Decay of Atmospheric Neutrinos

Sandhya Choubey
Harish-Chandra Research Institute, India
KTH Royal Institute of Technology, Sweden

PANE, ICTP, Trieste, Italy

Neutrino Decay

Non-Radiative Neutrino Decay

Chikashige, Mohapatra, Peccei, PLB 98, (1981)
Gelmini, Roncadelli, PLB 99 (1981)
Gelmini, Valle, PLB 142 (1984)

$$\nu_i \to \nu' + J$$

Acker, Pakvasa, Pantaleone, PRD 45 (1992)

$$\tau_i = \frac{16\pi}{g_{dk}^2} \frac{m_d^3}{\Delta m^2 (m_i + m_d)^2}$$

$$g_{dk}^2 \Delta m^2 = 16\pi\alpha_i (1 + m_d/m_i)^{-2} \qquad (\alpha_i = m_i/\tau_i)$$

Non-Radiative Neutrino Decay

visible neutrino decay

left-handed active neutrino?

$$\nu_i \rightarrow \nu' + J$$

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Gelmini, Roncadelli, PLB 99 (1981)
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Acker, Pakvasa, Pantaleone, PRD 45 (1992)

$$g_{dk}^2 \Delta m^2 = 16\pi \alpha_i (1 + m_d/m_i)^{-2} \qquad (\alpha_i = m_i/\tau_i)$$

Bounds from K-decays put a limit on g_{dk} $(g_{dk}^2 < 2.4 \times 10^{-4})$

Barger, Keung, Pakvasa, PRD 25 (1982)

$$\Delta m^2 > 0.7 \mathrm{eV}^2$$

Non-Radiative Neutrino Decay

Invisible neutrino decay

sterile neutrino?

$$\nu_i \rightarrow \nu' + J$$

Chikashige, Mohapatra, Peccei, PLB 98, (1981)
Gelmini, Roncadelli, PLB 99 (1981)
Gelmini, Valle, PLB 142 (1984)

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Acker, Pakvasa, Pantaleone, PRD 45 (1992)

$$g_{dk}^2 \Delta m^2 = 16\pi\alpha_i (1 + m_d/m_i)^{-2} \qquad (\alpha_i = m_i/\tau_i)$$

No bounds from K-decays on g_{dk}

Δm^2 unconstrained

Neutrino Decay as a Solution to Atmospheric Neutrino Problem

The idea that neutrino decay could have a role in atmospheric neutrinos was first introduced in

UNDPL

What the Atmospheric Neutrino Anomaly is Not

hep-ph/9809499

J.M. LoSecco

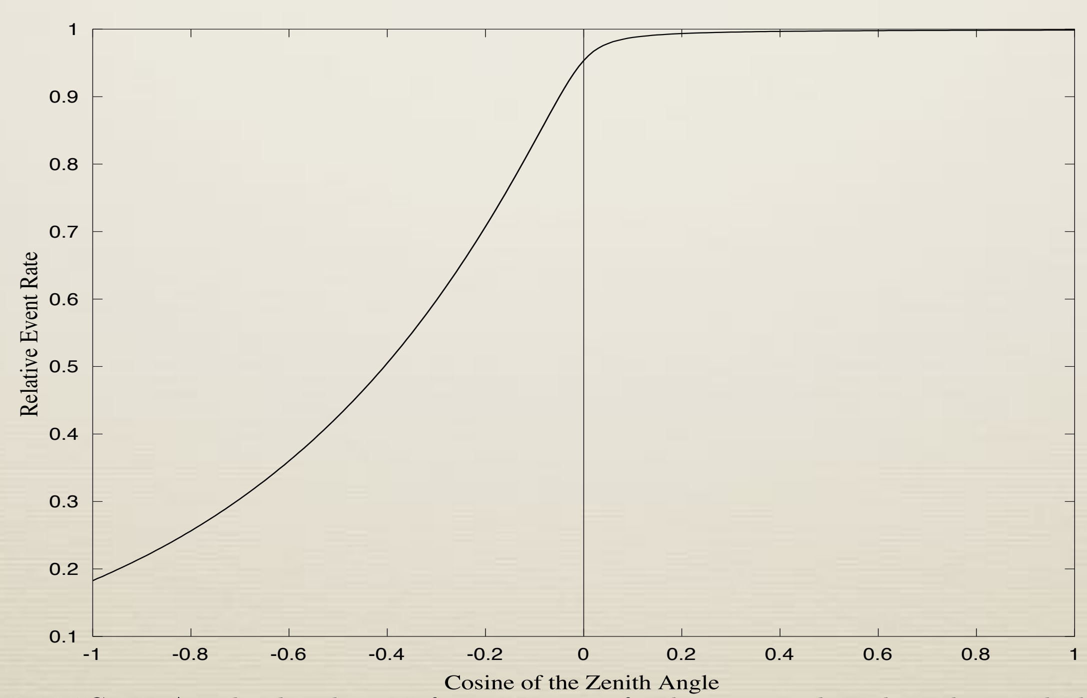


FIG. 3. Angular distribution of ν_μ interactions for the neutrino decay hypothesis. The lifetime was taken as $\frac{\tau}{m} = 0.033$ sec/GeV to enhance the effect. The momentum is taken as 750 MeV/c.

Pure decay with no mixing or oscillation effects taken

Visible Neutrino Decay with Mixing and Atmospheric Neutrino Problem

Neutrino Decay as an Explanation of Atmospheric Neutrino Observations

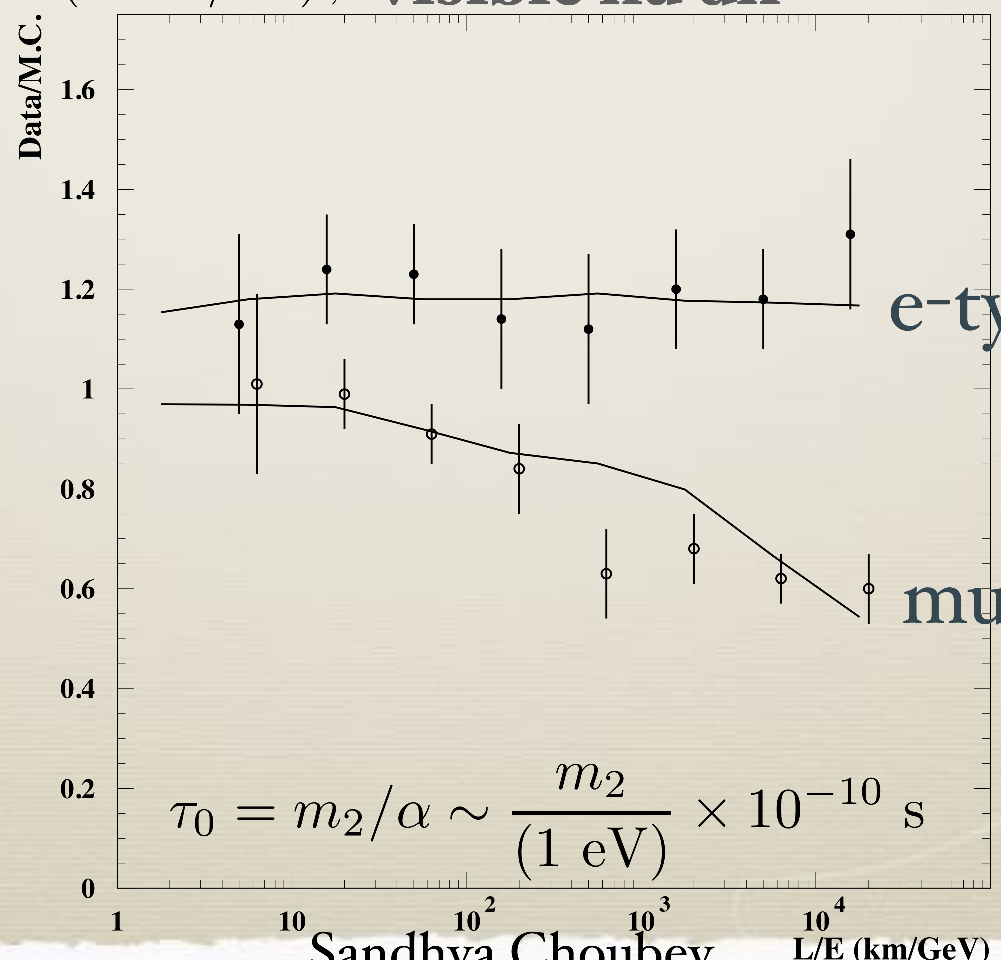
PRL 82 (1999)

[1,4]V. Barger, [2]J. G. Learned, [2]S. Pakvasa, and [3]T. J. Weiler

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \exp(-\alpha L/E) + 2\sin^2\theta\cos^2\theta\exp(-\alpha L/2E)\cos(\delta m^2 L/2E)\,,$$

$\Delta m^2 > 0.7\mathrm{eV}^2$ → **visible nu dk**

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \exp(-\alpha L/E)\,.$$



e-type events

mu-type events

$$\tau_0 = m_2/\alpha \sim \frac{m_2}{(1\ \mathrm{eV})} \times 10^{-10}\ \mathrm{s}$$

Visible Neutrino Decay with Mixing and Atmospheric Neutrino Problem

Super-Kamiokande data and atmospheric neutrino decay

hep-ph/9902267

G. L. Fogli, E. Lisi, A. Marrone, and G. Scioscia

Dipartimento di Fisica and Sezione INFN di Bari,

Via Amendola 173, I-70126 Bari, Italy

See also SC, Goswami, hep-ph/9904257

See also Lipari, Lusignoli, hep-ph/9901350

Abstract

Neutrino decay has been proposed as a possible solution to the atmospheric neutrino anomaly, in the light of the recent data from the Super-Kamiokande experiment. We investigate this hypothesis by means of a quantitative analysis of the zenith angle distributions of neutrino events in Super-Kamiokande, including the latest (45 kTy) data. We find that the neutrino decay hypothesis fails to reproduce the observed distributions of muons.

InVisible Neutrino Decay with Mixing and Atmospheric Neutrino Problem

$\nu_3 \rightarrow \nu_{sterile} + J$ Δm^2 unconstrained

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \exp(-\alpha L/E) + 2\sin^2\theta\cos^2\theta\exp(-\alpha L/2E)\cos(\delta m^2 L/2E)\,,$$

two possibilities

Δm^2 unconstrained

SC, Goswami, hep-ph/9904257

$\Delta m^2 \ll 10^{-4}$ eV^2

$$P(\nu_\mu \rightarrow \nu_\mu) = \left[\sin^2\theta + \cos^2\theta\exp\left(-m/2\tau \cdot L/E\right)\right]^2$$

Barger, Learned, Lipari, Lusignoli, Pakvasa, Weiler, hep-ph/9907421

disfavoured by SK L/E analysis compared to oscillations

SK Collab. hep-ex/0404034

InVisible Neutrino Decay with Mixing and Atmospheric Neutrino Problem

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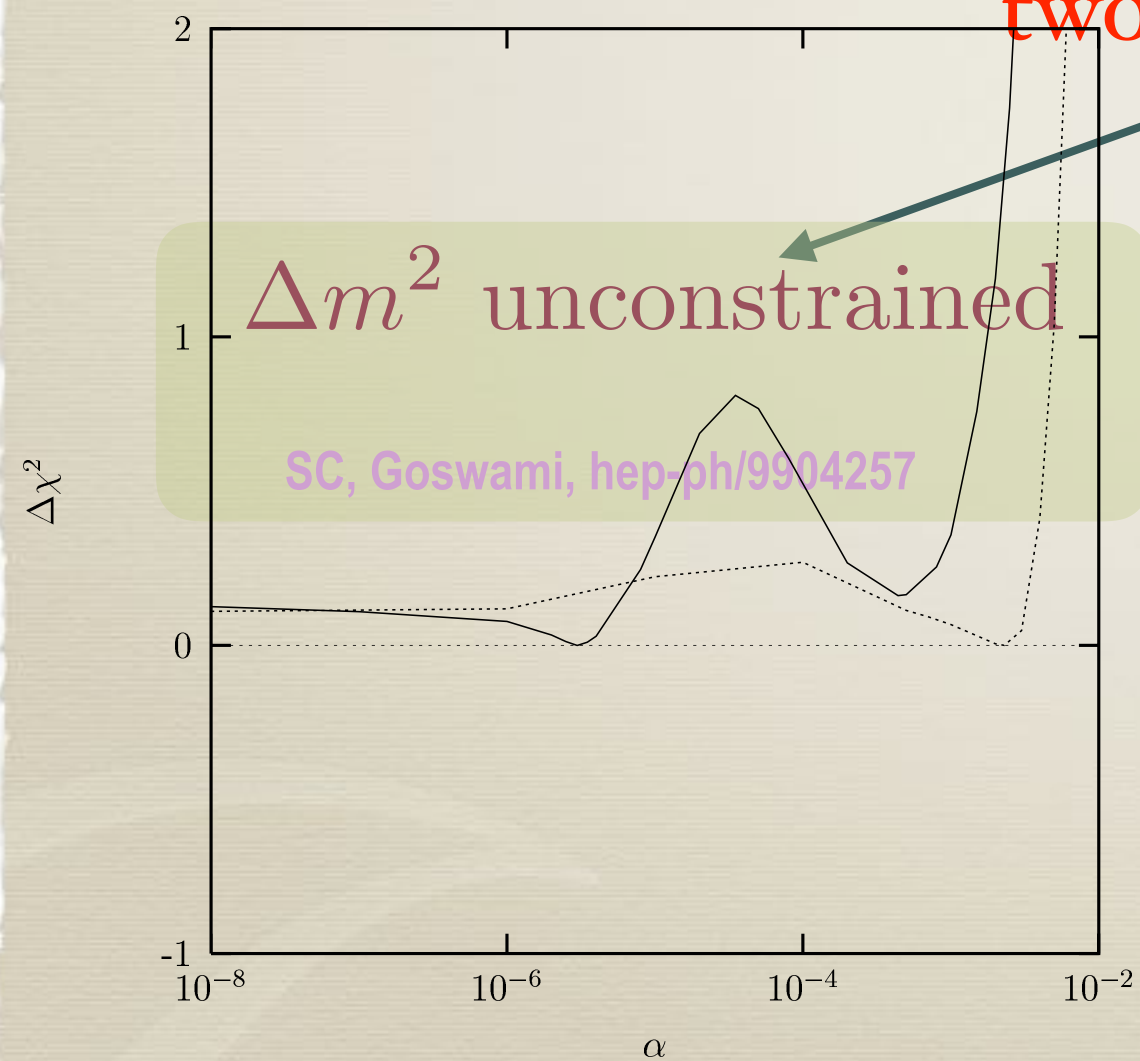

Δm^2 unconstrained

SC, Goswami, hep-ph/9904257

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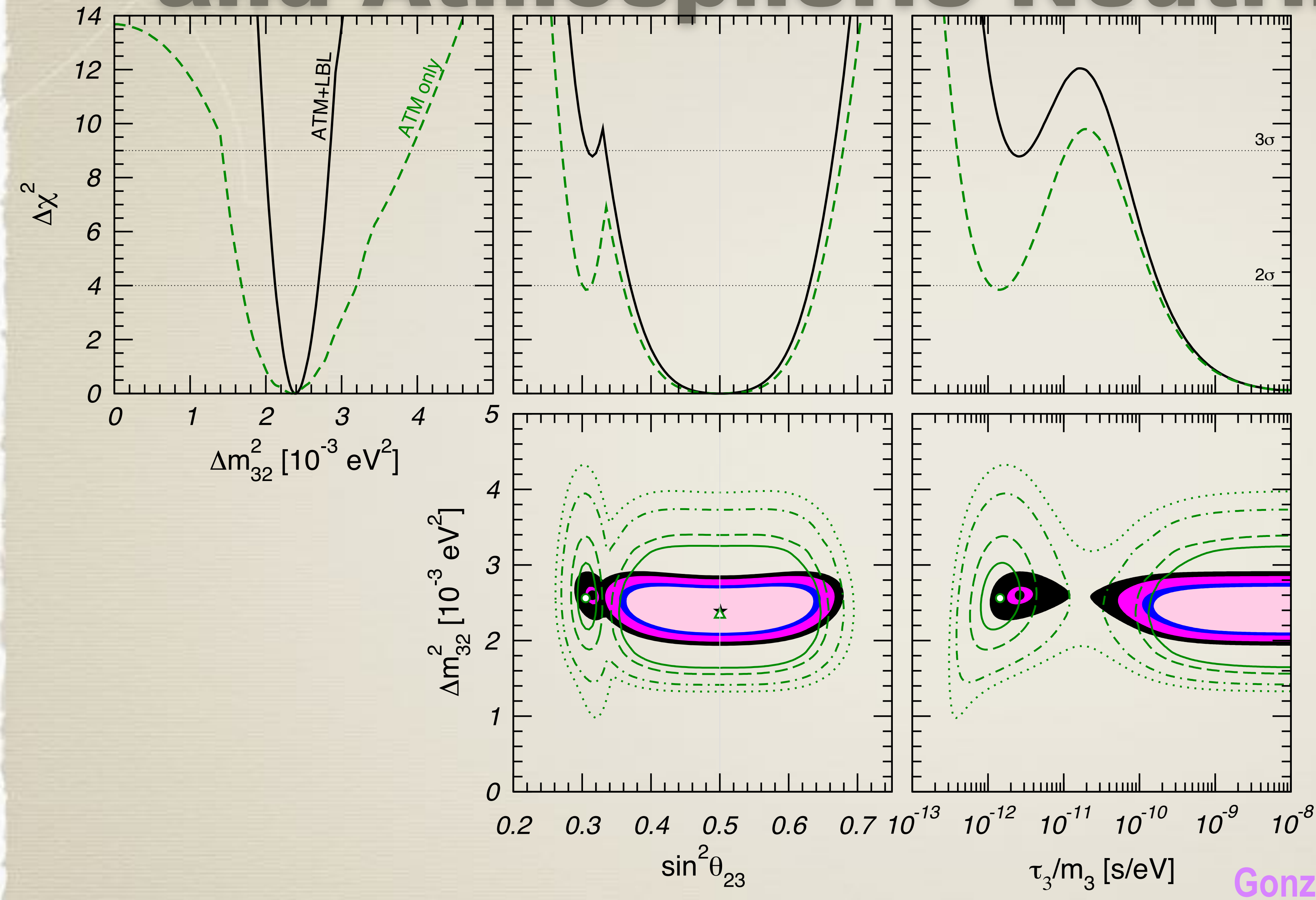
InVisible Neutrino Decay with Mixing and Atmospheric Neutrino Problem



Δm^2 unconstrained

Gonzales-Garcia, Maltoni PLB (2008)

$$\tau_3/m_3 \geq 2.9\ [0.93] \times 10^{-10}\ \text{s/eV at the } 90\%\ [99\%]\ \text{CL}$$

Neutrino Oscillation Probabilities

Two-Generations Vacuum

$$P_{\mu\mu}^{2G} = \left[\cos^2\theta_{23} + \sin^2\theta_{23}\exp(-m_3L/\tau_3E)\right]^2 - \sin^2 2\theta_{23}\exp(-m_3L/\tau_3E)\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

- The exponential suppression reduces the surv. probability
- The reduction is both in constant as well as osc term
- The mixing angle reduces the osc term of surv. probability
- Effect of decay can be compensated by increasing the mixing angle theta23

Three-Generations + Matter

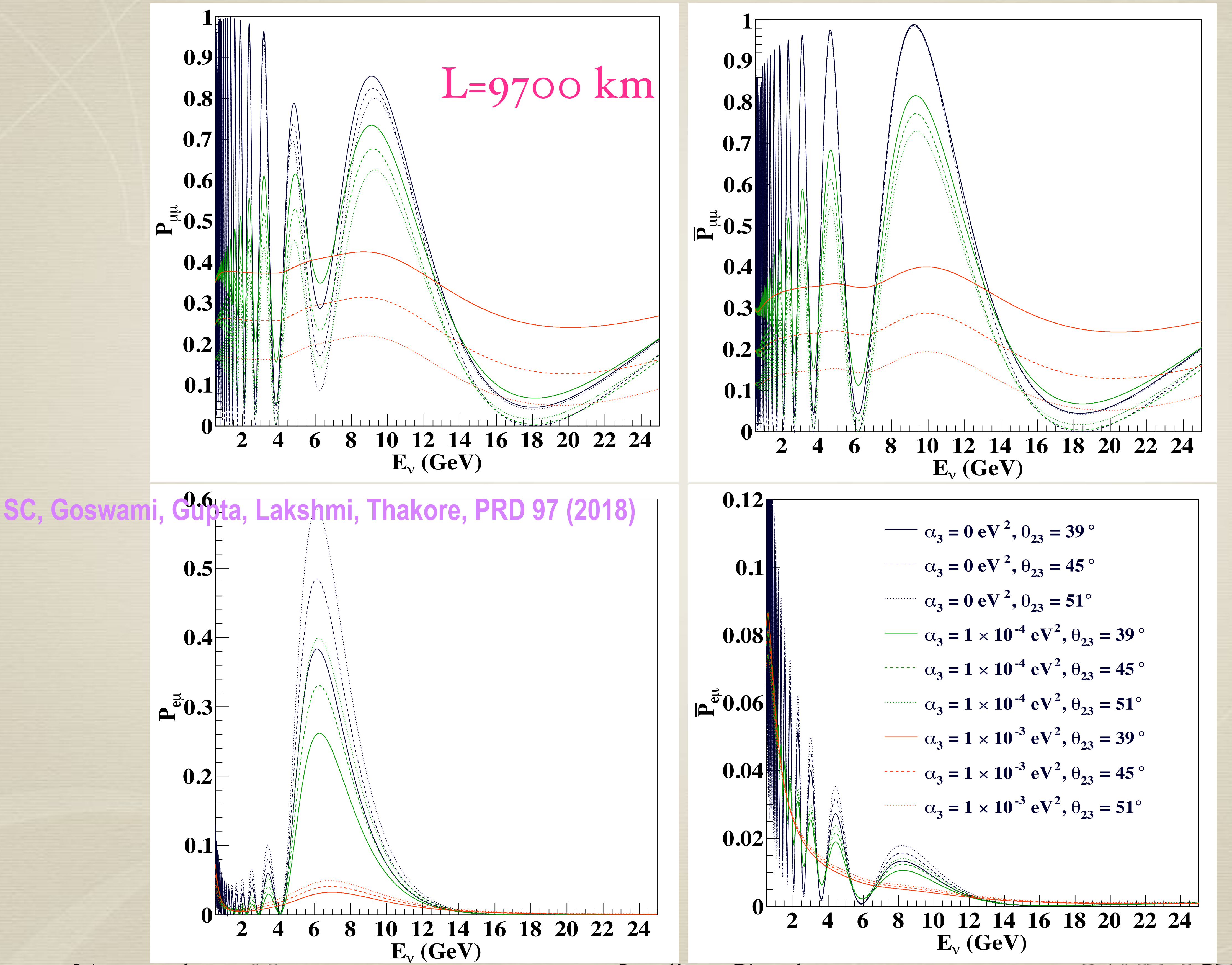
$$i\frac{d\tilde{\nu}}{dt} = \frac{1}{2E}\left[U\mathbb{M}^2U^\dagger + \mathbb{A}_{CC}\right]\tilde{\nu},$$

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

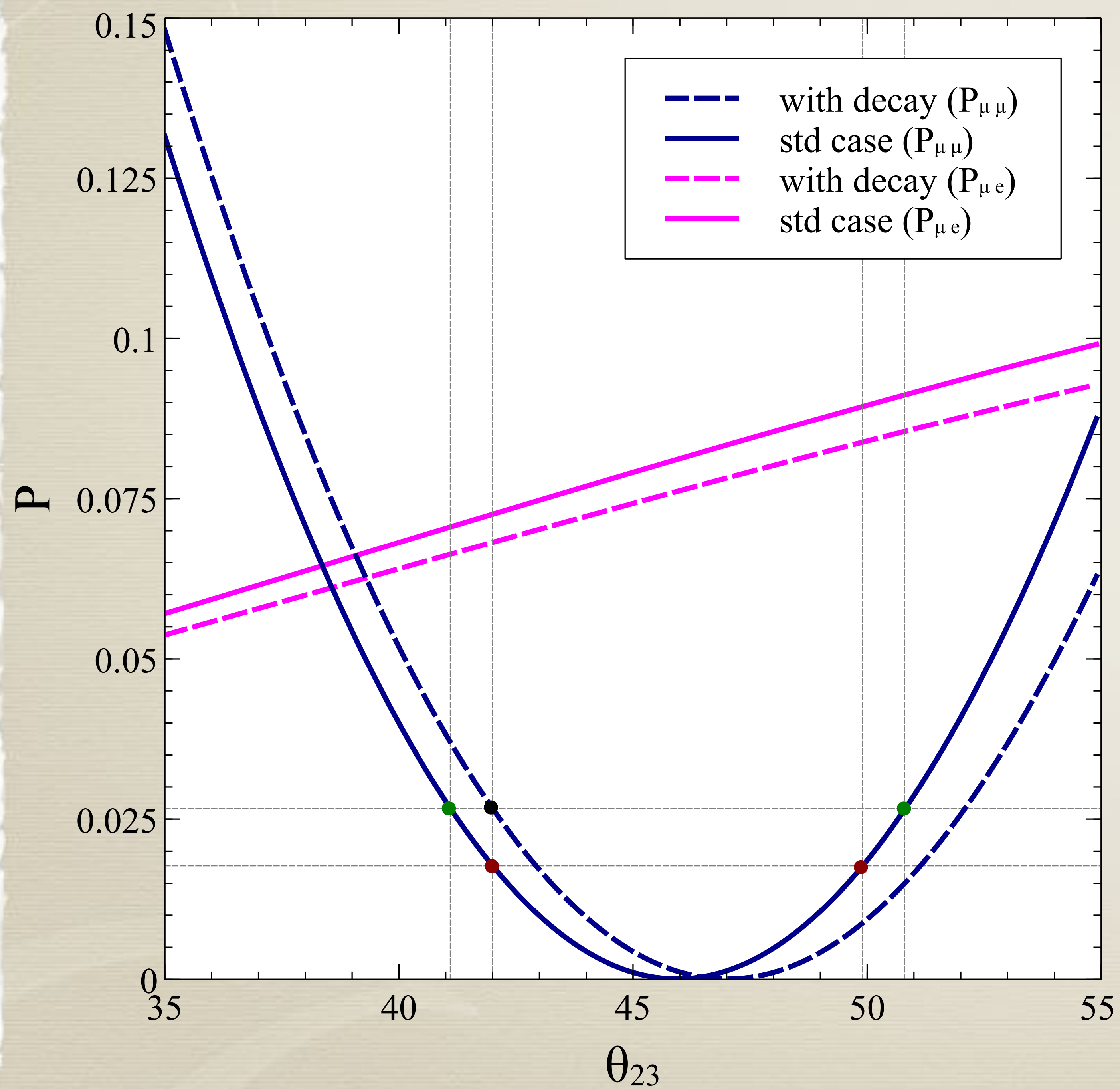
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

Oscillation Probabilities



Impact on θ_{23}



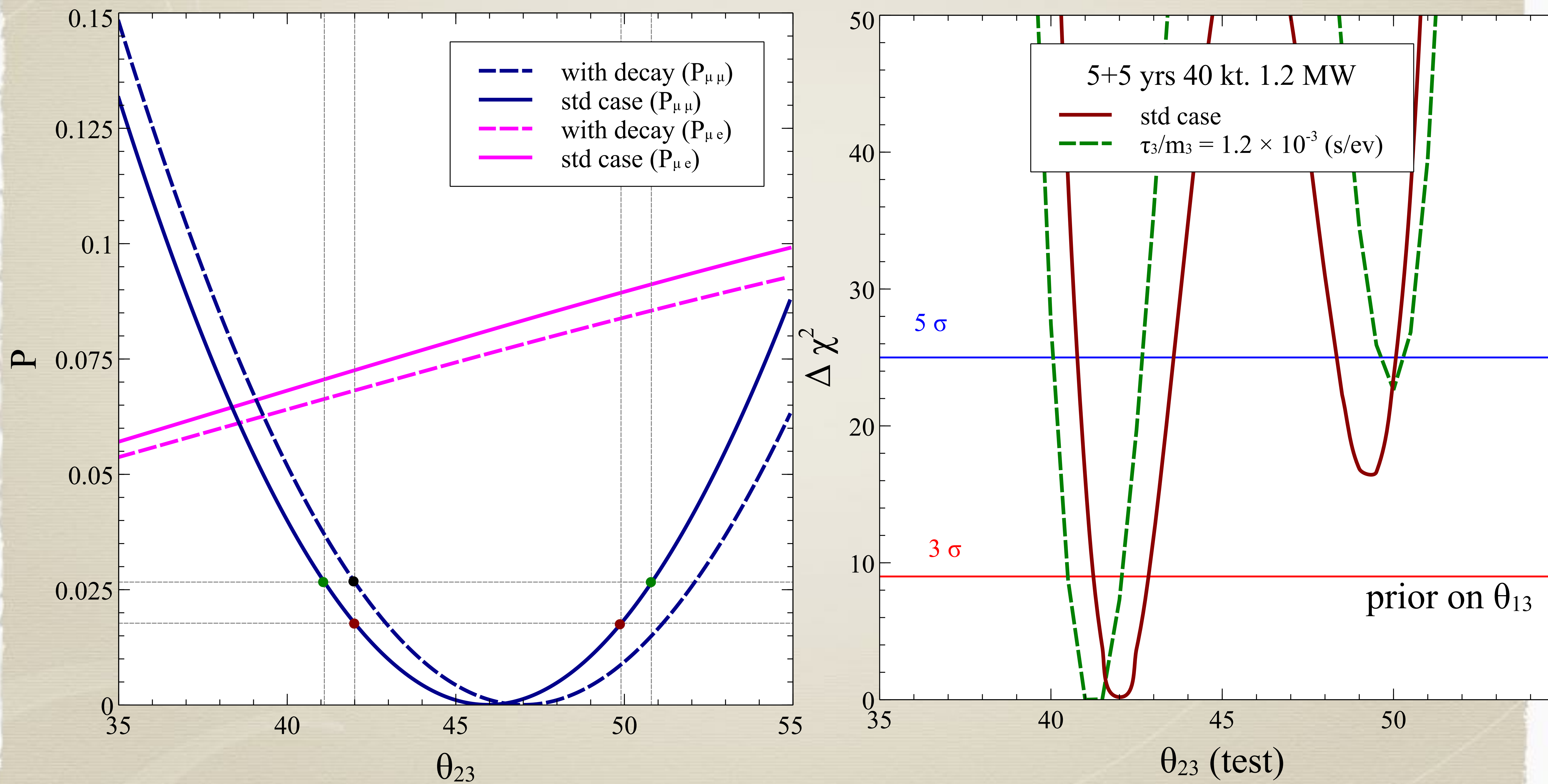
SC, Goswami, Pramanik, JHEP (2017)

$$\sin\theta_{23} = \frac{\sin\theta_{\mu\mu}}{\cos\theta_{13}}$$

Raut, MPL A28 (2013)

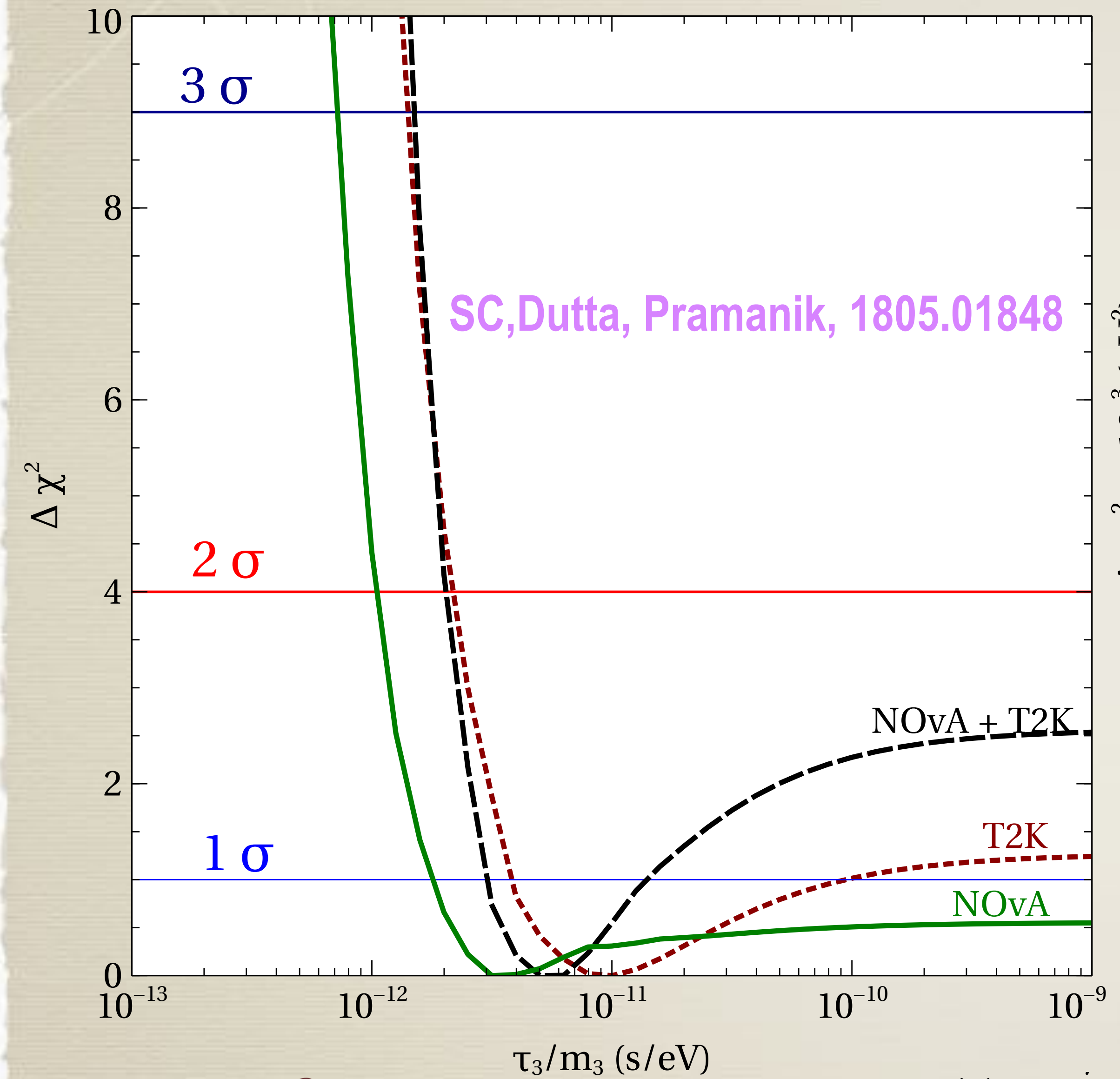
Effect of decay can be compensated by increasing the mixing angle theta23

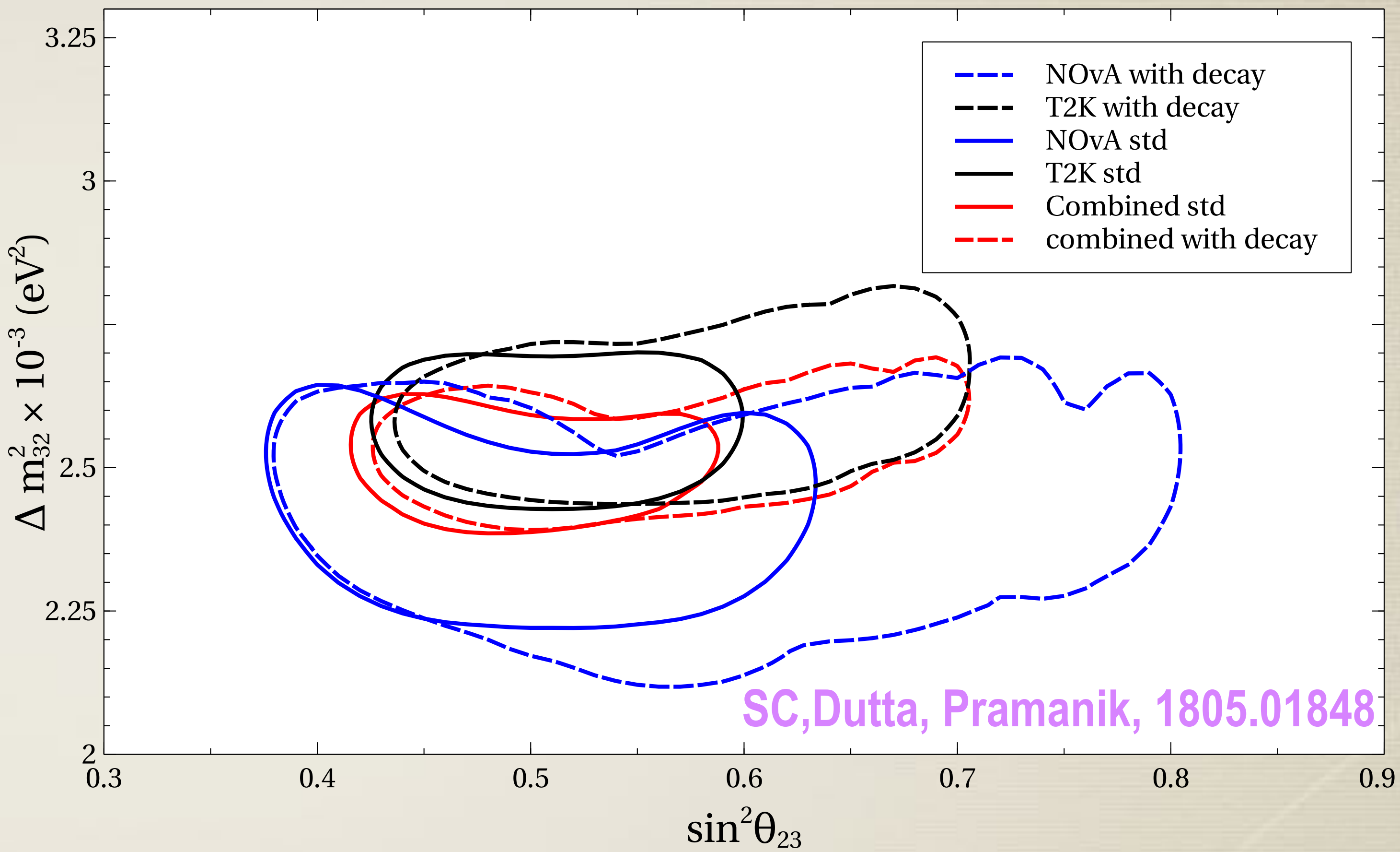
Impact on θ_{23}



SC, Goswami, Pramanik, JHEP (2017)

Constraints from T2K and NOvA



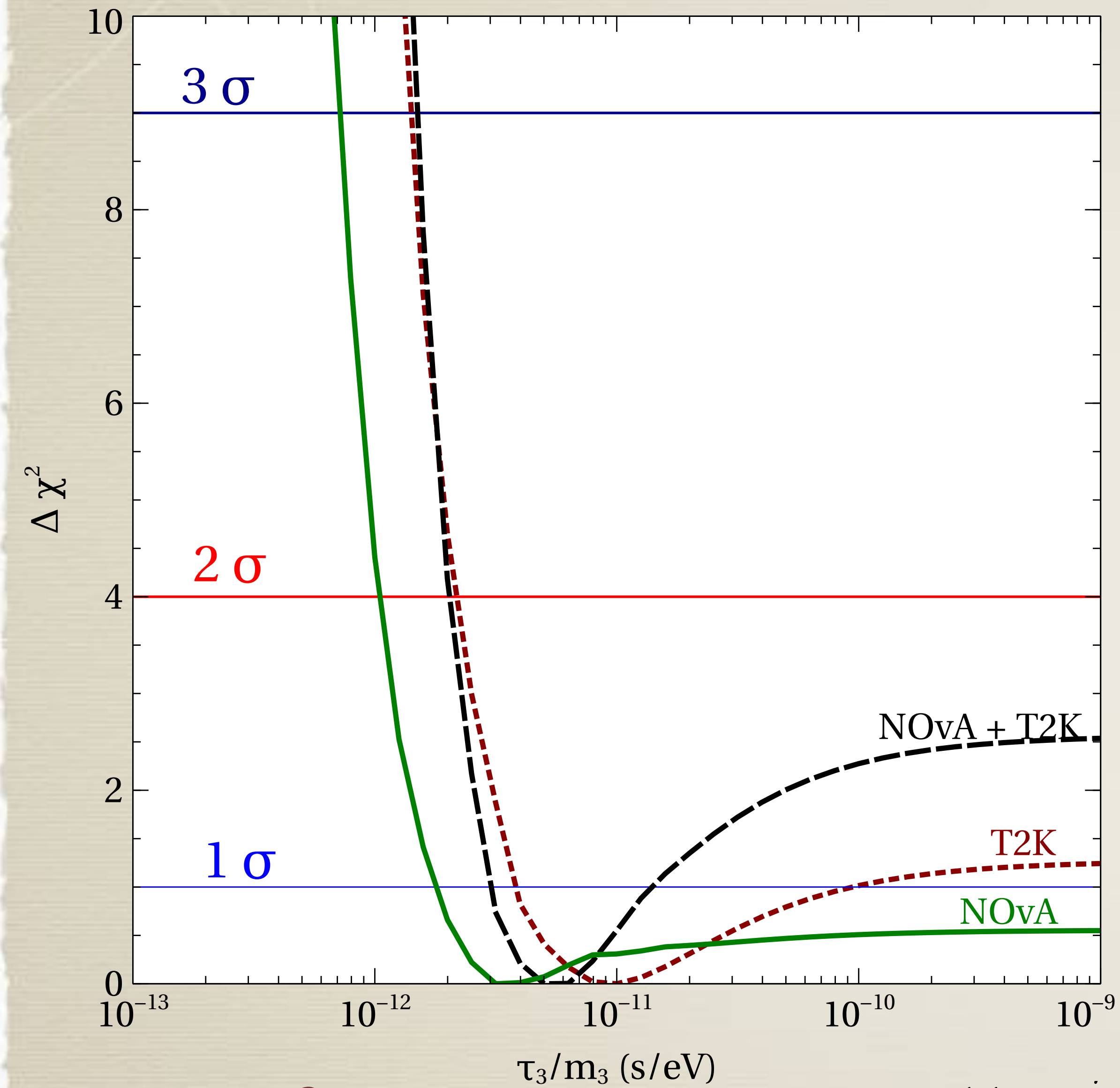


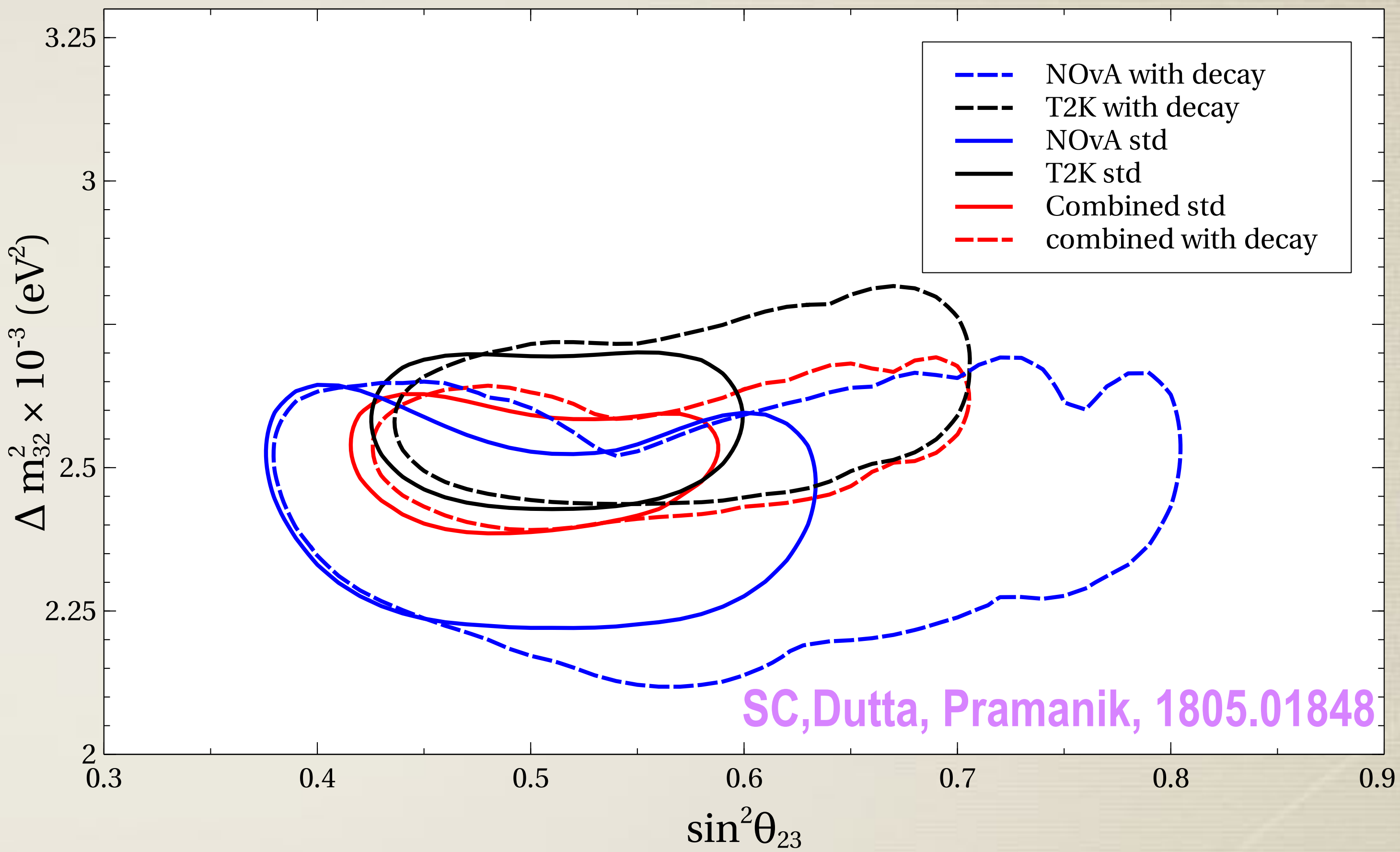
Best-fit: $\tau_3/m_3 = 1.0 \times 10^{-11}$ s/eV (T2K)
$\tau_3/m_3 = 3.16 \times 10^{-12}$ s/eV (NOvA)

$\tau_3/m_3 \geq 1.50 \times 10^{-12}$ s/eV at 3 sigma

See for earlier analysis with T2K+MINOS
Gomes, Gomes, Peres, 1407.5640

Constraints from T2K and NOvA





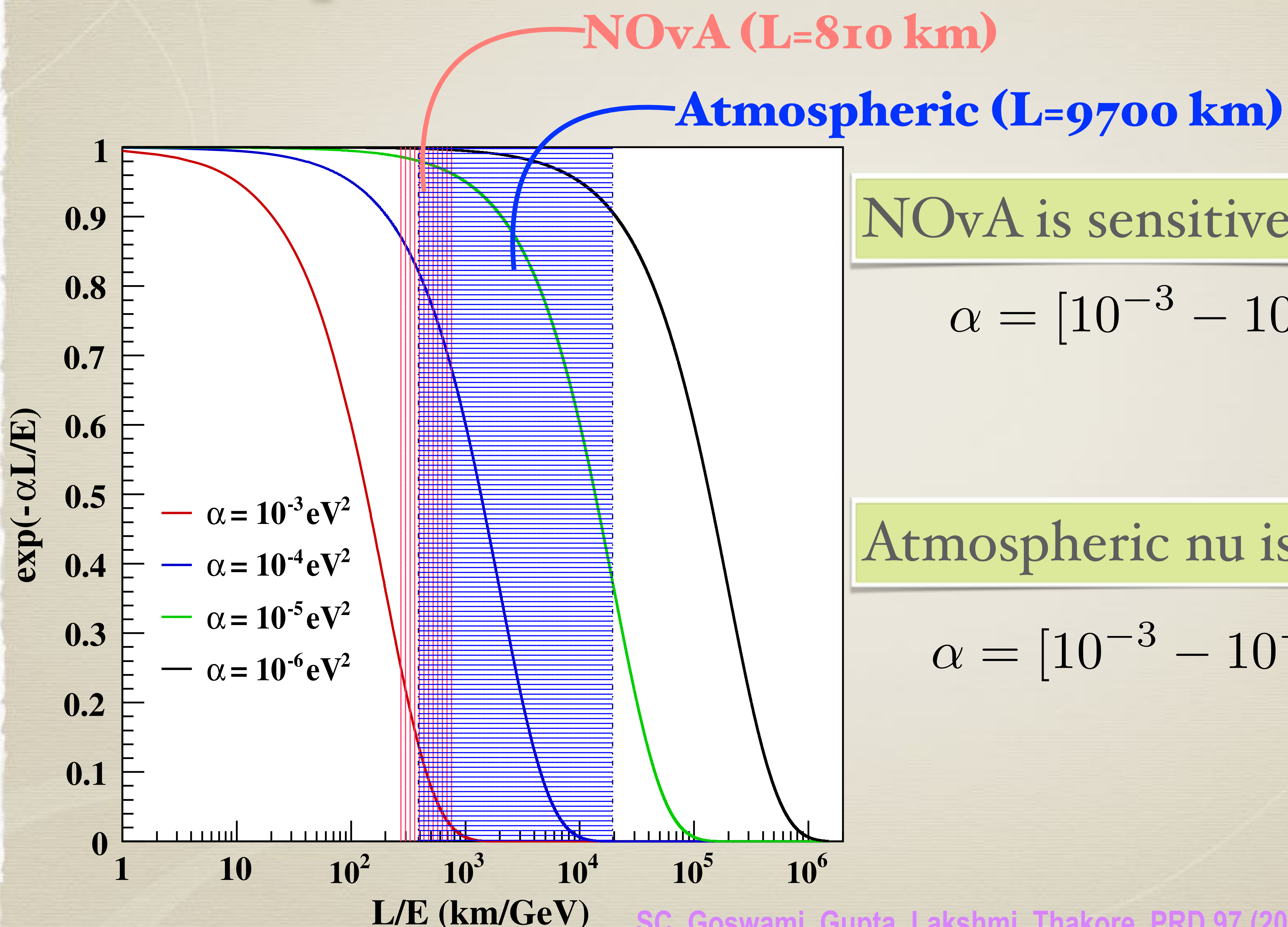
Best-fit: $\tau_3/m_3 = 1.0 \times 10^{-11}$ s/eV (T2K)
$\tau_3/m_3 = 3.16 \times 10^{-12}$ s/eV (NOvA)

Super-K bounds are stronger

$\tau_3/m_3 \geq 1.50 \times 10^{-12}$ s/eV at 3 sigma

See for earlier analysis with T2K+MINOS
Gomes, Gomes, Peres, 1407.5640

Dependence on L and E



SC, Goswami, Gupta, Lakshmi, Thakore, PRD 97 (2018)

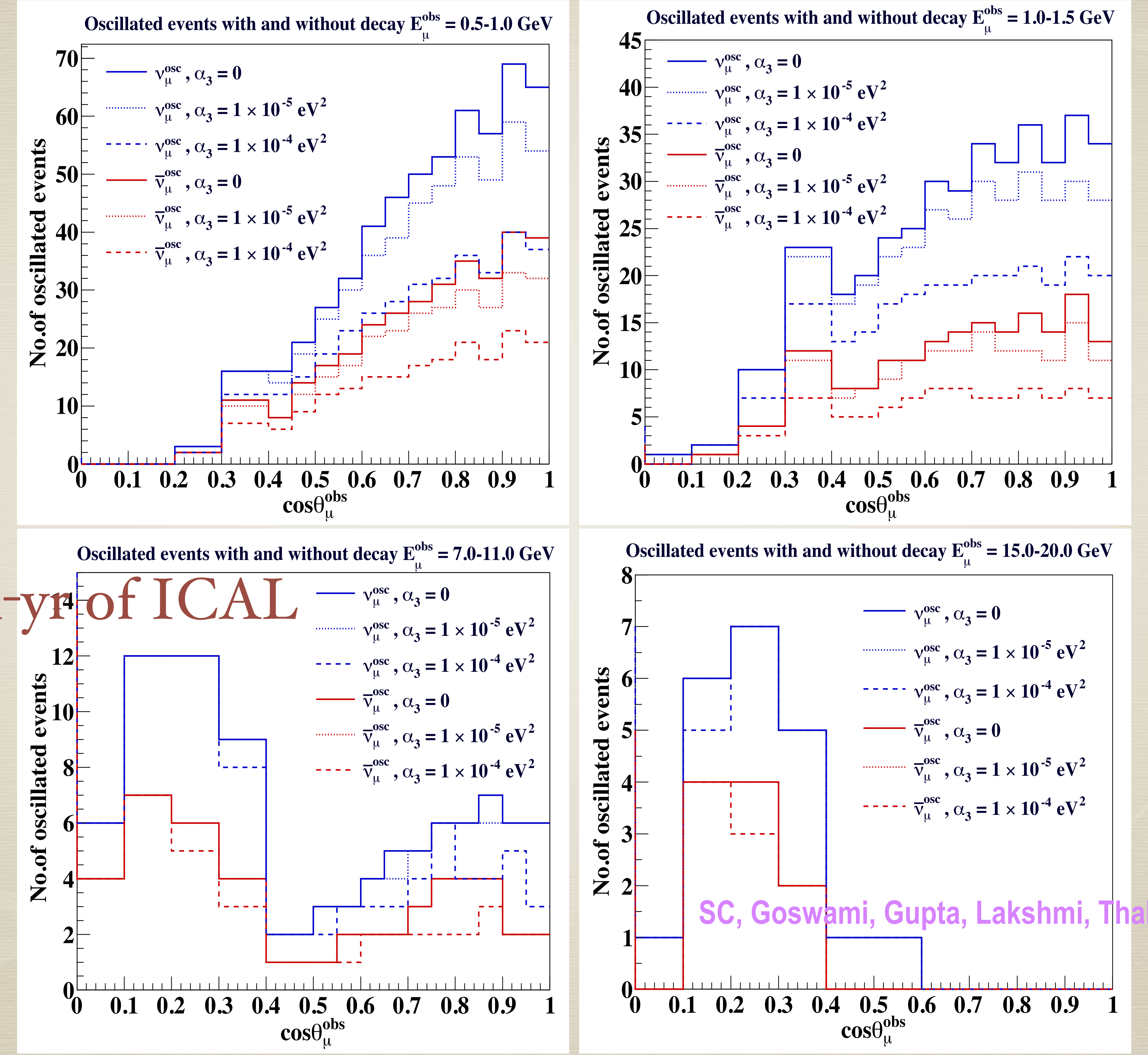
NOvA is sensitive to

$$\alpha = [10^{-3} - 10^{-4}] eV^2$$

Atmospheric nu is sensitive to

$$\alpha = [10^{-3} - 10^{-6}] eV^2$$

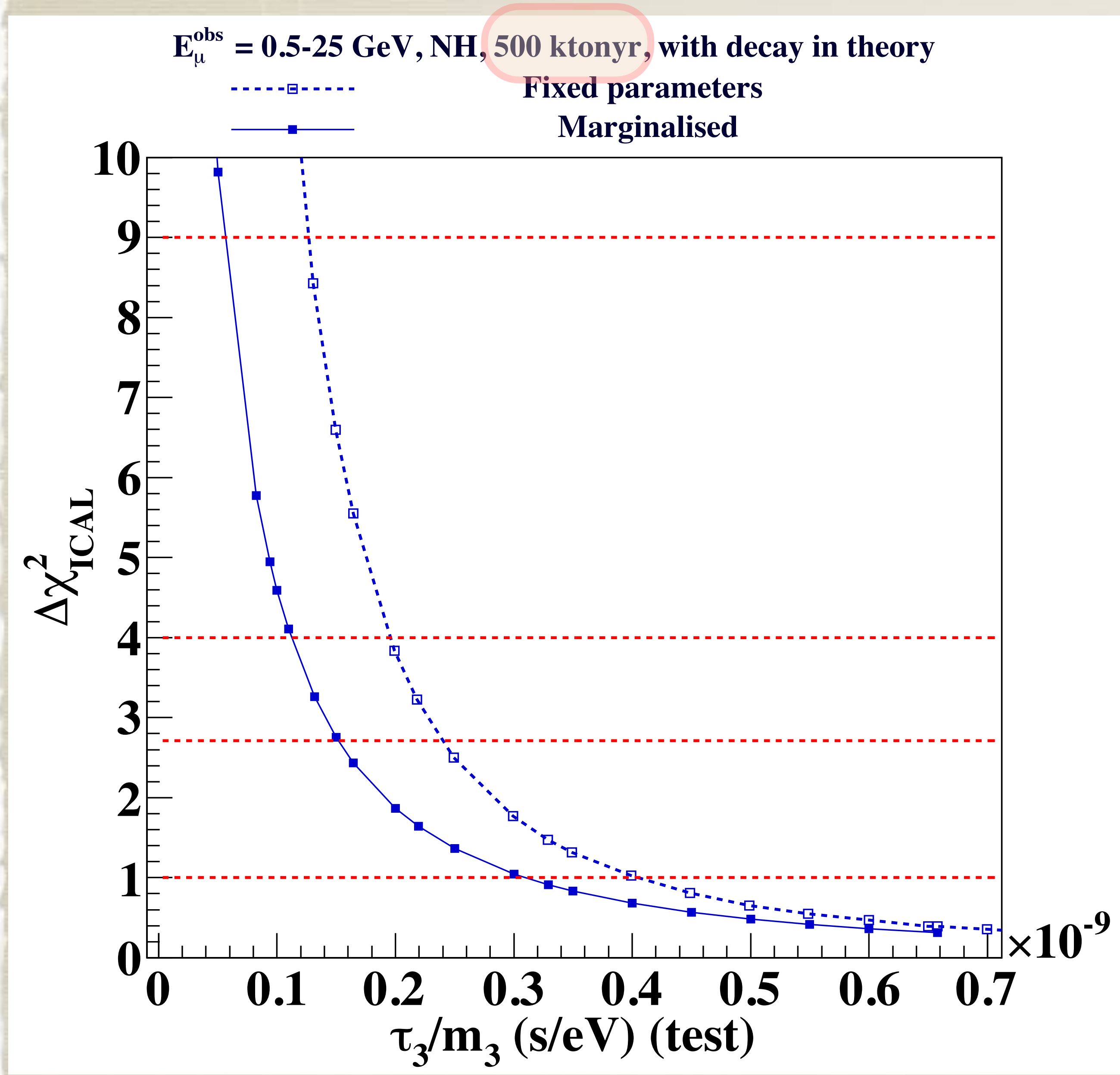
Atmospheric Neutrino Events



500 kton-yr of ICAL

SC, Goswami, Gupta, Lakshmi, Thakore, PRD 97 (2018)

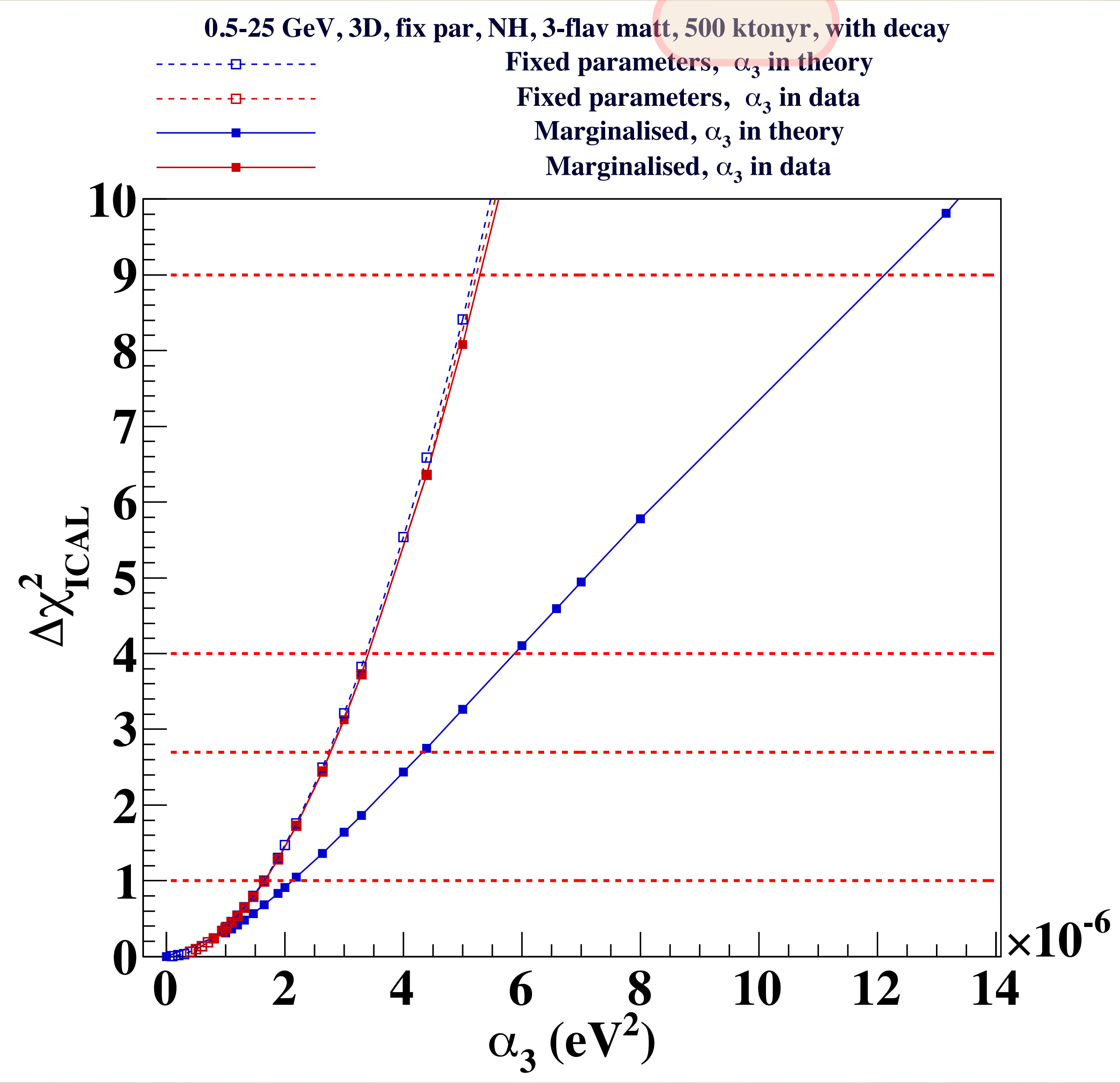
Sensitivity to Neutrino Lifetime



Analysis type	χ^2	α_3 (eV^2)	τ_3/m_3 (s/eV)
Fixed parameters	1	1.65×10^{-6}	4.35×10^{-10}
	2.71	2.78×10^{-6}	2.42×10^{-10}
	4	3.43×10^{-6}	1.97×10^{-10}
	9	5.31×10^{-6}	1.25×10^{-10}
Marginalised	1	2.97×10^{-6}	2.21×10^{-10}
	2.71	5.82×10^{-6}	1.14×10^{-10}
	4	7.82×10^{-6}	8.44×10^{-11}
	9	1.58×10^{-5}	4.21×10^{-11}

SC, Goswami, Gupta, Lakshmi, Thakore, PRD 97 (2018)

Discovering Nu Decay

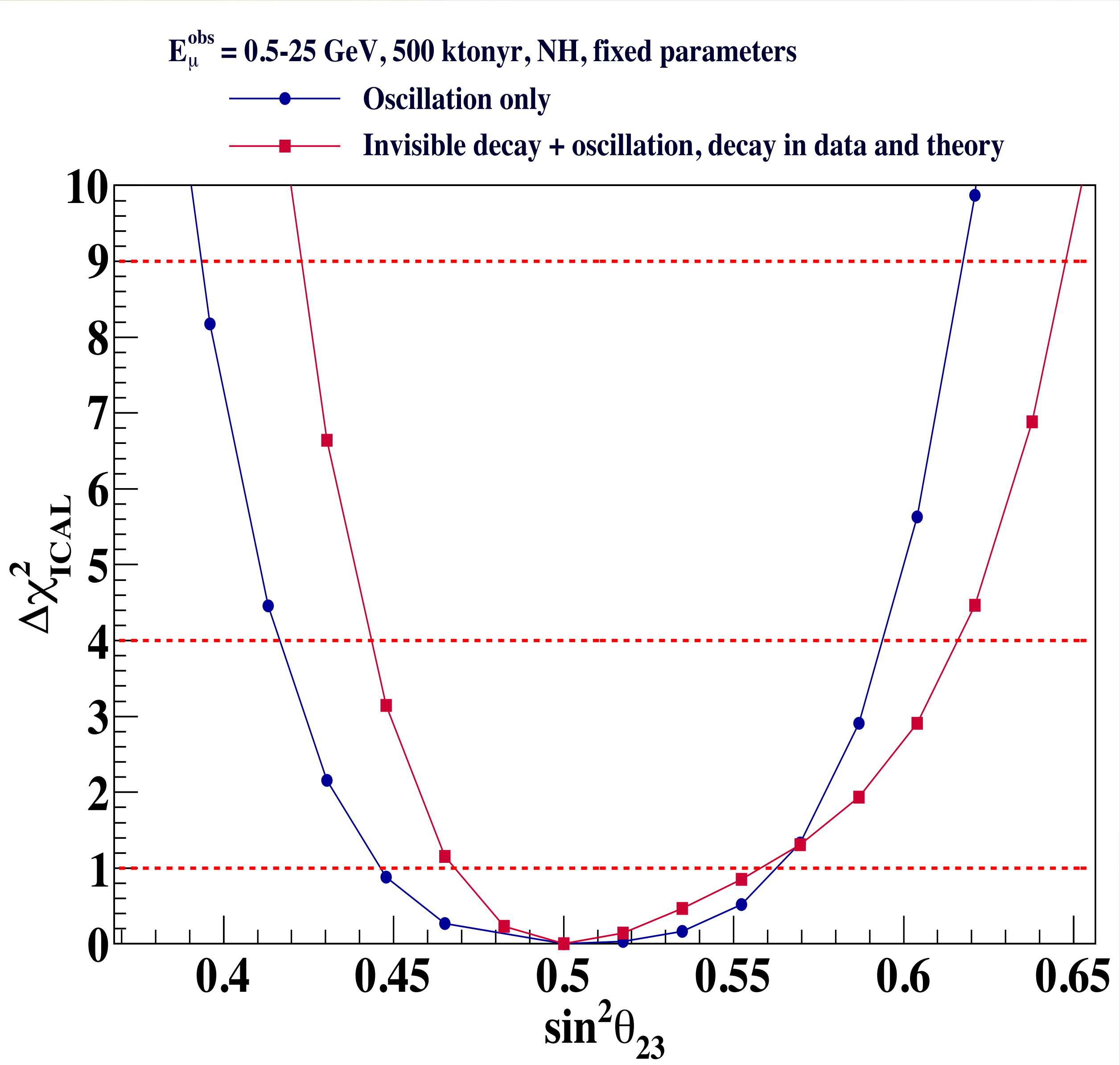


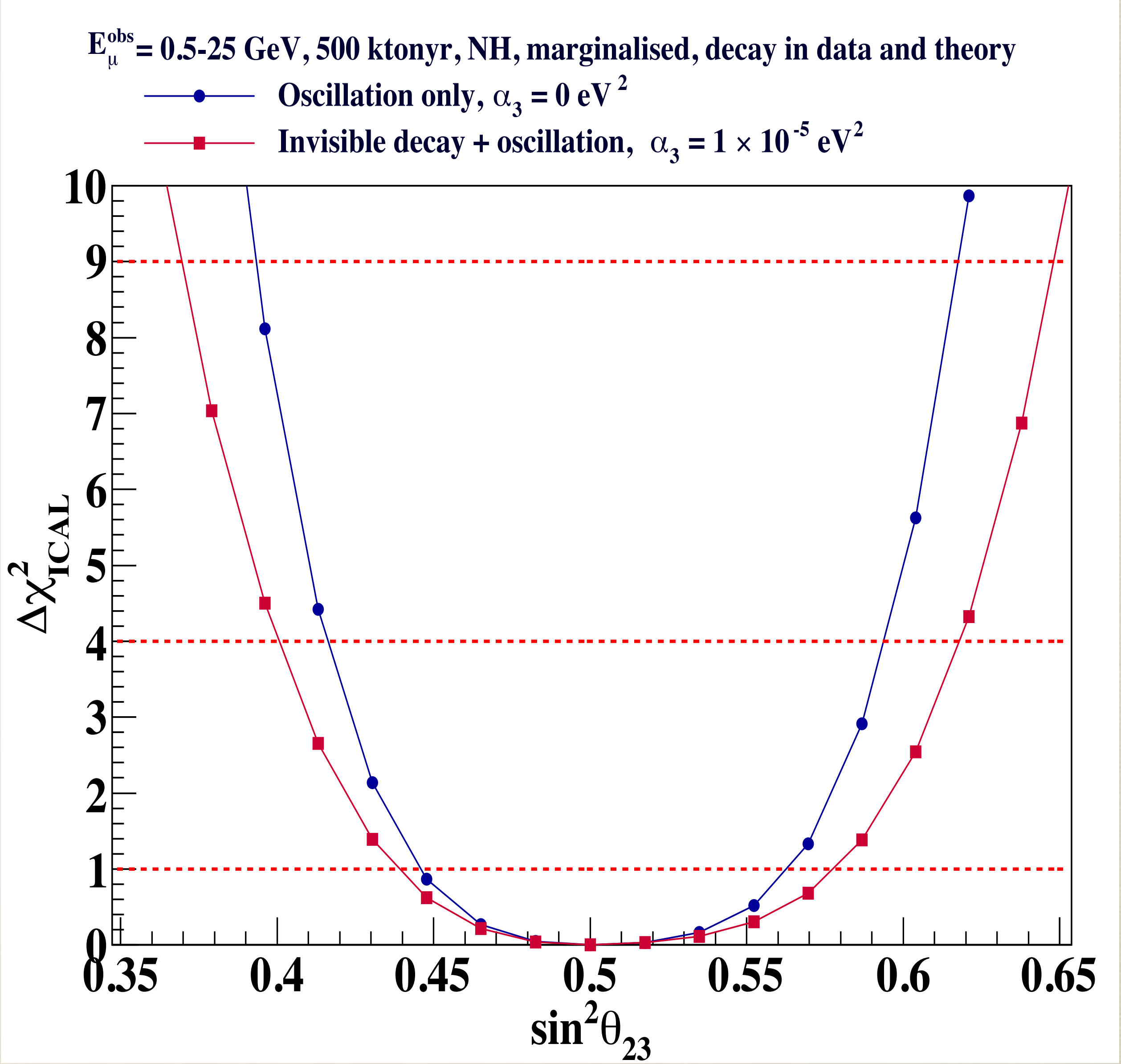
will be able to discover neutrino decay at the 90% C.L. if $\alpha_3 > 2.5 \times 10^{-6}$ eV^2

$\tau_3/m_3 > 1.86 \times 10^{-10}$ s/eV

SC, Goswami, Gupta, Lakshmi, Thakore, PRD 97 (2018)

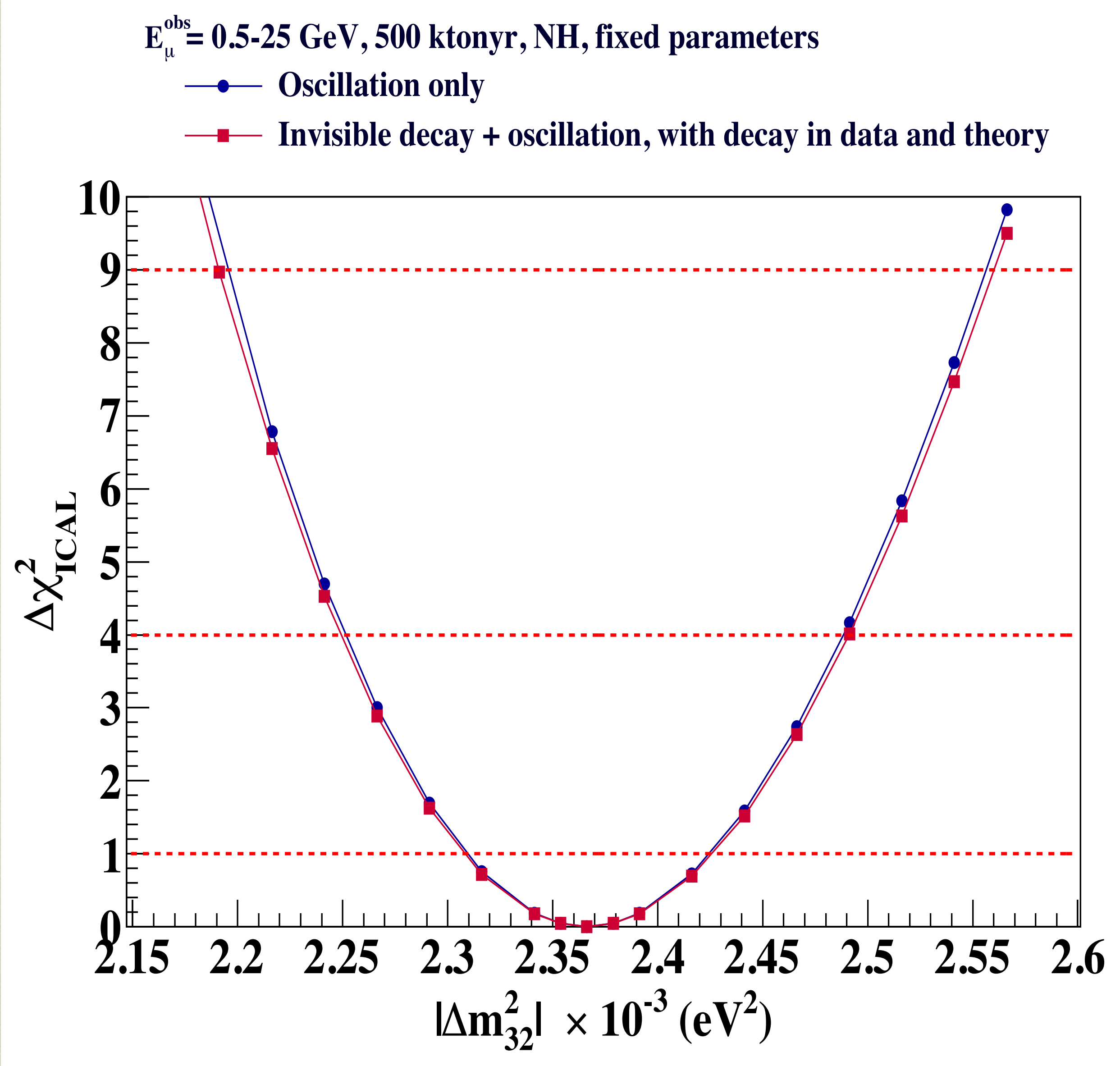
Impact on Δm^2_{32} and $\sin^2\theta_{23}$ Measurement

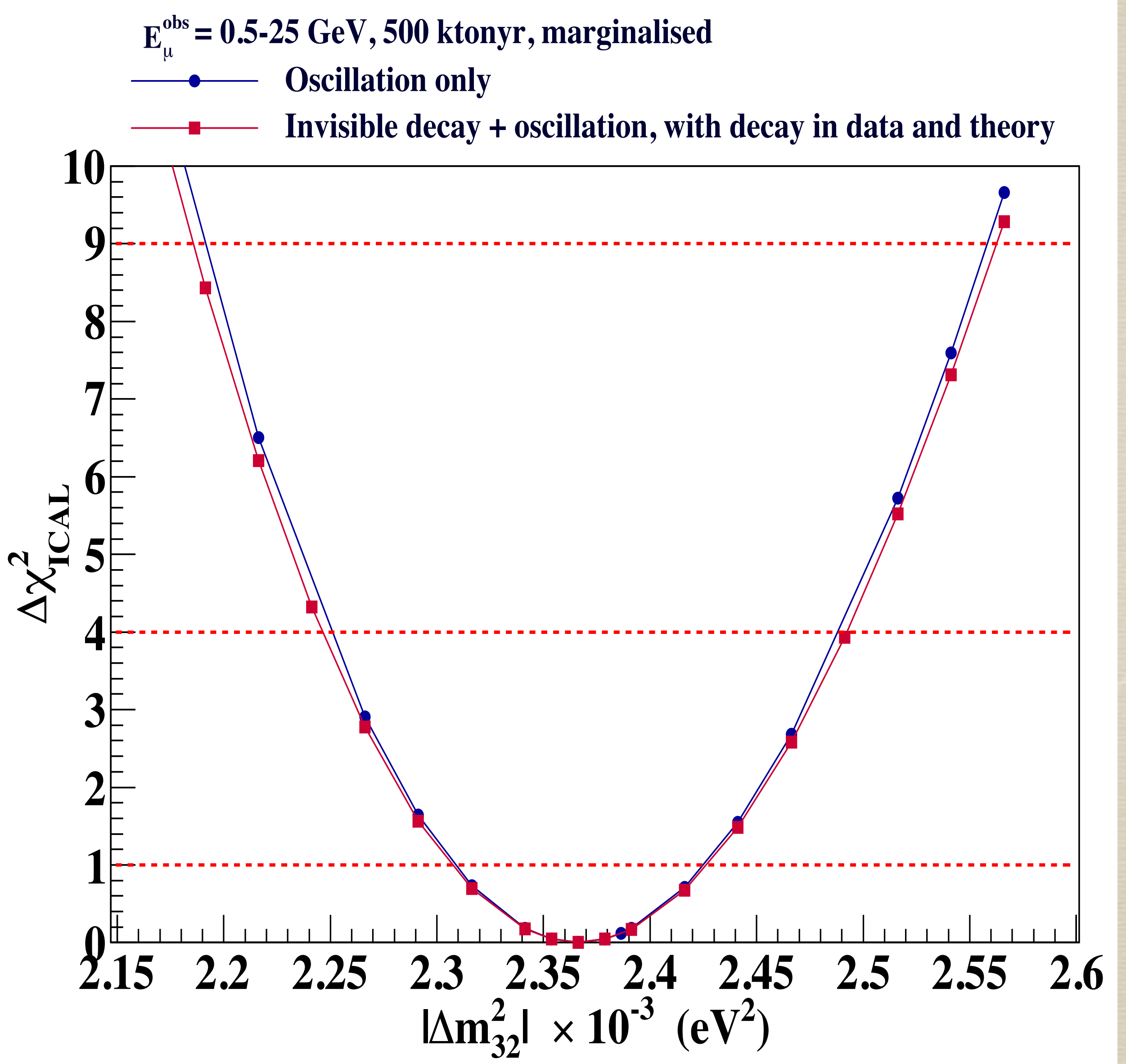




SC, Goswami, Gupta, Lakshmi, Thakore, PRD 97 (2018)

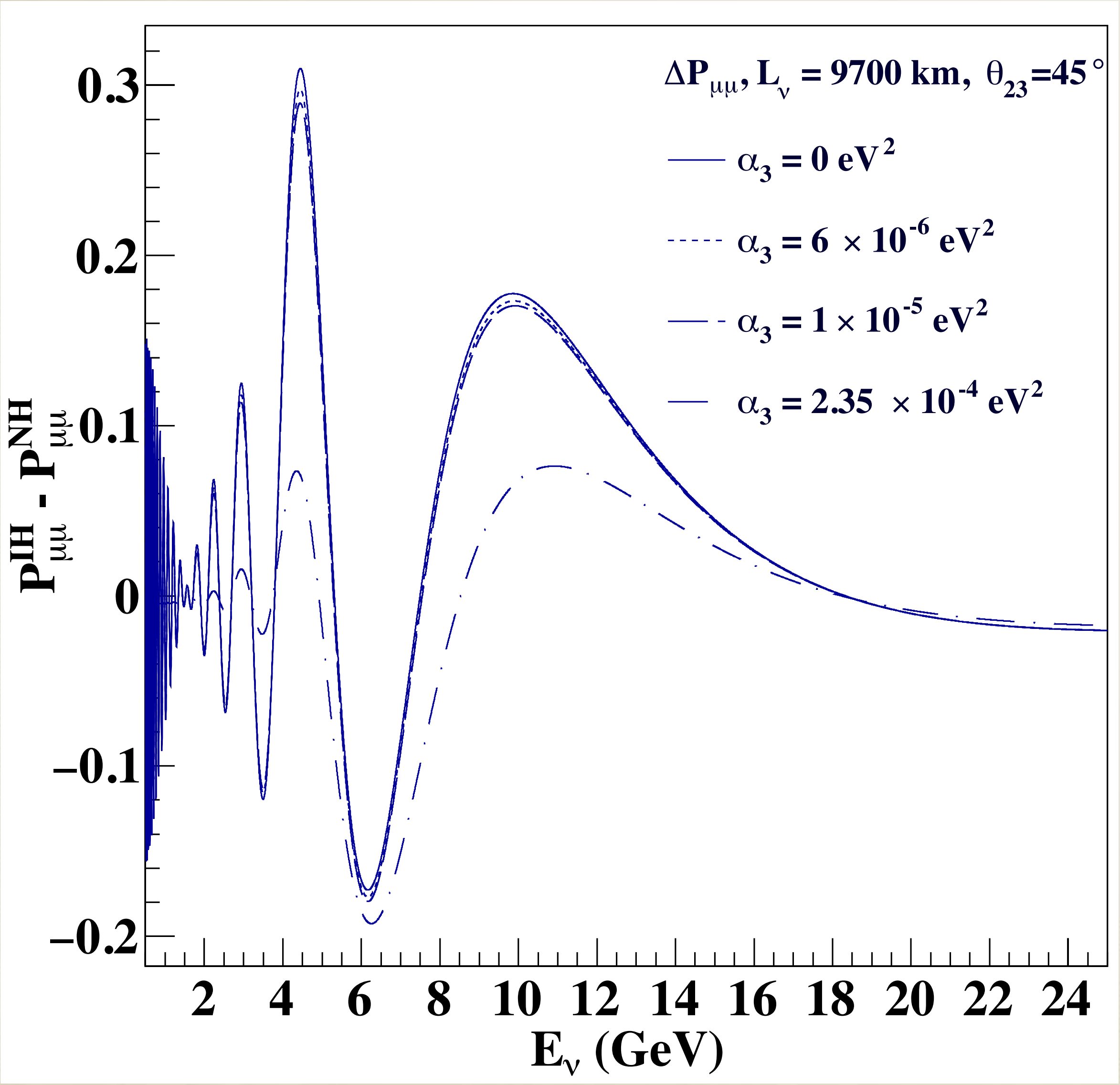
Impact on Δm^2_{32} and $\sin^2\theta_{23}$ Measurement

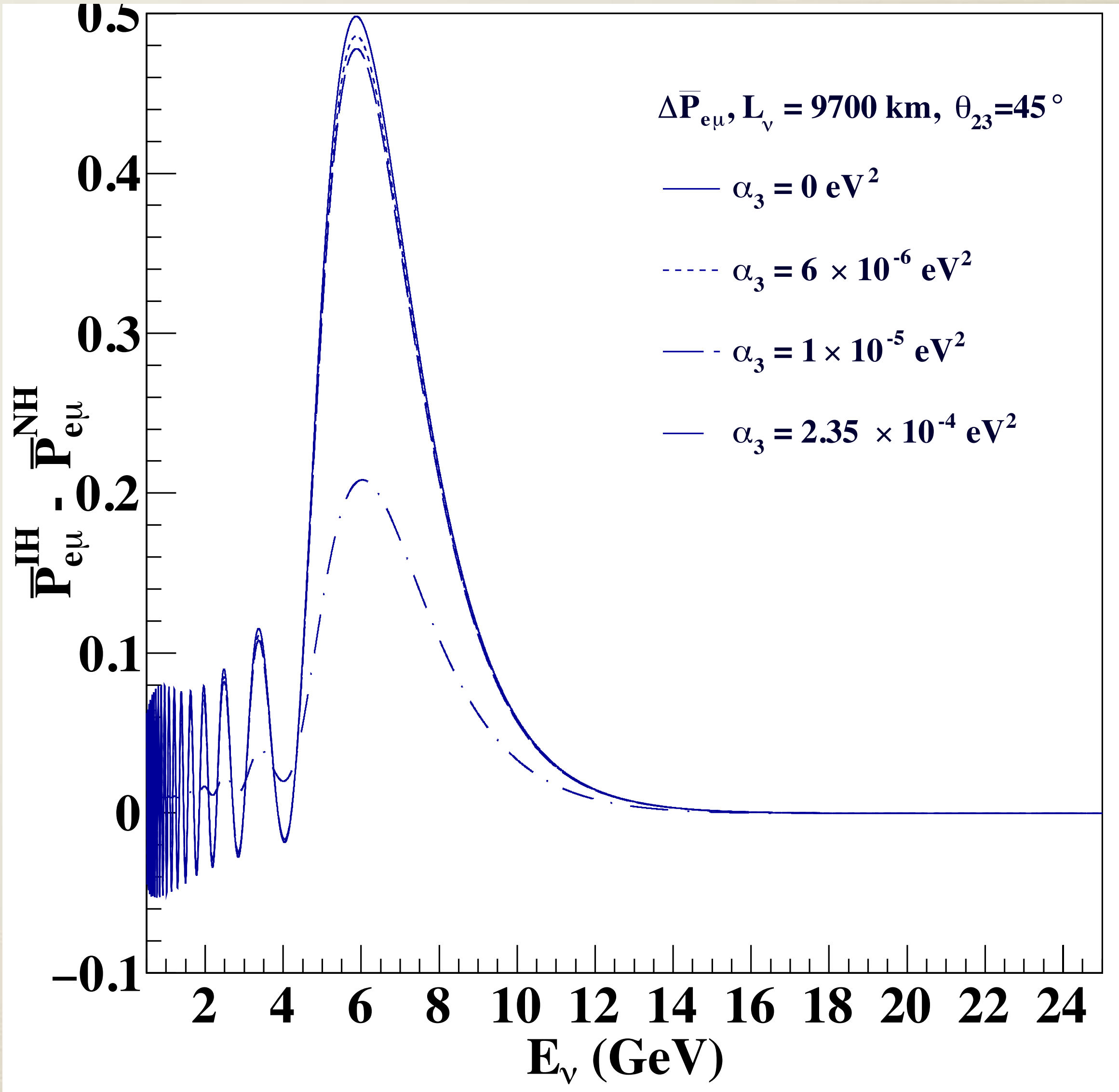




SC, Goswami, Gupta, Lakshmi, Thakore, PRD 97 (2018)

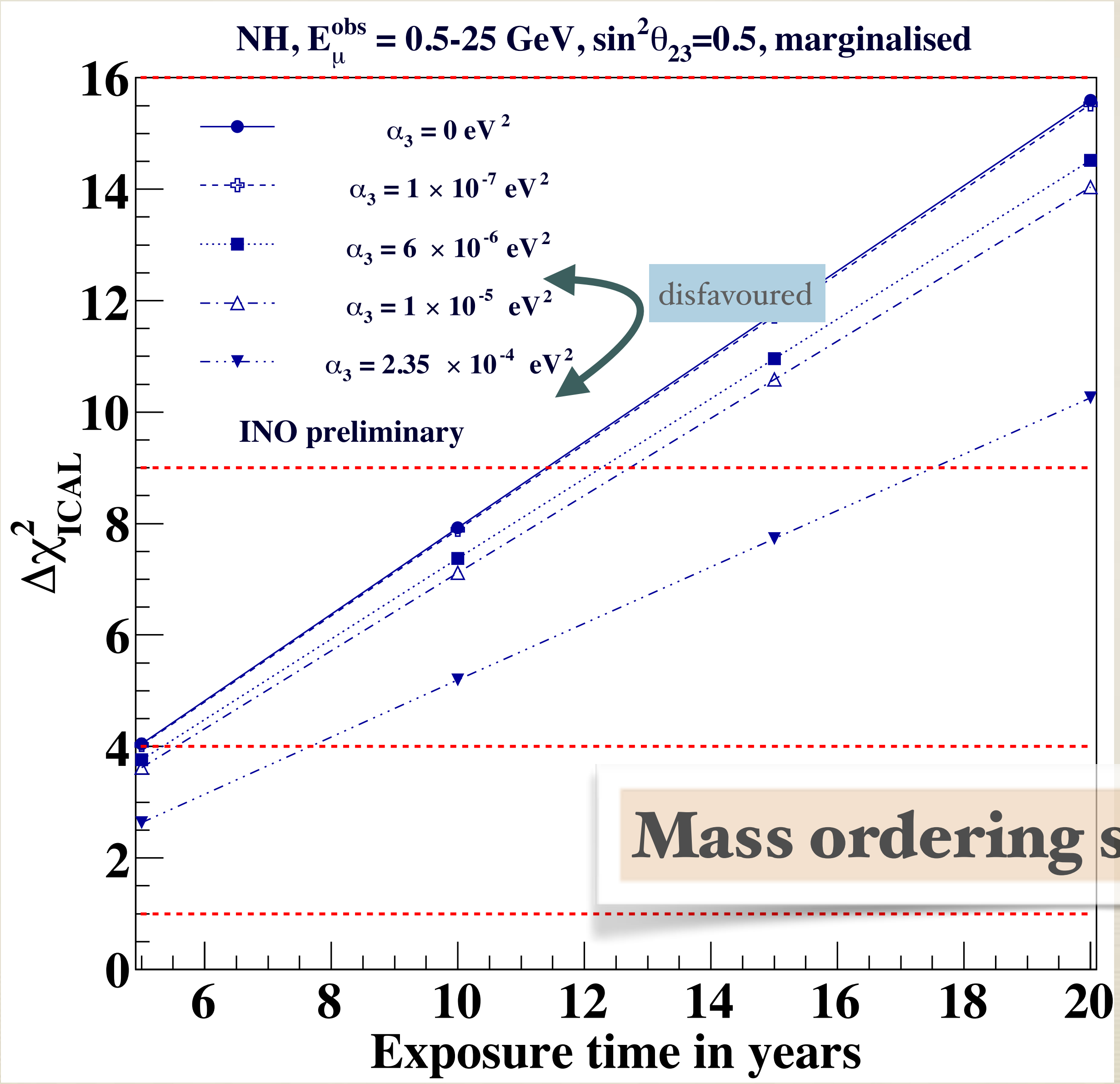
Impact on Mass Hierarchy Determination





Poster by Lakshmi S. Mohan

Impact on Mass Hierarchy Determination



Poster by Lakshmi S. Mohan

Conclusions

* Neutrino decay can give a zenith angle dependent depletion of atmospheric events
* The zenith angle and E spectra can thus be used to constrain and/or search for neutrino decay
* Atmospheric neutrinos with their wide E and L range are very suitable for these searches
* Presence of decay will affect the theta23 measurements - range as well as octant in all experiments
* Presence of decay will affect mass hierarchy measurement in atmospheric neutrino experiments