Sterile Neutrino Seacrhes

Josu Hernandez-Garcia

NuFact 2018 | WG5

Horizon 2020

Based on

- JHEP **04** (2017) 153. MB, PC, EFM, JHG & JLP.
- arXiv 1803.02362. MB, EFM, JG, JHG & JS.

In collaboration with


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Introduction

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The SM is successful and predicts a wide variety of phenomena that has been testes experimentally to an incredible accuracy.

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However, there are some open problems $\Rightarrow$ open oportunities

Represent our best window for New Physics

Introduction: SM Open Problems

- Dark Matter
- Matter-antimatter asymmetry (BAU)
- Neutrino masses
- Flavor Puzzle
- Hierarchy problem
- Strong CP, Unification, ...

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- Dirac neutrino masses

All fermions get masses through the Yukawa interaction

$$\overline{\psi_L} y_\psi \phi \psi_R \xrightarrow[\text{EWSB}]{\text{after}} y_\psi \frac{v_{\text{EW}}}{\sqrt{2}} \overline{\psi_L} \psi_R$$

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$d = 5 \Rightarrow$ Is SM low energy remnant of higher energy theory?

And therefore neutrinos are strictly massless in the SM.

The SM must be extended to account for neutrino oscillations.

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P. Minkowski, Phys. Lett. **B67** (1977) 421.
T. Yanagida. Proceedings of the Workshop on the Baryon Number of the Universe.
M. Gell-Mann, P. Ramond, and R. Slansky, Print-80-0576 (CERN).
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** (1980) 912.

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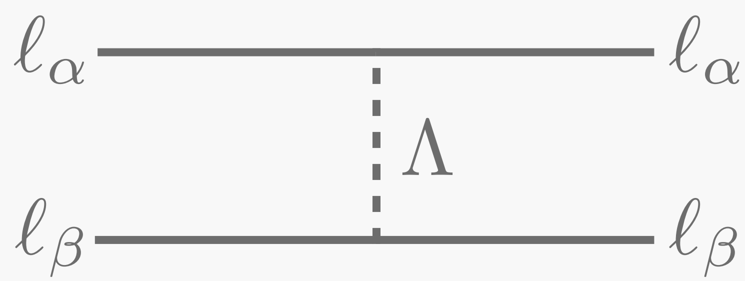

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J. Schechter and J. W. F. Valle, Phys. Rev. **D22** (1980) 2227.
C. Wetterich, Nucl. Phys. **B187** (1981) 343–375.
G. Lazarides, Q. Shafi, and C. Wetterich, Nucl. Phys. **B181** (1981) 287–300.
R. N. Mohapatra and G. Senjanovic, Phys. Rev. **D23** (1981) 165.

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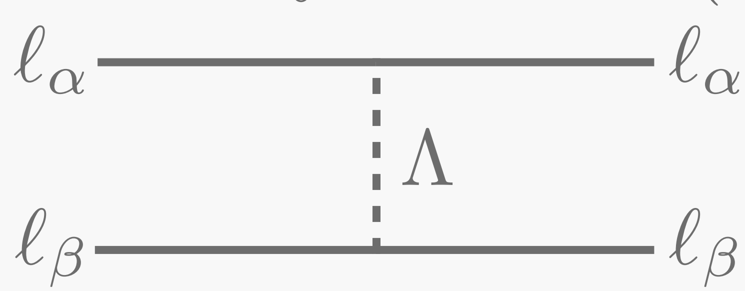
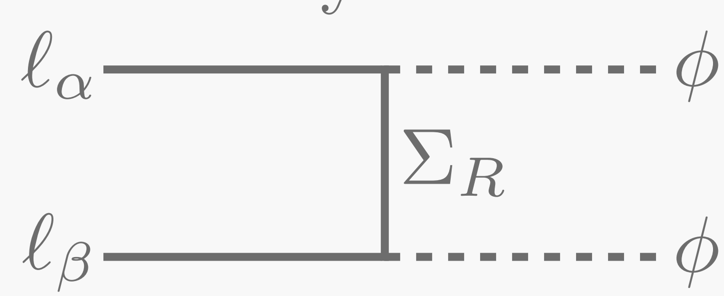


- Type III Seesaw: heavy fermionic $SU(2)_L$ triplets Σ_R



R. Foot, H. Lew, X. G. He, and G. C. Joshi, Z. Phys. **C44** (1989) 441. ...

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Introduction: SM + Type I Seesaw

The SM is enlarged by an arbitrary number of N_R

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\overline{N_R}\partial\!\!\!/ N_R - \left(\frac{1}{2}\overline{N_{Ri}}(M_N)_{ij}N^c_{Rj} + (y_N)_{i\alpha}\overline{N_{Ri}}\phi^\dagger \ell_{L\alpha}\right) + \mathrm{h.c.}$$

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Yukawa interaction

Dirac neutrino masses

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Allowed Majorana mass for N_R

New Physics scale

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Experimental verification needed.

Introduction: SM + Type I Seesaw

The neutrino mass matrix

$$U^T \begin{pmatrix} 0 & m_D^T \\ m_D & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

diagonalized by the full Unitary mixing matrix U

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

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$$U = \begin{array}{cl} \begin{array}{cc} \text{light} & \end{array} & \\ \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix} & \begin{array}{l} \text{active} \\ \end{array} \end{array}$$

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$$
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\end{array}
$$

with $N \equiv (I - \alpha)\, U_{\mathrm{PMNS}}$ and α lower triangular matrix

$$
\alpha = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix} \simeq \begin{pmatrix} \sum_{i=4}^{n} \frac{1}{2}|\Theta_{ei}|^2 & 0 & 0 \\ \sum_{i=4}^{n} \Theta_{\mu i}\Theta_{ei}^* & \sum_{i=4}^{n} \frac{1}{2}|\Theta_{\mu i}|^2 & 0 \\ \sum_{i=4}^{n} \Theta_{\tau i}\Theta_{ei}^* & \sum_{i=4}^{n} \Theta_{\tau i}\Theta_{\mu i}^* & \sum_{i=4}^{n} \frac{1}{2}|\Theta_{\tau i}|^2 \end{pmatrix}
$$

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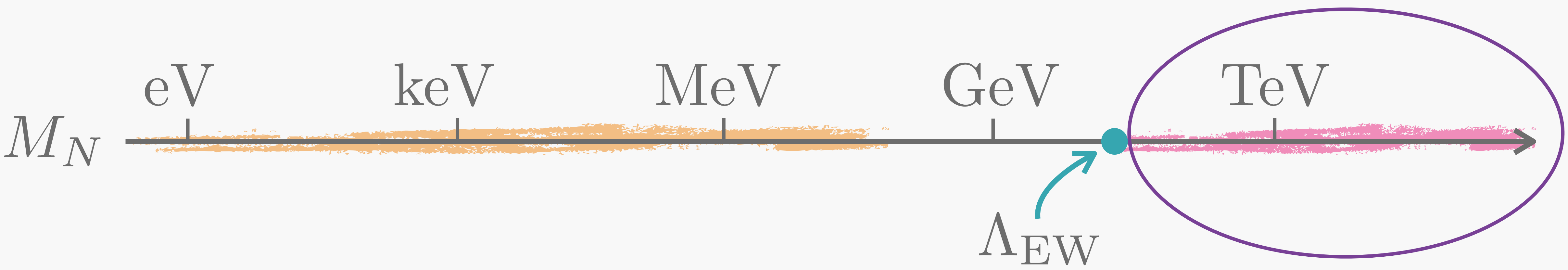
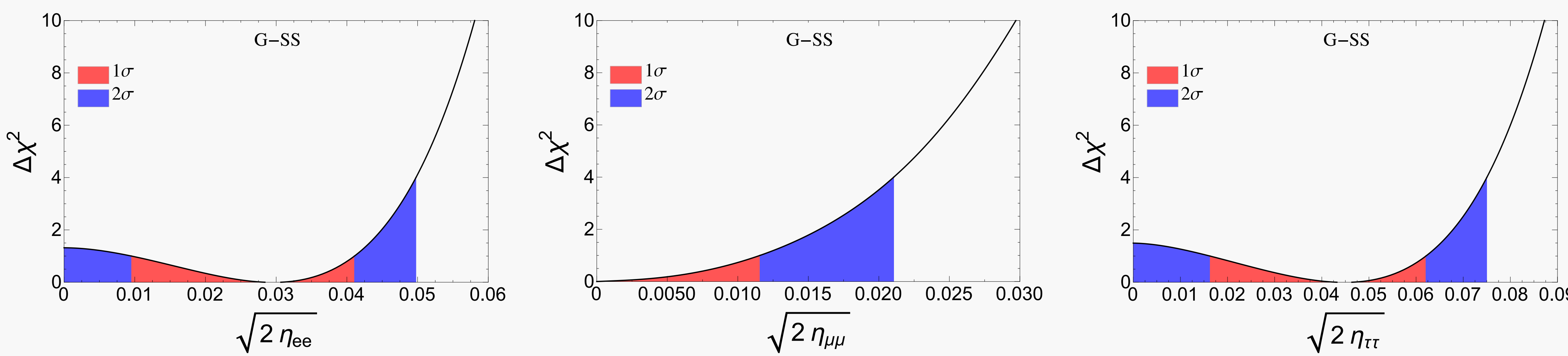


EW and flavor observables



$$\boxed{\theta \sim 10^{-2}}$$

E. Fernandez-Martinez, JHG, J. Lopez-Pavon, JHEP **08** 2016 033

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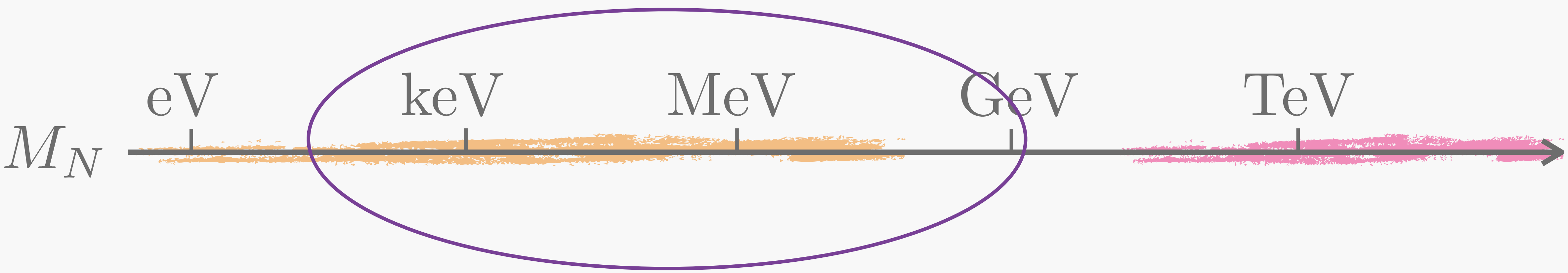
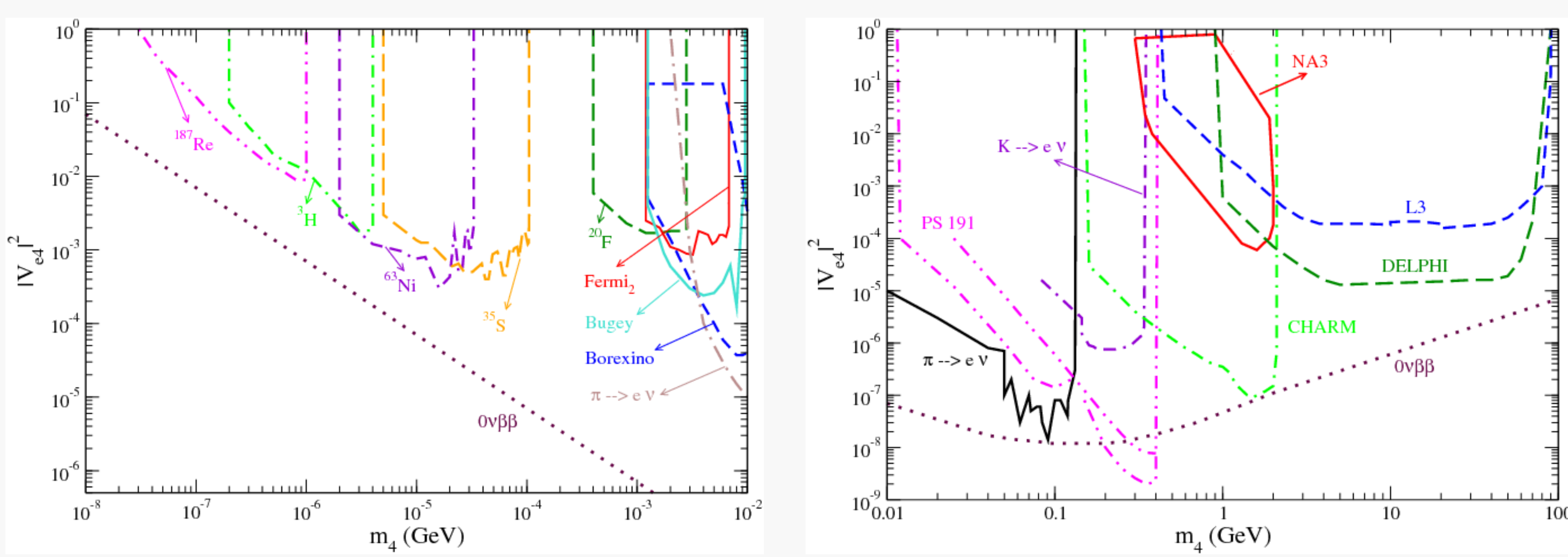


Kinks in β-decay and peaks
in meson decay searches



$\boxed{\theta \sim 10^{-4}}$

A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP **05** (2009) 030.

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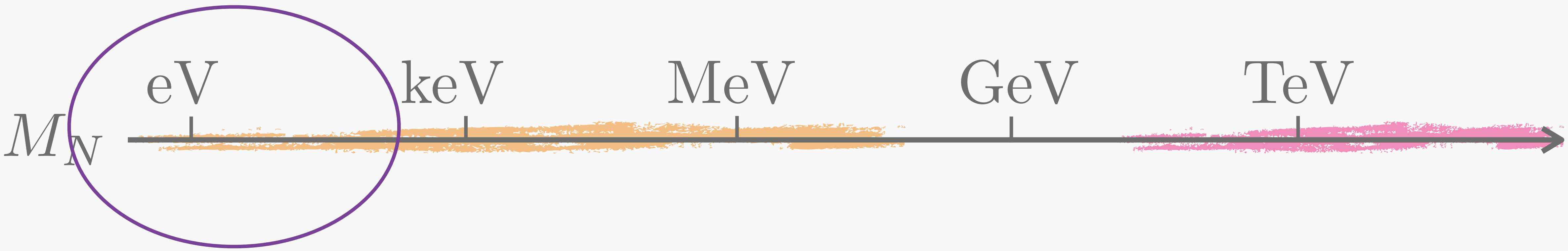
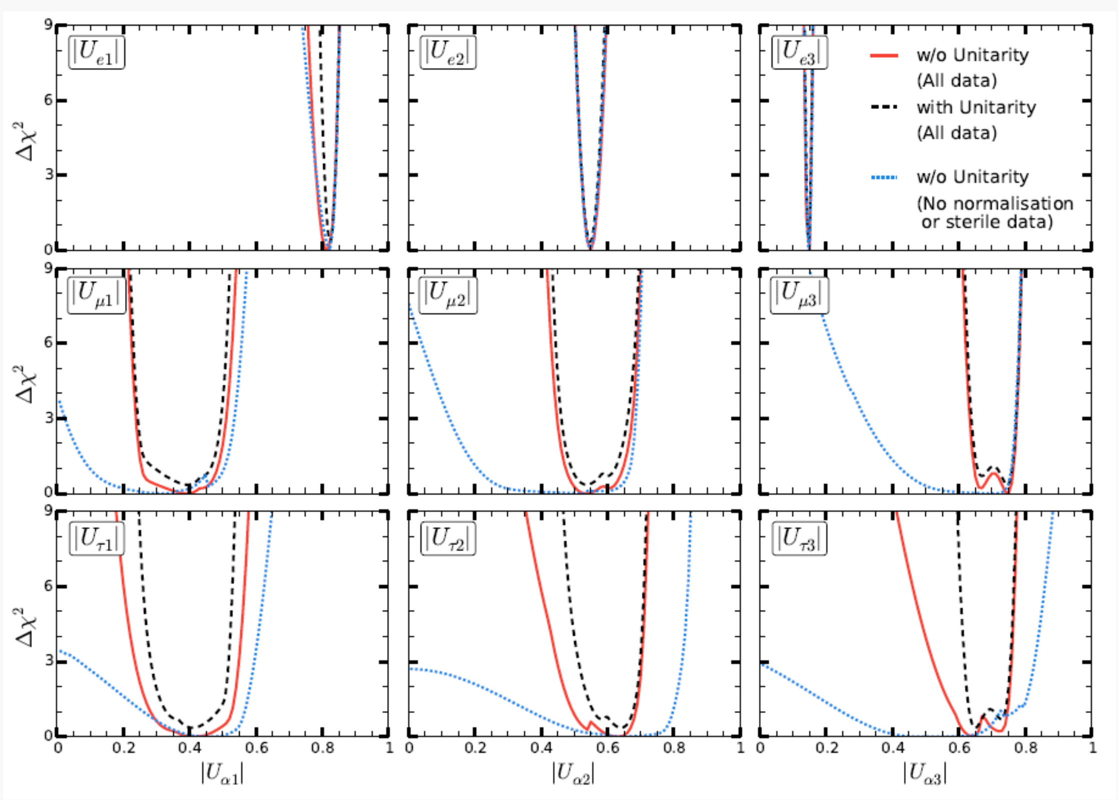


ν oscillation searches



$\boxed{\theta \sim 10^{-1}}$

S. Parke and M. Ross-Lonergan, arXiv:1508.05095.

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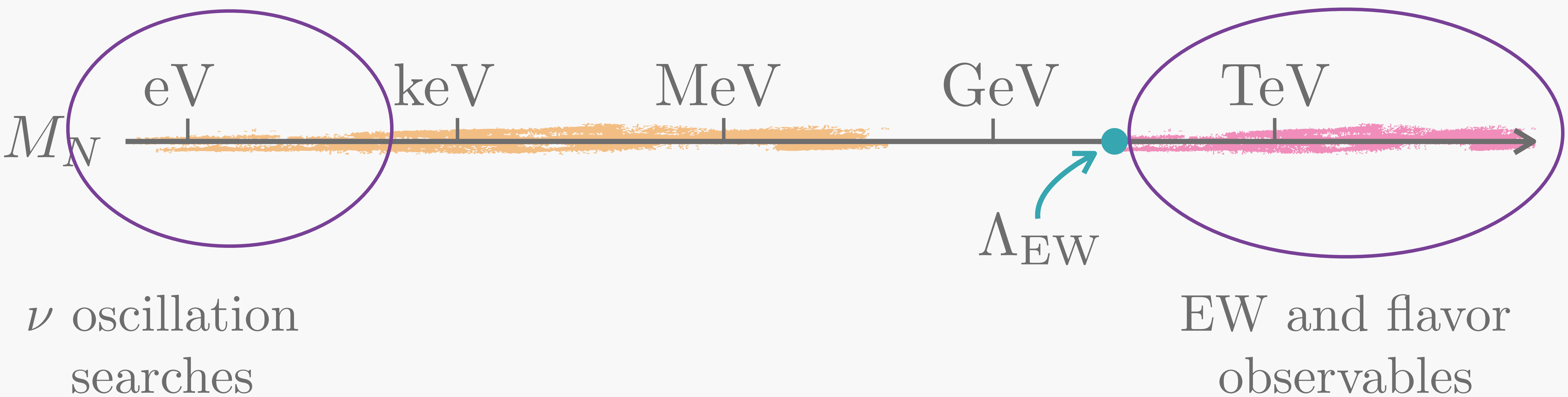

At some level, both limits

- Very high ($M_N > \Lambda_{\rm EW}$) neutrino $\rightarrow$ Non-Unitarity
- Very light ($M_N <$ keV) neutrino $\rightarrow$ sterile neutrinos

will impact neutrino oscillation searches.

Non-Unitarity vs Sterile Neutrinos at DUNE

Non-Unitarity vs Sterile Neutrinos

$$P_{\alpha\beta} = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

with

$$U = \begin{array}{cc} & \begin{array}{cc} \text{light} & \text{heavy} \end{array} \\ & \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix} \begin{array}{l} \text{active} \\ \text{sterile} \end{array} \end{array}$$

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Non-Unitarity vs Sterile Neutrinos

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Averaged-out limit $\frac{\Delta m^2_{iJ} L}{2E} \gg 1$

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$$+ \sum_{i,J} N_{\alpha i} N^*_{\beta i} \Theta^*_{\alpha j} \Theta_{\beta j} e^{-i\frac{\Delta m^2_{iJ} L}{2E}}$$

Averaged-out limit and at LO

Non-Unitarity vs Sterile Neutrinos

Non-Unitarity (very high masses) = Averaged-out sterile neutrinos (very light masses)

$$P_{\alpha\beta} = \sum_{i,j} N_{\alpha i} N^*_{\beta i} N^*_{\alpha j} N_{\beta j} e^{-i \frac{\Delta m^2_{ij} L}{2E}} \quad \text{at LO}$$

For $\dfrac{\Delta m^2_{ij}}{2E} \gg V_{\rm CC}, V_{\rm NC}$ this holds in matter.

However the bounds on the mixing in both limits are different.

Non-Unitarity vs Sterile Neutrinos

Present bounds on the two limits

- Non-Unitarity
  for $m > \Lambda_{\mathrm{EW}}$ (at 2σ)

$$
\begin{array}{ll}
\alpha_{ee} & 1.3 \cdot 10^{-3} \\
\alpha_{\mu\mu} & 2.2 \cdot 10^{-4} \\
\alpha_{\tau\tau} & 2.8 \cdot 10^{-3} \\
|\alpha_{\mu e}| & 6.8 \cdot 10^{-4} \\
|\alpha_{\tau e}| & 2.7 \cdot 10^{-3} \\
|\alpha_{\tau\mu}| & 1.2 \cdot 10^{-3}
\end{array}
$$

E. Fernandez-Martinez, JHG, J. Lopez-Pavon, JHEP **08** 2016 033

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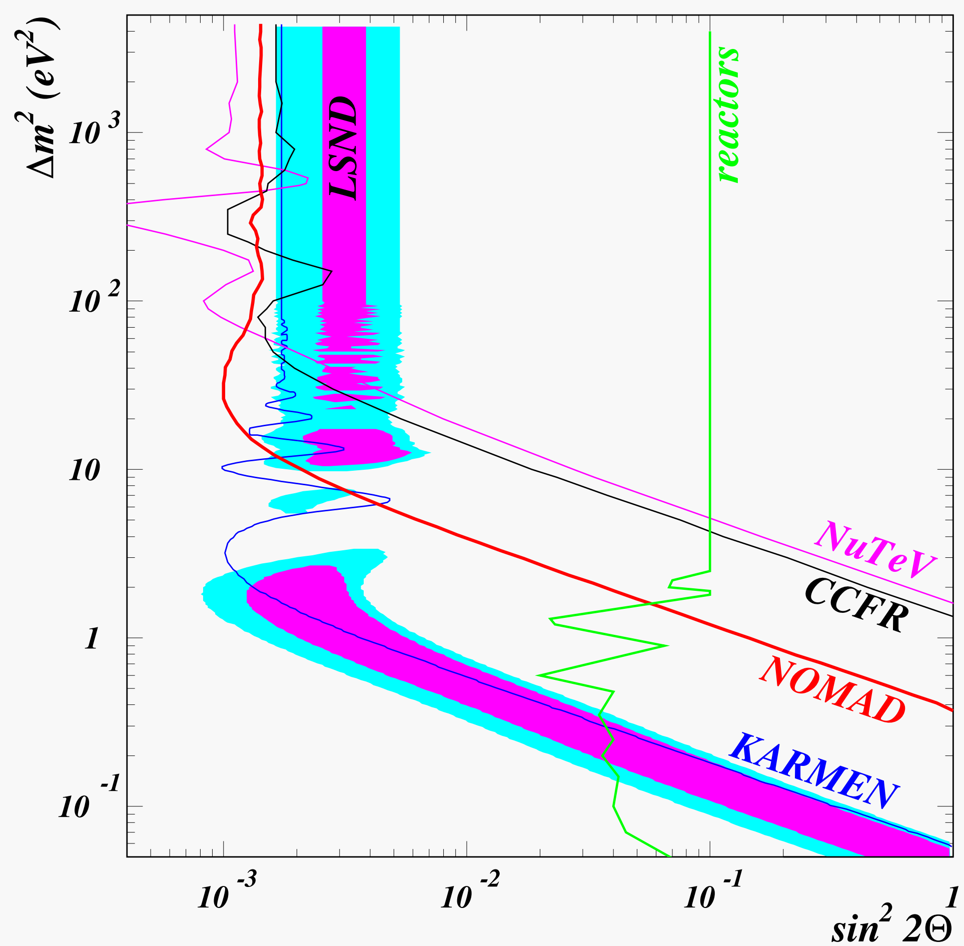
- Averaged-out sterile neutrinos



NOMAD Collaboration, Phys. Lett. **B570** (2003) 19–31.

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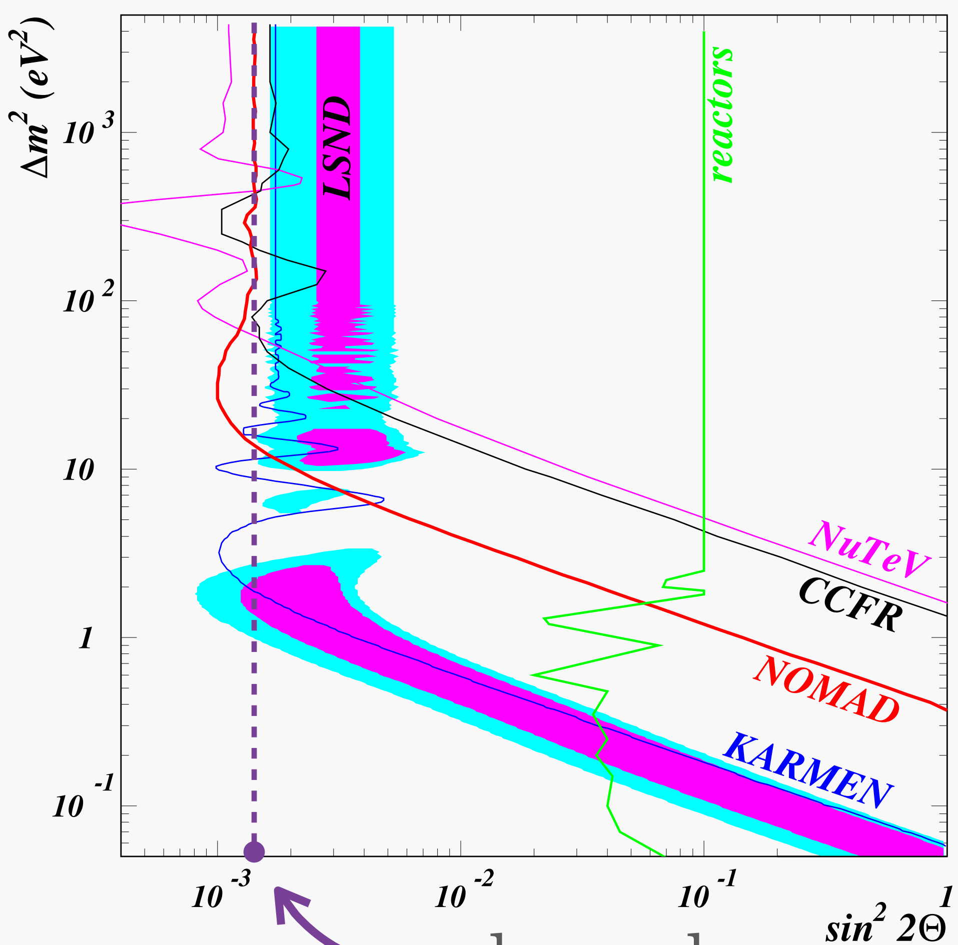

bound

NOMAD Collaboration, Phys. Lett. **B570** (2003) 19–31.

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- Averaged-out sterile neutrinos
  for $\Delta m^2 \gtrsim 100$ eV^2 (at 95% CL)

α_{ee}	$2.4 \cdot 10^{-2}$ [1]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-2}$ [2]
$\alpha_{\tau\tau}$	$1.0 \cdot 10^{-1}$ [3]
$\lvert\alpha_{\mu e}\rvert$	$2.5 \cdot 10^{-2}$ [4]
$\lvert\alpha_{\tau e}\rvert$	$6.9 \cdot 10^{-2}$
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[1] Bugey-3 [2] SK [3] MINOS [4,5] NOMAD

Non-Unitarity vs Sterile Neutrinos

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too small to be tested at
ν oscillation experiments

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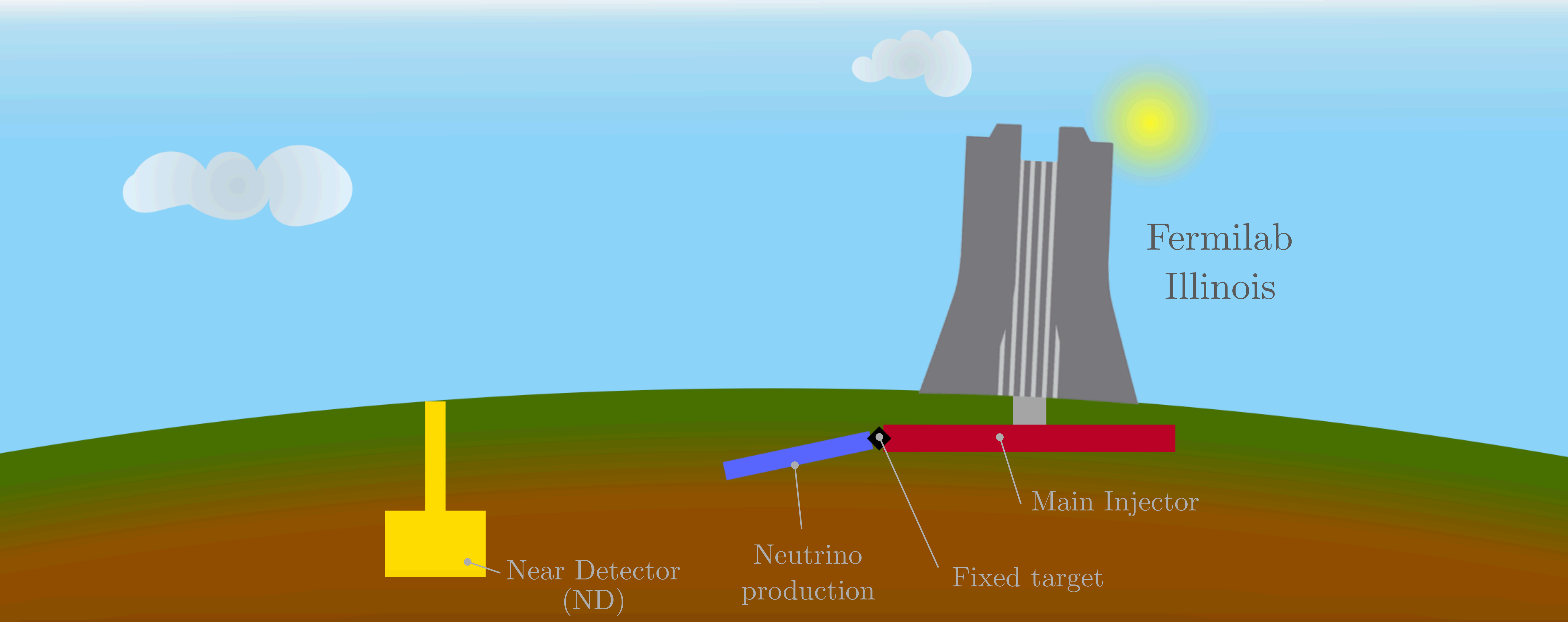
could be probed??

Non-Unitarity vs Sterile ν at DUNE

What is DUNE?

Deep Underground Neutrino Experiment



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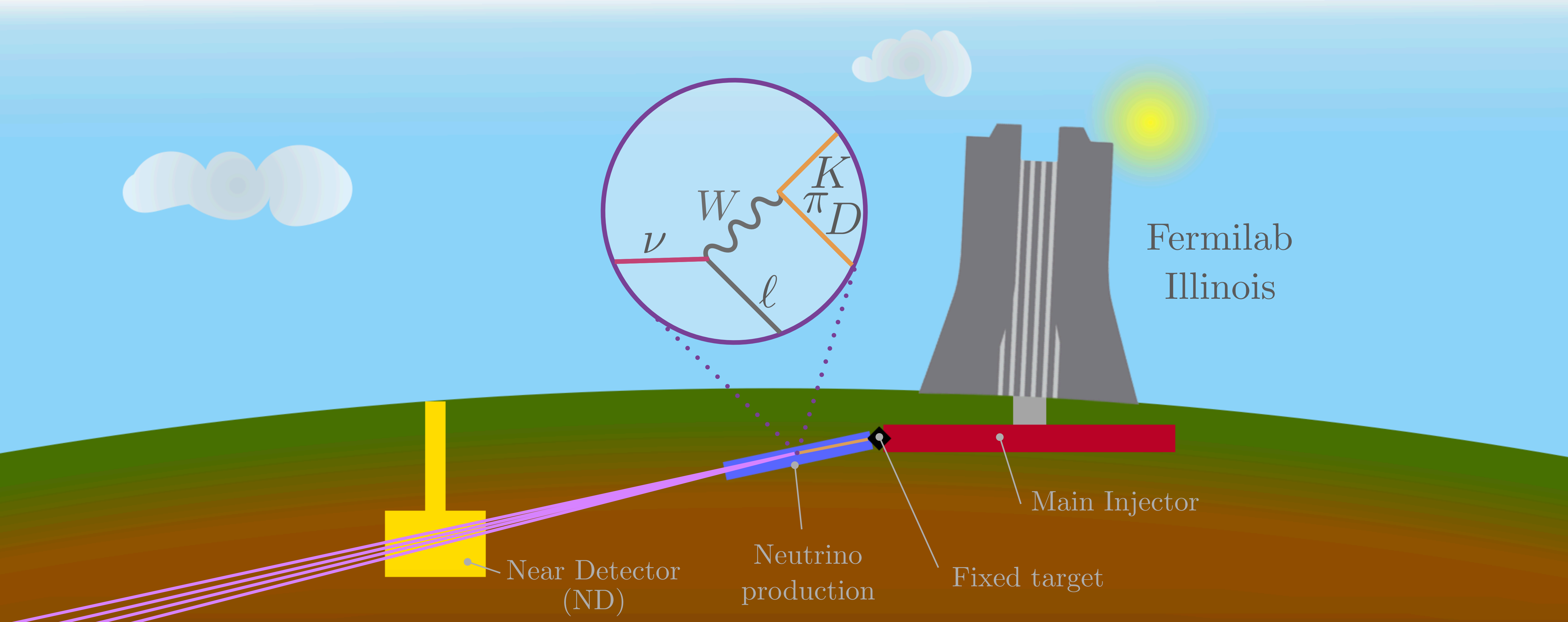

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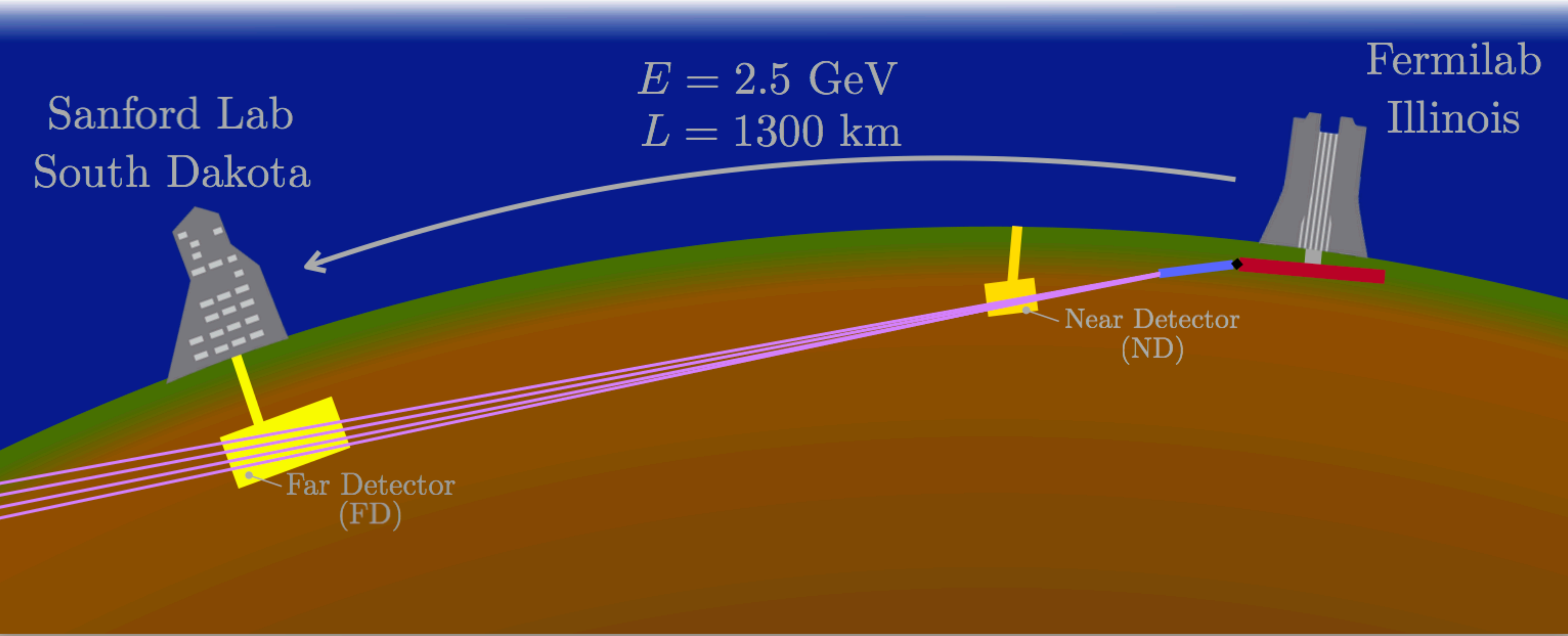

Non-Unitarity vs Sterile ν at DUNE

The role of the Near Detector (ND)

If flux and cross section at FD normalized with ND data

$$\overline{P}_{\alpha\beta} = \frac{P_{\alpha\beta}\left(L_{\mathrm{FD}}\right)}{P_{\alpha\beta}\left(L_{\mathrm{ND}}\right)}$$

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Non-Unitarity = sterile ν osc. averaged at the ND

DUNE setup $\rightarrow \Delta m^2 \gtrsim 100\ \mathrm{eV}^2$

Non-Unitarity vs Sterile ν at DUNE

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DUNE setup $\rightarrow \Delta m^2 \gtrsim 100$ eV^2

- No

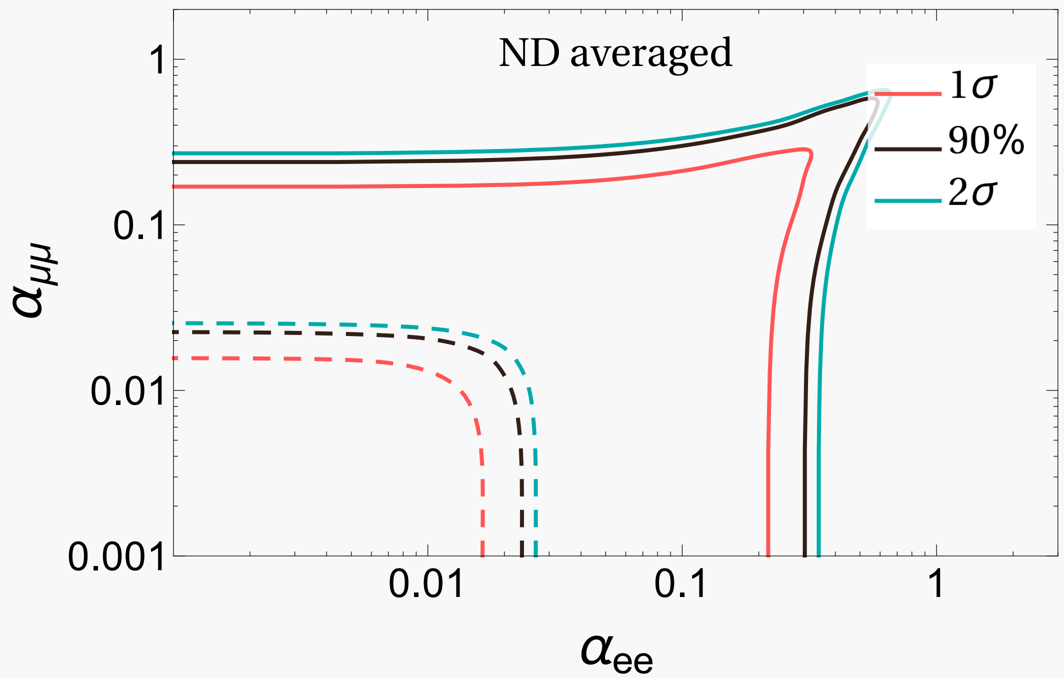
$$\overline{P}_{\alpha\beta} = \sum_{i,j} N_{\alpha i} N^*_{\beta i} N^*_{\alpha j} N_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

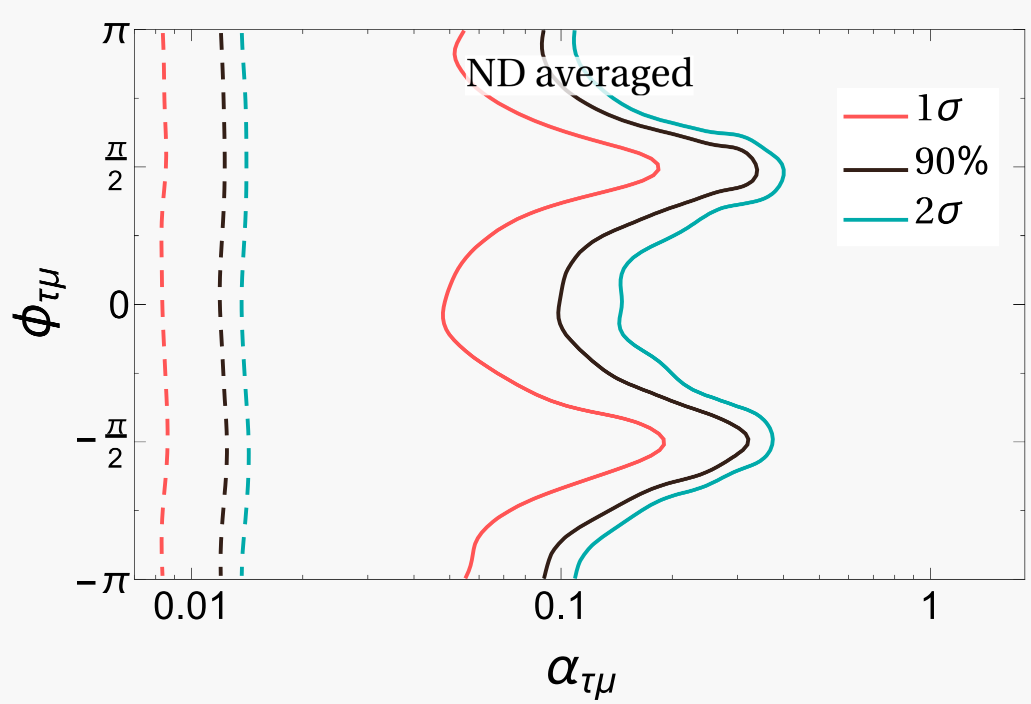
sterile neutrino oscillations undeveloped at the ND

DUNE setup $\rightarrow \Delta m^2 \sim (0.1, 1)$ eV^2

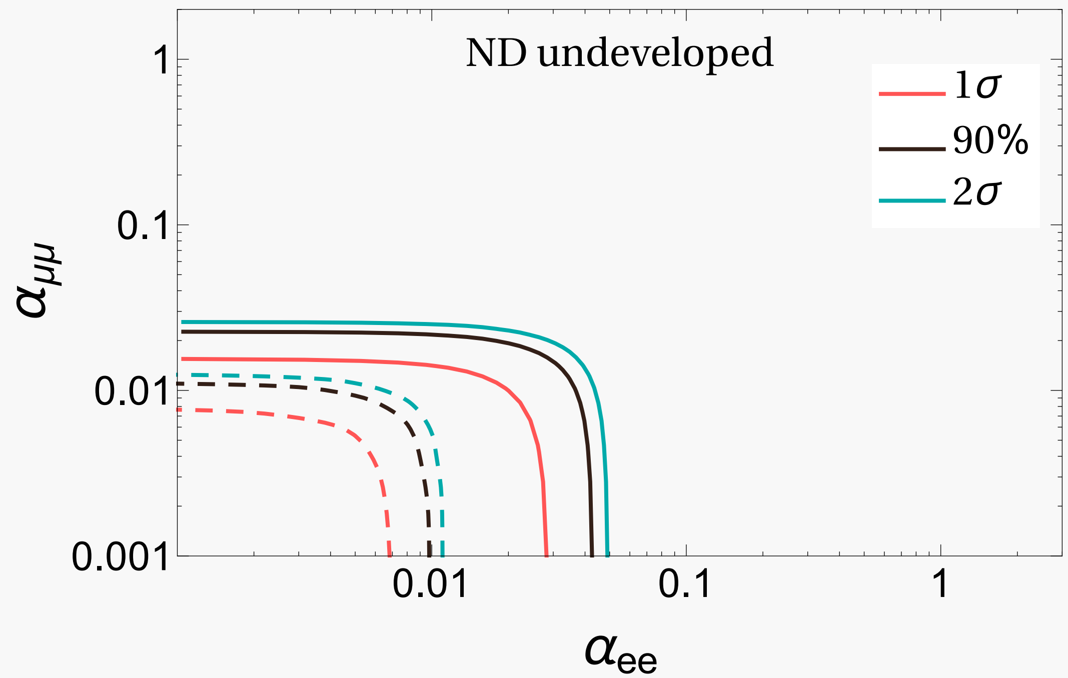
Non-Unitarity vs Sterile ν at DUNE

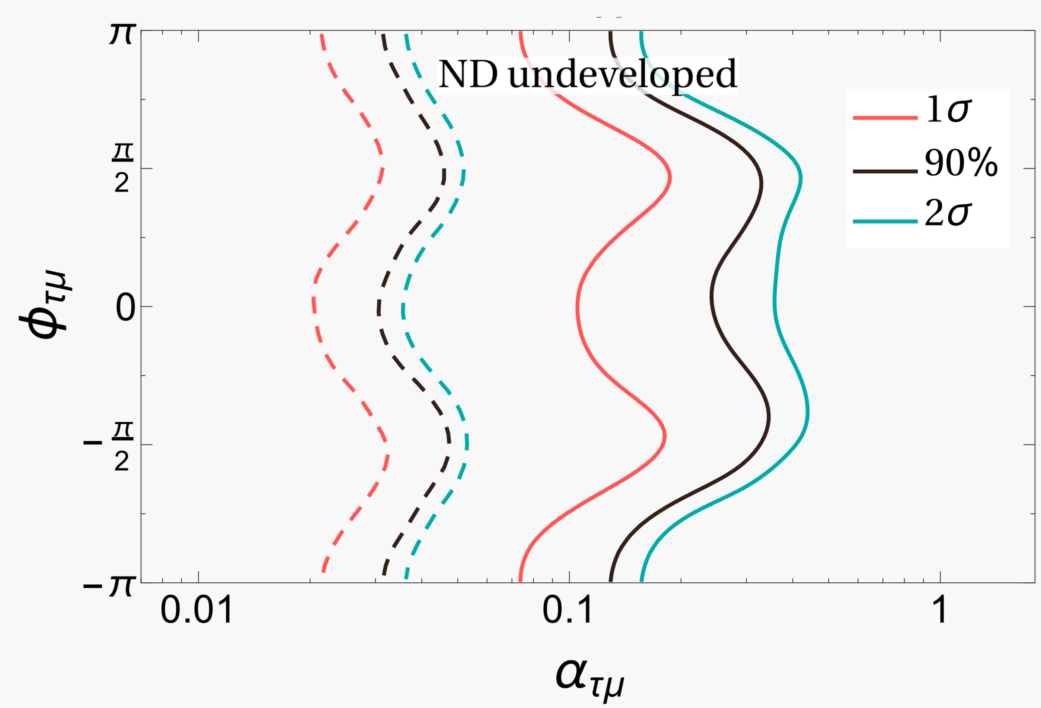
- Yes $\rightarrow$ ND averaged





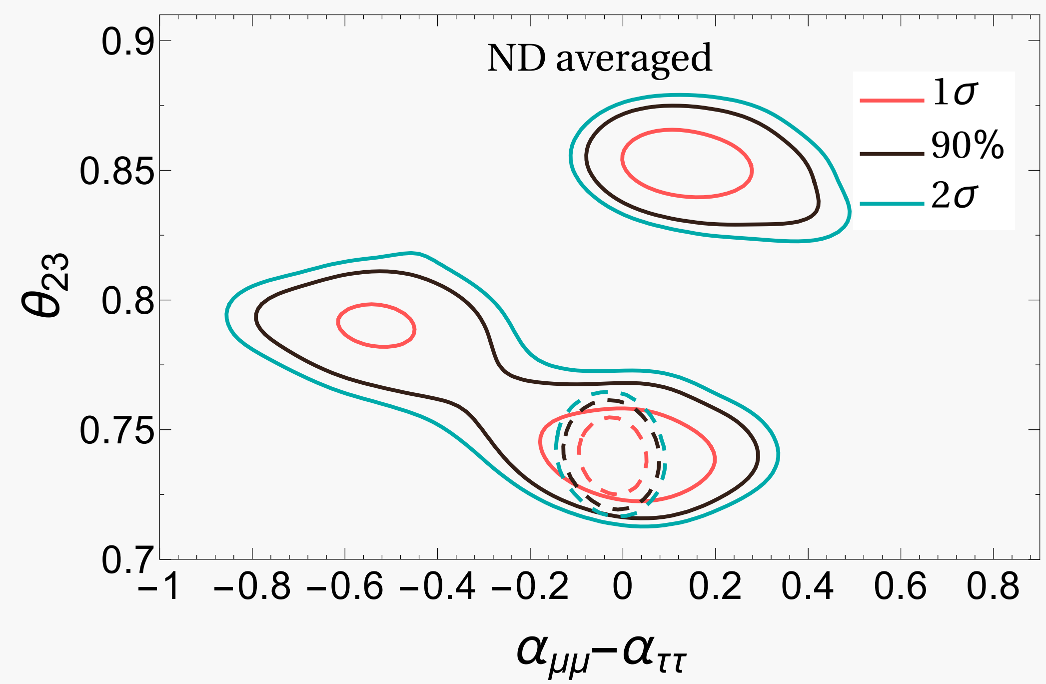
- No $\rightarrow$ ND undeveloped

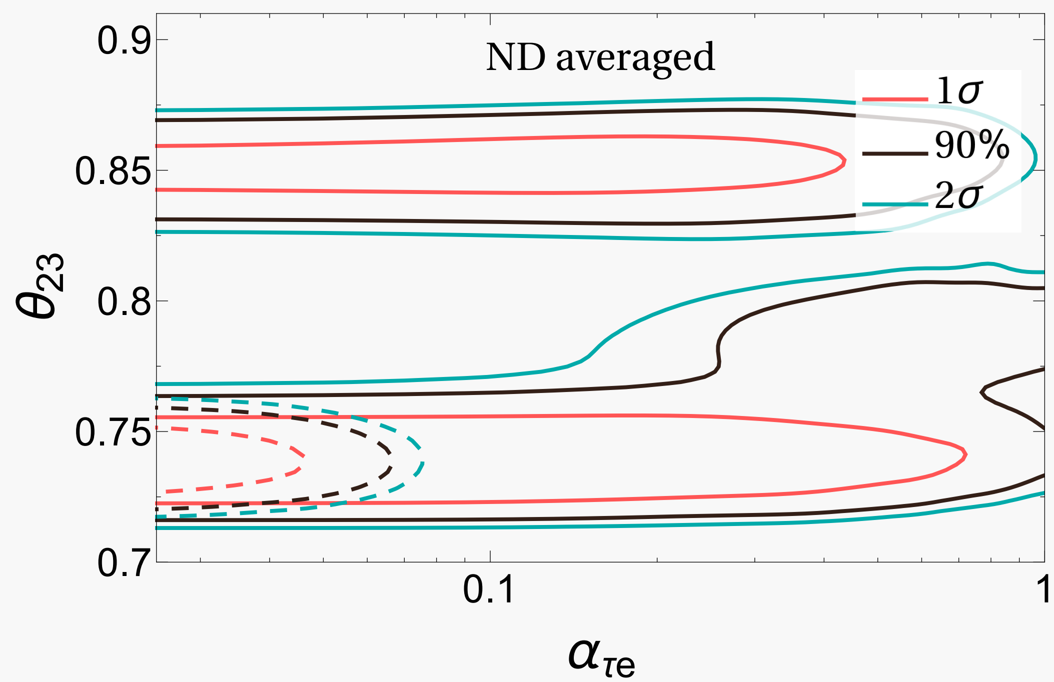




Non-Unitarity vs Sterile ν at DUNE

- Yes $\rightarrow$ ND averaged





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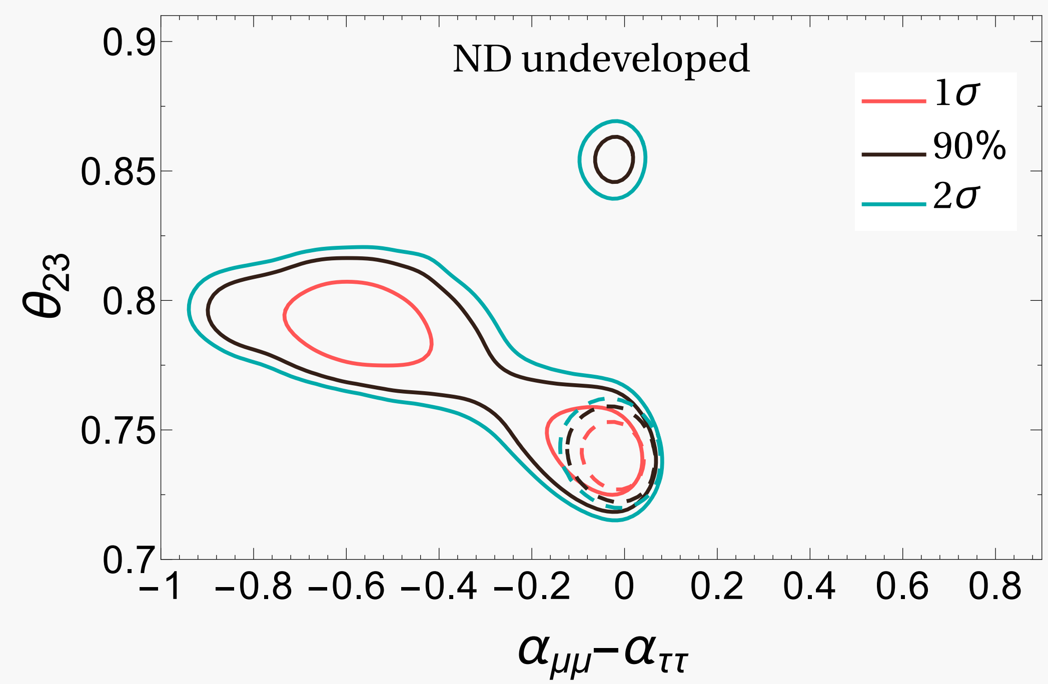
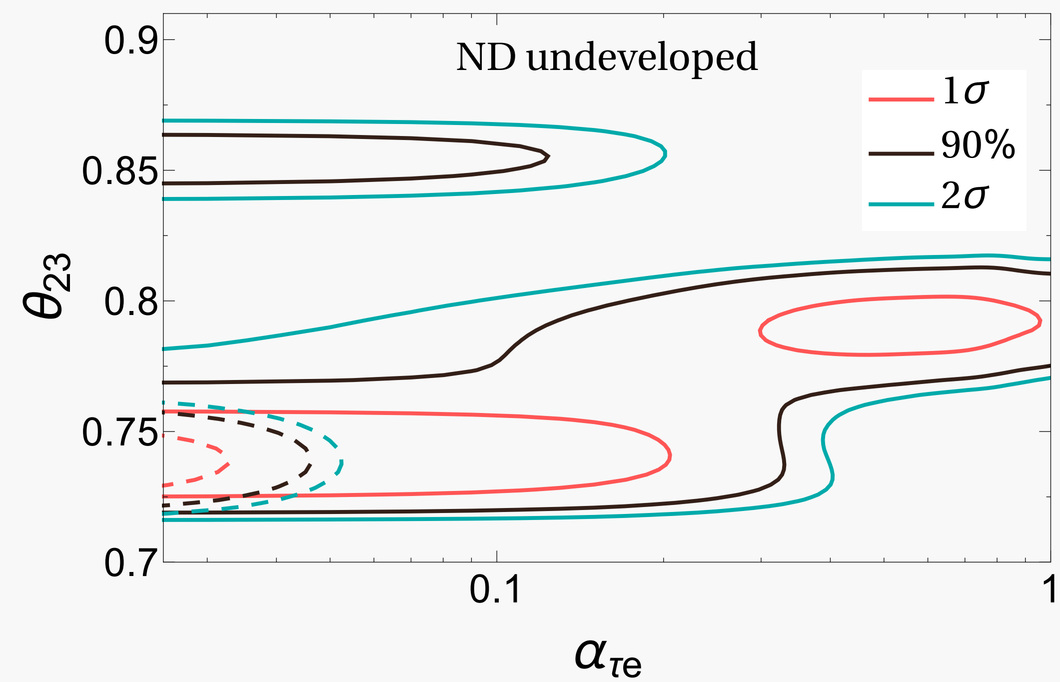
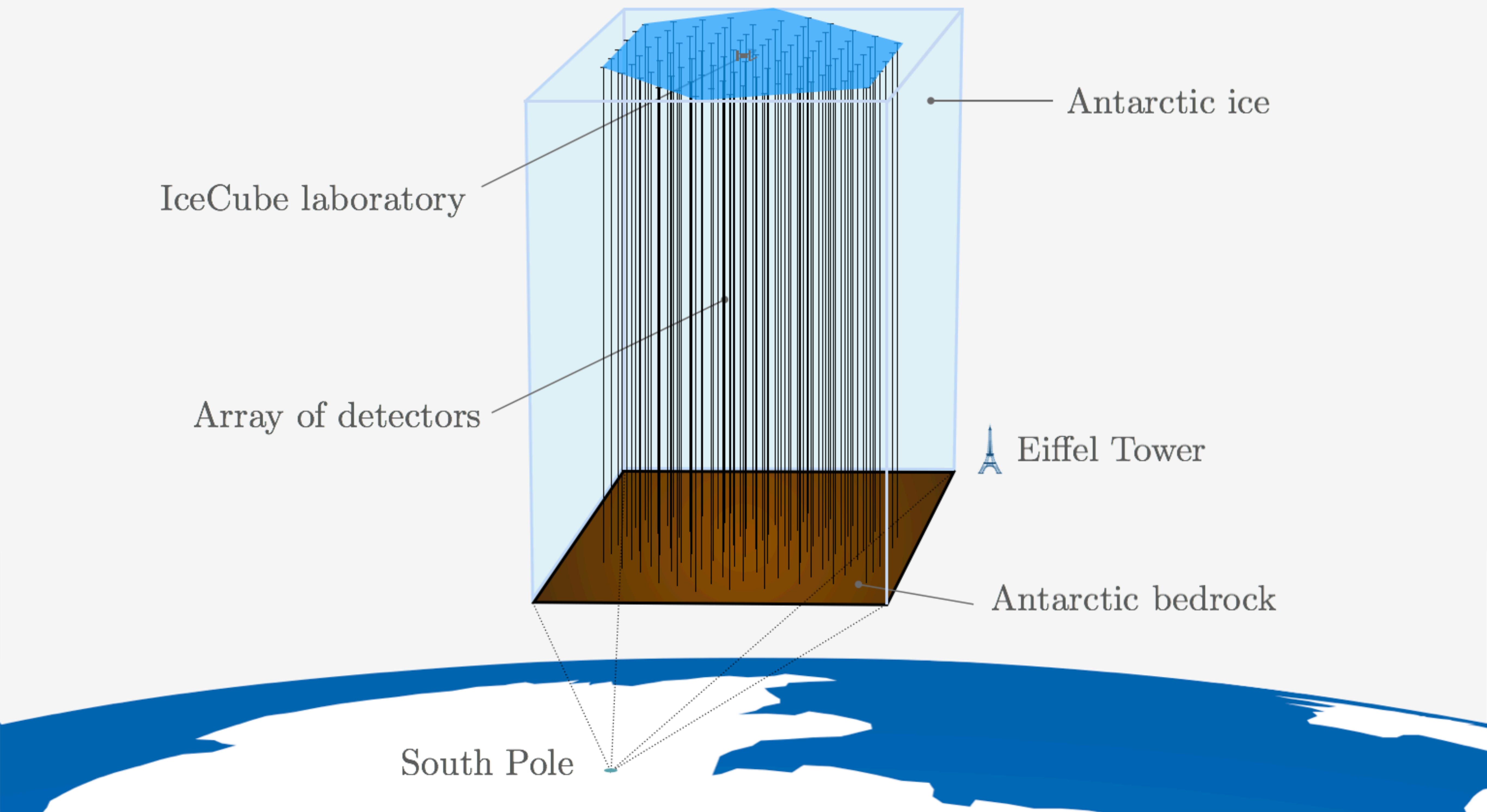




Sterile Neutrinos above 10 eV at IceCube

Sterile ν above 10 eV at IceCube

- What is IceCube?



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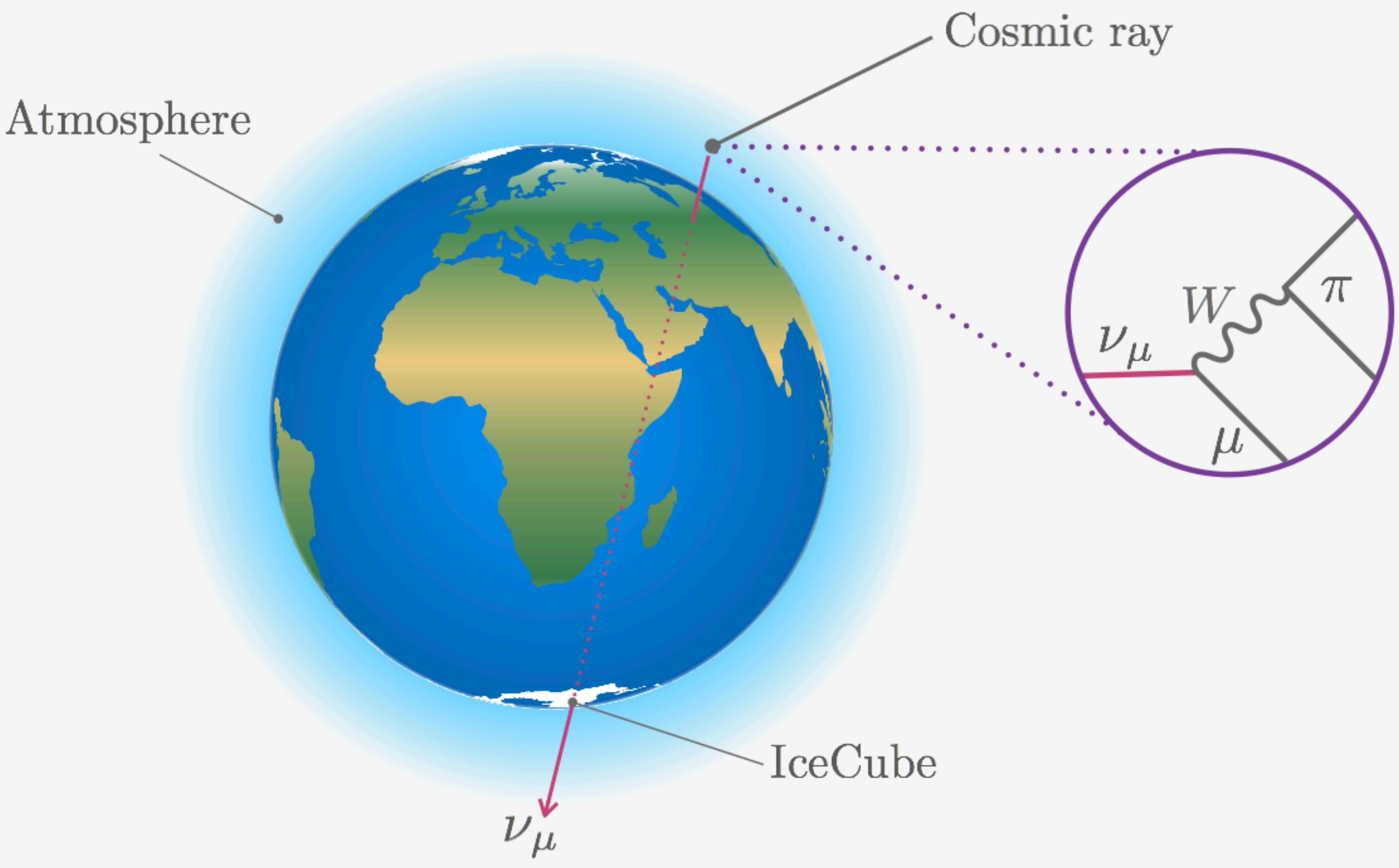

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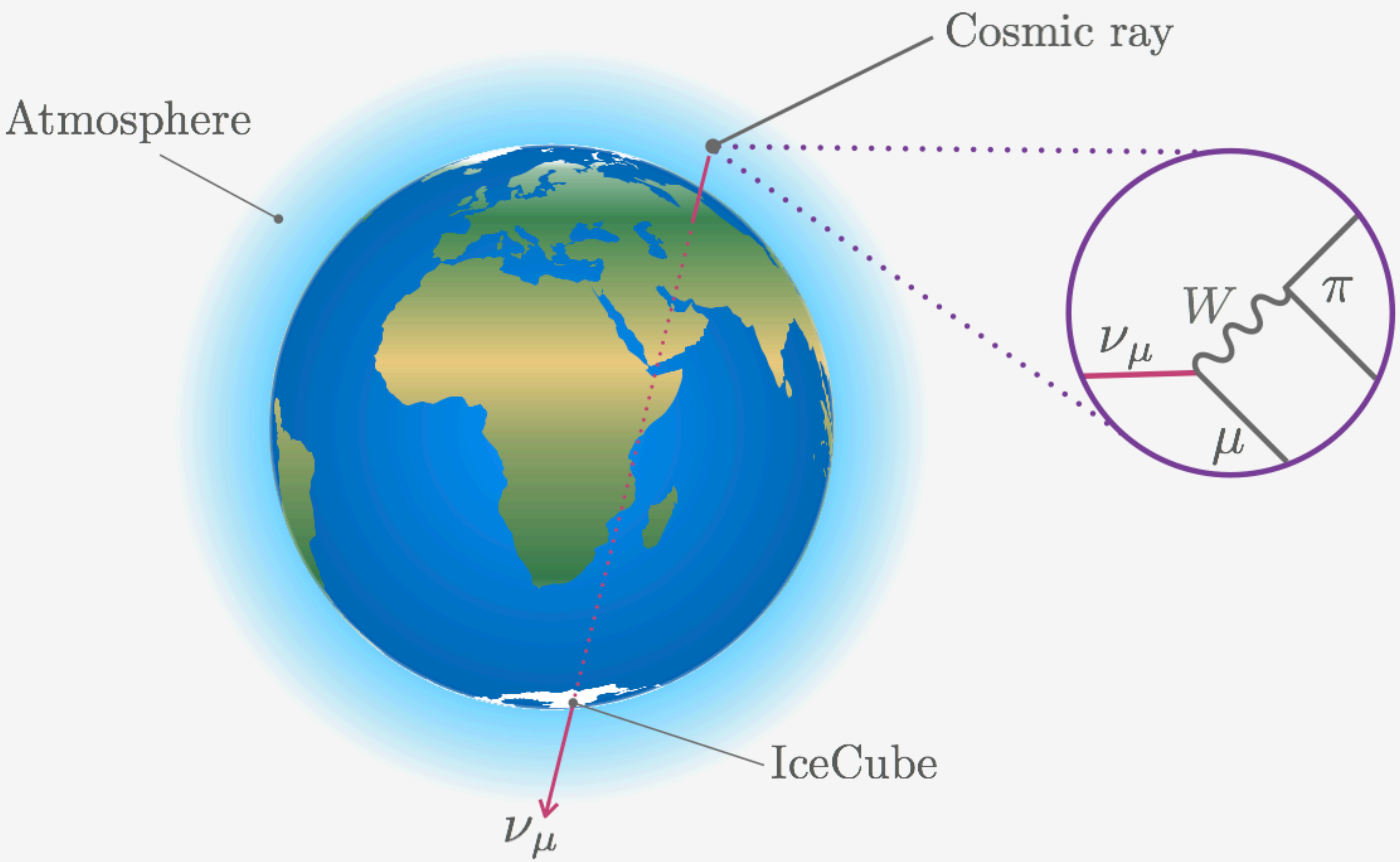

The ν_μ oscillates during its propagation

IceCube measures $P_{\mu\mu}$ with strong matter effects

Sterile ν above 10 eV at IceCube

- The neutrino oscillation probability

  We compute $\nu_\mu \to \nu_\mu$ probability $P_{\mu\mu}$ for
  - small heavy-active mixing angles
  - averaged-out regime $\Rightarrow$ large Δm^2 $\quad(\Delta m^2 \gtrsim 100\ \mathrm{eV}^2)$
  - ν_e does not participate in oscillations

$$P_{\mu\mu} = (1-\alpha_{\mu\mu})^4\left(1-\sin^2(2\theta_m)\sin^2\left(\frac{\Delta_m L}{2}\right)\right) + \sum_{s=4}^{n}|U_{\mu s}|^4$$

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C.S. Fong, H. Minakata, and H. Nunokawa, JHEP **02** 2017 114

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At leading order in α and neglecting Δm^2_{31}

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At leading order in α and neglecting Δm^2_{31}

$$P_{\mu\mu} \simeq 1 - V_{\rm NC}^2 |\alpha_{\tau\mu}|^2 L^2$$

For the particular case of just one extra neutrino

$$P_{\mu\mu} \simeq 1 - V_{\rm NC}^2 |U_{\tau 4}|^2 |U_{\mu 4}|^2 L^2$$

Sterile ν above 10 eV at IceCube

- Details of the analysis

The atmospheric neutrino flux has been computed with

HondaGaisser* + QGSJET II-04

The impact of different flux models has been studied.

T.K. Gaisser, T. Stanev, and S. Tilav, Front. Phys. (Beijing) **8** (2013) 748–758
S. Ostapchenko, Phys. Rev. **D83** (2011) 014018

*Gaisser-Hillas H3a correction

Sterile ν above 10 eV at IceCube

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The propagation of the neutrinos simulated using nuSQuIDS.

ν-SQuIDS: https://github.com/Arguelles/nuSQuIDS

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After propagating flux for every value of sterile ν parameter, the expected number of events N_i^{th} in every bin of reconstructed zenit angle computed using the provided MonteCarlo.

IceCube Collaboration, Phys. Rev. Lett. **117** no. 7, (2016) 071801

Sterile ν above 10 eV at IceCube

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  After propagating flux for every value of sterile ν parameter, the expected number of events $N_i^{\rm th}$ in every bin of reconstructed zenit angle computed using the provided MonteCarlo.

  The observable is energy independent $\Rightarrow$
  - only one energy bin
  - 40 bins for reconstructed zenit angle

Sterile ν above 10 eV at IceCube

- Details of the analysis

Log-likelihood computed

observed

$$L = -\sum_{i} \left[N_i^{\text{th}} - N_i^{\text{data}} + N_i^{\text{data}} \log\left(\frac{N_i^{\text{data}}}{N_i^{\text{th}}} \right) \right]$$

reconstructed
zenit angle bins

predicted

STERILE ν ABOVE 10 eV AT ICECUBE

- Details of the analysis

  Log-likelihood computed

$$L = -\sum_i \left[N_i^{\mathrm{th}} - N_i^{\mathrm{data}} + N_i^{\mathrm{data}} \log \left(\frac{N_i^{\mathrm{data}}}{N_i^{\mathrm{th}}} \right) \right]$$

  Minimized for nuisance parameters to include systematic errors
  - uncertainty in pion-kaon ratio of the initial flux
  - efficiency of the Digital Optical Modules (DOMs)
  - overall flux normalization

Sterile ν above 10 eV at IceCube

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  - uncertainty in pion-kaon ratio of the initial flux
  - efficiency of the Digital Optical Modules (DOMs)
  - overall flux normalization

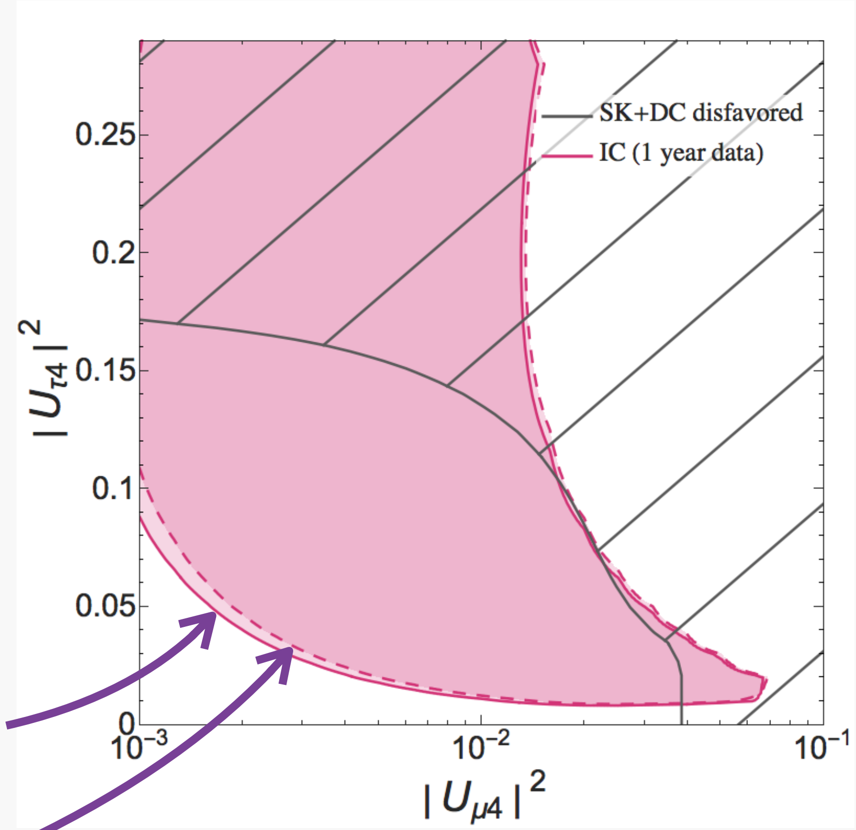
  Standard osc. parameters set to actual best-fit values of NuFIT.

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, T. Schwetz, JHEP **01** (2017) 087.

Sterile ν above 10 eV at IceCube

- Constraints obtained for the public 1 year-data

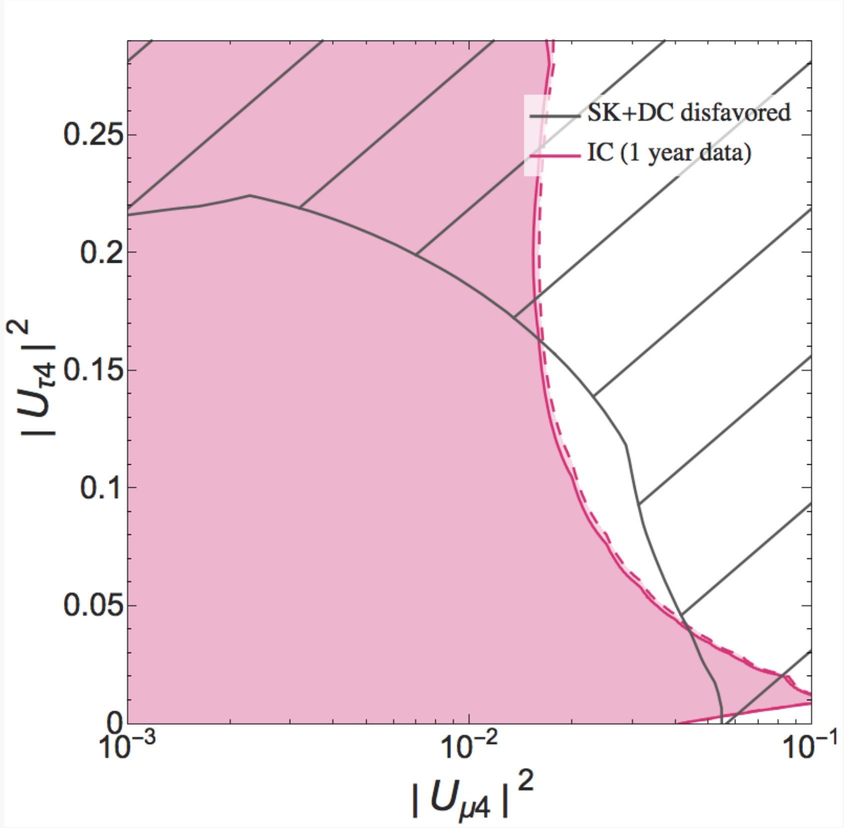
90%



$\delta_{24} = 0$

$\delta_{24} = \pi$

99%



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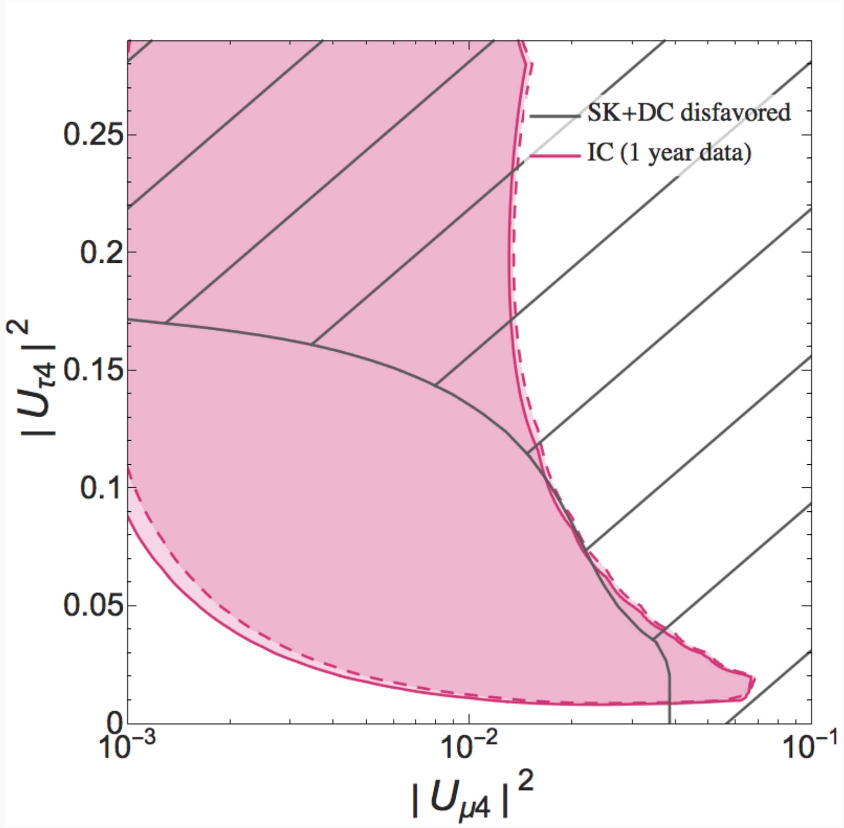
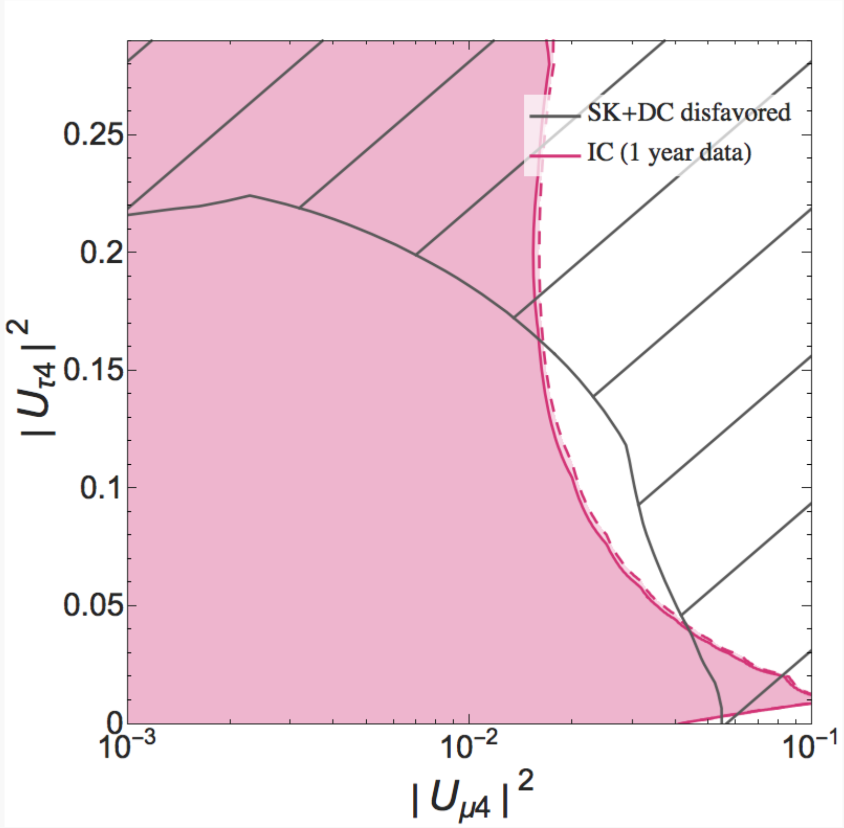


99%



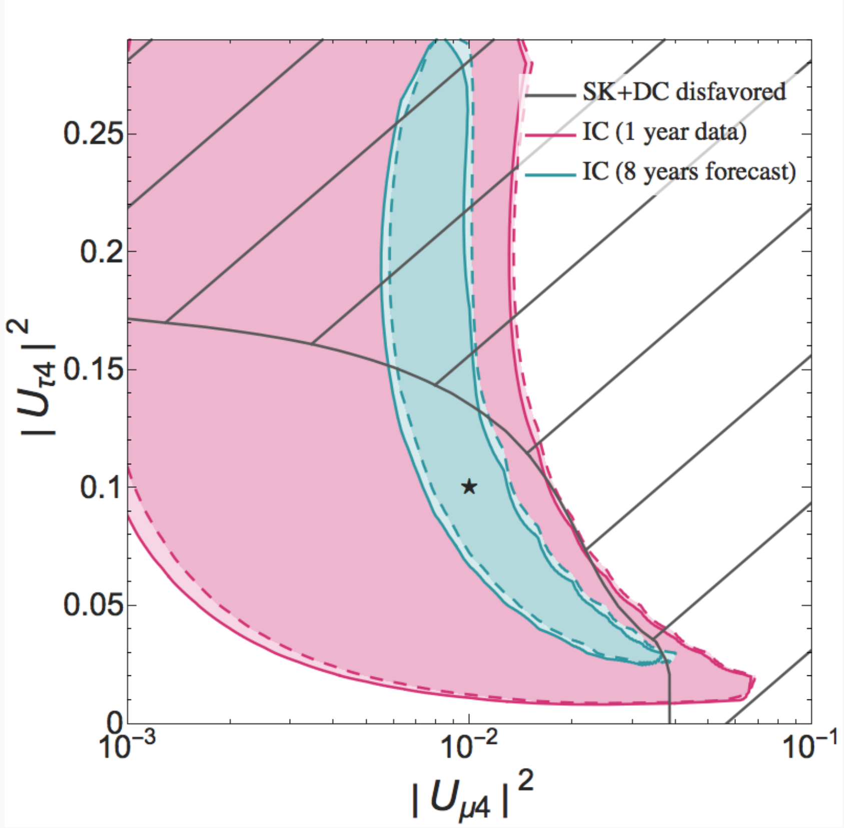
Mild preference (2.3σ 1 dof) for non-zero mixing

Between 0.75 and 3σ depending on the binning and flux adopted

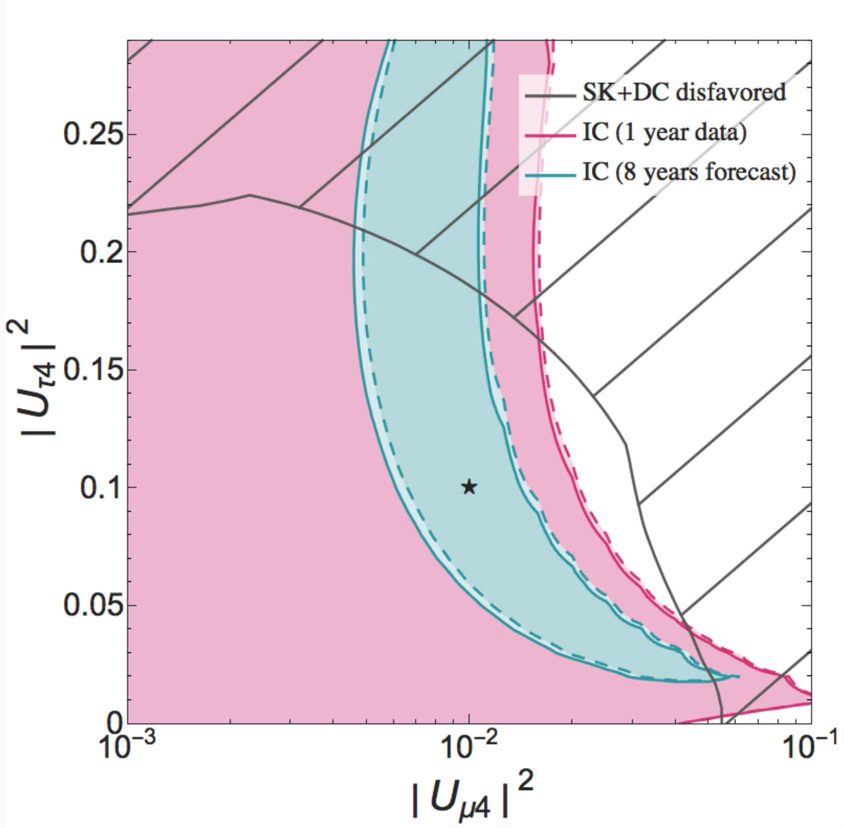
Sterile ν above 10 eV at IceCube

- Constraints obtained for the 8-years forecast

90%



99%



Sterile ν above 10 eV at IceCube

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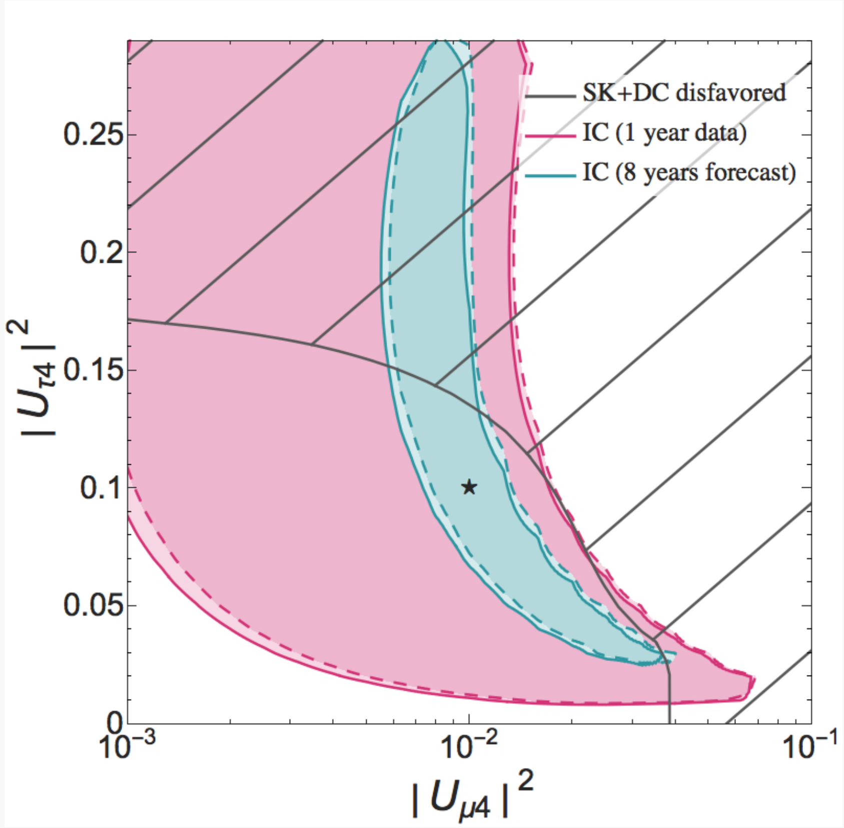
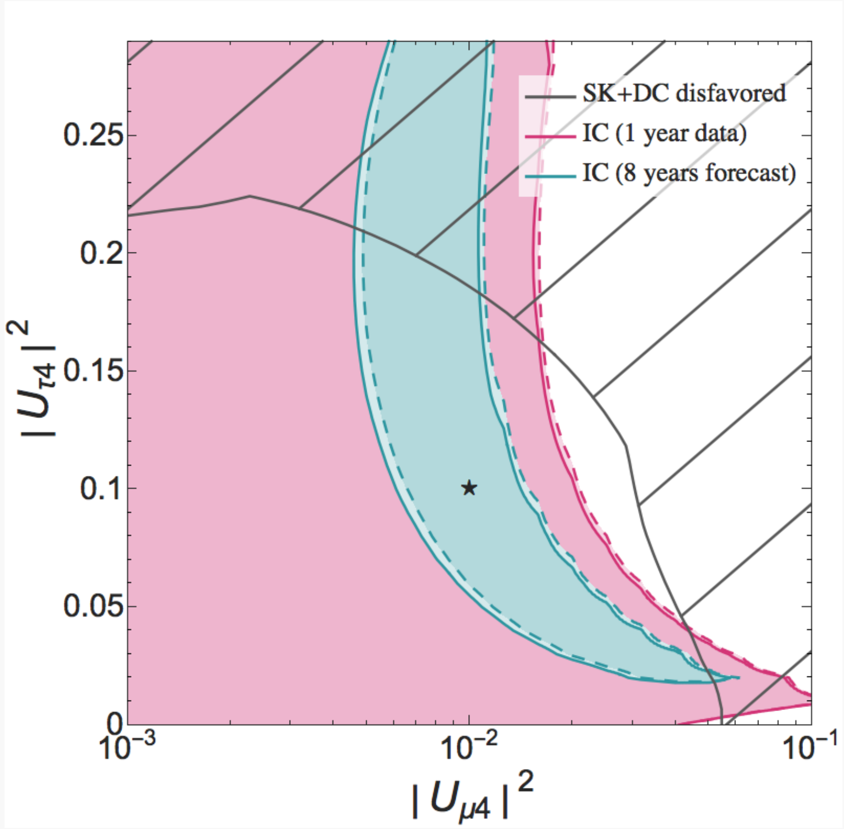
90%



99%



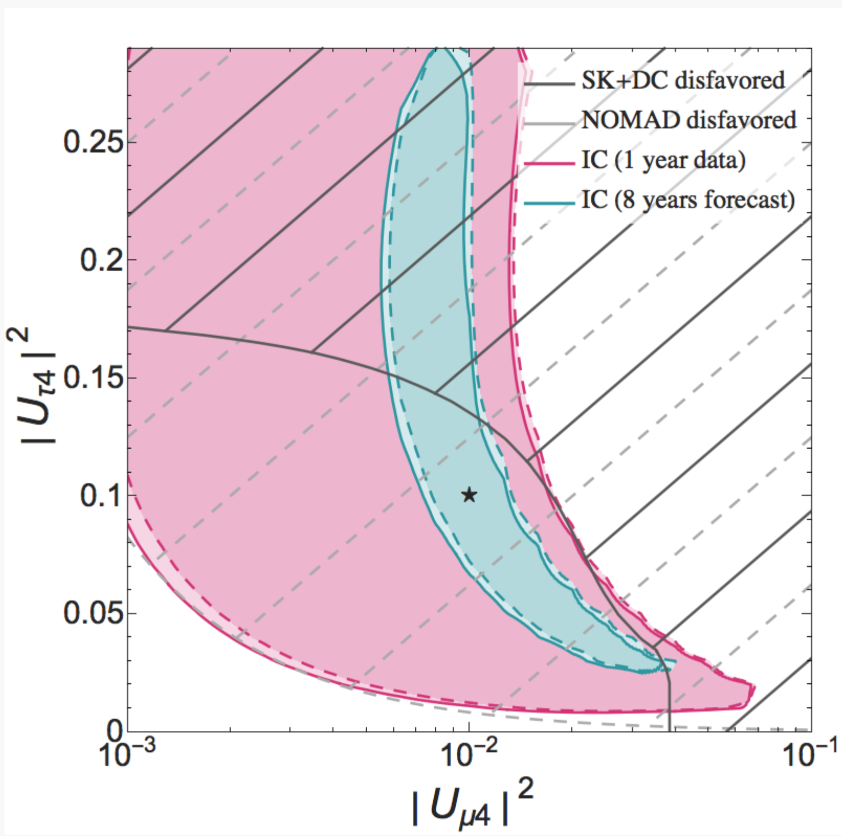
Overlap with sterile ν interpretation of upward shower observed by ANITA

P.W. Gorham et al., Phys. Rev. Lett. **117** no. 7, (2016) 071101

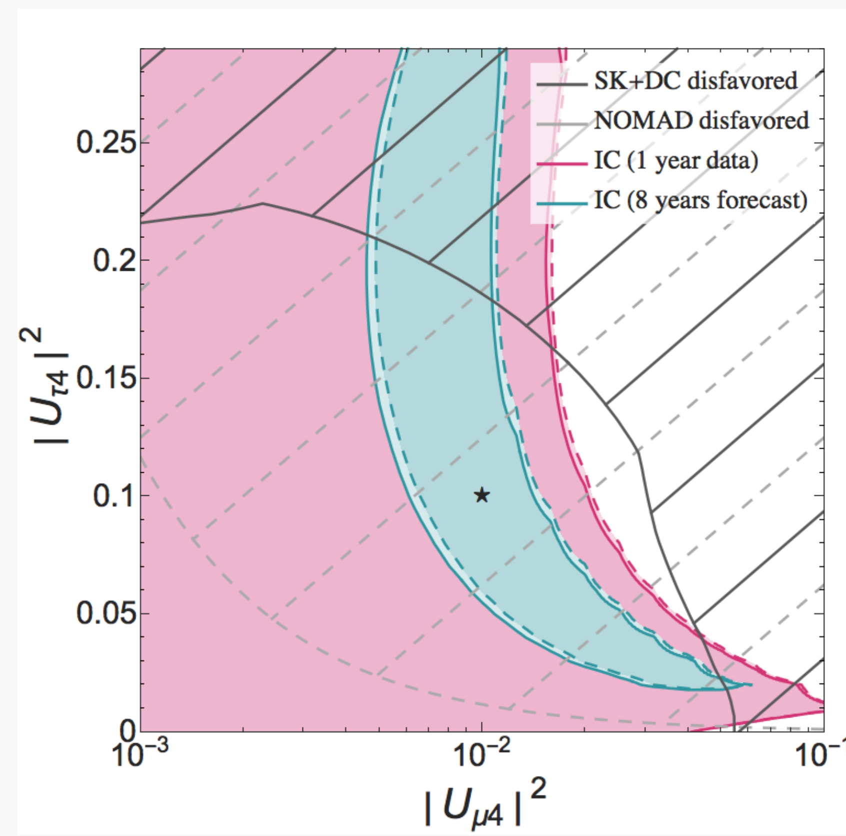
Sterile ν above 10 eV at IceCube

- Constraints obtained for the 8-years forecast

90%



99%



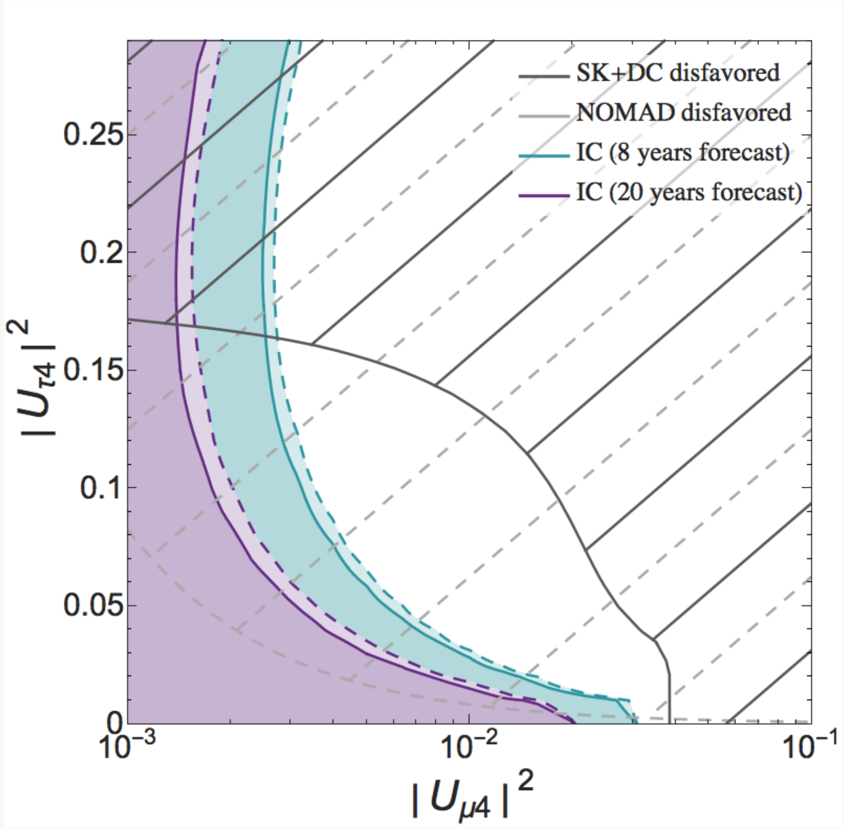
NOMAD explored $\nu_\mu \to \nu_\tau$ with negligible matter effects

$$P_{\mu\tau} \simeq 4|U_{\tau 4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \Rightarrow |U_{\mu 4}|^2|U_{\tau 4}|^2 < 8.3 \cdot 10^{-5} \text{ (90\% CL)}$$

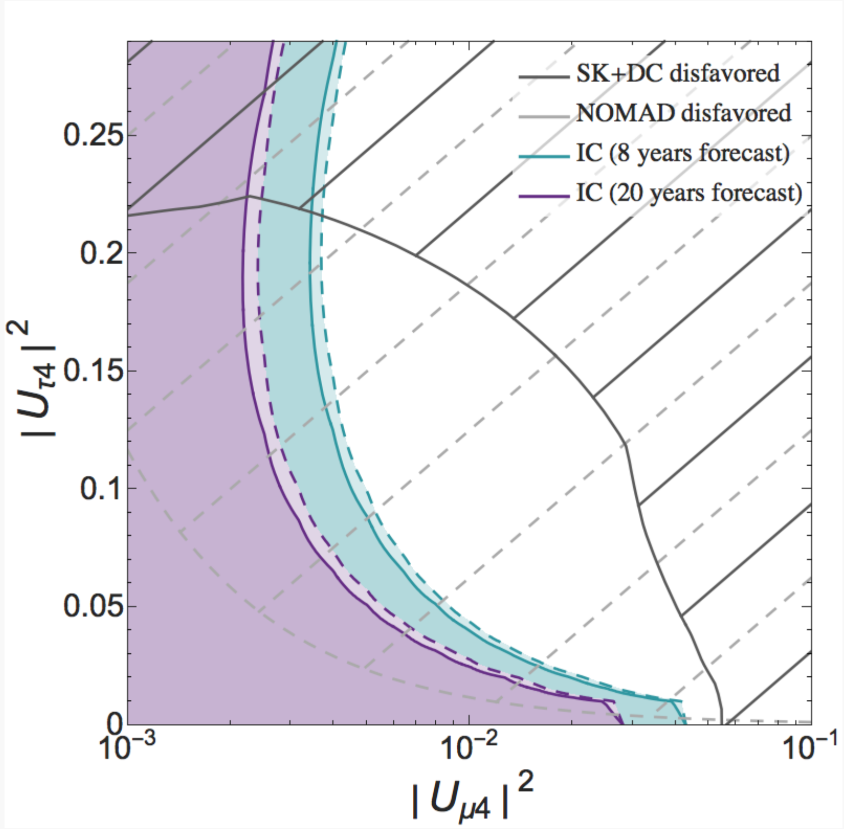
Sterile ν above 10 eV at IceCube

- Constraints obtained for 8-years and 20-years forecasts

90%



99%



Summary

Summary

Neutrino masses and mixings point to a New Physics scale where L is broken.

Non-Unitarity induced by heavy neutrinos and oscillations of light sterile neutrinos in the averaged out regime share the same phenomenology at leading order.

Non-Unitarity from heavy neutrinos beyond the reach of near-future neutrino oscillation experiments ($\theta \sim \mathcal{O}(10^{-2})$), contrary to previous claims in the literature.

Light sterile neutrino limit can be probed at present and near-future neutrino oscillation experiments ($\theta \sim \mathcal{O}(10^{-1})$).

Important to consider the role of the Near Detector.

Summary

The capabilities of IceCube to search for sterile ν above 10 eV by analyzing its atmospheric ν sample has been studied.

The 1-year data shows a mild preference for non-zero mixing, between 0.75 and 3σ depending on the binning and flux adopted.

At 99% CL the obtained bounds improve over the SK and DC present constrains in some part of the parameter space.

The results overlap with the favored region for the sterile ν interpretation of the upward shower observed by ANITA.

The preferred mixings are in tension with NOMAD data, and non-standard matter interactions needed to reconcile results.

8 years of IceCube data would be sufficient to confirm or exclude the present preference.

Thanks

This project has received funding/support from the European Union's
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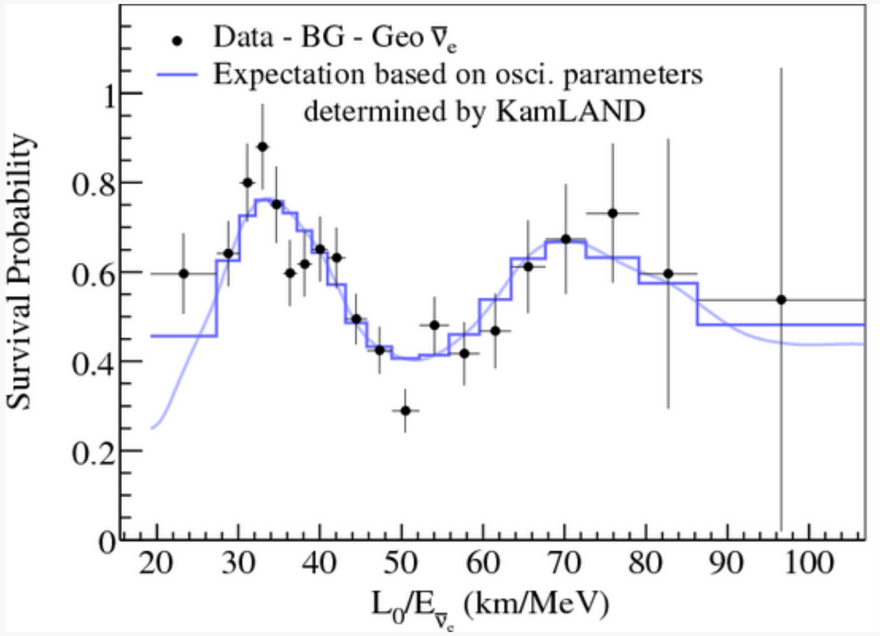
Marie Sklodowska-Curie grant agreement No 674896.

Back-Up

Introduction: SM Open Problems

- Dark Matter
- Matter-antimatter asymmetry (BAU)
- Neutrino masses

Experimental neutrino oscillation evidence



$\Rightarrow$ Neutrinos have masses

$\Rightarrow$ L_α violated

Introduction: SM Open Problems

- Dark Matter
- Matter-antimatter asymmetry (BAU)
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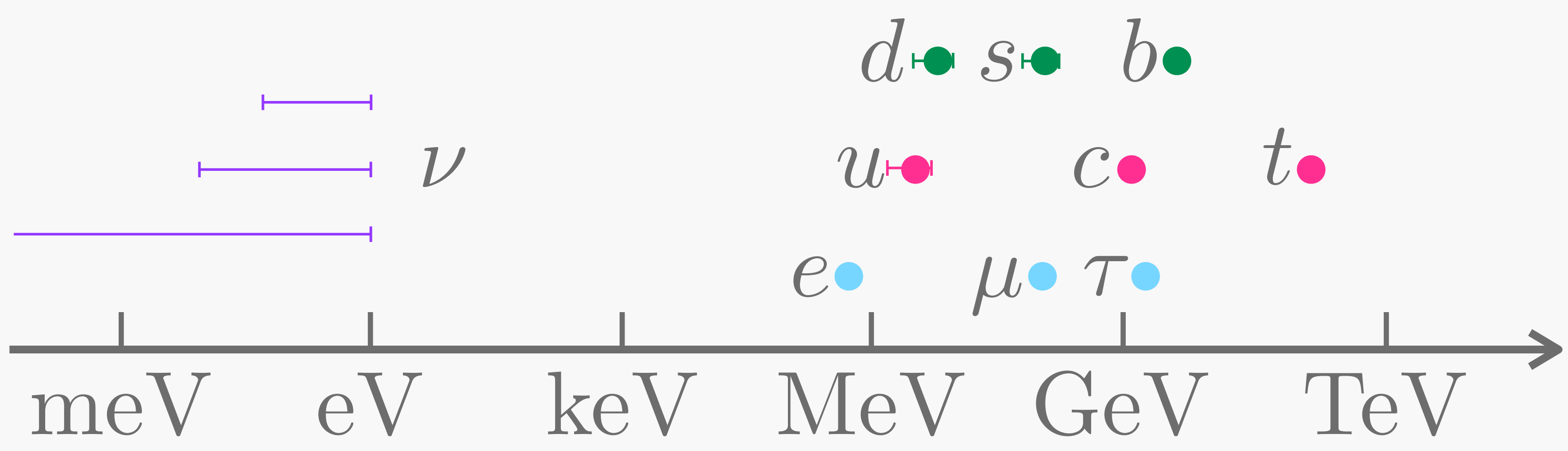
- Flavor Puzzle



No SM explanation for Yukawa ordering.

Introduction: SM Open Problems

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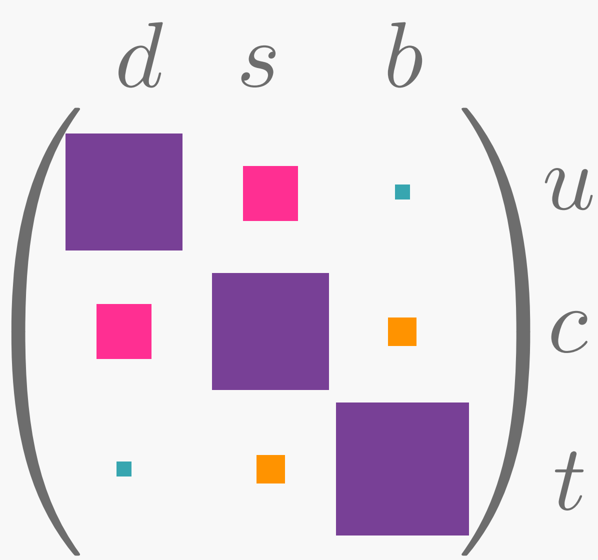
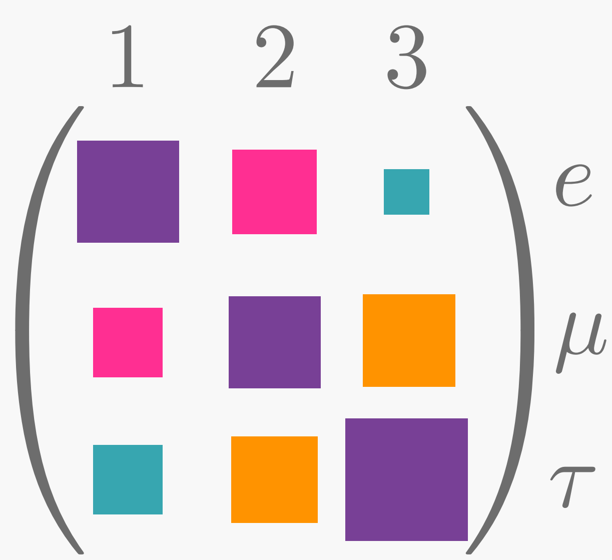
$V_{\text{CKM}} =$



$U_{\text{PMNS}} =$



Dissimilar pattern of quark and lepton mixings.

Introduction: Leptonic Mixing Matrix

If neutrinos are massive, it will be a misalignment between physical (mass) and flavor eigenstates

$$\nu_\alpha = (U_{\mathrm{PMNS}})_{\alpha i}\, \nu_i$$

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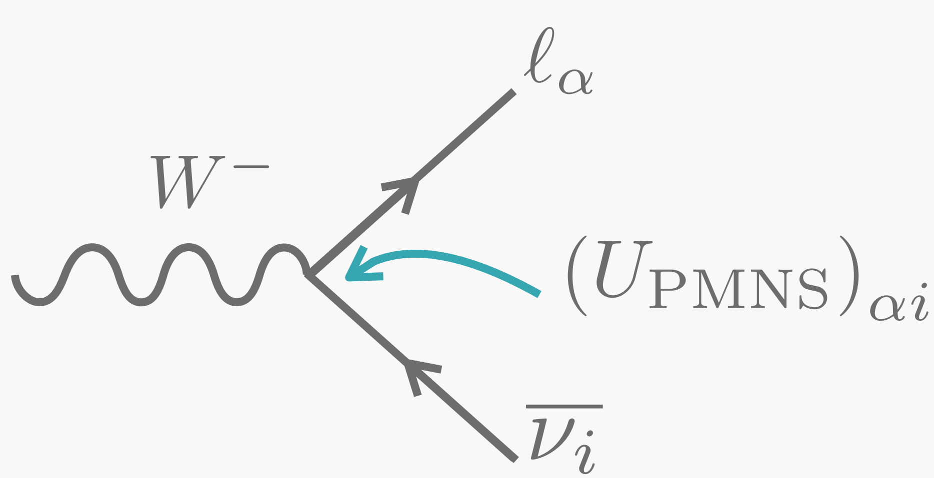
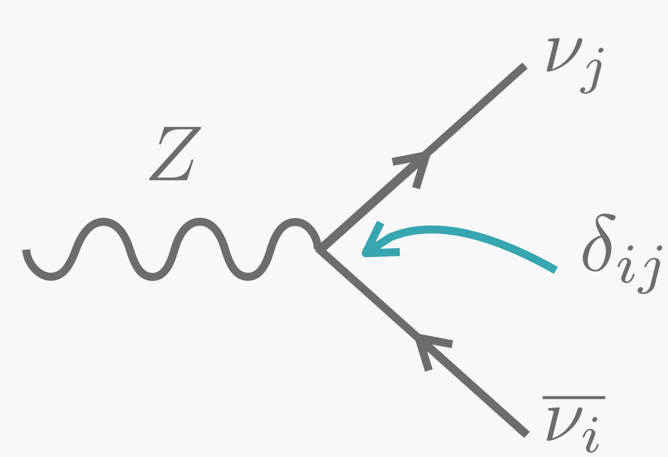
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix.

CC: $(U_{\mathrm{PMNS}})_{\alpha i} \nu_i \overline{\ell_\alpha} W^-$

NC: $\delta_{ij} \nu_i \overline{\nu_j} Z$





Sterile ν above 10 eV at IceCube

- About the IceCube public data

  1-year of high-energy through-going muons released by IceCube
  - IceCube detector stage with 86 strings
  - up-going track events (avoid background from cosmic μ)
  - distances traveled $L \sim 10^4$ km

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  The selected events have
  - reconstructed energies between 400 GeV and 20 TeV
  - reconstructed $\cos\theta_z$ between -1 and 0.2