Probing BSM Neutrinos at DUNE

(Participation of the Institute of Physics (IOP), Bhubaneswar in the DUNE Project - Part I)

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DUNE-India Meeting 2025, TIFR, Mumbai

About Institute of Physics (IOP), Bhubaneswar, India

- Autonomous research institute funded by Department of Atomic Energy (DAE), Government of India
- Faculty: ~17; Postdocs: ~40; Ph.D. students: ~50
- Strong theoretical and experimental programs in particle and astroparticle physics - theoretical and experimental high-energy physics, condensed-matter physics, nuclear physics and string theory
- Active in international collaborations: CMS, ALICE

Key area of research in particle physics

- Particle physics phenomenology (Neutrino and Beyond Standard Model Physics)
- Dark Matter and astroparticle physics
- Strong emphasis in collider physics
- Neutrino oscillation physics, IceCube collaboration.

Participation from Institute of Physics (IOP) in DUNE- Associate Member

1. Prof. Manimala Mitra, Associate Professor at Institute of Physics, Bhubaneswar

» **Recently IOP (Manimala Mitra and group members) joined DUNE collaboration as associate member institution**

Postdoctoral fellows and Ph.D students

2. Dr. Antara Dey, postdoctoral fellow at IOP

Research expertise: statistical analysis, neutrino cosmology, data analysis of Planck, mock data analysis for Square Kilometre Array (SKA)

3. Dr. Arvind R. Bhaskar, postdoctoral fellow at IOP

Research area: neutrino (HNL) phenomenology

4. Mr. Subham Saha, Ph.D student at IOP

Research area: HNL physics, application of ML techniques for HNL searches

Planning to supervise new Ph.D student from August, 2025 onward with a primary focus on DUNE-related research.

Research Interest and Expertise

Prof. Manimala Mitra, Associate Professor at Institute of Physics, Bhubaneswar

- ***Research Expertise:*** *Neutrino Physics and Heavy Neutral Lepton searches (HNL), Dark Matter and Astroparticle Physics* *(>70 publications in JHEP, PRD, PLB, and PRL)*

- *Pursued sensitivity study of eV sterile neutrino and CP violation in DUNE and other Long-Baseline neutrino experiments*

JHEP 09 (2021) 162, Nishat Fiza, Mehedi Masud, and Manimala Mitra

- *Pursued HNL phenomenology at SHiP, Belle-II, NA62, FCC-ee*

Phys. Rev. D 96 (2017) 3, 035023, Phys.Rev.D 100 (2019) 9, 095022, Phys.Rev.D 104 (2021) 9, 095009

- *Developed boosted HNL search strategy for Left Right Symmetric Model at the LHC (Phys. Rev. D 94 (2016), 095016), which was pursued by the ATLAS collaboration (Phys. Lett. B 798 (2019), 134942)*

- *Had been an ATLAS Analysis Consultant/Expert (ACE) for Boosted HNL search for LRSM (for the analysis of Phys. Lett. B 798 (2019), 134942)*

- *Prior PI on Indo-French CEFIPRA Grant and Royal Society International Exchange Grant*

- *Supervised four Ph.D students and mentored seven postdoctoral fellows*

In addition, Prof. Sanjib Kumar Agarwalla's group at IOP plays a key role in neutrino oscillation physics, contributing to physics at long-baseline experiments and high-energy neutrino studies.

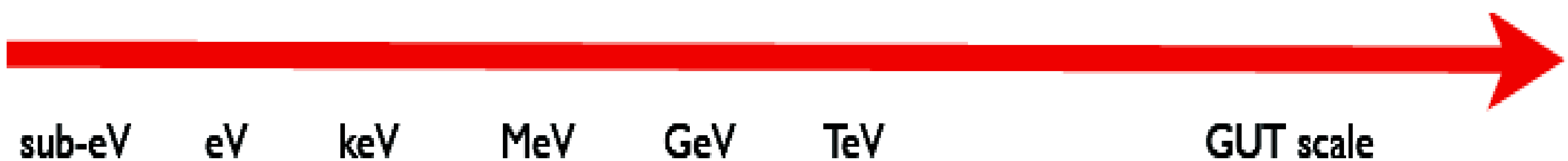
Sterile Neutrino:(HNL)

Heavy Neutrino N

Key ingredients behind neutrino mass generation

Heavy neutrino mass $M \sim$ eV- GUT scale

- Detection $\rightarrow$ Collider, Oscillation, Peak searches, Kink, $(\beta\beta)_{0\nu}$-decay,...
- And $\rightarrow$ LFV processes, Non-unitary effect,...

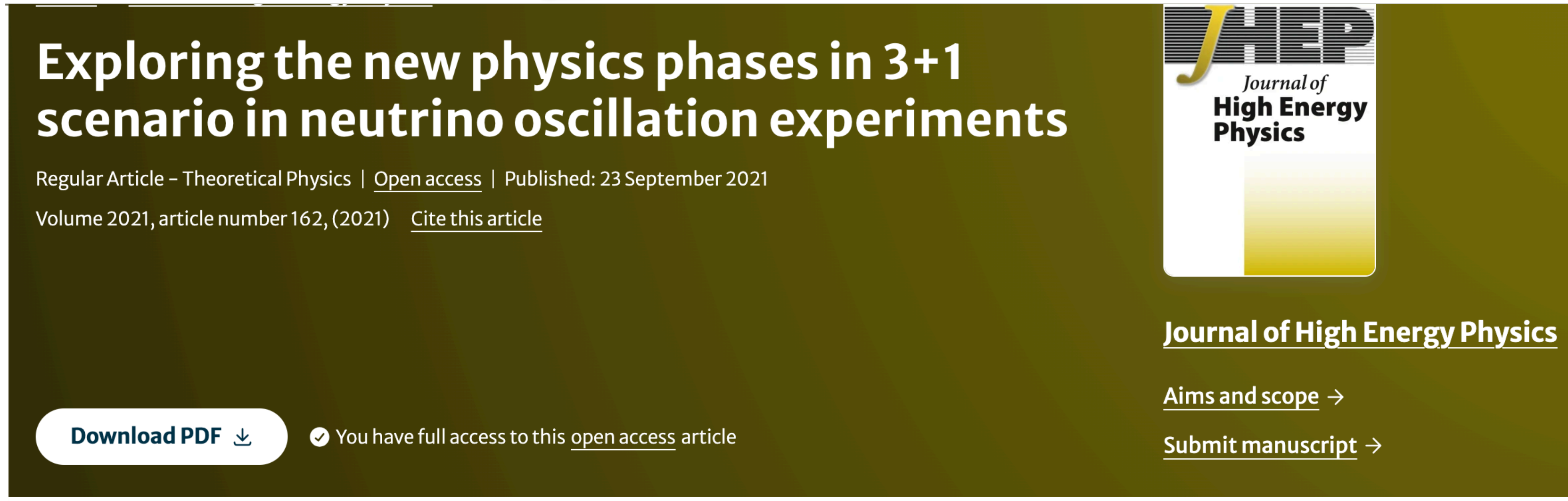


Oscillation Kinks Peak searches

Decay

Collider Searches

eV Scale HNL/Sterile Neutrino and CP Violation



Nishat Fiza, Mehedi Masud & Manimala Mitra

Use our pre-submission checklist

One eV scale sterile neutrino

CP phases $\delta_{13}, \delta_{24}, \delta_{34}$

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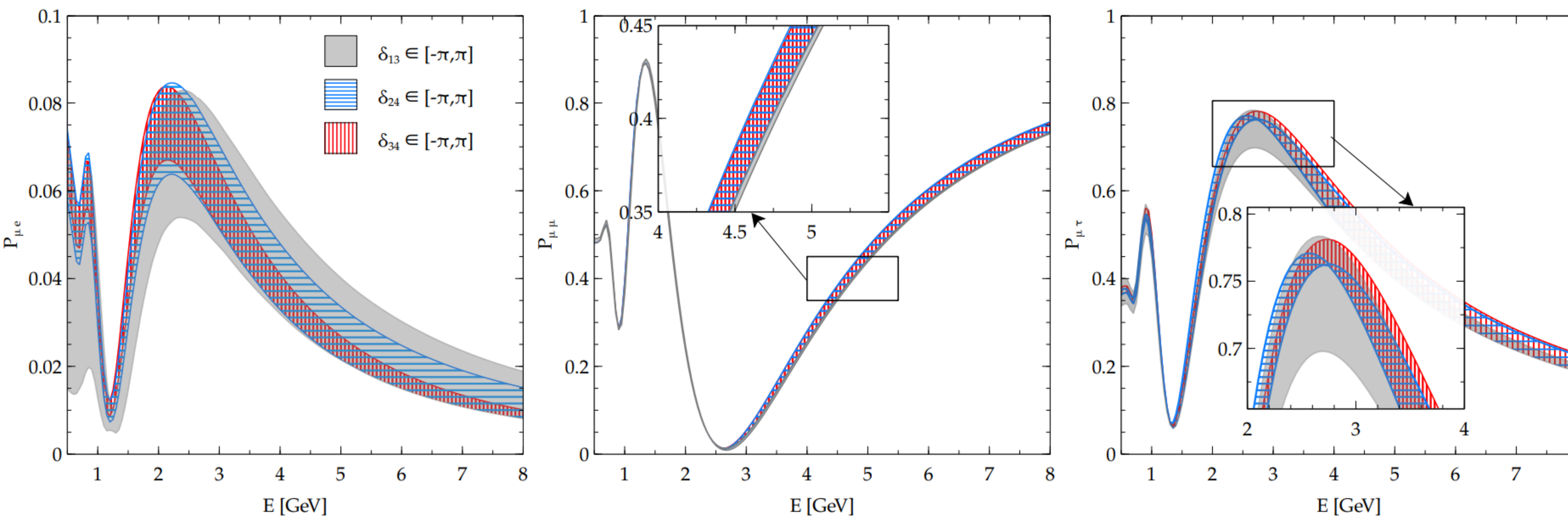
$$U^{3+1} = R(\theta_{34}, \delta_{34}) R(\theta_{24}, \delta_{24}) R(\theta_{14}) R(\theta_{13}) R(\theta_{23}, \delta_{13}) R(\theta_{12}),$$



Proposed Contributions to DUNE

Sensitivity studies, simulation and analysis

1. *Sensitivity studies of Heavy Neutral Lepton (HNL) at DUNE near detector and analysis for ProtoDUNE*
2. *HNL are SM gauge singlet leptons- essential ingredients of light neutrino mass generation*
3. *Machine Learning techniques for HNL reconstruction at DUNE near detector*
4. *Studies on light dark matter and quantum decoherence at DUNE*
5. *Immediate engagement in simulations and analysis*

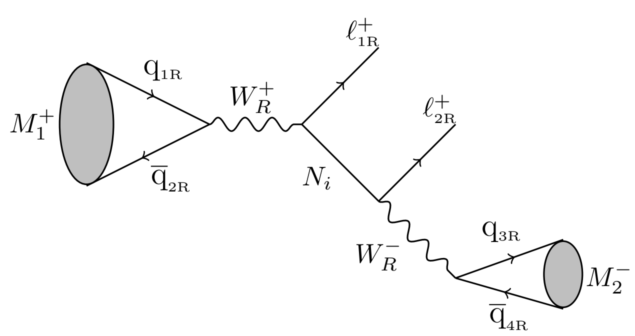
Long-term contributions to DUNE

- *Plan for expanding team including new students & postdocs*
- *Involvement in data acquisition and analysis, hardware development studies, and planned collaborative visits to Fermilab for students and postdocs*
- *IOP can contribute both in the near and far detector physics in the DUNE experiment. We look forward to obtaining Regular Membership in the near future*

1. Heavy Neutral Lepton as a Long Lived Particle,

- **Production from $K^{\pm}, D_s^{\pm}, M^{\pm} \to \ell^{\pm} N$ and also pair production NN from heavier meson decay or directly**

- **decay in near detector to $N \to (e^{\pm}, \mu^{\pm}, \tau^{\pm}) + \pi^{\mp}, \nu\gamma$, and fully hadronic final state (for NREFT framework)**

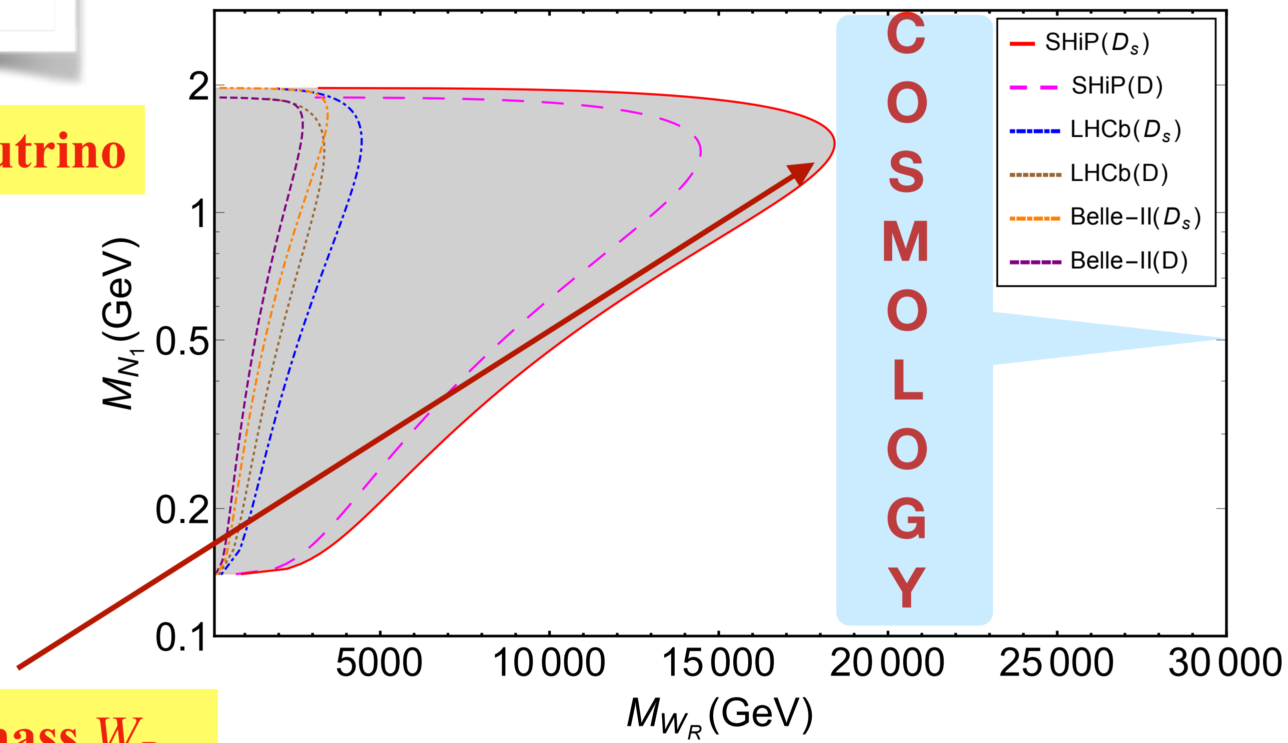


$$M^+ \to e^+ e^+ \pi^-$$

Sensitive to Sub-GeV Neutrino

S. Mandal, M. Mitra, N. Sinha,PRD 96 (2017) 3, 035023

- **M. Mitra et al., *Phys.Rev.D* 100 (2019) 9, 095022, *Phys.Rev.D* 104 (2021) 9, 095009**



Sensitive to a very high mass W_R

2. Application of ML in detection of neutrinos and LLPs in DUNE

(Extension/embedding in LArSoft and Pandora, NuGraph2)

3. Some of the other areas of interests: study of tau neutrino reconstruction, light dark matter, quantum decoherence

Summary and Outlook

- *Institute of Physics, Bhubaneswar is a new Associate Member of DUNE. The newly joined group has one associate professor, two postdoctoral fellows and one ph.D student (Manimala Mitra's group).*
- *The members have strong theoretical and computational capabilities and bring unique expertise in HNLs, ML applications, and we plan to contribute both theoretically and via detector studies.*
- *Planning to supervise a new Ph.D student from August, 2025 onwards with a primary focus on DUNE-related research.*
- *We propose to contribute to HNL searches, ML applications in particle reconstruction in the near detector, sensitivity studies for light dark matter and quantum decoherence at DUNE and analysis of ProtoDUNE.*
- *We plan to seek Regular Membership at DUNE in future. IOP currently has two active groups in neutrino physics. Prof. Mitra's group focusses on HNLs, BSM physics, and detector studies, while Prof. Agarwalla's group brings expertise in neutrino oscillation physics. Together, IOP can provide complementary and broad research contributions to DUNE, both near and far detectors.*
- *We look forward to engaging deeply with the DUNE collaboration and contributing to its scientific mission.*

Thank You

eV scale sterile neutrino

$$U^{3+1} = R(\theta_{34}, \delta_{34})R(\theta_{24}, \delta_{24})R(\theta_{14})R(\theta_{13})R(\theta_{23}, \delta_{13})R(\theta_{12}),$$

One eV scale sterile neutrino

CP phases $\delta_{13}, \delta_{24}, \delta_{34}$

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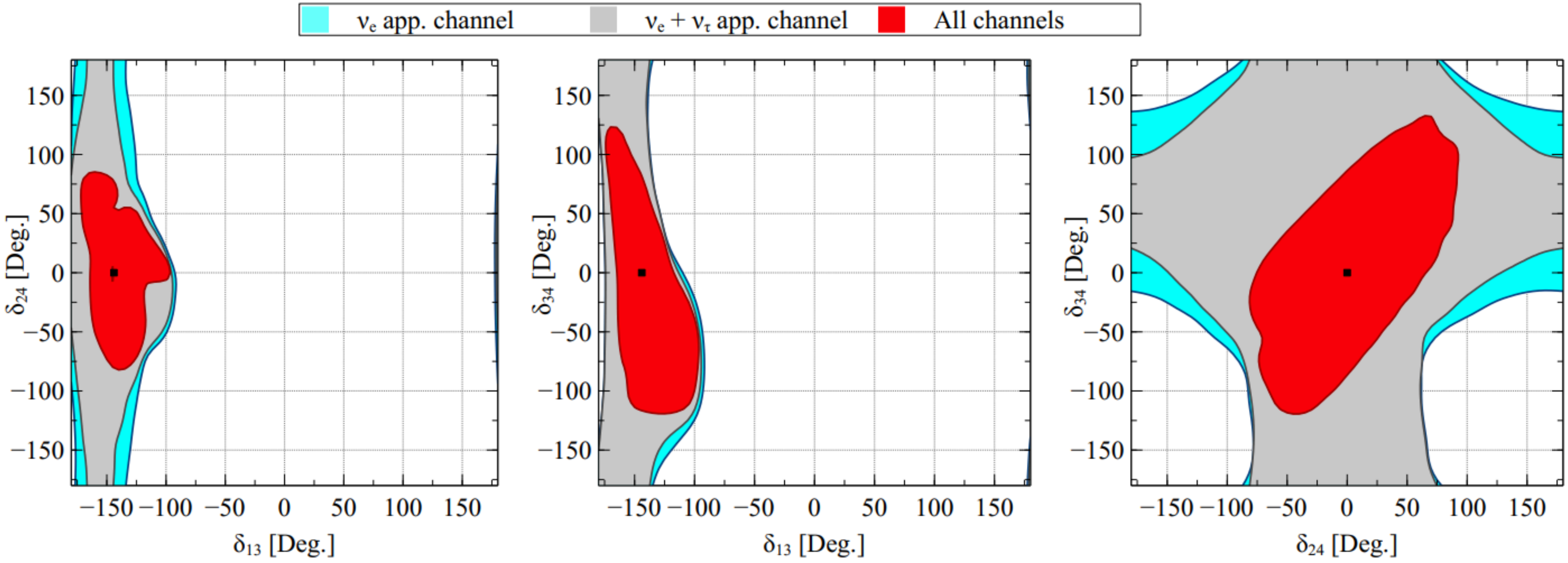
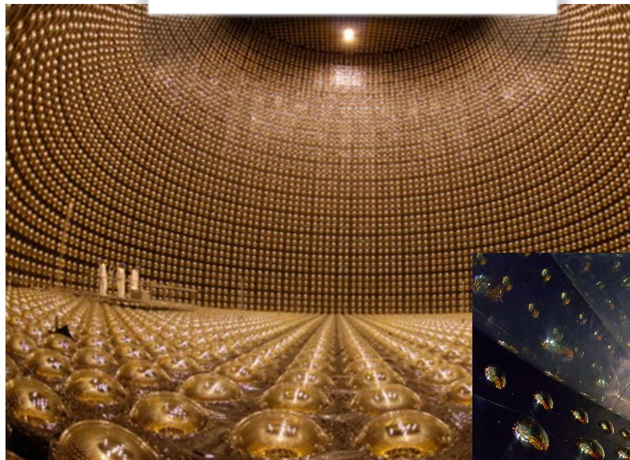


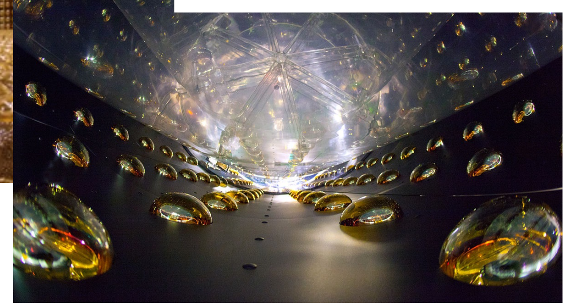
Experimental Observations

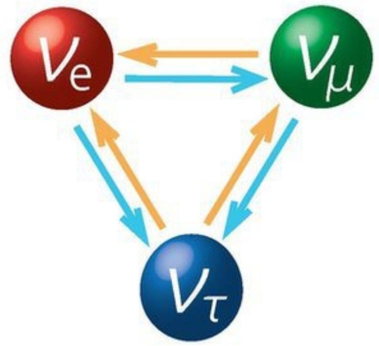
eV neutrino mass and mixing from oscillation and non-oscillation experiments

$$\nu_1, \nu_2, \nu_3 \longrightarrow m_1, m_2, m_3$$

Oscillation







Mass square differences and mixings

$$\Delta m^2_{21} = (6.92 - 8.05) \times 10^{-5}\, \mathrm{eV}^2$$

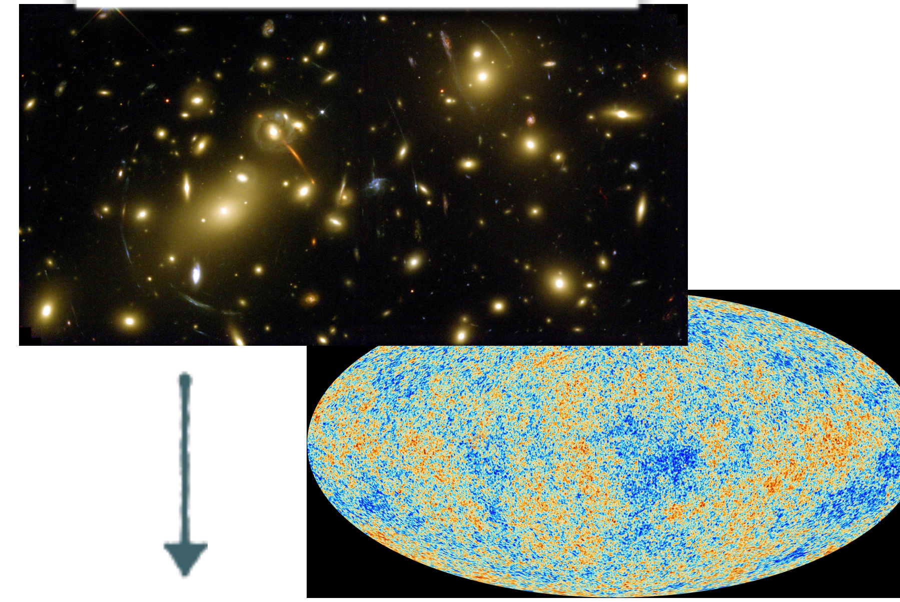
$$\Delta m^2_{31} = (2.46 - 2.60) \times 10^{-3}\, \mathrm{eV}^2$$

Large angle $\theta_{12} \sim 33.6^\circ, \theta_{23} \sim 48.5^\circ$

Non-zero $\theta_{13} \sim 8.5^\circ$ **(DAYA BAY, RENO)**

I. Esteban et al.,JHEP 12 (2024) 216, *JHEP* 09 (2020) 178

Non-Oscillation



Sum of neutrino masses

Bound from cosmology

$$\Sigma m_i < \mathcal{O}(0.12 - 0.72) \quad \mathrm{eV}$$

(Planck Collaboration, arXiv 1807.06209)

Beta decay and Neutrinoless double beta decay

$$m_\beta < 0.45\, \mathrm{eV},\ |\mathrm{m_{ee}}| < (28 - 122)\, \mathrm{meV}$$

KATRIN Collaboration 2024 and KAMLND-Zen 2024

Can not be explained with SM without adding any additional particle

Origin of Neutrino Mass

Seesaw

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979,

Yanagida 1979, Mohapatra, Senjanovic 1980

Majorana mass of the standard model neutrino is generated from higher dimensional operator

$\mathcal{L}_f(\phi,\chi)$ at higher scale $\xrightarrow{\chi \text{ integrated out}}$ $\mathcal{L}_{\text{eff}}(\phi)$ at lower scale

EFT Description

$$\hat{O}_5 = \frac{LLHH}{M}$$

- **Violates $B-L$ by 2 units**
- Gauge invariance (Weinberg, PRL 43, 1979)

$$\frac{y^2 LL\langle H\rangle\langle H\rangle}{M} \Rightarrow m_\nu = \nu^T C^{-1}\nu$$

$m_\nu \propto \frac{y^2 v^2}{\boxed{\text{M}}} \rightarrow$ **eV neutrino due to heavy M**

UV Completion

Type-I,II,III

Inverse Seesaw

Gauged B-L and Left Right Symmetric Model

Scotogenic model