacuum mixing angle

δb_{31} of the order of 4×10^{-23} GeV **, for not too small mixing angle**

Chatterjee, Gandhi, Singh, JHEP, 06 (2014) 045

Neutrino vs Antineutrino Parameters





Considered different true values of neutrino and antineutrino parameters and found out the capability of disfavouring null hypothesis

Kaur, Dar, Kumar, Naimuddin, Phys. Rev. D (2017) 9, 093005 , J.Phys. G (2019) , 46, 65001

Neutrino Decay

Invisible Neutrino Decay $\nu_3 \to \nu_s + J$

$$\begin{pmatrix}\nu_\alpha\\ \nu_s\end{pmatrix} = \begin{pmatrix}U & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\nu_i\\ \nu_4\end{pmatrix}$$

$$i\frac{d\tilde{\nu}}{dt} = \frac{1}{2E}\left[U\mathbb{M}^2U^\dagger + \mathbb{A}_{CC}\right]\tilde{\nu},$$

$$\mathbb{M}^2 = \begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31} - i\alpha_3\end{pmatrix}, \quad \text{and} \quad \mathbb{A}_{CC} = \begin{pmatrix}A_{cc} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix},$$

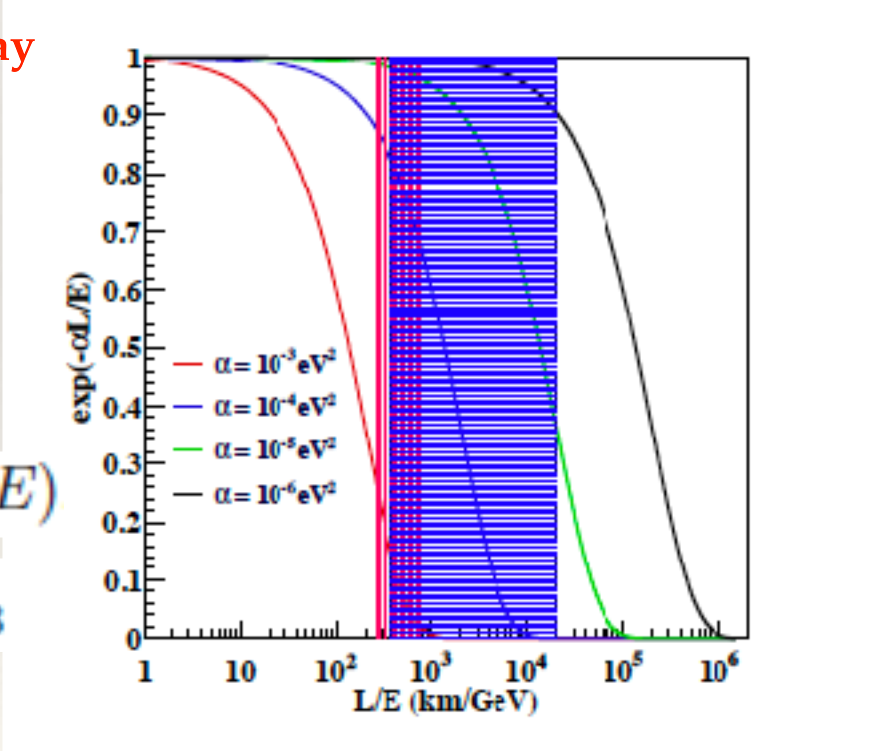
$$A_{cc} = 2\sqrt{2}G_F n_e E = 7.63 \times 10^{-5}\text{eV}^2\ \rho(\text{gm/cc})\ E(\text{GeV}),$$

No decay

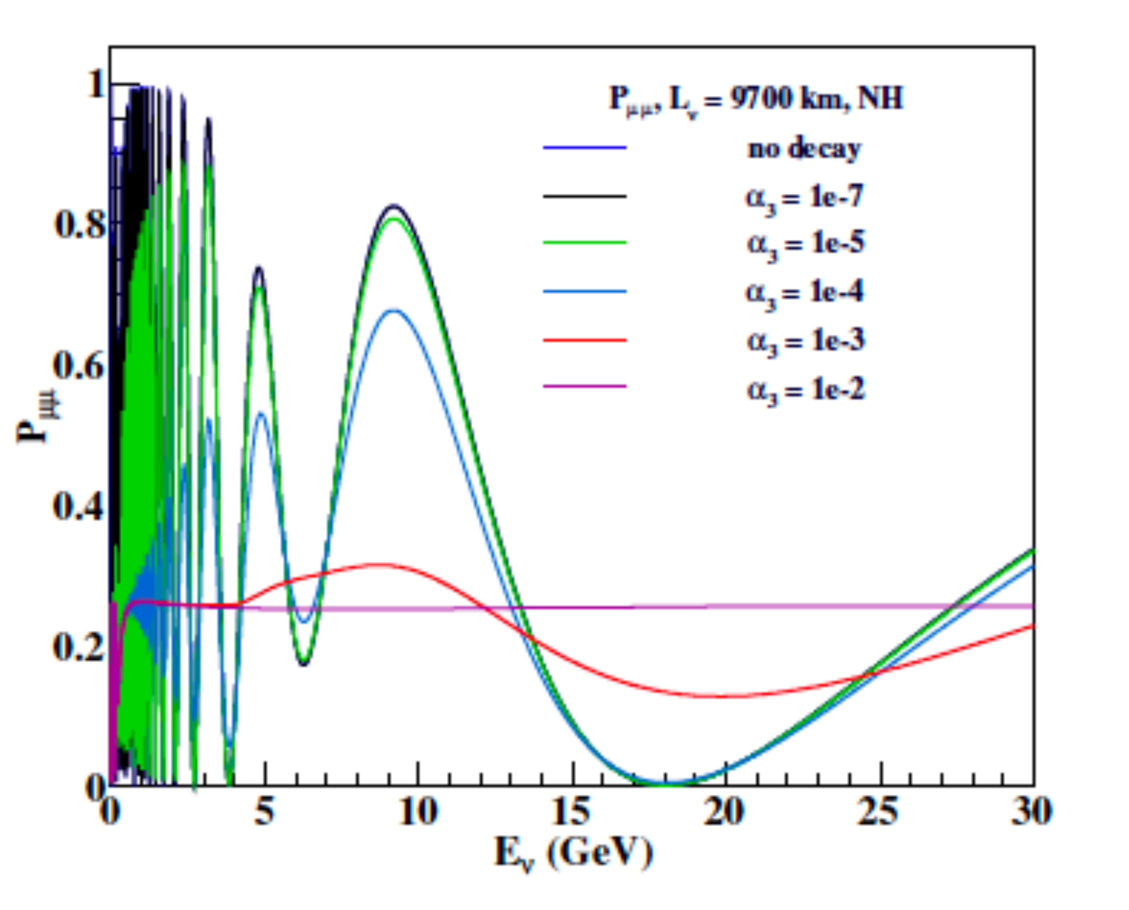
Decay

$\exp\left(-\alpha L/E\right)$

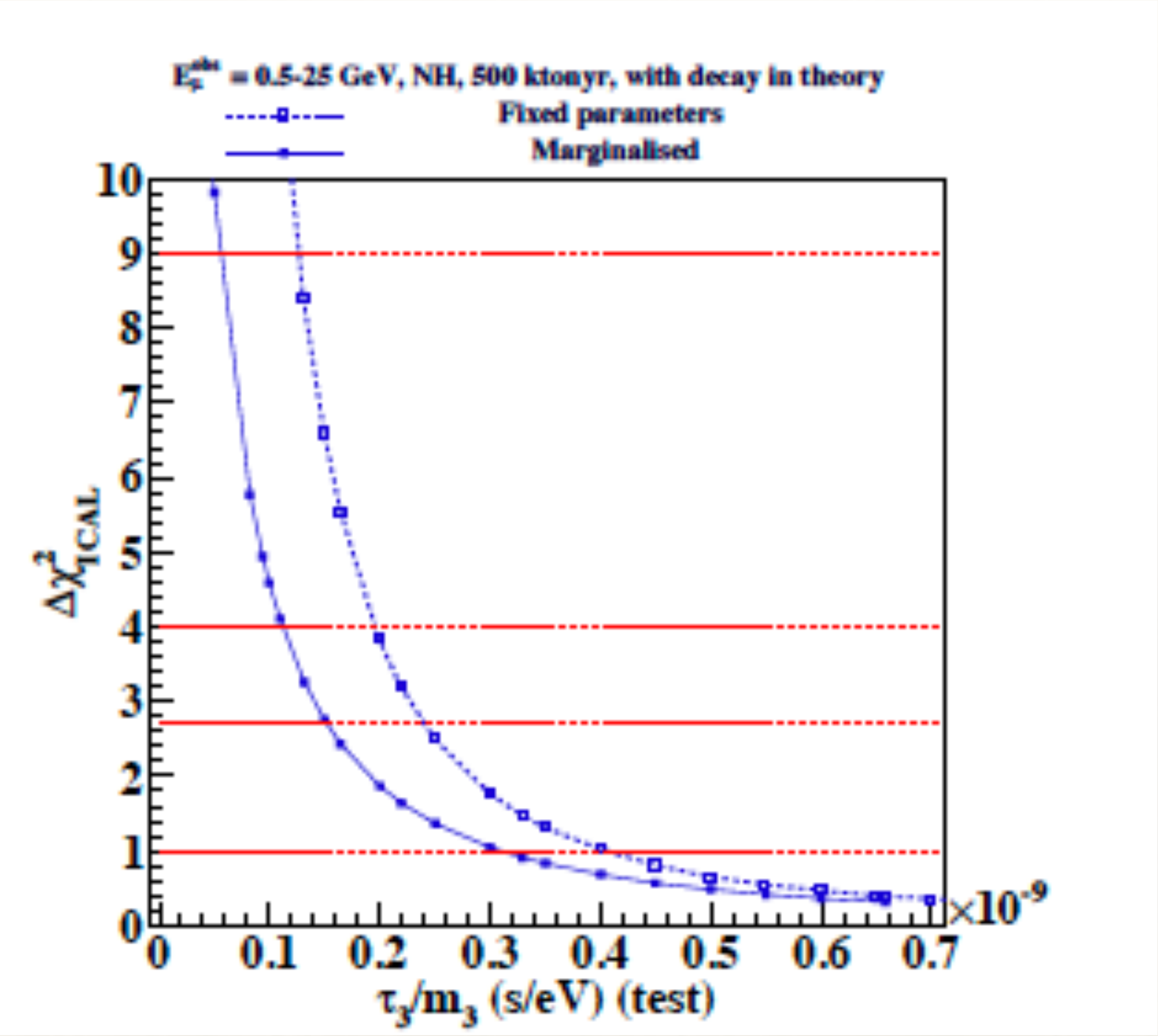
$\alpha_3 = m_3/\tau_3$



Complete decay



Results



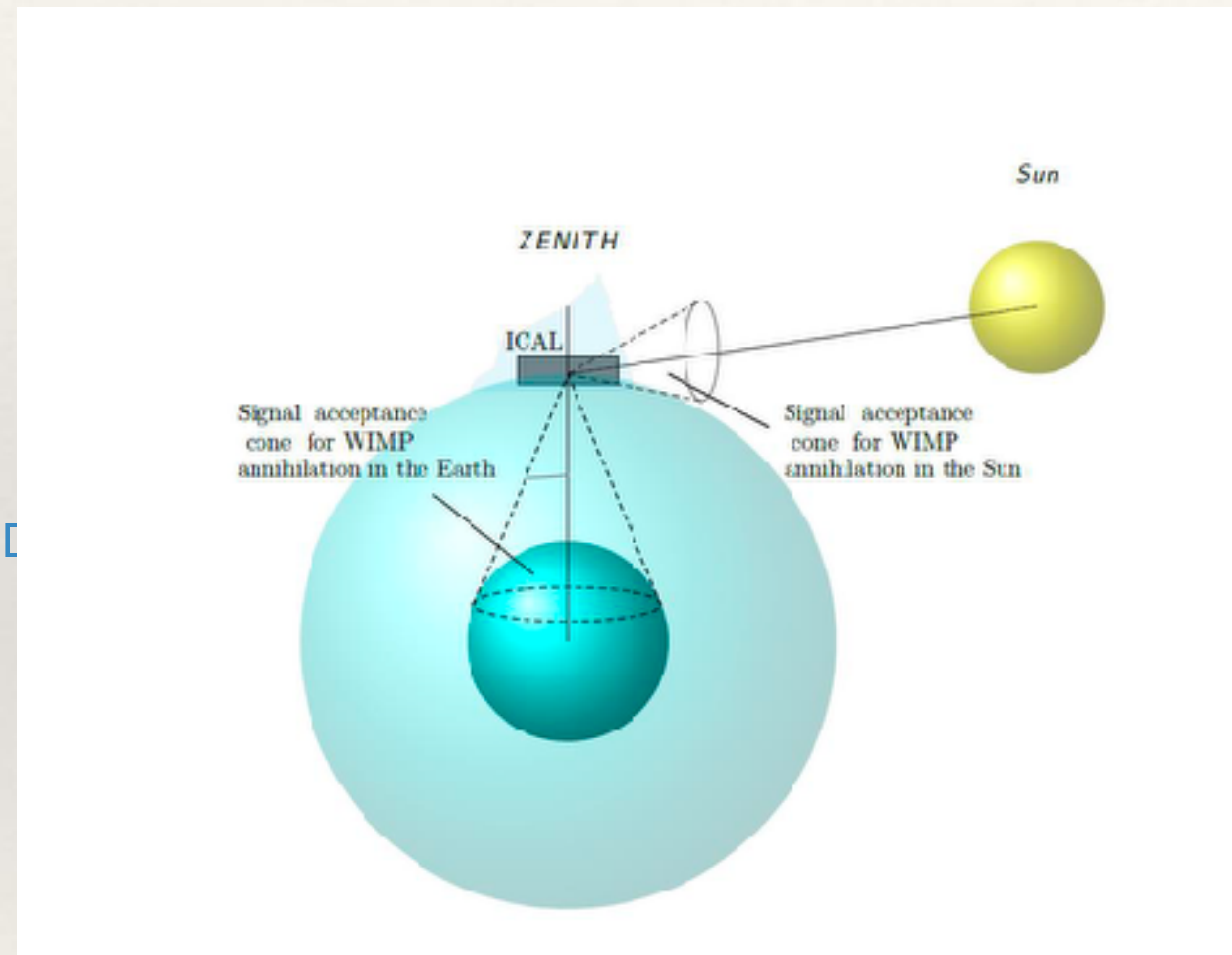
- ICAL@INO (500 kt·yr exposure):
  $\tau_3/m_3 > 1.51 \times 10^{-10}$ s/eV at 90% C.L.
  Choubey, Goswami, Gupta, Lakshmi, Thakore
  PRD 97 (2018) 3, 033005

Super-Kamiokande + K2K + MINOS:
$\tau_3/m_3 > 2.9 \times 10^{-10}$ s/eV at 90% C.L.
Gonzalez-Garcia, Maltoni, PLB 663 (2008) 405

- T2K + MINOS:
  $\tau_3/m_3 > 2.8 \times 10^{-12}$ s/eV at 90% C.L.
  Gomes, Gomes, Peres, PLB 740 (2015) 345

T2K + NOvA:
$\tau_3/m_3 > 1.5 \times 10^{-12}$ s/eV at 3σ C.L.
Choubey, Dutta, Pramanik, JHEP 08 (2018) 141

Search For WIMP Annihilation Signature



Indirect Detection of

WIMP annihilation in Sun

Sun [JCAP 05 (2018) 006]

WIMP annihilation in centre of Earth

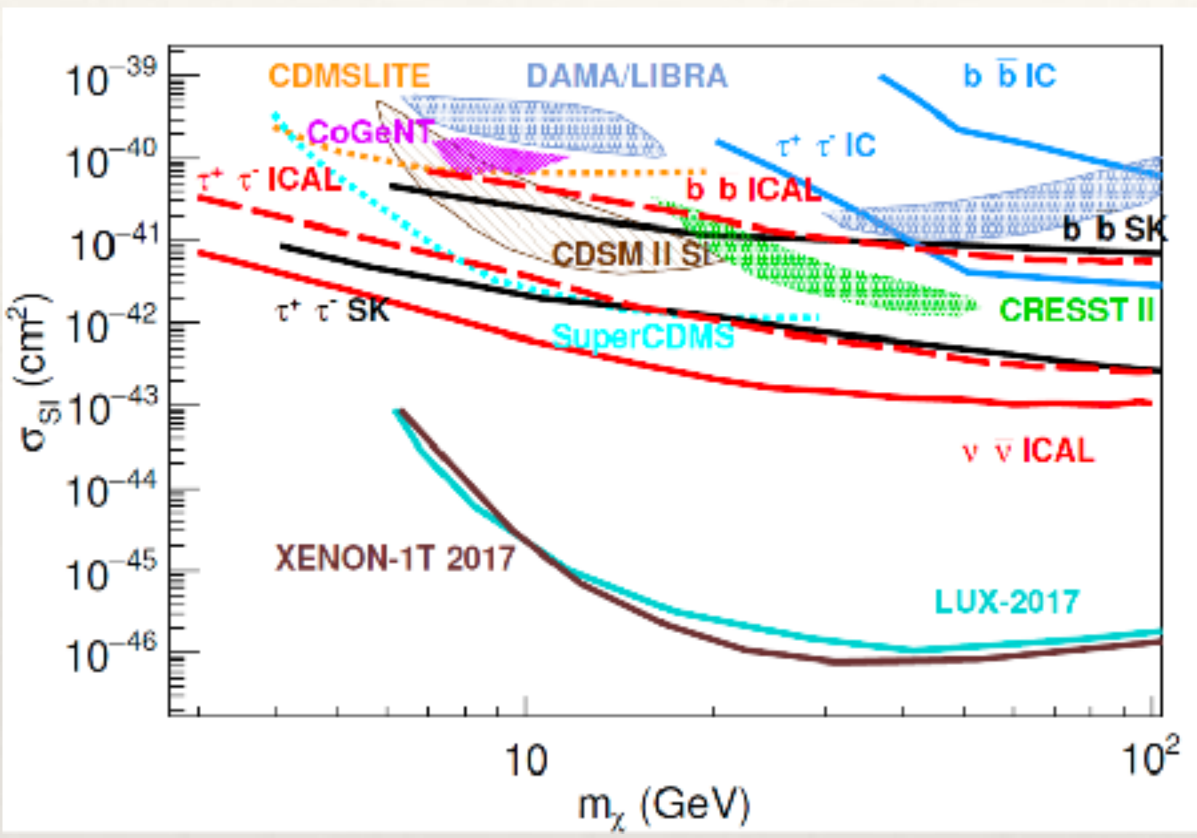
Earth [JHEP 05 (2019) 039]

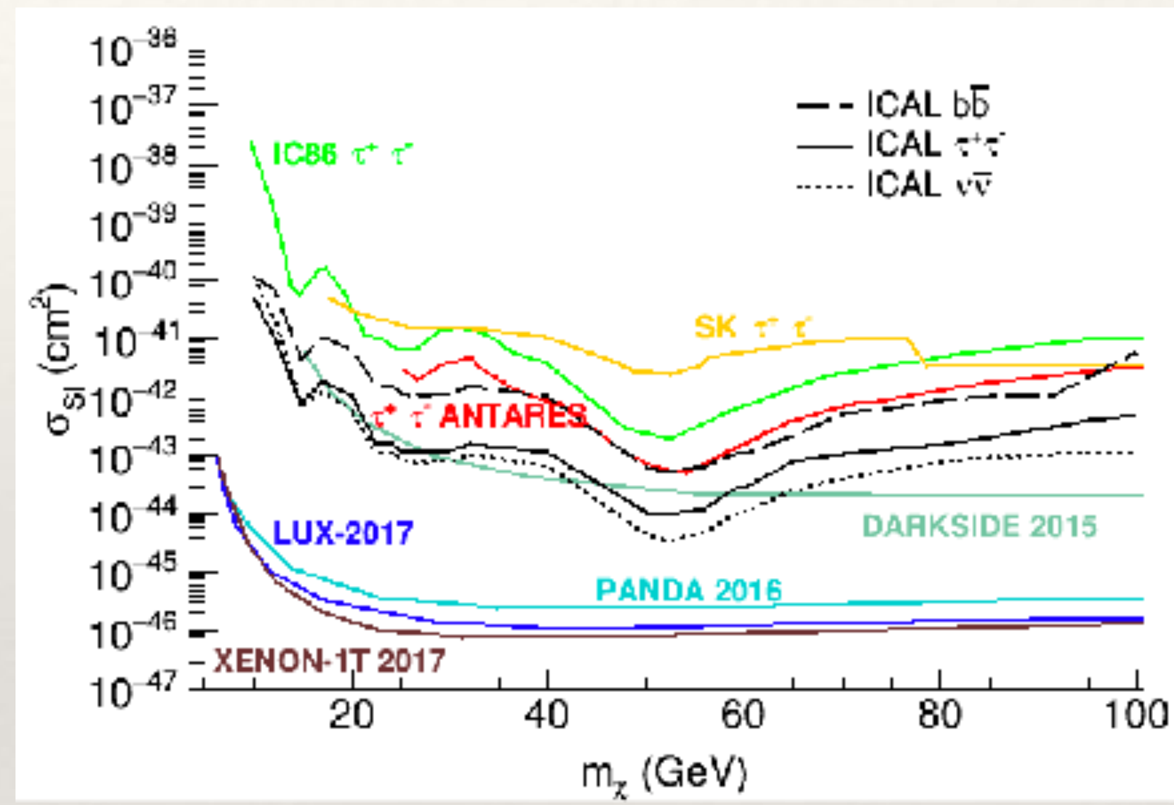
WIMP annihilation in Galactic Centre

Tiwari PhD thesis

D. Tiwari, S. Choubey & A. Ghosh

Results





$$\mathit{WIMPS} \xrightarrow{\mathit{annihilation/decay}} \tau^+\tau^-, b\bar{b}, \text{ other quarks, leptons, bosons etc.} \xrightarrow{\mathit{decay}} \nu\bar{\nu} \text{ fluxes.}$$

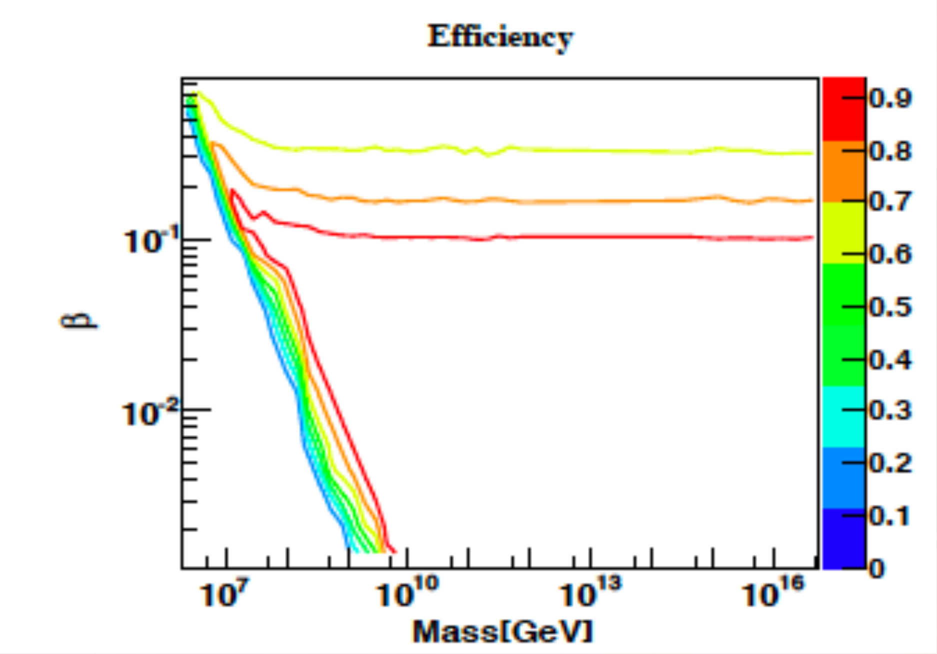
D. Tiwari, S. Choubey & A. Ghosh

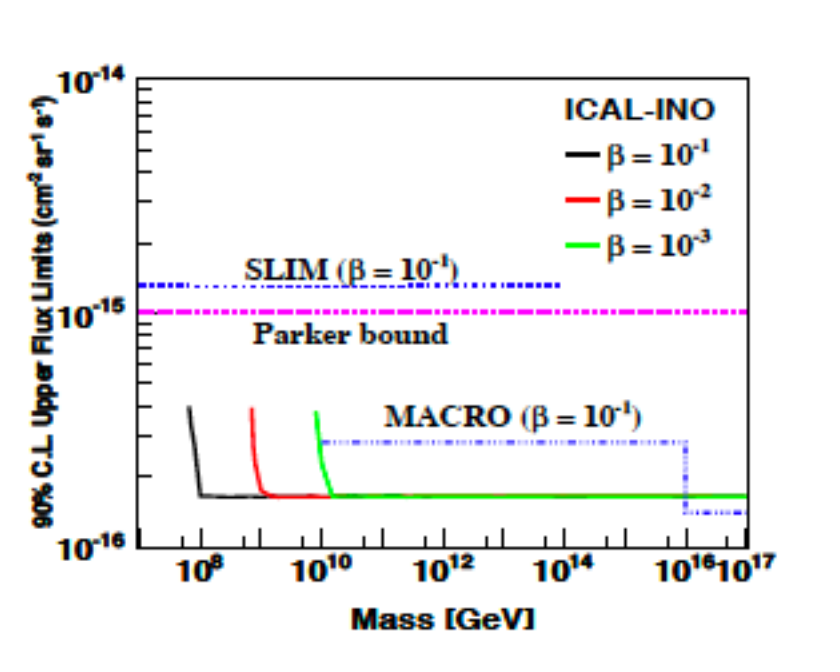
Search for magnetic monopoles

Magnetic Monopoles are predicted in Grand Unified theories

MM solutions of classical EOM in non-abelian gauge theories => $M_{MM} \geq M_X / G,$

Heavier Monopoles entering Earth can penetrate large distances





GEANT 4 Simulation

90% efficiency for $M_{MM} > 10^{12}$ GeV

$10^{-3} < \beta < 0.1$

Dash, Datar, Majumdar, AstroparticlePhysics, 70 (2015) ,33

Concluding Remarks

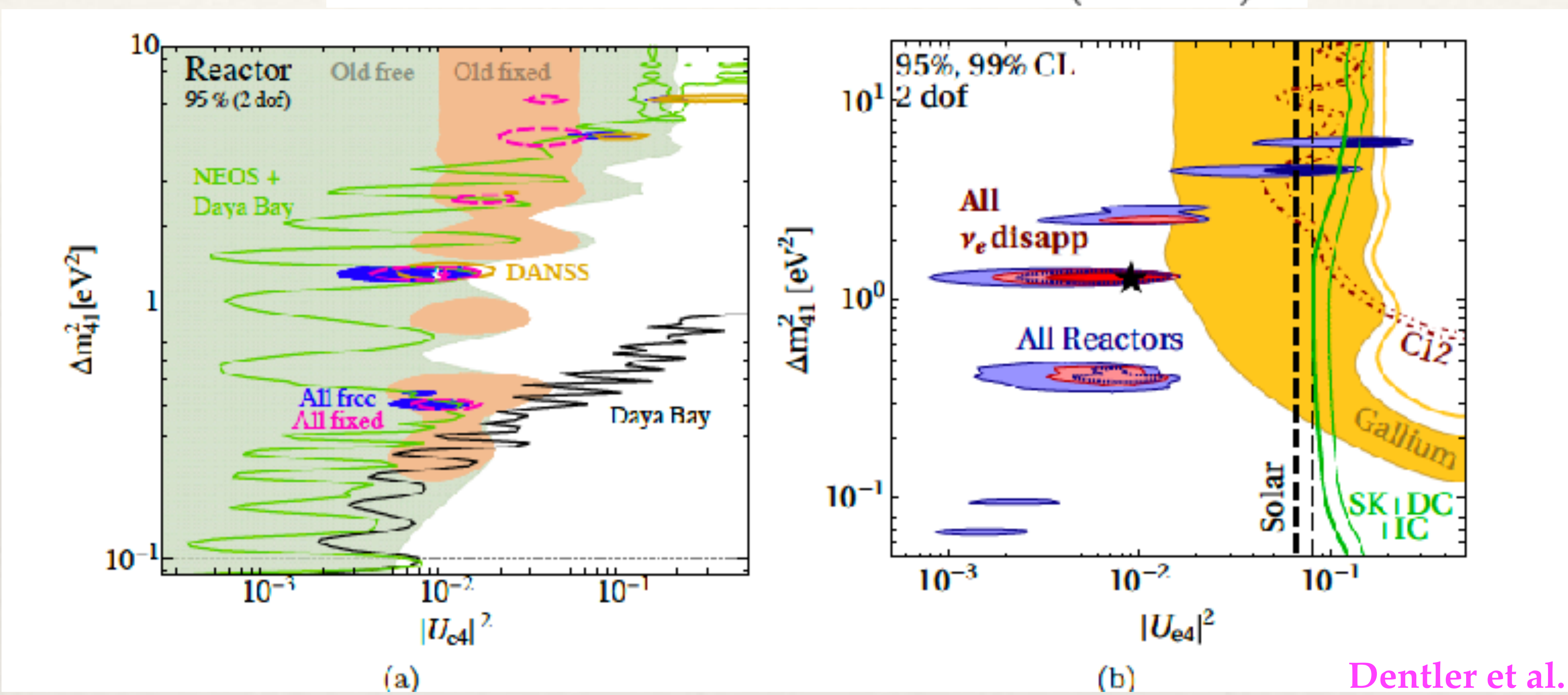
- BSM physics @low energies can be probed in next generation oscillation experiments
- Host of studies on probing BSM physics @ICAL
- Matter effect and hence charge-ID play important rol
- Degeneracies and synergy with LBL experiments

Acknowledgement : Sanjib Agarwalla, Amina Khatun, Deepak Tiwari, Anil Kumar, Sadasiv Sahoo


BACKUP

Bounds from reactor searches

$$P_{\alpha\alpha}^{\rm SBL} = 1 - 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$



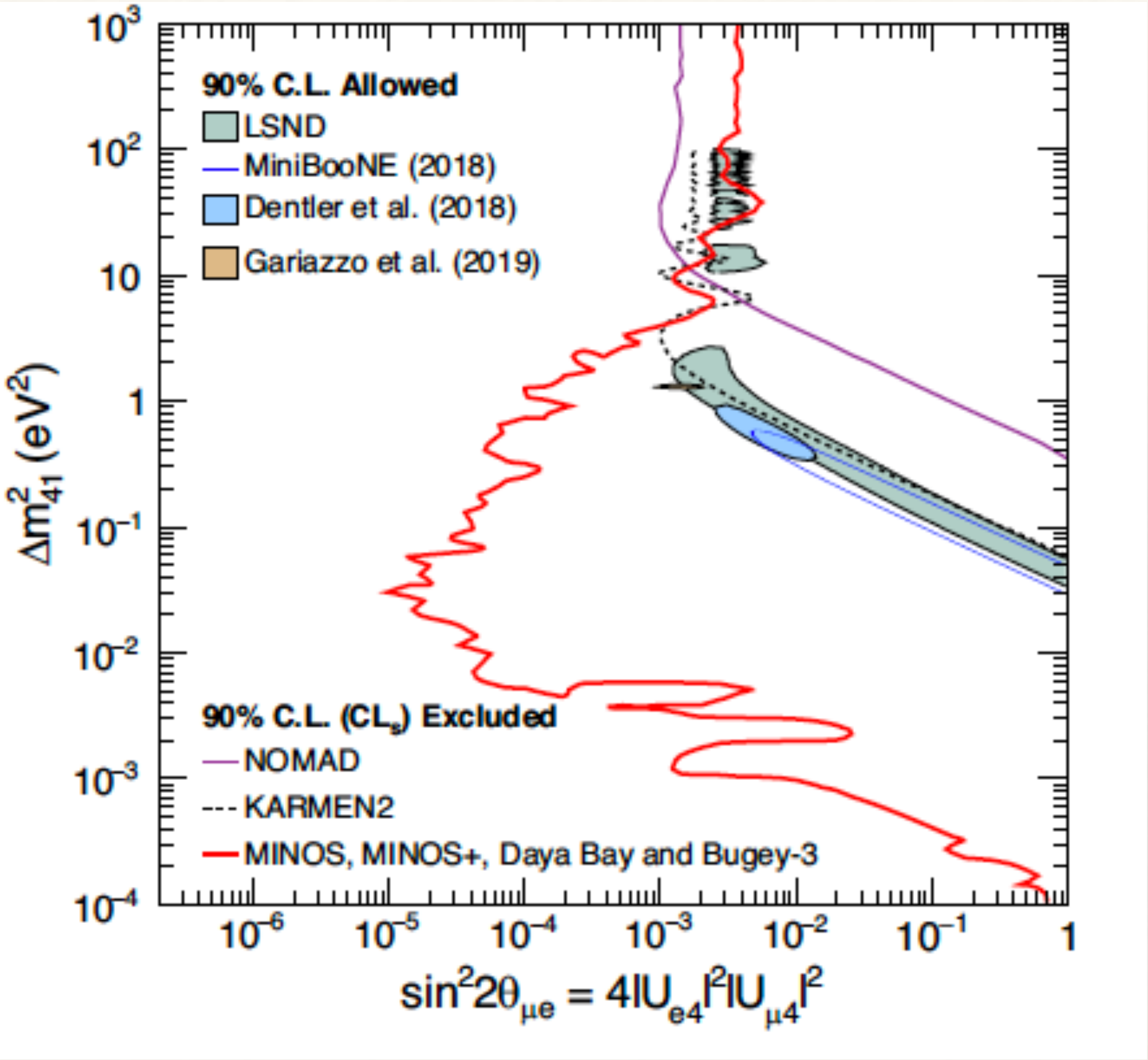
Dentler et al. JHEP 2018

Blue shaded regions allowed by fitting all reactor data with free fluxes

DANSS 2019 results give a lower Δm_{41}^2

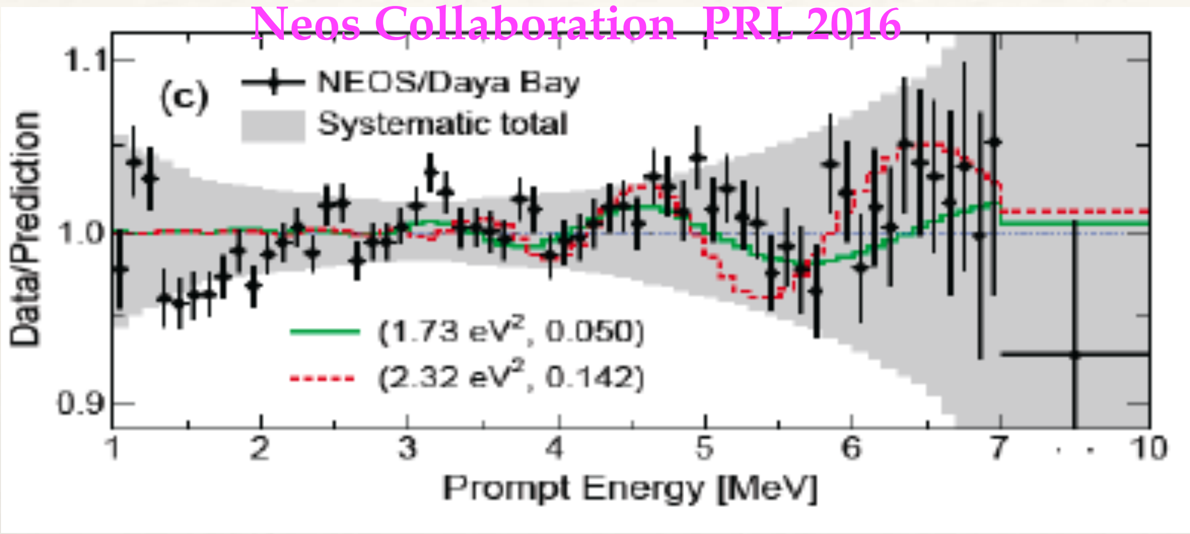
Danilov, talk at EPSHEP 2019
Ternes talk at CERN 2019

Daya Bay +Minos+Minos++Bugey3

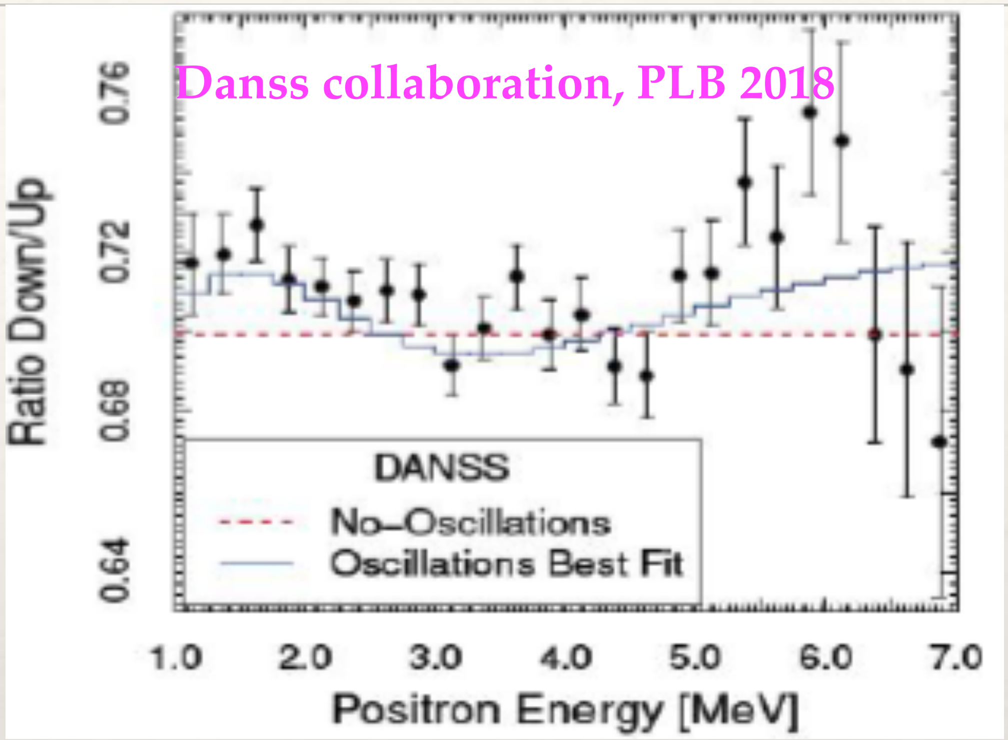


NEOS, DANSS, Neutrino4

Neos Collaboration PRL 2016



Danss collaboration, PLB 2018



Comparison of measured spectra at different baselines

Insensitive to flux calculation uncertainty