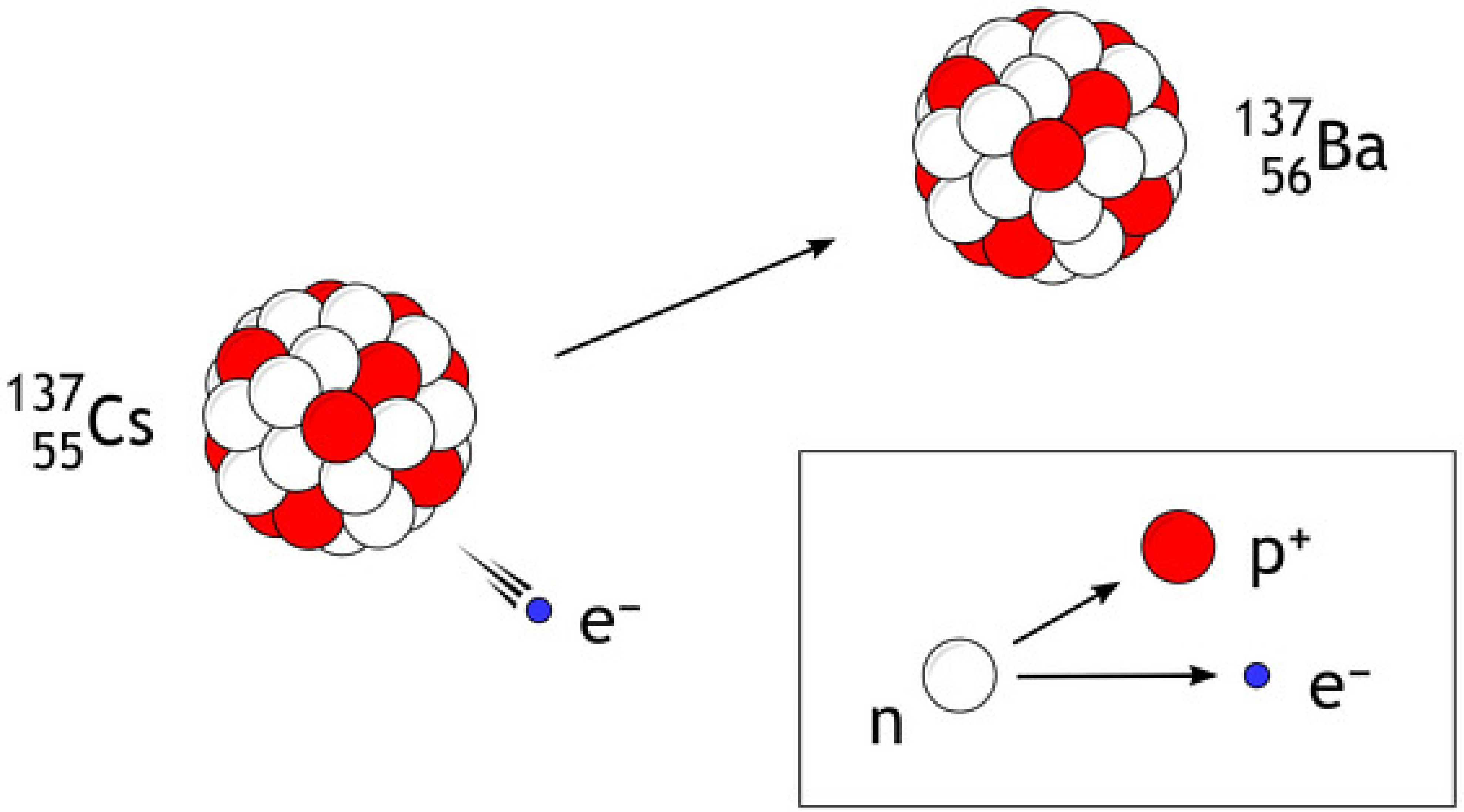
NEUTRINO PHYSICS

Andrés López Moreno (LAPP)
GRASPA 2025 School
Based on slides by Laura Zambelli

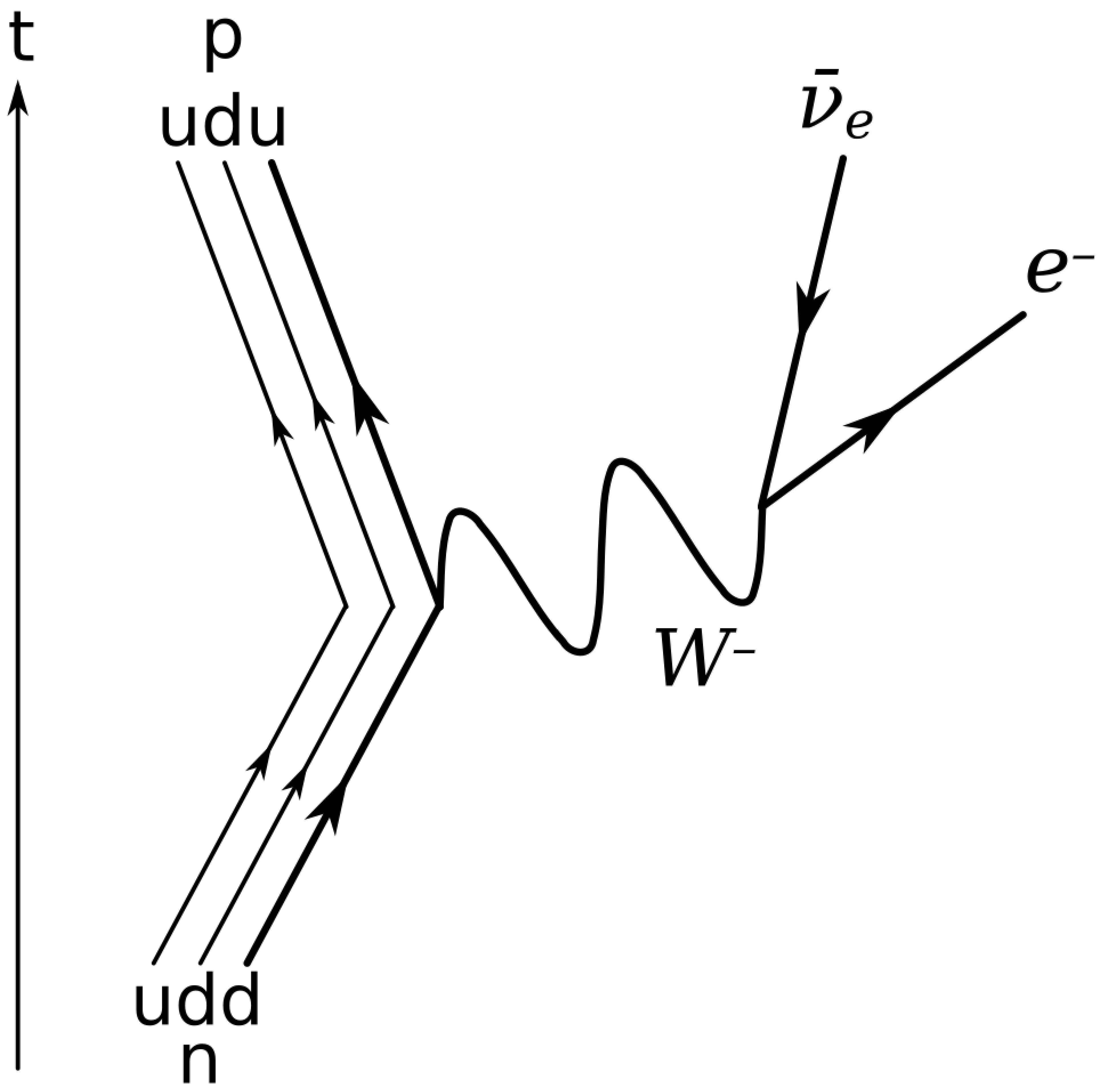
Overview

- Neutrinos: What, where, how?
- Neutrino Interactions
- Neutrino Oscillations
- Modern neutrino physics

The beta decay problem

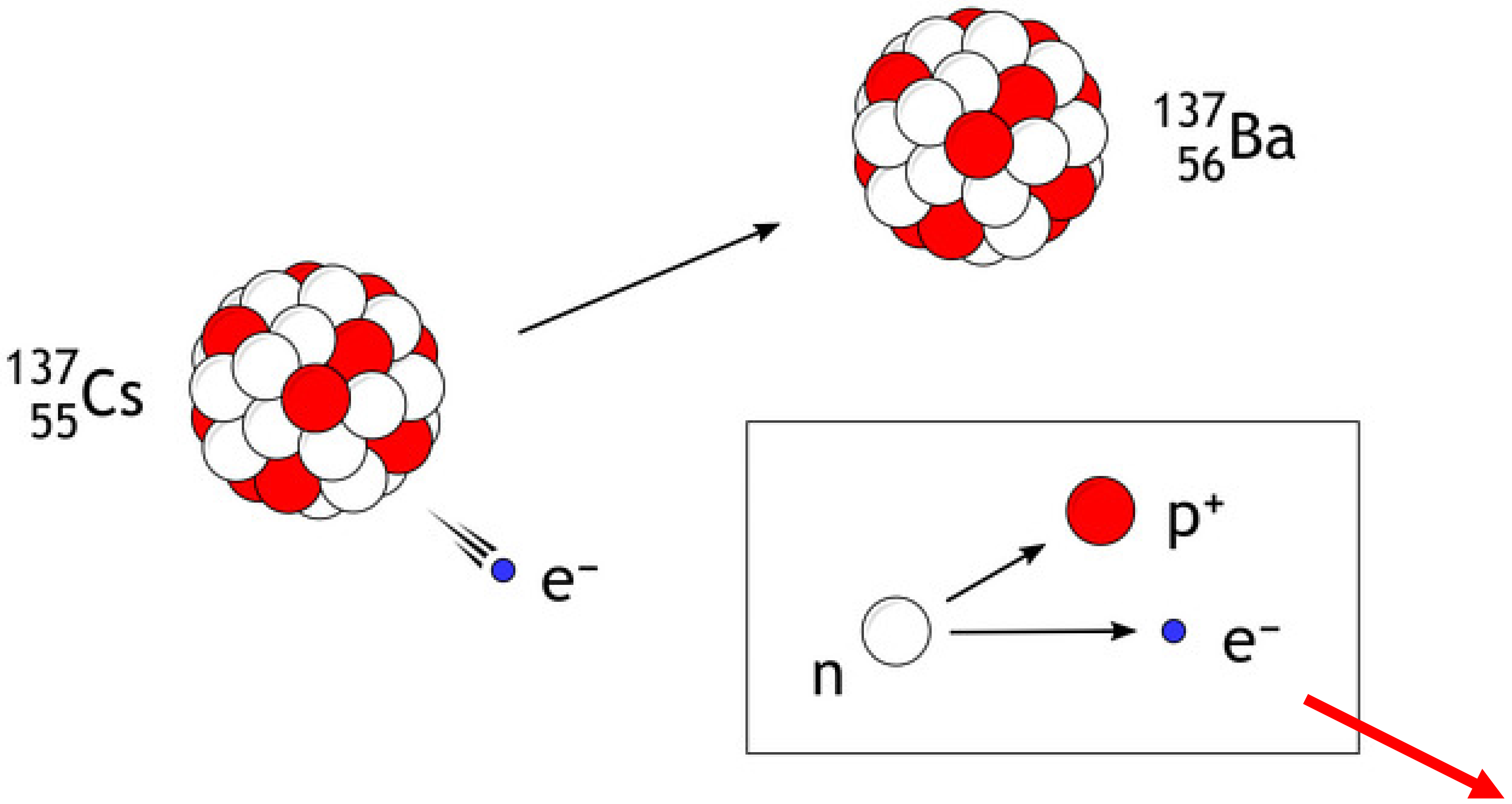


Stuff from the 1920s



(we didn't have this kind of understanding in the 1920s)

The beta decay problem



Conservation of 4-momentum (special relativity): $p_n = p_p + p_e$ --> $\mathbf{p_e = (p_n - p_p) \approx m_n - m_p}$

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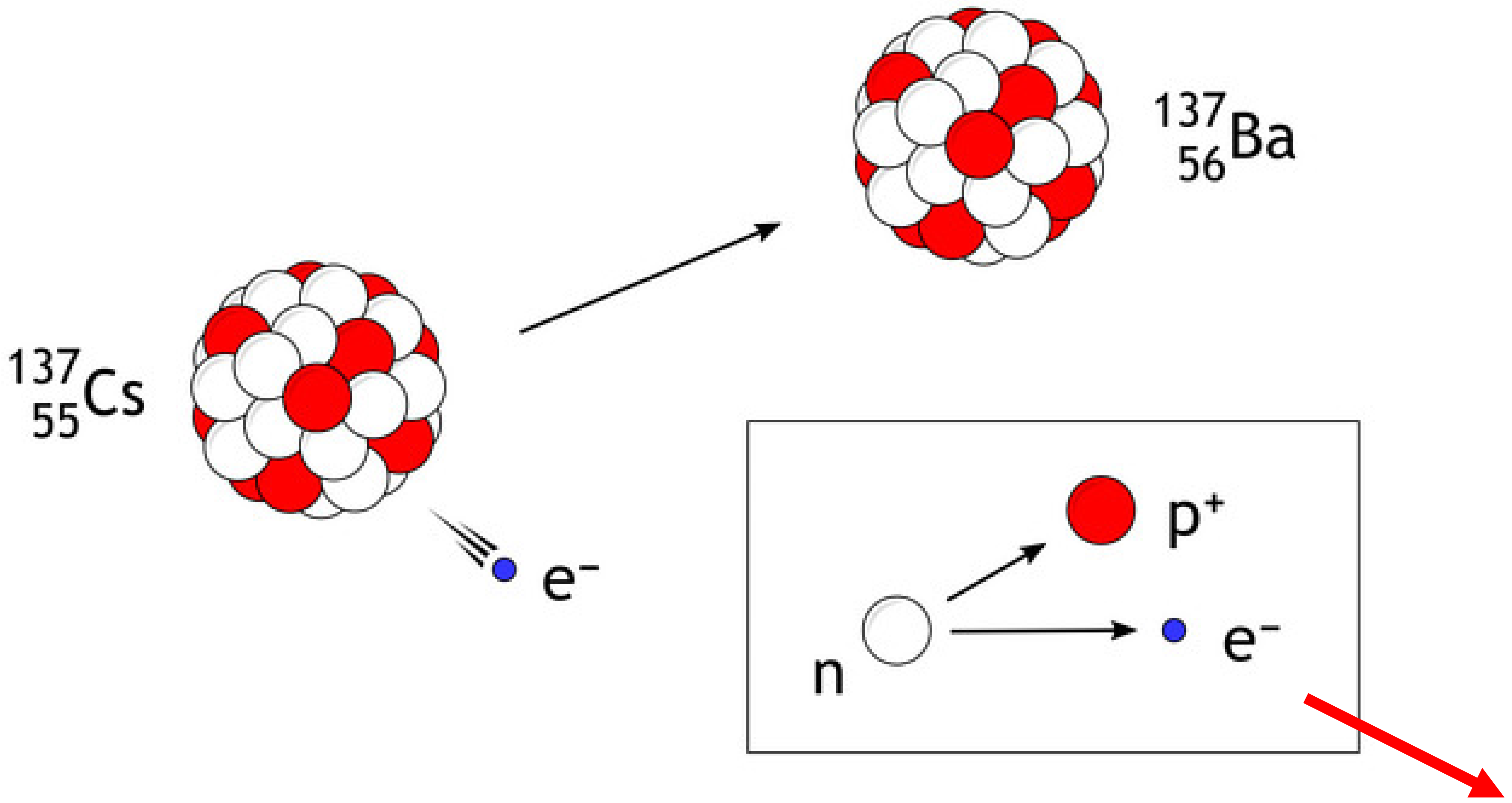

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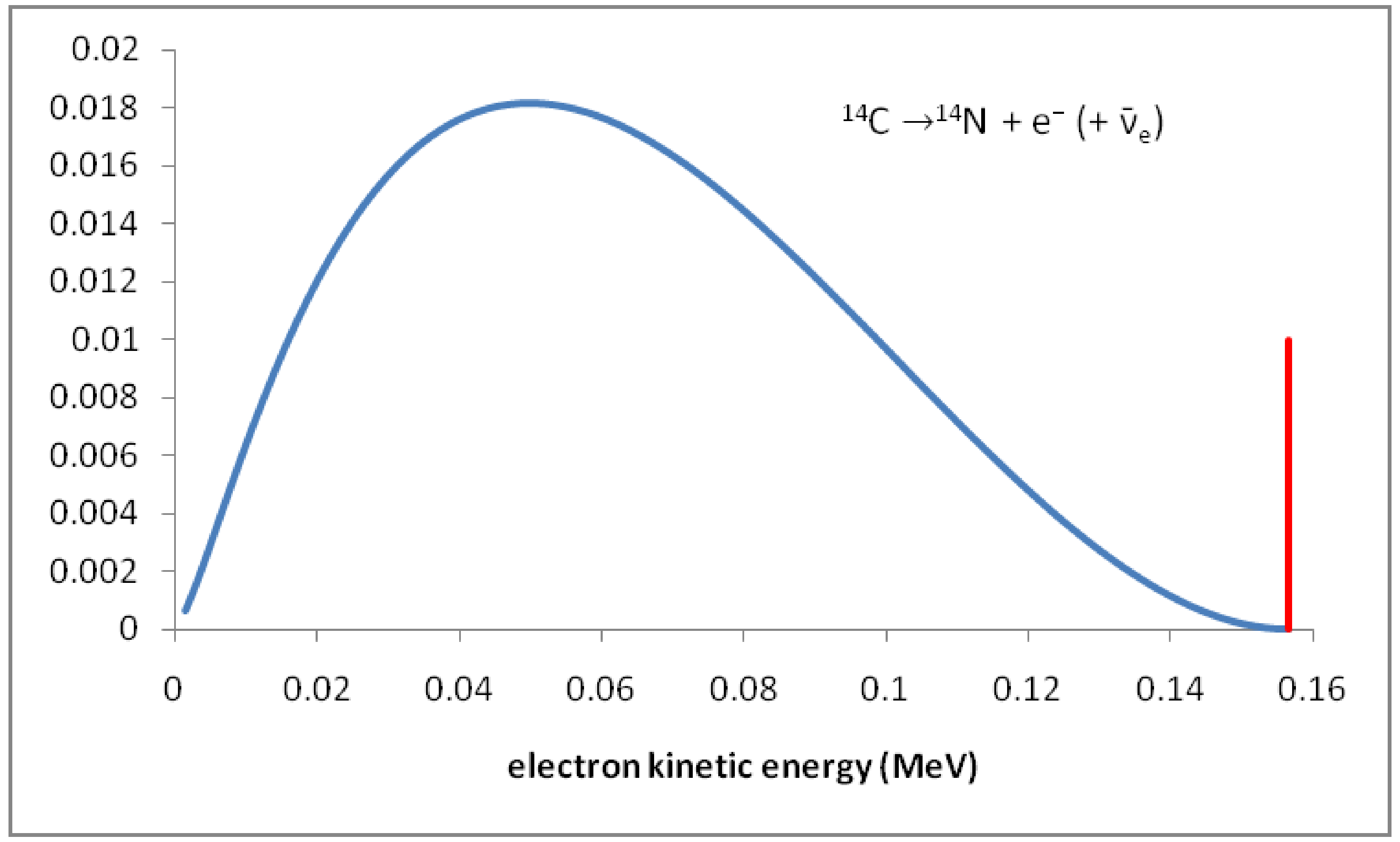

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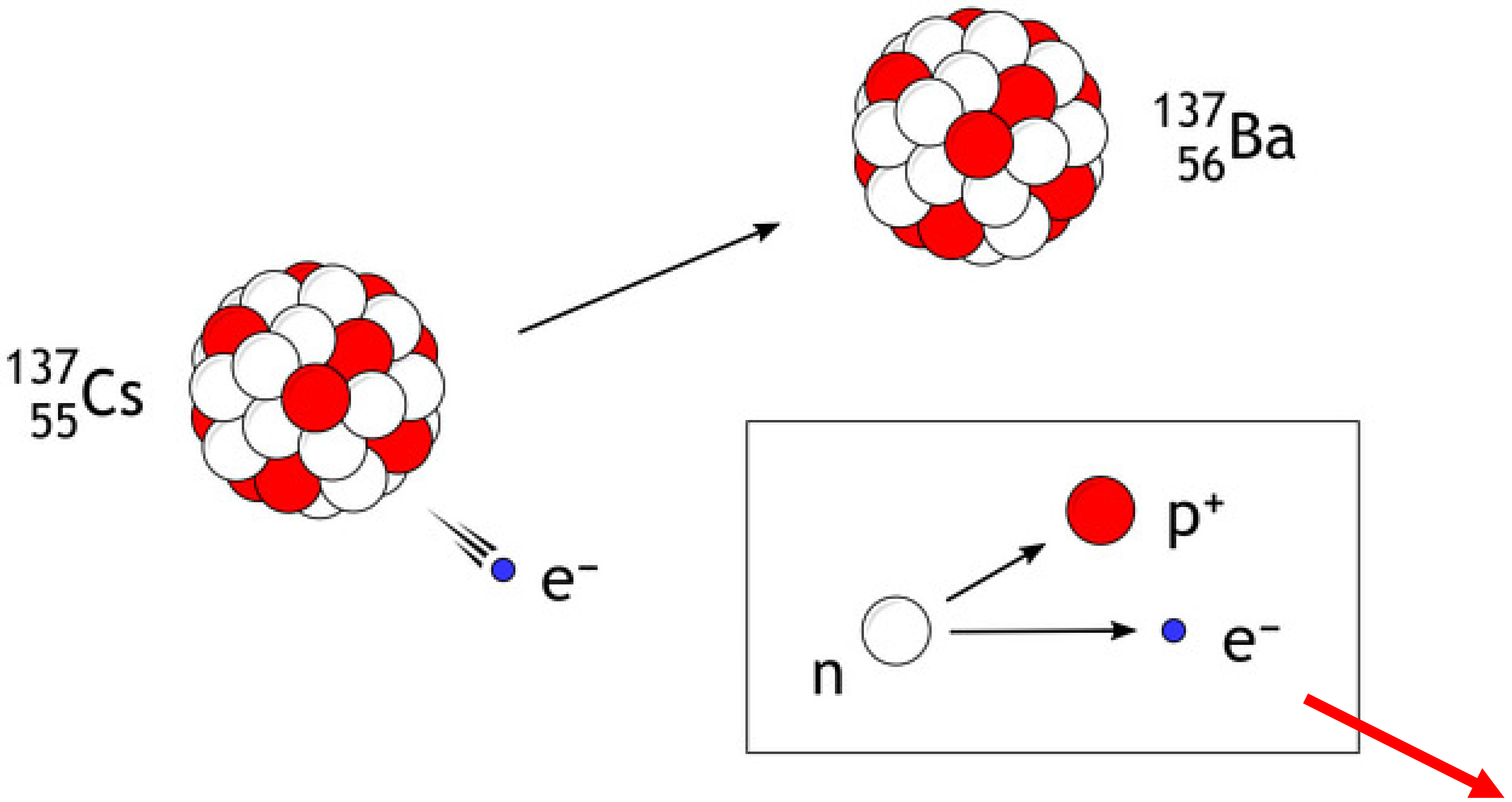

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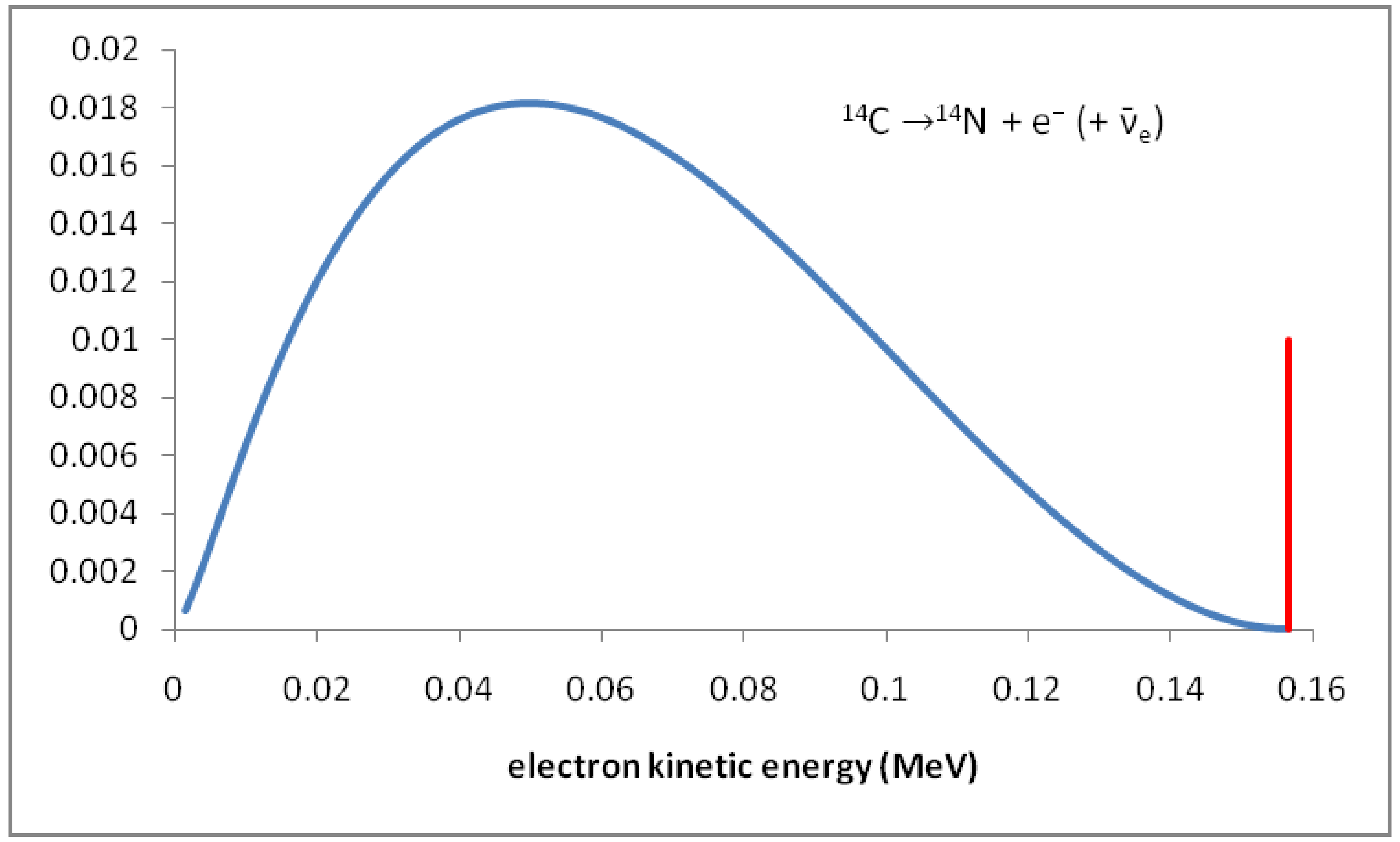
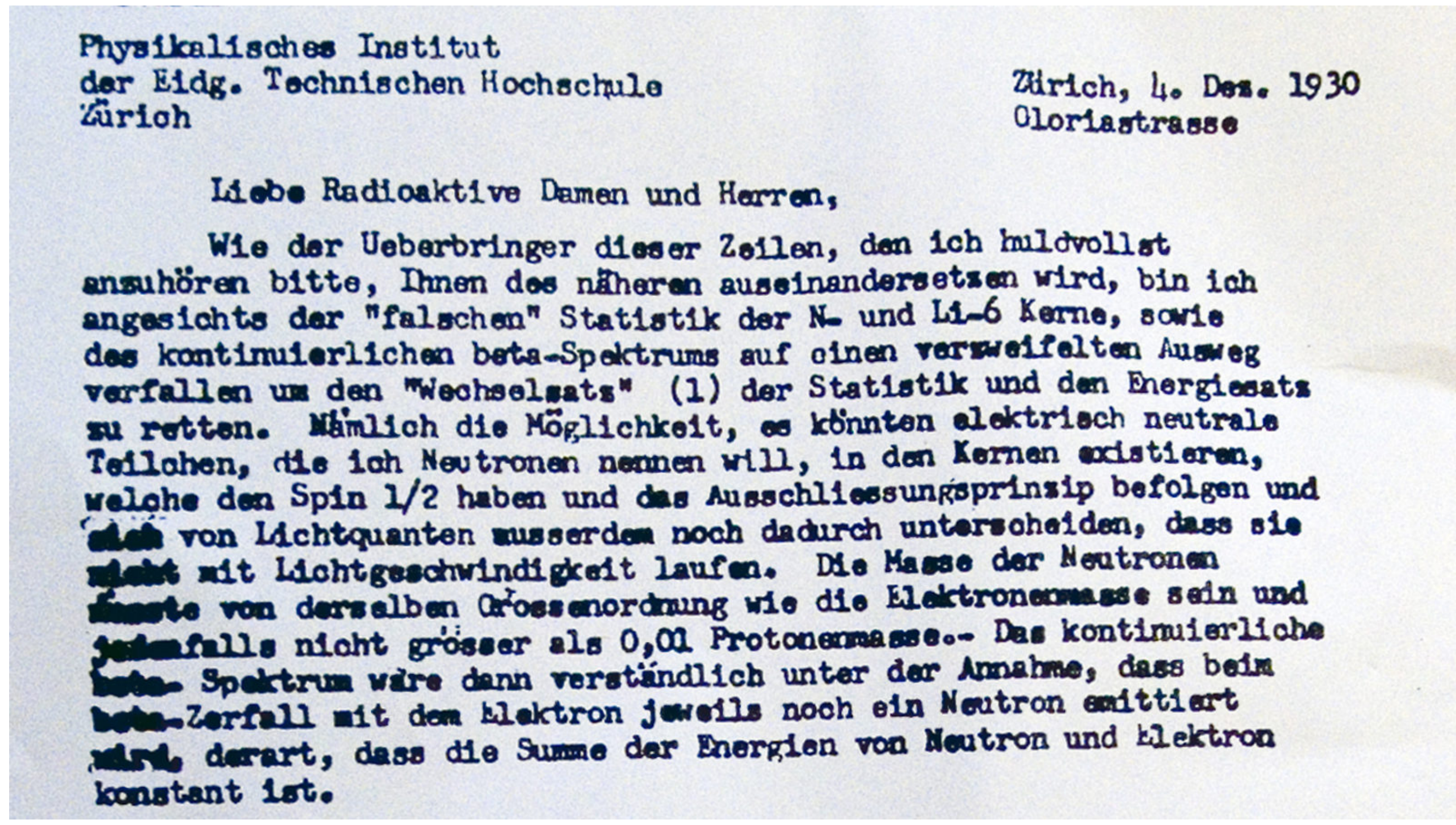




Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

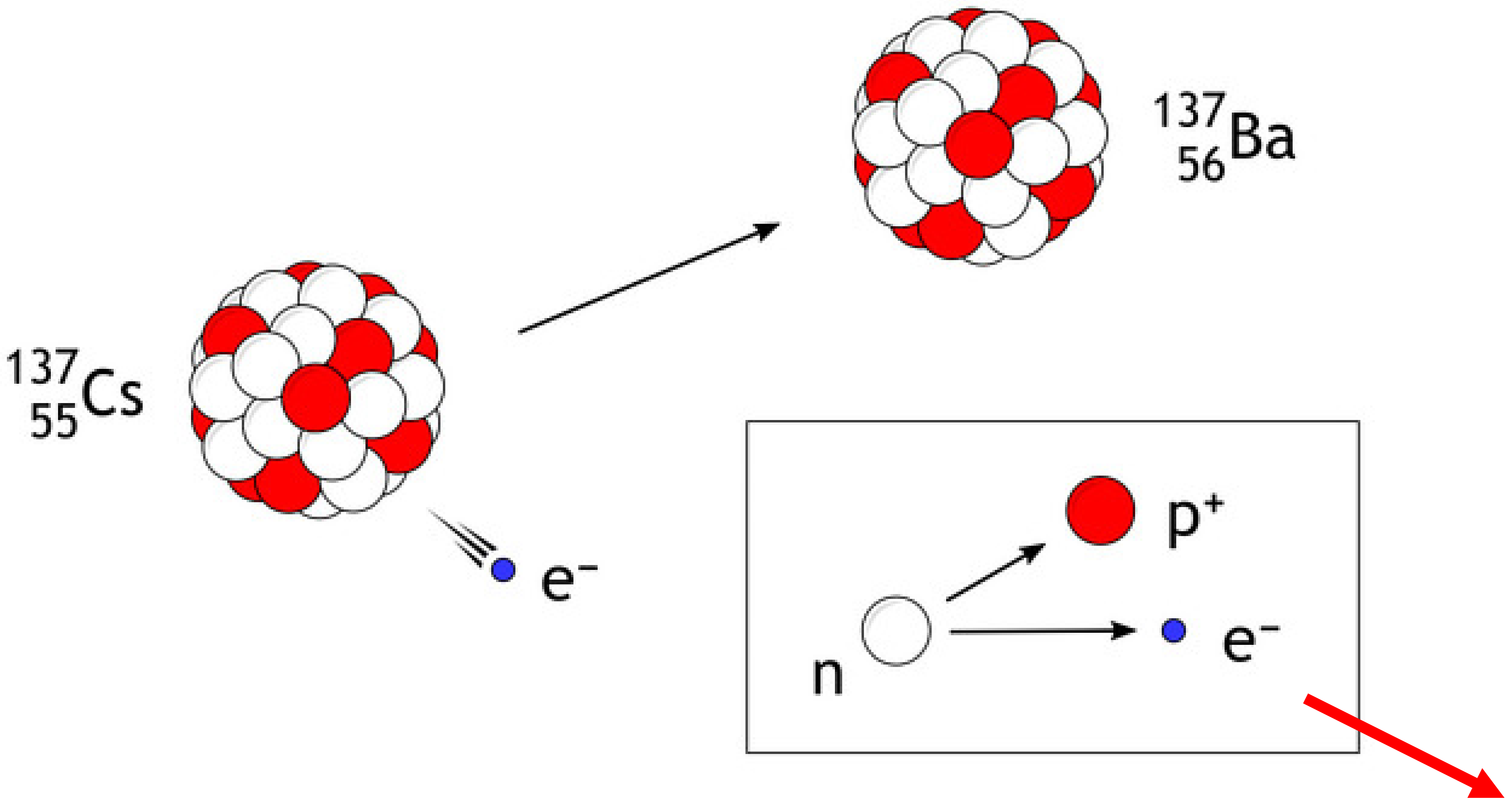
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

New electrically neutral (massless?) particle!

The beta decay problem



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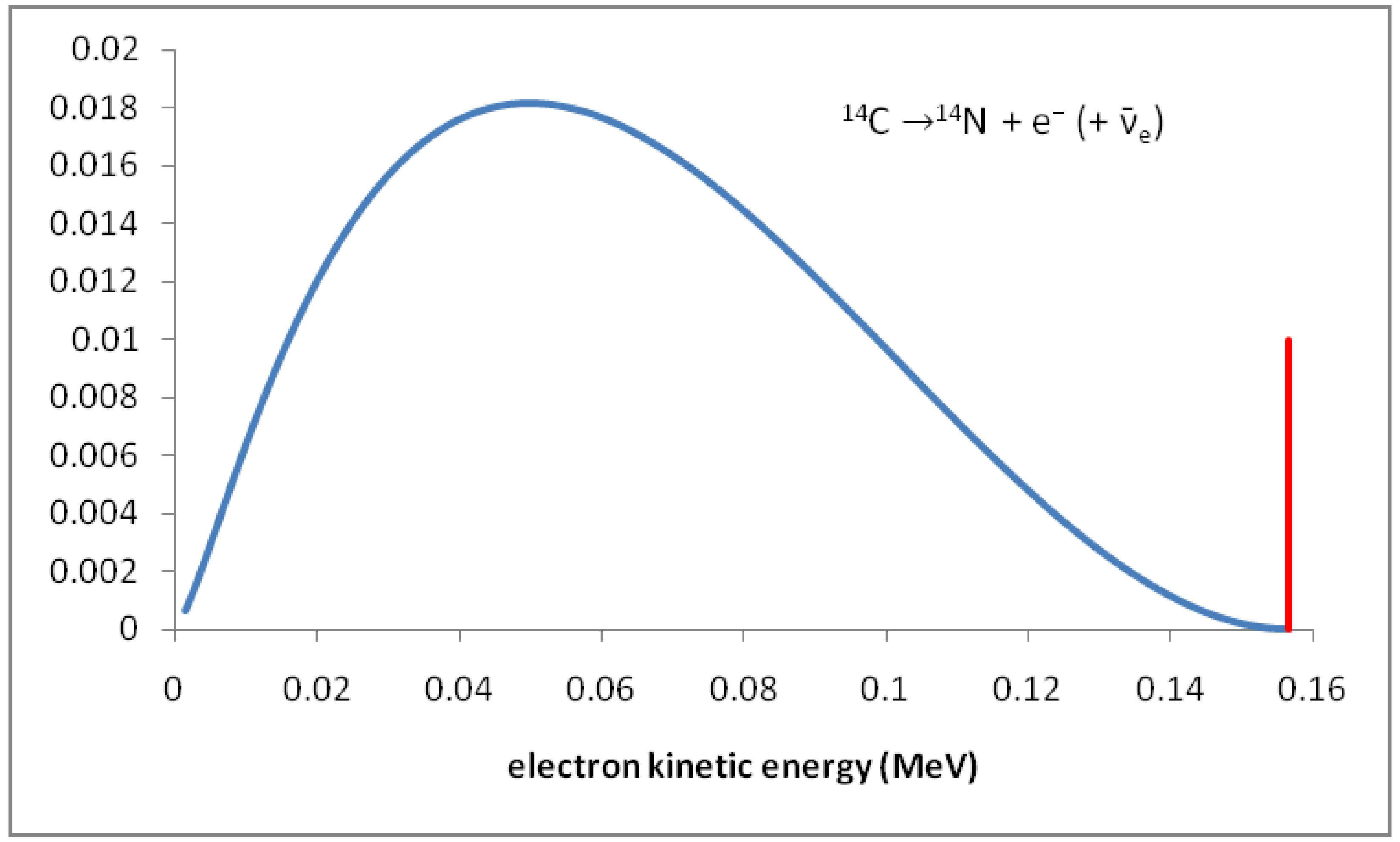

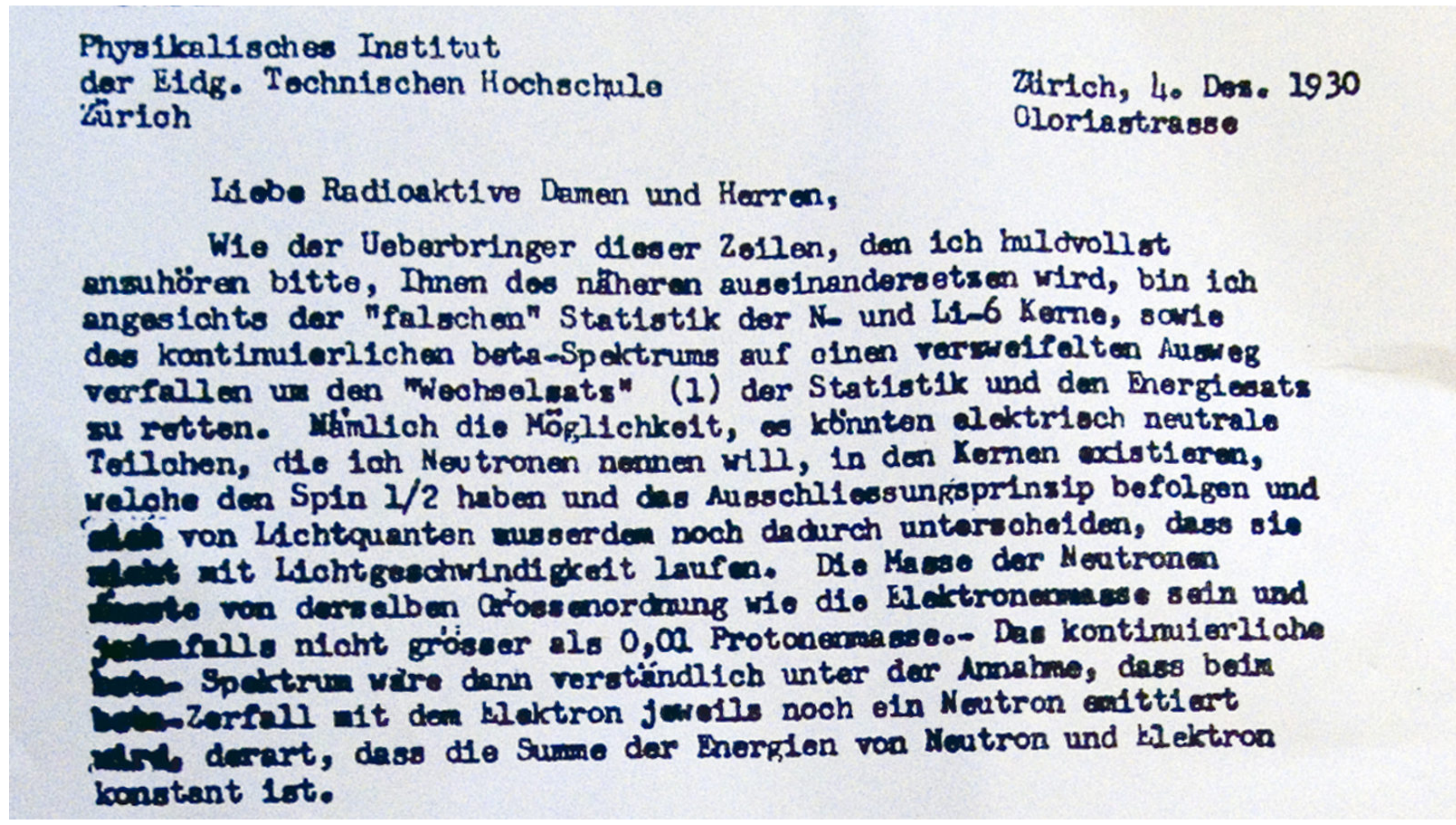

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How can we find this particle?

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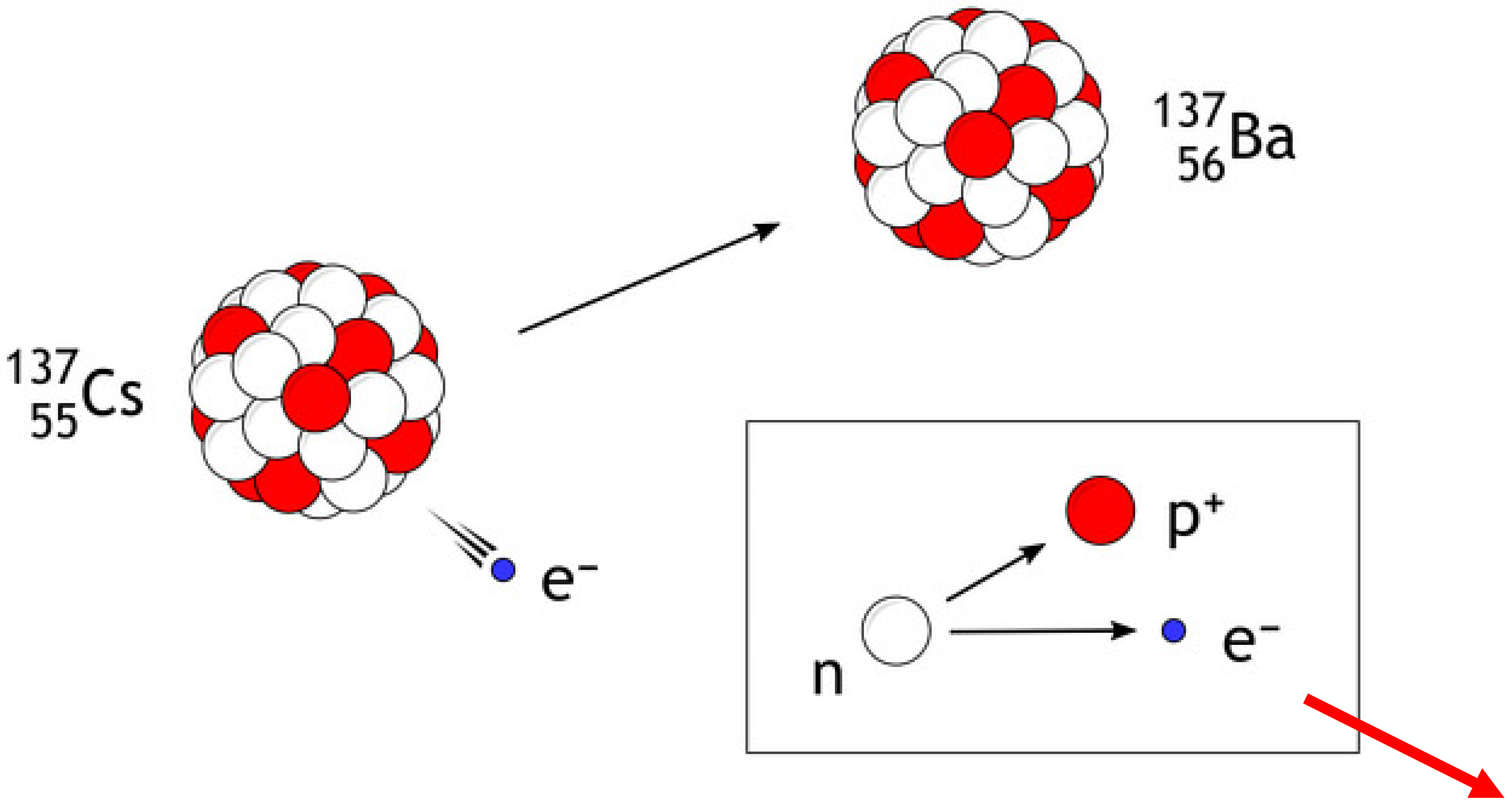
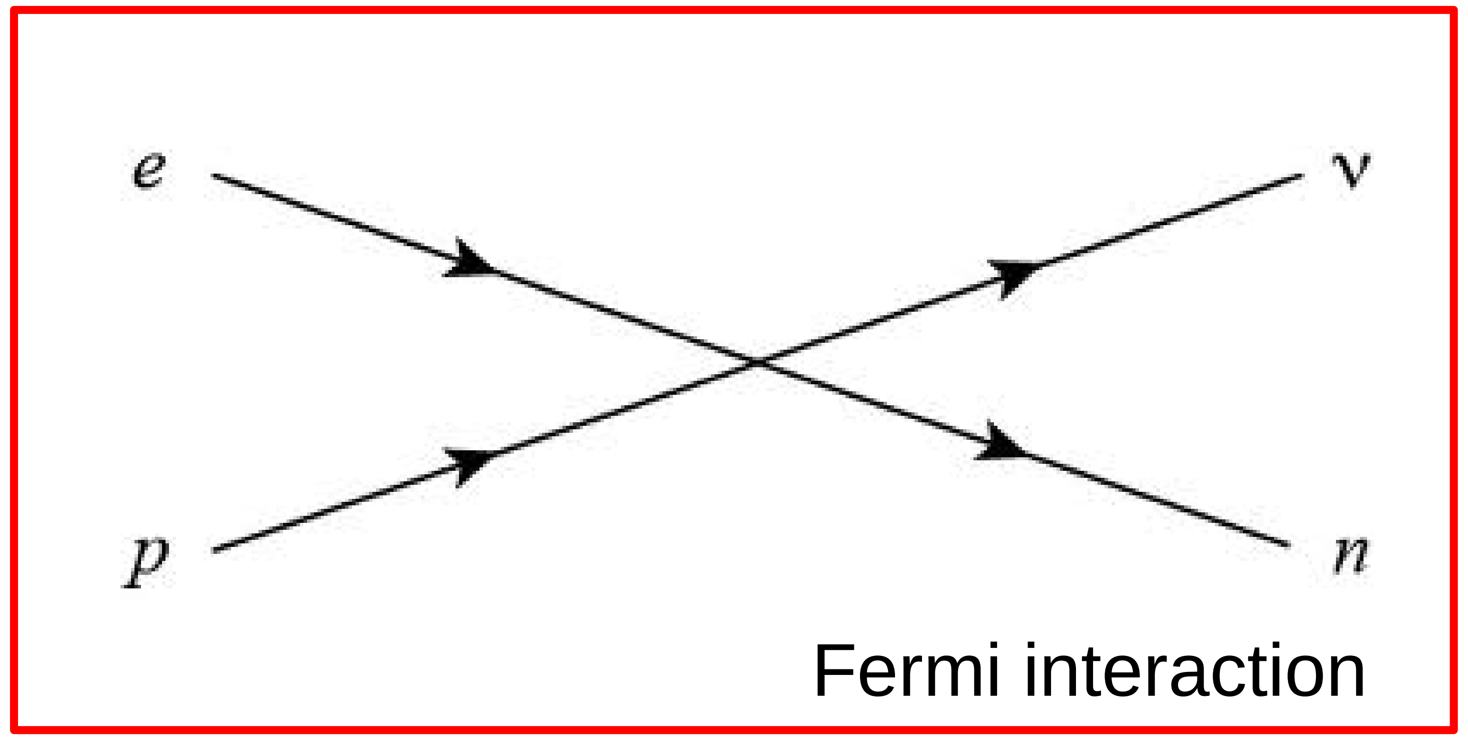


Beta decays are a form of weak interaction → Neutrinos must interact weakly!!!



Fermi interaction

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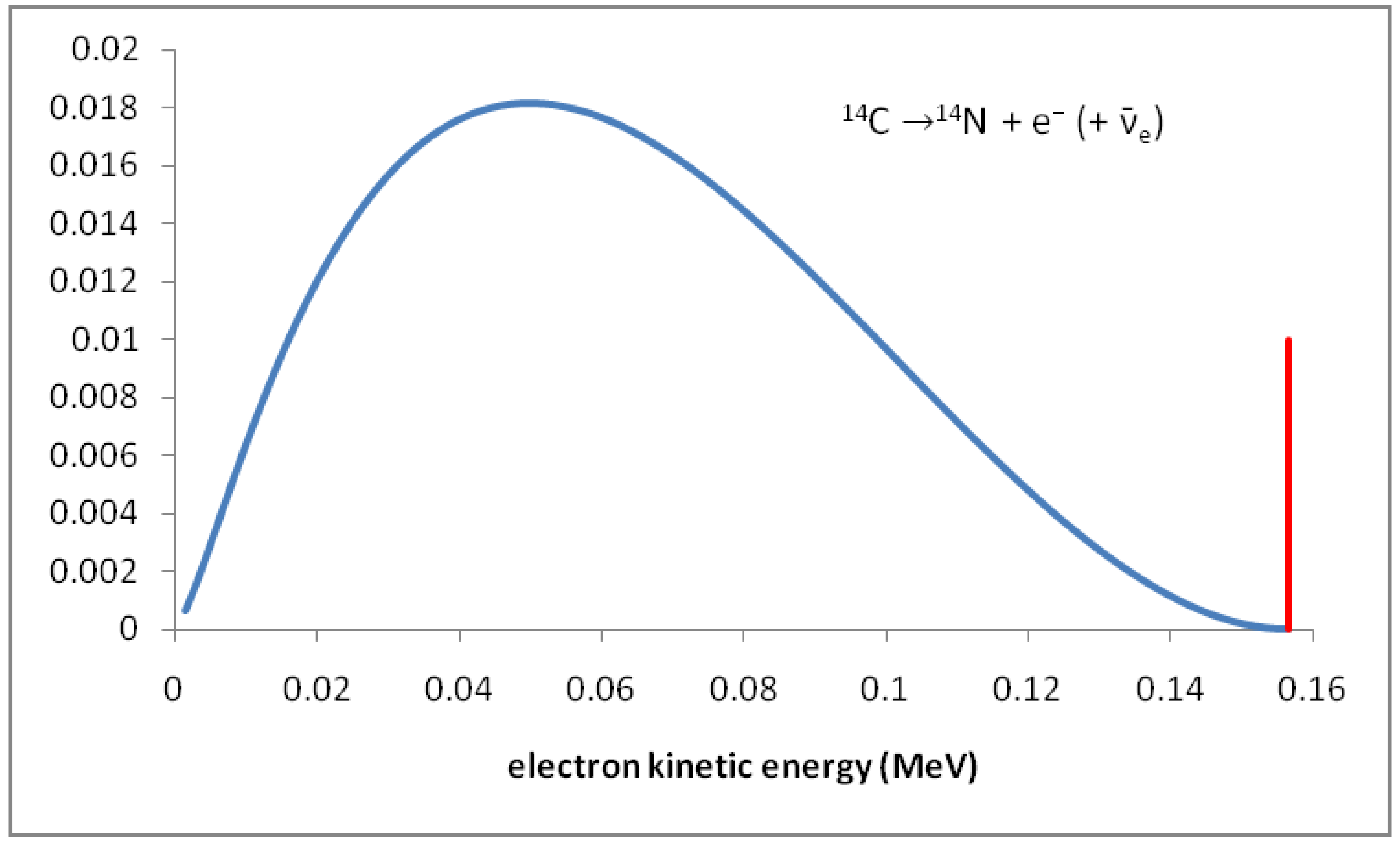

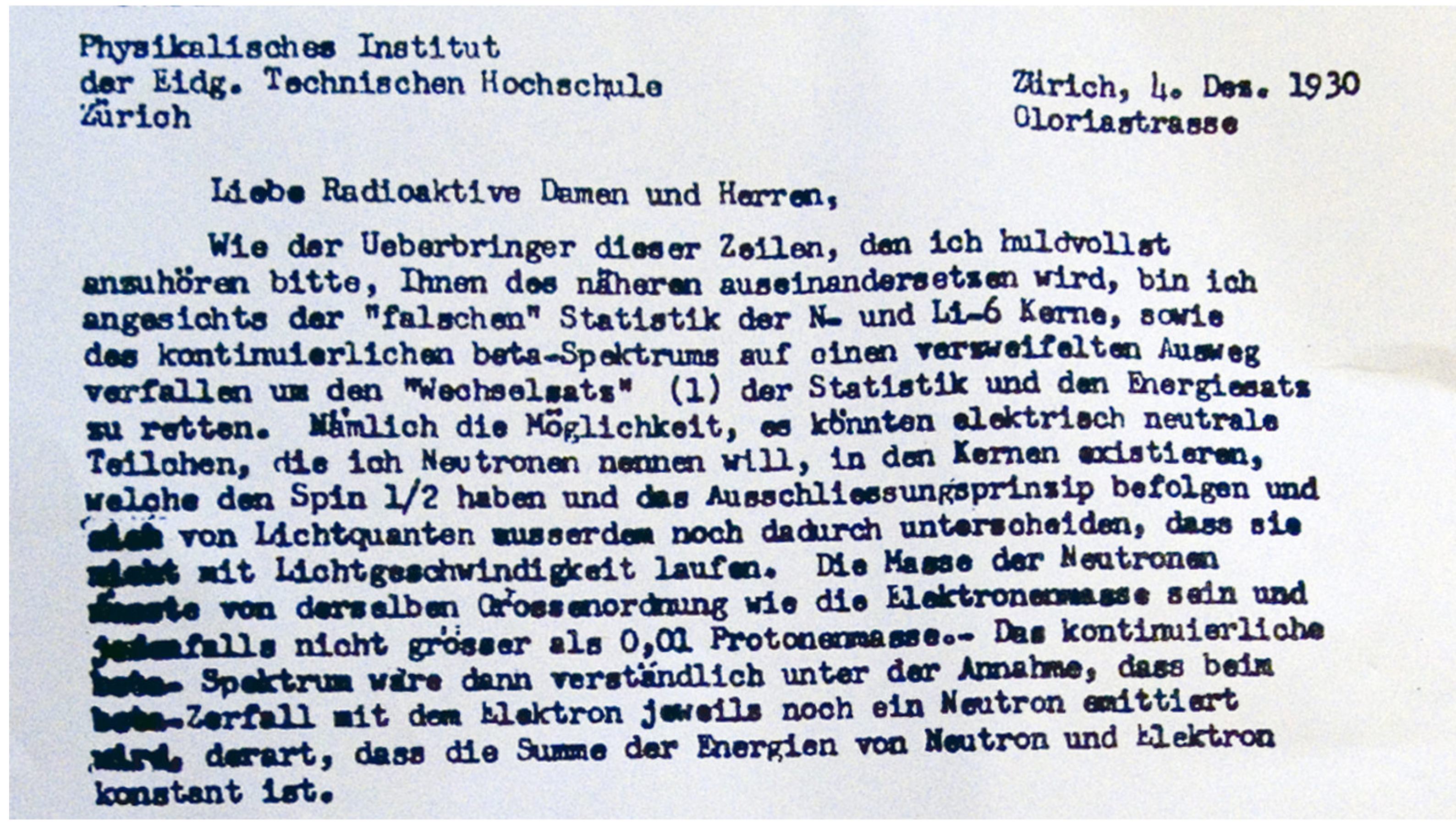
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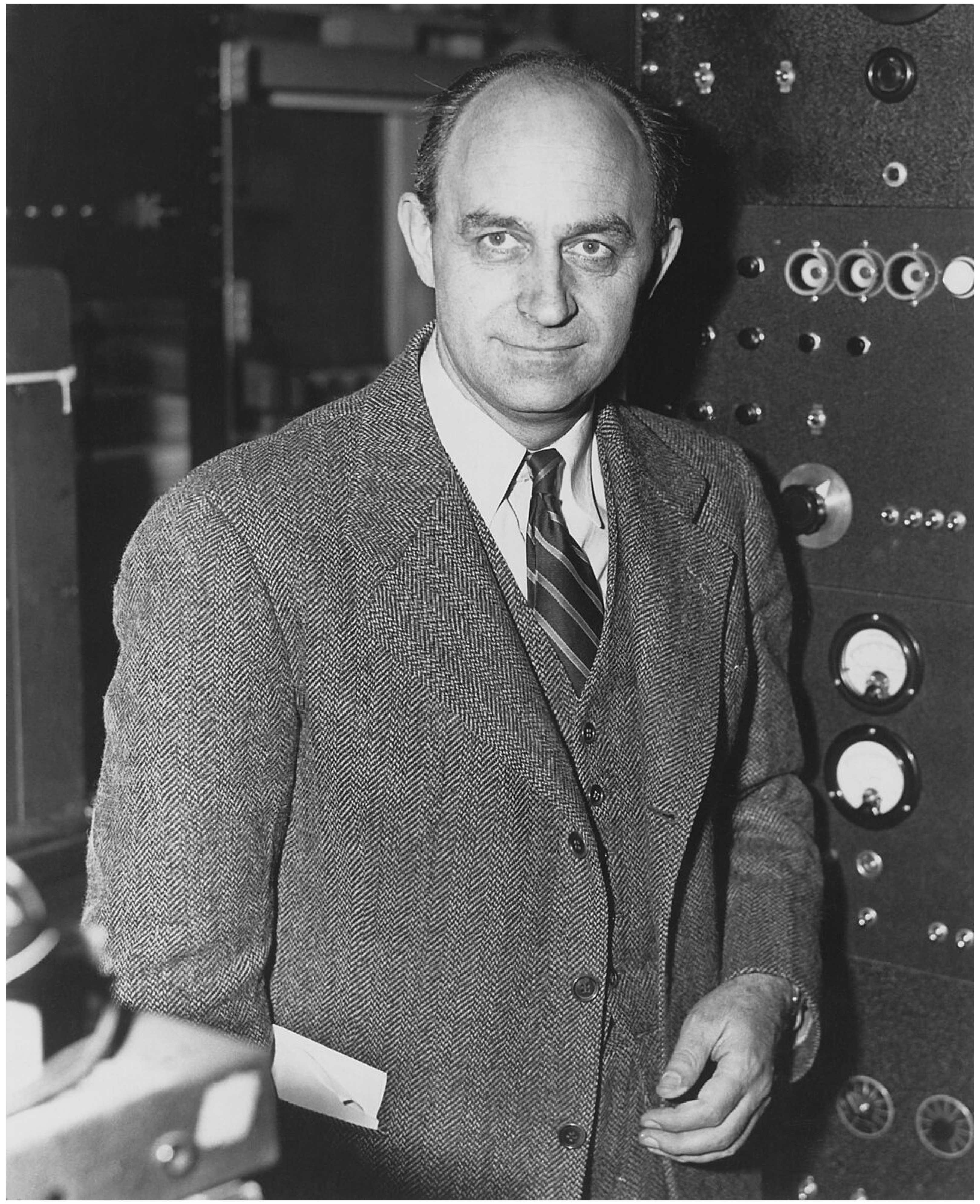
New electrically neutral (massless?) particle!

Thank you Pauli, thank you Fermi

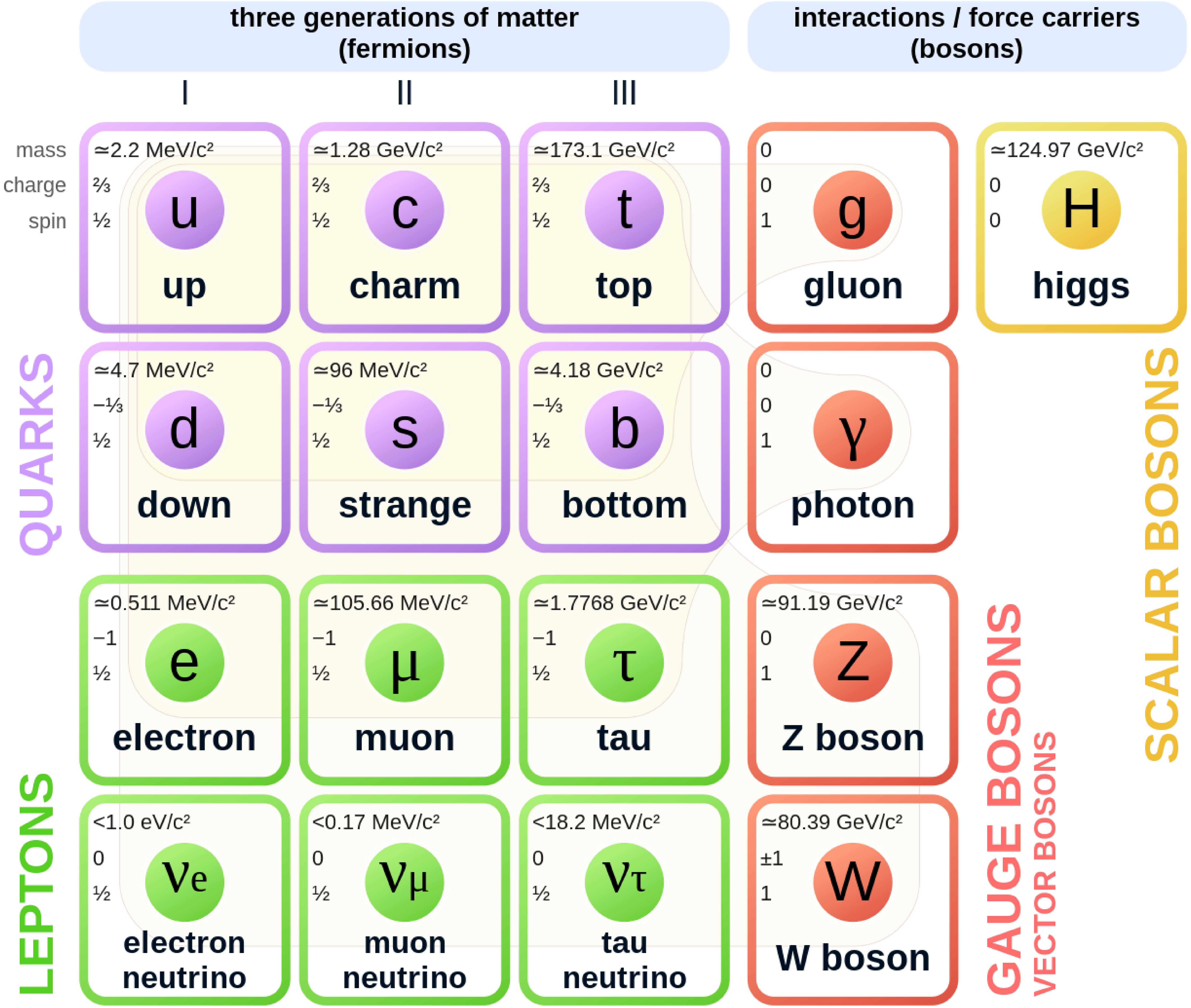
I came up with the idea!



I figured out how to make it work!

In the Standard Model

- ○ Neutrinos are leptons
- ○ 3 flavors linked to their corresponding charged counterpart
- ○ Can only interact through weak force (through $W^{\pm}$ and Z^0 bosons)
- ○ There are parallels between the 6 leptons and 6 quarks



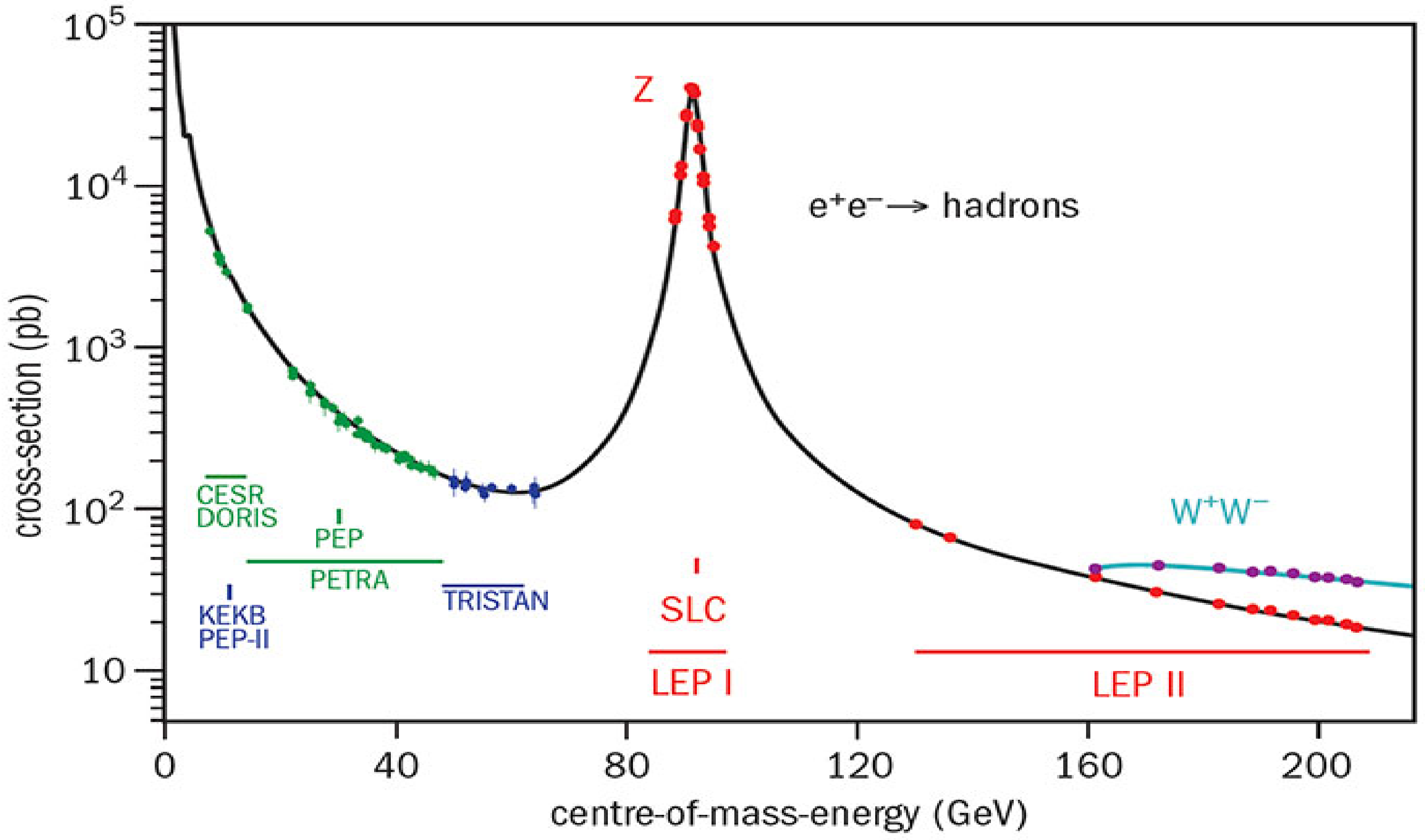
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
LEPTONS	<1.0 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	

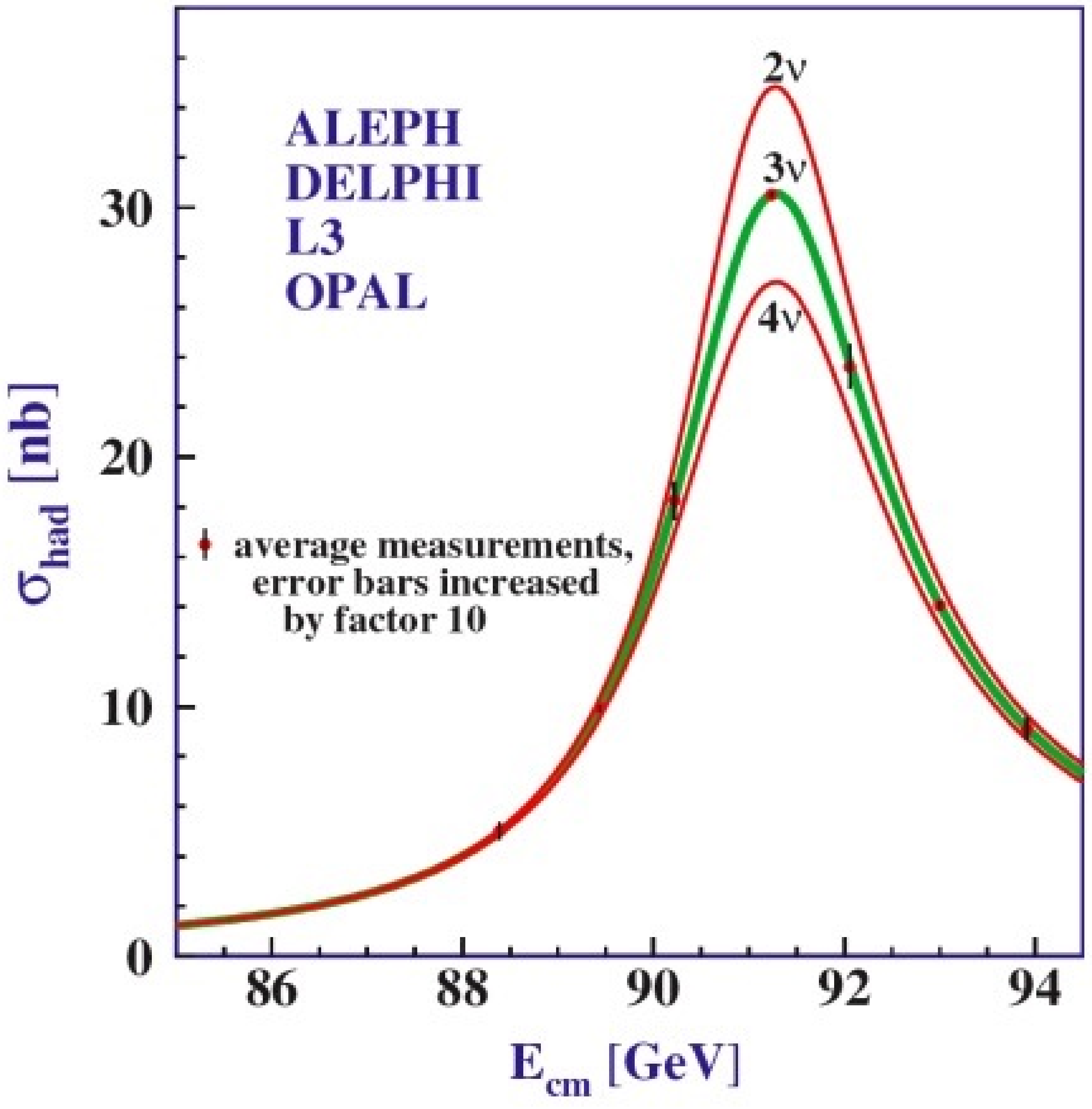
Key facts

- ○ Three flavors of light and active neutrinos named ν_e, ν_μ, ν_τ

→ In 1989, LEP mesures the Z invisible decay width :

$$N_\nu = 2.984 \pm 0.008$$





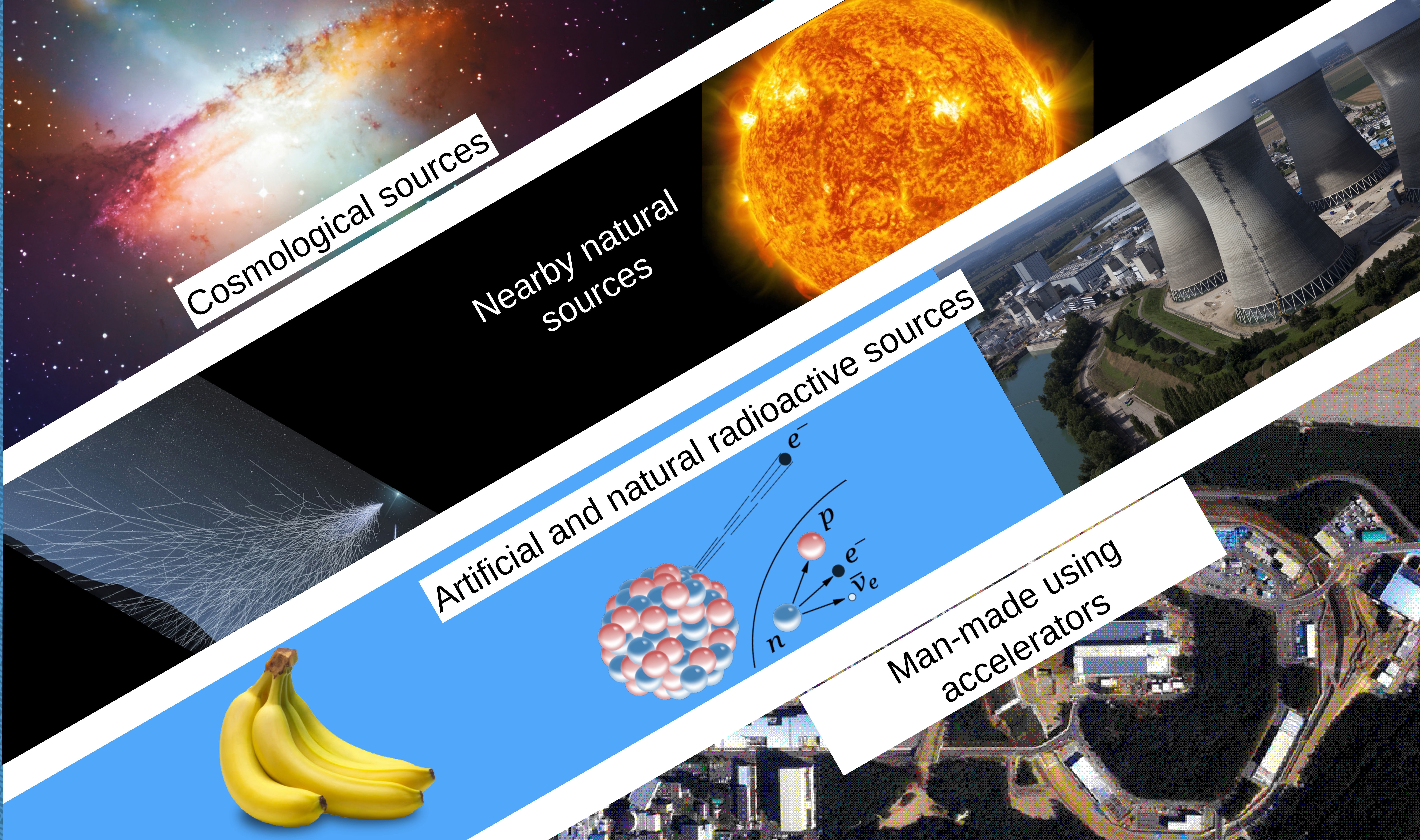
- ○ Neutrinos are only (observed to be) left-handed *(why?)*

→ Cannot couple to the Higgs field, therefore the neutrinos are considered massless in the Standard Model
→ But they in fact do have a mass:

$$m_\nu < 1 \text{ eV} \; ; \; \sum m_\nu > 0.06 \text{ eV}$$

We will soon see why...

Neutrinos: Where?



Cosmological sources

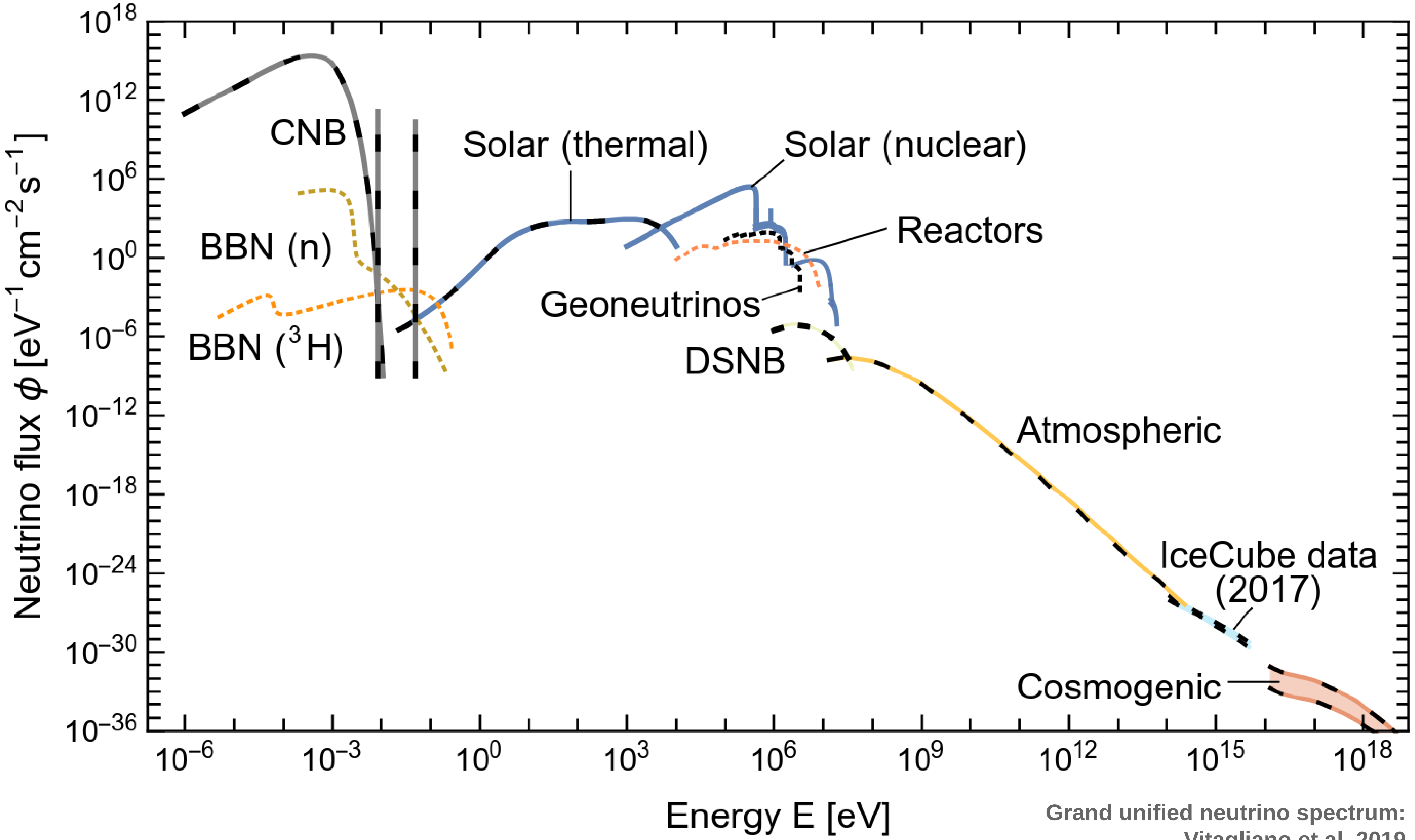
Nearby natural sources

Artificial and natural radioactive sources

Man-made using accelerators

Neutrino sources

Neutrinos are the most common massive particle in the universe (high-E p → ν!)



Grand unified neutrino spectrum:
Vitagliano et al. 2019

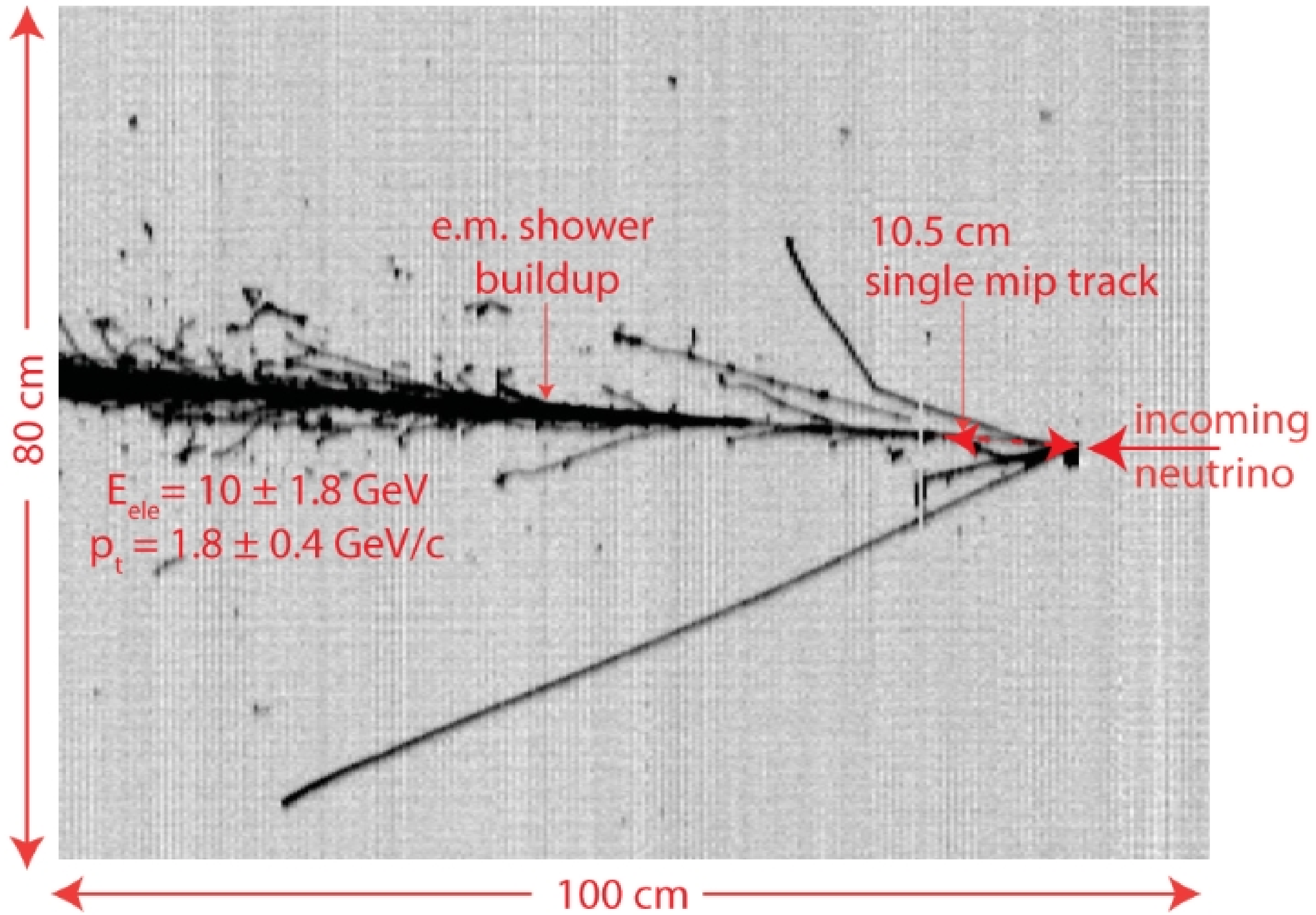
$\Phi_{sun} = 65\times10^{9}\ \nu_e/cm^2/s$ on earth
$\Phi_{reactor} = 2\times10^{20}\ \overline{\nu}_e/s/GW_{th}$
$\Phi_{atmo} = 4\times10^{2}\ \nu_{e+\mu}/m^2/s/sr$
$\Phi_{accelerator} \sim 1\times10^{12}\ \nu_\mu/m^2$

→ **only a 50% chance a ν_e from the sun interact in you in your lifetime**

Neutrino interactions

○ Only interact through weak interaction
→ Small cross section :
$\sigma \sim 10^{-42}$ cm^2 for IBD
$\sigma \sim 10^{-38}$ cm^2 at 1 GeV

○ Since they have no electric charge, we cannot observe them directly
→ Wait for a weak interaction, look at the products → Attempt to reconstruct the neutrino

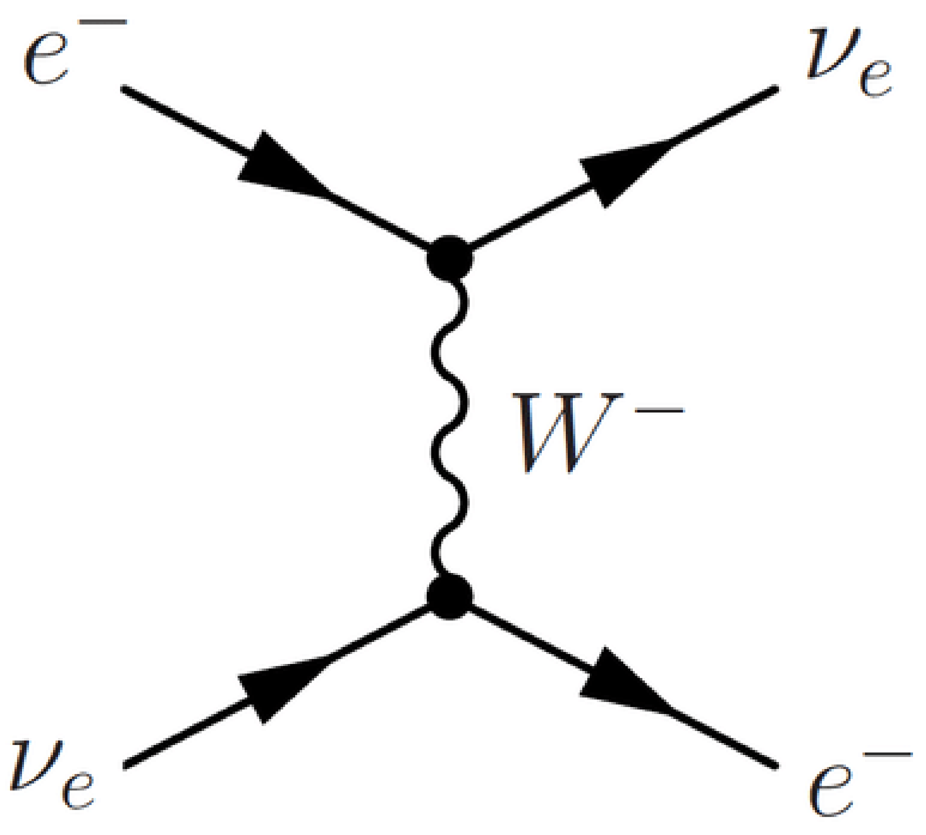


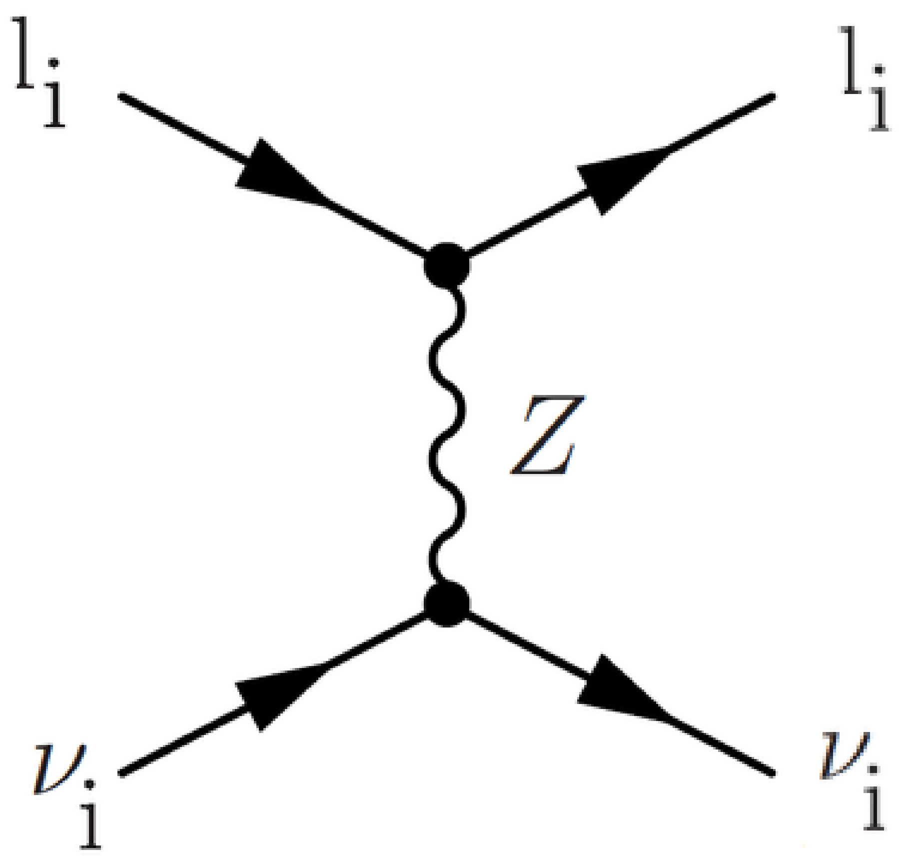
Like reconstructing a bullet from the impact holes!!

HOW TO DETECT NEUTRINOS

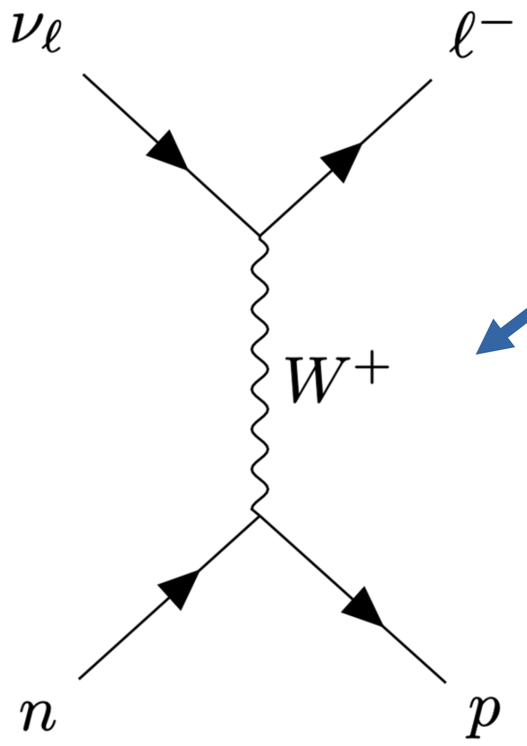
Charged and neutral currents

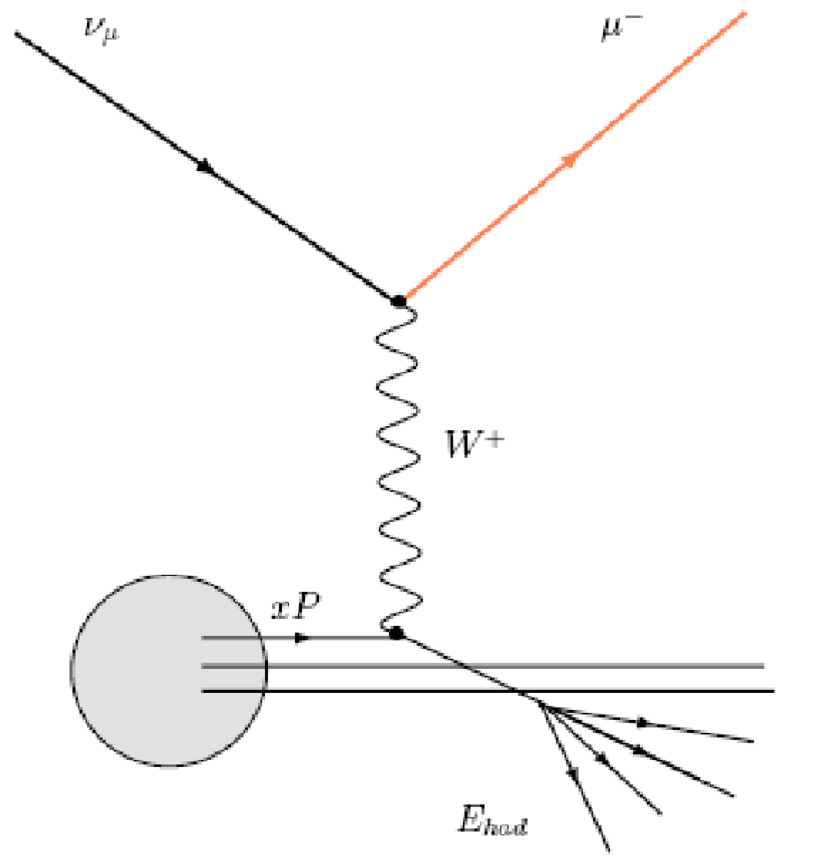
Weak interactions come in two types:
-> Through Z^0 exchange = Neutral Currents - flavour agnostic
-> Through $W^\pm$ exchange = Charged Currents - flavour sensitive





Interactions look very different at low vs high energies





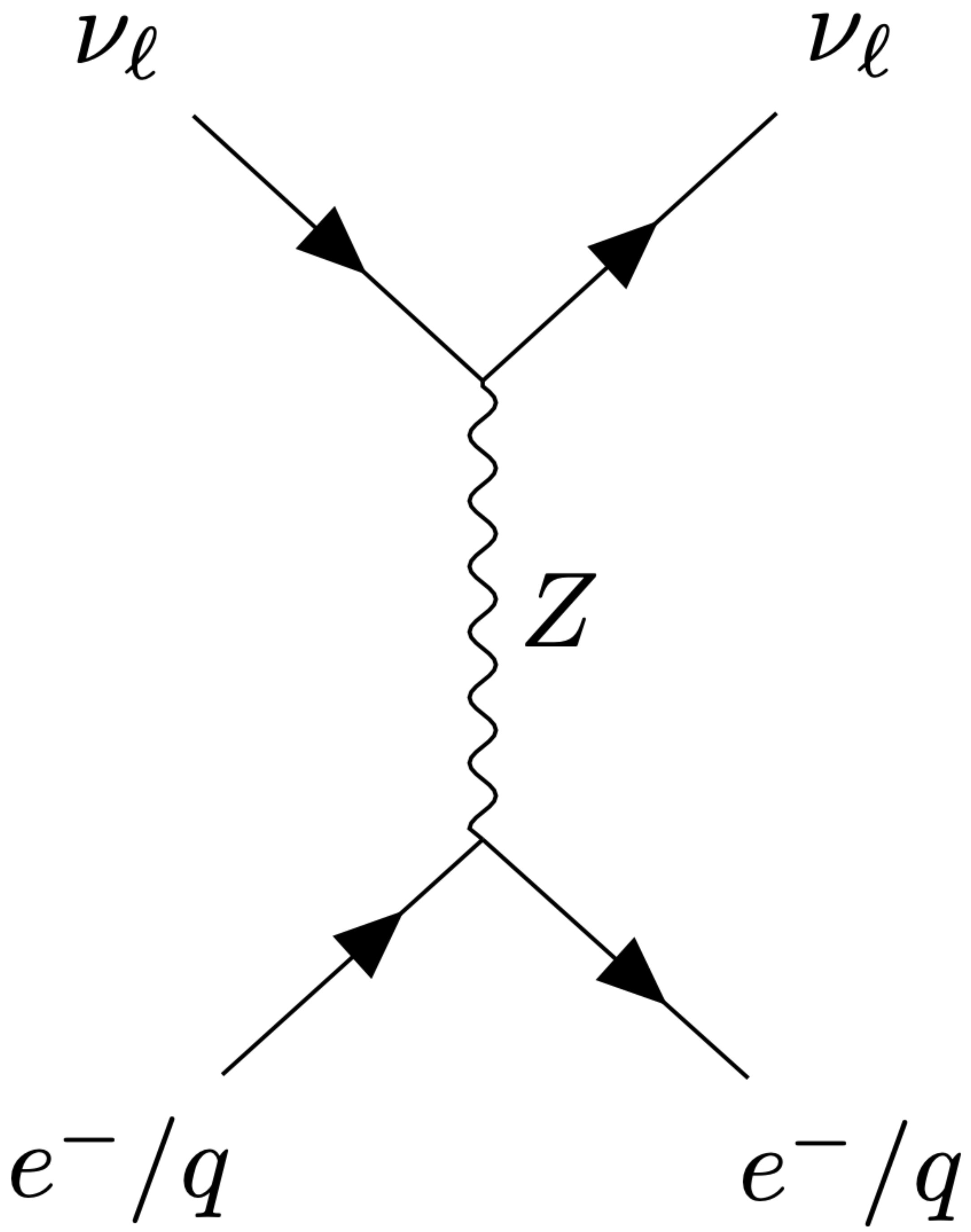
Neutral current interactions

- ○ Cannot identify the incoming neutrino flavour
- ○ All neutrinos interact with the same potential

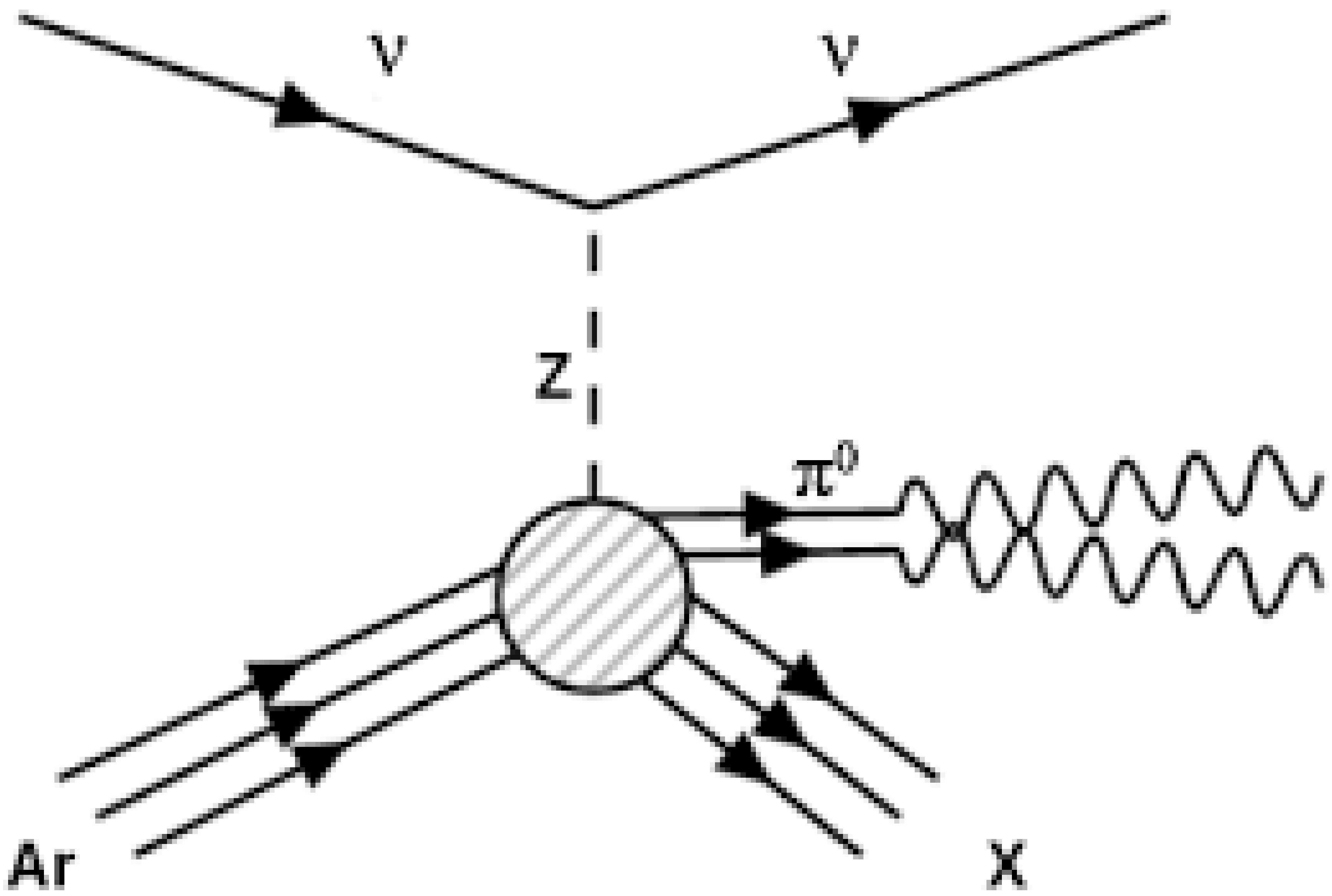
→ **Useful for measuring the total incoming neutrino flux (sum of all flavours)**

→ **Can be a difficult background for charged current searches**

Low energy: elastic scattering



High energy: π^0 production

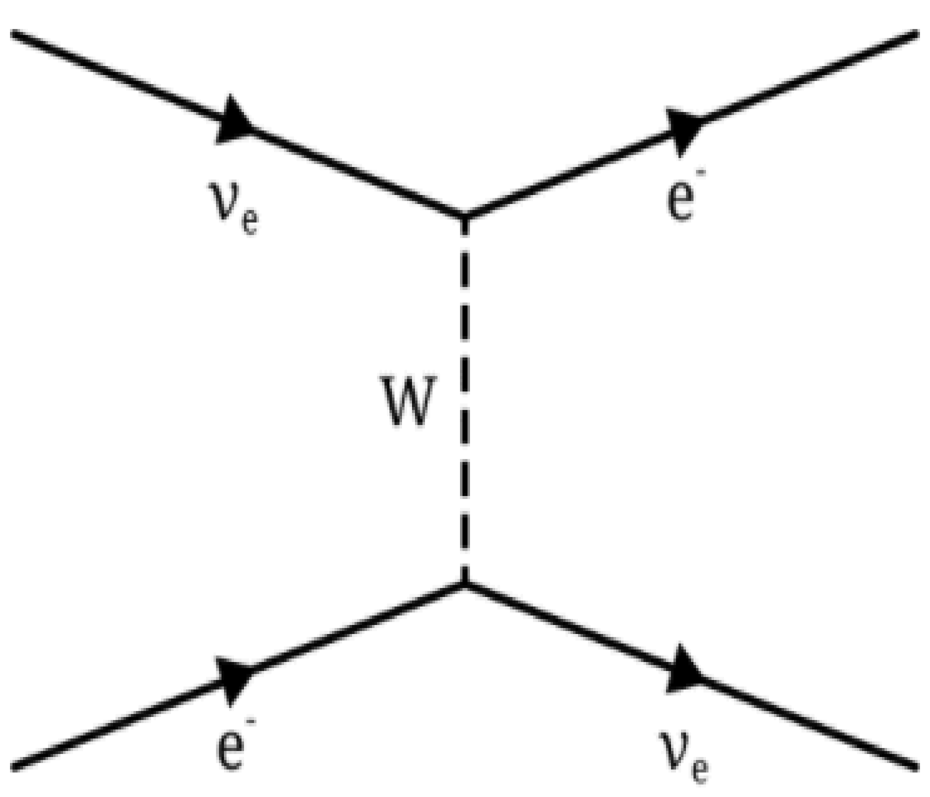


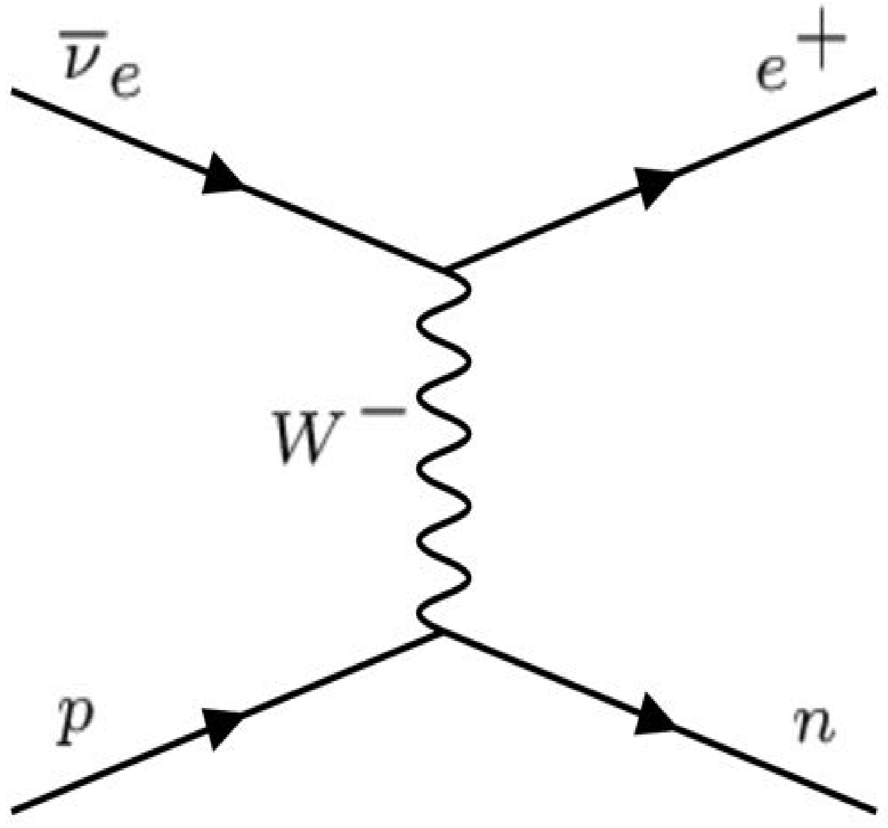
Charged current interactions

- ○ The outgoing lepton matches the flavour of the neutrino

Low energy:

Elastic scattering ***Inverse β-decay***





- ○ Solar neutrinos
- ○ Interactions with the medium during propagation

- ○ Reactor neutrinos
- ○ Interactions with free protons (hydrogen nucleii)

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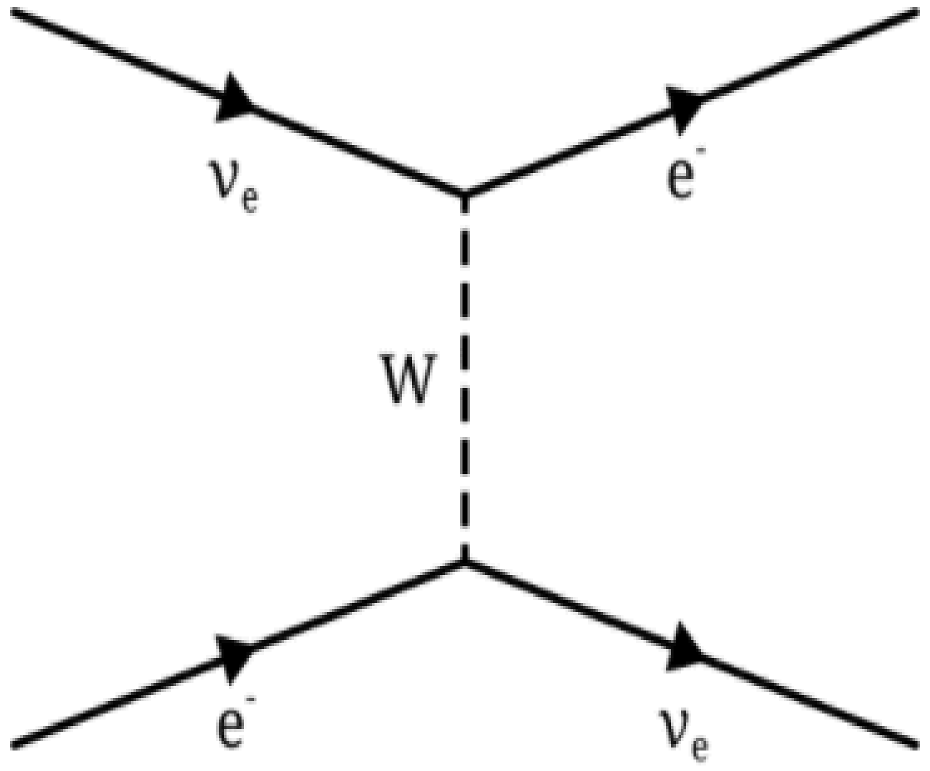
Low energy:

High energy (accelerators):

Elastic scattering



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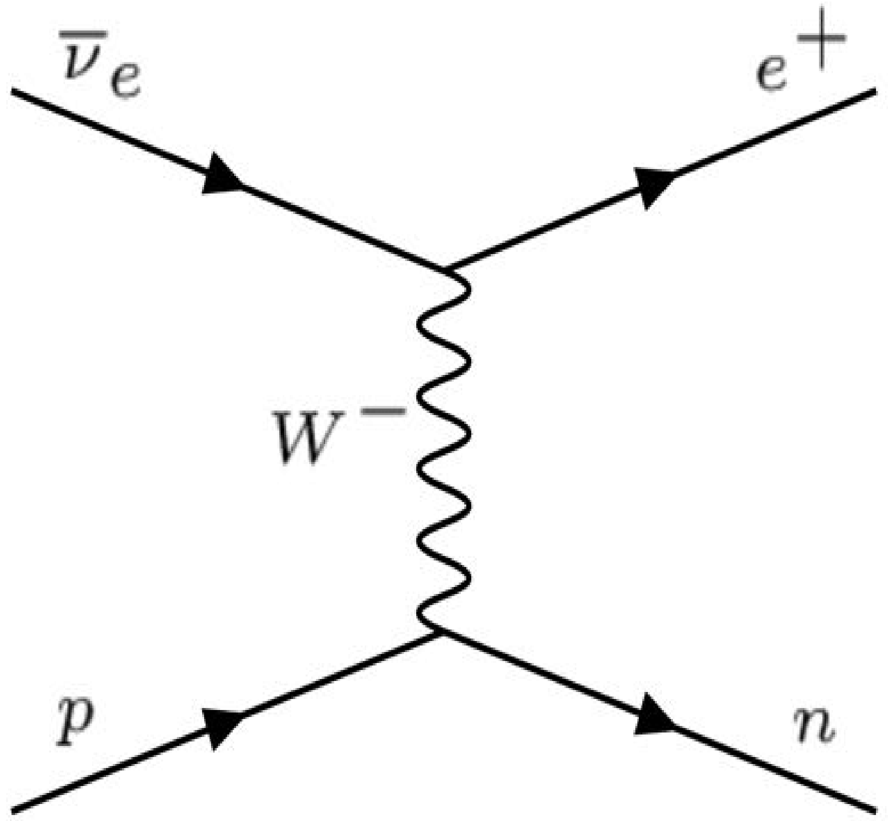

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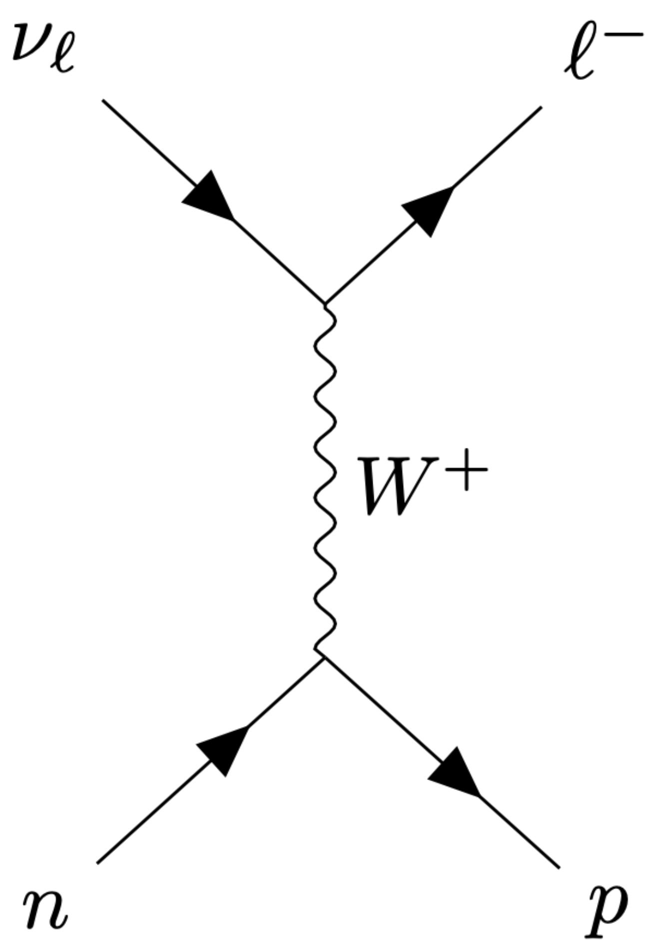
Quasi-elastic

The Golden Channel



- ○ Clean signal: a single lepton
- ○ Neutrino energy can be recovered from the lepton kinematics:

$$\boxed{E_\nu = \frac{m_f^2 - (m_i - E_b)^2 - m_\mu^2 + 2(m_i - E_b)E_\mu}{2(m_i - E_b - E_\mu + p_\mu \cos\theta_\mu)}}$$

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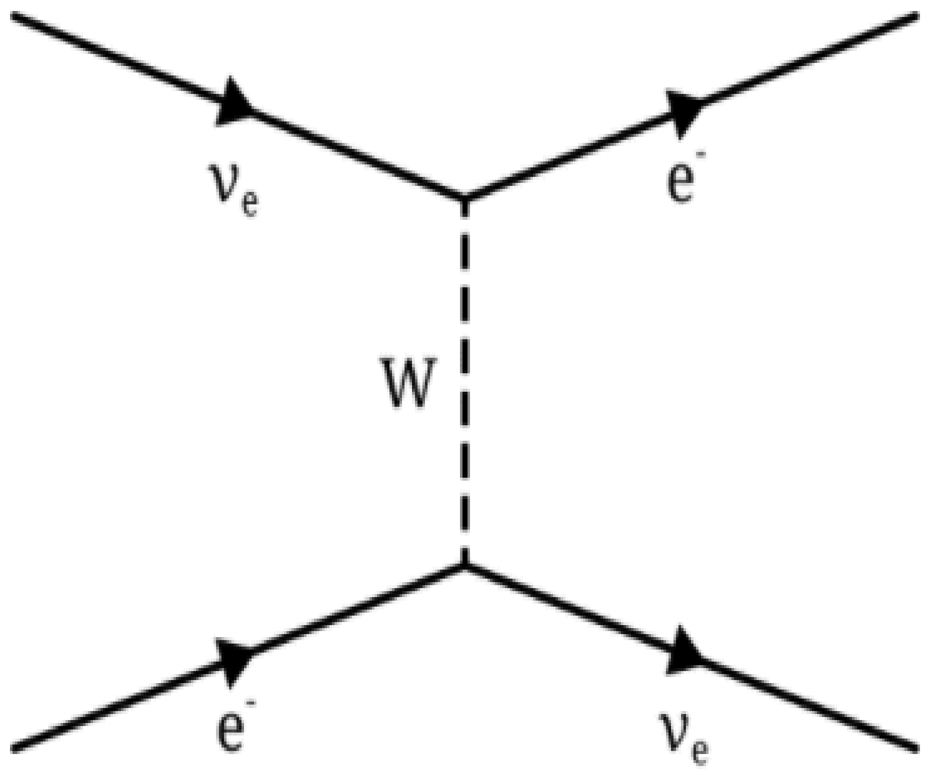

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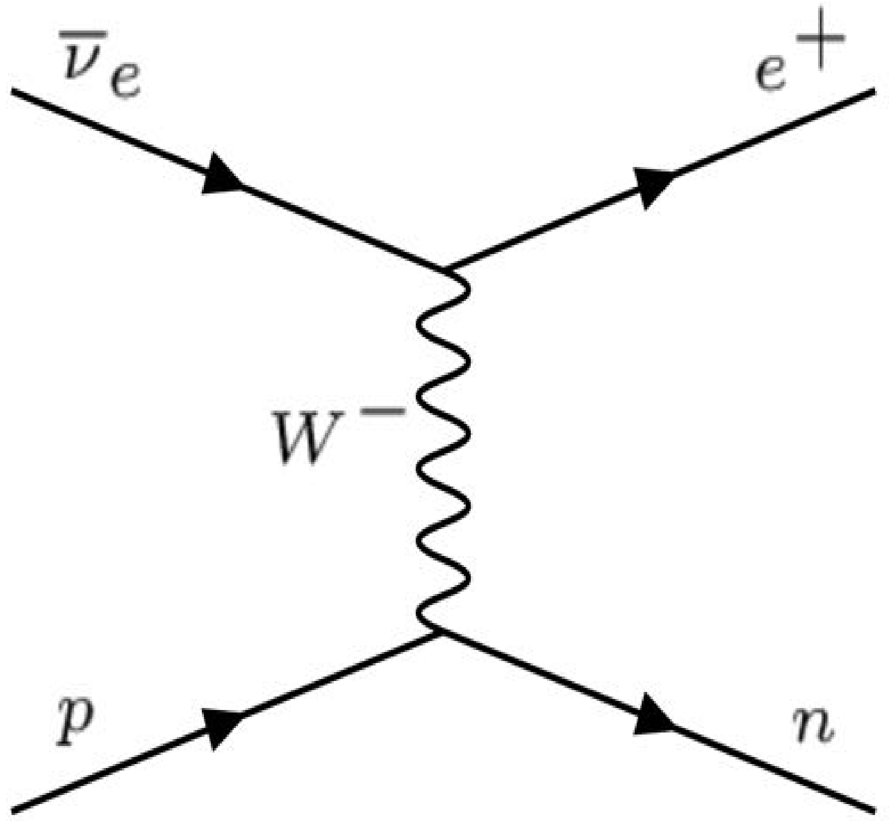

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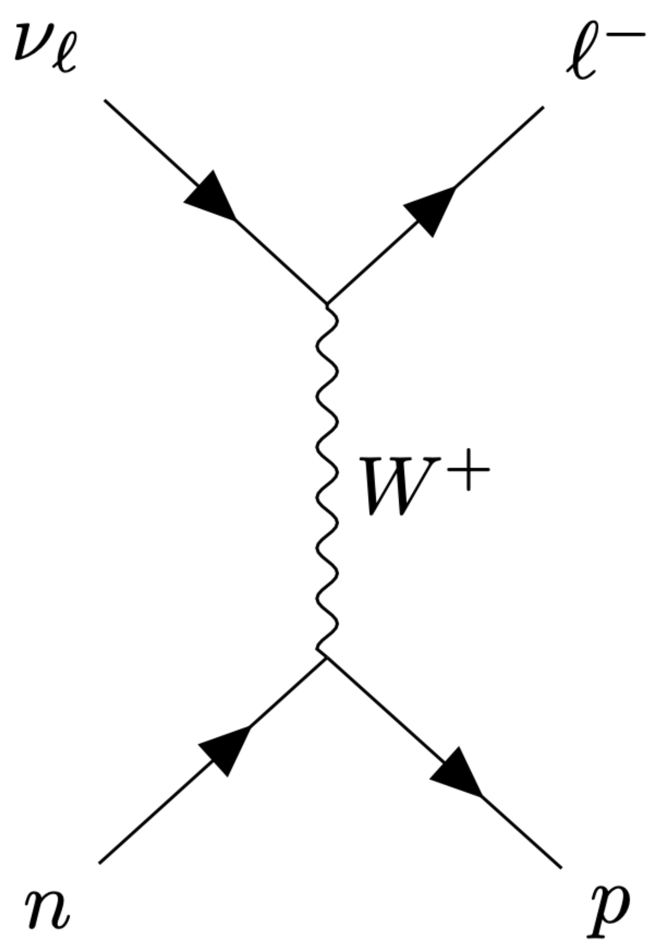

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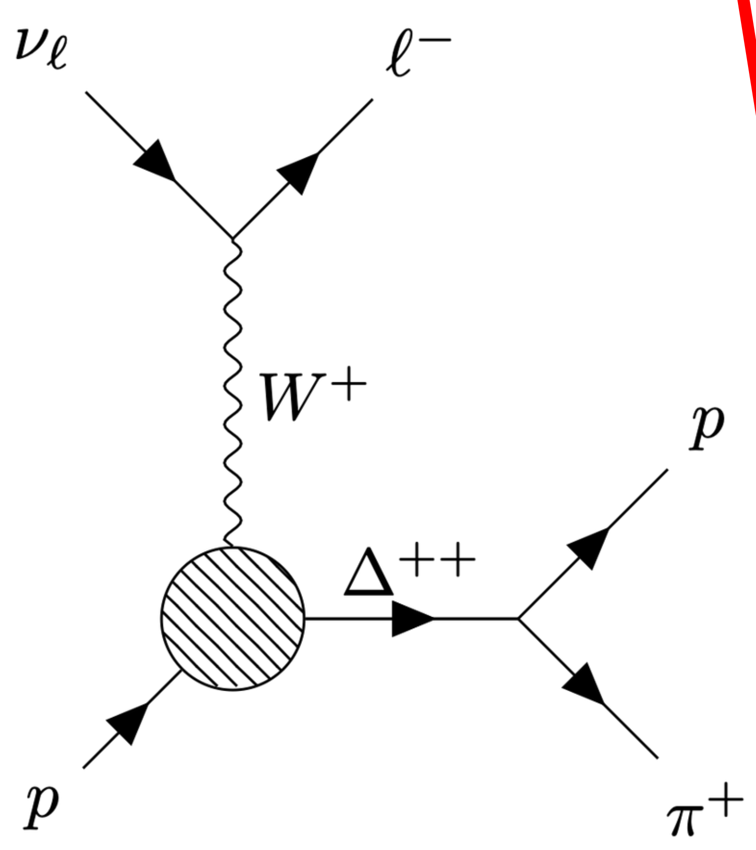
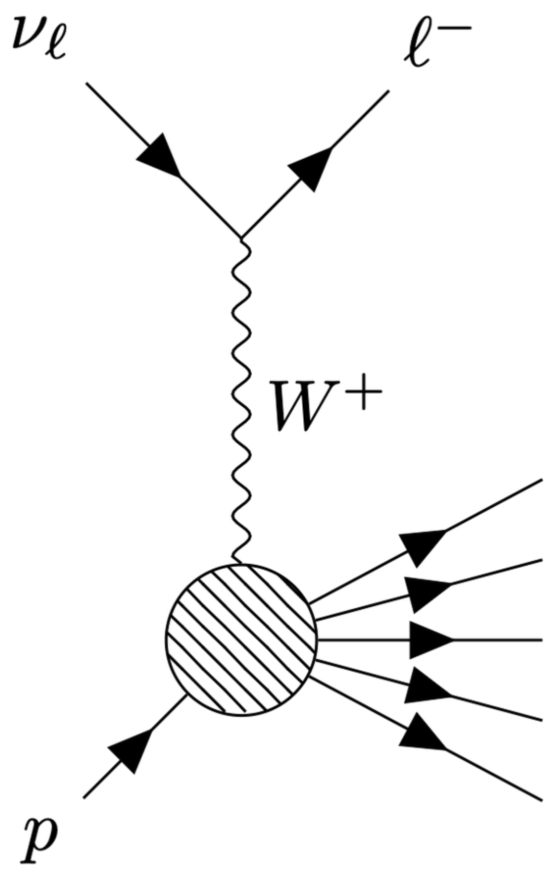
Resonant



Deep inelastic scattering



Complicated hadronic products

Charged current interactions

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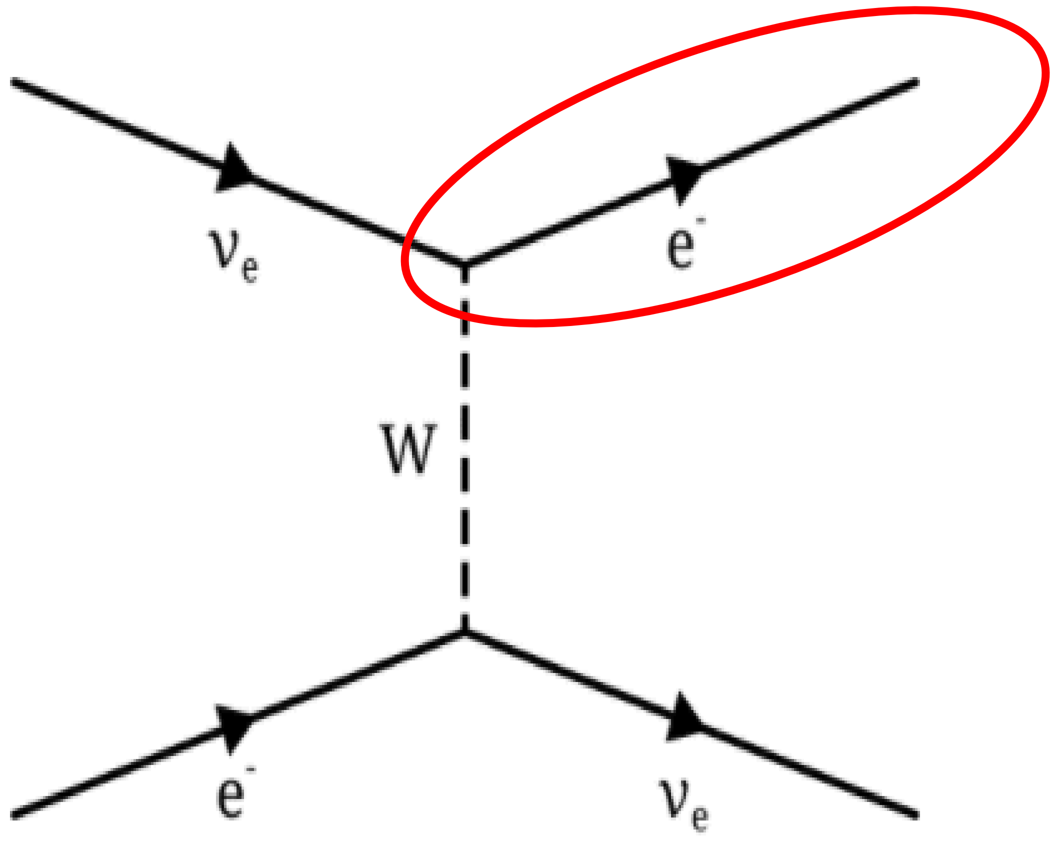
Complicated hadronic products

Low energy:

Elastic scattering



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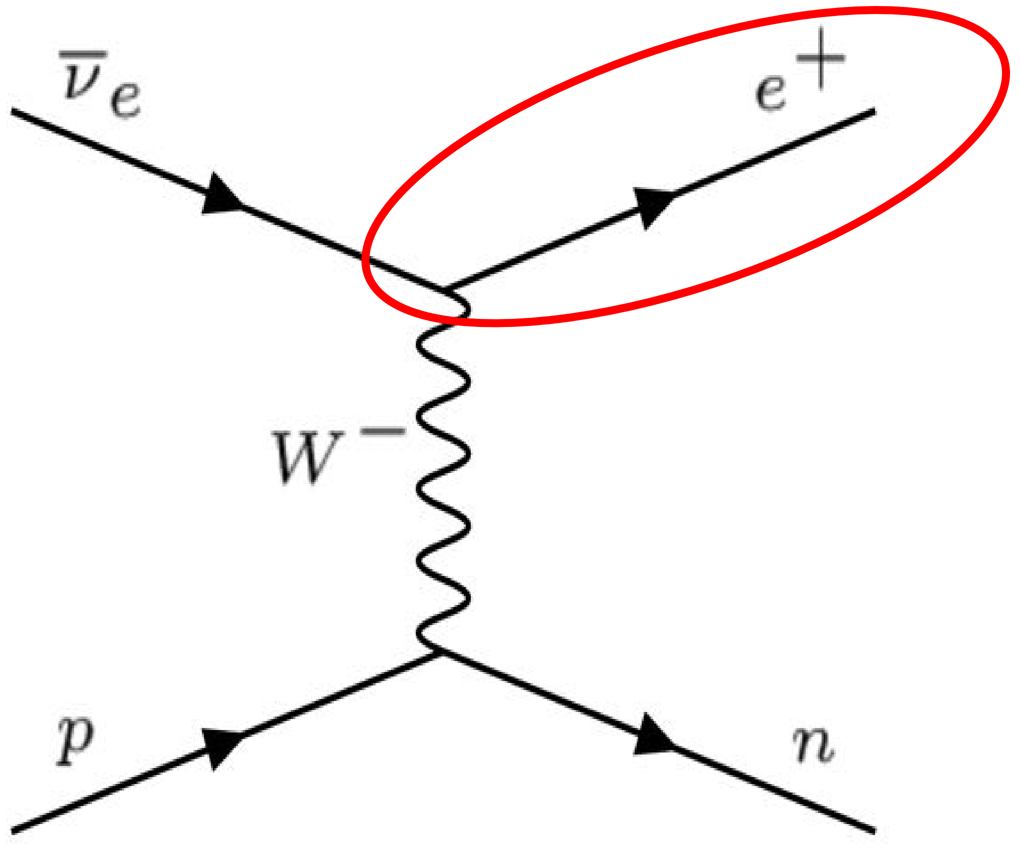

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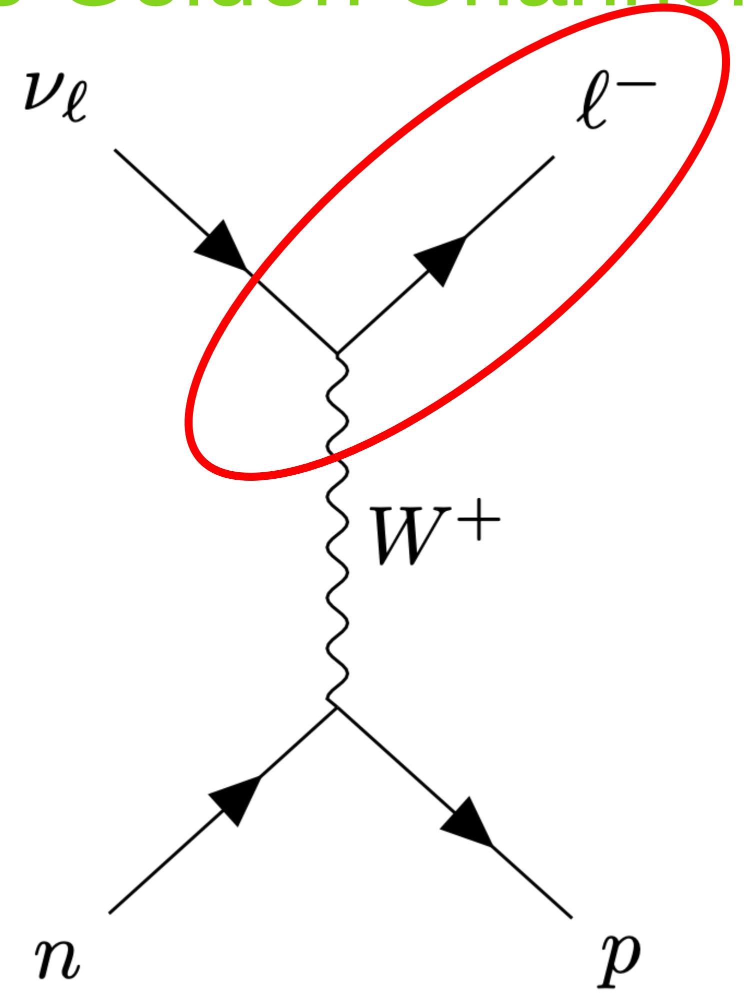
High energy (accelerators):

Quasi-elastic

The Golden Channel



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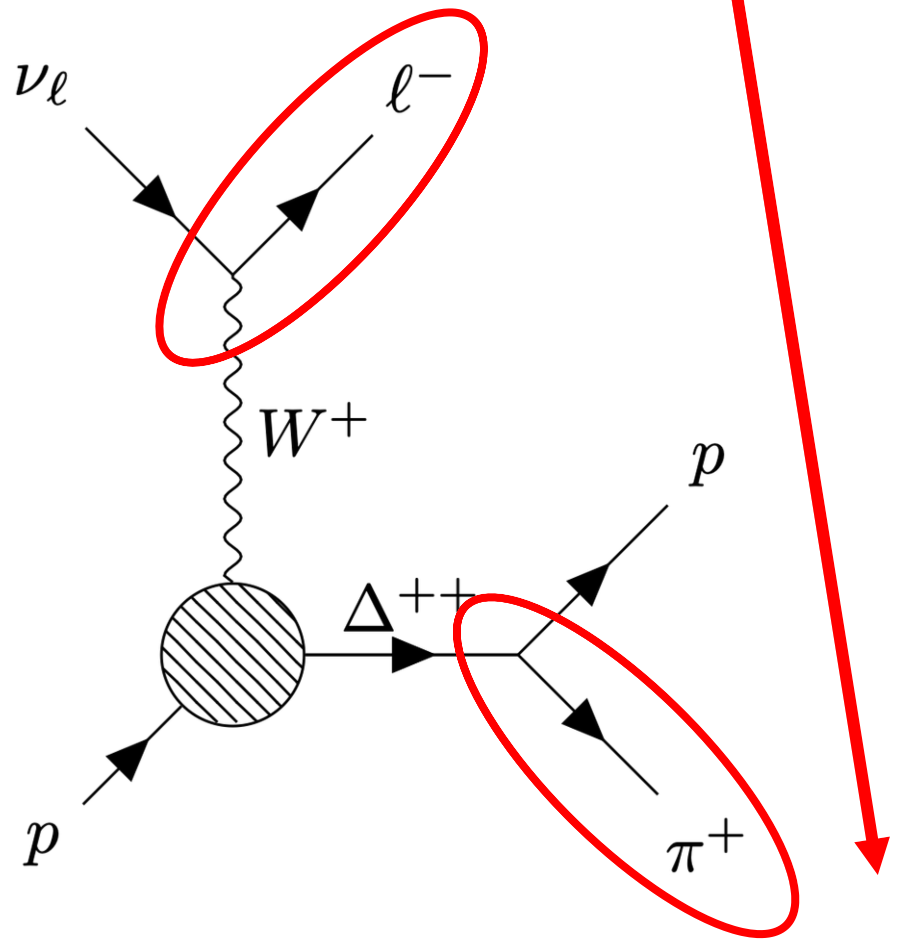

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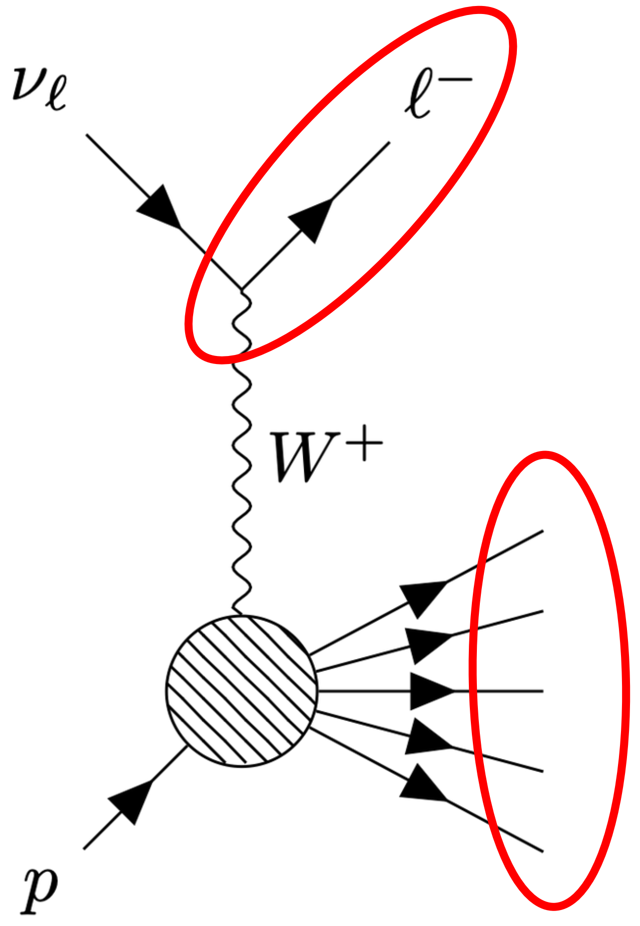
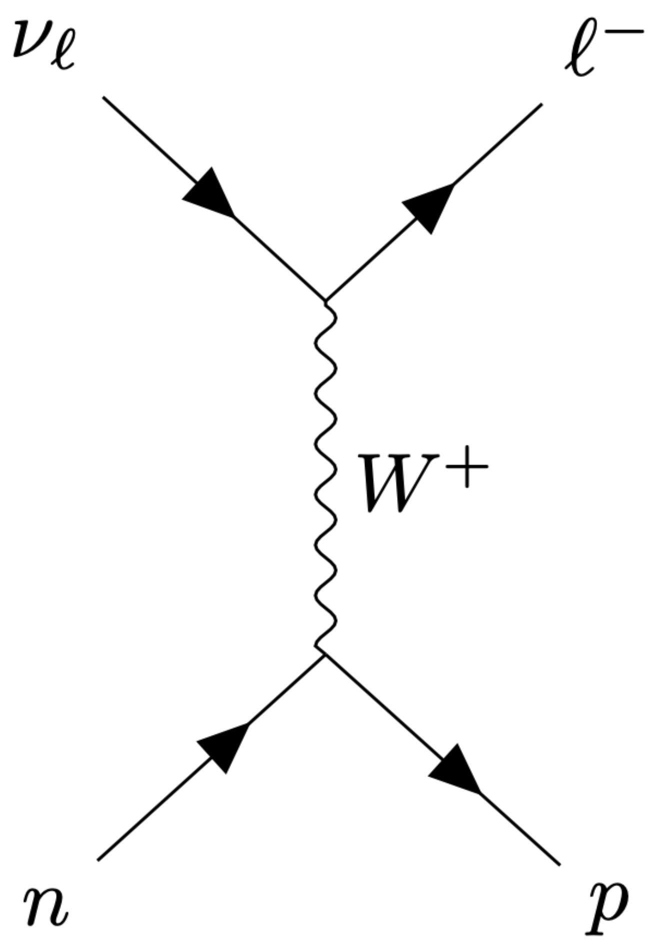
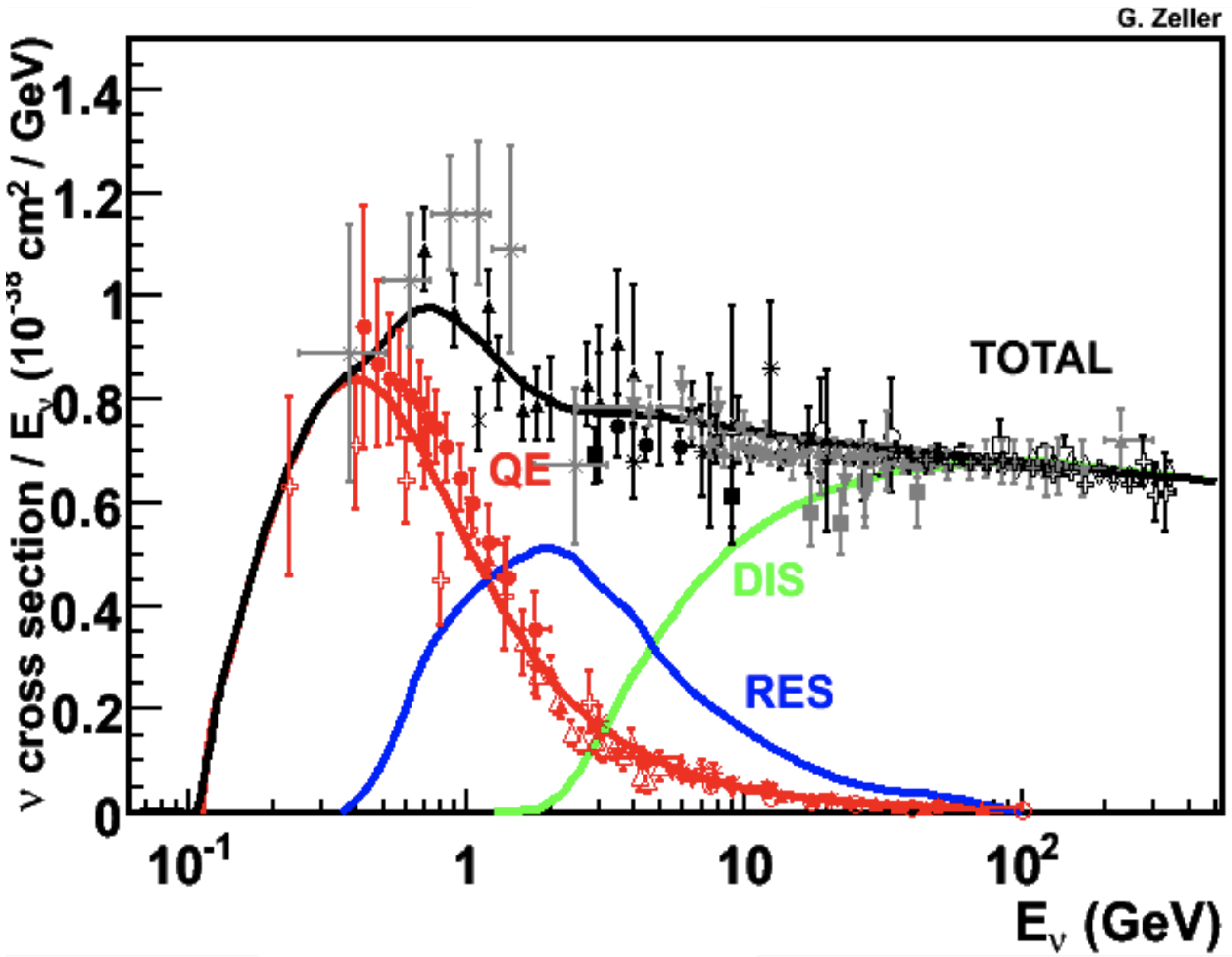


Charged currents interactions

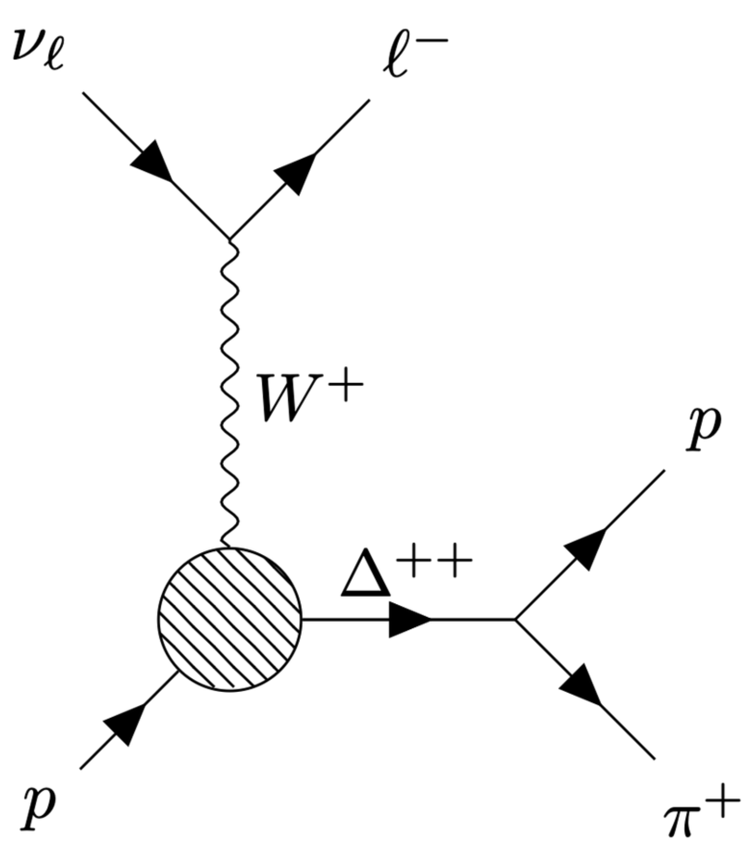
At accelerators, neutrino cross sections increase with energy but the final states are more complex

Quasi-elastic (QE)

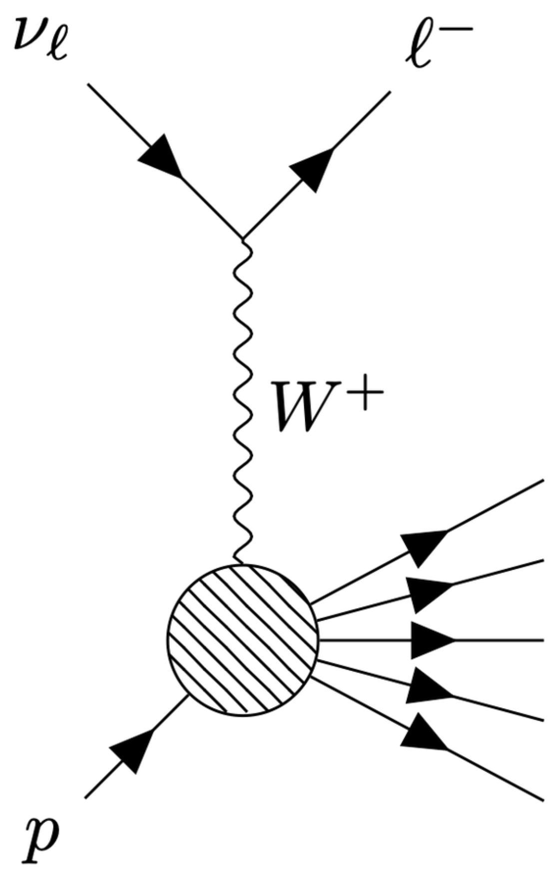




Resonant



DIS



Neutrino detection techniques

○ We must distinguish and reconstruct the products of the interactions: leptons (e, μ, τ), hadrons (p, n, $\pi^{\pm}$) and correlated gammas (π^0)

Neutrino detection techniques

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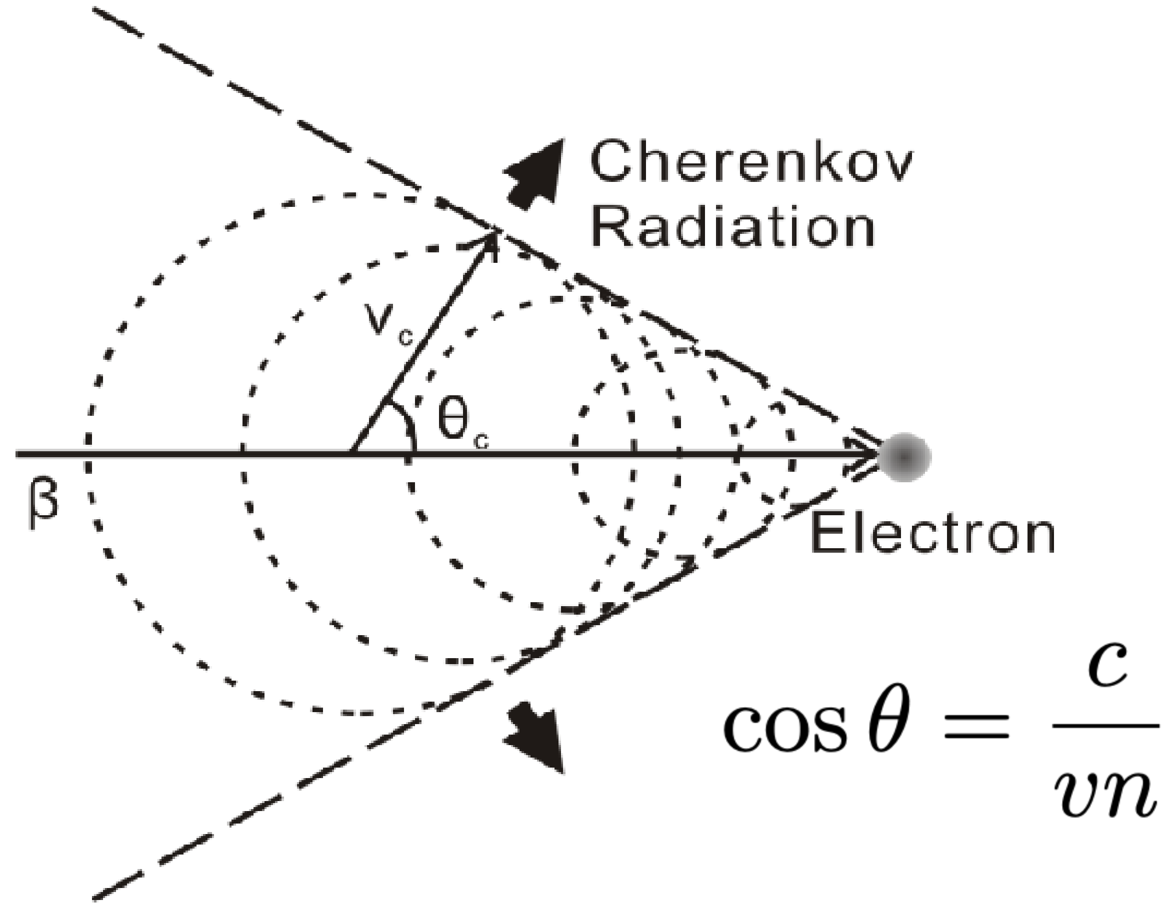
- Using the ionisation potential

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- Using the Cherenkov effect



$$\cos\theta = \frac{c}{vn}$$

Figure 1: Schematic of Cherenkov radiation

Neutrino detection techniques

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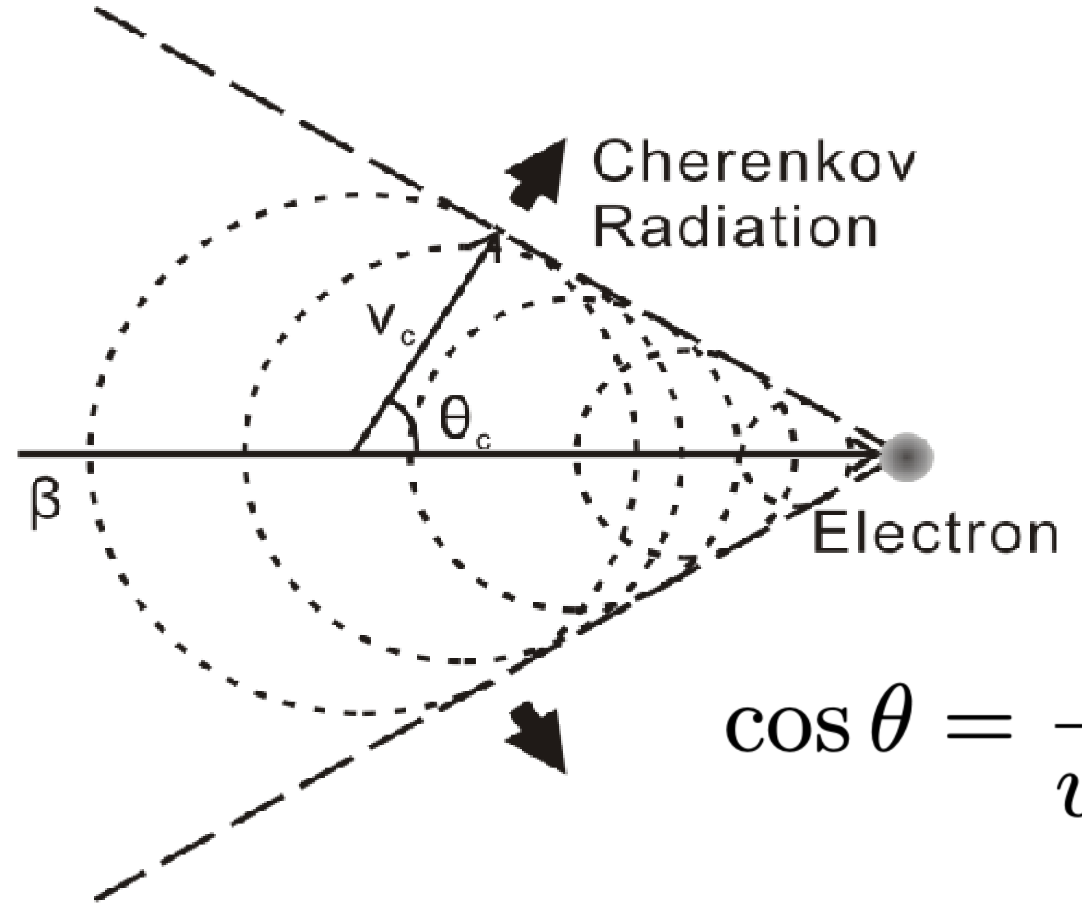


$$\cos\theta = \frac{c}{vn}$$

Figure 1: Schematic of Cherenkov radiation

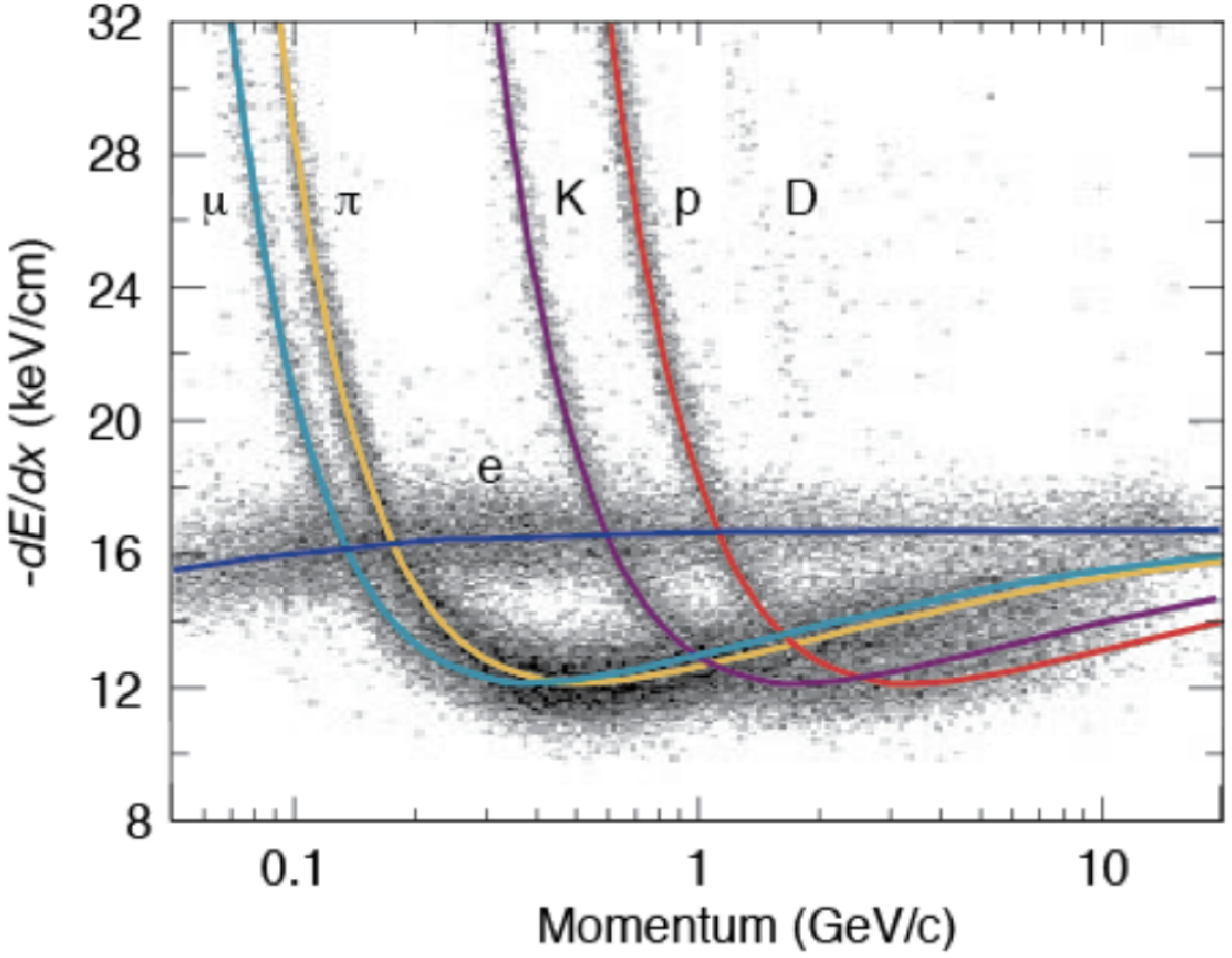
Determine the particle type and momentum of the products to recover the neutrino flavour and energy

Using the Ionization potential

Principle : When a charged particle crosses a medium, it loses energy through ionization.
The mean amount of energy lost per cm through ionization is parametrized by the Bethe Bloch formula and depends on the particle energy (βγ)

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

PEP-4 detector, gas mixture 80:20 of Ar:CH_4



If this energy loss can be resolved, one can have a 2D (or even 3D) image of the interaction.

We can identify the particle type through track topology analysis

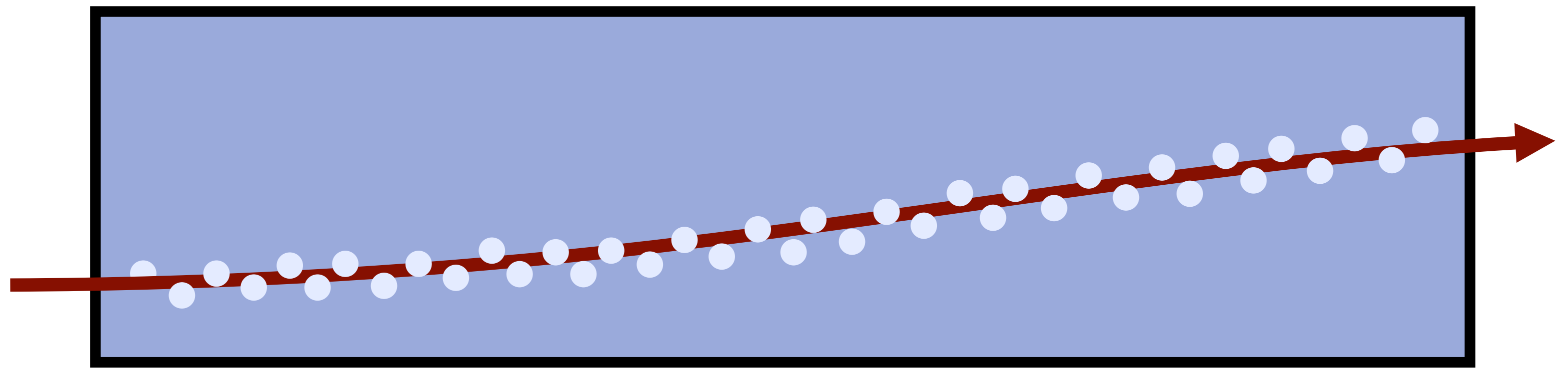
Moreover, if this energy can be collected, one can reconstruct the energy of the daughters, and hence fully reconstruct the interacting neutrino kinematics.

Using the Ionization potential

BEBC at CERN

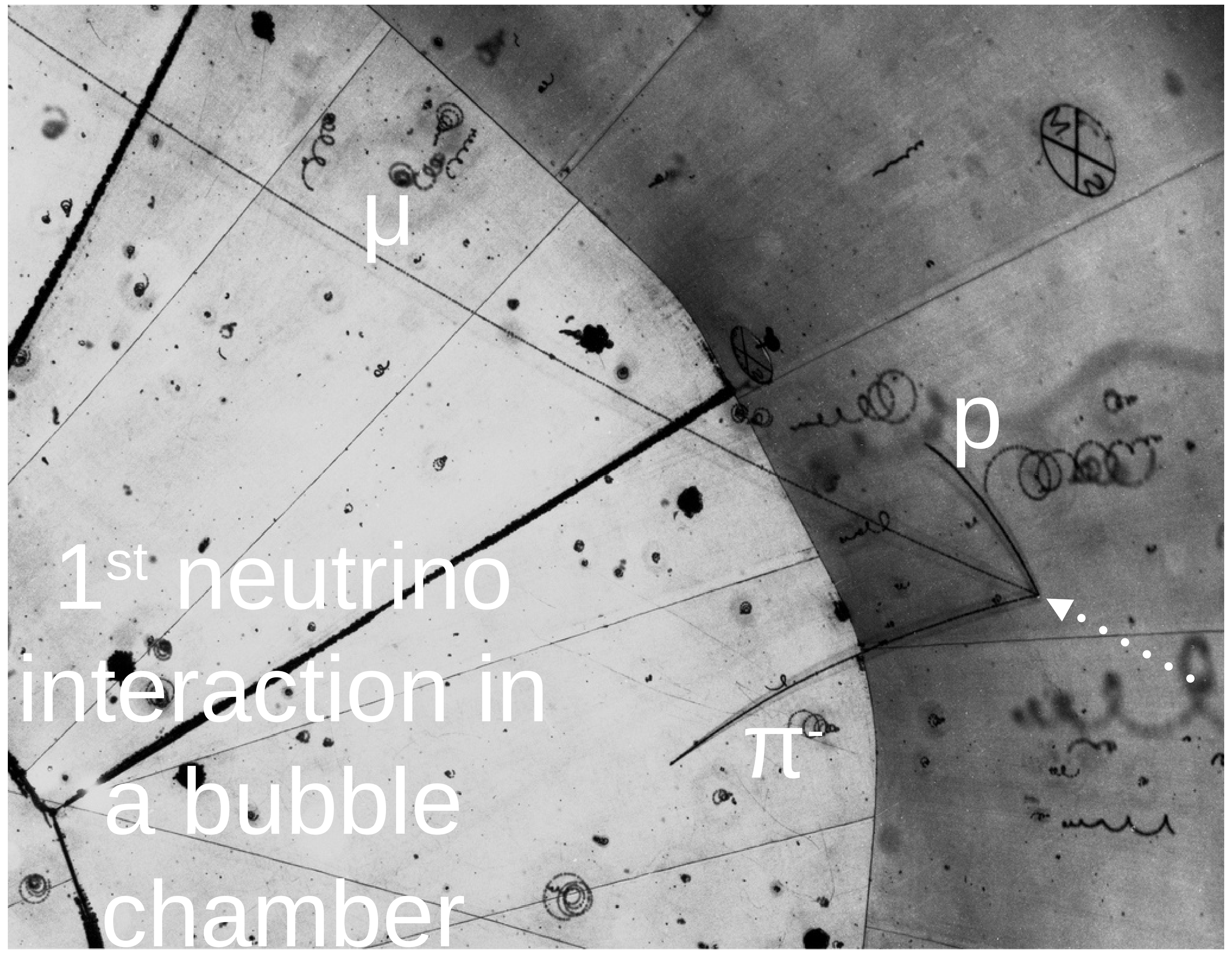
Bubble Chambers

Superheated fluid turns locally to gas (bubbles) when energy is deposited by a charged tracks :

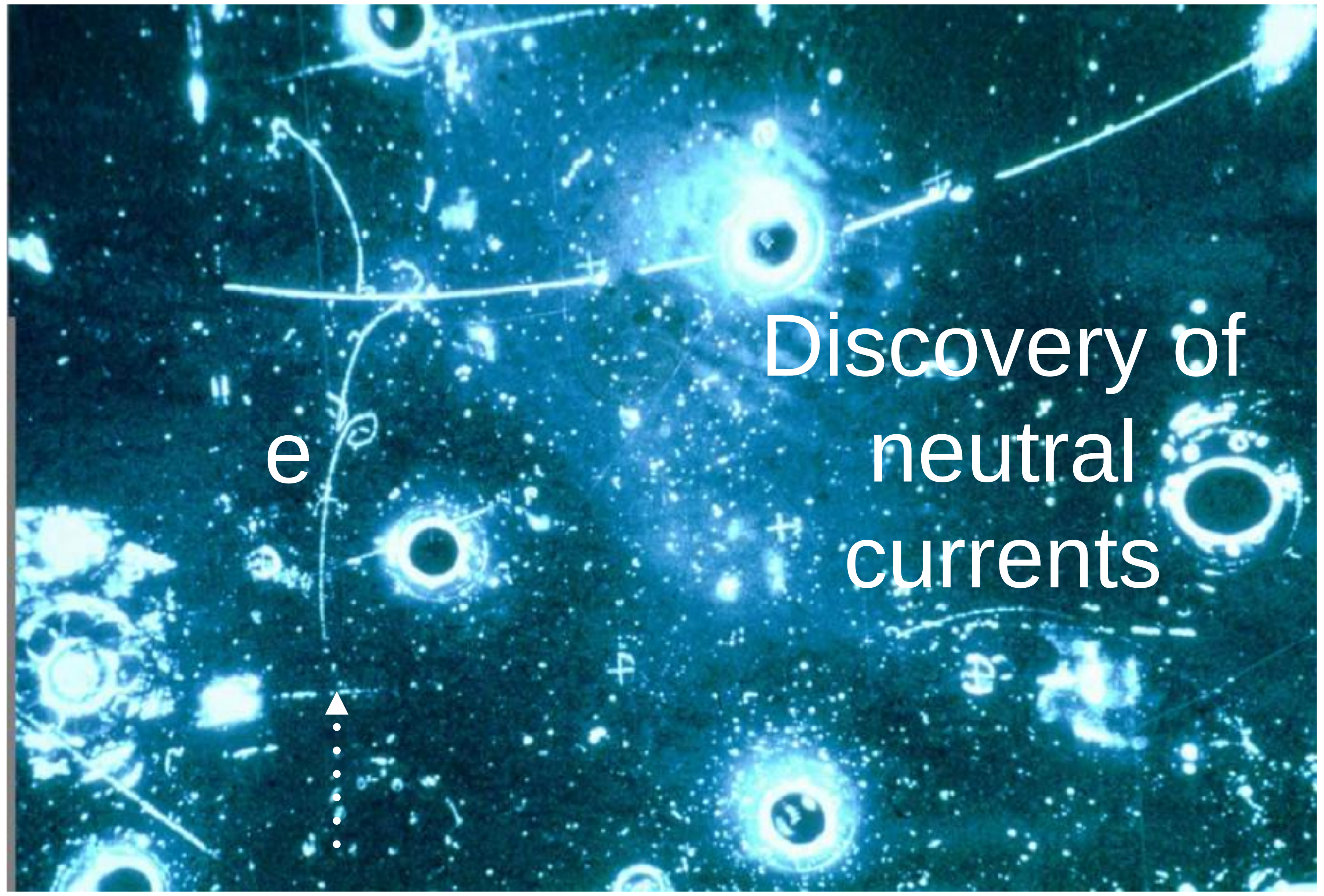


First bubble chambers where equipped with cameras, the pictures were scanned manually by the scanning ladies.

Scanning ladies

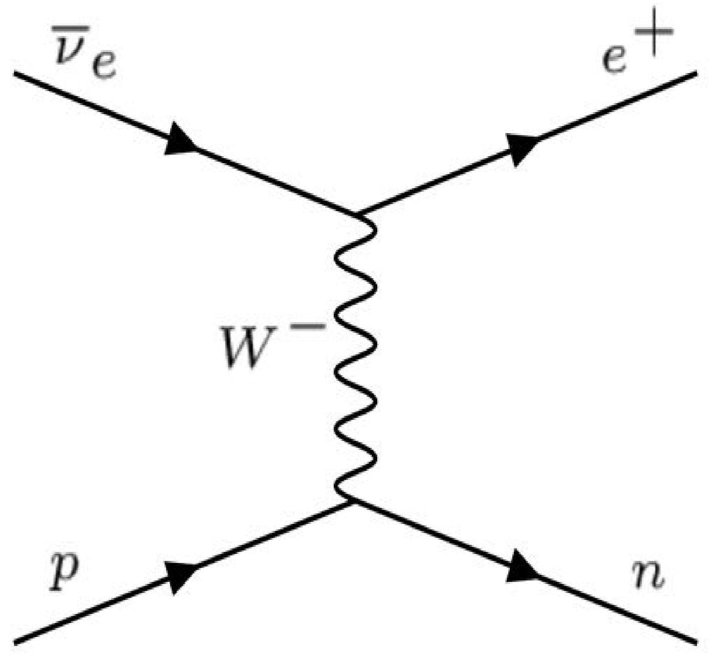


1st neutrino interaction in a bubble chamber



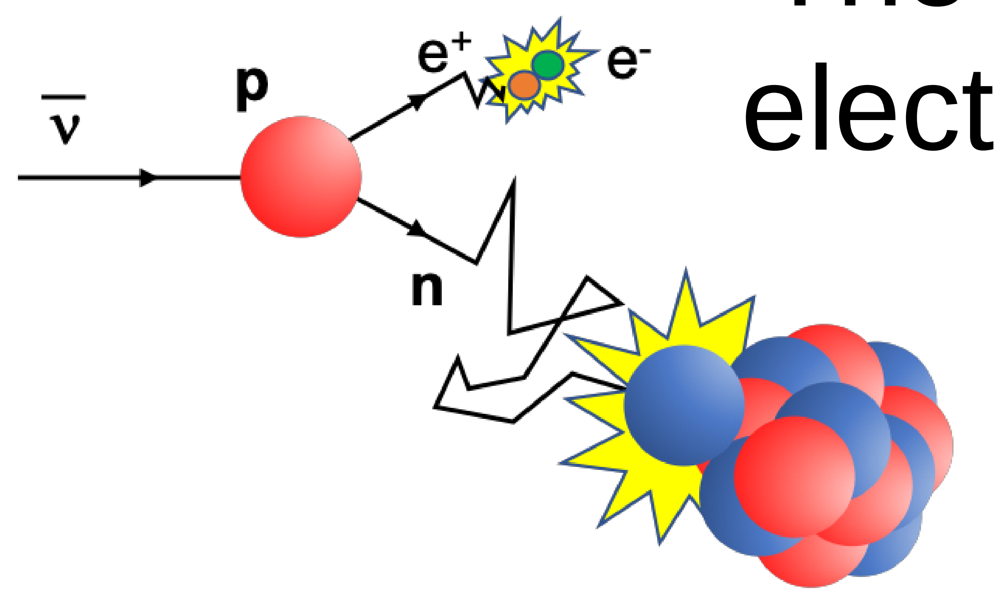
Discovery of neutral currents

Using the Ionization potential



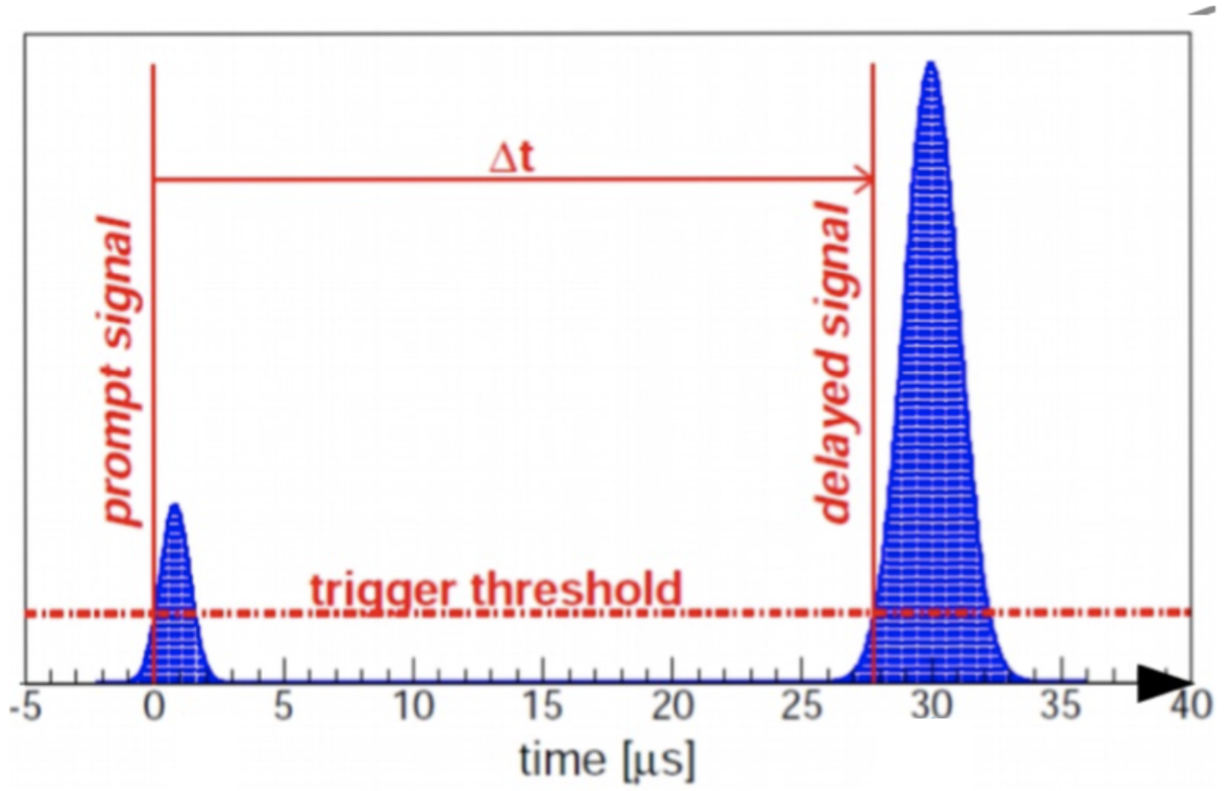
Liquid Scintillators

Organic liquid that scintillates when energy is deposited.
In neutrino physics, often used to tag (low energy) inverse β-decay interactions



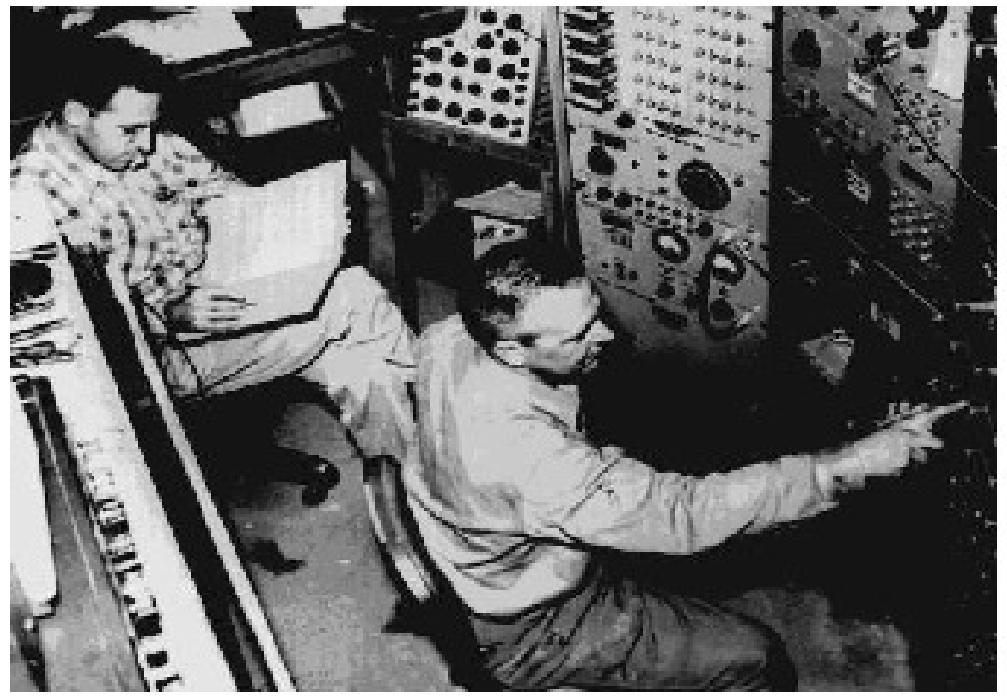
- The positron is quickly captured by an electron

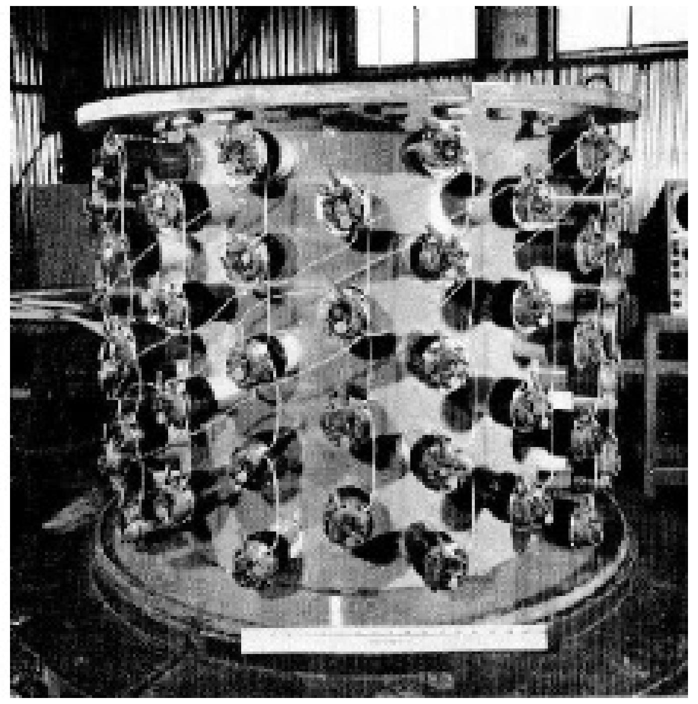
The neutron is captured later by a catcher-atom

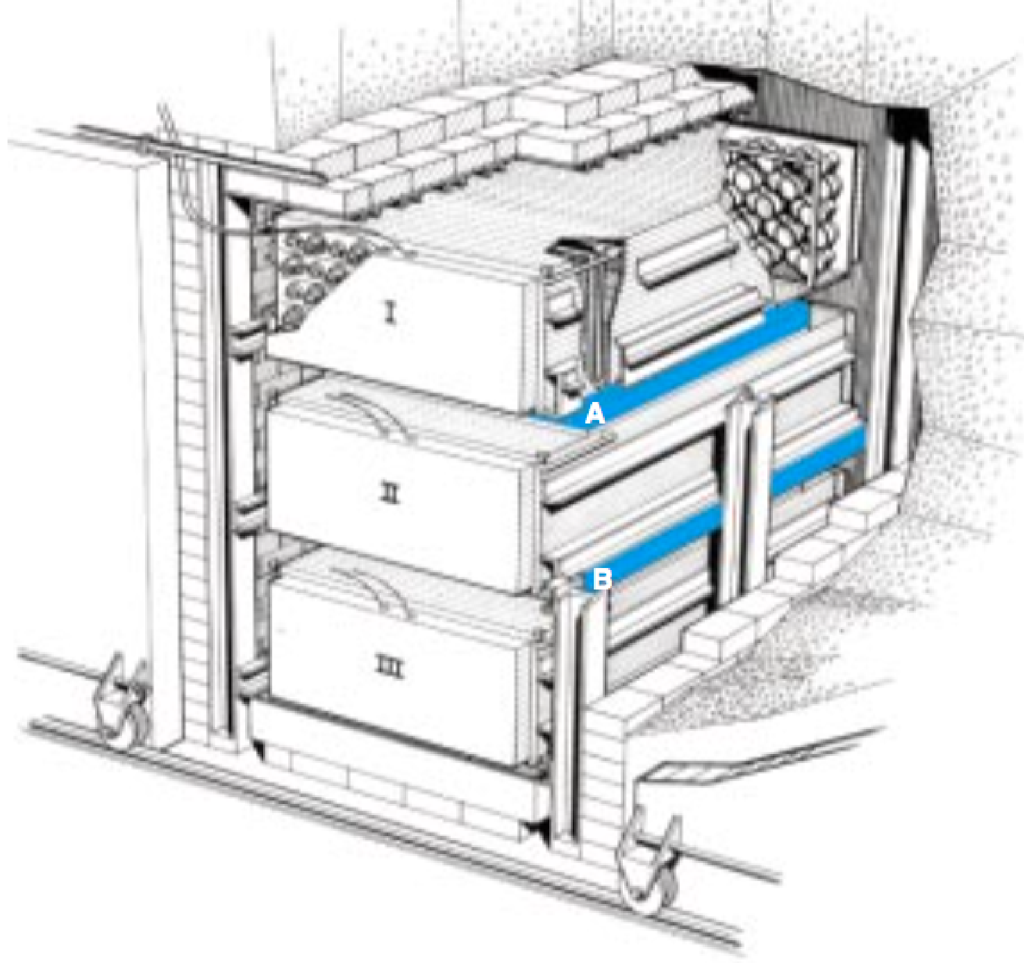


Savannah river experiment by Reines & Cowan in 1956

$\overline{\nu}e$ discovery !



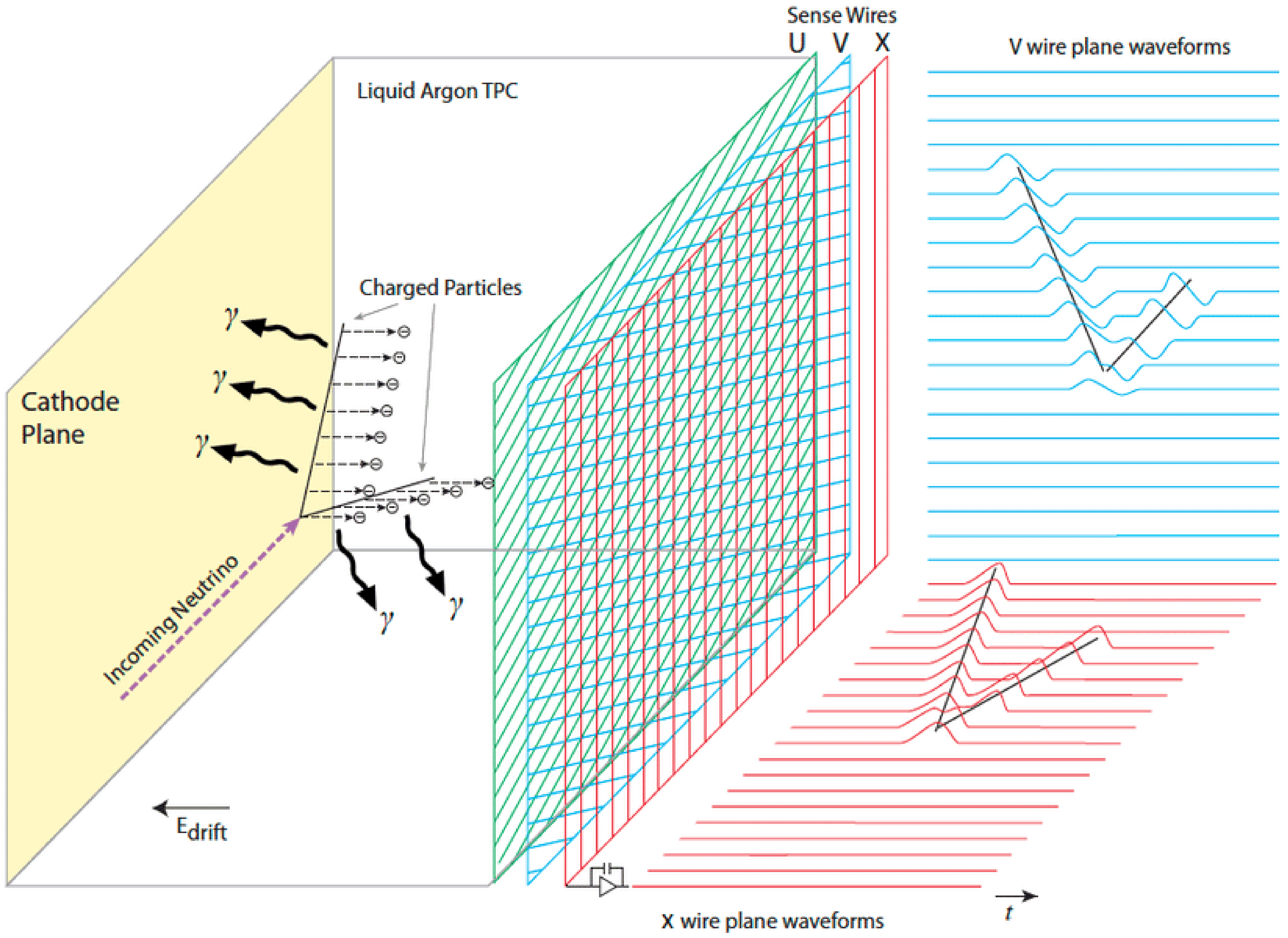




Using the Ionization potential

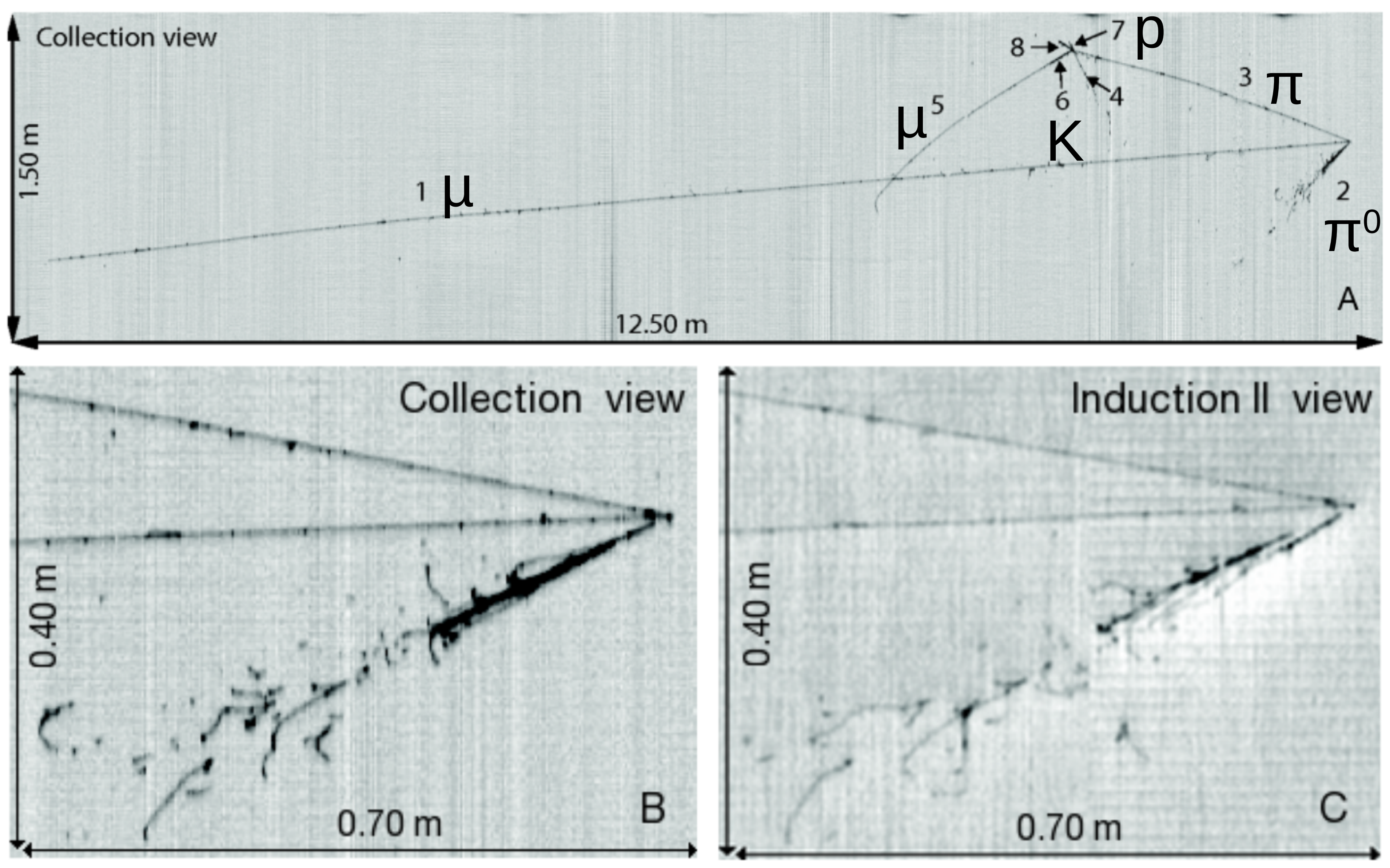
Time Projection Chamber [TPC]

Uses a chamber filled with gas or liquid with an electric field applied across.
Free electrons from ionization drift towards the anode plane where they are collected : that gives a 2D image. The e^- arrival time provides the 3rd coordinates. The amount of e^- collected/cm is a handle to retrieve the particle identity/energy.

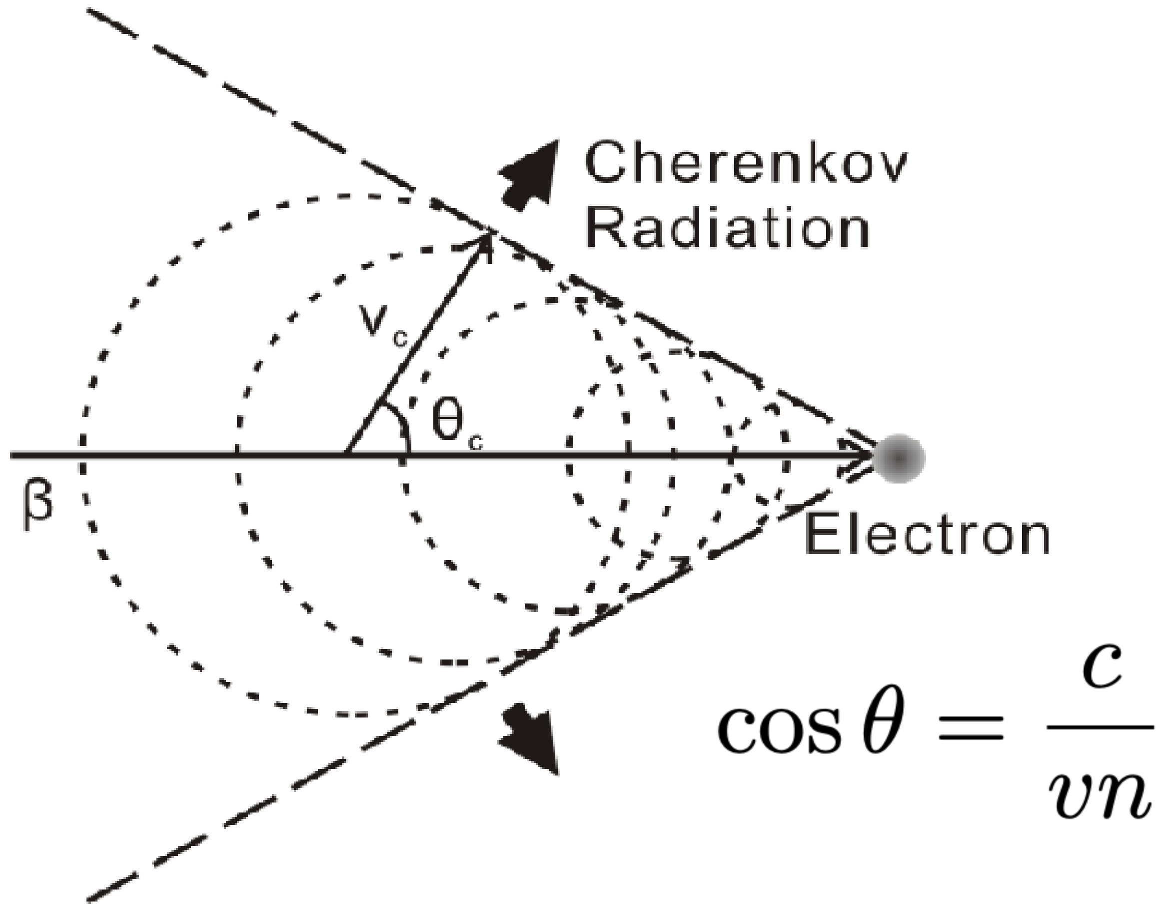


ICARUS experiment

- ν_μ interaction -



Using the Cherenkov effect



$$\cos\theta = \frac{c}{vn}$$

Figure 1: Schematic of Cherenkov radiation

Principle : When a charged particle travels at a speed *v* higher than the speed of light in a medium *c/n* its own EM field stacks and produces a cone of light :

Cherenkov detectors are widely used in neutrino physics :

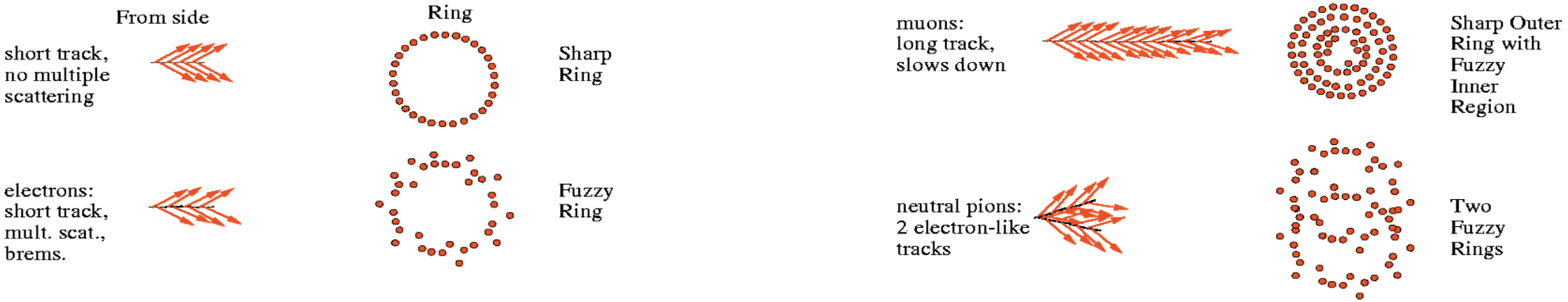
-> Can use cheap/free medium (ultra pure water, ice, sea)

-> Use photomultipliers to detect the light, very well known device

-> Can have large volume : bigger volume = more chances to catch a neutrino

-> Ring shape allows particle identification ; ring characteristics (diameter, nb of photons) is linked to the particle energy => Excellent e/µ separation

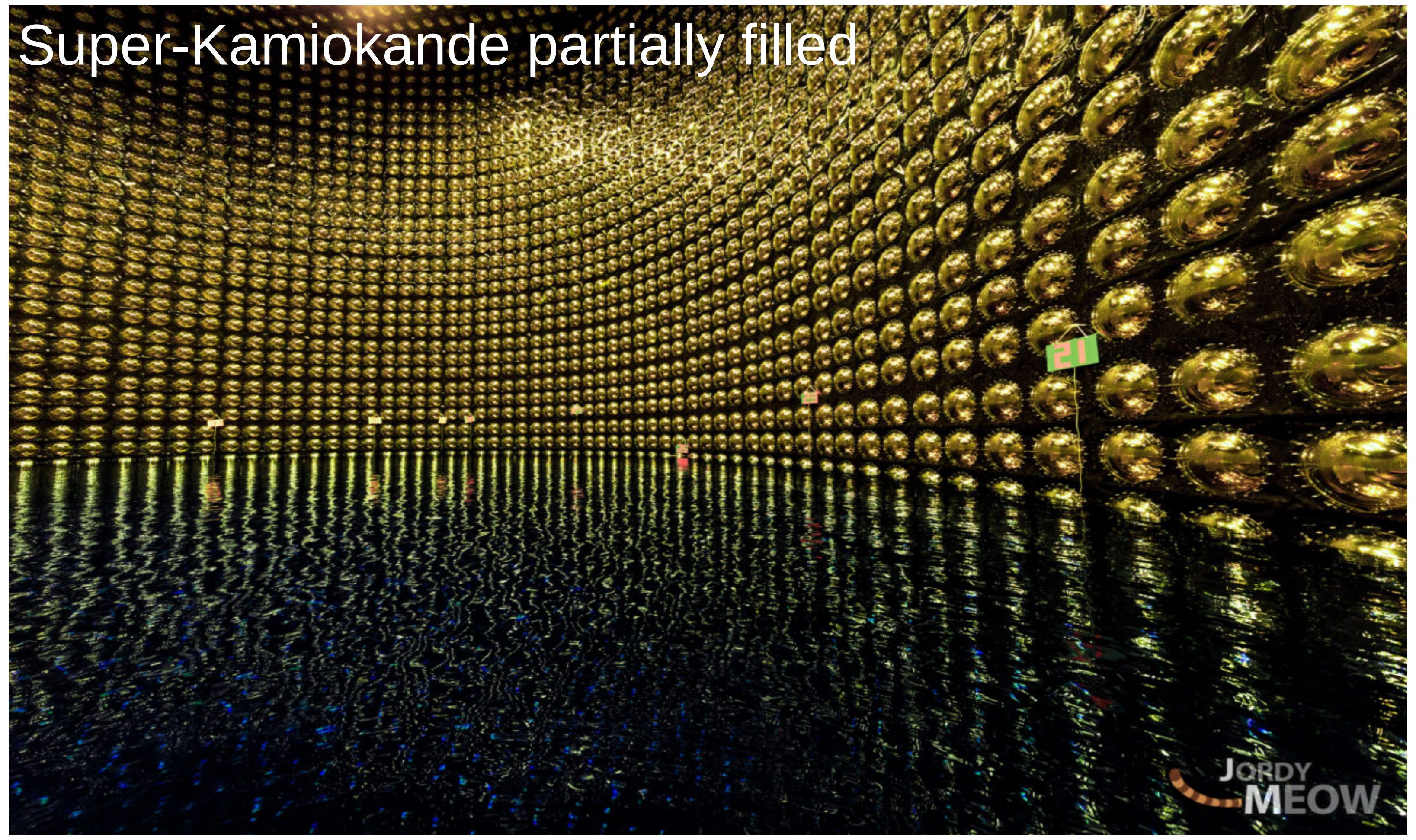
Particle identification using ring shape :

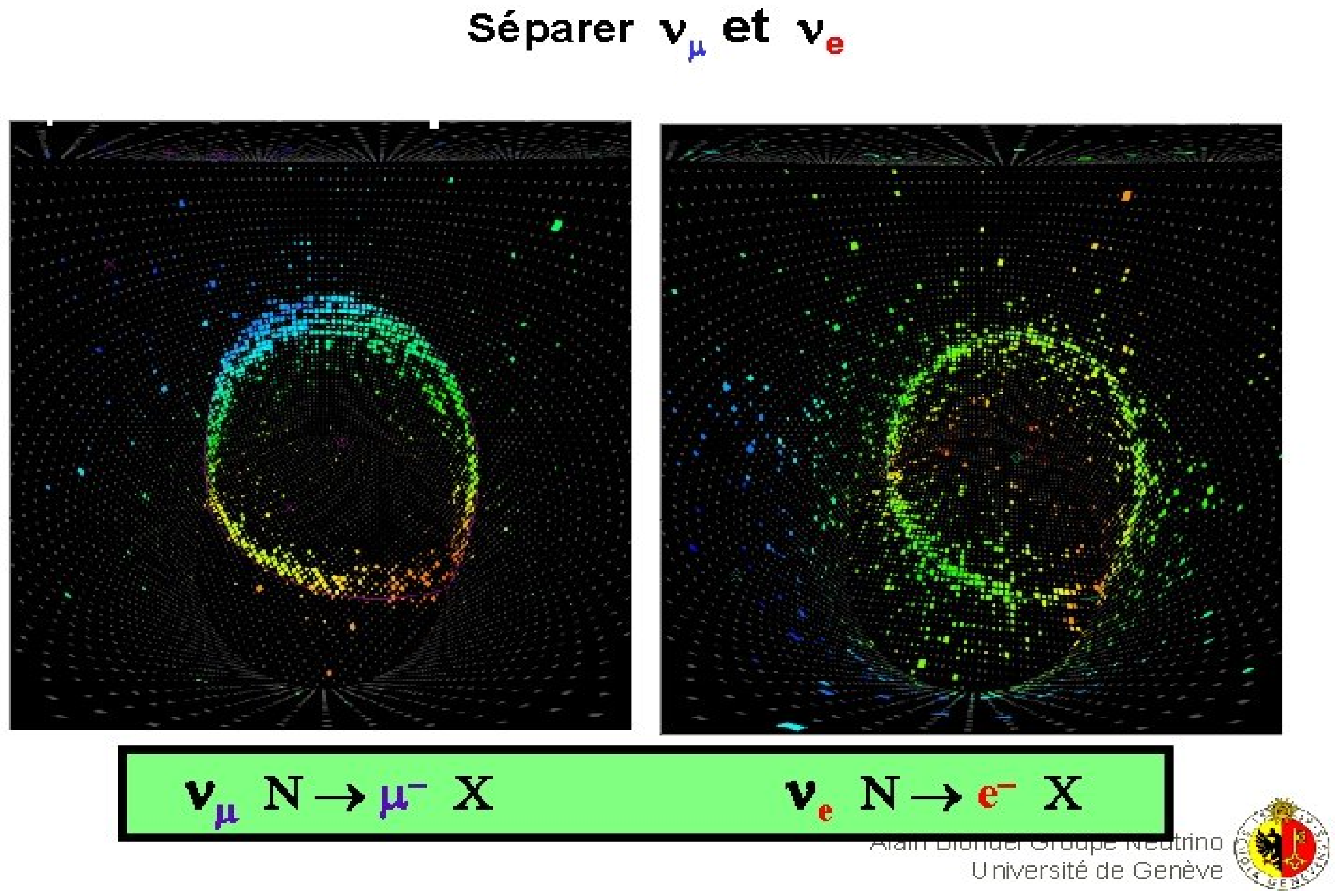


Using the Cherenkov effect

Super-Kamiokande in Japan

Tank of 50 kt of ultra pure water underneath a mountain, equipped with ~11k PMTs


Super-Kamiokande partially filled

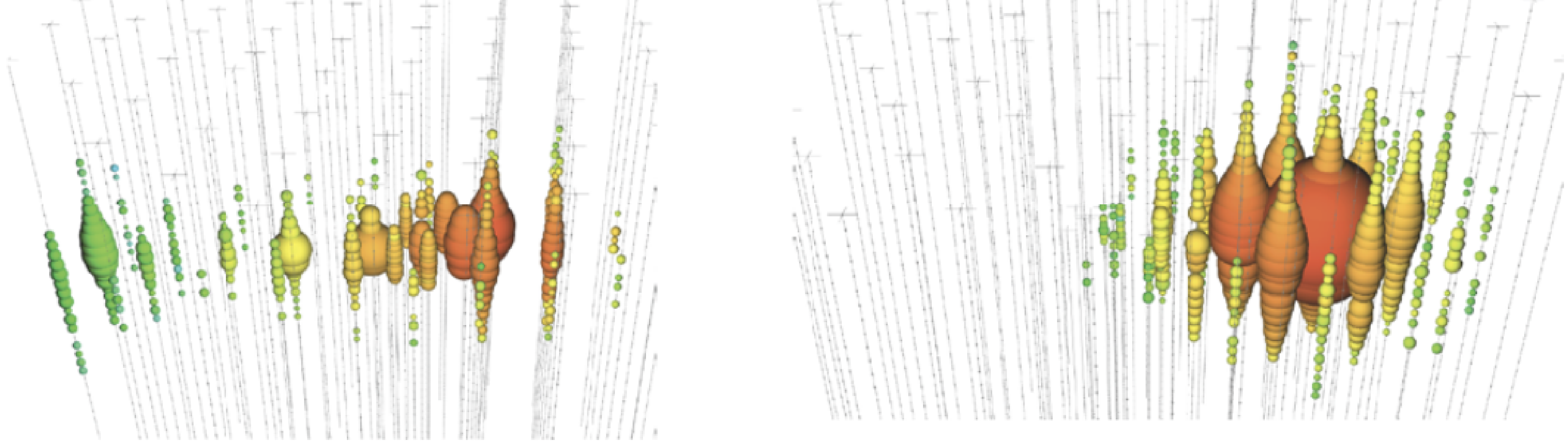


Color = # of photons collected

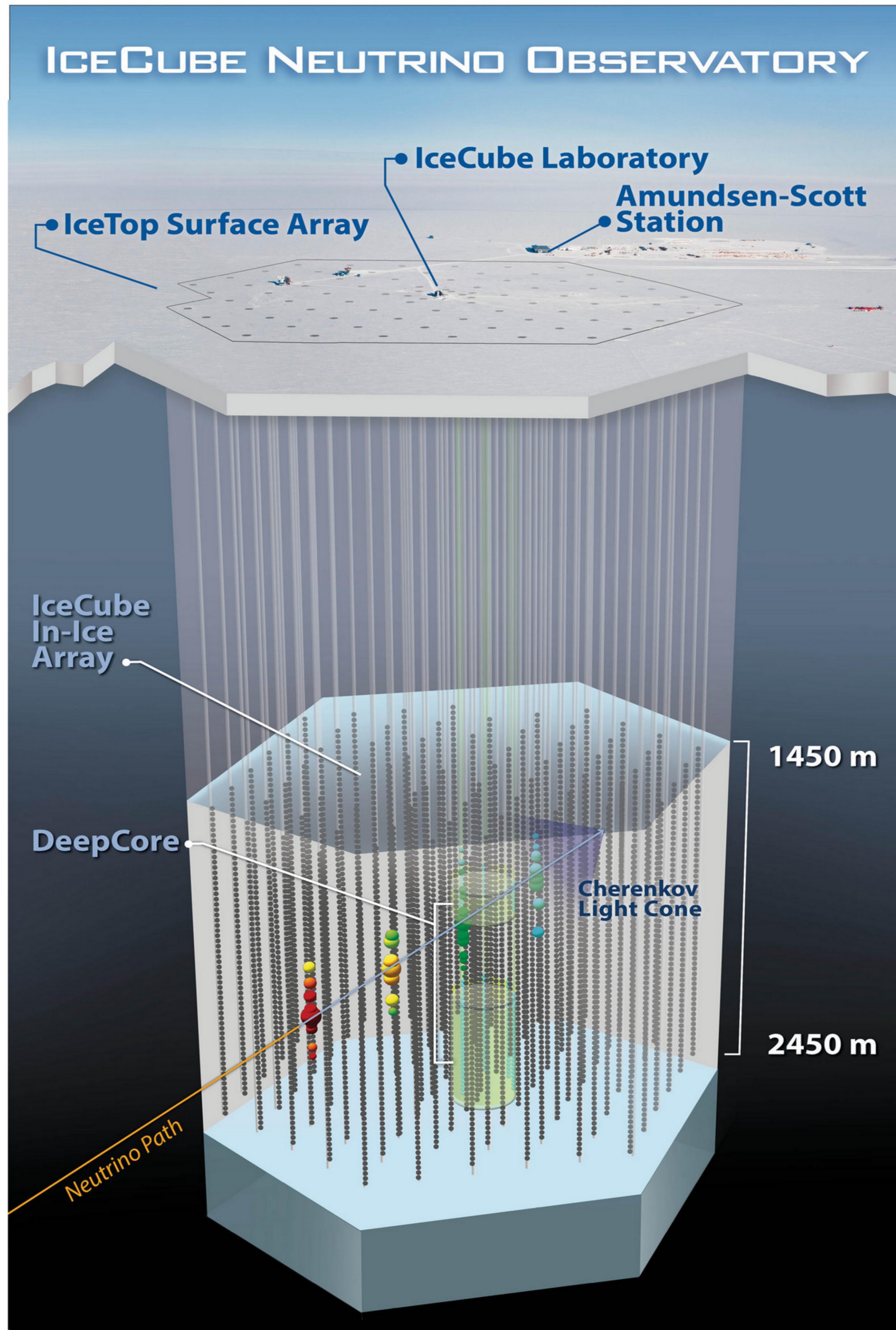
ICECUBE in Antartica

Giant detector in ice, equipped with 5k PTMs along 86 strings up to 2.4 km below the surface

ν_μ + N -> μ^- + N’ ν_e + N -> e^- + N’



Color = time
size = # of photons collected



Short break

NEUTRINO OSCILLATIONS

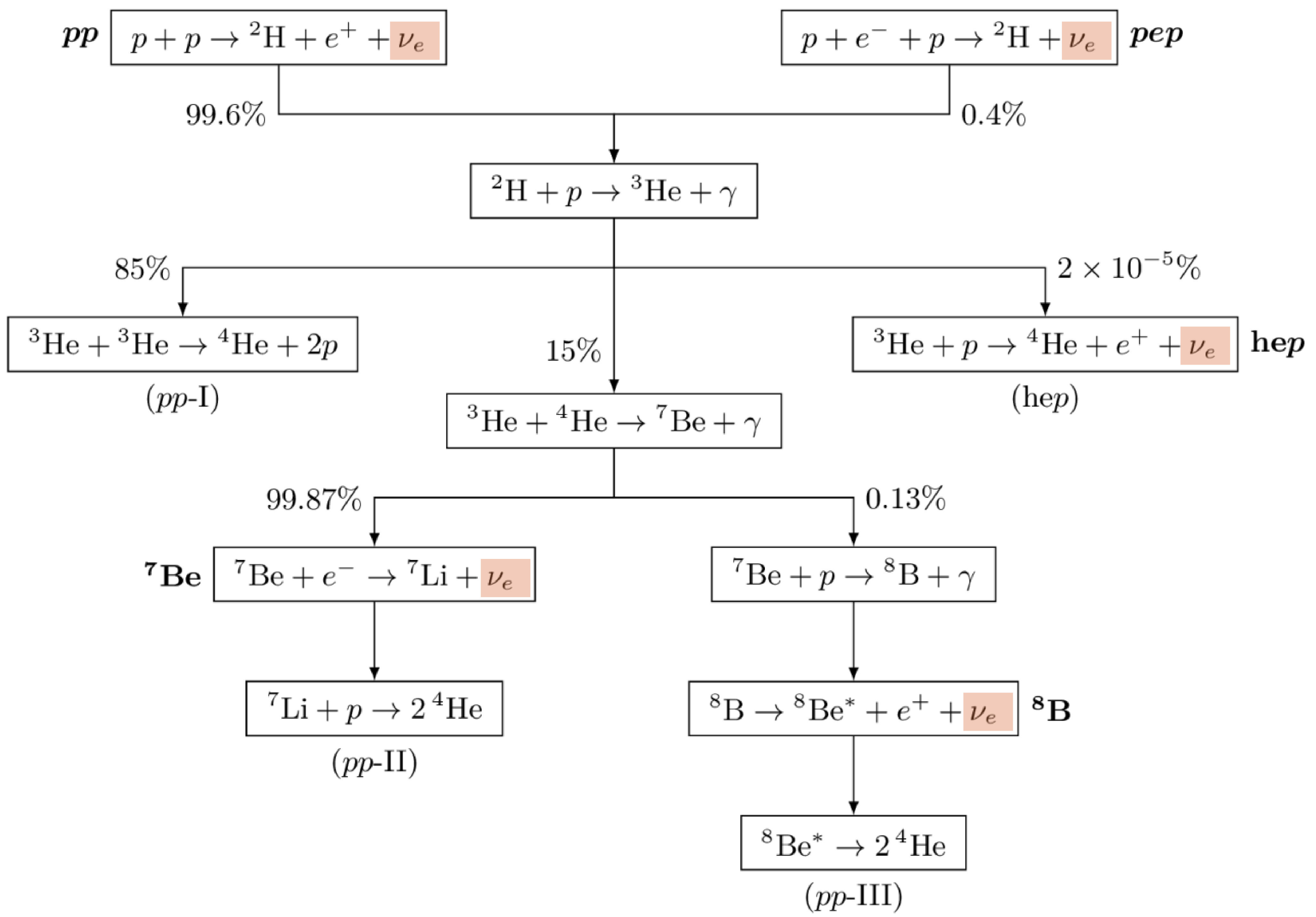
- The solar neutrino problem
- The atmospheric neutrino problem
- Neutrino masses
- 3 flavour neutrino oscillations

Solar neutrino flux

Most of 20th century research focused on nuclear reactions: radioactivity, fission and fusion.

This led to a near complete understanding of stellar nucleosynthesis.

Proton-proton fusion chain in sun-like stars



pp $p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e$

$p + e^{-} + p \rightarrow {}^{2}\mathrm{H} + \nu_e$ **pep**

99.6%

0.4%

${}^{2}\mathrm{H} + p \rightarrow {}^{3}\mathrm{He} + \gamma$

85%

$2 \times 10^{-5}\%$

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p$

(*pp*-I)

15%

${}^{3}\mathrm{He} + p \rightarrow {}^{4}\mathrm{He} + e^{+} + \nu_e$ **hep**

(hep)

${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

99.87%

0.13%

^{7}Be ${}^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_e$

${}^{7}\mathrm{Be} + p \rightarrow {}^{8}\mathrm{B} + \gamma$

${}^{7}\mathrm{Li} + p \rightarrow 2\,{}^{4}\mathrm{He}$

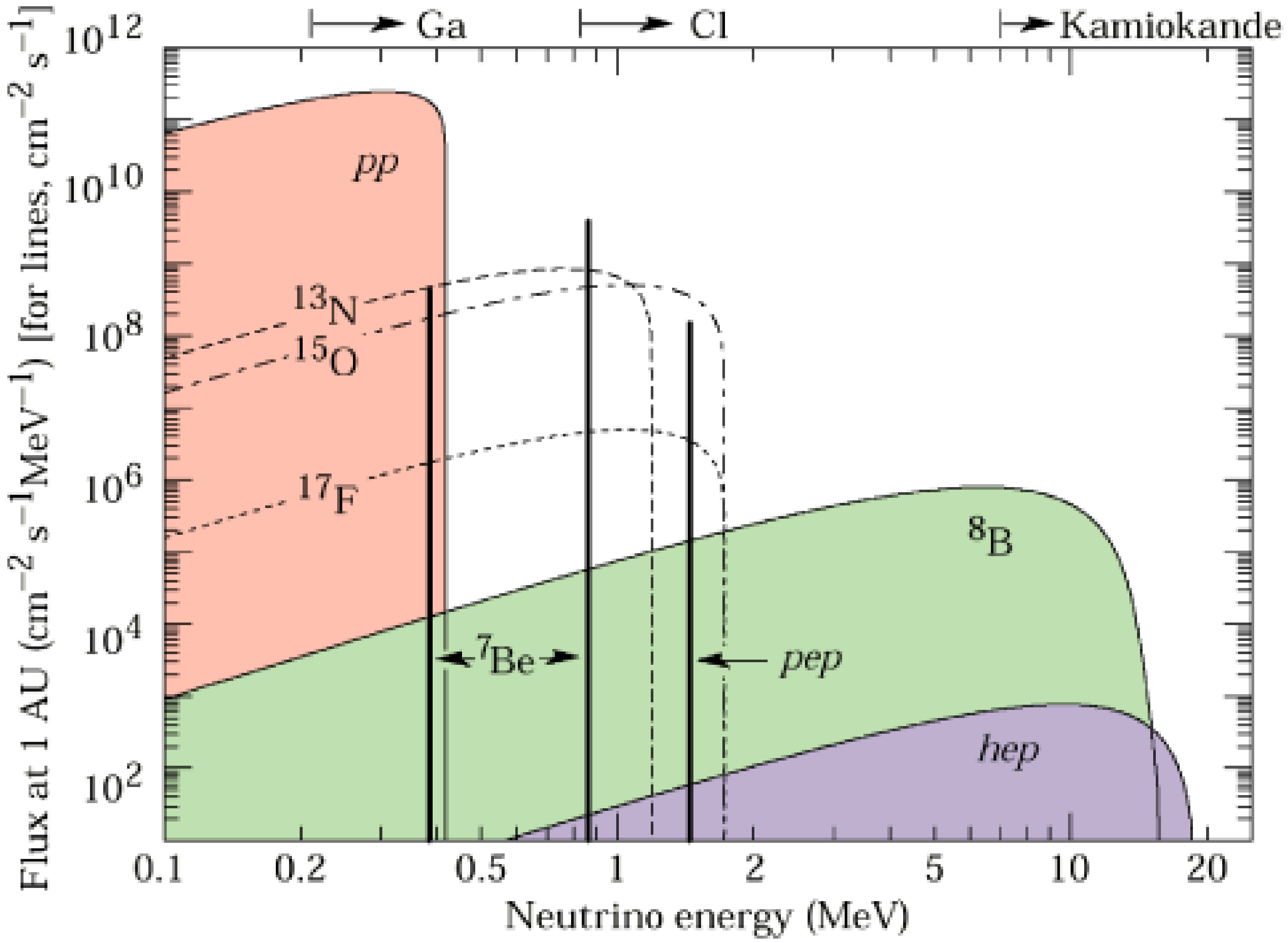
(*pp*-II)

${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e$ **^{8}B**

${}^{8}\mathrm{Be}^{*} \rightarrow 2\,{}^{4}\mathrm{He}$

(*pp*-III)

Bahcall made a prediction on the ν_e flux from the sun [1964]



Prediction:

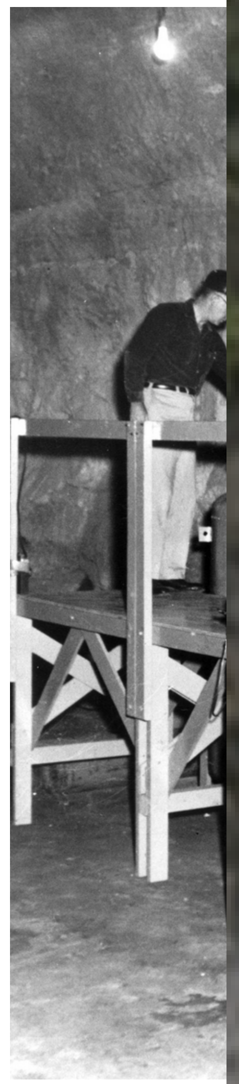
$$\phi^{\mathrm{sun}}_{\nu_e} = 6.4 \times 10^{10}\ \nu_e/s/\mathrm{cm}^2$$

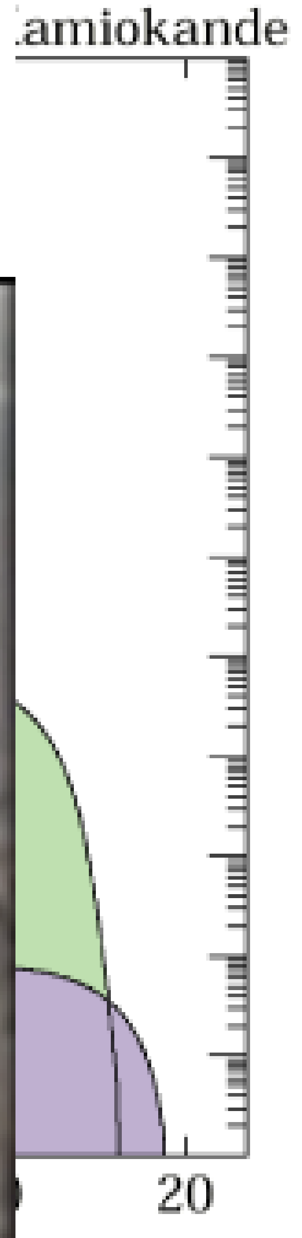
Due to their small cross-sections, neutrinos can escape the sun plasma unaffected. => They are an excellent probe of fusion processes inside the sun.

Solar neutrino deficit

Home
Obse

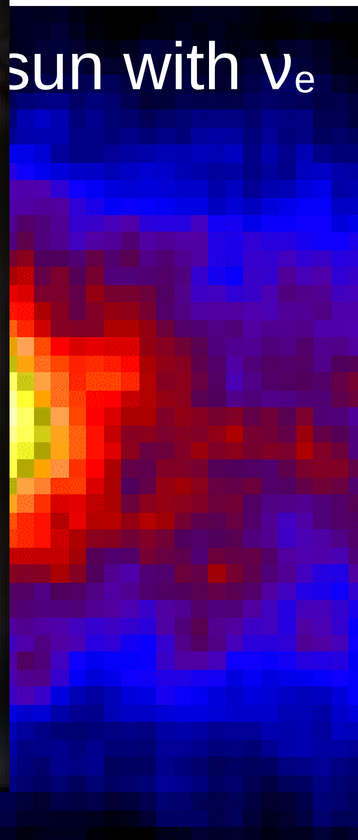
Measuring solar neutrino flux in 1960s





n/s/atom

The
Ge c



Solar neutrino deficit

Possible solutions:

○ Poor understanding of fusion chains

Powerful predictive power of stellar nucleosynthesis theory indicates otherwise

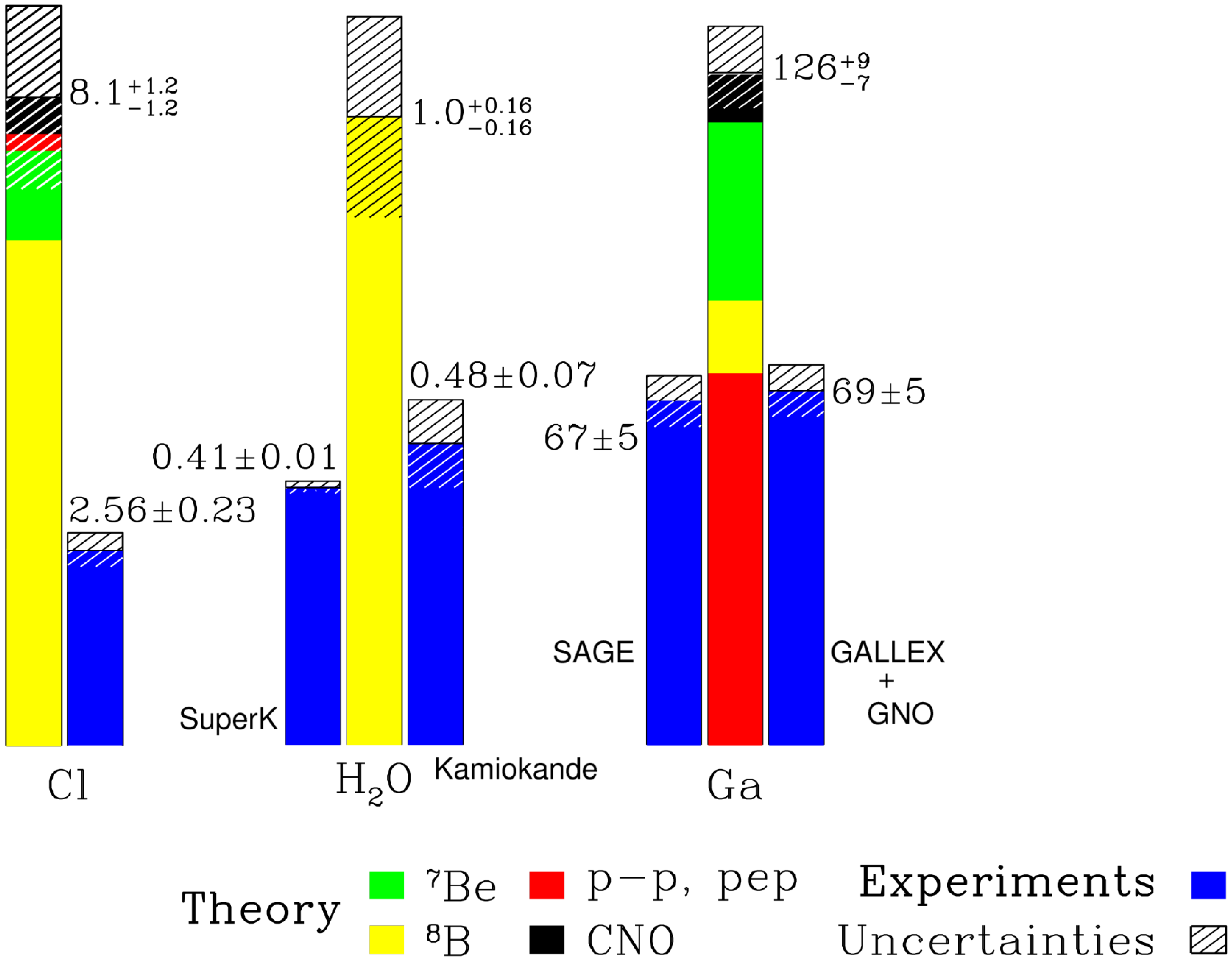
○ Overestimated neutrino cross-sections

Low-energy neutrino interactions are straightforward predictions of the very well-tested weak interaction theory

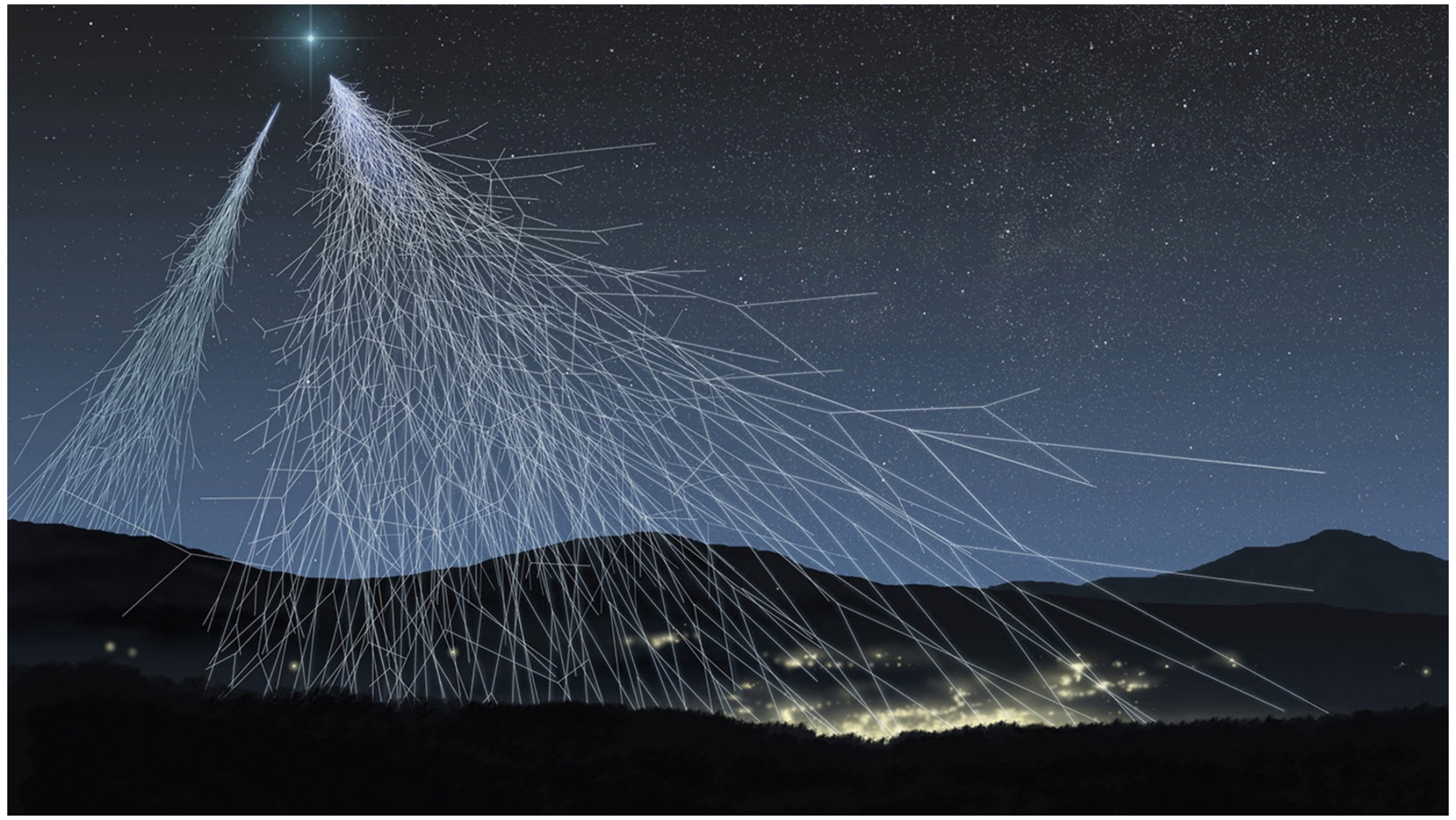
○ Neutrinos disappear before reaching the detector

Neutrino decay? Neutrino mixing?

Solar neutrino deficit



Atmospheric neutrino deficit

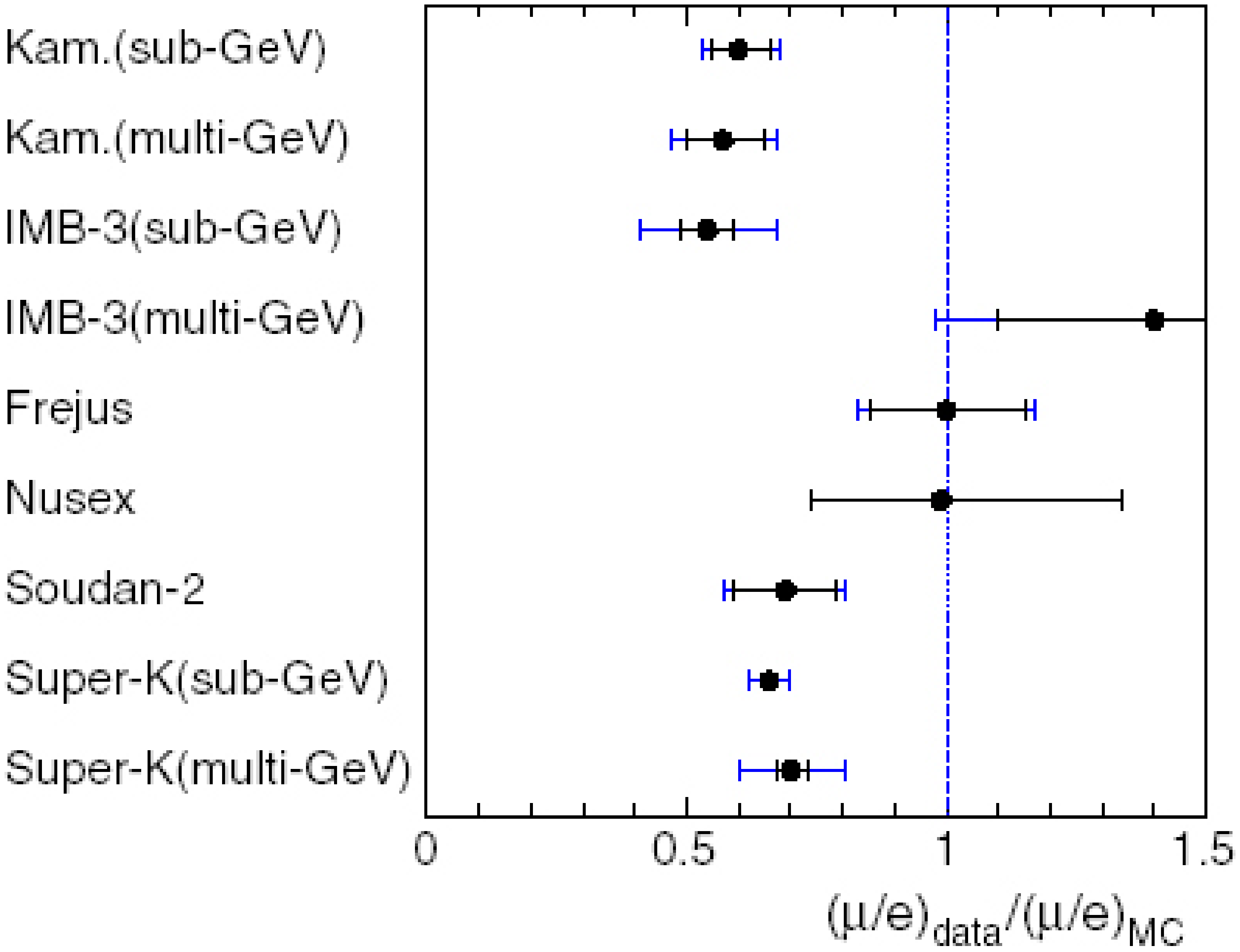


In parallel, we started looking at neutrinos produced by cosmic rays

=> When cosmic rays hit the atmosphere and produce pions and muons

$$p + atm \rightarrow \pi^+ + \ldots$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

At ground level, we expect:
$\nu_\mu : \nu_e = 2 : 1$ **A flux-independent measurement!!**



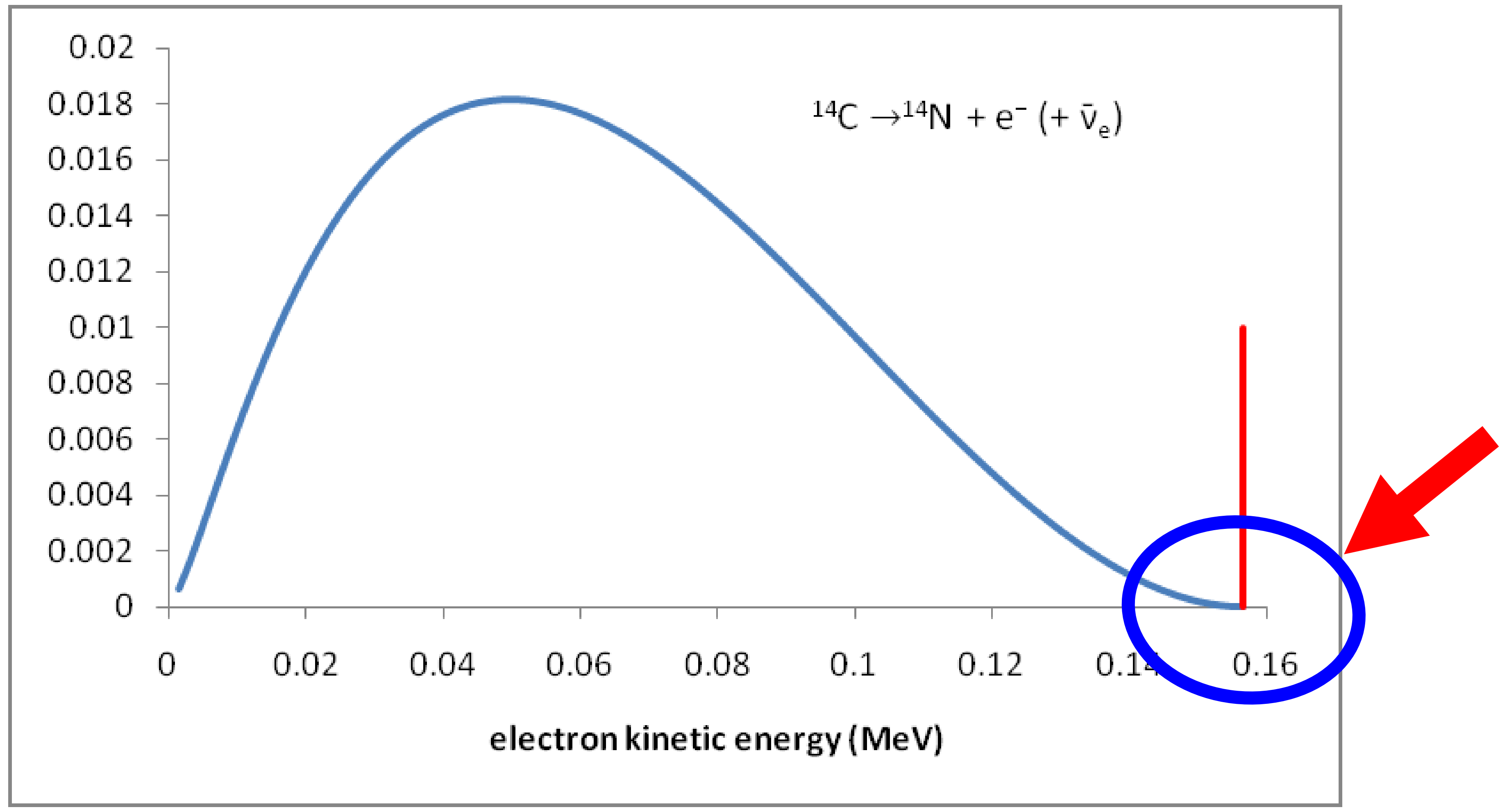
We found $\nu_\mu : \nu_e \approx 1$
About 50% of the ν_μ are missing!

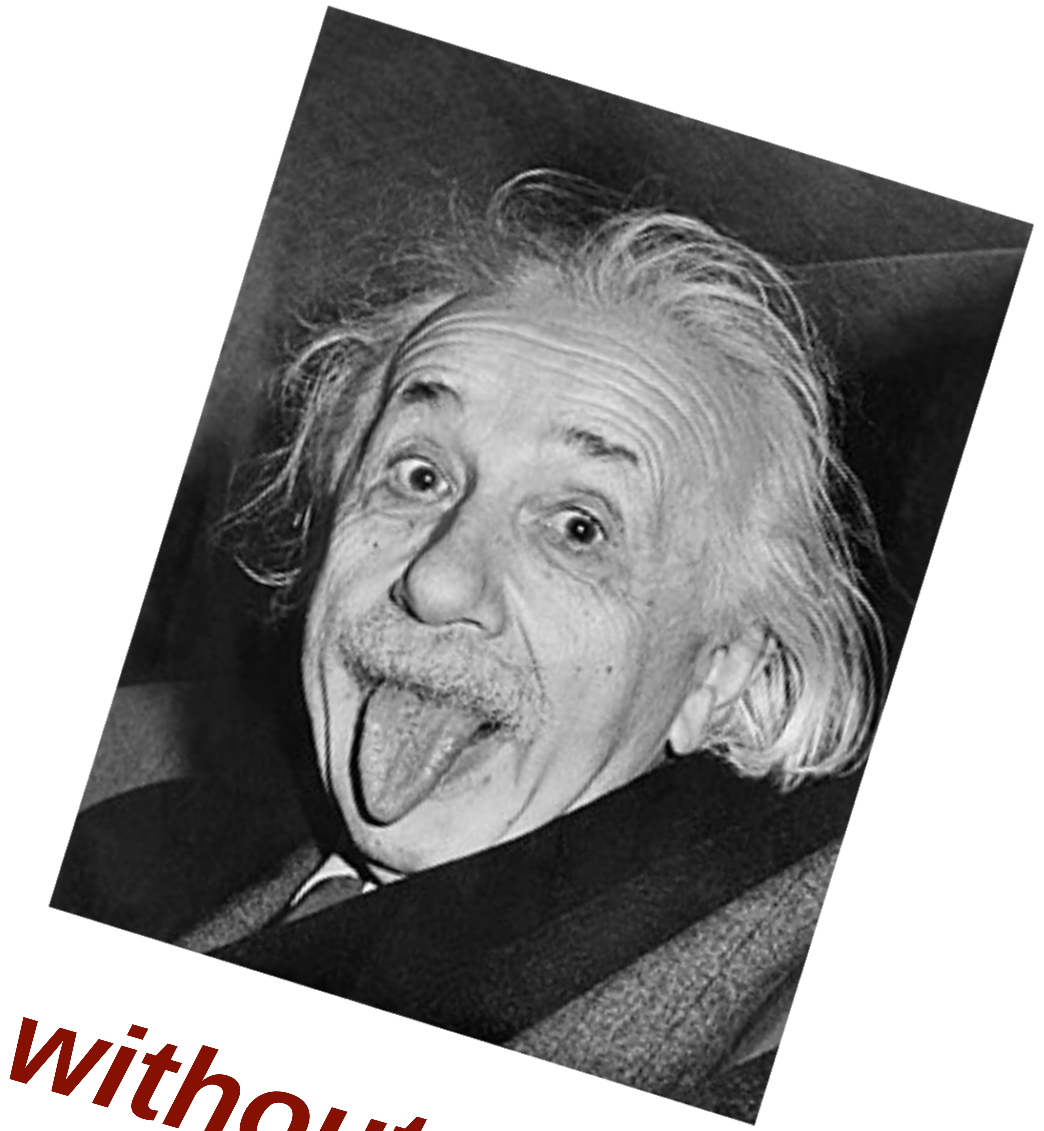
Understanding the anomalies

○ Something is up with neutrino propagation

- Many possible explanations: ν-decay, ν-decoherence, flavor changing neutral currents, oscillations, …

- In 1957, Pontecorvo suggested $\nu \rightarrow \nu$ oscillations, in analogy with $K^0 \rightarrow \overline{K}^0$ mixing





Not without mass!

Massive neutrinos?

You had a very easy lecture last week explaining flavour mixing :)

$$L_1 = \begin{pmatrix} \nu_{e(L)} \\ e_L \end{pmatrix}, \qquad L_2 = \begin{pmatrix} \nu_{\mu(L)} \\ \mu_L \end{pmatrix}, \qquad L_3 = \begin{pmatrix} \nu_{\tau(L)} \\ \tau_L \end{pmatrix}$$

$$R_1 = \begin{pmatrix} \nu_{e(R)} \\ e_R \end{pmatrix}, \qquad R_2 = \begin{pmatrix} \nu_{\mu(R)} \\ \mu_R \end{pmatrix}, \qquad R_3 = \begin{pmatrix} \nu_{\tau(R)} \\ \tau_R \end{pmatrix}$$

$$\phi = \frac{1}{\sqrt{2}}(v + H)\begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \phi^c = \frac{1}{\sqrt{2}}(v + H)\begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\mathcal{L}_{leptons,mass} = -\sqrt{2}(\bar{L}_i N_{ij} \phi R_j + \bar{R}_j N^*_{ij} \phi^\dagger L_i) \\ -\sqrt{2}(\bar{L}_i K_{ij} \phi^c R_j + \bar{R}_j K^*_{ij} (\phi^c)^\dagger L_i)$$

$N = V_N^\dagger N_D U_N$ and $K = V_K^\dagger K_D U_K$.

$$U_N^\dagger l'_R = l_R, \qquad U_K^\dagger \nu'_R = \nu_R$$

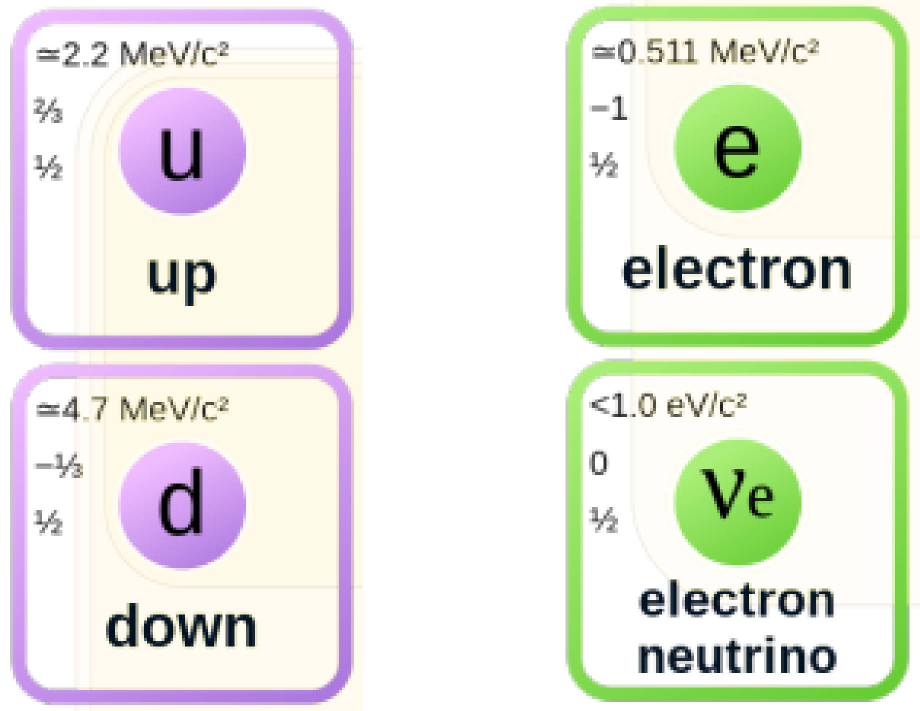
$$V_N^\dagger l'_L = l_L, \qquad V_K^\dagger \nu'_L = \nu_L$$

$$J^\mu = \bar{L}'\gamma^\mu(\sigma_1 + i\sigma_2)L' = 2\begin{pmatrix} \nu'_e & \nu'_\mu & \nu'_\tau \end{pmatrix}_L \gamma^\mu \begin{pmatrix} e' & \mu' & \tau' \end{pmatrix}^T_L \\ = 2\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix}_L \gamma^\mu (V_K^\dagger V_N) \begin{pmatrix} e & \mu & \tau \end{pmatrix}^T_L \\ = \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \gamma^\mu (1 - \gamma_5)(V_K^\dagger V_N) \begin{pmatrix} e & \mu & \tau \end{pmatrix}^T$$

$$\boxed{U \equiv V_K^\dagger V_N = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}$$

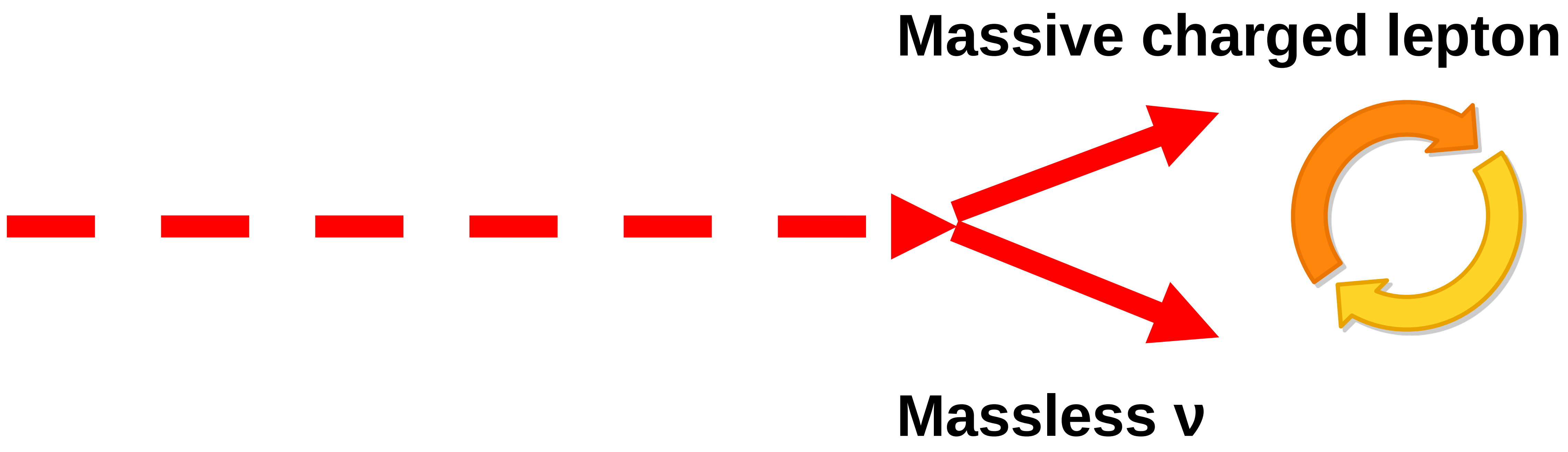
Massive neutrinos?

- **Every (weakly interacting) particle state has a weak interaction pair**



- **Particles always propagate in well-defined mass states (they don't have multiple velocities at once)**

- **Massless particles can (in principle) propagate in any state**



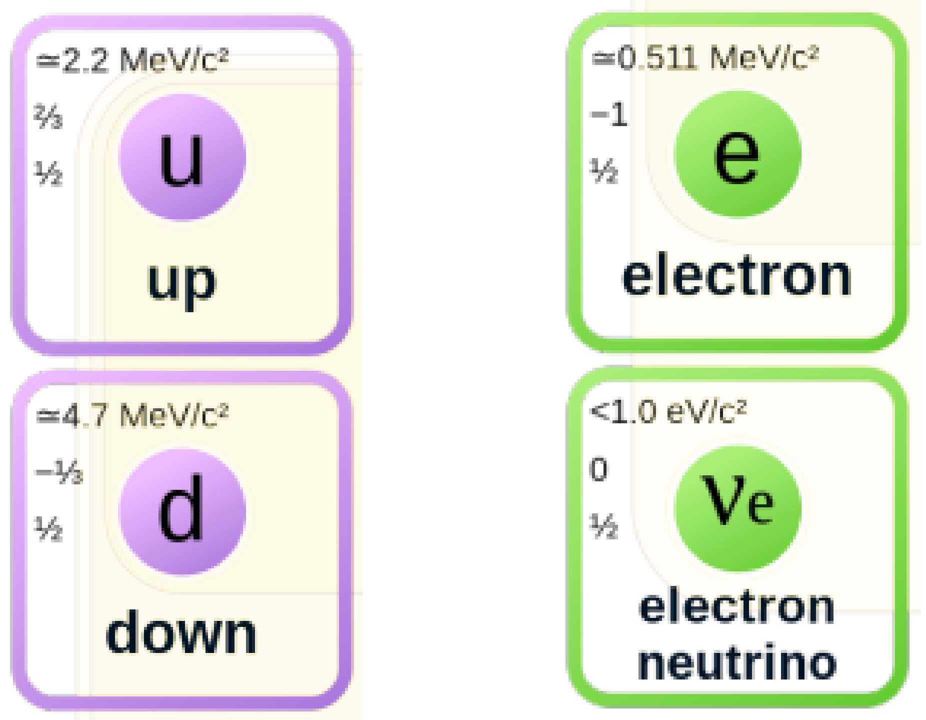
As long as we choose paired states, the weak interaction physics will stay the same

The neutrino can propagate in the partner state of the charged lepton's mass state

(we can respect the weak pairing when choosing the propagation states)

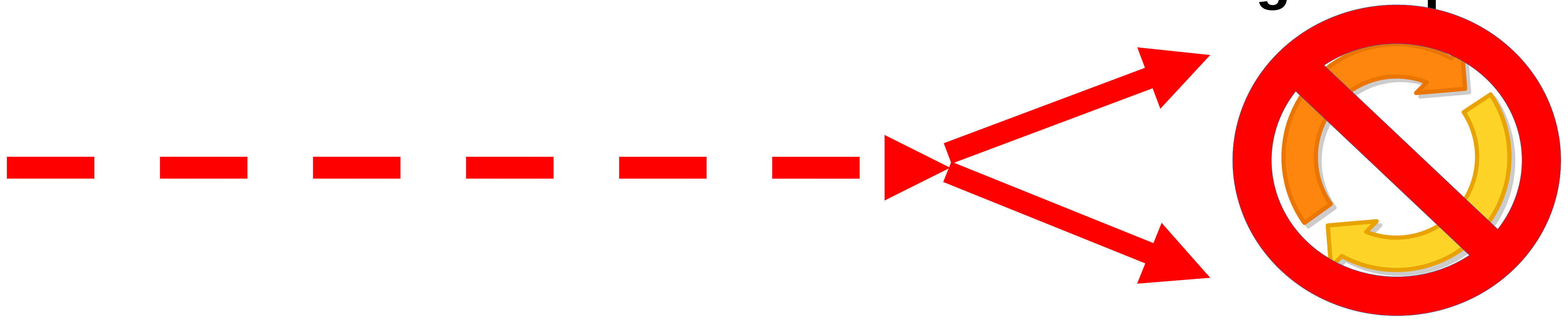
Massive neutrinos?

- ○ **Every (weakly interacting) particle state has a weak interaction pair**



- ○ **Particles always propagate in well-defined mass states (they don’t have multiple velocities at once)**

- ○ **Massive neutrinos force the propagation states:**



Massive charged lepton

Massive ν

The neutrino **must propagate in its mass state**

The charged lepton and neutrino mass states might not be each other’s pairs!!

We can choose to write the physics in the propagation state of one particle, but that fixes the other’s weak state

Massive neutrinos?

Choosing to write the interactions in the propagation states of the charged leptons ==> We must perform a change of basis to go from the corresponding neutrino “flavour” states to their propagation states

3 neutrinos ==> 3x3 change of basis matrix U $= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$

This matrix allows us to transform between produced states and propagation states

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

$$|\nu_i\rangle = \sum_{\alpha=1}^{3} U_{\alpha i}|\nu_\alpha\rangle$$

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3 flavour neutrino oscillations

The basis of neutrino interactions is different than the basis of neutrino propagation

How does this lead to oscillations?

We first define a few approximations:

○ Neutrino masses are very, very small ==> They propagate at the speed of light

○ The neutrino mass states resulting from a flavour neutrino state have the same momentum *(only approximately true, helps with the calculations but not necessary to arrive at the same conclusions)*

Then, we look at the propagator

In a time-independent potential, wavefunctions propagate as plane waves:

$$i\frac{d}{dt}|\nu_i(t)\rangle = \mathcal{H}|\nu_i(t)\rangle \longrightarrow |\nu_\alpha(t)\rangle = e^{-i\mathcal{H}t}|\nu_\alpha(0)\rangle$$

3 flavour neutrino oscillations

In a time-independent potential, wavefunctions propagate as plane waves:

$$|\nu_\alpha(t)\rangle = e^{-i\mathcal{H}t}\,|\nu_\alpha(0)\rangle$$

This is a matrix, which may not be diagonal!!

These are flavour states

But the hamiltonian ***is*** diagonal in the mass states (duh!)

We can rewrite the initial flavour states in terms of mass states using our mixing matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

This is now a diagonal matrix

$$|\nu_\alpha(t)\rangle = e^{-i\mathcal{H}t}\left[\sum_j U^*_{\alpha j}\,|\nu_j(0)\rangle\right]$$

But this is not quite what we are looking for: neutrinos are not in their mass states *ν_j* at *t = 0*

We need to use our matrix to transform back in terms of the flavour states

$$|\nu_i\rangle = \sum_{\alpha=1}^{3} U_{\alpha i}|\nu_\alpha\rangle$$

$$|\nu_\alpha(t)\rangle = e^{-i\mathcal{H}t}\left[\sum_j U^*_{\alpha j}\left(\sum_\beta U_{\beta j}\,|\nu_\beta(0)\rangle\right)\right]$$

Each mass state is its own sum of flavour states, so we end up with two summations

Cleaning things up a bit:

$$|\nu_\alpha(t)\rangle = \sum_j\sum_\beta\left(U^*_{\alpha j}U_{\beta j}\right)e^{-i\mathcal{H}t}\,|\nu_\beta(0)\rangle$$

In the mass basis, these are just the energy eigenvalues E_j

$$E_j = \sqrt{\vec{p}^{\,2} + m^2_j}$$

We square the amplitude to get the detection probability

$$P_{\nu_\beta\to\nu_\alpha}(t) = \sum_j\sum_k\left(U^*_{\beta j}U_{\alpha j}U_{\beta k}U^*_{\alpha k}\right)e^{-i\boxed{E_j-E_k}t}$$

But we still don't know what these are. Let's use the equal momentum and relativistic assumptions

$$E = |\vec{p}|$$

Set the energy to the momentum

$$E_k \simeq E + \frac{m^2_k}{2E}$$

$$E_j - E_k \simeq \frac{\Delta m^2_{jk}}{2E}$$

3 flavour neutrino oscillations

Putting everything together, and replacing time with distance (assuming we are traveling at the speed of light)

$$P_{\nu_\beta \to \nu_\alpha}(t) = \sum_j \sum_k \left(U^*_{\beta j} U_{\alpha j} U_{\beta k} U^*_{\alpha k} \right) e^{-i(E_j - E_k)t}$$

$$\downarrow$$

$$P_{\nu_\beta \to \nu_\alpha}(L/E) = \sum_j \sum_k \left(U^*_{\beta j} U_{\alpha j} U_{\beta k} U^*_{\alpha k} \right) \exp\left(-i \frac{\Delta m^2_{jk} L}{2E} \right)$$

- ○ The probability depends on complicated products of the elements of the mixing matrix
- ○ The probability depends on the differences of the square of the neutrino masses
- ○ The probability remains the same under complex rotations of the mixing matrix

You can check that this can be rewritten in the following way:

$$\boxed{\begin{aligned} P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} &- 4 \sum_{k>j} \mathfrak{Re}\left[U^*_{\alpha k} \, U_{\beta k} \, U_{\alpha j} \, U^*_{\beta j} \right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E} \right) \\ &+ 2 \sum_{k>j} \mathfrak{Im}\left[U^*_{\alpha k} \, U_{\beta k} \, U_{\alpha j} \, U^*_{\beta j} \right] \sin\left(\frac{\Delta m^2_{kj} L}{2E} \right) \end{aligned}}$$

Oscillation phenomenology

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right]\, \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$
$$+\, 2\sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right]\, \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

Oscillation formula

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

PMNS matrix

What would happen if $m_j = m_k$?

The oscillatory terms vanish and we do not see flavour transitions

What would happen if Δm^2 were very large ?

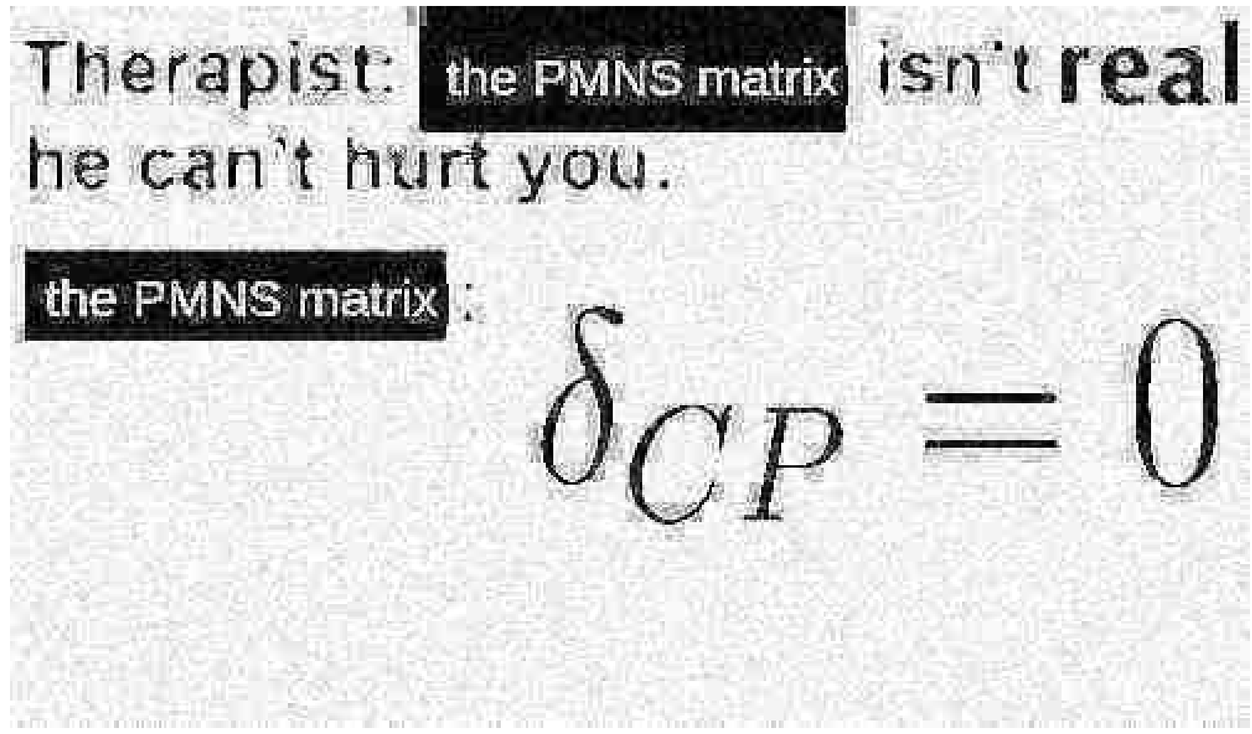
This is what happens in the quark and charged lepton sectors. The oscillations become decays very quickly

What would happen if the imaginary part of the product of $U_{\sigma j}$ is non-zero ?

Taking the complex conjugate would be non-trivial ==> CP (or T) violation

What happens to the imaginary part if $\alpha = \beta$?

It vanishes: CP violation is only possible in appearance probabilities



Therapist: the PMNS matrix isn't real he can't hurt you.

the PMNS matrix: $\delta_{CP} = 0$

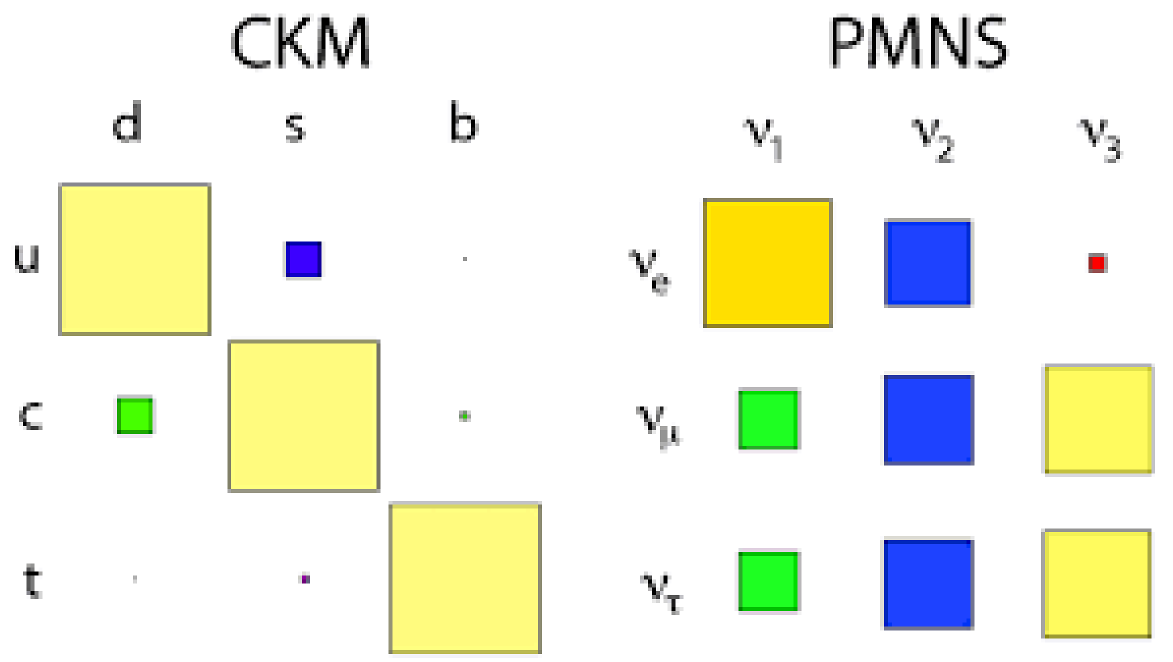
Oscillation phenomenology

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$
$$+ 2 \sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

Oscillation formula

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

PMNS matrix



How do we parameterise a non-diagonal 3x3 unitary matrix?

- **A generic 3x3 complex matrix has 18 free parameters. A unitary matrix has 9**
- **We are allowed to change the mixing matrix by global changes of phase ==> We can multiply by matrices with complex phases along the diagonals ==> This removes up to 5 more parameters**
- **We end up with 4 free parameters, which we choose to parameterise as 3 real angles and one complex phase:**

$$\nu_e, \nu_\mu, \nu_\tau = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} |\nu_i\rangle$$

This angle mixes ν_μ and ν_τ

This complex rotation is not so intuitive

This angle mixes ν_1 and ν_2

Oscillation phenomenology

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right]\ \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2\sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right]\ \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

Oscillation formula

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

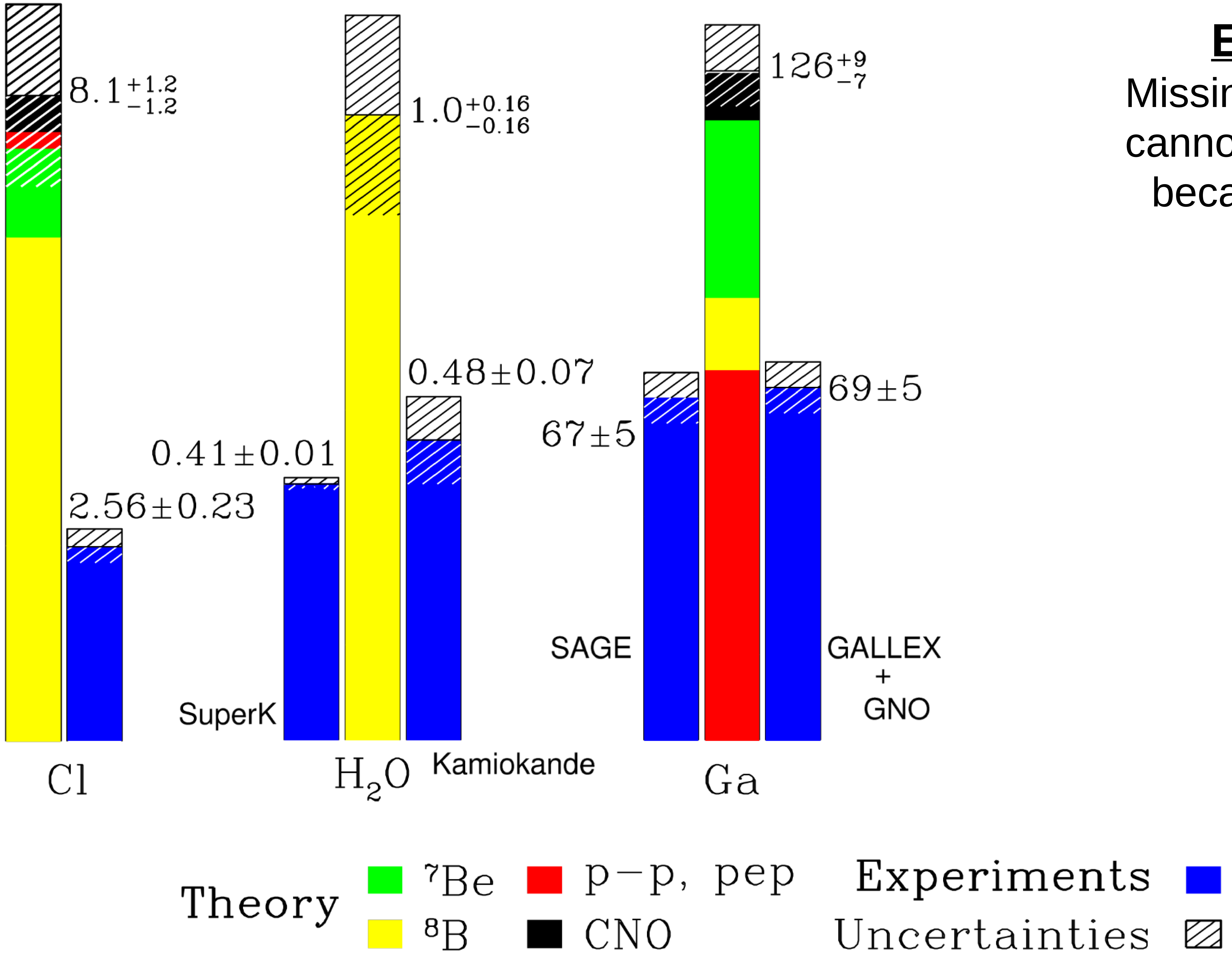
PMNS matrix

In the end we have 6 parameters: **Three real angles: θ_{12}, θ_{13}, θ_{23}**
One complex phase δ_{CP}
Two mass splittings Δm^2_{21} and Δm^2_{32} ($\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$)

$$\nu_e, \nu_\mu, \nu_\tau = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} |\nu_i\rangle$$

Oscillation phenomenology

Let us jump back into oscillation measurements for a minute

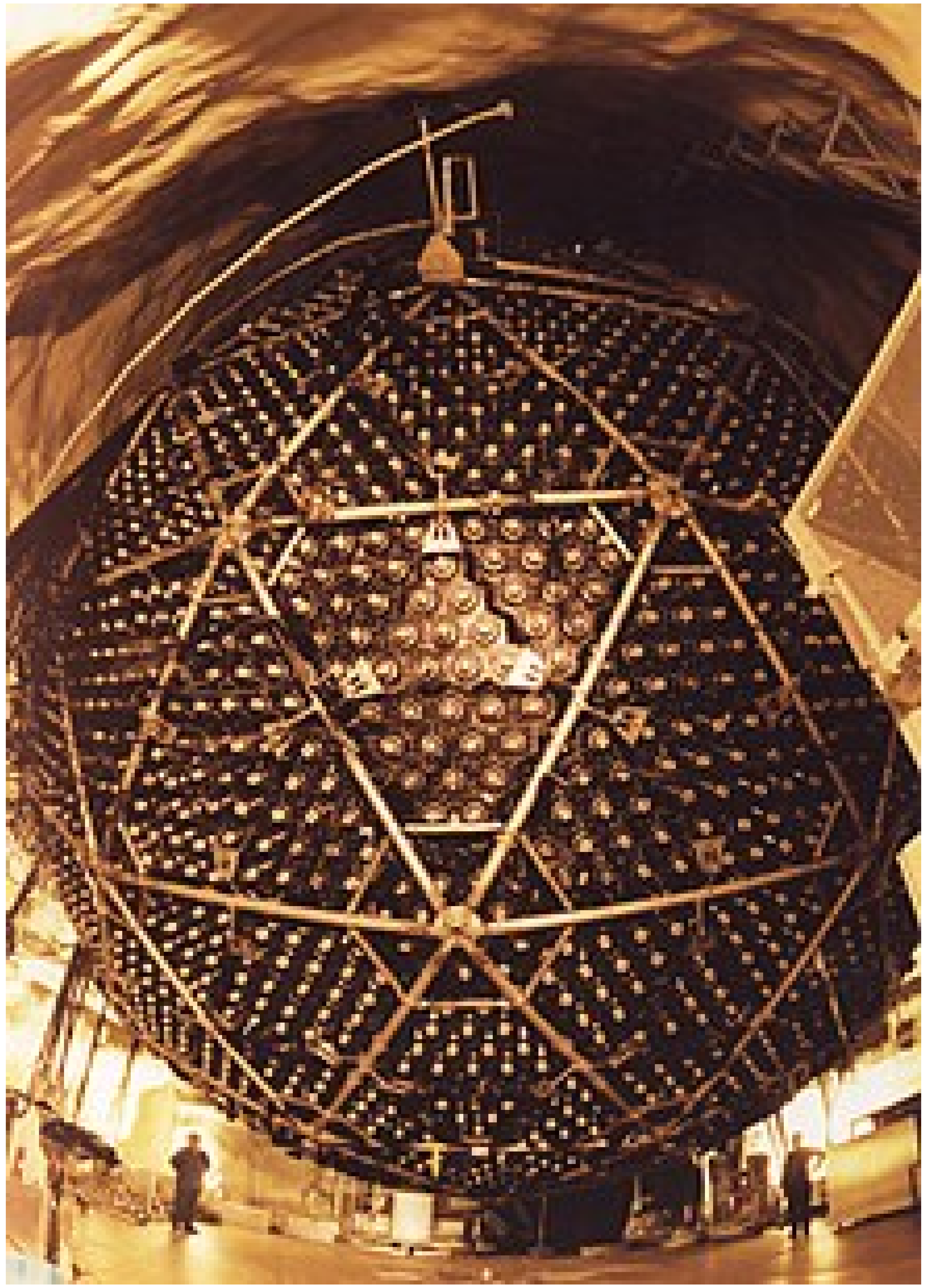


Explanation via oscillations:

Missing ν_e have oscillated into ν_μ and ν_τ and cannot be detected through CC interactions because the energy threshold is too high for our detectors

$E_{thr}(\nu_\mu)$ = 110 MeV
$E_{thr}(\nu_\tau)$ = 3.45 GeV

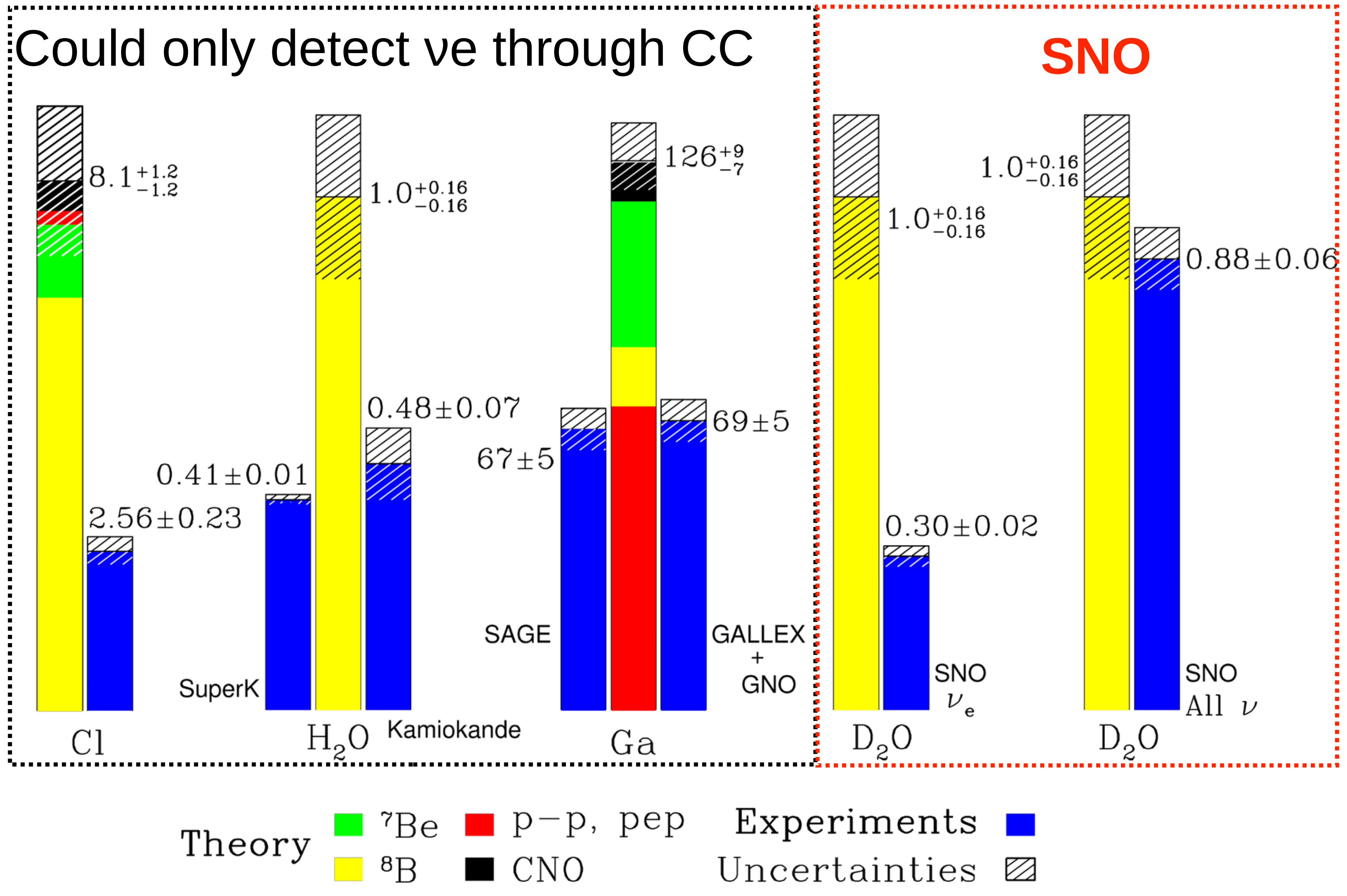
Oscillation phenomenology - Solar



SNO (1kton of heavy water) was designed to detect solar neutrinos through:

- **CC** interactions $\nu_e + d \rightarrow p + p + e^-$
  ν_e only (ν_μ & ν_τ don’t have enough energy)
- **ES** interactions $\nu_x + e^- \rightarrow \nu_x + e^-$
  all flavors
- **NC** interactions $\nu_x + d \rightarrow p + n + \nu_x$
  all flavors

Oscillation phenomenology - Solar



SNO (1kton of heavy water) was designed to detect solar neutrinos through:

- **CC** interactions $\nu_e + d \rightarrow p + p + e^-$
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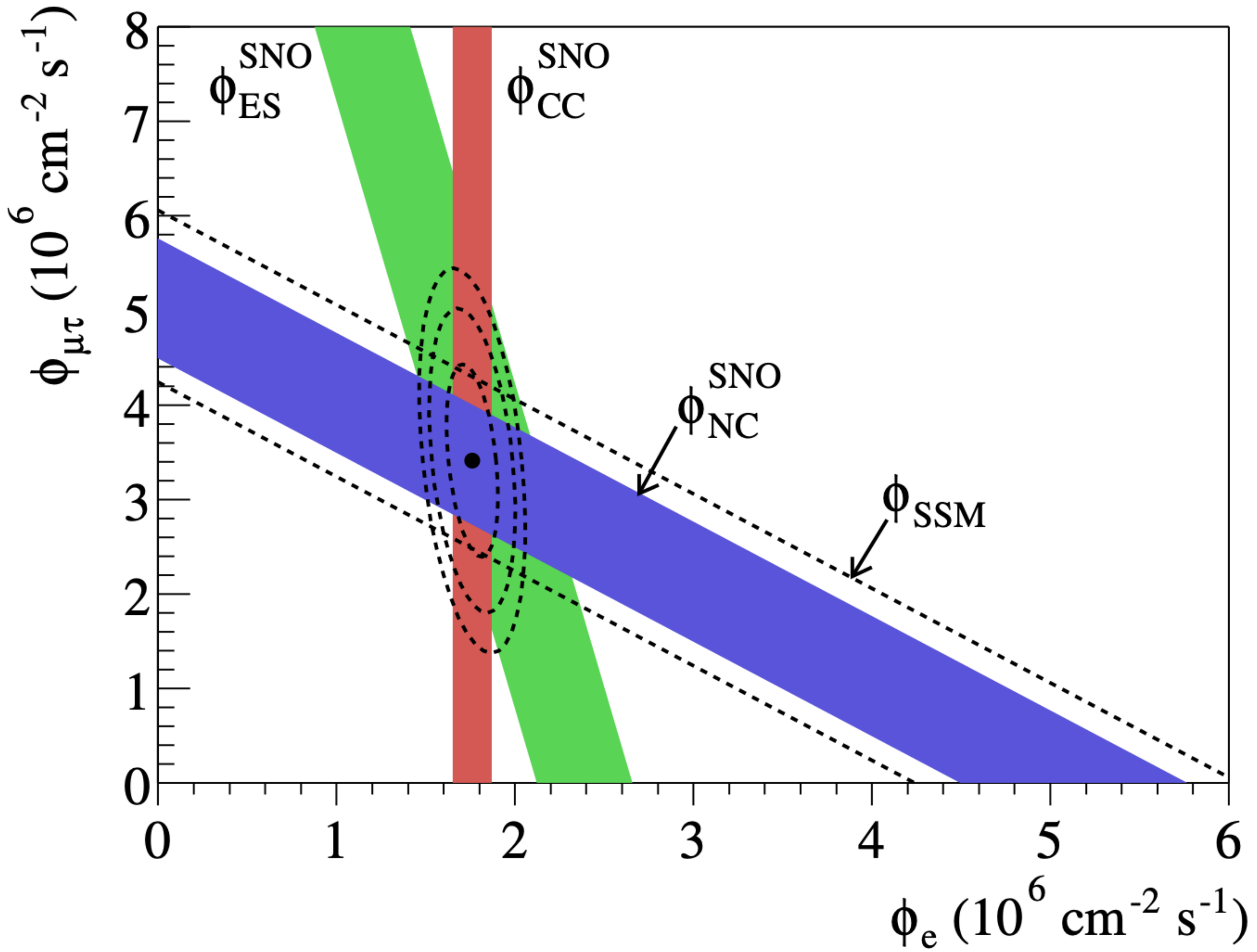
  all flavors
- **NC** interactions $\nu_x + d \rightarrow p + n + \nu_x$
  all flavors

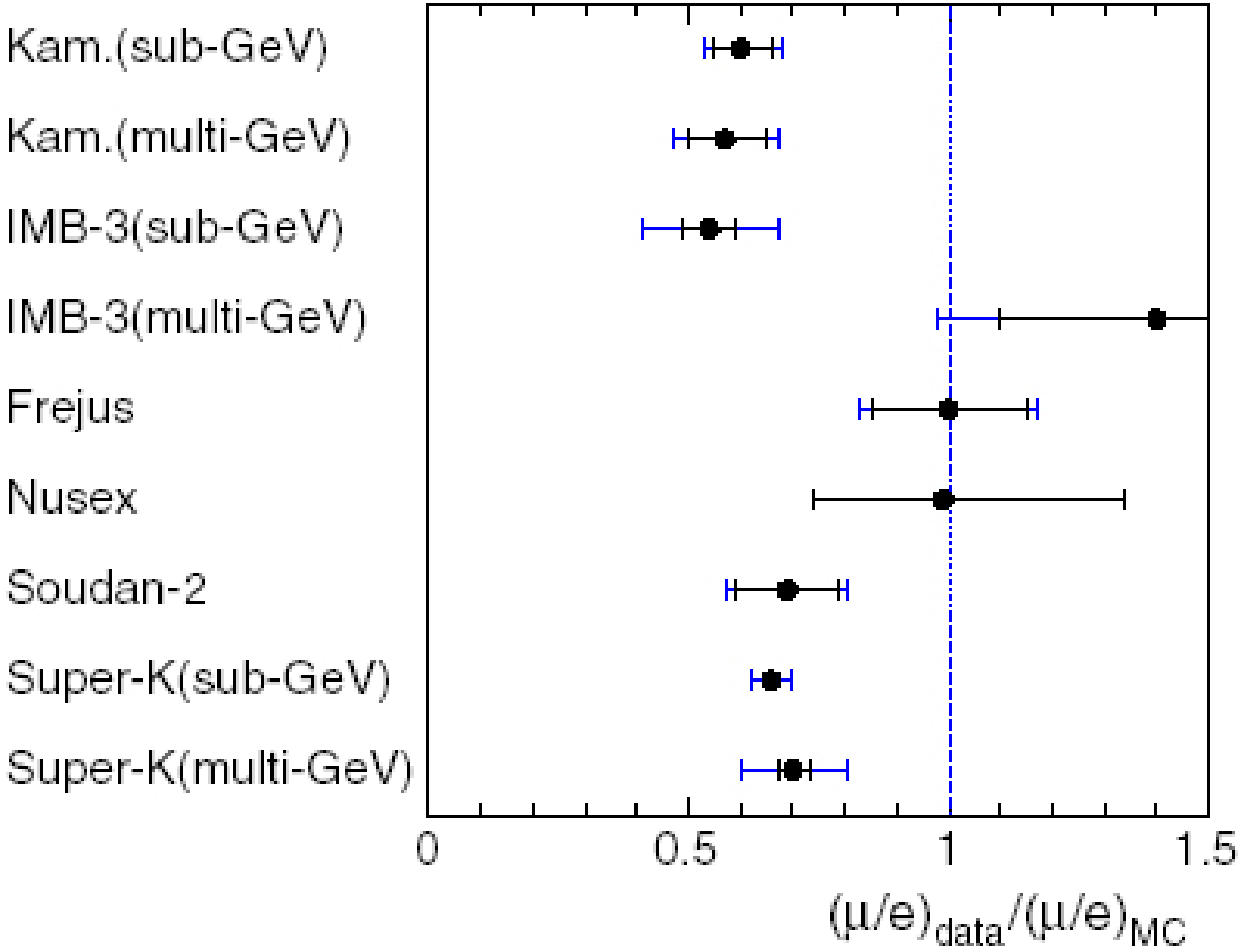


SNO measured the ratio $\frac{\Phi_{CC}}{\Phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$

And showed that the **total** flux of solar neutrino is **compatible** with the solar standard model

SNO proved that neutrinos change flavors

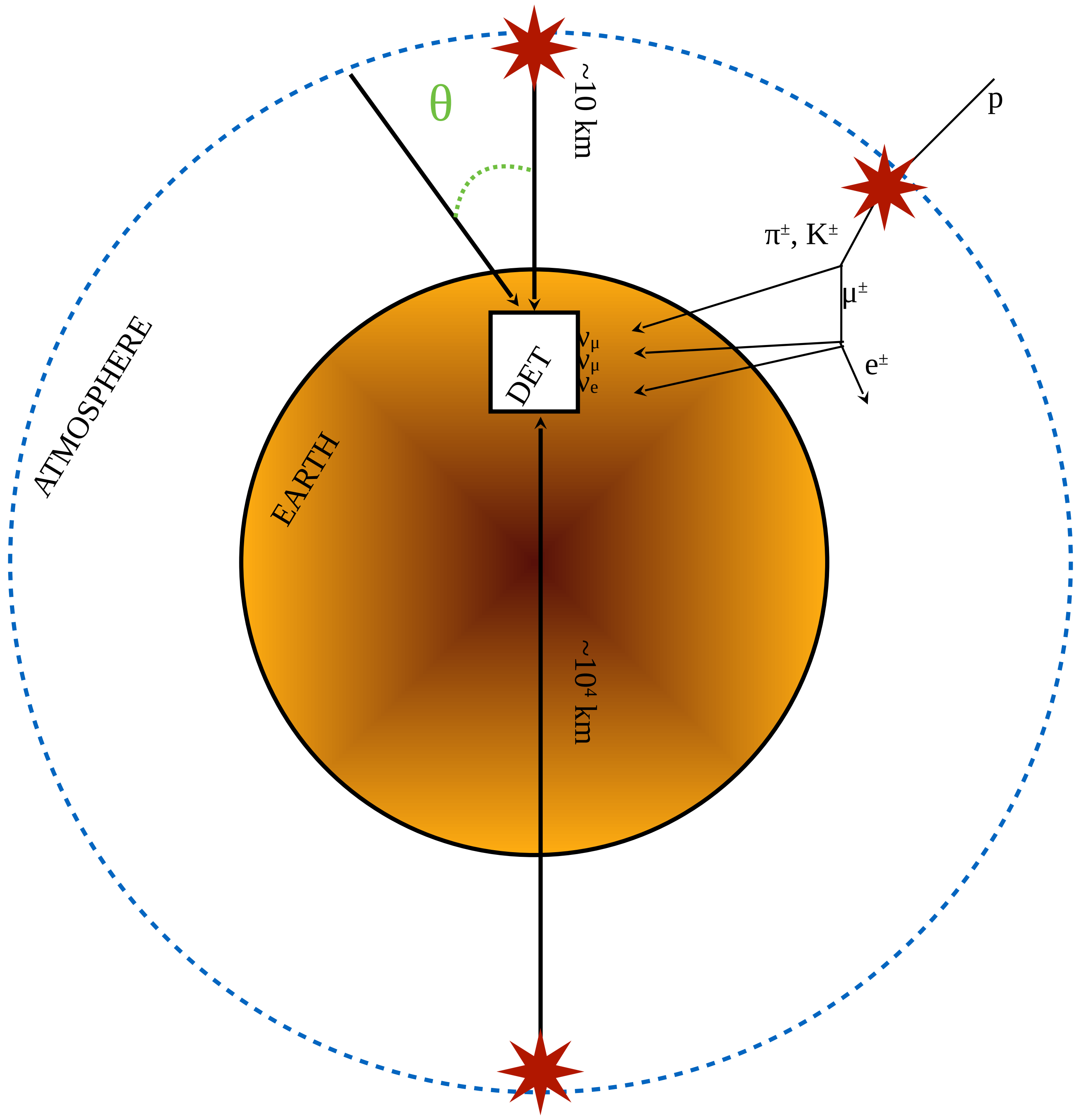
Oscillation phenomenology - Atmospheric



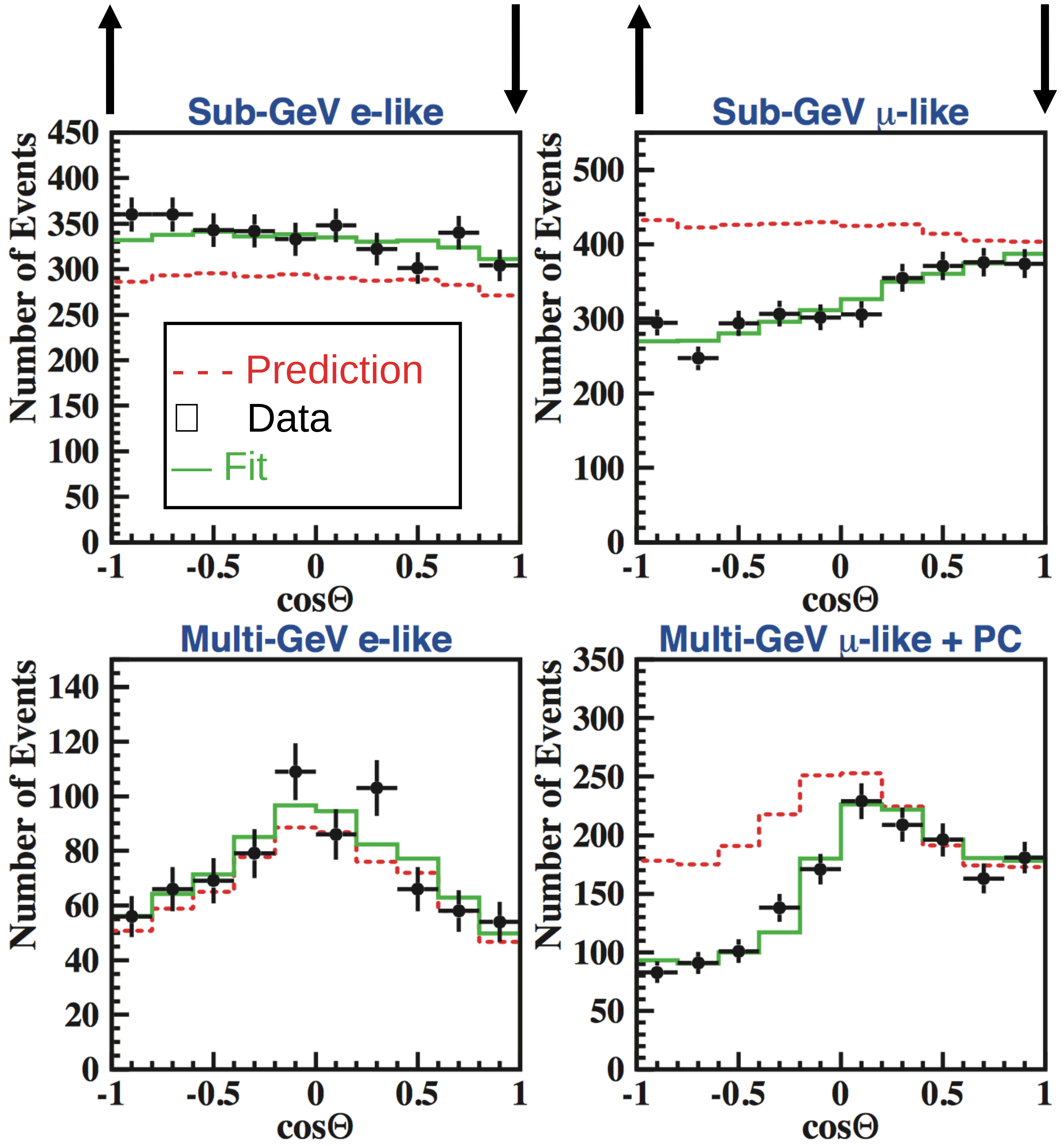
Explanation via oscillations:

Produced ν_e and ν_μ oscillate as they travel through the atmosphere and the earth, leading to different oscillation probabilities depending on the direction we look at

Oscillation phenomenology - Atmospheric



Super-Kamiokande measured the atmospheric ν_e and ν_μ energy as a function of cosθ ↔ L



For ν_e :

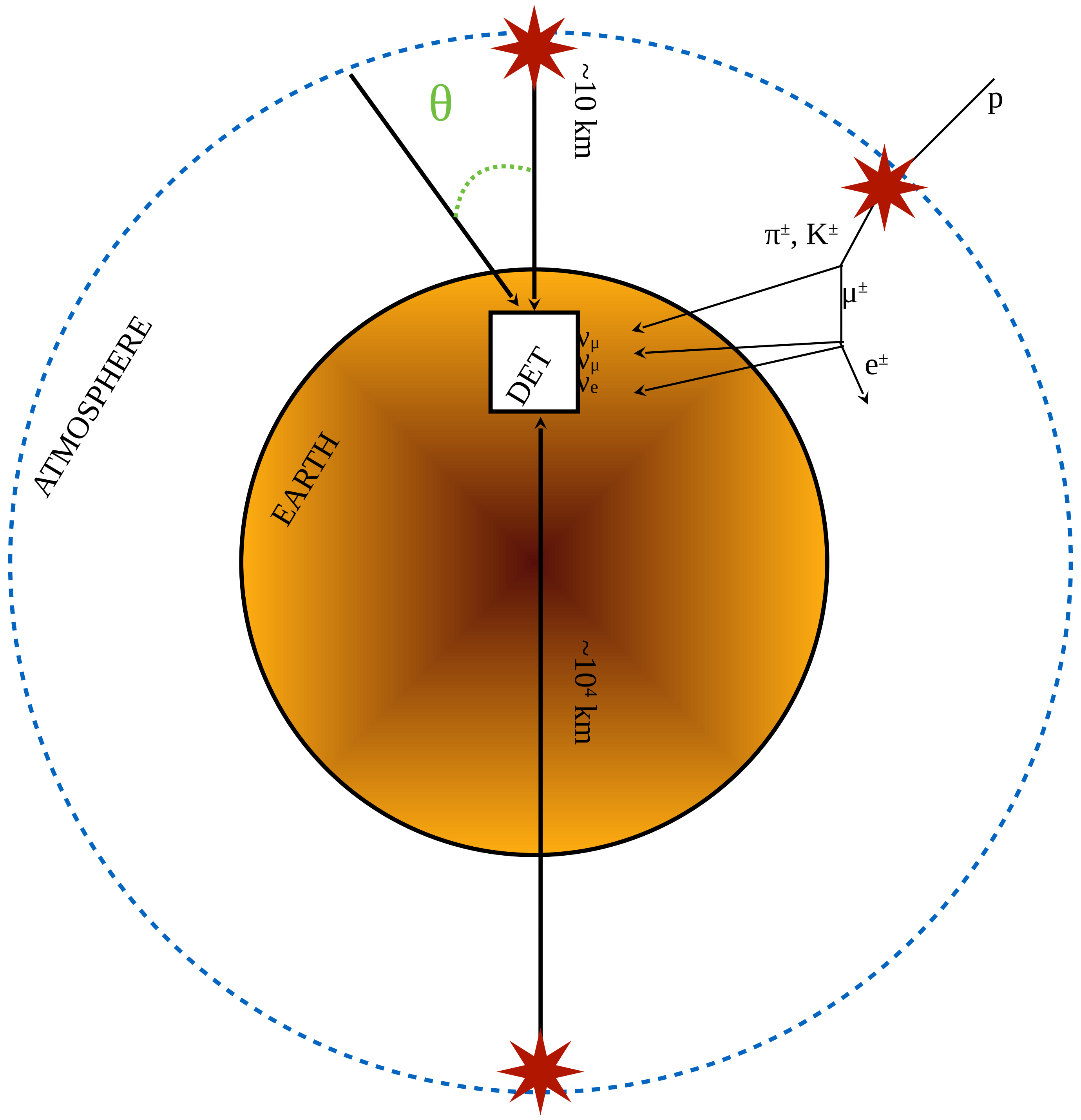
Flux agrees with predictions for all directions and energy

For ν_μ :

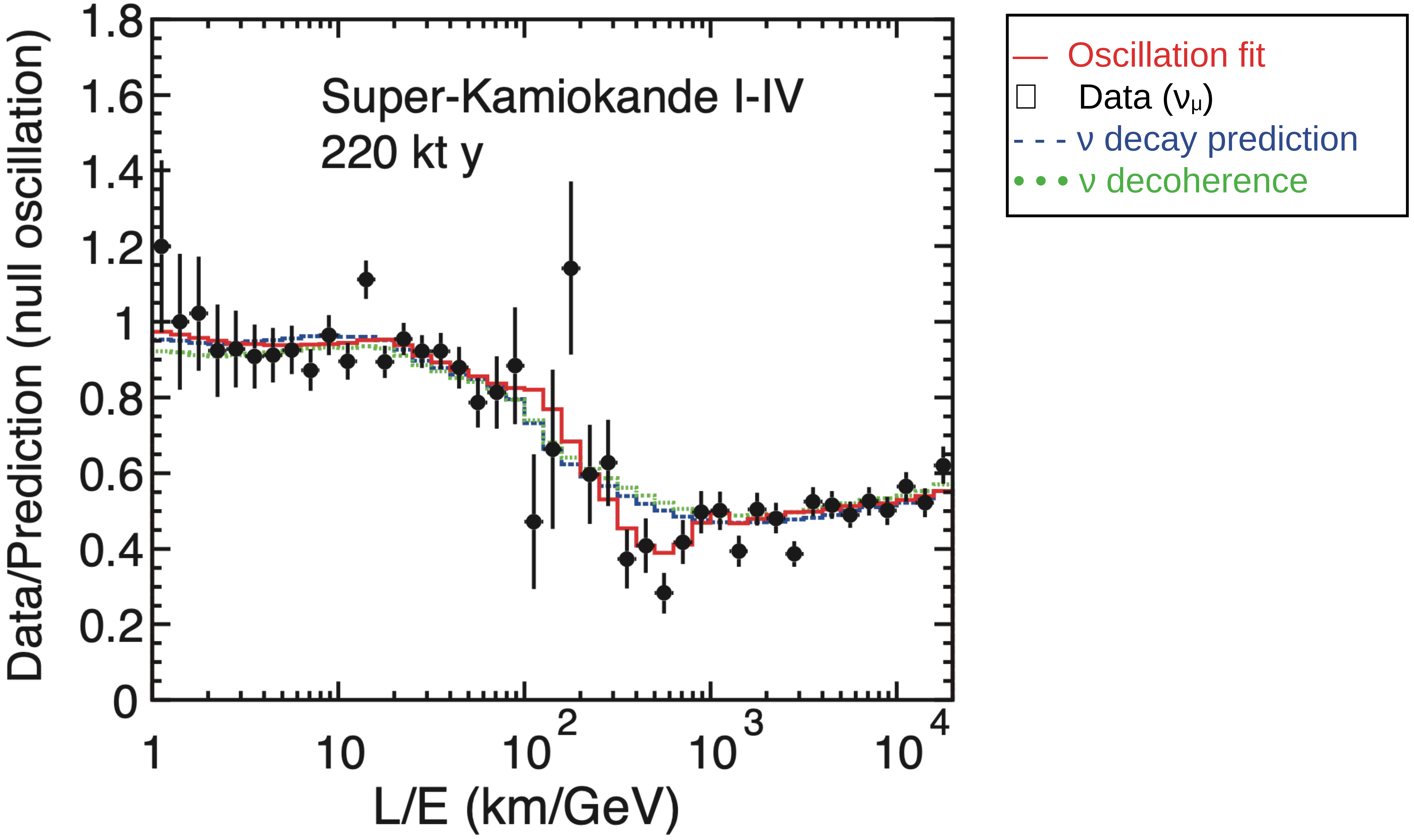
Disappearance of upwards going ν_μ (L ~ 10^4 km)

Flux agrees with predictions for downwards going ν_μ (L ~ 10 km)

Oscillation phenomenology - Atmospheric

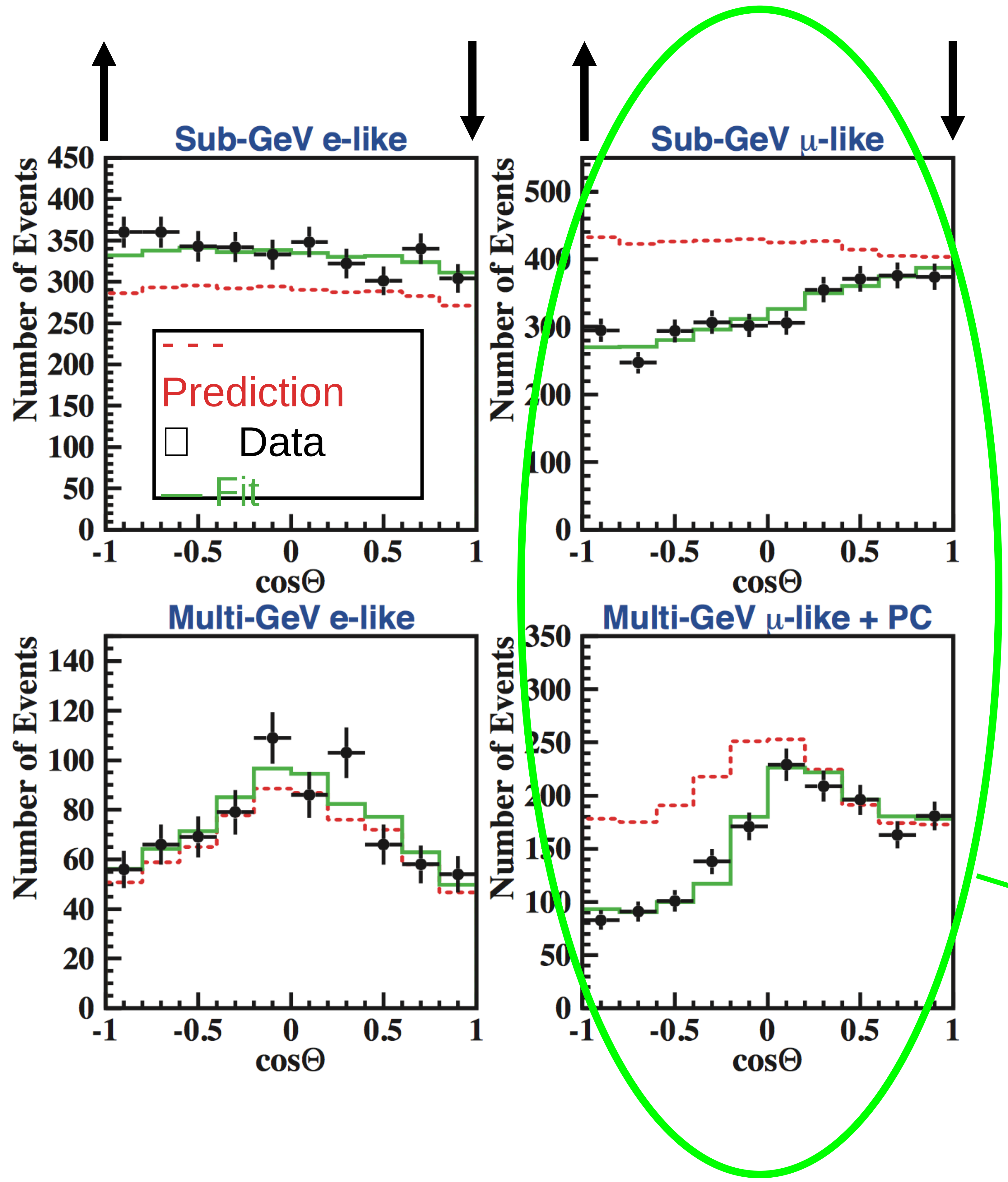


Super-Kamiokande measured the atmospheric ν_e and ν_μ energy as a function of cosθ ↔ L



Super-Kamiokande proved that ν_μ disappear as a function of L/E (possibly into ν_τ)

Digging deeper into the oscillations



It turns out that (by coincidence) the values of the mass differences make it so *that at the energies and distances of atmospheric neutrinos*, almost 100% of the oscillations are between ν_μ and ν_τ

$$\nu_e, \nu_\mu, \nu_\tau = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} |\nu_i\rangle$$

This angle mixes ν_μ and ν_τ

This complex rotation is not so intuitive

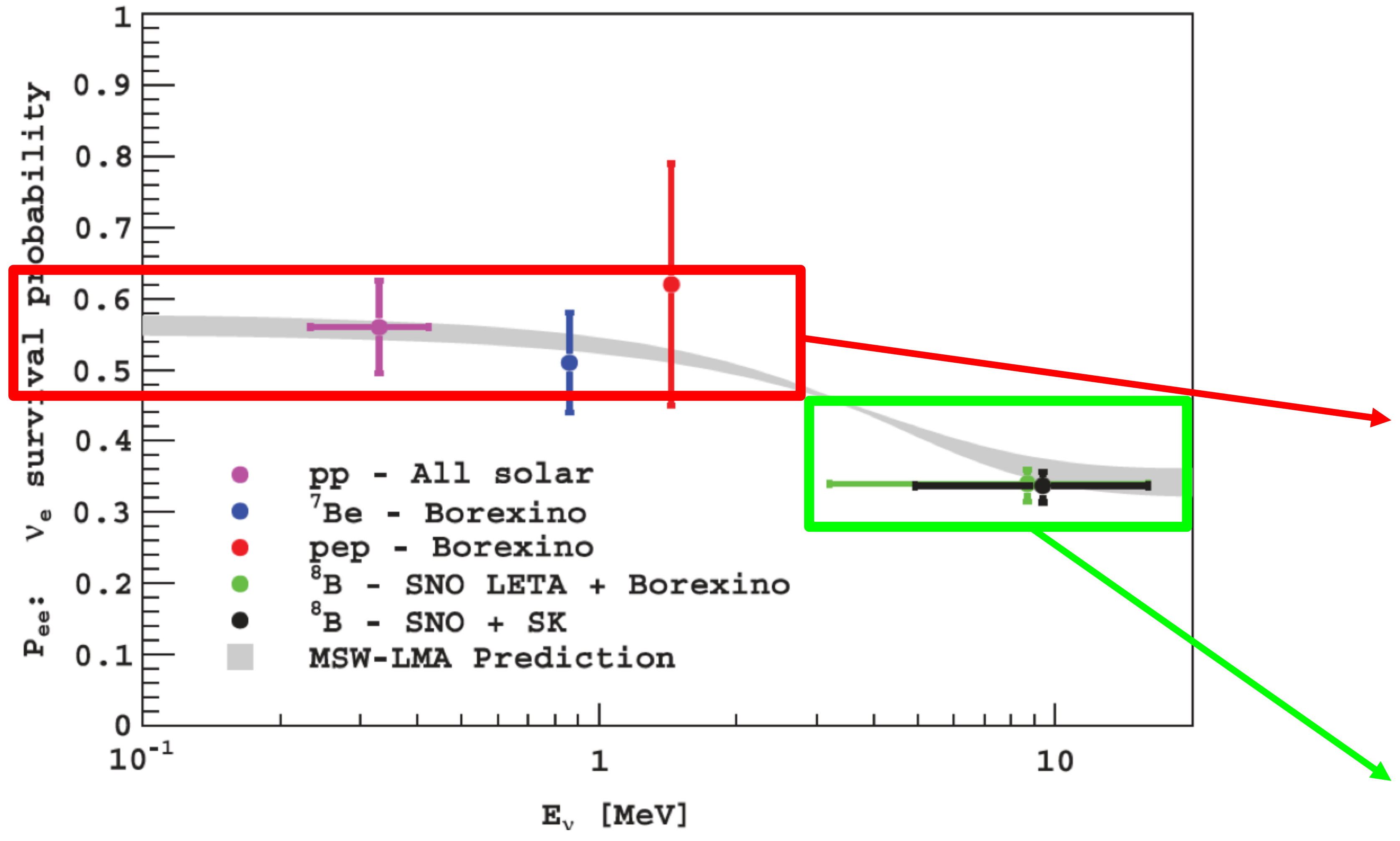
This angle mixes ν_1 and ν_2

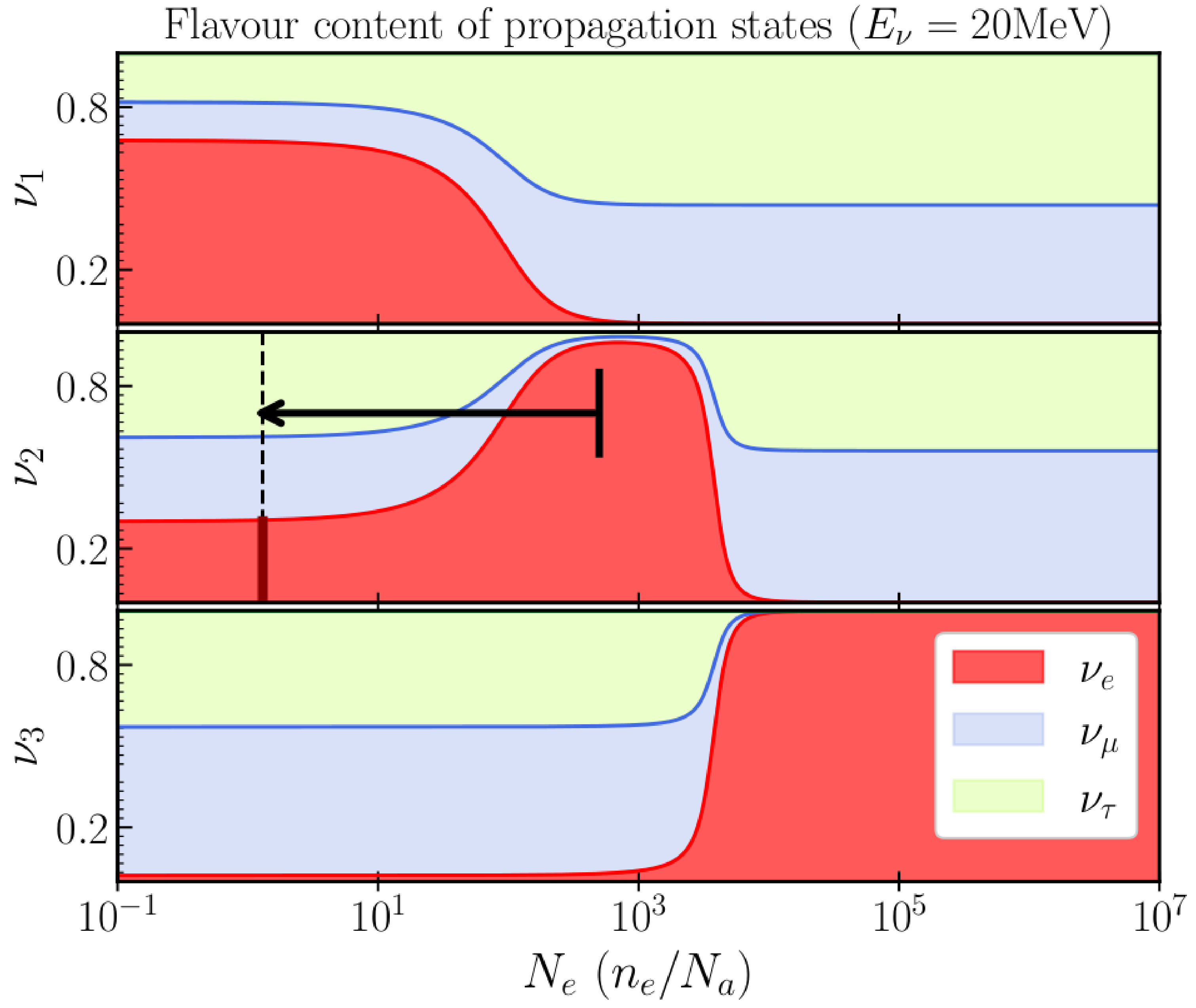
Conveniently, the amount of missing ν_μ is a clean measurement of the θ_{23} mixing angle

Also by coincidence, the Δm^2_{ij} are quite different from each other, and the term with the small one vanishes so that the shape of the deficit gives us Δm^2_{32}

Digging deeper into the oscillations

Solar oscillations are a bit more complicated: Neutrinos in the sun do not propagate like in vacuum





- ○ We do not see oscillatory behaviour because we have no way of knowing how far the neutrinos traveled => We only know the average oscillation probability at each energy
- ○ At low energies, $\sigma_{\nu\text{-}e}$ is so small that neutrinos cannot feel their propagation medium
- ○ At high energies, the propagation states are no longer the same as the mass states due to interference from the medium ==> The mixing matrix changes and the probabilities are affected

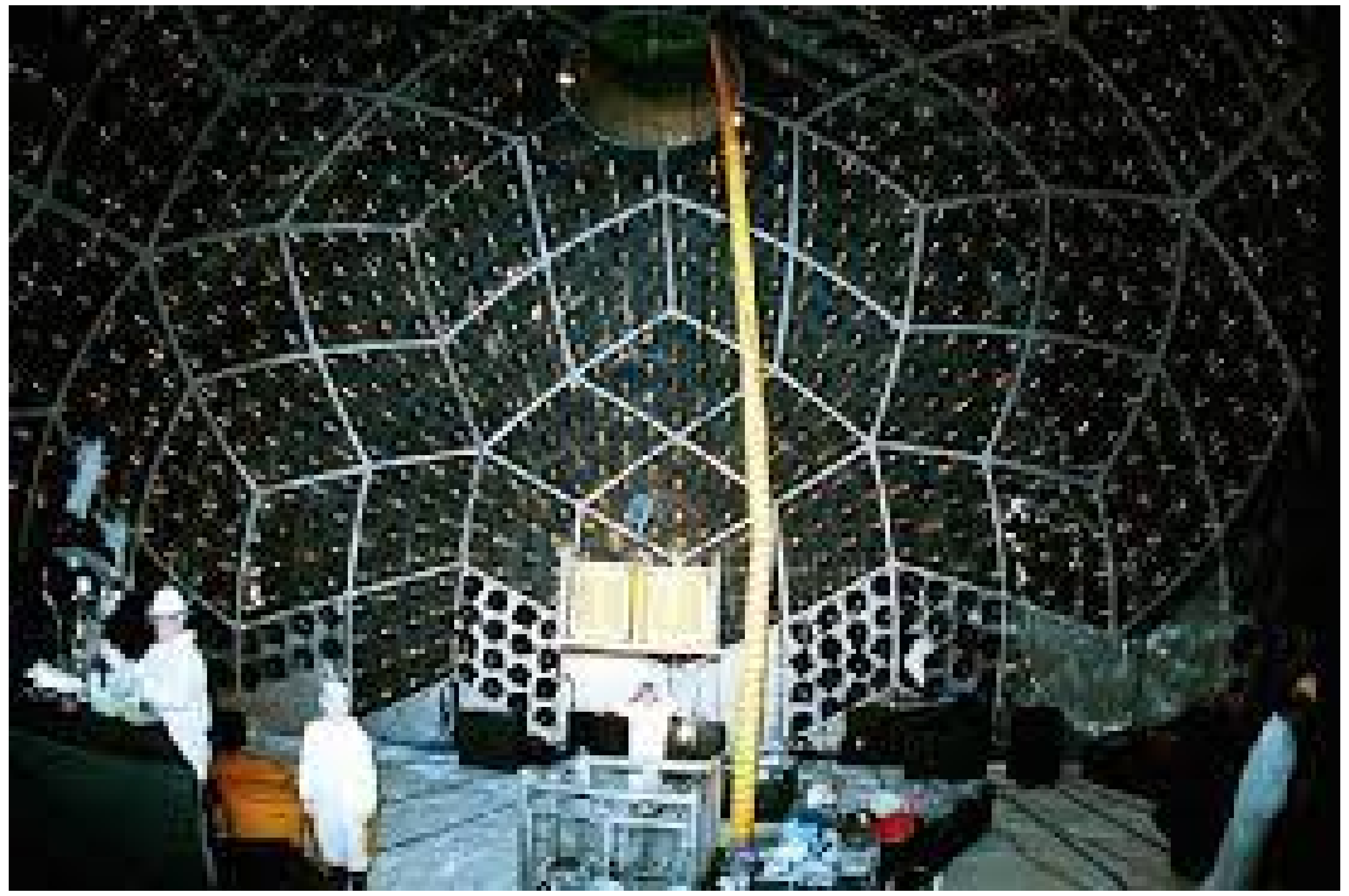
It just so happens (also a coincidence) that the difference between the low energy (vacuum) and high energy (dense medium) probabilities is closely related to the amount of mixing between the ν_1 and ν_2 states! ==> We get a measurement of the θ_{12} mixing angle.

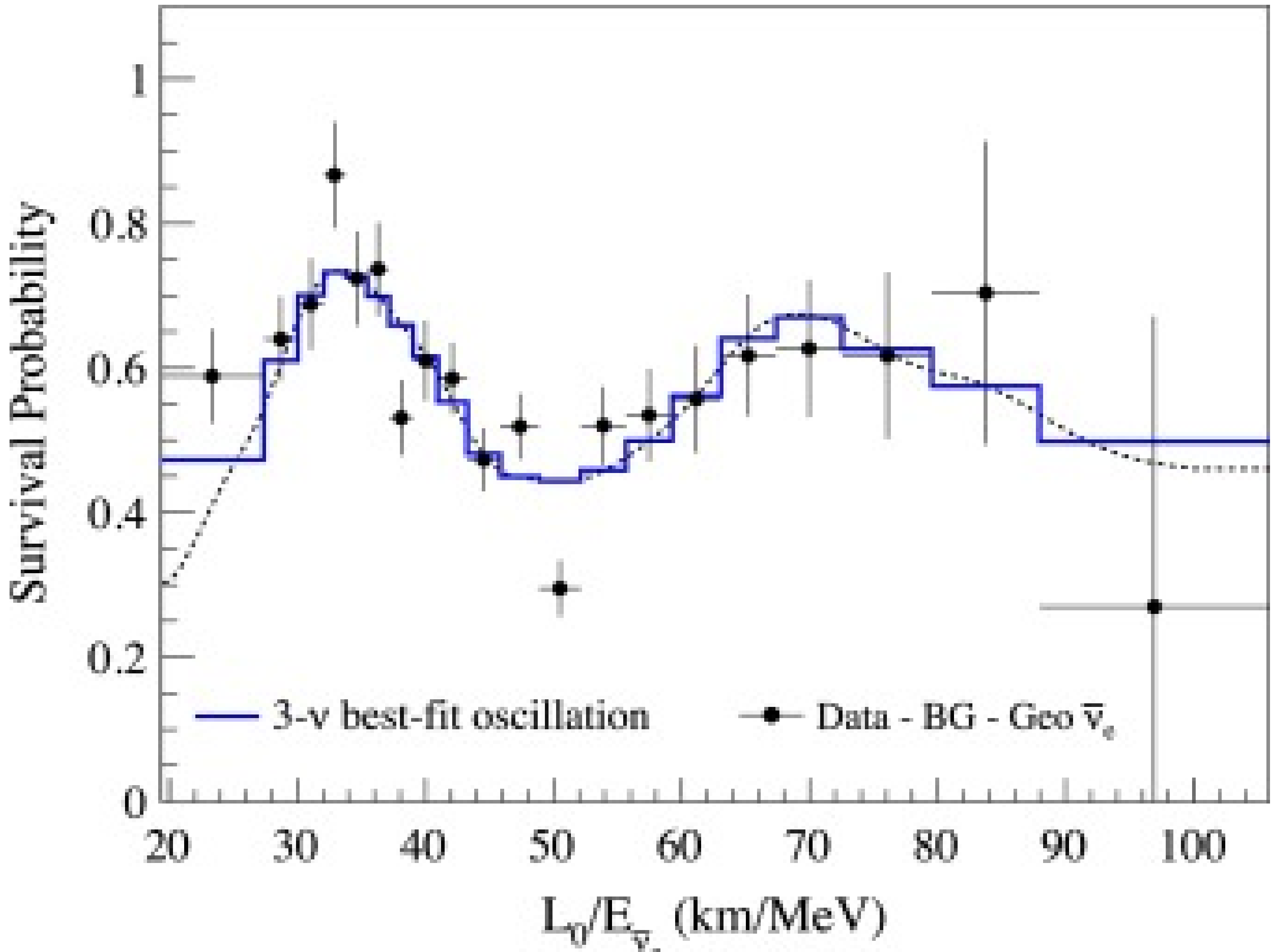
Also by coincidence, the energies and distances involved are such that the shape of the curve is related to Δm^2_{21} as the other term vanishes.

Digging deeper into the oscillations

We can also look at oscillations from man-made neutrinos: nuclear reactors and proton accelerators

KamLAND experiment in Japan

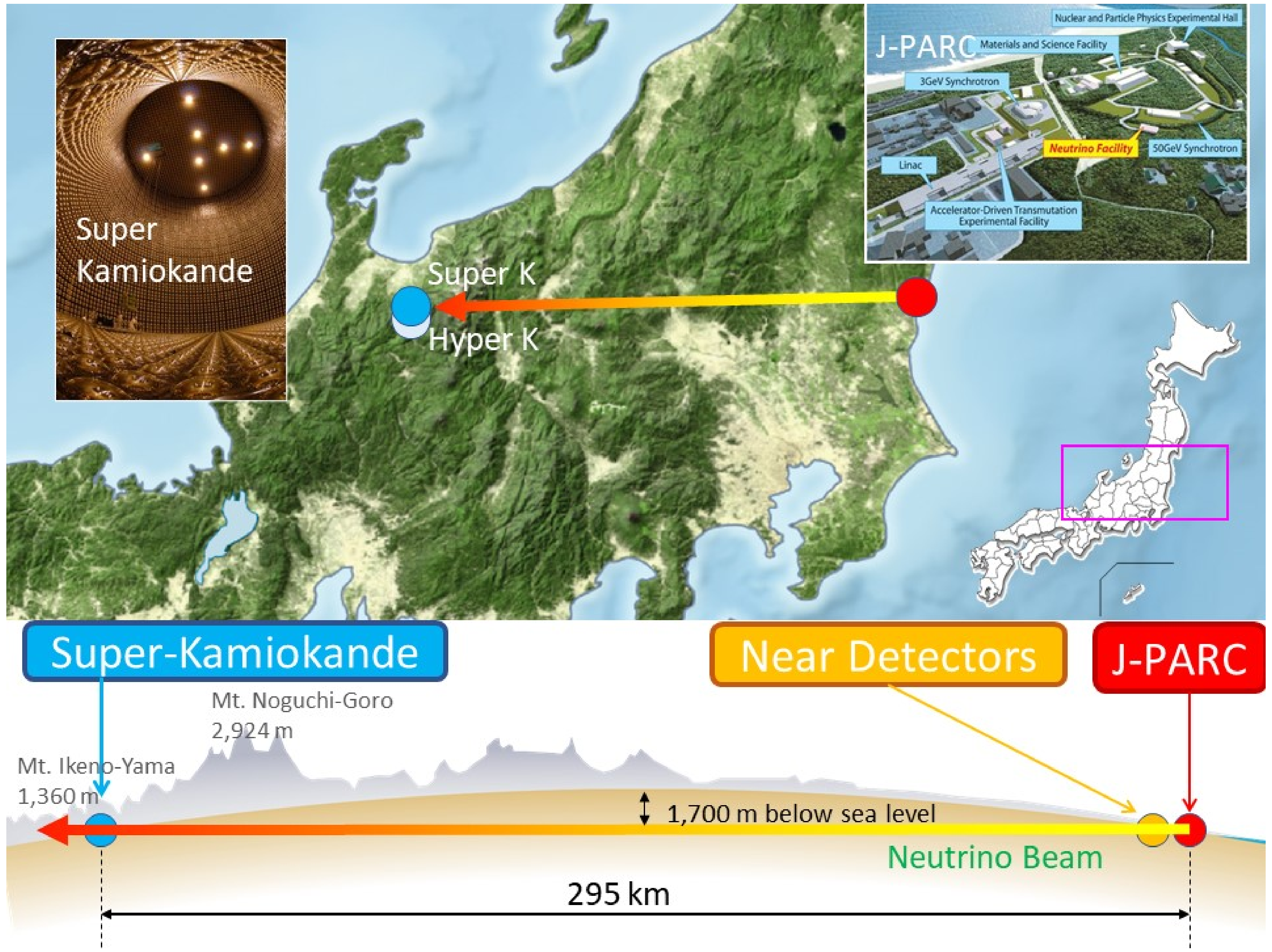




KamLAND proved that electron neutrinos oscillate as expected by our 3-flavour oscillation formalism

The benefit is that we can choose the distances, fluxes and energies

We build them so that we can measure the elusive 13 angle



T2K experiment (also in Japan)

Neutrinos oscillate!!

$$\nu_e, \nu_\mu, \nu_\tau = \boxed{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \boxed{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix}} \boxed{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}} |\nu_i\rangle$$

Measured by atmospheric experiments

Measured by reactor and accelerator experiments

Measured by solar experiments

Δm^2_{21} → **Measured by solar experiments. Turns out to be very small**

Δm^2_{32} → **Measured by atmospheric experiments. Turns out to be (relatively) large**

Neutrino oscillations

What are the values of the parameters?

δCP appears to be maximal ==> nearly as much CP violation as possible!

$$\nu_e, \nu_\mu, \nu_\tau = \boxed{\begin{bmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{bmatrix}}\boxed{\begin{bmatrix}c_{13}&0&s_{13}e^{-i\delta_{\mathrm{CP}}}\\0&1&0\\-s_{13}e^{i\delta_{\mathrm{CP}}}&0&c_{13}\end{bmatrix}}\boxed{\begin{bmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{bmatrix}}|\nu_i\rangle$$

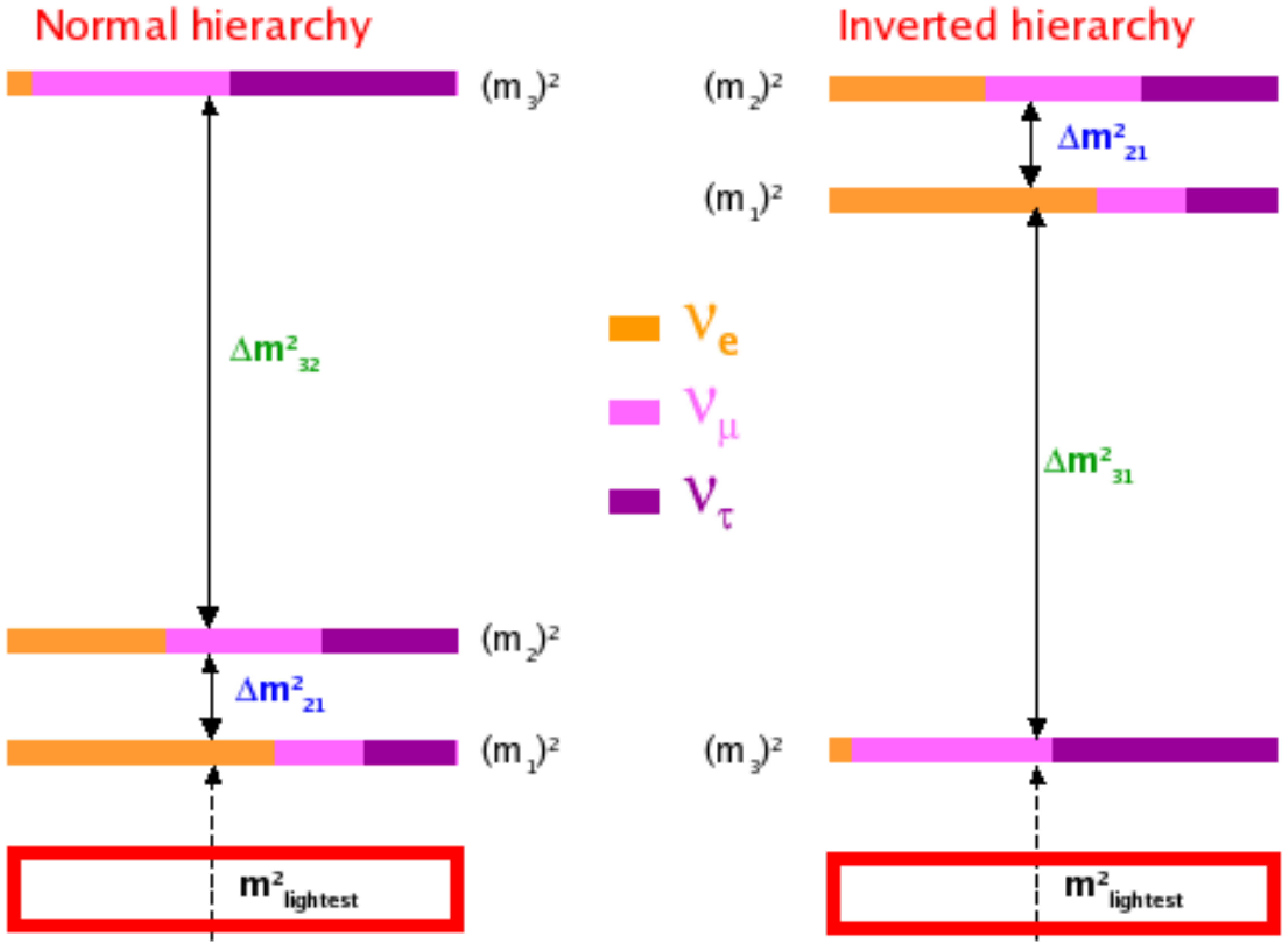
θ_{23} is approximately 45º ==> ν_μ and ν_τ are equidistant to the mass states

θ_{13} is very small ==> there is very little overlap between ν_e and ν_3

θ_{12} is approximately 30º ==> ν_1 is closer to ν_e than ν_2

Δm^2_{21}

Δm^2_{32}



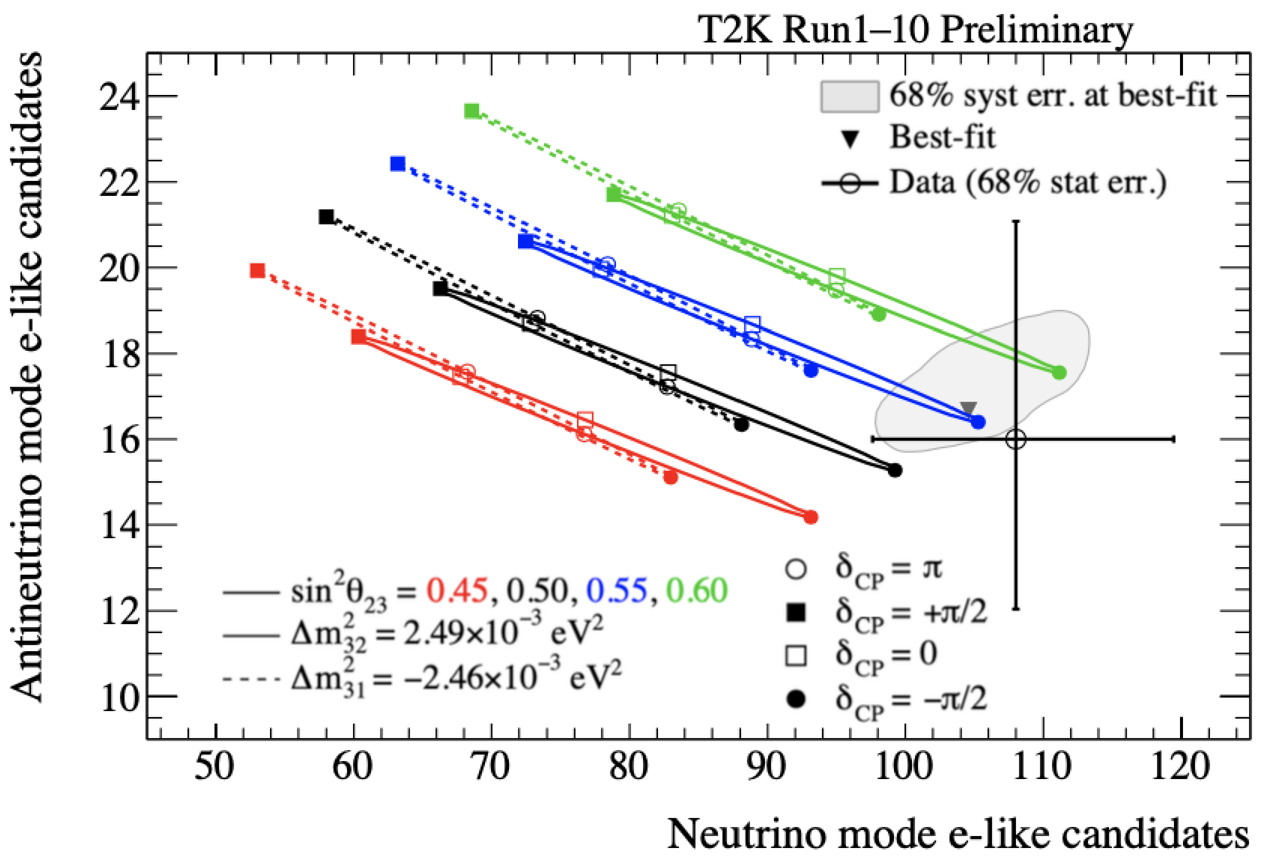
Hierarchy problem:

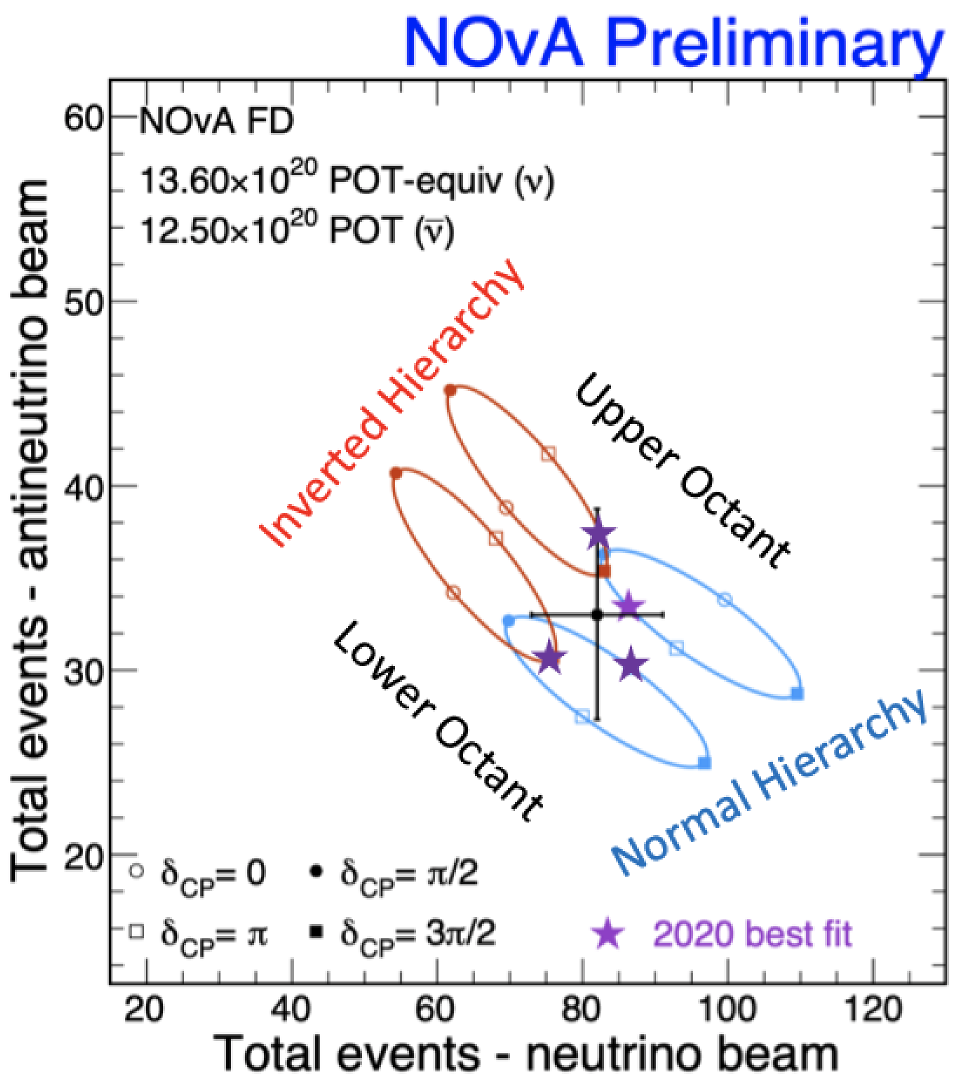
We know that two neutrinos are very similar in mass and one is either much lighter or much heavier, but we do not know which of the two it is.

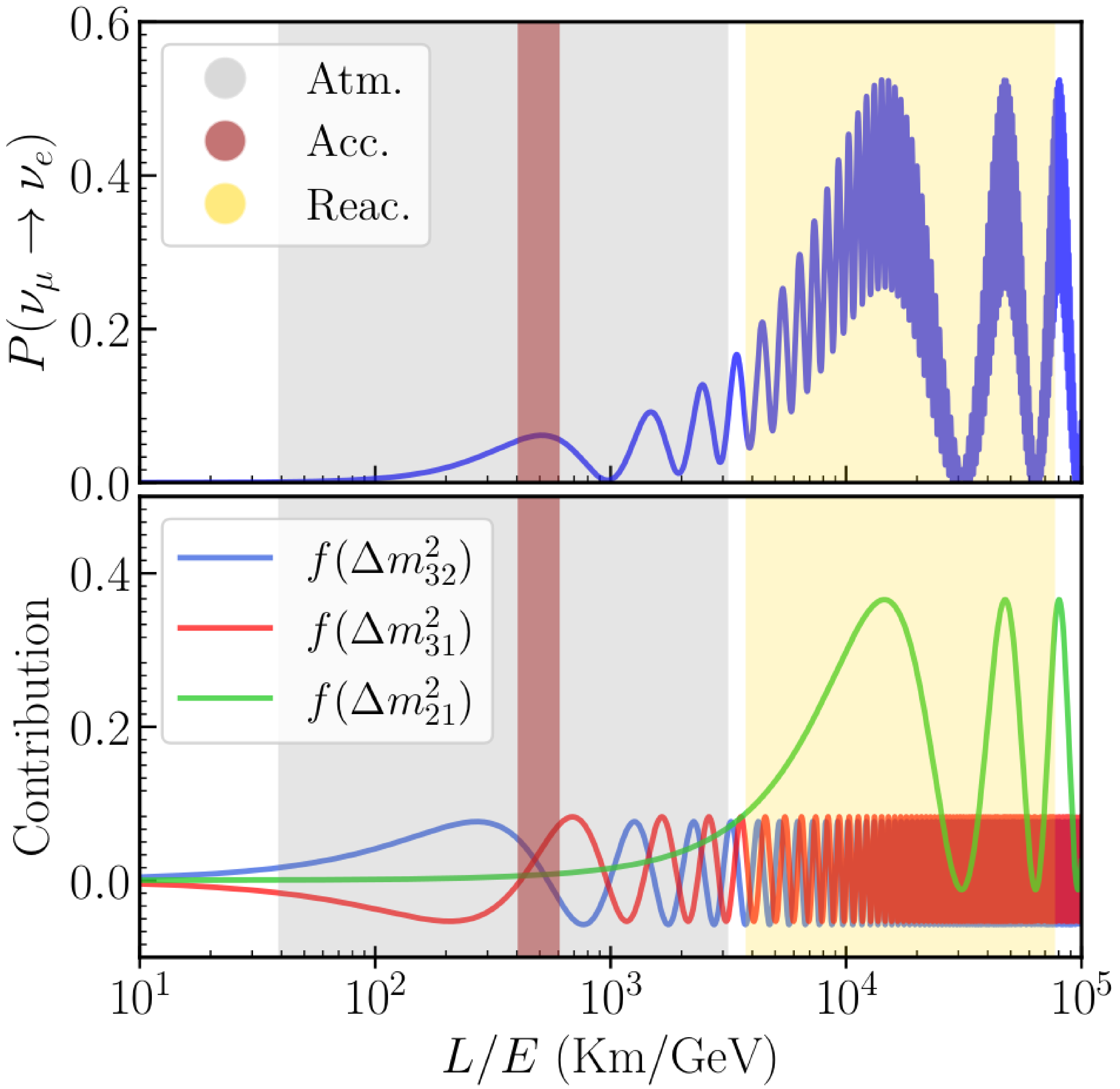
Putting everything together

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$
$$+ 2\sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

The "hierarchy" in the values of the angles and mass splittings, give a complicated oscillation signal ==> we need many different experimental setups to fully explore it



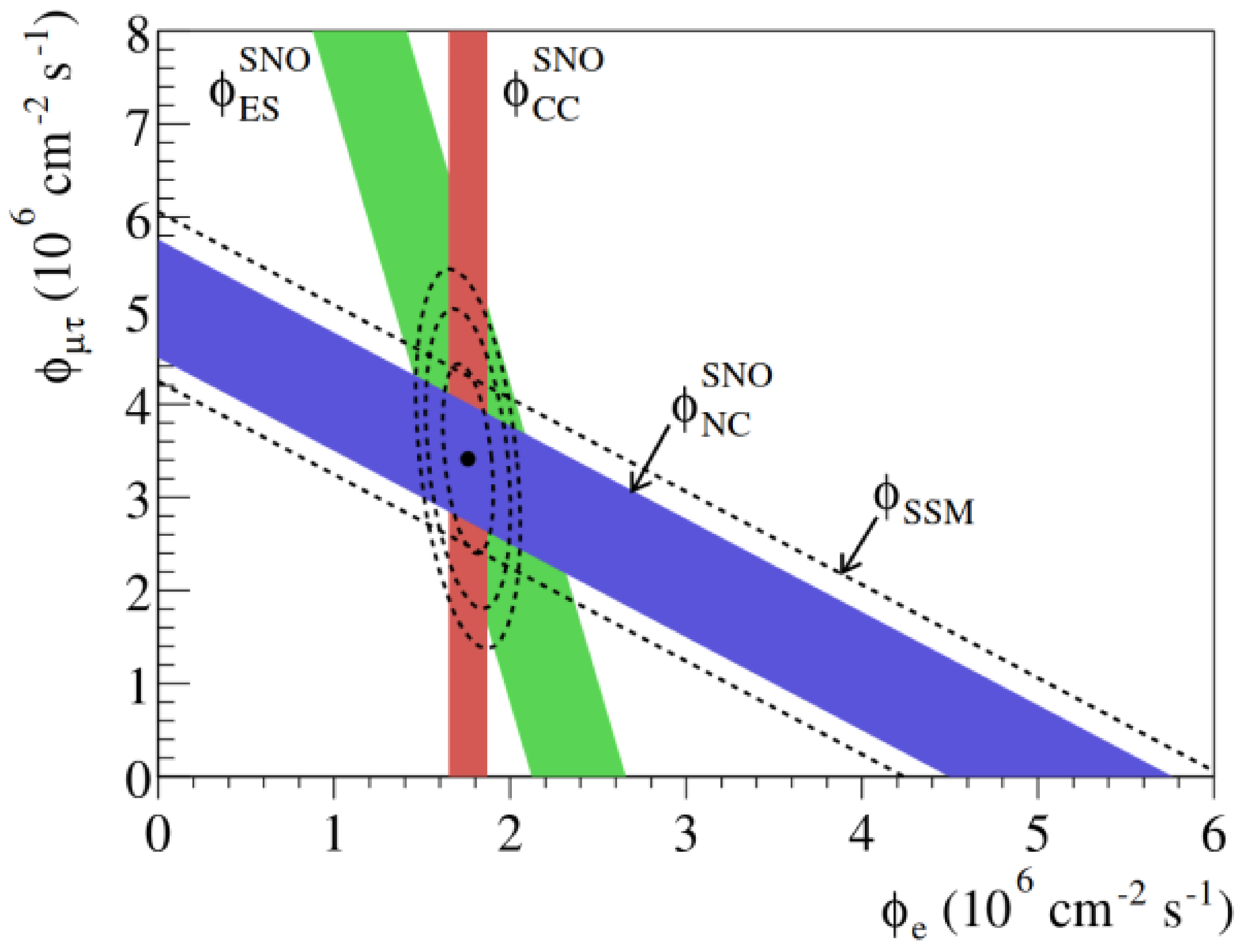


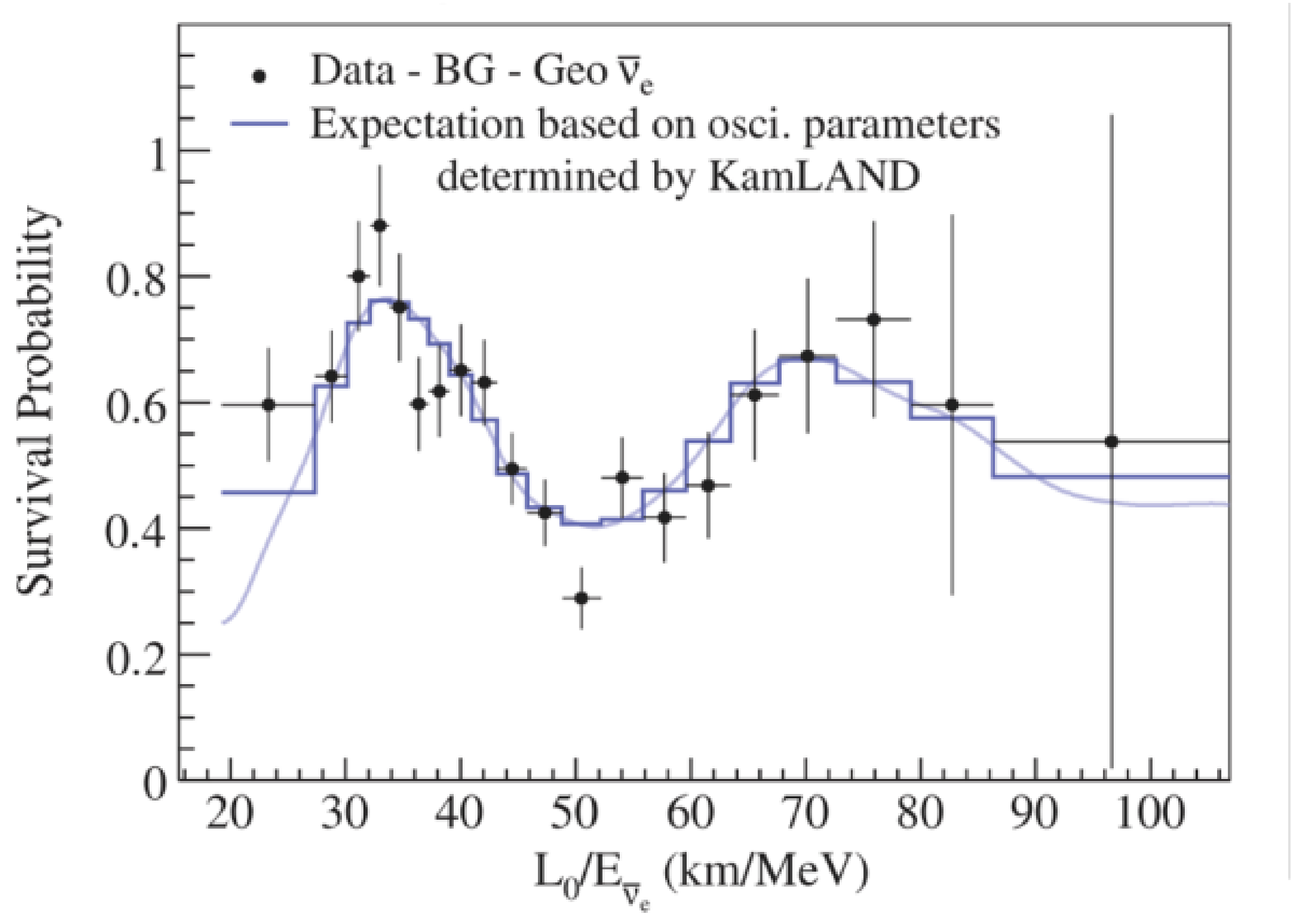


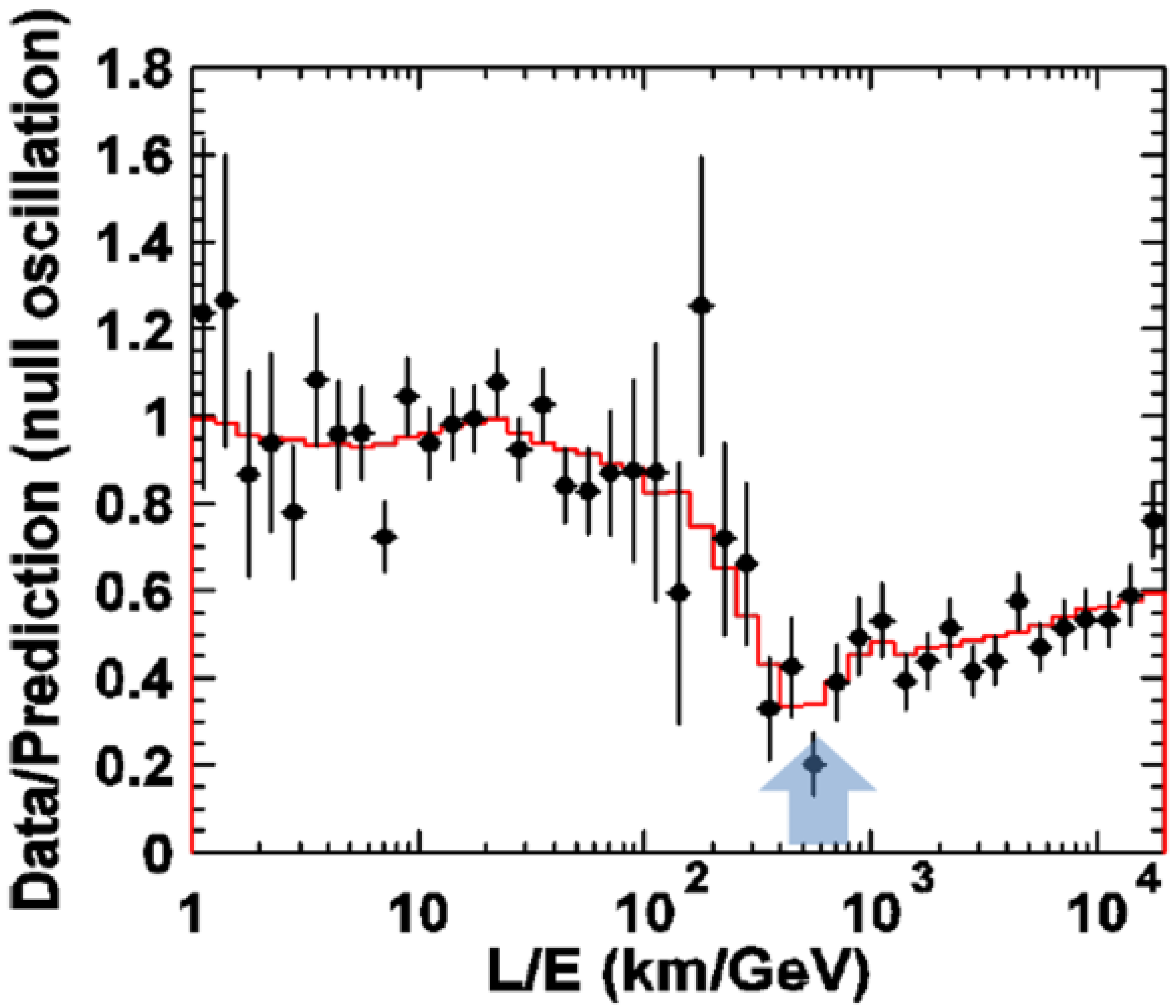
Experiments are full of blind spots and the parameters are often strongly correlated, making the measurement very difficult but also creating very exciting challenges

What do we look for in neutrino physics?

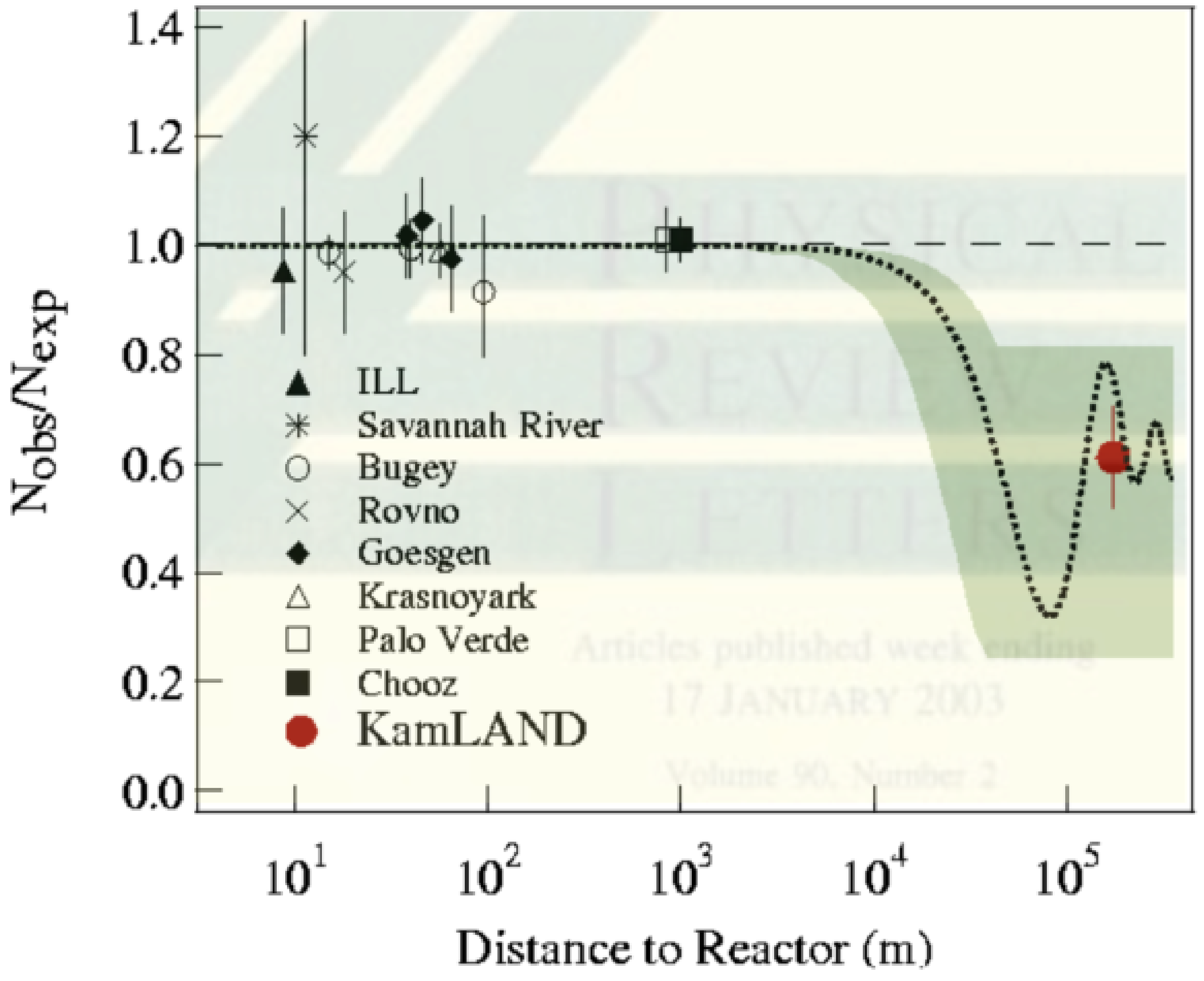
- We know that neutrinos oscillate and are therefore massive particles







First KamLAND Results (2002)

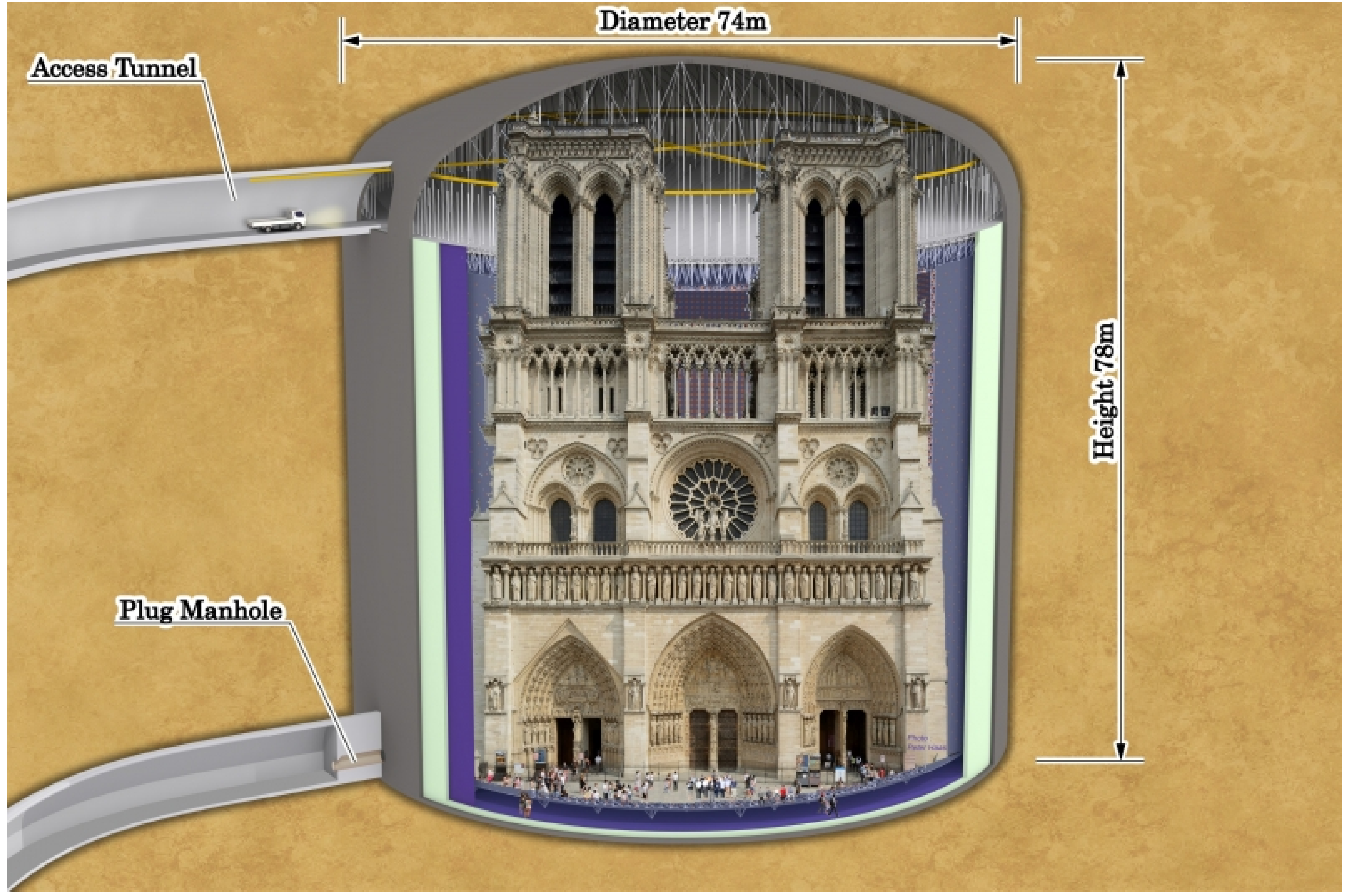


Neutrino physics today

What do we look for in neutrino physics?

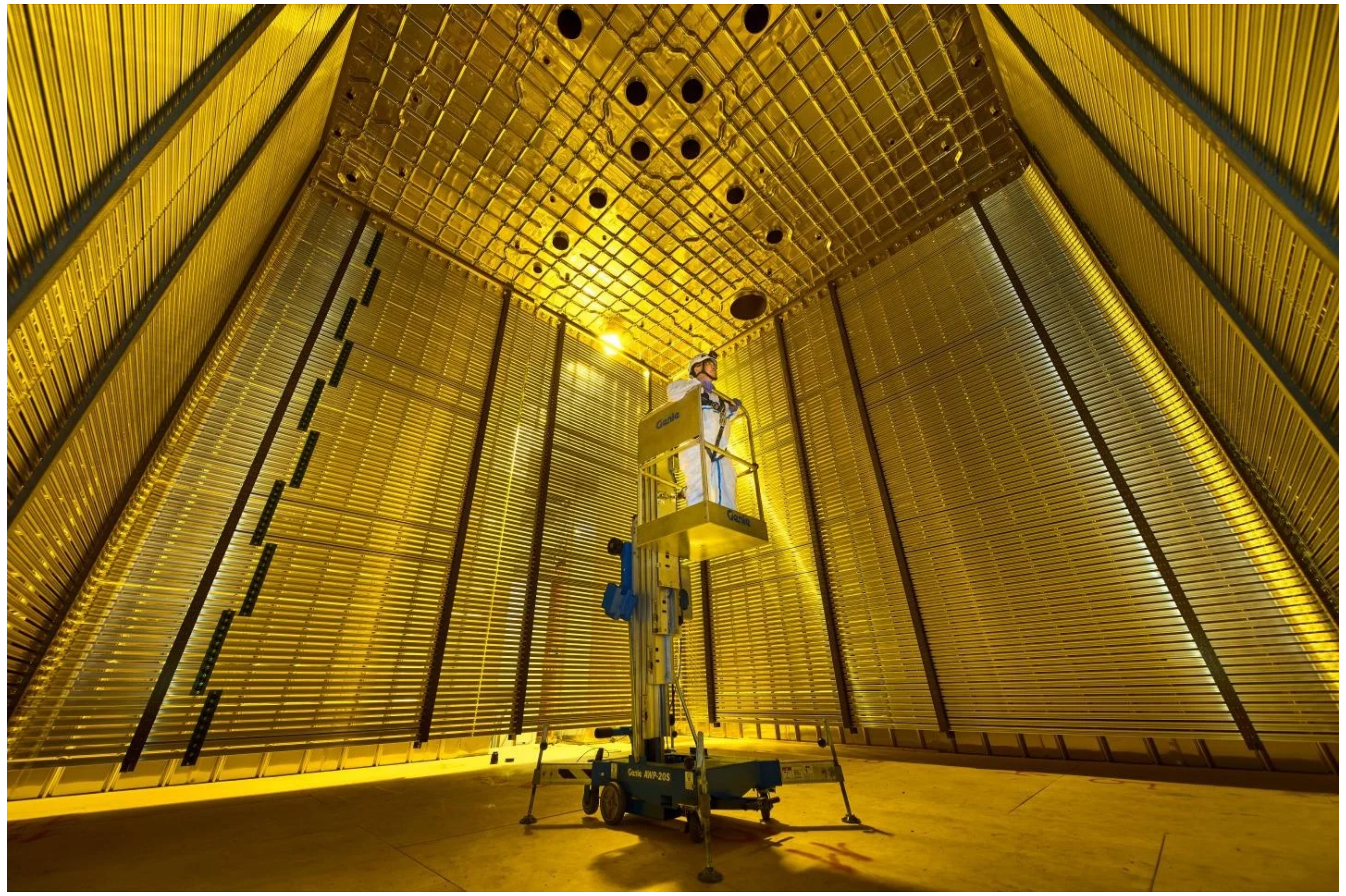
○ Is there enough CP violation to explain the asymmetry between matter and antimatter in the visible universe? → Many upcoming experiments aim to answer this question

T2HK in Japan



Notre-Dame will fit inside Hyper-Kamiokande !

DUNE in the US

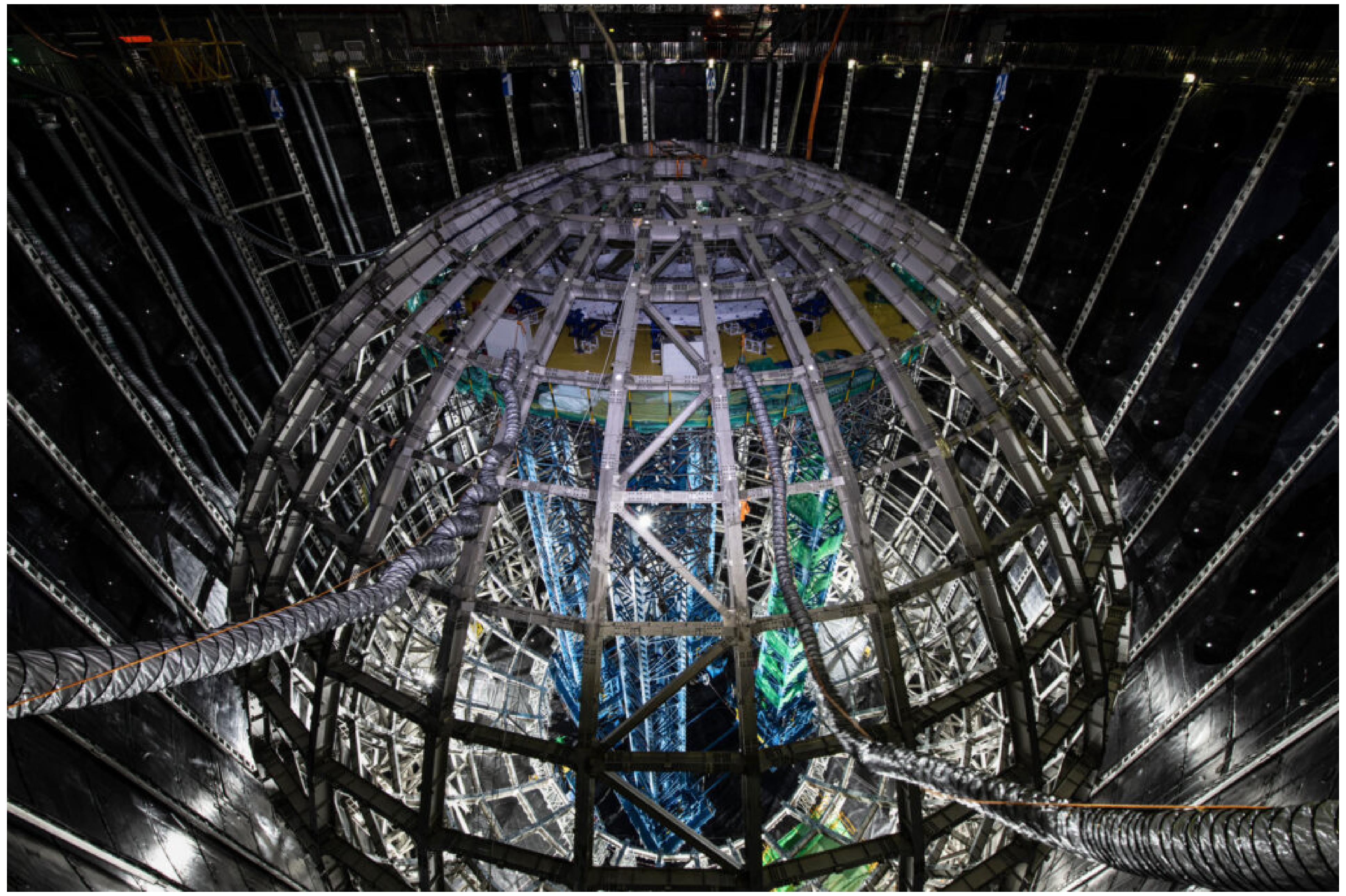


Inside DUNE prototype (6×6×6 m^3) at CERN
-> Future : 4 modules of 60×12×12 m^3 each

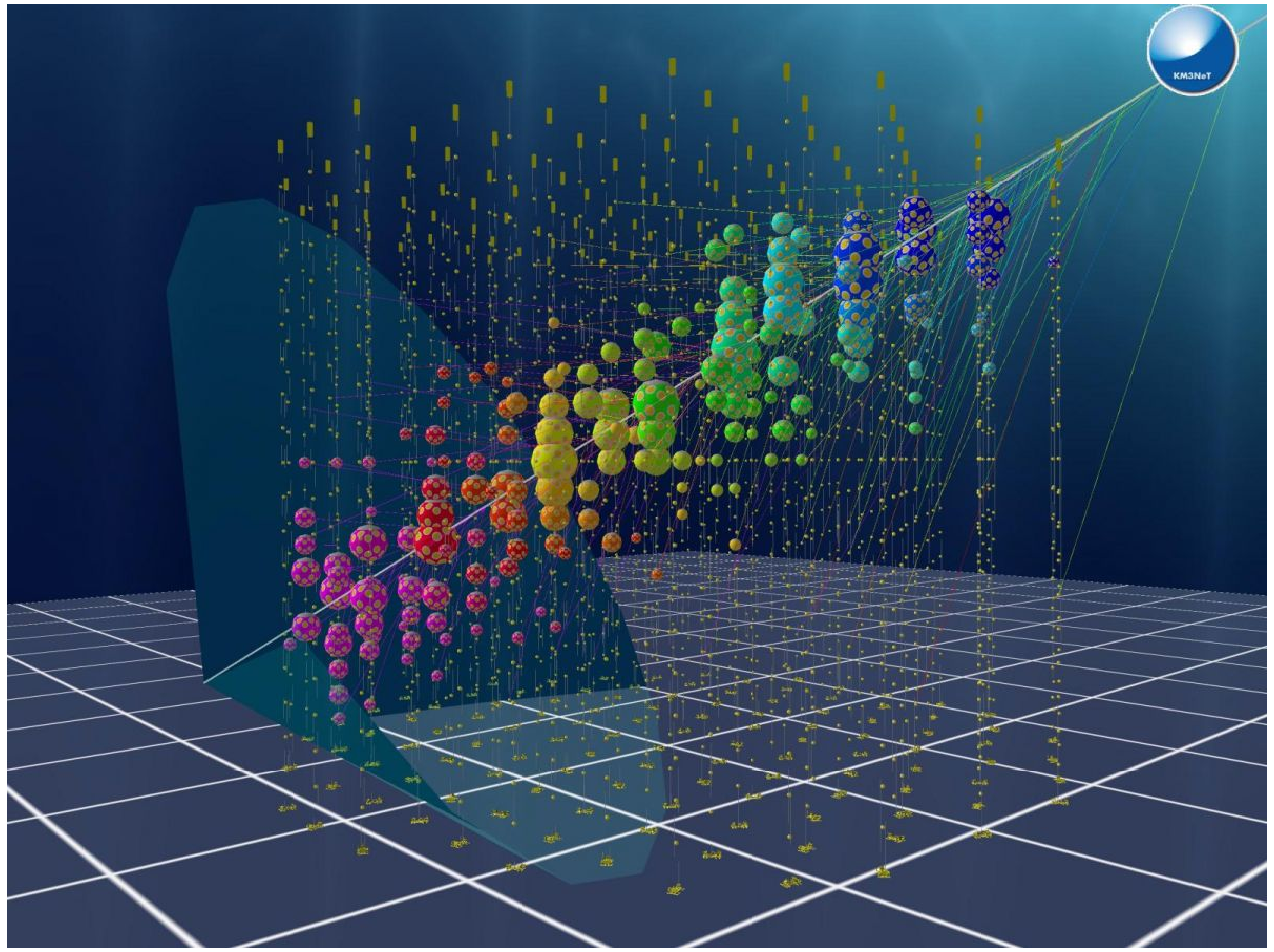
What do we look for in neutrino physics?

- Which mass hierarchy is the correct one?

Juno in China



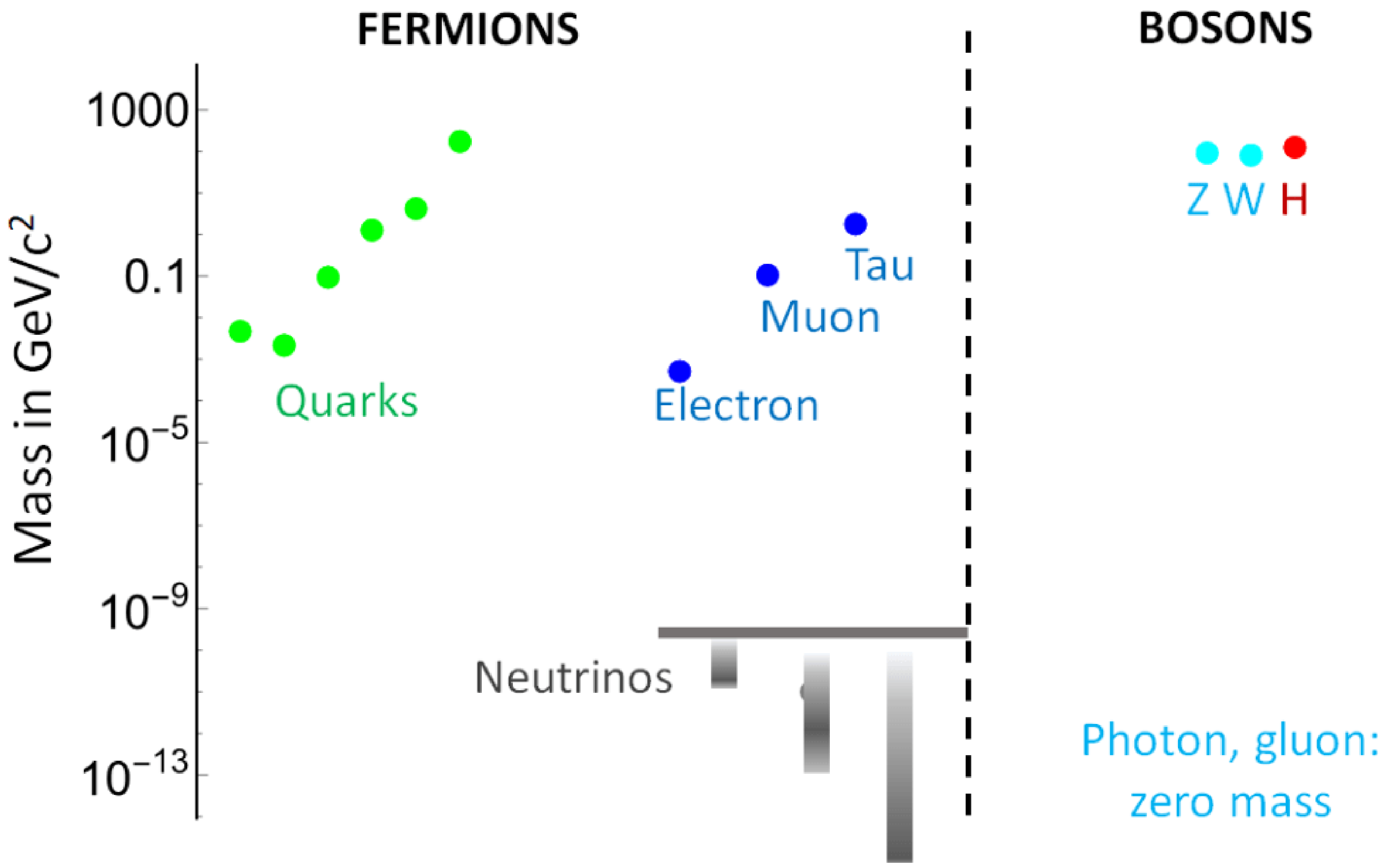
KM3Net in the Mediterranean



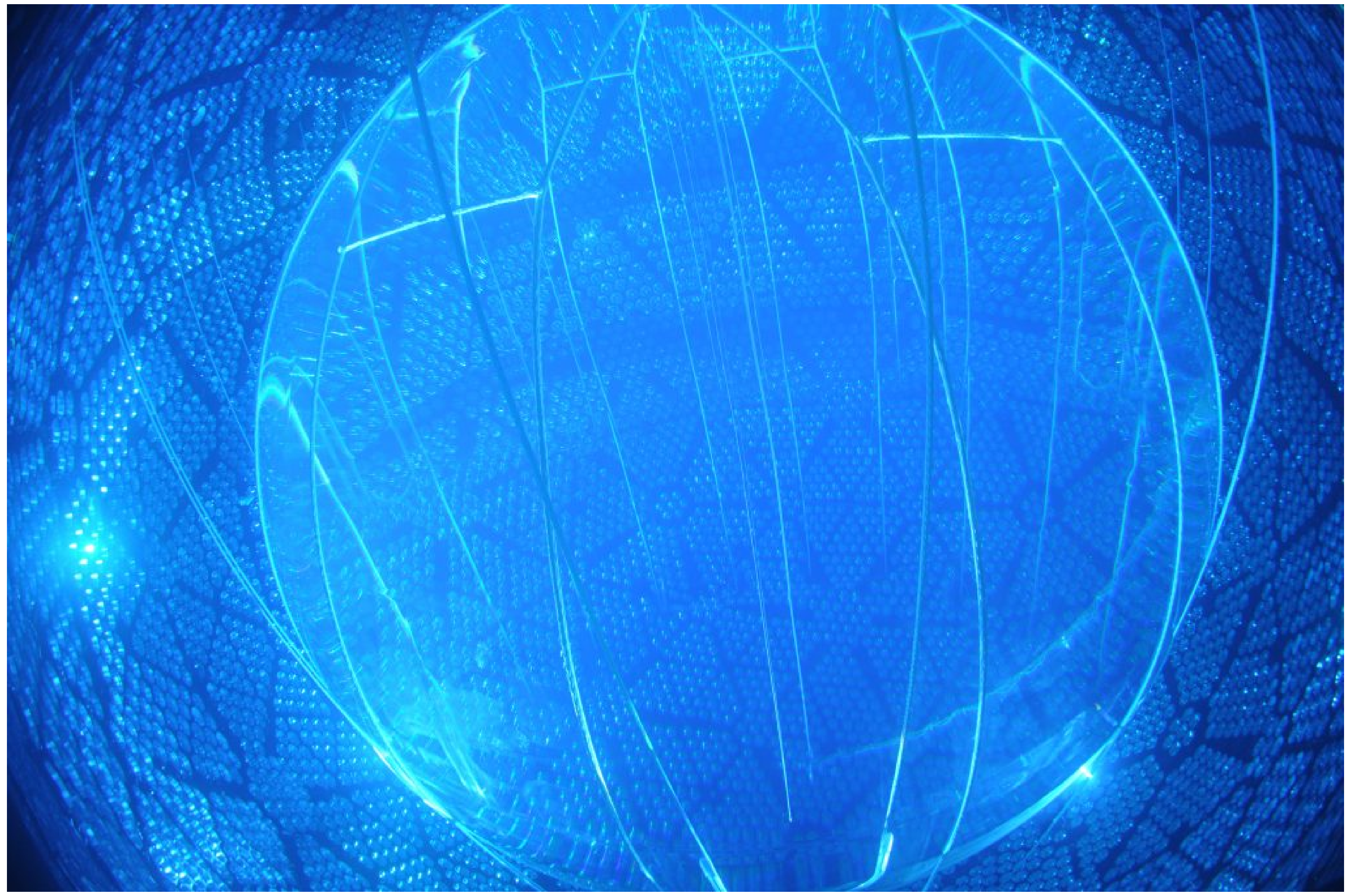
- θ_{23} appears to be close to 45°. This is unexpected for a random matrix. Are we looking at the broken remains of some high-energy symmetry?

What do we look for in neutrino physics?

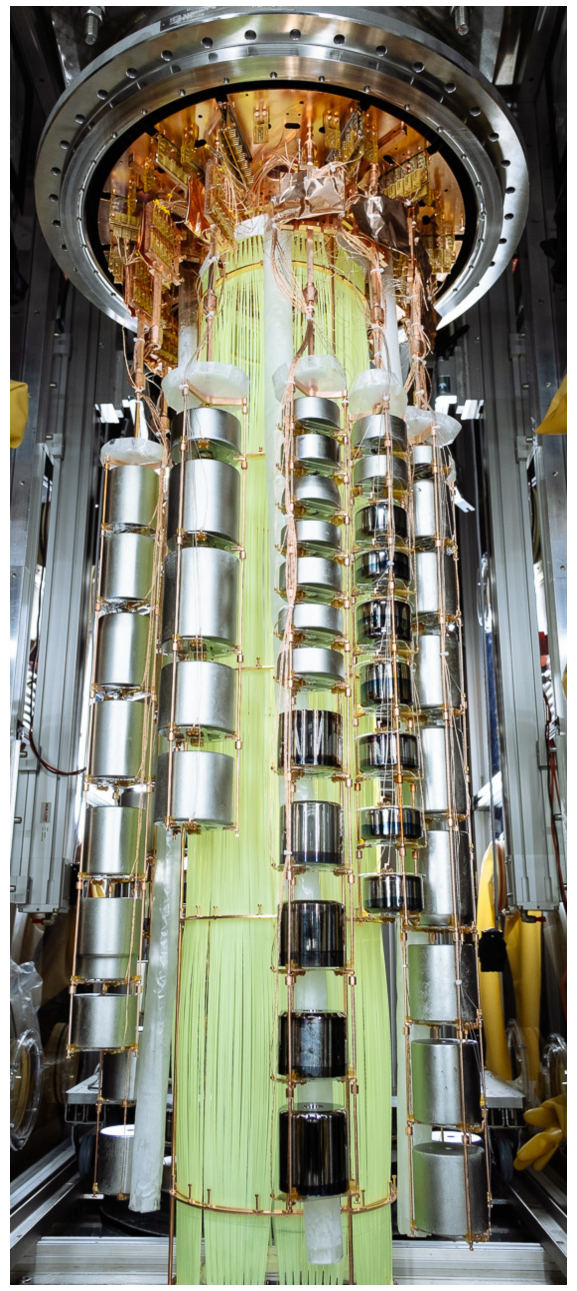
○ Do neutrinos acquire mass through the usual Higgs mechanism? Their couplings would have to be unreasonably small!



SNO+ in canada



Legend200 in Italy

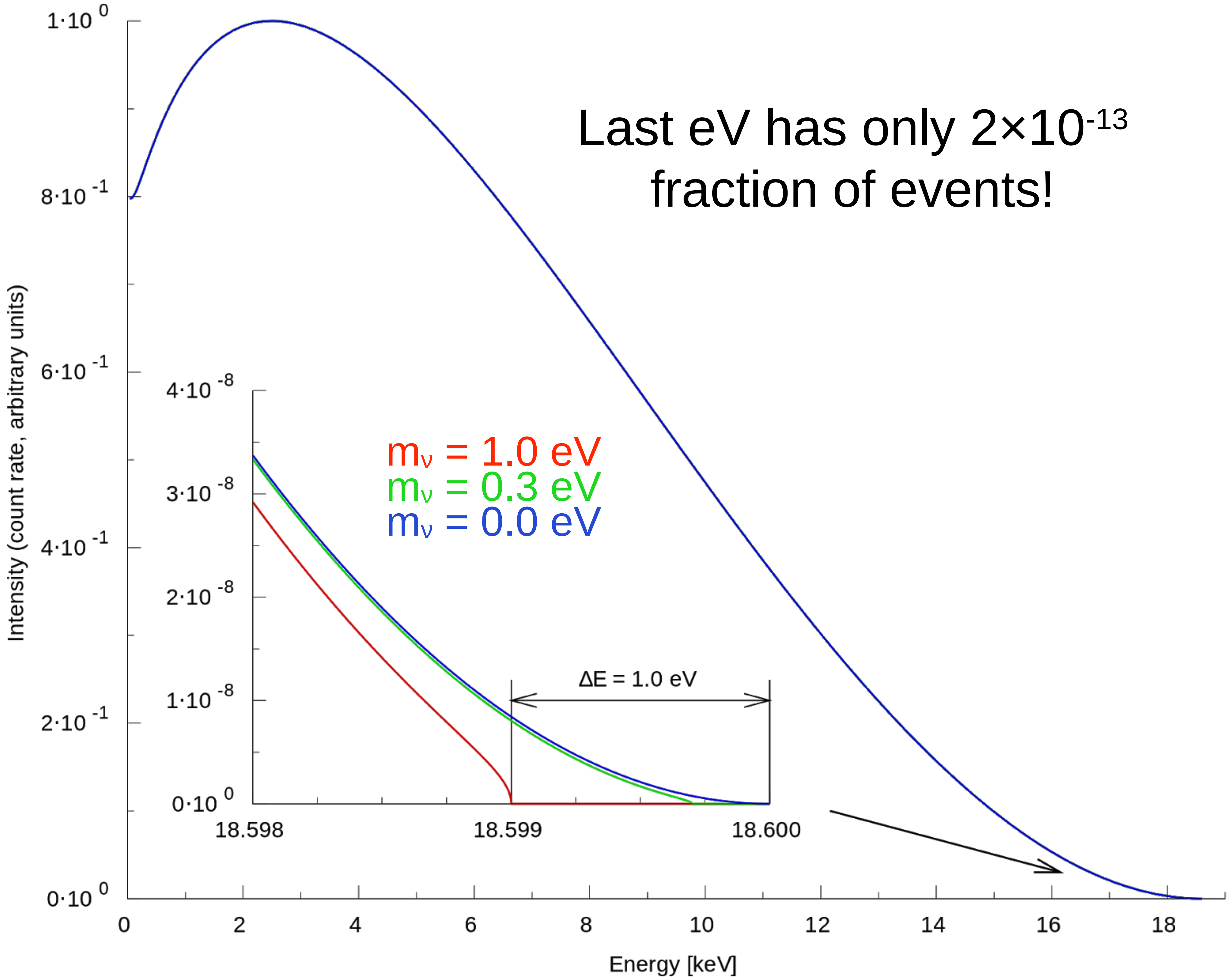


○ These couplings would be naturally suppressed if neutrinos were their own antiparticles. Some experiments look for interactions that would only be possible if this were the case!

What do we look for in neutrino physics?

○ What is the mass scale of the neutrinos (we know the mass differences, but not the actual mass values!)

Installation of KATRIN experiment

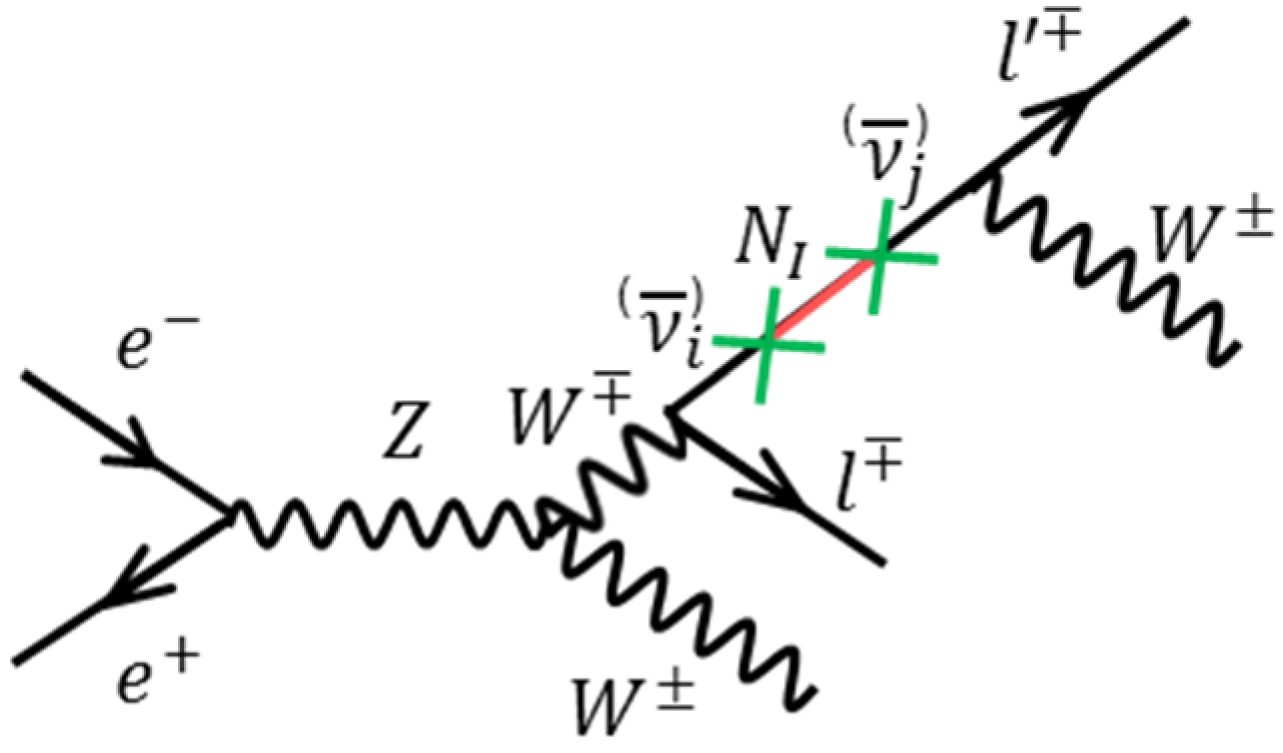


Last eV has only 2×10^{-13} fraction of events!

○ KATRIN is still looking at the tail-end of the same β-decay spectrum responsible for the idea of the neutrino 100 years ago!

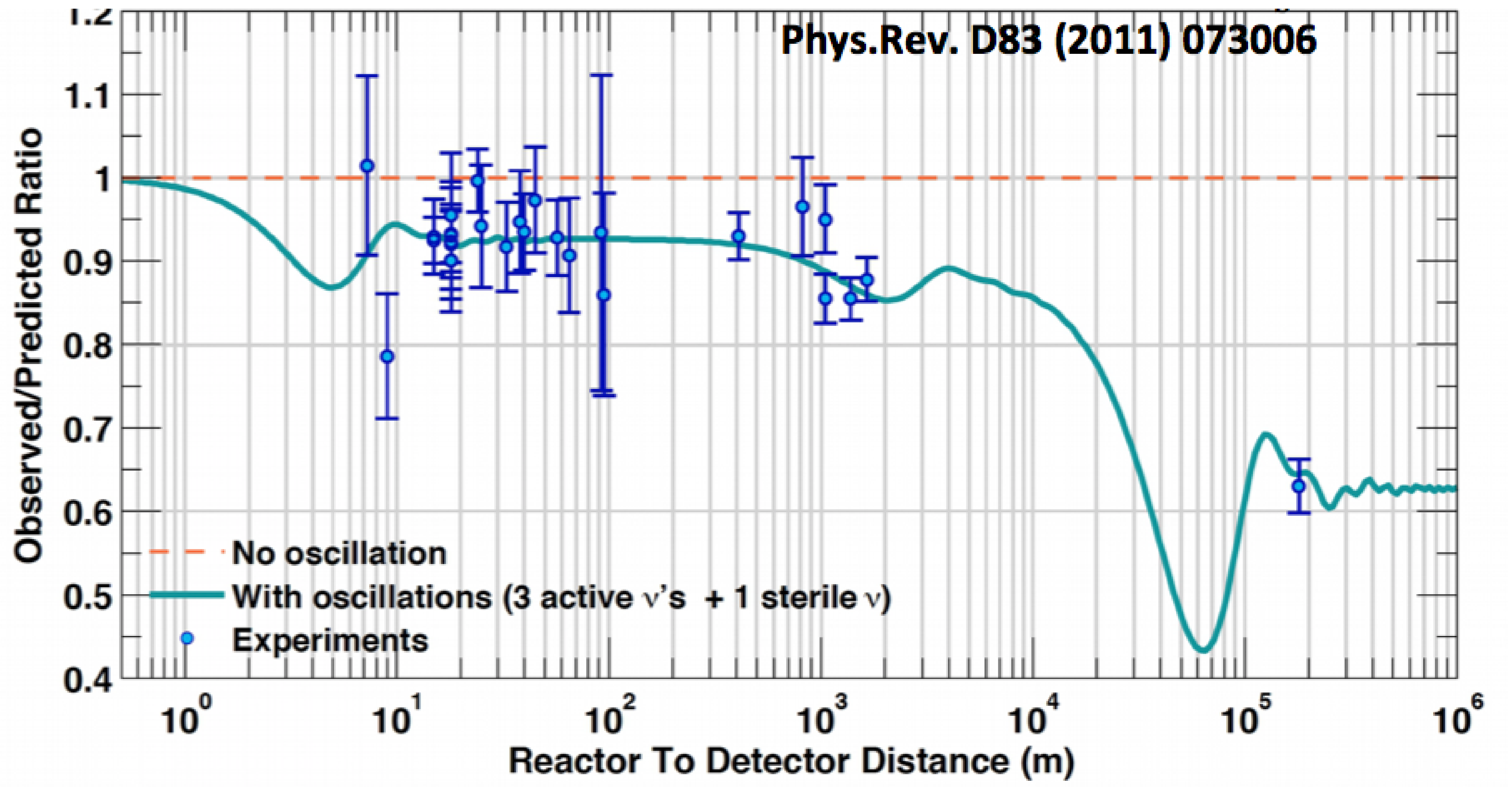
What do we look for in neutrino physics?

- ○ What would right-handed neutrinos be like? (The weak interaction only affects left-handed particles)



Could they be dark matter candidates?

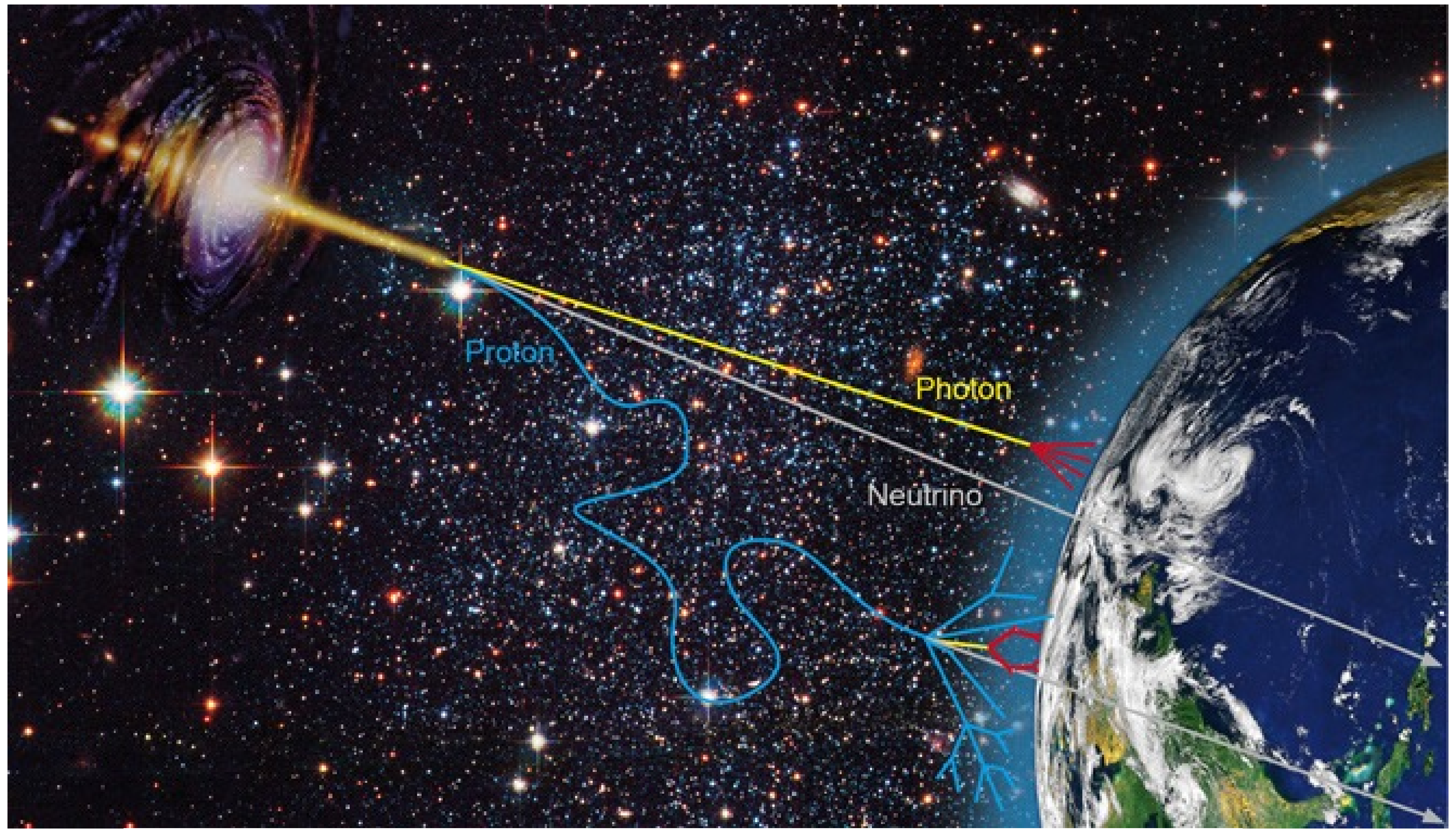
Some experimental discrepancies with the 3-flavour oscillation model can be explained by introducing a 4th oscillating neutrino state

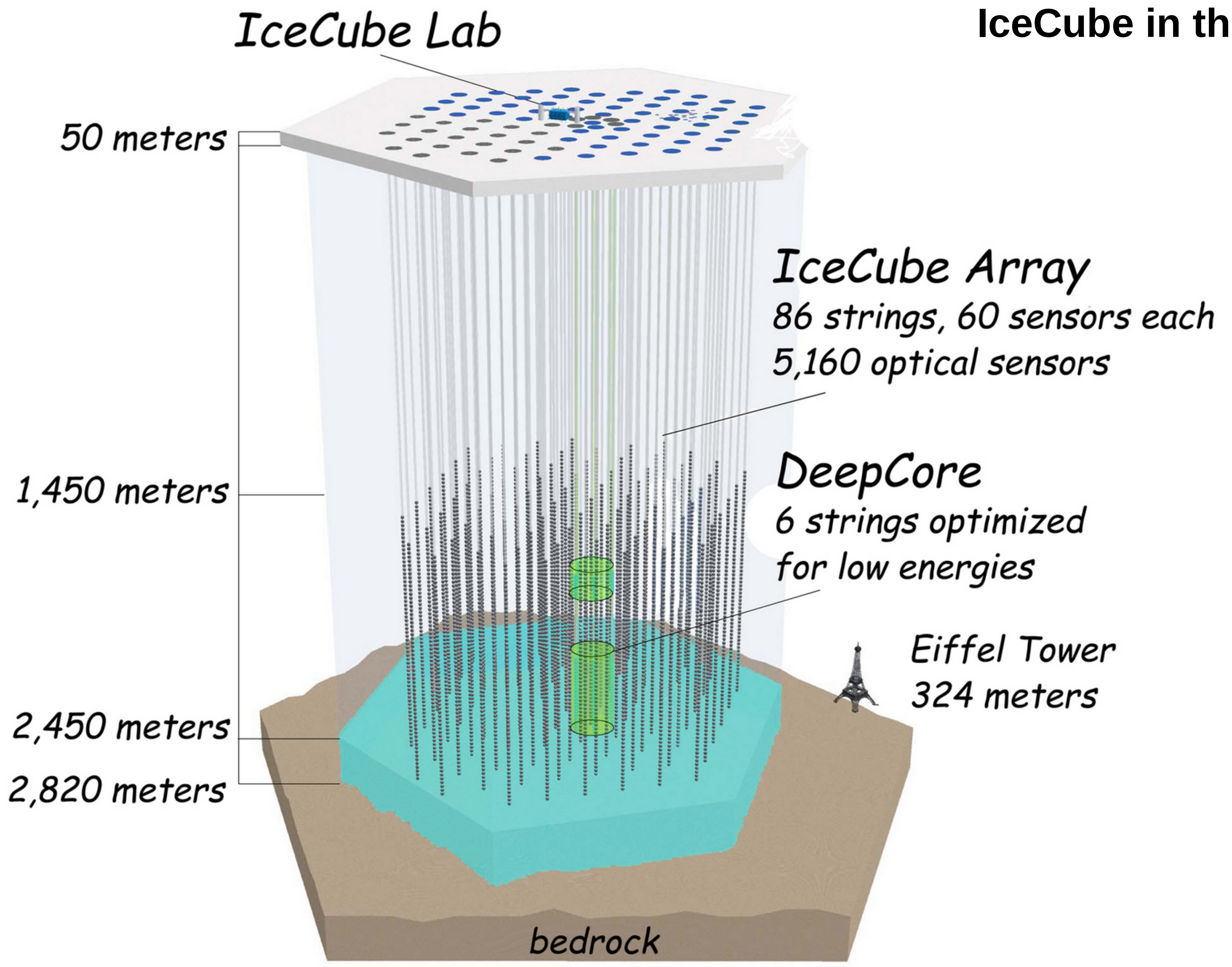


- ○ Only three generations of neutrinos couple to the Z boson. How do we know there are not additional 'sterile' generations?

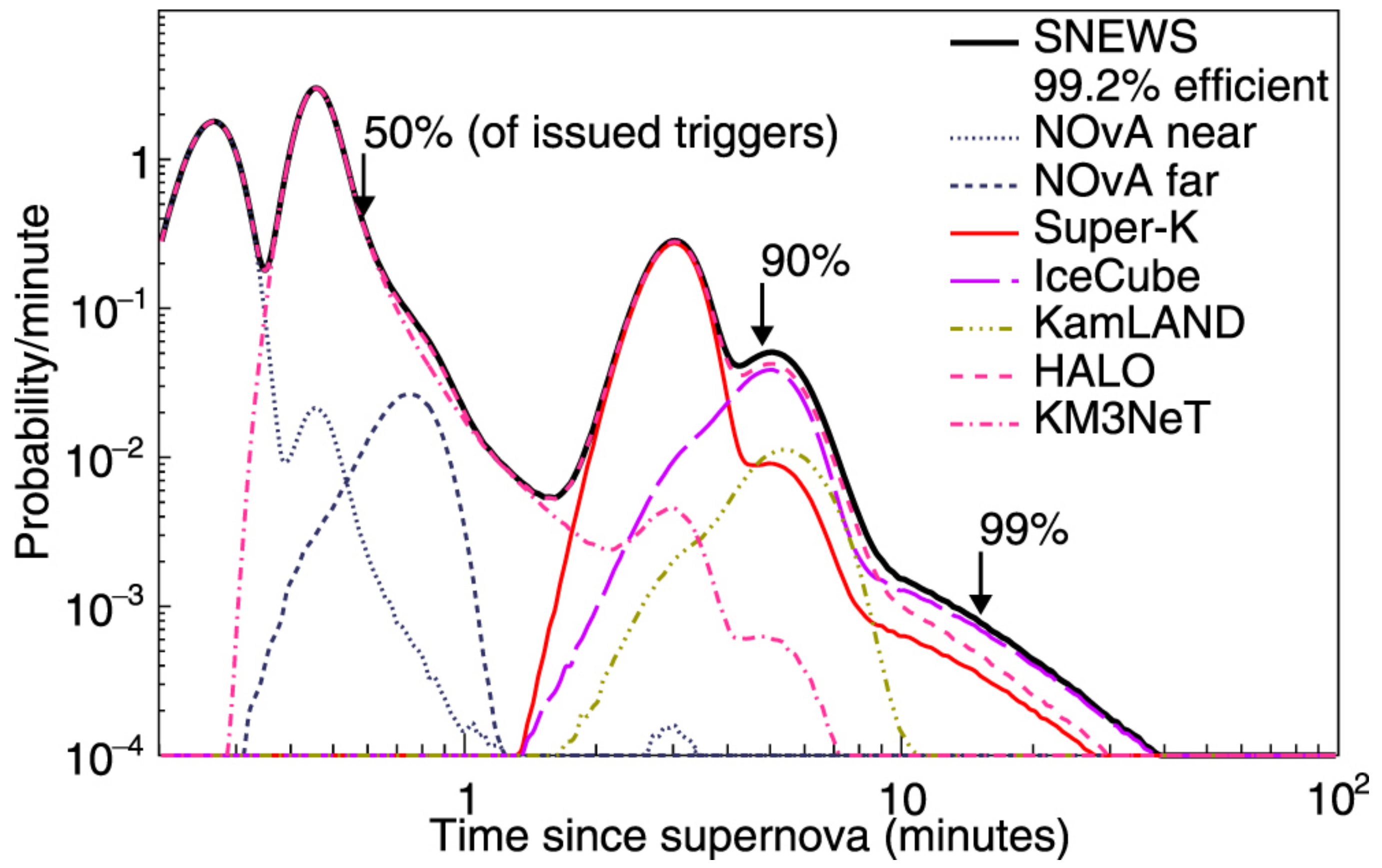
What do we look for in neutrino physics?

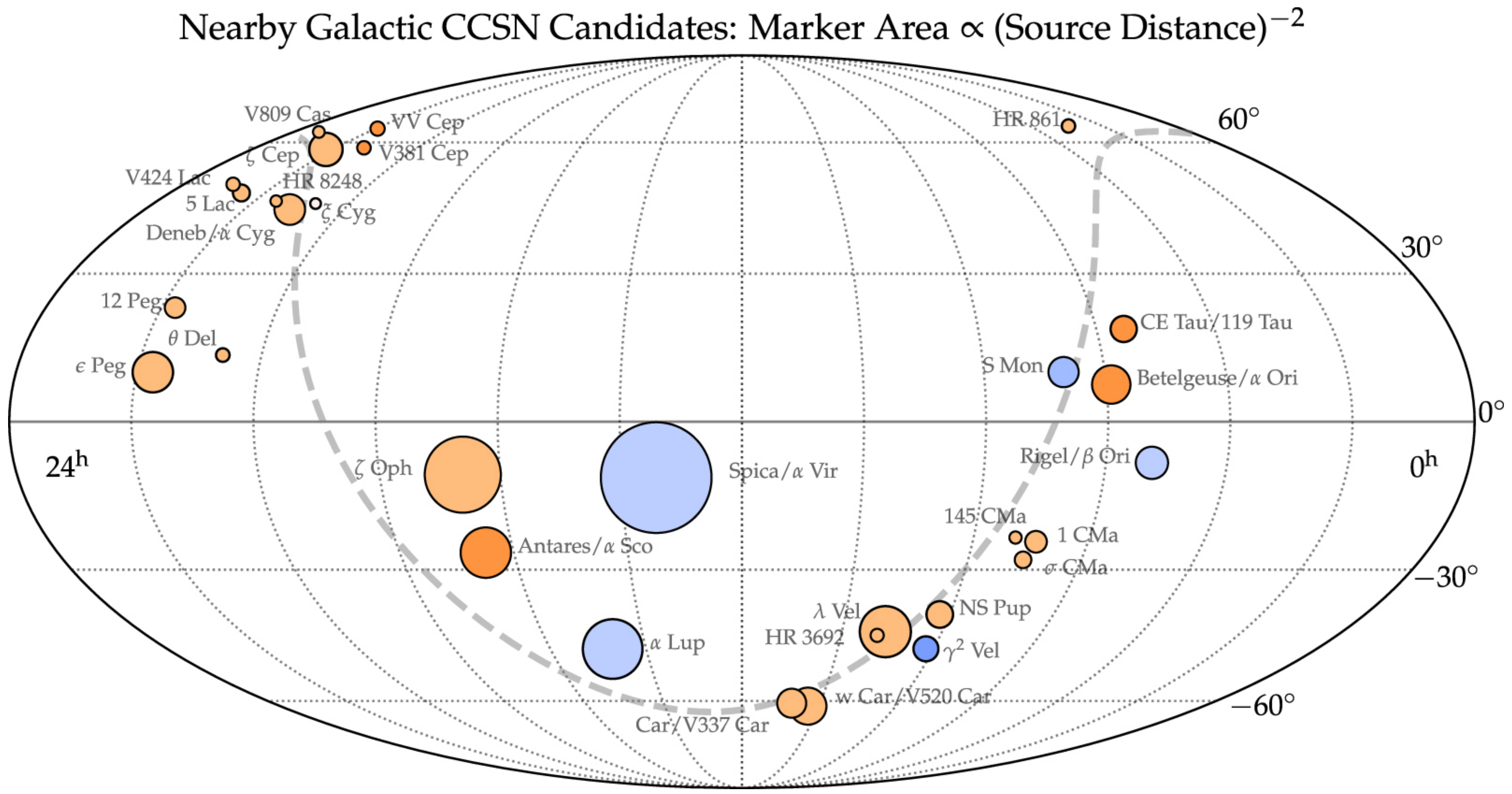
- What are the sources of astrophysical and cosmogenic neutrino signals?





IceCube in the South Pole





- Neutrinos allow for supernova model discrimination!

Conclusions

○ Neutrinos are massive weakly interacting particles that propagate in flavour-violating oscillations

○ We have a broad understanding of these oscillations but many details remain unanswered

○ We do not know how their masses are produced

○ In spite of being the most common massive particle in the universe, we do not know where exactly where extraterrestial signals come from

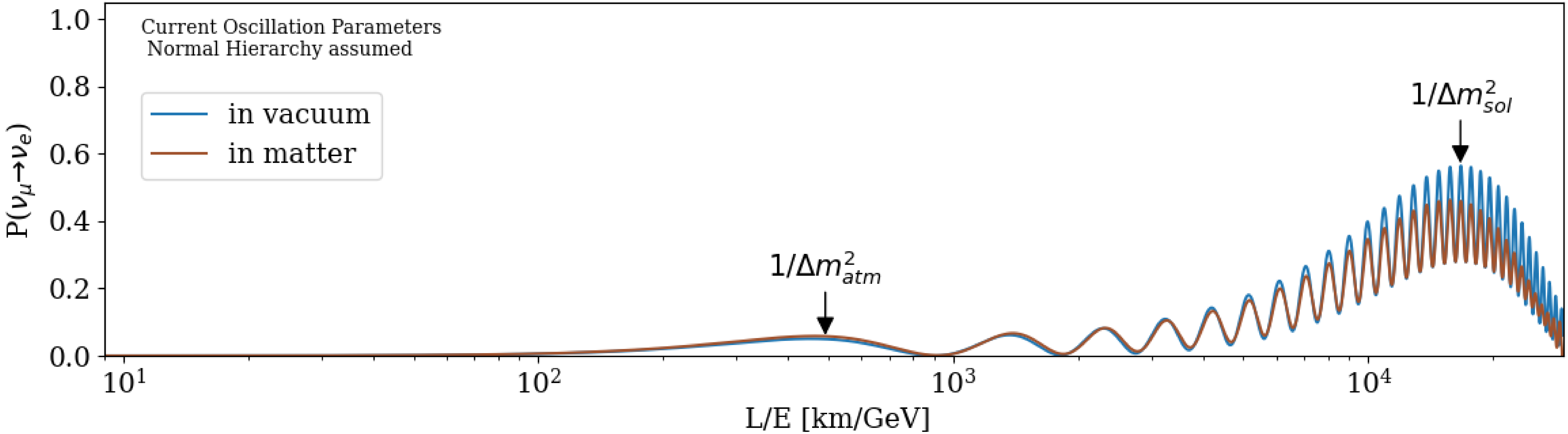
○ They are very challenging (and fun!) to measure, and there are a great many number of huge experiments planned for the “near” future

The end™

Backups and extra stuff

Oscillations with 3 flavors in matter

Even the earth crust has an impact on neutrino oscillations (denser matter -> stronger effect)



The earth density is not constant -> stronger modification of the neutrino oscillation probability when crossing the earth core

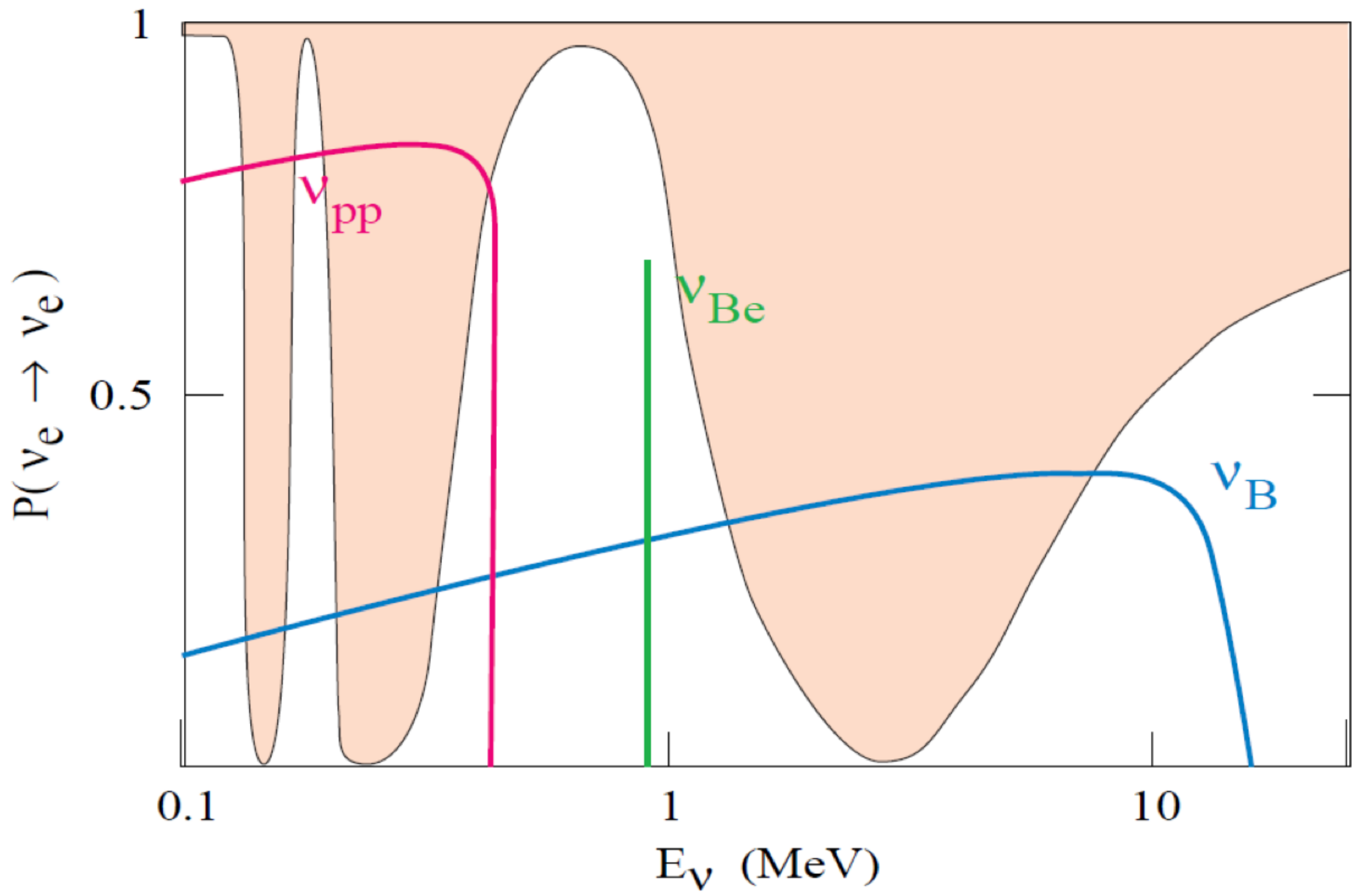
Oscillations parameters

Current values of the oscillation parameters:

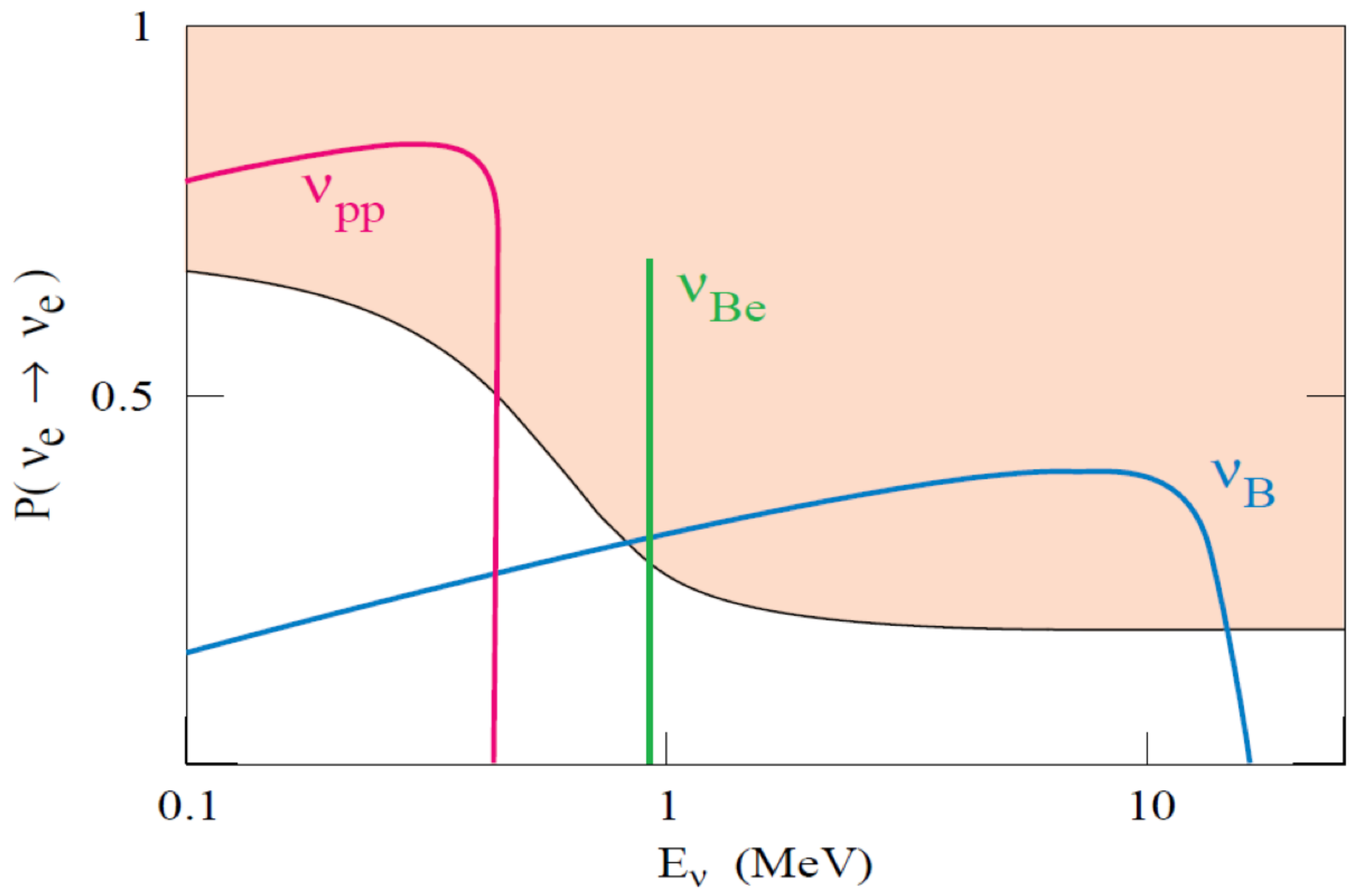
$$\begin{aligned}
\theta_{12} &= 33.45^{+0.77}_{-0.75} \\
\theta_{23} &= 42.1^{+1.1}_{-0.9} \\
\theta_{13} &= 8.62^{+0.12}_{-0.12} \\
\Delta m^2_{\rm sol} = \Delta m^2_{12} &= 7.42^{+0.21}_{-0.20} \times 10^{-5}\ {\rm eV}^2 \\
|\Delta m^2_{\rm atm}| = |\Delta m^2_{3\ell}| &= 2.510^{+0.027}_{-0.027} \times 10^{-3}\ {\rm eV}^2
\end{aligned}$$

- Oscillations in vacuum are not sensitive to the sign of Δm^2
- Matter effects helps to determine Δm^2 sign:
  - $m_2 > m_1$ from solar ν_e
    - Not yet resolved for m_3

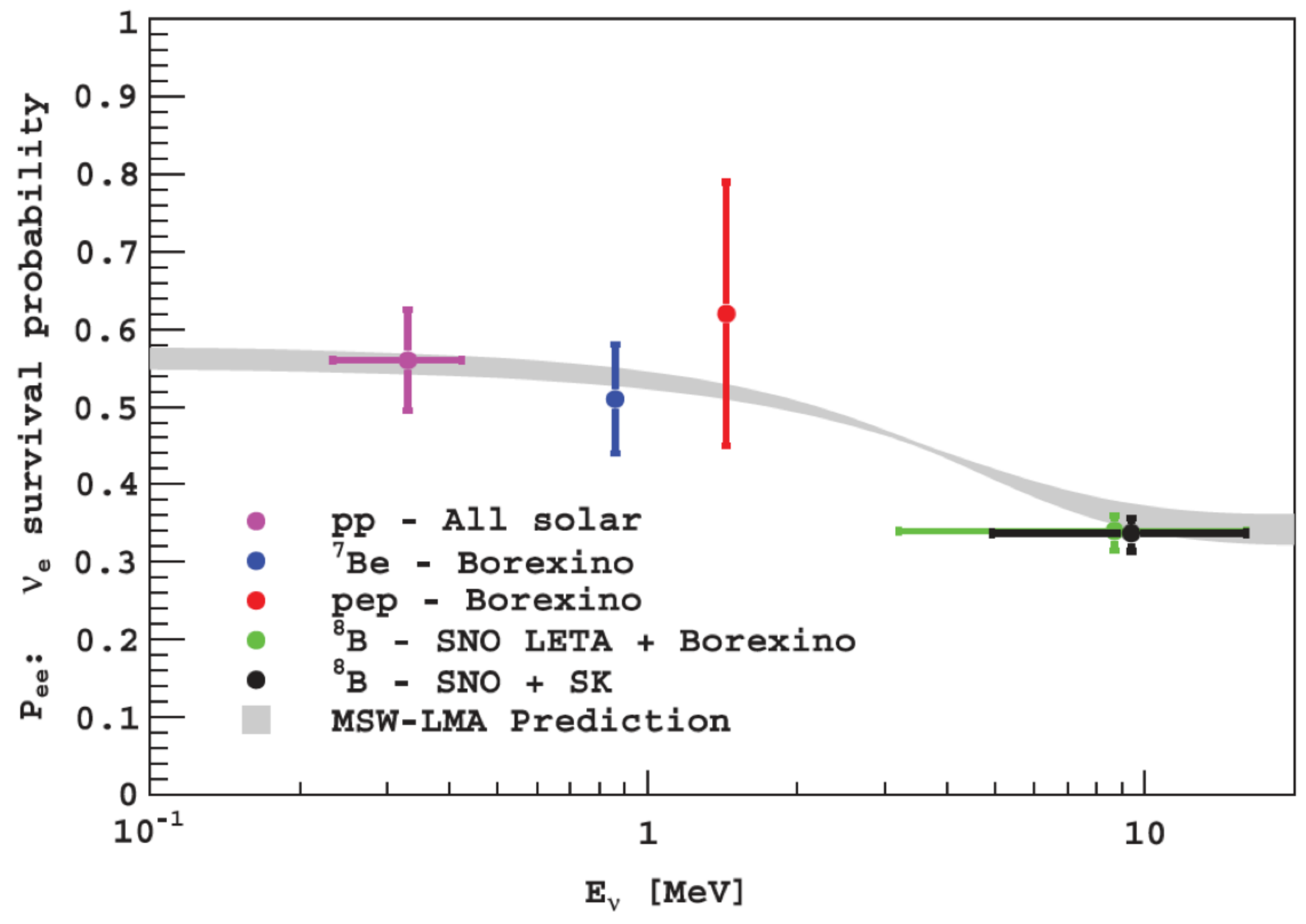
ν_e survival in vacuum



ν_e survival in matter

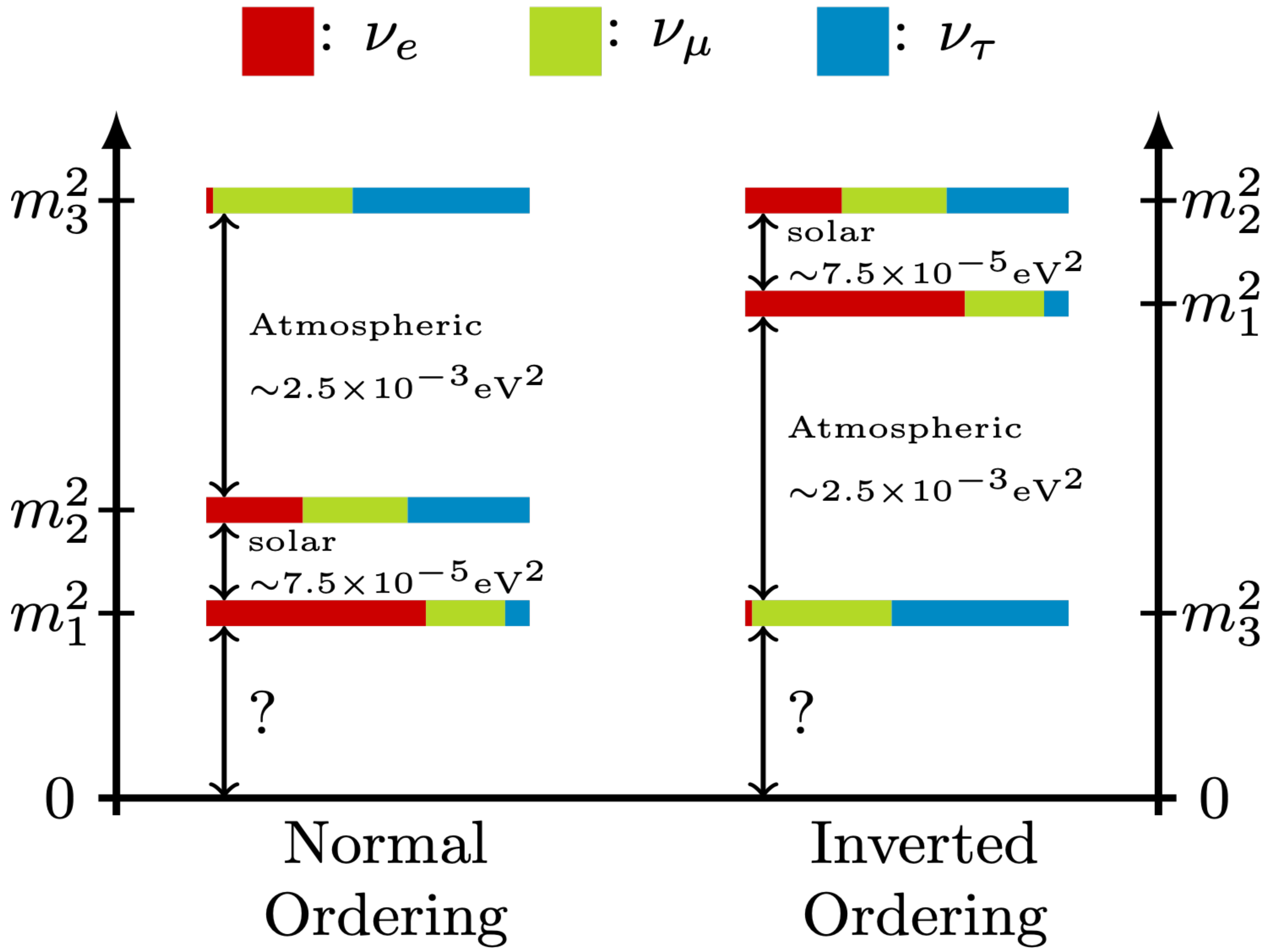


Solar ν_e flux measurement



Oscillations parameters

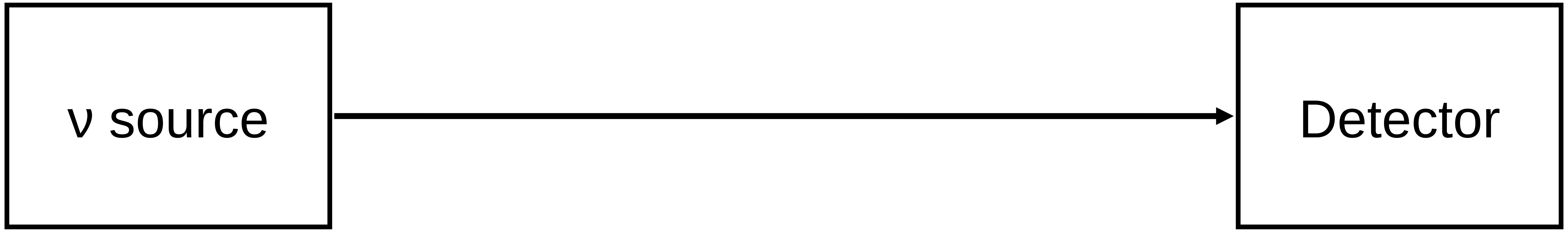
	Normal Ordering	Inverted Ordering
$\theta_{12} =$	$33.45^{+0.77}_{-0.75}$	$33.45^{+0.78}_{-0.75}$
$\theta_{23} =$	$42.1^{+1.1}_{-0.9}$	$49.0^{+0.9}_{-1.3}$
$\theta_{13} =$	$8.62^{+0.12}_{-0.12}$	$8.61^{+0.14}_{-0.12}$
$\Delta m^2_{\mathrm{sol}} = \Delta m^2_{12} =$	$7.42^{+0.21}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$	$7.42^{+0.21}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$
$\Delta m^2_{\mathrm{atm}} = \Delta m^2_{3\ell} =$	$+2.510^{+0.027}_{-0.027} \times 10^{-3}\ \mathrm{eV}^2$	$-2.490^{+0.026}_{-0.028} \times 10^{-3}\ \mathrm{eV}^2$



Three unknowns of neutrino oscillations :

- **Mass Hierarchy** : Normal or inverted ?
- **θ_{23} octant** : $\theta_{23} < 45°$ or $\theta_{23} > 45°$?
- **δ_{CP}** : Do ν behaves as $\bar{\nu}$?

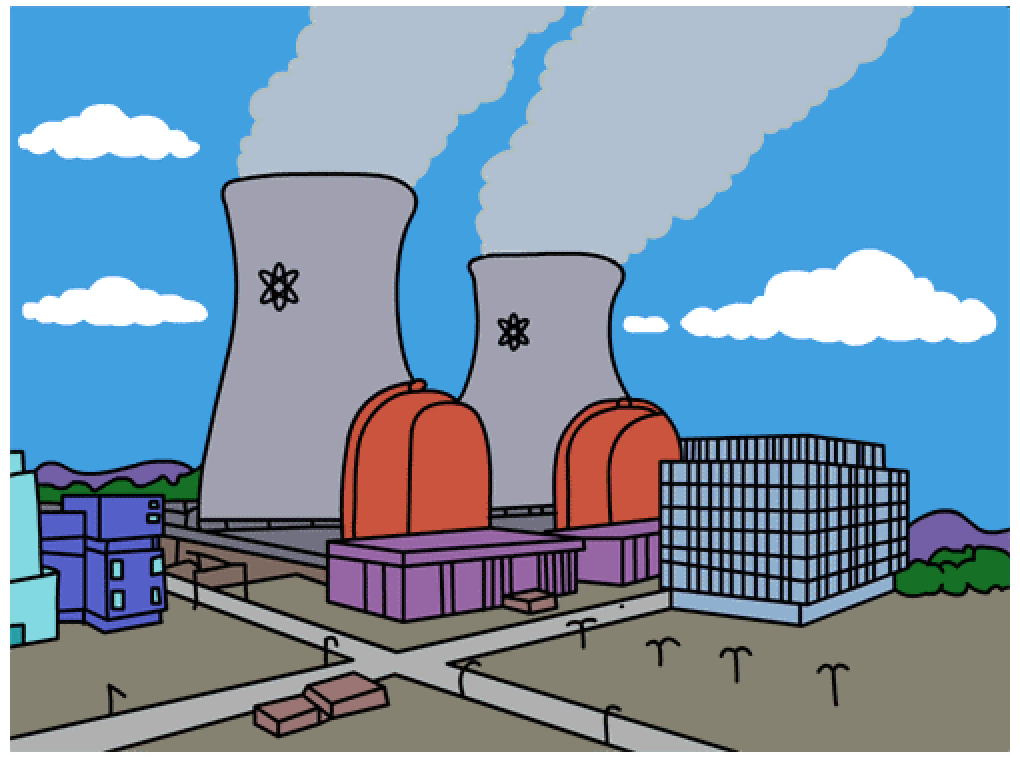
Principle for precision measurement



Requirements :
- Powerful source
- Initial location known
- Initial flavor content known
- Initial energy spectrum known

Requirements :
- At L/E for oscillation
- Able to distinguish e/μ/τ
- Energy reconstruction
- Big and/or dense

Experiments Using Reactors



Continuous powerful emission of $\bar{\nu}_e$ through the fission of ^{235}U, ^{239}Pu and ^{239}Pu.

Energy spectrum from 2 to 8 MeV

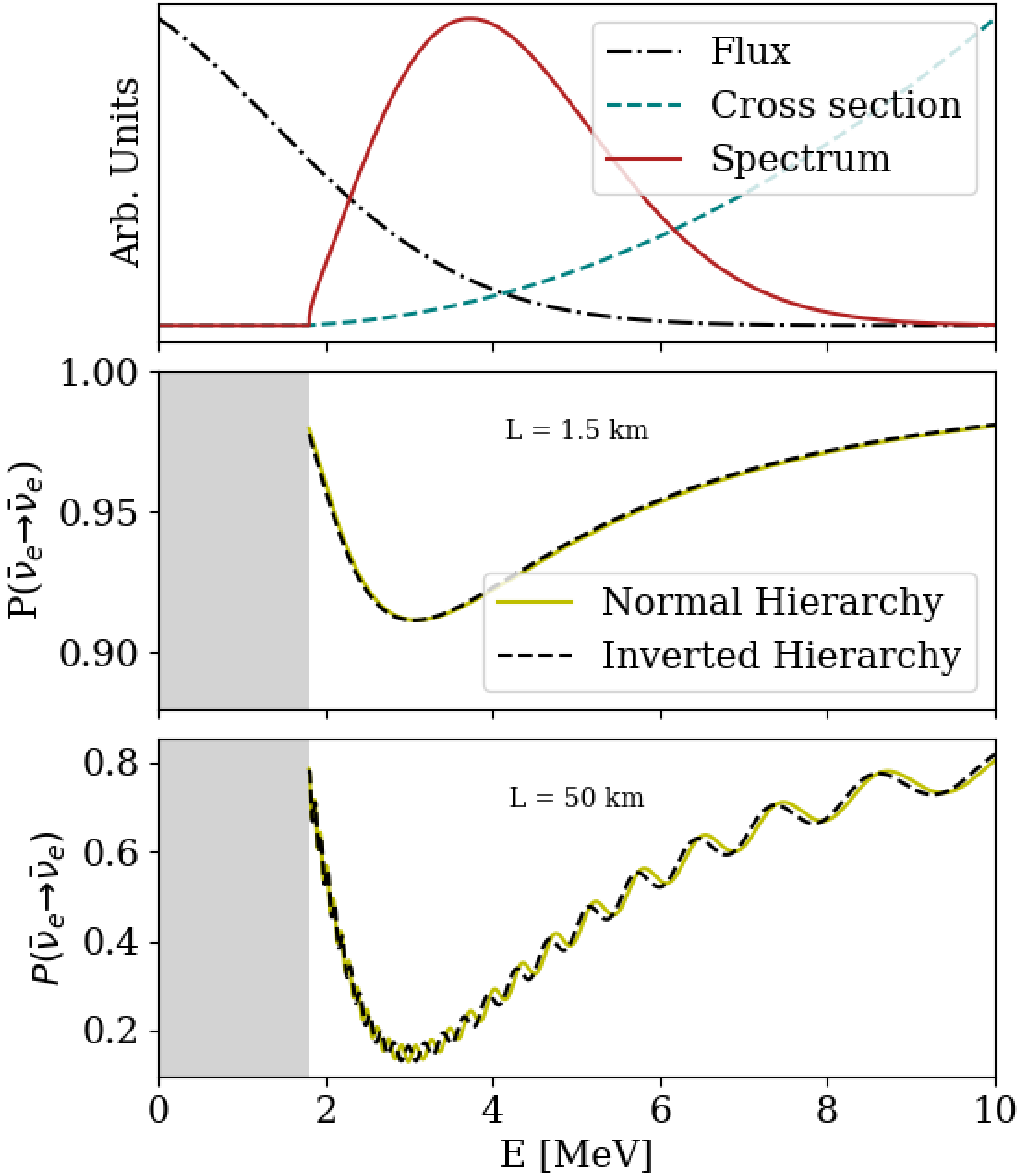
- ○ Cannot tag new flavor appearance ($\bar{\nu}_\mu$ or $\bar{\nu}_\tau$)
- ○ Only the disappearance measurement is possible

L ~ 1 km to be at atmospheric oscillation

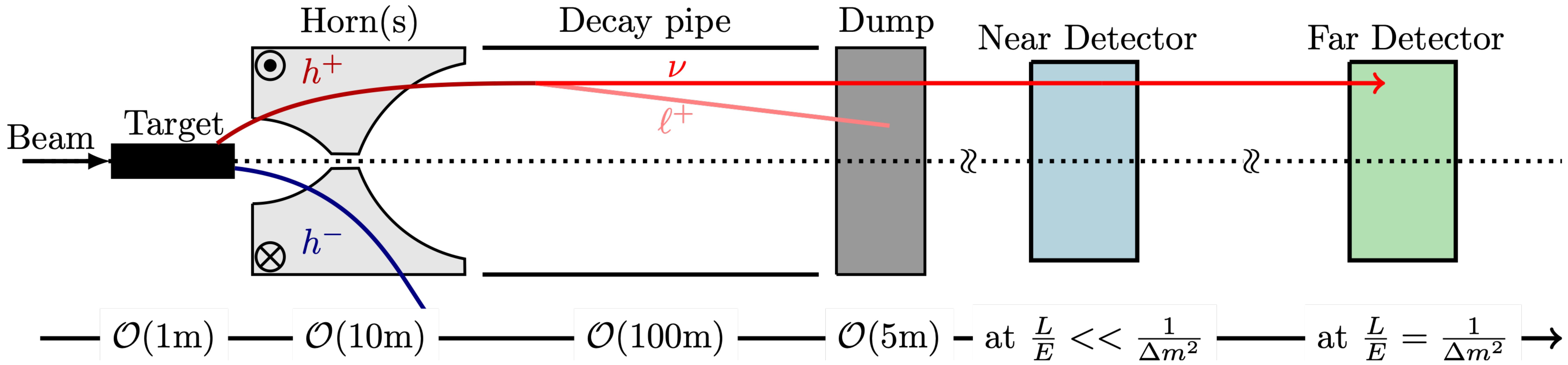
- ○ Considered to be in vacuum, the 2 flavor approximation is valid. No sensitivity to δ_{CP} or MH

L ~ 50 km to be at solar oscillation

- ○ Study of the interference between the 2 oscillations gives sensitivity to MH [***JUNO*** experiment]



Experiments Using Accelerators



<u>Principle</u> :

Accelerated proton collides into a target, produces mostly $\pi^{\pm}$.

$$\pi \rightarrow \mu + \nu_\mu$$

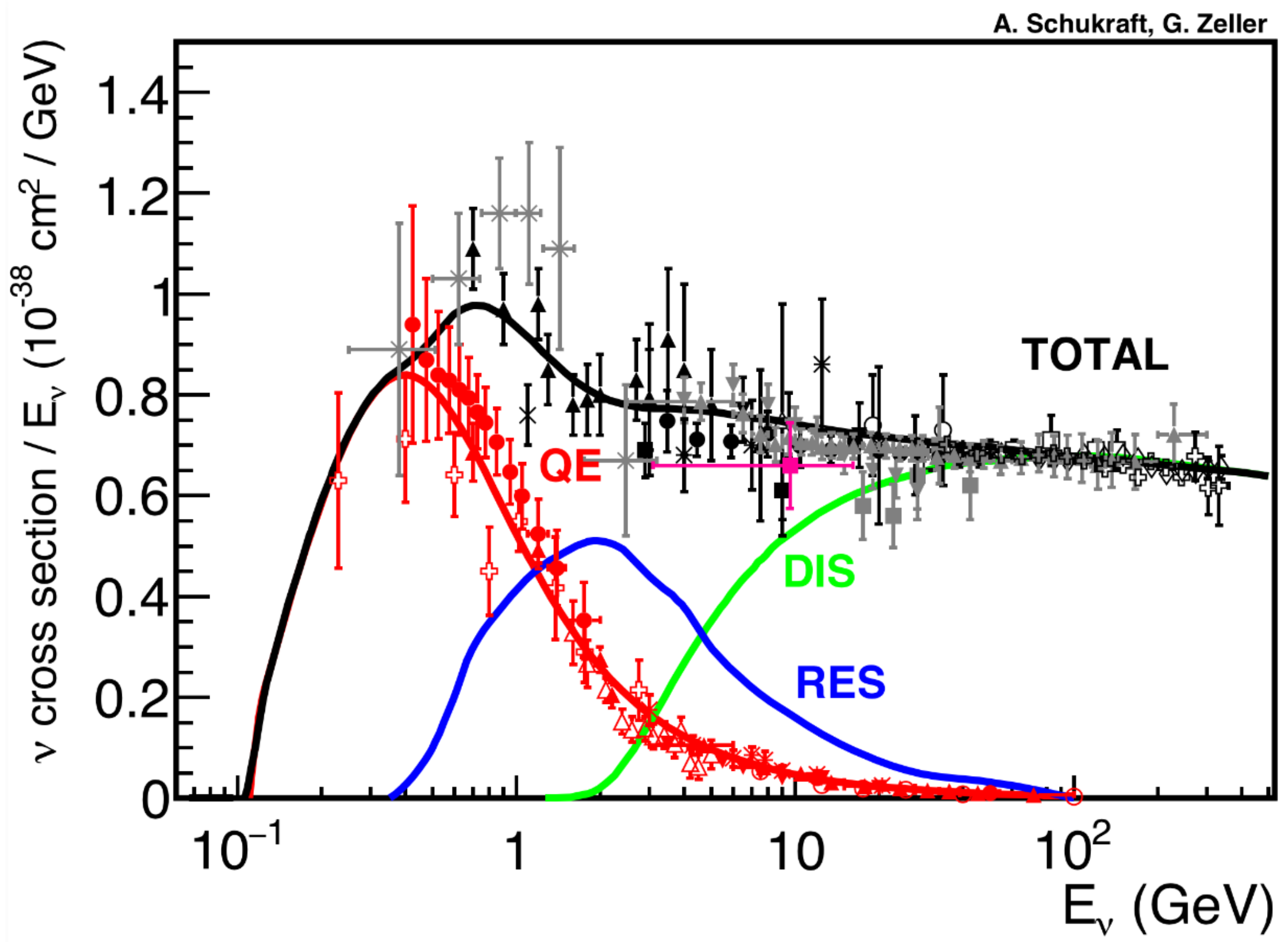
Pions main decay channel (99%) :

Focussing horns to select π^+ (ν_μ flux) or π^- ($\bar{\nu}_\mu$ flux)

A near detector to measure the flux *before* oscillations

A far detector at the L/E to observe oscillations

- ν beamline parameters tuned for optimal E



Experiments Using Accelerators

$$P(\nu_\mu \to \nu_\mu) \equiv P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

Three Channels possible (same for $\bar{\nu}_\mu$):

○ **$\nu_\mu \to \nu_\mu$:**

- No CP violation :
- Negligible matter effects

Experiments Using Accelerators

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Three Channels possible (same for $\bar{\nu}_\mu$):

○ **$\nu_\mu \to \nu_\mu$:**

- No CP violation :
- Negligible matter effects

○ **$\nu_\mu \to \nu_e$:** The Golden Channel

- Very sensitive to CP
- Very sensitive to MH with matter
- Very sensitive to θ_{23} octant

Experiments Using Accelerators

$$P(\nu_\mu \to \nu_\mu) \equiv P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

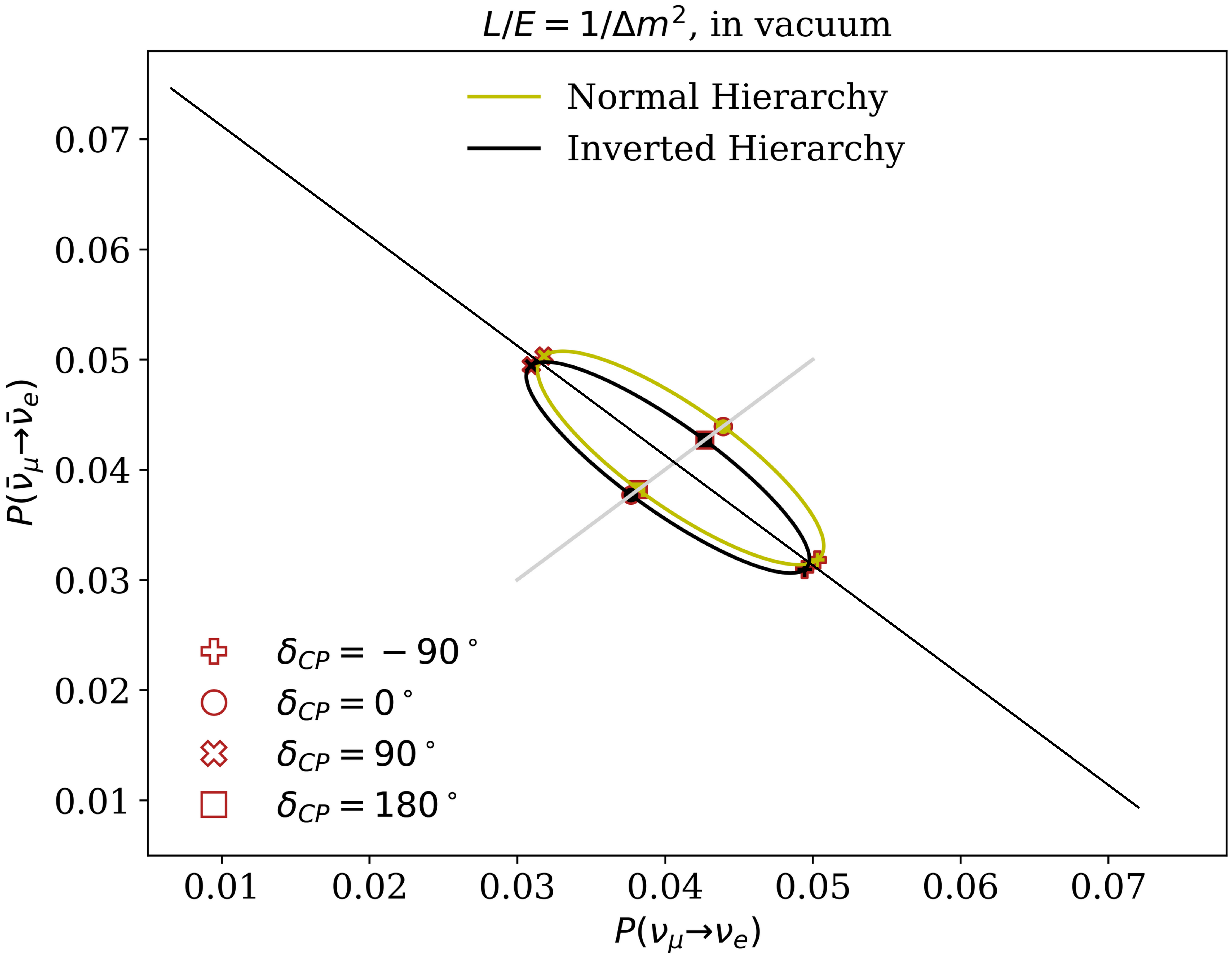
Three Channels possible (same for $\bar{\nu}_\mu$):

○ **$\nu_\mu \to \nu_\mu$:**
- No CP violation :
- Negligible matter effects

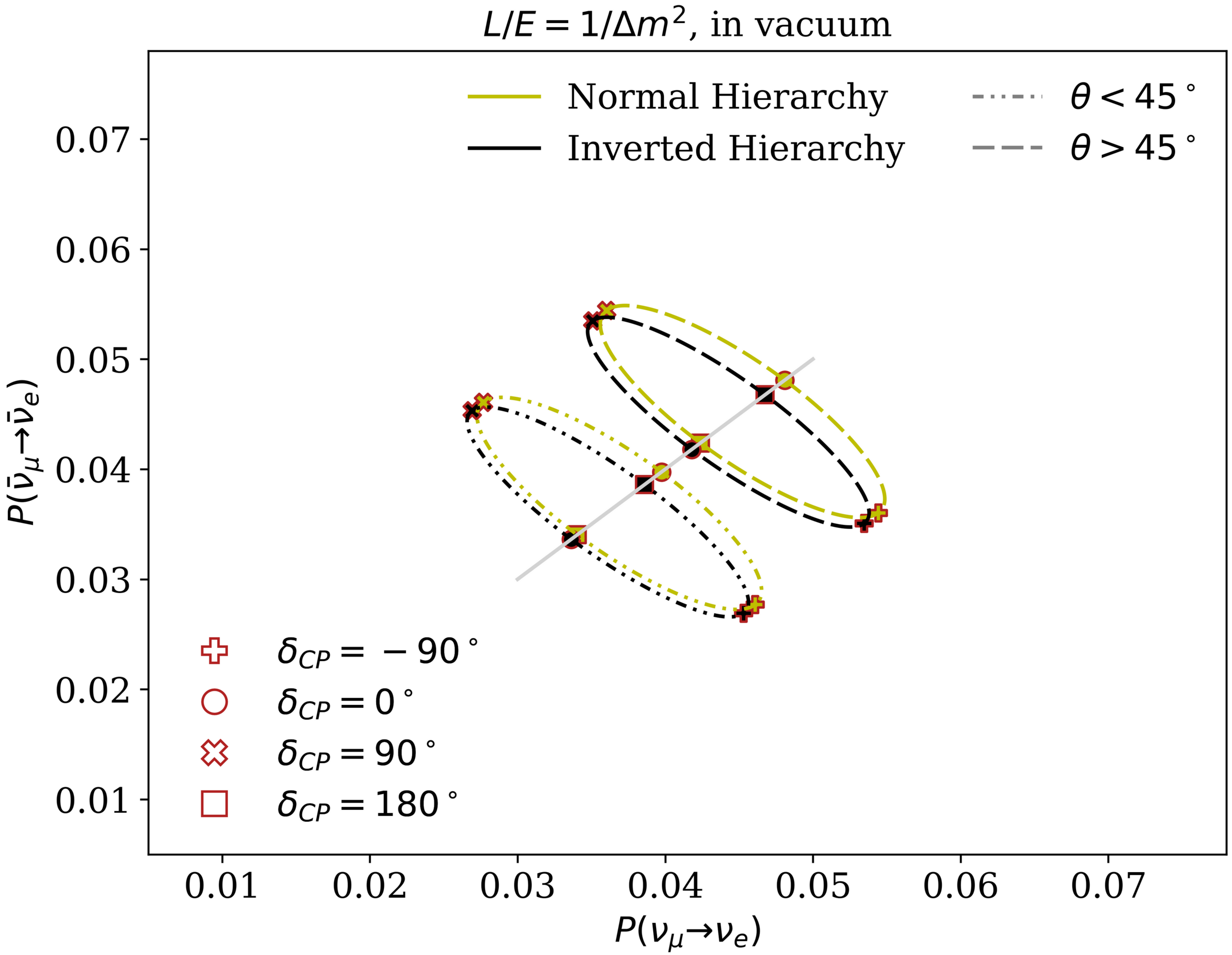
○ **$\nu_\mu \to \nu_e$:** The Golden Channel
- Very sensitive to CP
- Very sensitive to MH with matter
- Very sensitive to θ_{23} octant

○ **$\nu_\mu \to \nu_\tau$:**
- Similar discovery potential as ν_e appearance but:
  $m_\tau = 1.7$ GeV, $c\tau_\tau = 87$ µm and $\tau^\pm$ have hundreds of complicated decay channels

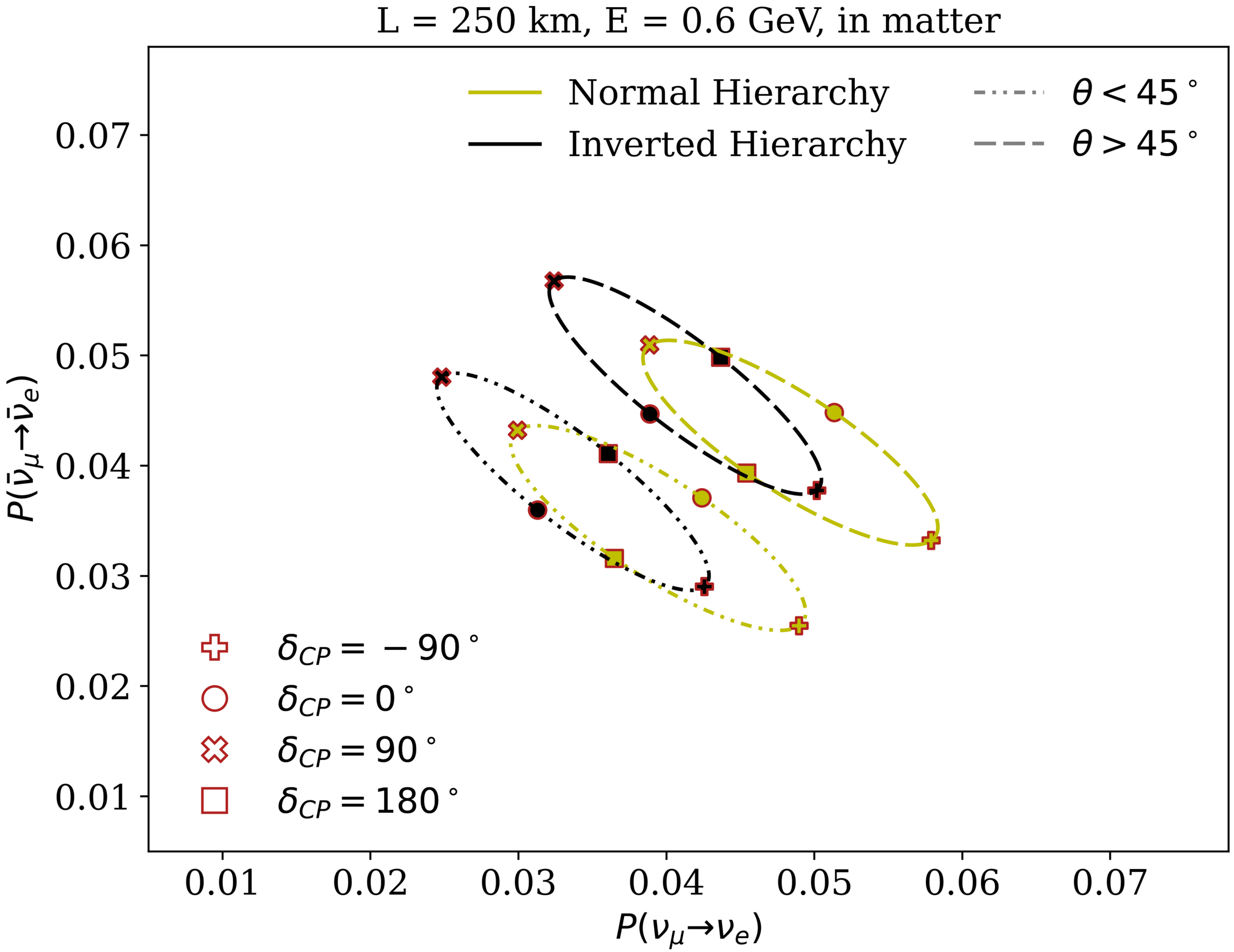
Experiments Using Accelerators



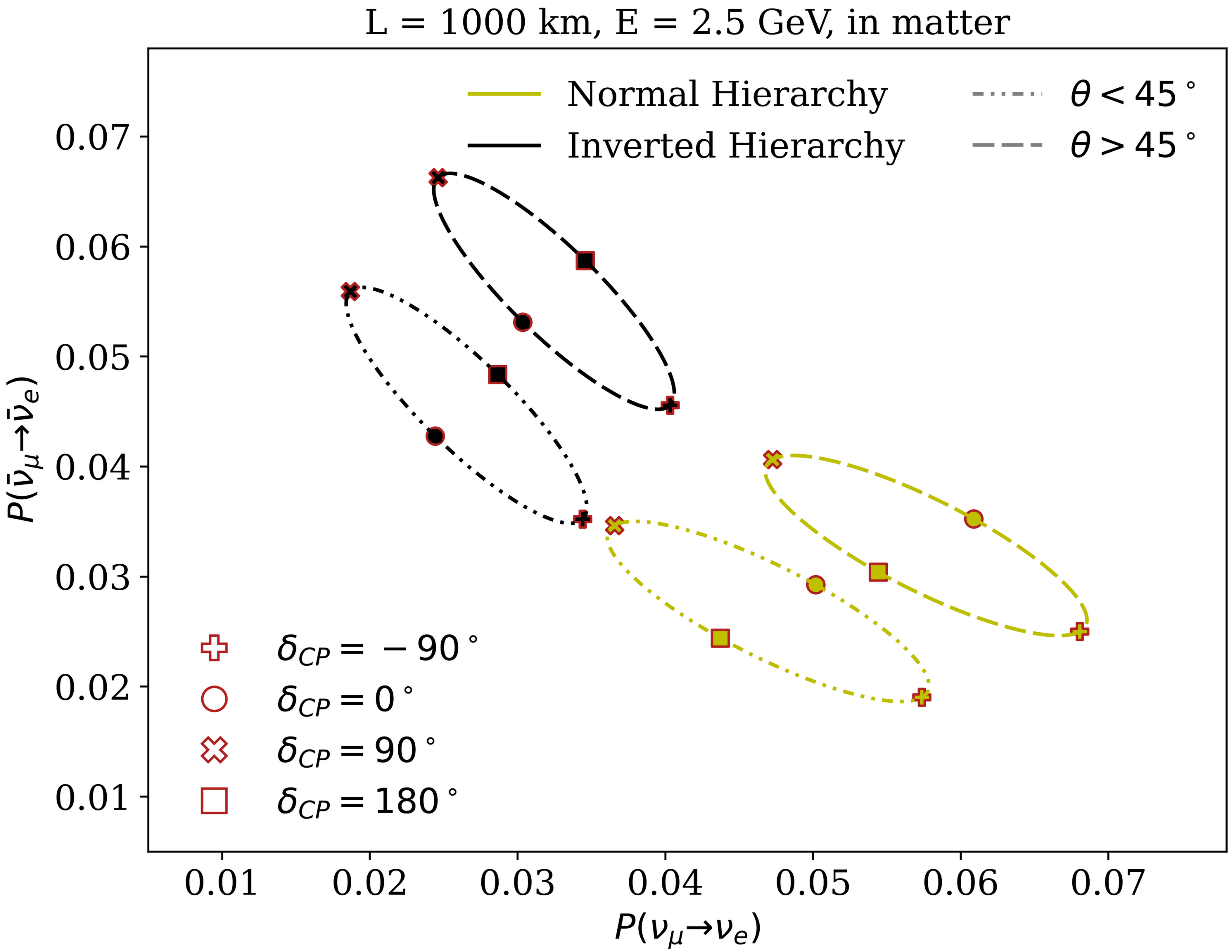
Experiments Using Accelerators



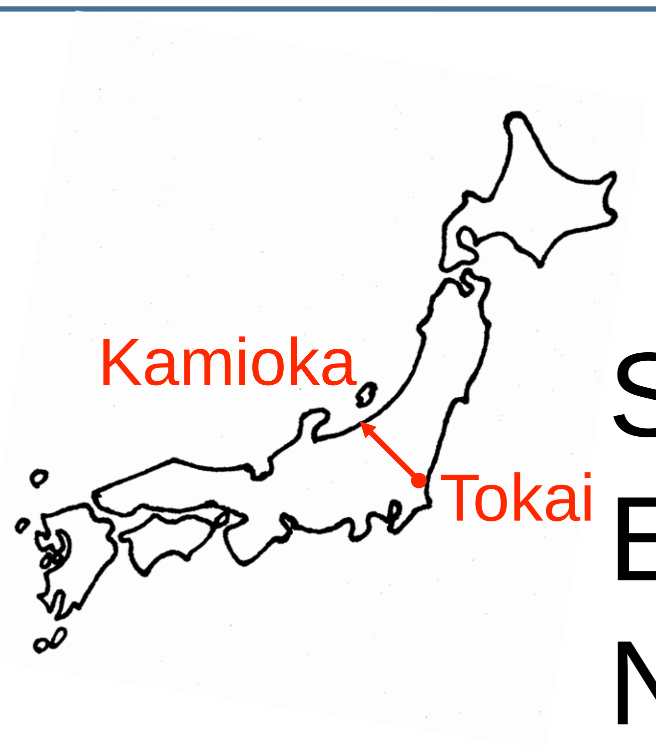
Experiments Using Accelerators



Experiments Using Accelerators



Current ν accelerator experiments



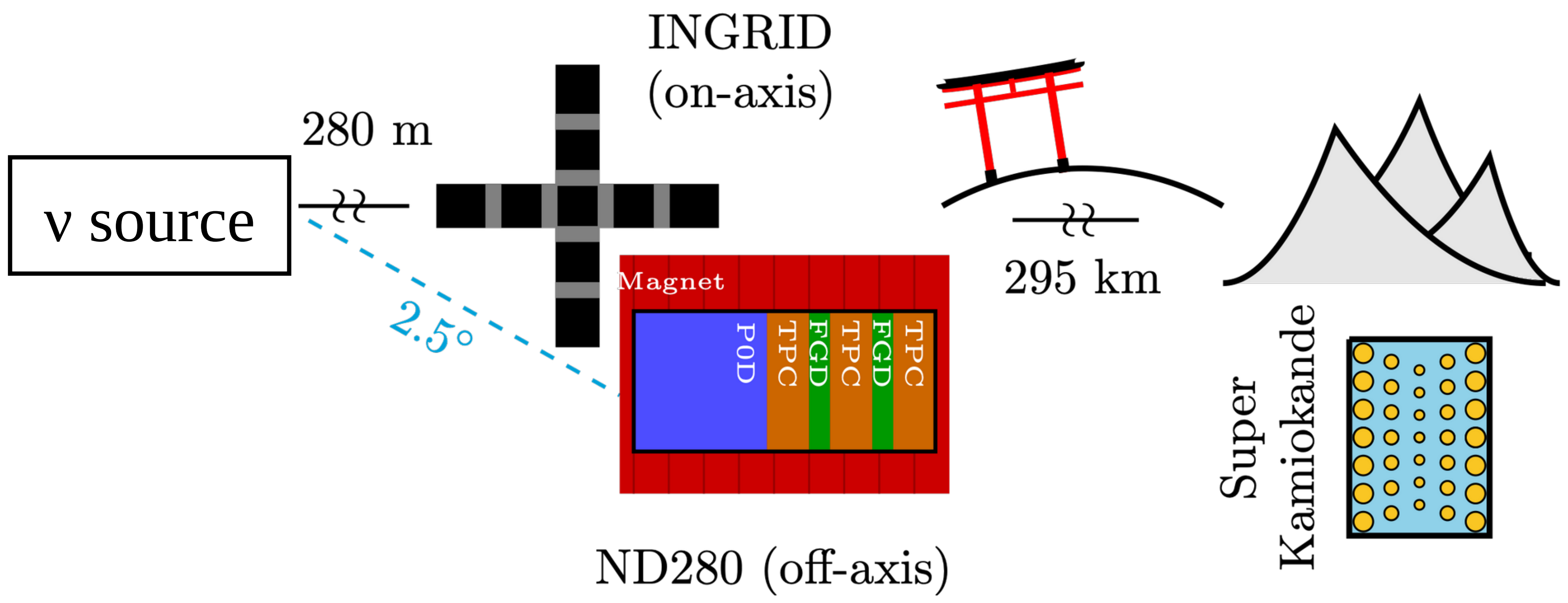
T2K in Japan

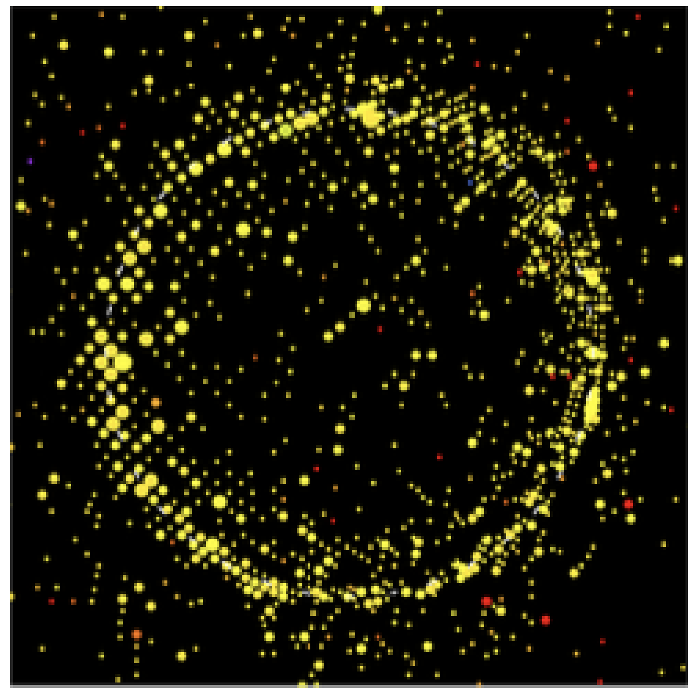
Since 2010, L = 295 km, E = 0.6 Ge

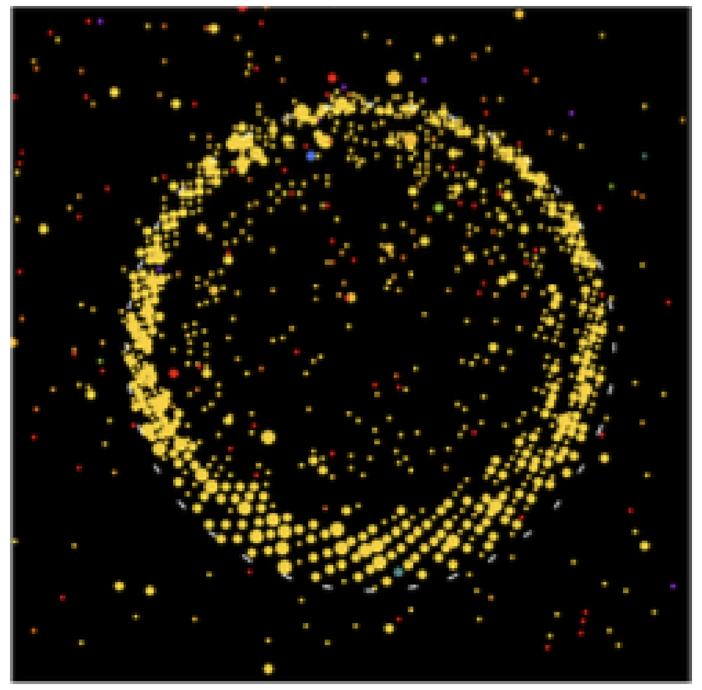
Equal ν and $\bar{\nu}$ runs

Near detector is a gaseous TPC

Far detector is Super-Kamiokande




ν_e-like

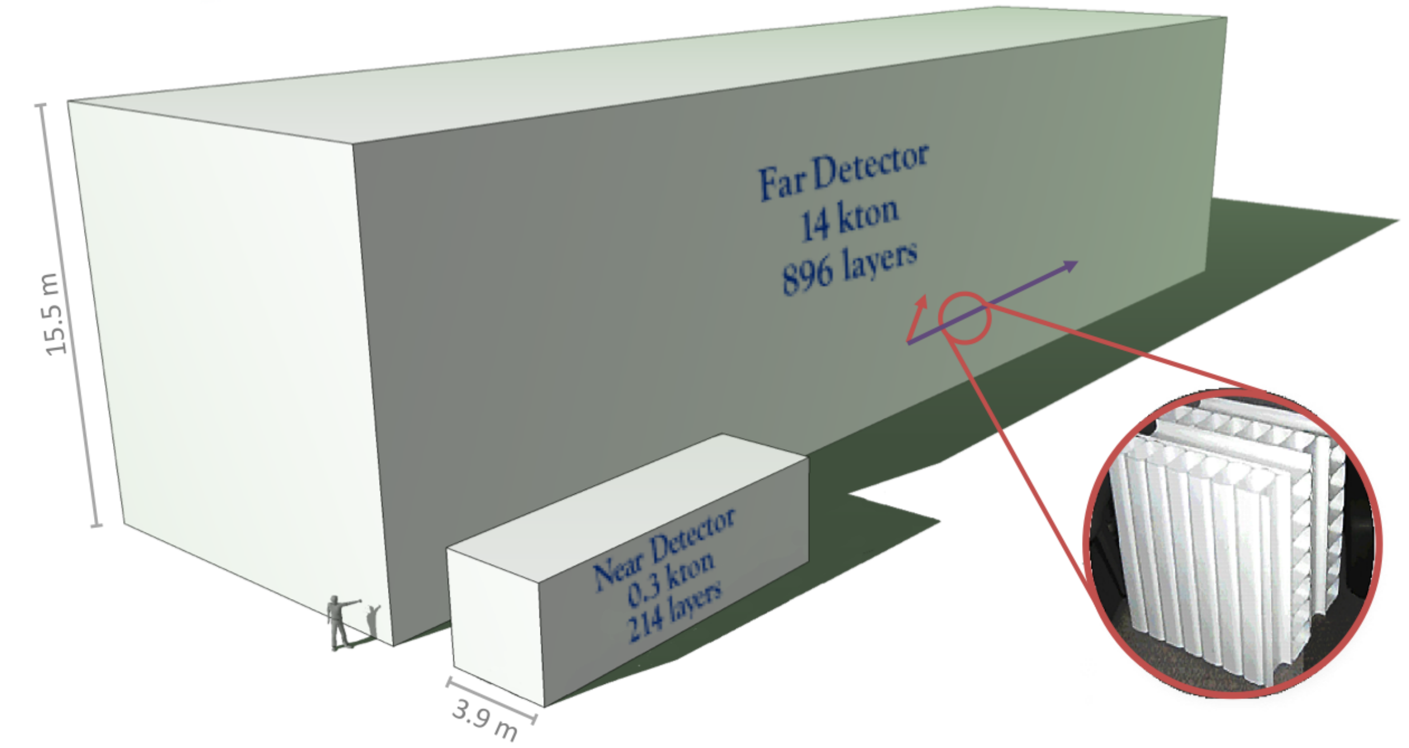

ν_μ-like

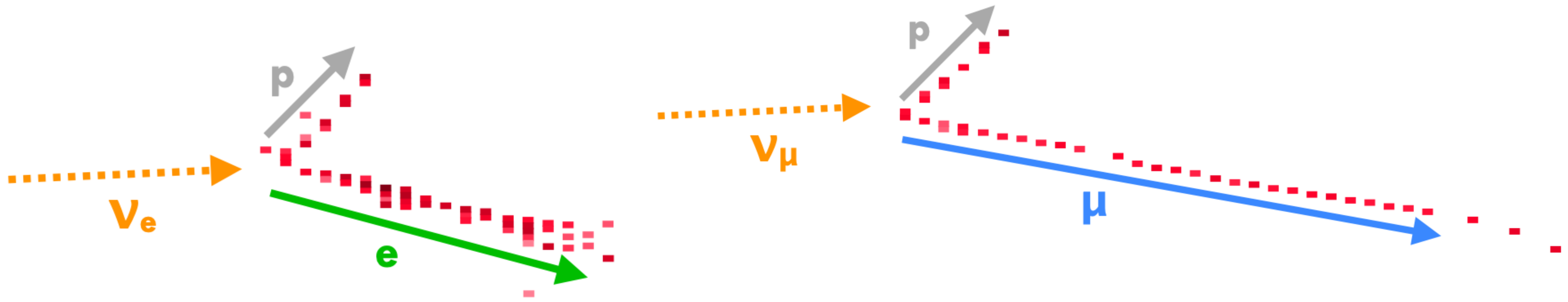
NOνA in the US

Since 2013, L = 810 km, E = 2 GeV

Equal ν and $\bar{\nu}$ runs

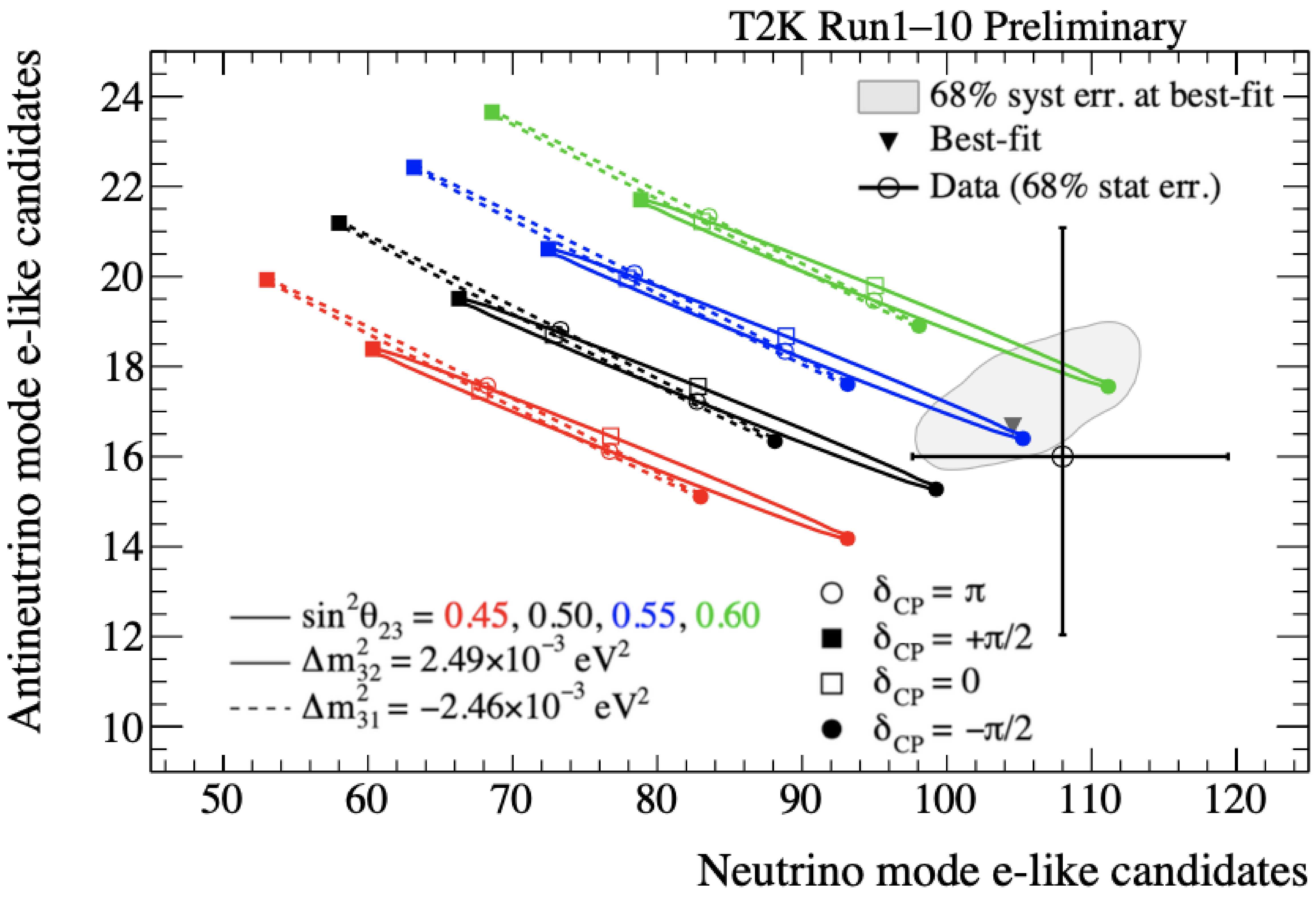
Near and Far detectors are plastic scintillators



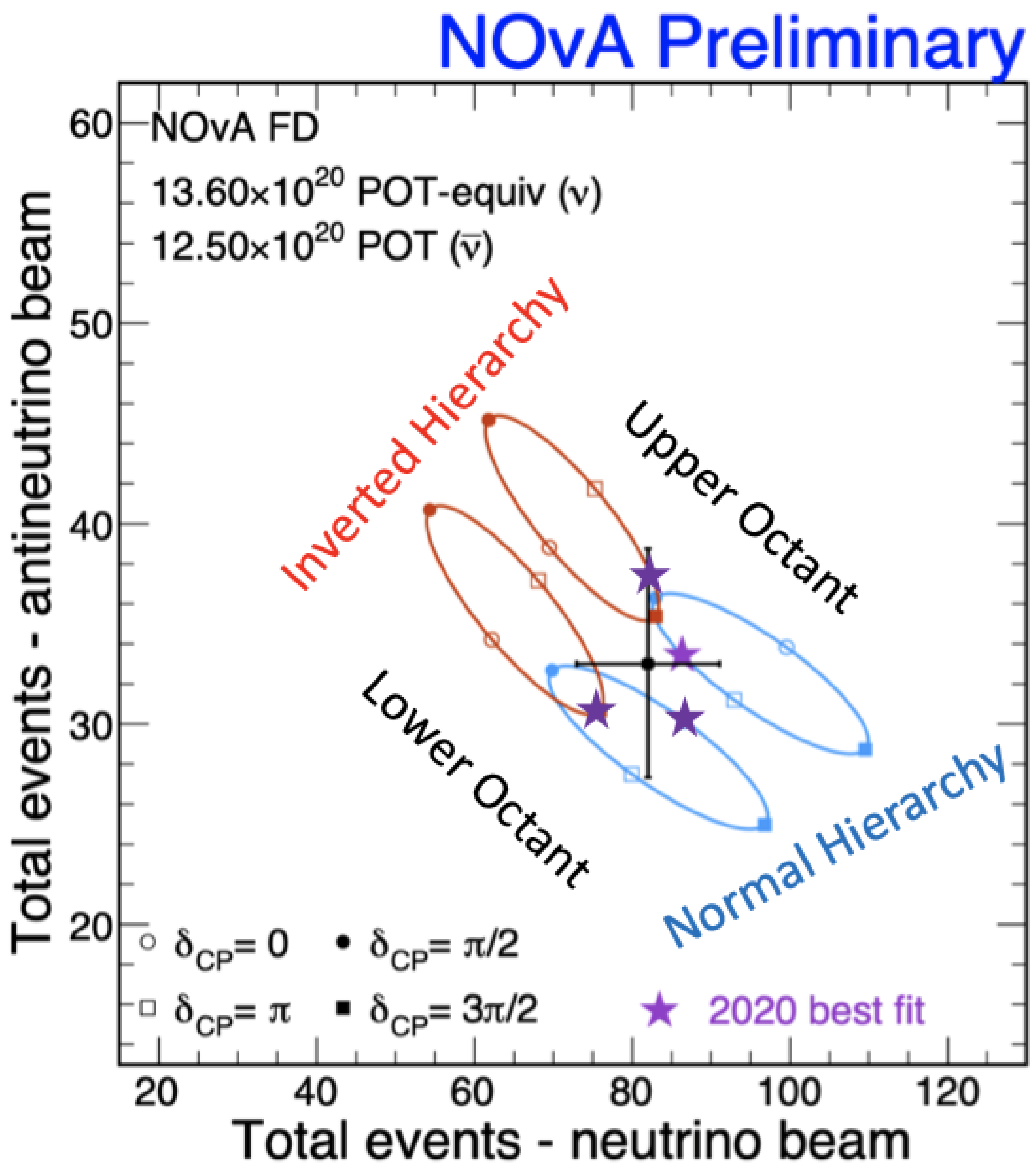


Current ν accelerator experiments

T2K in Japan

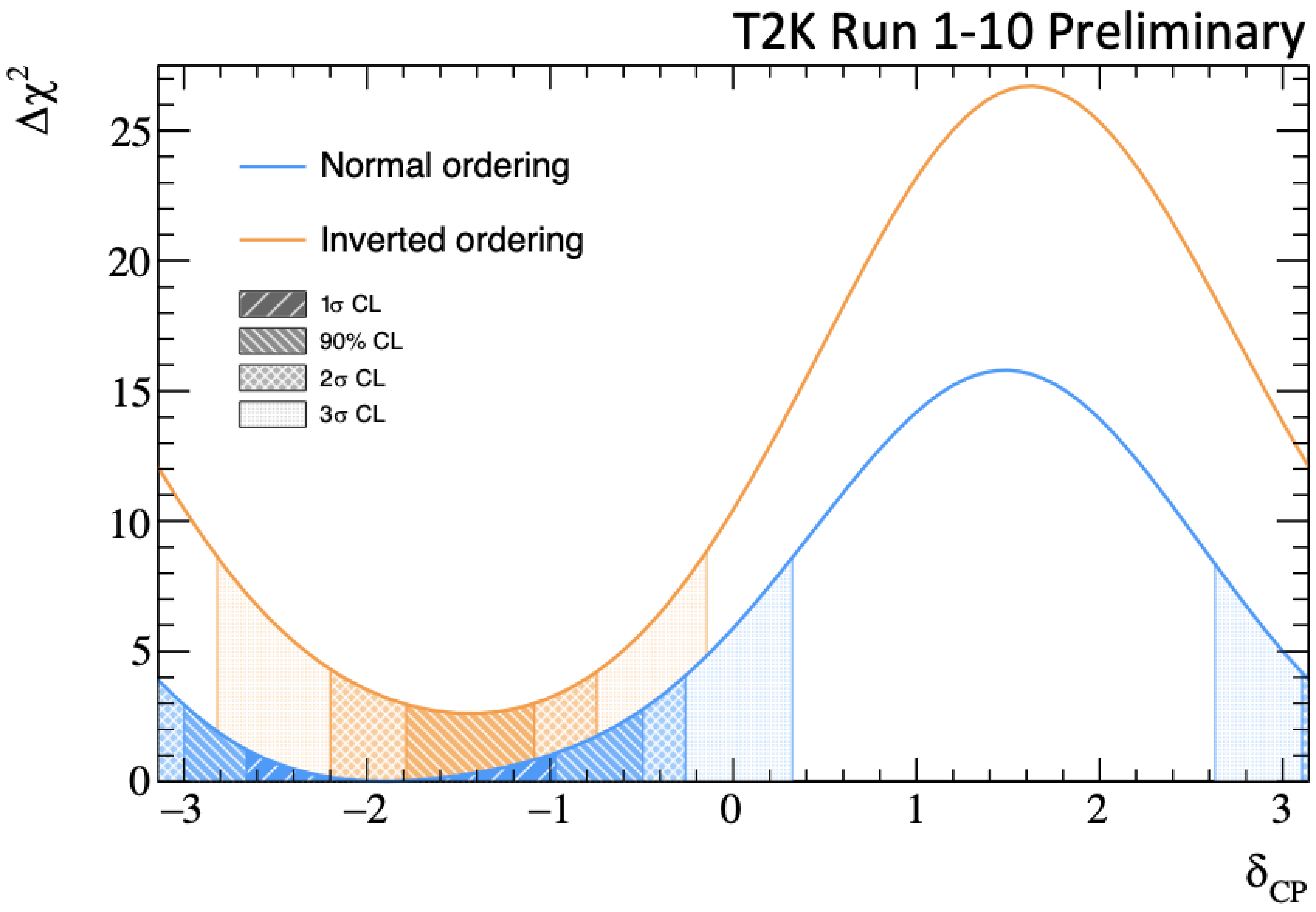


NOvA in the US

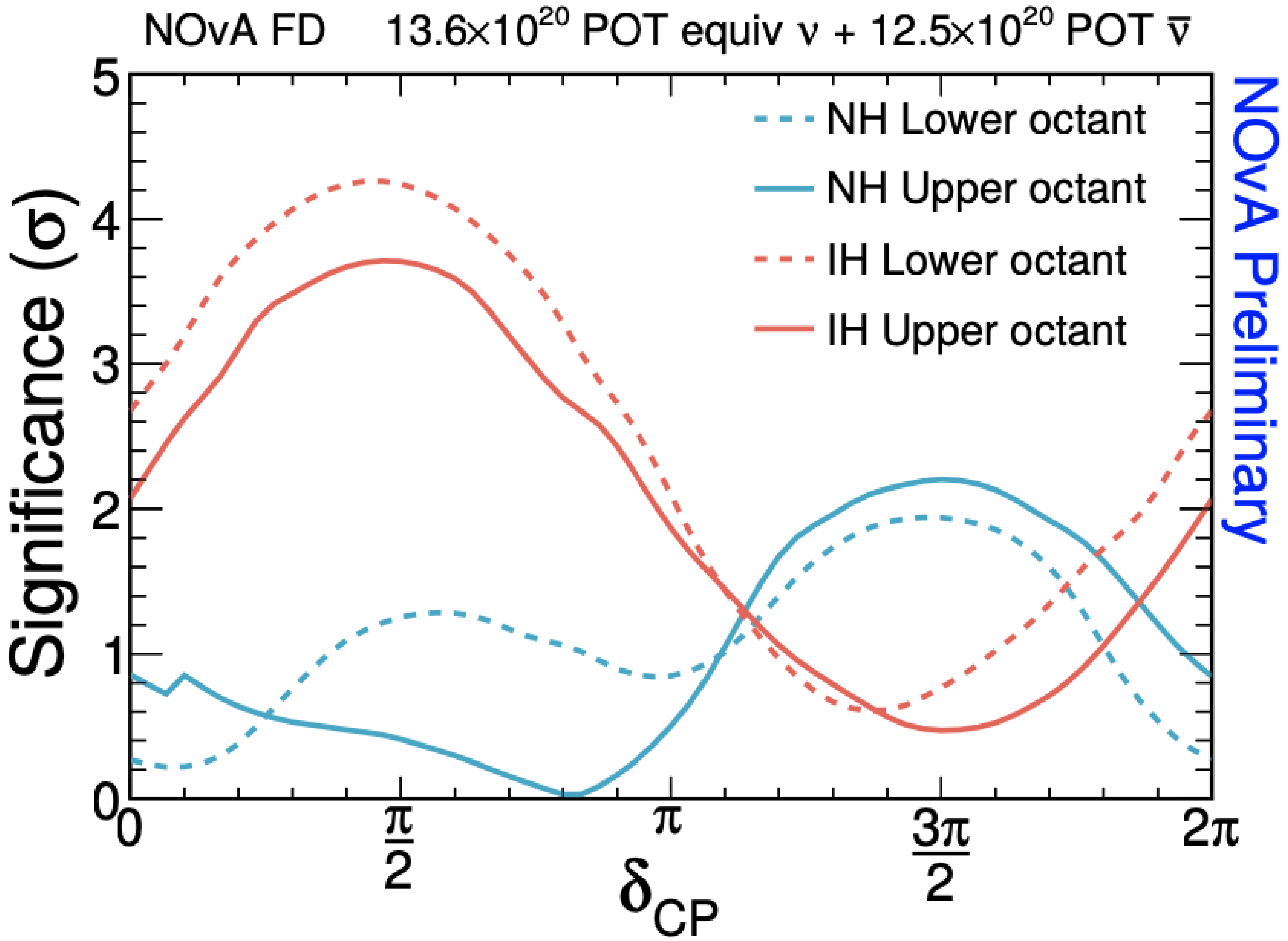


Current ν accelerator experiments

T2K in Japan



NOvA in the US

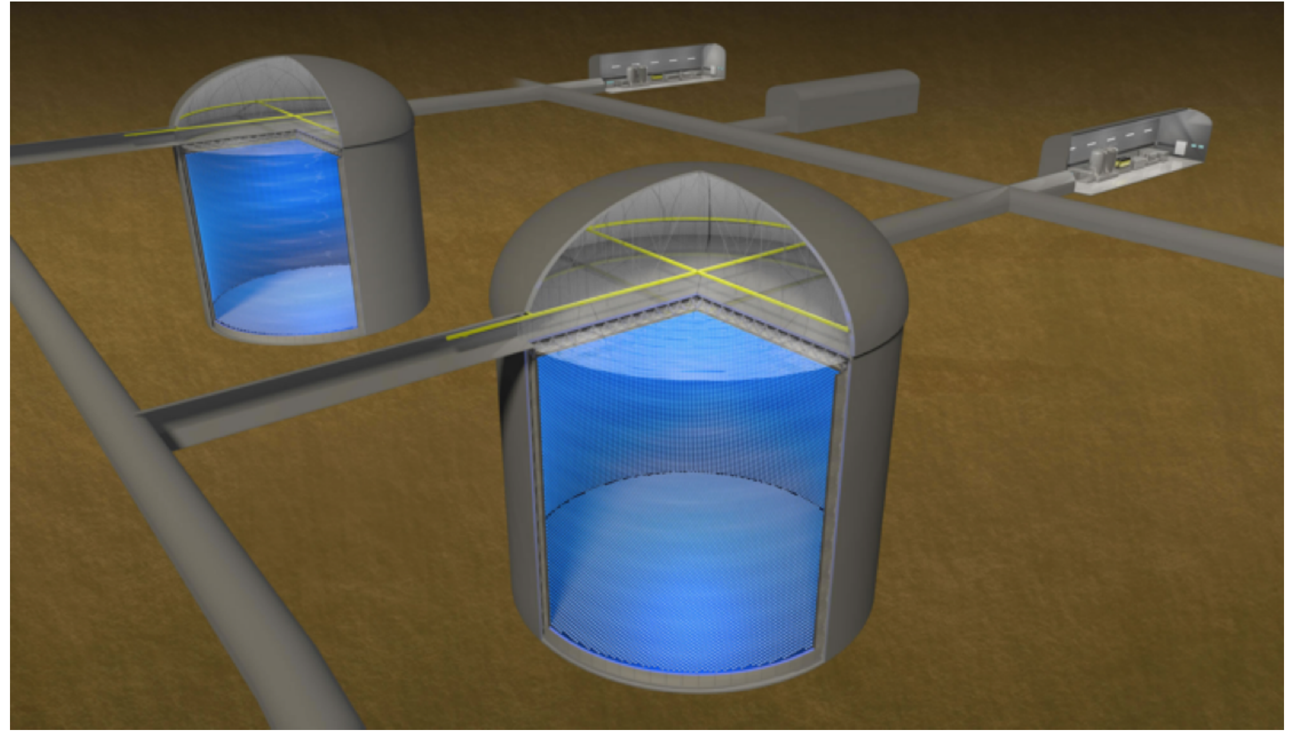


- ○ Slight preference for Normal Hierarchy
- ○ δ_{CP} = (0, π) excluded at 95% C.L. for both MH
- ○ Large range around δ_{CP} = +π/2 excluded at 3σ

- ○ Prefers Normal Hierarchy at 1.0σ
- ○ Exclude δ_{CP} = π/2 + IH at >3σ
- ○ Exclude δ_{CP} = 3π/2 + NH at 2σ

Future ν accelerator experiments

T2HK in Japan



L=300 km, E ~ 0.6 GeV

260 kt water Cherenkov detector

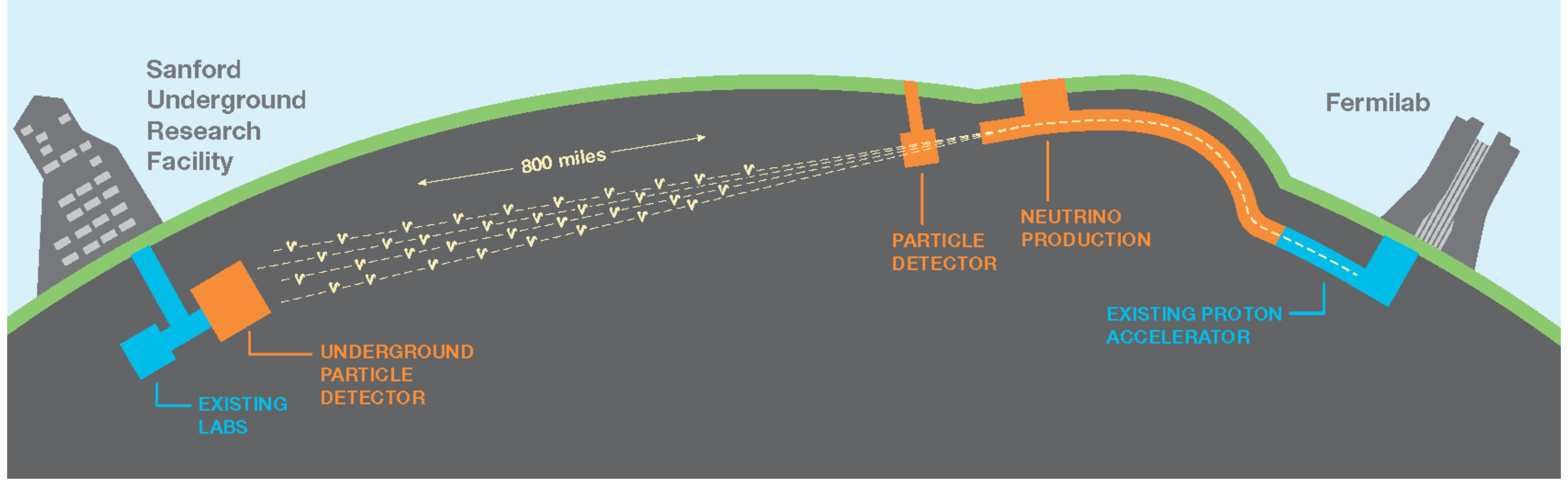
Proven and scalable technology

Excellent e-μ ring separation

Little R&D foreseen

Only low energy beam possible (< 1 GeV)

DUNE in the US



L=1300 km, E ~ 1-3 GeV

40 kt liquid argon TPC detector

3D imaging with high granularity for precise tracking

Low energy threshold (~10s MeV)

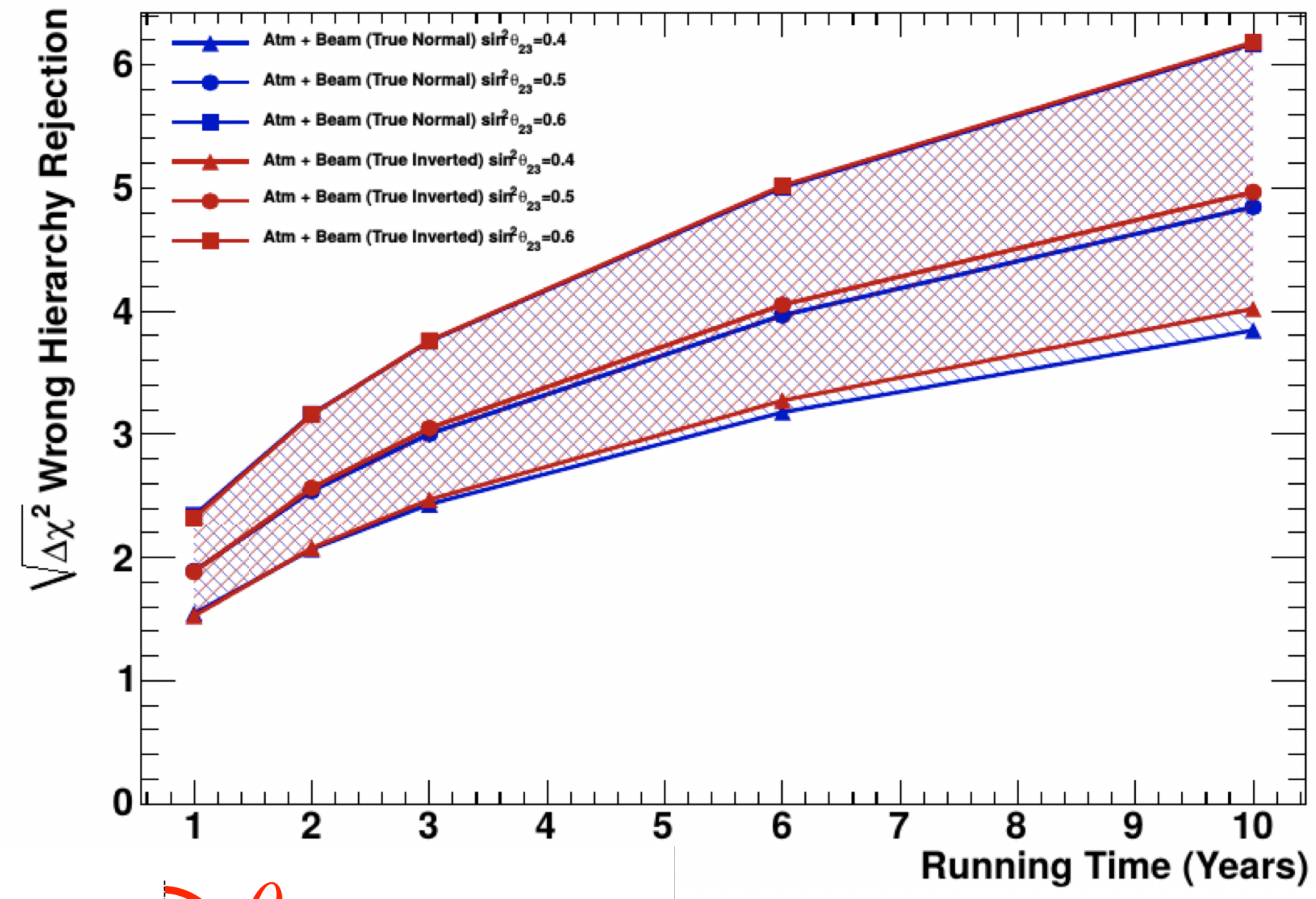
Important R&D efforts ongoing :

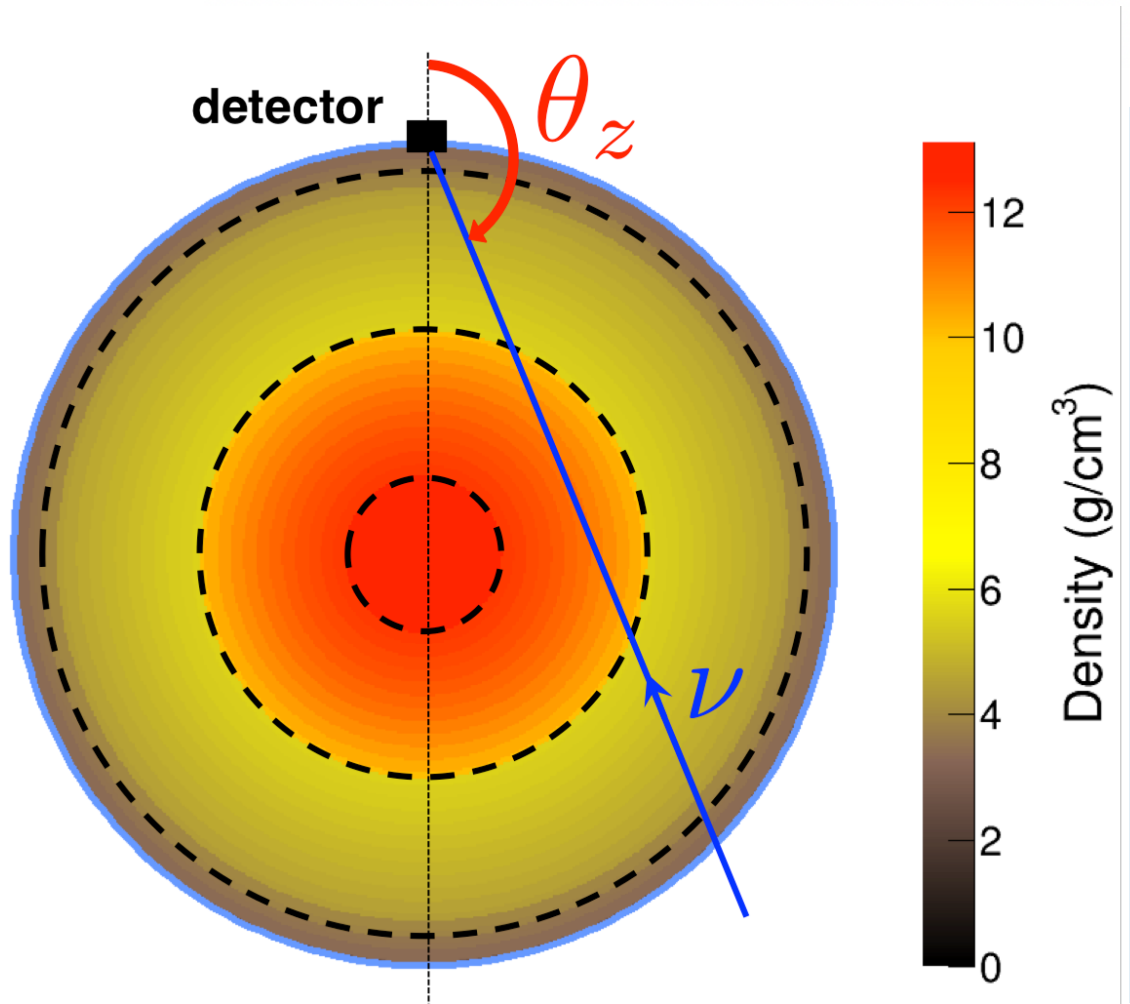
Scalability, Engineering

Both planning of starting data taking in ~2027

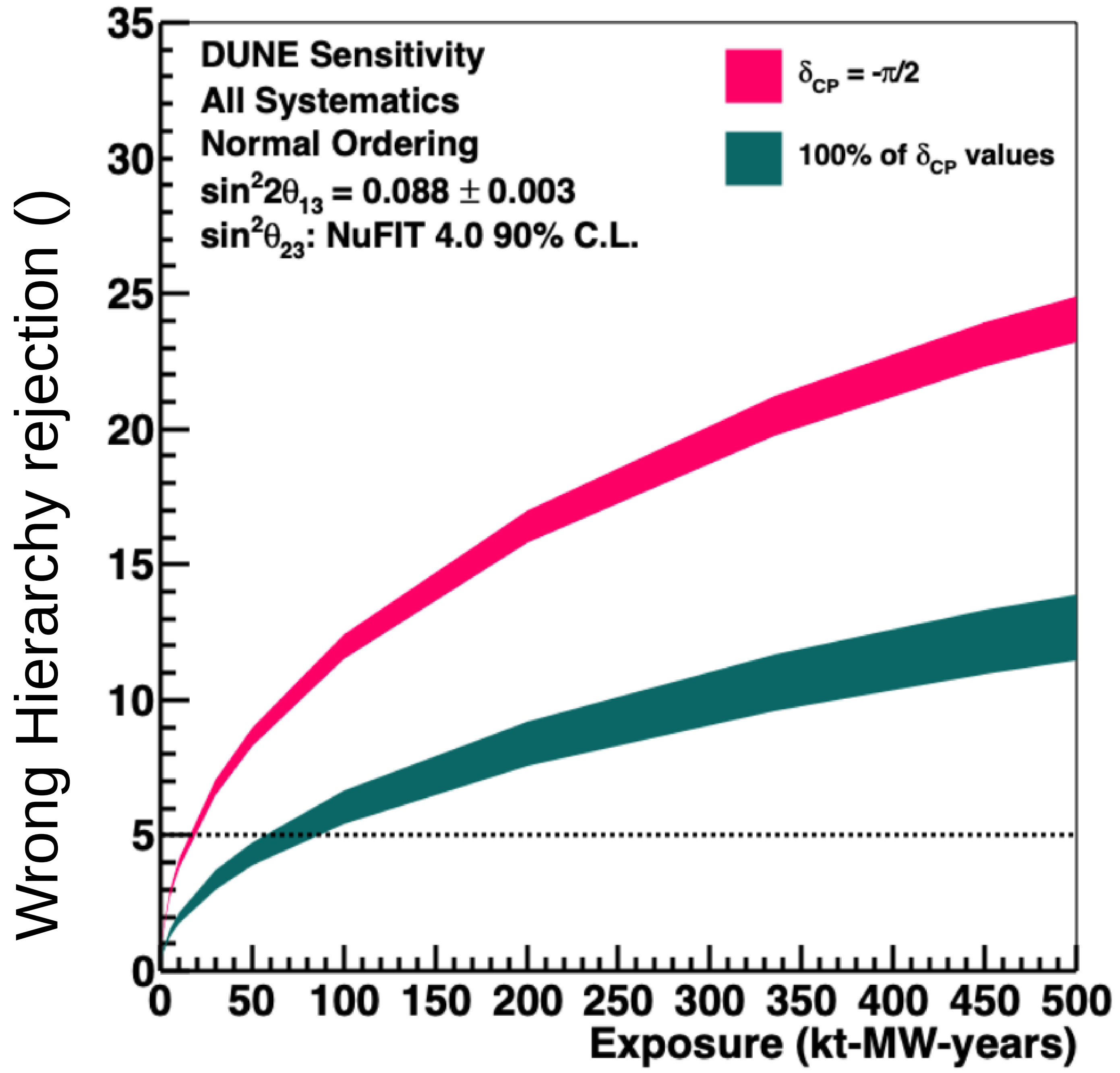
Future ν accelerator experiments

T2HK in Japan





DUNE in the US



DUNE default operation :
40 kton of LAr staged
Beam power at 1.2 ~ 2.4 MW

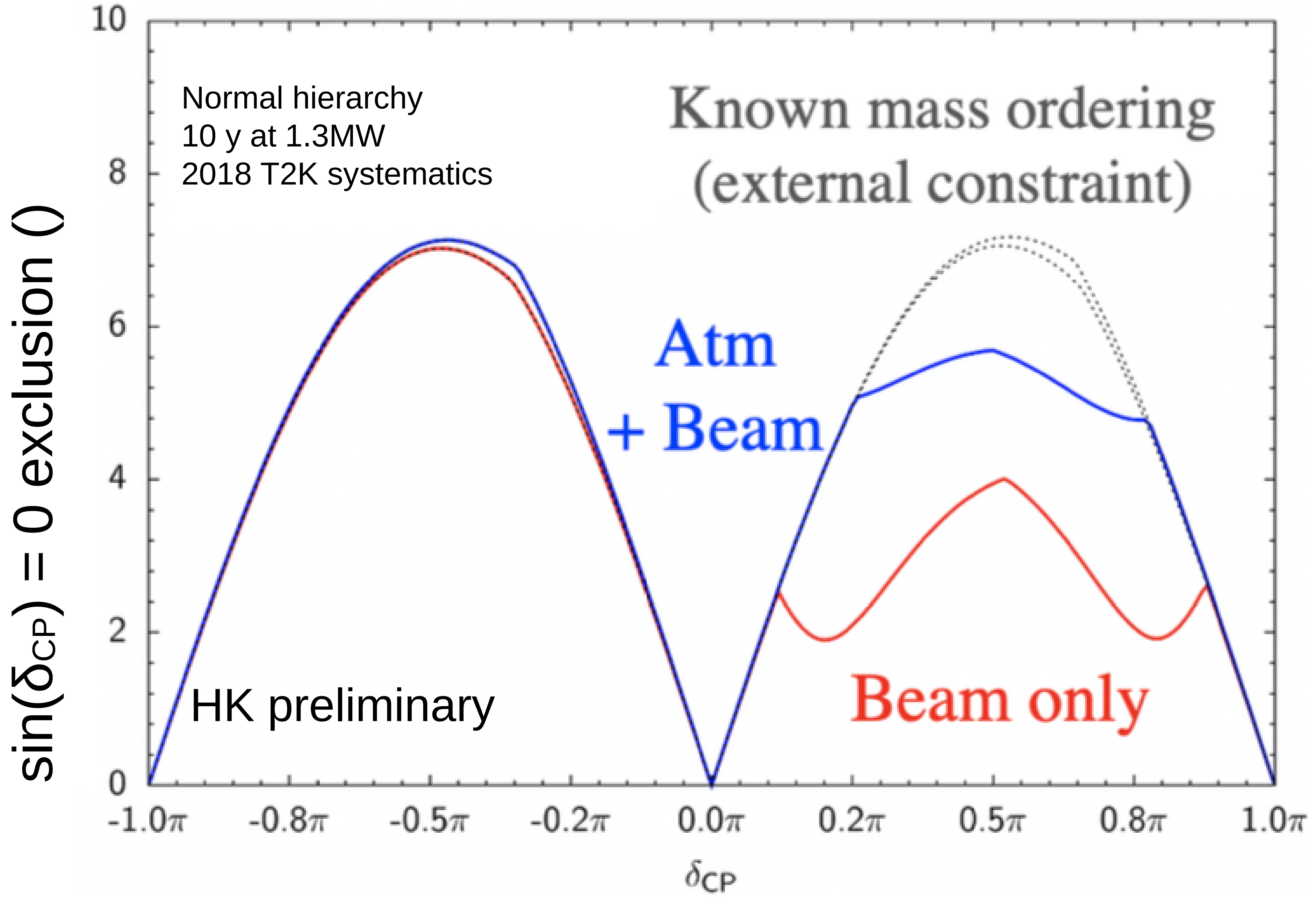
kt•MW•yr	Staged years
30	1.2
100	3.1
200	5.2
336	7
624	10
1104	15

In the ideal case of $\delta_{CP} = -\pi/2$

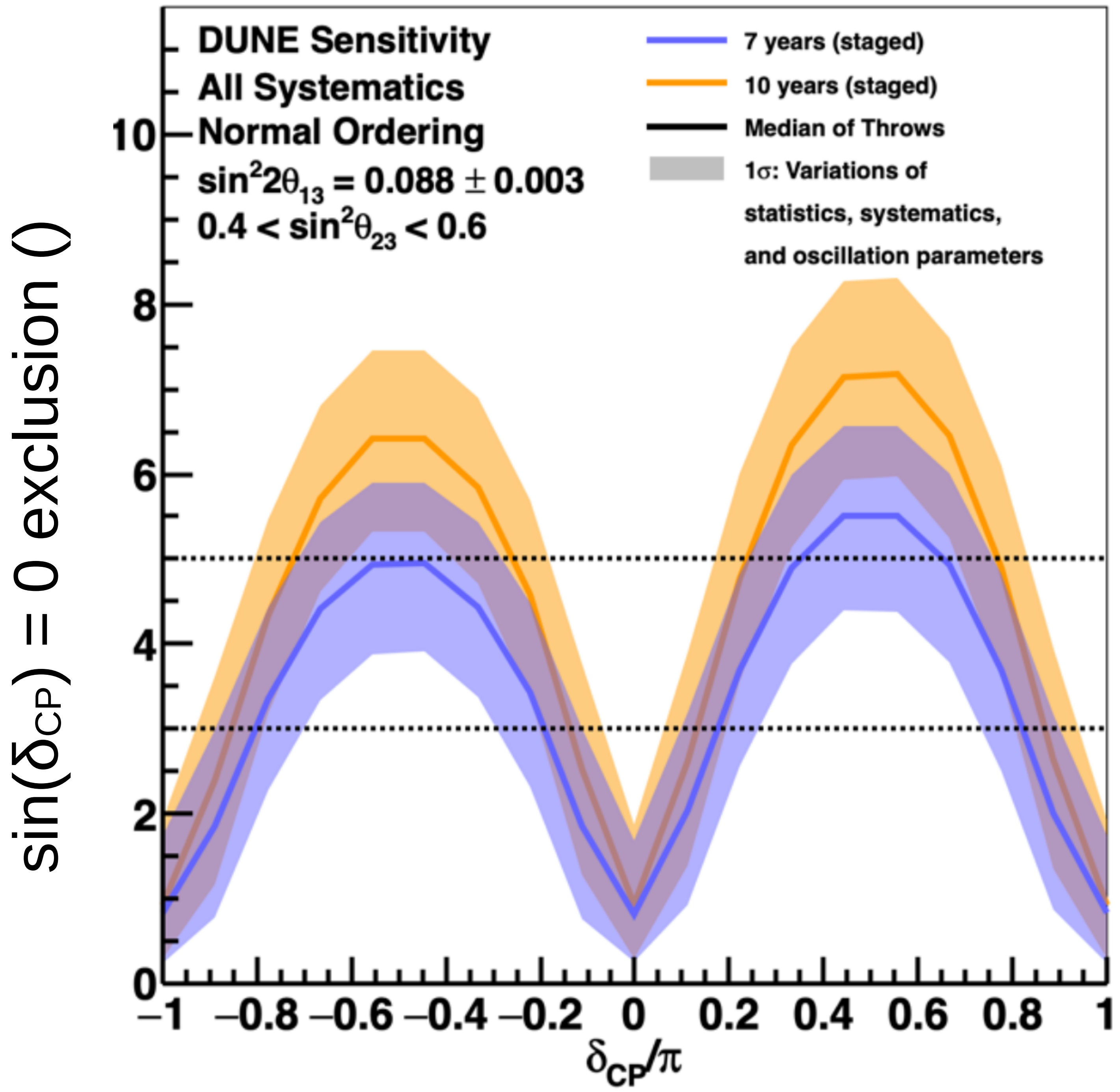
- ***DUNE*** will resolve the MH at 5σ in ~1.5y [3y to exclude the wrong MH for any δ_{CP} value]
- ***T2HK*** itself do not have a lot of sensitivity [can reach 5σ in 10y with beam + atmospheric ν]

Future ν accelerator experiments

T2HK in Japan



DUNE in the US



In 10 years of operation, if the MH is known:

- ○ ***DUNE*** can exclude $\delta_{CP} = (0, \pi)$ for 50% of δ_{CP} values
- ○ ***T2HK*** can reach 5σ for 60% of δ_{CP} values

How neutrinos get massive ? ***ββ0ν experiments (SuperNEMO, CUORE, SNO+)***

- The **Dirac** way

Through Higgs coupling
Need a sterile right handed ν

$$\mathcal{L}^D_{mass} = -m_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)$$

$$m_D = \frac{v}{\sqrt{2}}Y_v \leftarrow \sim 10^{-12} \text{ (why?)}$$

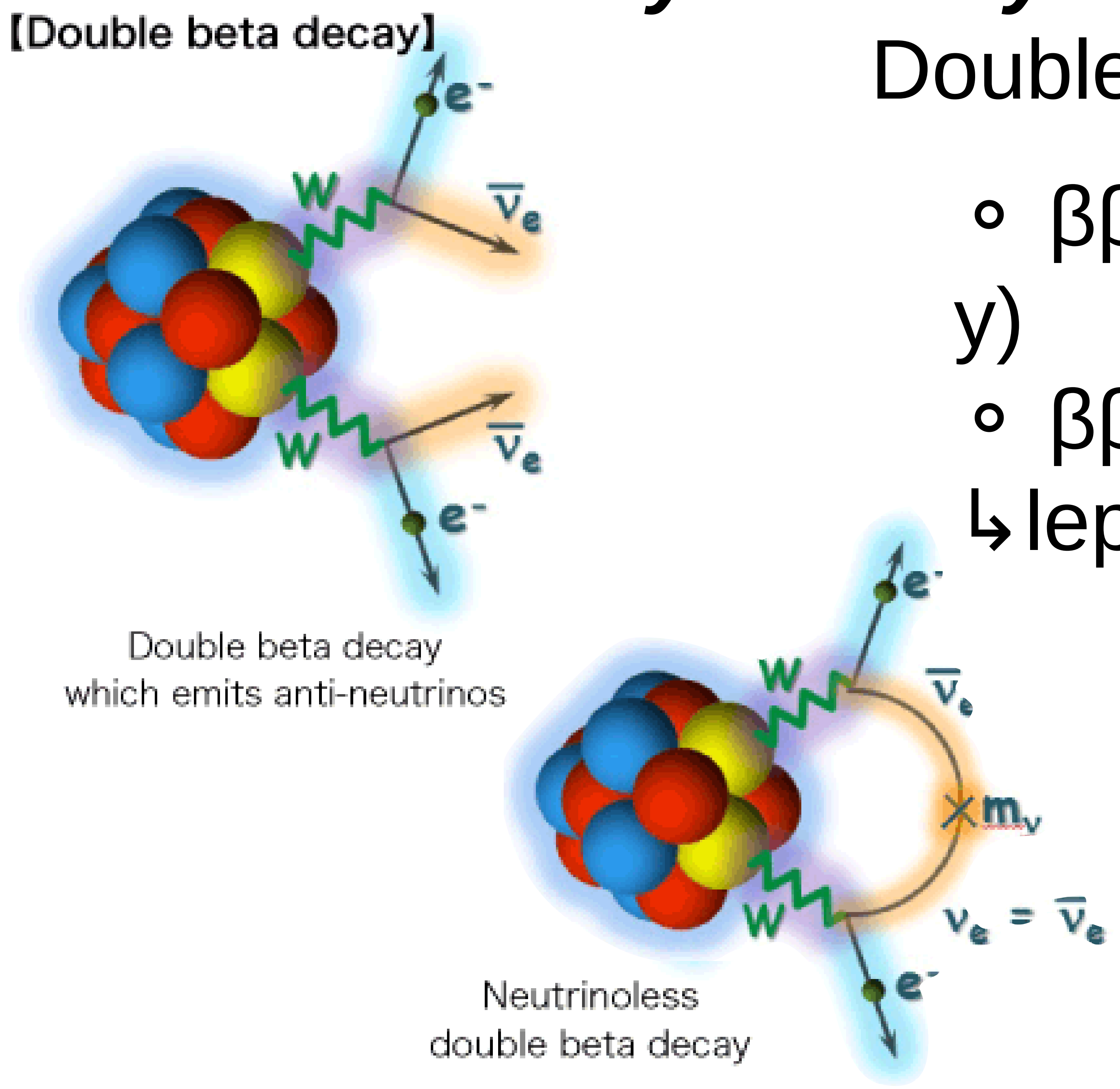
- The **Majorana** way

No distinction between ν and ν̄
Mass given by seesaw mechanism
Need massive neutrinos

$$\nu_R = C\bar{\nu}_L^T = \nu_L^C$$

$$m = \frac{m_D^2 \leftarrow \text{Dirac term}}{m_R \leftarrow \text{Very big}}$$

→ ***Only one way to prove that neutrino are Majorana particles :***
Double β decay with **no** neutrino emission

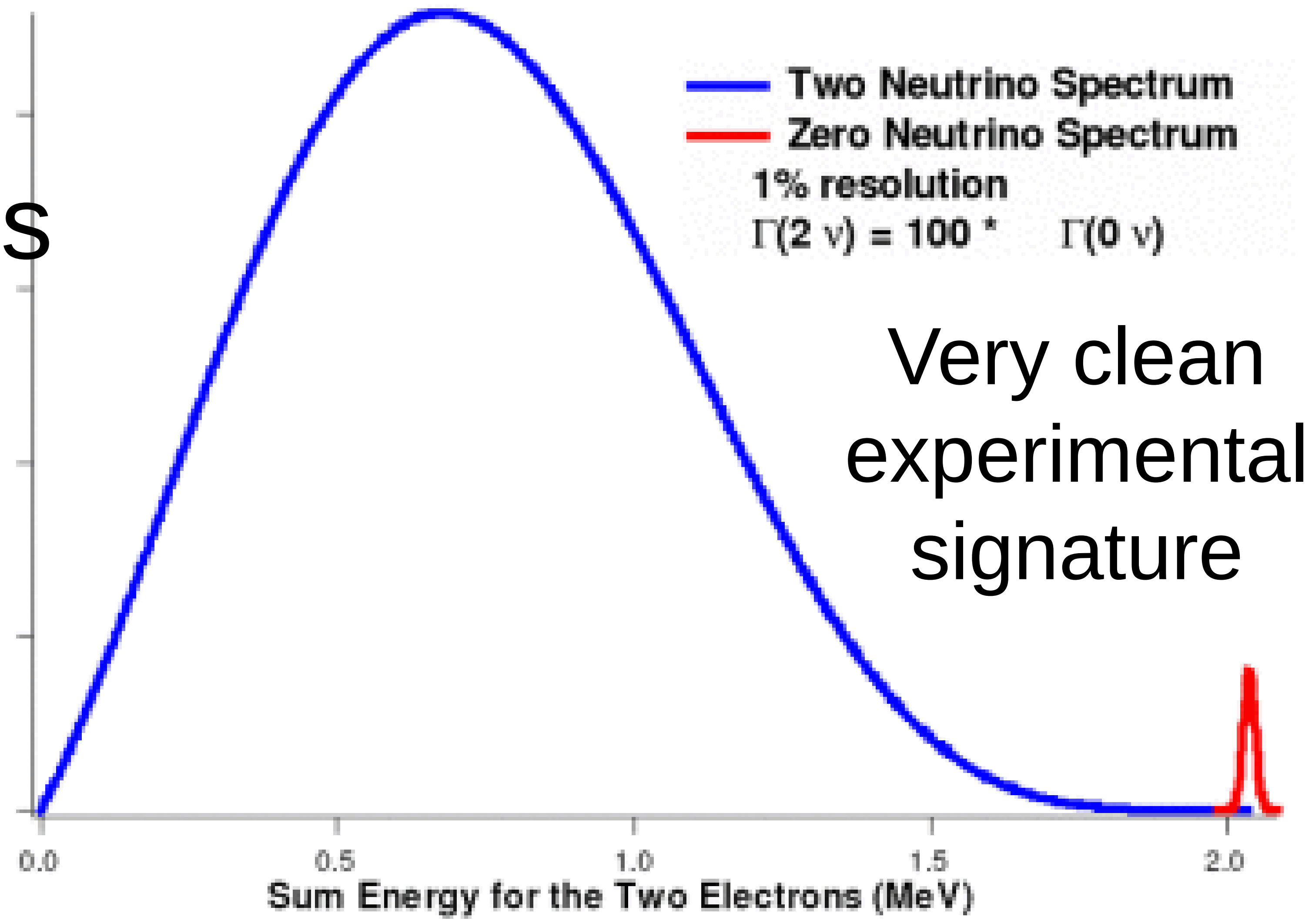


Double beta decay
which emits anti-neutrinos

Neutrinoless
double beta decay

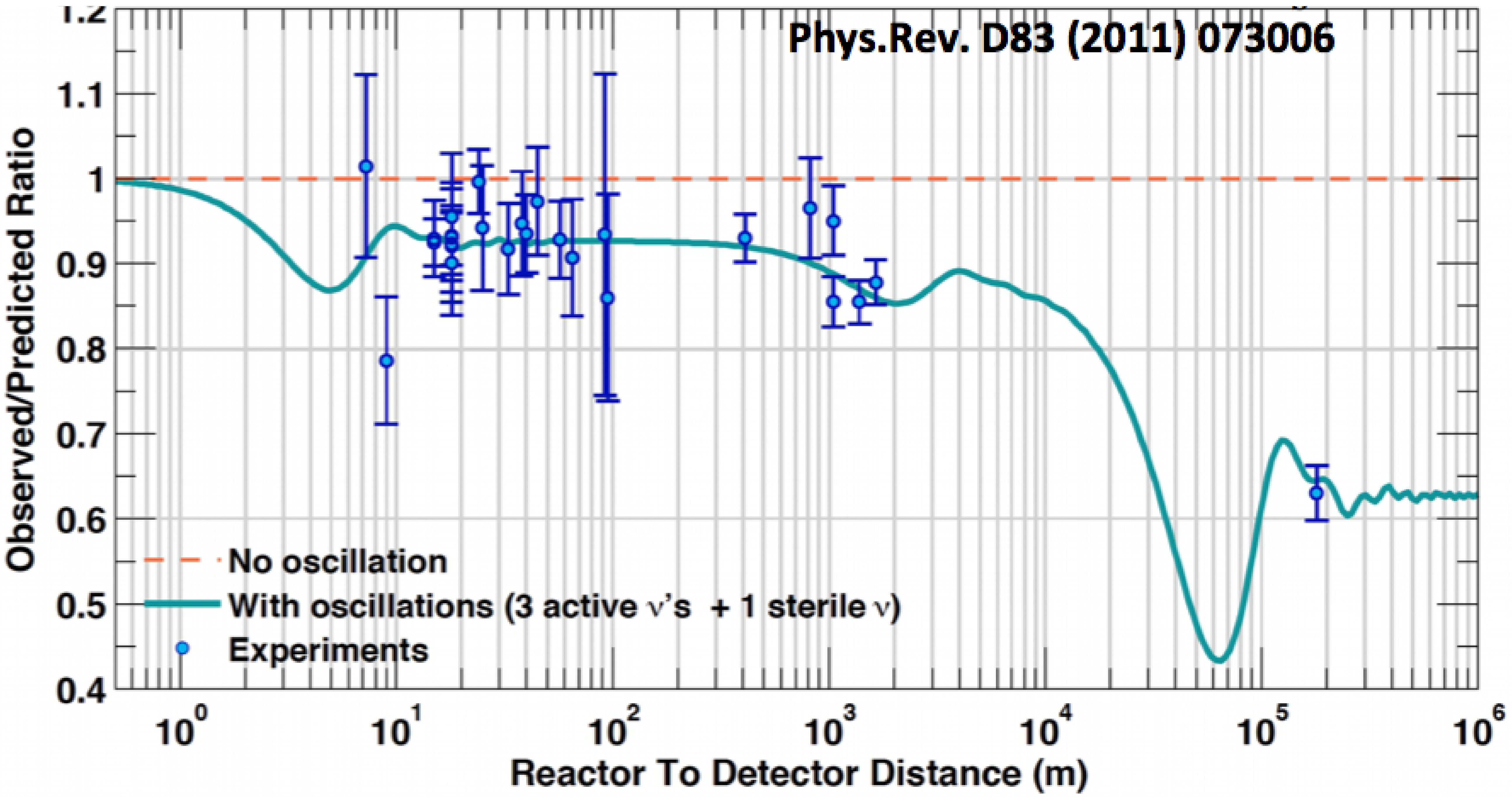
- ββ2ν is very rare (half life ~10^{18} - 10^{24} y)
- ββ0ν is **forbidden** in SM

↳lepton number violated by 2 units



Very clean experimental signature

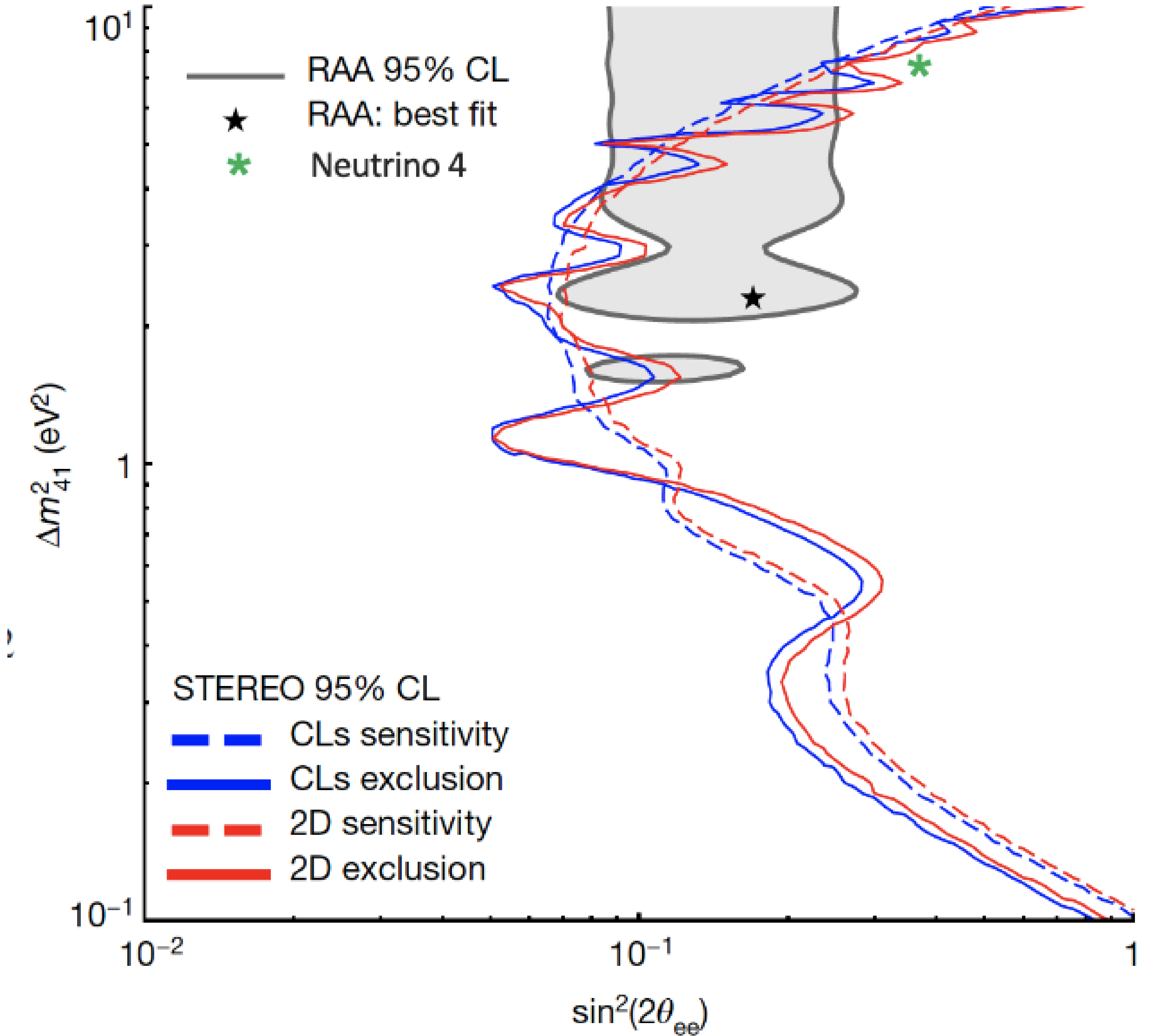
Only 3 Neutrinos ? ***STEREO, SOLID, PROSPECT,…***



A revised reactor $\overline{\nu}e$ flux analysis showed that all past ν experiments had a **~6% deficit** at small distances (3σ)

-> Problem with reactor flux ?
-> Existence of a sterile neutrinos ?

Latest results from STEREO



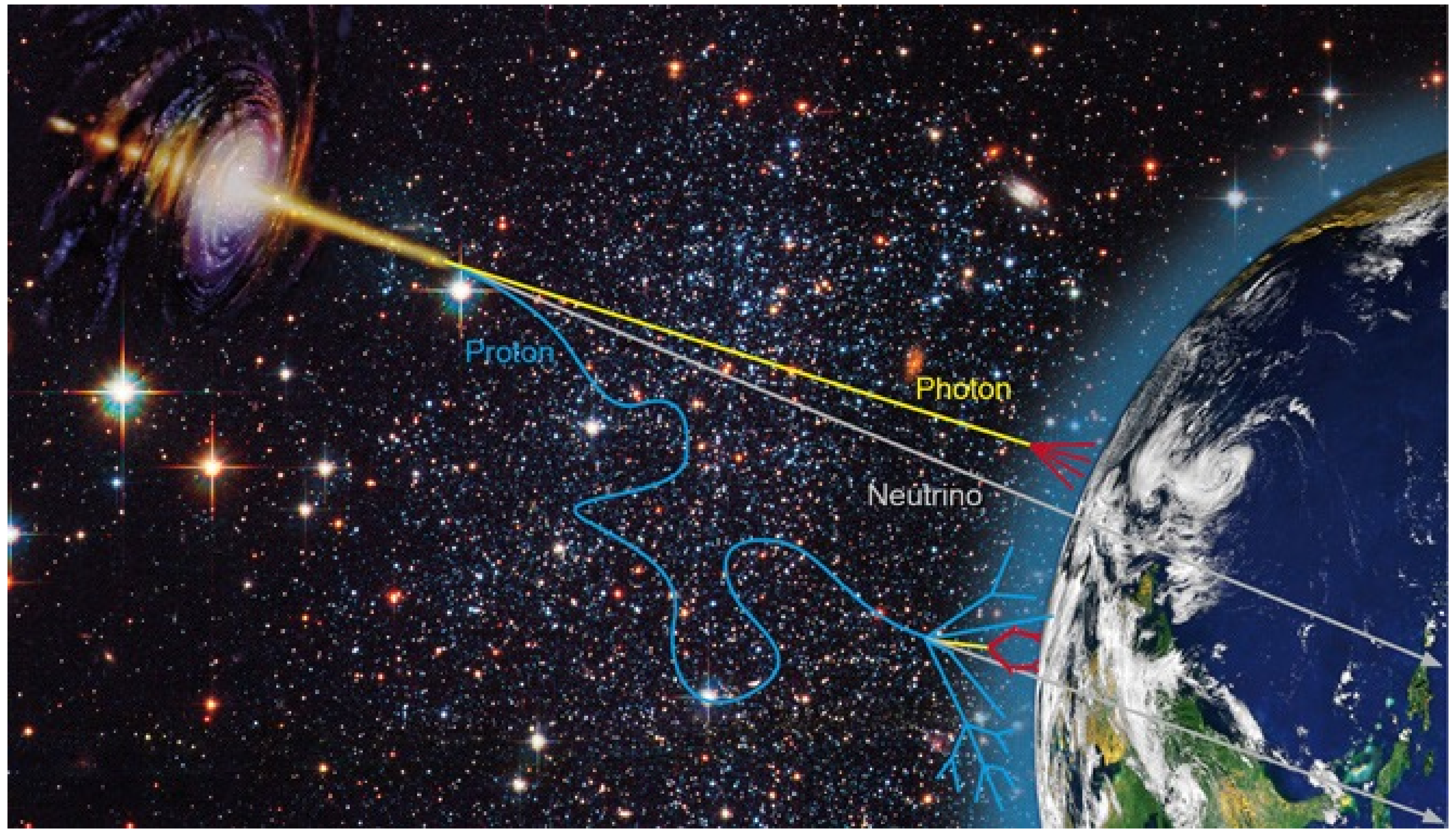
- Sterile because this neutrino cannot interact with weak force: it would be invisible
- But all 4 neutrinos could oscillate within each others

→ ***New mass splitting and new mixing angle***

Best fit parameters of reactor anomaly:

$\Delta m^2 \sim 2$ eV^2
$\sin^2(2\theta) \sim 0.15$
L_{osc} ~ few m

Neutrino Astronomy: ***ICECUBE, KM3NET***

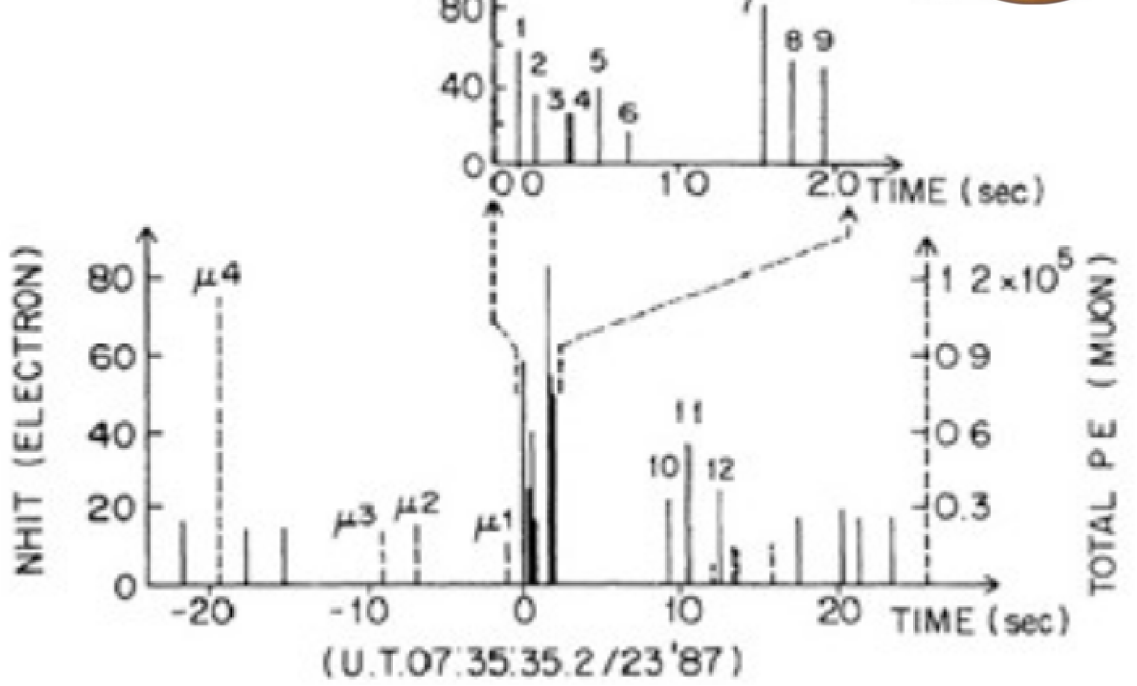


- Unlike protons & gammas, neutrinos **points to the sources**
- Can probe the inside of the structure
- **No GZK threshold** : can probe far away objects

On February 23rd 1987, a supernova exploded in the large magellan cloud (170 000 l.y

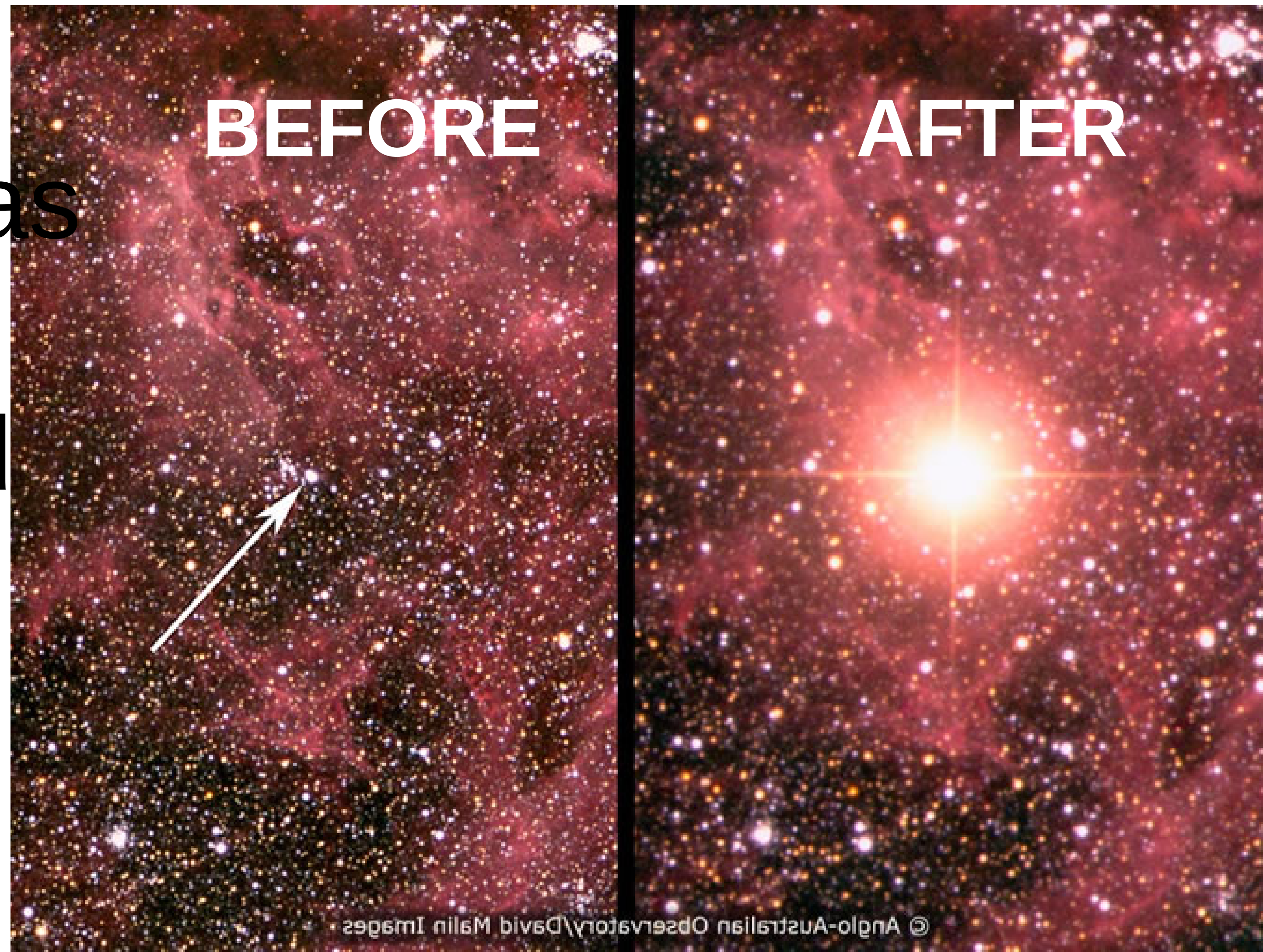
3h before the light signal, three neutrino detectors observed a large number of events in a very short time (**24 events in 13s**)

9 @ Kamiokande

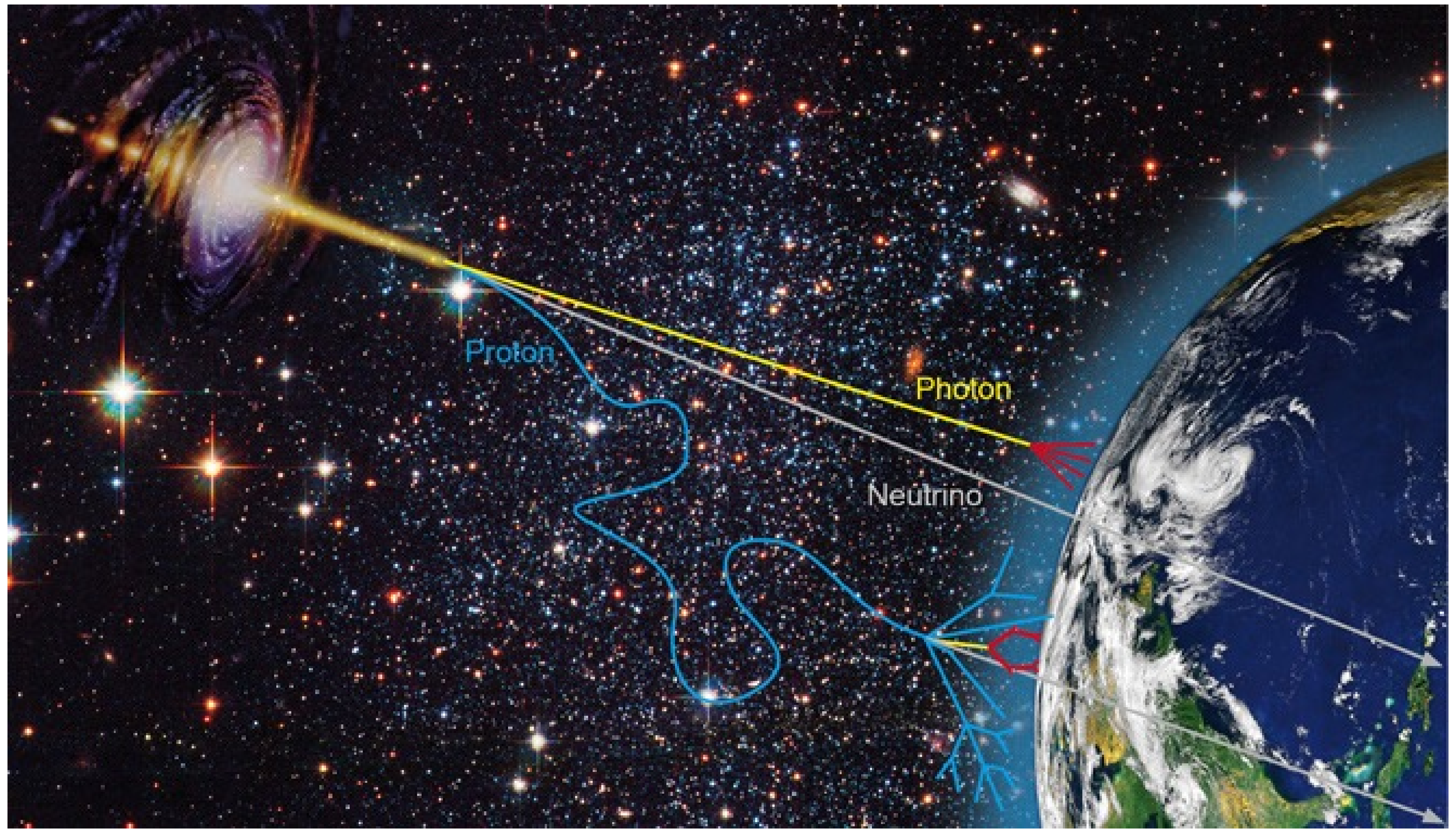


- 99% of the SN energy is released as neutrinos
- 1st case of neutrino astronomy and multi-messenger
- all ν experiments waiting for next nearby SN explosion

SN1987A



Neutrino Astronomy: ***ICECUBE, KM3NET***



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- Can probe the inside of the structure
- **No GZK threshold** : can probe far away objects

On September 22^nd^ 2017 : **Simultaneous** light & neutrino detection from the TXS 0506+056 blazar (3σ, $E_\nu = 290$ TeV)

(blazar = Active Galactic Nucleus with one jet pointing to earth)

- 1^{st} case of planned **multi-messenger** astronomy
- Confirmed that blazar emits neutrinos