The 20th International Workshop on Neutrinos from Accelerators

A short travel for neutrinos in Large Extra Dimensions

`Short-Baseline Neutrino Program - Fermilab` `arXiv:1503.01520`

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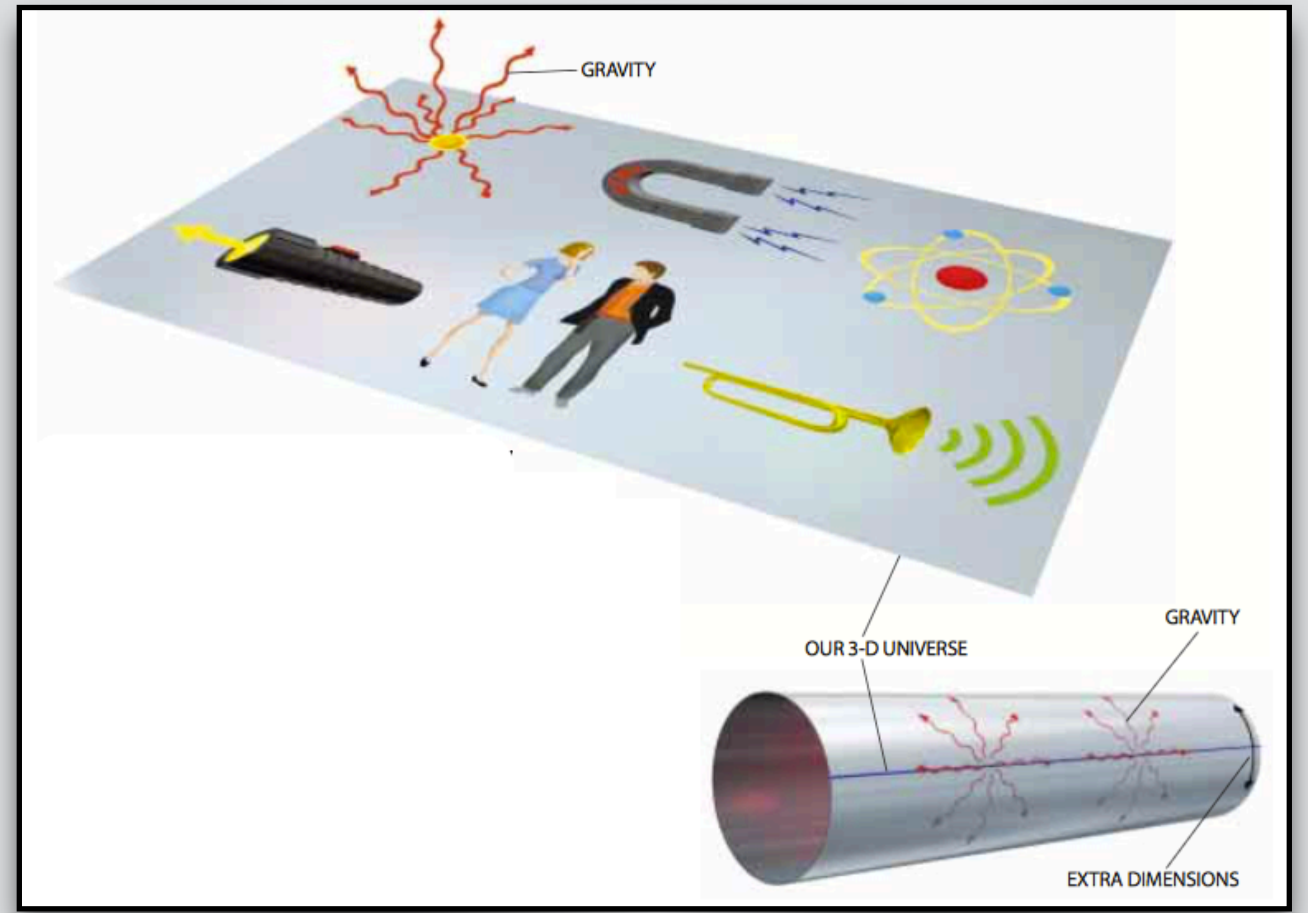
08/13/2018

Summary:

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



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

Why LED?

Hierarchy Problem

Why LED?

Hierarchy Problem

- **gravity is strong!**

Why LED?

Hierarchy Problem

Electroweak scale

$246\ \mathrm{GeV}$

Planck scale

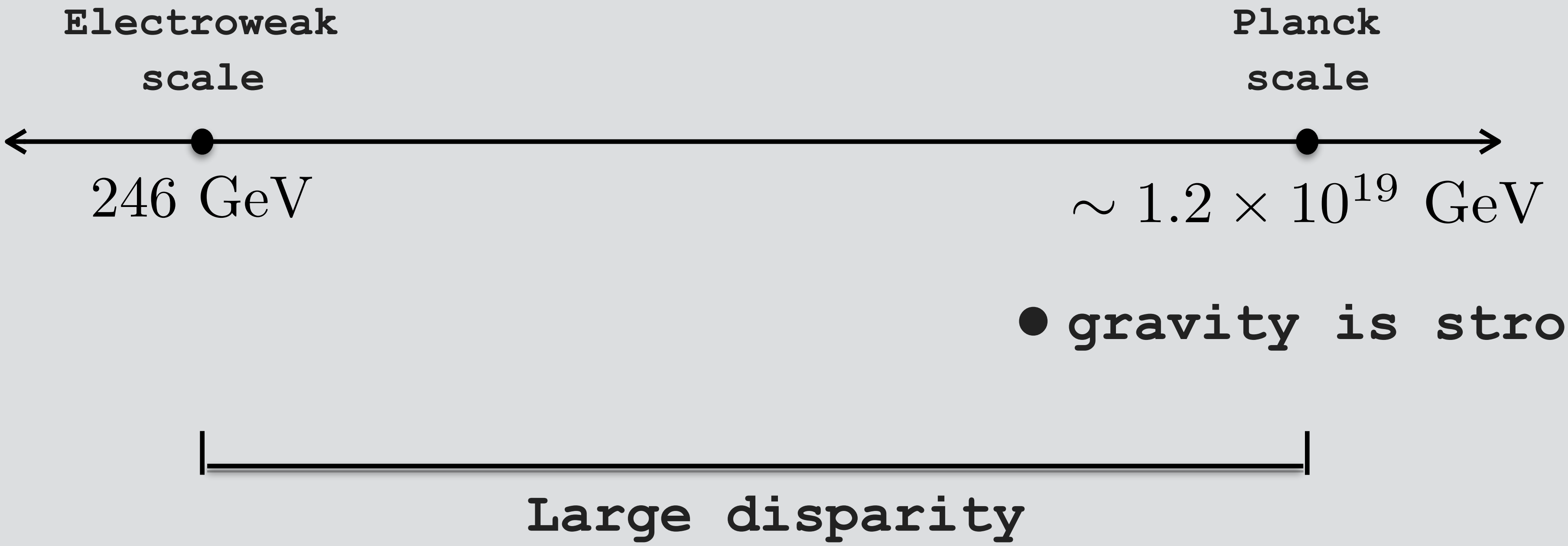
$\sim 1.2 \times 10^{19}\ \mathrm{GeV}$

- **gravity is strong!**

Large disparity

Why LED?

Hierarchy Problem

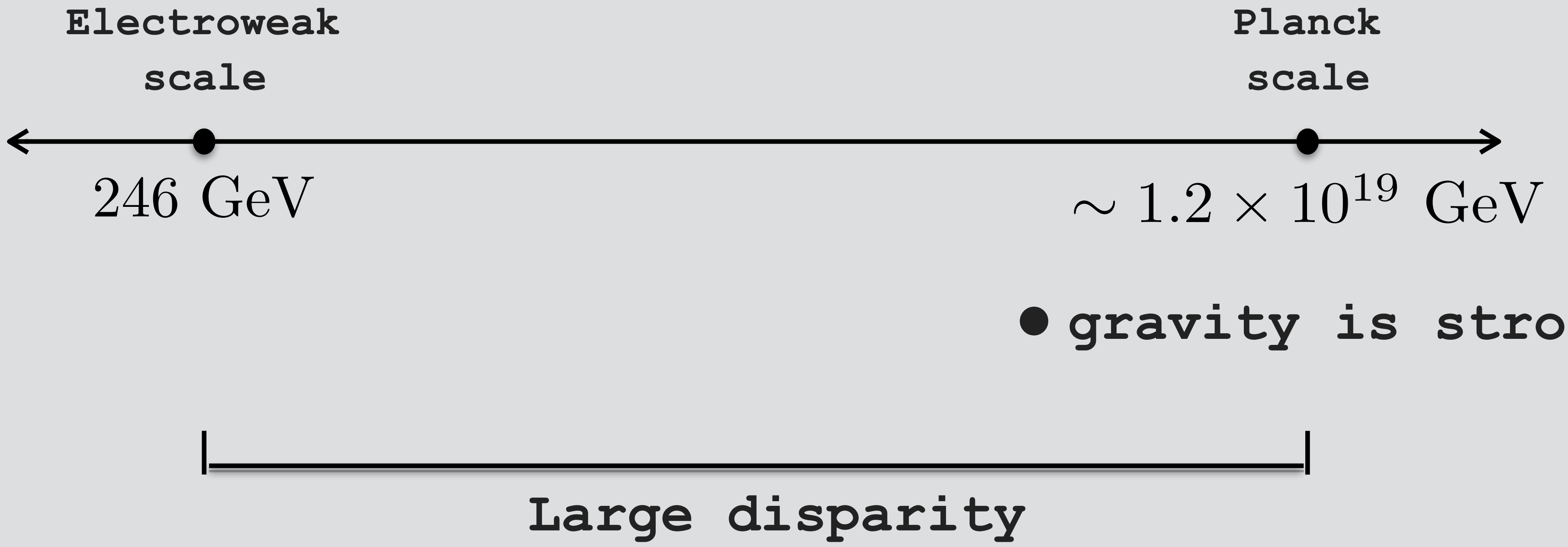


- **gravity is strong!**

Solution: graviton can propagate freely in the extra dimensions!

Why LED?

Hierarchy Problem



Electroweak scale

246 GeV

Planck scale

$\sim 1.2 \times 10^{19}$ GeV

- **gravity is strong!**

Large disparity

Solution: graviton can propagate freely in the extra dimensions!

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

Why LED?

Hierarchy Problem

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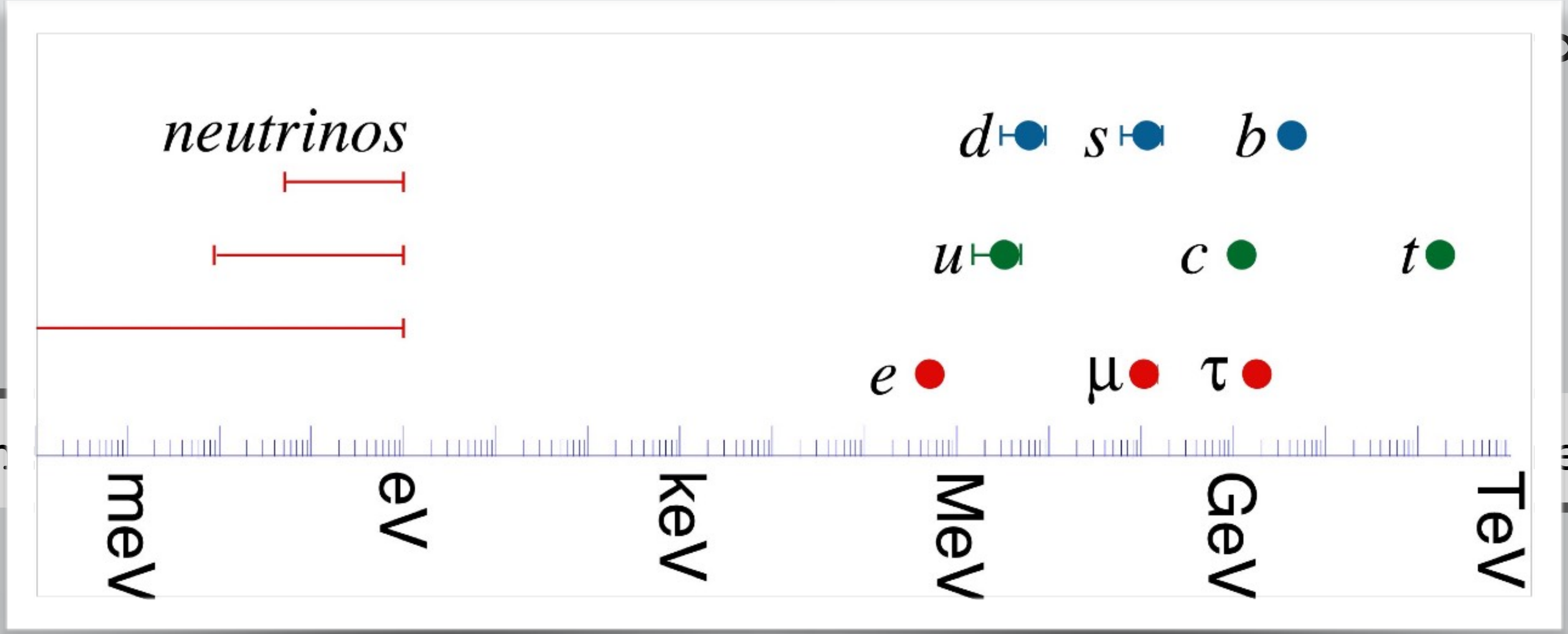


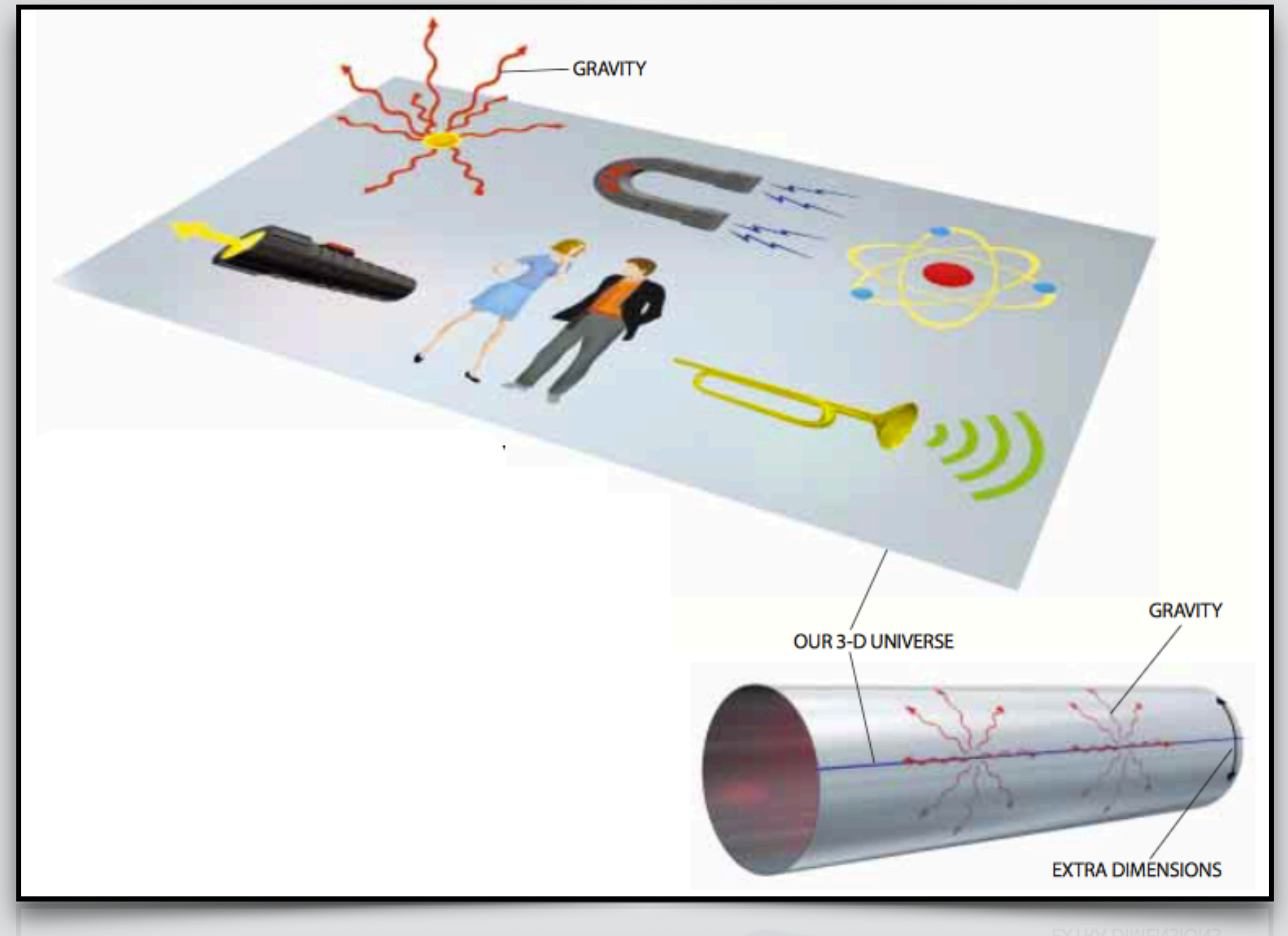
http://hitoshi.berkeley.edu/

Solution ensions!

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

Formalism

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



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

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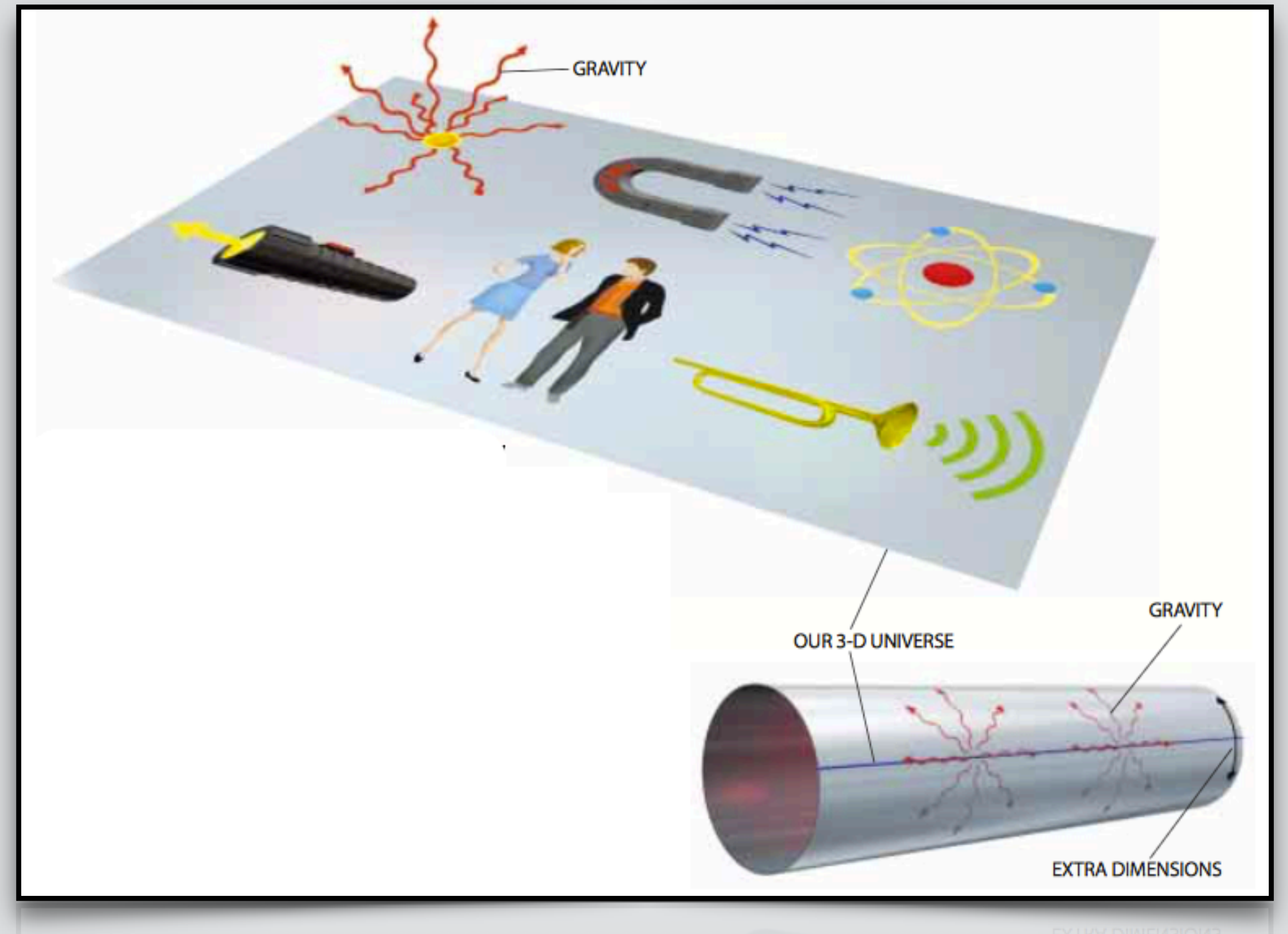

Arkani-Hamed, Dimopoulos and Dvali,
Scientific American, **August 2000**

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

Formalism

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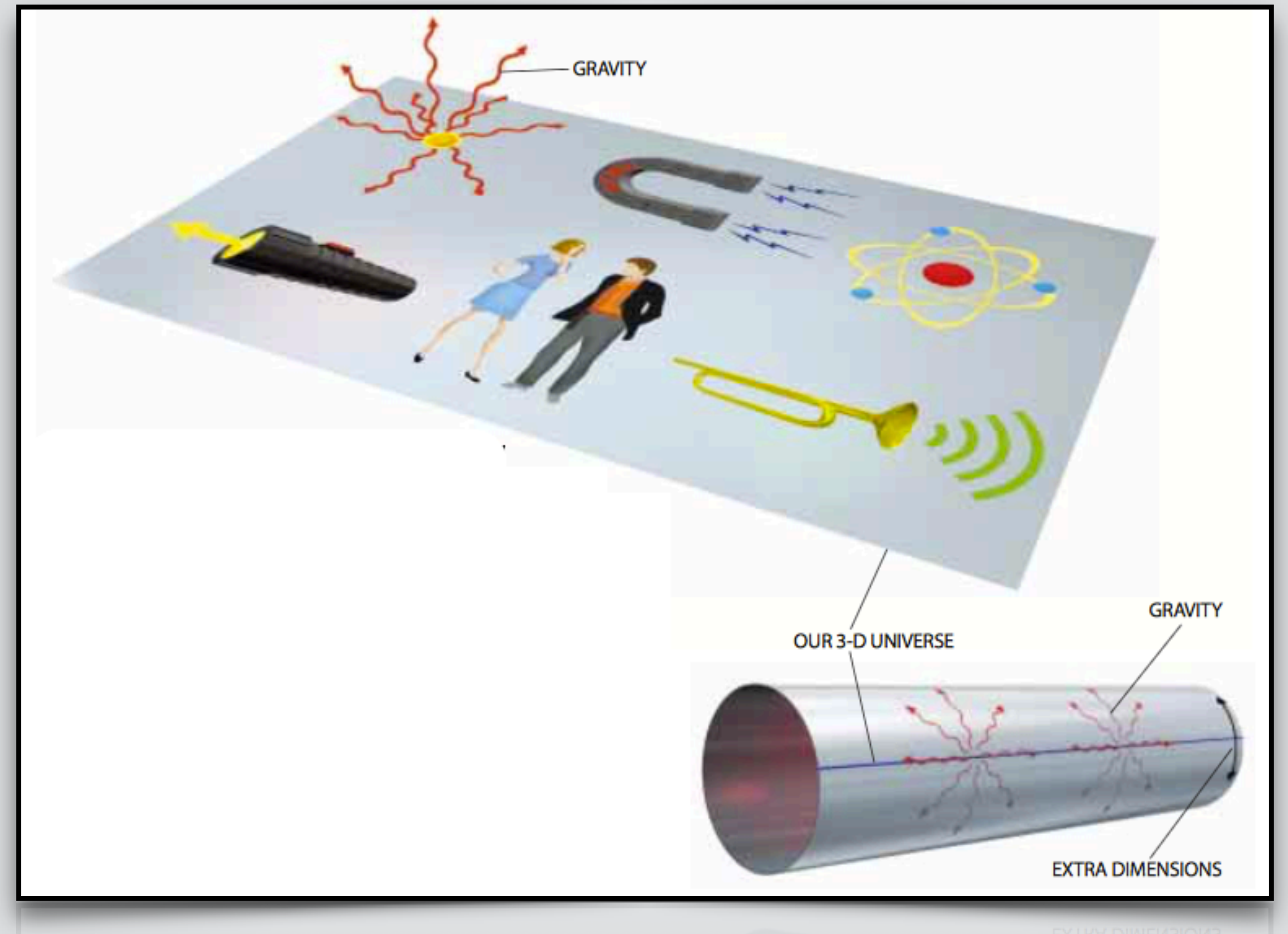

Arkani-Hamed, Dimopoulos and Dvali, *Scientific American*, **August 2000**

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

(asymmetric space)

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

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Extra Dimension

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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Higgs doublet

Formalism

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Yukawa coupling matrix

Formalism

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

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Interaction between field Ψ_α and the active neutrinos

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

After EWSSB:

$$\mathcal{L}_{\text{mass}} = m^{D\alpha\beta}\left(\bar{\nu}^{(0)}_{\alpha R}\nu_{\beta L} + \sqrt{2}\sum_{n=1}^{\infty}\bar{\nu}^{(n)}_{\alpha R}\nu_{\beta L}\right) + \sum_{n=1}^{\infty}\frac{n}{R_{\text{ED}}}\bar{\nu}^{(n)}_{\alpha R}\nu^{(n)}_{\alpha L} + \text{c.h.}$$
$$= \sum_{i=1}^{3}\bar{\mathcal{N}}_{iR} M_i \mathcal{N}_{iL} + \text{c.h.}$$

Formalism

Action of interaction between the active neutrinos and Ψ_α field is

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

Kaluza-Klein (KK) modes

After EWSSB:

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

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

Formalism

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

→ **Pseudo mass eigenstates**

$$M_i = \begin{bmatrix} m_i^D & 0 & 0 & 0 & \dots \\ \sqrt{2} m_i^D & 1/R_{\mathrm{ED}} & 0 & 0 & \dots \\ \sqrt{2} m_i^D & 0 & 2/R_{\mathrm{ED}} & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

→ **Need to be diagonalized!**

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

Eigenvalues:

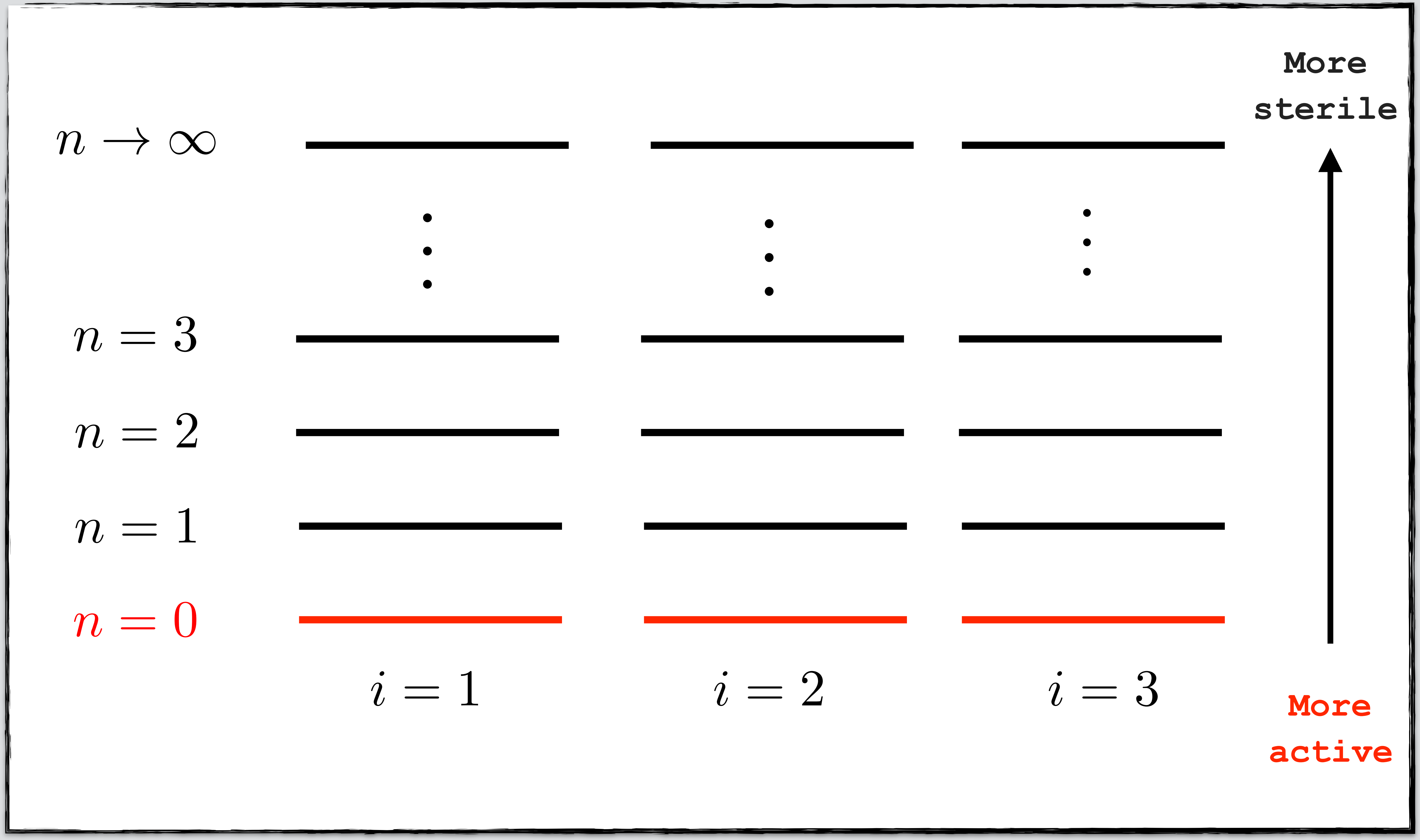
$$\lambda_i^{(n)} - \pi \left(m_i^D R_{\mathrm{ED}}\right)^2 \cot\left(\pi \lambda_i^{(n)}\right) = 0$$

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

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

Formalism

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



More sterile

$n \to \infty$

$n = 3$

$n = 2$

$n = 1$

$n = 0$

$i = 1$ $i = 2$ $i = 3$

More active

Oscillation Probability

3ν

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_{i=1}^{3} U_{\alpha i} U_{\beta i}^{*} \exp\left(-i \frac{m_i^2 L}{2E_\nu} \right) \right|^2$$

$$\Big\downarrow$$

Affects Neutrino Oscillation!

LED

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

$$m_i \to \frac{\lambda_i^{(n)}}{R_{\mathrm{ED}}} \qquad\qquad U_{\alpha i} \to U_{\alpha i} S_i^{0n}$$

$$\boxed{\lambda_i^{(n)}\left(m_0, R_{\mathrm{ED}}\right)} \qquad \boxed{S_i^{0n}\left(m_0, R_{\mathrm{ED}}\right)}$$

Oscillation Probability

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

$$m_i \to \frac{\lambda_i^{(n)}}{R_{\mathrm{ED}}}$$

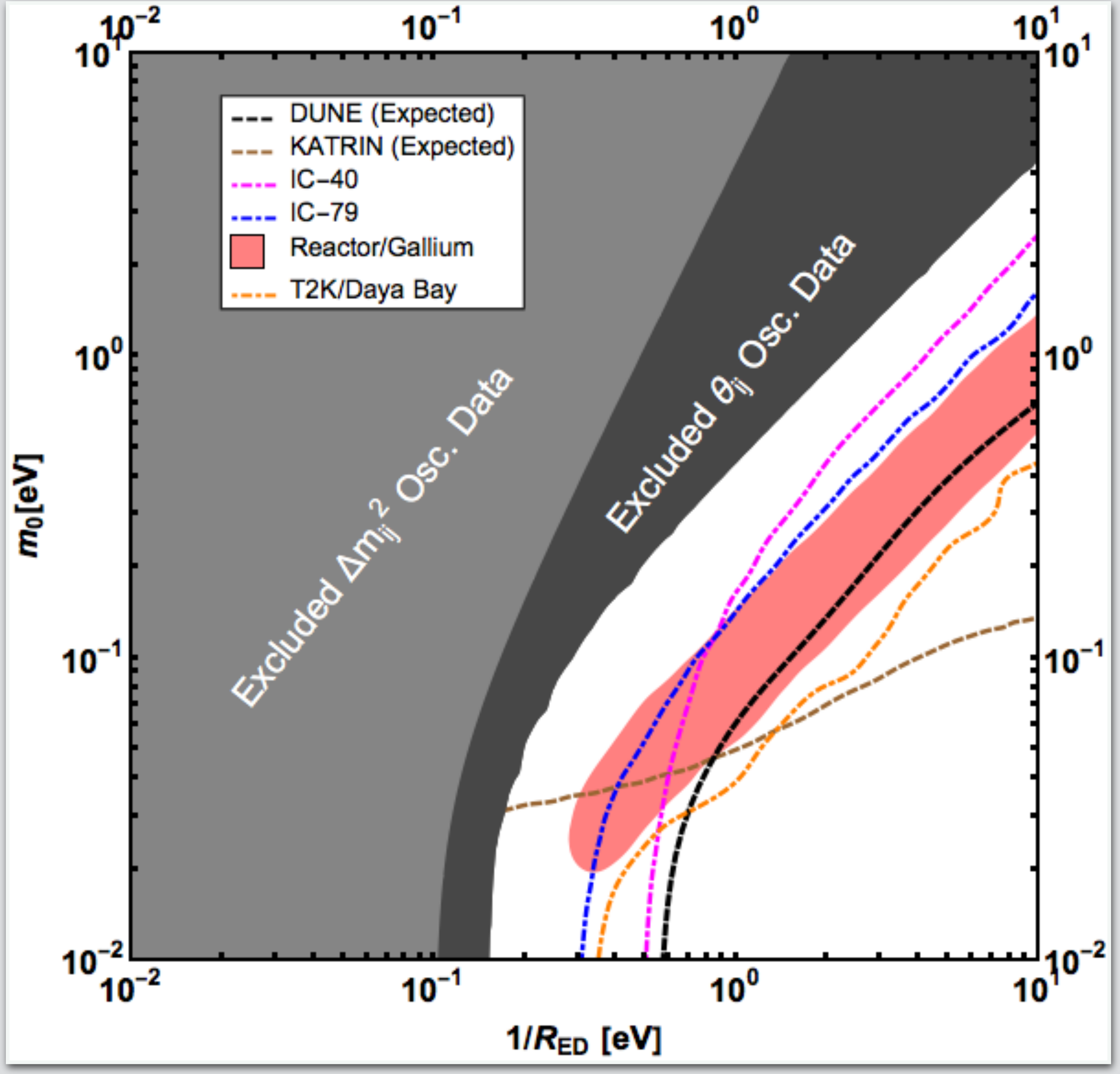
$$U_{\alpha i} \to U_{\alpha i} S_i^{0n}$$

$$\boxed{\lambda_i^{(n)}\left(m_0, R_{\mathrm{ED}}\right)} \qquad \boxed{S_i^{0n}\left(m_0, R_{\mathrm{ED}}\right)}$$

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

Look for LED evidence in NEUTRINO EXPERIMENTS!

Exclusion limits in the literature:



Normal Ordering

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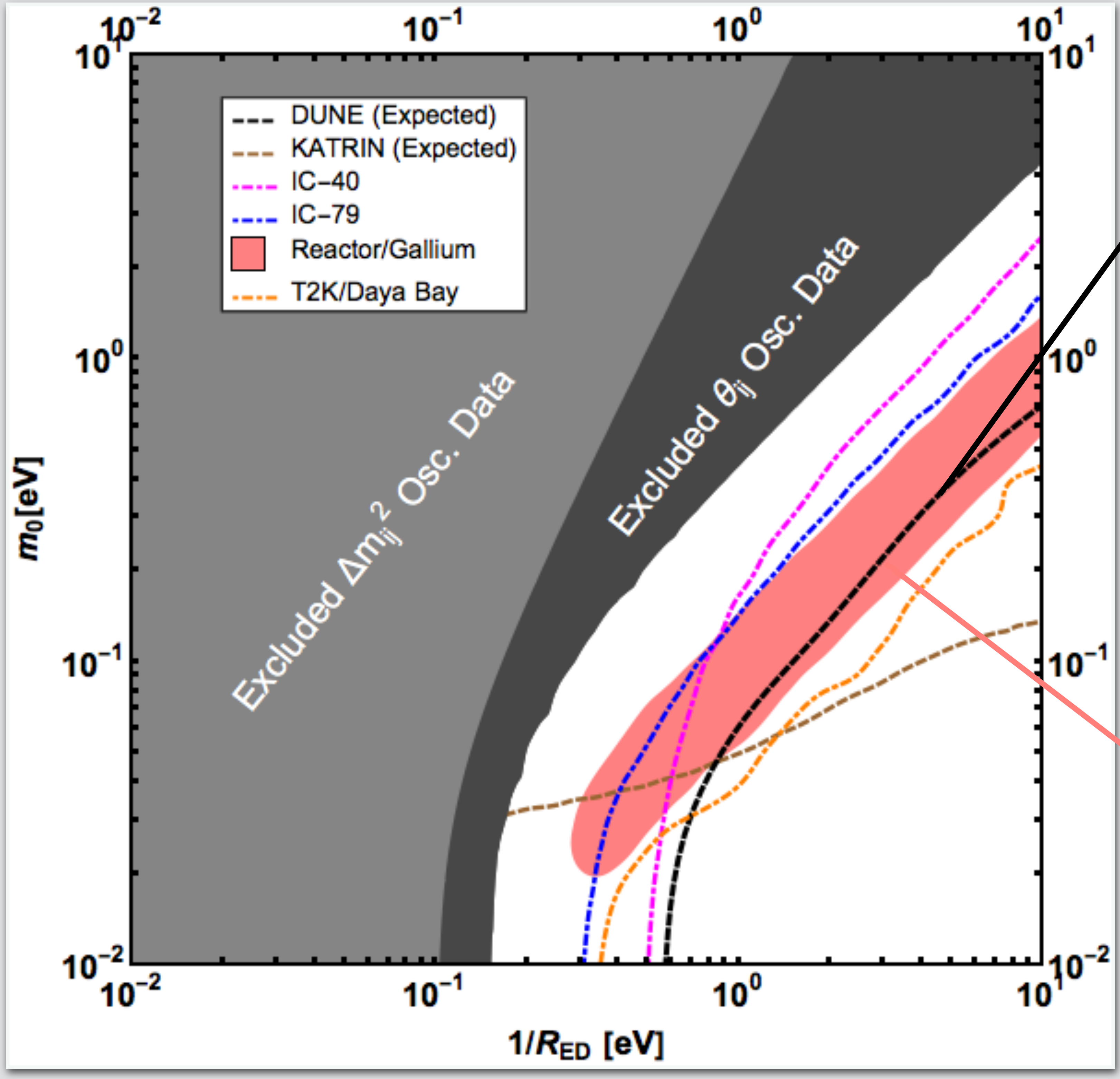


Normal Ordering

Berryman, Jeffrey M. et al. Phys.Rev. D94 (2016)

DUNE 95% C.L.

- 3 years neutrino beam plus 3 years anti-neutrino beam;

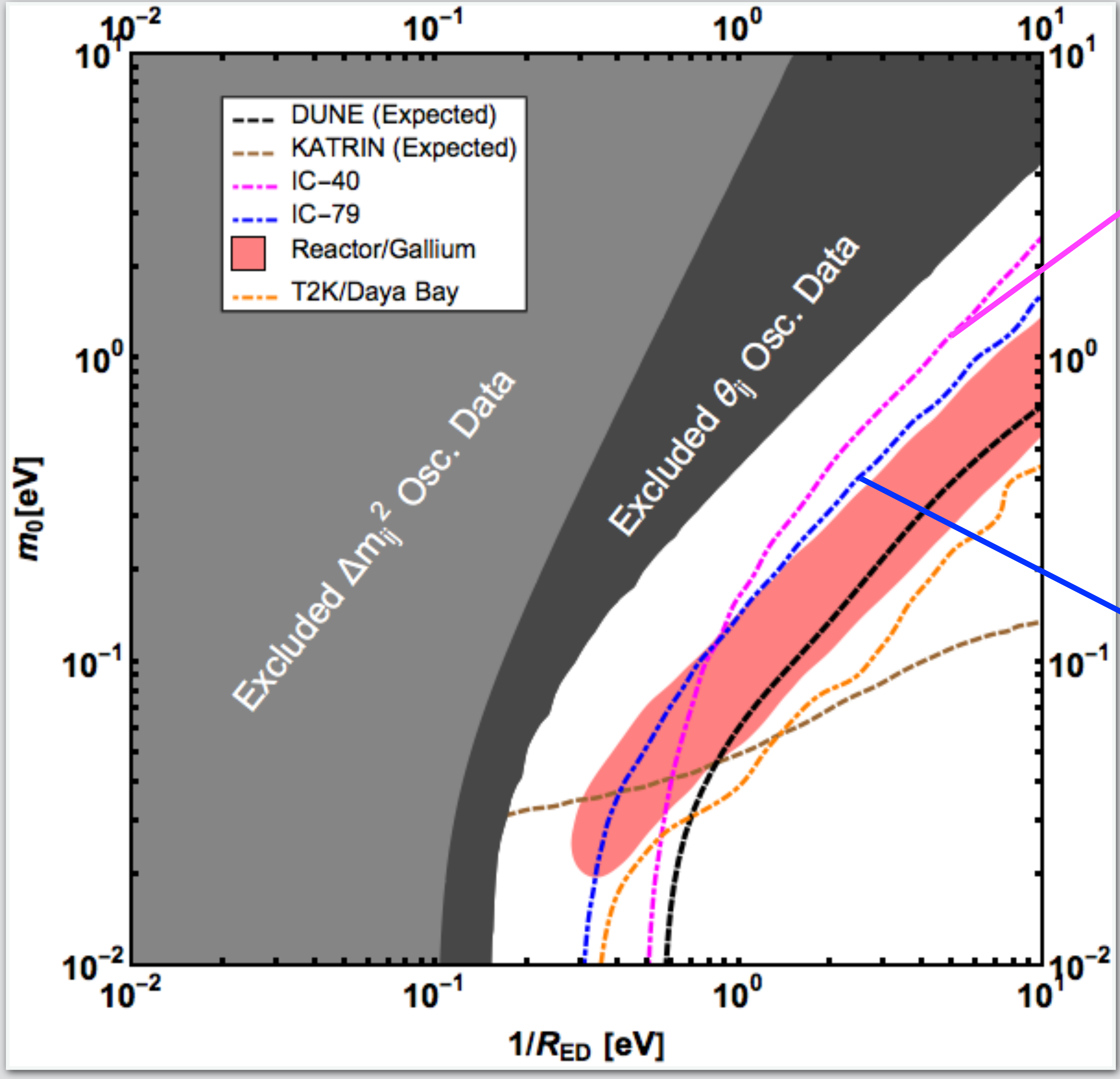
Machado, P.A.N. et al. Phys.Rev. D85 (2012)

Reactor/Gallium anomalies

- Preferred region at 95% C.L.

Exclusion limits in the literature:

Esmaili, Arman et al. JCAP 1412 (2014)



Normal Ordering

IceCube-40

- 359 days;
- 0.1 – 400 TeV.

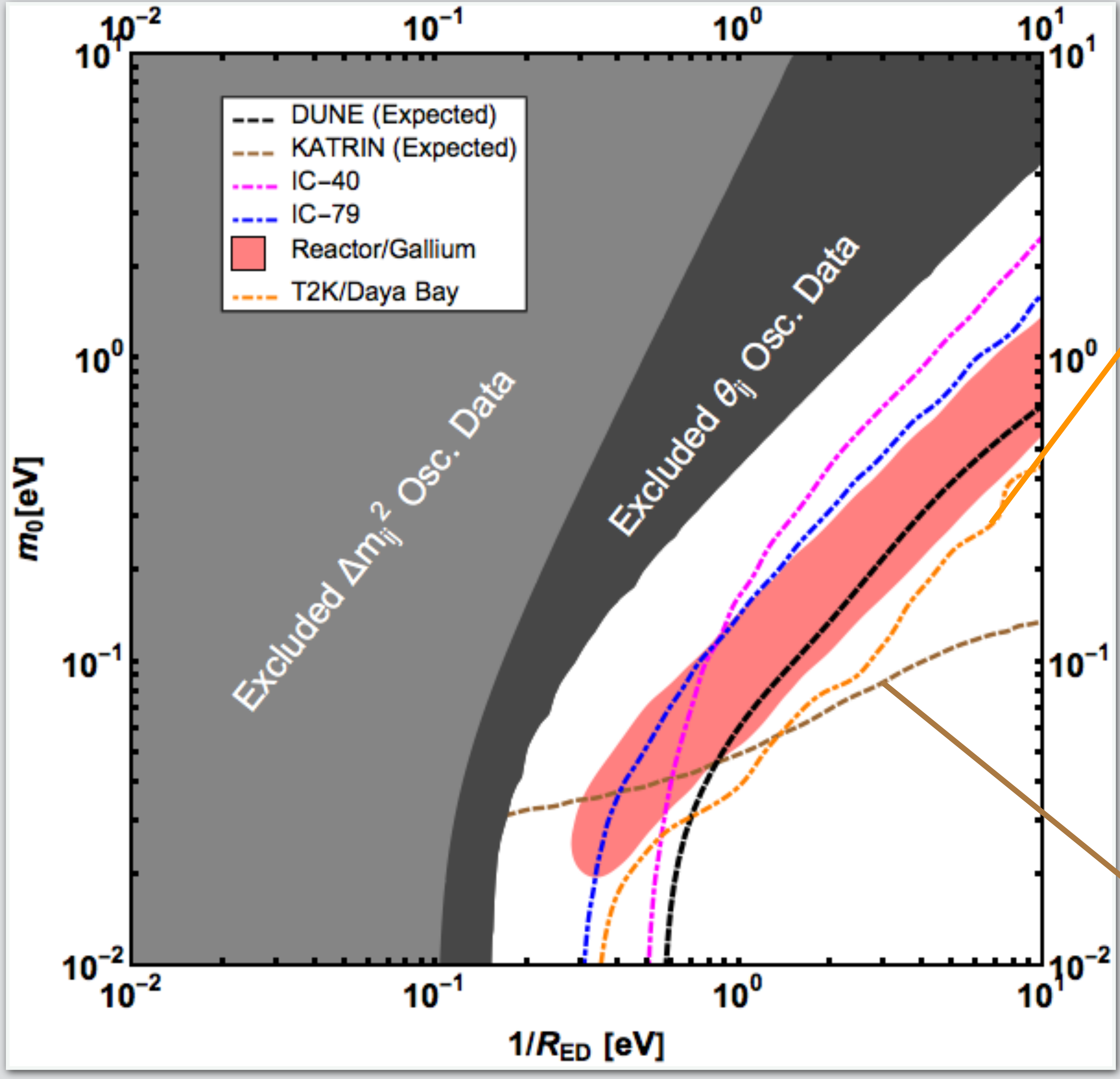
95% C.L.

$R_{\rm ED} \leq 4 \times 10^{-5}$ cm (2σ C.L.)

IceCube-79

- 319 days;
- 0.1 – 10 TeV.

Exclusion limits in the literature:



Normal Ordering

Di Iura, A. et al. J.Phys. G42 (2015)

95% C.L.

T2K/Daya Bay

- **Daya Bay 217 days;** $\bar{\nu}_e \to \bar{\nu}_e$
- **T2K**
  28 events $\nu_\mu \to \nu_e$
  120 events $\nu_\mu \to \nu_\mu$

$R_{\text{ED}} \leq 0.6\ \mu\text{m}\ (2\sigma\ \text{C.L.})$

Basto-Gonzalez, Victor S. et al. Phys.Lett. B718 (2013)

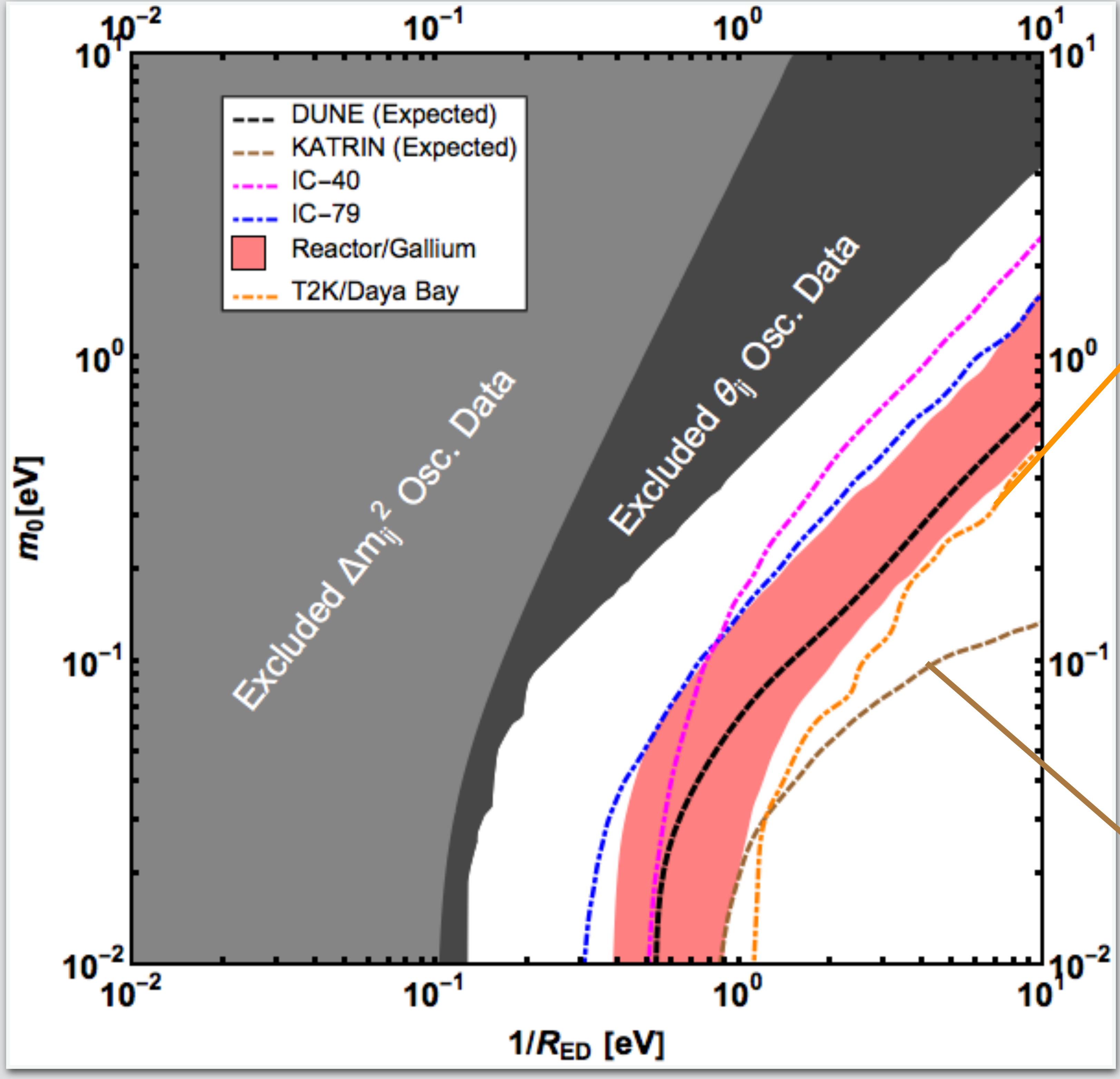
90% C.L.

KATRIN

- **3 years;**
- **Tritium Beta Decay**

$^3\text{H} \to\ ^3\text{He}^+ + \text{e}^- + \bar{\nu}_\text{e}$

Exclusion limits in the literature:



Inverted Ordering

Di Iura, A. et al. J.Phys. G42 (2015)

95% C.L.

T2K/Daya Bay

- **Daya Bay 217 days;** $\bar{\nu}_e \to \bar{\nu}_e$
- **T2K**
  28 events $\nu_\mu \to \nu_e$
  120 events $\nu_\mu \to \nu_\mu$

$$R_{\rm ED} \leq 0.17\ \mu{\rm m}\ (2\sigma\ {\rm C.L.})$$

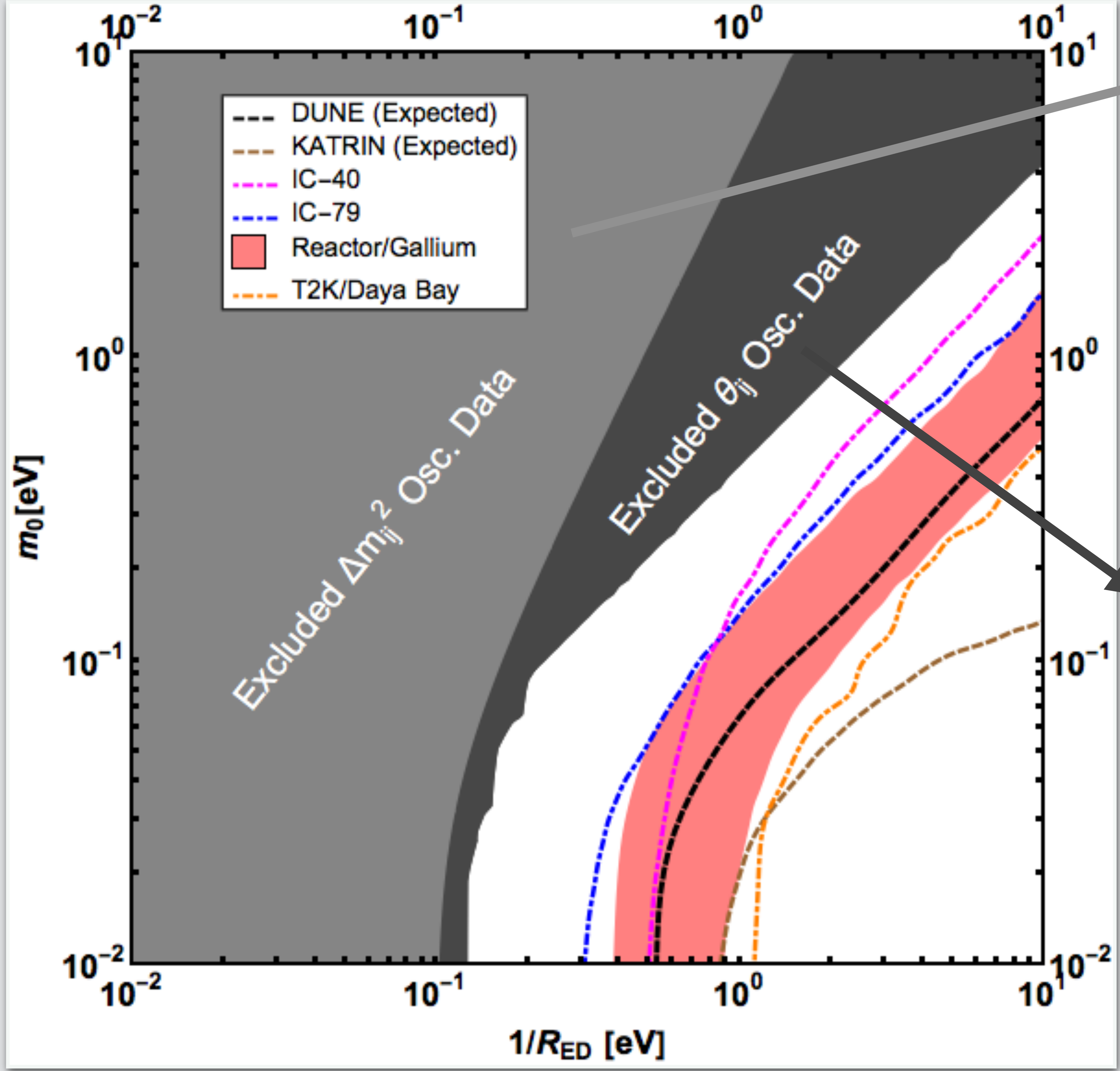
Basto-Gonzalez, Victor S. et al. Phys.Lett. B718 (2013)

90% C.L.

KATRIN

$$R_{\rm ED} \leq 2.3 \times 10^{-7}\ {\rm m}\ (90\%\ {\rm C.L.})$$

Exclusion limits in the literature:



Inverted Ordering

$$\frac{\left(\lambda_2^{(0)}\right)^2}{R_{\rm ED}^2} - \frac{\left(\lambda_1^{(0)}\right)^2}{R_{\rm ED}^2} = \Delta m_{21}^2$$

$$\frac{\left(\lambda_3^{(0)}\right)^2}{R_{\rm ED}^2} - \frac{\left(\lambda_1^{(0)}\right)^2}{R_{\rm ED}^2} = |\Delta m_{31}^2|$$

$$\left|U_{e3}^{3\nu}\right| \to \left|U_{e3}^{\rm LED}\right| \left(S_3^{00}\right)$$

$$\left|U_{e2}^{3\nu}\right| \to \left|U_{e2}^{\rm LED}\right| \left(S_2^{00}\right)$$

$$\left|U_{\mu3}^{3\nu}\right| \to \left|U_{\mu3}^{\rm LED}\right| \left(S_3^{00}\right)$$

Short-Baseline Neutrino Program

arXiv:1503.01520

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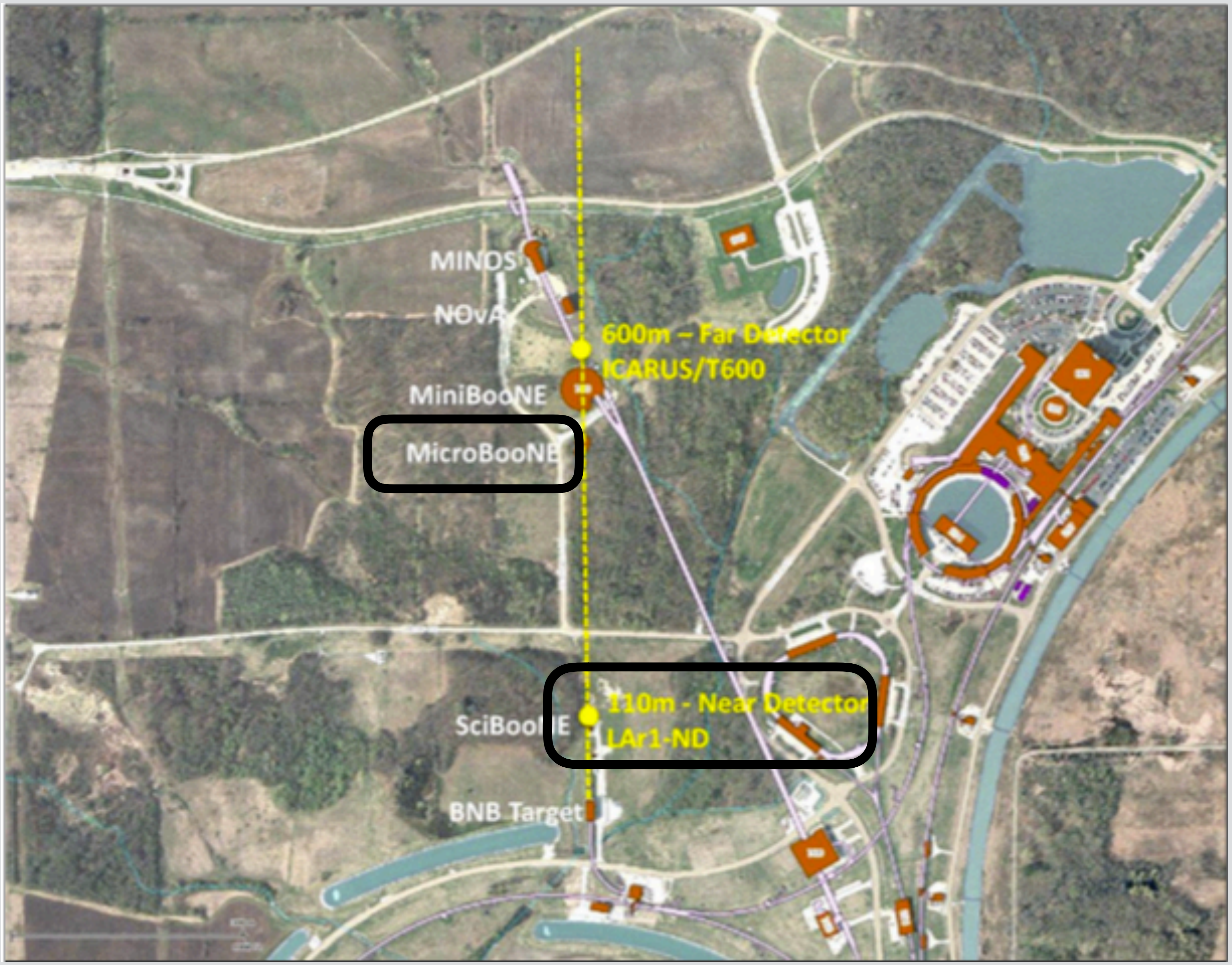
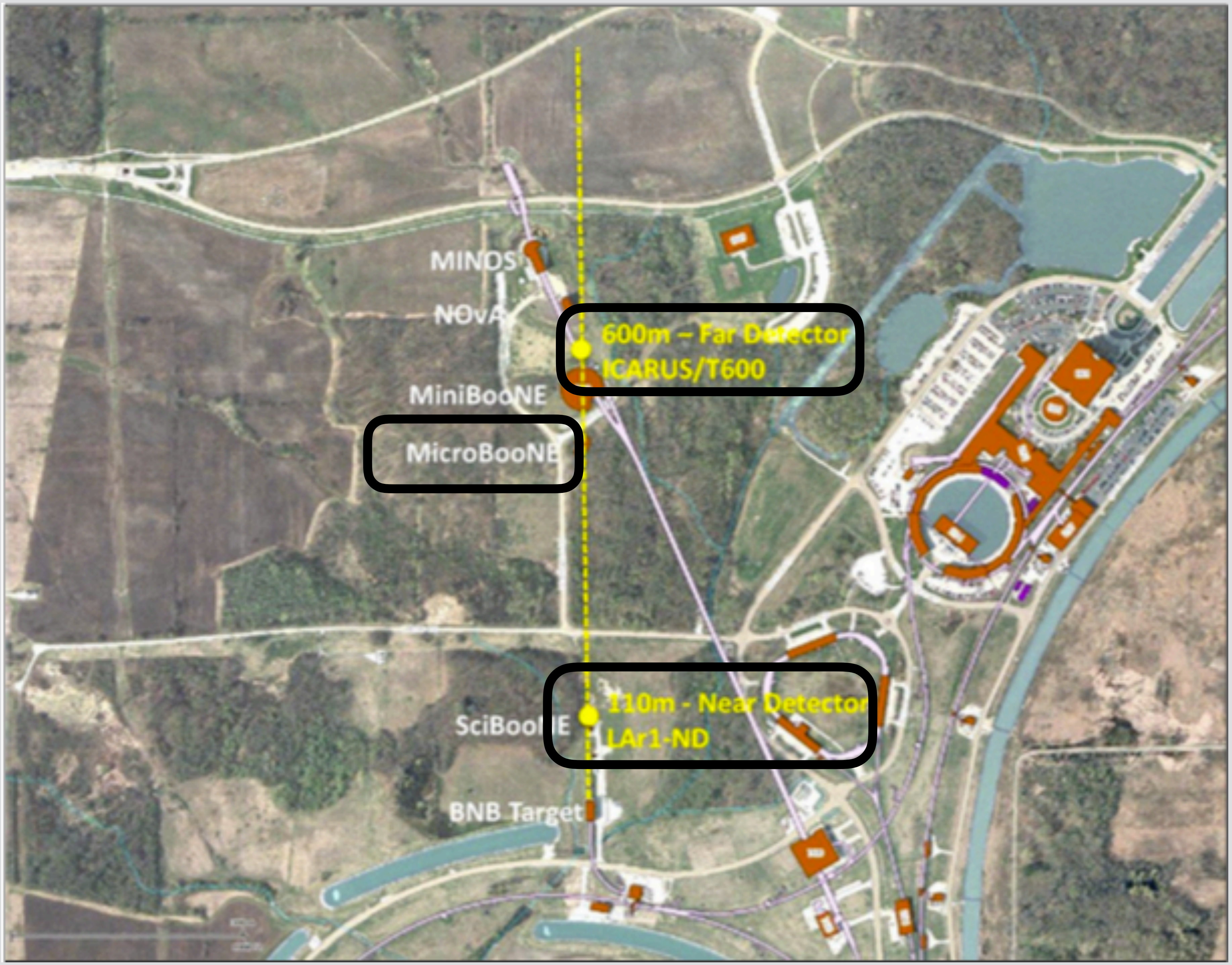
Short-Baseline Neutrino Program



arXiv:1503.01520

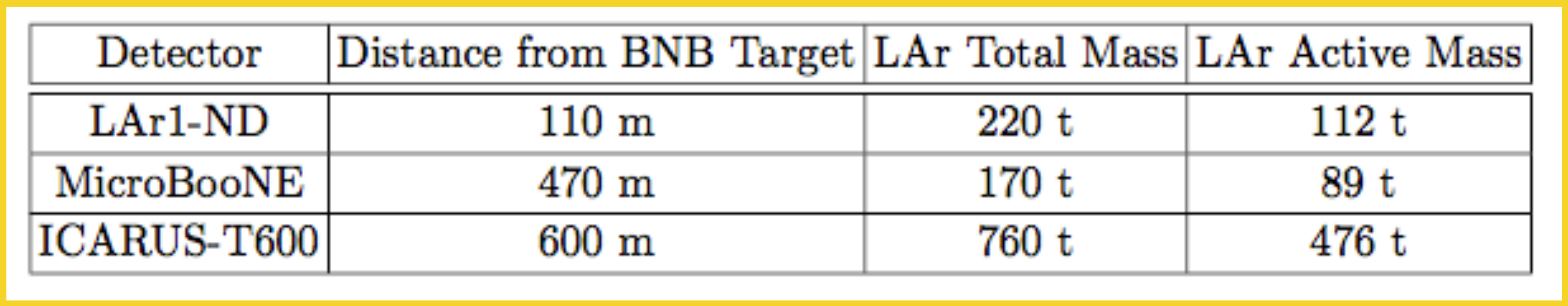
Short-Baseline Neutrino Program



arXiv:1503.01520

Short-Baseline Neutrino Program

3 Liquid Argon (LAr) Detectors:



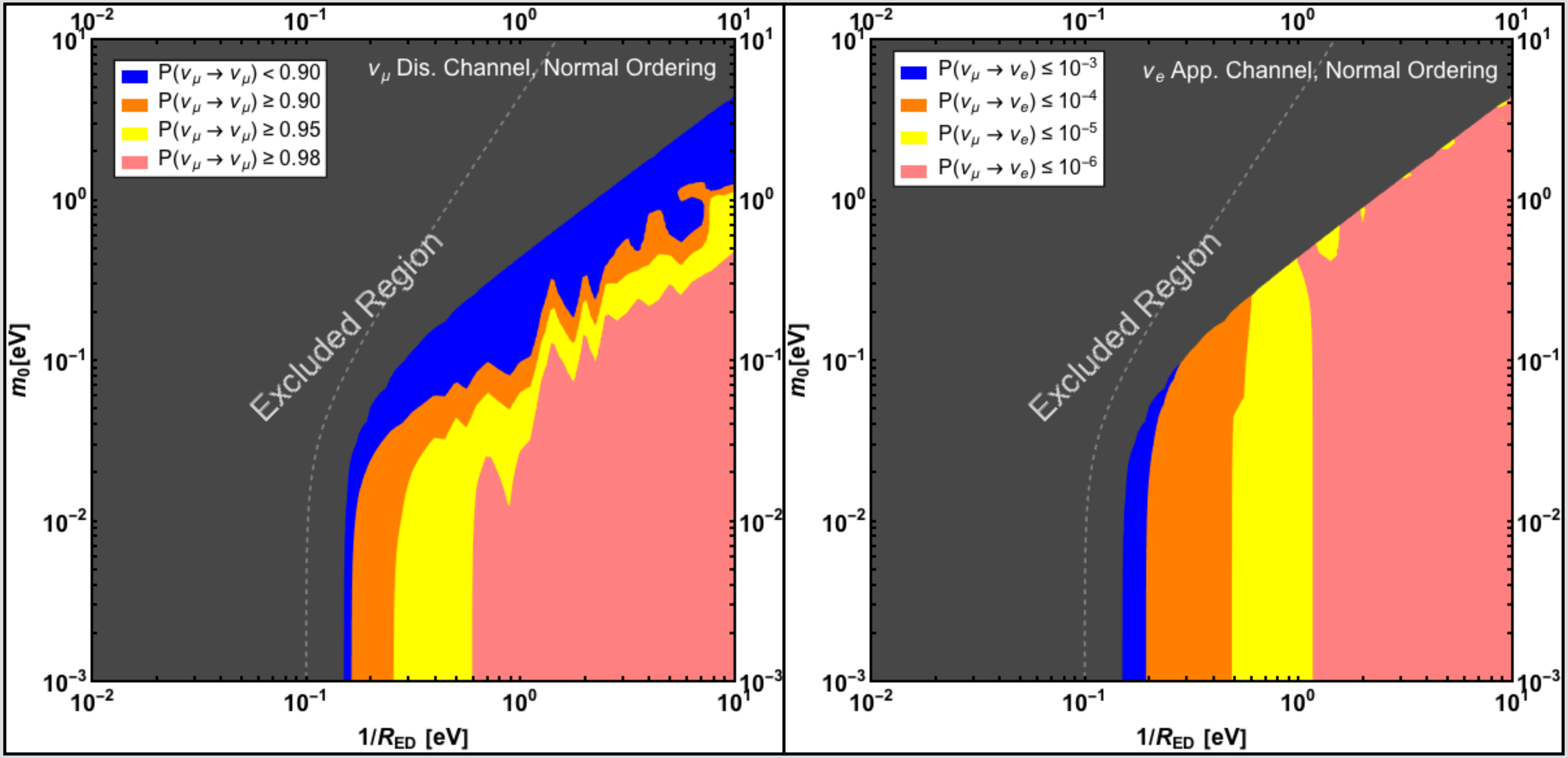
Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t

- **Energy Range: 0.2 - 3 GeV;**
- **2 Channels:** $\nu_\mu \rightarrow \nu_\mu$ **(Muon Neutrino Disappearance)**
  $\nu_\mu \rightarrow \nu_e$ **(Electron Neutrino Appearance)**
- **SBND (LAr1-ND): 2020**
- **MicroBooNE: 2015**
- **ICARUS-T600: 2019**

SBN motivation: search to date for sterile neutrinos at the eV mass-scale through both appearance and disappearance oscillation channels.

Oscillation Probability

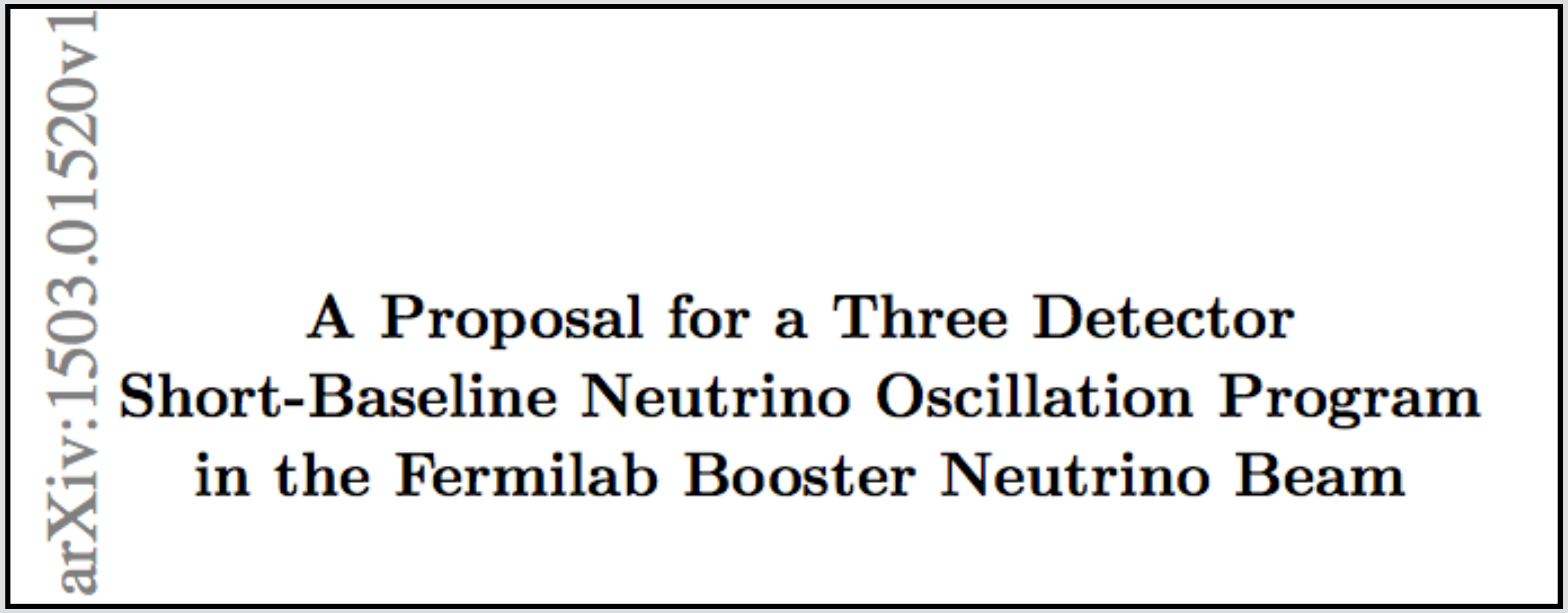
$$\frac{L}{E_\nu} = 1.2 \ \frac{\text{km}}{\text{GeV}}$$



Results:

GLoBES +

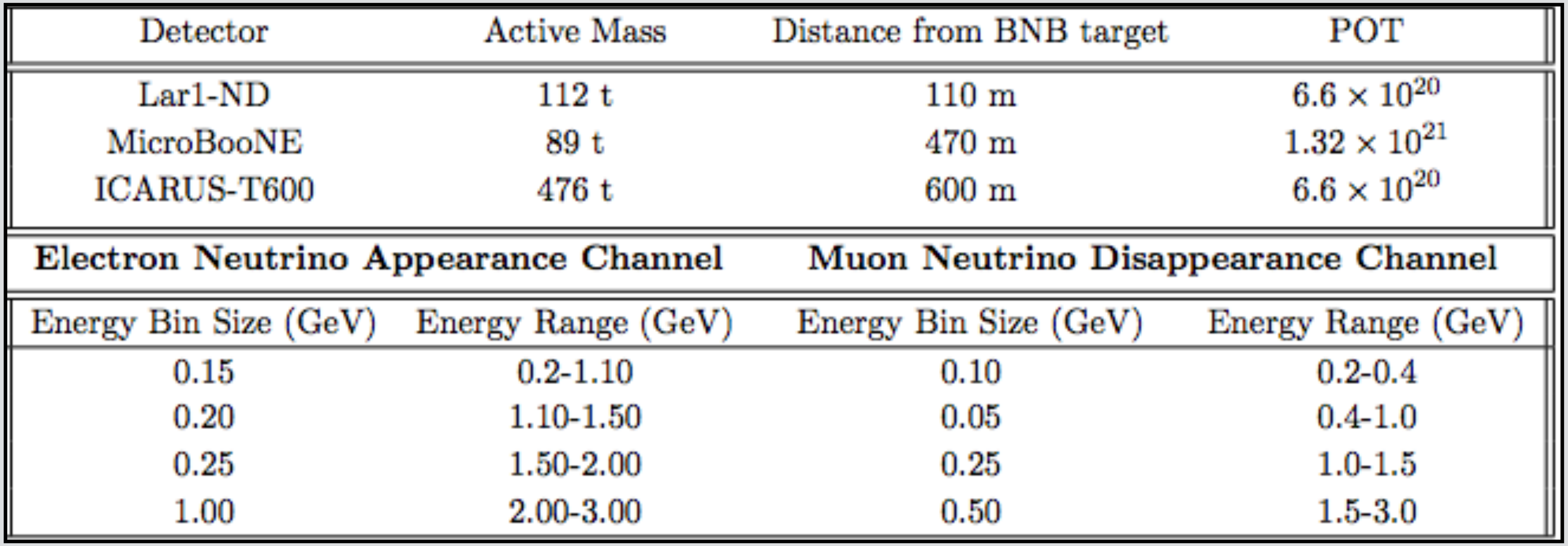
- ☑ Flux;
- ☑ Cross Sections;
- ☑ Energy Reconstruction;
- ☑ Efficiencies.



arXiv:1503.01520v1

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

arXiv:1503.01520



Detector	Active Mass	Distance from BNB target	POT
Lar1-ND	112 t	110 m	6.6×10^{20}
MicroBooNE	89 t	470 m	1.32×10^{21}
ICARUS-T600	476 t	600 m	6.6×10^{20}

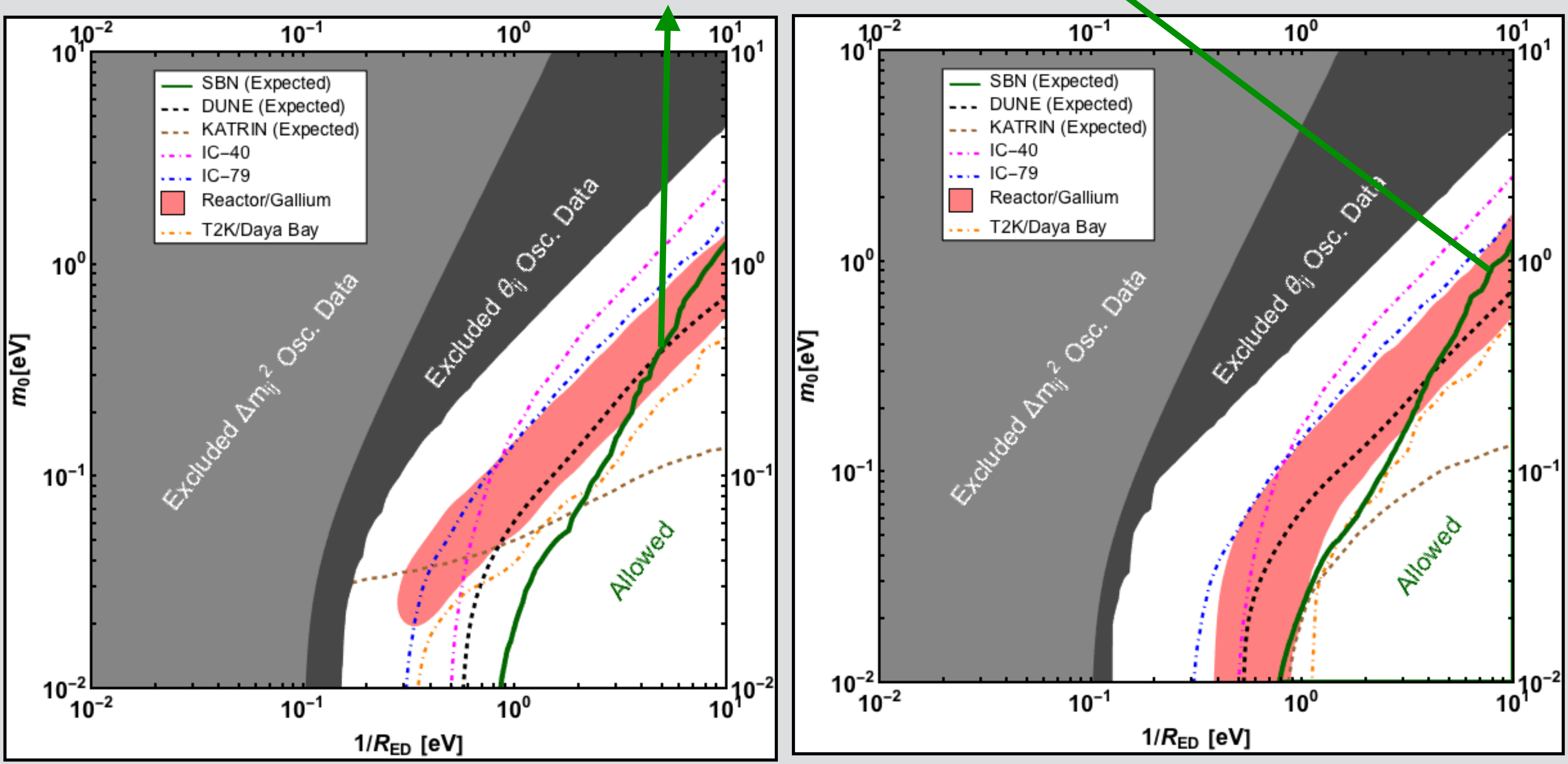
Electron Neutrino Appearance Channel		**Muon Neutrino Disappearance Channel**	
Energy Bin Size (GeV)	Energy Range (GeV)	Energy Bin Size (GeV)	Energy Range (GeV)
0.15	0.2-1.10	0.10	0.2-0.4
0.20	1.10-1.50	0.05	0.4-1.0
0.25	1.50-2.00	0.25	1.0-1.5
1.00	2.00-3.00	0.50	1.5-3.0

Results:

G. V. Stenico, D. V. Forero and O. L. G. Peres

90% C.L.

$R_{\text{ED}} < 1.25\ \text{eV}^{-1}$ (90% C.L.)



NH

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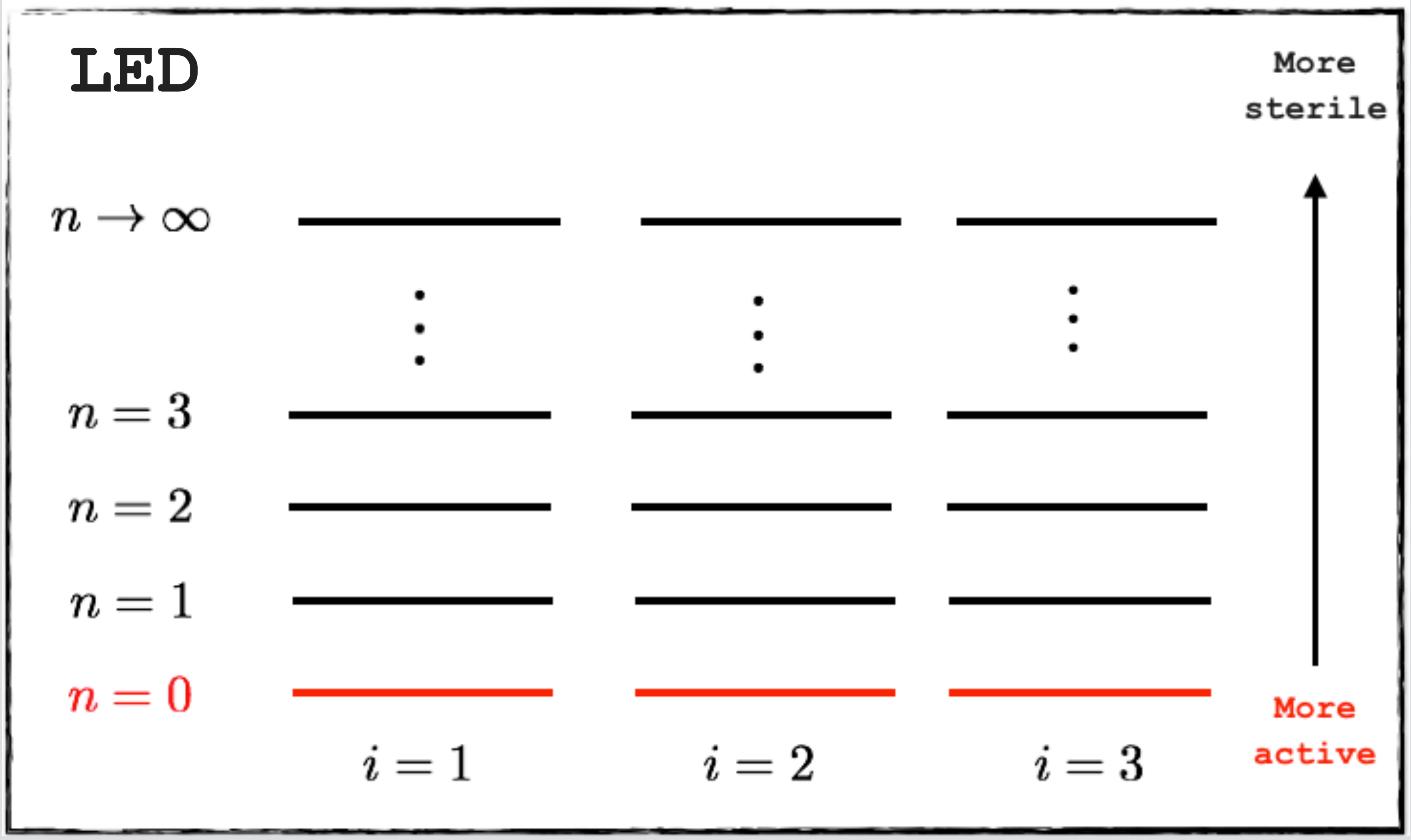
Discrimination power between LED scenario and the 3+1 scenario

Non-null result in SBN

Discrimination power between LED scenario and the 3+1 scenario

Non-null result in SBN →

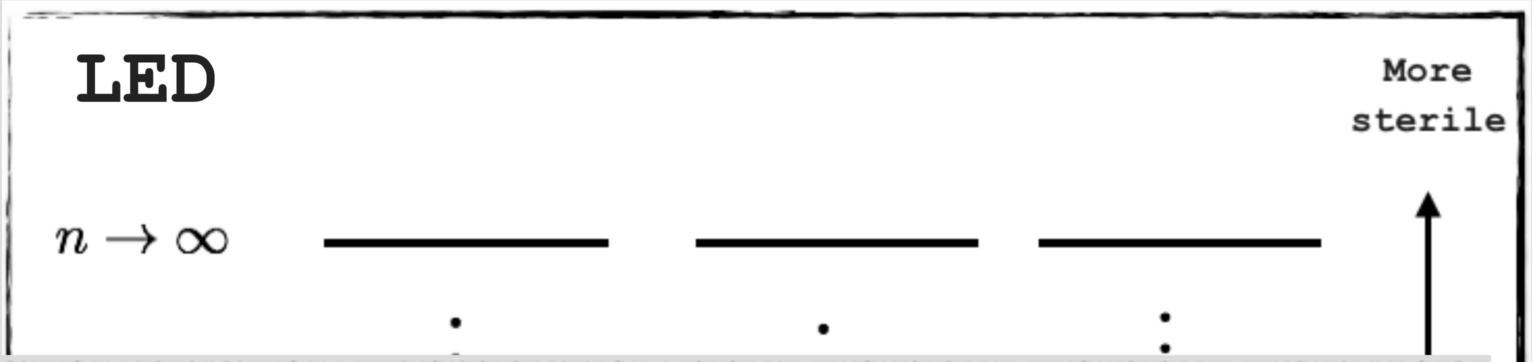
?

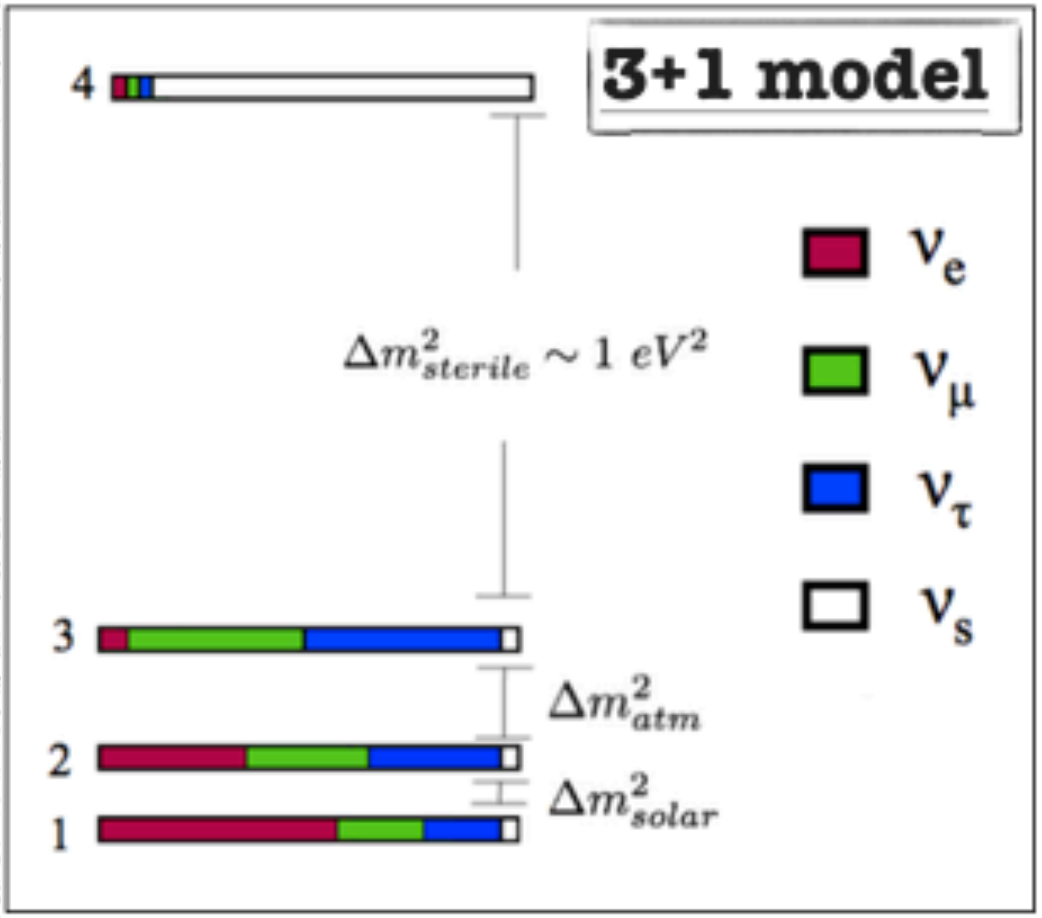


Discrimination power between LED scenario and the 3+1 scenario

Non-null result in SBN

?





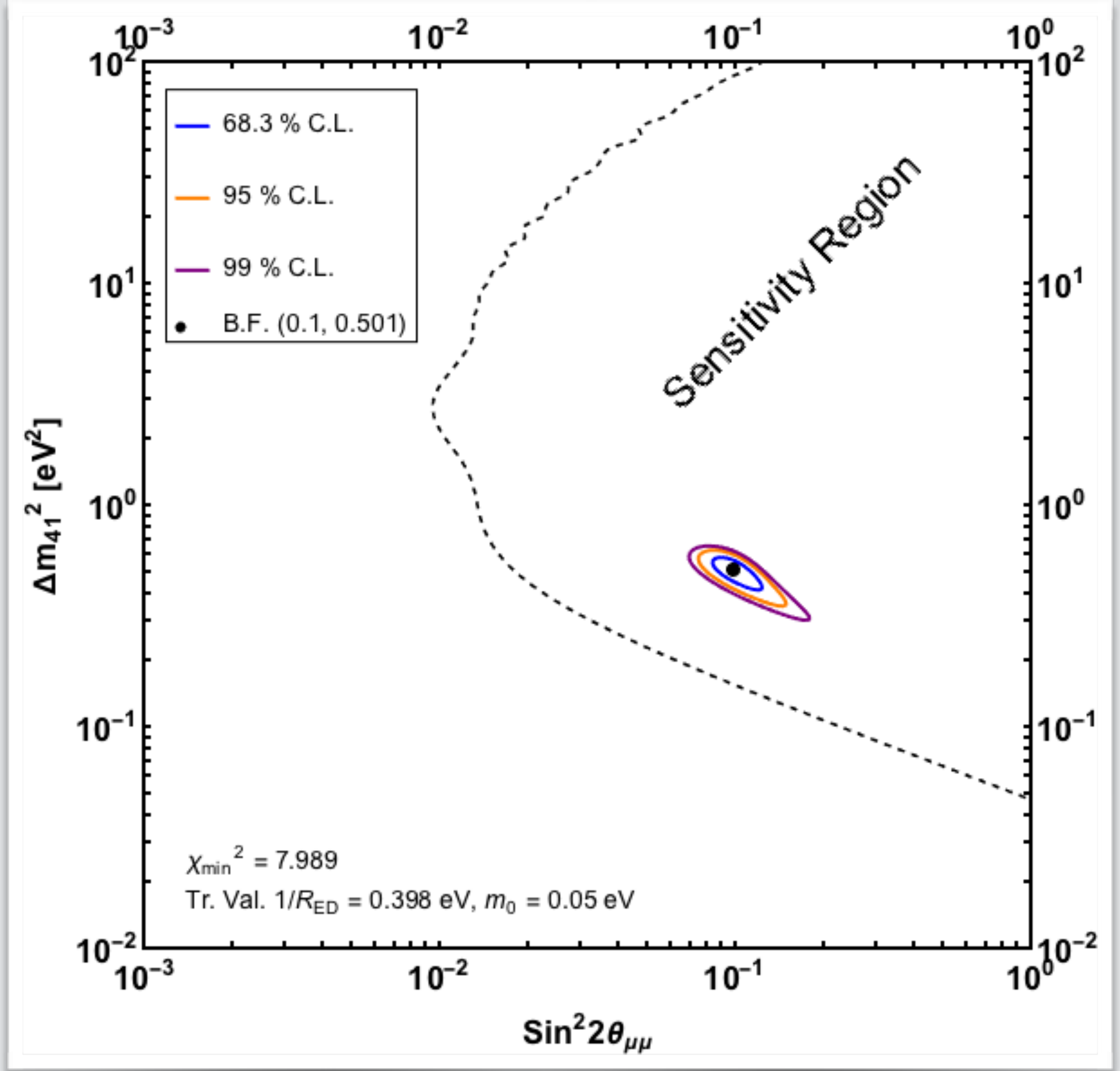
$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

SB approximation:

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

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

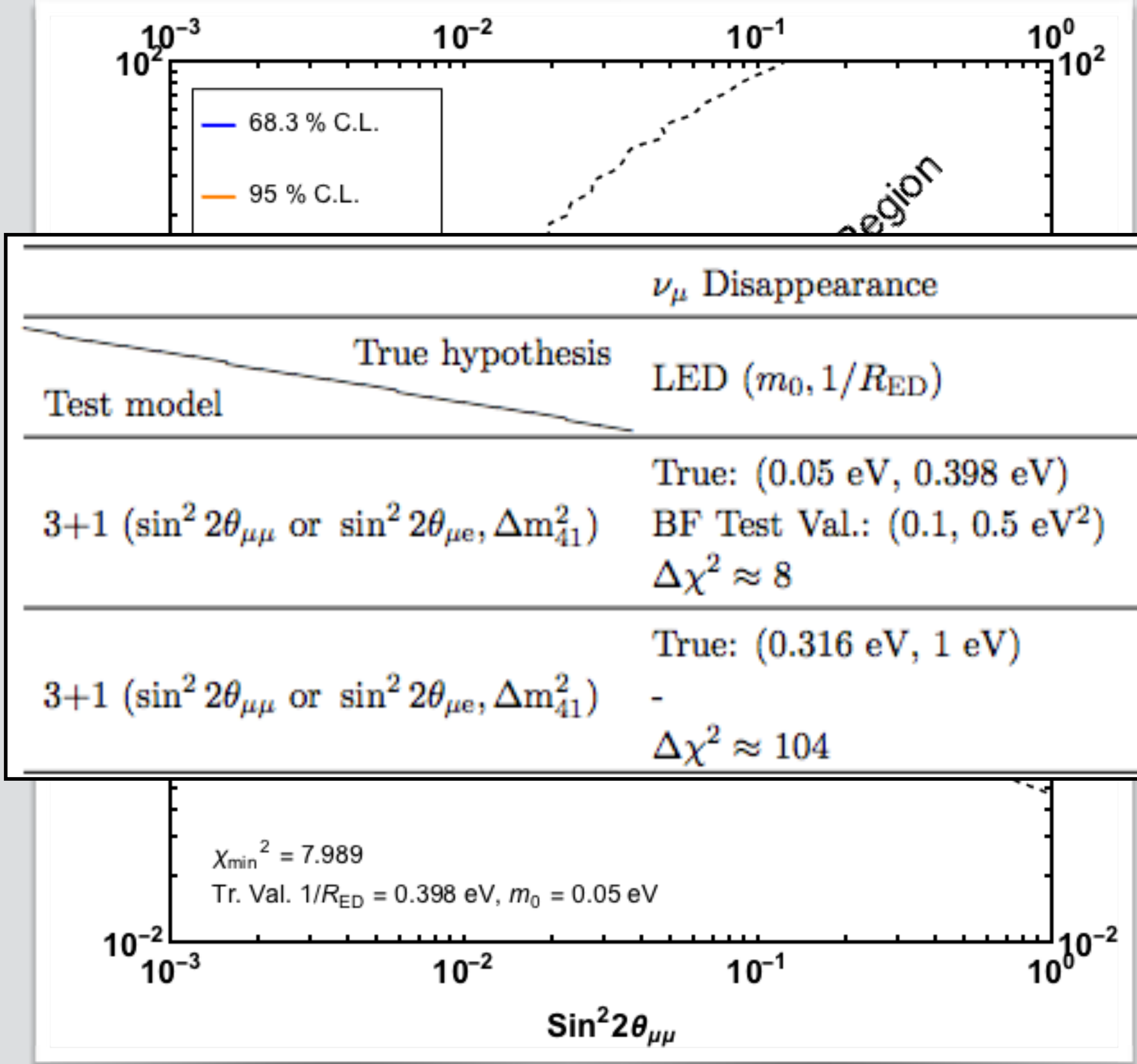
3+1 fit to the LED scenario



$$\Delta\chi^2 = \chi^2_{3+1} - \chi^2_{\mathrm{LED}} \approx 8$$

$$(2\sigma - 3\sigma)$$

3+1 fit to the LED scenario



$$\Delta\chi^2 = \chi^2_{3+1} - \chi^2_{\text{LED}} \approx 8$$

	ν_μ Disappearance	ν_e Appearance
True hypothesis Test model	LED $(m_0, 1/R_{\text{ED}})$	LED $(m_0, 1/R_{\text{ED}})$
3+1 $(\sin^2 2\theta_{\mu\mu}$ or $\sin^2 2\theta_{\mu e}, \Delta m^2_{41})$	True: (0.05 eV, 0.398 eV) BF Test Val.: (0.1, 0.5 eV^2) $\Delta\chi^2 \approx 8$	True: (0.05 eV, 0.398 eV) - $\Delta\chi^2 \approx 78$
3+1 $(\sin^2 2\theta_{\mu\mu}$ or $\sin^2 2\theta_{\mu e}, \Delta m^2_{41})$	True: (0.316 eV, 1 eV) - $\Delta\chi^2 \approx 104$	True: (0.316 eV, 1 eV) - $\Delta\chi^2 \approx 538$

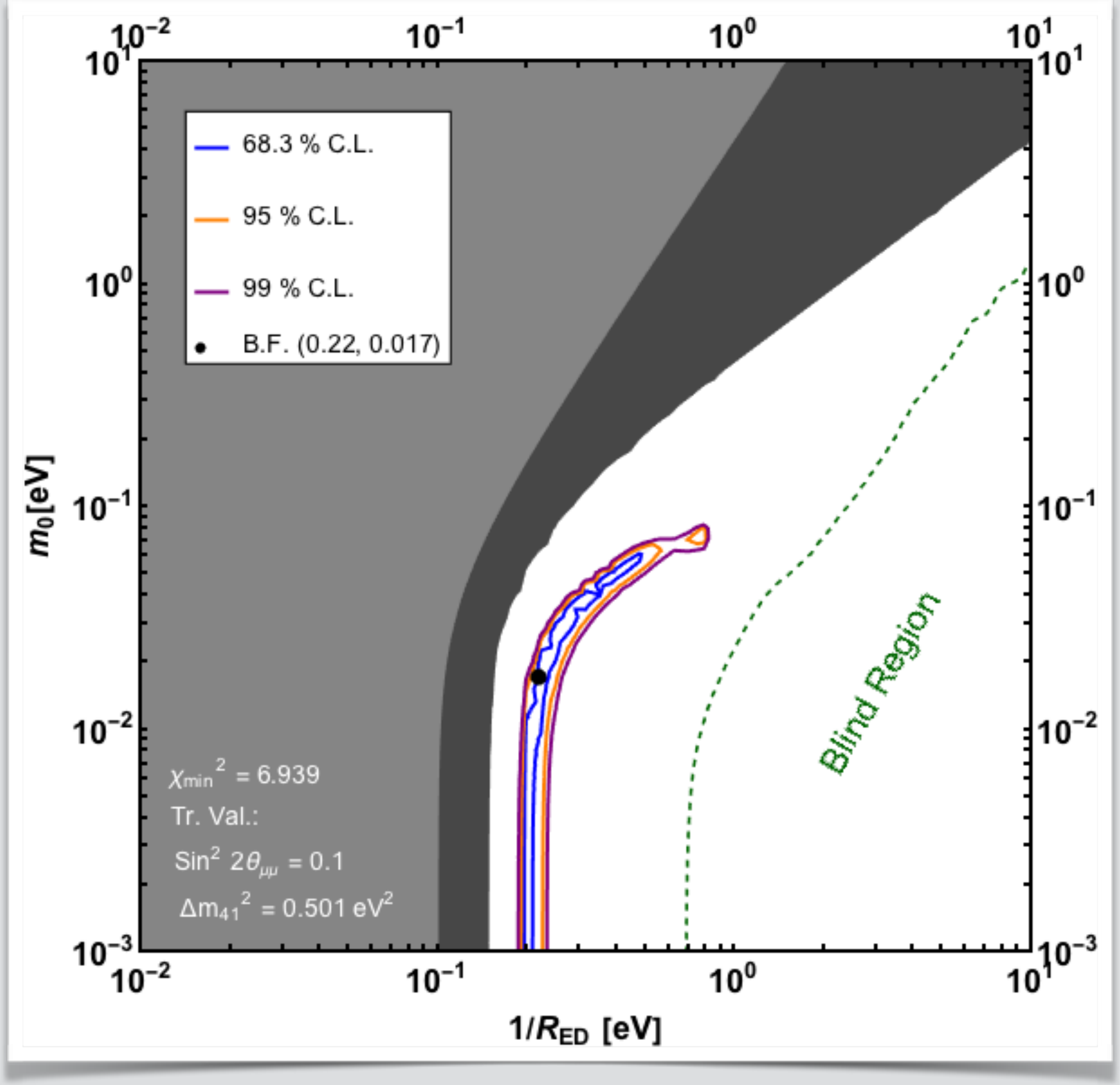
Conclusions

- ✱ LED can be very well explored in Neutrino Experiments;
- ✱SBN is sensitive to the oscillations predicted in the LED model and have the potential to constrain the LED parameter space better than any other oscillation experiment, for m_1^D < 0.1 eV;
- ✱In case SBN observes a departure from the three active neutrino framework, it also has the power of discriminate between sterile oscillations predicted in the 3+1 framework and the LED ones.

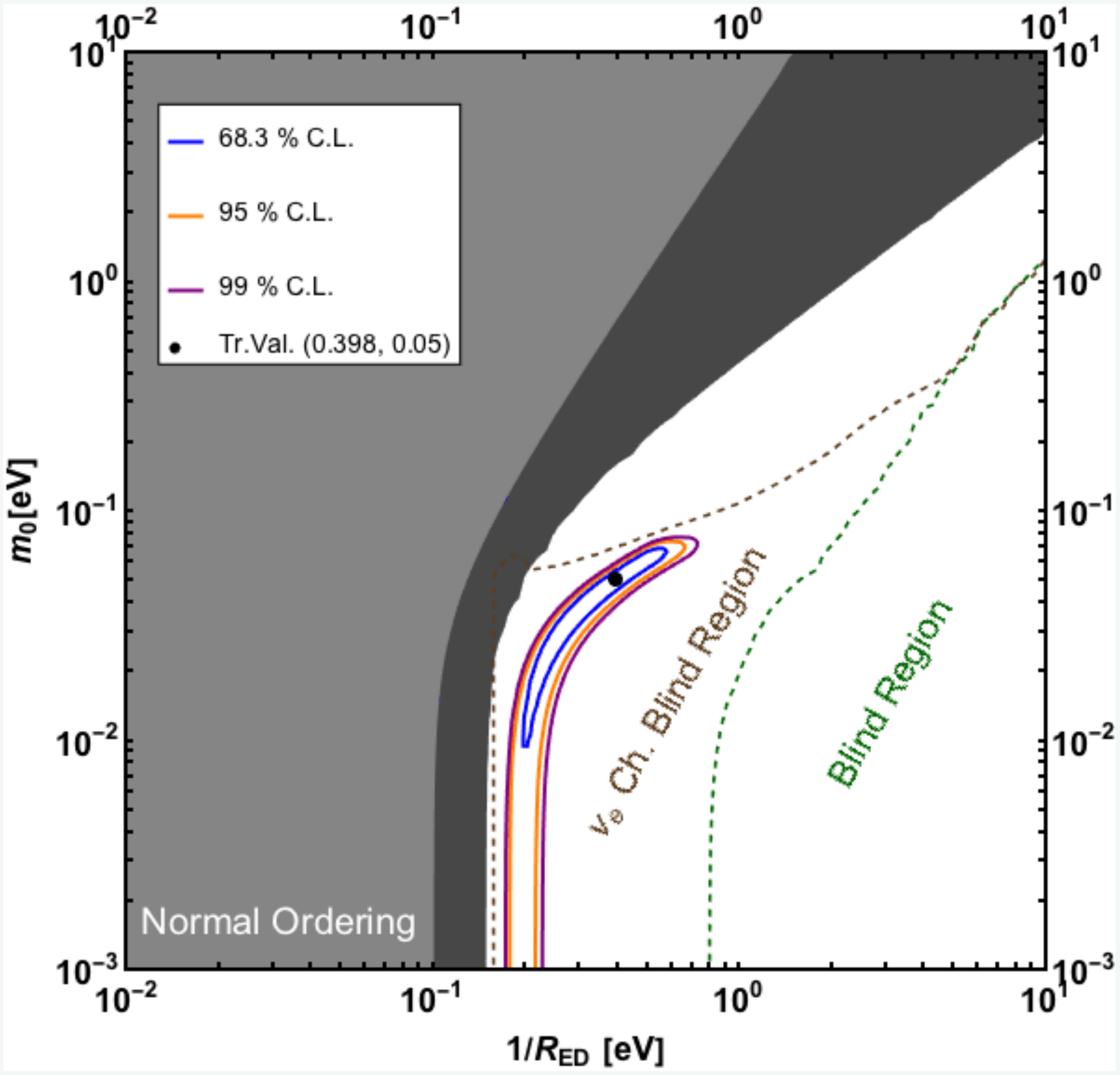
Thank you!

Backup

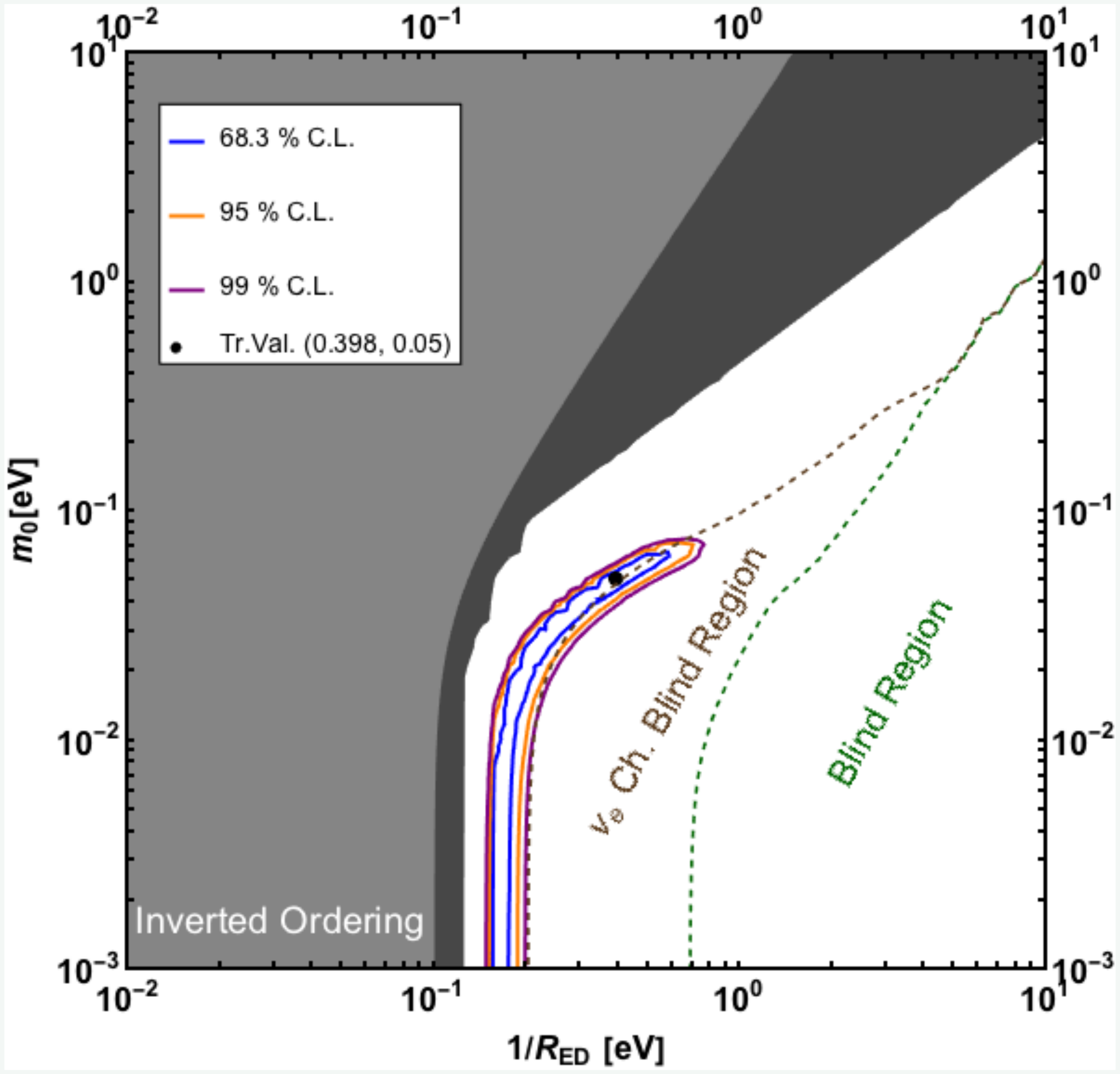
LED fit to the 3+1 scenario



Sensitivity to a non-zero LED oscillation effect on SBN

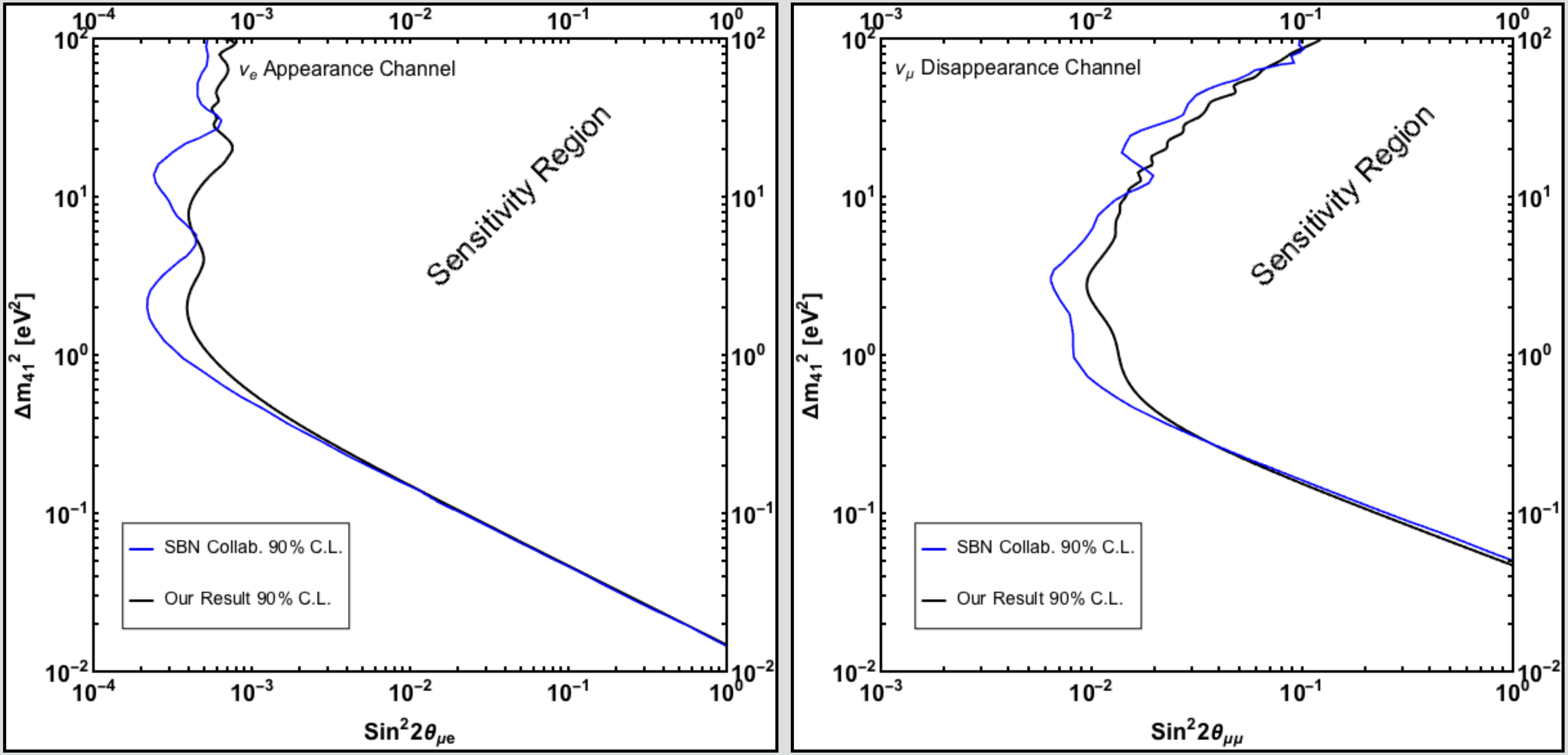


NH

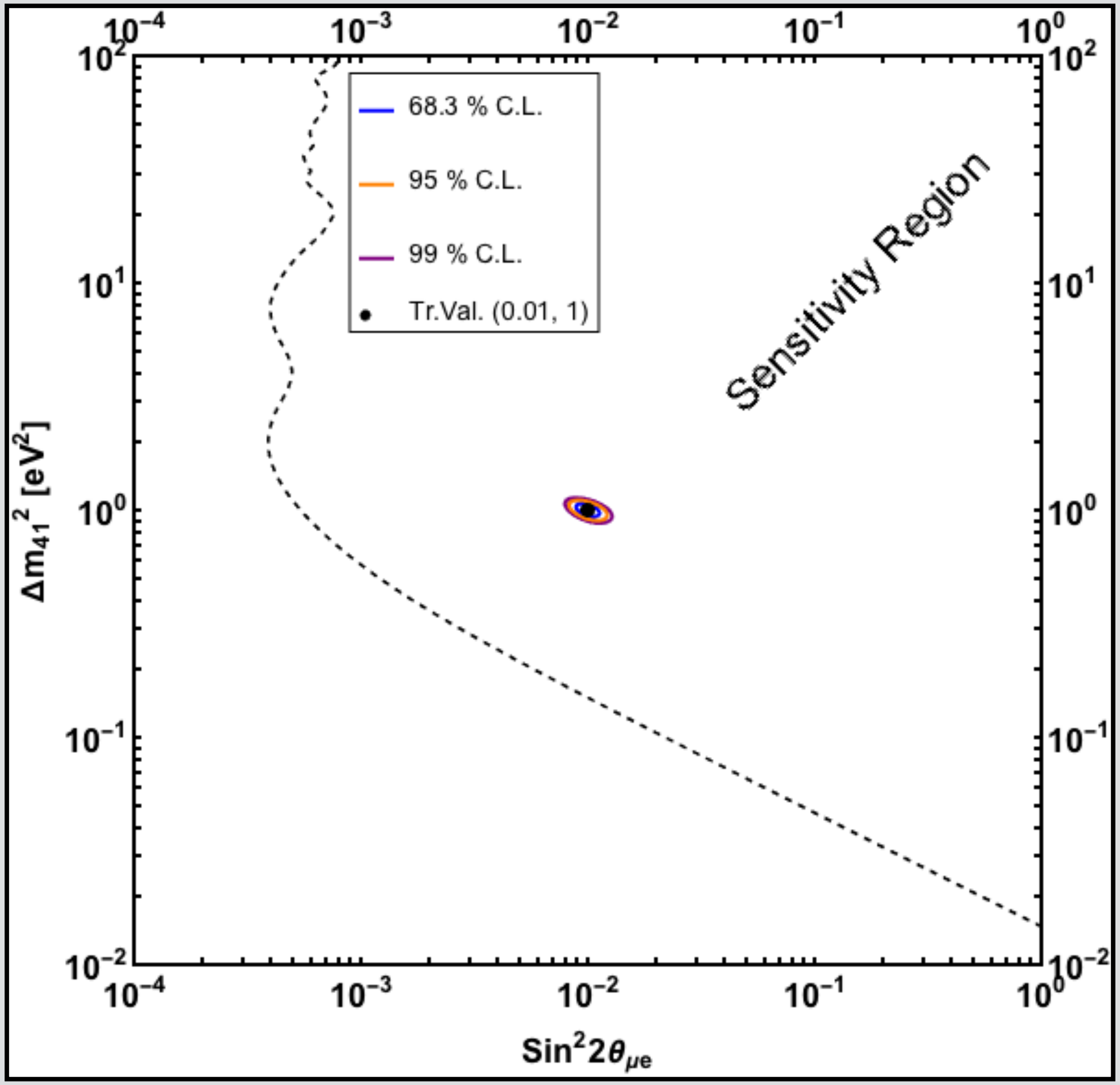


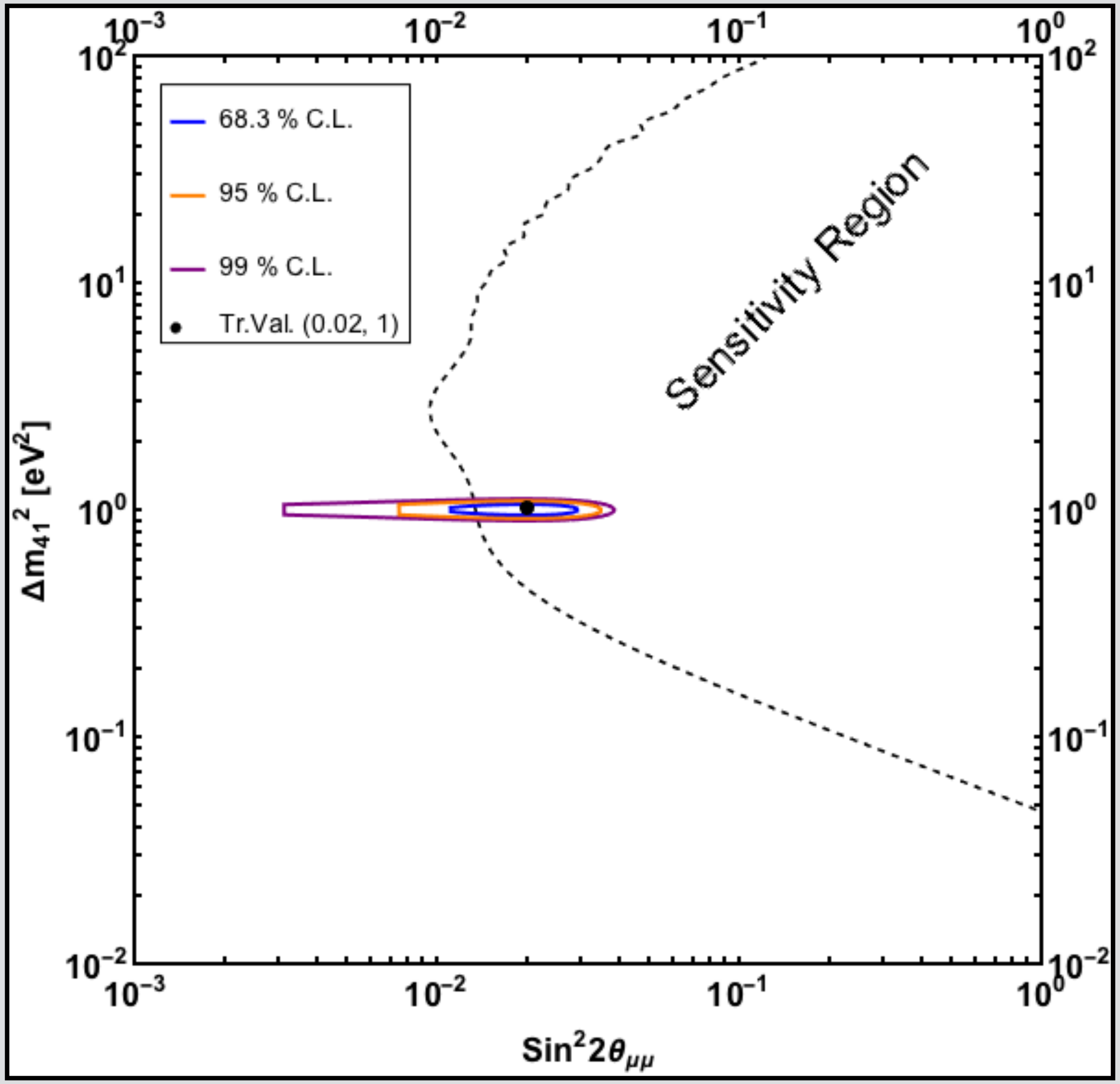
IH

3+1 scenario at SBN: sensitivity

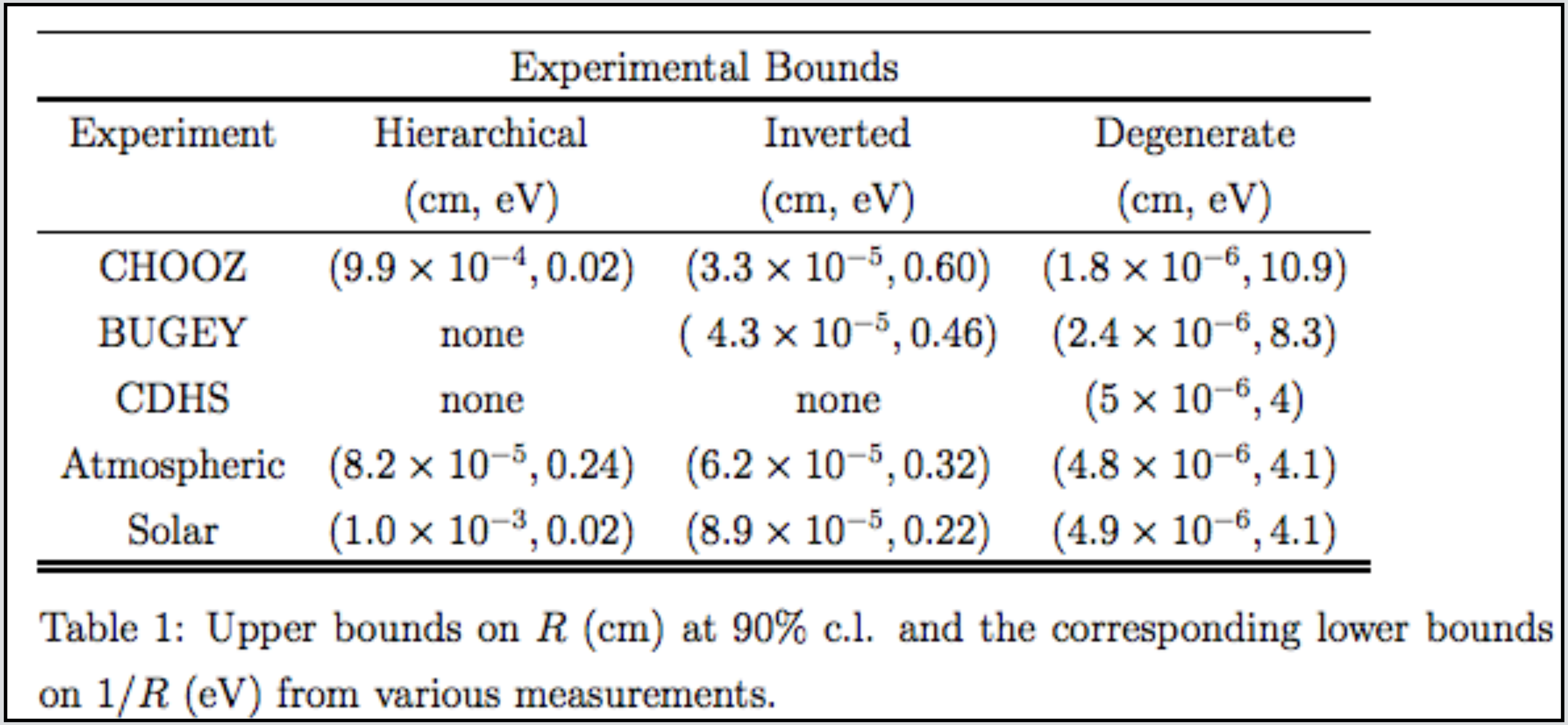


3+1 scenario at SBN: accuracy of the measurement





Other bounds on LED parameters

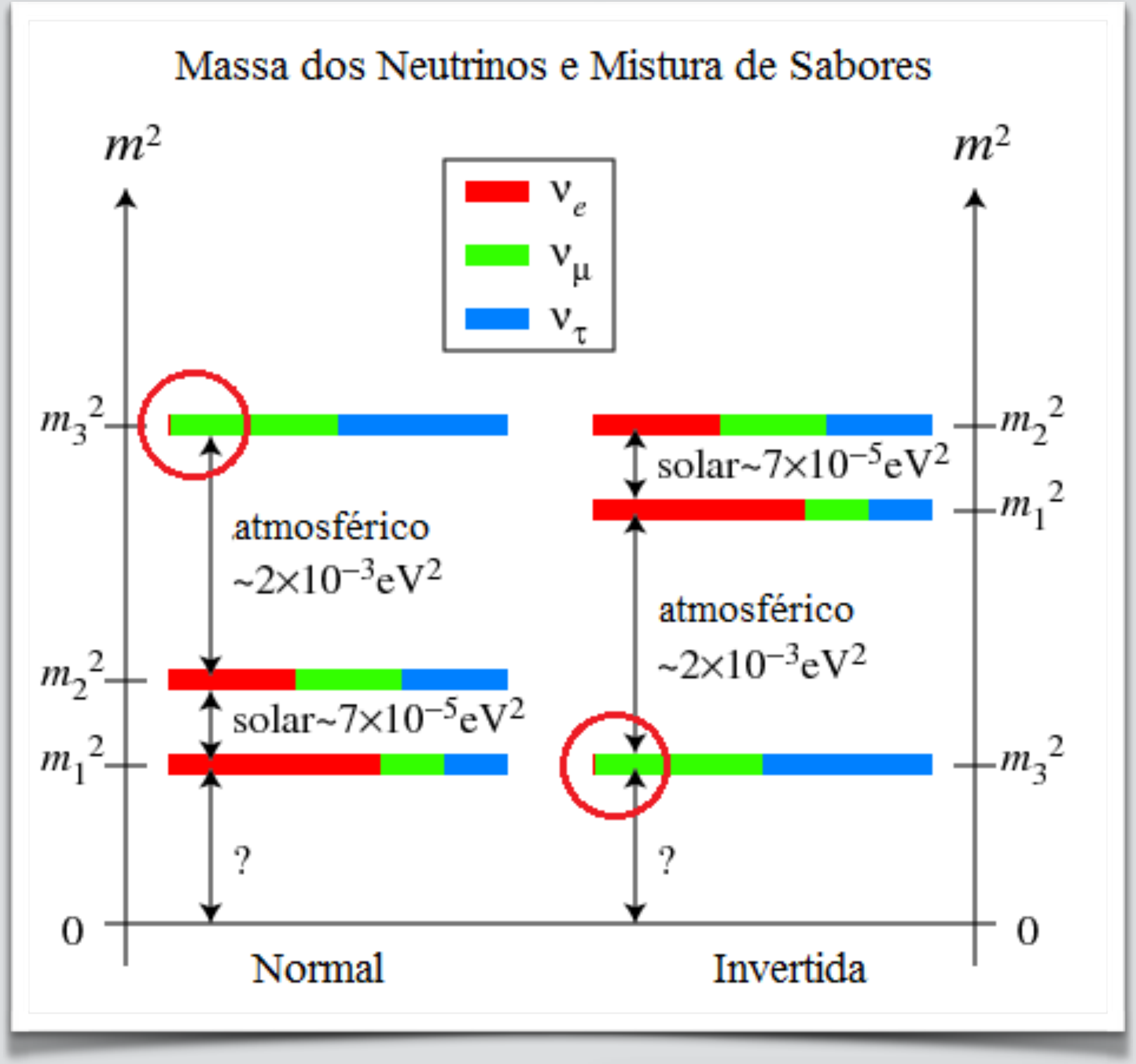


	Experimental Bounds		
Experiment	Hierarchical (cm, eV)	Inverted (cm, eV)	Degenerate (cm, eV)
CHOOZ	$(9.9 \times 10^{-4}, 0.02)$	$(3.3 \times 10^{-5}, 0.60)$	$(1.8 \times 10^{-6}, 10.9)$
BUGEY	none	$(4.3 \times 10^{-5}, 0.46)$	$(2.4 \times 10^{-6}, 8.3)$
CDHS	none	none	$(5 \times 10^{-6}, 4)$
Atmospheric	$(8.2 \times 10^{-5}, 0.24)$	$(6.2 \times 10^{-5}, 0.32)$	$(4.8 \times 10^{-6}, 4.1)$
Solar	$(1.0 \times 10^{-3}, 0.02)$	$(8.9 \times 10^{-5}, 0.22)$	$(4.9 \times 10^{-6}, 4.1)$

Table 1: Upper bounds on R (cm) at 90% c.l. and the corresponding lower bounds on $1/R$ (eV) from various measurements.

Davoudiasl, H. et al. Phys.Rev. D65 (2002)

Neutrino Oscillation



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

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

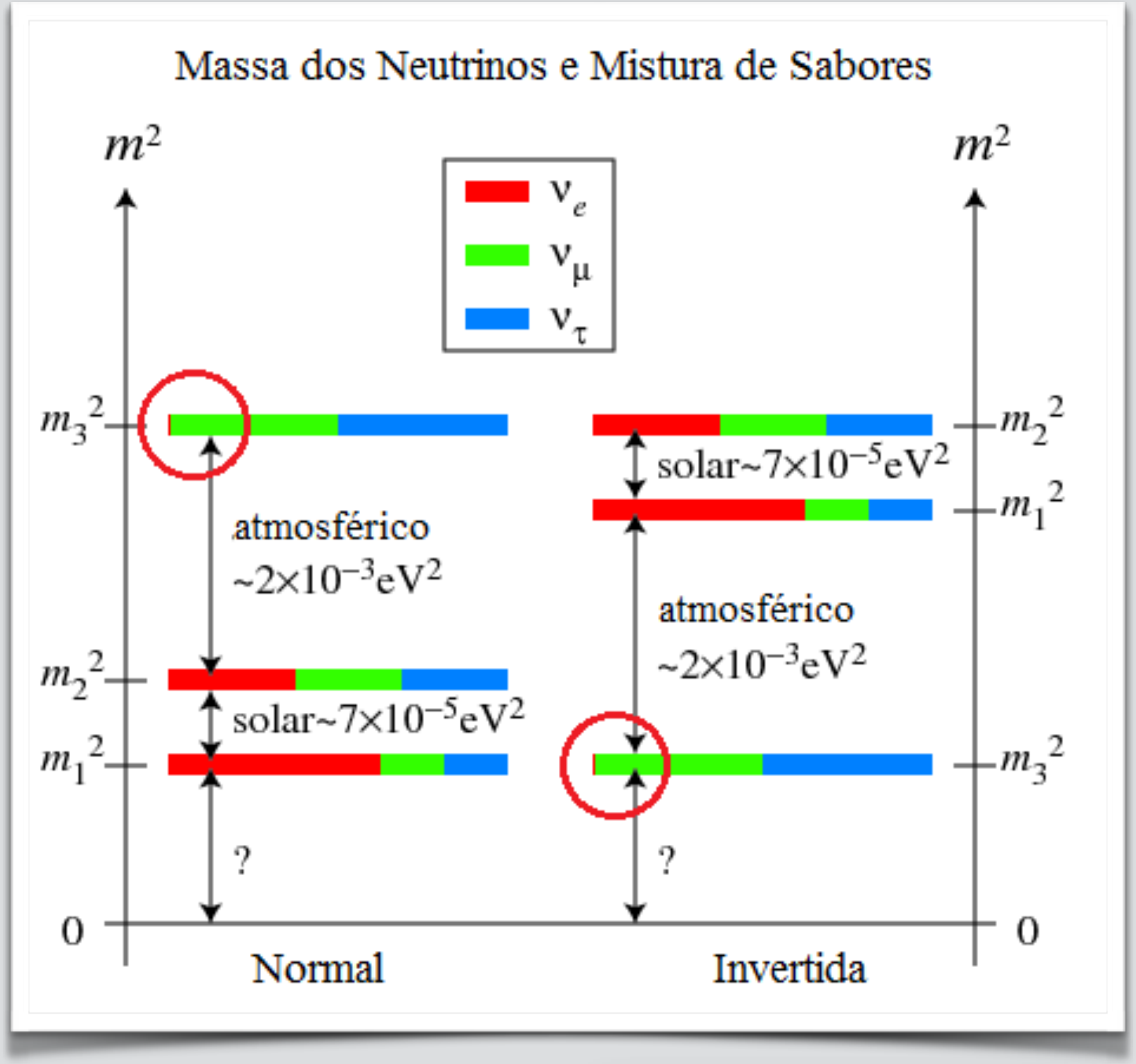
$(\alpha = e, \mu, \tau \quad \text{and} \quad \mathrm{i} = 1, 2, 3)$

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

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

Neutrino Oscillation

ν_e



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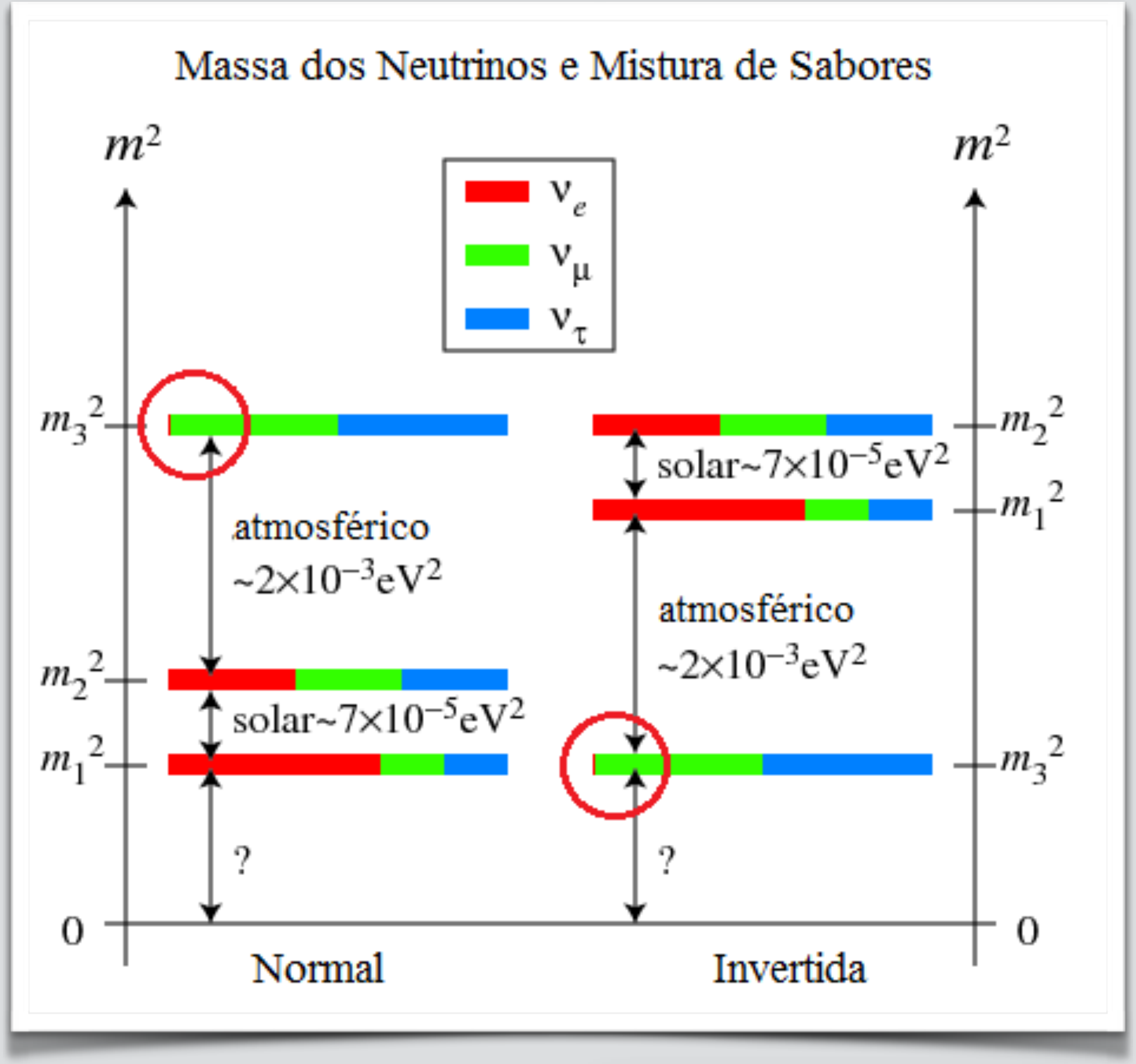
Neutrino Oscillation

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



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

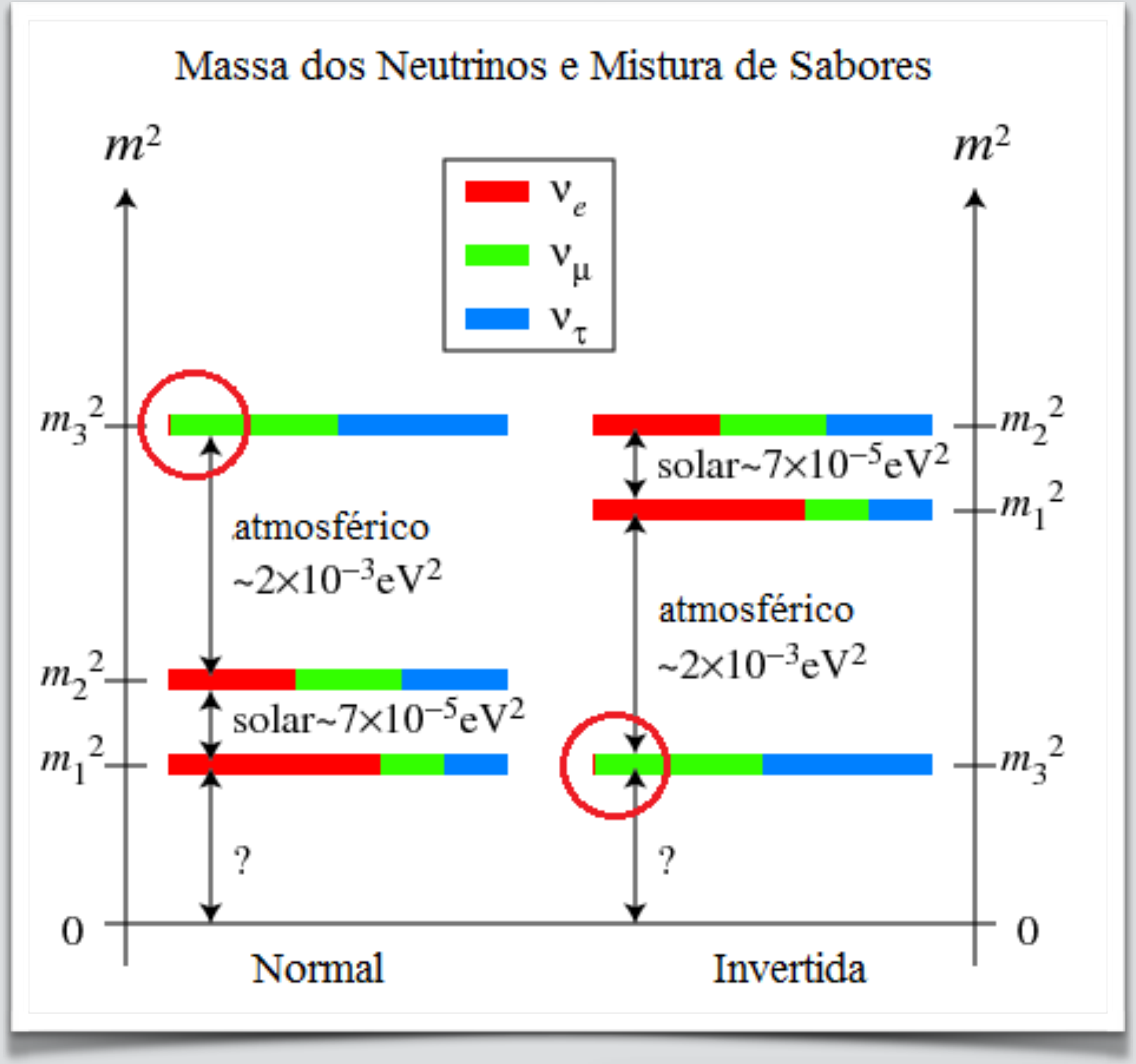
$$|\nu_\alpha\rangle = \sum_i U_i^* |\nu_i\rangle \quad (\alpha = e, \mu, \tau \quad \text{and} \quad \text{i} = 1, 2, 3)$$

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

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

Neutrino Oscillation

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



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Neutrino Oscillation

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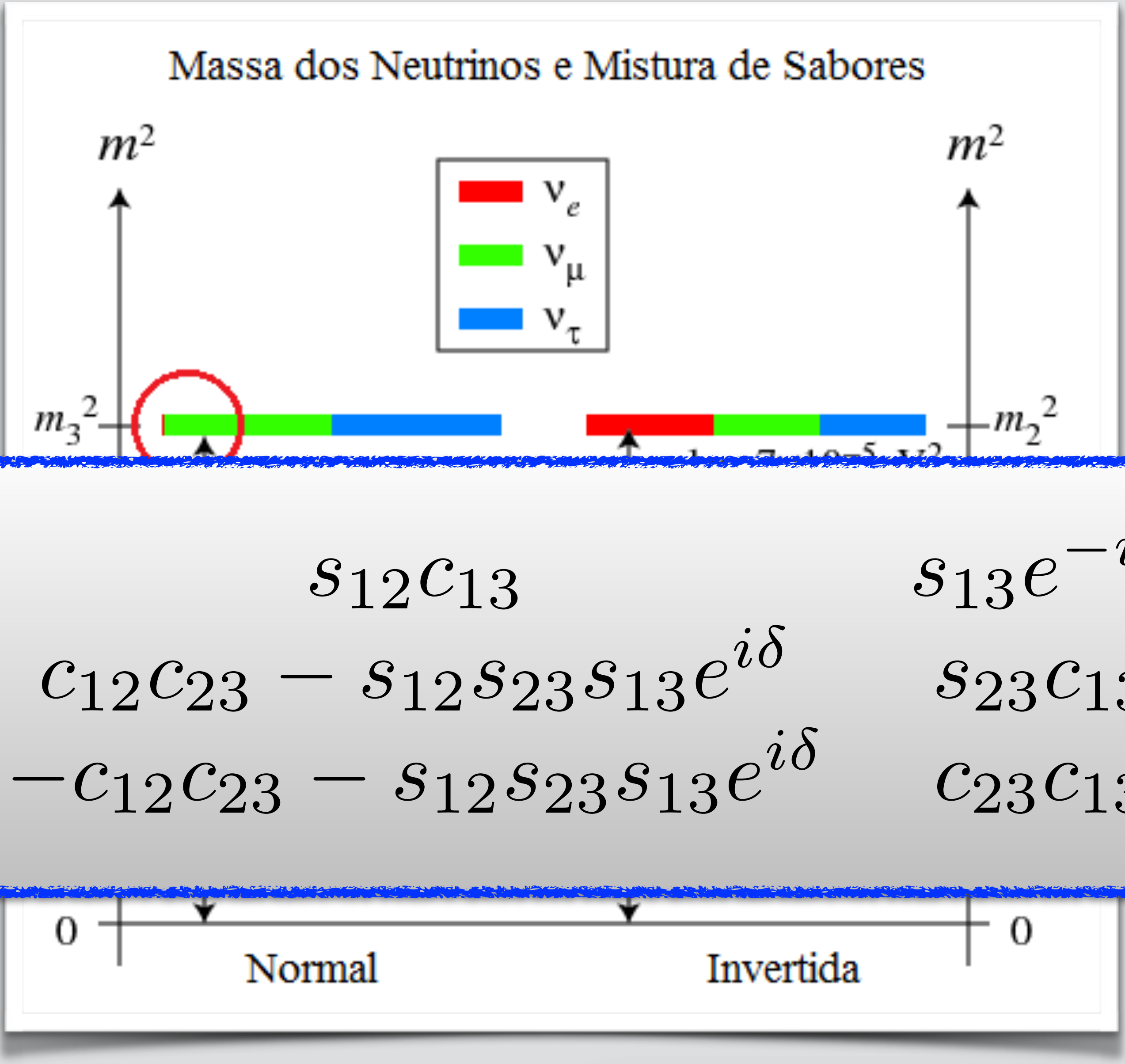


$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

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

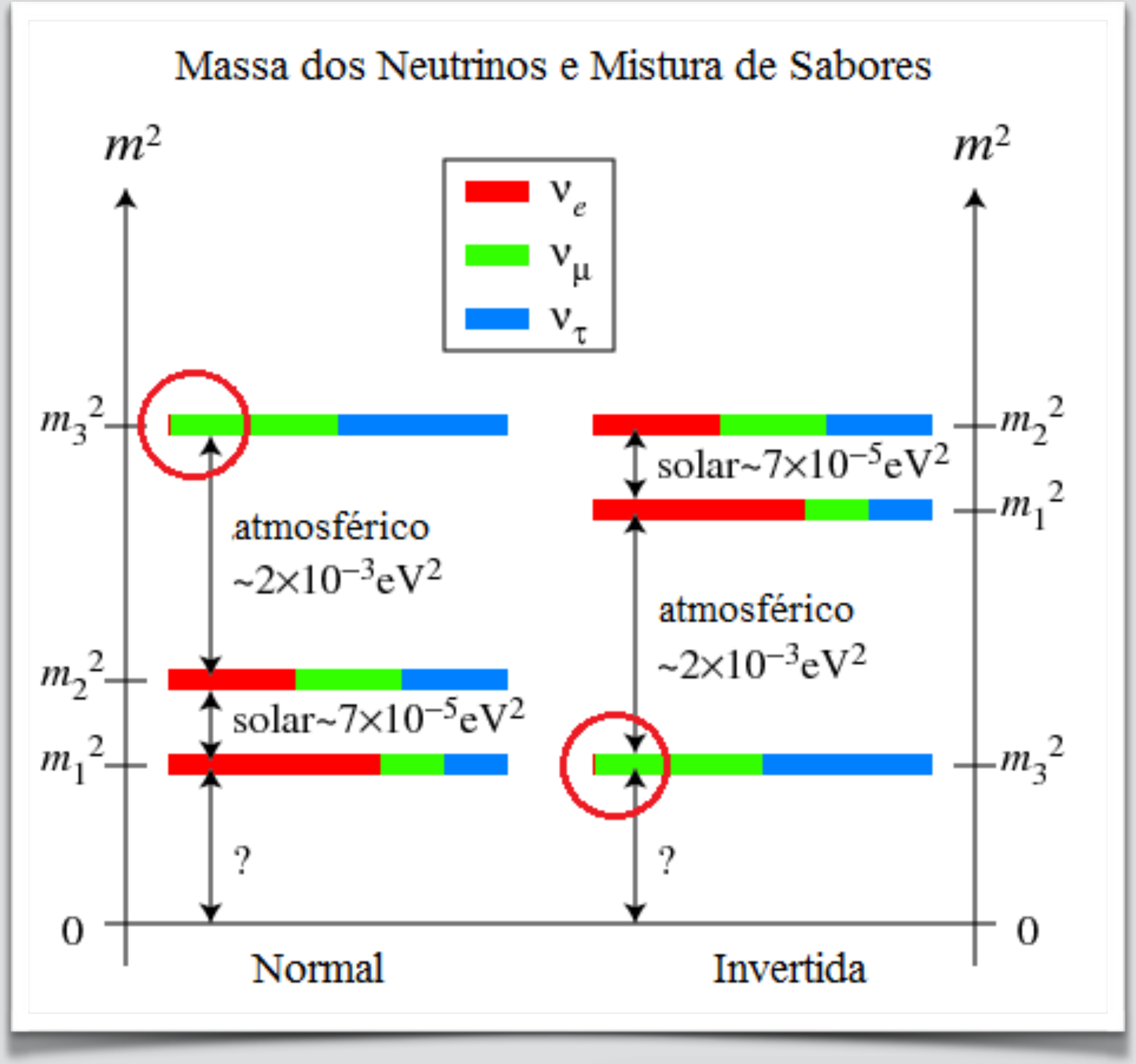
$(\alpha = e, \mu, \tau \quad \text{and} \quad \text{i} = 1, 2, 3)$

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

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

Neutrino Oscillation

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



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Neutrino Oscillation

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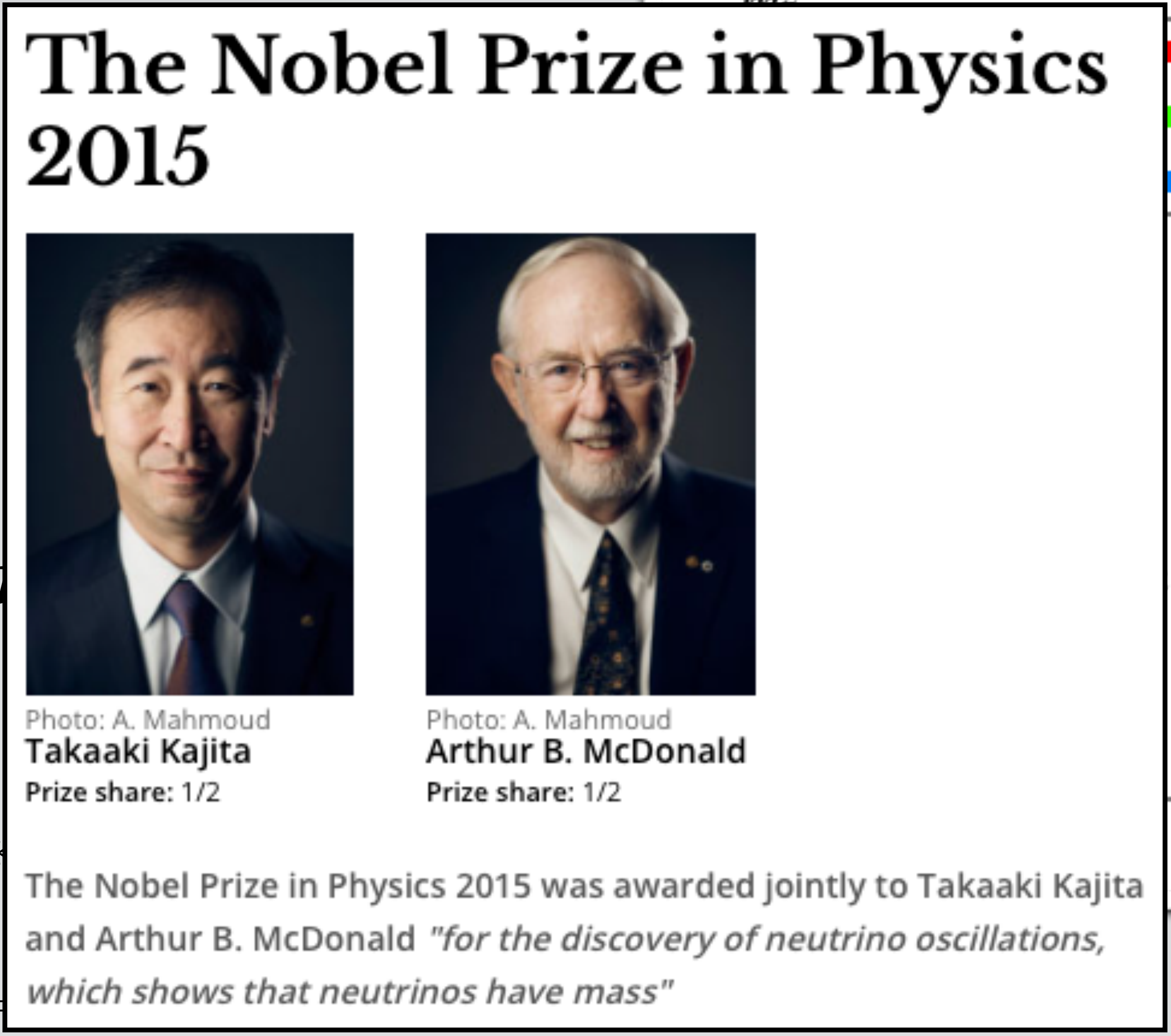
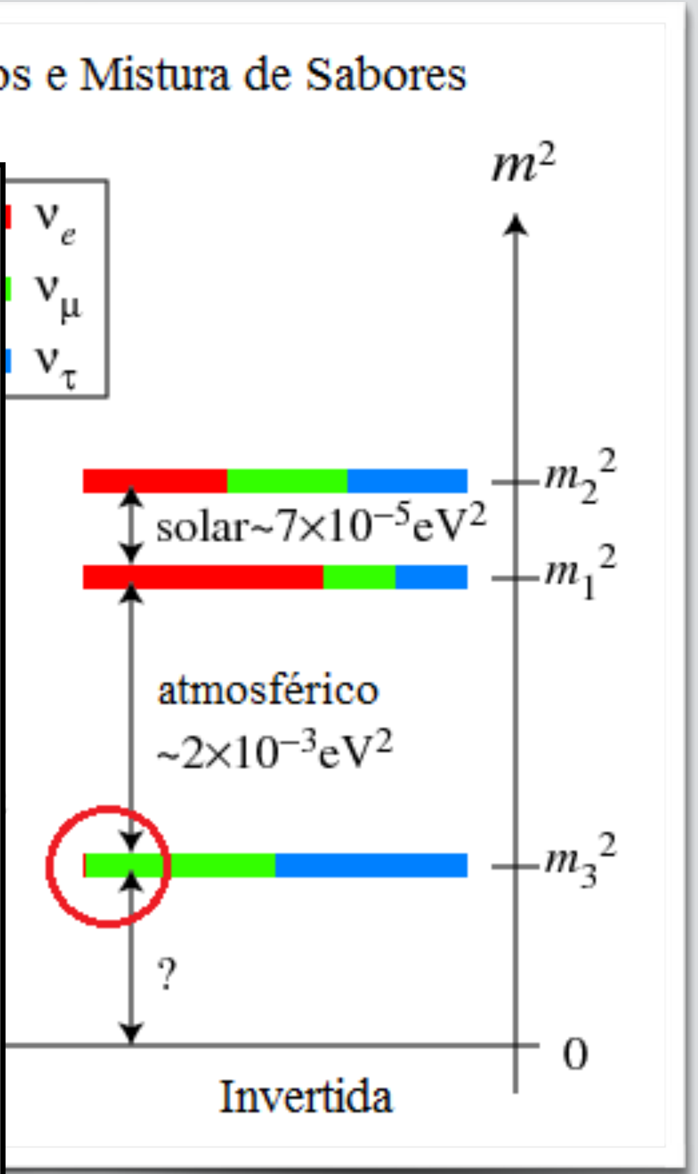


The Nobel Prize in Physics 2015

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"*



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

$$|\nu_\alpha\rangle = \sum_{i} U_i^*$$

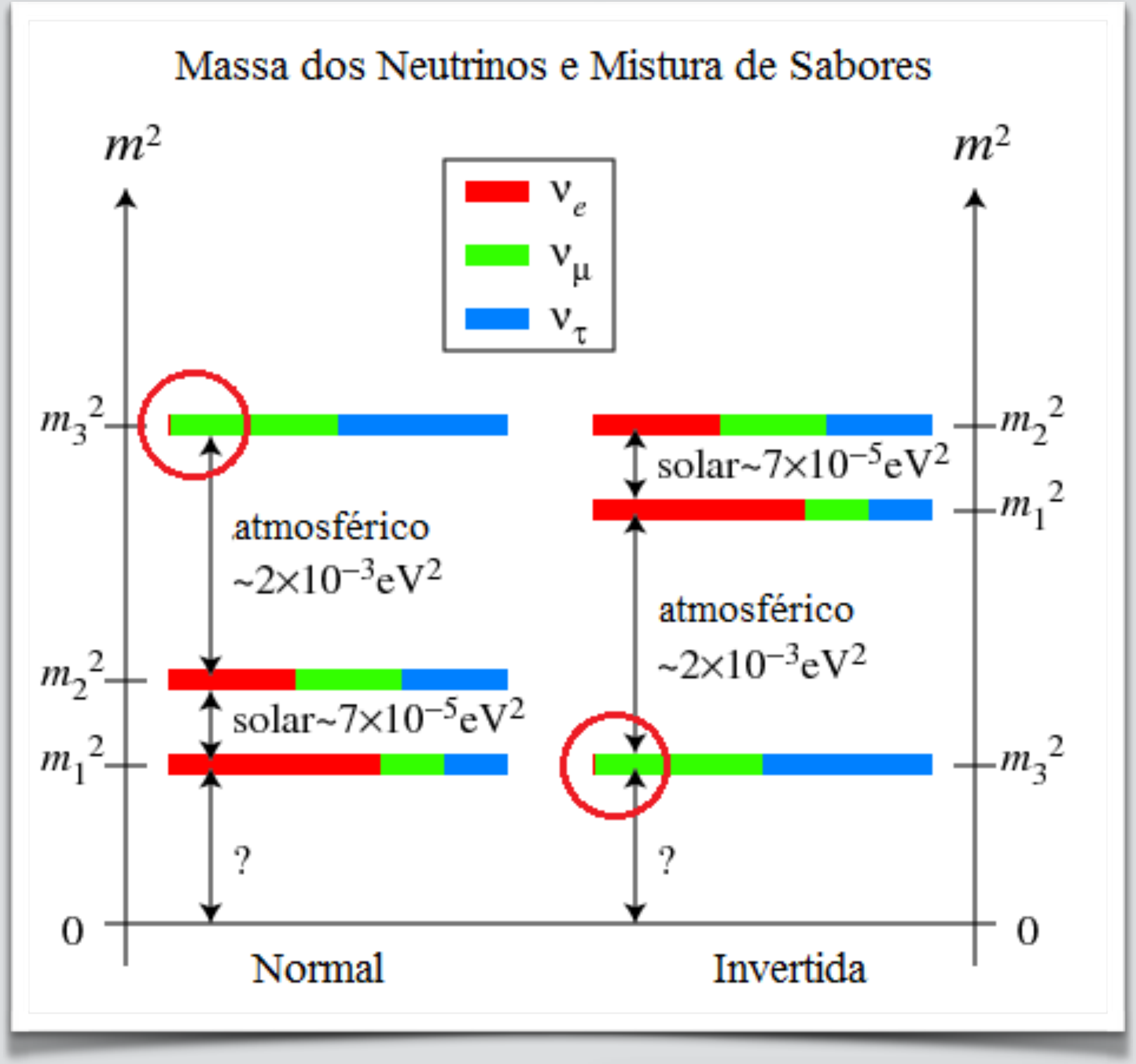
$(\alpha =$

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

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

Neutrino Oscillation

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



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

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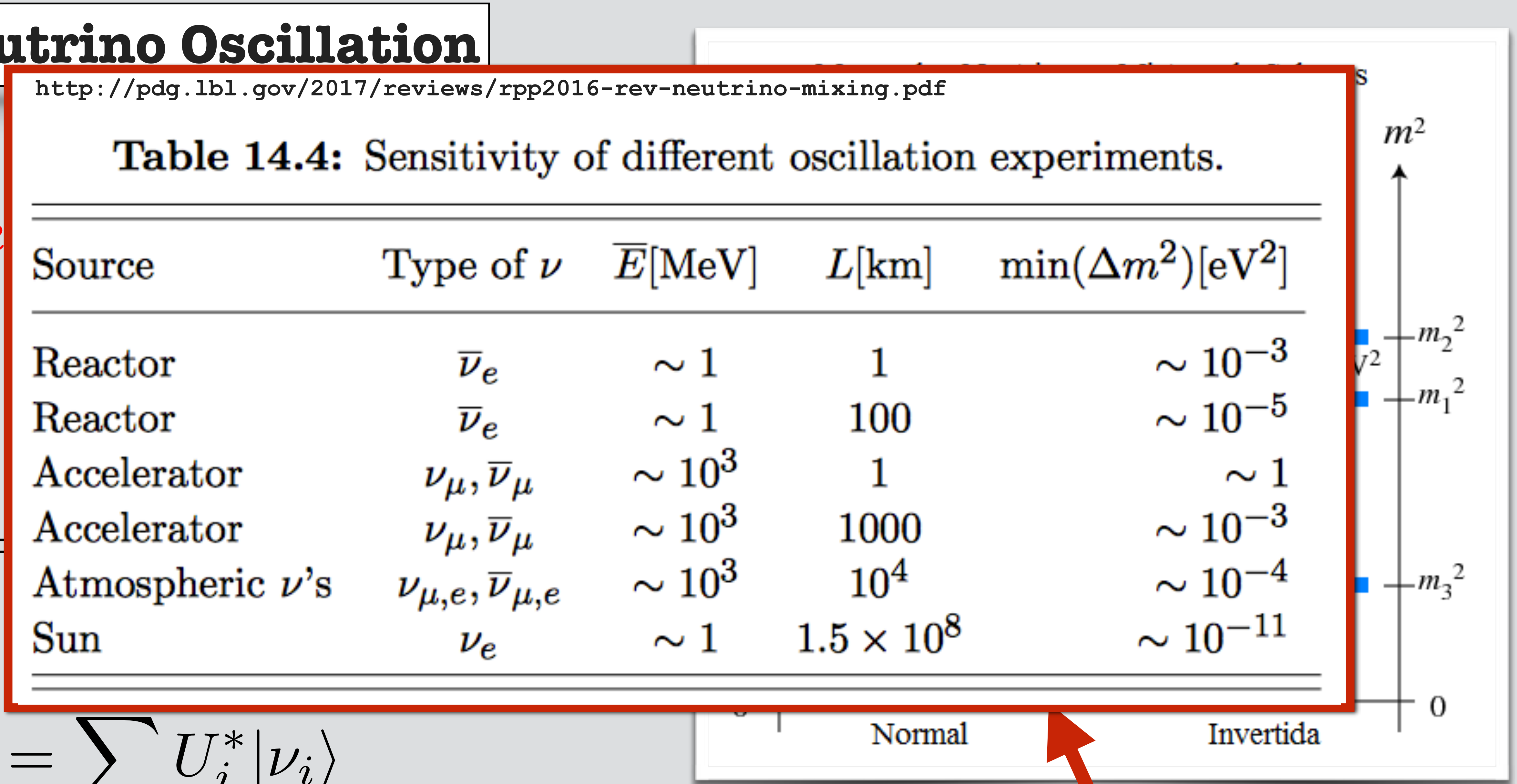
$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \exp\left(i \frac{m_j^2 - m_i^2}{2E} x\right)$$

Neutrino Oscillation

ν_e



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(Δm^2)[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	$\sim 10^{-11}$

$|\nu_i\rangle =$

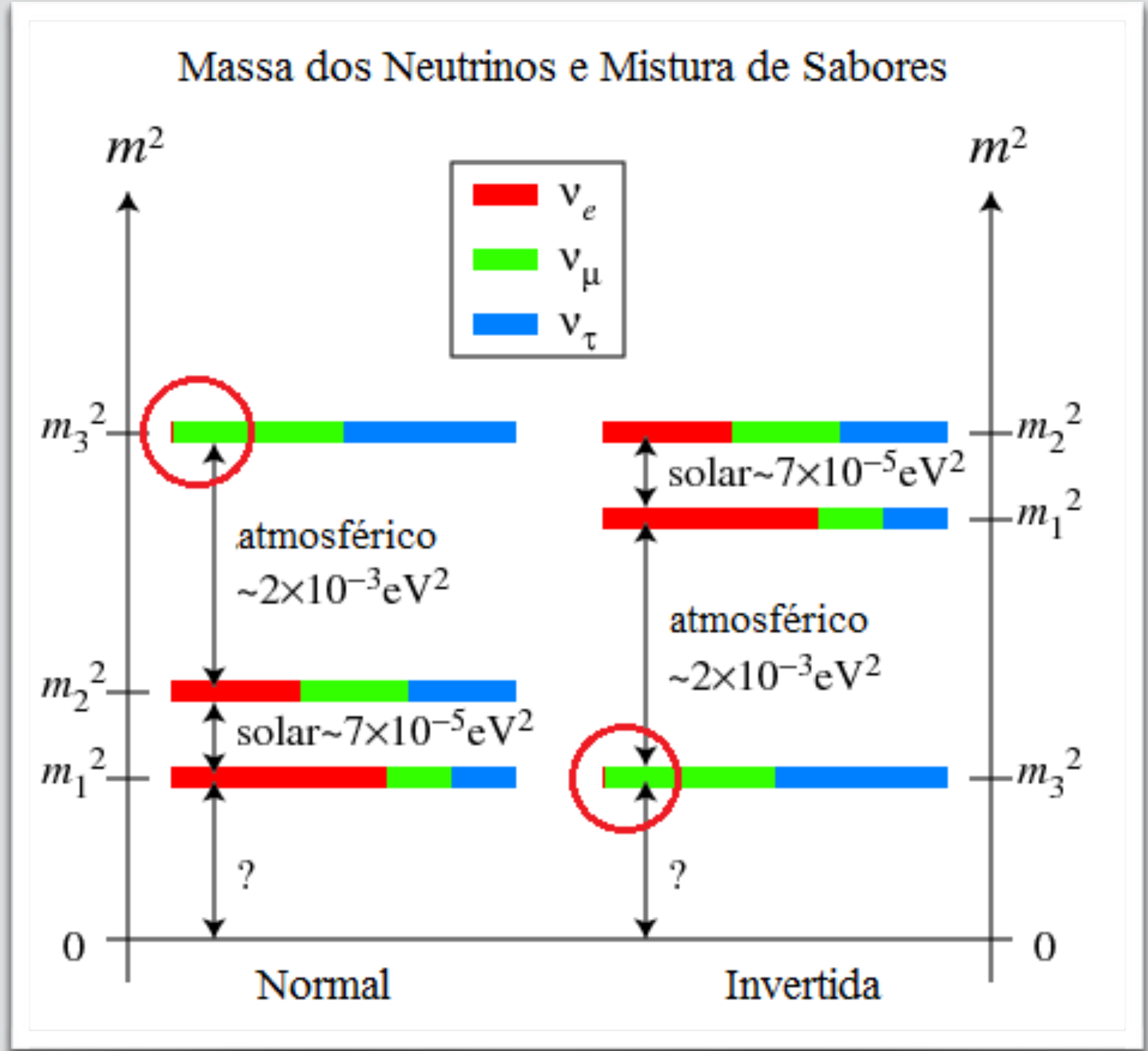
$$|\nu_\alpha\rangle = \sum_i U_i^* |\nu_i\rangle \quad (\alpha = e, \mu, \tau \ \text{ and } \ \mathrm{i} = 1, 2, 3)$$

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

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

Neutrino Oscillation

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



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

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

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

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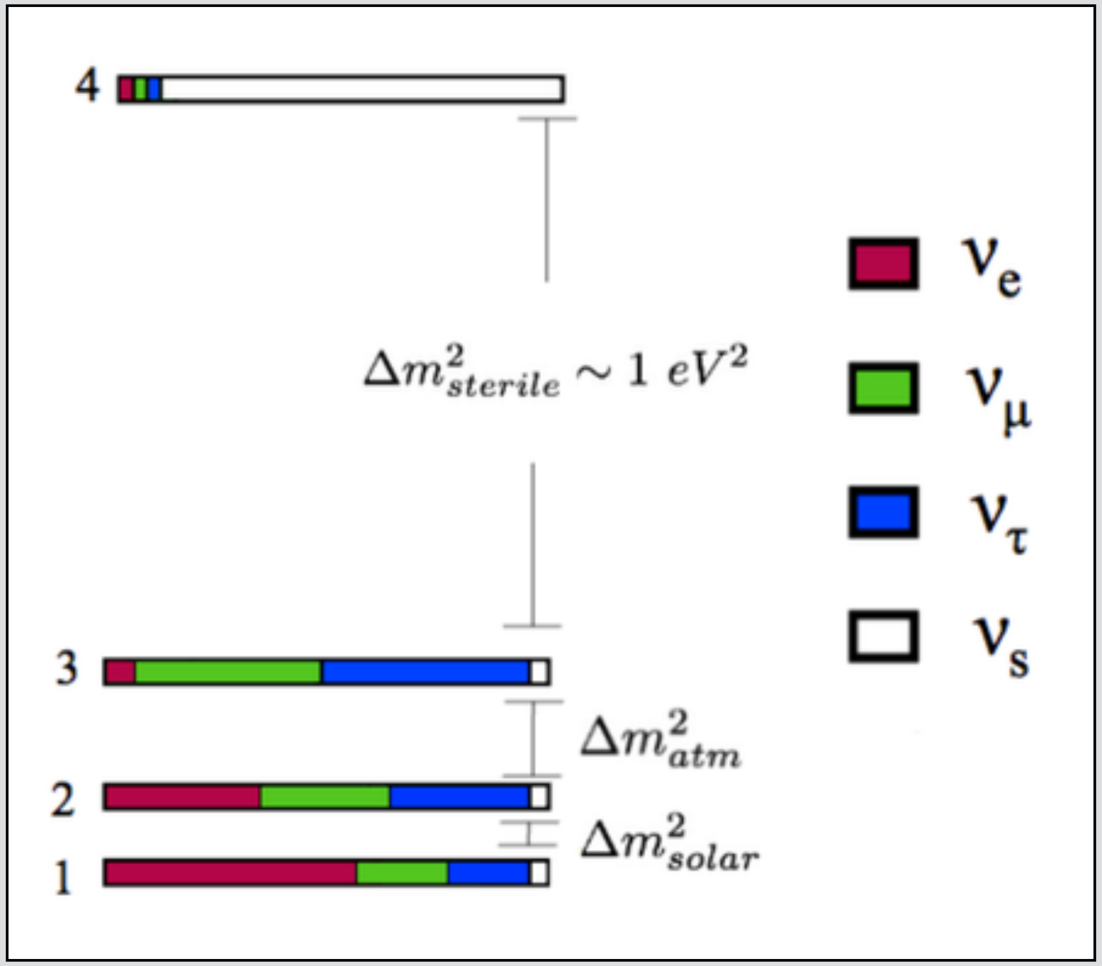
3+1 model



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

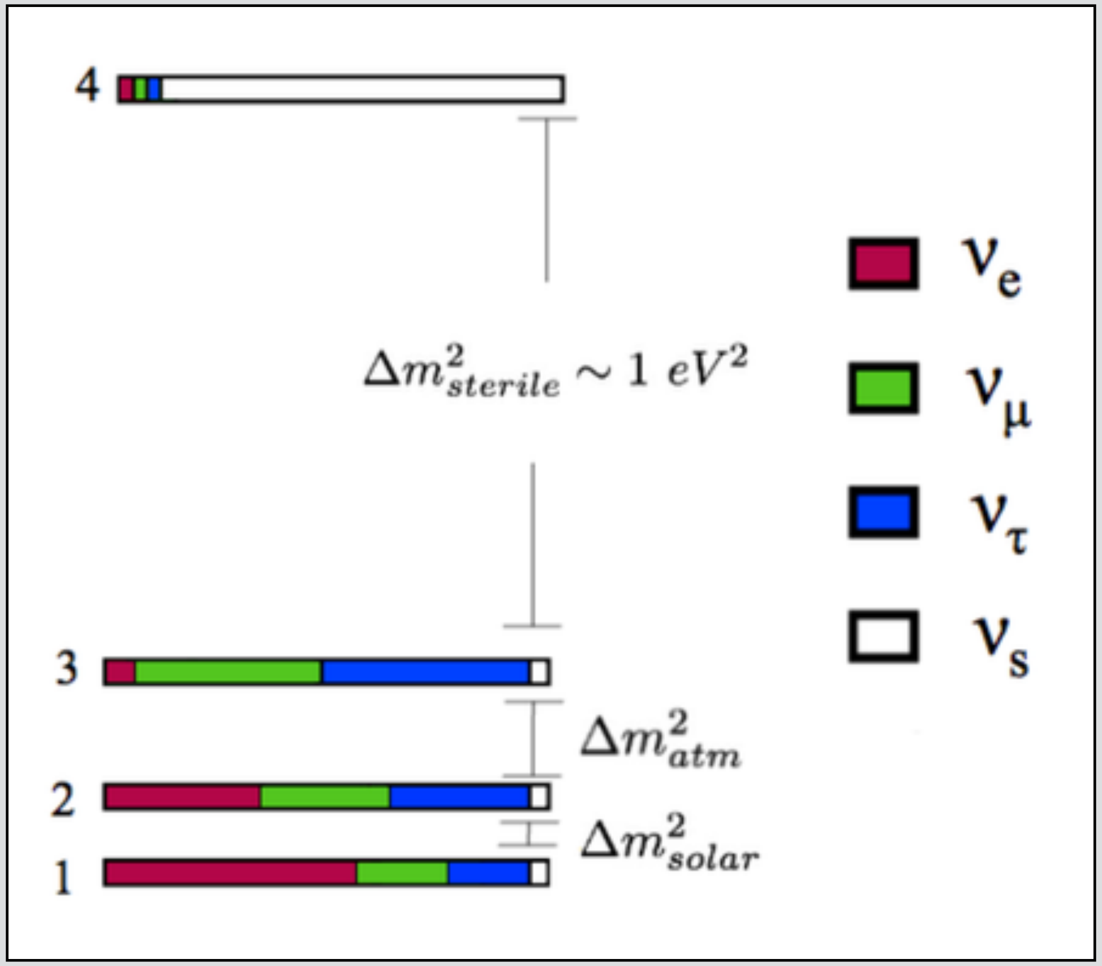
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu}) \sin^2(1.27 \Delta m^2_{41} L/E)$$

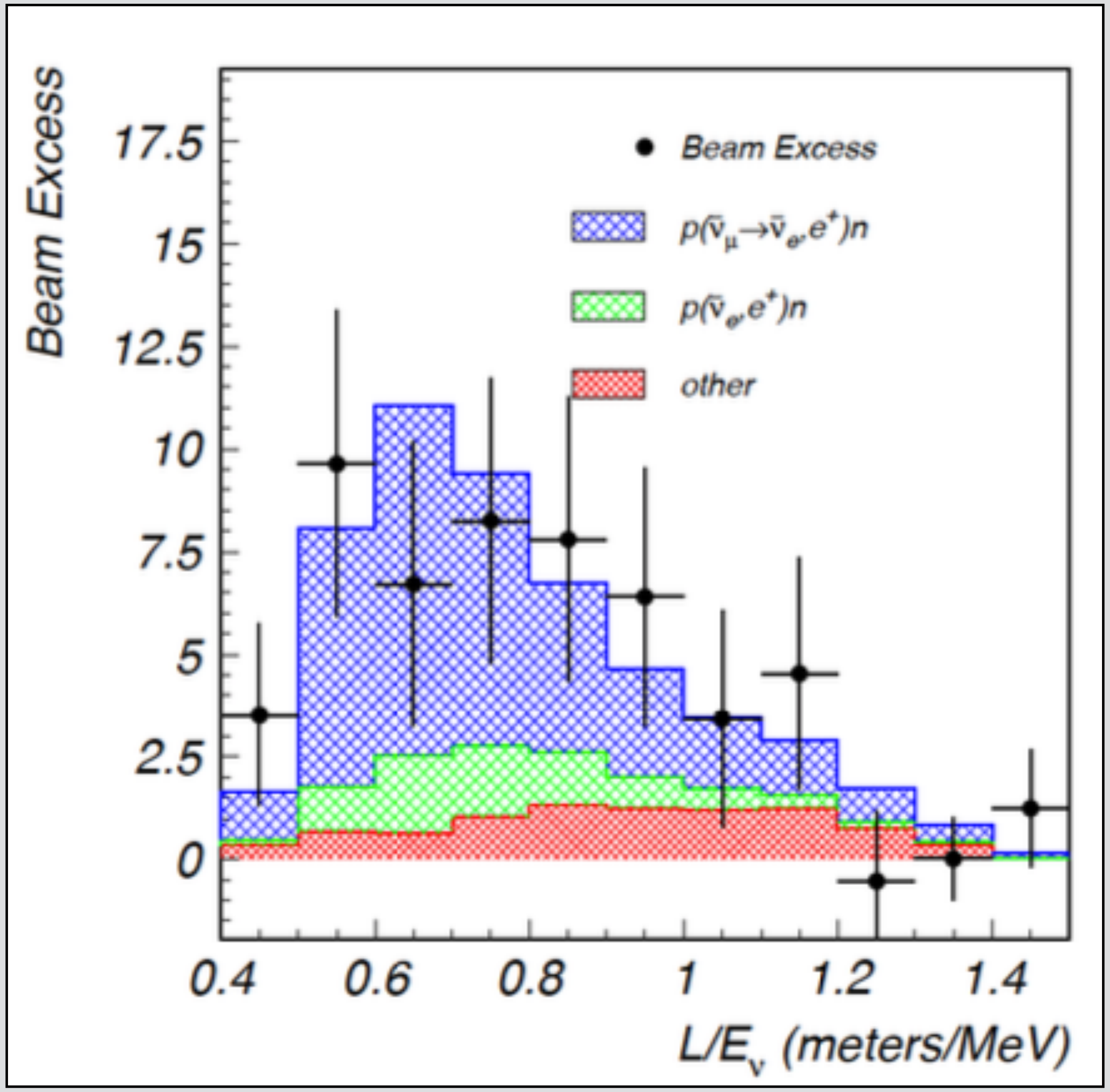
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e}) \sin^2(1.27 \Delta m^2_{41} L/E)$$

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

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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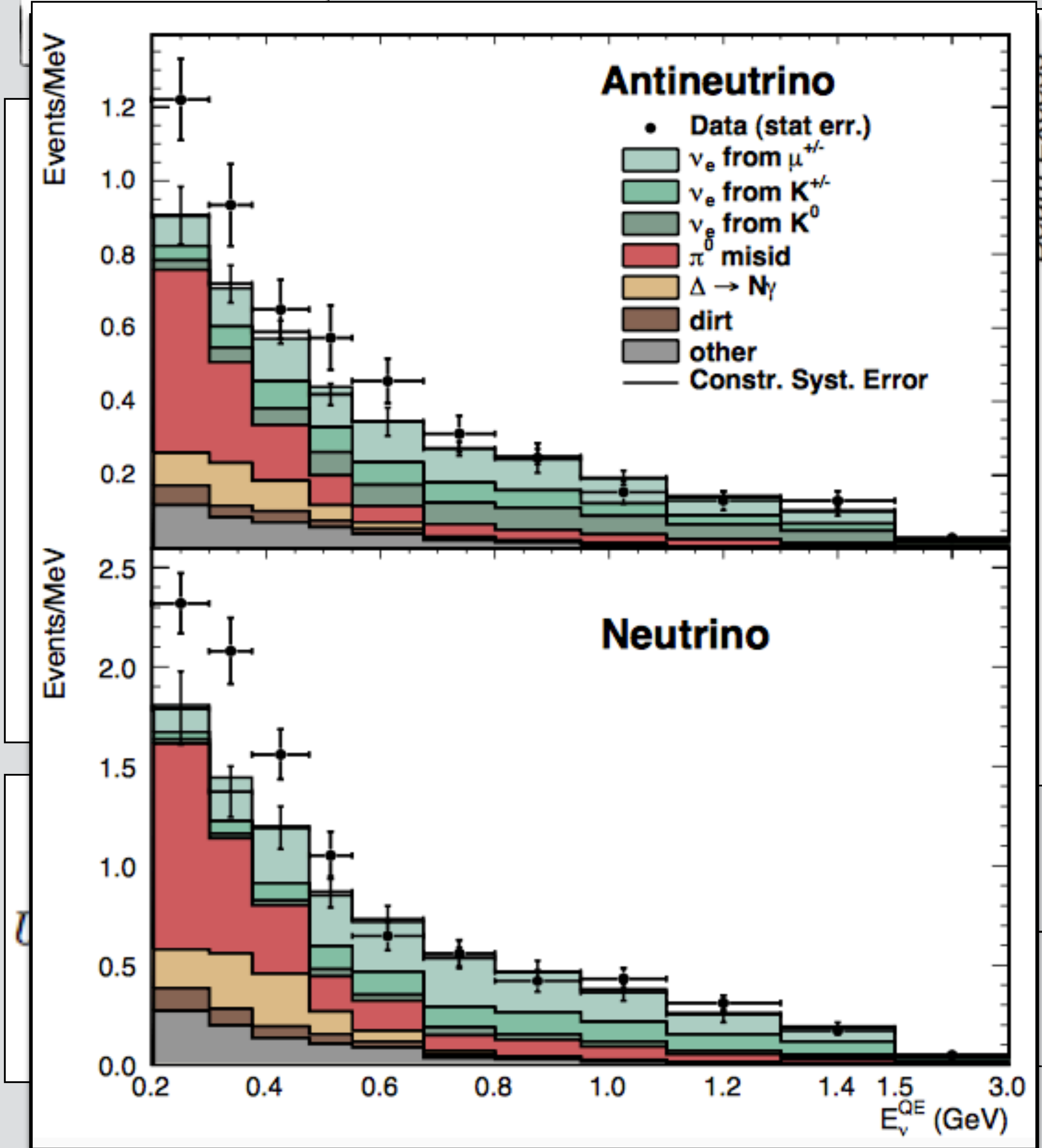
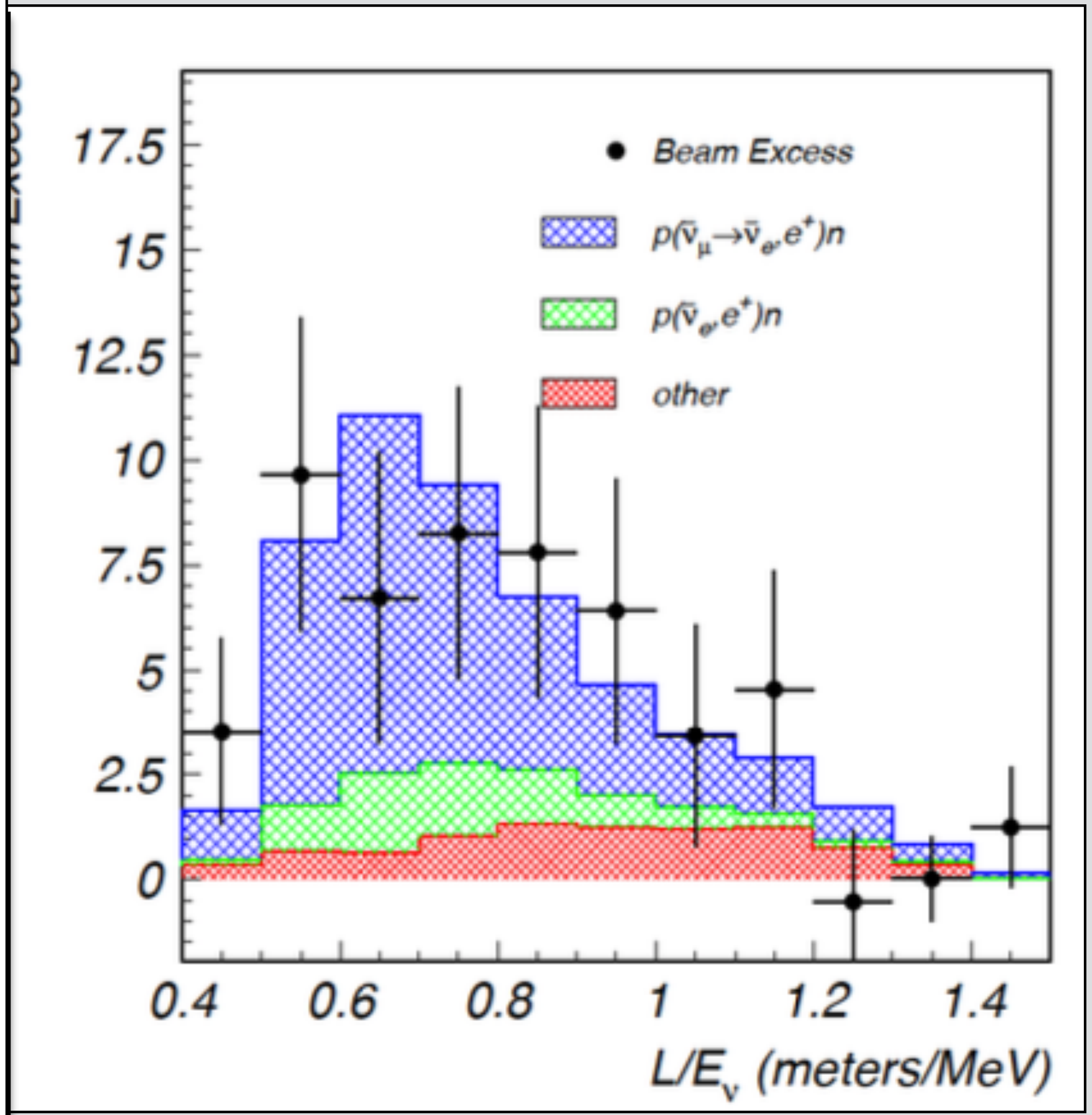


A. Aguilar-Arevalo et al., Phys. Rev. Lett. 110, 161801 (2013).

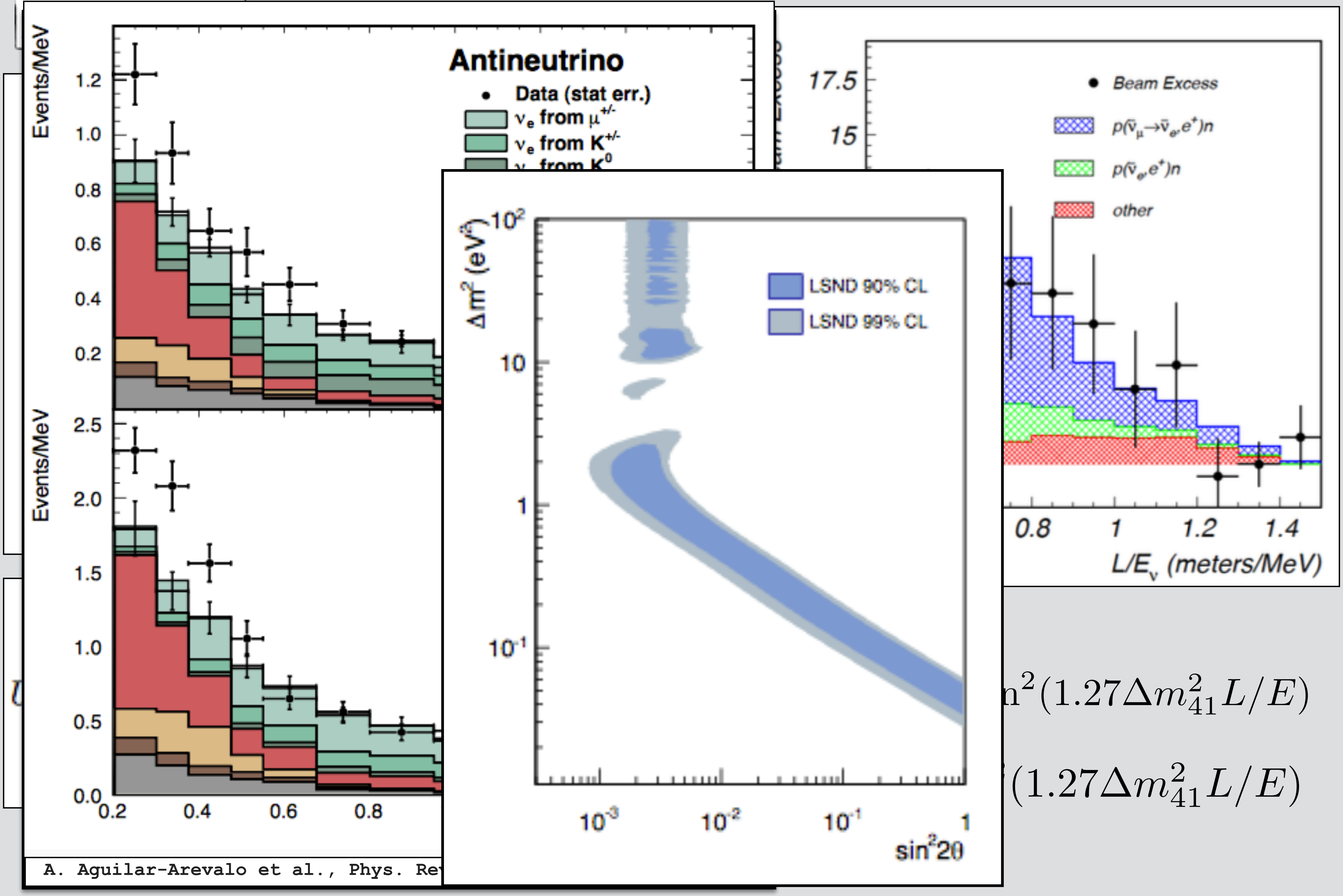


$$- \sin^2(2\theta_{\mu\mu}) \sin^2(1.27\Delta m^2_{41} L/E)$$

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

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

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



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

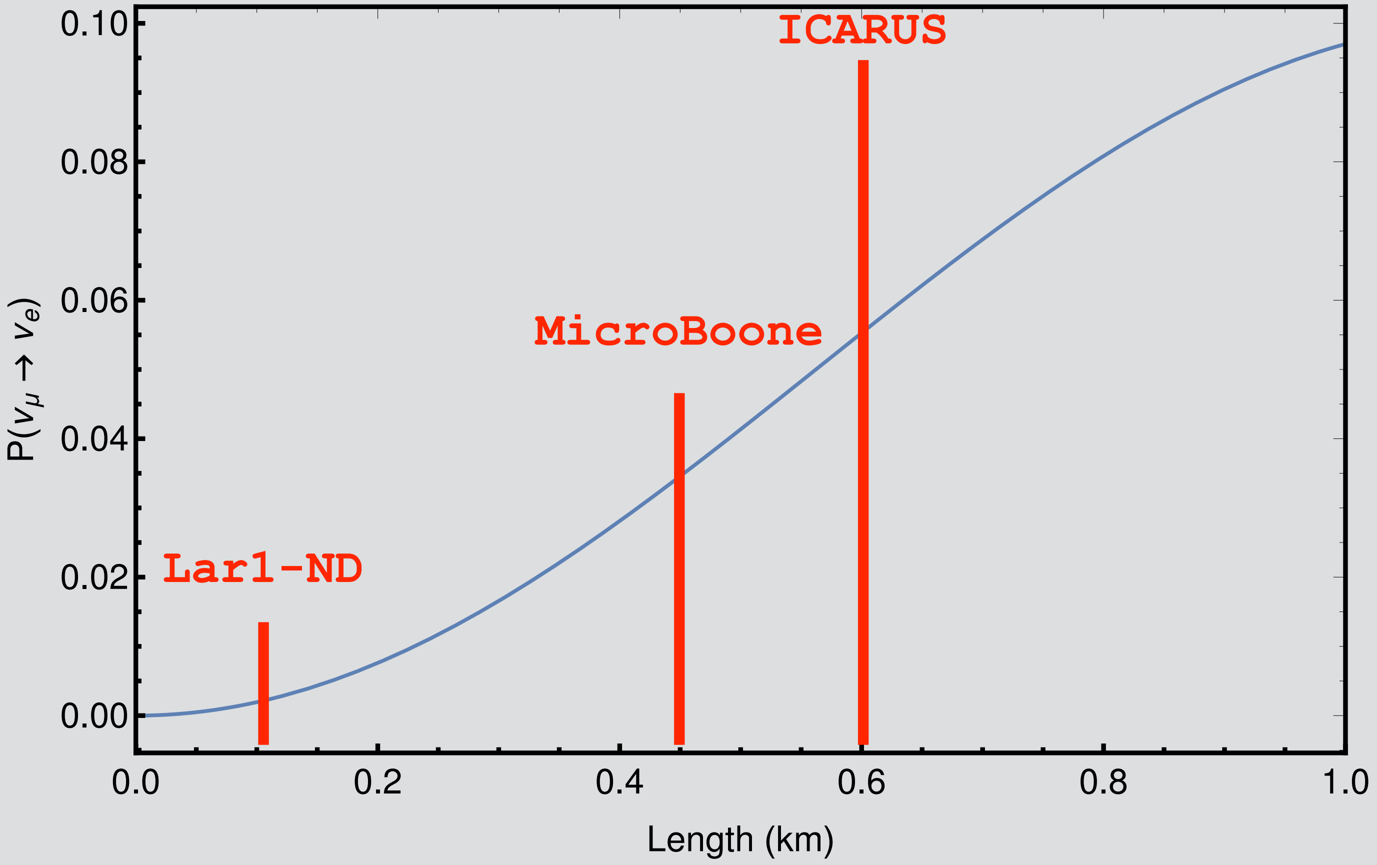
$$(1.27\Delta m^2_{41} L/E)$$

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

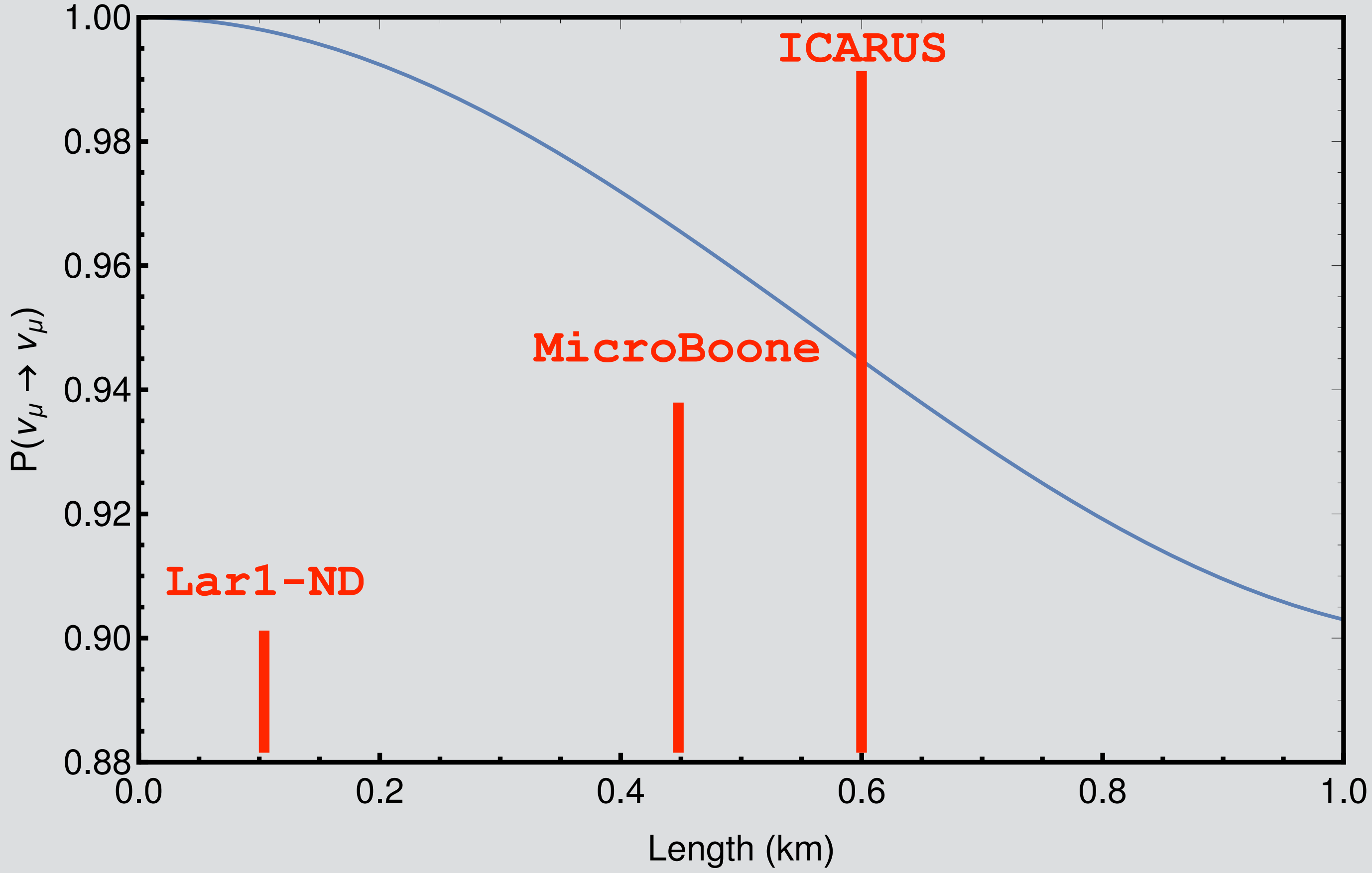
G. Cheng et al., Phys. Rev. D 86, 052009 (2012) [arXiv:1208.0322]

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

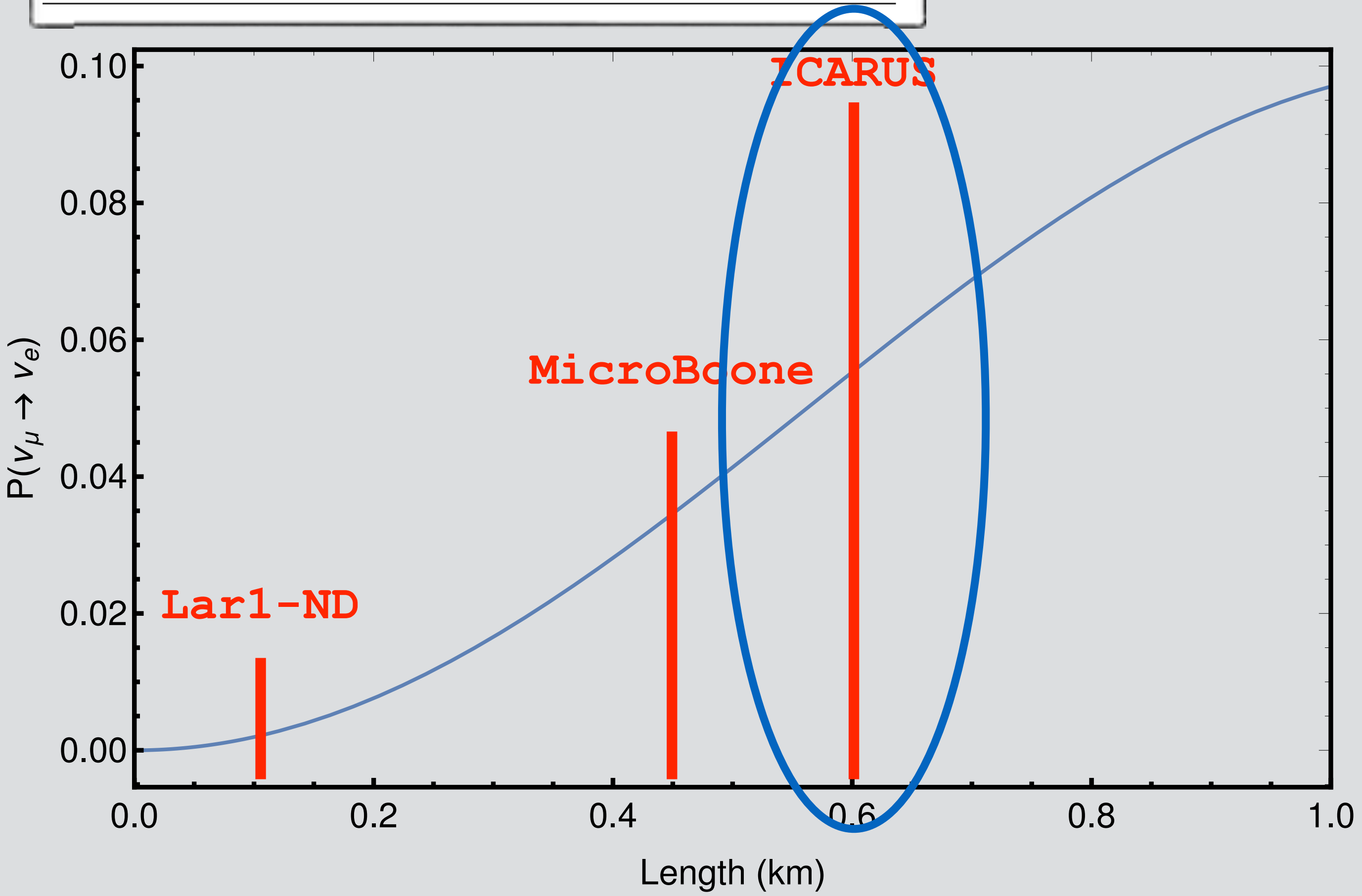
3+1 model at the SBN



$$\sin^2(2\theta_{\mu\mu}) = 0.1$$
$$\sin^2(2\theta_{\mu e}) = 0.1$$
$$\Delta m^2_{41} = 1.1 \text{ eV}^2$$



3+1 model at the SBN



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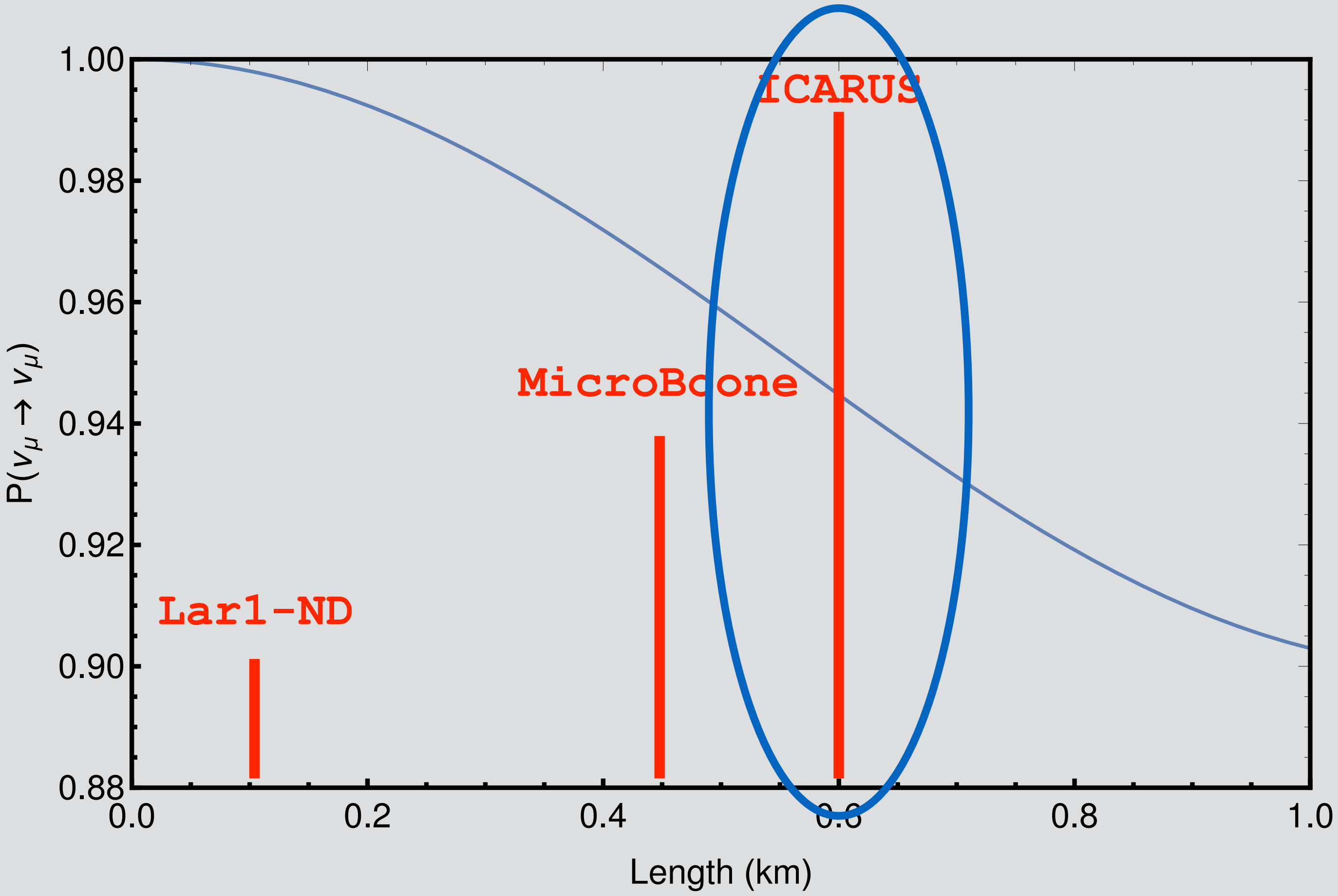
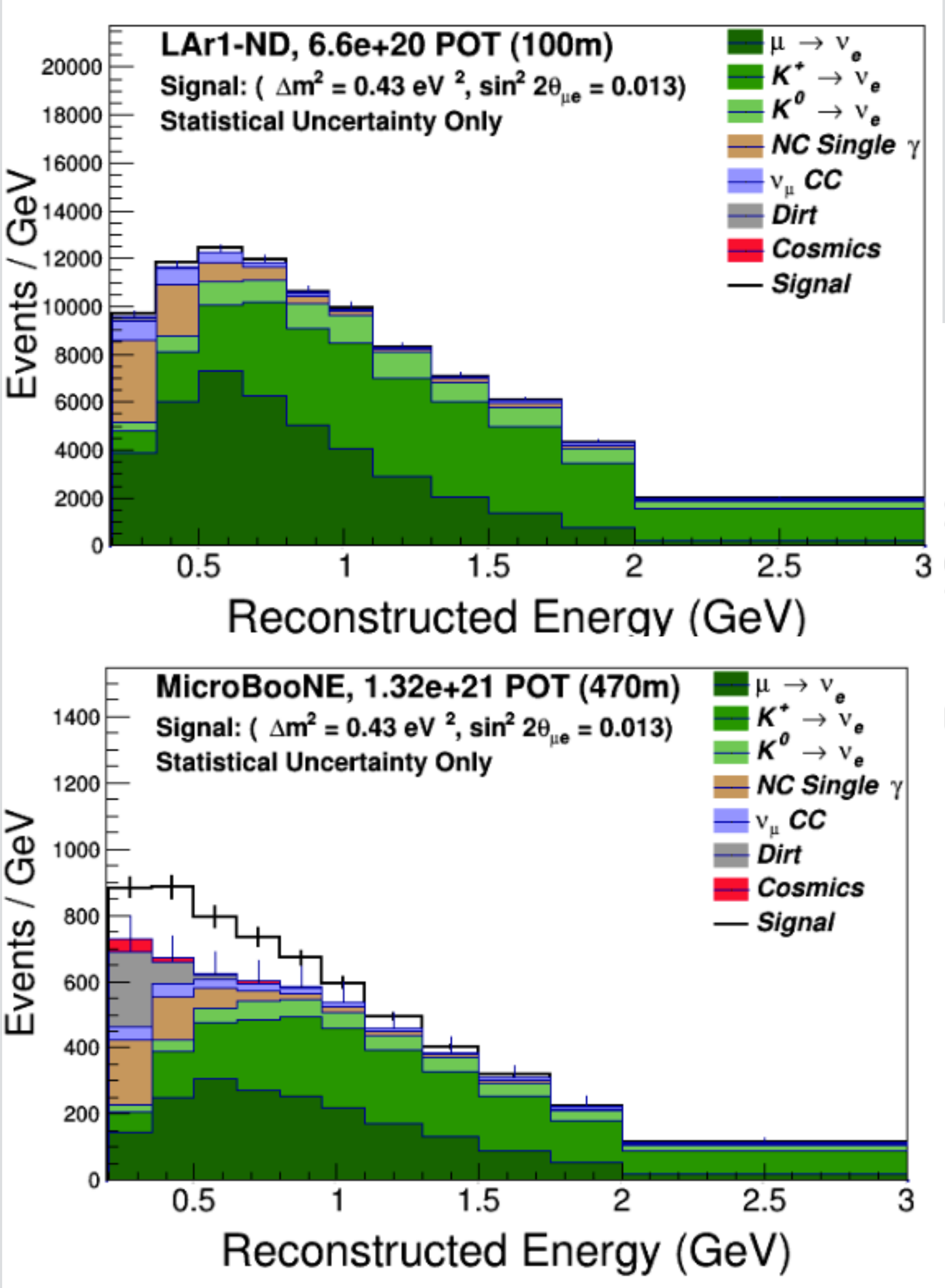
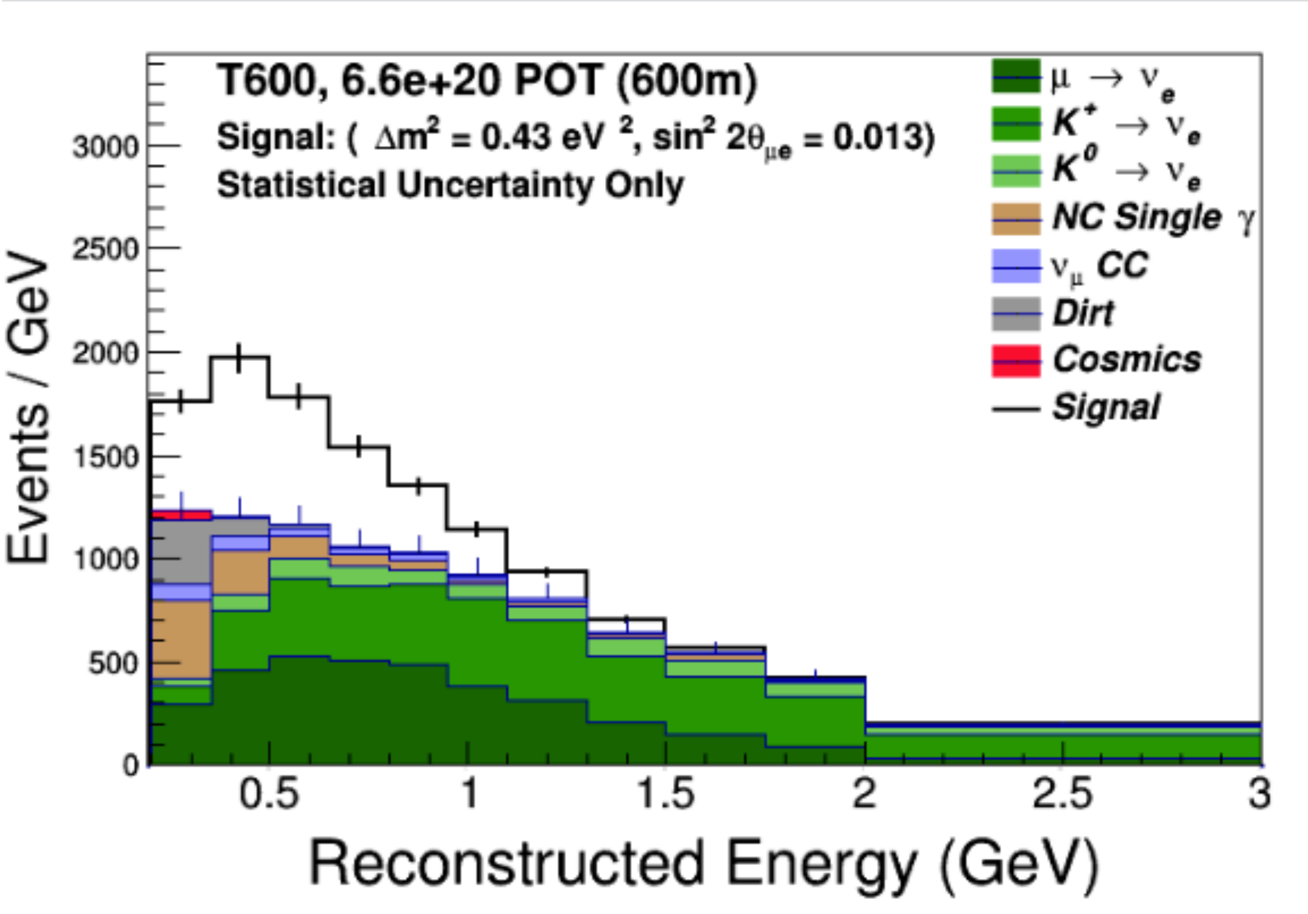


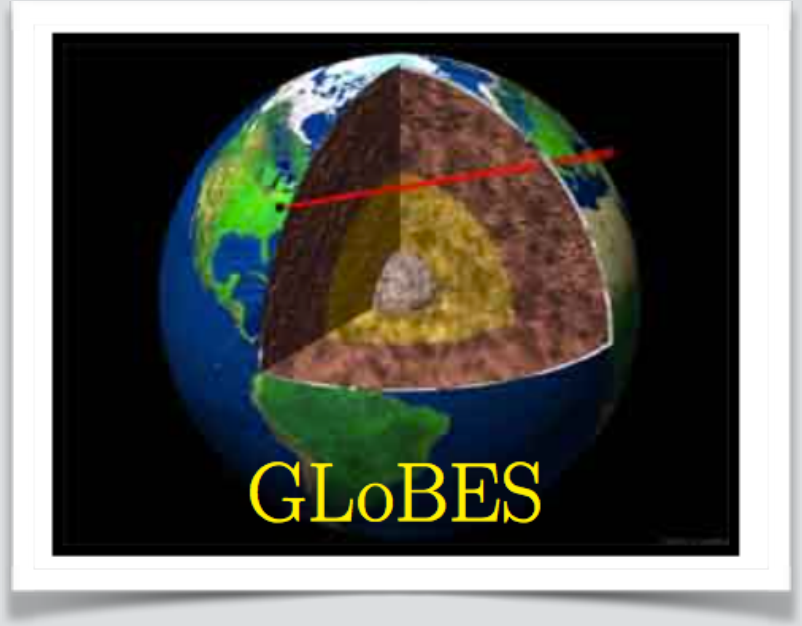
3+1 model at the SBN



arXiv:1503.01520



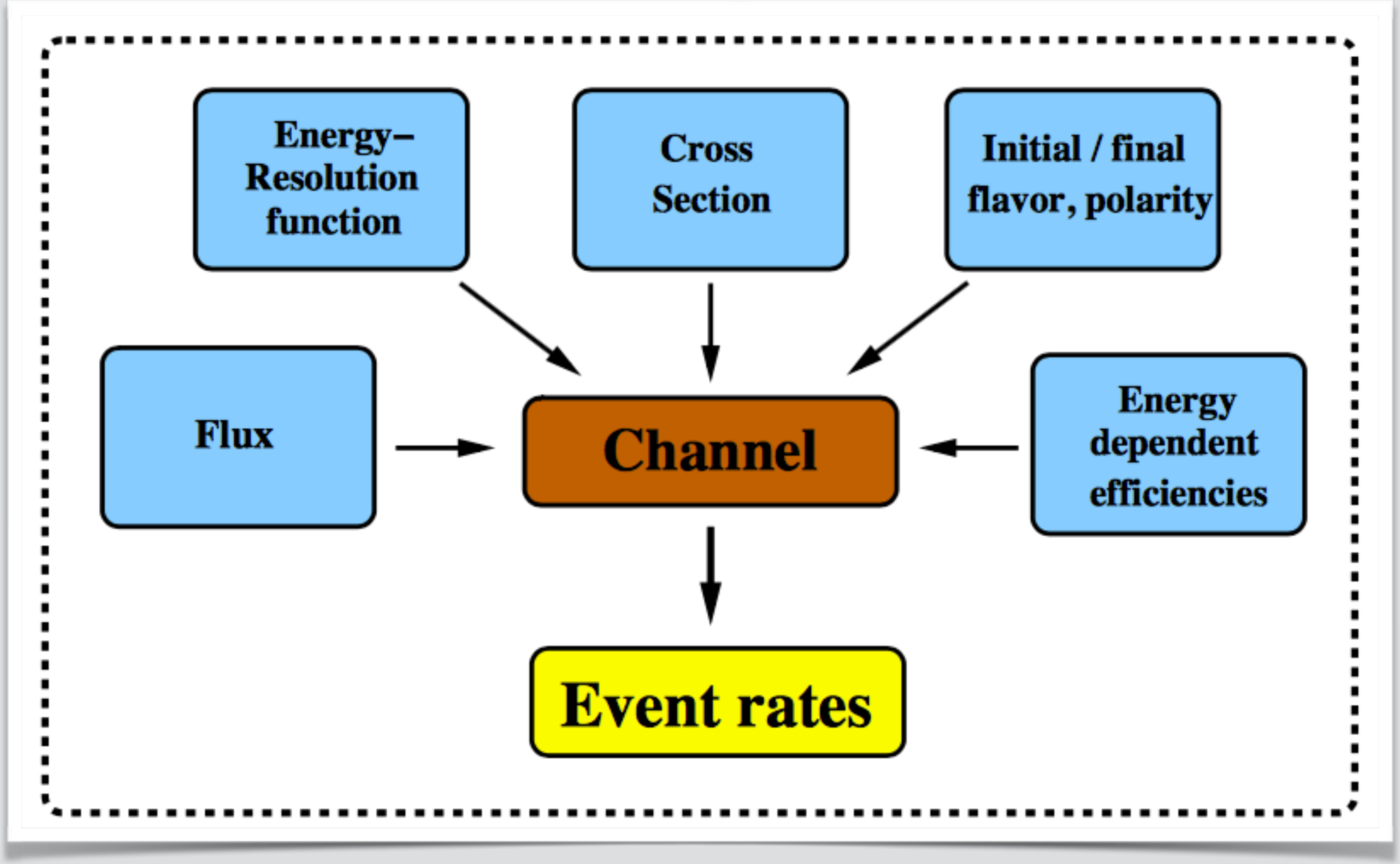
GLoBES



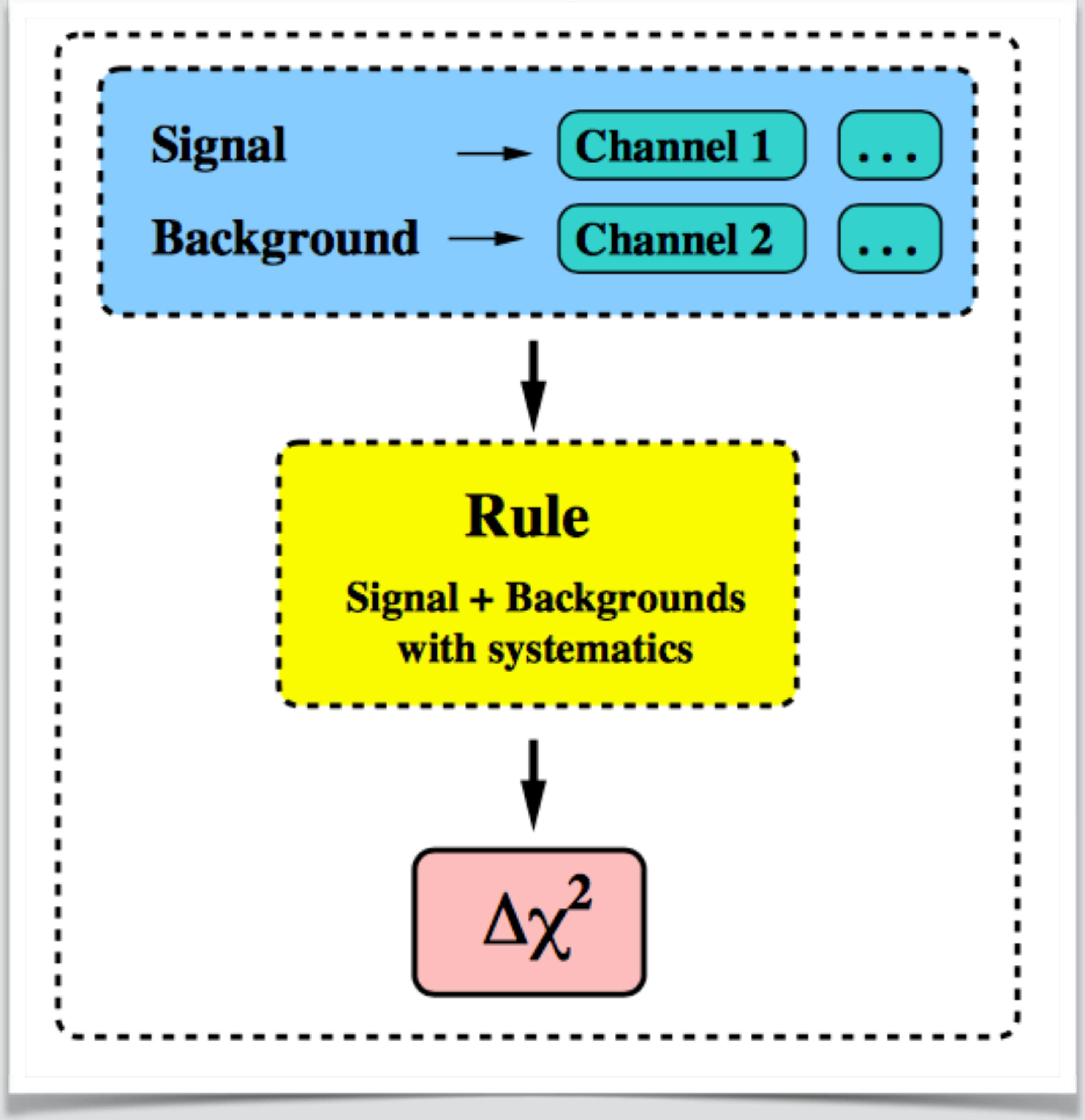
General Long Baseline Experiment Simulator

$$
\begin{aligned}
\frac{dn_\beta^{\mathrm{IT}}}{dE'} = \quad & N \int\limits_0^\infty \int\limits_0^\infty dE\, d\hat{E} \quad \underbrace{\Phi_\alpha(E)}_{\text{Production}} \times \\
& \underbrace{\frac{1}{L^2} P_{(\alpha\to\beta)}(E, L, \rho; \theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{31}, \Delta m^2_{21}, \delta_{\mathrm{CP}}) \times}_{\text{Propagation}} \\
& \underbrace{\sigma_f^{\mathrm{IT}}(E) k_f^{\mathrm{IT}}(E - \hat{E})}_{\text{Interaction}} \times \\
& \underbrace{T_f(\hat{E}) V_f(\hat{E} - E')}_{\text{Detection}},
\end{aligned}
$$

GLoBES


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

GLoBES


Signal → Channel 1 ...

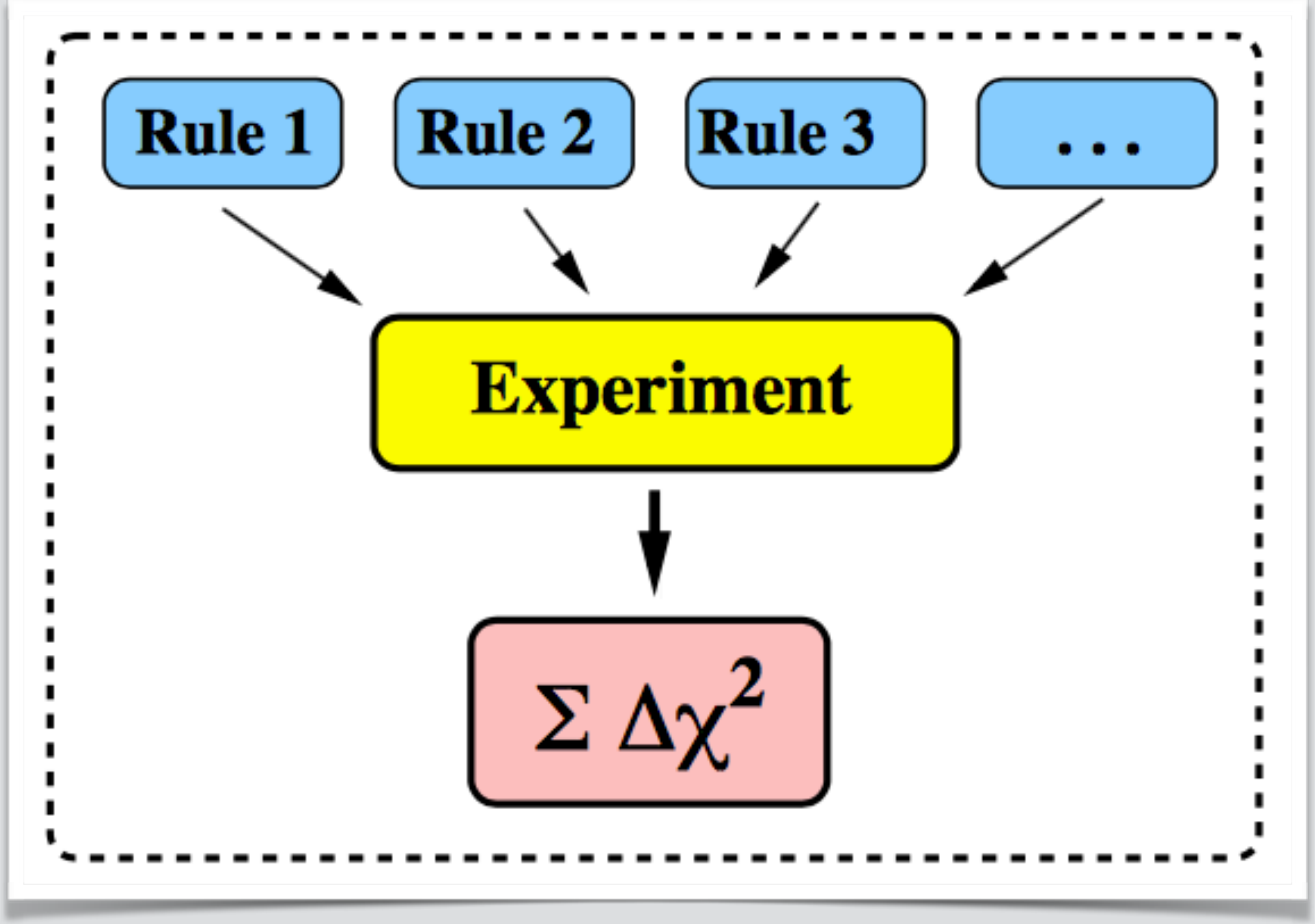
Background → Channel 2 ...

Rule

Signal + Backgrounds with systematics

$\Delta\chi^2$

GLoBES



Preliminary Results

There is no equivalence between LED and "3+1" model

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Short-baseline approximation with 1 KK tower

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

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$$\boxed{\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu1}|^2 \left(L_1^{01}\right)^2 \left(|U_{\mu1}|^2 \left(L_1^{00}\right)^2 + |U_{\mu2}|^2 \left(L_2^{00}\right)^2 + |U_{\mu3}|^2 \left(L_3^{00}\right)^2\right)}$$

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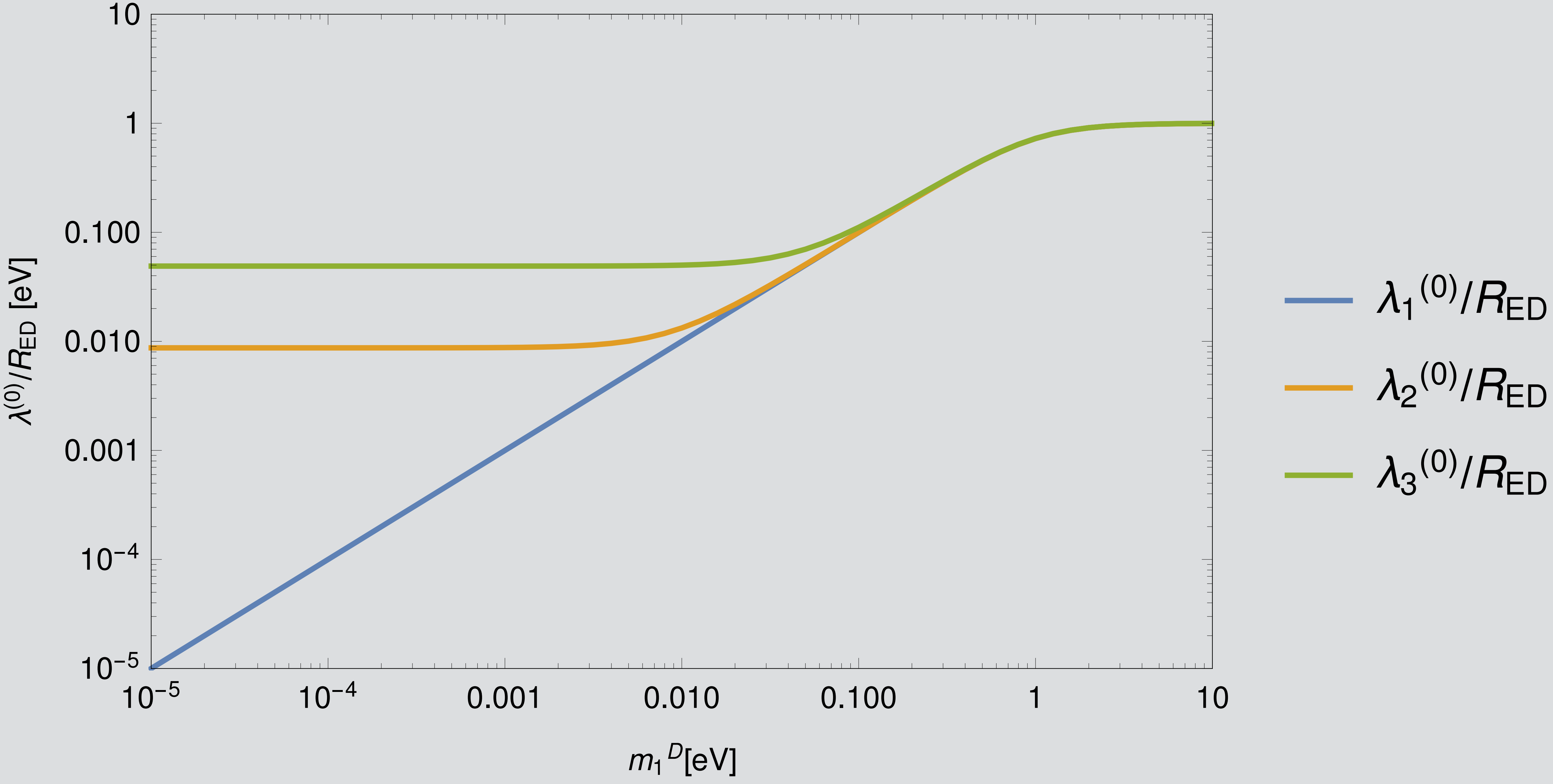
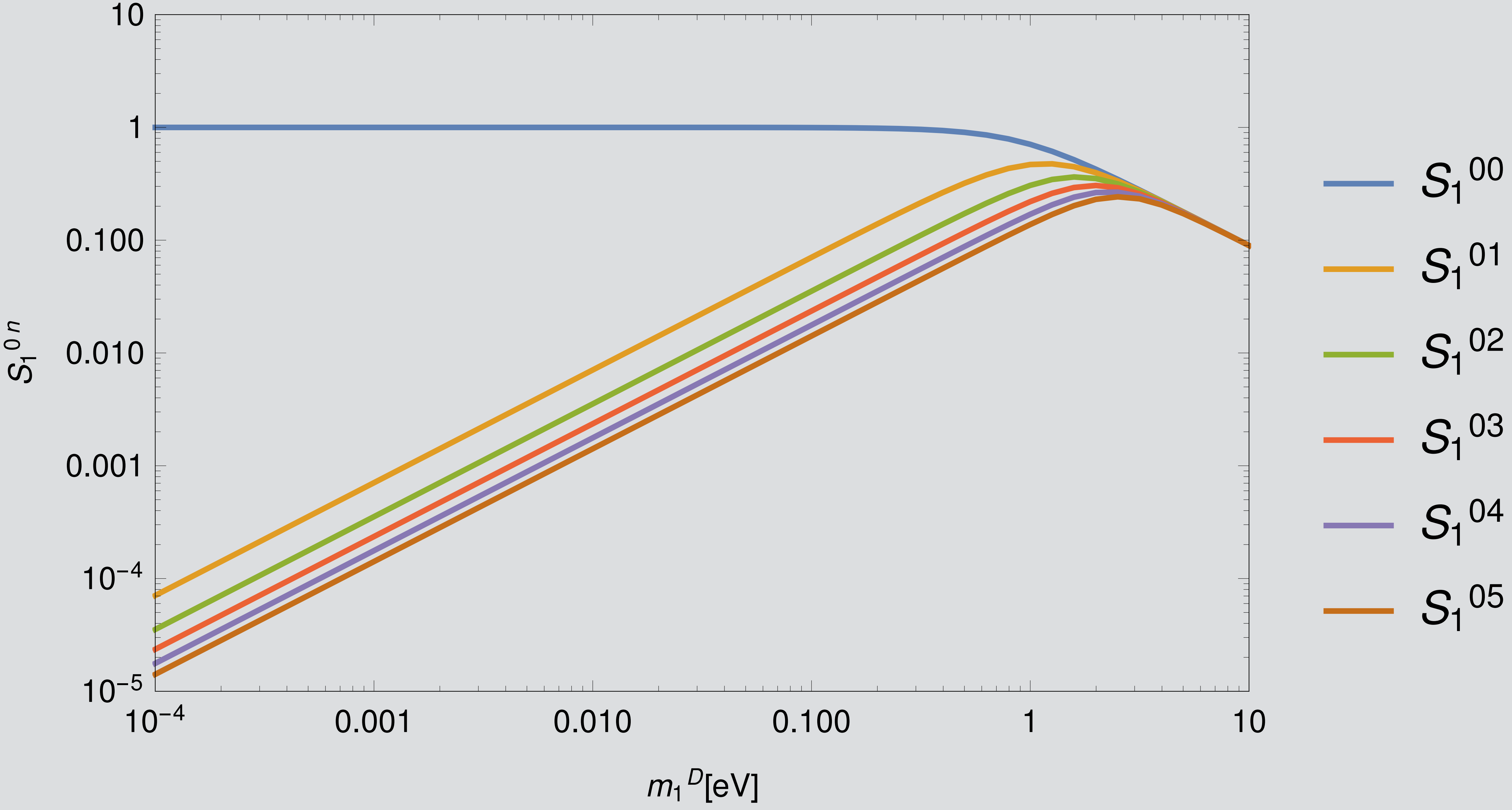
$P(\nu_\mu \to \nu_e) =?$ → **Imaginary term in LED expression (CP-violation?)**

Formalism



$R_{\mathrm{ED}} = 0.5\ \mathrm{eV}$

Formalism



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