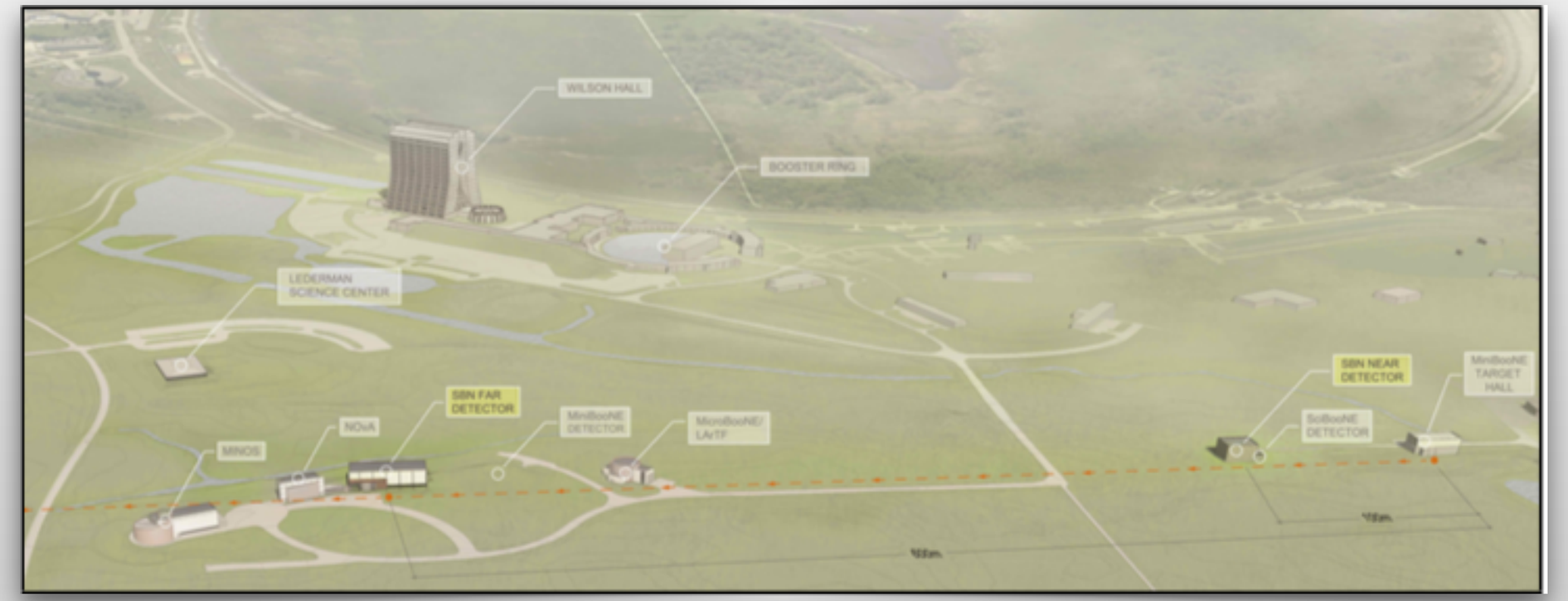
GEFAN

A short travel for neutrinos in Large Extra Dimensions



arXiv:1503.01520

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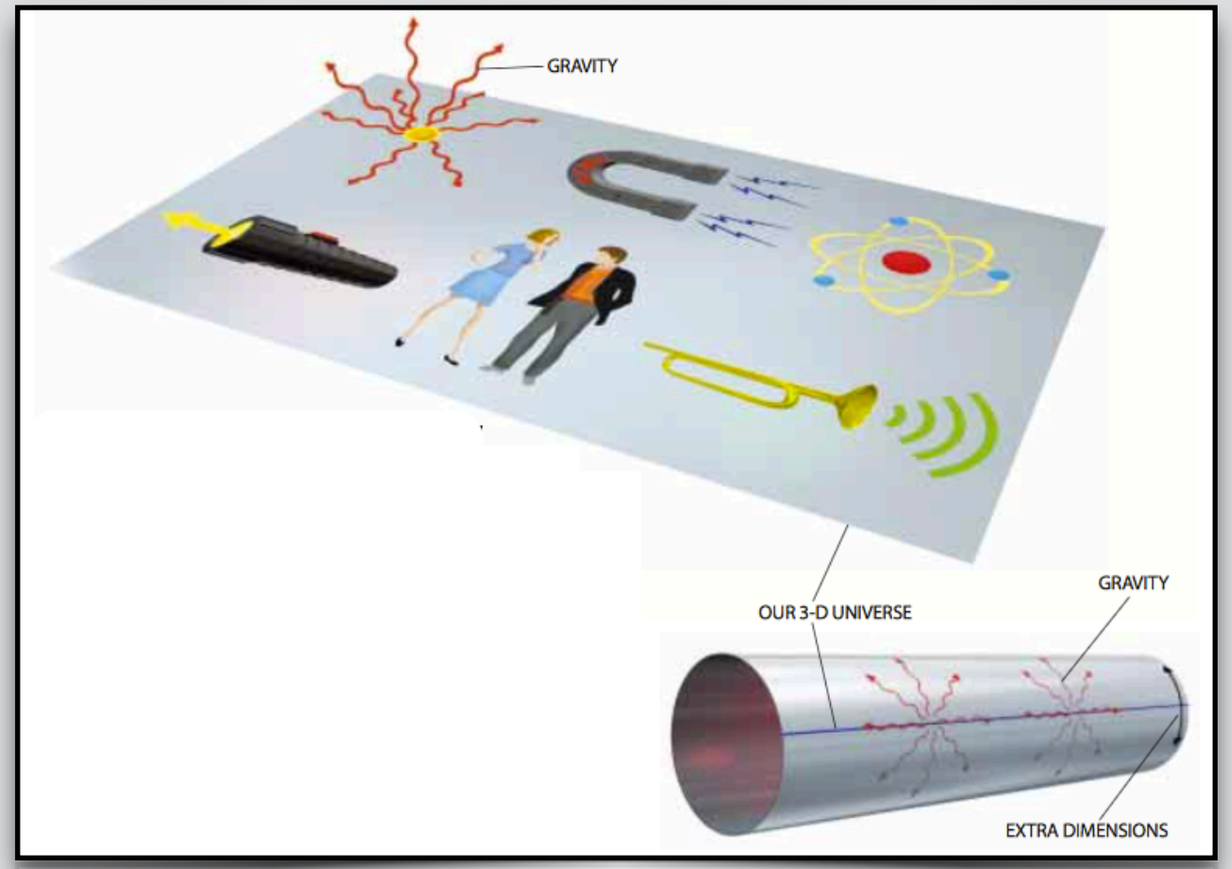
UNICAMP

06/19/2018

Summary:

- Why LED?
- Formalism
- Oscillation Probability
- SBN
- Results



Arkani-Hamed, Dimopoulos and Dvali,
Scientific American, **August 2000**

Why LED?

Hierarchy Problem

Why LED?

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- gravity is strong!

Why LED?

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- gravity is strong!

Why LED?

Hierarchy Problem

Solution: graviton can propagate freely in the extra dimensions!

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Bonus: **give a natural explanation for the smallness of neutrino masses!**

Why LED?

Hierarchy Problem

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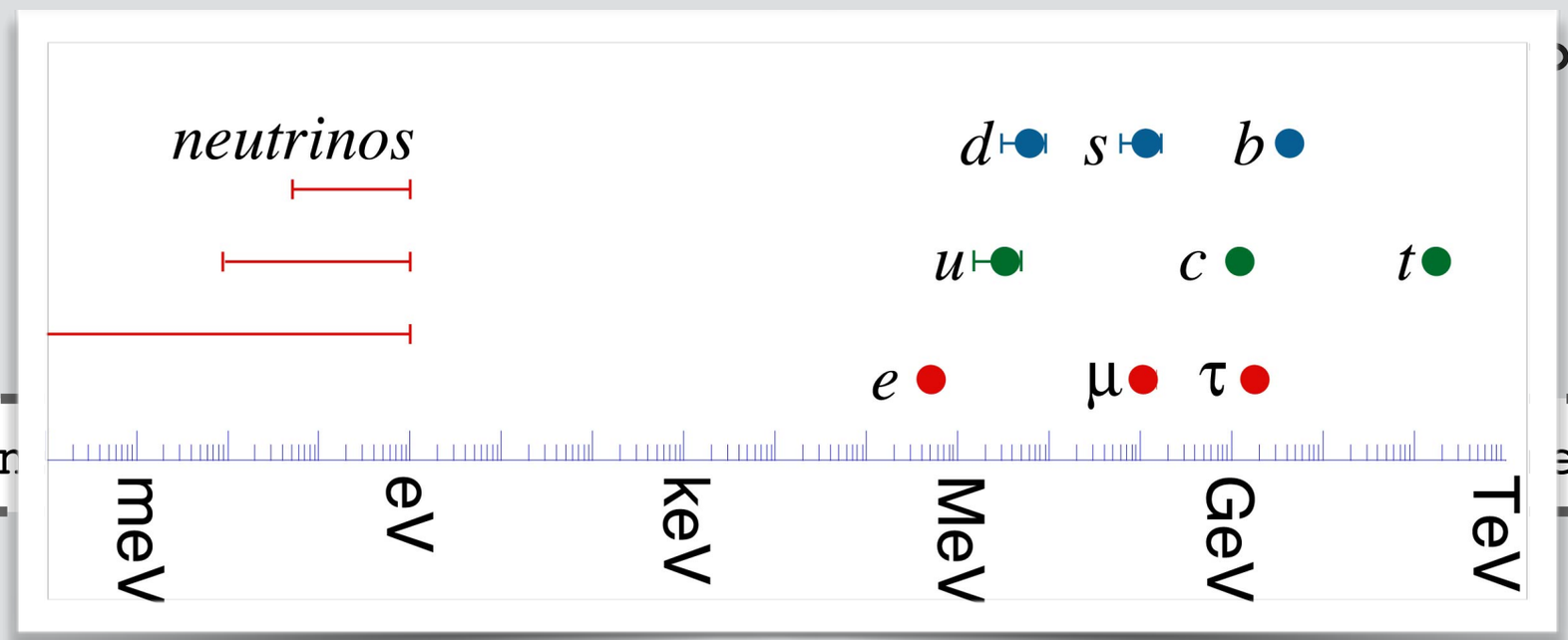


Solution

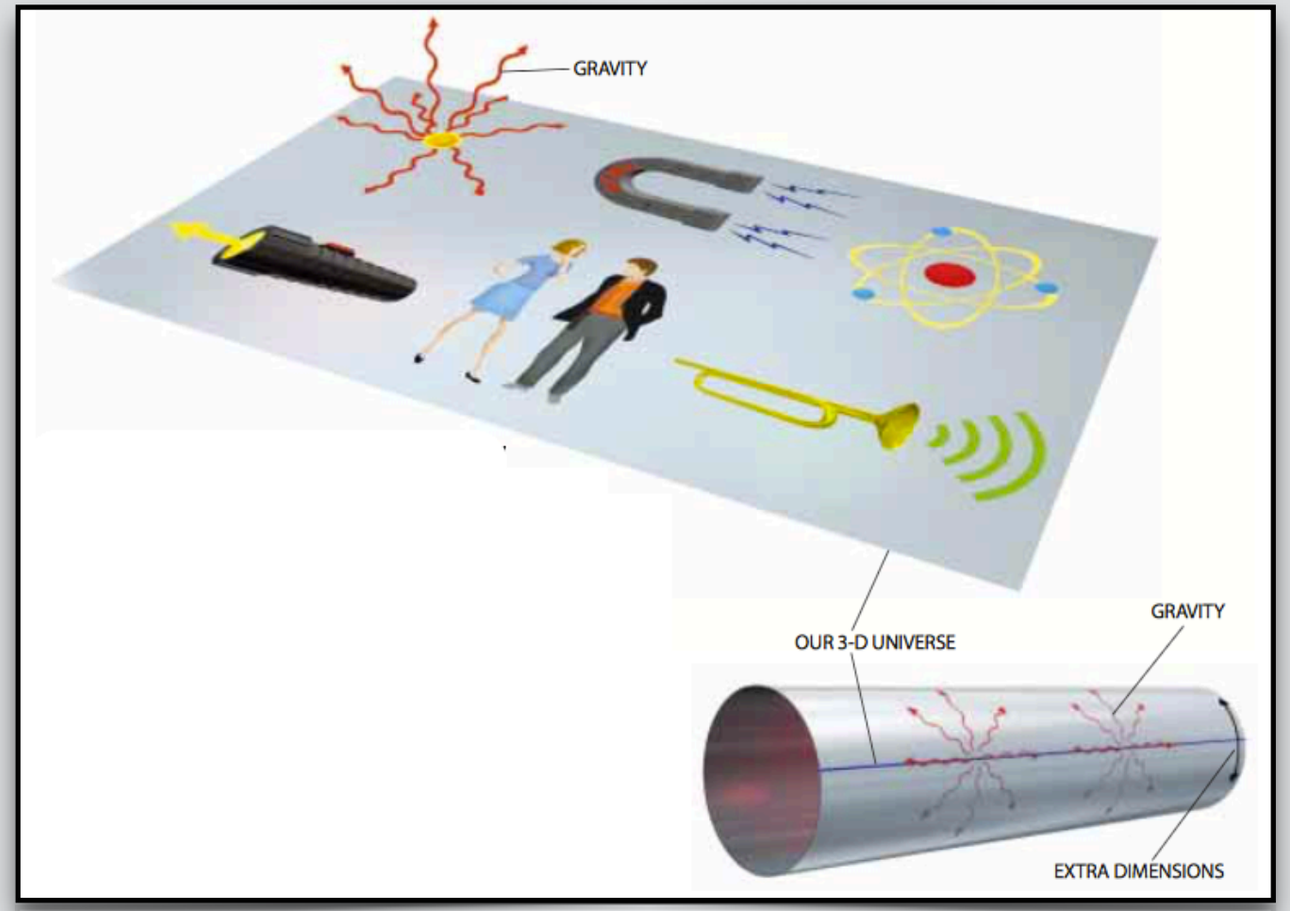
ensions!

http://hitoshi.berkeley.edu/

Bonus: **give a natural explanation for the smallness of neutrino masses!**

Formalism

Right-handed neutrino states: $\Psi_\alpha \; (\alpha = e, \mu, \tau)$



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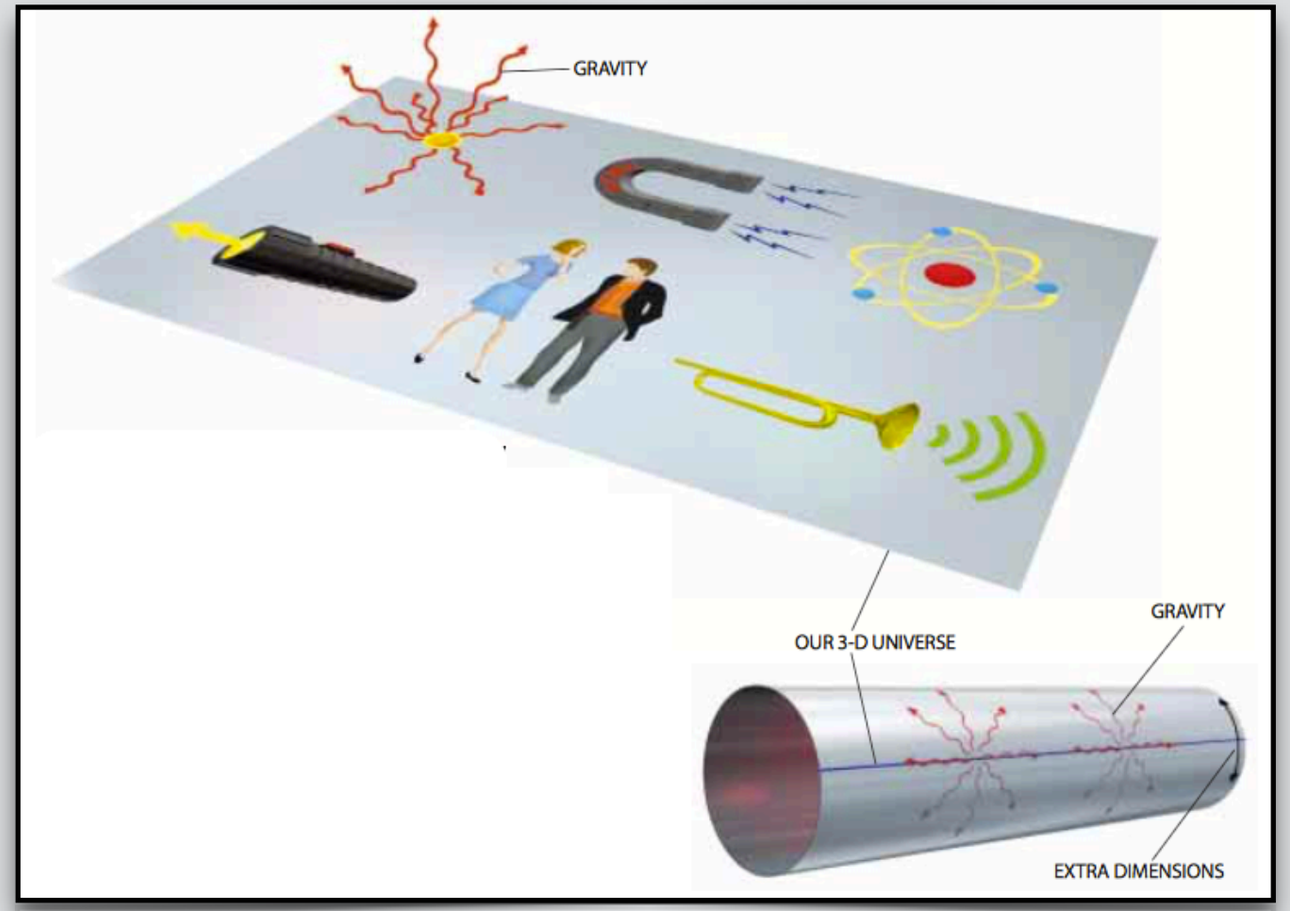

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D extra Dimensions with compactification radii $R_j \;\; (j = 1, 2, ...D)$

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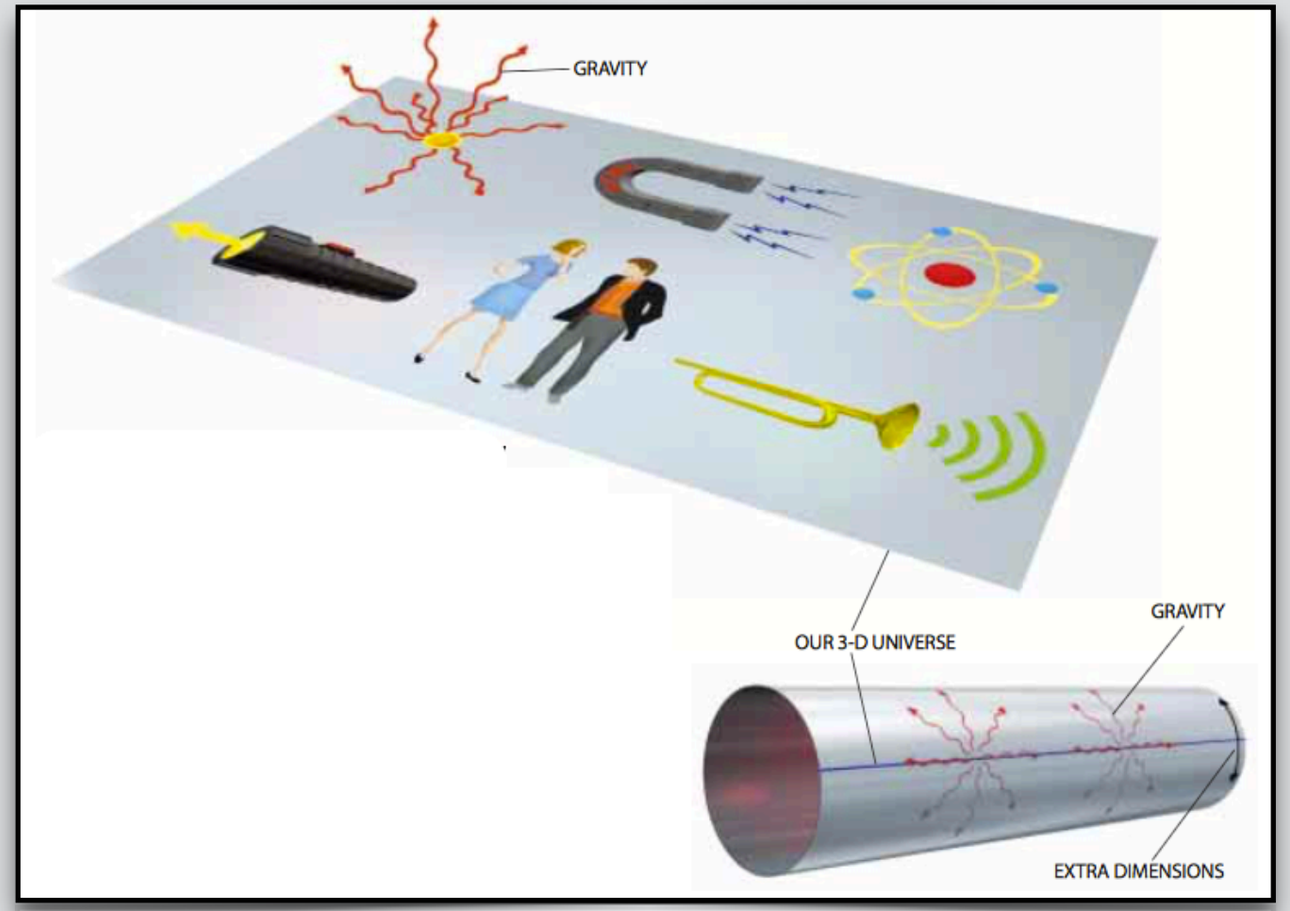

Arkani-Hamed, Dimopoulos and Dvali, *Scientific American*, August 2000

D extra Dimensions with compactification radii $R_j \;\; (j = 1, 2, ...D)$

(asymmetric space)

One large spatial scale with radius: $R_{\rm ED}$ (5-dimensional space)

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

$$S_\alpha = \int dx^4 dy i\bar{\Psi}_\alpha \Gamma^A \partial_A \Psi_\alpha + \int dx^4 [i\bar{\nu}_{\alpha L}\gamma^\mu \partial_\mu \nu_{\alpha L} + \kappa_{\alpha\beta} H \bar{\nu}_{\alpha L} \psi_{\beta R}(x, y=0)] + \mathbf{h.c.}$$

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Extra Dimension

Formalism

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Higgs doublet

Formalism

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Yukawa coupling matrix

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Right-handed neutrino field decomposed in $\Psi_\alpha = (\psi_{\alpha L}, \psi_{\alpha R})$

Formalism

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kinetic term of Ψ_α field

Formalism

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kinetic term of active neutrinos

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Interaction between field Ψ_α and the active neutrinos

Formalism

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After EWSSB:

$$\mathcal{L}_{\text{mass}} = m^{D\alpha\beta}\left(\bar{\nu}^{(0)}_{\alpha R}\nu_{\beta L} + \sqrt{2}\sum_{n=1}^{\infty}\bar{\nu}^{(n)}_{\alpha R}\nu_{\beta L}\right) + \sum_{n=1}^{\infty}\frac{n}{R_{\text{ED}}}\bar{\nu}^{(n)}_{\alpha R}\nu^{(n)}_{\alpha L} + \text{c.h.}$$

$$= \sum_{i=1}^{3}\bar{\mathcal{N}}_{iR} M_i \mathcal{N}_{iL} + \text{c.h.}$$

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Kaluza-Klein (KK) modes

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$$= \sum_{i=1}^{3}\bar{\mathcal{N}}_{iR}M_i\mathcal{N}_{iL} + \text{c.h.}$$

Formalism

$$\mathcal{N}_{iL(R)} = \left(\nu_i^{(0)}, \nu_i^{(1)}, \dots\right)^T_{L(R)} \longrightarrow$$ **Pseudo mass eigenstates**

$$M_i = \begin{bmatrix} m_i^D & 0 & 0 & 0 & \dots \\ \sqrt{2}m_i^D & 1/R_{\rm ED} & 0 & 0 & \dots \\ \sqrt{2}m_i^D & 0 & 2/R_{\rm ED} & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \longrightarrow$$ **Need to be diagonalized!**

Diagonalizing in the form: $S_i^\dagger M_i^\dagger M_i S_i$ **:**

$$\nu_{\alpha L} \cancel{\nu_{iL}} = \sum_{i=1}^{3} U_{\alpha i} \sum_{n=0}^{\infty} S_i^{0n} \nu_{iL}^{\prime(n)} \qquad (\alpha = e, \mu, \tau)$$

Formalism

The true neutrino masses are: $$m_i^{(n)} = \frac{\lambda_i^{(n)}}{R_{\rm ED}}$$

$$\lambda_i^{(n)} - \pi \left(m_i^D R_{\rm ED}\right)^2 \cot\left(\pi \lambda_i^{(n)}\right) = 0$$

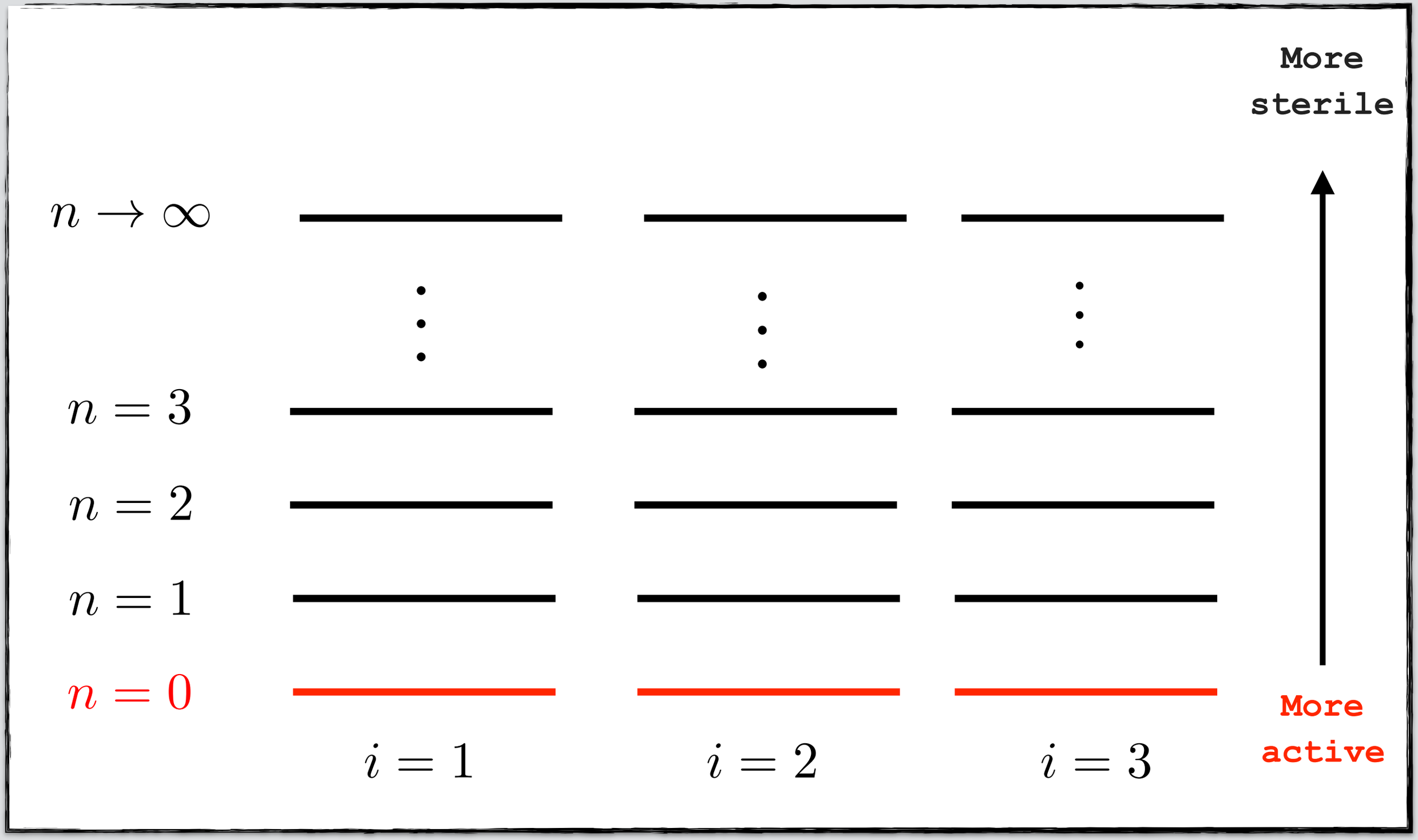
$$n \leq \lambda_i^{(n)} \leq n + 1/2$$

And

$$\left(S_i^{0n}\right)^2 = \frac{2}{1 + \pi^2 \left(m_i^D R_{\rm ED}\right)^2 + \left(\lambda_i^{(n)}\right)^2 / \left(m_i^D R_{\rm ED}\right)^2}.$$

Two new free parameters: $(m_1^D (m_3^D),\ R_{\rm ED})$

Formalism



Oscillation Probability

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_{i=1}^{3} U_{\alpha i} U^*_{\beta i} \sum_{n=0}^{\infty} \left(S_i^{0n}\right)^2 \exp\left(-i \frac{\lambda_i^{(n)2} L}{2E_\nu R_{\mathrm{ED}}^2}\right) \right|^2$$

Oscillation Probability

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$$\boxed{\frac{L}{E_\nu} = 1.2 \ \frac{\mathrm{km}}{\mathrm{GeV}}}$$

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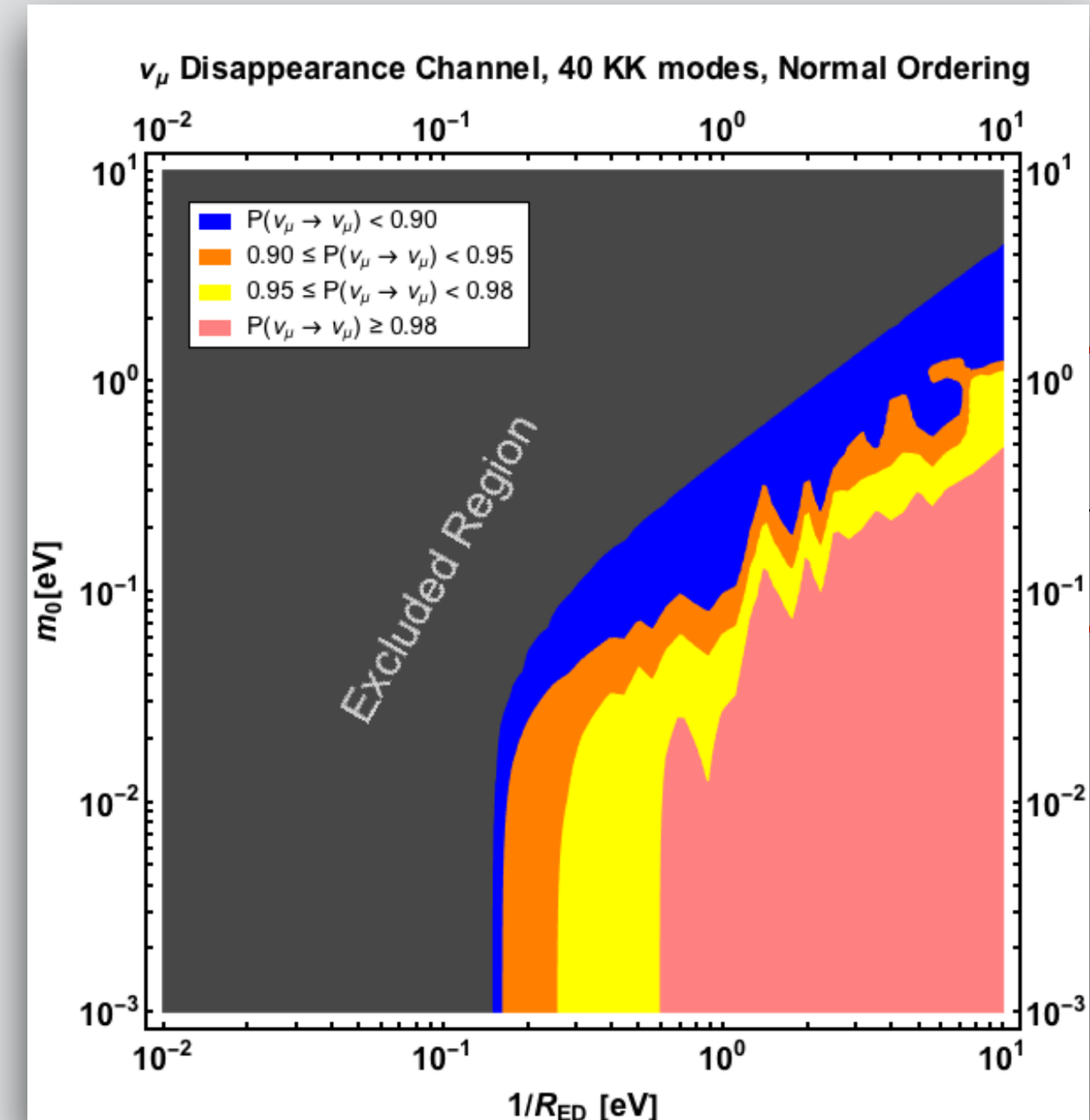

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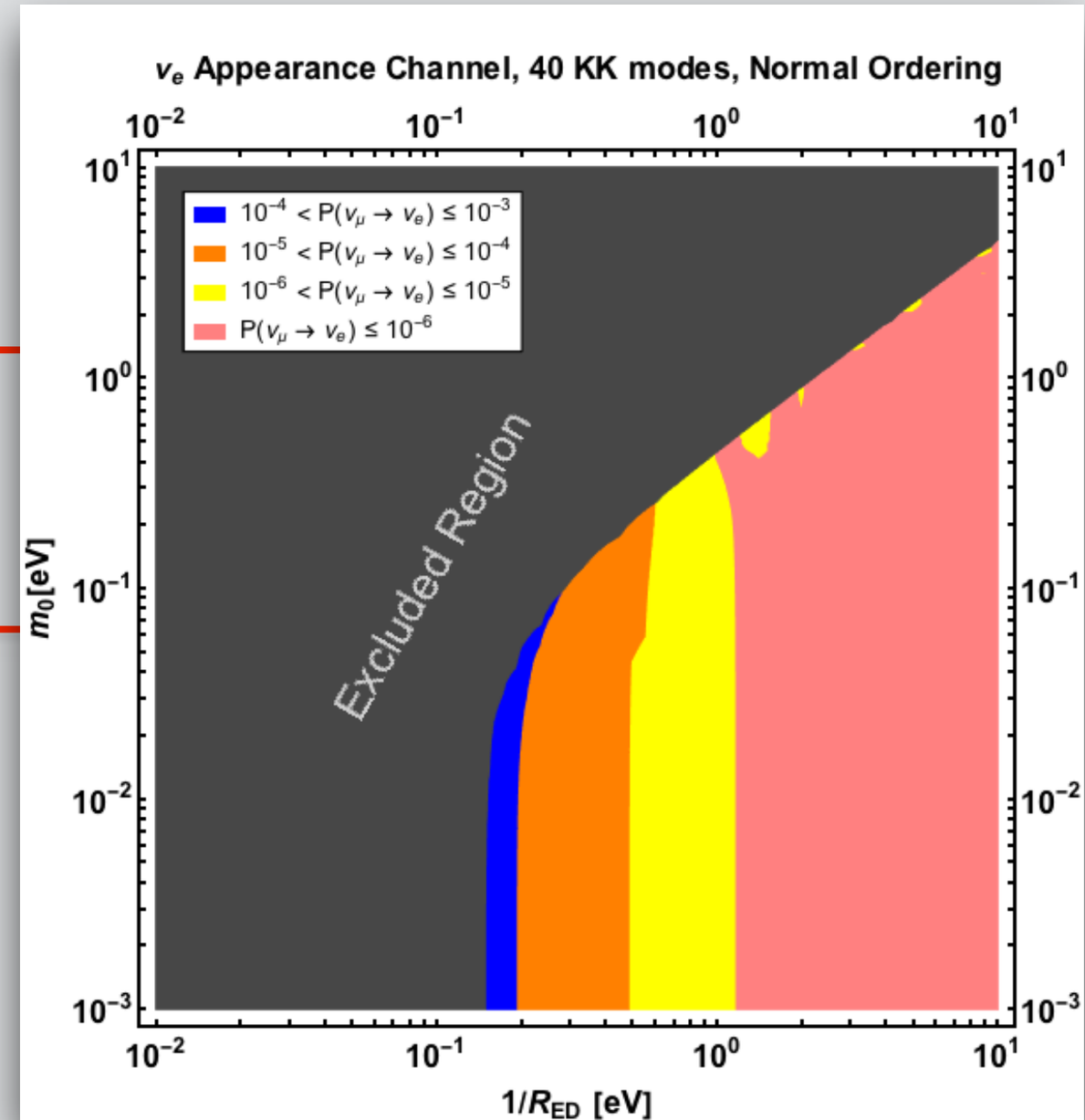

Short-Baseline Neutrino Program

arXiv:1503.01520

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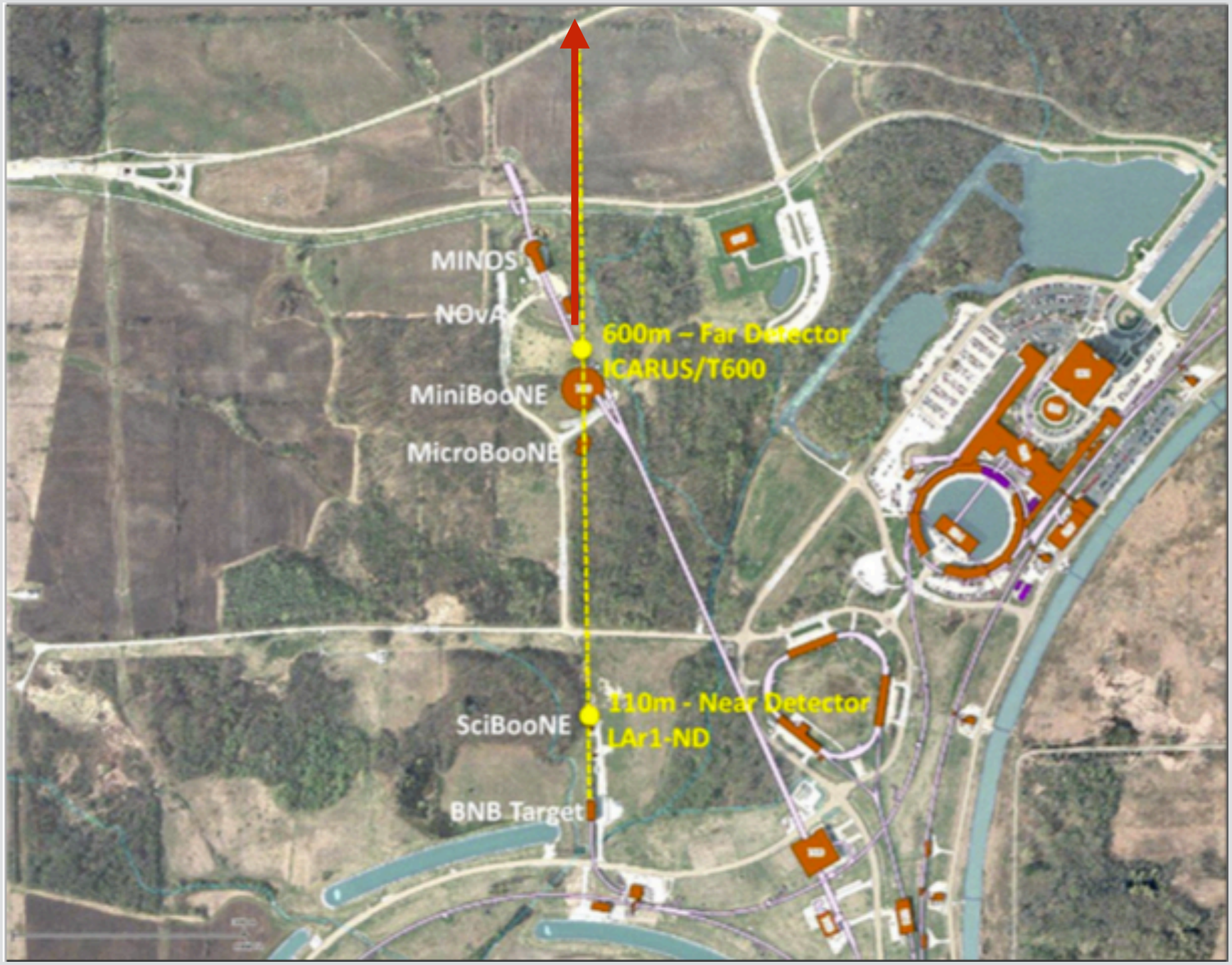

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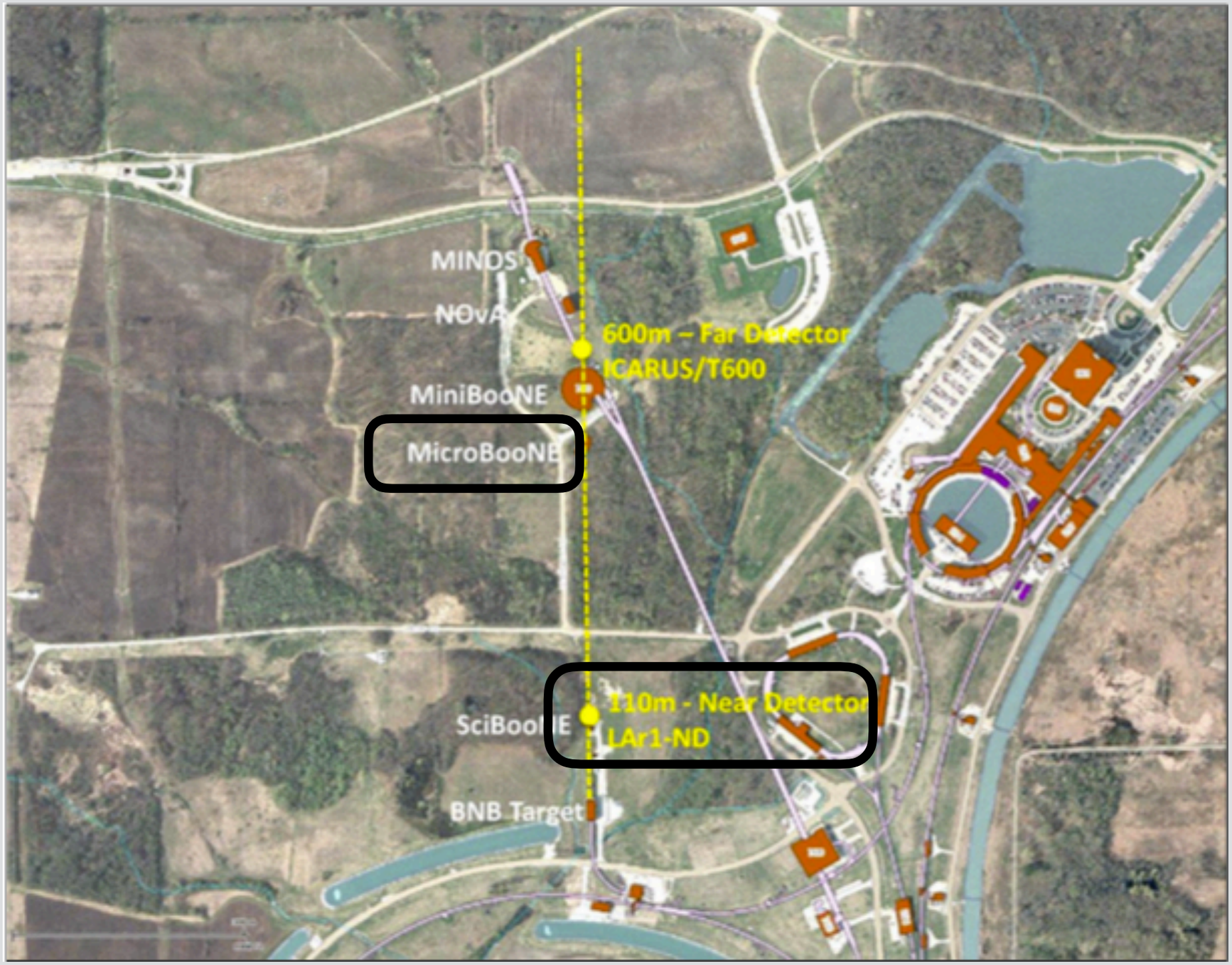

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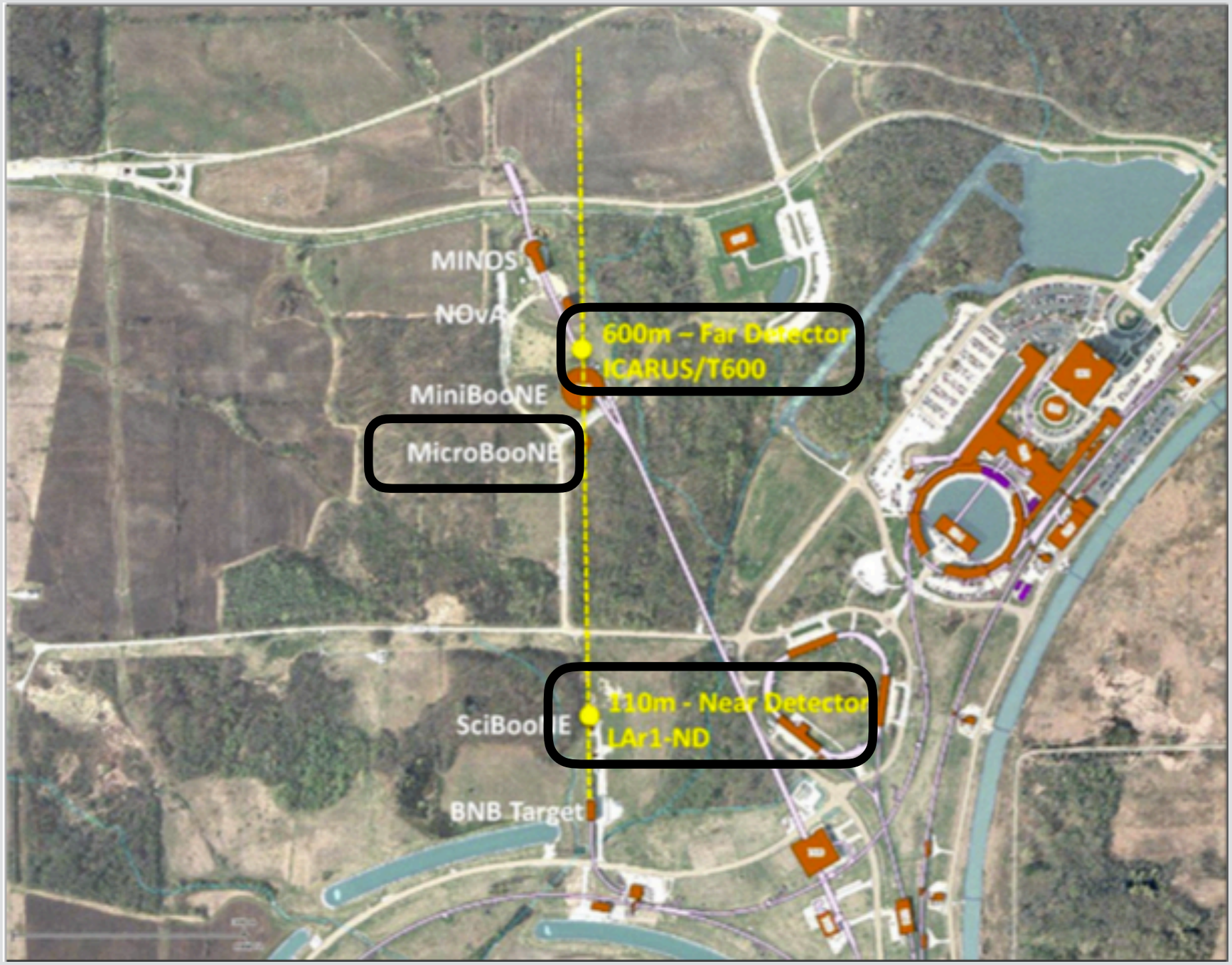

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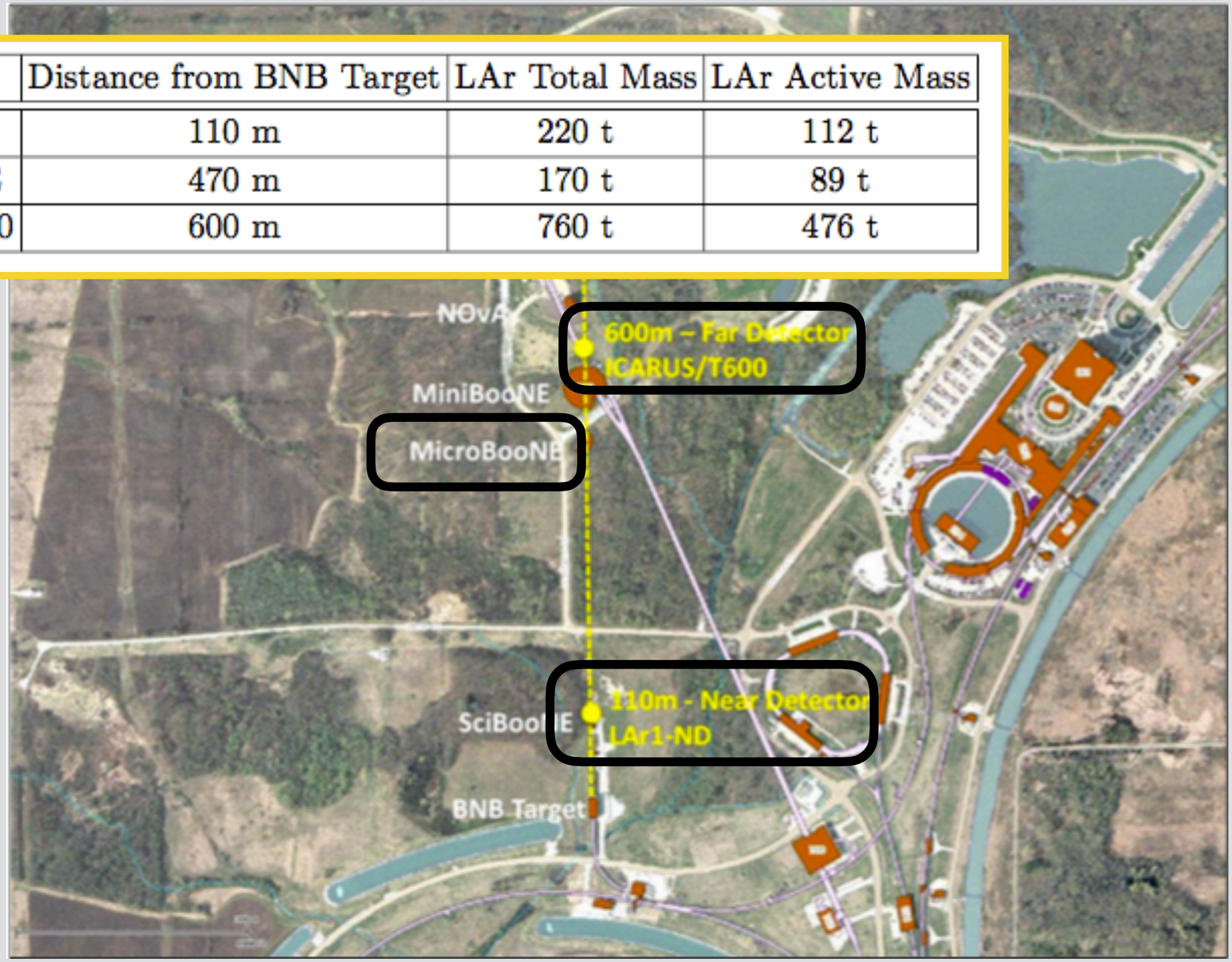
Short-Baseline Neutrino Program

Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t



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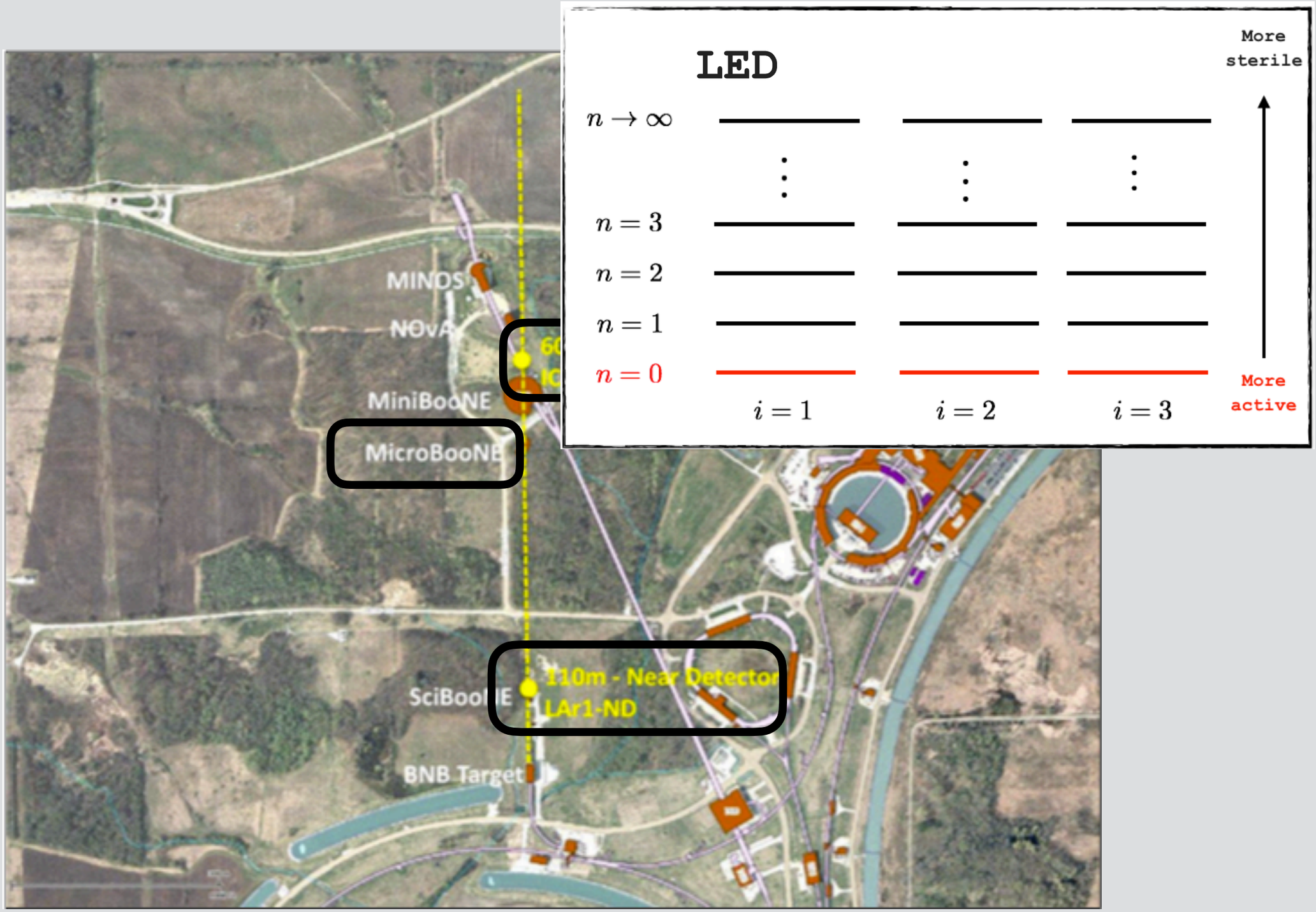

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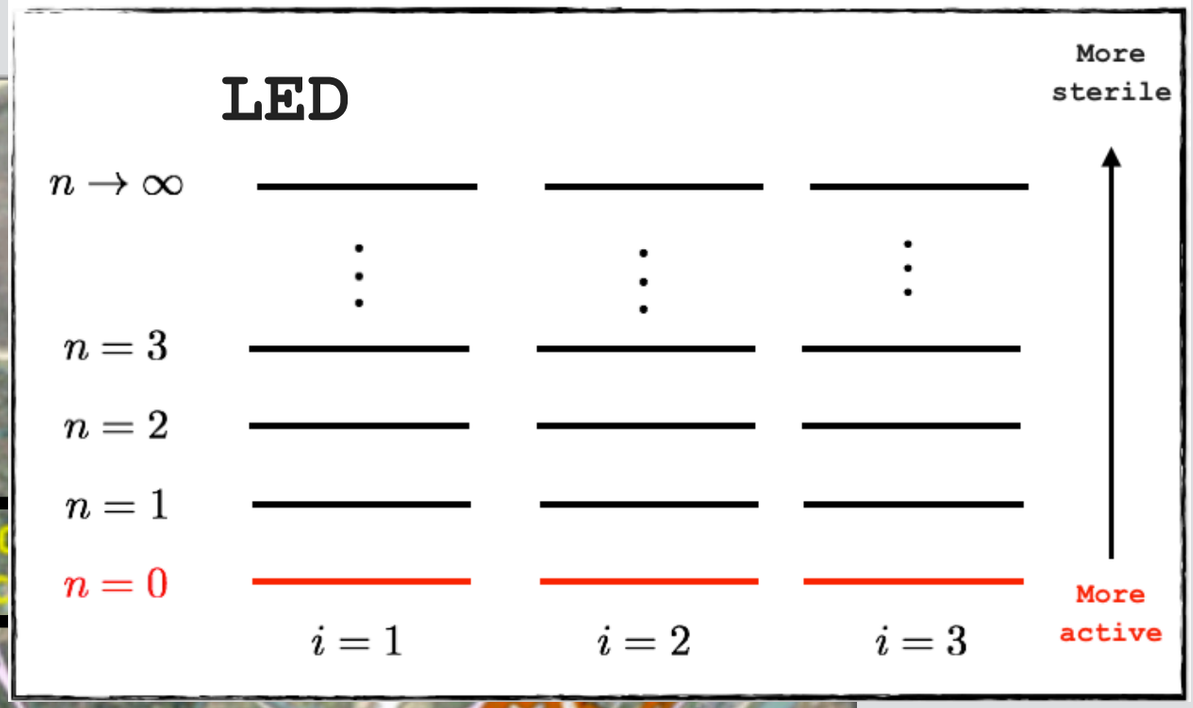

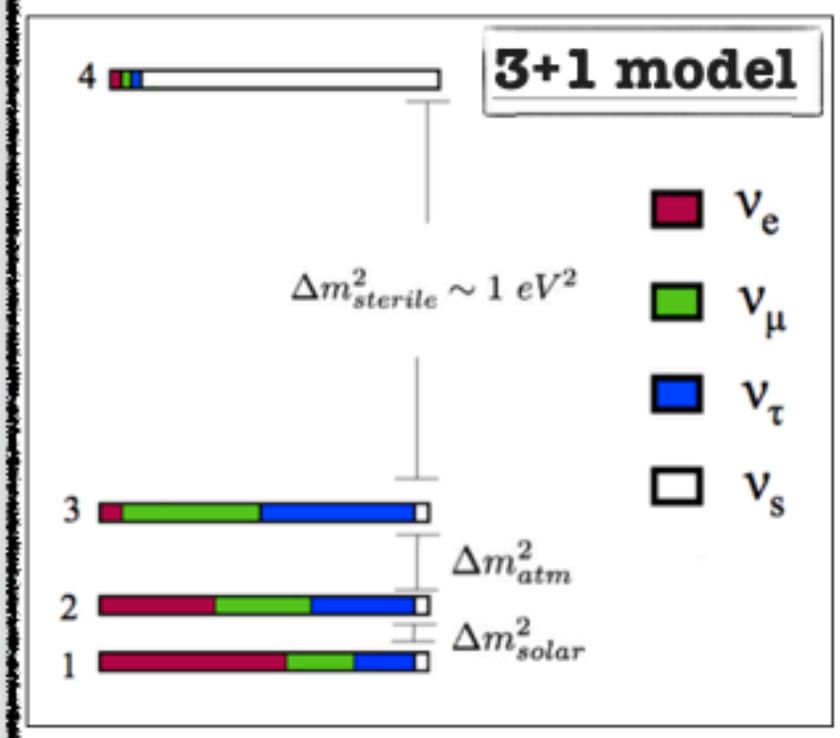

$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

SB approximation:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu}) \sin^2(1.27 \Delta m^2_{41} L/E)$$

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e}) \sin^2(1.27 \Delta m^2_{41} L/E)$$

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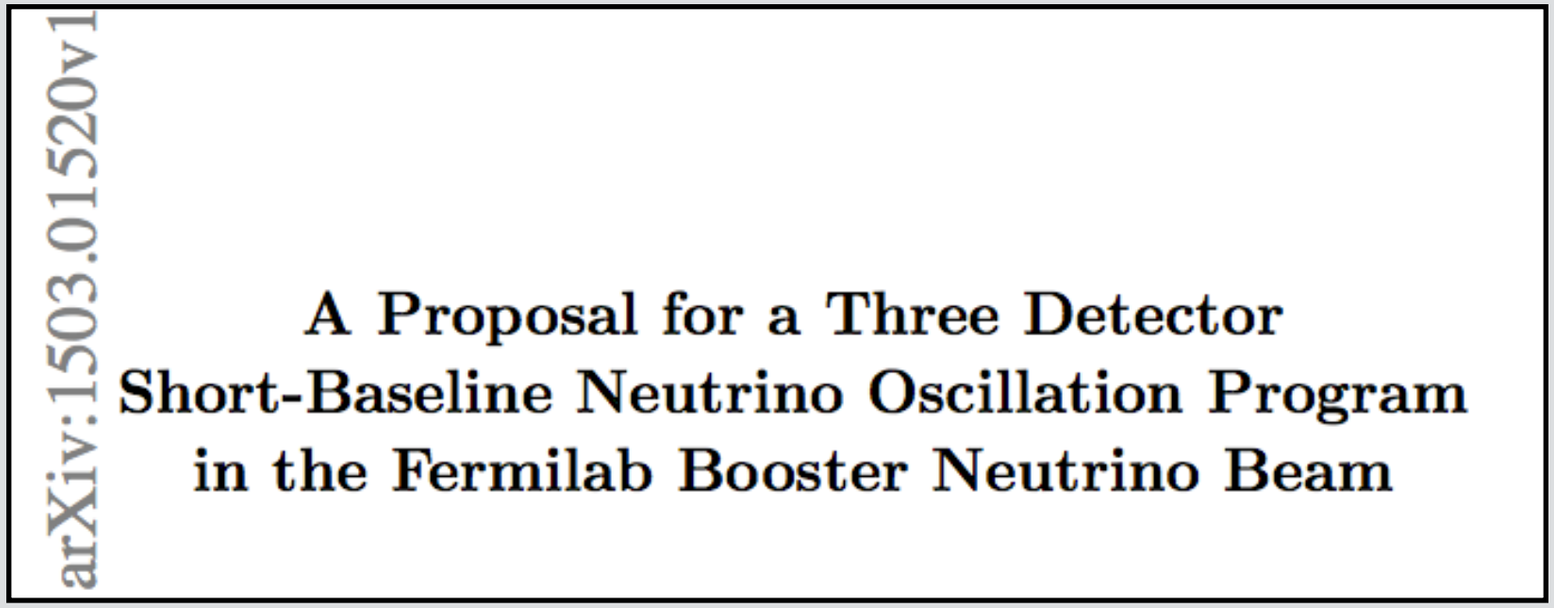
Results:

GLoBES +



arXiv:1503.01520

NH IH

Results:

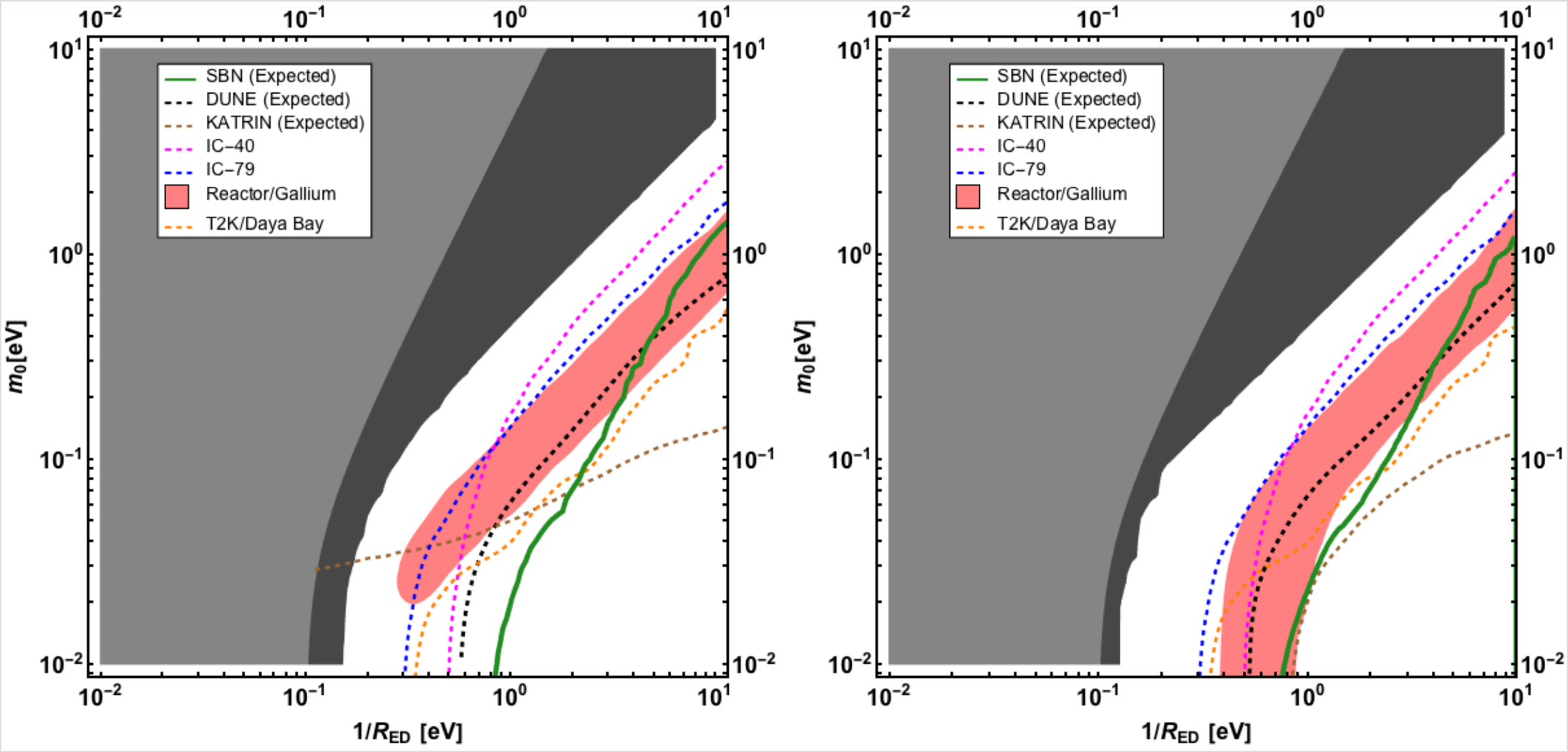
GLoBES +

arXiv:1503.01520v1

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

arXiv:1503.01520

Sensitivity analysis 90% CL



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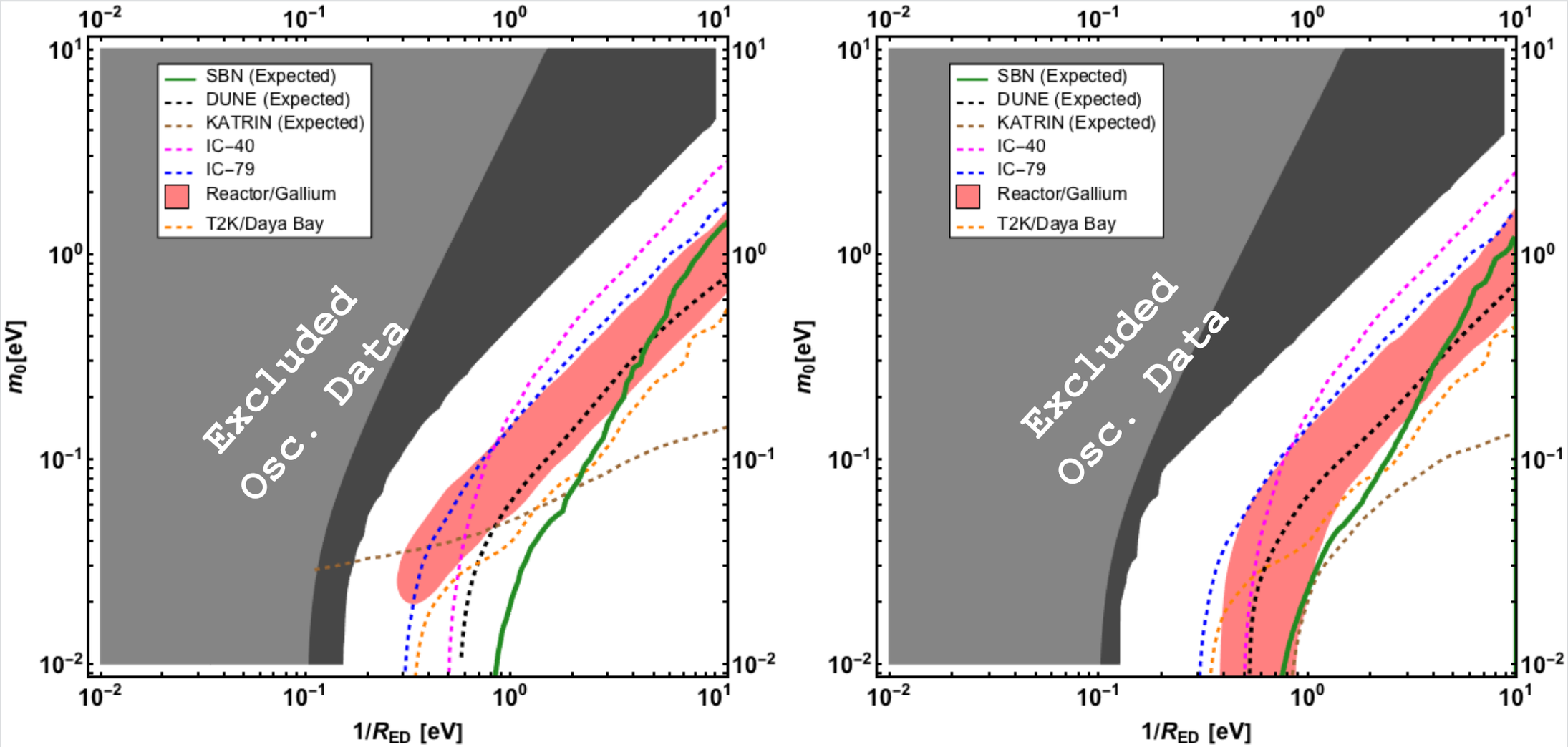


NH IH

Constrains by neutrino oscillation data:

Square mass differences:

$$\frac{\left(\lambda_2^{(0)}\right)^2 - \left(\lambda_1^{(0)}\right)^2}{R_{\rm ED}^2} = \Delta m^2_{\rm sol} \quad \text{and} \quad \left|\frac{\left(\lambda_3^{(0)}\right)^2 - \left(\lambda_1^{(0)}\right)^2}{\mathrm{R}_{\rm ED}^2}\right| = \Delta \mathrm{m}^2_{\rm atm}.$$

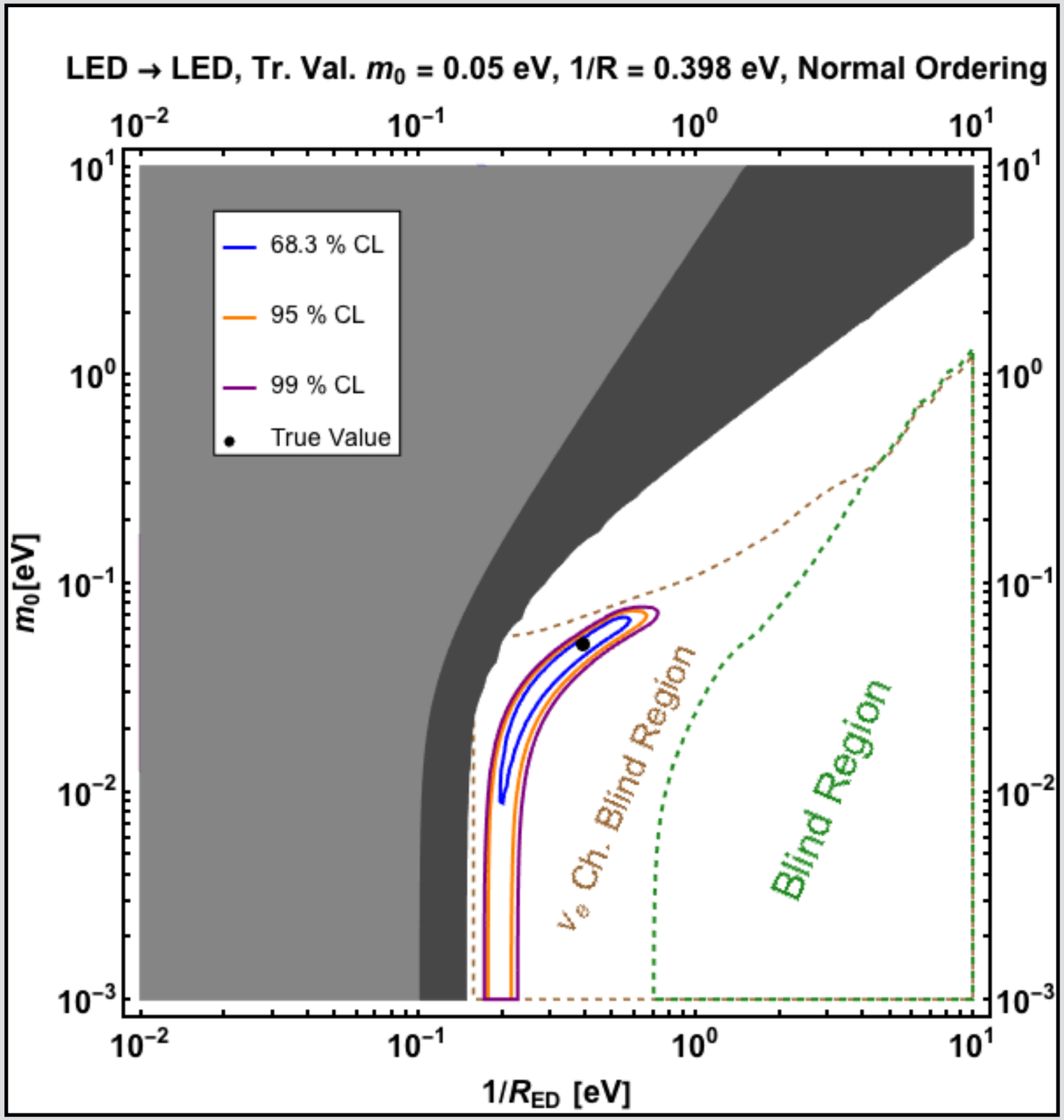
Mixing angles:

$$\sin\theta_{13}^{\rm LED} = \frac{\sin\theta_{13}^{3\nu}}{(S_3^{00})}$$

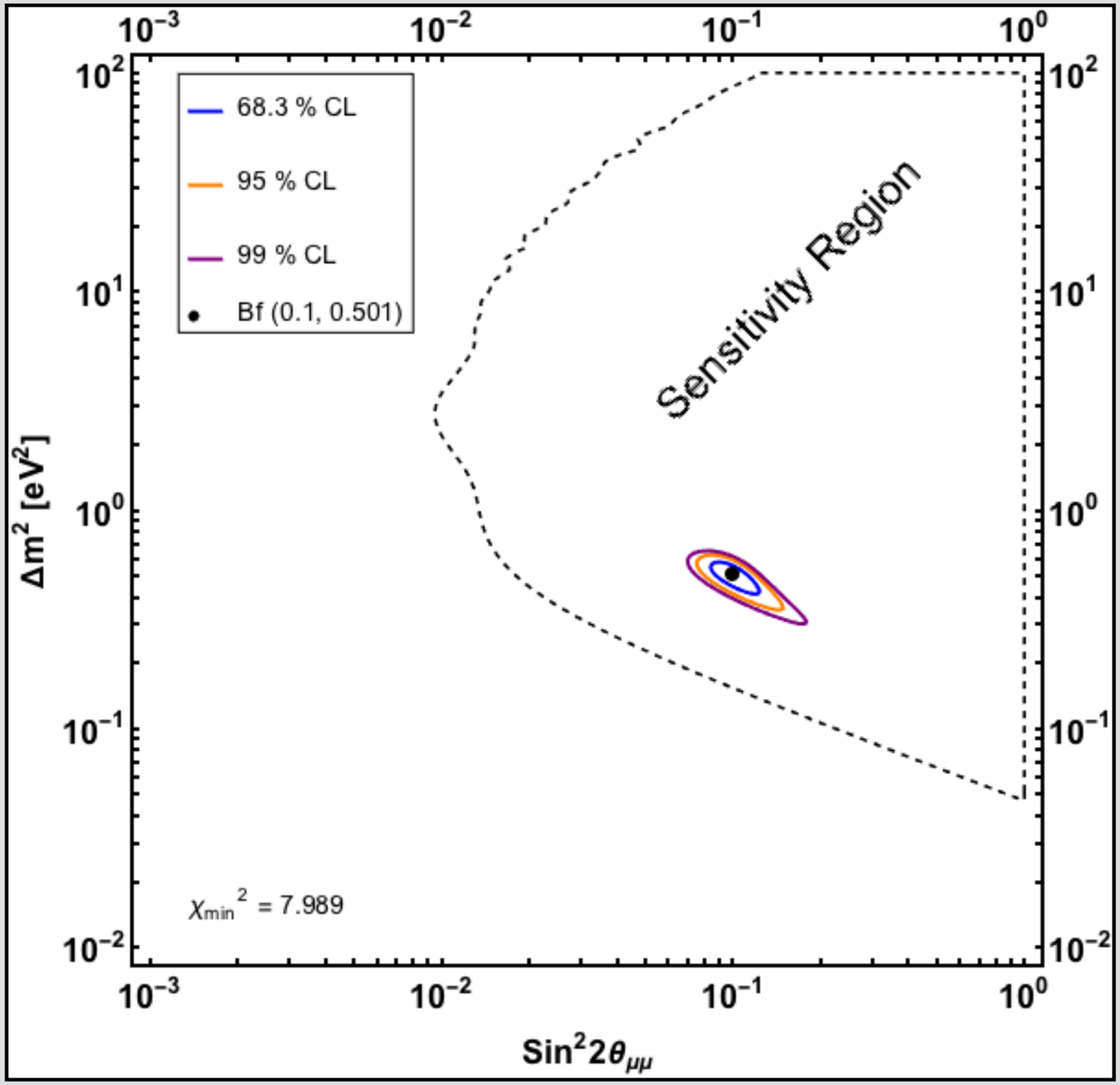
$$\cos\theta_{13}^{\rm LED}\sin\theta_{12}^{\rm LED} = \frac{\cos\theta_{13}^{3\nu}\sin\theta_{12}^{3\nu}}{(S_2^{00})}$$

$$\cos\theta_{13}^{\rm LED}\sin\theta_{23}^{\rm LED} = \frac{\cos\theta_{13}^{3\nu}\sin\theta_{23}^{3\nu}}{(S_3^{00})}$$

SBN potential to measure LED parameters

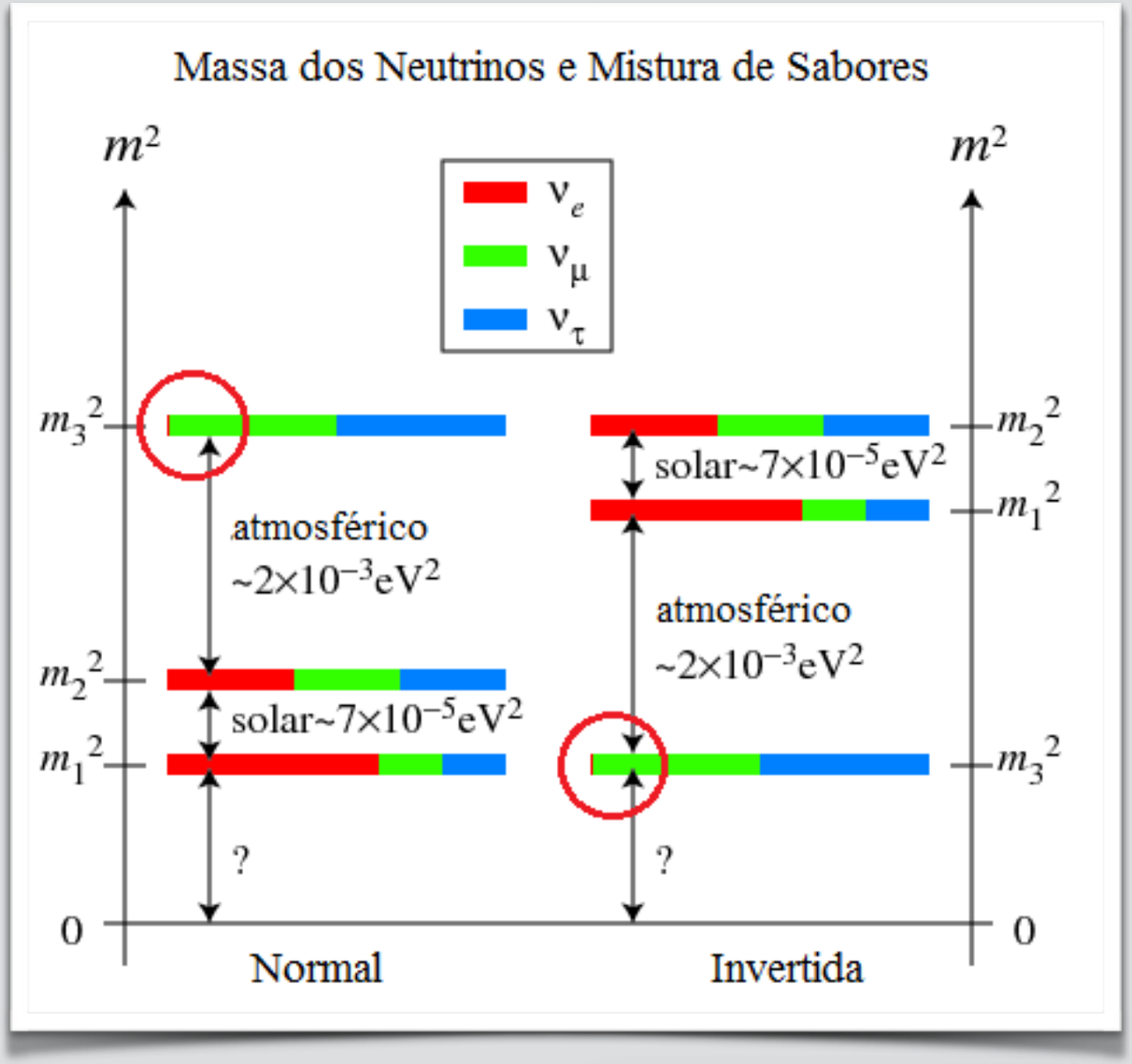


3+1 fit to the LED scenario



Thank you!

Neutrino Oscillation



$$|\nu_i\rangle = \sum_\alpha U_\alpha |\nu_\alpha\rangle$$

$$|\nu_\alpha\rangle = \sum_i U_i^* |\nu_i\rangle$$

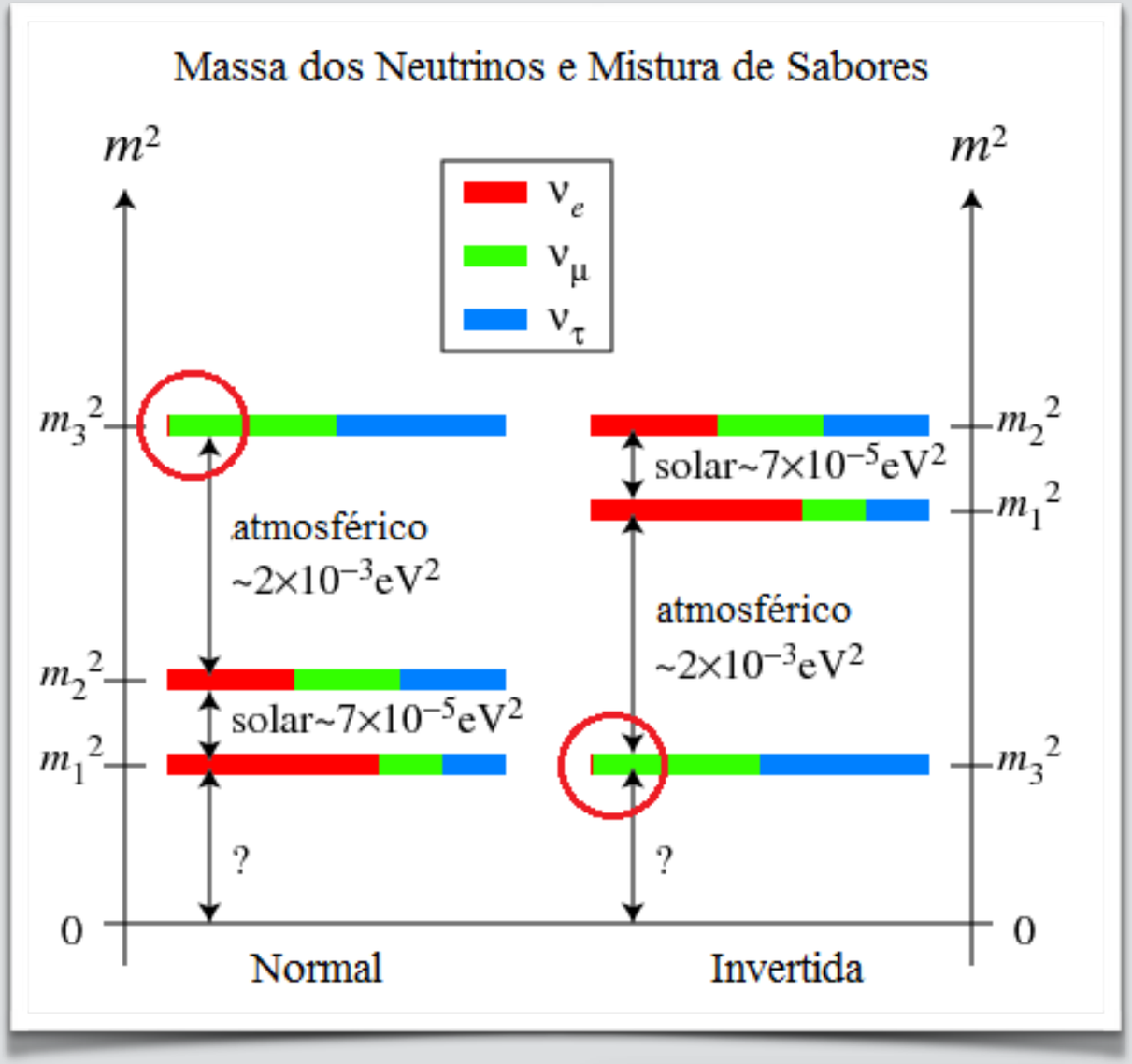
$(\alpha = e, \mu, \tau \;\text{ and }\; \mathrm{i} = 1, 2, 3)$

$$x_{\mathrm{osc}} = \frac{4\pi E}{\Delta m_{ij}^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \exp\left(i \frac{m_j^2 - m_i^2}{2E} x \right)$$

Neutrino Oscillation

ν_e



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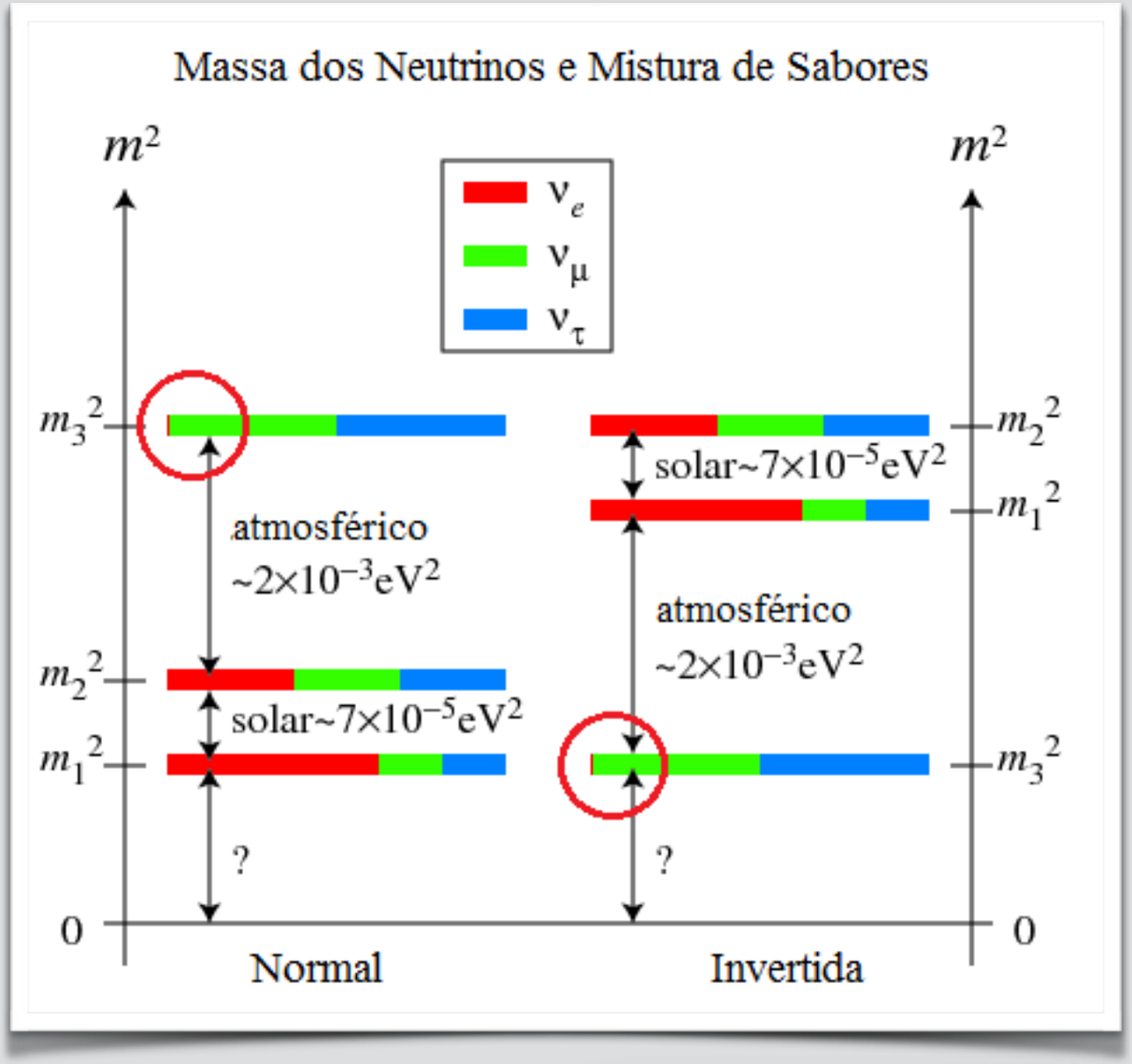
Neutrino Oscillation

$$\nu_e \xrightarrow[E,x]{}$$



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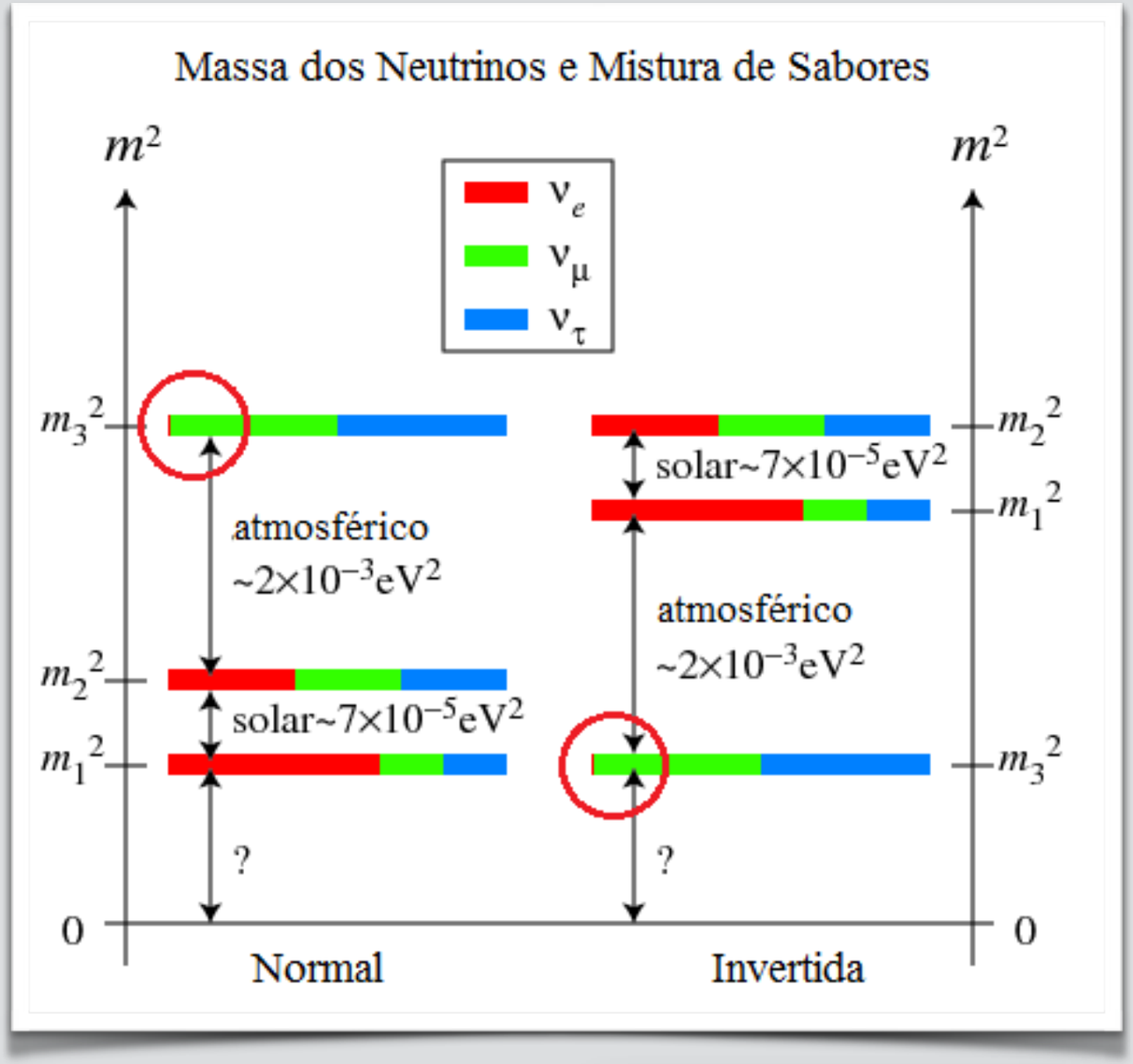
Neutrino Oscillation

$$\nu_e \xrightarrow[E,x]{} \nu_\tau$$



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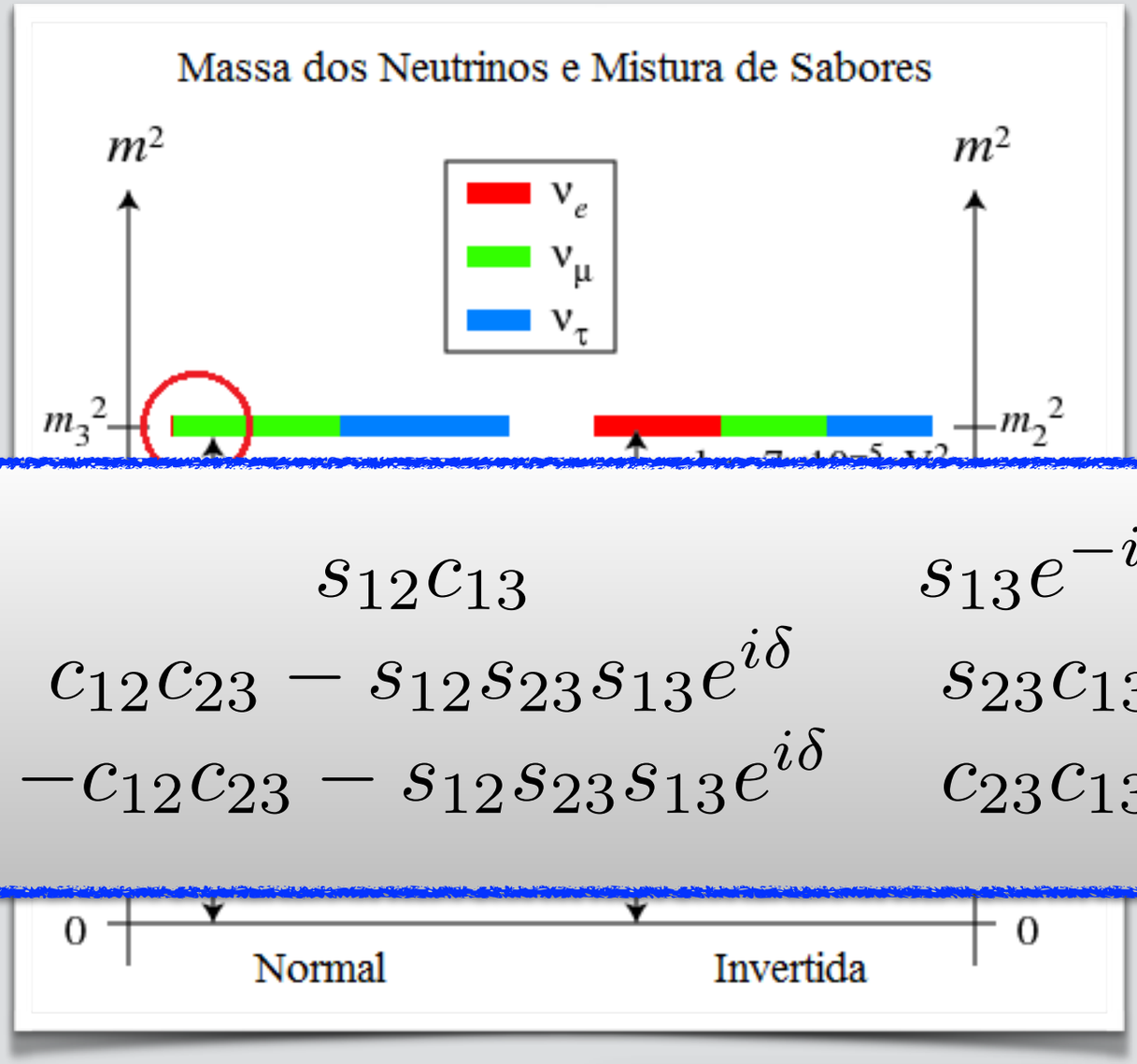
Neutrino Oscillation

$$\nu_e \xrightarrow[E,x]{} \nu_\tau$$



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

$$|\nu_\alpha\rangle = \sum_i U_i^* |\nu_i\rangle$$

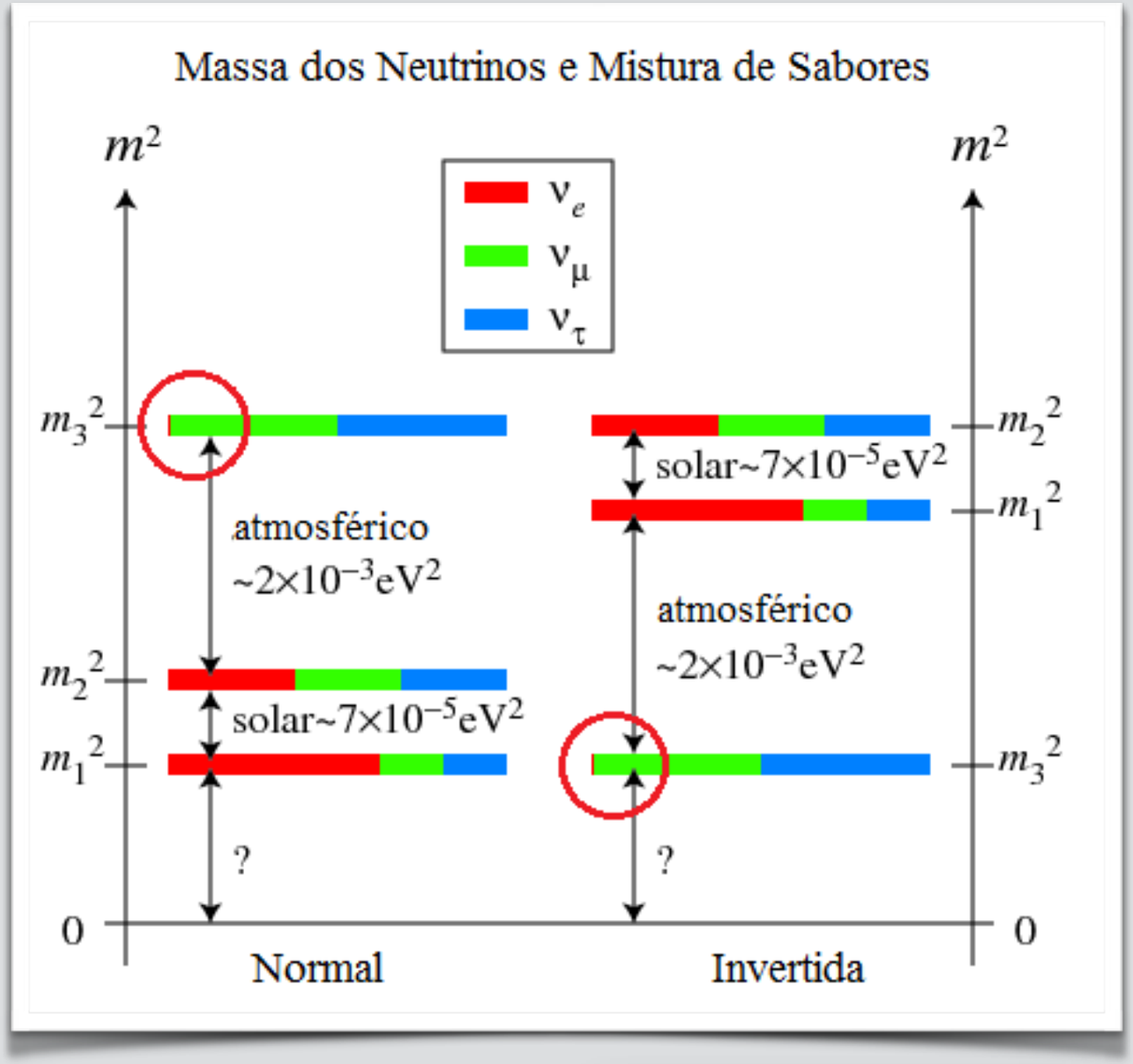
$(\alpha = e, \mu, \tau \text{ and } \mathrm{i} = 1, 2, 3)$

$$x_{\mathrm{osc}} = \frac{4\pi E}{\Delta m_{ij}^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \exp\left(i \frac{m_j^2 - m_i^2}{2E} x \right)$$

Neutrino Oscillation

$$\nu_e \xrightarrow[E,x]{} \nu_\tau$$



$$|\nu_i\rangle = \sum_\alpha U_\alpha |\nu_\alpha\rangle$$

$$|\nu_\alpha\rangle = \sum_i U_i^* |\nu_i\rangle$$

$(\alpha = e, \mu, \tau \text{ and } \mathrm{i} = 1, 2, 3)$

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Neutrino Oscillation

$$\nu_e \xrightarrow[E,x]{}$$

$$|\nu_i\rangle = \sum_\alpha U_\alpha |$$

$$|\nu_\alpha\rangle = \sum_i U_i^*$$

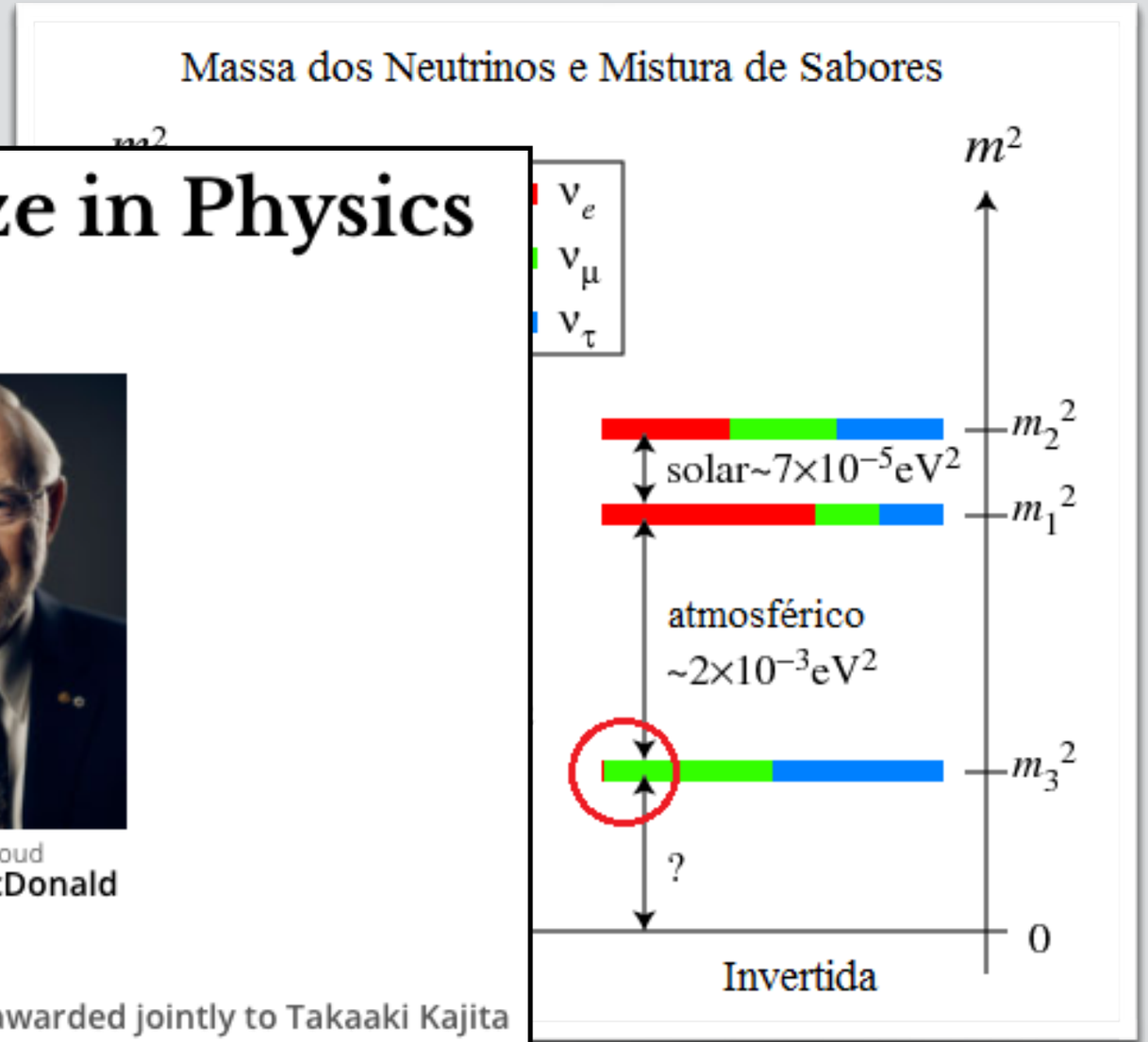
$(\alpha =$

The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

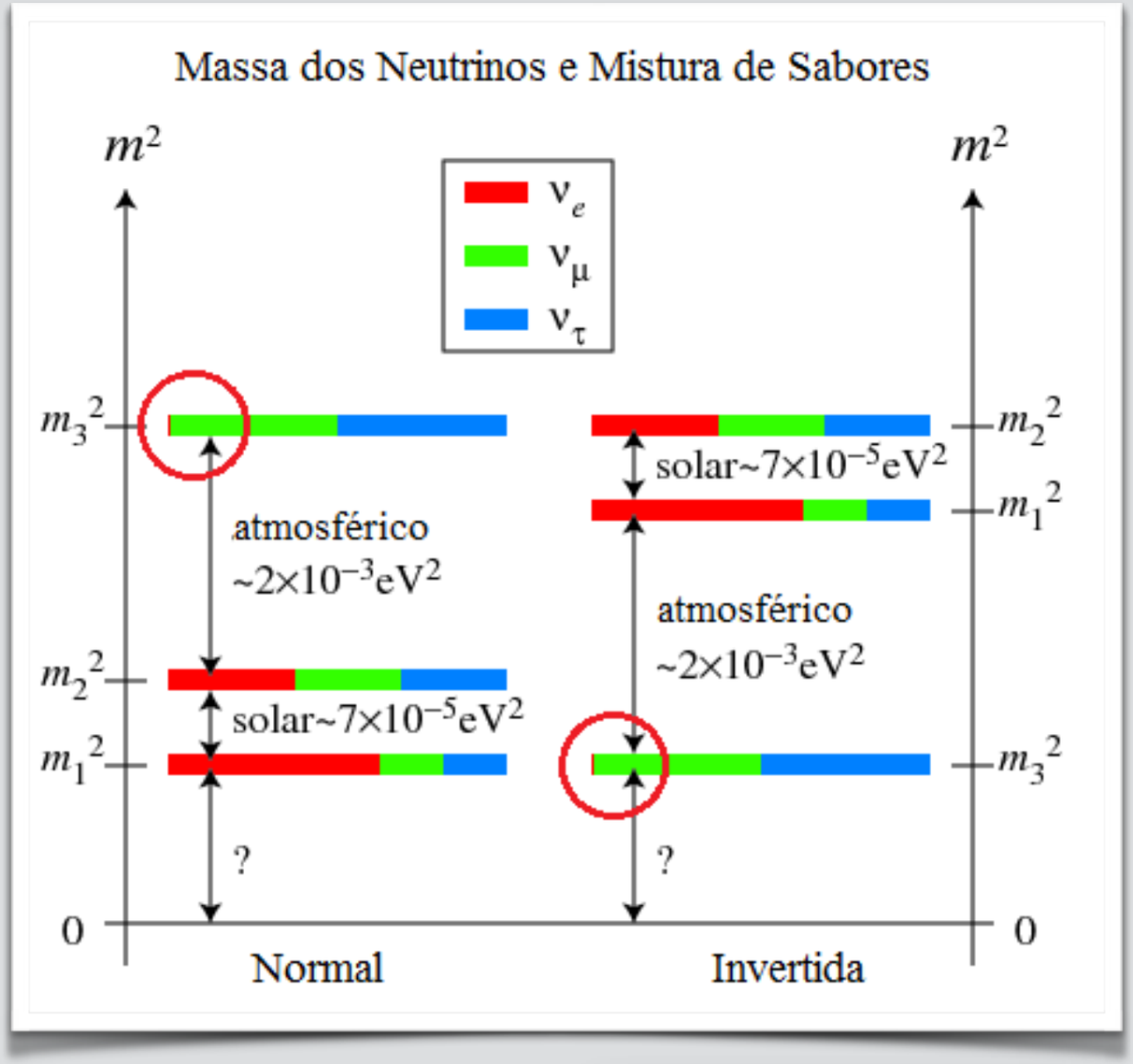


$$x_{\rm osc} = \frac{4\pi E}{\Delta m^2_{ij}}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \exp\left(i \frac{m_j^2 - m_i^2}{2E} x \right)$$

Neutrino Oscillation

$$\nu_e \xrightarrow[E,x]{} \nu_\tau$$



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$(\alpha = e, \mu, \tau \text{ and } \mathrm{i} = 1, 2, 3)$

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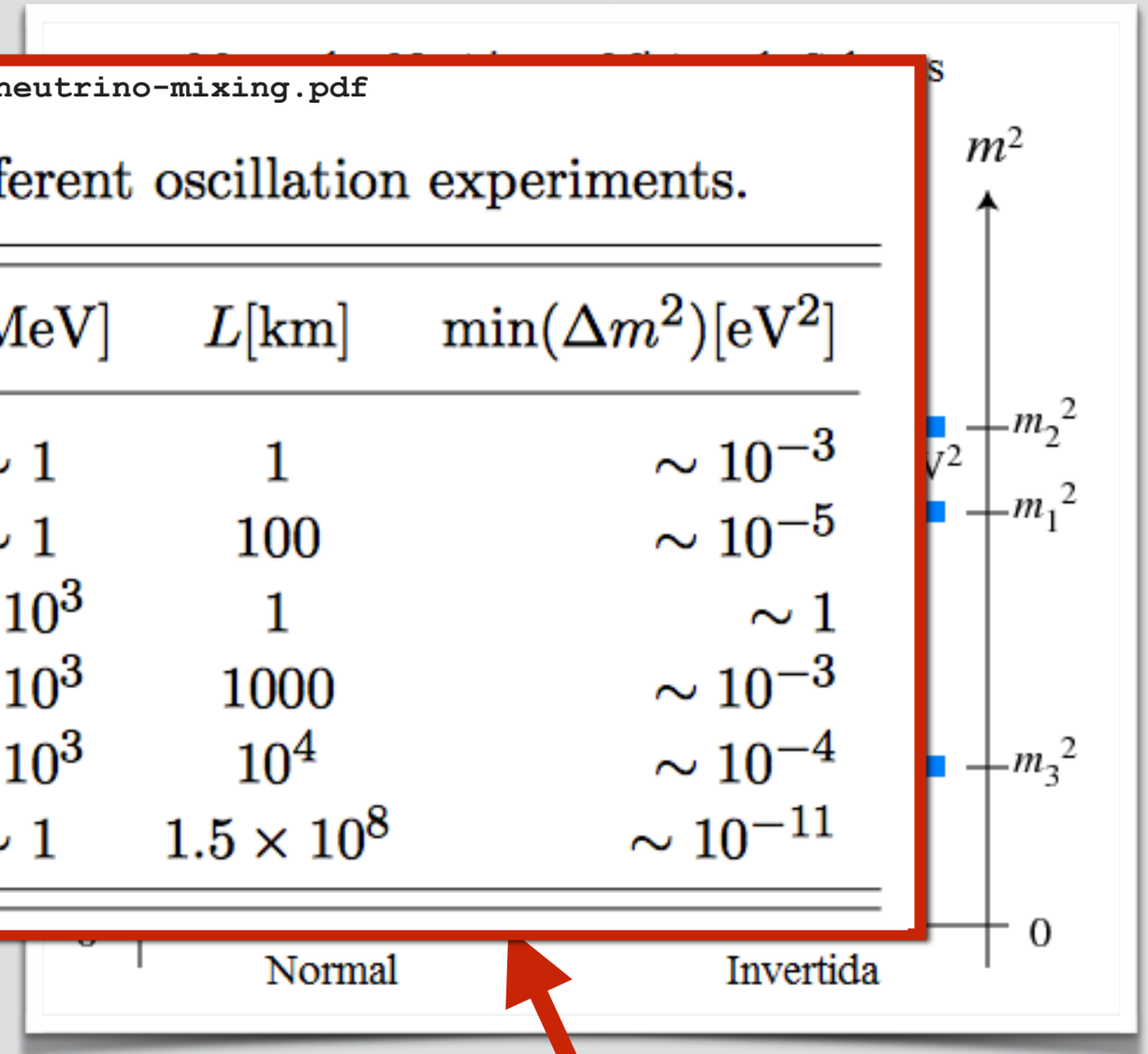
Neutrino Oscillation

http://pdg.lbl.gov/2017/reviews/rpp2016-rev-neutrino-mixing.pdf

Table 14.4: Sensitivity of different oscillation experiments.

Source	Type of ν	$\overline{E}$[MeV]	L[km]	$\min(\Delta m^2)[\mathrm{eV}^2]$
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$



ν_e

$|\nu_i\rangle =$

$$|\nu_\alpha\rangle = \sum_i U_i^* |\nu_i\rangle$$

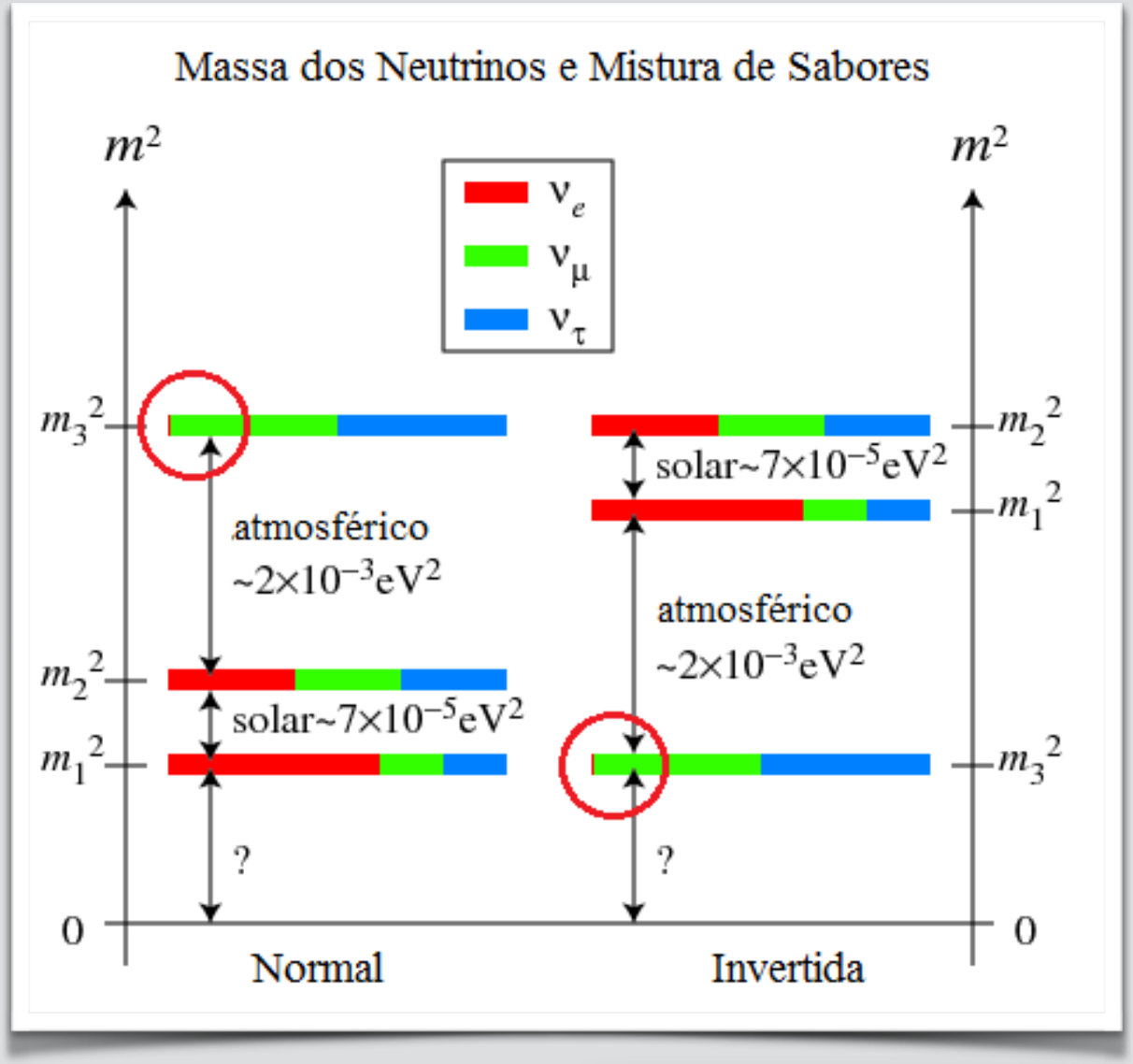
$(\alpha = e, \mu, \tau \;\text{ and }\; \mathrm{i} = 1, 2, 3)$

$$x_{\mathrm{osc}} = \frac{4\pi E}{\Delta m_{ij}^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \exp\left(i \frac{m_j^2 - m_i^2}{2E} x \right)$$

Neutrino Oscillation

$$\nu_e \xrightarrow[E,x]{} \nu_\tau$$



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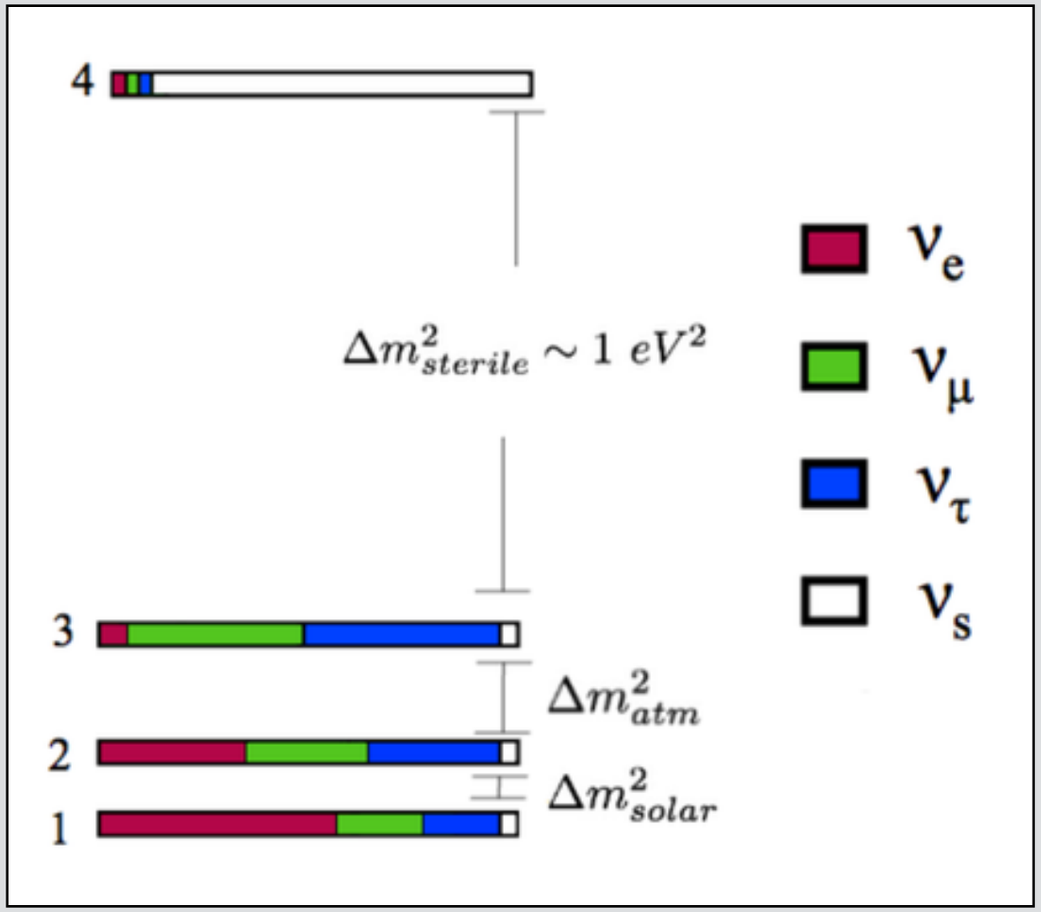
$$x_{\mathrm{osc}} = \frac{4\pi E}{\Delta m_{ij}^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \exp\left(i \frac{m_j^2 - m_i^2}{2E} x \right)$$

3+1 model



$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

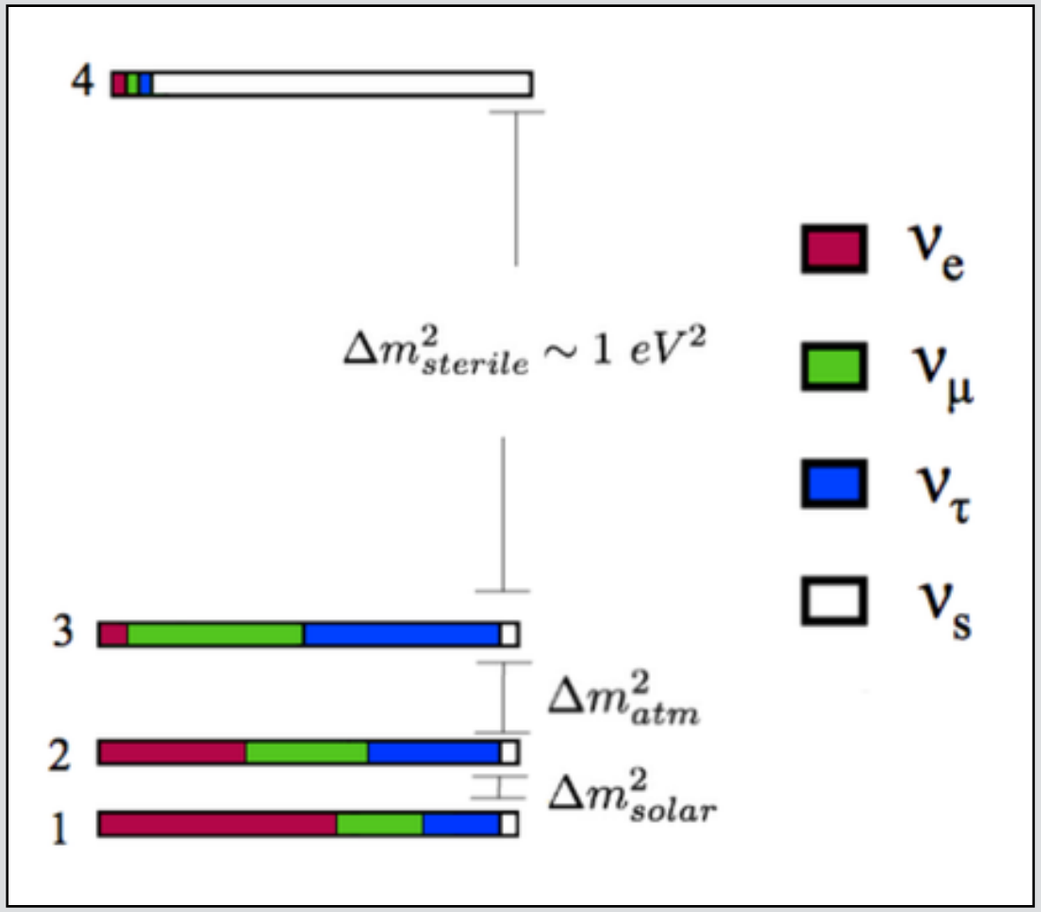
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu}) \sin^2(1.27 \Delta m^2_{41} L/E)$$

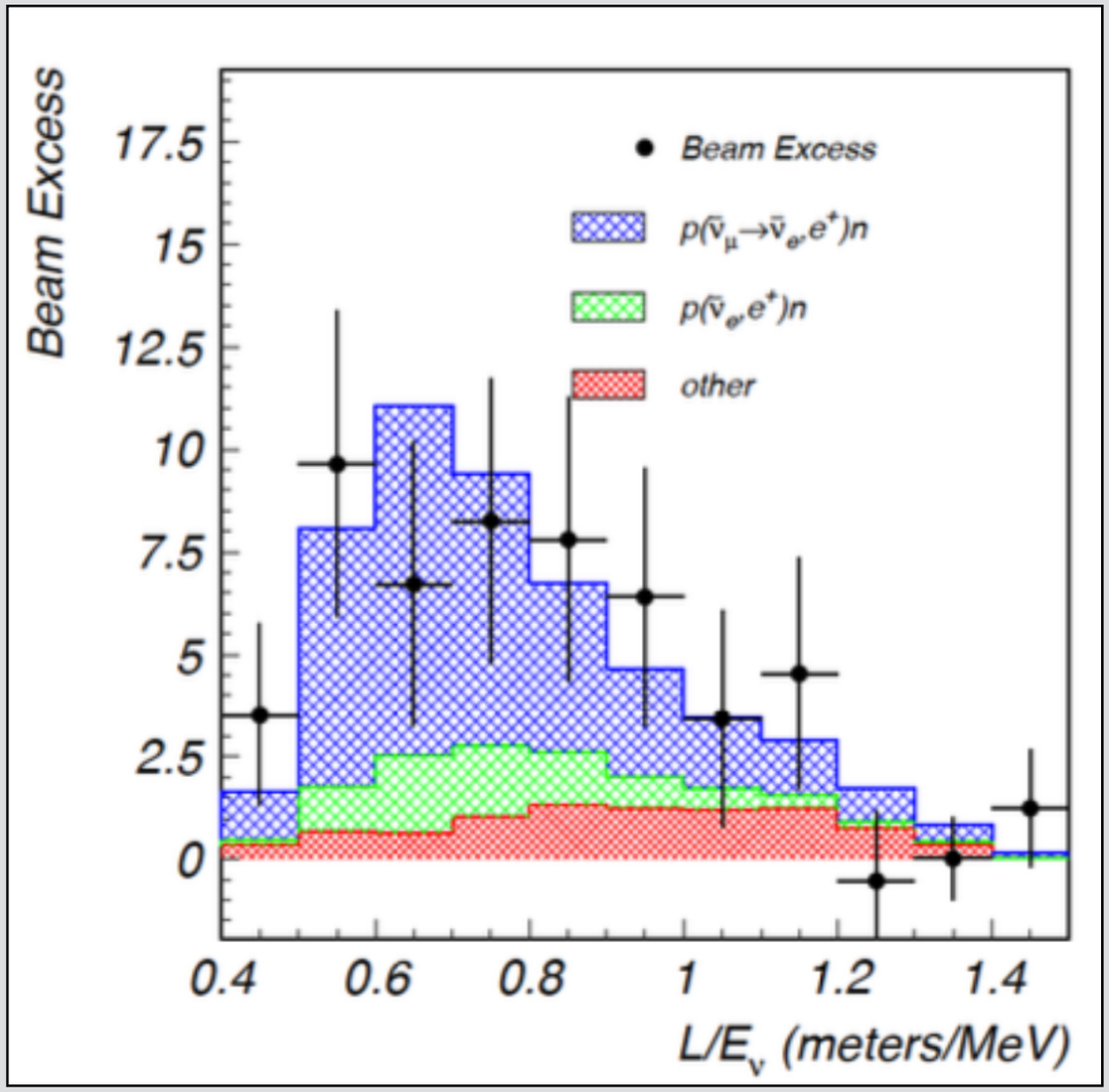
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e}) \sin^2(1.27 \Delta m^2_{41} L/E)$$

$$x_{\rm osc} \approx 1{\rm km}$$

3+1 model

A. Aguilar-Arevalo et al., Phys. Rev. D 64, 112007 (2001) [hep-ex/0104049]





$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

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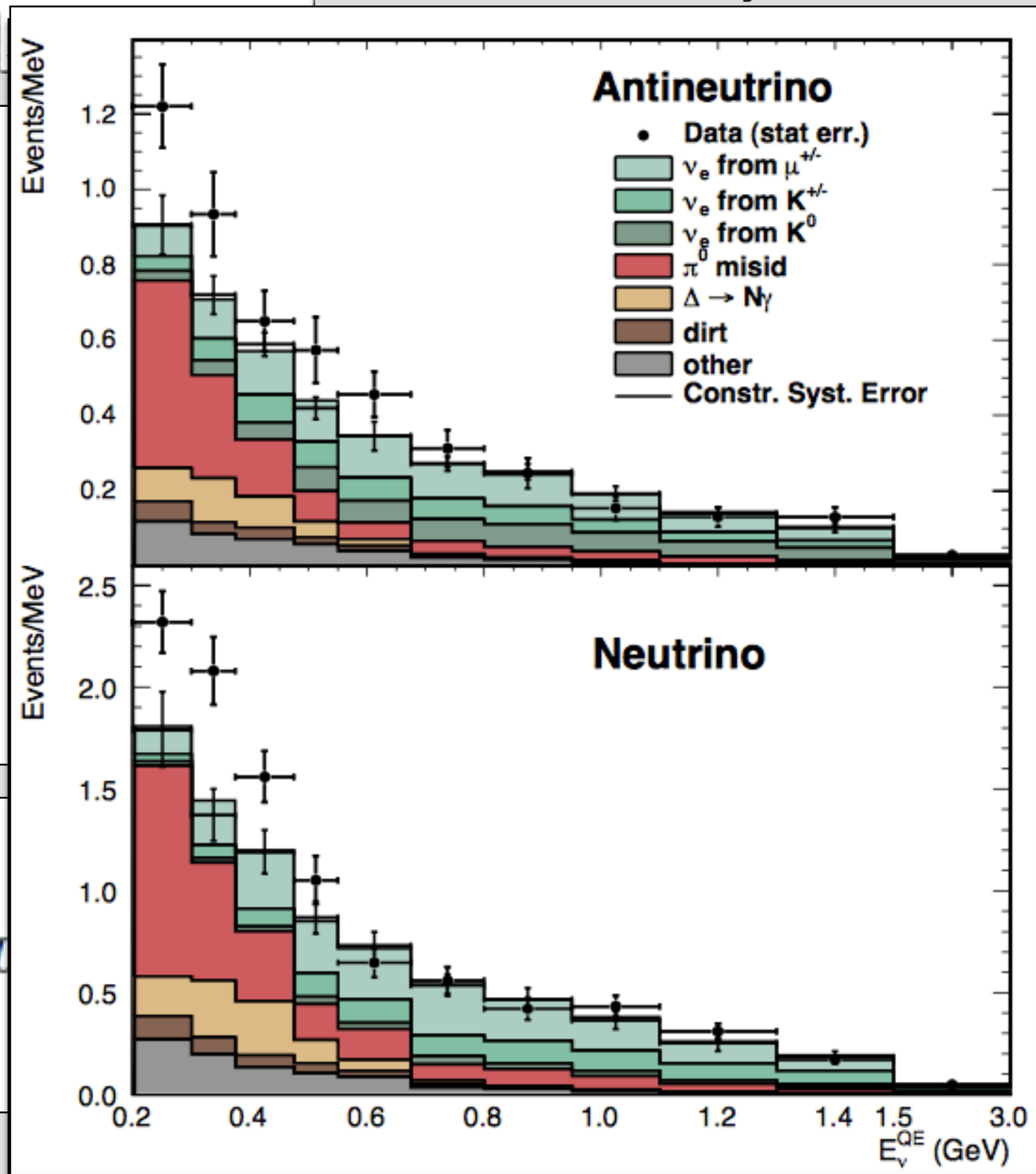
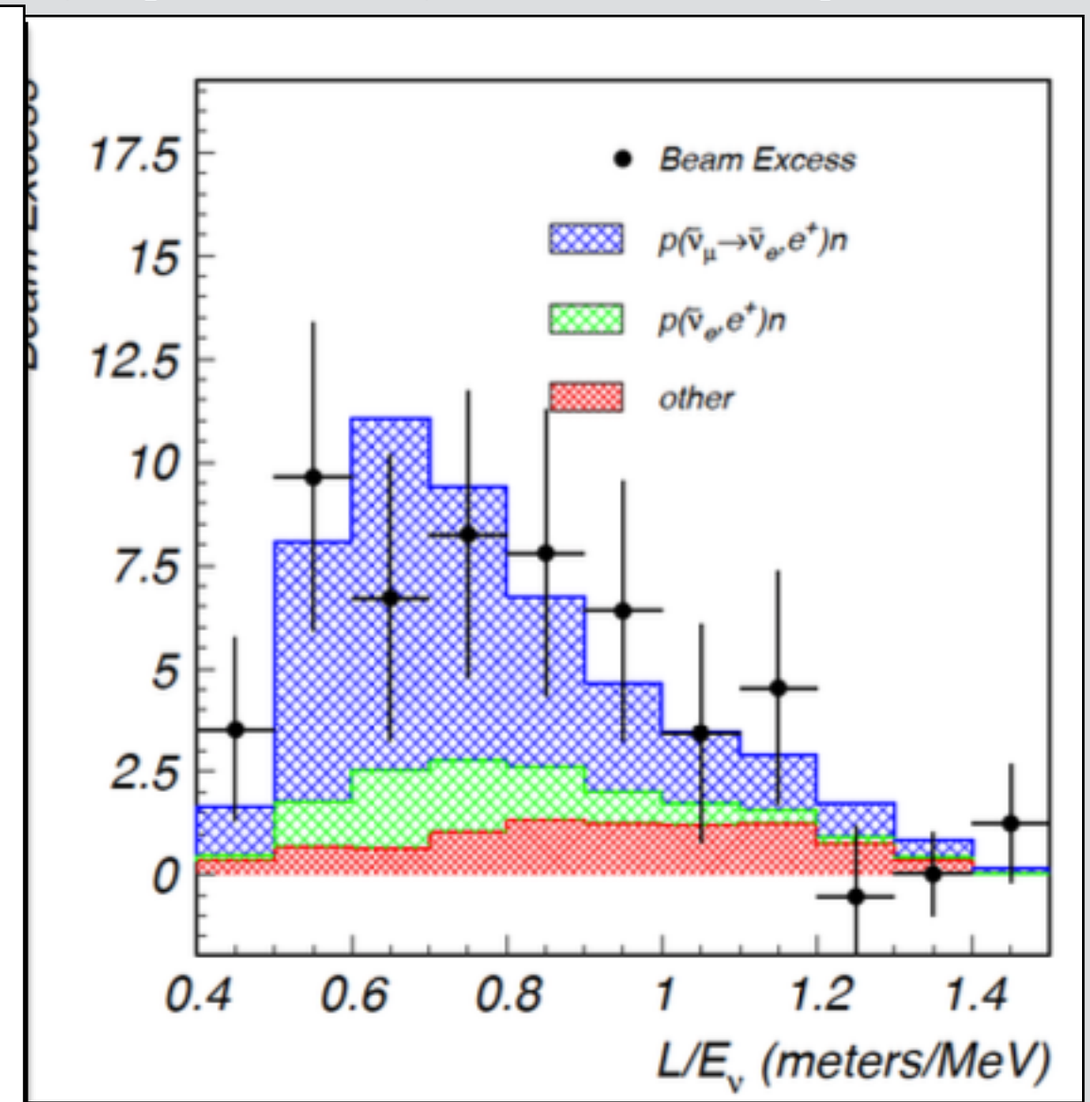
$$x_{\rm osc} \approx 1{\rm km}$$

A. Aguilar-Arevalo et al., Phys. Rev. D 64, 112007 (2001) [hep-ex/0104049]



A. Aguilar-Arevalo et al., Phys. Rev. Lett. 110, 161801 (2013).

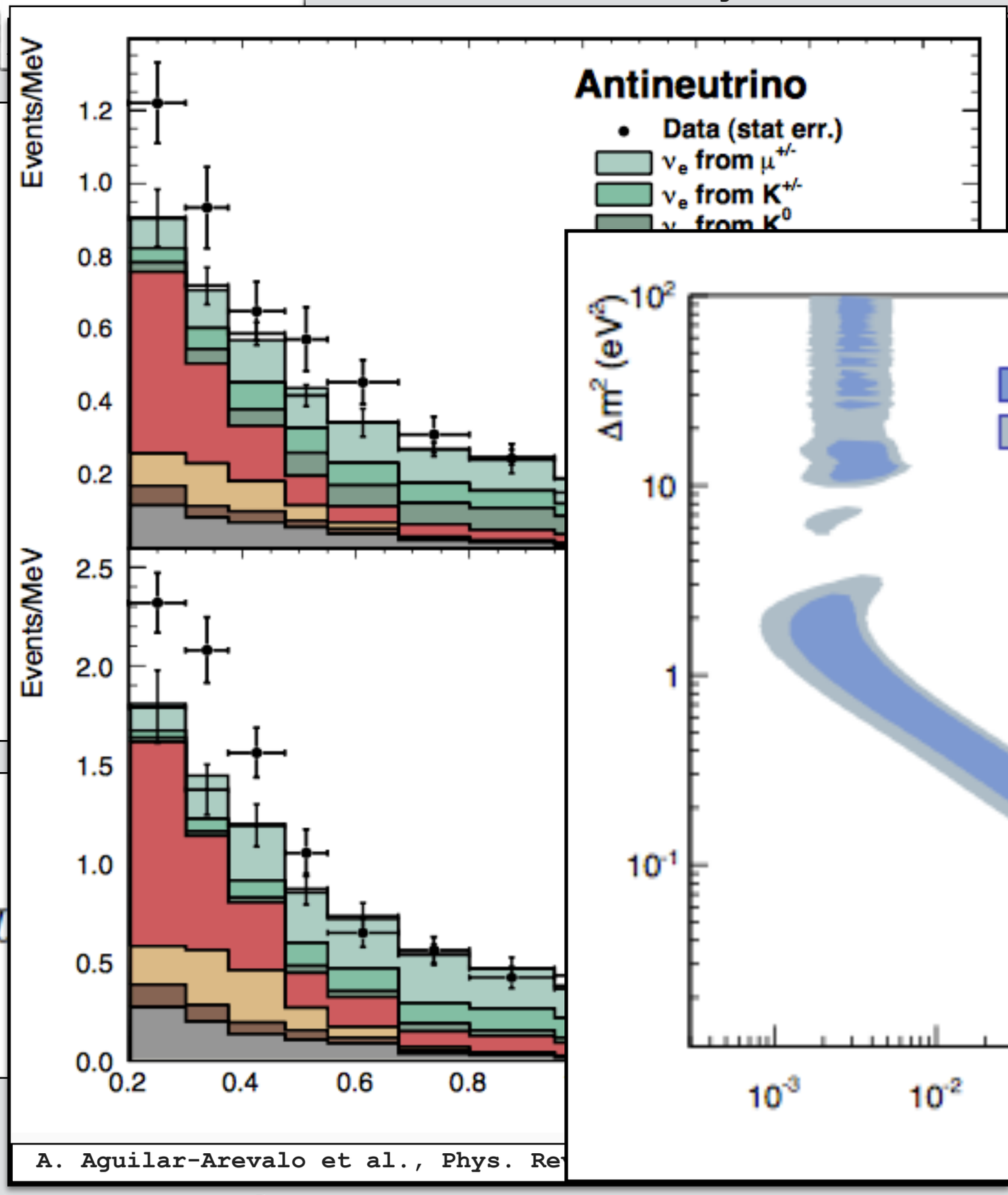


$$\sin^2(2\theta_{\mu\mu})\sin^2(1.27\Delta m^2_{41}L/E)$$

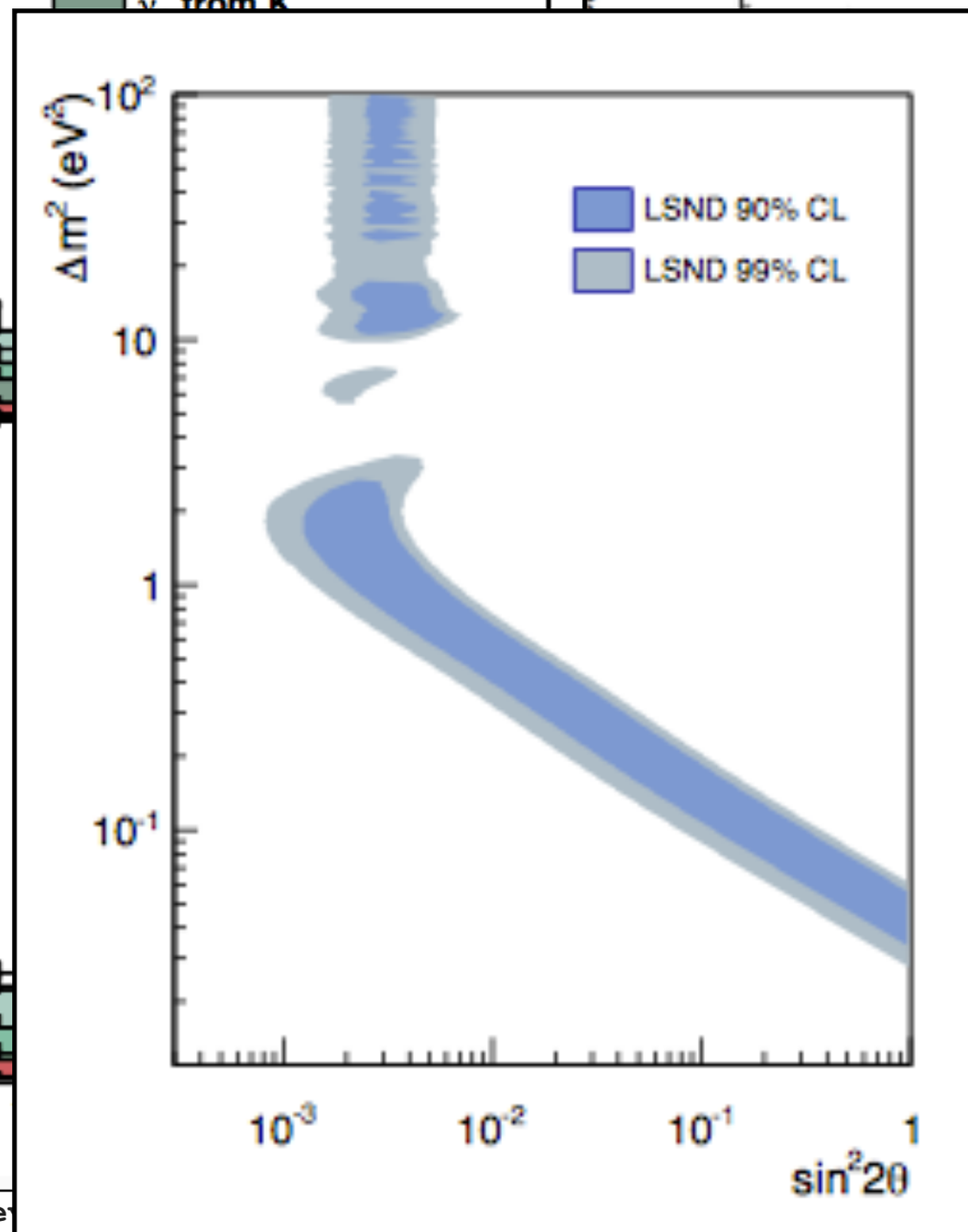
$$\sin^2(2\theta_{\mu e})\sin^2(1.27\Delta m^2_{41}L/E)$$

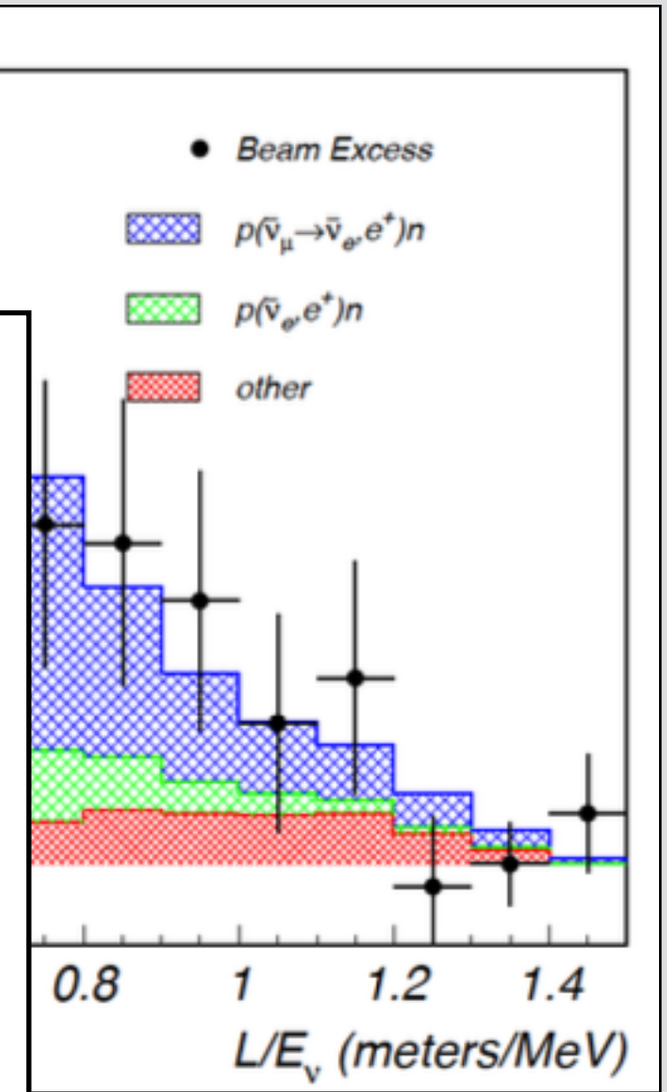
$$x_{\rm osc} \approx 1{\rm km}$$

A. Aguilar-Arevalo et al., Phys. Rev. D 64, 112007 (2001) [hep-ex/0104049]



A. Aguilar-Arevalo et al., Phys. Re





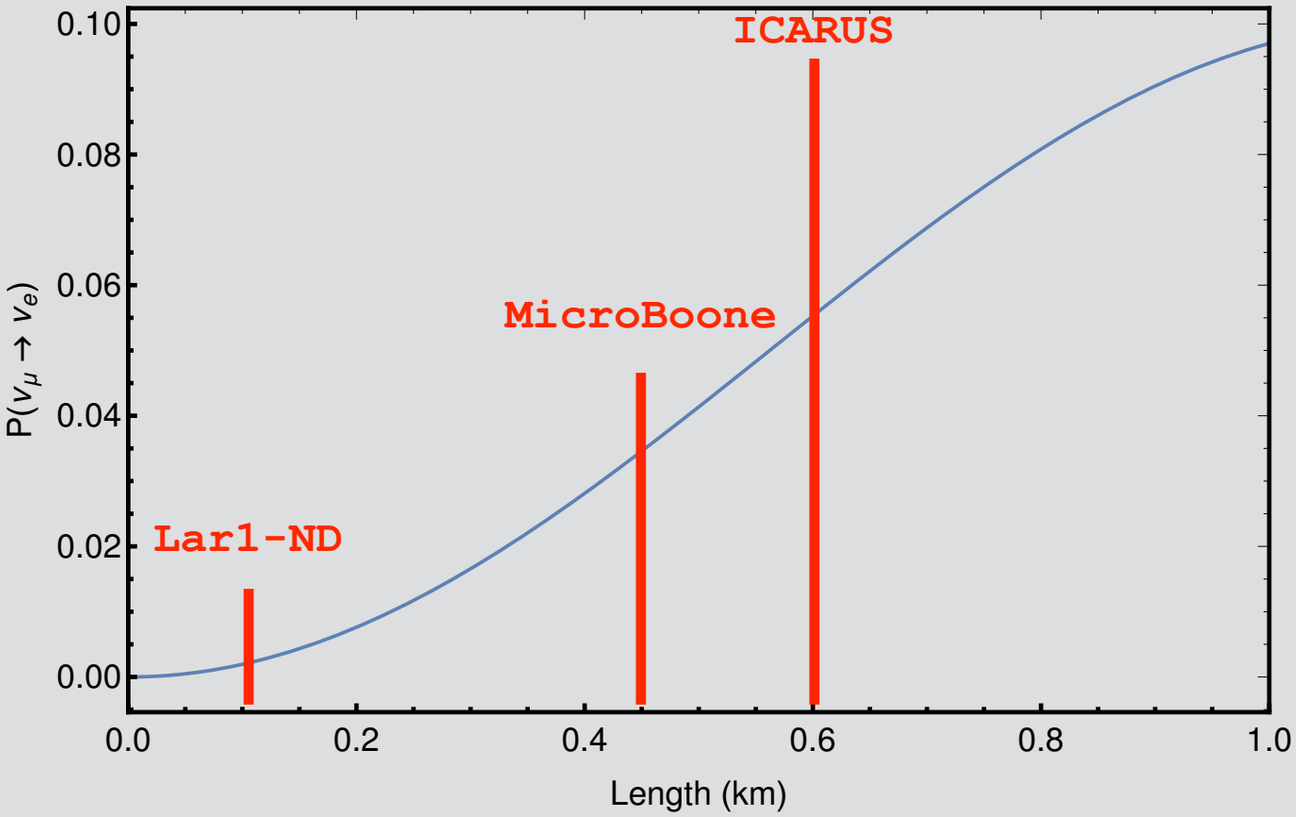
$\mathrm{n}^2(1.27\Delta m^2_{41} L/E)$

$(1.27\Delta m^2_{41} L/E)$

G. Cheng et al., Phys. Rev. D 86, 052009 (2012) [arXiv:1208.0322]

$x_{\rm osc} \approx 1\mathrm{km}$

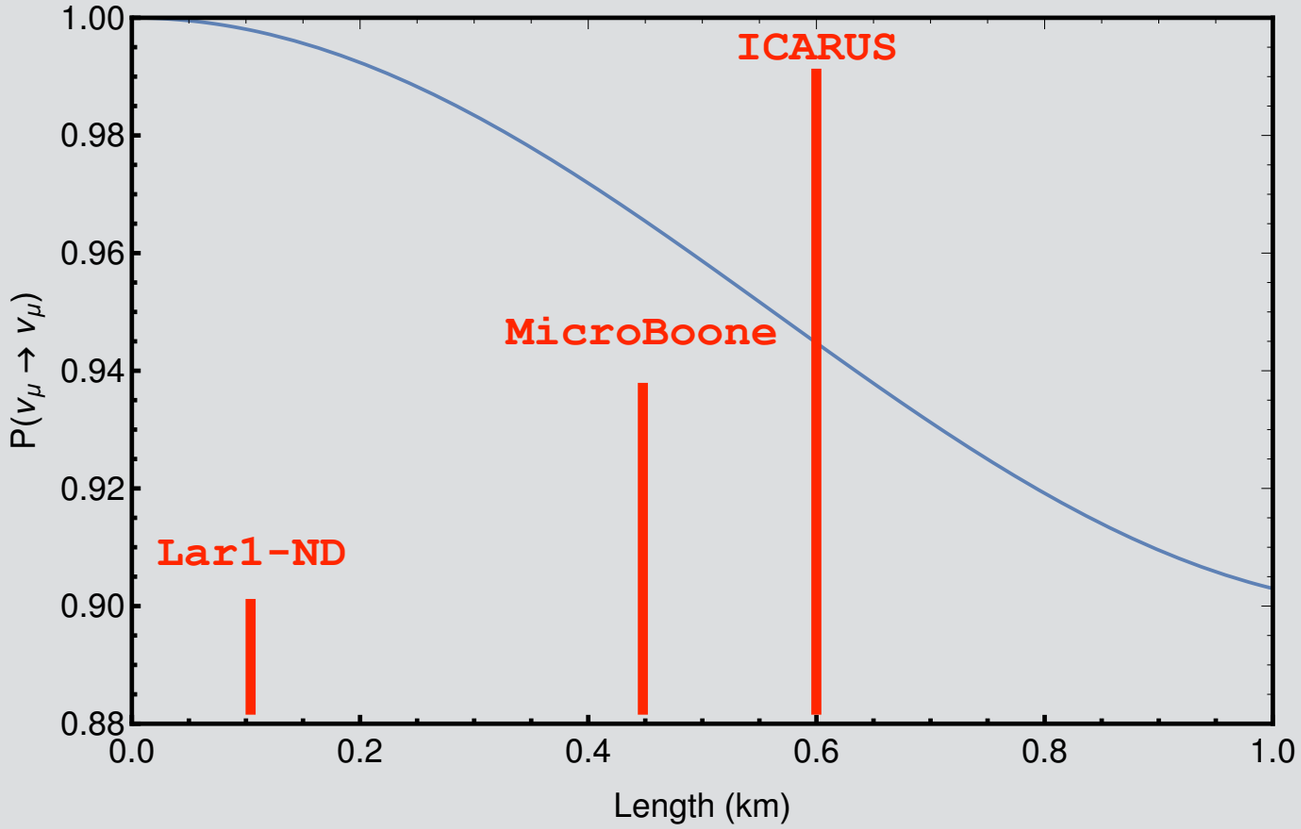
3+1 model at the SBNF



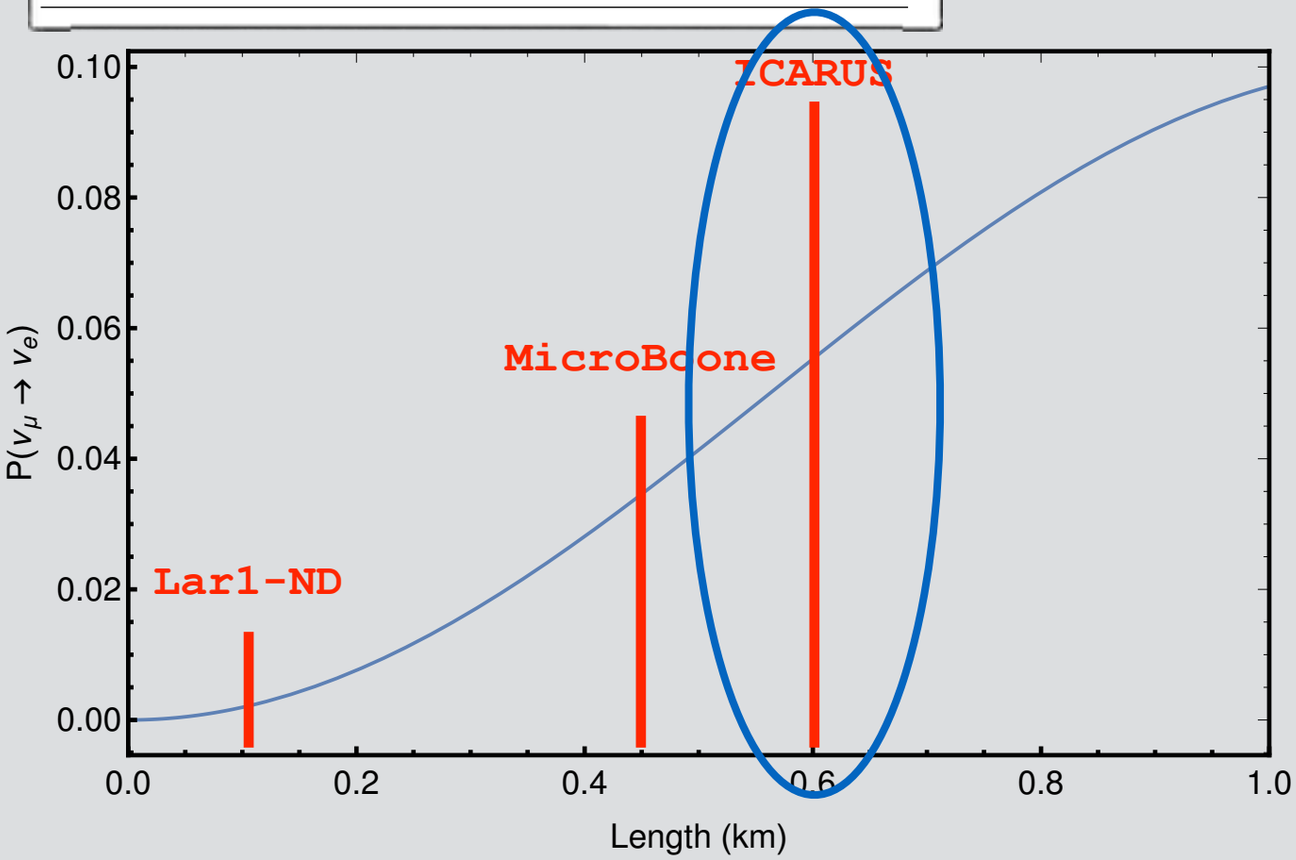
$$\sin^2(2\theta_{\mu\mu}) = 0.1$$

$$\sin^2(2\theta_{\mu e}) = 0.1$$

$$\Delta m^2_{41} = 1.1 \text{ eV}^2$$



3+1 model at the SBNF



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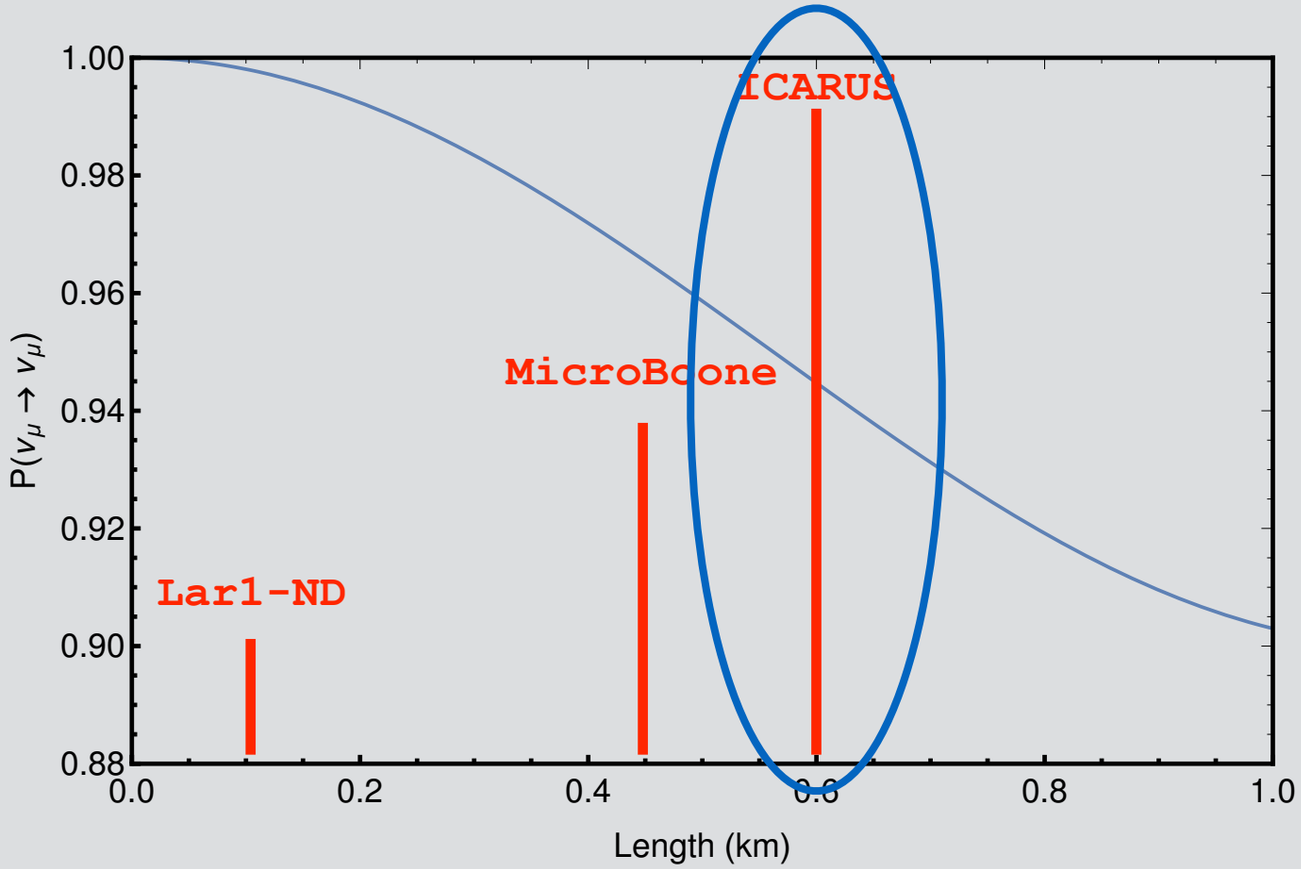


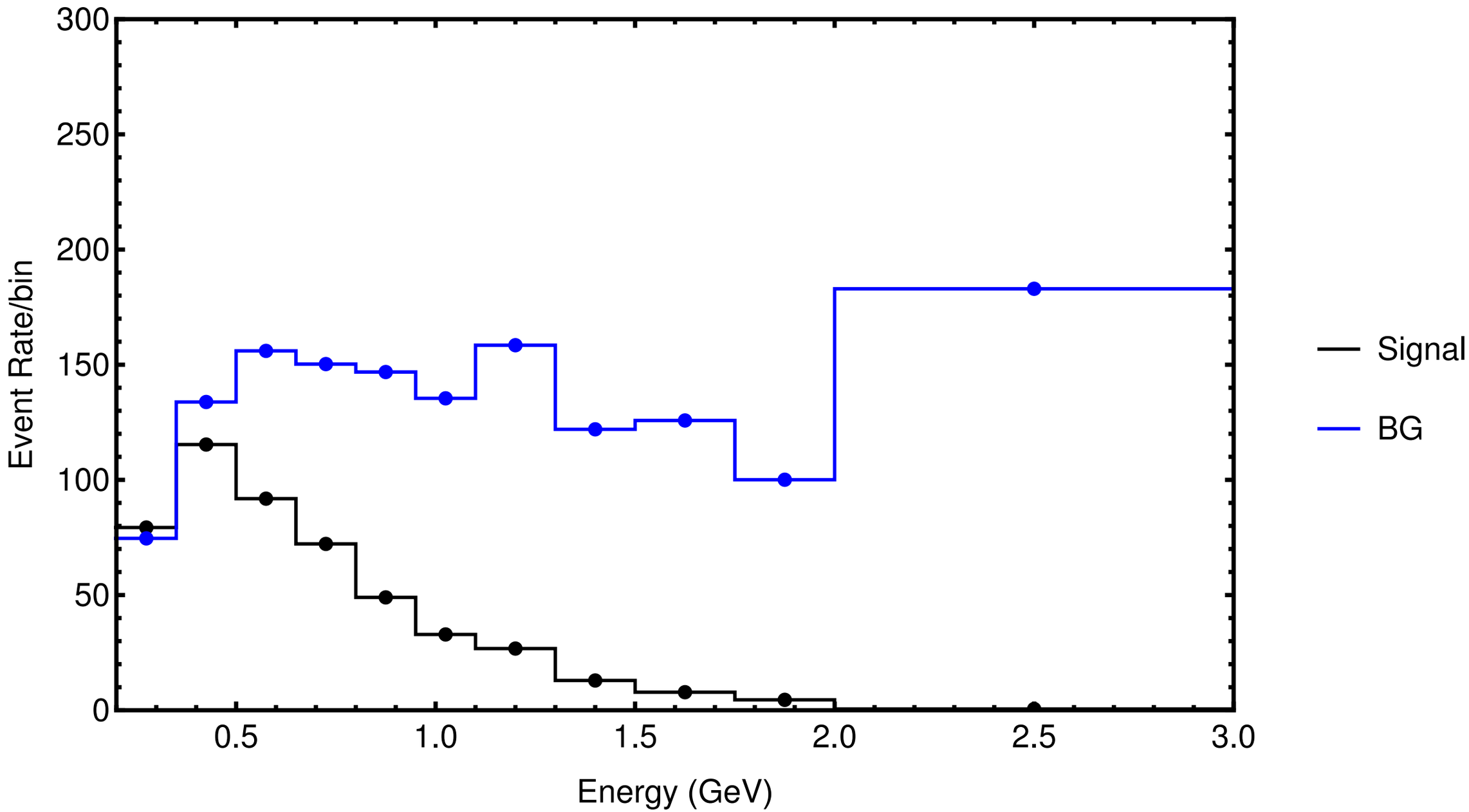
3+1 model at the SBNF

ν_e

ICARUS, 6.6×10^{20} POT (600m)

Signal : $(\Delta m^2_{41} = 0.43\ \mathrm{eV}^2,\ \sin^2 2\theta_{\mu e} = 0.013)$

Statistical Uncertainty Only



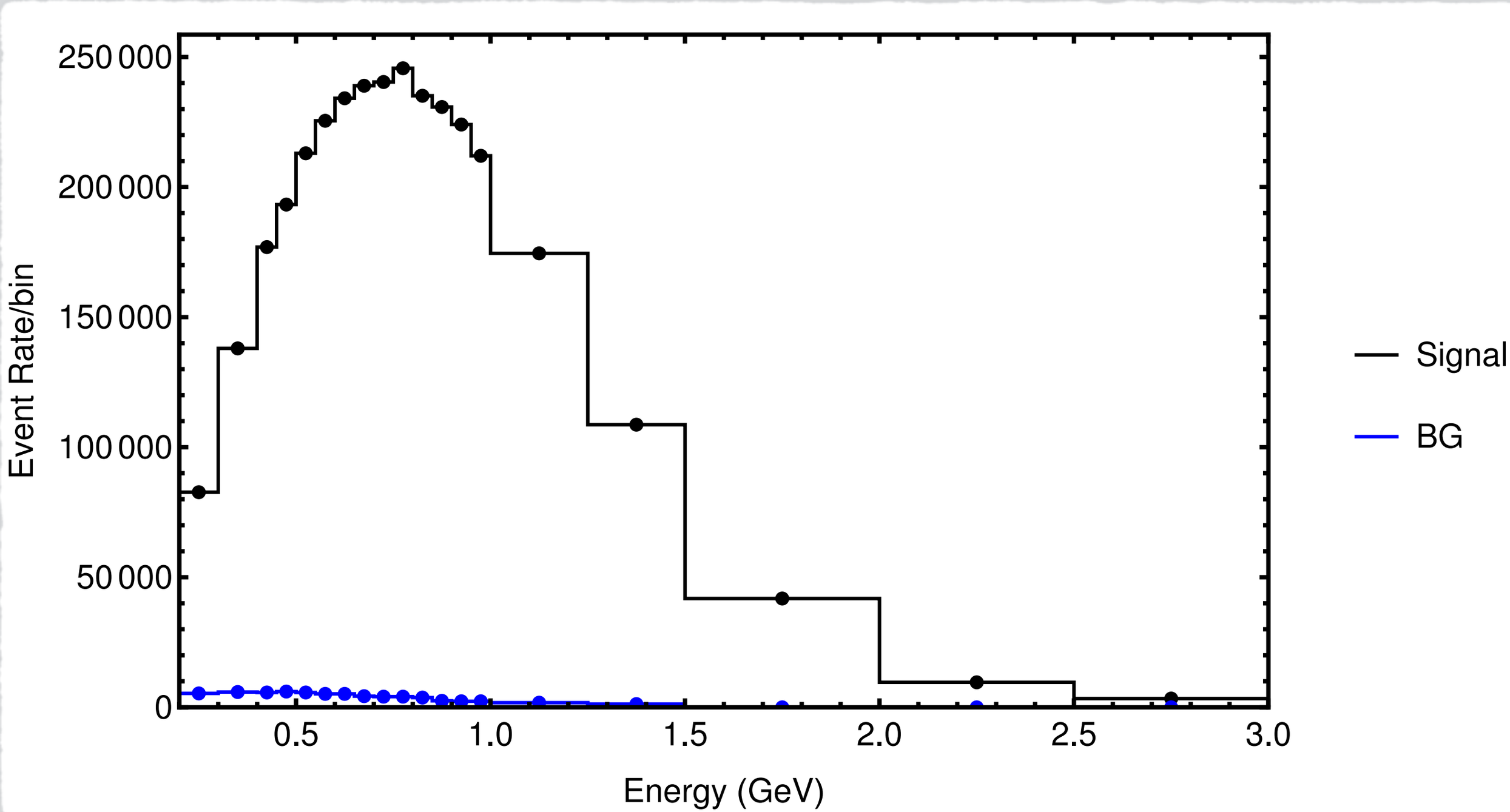
3+1 model at the SBNF

ν_μ

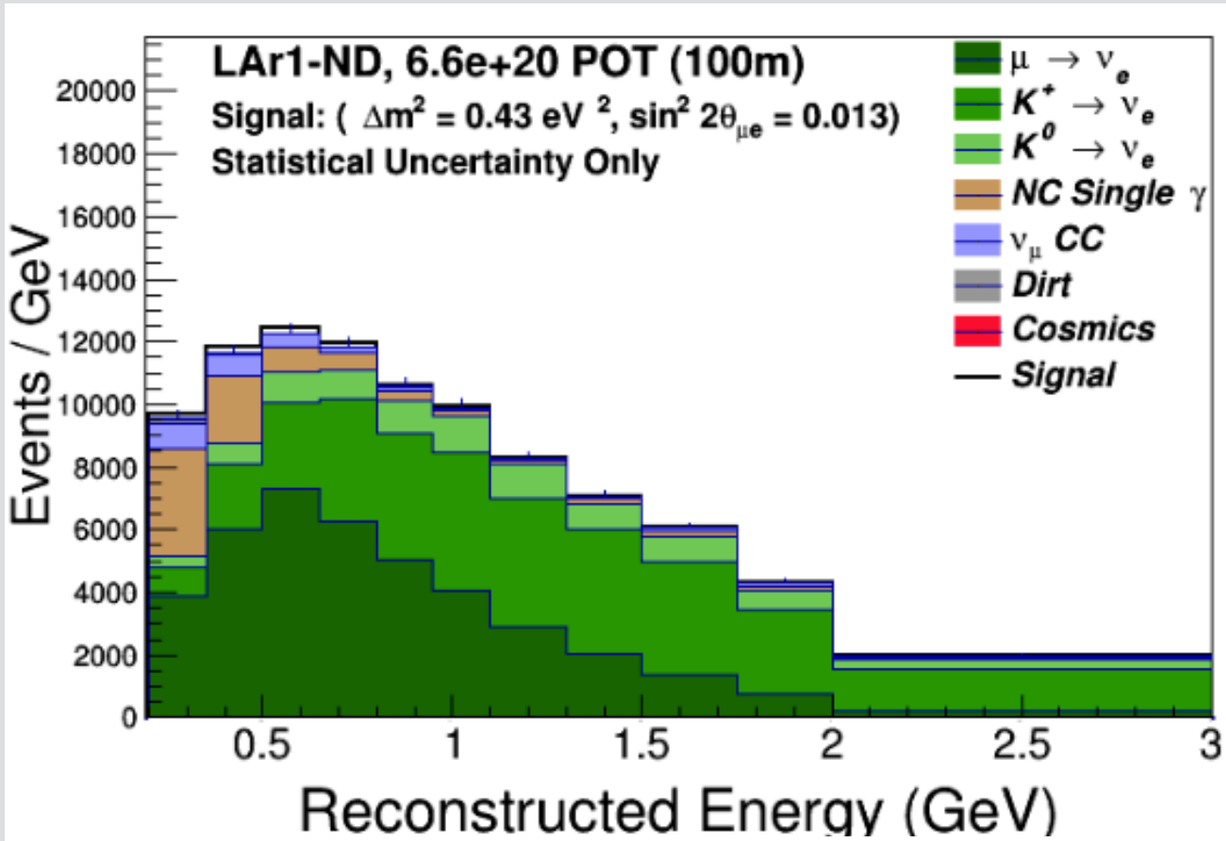
ICARUS, 6.6×10^{20} POT (600m)

Signal : $(\Delta m^2_{41} = 1.1\ \mathrm{eV}^2,\ \sin^2 2\theta_{\mu\mu} = 0.1)$

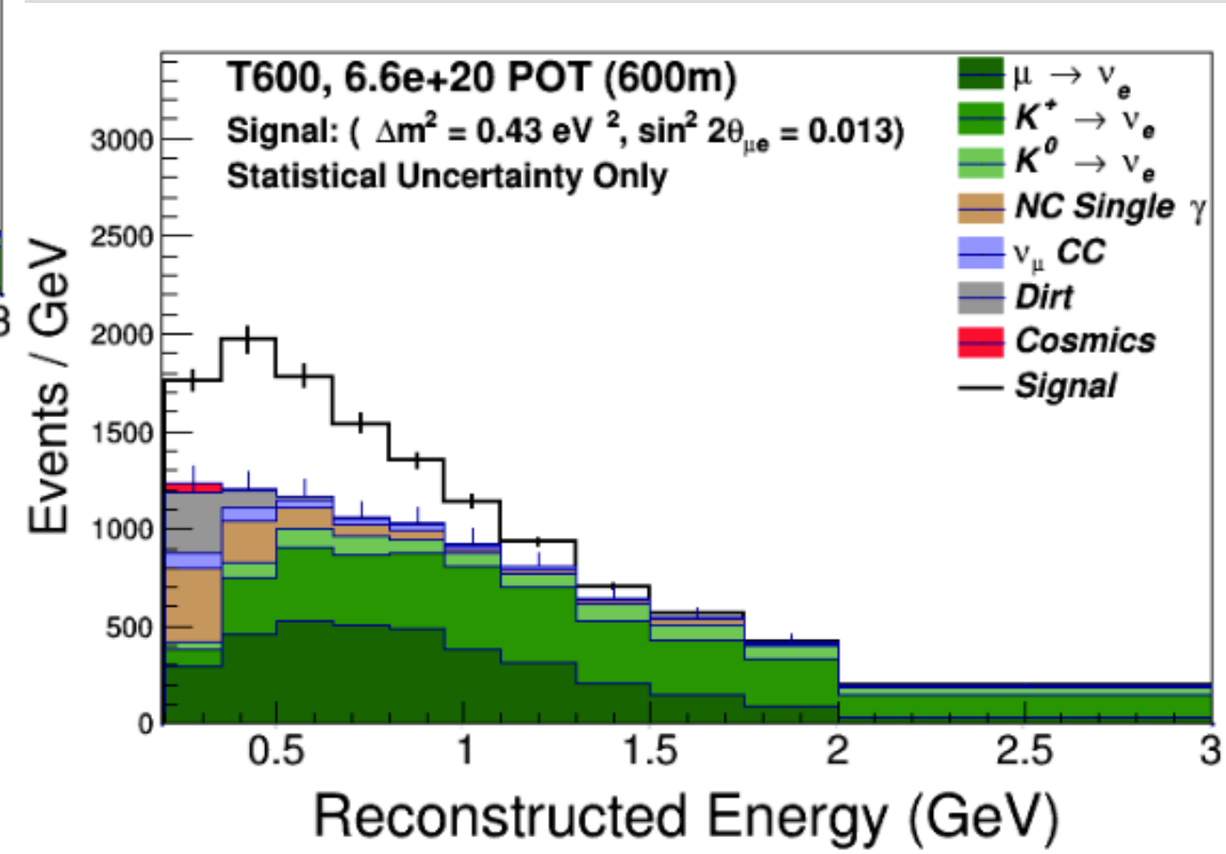
Statistical Uncertainty Only

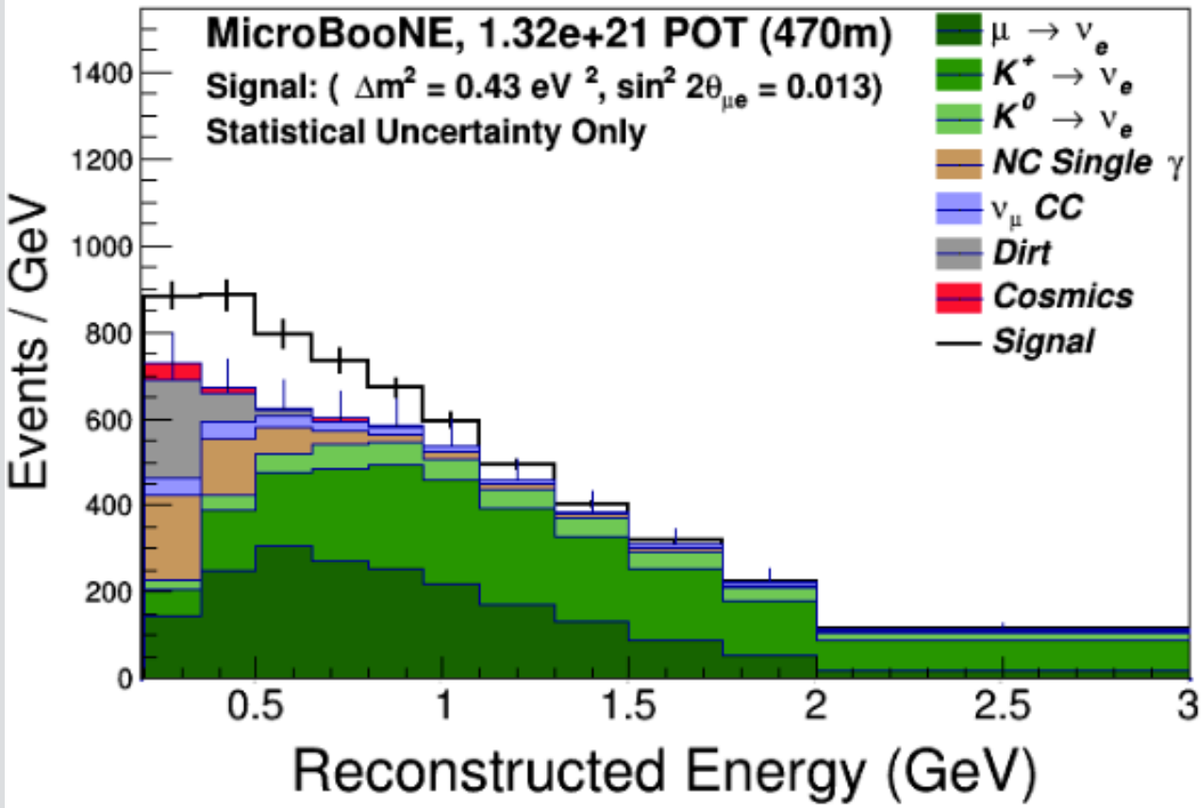


3+1 model at the SBNF



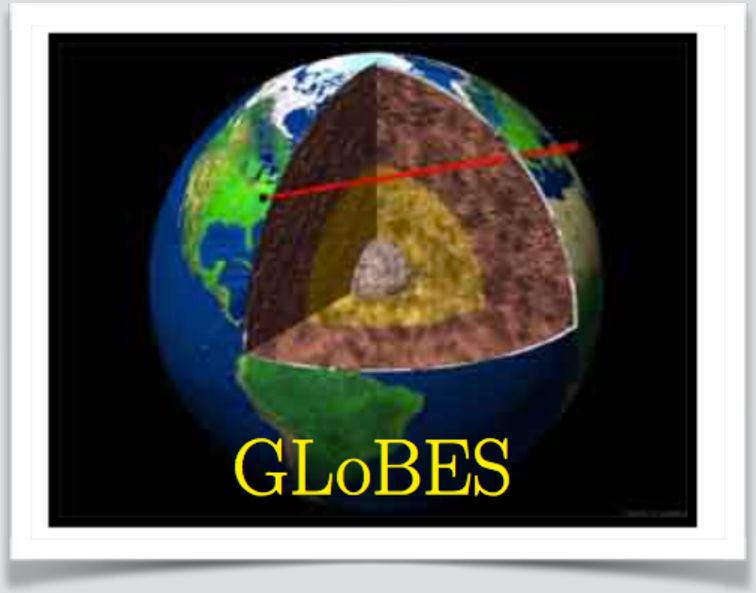
arXiv:1503.01520





GLoBES

General Long Baseline Experiment Simulator



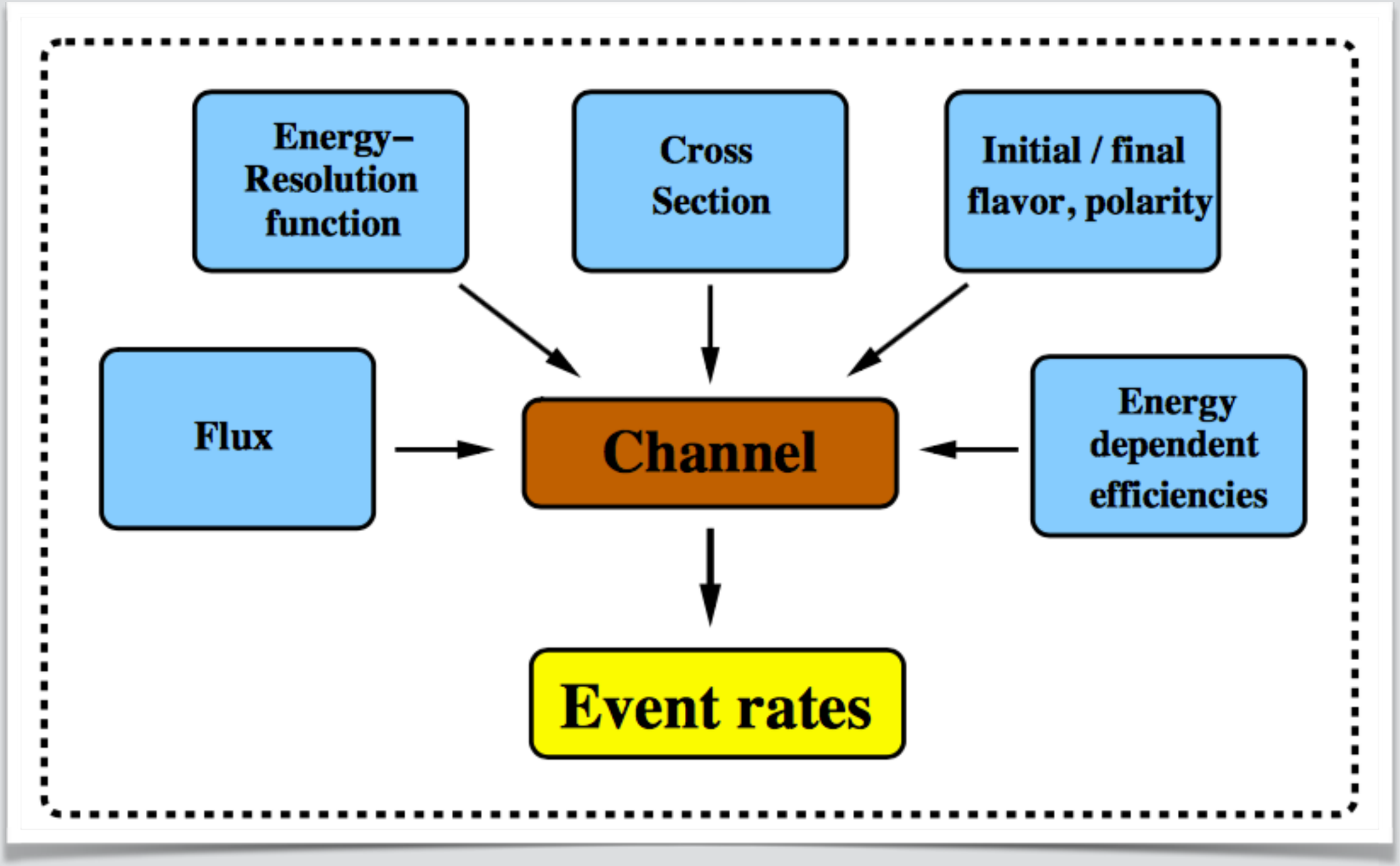
$$\frac{dn_\beta^{\rm IT}}{dE'} = N \int_0^\infty \int_0^\infty dE\, d\hat{E} \quad \underbrace{\Phi_\alpha(E)}_{\text{Production}} \times$$

$$\underbrace{\frac{1}{L^2} P_{(\alpha\to\beta)}(E, L, \rho; \theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{31}, \Delta m^2_{21}, \delta_{\rm CP})}_{\text{Propagation}} \times$$

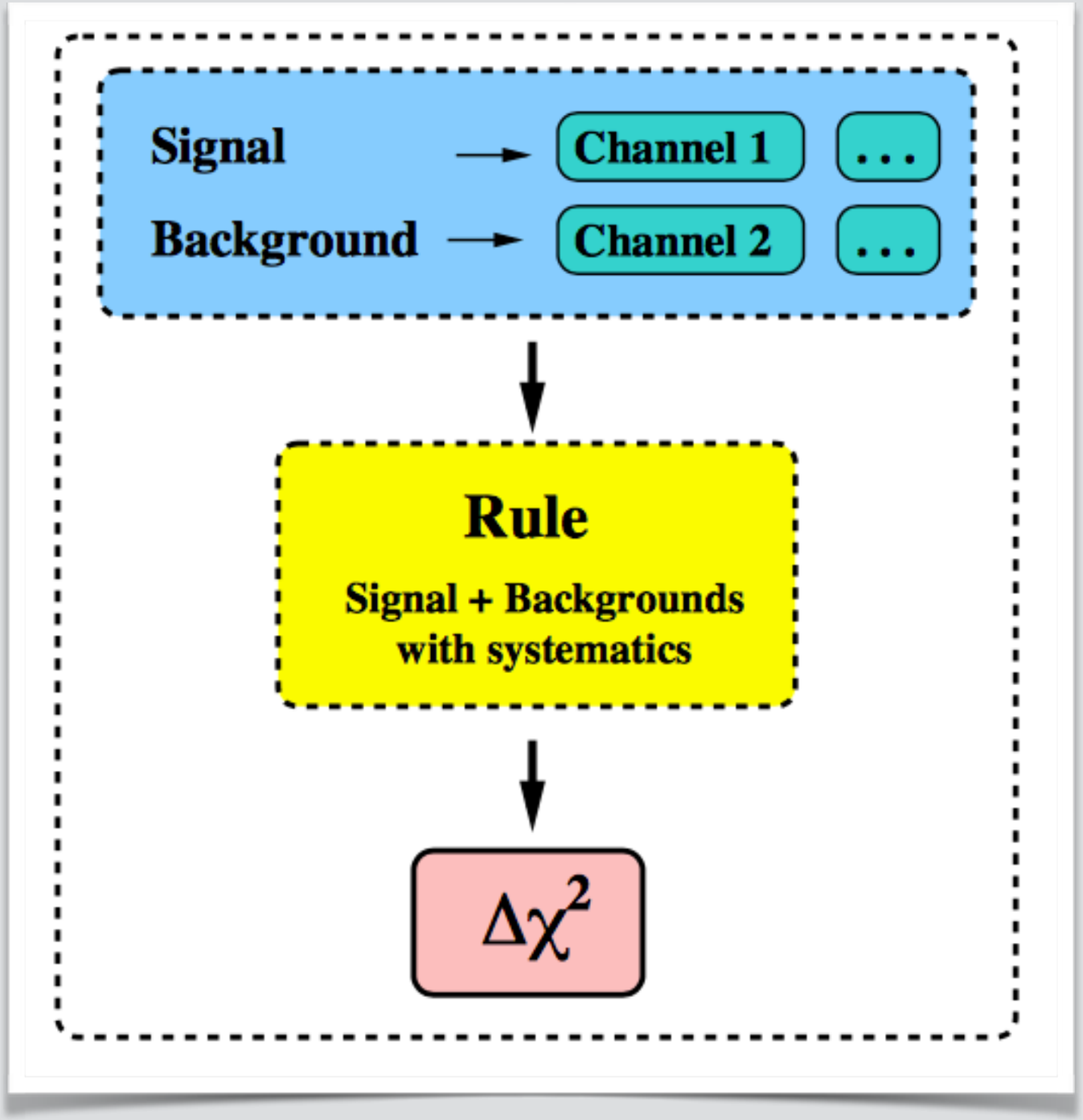
$$\underbrace{\sigma_f^{\rm IT}(E) k_f^{\rm IT}(E - \hat{E})}_{\text{Interaction}} \times$$

$$\underbrace{T_f(\hat{E}) V_f(\hat{E} - E')}_{\text{Detection}},$$

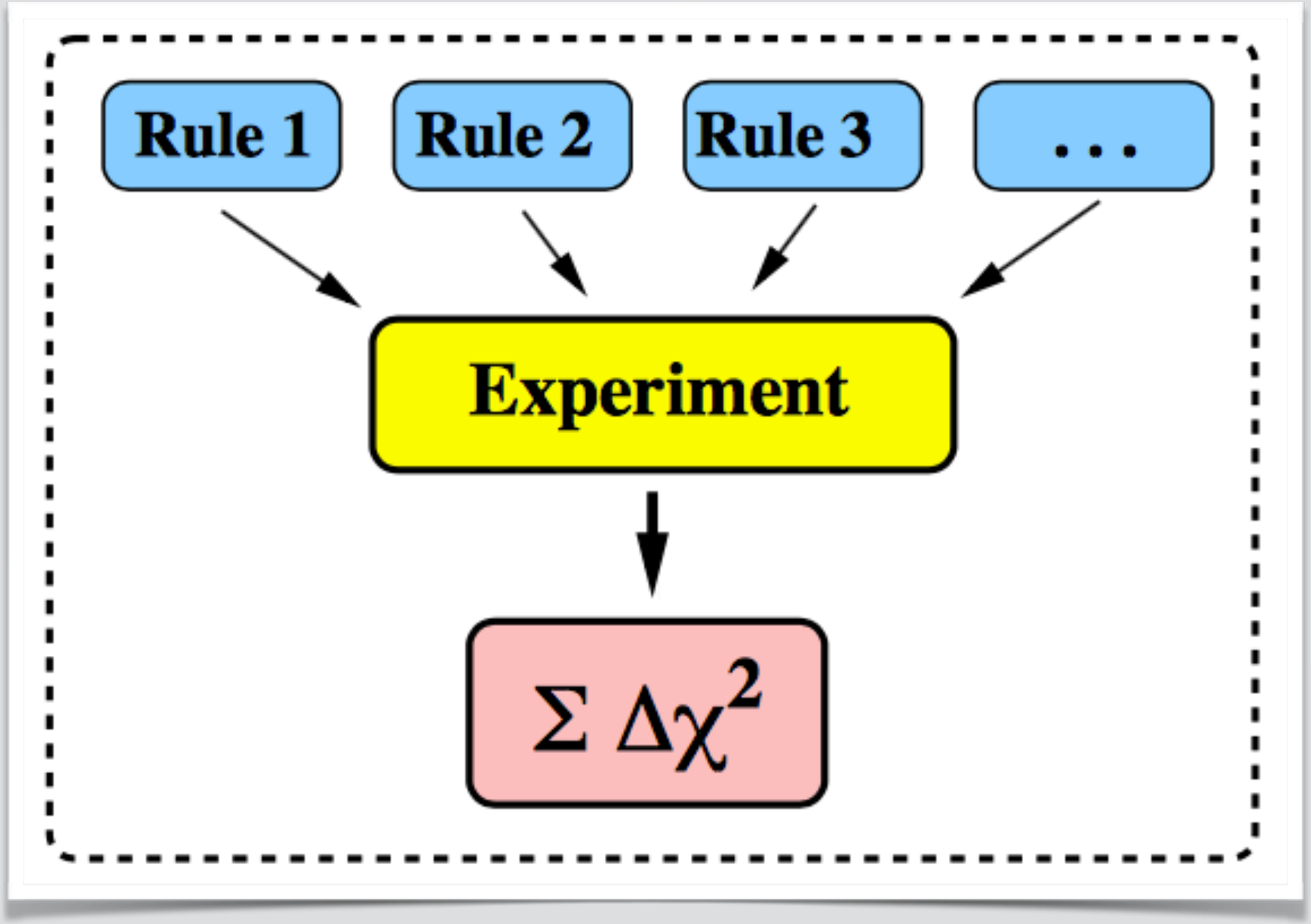
GLoBES


Energy–
Resolution
function
Cross
Section
Initial / final
flavor, polarity
Flux
Channel
Energy
dependent
efficiencies
Event rates

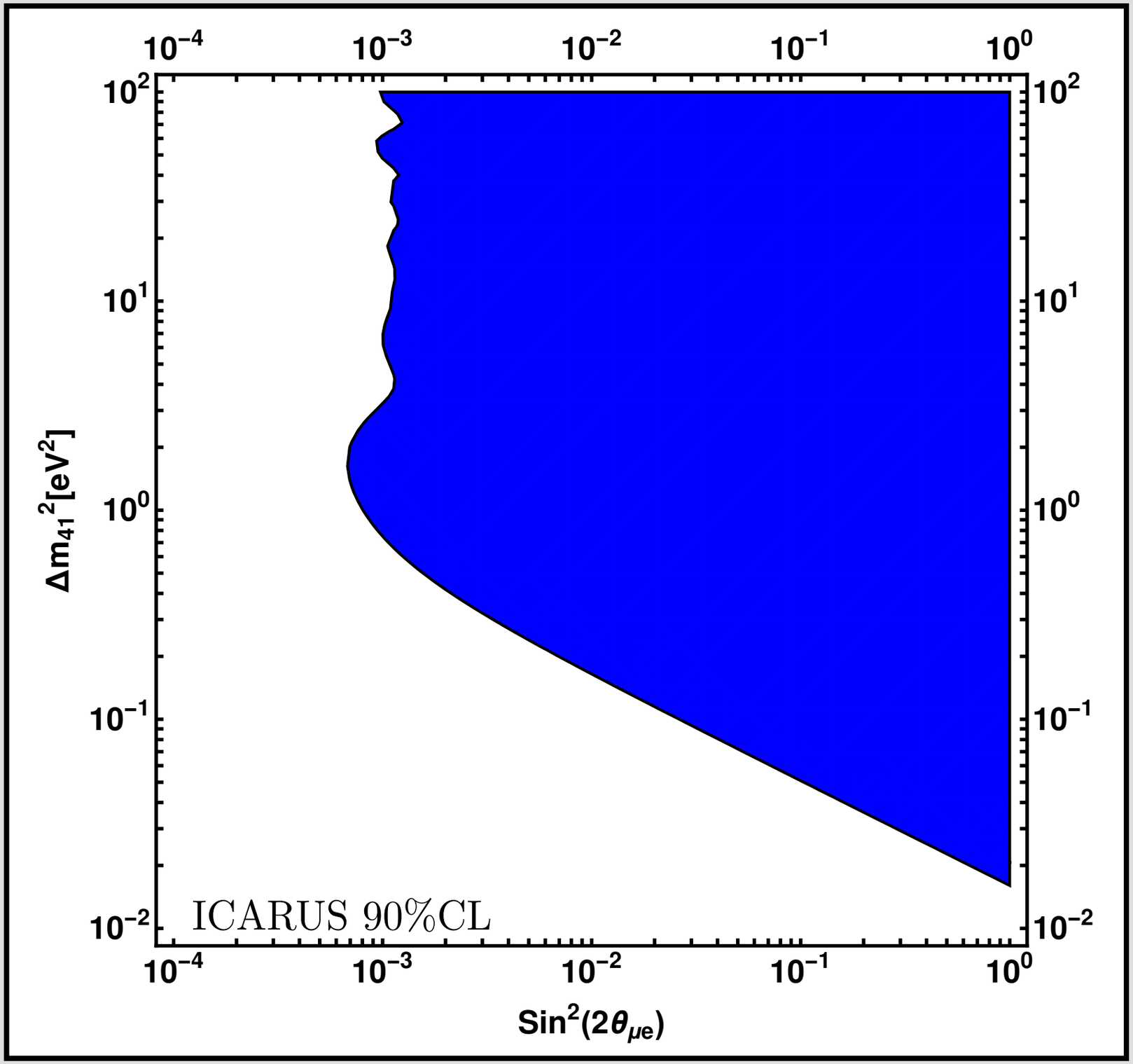
GLoBES


Signal
Channel 1
...
Background
Channel 2
...
Rule
Signal + Backgrounds
with systematics
$\Delta\chi^2$

GLoBES

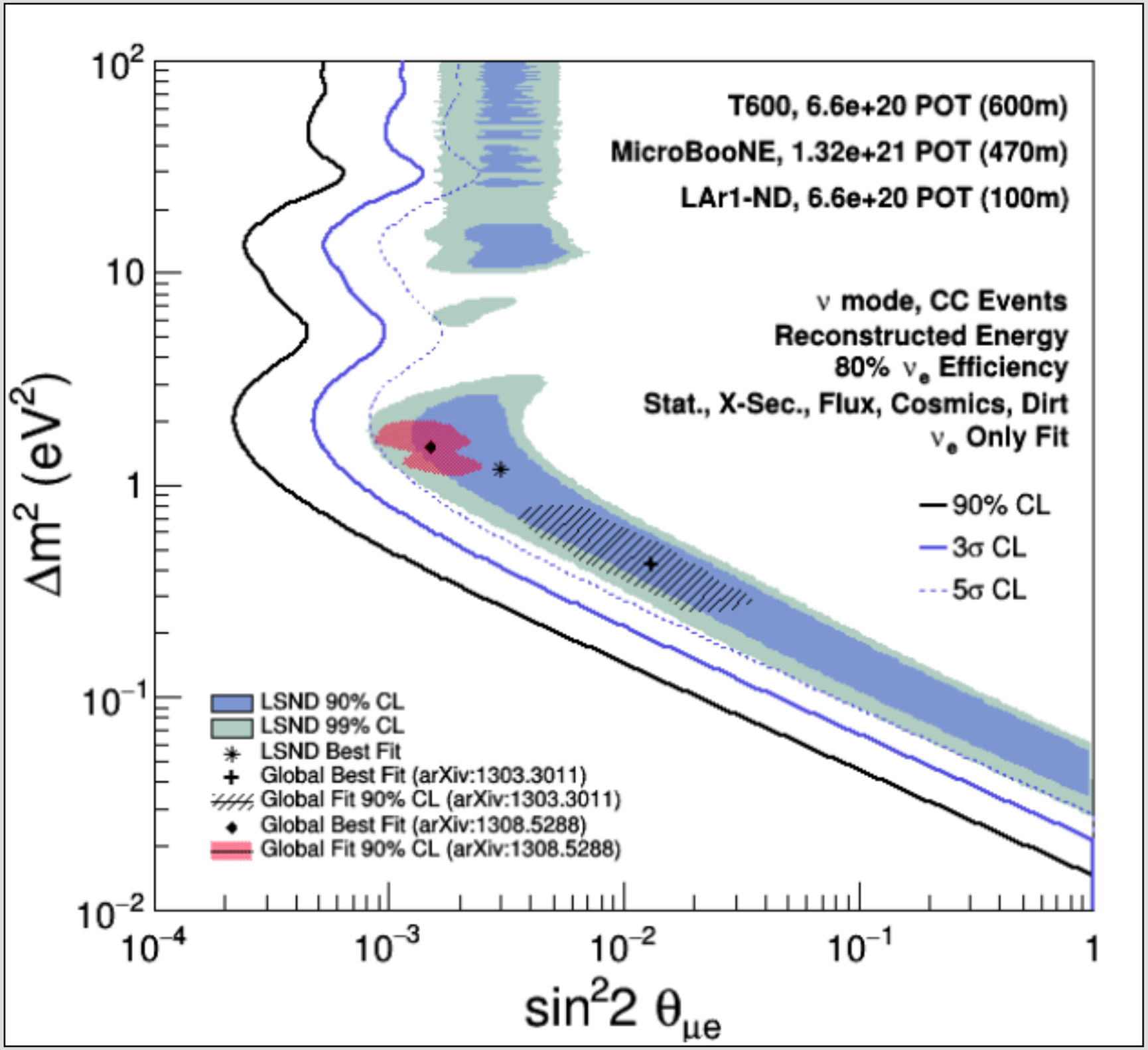


3+1 model at the SBNF

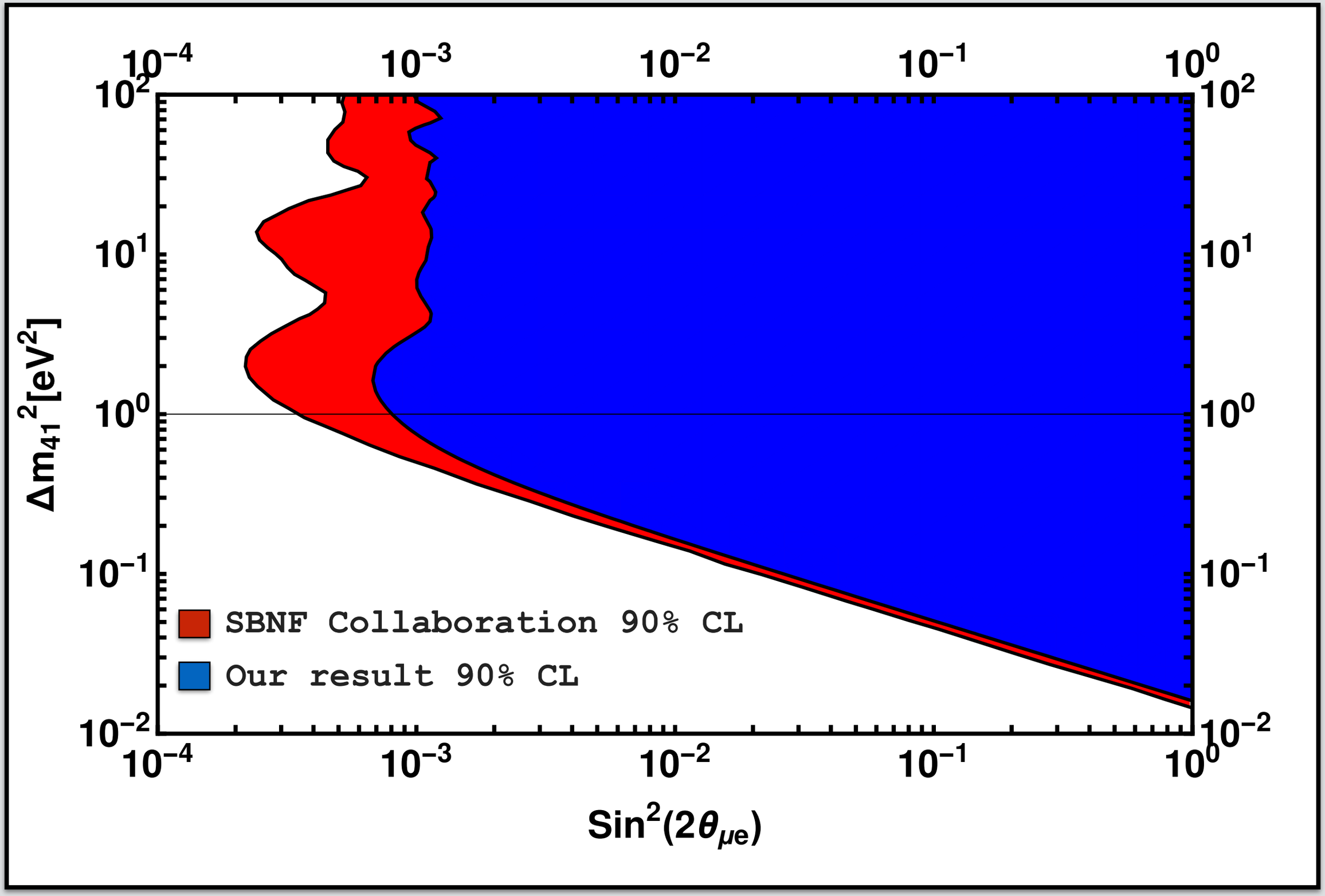


3+1 model at the SBNF

arXiv:1503.01520

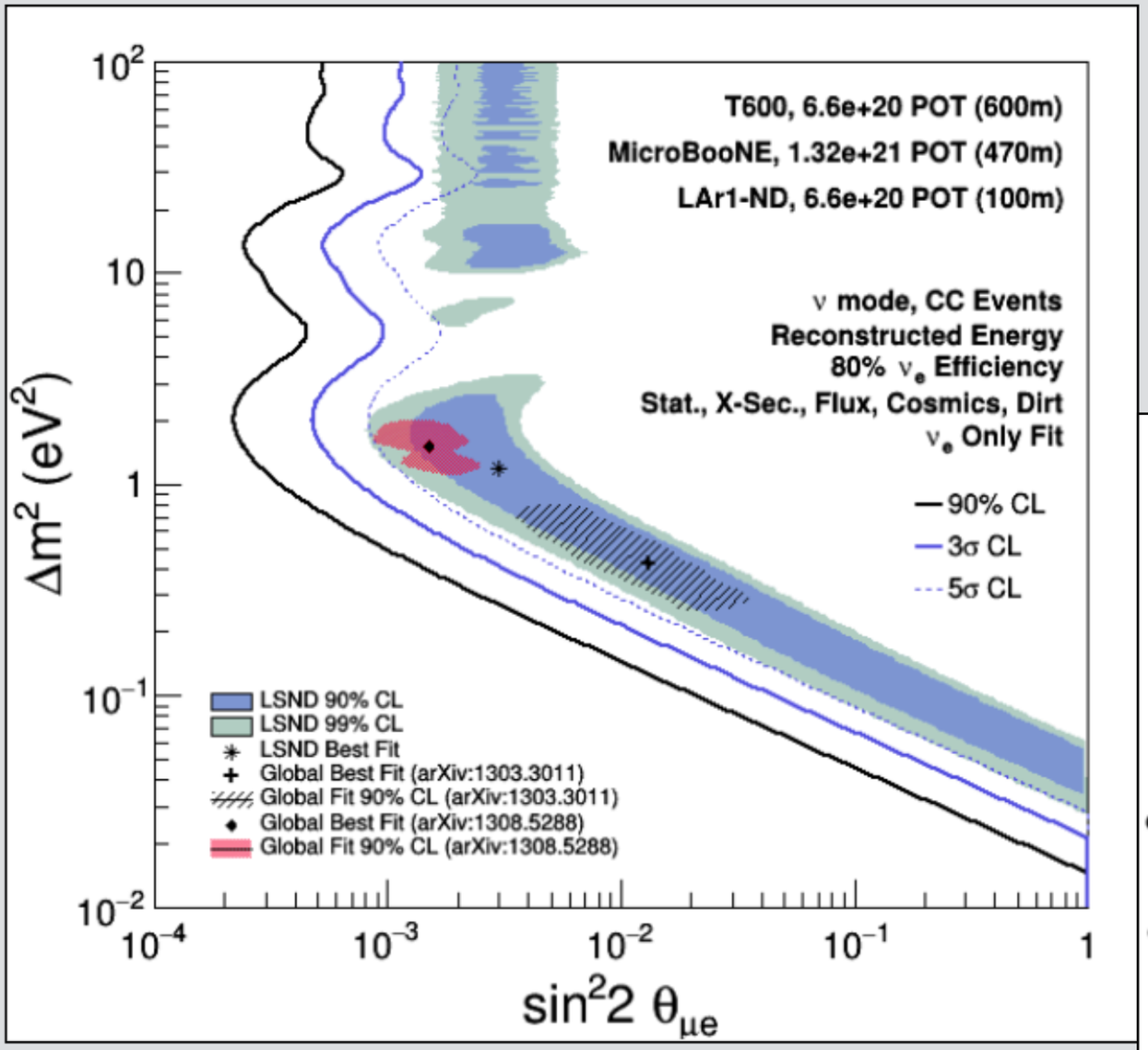


3+1 model at the SBNF



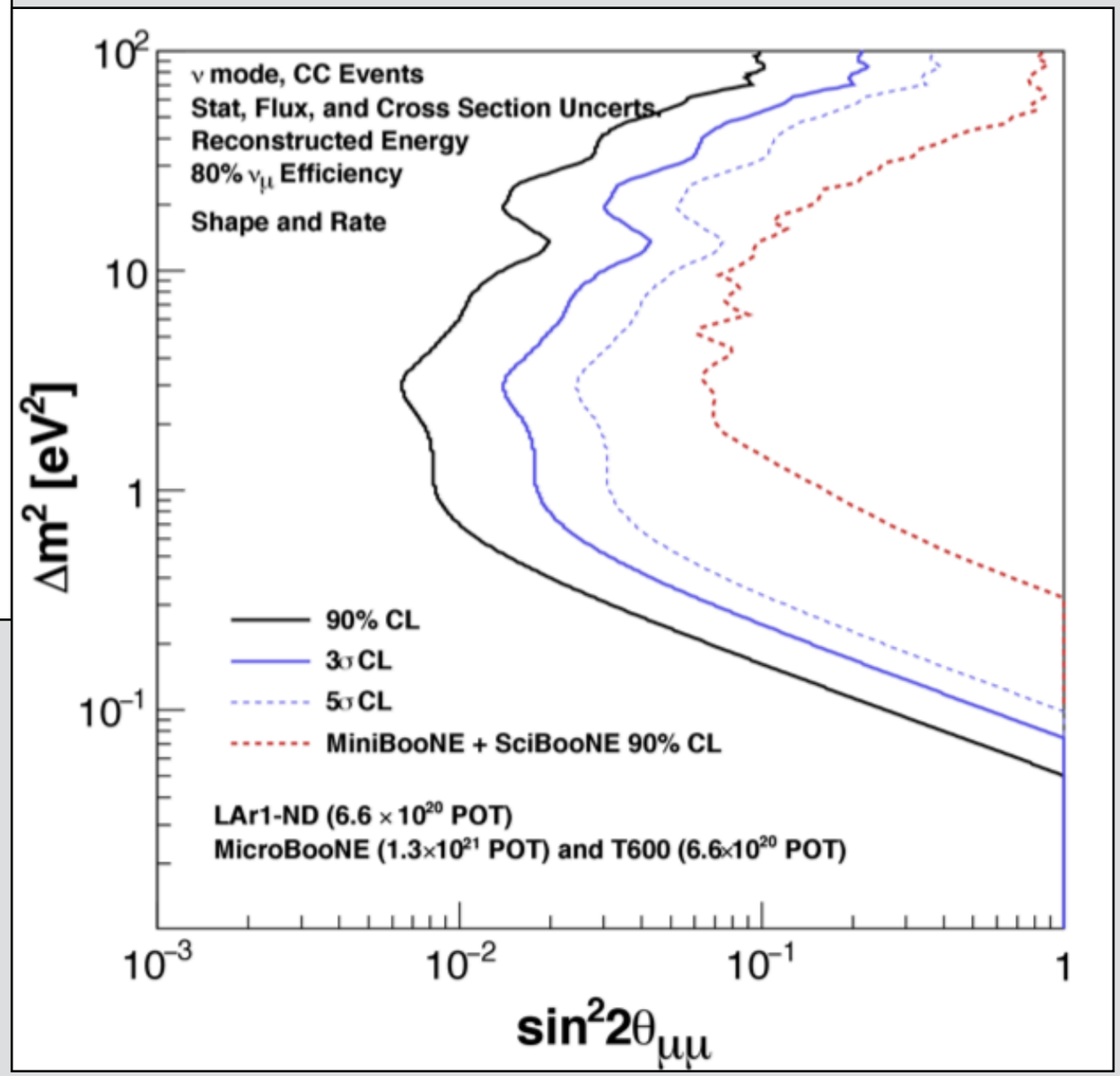
Preliminary Results

SBNF sensitivity curves for "3+1" model



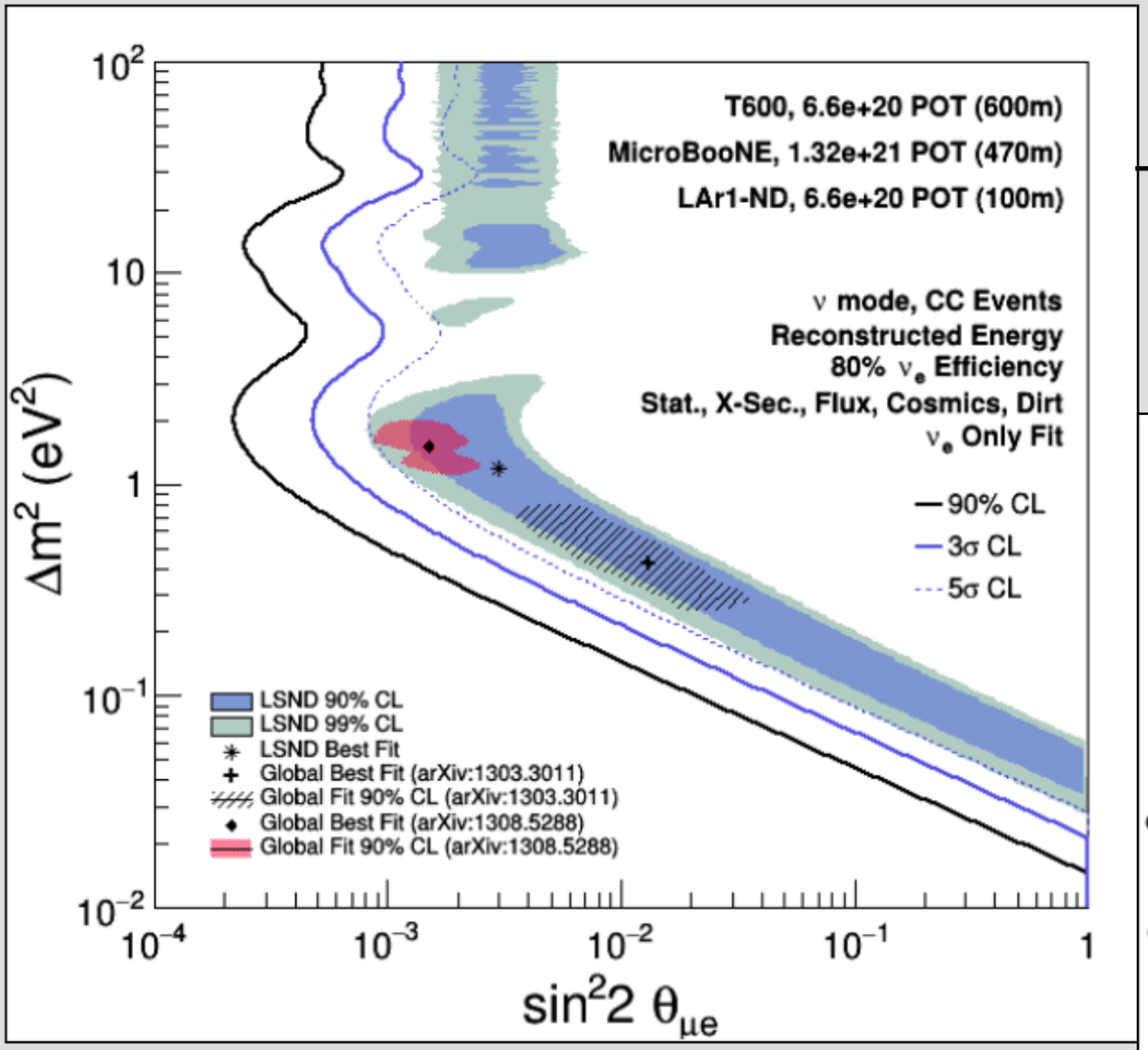
arXiv:1503.01520

arXiv:1503.01520



Preliminary Results

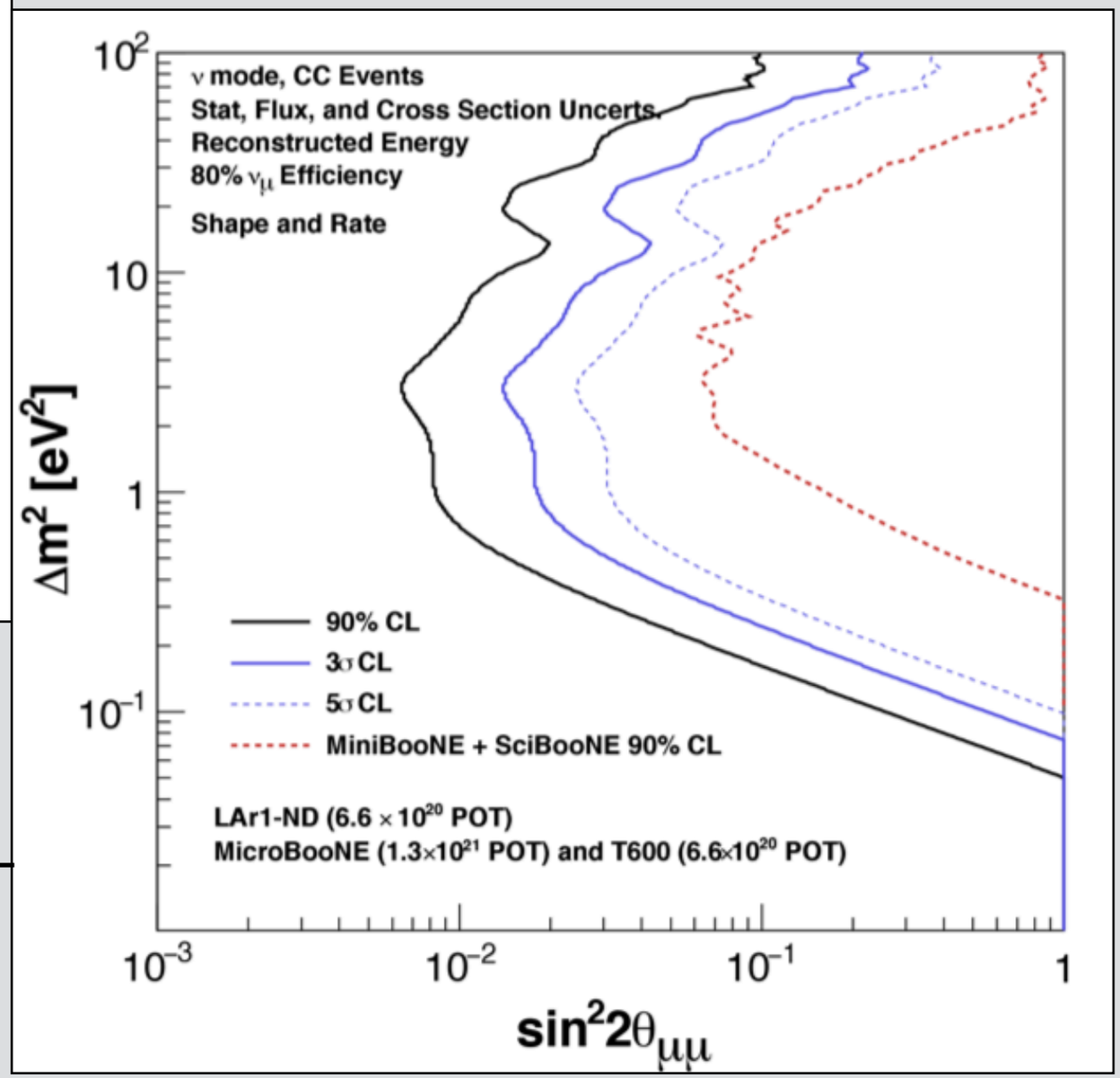
SBNF sensitivity curves for "3+1" model



arXiv:1503.01520

$$P(\nu_\mu \to \nu_e)$$

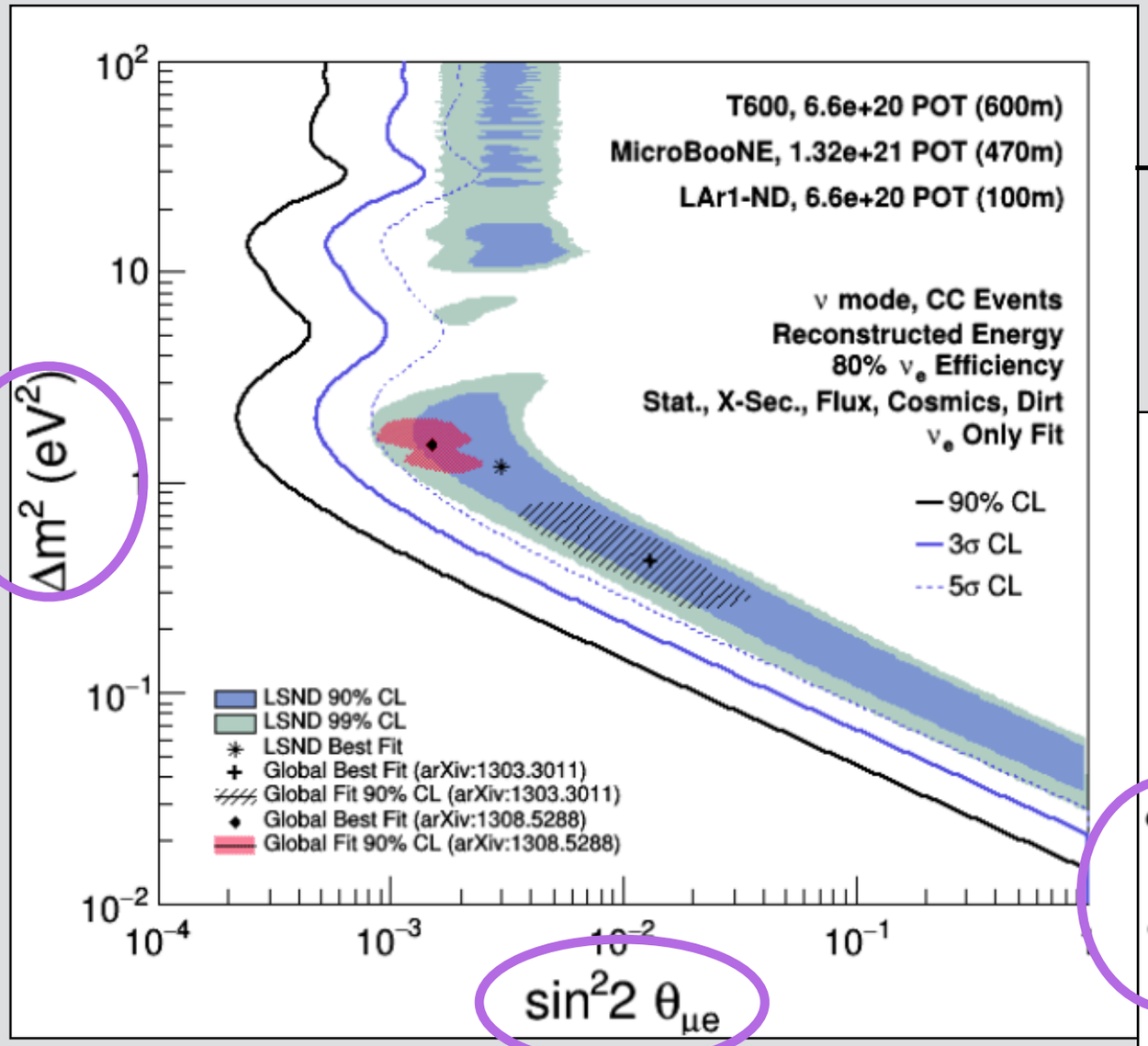
arXiv:1503.01520



$$P(\nu_\mu \to \nu_\mu)$$

Preliminary Results

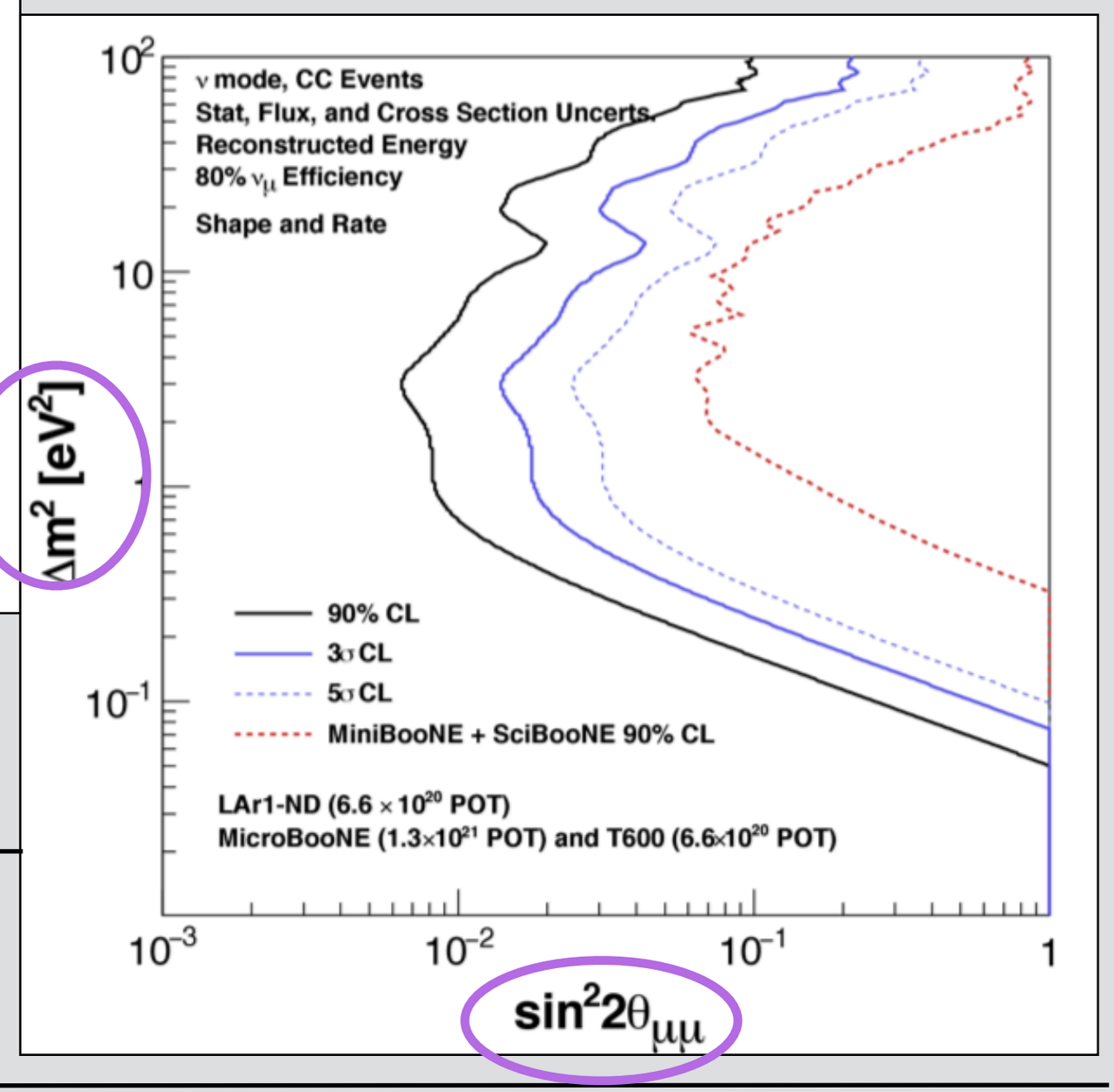
SBNF sensitivity curves for "3+1" model



$P(\nu_\mu \to \nu_e)$

arXiv:1503.01520

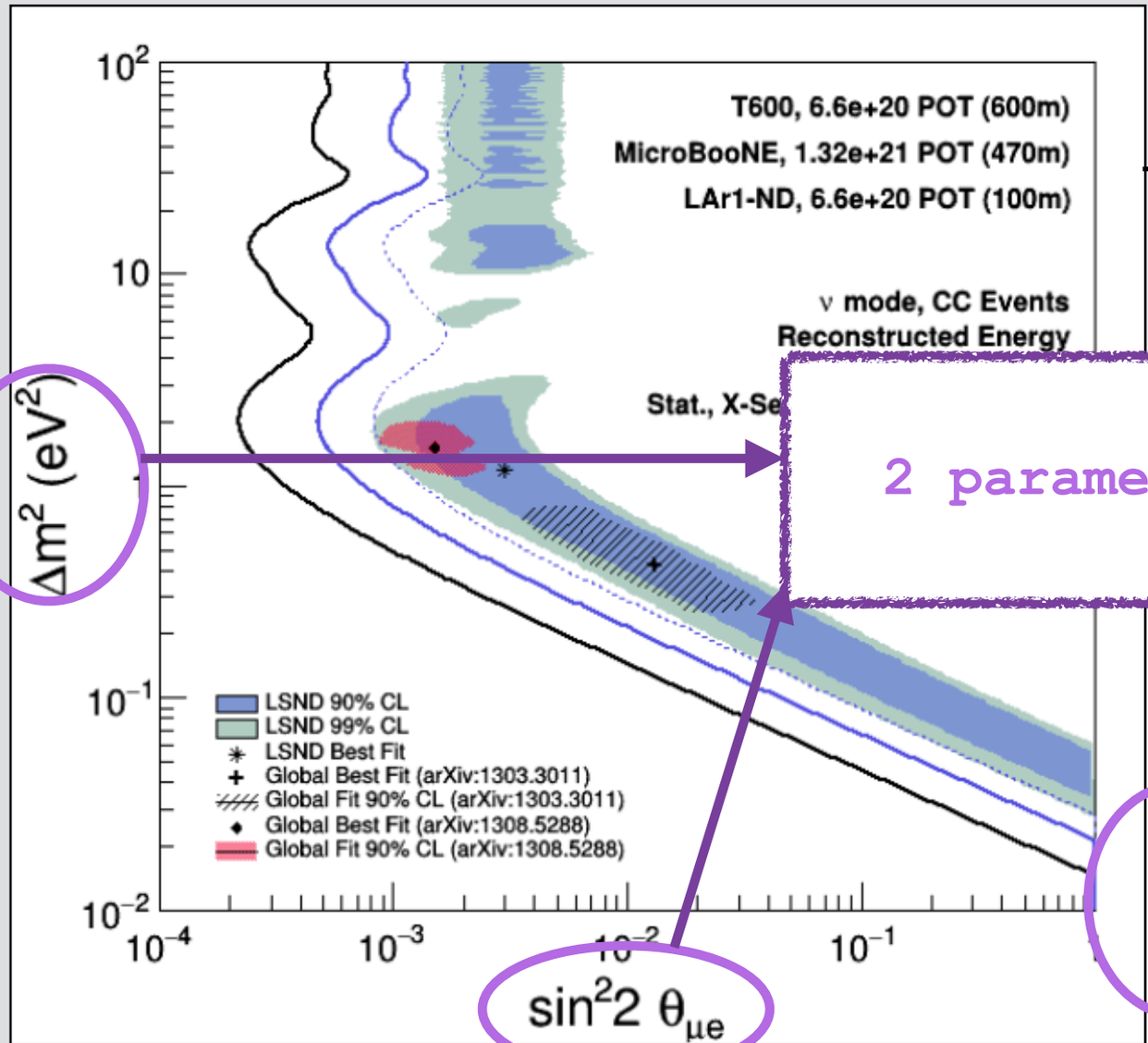
arXiv:1503.01520



$P(\nu_\mu \to \nu_\mu)$

Preliminary Results

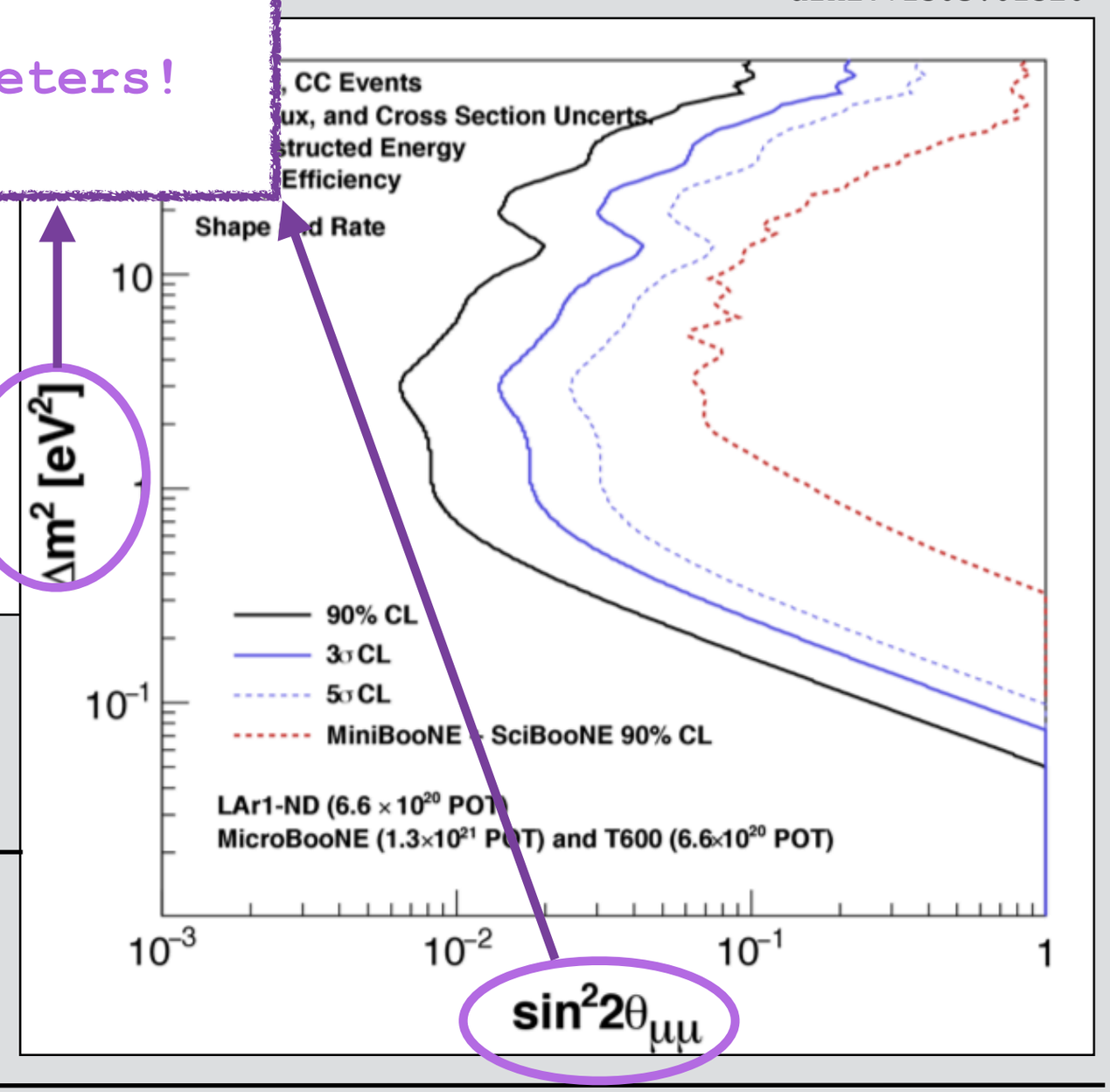
SBNF sensitivity curves for "3+1" model



$P(\nu_\mu \to \nu_e)$

arXiv:1503.01520

2 parameters!

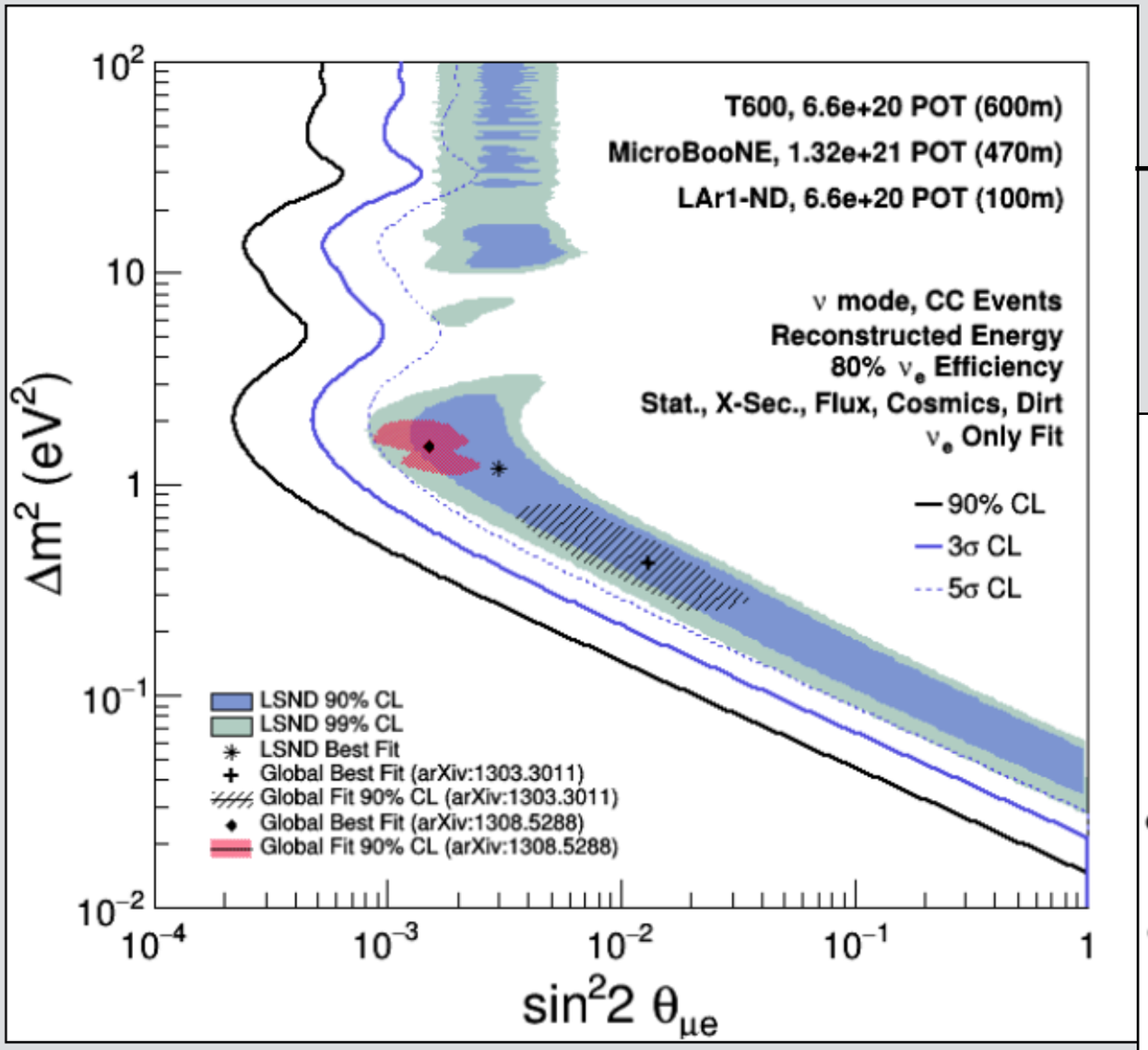


$P(\nu_\mu \to \nu_\mu)$

arXiv:1503.01520

Preliminary Results

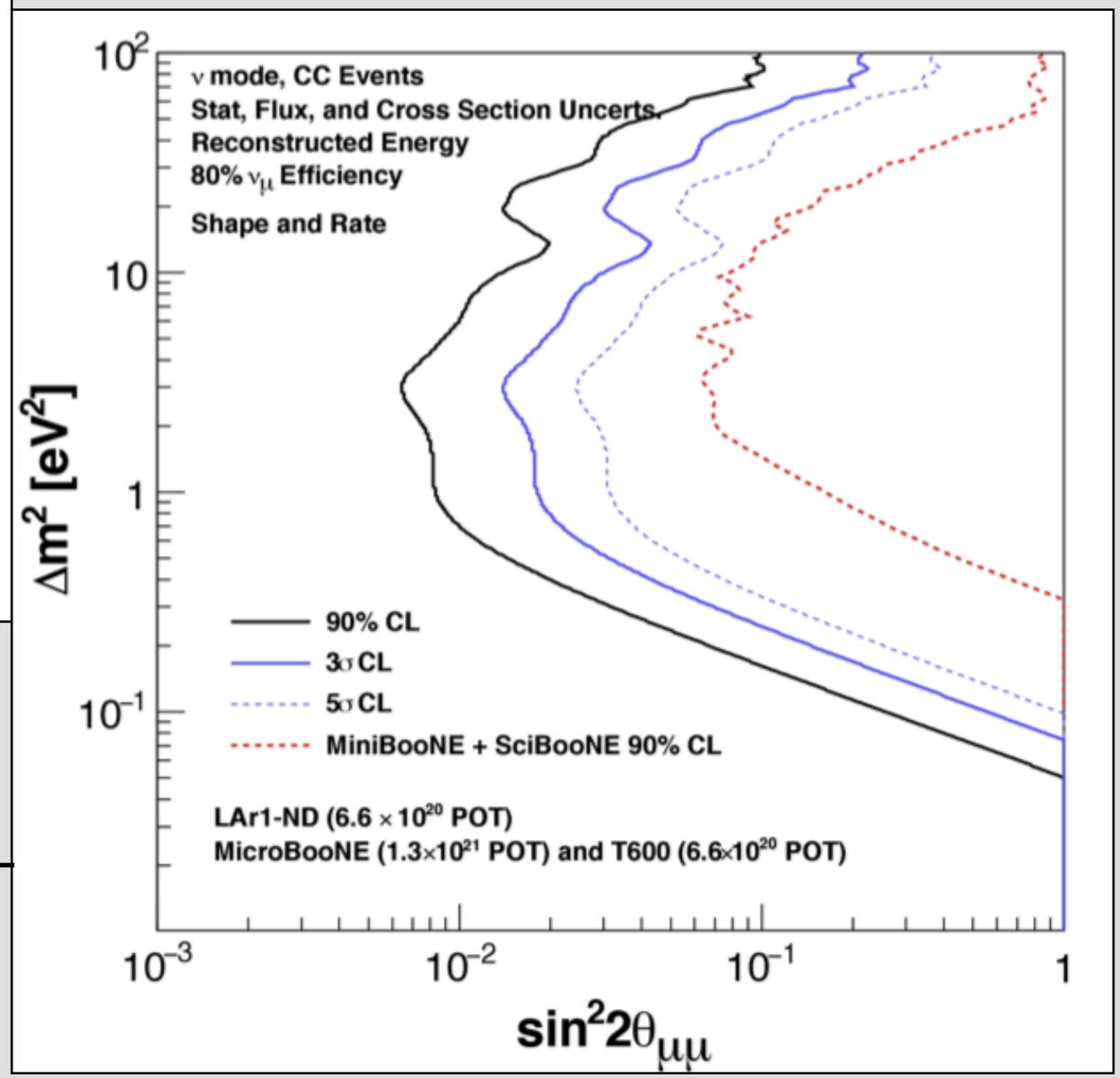
SBNF sensitivity curves for "3+1" model



arXiv:1503.01520

$$P(\nu_\mu \to \nu_e)$$

arXiv:1503.01520



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Preliminary Results

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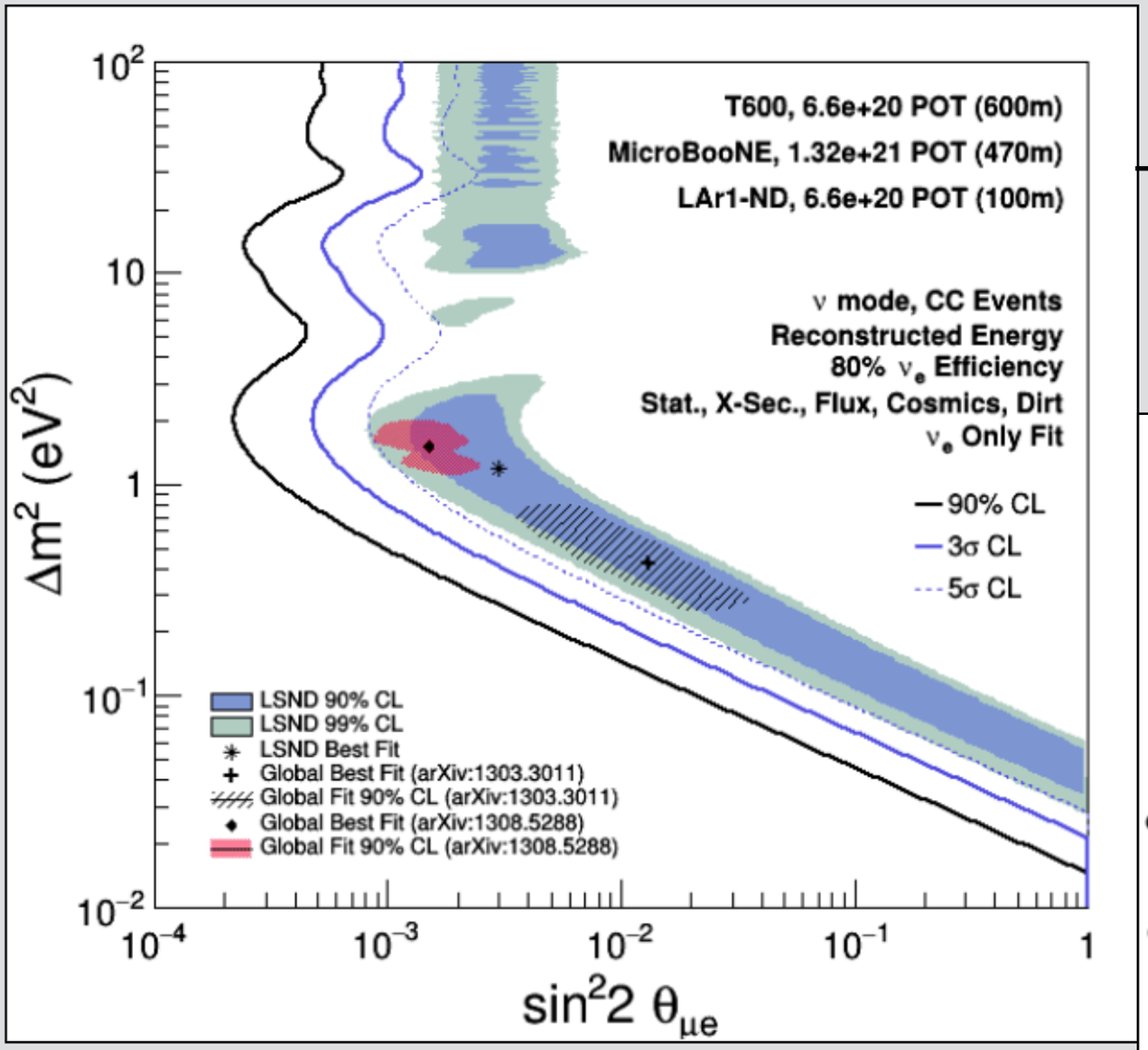

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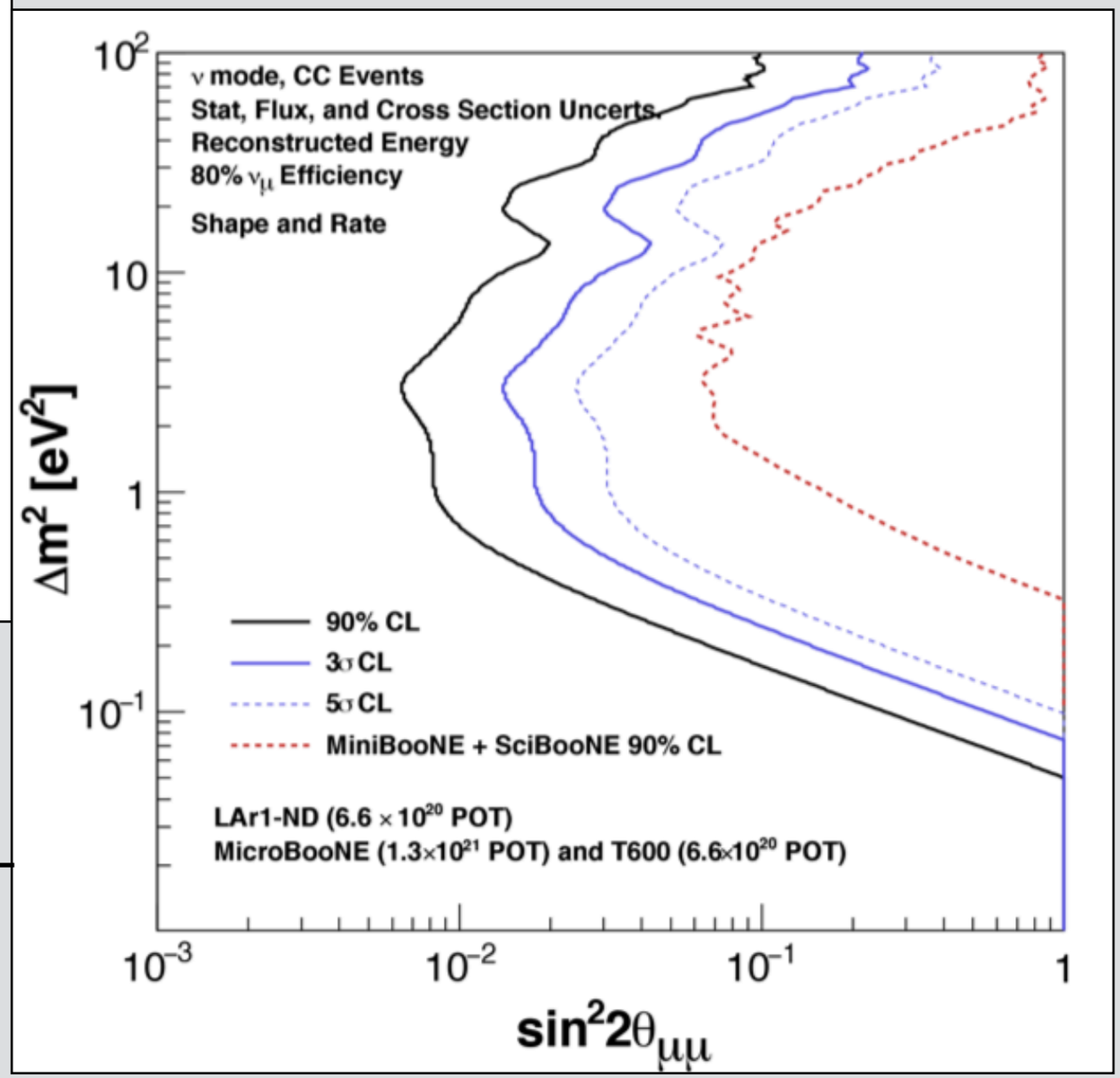

$(m_0^D, R_{\rm ED})$

$P(\nu_\mu \to \nu_\mu)$

Preliminary Results

There is no equivalence between LED and “3+1” model

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↓

Short-baseline approximation with 1 KK tower

Preliminary Results

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Short-baseline approximation with 1 KK tower

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 1}|^2 \left(S_1^{01}\right)^2 \left(|U_{\mu 1}|^2 \left(S_1^{00}\right)^2 + |U_{\mu 2}|^2 \left(S_2^{00}\right)^2 + |U_{\mu 3}|^2 \left(S_3^{00}\right)^2\right) \sin^2\left(1.27 \frac{\lambda_1^{(1)2} - \lambda_1^{(0)2}}{R_{\mathrm{ED}}^2} \frac{L}{E}\right)$$

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$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 1}|^2 \left(L_1^{01}\right)^2 \left(|U_{\mu 1}|^2 \left(L_1^{00}\right)^2 + |U_{\mu 2}|^2 \left(L_2^{00}\right)^2 + |U_{\mu 3}|^2 \left(L_3^{00}\right)^2\right)$$

$$\Delta m_{41}^2 \equiv \frac{\lambda_1^{(1)2} - \lambda_1^{(0)2}}{R_{ED}^2}$$

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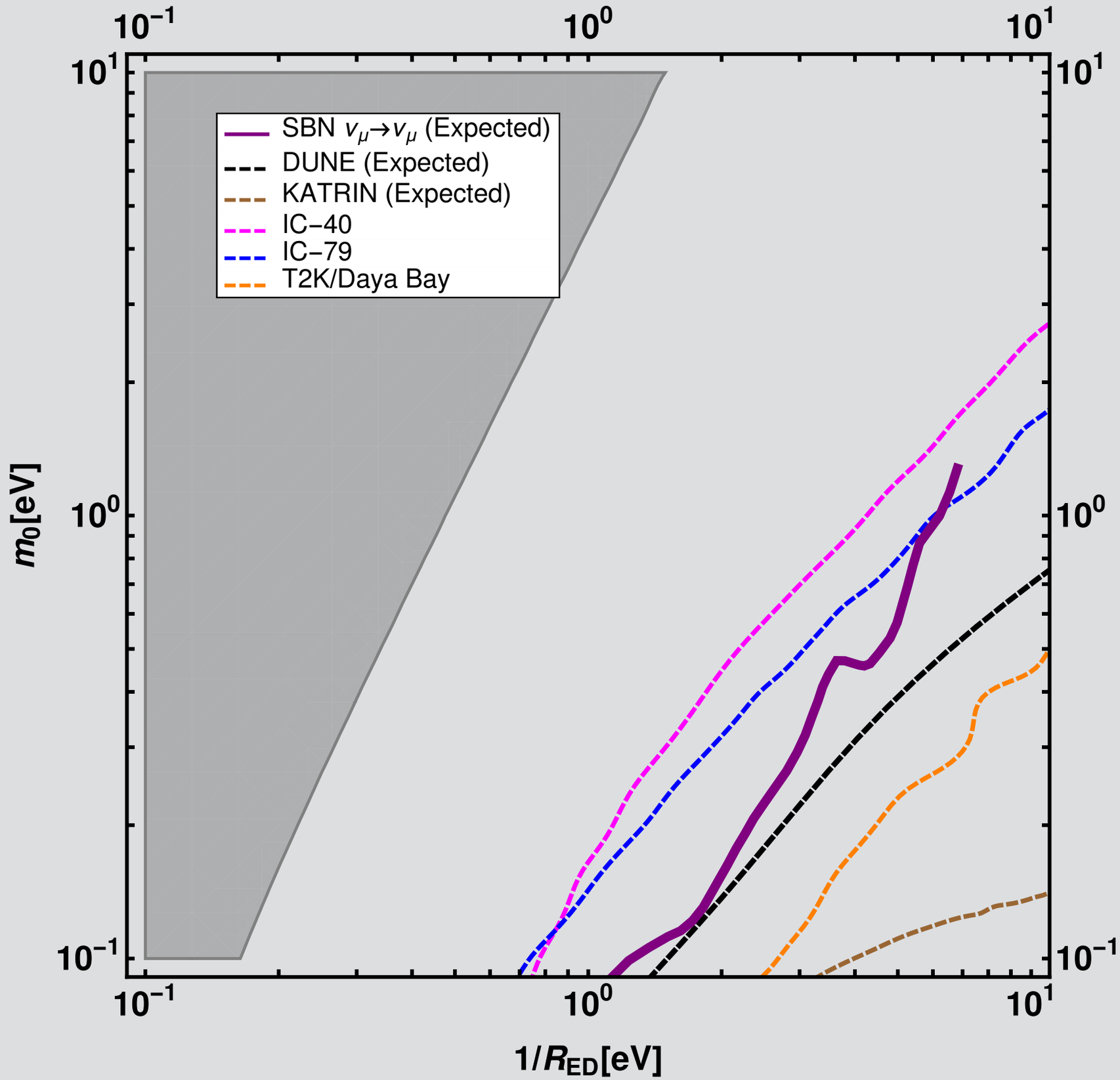
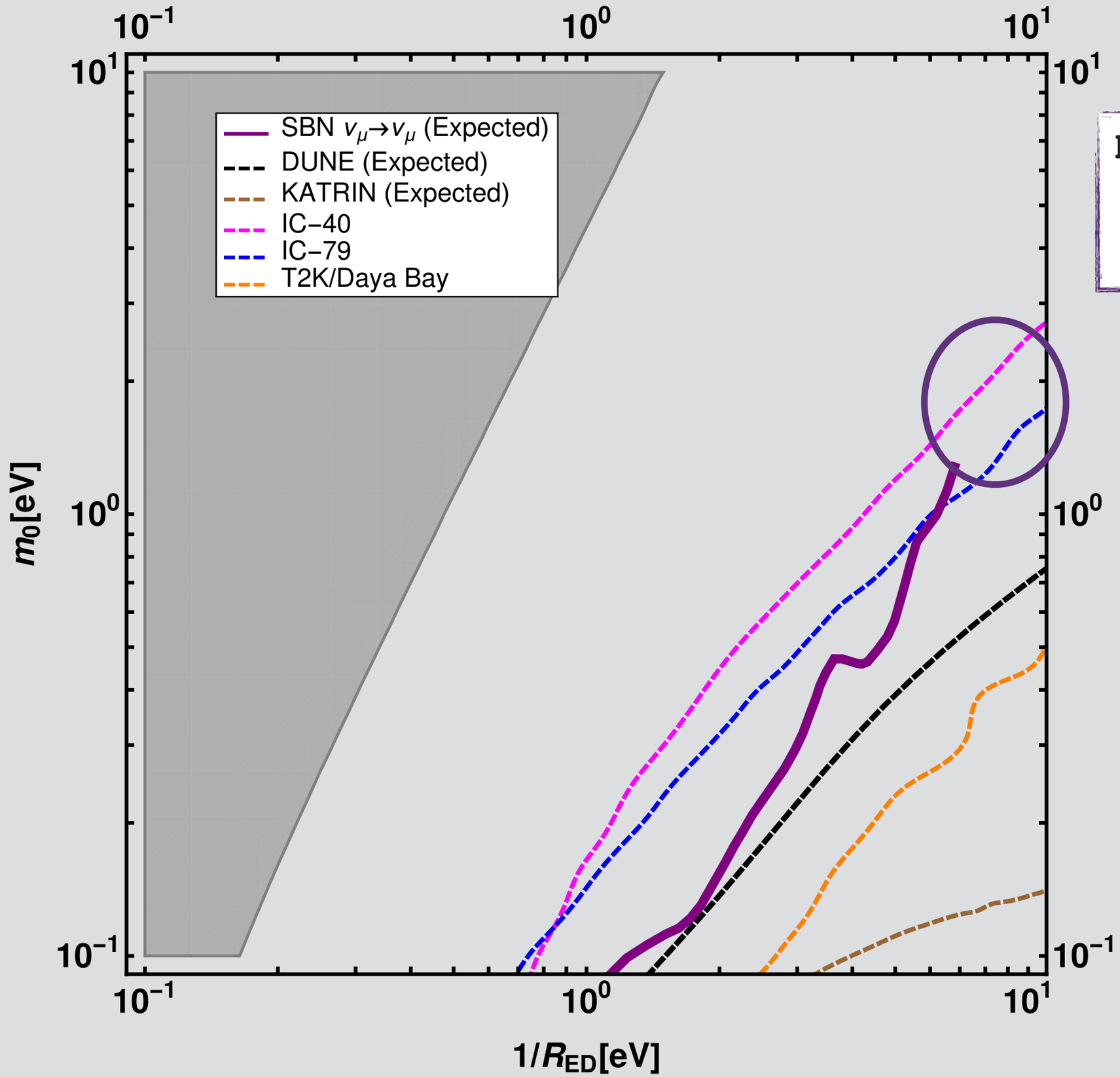
$P(\nu_\mu \to \nu_e) = ?$ → **Imaginary term in LED expression (CP-violation?)**

Preliminary Results



Preliminary Results



Max value of LED amplitude

$\approx 2 \times 10^{-2}$

What do we have for LED?

We want to do the same analysis for LED

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↓

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↓

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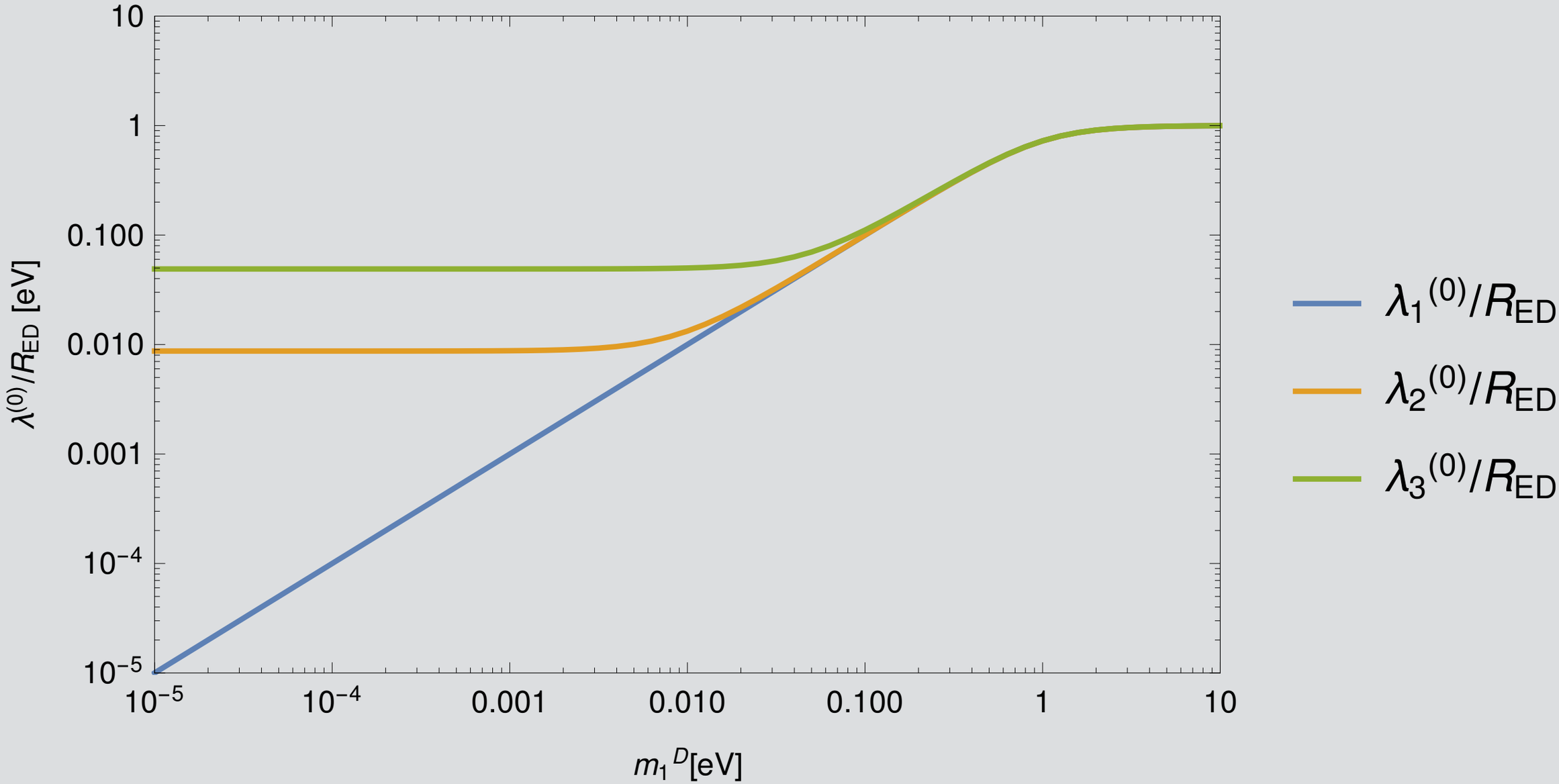
↓

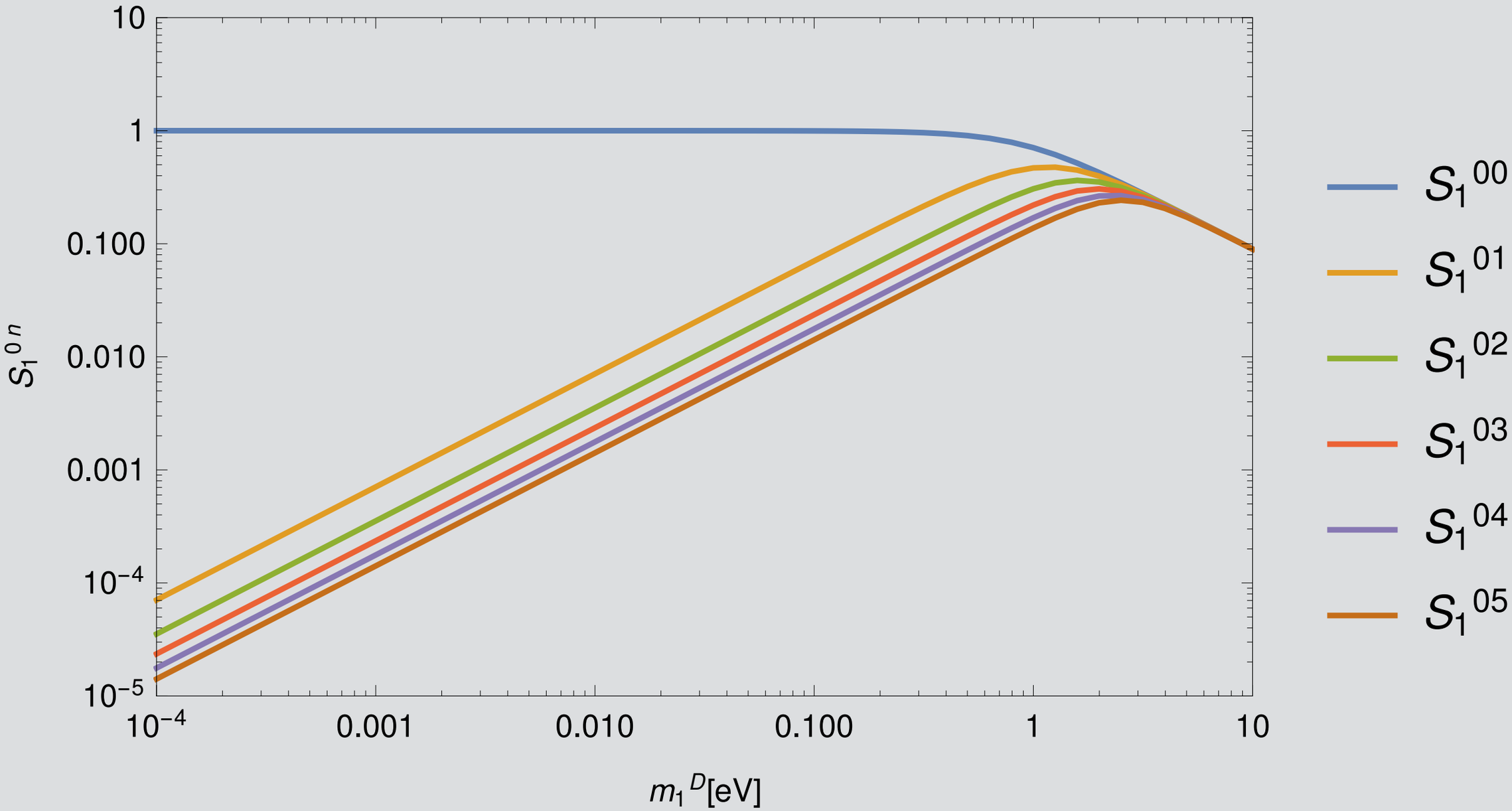
How to implement it in GLoBES?

Formalism



$R_{\rm ED} = 0.5$ eV

Formalism



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