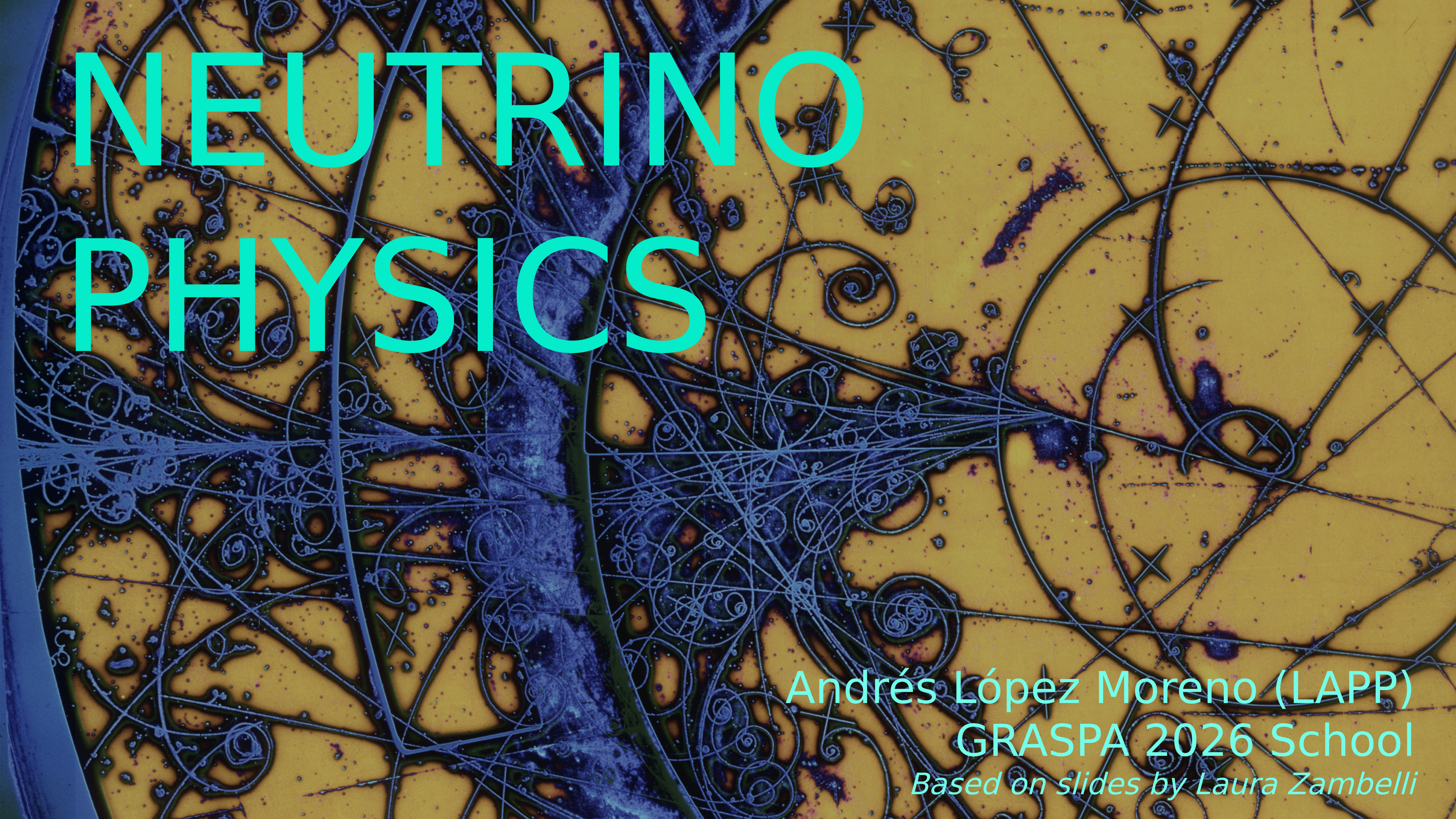




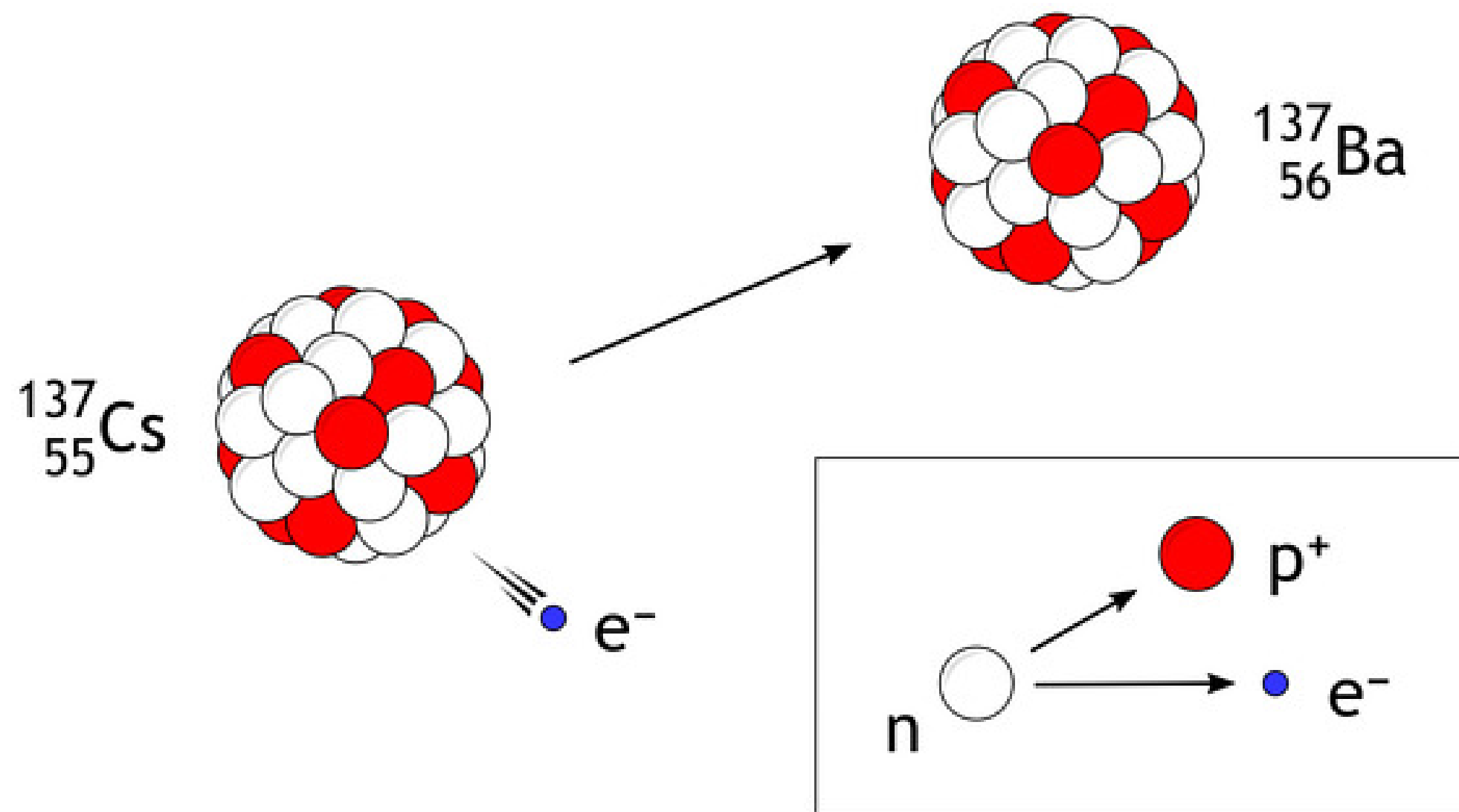
NEUTRINO PHYSICS

Andrés López Moreno (LAPP)
GRASPA 2026 School
Based on slides by Laura Zambelli

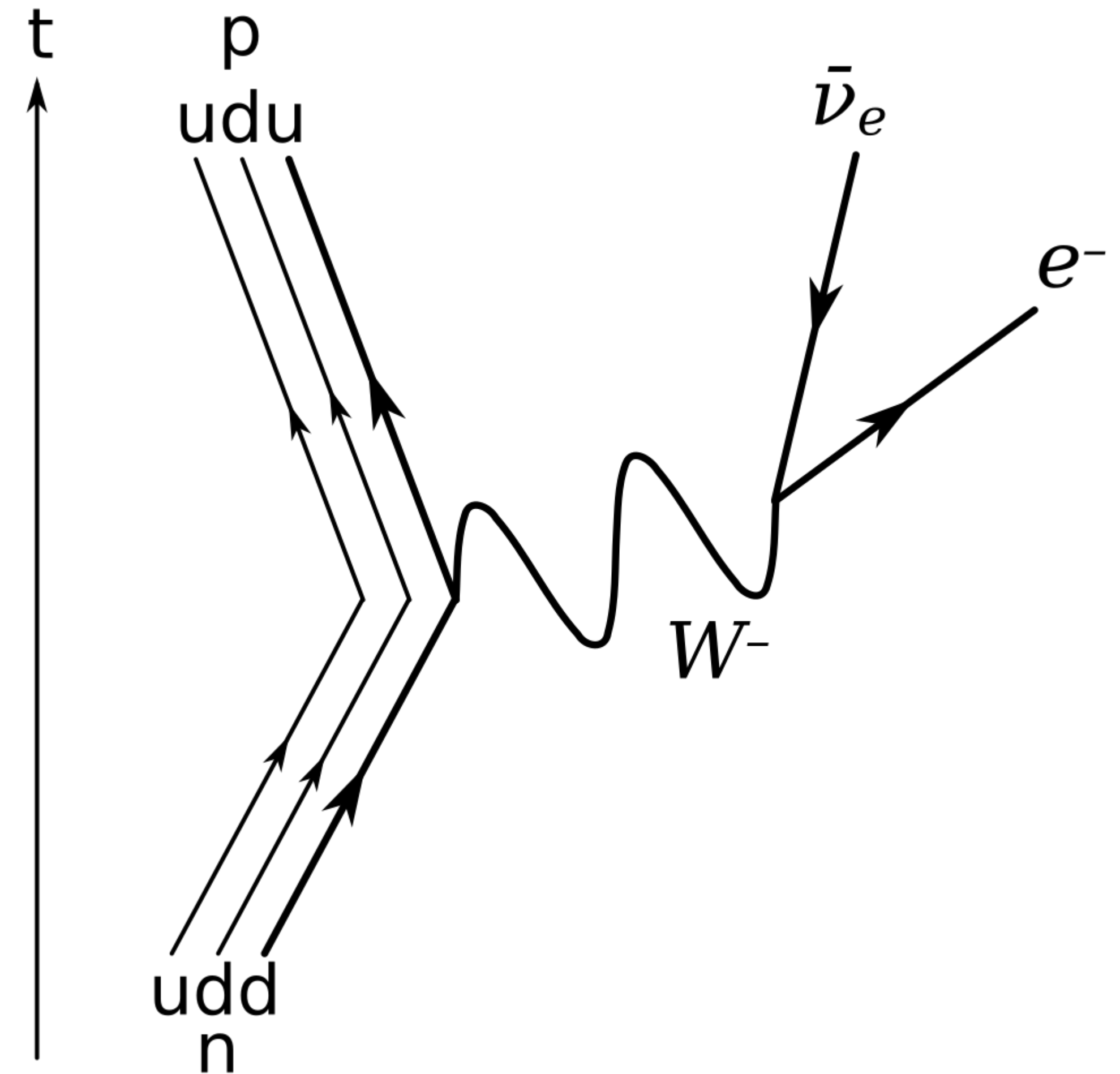
- Neutrinos: What, where, how?
- Neutrino Interactions
- Neutrino Oscillations
- Modern neutrino physics



The beta decay problem

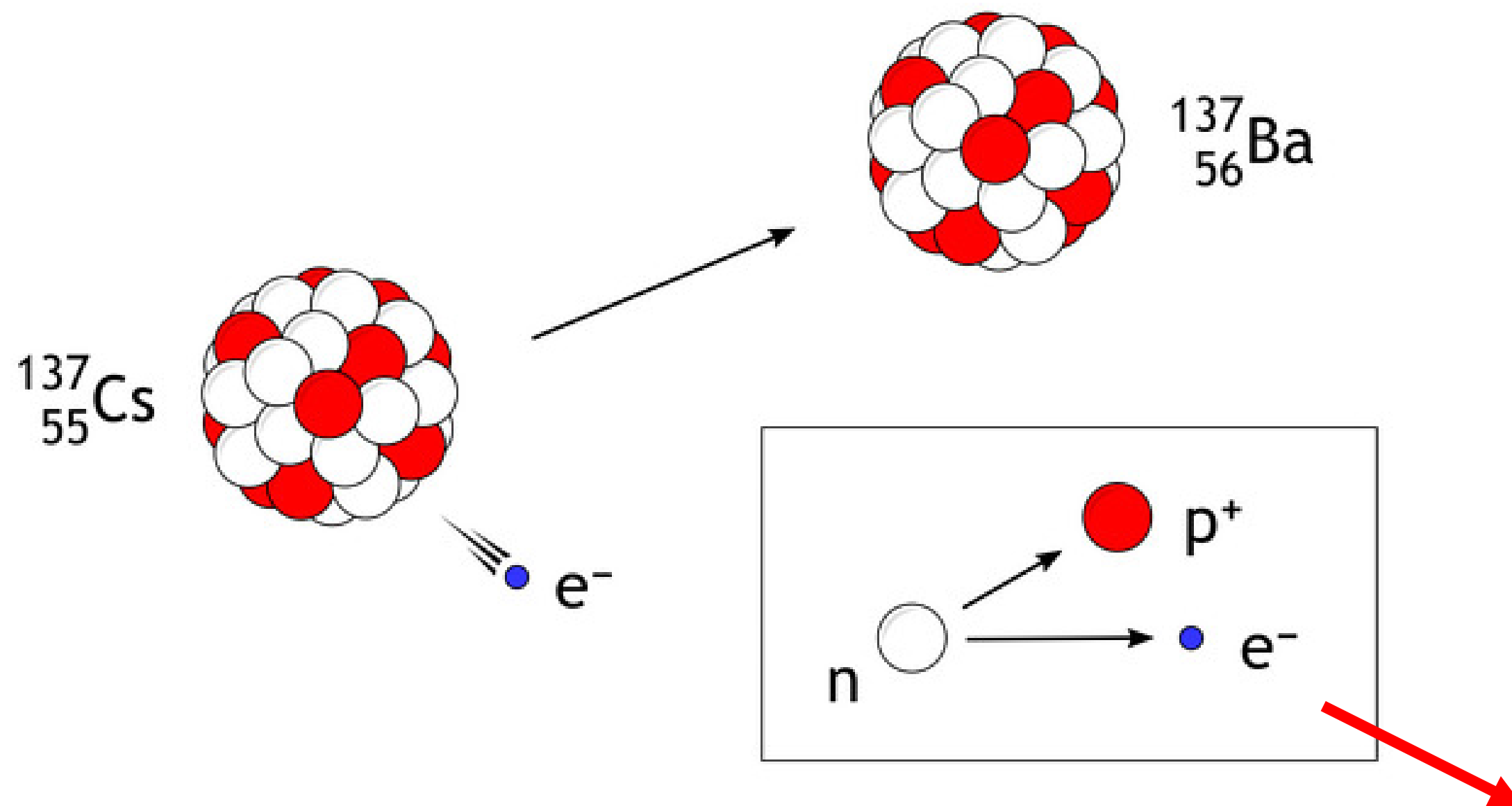


Stuff from the 1920s



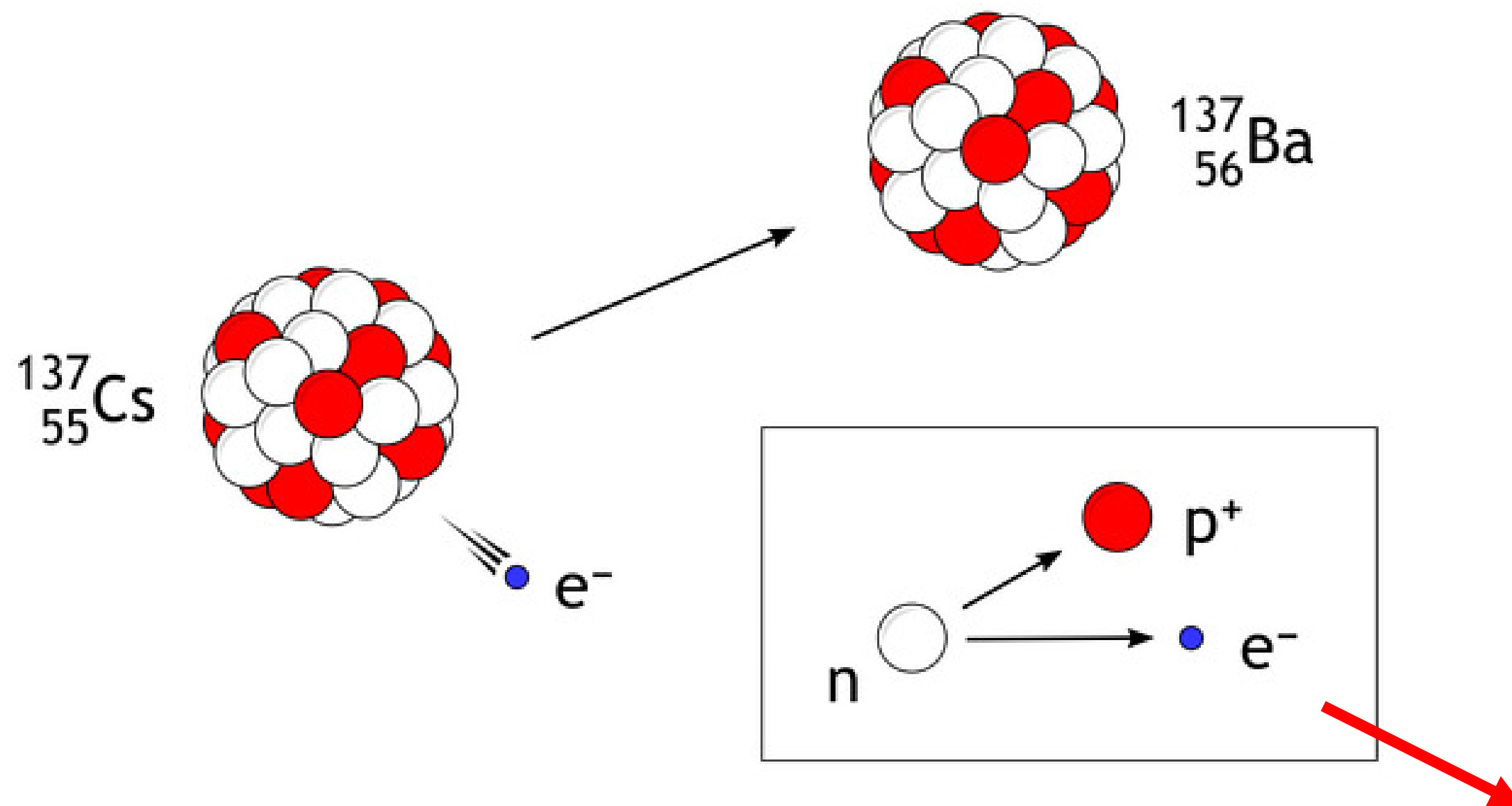
(we didn't have this kind of understanding in the 1920s)

The beta decay problem

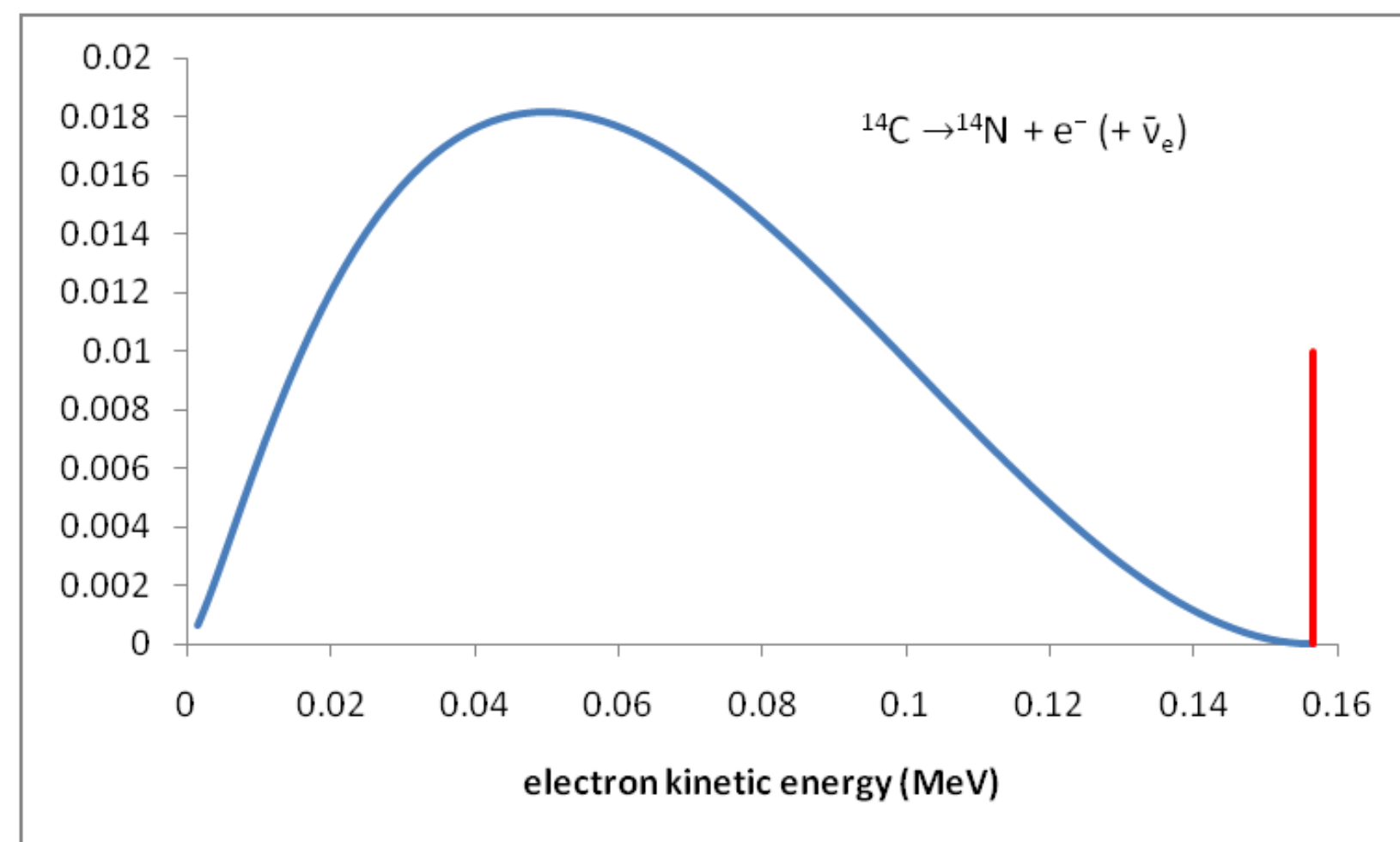


Conservation of 4-momentum (special relativity): $p_n = p_p + p_e \rightarrow p_e = (p_n - p_p) \approx m_n - m_p$

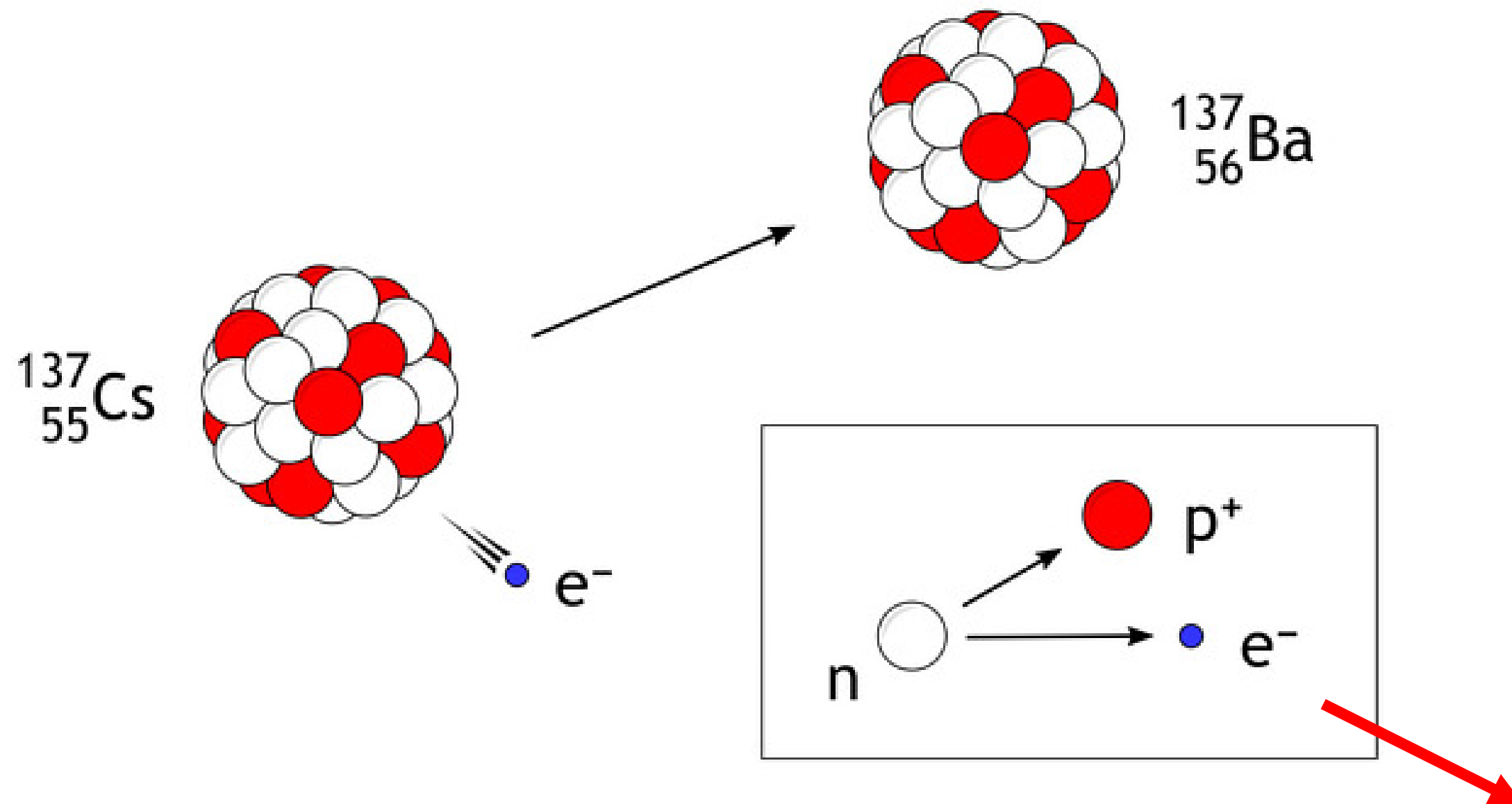
The beta decay problem



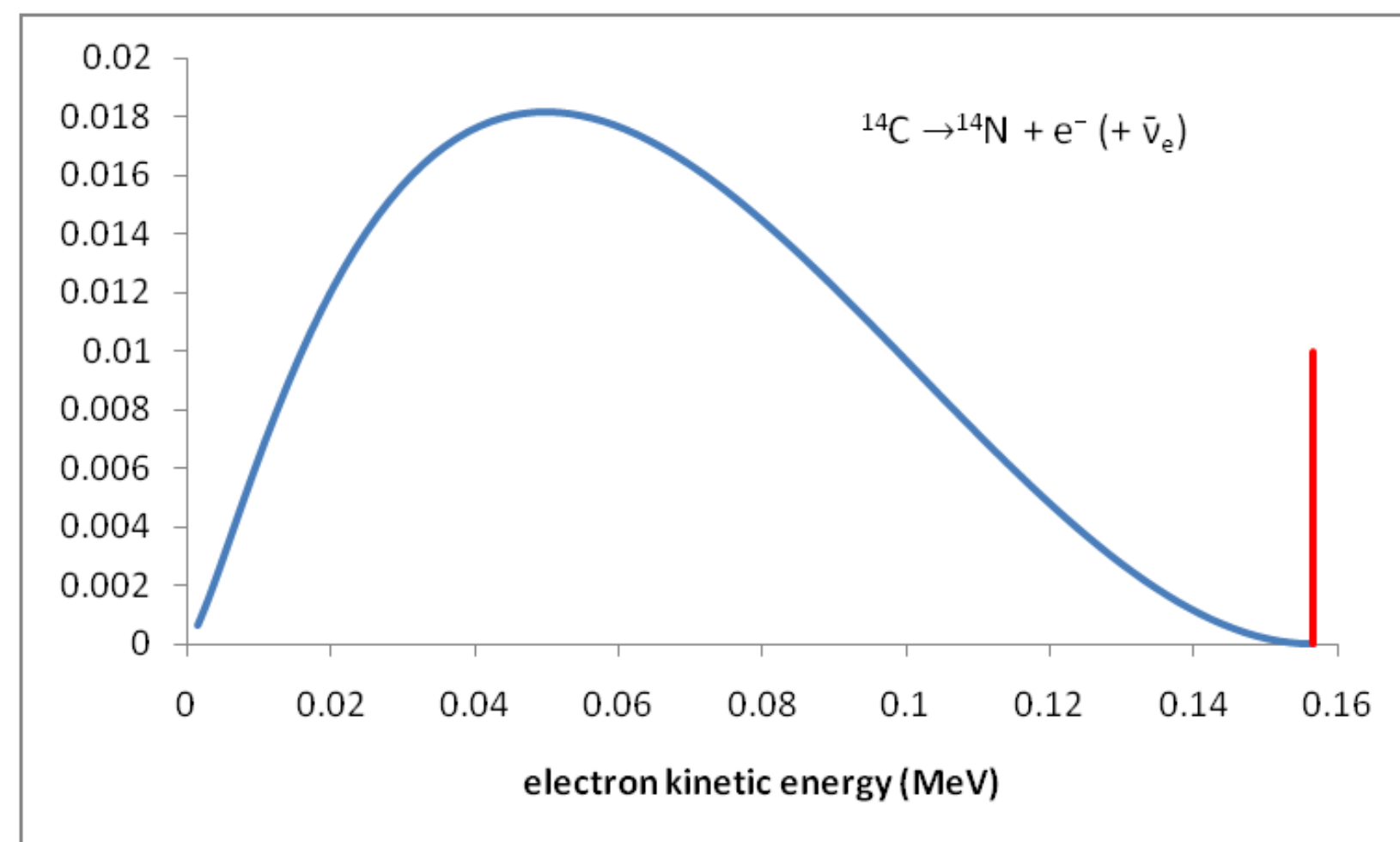
Conservation of 4-momentum (special relativity): $p_n = p_p + p_e \rightarrow p_e = (p_n - p_p) \approx m_n - m_p$



The beta decay problem



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



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

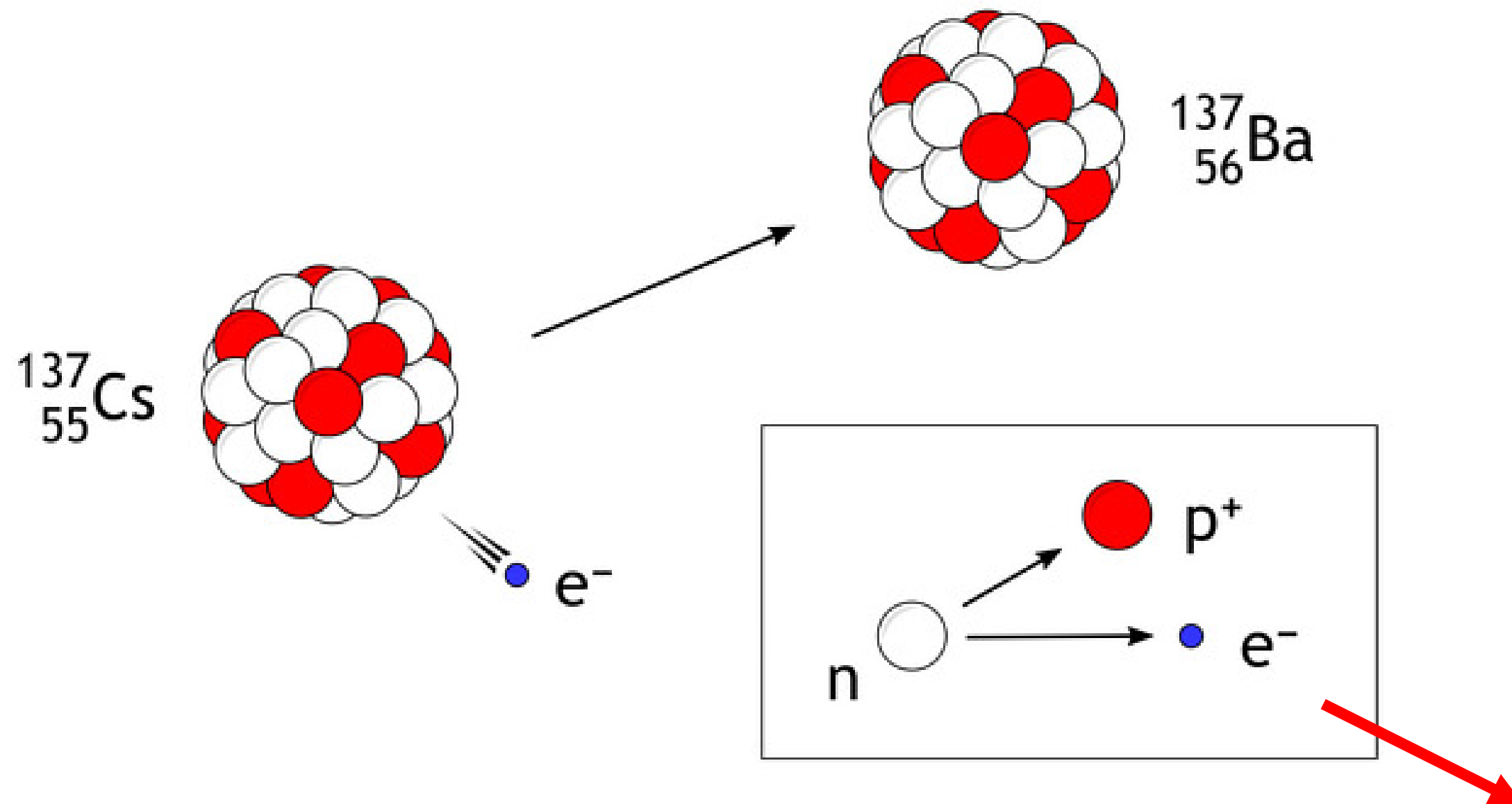
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

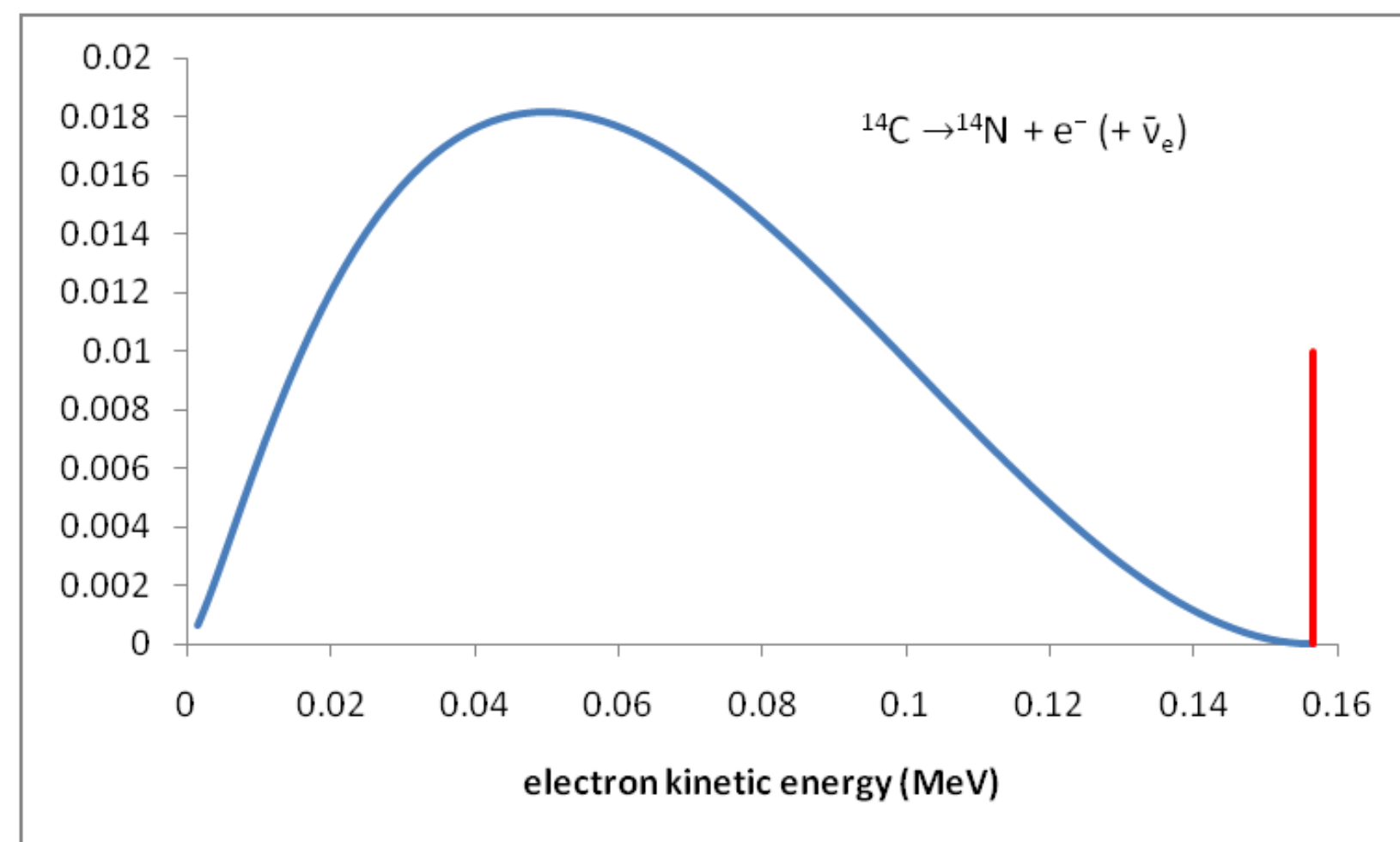
Wie der Ueberbringer dieser Zeilen, den ich kuldvollst
ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg
verfallen um den "Wechselsatz" (1) der Statistik 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
müsse 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.

**New electrically
neutral (massless?)
particle!**

The beta decay problem



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



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

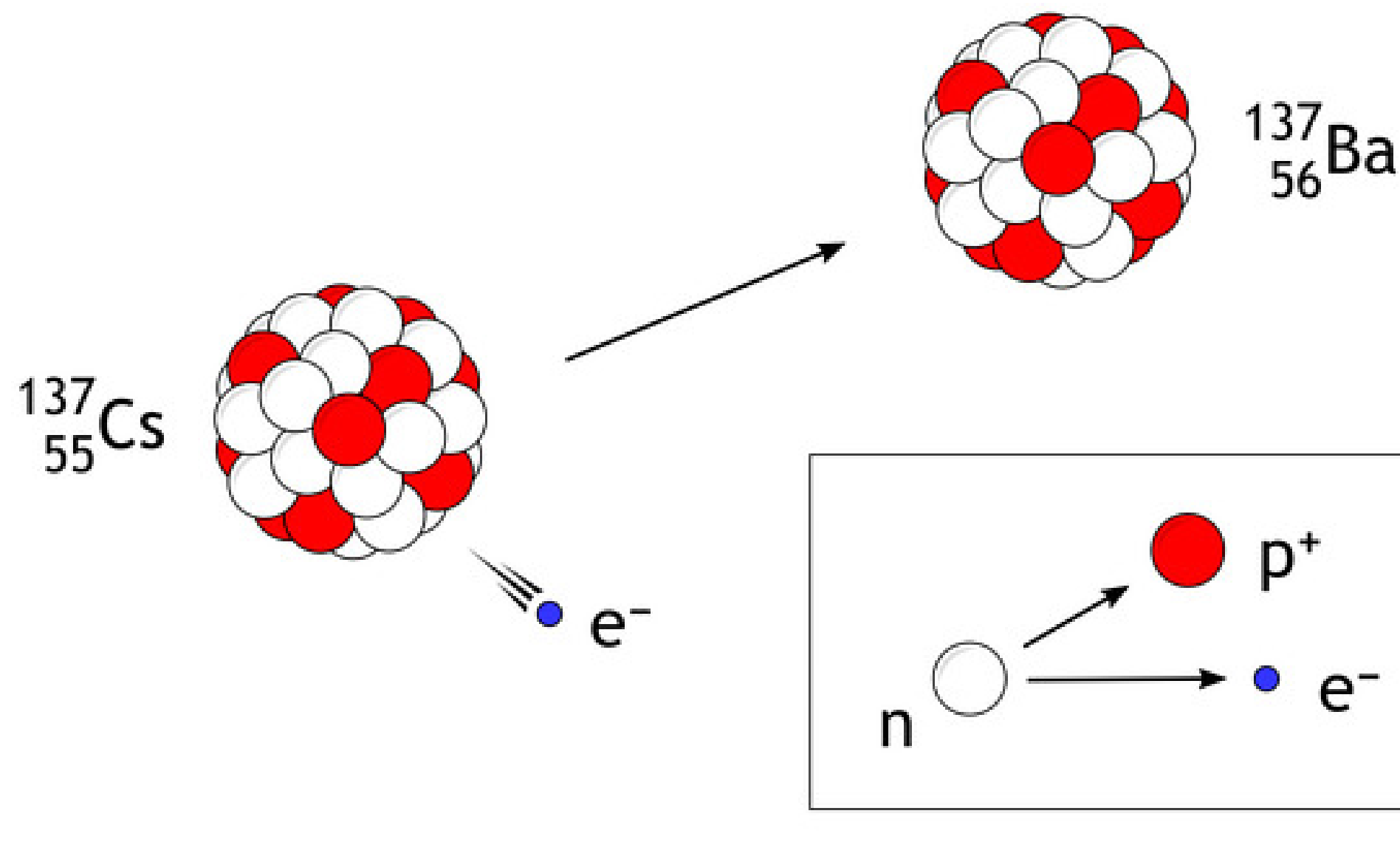
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich kuldvollst
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 verzweiferten 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.

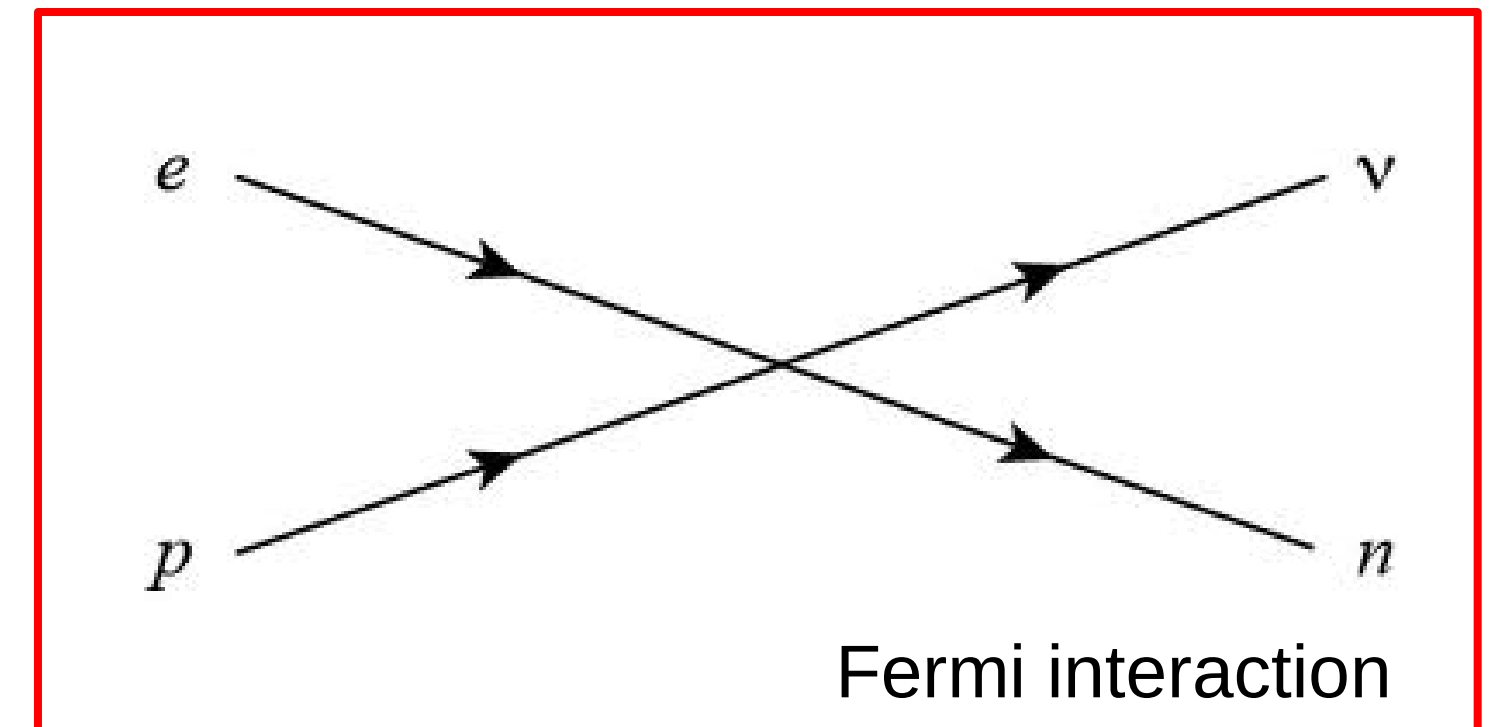
How can we
find this
particle?

New electrically
neutral (massless?)
particle!

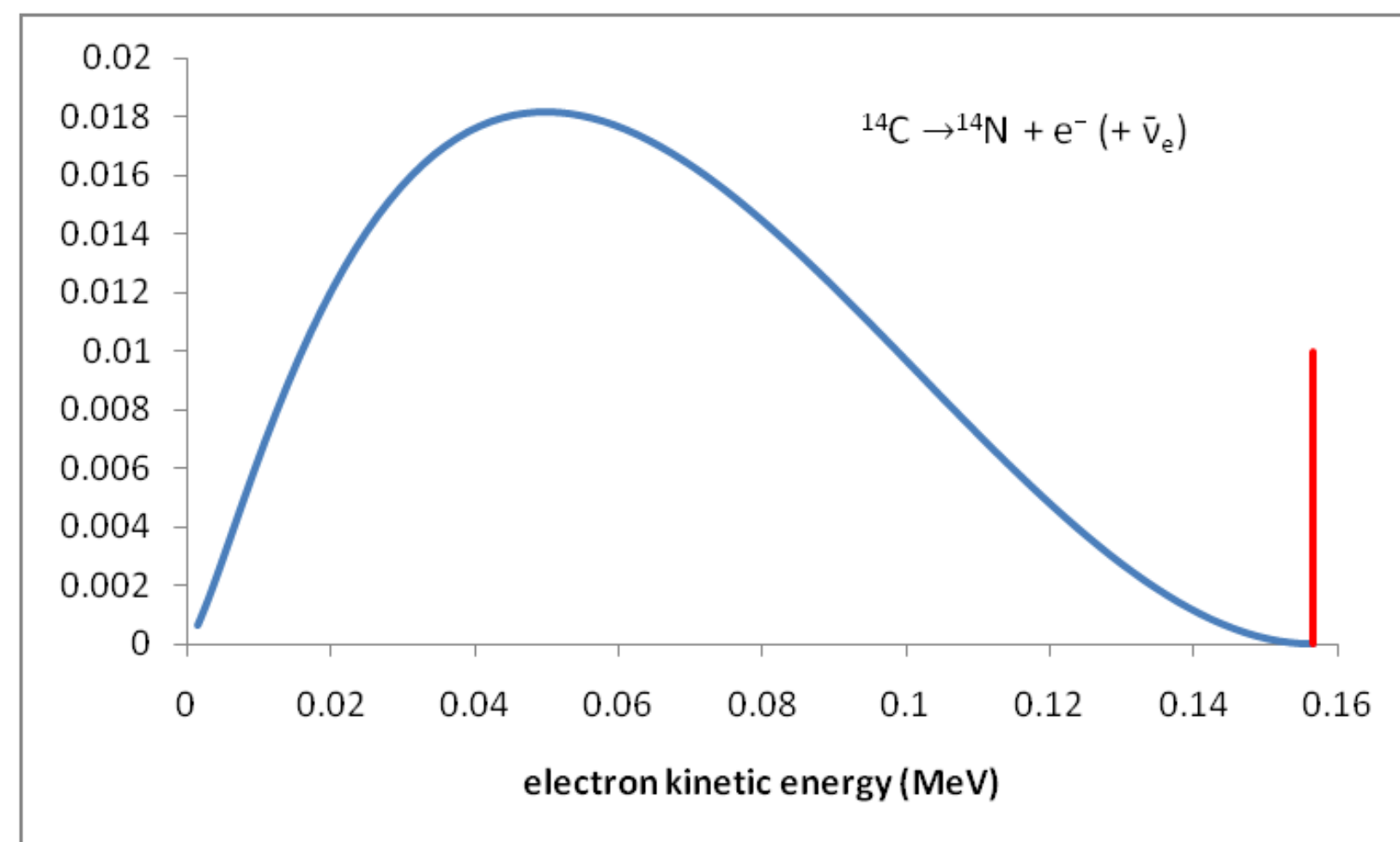
The beta decay problem



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



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



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich kuldvollst
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.

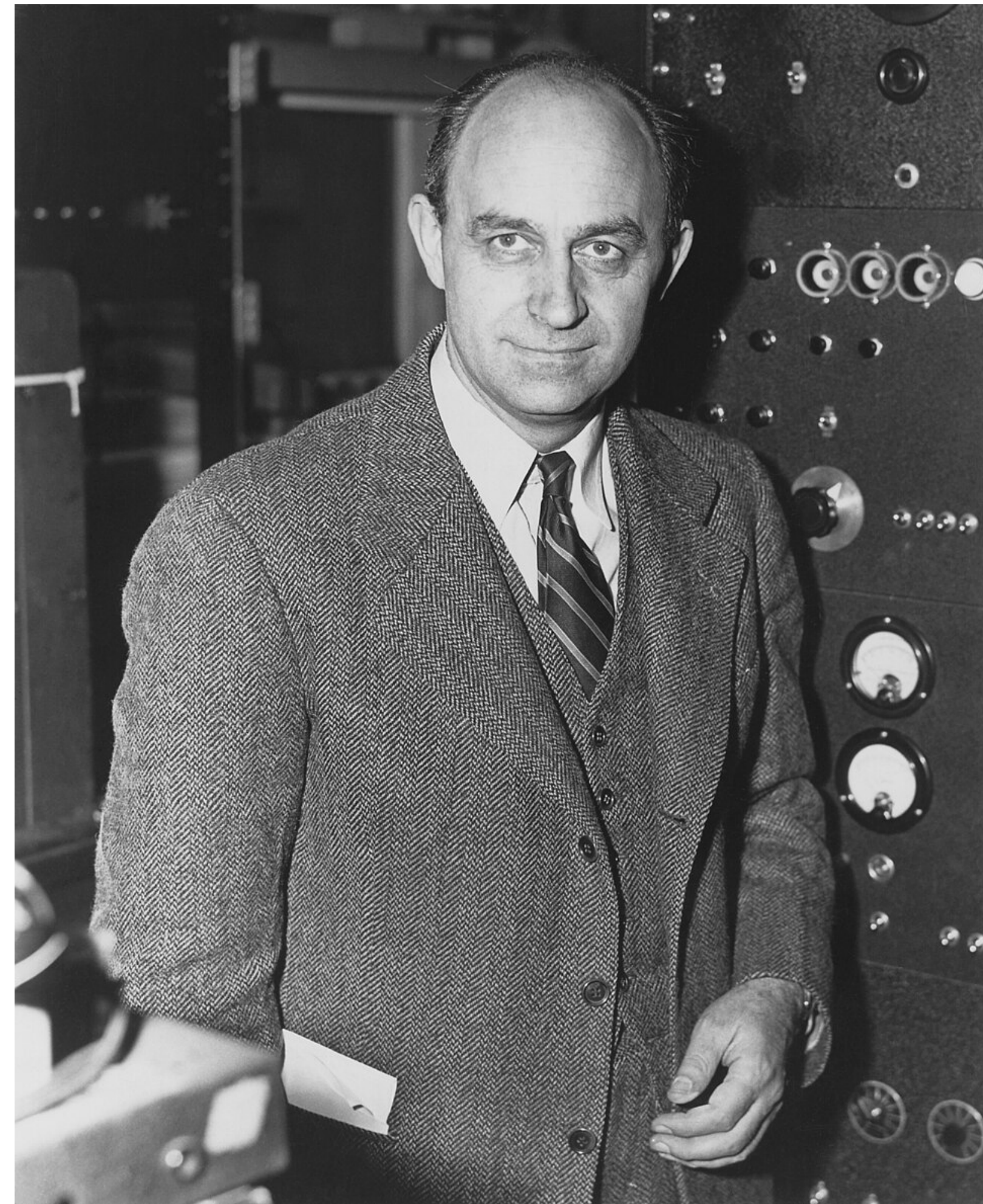
How can we
find this
particle?

New electrically
neutral (massless?)
particle!

Thank you Pauli, thank you Fermi



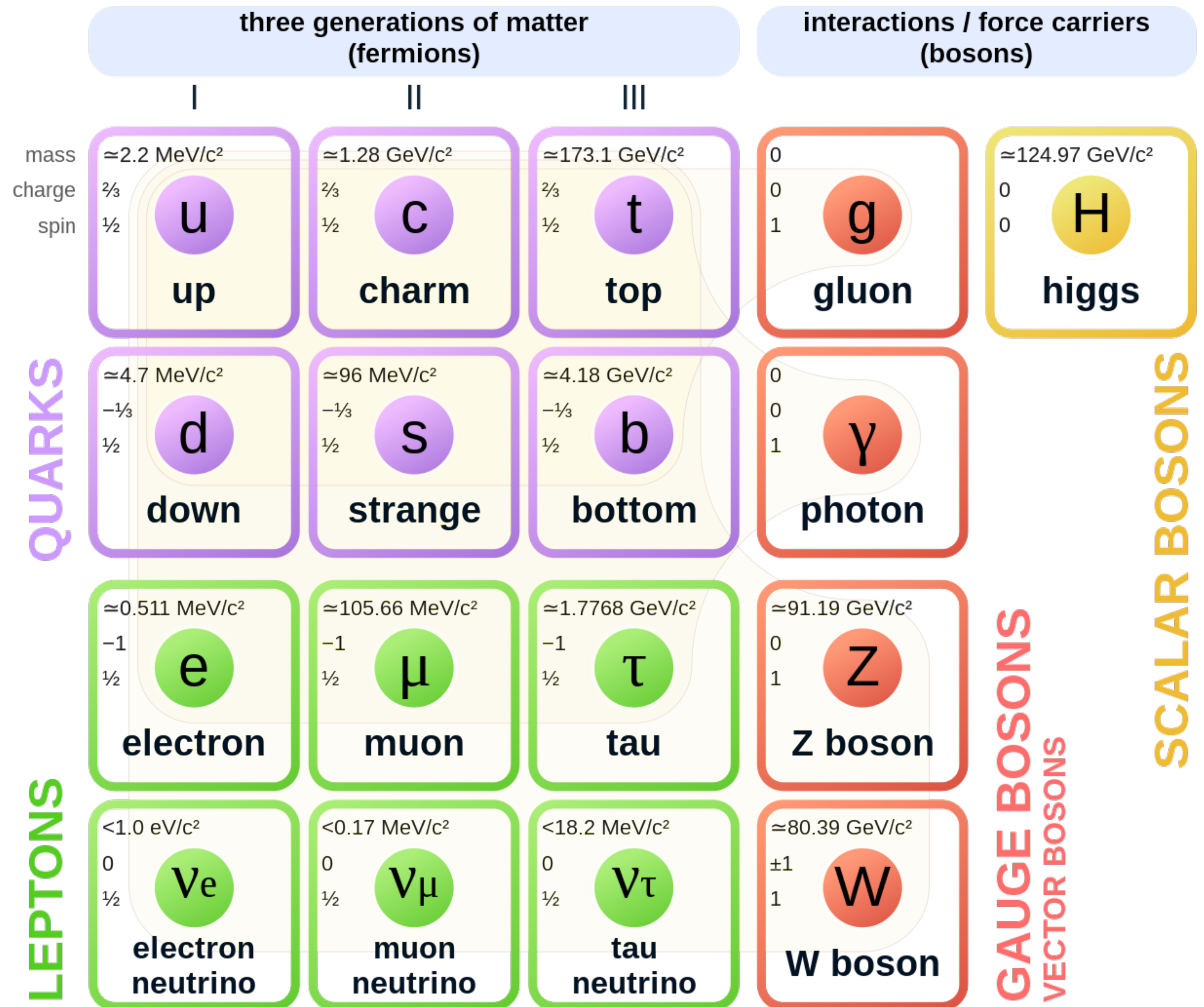
I came up with the idea!



I figured out how to make it work!

In the Standard Model

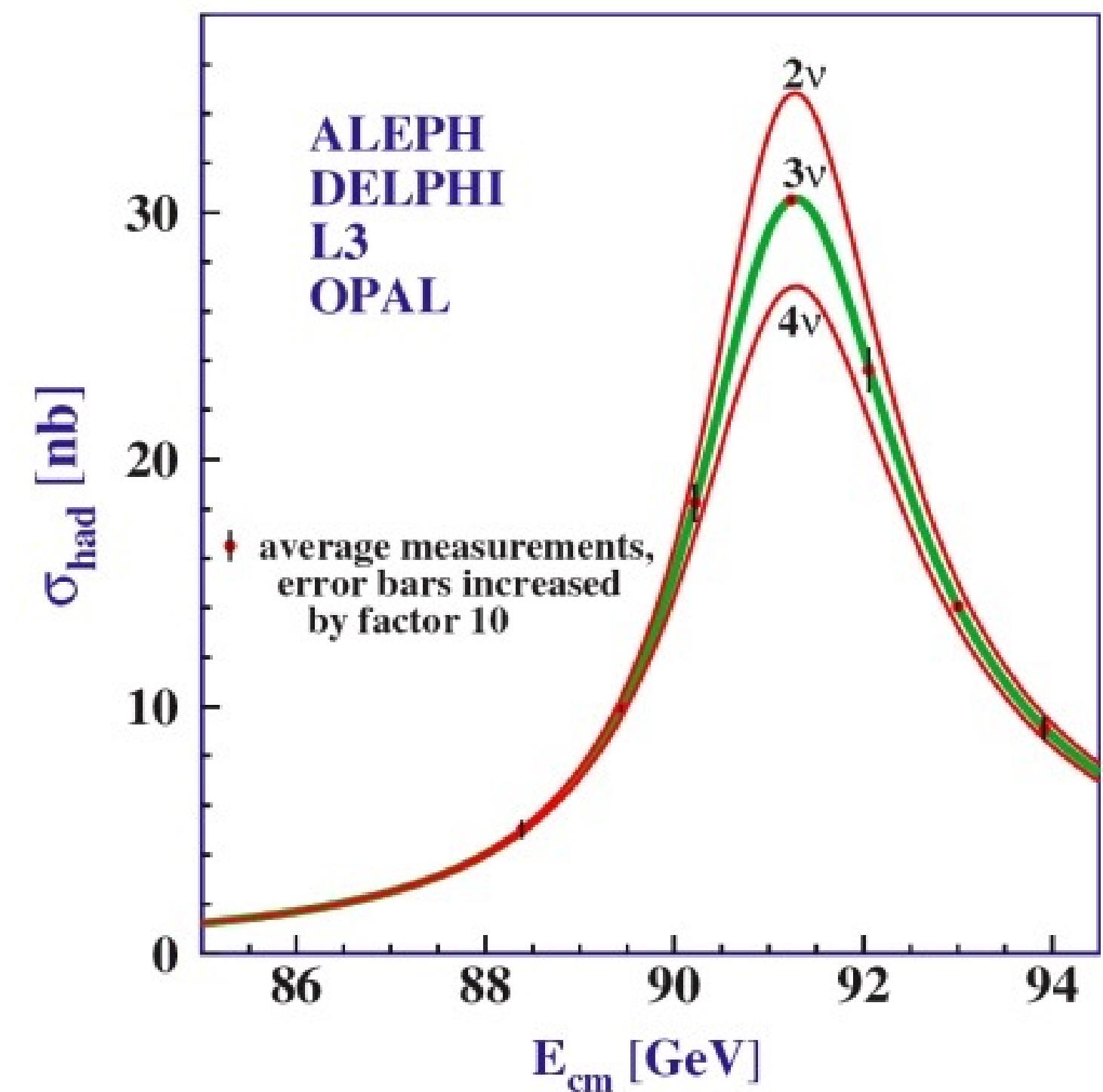
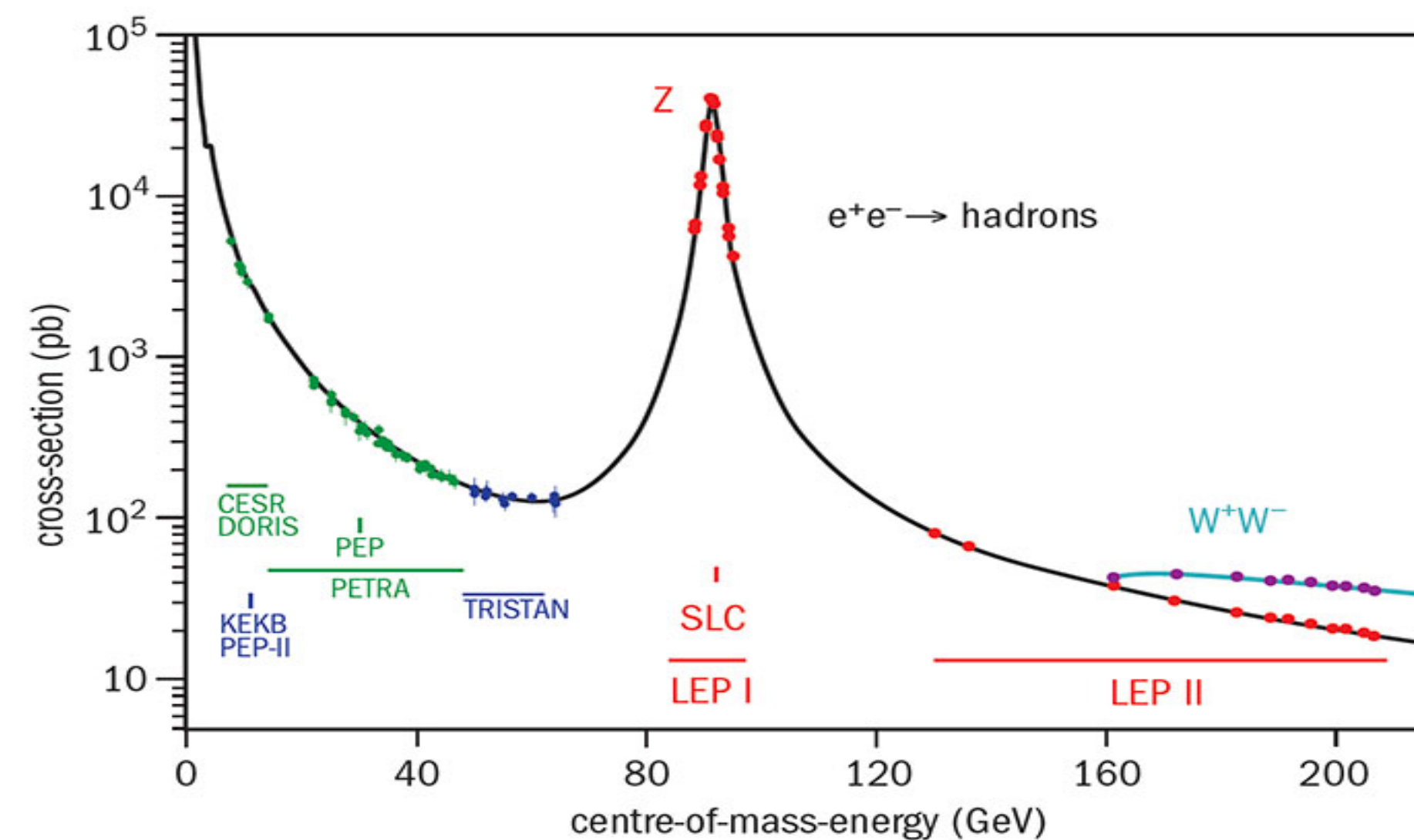
- Neutrinos are leptons
- 3 flavors linked to their corresponding charged counterpart
- Can only interact through weak force (through $W^\pm$ and Z^0 bosons)
- There are parallels between the 6 leptons and 6 quarks



Key facts

- Three flavors of light and active neutrinos named ν_e , ν_μ , ν_τ
- In 1989, LEP measures 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:

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

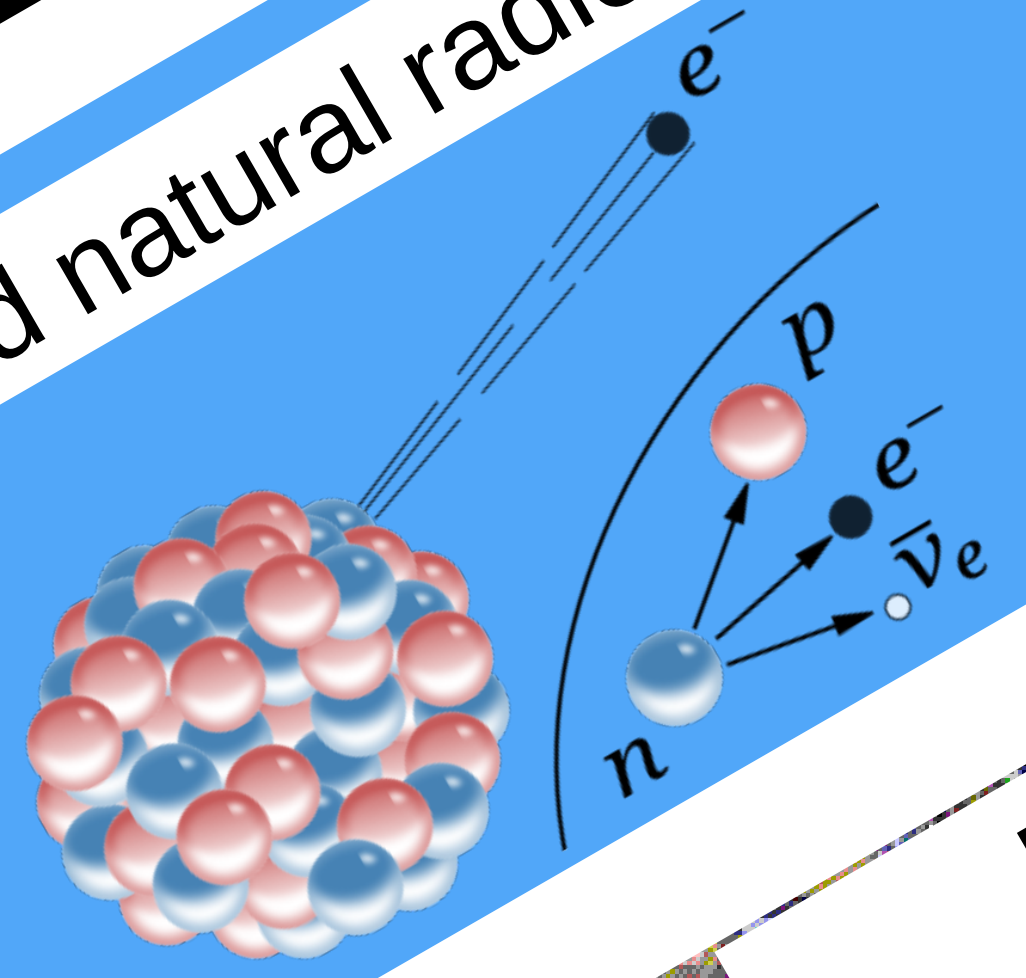
We will soon see why...

Cosmological sources

Nearby natural sources

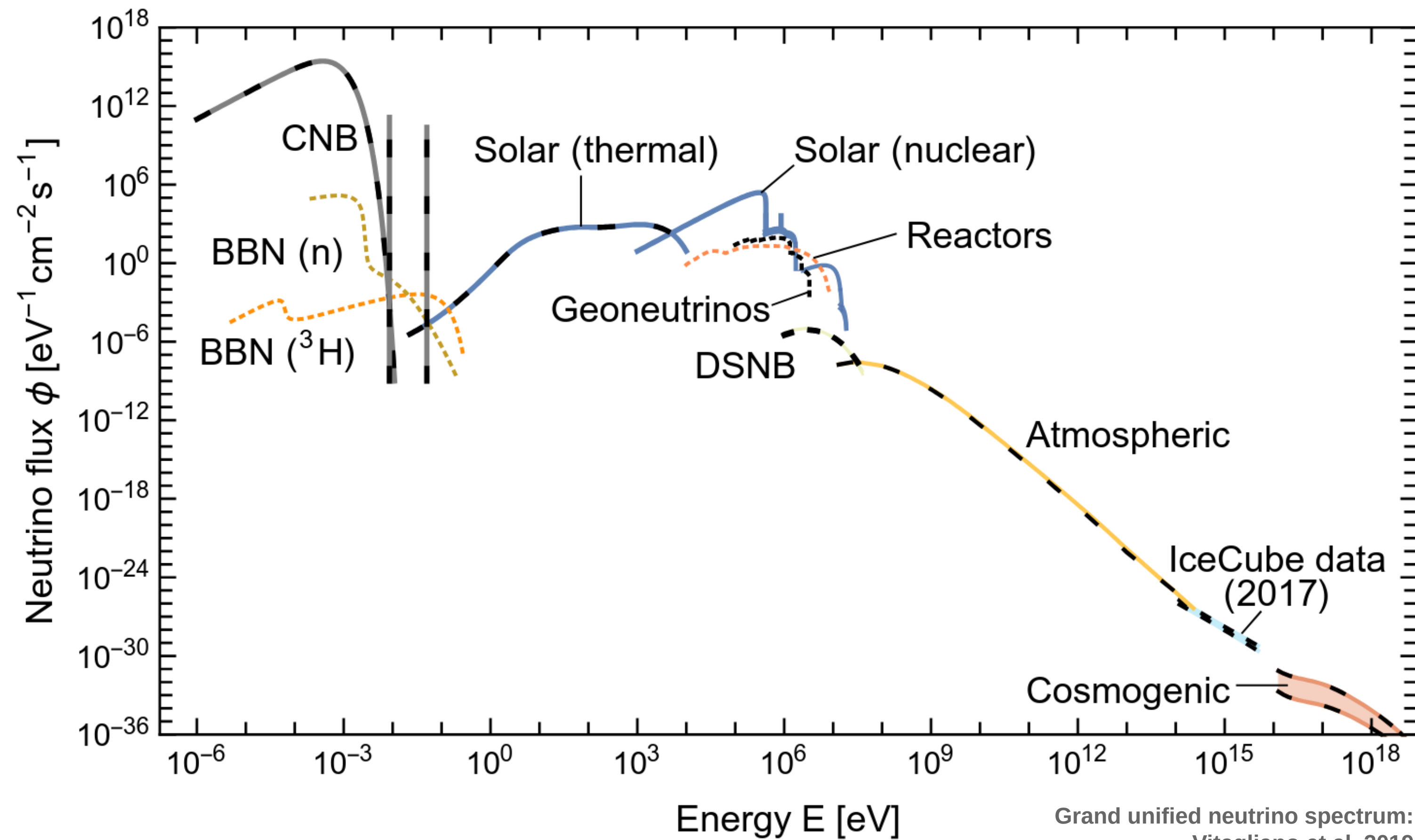
Artificial and natural radioactive sources

Man-made using accelerators



Neutrino sources

Neutrinos are the most common massive particle in the universe (high-E $p \rightarrow \nu$!)



$$\Phi_{\text{sun}} = 65 \times 10^9 \nu_e / \text{cm}^2 / \text{s on earth}$$

$$\Phi_{\text{reactor}} = 2 \times 10^{20} \bar{\nu}_e / \text{s} / \text{GW}_{\text{th}}$$

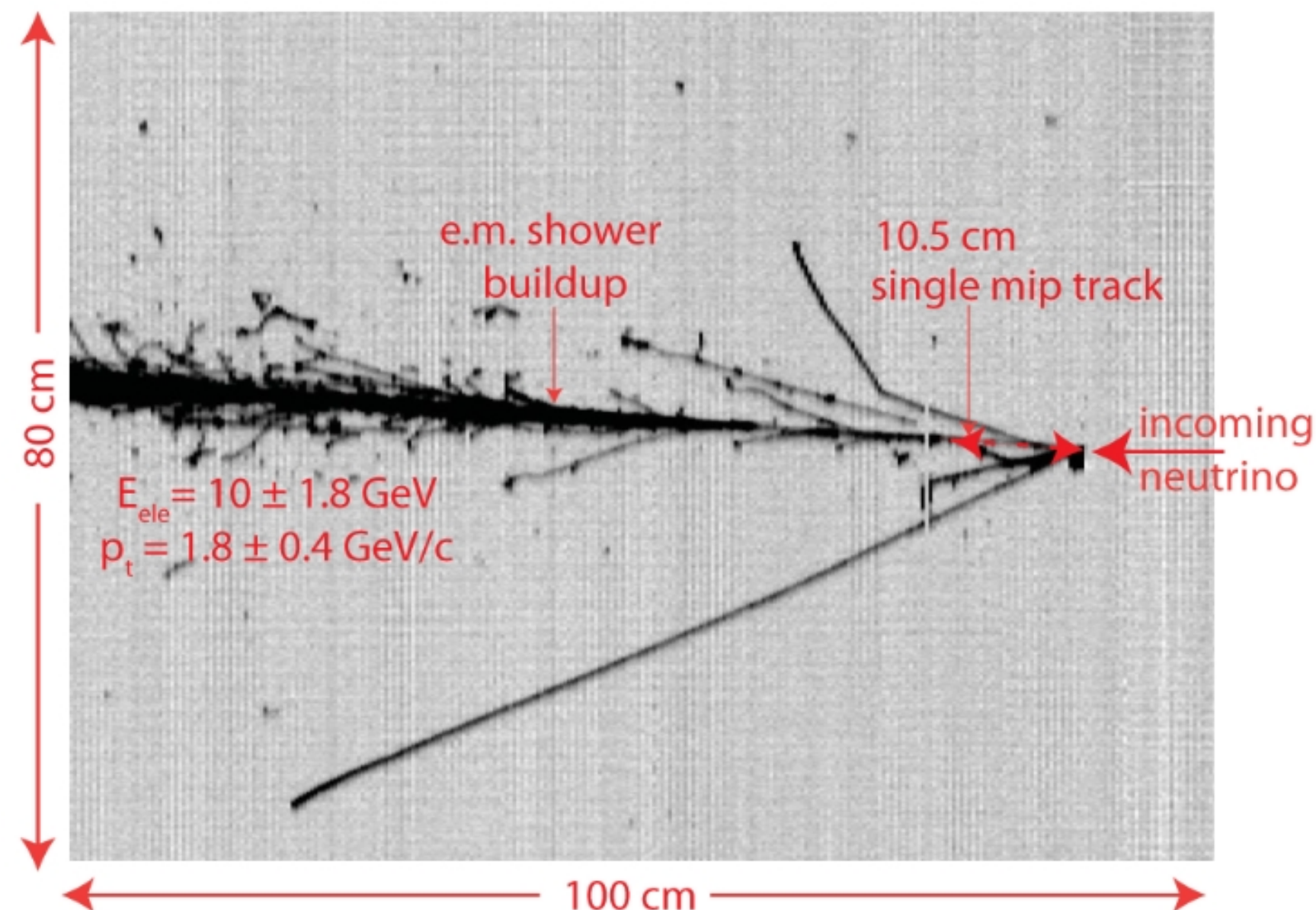
$$\Phi_{\text{atmo}} = 4 \times 10^2 \nu_{e+\mu} / \text{m}^2 / \text{s} / \text{sr}$$

$$\Phi_{\text{accelerator}} \sim 1 \times 10^{12} \nu_{\mu} / \text{m}^2$$

→ **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 :
 - $\sigma \sim 10^{-42} \text{ cm}^2$ for IBD
 - $\sigma \sim 10^{-38} \text{ cm}^2$ 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!!

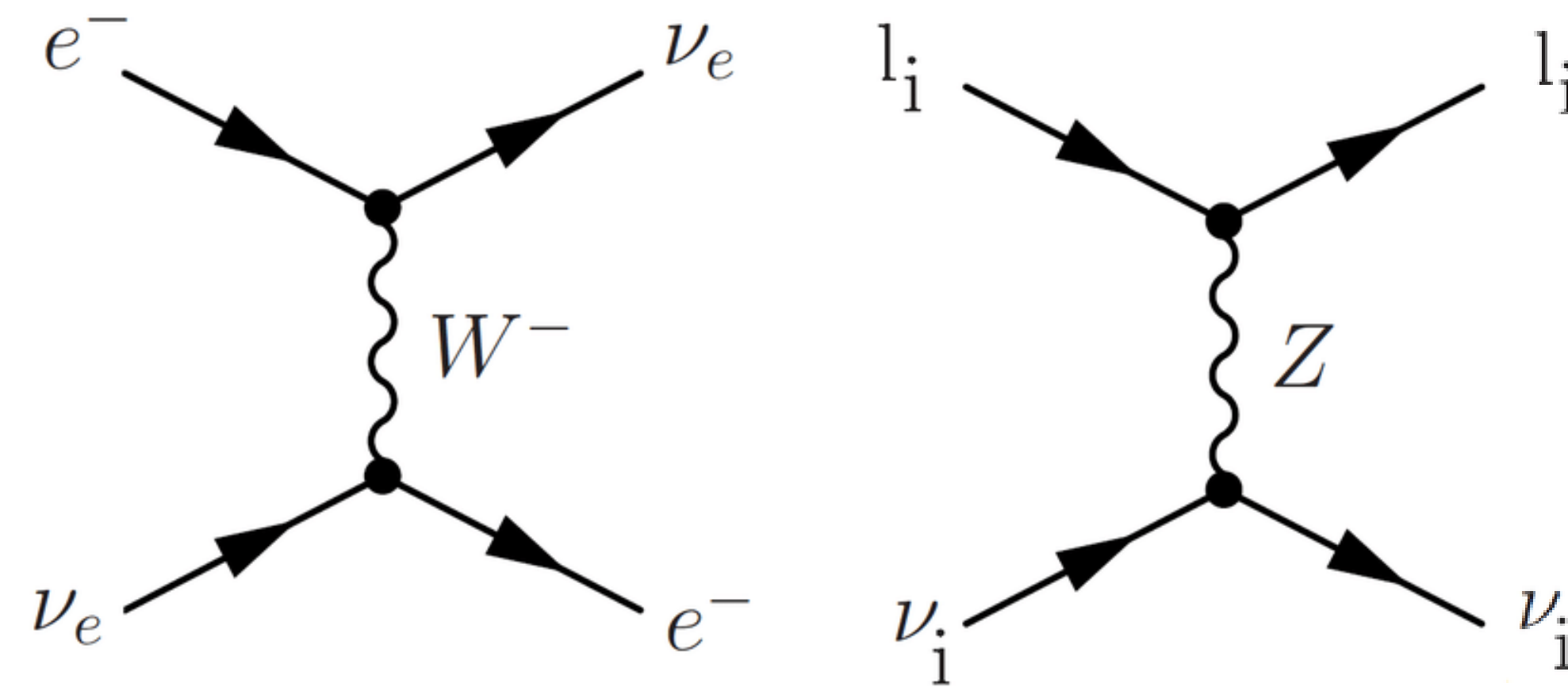


HOW TO DETECT NEUTRINOS

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



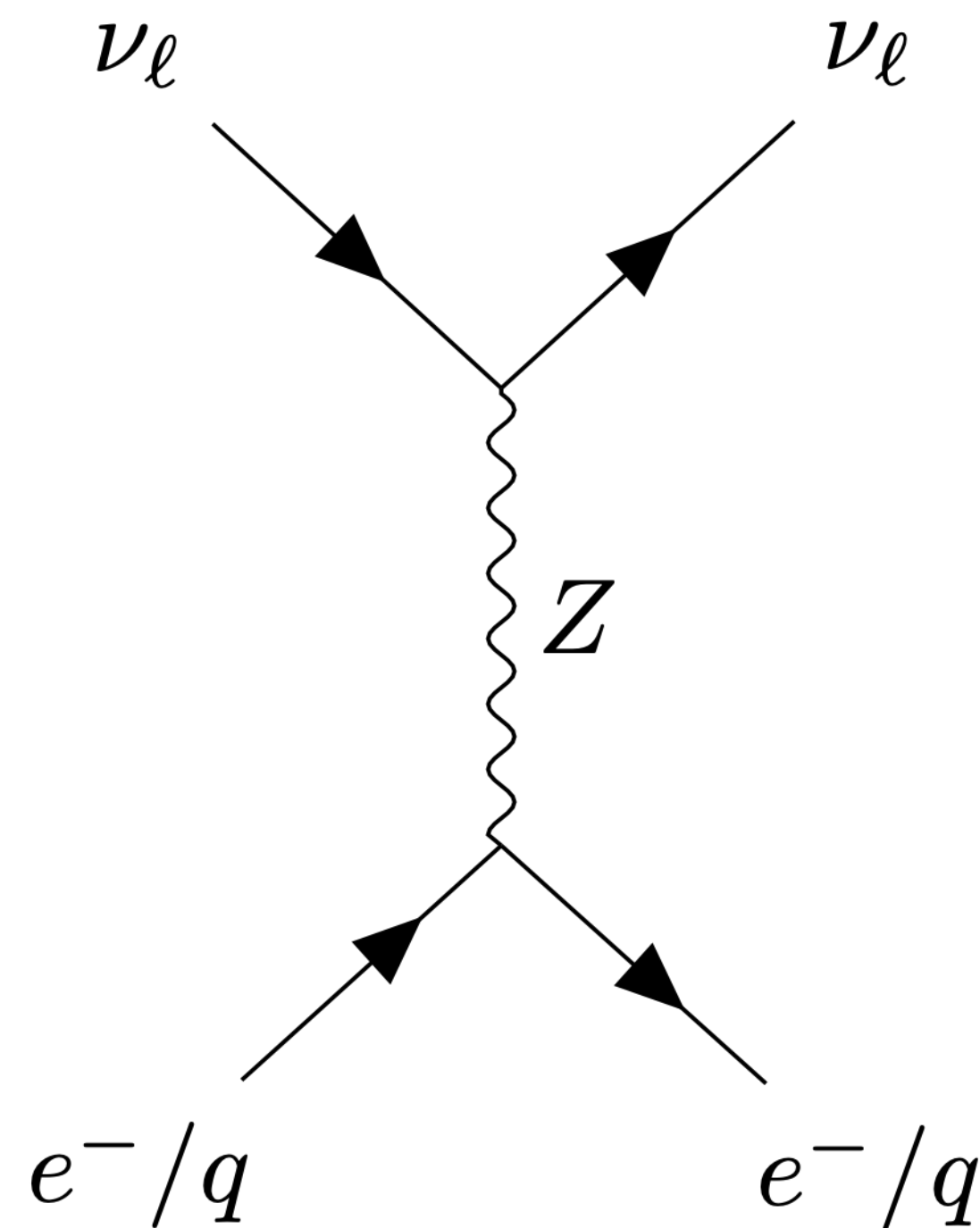
Interactions look very different at low vs high energies



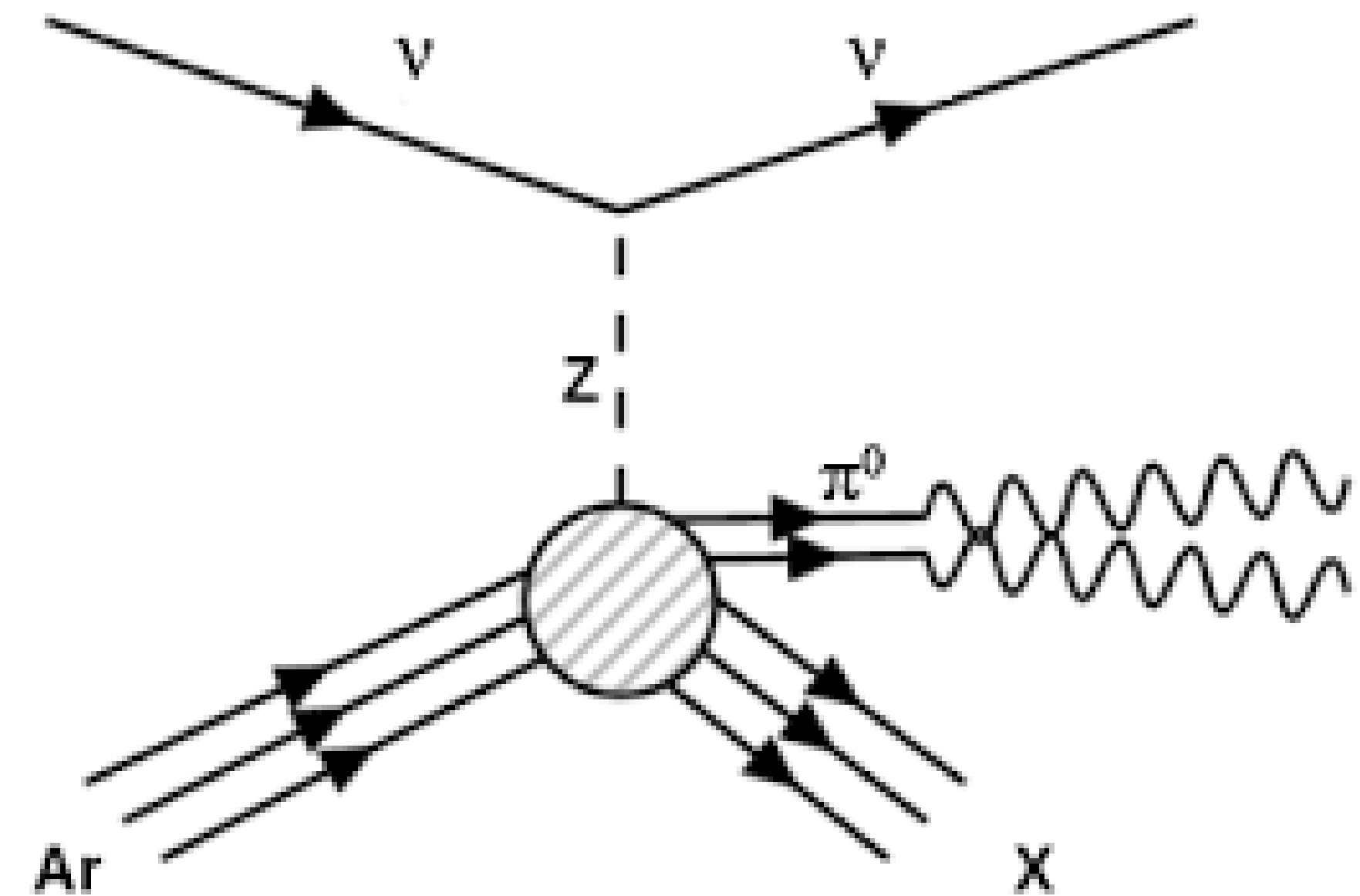
Neutral current interactions

- 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

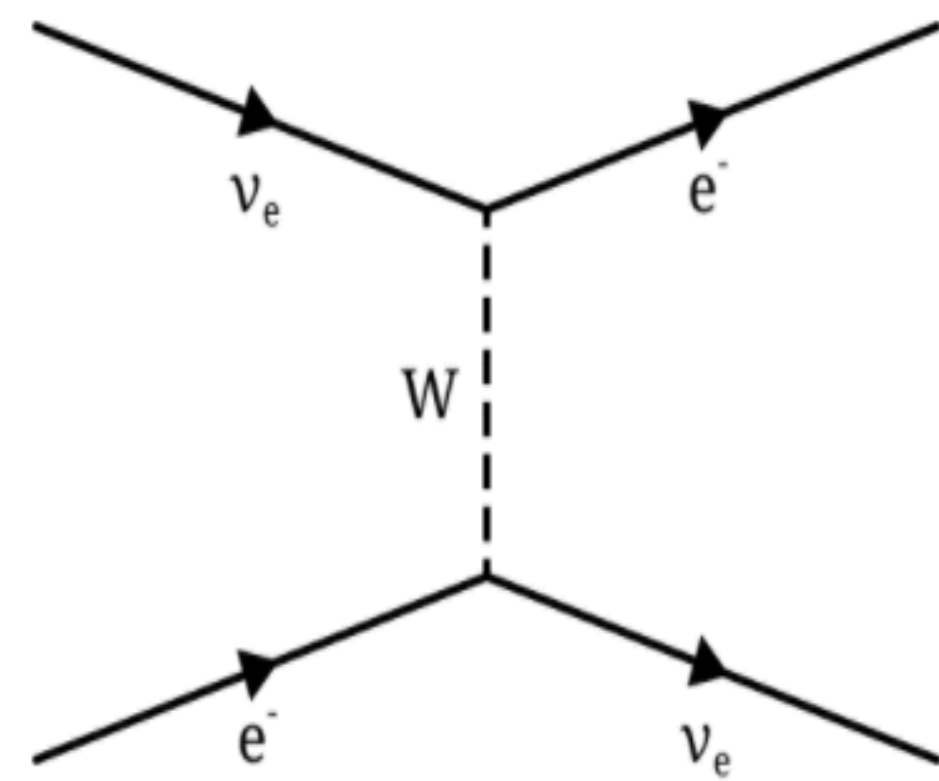


Charged current interactions

- The outgoing lepton matches the flavour of the neutrino

Low energy:

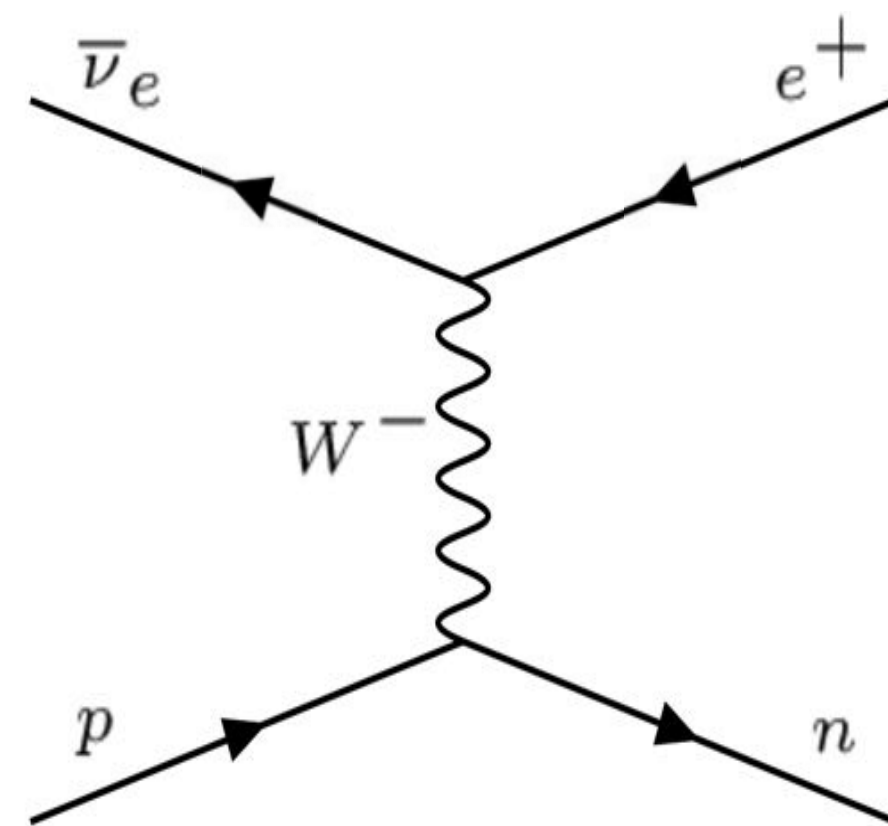
Elastic scattering



- Solar neutrinos

- Interactions with the medium during propagation

Inverse β -decay



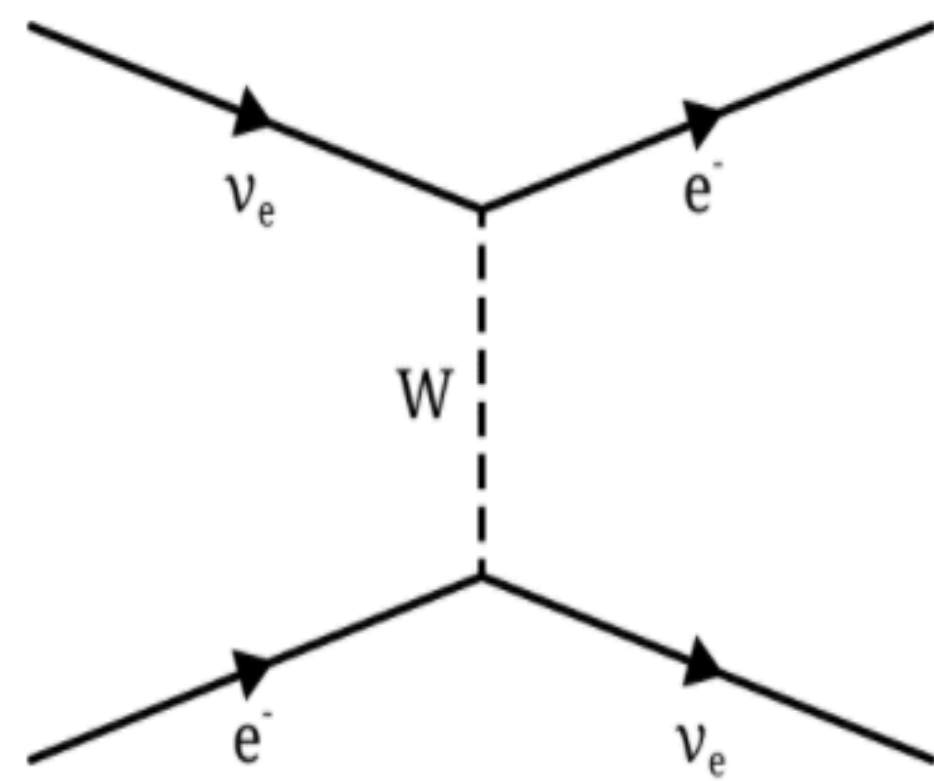
- Reactor neutrinos

- Interactions with free protons (hydrogen nuclei)

Charged current interactions

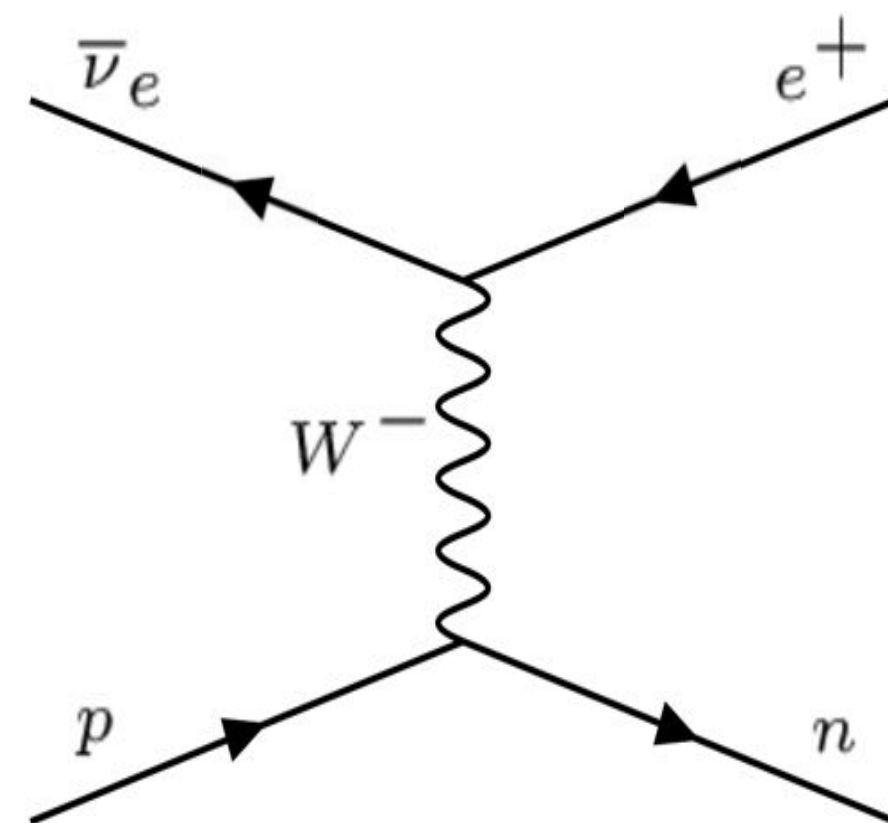
- The outgoing lepton matches the flavour of the neutrino

Low energy:
Elastic scattering **Inverse β -decay**



- Solar neutrinos

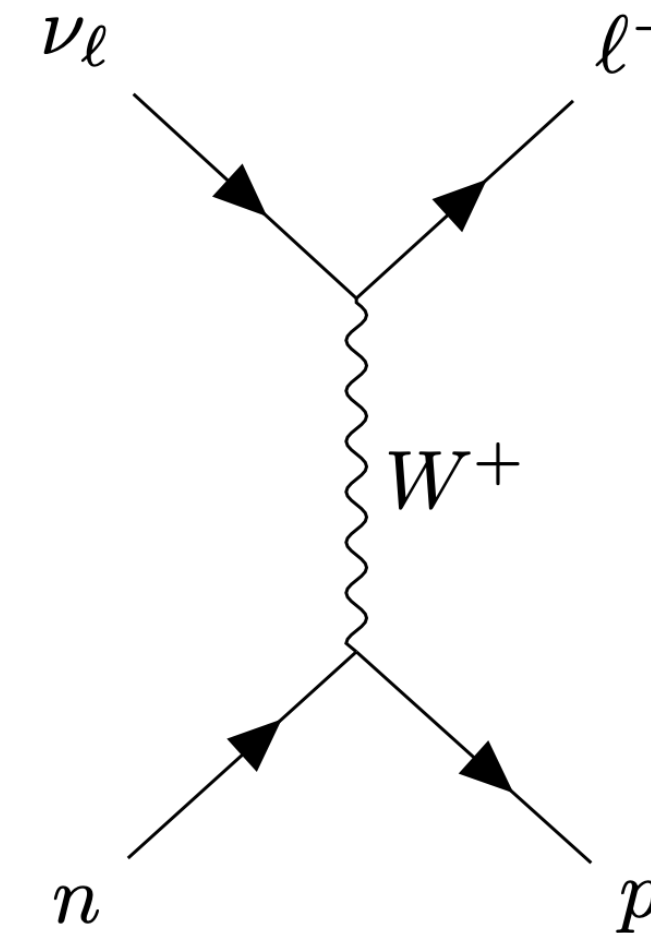
- Interactions with the medium during propagation



- Reactor neutrinos

- Interactions with free protons (hydrogen nuclei)

High energy (accelerators):
Quasi-elastic
The Golden Channel



- Clean signal: a single lepton

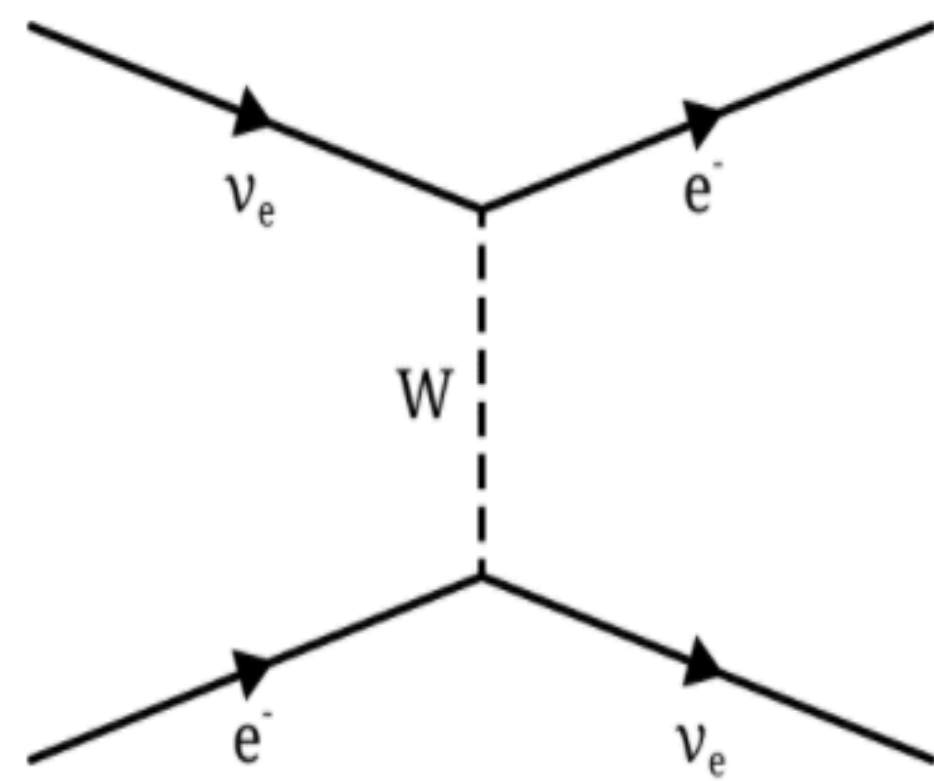
- Neutrino energy can be recovered from the lepton kinematics:

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

Charged current interactions

- The outgoing lepton matches the flavour of the neutrino

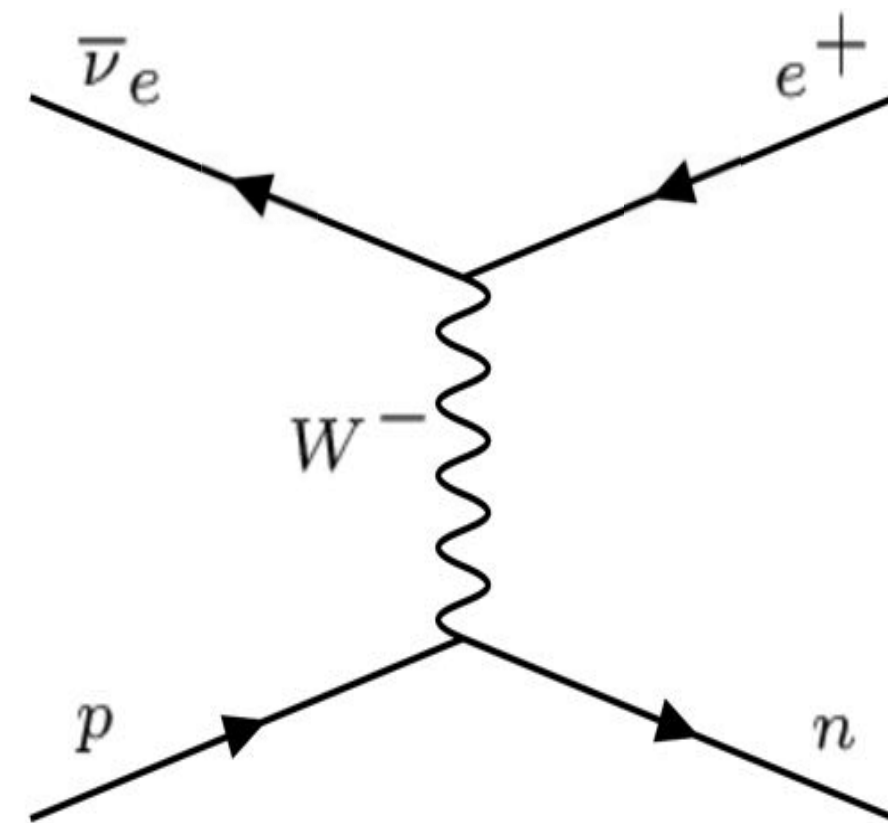
Low energy: Elastic scattering



- Solar neutrinos

- Interactions with the medium during propagation

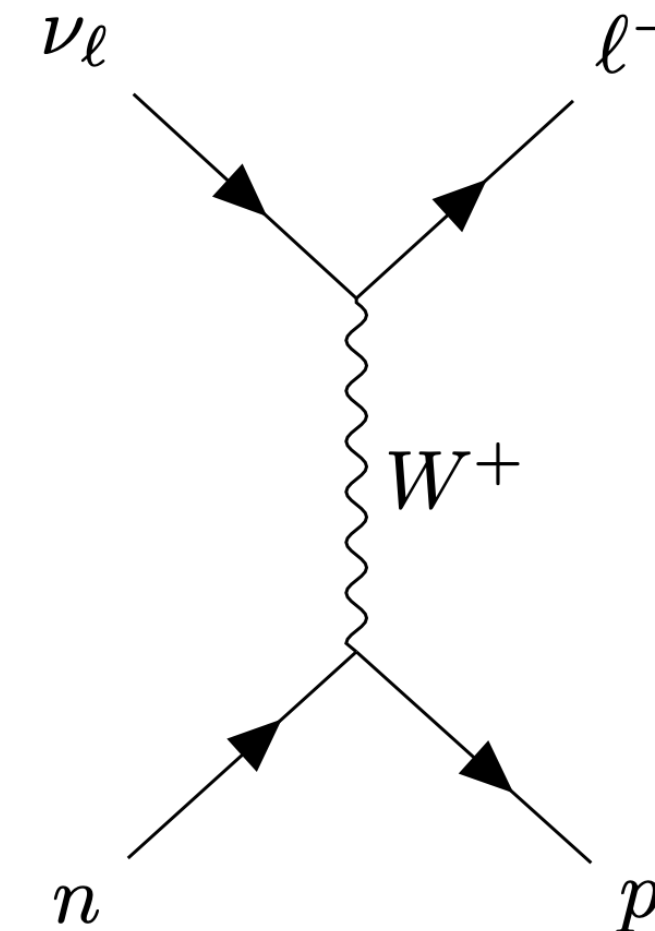
Inverse β -decay



- Reactor neutrinos

- Interactions with free protons (hydrogen nuclei)

High energy (accelerators): Quasi-elastic The Golden Channel



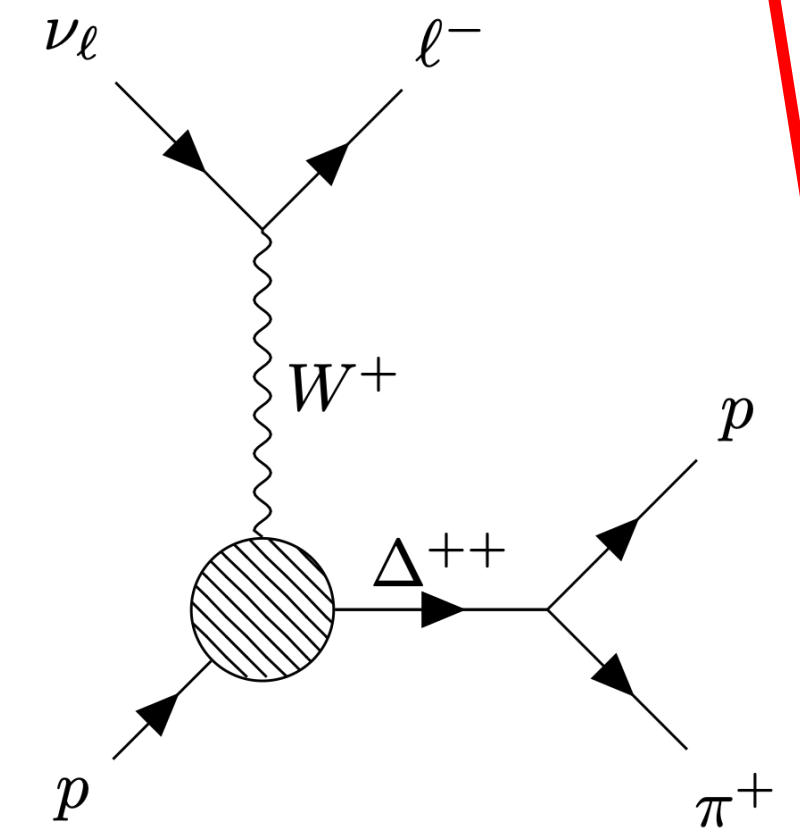
- Clean signal: a single lepton

- Neutrino energy can be recovered from the lepton kinematics:

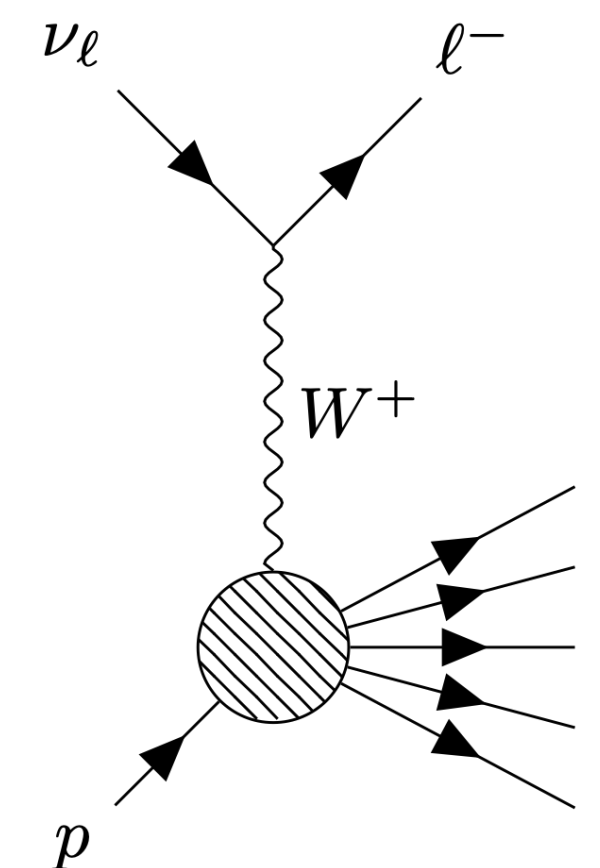
$$E_\nu = \frac{m_f^2 - (m_i - E_b)^2 - m_\mu^2 + 2(m_i - E_b)E_\mu}{2(m_i - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$

Complicated hadronic products

Resonant



Deep inelastic scattering

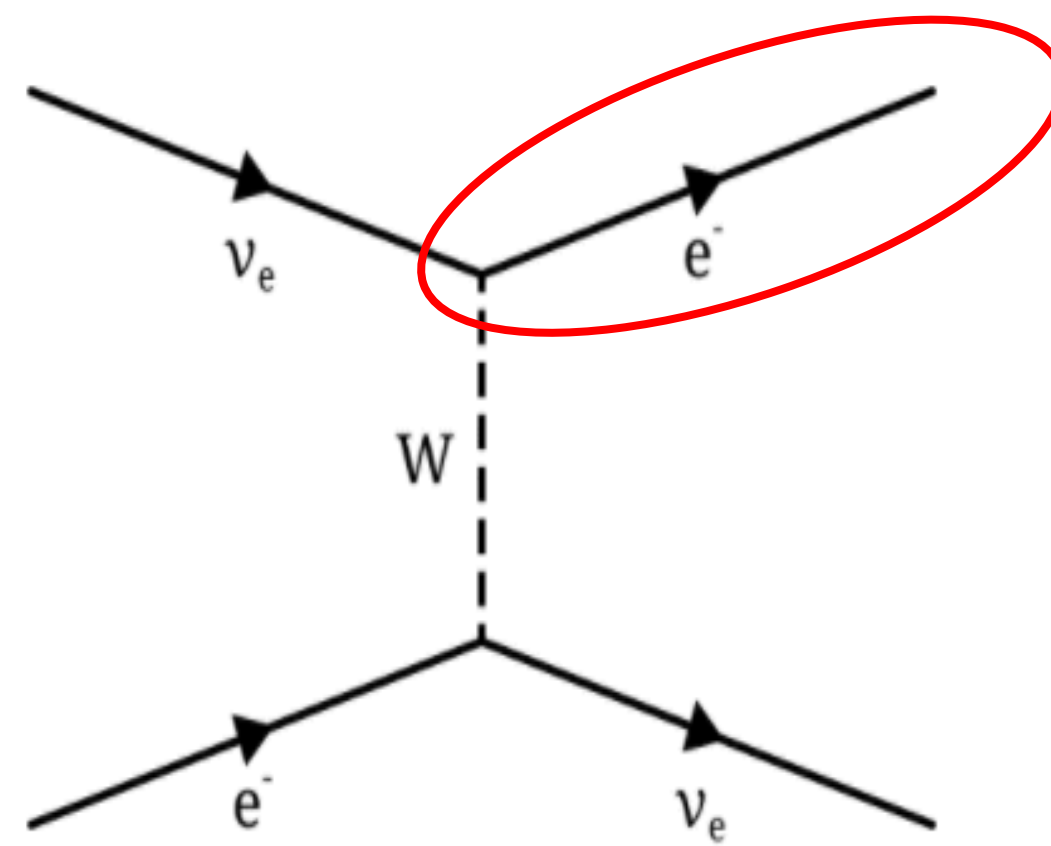


Charged current interactions

- The outgoing lepton matches the flavour of the neutrino

Low energy:

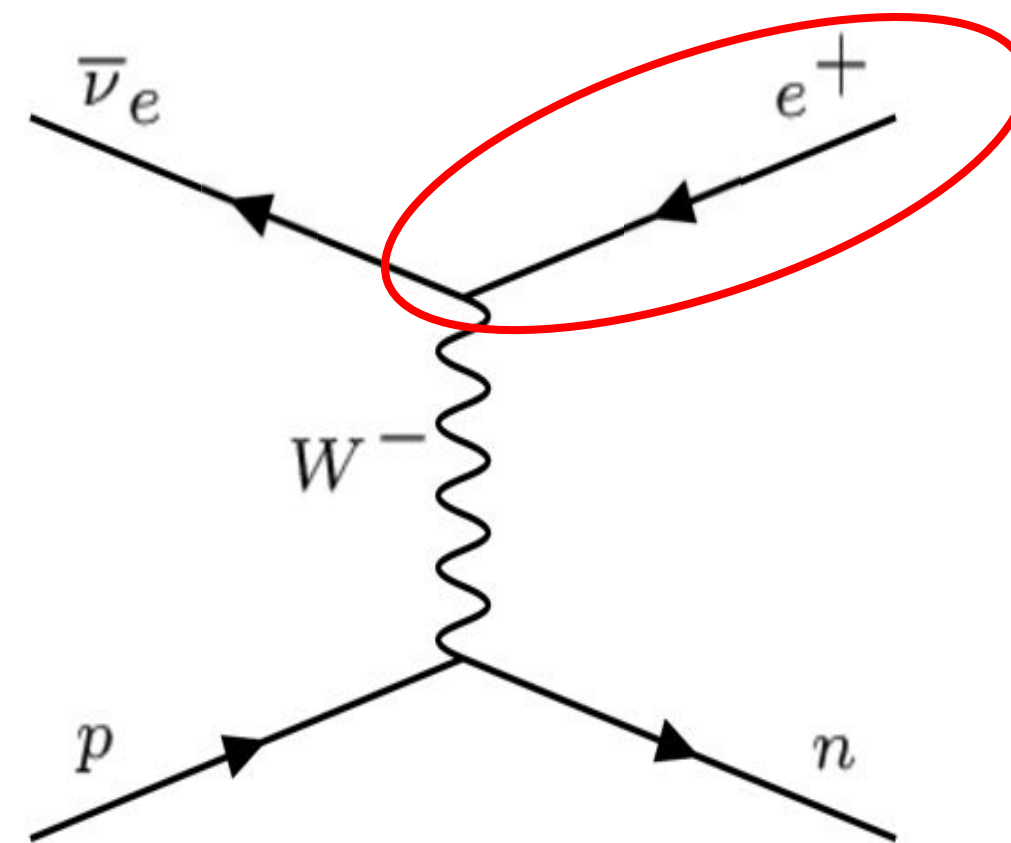
Elastic scattering



- Solar neutrinos

- Interactions with the medium during propagation

Inverse β -decay



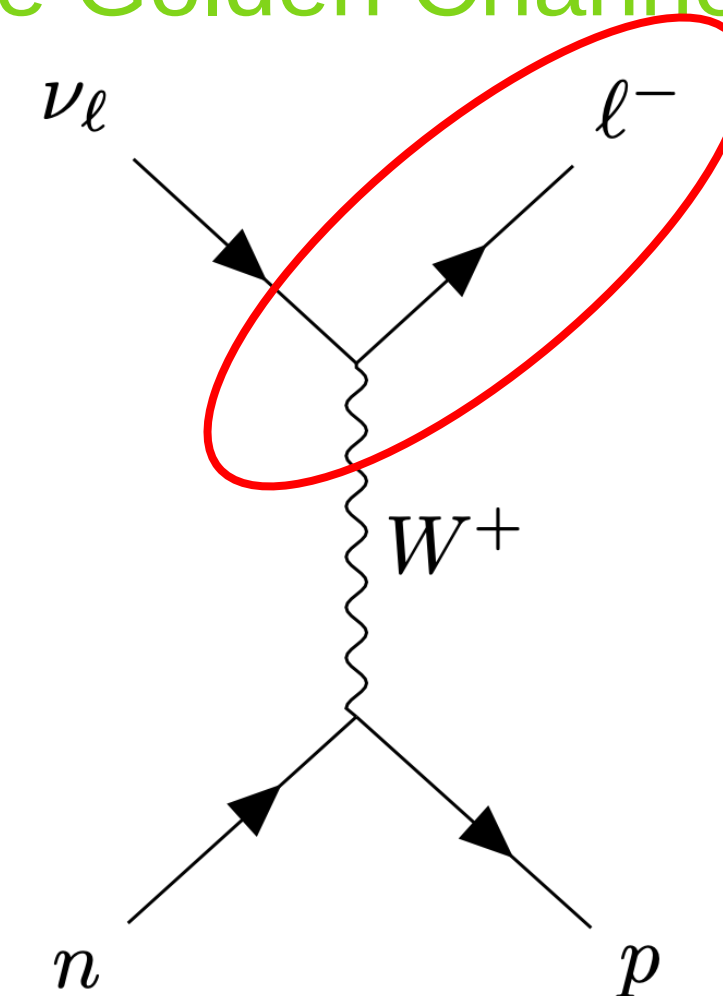
- Reactor neutrinos

- Interactions with free protons (hydrogen nuclei)

High energy (accelerators):

Quasi-elastic

The Golden Channel



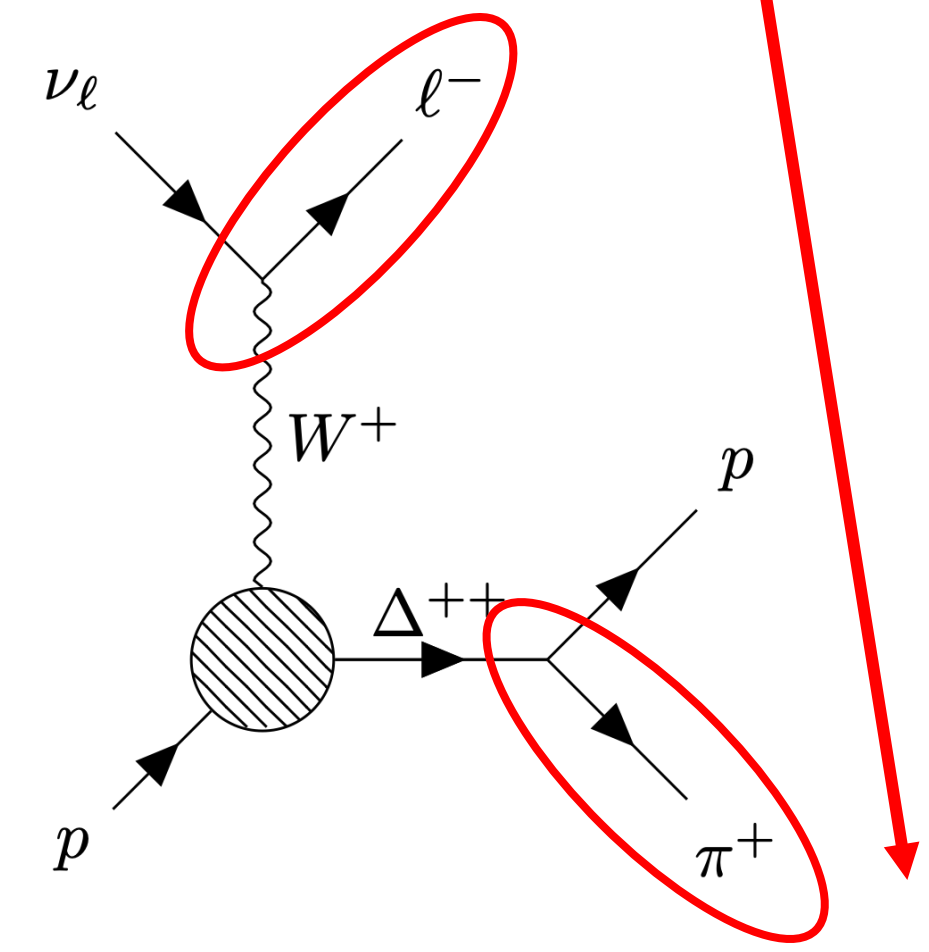
- Clean signal: a single lepton

- Neutrino energy can be recovered from the lepton kinematics:

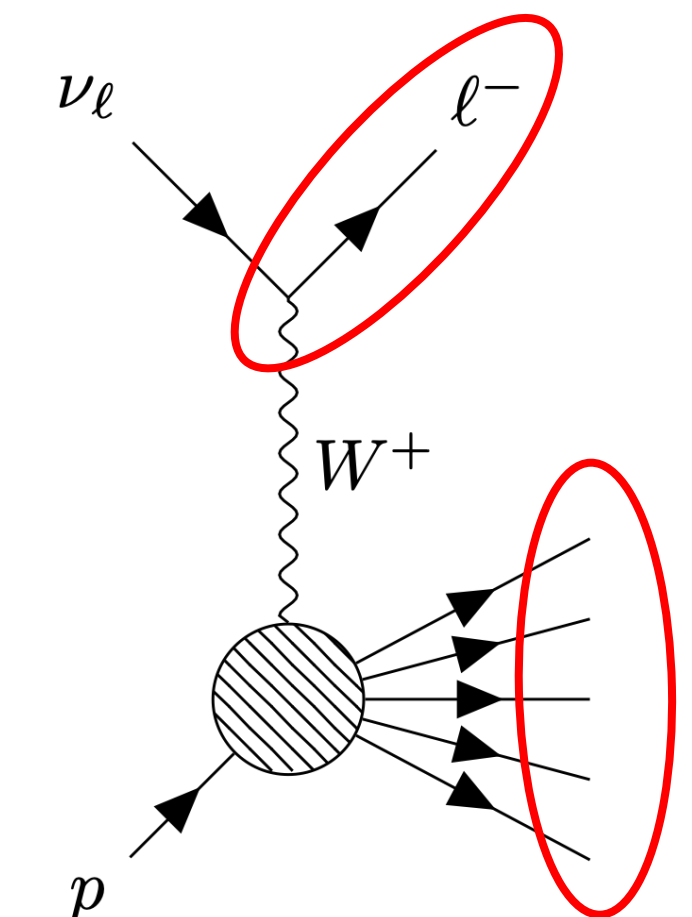
$$E_\nu = \frac{m_f^2 - (m_i - E_b)^2 - m_\mu^2 + 2(m_i - E_b)E_\mu}{2(m_i - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$

Complicated hadronic products

Resonant



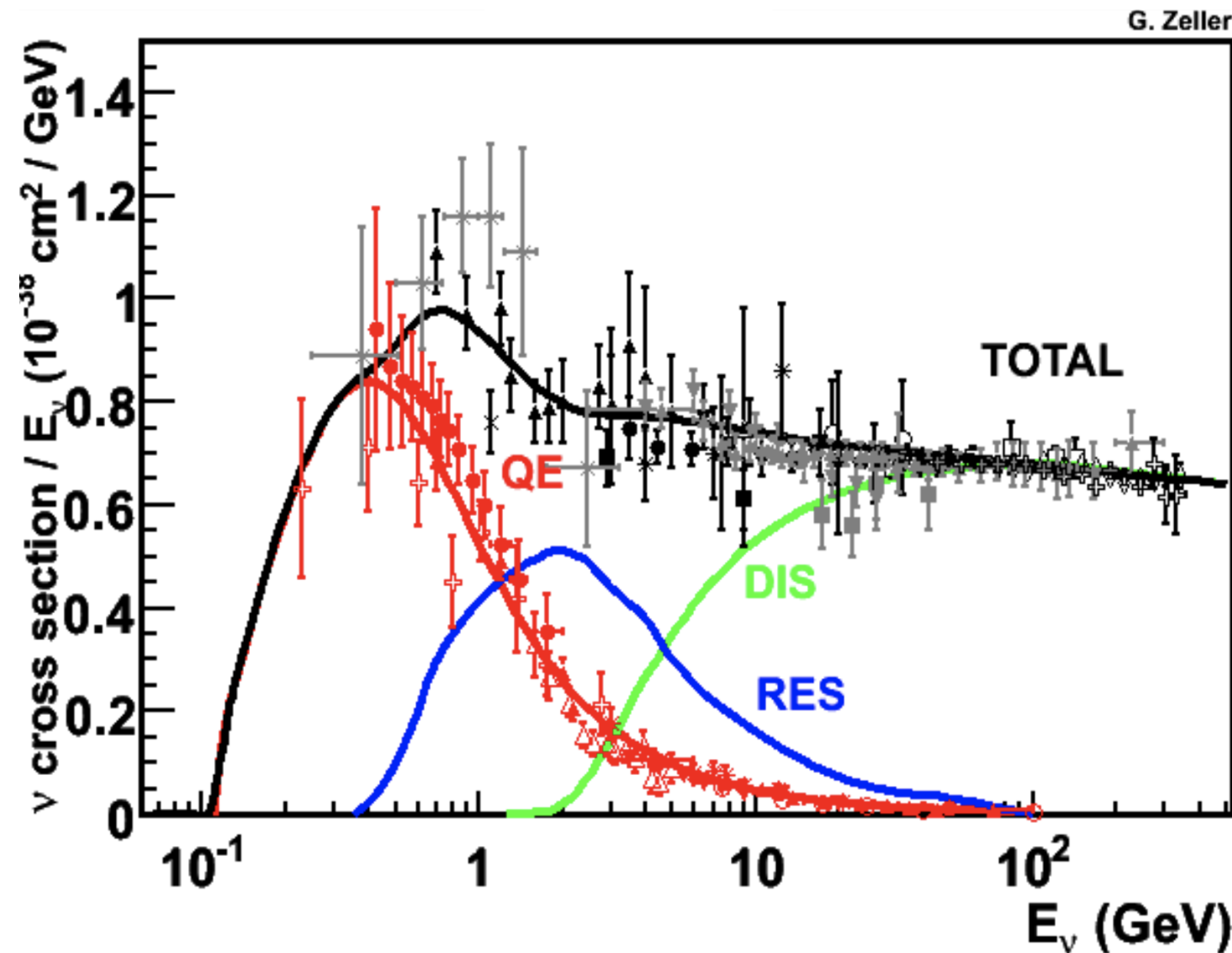
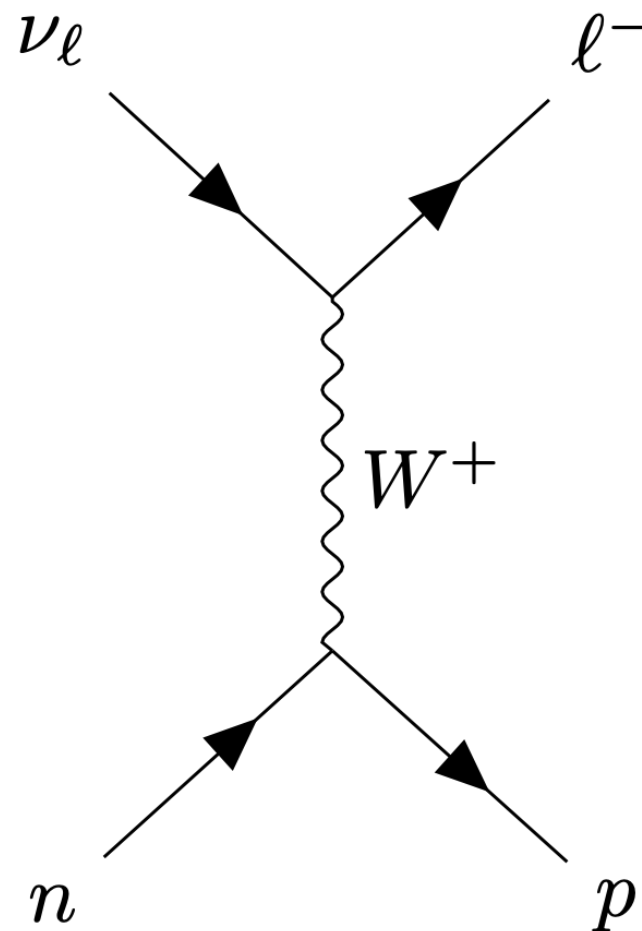
Deep inelastic scattering



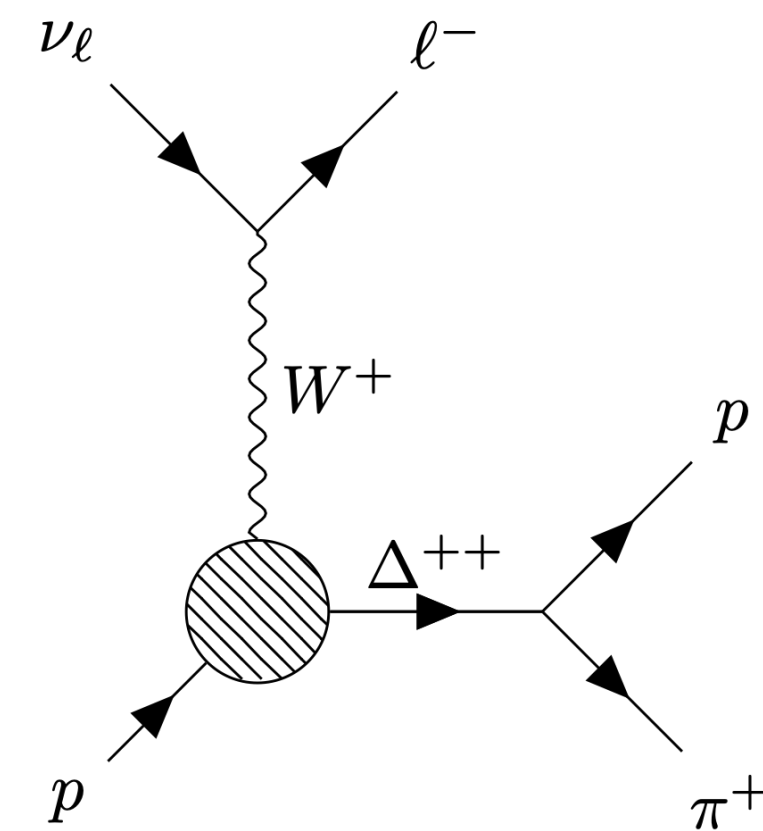
Charged currents interactions

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

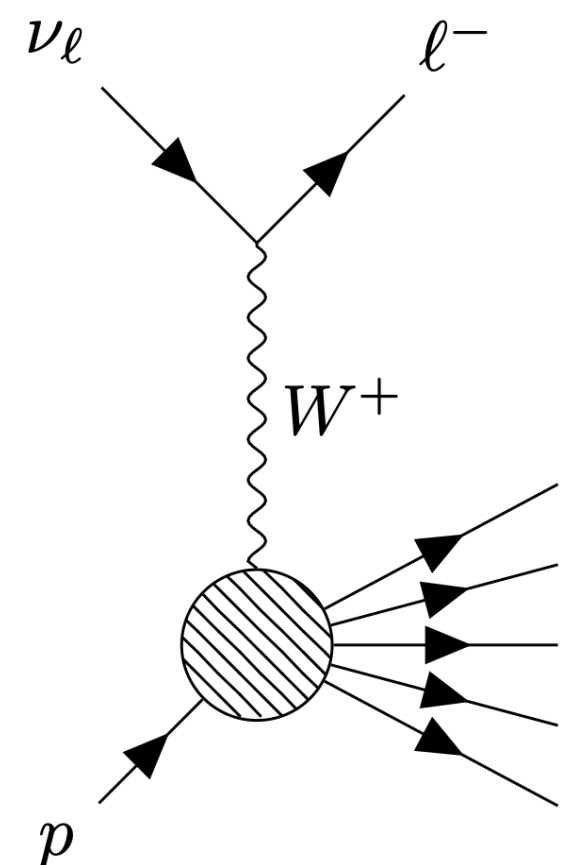
Quasi-elastic (QE)



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

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

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

- Using the Cherenkov effect

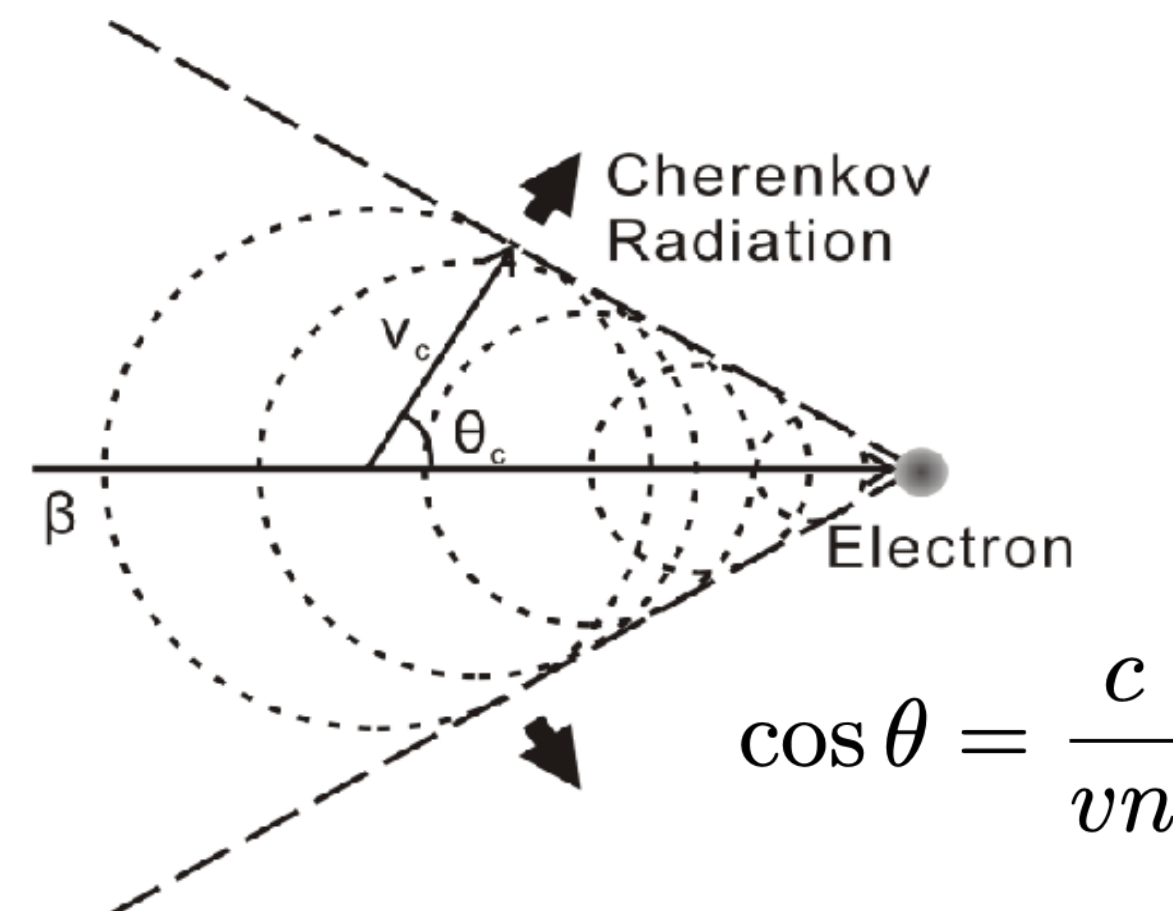


Figure 1: Schematic of Cherenkov radiation

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)

- Using the ionisation potential

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

- Using the Cherenkov effect

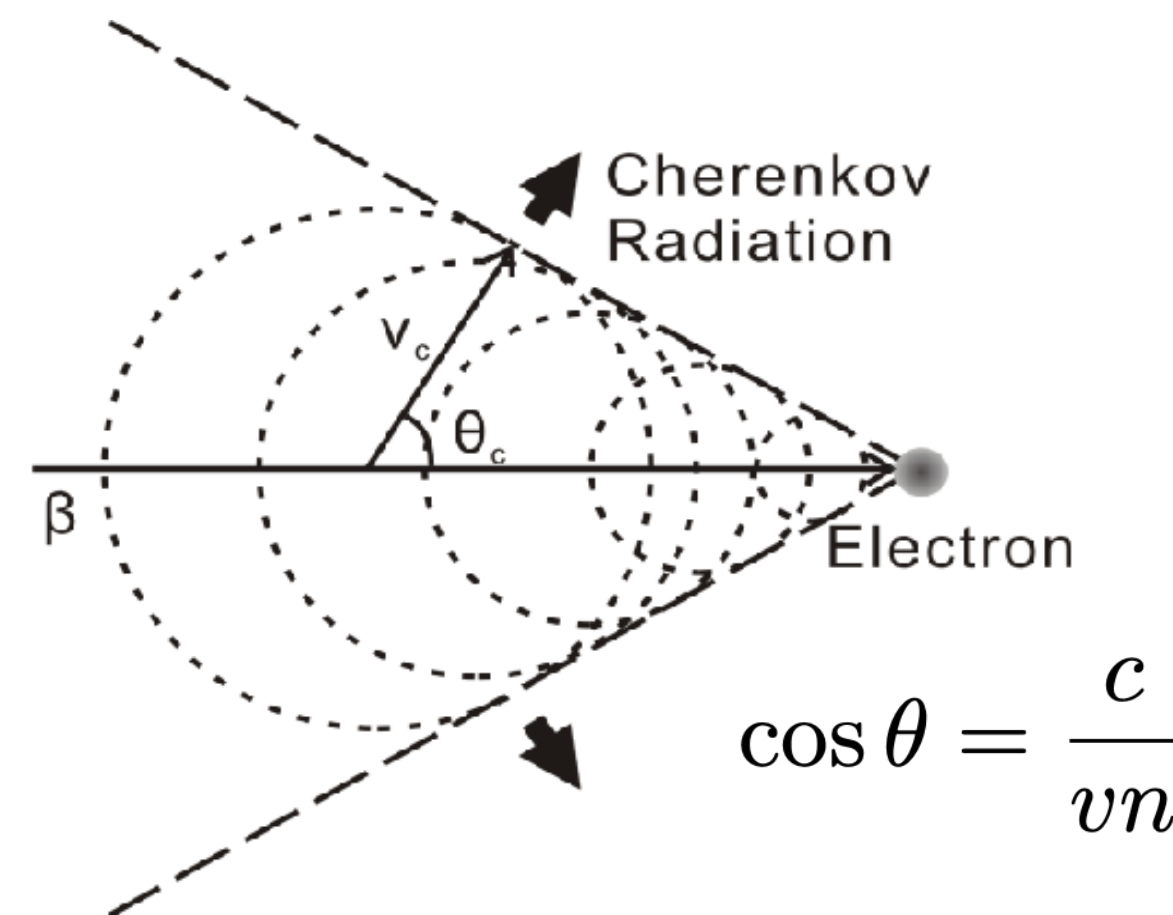


Figure 1: Schematic of Cherenkov radiation

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

Using the Ionization potential

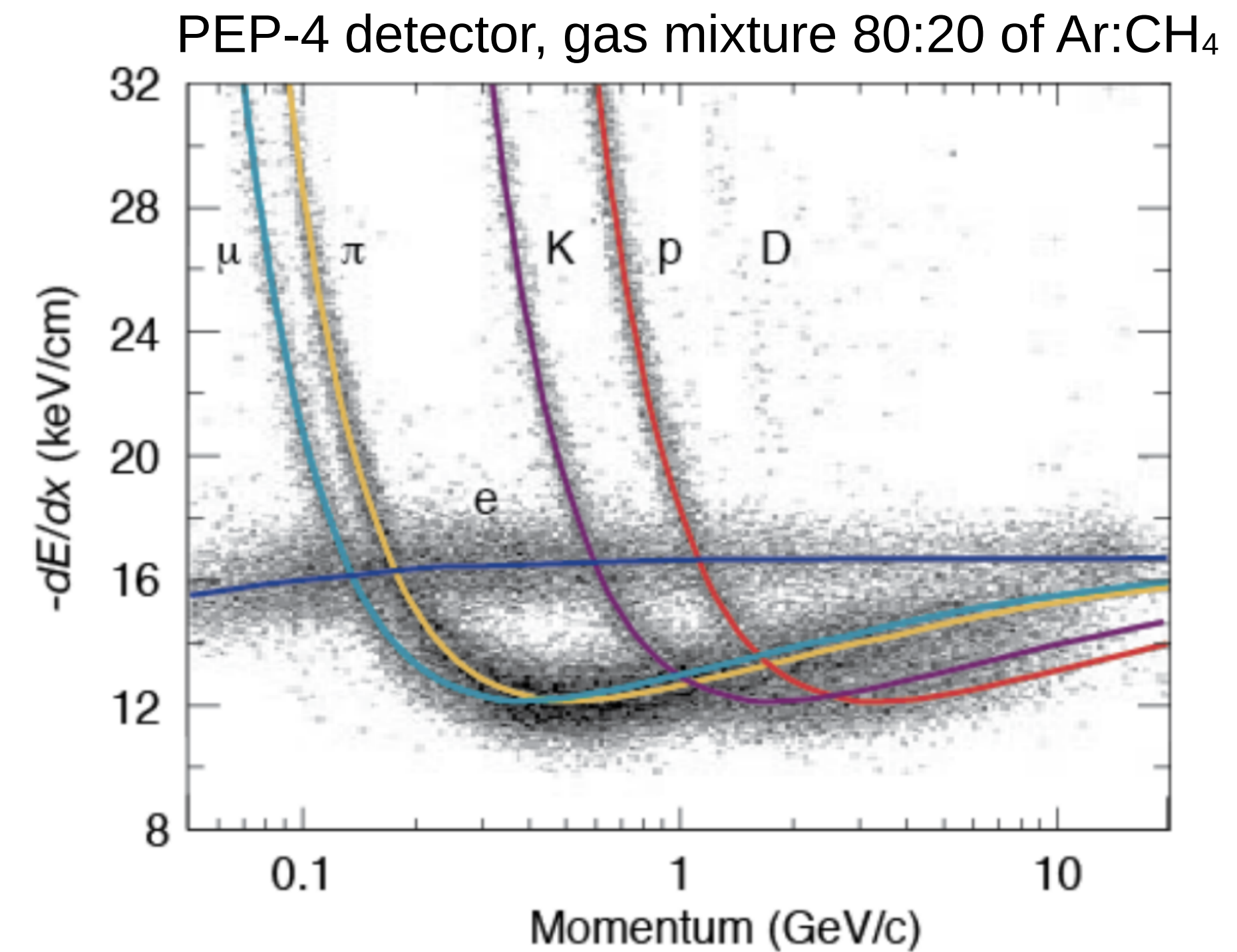
Principle : When a charged particle crosses a medium, it loses energy through ionization. The mean amount of energy lost per cm through ionization is parametrized by the Bethe Bloch formula and depends on the particle energy ($\beta\gamma$)

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

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.



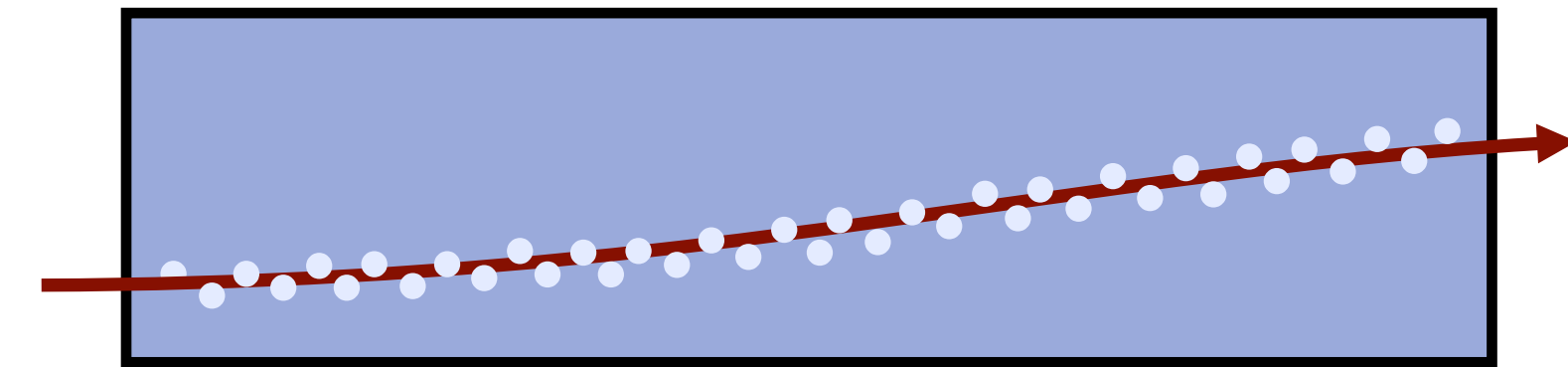
Using the Ionization potential

BEBC at CERN



Bubble Chambers

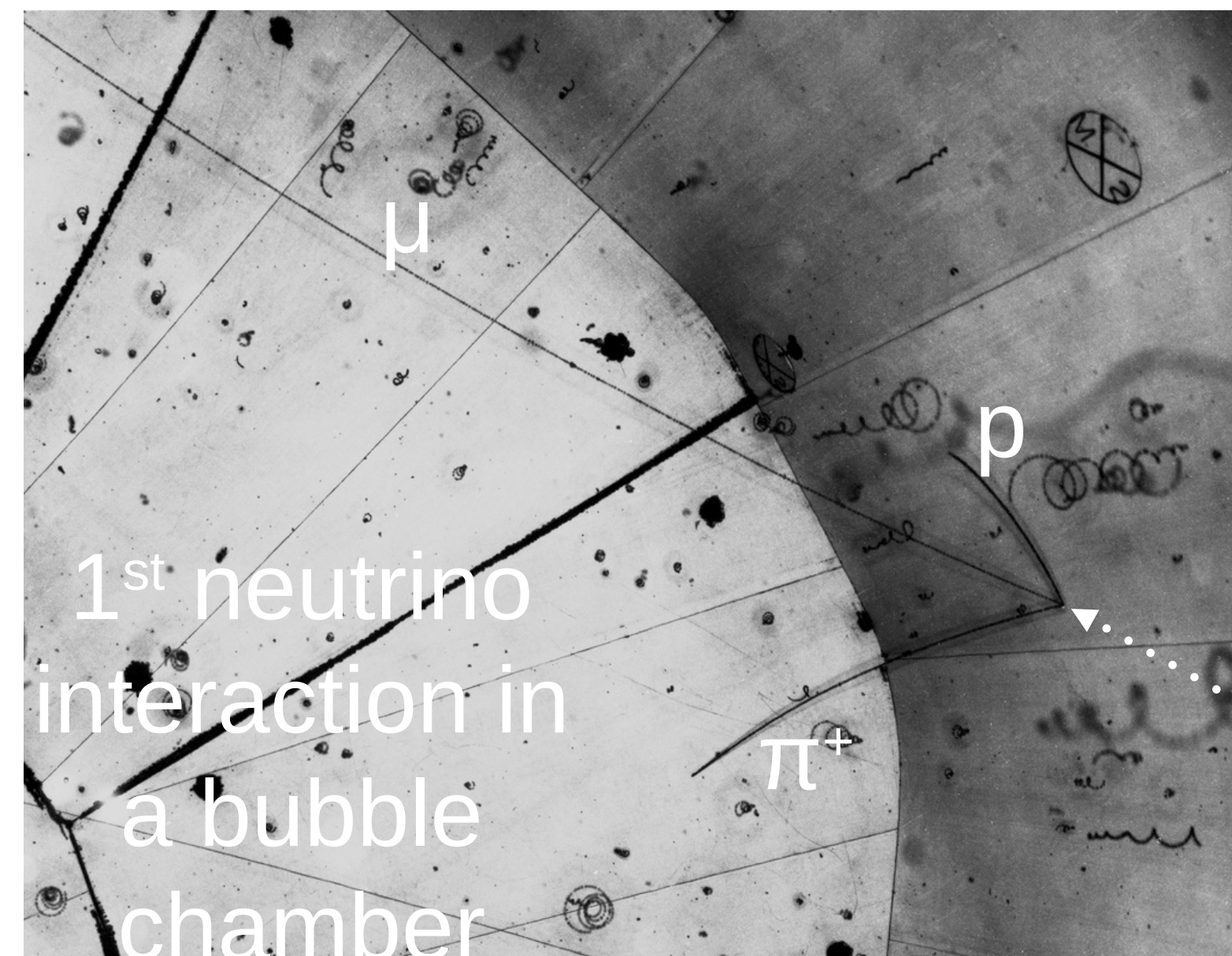
Superheated fluid turns locally to gas (bubbles) when energy is deposited by a charged track:



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



Scanning ladies

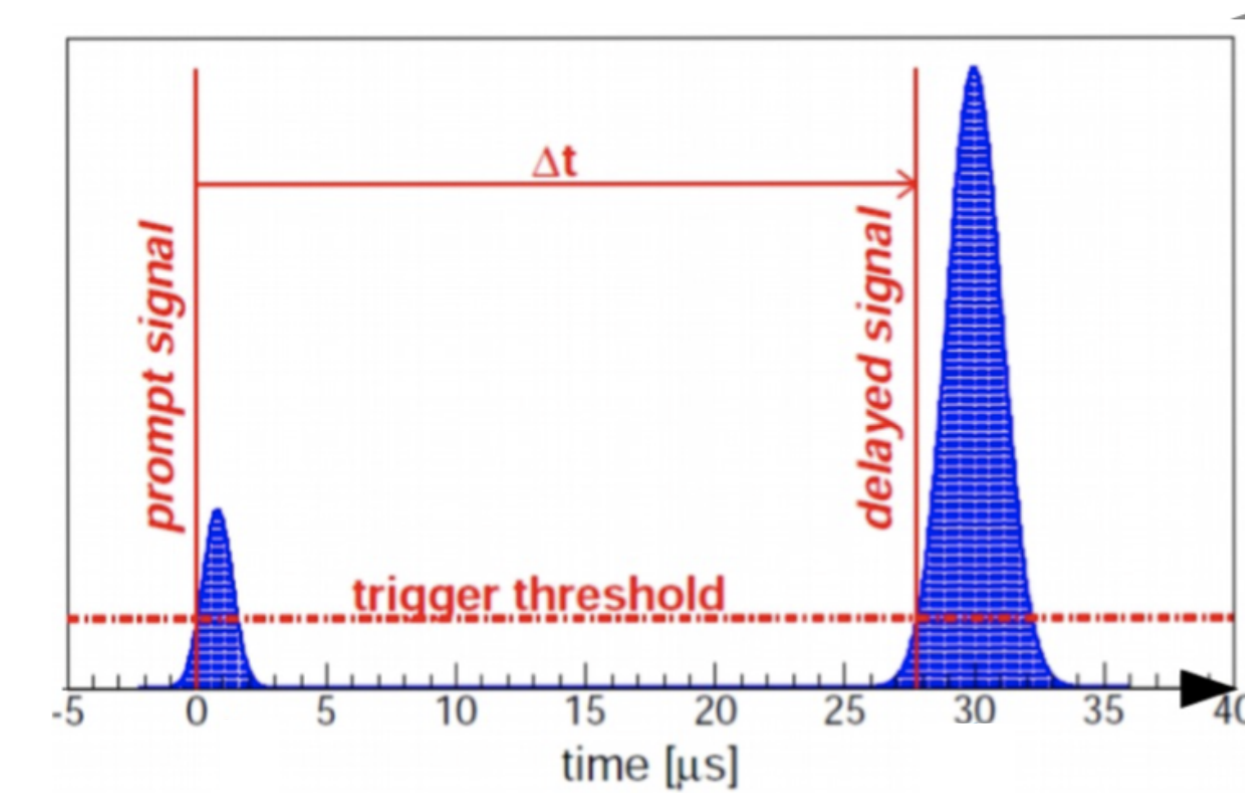
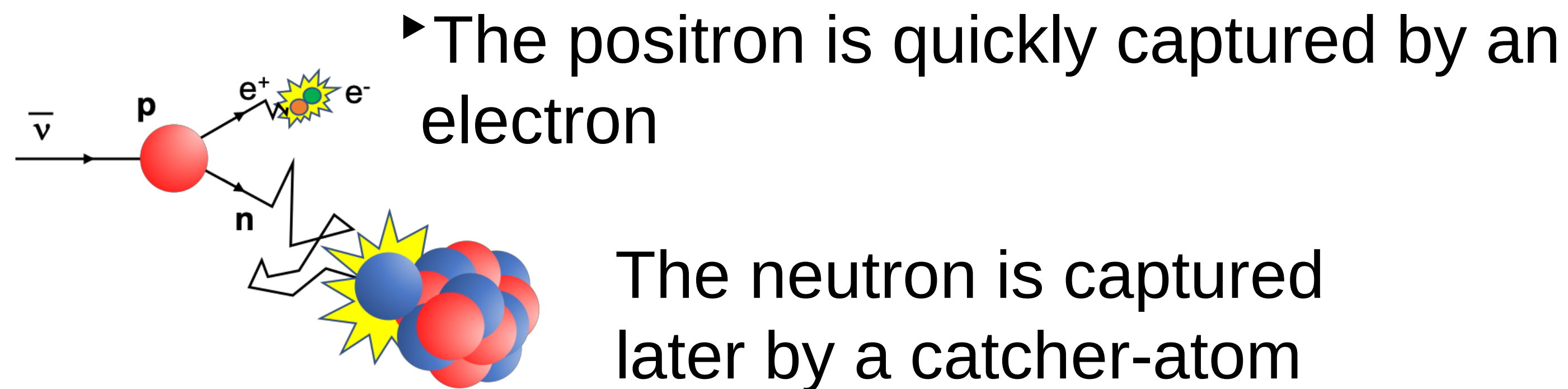
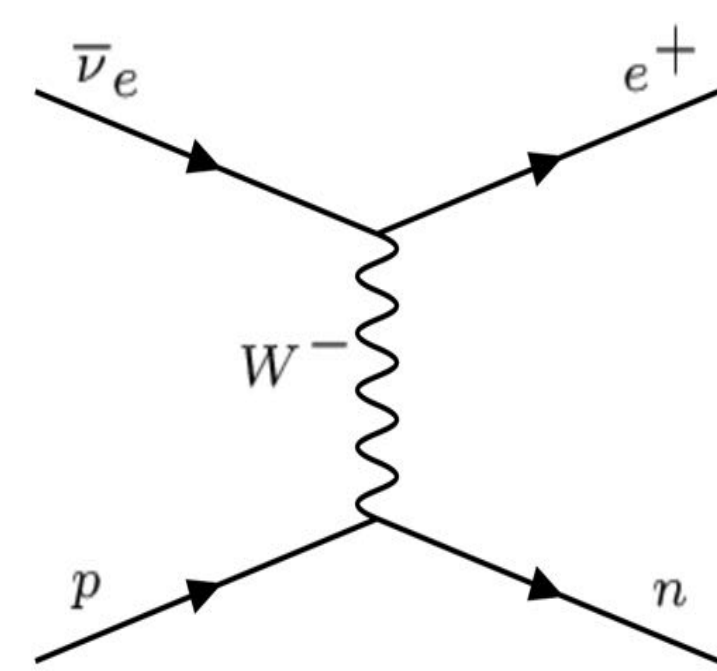


Using the Ionization potential

Liquid Scintillators

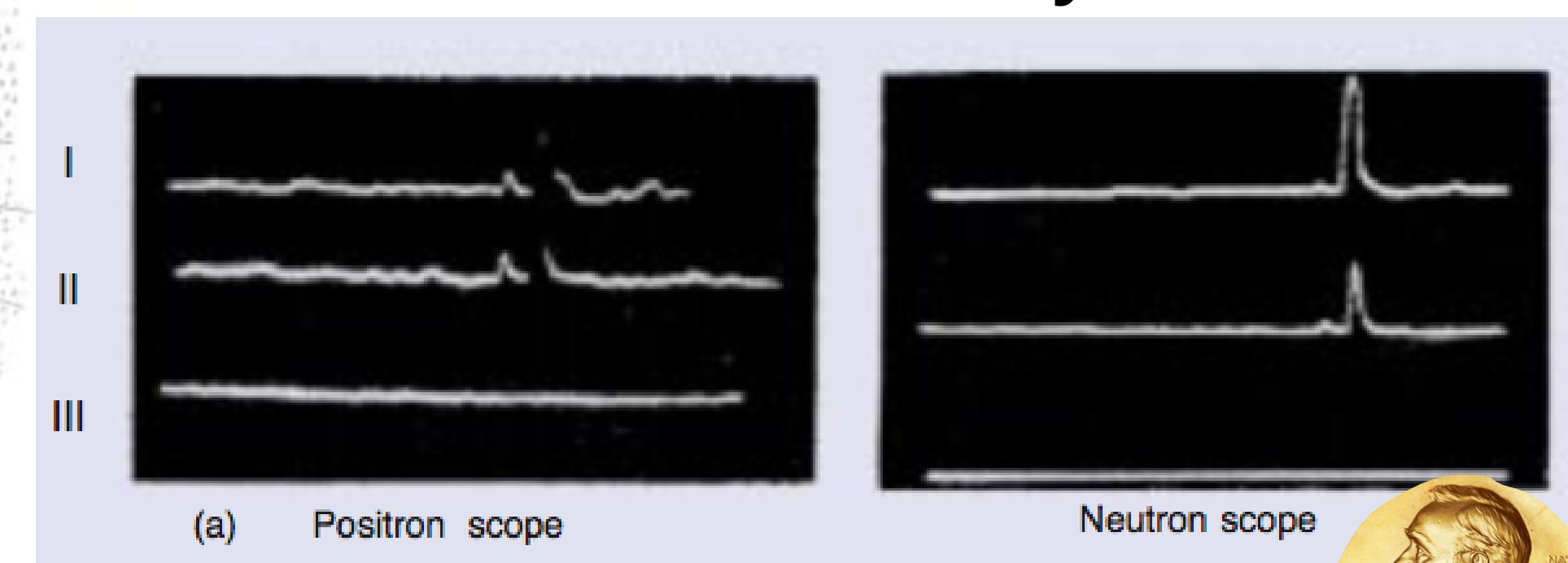
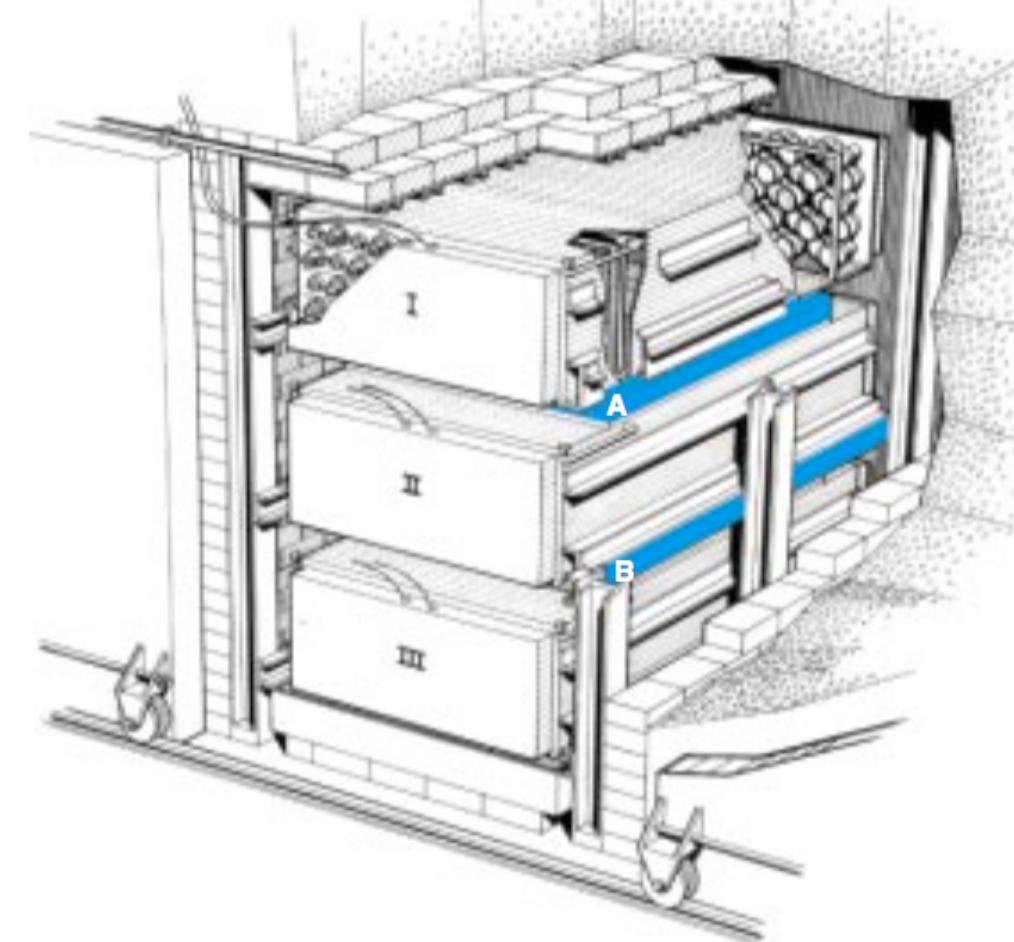
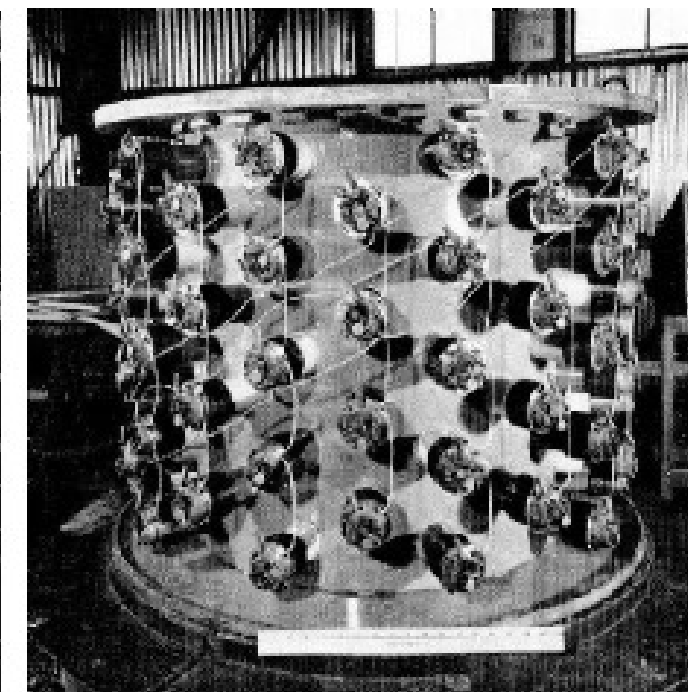
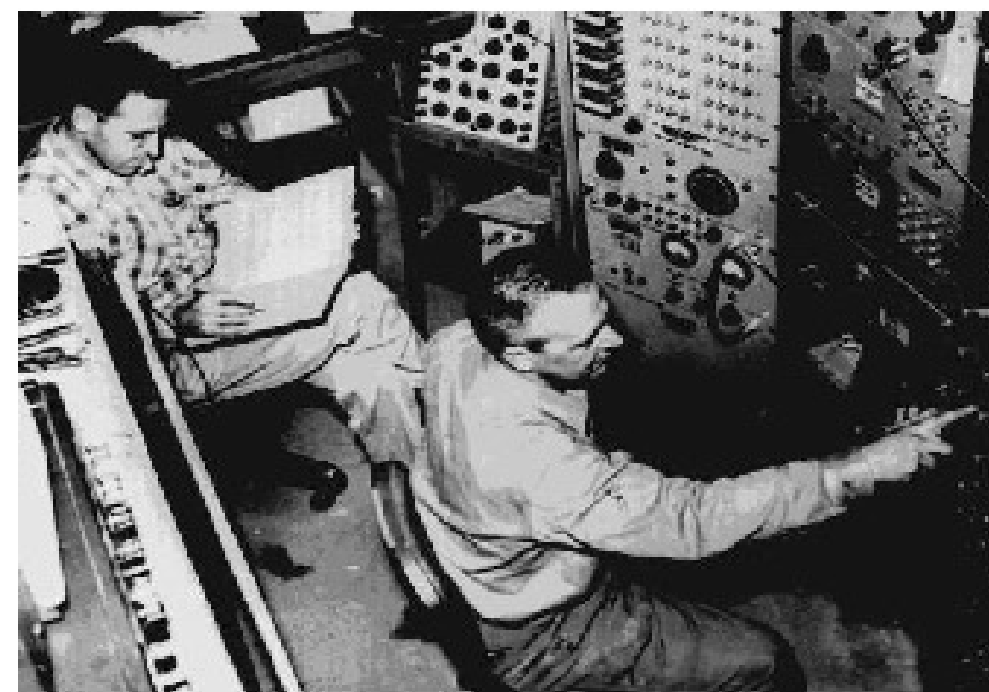
Organic liquid that scintillates when energy is deposited.

In neutrino physics, often used to tag (low energy) inverse β -decay interactions



Savannah river experiment by Reines & Cowan in 1956

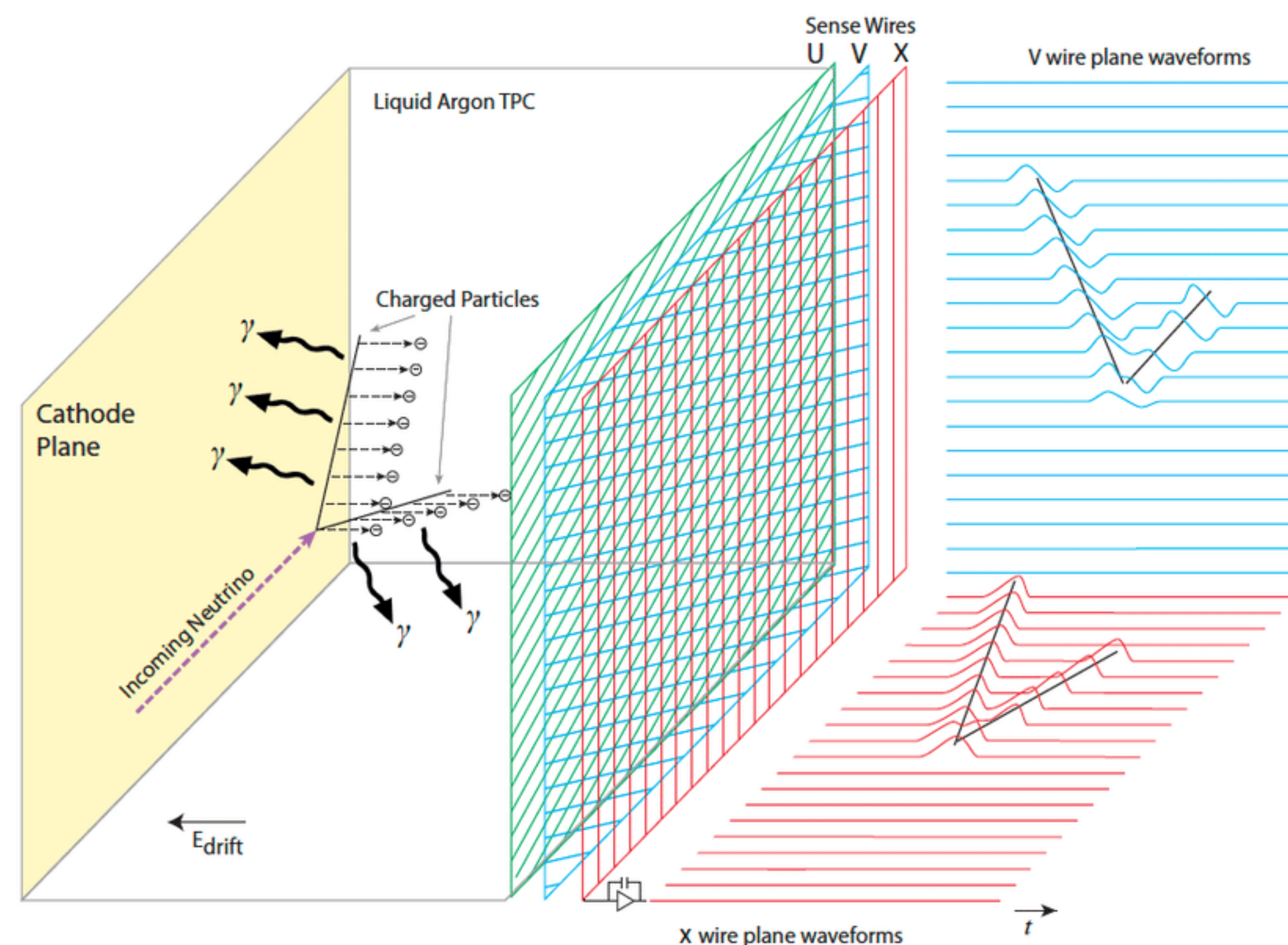
$\bar{\nu}_e$ discovery !



Using the Ionization potential

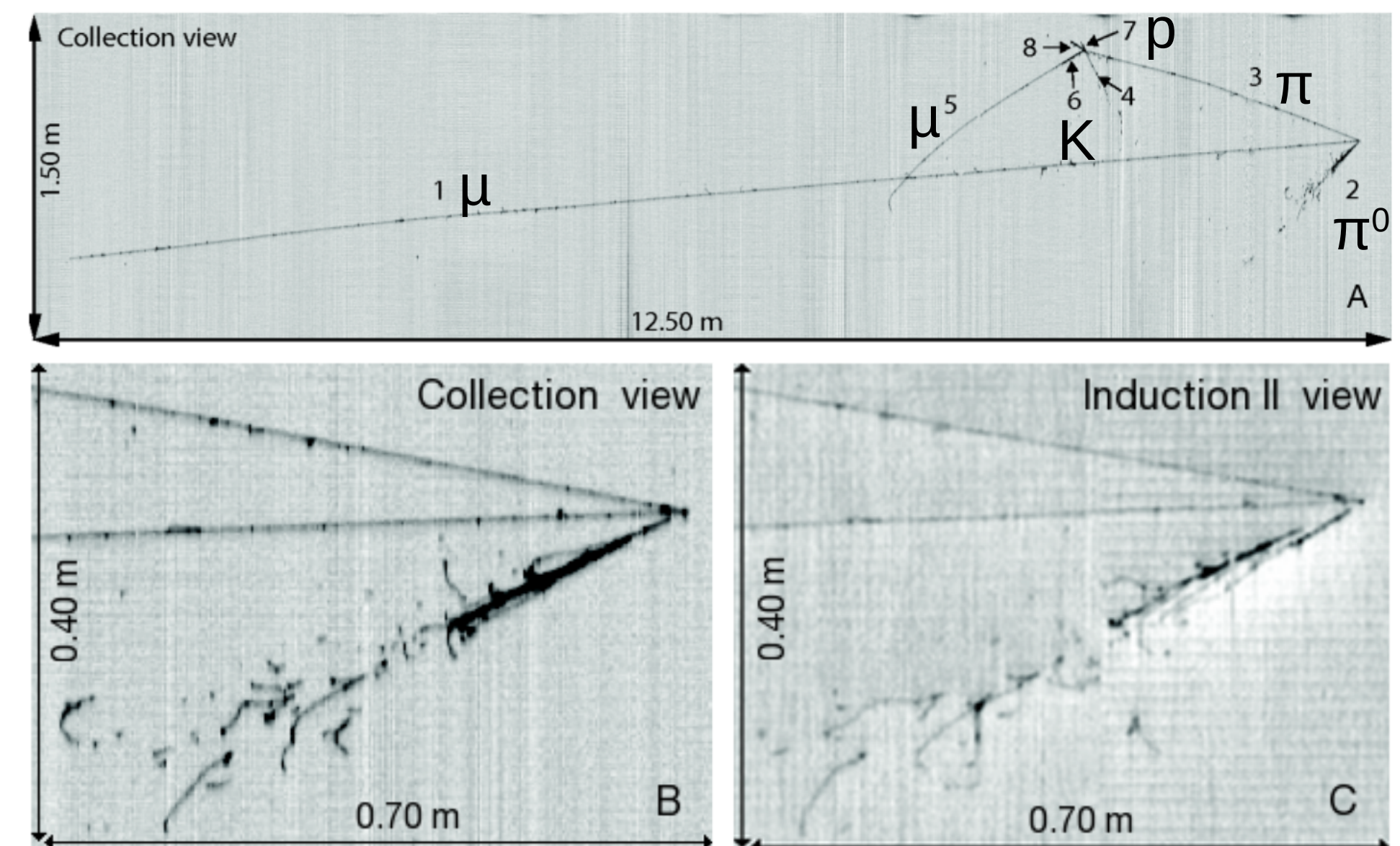
Time Projection Chamber [TPC]

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 -

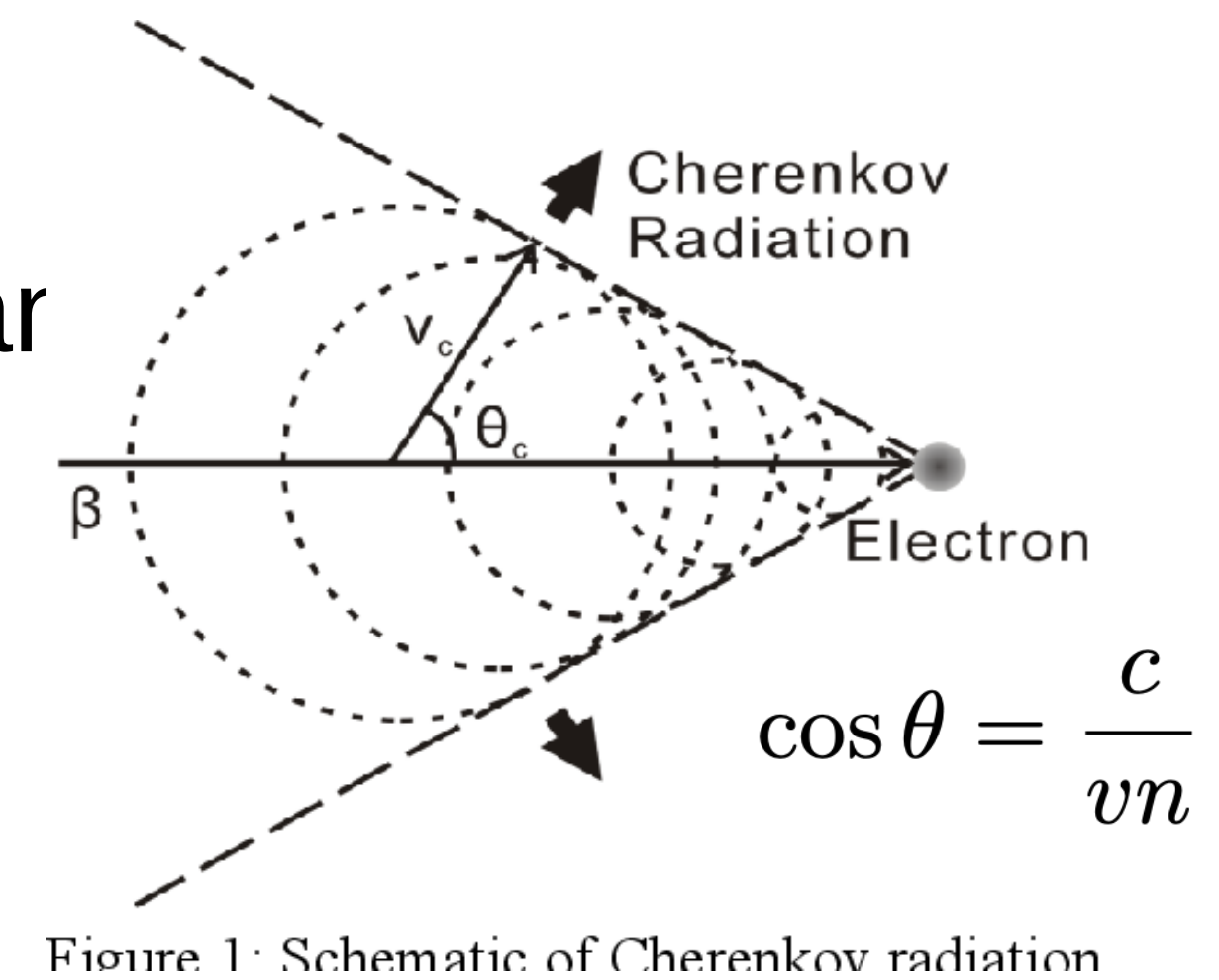


Using the Cherenkov effect

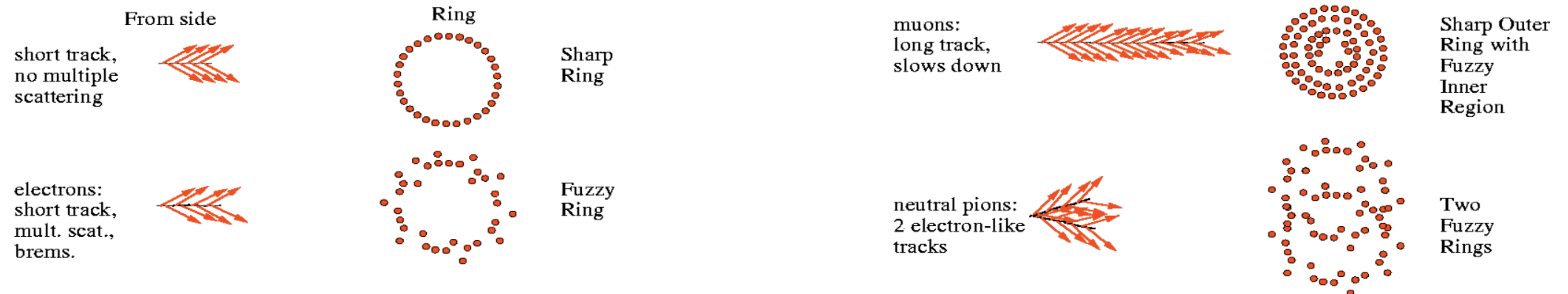
Principle : When a charged particle travels at a speed v higher than the speed of light in a medium c/n its own EM field stacks and produces a cone of light :

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



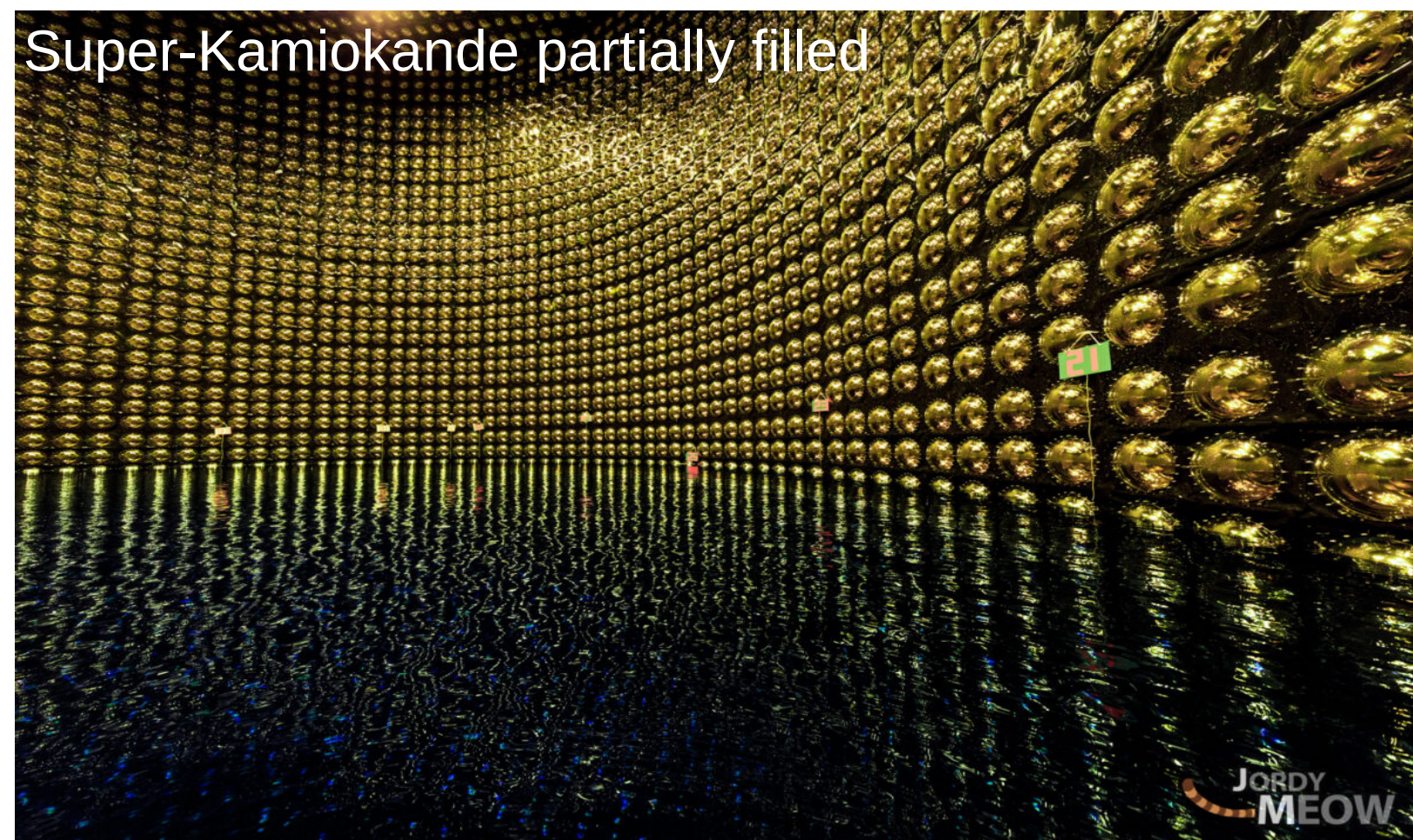
Particle identification using ring shape :



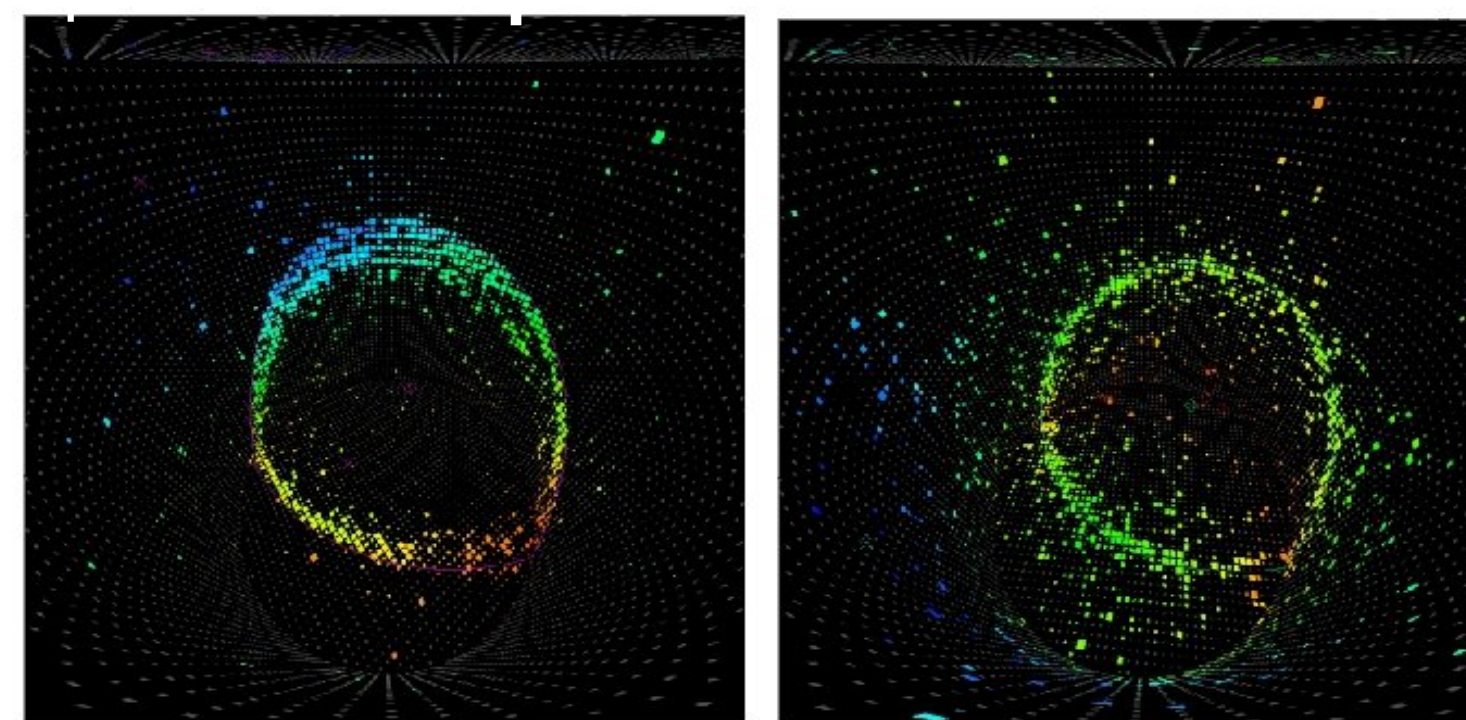
Using the Cherenkov effect

Super-Kamiokande in Japan

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



Séparer ν_μ et ν_e



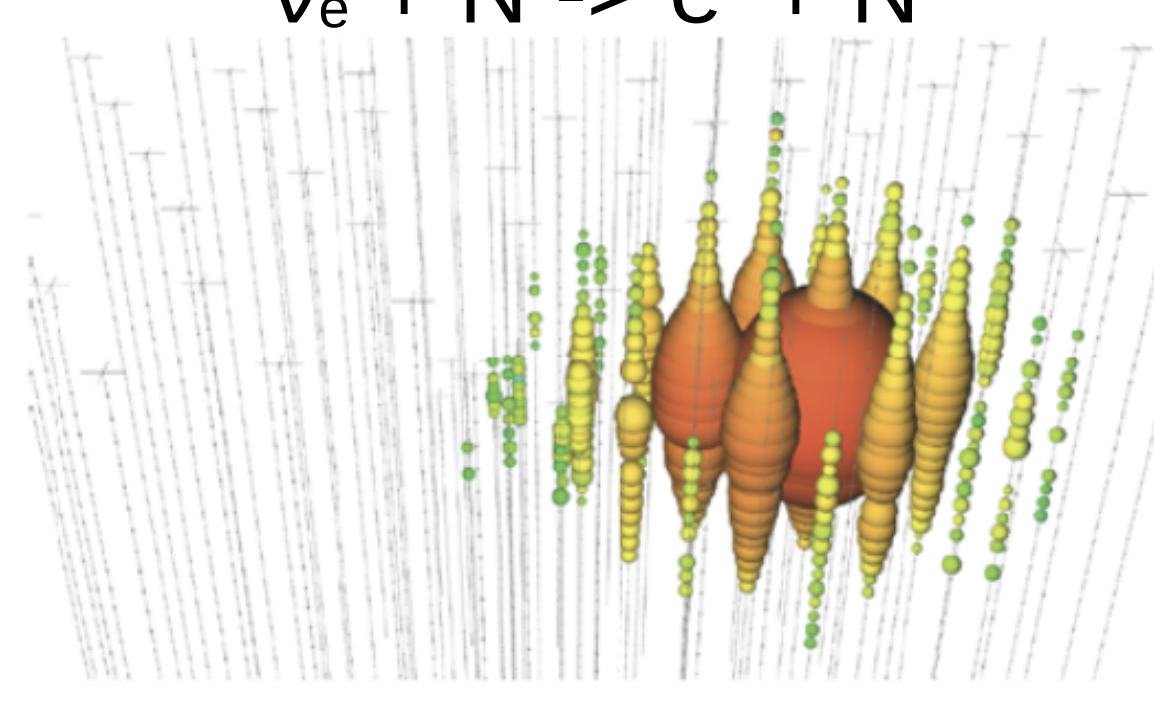
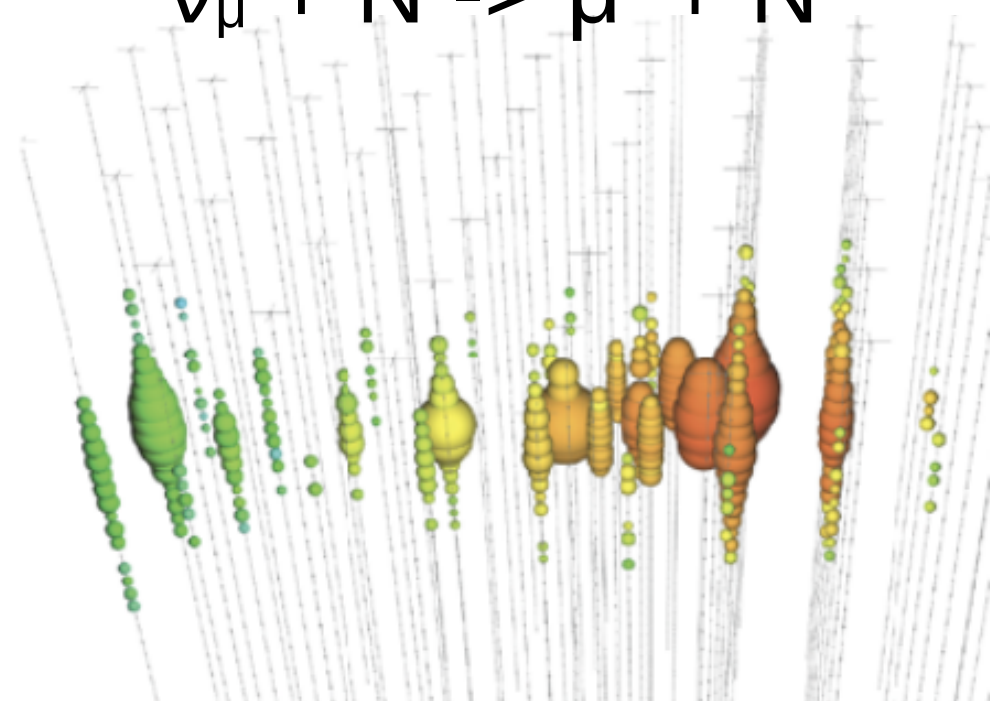
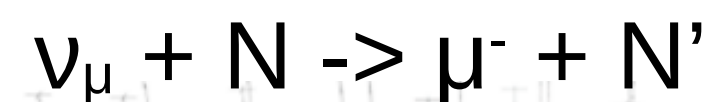
Color = # of photons collected



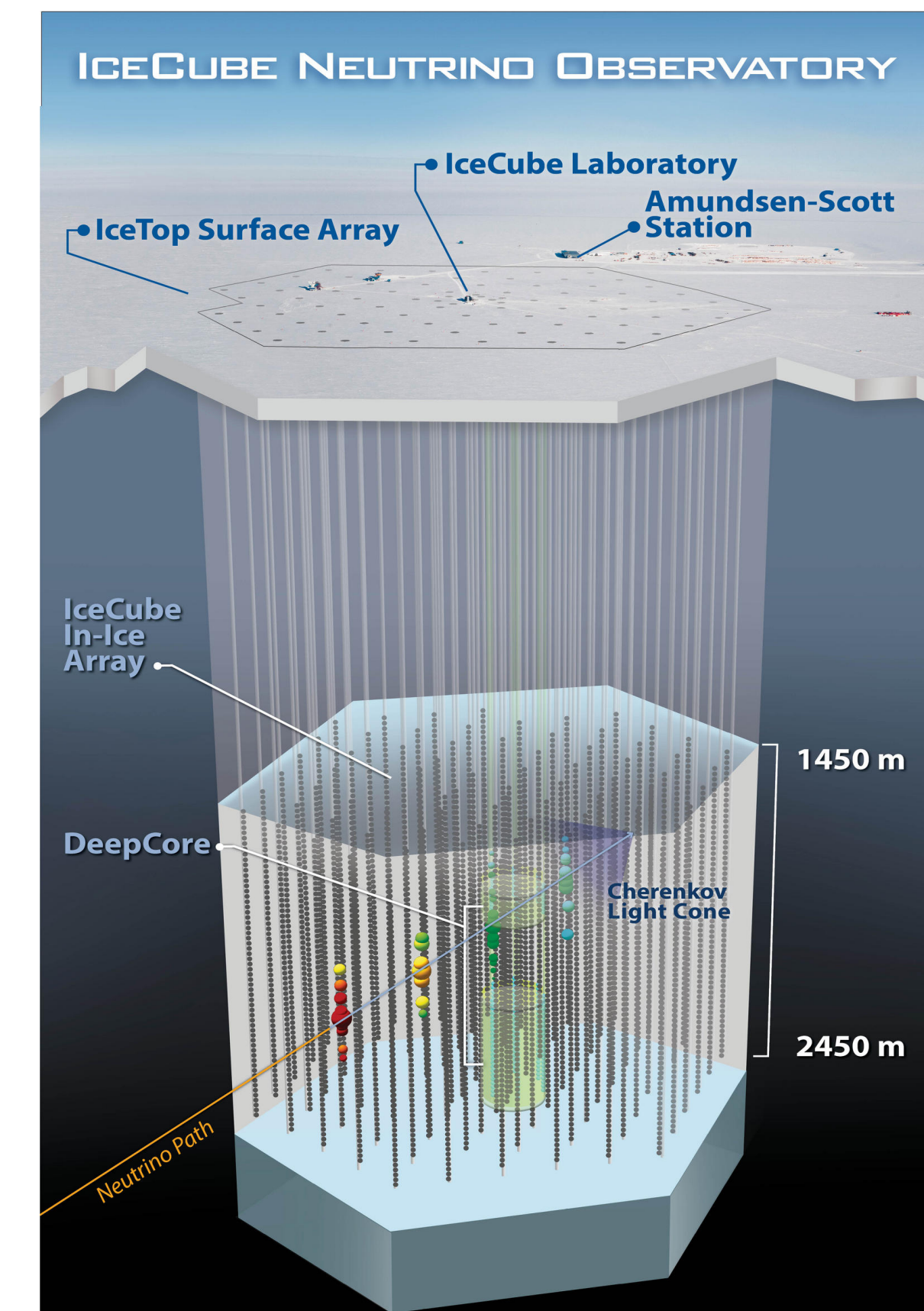
Alain Blondel Groupe Neutrino
Université de Genève

ICECUBE in Antarctica

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



Color = time
size = # of photons collected





Short break



NEUTRINO OSCILLATIONS

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

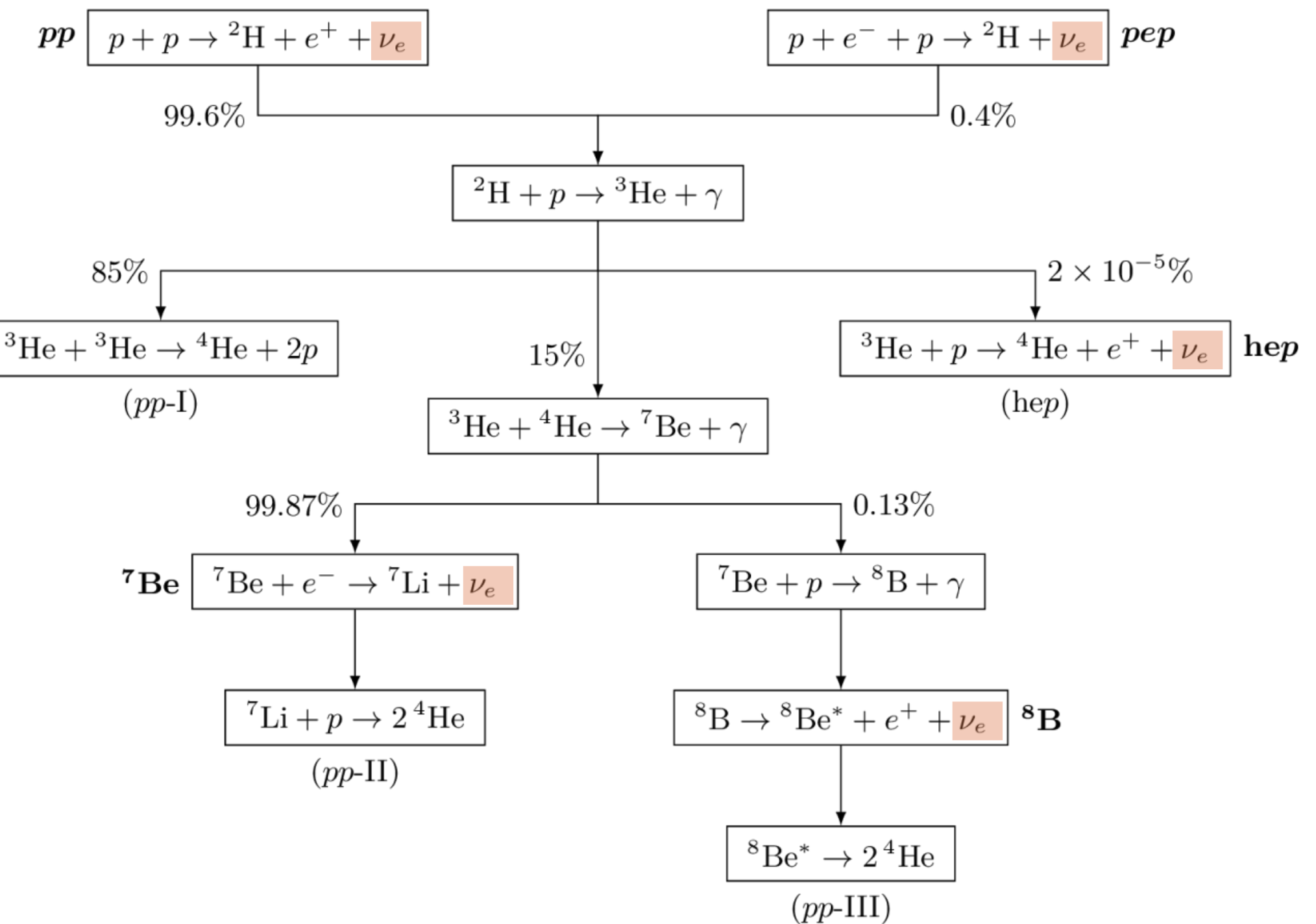
Solar neutrino flux

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

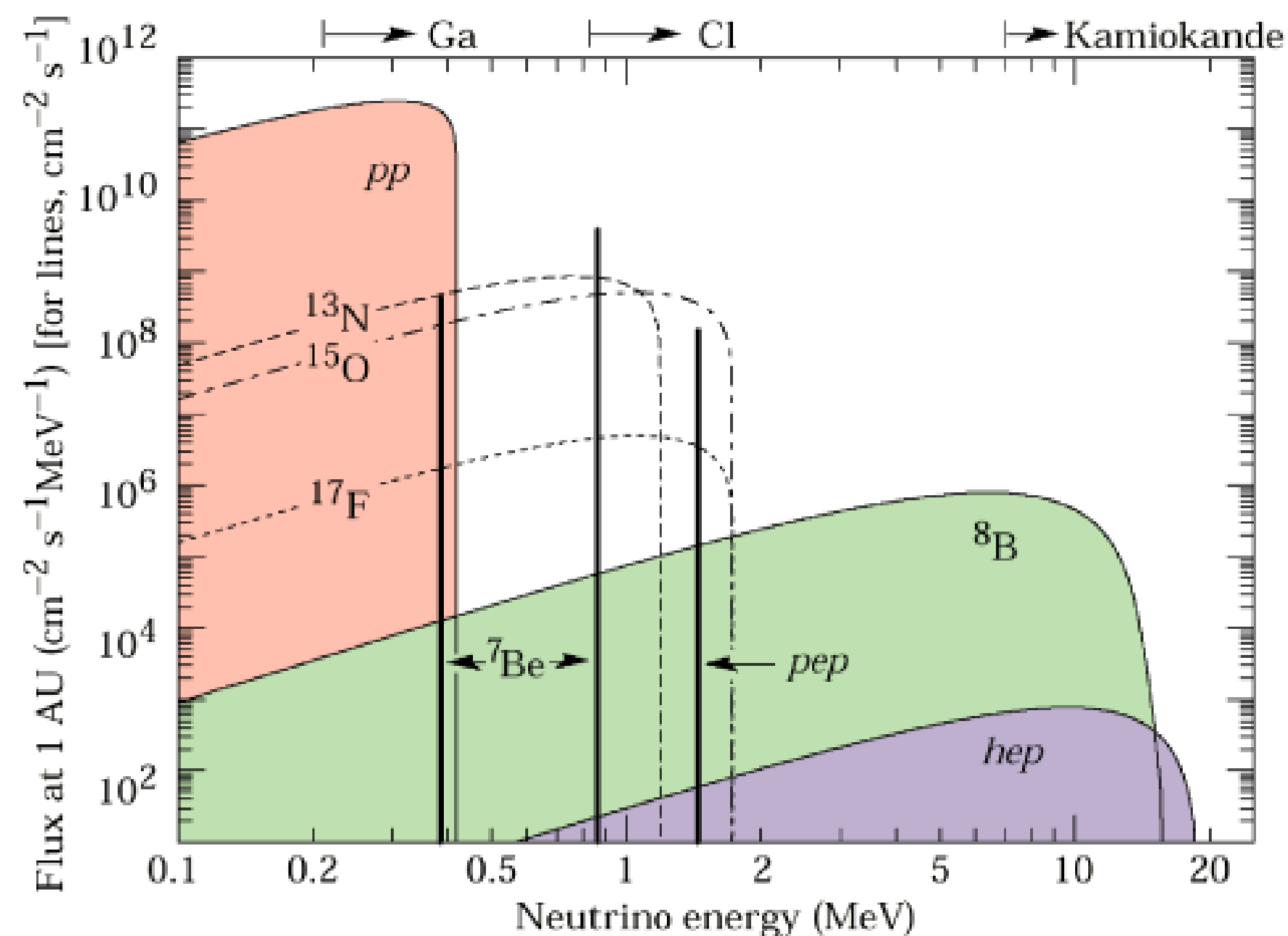
This led to a near complete understanding of stellar nucleosynthesis.



Proton-proton fusion chain in sun-like stars



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



Prediction:

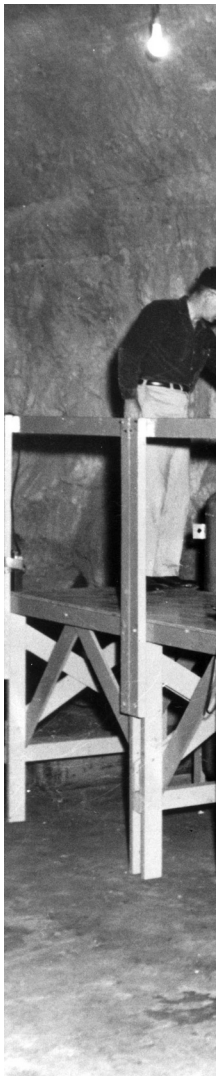
$$\phi_{\nu_e}^{\text{sun}} = 6.4 \times 10^{10} \nu_e/s/\text{cm}^2$$

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

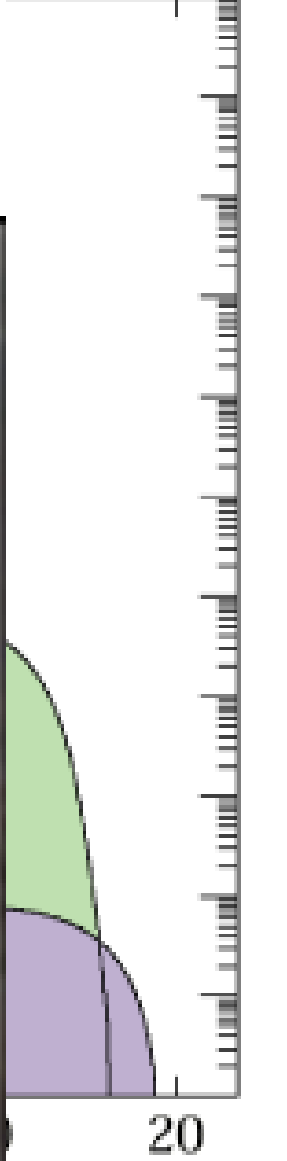


The
Ge c



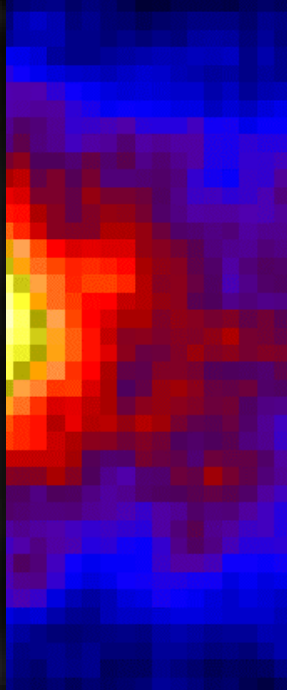
Less than half of what I'd hoped for

amiokande



n/s/atom

sun with ν_e



Solar neutrino deficit

Possible solutions:

- Poor understanding of fusion chains

Powerful predictive power of stellar nucleosynthesis theory indicates otherwise

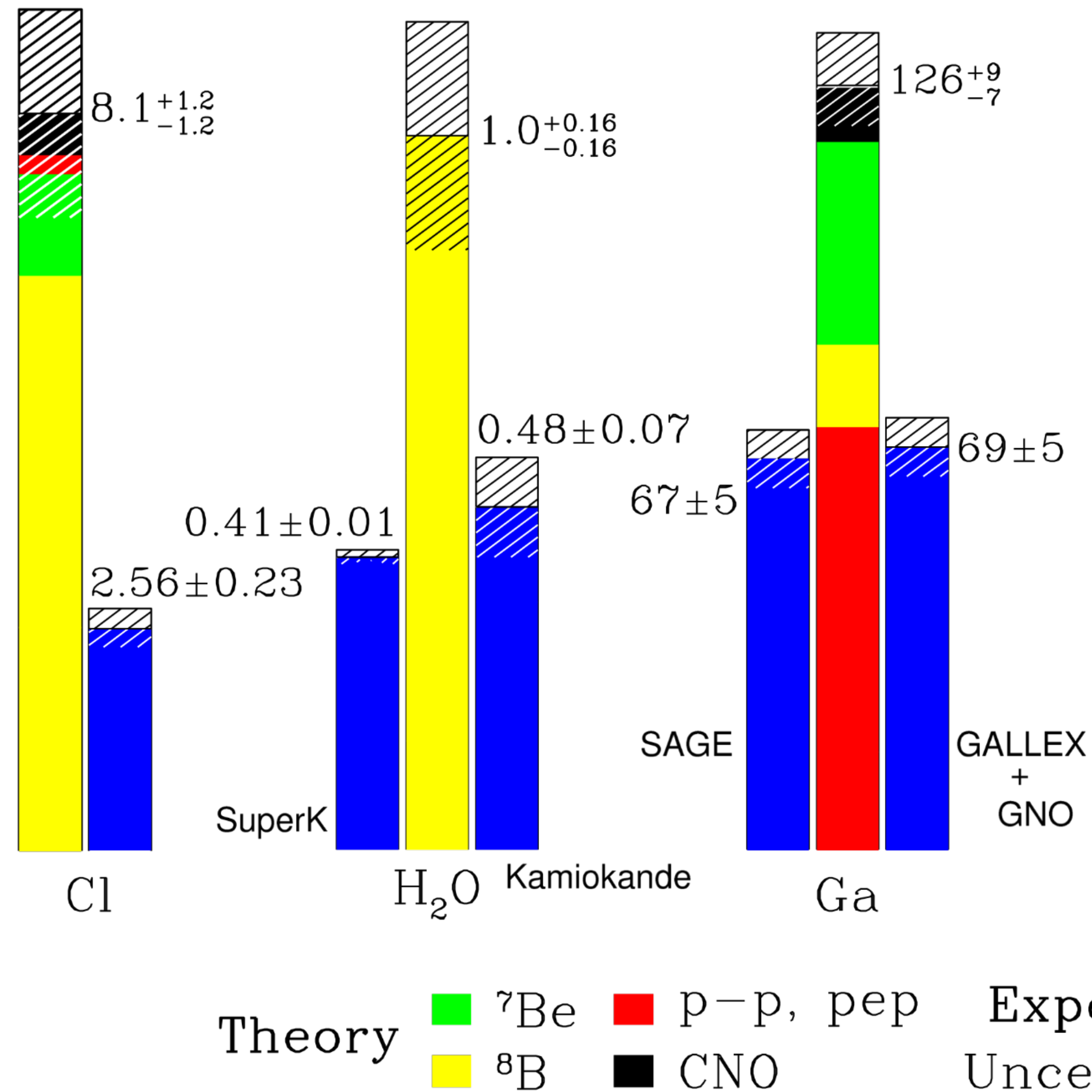
- Overestimated neutrino cross-sections

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

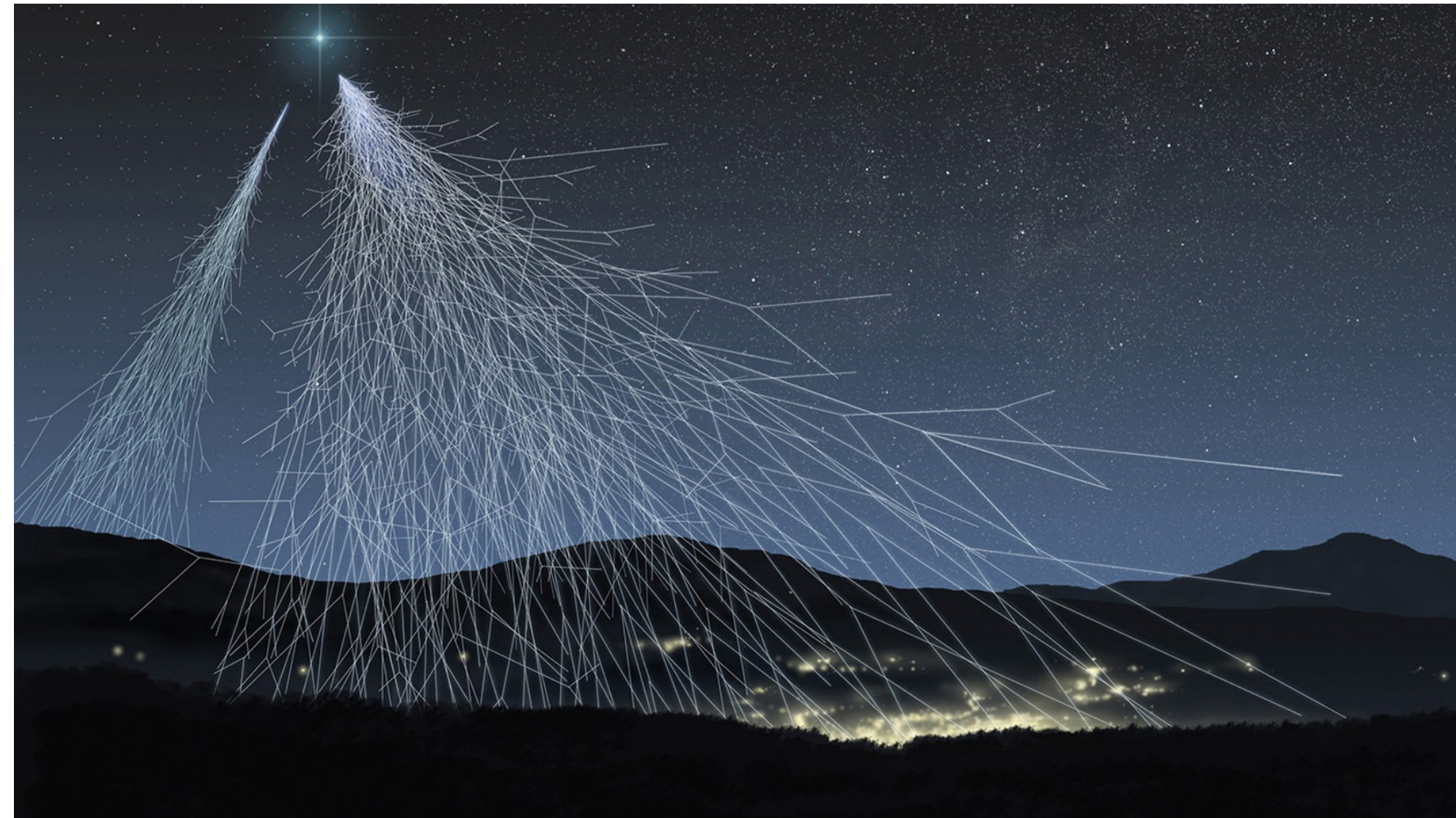
- Neutrinos disappear before reaching the detector

Neutrino decay? Neutrino mixing?

Solar neutrino deficit

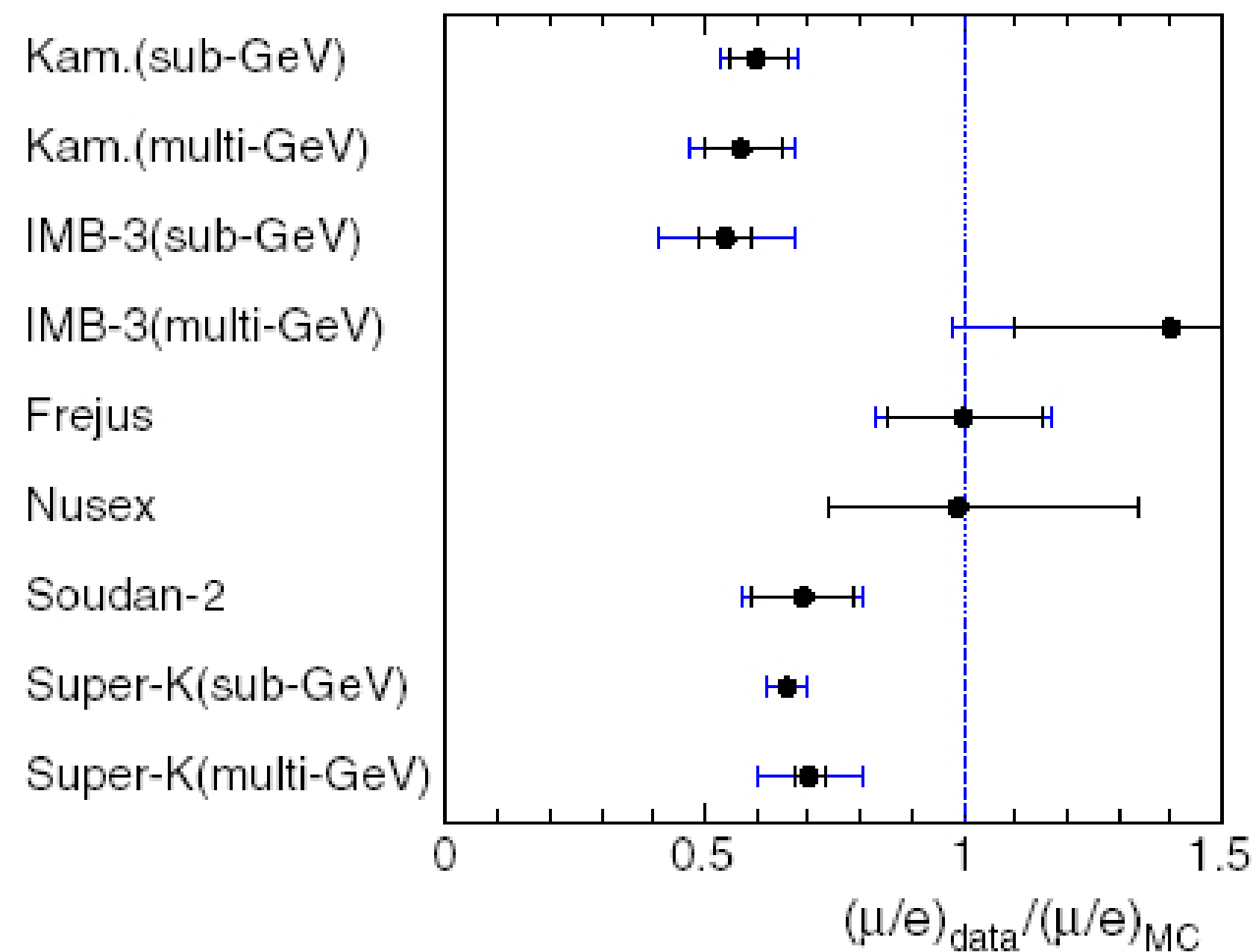
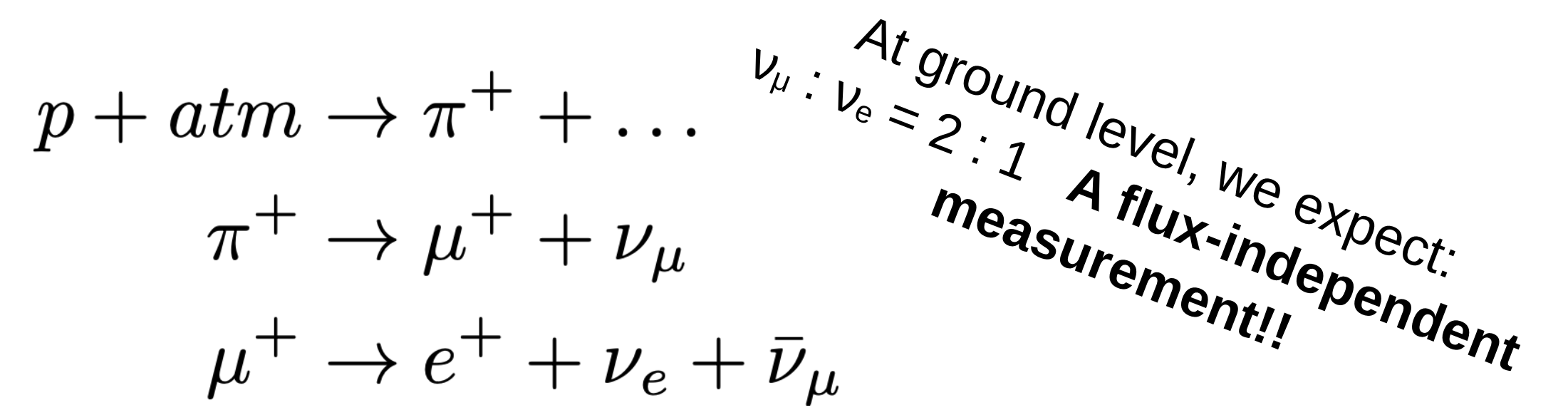


Atmospheric neutrino deficit



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

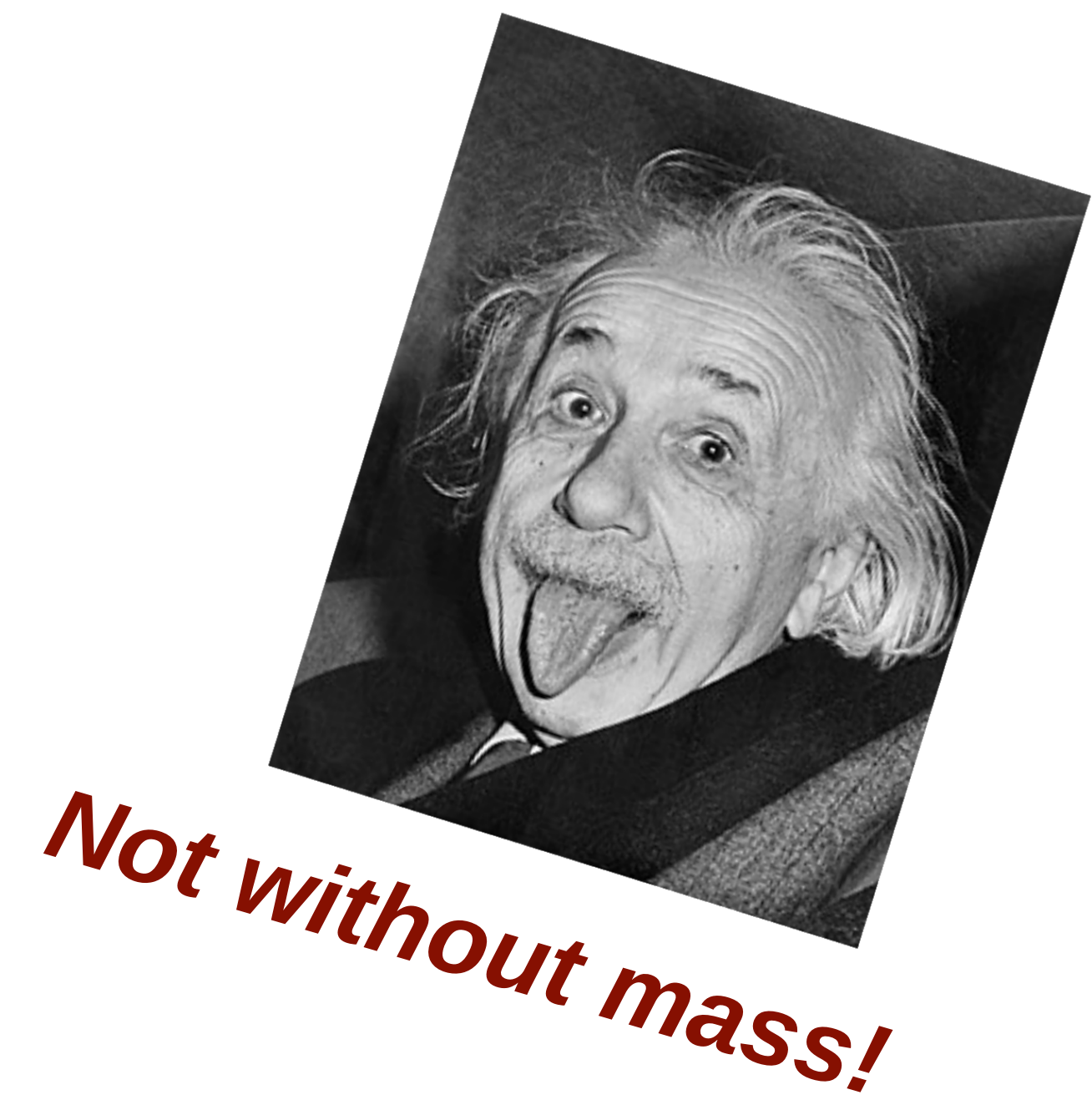
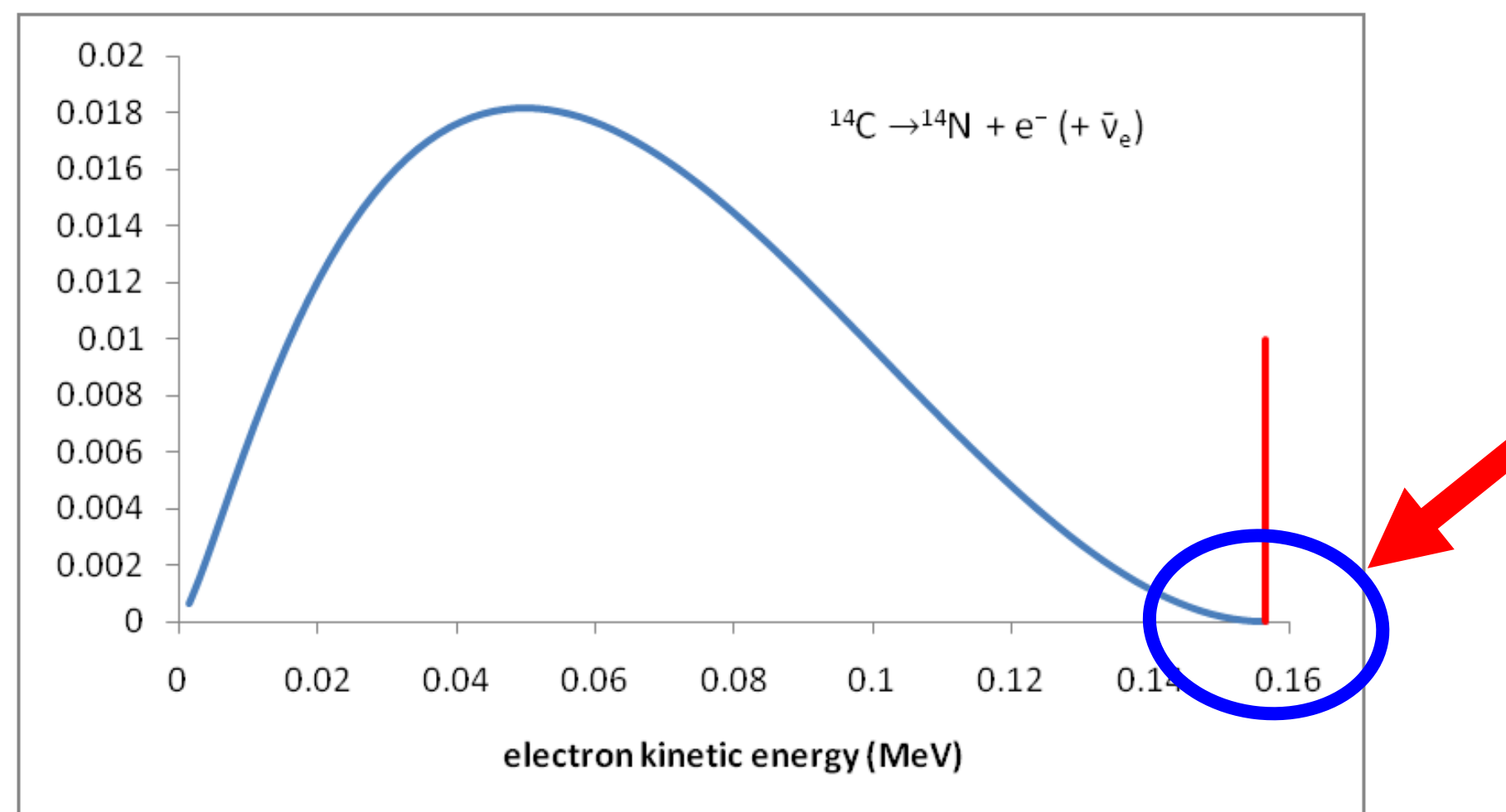
=> When cosmic rays hit the atmosphere and produce pions and muons



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 $K^0 \rightarrow \bar{K}^0$ mixing



Massive neutrinos?

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

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

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

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

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

$$N = \bar{V}_N^\dagger N_D U_N \text{ and } K = V_K^\dagger K_D U_K.$$

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

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

$$J^\mu = \bar{L}' \gamma^\mu (\sigma_1 + i\sigma_2) L' = 2 \begin{pmatrix} \nu'_e & \nu'_\mu & \nu'_\tau \end{pmatrix}_L \gamma^\mu \begin{pmatrix} e' & \mu' & \tau' \end{pmatrix}_L^T$$

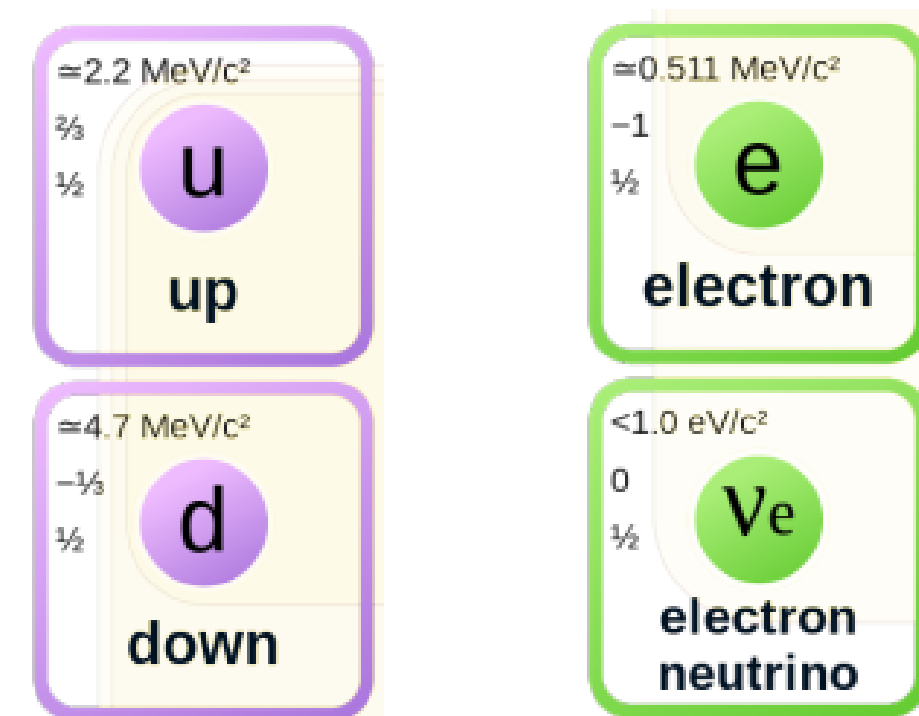
$$= 2 \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix}_L \gamma^\mu (V_K^\dagger V_N) \begin{pmatrix} e & \mu & \tau \end{pmatrix}_L^T$$

$$= \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \gamma^\mu (1 - \gamma_5) (V_K^\dagger V_N) \begin{pmatrix} e & \mu & \tau \end{pmatrix}^T$$

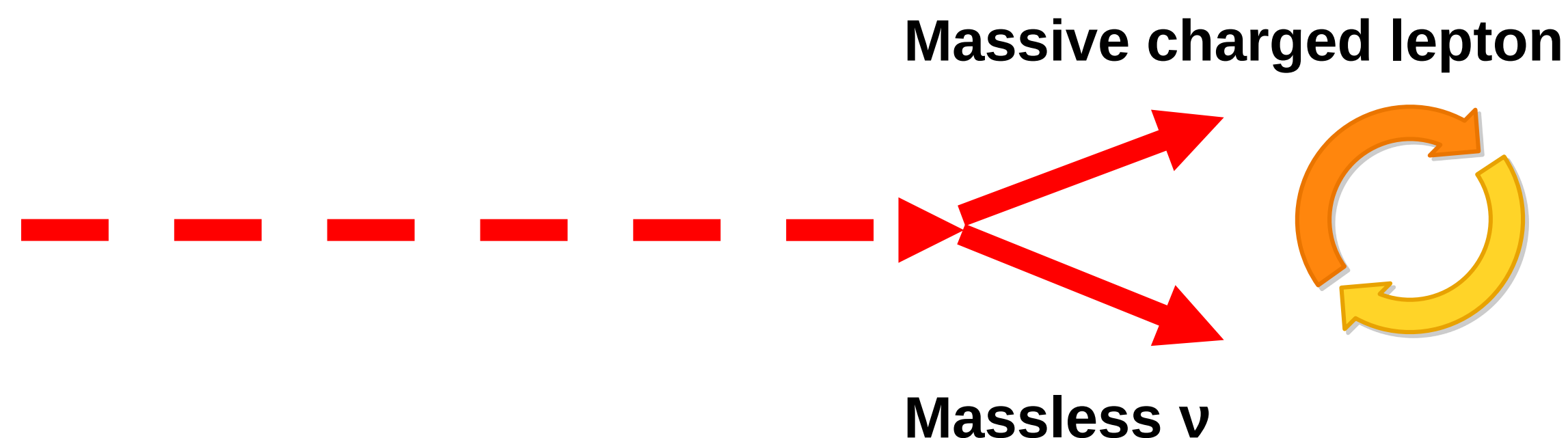
$$U \equiv V_K^\dagger V_N = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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**



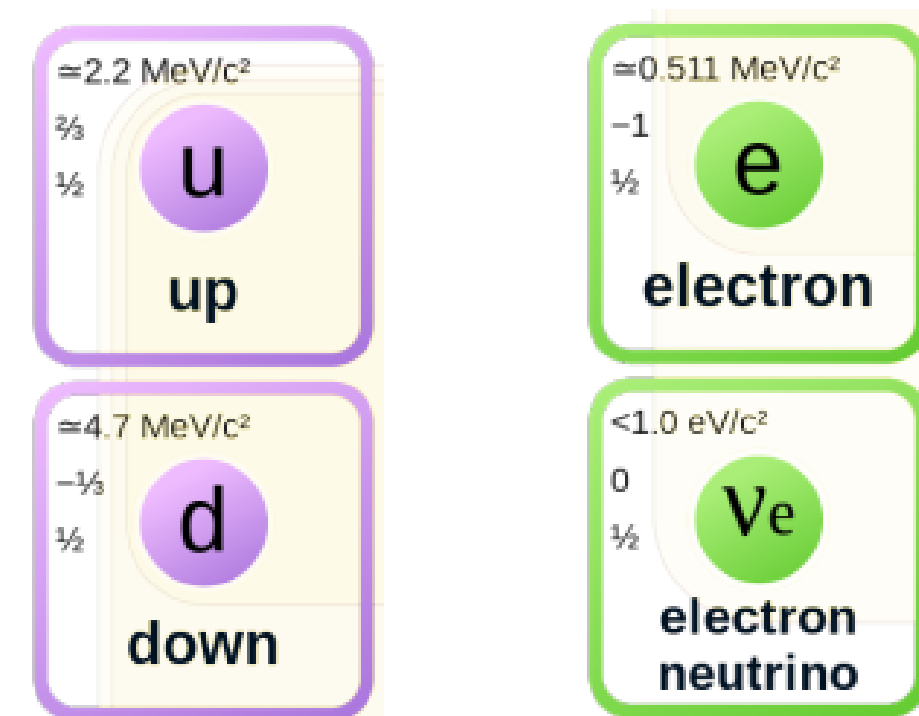
As long as we choose paired states, the weak interaction physics will stay the same

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

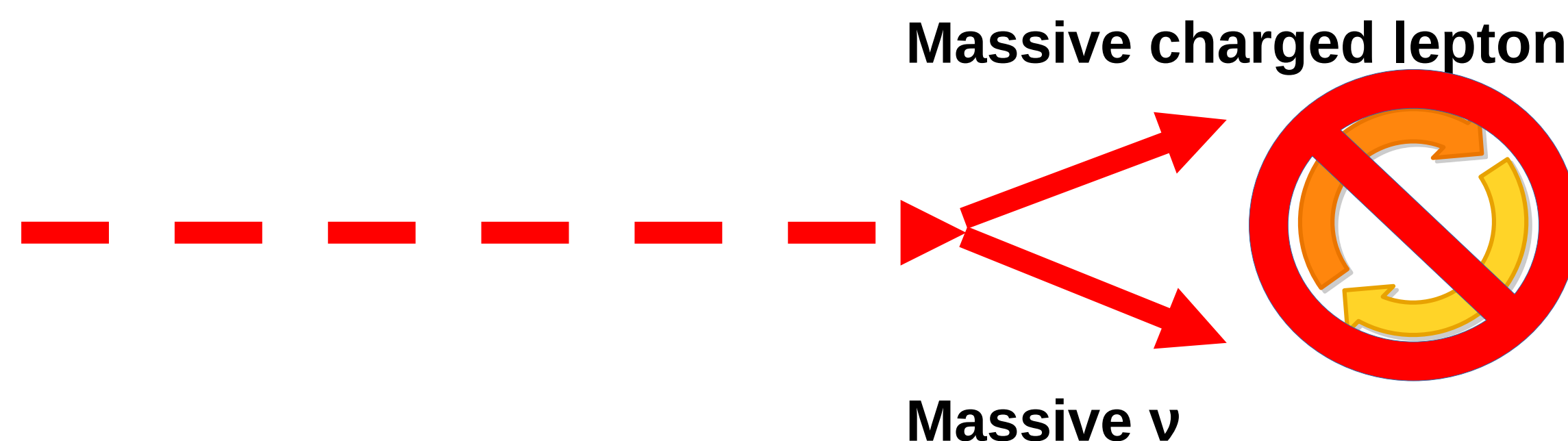
(we can respect the weak pairing when choosing the propagation states)

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:



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

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

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

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

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

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

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

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

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 $\Rightarrow$ 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:

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

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

$$|\nu_i\rangle = \sum_{\alpha=1}^3 U_{\alpha i} |\nu_\alpha\rangle \quad |\nu_\alpha(t)\rangle = e^{-i\mathcal{H}t} \left[\sum_j U_{\alpha j}^* \left(\sum_\beta U_{\beta j} |\nu_\beta(0)\rangle \right) \right]$$

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

$$E_j = \sqrt{\vec{p}^2 + m_j^2}$$

We square the amplitude to get the detection probability

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

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

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

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

3 flavour neutrino oscillations

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

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

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

- 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:

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

Oscillation phenomenology

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

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 ?

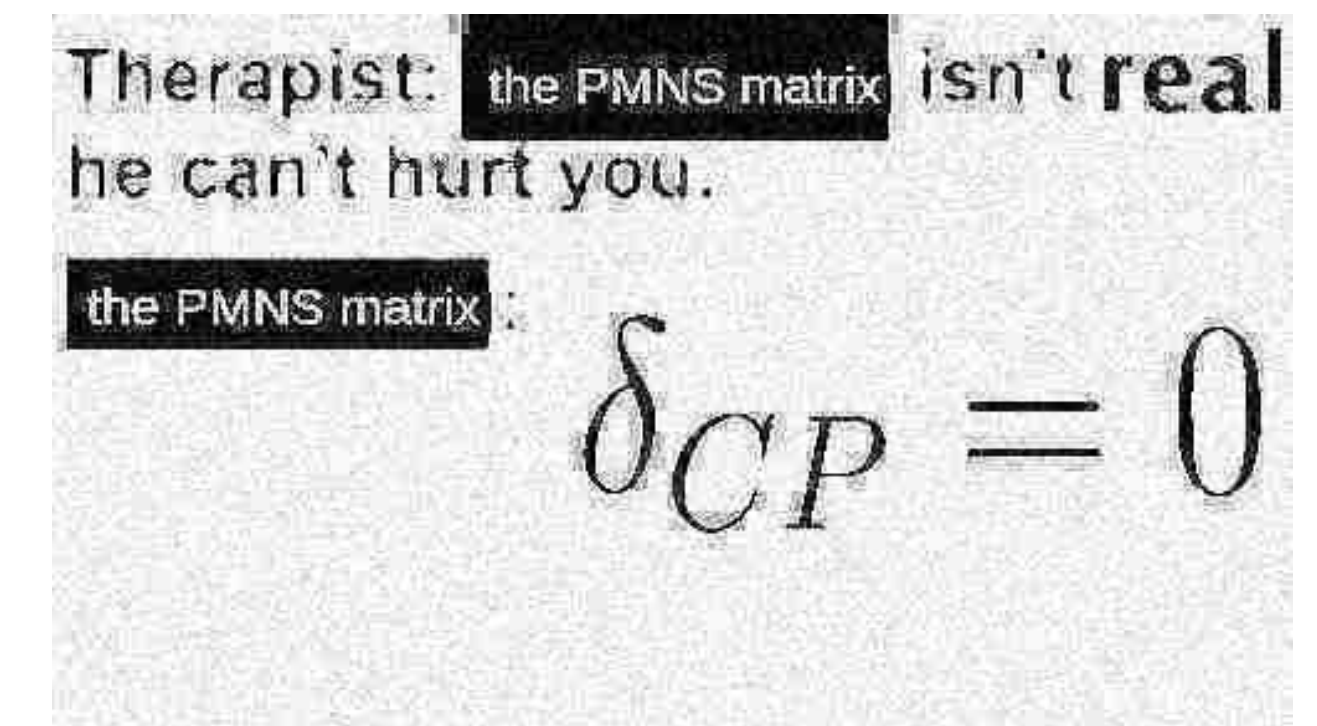
This is what happens in the quark and charged lepton sectors. The oscillations become decays very quickly

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 $\Rightarrow$ CP (or T) violation

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

It vanishes: CP violation is only possible in appearance probabilities



Oscillation phenomenology

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

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?

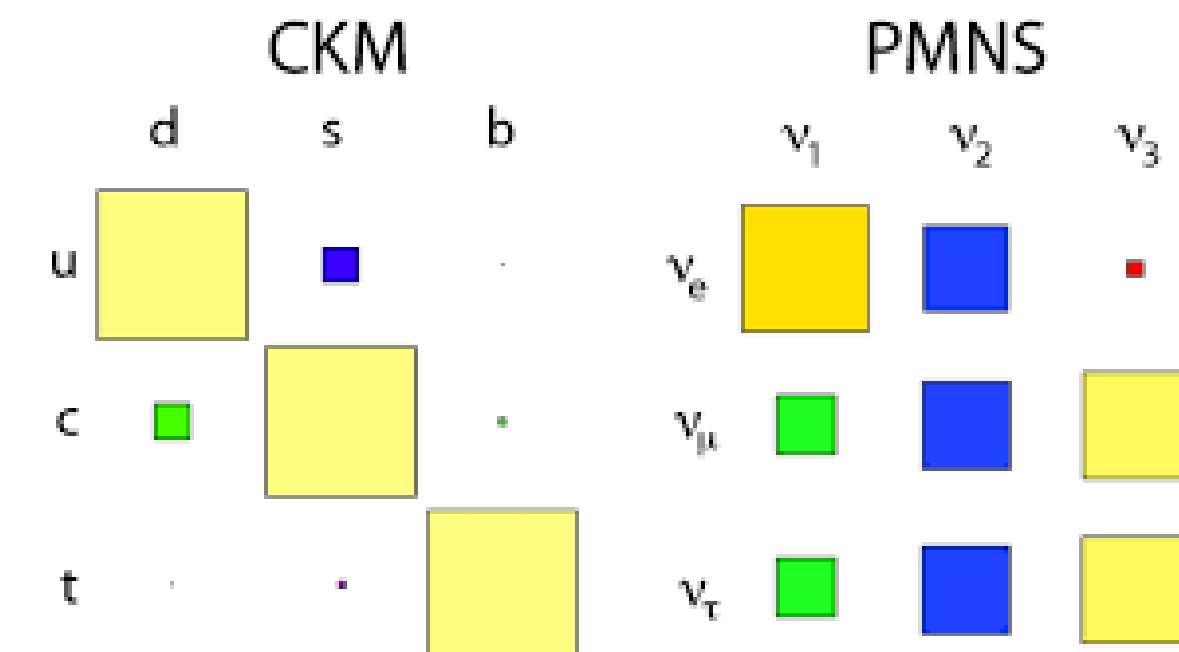
- A generic 3x3 complex matrix has 18 free parameters. A unitary matrix has 9
- We are allowed to change the mixing matrix by global changes of phase ==> We can multiply by matrices with complex phases along the diagonals ==> This removes up to 5 more parameters
- We end up with 4 free parameters, which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

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

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

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

Oscillation formula

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

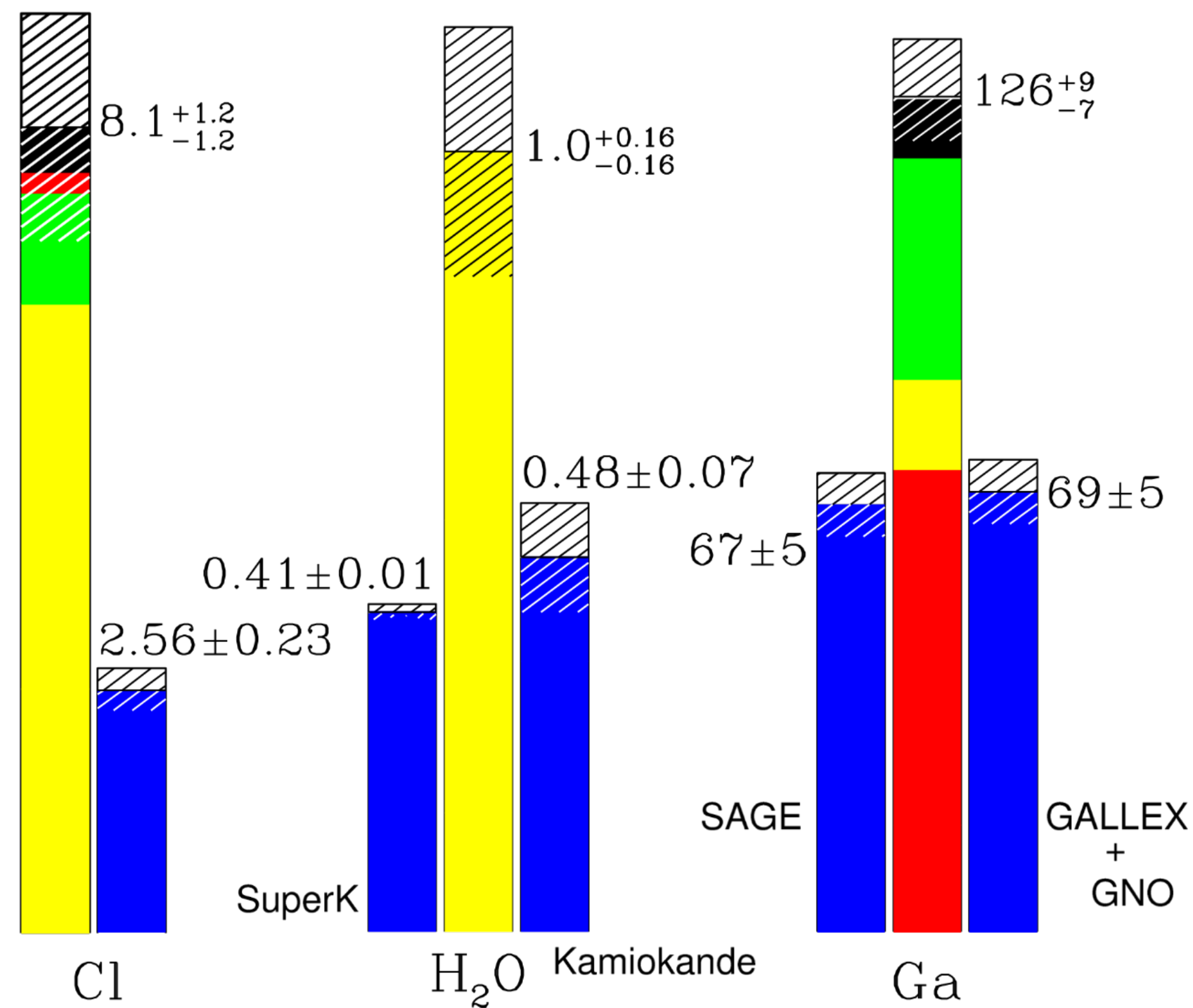
PMNS matrix

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

$$\mathbf{v}_e, \mathbf{v}_\mu, \mathbf{v}_\tau = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} |\nu_i\rangle$$

Oscillation phenomenology

Let us jump back into oscillation measurements for a minute



Explanation via oscillations:

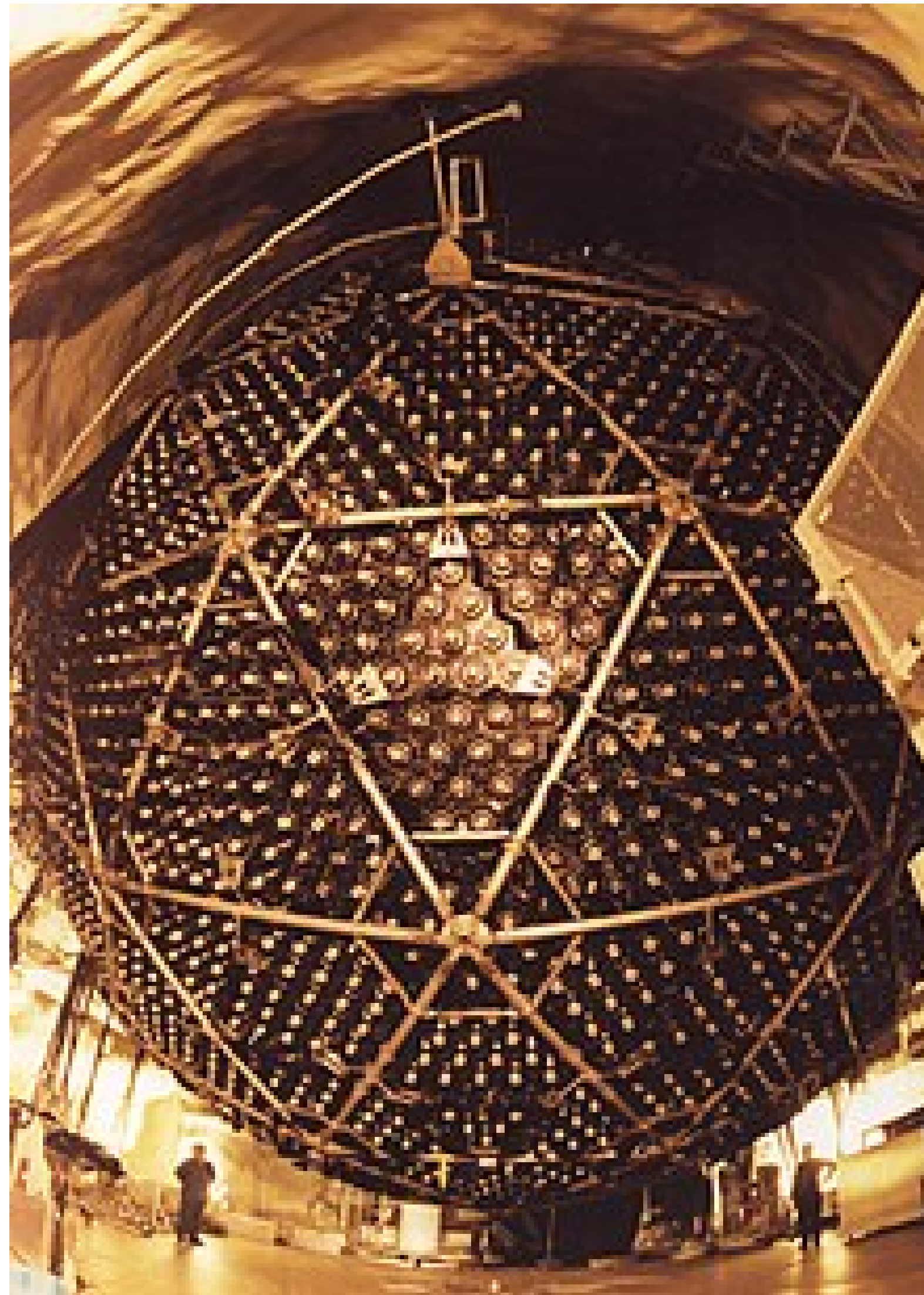
Missing ν_e have oscillated into ν_μ and ν_τ and cannot be detected through CC interactions because the energy threshold is too high for our detectors

$$E_{\text{thr}}(\nu_\mu) = 110 \text{ MeV}$$

$$E_{\text{thr}}(\nu_\tau) = 3.45 \text{ GeV}$$

Theory ■ ${}^7\text{Be}$ ■ $p-p, \text{ pep}$ Experiments ■
■ ${}^8\text{B}$ ■ CNO Uncertainties

Oscillation phenomenology - Solar



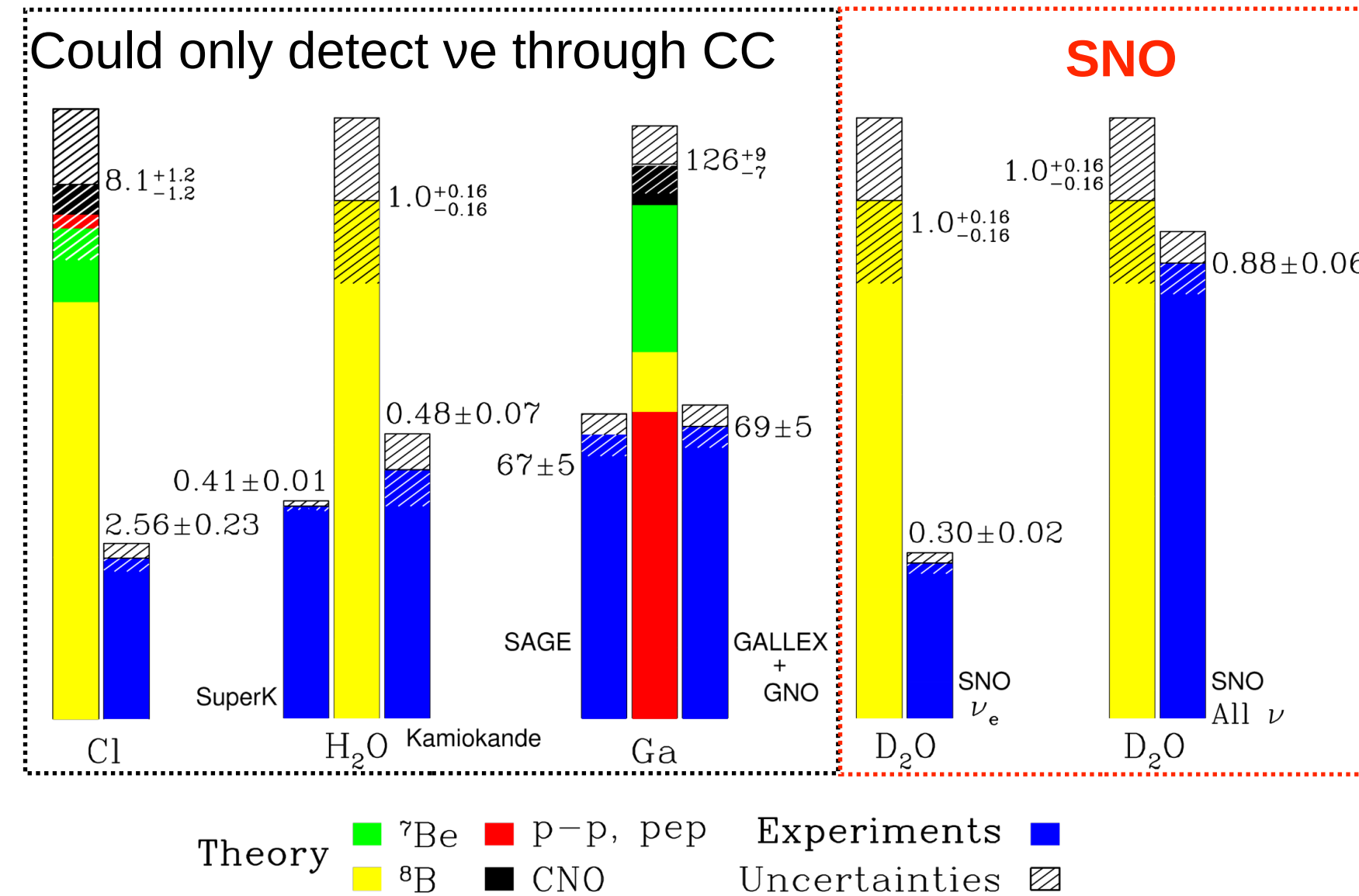
SNO (1kton of heavy water) was designed to detect solar neutrinos through:

- **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

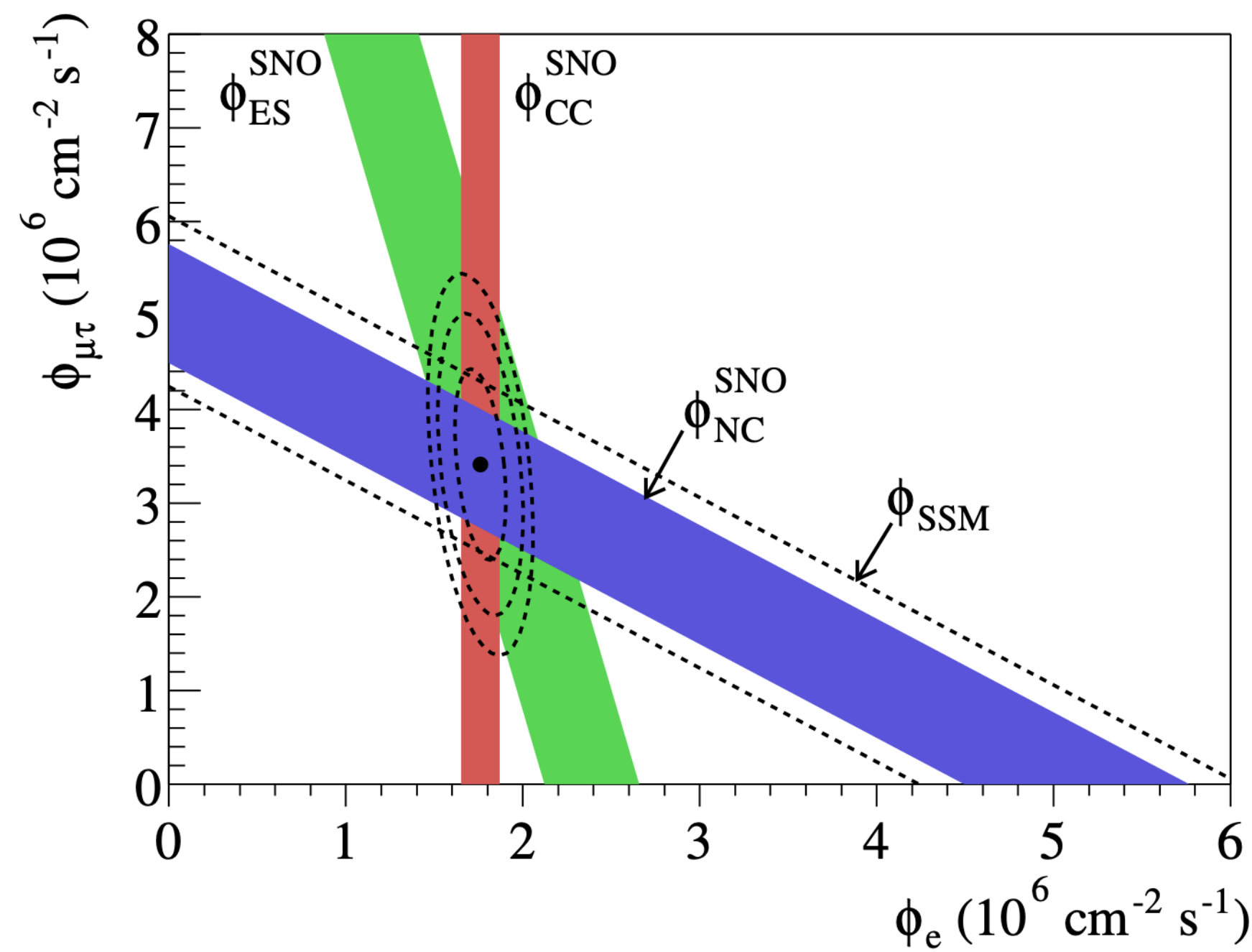
- ▣ **NC** interactions $\nu_x + d \rightarrow p + n + \nu_x$
all flavors

Oscillation phenomenology - Solar



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

- CC** interactions $\nu_e + d \rightarrow p + p + e^-$
 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



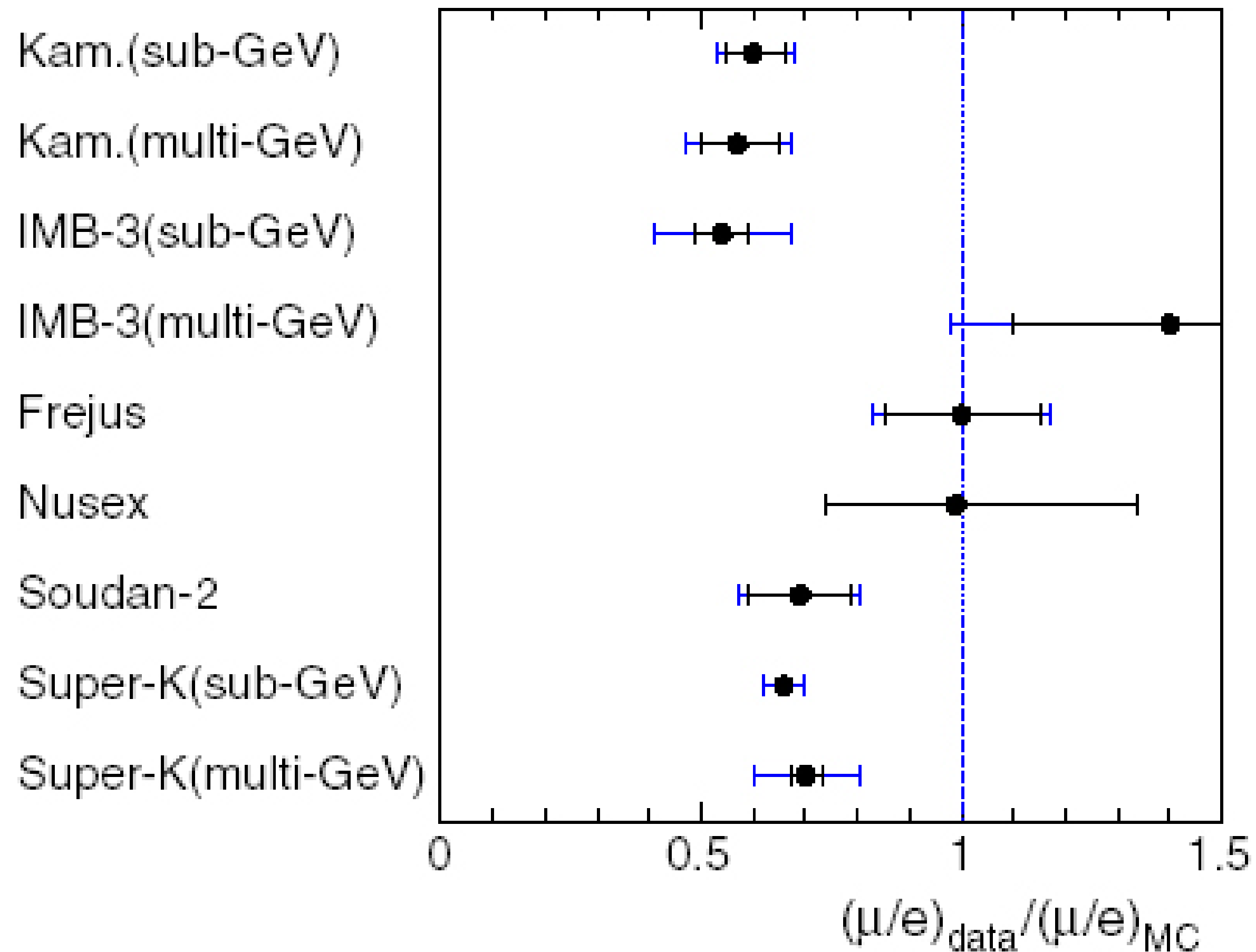
SNO measured the ratio $\frac{\Phi_{CC}}{\Phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$

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

SNO proved that neutrinos change flavors



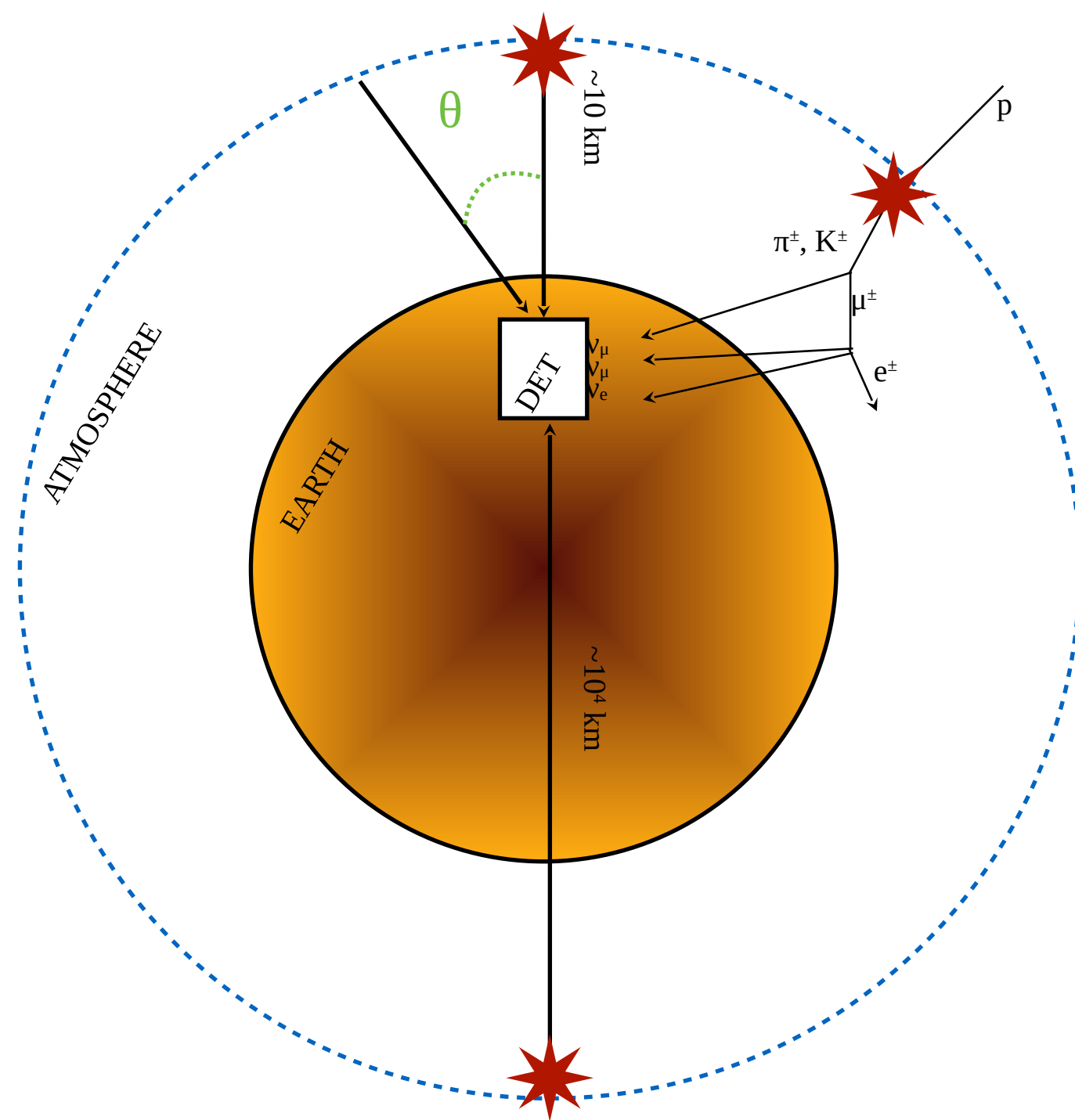
Oscillation phenomenology - Atmospheric



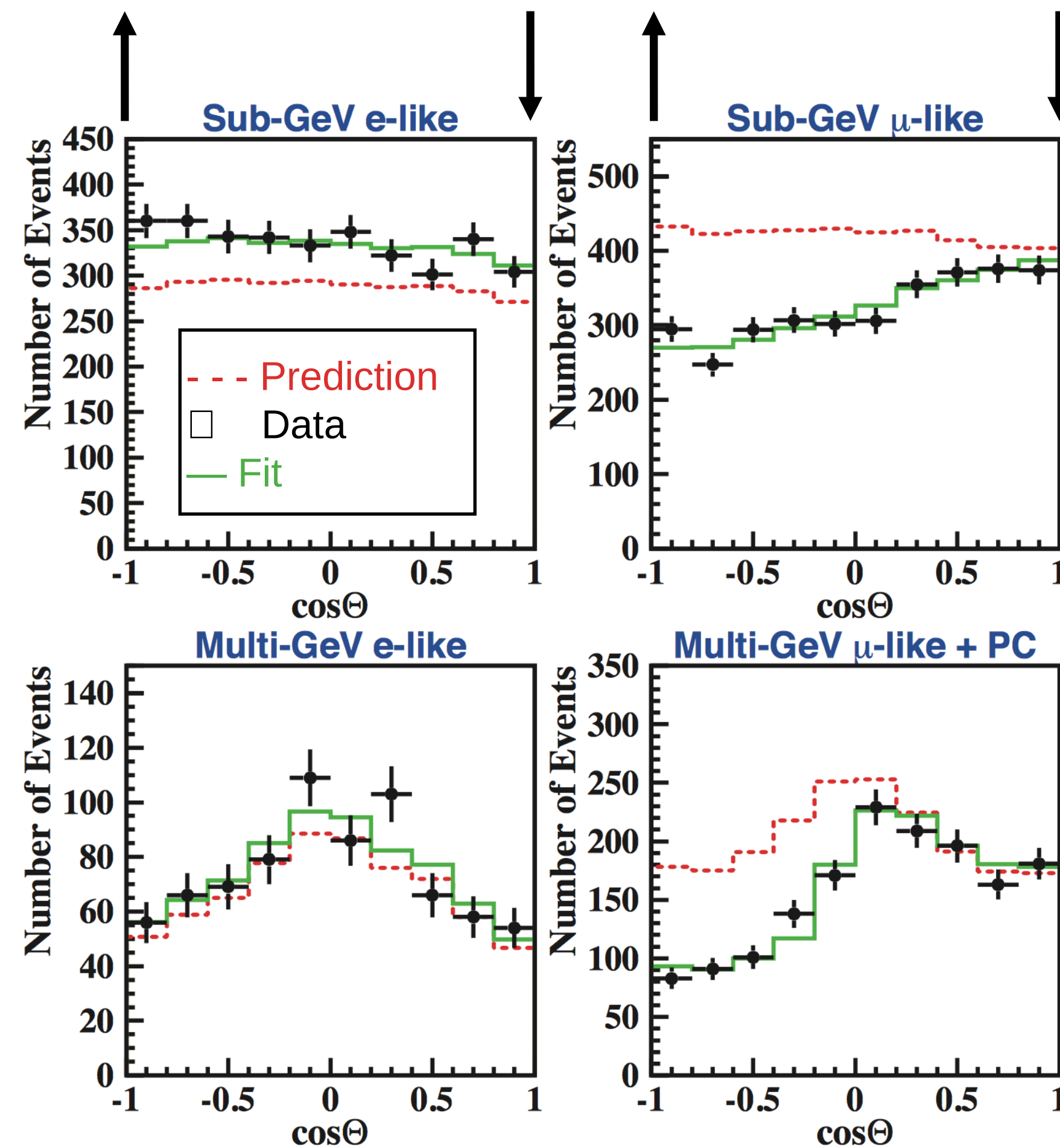
Explanation via oscillations:

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 $\cos\theta \leftrightarrow L$



For ν_e :

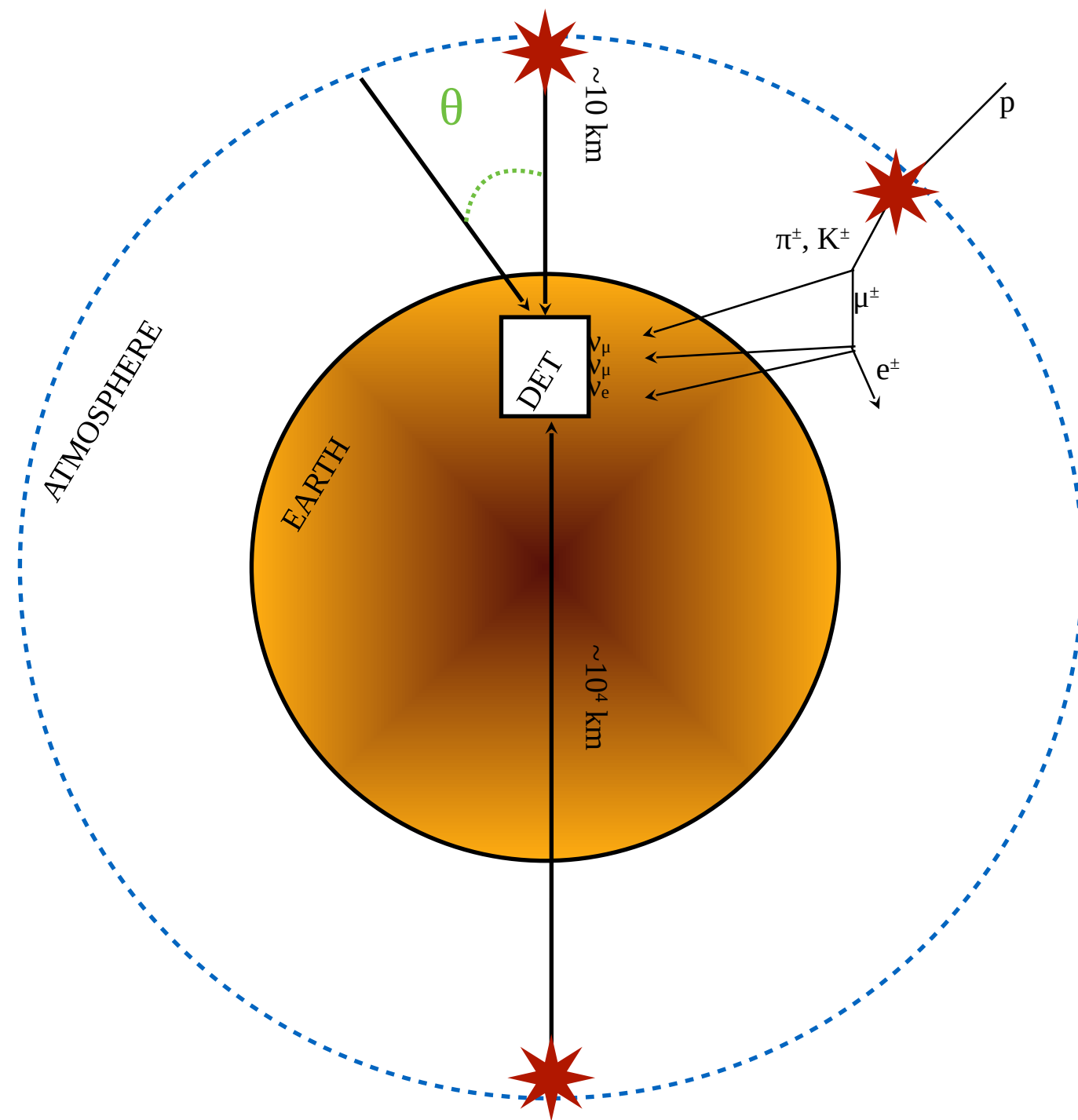
Flux agrees with predictions for all directions and energy

For ν_μ :

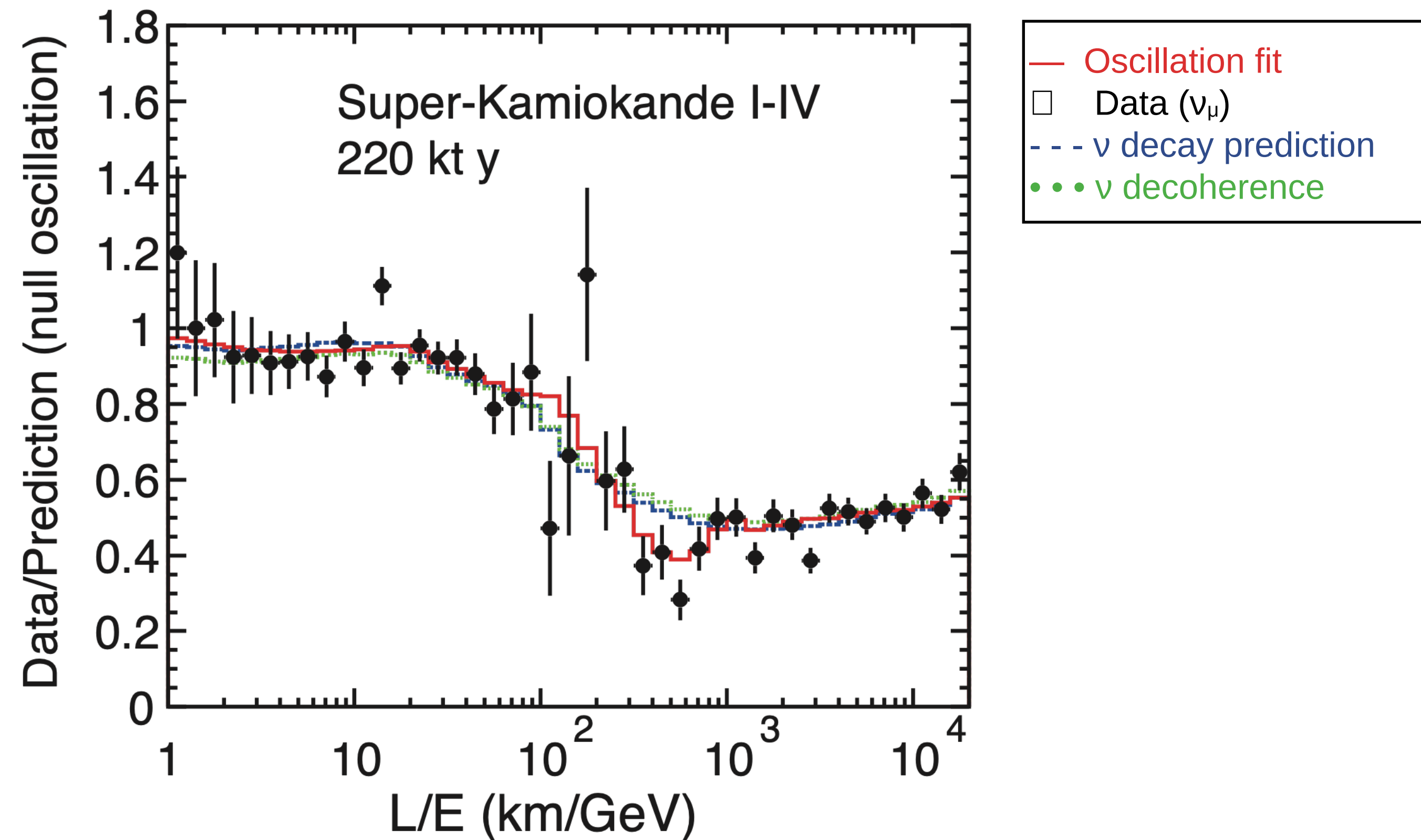
Disappearance of upwards going ν_μ ($L \sim 10^4$ km)

Flux agrees with predictions for downwards going ν_μ ($L \sim 10$ km)

Oscillation phenomenology - Atmospheric



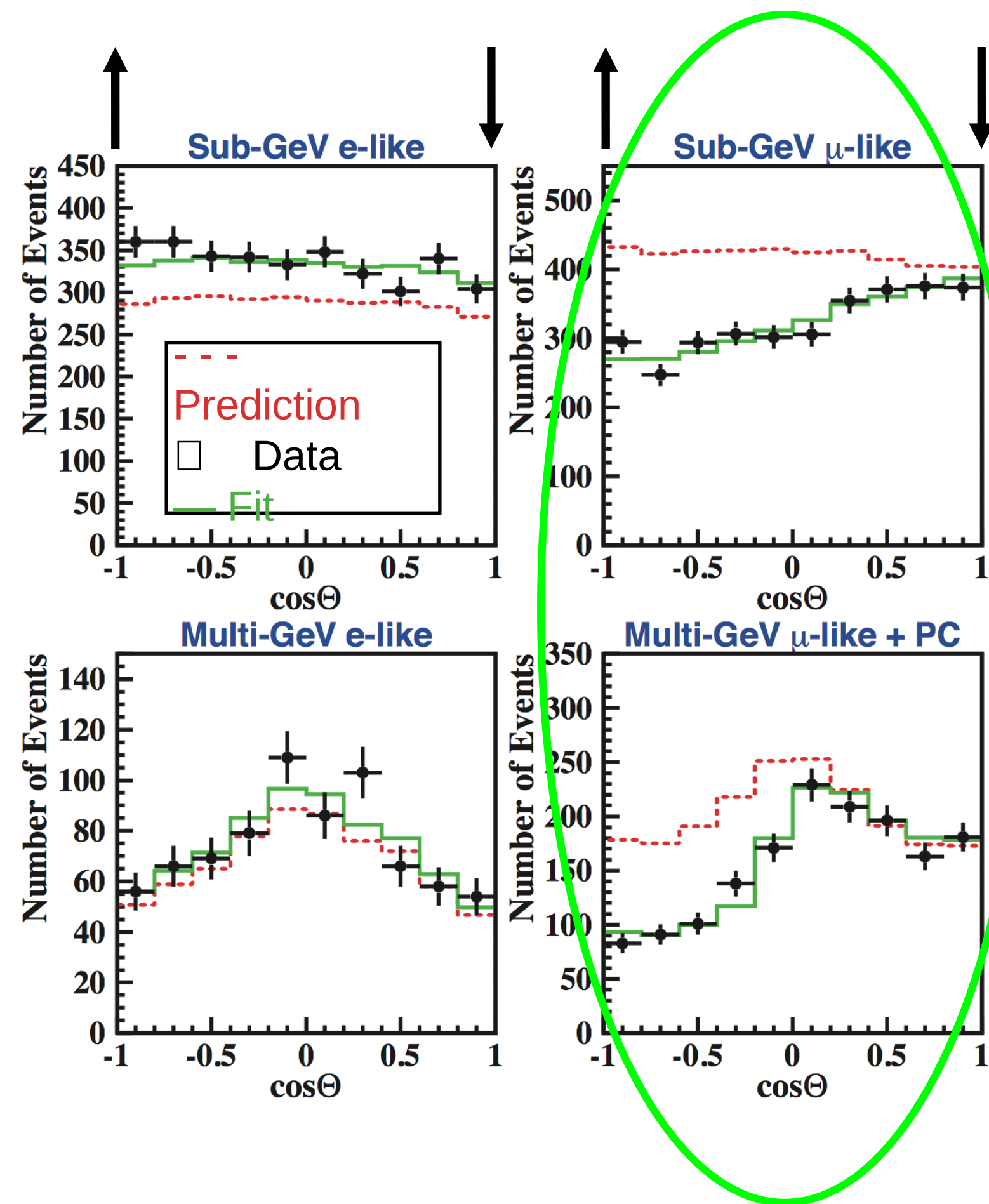
Super-Kamiokande measured the atmospheric ν_e and ν_μ energy as a function of $\cos\theta \leftrightarrow L$



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

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

This angle mixes ν_μ and ν_τ

This complex rotation is not so intuitive

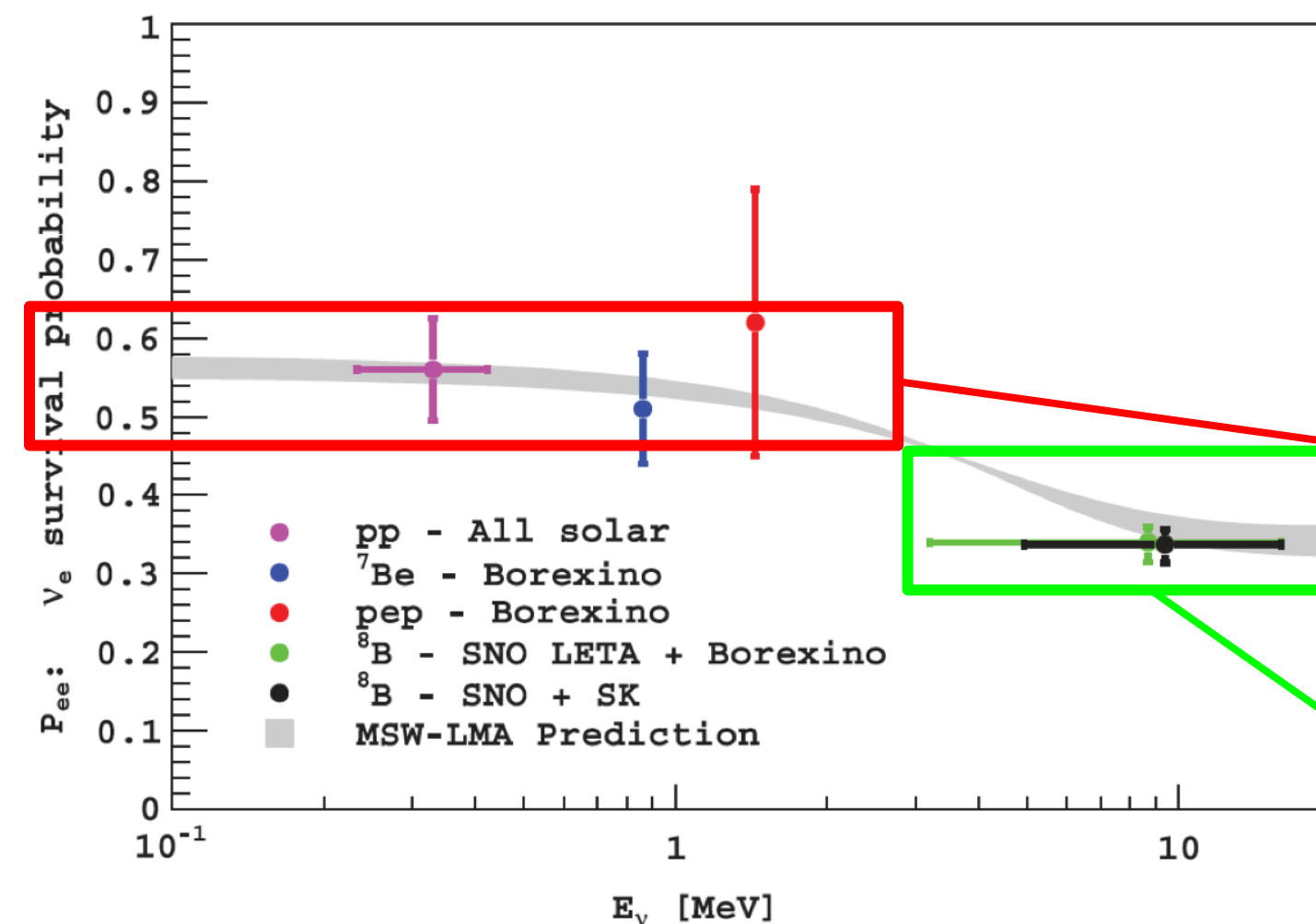
This angle mixes ν_1 and ν_2

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

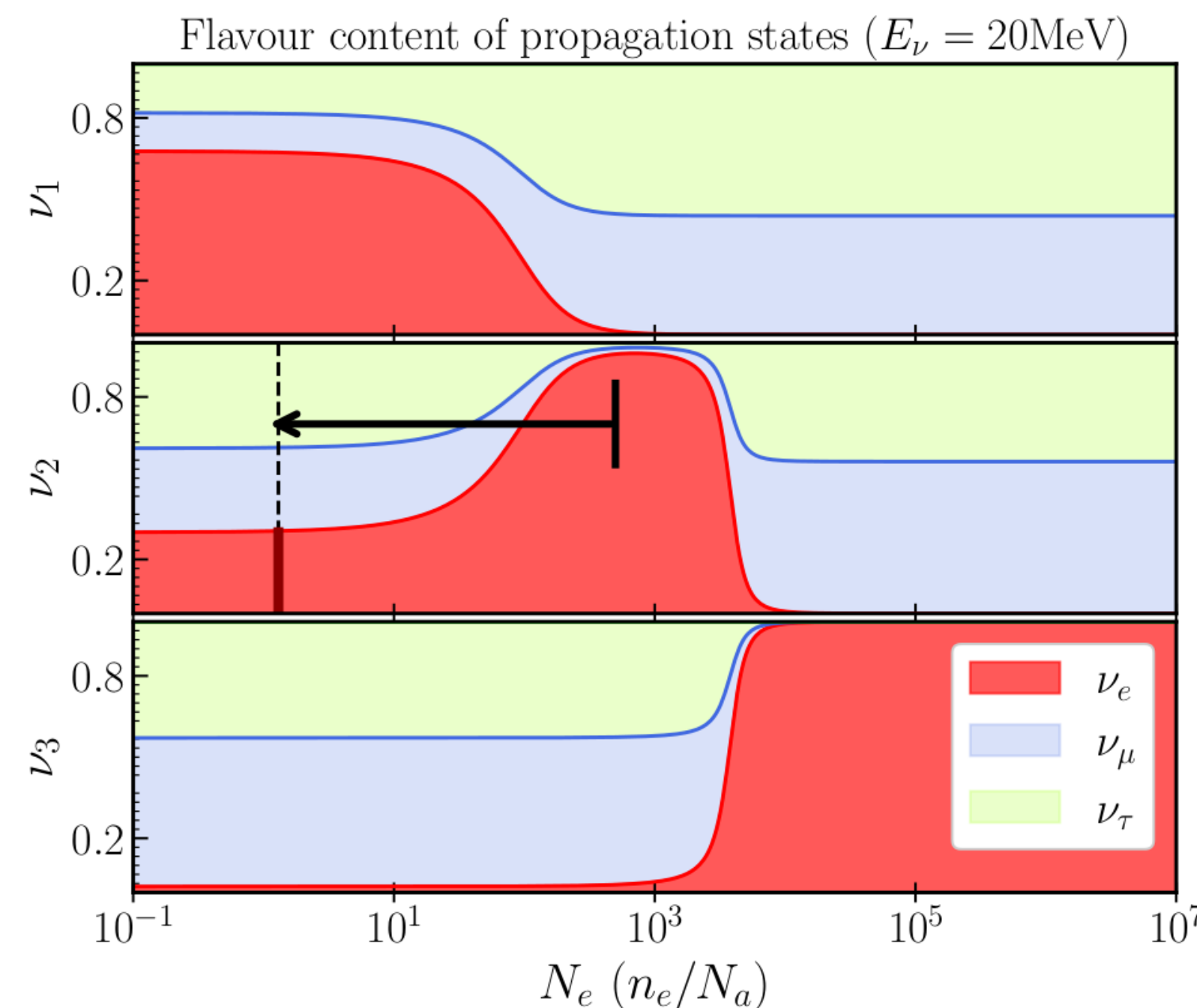
Solar oscillations are a bit more complicated: Neutrinos in the sun do not propagate like in vacuum



○ 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, $\sigma_{\nu-e}$ 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



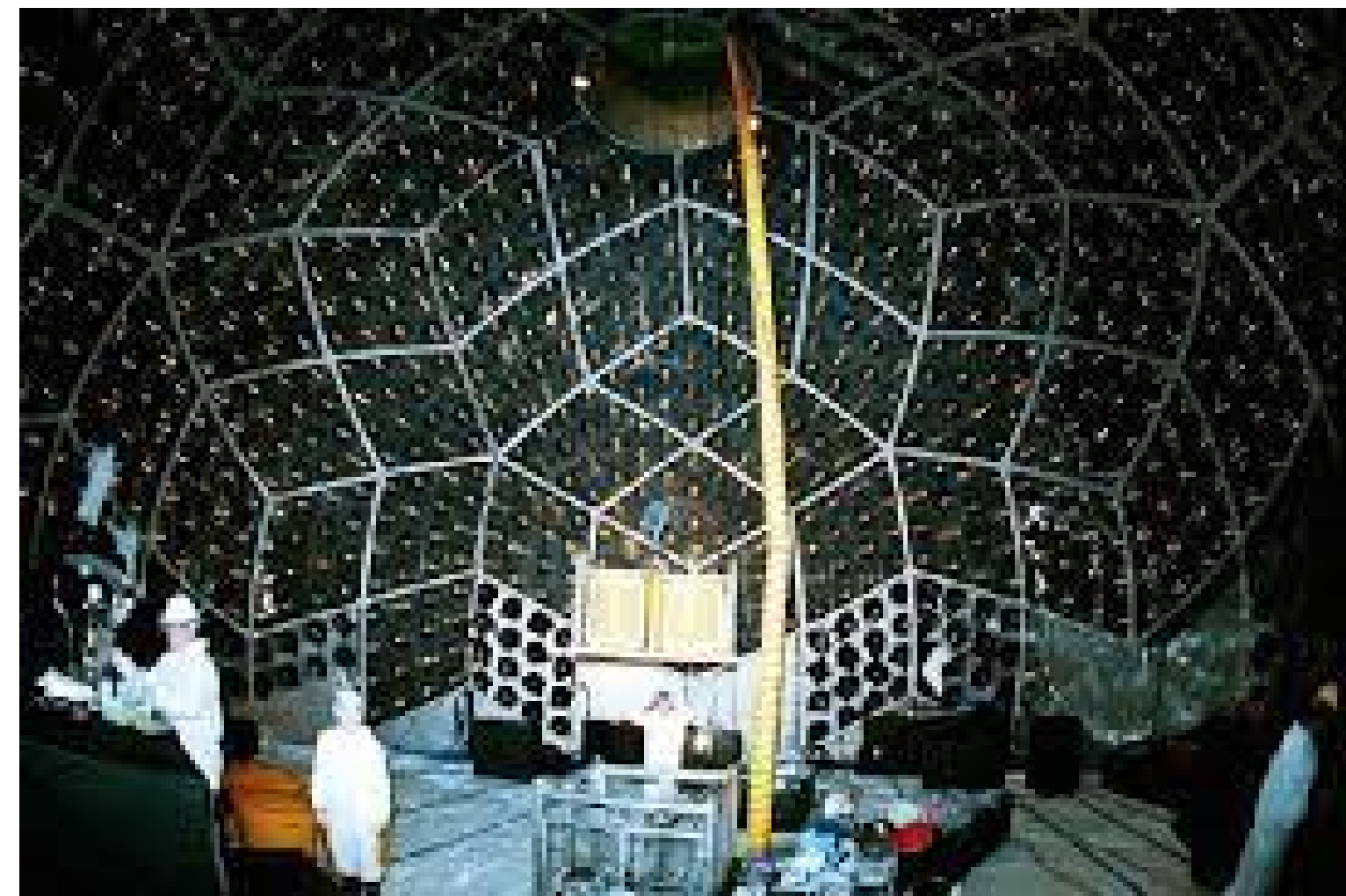
It just so happens (also a coincidence) that the difference between the low energy (vacuum) and high energy (dense medium) probabilities is closely related to the amount of mixing between the ν_1 and ν_2 states! ==> We get a measurement of the θ_{12} mixing angle.

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

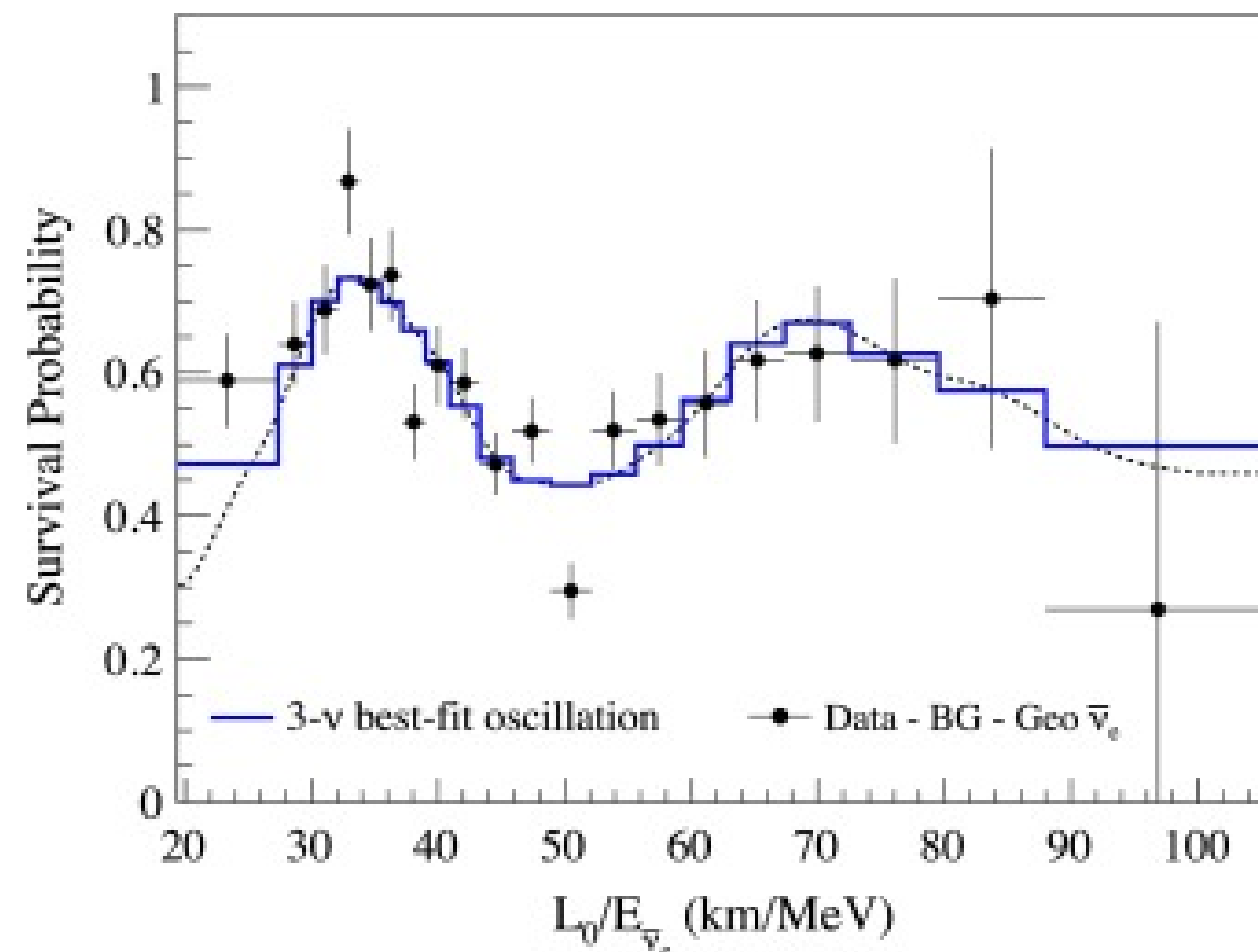


The benefit is that we can choose the distances, fluxes and energies

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



T2K experiment (also in Japan)



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

Neutrinos oscillate!!

$$\mathbf{v}_e, \mathbf{v}_\mu, \mathbf{v}_\tau = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} |\nu_i\rangle$$

Measured by atmospheric experiments

Measured by reactor and accelerator experiments

Measured by solar experiments

Δm^2_{21} $\longrightarrow$ Measured by solar experiments. Turns out to be very small

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

What are the values of the parameters?

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

δ_{CP} appears to be maximal $\Rightarrow$ nearly as much CP violation as possible!

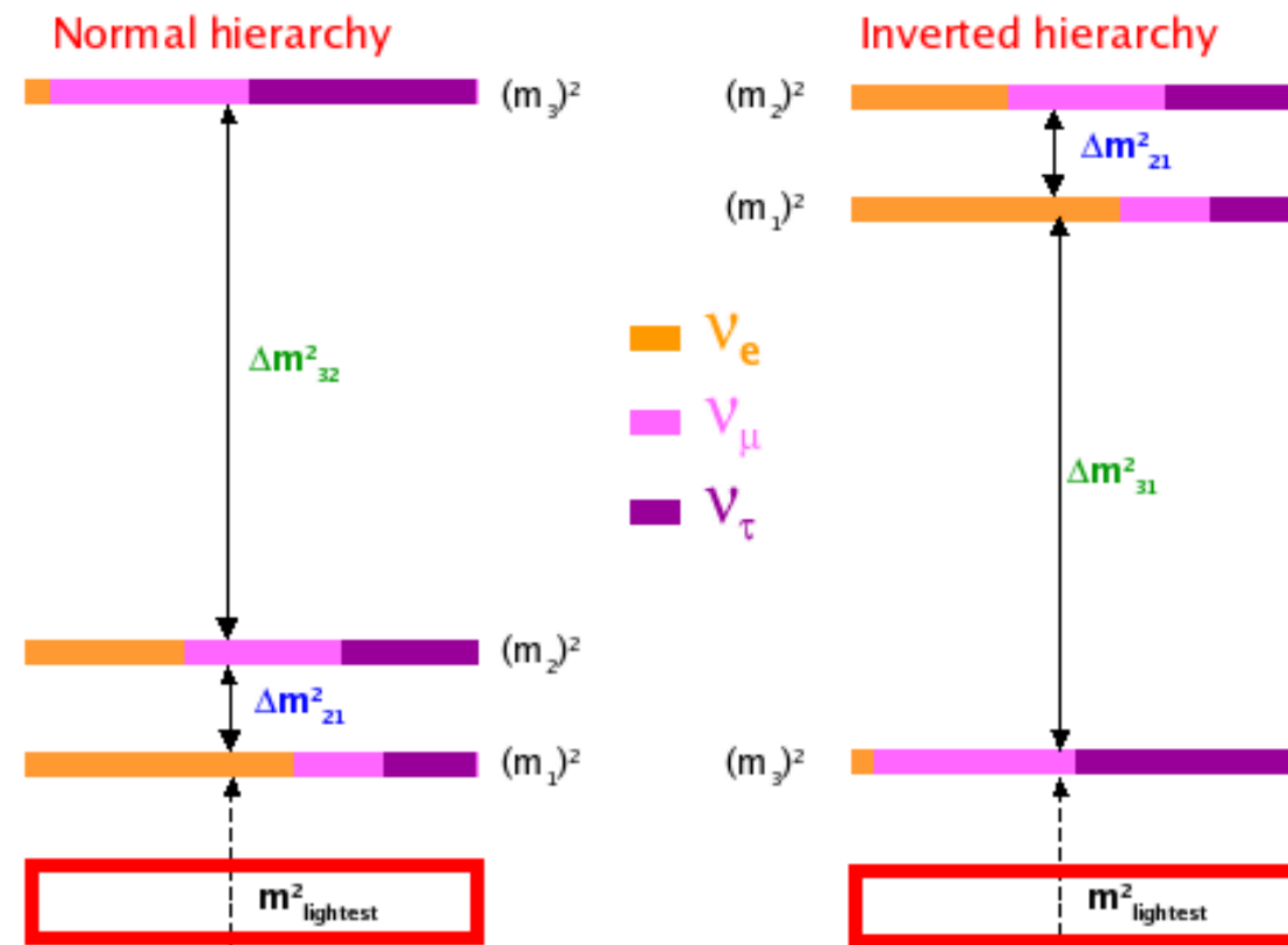
θ_{23} is approximately $45^\circ \Rightarrow \nu_\mu$ and ν_τ are equidistant to the mass states

θ_{13} is very small $\Rightarrow$ there is very little overlap between ν_e and ν_3

θ_{12} is approximately $30^\circ \Rightarrow \nu_1$ is closer to ν_e than ν_2

Δm^2_{21} $\longrightarrow$

Δm^2_{32} $\longrightarrow$



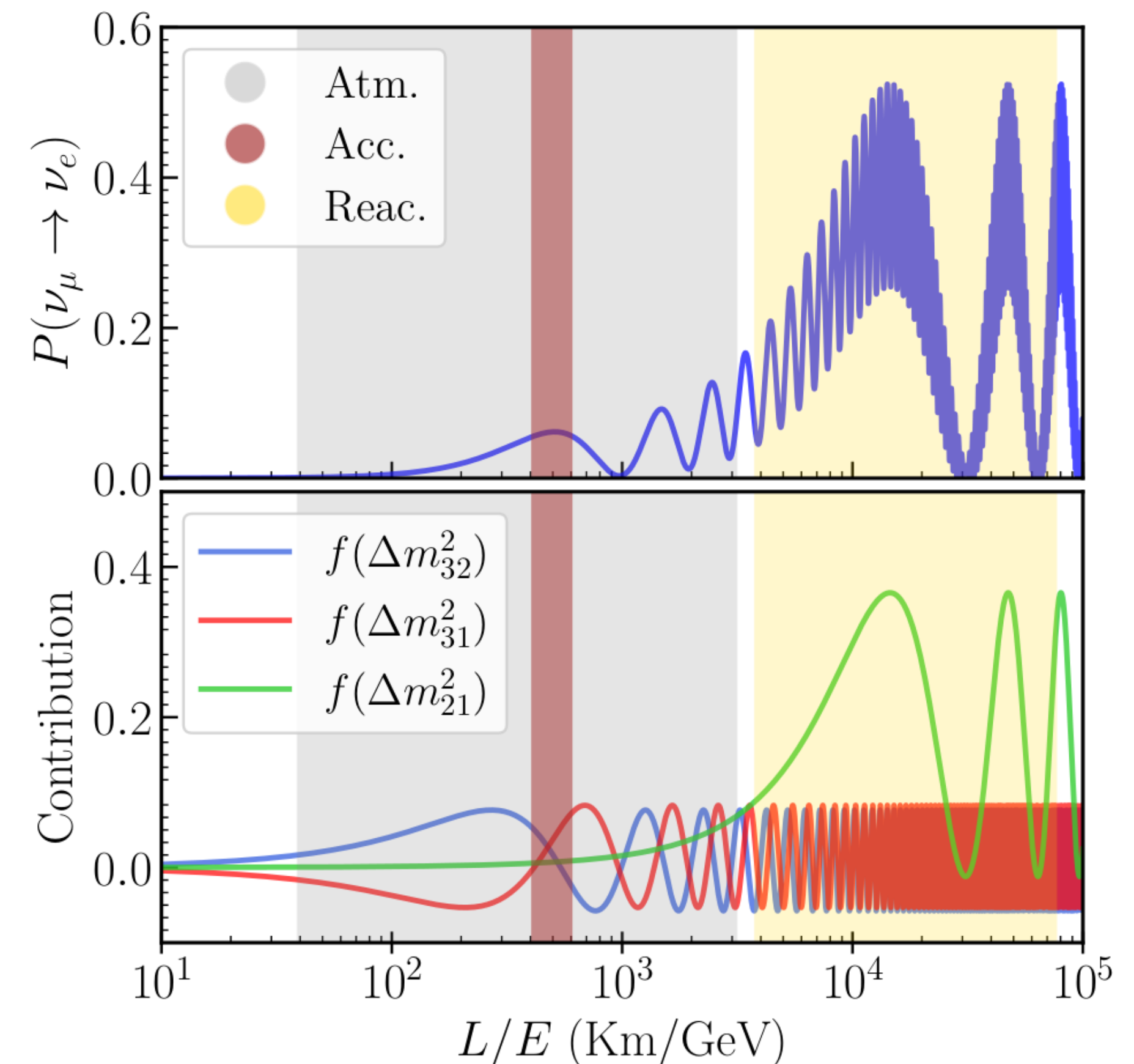
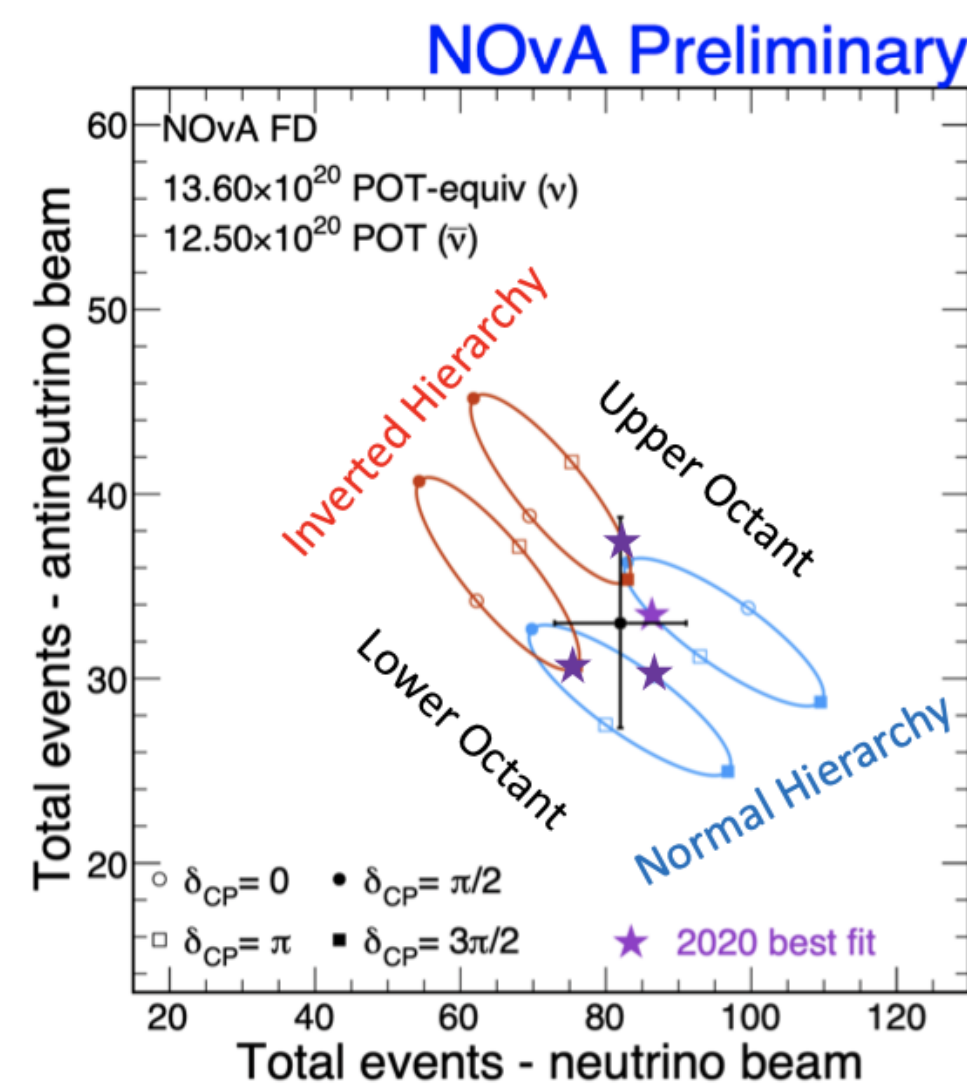
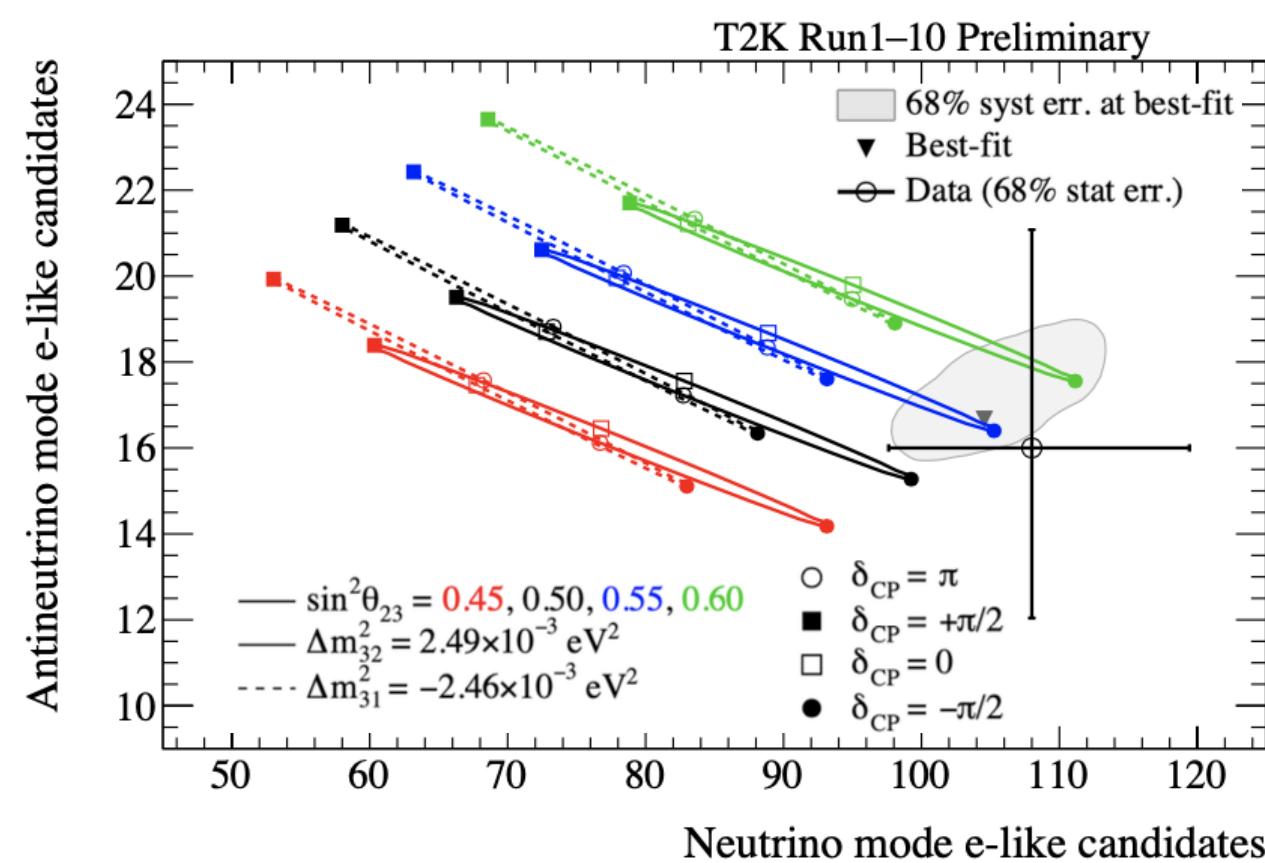
Hierarchy problem:

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

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

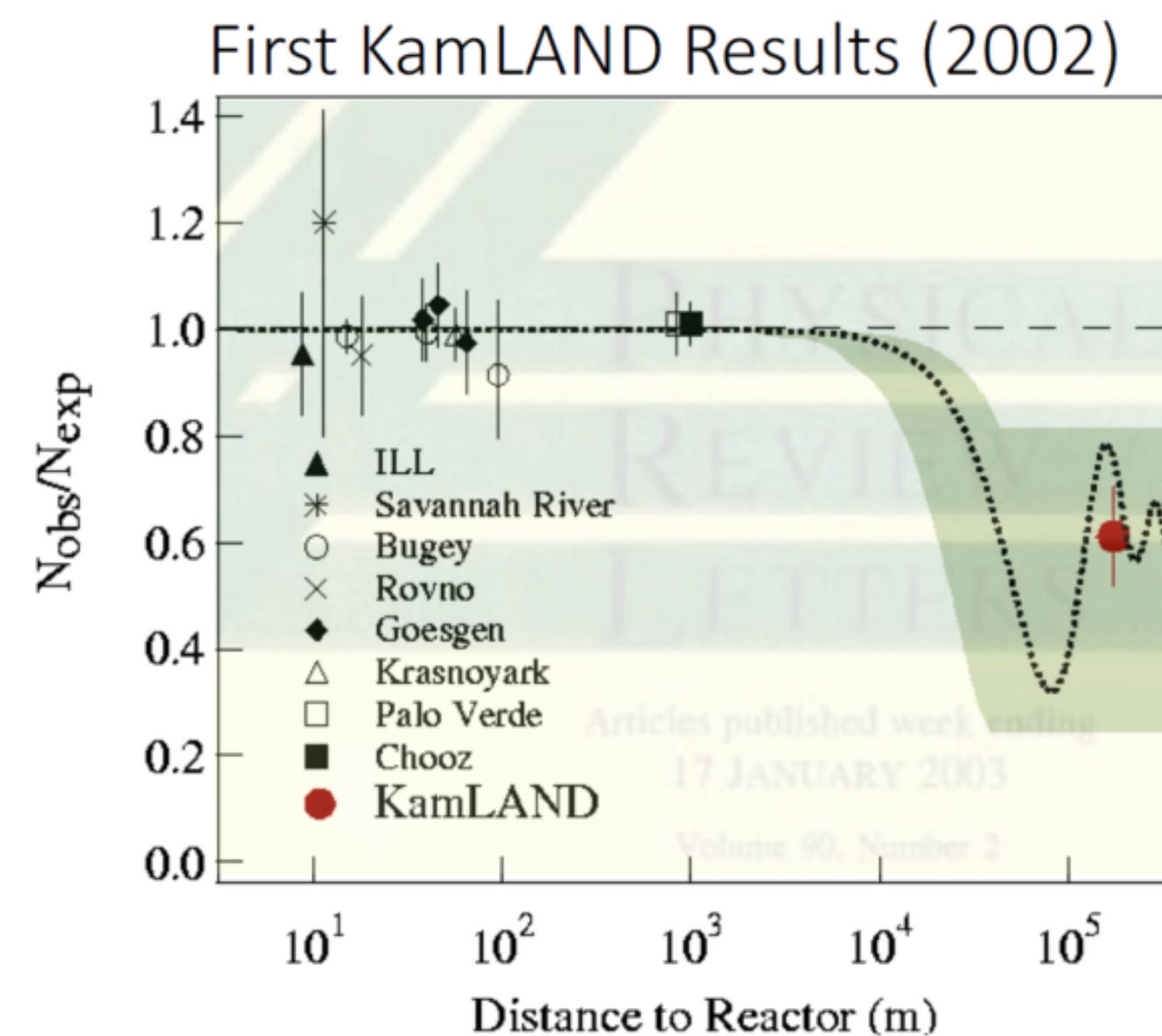
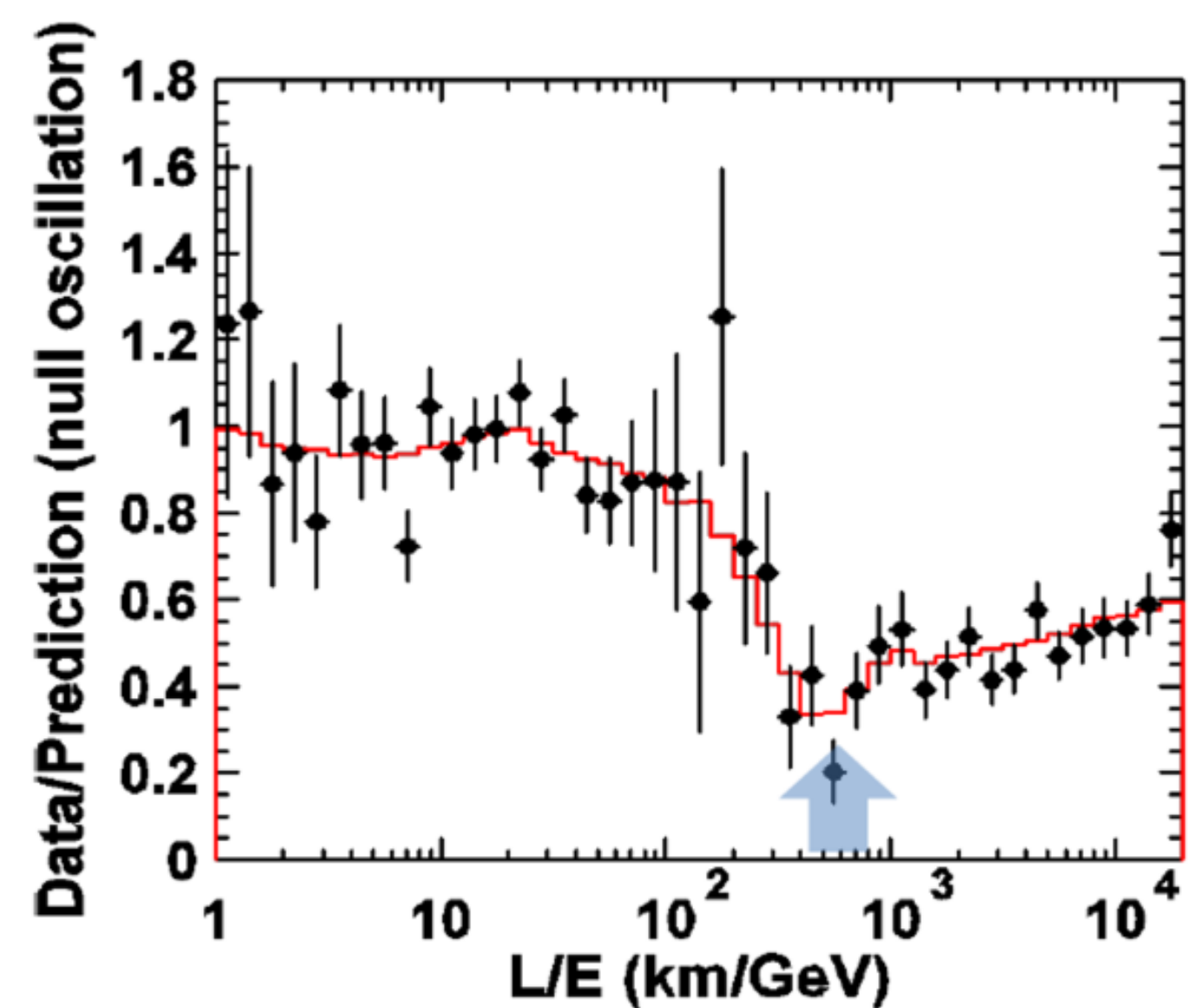
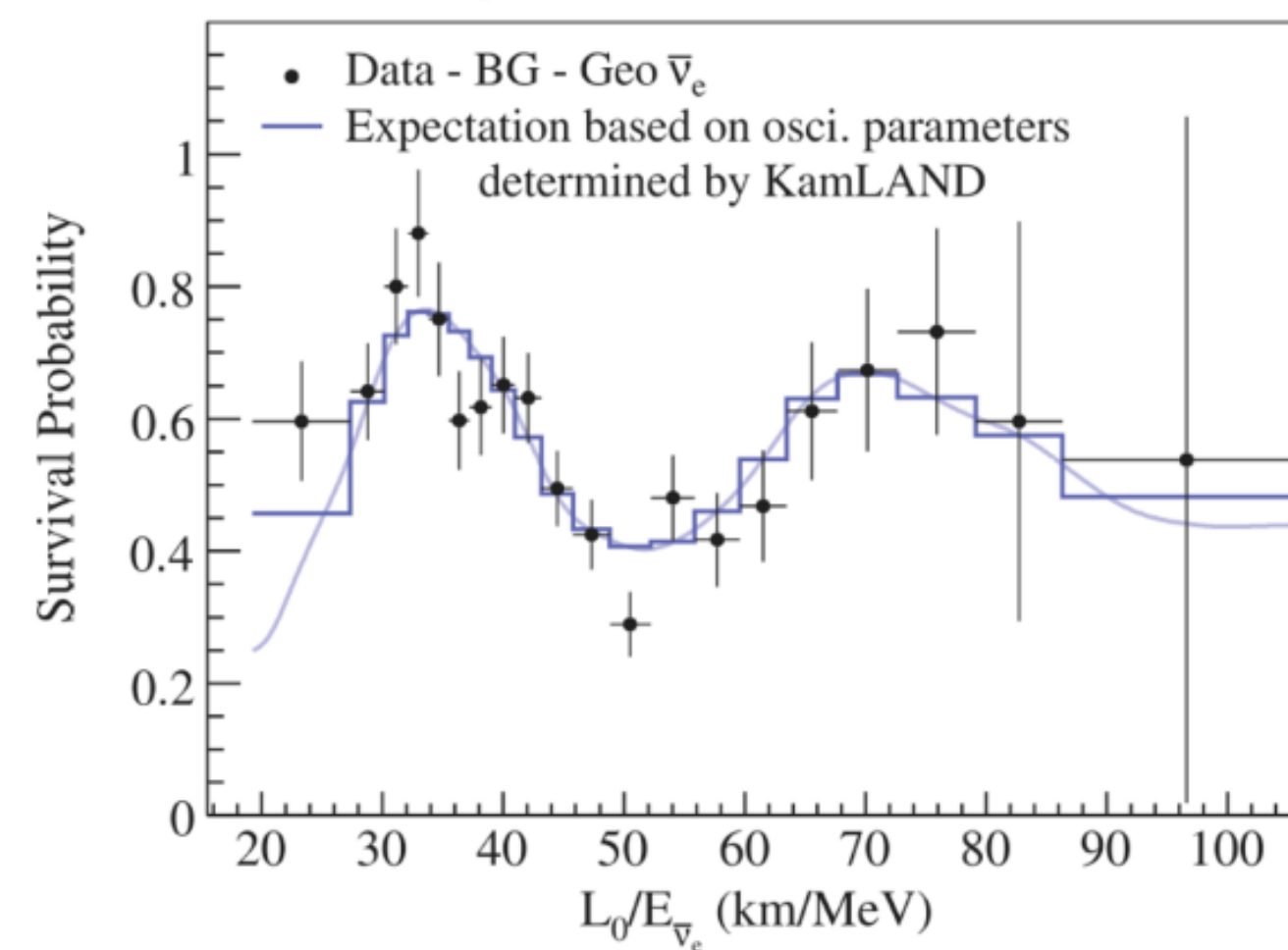
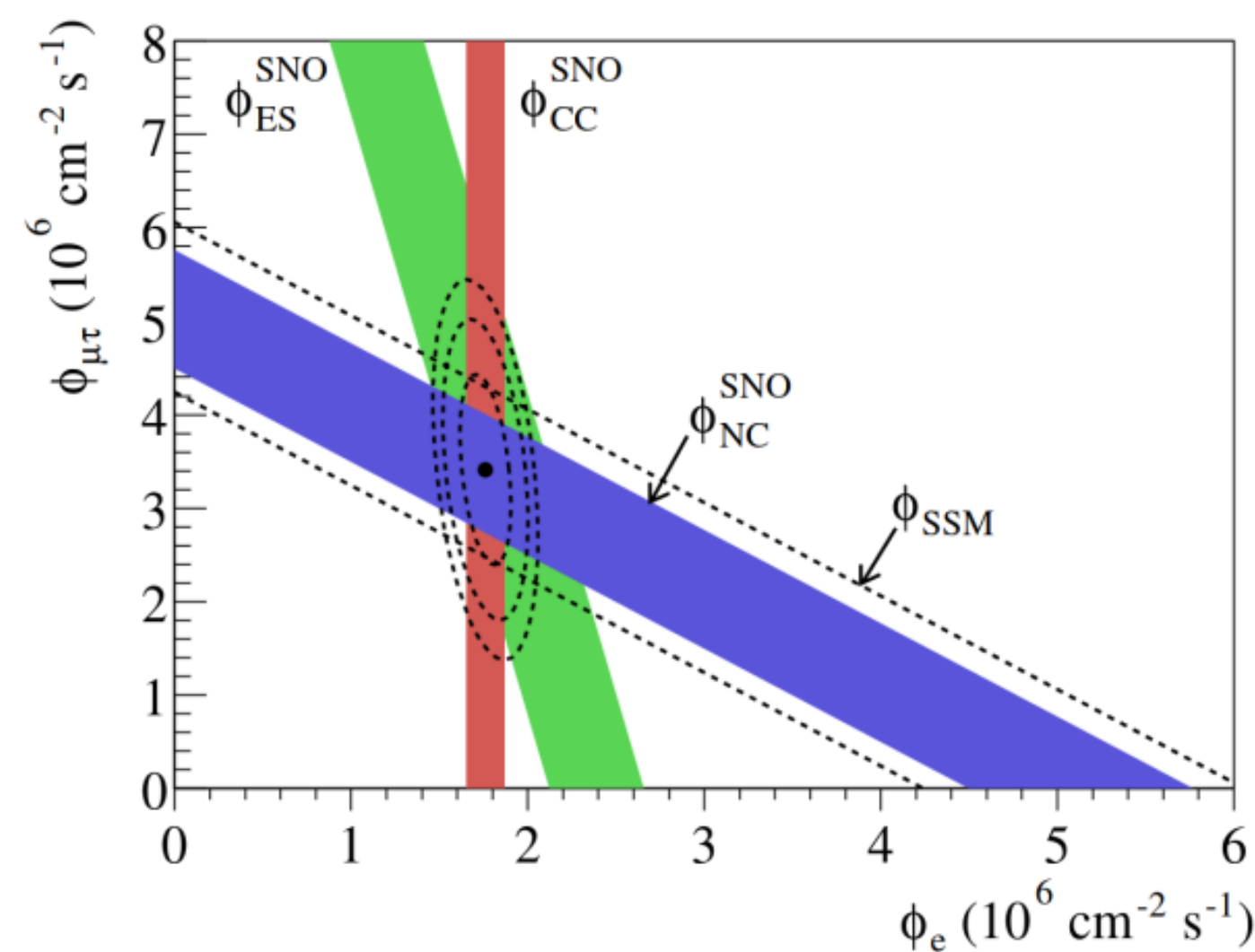
The “hierarchy” in the values of the angles and mass splittings, give a complicated oscillation signal ==> we need many different experimental setups to fully explore it



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?

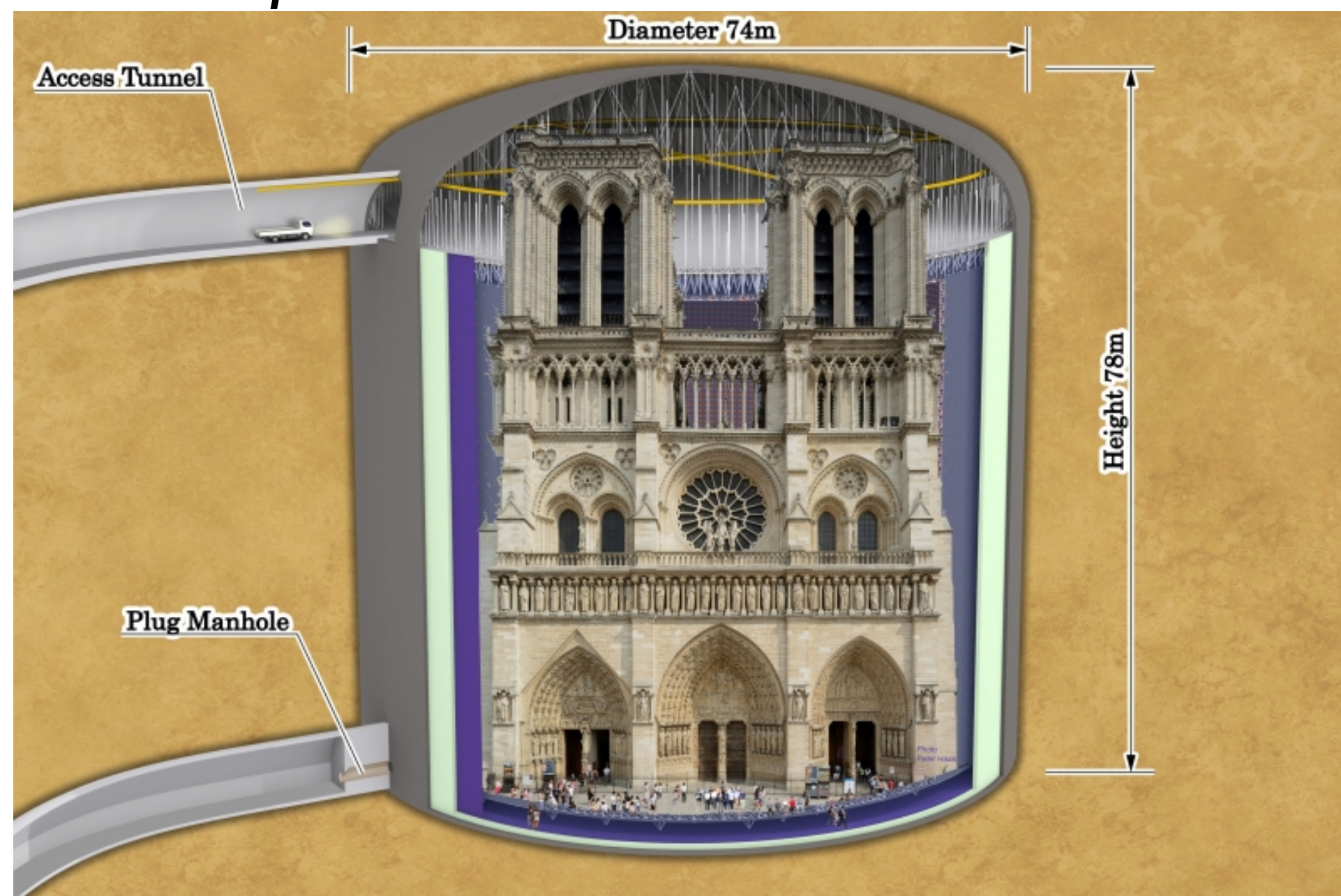
- We know that neutrinos oscillate and are therefore massive particles



What do we look for in neutrino physics?

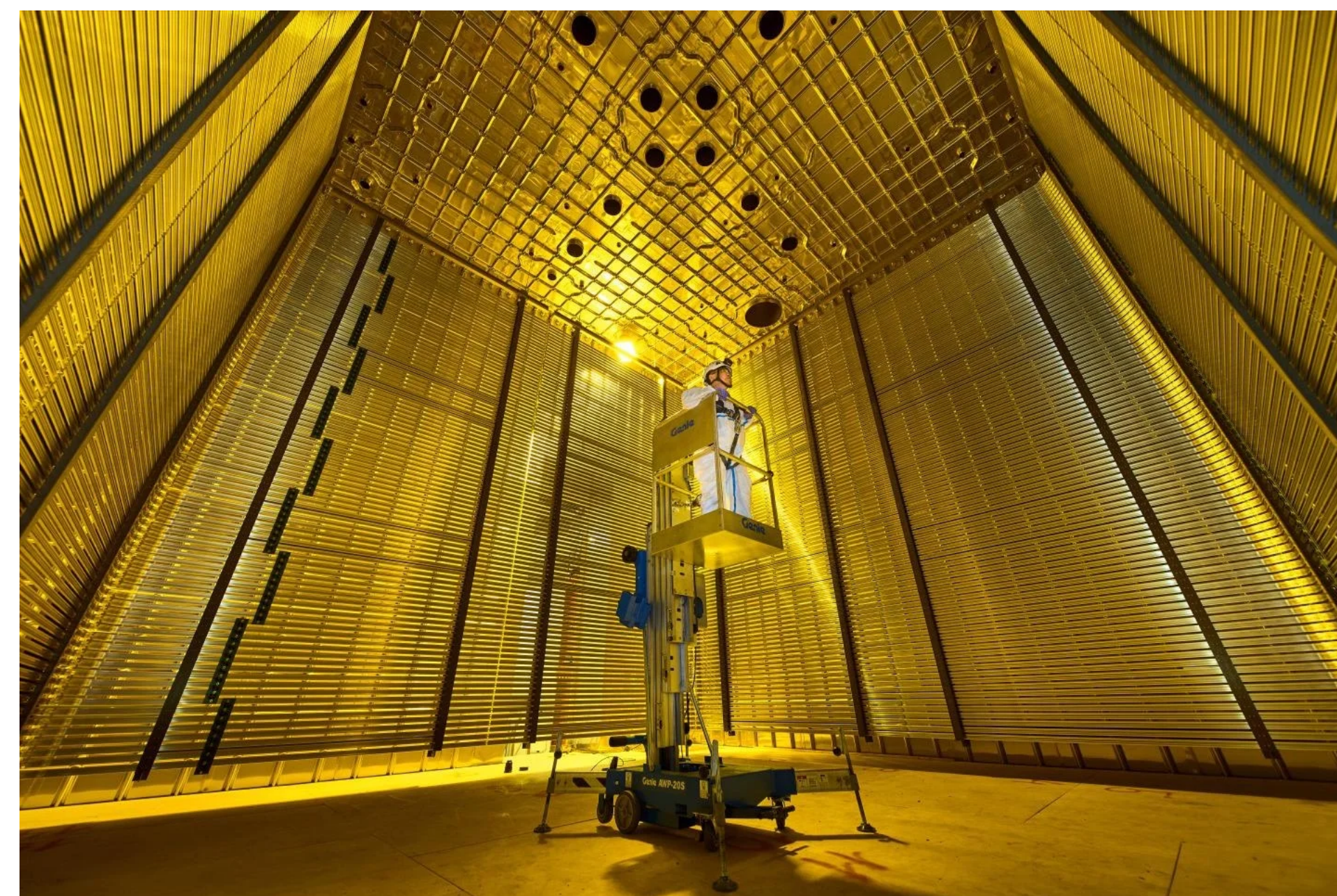
- Is there enough CP violation to explain the asymmetry between matter and antimatter in the visible universe? ➡ Many upcoming experiments aim to answer this question

T2HK in Japan



Notre-Dame will fit inside Hyper-Kamiokande !

DUNE in the US

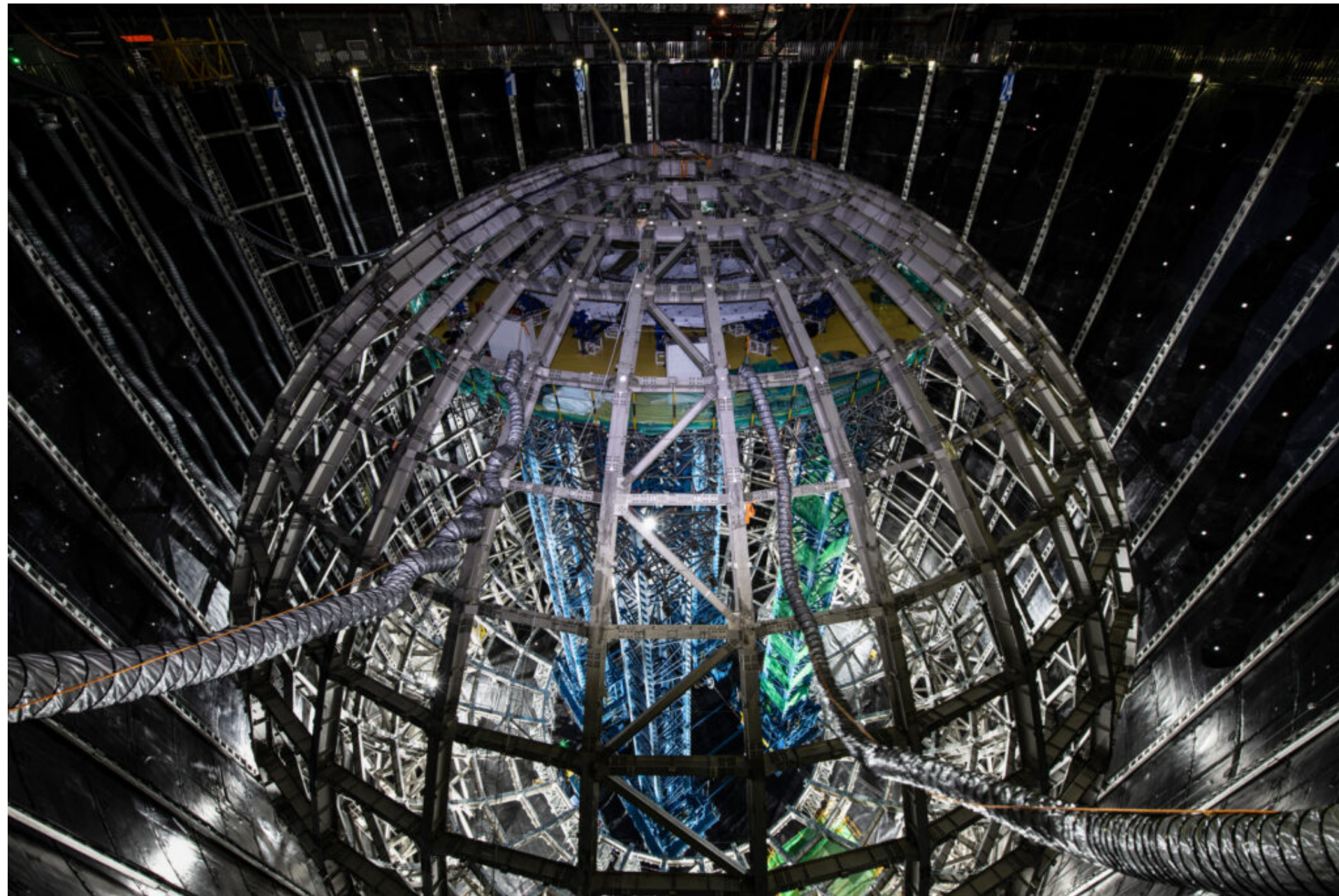


Inside DUNE prototype ($6 \times 6 \times 6 \text{ m}^3$) at CERN
 -> Future : 4 modules of $60 \times 12 \times 12 \text{ m}^3$ each

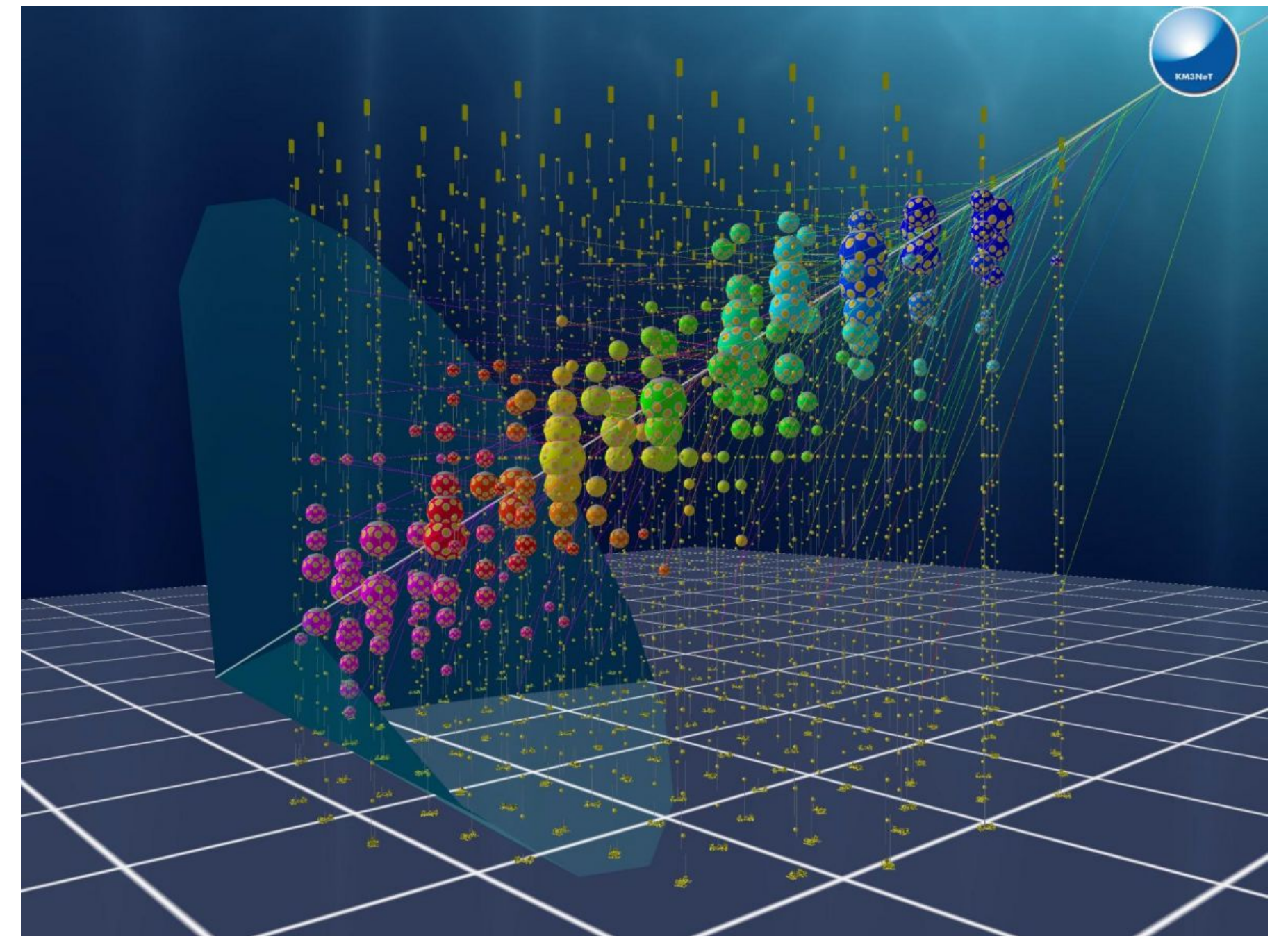
What do we look for in neutrino physics?

- Which mass hierarchy is the correct one?

Juno in China



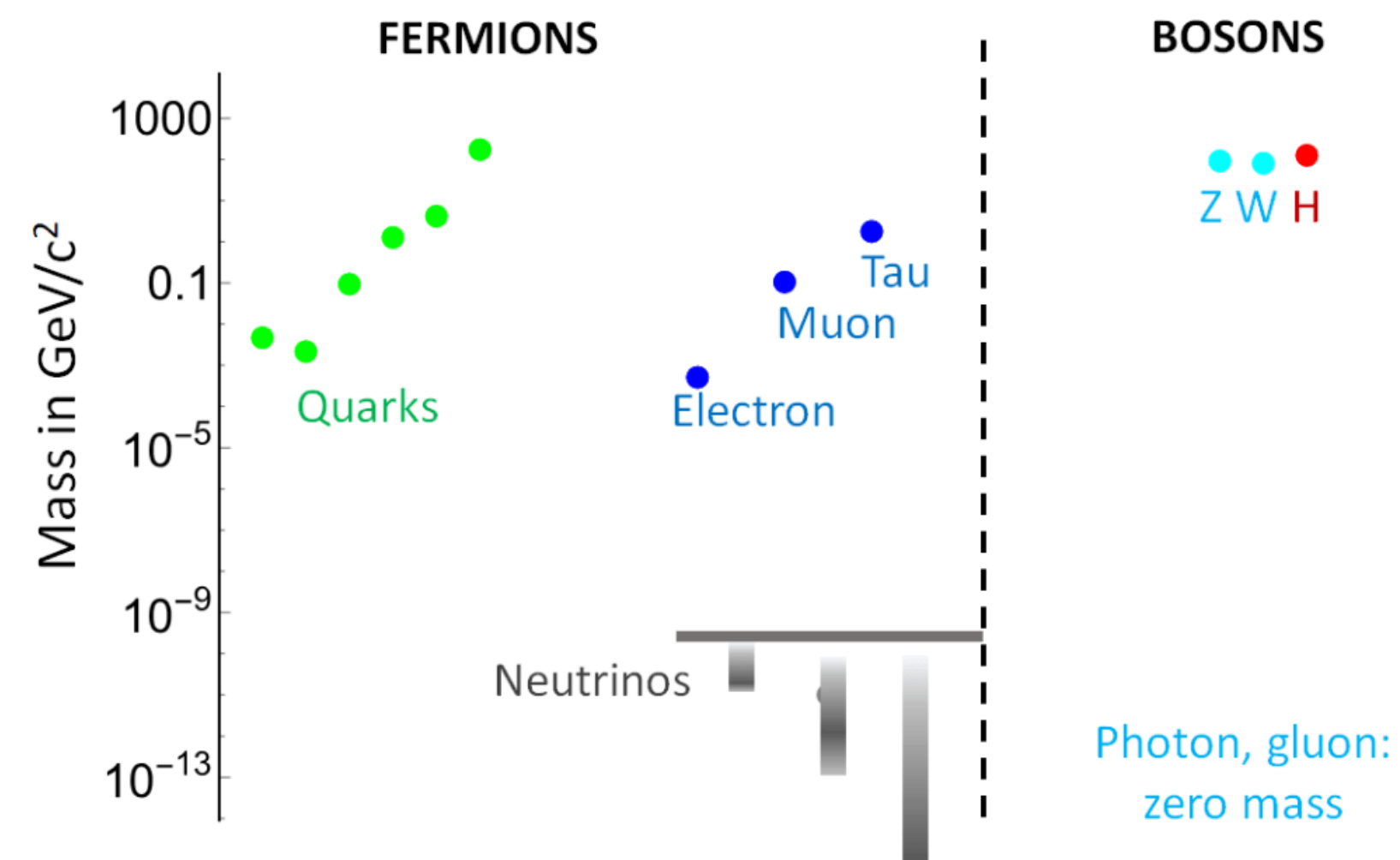
KM3Net in the Mediterranean



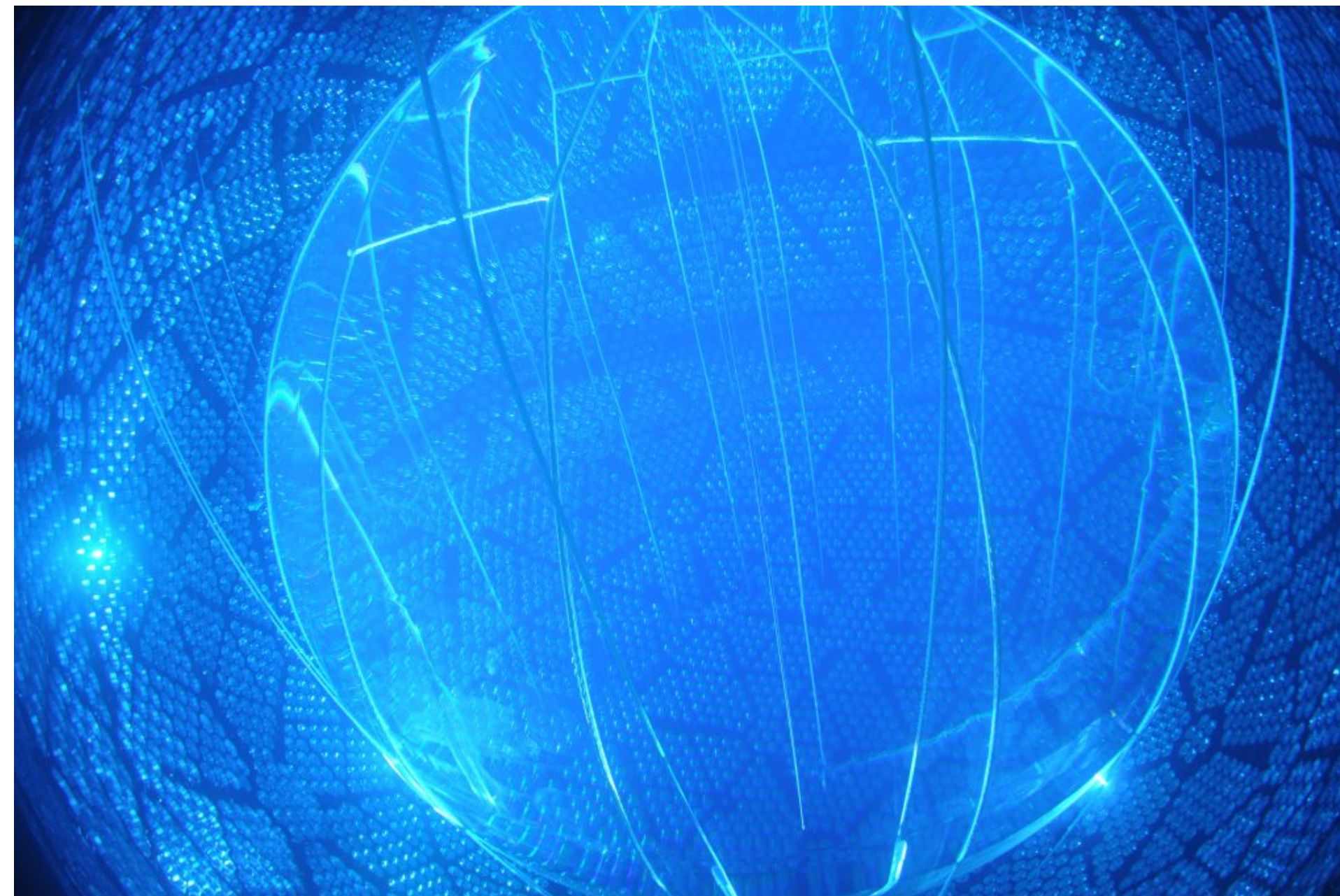
- θ_{23} appears to be close to 45° . This is unexpected for a random matrix. Are we looking at the broken remains of some high-energy symmetry?

What do we look for in neutrino physics?

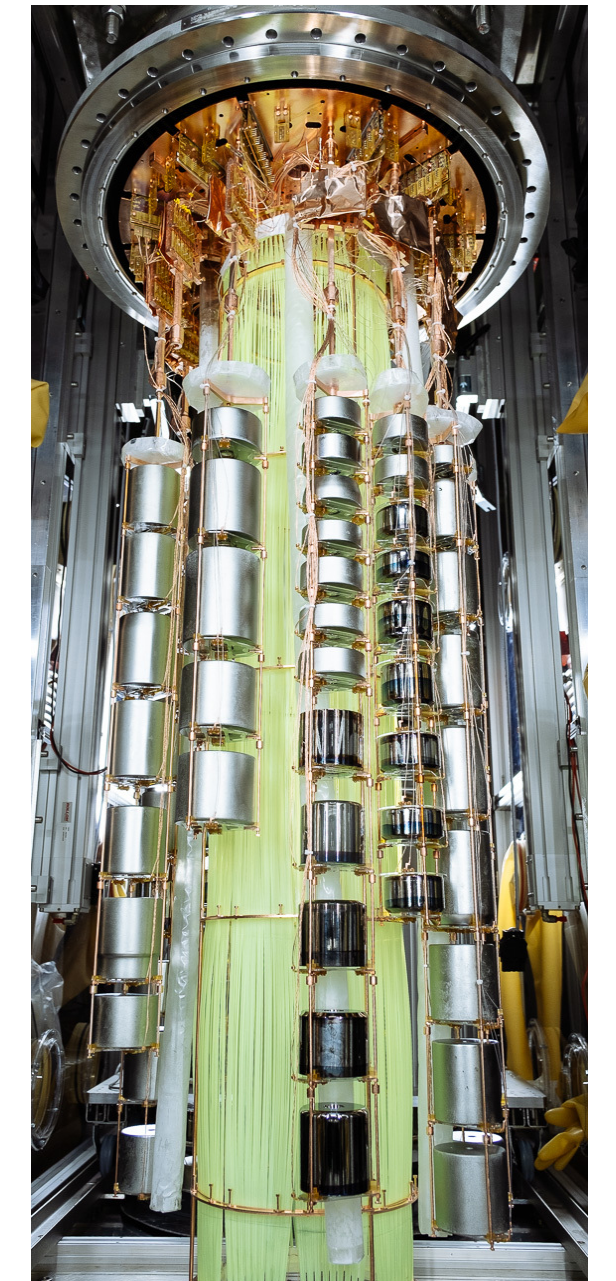
- Do neutrinos acquire mass through the usual Higgs mechanism? Their couplings would have to be unreasonably small!



SNO+ in Canada



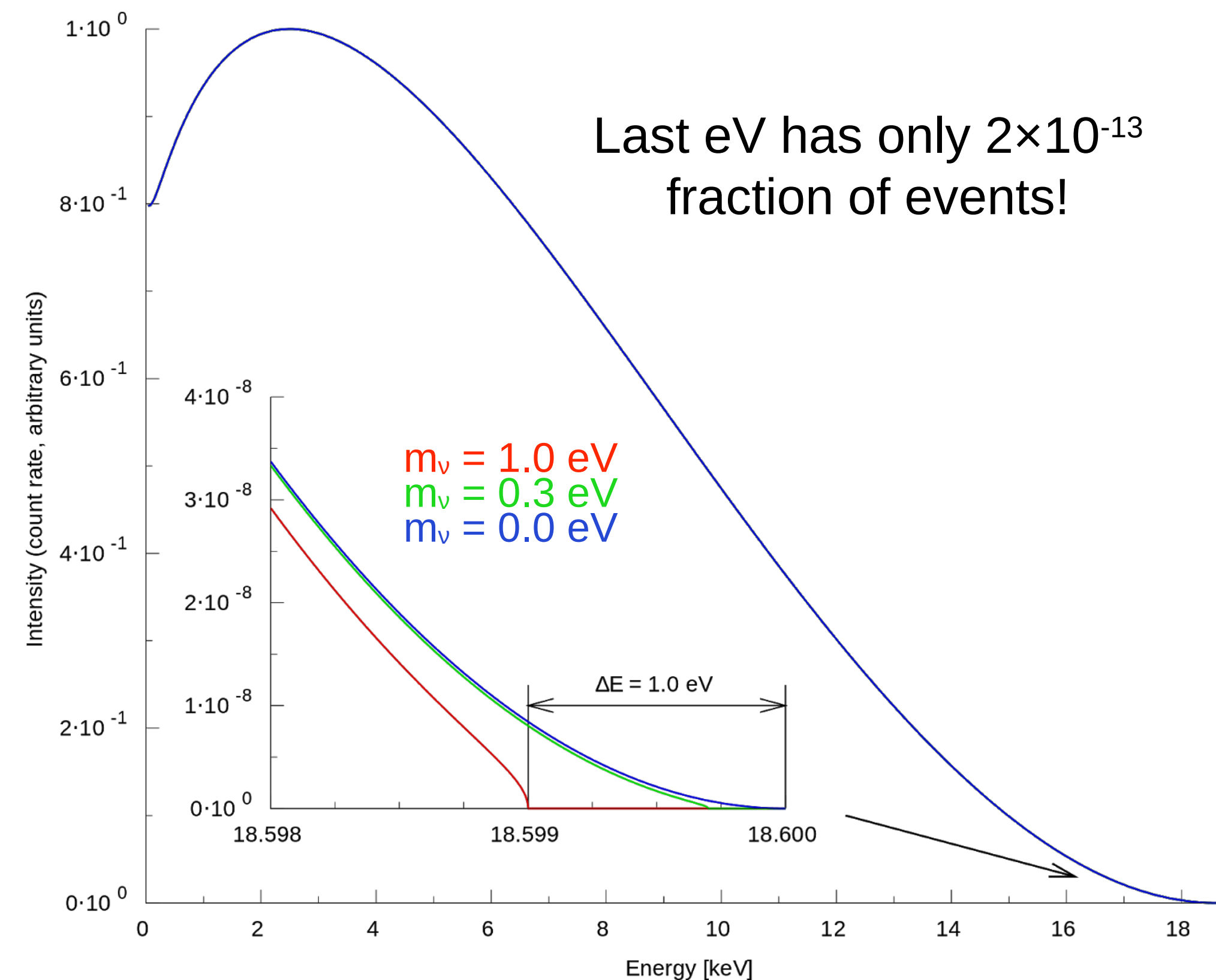
Legend200 in Italy



- 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?

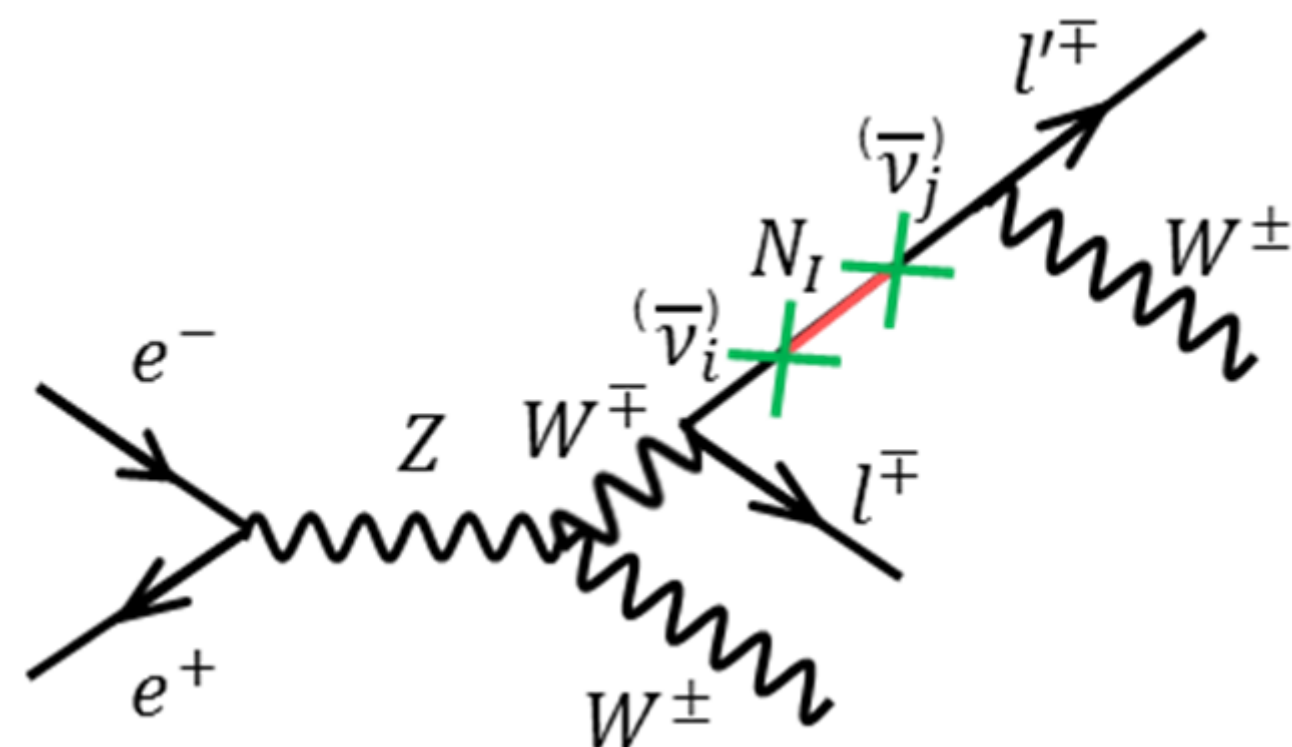
- What is the mass scale of the neutrinos (we know the mass differences, but not the actual mass values!)



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

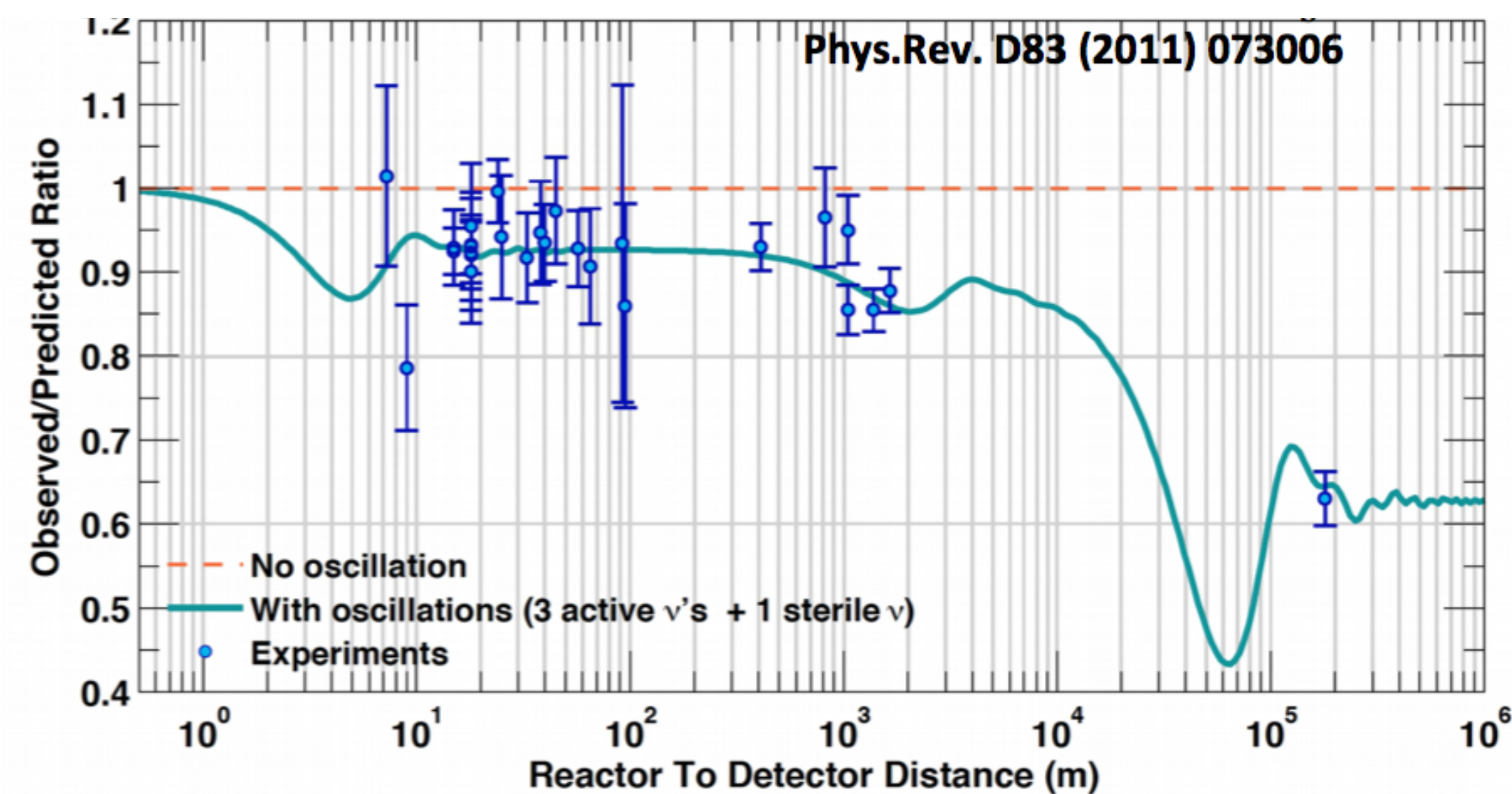
What do we look for in neutrino physics?

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



Could they be dark matter candidates?

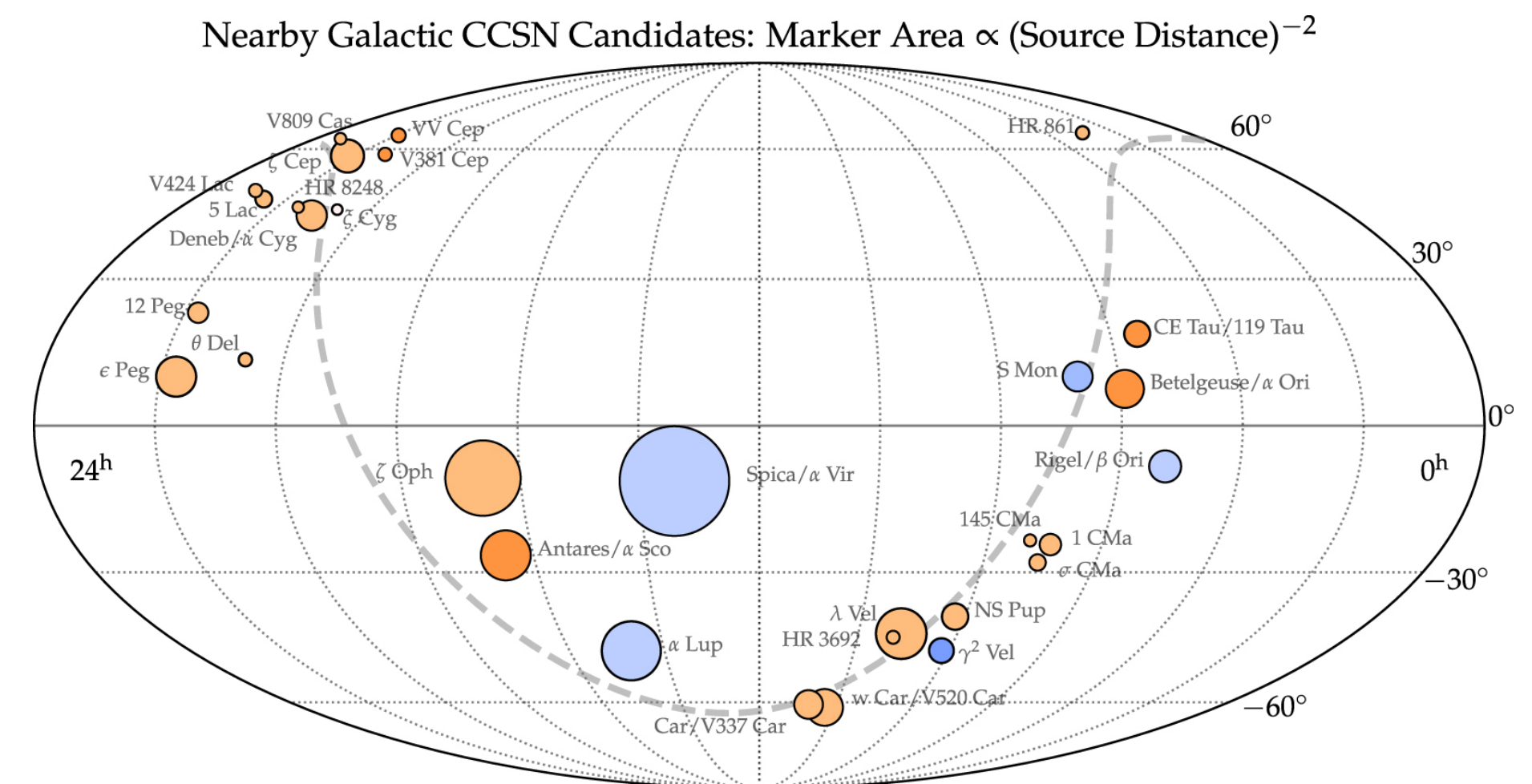
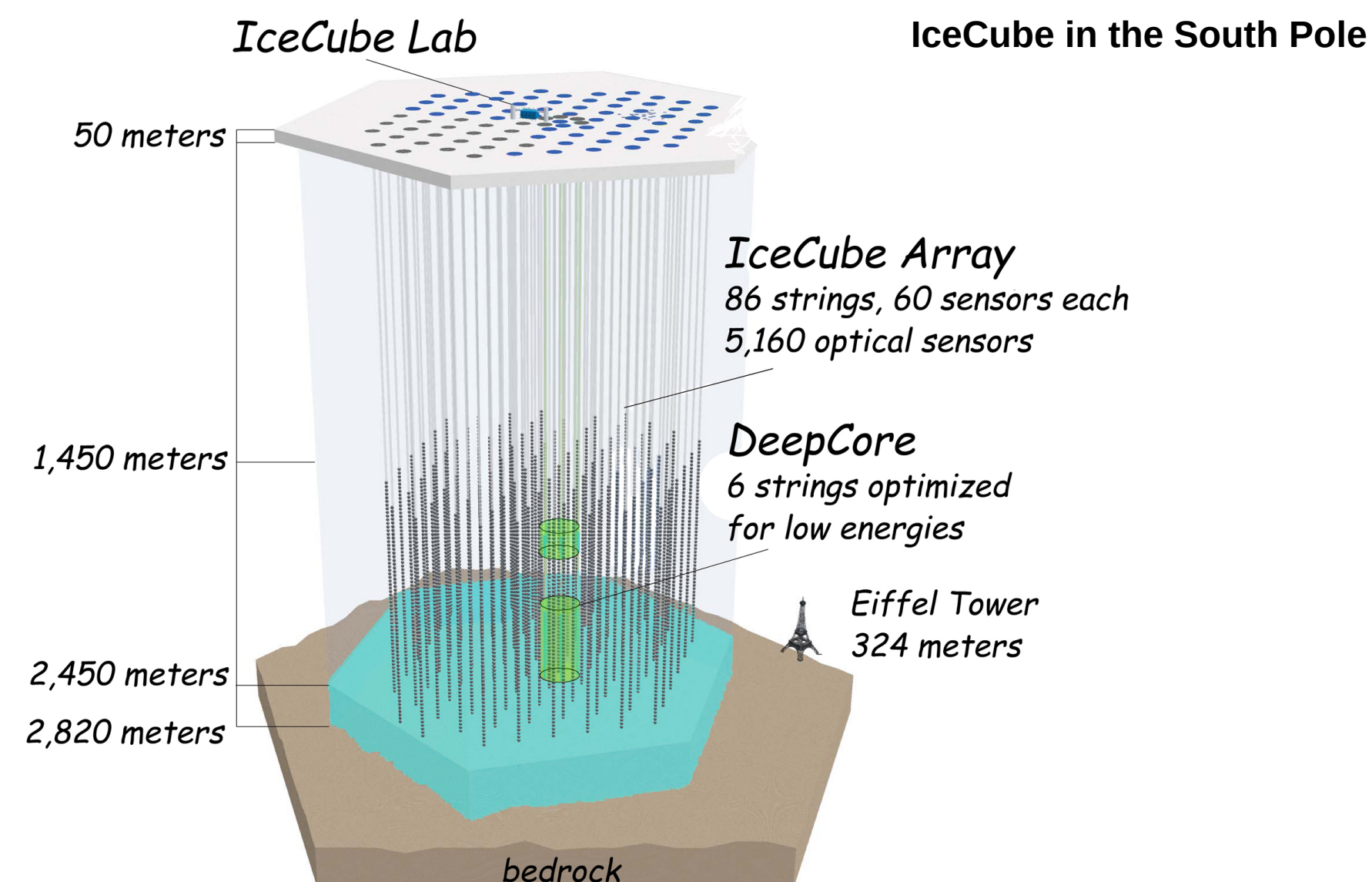
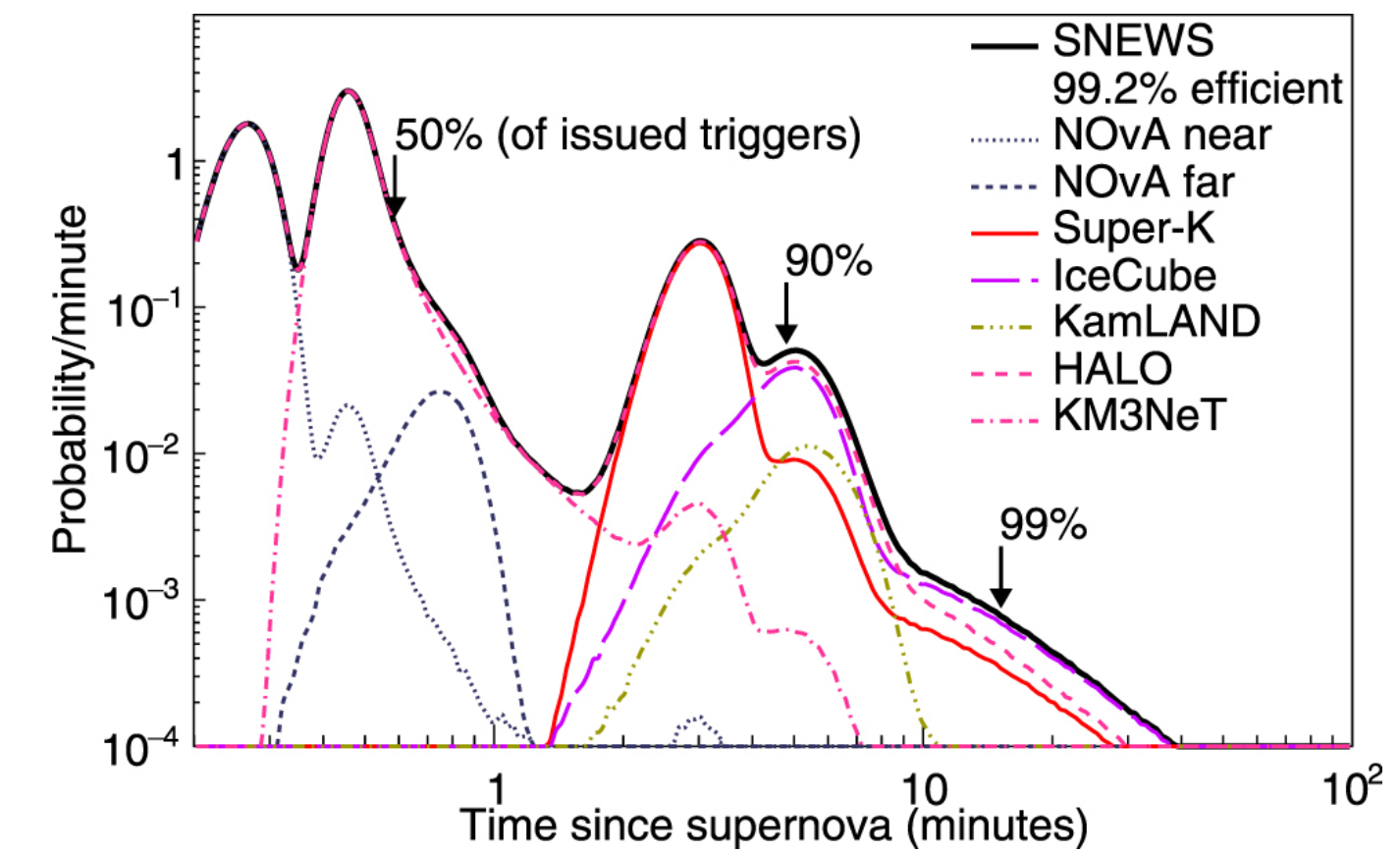
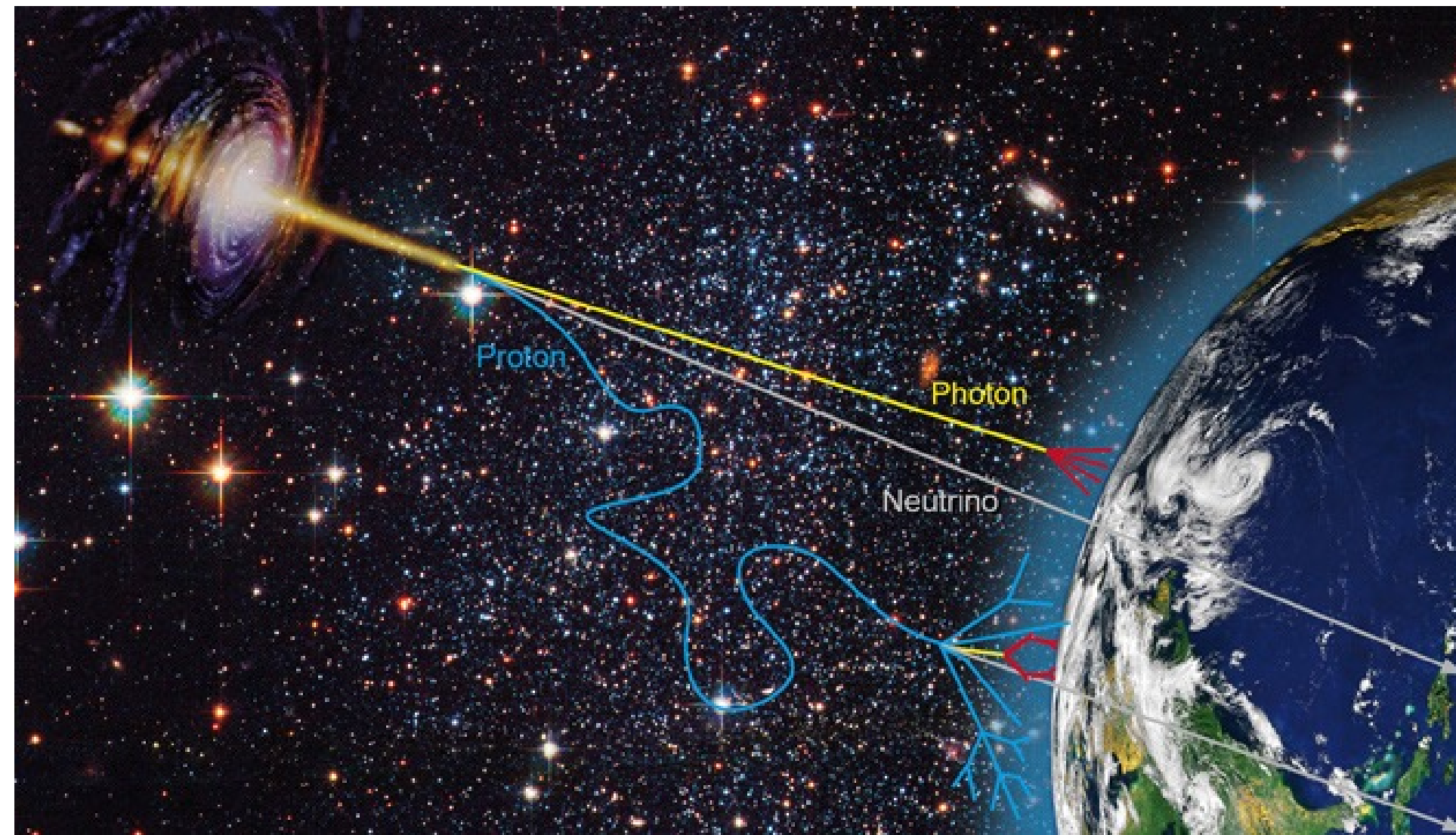
Some experimental discrepancies with the 3-flavour oscillation model can be explained by introducing a 4th oscillating neutrino state



- 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?



- Neutrinos allow for supernova model discrimination!

- 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 extraterrestrial 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

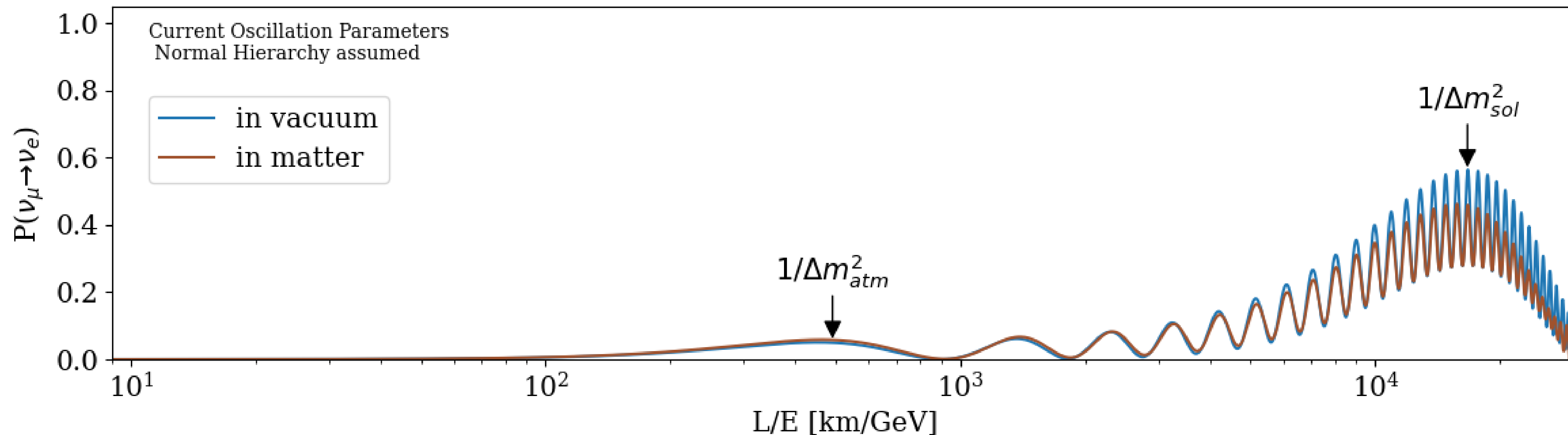


The end™

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:

$$\theta_{12} = 33.45^{+0.77}_{-0.75}$$

$$\theta_{23} = 42.1^{+1.1}_{-0.9}$$

$$\theta_{13} = 8.62^{+0.12}_{-0.12}$$

$$\Delta m_{\text{sol}}^2 = \Delta m_{12}^2 = 7.42^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{\text{atm}}^2| = |\Delta m_{3\ell}^2| = 2.510^{+0.027}_{-0.027} \times 10^{-3} \text{ eV}^2$$

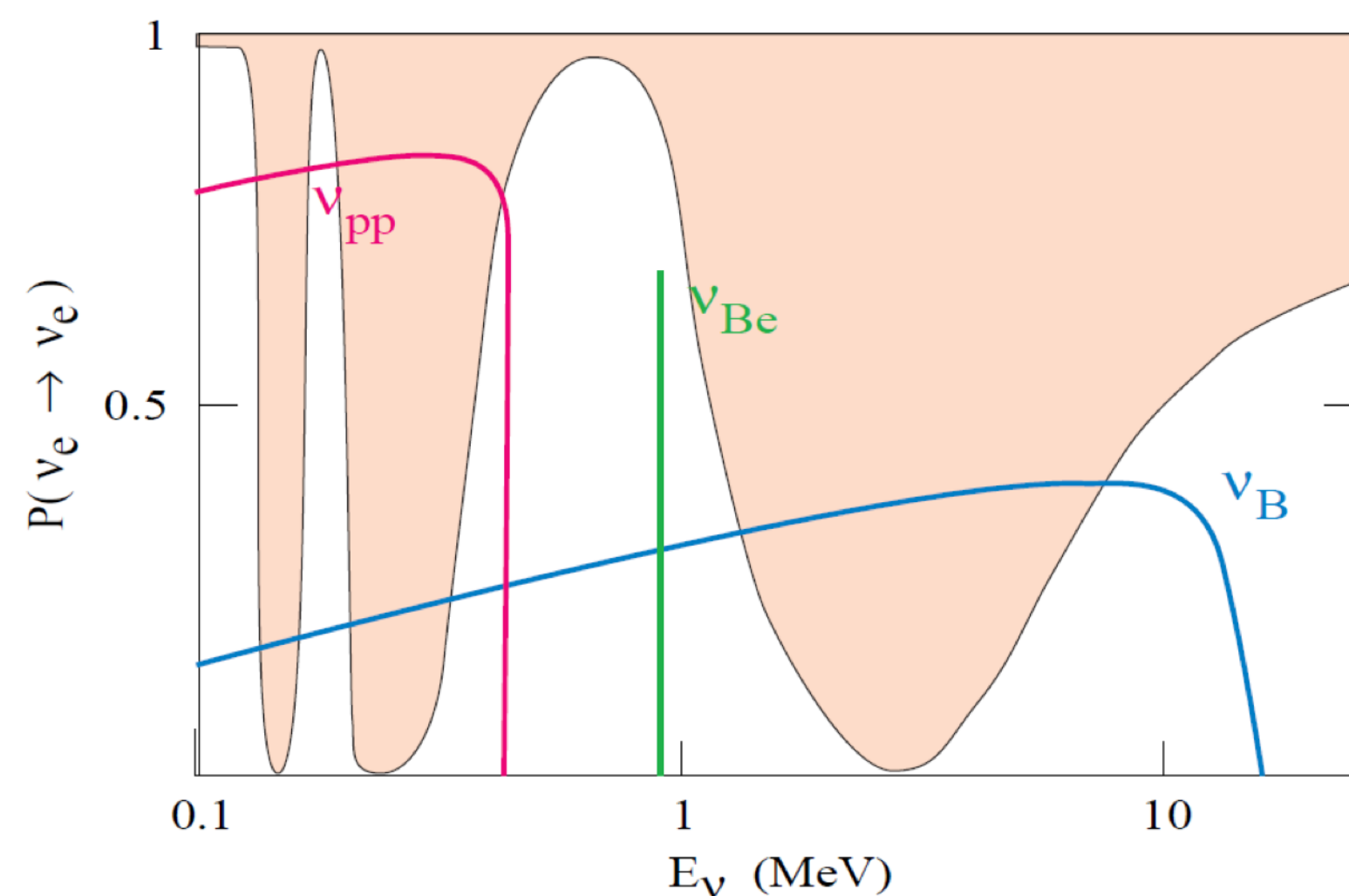
○ Oscillations in vacuum are not sensitive to the sign of Δm^2

○ Matter effects helps to determine Δm^2 sign:

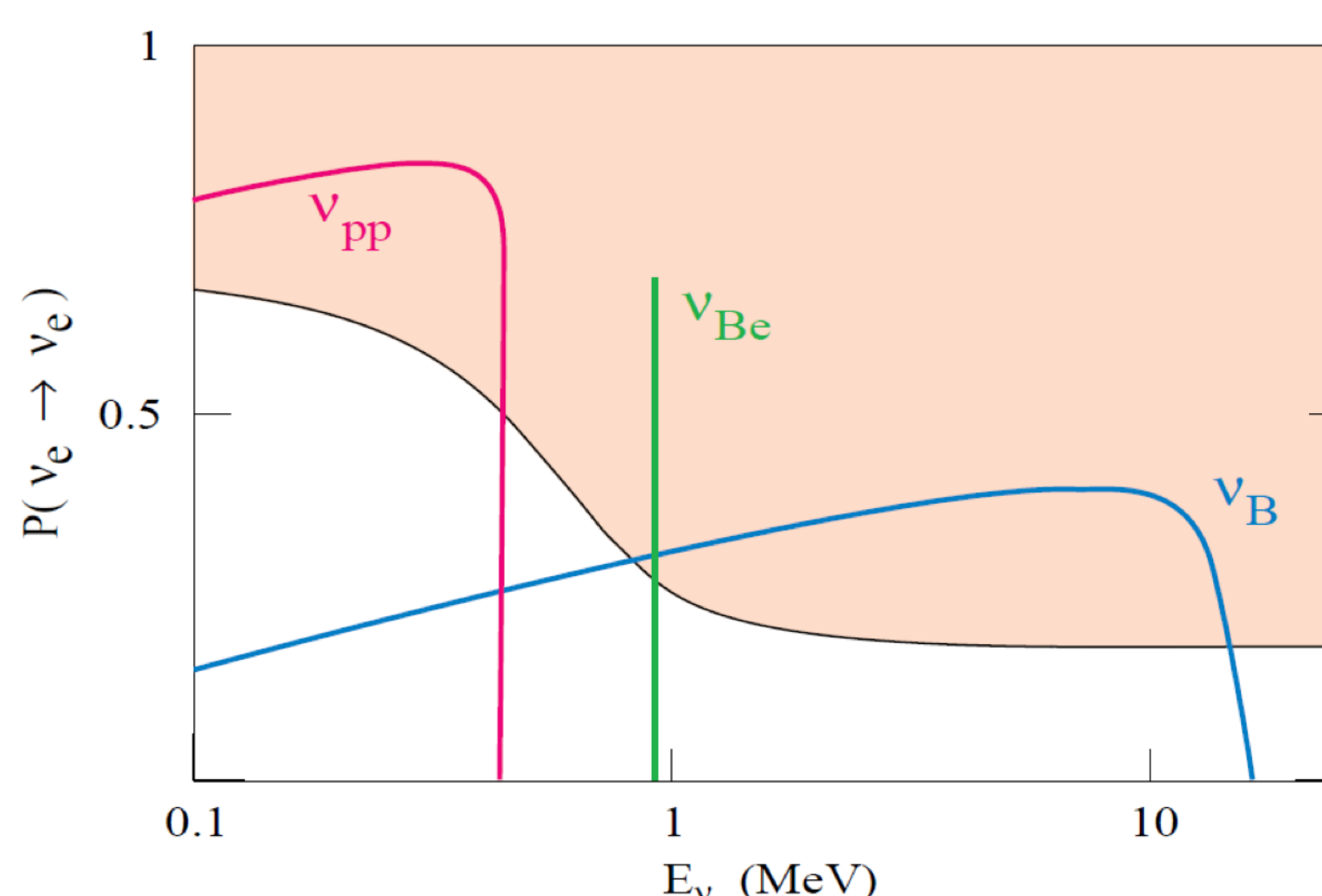
► $m_2 > m_1$ from solar ν_e

□ Not yet resolved for m_3

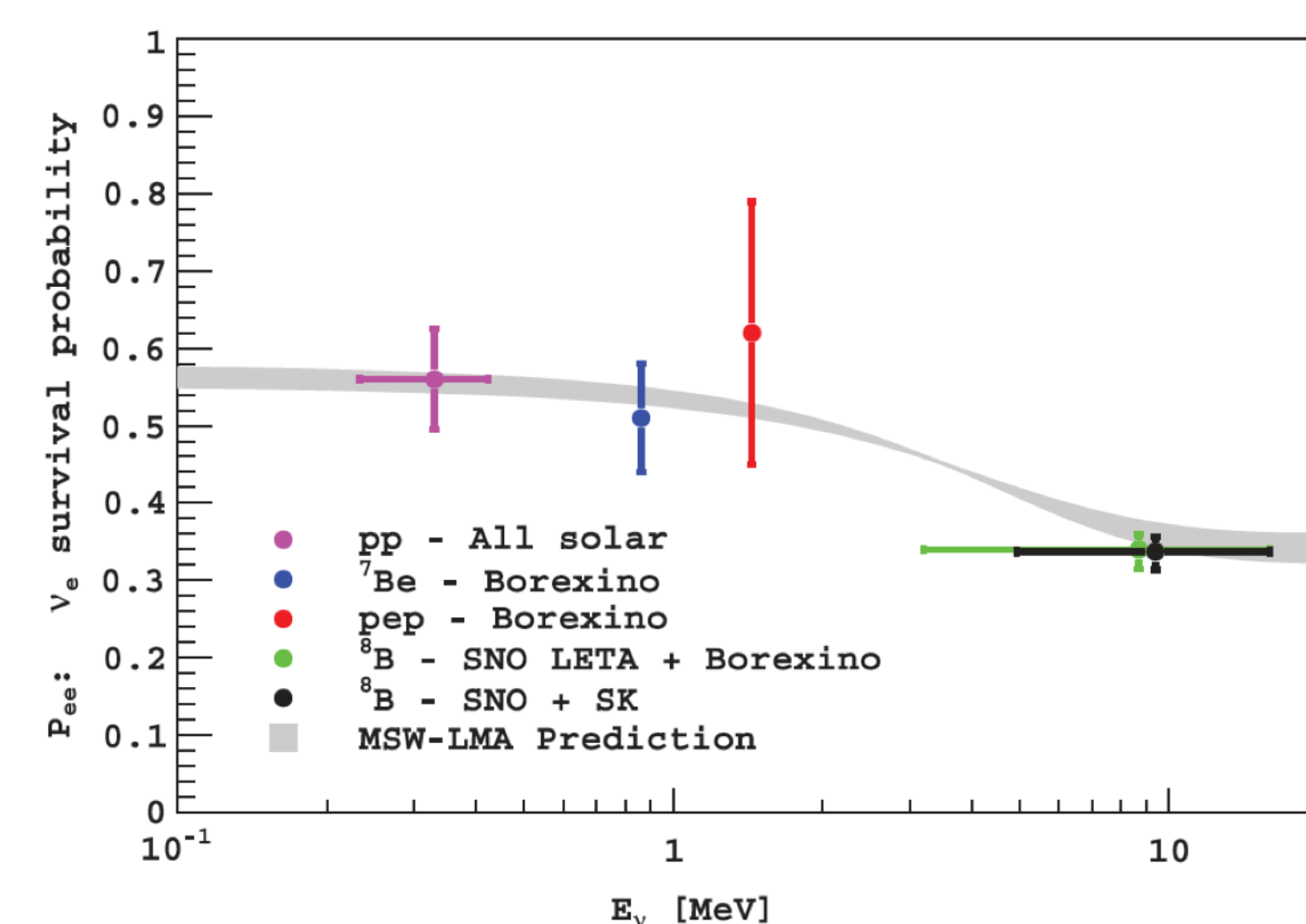
ν_e survival in vacuum



ν_e survival in matter

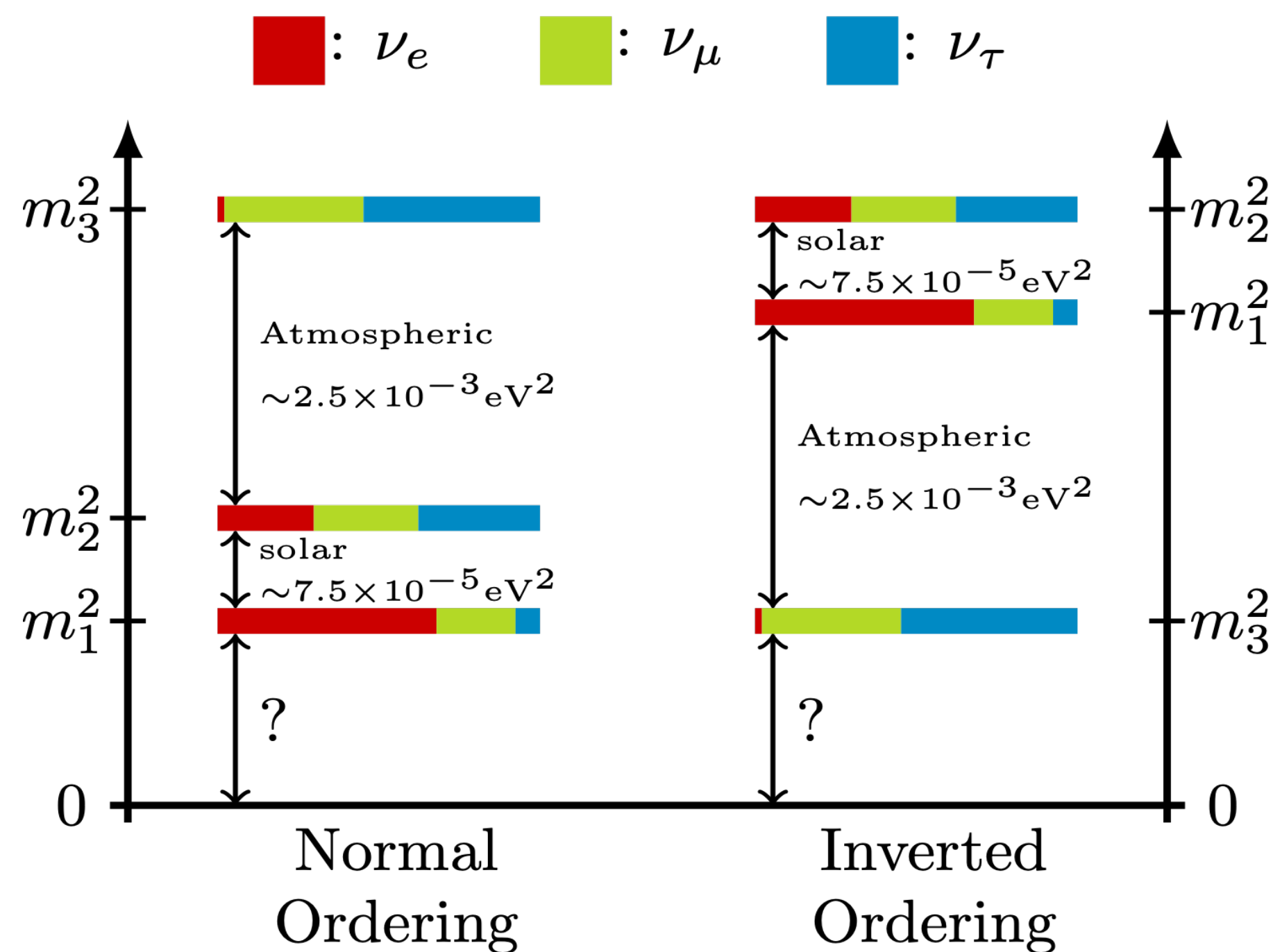


Solar ν_e flux measurement



Oscillations parameters

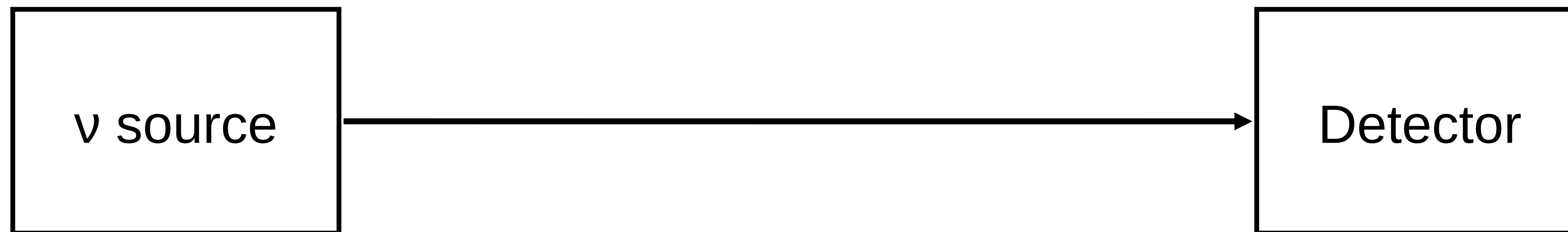
	Normal Ordering	Inverted Ordering
$\theta_{12} =$	$33.45^{+0.77}_{-0.75}$	$33.45^{+0.78}_{-0.75}$
$\theta_{23} =$	$42.1^{+1.1}_{-0.9}$	$49.0^{+0.9}_{-1.3}$
$\theta_{13} =$	$8.62^{+0.12}_{-0.12}$	$8.61^{+0.14}_{-0.12}$
$\Delta m^2_{\text{sol}} = \Delta m^2_{12} =$	$7.42^{+0.21}_{-0.20} \times 10^{-5}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



Three unknowns of neutrino oscillations :

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

Principle for precision measurement



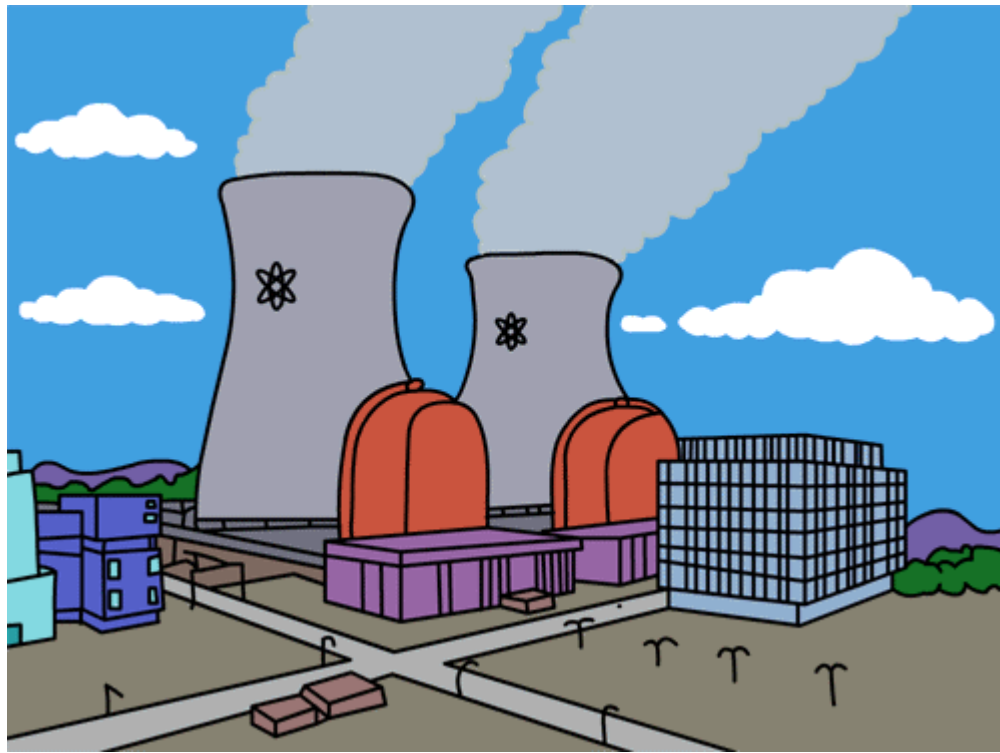
Requirements :

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

Requirements :

- At L/E for oscillation
- Able to distinguish $e/\mu/\tau$
- 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 ^{241}Pu .

Energy spectrum from 2 to 8 MeV

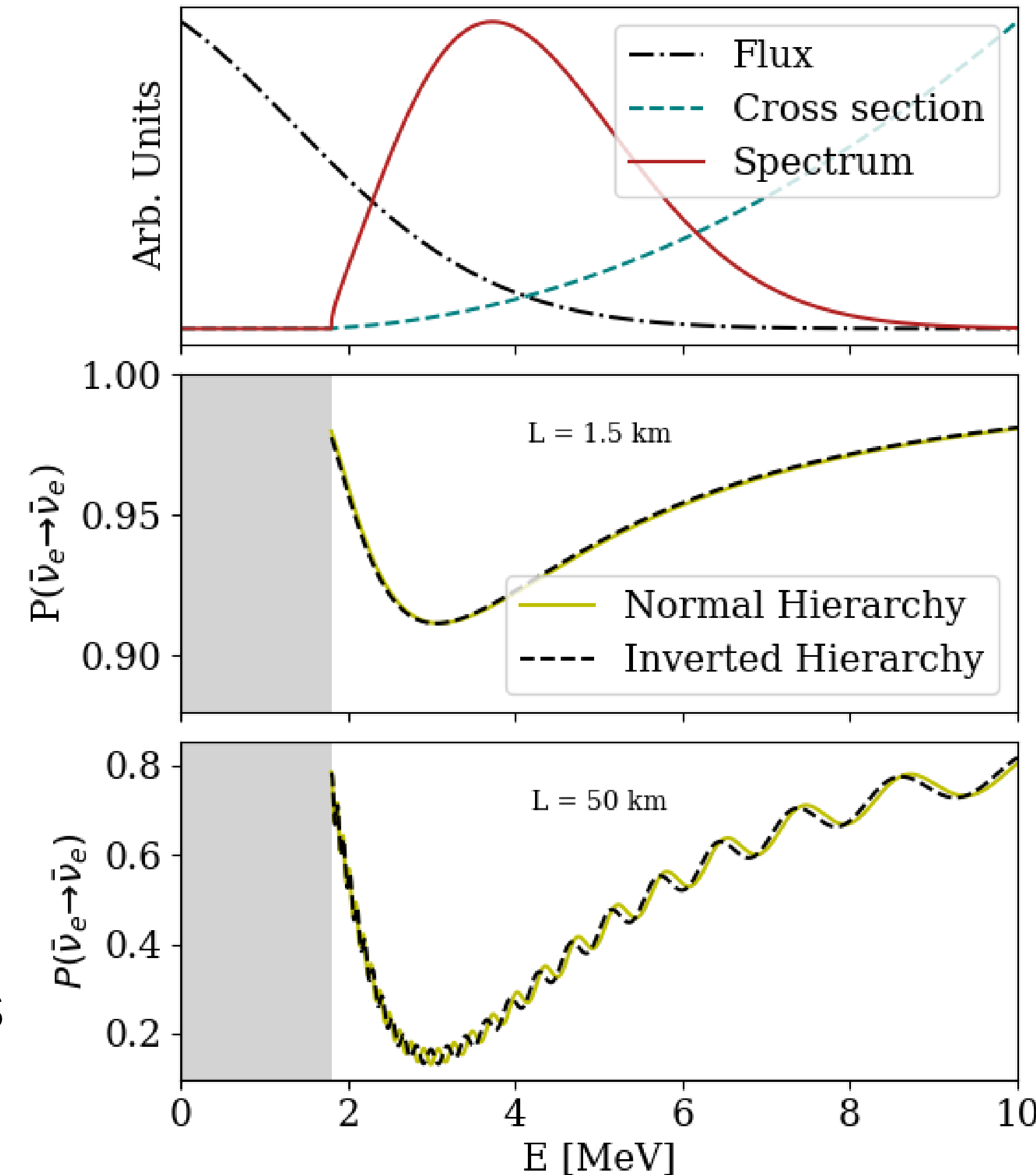
- Cannot tag new flavor appearance ($\bar{\nu}_\mu$ or $\bar{\nu}_\tau$)
- Only the disappearance measurement is possible

$L \sim 1 \text{ km}$ to be at atmospheric oscillation

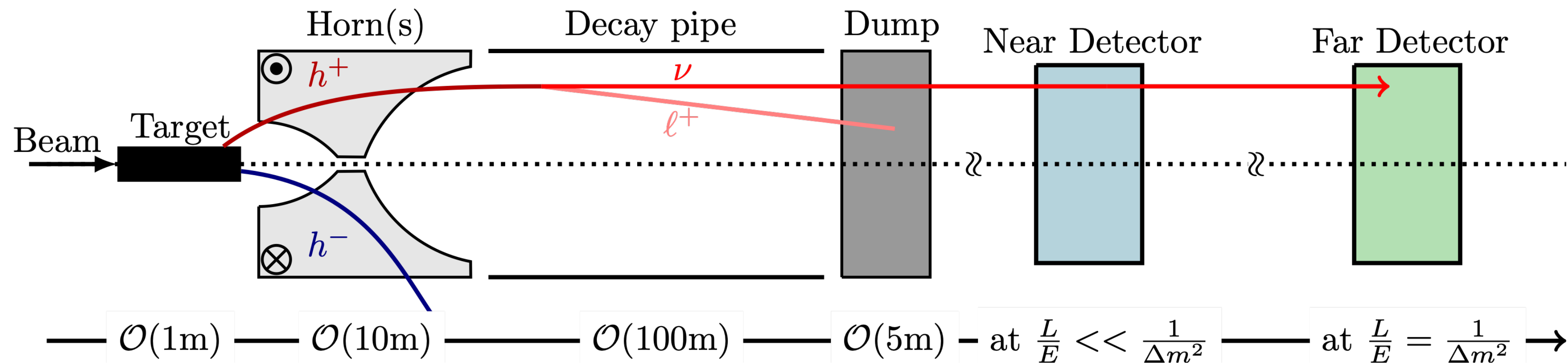
- Considered to be in vacuum, the 2 flavor approximation is valid. No sensitivity to δ_{CP} or MH

$L \sim 50 \text{ km}$ to be at solar oscillation

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



Experiments Using Accelerators



Principle :

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

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

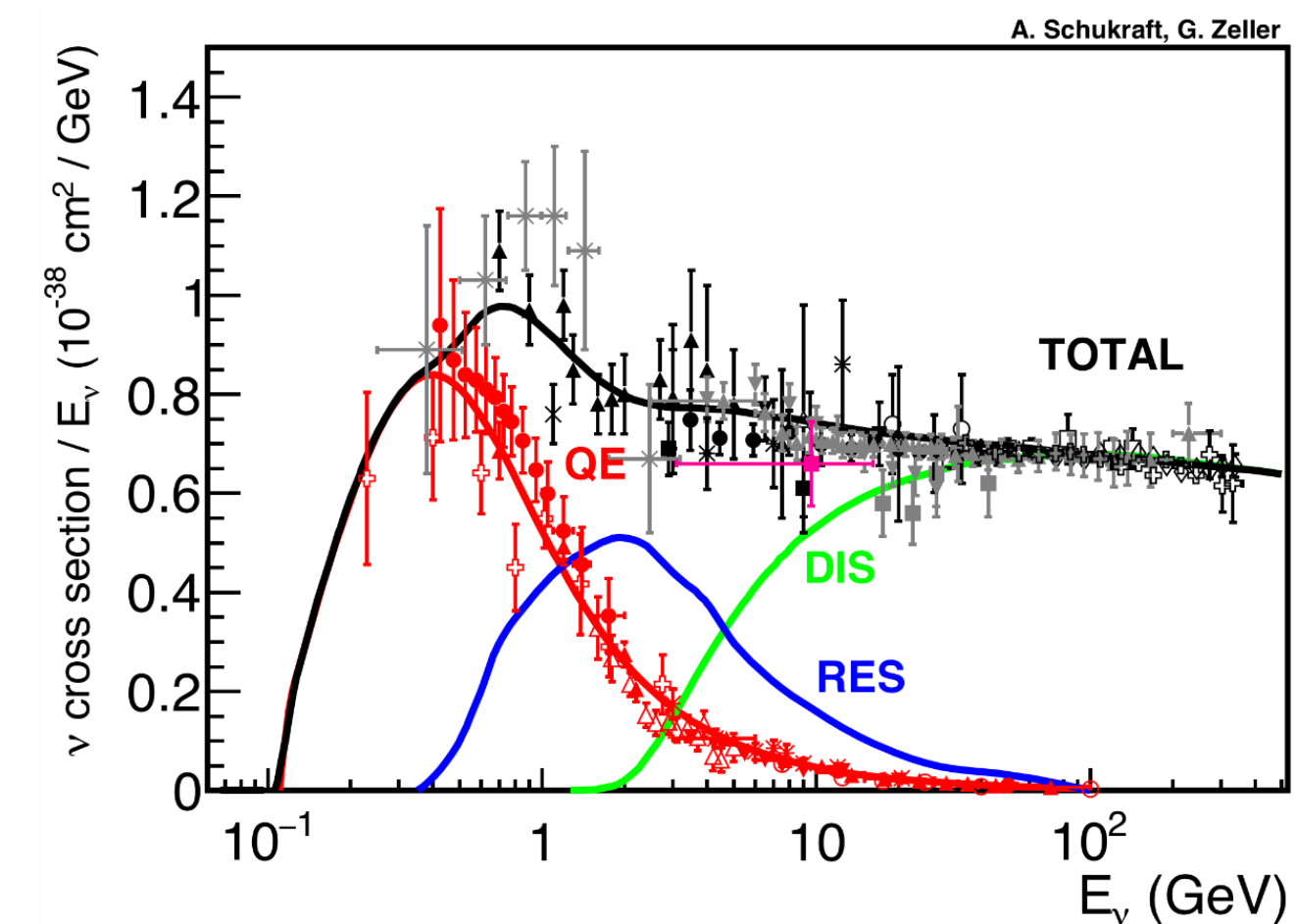
Pions main decay channel (99%) :

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

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

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

○ $\nu_\mu \rightarrow \nu_\mu$:

- No CP violation :
- Negligible matter effects

Experiments Using Accelerators

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

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

○ $\nu_\mu \rightarrow \nu_\mu$:

- No CP violation :
- Negligible matter effects

○ $\nu_\mu \rightarrow \nu_e$: The Golden Channel

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

Experiments Using Accelerators

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

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

○ $\nu_\mu \rightarrow \nu_\mu$:

- No CP violation :
- Negligible matter effects

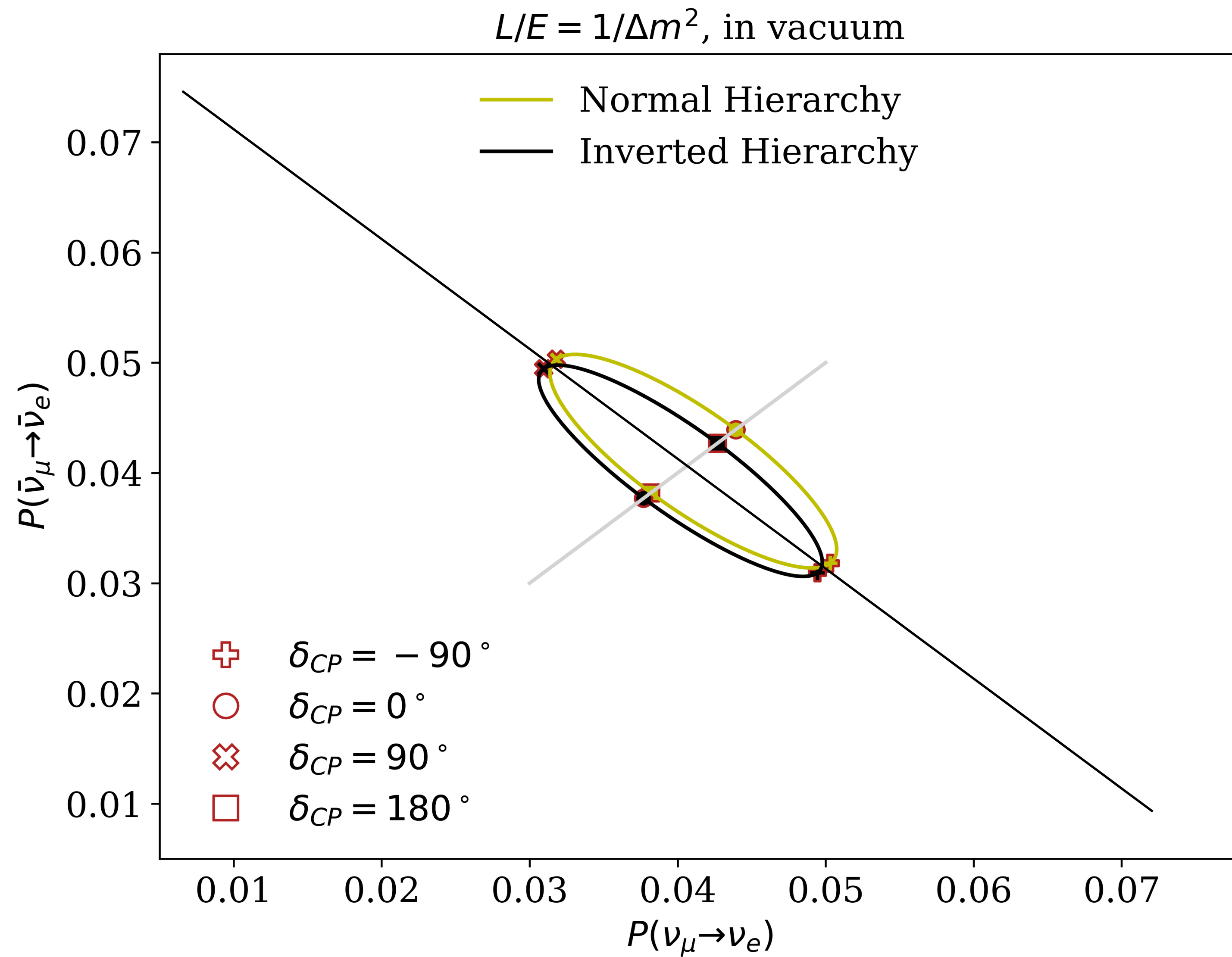
○ $\nu_\mu \rightarrow \nu_e$: The Golden Channel

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

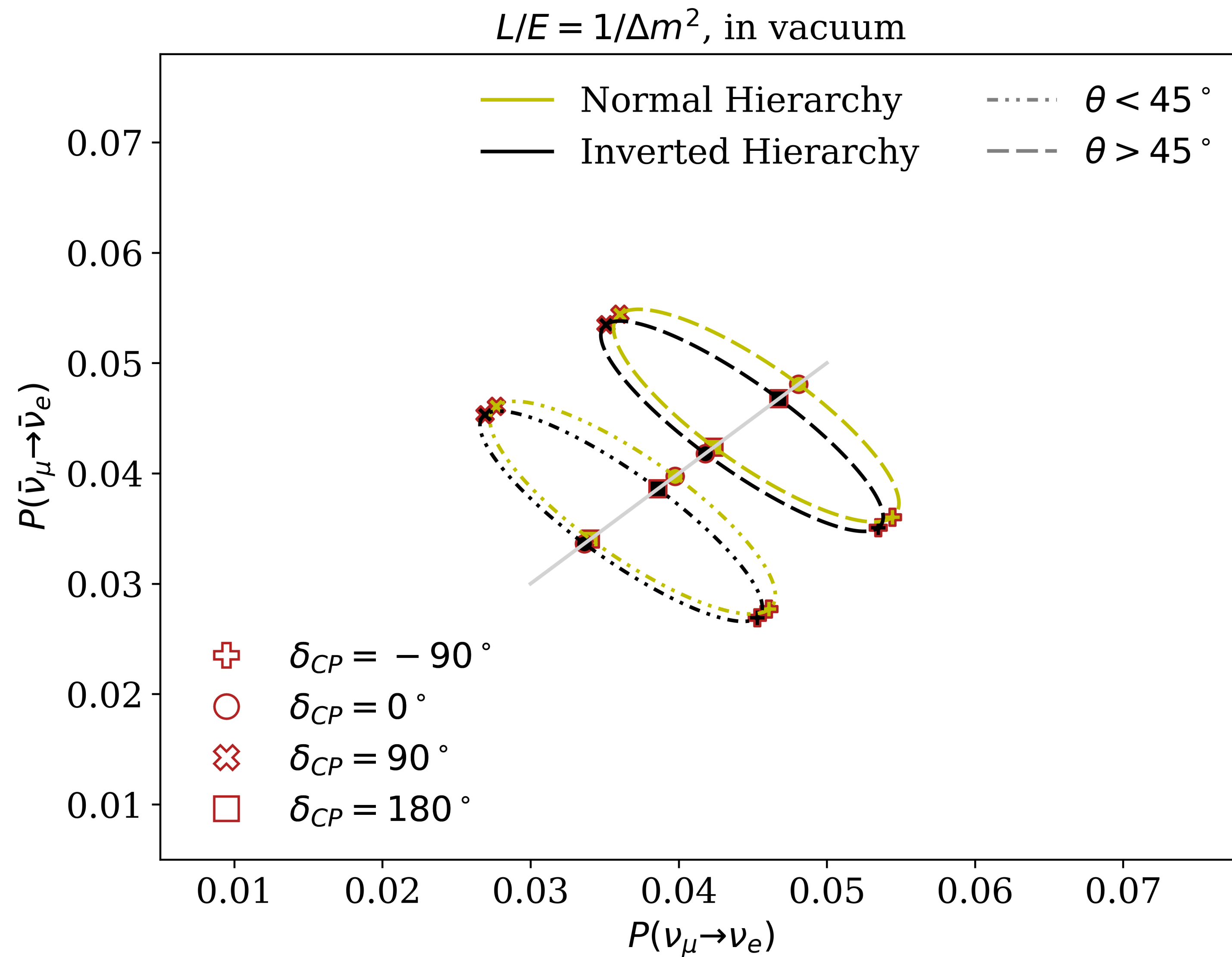
○ $\nu_\mu \rightarrow \nu_\tau$:

- Similar discovery potential as ν_e appearance but:
 $m_\tau = 1.7 \text{ GeV}$, $c\tau_\tau = 87 \text{ }\mu\text{m}$ and $\tau^\pm$ have hundreds of complicated decay channels

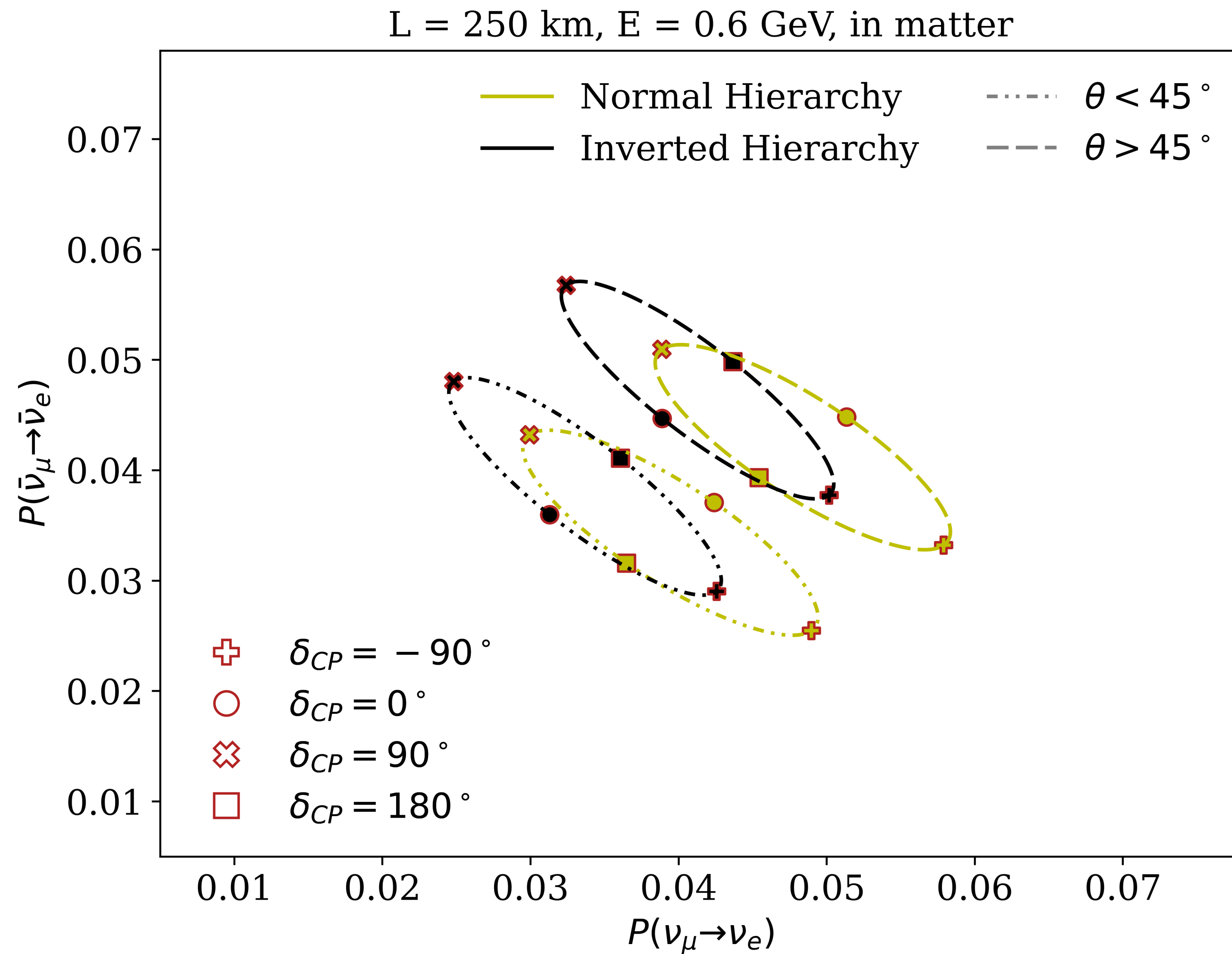
Experiments Using Accelerators



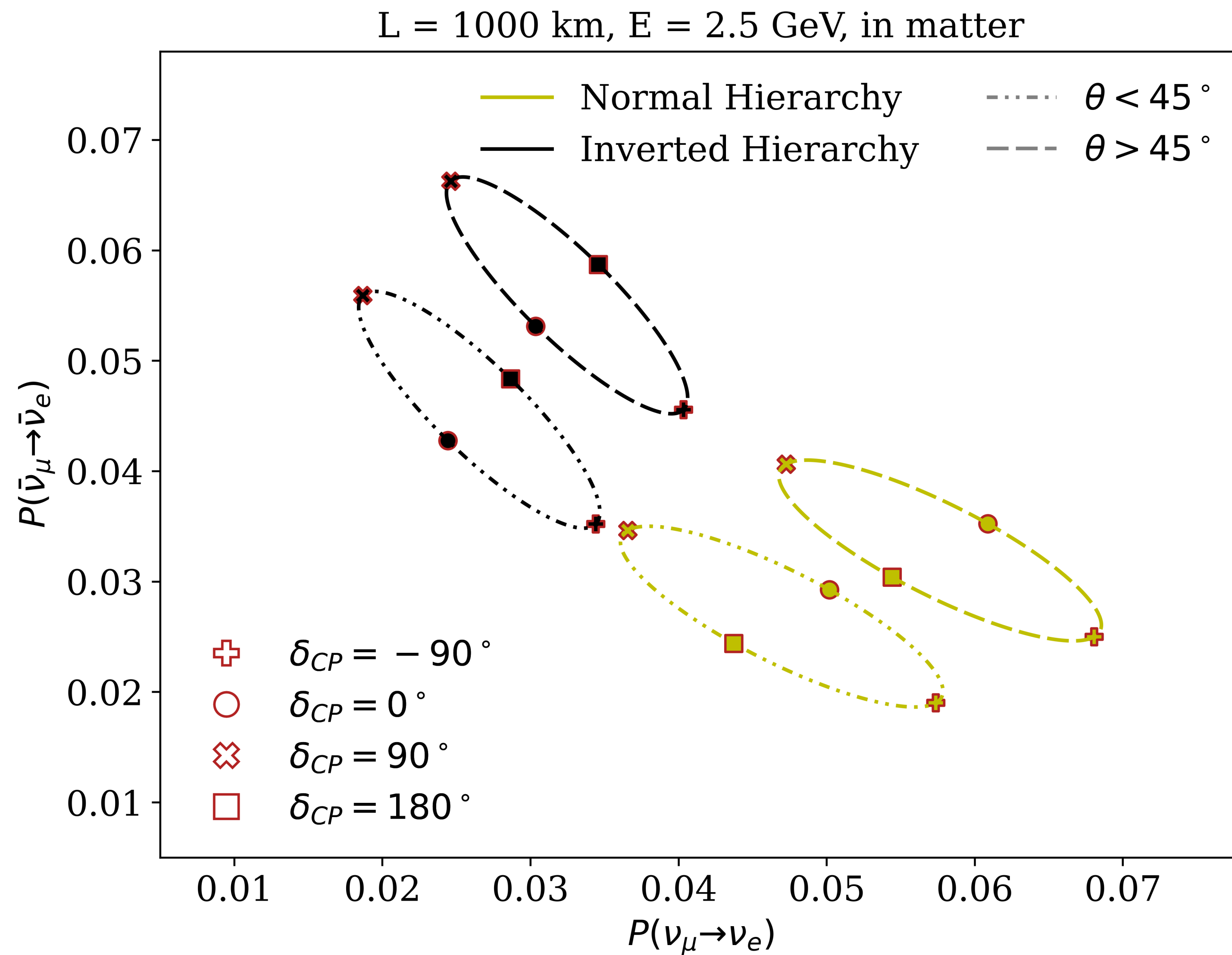
Experiments Using Accelerators



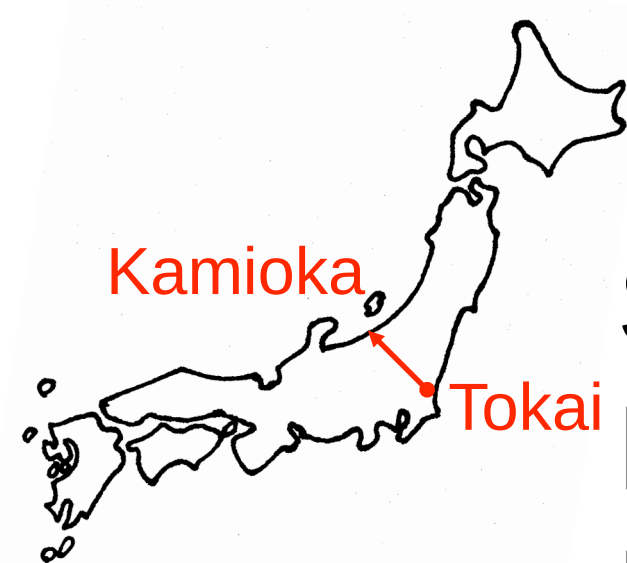
Experiments Using Accelerators



Experiments Using Accelerators



Current ν accelerator experiments



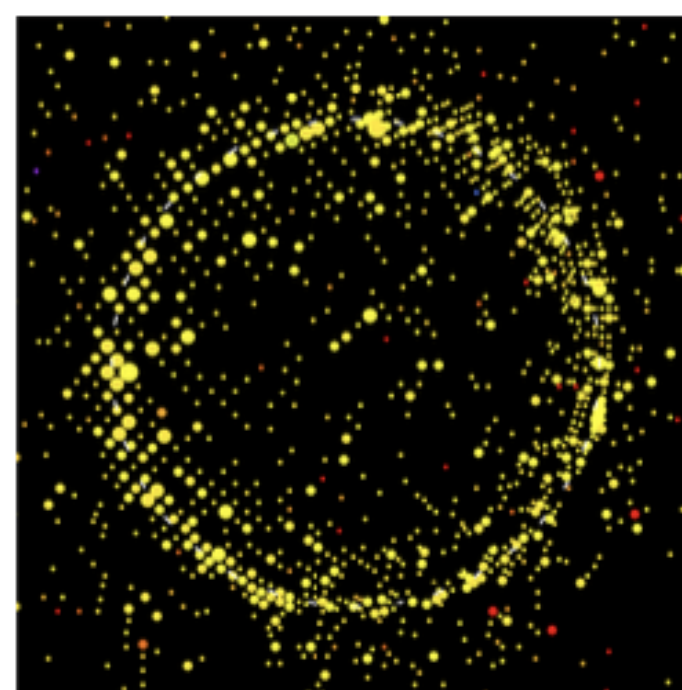
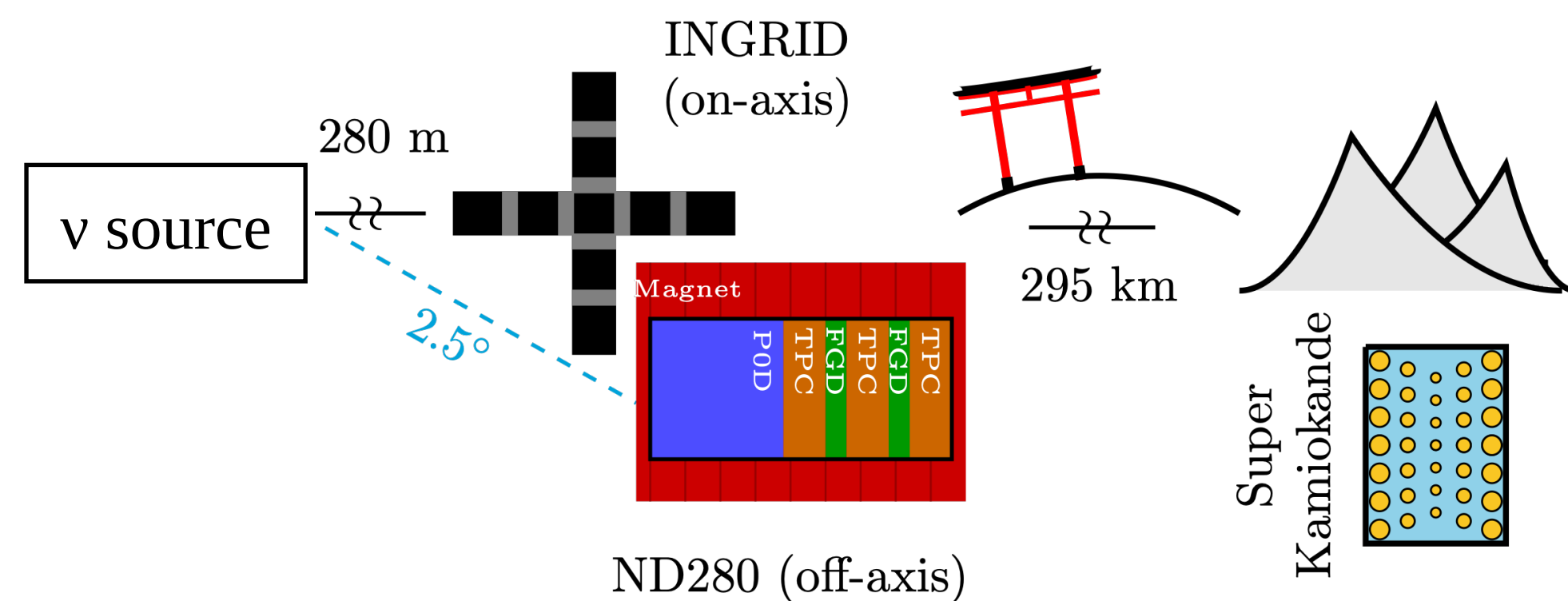
T2K in Japan

Since 2010, $L = 295$ km, $E = 0.6$ GeV

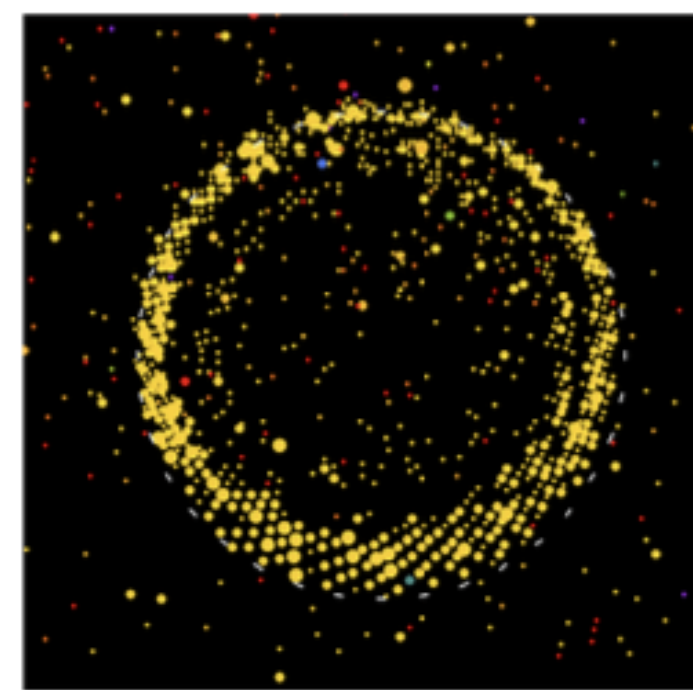
Equal ν and $\bar{\nu}$ runs

Near detector is a gaseous TPC

Far detector is Super-Kamiokande



ν_e -like



ν_μ -like

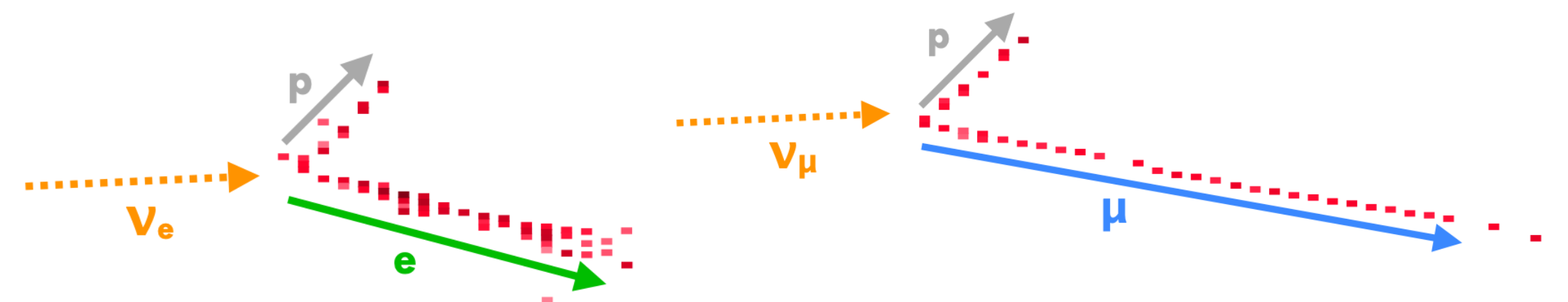
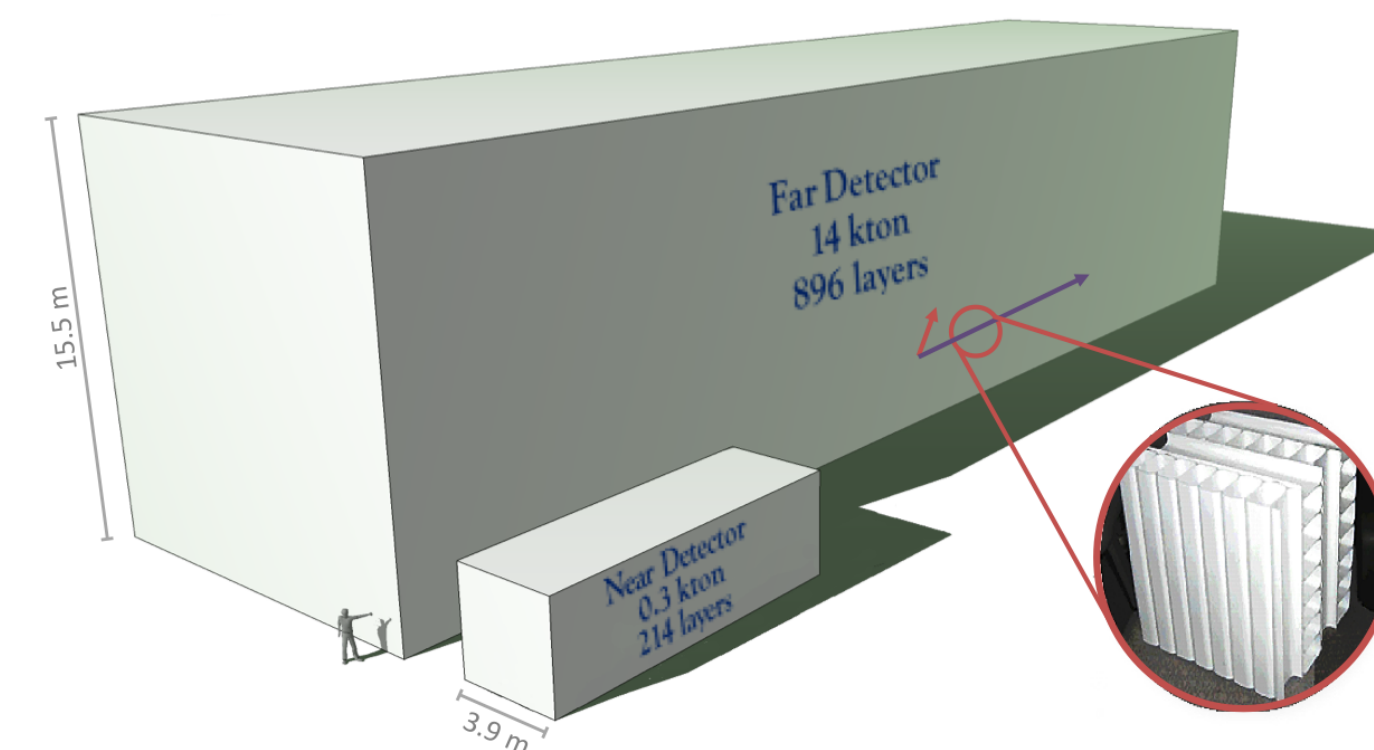


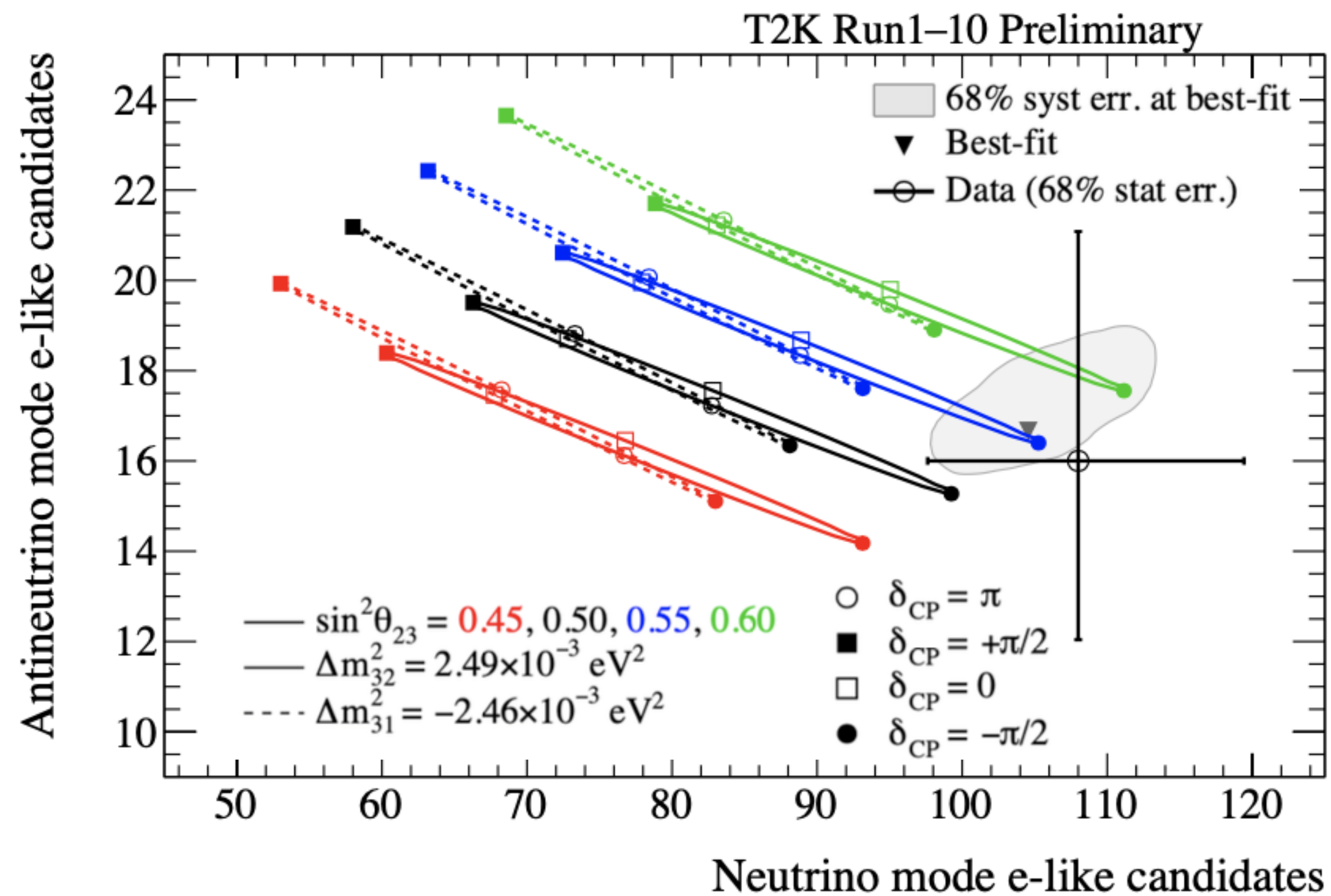
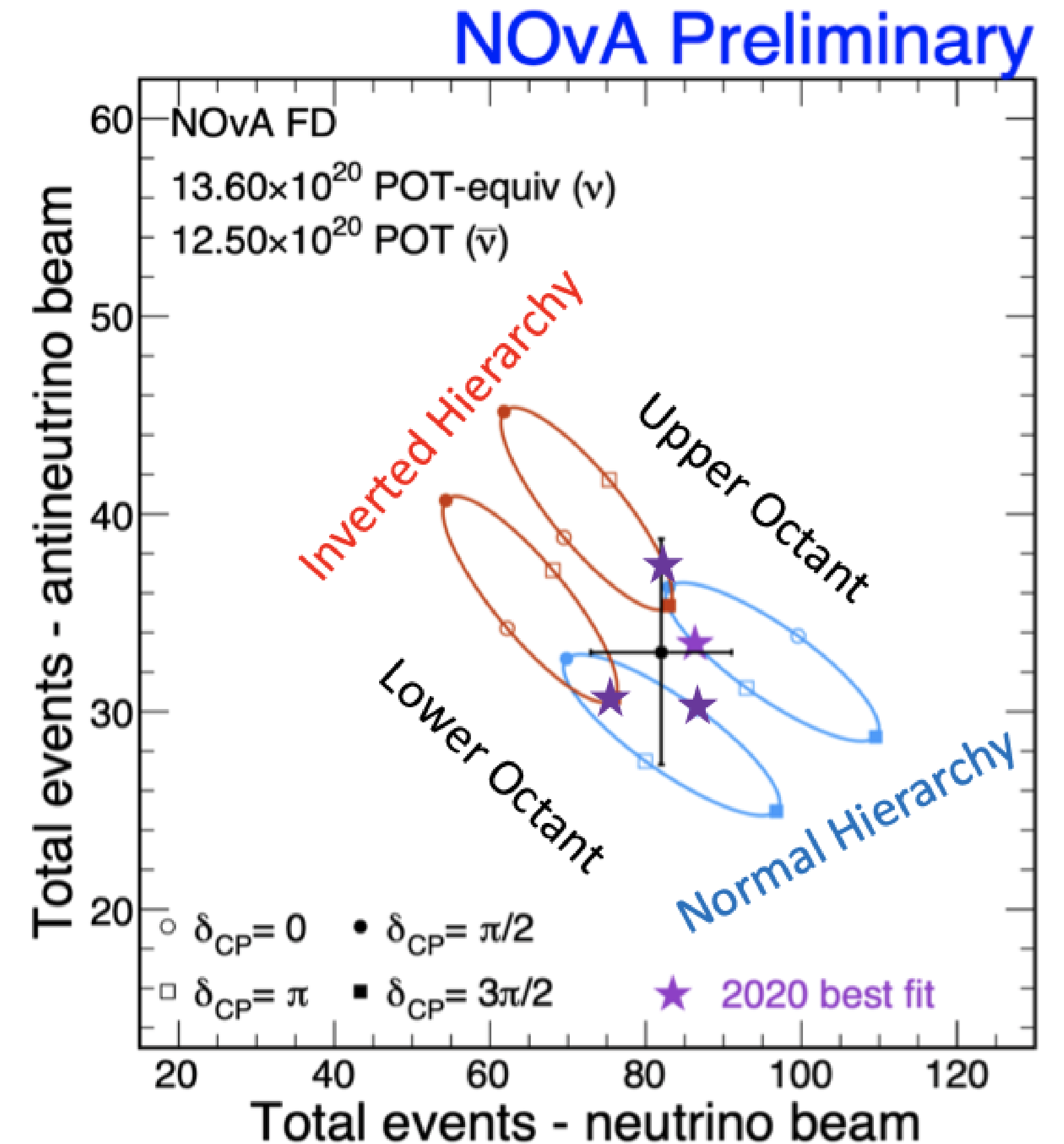
NOvA in the US

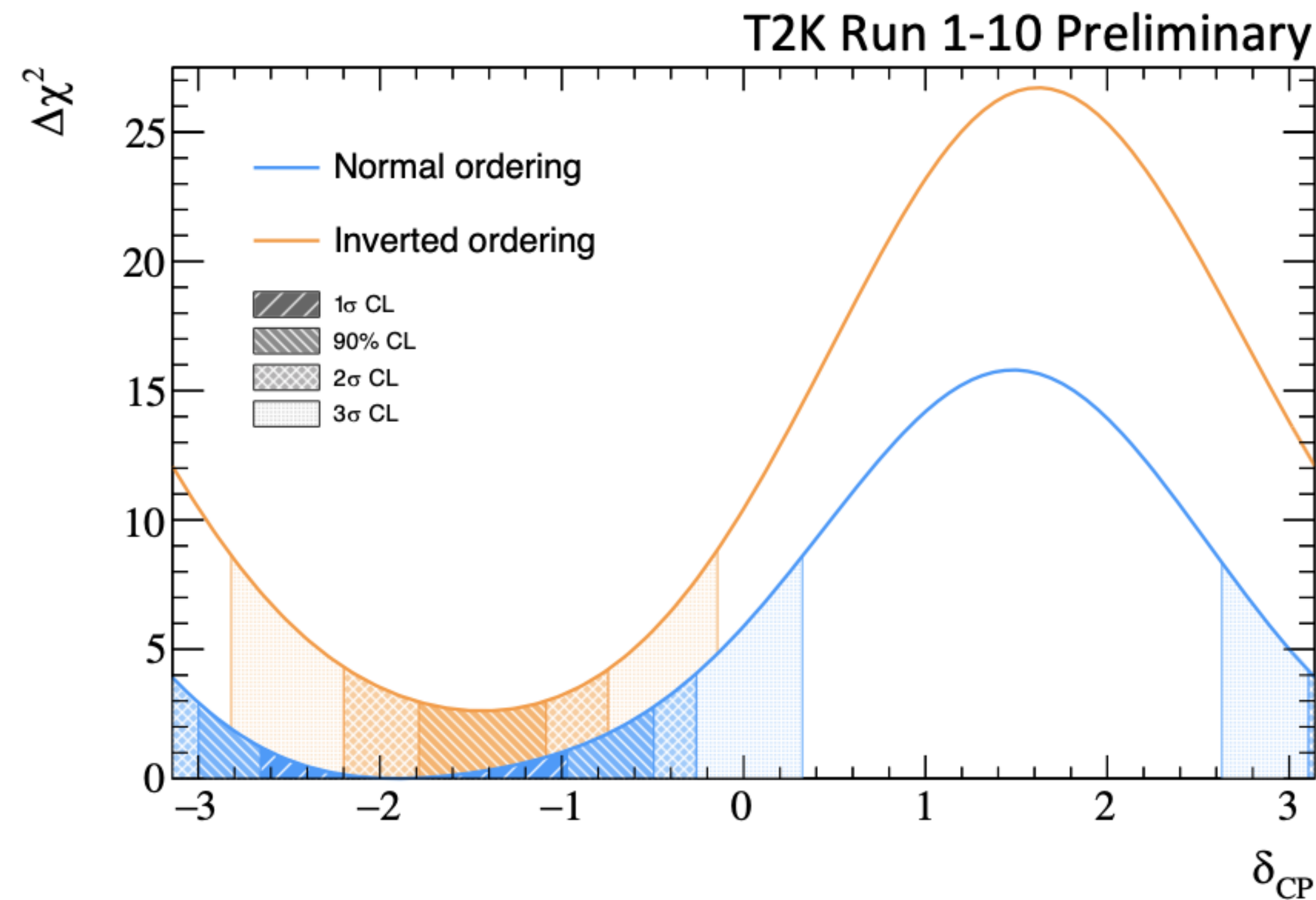
Since 2013, $L = 810$ km, $E = 2$ GeV

Equal ν and $\bar{\nu}$ runs

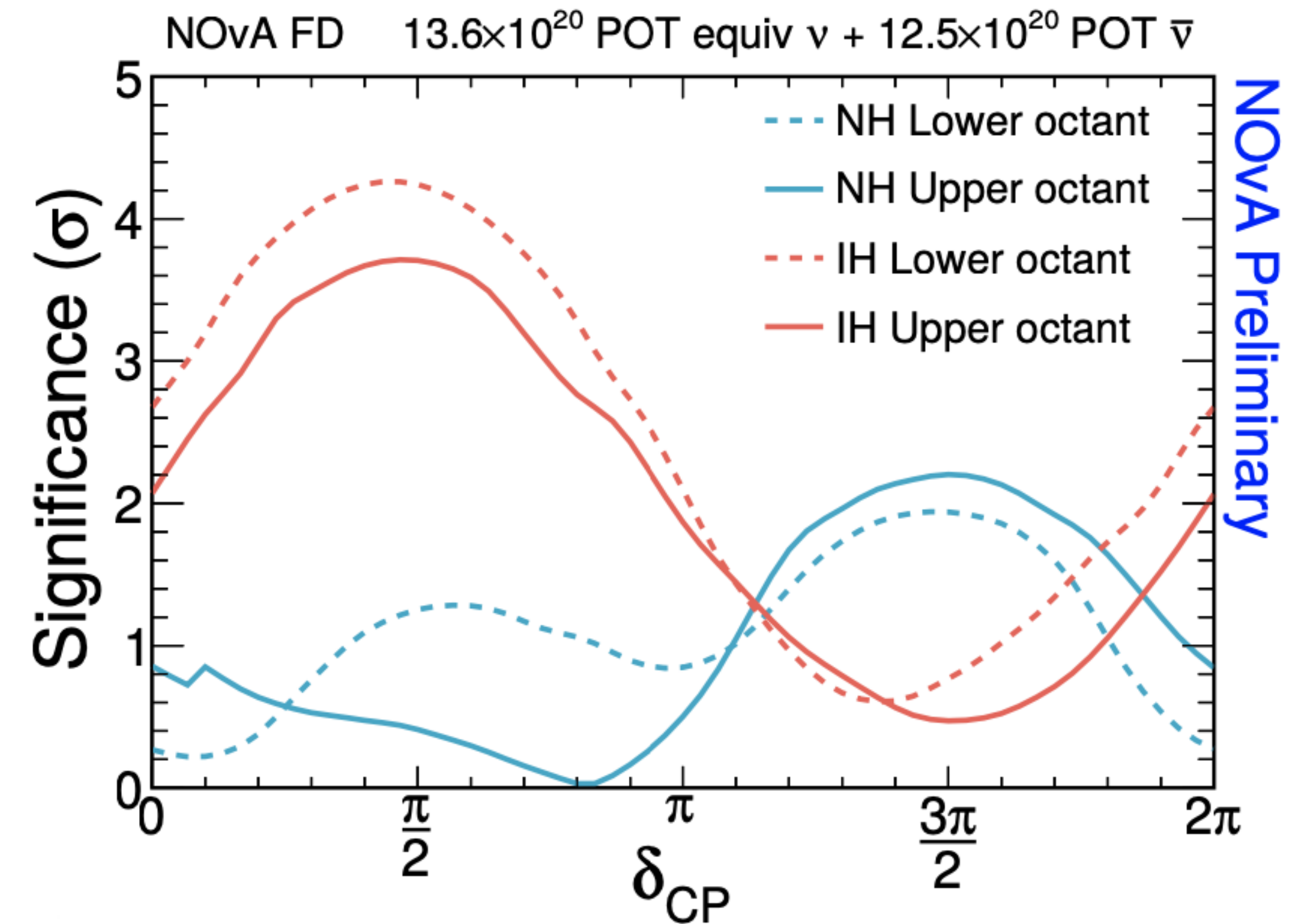
Near and Far detectors are plastic scintillators



Current ν accelerator experiments*T2K in Japan**NOvA in the US*

Current ν accelerator experiments***T2K in Japan***

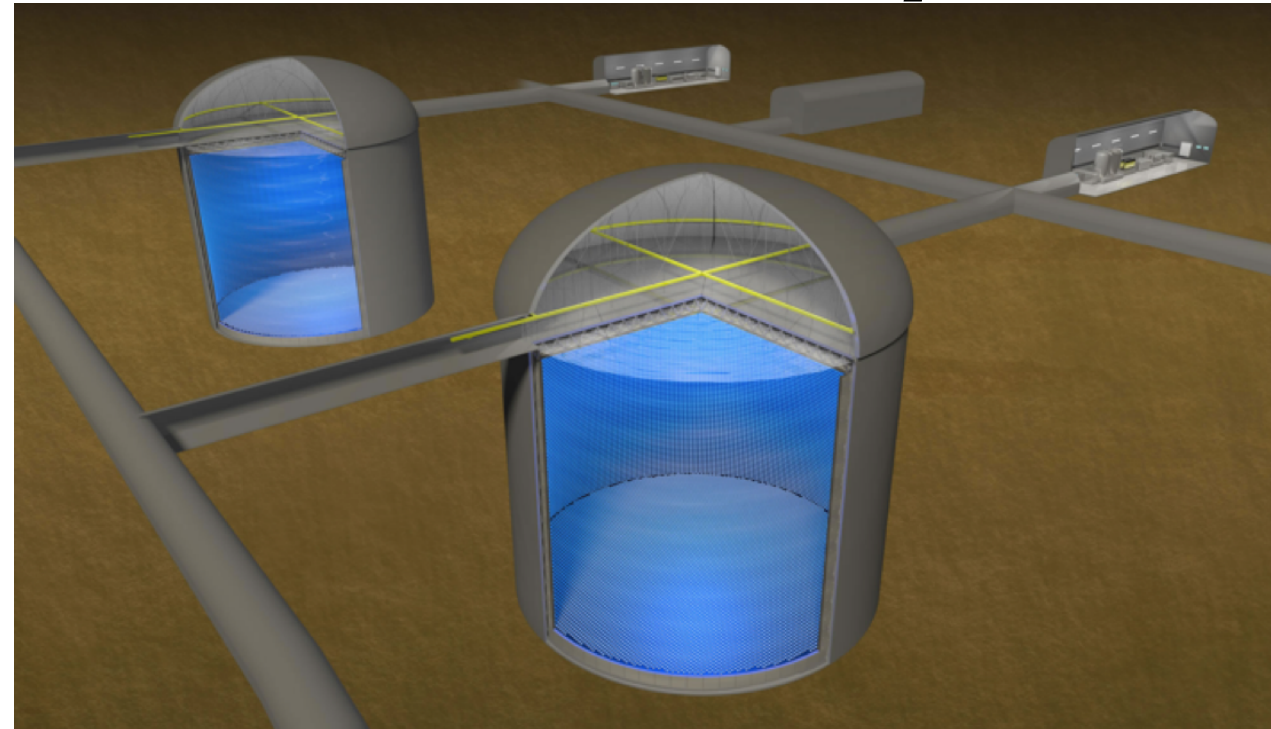
- Slight preference for Normal Hierarchy
- $\delta_{CP} = (0, \pi)$ excluded at 95% C.L. for both MH
- Large range around $\delta_{CP} = +\pi/2$ excluded at 3 σ

NOvA in the US

- Prefers Normal Hierarchy at 1.0 σ
- Exclude $\delta_{CP} = \pi/2 + \text{IH}$ at >3 σ
- Exclude $\delta_{CP} = 3\pi/2 + \text{NH}$ at 2 σ

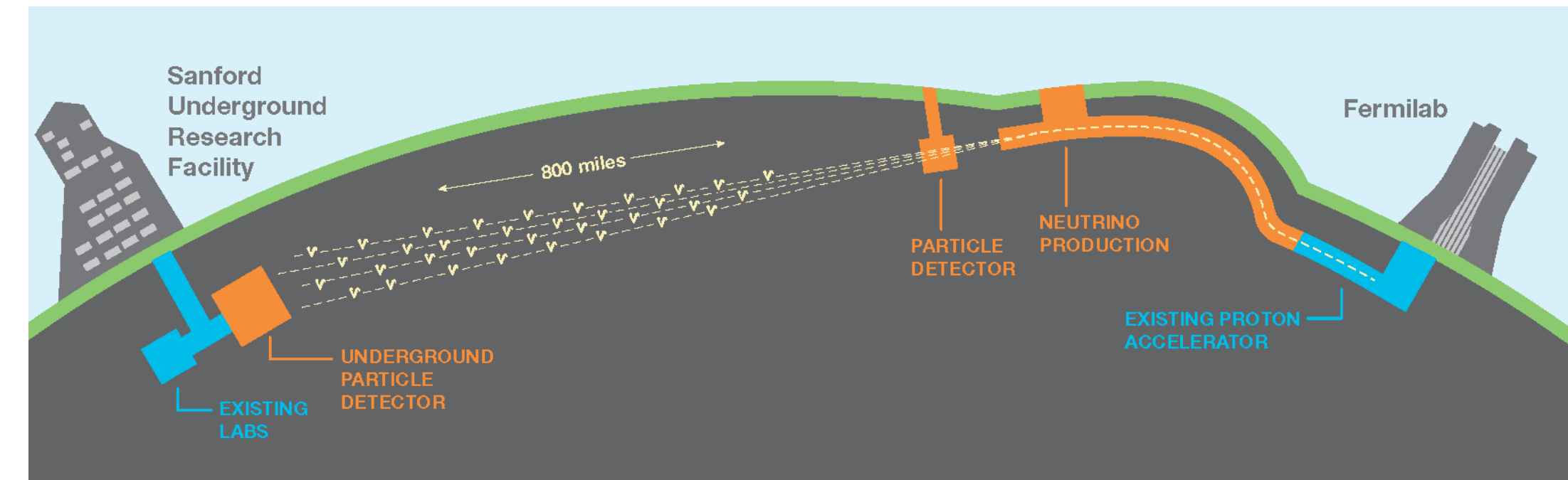
Future ν accelerator experiments

T2HK in Japan



$L=300$ km, $E \sim 0.6$ 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

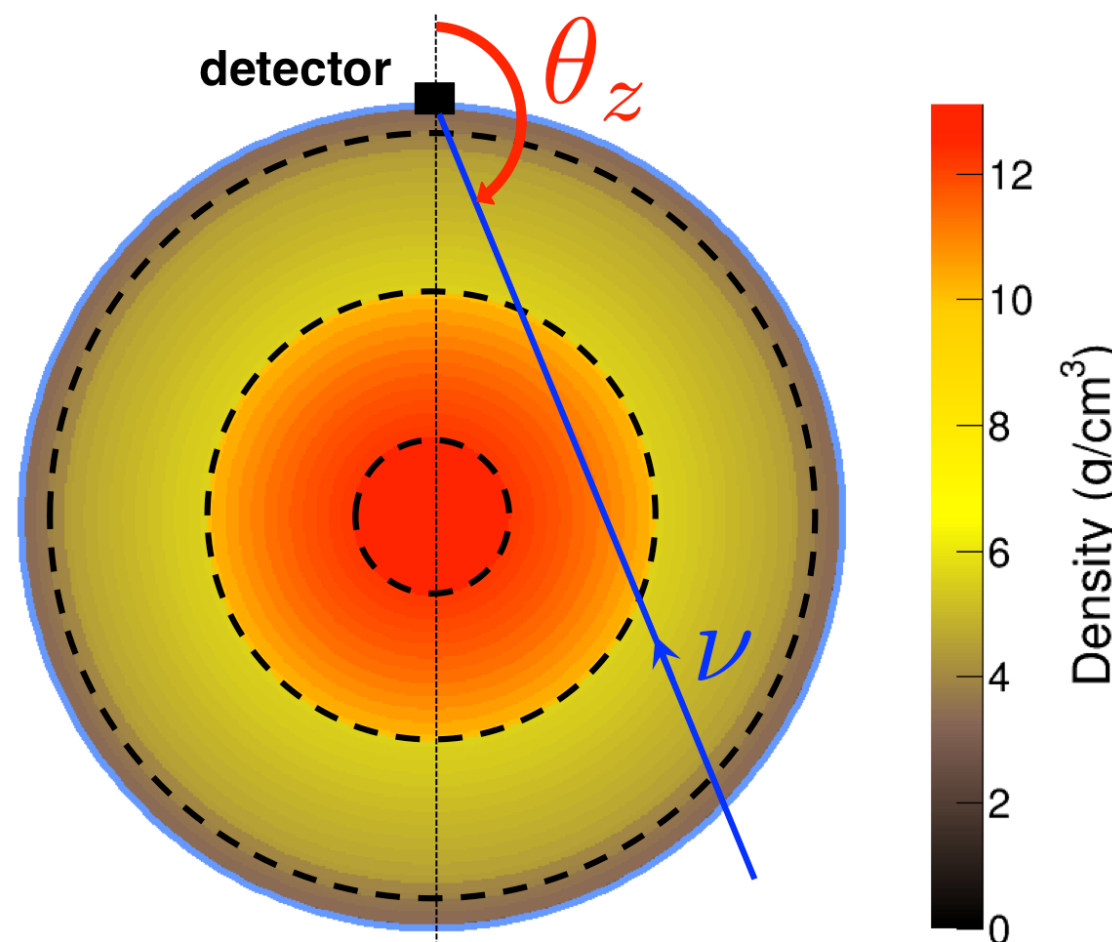
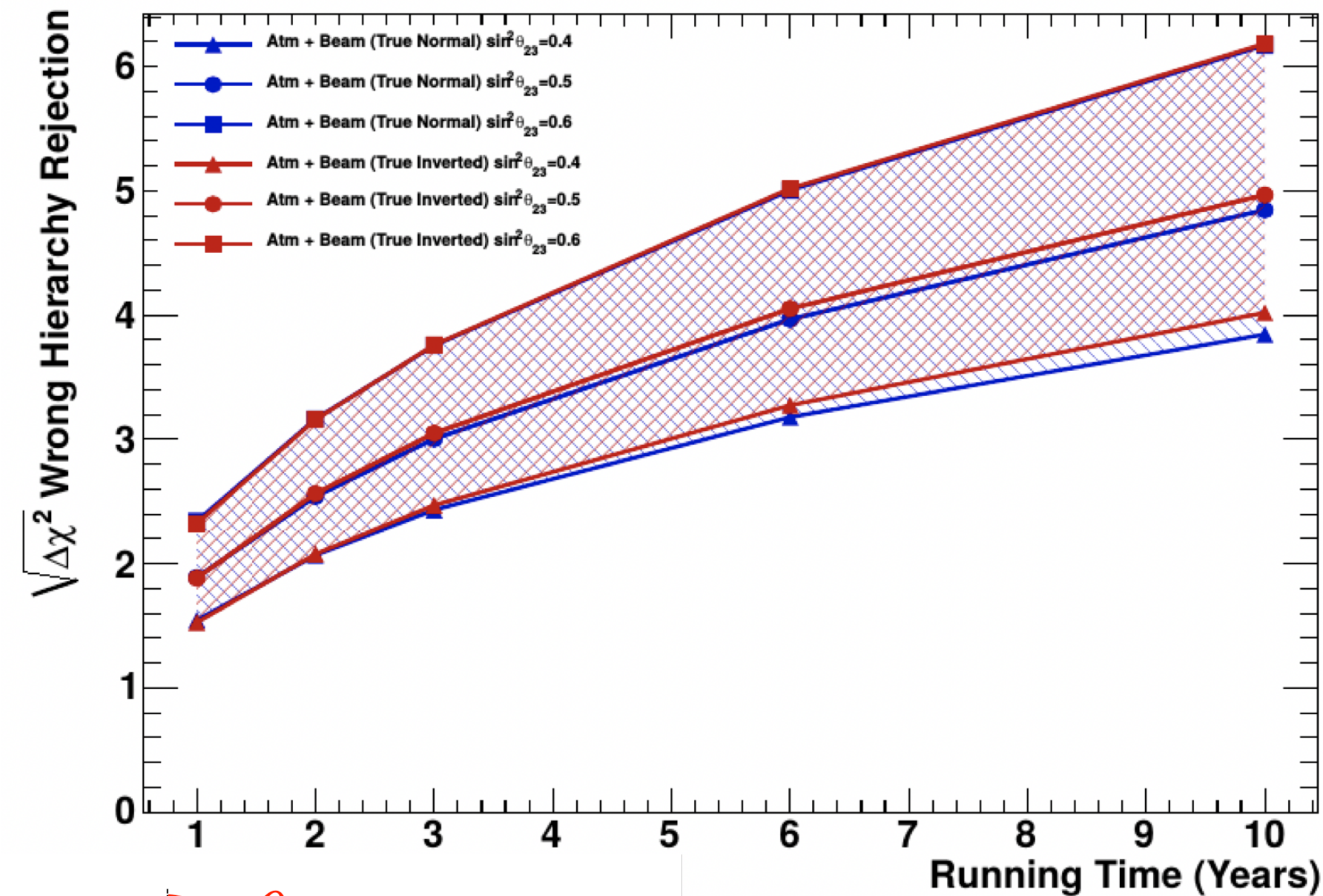


$L=1300$ km, $E \sim 1$ -3 GeV
40 kt liquid argon TPC detector
3D imaging with high granularity for precise tracking
Low energy threshold (~ 10 s MeV)
Important R&D efforts ongoing :
Scalability, Engineering

Both planning of starting data taking in ~ 2027

Future ν accelerator experiments

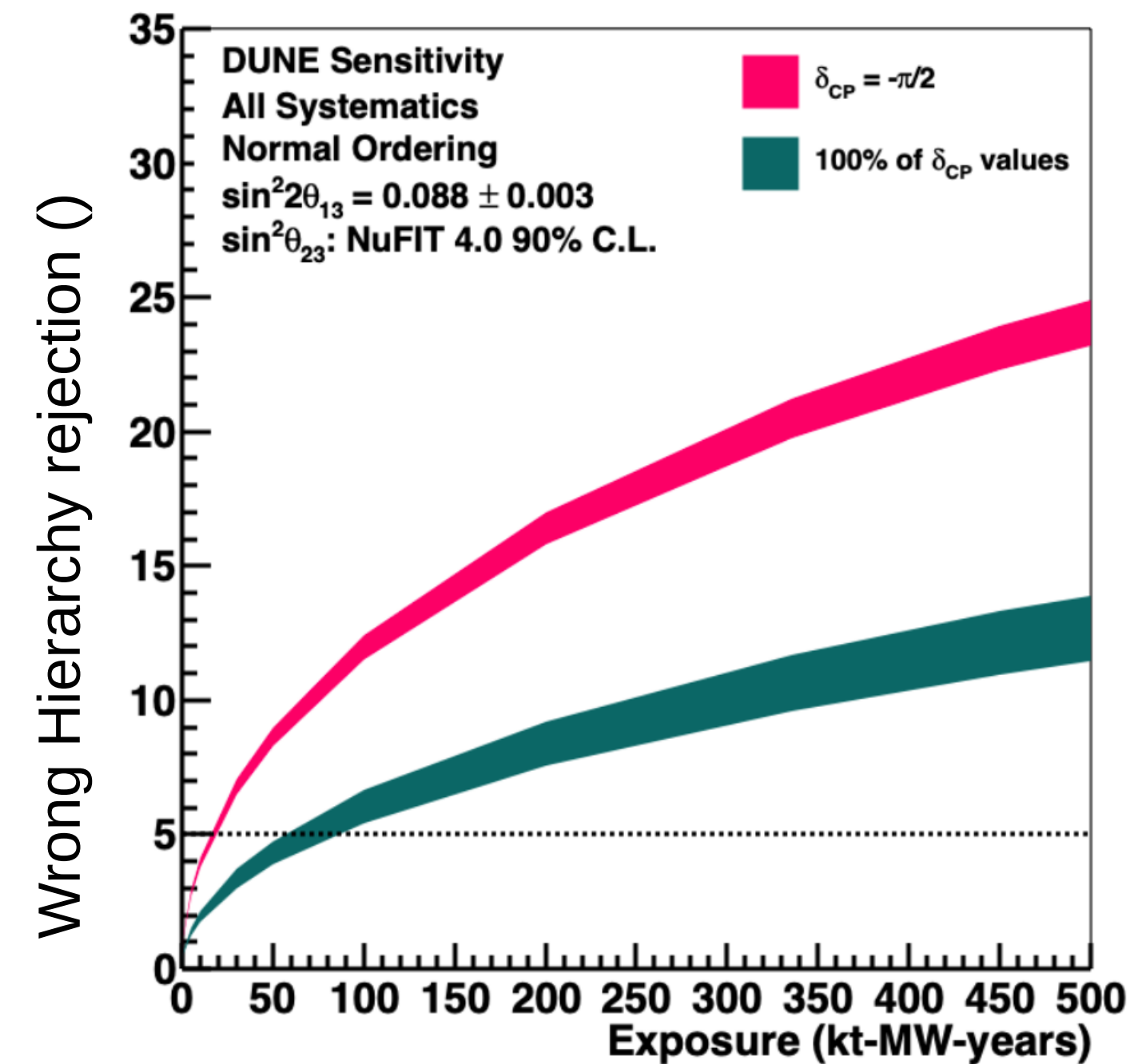
T2HK in Japan



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

- **DUNE** will resolve the MH at 5σ in $\sim 1.5y$
[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]

DUNE in the US

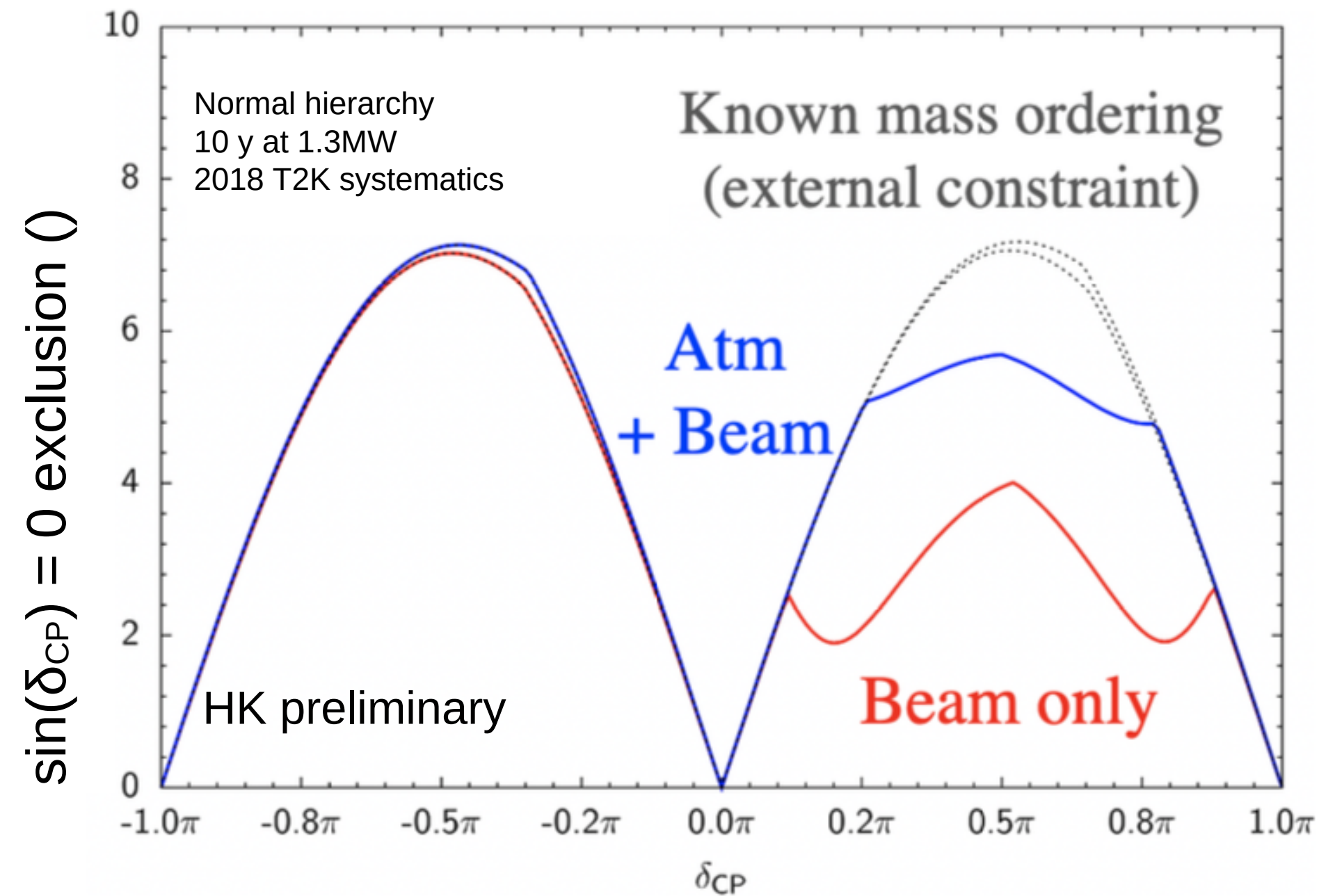


DUNE default operation :
40 kton of LAr staged
Beam power at 1.2 ~ 2.4
MW

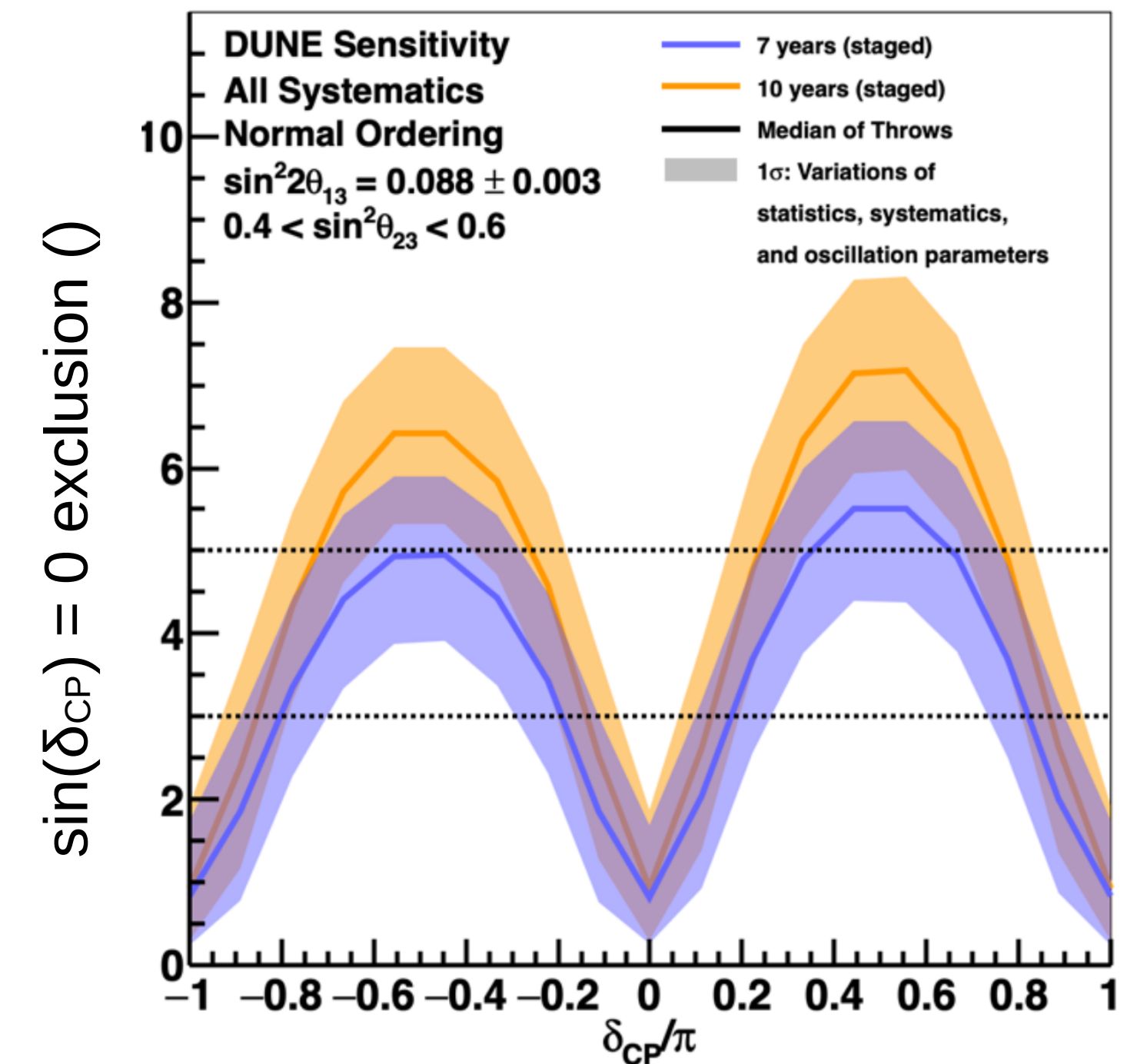
kt•MW•yr	Staged years
30	1.2
100	3.1
200	5.2
336	7
624	10
1104	15

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 ? $\beta\beta 0\nu$ experiments (SuperNEMO, CUORE, SNO+)

- The **Dirac** way
- Through Higgs coupling
- Need a sterile right handed ν

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

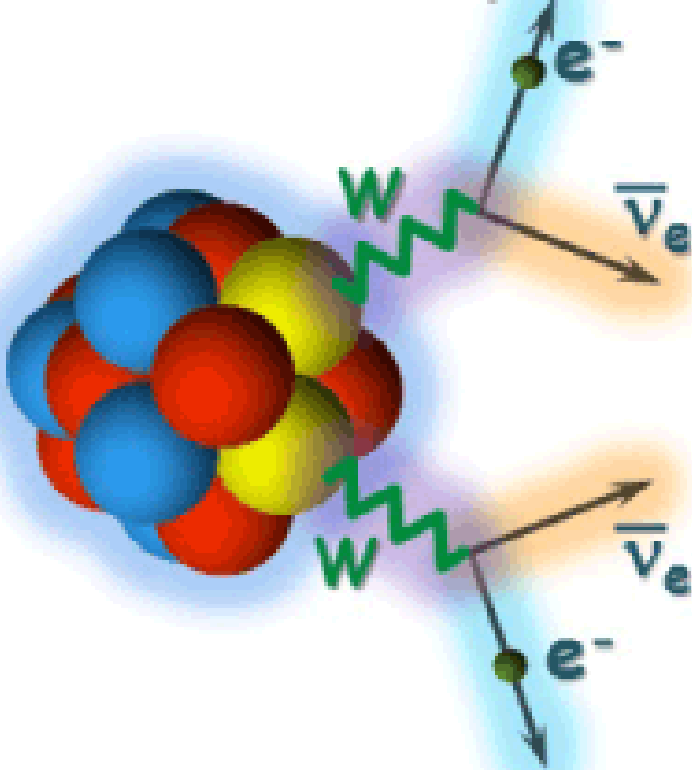
$$m_D = \frac{v}{\sqrt{2}}Y_v \leftarrow \sim 10^{-12} \text{ (why?)}$$

- The **Majorana** way
 - No distinction between ν and $\bar{\nu}$
 - Mass given by seesaw mechanism
 - Need massive neutrinos
- $$\nu_R = C\bar{\nu}_L^T = \nu_L^C$$
- $$m = \frac{m_D^2}{m_R} \leftarrow \begin{matrix} \text{Dirac term} \\ \text{Very big} \end{matrix}$$

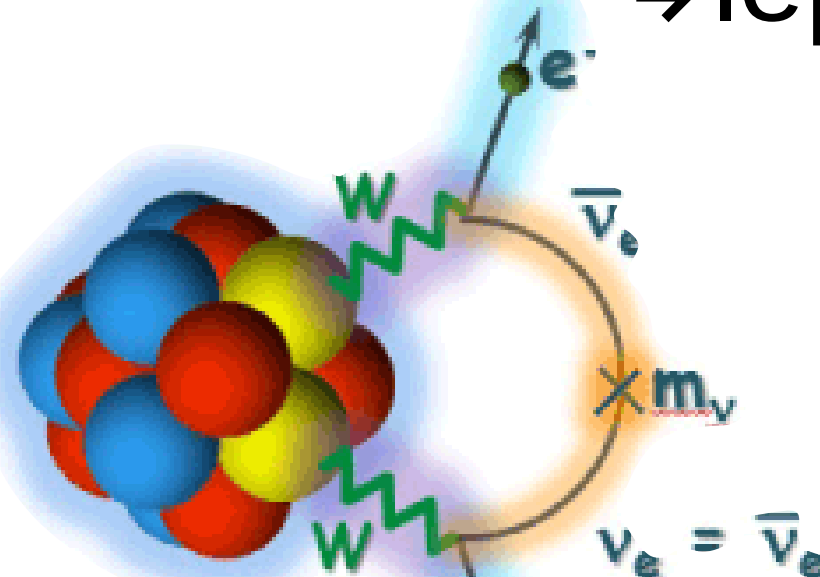
→ **Only one way to prove that neutrino are Majorana particles :**

[Double beta decay]

Double β decay with **no** neutrino emission

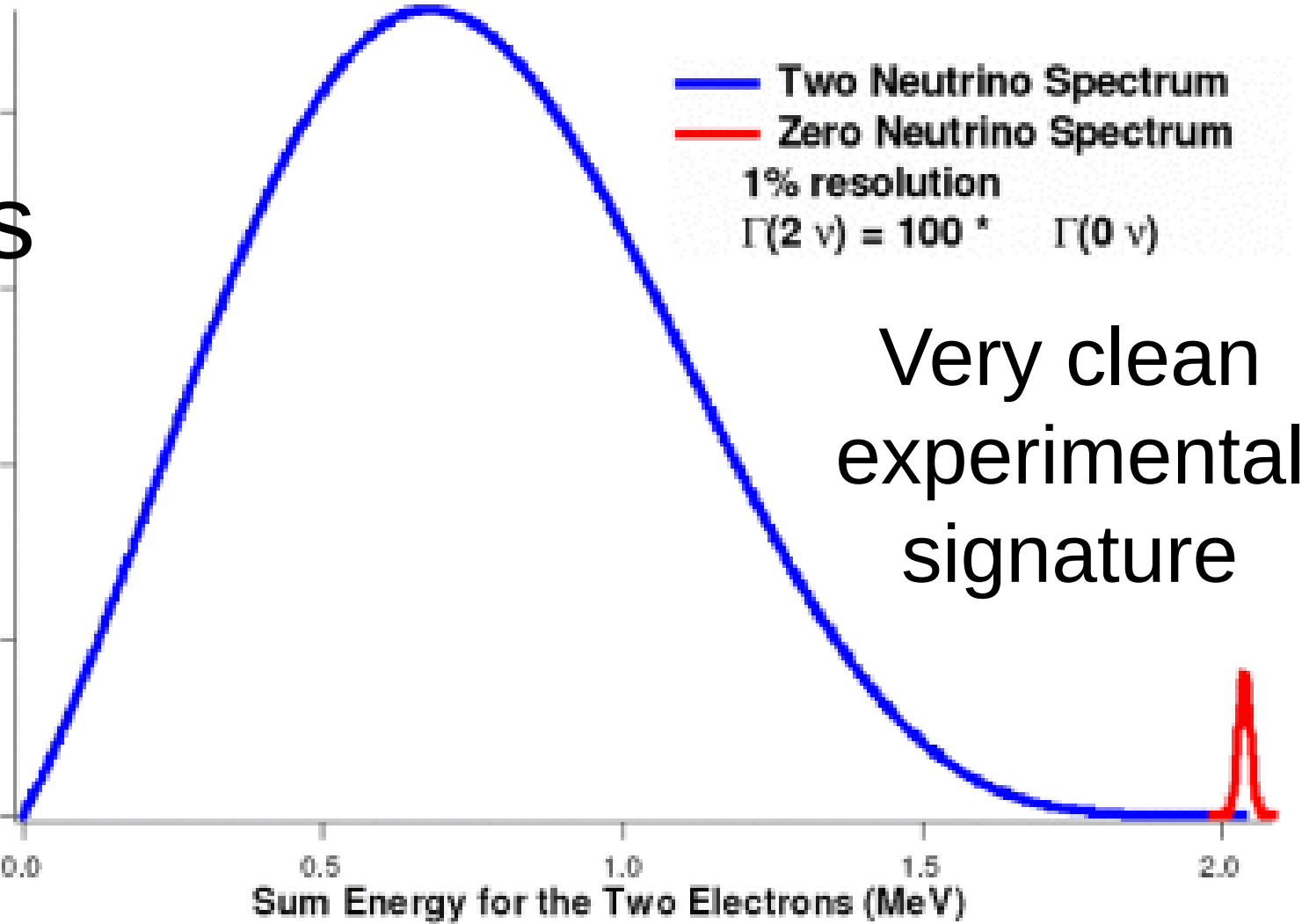


Double beta decay
which emits anti-neutrinos

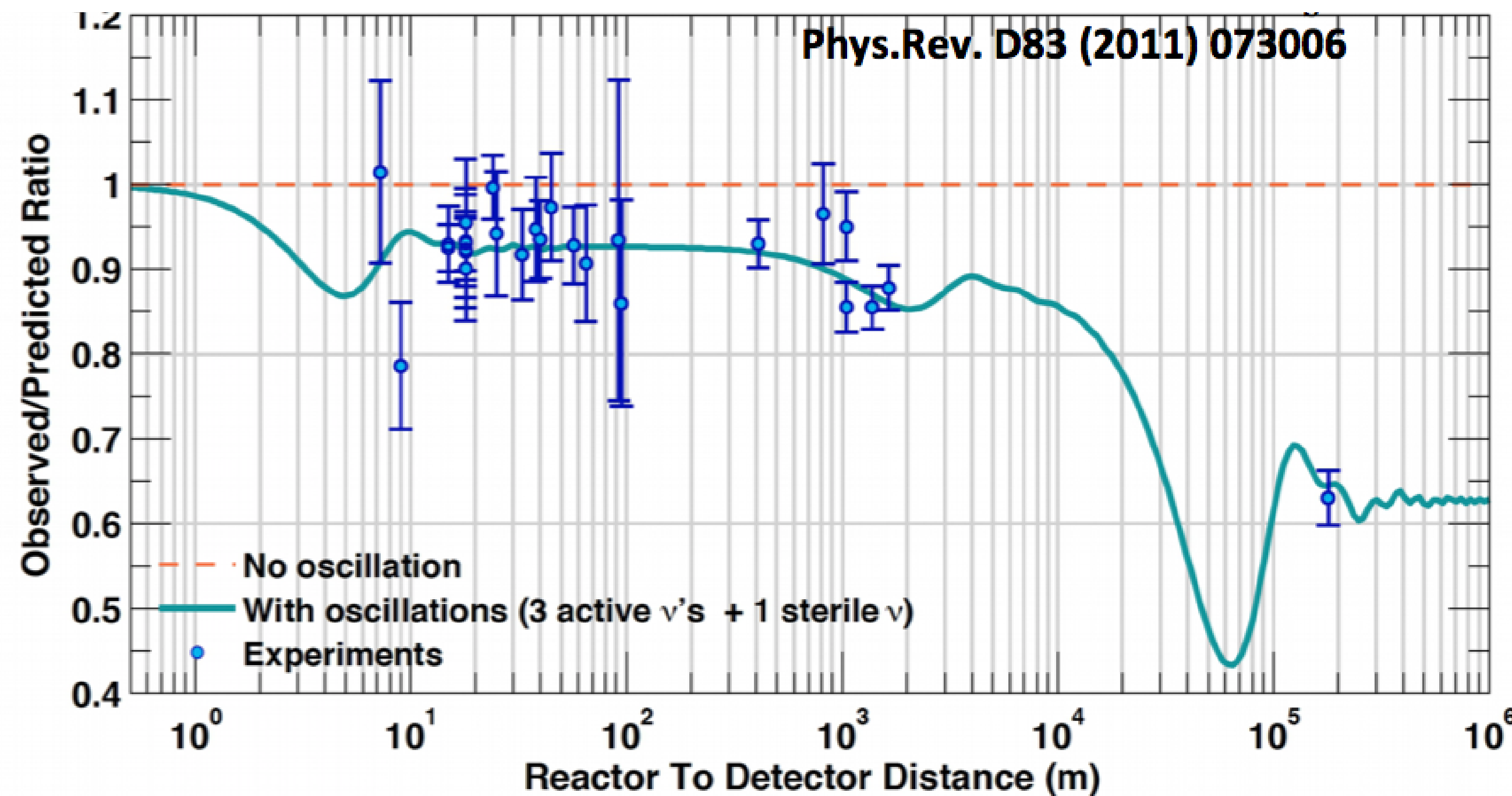


Neutrinoless
double beta decay

- $\beta\beta 2\nu$ is very rare (half life $\sim 10^{18} - 10^{24}$ y)
- $\beta\beta 0\nu$ is **forbidden** in SM
- ↳ lepton number violated by 2 units



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



A revised reactor $\bar{\nu}e$ 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 ?

- 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***

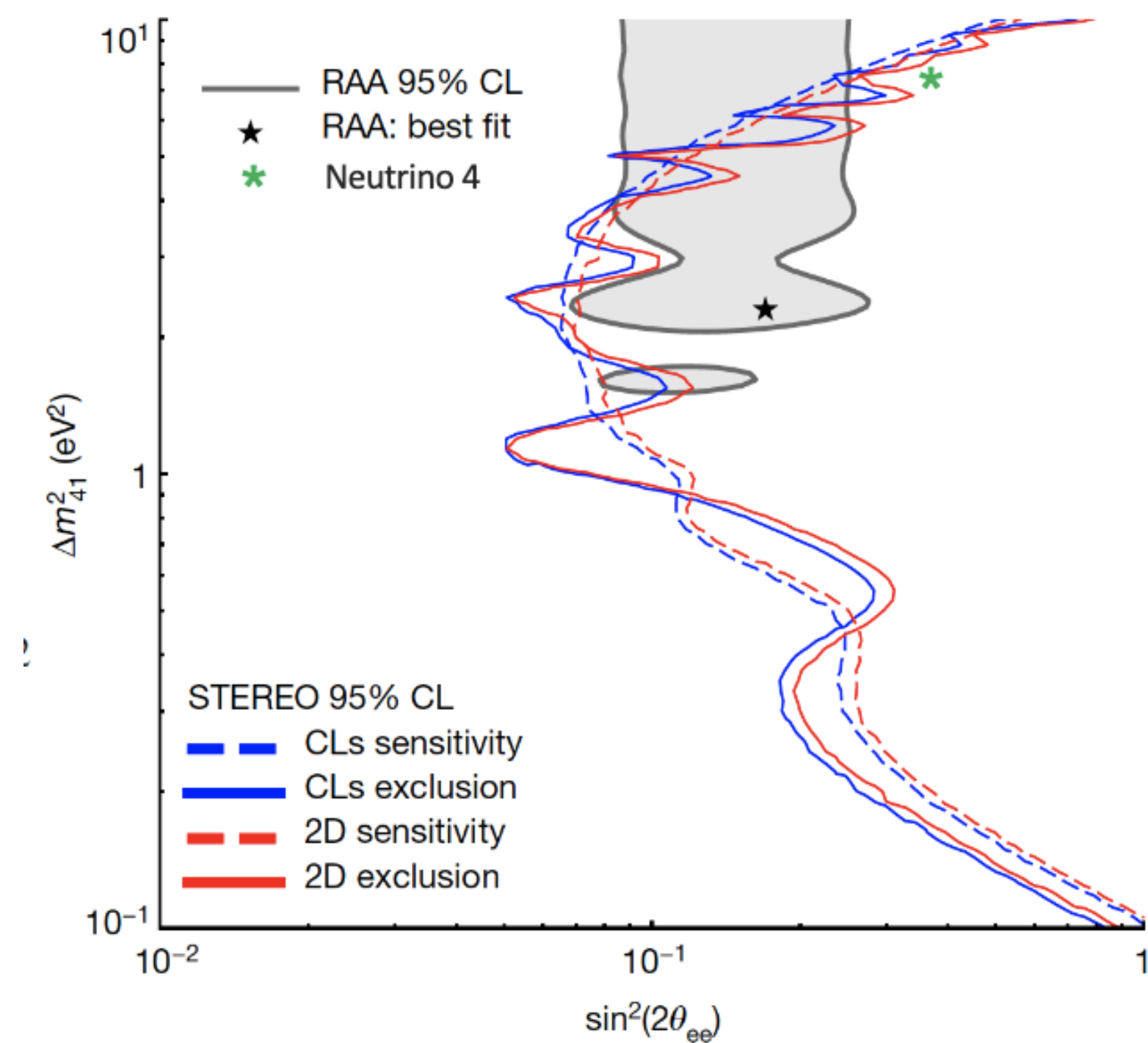
Best fit parameters of reactor anomaly:

$$\Delta m^2 \sim 2 \text{ eV}^2$$

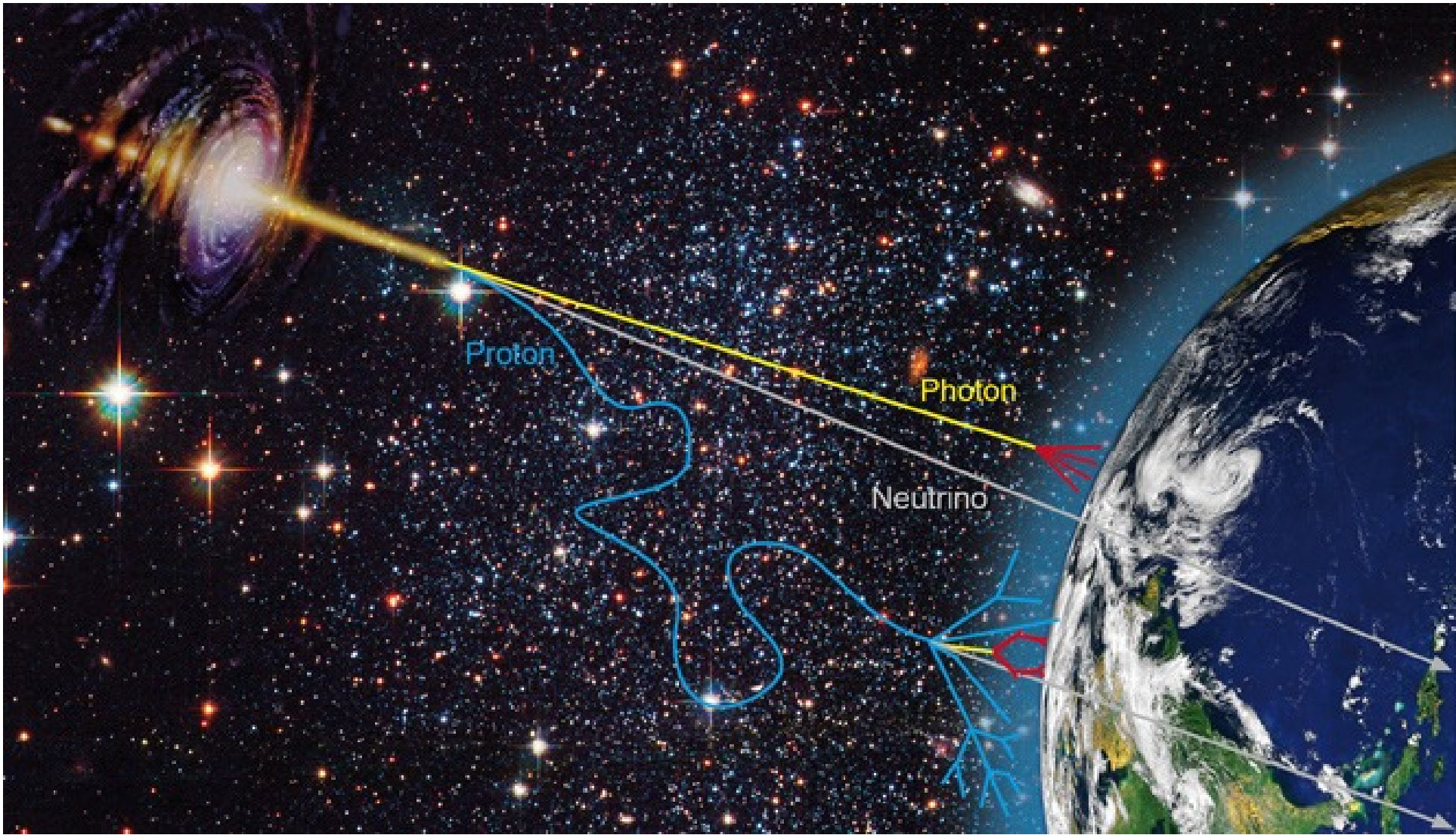
$$\sin^2(2\theta) \sim 0.15$$

$$L_{\text{osc}} \sim \text{few m}$$

Latest results from STEREO



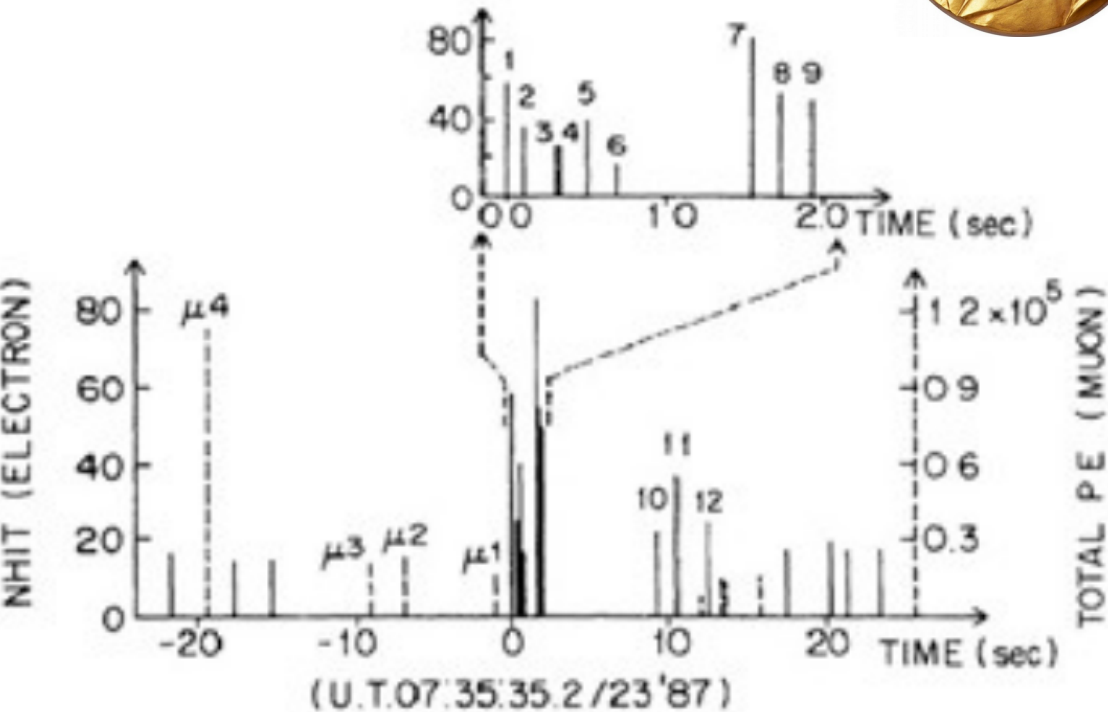
Neutrino Astronomy: *ICECUBE, KM3NET*



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

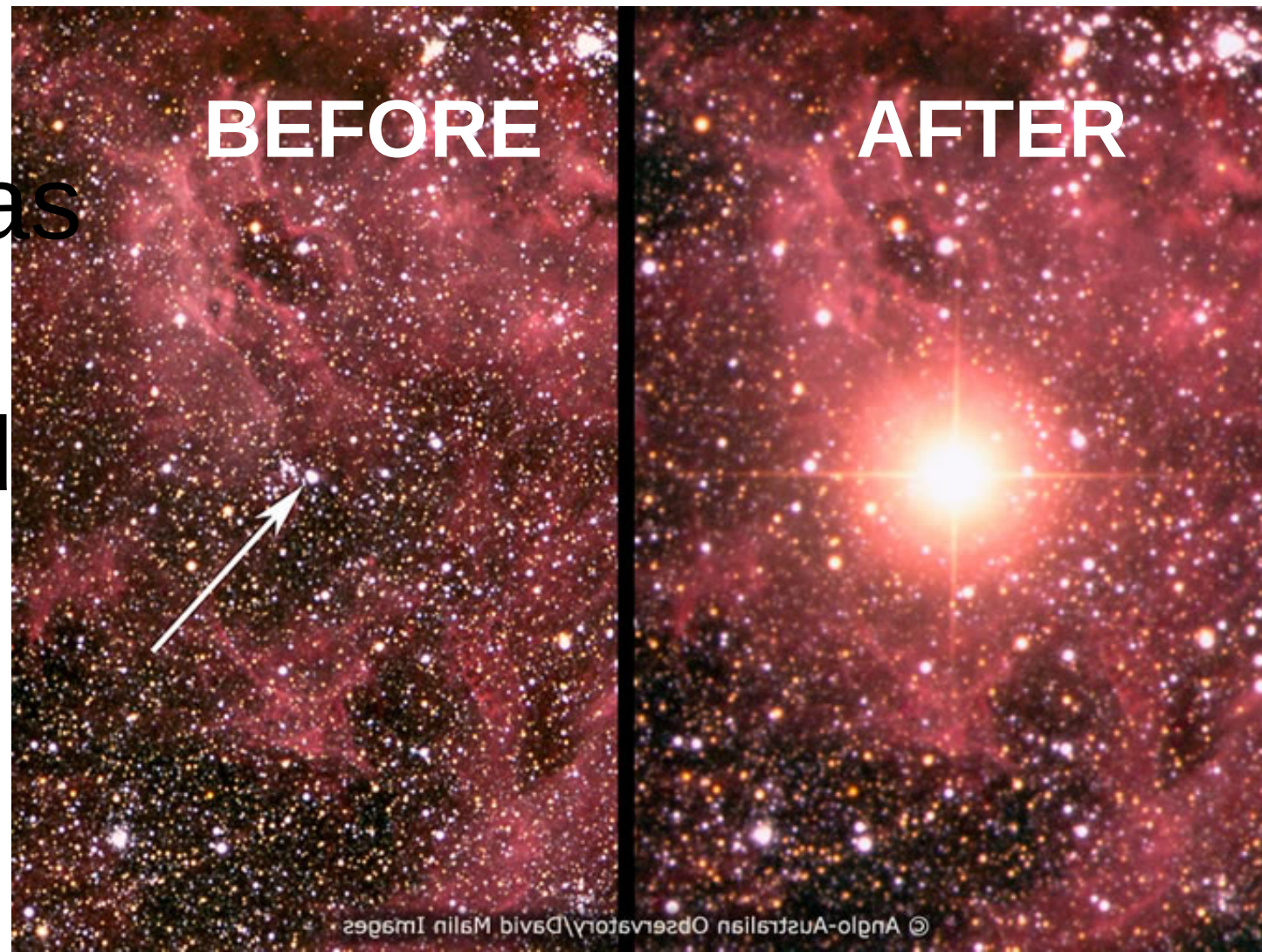
On February 23rd 1987, a supernova exploded in the large magellan cloud (170 000 l.y)
 3h before the light signal, three neutrino detectors observed a large number of events in a very short time (**24 events in 13s**)

9 @ Kamiokande

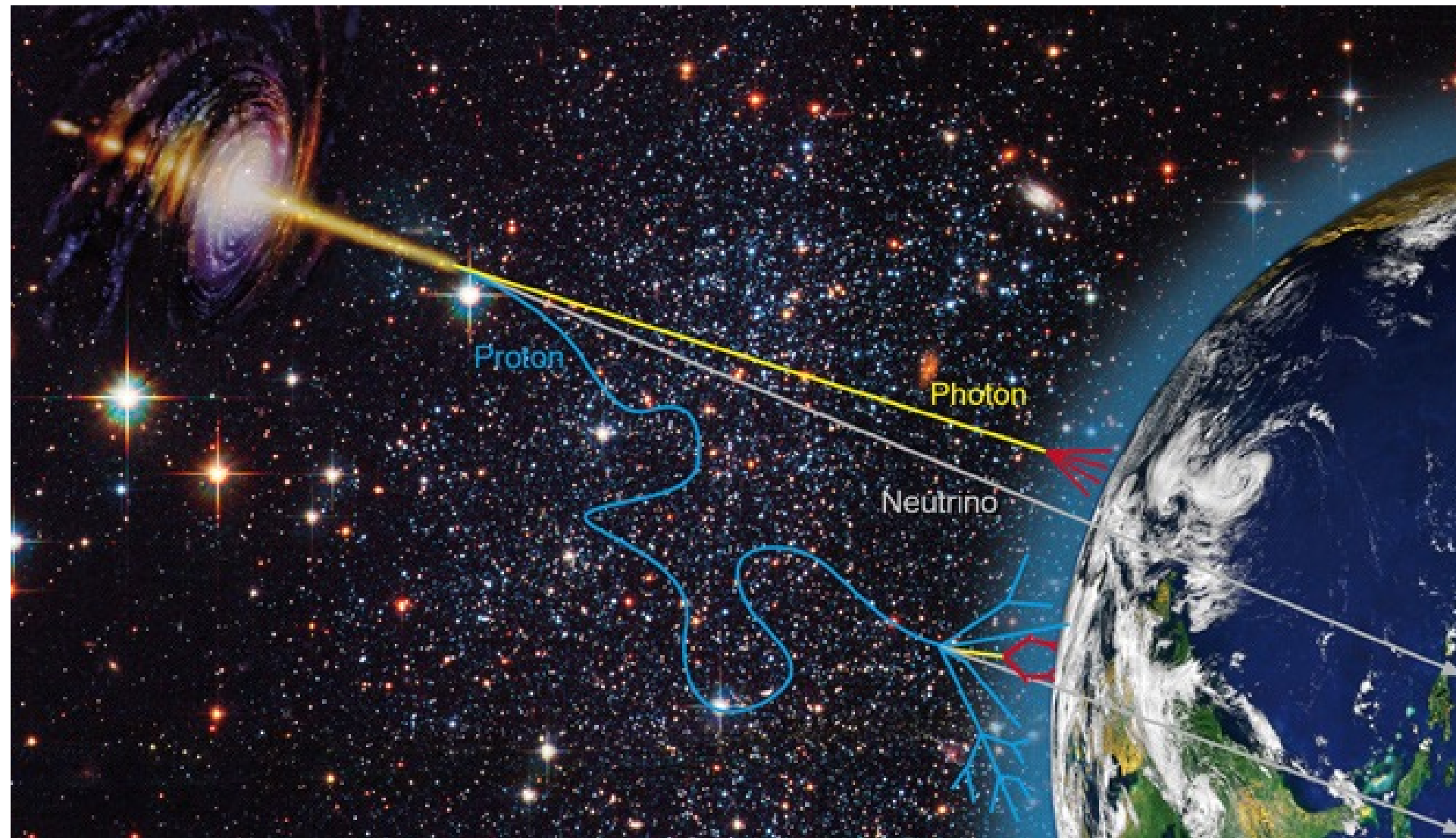


- 99% of the SN energy is released as neutrinos
- 1st case of neutrino astronomy and multi-messenger
- all ν experiments waiting for next nearby SN explosion

SN1987A



Neutrino Astronomy: *ICECUBE*, *KM3NET*



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

On September 22nd 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)

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

