Neutrino Mass and Mixing: From Particle Physics to Astrophysics

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The 2025 STFC HEP Summer School

Durham University

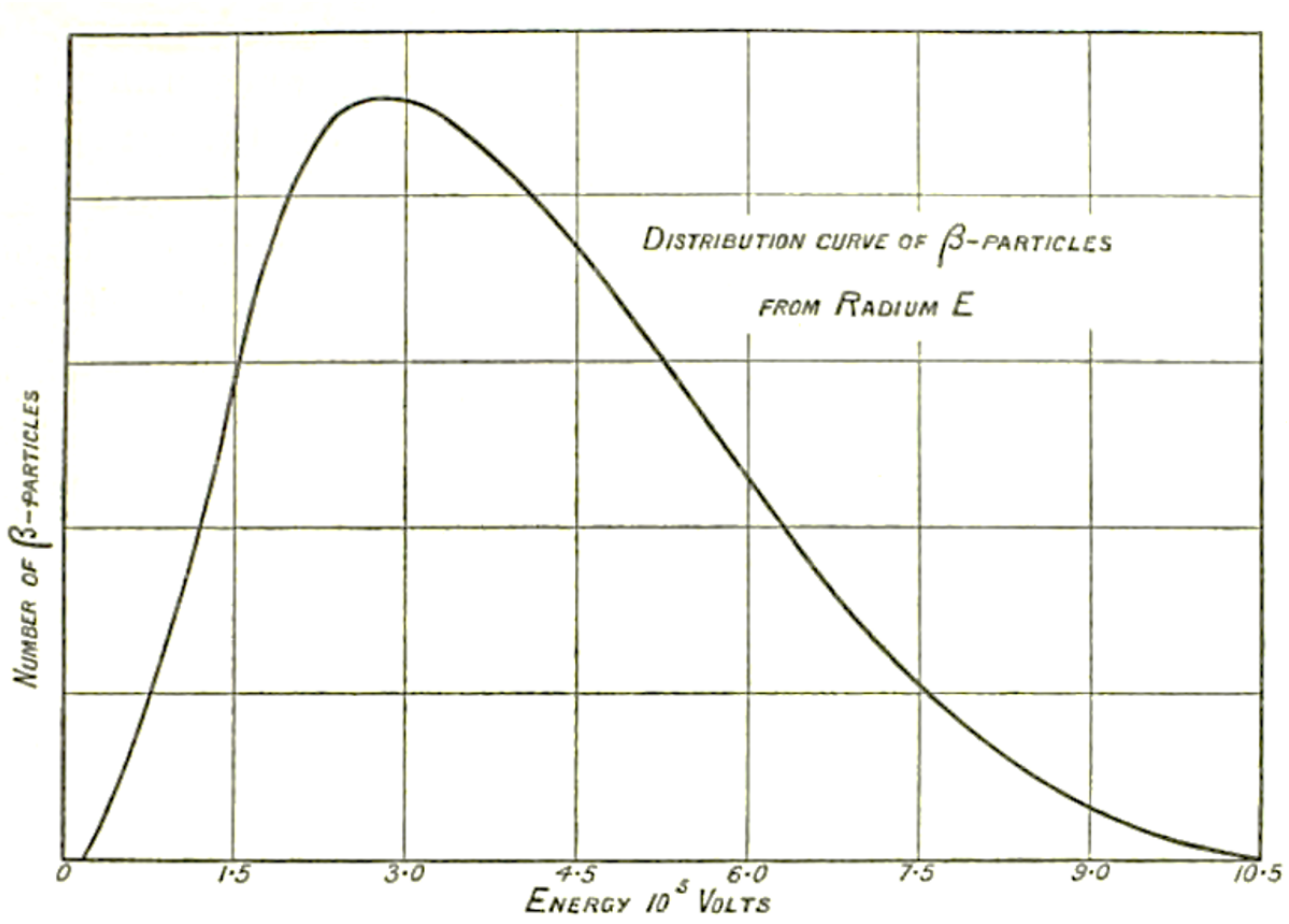
IP3

Content:

- Neutrinos in the Standard Model and Beyond
- Flavor Oscillations
- Neutrino Sources
- Mass Measurements
- Neutrino Astronomy

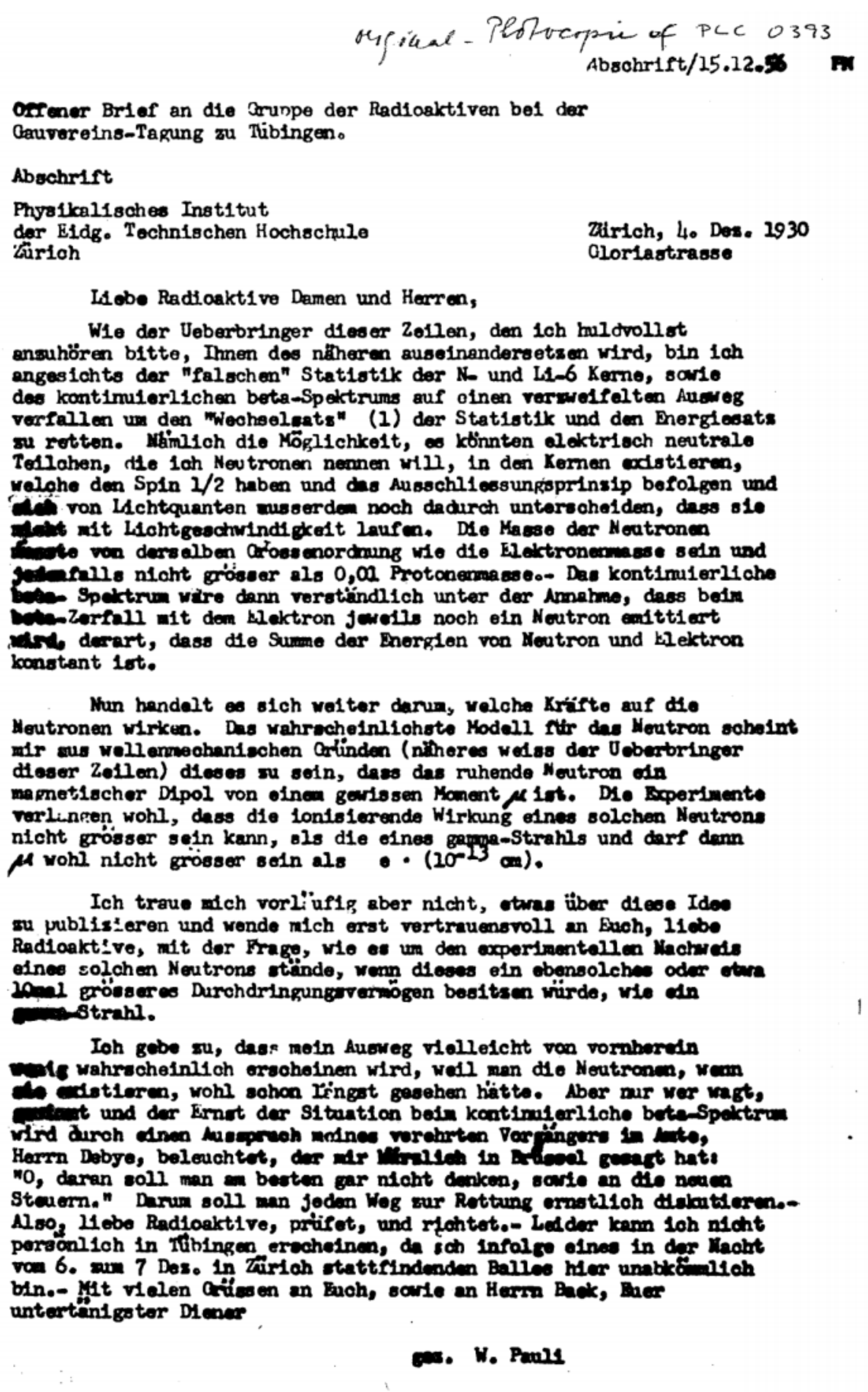
β-decay

In 1914, Lise Meitner, Otto Hahn, and James Chadwick showed that the **energy distribution** of the electrons in the beta decays follows a **continuous spectrum**



$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^{-}$$

Is the energy conserved?



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Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Aussprach meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Neutrinos

Pauli, in a letter addressed to the “Dear Radioactive Ladies and Gentlemen”, resolved the issue of energy conservation by proposing that the electron is accompanied by a **light-neutral particle** that carries away part of the energy

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^{-} + \overline{\nu_e} $$

Neutrinos

Pauli suggested that the new particles should have:

- Mass comparable to the electron
- The spin should be 1/2
- Weakly interacting

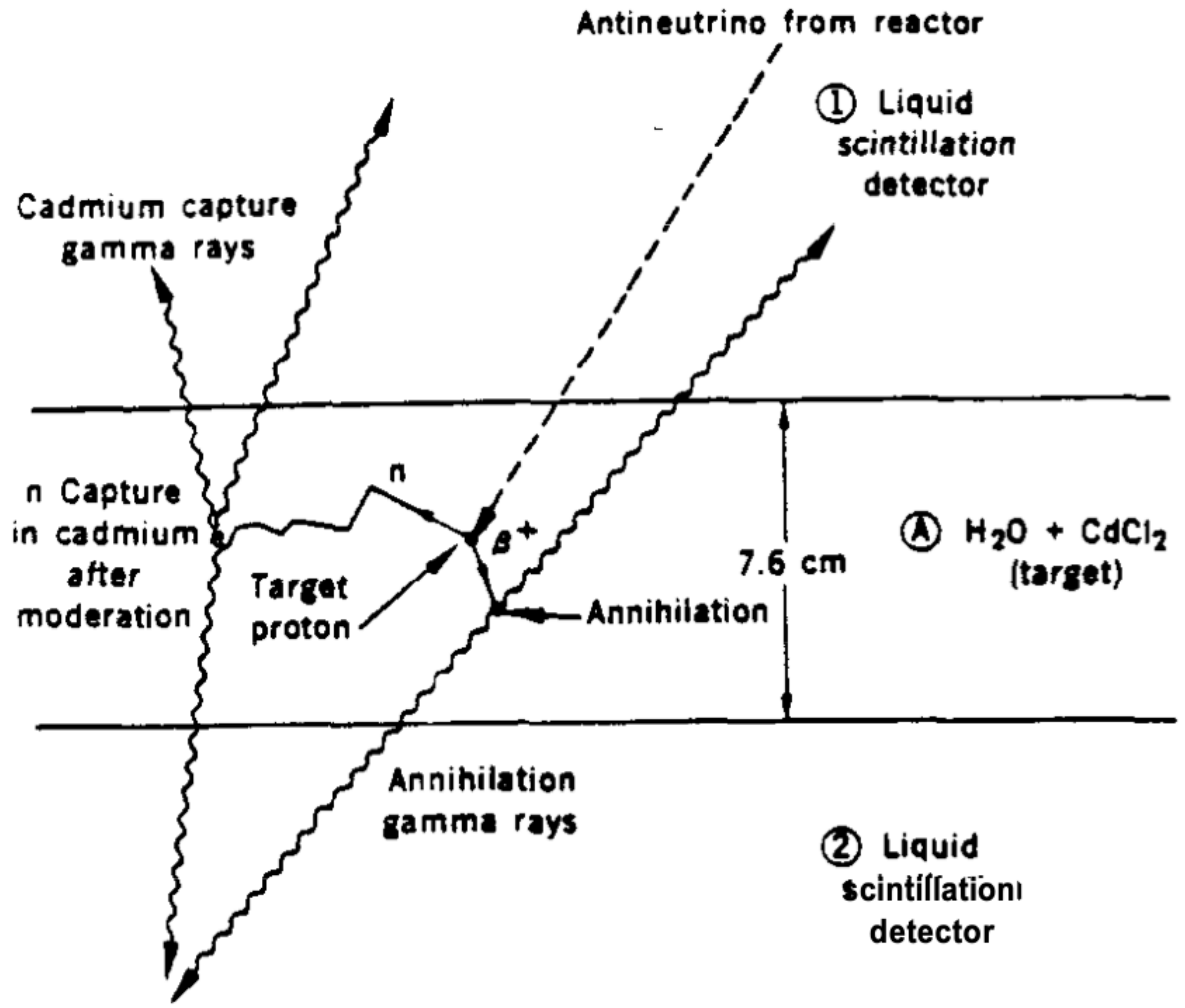
Pauli’s knew that it was hard to detect:
“I have done a terrible thing, I have postulated a particle that cannot be detected”

Project Poltergeist

Neutrinos were detected for the first time by Reines and Cowan in 1953

The first idea was to use a nuclear bomb!

They finally used the nuclear reactor at the Savannah River Plant



$$\bar{\nu}_e + p \to n + e^+$$

Frank Reines, Nobel lecture

Homestake Experiment

Following the discovery of neutrinos, several experiments were developed to detect neutrinos from various sources

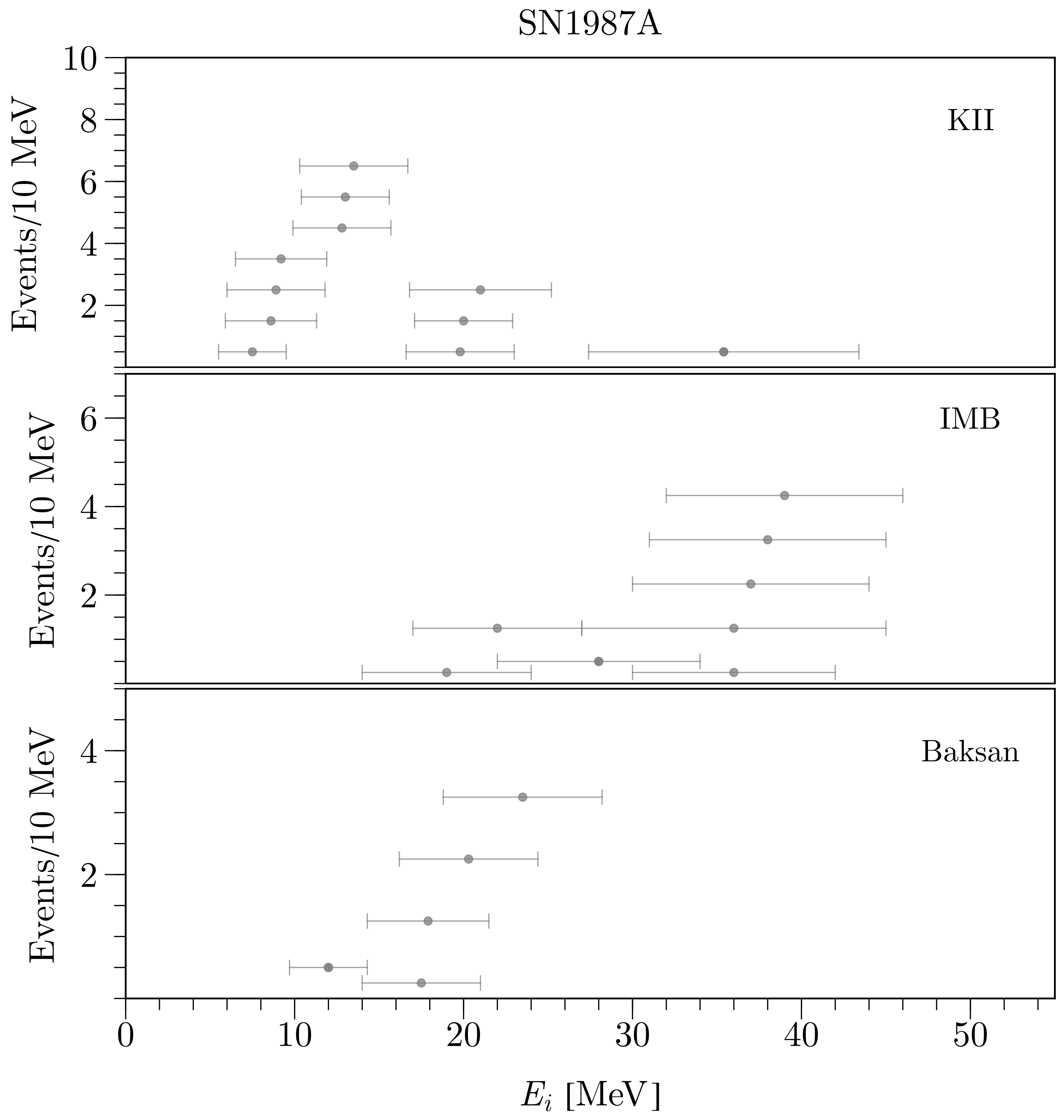
In the 1970, Ray Davis and John Bahcall measured neutrinos emitted by the Sun using a chlorine-based detector

$$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar}^+ + e^-$$

Only about a third of the expected neutrinos were detected, leading to what became known as the **solar neutrino problem**

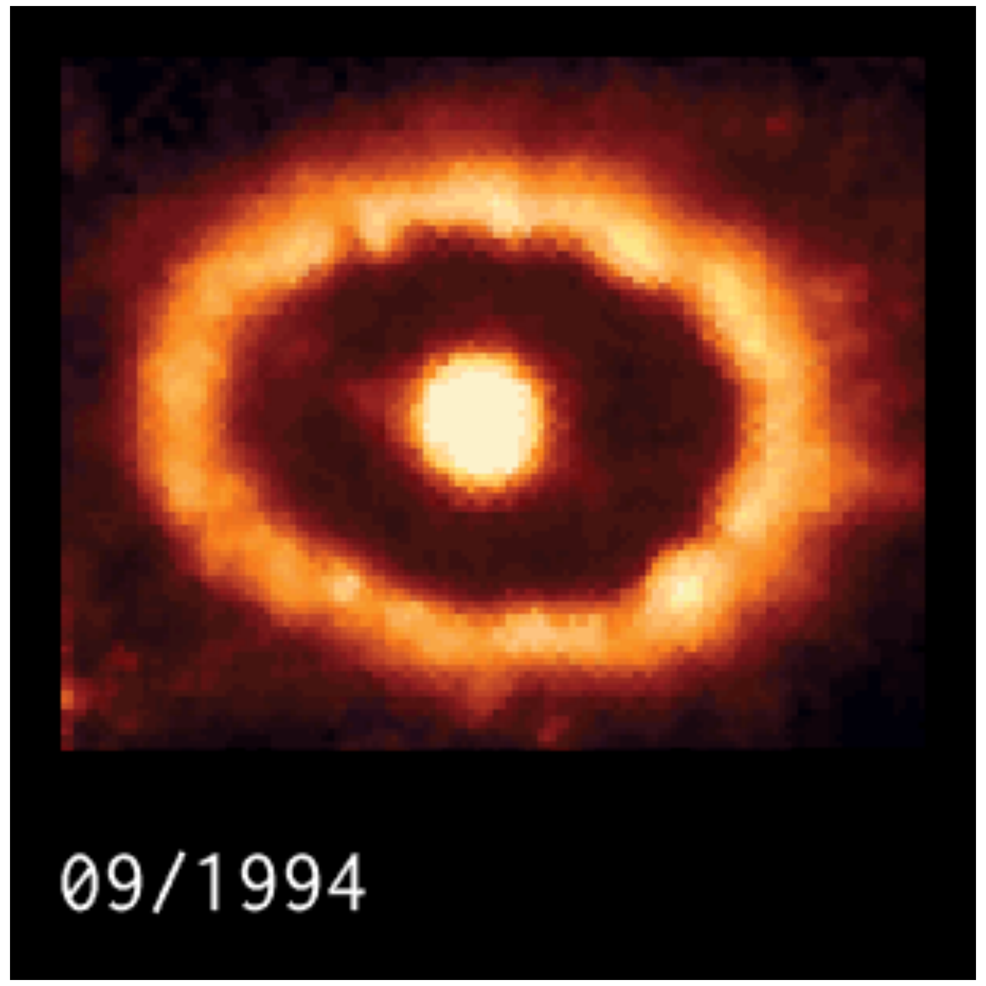
SN 1987A

In 1987, three experiments, Kamiokande II, IMB, and Baksan, detected neutrinos from a Type II supernova in the Large Magellanic Cloud, marking the beginning of **neutrino astronomy**



These experiments used IBD to detect neutrinos, registering around 25 events

$$\bar{\nu}_e + p \rightarrow n + e^+$$



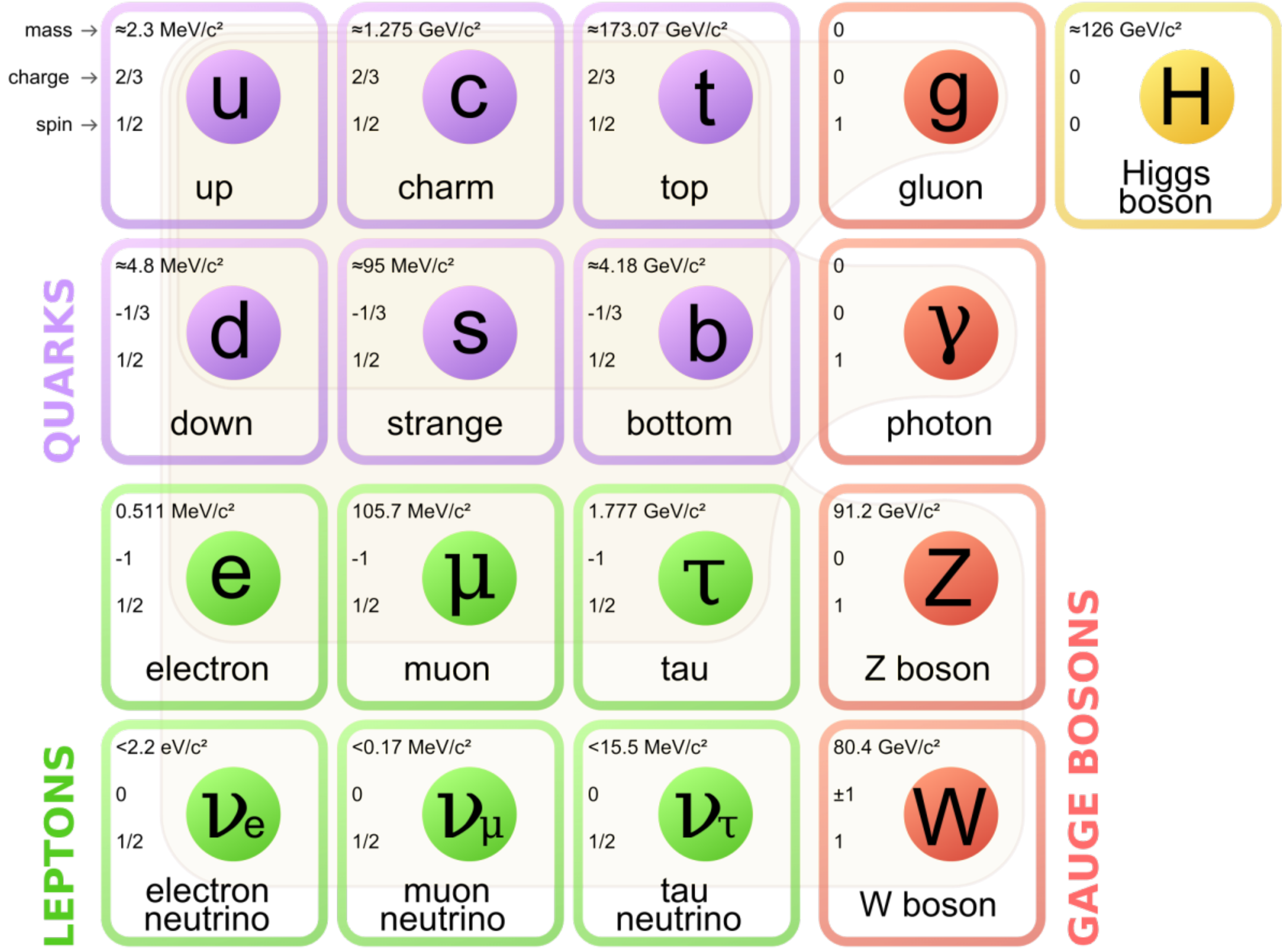
- Distance ~ 50kpc
- Progenitor mass of $\sim 20 M_\odot$

Neutrinos in the Standard Model

ν in the Standard Model

The SM is a gauge theory based on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$

There are 3 generations of fermions



The SM contains accidental global symmetriess

- Each individual **lepton number is conserved**
- The total lepton number is conserved

  $(L = L_e + L_\mu + L_\tau)$
- The baryon number is also conserved

ν in the Standard Model

All fermions can be arranged into irreducible representations of the SM gauge group $(q_{SU(3)}, q_{SU(2)}, q_{U(1)})$

$(1,2,-\frac{1}{2})$	$(3,2,-\frac{1}{6})$	$(1,1,-1)$	$(3,1,\frac{-2}{3})$	$(3,1,\frac{-1}{3})$
$\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L$	$\begin{pmatrix}u \\ d\end{pmatrix}_L$	e_R	u_R	d_R
$\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c \\ s\end{pmatrix}_L$	μ_R	c_R	s_R
$\begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t \\ b\end{pmatrix}_L$	τ_R	t_R	b_R

- Neutrinos are singlets of the strong force
- The electric charge is given by the hypercharge ($q_{U(1)}$) and the isospin (I_3)

$$Q_{em} = I_3 + q_{U(1)}$$

- Neutrinos do not have electric charge

ν in the Standard Model

All fermions have a well-defined **chirality.** They are left (right)-handed fields, if the eigenvalue of γ_5 is +1 (-1)

$(1,2,-\frac{1}{2})$	$(3,2,-\frac{1}{6})$	$(1,1,-1)$	$(3,1,\frac{-2}{3})$	$(3,1,\frac{-1}{3})$
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$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t\\ b\end{pmatrix}_L$	τ_R	t_R	b_R

A spinor can be splitted into its left/right-handed components using the projection matrices

$$\psi_{R/L} = P_{R/L}\psi \qquad P_{R/L} = \frac{1 \pm \gamma_5}{2}$$

They are two-component spinors (Weyl fermions)

ν in the Standard Model

The Hamiltonian for a massive fermion is given

$$H = \overline{\psi}(-i \sum_j \gamma^j \partial_j + m)\psi$$

The equations of motions are given by

$$(\gamma^\mu p_\mu \pm m)u = 0$$

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- The Hamiltonian does not commute with chirality $[H, \gamma_5] \neq 0$

- The momentum does not commute with the total angular momentum ($\overrightarrow{J} = \vec{s} + \overrightarrow{L}$)

$$[\overrightarrow{p}, \overrightarrow{J}] \neq 0$$

The total angular momentum neither the chirality can be used to charactirize a massive particle together with its energy and momentum

ν in the Standard Model

The **helicity** is defined as the projection of the spin into the direction of motion $h = \vec{s} \cdot \hat{p}$

$$[H, \vec{s} \cdot \hat{p}] = 0 \qquad\qquad [\vec{p}, \vec{s} \cdot \hat{p}] = 0$$

ν in the Standard Model

The **helicity** is defined as the projection of the spin into the direction of motion $h = \vec{s} \cdot \hat{p}$

In the case of massive particles, helicity depends on the reference frame

$\vec{s} \cdot \hat{p} \,|\, m, s > = 1/2 \,|\, m, s >$ right-handed

$\vec{s} \cdot \hat{p} \,|\, m, s > = -1/2 \,|\, m, s >$ left-handed

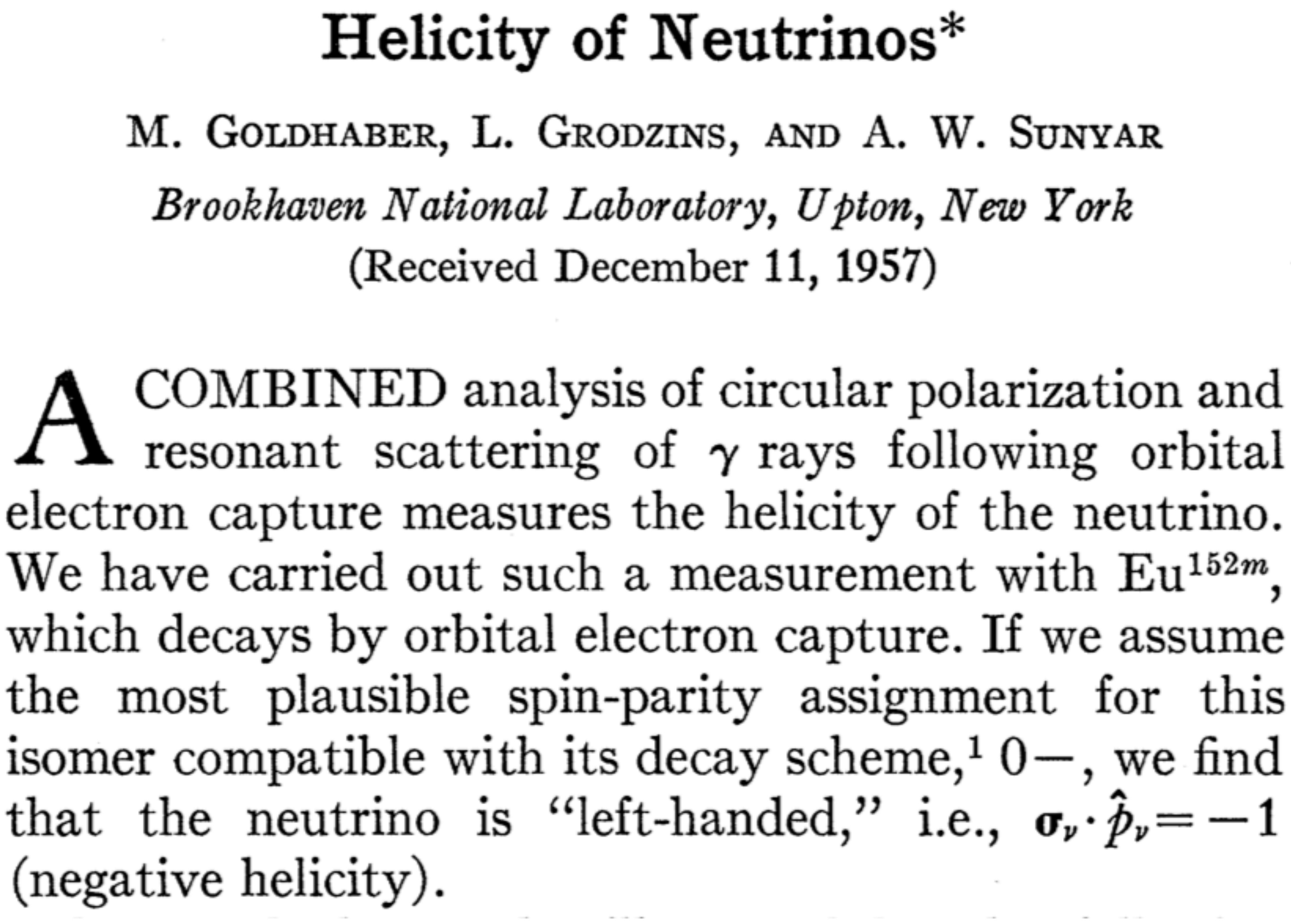
For massless fermions the chiral projectors are equivalent to the helicity projectors

$$P_{R/L} = \frac{1 \pm \gamma_5}{2} = \frac{1}{2}(1 \pm \vec{s} \cdot \hat{p}) + o(m/E)$$

ν in the Standard Model

- Neutrino helicity was inferred from photon helicity measurements in nuclear decays involving electron capture.

- It was found that neutrinos are left-handed.



Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

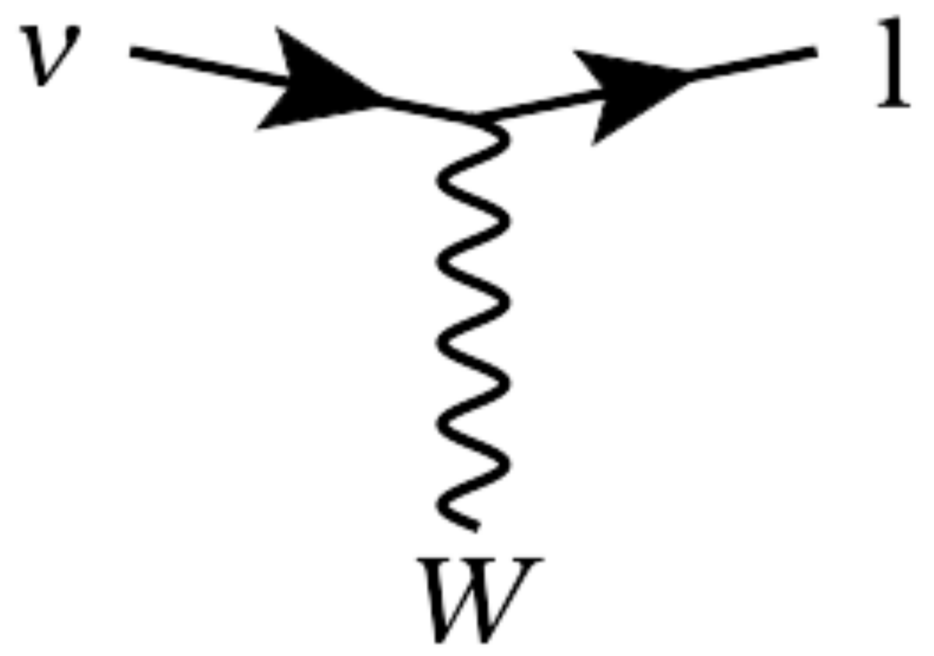
ν in the Standard Model

In the SM, neutrinos interact via the weak force

The three active neutrinos interact with the charged lepton through **charged currents**

$$\mathscr{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{\alpha} \overline{\nu_\alpha} \gamma_\mu P_L l_\alpha W^+_\mu$$

Charge Current



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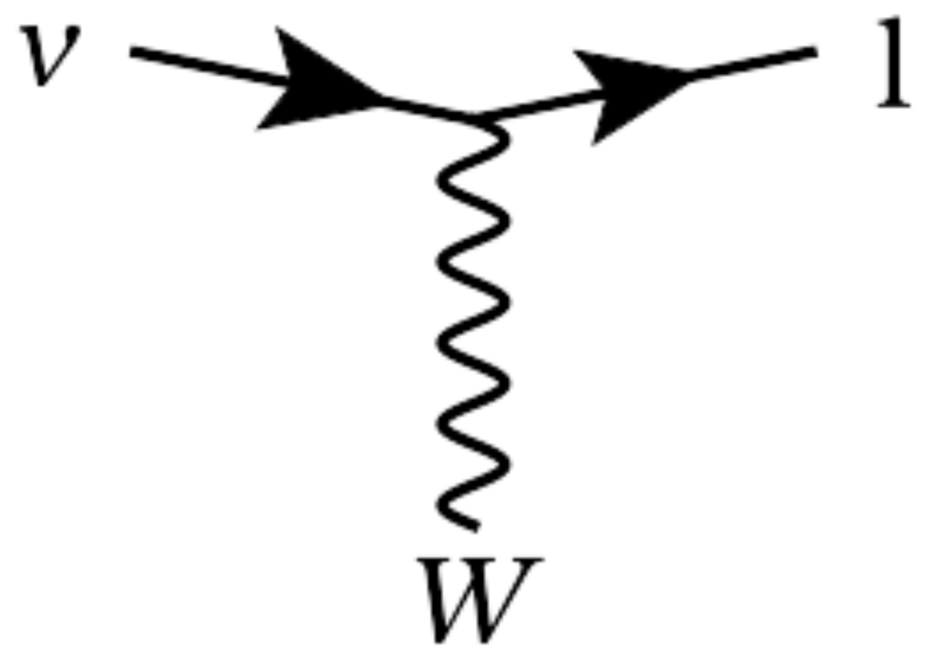
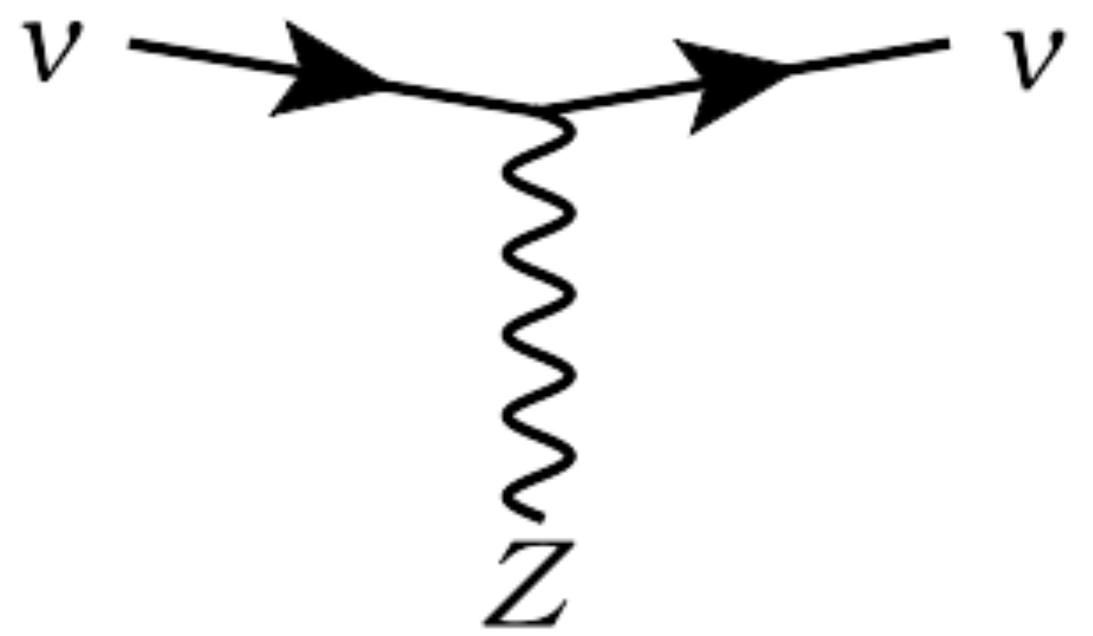


The three active neutrinos interact with the charged lepton through **charged currents**

$$\mathscr{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{\alpha} \overline{\nu_{\alpha}} \gamma_{\mu} P_L l_{\alpha} W_{\mu}^{+}$$

Neutrinos also carry **neutral current** interactions

Neutral Current



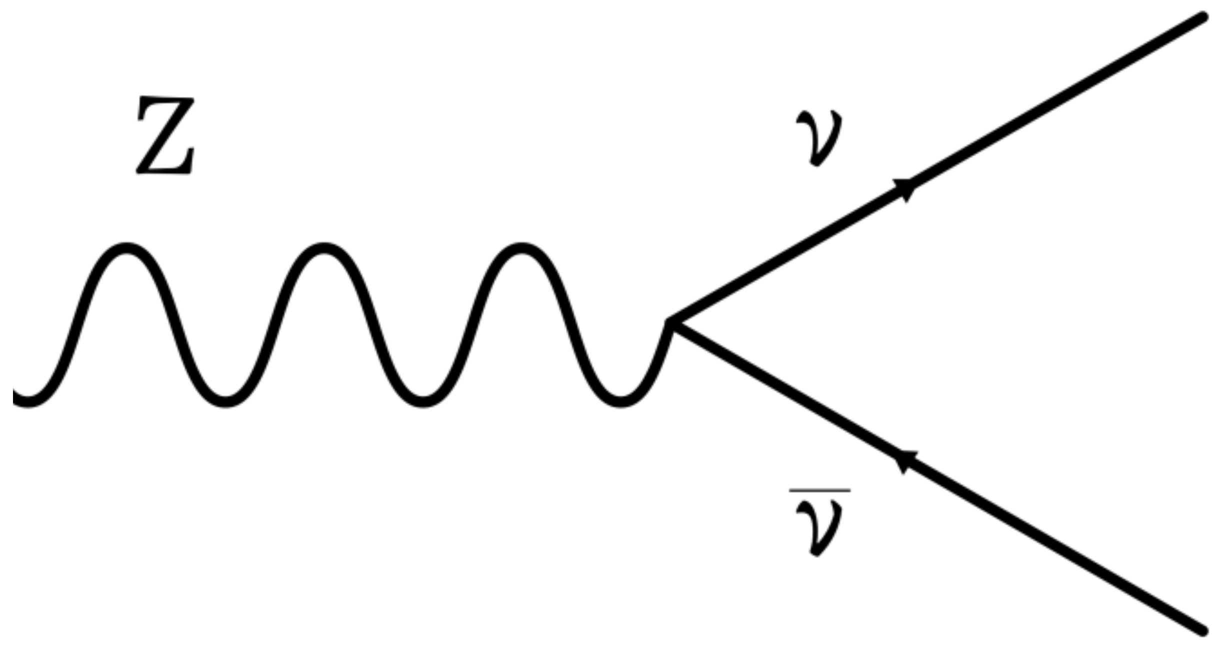
$$\mathscr{L}_{NC} = \frac{g}{2\cos\theta_w} \sum_{\alpha} \overline{\nu_{\alpha}} \gamma_{\mu} P_L \nu_{\alpha} Z_{\mu}^{+}$$

ν in the Standard Model

The **number of active neutrinos** was measured by studying the decay width of the Z-boson into invisible particles

The total decay width of the Z-boson

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + N_\nu \Gamma_{\nu\nu}$$



The number of neutrinos is given by

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu} = \frac{\Gamma_Z - 3\Gamma_{ll} - \Gamma_{had}}{\Gamma_\nu}$$

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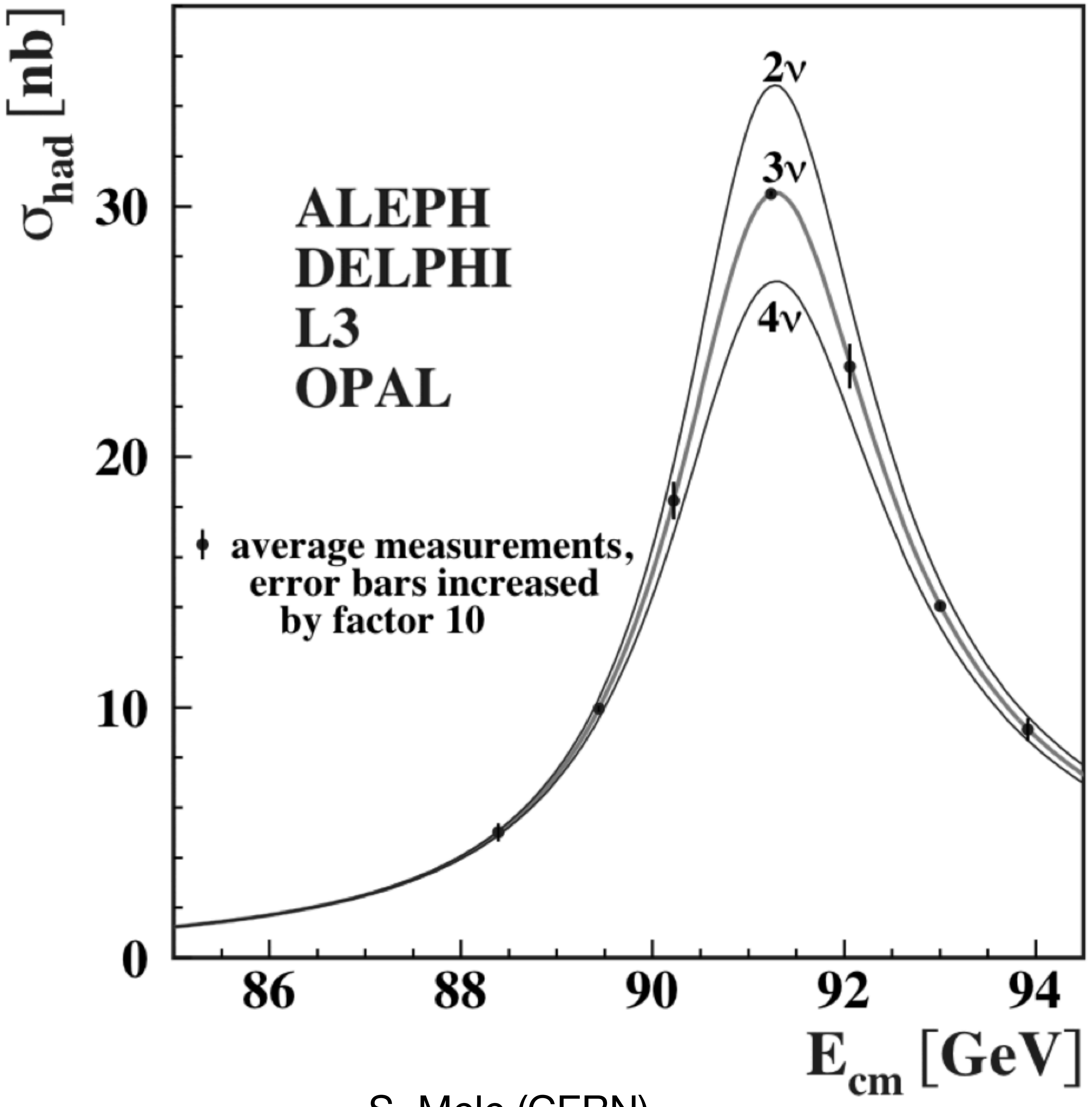
$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu} = \frac{\Gamma_Z - 3\Gamma_{ll} - \Gamma_{had}}{\Gamma_\nu}$$

The measurements showed

$$N_\nu = 2.984 \pm 0.0082$$



S. Mele (CERN)

ν in the Standard Model

The mass term for fermions arises from the coupling between the left-handed and right-handed fields

$$\mathscr{L}_m = m_f \bar{\psi}_L \psi_R$$

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In the SM, the mass term originates from the spontaneous symmetry-breaking (SSB)

$$\mathscr{L}_Y = Y_{ij} \overline{L}_{iL} E_{Rj} \phi + \text{h.c.} \qquad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

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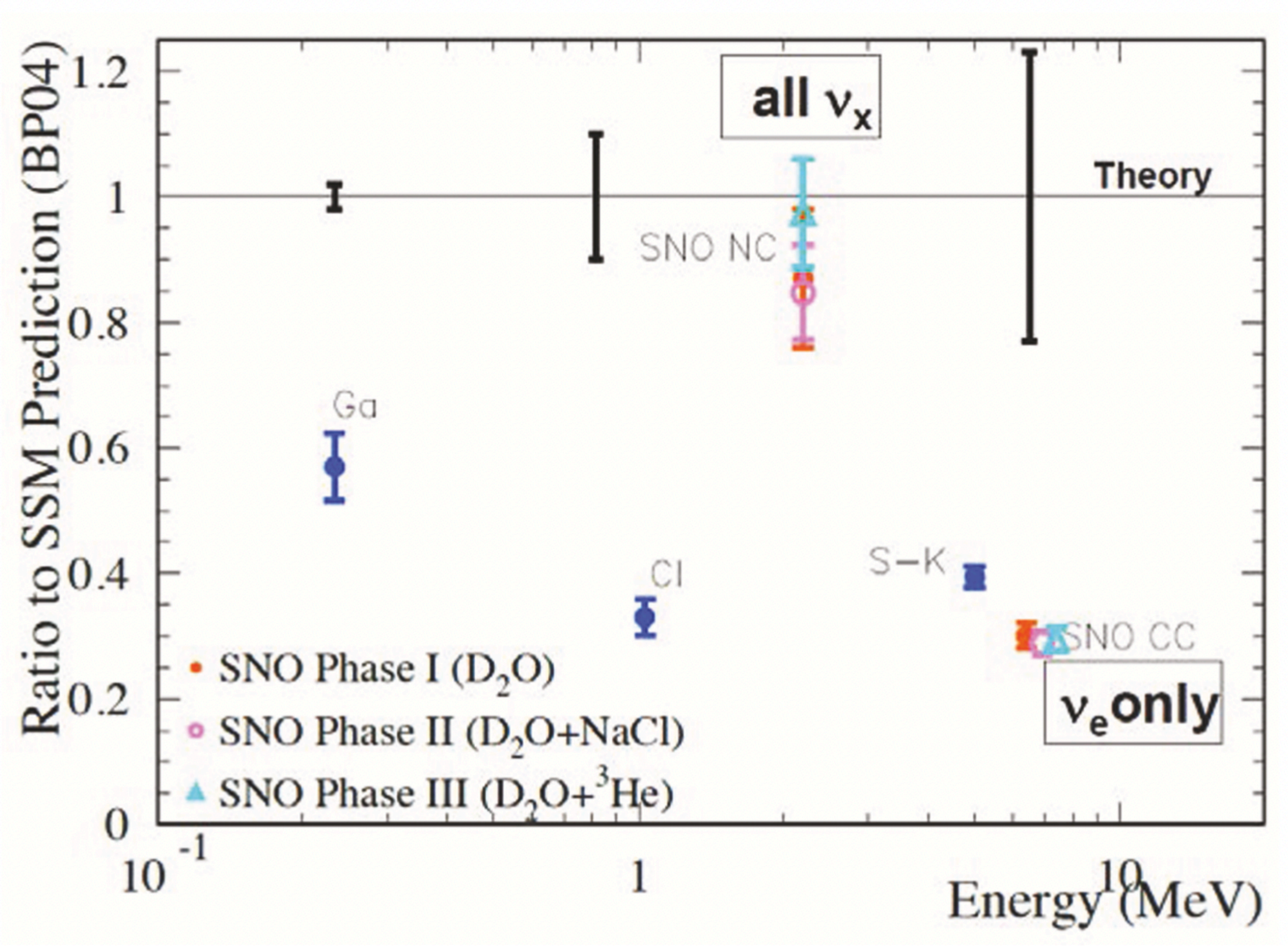
After the SSB

$$\phi = \begin{pmatrix} 0 \\ \frac{\text{v} + h}{\sqrt{2}} \end{pmatrix} \qquad \mathscr{L}_m = \frac{Y\text{v}}{\sqrt{2}} \overline{E}_L E_R + \text{h.c.}$$

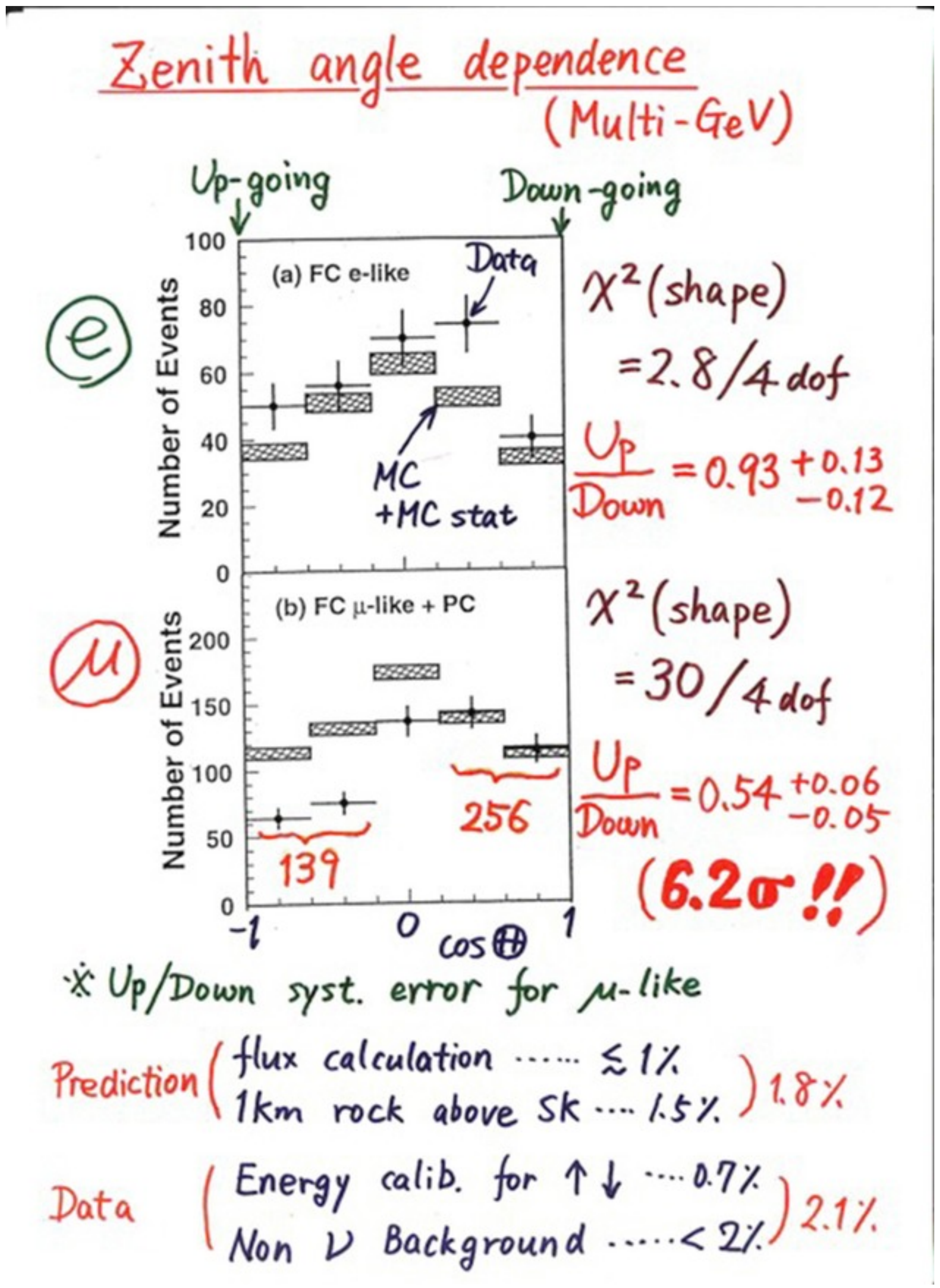
→ **Neutrinos are massless in the SM!!!**

BSM in the ν Sector

Experiments have shown that **lepton flavor is not conserved**, which indicates the existence of BSM physics in the neutrino sector



Arthur MacDonald. Nobel lecture



Takaaki Kajita (Super-kamiokande) Neutrino 98

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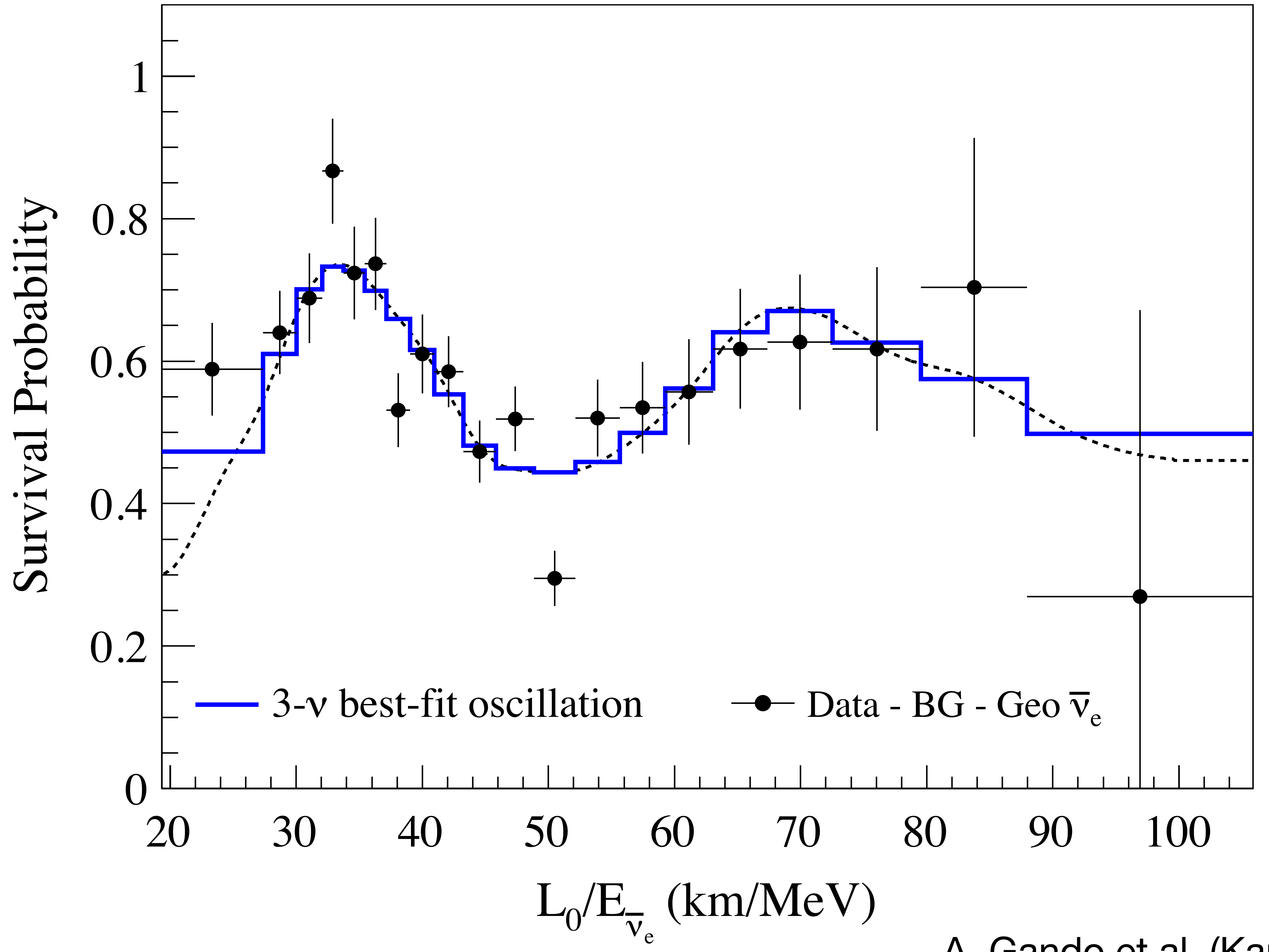
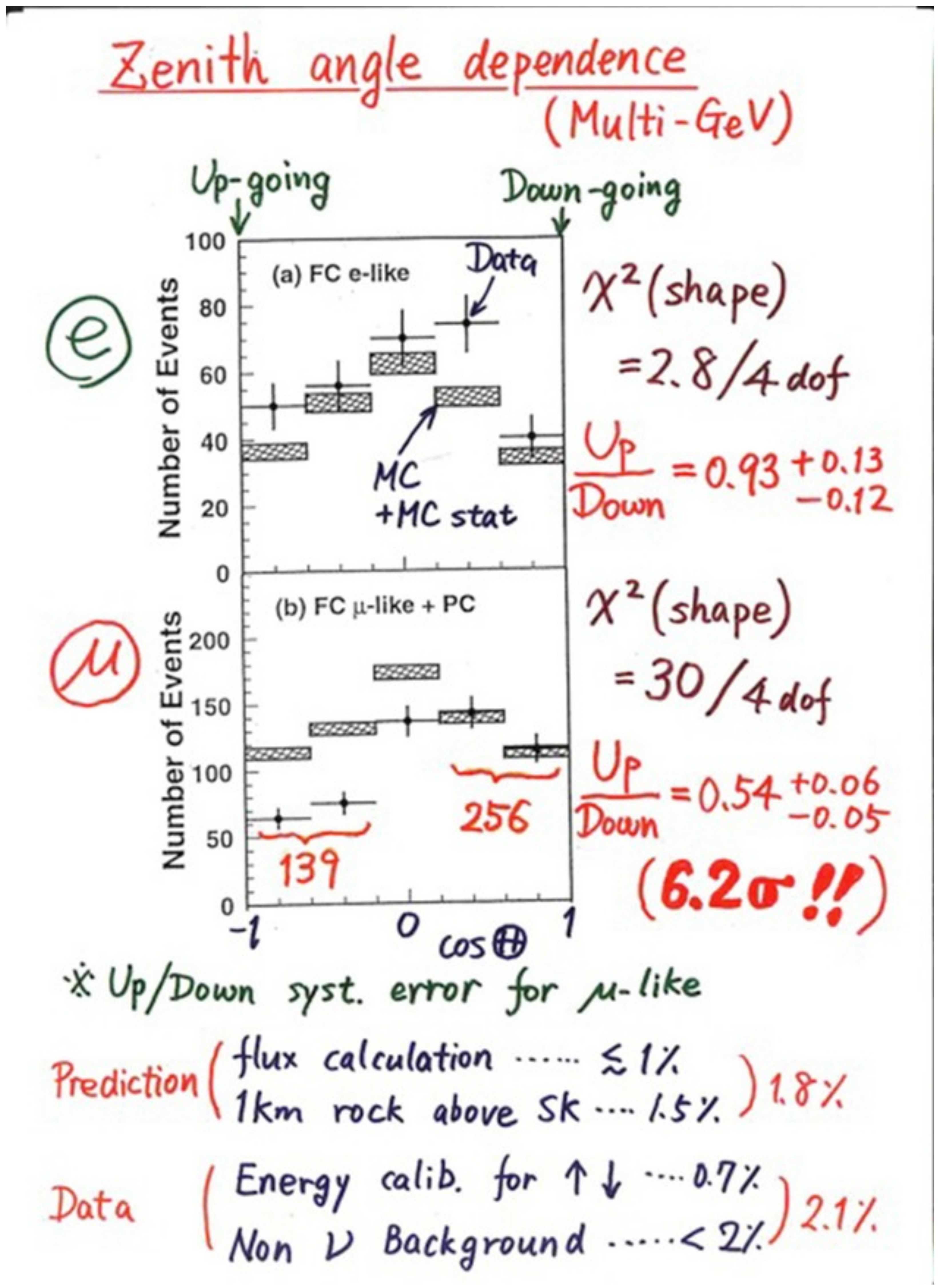


[A. Gando et al. (KamLAND) PRD 88 (2013)](#)

The flavor **oscillates** as a function of **L/E**



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ν are Massive Particles

To explain why flavor oscillations depend on L/E, we need to consider that neutrinos are massive particles

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Dirac particles:

- The SM is extended by adding right-handed neutrinos (ν_R)

$$\mathscr{L}_{mass} \supset \bar{\nu} m_D \nu = \overline{\nu_L} \nu_R m_D + \text{h.c.}$$

Ivan Martinez-Soler (IPPP)

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- In general m_D is a matrix, and to determine the neutrino masses, we need to diagonalize it.

$$V_{\nu L} m_D V_{\nu R}^{\dagger} = \text{diag}(m_i)$$

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- The relation between the interaction ("flavor") basis and the mass basis is given by a unitary transformation

$$\nu_{mass} = V_{\nu L}^\dagger \nu_L + V_{\nu R}^\dagger \nu_R$$

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- Neutrinos differ from anti-neutrinos. To describe neutrinos fully, we require four chiral fields $\nu_L, \nu_R, \overline{\nu_L}, \overline{\nu_R}$.

ν are Massive Particles

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$$\mathscr{L}_{mass} \supset \bar{\nu} m_D \nu = \overline{\nu_L} \nu_R m_D + \text{h.c.}$$

- Under a U(1) transformation, the fields transform as follow

$$\nu \to e^{i\alpha}\nu \qquad \bar{\nu} \to e^{-i\alpha}\bar{\nu}$$

The **total lepton number is conserved** in the presence of a **Dirac mass term** for the neutrinos

ν are Massive Particles

Neutrinos are charless fermions; they can be their own antiparticle ($\nu = \nu^C$). Neutrinos can be **Majorana** fermions

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- $\nu^C = C\nu_L$ is a right-handed field
- We can build a mass term for the neutrinos using only left-handed fields

$$\mathscr{L}_{mass} \supset \frac{1}{2}\overline{\nu^C} m_M \nu = \frac{1}{2}\overline{\nu_L} C^\dagger \nu_L m_M + \text{h.c.}$$

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- For multiple ν_L, the mass eigenstates can be found by diagonalizing m_M as $V_\nu^T m_D V_\nu = \text{diag}(m_i)$

$$V_\nu^T m_D V_\nu = \text{diag}(m_i) \qquad \nu_{mass} = V_\nu^\dagger \nu_L + (V_\nu^\dagger \nu_L)^c$$

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- A Majorana fermion is described by two chiral fields, ν, ν^C

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- Under a U(1) transformation, the fields transform

$$\nu \to e^{i\alpha}\nu \qquad \nu^C \to e^{-i\alpha}\nu^C \qquad \overline{\nu^C} \to e^{i\alpha}\overline{\nu^C}$$

The Majorana mass term **violates the U(1) symmetry** $\mathscr{L}_{mass} \to e^{i2\alpha}\mathscr{L}_{mass}$

ν are Massive Particles

The Majorana mass term can be generated via a dimensional 5 operator

$$\mathscr{L}_{mass} \supset \frac{Y}{\Lambda}\overline{L}_L\tilde{\phi}^* C^\dagger \tilde{\phi}^\dagger L_L + \text{h.c.} \qquad \text{where} \qquad \tilde{\phi} = i\sigma_2\phi^*$$

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where $\tilde{\phi} = i\sigma_2\phi^*$

After the spontaneous symmetry breaking, we recover the Majorana mass term $\longrightarrow$ $\tilde{\phi} = \begin{pmatrix} \text{v}/\sqrt{2} \\ 0 \end{pmatrix}$

$$\mathscr{L}_{mass} \supset \frac{Y\text{v}^2}{2\Lambda}\overline{\nu_L}C^\dagger \nu_L + \text{h.c.}$$

ν are Massive Particles

In the presence of ν_L and ν_R, we can have a Dirac and a Majorana mass term

$$\mathscr{L}_{D+M} = -\overline{\nu_L}\nu_R m_D + \frac{1}{2}\overline{\nu_R}C^\dagger \nu_R m_M + \text{h.c.}$$

ν are Massive Particles

In the presence of ν_L and ν_R, we can have a Dirac and a Majorana mass term

$$\mathscr{L}_{D+M} = -\overline{\nu_L}\nu_R m_D + \frac{1}{2}\overline{\nu_R}C^\dagger\nu_R m_M + \text{h.c.}$$

Defining $N_L = \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix}$ $\rightarrow$ $\mathscr{L}_{D+M} = \frac{1}{2}\overline{N_L^C}\mathscr{M}N_L$

The mass matrix is given by

$$\mathscr{M} = \begin{pmatrix} 0 & m_D \\ m_D^\dagger & m_M \end{pmatrix}$$

- As ν_R are singlets in the SM, a Majorana mass term can be added without breaking the lepton number

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ν **Mixing**

The CC term in the Lagrangian can be written in the mass basis

$$\mathscr{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{\alpha} \overline{N_{\alpha L}} \gamma_\mu P_L l_\alpha W_\mu^+ - \frac{1}{2} \overline{N_L^C} \mathscr{M}_\nu N_L - \overline{l_L} \mathscr{M}_l l_R + \text{h.c.}$$

- $\mathscr{M}_\nu$ and $\mathscr{M}_l$ are the neutrino and charged lepton mass matrices

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- $\mathscr{M}_{\nu}$ and $\mathscr{M}_l$ are the neutrino and charged lepton mass matrices

To switch to the mass basis, we can use a unitary matrix that diagonalizes the mass matrix

diag$(m_e, m_\mu, m_\tau) = V^{l\dagger}_L \mathscr{M}_l V^l_R$ $\quad l^m_{L/R} = V^{l\dagger}_{L/R} l_{L/R}$ $\quad$ Where $V^l_{L/R}$ is a 3x3 unitary matrix

diag$(m_1, m_2, \cdots, m_n) = V^{\nu\dagger}\mathscr{M}_{\nu}V^{\nu}$ $\quad N^m_L = V^{\nu\dagger}N_L$ $\quad$ Where V^{ν} is an nxn unitary matrix

- n is the number of massive neutrinos

ν Mixing

Changing to the mass basis, we get

$$\mathscr{L}_{CC} = -\frac{g}{\sqrt{2}}\overline{N^m_{jL}}(V^{\dagger\nu}V^l_L)_{ij}\gamma_\mu l^m_{iL}W^+_\mu + \text{h.c.}$$

$U_{PMNS} = V^{\dagger l}_L V^\nu$ $\quad$ U_{PMNS} is a 3xn mixing matrix

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$U_{PMNS} = V^{\dagger l}_L V^\nu$

U_{PMNS} is a 3xn mixing matrix

The number of degrees of freedom of U_{PMNS} depends on the number of fields required to describe the neutrino.

Dirac: 3(n-2) angles and 2n -5 phases
Majorana: 3(n-2) angles and 3(n-2) phases

Dirac and Majorana differs only in the number of phases

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ν Mixing

A standard parametrization of U_{PMNS} in the case of 3 massive neutrinos is given by

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Dirac neutrinos

In the case of **Majorana** neutrinos

$$\tilde{U}_{PMNS} = U_{PMNS} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

Neutrino Oscillations

ν Mixing

To explain neutrino flavor oscillations, we can describe the flavor states as a superposition of massive states.

$$|\nu_\alpha\rangle = \sum U^\dagger_{\alpha i} |\nu_i\rangle$$

ν_i are the states that describe the evolution in vacuum

Considering three massive states, the mixing matrix is parametrized as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Flavor Oscillation

In the **3ν scenario**, neutrino evolution is described by the Schrödinger equation

$$i\frac{d|\nu_k\rangle}{dt} = \mathscr{H}\,|\nu_k\rangle$$

$$\mathscr{H}\,|\nu_k\rangle = E_k|\nu_k\rangle$$

The massive states are the eigenstates of the Hamiltonian

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The massive states are the eigenstates of the Hamiltonian

For ultrarelativistic neutrinos, the energy of each massive state can be approximated as

$$E_k \simeq E + \frac{m_k^2}{2E}$$

Where we are considering $E = |\overrightarrow{p}|$

Flavor Oscillation

The neutrino evolution in the flavor basis would be obtained by solving the following equation

$$i\frac{d|\nu_\alpha\rangle}{dx} = \left(E + U^\dagger_{\alpha k}\frac{m_k^2}{2E}U_{\beta k}\right)|\nu_\beta\rangle$$

We used the equivalence $t \simeq x$

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Global phase
Independent of the flavor

Flavor dependent term

We used the equivalence $t \simeq x$

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Under the approximation that neutrinos propagate as a plane wave, its massive state propagates as

$$|\nu_i(t)\rangle = e^{iE_it}|\nu_i(t=0)\rangle$$

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$$|\nu_i(t)\rangle = e^{iE_it}|\nu_i(t=0)\rangle$$

Solving that equation, we find that the probability $|\nu_\alpha\rangle \to |\nu_\beta\rangle$ is given by

$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2|U_{\beta k}|^2 + 2\mathrm{Re}\sum_{k>j} U_{\alpha k}U^\dagger_{\beta k}U^\dagger_{\alpha j}U_{\beta j}\exp\left(-i\frac{\Delta m^2_{jk}L}{2E}\right)$$

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Flavor Oscillation

The flavor oscillation probability depends on:

$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\text{Re} \sum_{k>j} U_{\alpha k} U^\dagger_{\beta k} U^\dagger_{\alpha j} U_{\beta j} \exp\left(-i\frac{\Delta m^2_{jk} L}{2E}\right)$$

- Flavor oscillations depend on the mass difference: $\Delta m^2_{ij} = m^2_i - m^2_j$
-
- Depends on the ratio L/E (baseline/neutrino energy)
- $U_{\alpha i}$ mixing between flavor and massive states
- Independent of the Majorana phases

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Flavor Oscillation

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We can define the oscillation length as

$$L^{osc}_{ij} = \frac{2\pi E}{\Delta m^2_{ij}}$$

For $\Delta m^2_{ij} \sim 10^{-3}\text{eV}^2$ ➡ $L^{osc} \sim 2000 \times (E/\text{GeV})\text{km}$

Flavor Oscillation

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Antineutrinos are produced in CC involving charged antileptons

$$\mathscr{L}^{\bar{\nu}}_{CC} = -\frac{g}{\sqrt{2}} \overline{l^m_{iL}} U^{PMNS}_{ij} \gamma_\mu N^m_{jL} W^-_\mu$$

The oscillation probability for antineutrinos is obtained by $U \to U^\dagger$

Flavor Oscillation

The oscillation probability can be rewritten as

$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\sum_{k>j} \text{Re}\left[U_{\alpha k}U^\dagger_{\beta k}U^\dagger_{\alpha j}U_{\beta j}\right] \cos\left(-i\frac{\Delta m^2_{jk}L}{2E}\right)$$

$$+2\sum_{k>j} \text{Im}\left[U_{\alpha k}U^\dagger_{\beta k}U^\dagger_{\alpha j}U_{\beta j}\right] \sin\left(-i\frac{\Delta m^2_{jk}L}{2E}\right)$$

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At very large distances or very low energies, the oscillation terms average out.

$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2$$

This corresponds to oscillations on astrophysical scales

Flavor Oscillation

The oscillation probability can be rewritten as

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- The first two terms are the same for ν and $\overline{\nu}$, conserving CP, but still depends on δ_{CP} through U^{PMNS}

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- The first two terms are the same for ν and $\overline{\nu}$, conserving CP, but still depends on δ_{CP} through U^{PMNS}
- The second line has the opposite sign for ν and $\overline{\nu}$. Violates CP.
- CP violation happens for $\alpha \neq \beta$. If $\alpha = \beta \ \rightarrow$ $\text{Im}\left[U_{\alpha k}U^\dagger_{\beta k}U^\dagger_{\alpha j}U_{\beta j}\right] = \text{Im}\left[|U_{\alpha k}|^2 |U^\dagger_{\alpha j}|^2\right] = 0$

Flavor Oscillation

CP violation in neutrino oscillations can be probed by

$$A^{CP}_{\alpha\beta} = P_{\nu_\alpha \to \nu_\beta} - P_{\overline{\nu_\alpha} \to \overline{\nu_\beta}} = 4 \sum_{k>j} \mathrm{Im}\left[U_{\alpha k} U^\dagger_{\beta k} U^\dagger_{\alpha j} U_{\beta j}\right] \sin\left(-i \frac{\Delta m^2_{jk} L}{2E}\right)$$

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The CP asymmetry is parametrized by the Jarlskog invariant

$$J_{CP} = \text{Im}[\mathrm{U}_{\alpha \mathrm{i}} \mathrm{U}^{*}_{\alpha \mathrm{j}} \mathrm{U}^{*}_{\beta \mathrm{i}} \mathrm{U}_{\beta \mathrm{j}}] = \mathrm{J}^{\max}_{\mathrm{CP}} \sin \delta_{\mathrm{CP}} \longrightarrow A^{CP}_{\alpha\beta} = 4 \sum_{k>j} J^{kj}_{CP} \sin \delta_{CP} \sin\left(-i \frac{\Delta m^2_{jk} L}{2E}\right)$$

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- The quartic product of $U_{\alpha j}$ is invariant under a global rephase $U_{\alpha j} \rightarrow e^{i\alpha}U_{\alpha j}e^{-ij}$

→ CP violation only depends on the Dirac phase

Flavor Oscillation

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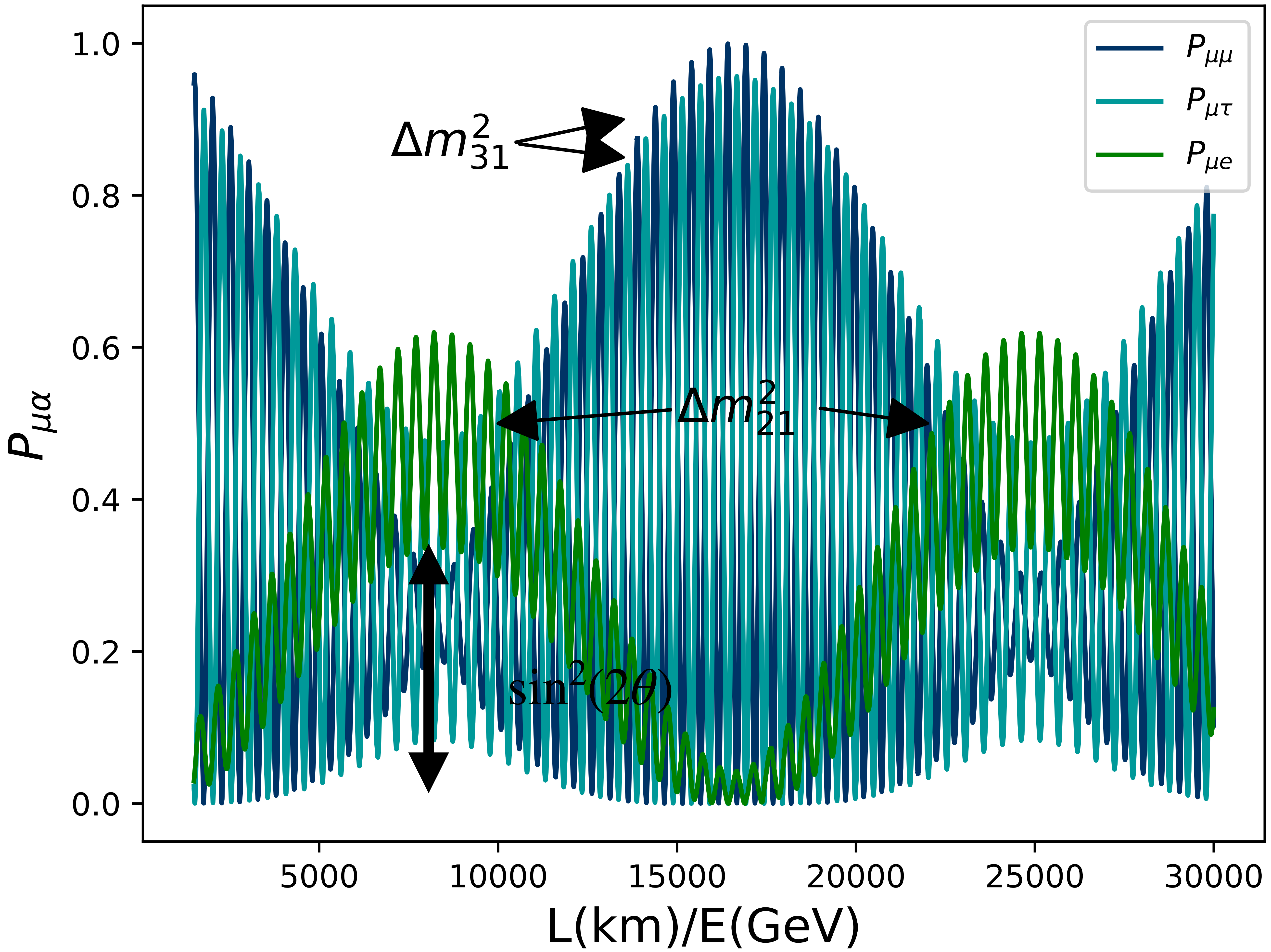
The CP violation effects are observables if neutrinos oscillate:

- For small L or large E, the oscillation phase vanishes, cancelling the CP asymmetry
- For large phases, the oscillation is averaged out and A^{CP} cancels due to the unitarity relations

$$\sum_{k>j} \text{Im}\left[U_{\alpha k} U^\dagger_{\beta k} U^\dagger_{\alpha j} U_{\beta j}\right] = 0$$

Flavor Oscillation

In the3 neutrino mixing scenario, the oscillation probability has two oscillation wavelengths



Wavepacket Description

- Neutrino oscillation happens while there is an **interference between the massive states**

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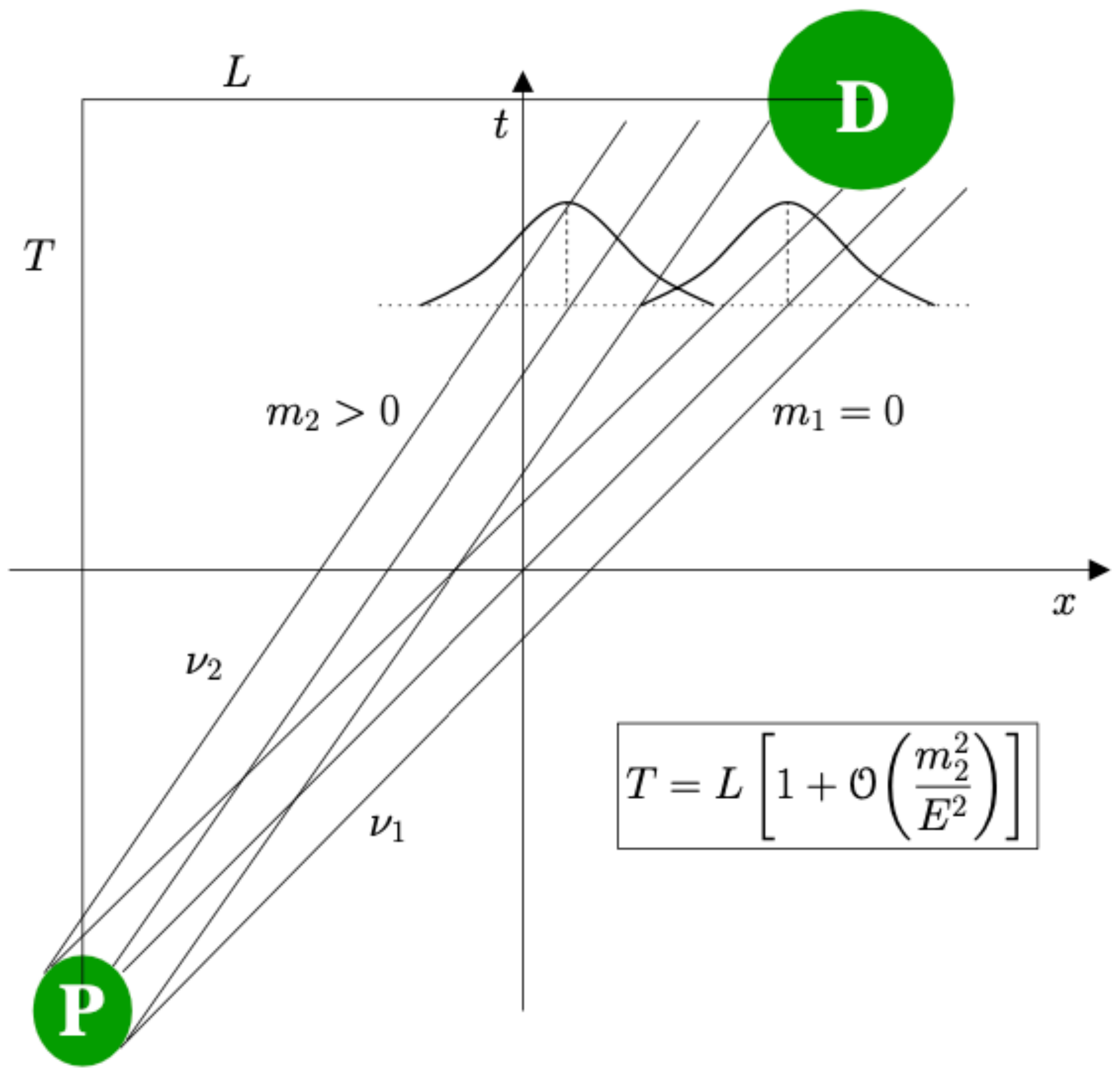
- Considering neutrinos as **plane waves**, the mixing happens at all the points along the trajectory

- Real particles are localized objects described by **wavepackets.**

- The **oscillation stops** for small wavepackets/long distances due to the **wavepacket separation** (incoherent superposition of states).

- Incoherent neutrino flux: Sun, astrophysical sources…



Giunti and Kim, “Fundamental Neutrino Physics and Astrophysics”

Wavepacket Description

The flavor state is given by the sum over all the massive states weighted by the momentum distribution

$$|\nu_\alpha\rangle = \sum_k U^\dagger_{\alpha k}\psi_k|\nu_k\rangle$$

Each massive state is described by the sum over all the momentum distributions

$$\psi_k = \int \frac{dp}{\sqrt{2\pi}} \frac{e^{-\frac{(p-p_k)^2}{4\sigma_p^2}}}{(2\pi\sigma_p^2)^{1/4}} e^{ipx - iE_k t}$$

- p_k: average neutrino momentum
- σ_p: momentum uncertainty

The spatial width of the wavepacket is obtained from the uncertainty principle

$$\sigma_x \sim \frac{1}{2\sigma_p}$$

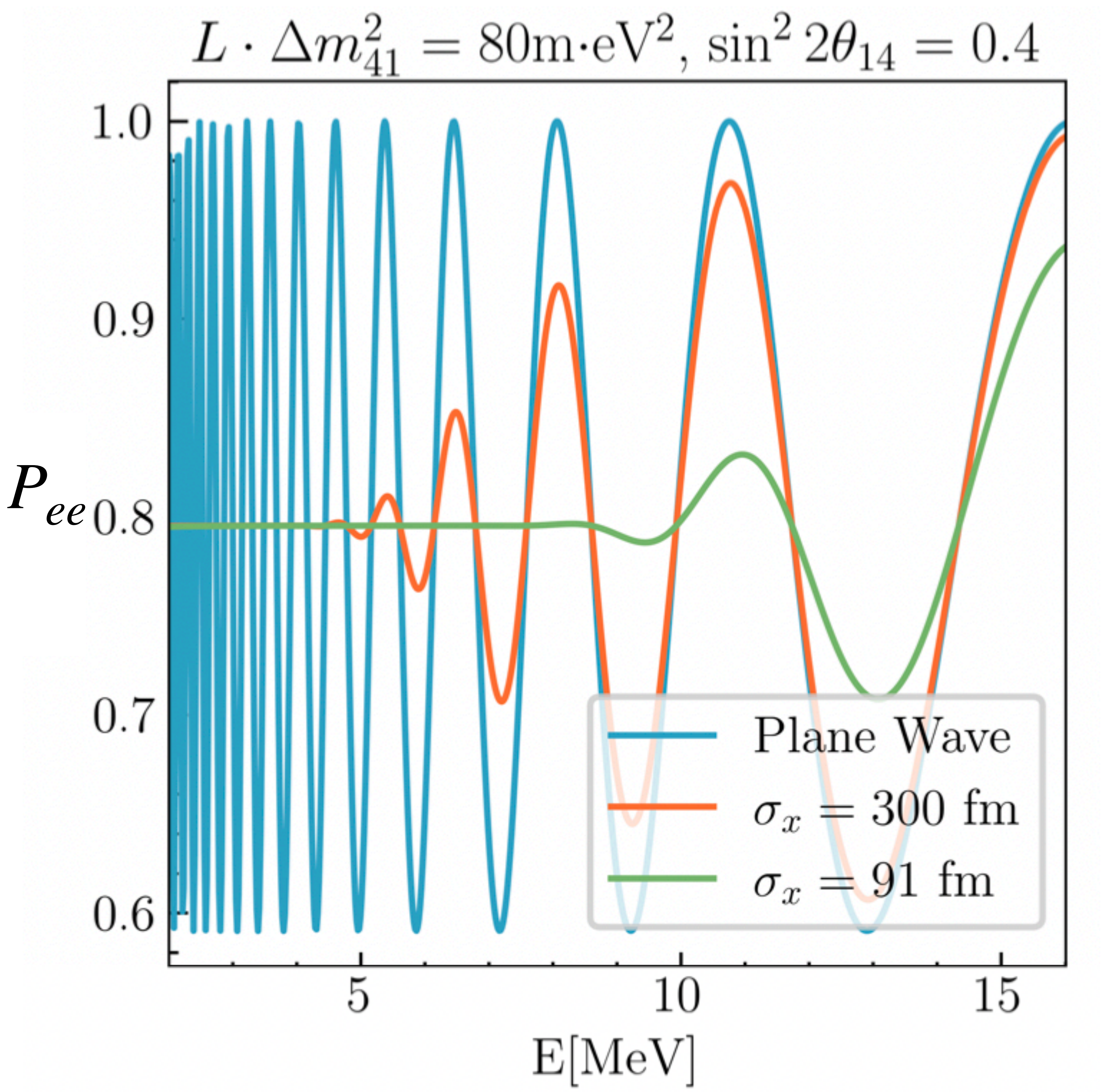
Wavepacket Description

The wavepacket separation manifest as a damping effect in the oscillation

$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\text{Re} \sum_{k>j} U_{\alpha k} U^{\dagger}_{\beta k} U^{\dagger}_{\alpha j} U_{\beta j} \exp\left(-i \frac{\Delta m^2_{jk} L}{2E} - \left(\frac{L}{L^{coh}_{kj}} \right)^2 \right)$$

The coherence length depends on the wave packet size (σ_x)

$$L^{coh} = 0.2\text{pc} \left(\frac{E}{100\text{TeV}} \right)^2 \left(\frac{\sigma_x}{100\text{fm}} \right) \left(\frac{\text{eV}^2}{\Delta m^2} \right)$$



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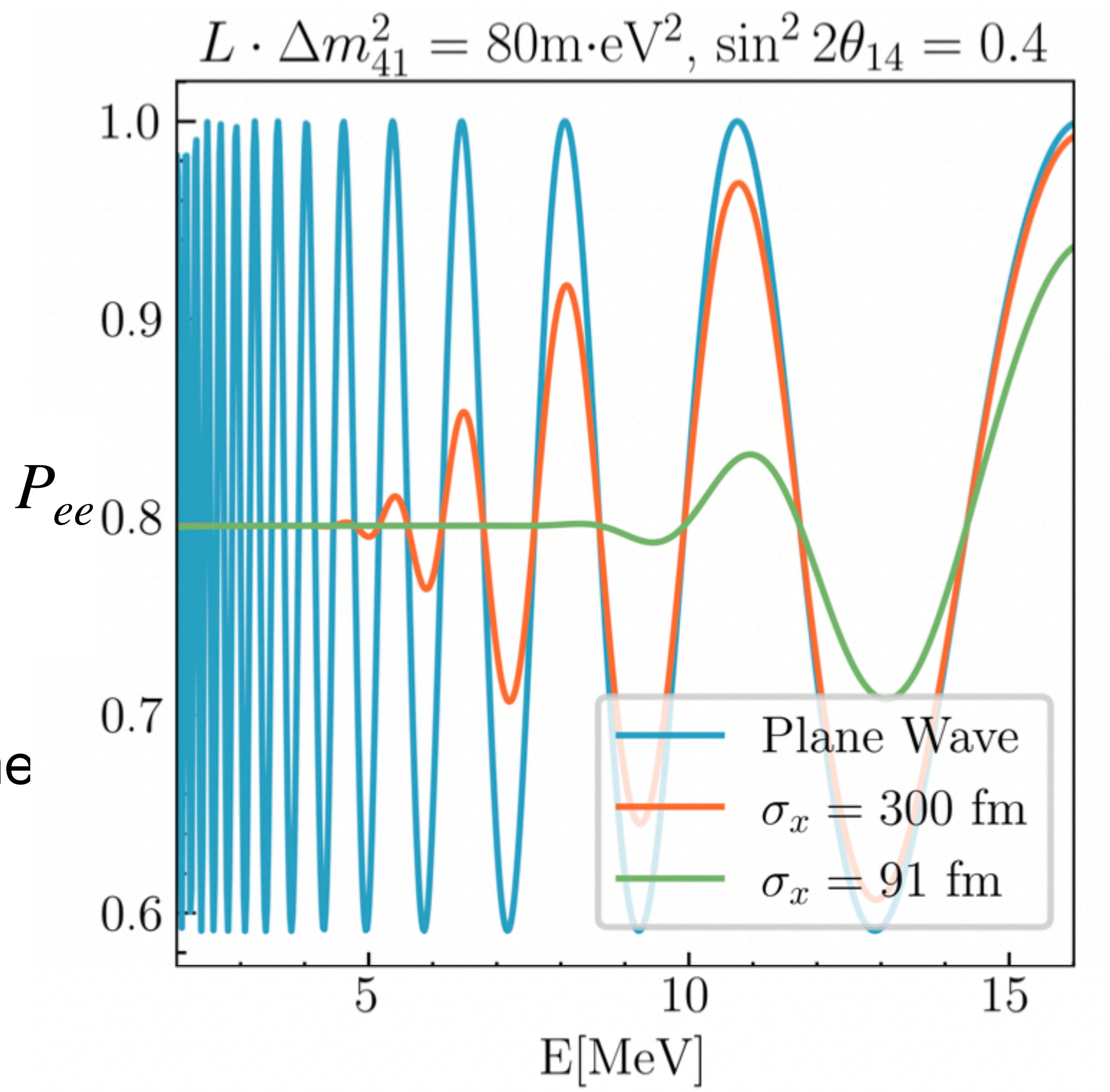

For very long distances ($L >> L^{coh}$), the oscillation probability become an incoherent sum of states

$$P_{\alpha\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2$$

Matter Effects

- As neutrinos propagate through matter, their interaction with it can modify their propagation.

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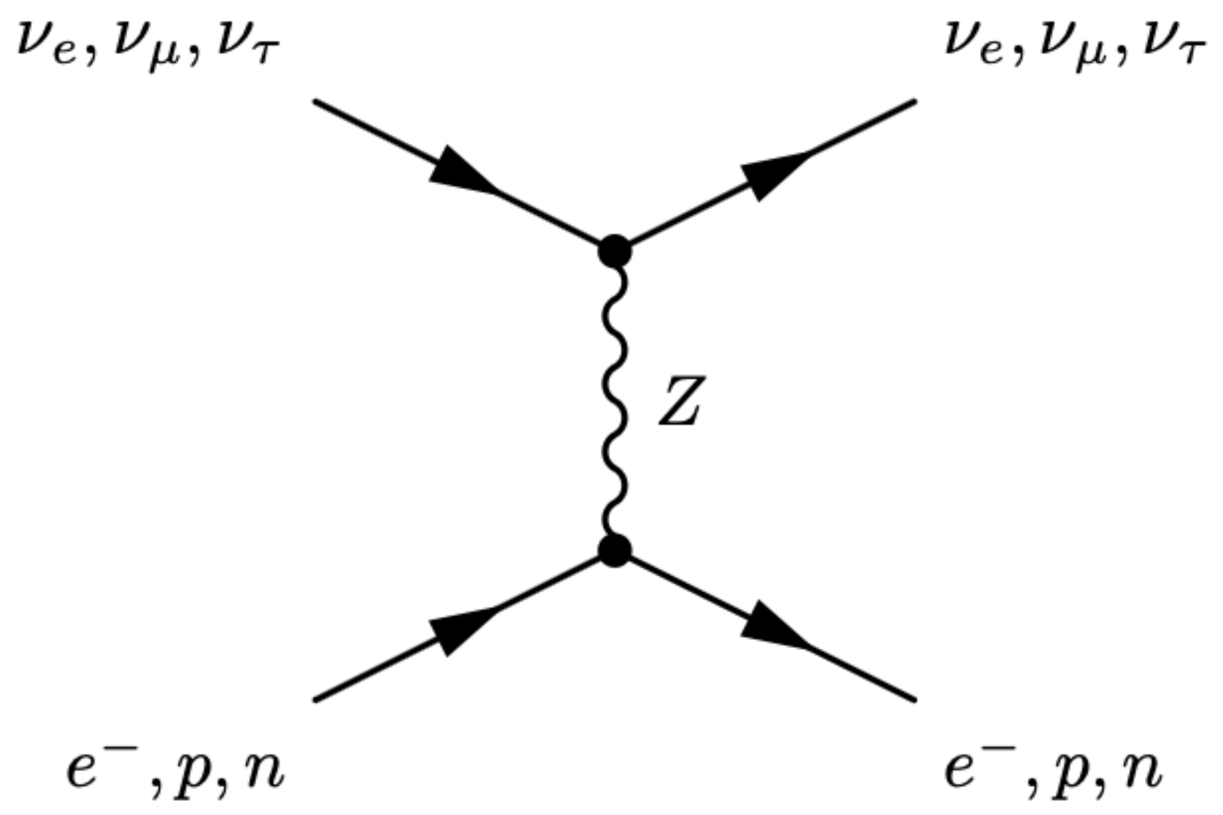
- At lower energies, the coherent forward elastic scattering of the neutrinos with the medium can modify the effective neutrino mass, leading to a modification of the flavor oscillations

Matter Effects

Neutrinos interact via NC with electrons, protons and neutrons in matter

$$V_{NC}^f = \sqrt{2} G_F N_f g_v^f$$

$$g_v^e = -\frac{1}{2} + 2\sin^2\theta_w \qquad g_v^p = \frac{1}{2} - 2\sin^2\theta_w \qquad g_v^n = -\frac{1}{2}$$



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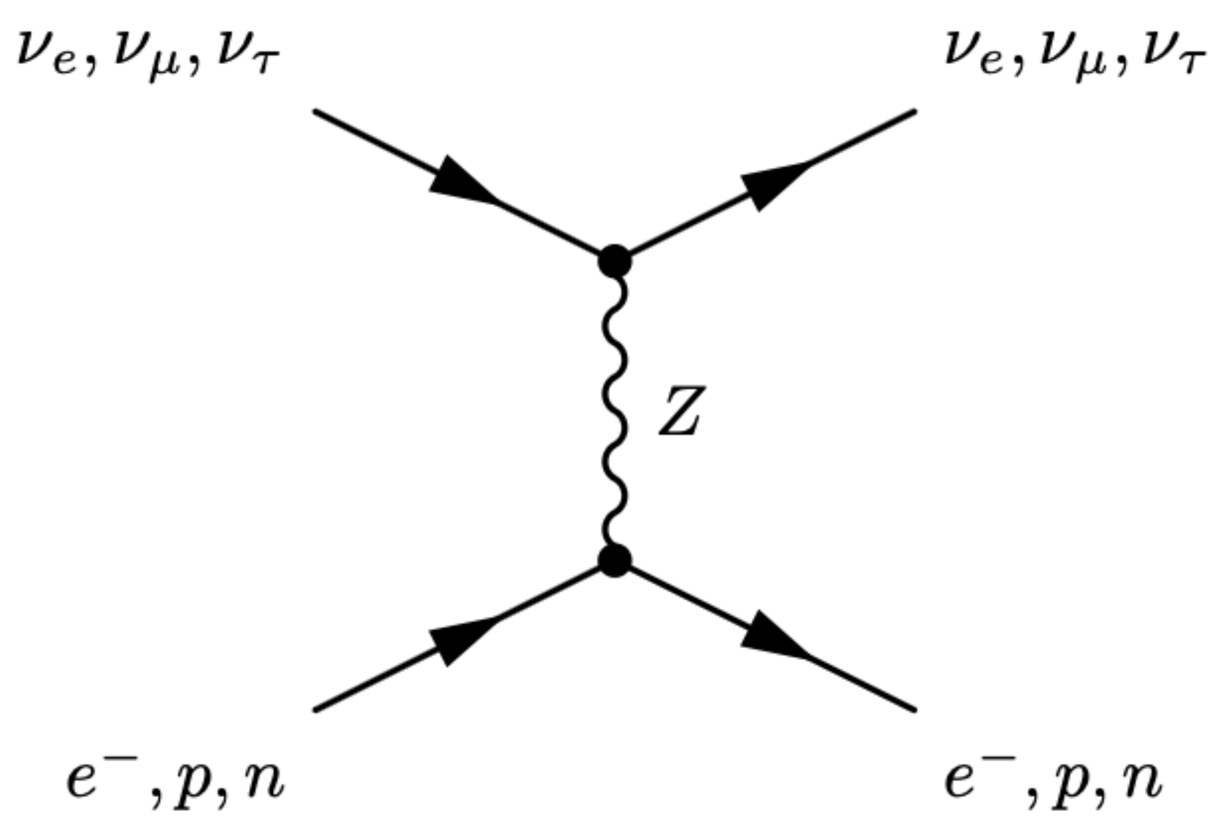

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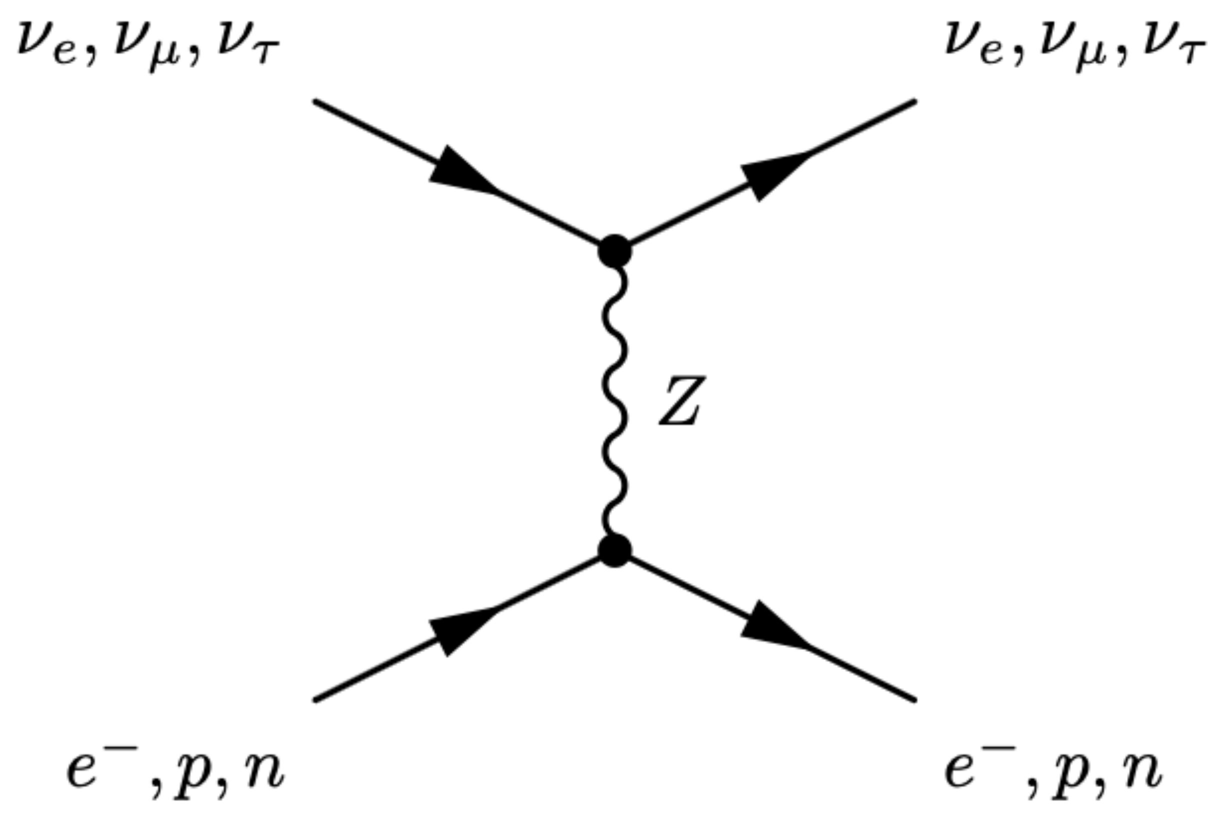

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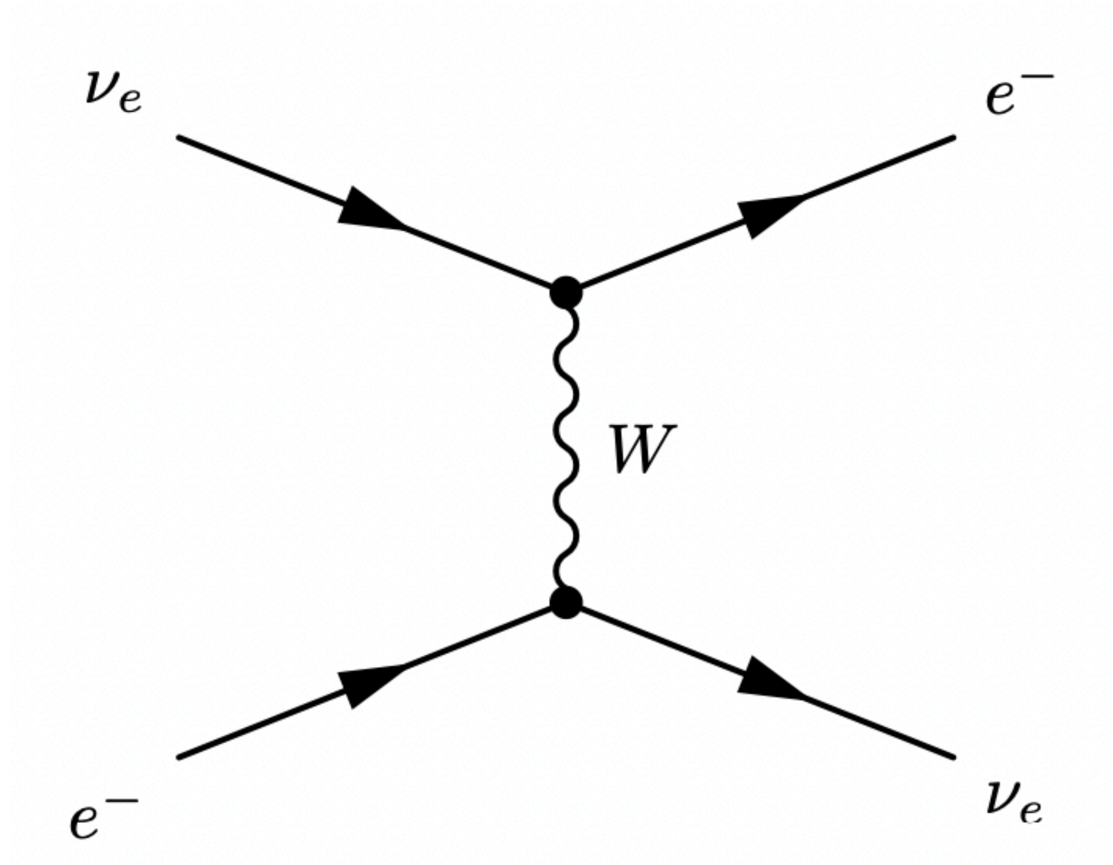
Electron neutrinos have a CC interaction with the electrons in the medium

$$V_{CC} = \sqrt{2} G_F N_e$$



Matter Effects

The effective matter potential for the neutrinos is given by

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- For antineutrinos, the effective potential has the opposite sign

$$V_\alpha^\nu = - V_\alpha^{\bar{\nu}}$$

Matter Effects

The evolution of the neutrinos in matter is described by the Schrödinger equation

$$i\frac{d\nu}{dE} = \frac{1}{2E_\nu}\left(U^\dagger \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) U \pm V_\alpha\right)\nu \qquad V_\alpha = 2\sqrt{2} G_F N_e E_\nu \text{diag}(1,0,0)$$

- The mixing between flavor and massive states depends on the electron density

- The effective neutrino mass is also affected by the matter effects

Matter Effects

Let's consider a two neutrino scenario, in this case, the neutrino evolution depends on θ and Δm^2

$$i\frac{d}{dE}\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix} = \left(\frac{1}{2E}\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix} + \begin{pmatrix}V_{CC} & 0\\ 0 & 0\end{pmatrix}\right)\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}$$

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After removing the global phases, the hamiltonian discribing the evolution is given by

$$H_{2x2} = \frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta + 2EV_{CC} & \Delta m^2 \sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta - 2EV_{CC}\end{pmatrix}$$

Matter Effects

Let's consider a two neutrino scenario, in this case, the neutrino evolution depends on θ and Δm^2

$$i\frac{d}{dE}\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix} = \left(\frac{1}{2E}\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix} + \begin{pmatrix}V_{CC} & 0\\ 0 & 0\end{pmatrix}\right)\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}$$

After removing the global phases, the hamiltonian discribing the evolution is given by

$$H_{2x2} = \frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta + 2EV_{CC} & \Delta m^2 \sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta - 2EV_{CC}\end{pmatrix}$$

The mixing between the flavor and the massive states in matter are obtained diagonalizing the effective Hamiltonian

$$U^T(\tilde{\theta})H_{2\times 2}U(\tilde{\theta}) = \frac{1}{4E}\text{diag}(-\Delta\tilde{m}^2, \Delta\tilde{m}^2)$$

For constant matter

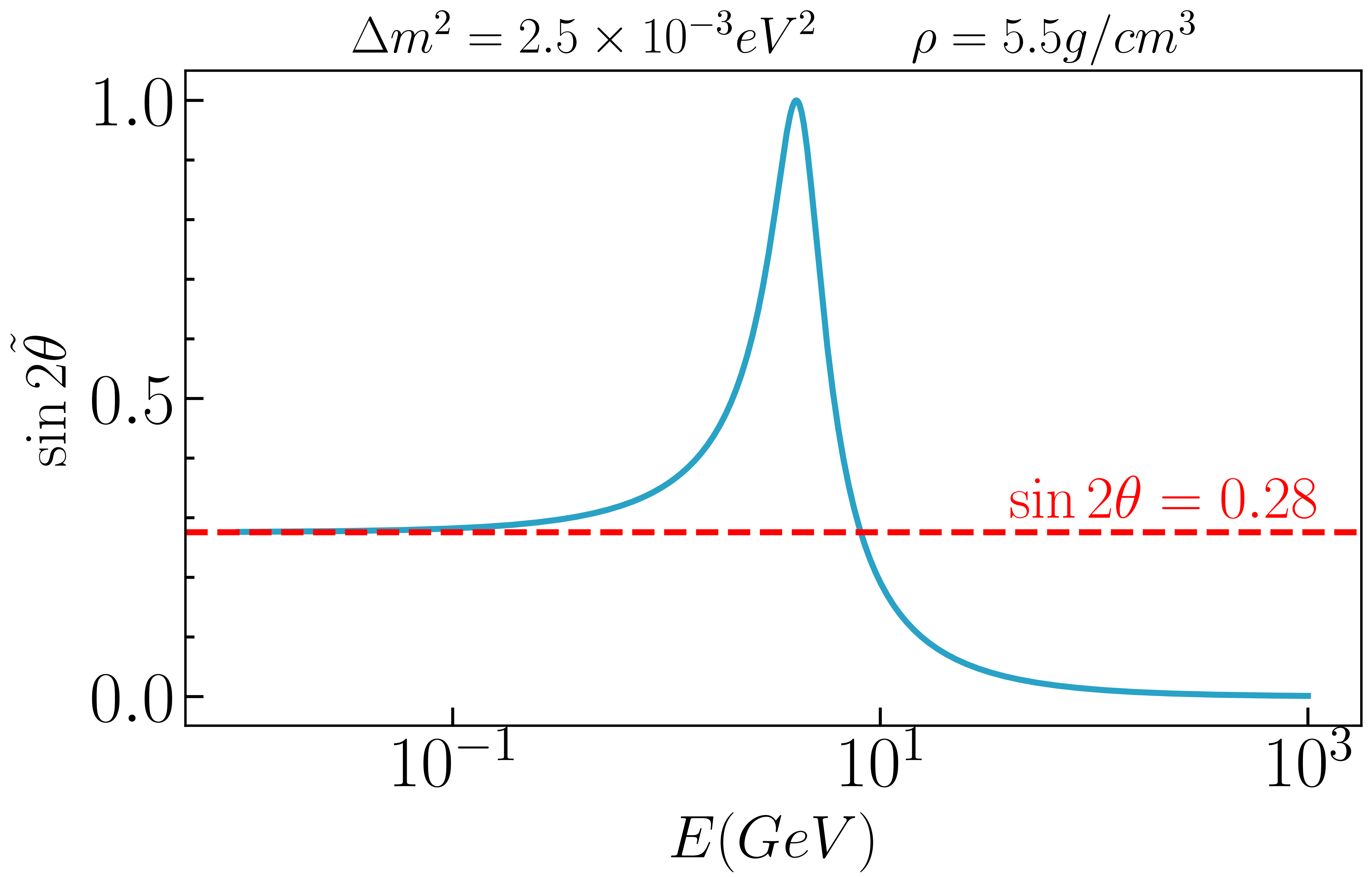
Matter Effects

The mixing between the flavor and the massive states in matter are obtained diagonalizing the effective Hamiltonian

$$U^T(\tilde{\theta})H_{2\times2}U(\tilde{\theta}) = \frac{1}{4E}\text{diag}(-\Delta\tilde{m}^2, \Delta\tilde{m}^2)$$

The mixing can be enhanced due to the matter effects

$$\sin 2\tilde{\theta} = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - 2EV_{CC}/\Delta m^2)^2 + \sin^2 2\theta}}$$



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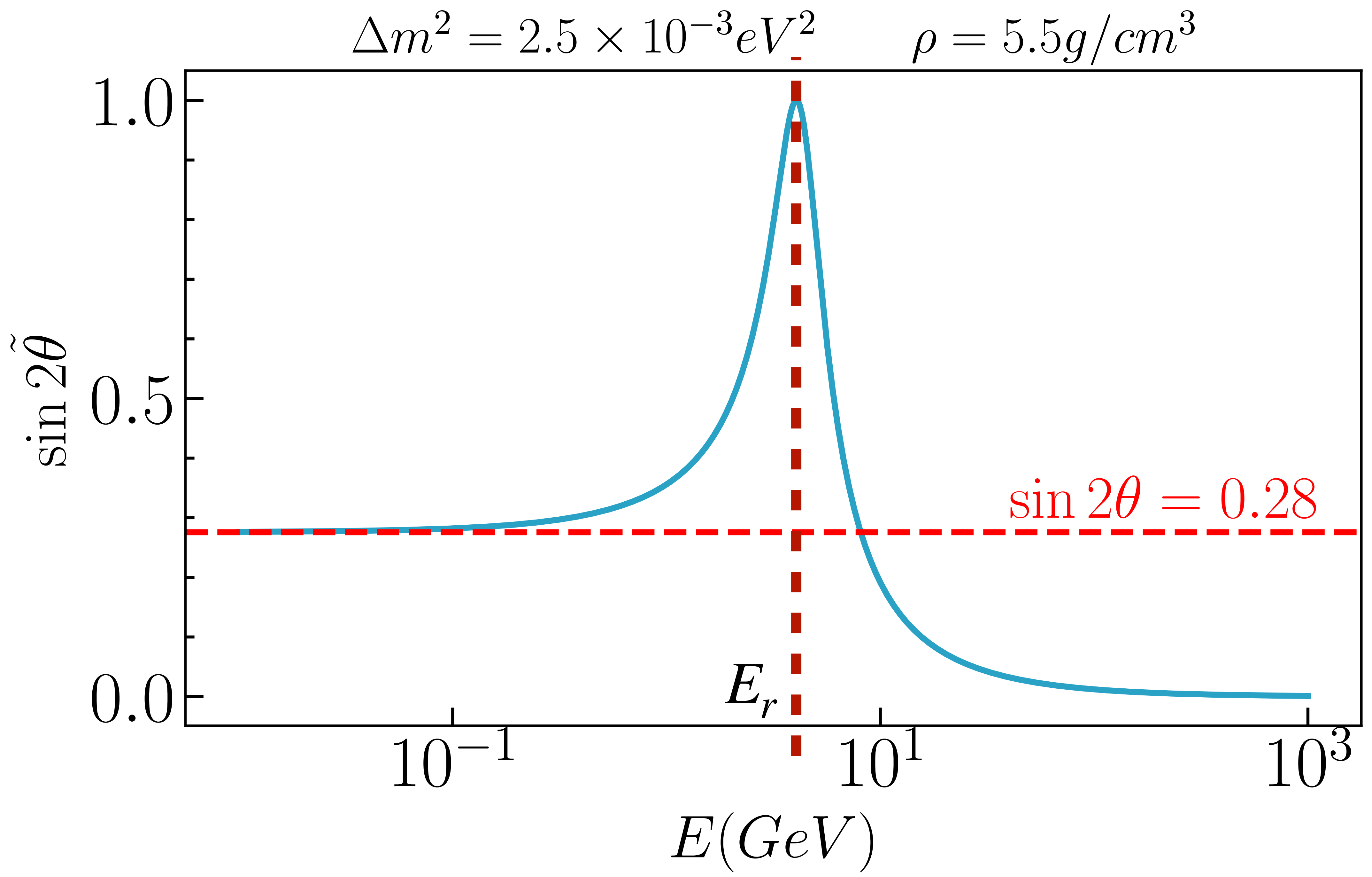
$$\sin 2\tilde{\theta} = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - 2EV_{CC}/\Delta m^2)^2 + \sin^2 2\theta}}$$

For some values of E and density, there is a resonant flavor conversion

$$\cos 2\theta \Delta m^2 = 2E_r V^r_{CC} \quad \longrightarrow \quad \tilde{\theta} = 45^\circ$$



Matter Effects

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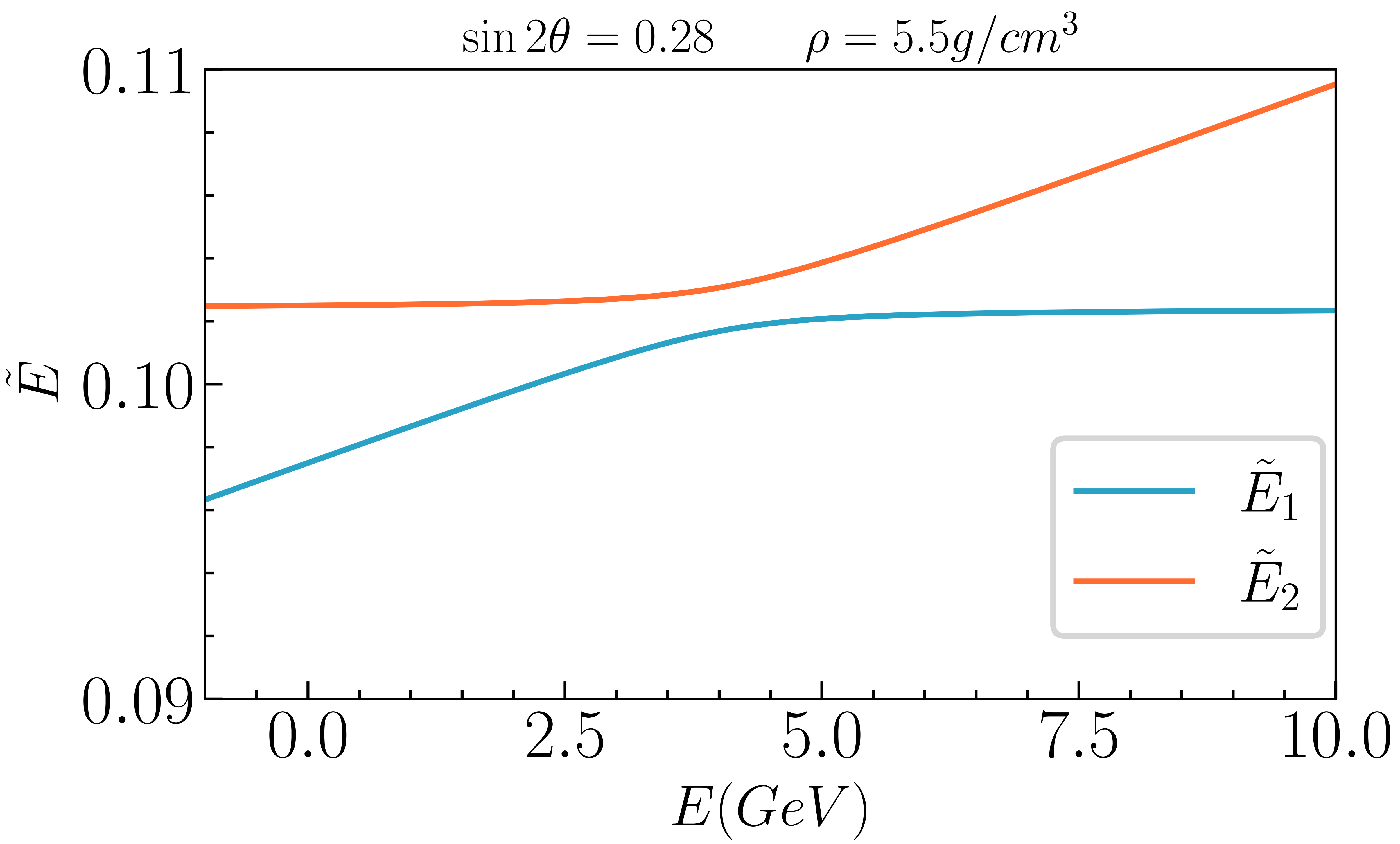
$$U^T(\tilde{\theta})H_{2\times 2}U(\tilde{\theta}) = \frac{1}{4E}\text{diag}(-\Delta\tilde{m}^2, \Delta\tilde{m}^2)$$

The effective neutrino mass changes in matter

$$\tilde{E}_{1,2} = \frac{E_1 + E_2}{2} + V_{CC}E$$
$$\mp \Delta m^2 \sqrt{(\cos 2\theta - 2EV_{CC}/\Delta m^2)^2 + \sin^2 2\theta}$$



Ivan Martinez-Soler (IPPP)

Matter Effects

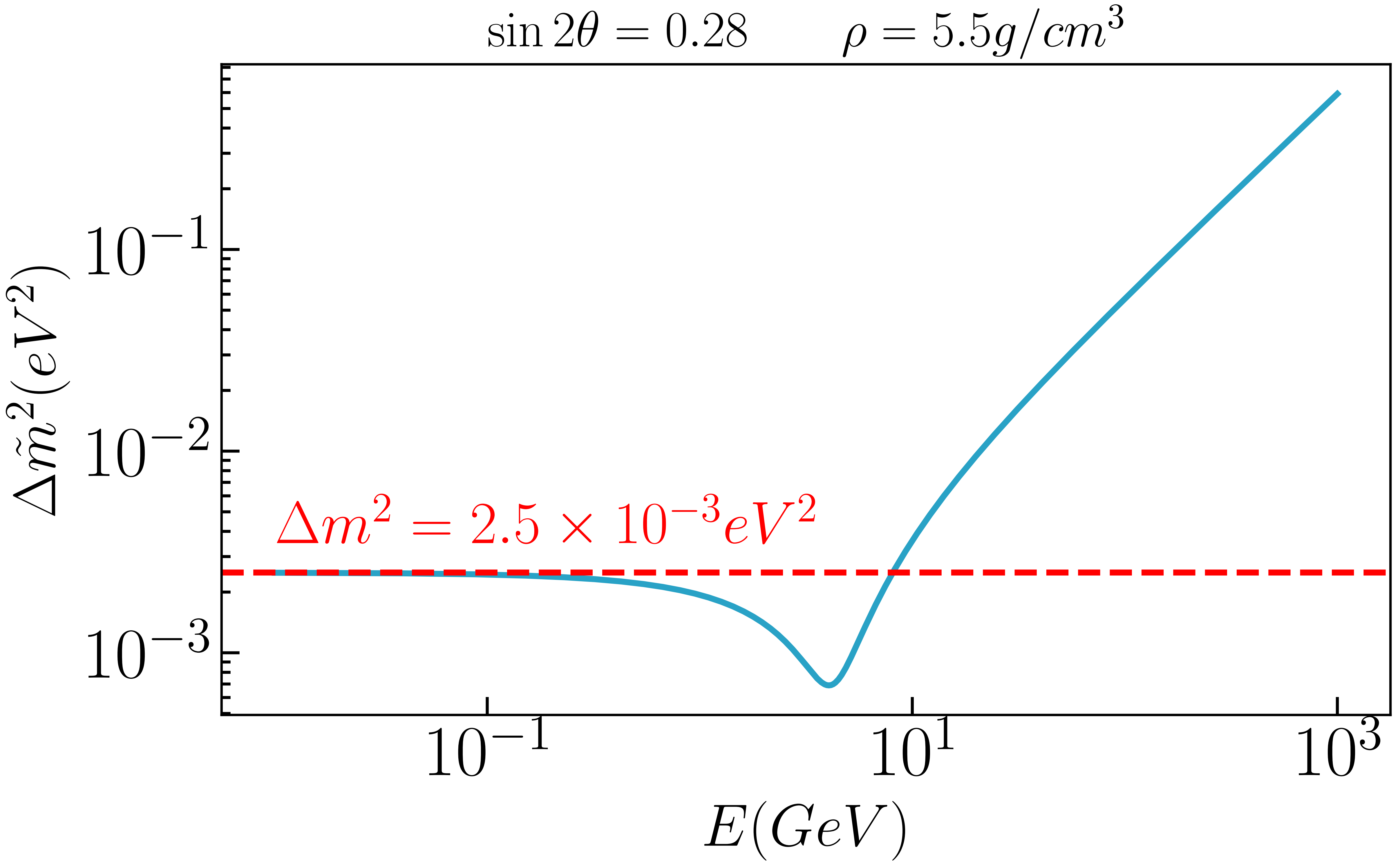
The mixing between the flavor and the massive states in matter are obtained diagonalizing the effective Hamiltonian

$$U^T(\tilde{\theta})H_{2\times 2}U(\tilde{\theta}) = \frac{1}{4E}\text{diag}(-\Delta\tilde{m}^2, \Delta\tilde{m}^2)$$

The oscillation length also gets modified in matter

$$L^{osc} = \frac{2\pi E}{\Delta\tilde{m}^2}$$

$$\Delta\tilde{m}^2 = \Delta m^2\sqrt{(\cos 2\theta - 2EV_{CC}/\Delta m^2)^2 + \sin^2 2\theta}$$



Matter Effects

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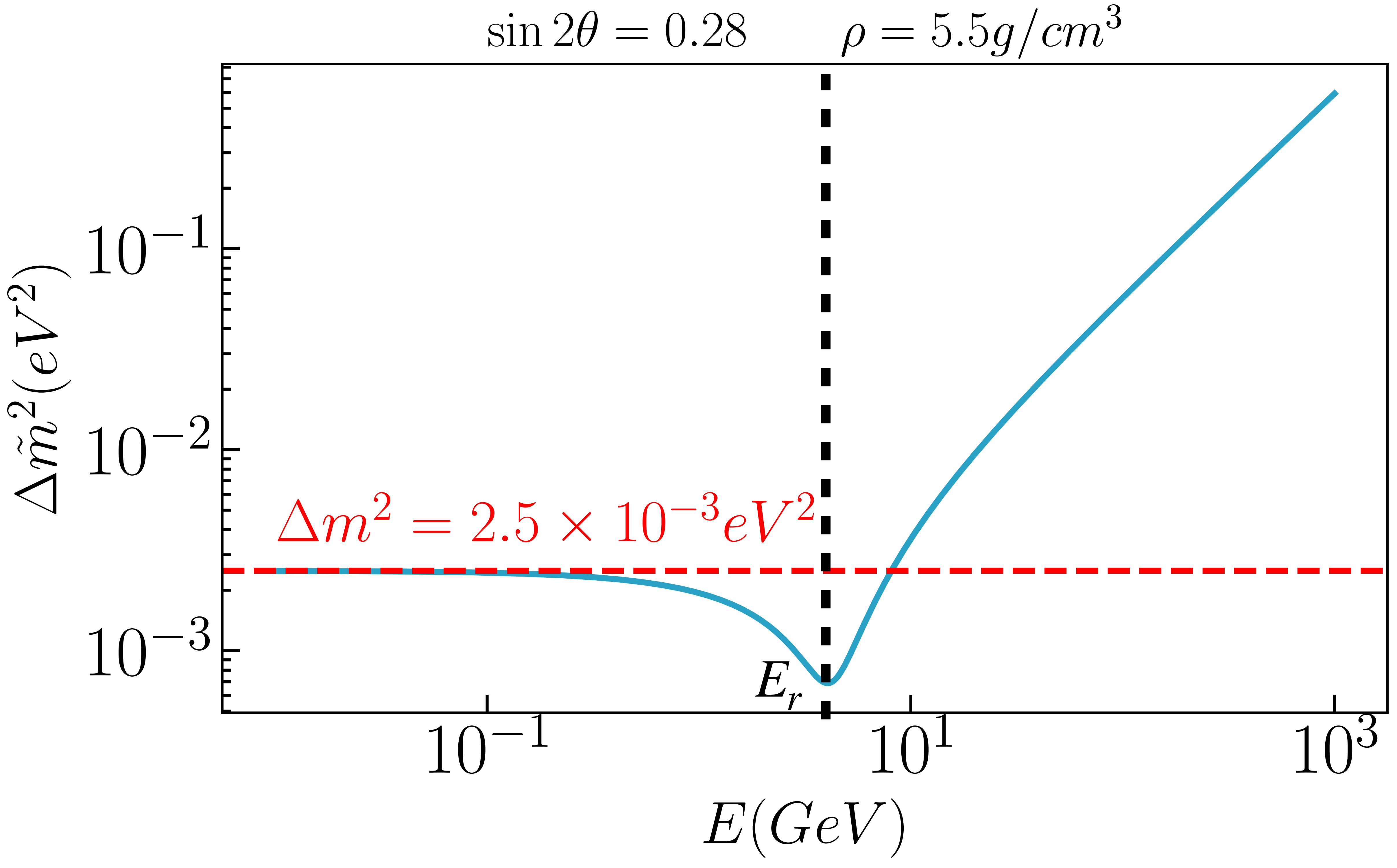
$$U^T(\tilde{\theta})H_{2\times 2}U(\tilde{\theta}) = \frac{1}{4E}\text{diag}(-\Delta\tilde{m}^2, \Delta\tilde{m}^2)$$

At the resonance, the oscillation length becomes larger than in vacuum

$$L_r^{osc} = \frac{L_{vac}^{osc}}{\sin 2\theta}$$

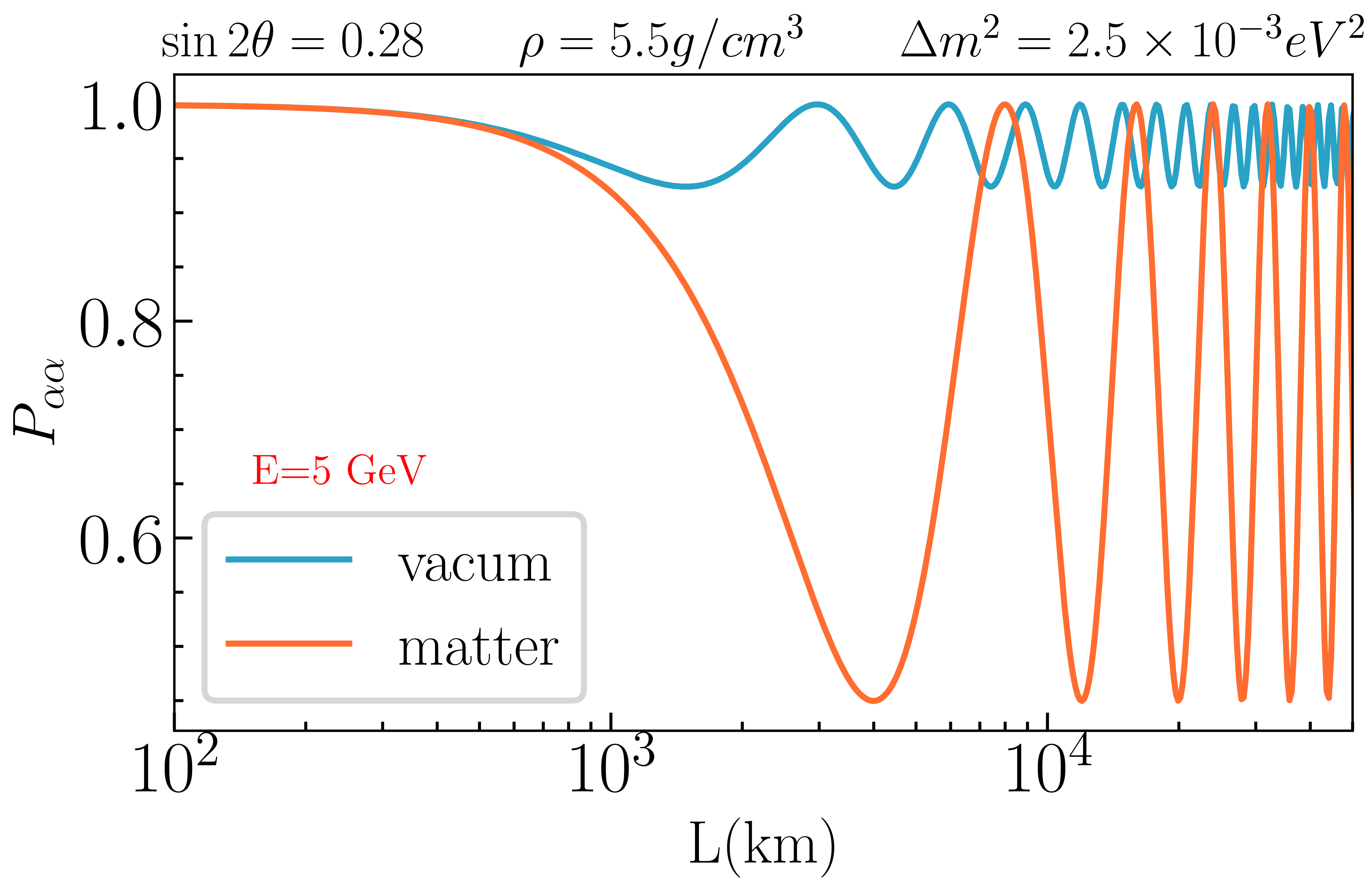


Matter Effects

In the case of constant matter, and for the two-neutrino approximation, the oscillation probability is given by

$$P^{const}_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\tilde{\theta} \sin^2\left(\frac{\Delta\tilde{m}^2 L}{4E}\right)$$

Matter effects modify both the **oscillation length** and **amplitude**



Matter Effects: MSW

If matter varies along the neutrino trajectory, the same happens with the effective mass and the mixing

Matter Effects: MSW

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In the mass basis, the Hamiltonian is non-diagonal

$$i\frac{d}{dE}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \frac{1}{4E}\begin{pmatrix}-\Delta\tilde{m}^2(x) & 4Ed\tilde{\theta}/dx\\ -4Ed\tilde{\theta}/dx & \Delta\tilde{m}^2(x)\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

- The off-diagonal term generates a transition between ν_1 and ν_2

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- The off-diagonal term generates a transition between ν_1 and ν_2

- The transition between the massive states will not happen if the diagonal terms are larger than the off-diagonal (adiabatic regime)

$$\gamma = \frac{\Delta\tilde{m}^2}{4Ed\tilde{\theta}/dx} >> 1$$

⟵ Adiabatic condiction

Matter Effects: MSW

In the adiabatic limit, each massive state evolves independently

$$P^{adb}_{\nu_\alpha \to \nu_\alpha} = \frac{1}{2} + \frac{1}{2}\cos 2\tilde{\theta}^i \cos 2\tilde{\theta}^f + \frac{1}{2}\sin 2\tilde{\theta}^i \sin 2\tilde{\theta}^f \cos\left(\int dx \frac{\Delta\tilde{m}^2(x)}{2E}\right)$$

- Oscillation probability depends only on mixing at the initial ($\tilde{\theta}^i$) and final ($\tilde{\theta}^f$) points of the path

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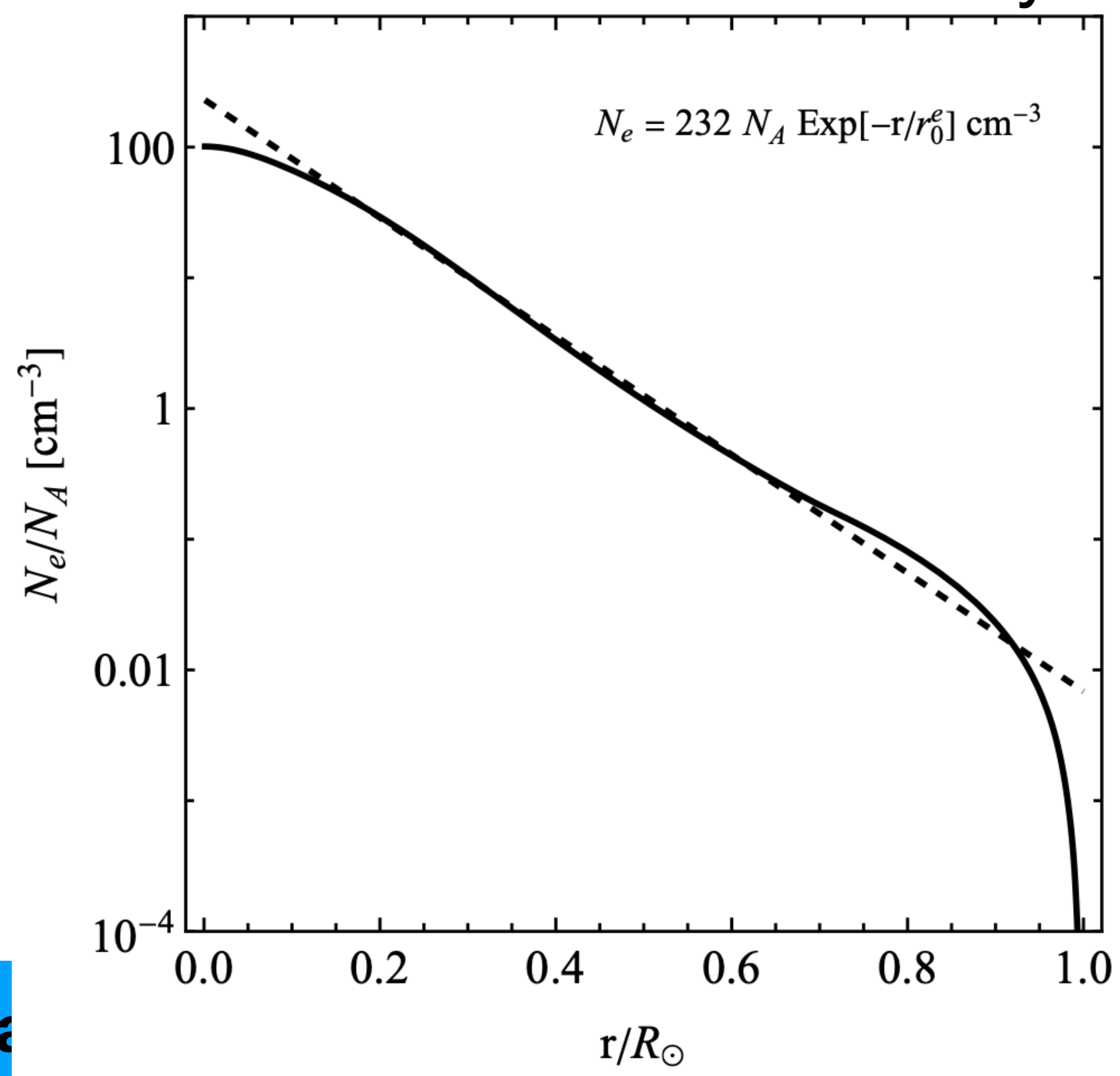
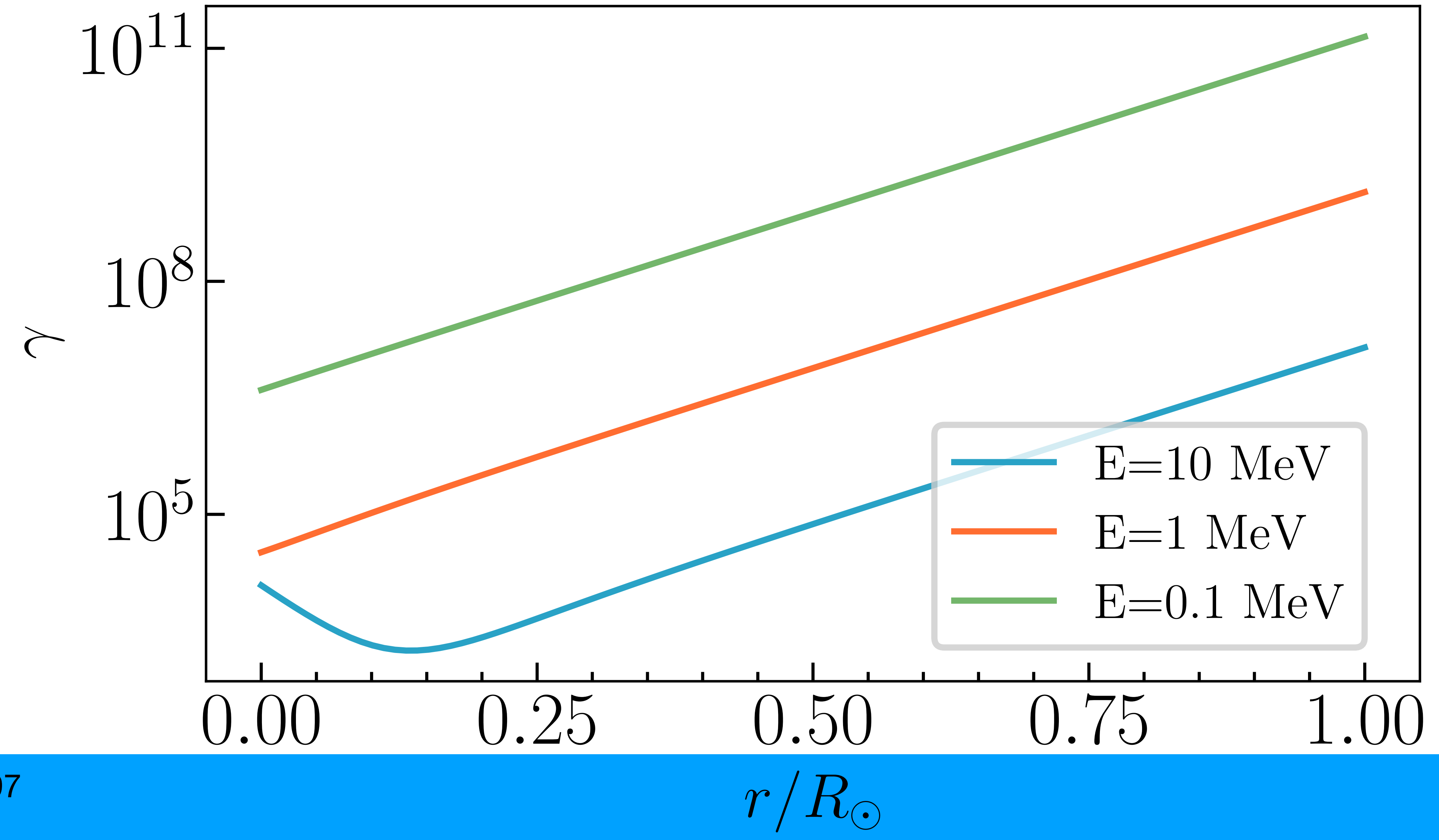
- Oscillation probability depends only on mixing at the initial ($\tilde{\theta}^i$) and final ($\tilde{\theta}^f$) points of the path
- The adiabatic regime describes the neutrino evolution inside the stars: the Sun, supernovas…

Solar electron density



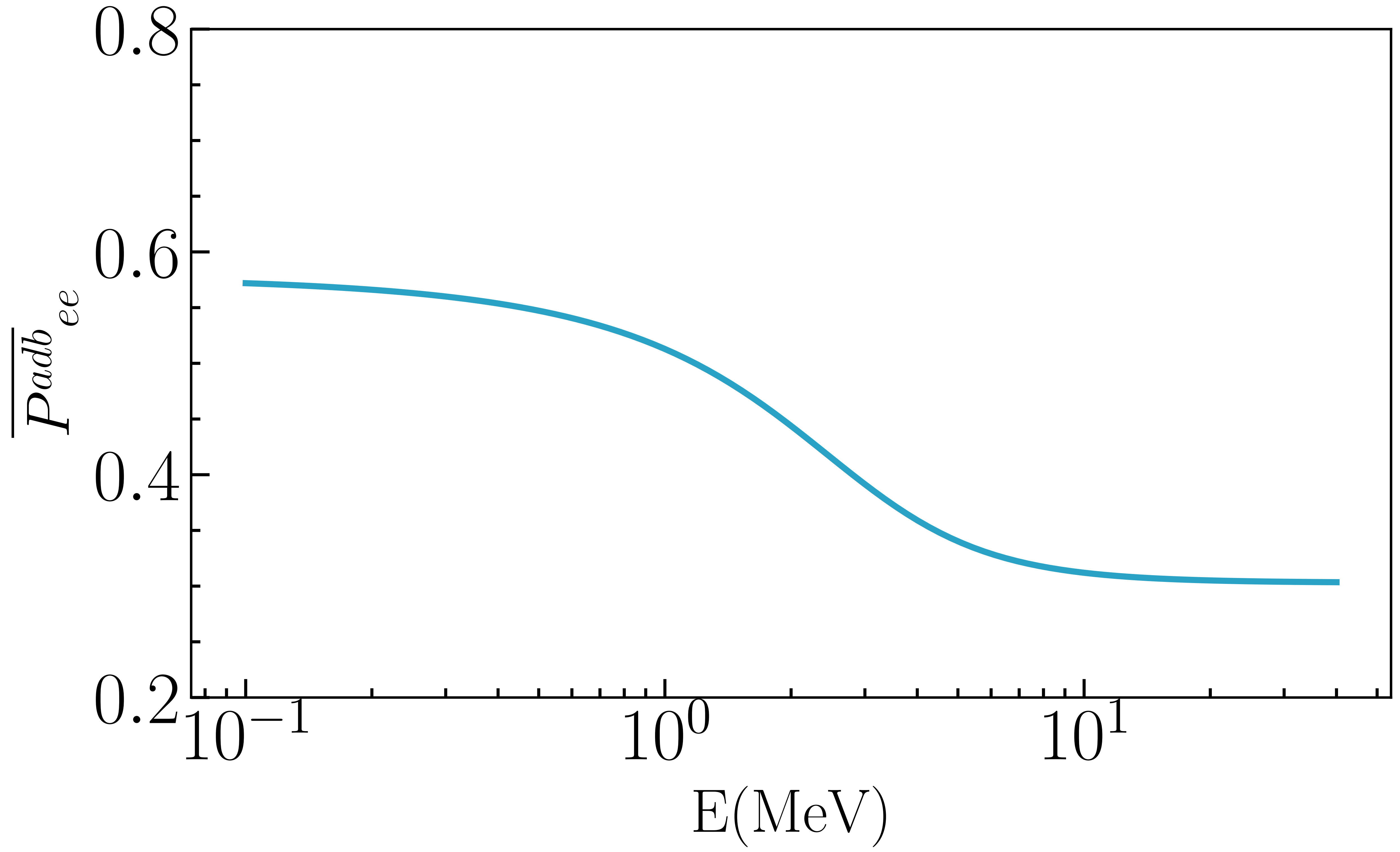
For the solar potential $\gamma > 1$



Matter Effects: MSW

In the case of the Sun, the long distance averages out the phase term

$$\overline{P^{adb}}_{\nu_e\to\nu_e} = \frac{1}{2} + \frac{1}{2}\cos 2\tilde{\theta}^i \cos 2\theta$$



Ivan Martinez-Soler (IPPP)

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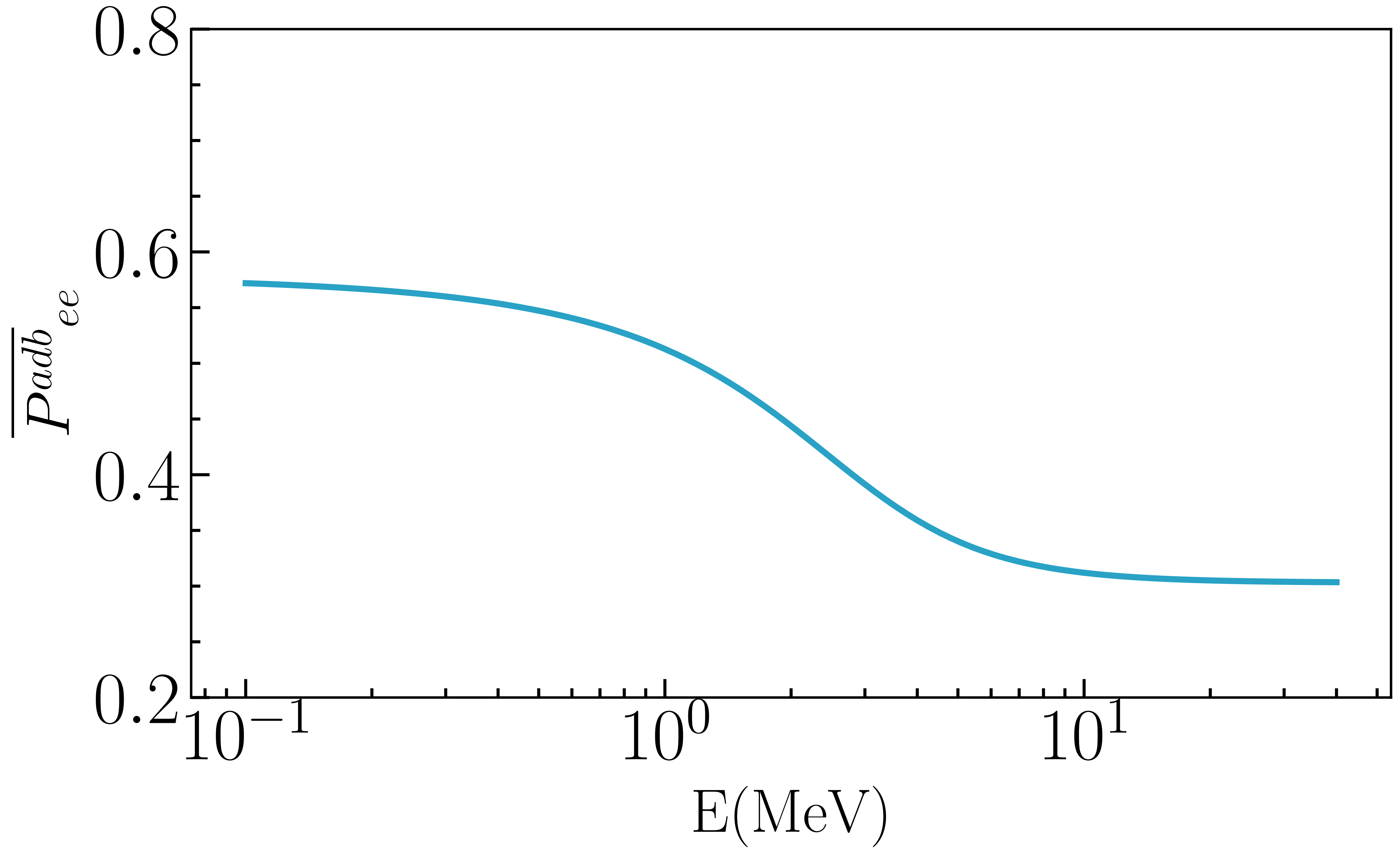
At the end of the path, the mixing coincides with vacuum

$$\tilde{\theta}^f = \theta$$



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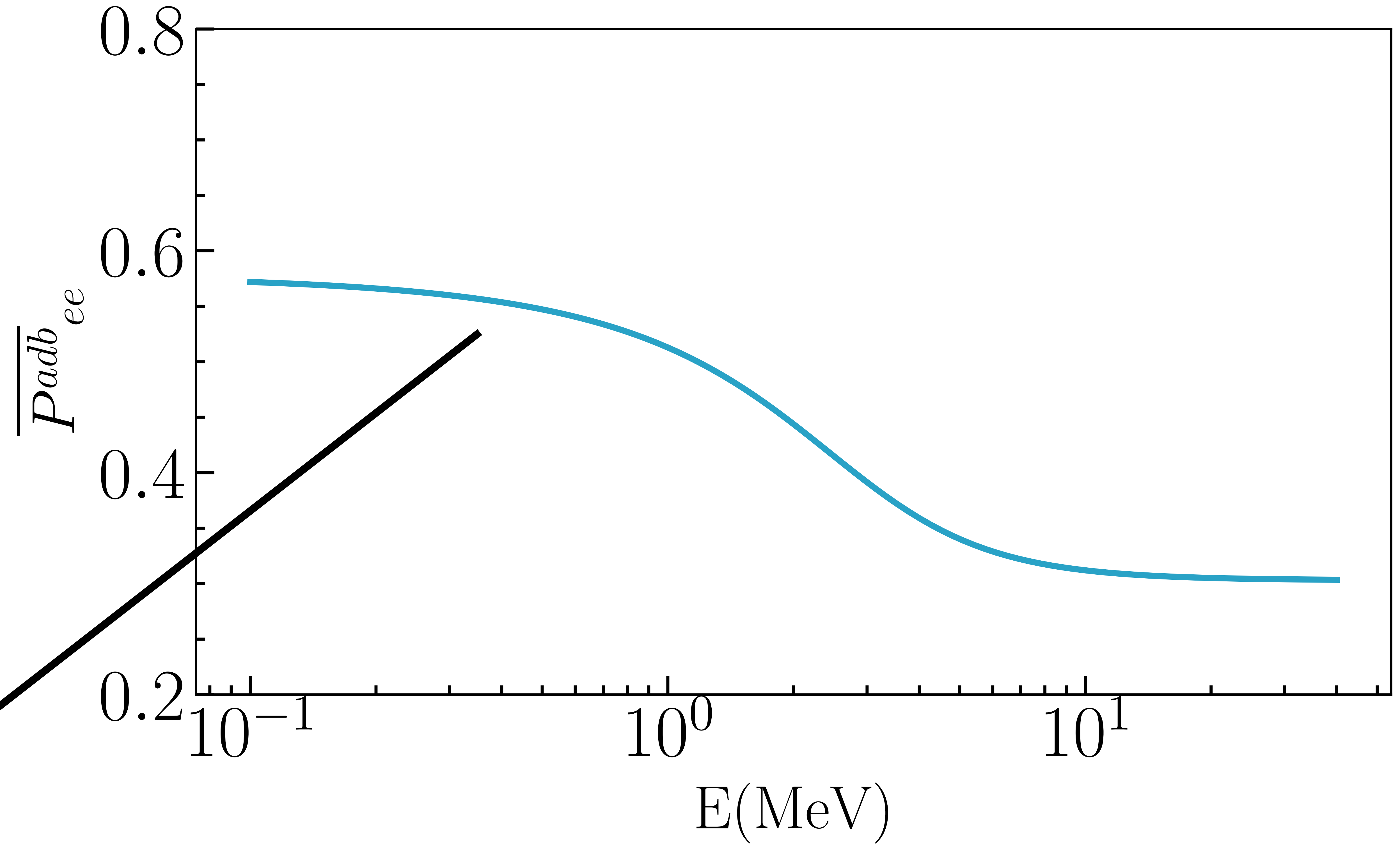

At low energies, matter effects are small, and neutrino evolution is effectively **vacuum-like**

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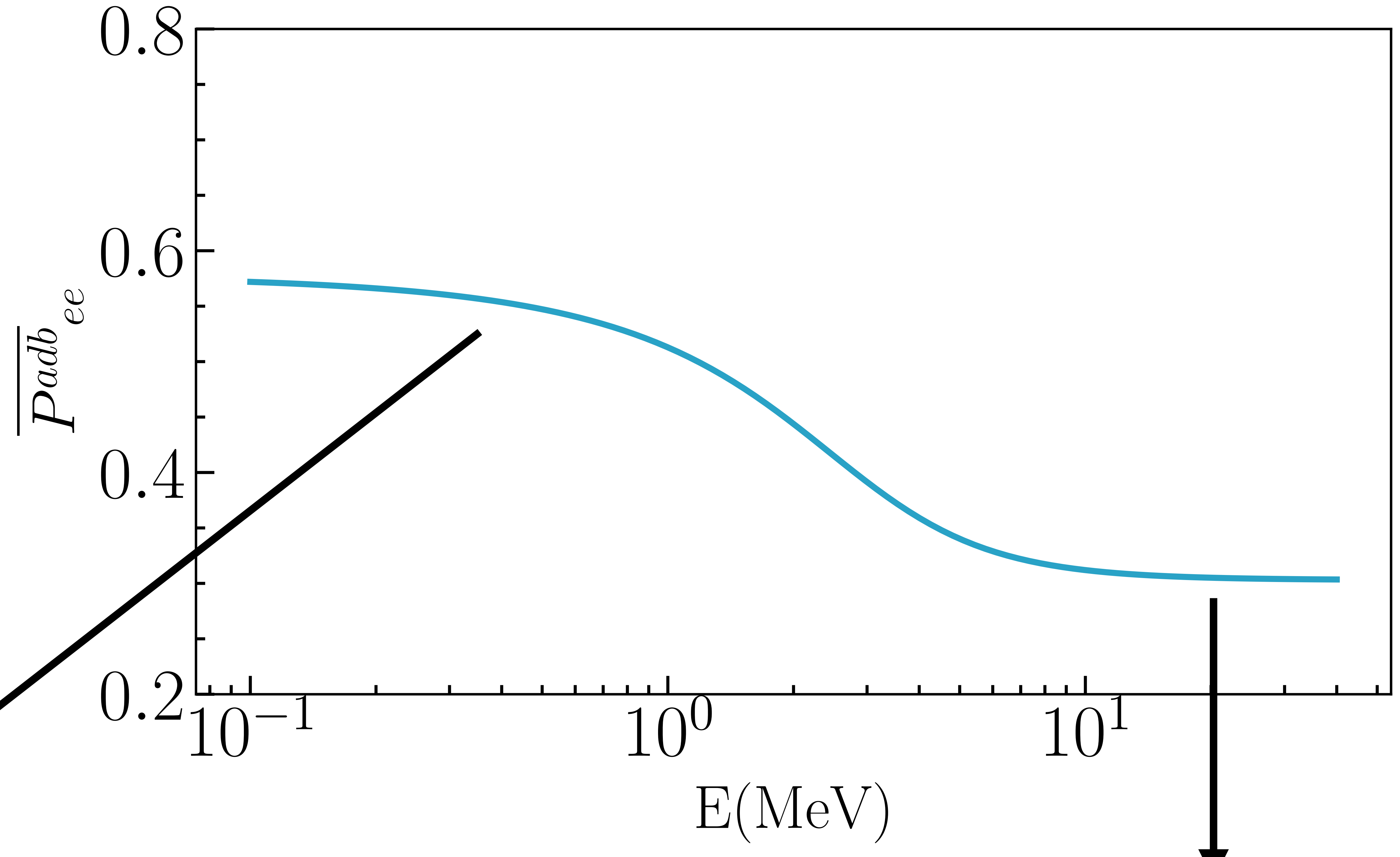

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$$\tilde{\theta}^i = \theta$$

At higher energies, **matter** effects **dominate**

$$\tilde{\theta}^i = 90^\circ \longrightarrow \nu_e \simeq \nu_2$$

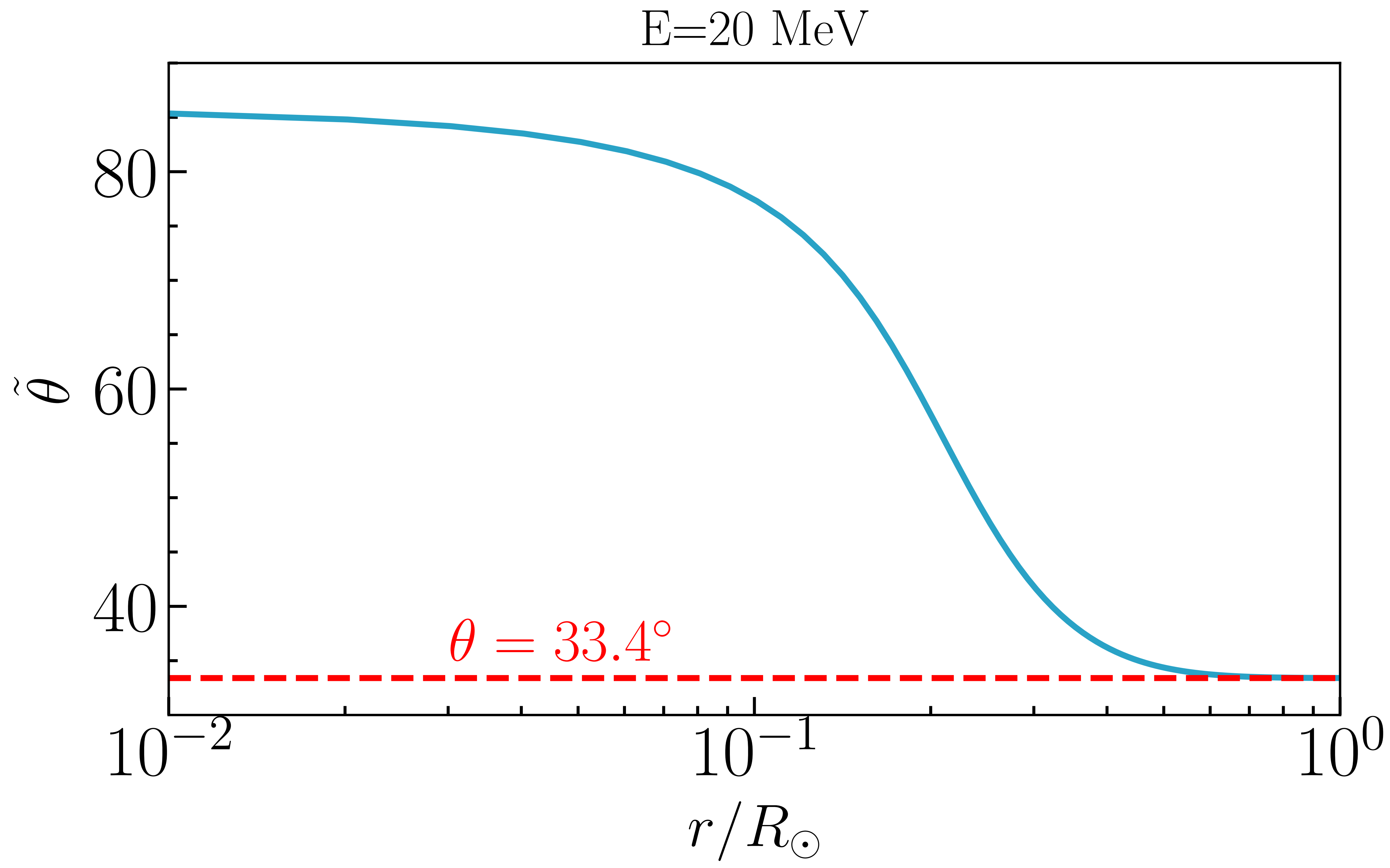
In the denser region of the Sun

Matter Effects: MSW

To understand flavor evolution, we study how the effective mixing angle changes inside the Sun

Let's consider

$$|\nu_2\rangle \simeq \sin\tilde{\theta}|\nu_e\rangle \simeq +\cos\tilde{\theta}|\nu_x\rangle$$



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Good approximation if θ_{13} is small, $\theta = \theta_{12}$ and

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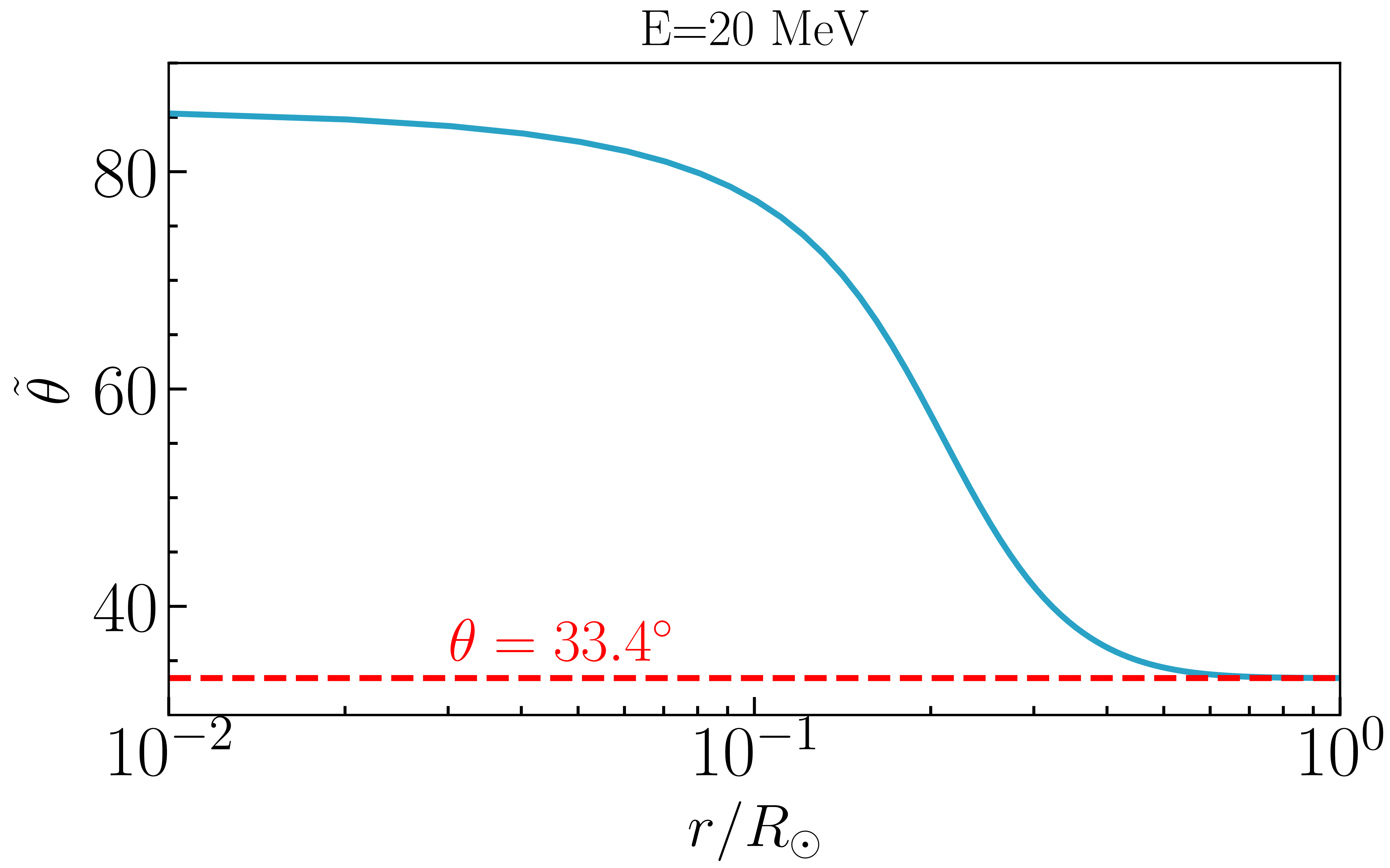

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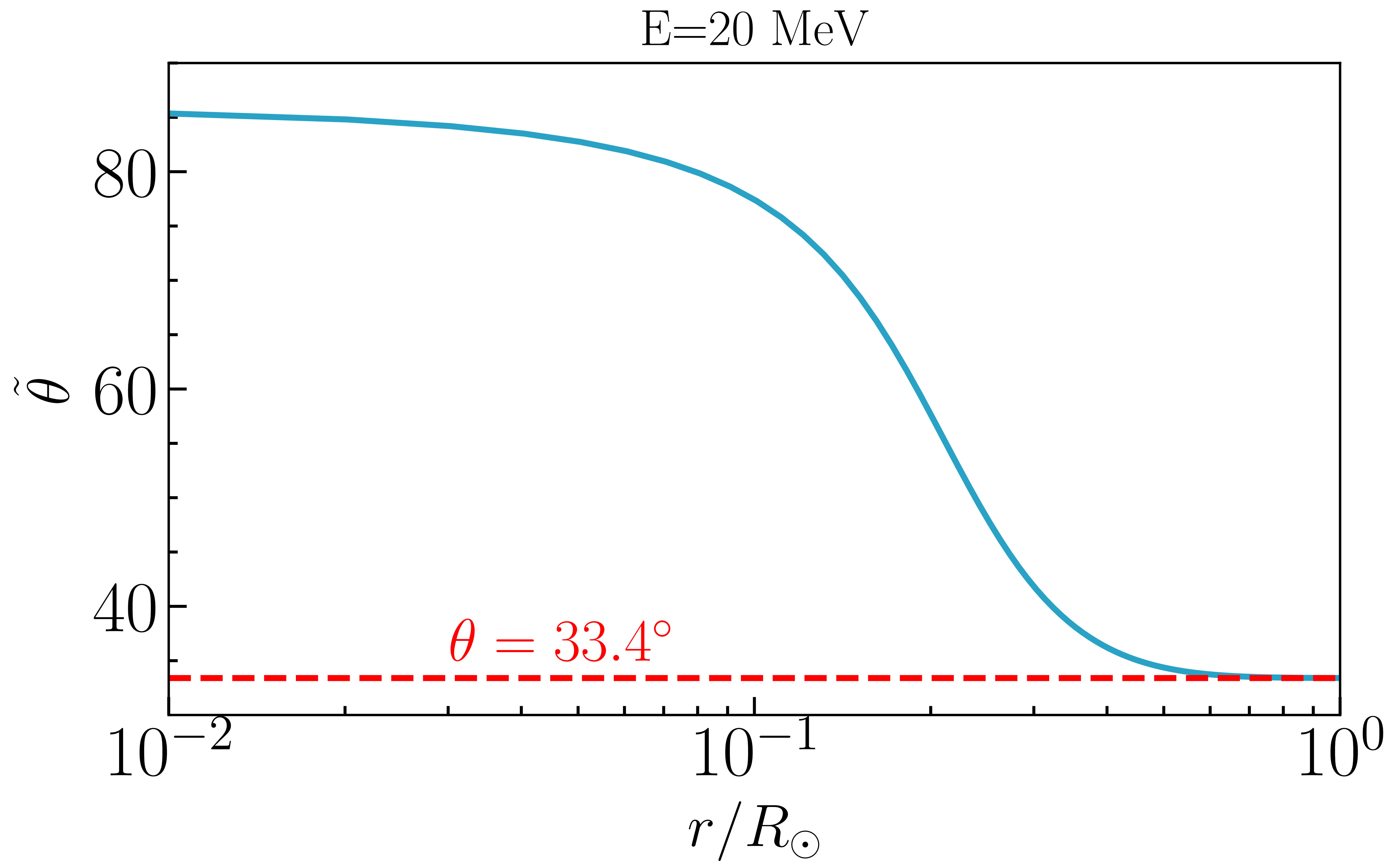

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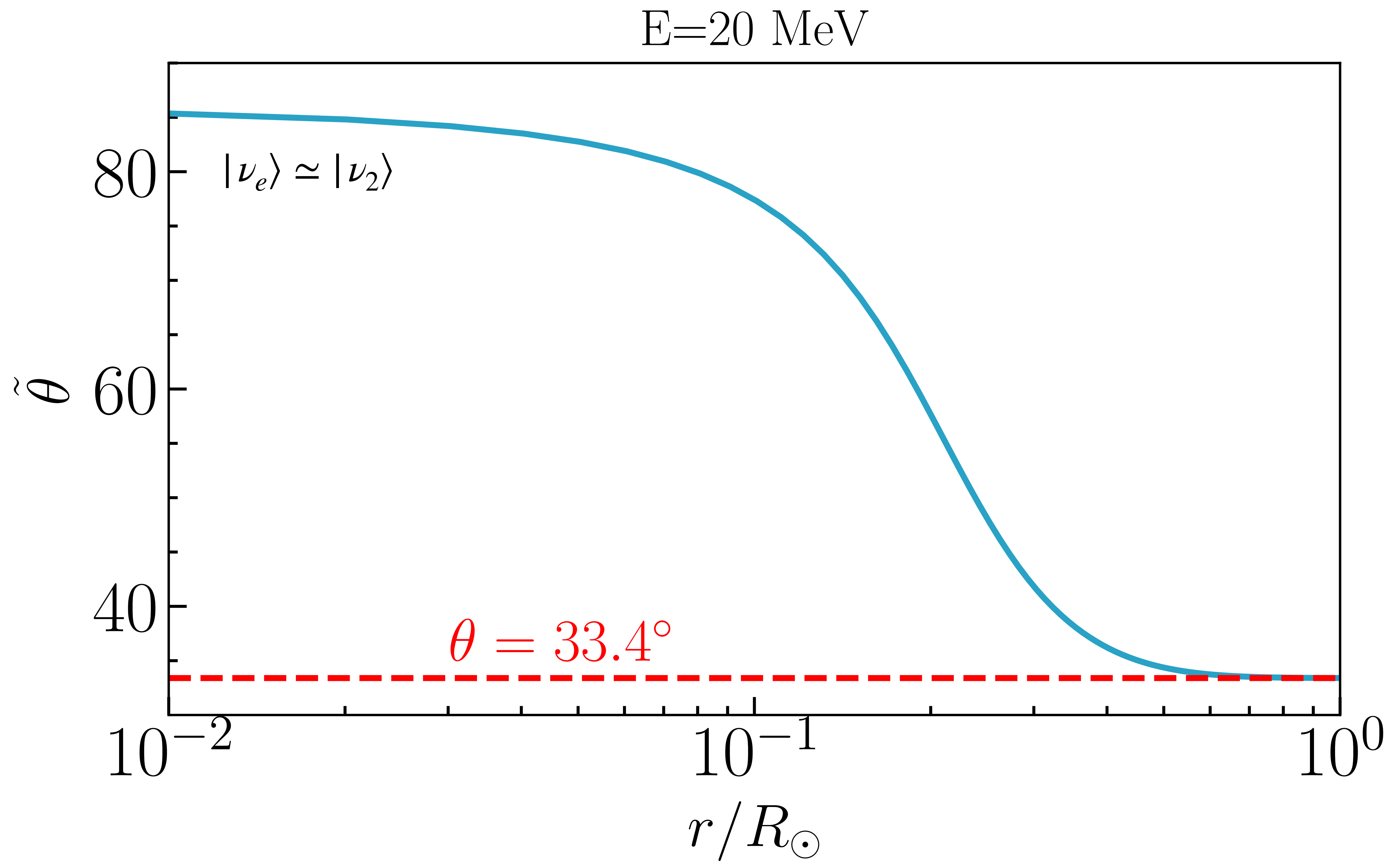

The Sun mainly produces ν_e:

- In the denser part of the Sun $|\nu_e\rangle \simeq |\nu_2\rangle$

Ivan Martinez-Soler (IPPP)

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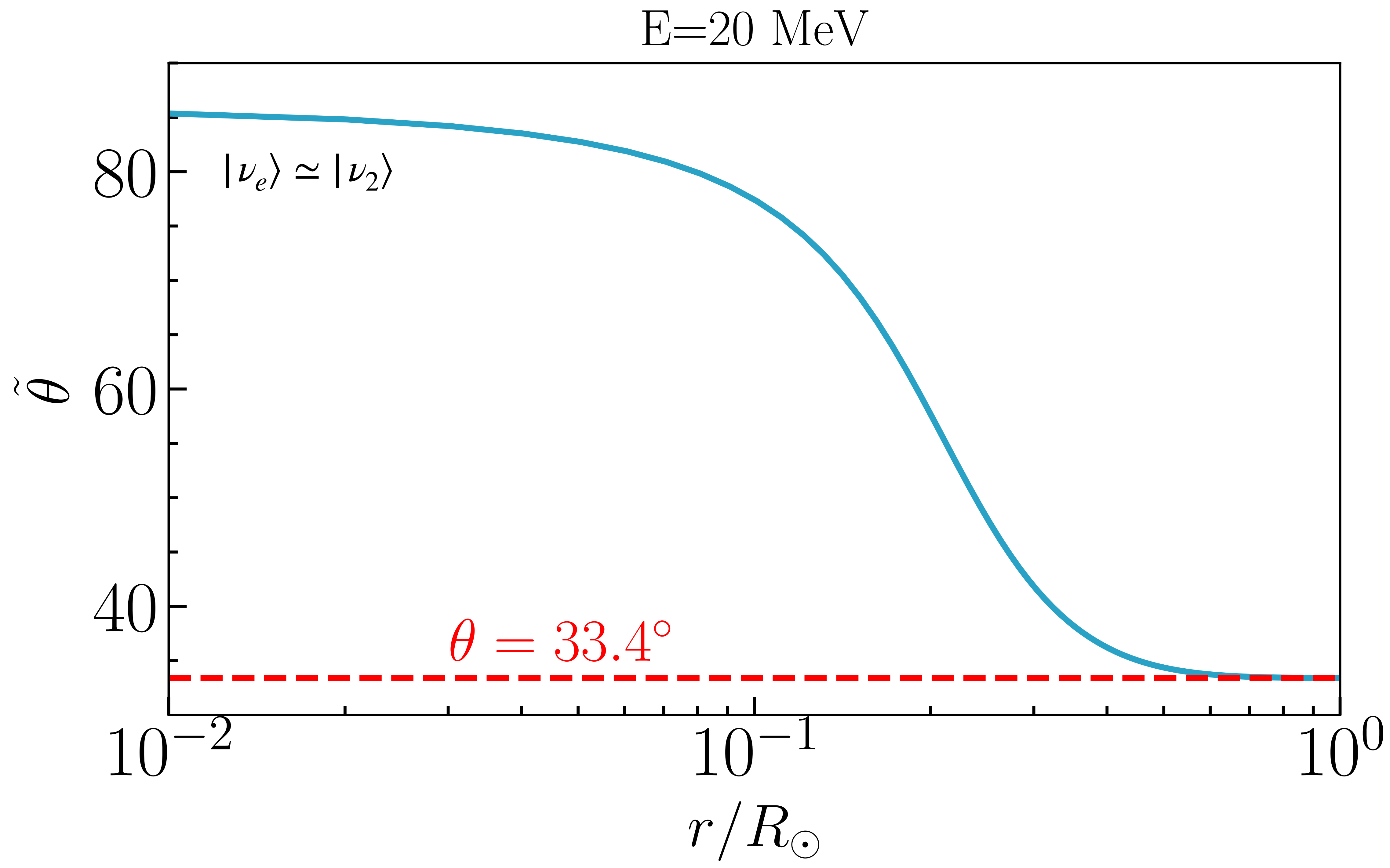

The Sun mainly produces ν_e:

- In the denser part of the Sun $|\nu_e\rangle \simeq |\nu_2\rangle$
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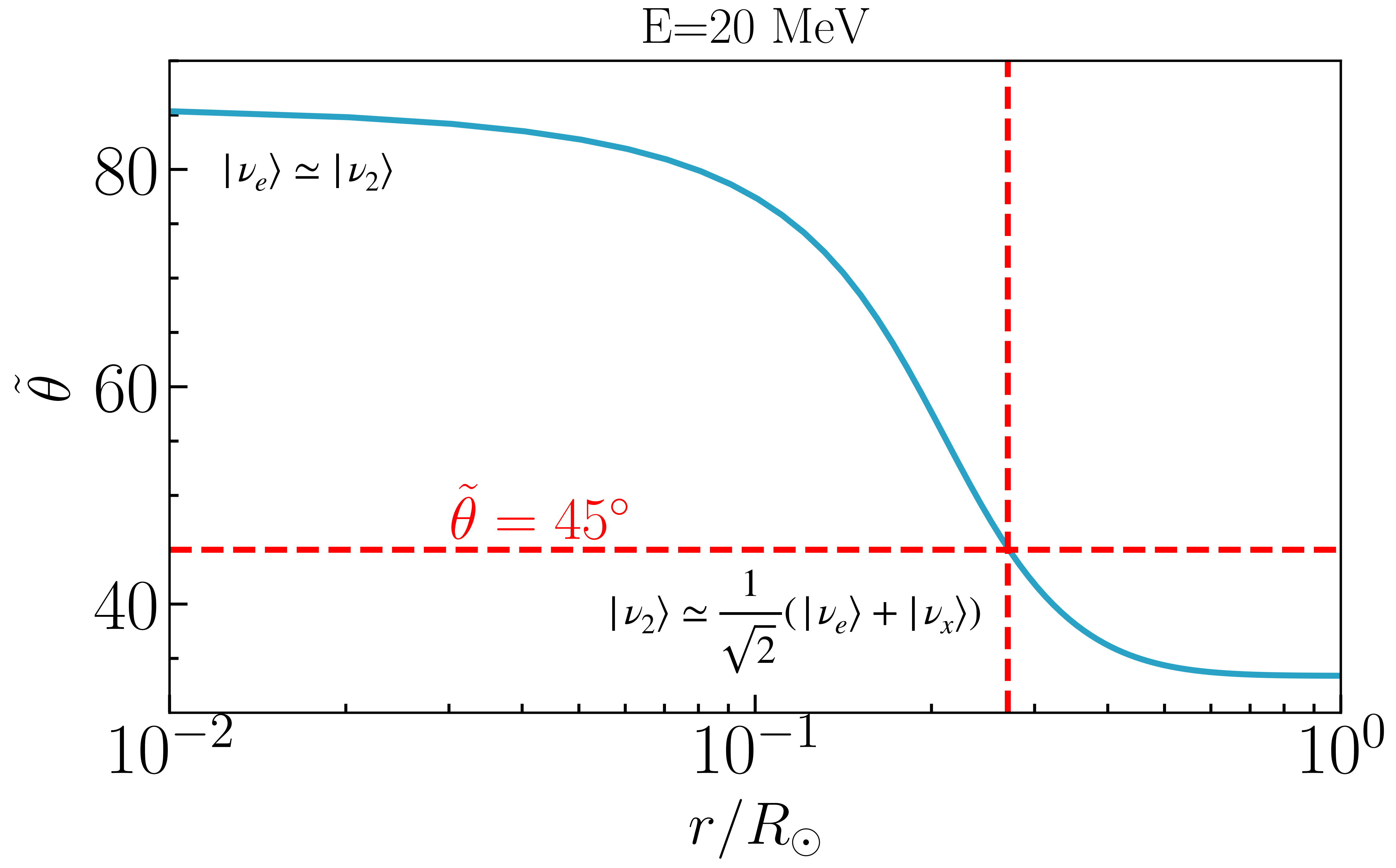

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Matter Effects: MSW

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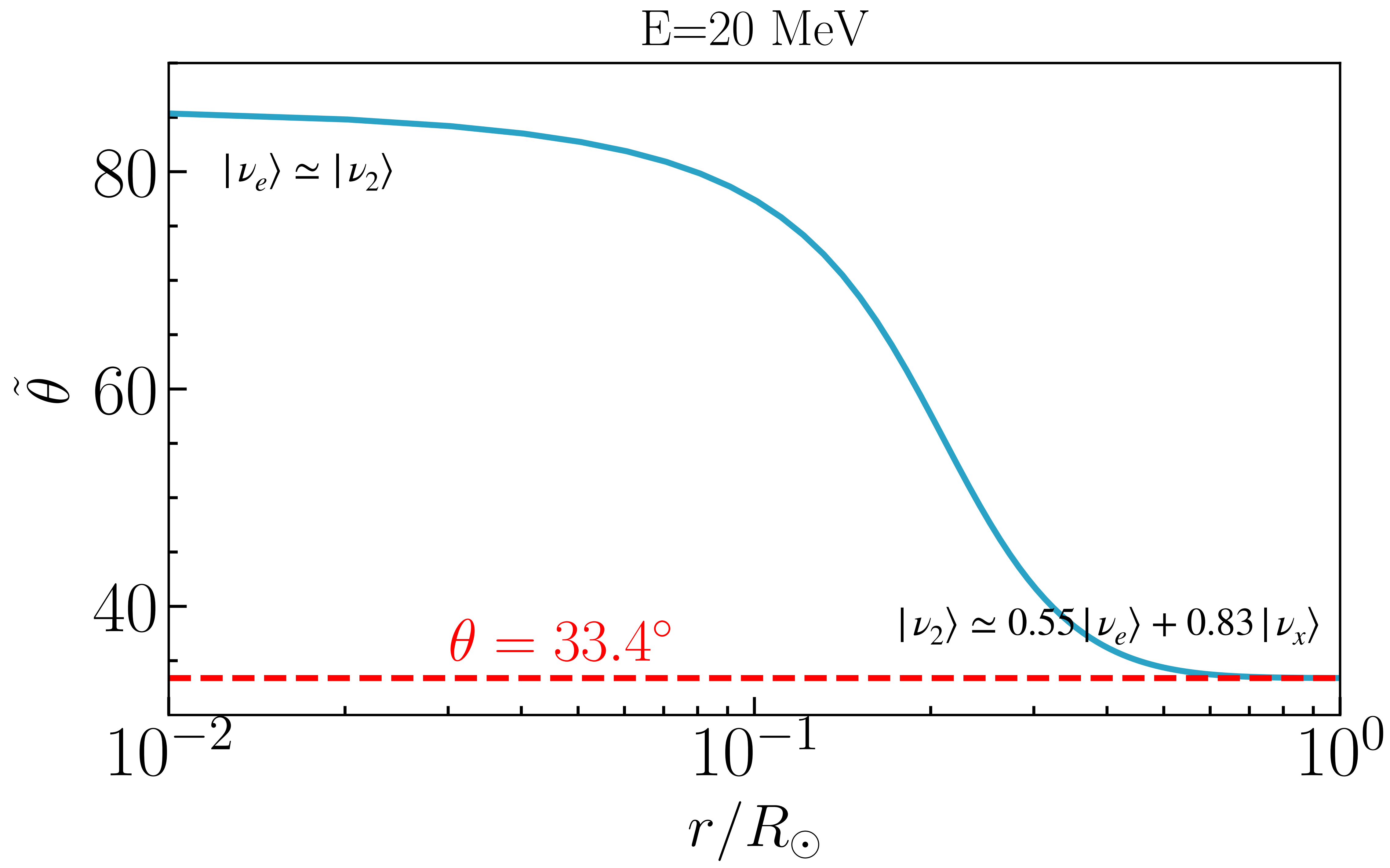

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- As the flux exists the Sun, the flux is dominated by ν_x

Matter Effects: MSW

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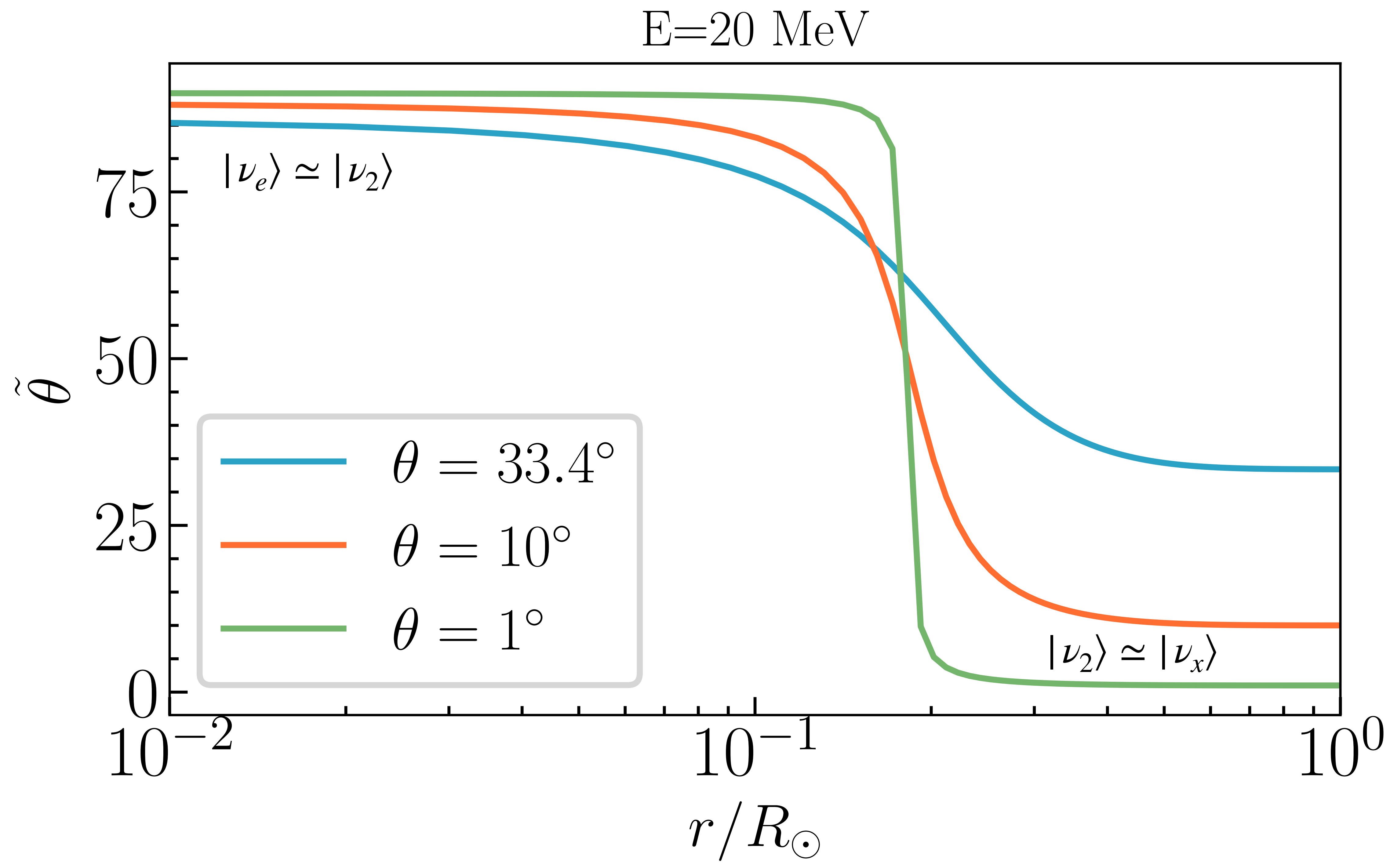
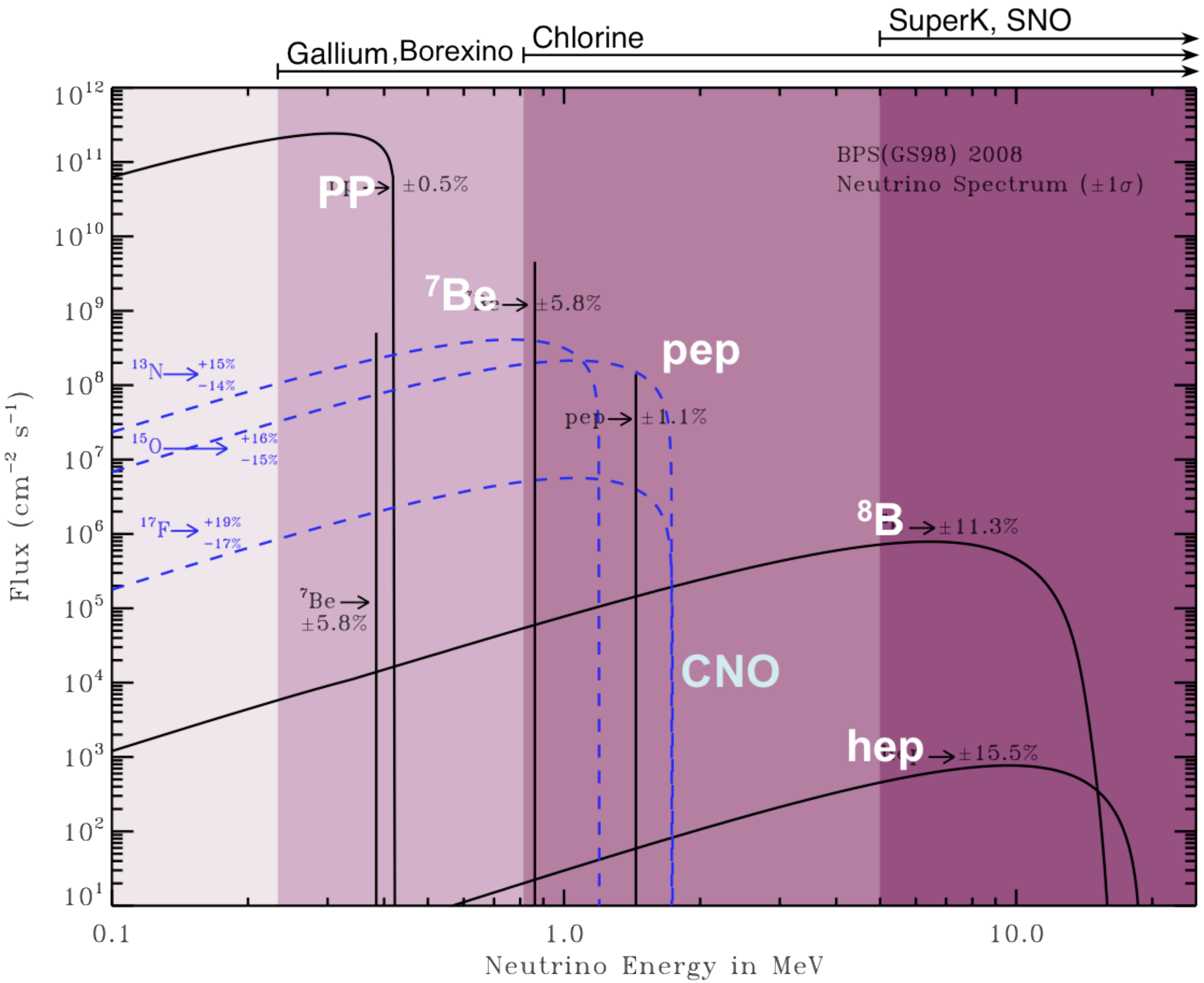


Smaller vacuum mixing angles lead to a **larger** flavor conversion

Neutrino Sources

Solar Neutrinos

Solar neutrinos are produced by **nuclear fusion reactions**: pp chains and CNO cycles



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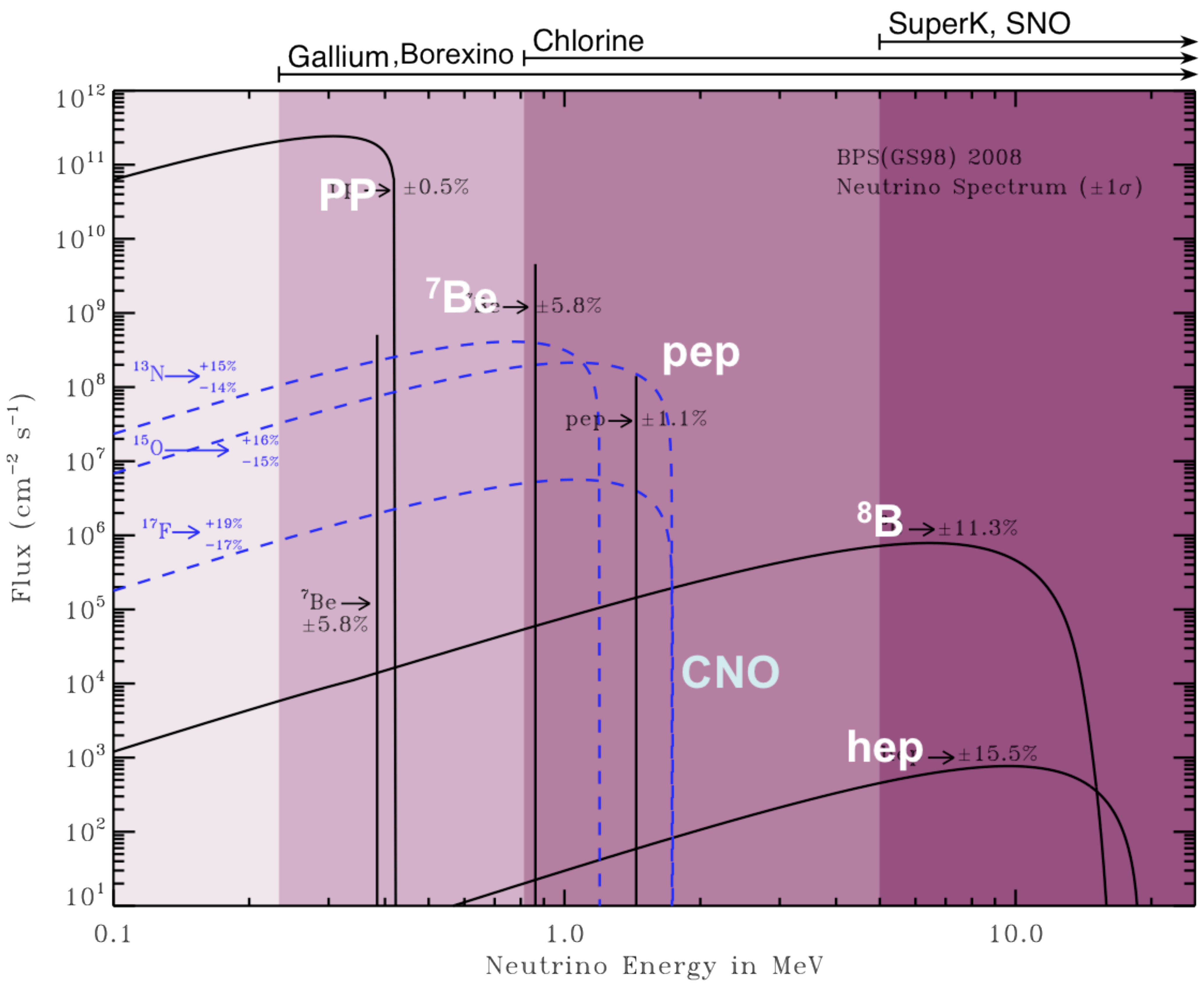
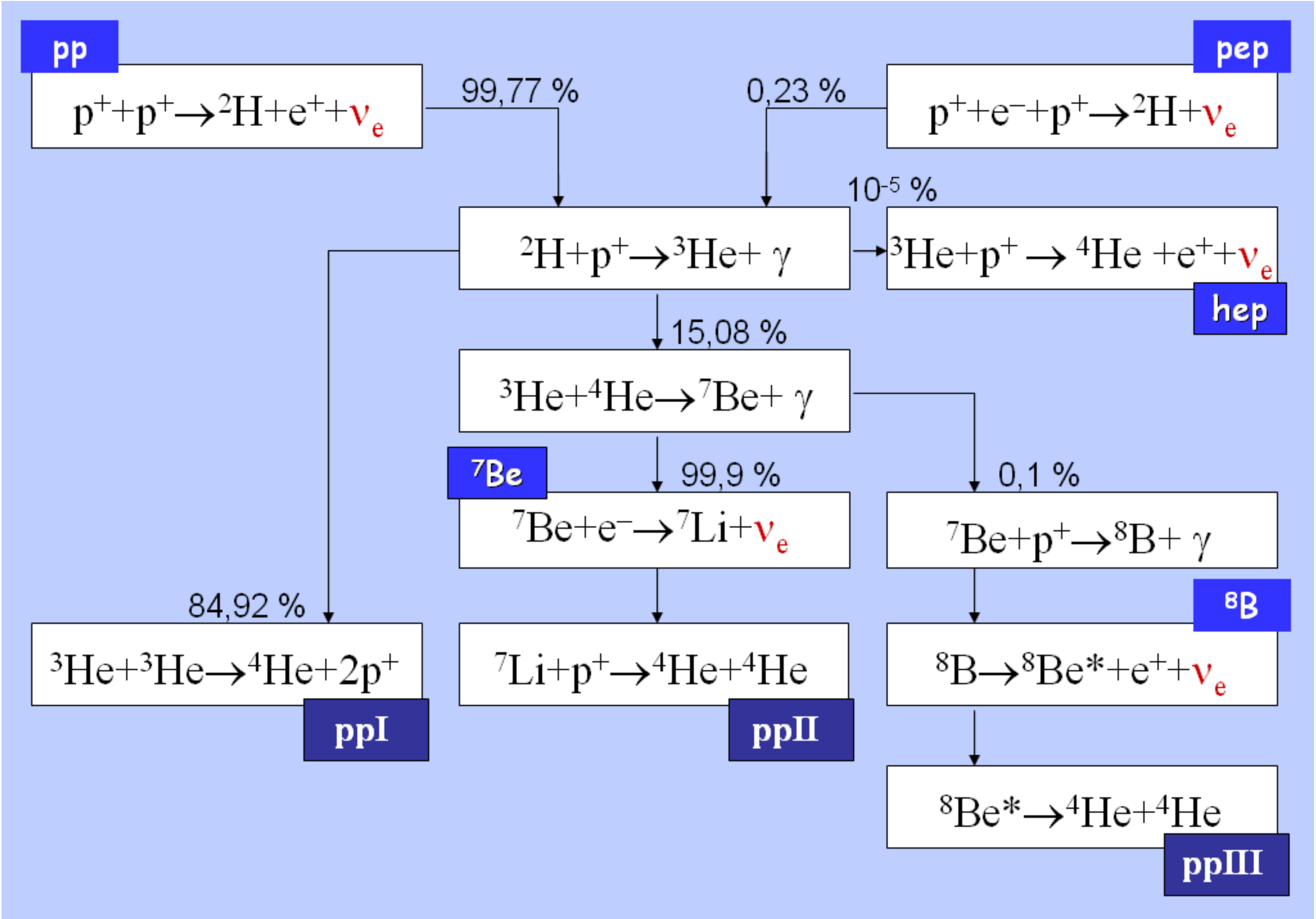
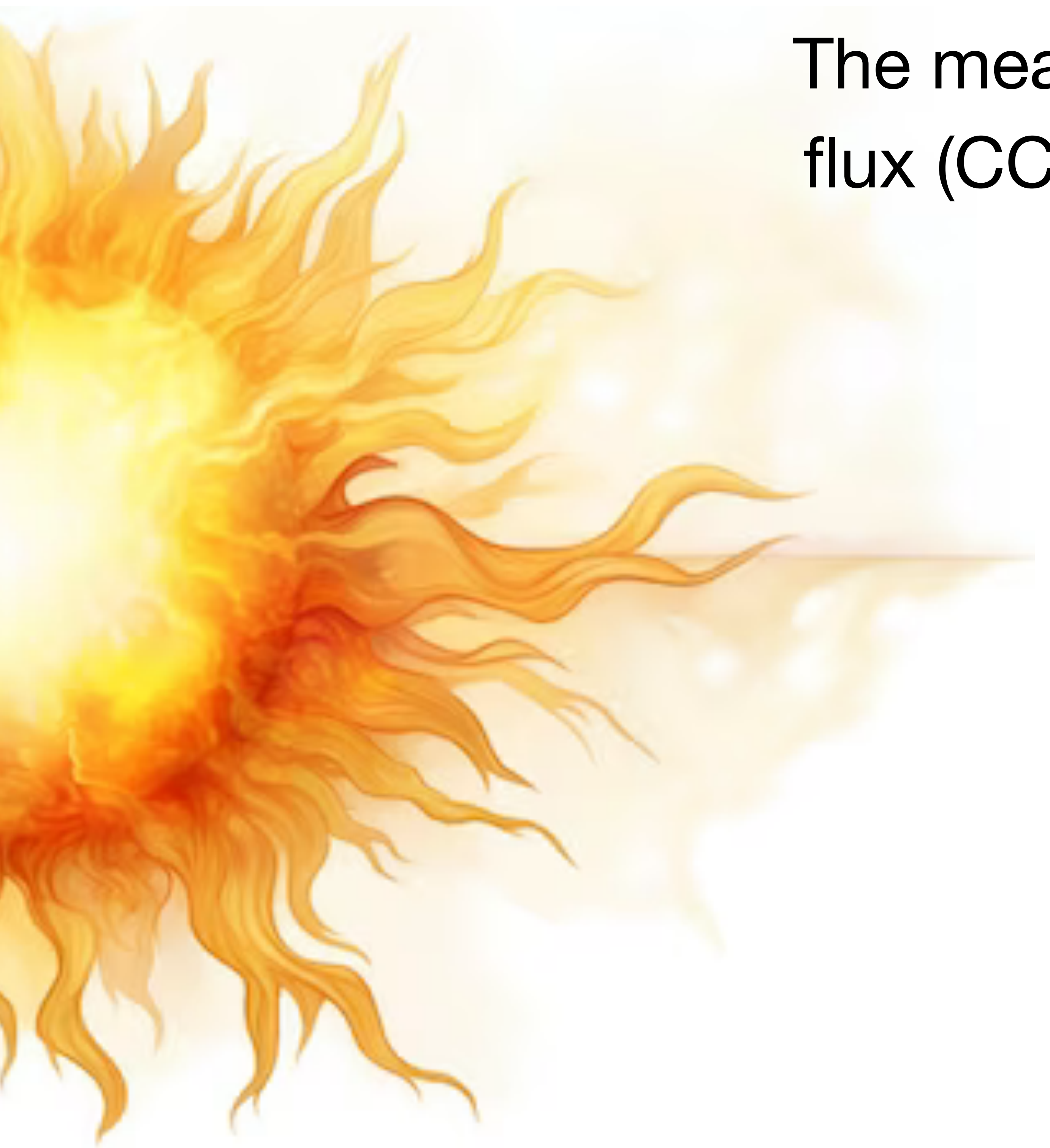


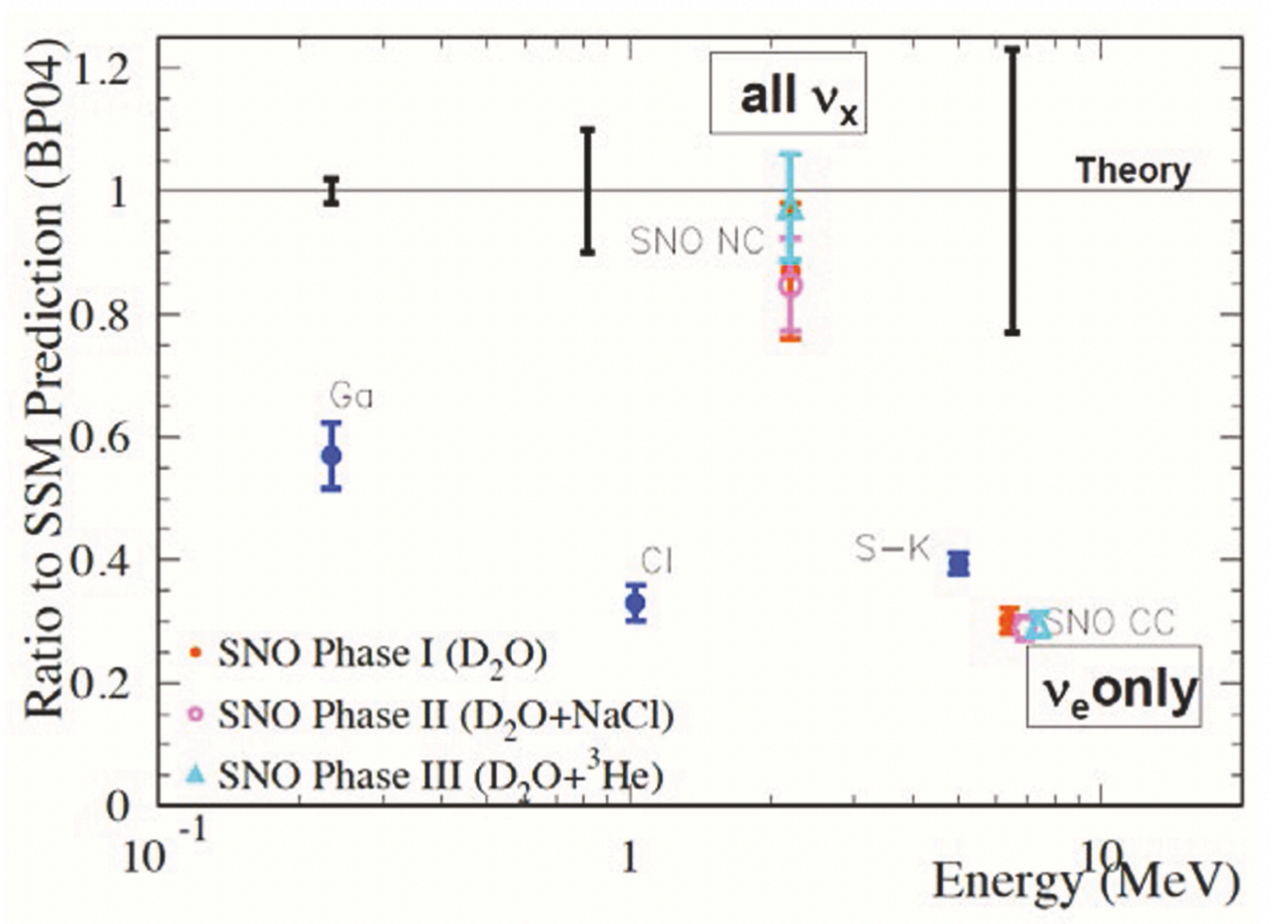
A flux of ν_e with MeV energies is produced



Solar Neutrinos



The measurement of the **solar neutrino** flux (CC) shows a **disappearance** of ν_e



The **all-flavor** measurement of the solar neutrino flux (NC) showed **oscillations** among the flavor states.

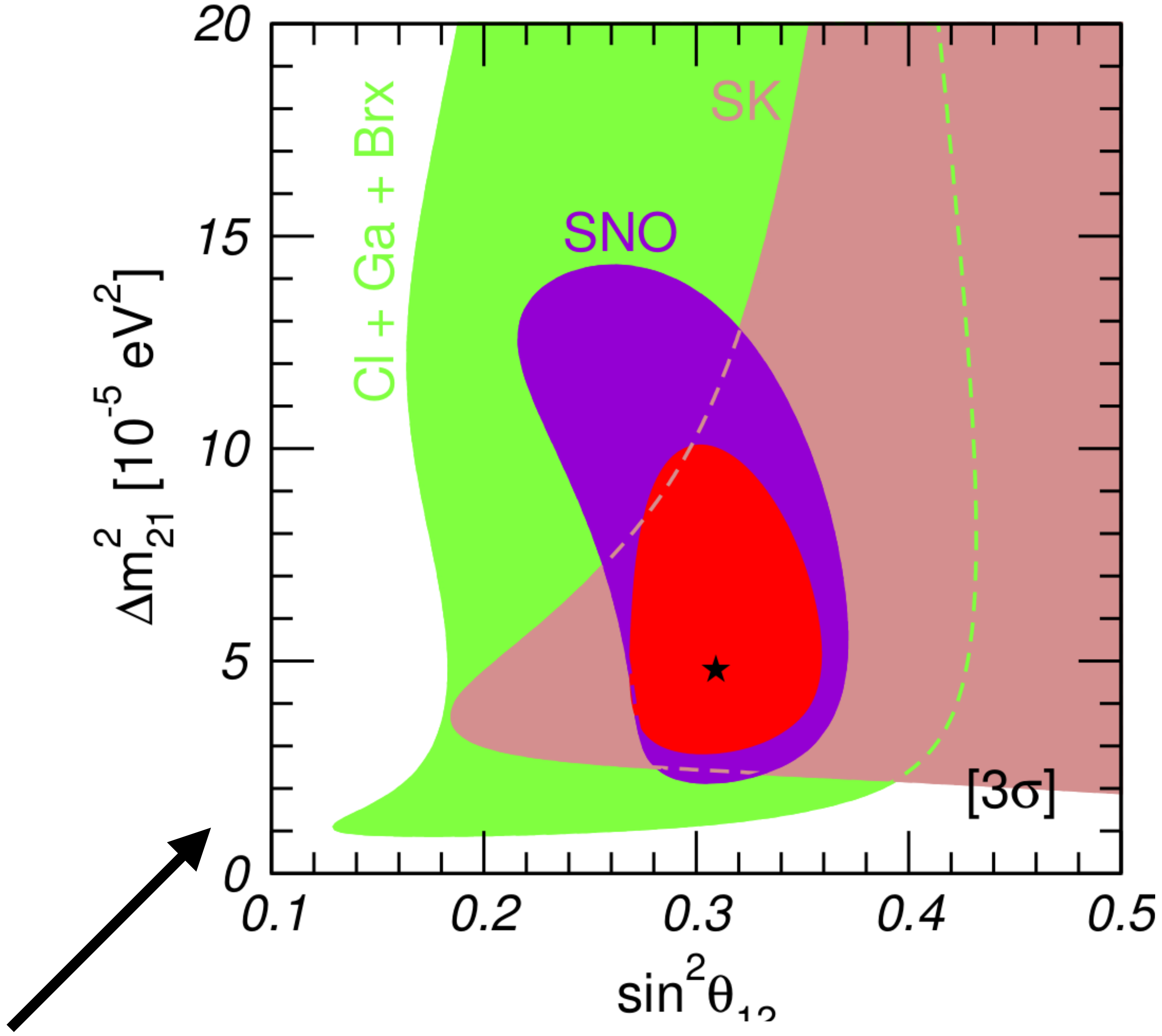
Arthur MacDonald. Nobel lecture

Solar Neutrinos

Survival probability for neutrinos from dense solar regions

$$P_{eff}^{3\nu}(\Delta m^2_{21}, \theta_{12}) = \cos^2\tilde{\theta}_{13}\cos^2\theta_{13}\frac{1}{2}(1+\cos\tilde{\theta}_{12}\cos\theta_{12})$$
$$+\sin^2\tilde{\theta}_{13}\sin^2\theta_{13}$$

- Solar neutrinos are mainly sensitive to θ_{12}



Maltoni and Smirnov, EPJA 52 (2016)
arXiv:1507.05287

The constraint over θ_{12} are mainly driven by **SK+SNO**

Solar Neutrinos

Survival probability for neutrinos from dense solar regions

$$P_{eff}^{3\nu}(\Delta m_{21}^2, \theta_{12}) = \cos^2\tilde{\theta}_{13}\cos^2\theta_{13}\frac{1}{2}(1+\cos\tilde{\theta}_{12}\cos\theta_{12})$$
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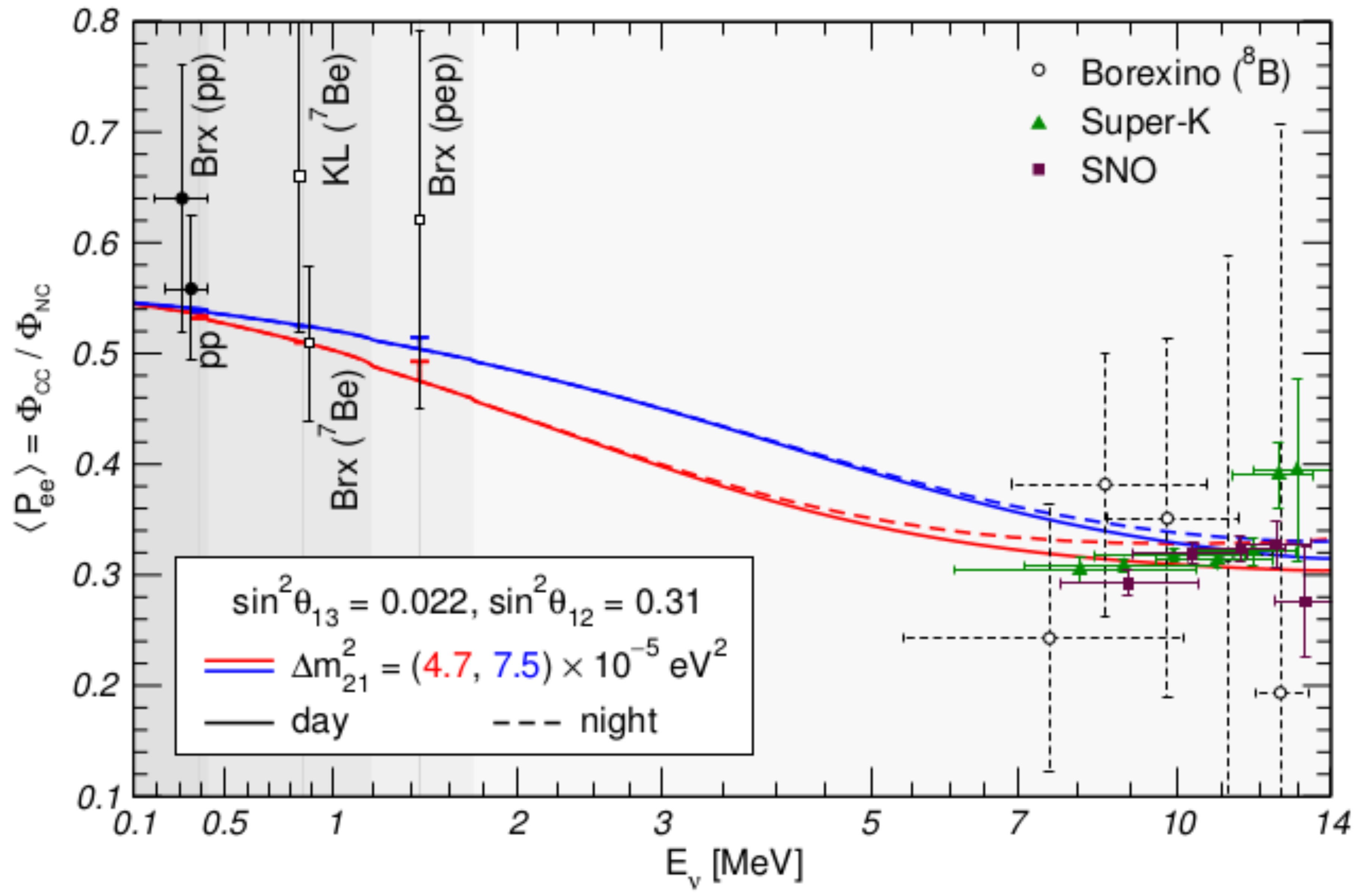
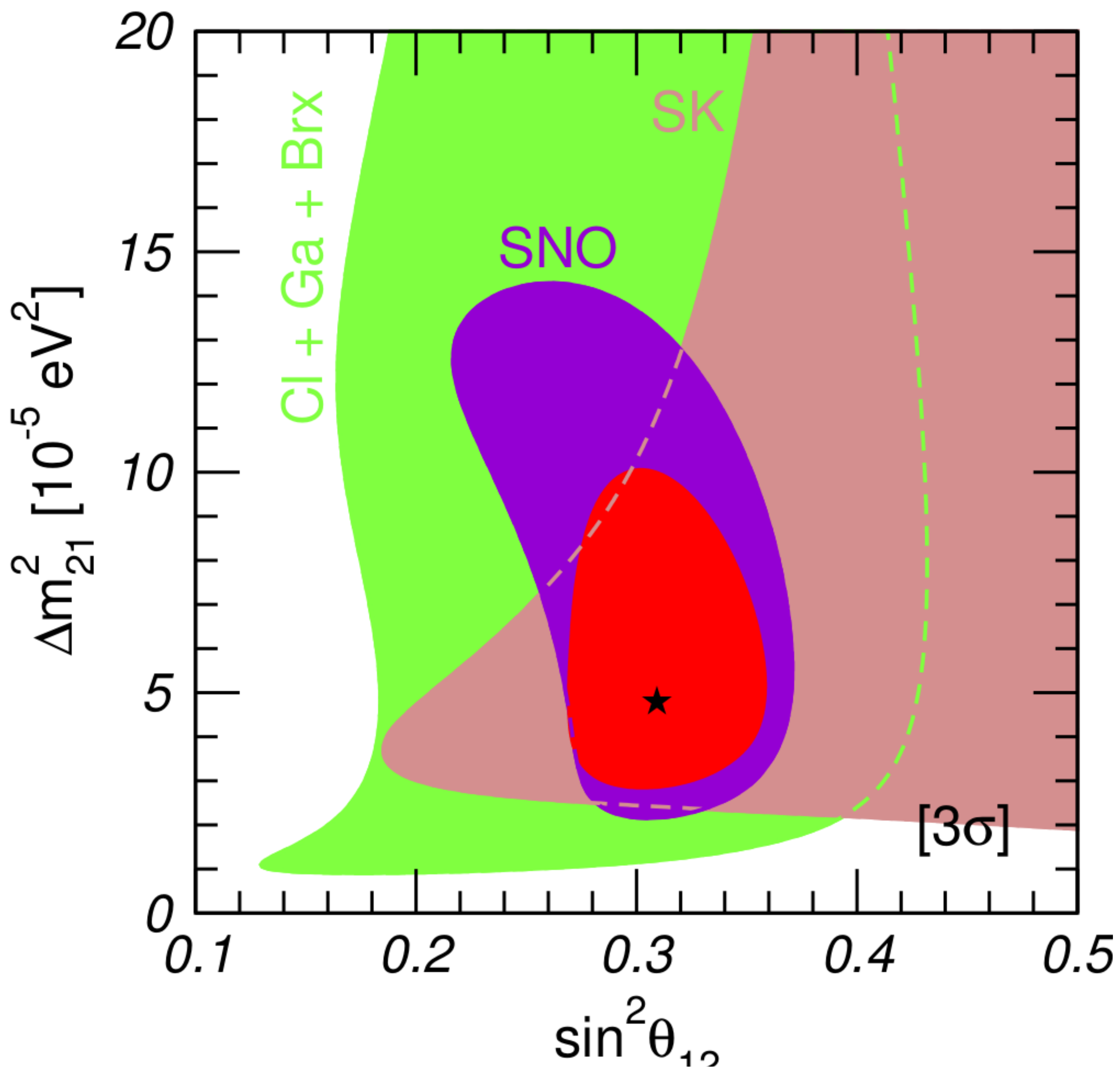
Matter effects brings sensitivity over Δm_{21}^2





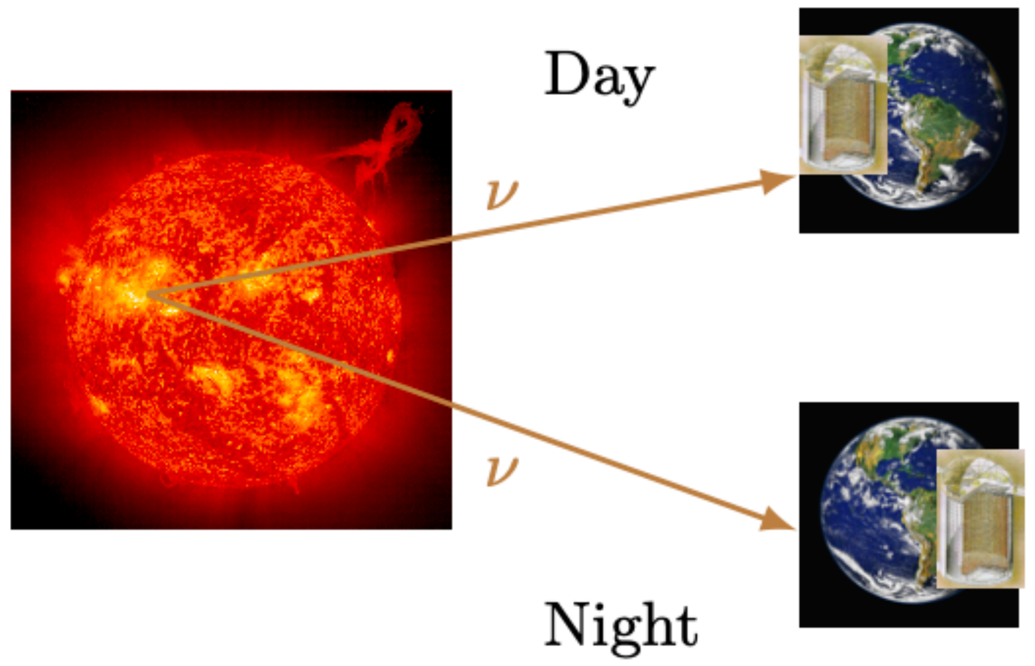
Maltoni and Smirnov, EPJA 52 (2016)
arXiv:1507.05287

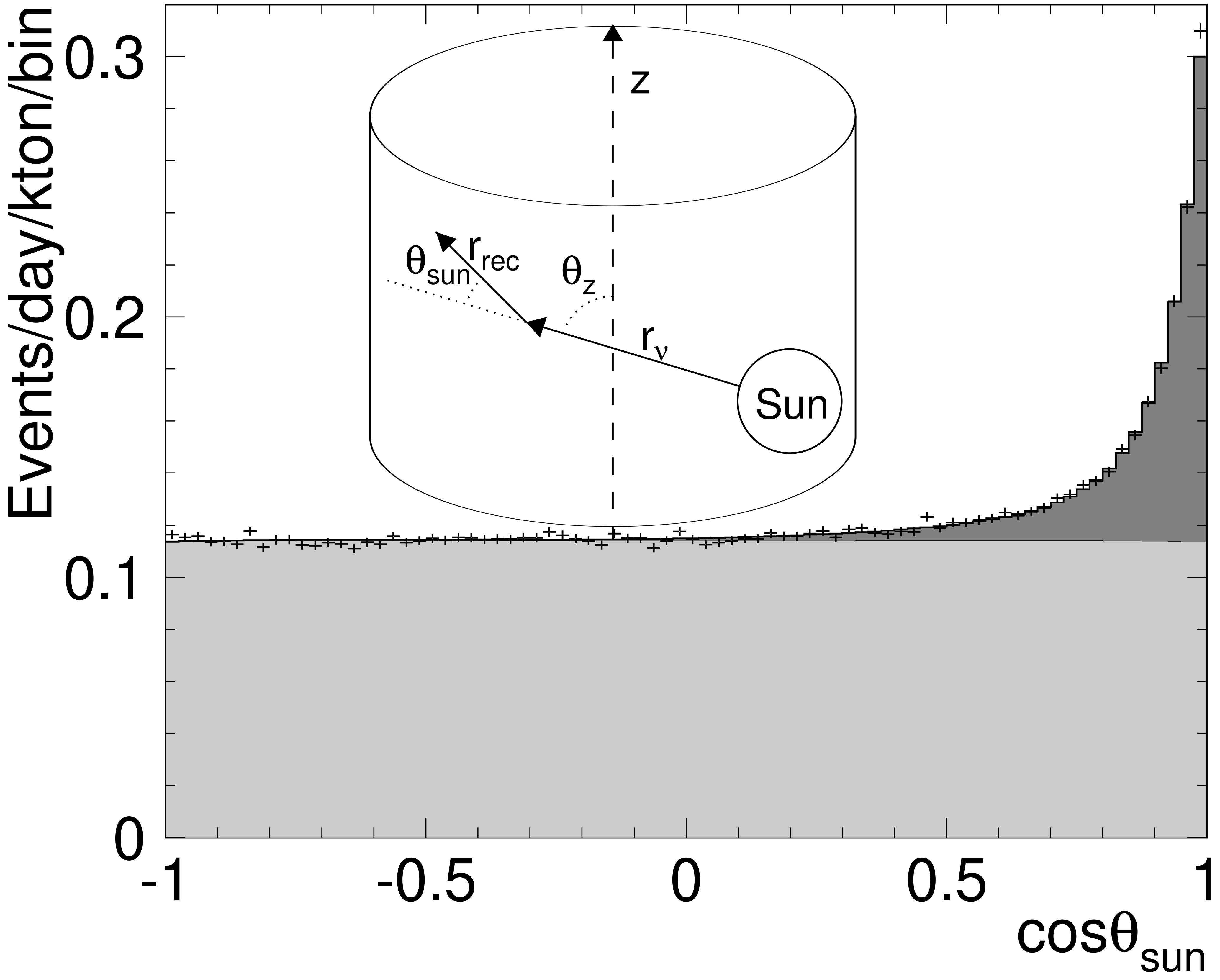
Δm_{21}^2 modifies the transition from lower to higher energies

Solar Neutrinos

The matter effects on the Earth lead to an enhacement of the electron neutrino flux

Introduces an **asymmetry** between neutrinos detected during the **day** and at **night**



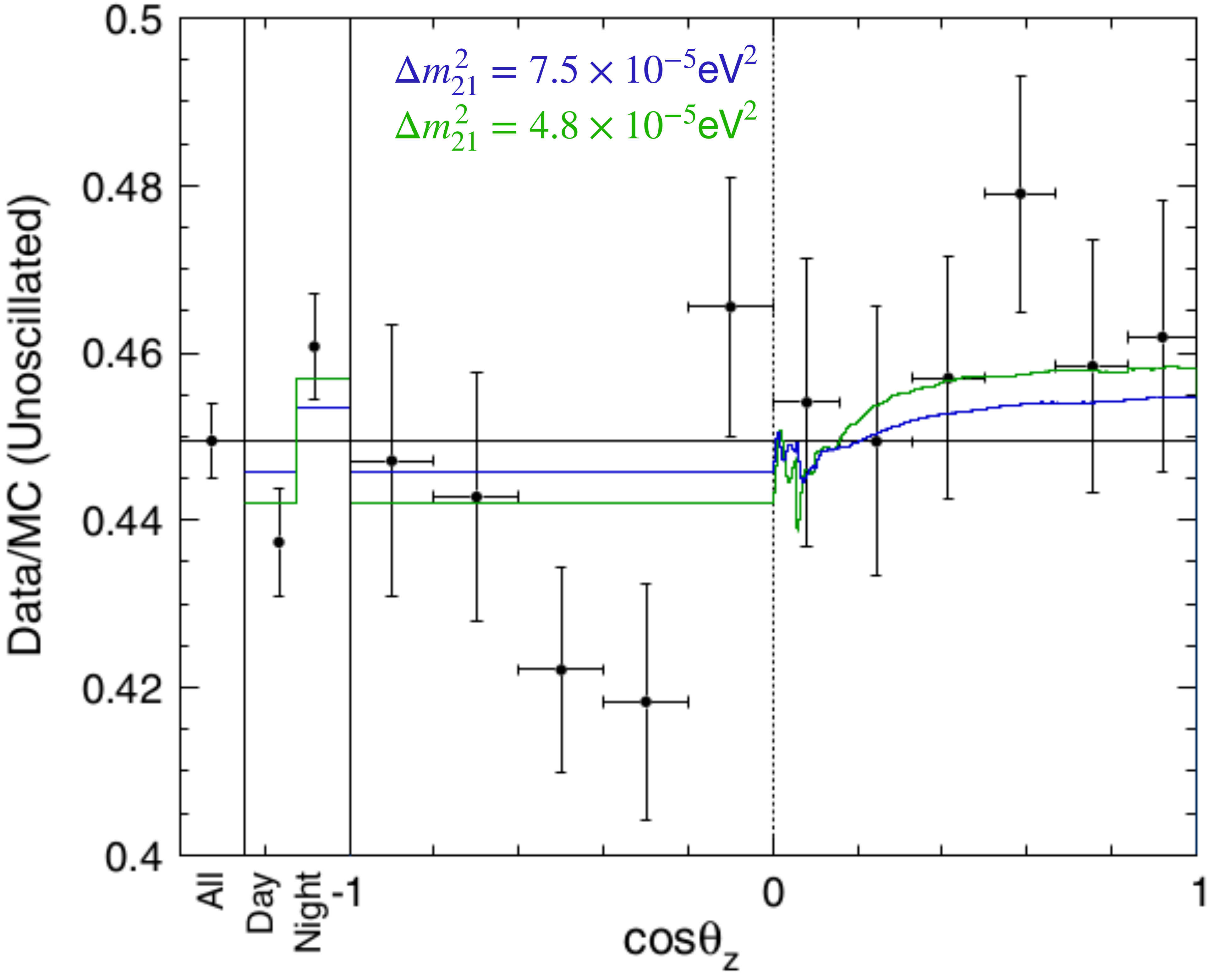


K. Abe et al., PRD 94 (2016) arXiv:1606.07538

Solar Neutrinos

The day-night asymmetry can be used to measure the oscillation parameters

$$A_{D/N} = \frac{\Phi_{\text{day}} - \Phi_{\text{night}}}{0.5 * (\Phi_{\text{day}} + \Phi_{\text{night}})}$$



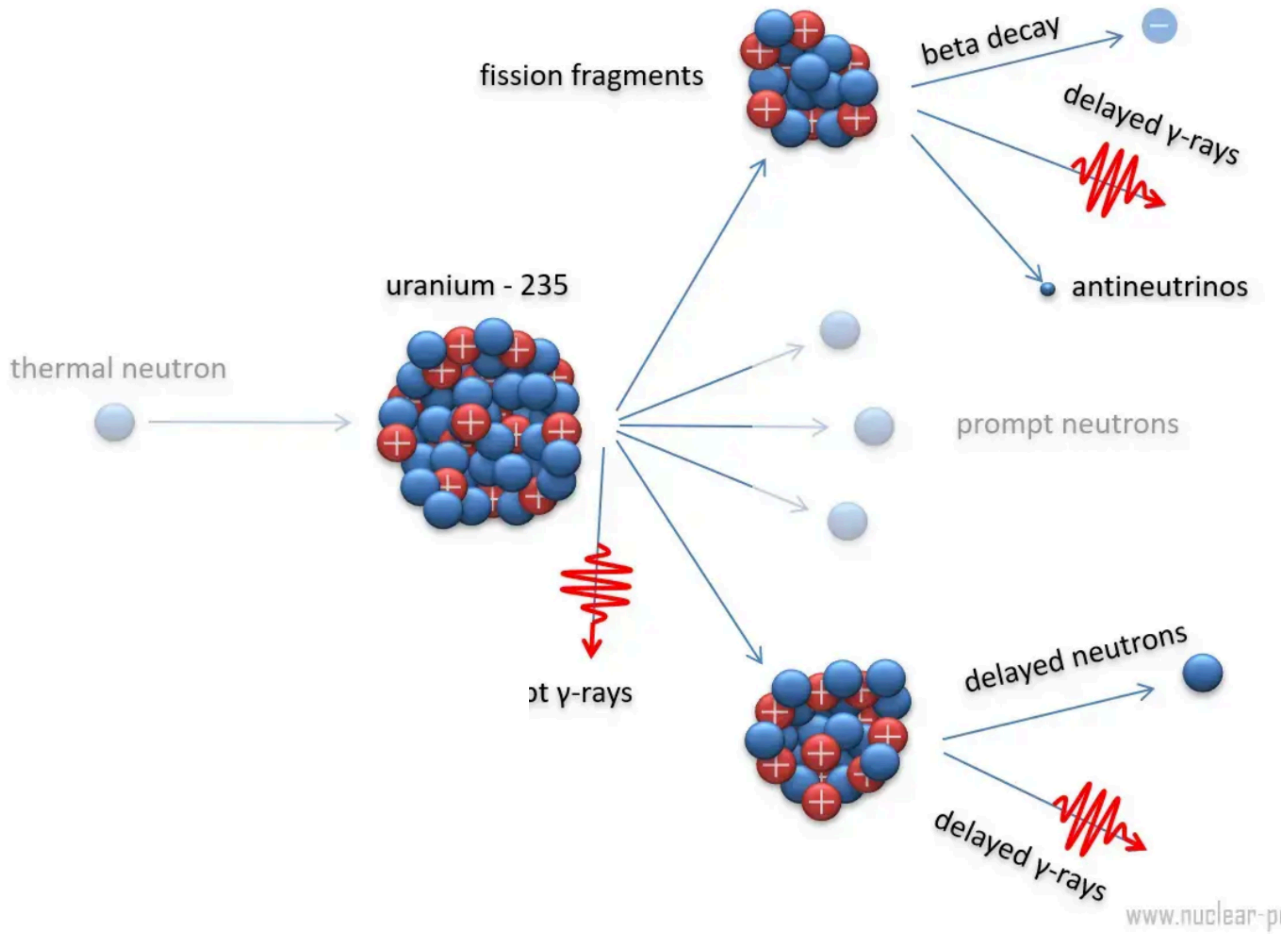
The asymmetry is a small effect ⟶ $-2.1\ \%$ SK4-2970

K. Abe et al., PRD 94 (2016) arXiv:1606.07538

Day-night asymmetry shows a **preference for a small value of** Δm^2_{21}

Nuclear Reactors

In reactor experiments, a flux of $\bar{\nu}_e$ is created with energies around the ~ MeV



The neutrino flux is created due to the **fission of four different isotopes**:

$$^{235}\mathrm{U}(\sim 56\%),^{238}\mathrm{U}(\sim 8\%),^{239}\mathrm{Pu}(\sim 30\%),^{241}\mathrm{Pu}(\sim 6\%)$$

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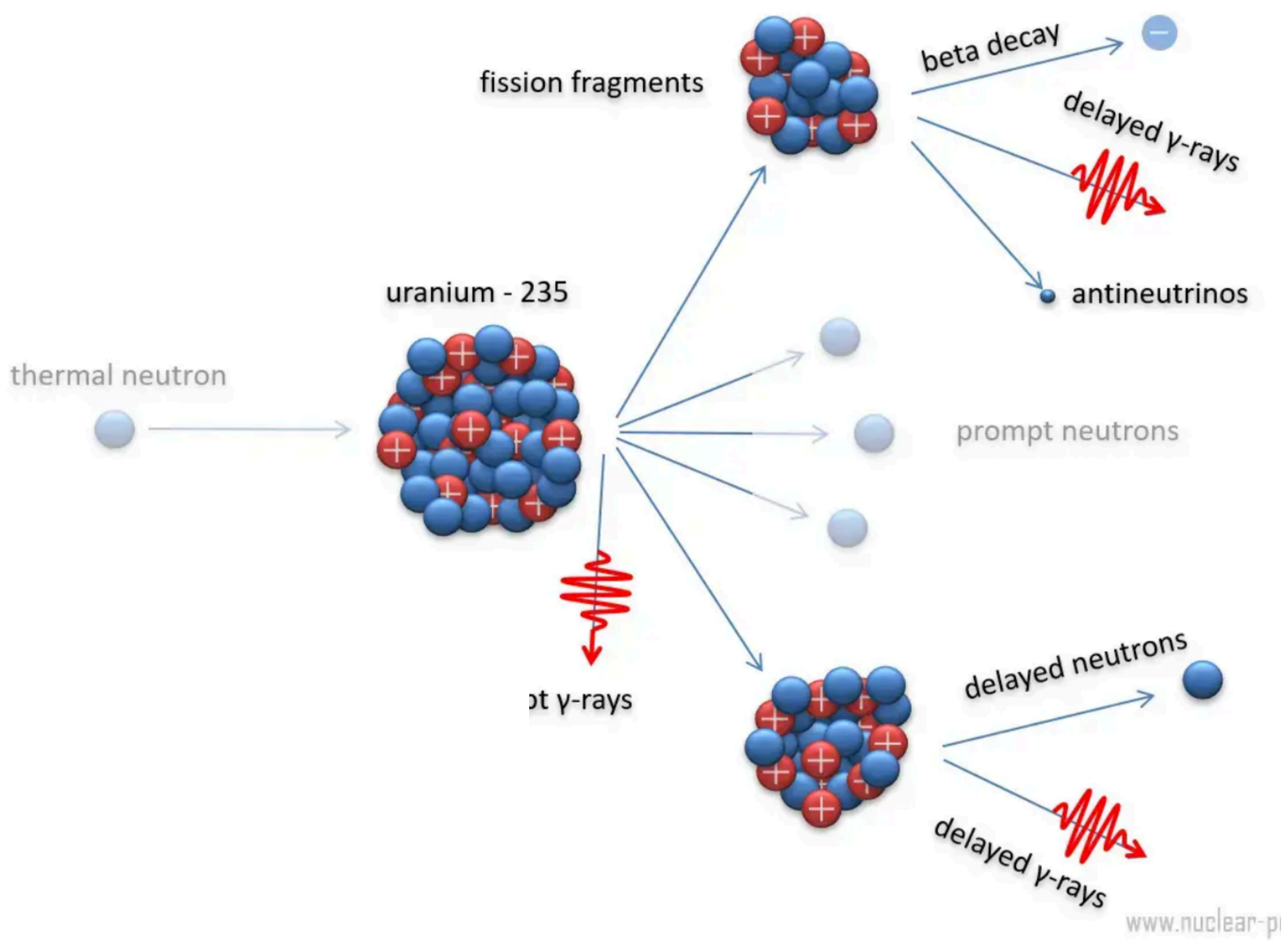
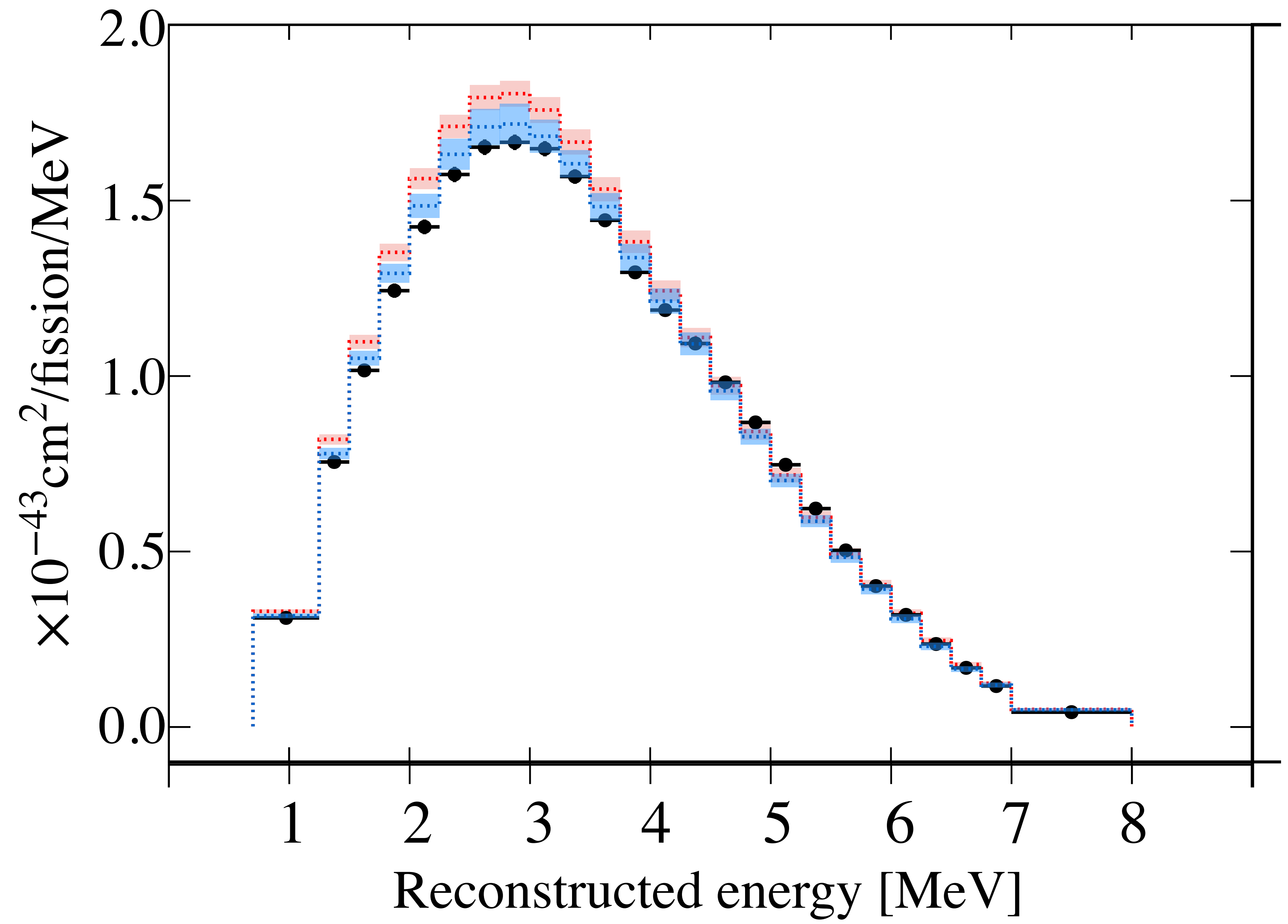
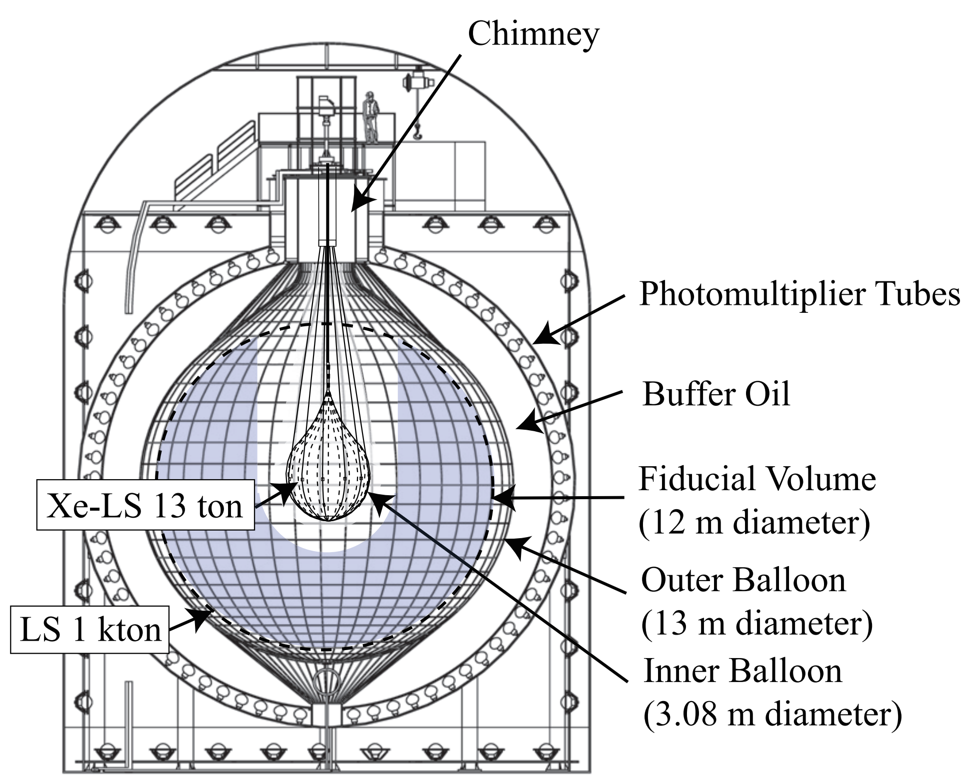


The spectrum lies in the MeV range



Zhongstan U. et al. (Daya Bay), PRL 134 (2025) 20

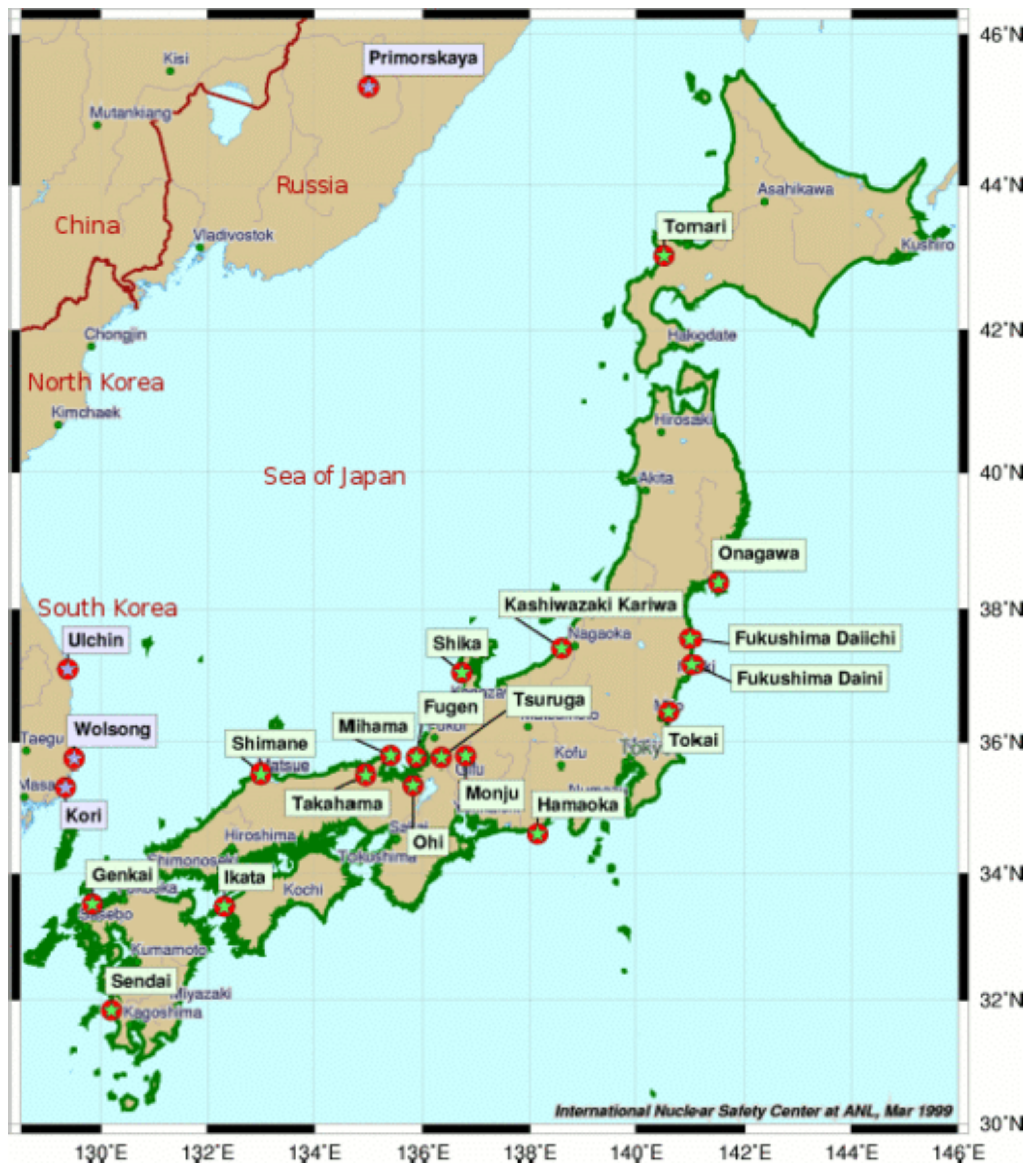
Nuclear Reactors



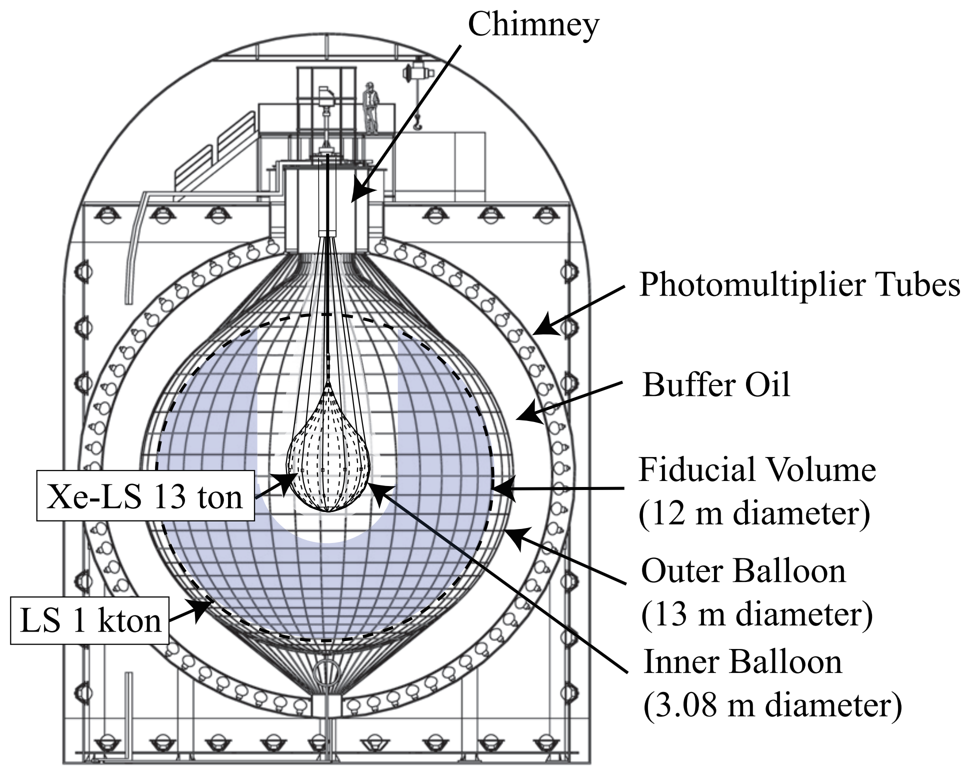
A. Gando et al. (KamLAND) PRD 88 (2013)

KamLAND is an LS detector that collected all the $\bar{\nu}_e$ emitted by power plants in Japan

- Detected via inverse $\beta-$decay $\bar{\nu}_e + p \to e^+ + n$
- The average baseline is $L \sim 200$km



Nuclear Reactors



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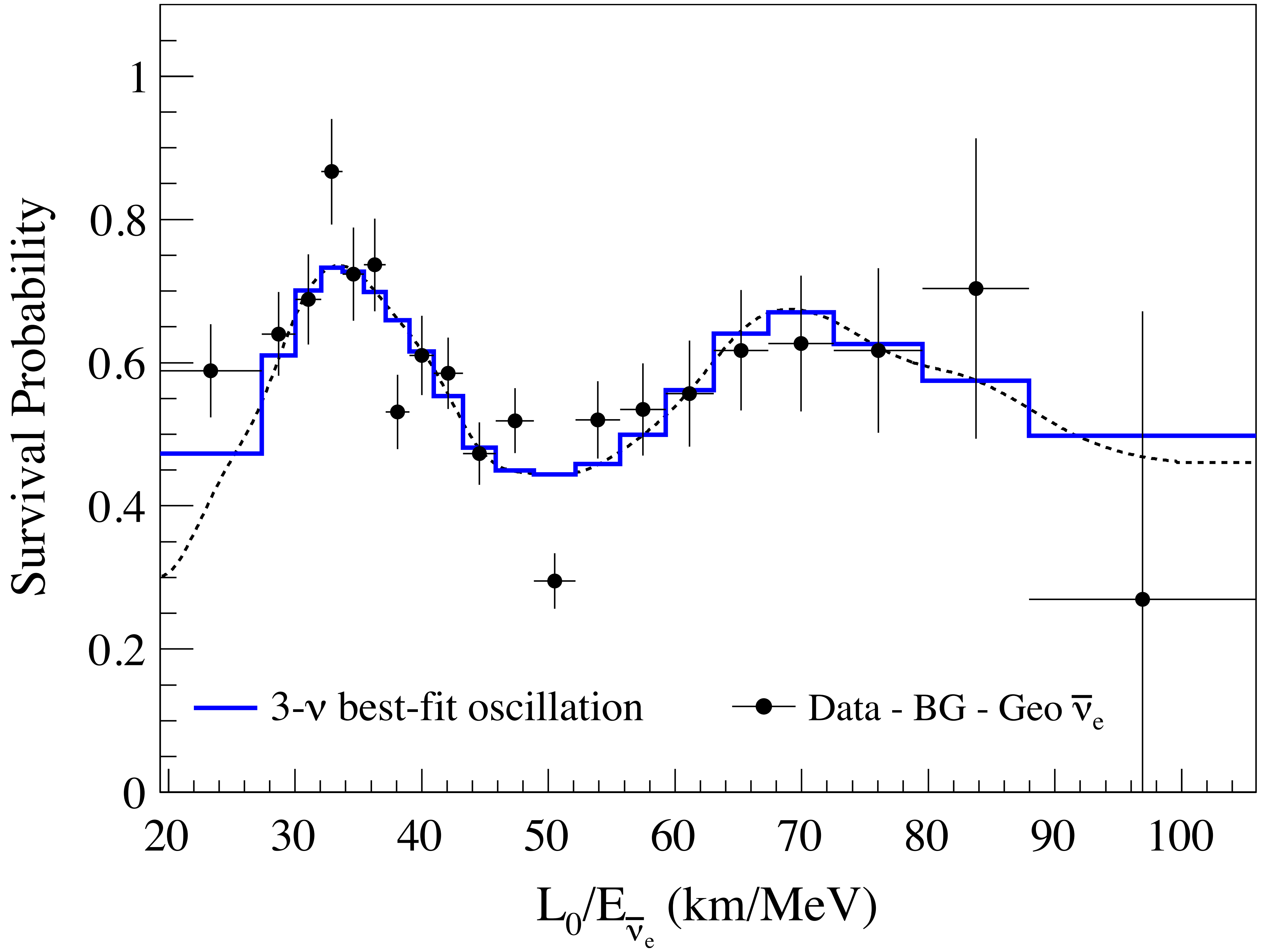
- The average baseline is $L \sim 200$km

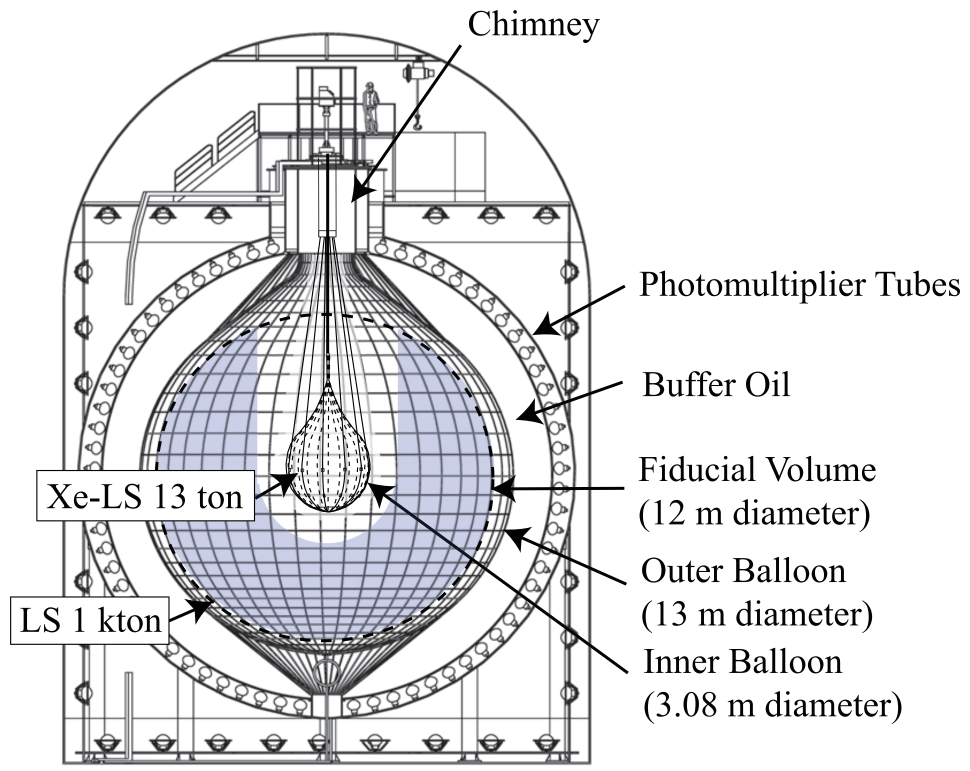
For reactor neutrinos can be described in vacuum

$$P_{ee}^{3\nu} = c_{13}^4 \left(1 - \frac{1}{2} \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m_{21}^2 L}{2E} \right) + s_{13}^4$$



Ivan Martinez-Soler (IPPP)

Nuclear Reactors



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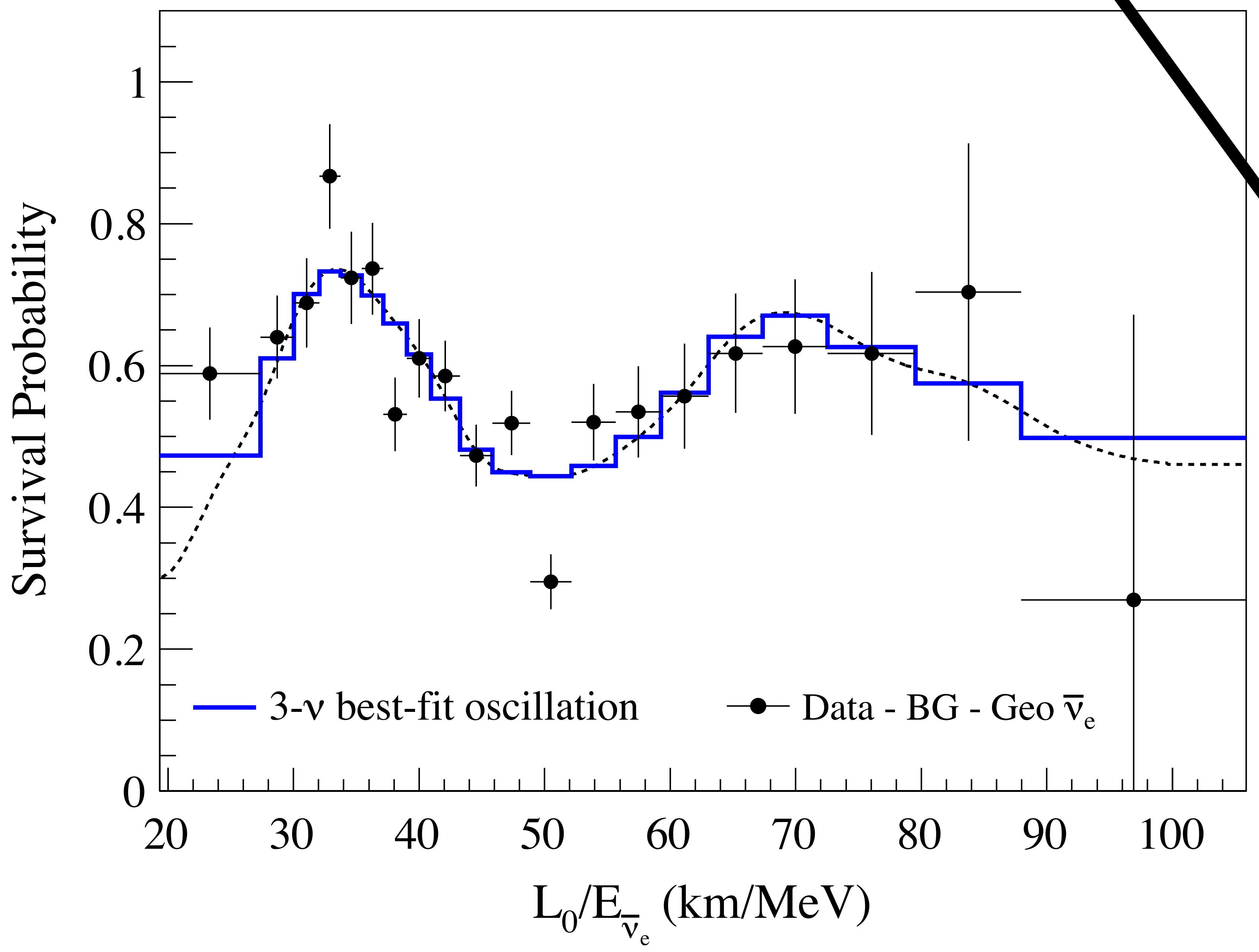
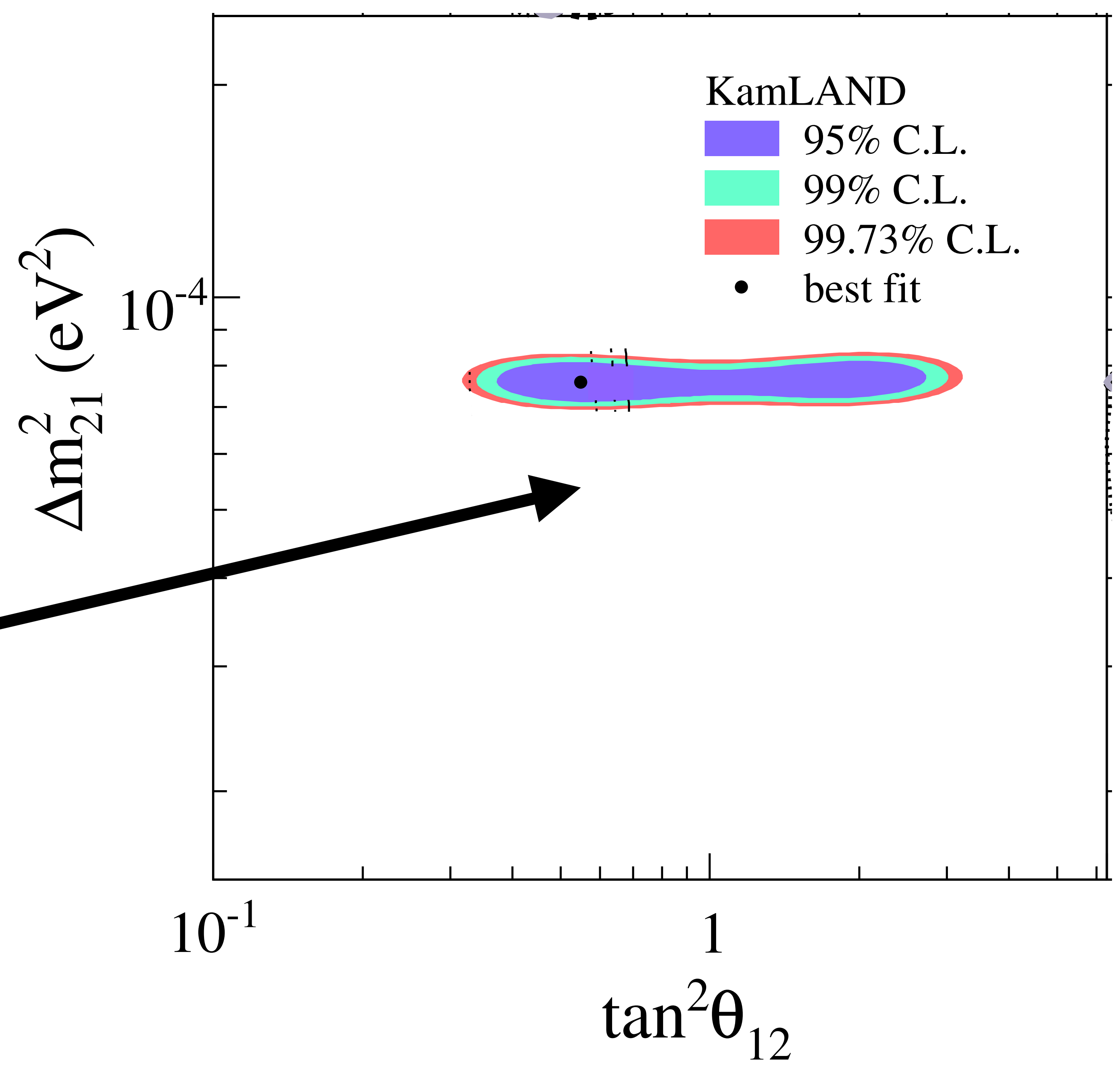


Precise measurement of Δm_{21}^2

Vacuum oscillation probability cannot resolve the octant of θ_{12}

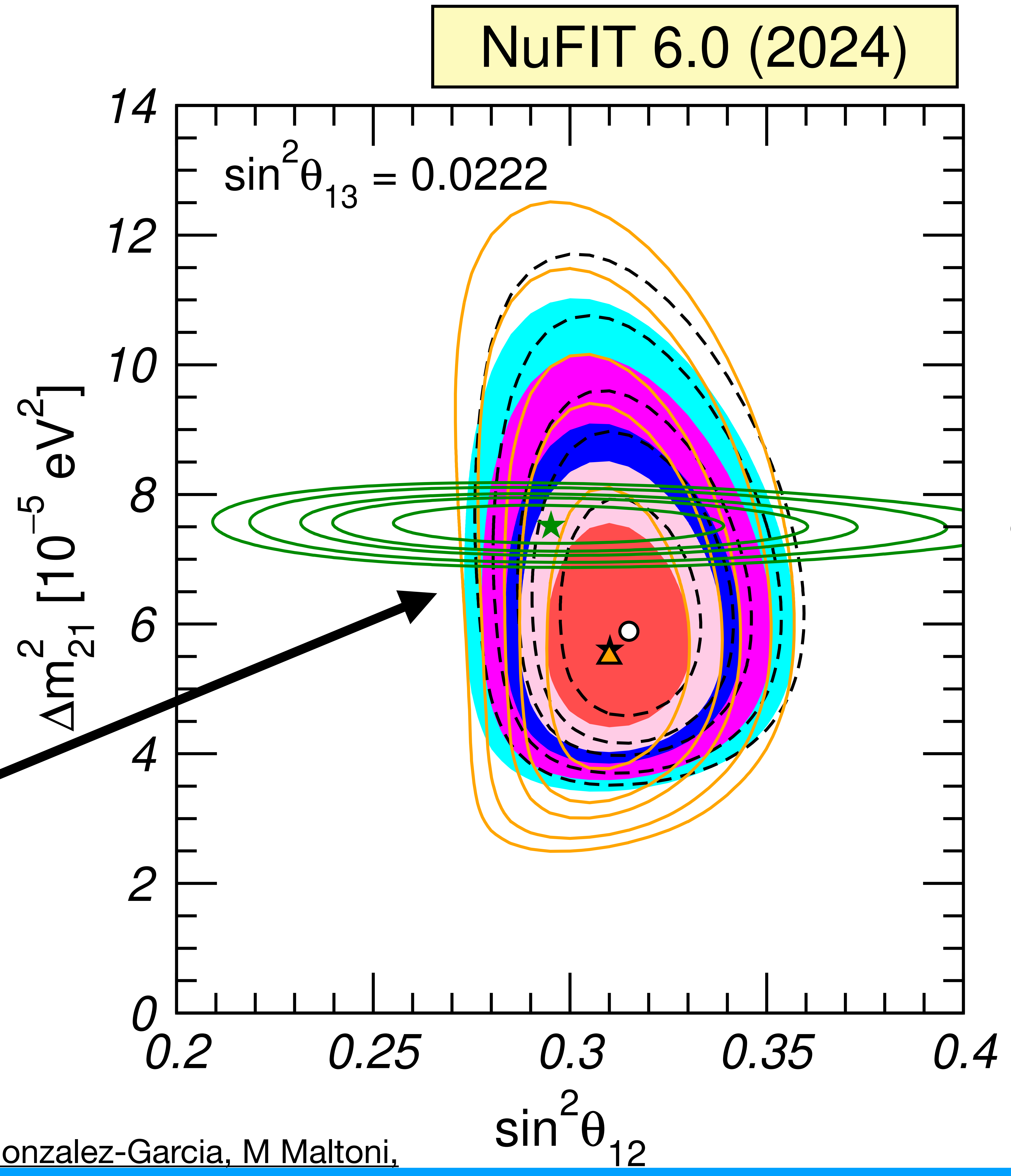


Solar Sector: θ_{12} and Δm^2_{21}

Combining solar and reactor measurements, we can resolve the octant of θ_{12}

- **KamLAND** determined Δm^2_{21}
- **Solar** experiments determined θ_{12}

Tension in the determination of Δm^2_{21} between reactor and solar experiments

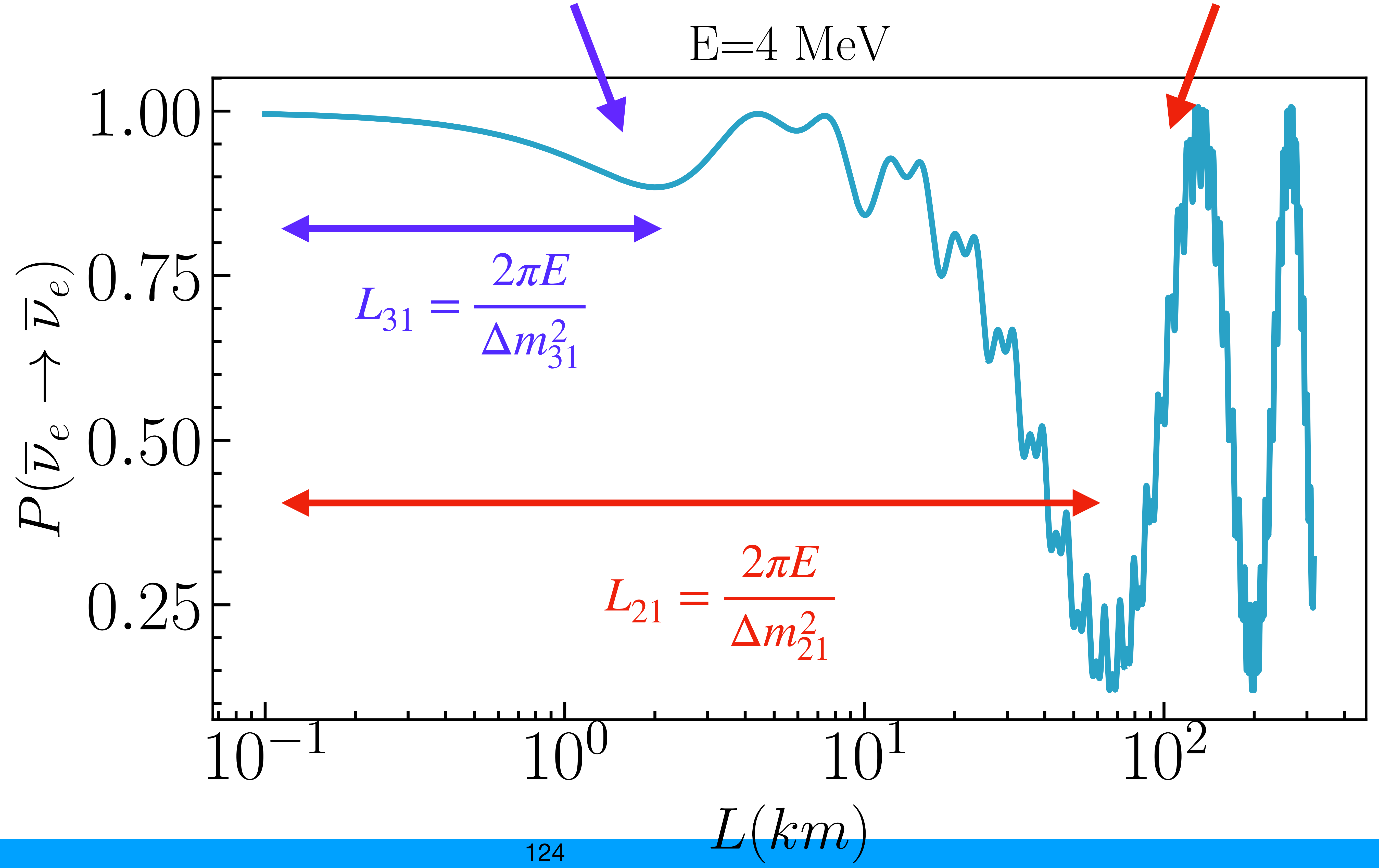


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS, JP Pinheiro, T Schwetz, JHEP 12 (2025)

Reactor neutrinos: θ_{13} and Δm^2_{31}

At shorter distances, neutrino evolution is dominated by Δm^2_{31} and θ_{13}

$$P_{ee} = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$



Reactor neutrinos: θ_{13} and Δm^2_{31}

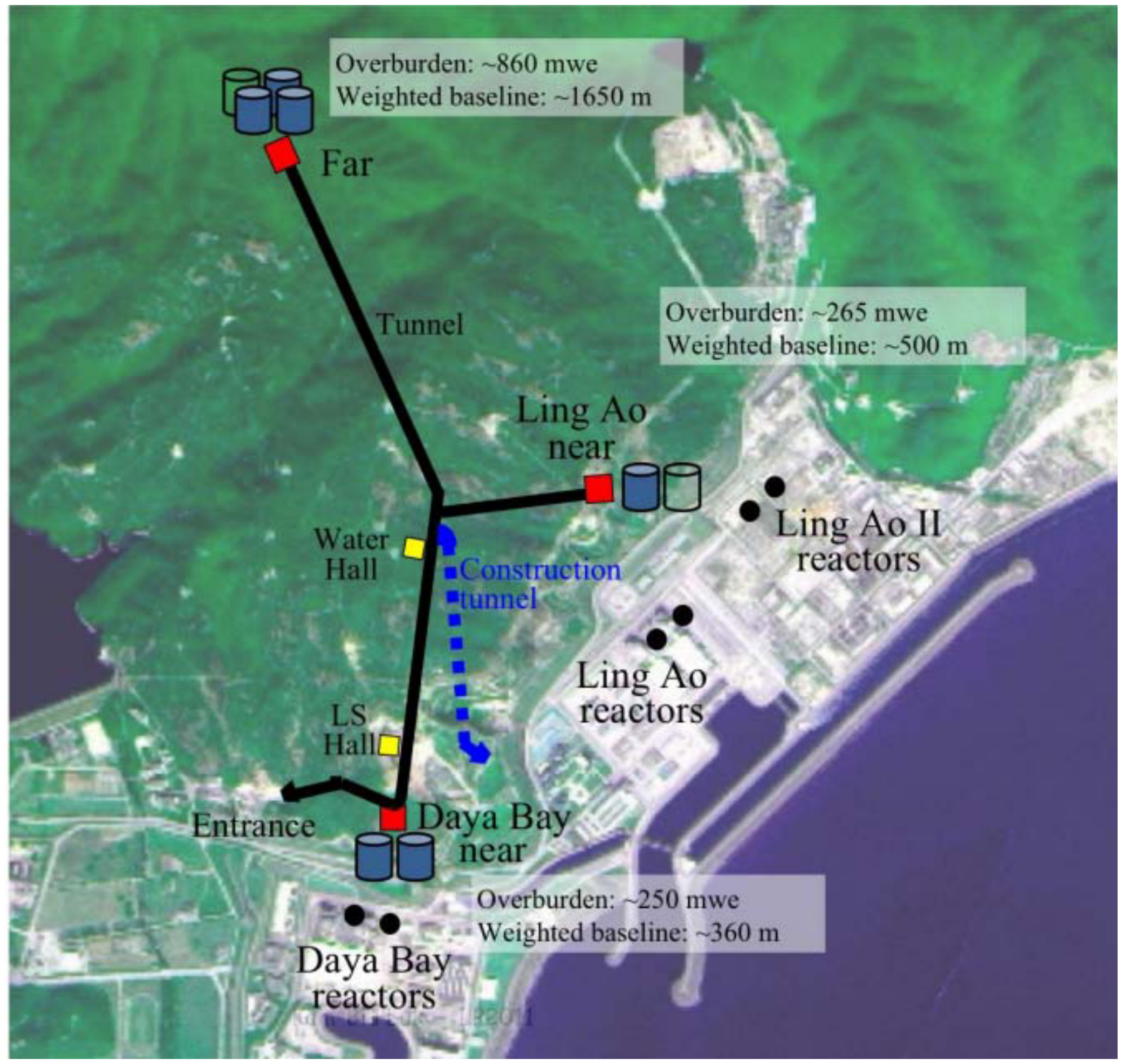
At shorter distances, neutrino evolution is dominated by Δm^2_{31} and θ_{13}

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

$$\Delta m^2_{ee} = \Delta m^2_{31} - \sin^2\theta_{12}\Delta m^2_{21}$$

- To reduce the flux uncertainties, the flux is measured at both a **near** (~300m) and a **far** detector (~1000 m)

Daya Bay



Similar configuration used by RENO and Double Chooz

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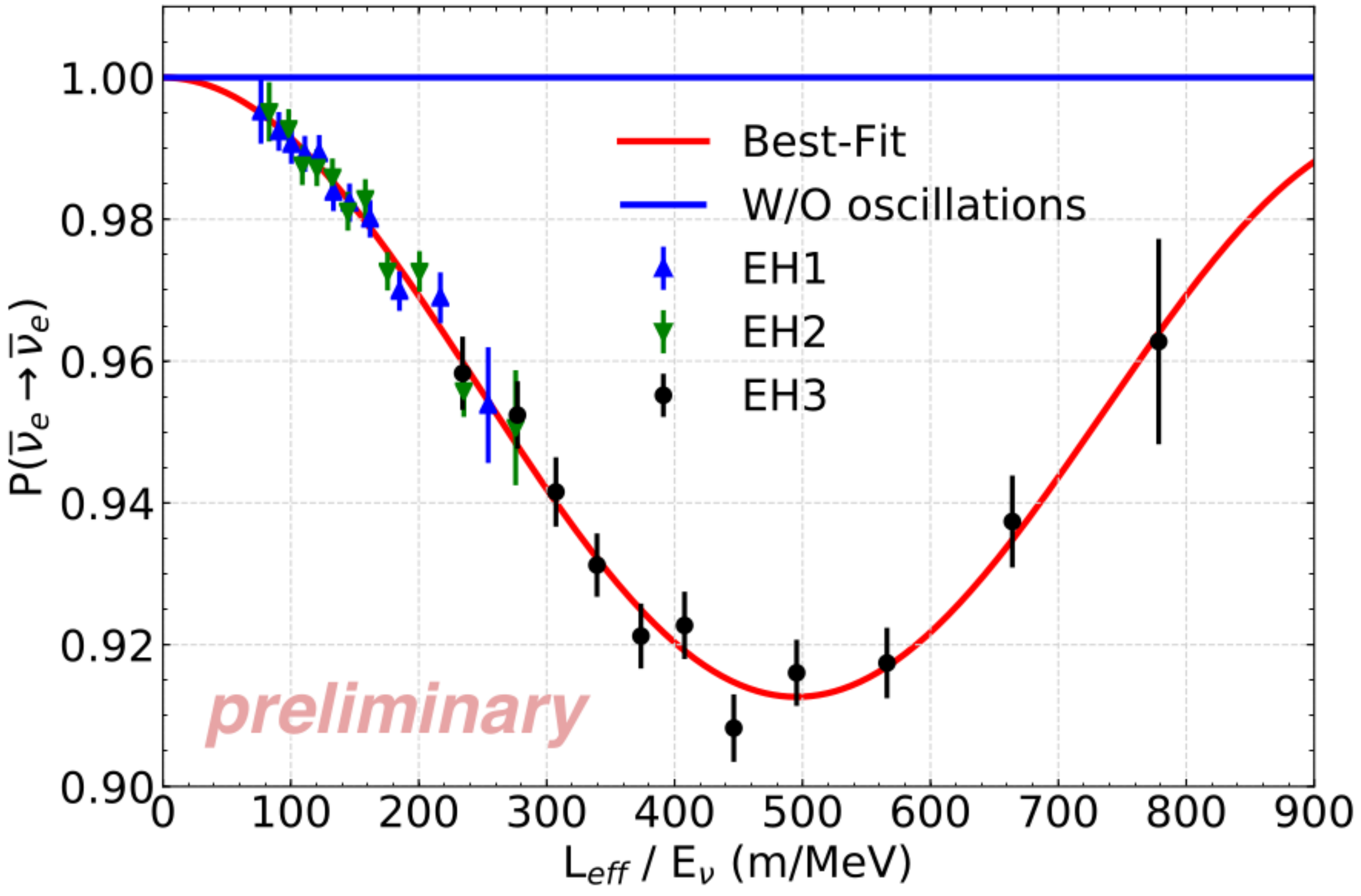

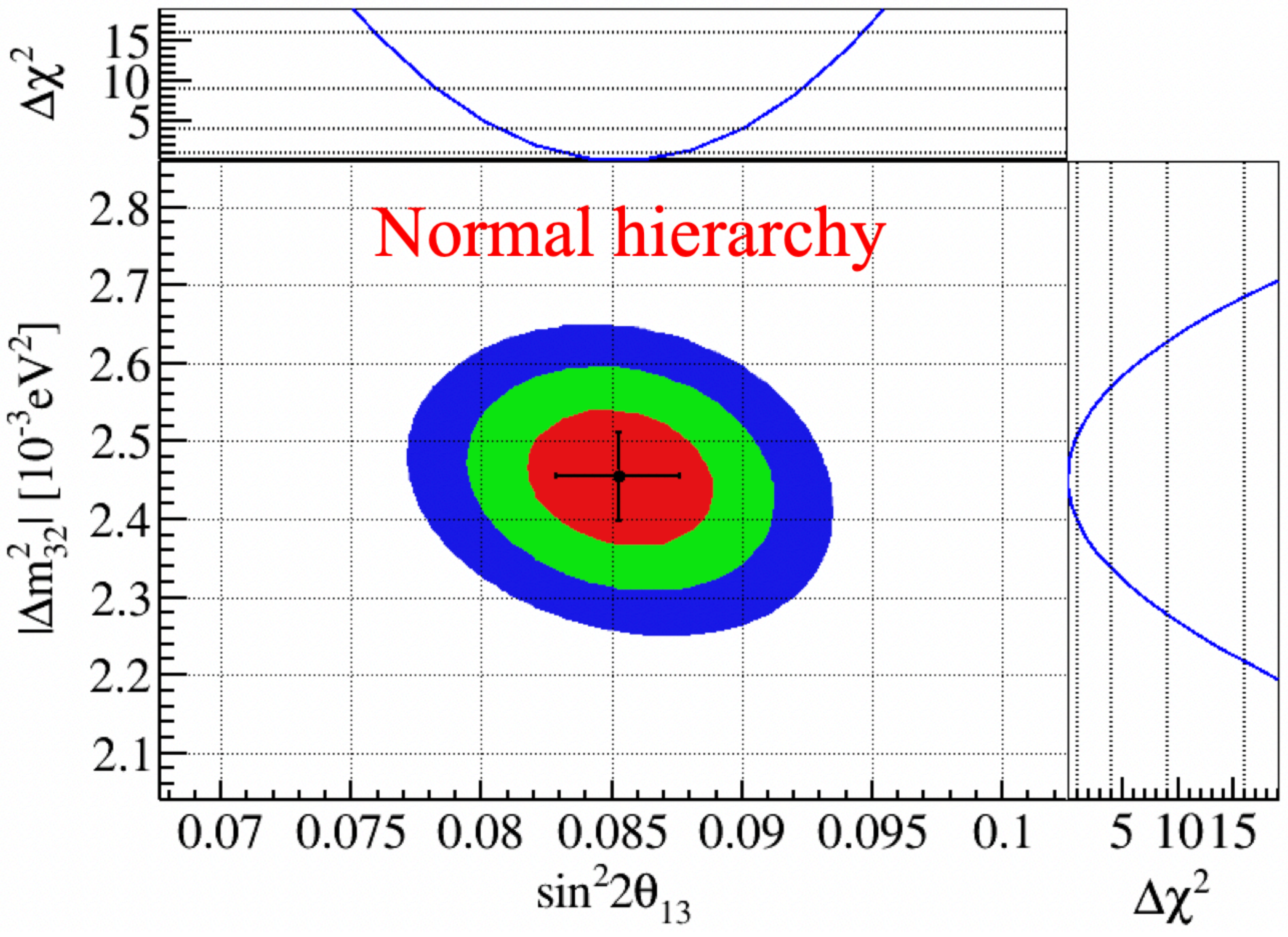

- Near detector imposes an upper bound over Δm^2_{31}
- The oscillation measured at the far detector imposes a lower bound on θ_{13} and Δm^2_{31}

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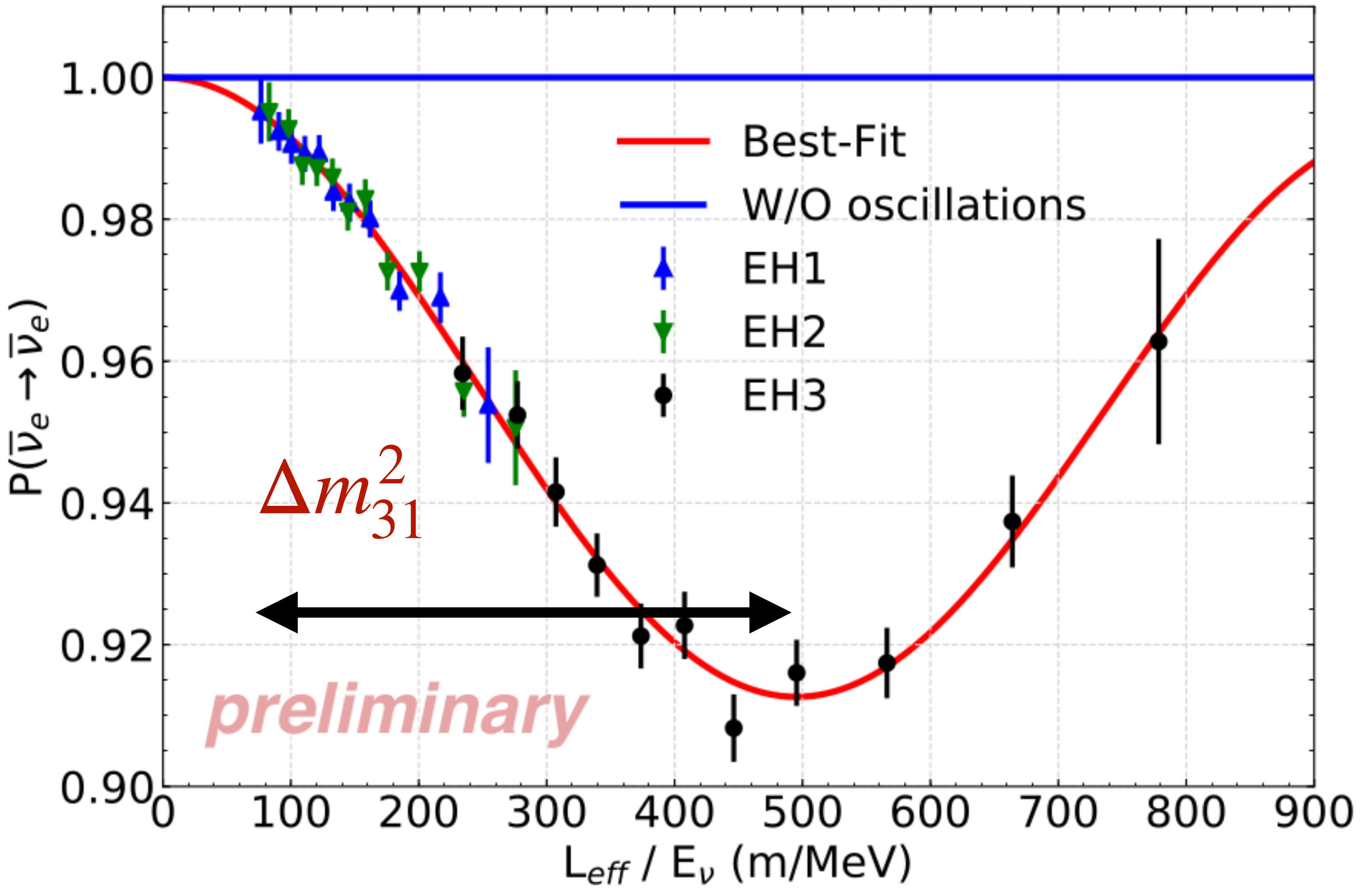

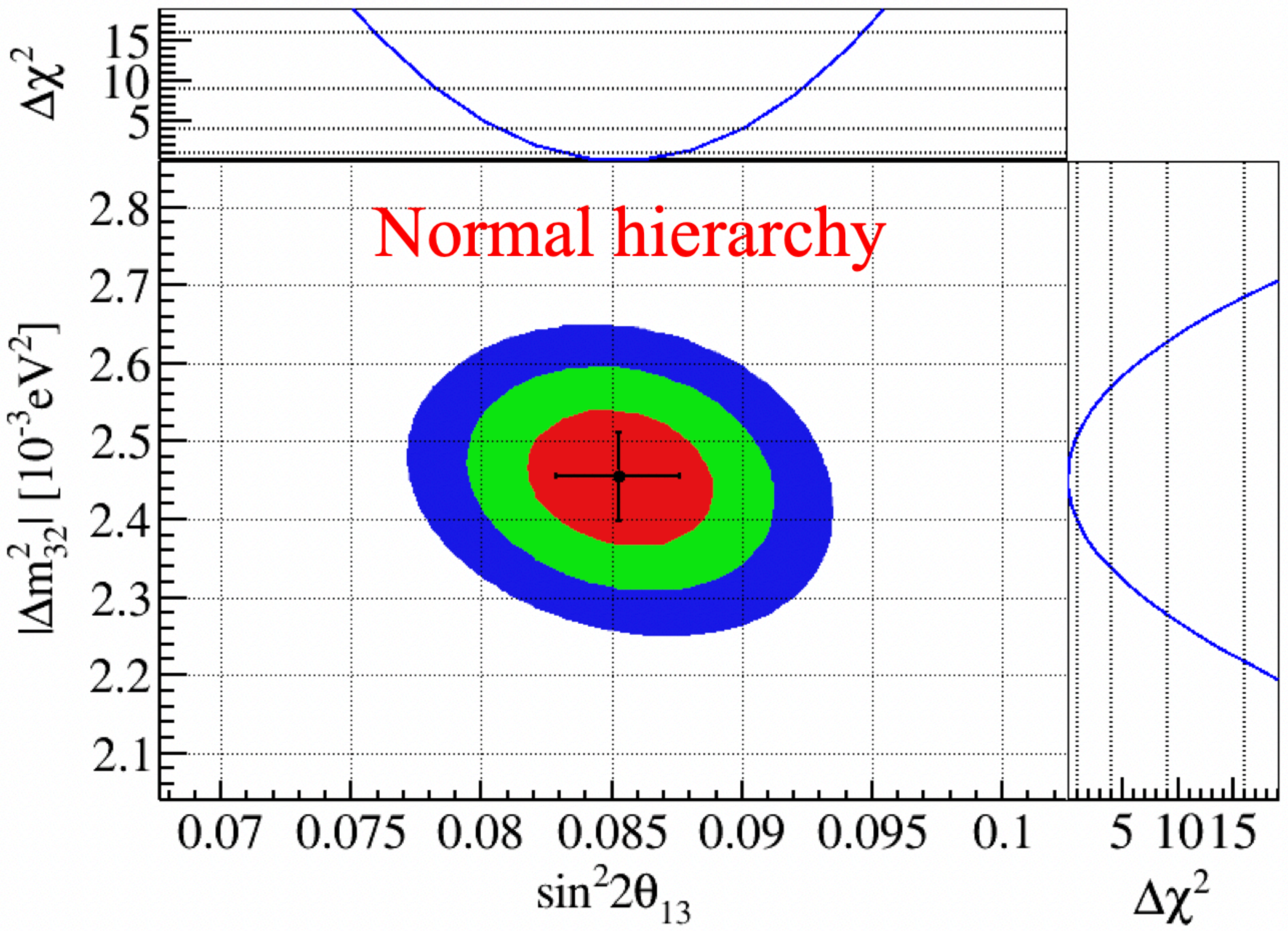

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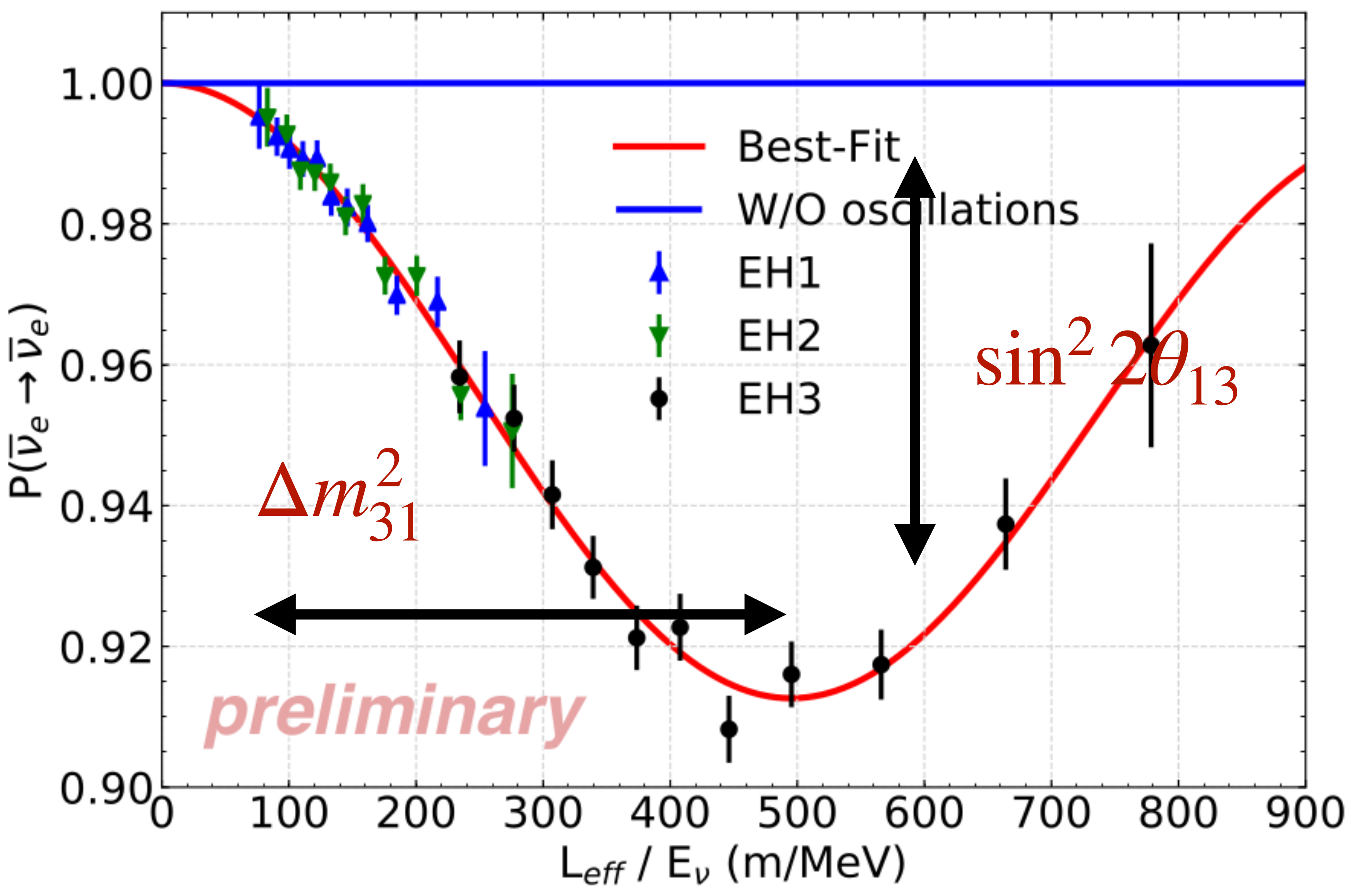

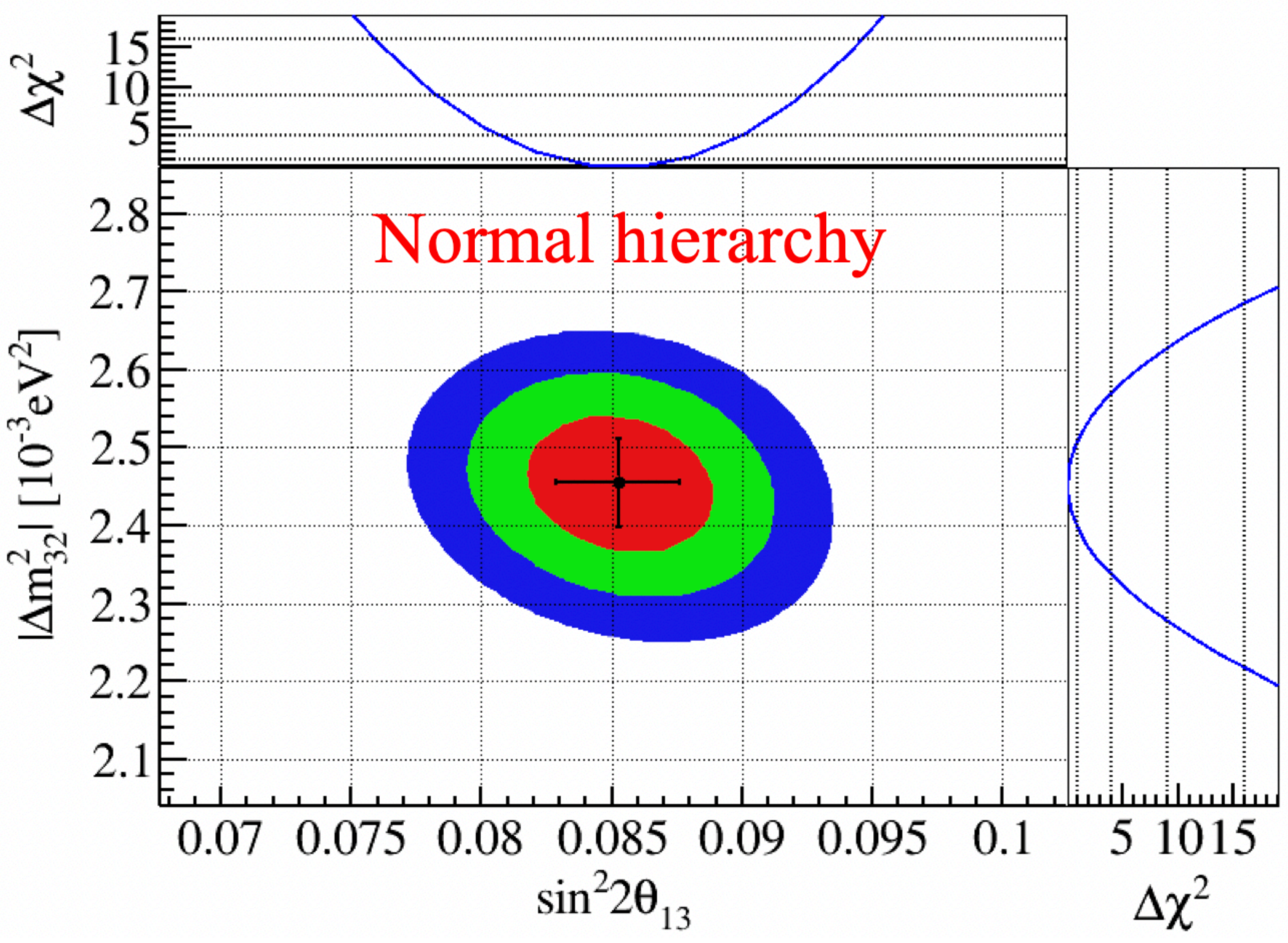

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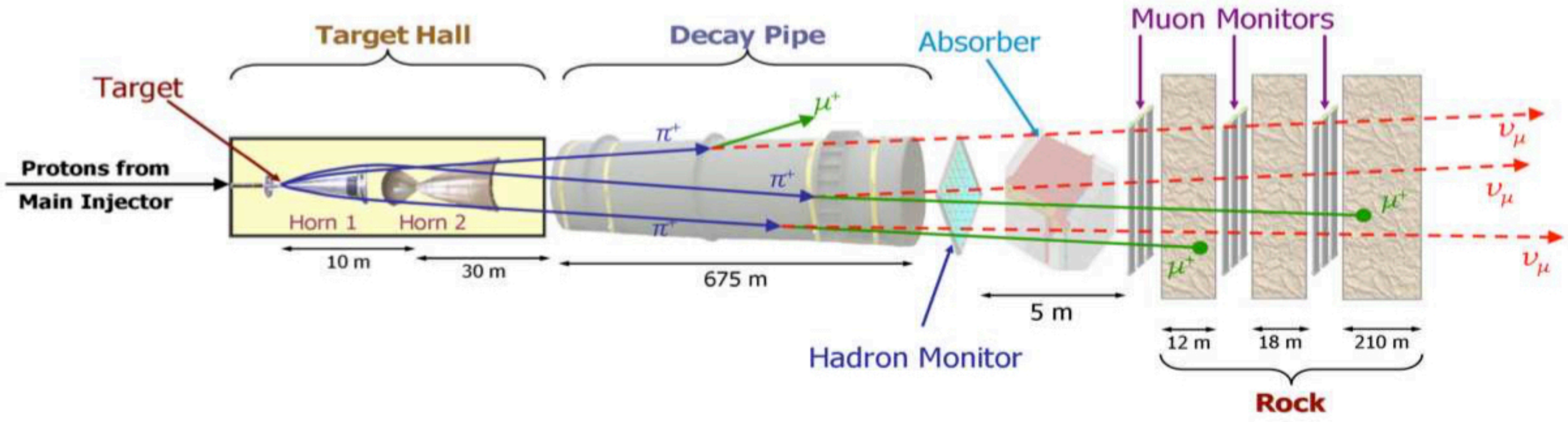
Long-Baseline Accelerators

Neutrinos are generated from **pion/kaon decays** caused by an accelerated proton beam hitting a target.

$$\pi^{\pm} \to \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

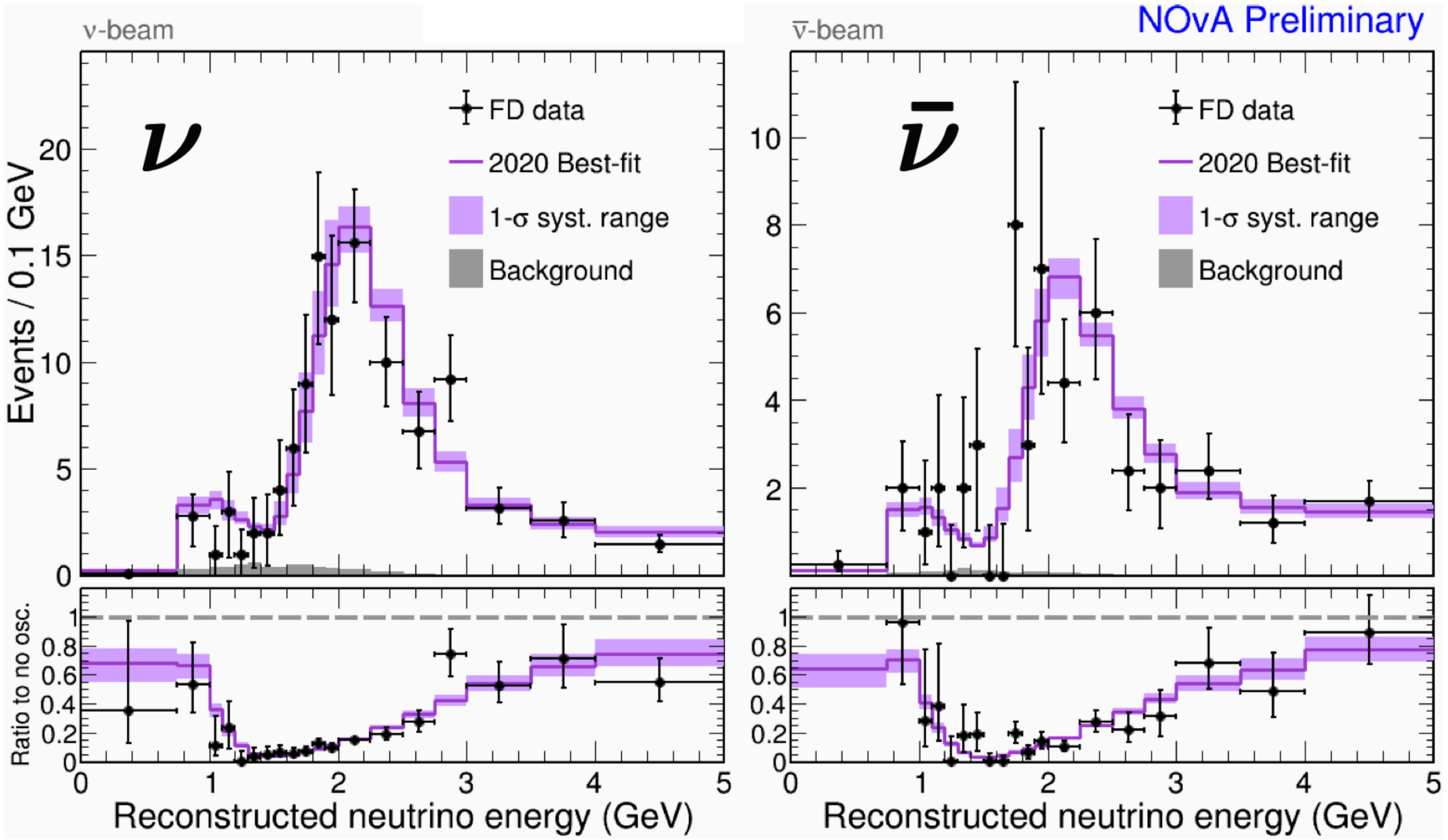


NuMI Beam

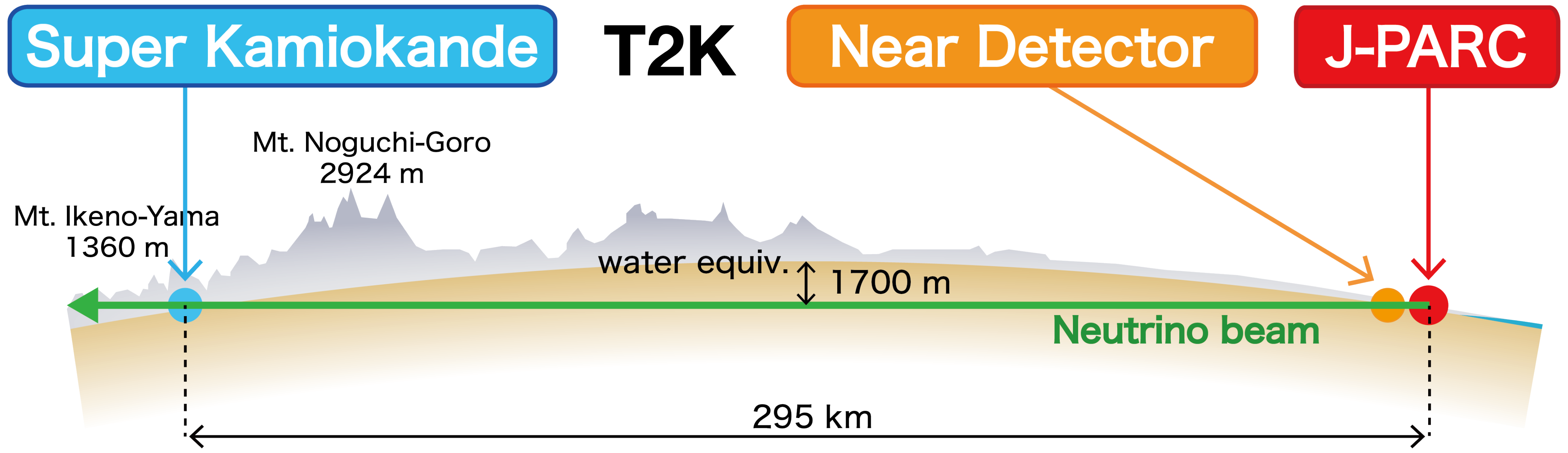
Long-Baseline Accelerators

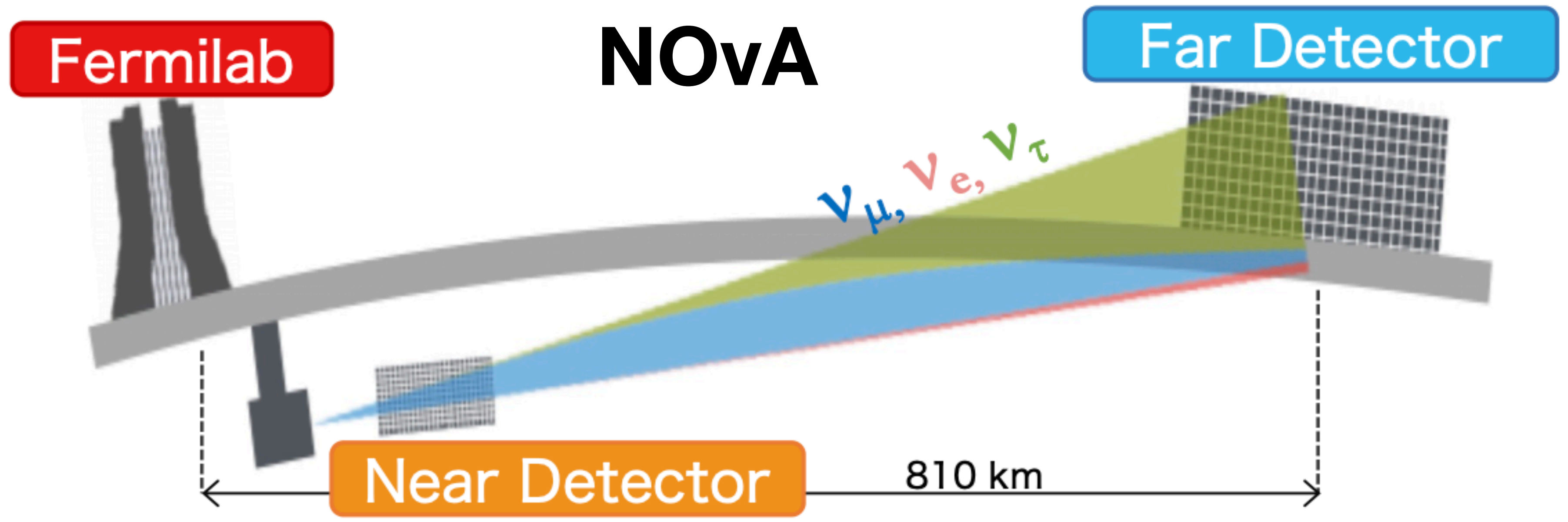
Neutrinos are generated from **pion/kaon decays** caused by an accelerated proton beam hitting a target.

Neutrinos travel ~ 100 Km and have energies $E \sim 1$ GeV, making these experiments sensitive to the oscillation driven by Δm^2_{31}



Nosek (NOvA Collaboration) Fermilab





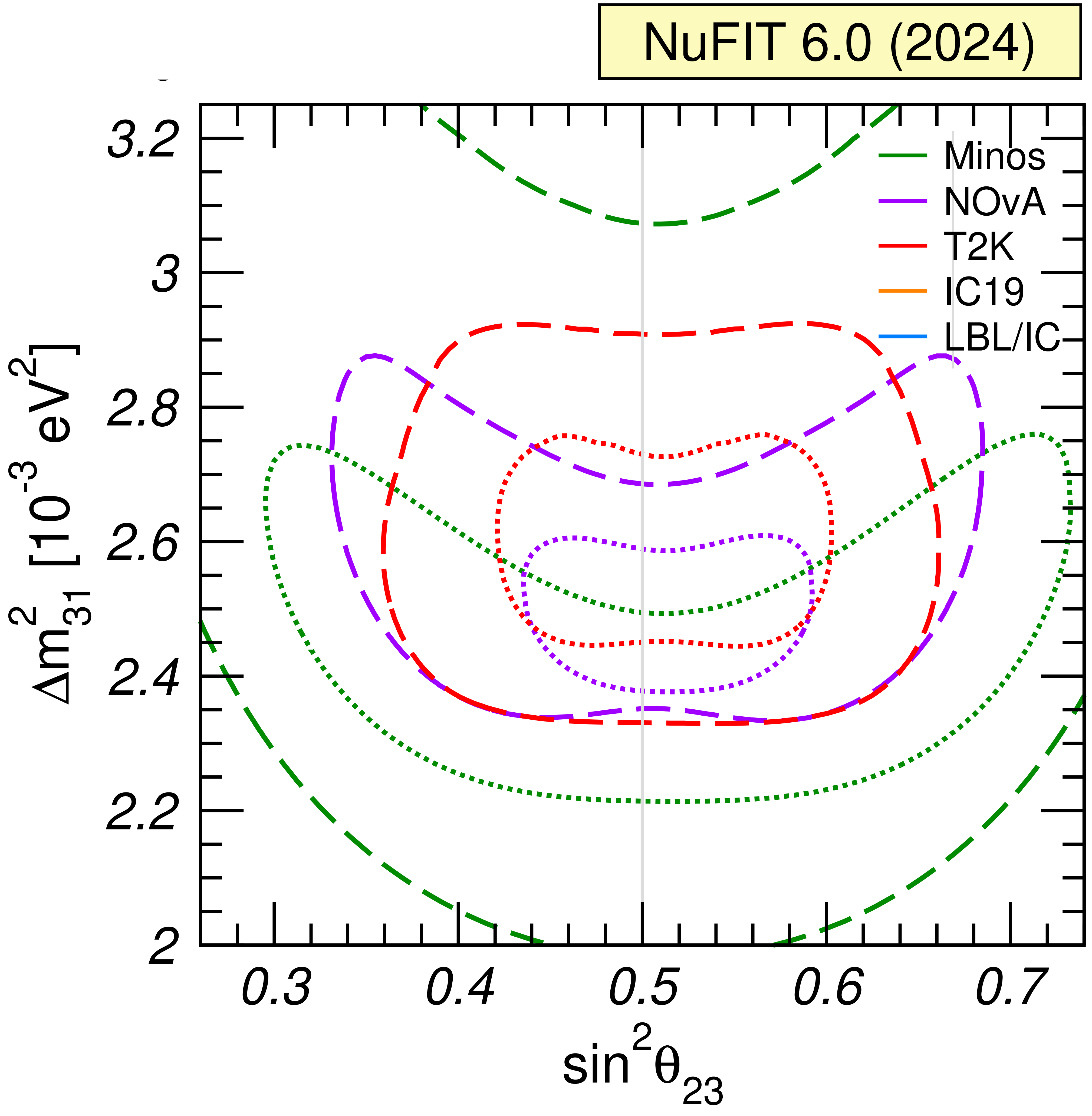
Long-Baseline Accelerators

Accelerator experiments are sensitive to Δm^2_{31} and $\sin^2 2\theta_{23}$, searching for ν_μ**-disappearance**

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E} + o(\frac{2EV_{CC} \sin^2 \theta_{13}}{\Delta m^2_{31}})$$

$$\Delta m^2_{\mu\mu} = \Delta m^2_{31} - \cos^2 \theta_{12} \Delta m^2_{21} + \cos \delta_{cp} \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23} \Delta m^2_{21}$$

$$\sin^2 \theta_{\mu\mu} = \cos^2 \theta_{13} \sin^2 \theta_{23}$$



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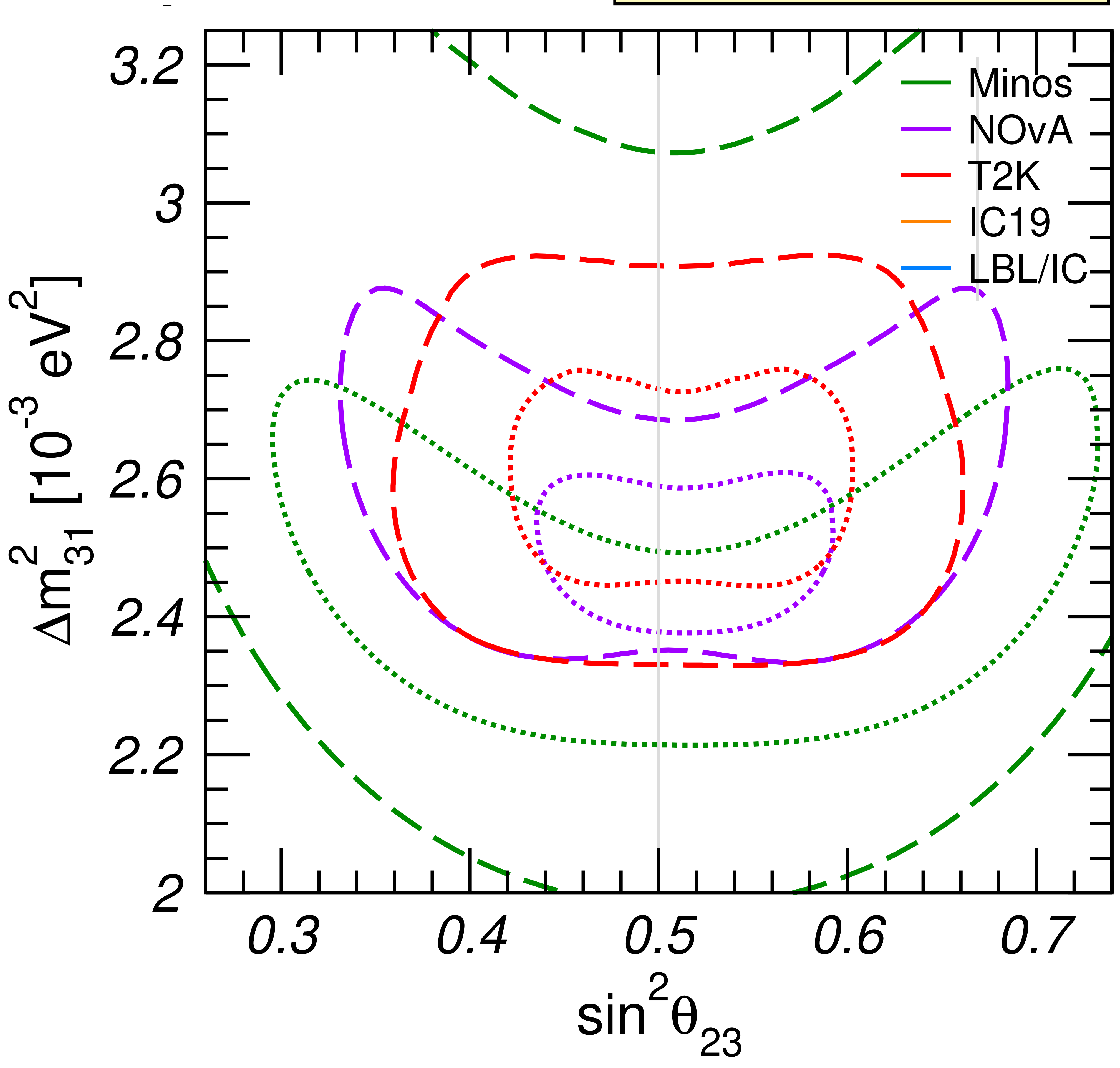
- Matter effects are small for this channel

NuFIT 6.0 (2024)



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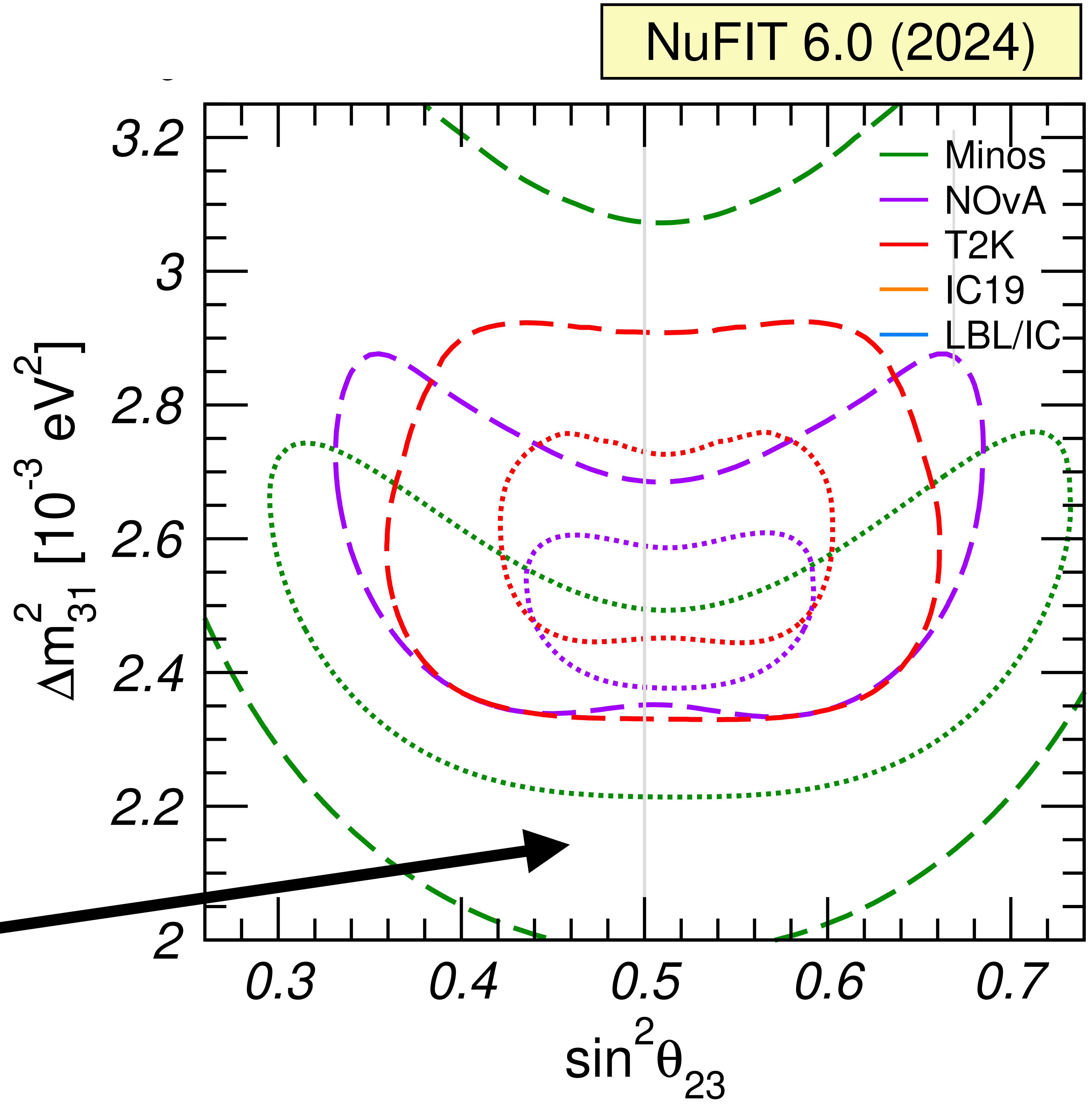
- Matter effects are small for this channel

- Cannot resolve the octant of θ_{23}

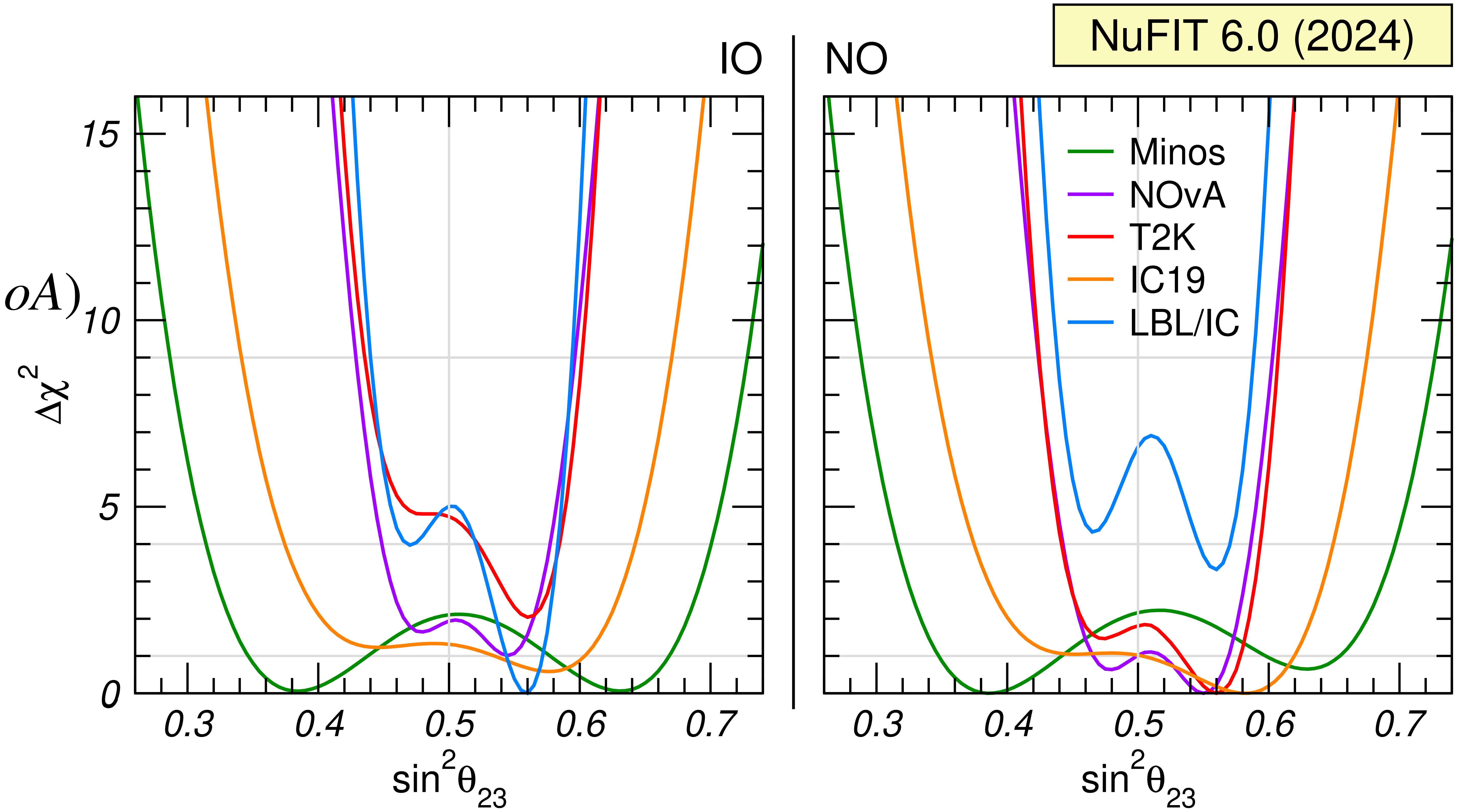
$$\sin^2\theta_{\mu\mu} \approx \sin^2\theta_{23}$$



Long-Baseline Accelerators

Accelerator experiments can search for ν_e-**appearance**

$$P_{\nu_\mu \to \nu_e} \approx 4\sin^2\theta_{13}\sin^2\theta_{23}(1+2oA) - C\sin\delta_{cp}(1+oA)$$



$$o = sign(\Delta m^2_{31}) \qquad A = |2EV/\Delta m^2_{31}| \qquad C = \frac{\Delta m^2_{21}L}{4E}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

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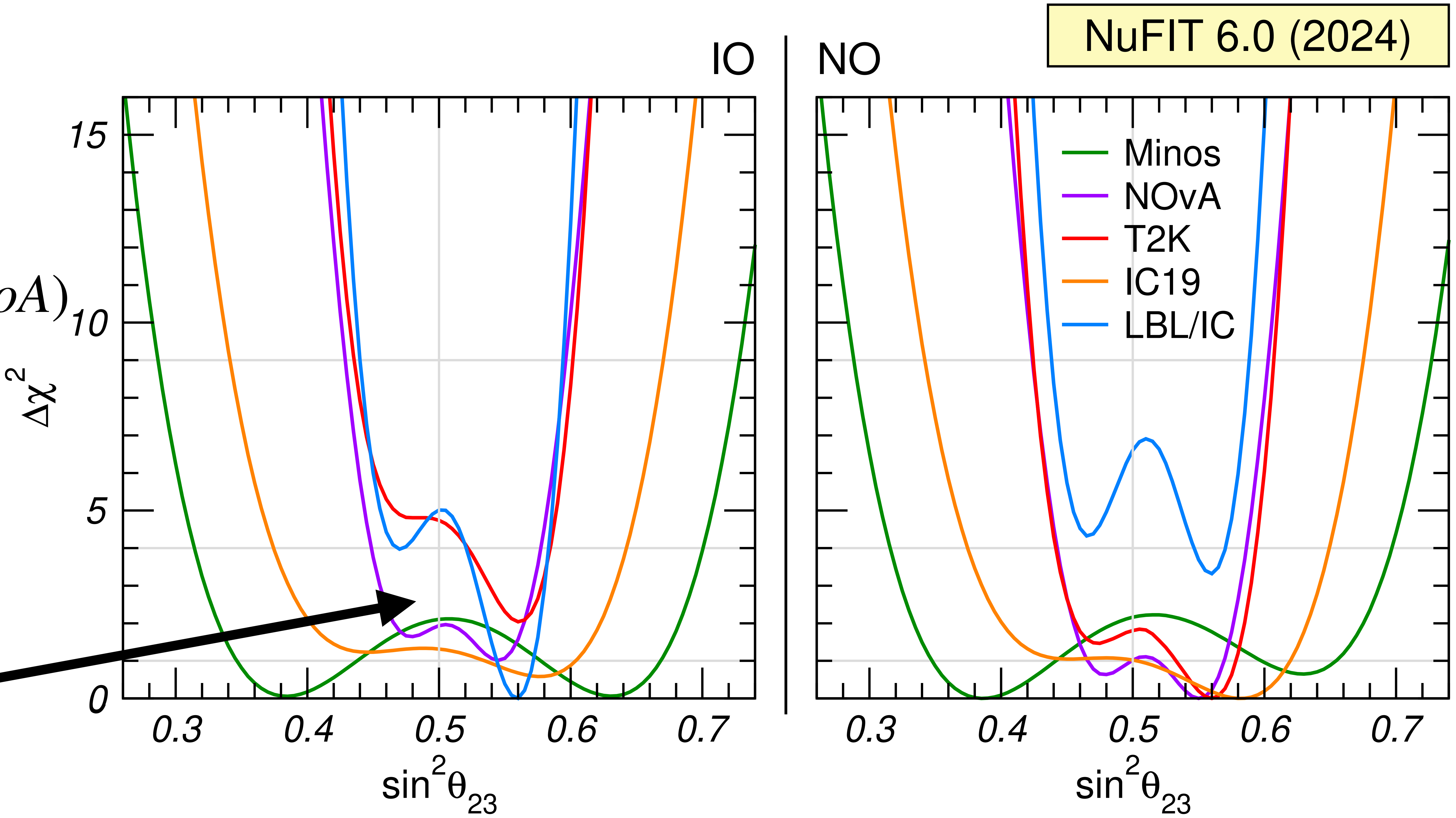
Octant θ_{23}

The dependence of $\sin^2\theta_{23}$ breaks the **octant** degeneracy



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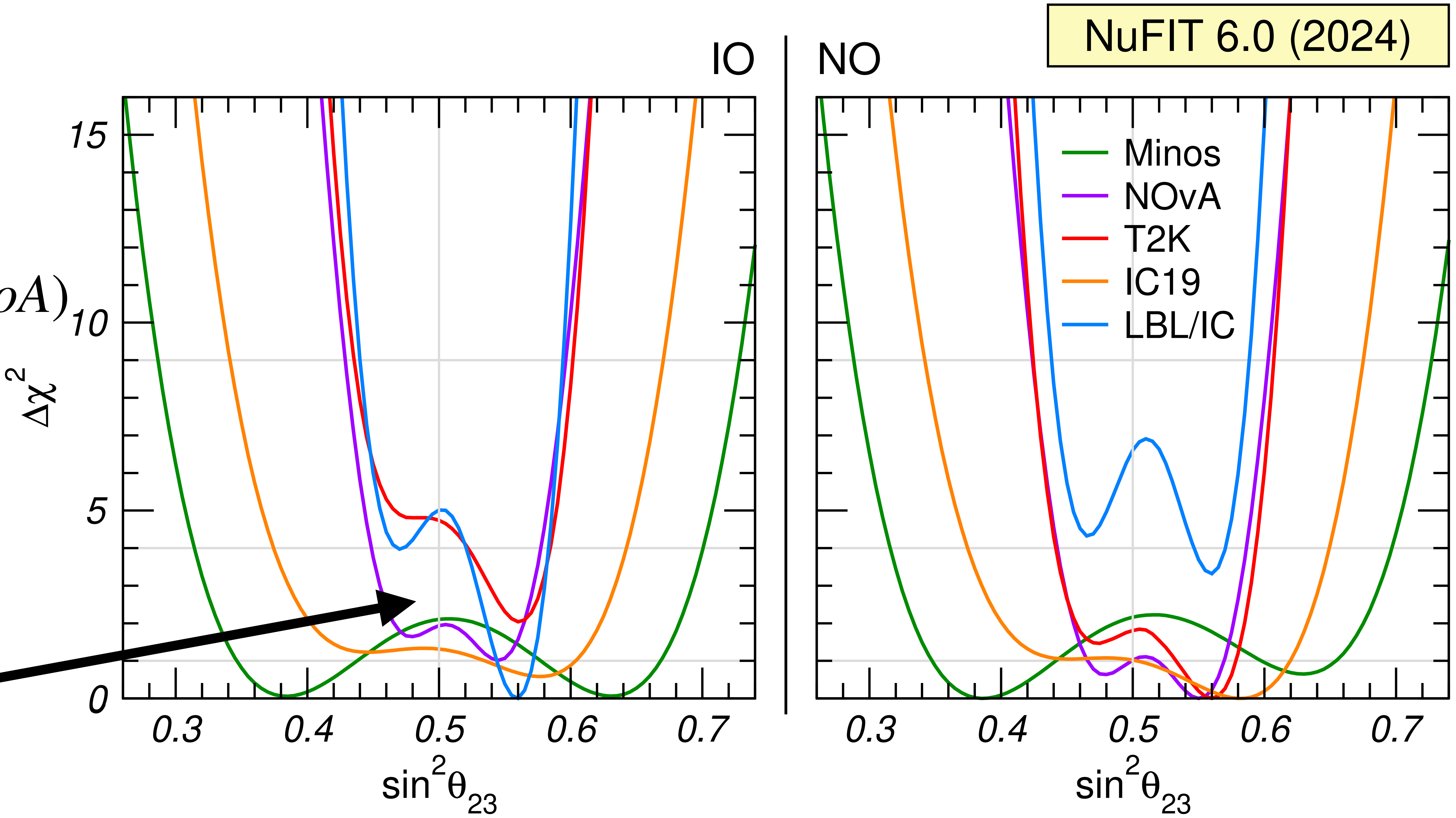
Ordering

The appearance depends on the **mass ordering**



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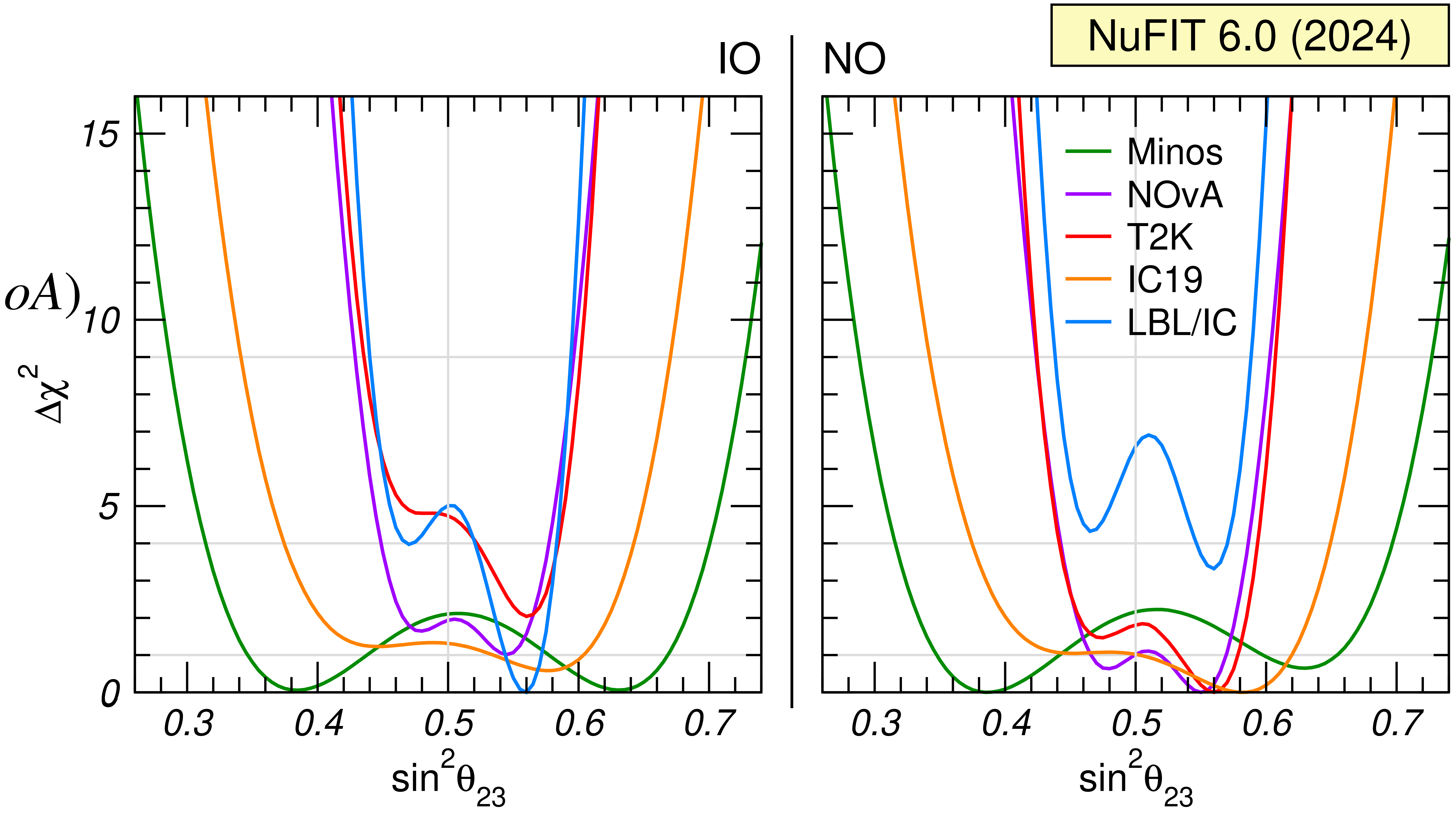
CP-violation

The appearance depends on the **CP-phase**



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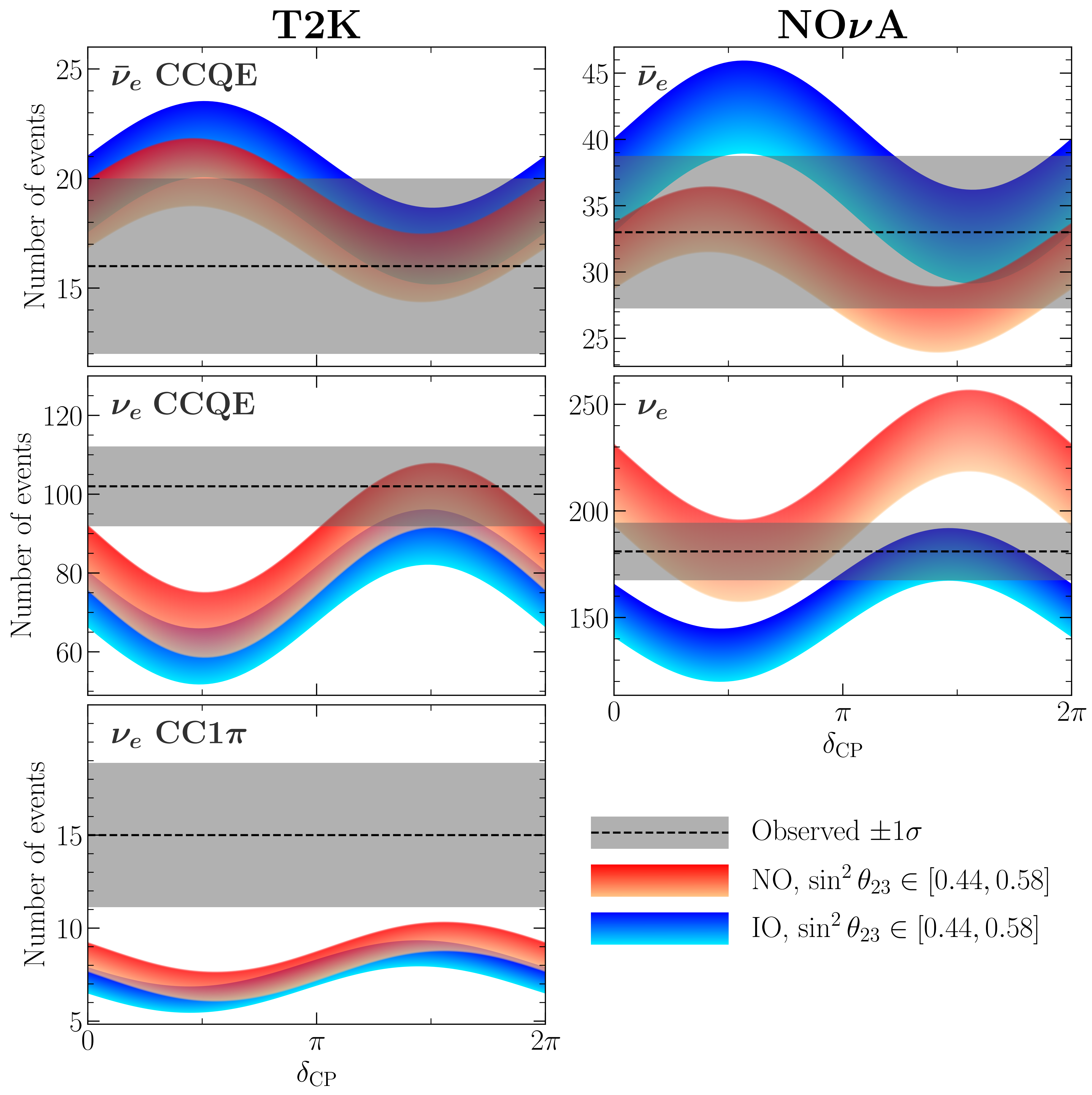
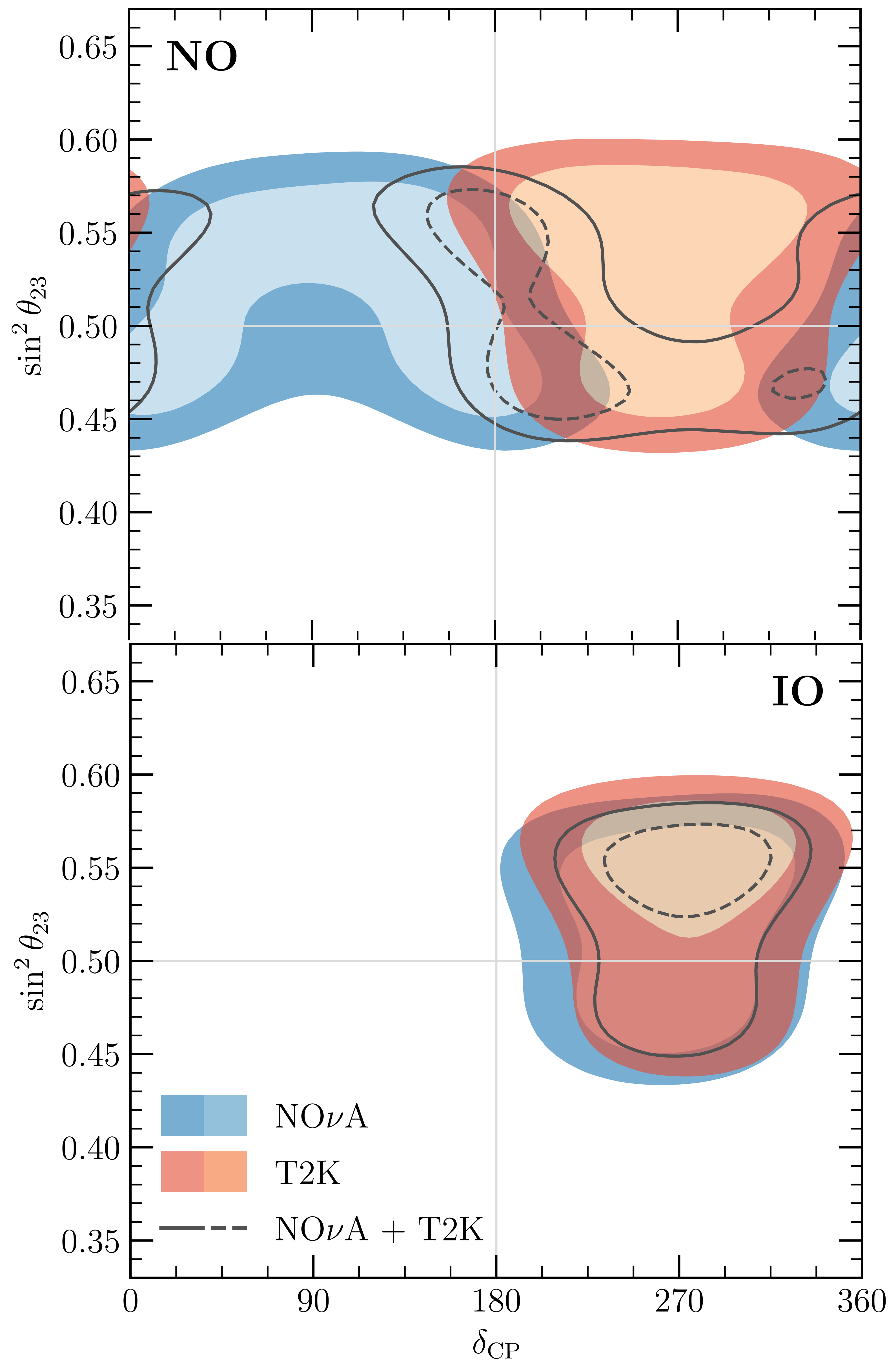
I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

T2K vs NOvA

The **tension** between **T2K** and **NOvA** over δ_{CP} and NO shifts the LBL preference toward **IO**

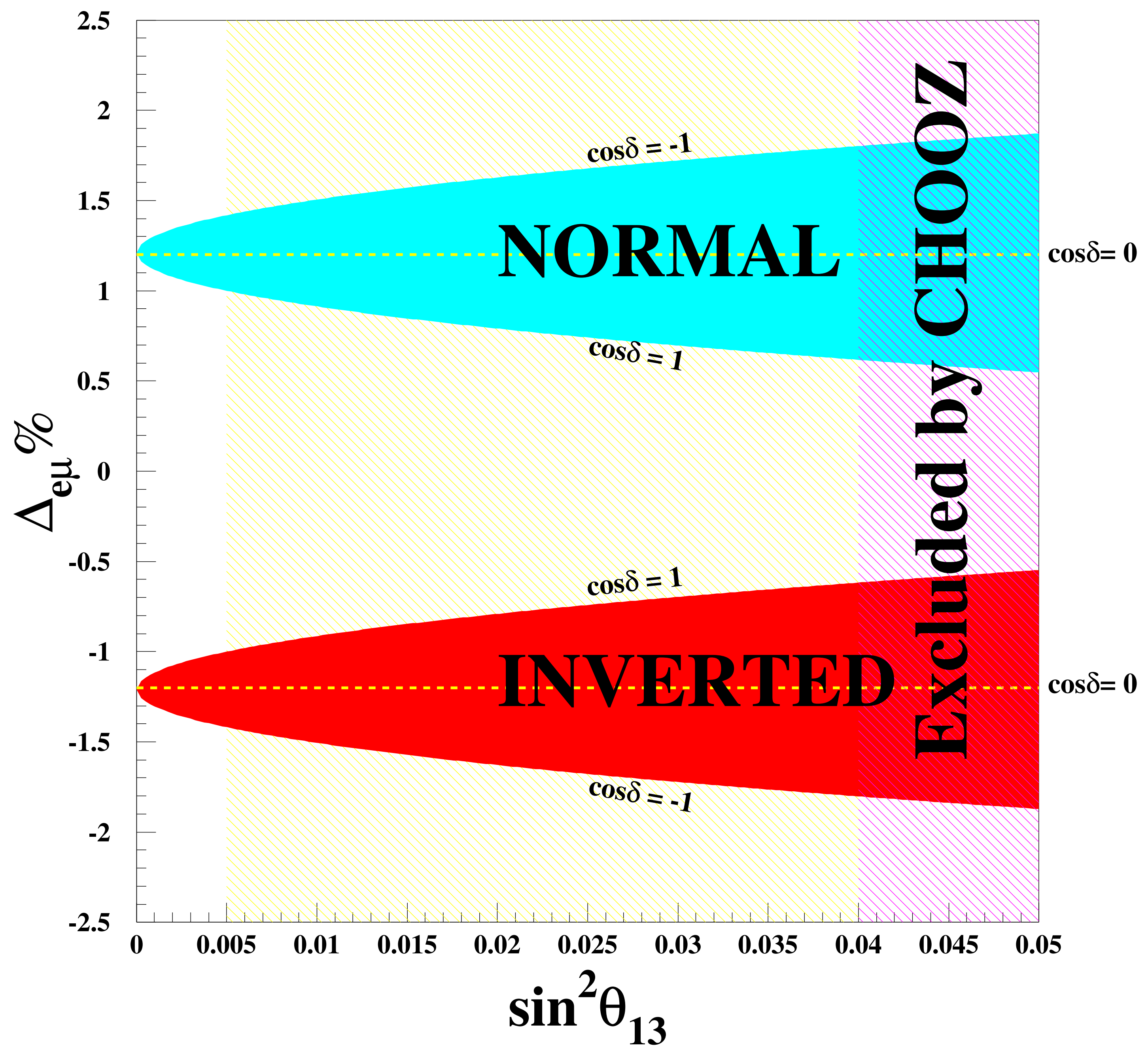




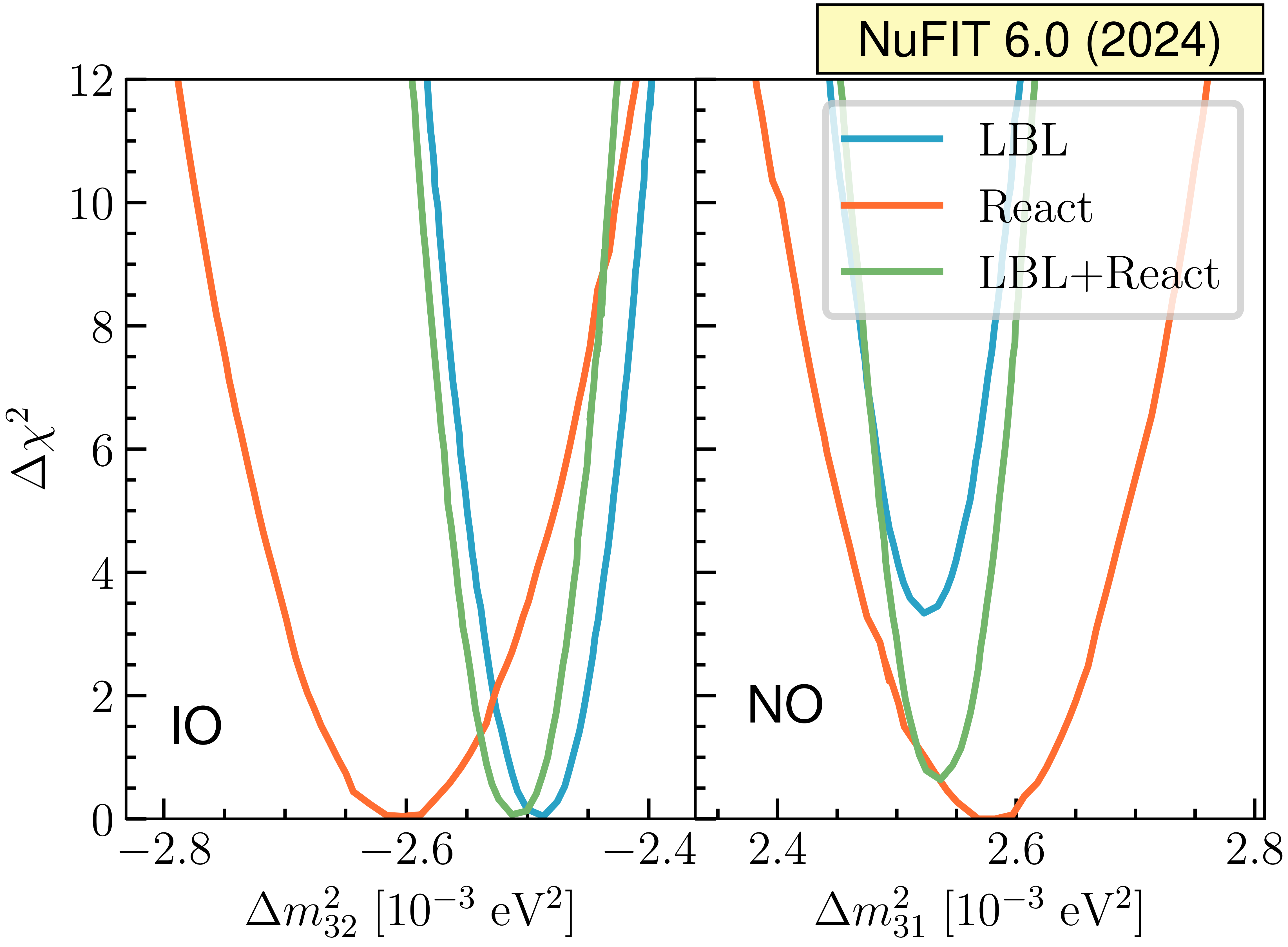
LBL+Reactors

Full LBL-reactor combo eases T2K-NOvA tension

$$\Delta_{e\mu} = (|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}|)/\Delta m^2$$



Nunokawa, Parke, Funchal, PRD 72(2005) arXiv: hep-ph/0503283



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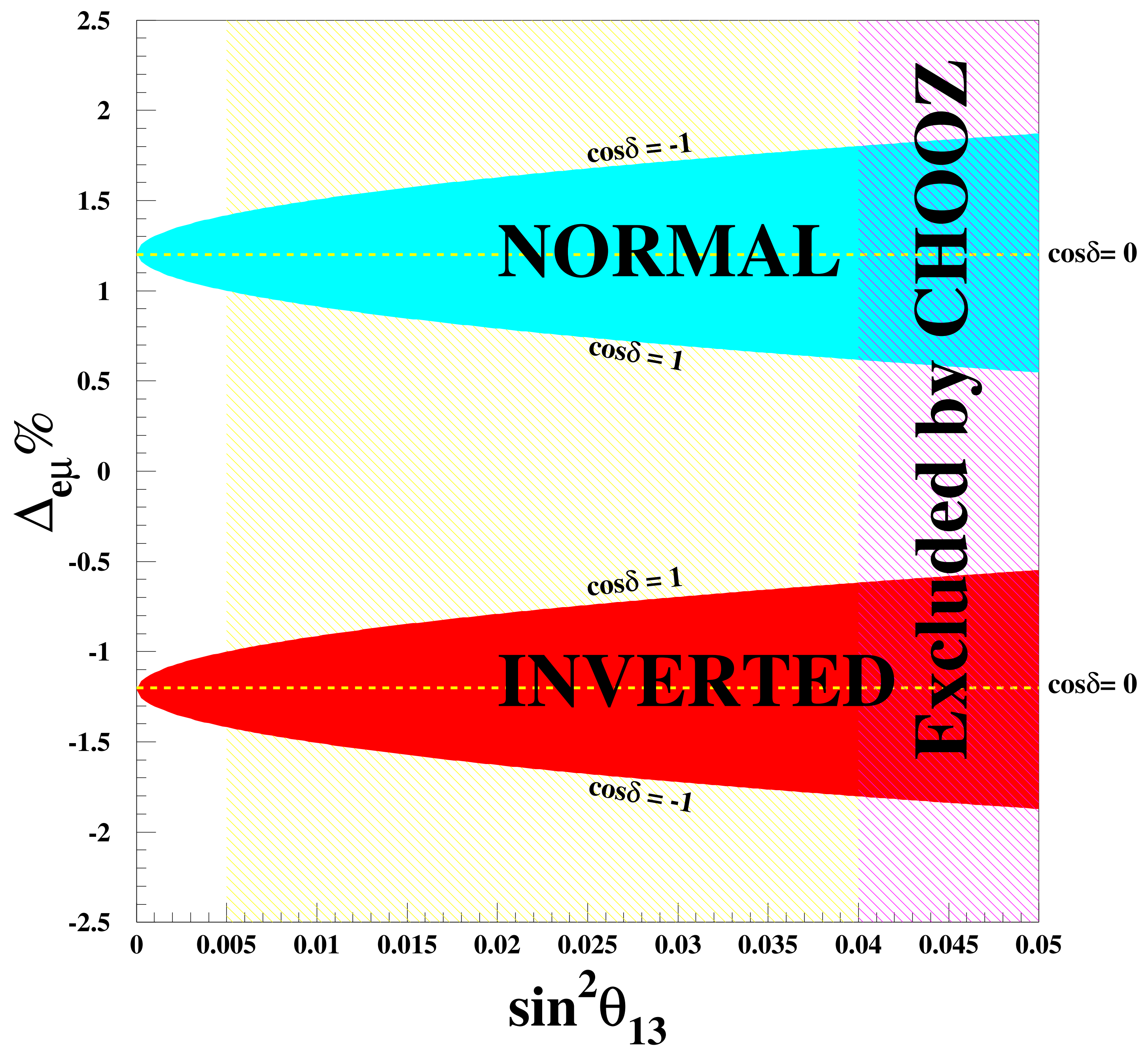
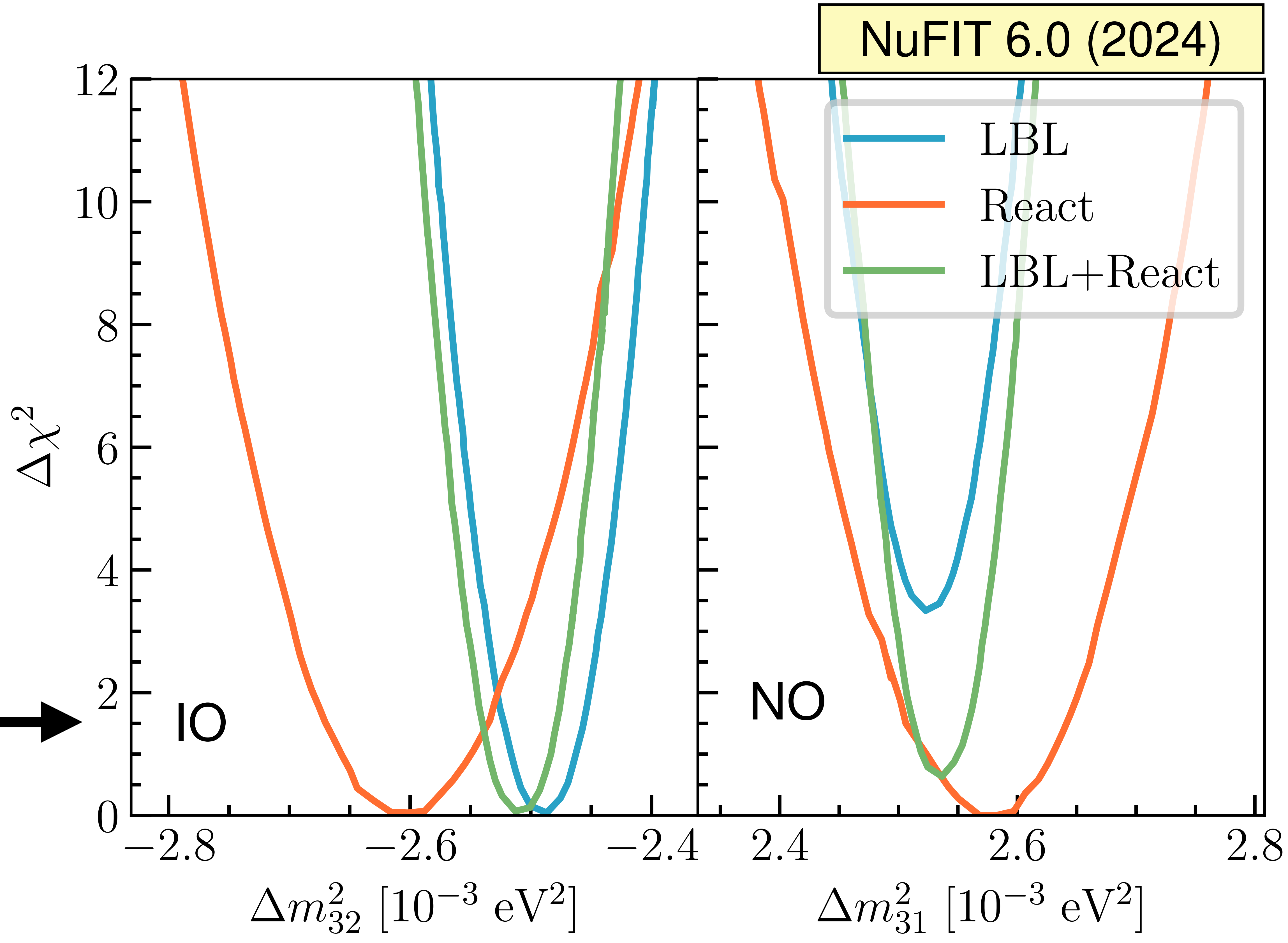


Nunokawa, Parke, Funchal, PRD 72(2005) arXiv: hep-ph/0503283

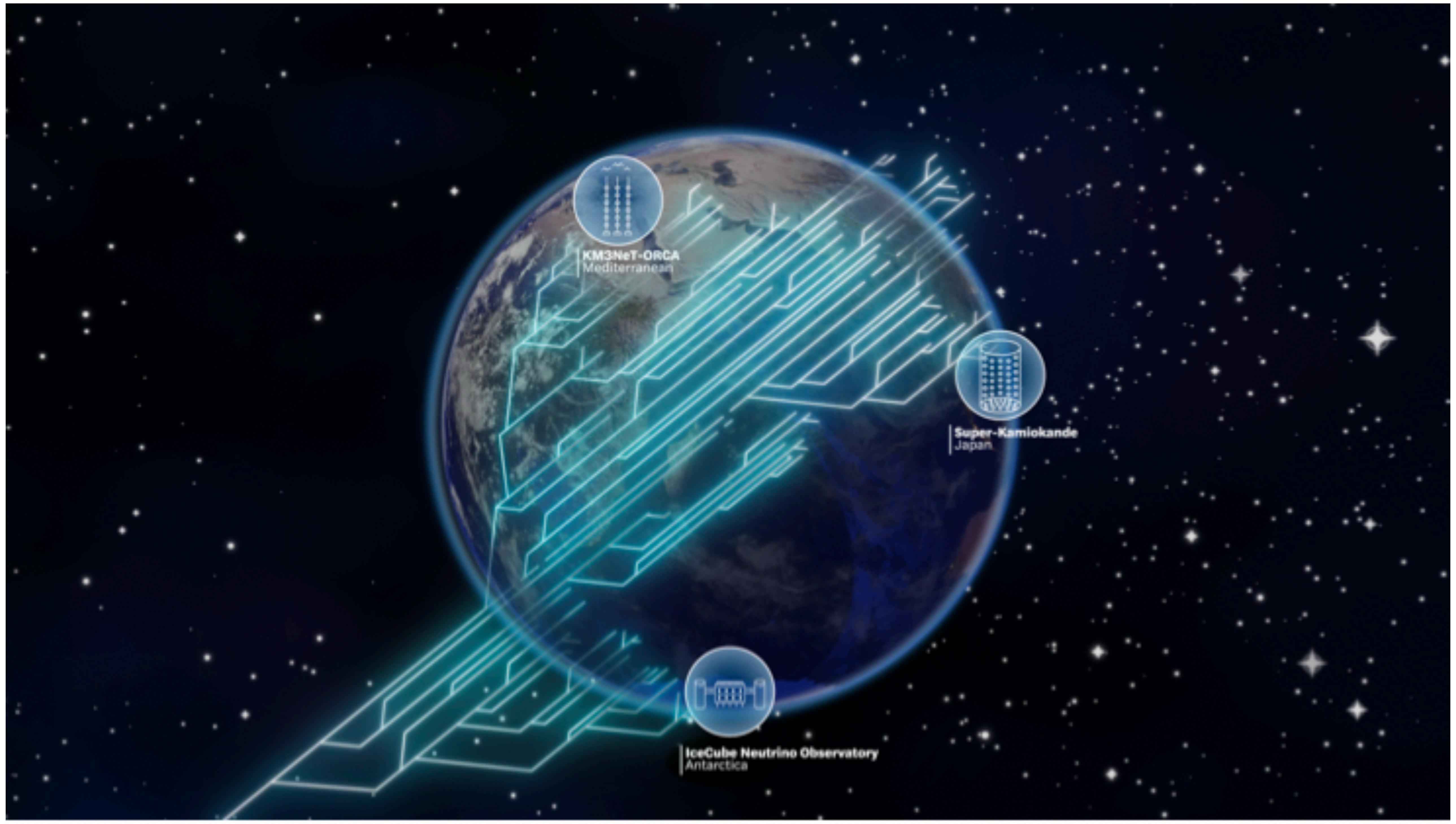
Preference for $\Delta_{e\mu} > 0$

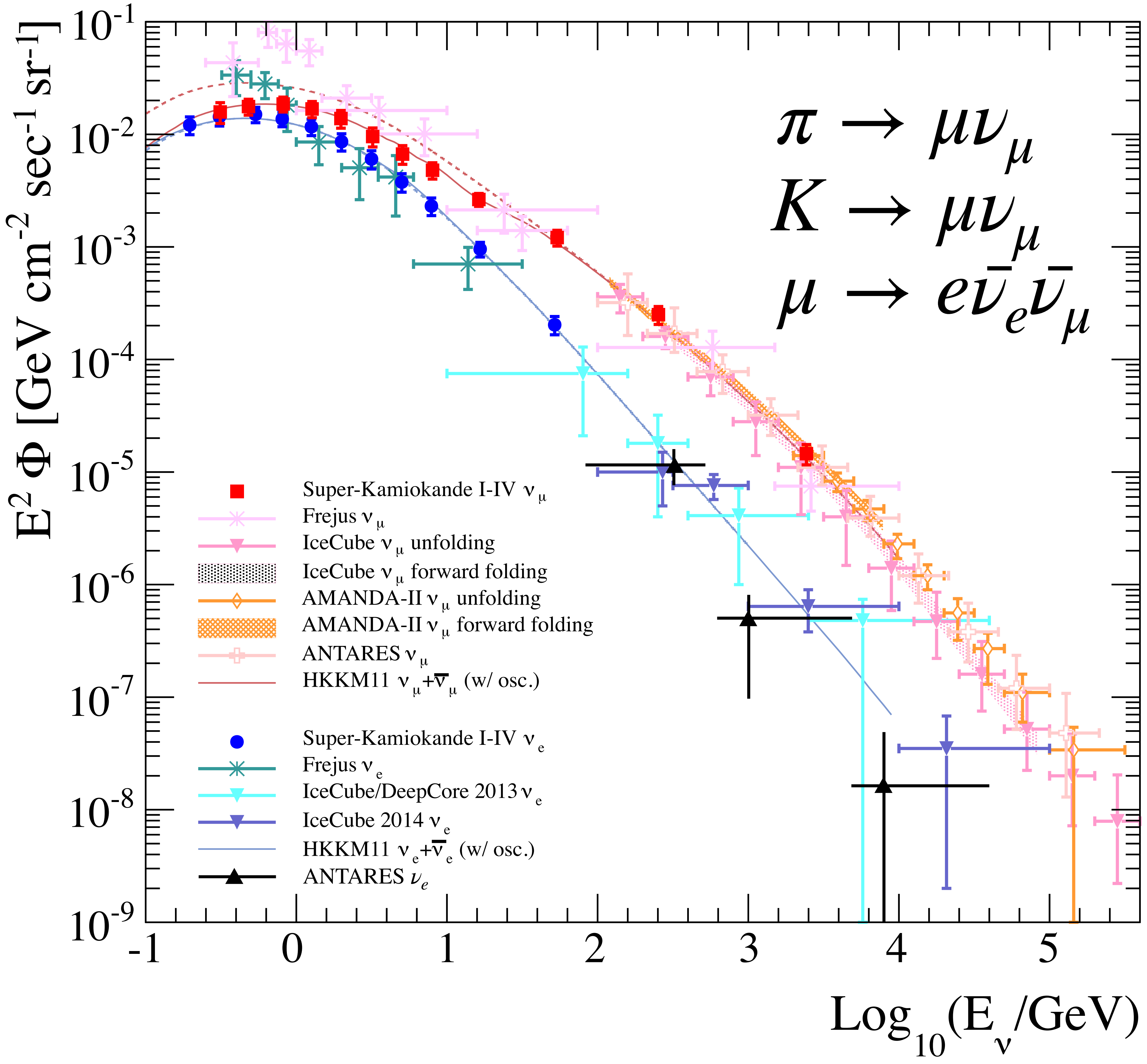


- Combining LBL($\Delta m^2_{\mu\mu}$) and reactors (Δm^2_{ee}) strengthens NO preference

Atmospheric Neutrinos

Atmospheric neutrinos are created in the collision of cosmic rays with the atmospheric nuclei





E. Richard et al. (SK), PRD 94 (2016) 5

Atmospheric Neutrinos

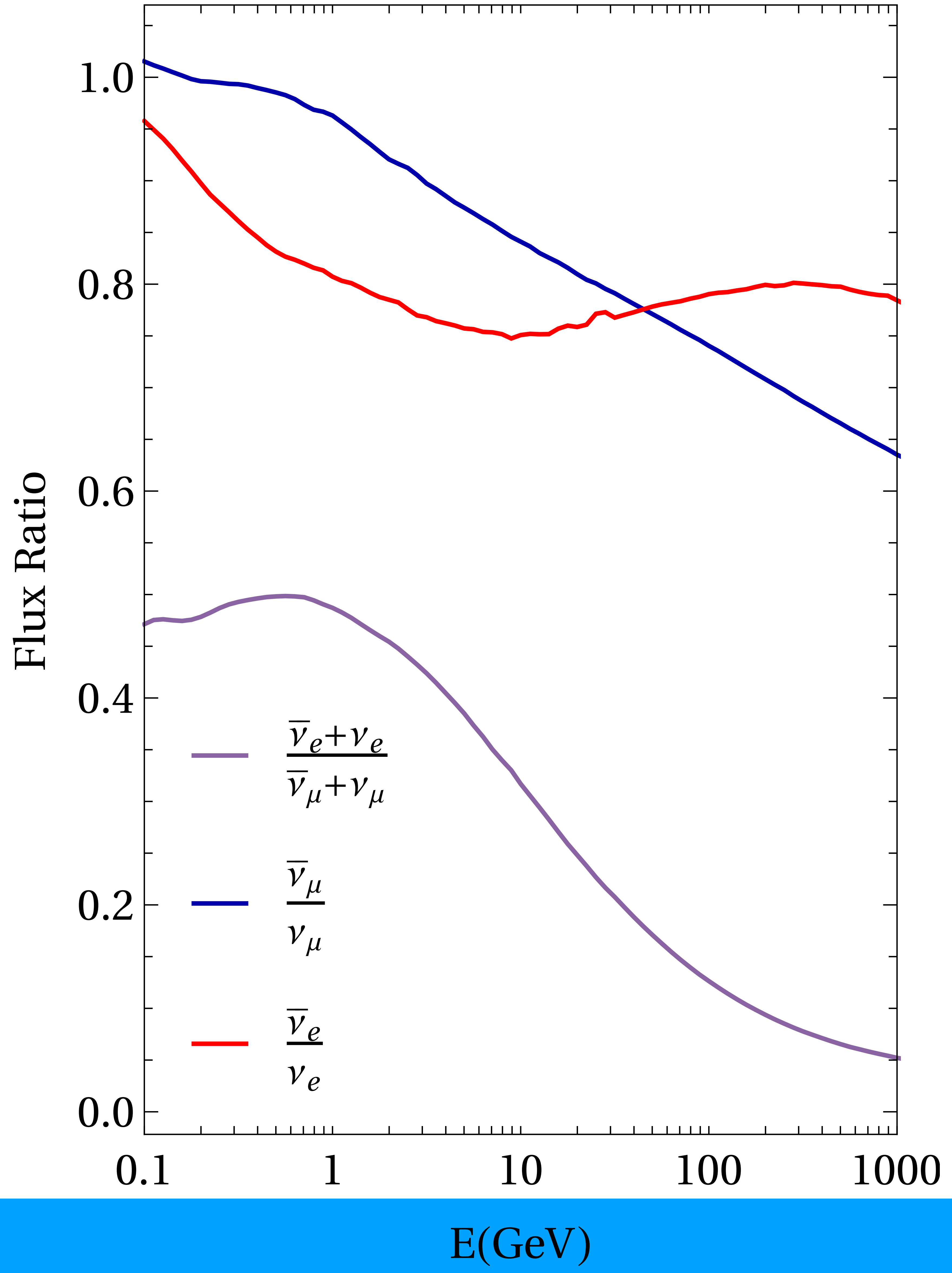
The most recent atmospheric neutrino flux estimations are based on 3D-MC simulation

$$\phi_{\nu_i} = \phi_p \otimes R_p \otimes Y_{p\to\nu_i} + \sum_A \phi_A \otimes R_A \otimes Y_{A\to\nu_i}$$

The main components in the flux calculations are:

- **Cosmic ray flux** (ϕ_p)
- **Geomagnetic effects** (R)
- **Hadronic interactions** (Y)

The atmospheric flux **composition changes** with the energy



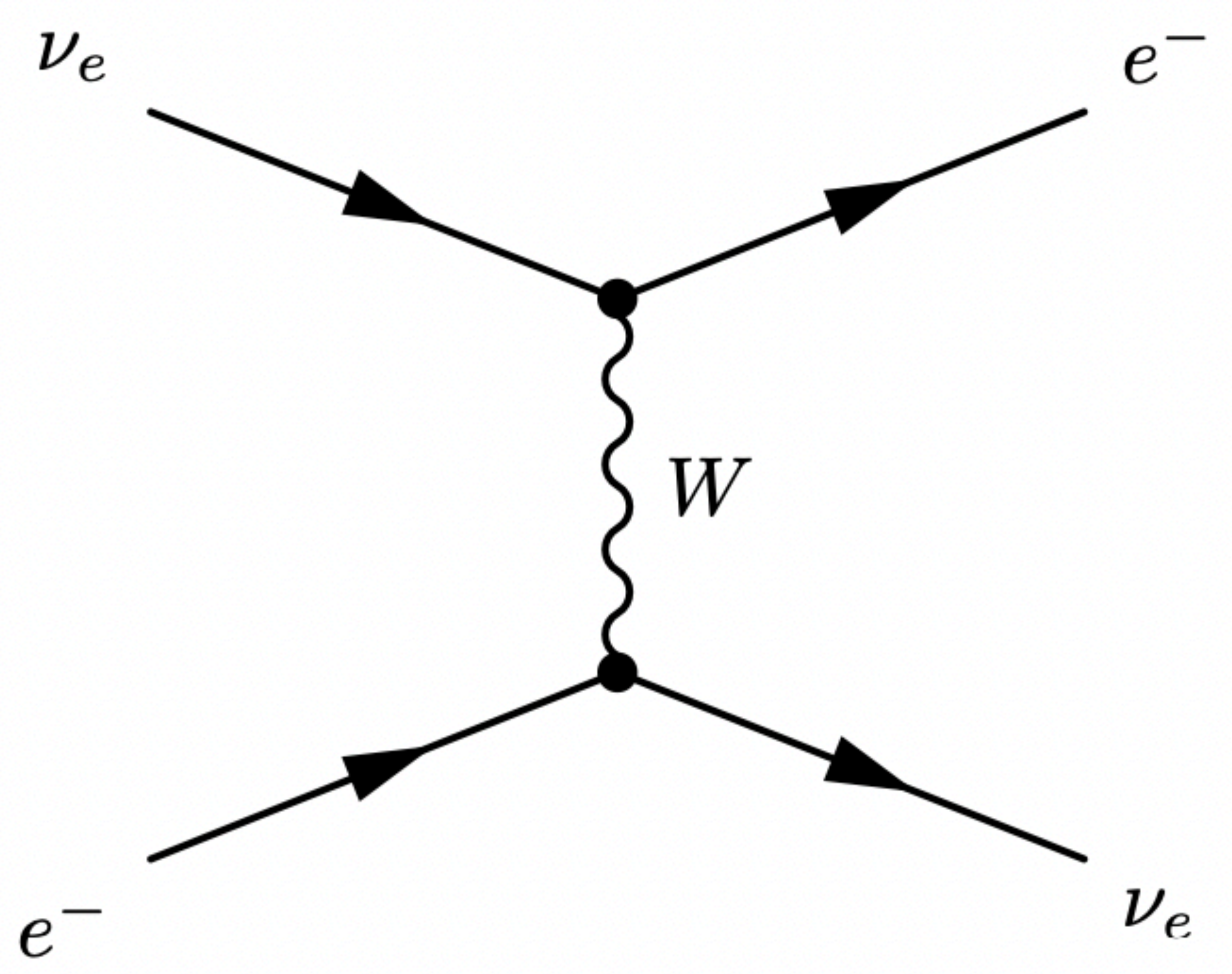
Honda, Sajjad Athar, Kajita, Kasahara, Midorikawa Phys.Rev.D 92 (2015)

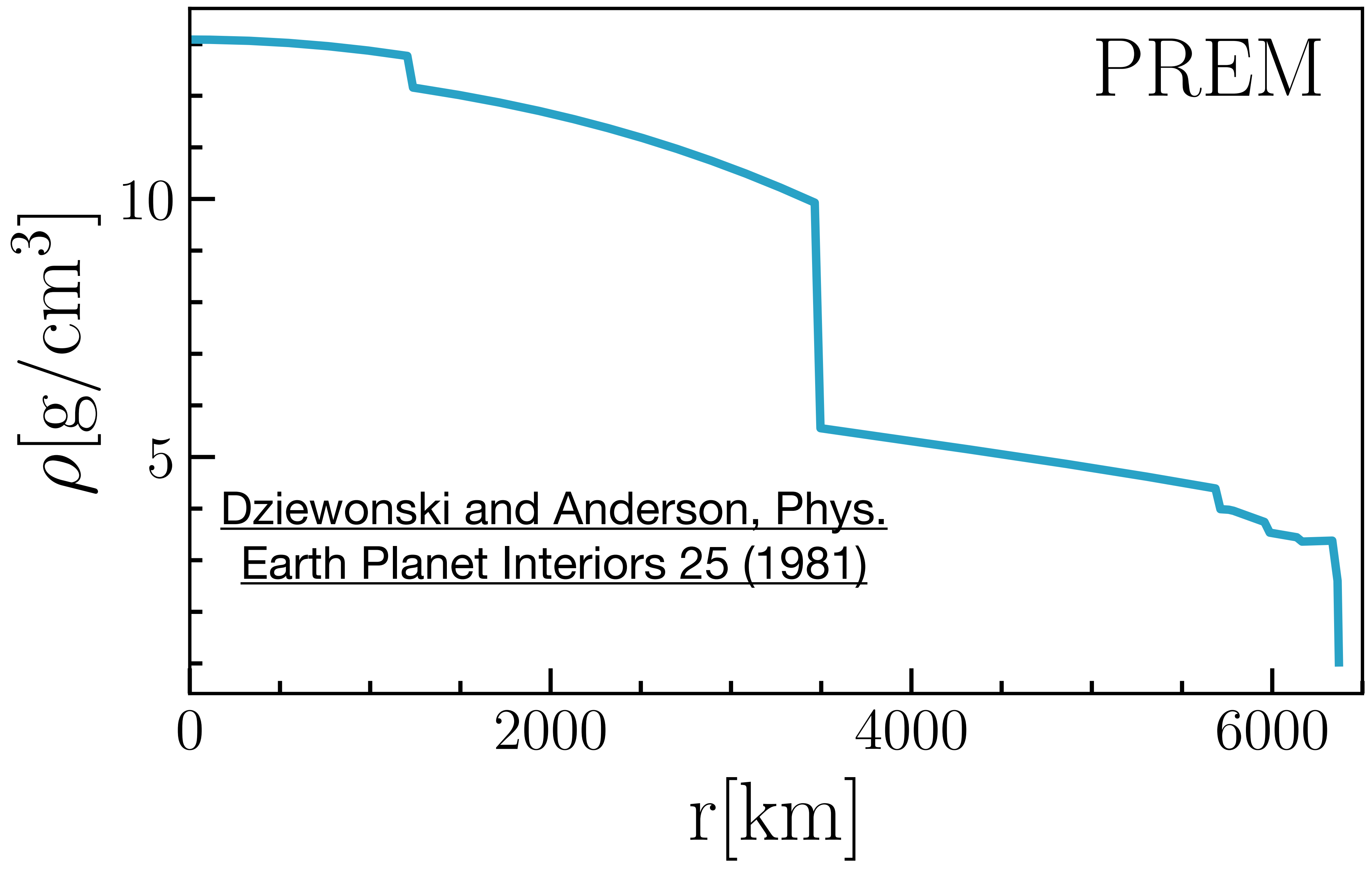
Atmospheric Neutrinos

Matter effects play a crucial role in the evolution of atmospheric neutrinos

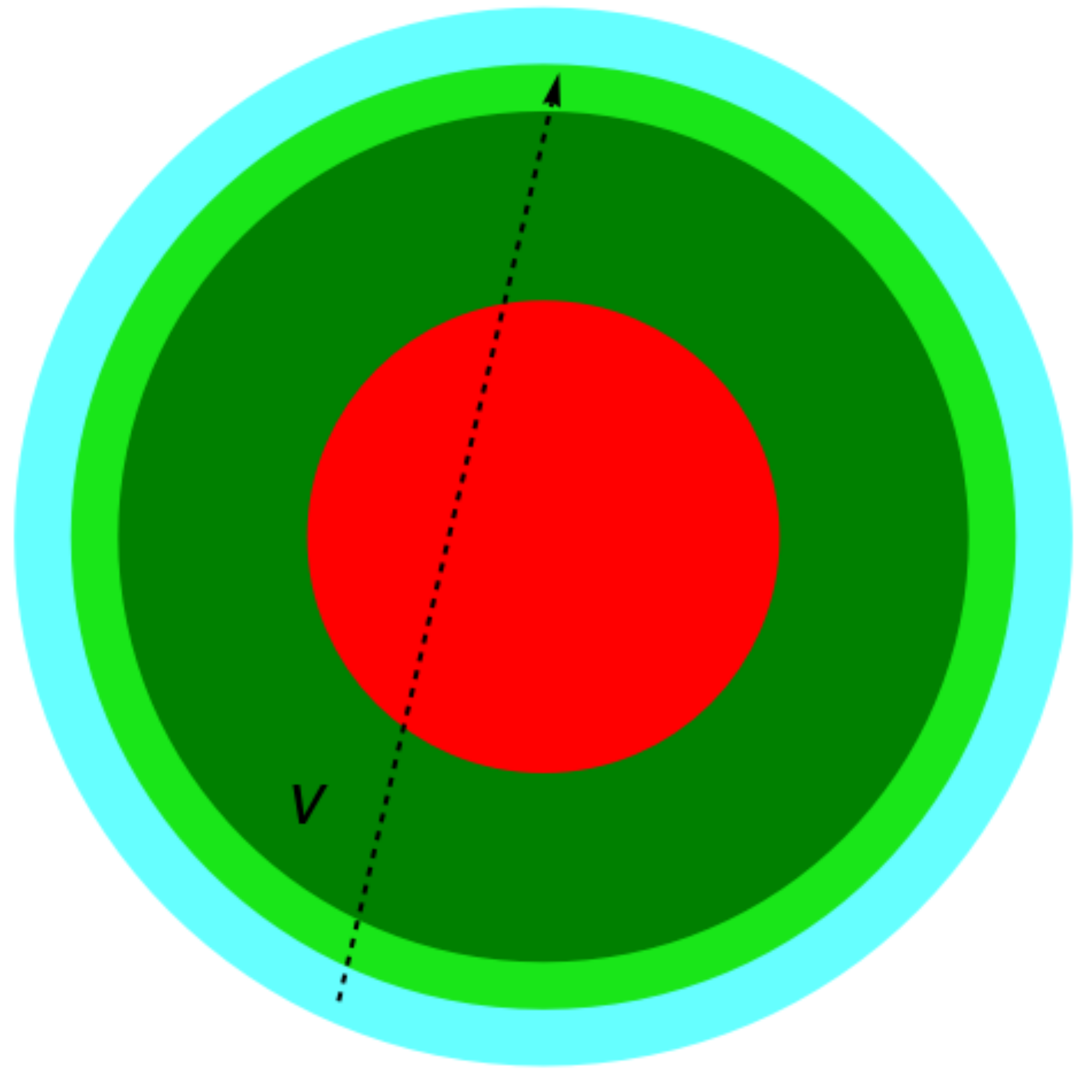
$$i\frac{d\nu}{dE} = \frac{1}{2E_\nu}\left(U^\dagger \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) U \pm V_\alpha\right)\nu$$

$$V_\alpha = 2\sqrt{2} G_F N_e E_\nu \text{diag}(1,0,0)$$





Dziewonski and Anderson, Phys. Earth Planet Interiors 25 (1981)



Wolfenstein, PRD 17 (1978)
Mikheyev and Smirnov, Yad.Fix 42 (1985)

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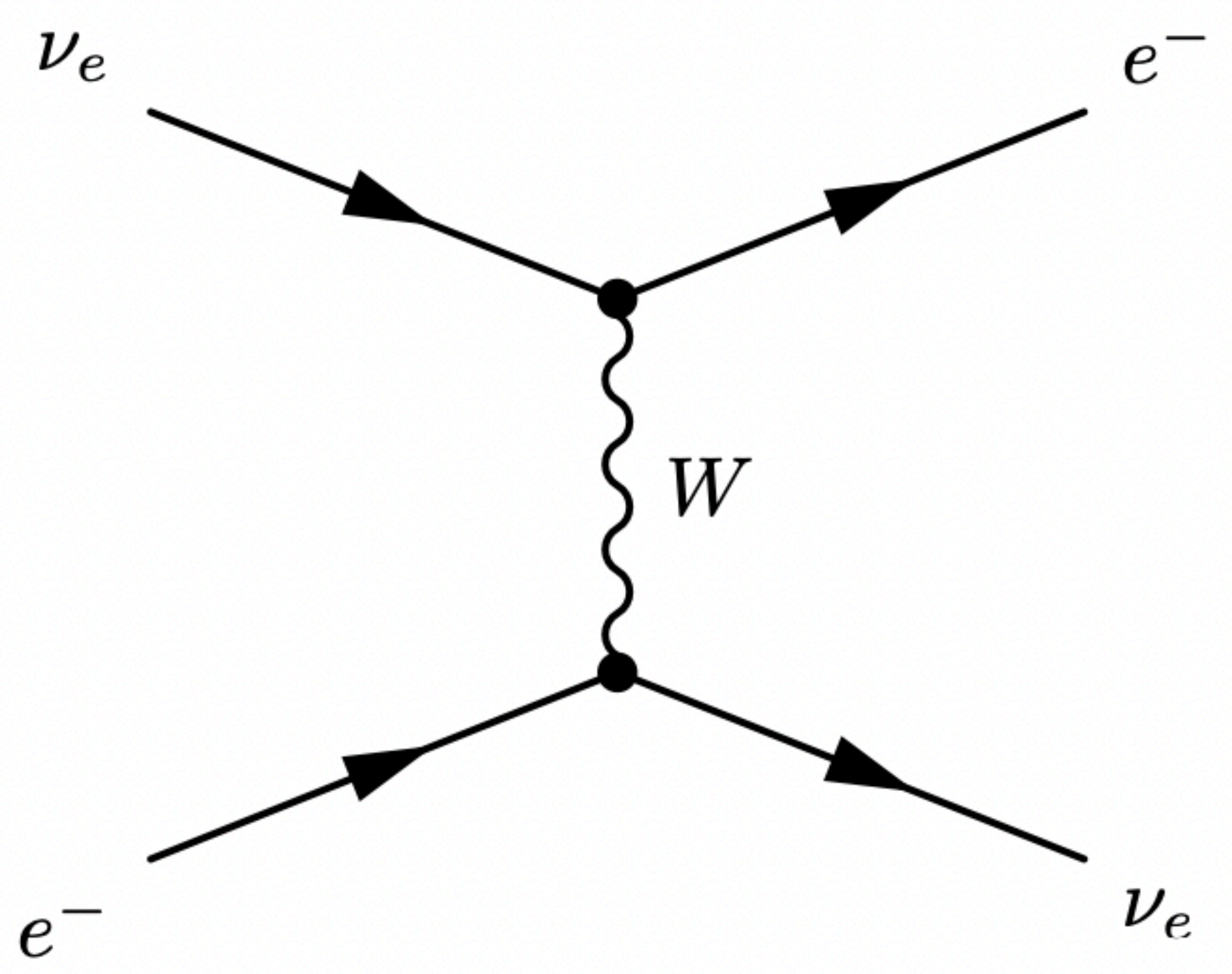
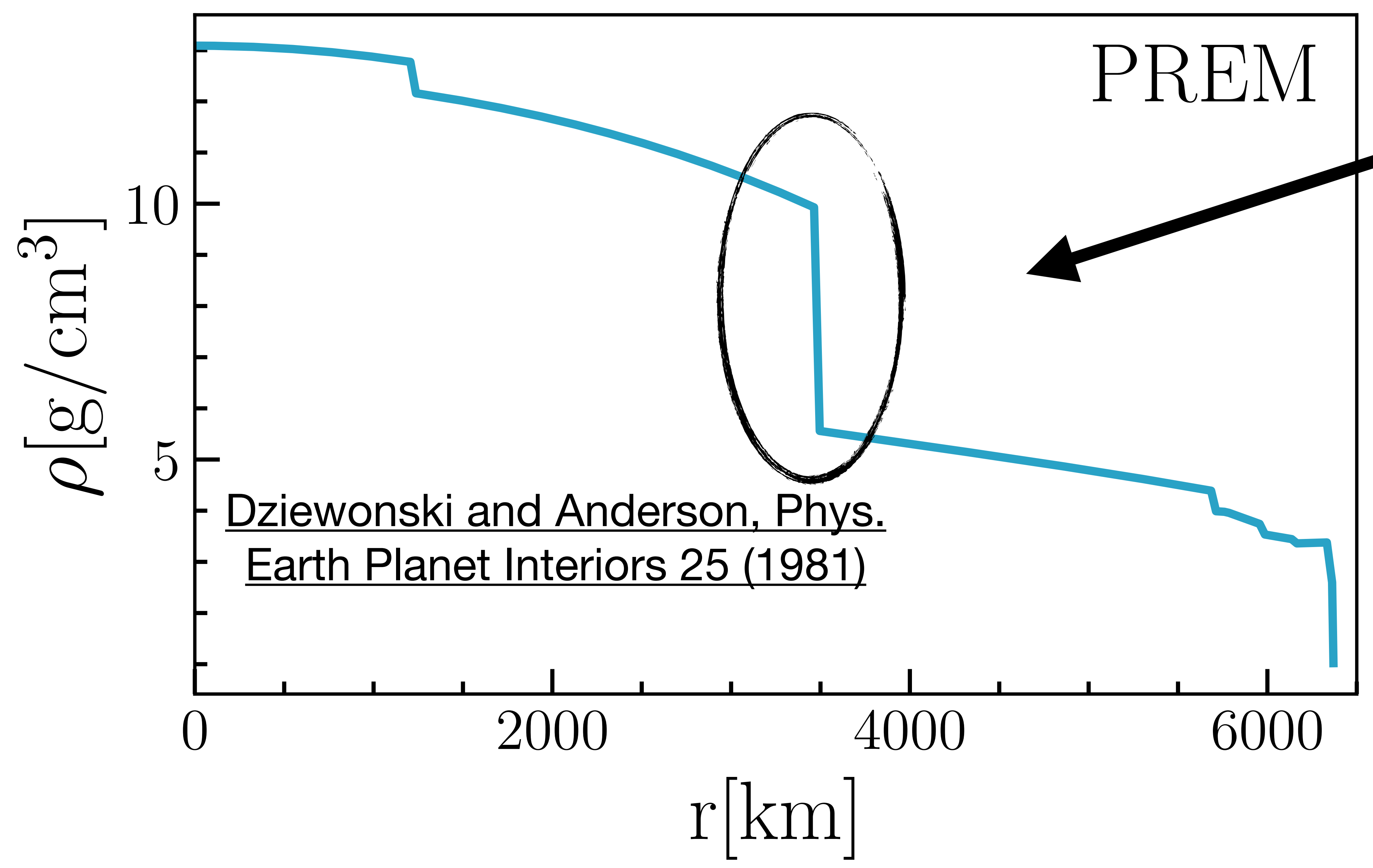
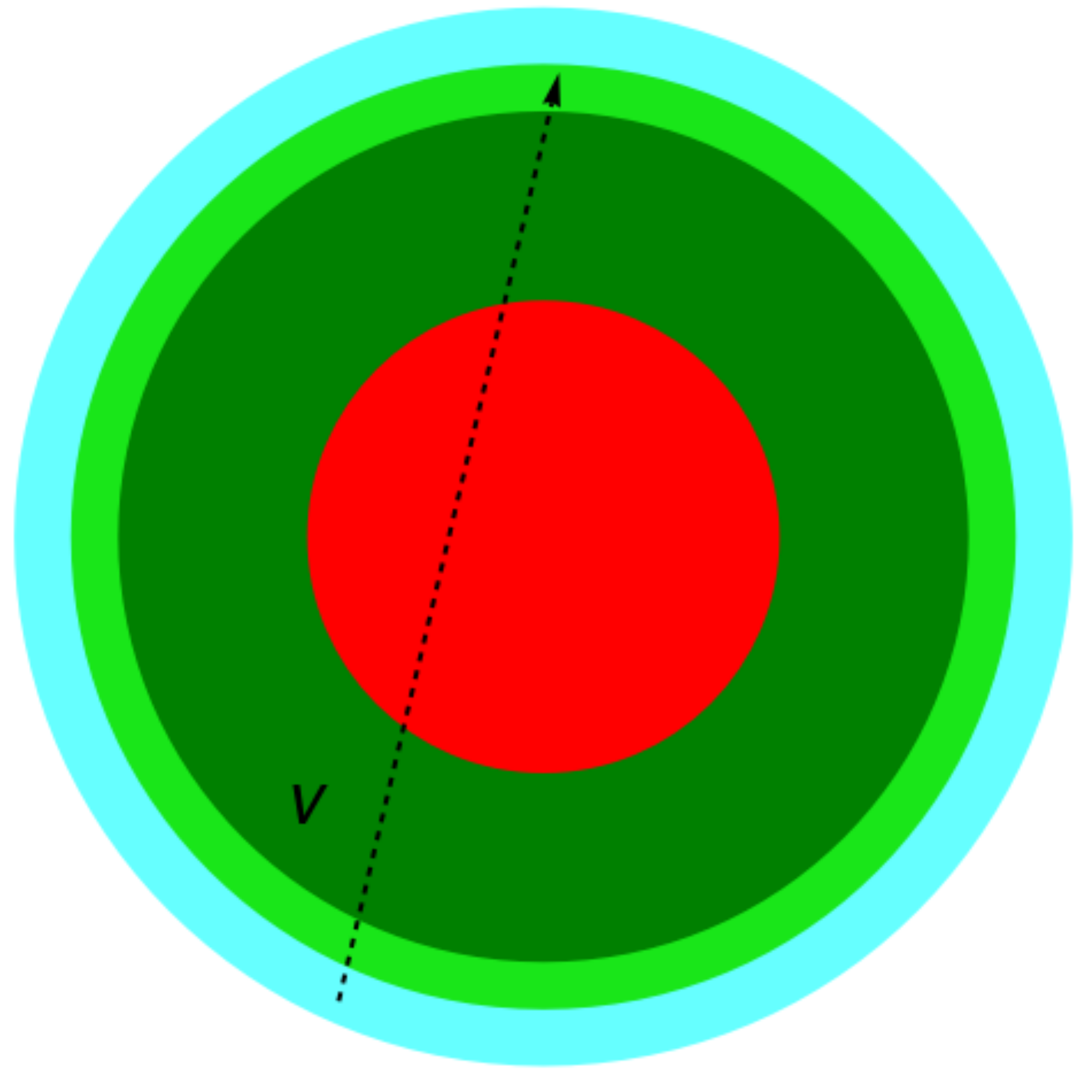
$$V_\alpha = 2\sqrt{2} G_F N_e E_\nu \text{diag}(1,0,0)$$





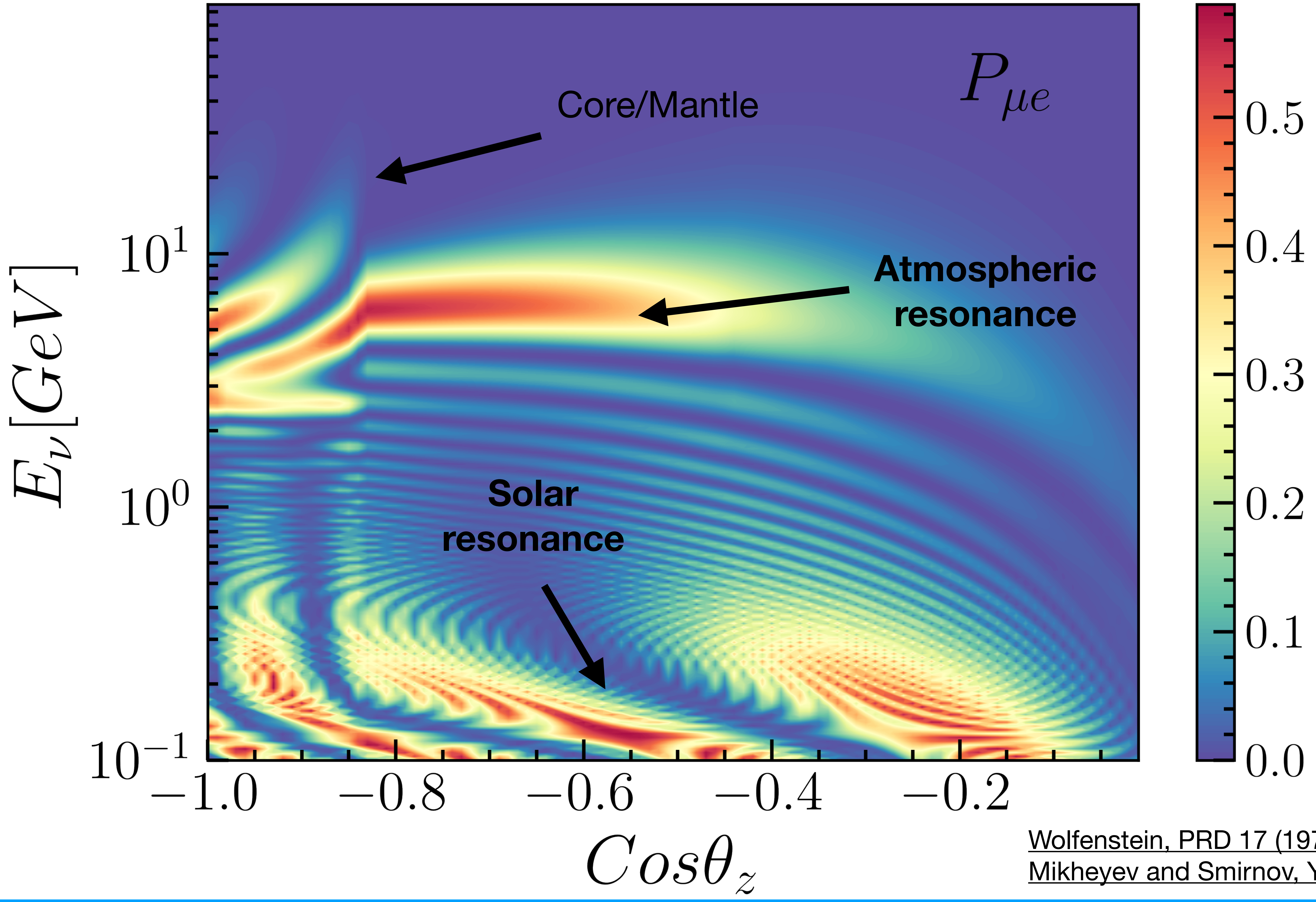
Evolution in the Earth is not adiabatic



Wolfenstein, PRD 17 (1978)
Mikheyev and Smirnov, Yad.Fix 42 (1985)

Atmospheric Neutrinos

Neutrino oscillation is modified by matter effects



Wolfenstein, PRD 17 (1978)
Mikheyev and Smirnov, Yad.Fix 42 (1985)

Ivan Martinez-Soler (IPPP)

Sub-GeV

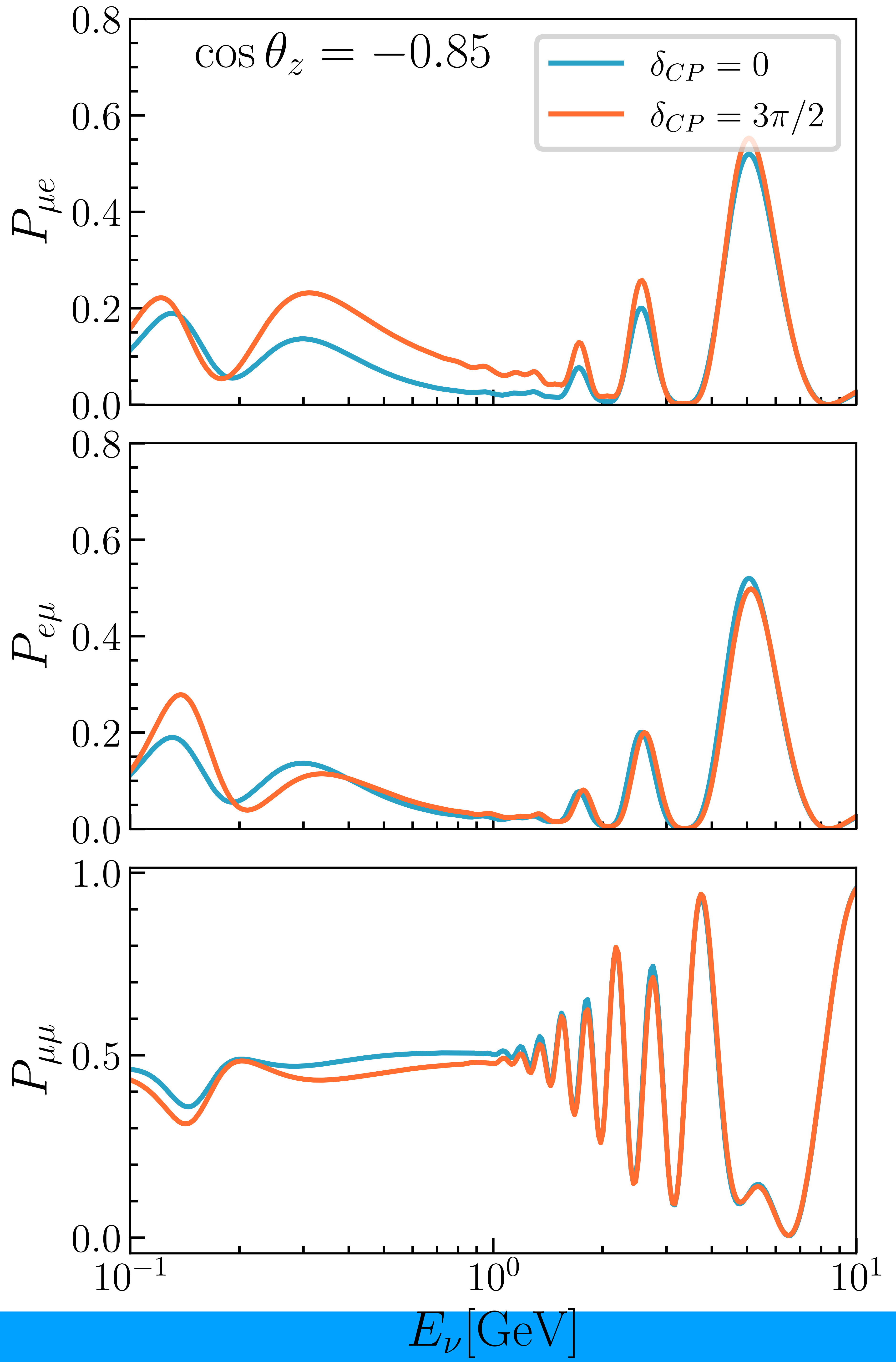
For atmospheric neutrinos, both fluxes are sensitive to δ_{CP}

- In the case of $\delta_{cp} \neq 0$, **the CPT conservation** implies

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

- The impact of δ_{cp} depends mainly on the neutrino direction

- $P_{\mu\mu}$ contribute to measuring the phase via $\cos\delta_{CP}$

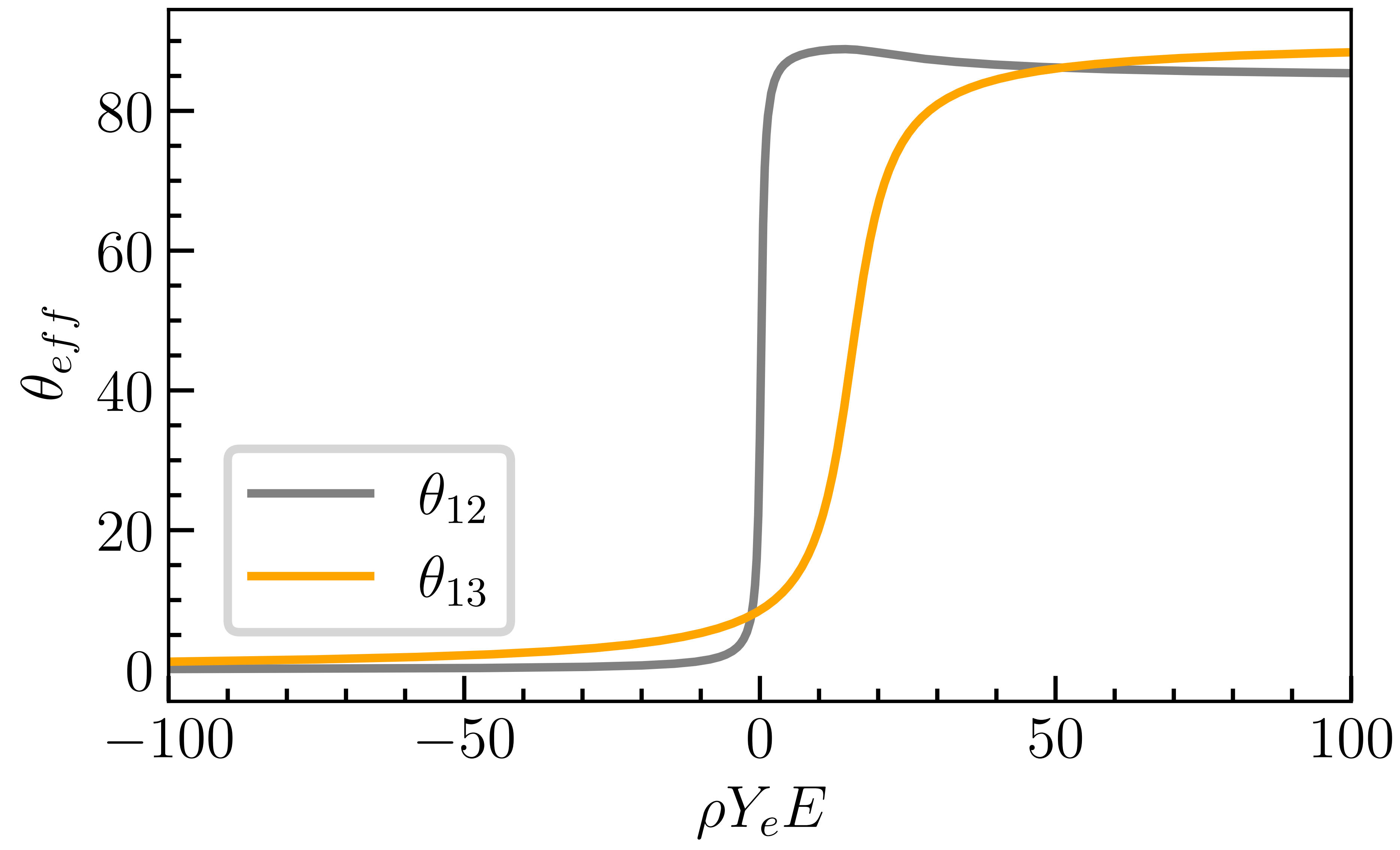


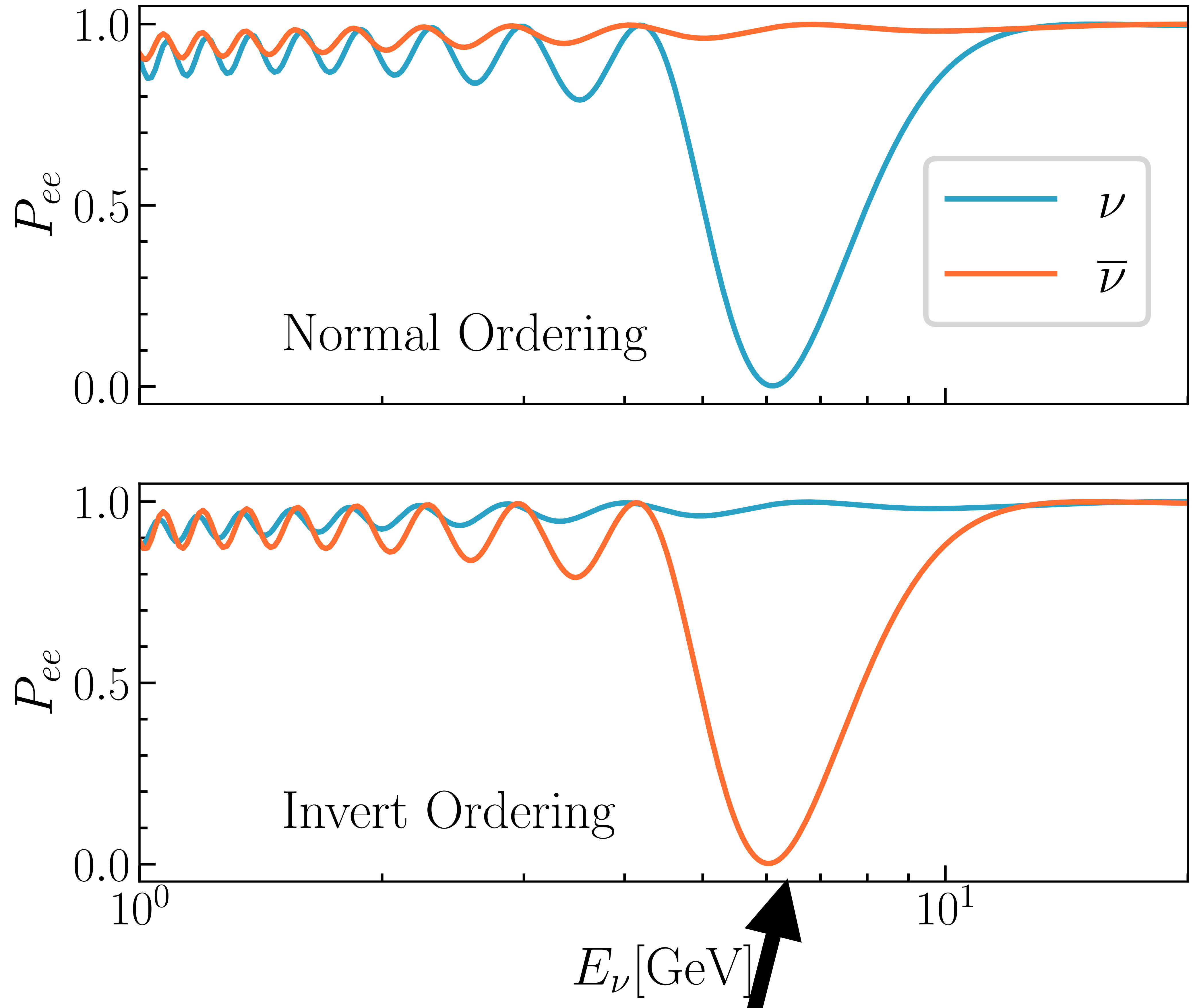
Minakata, Nunokawa, Parke, PLB 537 (2002)   Minakata, Nunokawa, Parke, PRD 66 (2002)
Denton and Parke, PRD 109 (2024)

Multi-GeV

At the **GeV scale**, trajectories crossing the mantle experience an **MSW** resonance, making neutrinos sensitive to the **mass ordering**:

- The matter effect enhances the oscillation of neutrinos (anti-neutrinos) for NO (IO)





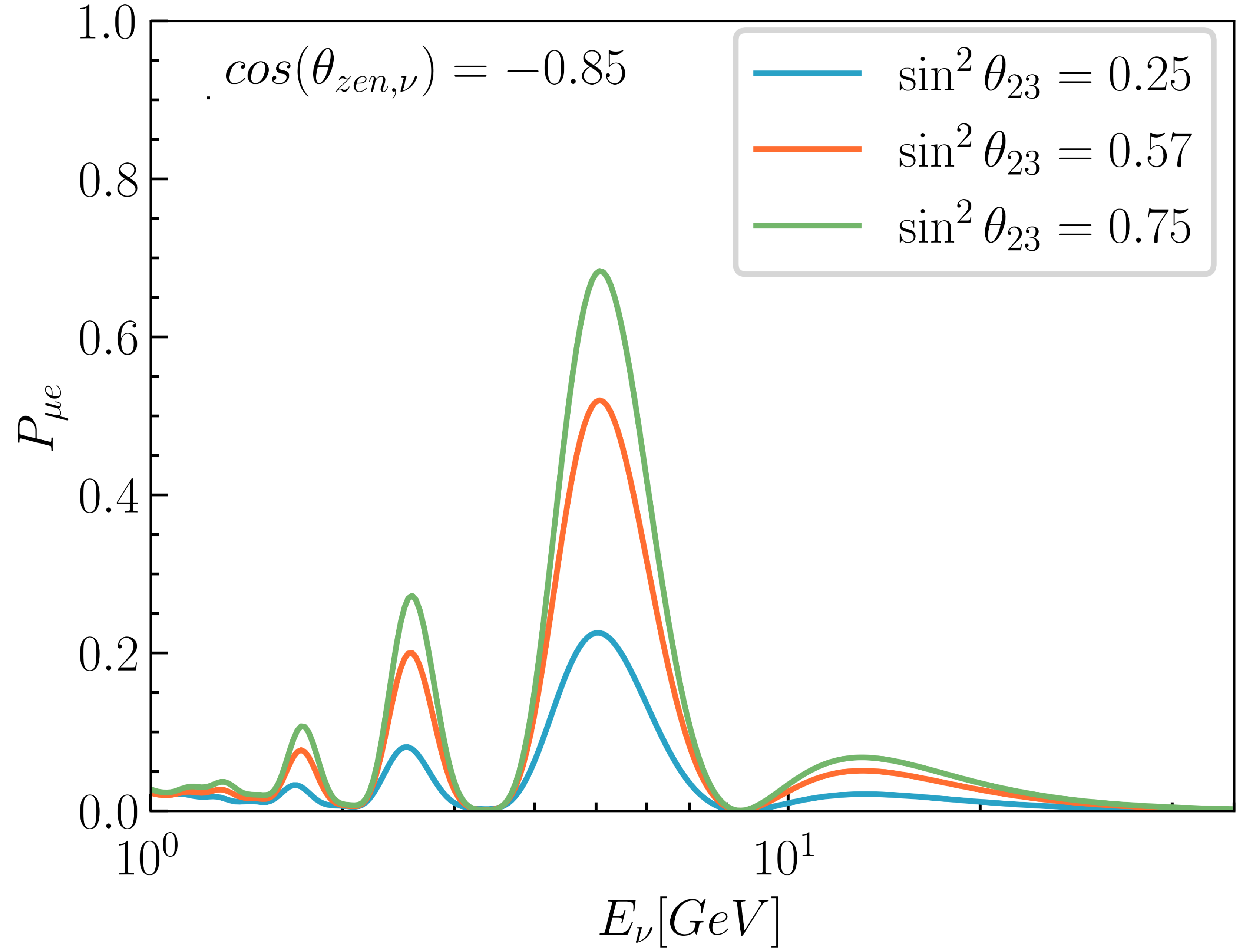
The enhancement of θ_{13}^{eff} lead to a deep in P_{ee} for ν ($\overline{\nu}$) for NO (IO)

Palomares-Ruiz and Petcov, NPB 712 (2005)

Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

Multi-GeV

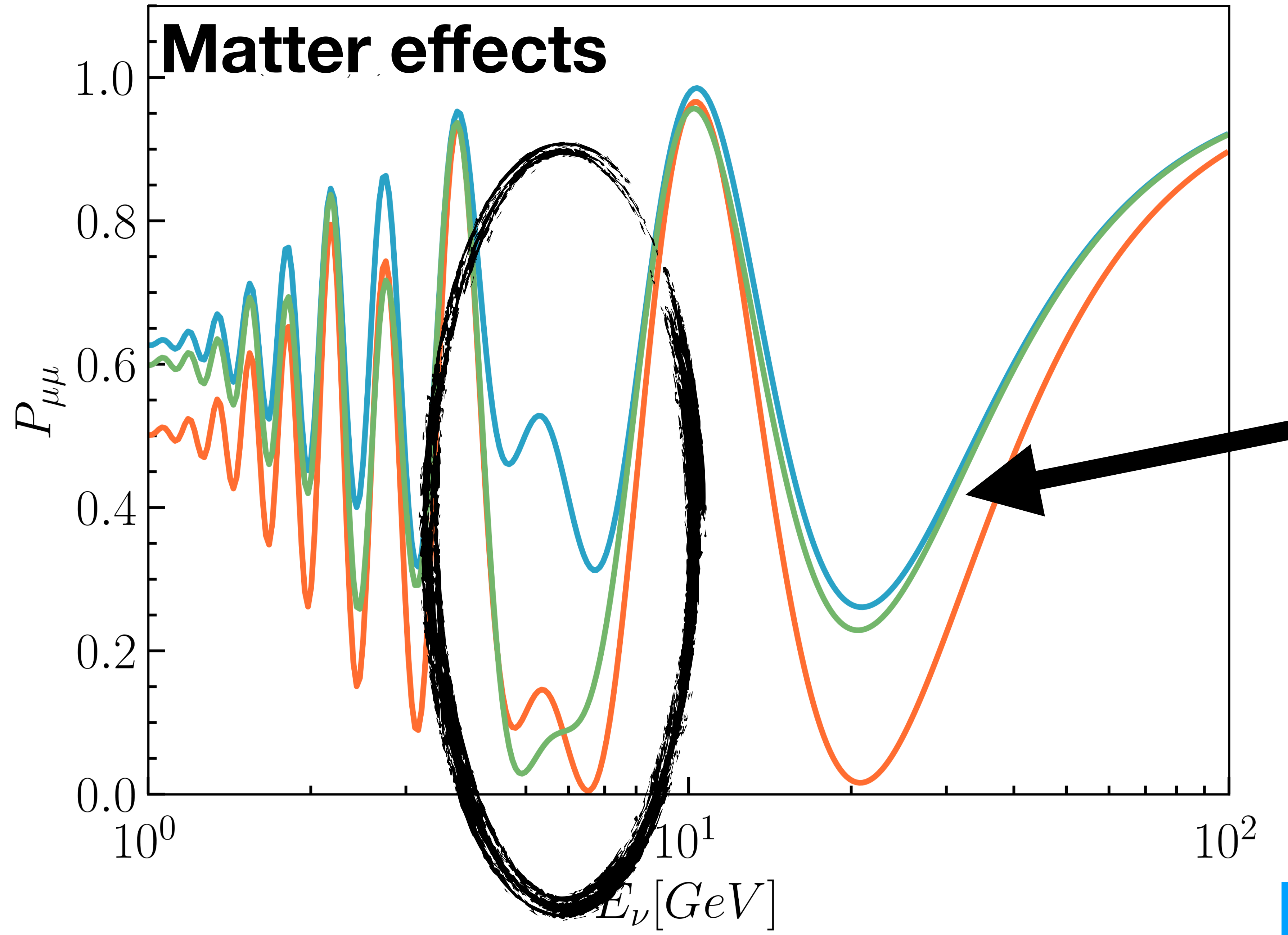
In the multi-GeV region, neutrino evolution is dominated by Δm^2_{31} and $\sin^2\theta_{23}$



- $P_{\mu e}$ shows a linear dependence on the octant of θ_{23}

- $P_{\mu\mu}$ can determine whether θ_{23} is **maximal mixing**.

- The **matter effects** can **resolve** the degeneracy between the two **octants**.



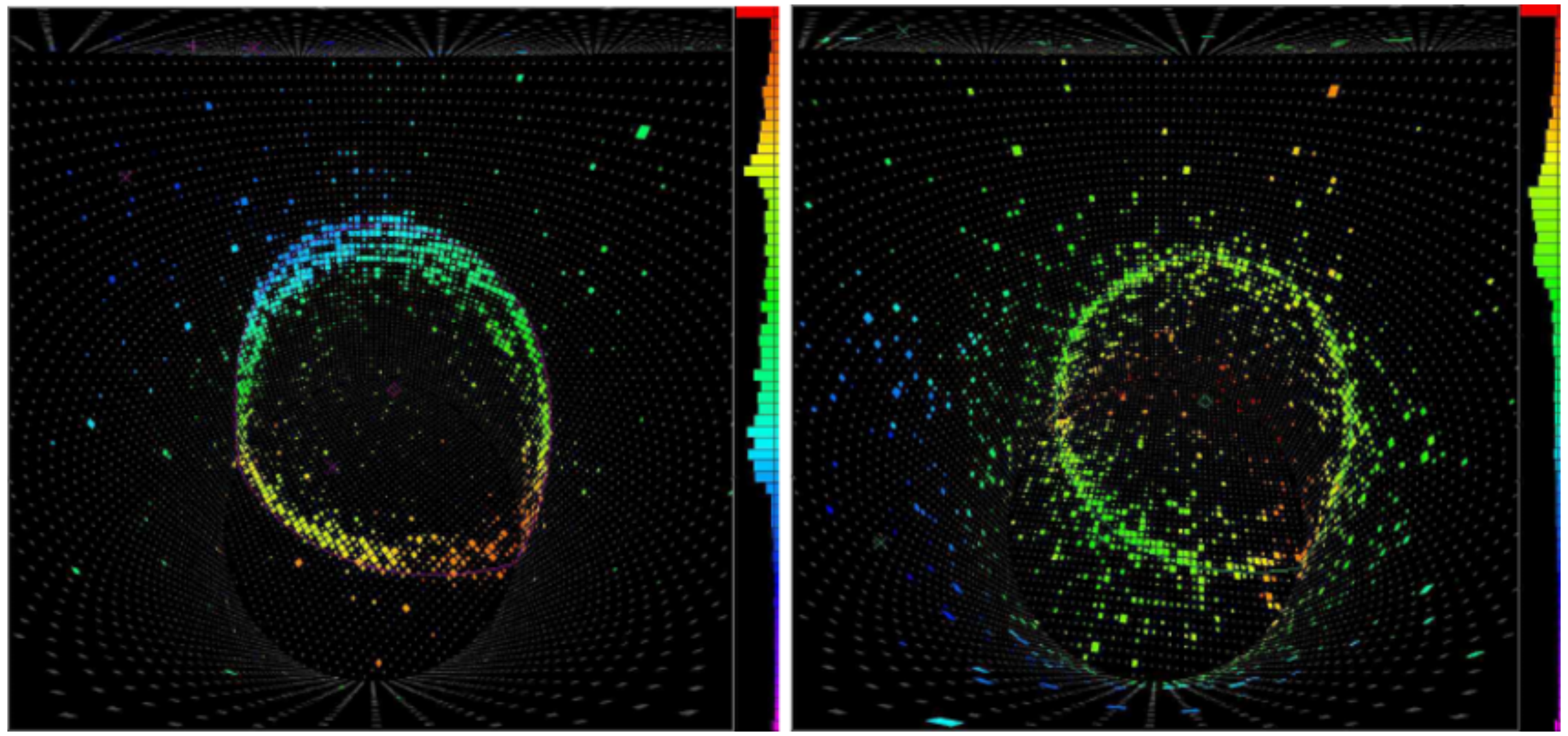
Symmetric with respect to θ_{23} octant

Super-Kamiokande

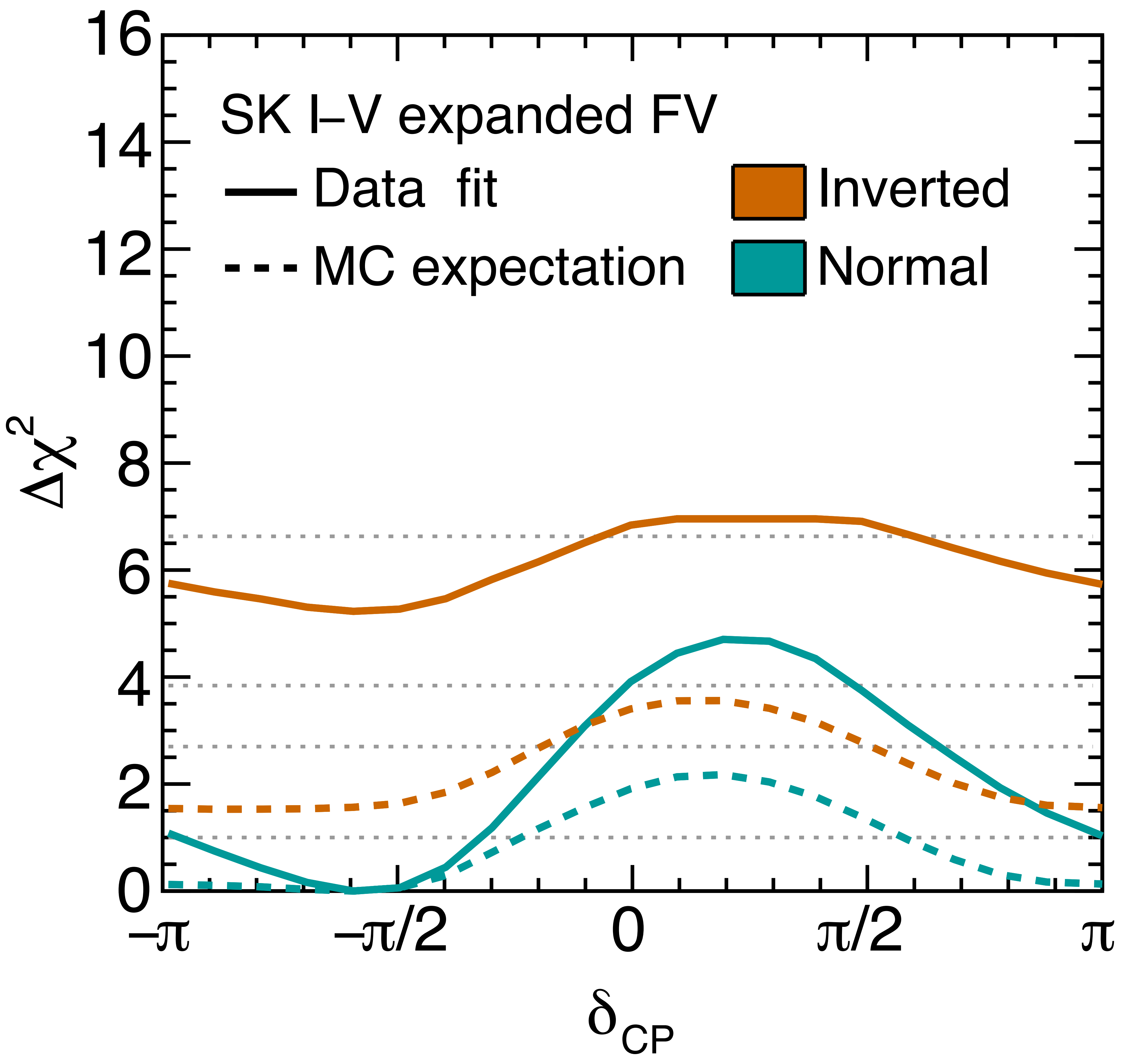
Several experiments have measured the atmospheric neutrino flux, with **SK** starting from the **sub-GeV scale**.

Super-Kamiokande (SK)

- 22.5 kton water Cherenkov
- Small sample at multi-GeV due to the volume
- The event sample is divided in FC, PC and Up-μ



Abe et al. (Super-Kamiokande), PRD 97 (2018)

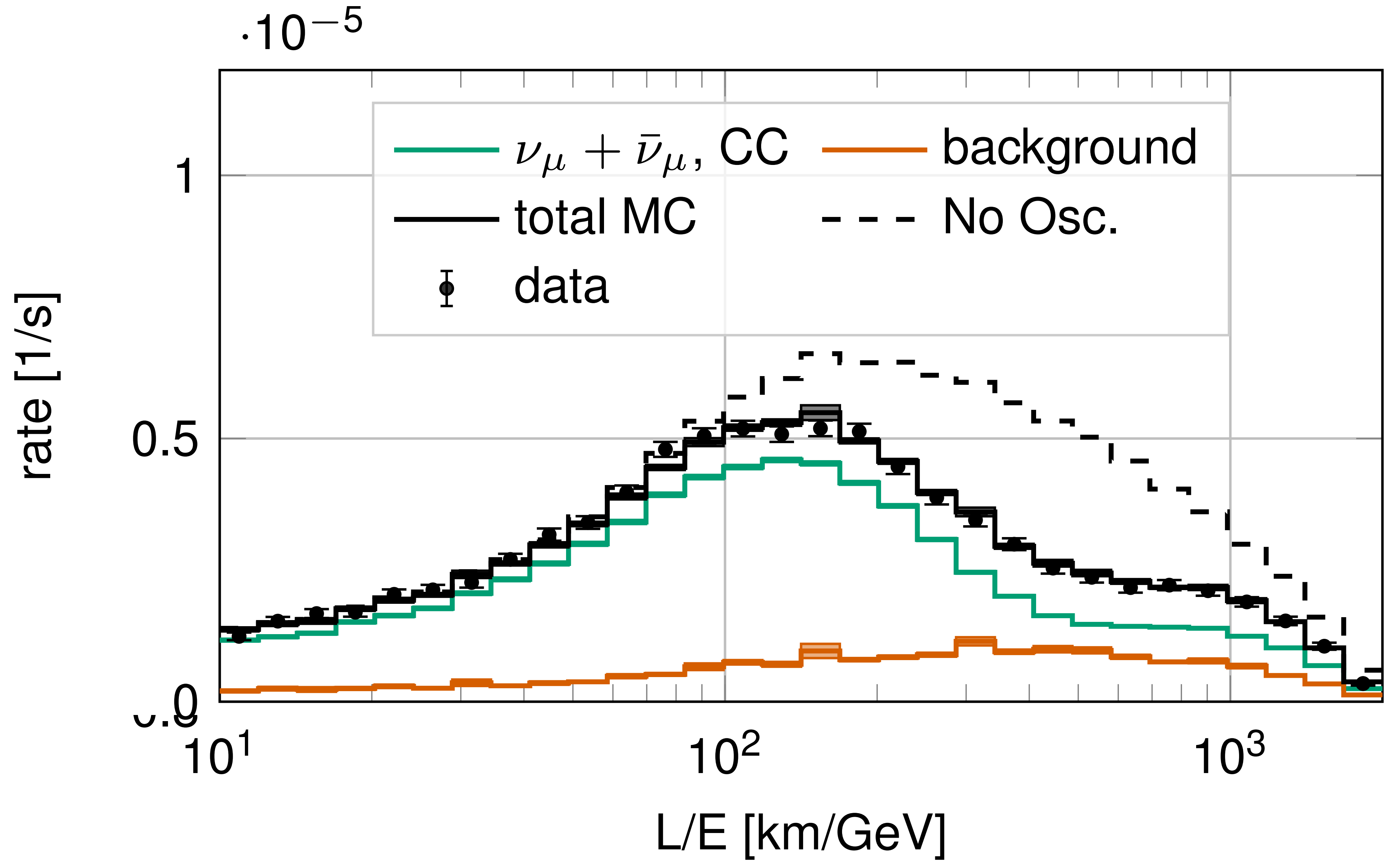


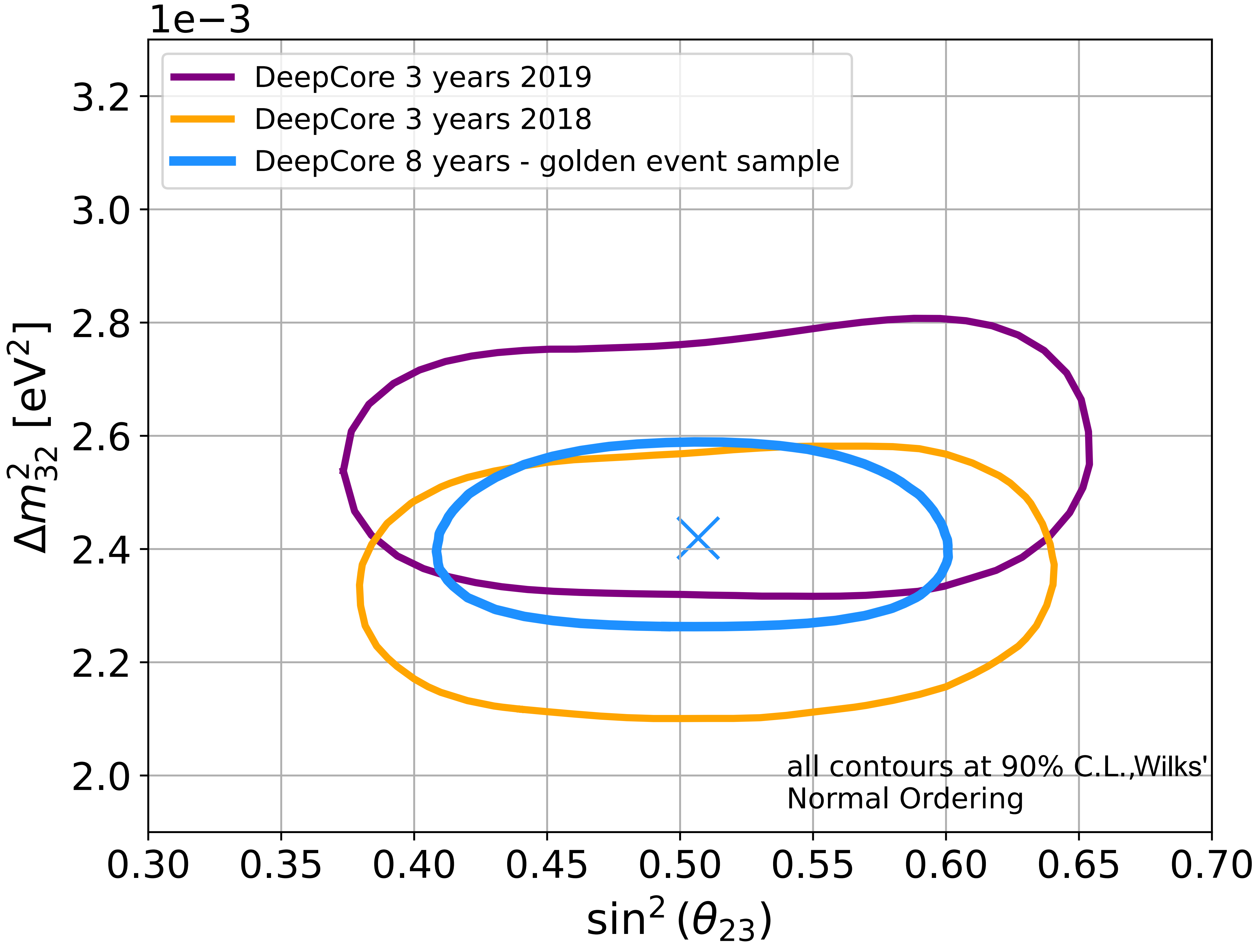
Wester et al. (Super-Kamiokande), arXiv: 2311.05105

IceCube

The **neutrino telescopes** measure the atmospheric neutrino flux from the **multi-GeV** scale

- $\sim 1\text{km}^3$ ice Cherenkov
- The sample is divided into tracks and cascades



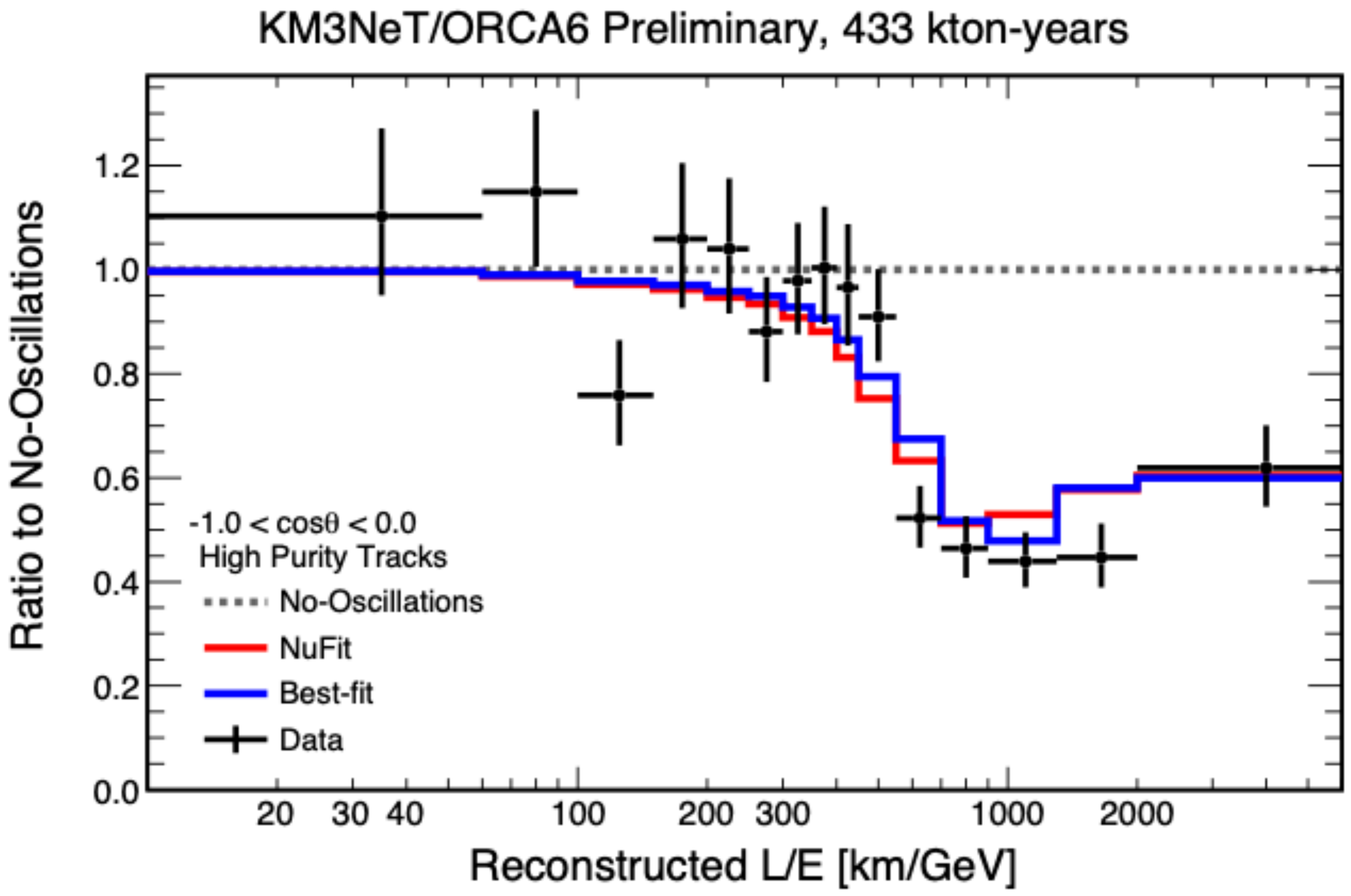


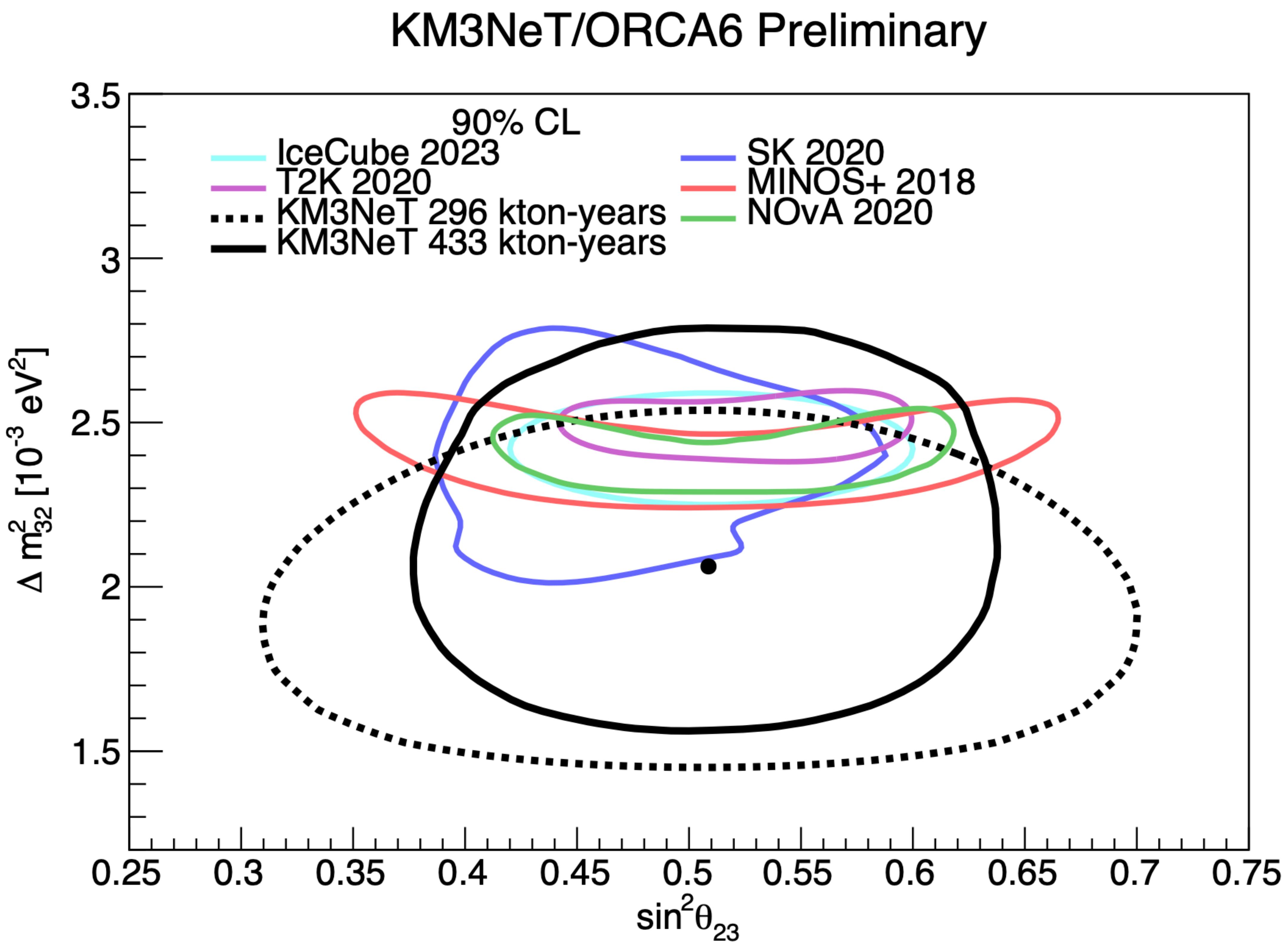
Abbasi et al. (IceCube), PRD 108 (2023)
Abbasi et al. (IceCube), arXiv: 2405.02163

ORCA

ORCA measures the multi-GeV component of the atmospheric neutrino flux from **~2GeV**

The total expected volume is 7 Mt, with events classified into high-purity tracks, low-purity tracks, and showers



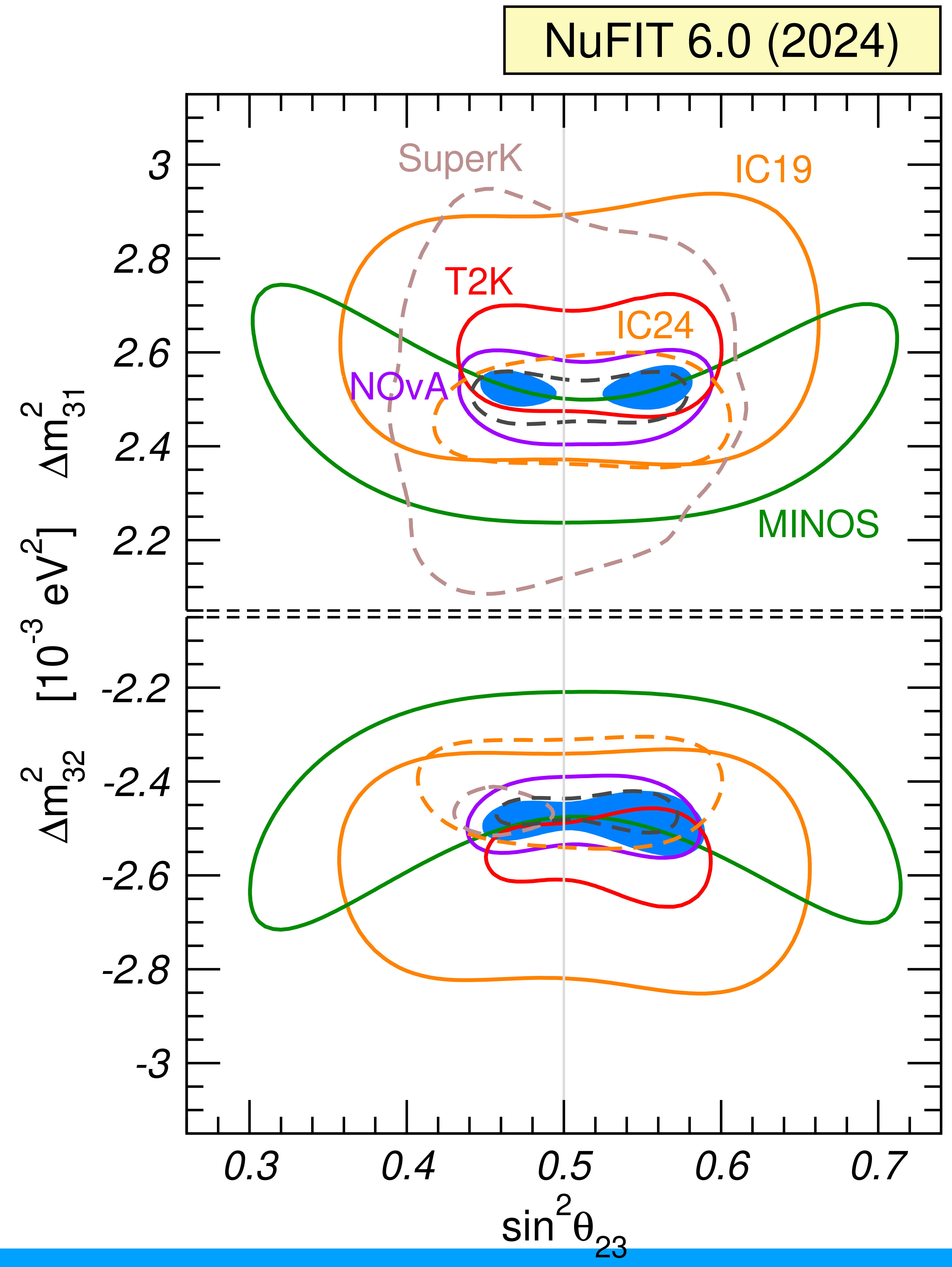


Carretero et al. (KM3NeT), PoS ICRC2023
Aiello (KM3NeT), EPJC 82, 26 (2022)

Atmospheric Mass-Squared Splitting

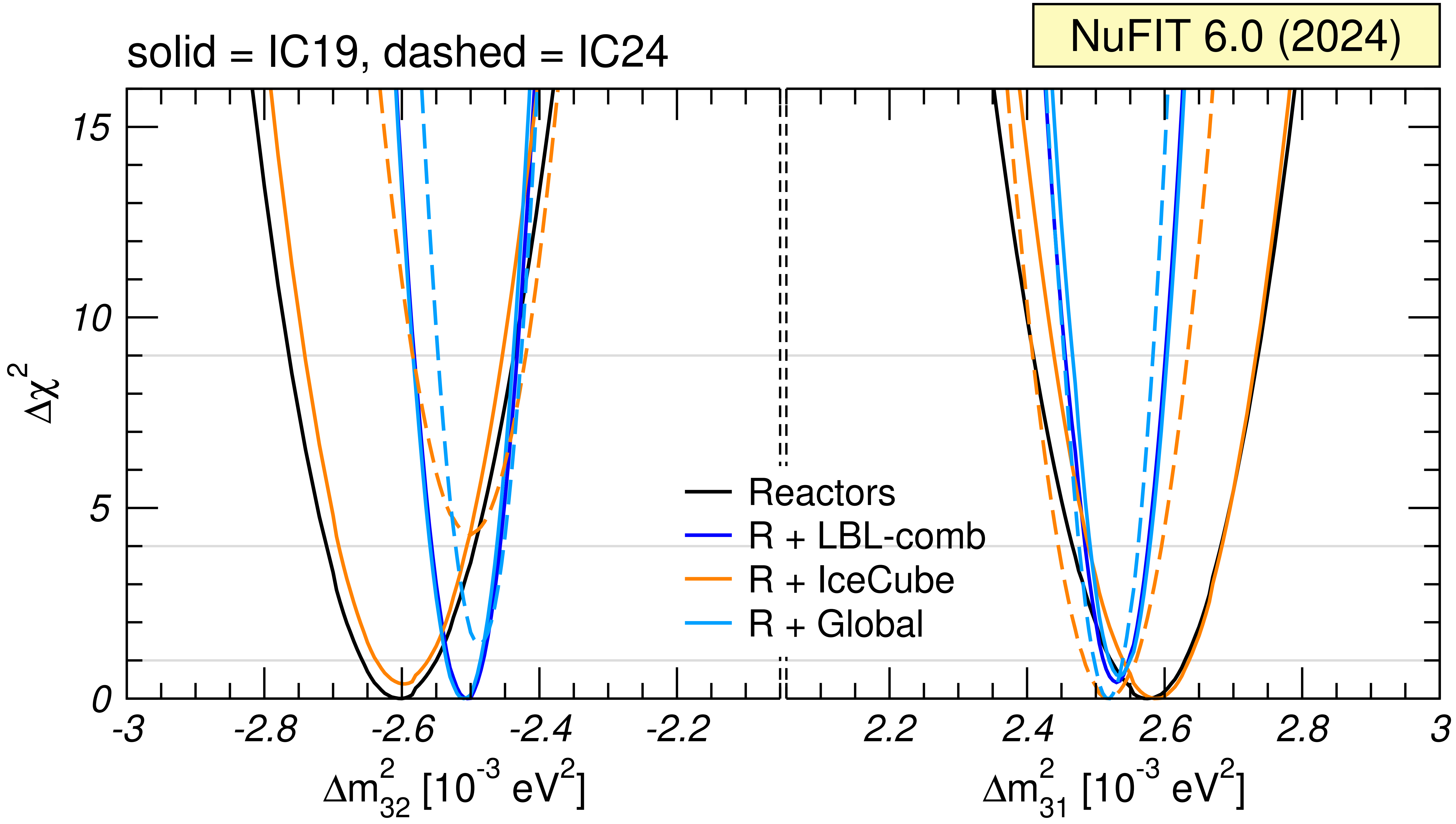
Combining different datasets results in significant **synergy**, as the global **regions are smaller** than the individual ones.

- Colored regions: LBL+IC19
- Black-dashed: LBL+IC24+SK
- Good agreement with **reactor** experiments
- Preference for the higher octant $(\sin^2\theta_{23} = 0.561)$



Mass Ordering

- Combining **IC24+Reactors**, we get a preference for NO of $\Delta\chi^2 \sim 4.5$
- **Super-Kamiokande** alone shows a preference for NO of $\Delta\chi^2 \sim 5.7$
- **Combining IC+SK+global fit** results in a preference for NO of $\Delta\chi^2 \sim 6.1$

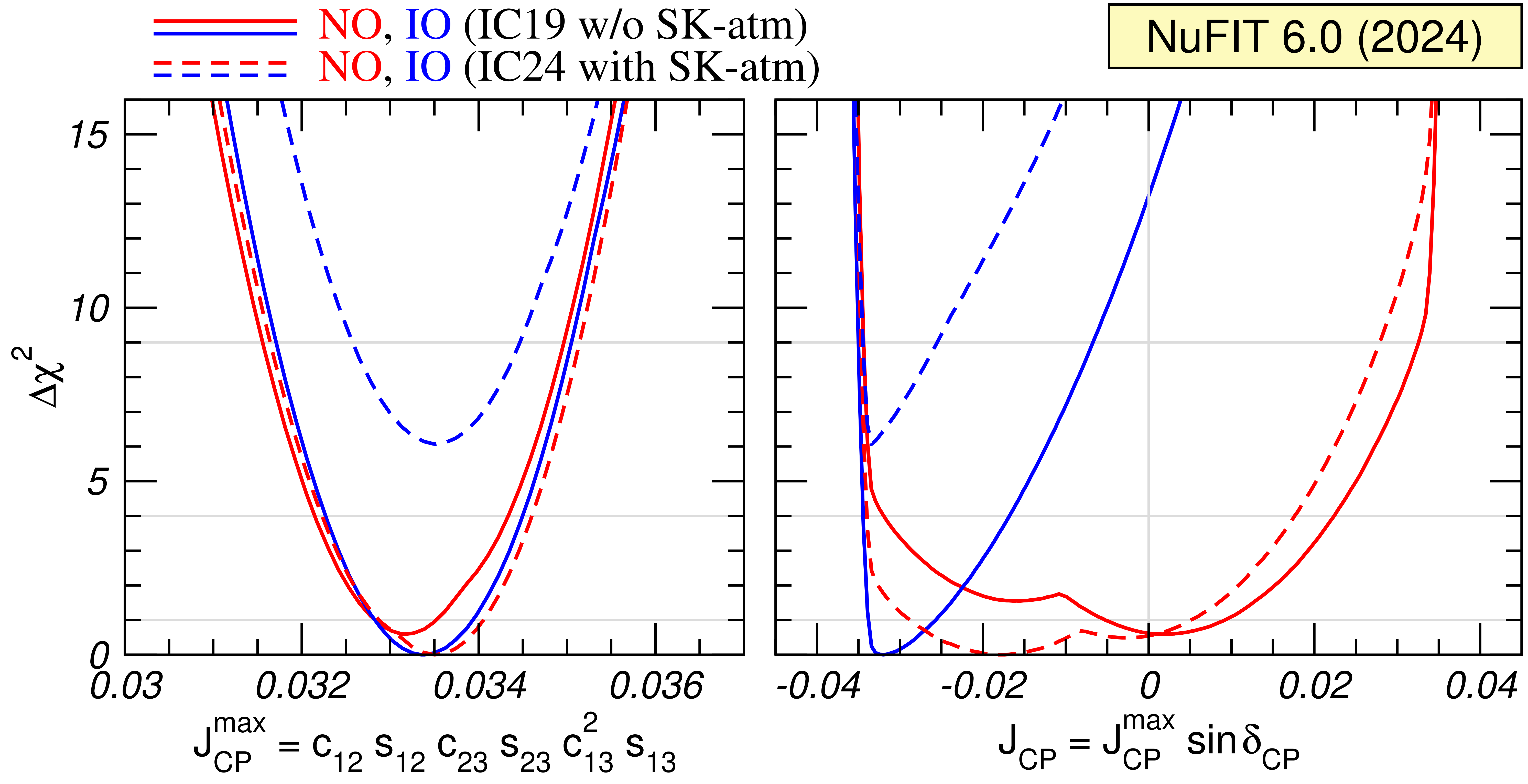


CP-violation

The Jarlskog invariant provides a convention-independent measurement of the violation of the CP symmetry

CP-conservation is margnizaly disfavored

$$J_{CP} = \mathrm{Im}[U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j}]$$
$$= J_{CP}^{max} \sin \delta_{CP}$$



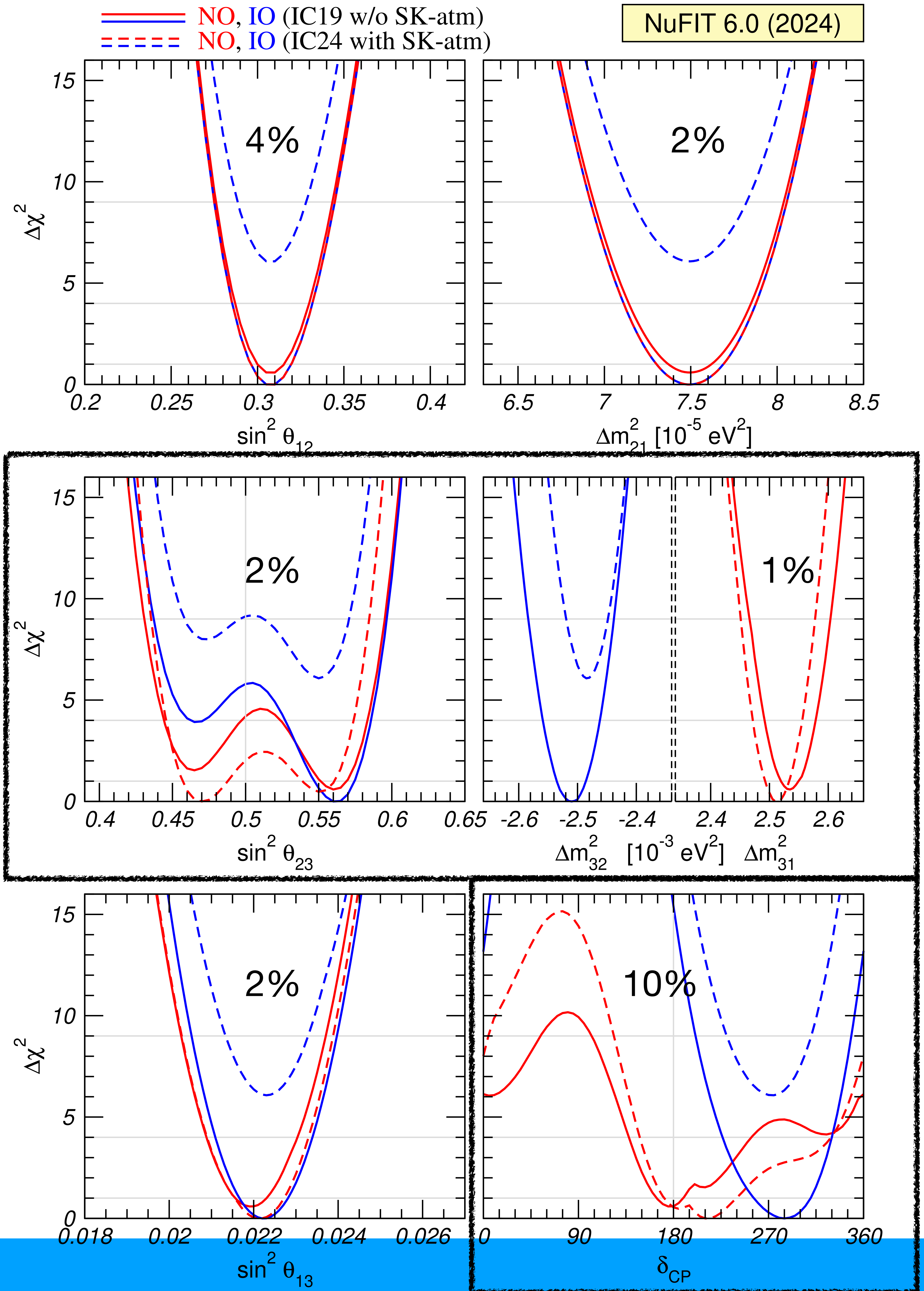
3ν mixing

Most parameters are known at the **percent level**, but several open questions remain:

- For θ_{23}, small preference for the **lower octant** (higher octant), combining IC24+SK+global fit (global)

- For δ_{cp}, almost **the entire region is allowed**, with CP-conservation preferred for NO and maximal CP-violation for IO.

- **Mass ordering** shows small preference until IC24+SK is included, which favors NO.



Neutrino Mass

Neutrino Mass

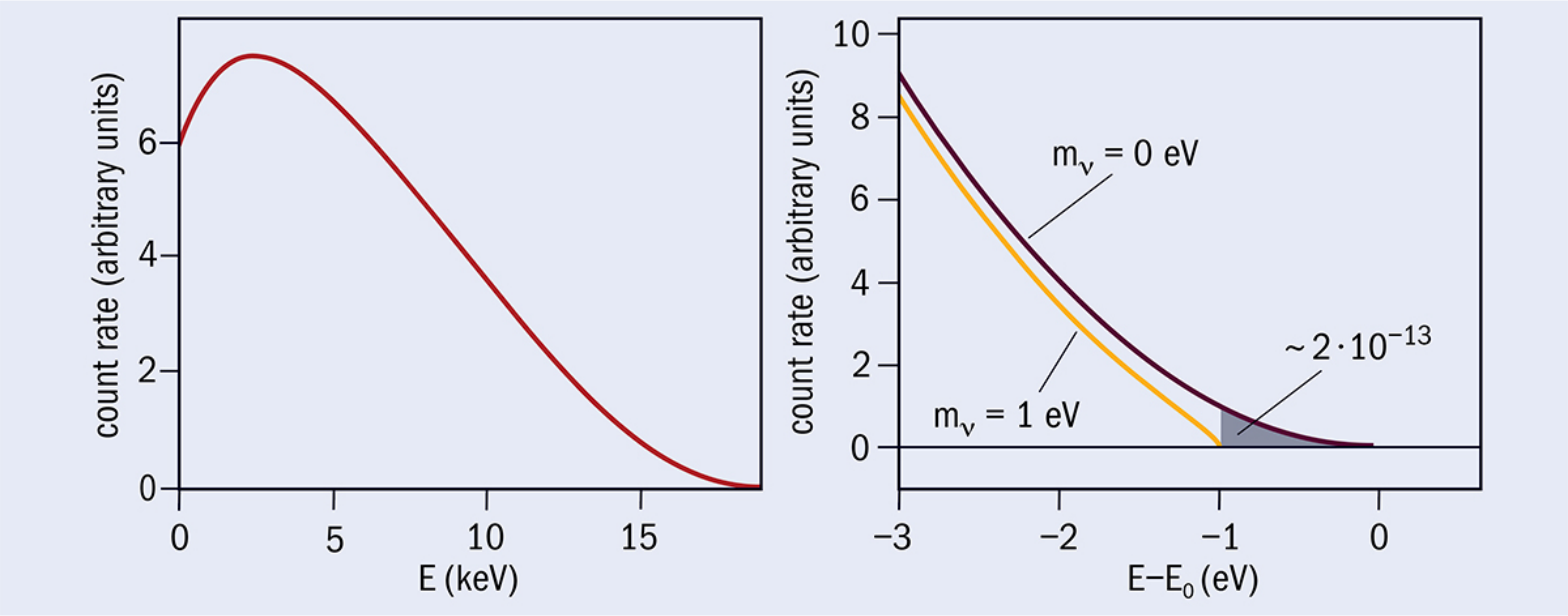
- Neutrino oscillation experiments cannot probe the absolute neutrino mass scale

Neutrino Mass

- Neutrino oscillation experiments cannot probe the absolute neutrino mass scale

- The maximum energy accessible to e^- in β-decays is modified if neutrinos are massive particles

$$^A_Z X \rightarrow ^A_{Z+1} X + e^- + \overline{\nu_e}$$



CERN

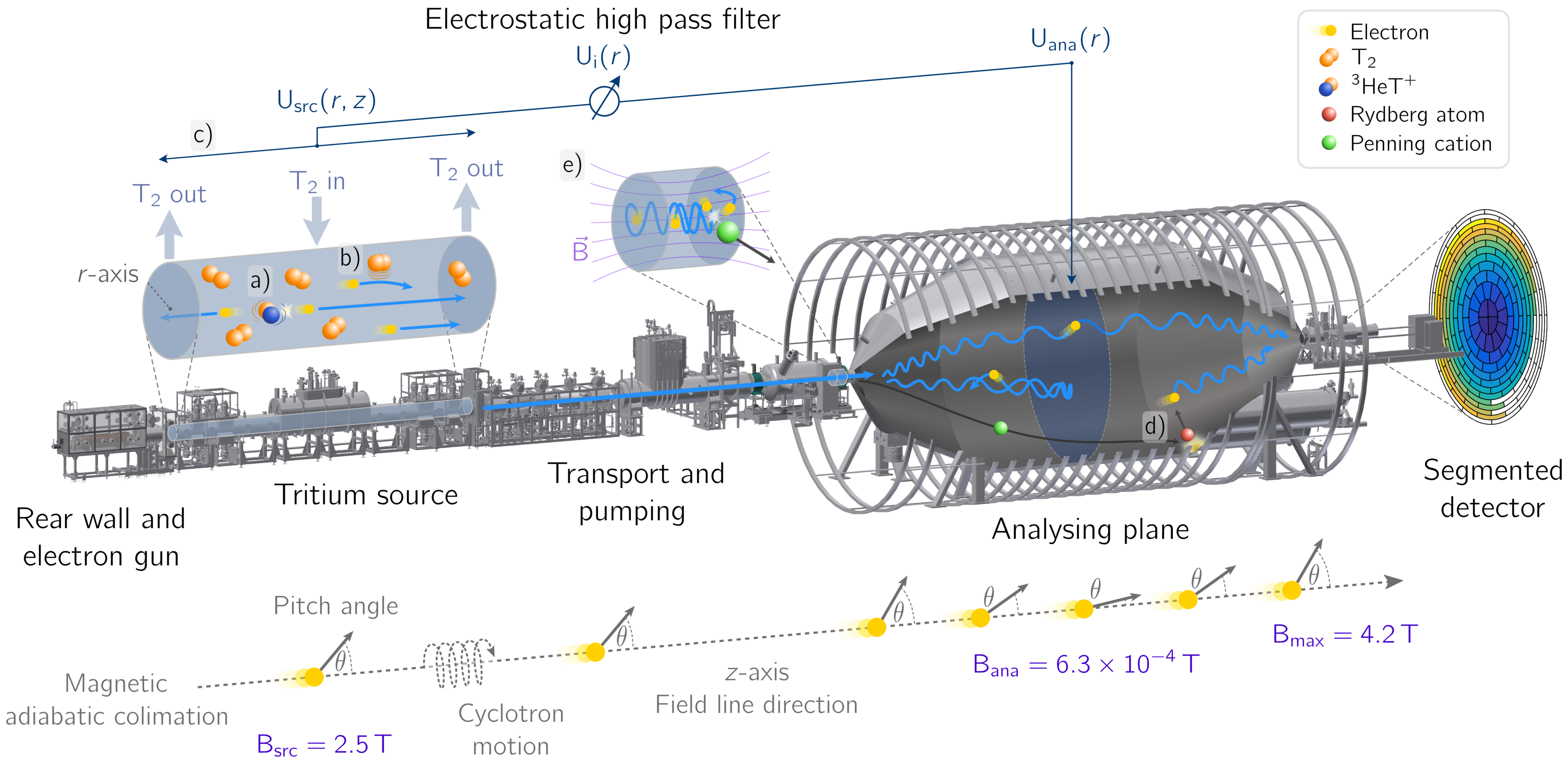
Ivan Martinez-Soler (IPPP)

Neutrino Mass

KATRIN explores the e^- energy spectrum in tritium decays

$$T_2 \rightarrow ^3He\,T^+ + e^- + \bar{\nu}_e$$

β-spectrum end point at 18.6 keV



M. Aker et al (KATRIN) Nature Phys. 18 (2022)

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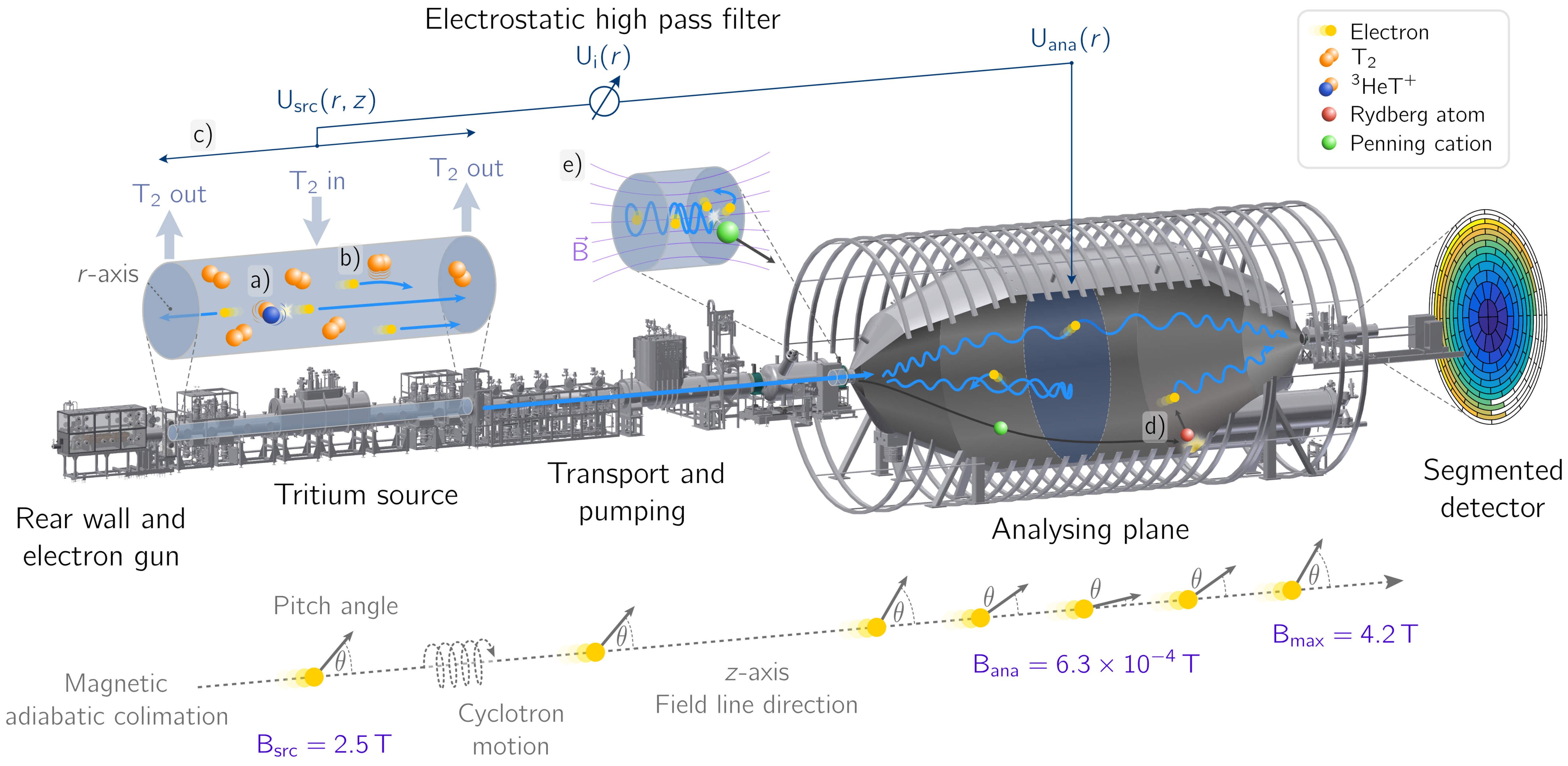
$$T_2 \to {}^3He\,T^+ + e^- + \bar{\nu}_e$$

β-spectrum end point at 18.6 keV

It is sensitive to the $\bar{\nu}_e$

$$m_{\nu_e} = \sqrt{\sum_i U_{ei}^2 m_i^2}$$

$$= \sqrt{m_1^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 + \Delta m_{31}^2 s_{13}^2}$$



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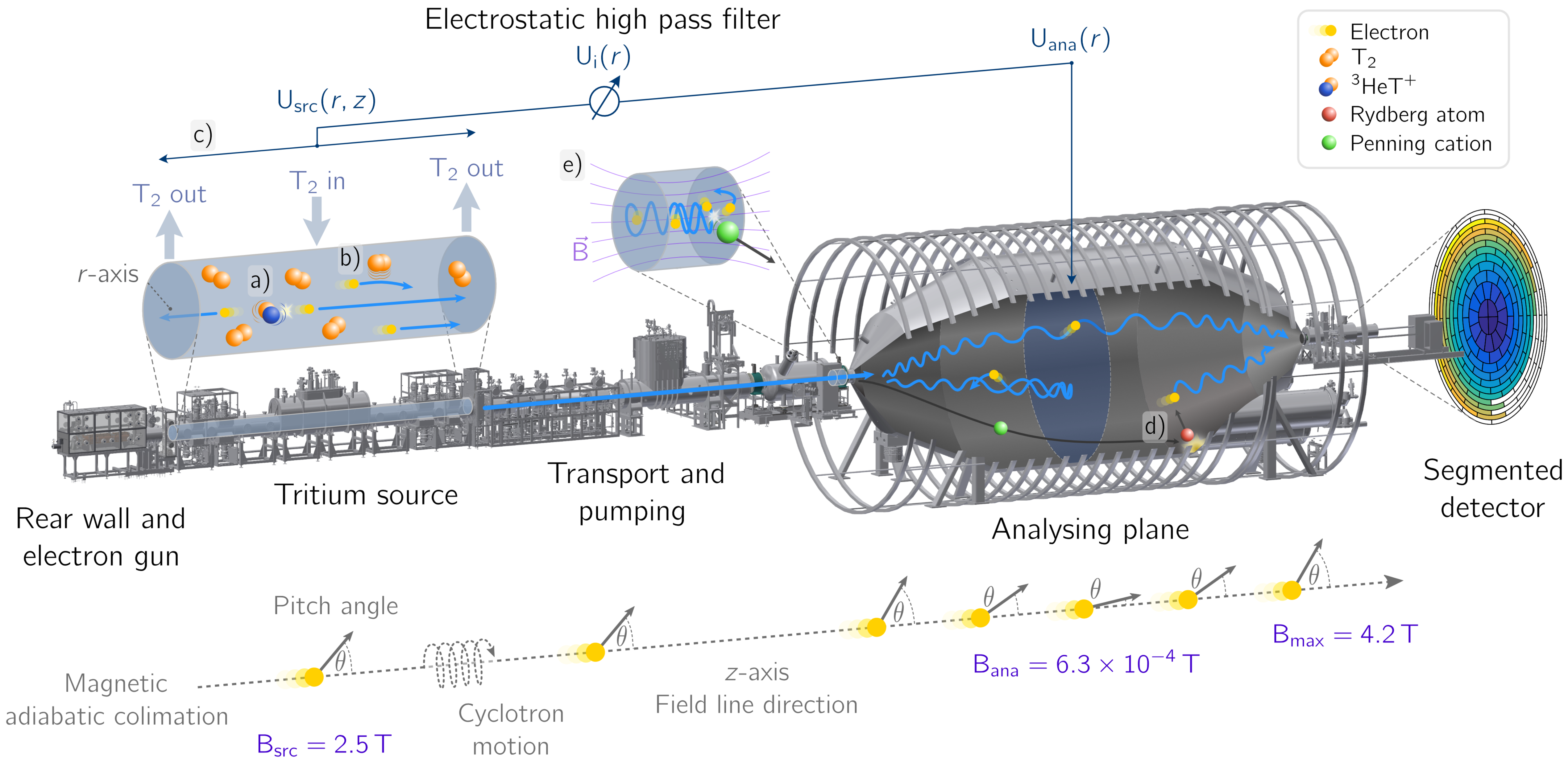


M. Aker et al (KATRIN) Nature Phys. 18 (2022)

From oscillation:

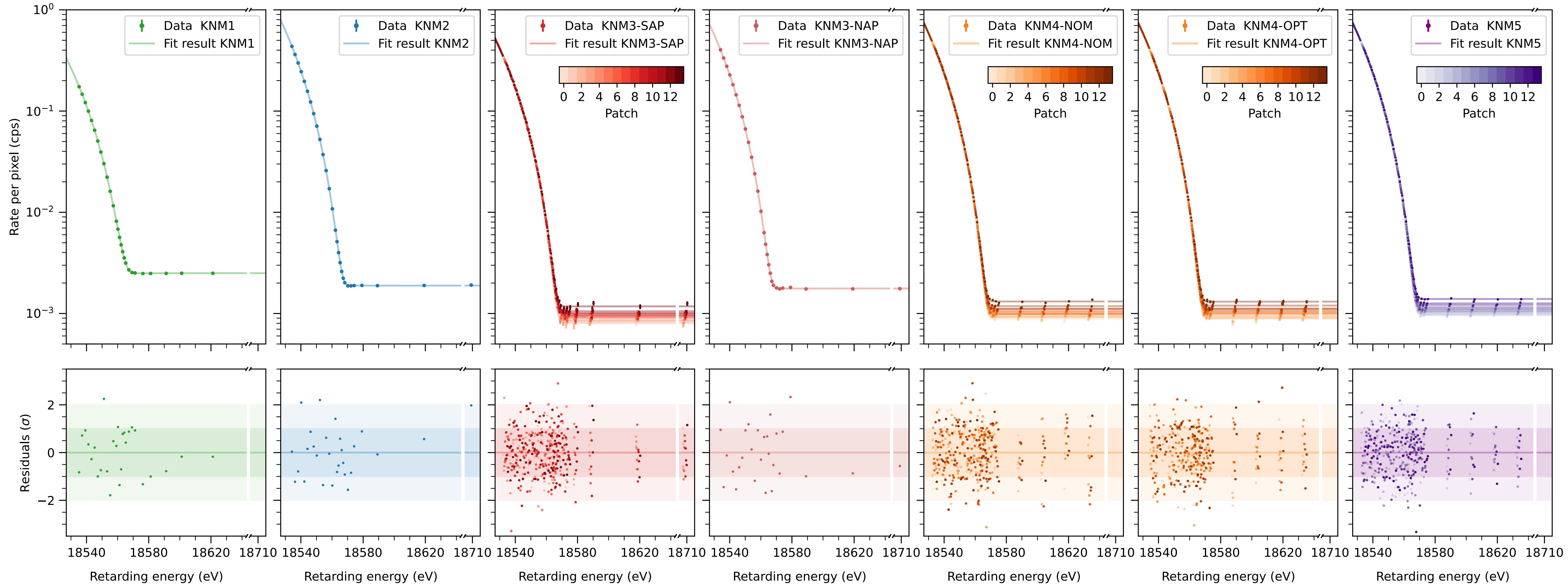
NO: 9×10^{-3} eV $\leq m_{\nu_e}$

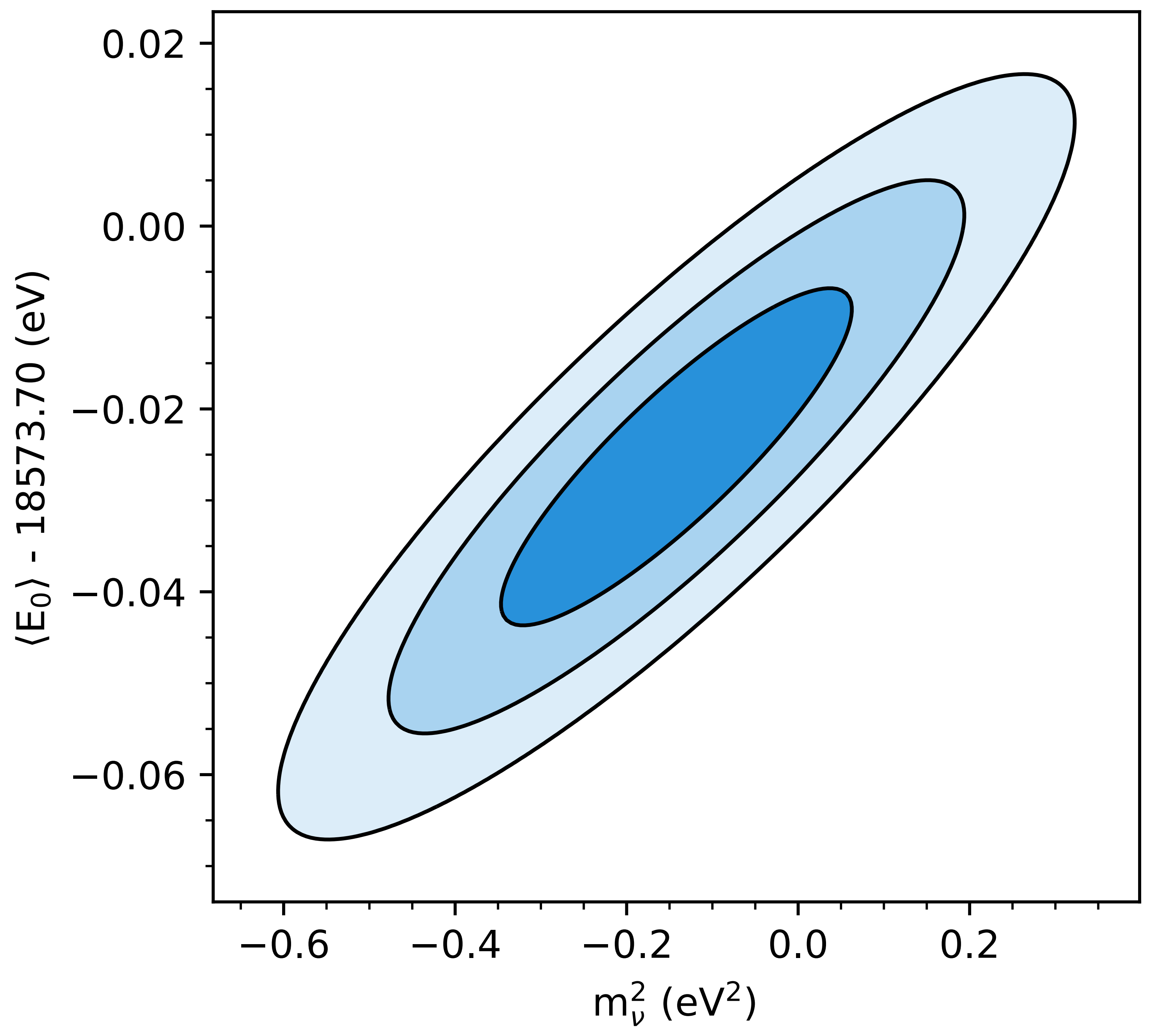
IO: 5.8×10^{-2} eV $\leq m_{\nu_e}$

Neutrino Mass

The analysis of the spectral distribution showed no evidence for the neutrino masses

$m_{\nu_e} < 0.45$ eV → NO: 9×10^{-3} eV $\leq m_{\nu_e} \leq 0.4$ eV
IO: 5.8×10^{-2} eV $\leq m_{\nu_e} \leq 1.2$ eV





M. Aker et al (KATRIN) Science 388 (2025)

Ivan Martinez-Soler (IPPP)

Neutrinoless Double-Beta Decay

A fundamental question remains: are neutrinos their own antiparticles?

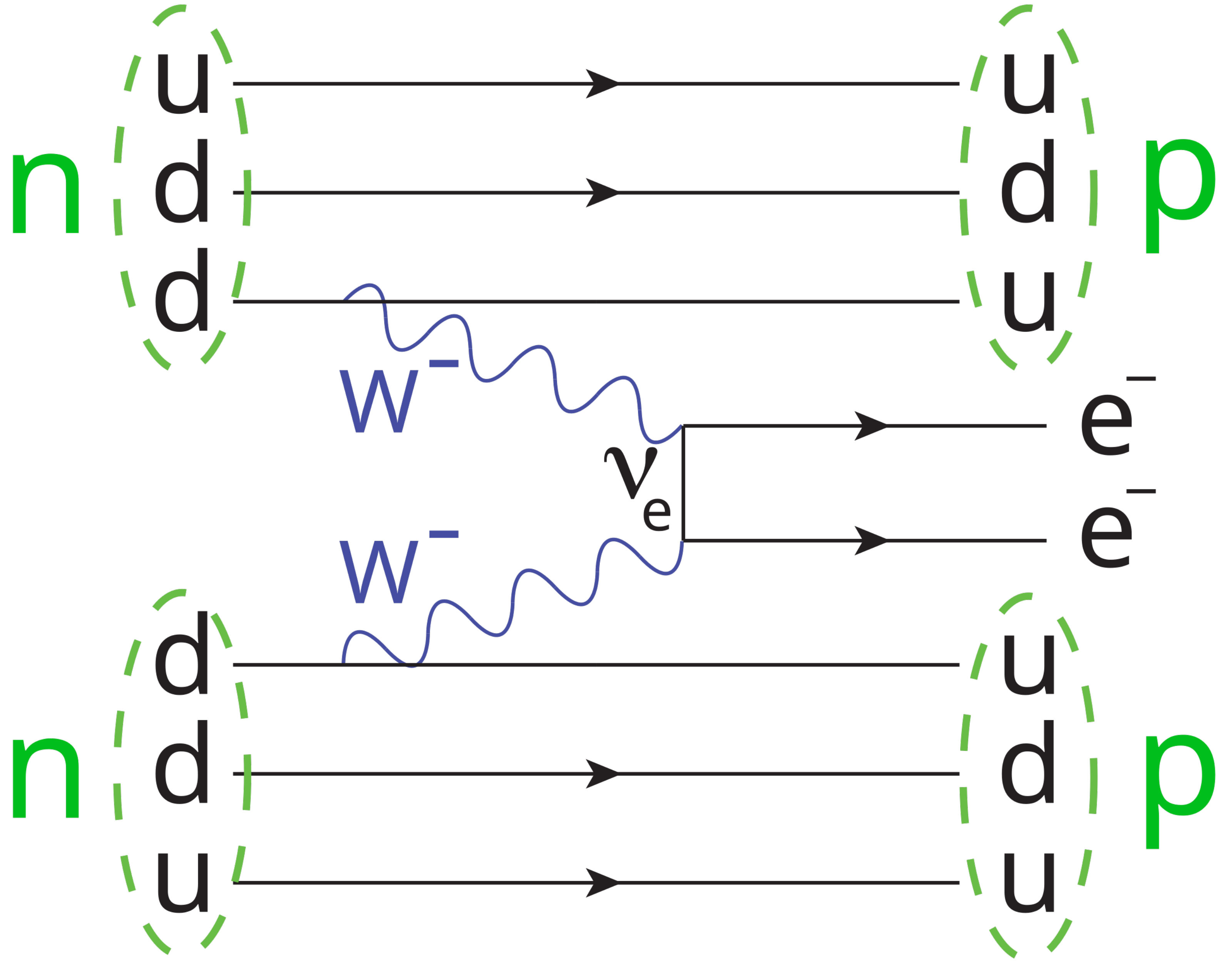
Neutrinoless Double-Beta Decay

A fundamental question remains: are neutrinos their own antiparticles?

If neutrinos are Majorana particles the lepton number is not conserved

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

Lepton number violated by 2 units



Neutrinoless Double-Beta Decay

Neutrinoless double beta decay is sensitive to the absolute scale of the neutrino masses

The half-life of the process is

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

Phase space

Nuclear matrix element

$$m_{\beta\beta} = |\sum_i U^2_{ei} m_i|$$

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Phase space

Nuclear matrix element

$$m_{\beta\beta} = |\sum_i U^2_{ei} m_i|$$

The mixing matrix contains two additional phases

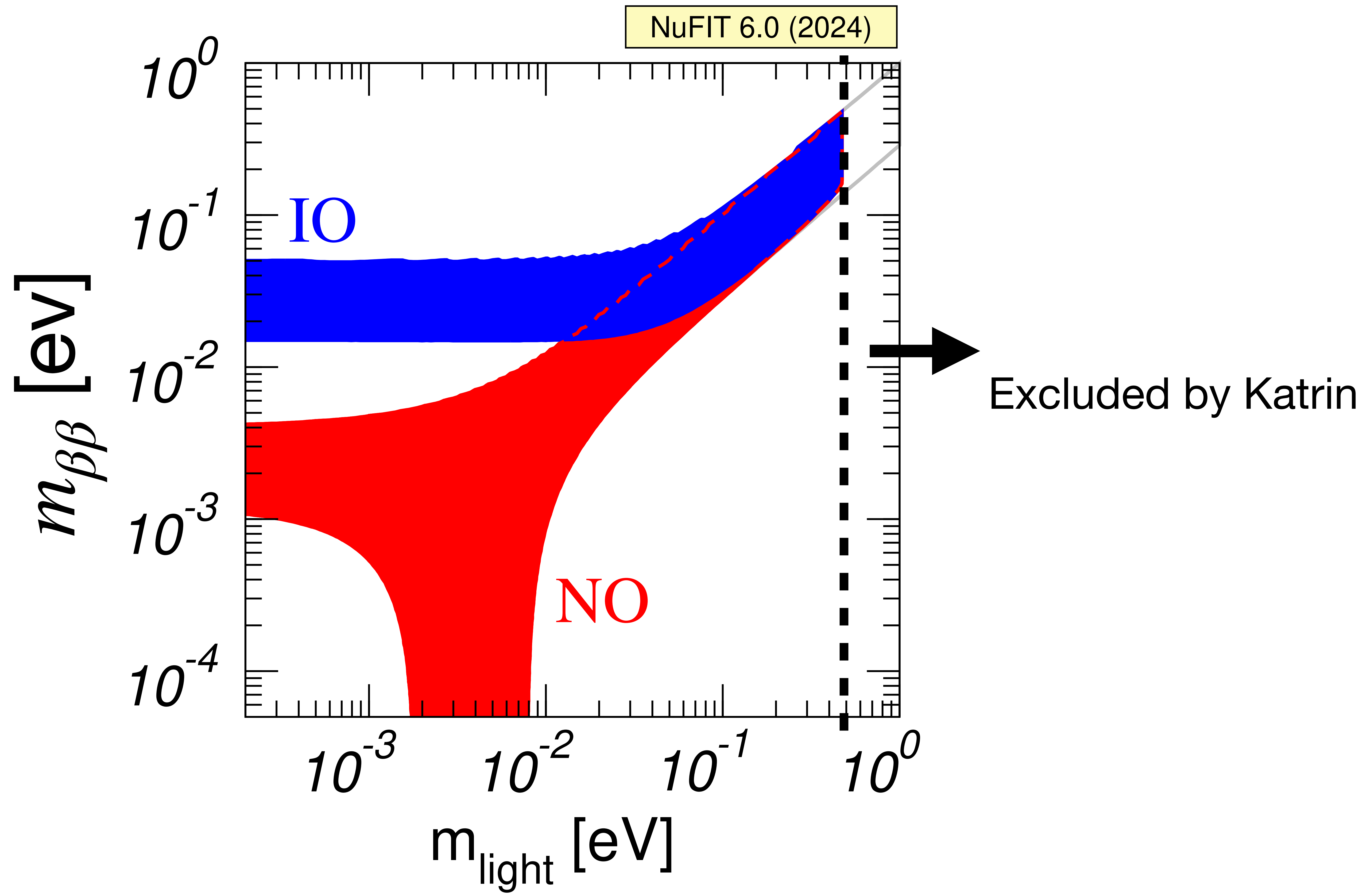
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

Ivan Martinez-Soler (IPPP)

Neutrinoless Double-Beta Decay

The main uncertainties over $m_{\beta\beta}$ come from the Majorana phases

$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

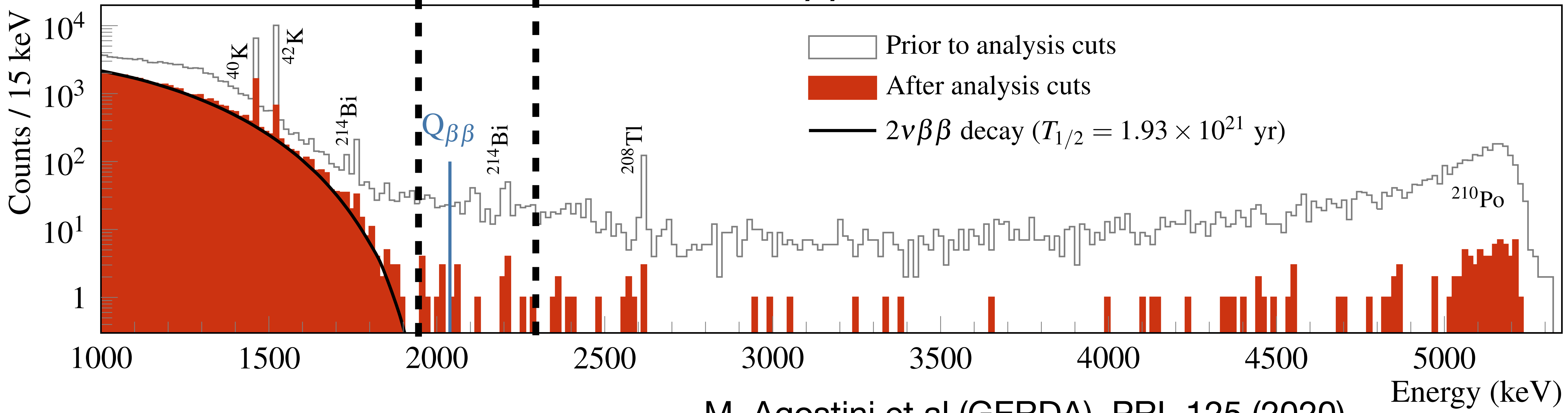


$0\nu\beta\beta$: GERDA

A Germanium detector using 127.2 kg yr exposure has not found evidence

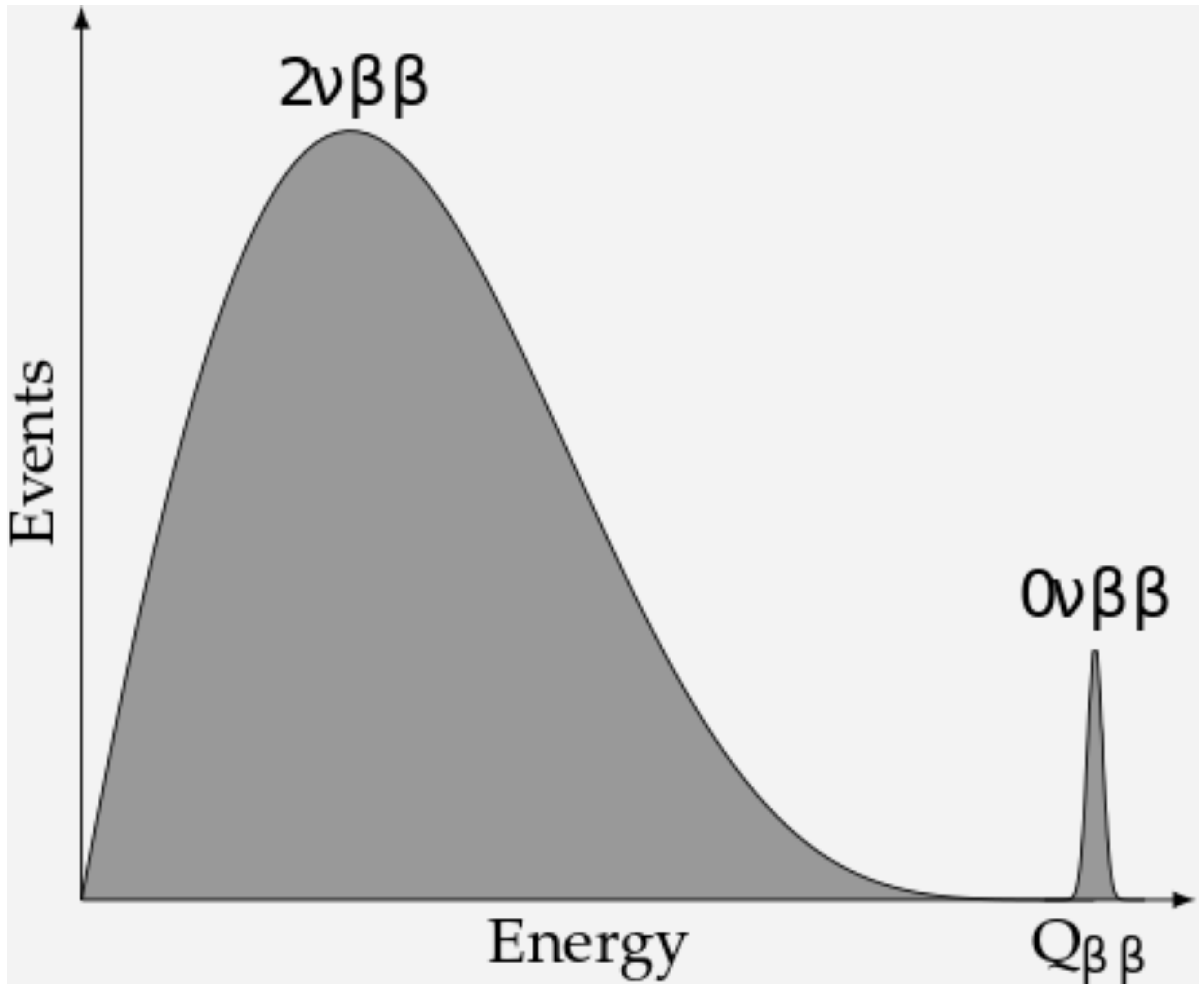
$$1.8 \times 10^{26} \text{ yr} < T_{1/2}^{0\nu} \longrightarrow m_{\beta\beta} < 79 - 180 \text{ meV}$$

Energy range used for $0\nu\beta\beta$



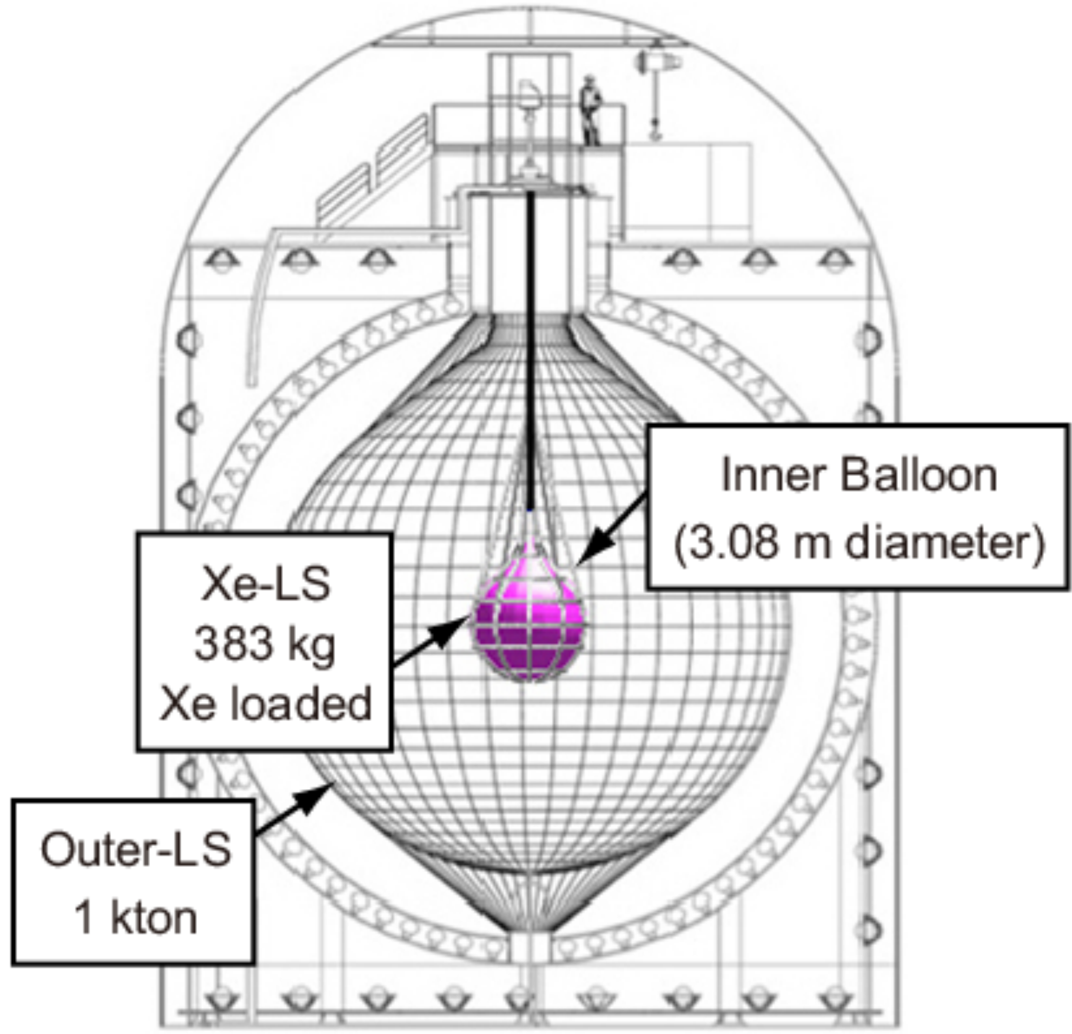
M. Agostini et al (GERDA), PRL 125 (2020)

Expected signal



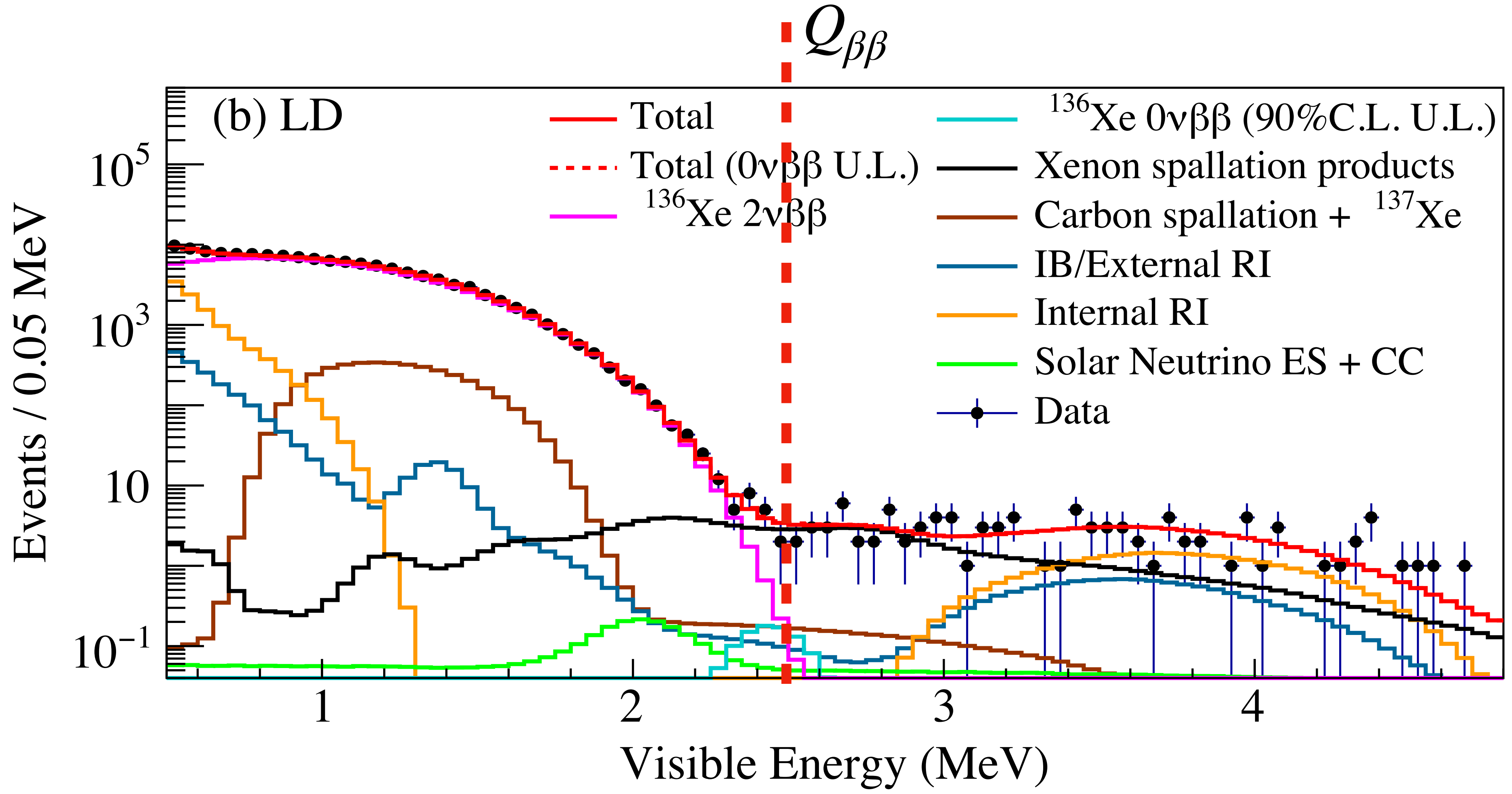
GERDA (Zurich)

$0\nu\beta\beta$: KamLAND-Zen

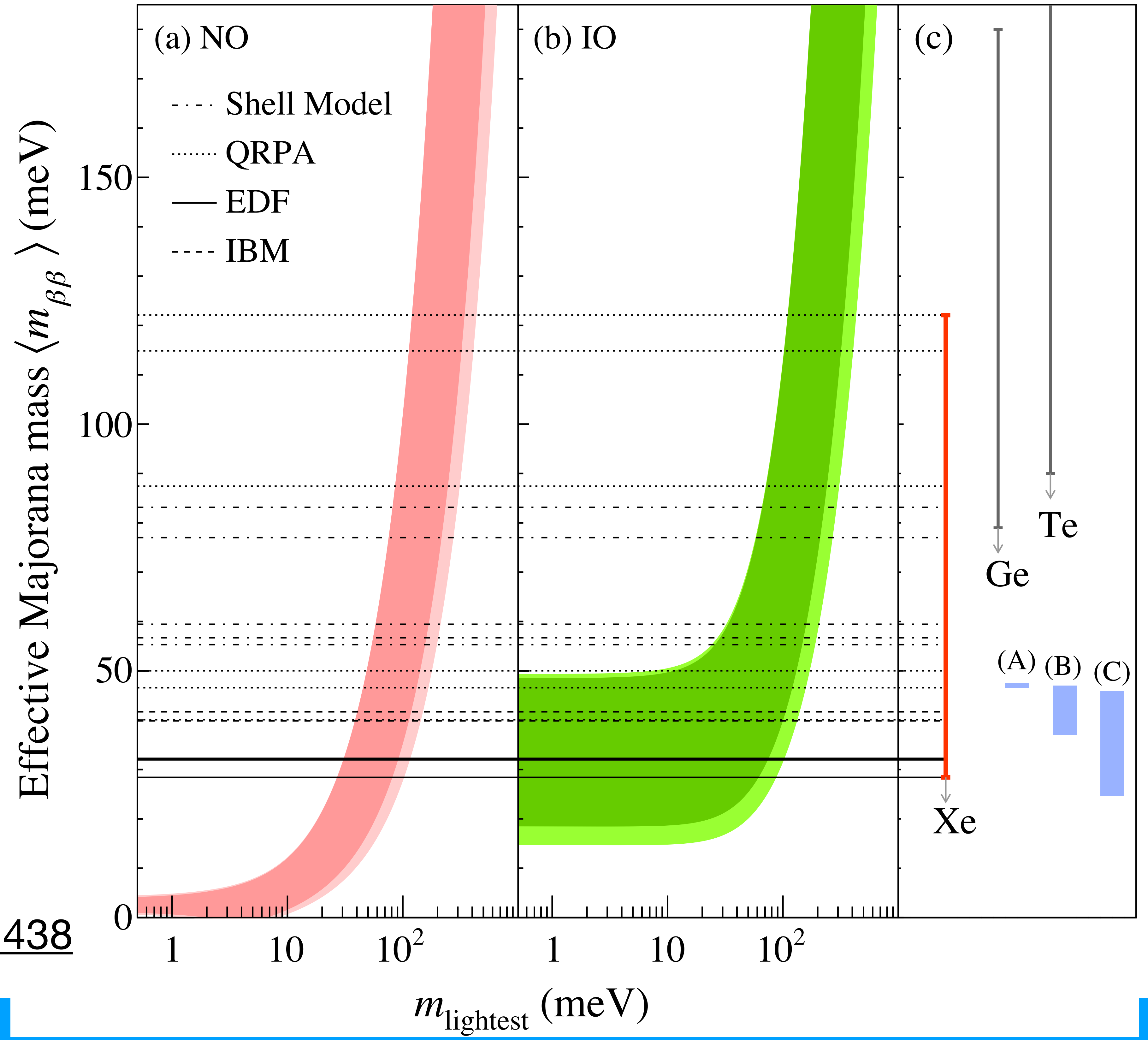


KamLAND-Zen uses 745 kg of Xenon to search for $0\nu\beta\beta$

3.8×10^{26} yr $< T^{0\nu}_{1/2}$ $\longrightarrow$ $m_{\beta\beta} < 28 - 122$ meV

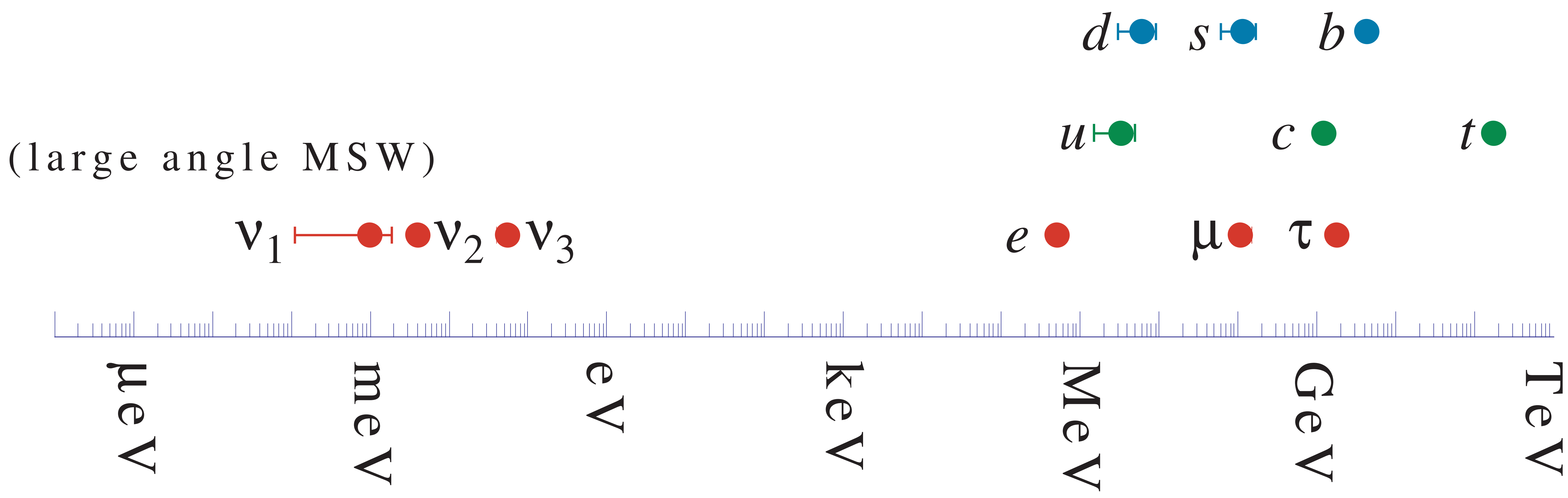


S. Abe et al. (KamLED-Zen), arXiv:2406.11438



Neutrino Mass

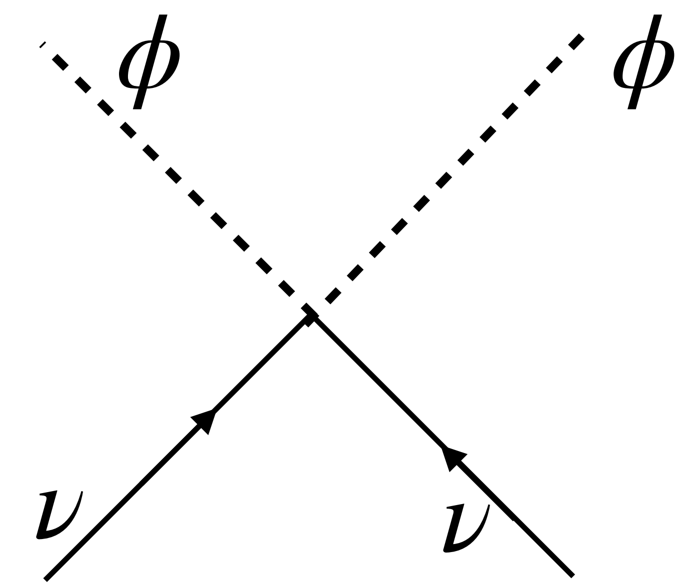
There is a large mass gap between neutrinos and the other fermions, which could signal BSM physics



P. Hernandez, CLASHEP2015 arXiv:1708.01046

Neutrino Mass

If neutrinos are Majorana particles, they can get their masses via the Weinberg operator



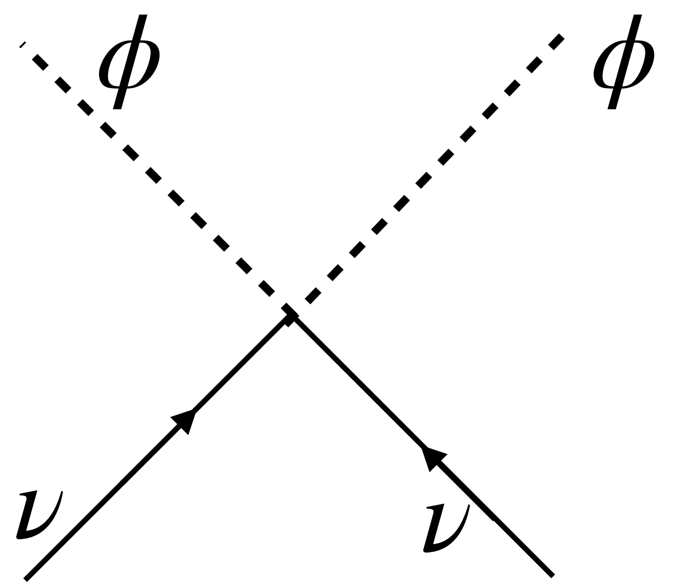
$$\mathscr{L}_{mass} \supset \frac{Y}{\Lambda}\overline{L}_L\tilde{\phi}^*C^\dagger\tilde{\phi}^\dagger L_L + \text{h.c.}$$

The smallness of the neutrino mass could be explained by the suppression of the new physics scale → $m_\nu \sim \frac{Yv^2}{2\Lambda}$

Ivan Martinez-Soler (IPPP)

Neutrino Mass: see-saw mechanism

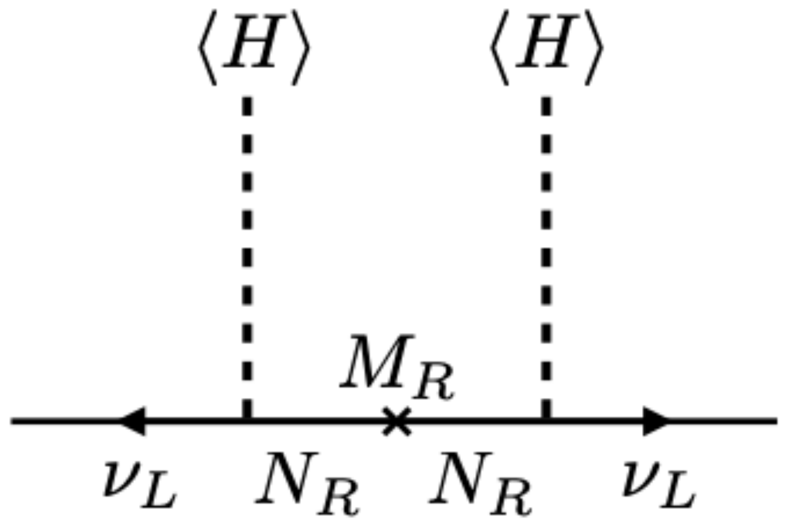
If neutrinos are Majorana particles, they can get their masses via the Weinberg operator



$$\mathscr{L}_{mass} \supset \frac{Y}{\Lambda}\overline{L}_L\tilde{\phi}^* C^\dagger \tilde{\phi}^\dagger L_L + \text{h.c.}$$

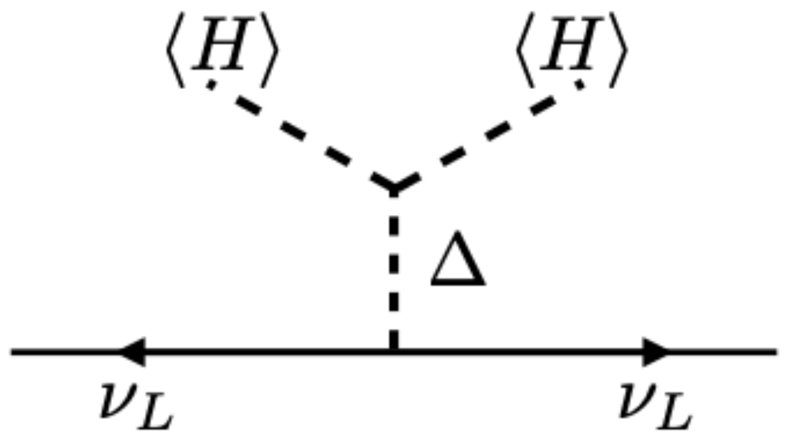
At the tree level, the Weinberg operator can be generated as the exchange of a massive particle

See-saw type I



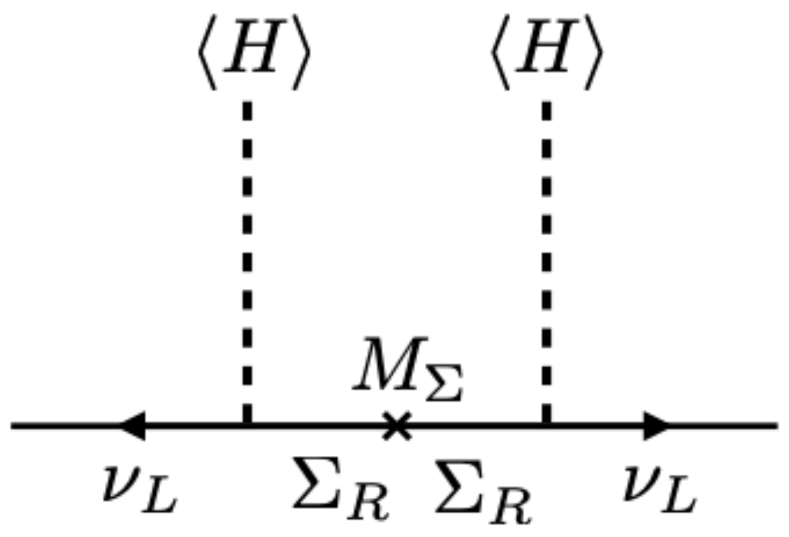
Singlet fermion

See-saw type II



Triplet scalar

See-saw type III



Triplet fermion

See-saw type I

By adding a right-handed neutrino to the SM, we can construct a Dirac and Majorana mass terms

$$\mathscr{L}_{TypeI} = \frac{1}{2}\overline{N_L^C}\mathscr{M}N_L + \text{h.c.} \qquad \text{where} \qquad N_L = \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix} \qquad \mathscr{M} = \begin{pmatrix} 0 & m_D \\ m_D^\dagger & m_M \end{pmatrix}$$

Ivan Martinez-Soler (IPPP)

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In case of $m_M \gg m_D$ we found a light and a heavy state

$$m_l \simeq \frac{m_D^T m_D}{m_M} \quad m_h \simeq m_M \quad \text{where} \quad m_D = \frac{Yv}{\sqrt{2}}$$

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For $m_M \sim 10^{14}$ GeV and $Y \sim o(1)$ ➡ $m_D \sim 0.1$ eV

Ivan Martinez-Soler (IPPP)

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$$m_l \simeq \frac{m_D^T m_D}{m_M} \quad m_h \simeq m_M \quad \text{where} \quad m_D = \frac{Yv}{\sqrt{2}}$$

The mixing is very suppressed $\theta \simeq \frac{m_D}{m_M} \sim 10^{-12}$ For $m_M \sim 10^{14}$ GeV

Heavy Neutral Leptons

In the presence of N_R, the flavor states can be written as a superposition of massive states as

$$\nu_{\alpha L} = \sum U_{\alpha m}\nu_{mL} + U_{\alpha 4}N$$

$$U_{\alpha N} = \frac{Y_\alpha v}{\sqrt{2}m_N}$$

$U_{\alpha m}$ 3x3 matrix that is not unitary

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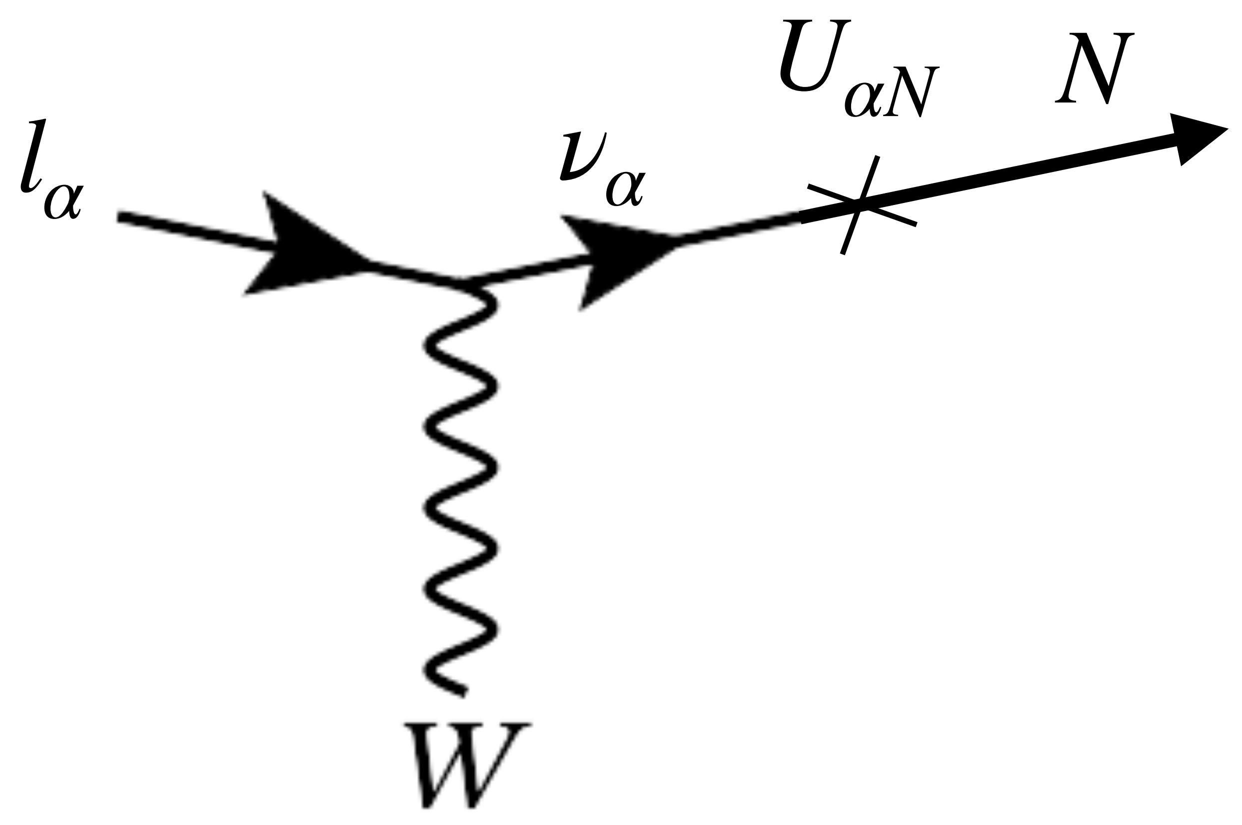
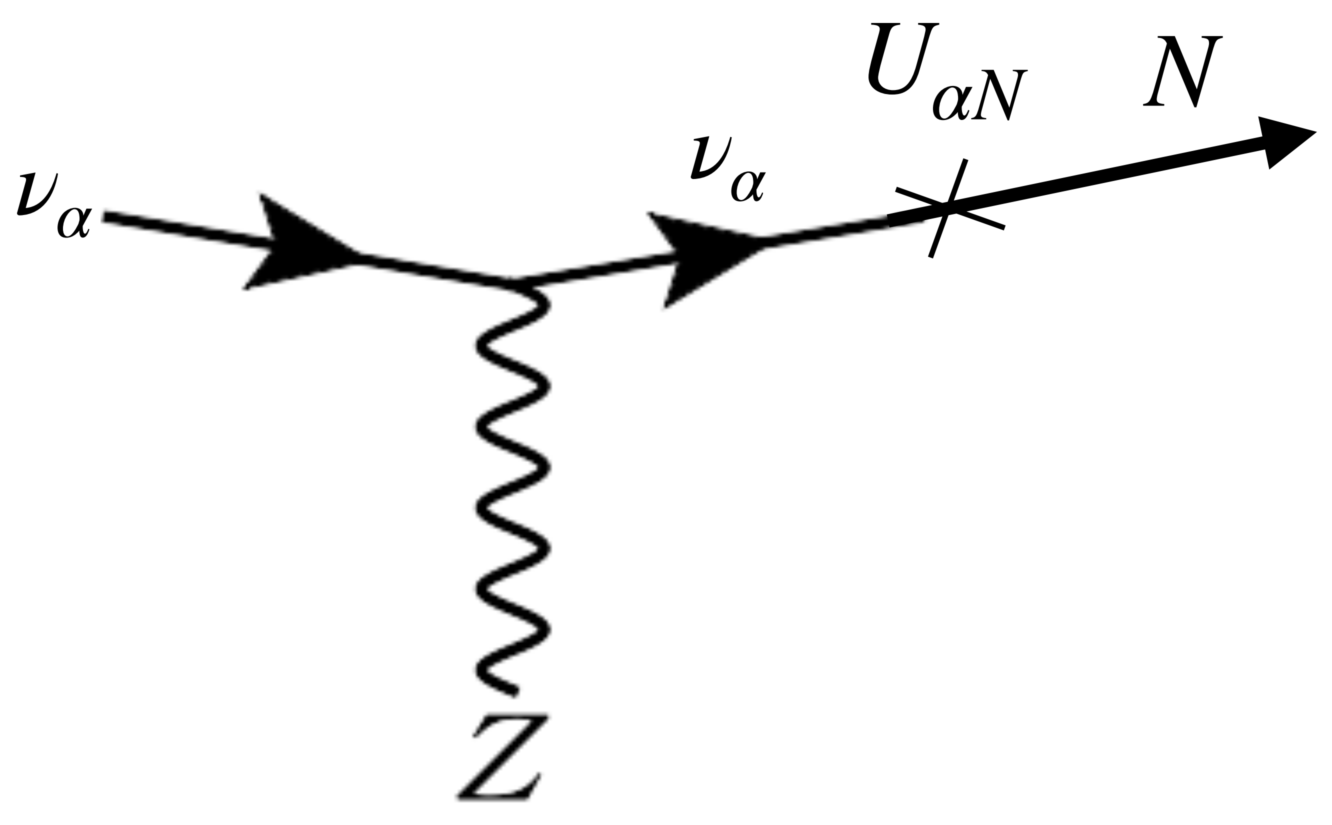
$$\nu_{\alpha L} = \sum U_{\alpha m} \nu_{mL} + U_{\alpha 4} N \qquad U_{\alpha N} = \frac{Y_\alpha v}{\sqrt{2} m_N}$$

HNLs are produced through the same weak interactions as active neutrinos



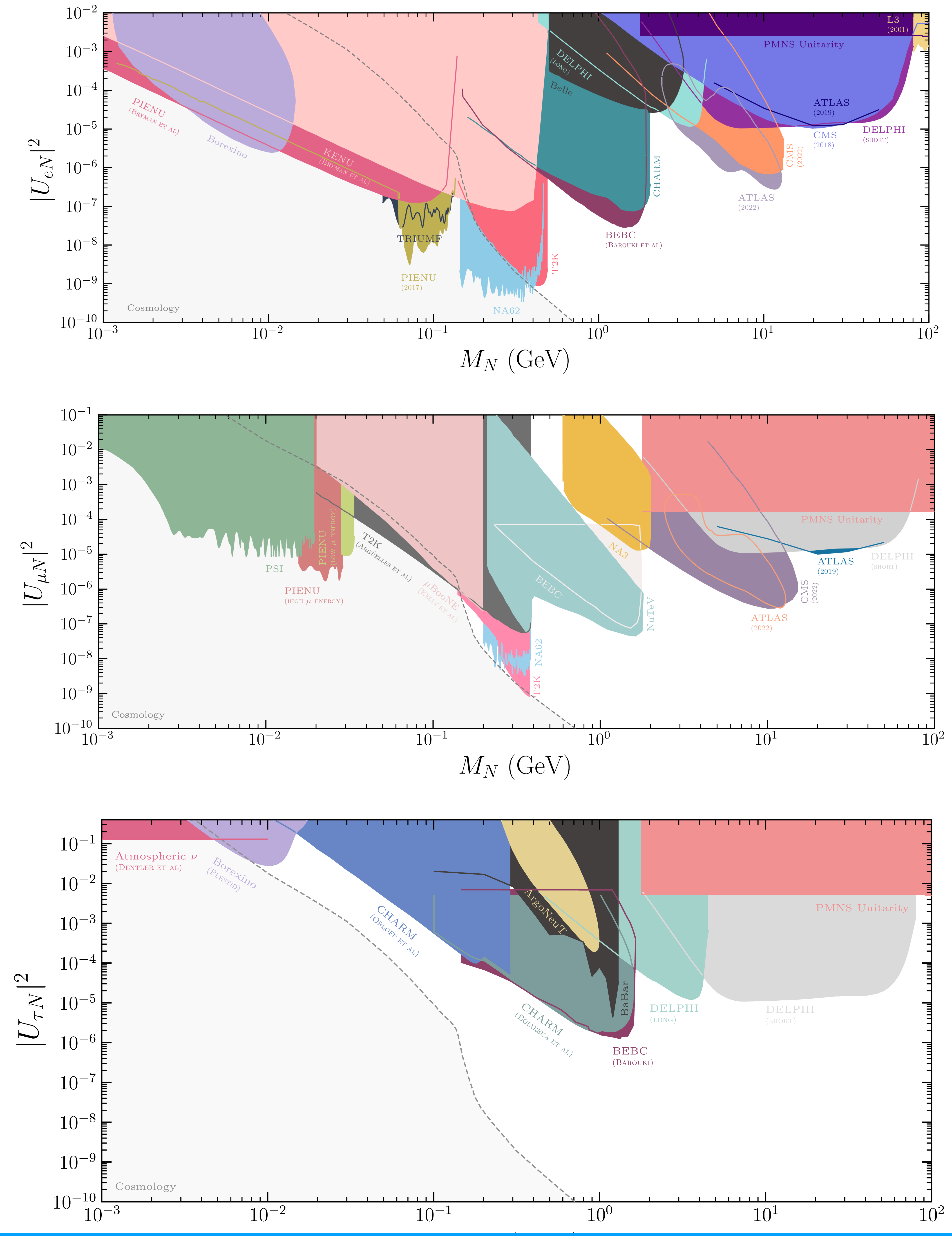


Ivan Martinez-Soler (IPPP)

Heavy Neutral Leptons

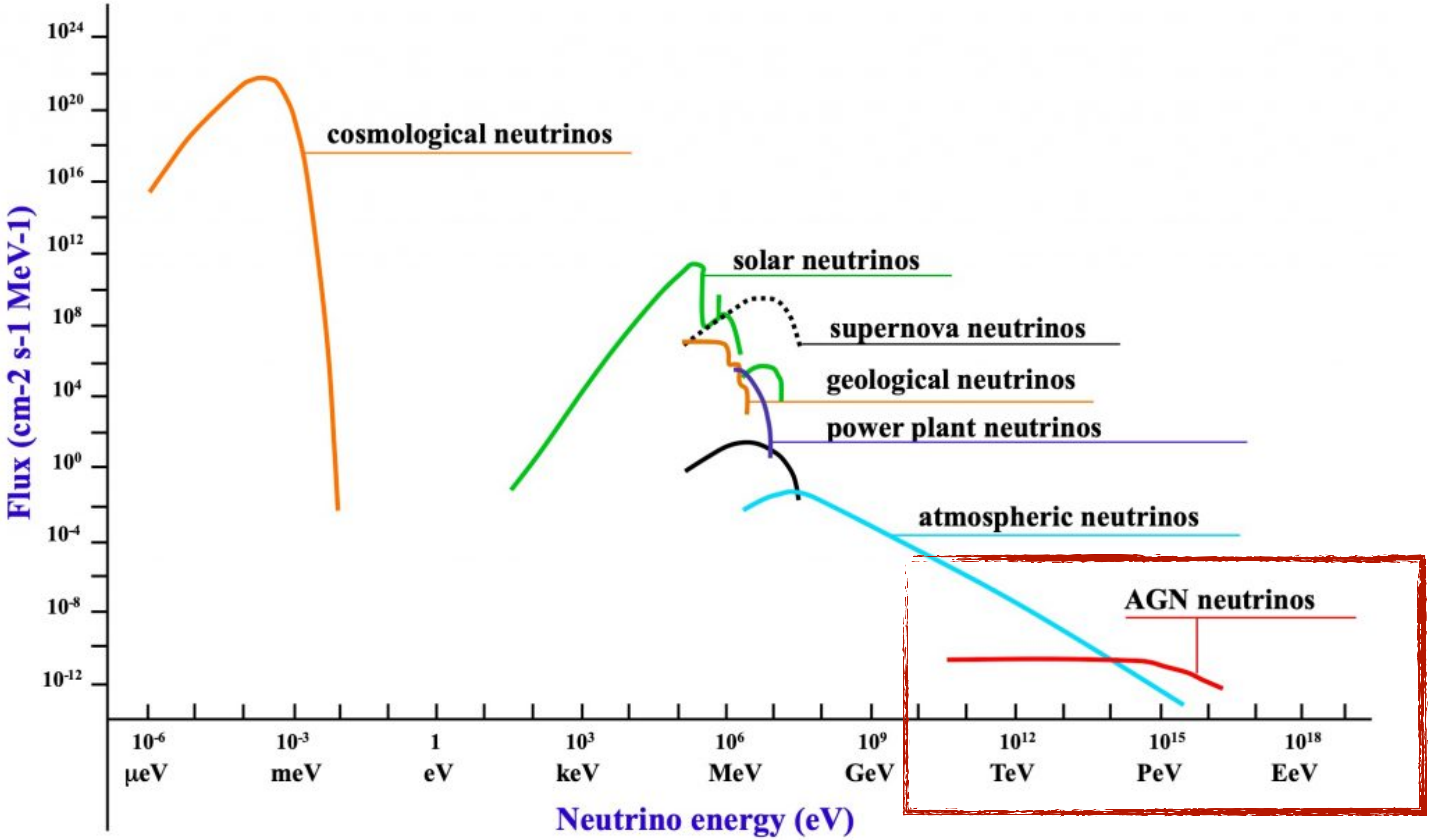
In the presence of N_R, the flavor states can be written as a superposition of massive states as

$$\nu_{\alpha L} = \sum U_{\alpha m}\nu_{mL} + U_{\alpha 4}N_{4L}$$



[Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia, Hostert, Lopez-Pavon, JHEP 09 (2023)]

Neutrino Astronomy



Neutrino Astronomy

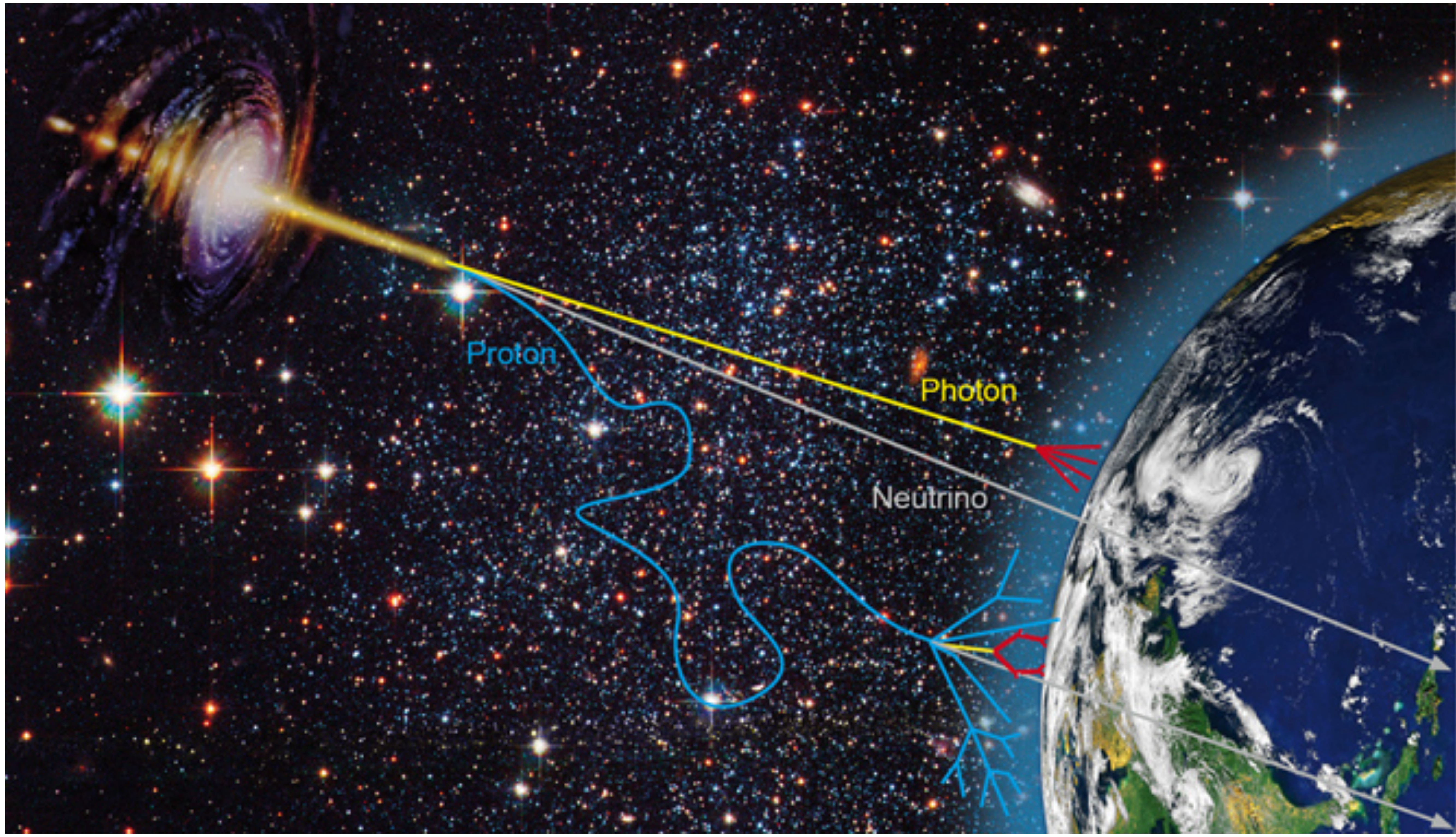
Why neutrinos?

- At 100 TeV, the universe is opaque to photons due to their interactions with the cmb before they reaching the Earth

$$\gamma + \gamma \rightarrow e^+ + e^-$$

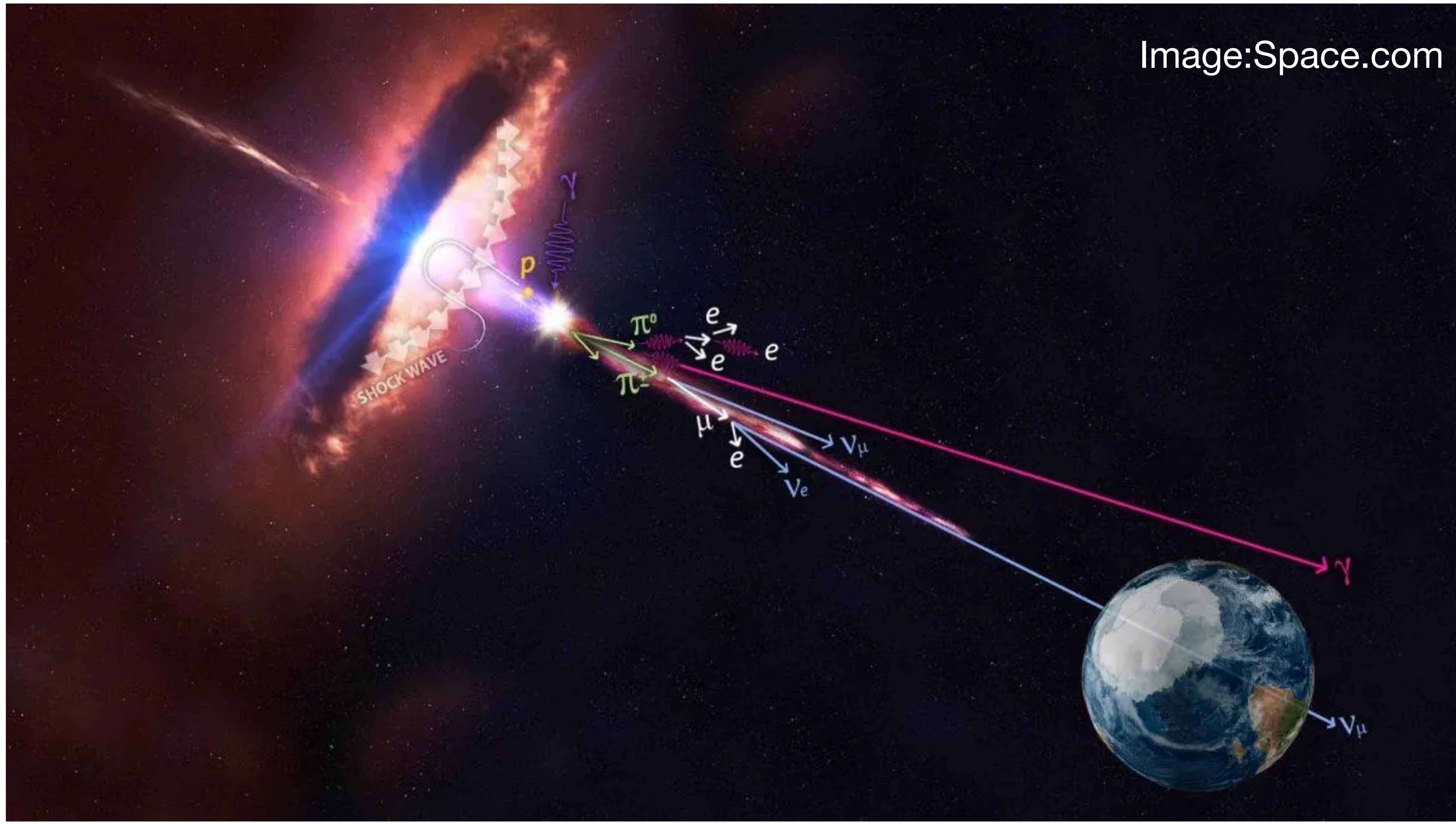
- Cosmic rays are deflected by magnetic fields as they travel to Earth.

- Neutrinos are neutral particles that interact weakly, allowing their detection to directly trace back to their source.



Neutrino Astronomy

Neutrinos can originate from sources of UHE cosmic rays



IceCube/NASA

Interaction with matter

$$p + p \rightarrow p + p + \pi^+ + \pi^-$$

$$p + p \rightarrow p + p + \pi^0$$

Interaction with radiation fields

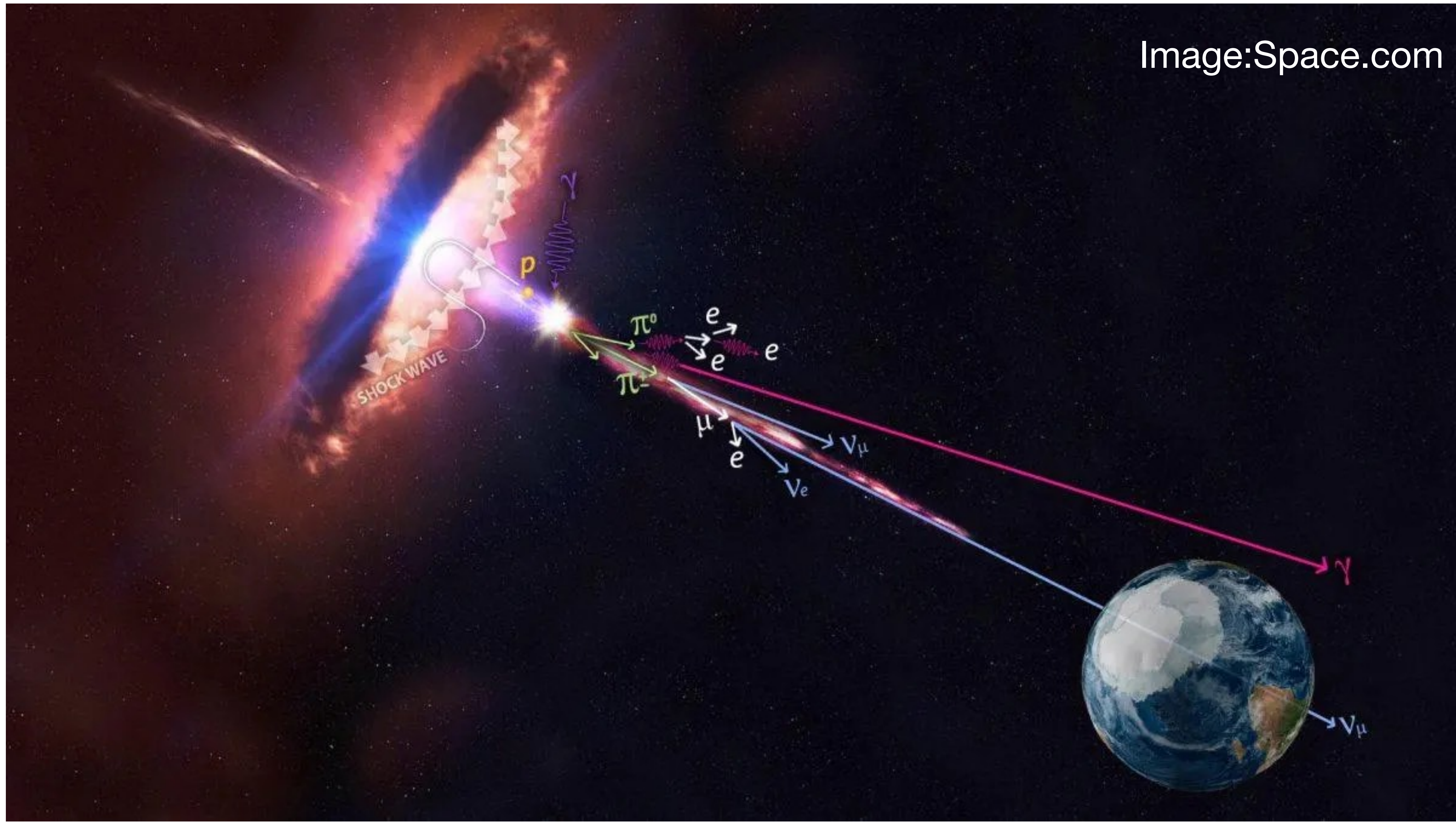
$$p + \gamma \rightarrow n + \pi^+$$

$$p + \gamma \rightarrow p + \pi^0$$

Detecting them provides insights into cosmic ray acceleration and their interaction with gas or photons.

Neutrino Astronomy

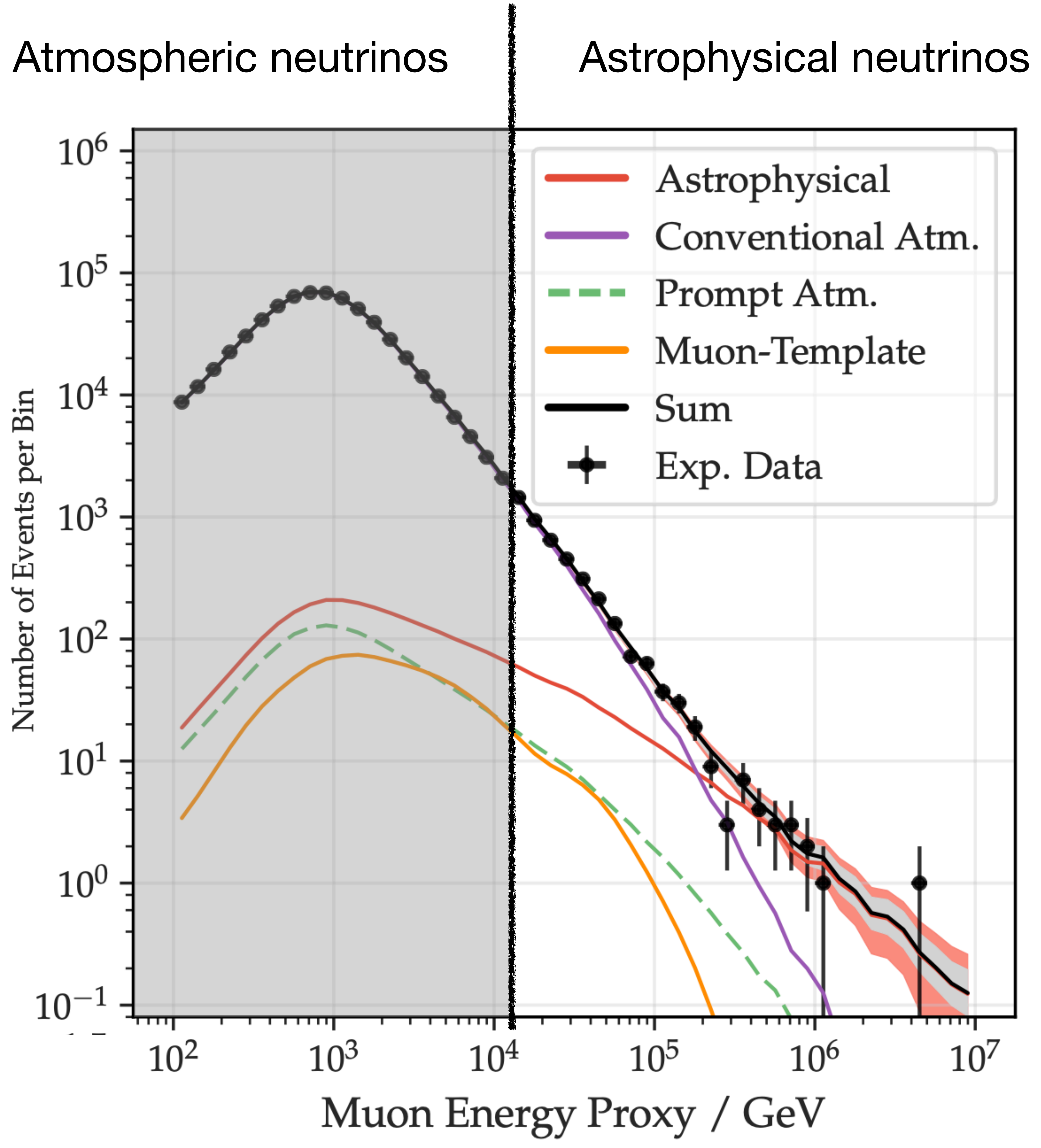
- The predicted flux follows $\phi \sim E^{-\gamma}$
- The normalization and the spectral index reveal information about the neutrino source and its environment
- They travel vast distances, ranging from kpc to Gpc, before reaching the Earth
- Due to their low flux, large detectors are necessary for their detection.



IceCube/NASA

Astrophysical neutrinos

At energies above ~10 TeV, the flux reaching the Neutrino Telescopes is dominated by astrophysical sources.

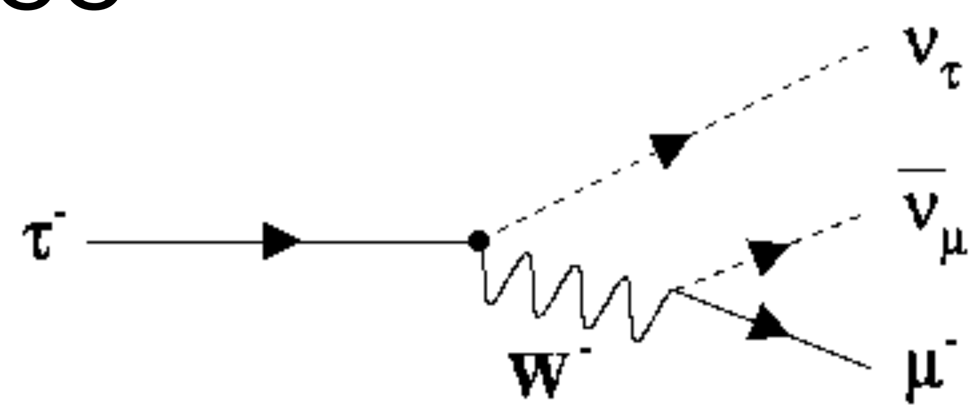


R. Abbasi, et al. (IceCube), Astrophys.J. 928 (2022) 1, 50

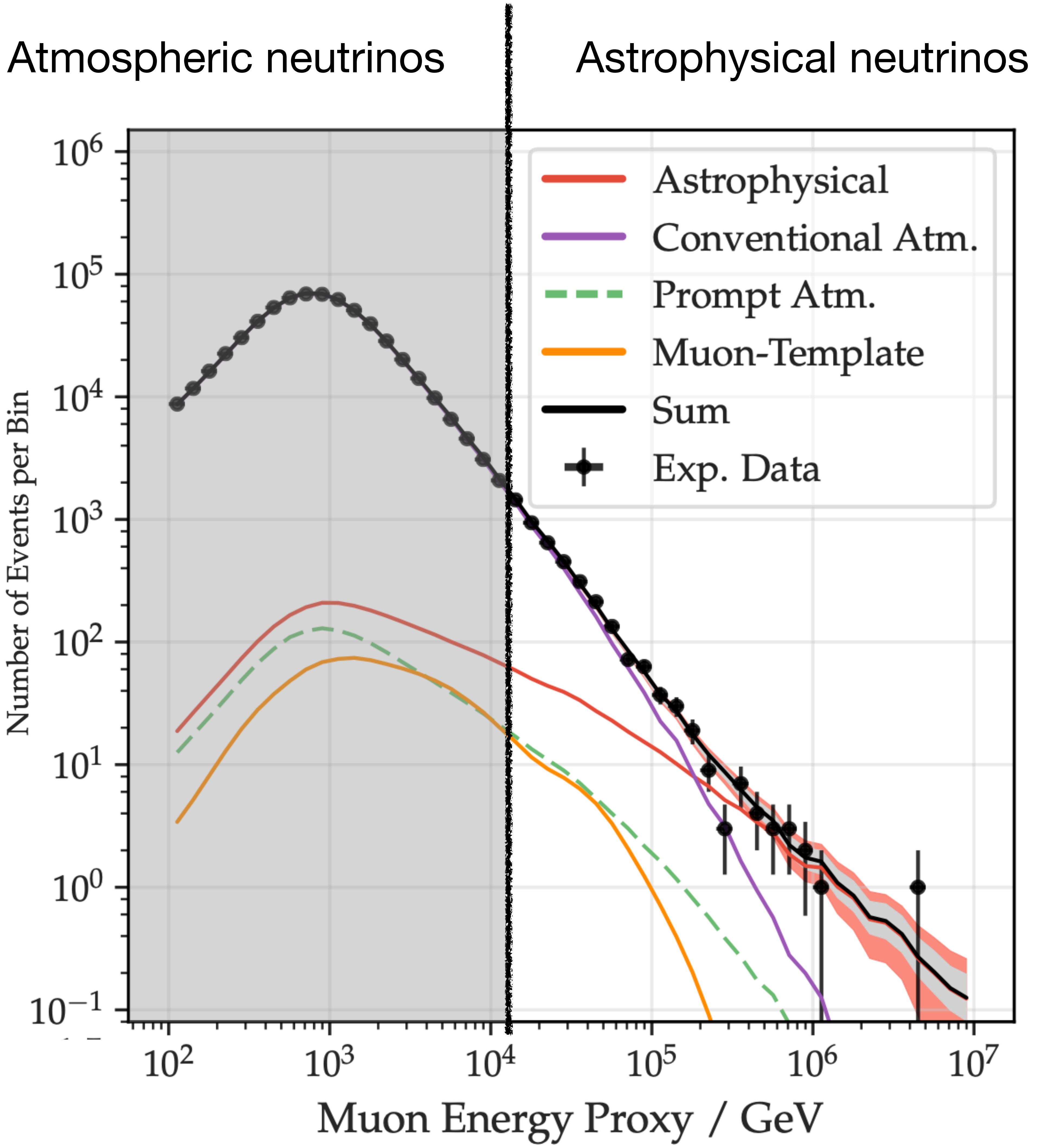
Through-going Muons

IceCube has measured the astrophysical muon-neutrino flux

- It includes both starting and through-going samples.
- The measurement is dominated by ν_μ CC, with a small contribution from ν_τ CC



- To minimize the background, only up-going events have been considered ($\theta_{zenith} > 85°$)
- The energy range considered is 15 TeV to 5 PeV

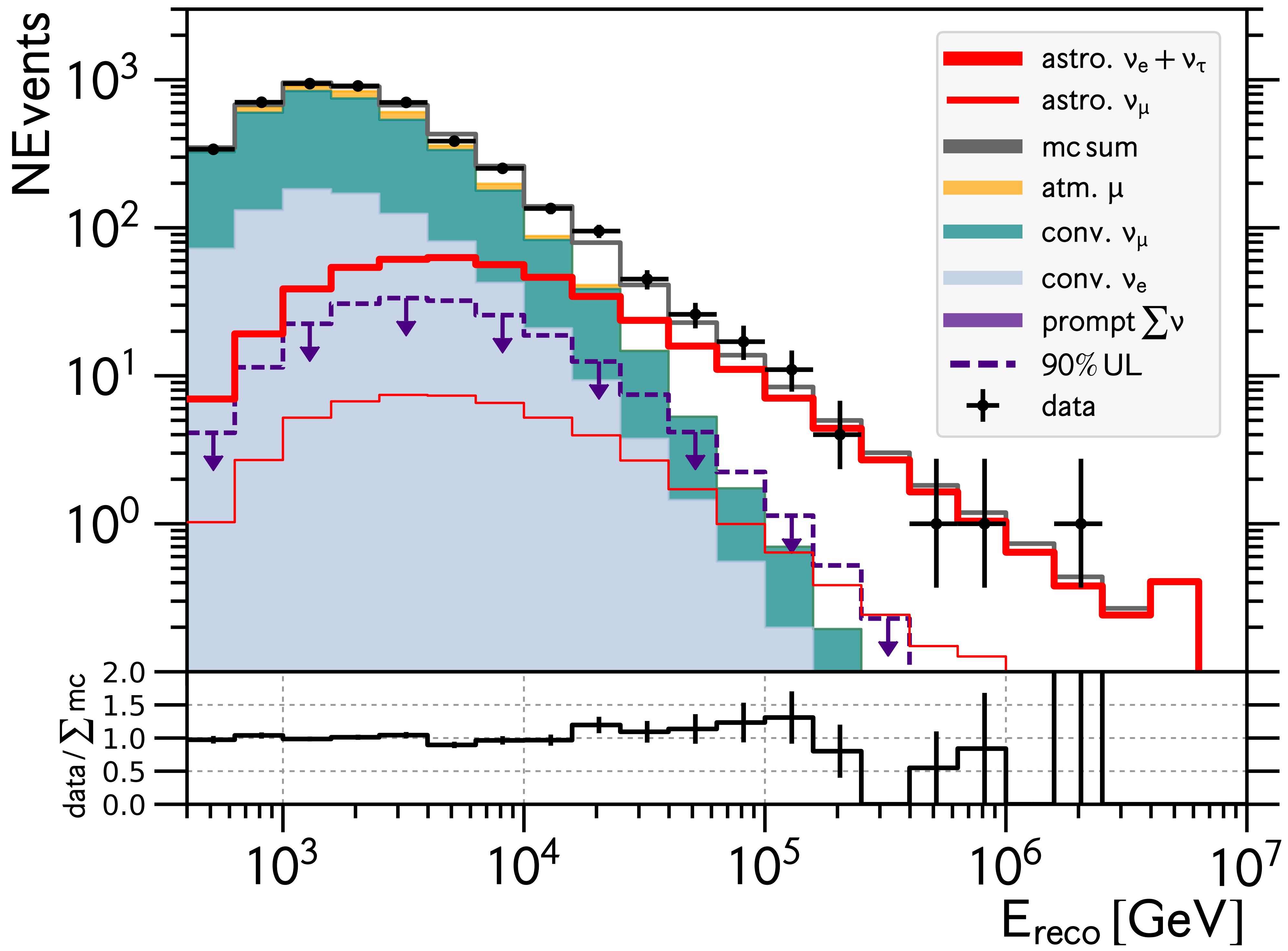


R. Abbasi, et al. (IceCube), Astrophys.J. 928 (2022) 1, 50

Electron and Tau Neutrinos

IceCube has searched for astrophysical events using cascades

- This analysis is dominated by ν_e and ν_τ
- The astrophysical neutrino flux at Earth assumes an equal number of neutrinos and anti-neutrinos, with an equal flavor composition
- The energy range considered spans from 16 TeV to 2.6 PeV
- Cascades from all the sky are included.



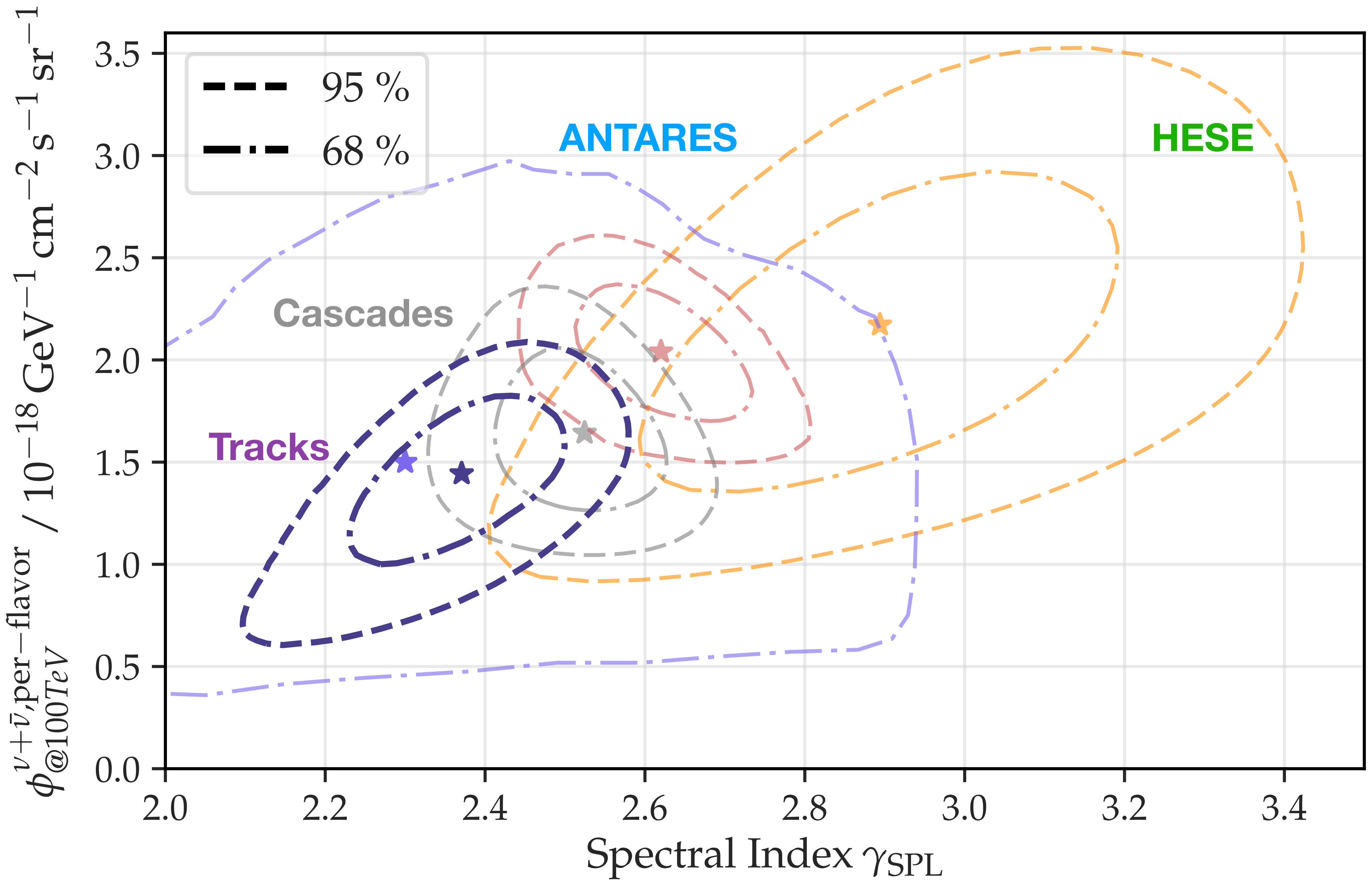
M.G. Aartsen, et al. (IceCube), PRL 125 (2020)

Electron and Tau Neutrinos

Assuming the astrophysical flux follows a power law

$$\phi_\nu(E) = \phi_0 \left(\frac{E}{E_0}\right)^\gamma$$

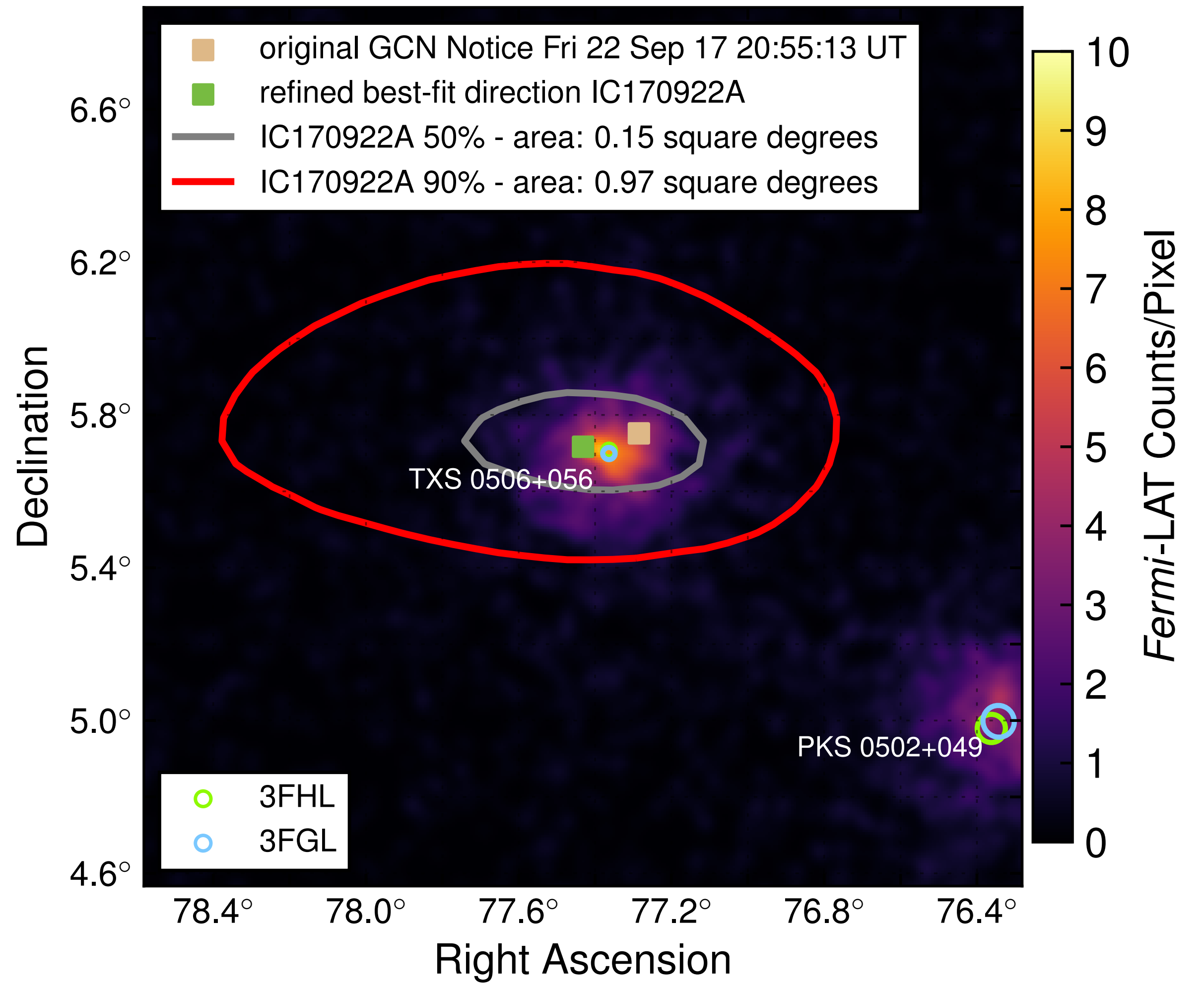
- Compared to the muon analysis, there is a good agreement in both normalization and γ



R. Abbasi, et al. (IceCube), Astrophys.J. 928 (2022) 1, 50

Where Do Neutrinos Come From?

Point Sources

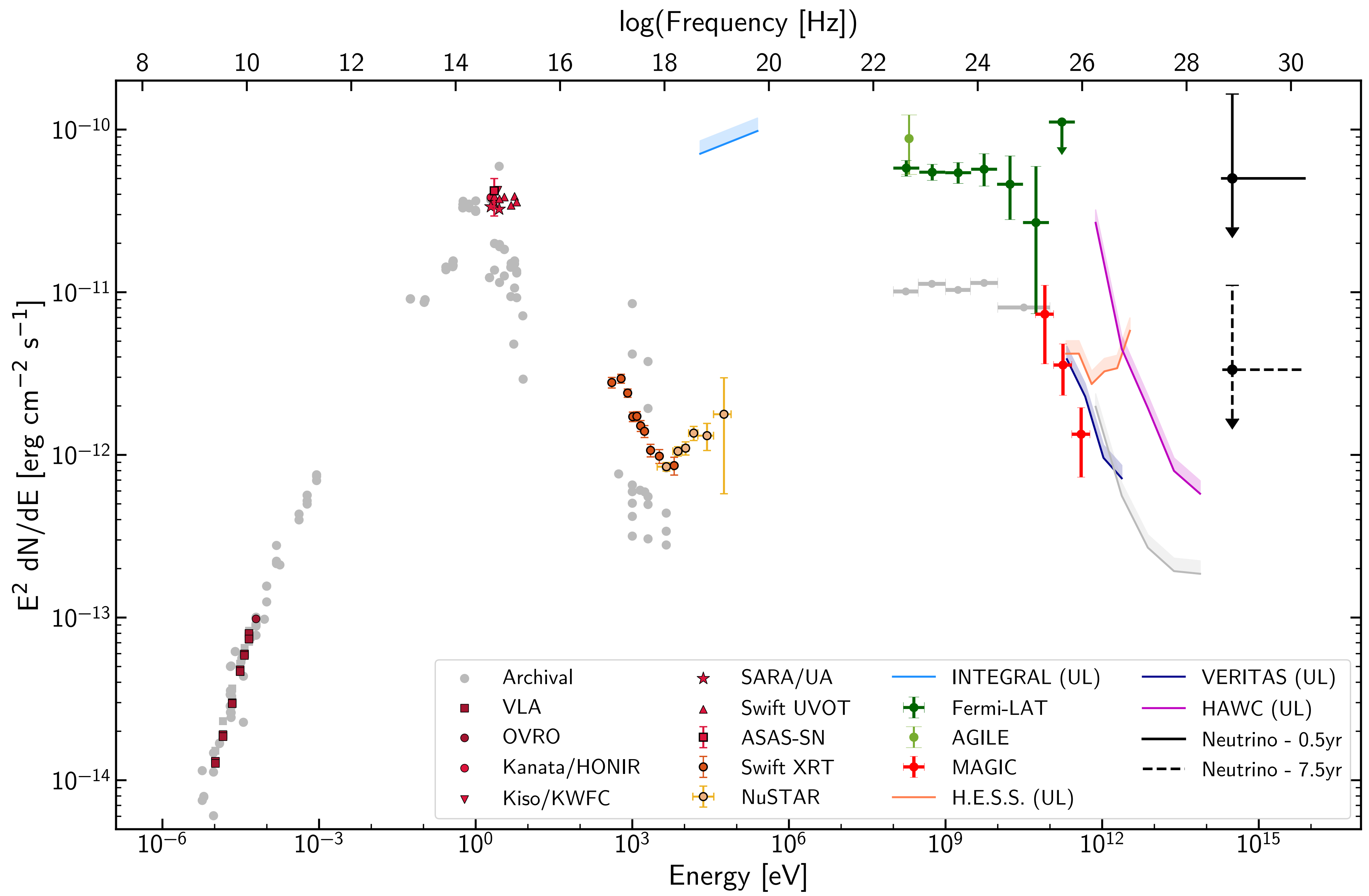


- On 22 September 2017, IceCube's alert system detected a high-energy track (290 TeV)

- FermiLAT confirmed it coincided with a period of intense γ-ray activity from TXS 0506+056

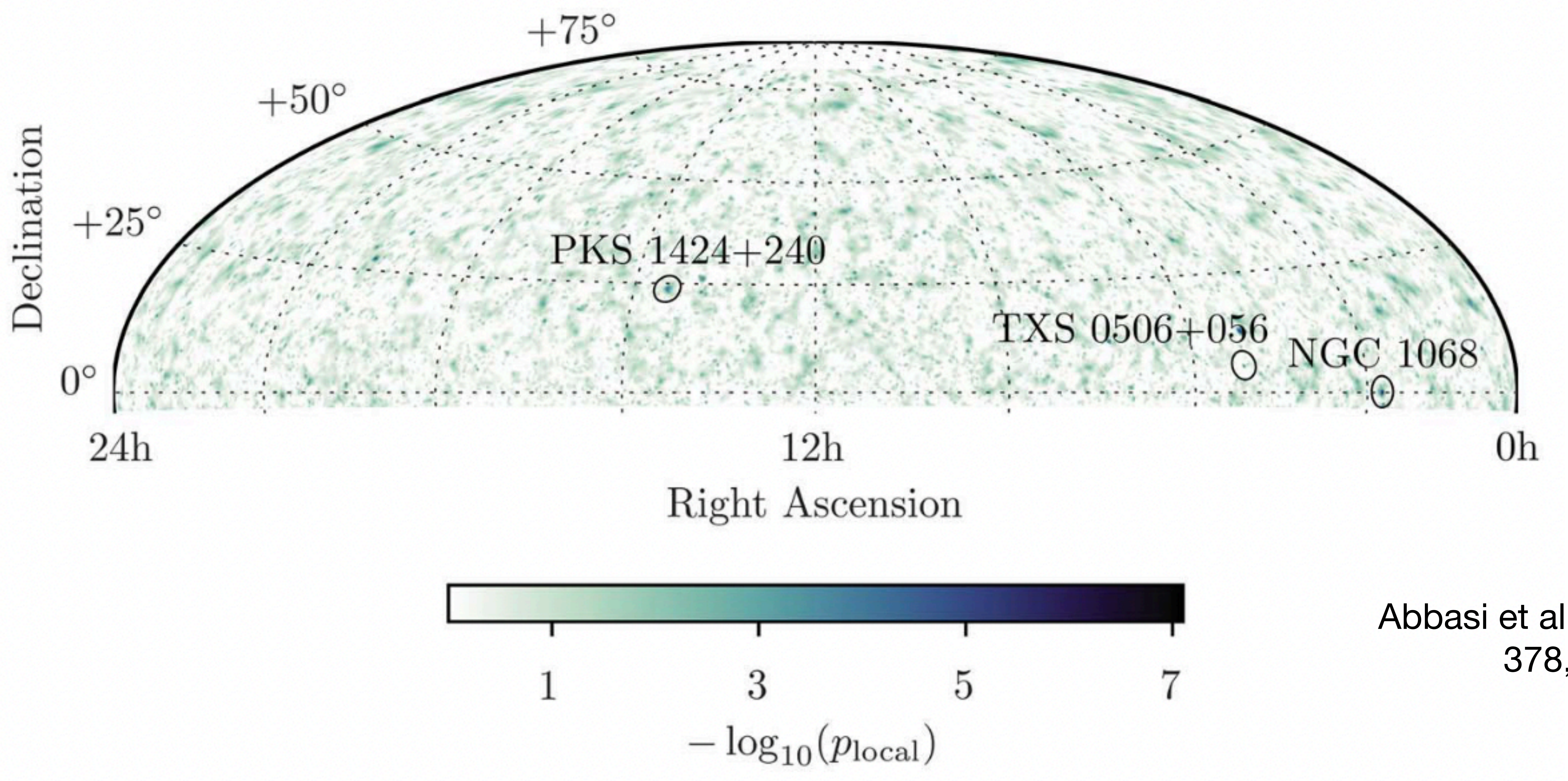
- Subsequent observation by MAGIC and other experiments also detected high-energy γ-ray

- The significance of that source is 3.5σ



M.G. Aartsen, et al. (IceCube), Science 361, 147 (2018)

Point Sources

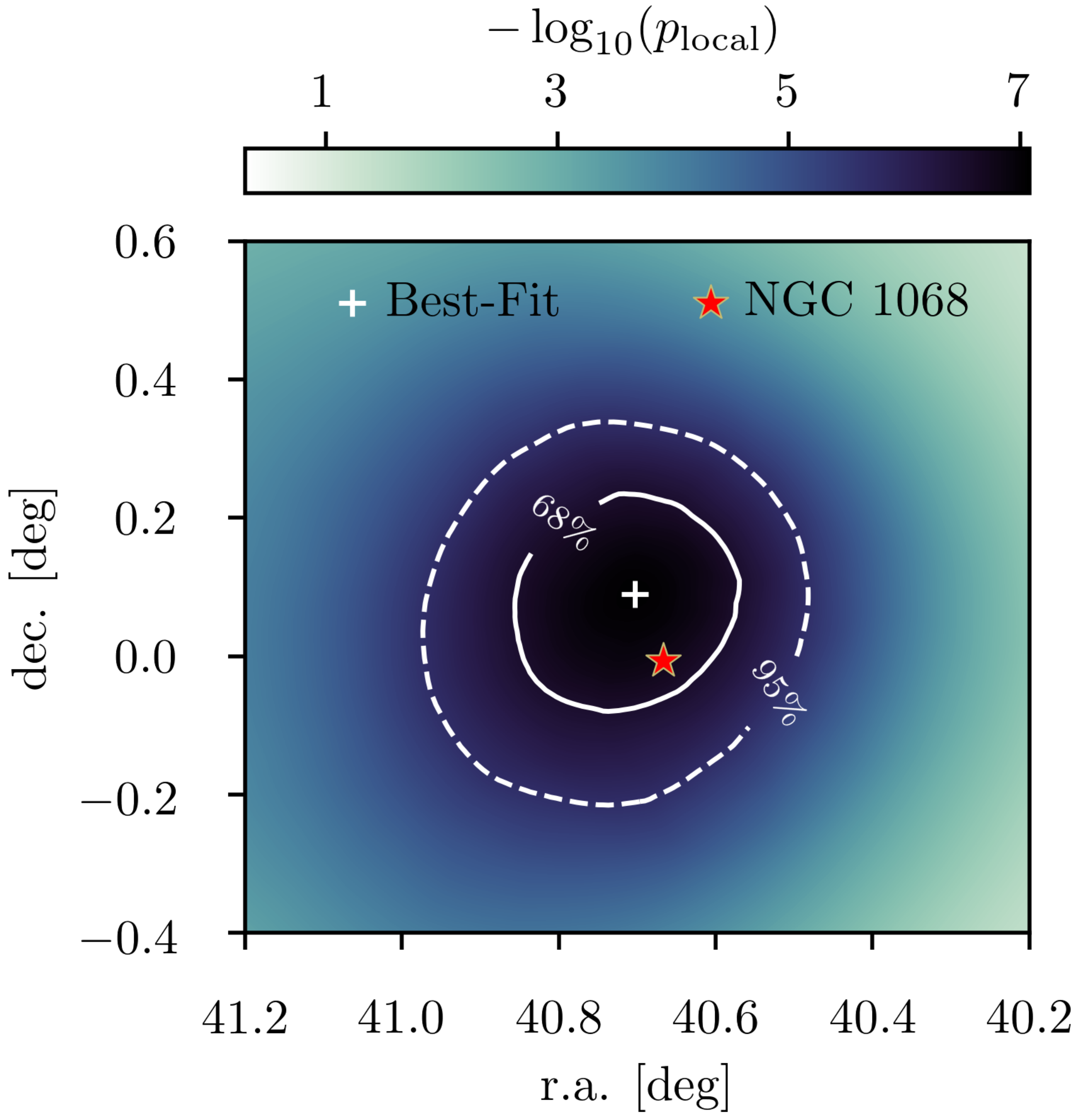


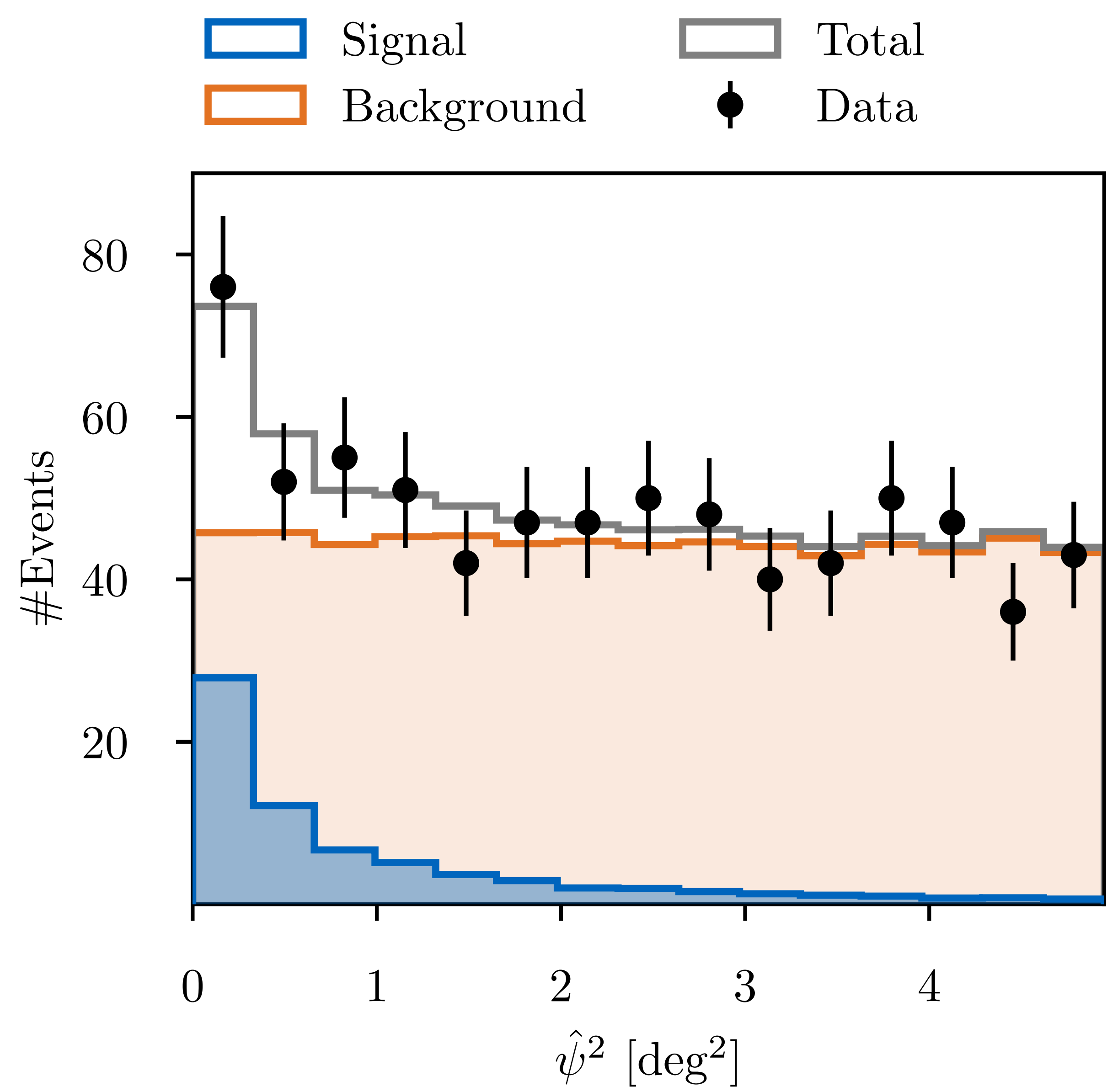
Abbasi et al. (IceCube) Science 378, 538 (2022)

Point Sources

The most significant source observed by IceCube is **NGC 1068** with a significance of 4.2σ

- The analysis is optimized for searching tracks from the Northern Hemisphere
- The analysis assumes a single power law finding a preference for $\gamma = 3.2 \pm 0.2$ and an excess of 79^{+22}_{-20} events
- Most of the events have energies between 1.5TeV and 15TeV

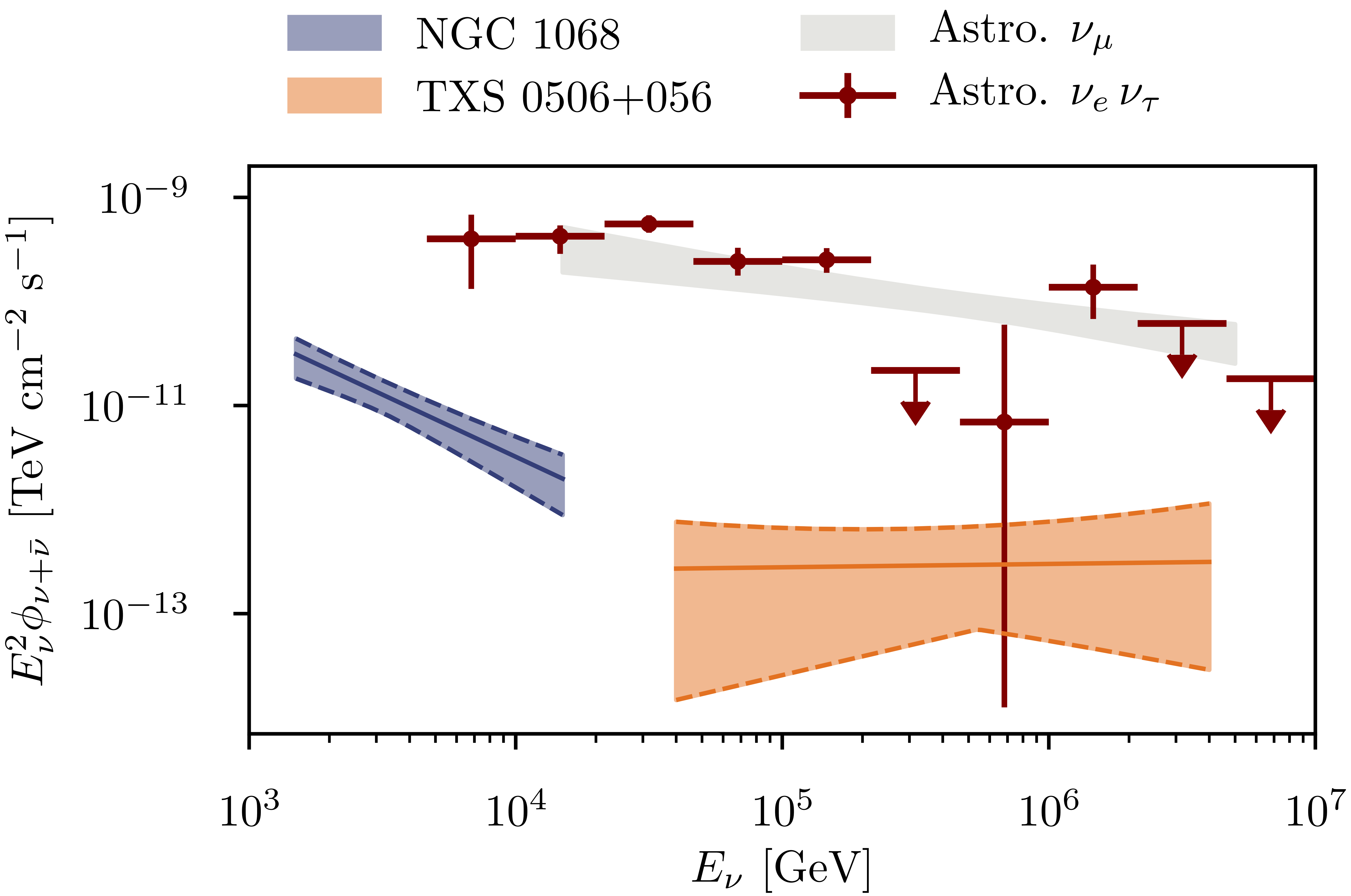




Abbasi et al. (IceCube) Science 378, 538 (2022)

Point Sources

These sources contribute no more than $\sim 1\,\%$ to the total diffuse flux measured.

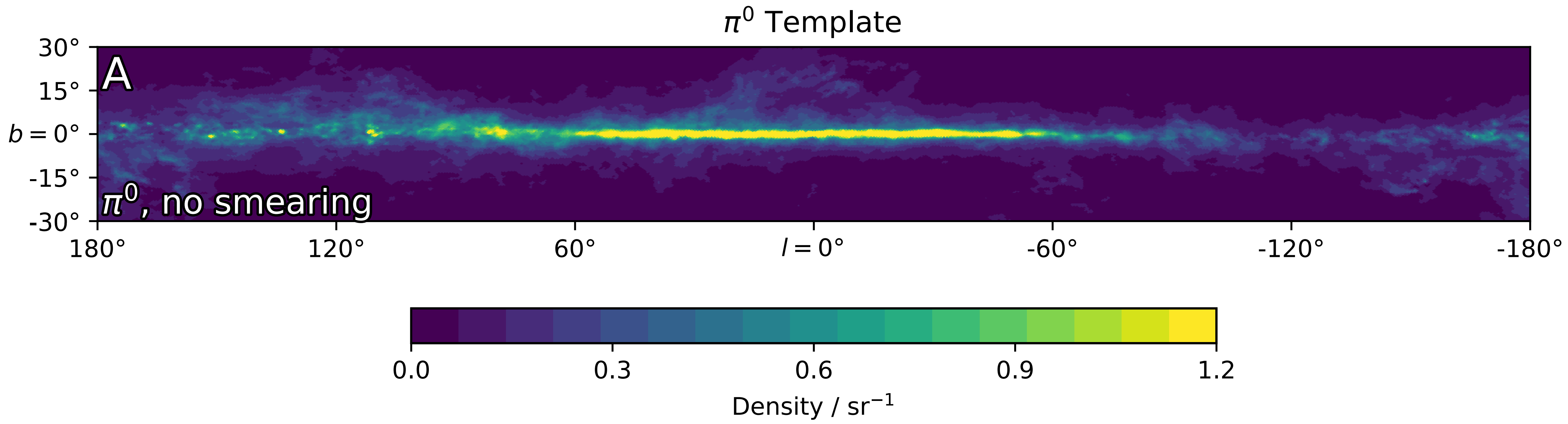


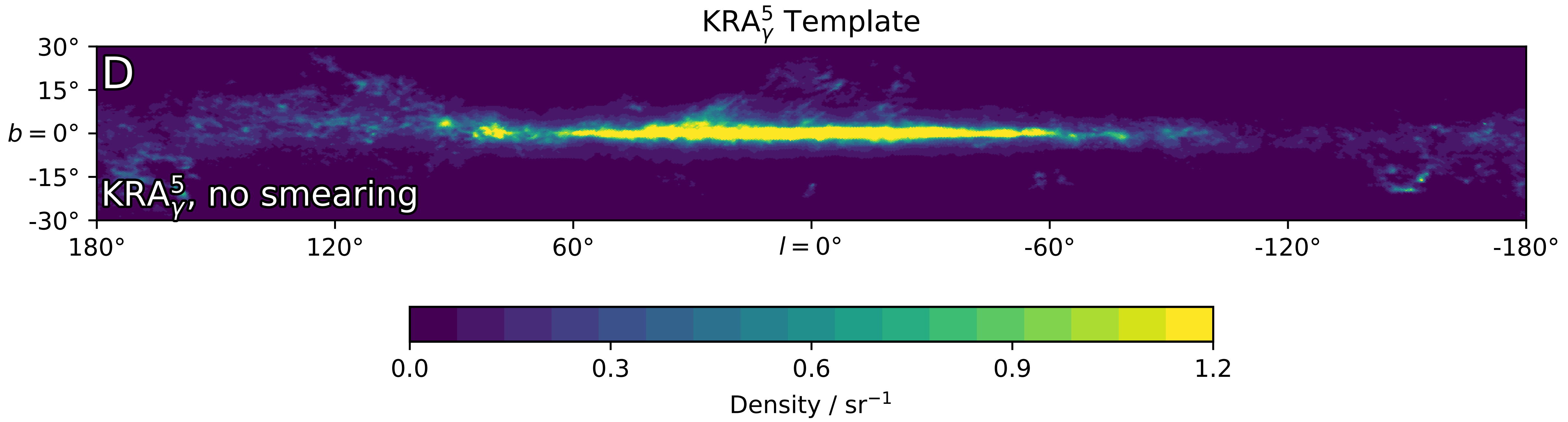
Abbasi et al. (IceCube) Science 378, 538 (2022)

Galactic Plane

- The highest neutrino production in the galaxy is expected near the Galactic Center

- Three models of Galactic diffuse neutrino emission have been considered, differing in energy spectrum and emission location.

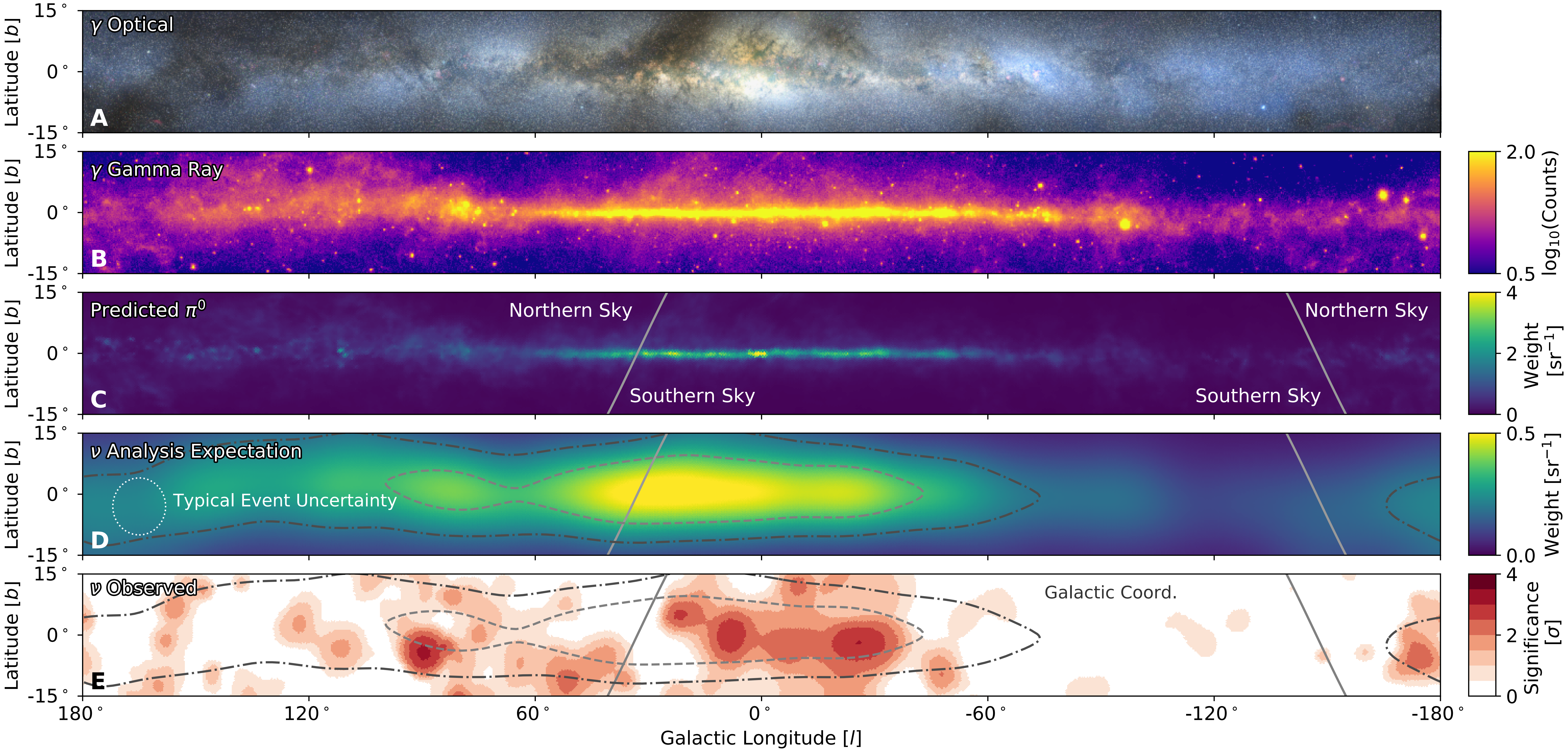




IceCube, Science 380 (2023) 1338

Galactic Plane

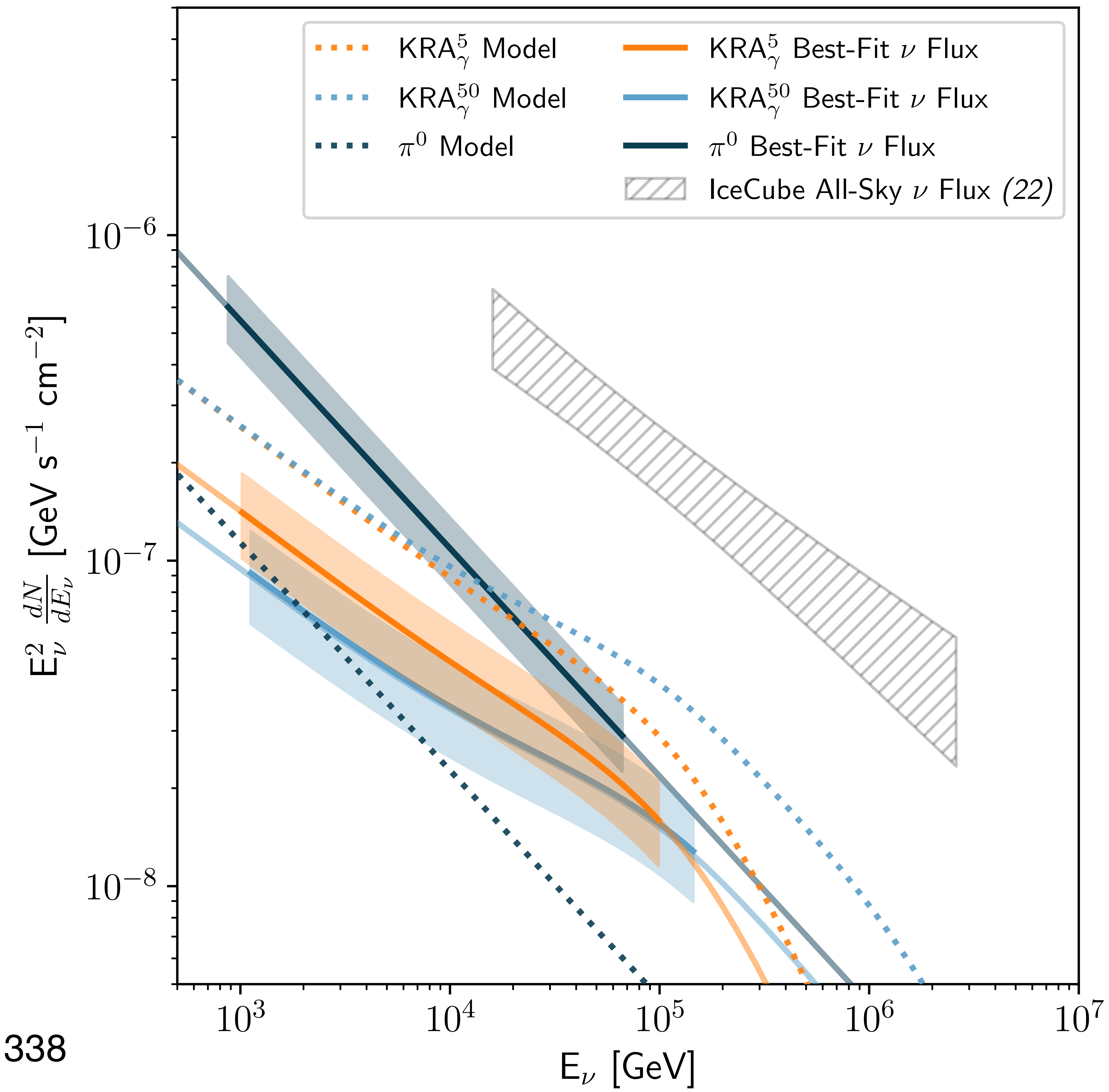
The larger neutrino production in the galaxy can be expected in the Galactic Center



IceCube, Science 380 (2023) 1338

Galactic Plane

- Neutrino emission from the Galactic Plane is found at 4.5σ
- The flux from the galactic plane will contribute between 6-13% to the diffuse flux at 30TeV



IceCube, Science 380 (2023) 1338

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