

# **Neutrino Mass and Mixing: From Particle Physics to Astrophysics**

**Iván Martínez Soler**

**The 2026 STFC HEP Summer School**

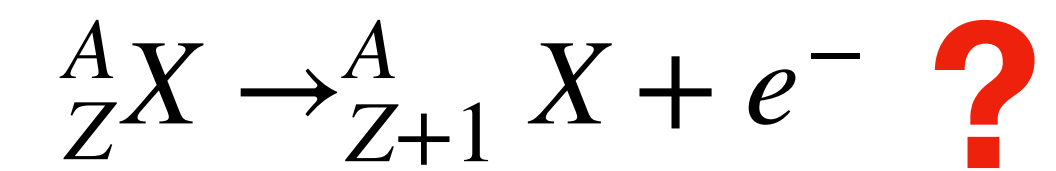
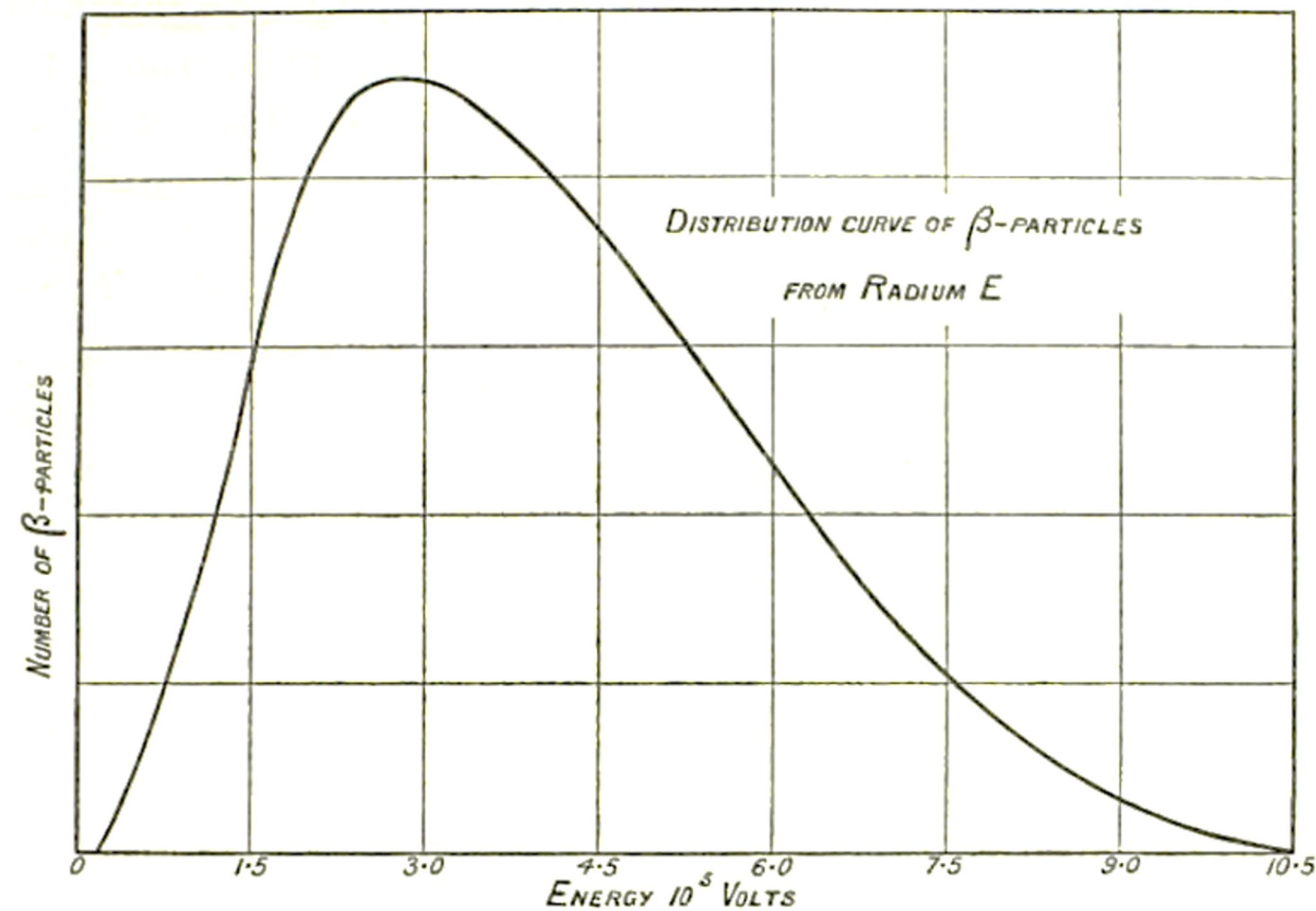
## **Content:**

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



# $\beta$ -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**



Is the energy conserved?

Original - Photocopy of PCC 0393  
Abschrift/15.12.95

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  
ansuhören 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 Grössenordnung wie die Elektronenmasse sein und  
jedemfalls 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  $\mu$  ist. Die Experimente  
verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons  
nicht grösser sein kann, als die eines gamma-Strahls und darf dann  
 $\mu$  wohl nicht grösser sein als  $e \cdot (10^{-13} \text{ cm})$ .

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.

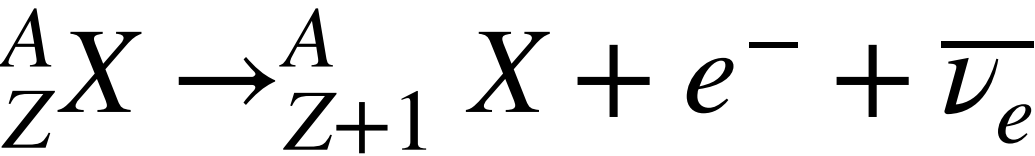
Ich gebe zu, dass mein Ausweg vielleicht von vornherein  
wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn  
sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt,  
gemut und der Ernst der Situation beim kontinuierliche beta-Spektrum  
wird durch einen Ausspruch meines verehrten Vorgängers im Amt,  
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 Baek, Euer  
untertänigster Diener

ges. 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



# Neutrinos



Pauli suggested that the new particles should have:

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

Pauli knew that it was hard to detect:

“I have done a terrible thing; I have postulated a particle that cannot be detected”

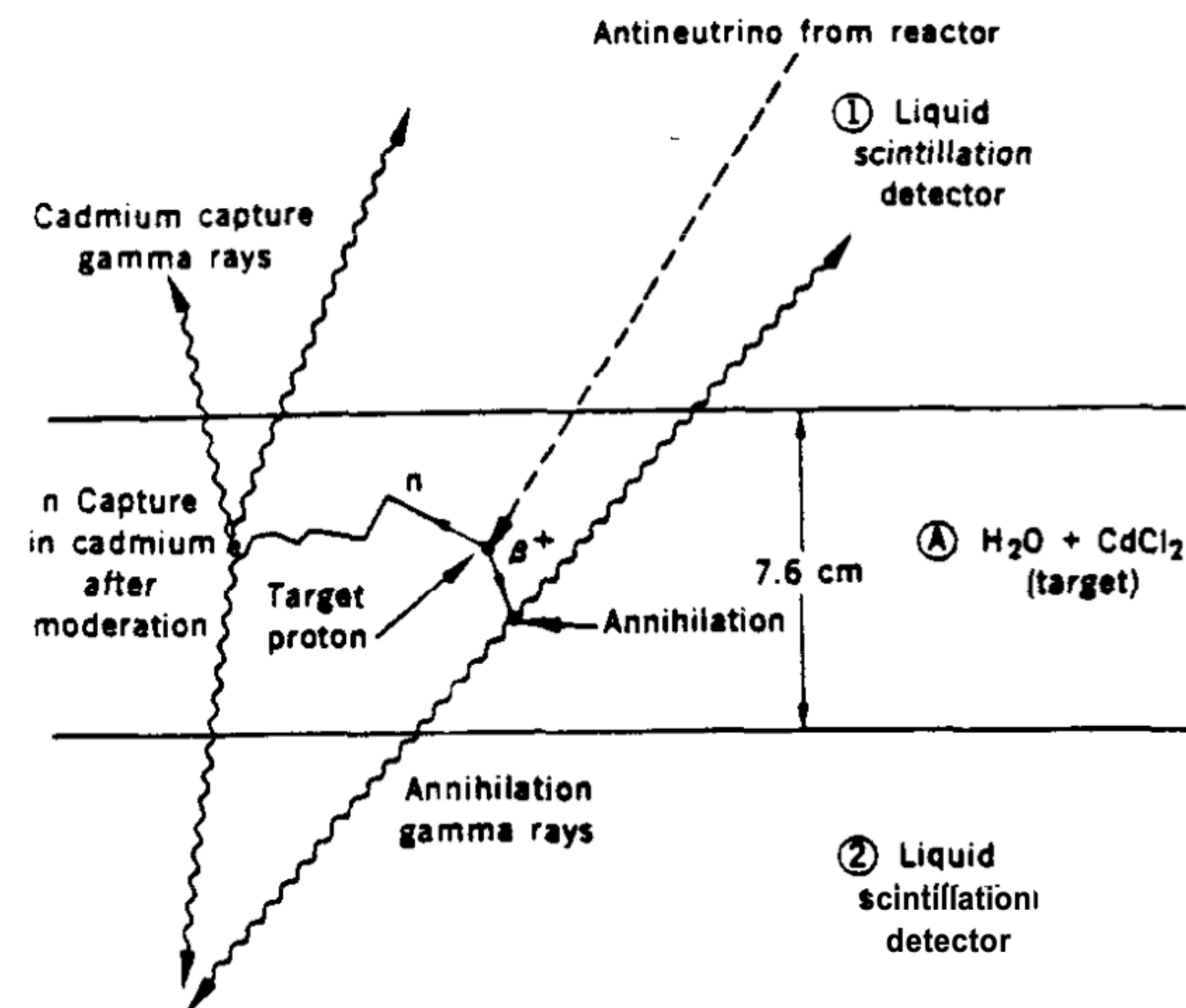


# Project Poltergeist

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



Frank Reines, Nobel lecture



# Project Poltergeist

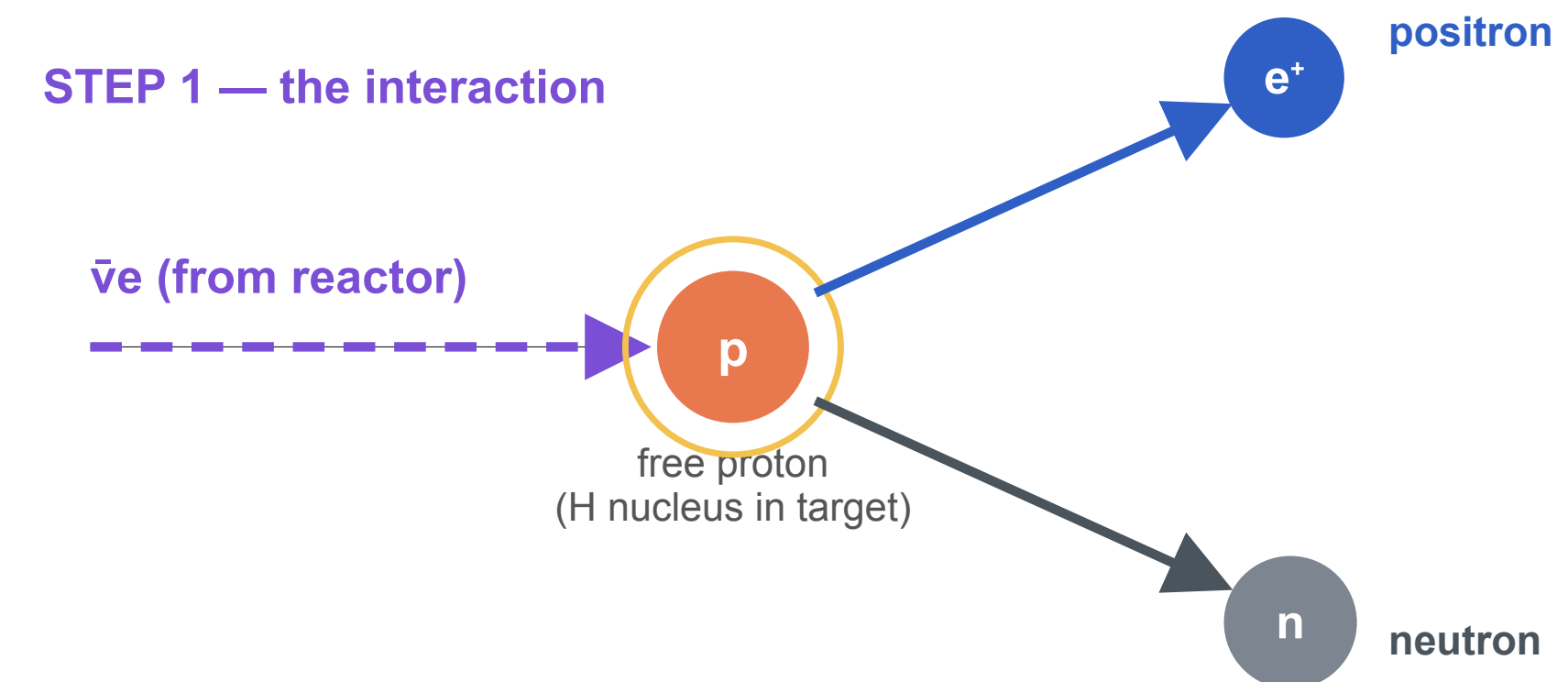
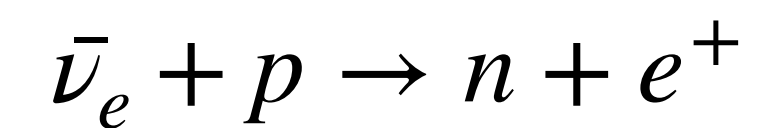
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The detection happens via **Inverse Beta Decay (IBD)**

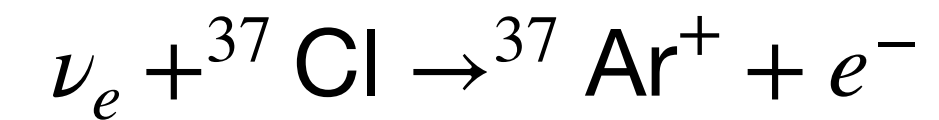




# Homestake Experiment

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

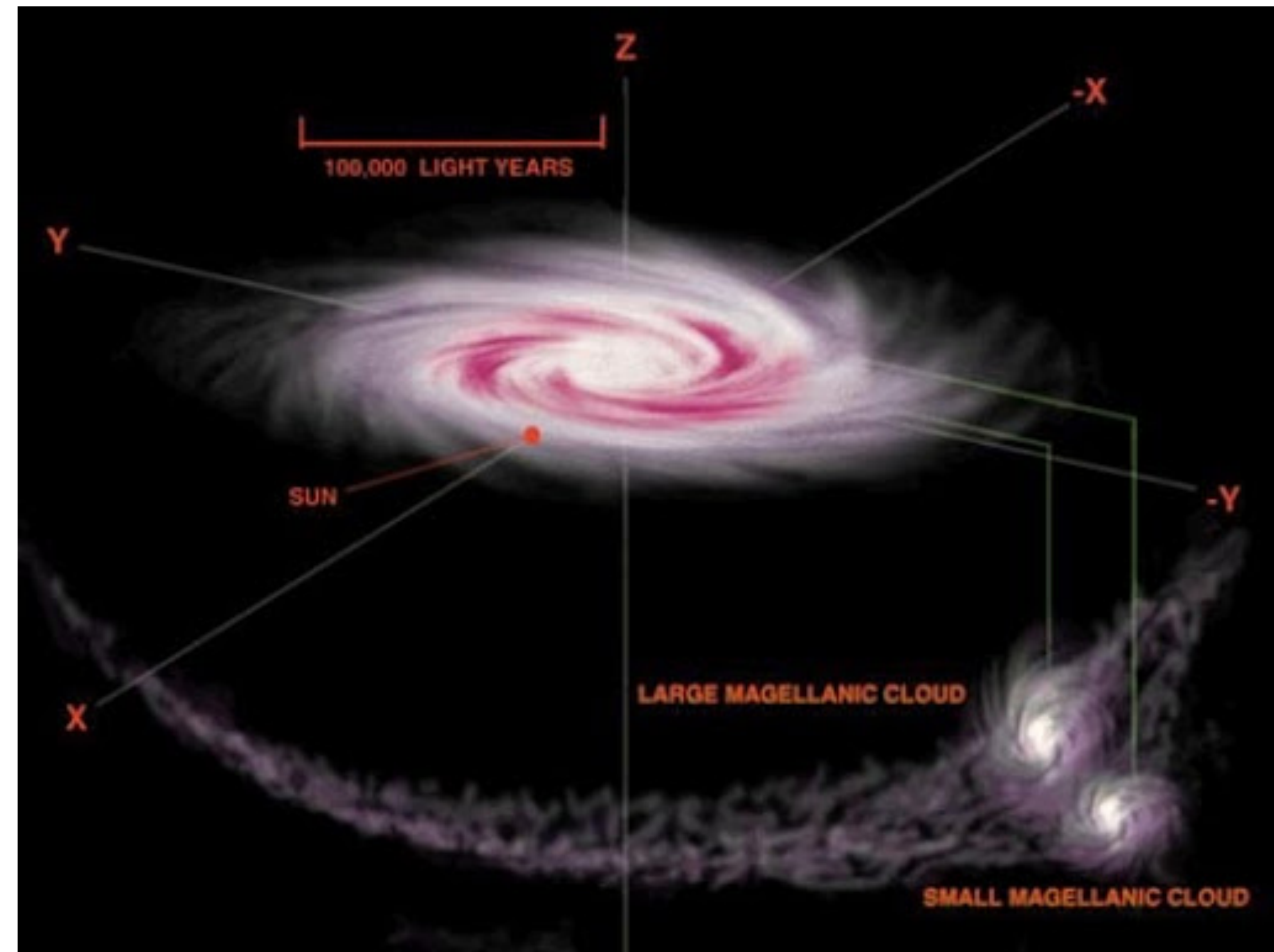


Only about a third of the expected neutrinos were detected, leading to what became known as the **solar neutrino problem**



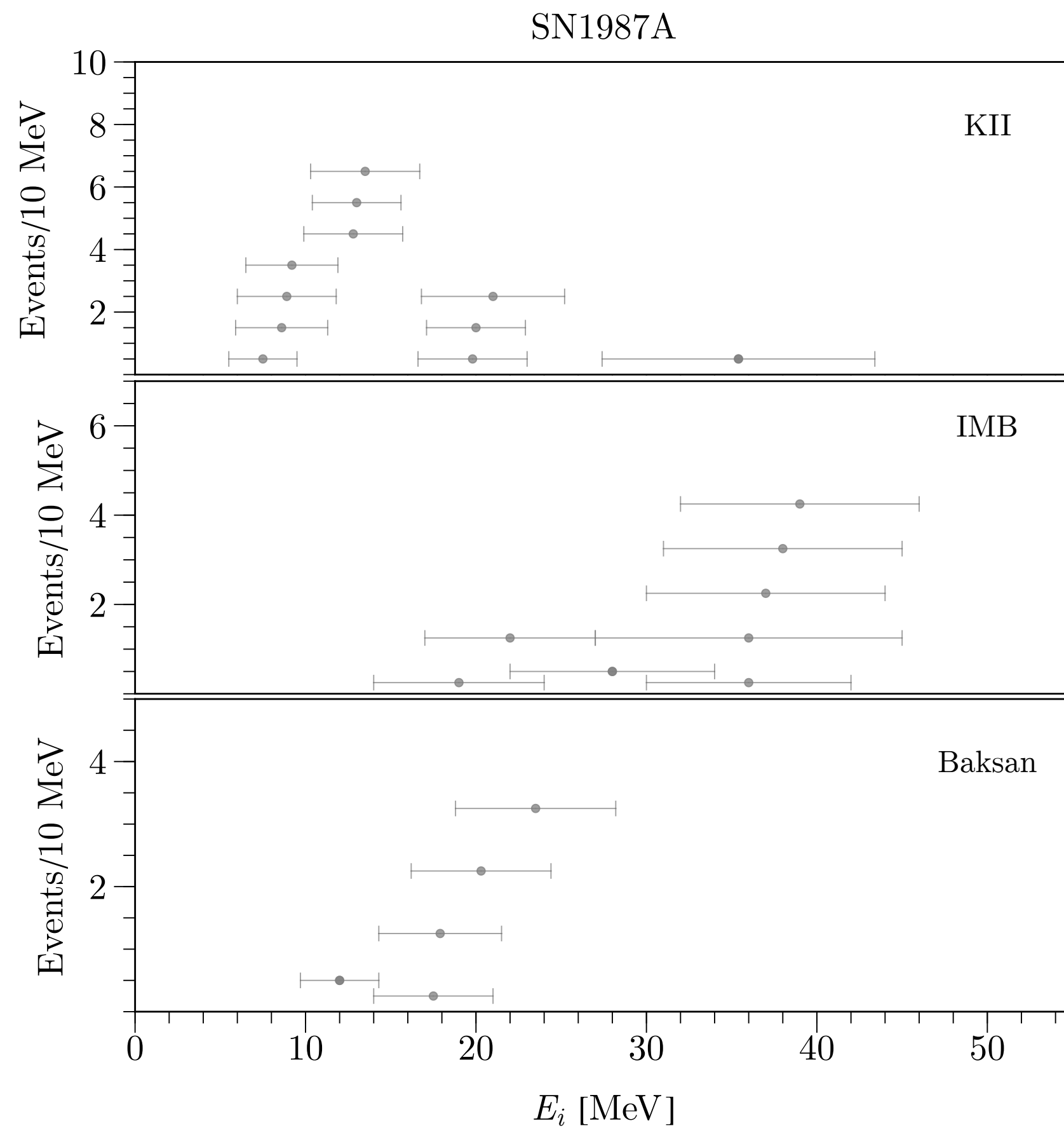
# SN 1987A

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**

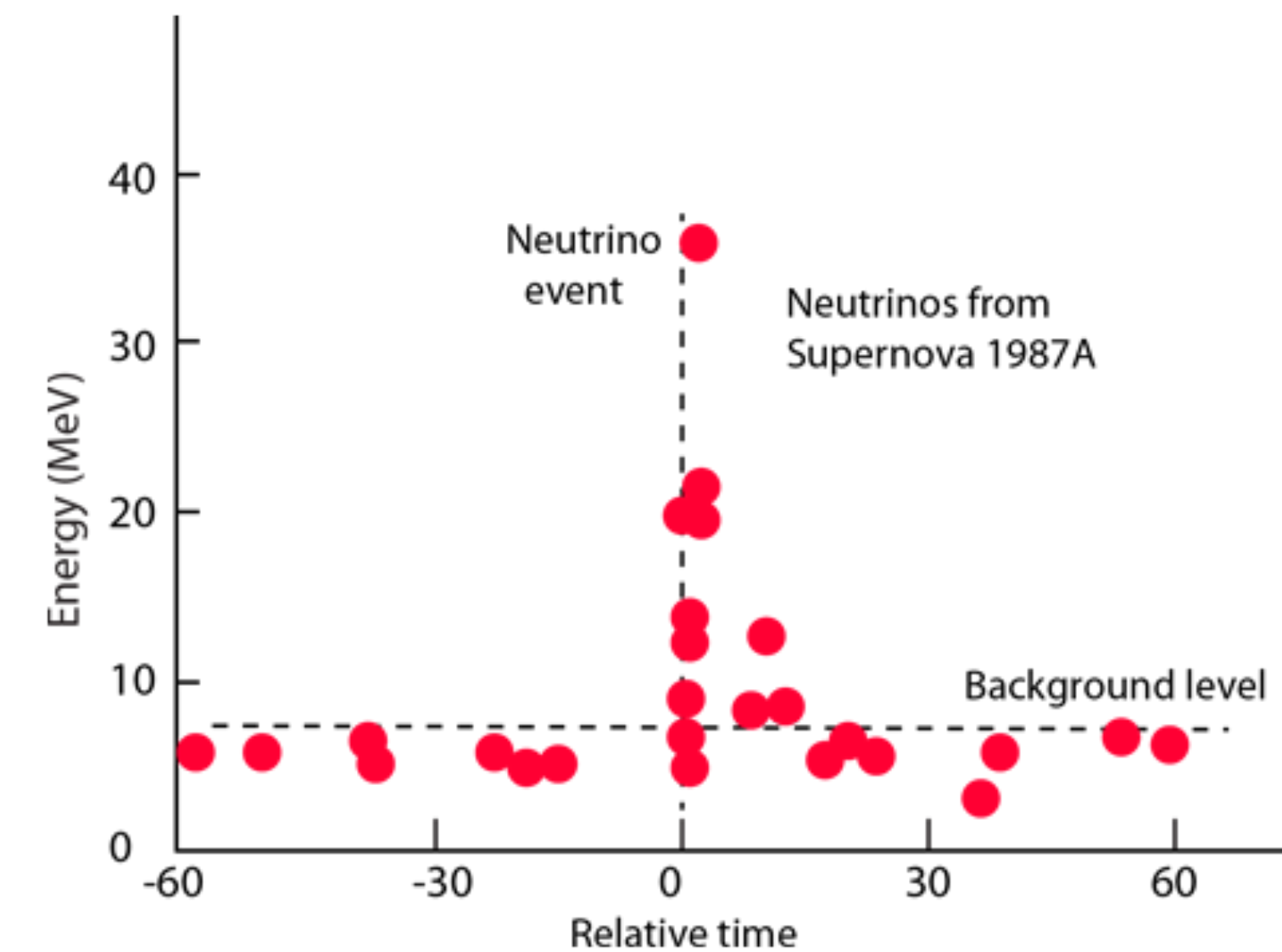
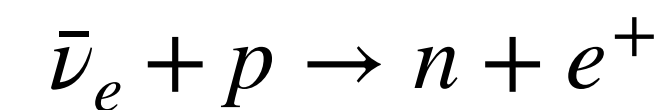


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These experiments used IBD to detect neutrinos, registering around 25 events



- Distance  $\sim 50\text{kpc}$
- Progenitor mass of  $\sim 20M_{\odot}$



# Neutrinos in the Standard Model

# $\nu$ in the Standard Model

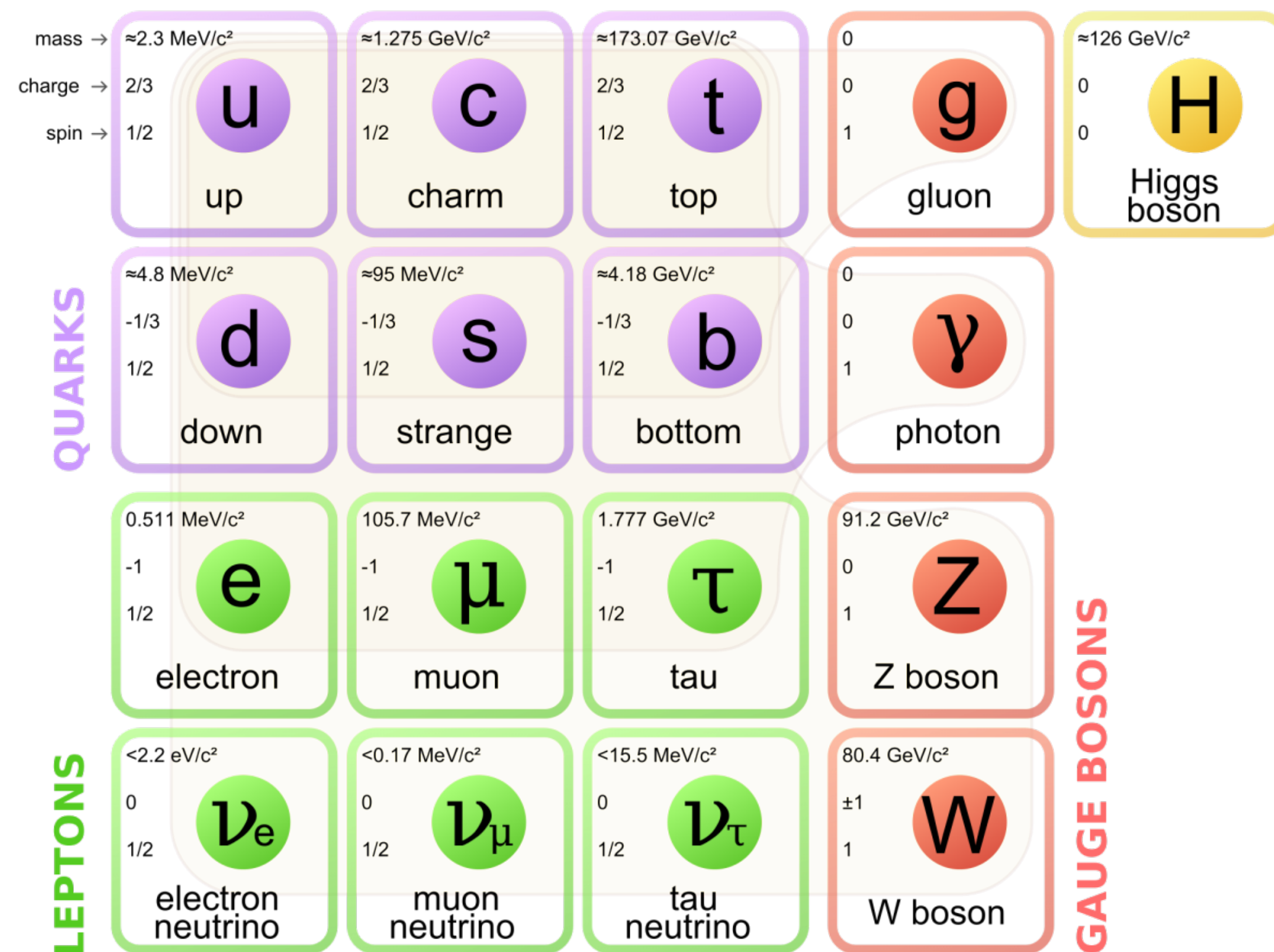
The SM is a gauge theory based on the symmetry group  $SU(3)_C \times SU(2)_L \times U(1)_Y$



# $\nu$ 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 symmetries

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

$$(L = L_e + L_\mu + L_\tau)$$

# $\nu$ in the Standard Model

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

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

- 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



# $\nu$ in the Standard Model

All fermions have a well-defined **chirality**. They are left (right)-handed fields, if the eigenvalue of  $\gamma_5$  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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A spinor can be splitted into its left/right-handed components using the projection matrices

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

They are two-component spinors (Weyl fermions)

There is no right-handed neutrinos in the SM!!!

# $\nu$ in the Standard Model

The Hamiltonian for a massive fermion is given

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

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 ( $\vec{J} = \vec{S} + \vec{L}$ )

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

Neither the total angular momentum and the chirality can be used to characterize a massive particle together with its energy and momentum



# $\nu$ in the Standard Model

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

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

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

# $\nu$ 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

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

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

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

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

# $\nu$ 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  $\gamma$  rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with  $\text{Eu}^{152m}$ , which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,<sup>1</sup>  $0^-$ , we find that the neutrino is “left-handed,” i.e.,  $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$  (negative helicity).

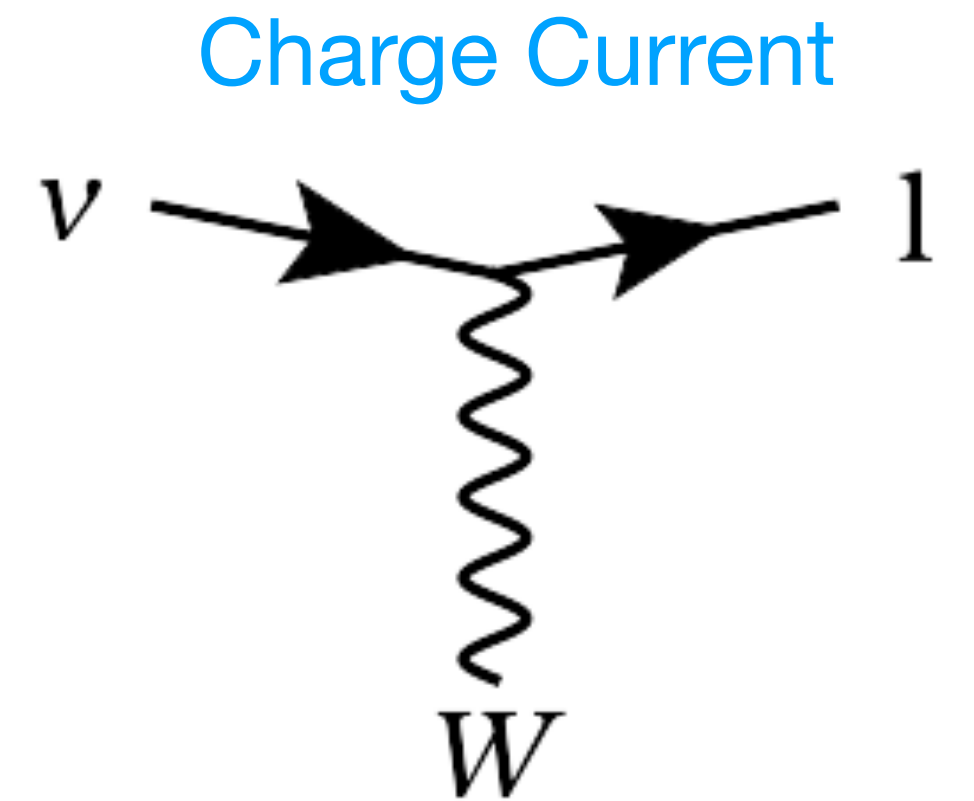


# $\nu$ in the Standard Model

In the SM, neutrinos interact via the weak force

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

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{\alpha} \bar{\nu}_{\alpha} \gamma_{\mu} P_L l_{\alpha} W_{\mu}^{+}$$

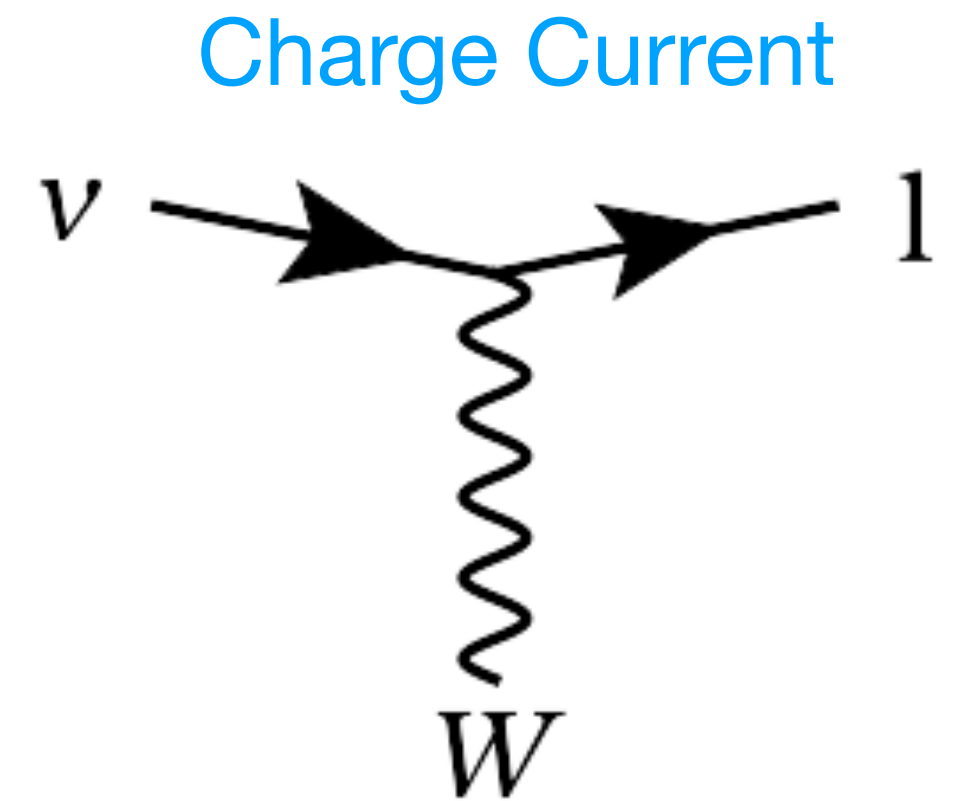


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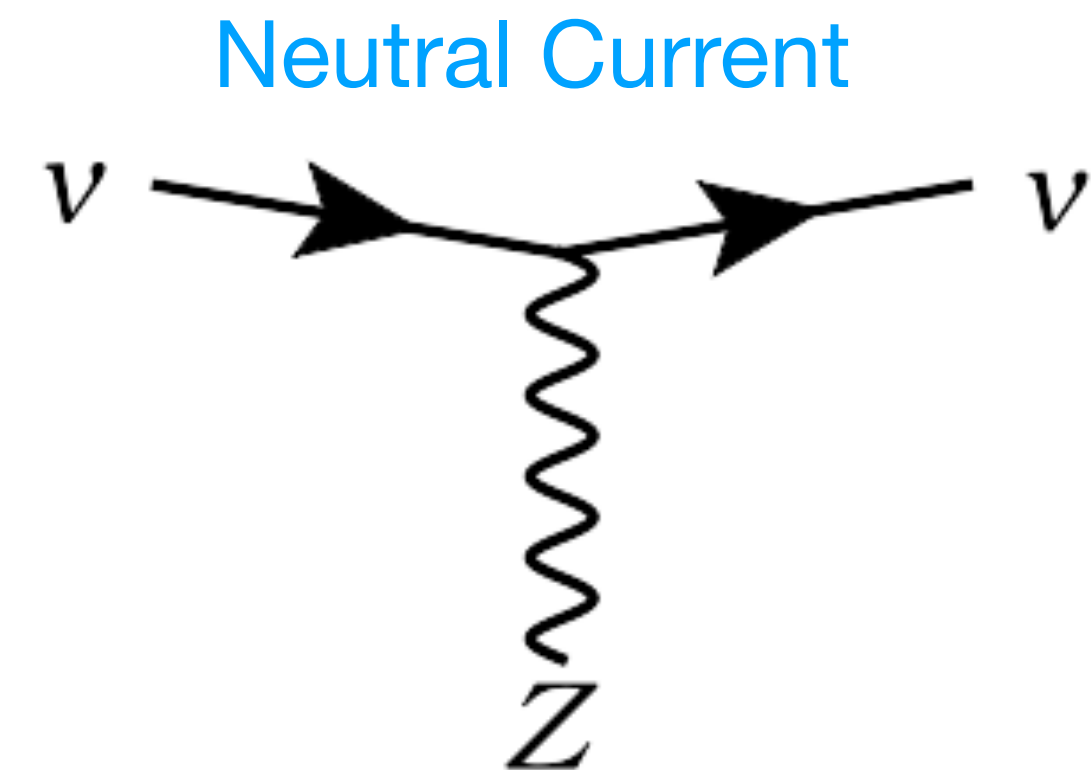
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$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{\alpha} \bar{\nu}_{\alpha} \gamma_{\mu} P_L l_{\alpha} W_{\mu}^{+}$$



Neutrinos also carry **neutral current** interactions

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



# $\nu$ in the Standard Model

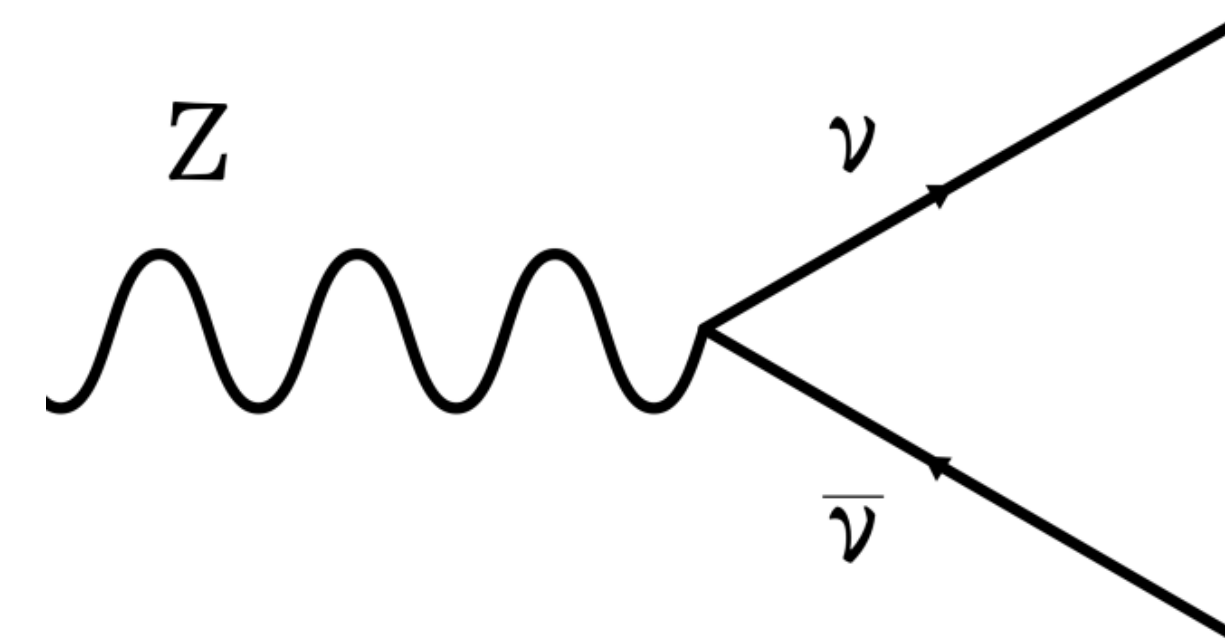
The **number of active neutrinos** was measured by studying the decay width of the Z-boson into invisible particles

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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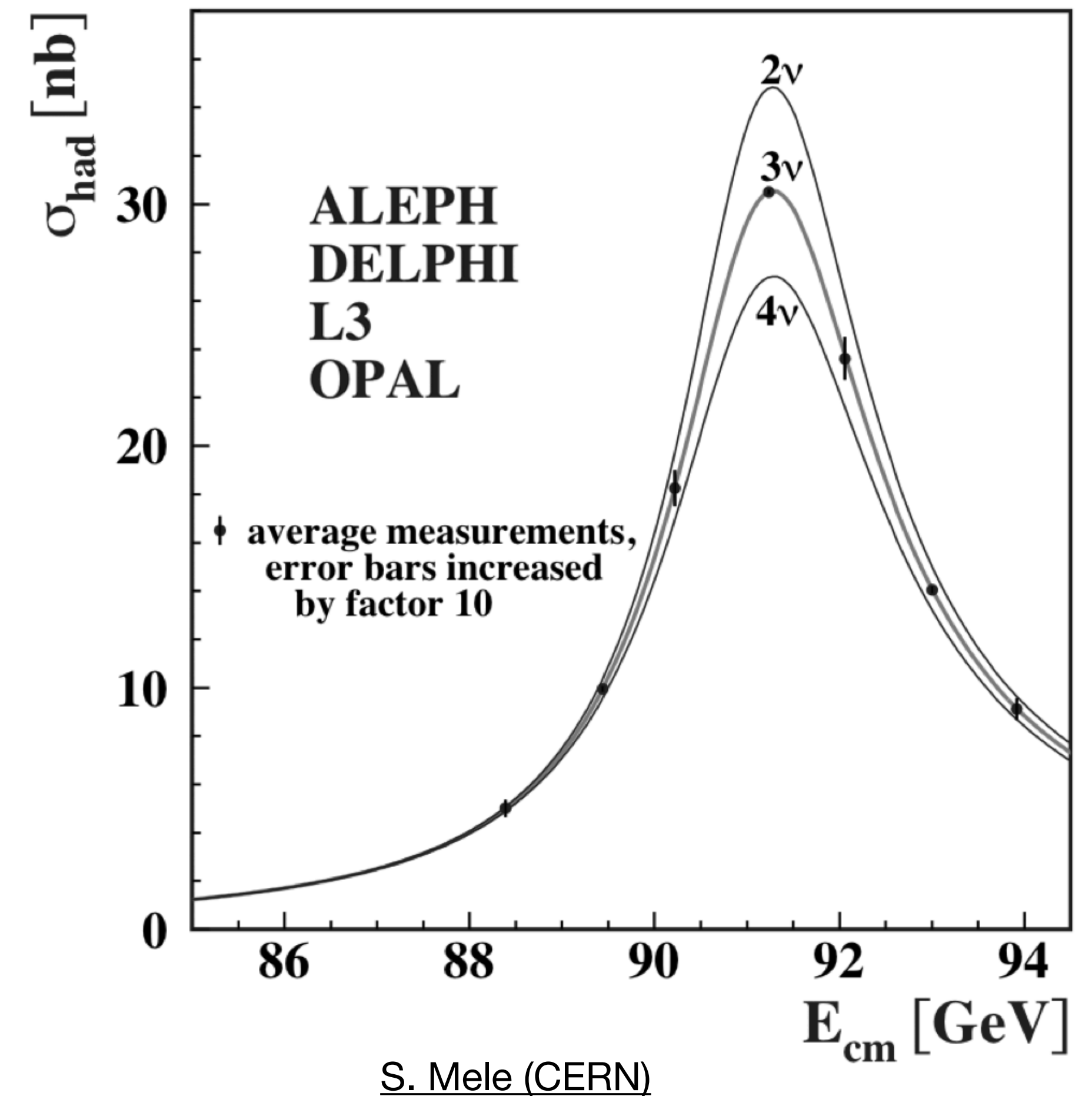
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The number of neutrinos is given by

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

The measurements showed

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



# $\nu$ in the Standard Model

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

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

$$\mathcal{L}_Y = Y_{ij} \bar{L}_{iL} E_{Rj} \phi + \text{h.c.}$$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$



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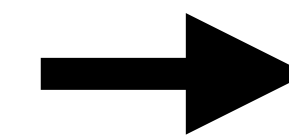
$$\mathcal{L}_Y = Y_{ij} \bar{L}_{iL} E_{Rj} \phi + \text{h.c.}$$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

After the SSB

$$\phi = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_m = \frac{Yv}{\sqrt{2}} \bar{E}_L E_R + \text{h.c.}$$

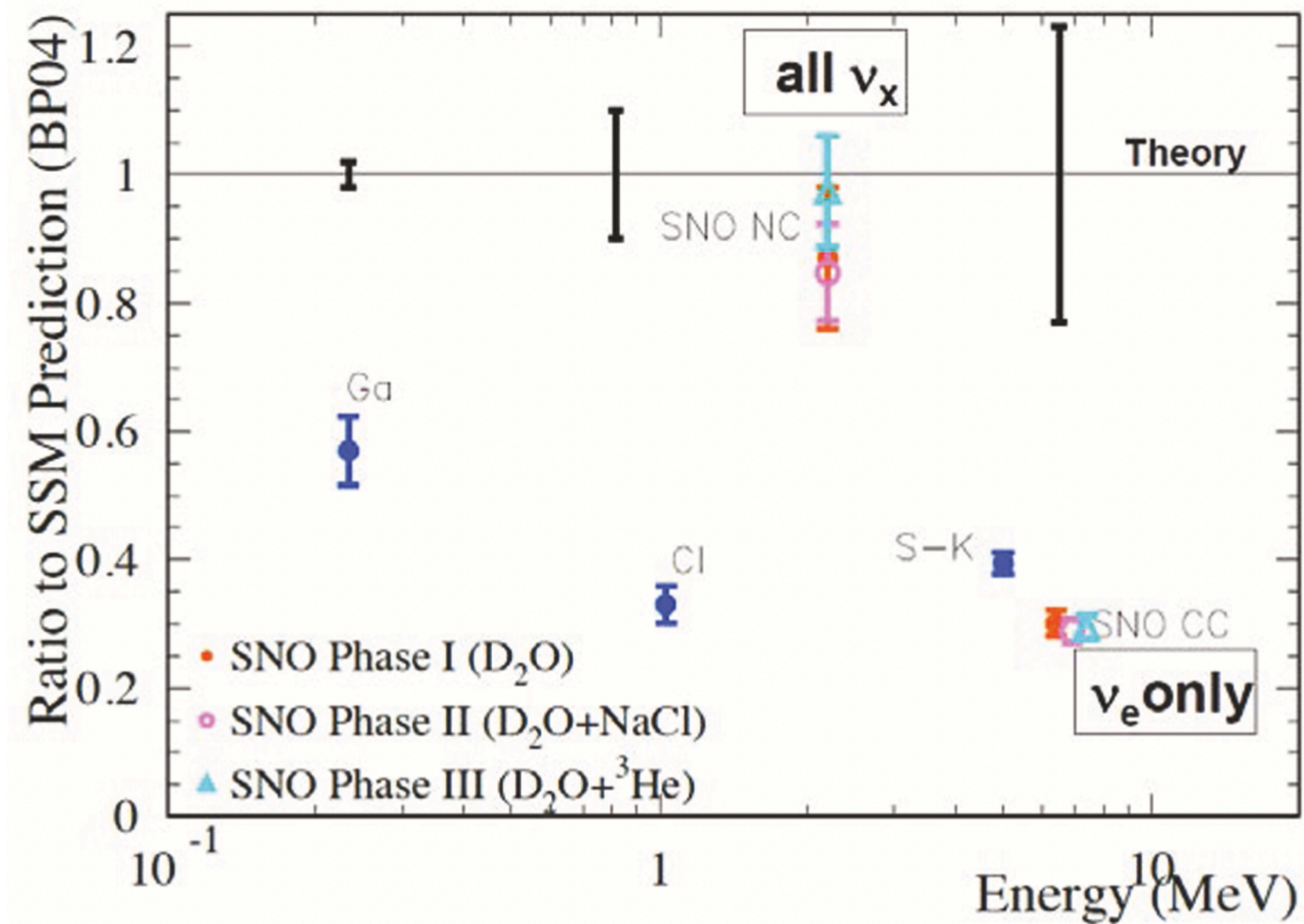


**Neutrinos are massless in the SM!!!**

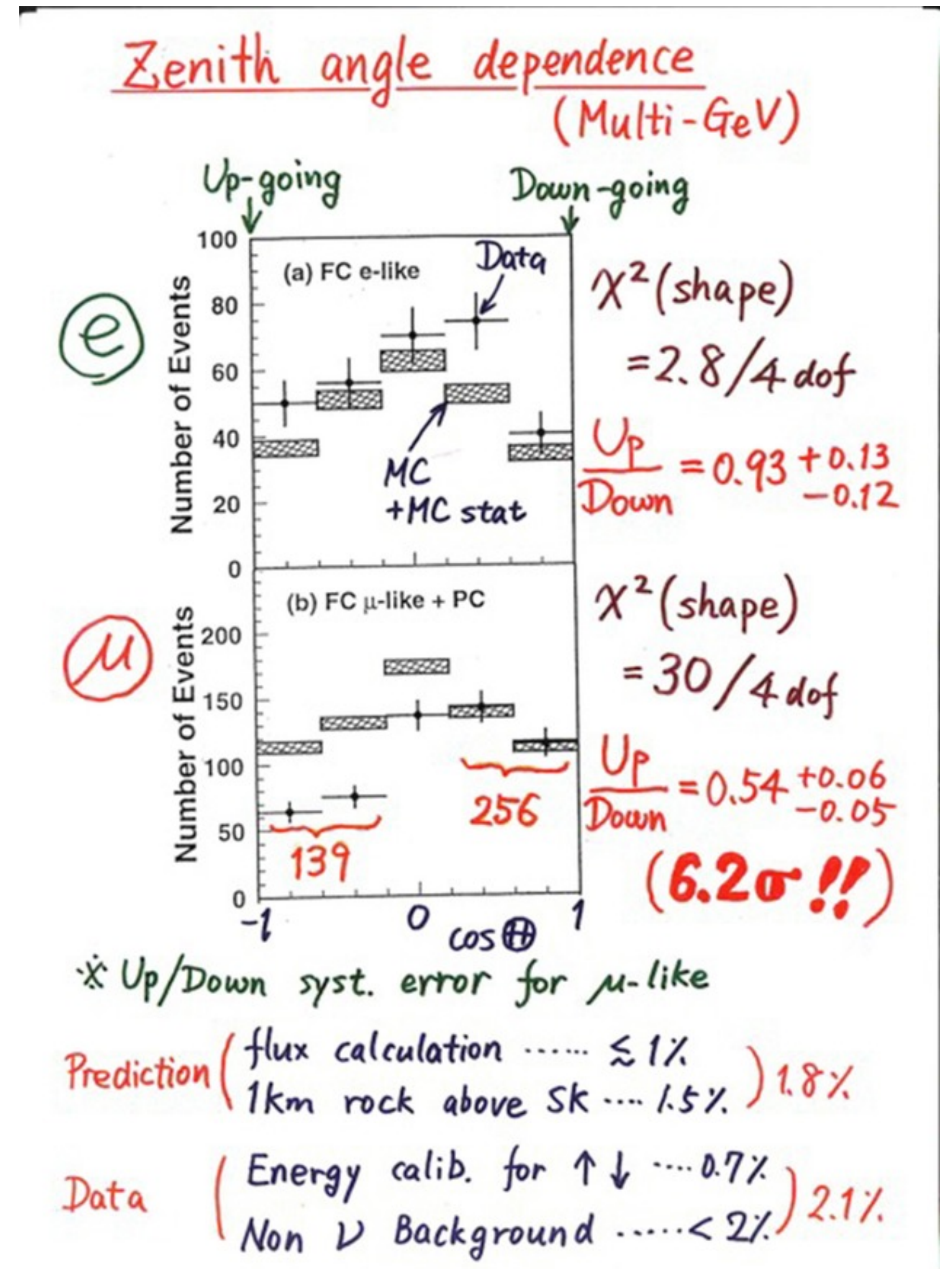


# BSM in the $\nu$ Sector

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



Arthur MacDonald. Nobel lecture

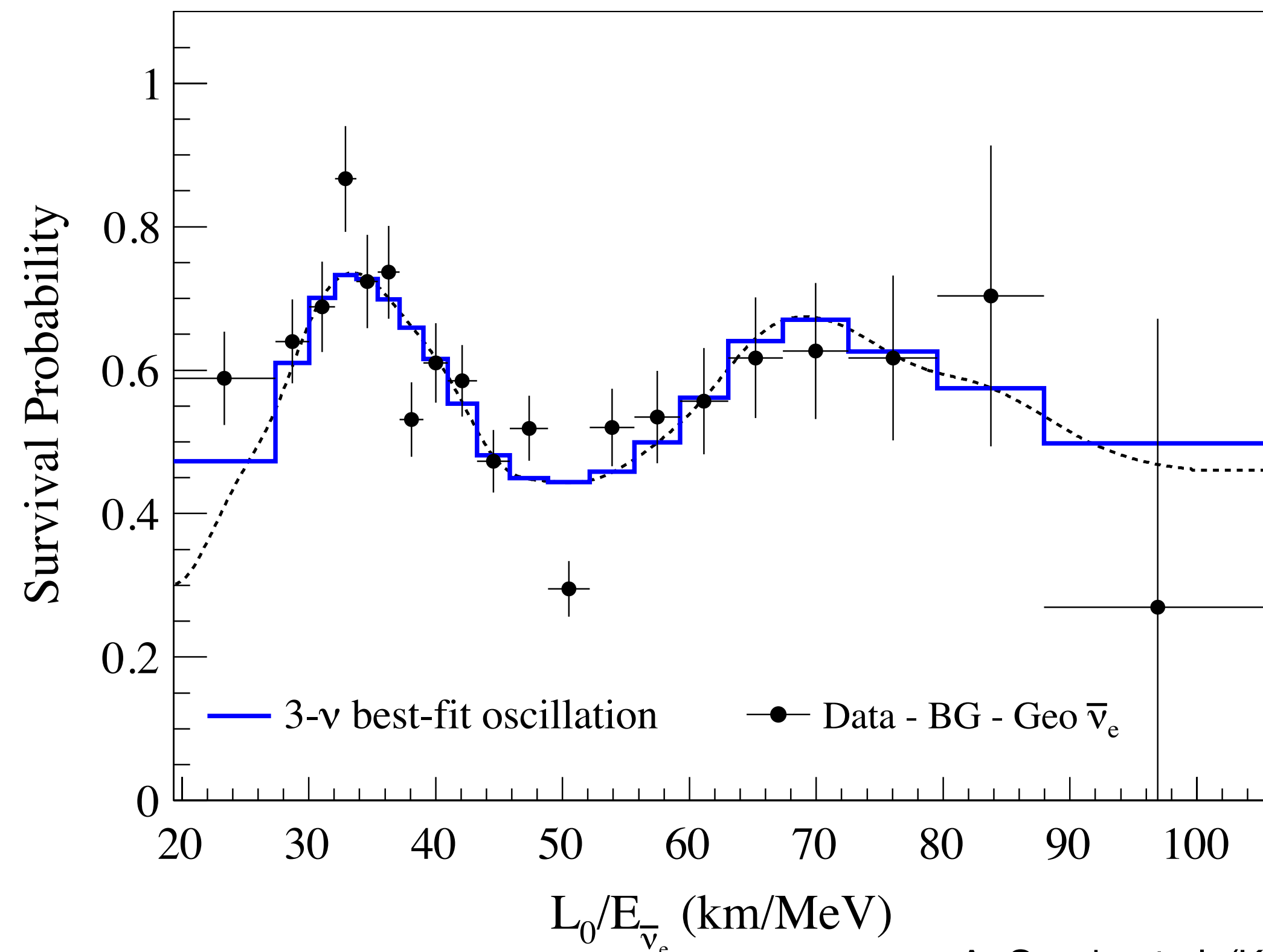


Takaaki Kajita (Super-kamiokande) Neutrino 98



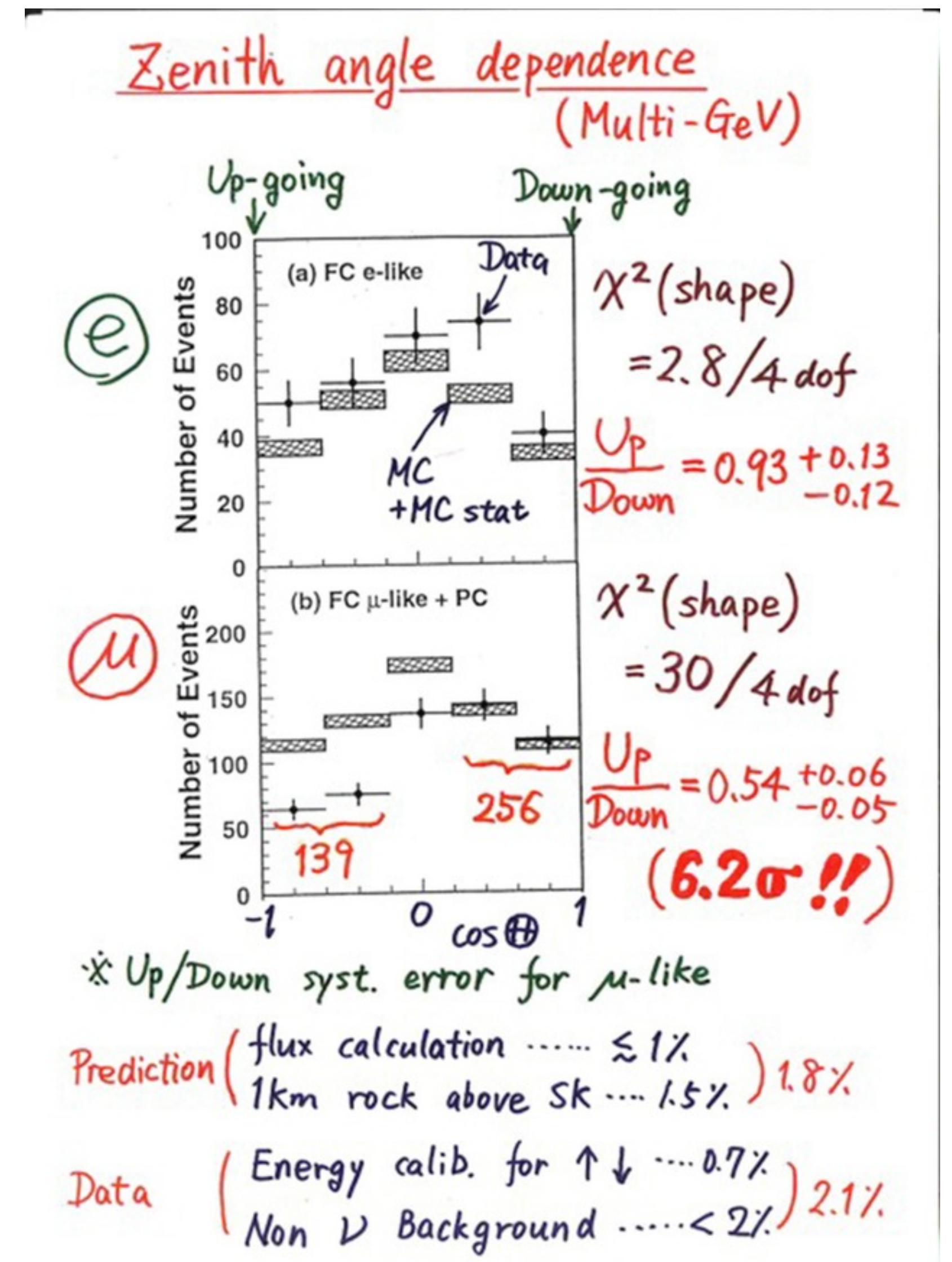
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A. Gando et al. (KamLAND) PRD 88 (2013)

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



Takaaki Kajita (Super-kamiokande) Neutrino 98

# $\nu$ 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 ( $\nu_R$ )

$$\mathcal{L}_{mass} \supset \bar{\nu} m_D \nu = \bar{\nu}_L \nu_R m_D + \text{h.c.}$$



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

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



# $\nu$ are Massive Particles

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$$\mathcal{L}_{mass} \supset \bar{\nu} m_D \nu = \bar{\nu}_L \nu_R m_D + \text{h.c.}$$

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

$$\nu \rightarrow e^{i\alpha} \nu \quad \bar{\nu} \rightarrow e^{-i\alpha} \bar{\nu}$$

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



# $\nu$ are Massive Particles

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- We can build a mass term for the neutrinos using only left-handed fields

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

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- A Majorana fermion is described by two chiral fields,  $\nu, \nu^C$



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

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

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

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

$$\nu \rightarrow e^{i\alpha} \nu \quad \nu^C \rightarrow e^{-i\alpha} \nu^C \quad \overline{\nu^C} \rightarrow e^{i\alpha} \overline{\nu^C}$$

The Majorana mass term **violates the U(1) symmetry**

$$\mathcal{L}_{mass} \rightarrow e^{i2\alpha} \mathcal{L}_{mass}$$

# $\nu$ are Massive Particles

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

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

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After the spontaneous symmetry breaking,  
we recover the Majorana mass term



$$\tilde{\phi} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$$

$$\mathcal{L}_{mass} \supset \frac{Yv^2}{2\Lambda} \bar{\nu}_L C^\dagger \nu_L + \text{h.c.}$$



# $\nu$ are Massive Particles

In the presence of  $\nu_L$  and  $\nu_R$ , we can have a Dirac and a Majorana mass term

$$\mathcal{L}_{D+M} = -\bar{\nu}_L \nu_R m_D + \frac{1}{2} \bar{\nu}_R C^\dagger \nu_R m_M + \text{h.c.}$$



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Defining  $N_L = \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix} \longrightarrow \mathcal{L}_{D+M} = \frac{1}{2} \bar{N}_L^C \mathcal{M} N_L$

The mass matrix is given by

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

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

# $\nu$ Mixing

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

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

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

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- $\mathcal{M}_{\nu}$  and  $\mathcal{M}_l$  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

$$\text{diag}(m_e, m_{\mu}, m_{\tau}) = V_L^{l\dagger} \mathcal{M}_l V_R^l$$

$$l_{L/R}^m = V_{L/R}^{l\dagger} l_{L/R}$$

Where  $V_{L/R}^l$  is a 3x3 unitary matrix

$$\text{diag}(m_1, m_2, \dots, m_n) = V^{\nu\dagger} \mathcal{M}_{\nu} V^{\nu}$$

$$N_L^m = V^{\nu\dagger} N_L$$

Where  $V^{\nu}$  is a 3xn unitary matrix

- n is the number of massive neutrinos



# $\nu$ Mixing

Changing to the mass basis, we get

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \overline{N}_{jL}^m (V^{\dagger\nu} V_L^l)_{ij} \gamma_\mu l_{iL}^m W_\mu^+ + \text{h.c.}$$

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



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$$U_{PMNS} = V_L^{\dagger l} V^\nu \quad U_{PMNS} \text{ is a } 3 \times n \text{ mixing matrix}$$

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 differ only in the  
number of phases

# $\nu$ Mixing

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

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

In the case of **Majorana** neutrinos

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

Majorana phases cannot be measured in oscillation experiments

# Dirac vs Majorana

## Dirac ( $\nu \neq \bar{\nu}$ )

Conserves lepton number

Requires an additional field ( $\nu_R$ )

Four chiral fields are needed

One Phase in the mixing matrix

## Majorana ( $\nu = \bar{\nu}$ )

Lepton number violated

No need for extra fields

Two chiral fields are needed

Three phases in the mixing matrix



# Neutrino Oscillations

# $\nu$ Mixing

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

$$|\nu_\alpha\rangle = \sum U_{\alpha i}^\dagger |\nu_i\rangle$$

$\nu_i$  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

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

$$\mathcal{H} |\nu_k\rangle = E_k |\nu_k\rangle$$

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  $E = |\vec{p}|$

# Flavor Oscillation

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

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

We used the equivalence  $t \simeq x$



# Flavor Oscillation

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

$$i \frac{d|\nu_\alpha\rangle}{dx} = \left( \underbrace{E}_{\substack{\text{Global phase} \\ \text{Independent of the flavor}}} + \underbrace{U_{\alpha k}^\dagger \frac{m_k^2}{2E} U_{\beta k}}_{\substack{\text{Flavor dependent term}}} \right) |\nu_\beta\rangle$$

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

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The amplitude  $|\nu_\alpha\rangle \rightarrow |\nu_\beta\rangle$  is given by

$$A_{\alpha\beta} = \langle \nu_\beta | \nu_\alpha(x) \rangle = U_{\alpha i}^\dagger e^{iE_i x} U_{\beta i}$$

# Flavor Oscillation

The flavor oscillation probability is given by:

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

- Flavor oscillations depend on the mass difference:  $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- 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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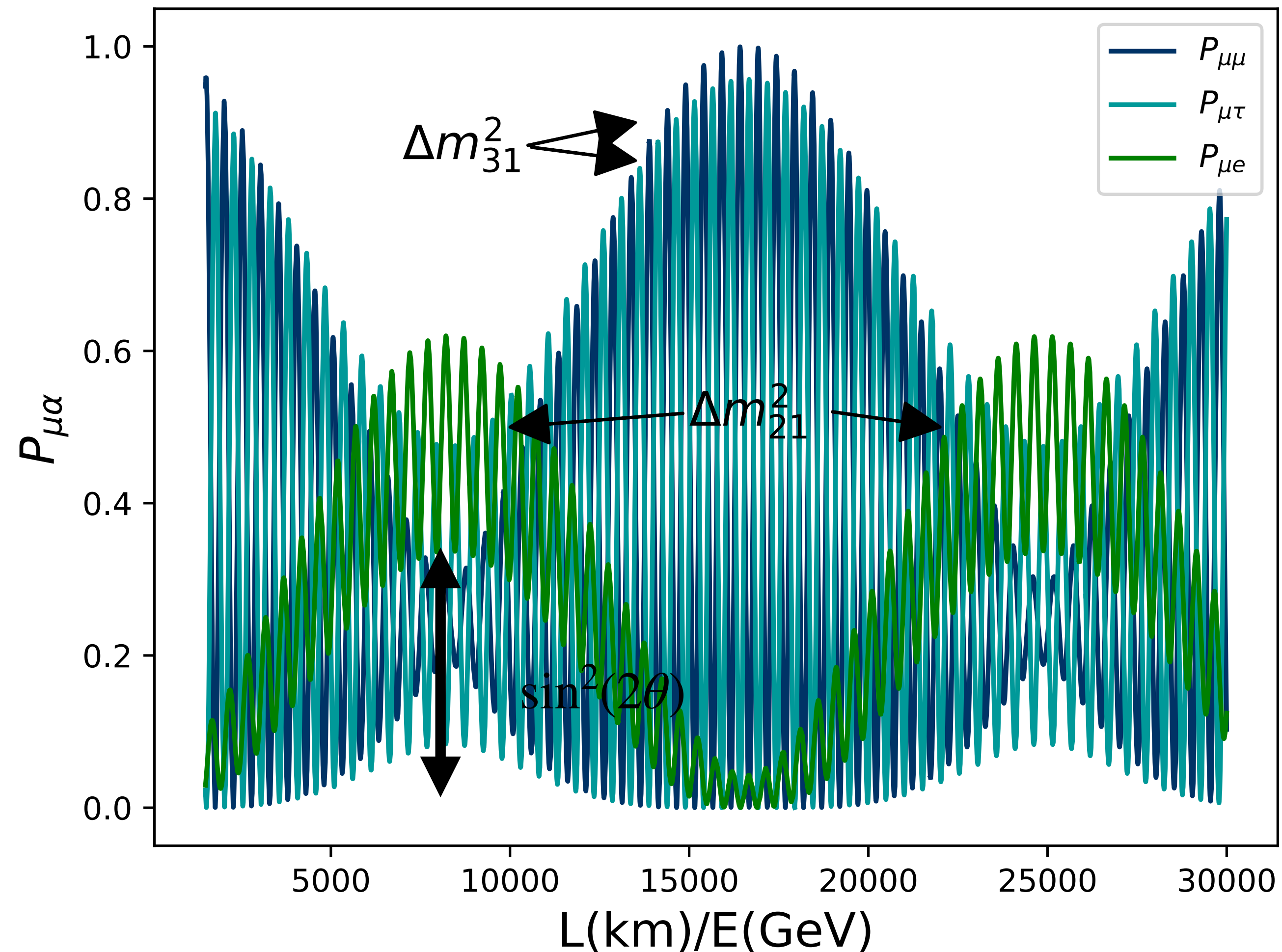
We can define the oscillation length as

$$L_{ij}^{osc} = \frac{2\pi E}{\Delta m_{ij}^2} \quad \text{For } \Delta m_{ij}^2 \sim 10^{-3} \text{eV}^2 \quad \longrightarrow \quad L^{osc} \sim 2000 \times (E/\text{GeV})\text{km}$$



# Flavor Oscillation

In the 3 neutrino mixing scenario, the oscillation probability has two oscillation wavelengths



# Flavor Oscillation

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Antineutrinos are produced in CC involving charged antileptons

$$\mathcal{L}_{CC}^{\bar{\nu}} = -\frac{g}{\sqrt{2}} \bar{l}_{iL}^m U_{ij}^{PMNS} \gamma_\mu N_{jL}^m W_\mu^-$$

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



# Flavor Oscillation

The oscillation probability can be rewritten as

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

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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

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



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- The third term has the opposite sign for  $\nu$  and  $\bar{\nu}$  if  $\delta_{CP} \neq 0, \pi$

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \quad \longrightarrow \quad \text{CP violation}$$

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- The third term has the opposite sign for  $\nu$  and  $\bar{\nu}$  if  $\delta_{CP} \neq 0, \pi$
- CP violation happens for  $\alpha \neq \beta$ . If  $\alpha = \beta \rightarrow \text{Im} \left[ U_{\alpha k} U_{\beta k}^\dagger U_{\alpha j}^\dagger U_{\beta j} \right] = \text{Im} \left[ |U_{\alpha k}|^2 |U_{\alpha j}|^2 \right] = 0$



# Flavor Oscillation

CP violation in neutrino oscillations can be probed by

$$A_{\alpha\beta}^{CP} = P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} = 4 \sum_{k>j} \text{Im} \left[ U_{\alpha k} U_{\beta k}^\dagger U_{\alpha j}^\dagger U_{\beta j} \right] \sin \left( -i \frac{\Delta m_{jk}^2 L}{2E} \right)$$

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The CP asymmetry is parametrized by the Jarlskog invariant

$$J_{CP} = \text{Im}[U_{\alpha i} U_{\alpha j}^* U_{\beta i}^* U_{\beta j}] = J_{CP}^{\max} \sin \delta_{CP} \quad \longrightarrow \quad A_{\alpha\beta}^{CP} = 4 \sum_{k>j} J_{CP}^{kj} \sin \delta_{CP} \sin \left( -i \frac{\Delta m_{jk}^2 L}{2E} \right)$$

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

$\longrightarrow$  CP violation only depends on the Dirac phase



# Flavor Oscillation

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$$A_{\alpha\beta}^{CP} = P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} = 4 \sum_{k>j} \text{Im} \left[ U_{\alpha k} U_{\beta k}^\dagger U_{\alpha j}^\dagger U_{\beta j} \right] \sin \left( -i \frac{\Delta m_{jk}^2 L}{2E} \right)$$

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.

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

# Wavepacket Description

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

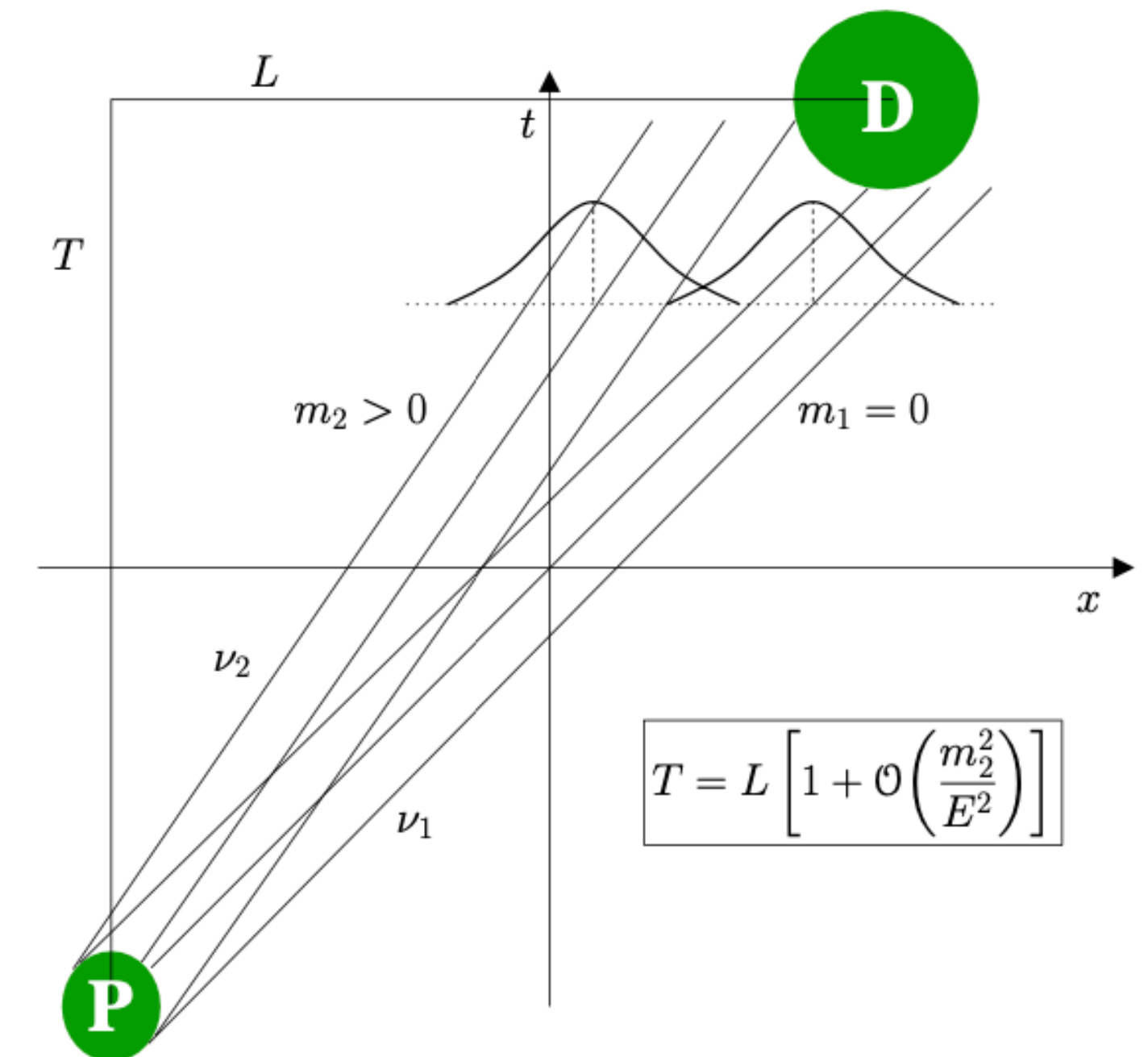


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- Considering neutrinos as **plane waves**, the mixing happens at all the points along the trajectory
- Real particles are localized objects described by **wavepackets**.
- The **oscillation stops** for small wavepackets/long distances due to the **wavepacket 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

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^\dagger \psi_k |\nu_k\rangle$$

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
- $\sigma_p$ : momentum uncertainty

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

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



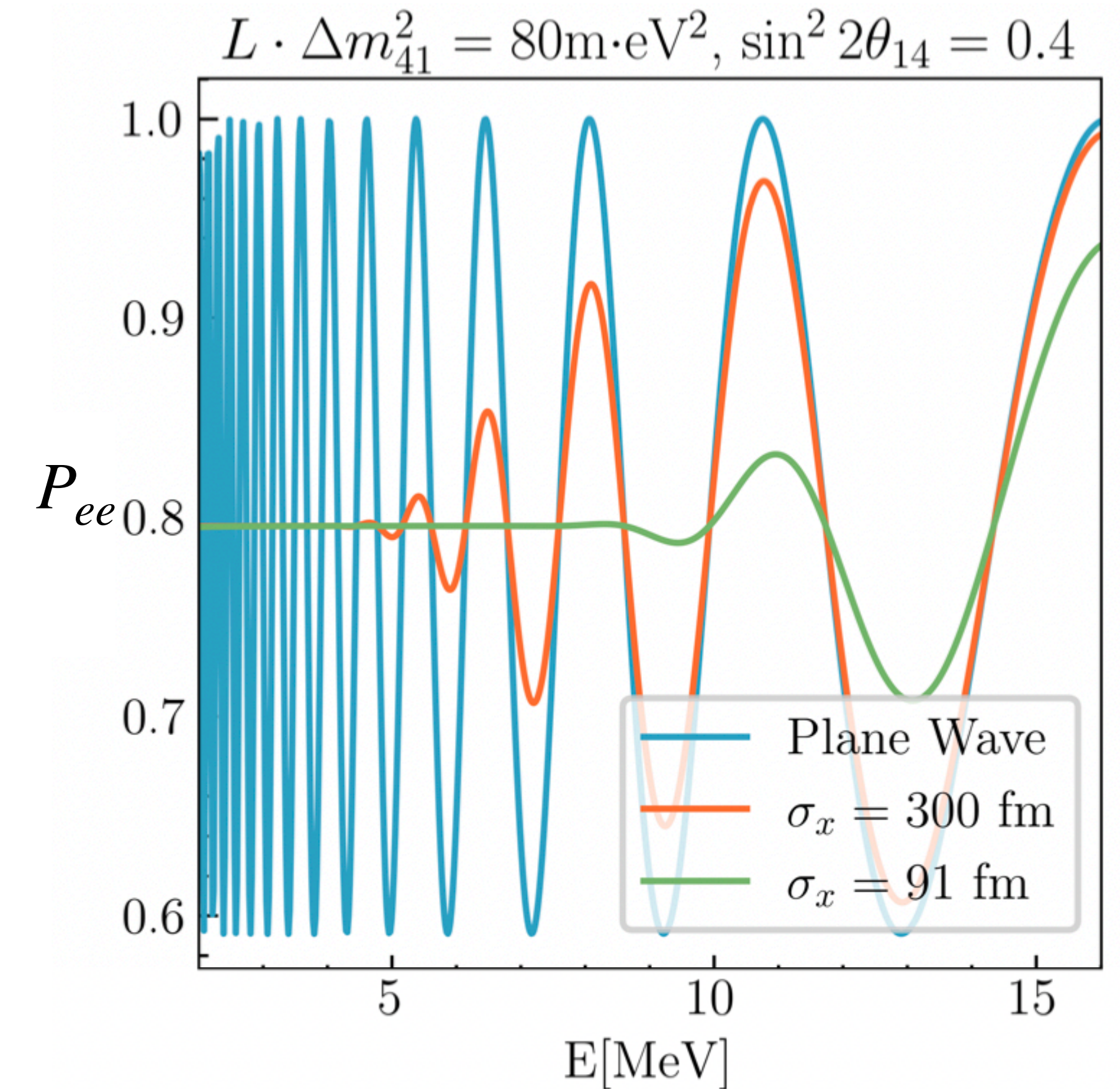
# Wavepacket Description

The wavepacket separation manifests as a damping effect in the oscillation

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

The coherence length depends on the wave packet size ( $\sigma_x$ )

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





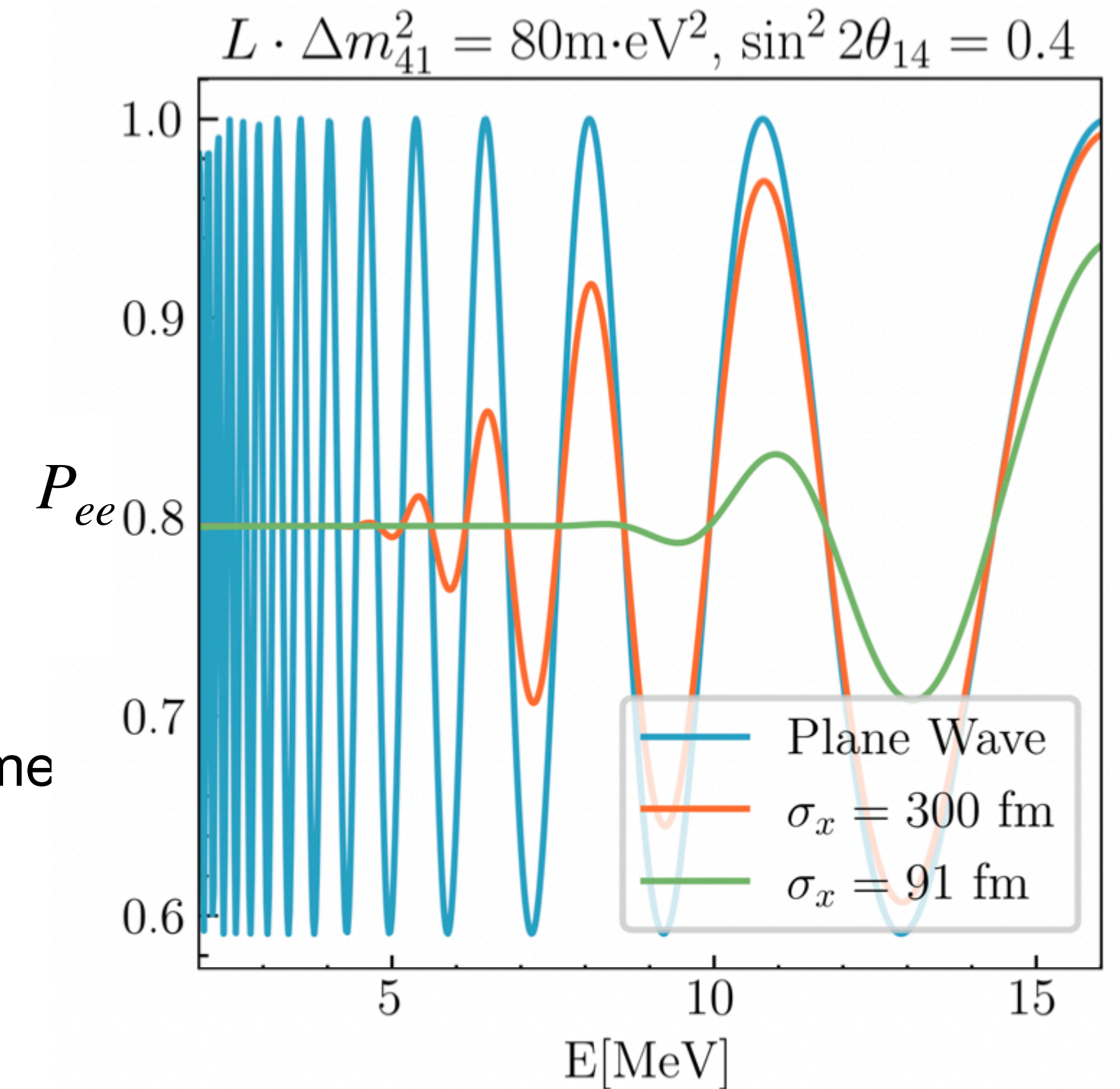
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For very long distances ( $L \gg L^{coh}$ ), the oscillation probability become an incoherent sum of states

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



# Neutrino Evolution in Matter



# 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

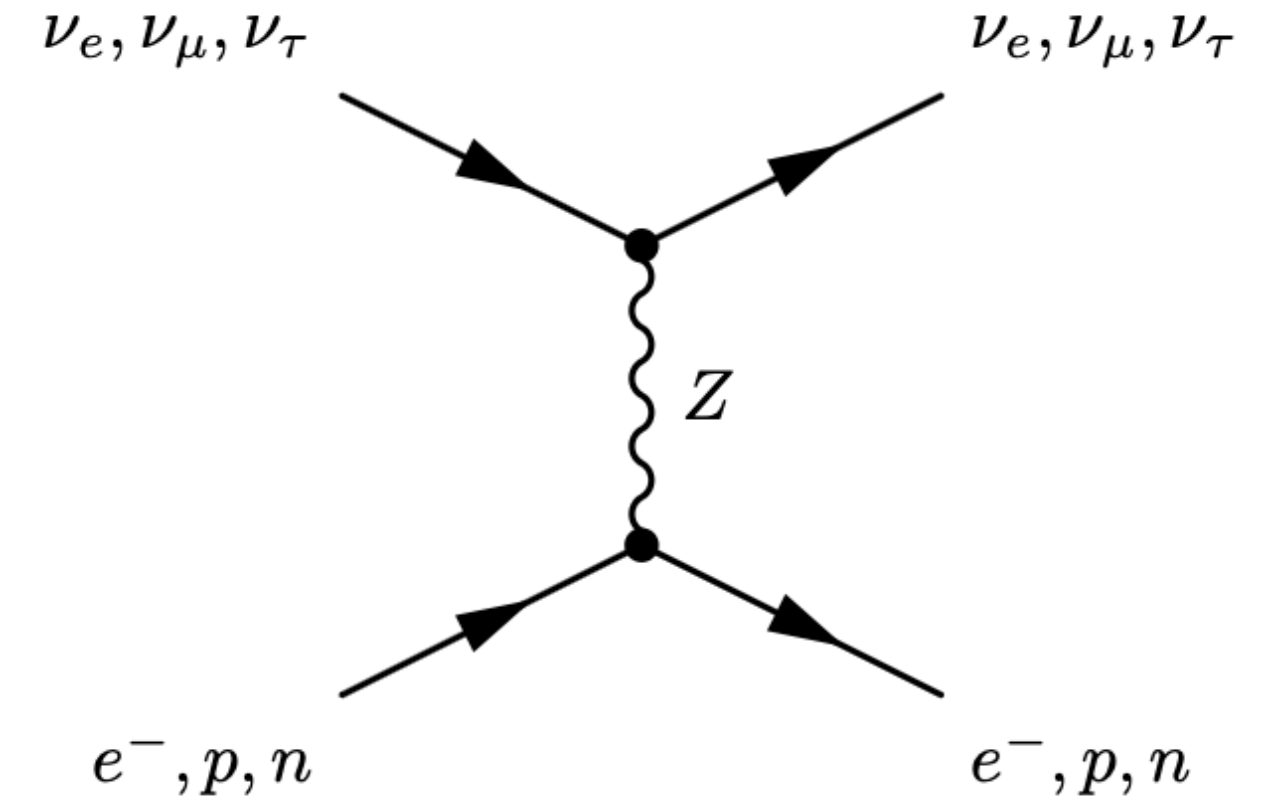
Neutrinos interact via NC with electrons, protons and neutrons in matter

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

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

$$g_v^p = \frac{1}{2} - 2 \sin^2 \theta_w$$

$$g_v^n = -\frac{1}{2}$$



# Matter Effects

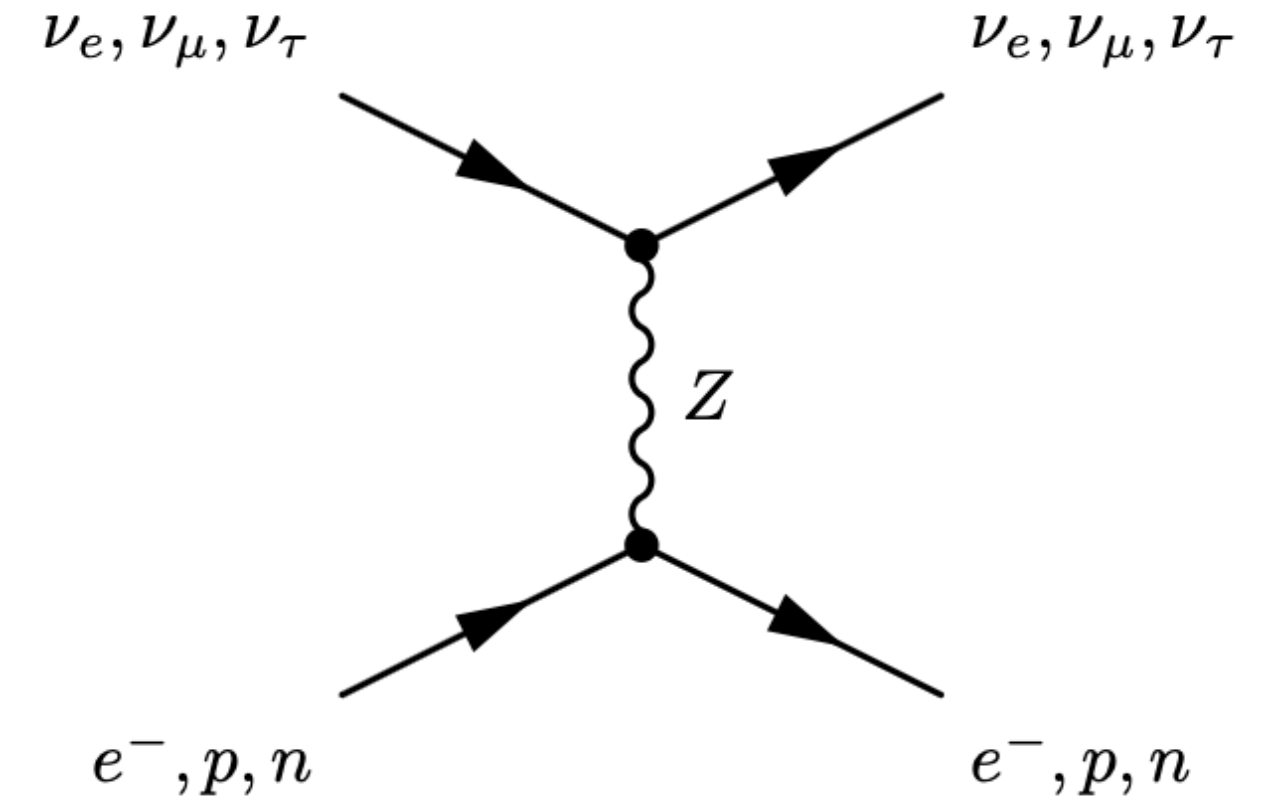
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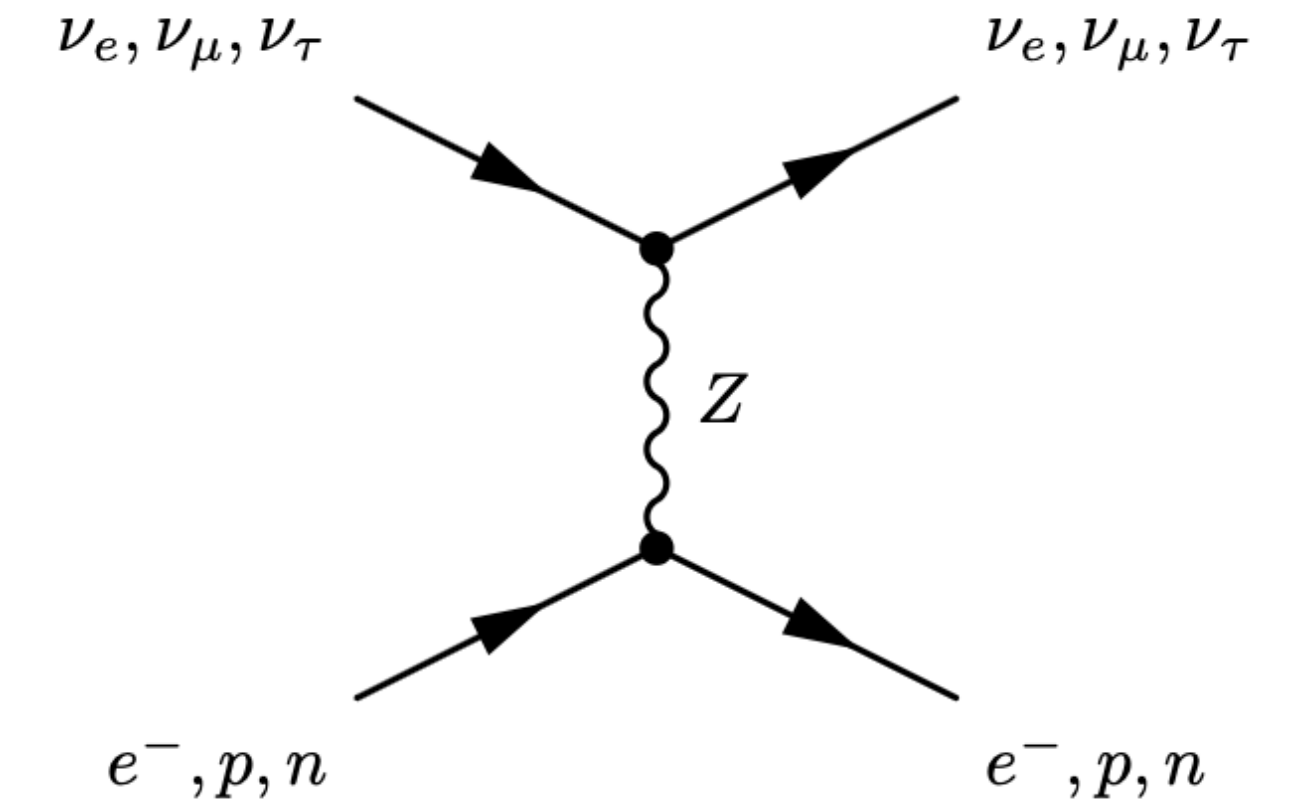


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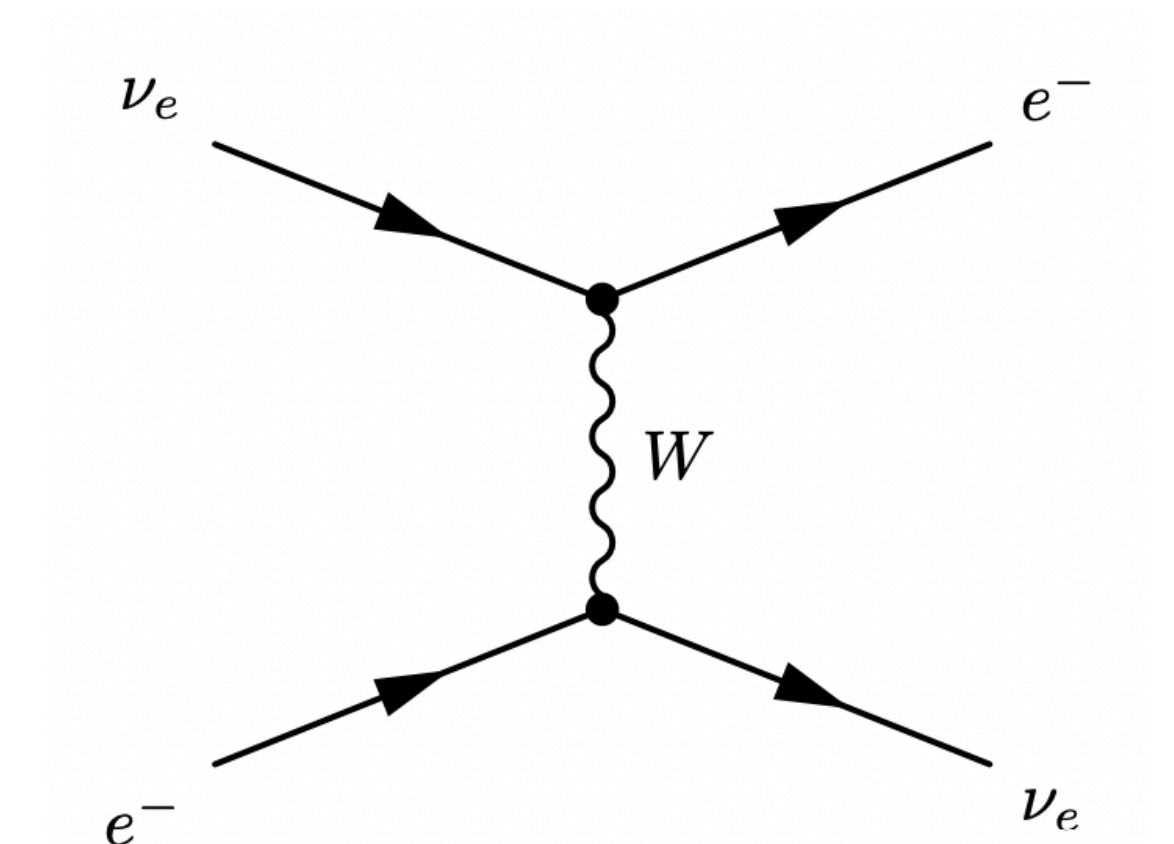


For neutral matter, only neutrons contribute to the NC potential

$$V_{NC} = -\frac{1}{\sqrt{2}} G_F N_n$$

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

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



# Matter Effects

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- The NC term is flavor independent, acting as a global phase, therefore it doesn't affect the flavor oscillations
- 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

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

- 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  $\theta$  and  $\Delta m^2$

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



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

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

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

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

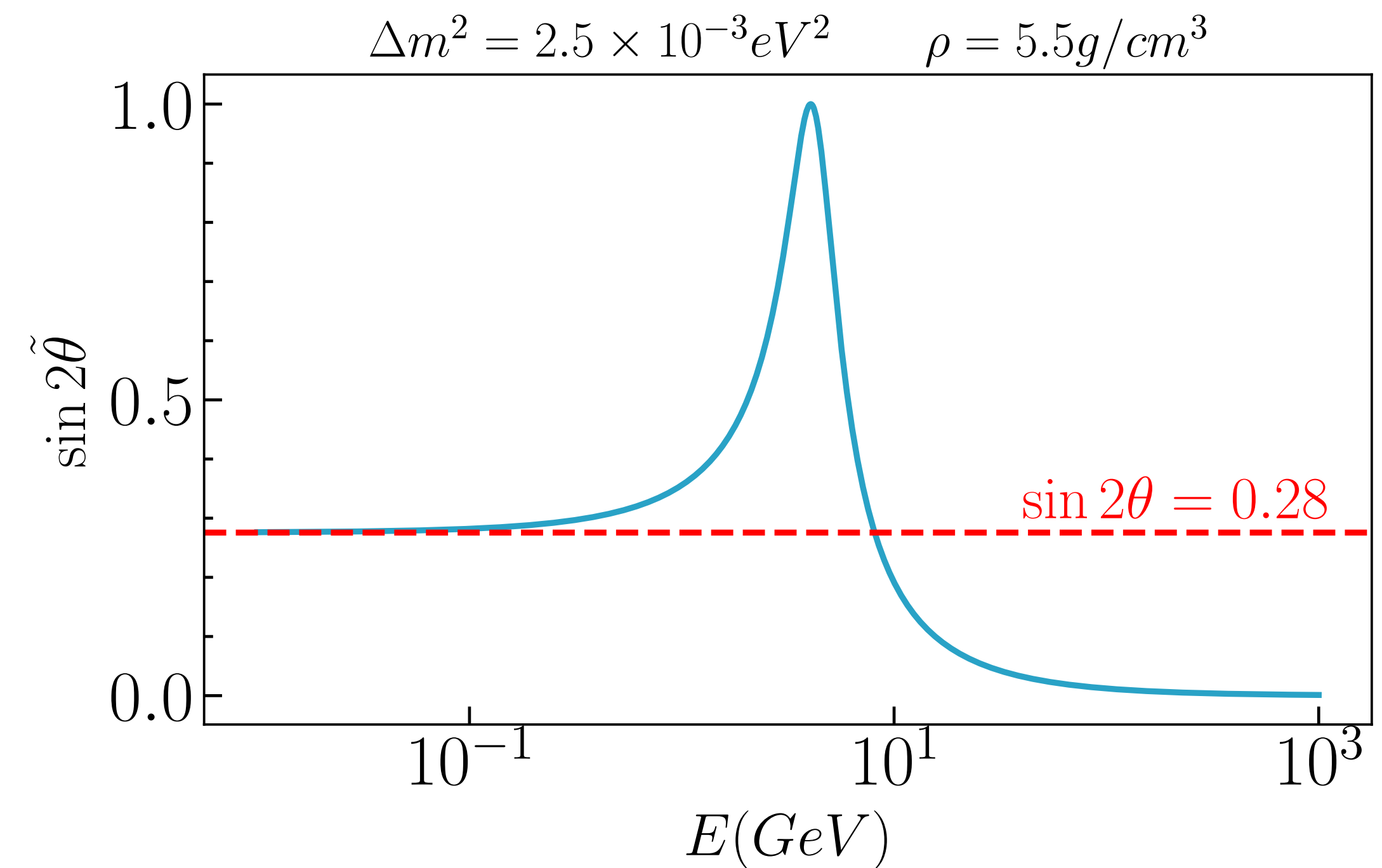
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The mixing can be enhanced due to the matter effects

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





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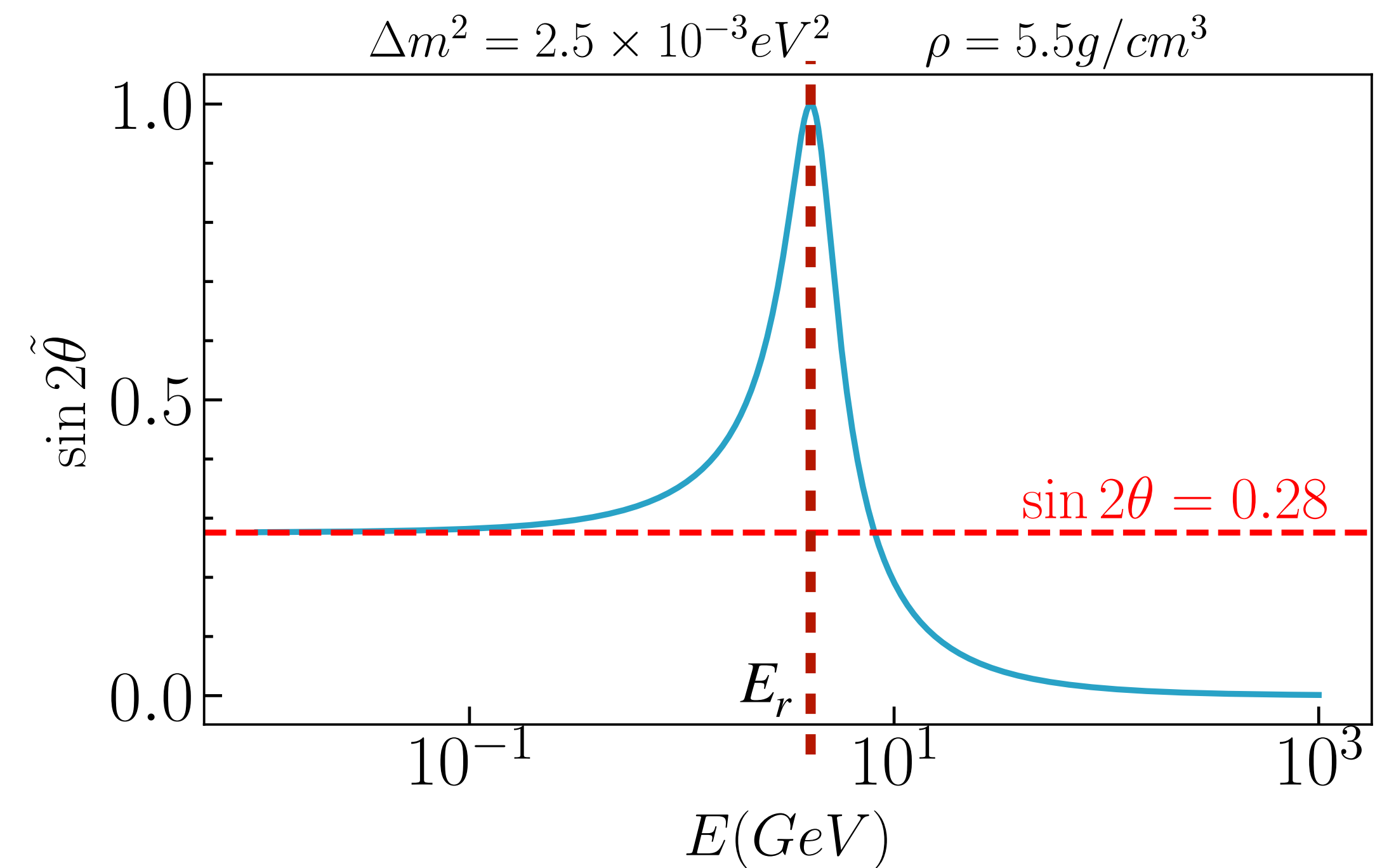
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For some values of E and density, there is a resonant flavor conversion

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



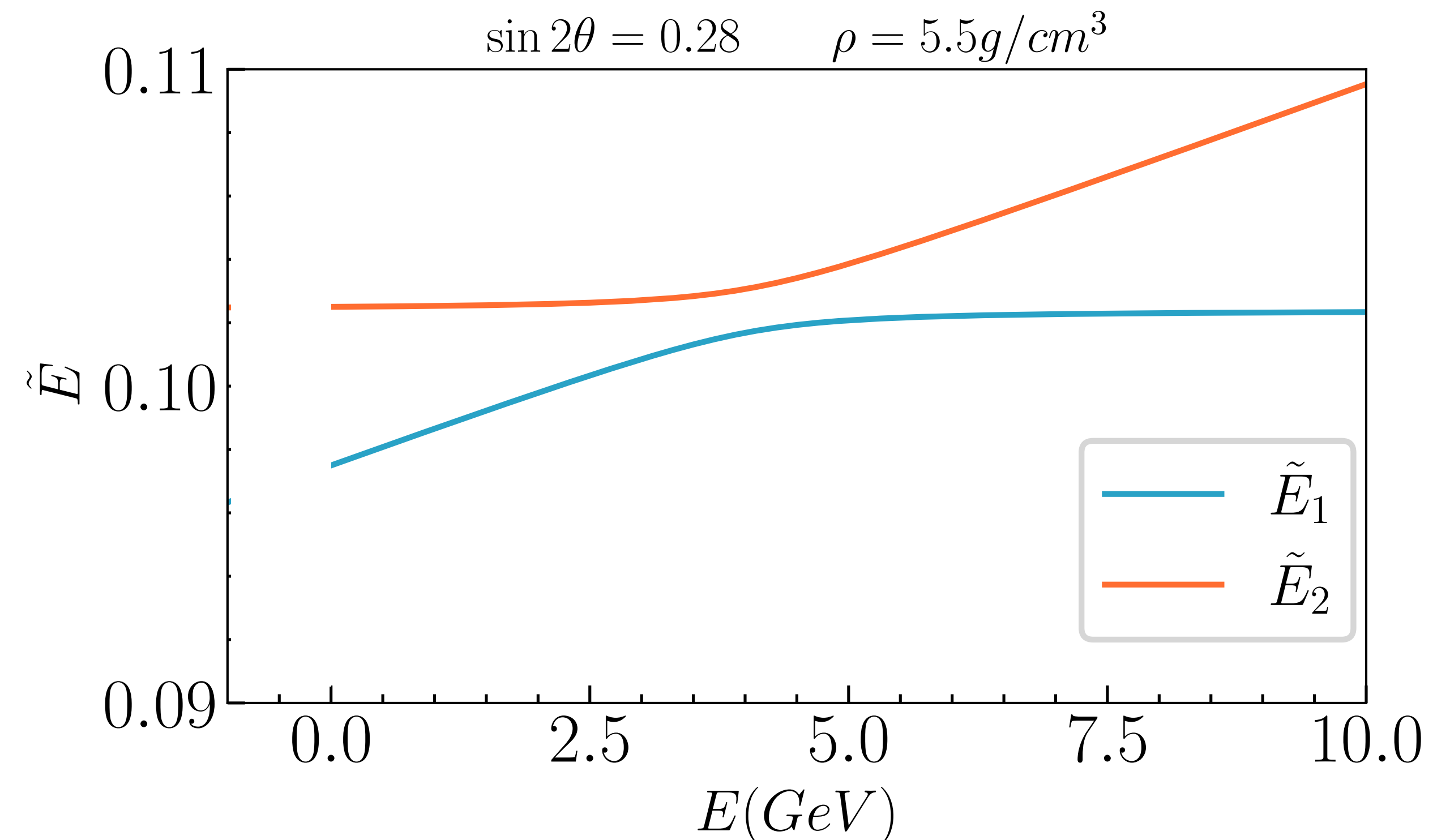
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The effective neutrino mass changes in matter

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



# Matter Effects

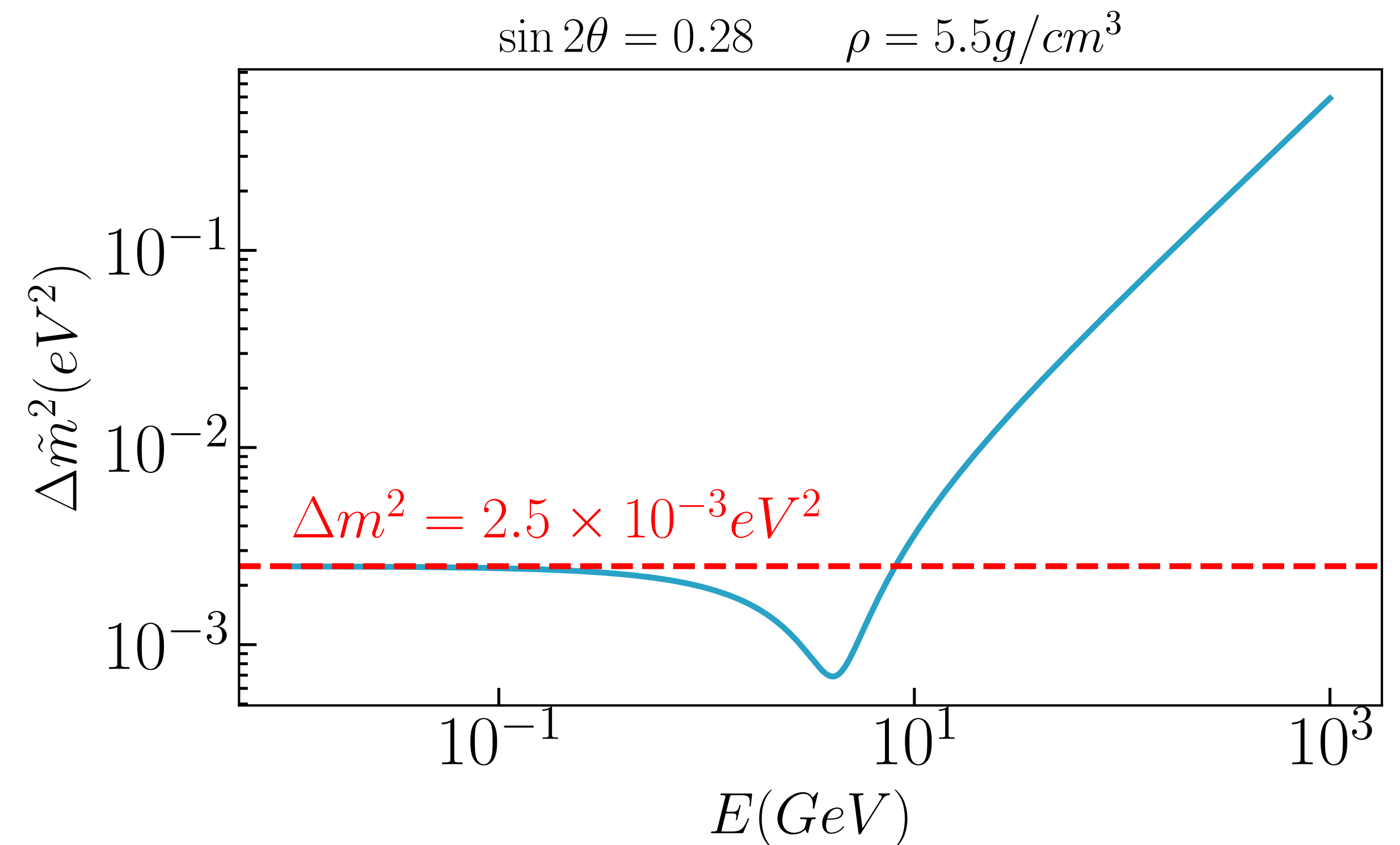
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The oscillation length also gets modified in matter

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

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





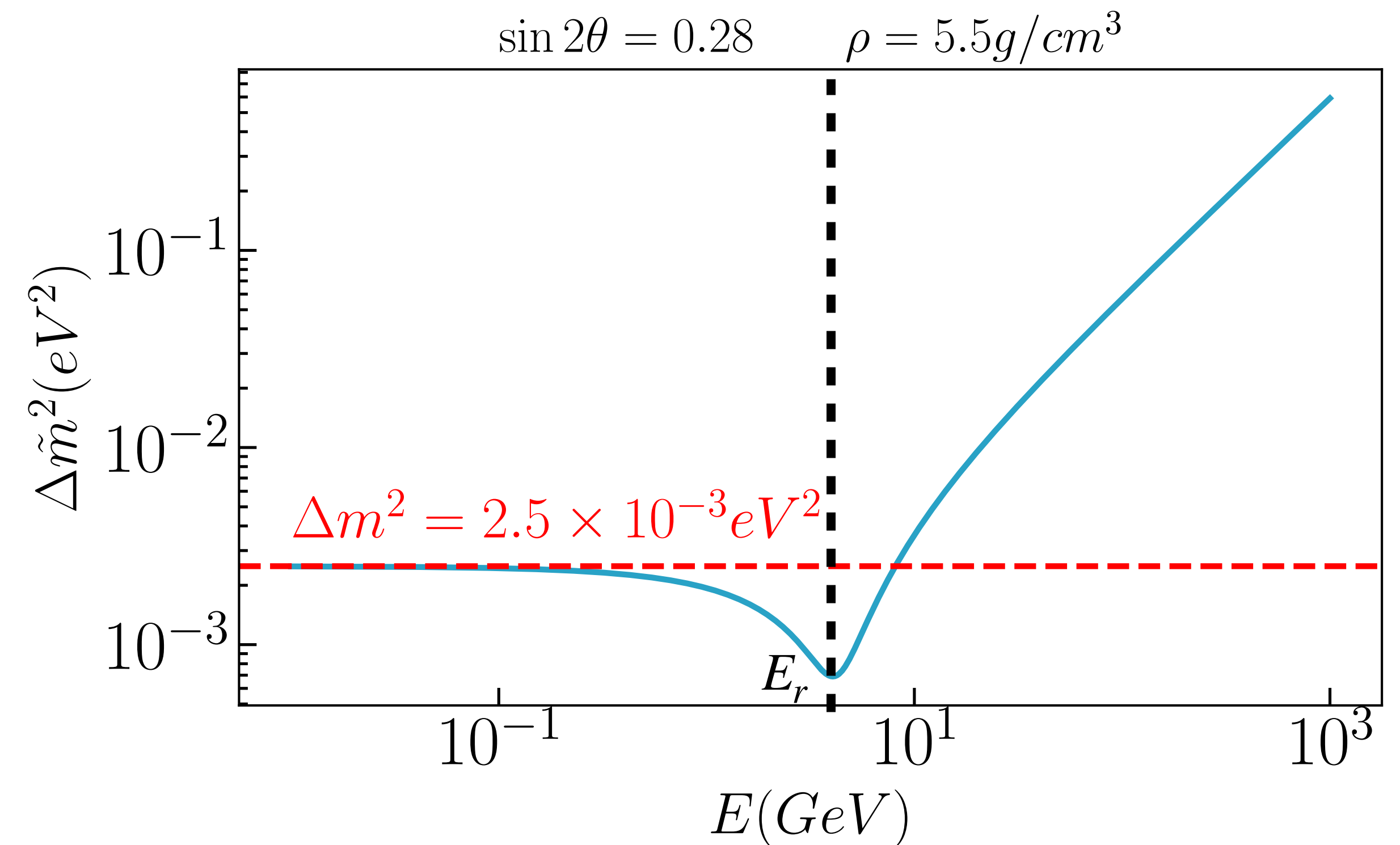
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$$U^T(\tilde{\theta})H_{2\times 2}U(\tilde{\theta}) = \frac{1}{4E}\text{diag}(-\Delta\tilde{m}^2, \Delta\tilde{m}^2)$$

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

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

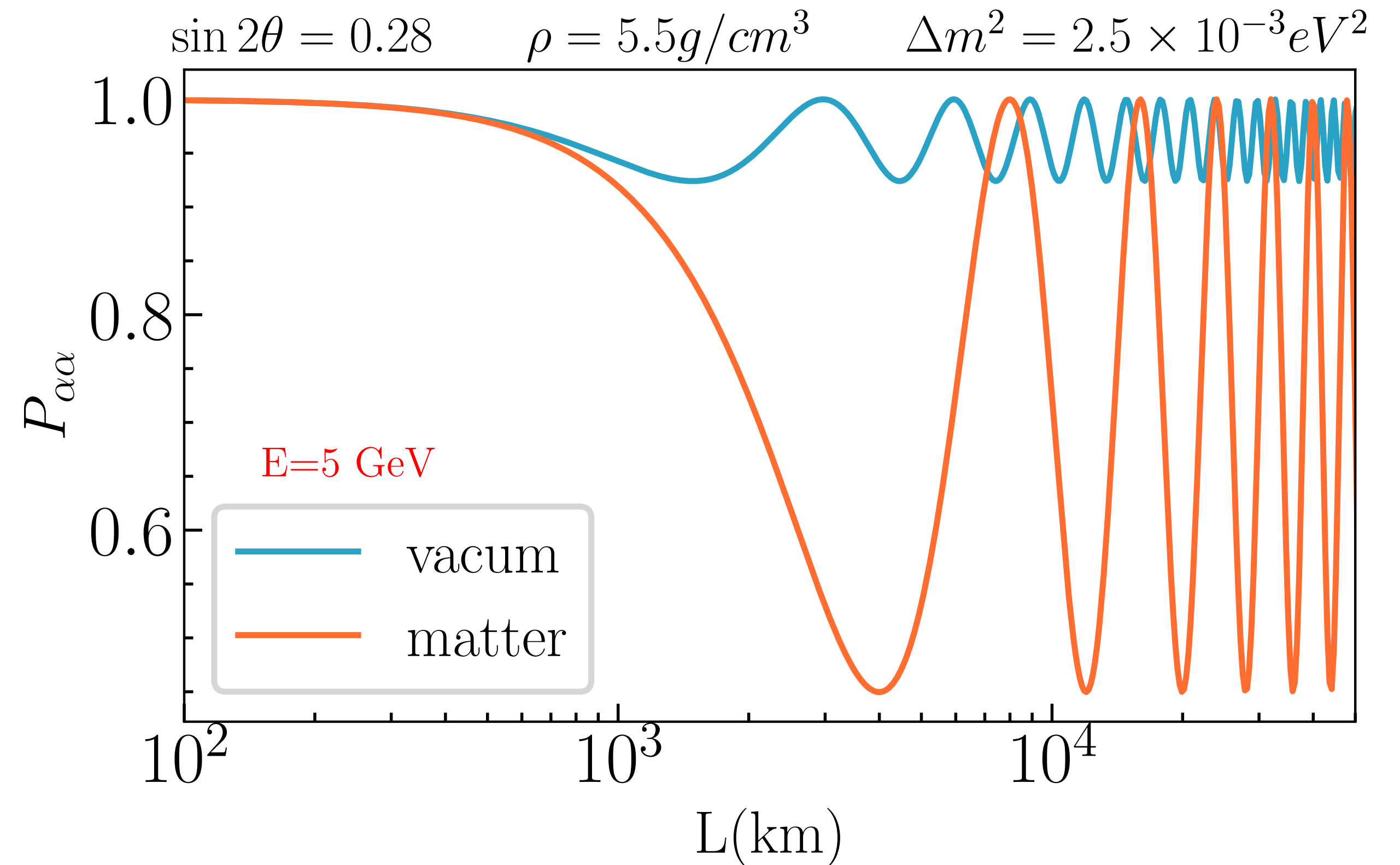


# Matter Effects

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

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

**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



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In the mass basis, the Hamiltonian is non-diagonal

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

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- The off-diagonal term generates a transition between  $\nu_1$  and  $\nu_2$
- The transition between the massive states will not happen if the diagonal terms are larger than the off-diagonal (adiabatic regime)

$$\gamma = \frac{\Delta\tilde{m}^2}{4Ed\tilde{\theta}/dx} \gg 1 \quad \leftarrow \text{Adiabatic condition}$$

# Matter Effects: MSW

In the adiabatic limit, each massive state evolves independently

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

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

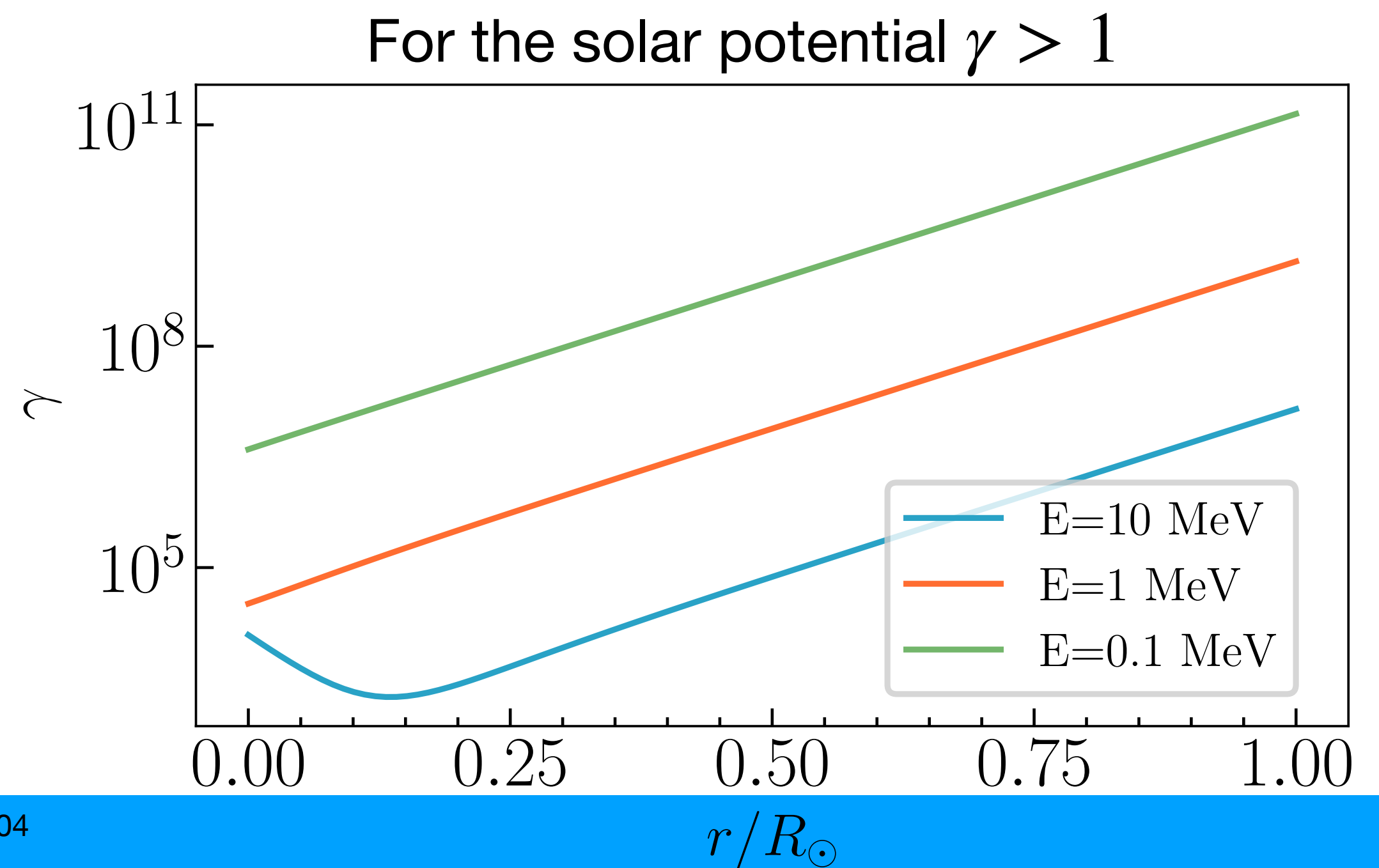
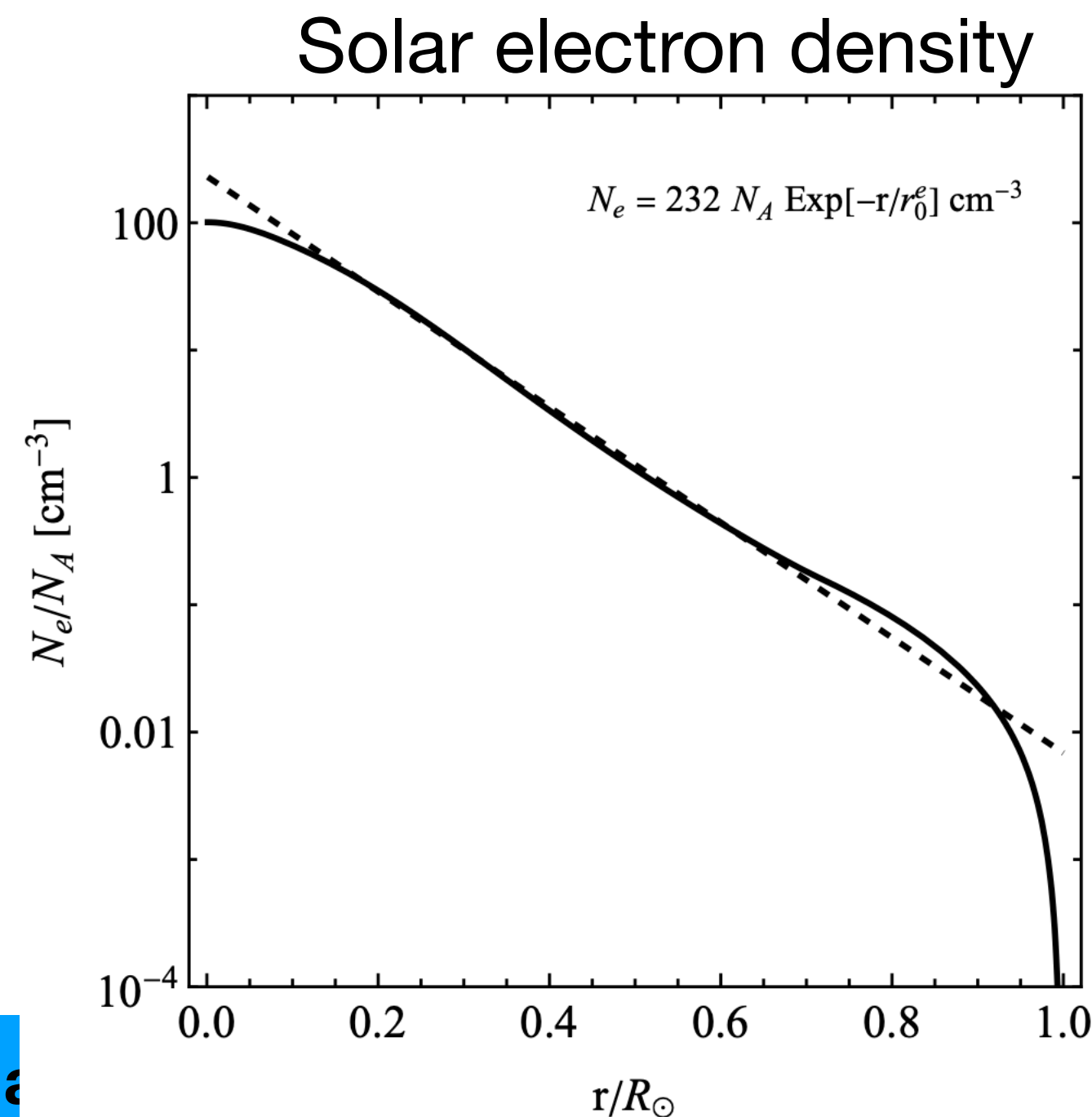


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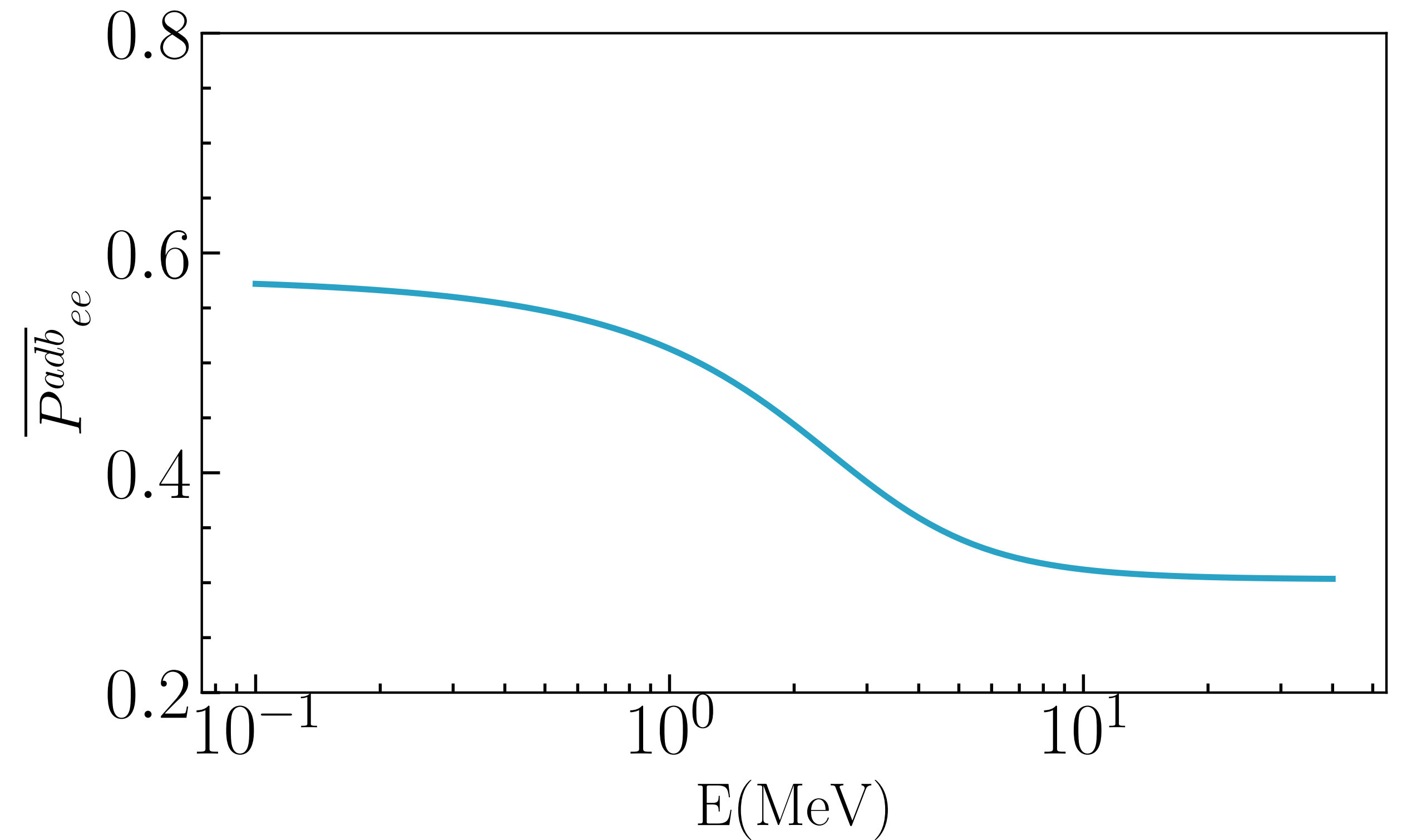
- Oscillation probability depends only on mixing at the initial ( $\tilde{\theta}^i$ ) and final ( $\tilde{\theta}^f$ ) points of the path
- The adiabatic regime describes the neutrino evolution inside the stars: the Sun, supernovas...



# Matter Effects: MSW

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

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



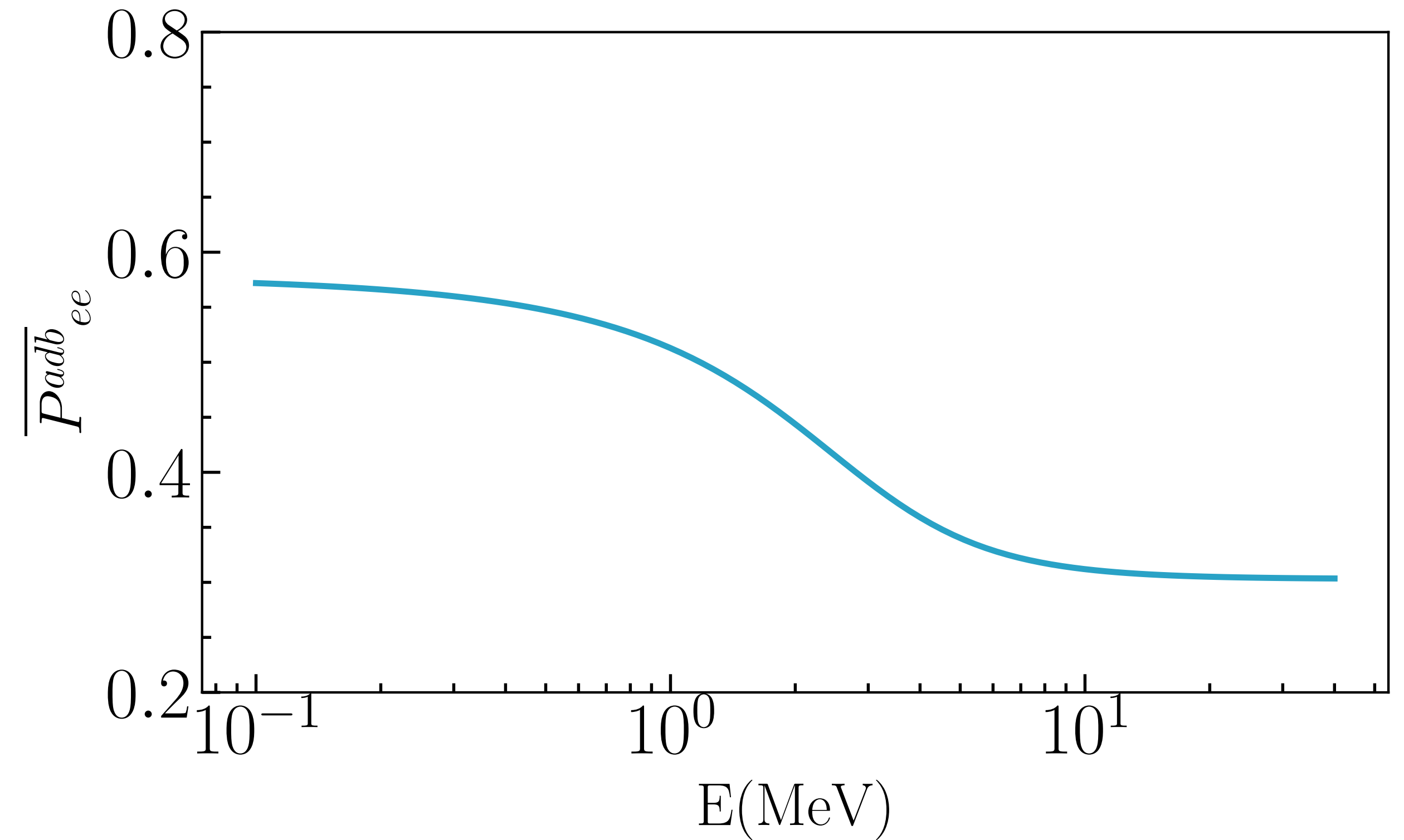
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$$\tilde{\theta}^f = \theta$$





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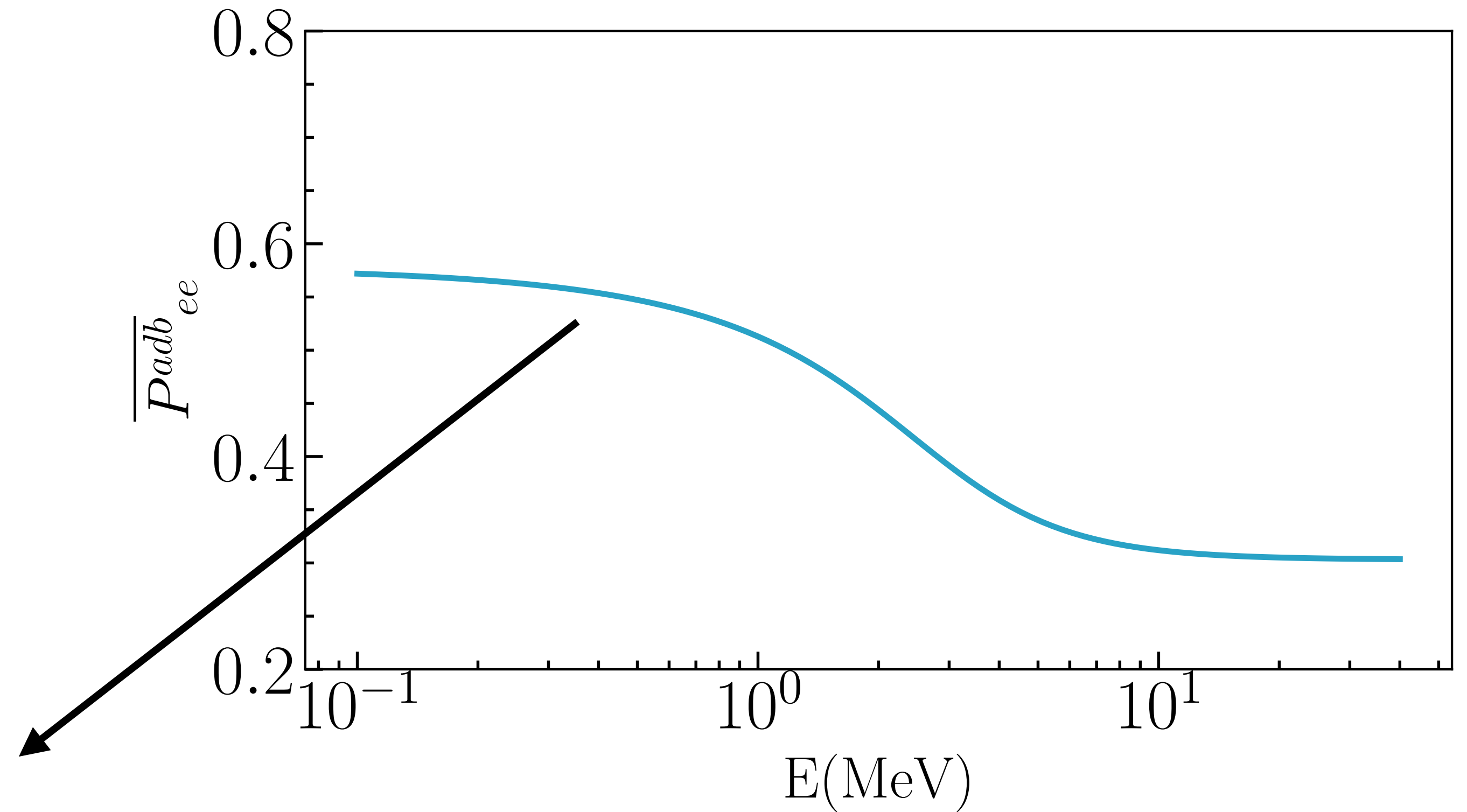
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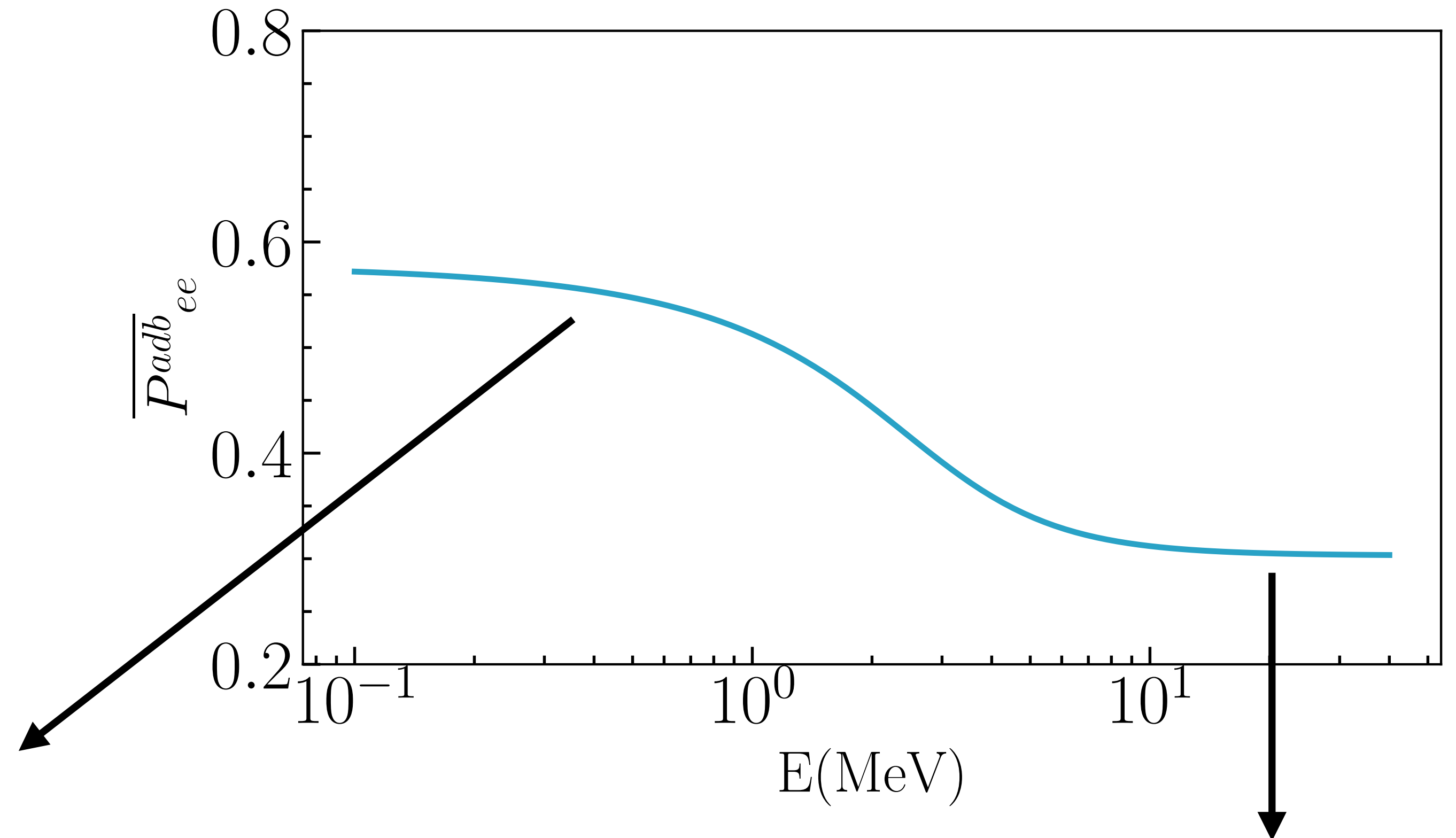
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At higher energies, **matter** effects **dominate**

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

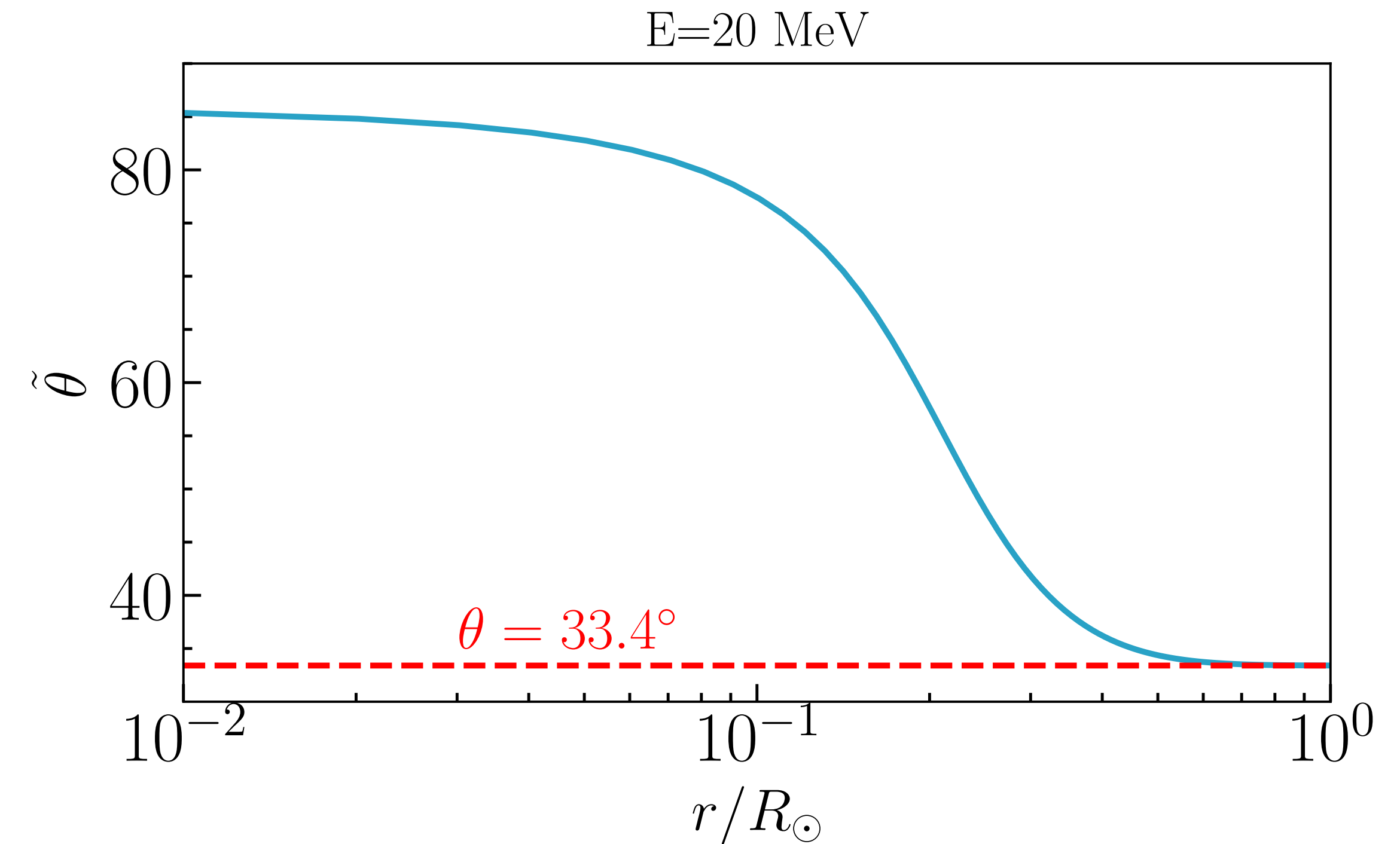
In the denser region of the Sun

# Matter Effects: MSW

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

Let's consider

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





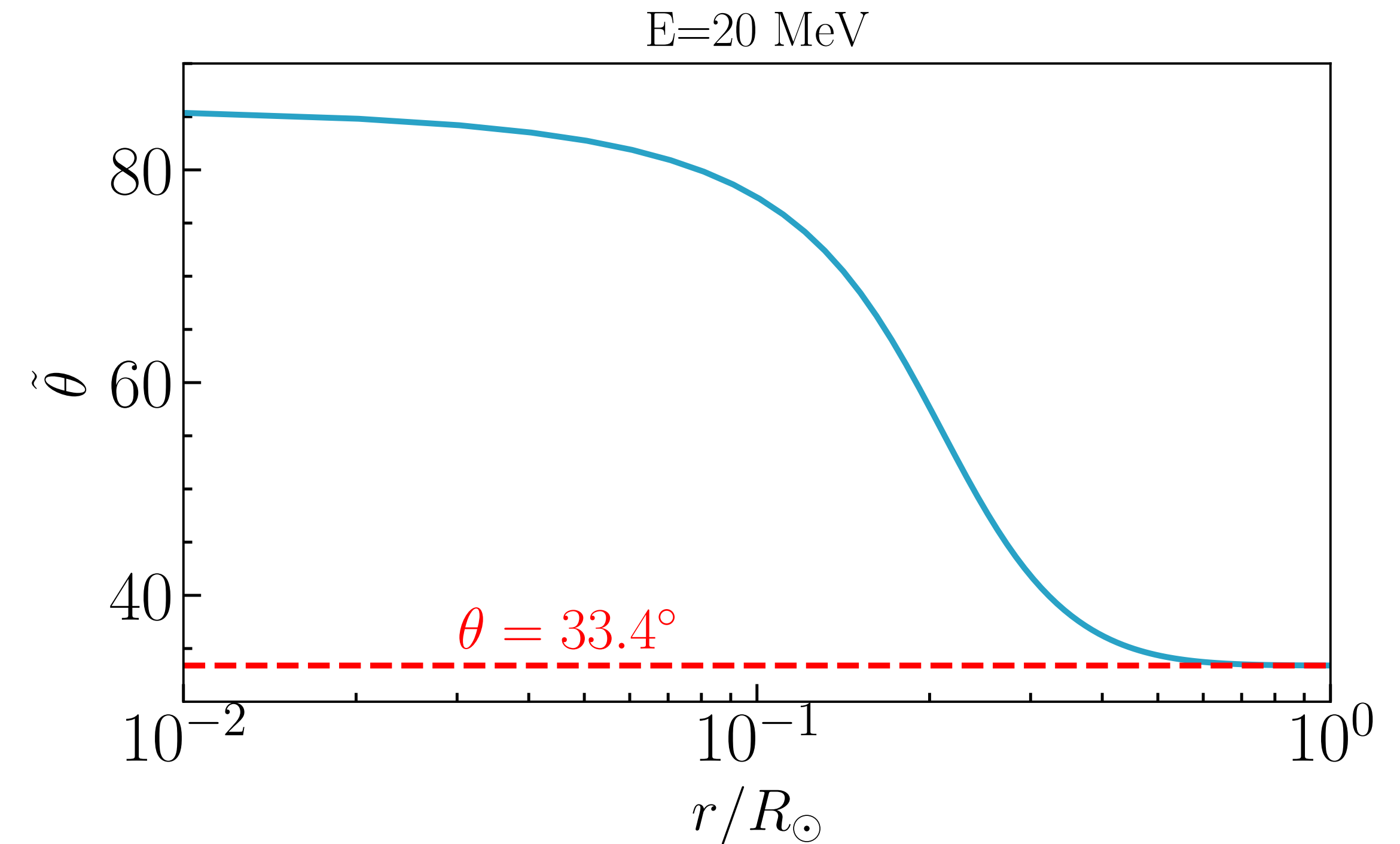
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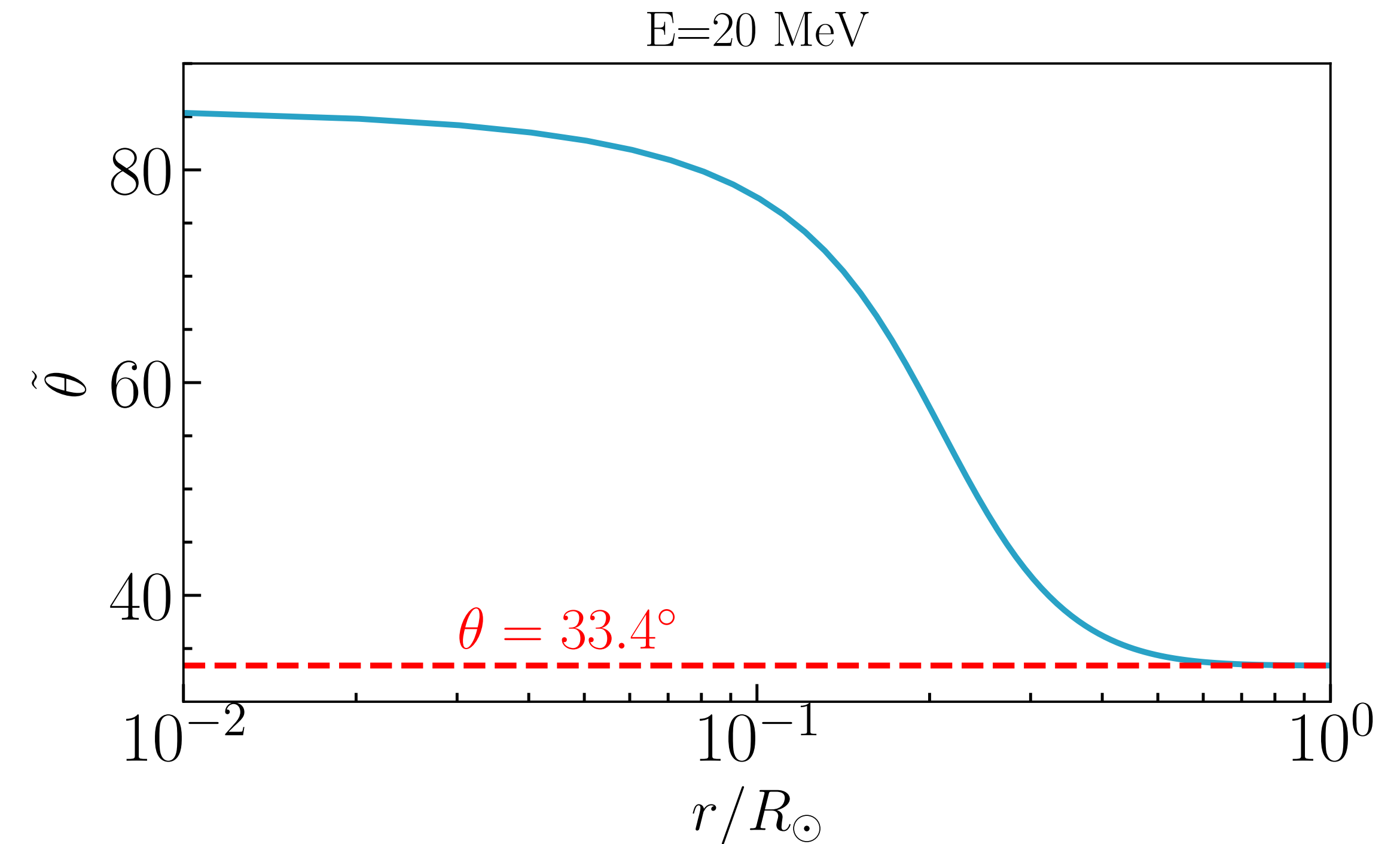
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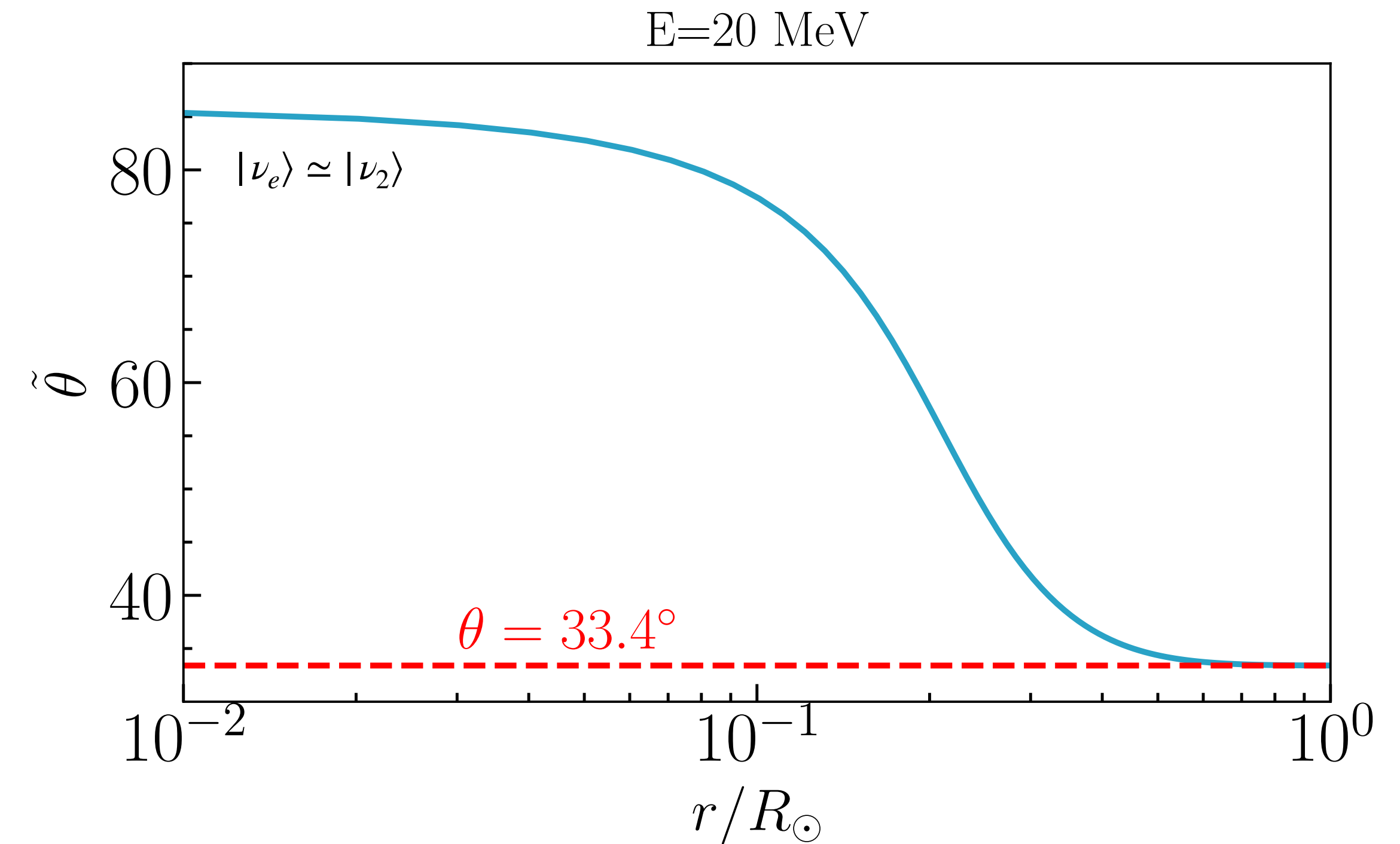
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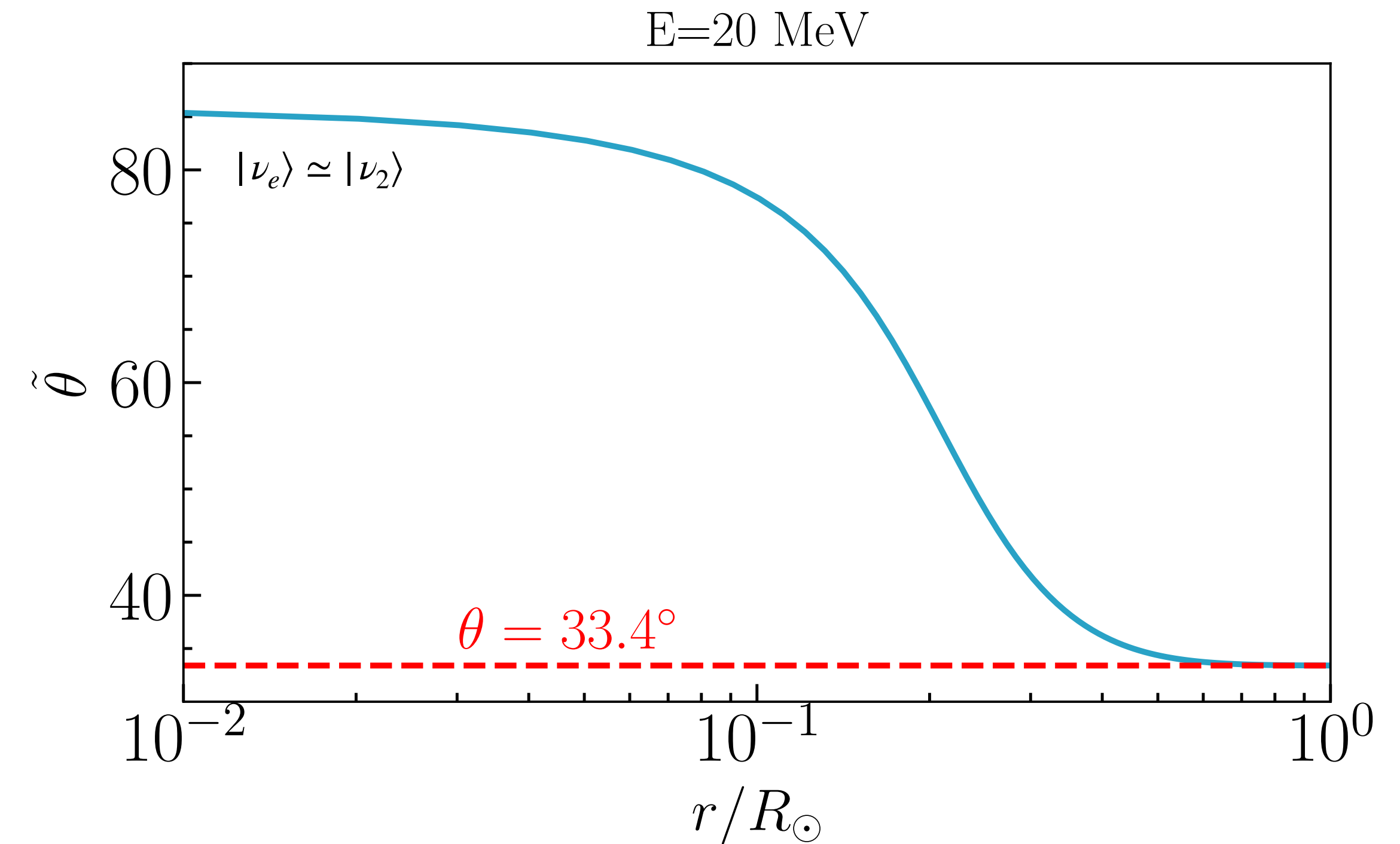
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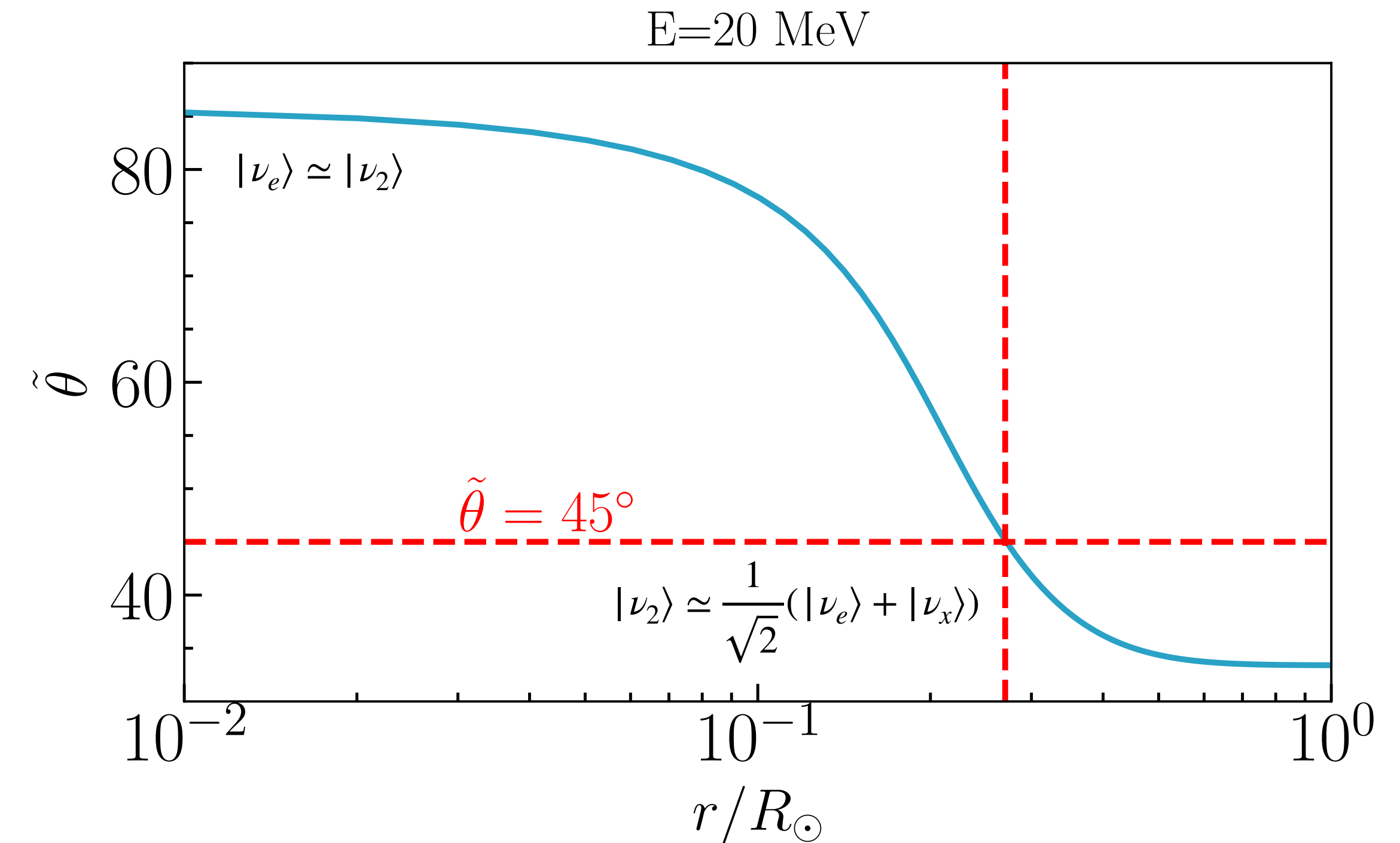
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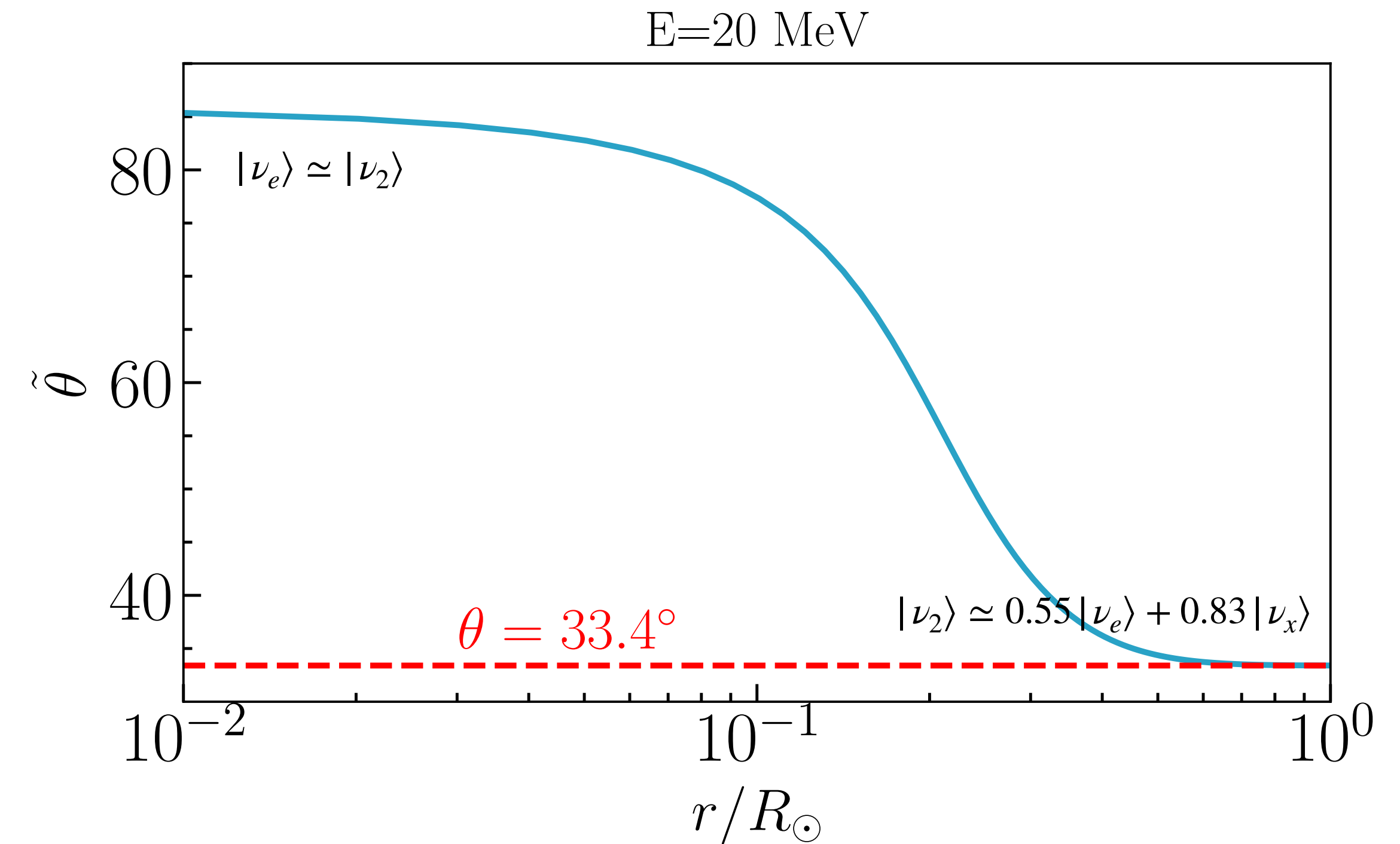
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- As the flux exits the Sun, the flux is dominated by  $\nu_x$



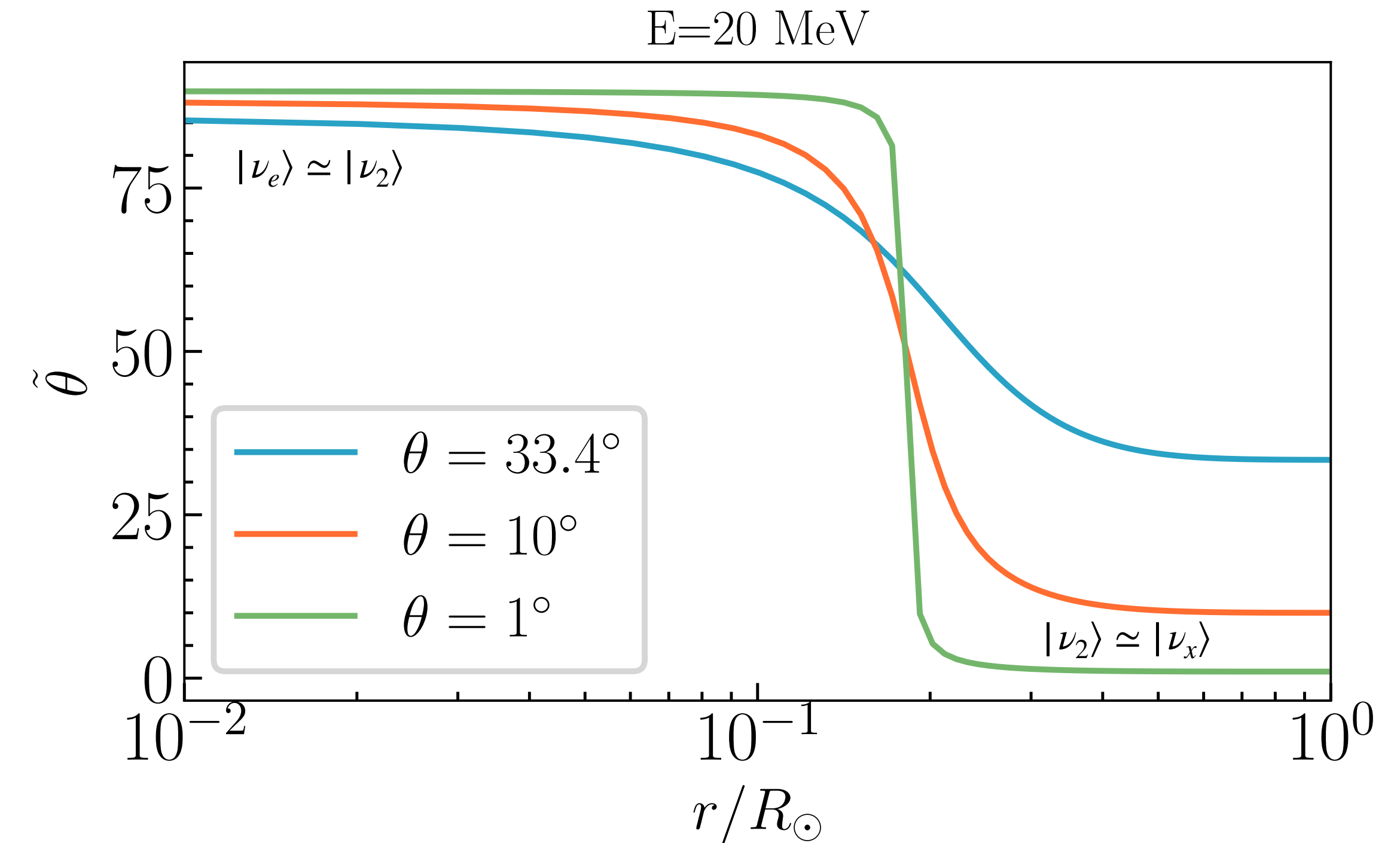
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**Smaller** vacuum mixing angles lead to a **larger** flavor conversion

# Neutrino Sources

# 3ν Mixing

In the 3ν **scenario**, neutrino evolution is described by six parameters

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

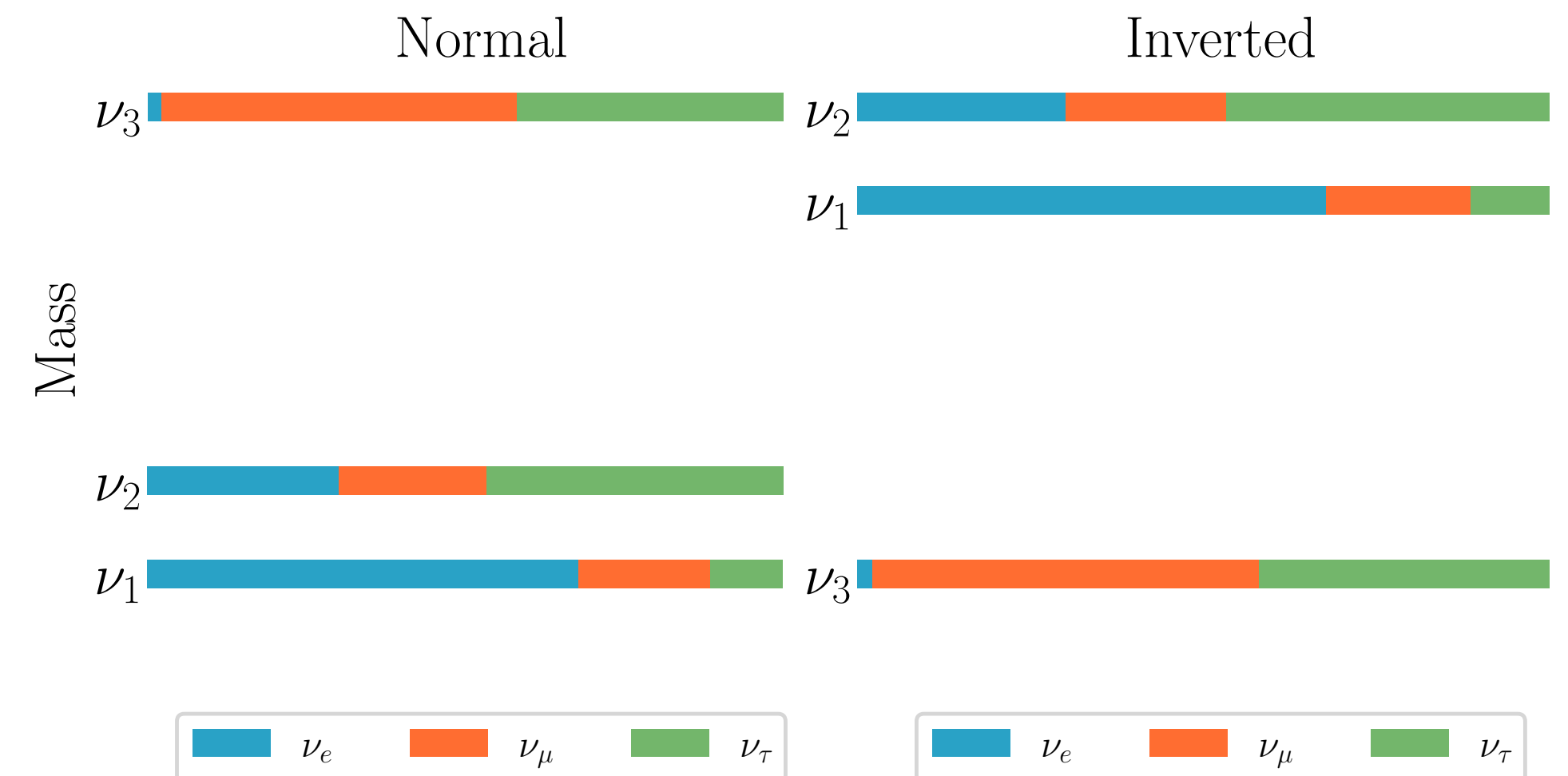
$$V_\alpha = 2\sqrt{2}G_F N_e E_\nu \text{diag}(1, 0, 0)$$

$$\nu_\alpha = \sum U_{\alpha i}^\dagger \nu_i$$

PMNS matrix

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

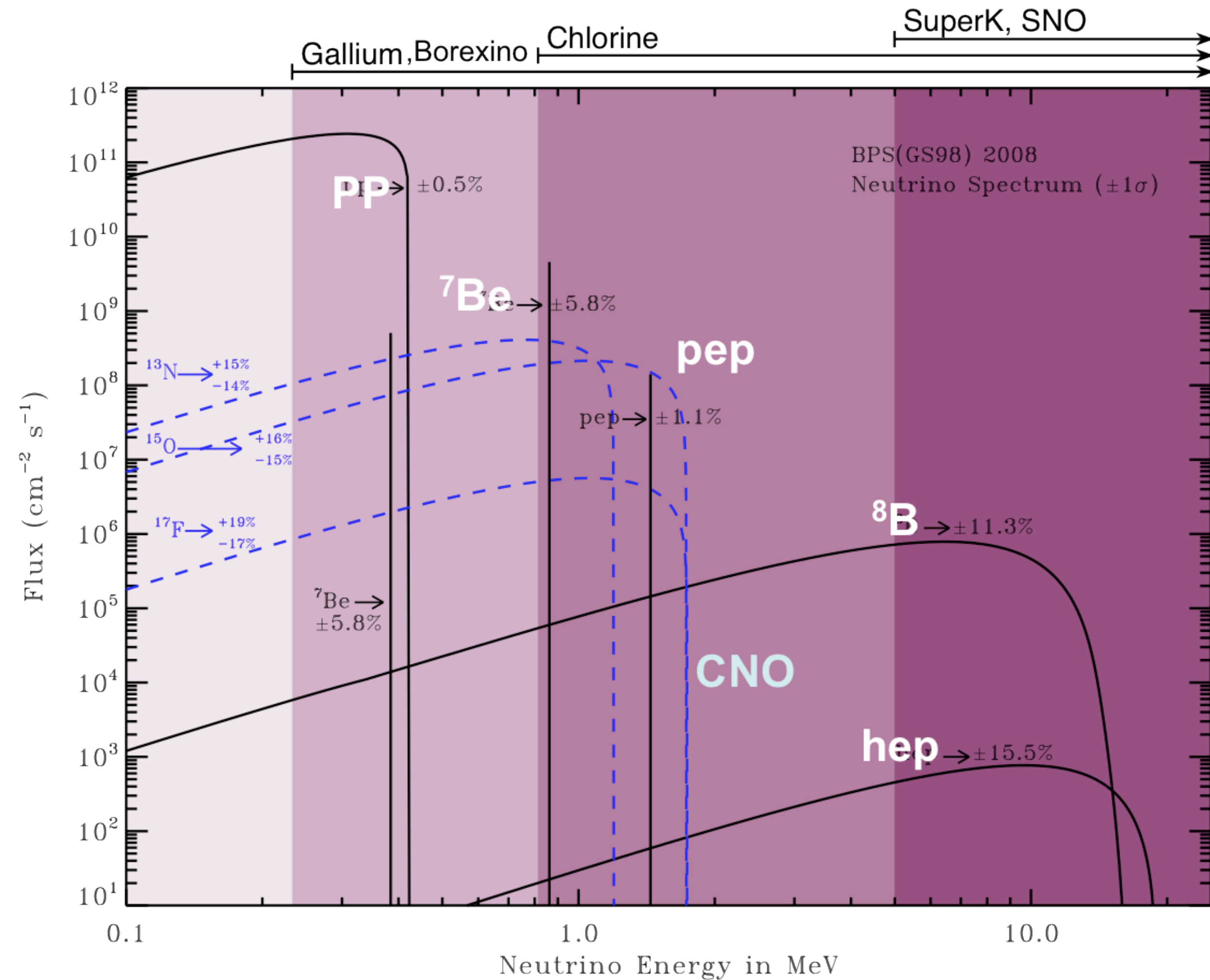
Mass ordering





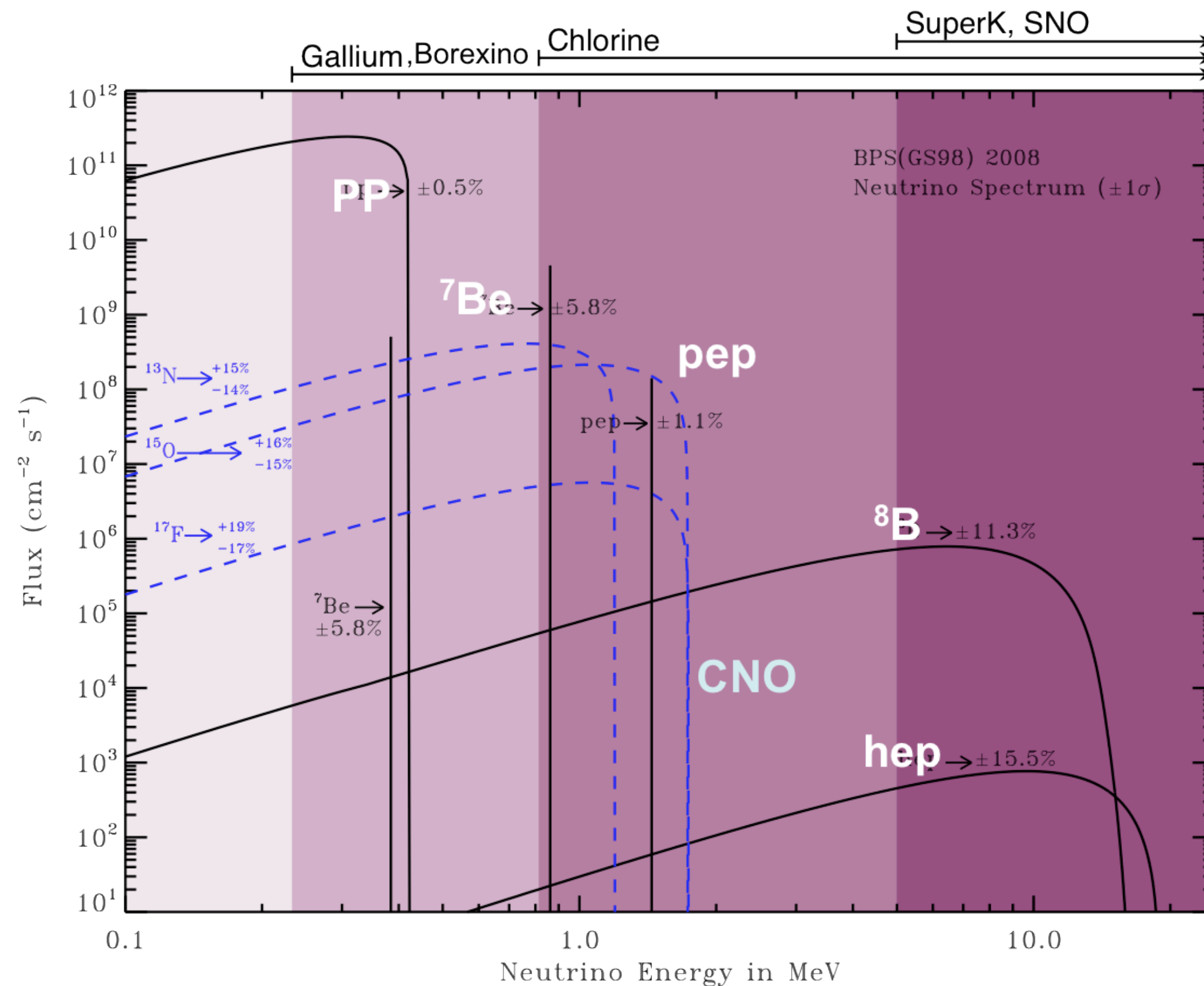
# Solar Neutrinos

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

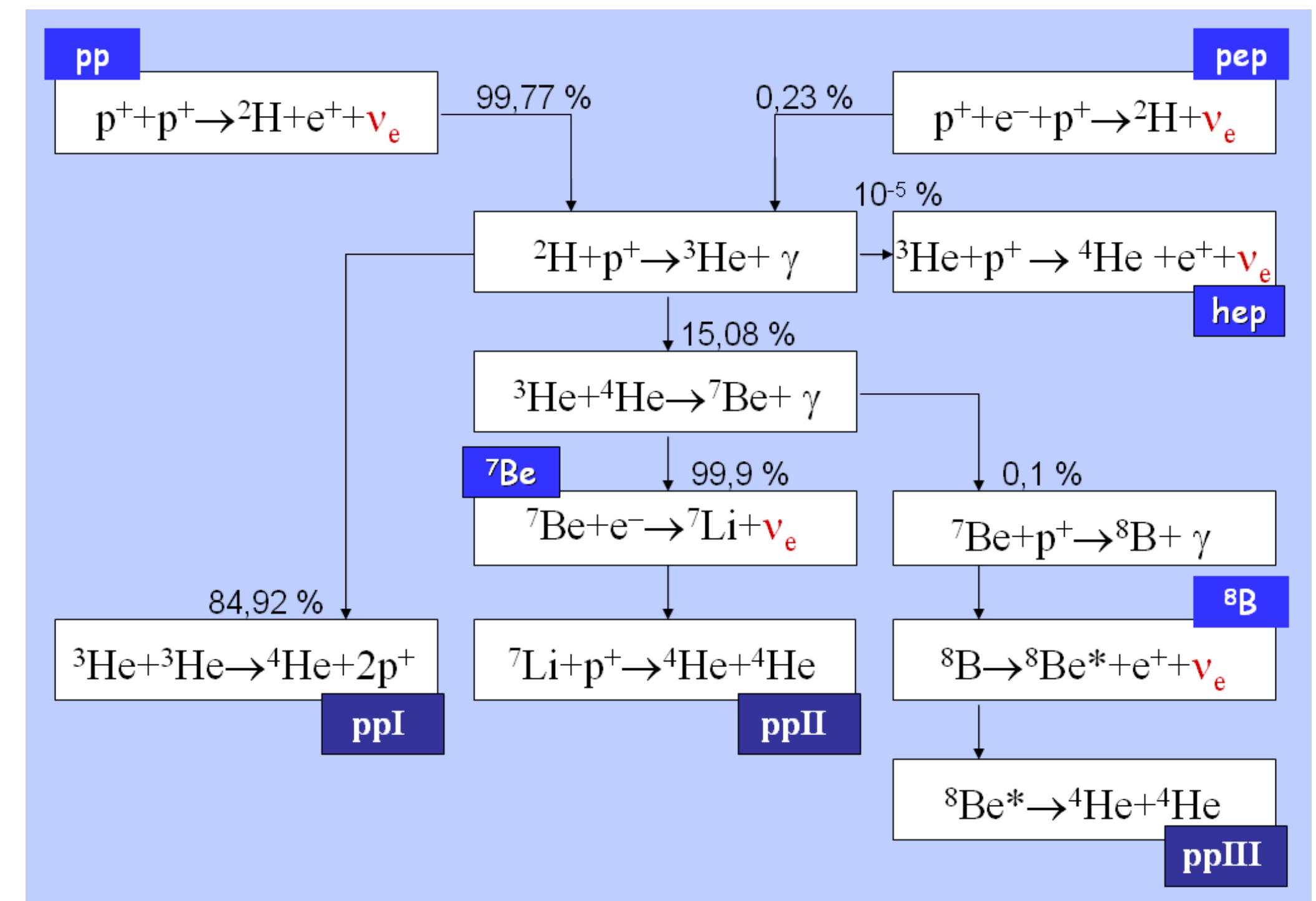


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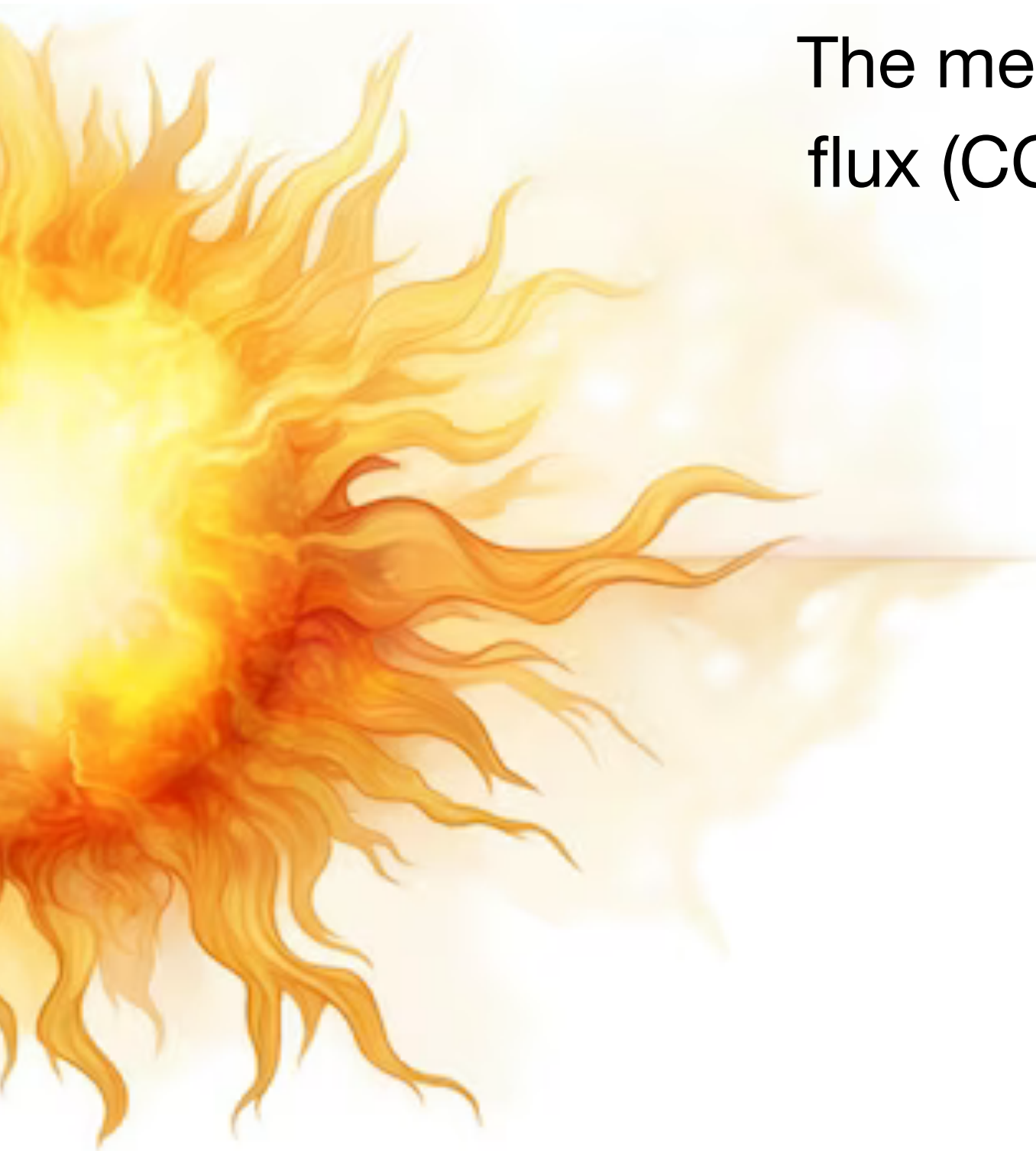


A flux of  $\nu_e$  with MeV energies is produced

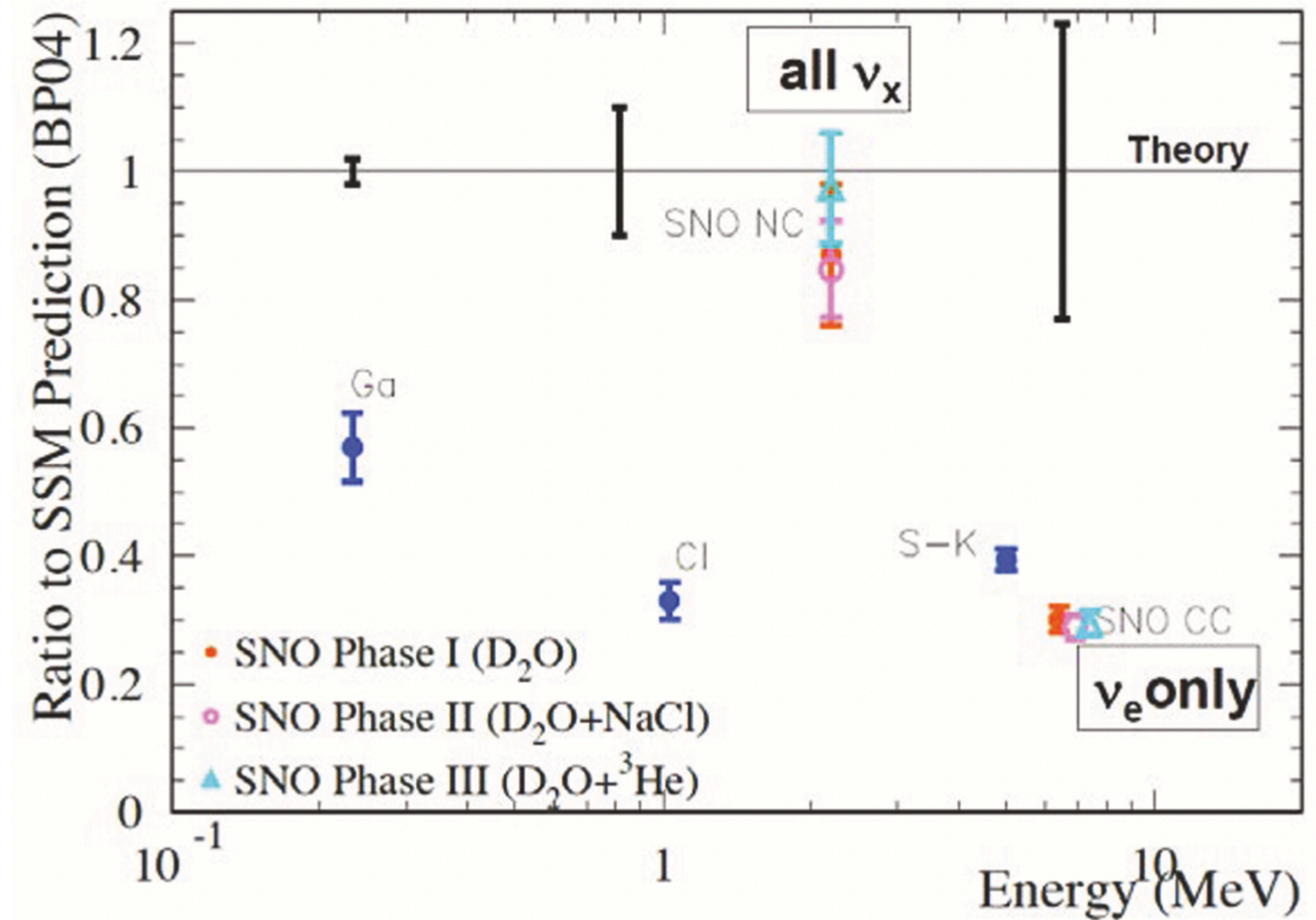




# Solar Neutrinos



The measurement of the **solar neutrino** flux (CC) shows a **disappearance** of  $\nu_e$



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

Arthur MacDonald. Nobel lecture



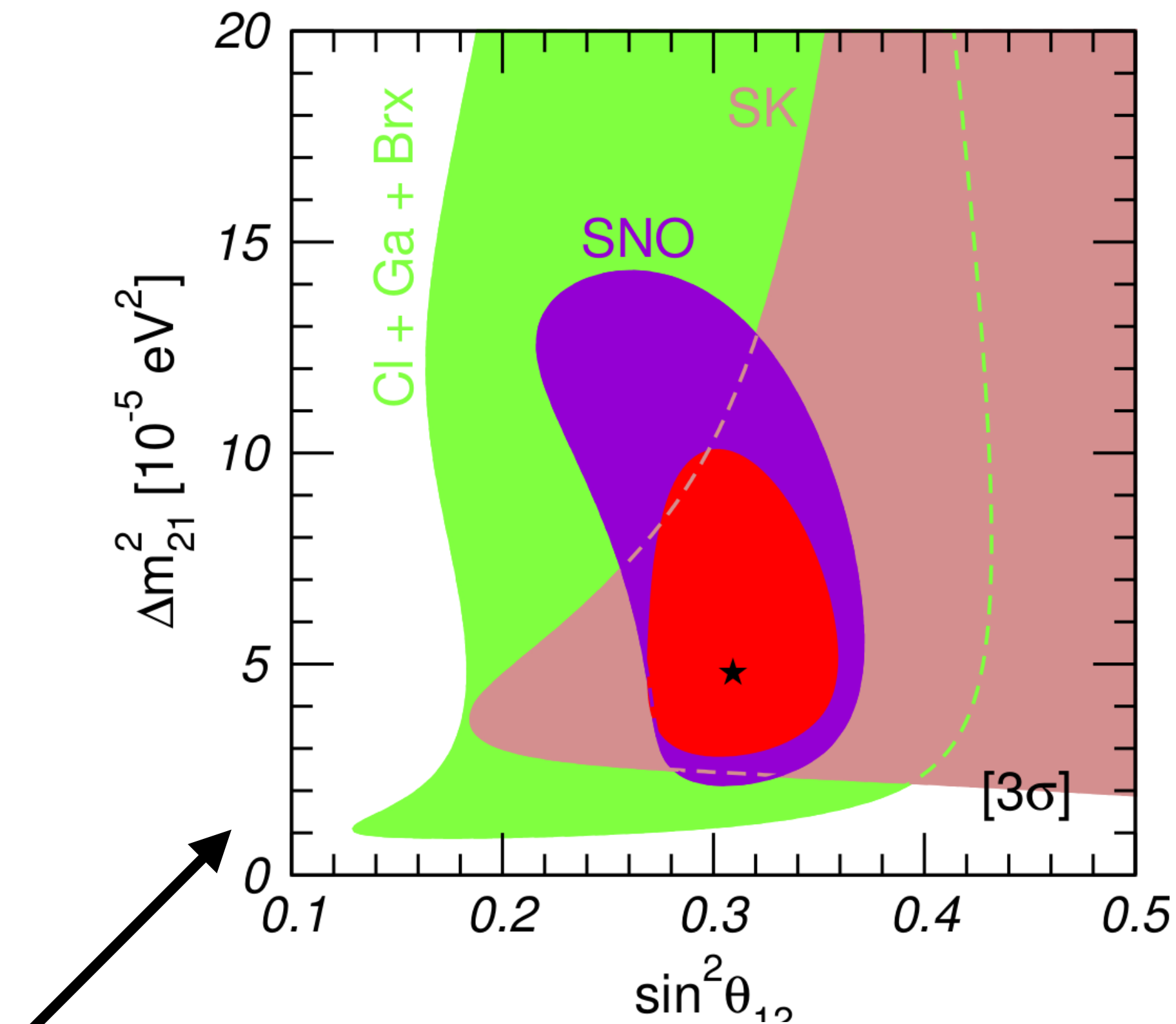
# Solar Neutrinos

**Survival probability** for neutrinos from dense solar regions

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

- Solar neutrinos are mainly sensitive to  $\theta_{12}$

The constraint over  $\theta_{12}$  are mainly driven by **SK+SNO**



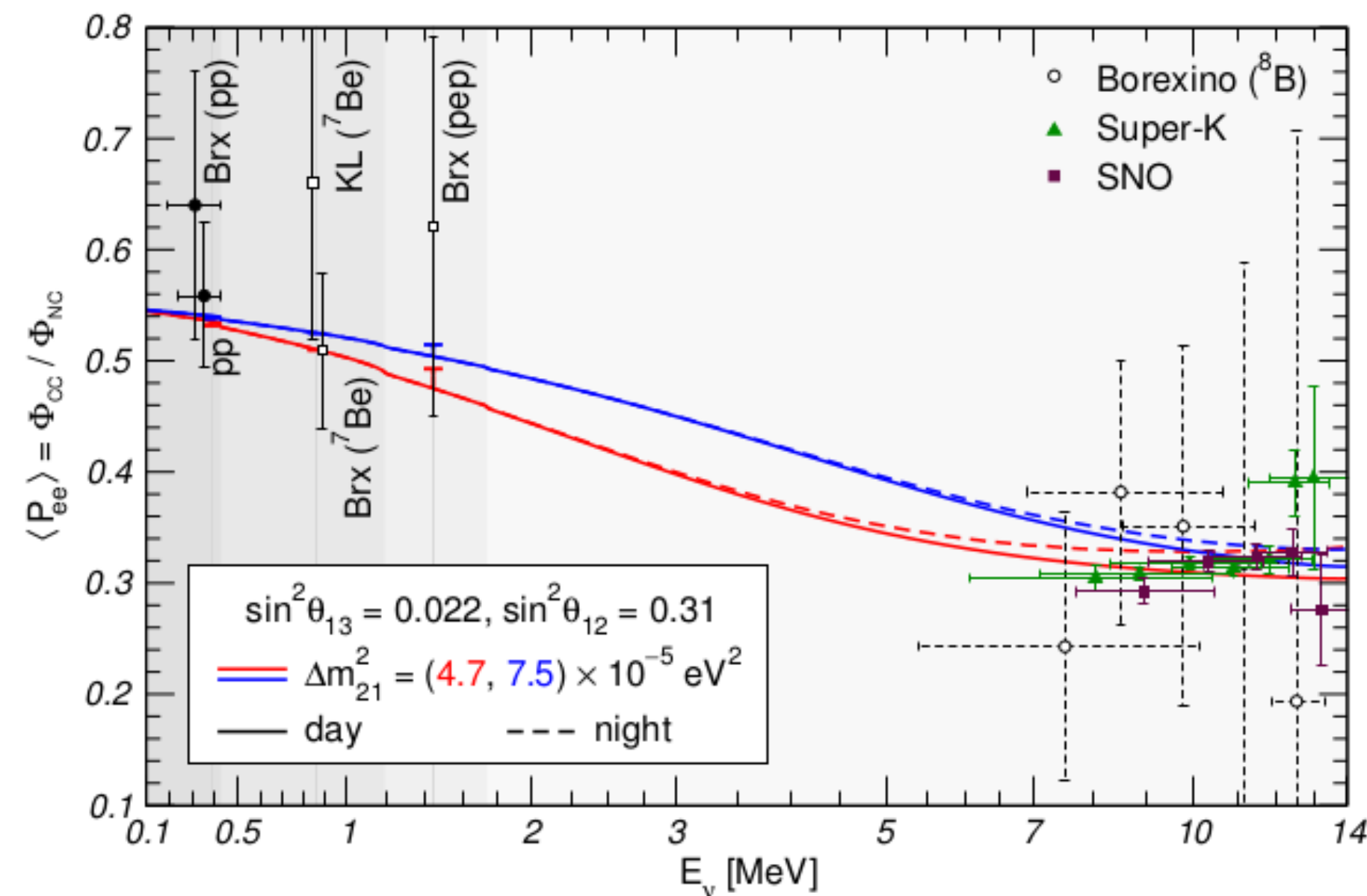
Maltoni and Smirnov, EPJA 52 (2016)  
arXiv:1507.05287

# Solar Neutrinos

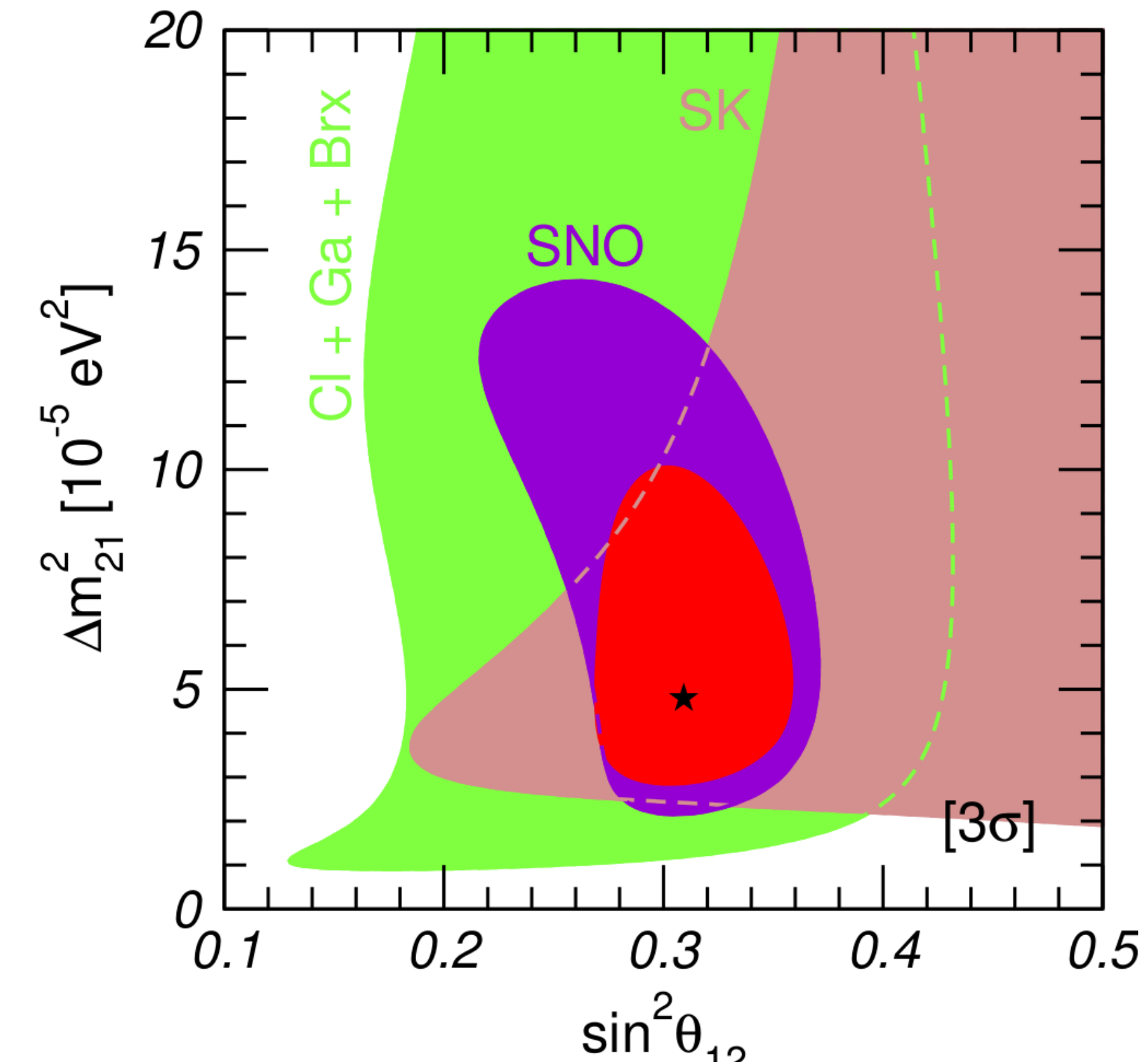
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Matter effects brings sensitivity over  $\Delta m_{21}^2$



←  $\Delta m_{21}^2$  modifies the transition from lower to higher energies

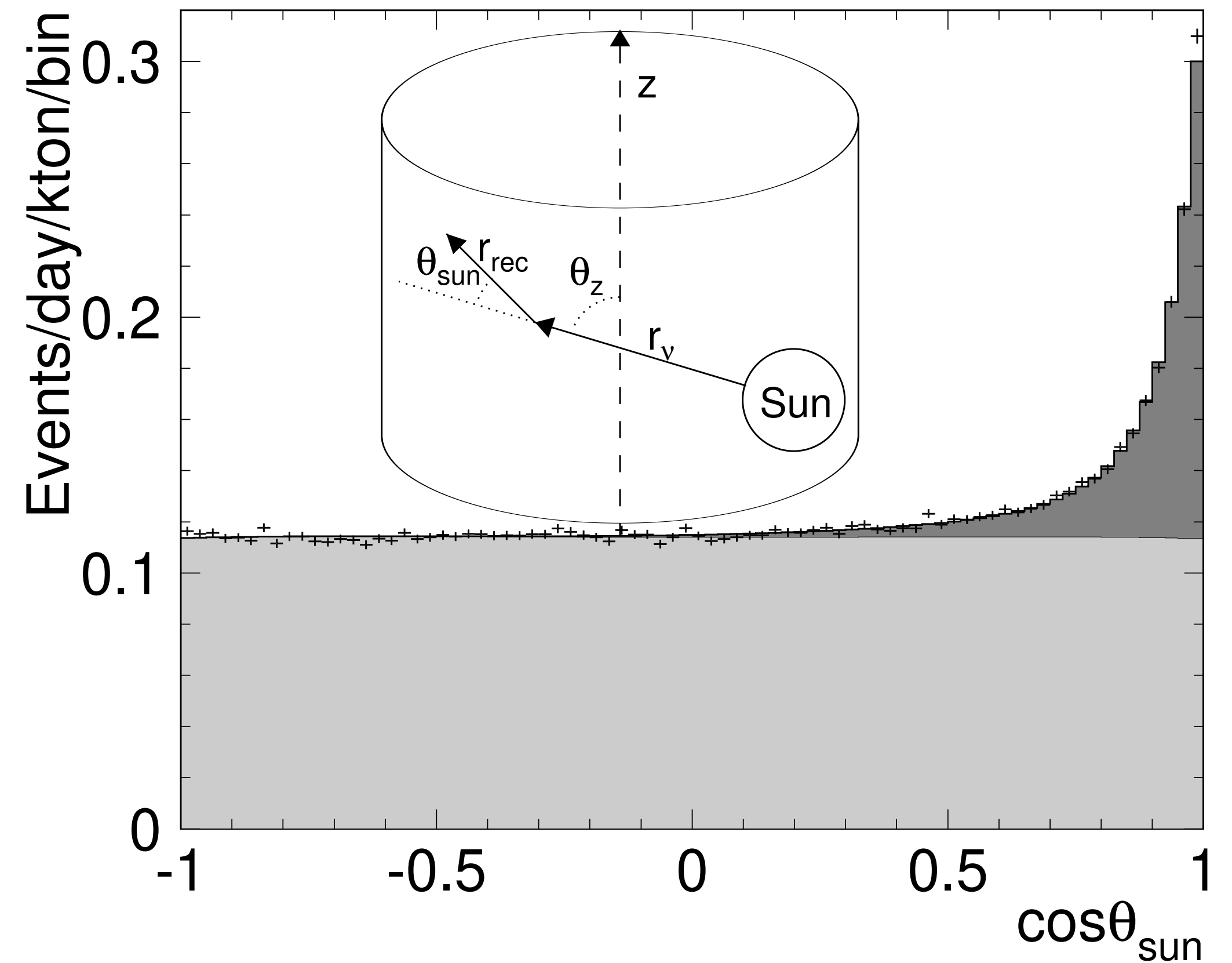
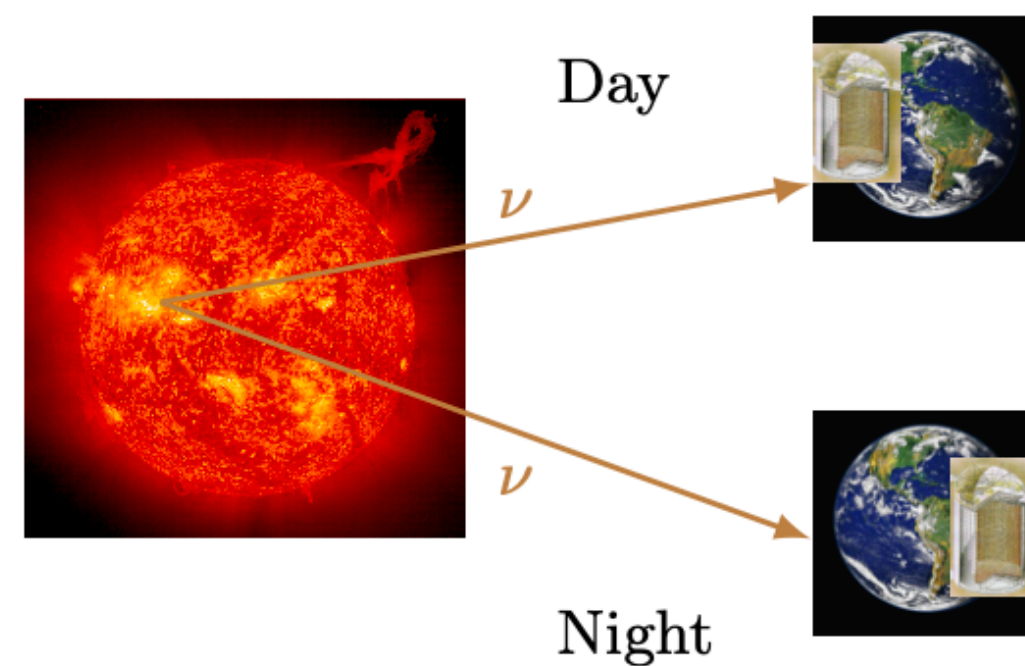


Maltoni and Smirnov, EPJA 52 (2016)  
arXiv:1507.05287

# Solar Neutrinos

The matter effects on the Earth lead to an enhancement 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



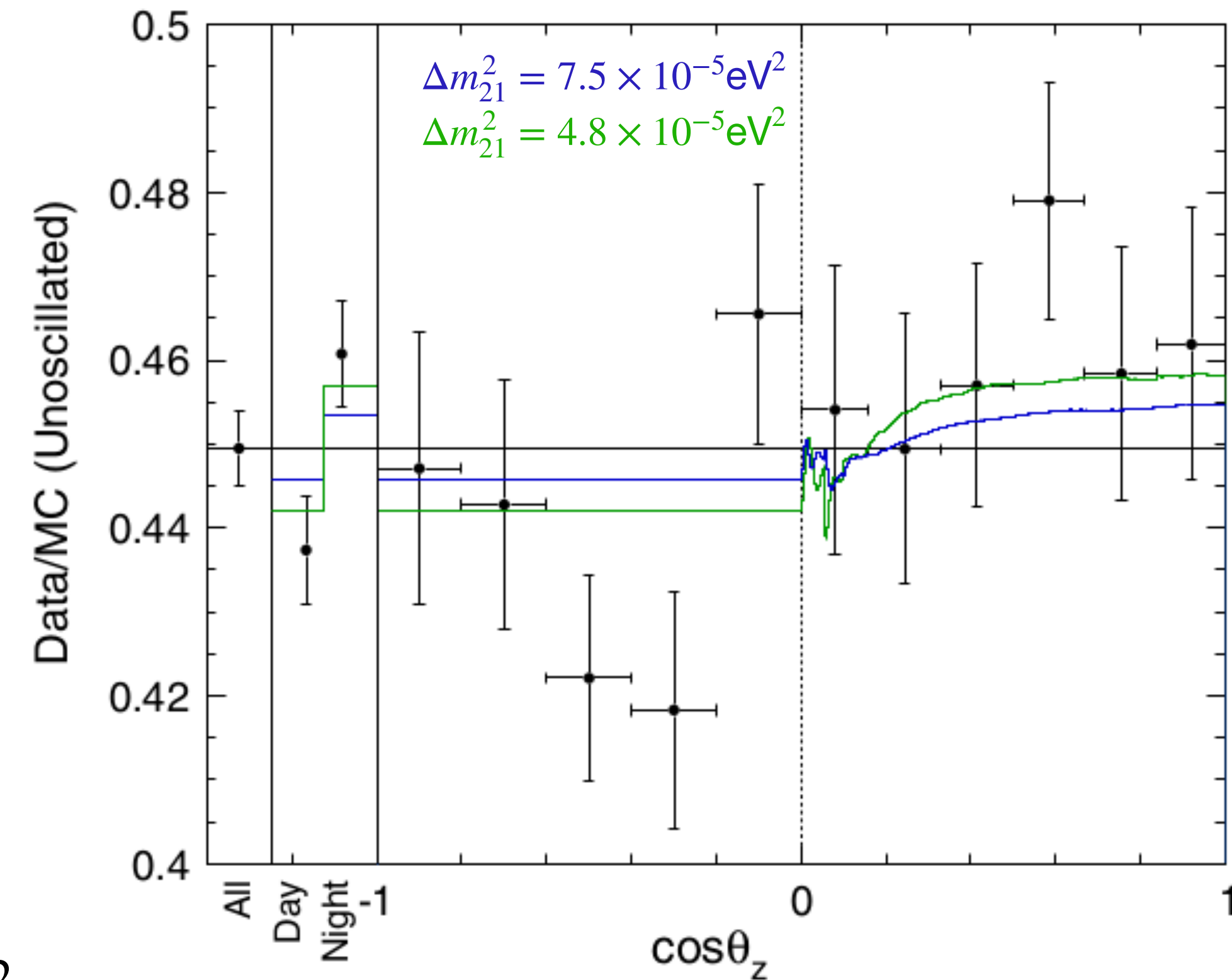
# Solar Neutrinos

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  $\longrightarrow$   $-2.1\%$  SK4-2970

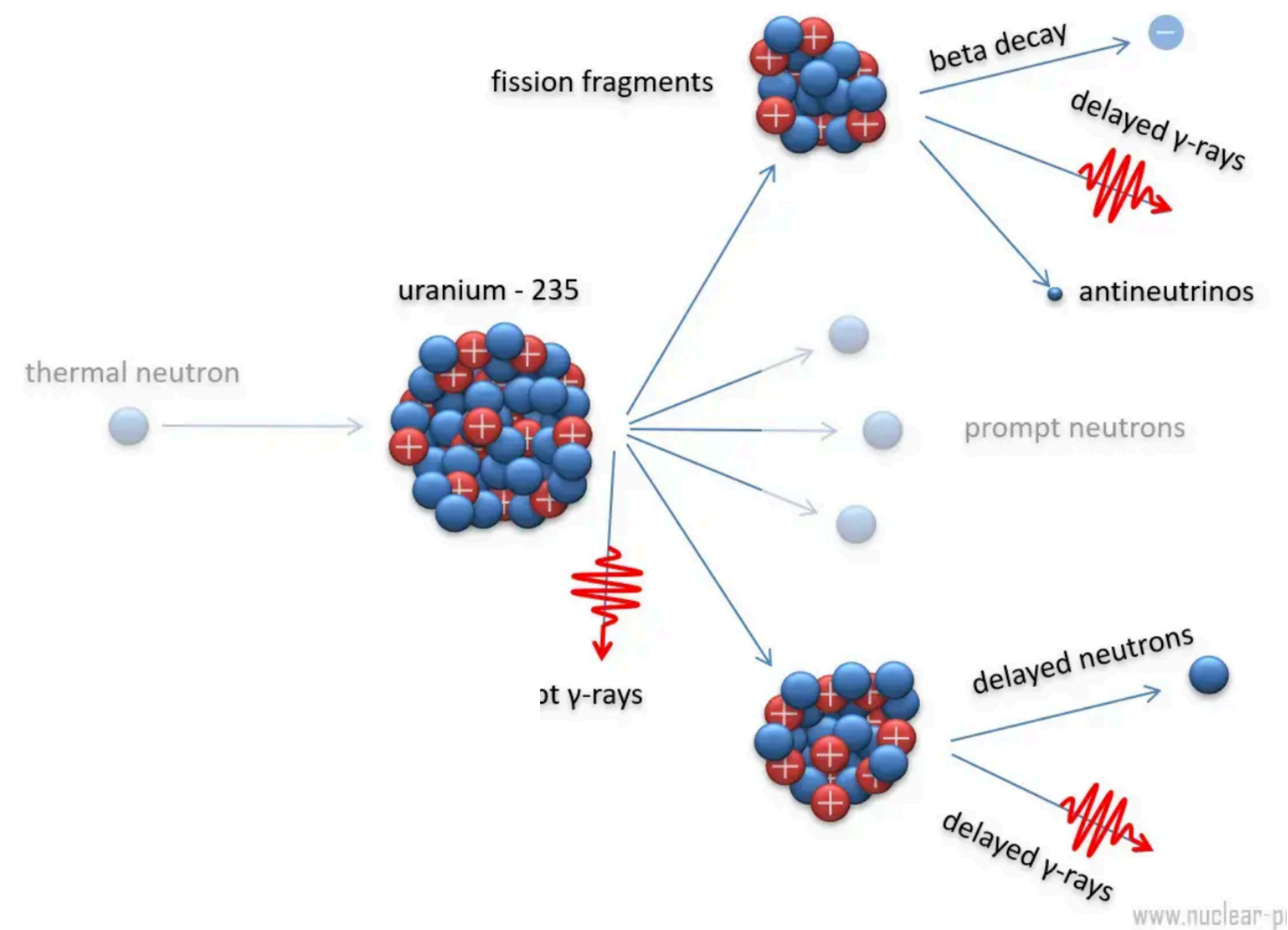
Day-night asymmetry shows a **preference for a small value of  $\Delta m_{21}^2$**



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

# Nuclear Reactors

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



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

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

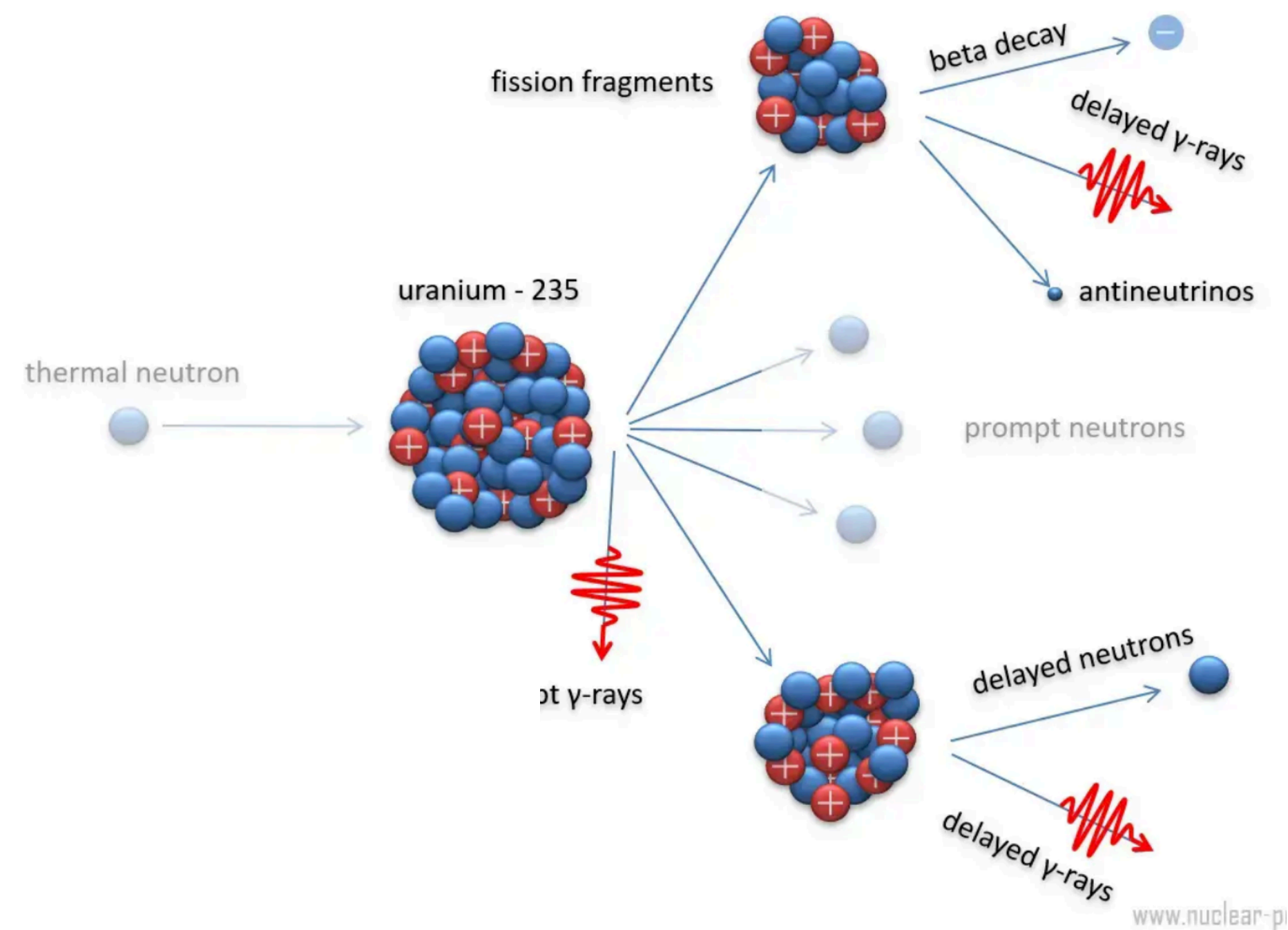


# Nuclear Reactors

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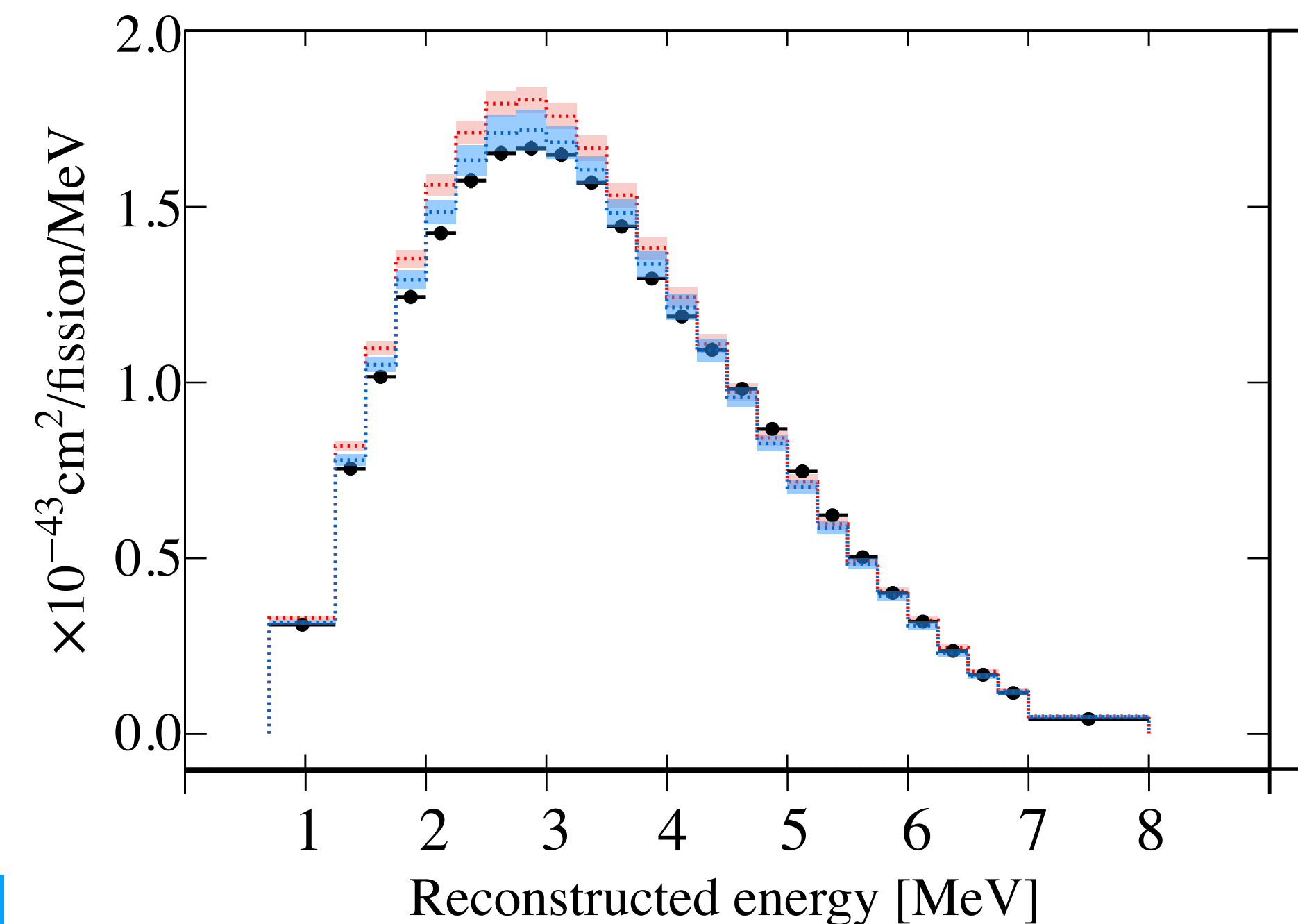
The neutrino flux is created due to the **fission of four different isotopes:**

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



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

The spectrum lies in the MeV range





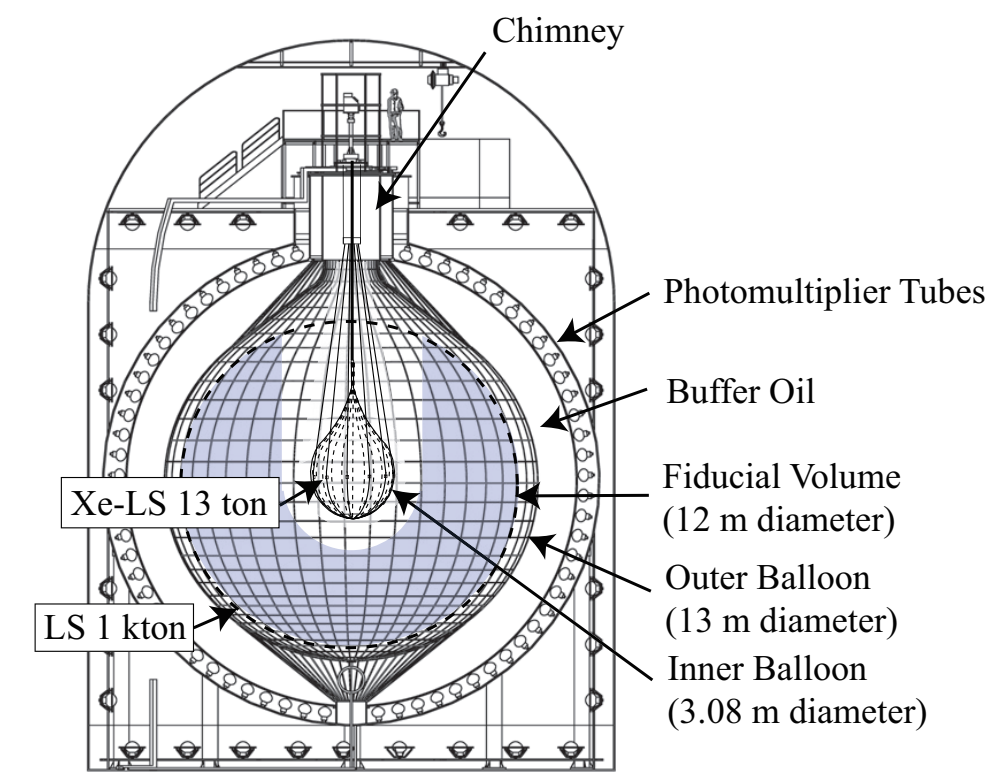
# Nuclear Reactors

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

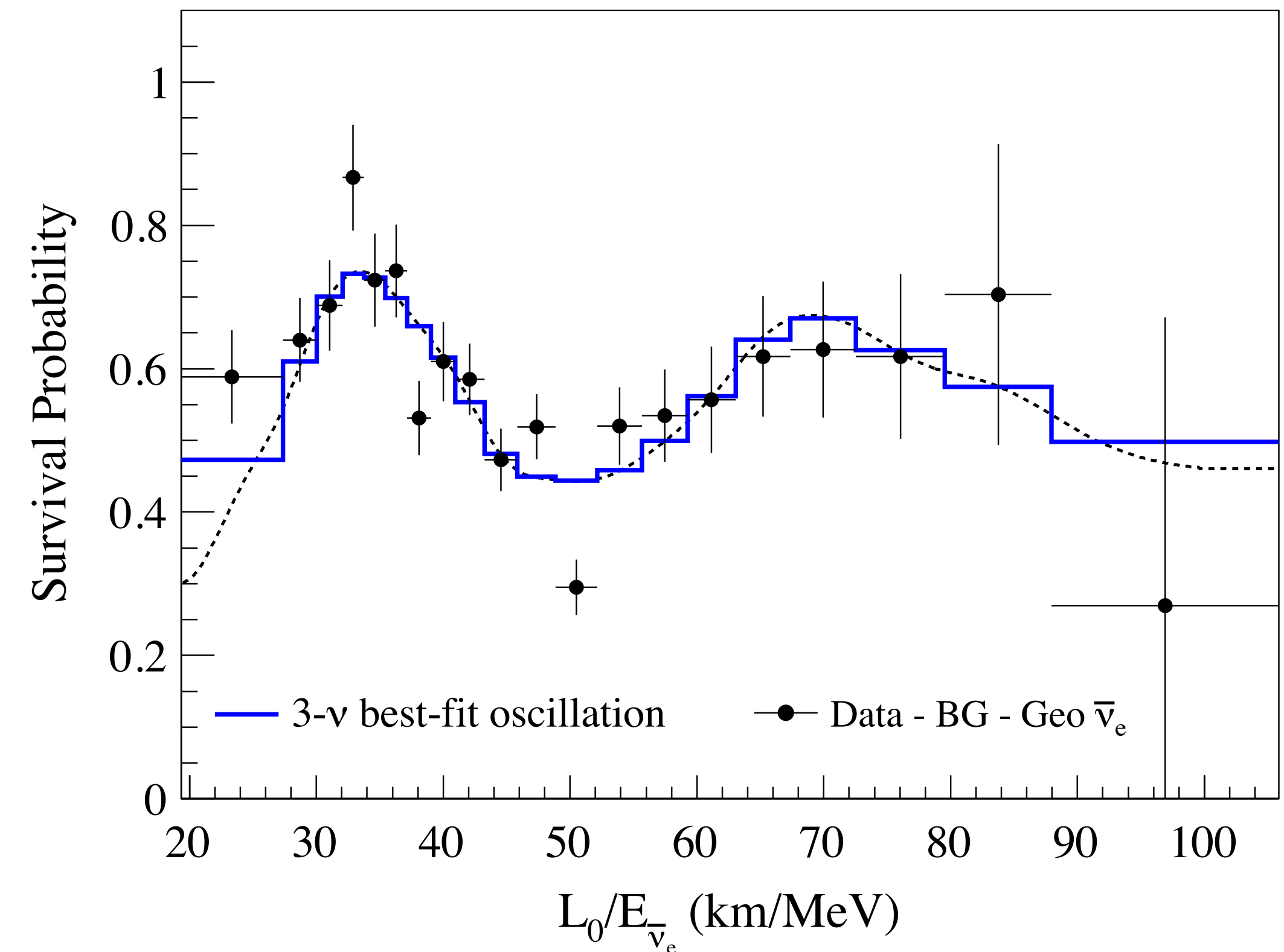
- Detected via inverse  $\beta$ -decay  $\bar{\nu}_e + p \rightarrow e^+ + n$
- The average baseline is  $L \sim 200\text{km}$

For reactor neutrinos can be described in vacuum

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



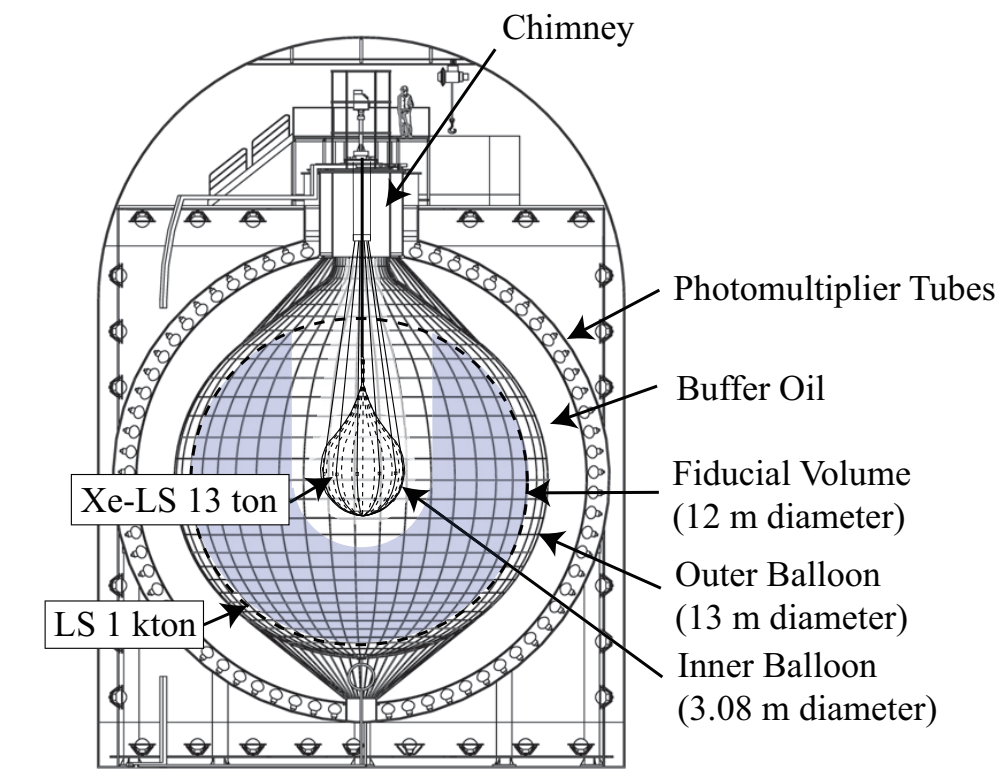
A. Gando et al. (KamLAND) PRD 88 (2013)



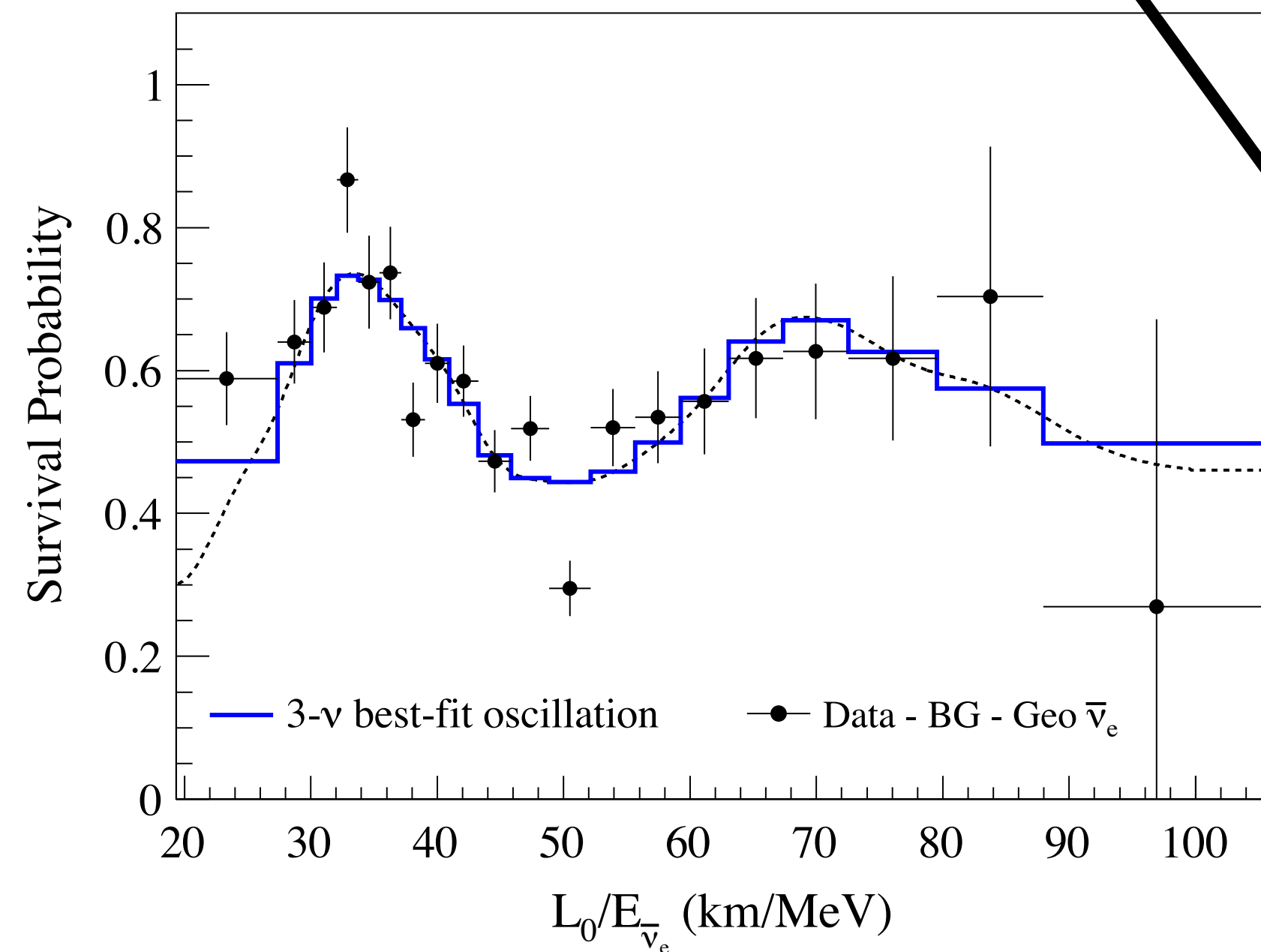
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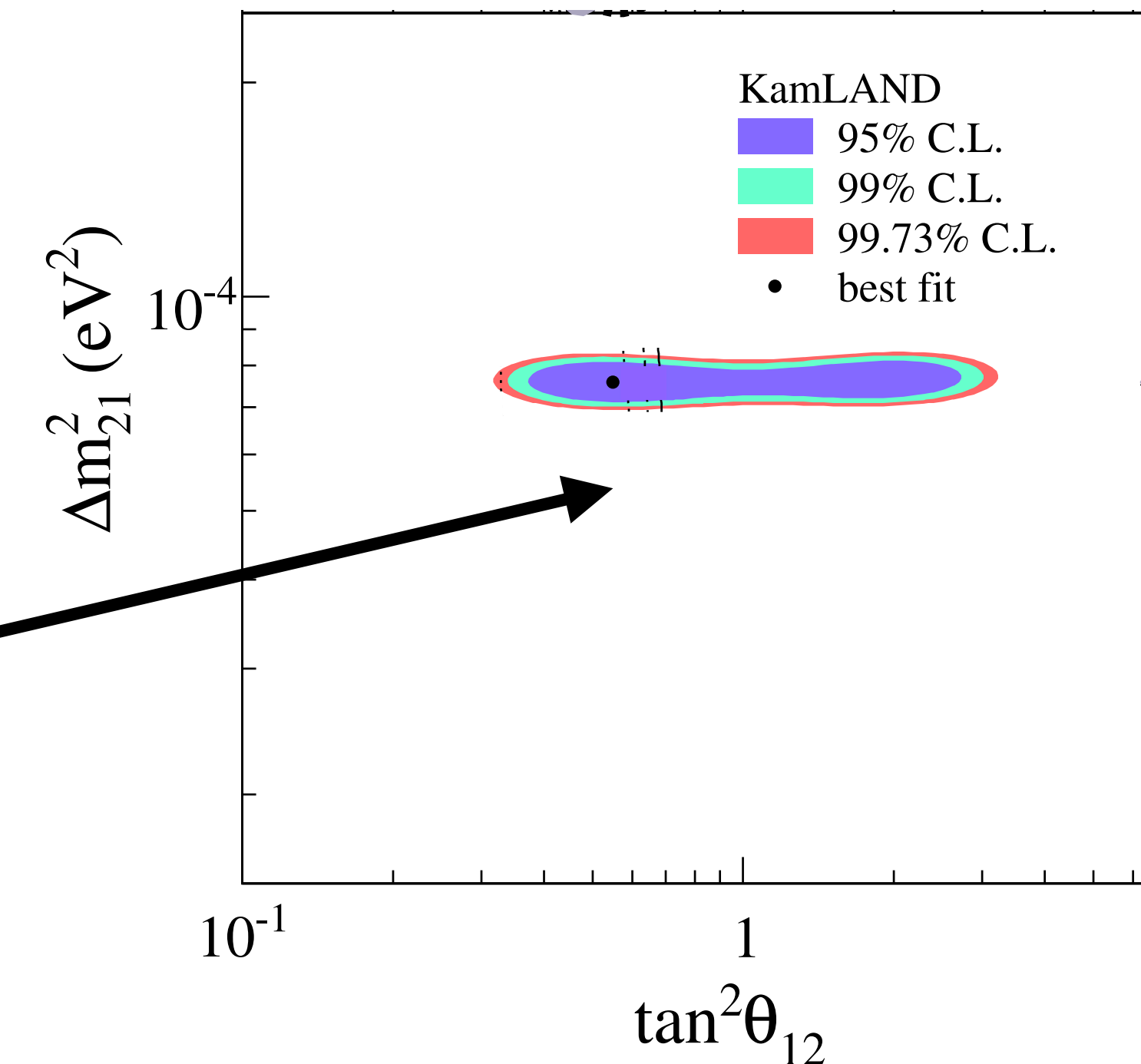


A. Gando et al. (KamLAND) PRD 88 (2013)



Precise measurement of  $\Delta m_{21}^2$

Vacuum oscillation probability cannot resolve the octant of  $\theta_{12}$

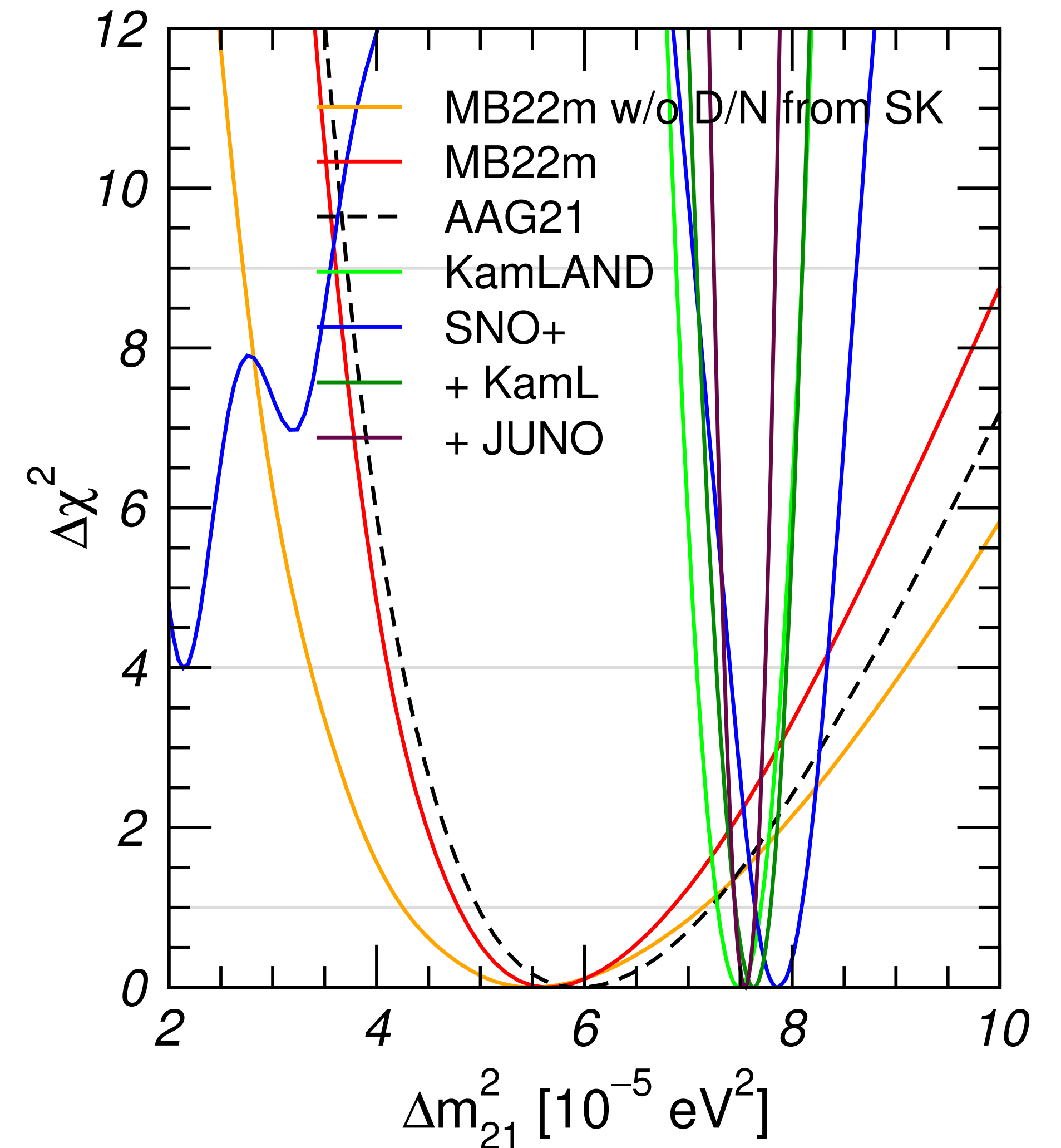
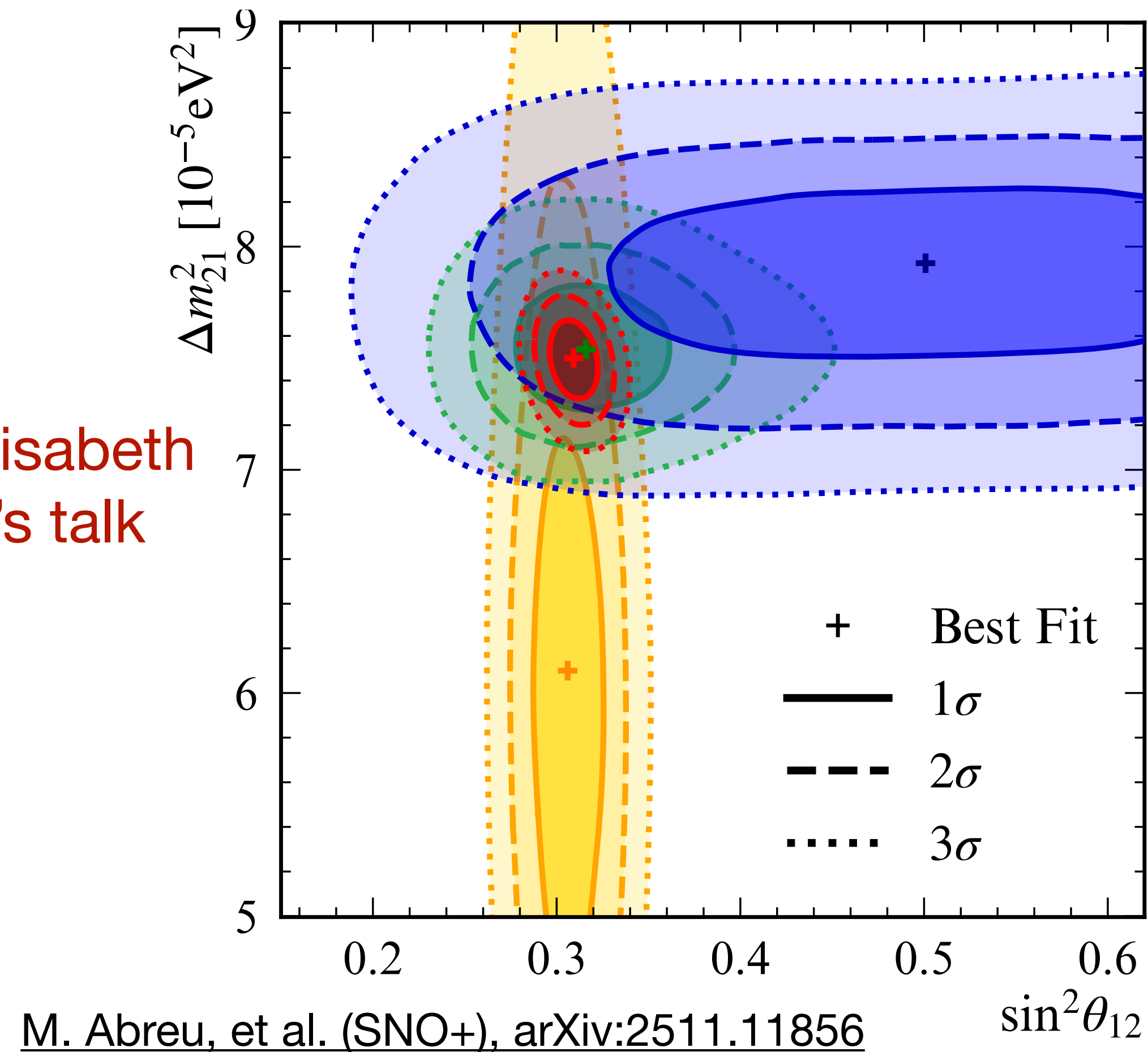


# Nuclear Reactors

**SNO+** has increased the dataset showing **good agreement** with other reactor and solar measurements

NuFIT 6.1 (2025)

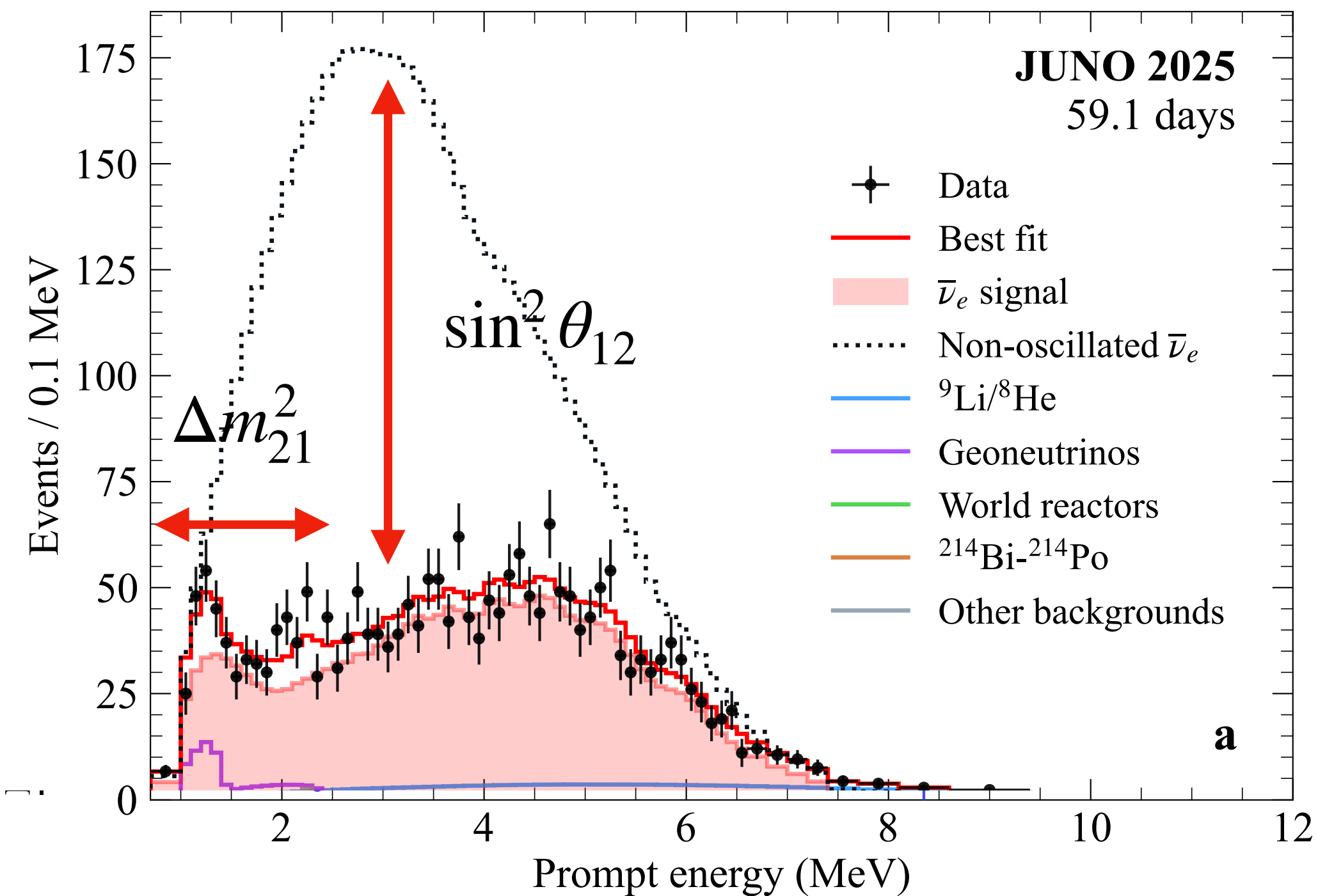
See Elisabeth  
Falk's talk



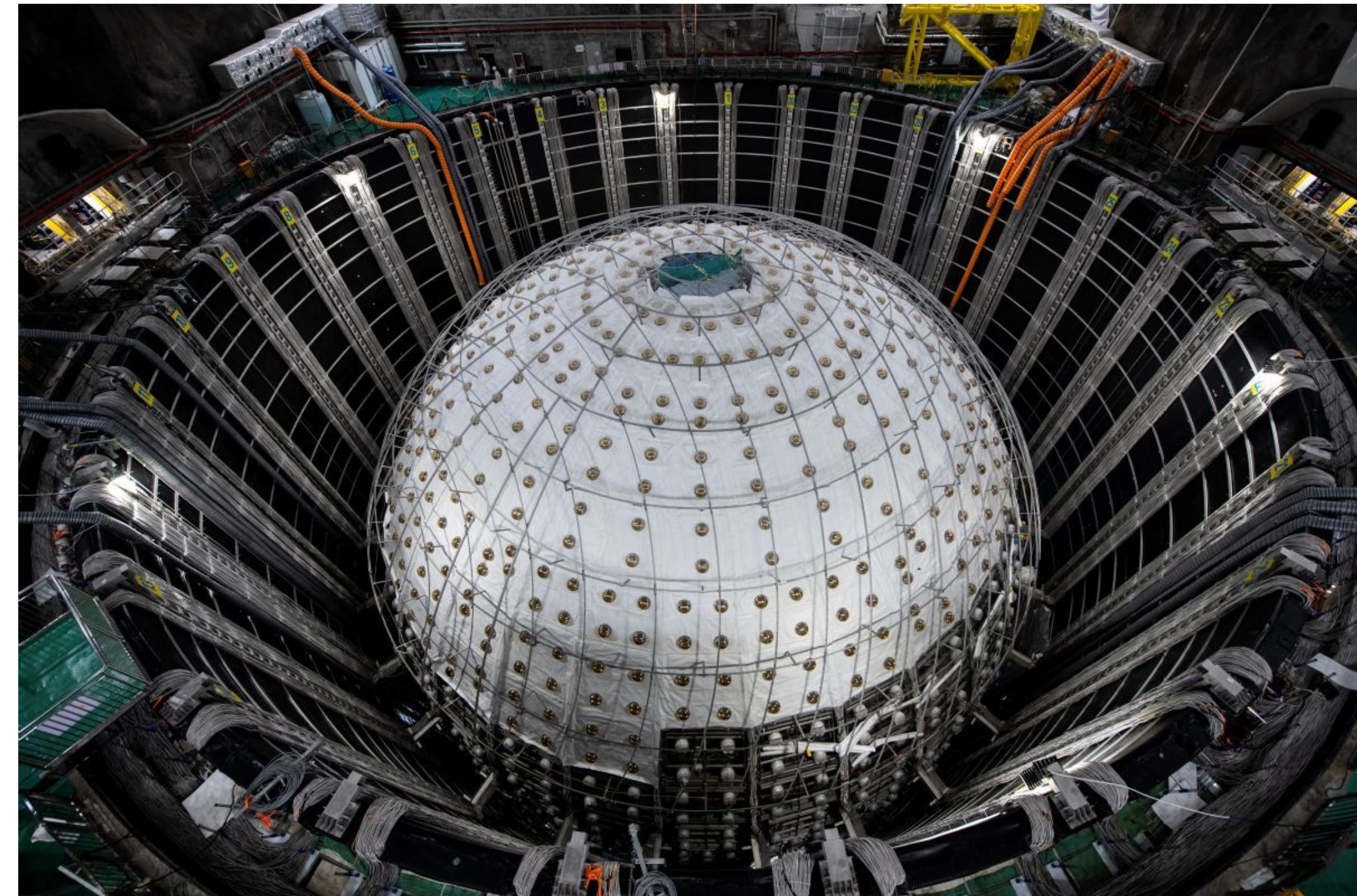


# Nuclear Reactors

**JUNO** has performed the most precise measurement of  $\Delta m_{12}^2$  and  $\sin^2 \theta_{12}$



A. Abusleme et al. (JUNO),  
[arXiv:2511.14593](https://arxiv.org/abs/2511.14593)



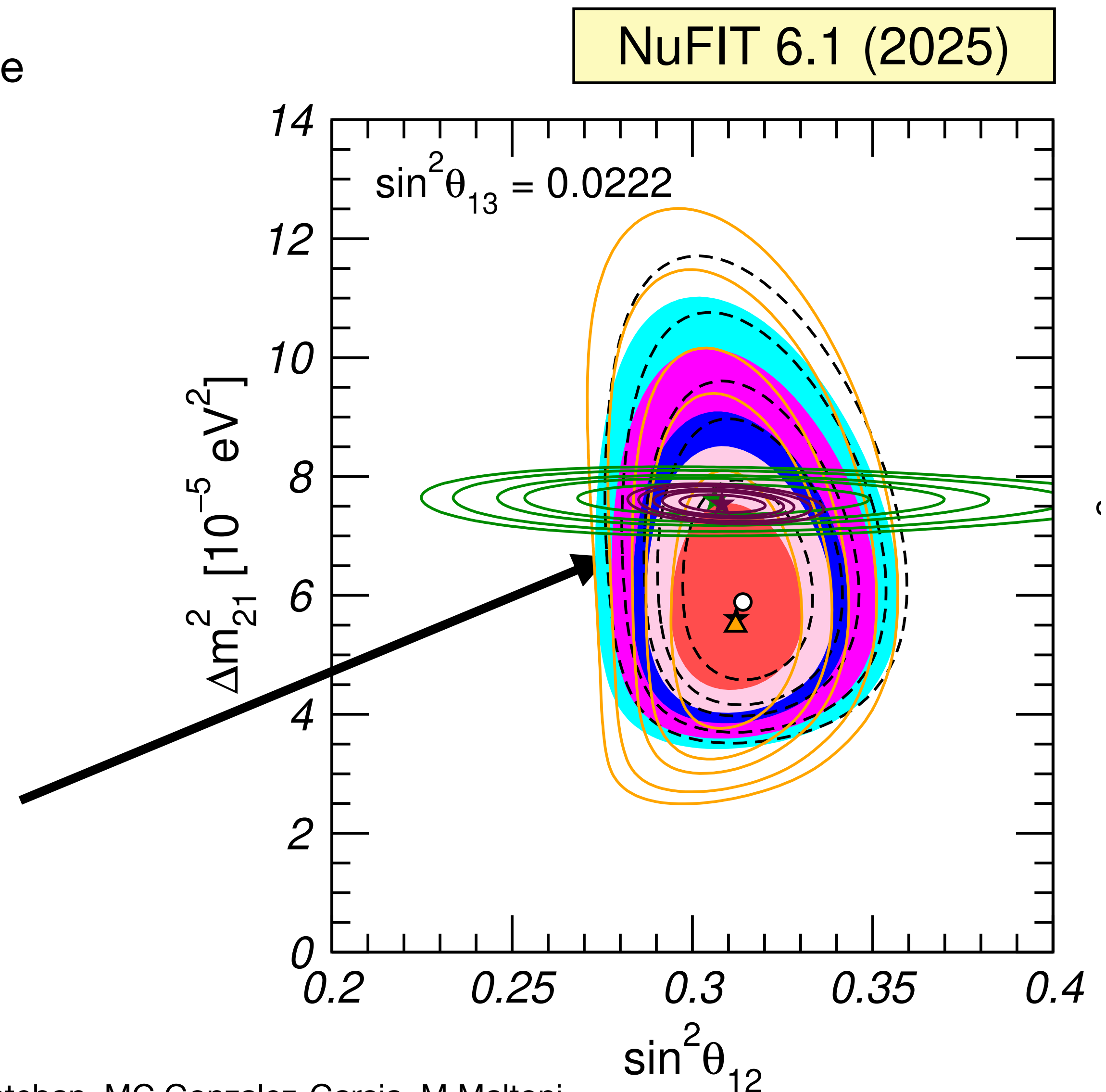


# Solar Sector: $\theta_{12}$ and $\Delta m_{21}^2$

Combining solar and reactor measurements, we can resolve the octant of  $\theta_{12}$

- **JUNO and KamLAND** determined  $\Delta m_{21}^2$
- **JUNO and Solar** experiments determined  $\theta_{12}$

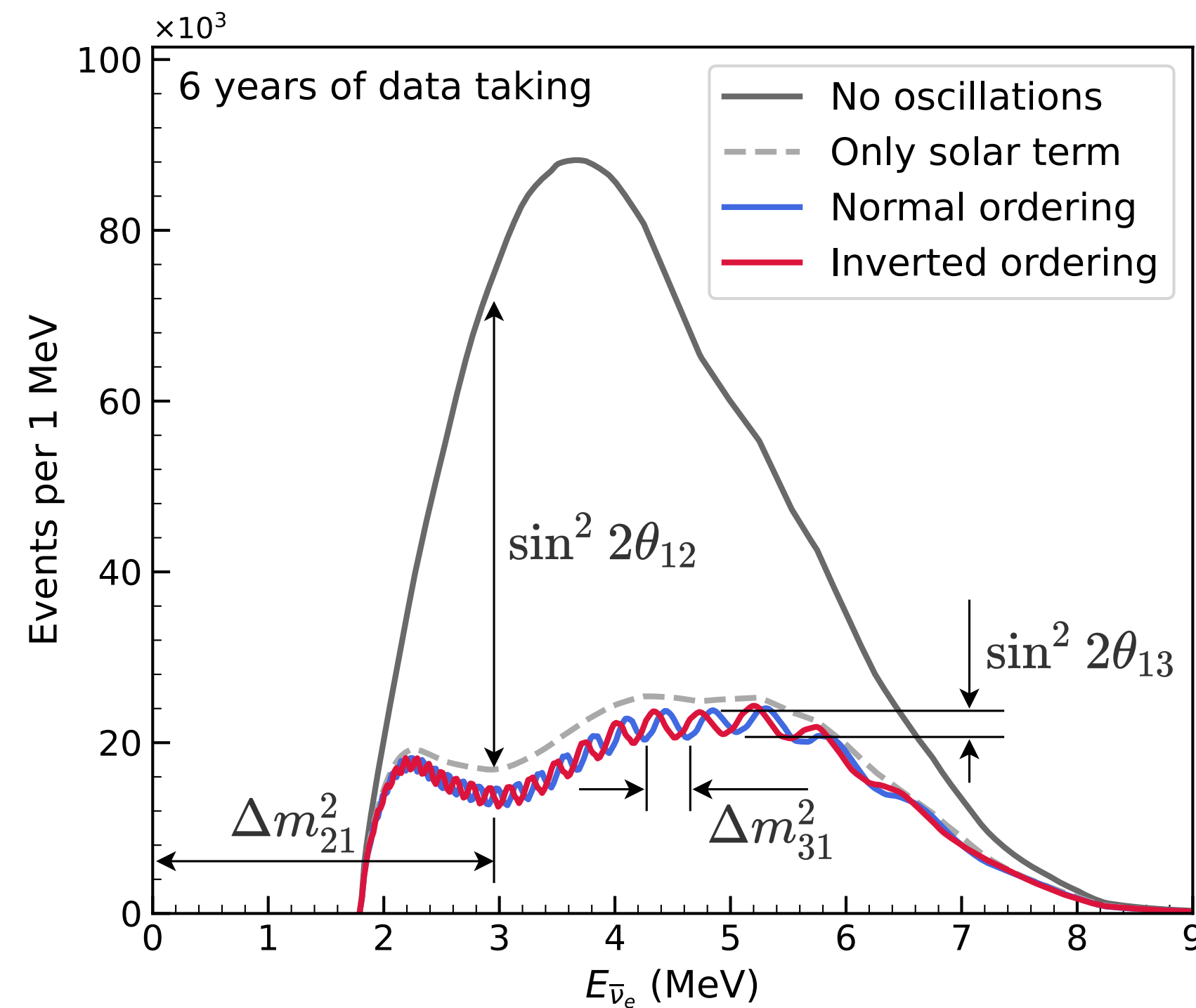
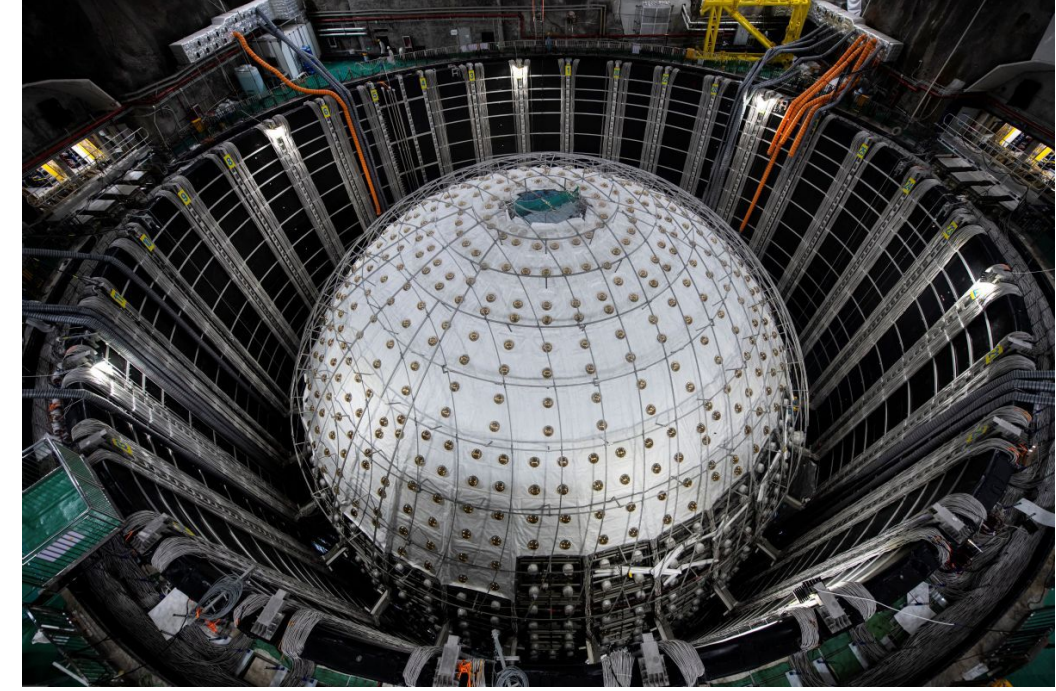
Tension in the determination of  $\Delta m_{21}^2$   
between reactor and solar experiments



# JUNO

Together with the solar parameters, JUNO is capable of measuring  $\Delta m_{31}^2$

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

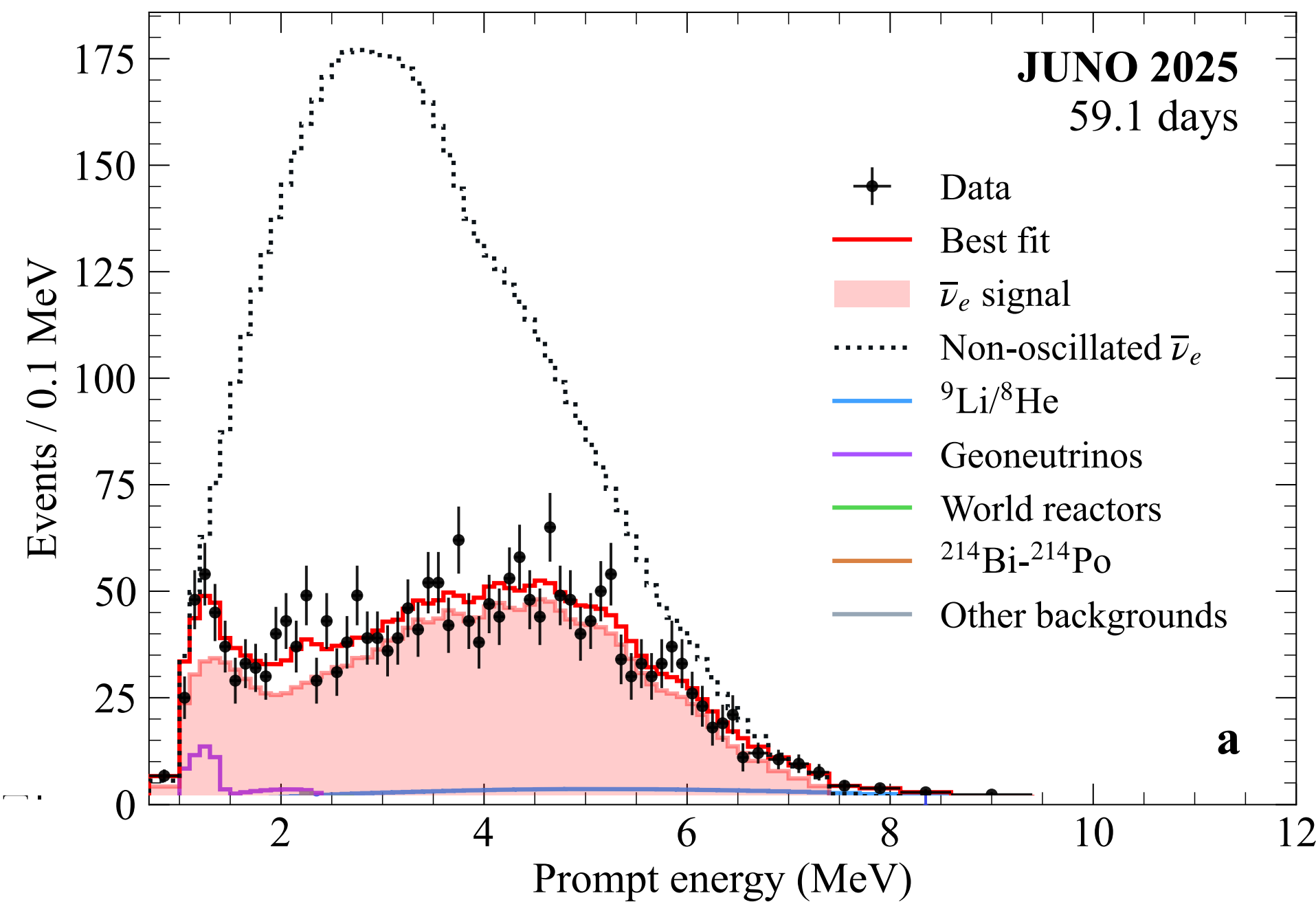




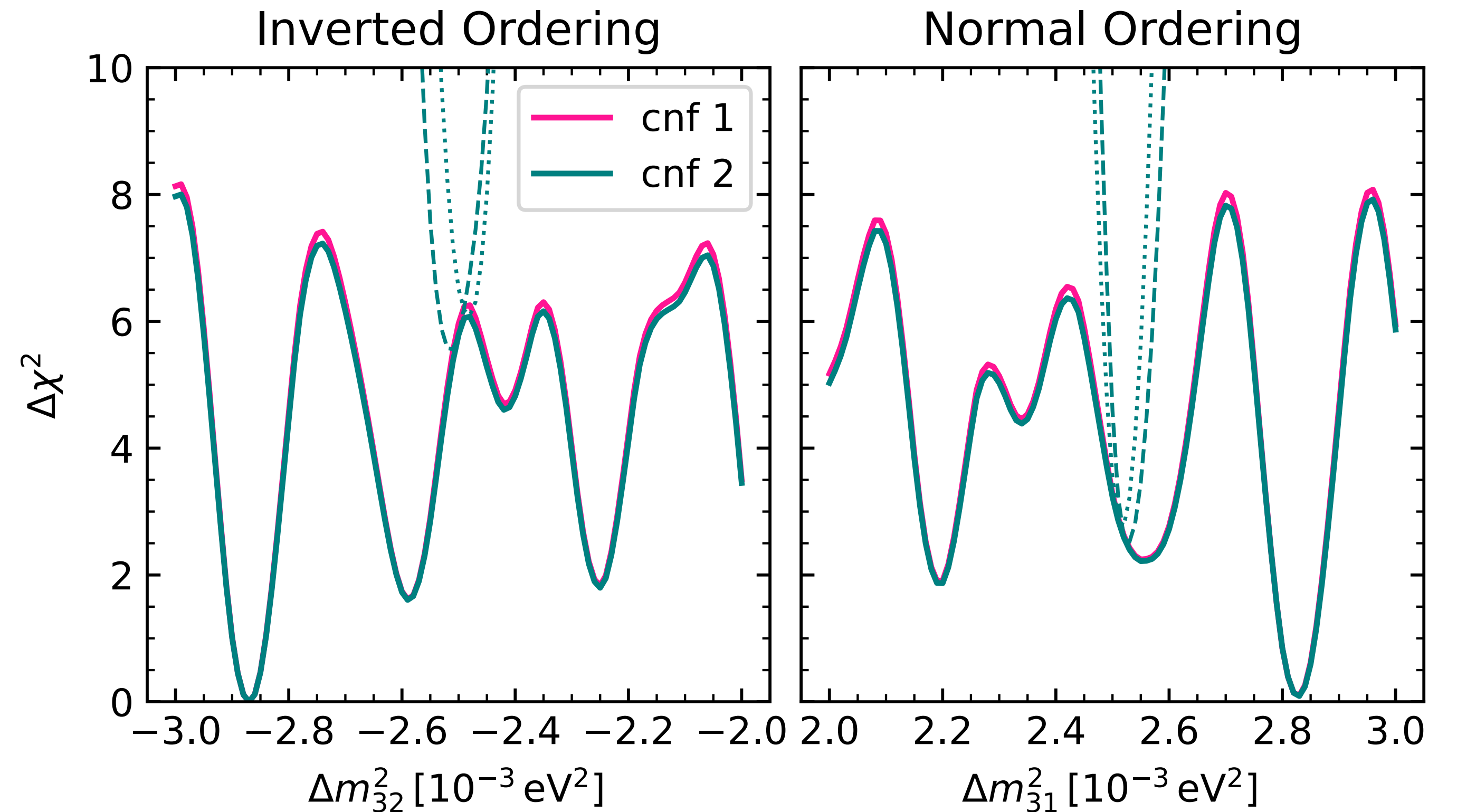
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A. Abusleme et al. (JUNO),  
arXiv:2511.14593

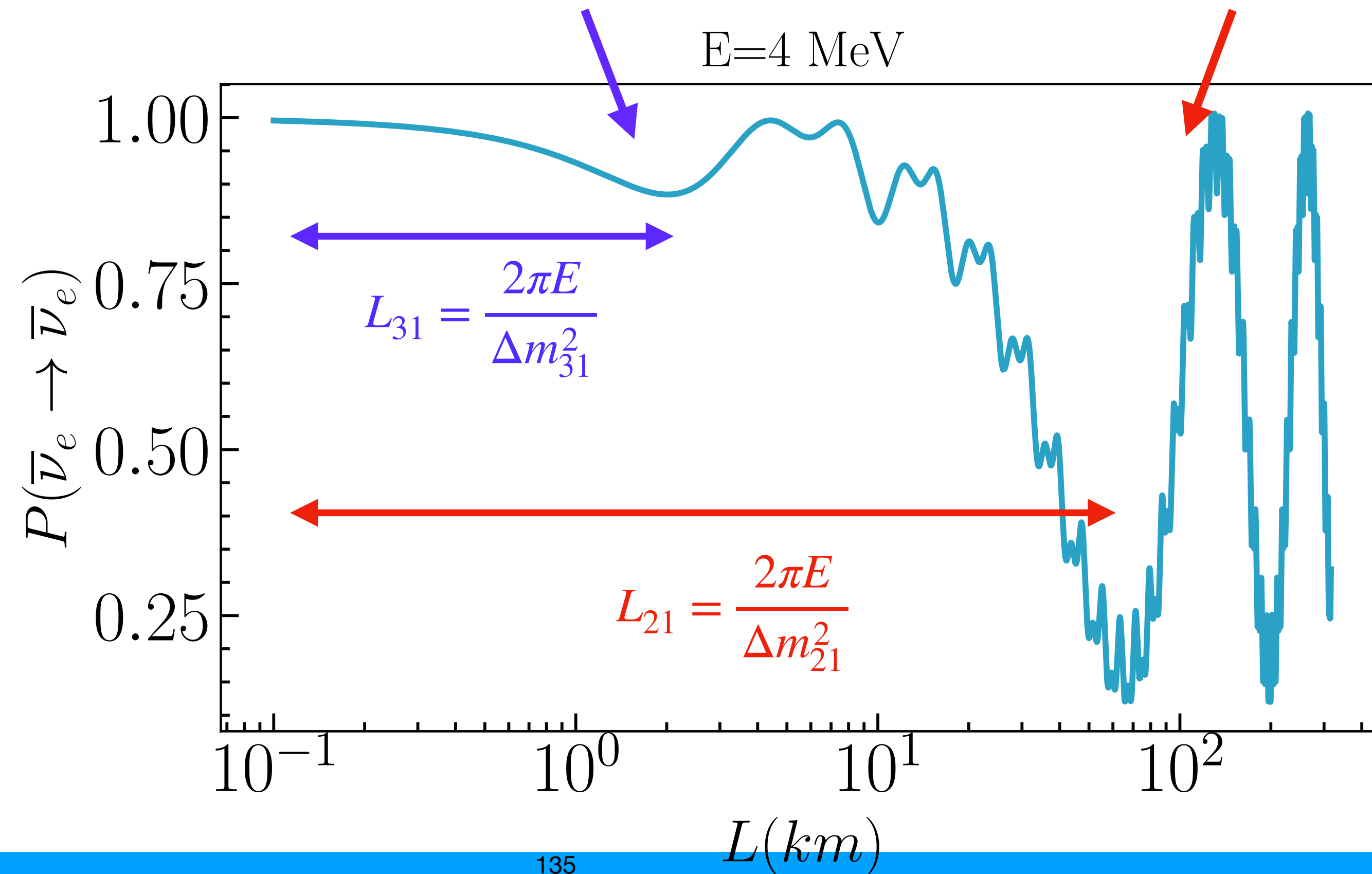


Solid: JUNO      Dashed/dotted:  $|\Delta m_{3l}^2|$  from the global-fit

# Reactor neutrinos: $\theta_{13}$ and $\Delta m_{31}^2$

At shorter distances, neutrino evolution is dominated by  $\Delta m_{31}^2$  and  $\theta_{13}$

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





# Reactor neutrinos: $\theta_{13}$ and $\Delta m_{31}^2$

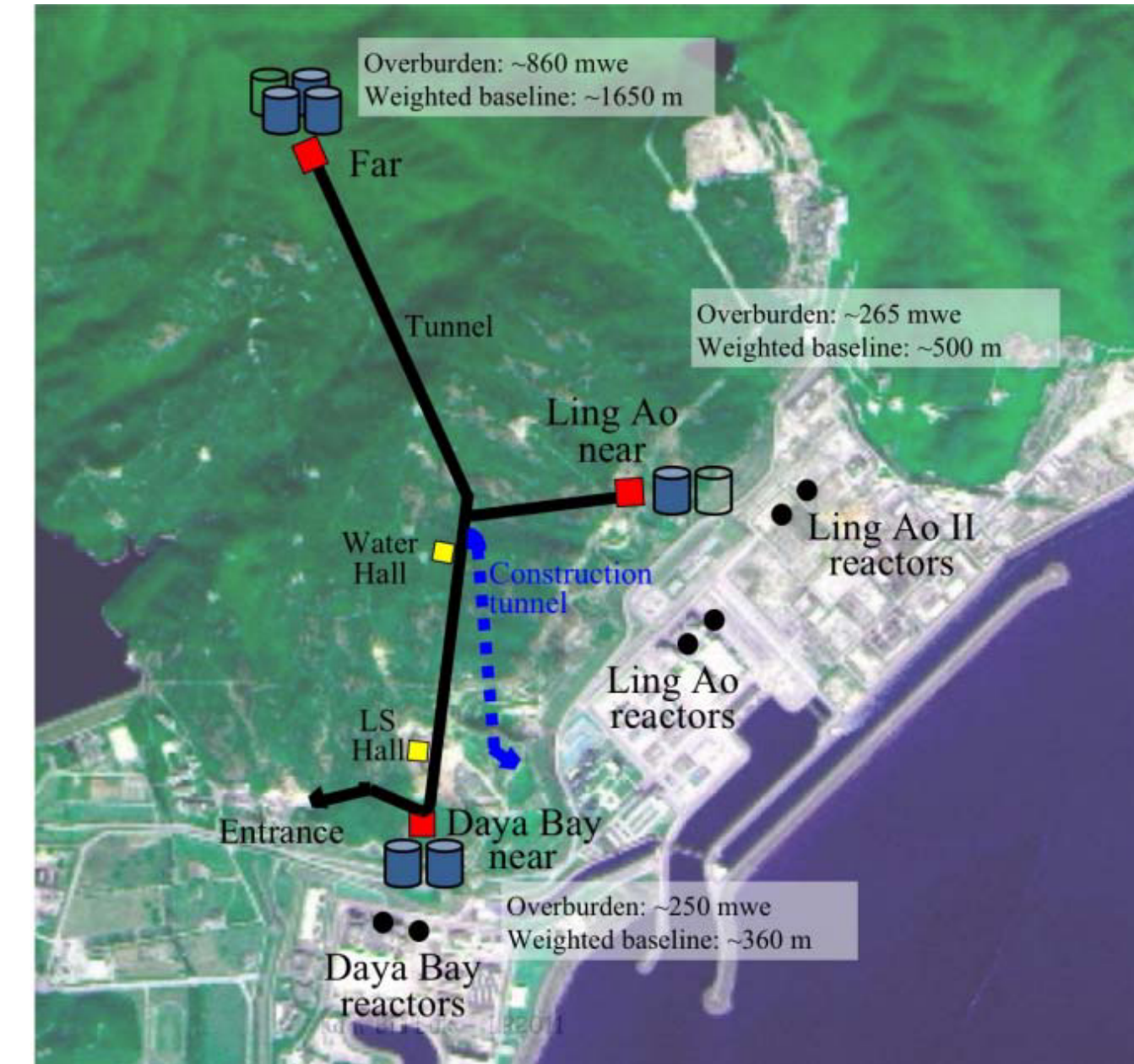
At shorter distances, neutrino evolution is dominated by  $\Delta m_{31}^2$  and  $\theta_{13}$

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

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

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

Daya Bay



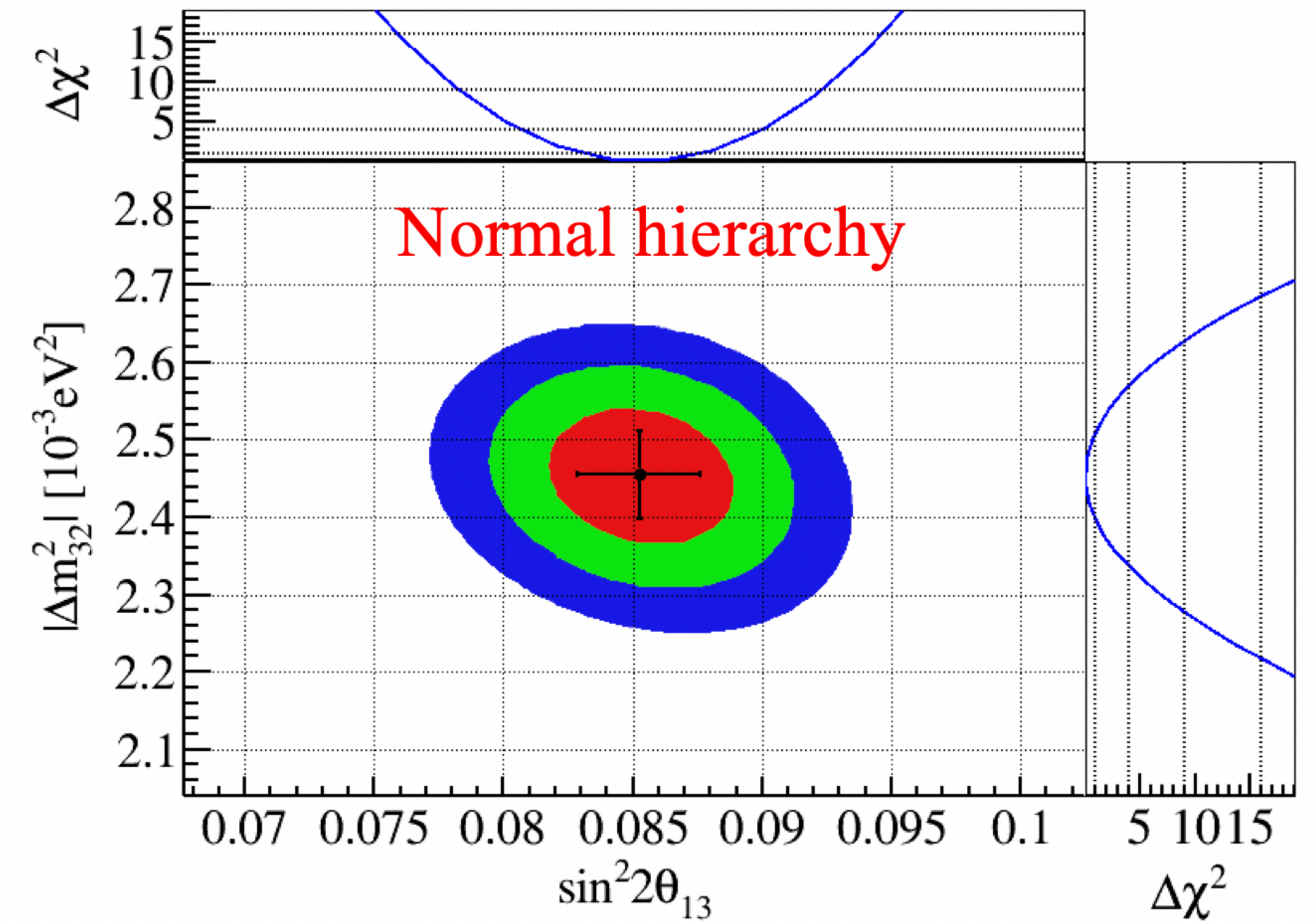
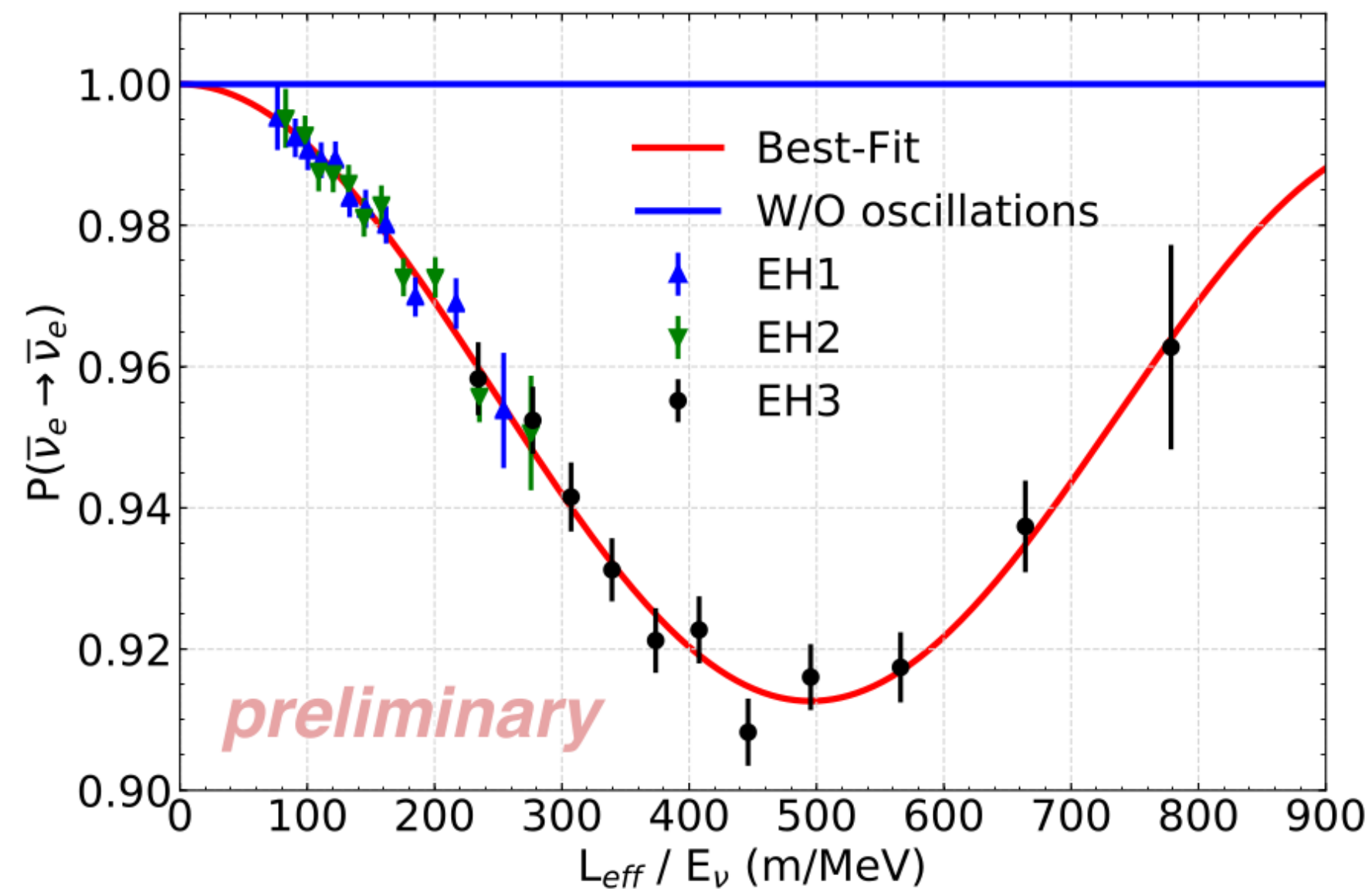
Similar configuration used by RENO and Double Chooz



# Reactor neutrinos: $\theta_{13}$ and $\Delta m_{31}^2$

At shorter distances, neutrino evolution is dominated by  $\Delta m_{31}^2$  and  $\theta_{13}$

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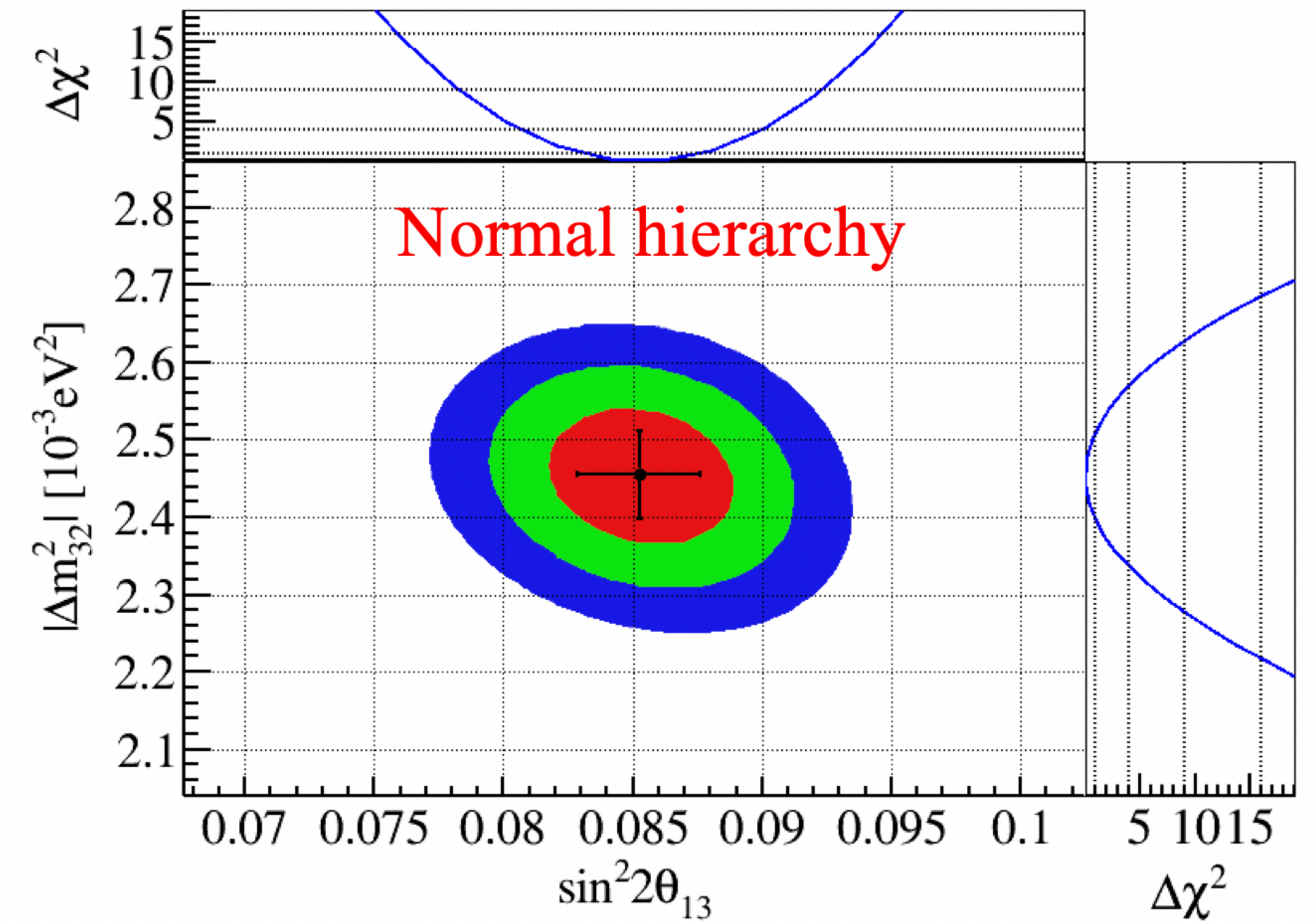
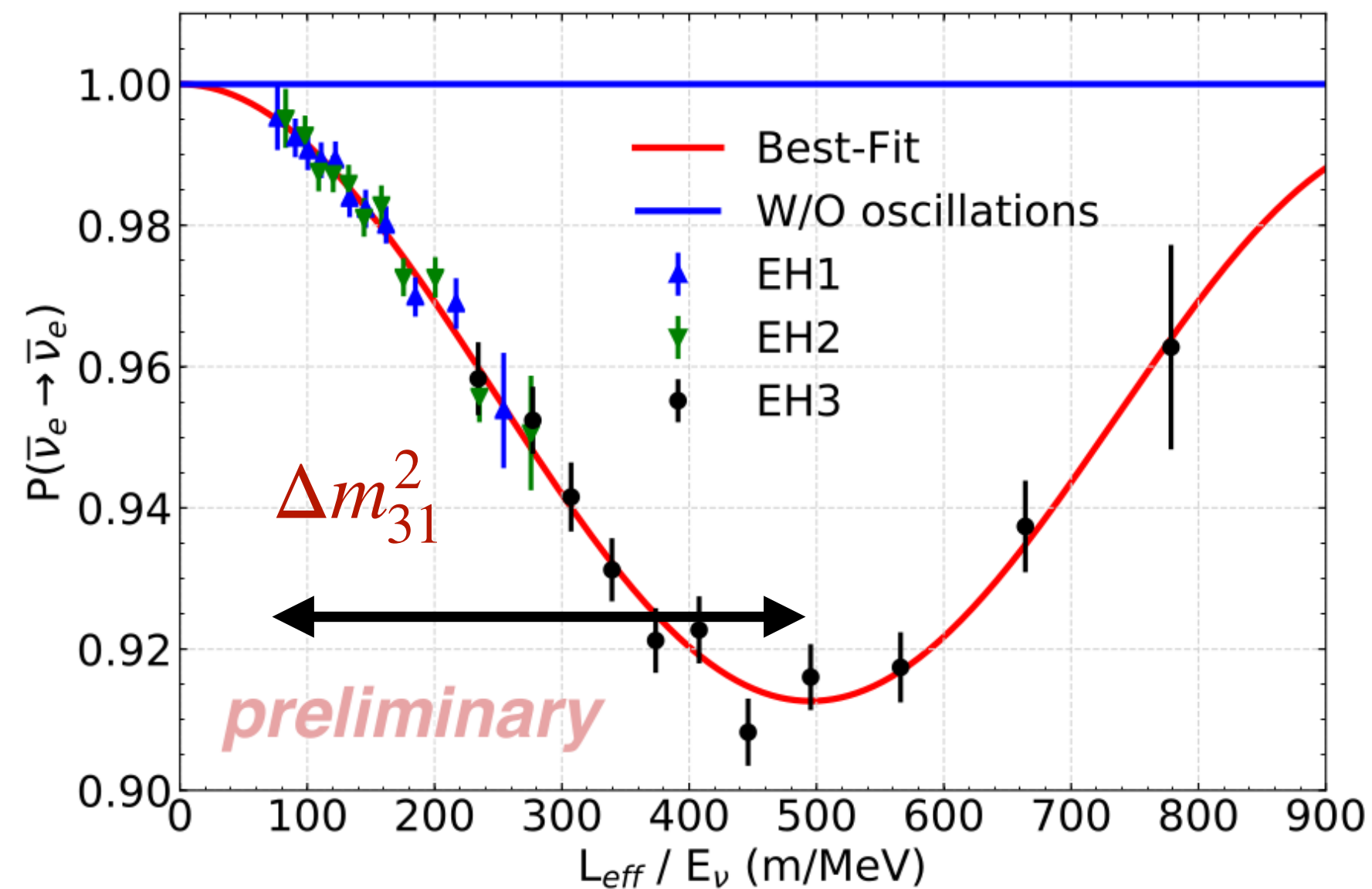
- Near detector imposes an upper bound over  $\Delta m_{31}^2$
- The oscillation measured at the far detector imposes a lower bound on  $\theta_{13}$  and  $\Delta m_{31}^2$



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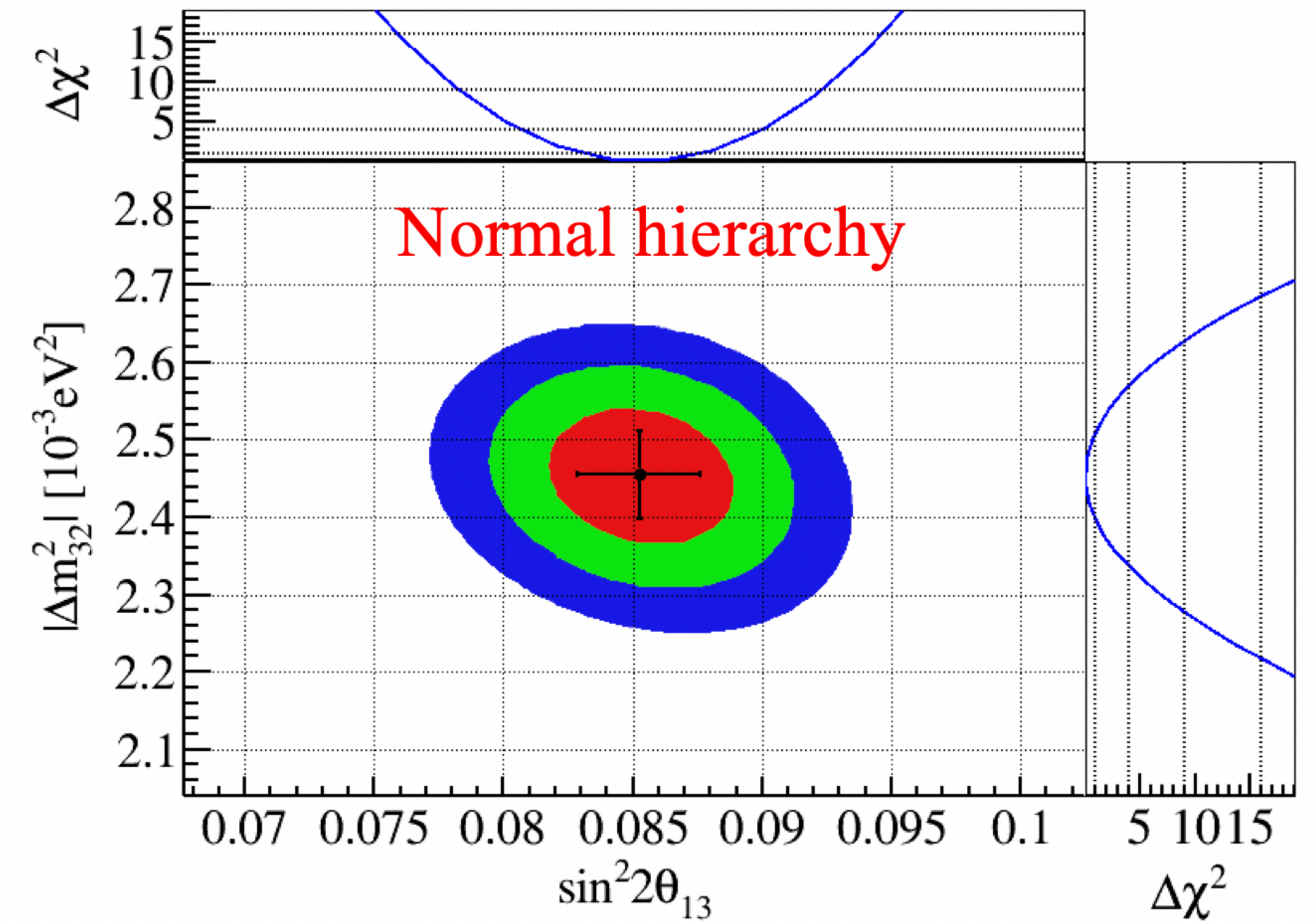
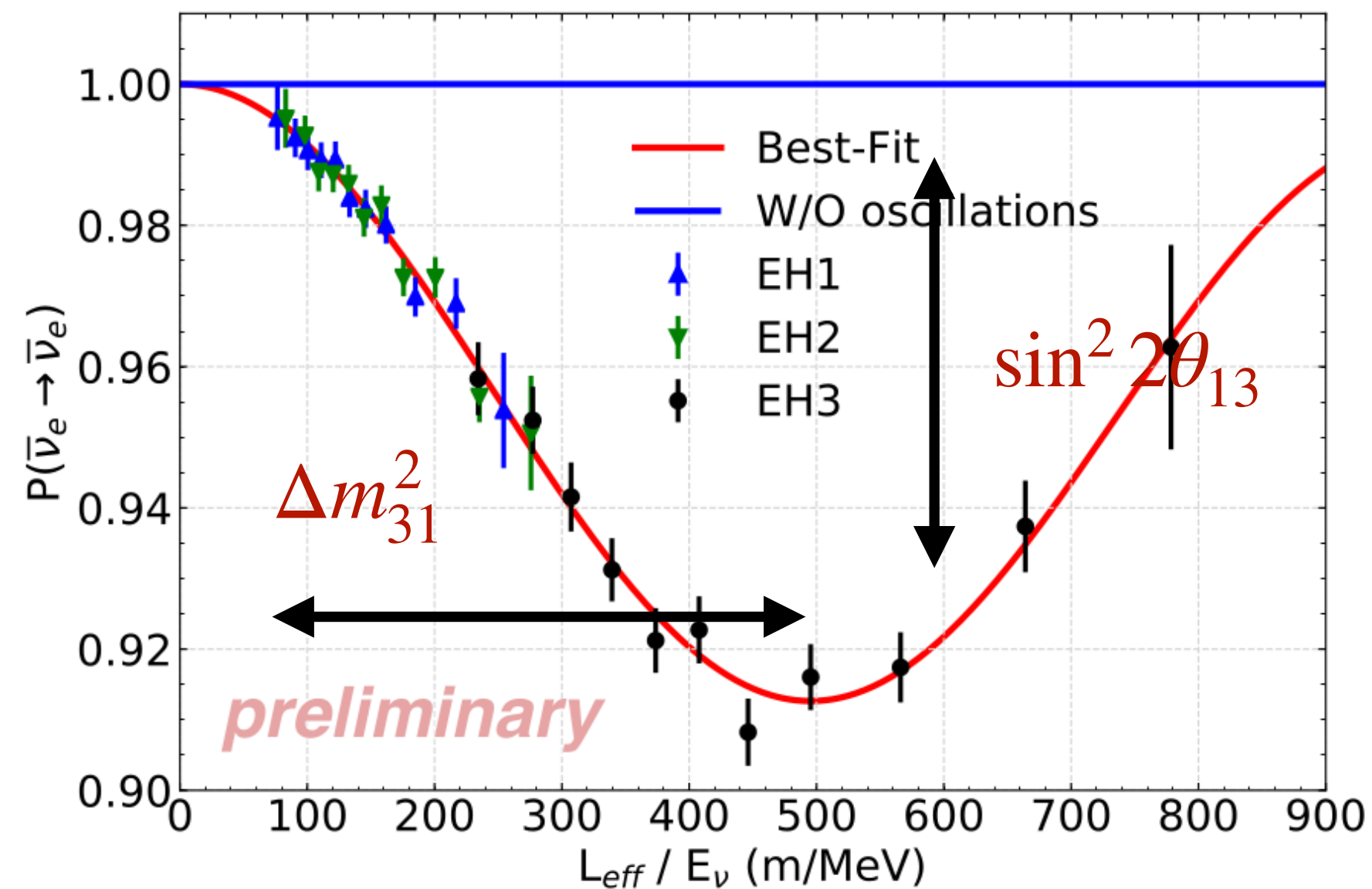
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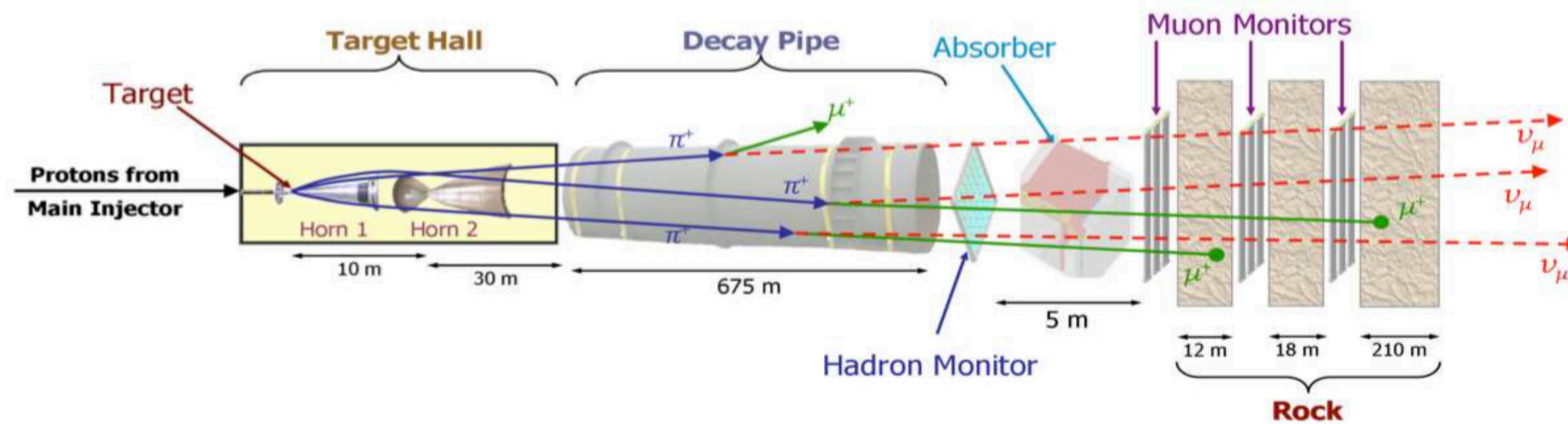
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# Long-Baseline Accelerators

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

$$\pi^{\pm} \rightarrow \mu^{\pm} + \bar{\nu}_{\mu}^{(-)}$$

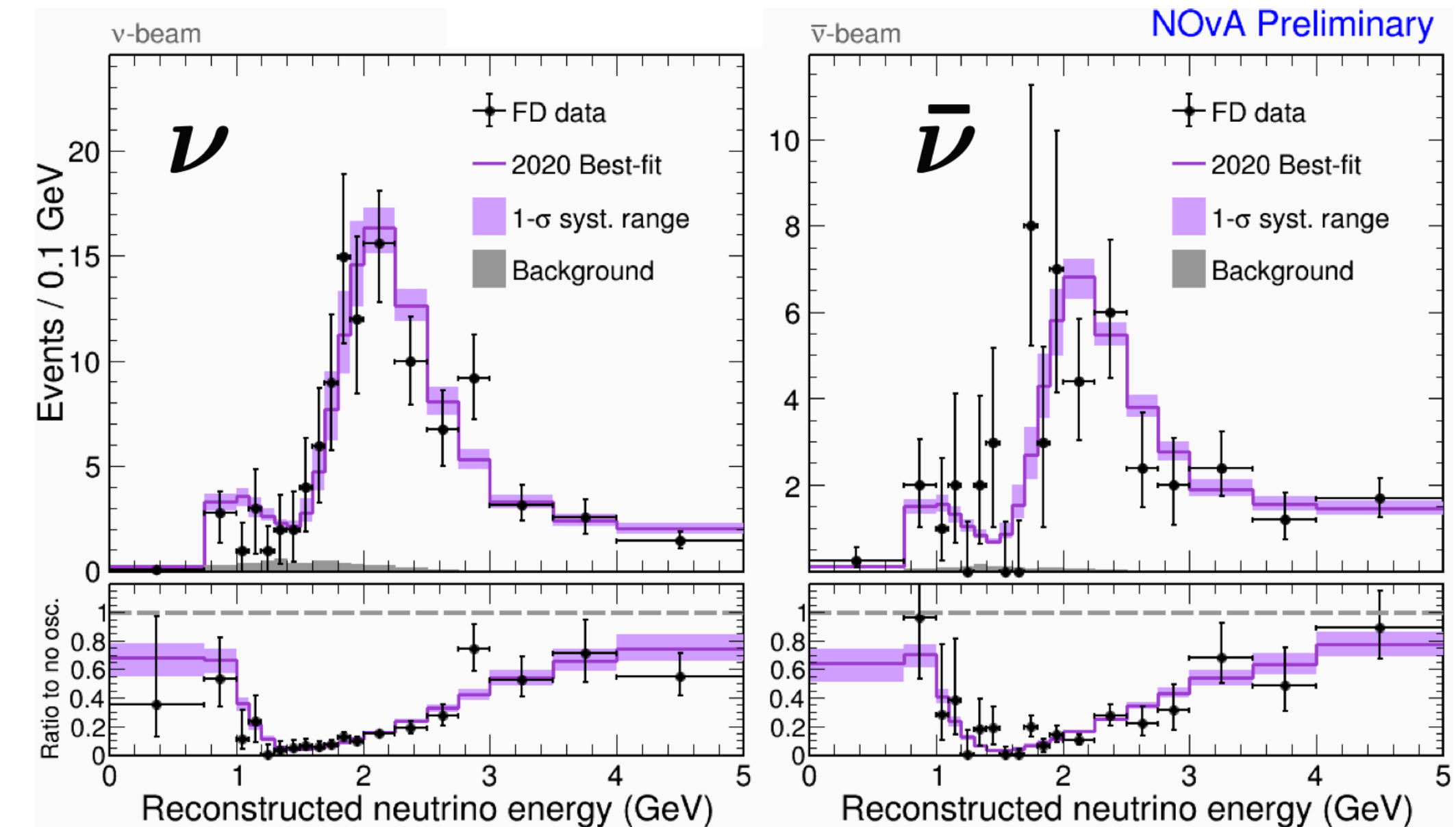


NuMI Beam

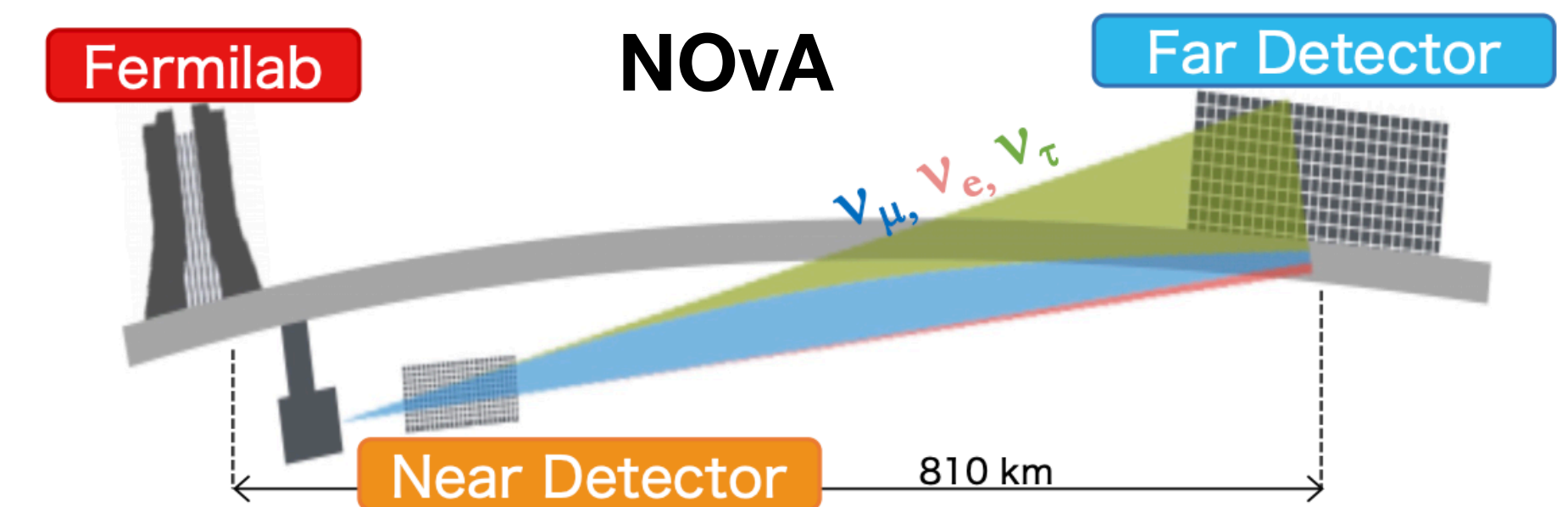
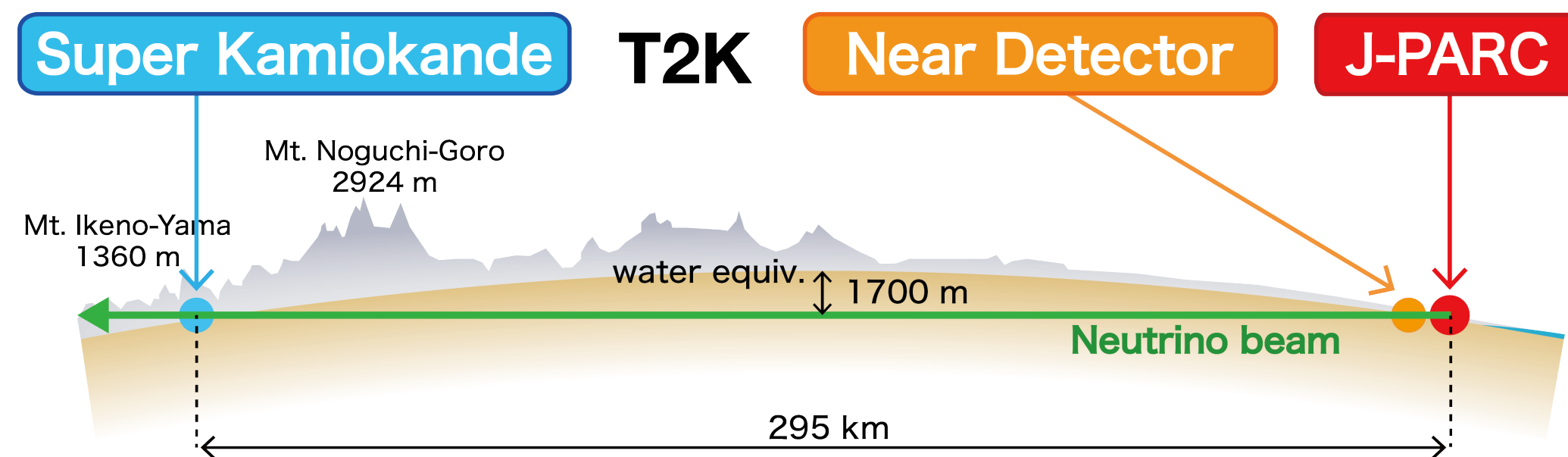
# Long-Baseline Accelerators

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

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



Nosek (NOvA Collaboration) Fermilab



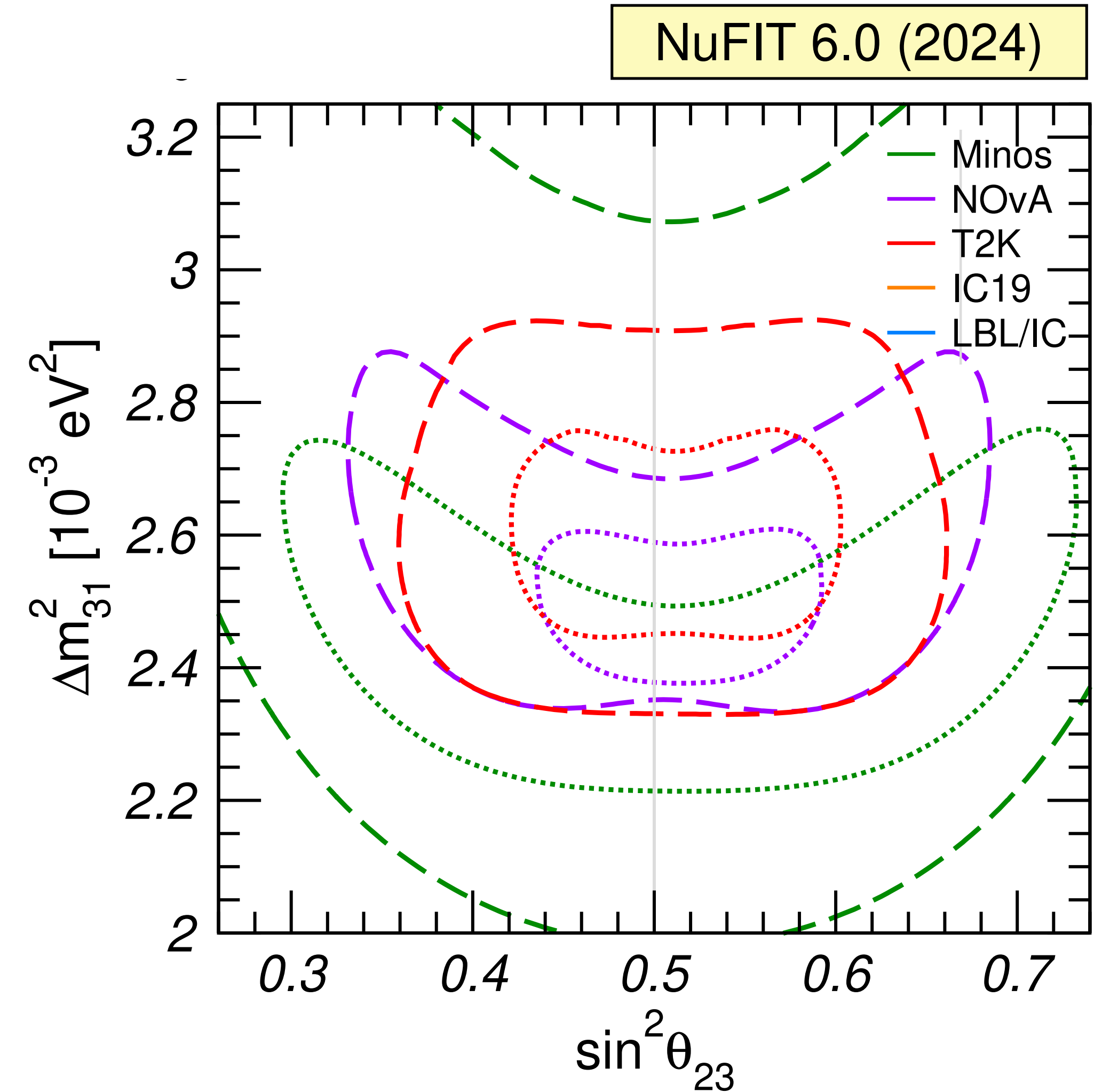
# Long-Baseline Accelerators

Accelerator experiments are sensitive to  $\Delta m_{31}^2$  and  $\sin^2 2\theta_{23}$ , searching for  $\nu_\mu$ -**disappearance**

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

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

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





# Long-Baseline Accelerators

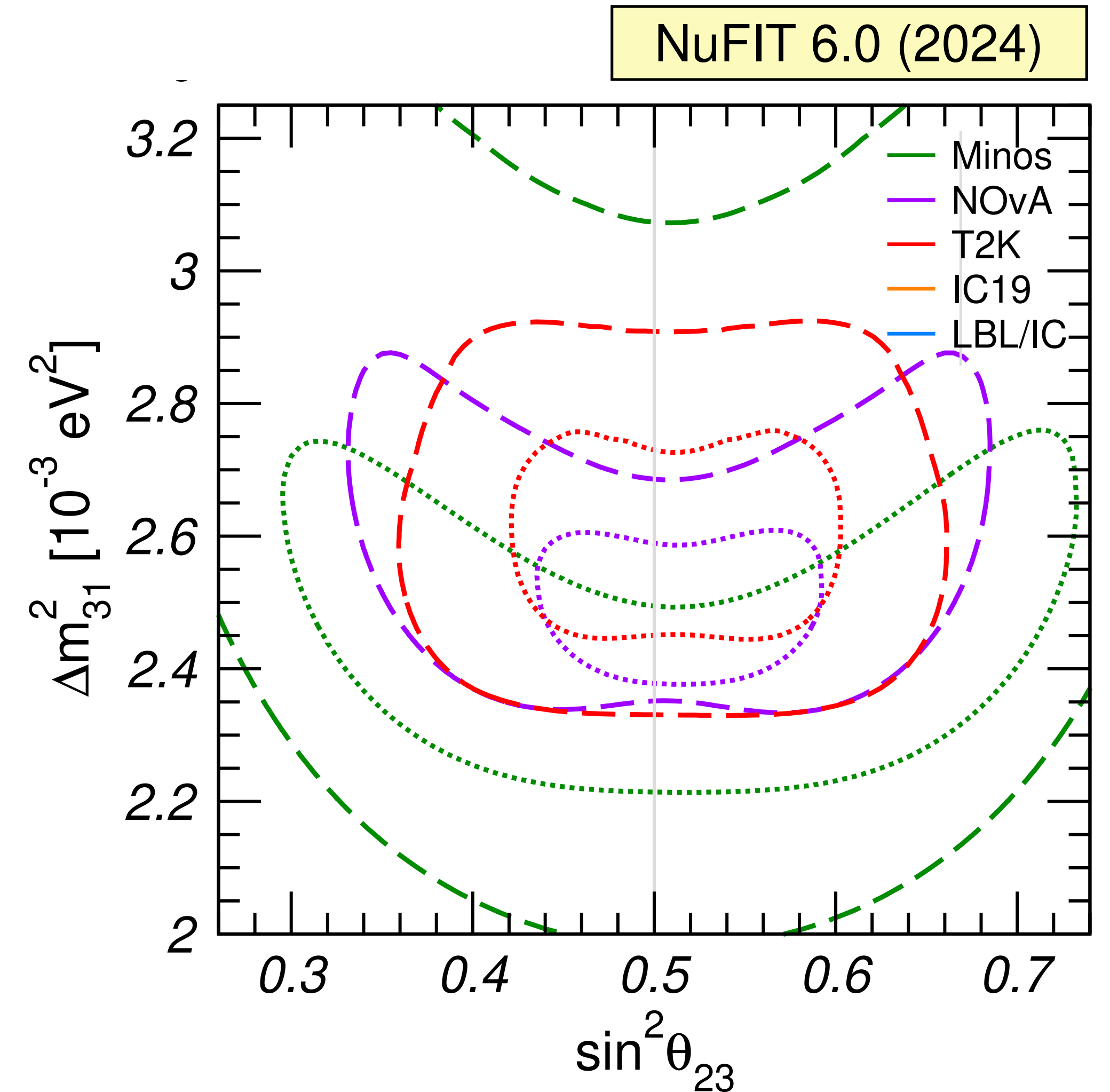
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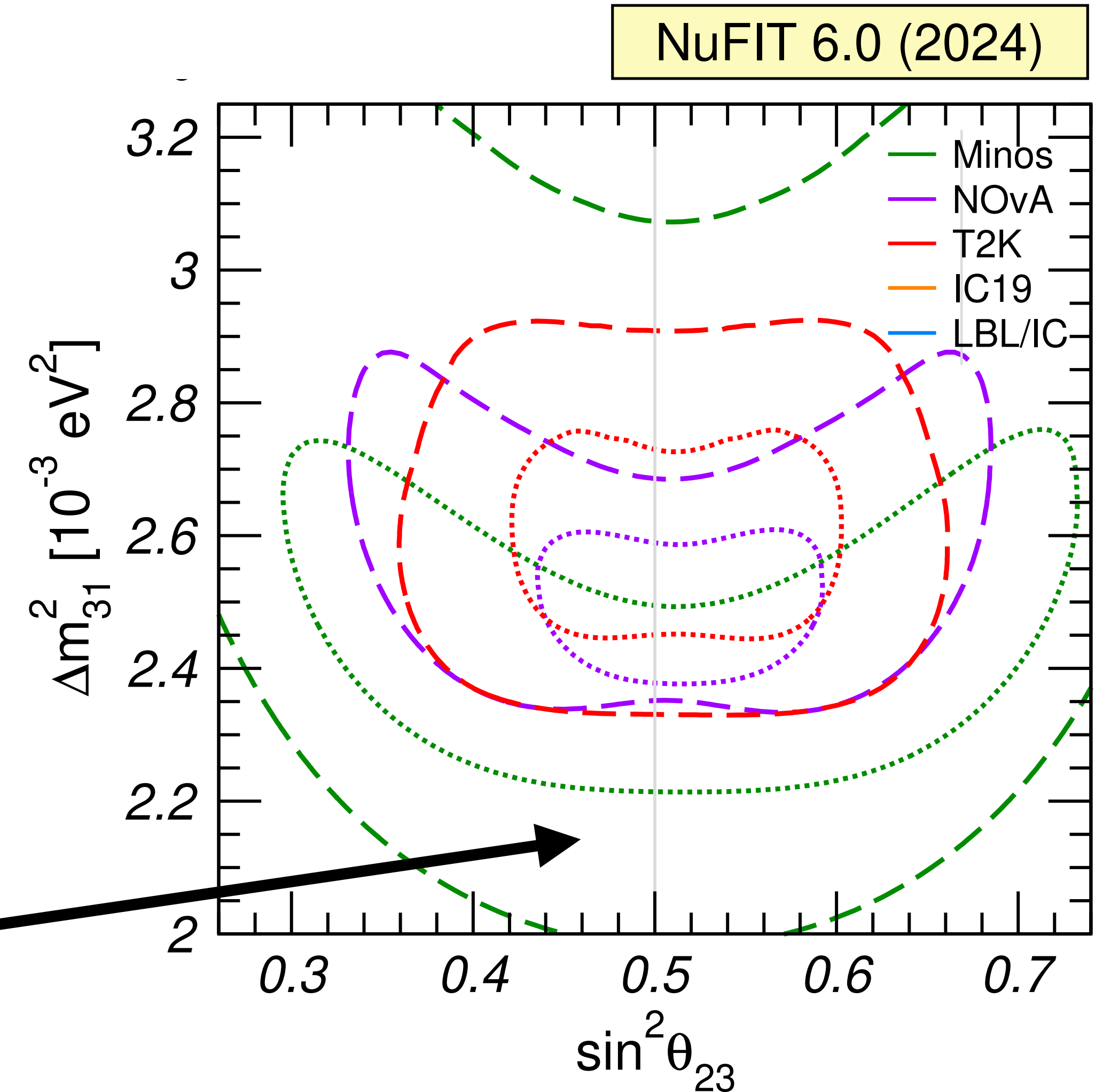
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$$\sin^2 \theta_{\mu\mu} = \cos^2 \theta_{13} \sin^2 \theta_{23}$$

- Matter effects are small for this channel
- Cannot resolve the octant of  $\theta_{23}$

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

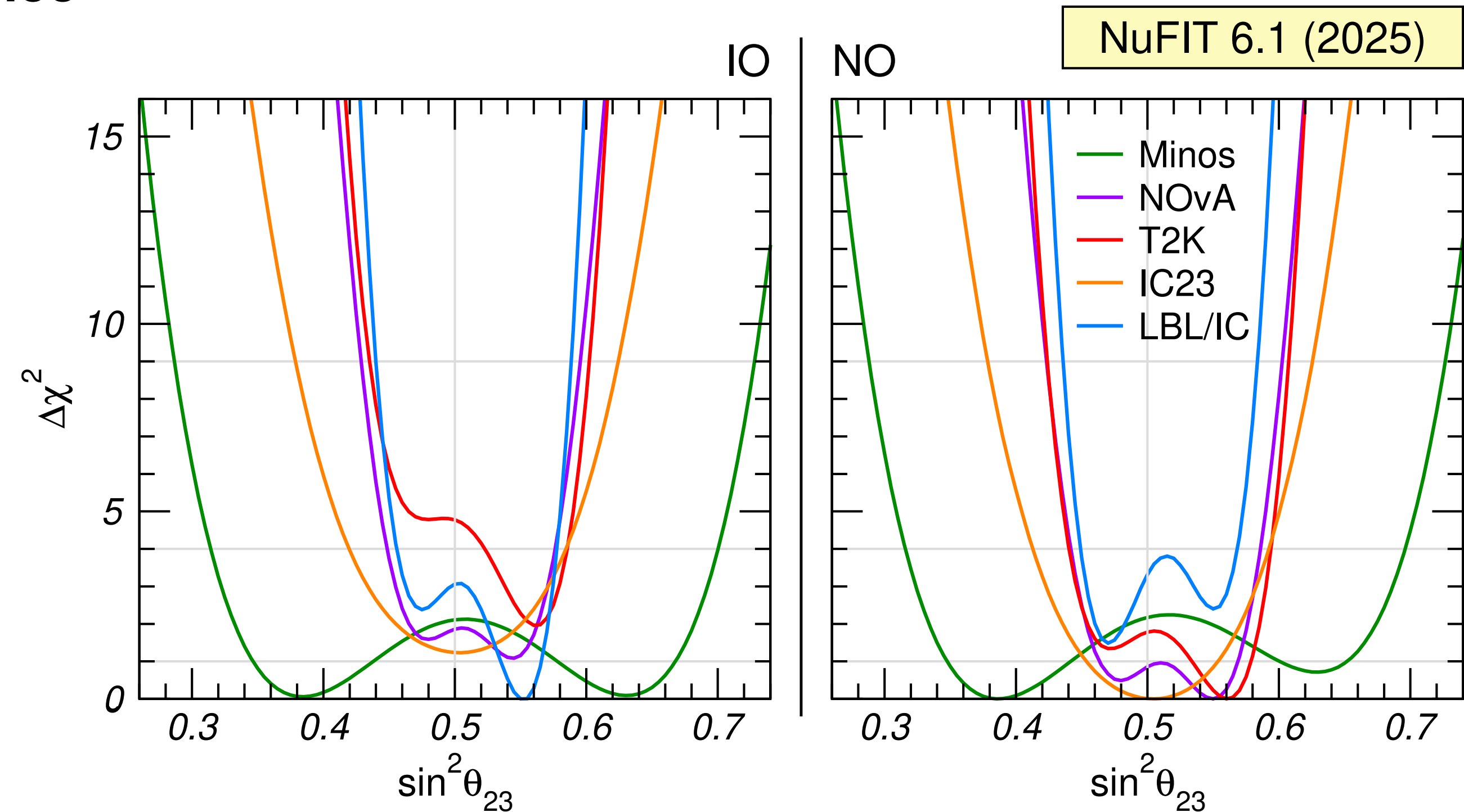




# Long-Baseline Accelerators

Accelerator experiments can search for  $\nu_e$ -**appearance**

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



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

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

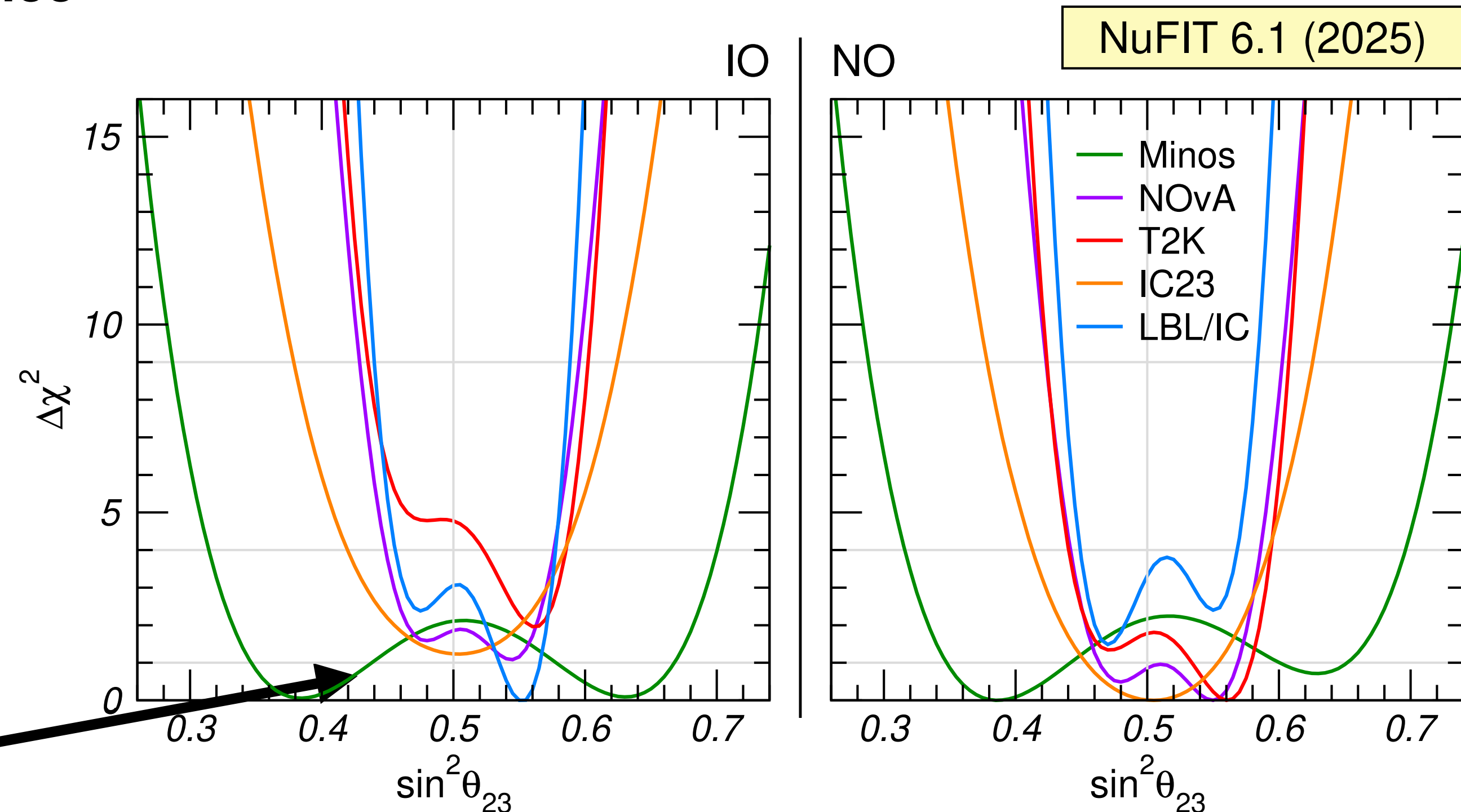
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**Octant**  $\theta_{23}$

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



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

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

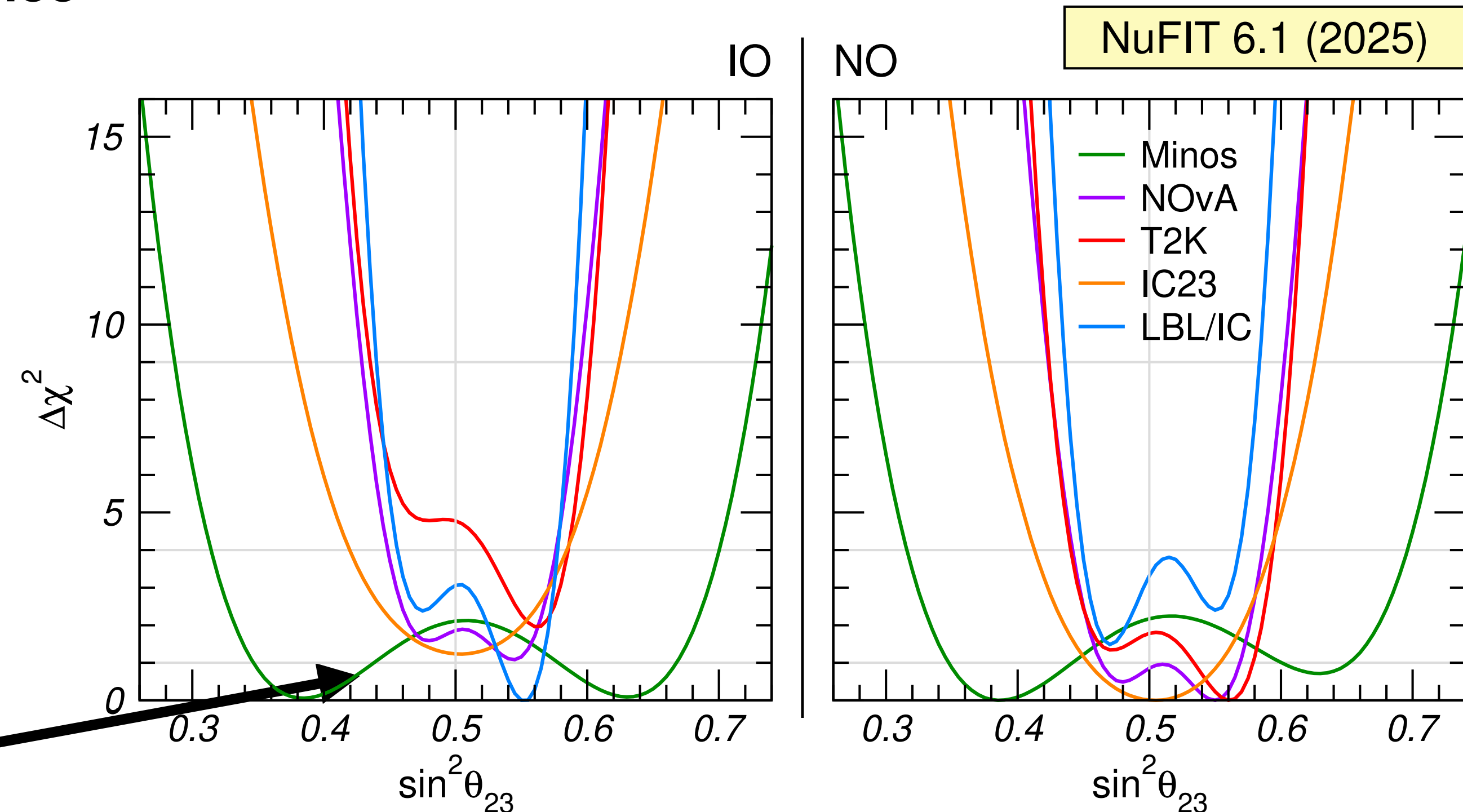
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**Ordering**

The appearance depends on the **mass ordering**



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

I Esteban, MC Gonzalez-Garcia, M Maltoni,  
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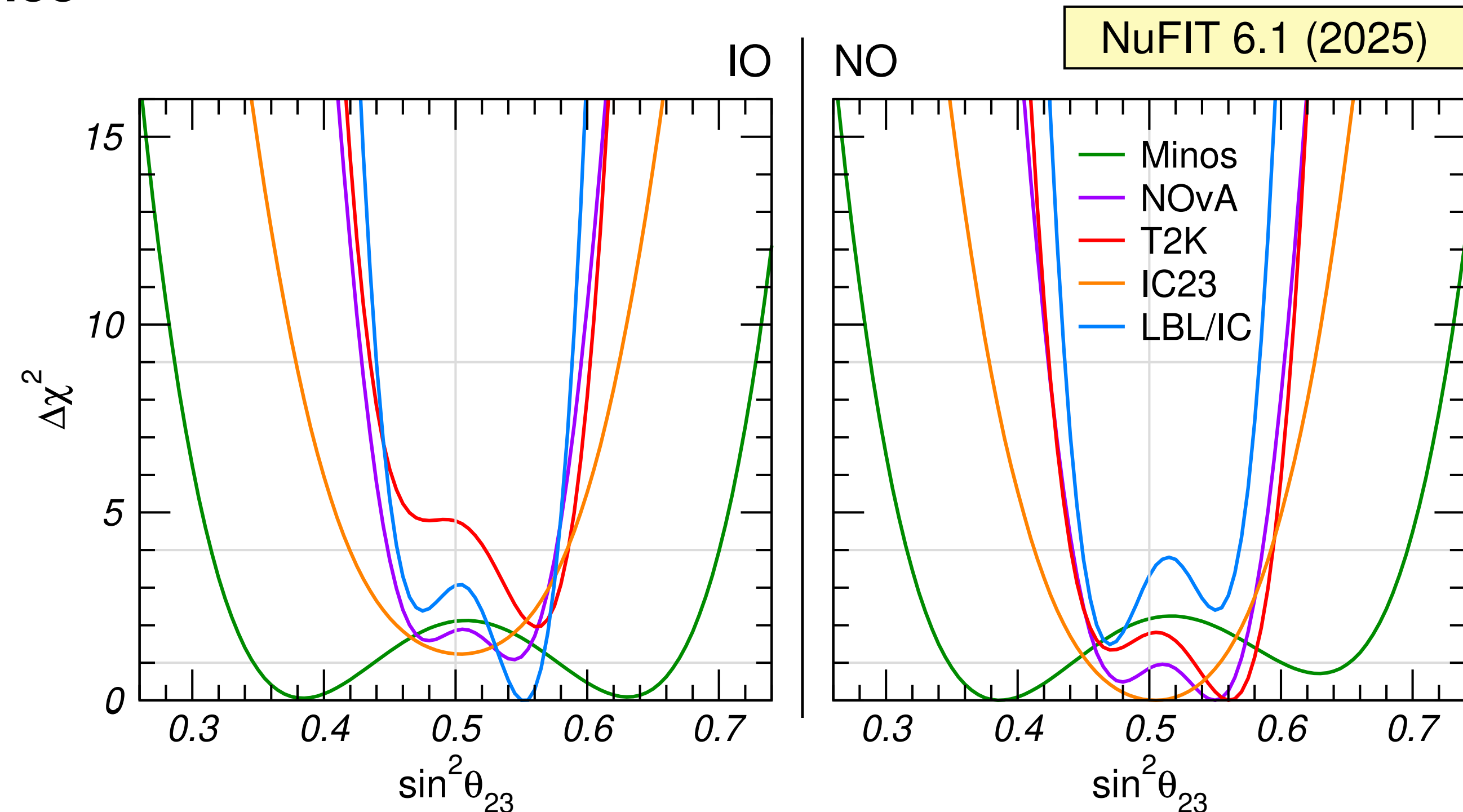
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**CP-violation**

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



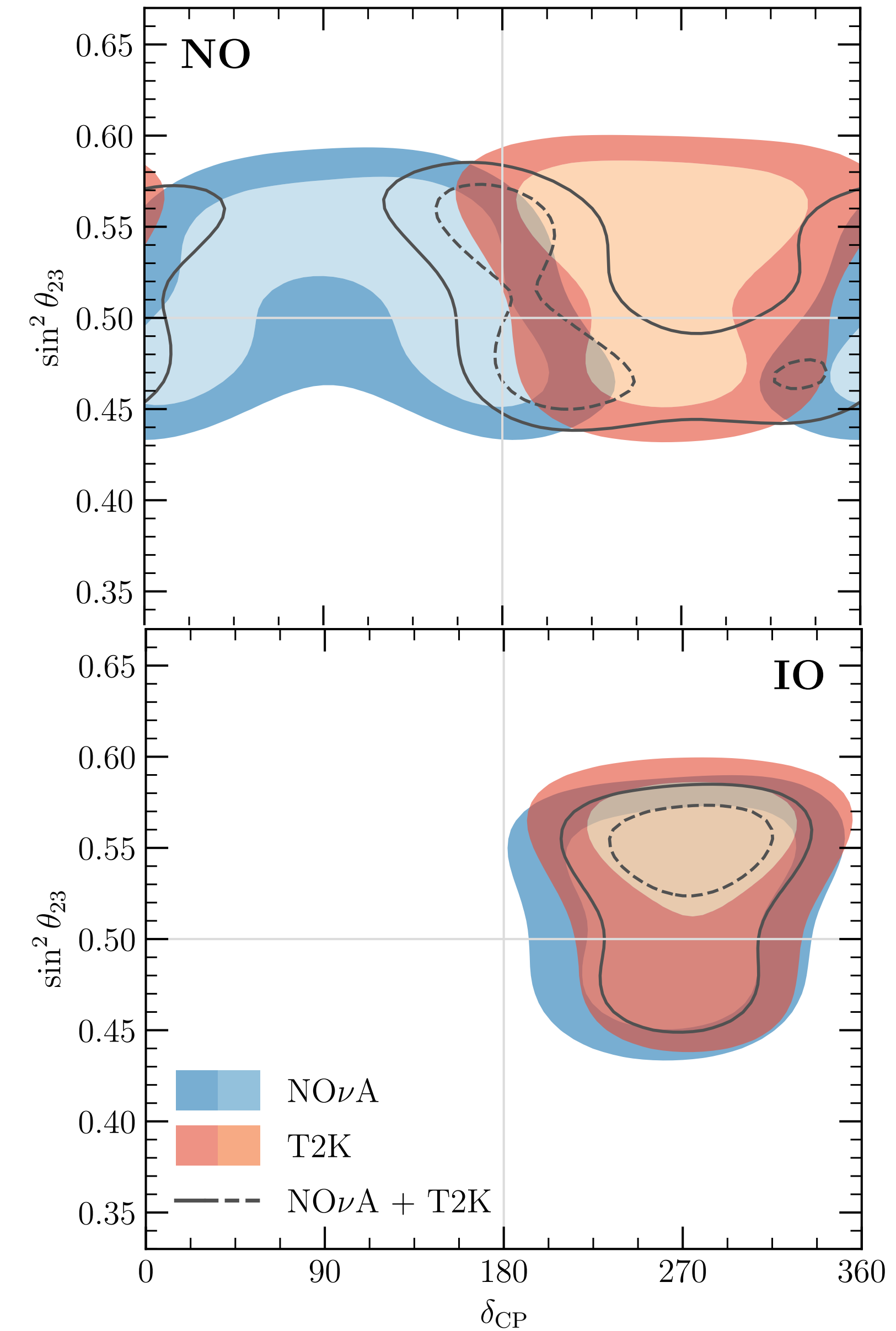
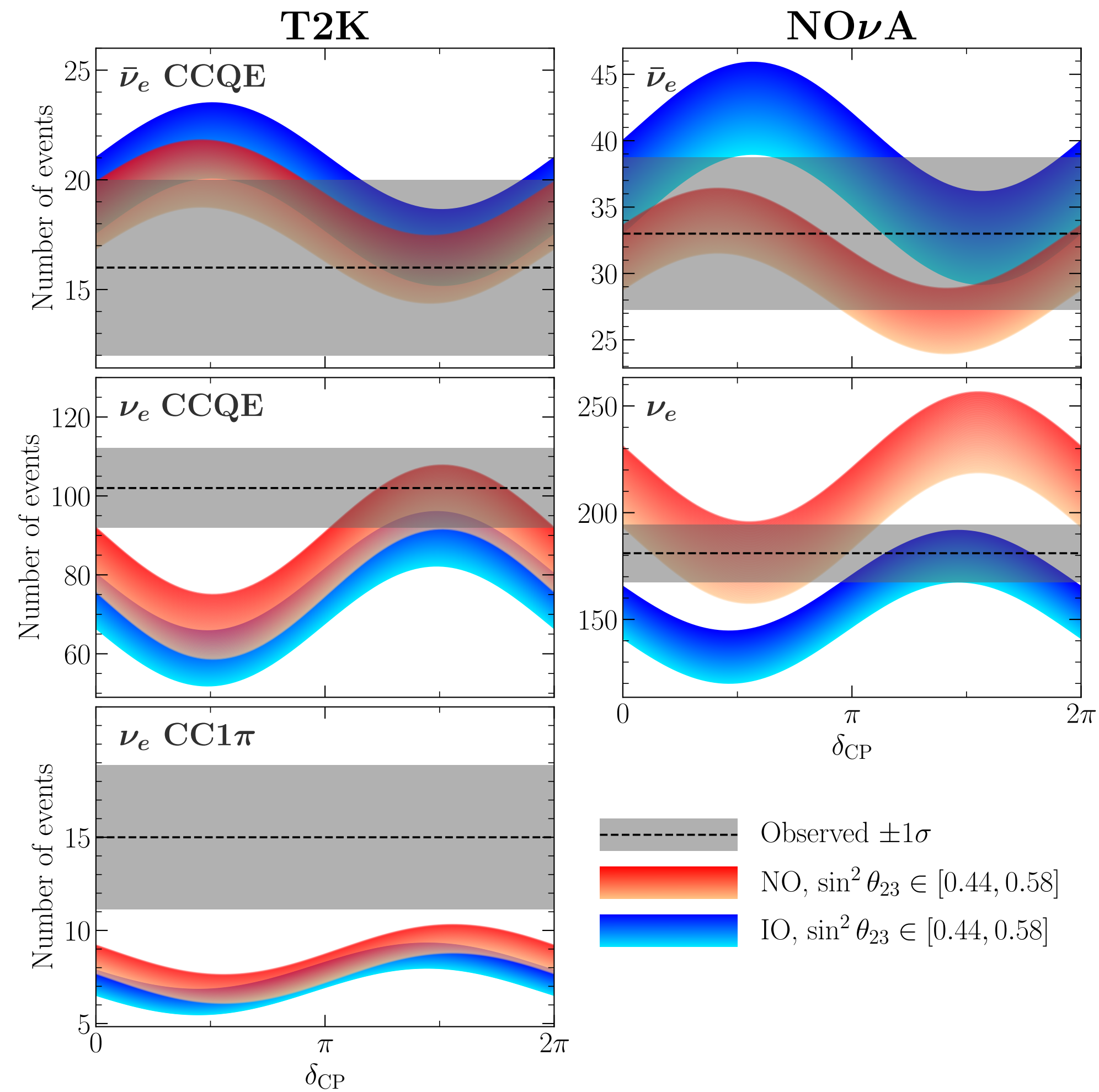
$$o = \text{sign}(\Delta m_{31}^2) \quad A = |2EV/\Delta m_{31}^2| \quad C = \frac{\Delta m_{21}^2 L}{4E} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

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



# T2K vs NOvA

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

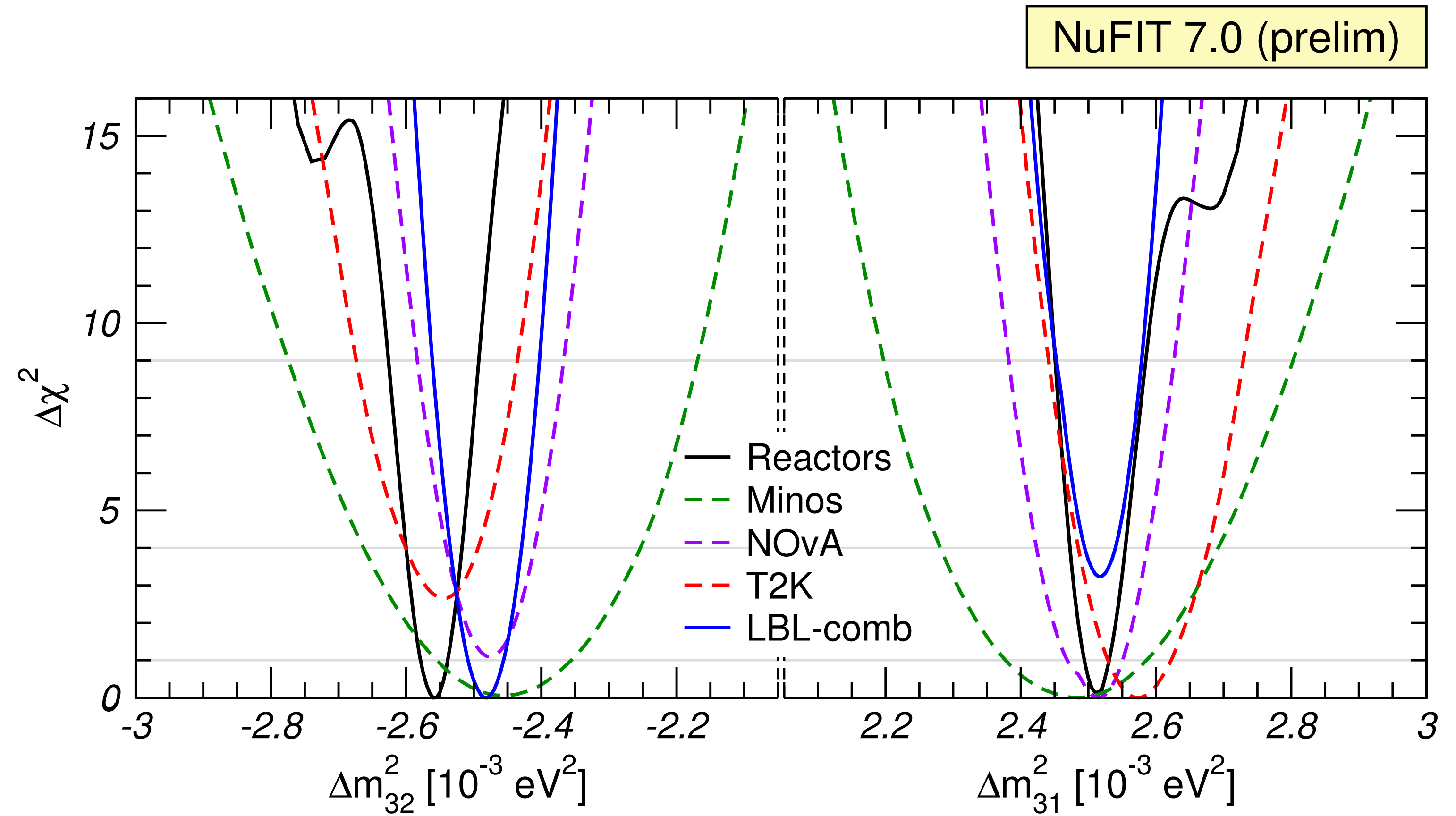
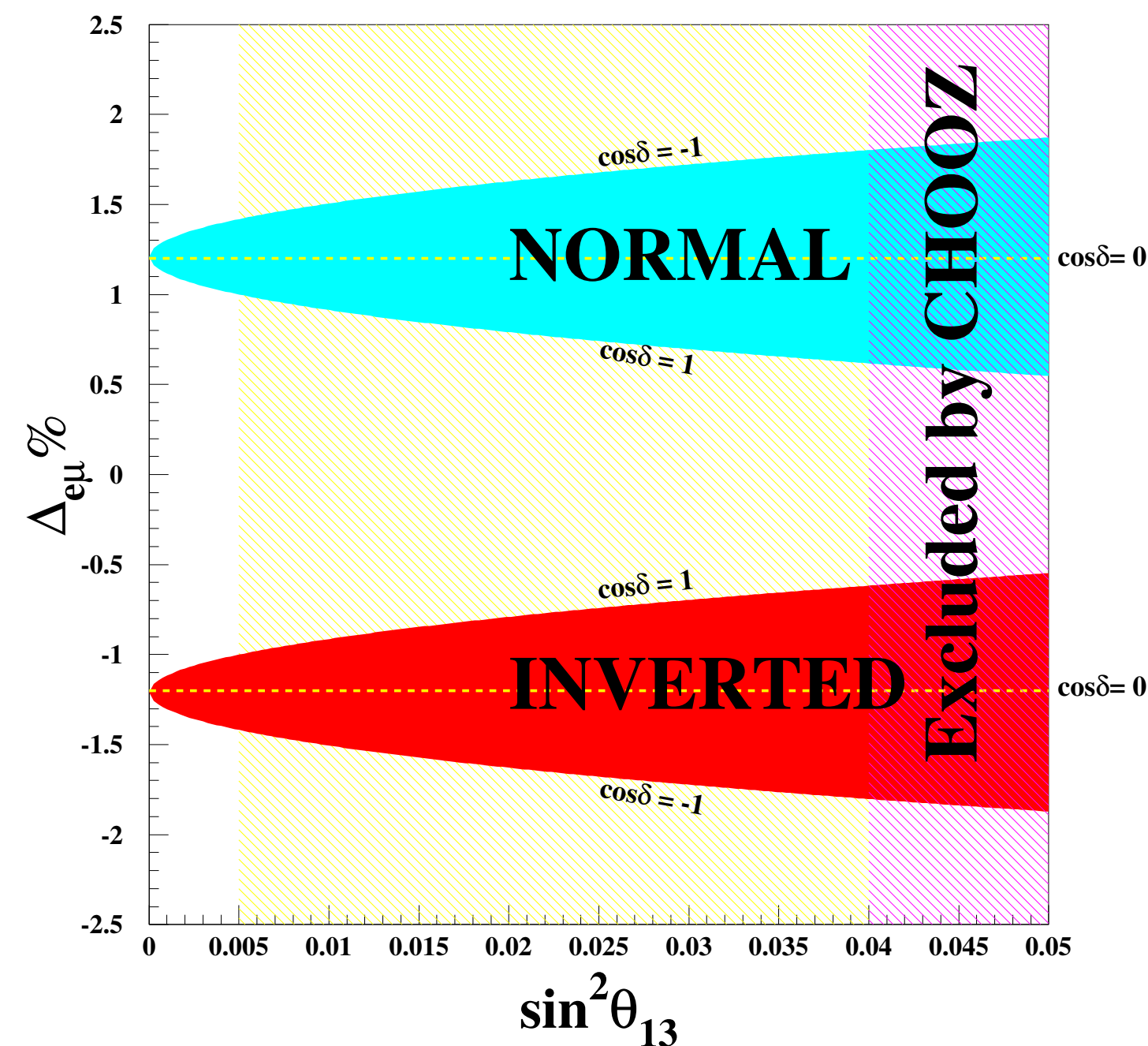




# LBL+Reactors

Full LBL-reactor combo eases T2K-NOvA tension

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

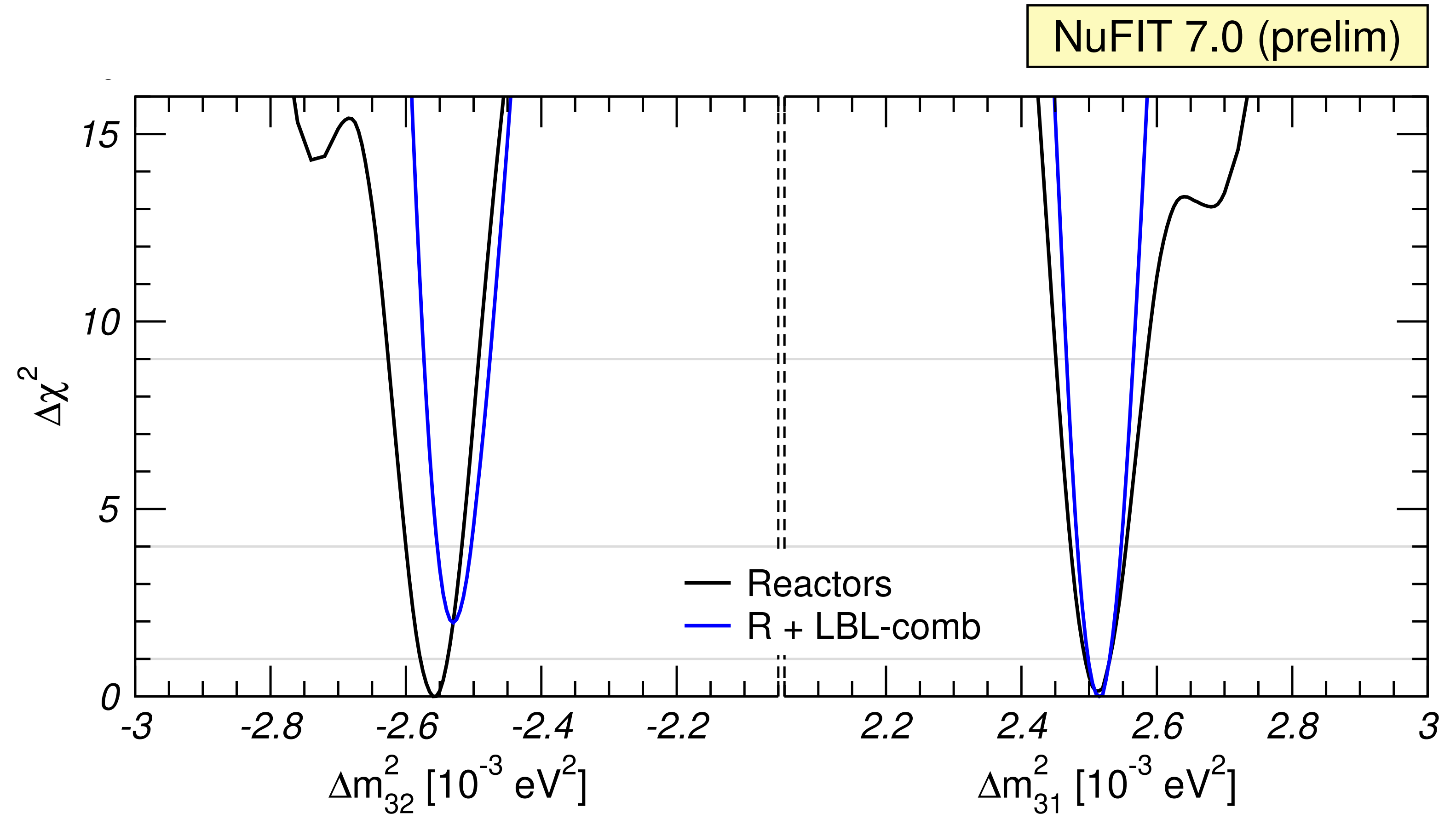
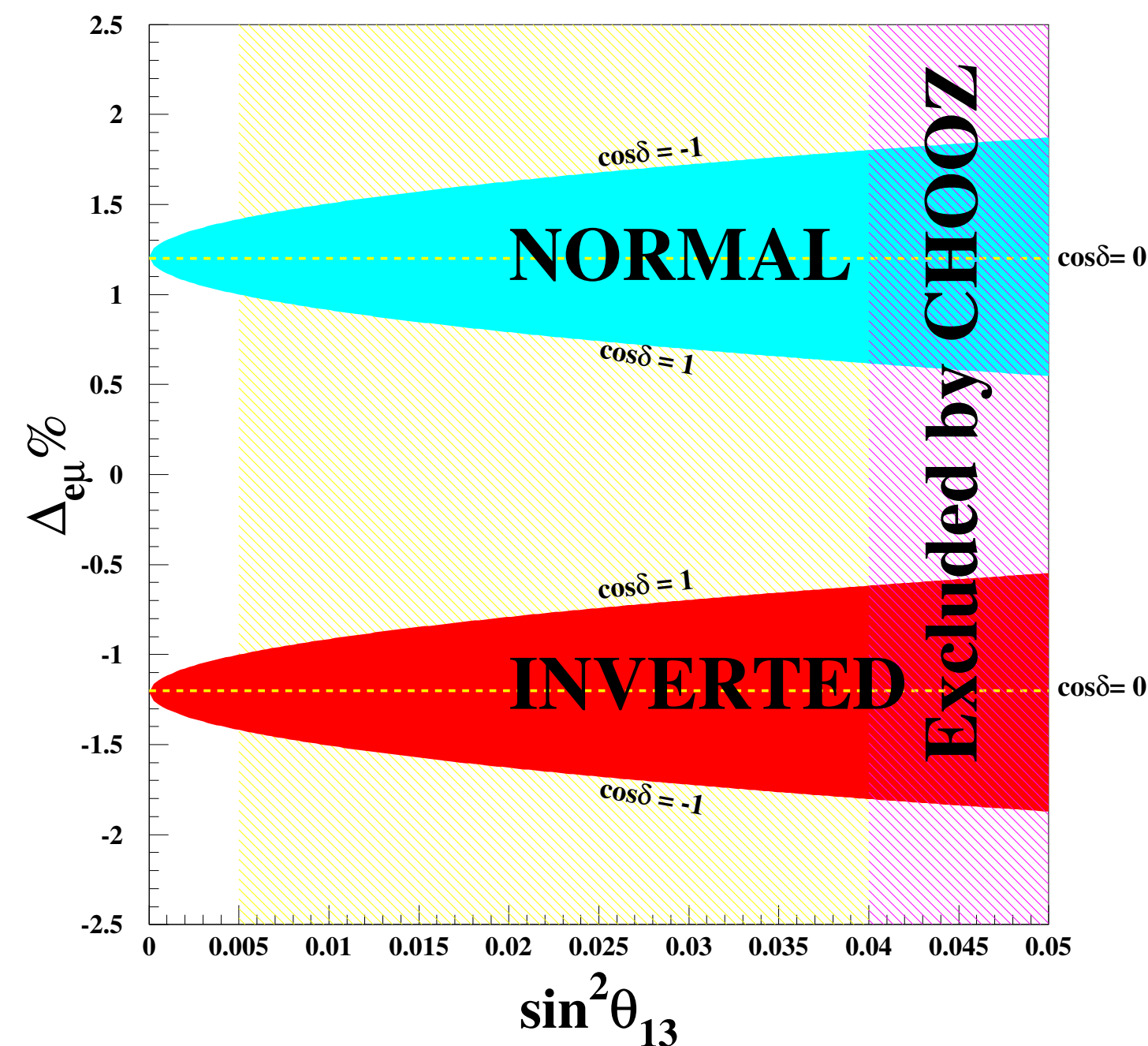


Nunokawa, Parke, Funchal, PRD 72(2005) arXiv: hep-ph/0503283

# LBL+Reactors

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

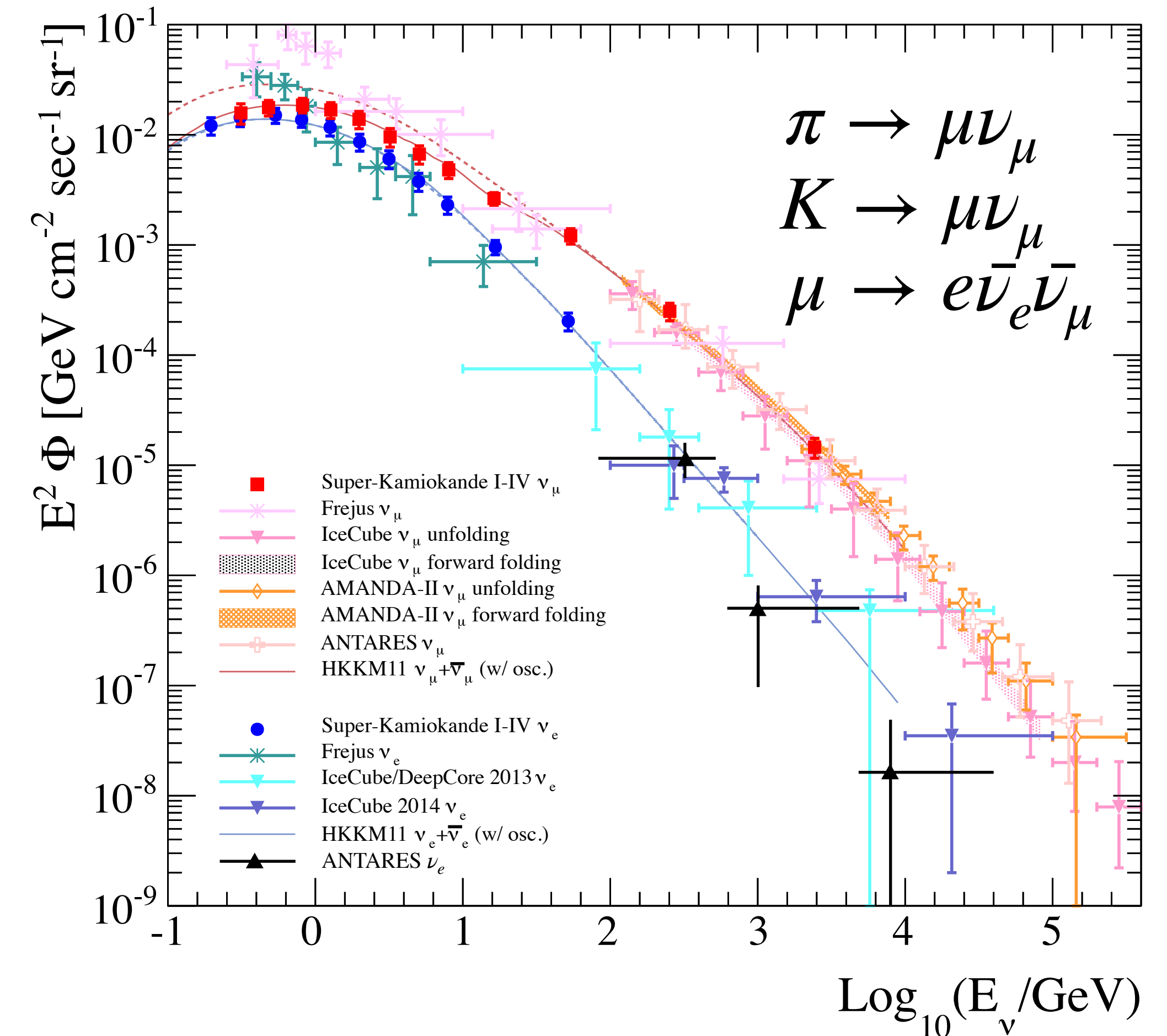
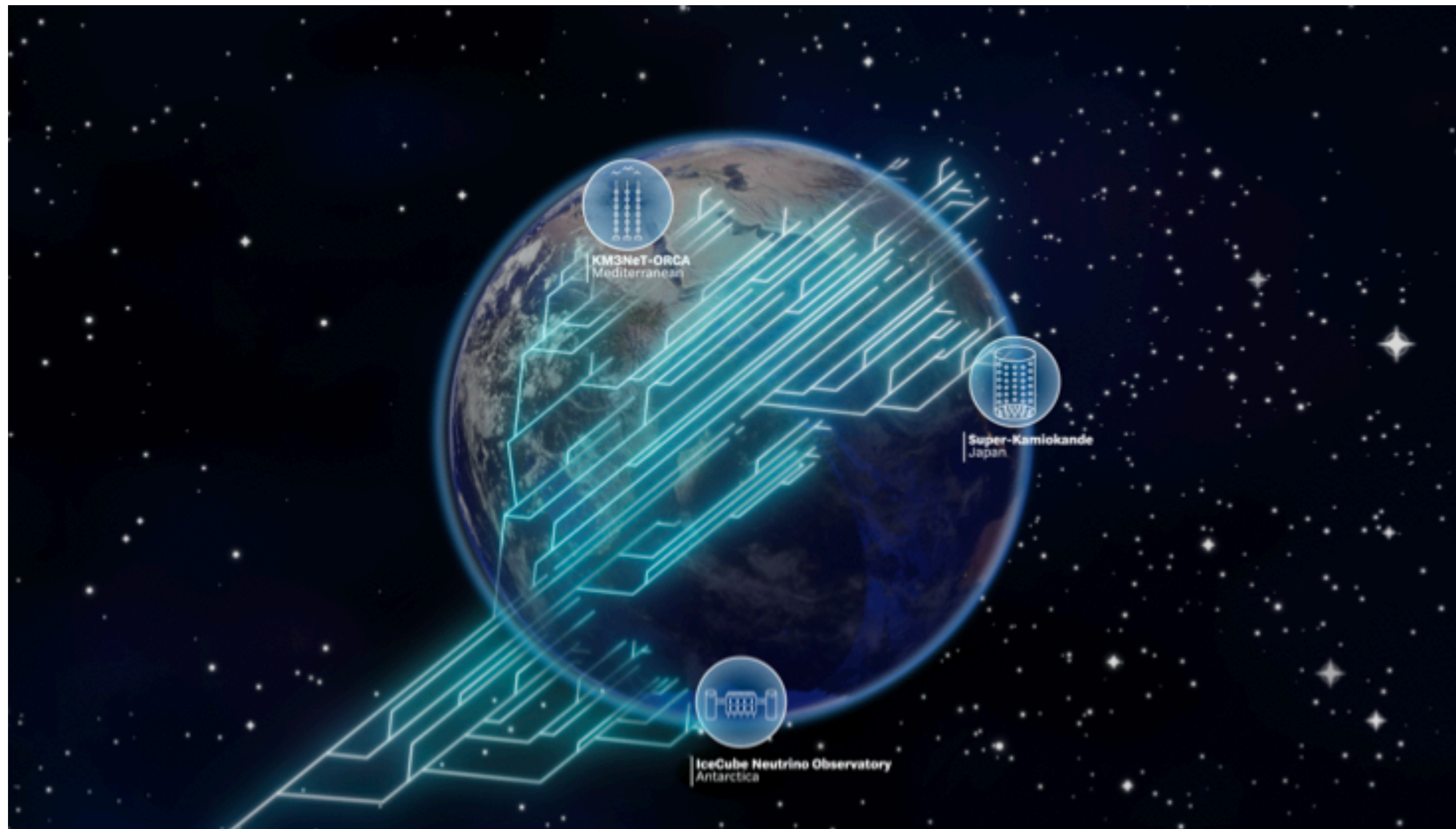


Nunokawa, Parke, Funchal, PRD 72(2005) arXiv: hep-ph/0503283



# 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

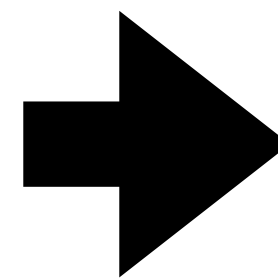
The most recent atmospheric neutrino flux estimations are based on 3D-MC simulation

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

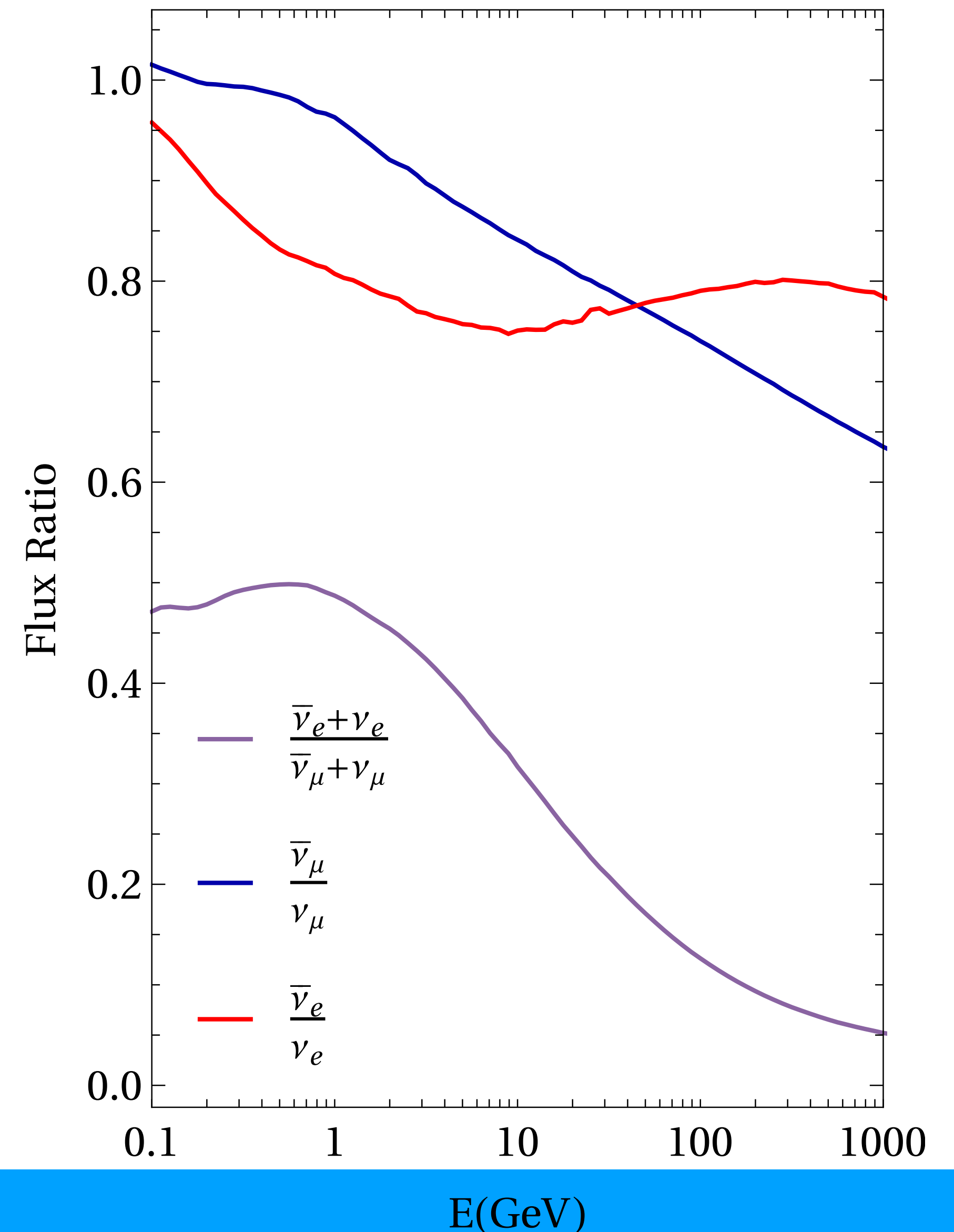
The main components in the flux calculations are:

- **Cosmic ray flux** ( $\phi_p$ )
- **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)



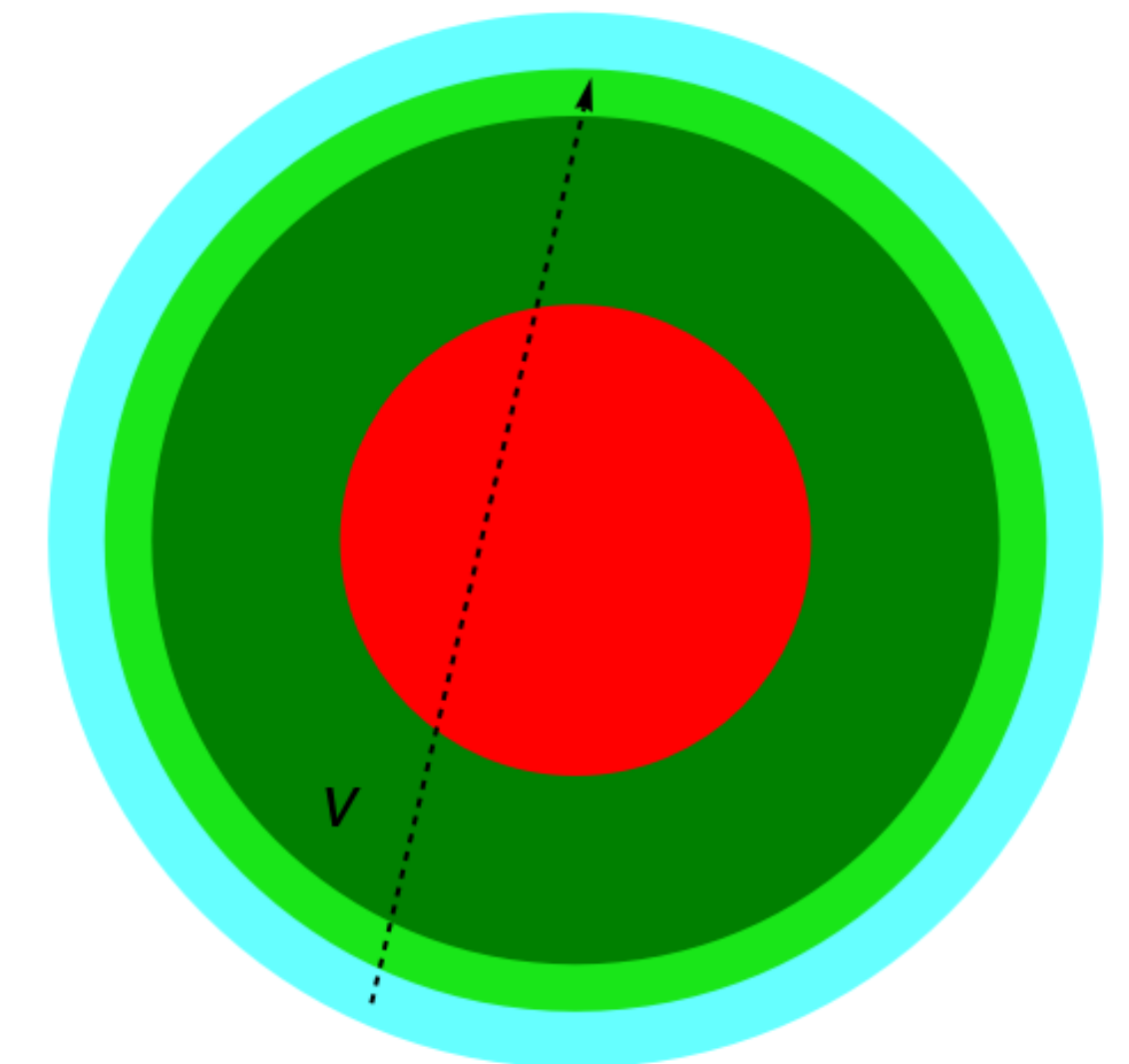
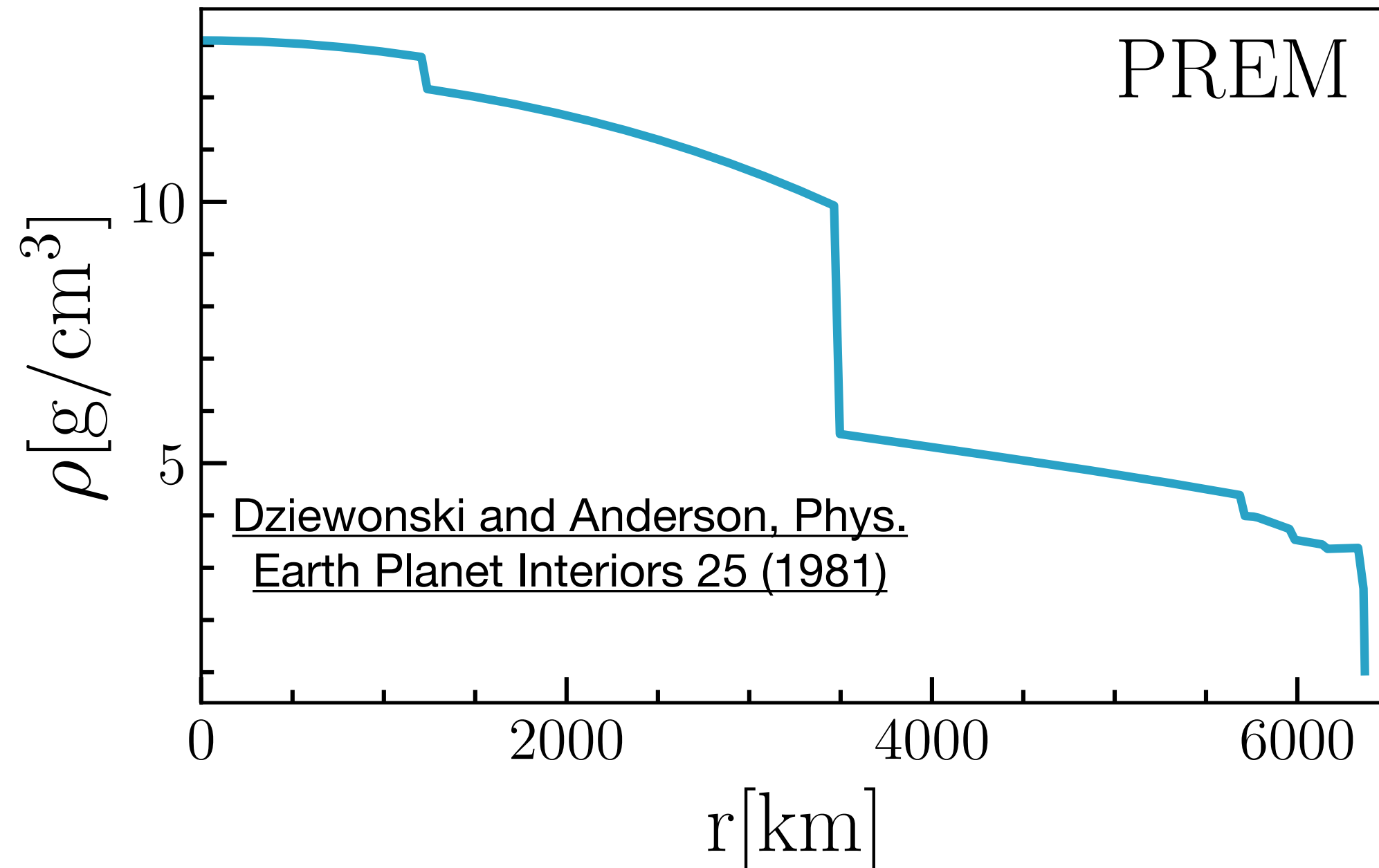
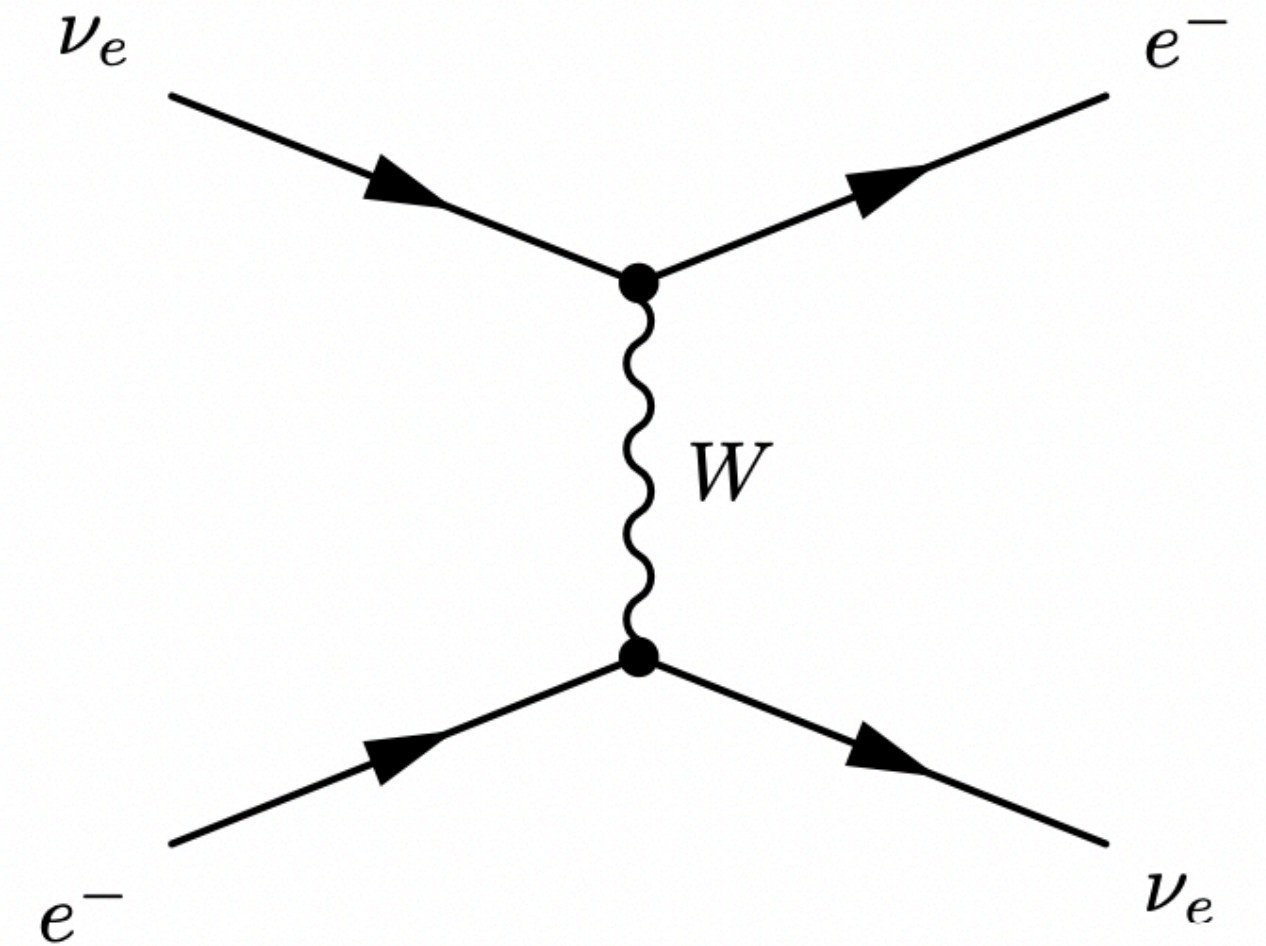


# Atmospheric Neutrinos

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

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

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



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

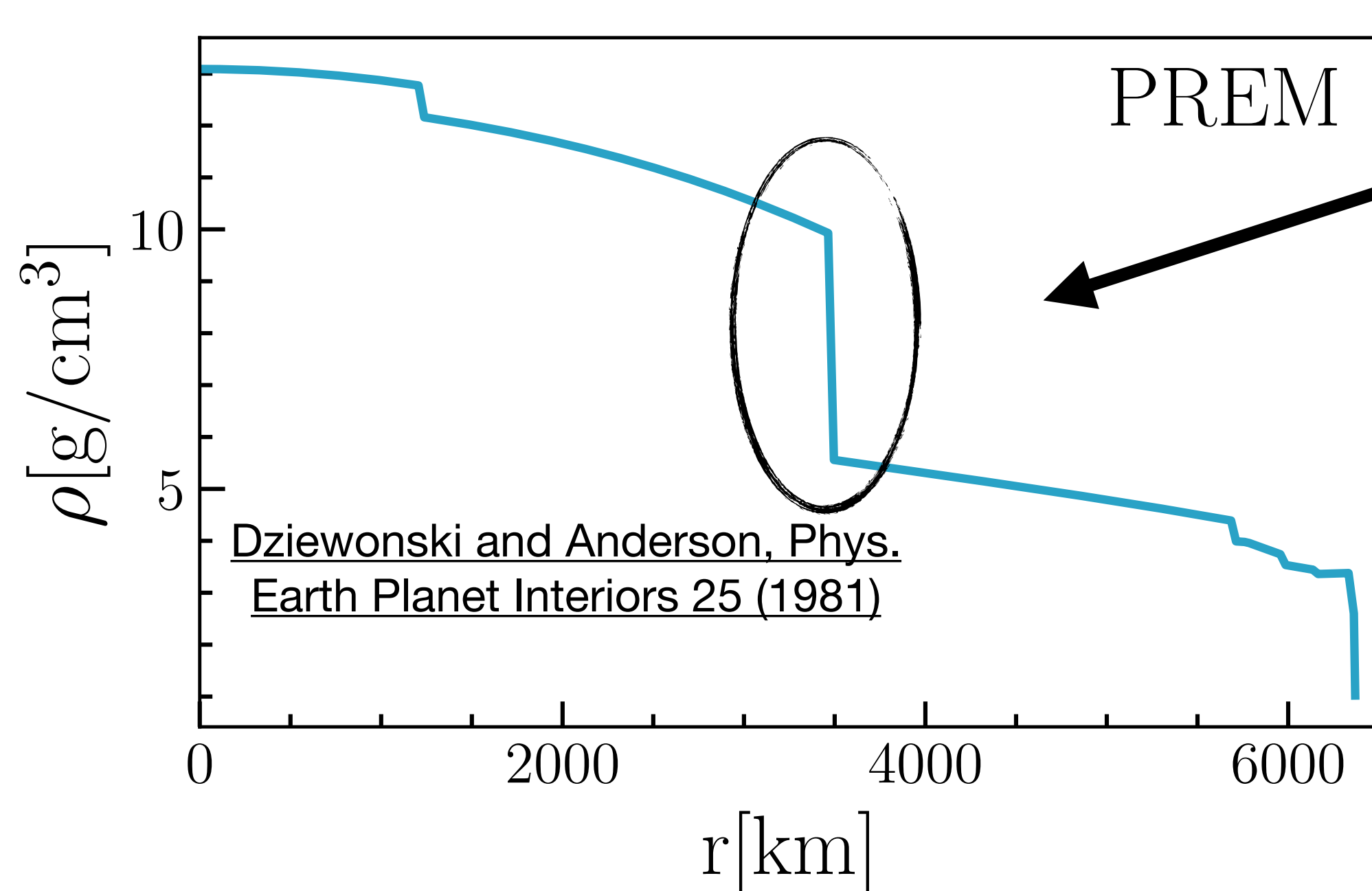
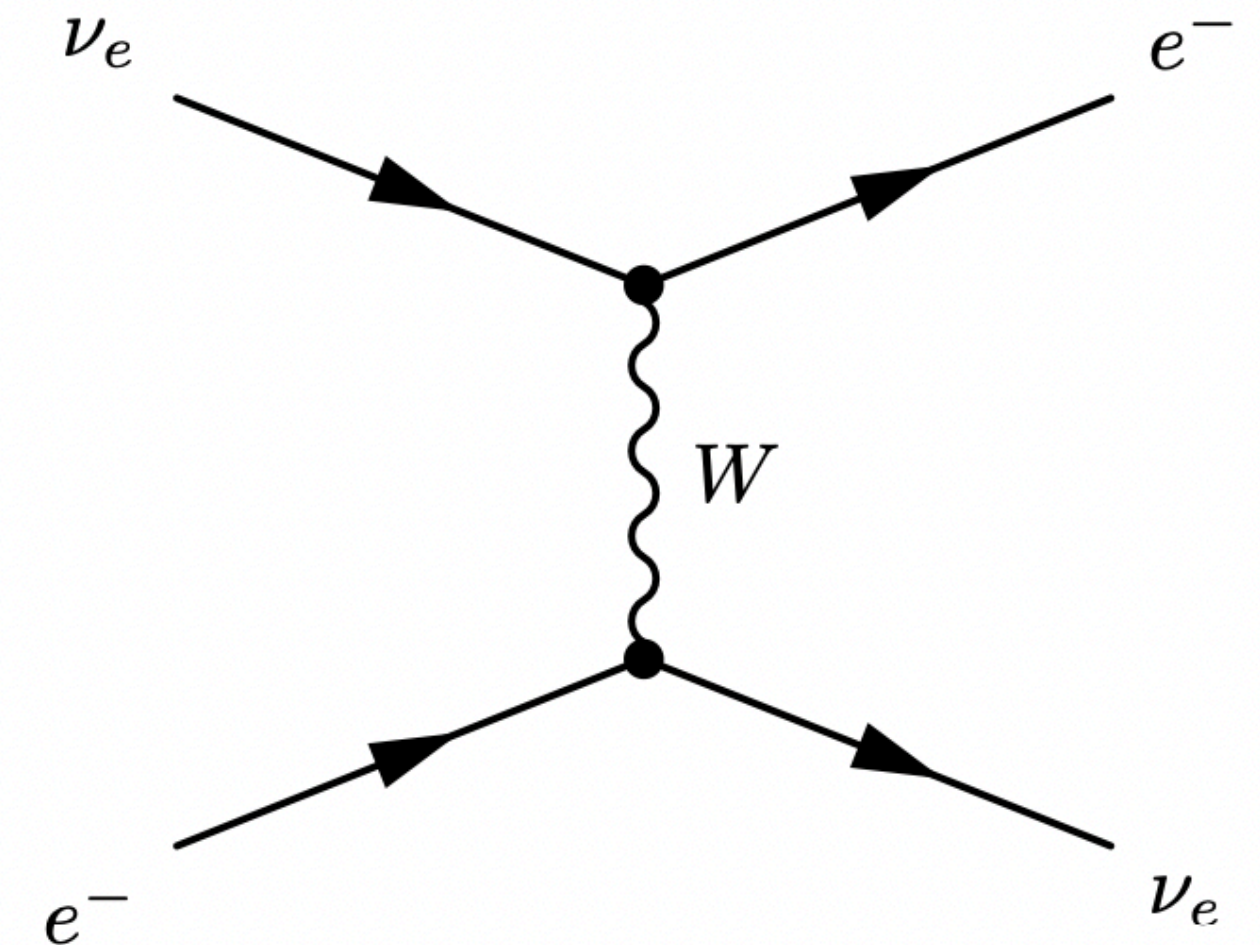


# Atmospheric Neutrinos

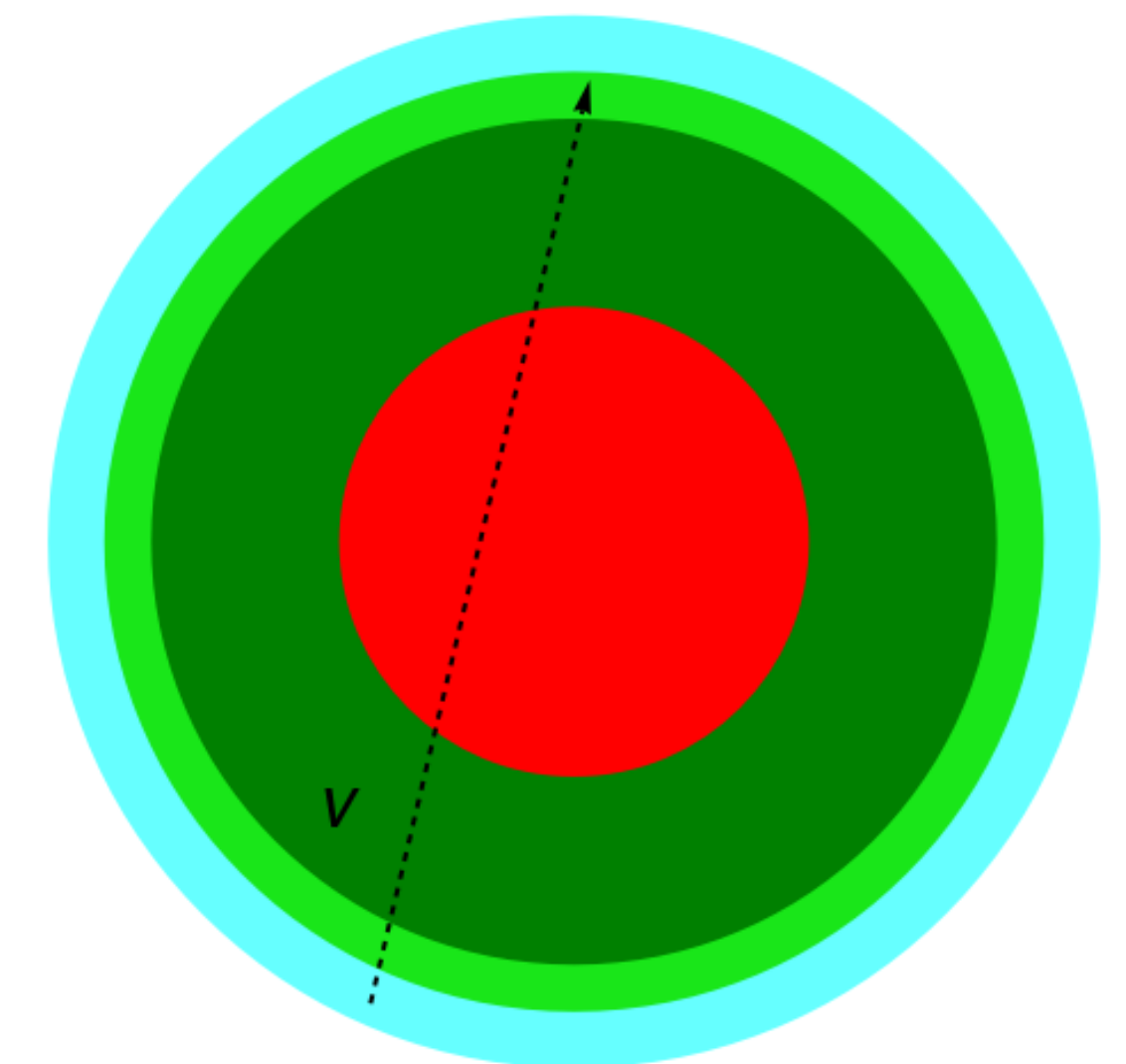
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$$V_\alpha = 2\sqrt{2} G_F N_e E_\nu \text{diag}(1, 0, 0)$$



Evolution in the Earth is not adiabatic

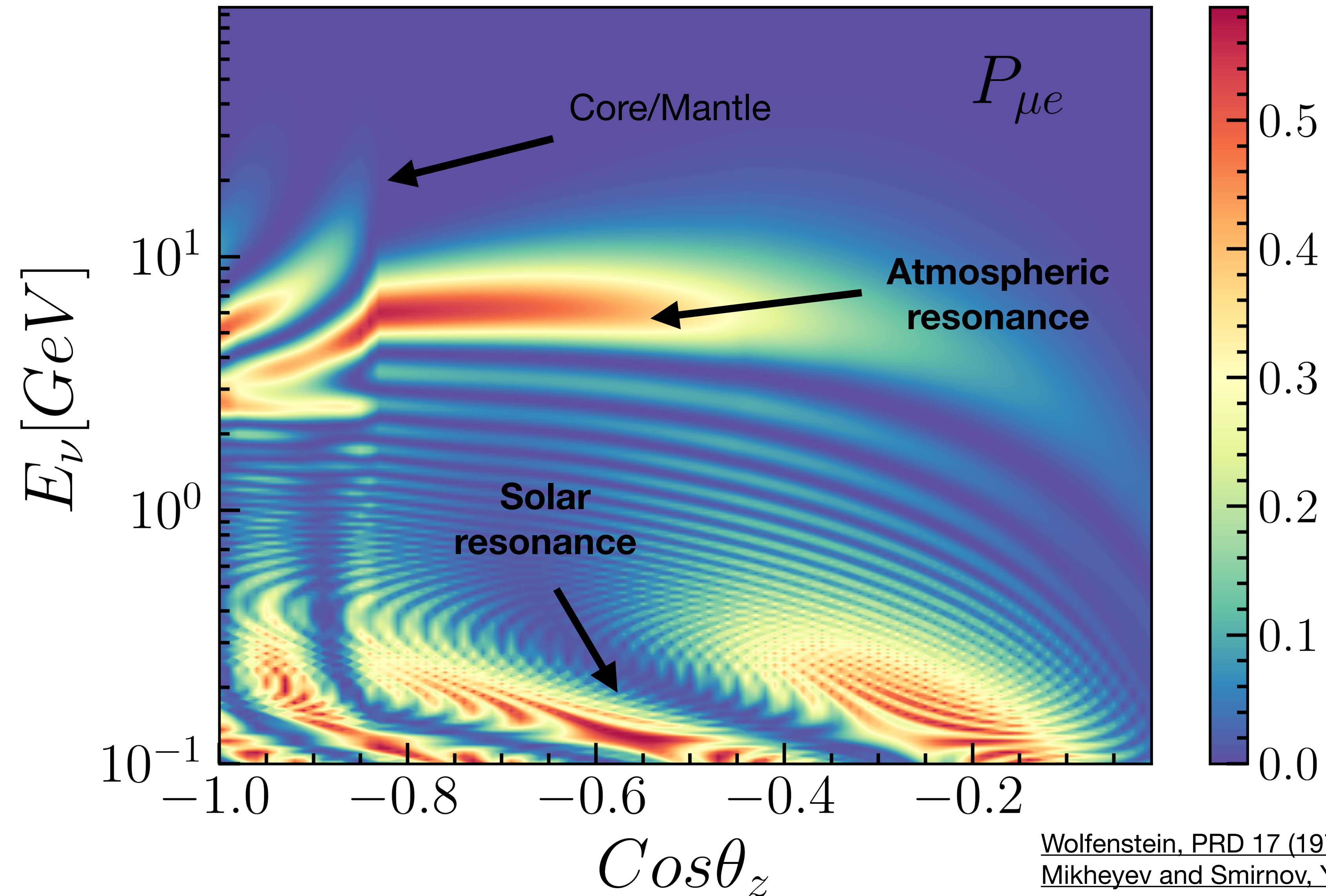


Wolfenstein, PRD 17 (1978)

Mikheyev and Smirnov, Yad. Fiz. 42 (1985)

# Atmospheric Neutrinos

Neutrino oscillation is modified by matter effects





# Sub-GeV

For atmospheric neutrinos, both fluxes are sensitive to  $\delta_{CP}$

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

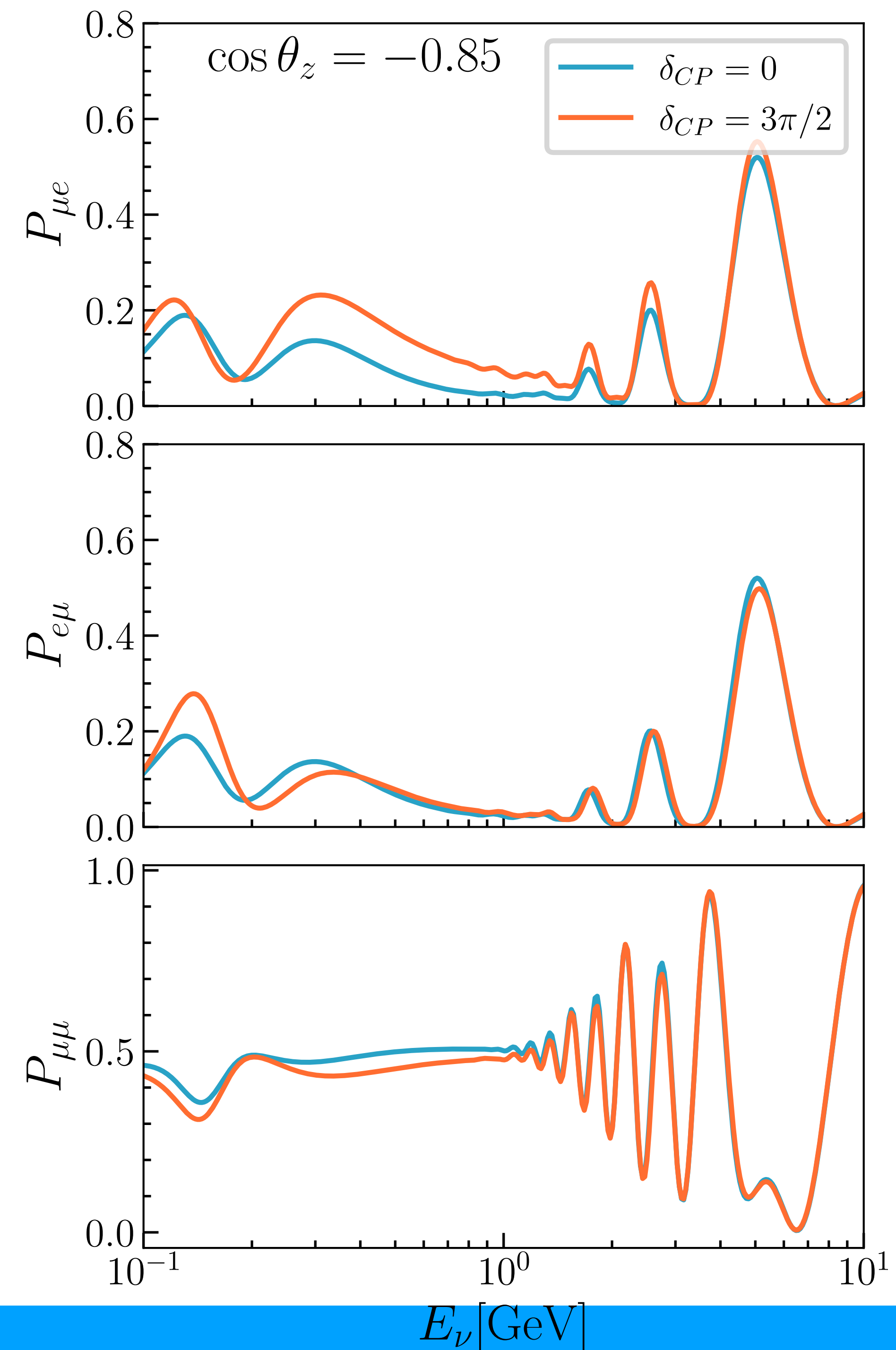
$$P(\nu_\mu \rightarrow \nu_e) \neq P(\nu_e \rightarrow \nu_\mu)$$

- The impact of  $\delta_{cp}$  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)

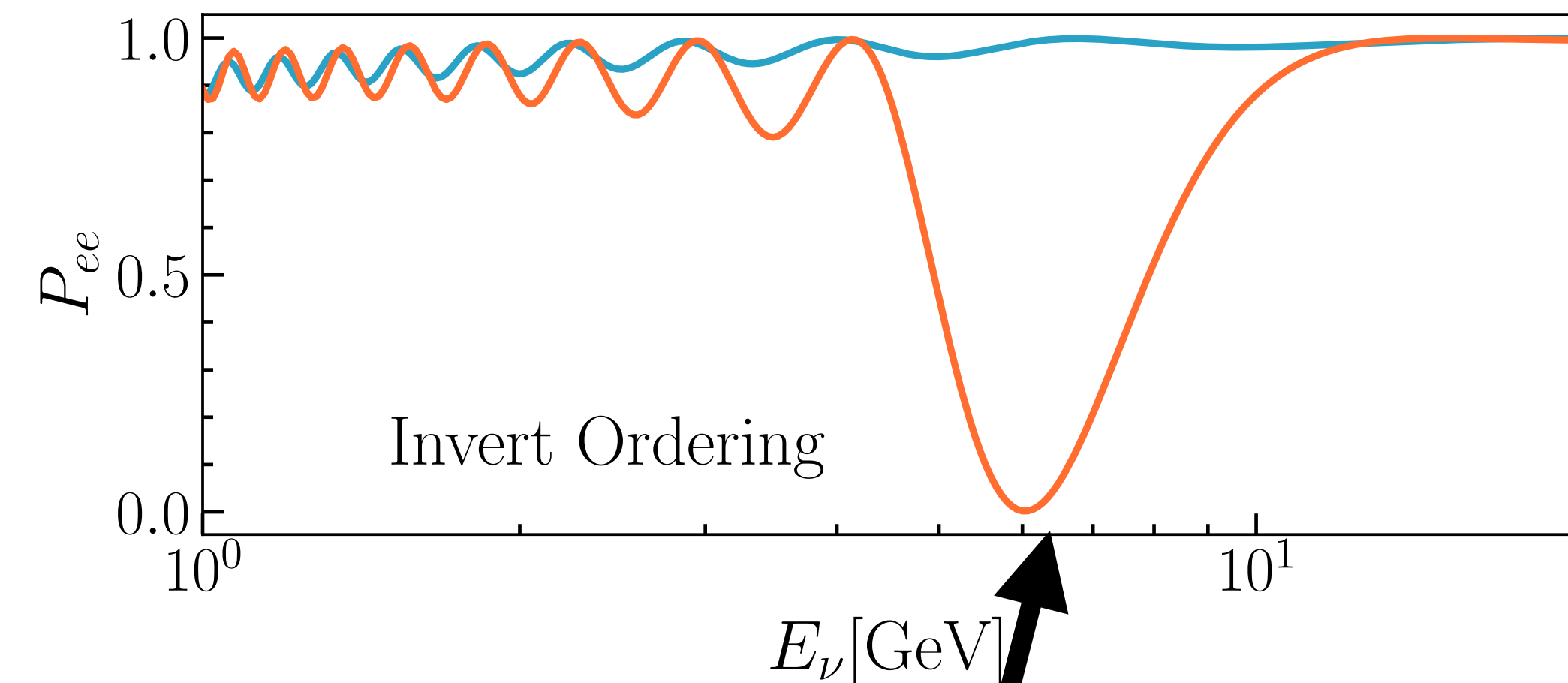
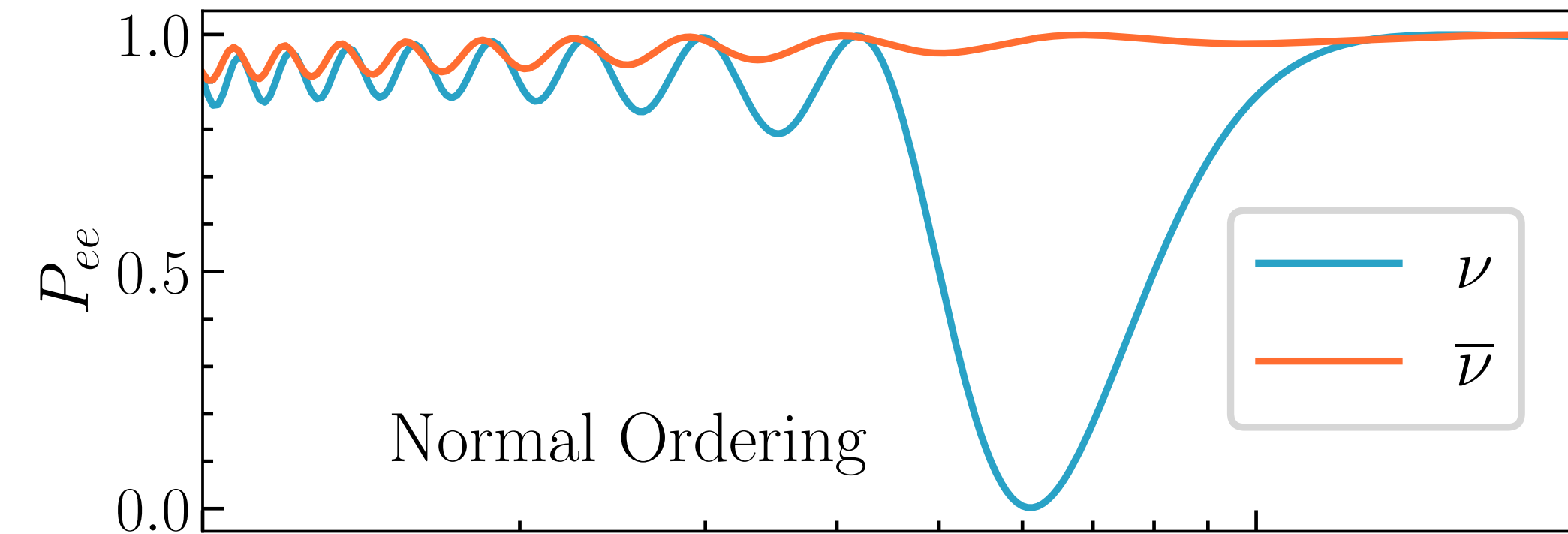
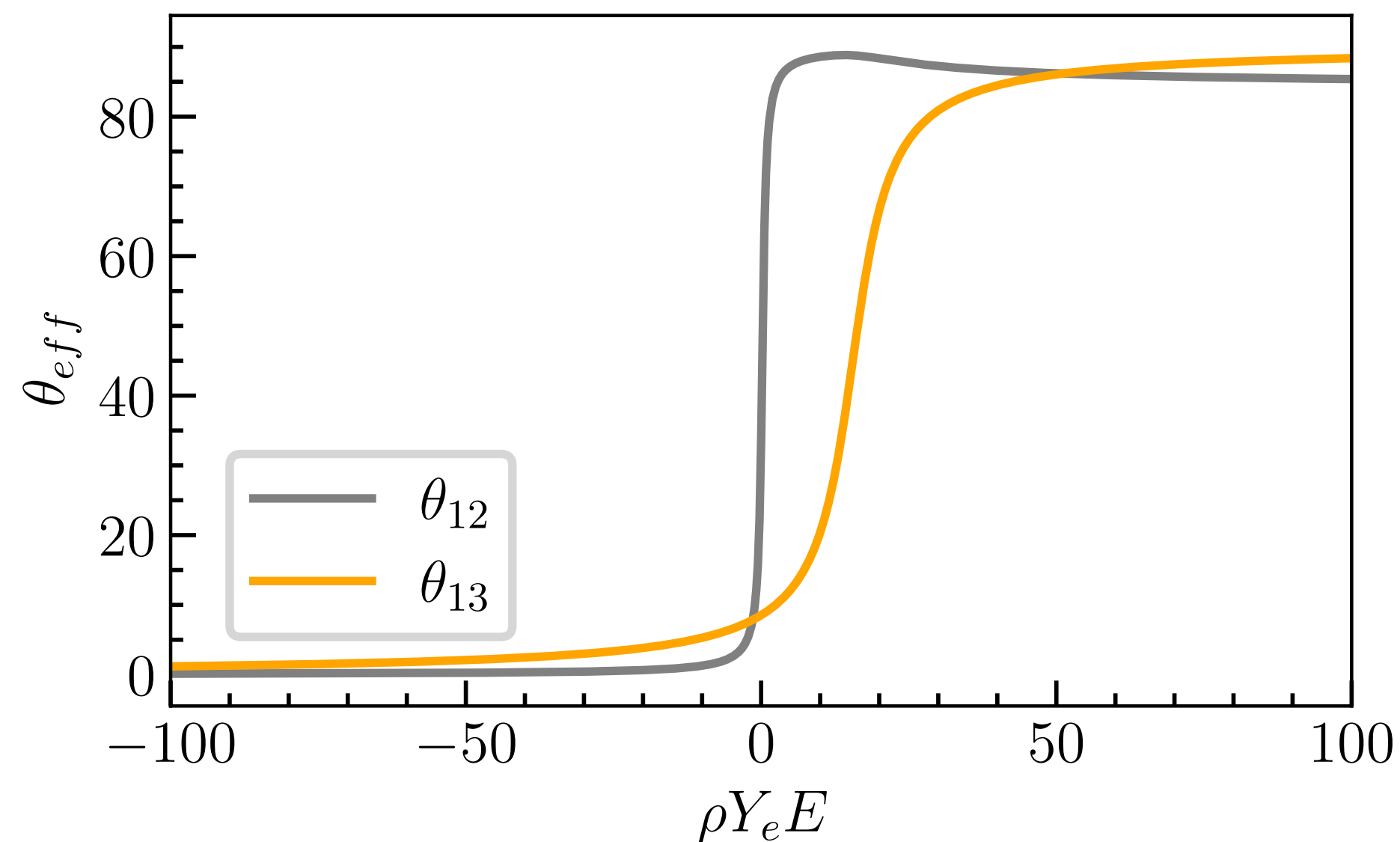
Denton and Parke, PRD 109 (2024)



# 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  $\theta_{13}^{eff}$  lead to a deep  
in  $P_{ee}$  for  $\nu$  ( $\bar{\nu}$ ) for NO (IO)

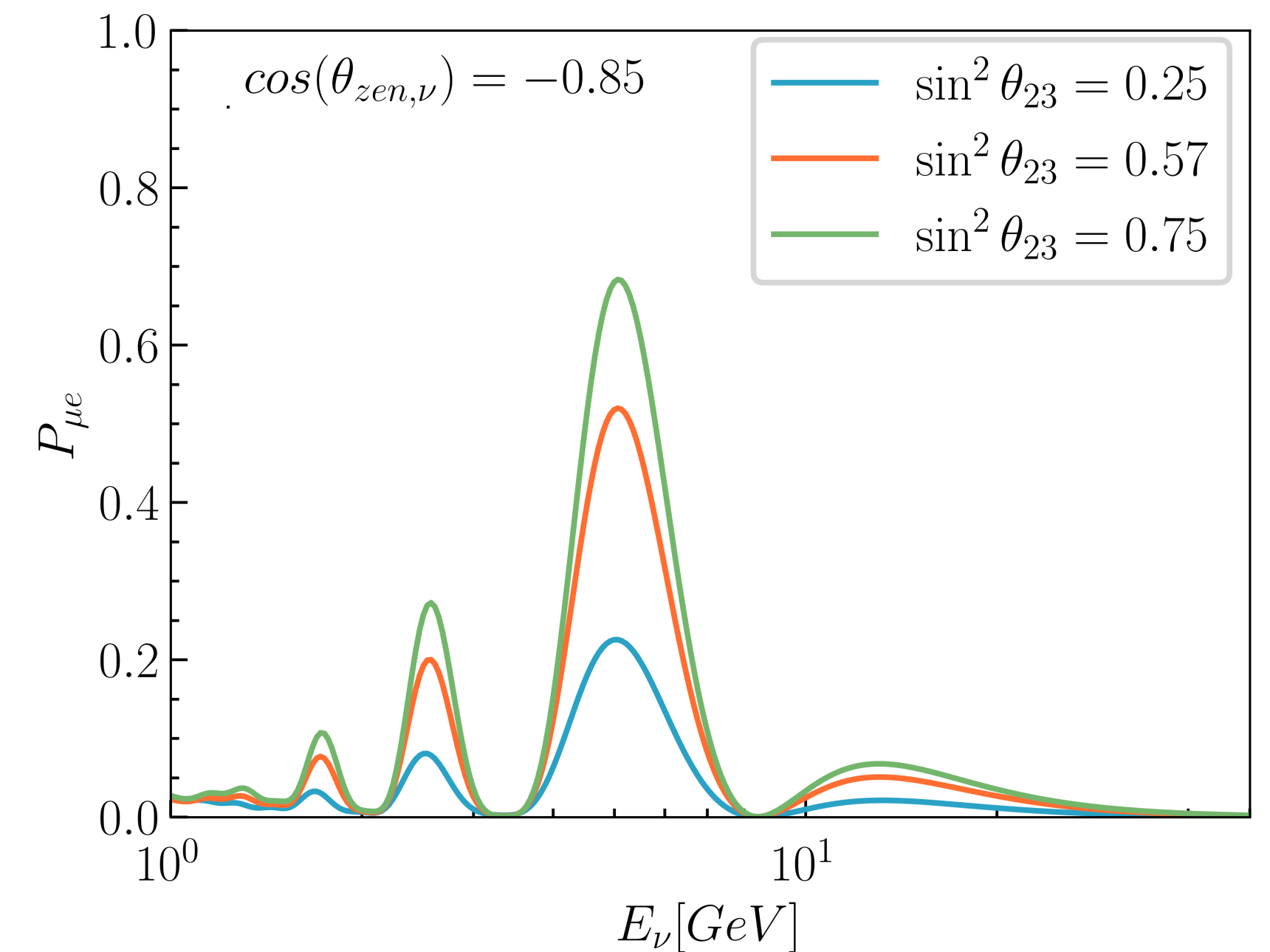
Palomares-Ruiz and Petcov, NPB 712 (2005)

Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

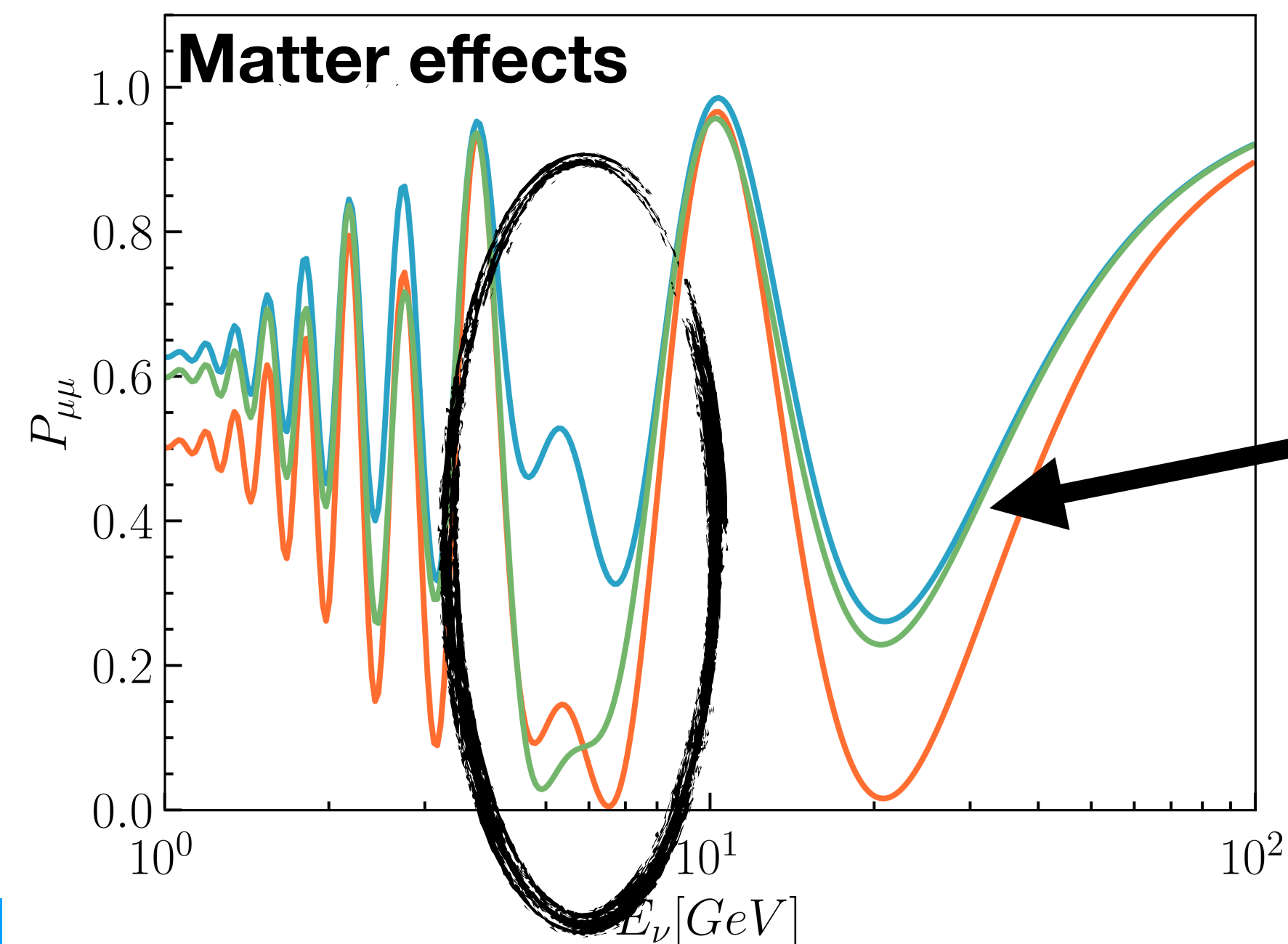
# Multi-GeV

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

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



- $P_{\mu\mu}$  can determine whether  $\theta_{23}$  is **maximal mixing**.
- The **matter effects** can **resolve** the degeneracy between the two **octants**.



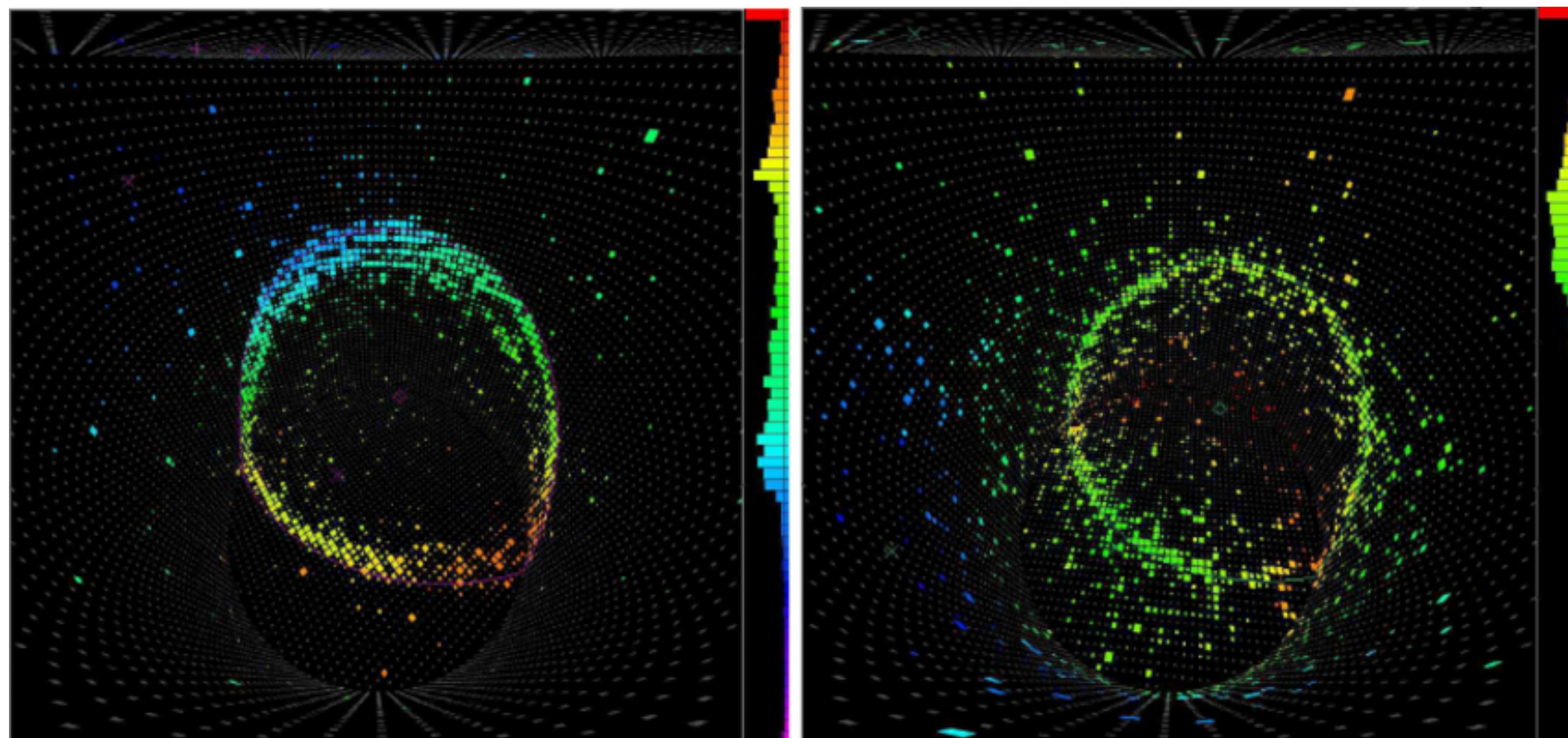


# Super-Kamiokande

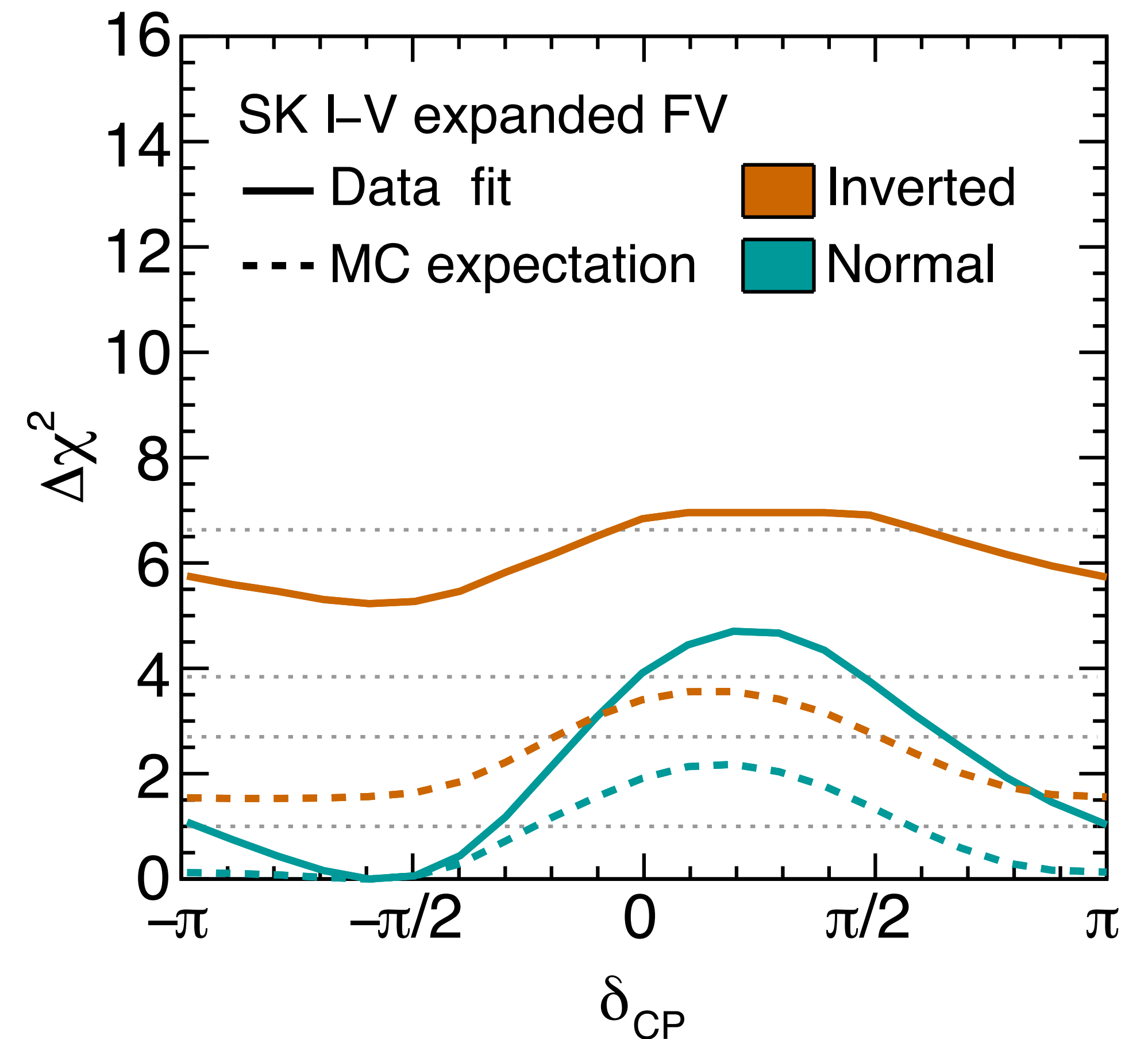
Several experiments have measured the atmospheric neutrino flux, with **SK** starting from the **sub-GeV scale**.

## 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- $\mu$



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

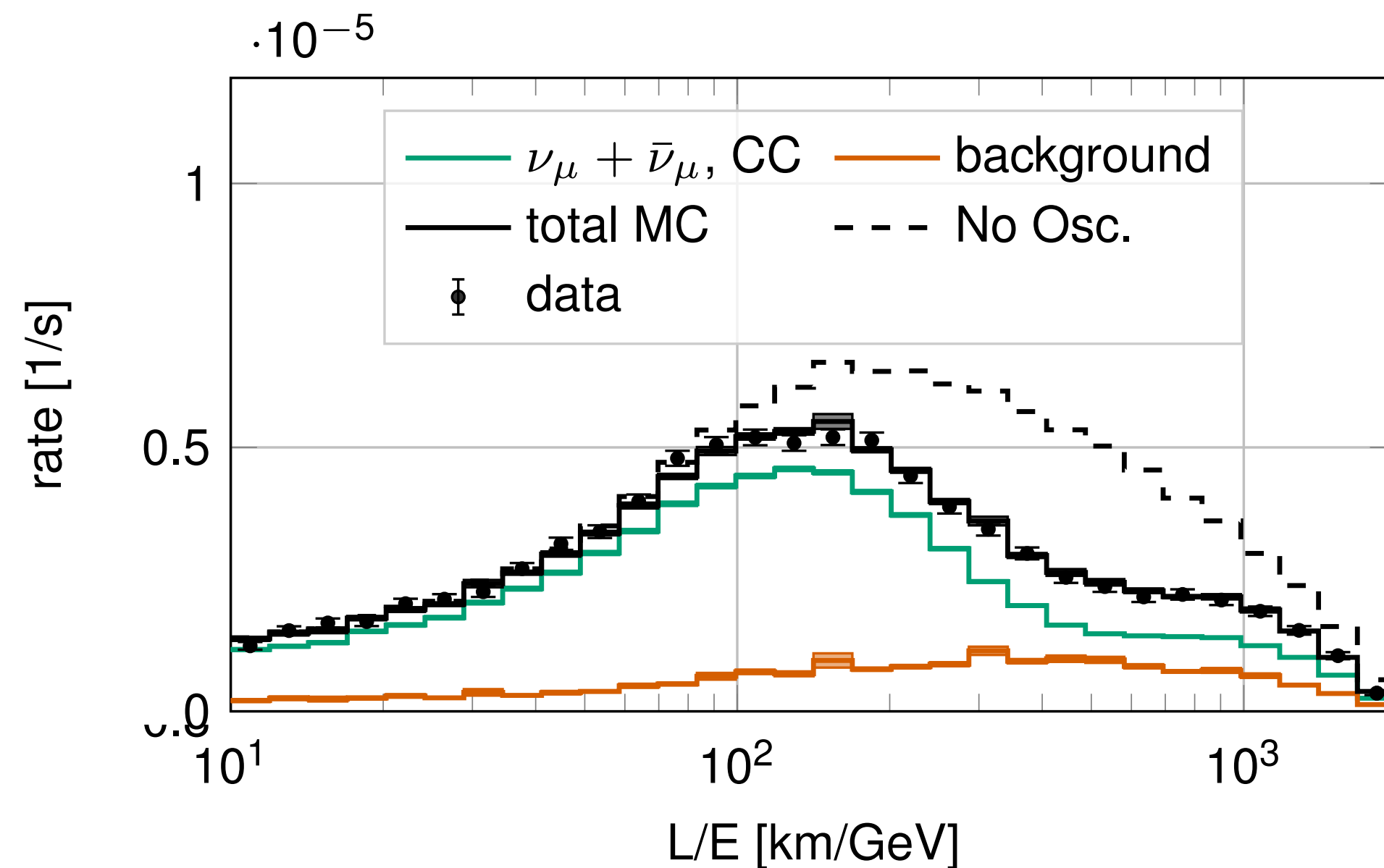


Wester et al. (Super-Kamiokande), arXiv: 2311.05105

# IceCube

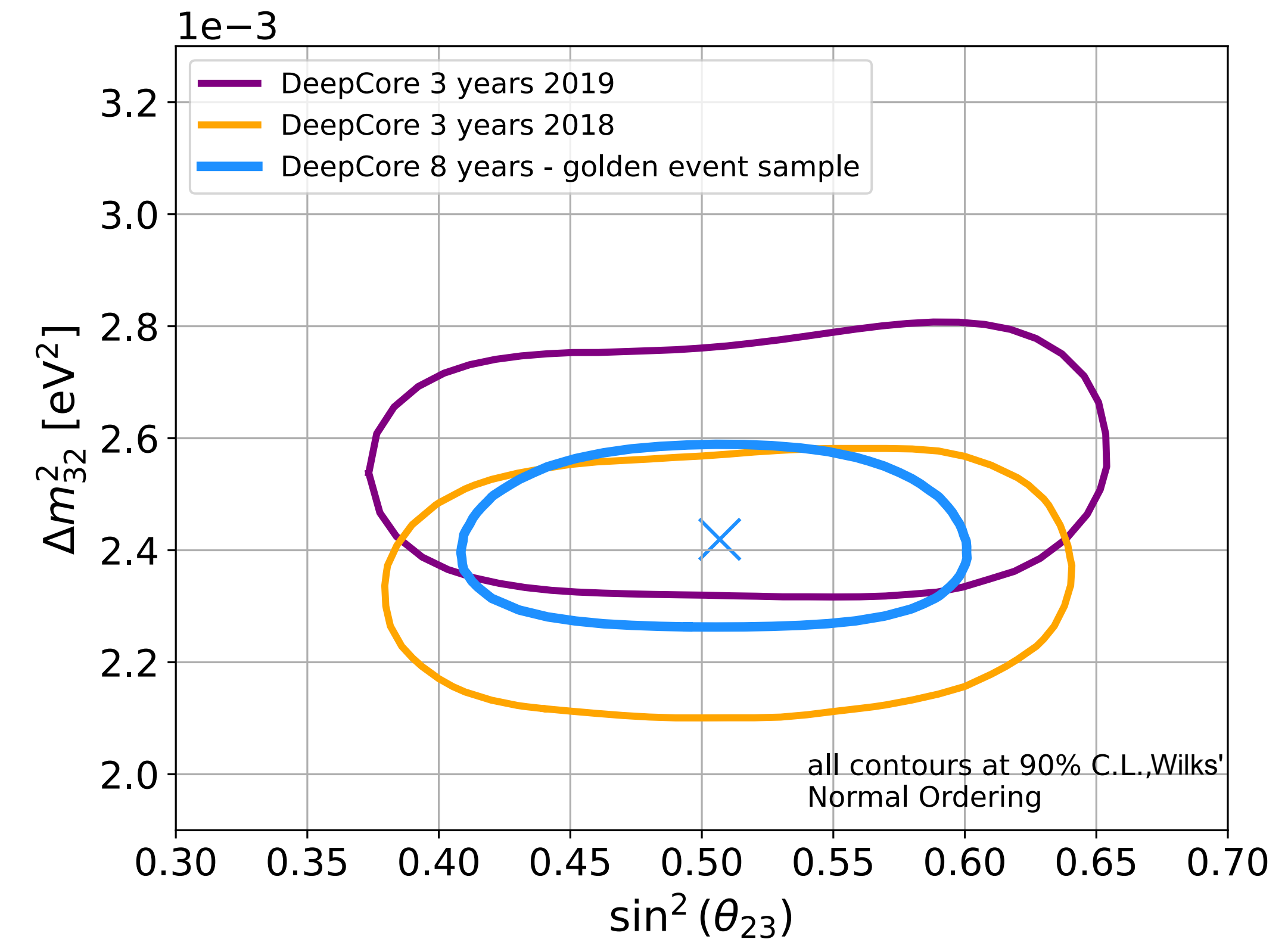
The **neutrino telescopes** measure the atmospheric neutrino flux from the **multi-GeV** scale

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



[Abbasi et al. \(IceCube\), PRD 108 \(2023\)](#)

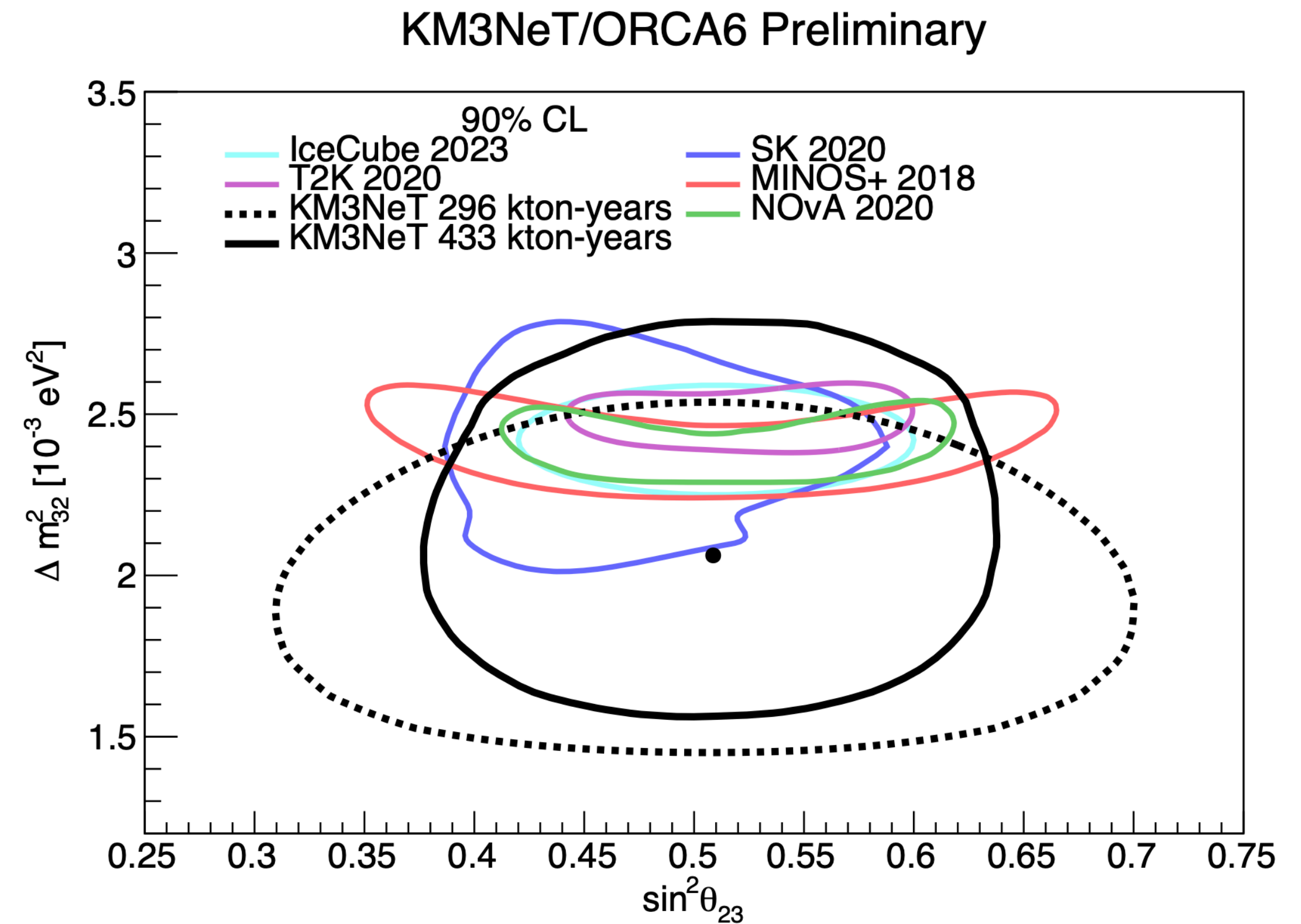
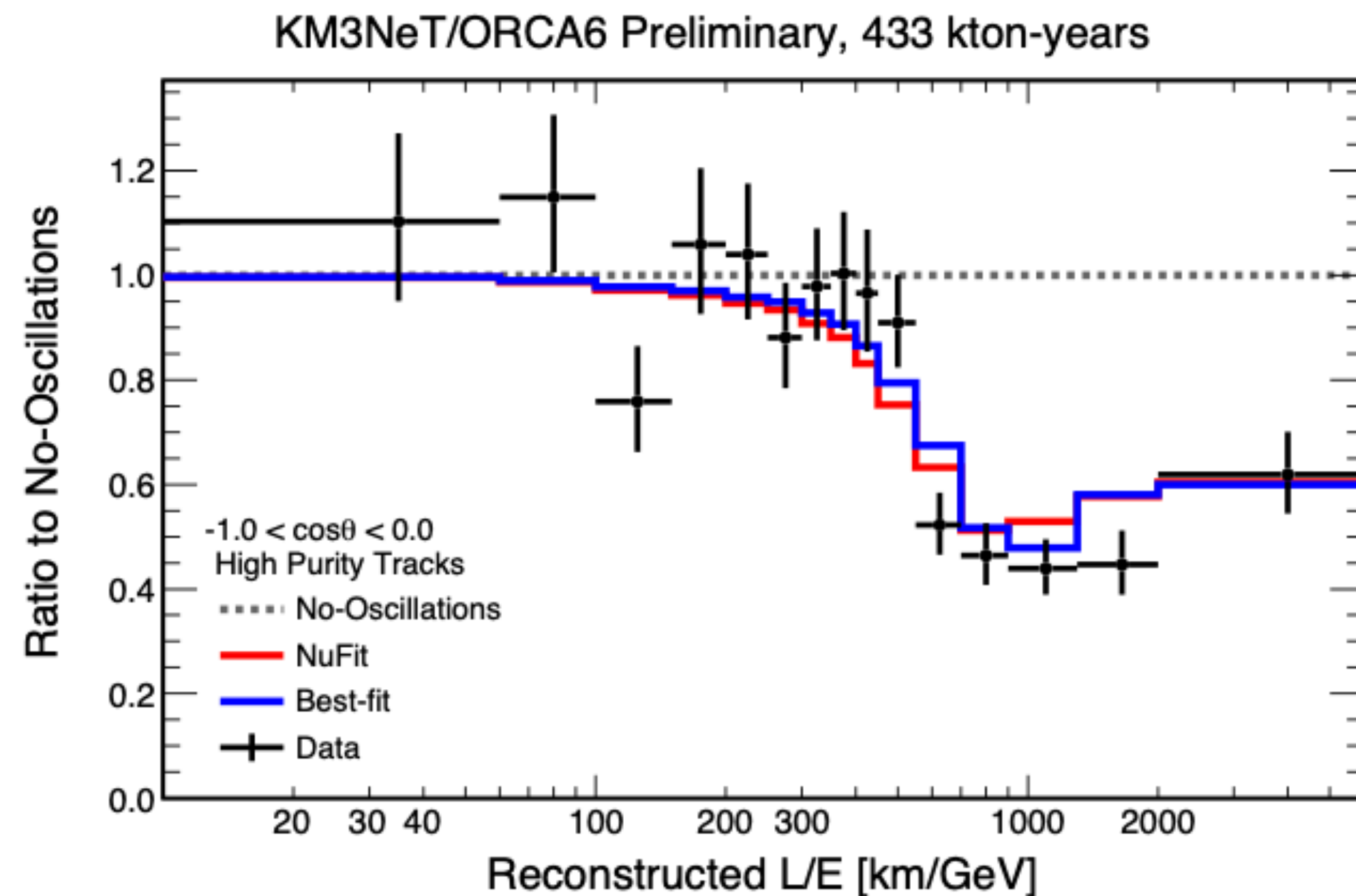
[Abbasi et al. \(IceCube\), arXiv: 2405.02163](#)



# 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



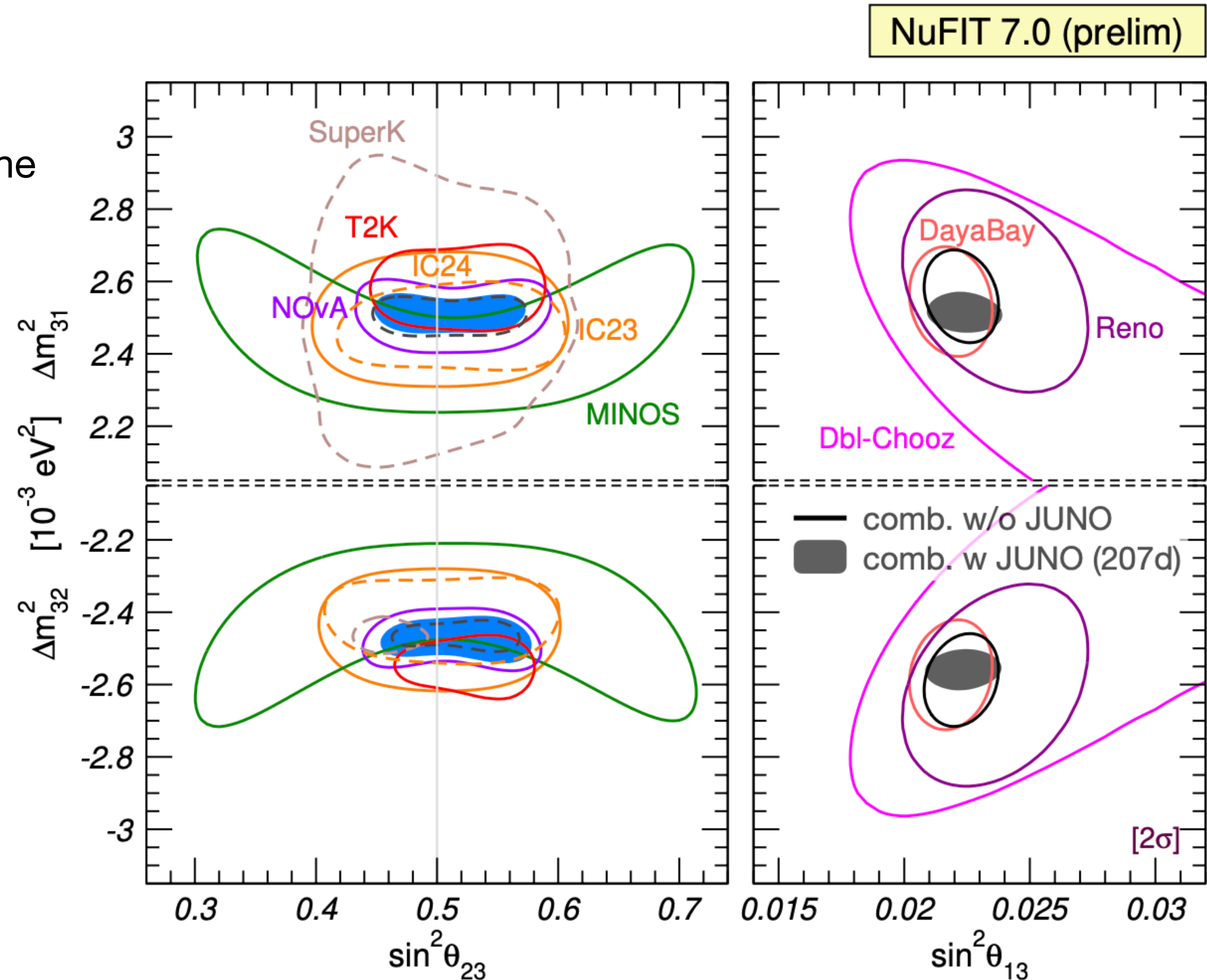
Carretero et al. (KM3NeT), PoS ICRC2023  
Aiello (KM3NeT), EPJC 82, 26 (2022)



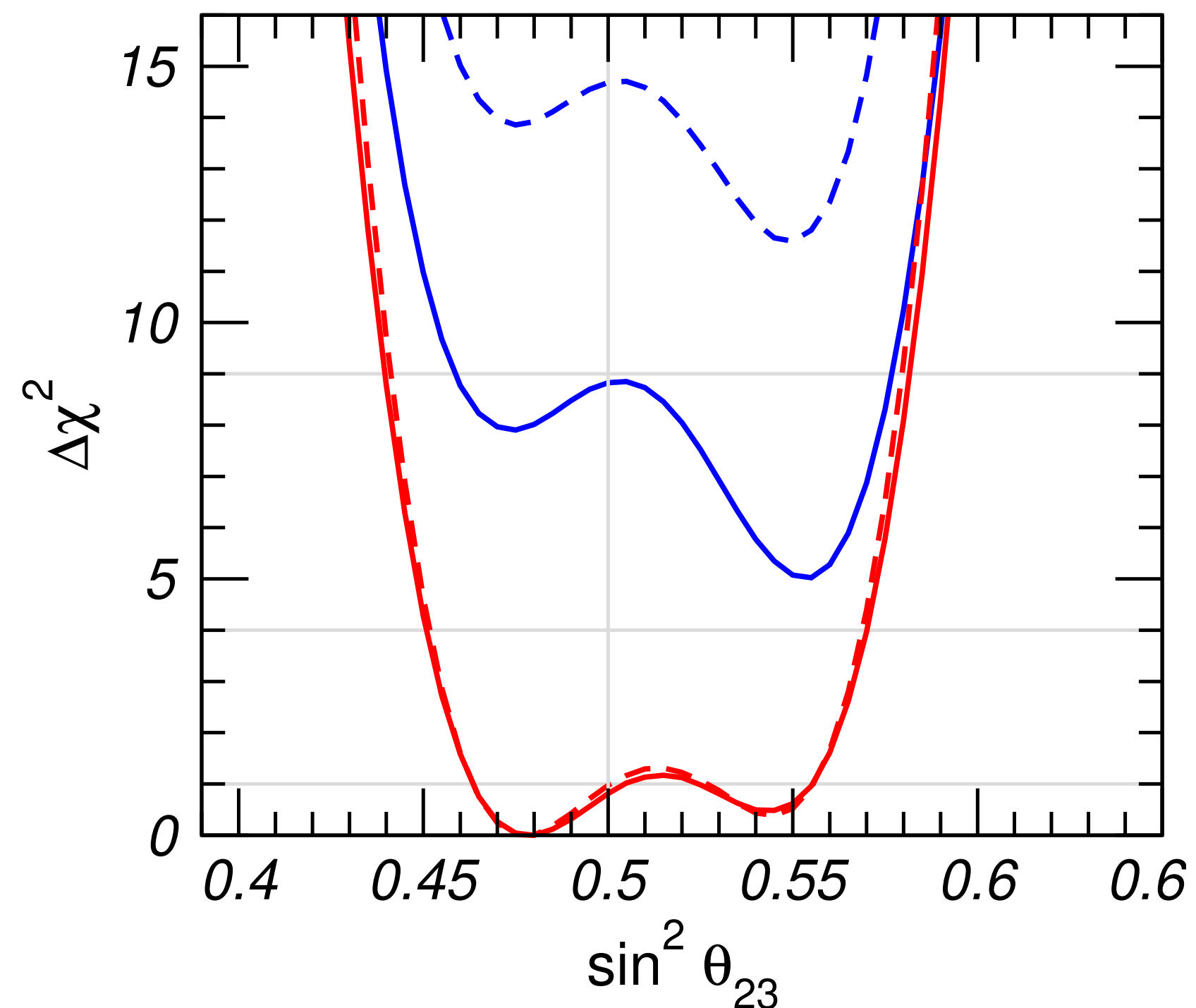
# Synergies in the Global Fit

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

- Colored regions: LBL+IC23
- Black-dashed: LBL+IC24+SK
- Good agreement with **reactor** experiments



# Synergies in the Global Fit



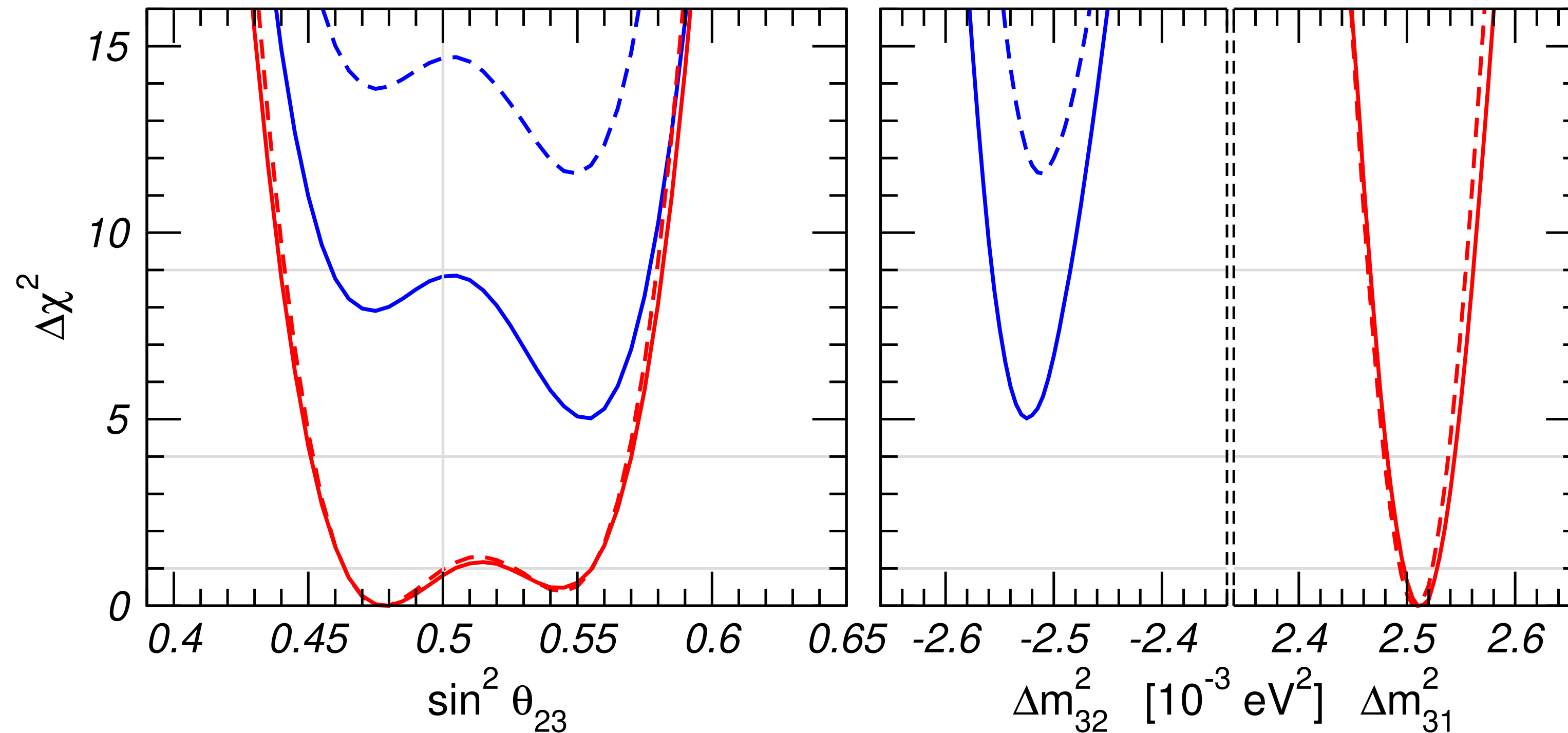
- NuFit 7 prelim: Preference for the **lower octant**, but below  $\Delta\chi^2 = 1$
- Compared to NuFit 6.1, the preference for the lower octant has decreased

— NO, IO (IC23 w/o SK-atm)  
-- NO, IO (IC24 with SK-atm)

NuFIT 7.0 (prelim)



# Synergies in the Global Fit



Preference for NO

LBL+JUNO+IC23  $\Delta\chi^2 \sim 5$

LBL+JUNO+IC24+SK  $\Delta\chi^2 \sim 11.6$

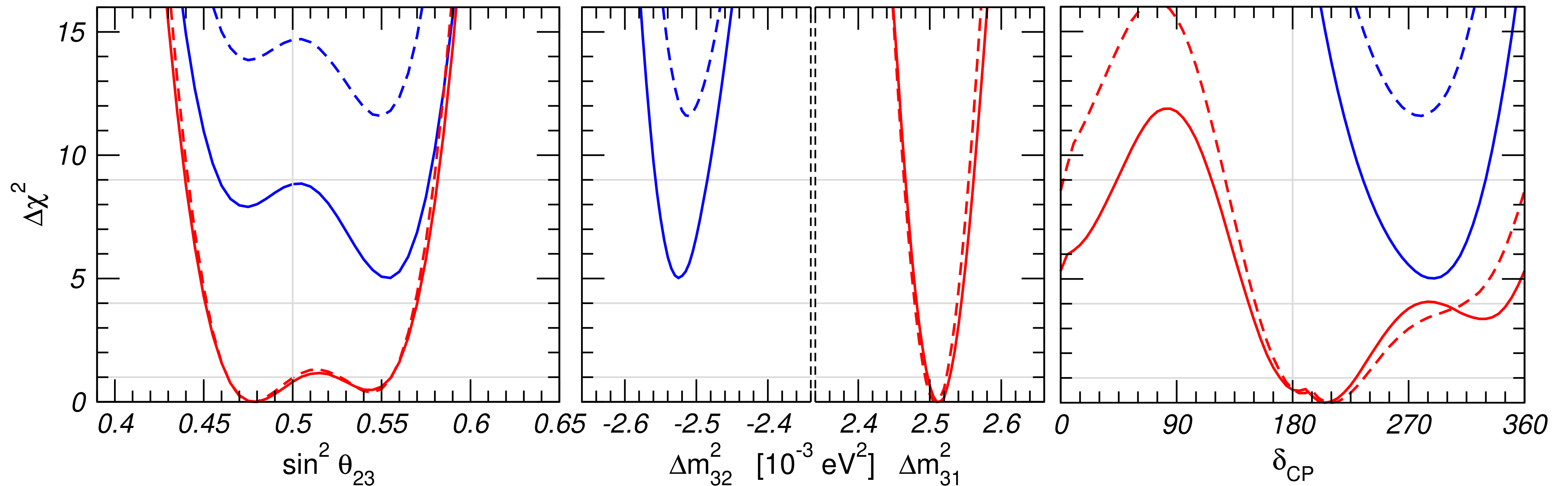
Compared to NuFit 6.1, the  
preference for NO has increased  
by 3.5 (5.6)

— NO, IO (IC23 w/o SK-atm)  
-- NO, IO (IC24 with SK-atm)

NuFIT 7.0 (prelim)

# Synergies in the Global Fit

For  $\delta_{CP}$  only about 20% is excluded at more than  $\Delta\chi^2 > 9$



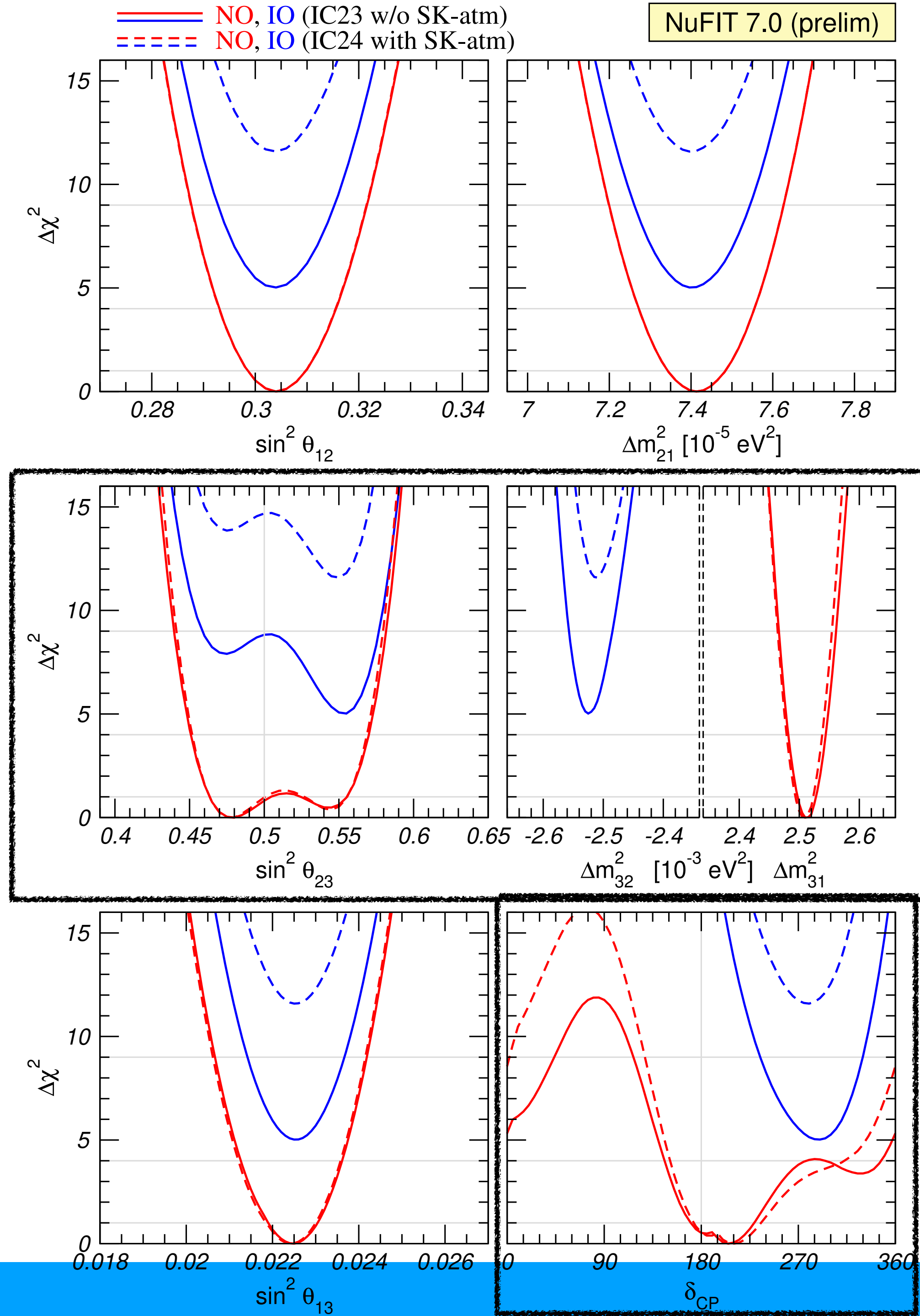
— NO, IO (IC23 w/o SK-atm)  
-- NO, IO (IC24 with SK-atm)

NuFIT 7.0 (prelim)

# $3\nu$ Mixing

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

- For  $\theta_{23}$ , small preference for the **lower octant** (higher octant), combining IC24+SK+global fit (global)
- For  $\delta_{cp}$ , almost **the entire region is allowed**, with CP-conservation preferred for NO and maximal CP-violation for IO.
- **Mass ordering** shows a preference for NO, but it comes from the contribution of several experiments.





# Neutrino Mass

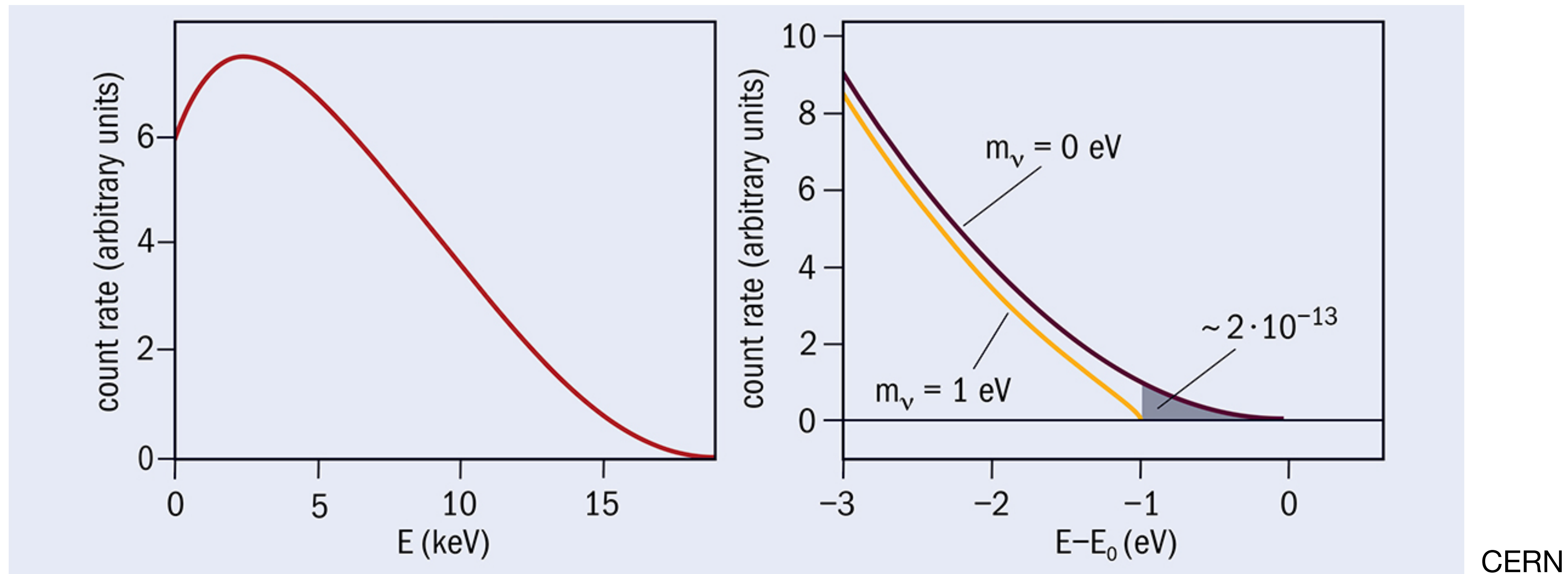
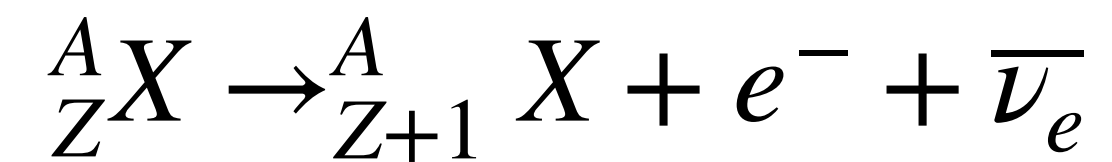
# Neutrino Mass

- Neutrino oscillation experiments cannot probe the absolute neutrino mass scale



# Neutrino Mass

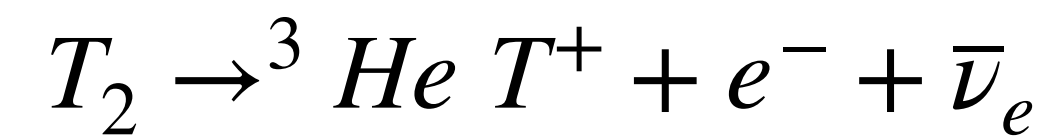
- Neutrino oscillation experiments cannot probe the absolute neutrino mass scale
- The maximum energy accessible to  $e^-$  in  $\beta$ -decays is modified if neutrinos are massive particles



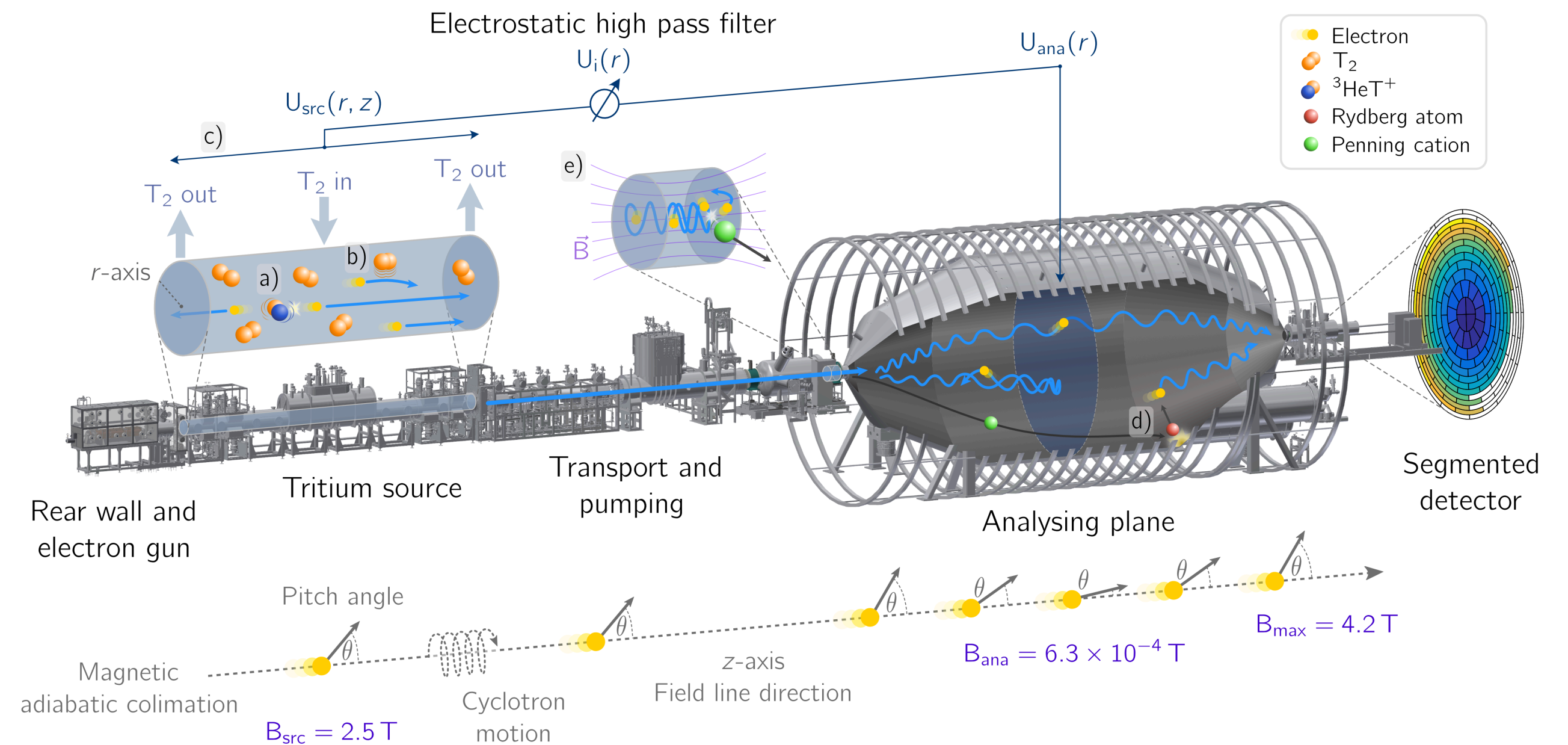
CERN

# Neutrino Mass

KATRIN explores the  $e^-$  energy spectrum in tritium decays



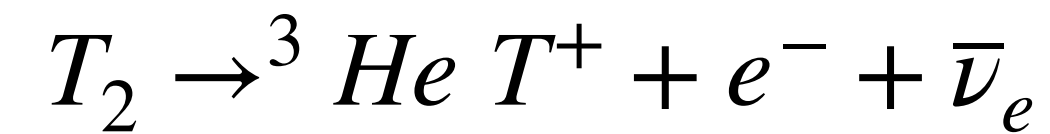
$\beta$ -spectrum end point at 18.6 keV



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

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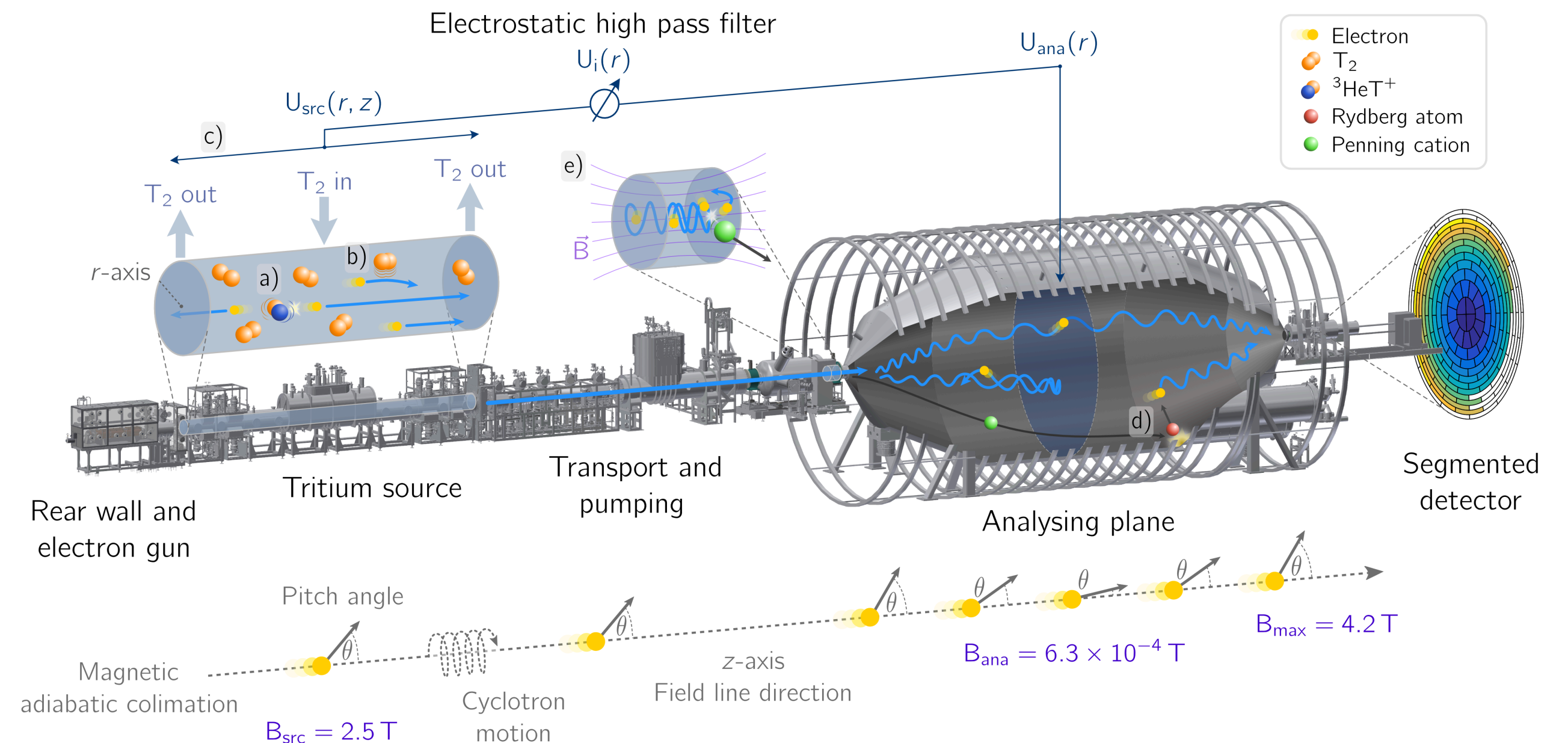


$\beta$ -spectrum end point at 18.6 keV

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

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

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

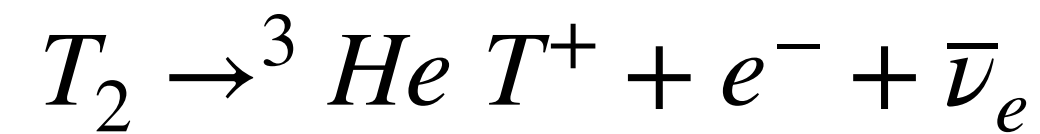


M. Aker et al (KATRIN) Nature Phys. 18 (2022)



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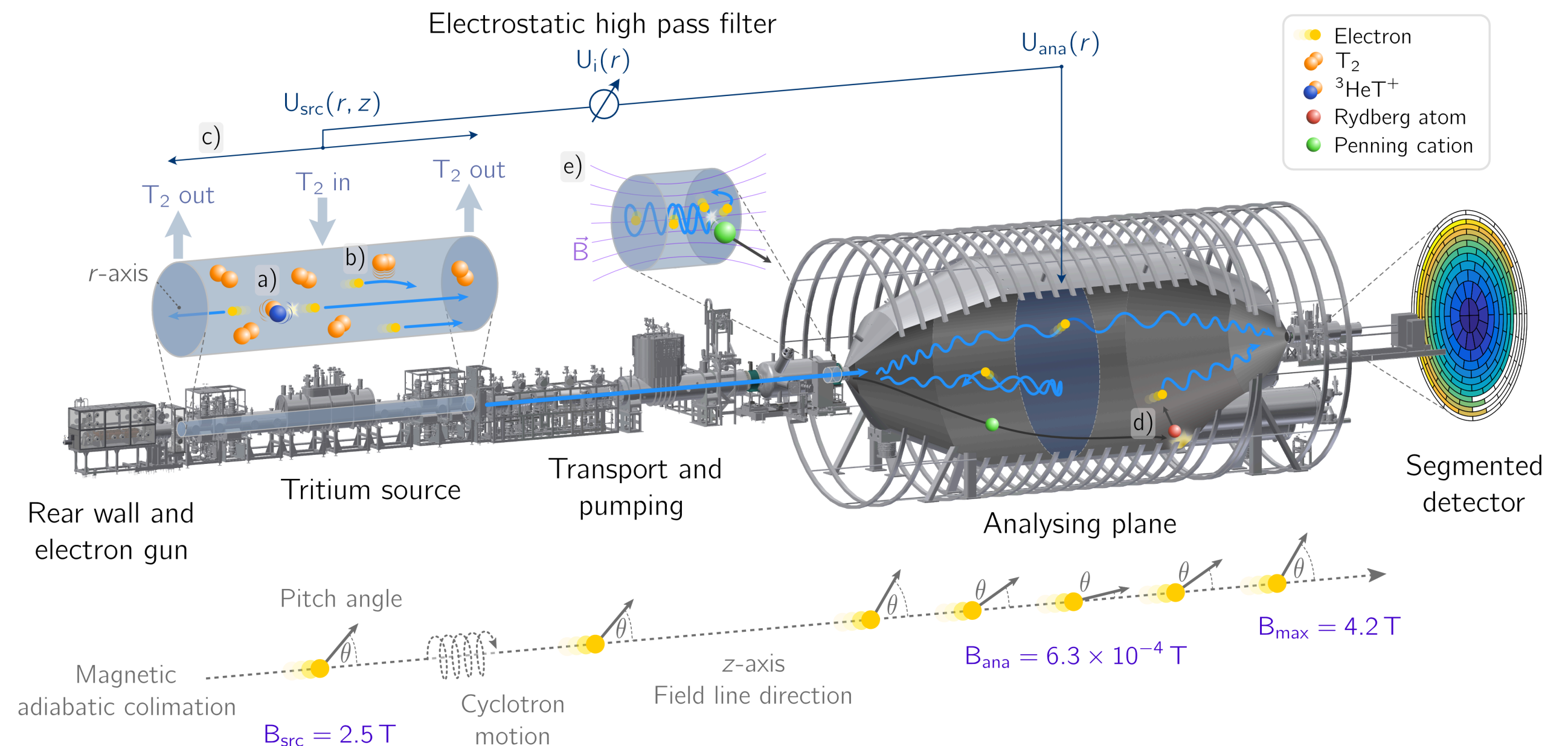
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$$= \sqrt{m_1^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 + \Delta m_{31}^2 s_{13}^2}$$

From oscillation:

NO:  $9 \times 10^{-3} \text{ eV} \leq m_{\nu_e}$

IO:  $5.8 \times 10^{-2} \text{ eV} \leq m_{\nu_e}$

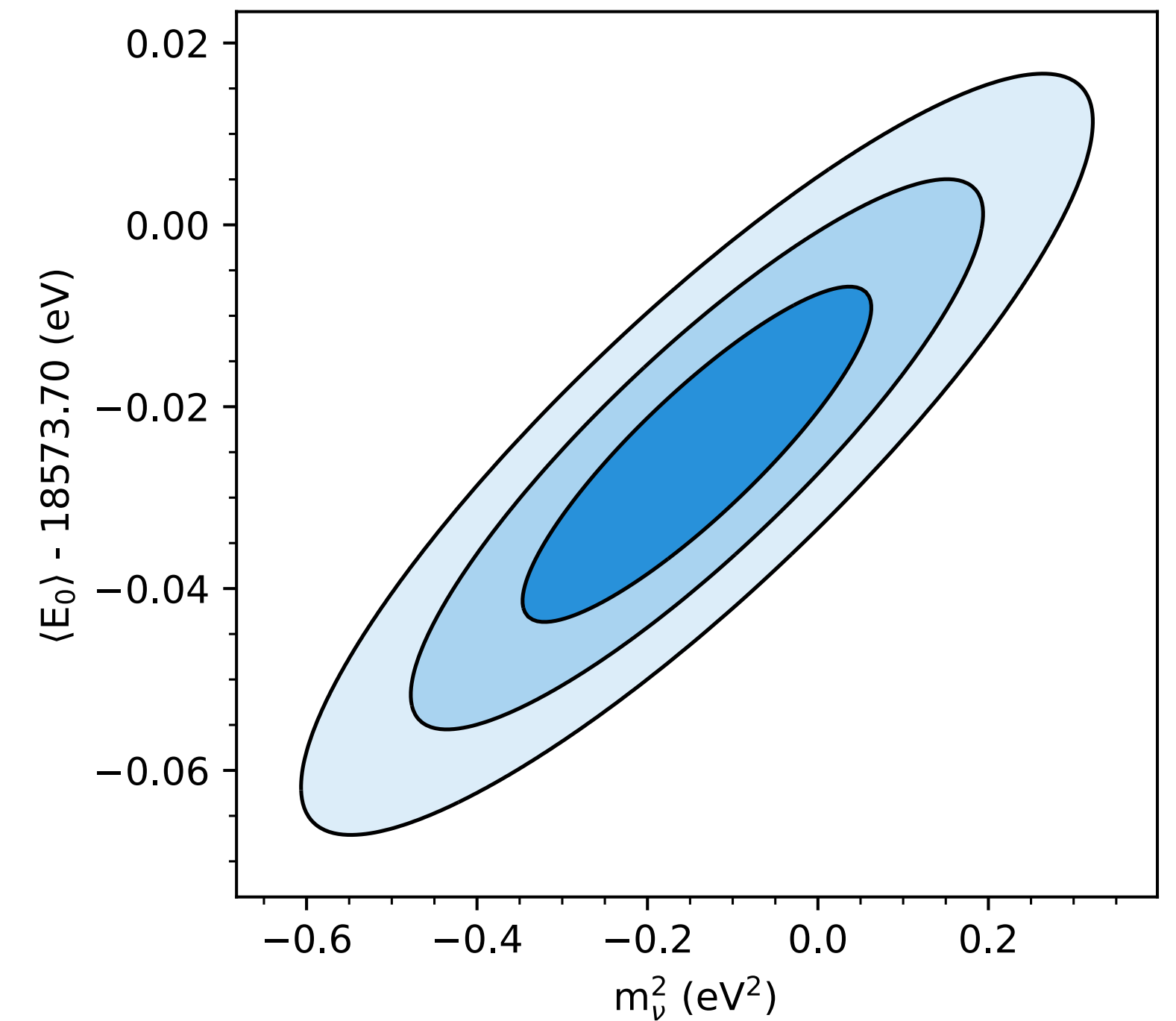
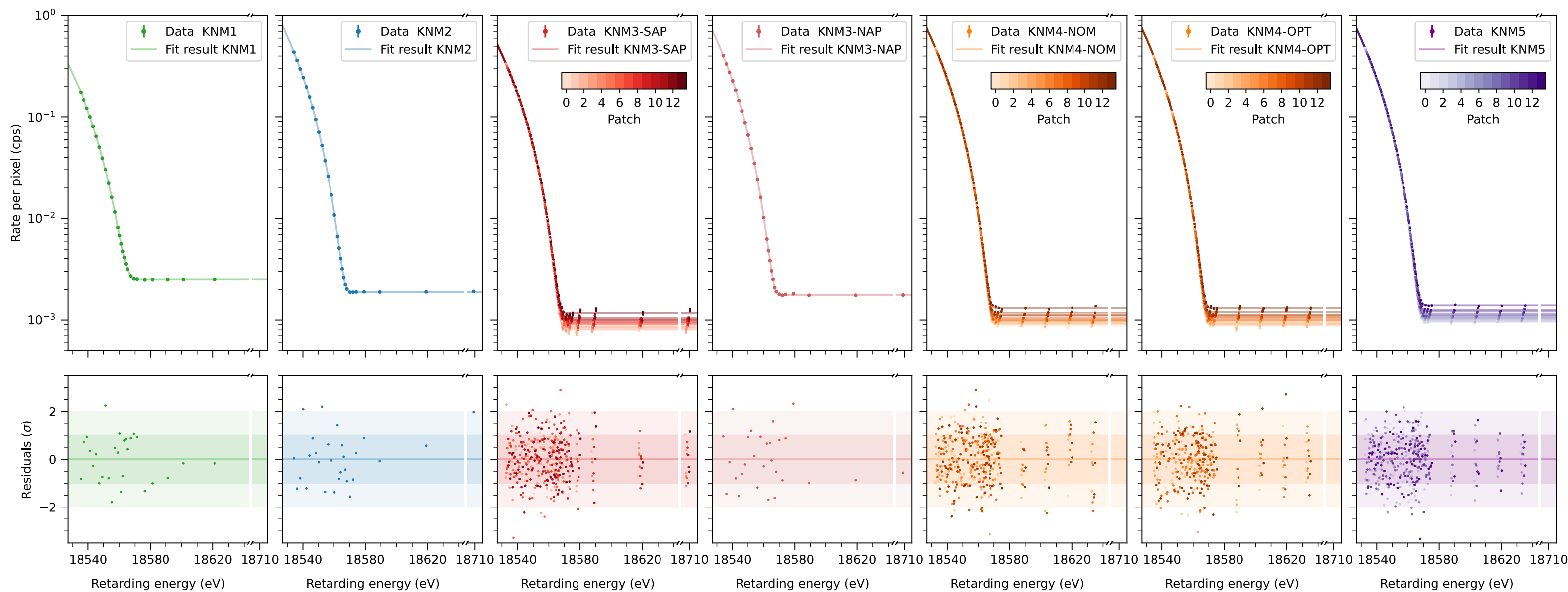


M. Aker et al (KATRIN) Nature Phys. 18 (2022)

# Neutrino Mass

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

$$m_{\nu_e} < 0.45 \text{ eV} \quad \rightarrow \quad \begin{aligned} \text{NO: } 9 \times 10^{-3} \text{ eV} &\leq m_{\nu_e} \leq 0.4 \text{ eV} \\ \text{IO: } 5.8 \times 10^{-2} \text{ eV} &\leq m_{\nu_e} \leq 1.2 \text{ eV} \end{aligned}$$



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



# Neutrinoless Double-Beta Decay

A fundamental question remains: are neutrinos their own antiparticles?

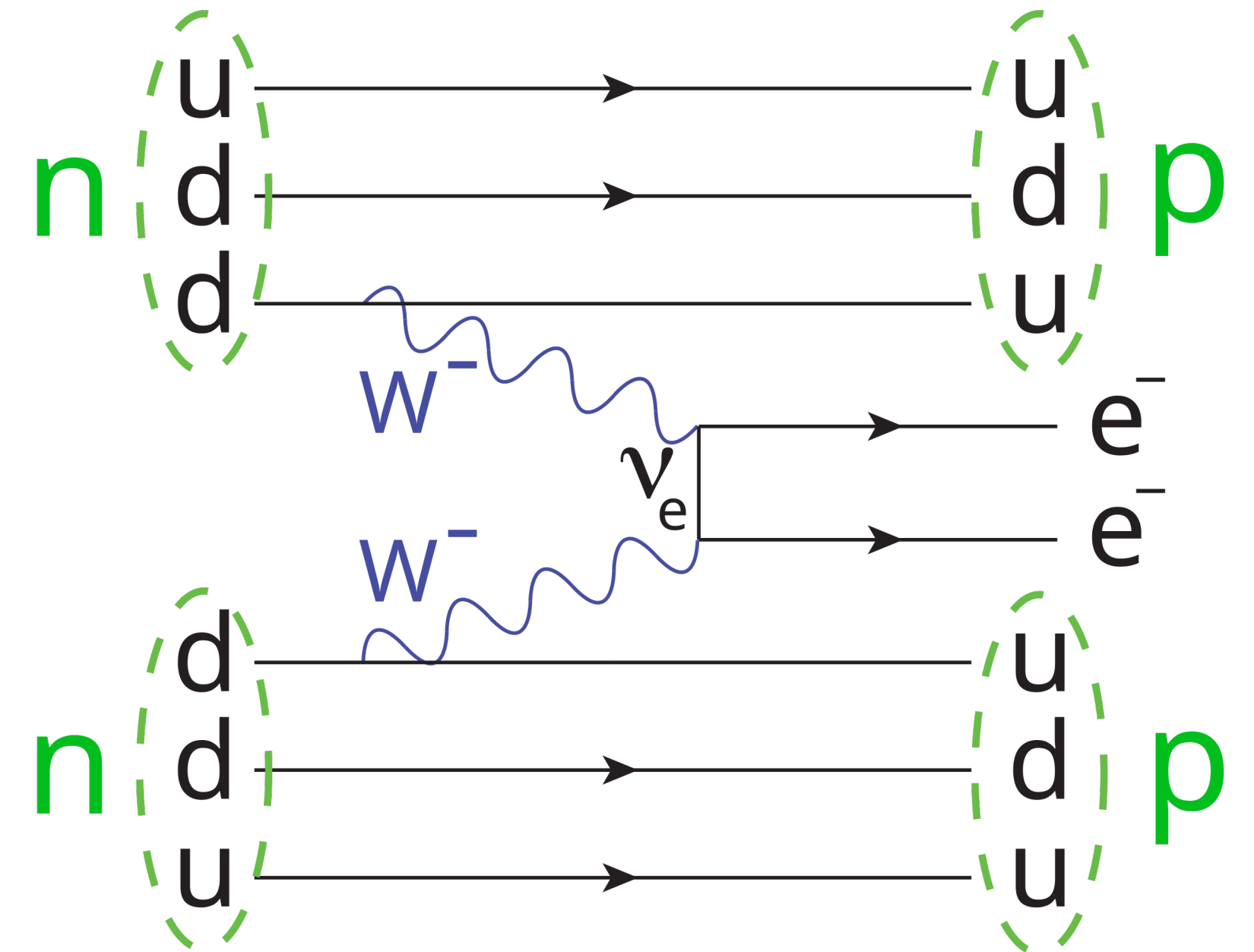
# Neutrinoless Double-Beta Decay

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

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

Phase space

Nuclear matrix element

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

The diagram illustrates the components of the half-life equation for neutrinoless double beta decay. It features three main elements: 'Phase space' on the left, 'Nuclear matrix element' in the center, and the equation  $m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$  on the right. Arrows point from 'Phase space' and 'Nuclear matrix element' to the central equation, while an arrow points from the equation to the  $m_{\beta\beta}^2$  term in the main equation above.



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Phase space
Nuclear matrix element
 $m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$

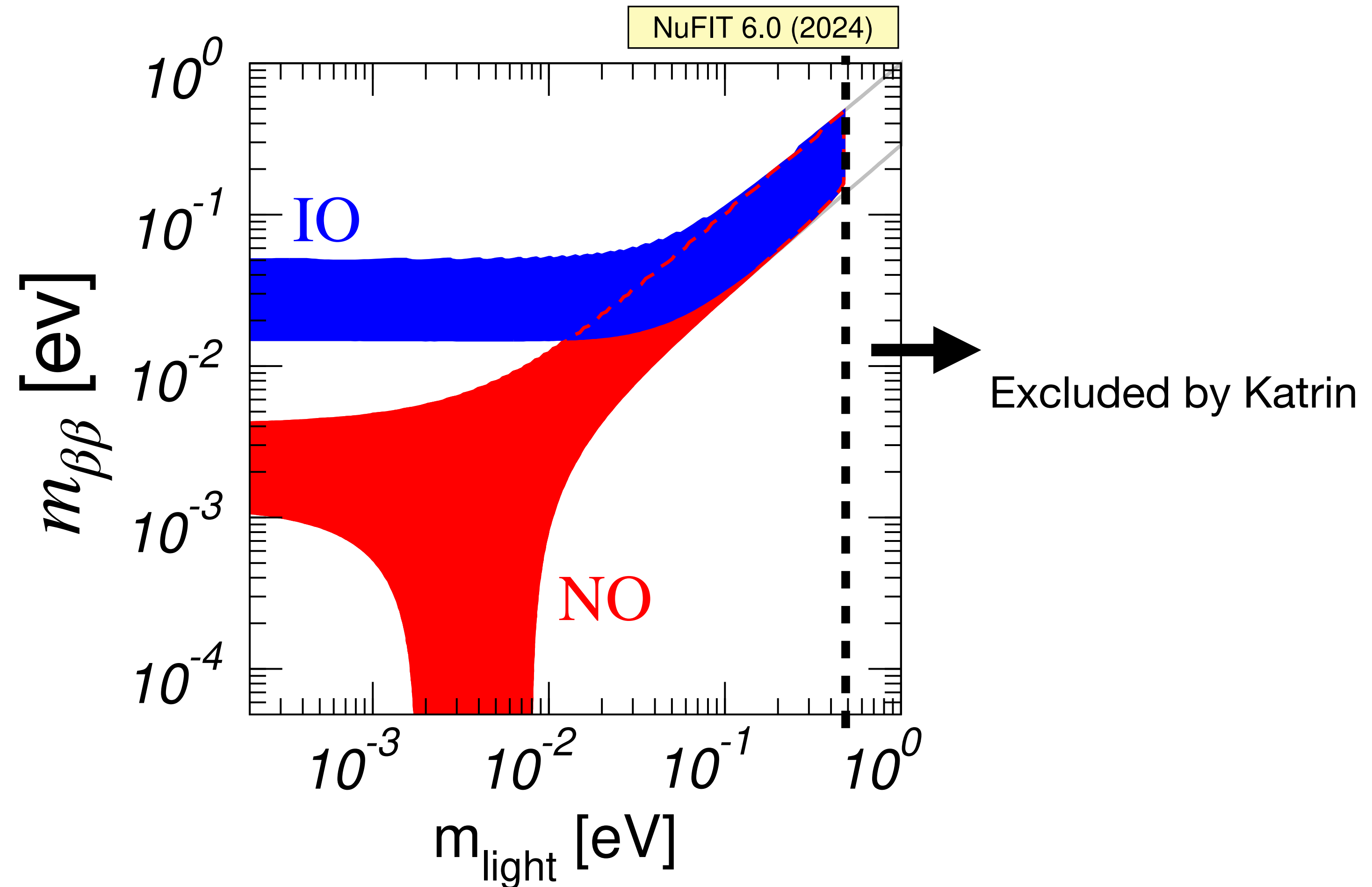
The mixing matrix contains two additional phases

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

# Neutrinoless Double-Beta Decay

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

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





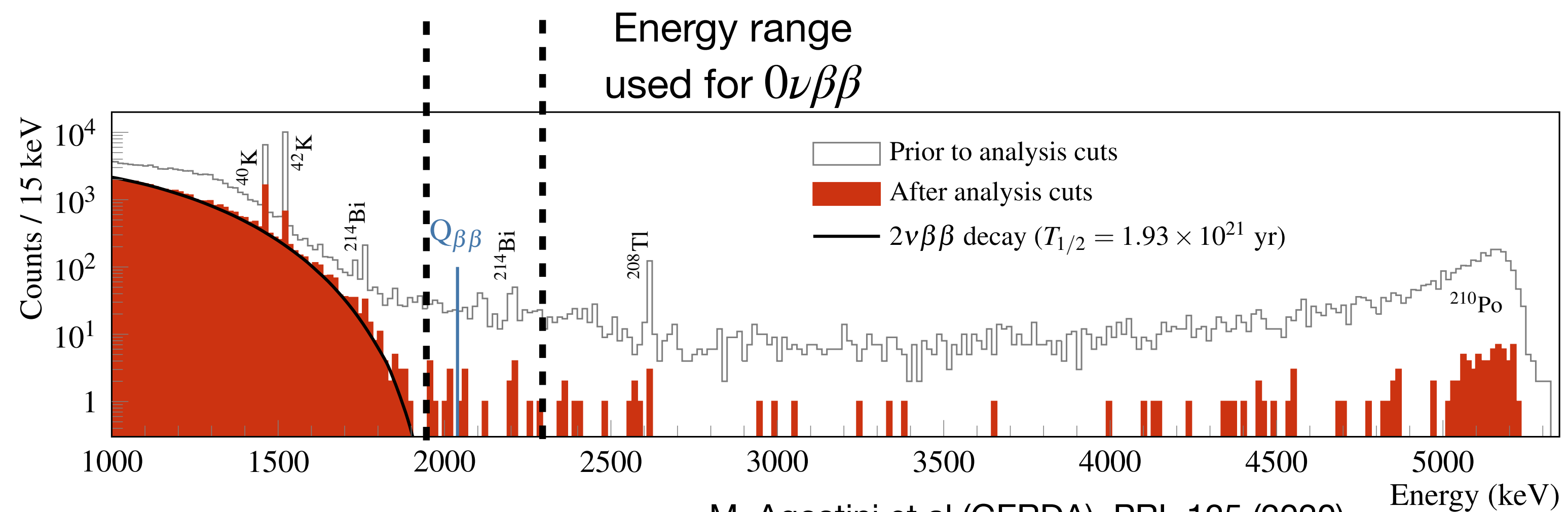
# $0\nu\beta\beta$ : GERDA

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

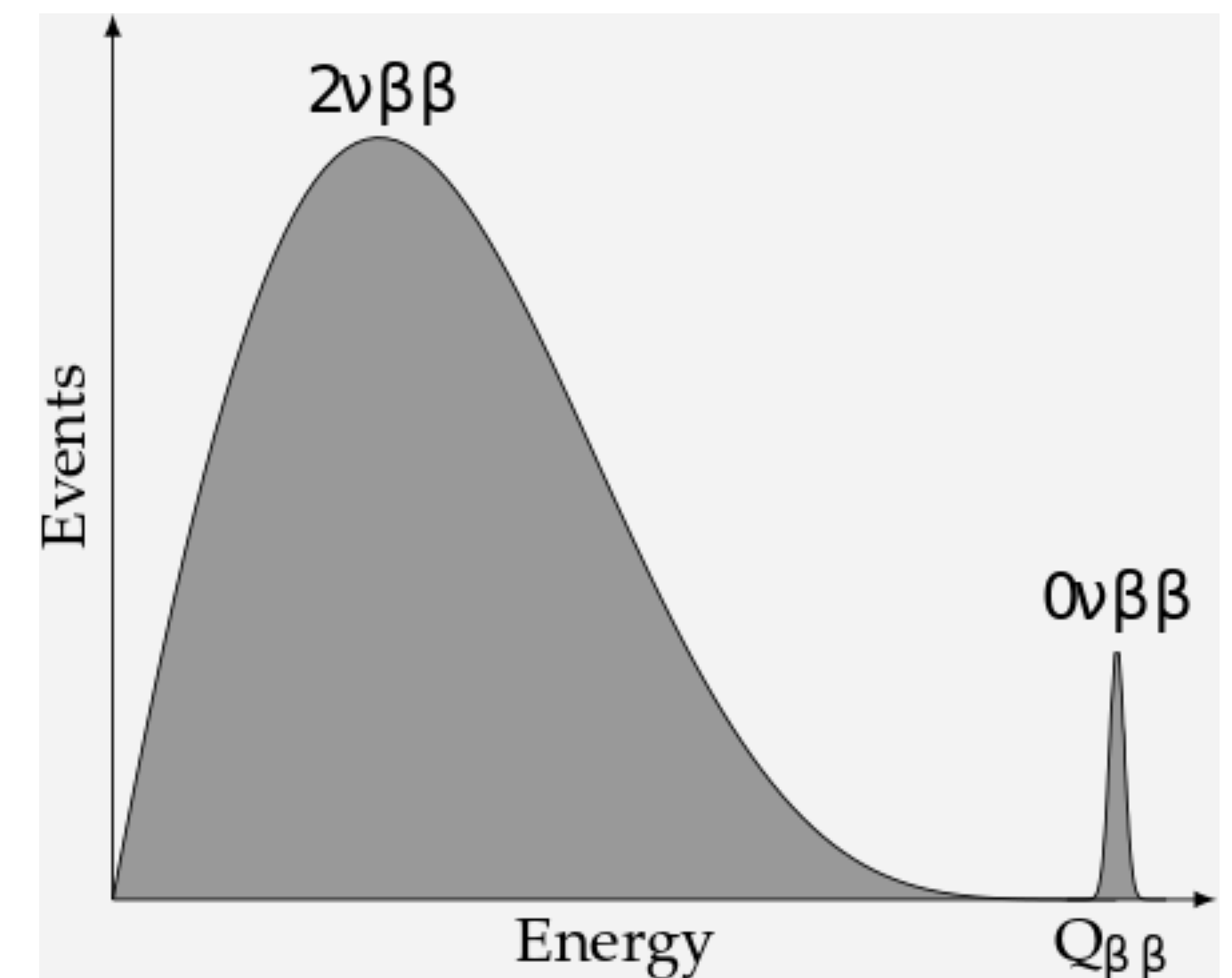
$$1.8 \times 10^{26} \text{ yr} < T_{1/2}^{0\nu} \longrightarrow m_{\beta\beta} < 79 - 180 \text{ meV}$$



Expected signal



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

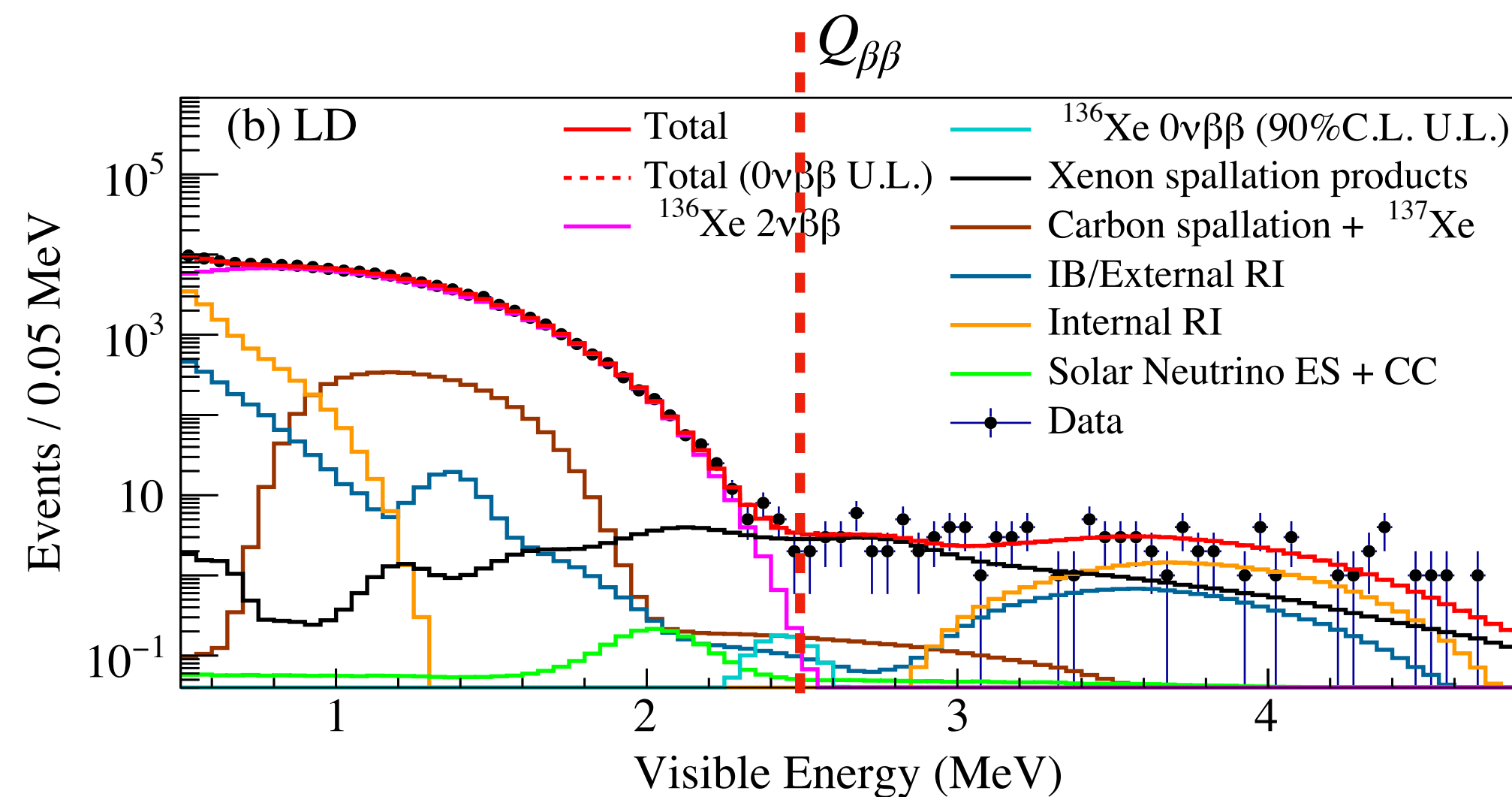
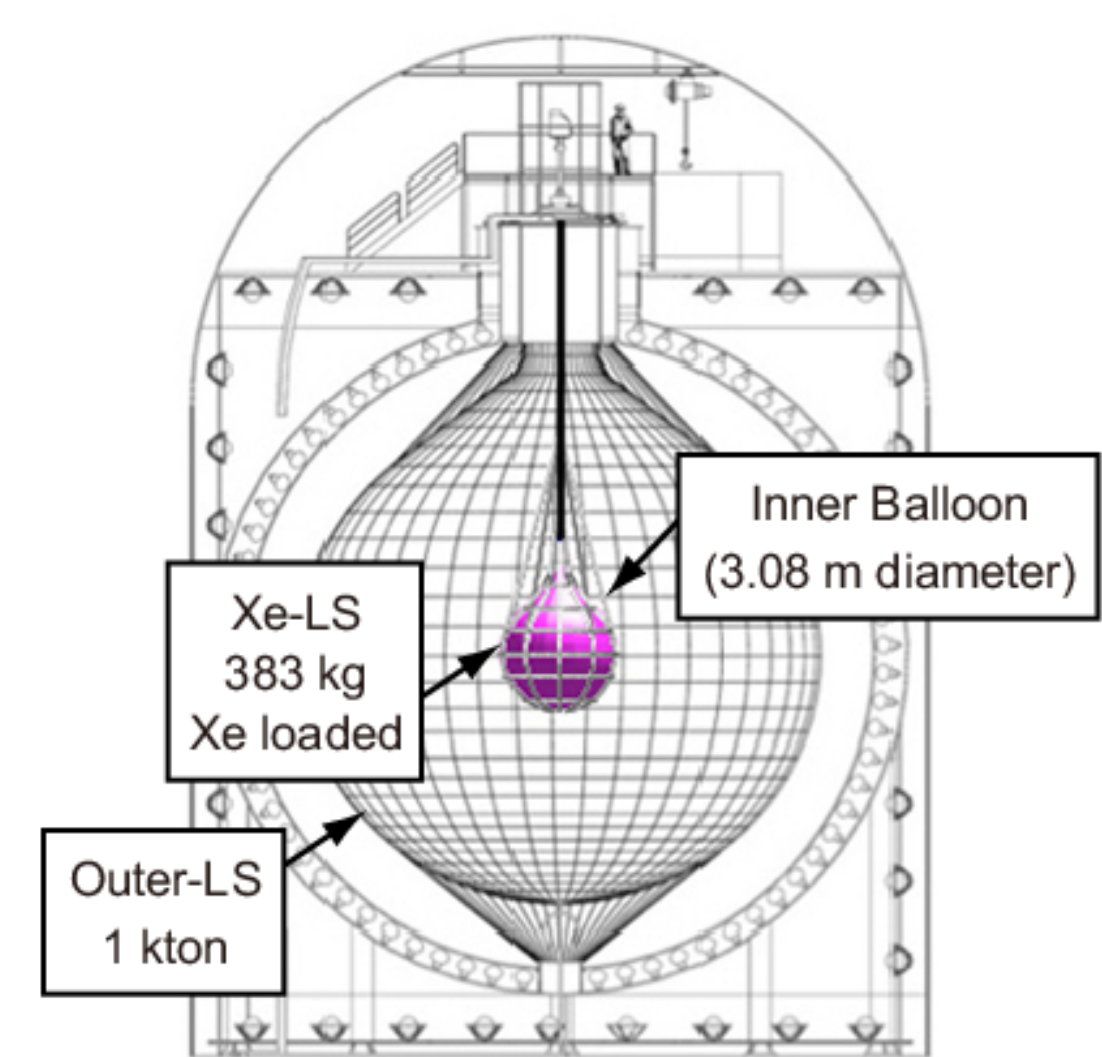


GERDA (Zurich)

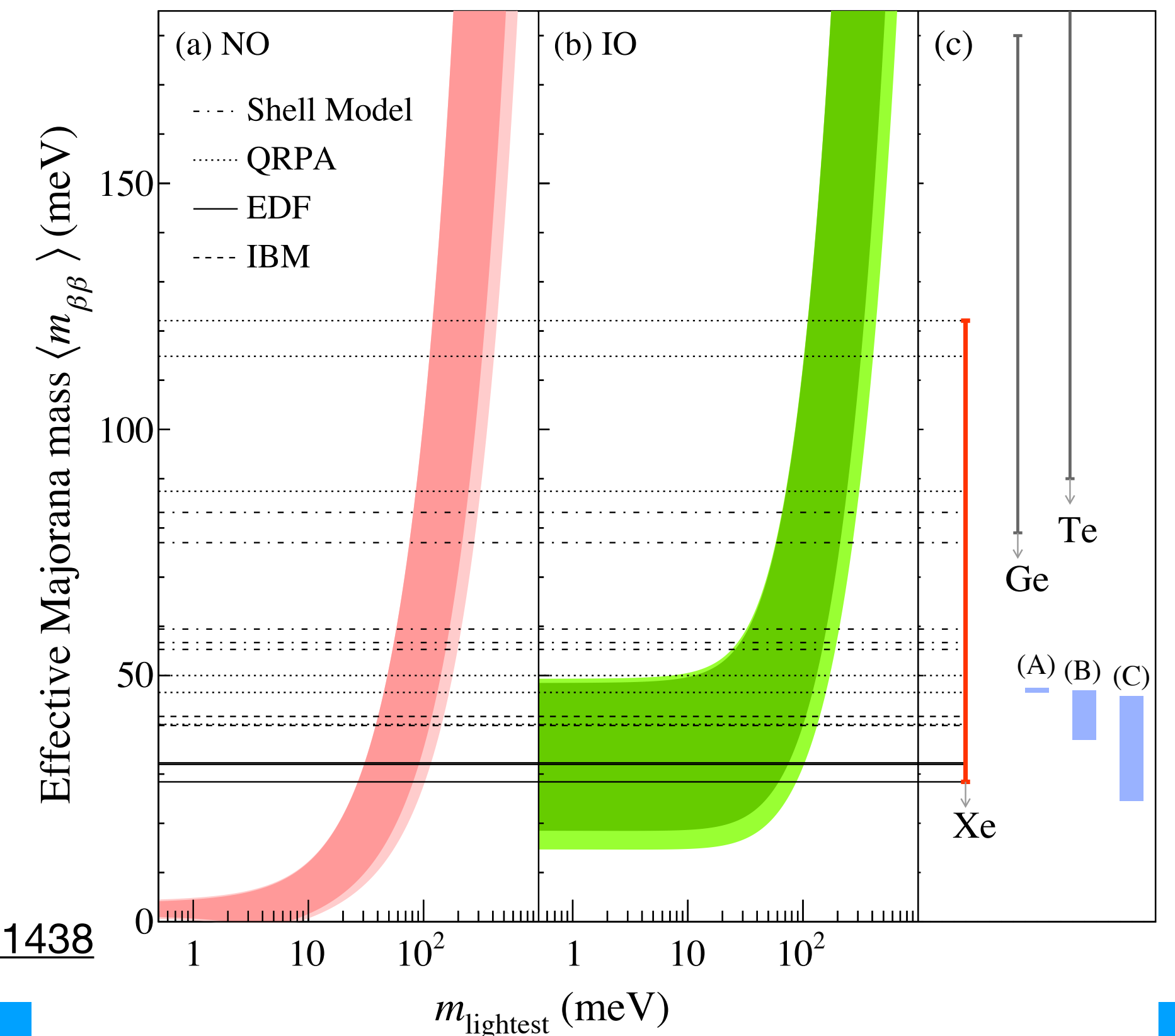
# $0\nu\beta\beta$ : KamLAND-Zen

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

$$3.8 \times 10^{26} \text{ yr} < T_{1/2}^{0\nu} \longrightarrow m_{\beta\beta} < 28 - 122 \text{ meV}$$

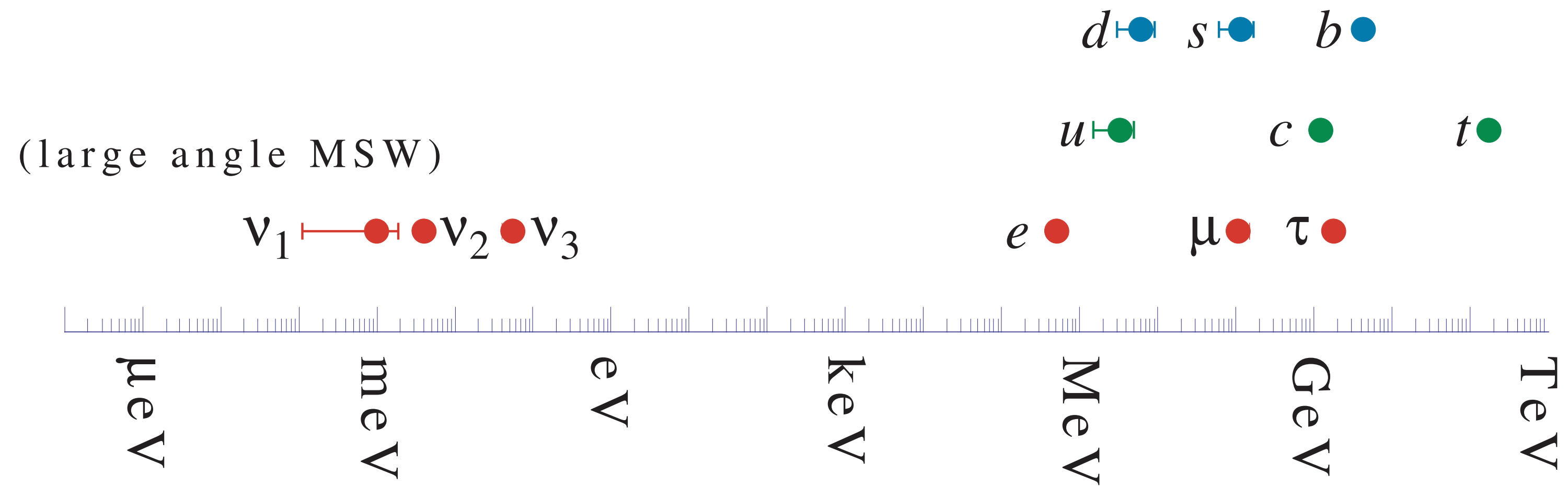


S. Abe et al. (KamLED-Zen), arXiv:2406.11438



# Neutrino Mass

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



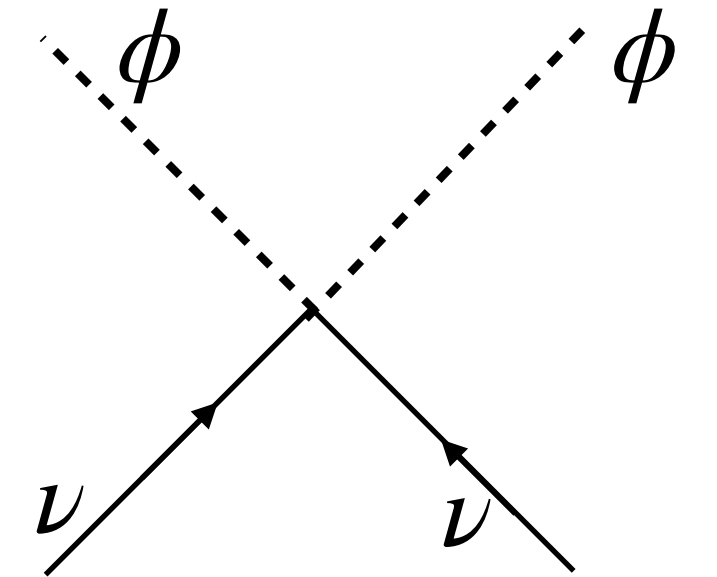
P. Hernandez, CLASHEP2015 arXiv:1708.01046



# Neutrino Mass

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

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



The smallness of the neutrino mass could be explained by the suppression of the new physics scale

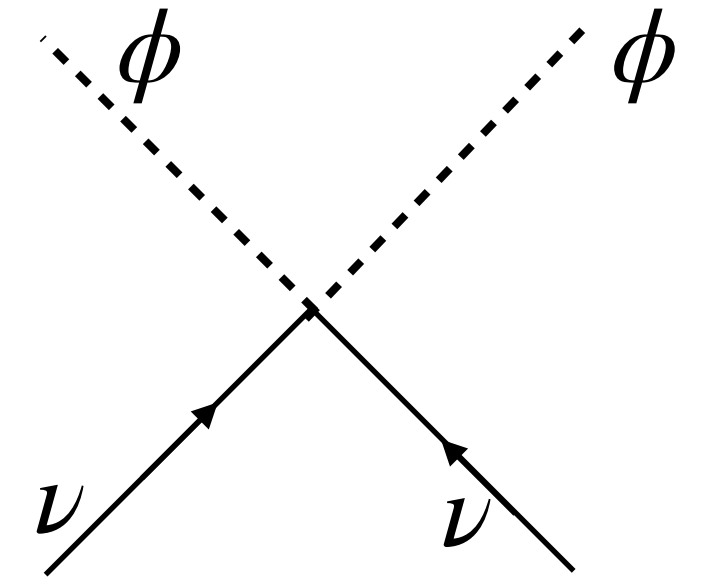


$$m_\nu \sim \frac{Y v^2}{2\Lambda}$$

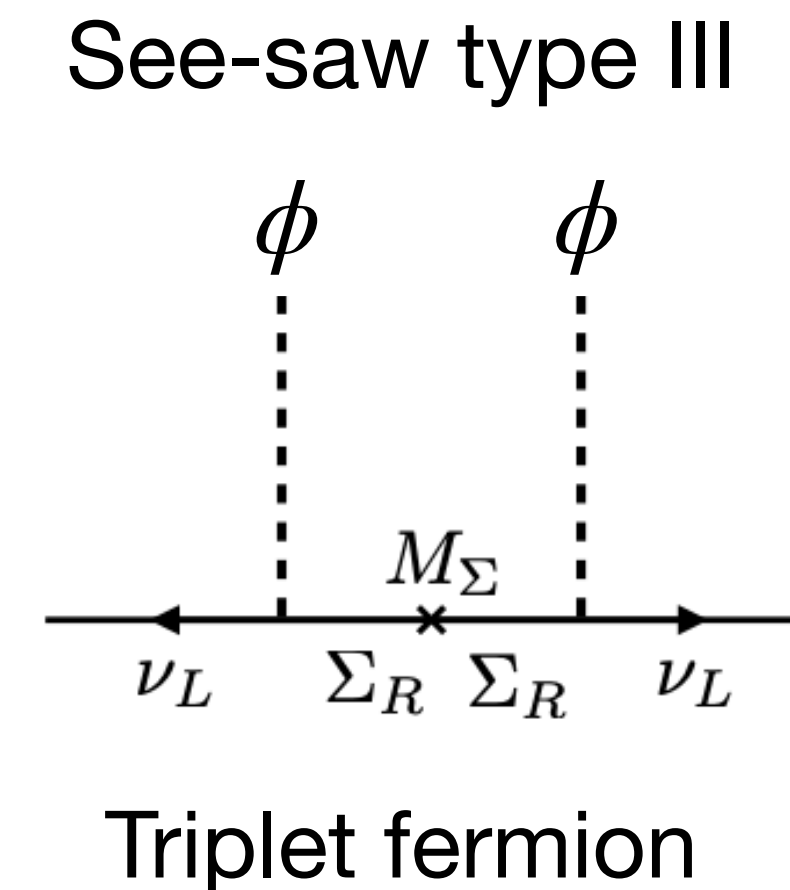
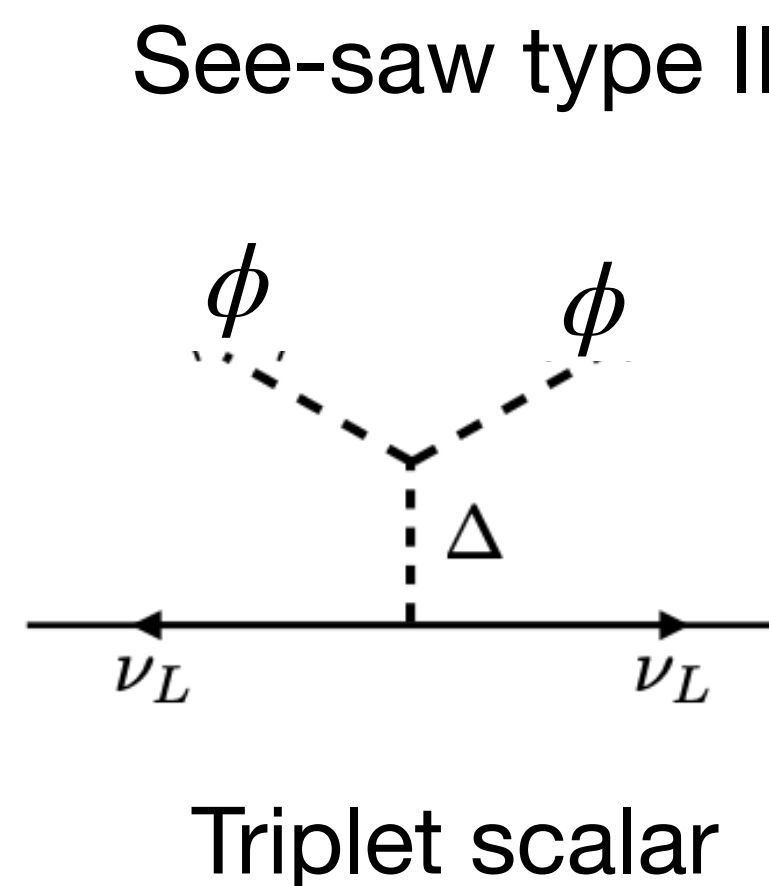
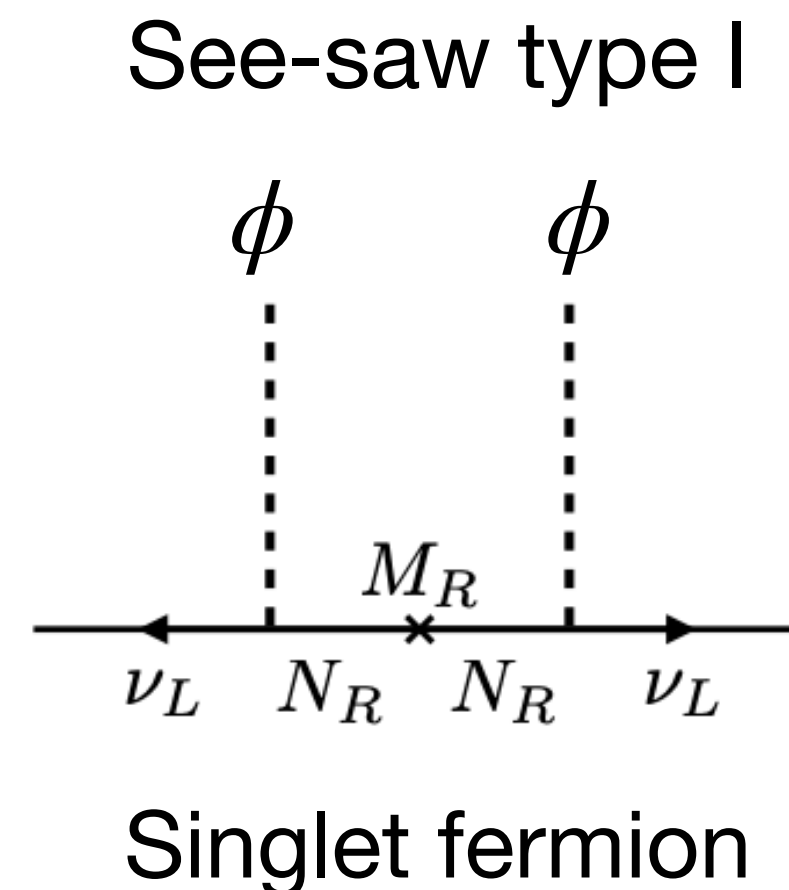
# Neutrino Mass: see-saw mechanism

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



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





# See-saw type I

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

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

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

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

# See-saw type I

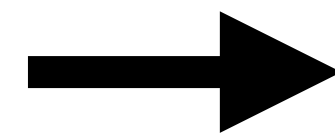
By adding a right-handed neutrino to the SM, we can construct a Dirac and Majorana mass terms

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

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

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

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



$m_D \sim 0.1$  eV



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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

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

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

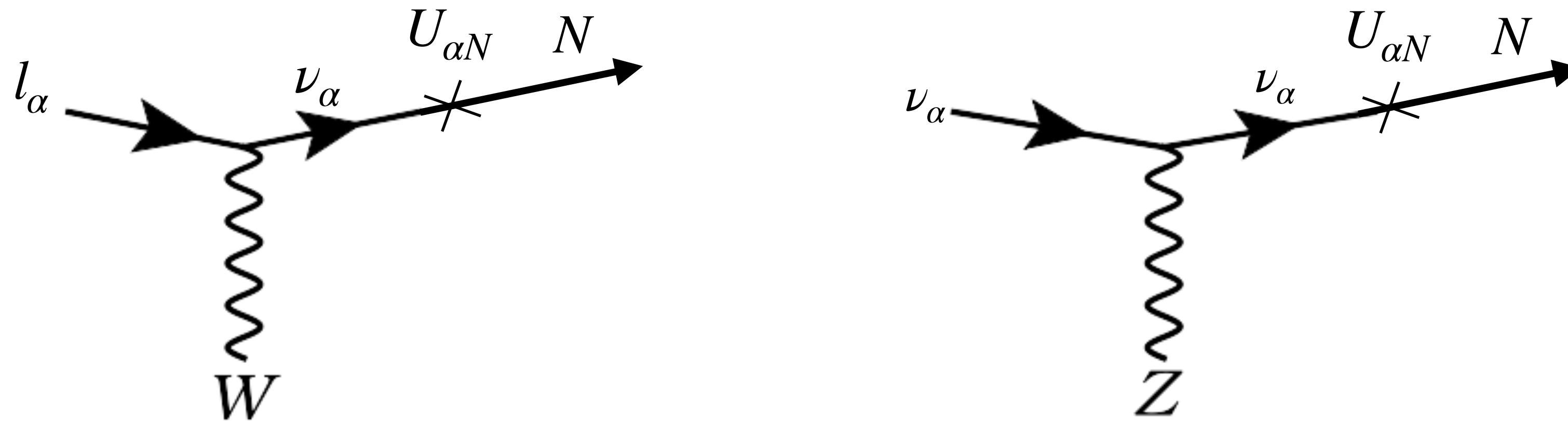


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HNLs are produced through the same weak interactions as active neutrinos

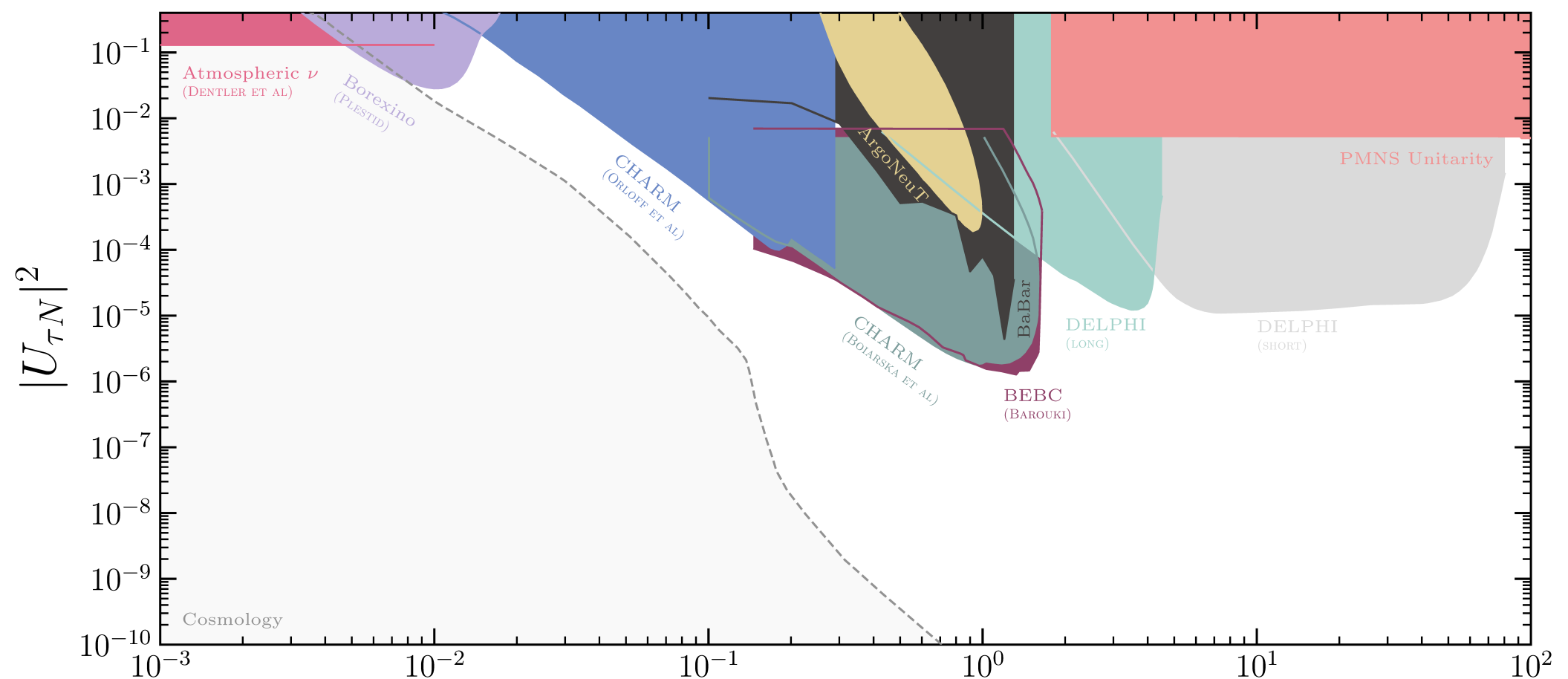
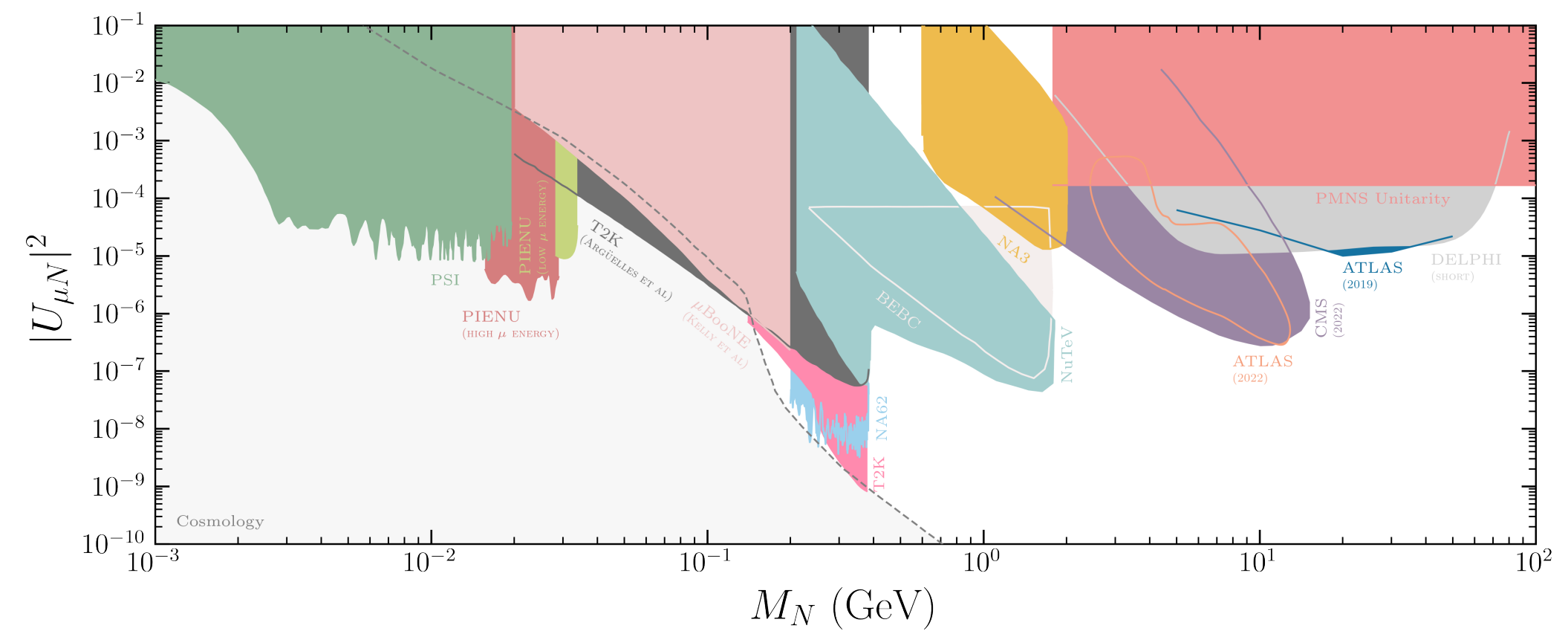
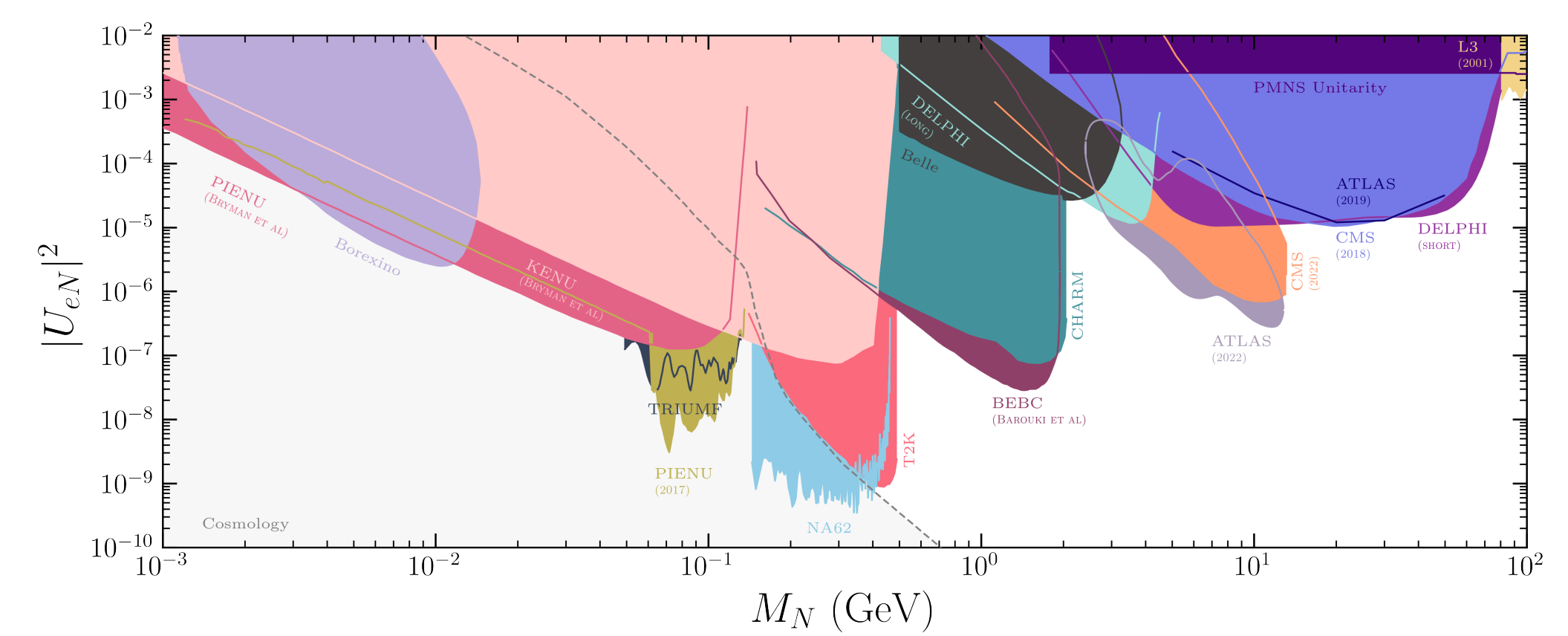


# Heavy Neutral Leptons

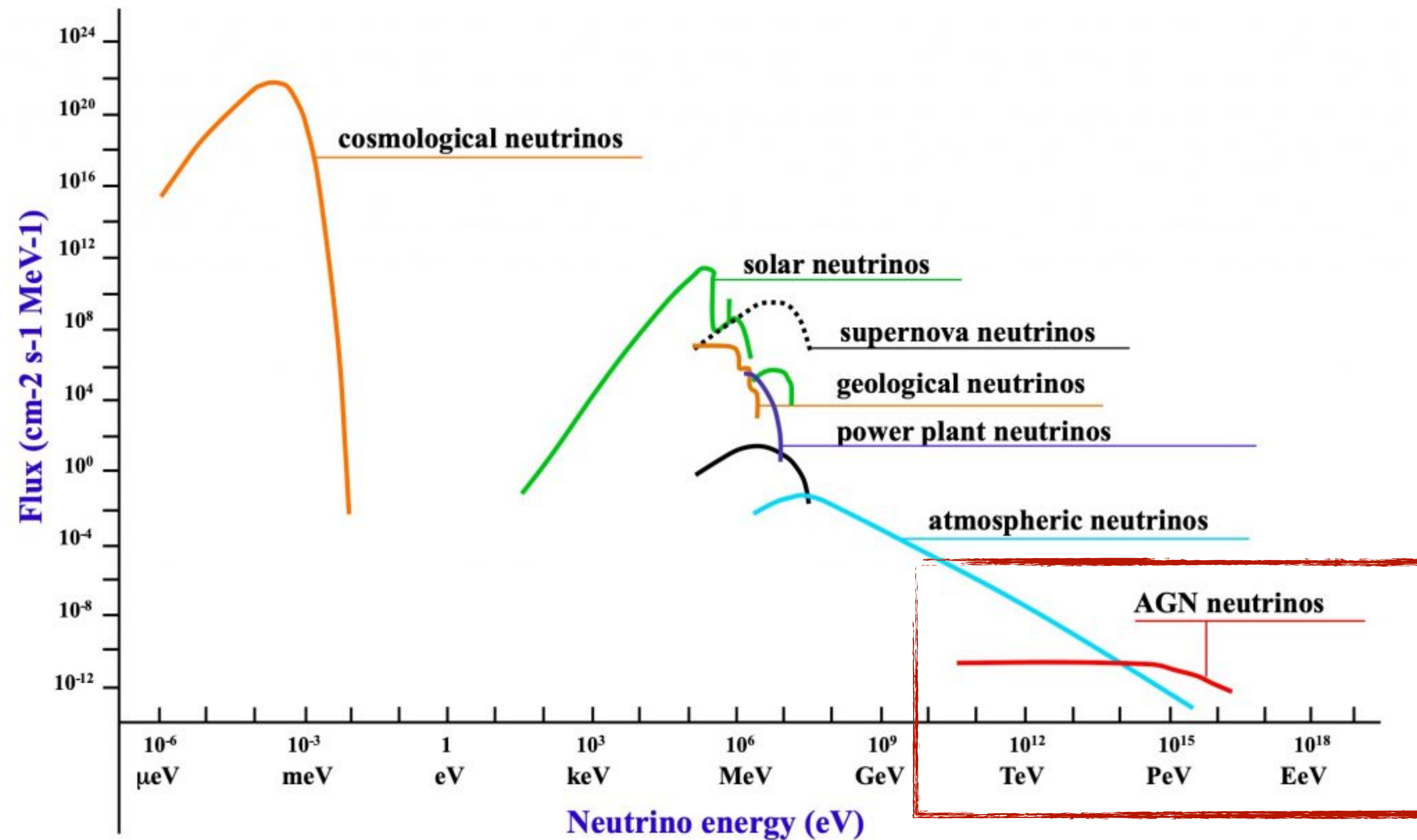
In the presence of  $N_R$ , the flavor states can be written as a superposition of massive states as

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

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



# Neutrino Astronomy





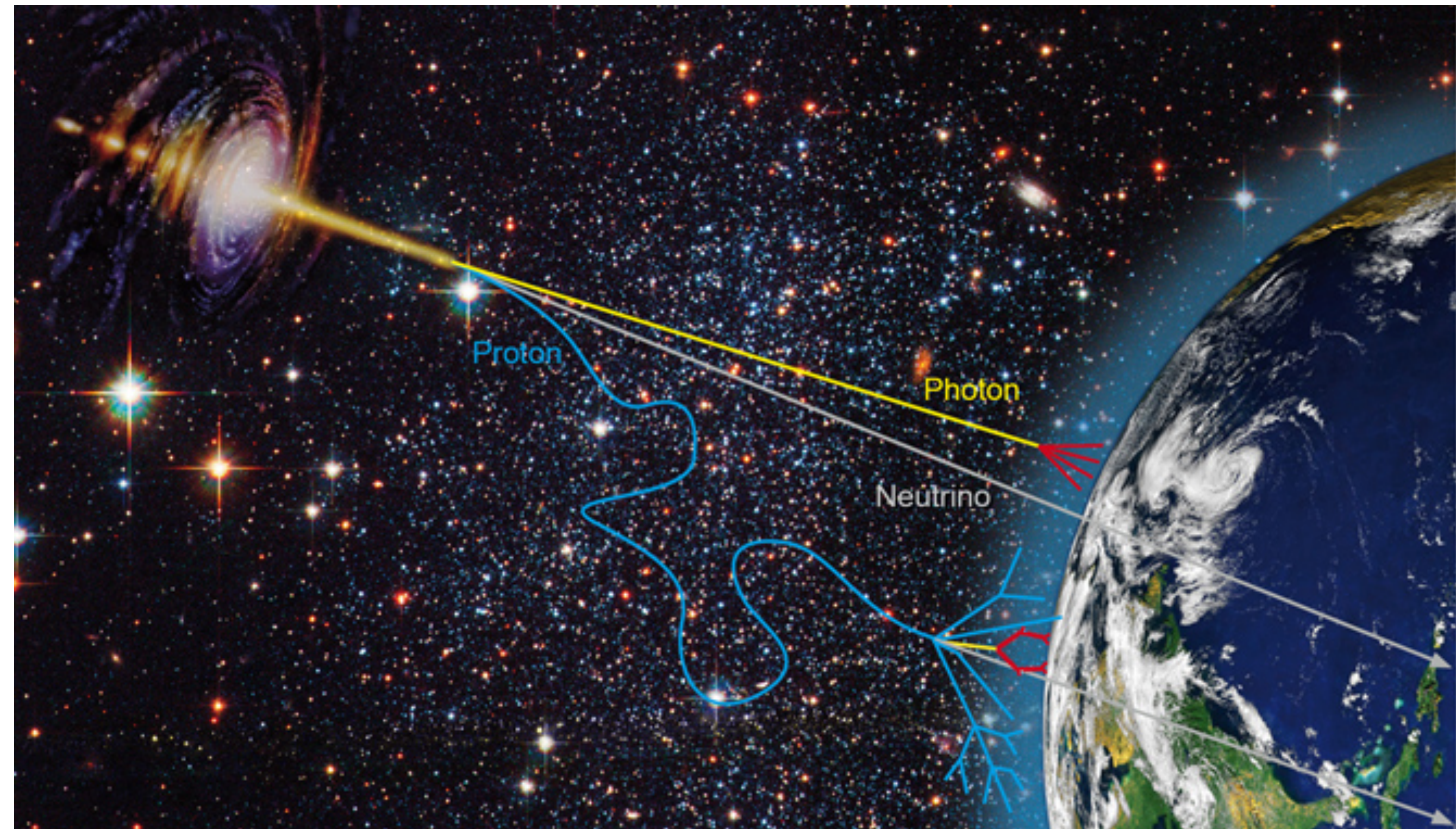
# Neutrino Astronomy

## 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

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.

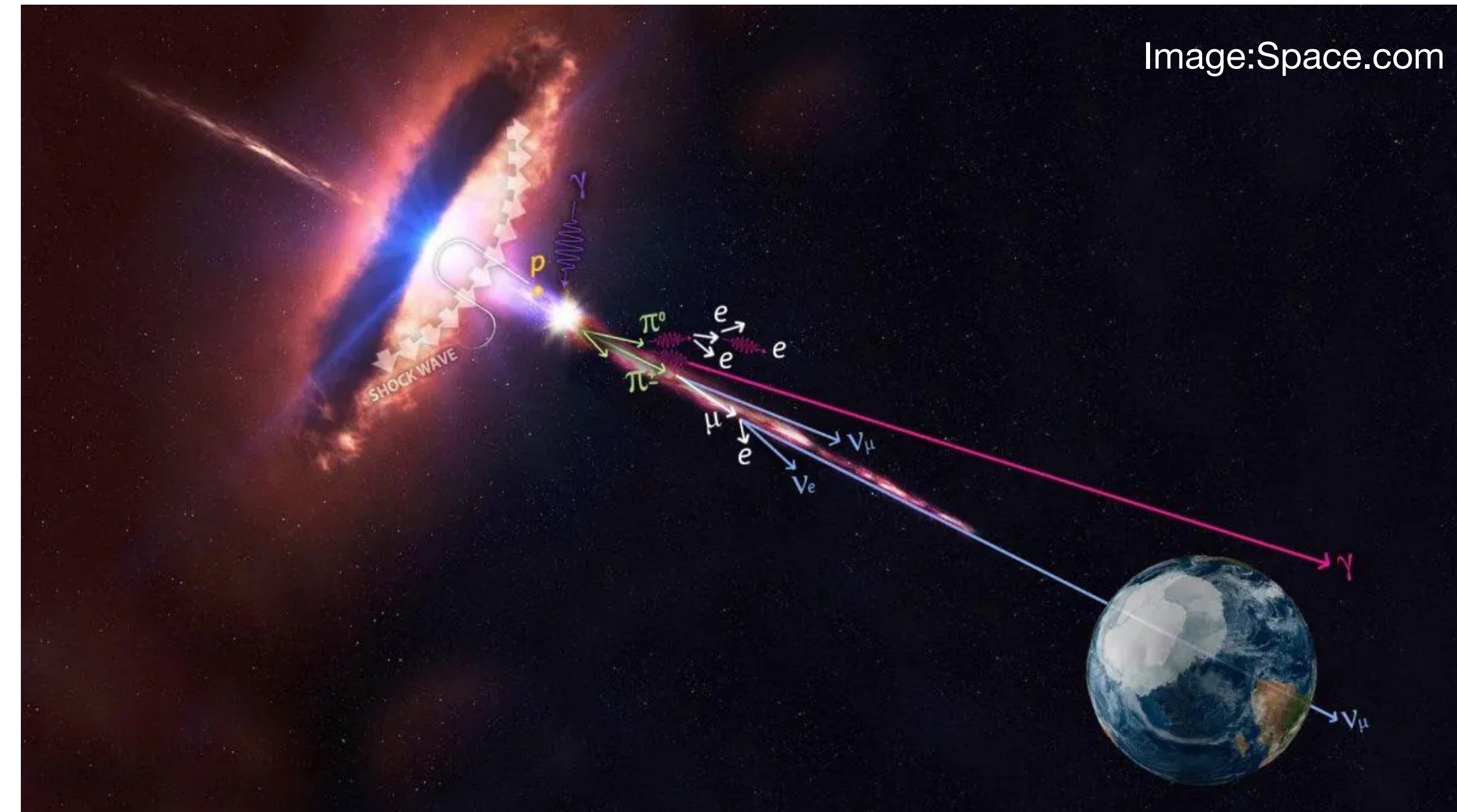


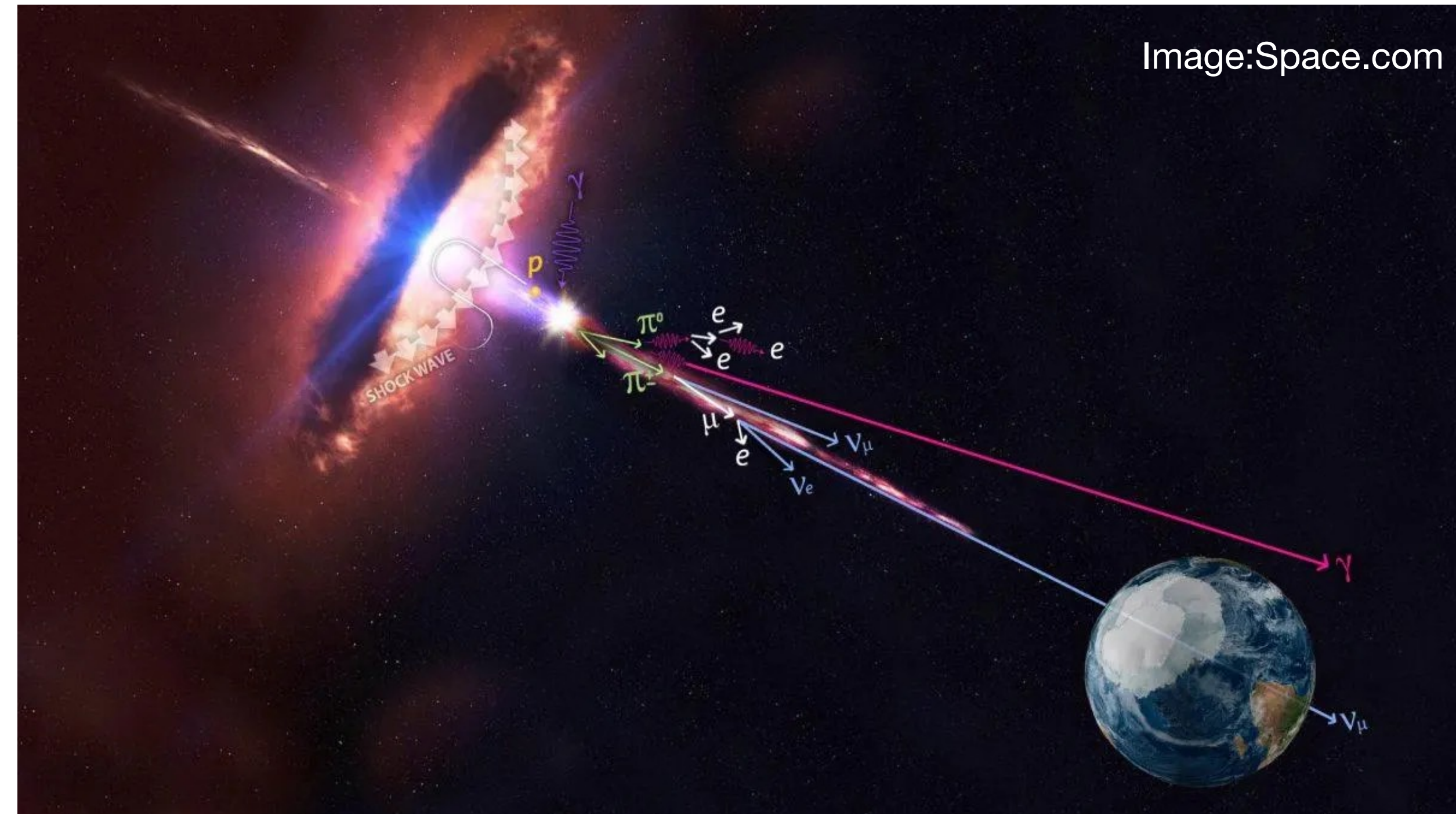
Image:Space.com

IceCube/NASA



# 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.



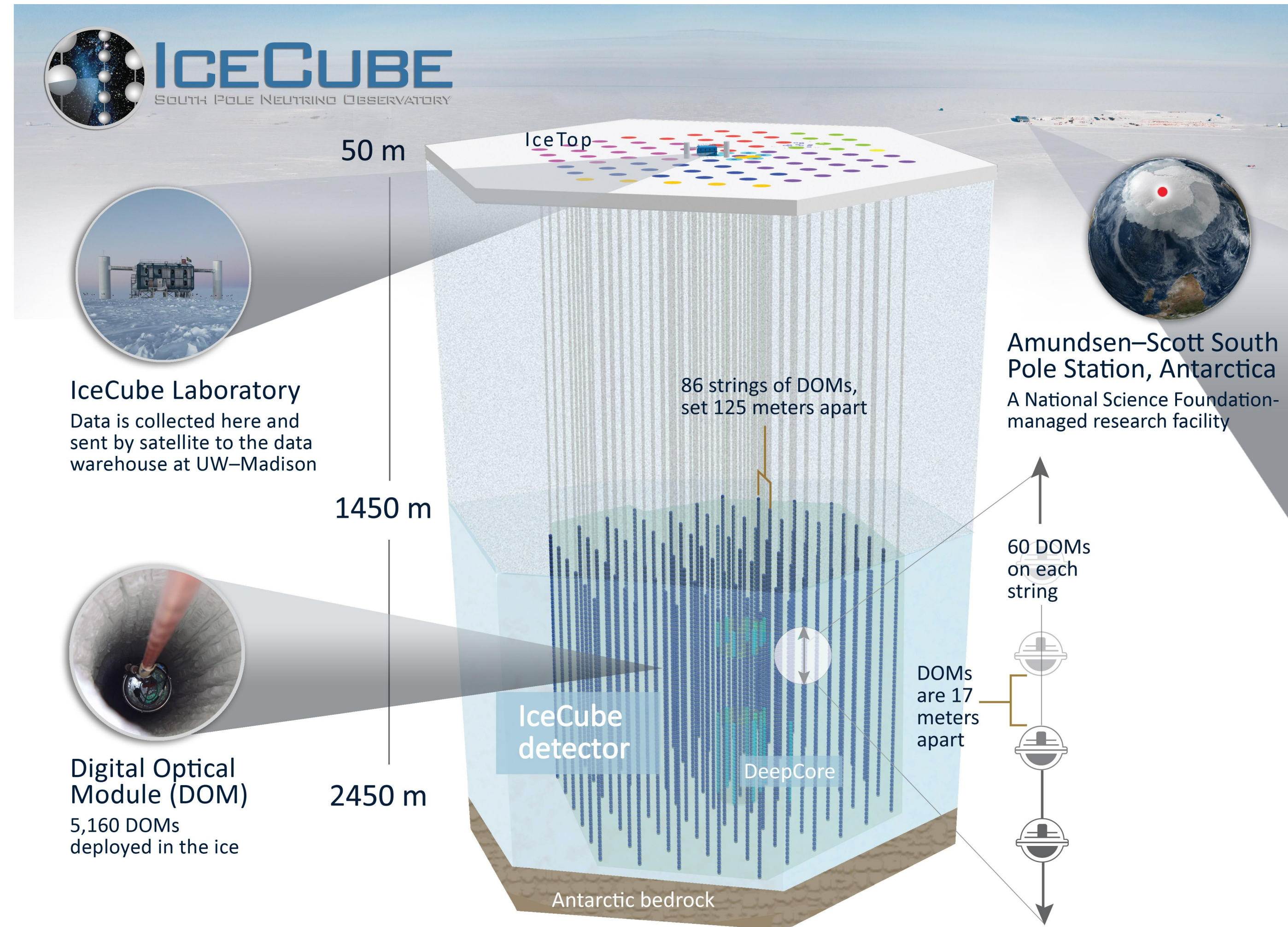
IceCube/NASA



# IceCube

IceCube is a neutrino telescope in the south pole.

- $\sim 1\text{km}^3$  ice Cherenkov
- Contains 5160 DOMs
- 86 strings
- Approximately  $\sim 2$  km below the surface
- IceTop
- The main background is muons from cosmic-rays-induced air showers.



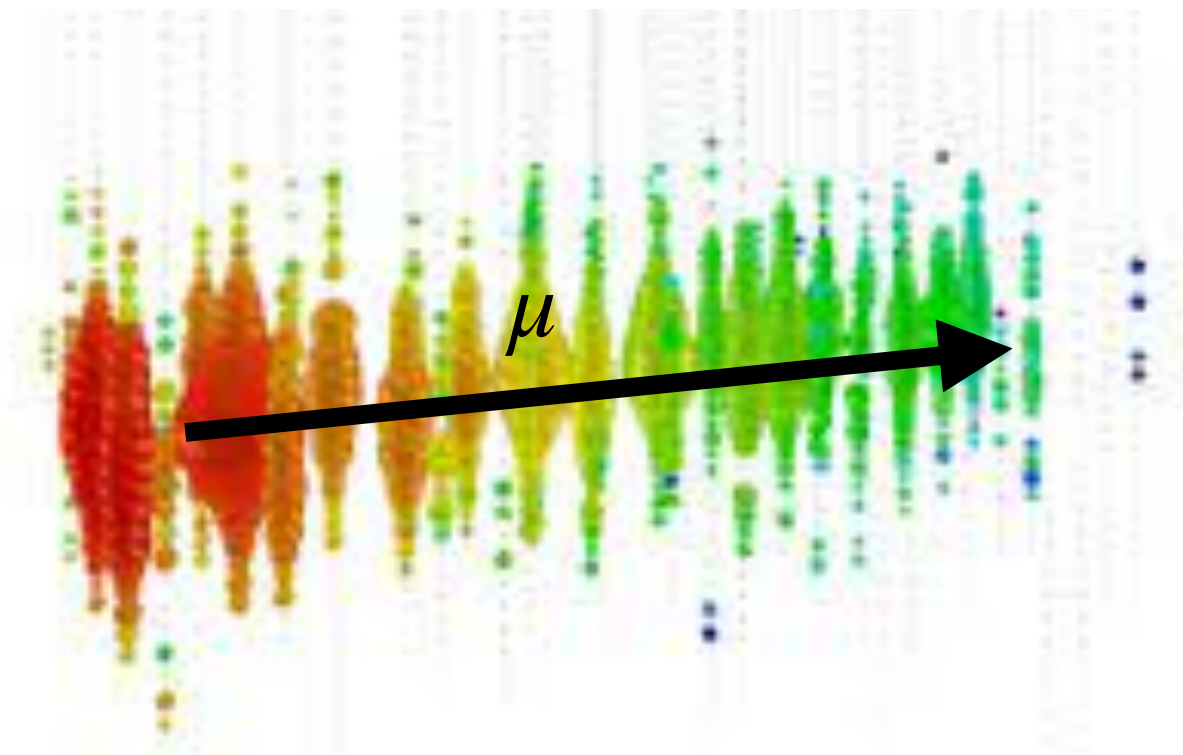


# IceCube

IceCube can distinguish different event topologies depending on the interaction type and the neutrino flavor

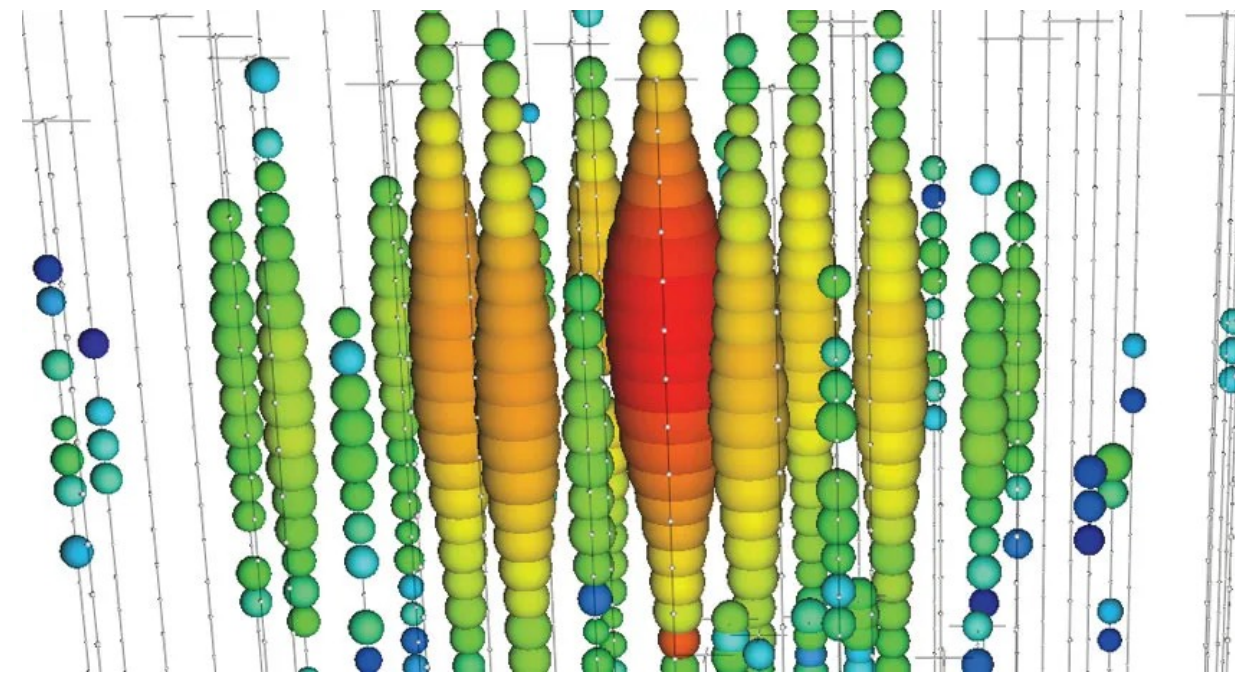
## Tracks

- Origin: Produced by  $\mu$  ( $\nu_\mu$  CC interactions)
- Feature: Good angular resolution ( $< 1^\circ$ )



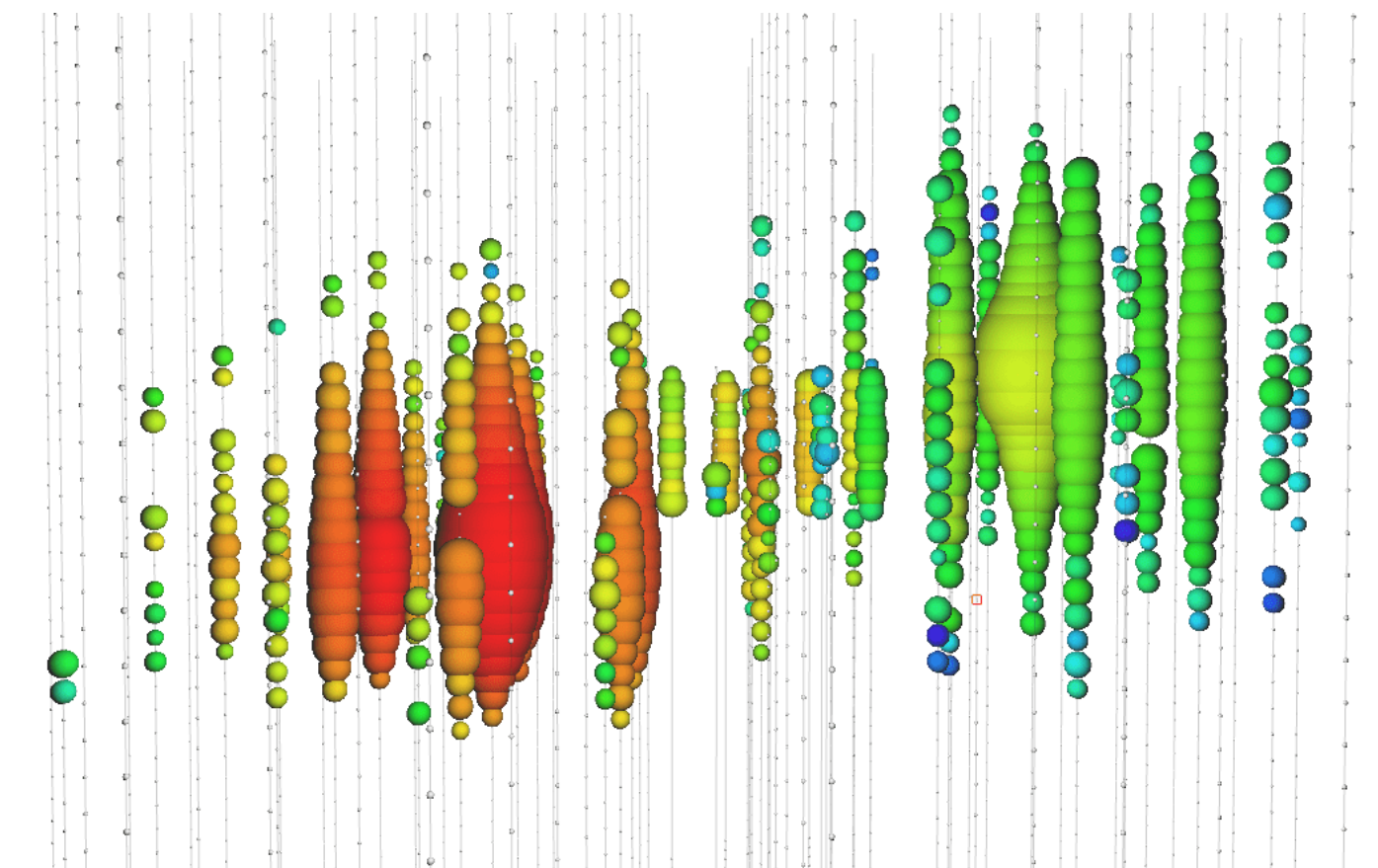
## Cascades

- Origin: Produced by NC,  $\nu_e$  CC and low-energy  $\nu_\tau$  CC
- Feature: Angular resolution  $\sim 10^\circ$  at high-energies
- Feature: Good energy resolution ( $\sim 15\%$ )



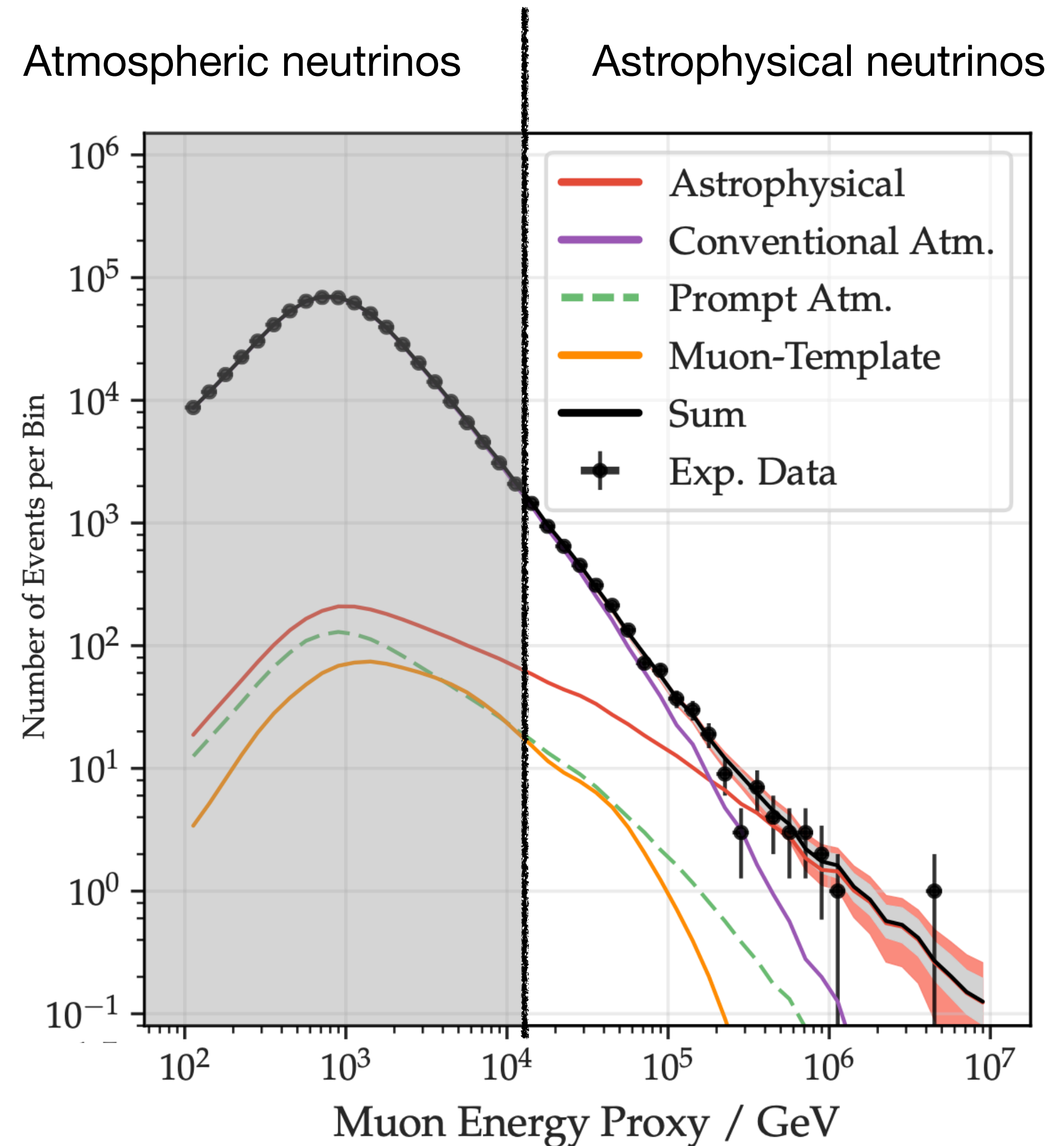
## Double-Bangs

- Origin: Produced by  $\nu_\tau$  CC
- Feature: Observable at very high energies due to the short lifetime of  $\tau$  leptons



# Astrophysical neutrinos

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



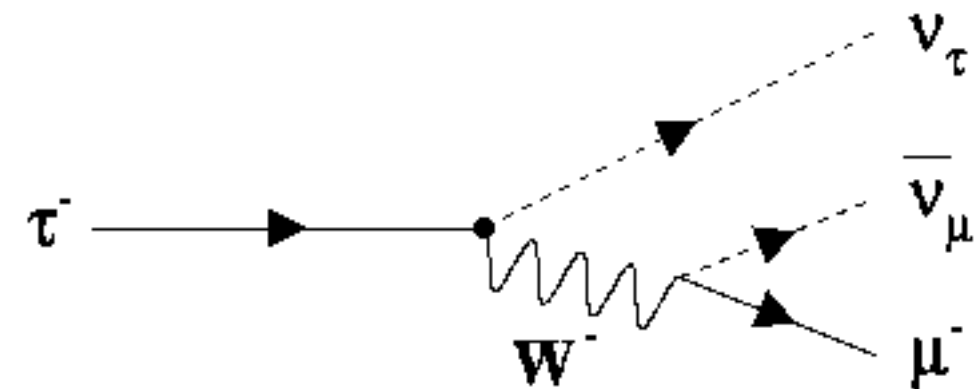
R. Abbasi, et al. (IceCube), *Astrophys.J.* 928 (2022) 1, 50



# Through-going Muons

IceCube has measured the astrophysical muon-neutrino flux

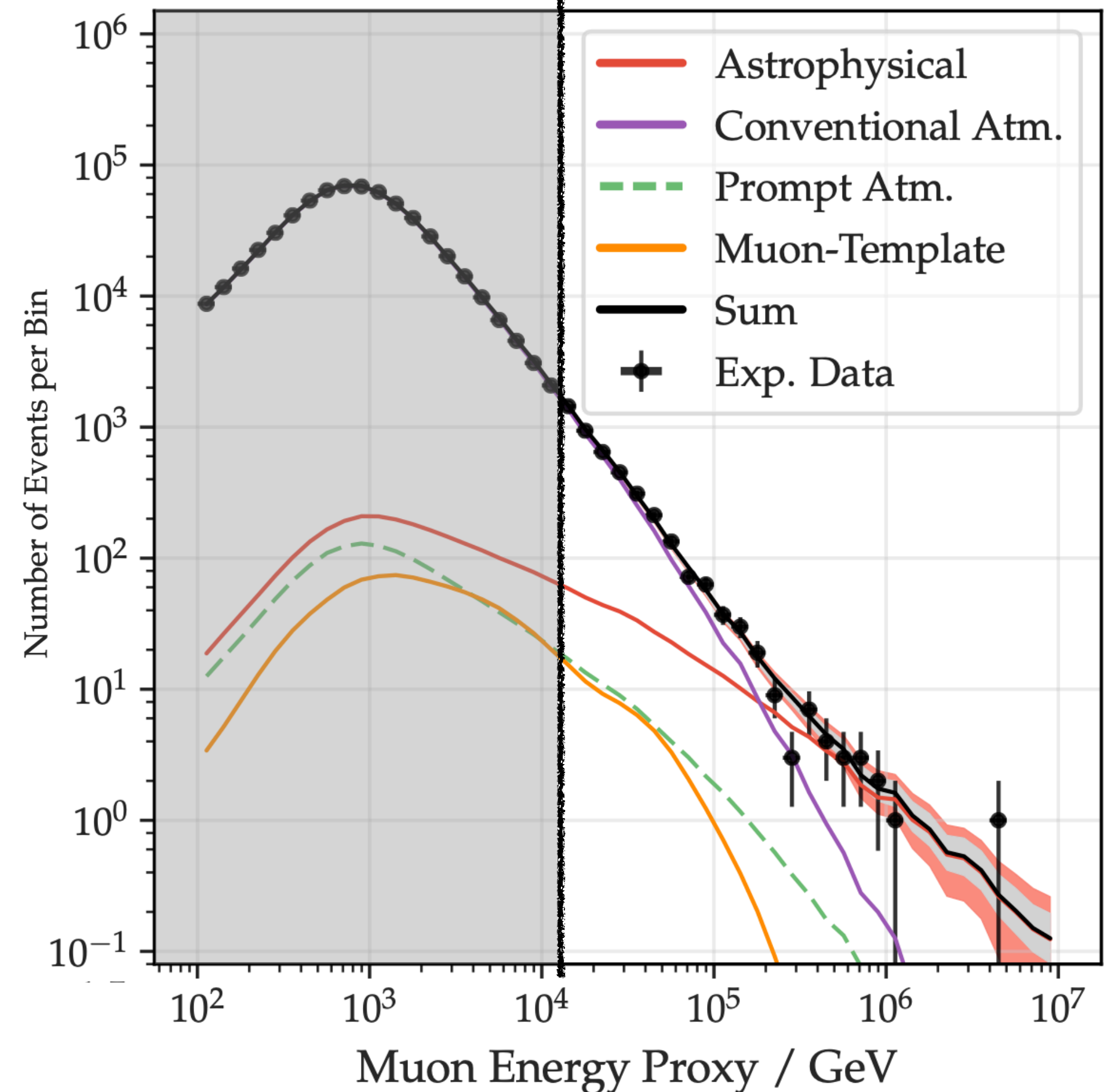
- It includes both starting and through-going samples.
- The measurement is dominated by  $\nu_\mu$  CC, with a small contribution from  $\nu_\tau$  CC



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

Atmospheric neutrinos

Astrophysical neutrinos



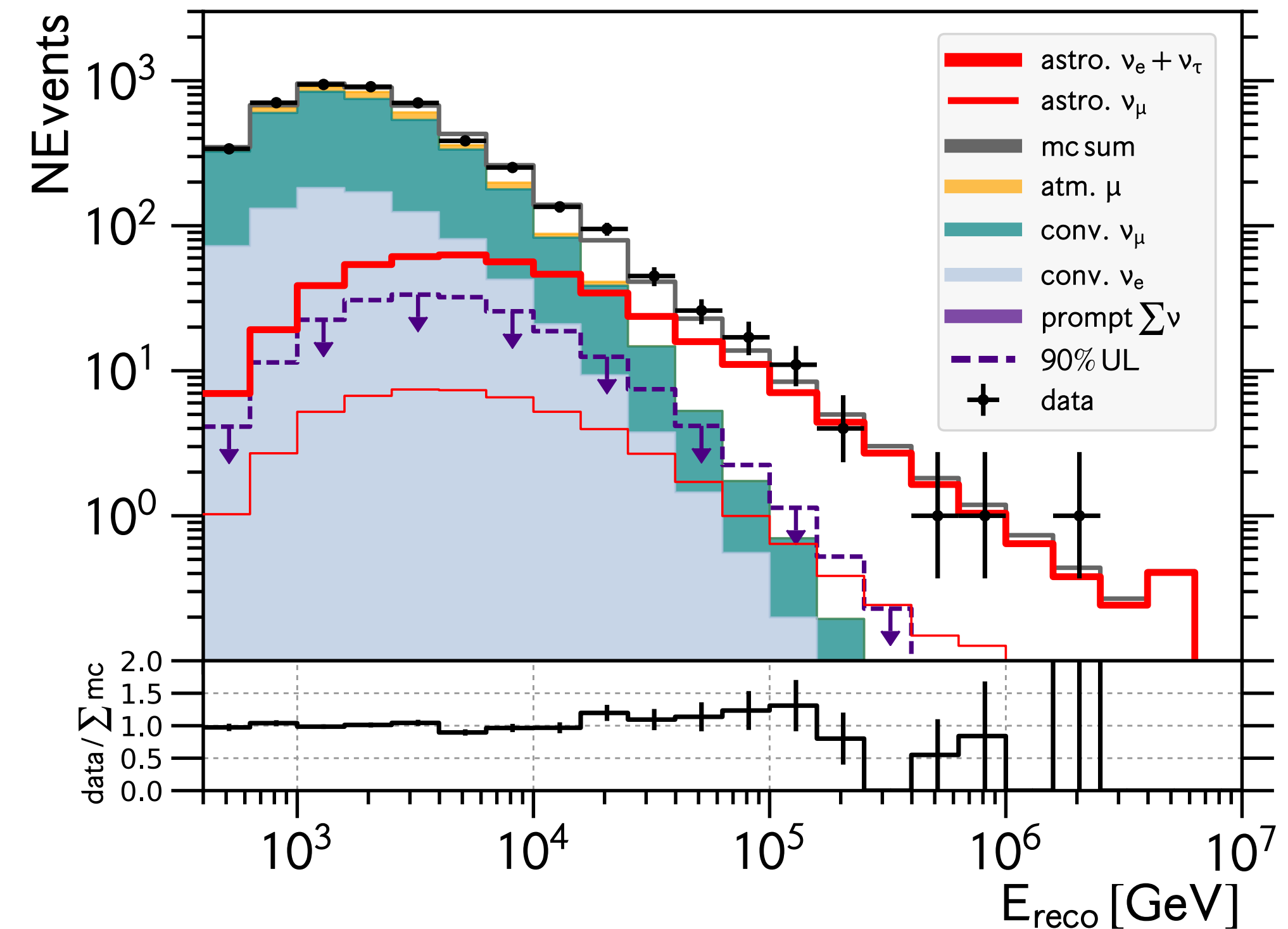
R. Abbasi, et al. (IceCube), Astrophys.J. 928 (2022) 1, 50



# Electron and Tau Neutrinos

IceCube has searched for astrophysical events using cascades

- This analysis is dominated by  $\nu_e$  and  $\nu_\tau$
- 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.



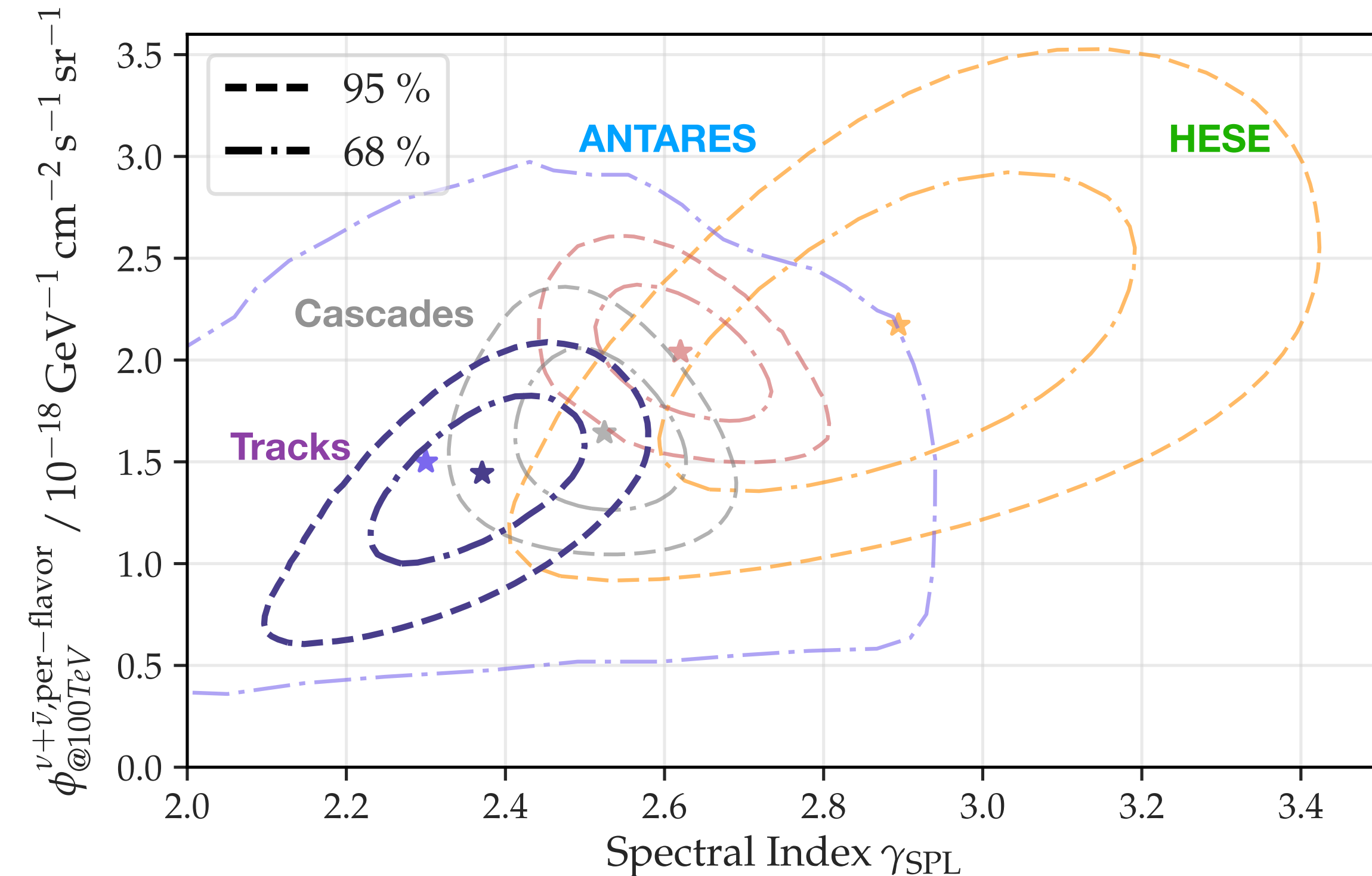
M.G. Aartsen, et al. (IceCube), PRL 125 (2020)

# 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  $\gamma$



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

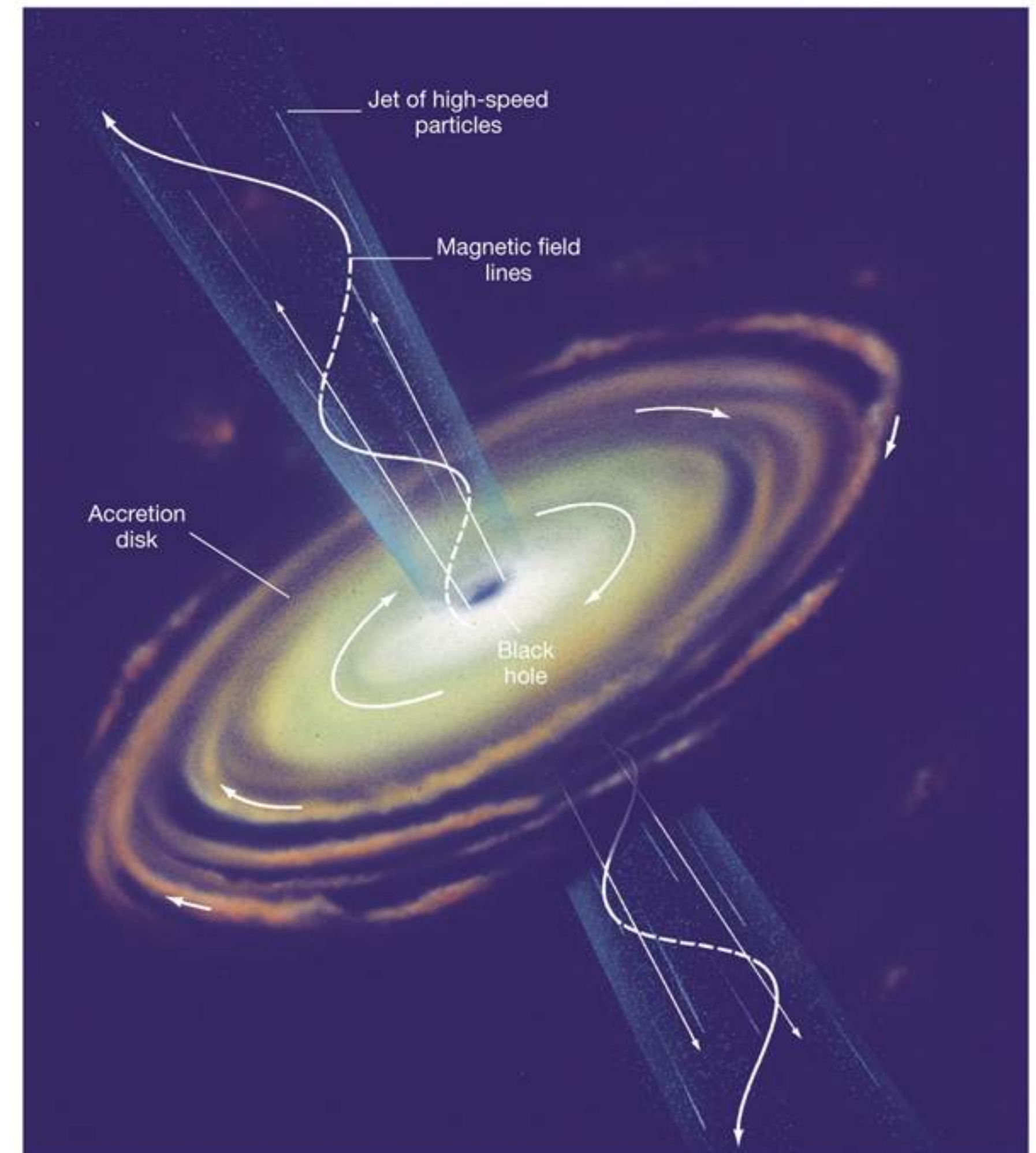
# **Where Do Neutrinos Come From?**



# Point Sources

The first candidate source identified by IceCube (TXS 050+056) was observed when a high-energy neutrino (  $\sim 290$  TeV) coincided with an active phase of a  $\gamma$ -ray emitting AGN.

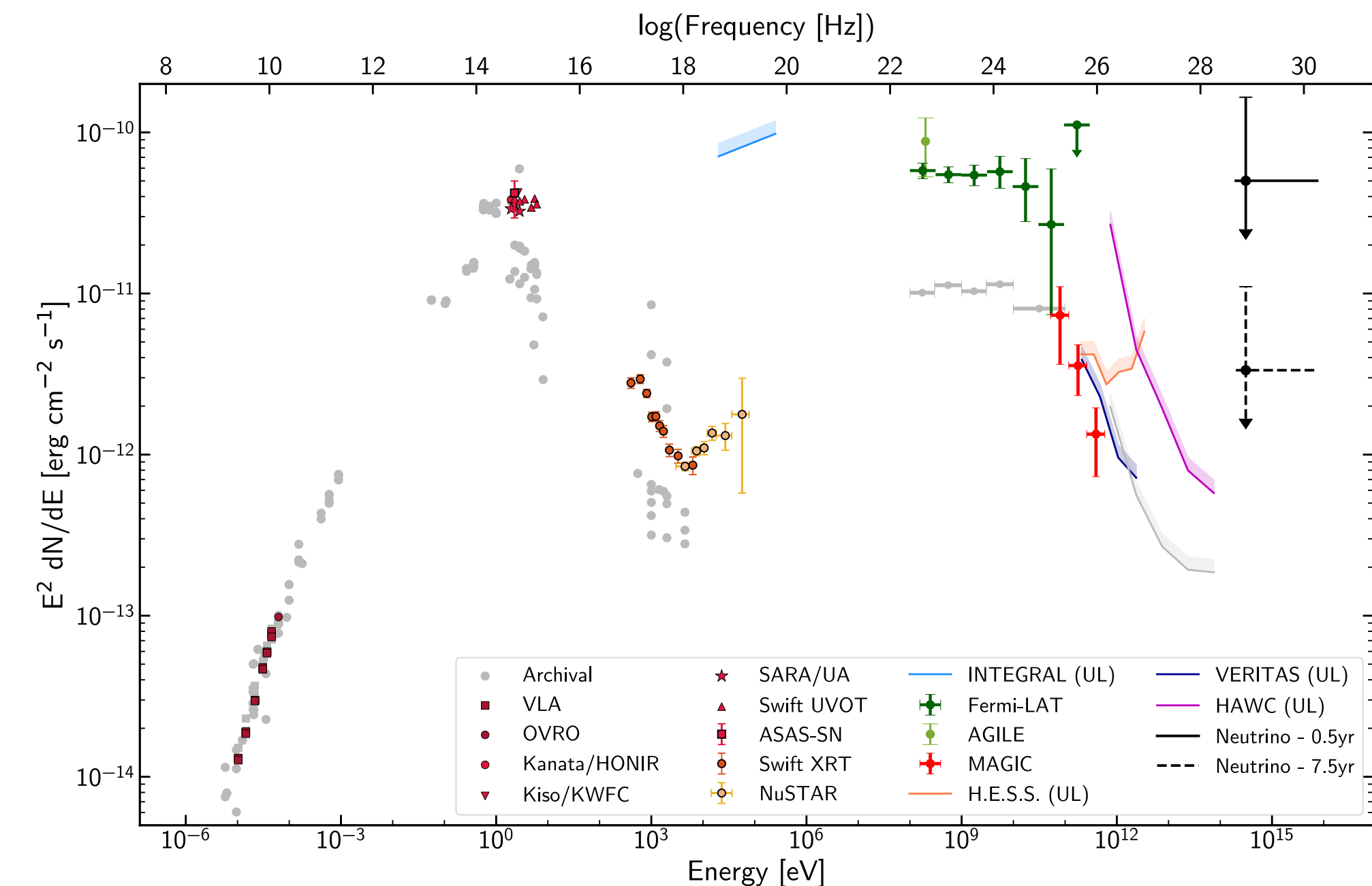
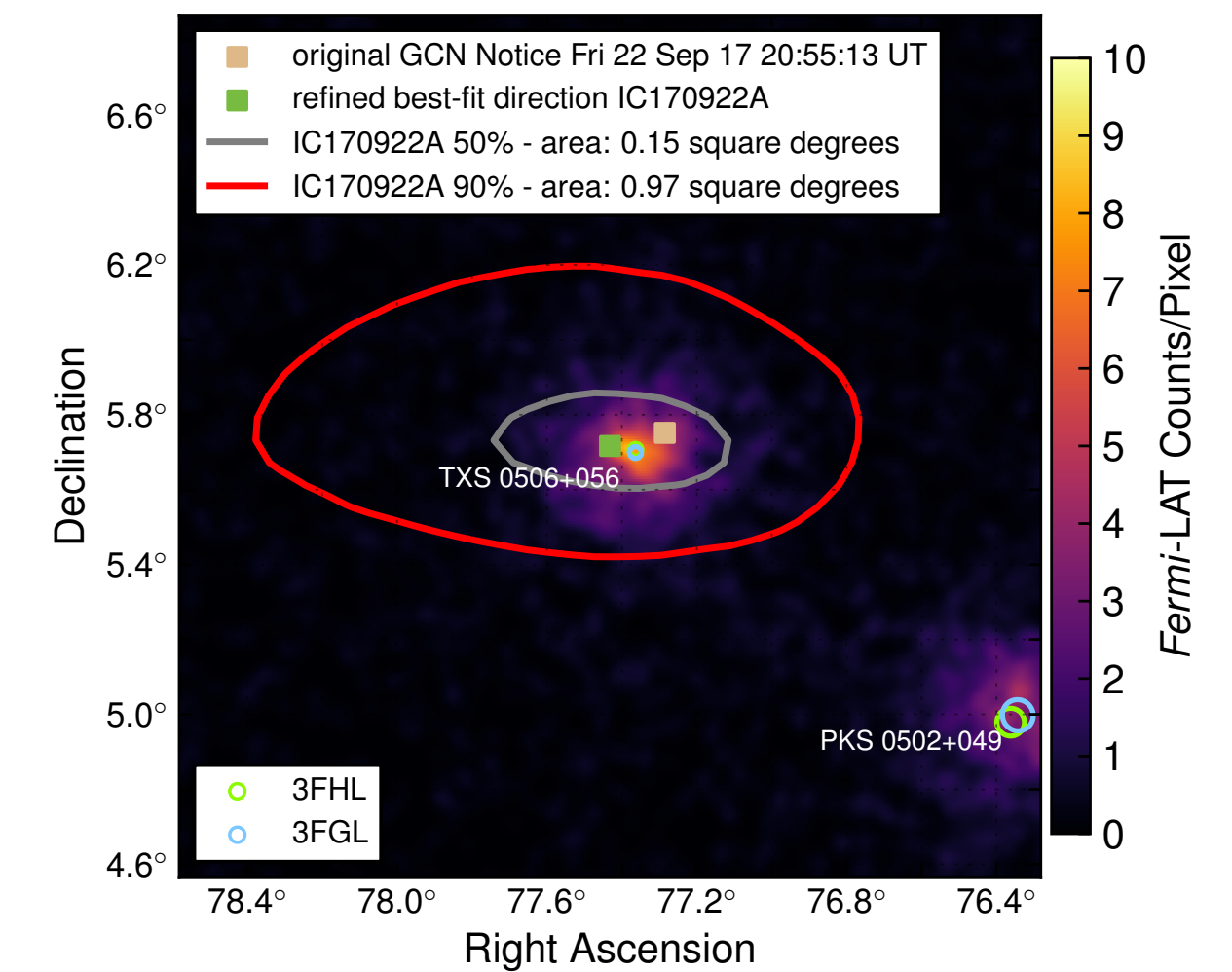
- In AGN, supermassive black holes can convert the energy of accreting matter into powerful jets.
- These jets can interact with radiation and matter, producing pions
- Correlated neutrino and photon signals would indicate AGN as sources of UHE cosmic rays





# Point Sources

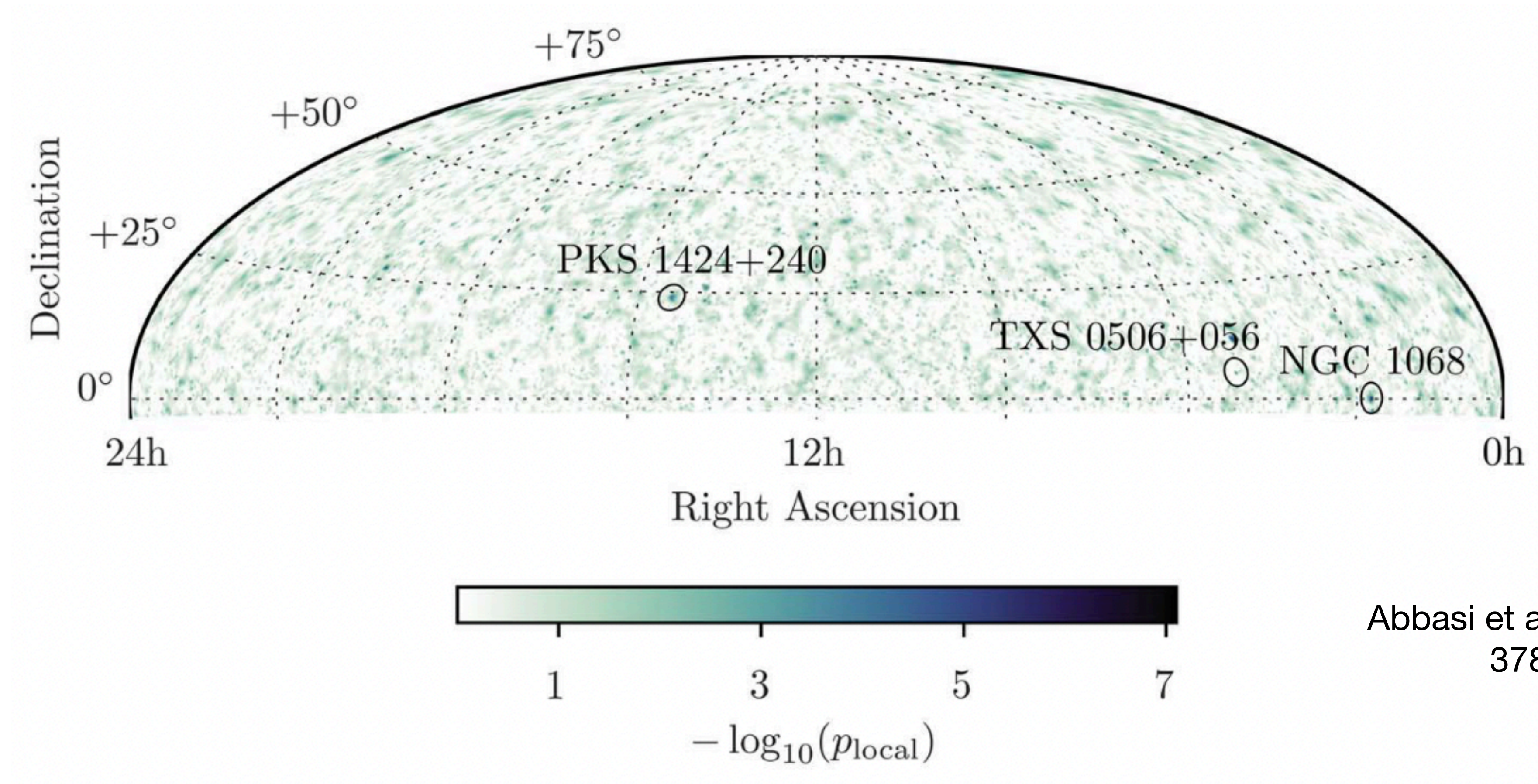
- On 22 September 2017, IceCube's alert system detected a high-energy track (290 TeV)
- FermiLAT confirmed it coincided with a period of intense  $\gamma$ -ray activity from TXS 0506+056
- Subsequent observation by MAGIC and other experiments also detected high-energy  $\gamma$ -ray
- The significance of that source is  $3.5\sigma$



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



# Point Sources



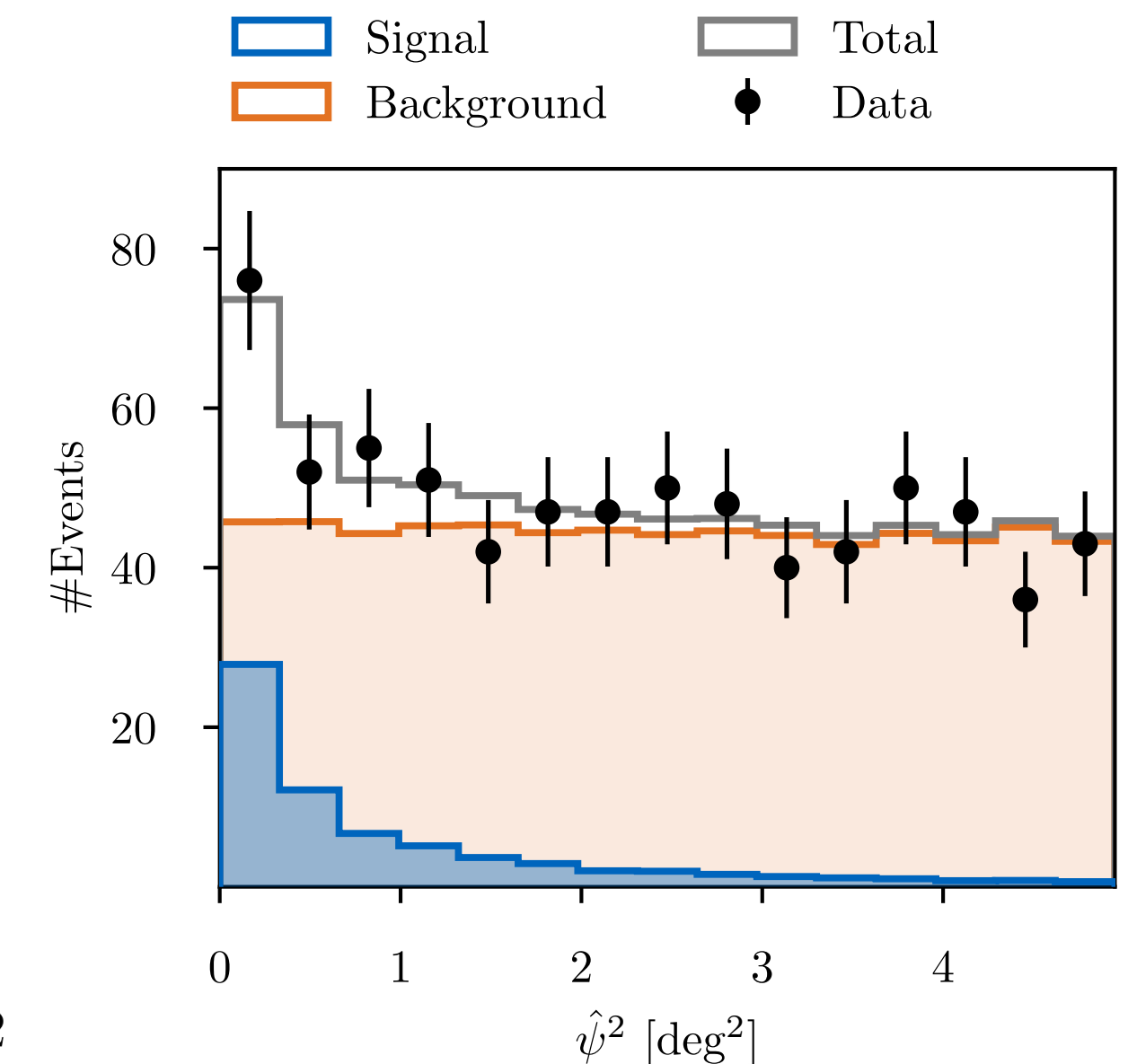
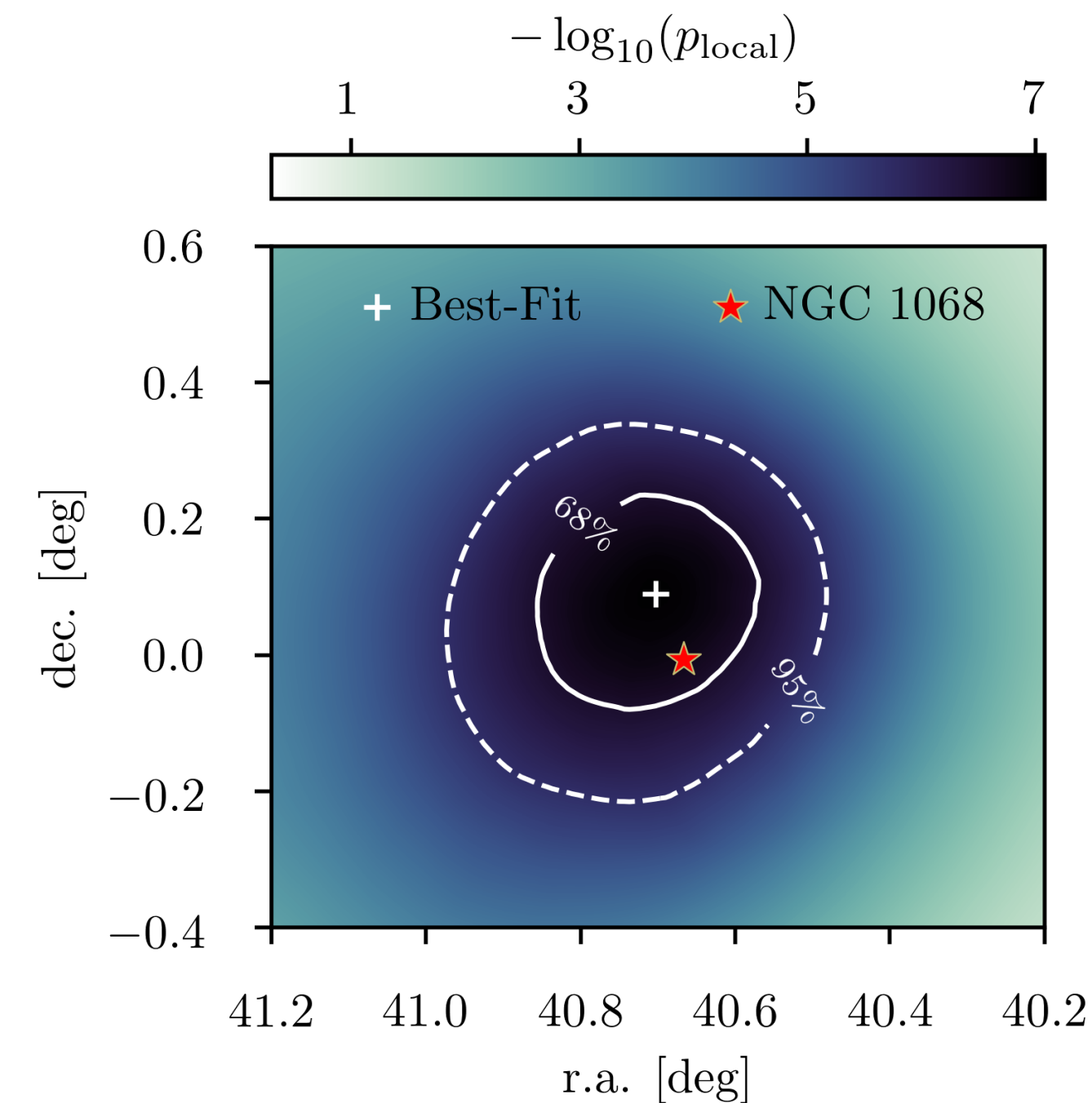
Abbasi et al. (IceCube) Science  
378, 538 (2022)



# Point Sources

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

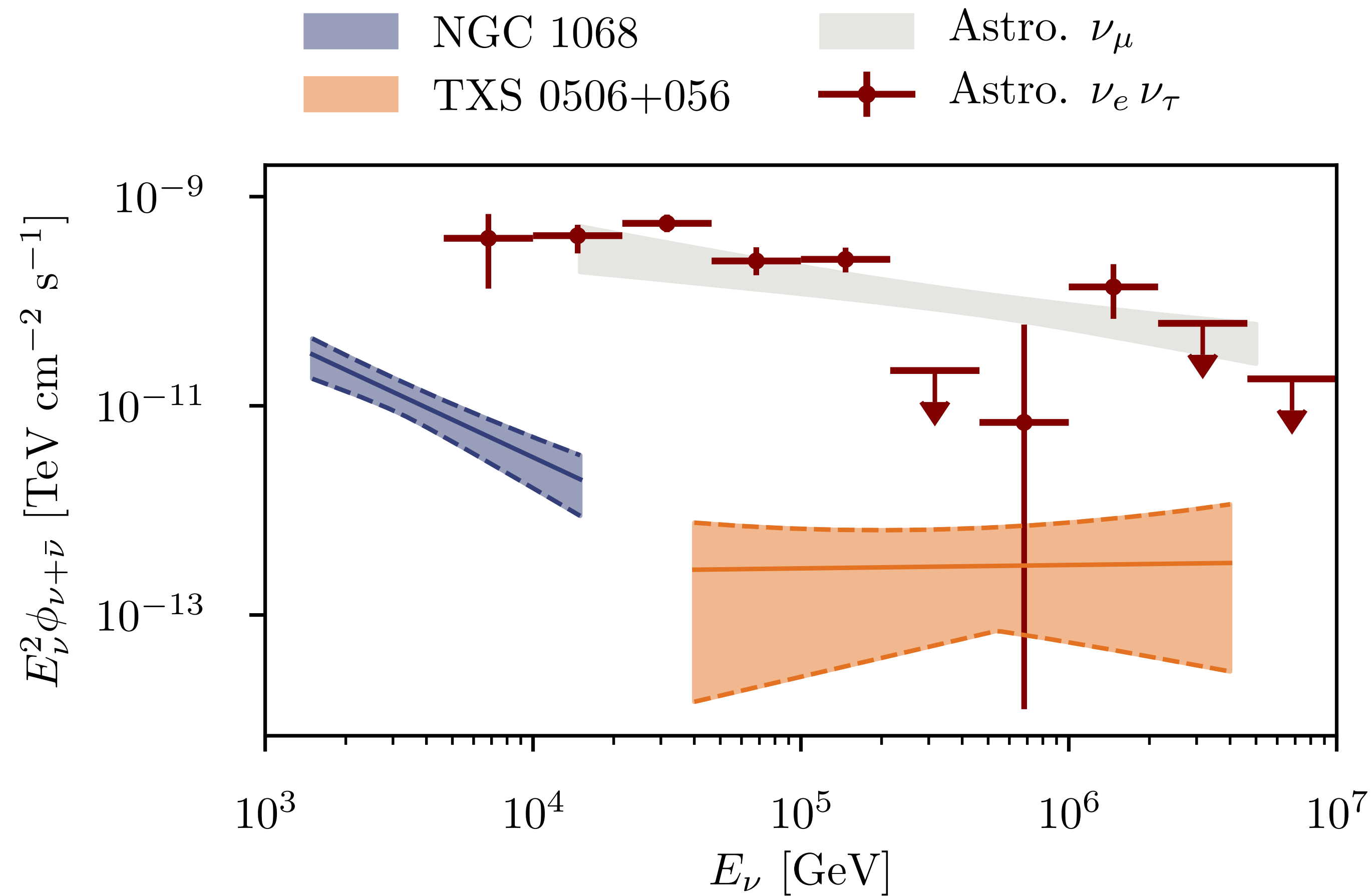
- The analysis is optimized for searching tracks from the Northern Hemisphere
- The analysis assumes a single power law finding a preference for  $\gamma = 3.2 \pm 0.2$  and an excess of  $79^{+22}_{-20}$  events
- Most of the events have energies between 1.5TeV and 15TeV



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

# Point Sources

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

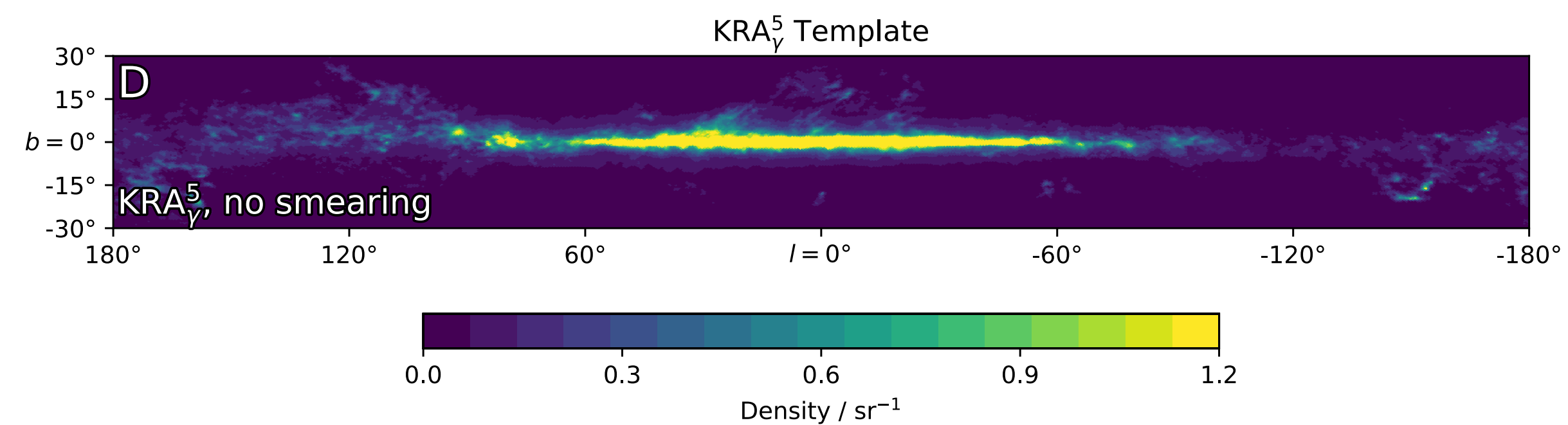
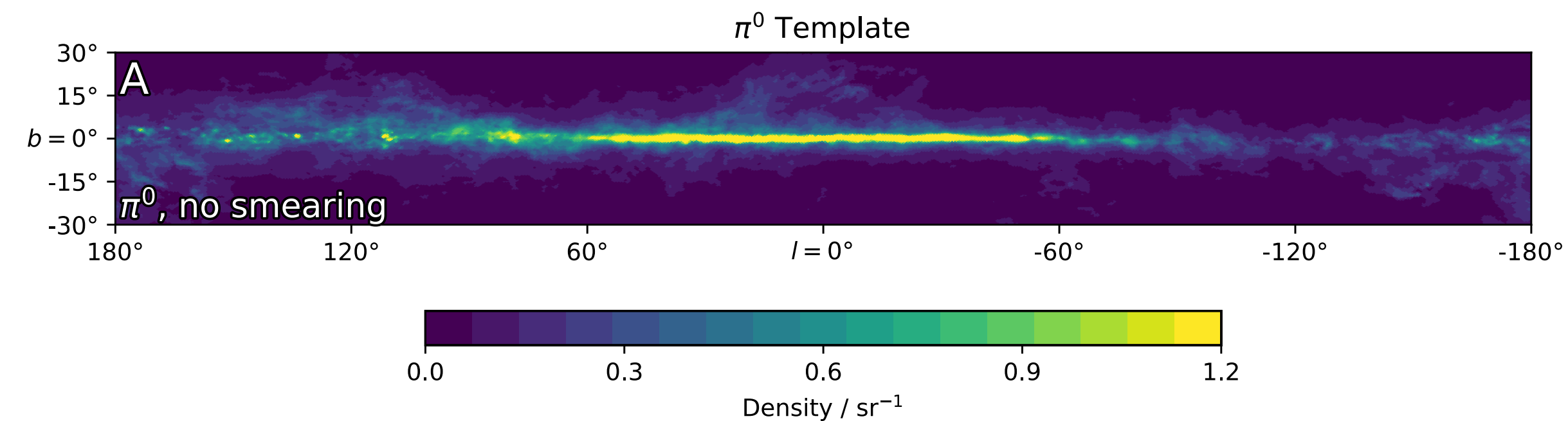


Abbasi et al. (IceCube) Science  
378, 538 (2022)



# 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.

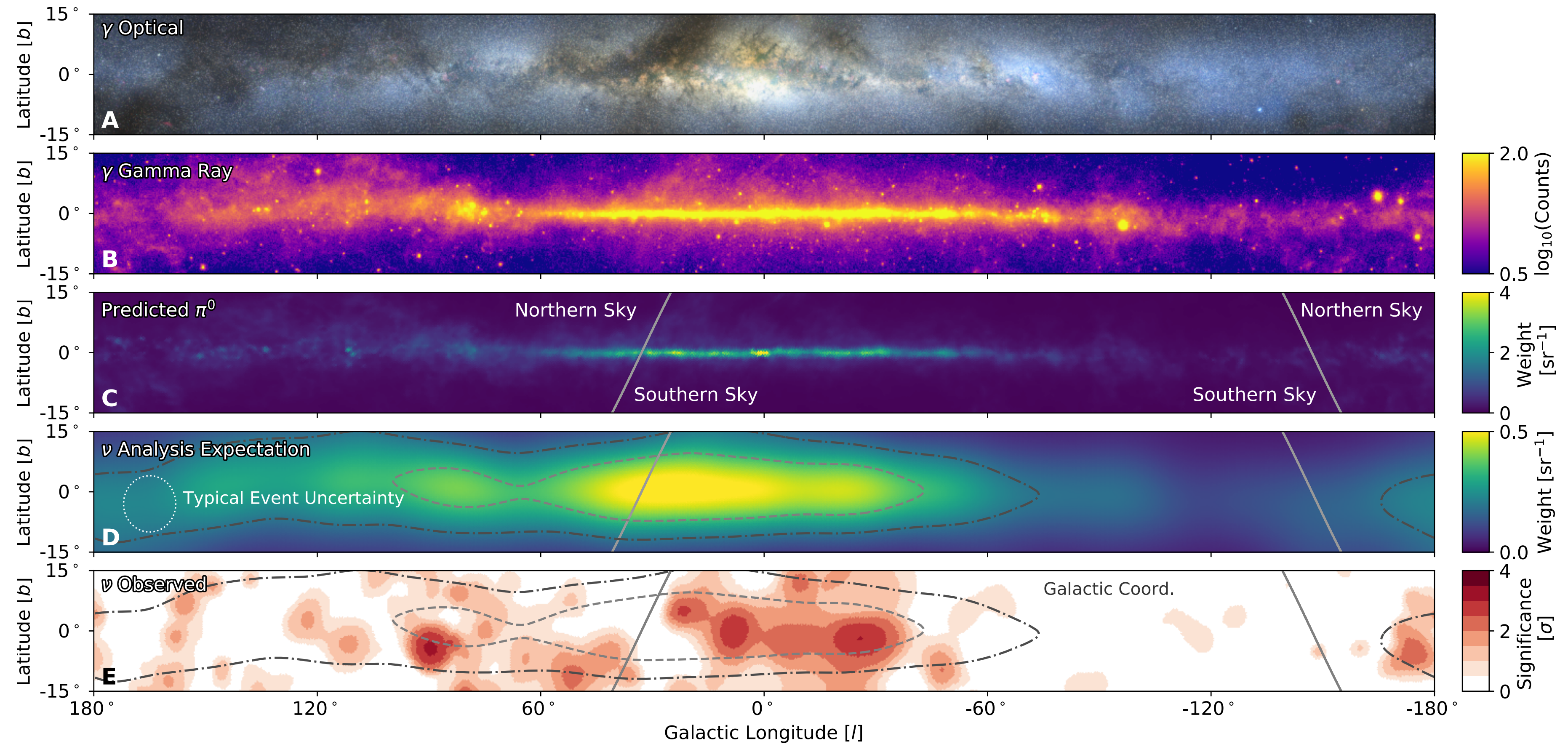


IceCube, Science 380 (2023) 1338



# Galactic Plane

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

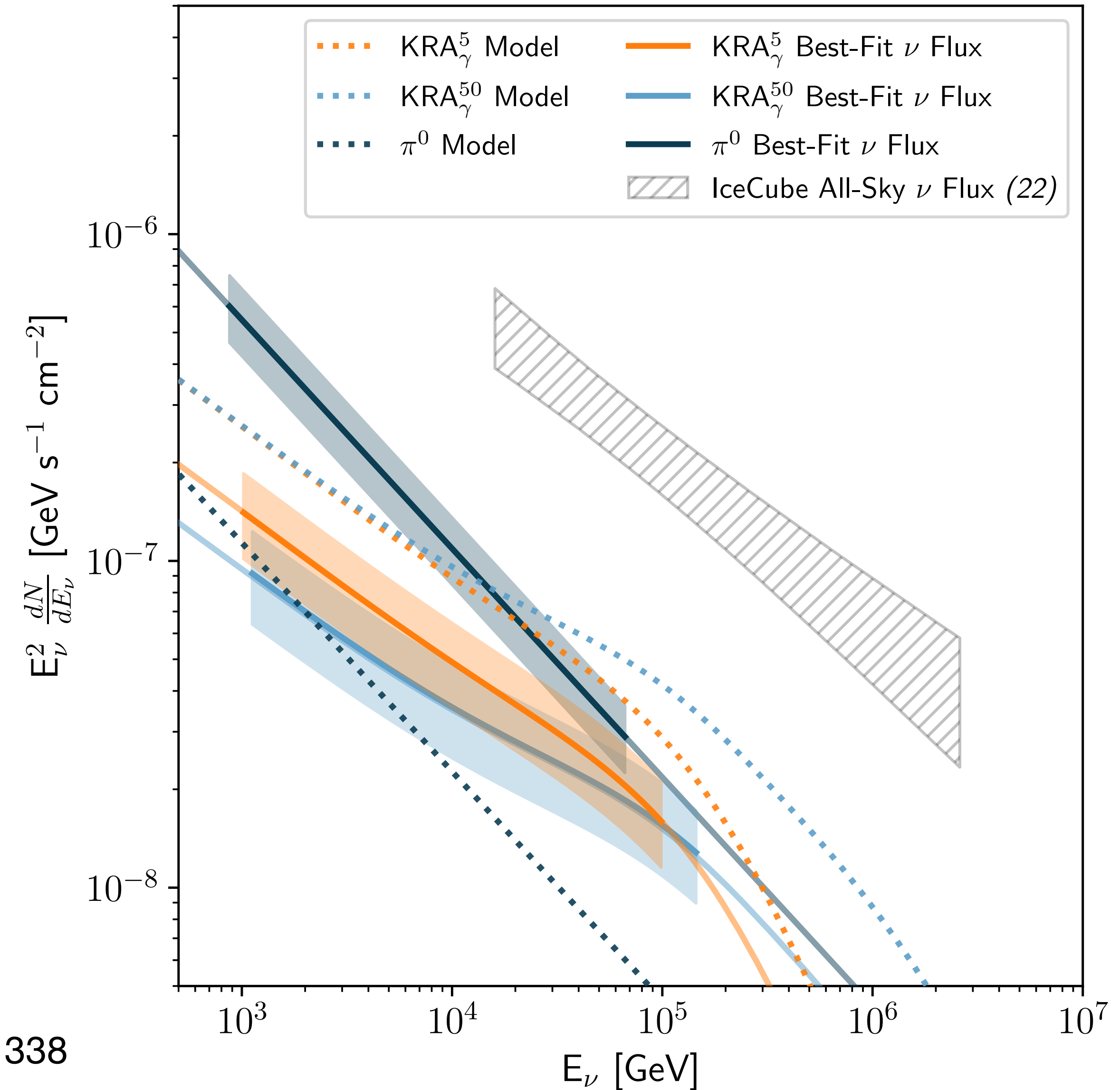


IceCube, Science 380 (2023) 1338



# Galactic Plane

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



IceCube, Science 380 (2023) 1338

## References:

- Fundamentals of Neutrinos in Physics and Astrophysics, C. Giunti and C.W. Kim
- *Phenomenology with Massive Neutrinos*, M.C. Gonzalez-Garcia and M. Maltoni, Phys.Rept 460 (2008)
- Introduction to Phenomenology With Massive Neutrinos in 2024, M.C. Gonzalez-Garcia, YETI School 2024
- *Neutrino Physics*, S. Pascoli, Proceedings of the 2018 European School of High-Energy Physics
- *Neutrino Physics*, P. Hernandez, CLASHEP2015
- TASI LECTURES ON NEUTRINO PHYSICS, A. De Gouvea, TASI 2004
- *Neutrino*, J. Turner, The 2024 STFC HEP Summer School
- Neutrino Physics, Z.z. Xing, AEPSHEP