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Neutrino physics

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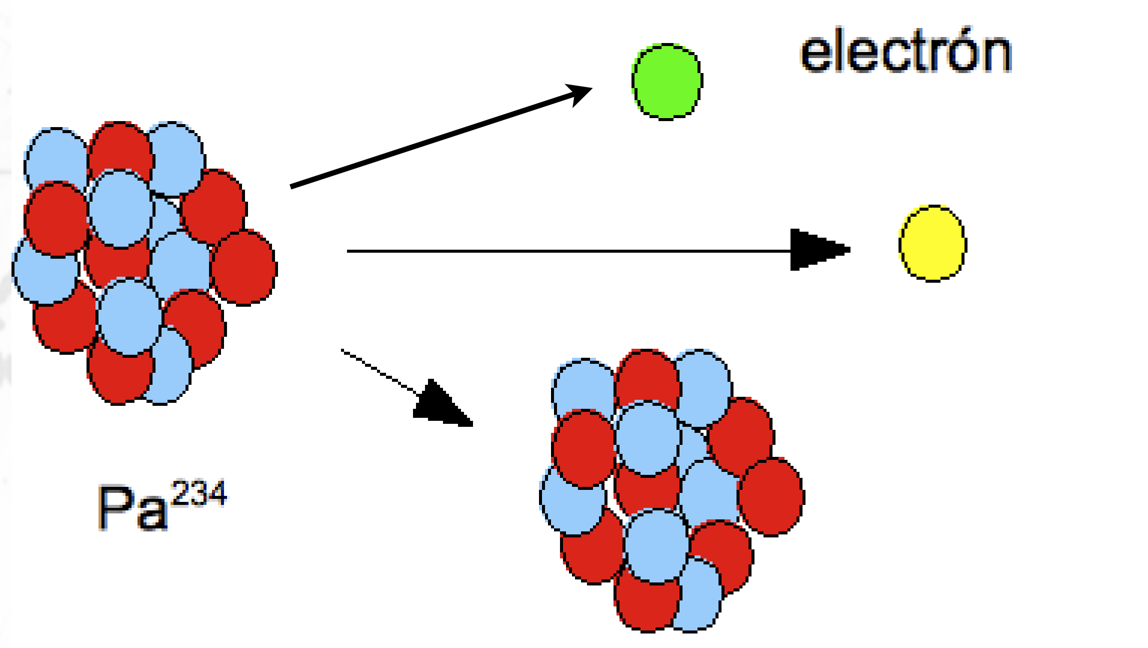
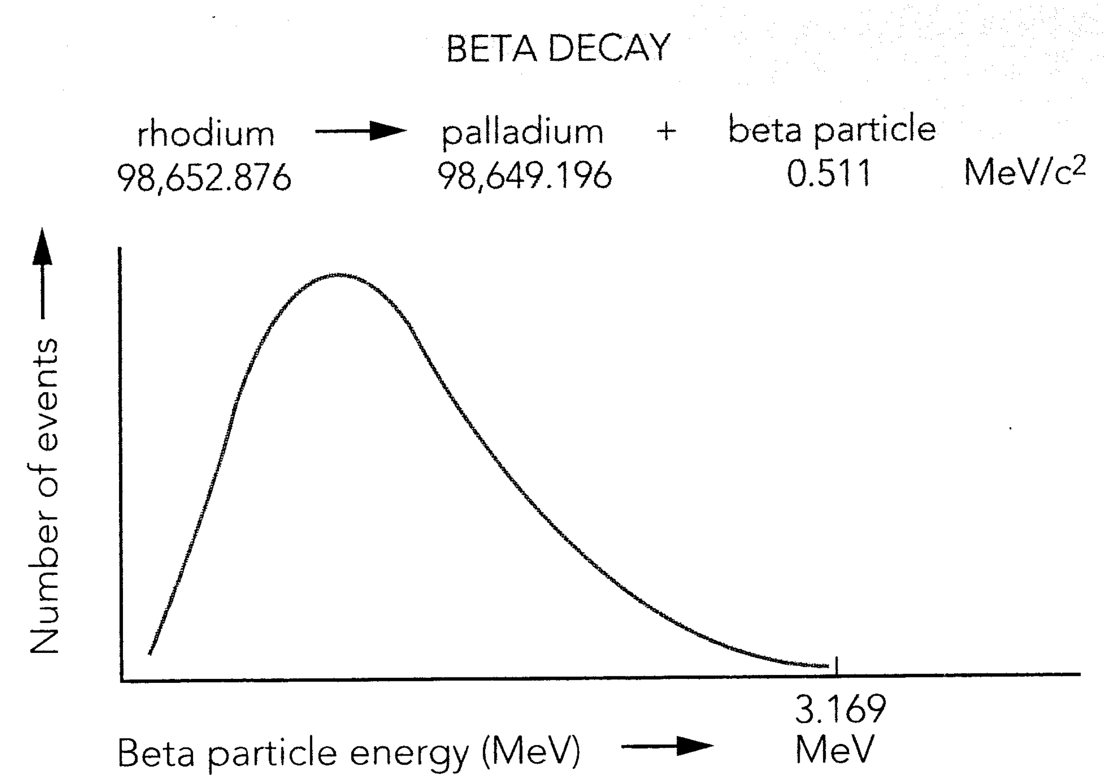
Outlook

- Neutrinos: discovery and early ideas.
- What are neutrinos.
- Neutrino interactions.
- Oscillation phenomenology:
  - Solar neutrinos
  - Atmospheric neutrinos + Long Base line experiments.
  - θ_{13} & CP violation.
- Majorana mass & $0\nu 2\beta$
- Neutrinos and cosmology
- Closing remarks

Neutrinos

- Neutrinos were proposed in 1931 by Pauli in a desperate attempt to understand the beta spectrum.
- Neutrinos were also able to explain the integer number of the Nitrogen nuclei.
- He proposed the existence of an almost massless particle that is invisible:
  - no charge
  - weakly interacting.
  - spin 1/2





Neutrinos

We know now that Pauli was basically right

- Neutrinos are fermions of spin 1/2
- No electric charge and no QCD color (no electromagnetic or strong interactions).
- They interact only through weak and gravitation interactions (feeble).
- Very low mass: < 10^{-6} times the electron mass.
- After discovery of the parity violation in β-decays, the two-component neutrino theory (Landau , Lee and Yang and Salam, 1957) was the first theoretical idea about neutrino masses.
  - *T*wo neutrinos (Left-Right), one of them is “sterile” (do not interact) so it is not “needed”.

Chirality & interactions

- There are 4 independent solutions to the Dirac Equation:

$$i\gamma^\alpha \partial_\alpha \nu_L(x) - m_\nu \nu_R(x) = 0$$
$$i\gamma^\alpha \partial_\alpha \nu_R(x) - m_\nu \nu_L(x) = 0$$

Relativistic spin 1/2 plane wave equation

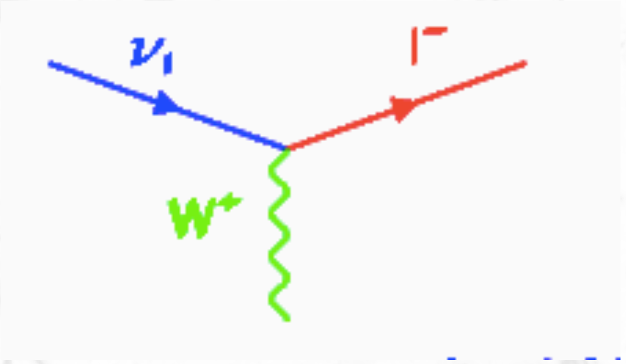
- The 4 solutions (2 particle and 2 antiparticles) can be represented as eigenstates of the (chirality) projector:

Chirality is Lorentz invariant

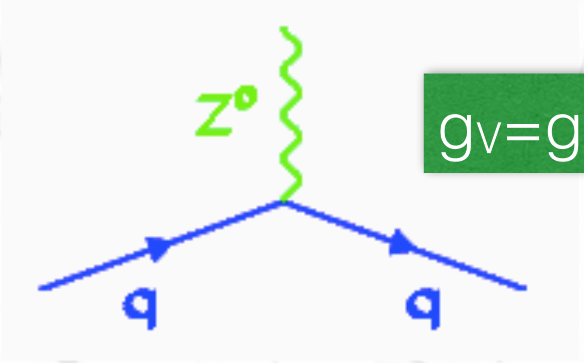
$$P^{R,L} = \frac{1}{2}(1 \pm \gamma^5)$$

- It turns out that nature relates chirality to the weak interactions.

$$-i\frac{g}{\sqrt{2}}\gamma^\mu \frac{1}{2}(1-\gamma^5)$$



$$-i\frac{g}{\cos\theta_W}\gamma^\mu \frac{1}{2}(g_V - g_A\gamma^5)$$



$g_V = g_A = 1$ for neutrinos

Chirality & interactions

- Only Left handed neutrinos and right handed neutrinos interact as a consequence of the weak interaction.

    - It is not true for charged leptons where right handed partners interact through neutral currents and electromagnetic….

Z Couplings	g_L	g_R
ν_e, ν_μ, ν_τ	$1/2$	0
e, μ, τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u, c, t	$1/2 - 2/3 \sin^2\theta_W$	$-2/3 \sin^2\theta_W$
d, s, b	$-1/2 + 1/3 \sin^2\theta_W$	$1/3 \sin^2\theta_W$

- A "traditional" mass term requires the existence of Right handed partners:

Dirac

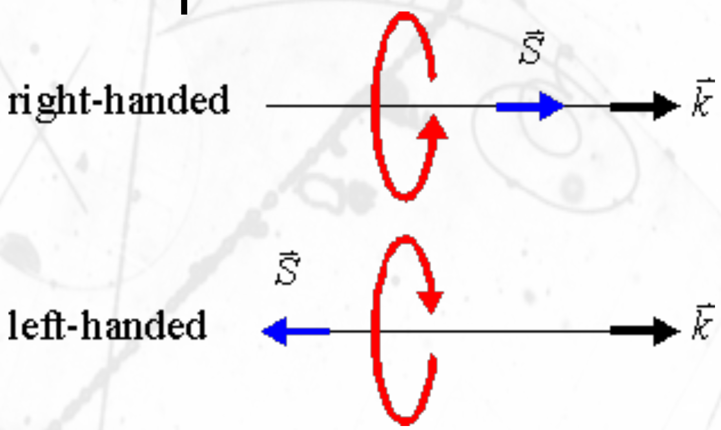
$$\mathcal{L}_D = -m_D \bar{\nu}_L \nu_R + h.c.$$

- But, those partners are sterile (do not interact) in the Standard Model.

If they do not interact, they are not needed, so theoretically
m_ν= 0 is (was) the preferred solution.

Helicity

- Helicity is related to the projection of spin in the direction of movement:



Helicity is **not** a Lorentz invariant Lorentz boost will change particle direction but not the spin rotation sense.

- The helicity projector is

$$P^{L,R} = \frac{1}{2}\left(1 \pm \frac{\vec{\sigma}\cdot\vec{p}}{|p|}\right)$$

- The limit for ultra relativistic particles (or massless) is chirality projector:

$$\lim_{v\to c} P^{L,R} = \lim_{v\to c} \frac{1}{2}\left(1 \pm \frac{\vec{\sigma}\cdot\vec{p}}{|p|}\right) = \frac{1}{2}(1 \pm \gamma^5)$$

- This is the origen of confusion between the two terms.

For massive particles, Lorentz boost can **swap** a **left handed chiral** and **left handed helicity** into a **right handed helicity** state.

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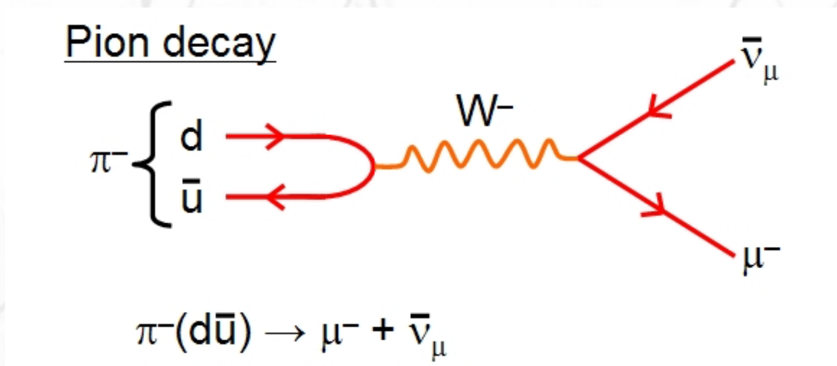
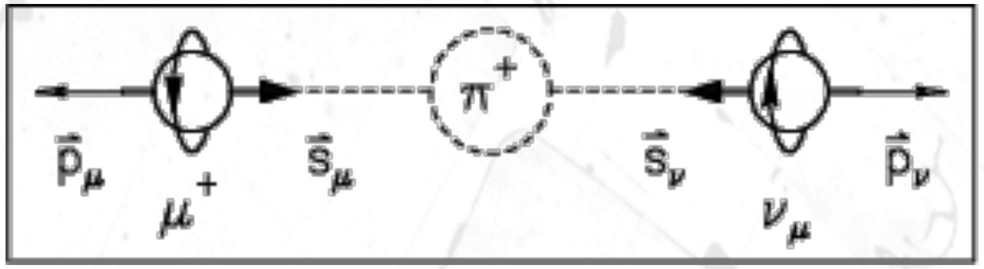
Helicity vs Chirality

- This concept is important to understand the charged pion decay.
- Charged pion is spin 0 particle decaying to neutrino and charged lepton.



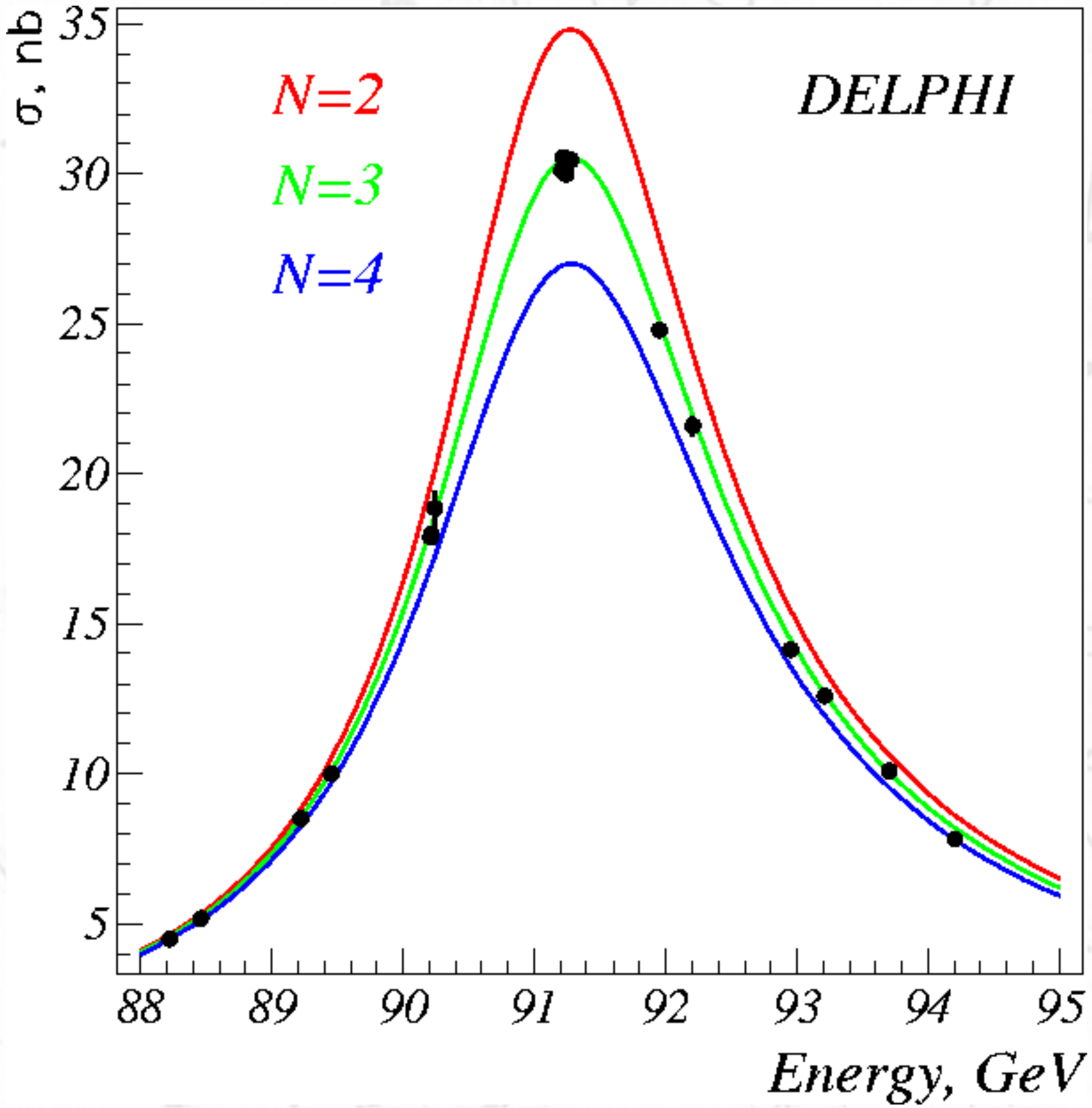


- Spin = 0 forces the final state leptons to have **opposite spin and helicity.**
- But, weak interactions requires both to be **left handed chiral.**

This is a consequence of $(1-\gamma^5)$

- The chiral state has always small component of **“wrong helicity” proportional to the lepton mass.**
  - **Decay to muon** is more **probable than** to **electron** even if it is not favoured by the available phase space.

Number of neutrinos



- Measure as the width of the Z boson scanning the production as function of the center of mass energy

$$e^+e^- \rightarrow Z^0 \rightarrow visible$$

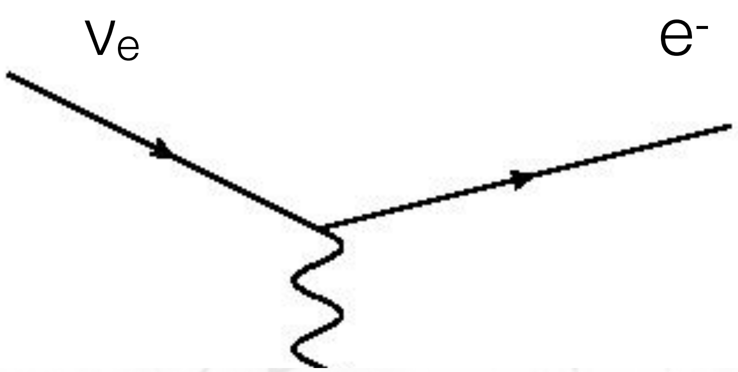
- The width is the sum of the width to all possible disintegration channels

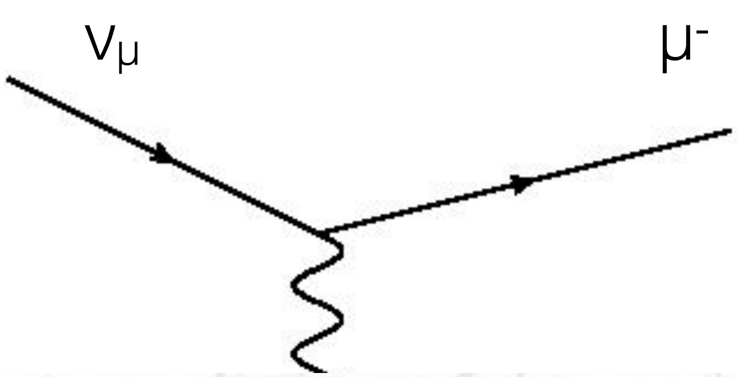
$$\Gamma = \sum_{\nu} \Gamma_\nu + \sum_{q\bar{q}} \Gamma_{q\bar{q}} + \sum_{l^+l^-} \Gamma_{l^+l^-}$$

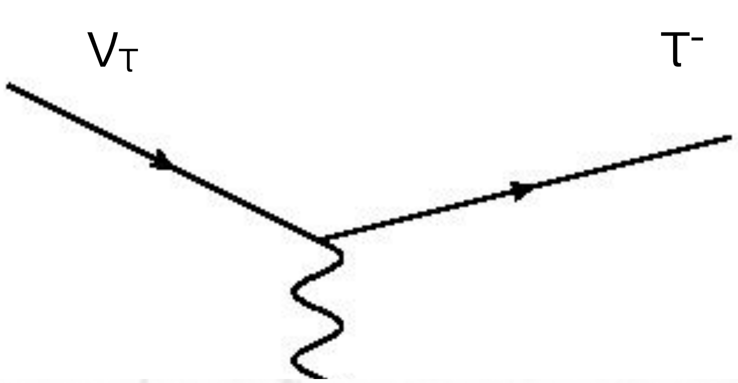
ACTIVE NEUTRINOS WITH MASS < $M_Z/2$ ~ 45 GeV

Neutrino flavours

neutrinos spices= # lepton spices







- Depending on the massive lepton partner in weak interactions, neutrinos are grouped in :
    - ν_e, appears(disappears) associated to electrons/positrons.
    - ν_μ, appears(disappears) associated to muons/antimuons.
    - ν_τ appears(disappears) associated to taus/antitaus.

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Neutrino interactions

What is weak ?

- Neutrinos interact solely through weak interactions.
  - both charged and neutral currents.
- These forces are mediated by massive W and Z bosons.

$$\frac{d\sigma}{dq^2} \propto \frac{\sqrt{2}g_w^2}{8(q^2 - M^2)} \rightarrow \frac{\sqrt{2}g_w^2}{8M^2} = 1.17 \times 10^{-5}/GeV^2$$

  - M_W ~ 80 GeV and g_w ~ 0.7
- This is between 10^4 and 10^7 weaker (depending of q^2) than the electromagnetic interactions.

Mainly because of the massive propagator.

- For very large values of q^2 both are more similar.

Neutrino interactions

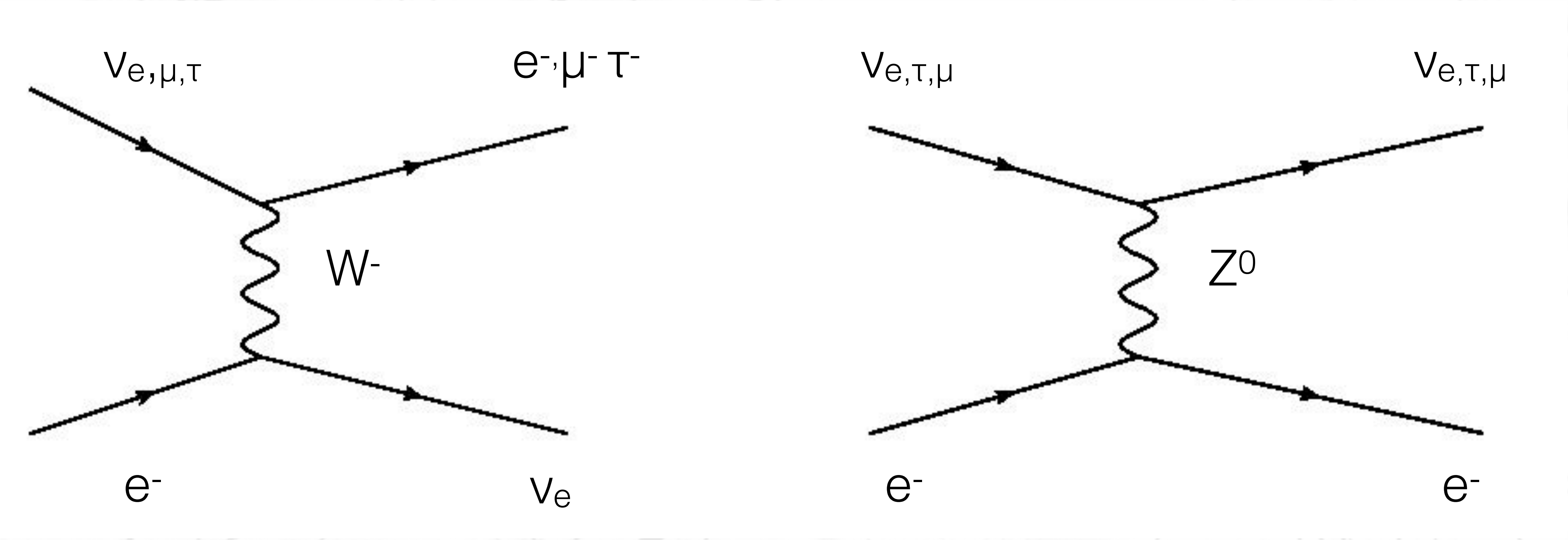
- Being so weak, the detection of neutrinos needs very massive targets: matter!.
  - **Avogadro's number** help!

do not try a ν-ν collider!

- In matter, the neutrino will find:
  - electrons, protons/neutrons & nuclei.
- Significant differences in cross-sections between antineutrinos, neutrinos, neutrino flavours and target type

Neutrino-electron scattering

- All neutrino pieces interact through neutral current with electrons.
- Only electron neutrinos has charged current interactions unless the energy of the neutrino is larger than the lepton mass.



Muon and tau production is only possible if $E_{\nu_{\mu,\tau}} > m_{\mu,\tau}$

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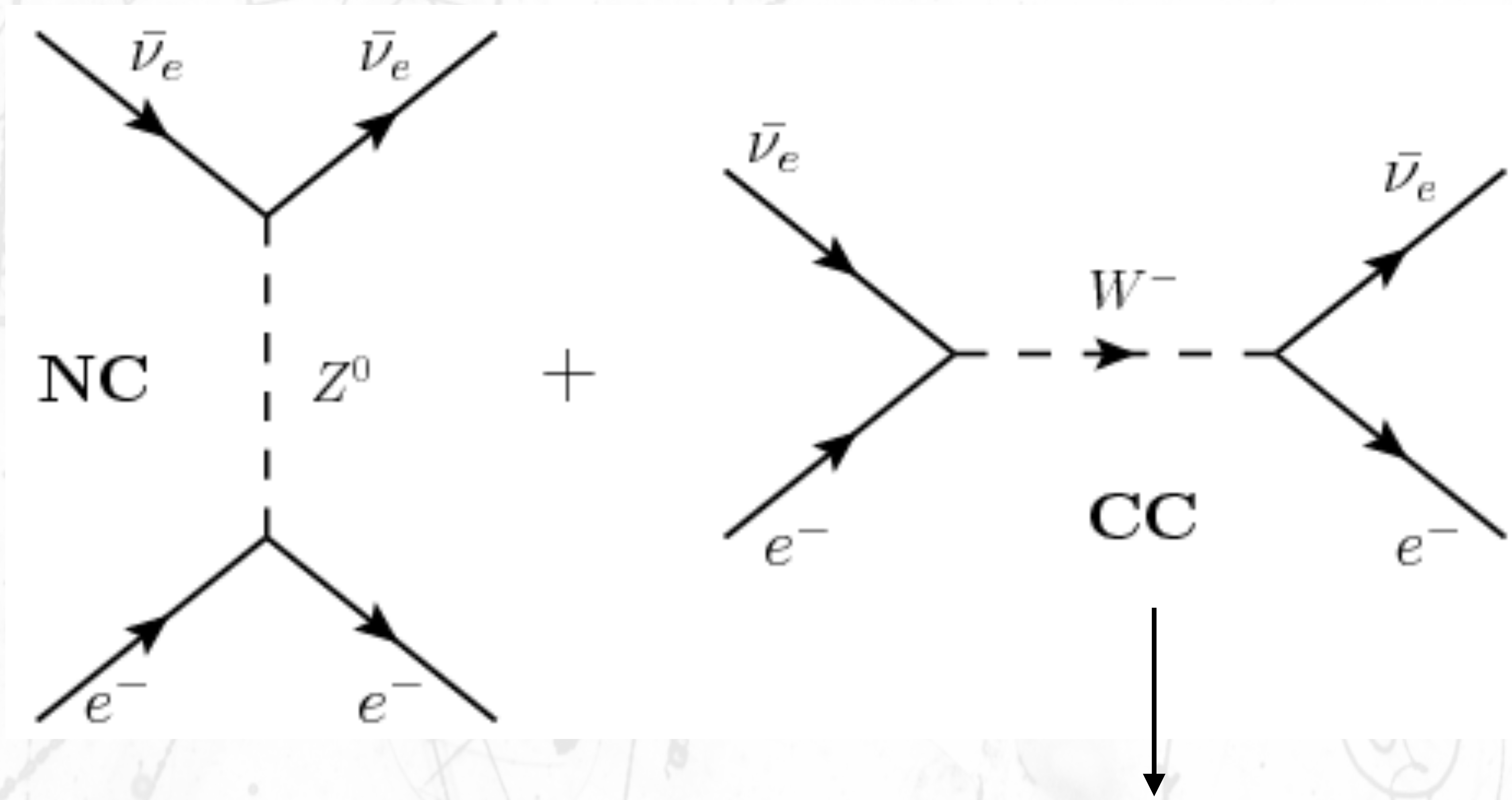
Antineutrino-electron

- All anti-neutrinos interact through neutral current with electrons.
- Only electron anti-neutrinos suffer charged current interactions



If $E_{\bar{\nu}_e} > m_{\mu,\tau}$ muon and tau neutrinos possible in final state.

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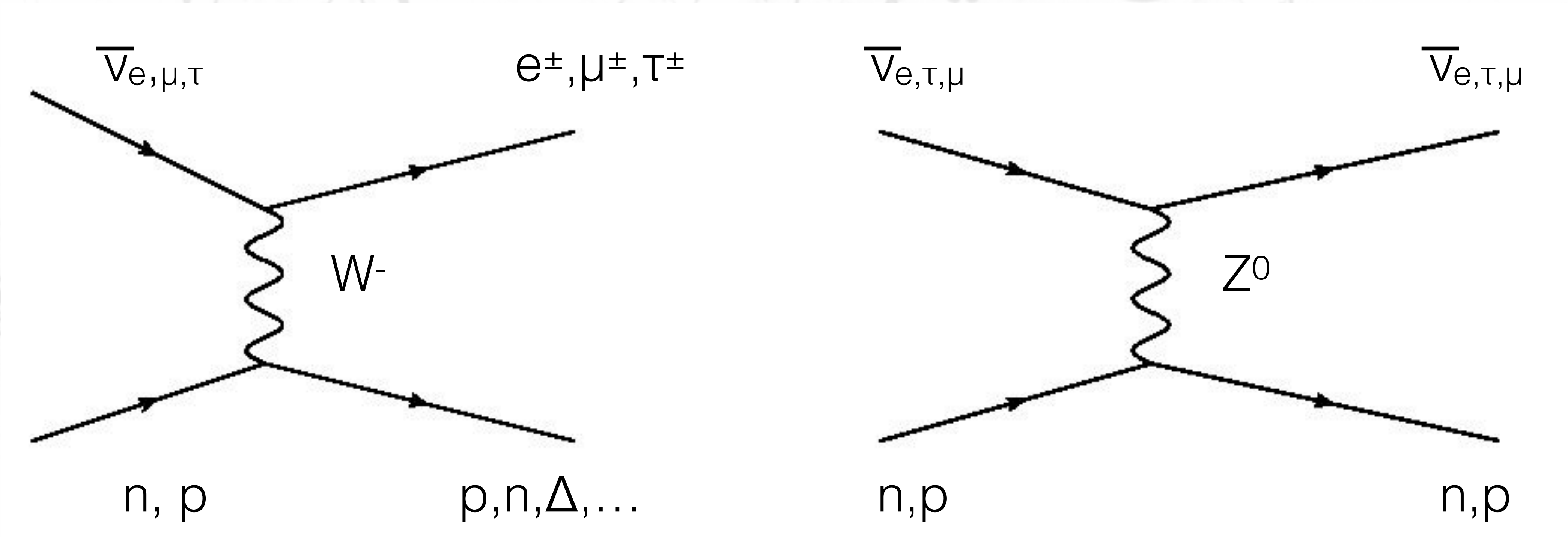
Neutrino-nucleon

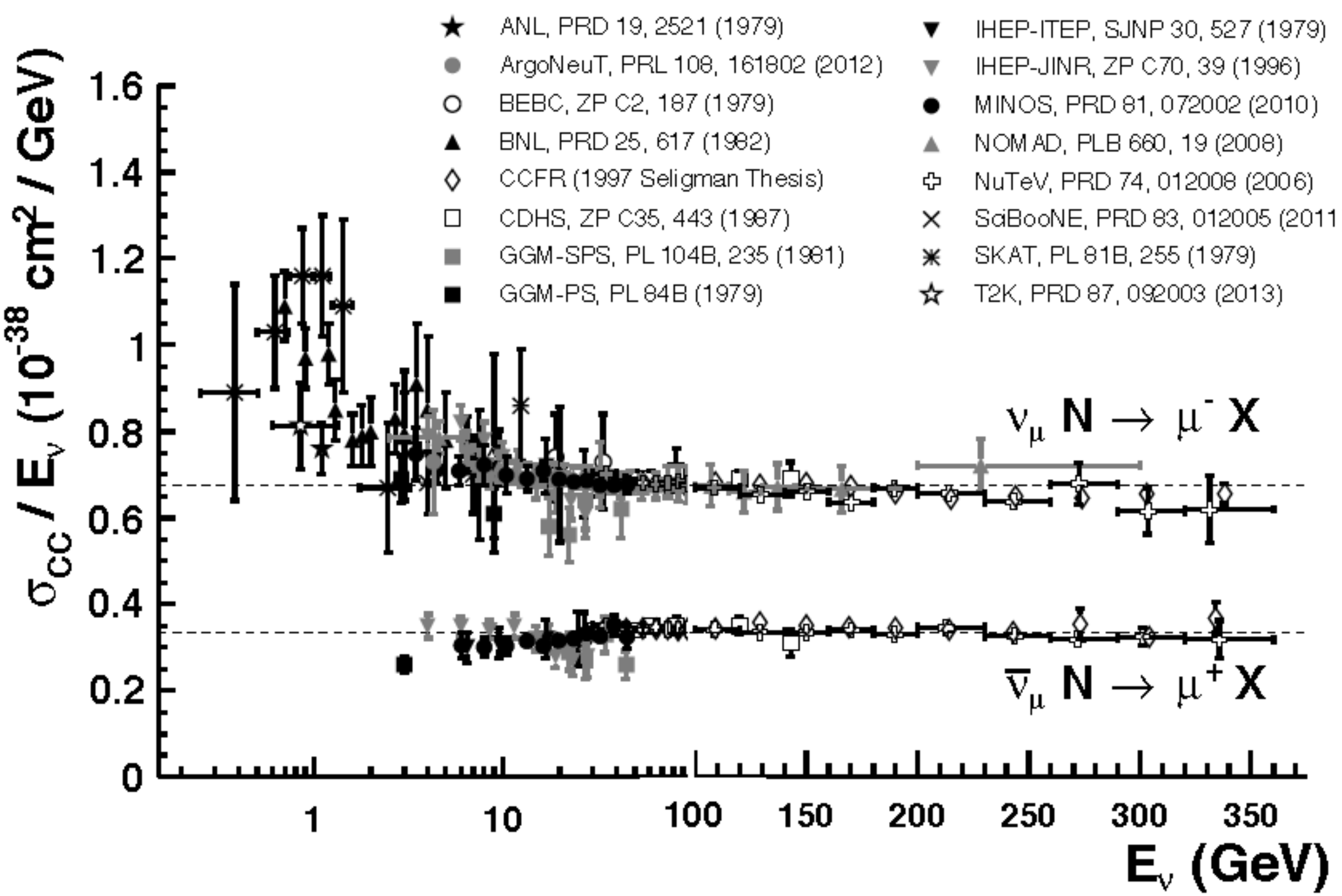
- Both neutrino and antineutrinos have charged and neutral current interactions with nucleons.



- But with different strength.

$$\sigma_{\nu,CC} \approx 2\sigma_{\bar{\nu},CC}$$

Neutrino-nucleon



Neutrino-nucleon

- Several interaction channels depending on the hadronic final states. (Equivalent for neutral currents)

CCQE

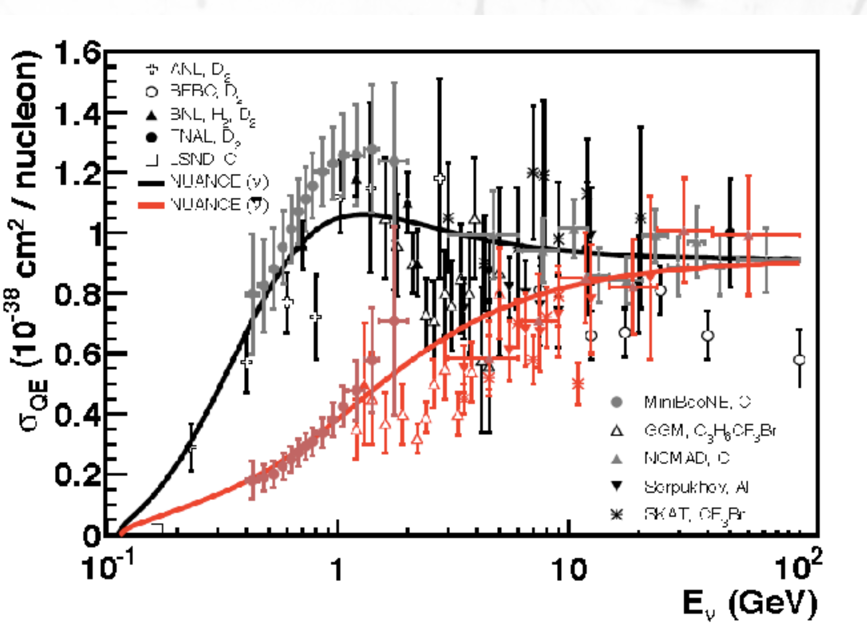
$$\nu_\mu n \to \mu^- p$$
$$\bar{\nu}_\mu p \to \mu^+ n$$

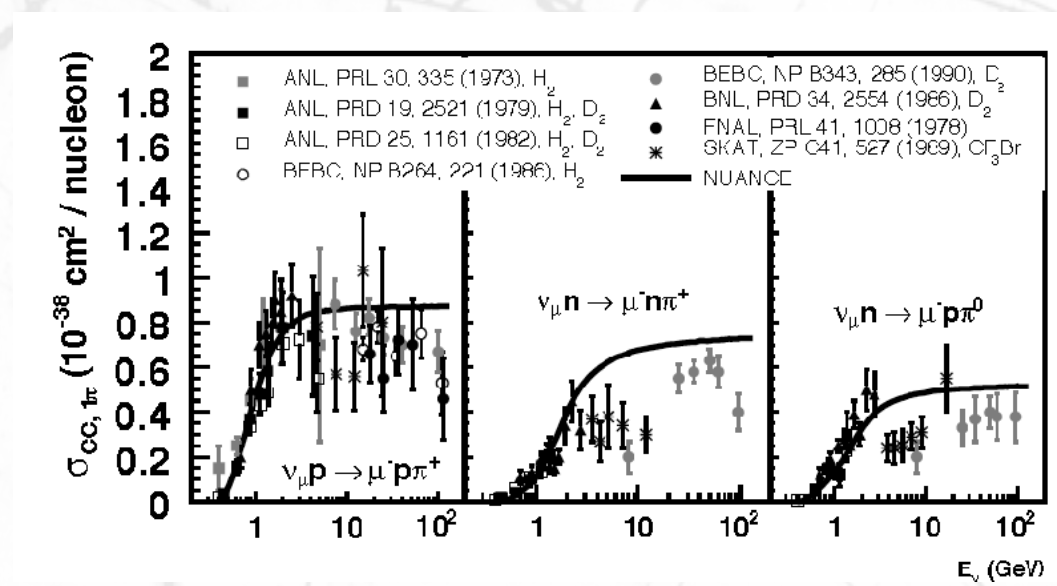
CCRes

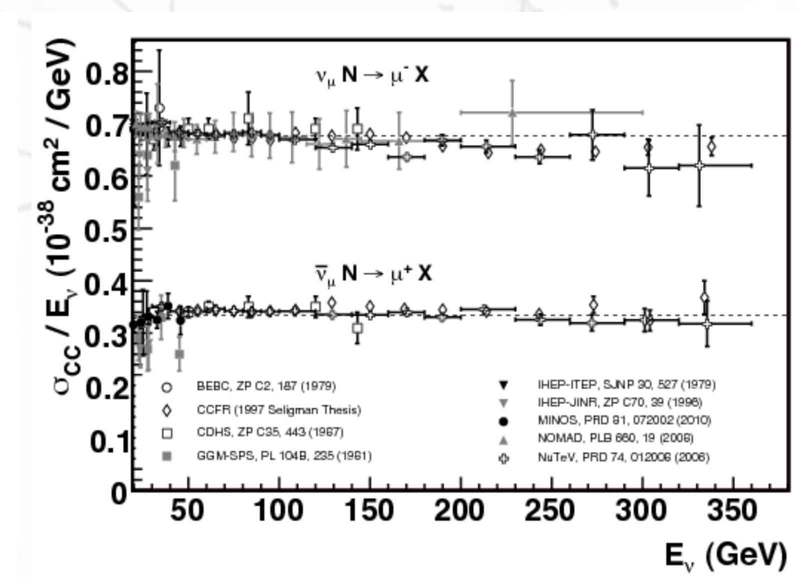
$$\bar{\nu}_\mu p \to \mu^+ \Delta^0$$
$$\bar{\nu}_\mu n \to \mu^+ \Delta^-$$
$$\nu_\mu p \to \mu^- \Delta^{++}$$
$$\nu_\mu n \to \mu^- \Delta^+$$

CCDIS

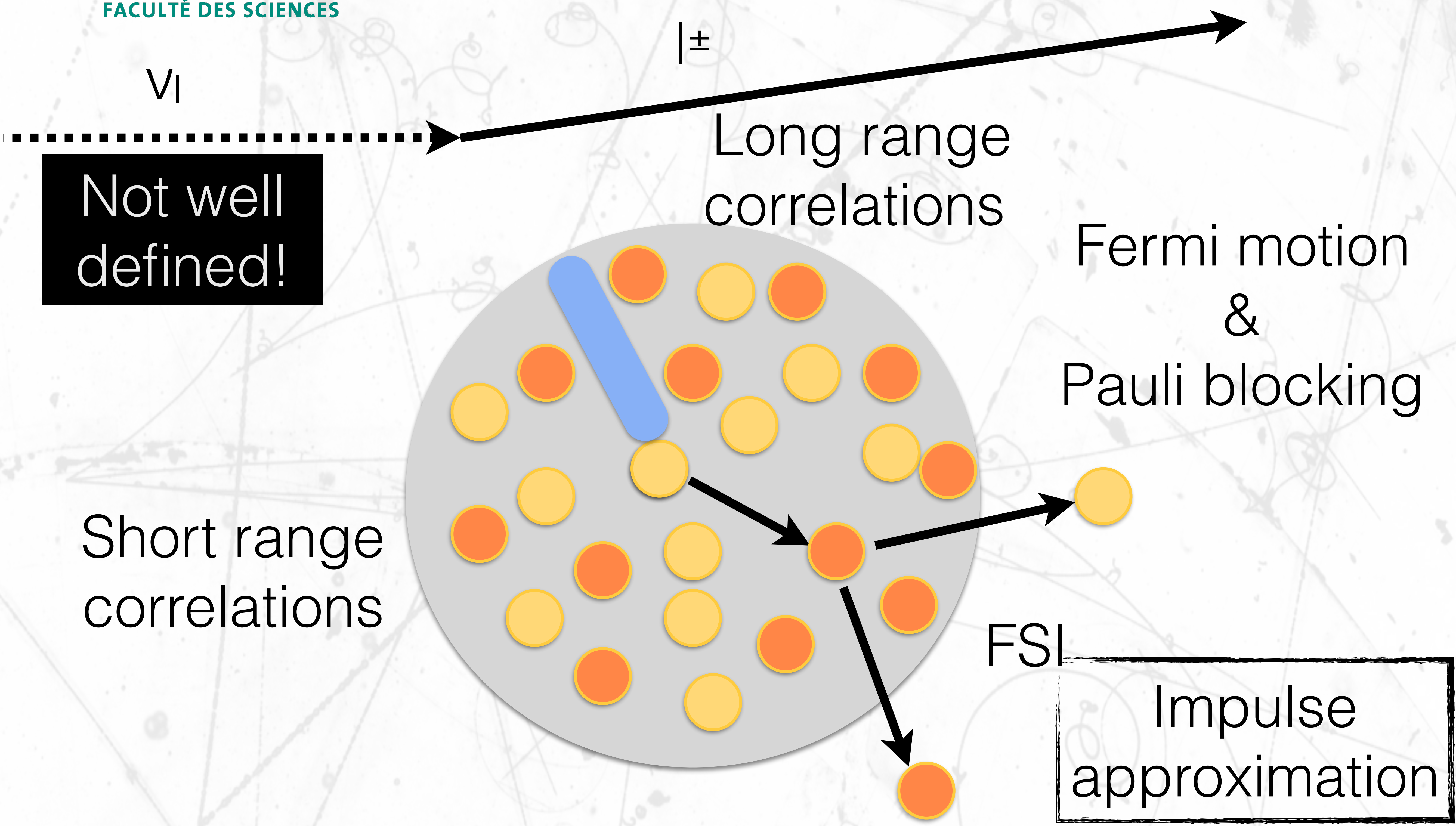
$$\bar{\nu}_\mu N \to \mu^+ X$$
$$\nu_\mu N \to \mu^- X$$



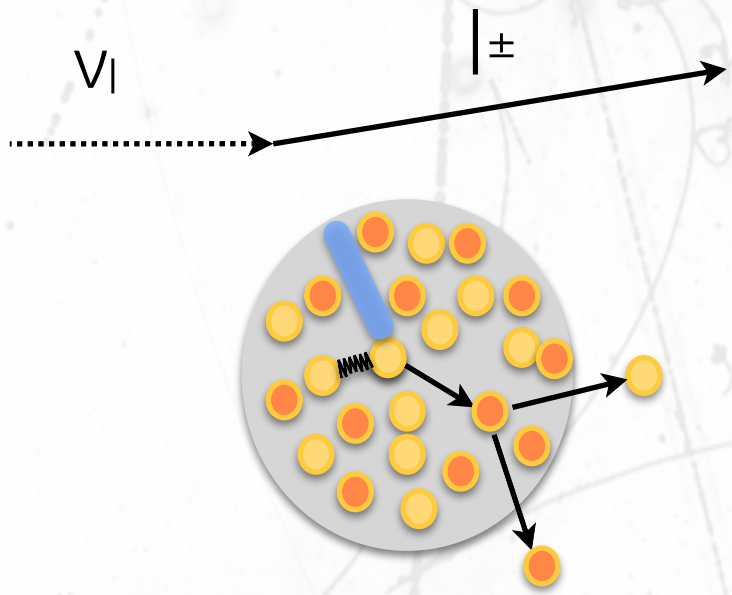




Neutrino - Nuclei

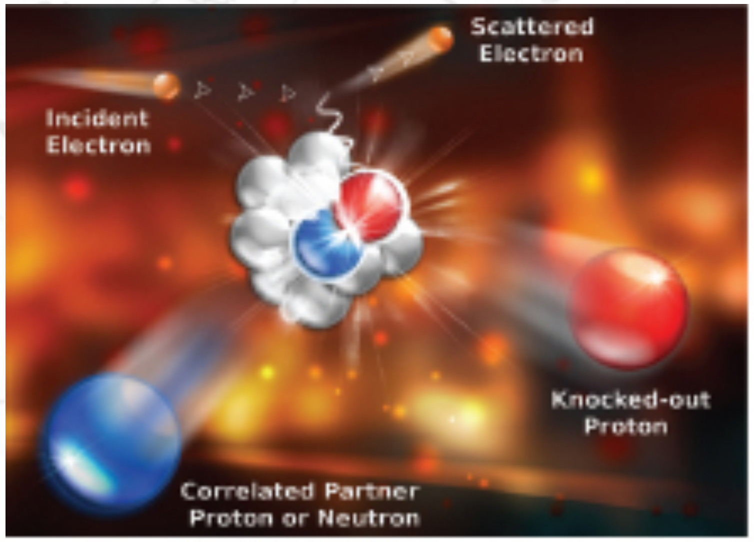


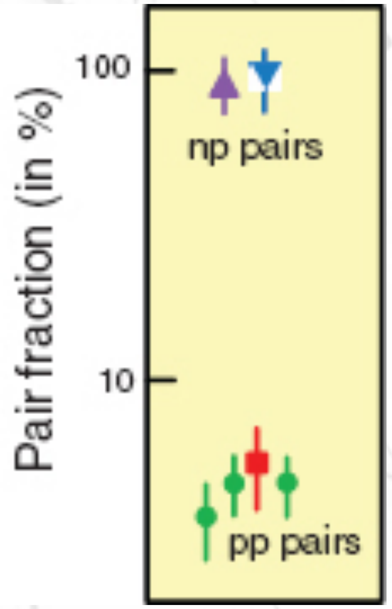
Modelling interactions



- Normally considered the "impulse approximation" or factorisation:
  - nucleon **assumed** free in nuclear media !
  - nucleon free in nuclear potential: no nucleon correlations!.

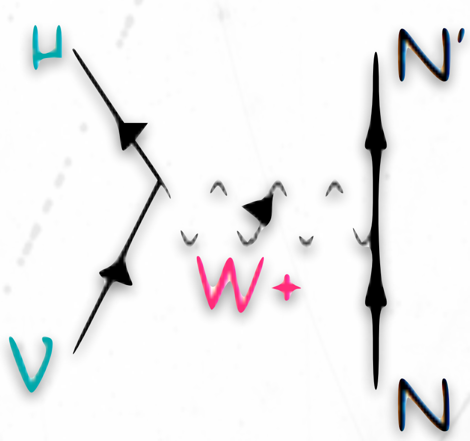
- Nuclear effects added on the top:
  - Fermi momentum.
  - Pauli blocking.
  - Short and long range nuclear correlations.



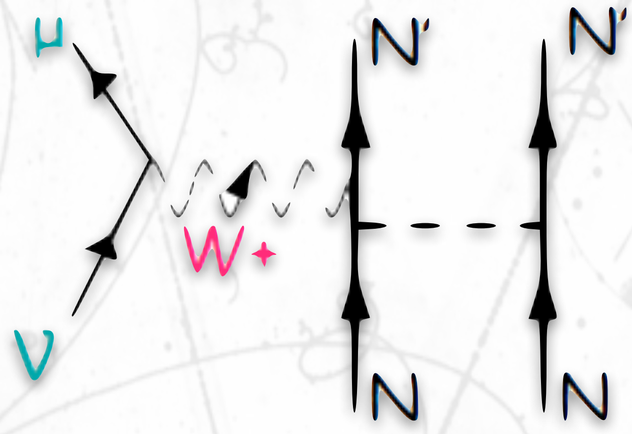


Modelling interactions

A very special case: 2p2h



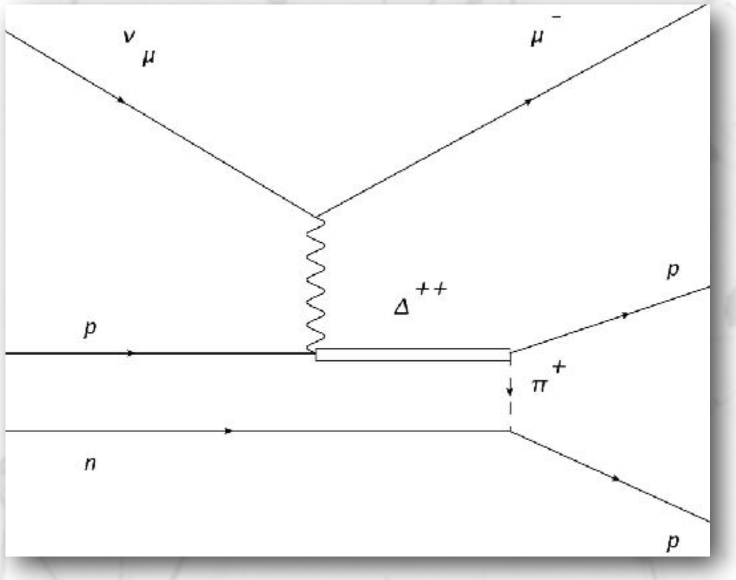
CCQE

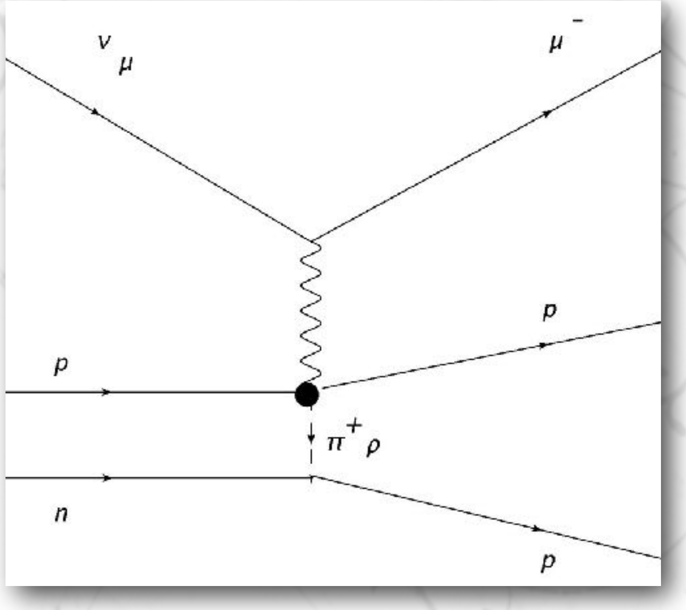


CC-2p2h

- Charge current without pions are made of several interactions
- 2p2h is basically the exchange of a meson between two close by nucleons in the nucleons with the emission of 2 nucleons.

2p2h is ~20/30% of the interaction with one nucleon





- The pion can be produced in a contact point or virtual Δ^{++}.

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Neutrino and its mass

Neutrino oscillation

Early ideas

- **Pontecorvo** proposed, back in **1957**, that the lepton sector might show oscillation phenomena similar to that of the K^0 meson. Neutrinos were neutral particles, and the lepton-hadron analogy was assumed.

- At that time Davis was doing experiments with anti-neutrinos from a reactor looking for the reaction:

$$\bar{\nu}_e \ {}^{37}Cl \rightarrow e^- \ {}^{37}Ar$$

As many other times there were hints that finally vanished.

  - And observed some events.

- At that time only one neutrino especie was known and then the one option was to have oscillations (also similar to K^0 system) was:

$$\nu \rightleftharpoons \bar{\nu}$$

- In his model, he was already proposing that ν were a mixed system of **two "Majorana particles" with different mass (ν_1,ν_2). (We will come back to this!)**

Neutrino oscillation

- The $\boldsymbol{\nu_\mu}$ was discovered at Brookhaven in **1962** by **Lederman, Schwartz and Steinberger.**

- At this time, **Pontecorvo** proposed the alternative model based on $\boldsymbol{\nu_\mu \leftrightharpoons \nu_e}$ **oscillations.**

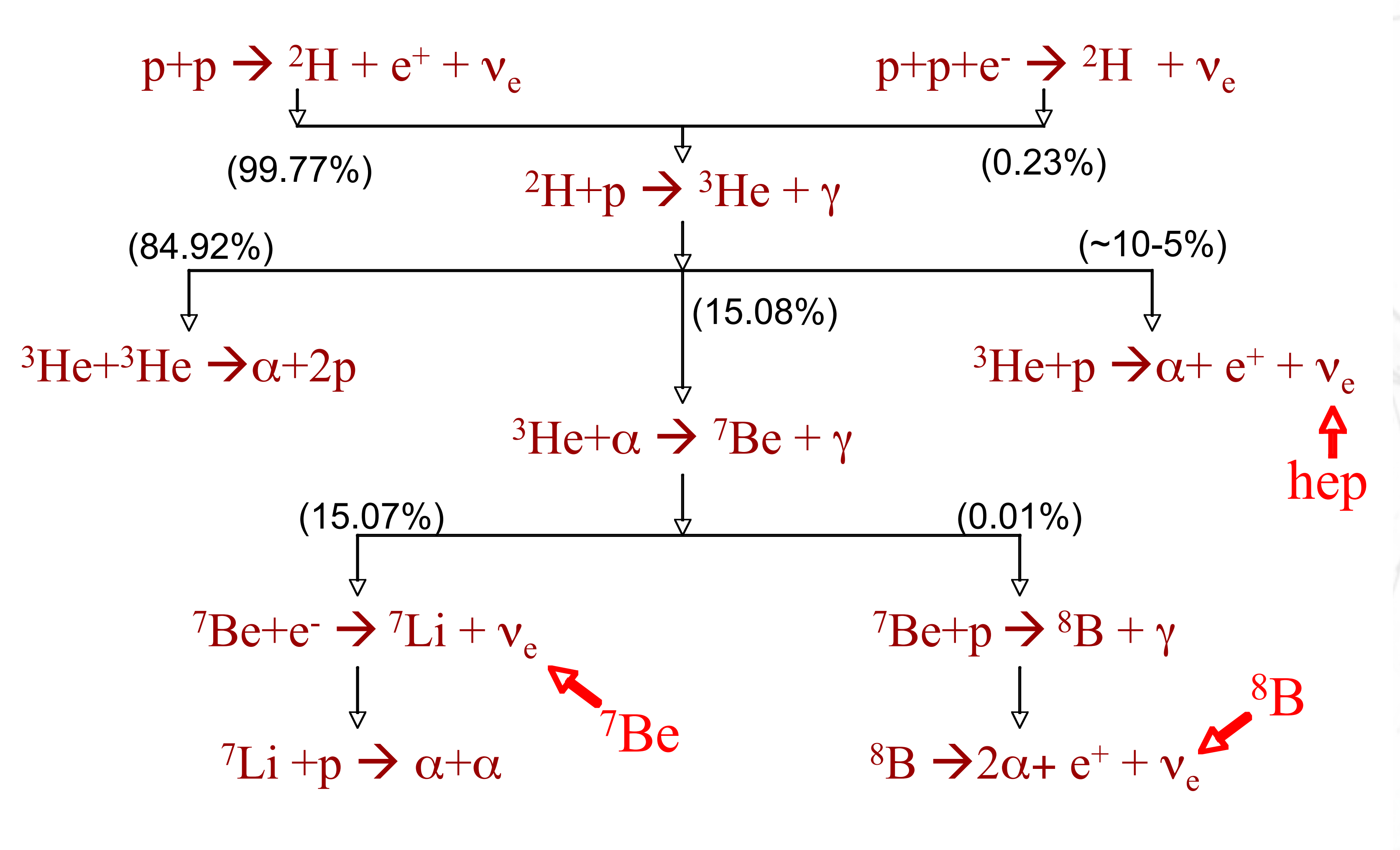
  - The model "only" required that **neutrinos were massive.**

- Around this time, the first experiments to detect **Solar neutrinos** were proposed by Davis & Bahcall. Pontecorvo suggested that if neutrinos oscillate, the experiments will see fraction of the predicted neutrinos from the sun …

  - $\nu_e \rightarrow \nu_\mu$
  - $+$ *not enough energy to produce a muon, so* ν_μ *is invisible*.

Solar neutrinos

- The sun is a thermal fusion nuclear reactor.
- The sequence of reactions is known to a good level.
- This allows to predict a relation between the neutrinos and the sun luminosity in photons.



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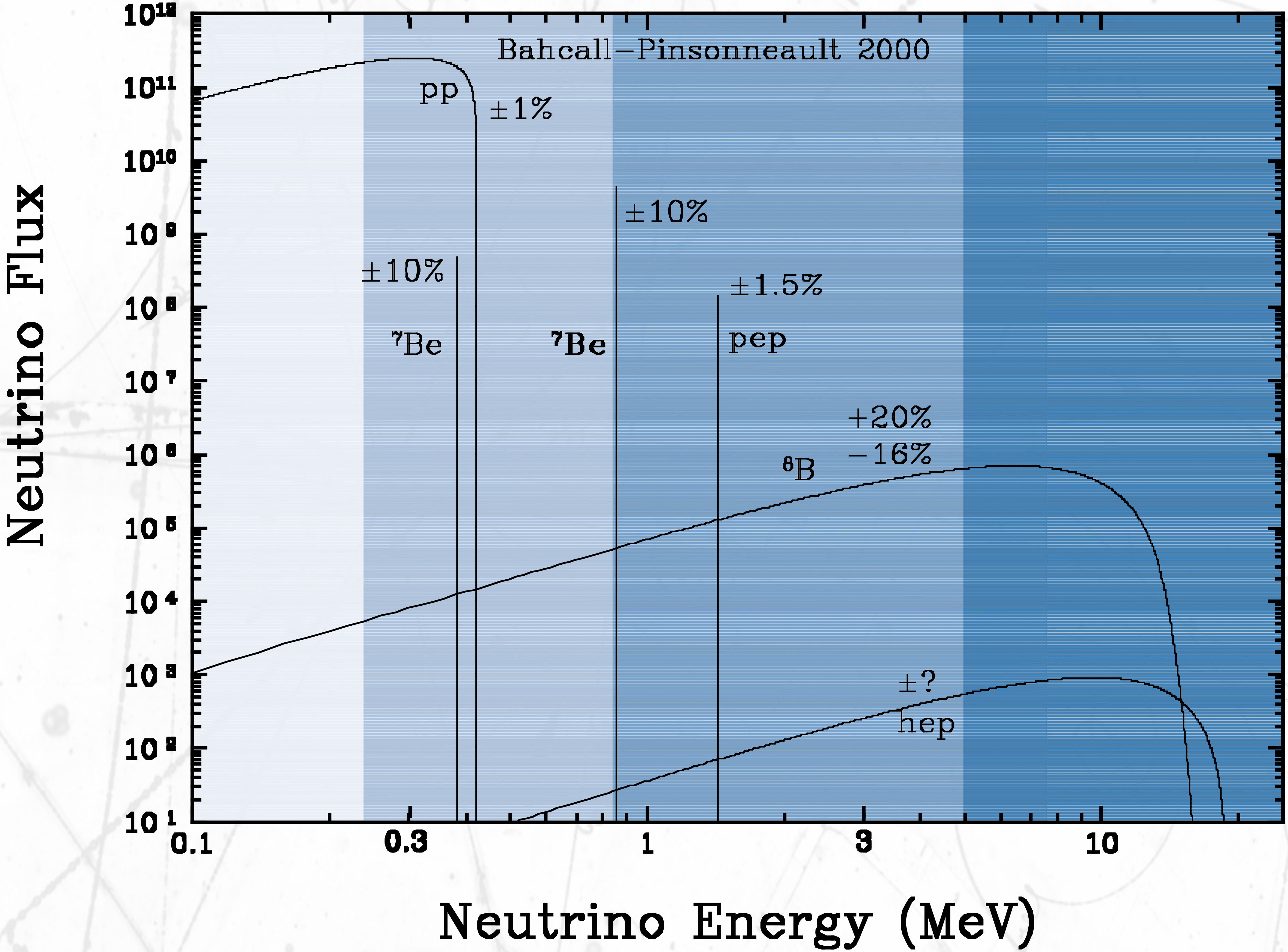
Solar neutrinos

- Solar net reaction is **$4p \rightarrow {}^4He\ \ 2e^+\ \ 2\,\nu_e$**
- The sun releases **25.7MeV/c^2, or 4.12x10^{-12} Jules per Helium nucleus produced (or ½ of that per neutrino).**
  - The solar constant is **1370 Watts/m^2** at Earth's orbit.
  - The neutrino flux should be then 1370/(2.06x10^{-12})/m^2/sec or
    - **6.65x10^{10}/cm^2/sec.**
- This number is known to ~10% level.

The sun produces neutrinos, not antineutrinos!

Solar neutrinos



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Solar Neutrinos

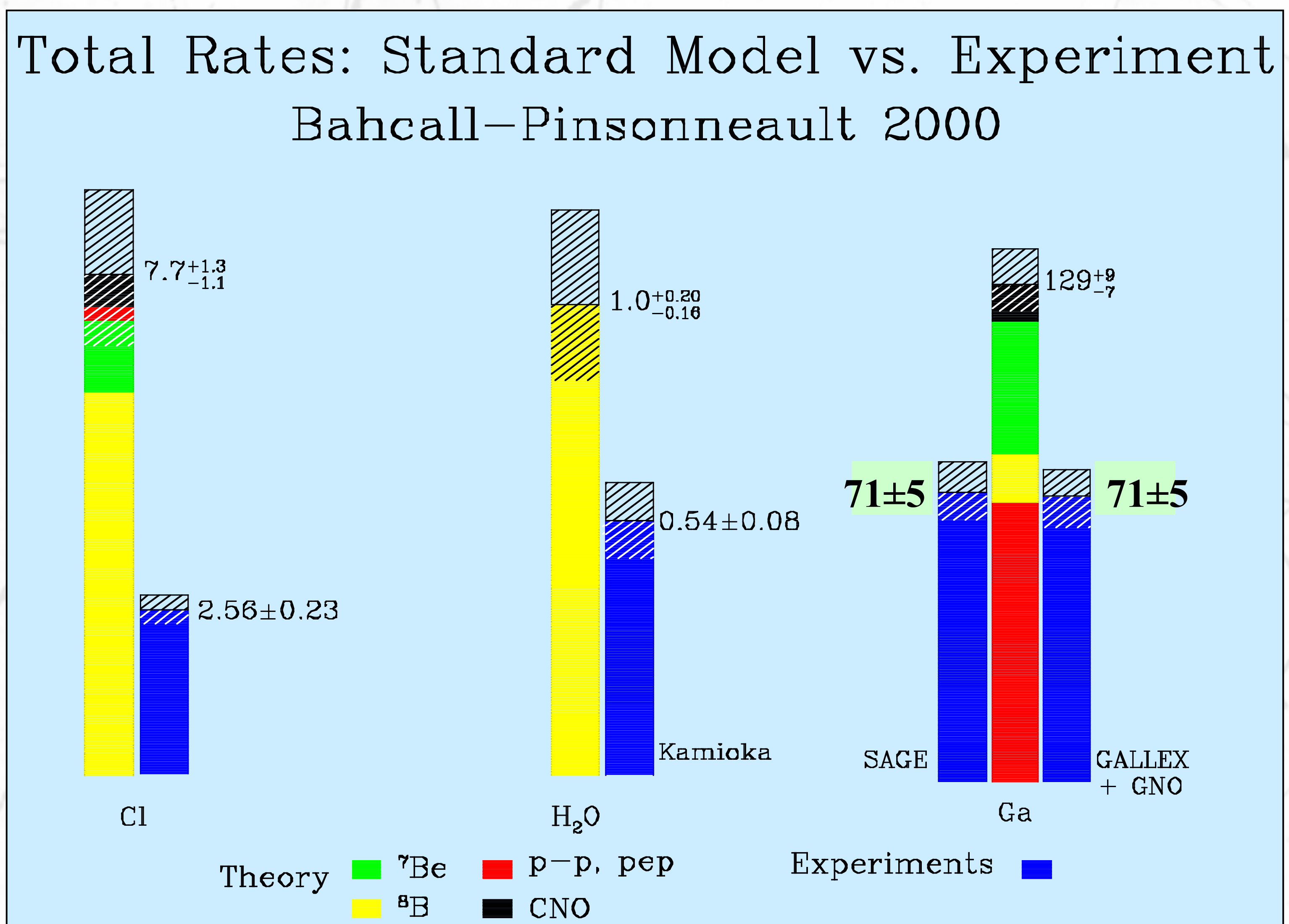
The experiments

- The first experiments were based on **radiochemical** detection:
  - Chlorine: $\nu_e\,^{37}Cl \rightarrow {}^{37}Ar\ e^-$ ($E_\nu > 0.8$ MeV ~ $M_{Ar}+m_e-M_{Cl}$)
  - SAGE/Gallex/GNO: $\nu_e\,^{71}Ga \rightarrow {}^{71}Ge\ e^-$ ($E_\nu > 0.2$ MeV ~$M_{Ge}+m_e-M_{Ga}$)
- Later the water **Cherenkov detector Kamiokande** was added to the list with a threshold of ~6 MeV (much larger than the radiochemical experiments!)
  - Water Cherenkov added the possibility of online event recording and the determination of neutrino direction:
    - Reduced background, Day/Night and seasonal effects...

Solar neutrinos

- All of them detected neutrinos, but at a **smaller rate** than expected:
  - solar model?, detector efficiencies?, neutrino deficit through oscillations?,…
- This disagreement was called for years **“the solar neutrino problem”.**

The experiments



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Solar neutrino problem

The strength of paradigm

- Pontecorvo: "Unfortunately, the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos..."

- Georgi & Luke: "Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3..."

- Yang: "I did not believe in neutrino oscillations even after Davis' painstaking work and Bahcall's careful analysis. The oscillations were, I believed, uncalled for."

- Drell: "… the success of the Standard Model was too dear to give up."

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What are neutrino oscillation?

The theory

- The first **phenomenological** neutrino oscillation model was elaborated by **Gribov and Pontecorvo in 1969.**

- The model assumed that:

  - **neutrinos have mass,** albeit a very small one.

  - **neutrinos interacts as ν_e or ν_μ** (neutrino flavour).

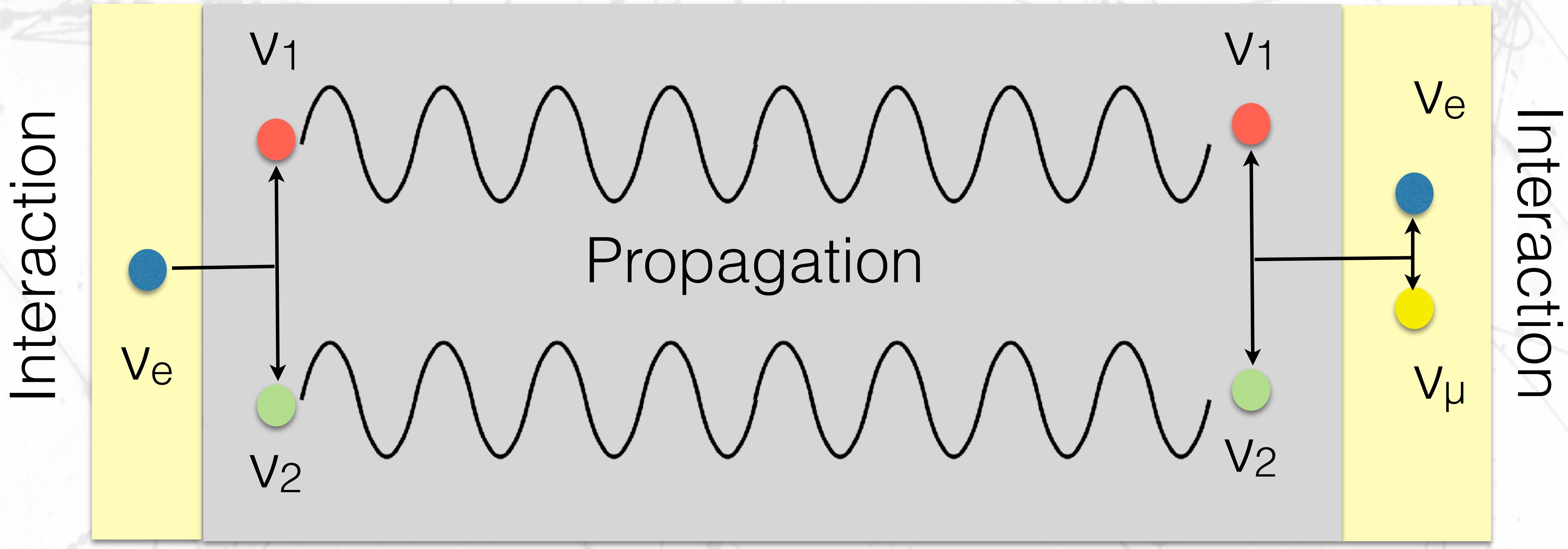
  - the **eigenstates of flavour and mass(Lorentz) are not the same**. They can be related via a linear combination or rotation between the two bases.

$$
\begin{aligned}
|\nu_e > &= \cos\theta|\nu_1 > + \sin\theta|\nu_2 > \\
|\nu_\mu > &= -\sin\theta|\nu_1 > + \cos\theta|\nu_2 >
\end{aligned}
$$

Neutrino oscillation

The theory

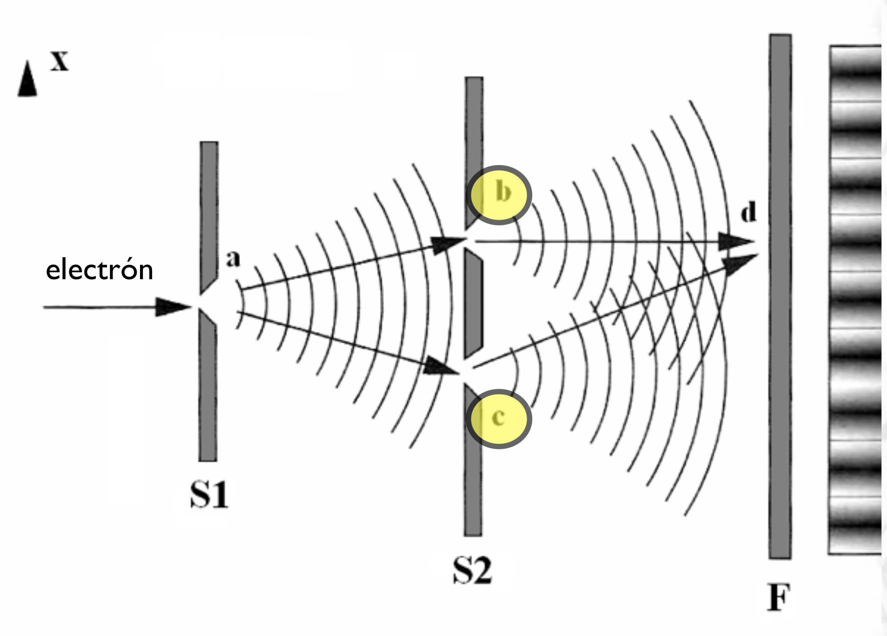
If neutrinos 1 & 2 propagate at different speeds (mass) and they keep the coherence at the interaction point the proportions are changed and it might appear other neutrino flavour.



Neutrino oscillation: analogy

Neutrino oscillations is similar to the **double slit** experiment.

Analogy



Each **slit** is equivalent to a **mass state** in the neutrino case. It is a different path to go from emission to detection.

- Neutrinos are produced always as a flavour neutrino but they propagate in vacuum as mass eigenstates. They follow **two paths**!

Particles go from source to detector through **both slits.**

Neutrinos fly through **both mass** states at the same time.

Every slit gives a different **path length** (**phase**) → **interference**

Every mass state gives a different **path length** (**phase**) → **interference**

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Neutrino Oscillation

The theory

- When we produce electron neutrino:

$$|\nu_e> \quad = \quad \cos\theta|\nu_1> + \sin\theta|\nu_2>$$

- Neutrinos are transported in vacuum following the Schrödinger equation in vacuum:

$$i\hbar\frac{\partial\nu}{\partial t} = H\,\nu = E\,\nu = \sqrt{m_\nu^2 + p^2}\,\nu$$

- $m_\nu << p$: $E = \sqrt{p^2+m^2} = p\sqrt{1+\frac{m^2}{p}} \approx p(1+\frac{1}{2}\frac{m^2}{p}) = p + \frac{1}{2}\frac{m^2}{p}$

$$i\hbar\frac{\partial\nu}{\partial t} = (p + \frac{m_\nu^2}{2p})\nu$$

$$\nu(t) = e^{i(p+\frac{m_\nu^2}{2p\hbar})t}\nu(0)$$

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Neutrino Oscillation

The theory

- If we produce a ν_e, after some time the state is:

$$|\nu_e; t >= \cos\theta e^{i(p+\frac{m_1^2}{2p})\frac{t}{\hbar}}|\nu_1; 0> + \sin\theta e^{i(p+\frac{m_2^2}{2p})\frac{t}{\hbar}}|\nu_2; 0>=$$
$$e^{i(p+\frac{m_1^2}{2p})}(\cos\theta|\nu_1; 0> + \sin\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}|\nu_2; 0>)$$

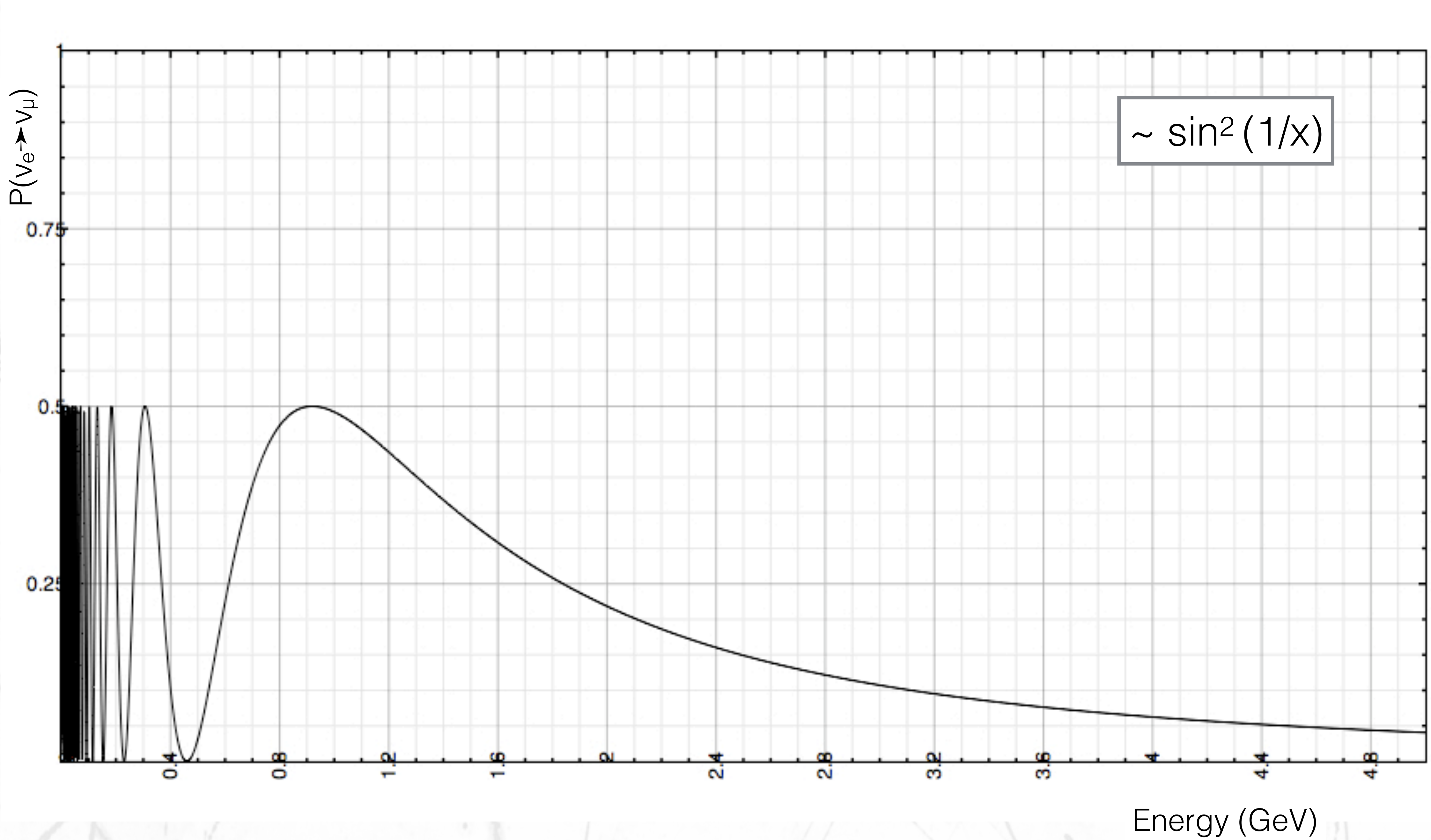
- The probability of getting a ν_μ at the interaction is then:

$$\begin{aligned} |<\nu_\mu|\nu_e; t>|^2 &= |-\cos\theta\sin\theta <\nu_1|\nu_1; 0> + \sin\theta\cos\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}} <\nu_2|\nu_2; 0>|^2 \\ &= \sin^2\frac{\theta}{2}\sin^2\frac{m_2^2-m_1^2}{4p}\frac{t}{\hbar} = \sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km} \end{aligned}$$

- Flavour-lepton number is not conserved!. Opens the possibility for flavour violation in lepton decay & production.

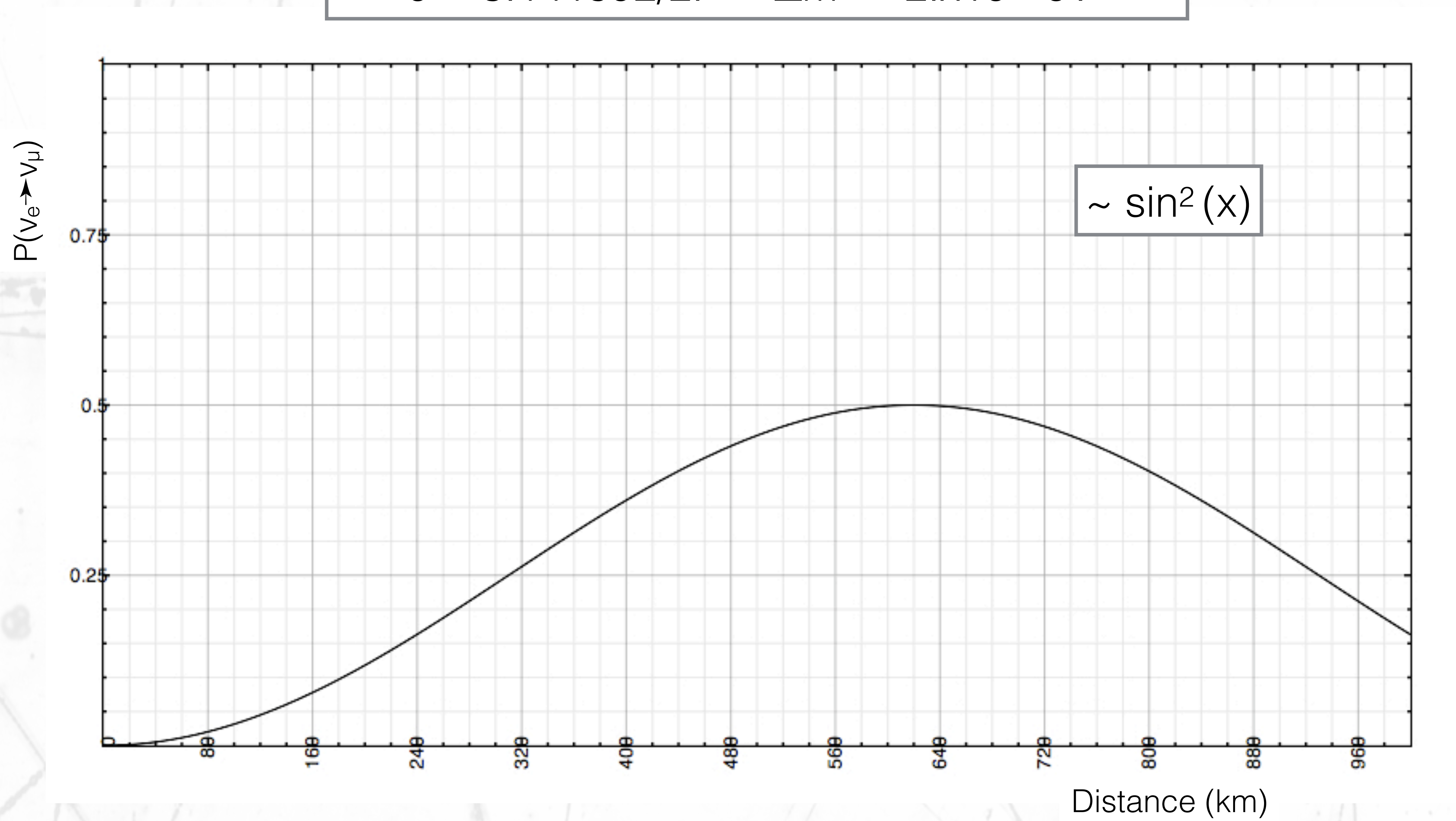
Neutrino Oscillation

$\theta = 3.141592/2.$ $\Delta m^2 = 2.\text{x}10^{-3}\ eV^2$



Neutrino Oscillation

θ = 3.141592/2. $\Delta m^2 = 2.\text{x}10^{-3}\ eV^2$



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Quantum coherence

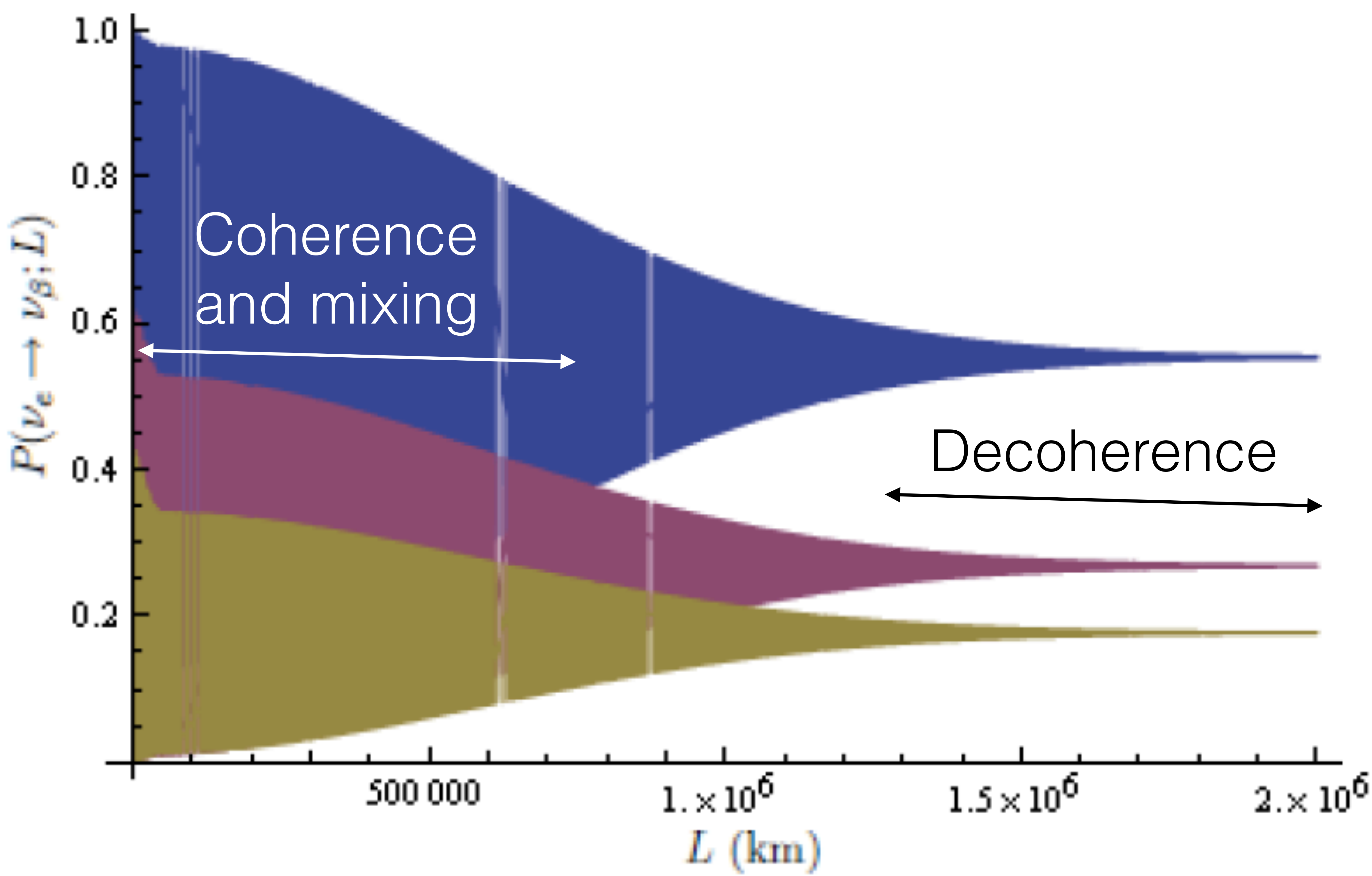
- In quantum mechanics the **coherence** of two states is essentially their ability to **interfere**.
    - Fully **coherent** states can be described by a superposition of the states, and **interference** may take place.
    - If the states are, instead, fully **incoherent**, there will be **no interference**.
- Neutrino oscillation **happen only in the coherent period.**
    - Neutrino wave packages need to **overlap in space** to ensure the coherence.
- When the 3 mass state neutrinos wave packages are separated (L >> L^{coh}) the oscillation stops.

$$L_{ij}^{coh} = \frac{\sqrt{32}\sigma_x E^2}{|\Delta m_{ij}^2|}$$

arXiv:hep-ph/9711363

- Int this limit, get then **3 mass states** with **undefined flavour.**

Quantum coherence



Coherence & Heisenberg

- If we get **two different mass** states with same energy we'll get **two different momenta** through the dispersion relation.
- Actually the **neutrino is a superposition of plane waves** with "slightly" **different Energy and momentum**.
- The **conservation of energy and momentum** should be verified **within the uncertainties: σ_p & σ_E**

Assume same E

$$\sigma_p \sigma_x \geq \frac{\hbar}{2}$$

Assume same p

$$\sigma_E \sigma_t \geq \frac{\hbar}{2}$$

What happens if this condition is not fulfilled ?

?

Why is this possible with ν ?

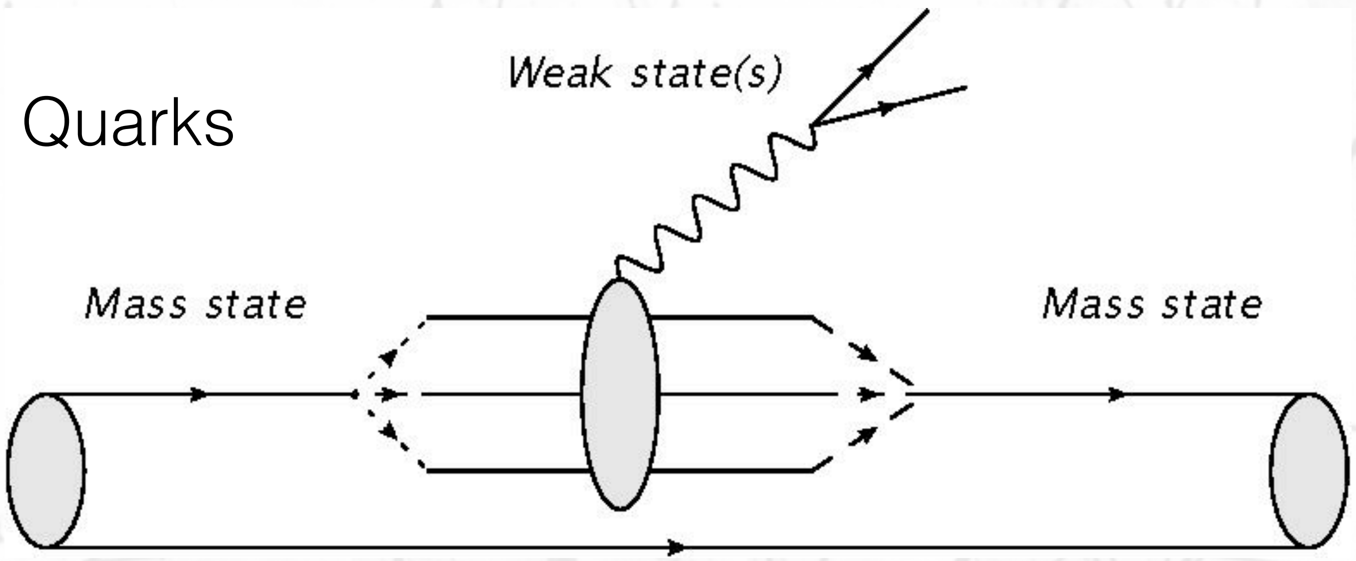
Oscillations with 3 ν's

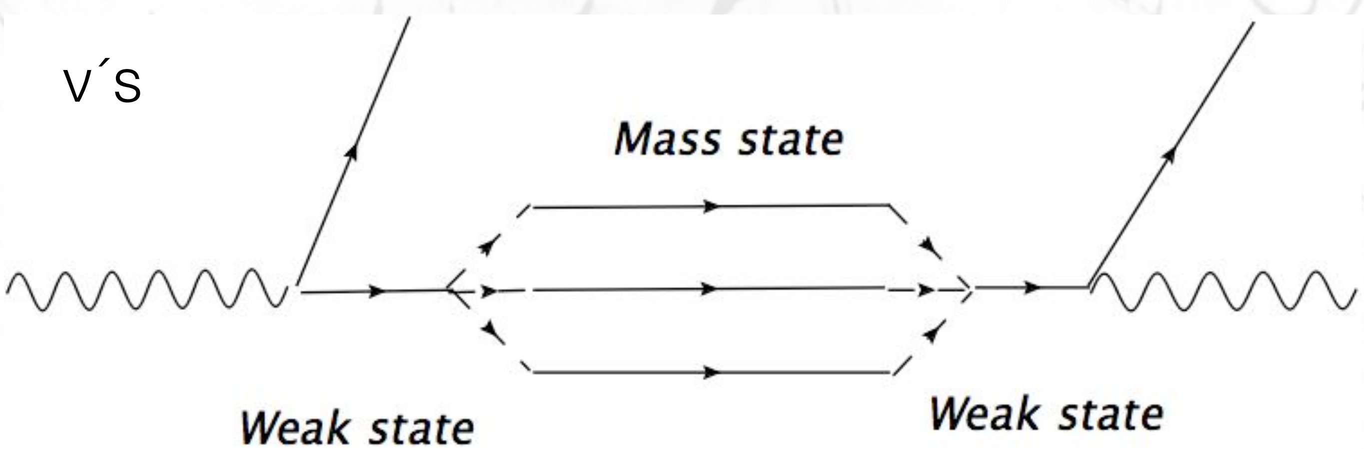
- With 3ν, there are **3 angles** and **1 imaginary phase:**
- The **phase** allows for **CP violation** similar to the quark sector.
- There are also **2 values of Δm^2**, traditionally Δm^2_{12} &Δm^2_{31}.

$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS} \begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$

$$U_{PNMS} = \begin{pmatrix}1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1\end{pmatrix}$$

Lepton & quark mixing





- **Quarks** exist in **matter** as mass eigenstate.
    - In **quark mixing**, the **quark** is at the **mass state at the initial and final state.**
- **neutrinos** exists in **vacuum** as mass eigentstates.
    - In **neutrino oscillations**, the mass state are intermediate states, **initial and final are flavour states.**
- There are cases where the neutrino behaves “as the quarks do”: i.e. **lepton flavour violation in decays.**

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What happens with neutrinos in matter?

The theory

- Neutrinos can have **two types** of interaction with matter:
  - **Incoherent inelastic:**

    We already discussed this type

    - $\sigma \sim 10^{-43} (E/MeV)^2 \, cm^2$
  - **Coherent:**
    - The **medium is unchanged** and the **scattered and un-scattered waves interfere enhancing the effect.**
    - **Coherent interactions introduces a phase in the propagation,** that can be **invisible**…

Except for the fact that matter has electrons but no muons or taus!

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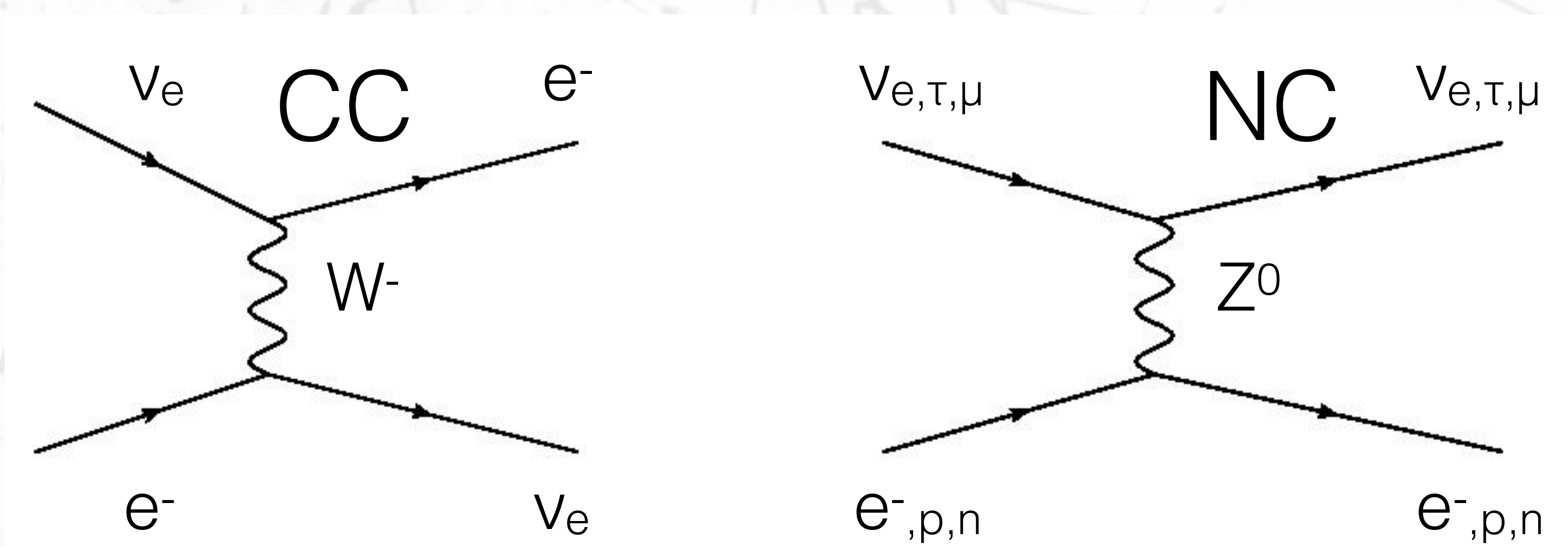
Neutrinos in matter

The theory

- The coherent interaction potential (real V_C) introduces a phase that depends on the neutrinos flavour.

- The Schrödinger equation of ν in matter is then shown as:

$$i\hbar\frac{\partial \nu_i}{\partial t} = (\frac{m_i^2}{2E} + V_C^i)\nu_i$$



Neutrinos in matter

- During the evolution of the neutrino in matter, it will be a **linear combination of the three neutrino flavour** with a **different phase.**
- The **NC phase is common and factorises.** The **CC phase** remains and it **applies to electron neutrinos** only:

$$V_c = diag(\pm\sqrt{2}G_F n_e + V_\beta, V_\beta, V_\beta) \equiv diag(\pm\sqrt{2}G_F n_e, 0, 0)$$

- This is like adding an **index of refraction** to the electron neutrino.
- **mass eigenstates and eigenvalues are changed:**

Matter introduces an effective mass splitting and mixing angle.

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Neutrinos in matter

The theory

- The new mass levels and mixing angles can be computed (for 2 neutrinos) to be:

$$\mu^2_{1,2}(x) = \frac{m_1^2+m_2^2}{2} + E_\nu(V_\alpha + V_\beta) \mp \frac{1}{2}\sqrt{[\Delta m^2 \cos 2\theta - A]^2 + [\Delta m^2 \sin 2\theta]^2}$$

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$$

$$A = 2E_\nu(V_\alpha - V_\beta)$$

- Taking $V_\alpha = \pm\sqrt{2}\, G_F\, n_e$, $V_\beta=0$

- When crossing **$A \sim \Delta m^2 \cos(2\theta)$,** $\tan(2\theta_m)$ changes sign:

The proportions of **1&2 invert for α & β states** (“level crossing”).

A depends on **neutrino energy and electron density:**

A matter effect is smaller for smaller E_ν & electron density n_e

Matter effects are more or less relevant depending on mixing angle and Δm^2

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Phenomenology with 3 ν's

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$\nu_\mu \rightarrow \nu_\mu$

$$P(\nu_\mu \rightarrow \nu_\mu) =$$

$$1 - \sin^2 2\theta_{23} \sin^2 \theta_{m,13} \sin^2\left(\frac{\Delta m^2_{12}}{4E}\right)$$

$$- \sin^4 \theta_{23} \sin^2 2\theta_{m,13} \sin^2\left(\frac{\Delta m^2_{31}}{4E}\sqrt{\left(\frac{a}{\Delta m^2_{31}} \mp \cos 2\theta_{31}\right)^2 \pm \sin^2 2\theta_{31}}\right)$$

$$- \sin^2 2\theta_{23} \cos^2 2\theta_{m,13} \sin^2\left(\frac{\Delta m^2_{31}}{4E}\sqrt{\left(\frac{a}{\Delta m^2_{31}} \mp \cos 2\theta_{31}\right)^2 \pm \sin^2 2\theta_{31}} + \frac{\Delta m^2_{12}}{4E}\Delta\right)$$

$$\sin^2 2\theta_{m,13} = \frac{\sin^2 2\theta_{13}}{\left(\frac{a}{\Delta m^2_{13}} \mp \cos 2\theta_{13}\right)^2 \pm \sin^2 2\theta_{13}}$$

- This oscillation allows to measure the atmospheric mixing angle (θ_{23}), mass splitting (Δm^2_{31}) and matter effects (a).

$\nu_\mu \to \nu_e$

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

leading
$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E}\left(1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2\right)$$

CPC
$$+\,8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{23}s_{13})\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

CPV
$$\mp 8c_{13}^2 C_{12} C_{s3} s_{12} s_{13} s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

Solar
$$+\,4s_{12}c_{13}(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin\frac{\Delta m_{21}^2 L}{4E}$$

Matter
$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{21}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}(1-2s_{13}^2)$$

- Angle θ_{13} can be measured in this case, but related to the value of the δ_{CP}.
- Comparison between neutrinos and antineutrinos allows to derive **δ_{CP} and hierarchy** through matter effects.
- The probability is a complex mixture of all mixing parameters.

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) =$$

$$1 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$- 2s_{13}^2 c_{13}^2 \left(1 - \sqrt{1 - 4s_1^2 2c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}} \cos(2|\Delta_{ee}| \pm \phi) \right)$$

$$\Delta_{ee} = \frac{c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2}{4E}$$

$$sin\phi = \frac{c_{12}^2 \sin(2s_{12}^2 \frac{\Delta m_{21}^2}{4E}) - s_{12}^2 \sin(2c_{12}^2 \frac{\Delta m_{21}^2}{4E})}{\sqrt{1 - 4s_1^2 2c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}}}$$

$$cos\phi = \frac{c_{12}^2 \sin(2s_{12}^2 \frac{\Delta m_{21}^2}{4E}) + s_{12}^2 \sin(2c_{12}^2 \frac{\Delta m_{21}^2}{4E})}{\sqrt{1 - 4s_1^2 2c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}}}$$

The neutrino oscillation in vacuum also contains information about the hierarchy through a phase!.

This is not **CP violation!**

- Precise measurement of solar term (θ_{12}) and θ_{13} angles plus the mass split ($\Delta m^2{}_{12}$) and ($\Delta m^{2}{}^{3}{}_{2}$)

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CP violation

A complex matrix of 2x2 can factorise all the phases so they disappear in the probability.

A disappearance is like an oscillation between 2 neutrino flavours ($\nu_e \Leftrightarrow \bar{\nu}_e$).

In this case there can't be CP violation.

A complex matrix of 3x3 will have always on phase that cannot be factorised in the amplitude (disappearing in the probability).

CP violation requires an explicit 3 neutrino oscillation. This is achieved with an oscillation between exclusive flavours ($\nu_\mu \Leftrightarrow \nu_e$).

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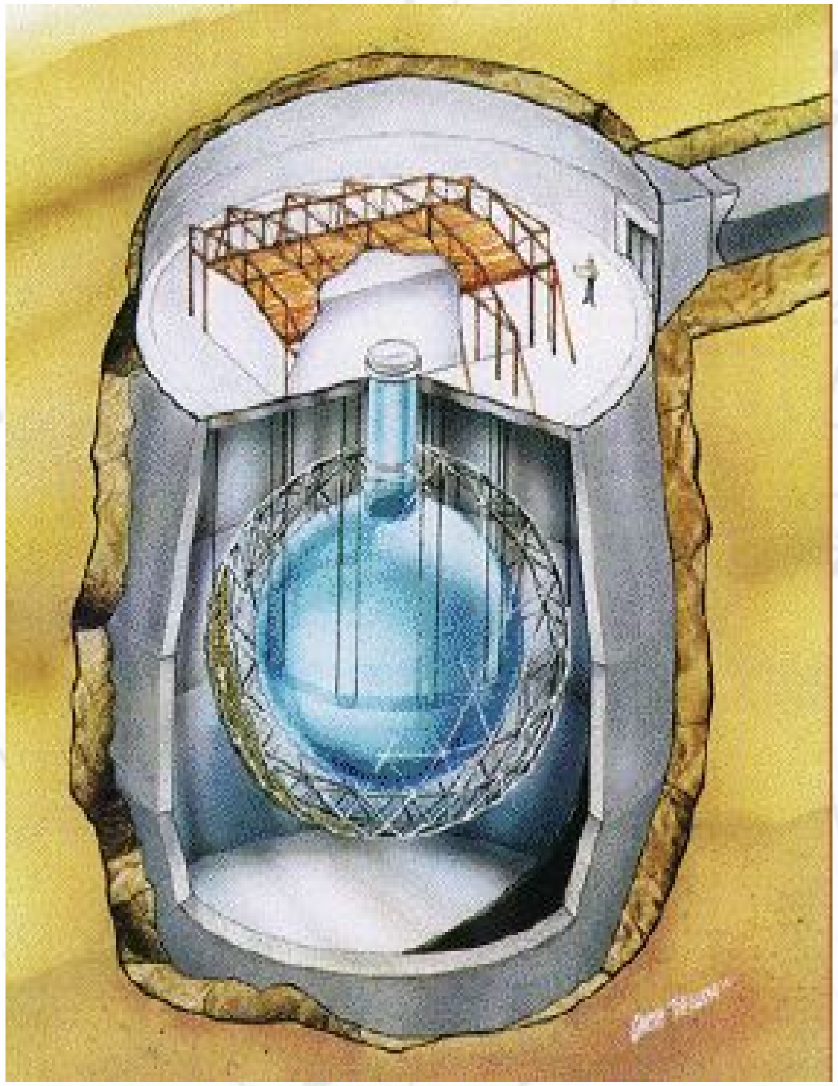
Experimental evidences

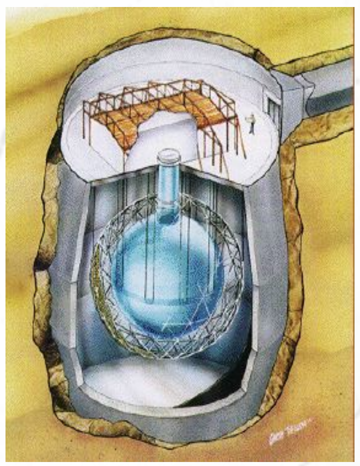
SNO

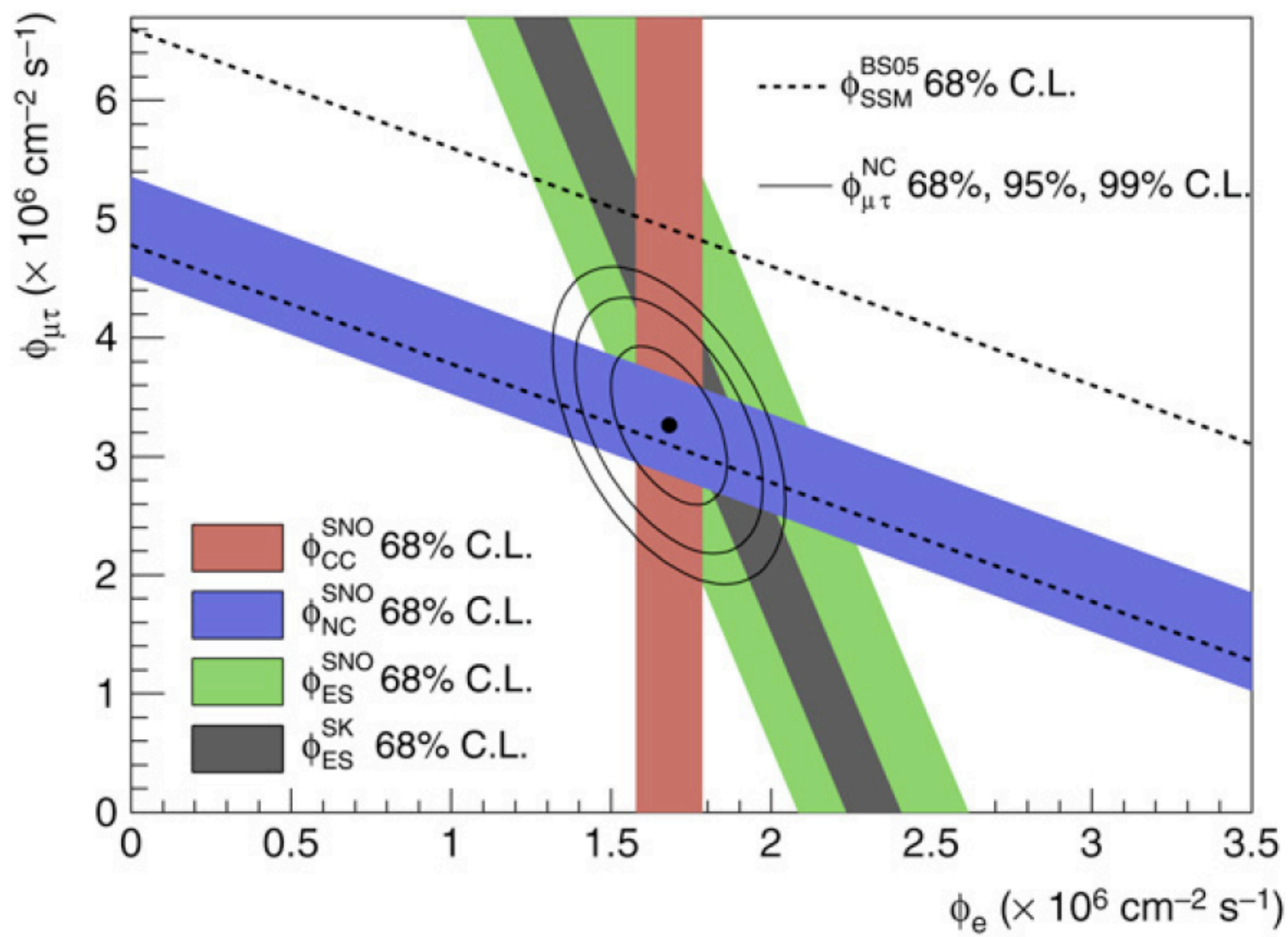
Solving the solar neutrino problem



- SNO experiment was proposed to measure the total solar neutrino flux and the electron component.
  - Elastic scattering: ν_x $e^- \rightarrow \nu_x$ e^-
    - ν_e is 7 times larger than $\nu_{\mu,\tau}$
  - Charged current: ν_e d $\rightarrow$ p p e^-
    - direction and spectrum
  - Neutral current: ν_x d $\rightarrow$ ν_x n p
    - unbiassed total neutrino flux.

SNO





$$\Phi_{SNO}^{CC} = \left(1.68^{+0.06}_{-0.06}\,{}^{+0.08}_{-0.09}\right) \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \Rightarrow \frac{\Phi_{SNO}^{CC}}{\Phi_{SSM}} = 0.29 \pm 0.02,$$

$$\Phi_{SNO}^{ES} = (2.35 \pm 0.22 \pm 0.15) \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \Rightarrow \frac{\Phi_{SNO}^{ES}}{\Phi_{SSM}} = 0.41 \pm 0.05,$$

$$\Phi_{SNO}^{NC} = (4.94 \pm 0.21^{+0.38}_{-0.34}) \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \Rightarrow \frac{\Phi_{SNO}^{NC}}{\Phi_{SSM}} = 0.87 \pm 0.08.$$

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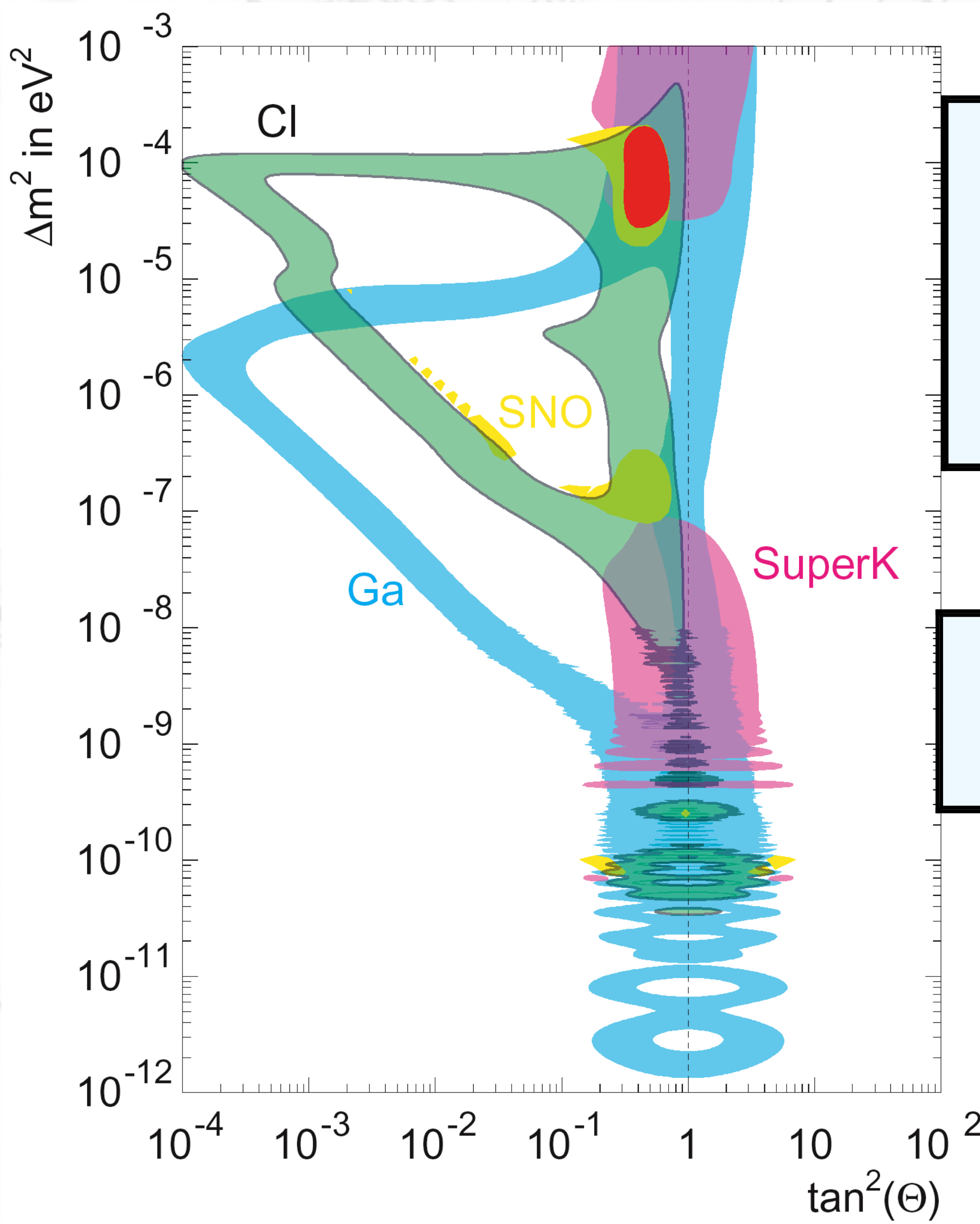
Oscillation from sun

Status after first SNO data



Solar matter oscillations

Oscillations inside the sun

Vacuum oscillations

Oscillations between sun & earth

Remember

Matter effects are more or less relevant depending on mixing angle and Δm^2

Solar neutrinos

Mikeev, Smirnov, Wolfenstein (MSW) effect

- The sun produces ν_e. The neutrino propagates in a **high density matter** with **strong radial dependency.**
- In the sun, the **matter hamiltonian dominates the vacuum hamiltonian.** (A>>$\Delta m^2 \cos(2\theta)$). (at least for high energy ν)
- **Matter hamiltonian is diagonal in flavour**. The sun produces an **electron neutrino that is also eigenstate of the Hamiltonian,** with the highest effective mass (V>0).

$$\mu_1^2 = \frac{m_1^2 + m_2^2}{2}$$
$$\mu_2^2 = \frac{m_1^2 + m_2^2}{2} + 2E_\nu V_{\nu_e}$$

Solar neutrinos

- The electron density varies **adiabatically** (i.e. slowly)… so the solution of the Shrödinger can be obtained without time dependency. The **neutrino is always an eigenstate of the Hamiltonian.**

- When the neutrino leaves the sun, it is still in **eigenstate of the propagation**, but this time "in vacuum" (ν_2)

$$\mu_2^2 = m_2^2$$

It is produced a pure vacum Lorentz eigenstate.

- The vacuum **state v_2, propagates without interference to the Earth ⇒ no seasonal dependency.**

know why ?

- This effect occurs because locally the **off-diagonal terms of the Hamiltonian are negligible** with respect to the diagonal.

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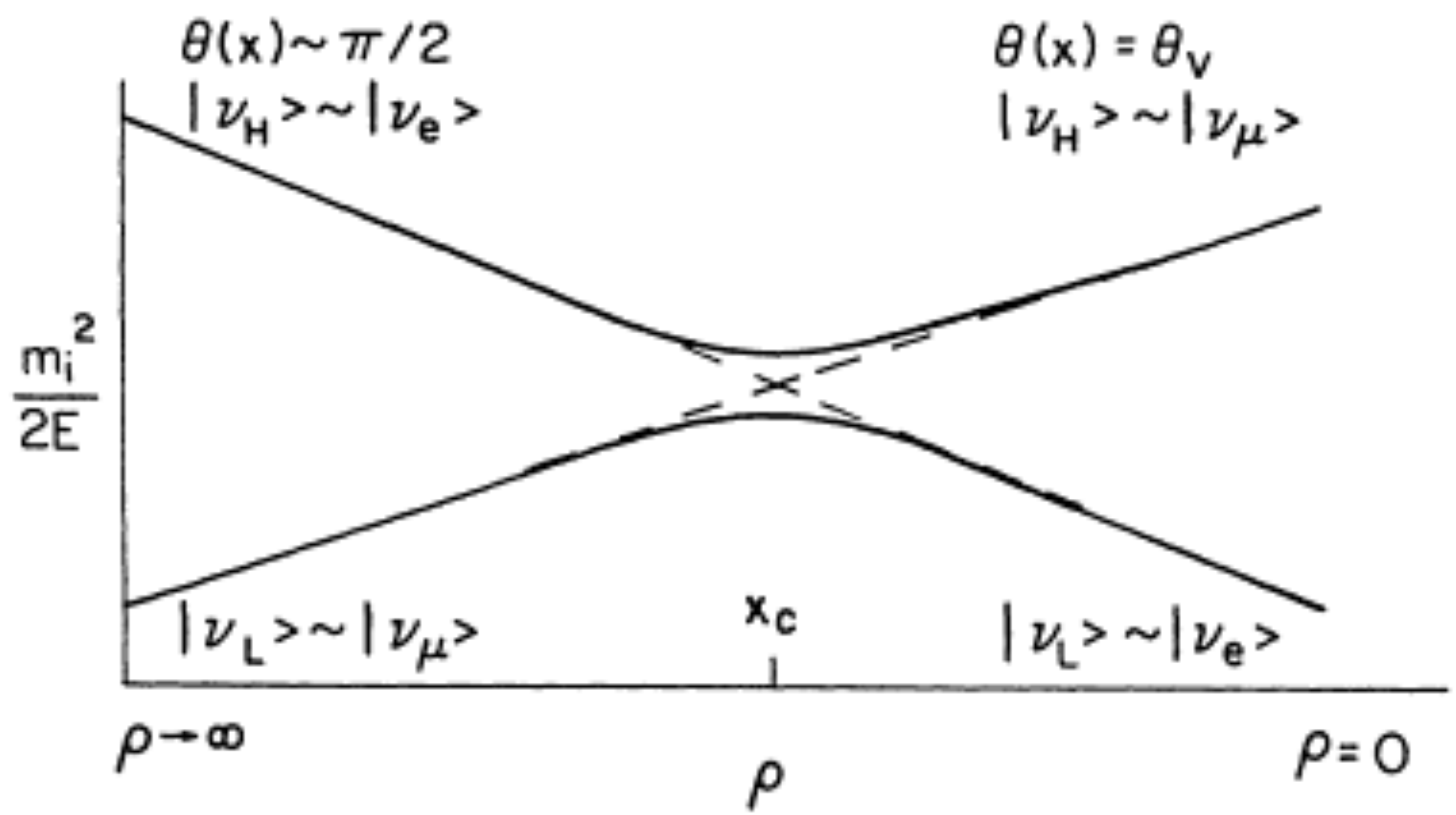
Solar neutrinos

The theory



- Because, there is **"level crossing"**, the main state in matter is the **opposite to the most probable mass state from ν_e in vacuum.**

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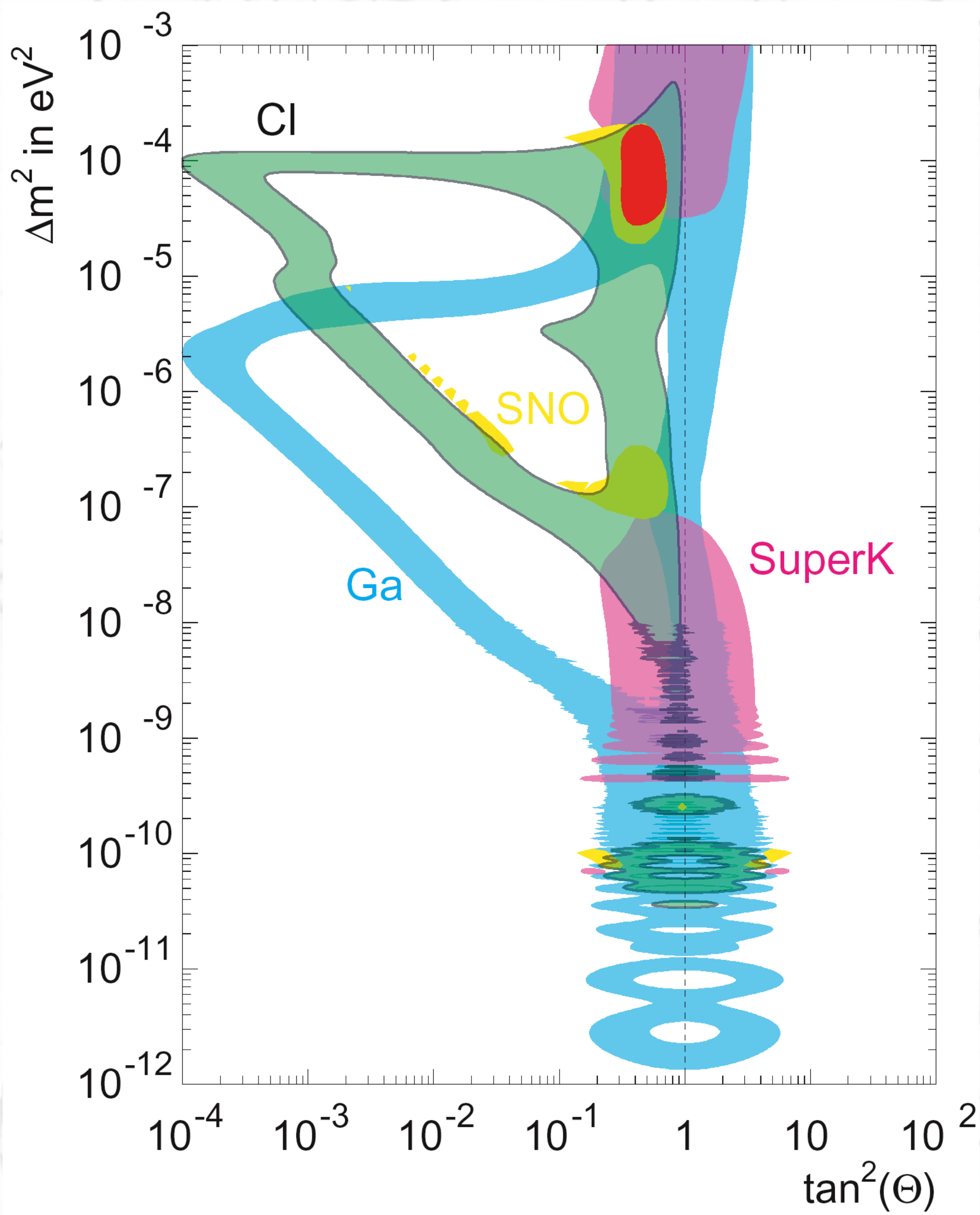
Oscillation from sun

The experiments

Status after first SNO data

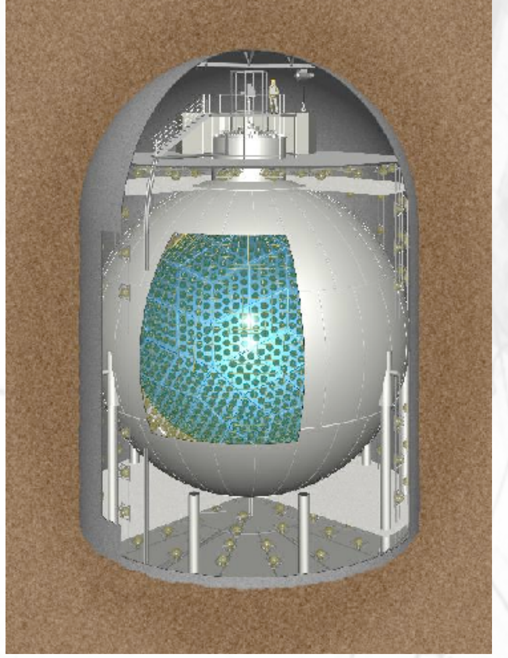


Solar matter oscillations

Need good Δm^2, $\tan(\theta)$, day-night or seasonal effect determination.

Vacuum oscillations

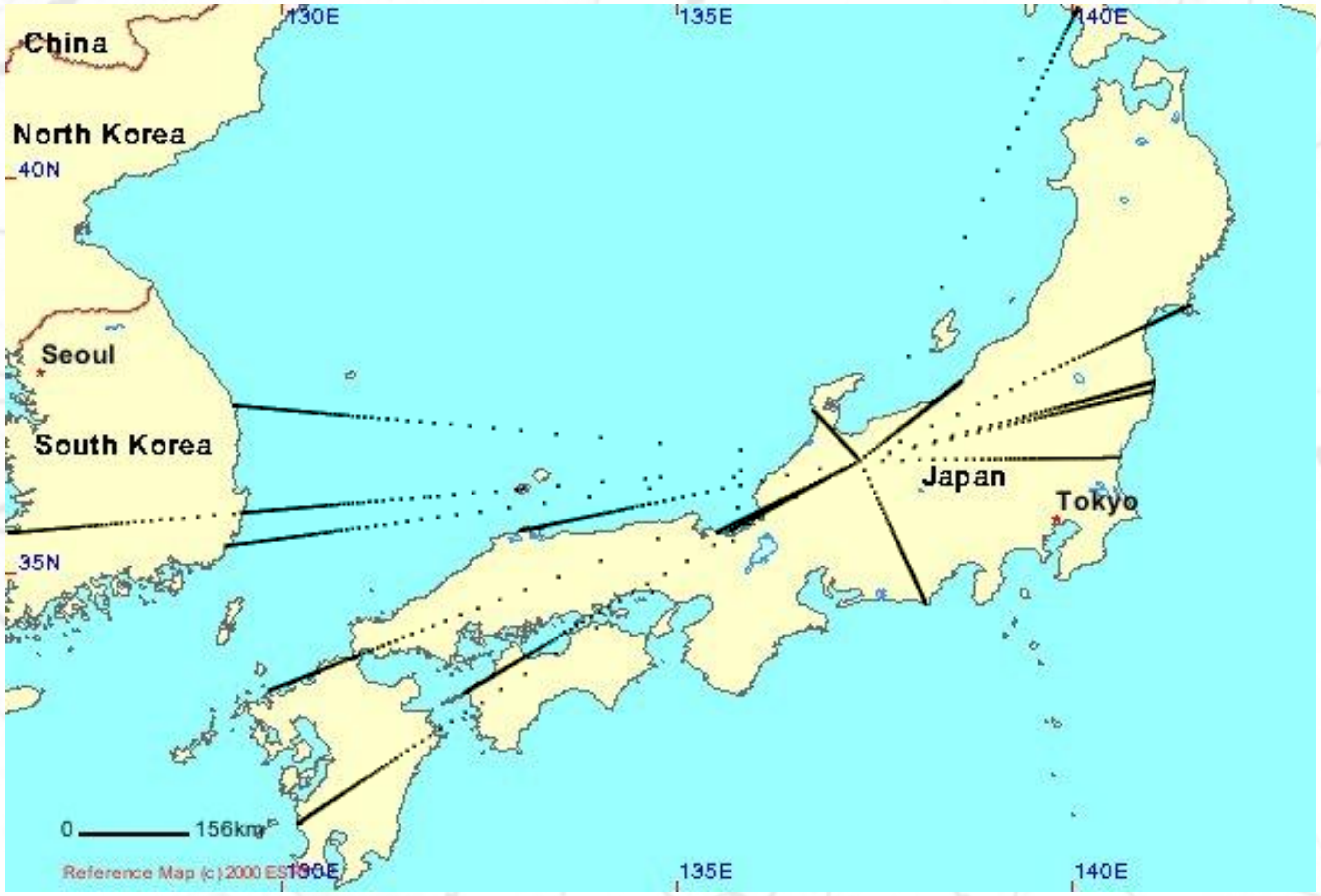
Kamland



Solving the solar neutrino problem with man-made sources!

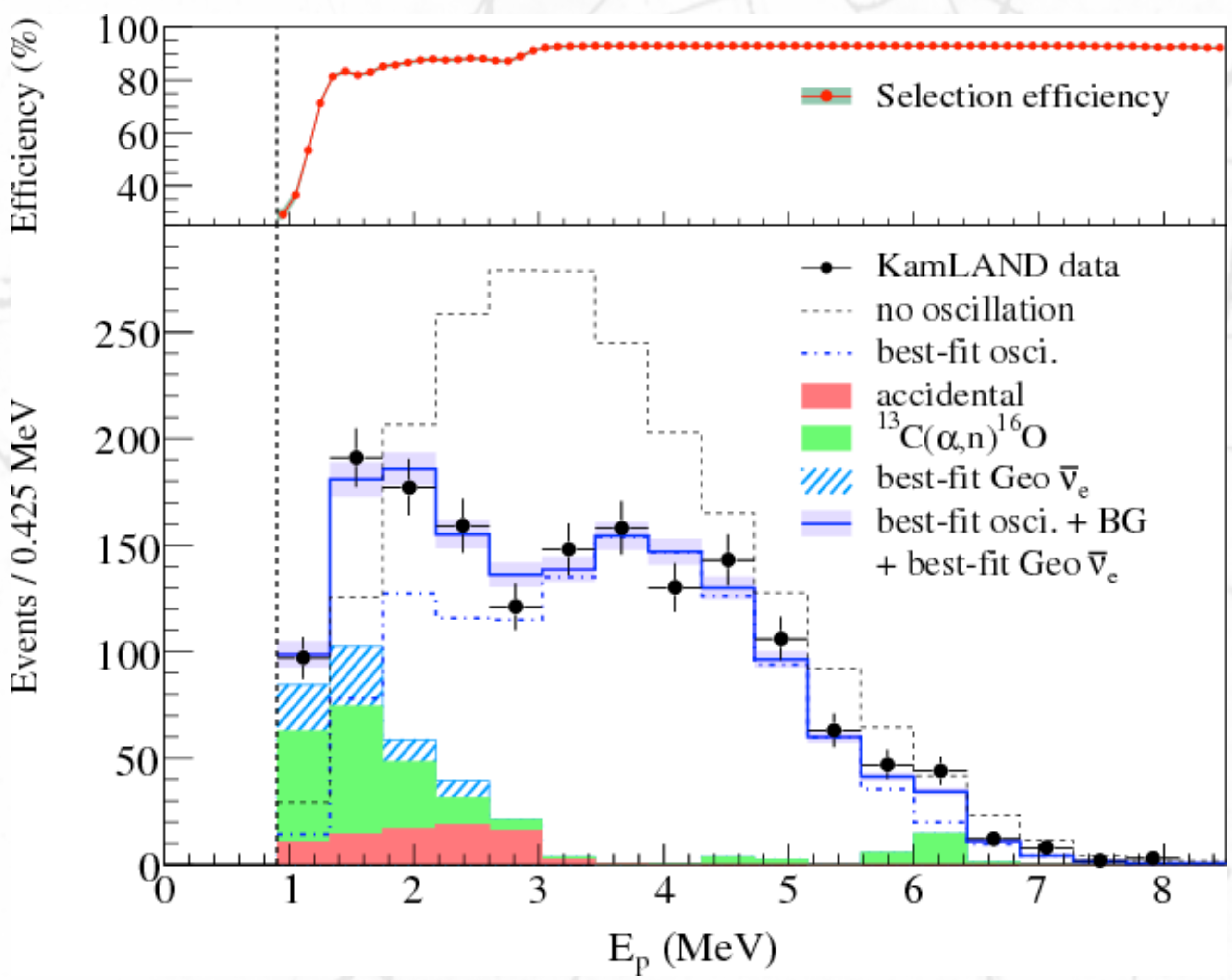
The experiments

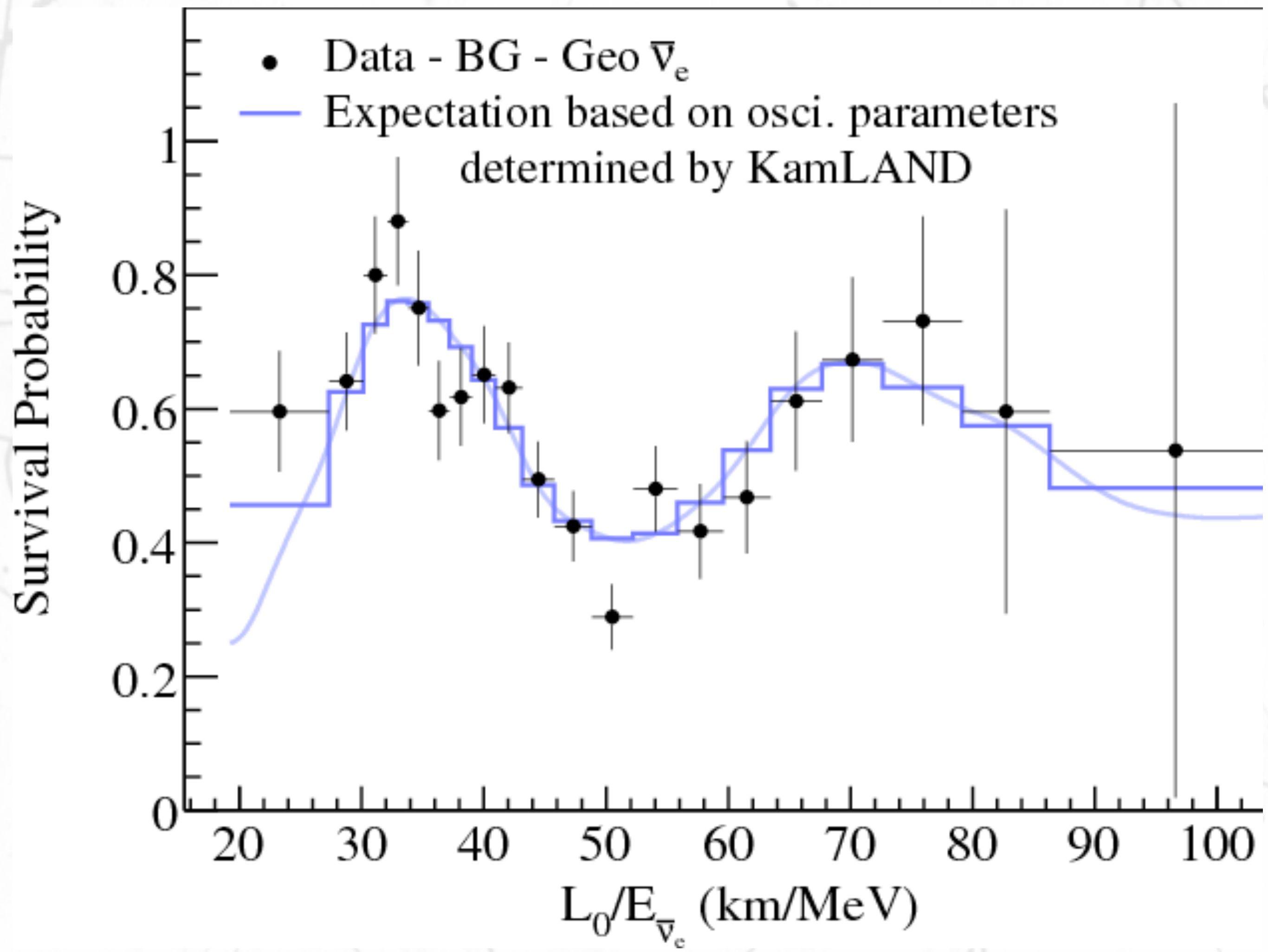
- Search for $\bar{\nu}_e$ **oscillations from nuclear reactors.**
- Average distance: ~180km.
- Average Energy: ~4 MeV.
- Sensitive to $\Delta m^2 \sim 10^{-4}$ eV^2
- In this case, **matter effects are small,** so we measure vacuum oscillation parameters.



Kamland

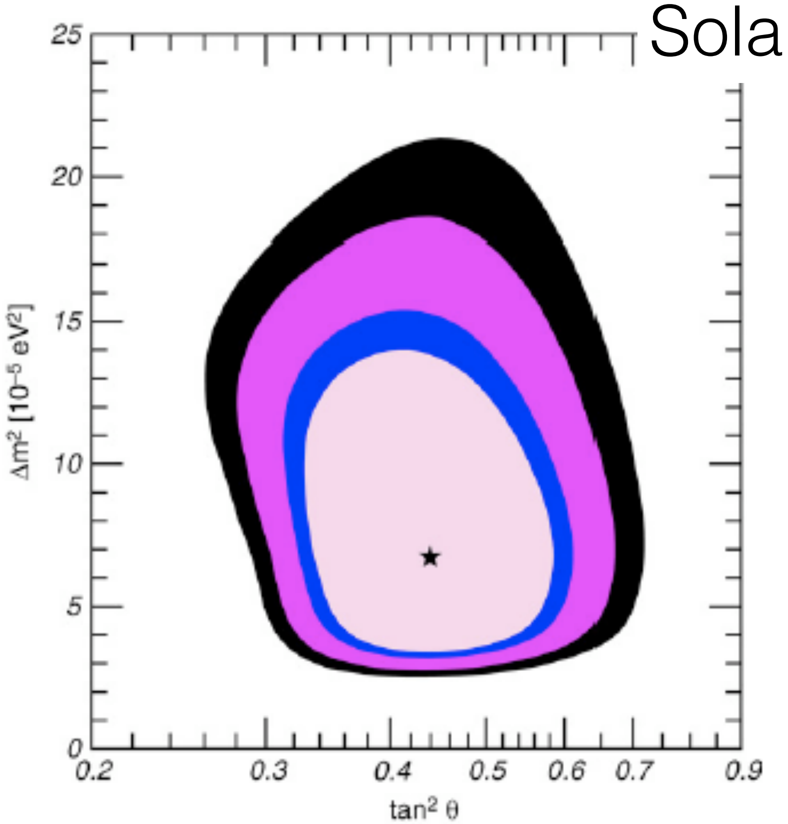
Oscillation pattern clearly seen!
Distance is not the same for all sources:
weighted distance!

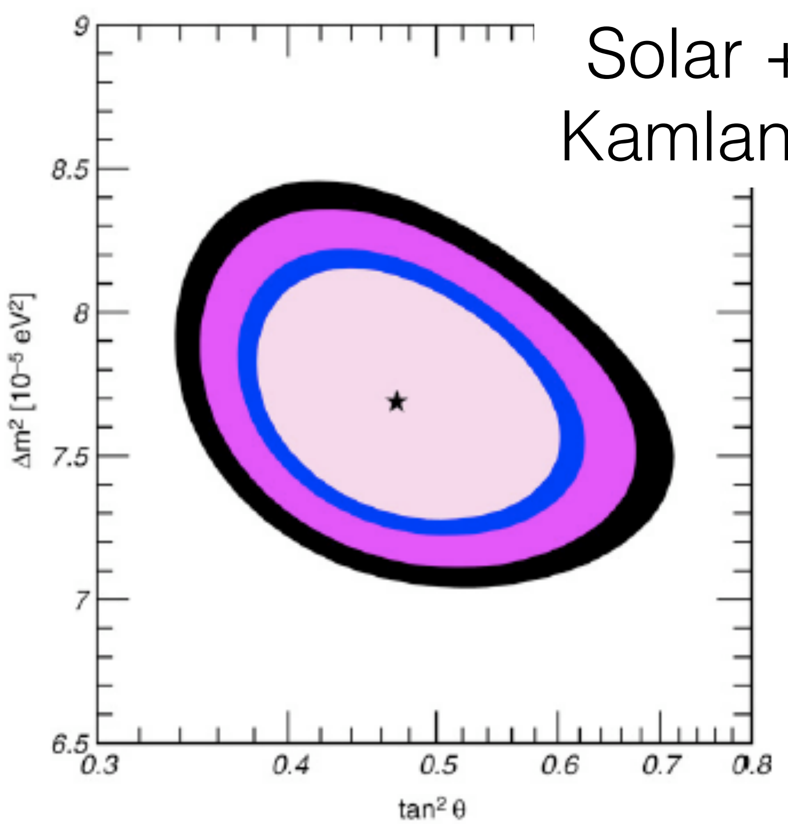




Solar neutrinos now

The experiments





- Chlorine, Gallium, SNO & SK:
  - SNO energy dependency.
  - SK day-night asymmetry.
- Kamland Δm^2 (main sensitivity parameter)
  - Assumption $\nu \equiv \bar{\nu}$.
- **Solar neutrinos follow the LMA $\Rightarrow$ adiabatic oscillation in the sun.**

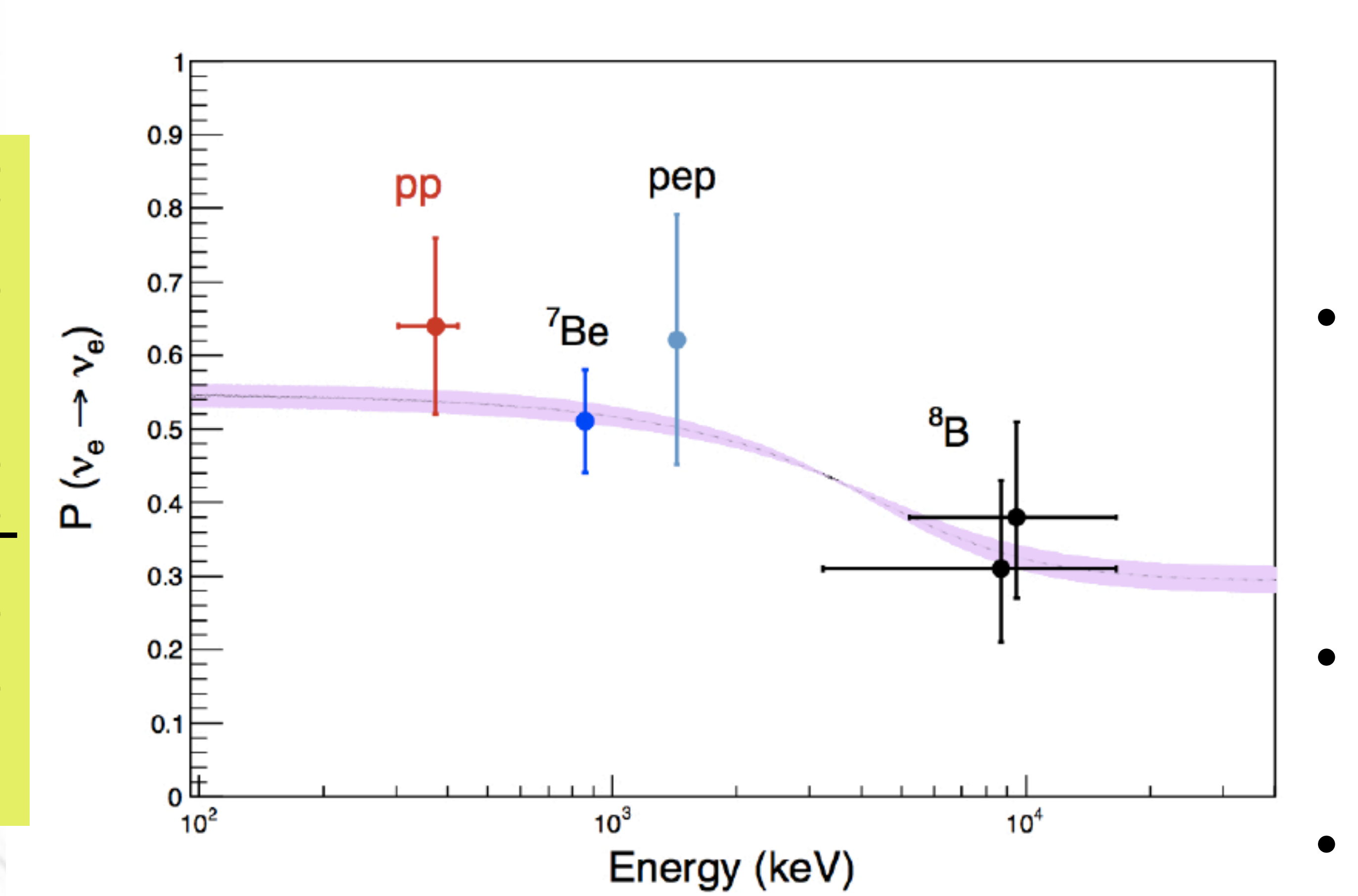
Not only check the value of the mixing parameters but demonstrate also MSW effect!!!

Borexino & LMA

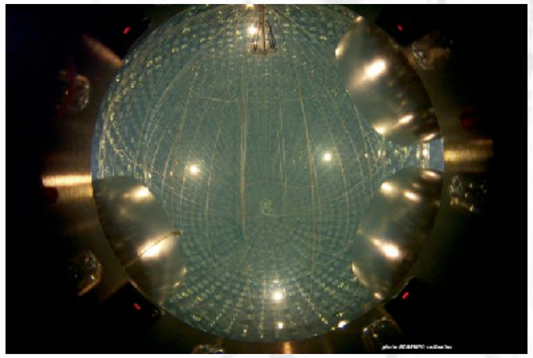
More checks on MSW

The experiments

Checking MSW effects!



- Borexino, low energy solar neutrino experiment, was able to check the LMA transition.
- The MSW-LMA result depends on the neutrino energy via the A parameter below.
- A depends on the neutrino energy.
- We should expect a transition when this happens.

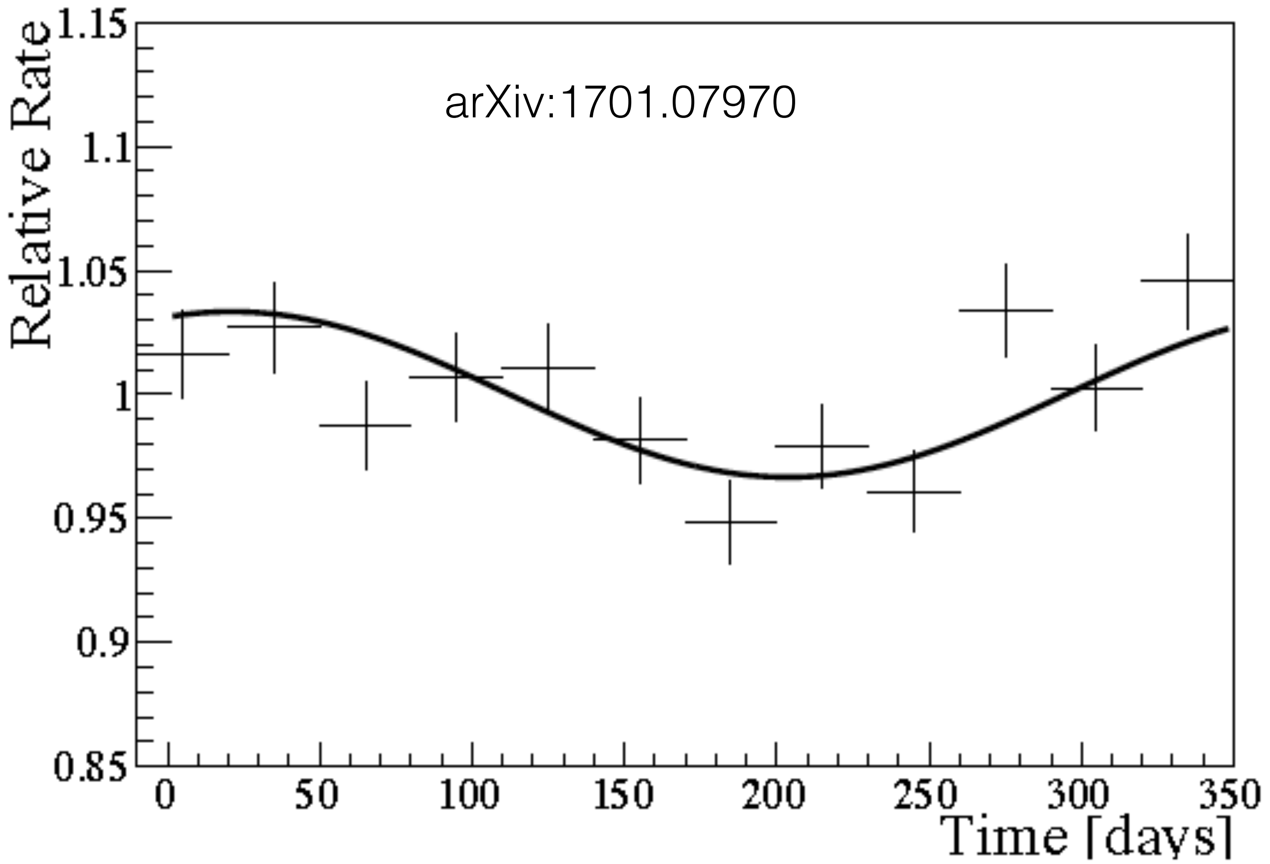


$$\mu^2_{1,2}(x) = \frac{m_1^2 + m_2^2}{2} + E_\nu(V_\alpha + V_\beta) \mp \frac{1}{2}\sqrt{[\Delta m^2 \cos 2\theta - A]^2 + [\Delta m^2 \sin 2\theta]^2}$$

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$$

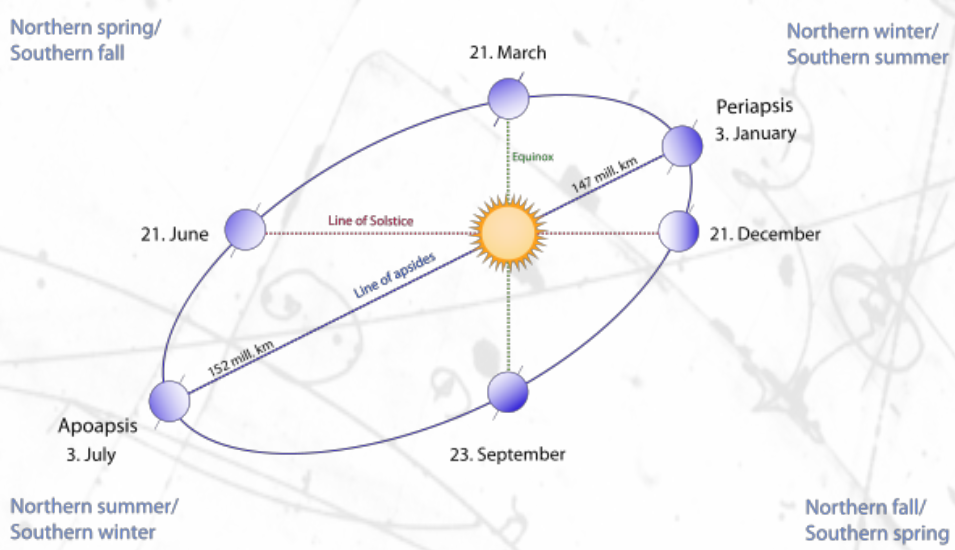
$$A = 2E_\nu(V_\alpha - V_\beta)$$

Seasonal variation



More checks on MSW

Checking seasonal effects!



- Accumulated 4 years of data.
- Borexino **showed the annual variation** of the neutrinos to be **consistent with earth orbit.**
    - Because neutrinos oscillate inside the sun **this shape should resemble the variation of $1/R^2$**
- This proves again the sun as the source of detected neutrinos.

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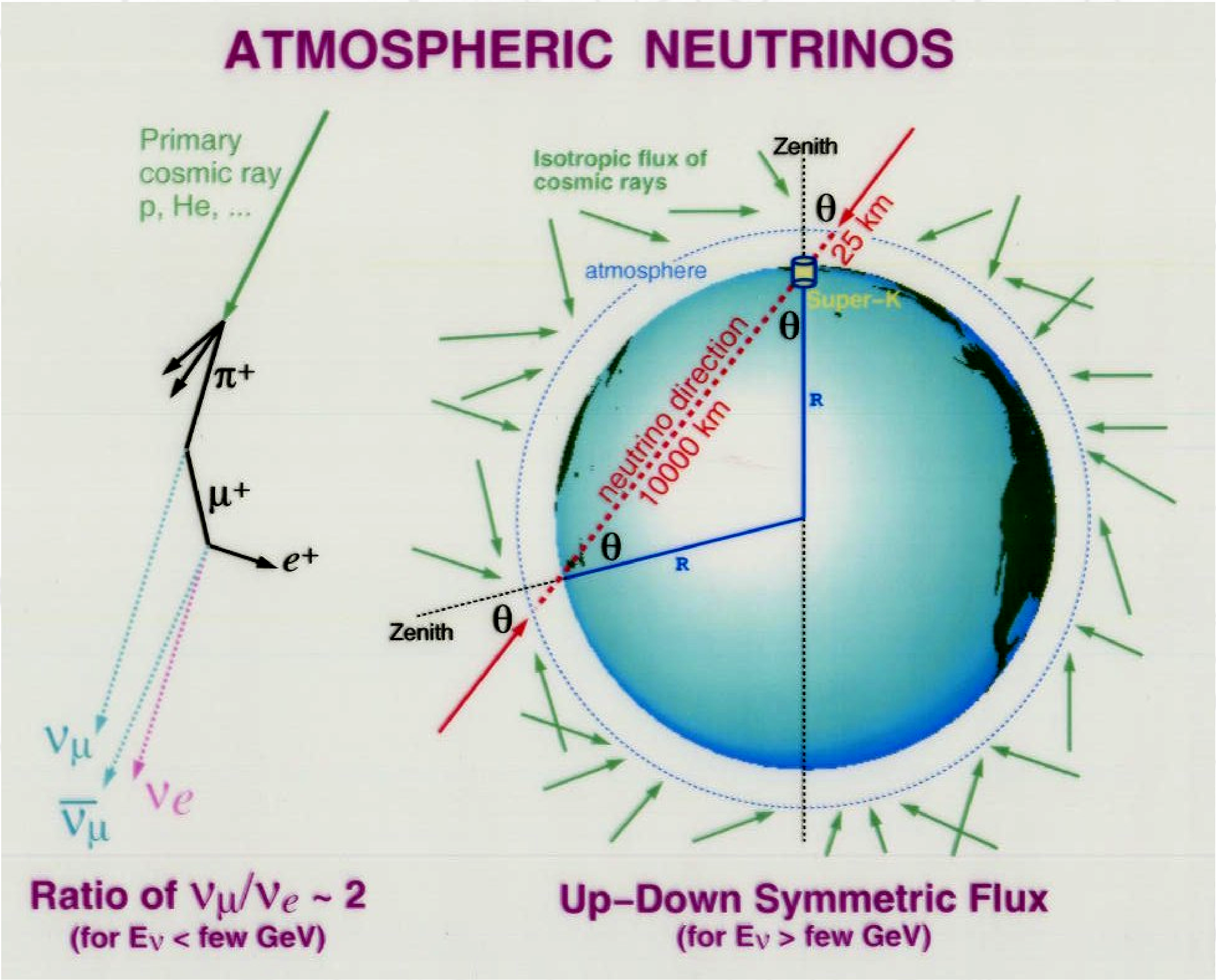
Atmospheric ν

- Up to now we have been looking at ν_e disappearance:
  - Is the $\boldsymbol{\nu_e}$ **oscillating to** $\boldsymbol{\nu_\mu}$ **or** $\boldsymbol{\nu_\tau}$ **?**
  - **What about the** $\boldsymbol{\nu_\mu}$ **and** $\boldsymbol{\nu_\tau}$ **?**
- Some trivialities:
  - **Solar neutrinos (~MeV) do not have energy to produce μ (106MeV) or τ(1777MeV).**
    - We can't experimentally distinguish them. Only NC are possible (SNO).
  - We need another **"abundant" source of "higher" energy neutrinos: the atmosphere!!.**

Atmospheric ν



$$\pi^+ \to \mu^+ \nu_\mu \to e^+ \bar{\nu}_\mu \nu_e \nu_\mu$$

$$\frac{N_{\nu_\mu}}{N_{\nu_e}} \approx 2.0 \quad for \quad E_\nu < few\,GeV$$

- Total flux is not known, but we "almost" know:
    - Ratio muon to electron.
    - Energy distribution.
    - distance from production.
- With this information we can do:
    - $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\tau$
    - $\nu_e \to \nu_\mu$, $\nu_e \to \nu_\tau$
    - as function of energy and distance (L/E parameter). (unfortunately not precisely)

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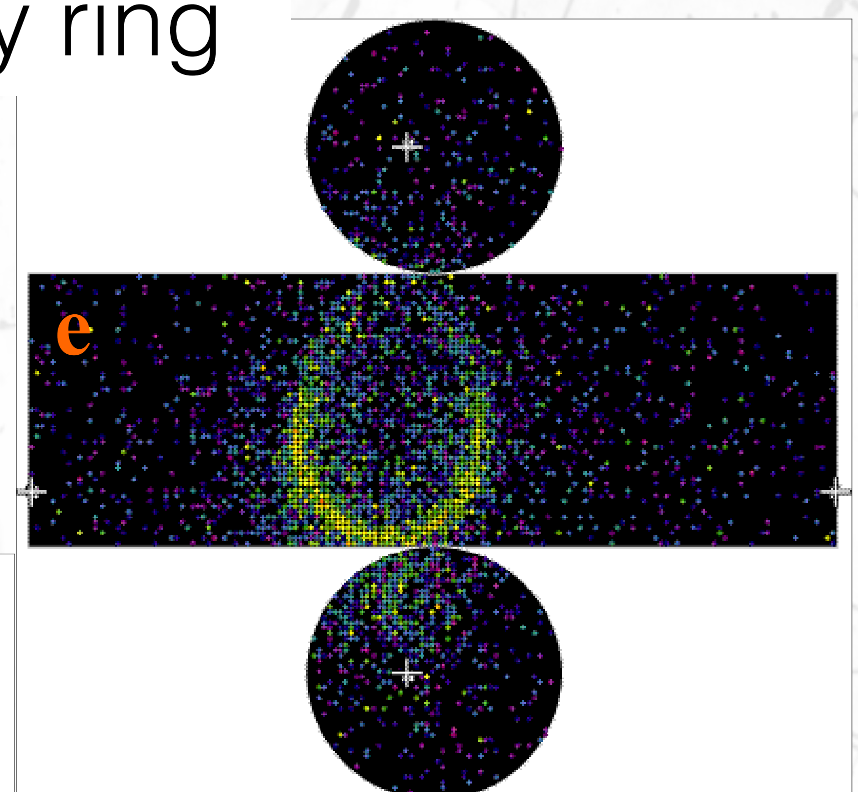
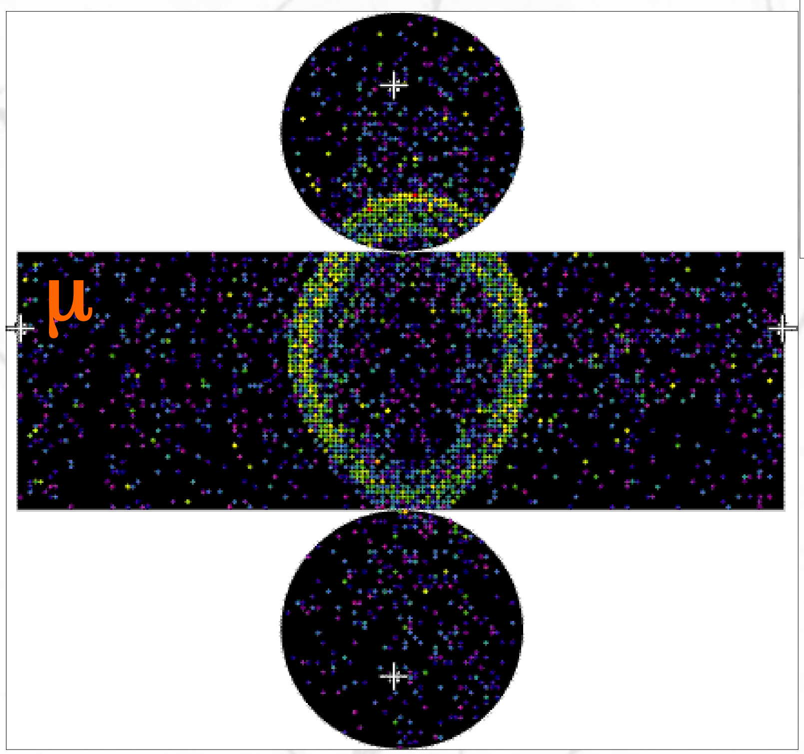
Superkamiokande

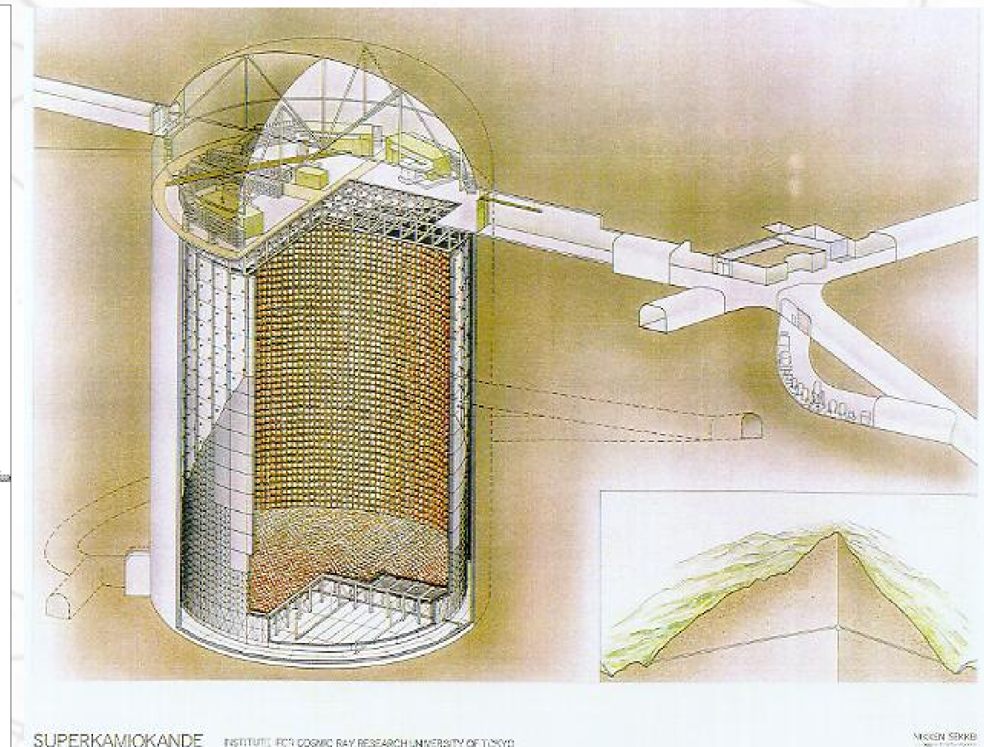
The experiments

e: fuzzy ring



μ: Sharp ring

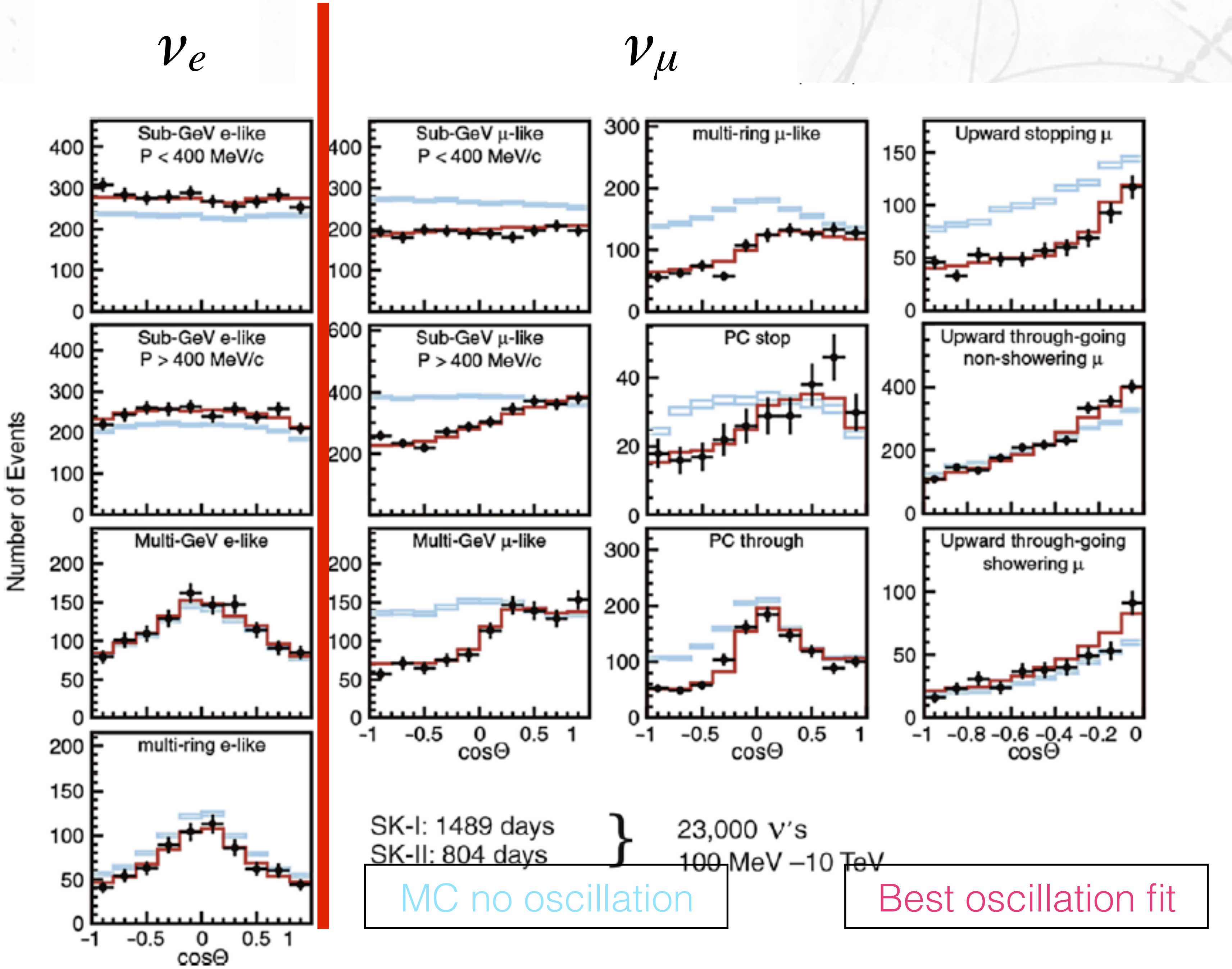




Massive water Cherenkov detector (40 kton) for proton decay, and neutrino physics (solar, atmospheric, SuperNovas and beam).

Neutrinos interact in the water, the particles from the interaction generate Cherenkov light while traversing the water: direction, energy (lenght & multiplicity) & particle identification.

Atmospheric ν in SK



Agreement for ν_e . The change is due to normalisation only.

Strong distortion for ν_μ

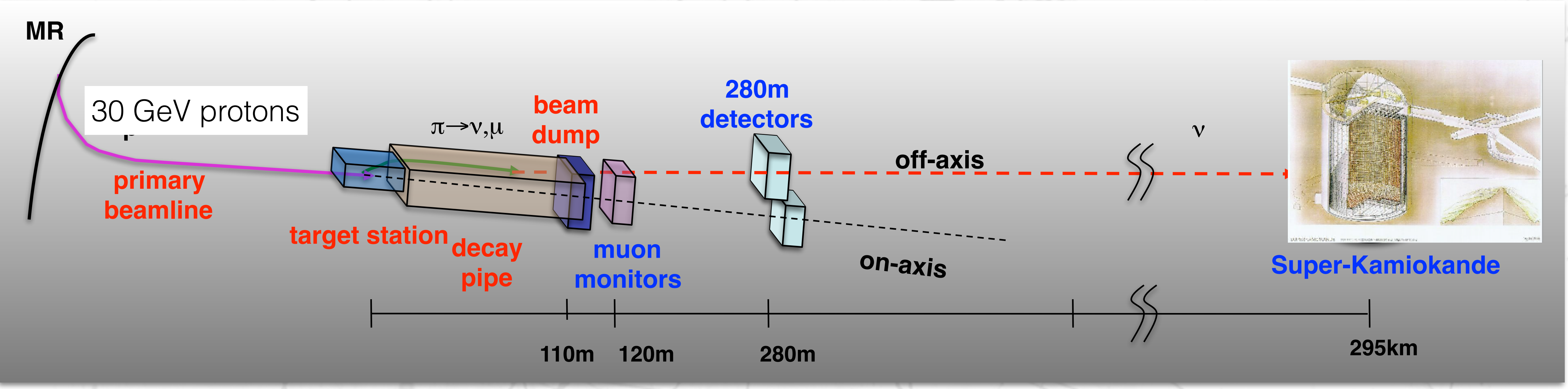
Distortion as function of zenith angle.

Most probably $\nu_\mu \rightarrow \nu_\tau$

The experiments

Long Base Line

Typical Long Base Line experiment layout



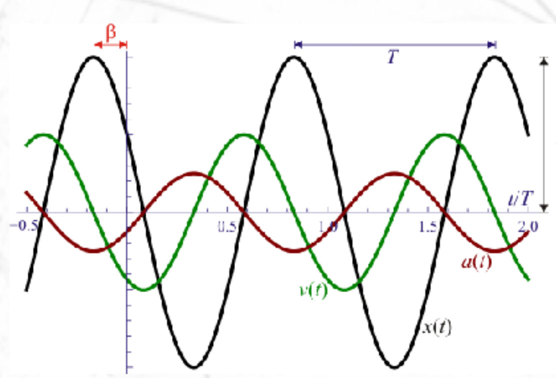
Neutrinos produced in a particle accelerators:

$pA \to \pi^+ \pi^+ \pi^- \ldots$

$\pi^+ \to \mu^+ \nu$

$\pi^- \to \mu^- \bar{\nu}$

Neutrino flux meas



Neutrino flux meas

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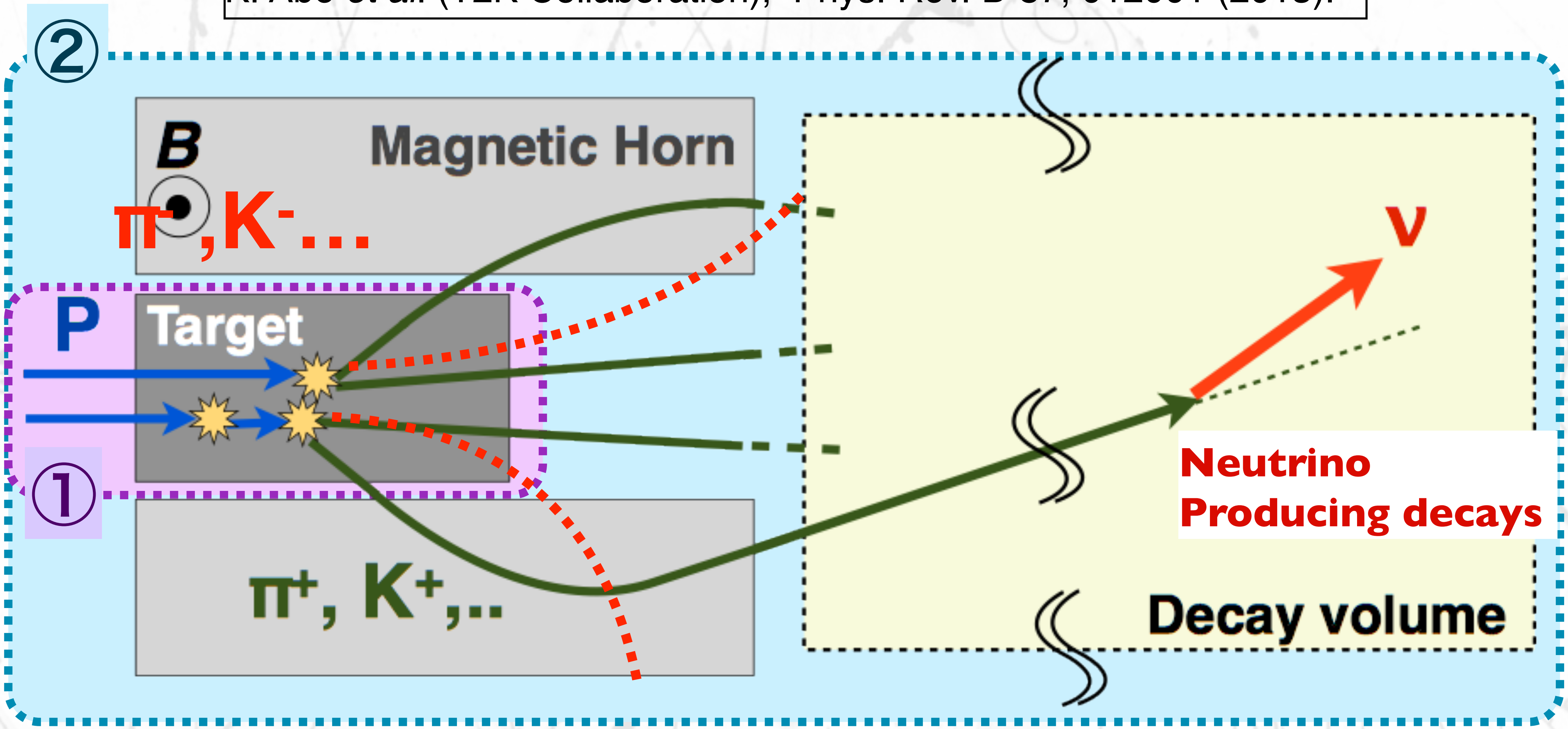
Accelerator neutrinos

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\pi^- \to \mu^- \bar{\nu}_\mu$$

K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



Other source of neutrinos is the low energy electron antineutrinos from nuclear reactors.

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Long base line

- Neutrino oscillation experiments are carried out by comparing neutrino interactions at a near and far sites.
  - The number of events depends on the cross-section & flux:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

  - at the far detector

$$N^{far}_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)P_{osc}(E_\nu)$$

- The ratio cancels flux and cross-section:

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

-

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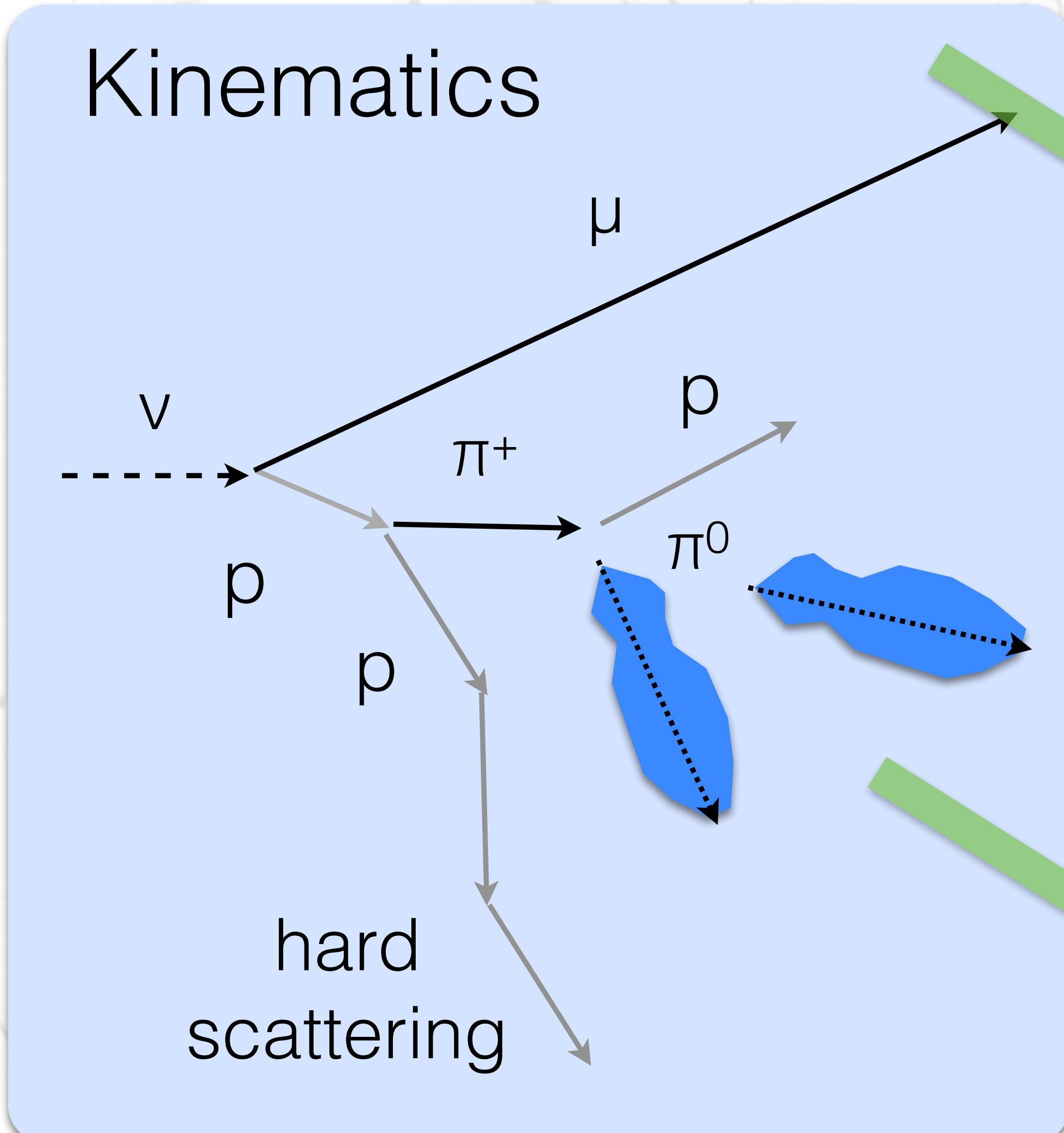
Long base line

- Since the neutrino energy is not monochromatic:
  - we need to determine event by event the energy of the neutrino.
- This estimation is not perfect and the cross-section does not cancels out in the ratio.

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

ν Energy reconstruction



- From conservation of momentum and energy:

$$E_{reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

- Assumptions:

  We know the reaction channel: CCQE, CCΔ, etc…

  Normally identified with presence of pions in the event.

  The target nucleon is at rest (no fermi momentum).

- Only a fraction of the energy is visible.
- Rely on channel interaction id.

ν Energy reconstruction

- The energy is reconstructed by summing all detected energy:

$$E_{reco} = E_\mu + \sum_{hadron} E_{hadron}$$

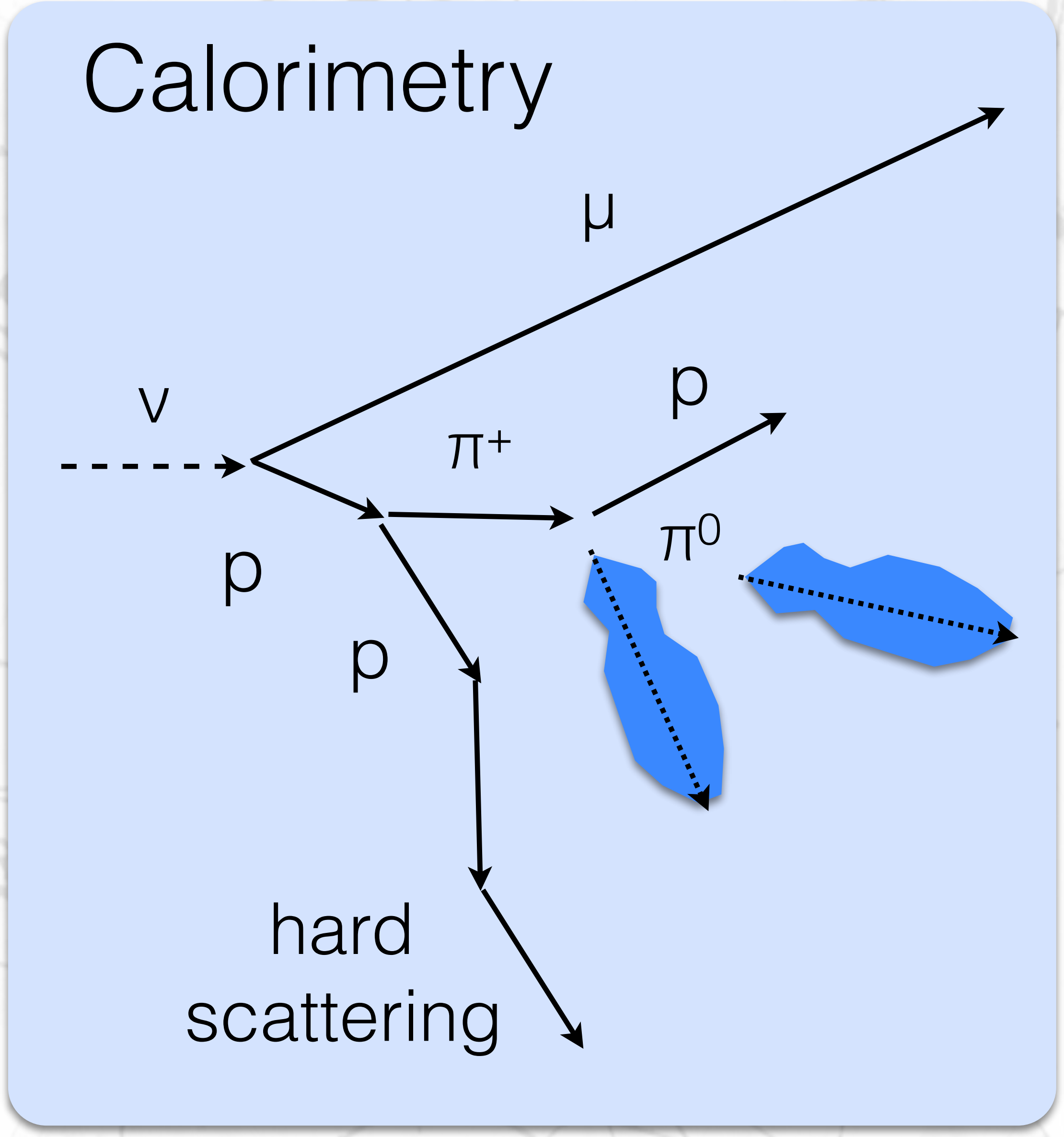
- The deposited energy is only the kinetic energy. The total energy requires the identification of particles:

$$E = E_{kin} + mass$$

- This approach requieres:

fully sensitive detector.

Understanding of the energy deposition by different particles.



- The visible energy is altered by the hadronic interactions and it depends on hadron nature.

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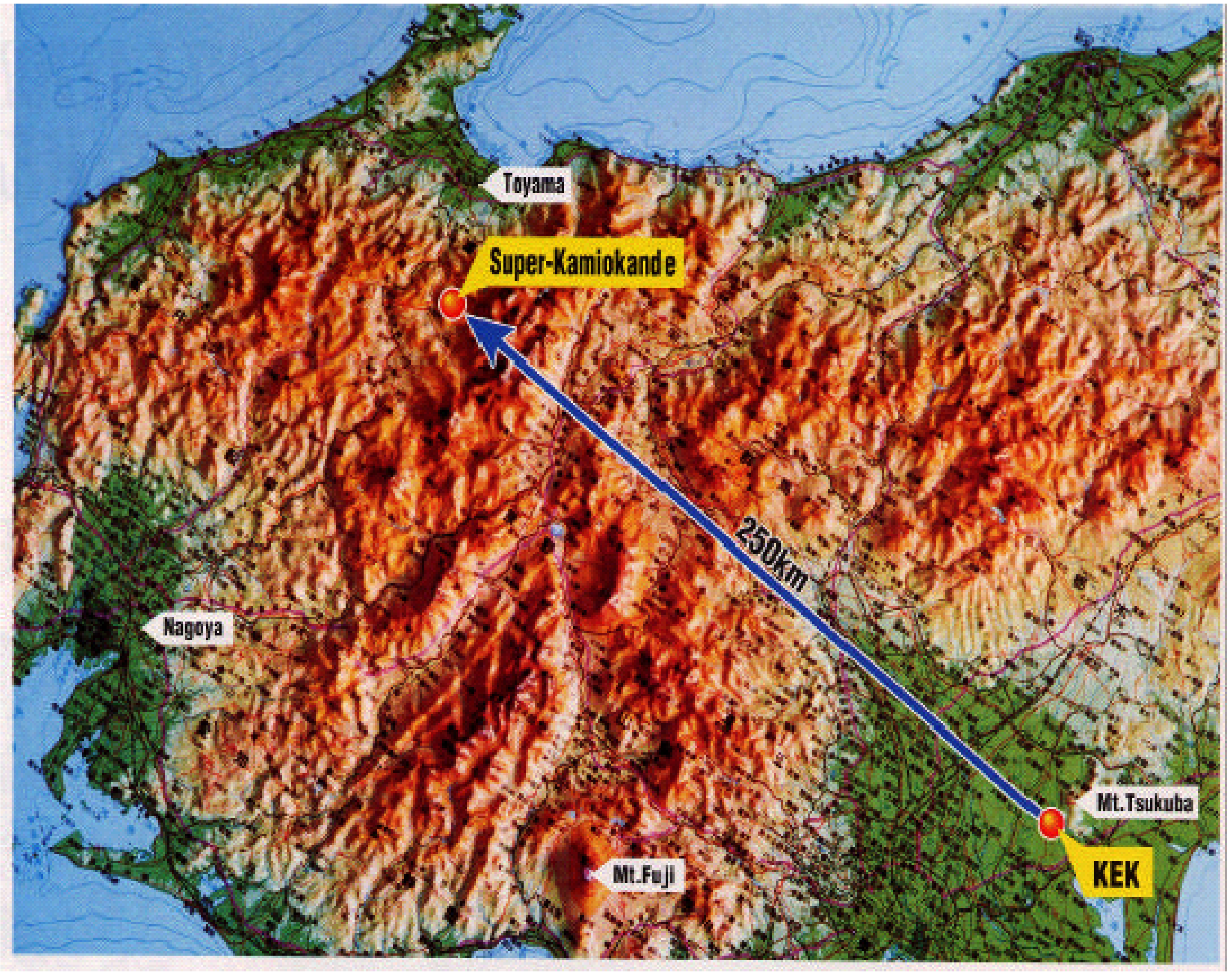
K2K: the confirmation

The experiments

Checking atmospheric oscillations
with man-made sources!

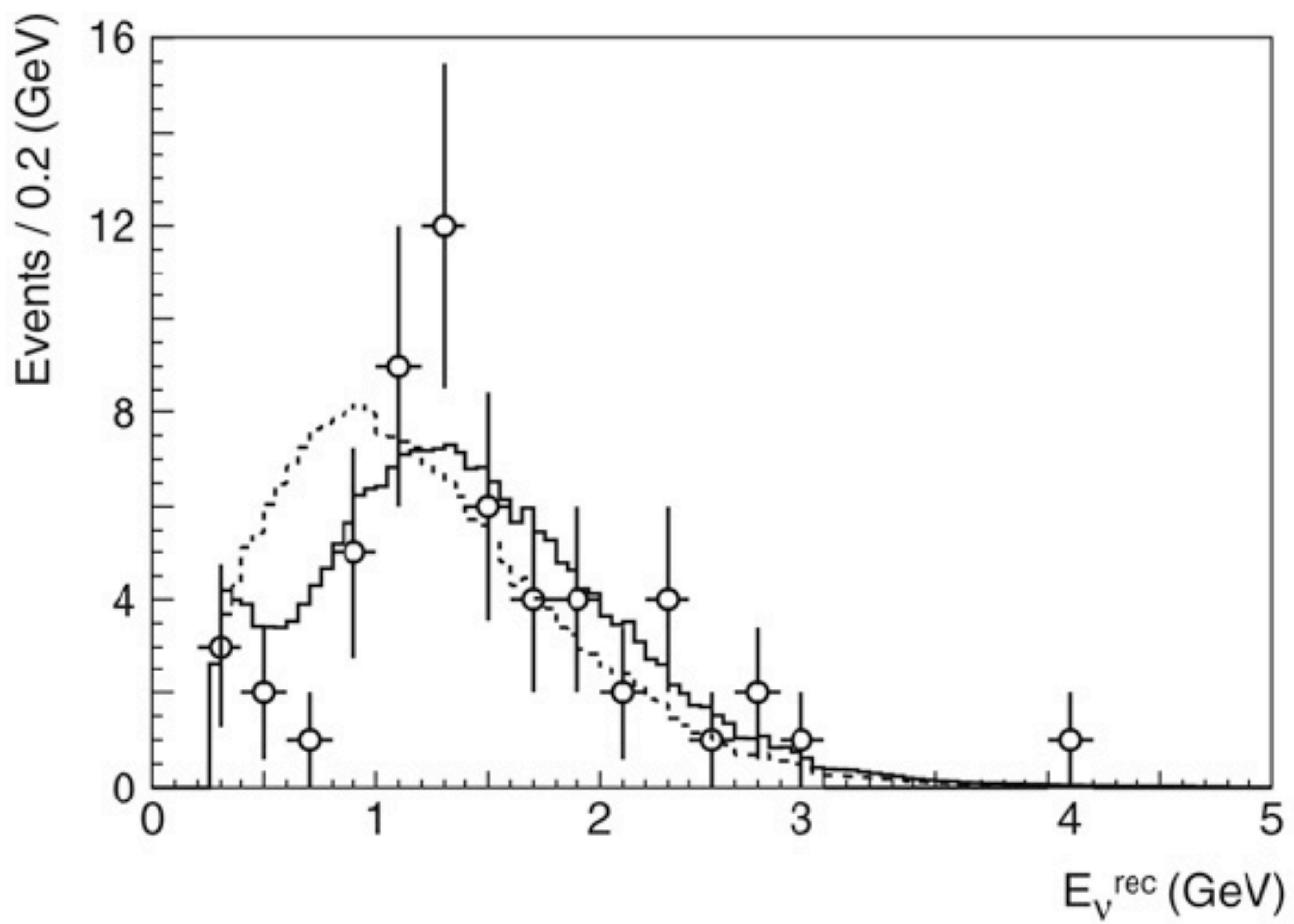


- Artificial neutrinos of ~1.6 GeV are produced in the east coast of Japan.
- Neutrino flux and spectrum is measured at a near detector to reduce uncertainties (“a priori” large)
- Neutrinos are detected at 250 km in Superkamiokande.

The confirmation: K2K

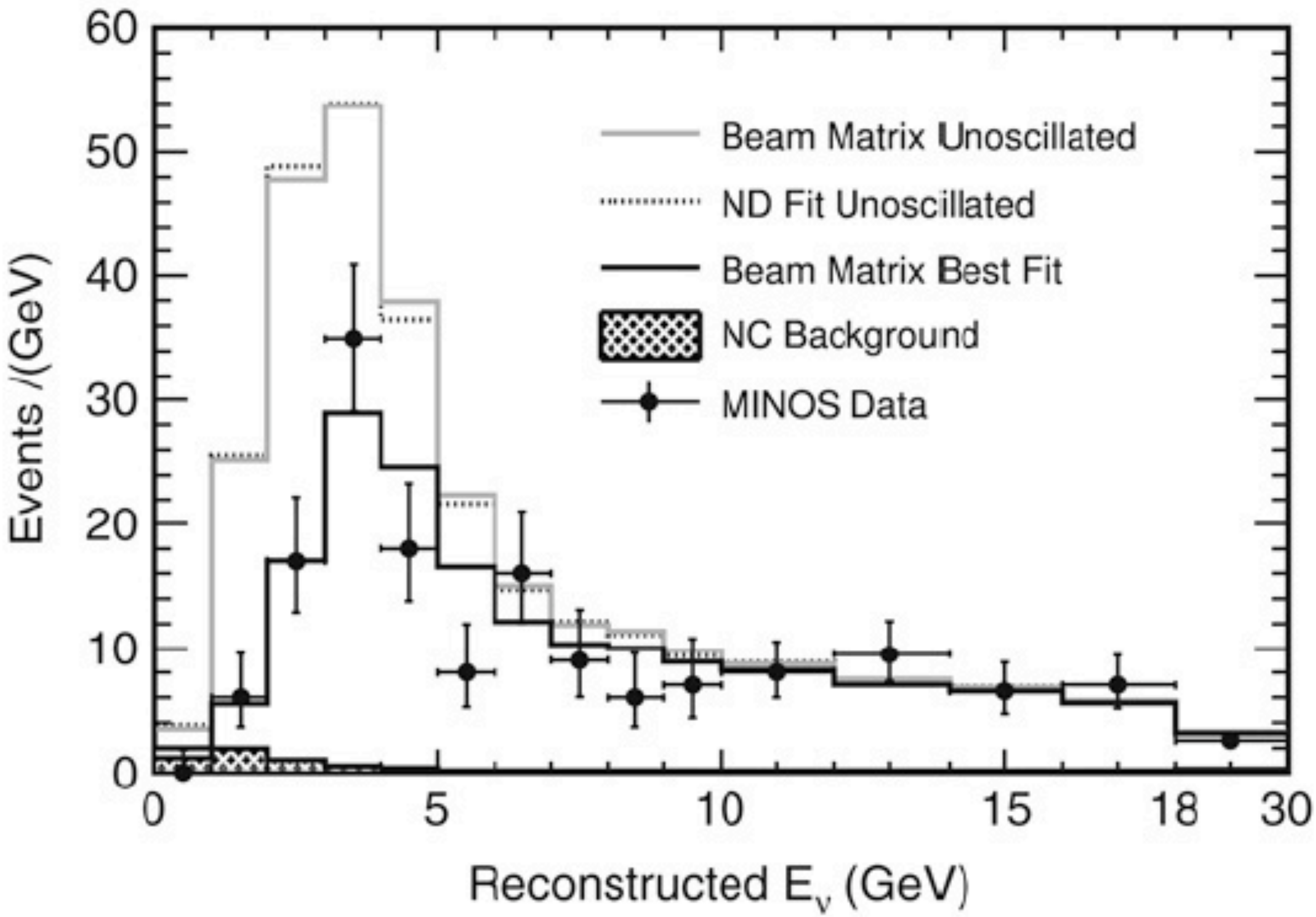
- 1st long base line experiment: prove of principle and technology.
- Deficit and spectrum distortion compatible with SK results.

The experiments



The areas are normalized for the two hypothesis to the number of events detected.

The confirmation: Minos



Solar vs atmospheric

- The observed oscillations are:
  - $\nu_e \rightarrow \nu_{\mu,\tau}$ (SOLAR)
  - $\nu_\mu \rightarrow \nu_\tau$ (ATMOSPHERIC)

Solar & atmospheric appear to us like two decoupled oscillations

- To observe $\nu_\mu \rightarrow \nu_e$ from solar parameters,
  - the energy should be similar to solar neutrinos or the distance should be very large.

$$\frac{\Delta m^2_{23}}{\Delta m^2_{12}} \approx 30.$$

  - We need energies 30x smaller (~30MeV ν_μ production & detection is difficult) or distances 30x larger (tough, we can't make earth 30 times larger!) than standard atmospheric experiments.
  - Similar arguments for the "inverse" atmospheric detection.

Solar vs atmospheric

- Natural sources are not good to invert the measurements.
- We do not know how to "efficiently" make a beam of ν_e of high energy (enough to see μ from ν_μ).
  - *This is were the Neutrino Factory and Beta Beams appear, but this is another story.*
- We do not know how to "efficiently" make a beam of ν_μ of low energy (to adapt to terrestrial distances and solar Δm^2).
- However, the transitions: $\nu_\mu \longrightarrow \nu_e$ at high energy and $\nu_e \longrightarrow \nu_e$ with Δm^2_{atm} are still useful for determining the third angle.

In a sense, we have been very lucky

Measuring δ_{CP}

- To measure CP we need:
  - $\theta_{13} \neq 0$.
    - *If 0, this is like a 2 neutrino mixing and the phase is cancelled.*
  - *Neutrino appearance:*
    - *If we look at disappearance only, it is like two neutrino oscillation and the phase cancelled out.*
  - *Compare* ν *and* $\bar{\nu}$ *transitions.*
  - *Compare disappearance (no CP effect) to appearance experiment (CP effect) so we can derive the phase.*

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Measuring δCP

- CP violation is only possible with more than 2 neutrino species (property of 3x3 imaginary matrices).

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  - With less than 3, the phase can factorised (no CP violation).
  - With more than 3 we hace more than 1 CP phase.

- Since disappearance is like 2 neutrino oscillations (neutrino → all others) , no direct CP can be observed.

$$P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$$

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Measuring θ13 & δCP

The theory

- There are two possibilities:
  - $\nu_\mu \longrightarrow \nu_e$ with atmospheric Δm^2 (long base line: T2K, Nova)

$$
\begin{aligned}
P_{\nu_\mu,\nu_e} \approx & \quad \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
\pm & \quad \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E} \\
- & \quad \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E} \\
+ & \quad \left(\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right)^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}
\end{aligned}
$$

    - Sensitive to CP.

  - $\nu_e \longrightarrow \nu_e$ with “atmospheric” Δm^2

$$P_{\nu_e,\nu_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

    - Insensitive to CP phase.

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Hierarchy

Hierarchy ➡ $\Delta m^2_{23} > 0$ or $\Delta m^2_{23} < 0$? ➡ 1,2,3 or 3,1,2 ordering

- Δm^2_{12} is fixed positive by definition. **We defined 2 to be heavier than 1.**
- In absence of matter effects, the probability is not sensitive to hierarchy.

$$
\begin{aligned}
P_{\nu_\mu,\nu_e} \approx\ & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
\pm\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E} \\
-\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E} \\
+\ & (\frac{\Delta m^2_{12}}{\Delta m^2_{31}})^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}
\end{aligned}
$$

- Matter effects alters the values of the mass and the mixing angle, allowing to measure the hierarchy,

$$
\begin{aligned}
\mu^2_{1,2}(x) &= \frac{m_1^2 + m_2^2}{2} + E_\nu(V_\alpha + V_\beta) \mp \frac{1}{2}\sqrt{[\Delta m^2 \cos 2\theta - A]^2 + [\Delta m^2 \sin 2\theta]^2} \\
\tan 2\theta_m &= \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A} \\
A &= 2E_\nu(V_\alpha - V_\beta)
\end{aligned}
$$

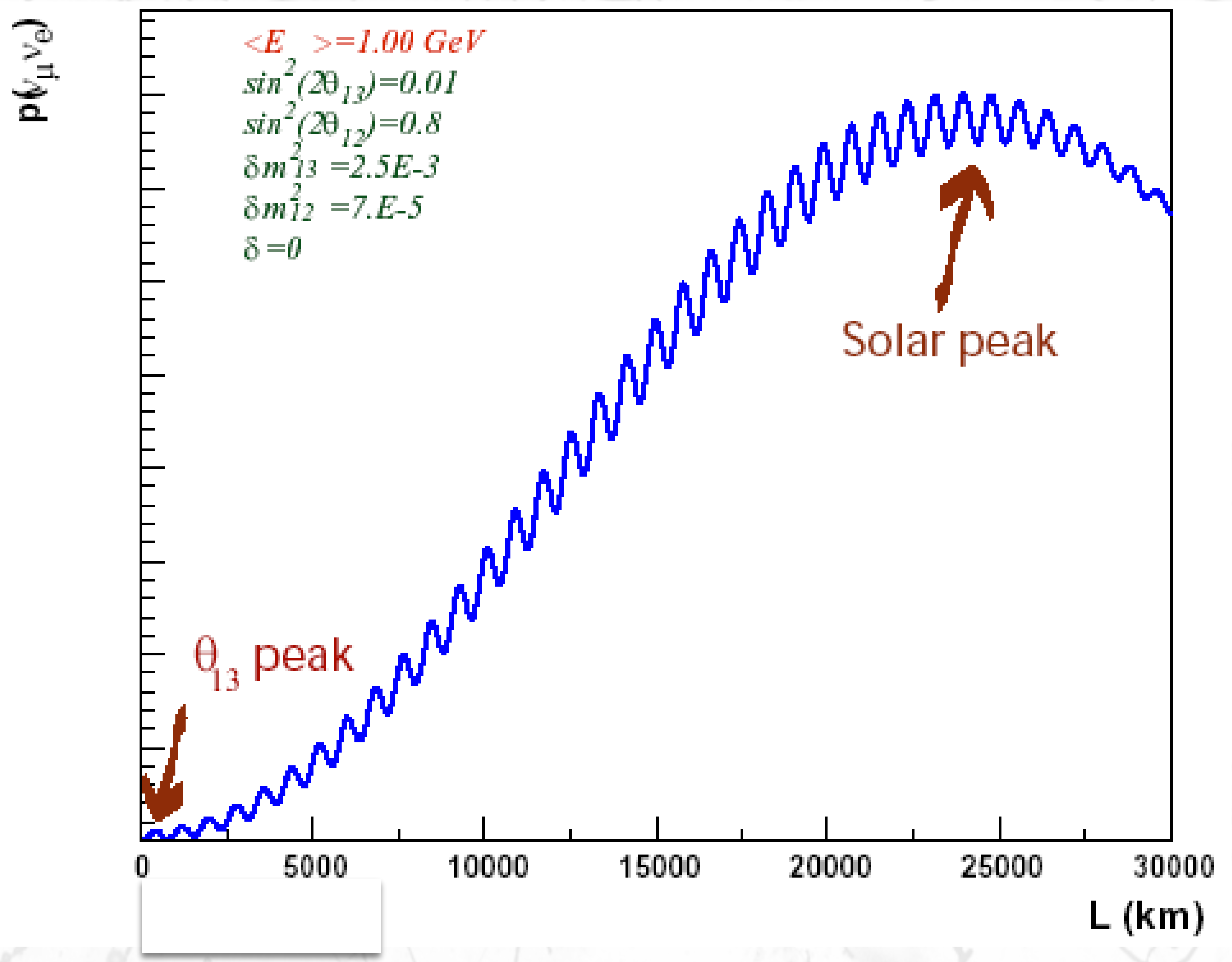
$$V_\alpha = \pm\sqrt{(2)}G_F n_e$$
$$V_\beta = 0.$$

$\nu \mathrel{!}= \bar{\nu}$

- Hierarchy and mass effects “mimic” CP violation ☞ degeneracies!

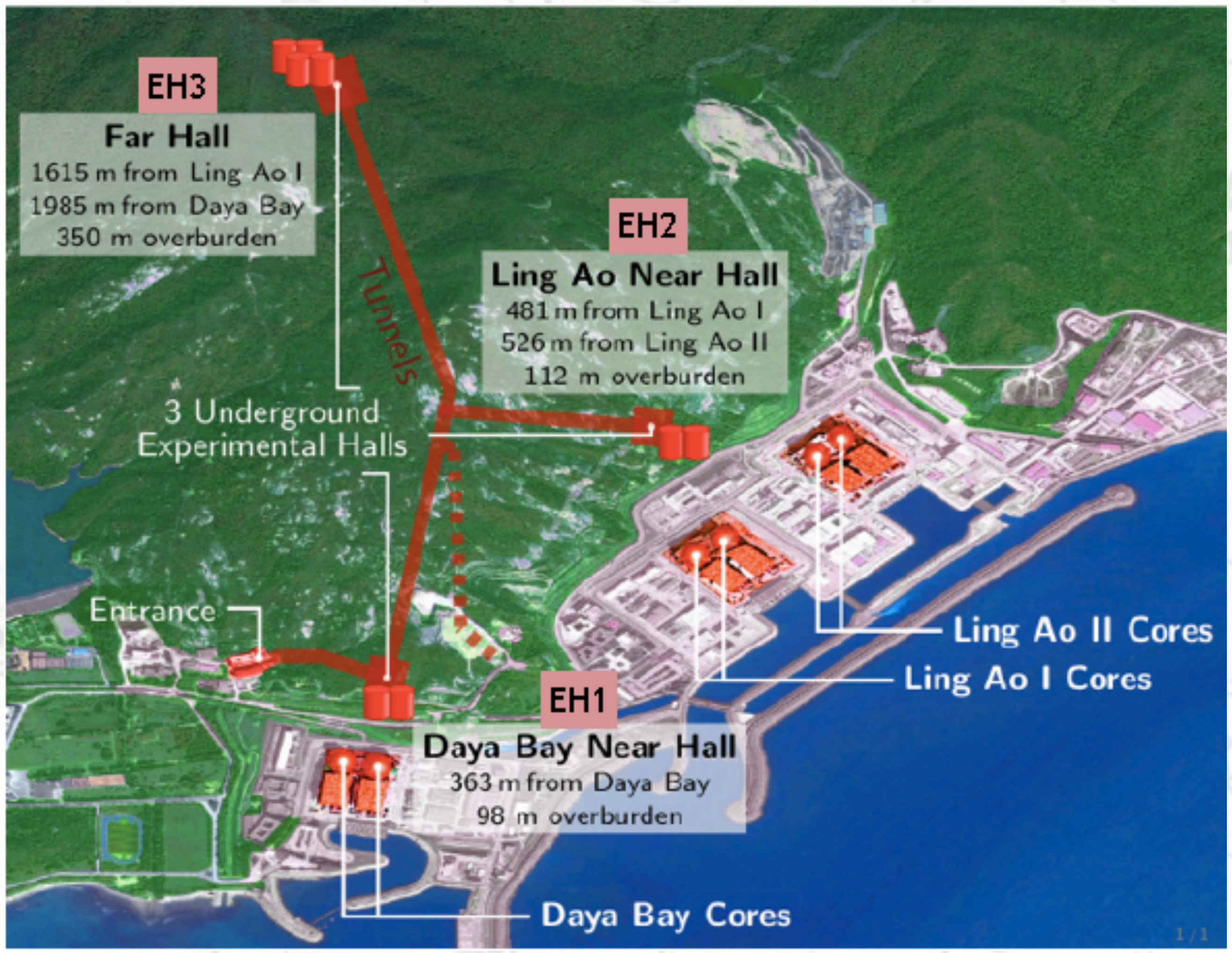
Measuring θ13

The theory



- $\nu_\mu \longrightarrow \nu_e$ compites with the Solar oscillation.
- decoupled only from the L/E value.

Daya Bay



- $\bar{\nu}_e \rightarrow \bar{\nu}_e$ from nuclear reactor.
- 8 identical detectors for relative normalisation.
- Base Line ~ 1.6 km
- Energy ~ 3MeV
- Sensitive to θ_{13}

Main concerns are the detector radiopurity & flux determination

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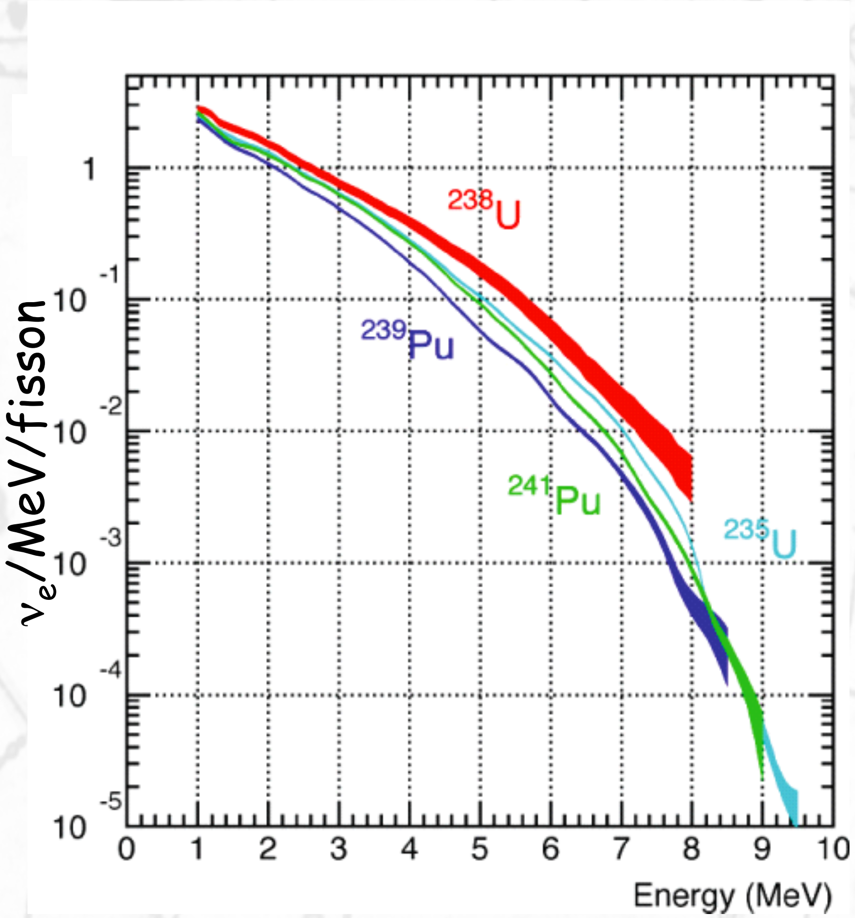
Reactor neutrinos

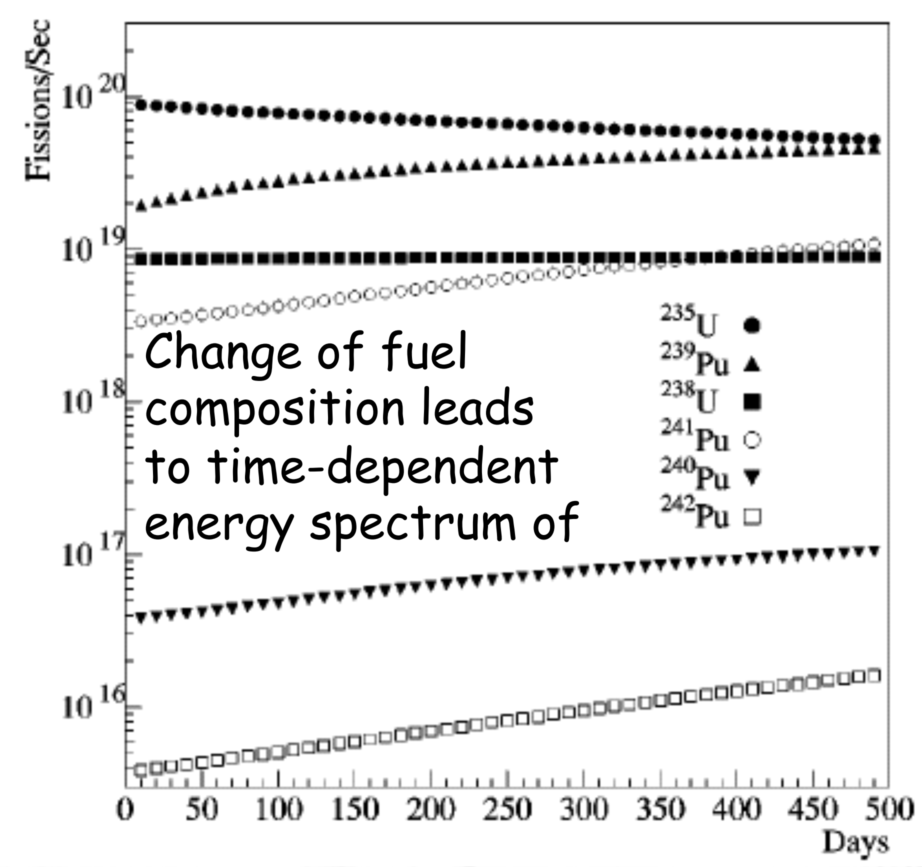
- Fission processes in nuclear reactors produce huge number of low energy anti-neutrinos:

1 $GW_{Thermal}$ ~ 2 x 10^{20} antineutrinos/second

10-20% of total produced energy

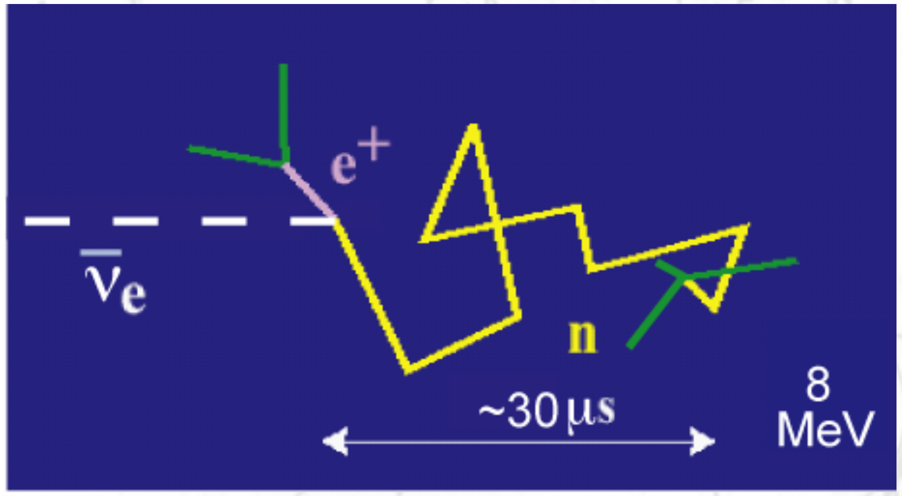
- Antineutrinos come from the beta disintegration of neutron reach nuclear debris.





Inverse beta decay

Inverse beta decay reaction in 0.1% Gd-doped scintillator

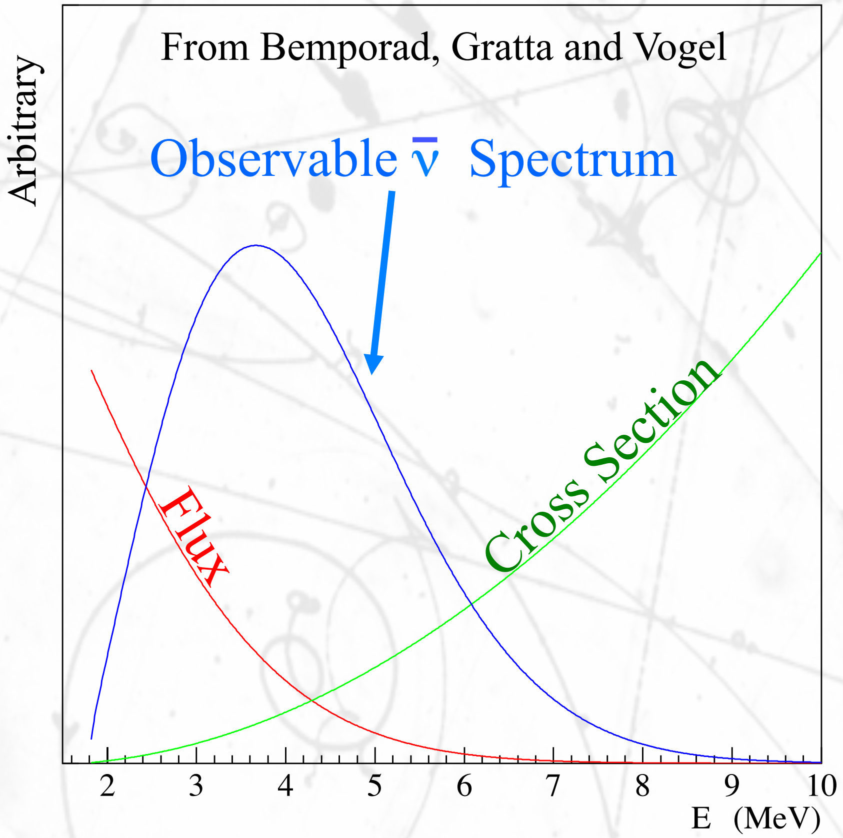


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

→ + p → D + γ(2.2 MeV) (τ~180μs)

→ + Gd → Gd* ~150000 more probable.

→ Gd + γ's(8 MeV) (τ~30μs)



Recorded times and energy reduce the backgrounds

Fast neutrons, accidental coincides, cosmic ray activation, radioactive elements.

Neutrino energy approximated to electron energy

$$E_{\bar{\nu}} \approx T_{e^+} + T_n + (m_n - m_p) + m_{e^+} \approx T_{e^+} + 1.8MeV$$

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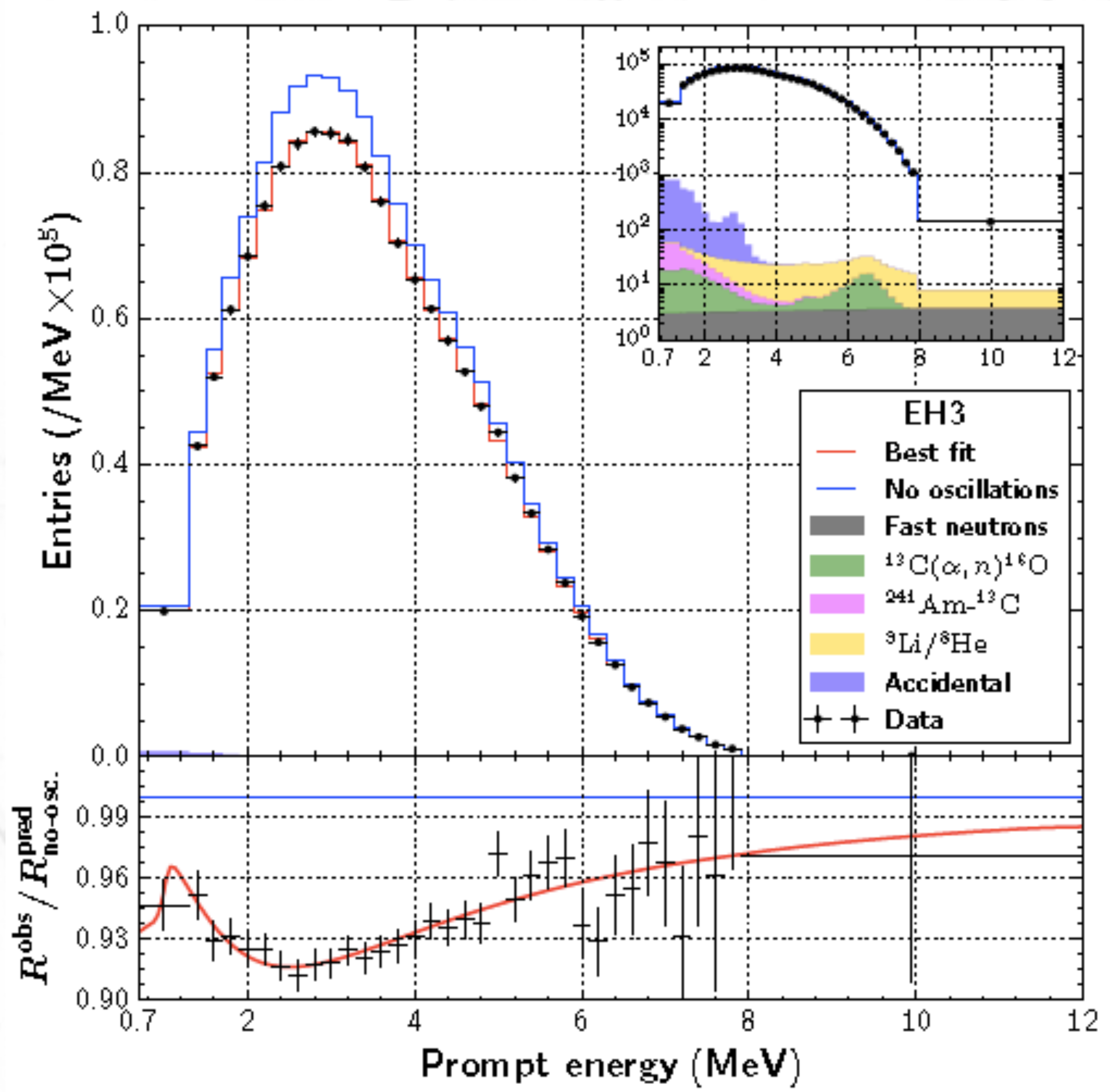
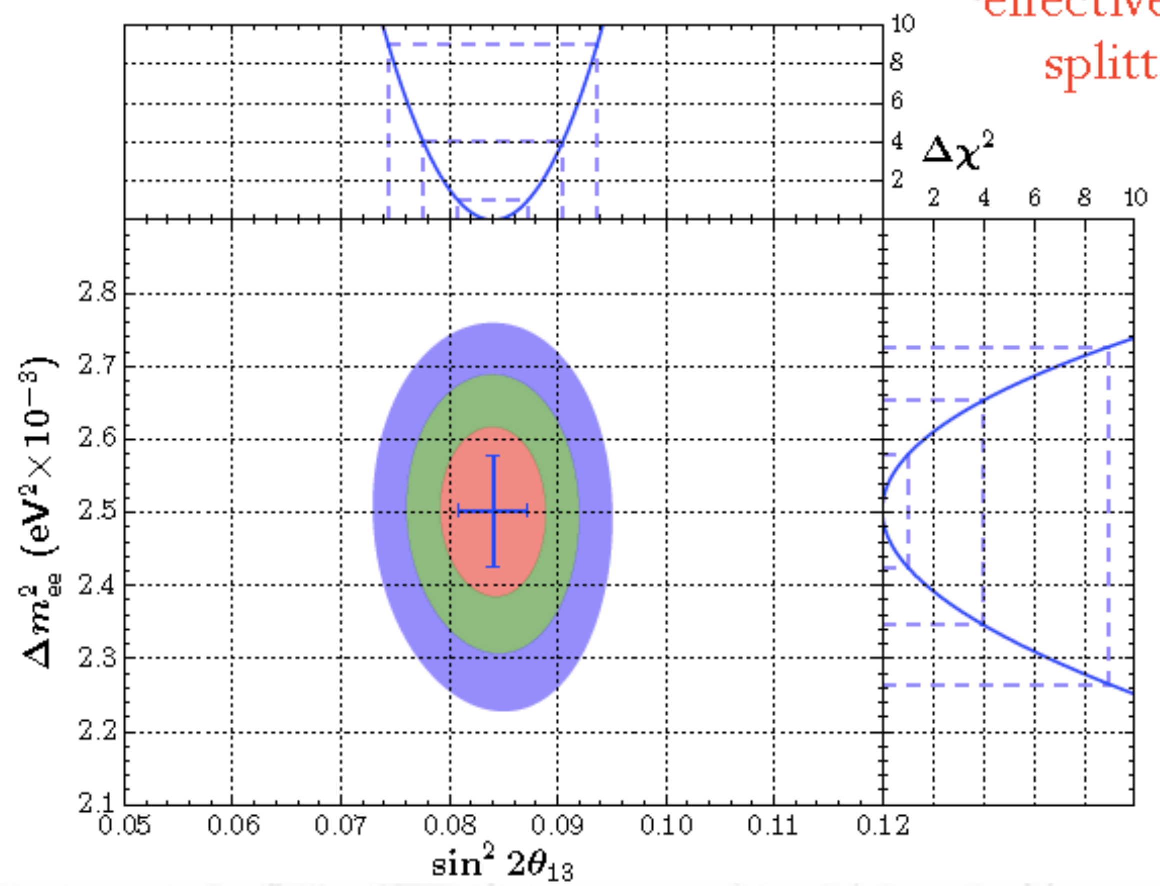
Daya Bay



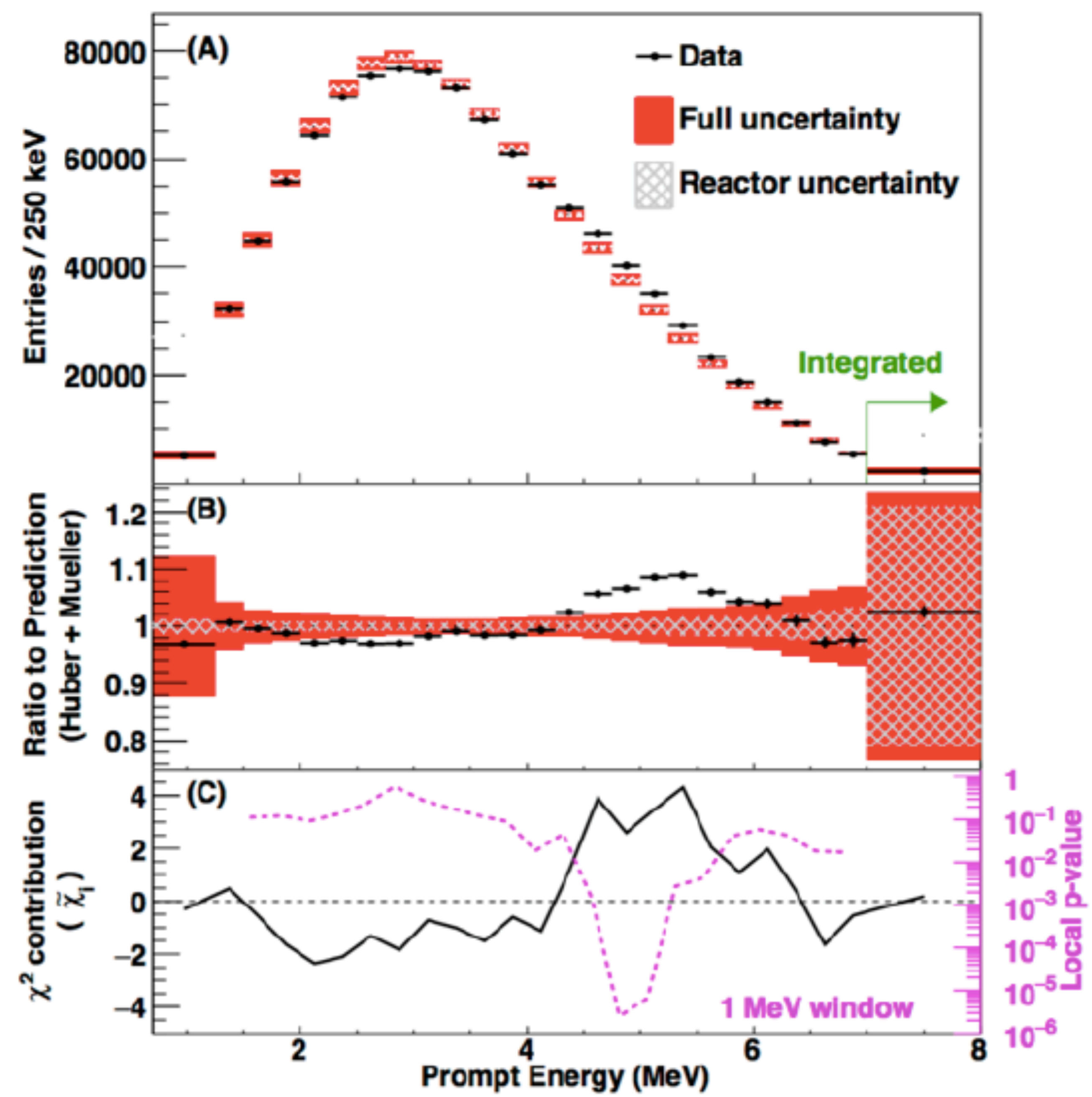
$$P\left(\bar{\nu}_e \to \bar{\nu}_e\right) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}$$

effective mass splitting



Spectrum anomaly

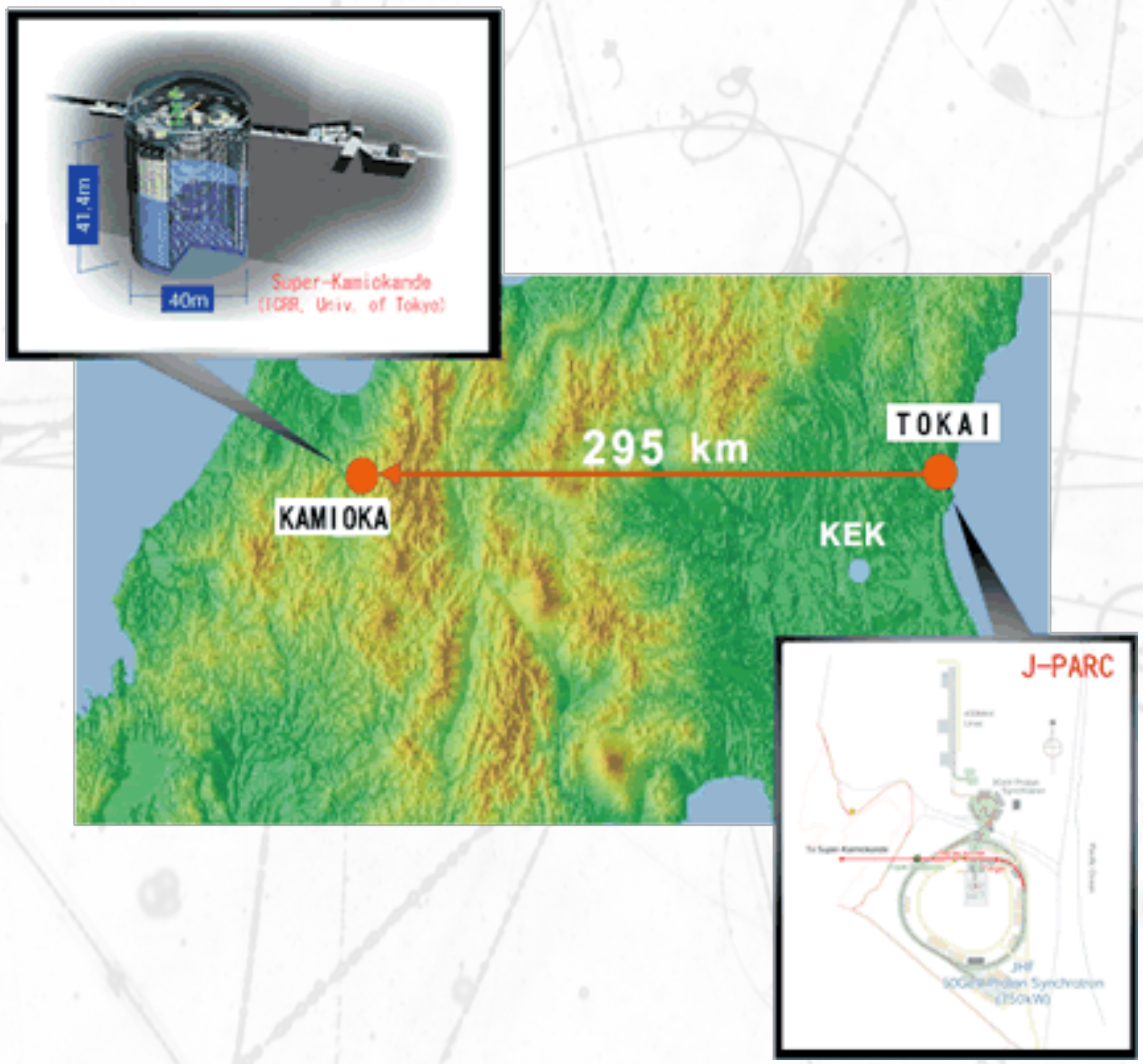
- Modelling neutrinos from reactors is not trivial.
  - It changes also depending on the history of the operation.
- Recently the experiments has seen an excess around 5 MeV.
- Near detectors (before oscillations) help to control deviation from the model.

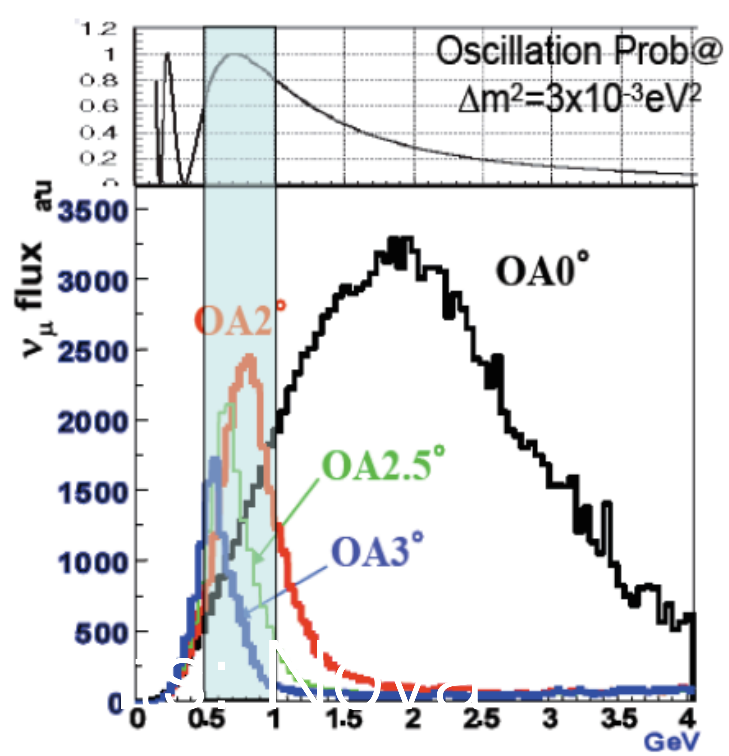


The experiments

T2K

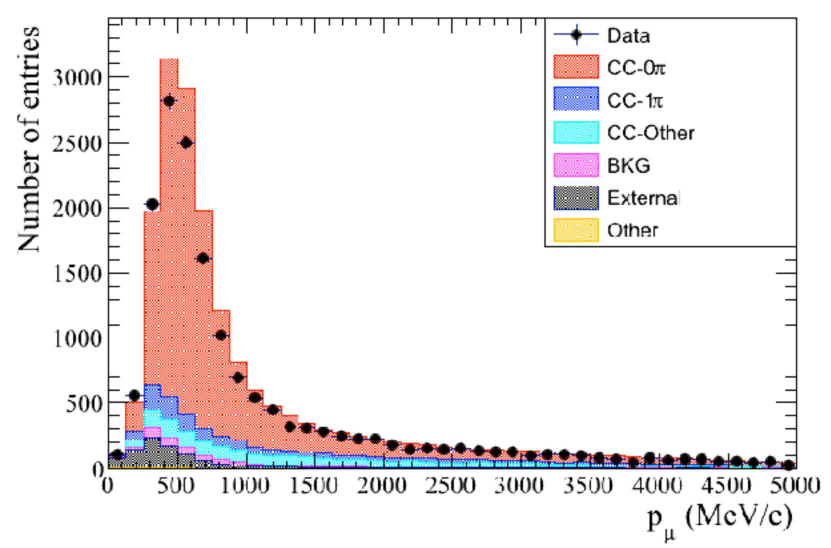
- $\nu_\mu \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_\mu$ from high intensity accelerator.
- E_ν ~ 700 MeV.
- Oscillation distance: 295km.
- Off-axis technique → narrow energy spectrum.





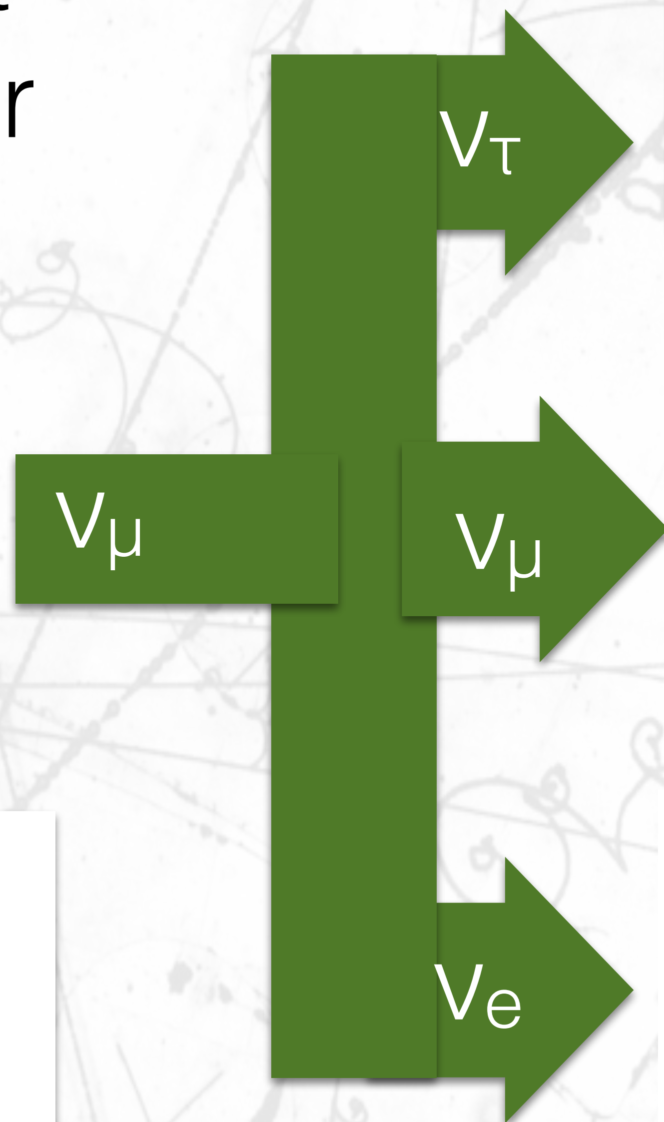
Measurement concept

Measurement at the near detector



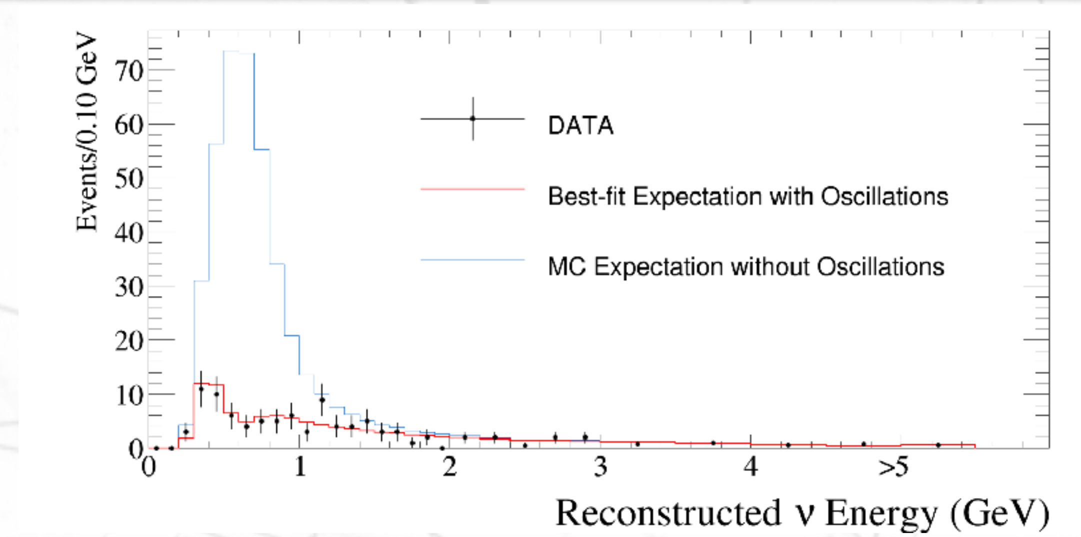
Measurements

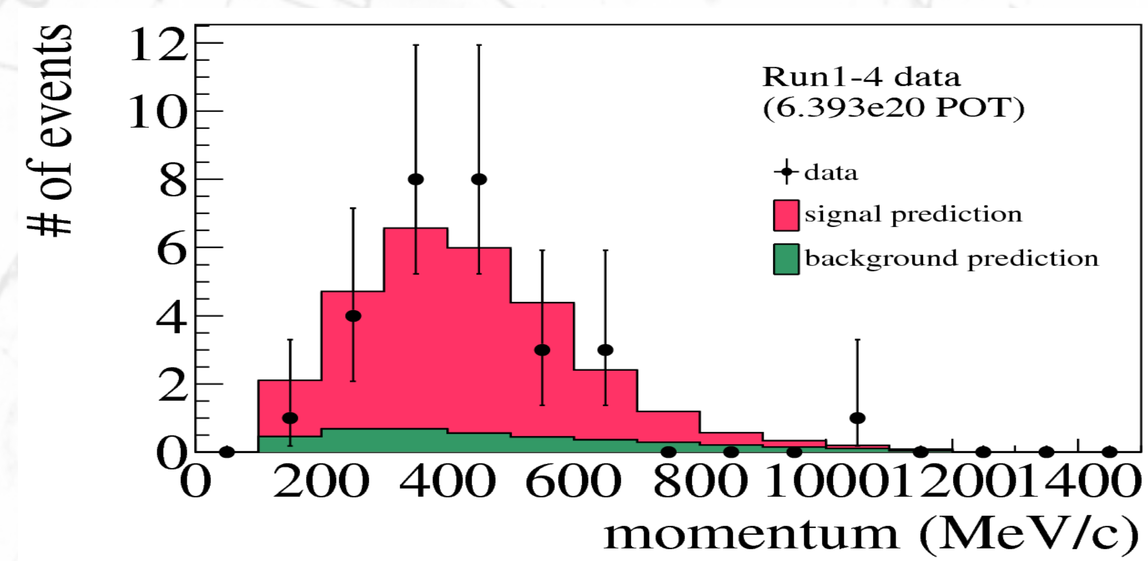
Predictions



Super-Kamiokande

Invisible @ T2K
Not enough energy.





How does it look like ?

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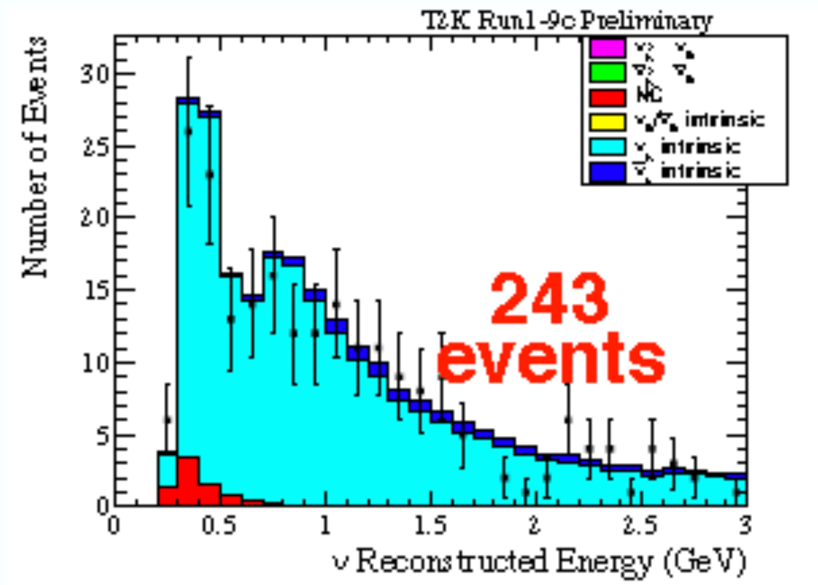
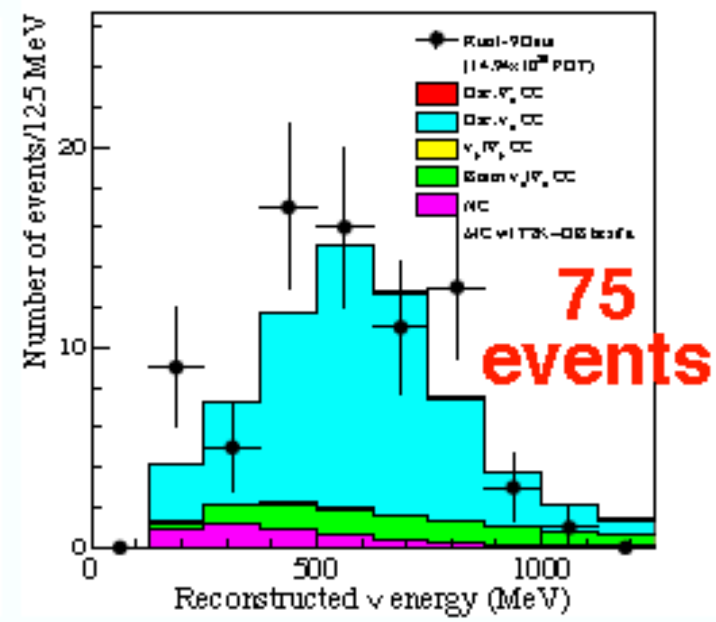
T2K preliminary

Forward horn current

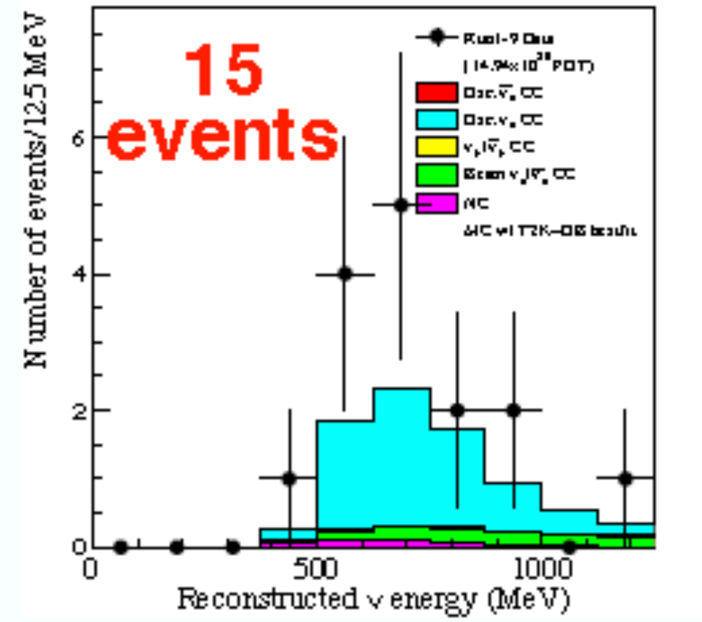
ν_μ CCQE



ν_e CCQE

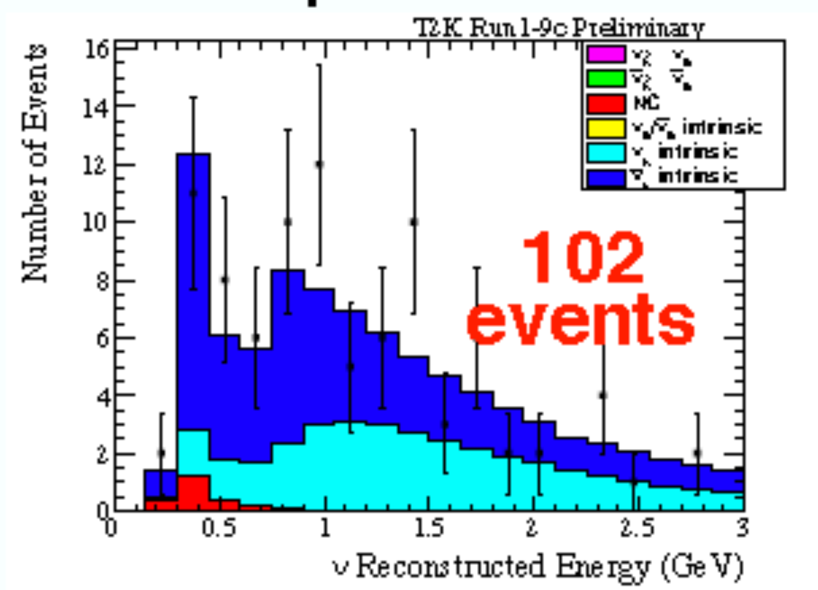


ν_e CC1π

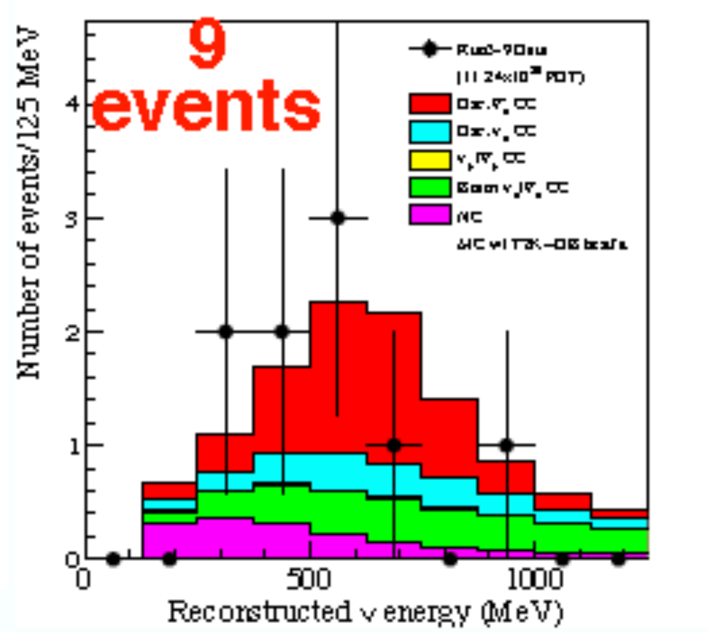


Reversed horn current

$\bar{\nu}_\mu$ CCQE



$\bar{\nu}_e$ CCQE

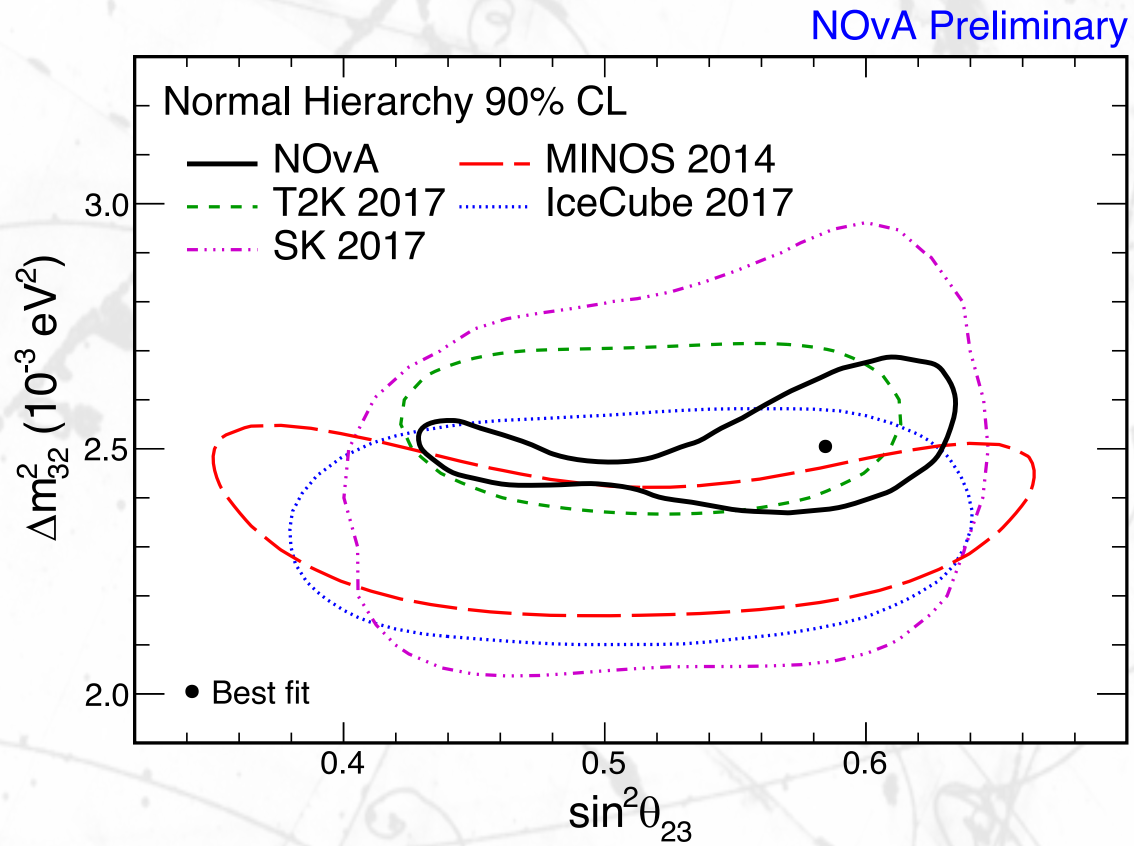


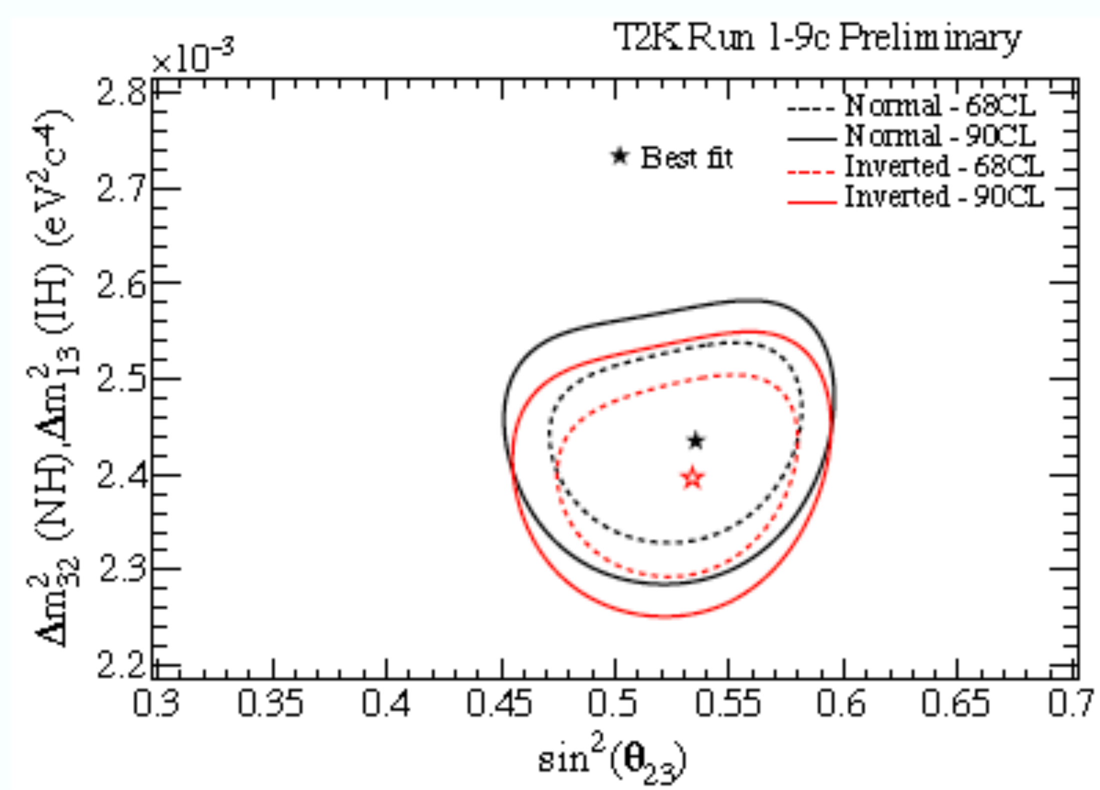
MC assumption

- δ=−1.601
- Normal hierarchy
- $\sin^2\theta_{23}$=0.528
- $\sin^2\theta_{13}$=0.0219

θ_{23}

- Precise measurement.
- Tension between experiments starts to develop:
  - different experiment and assumptions for energy reconstruction!
- Disappearance do not resolve neutrinos from antineutrinos ☞ CPT violation.
- Measured for neutrinos & antineutrinos in T2K and Minos.





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θ_{23}

θ_{23} is relevant for two reasons

Theory

- θ_{23} is the only angle in PNMS close to 45º (maximal mixture)

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- Extremes are relevant information to understand the origin and structure of the mixing matrix.

Experiment

- θ_{23} affects the sensitivity to CP violation:

$$\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\sin 2\theta_{13}\sin\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin^3\frac{\Delta m^2_{31}L}{4E}$$

- Also, measuring the extreme value of 45º is challenging.

$$\frac{dP(\nu_\mu\to\nu_\mu)}{d\theta_{23}}\approx 2.\sin 2\theta_{23}\cos 2\theta_{23}\sin^2\frac{\Delta m^2_{31}L}{4E}\approx 0.$$

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δ_{CP}

δ_{CP} from reactor & LBL

- Take θ_{13} from reactor experiments.
- $$P_{\nu_e,\nu_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$
- Measure the effective θ_{13} in LBL experiments.

$$P(\nu_\mu \to \nu_e) = A \sin^2 2\theta_{13} + B \sin\theta_{13} \cos\theta_{13} \sin\delta$$

@ maximum oscillation energy

- This approach is model dependent!.
  - We measure the CP phase under the assumption of PNMS.
- But, it is the more precise calculation as of today.

δ_{CP}

Comparing neutrinos and antineutrinos

- The asymmetry of the oscillation probability

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

- Is proportional to sin δ_{CP}

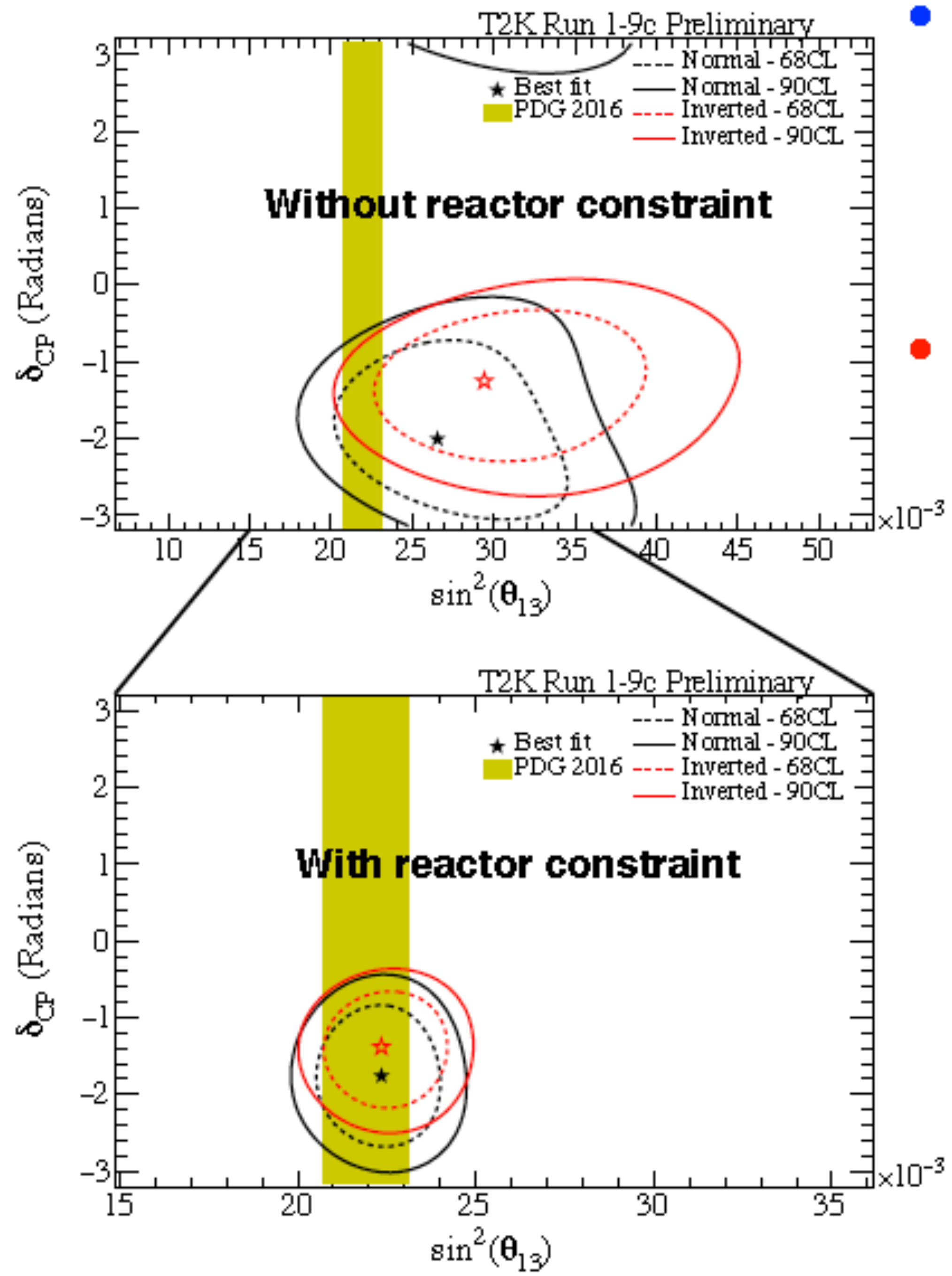
$$A_{CP} \approx 2 \frac{\Delta m^2_{12} \cos\theta_{13} \sin 2\theta_{12}}{\Delta m^2_{31} \sin 2\theta_{13} \sin 2\theta_{23}} \sin\delta_{CP}$$

Oversimplified!

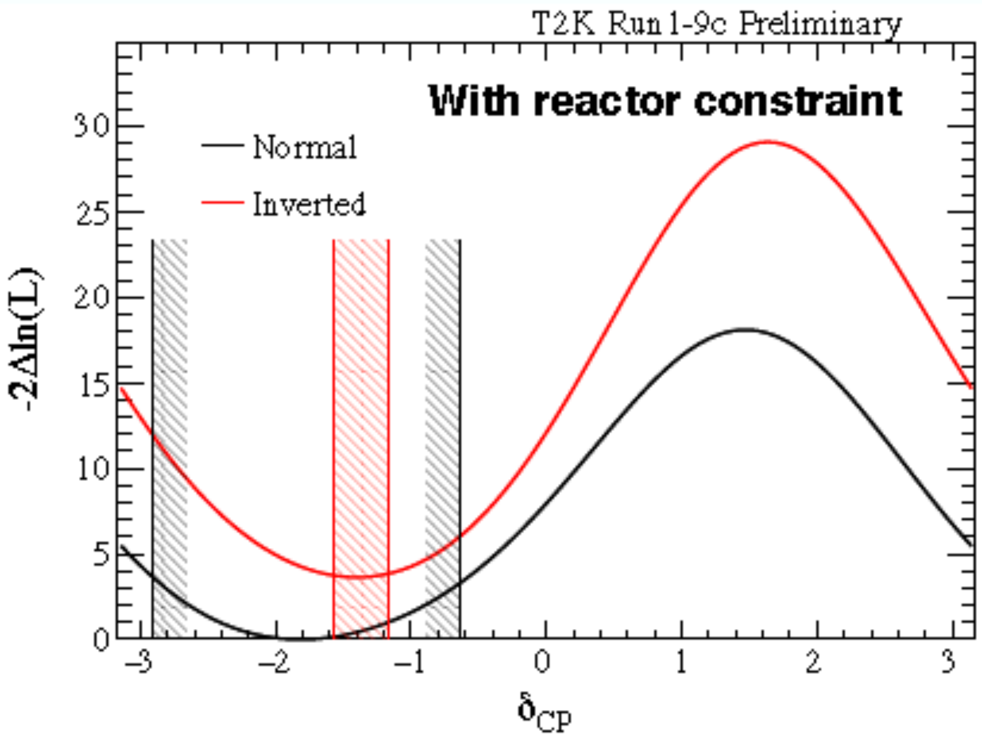
- This is model independent but very inefficient:
  - Mass term : $\frac{\Delta m^2_{23}}{\Delta m^2_{12}} \approx 30.$
  - Producing and detecting neutrinos is ~6 times more efficient than antineutrinos.

@ maximum oscillation energy

θ_{13} & δ_{CP}



- **2σ interval calculated with Feldman&Cousins method**
  - NH : [-2.914, -0.642]
  - IH : [-1.569, -1.158]
- **CP conserving values (0, ±π) outside of 2σ region for both hierarchies**

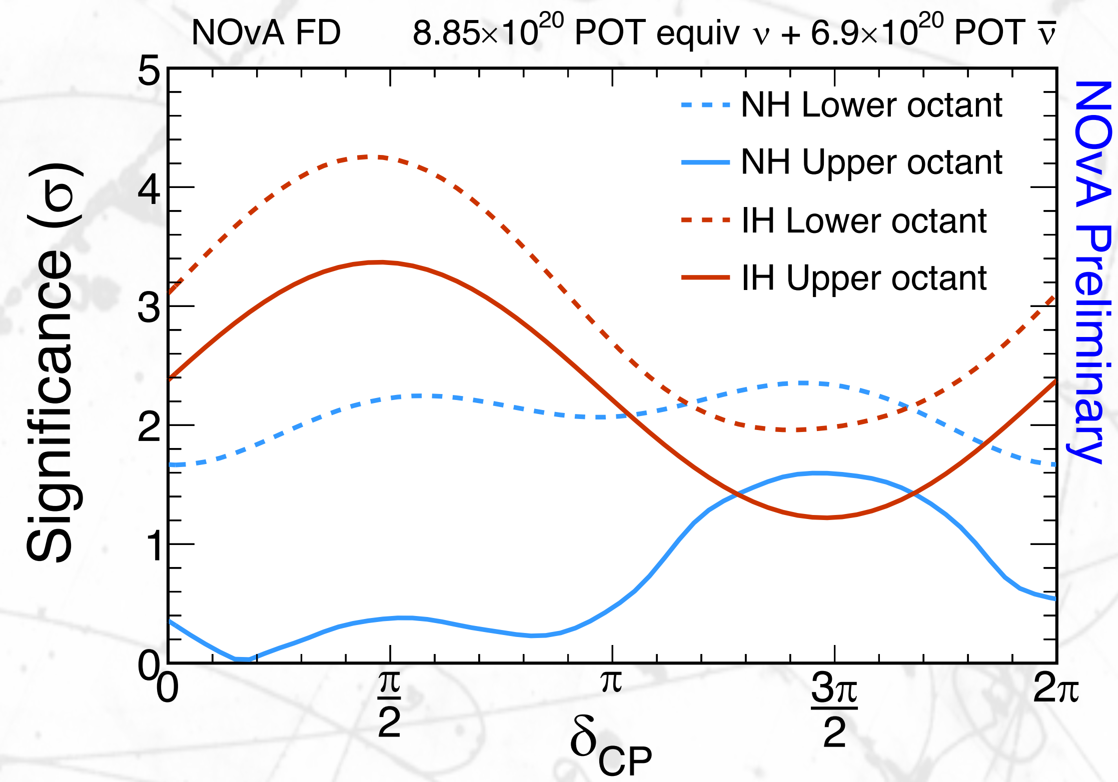


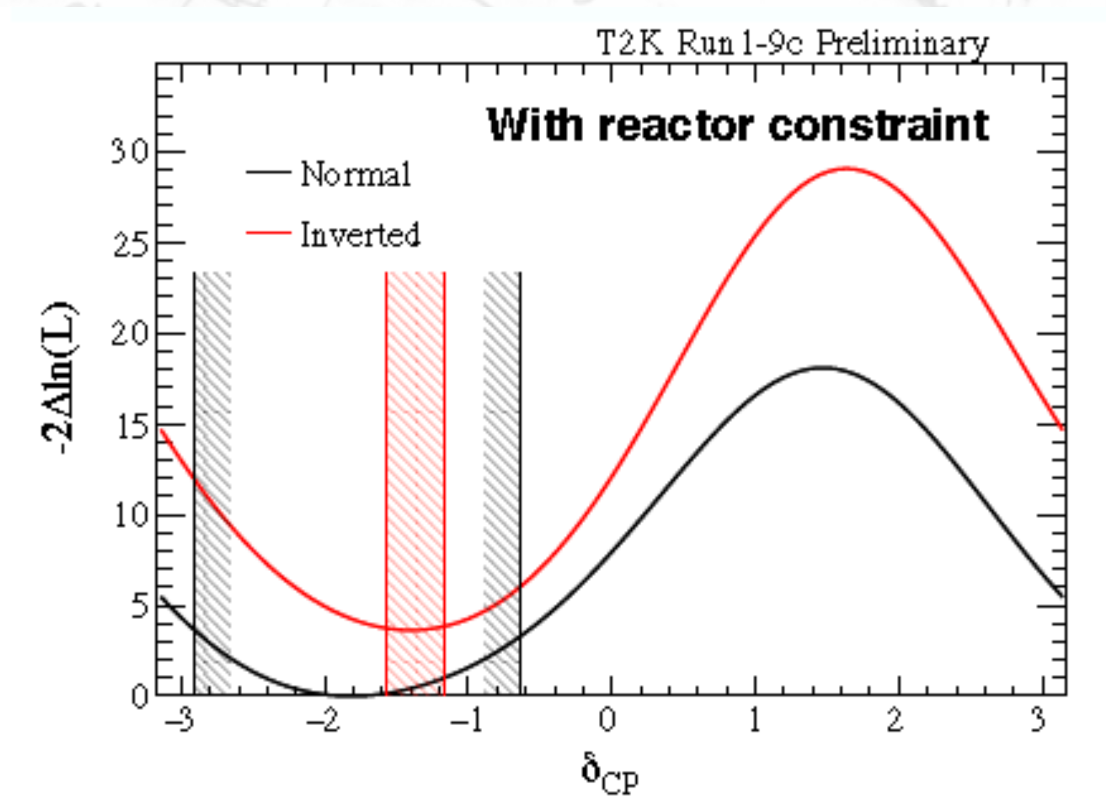
- Combining the two techniques in a global fit. T2K & Nova obtain first results of CP violation.

θ_{13} & δ_{CP}

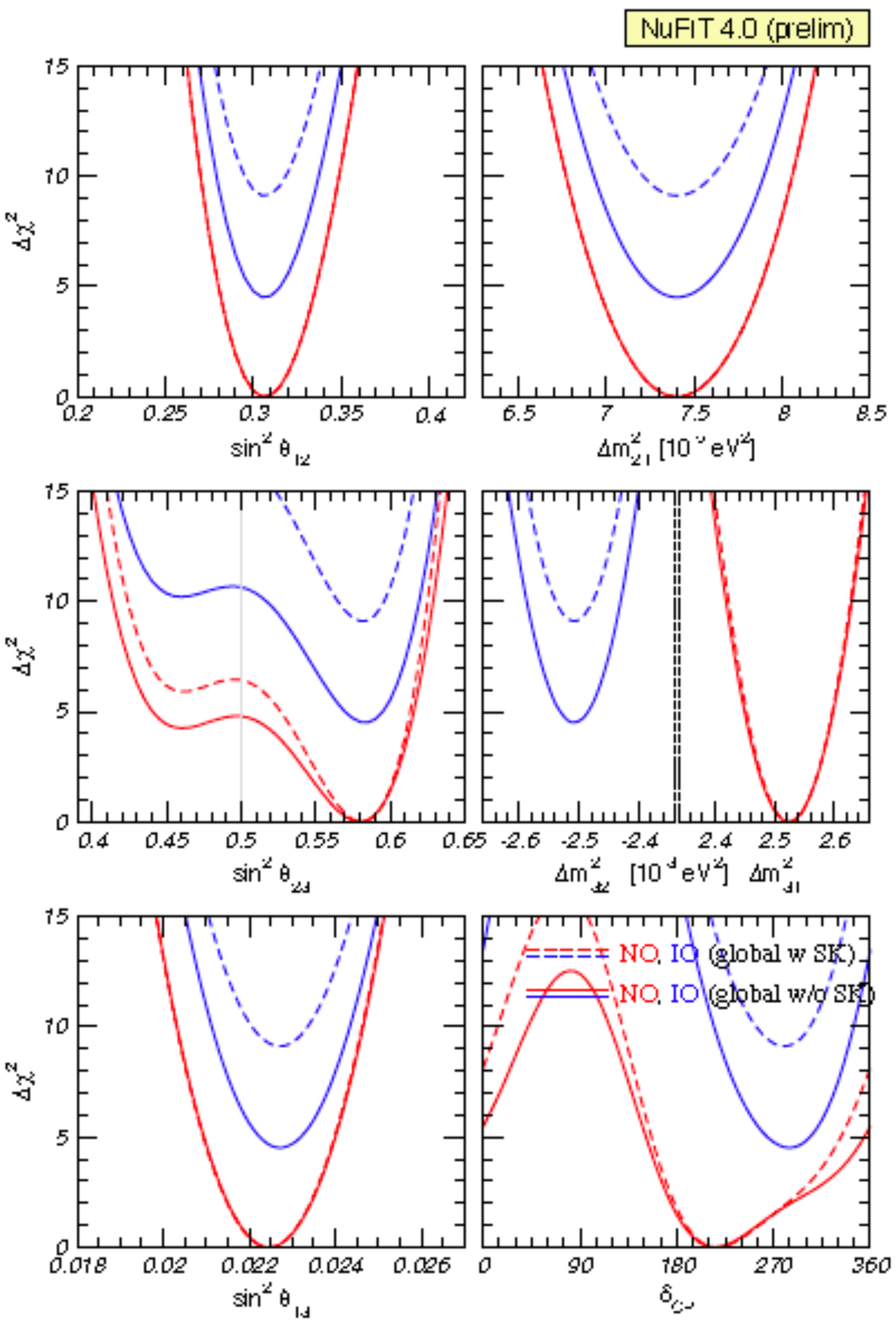
- Not all experiments show the same result.
- Is this :
  - just statistical fluctuation ?
  - detector systematics ?
  - cross-section systematics ?

Complex experiments with low statistics!





Global fits!



- From Global Analysis w ATM IC/DC w/o SK :

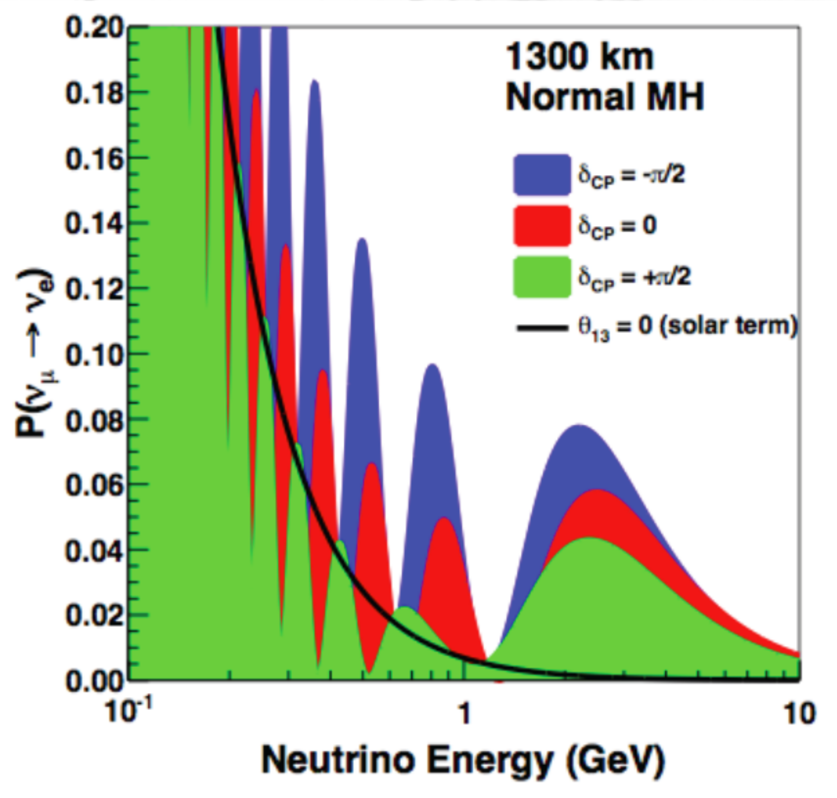
	NO	
	bf $\pm 1\sigma$	3σ
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$
$\sin^2\theta_{13}$	$0.02246^{+0.00069}_{-0.00067}$	$0.02043 \to 0.02453$
$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\,\mathrm{eV}^2}$	2.523 ± 0.033	$2.424 \to 2.623$
$\sin^2\theta_{23}$	$0.580^{+0.018}_{-0.021}$	$0.417 \to 0.627$
δ_{CP}	215^{+41}_{-29}	$125 \to 393$

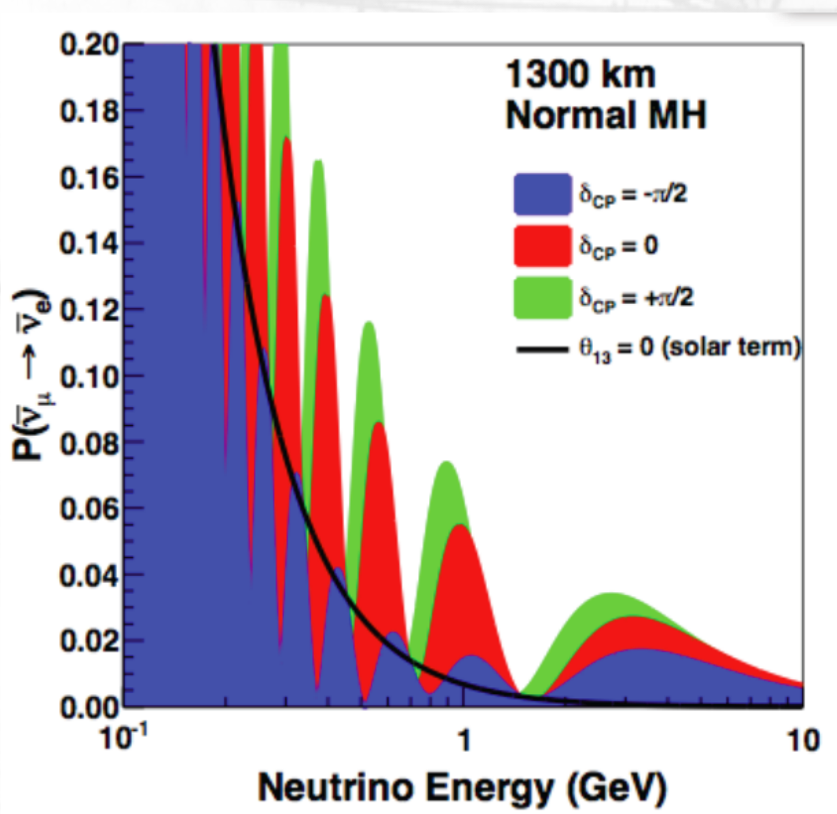
	IO $\Delta\chi^2 = 4.5$	
	bf $\pm 1\sigma$	3σ
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$
$\sin^2\theta_{13}$	$0.02271^{+0.00070}_{-0.00068}$	$0.02068 \to 0.02480$
$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\,\mathrm{eV}^2}$	$-2.510^{+0.035}_{-0.032}$	$-2.610 \to -2.409$
$\sin^2\theta_{23}$	$0.583^{+0.017}_{-0.020}$	$0.423 \to 0.629$
δ_{CP}	285^{+27}_{-30}	$193 \to 360$

$\Rightarrow$ Including SK:

- NO vs IO: $\Delta\chi^2 = 4.5 \Rightarrow 9.1$
- NO: $\theta_{23} = \frac{\pi}{4}$: $\Delta\chi^2 = 4.4 \Rightarrow 6.2$
- NO: CP conserv: $\Delta\chi^2 = 1.7 \Rightarrow 1.8$

Beyond 1st oscillation





- The first and second oscillation maximum changes for different values of hierarchy & δ_{CP}
- Better sensitivity and reduced systematic uncertainties !
- Two ways to get 2nd maximum ($\sin^2(\alpha L/E)$):
    - Change Energy (E)
    - Change travel distance (L)

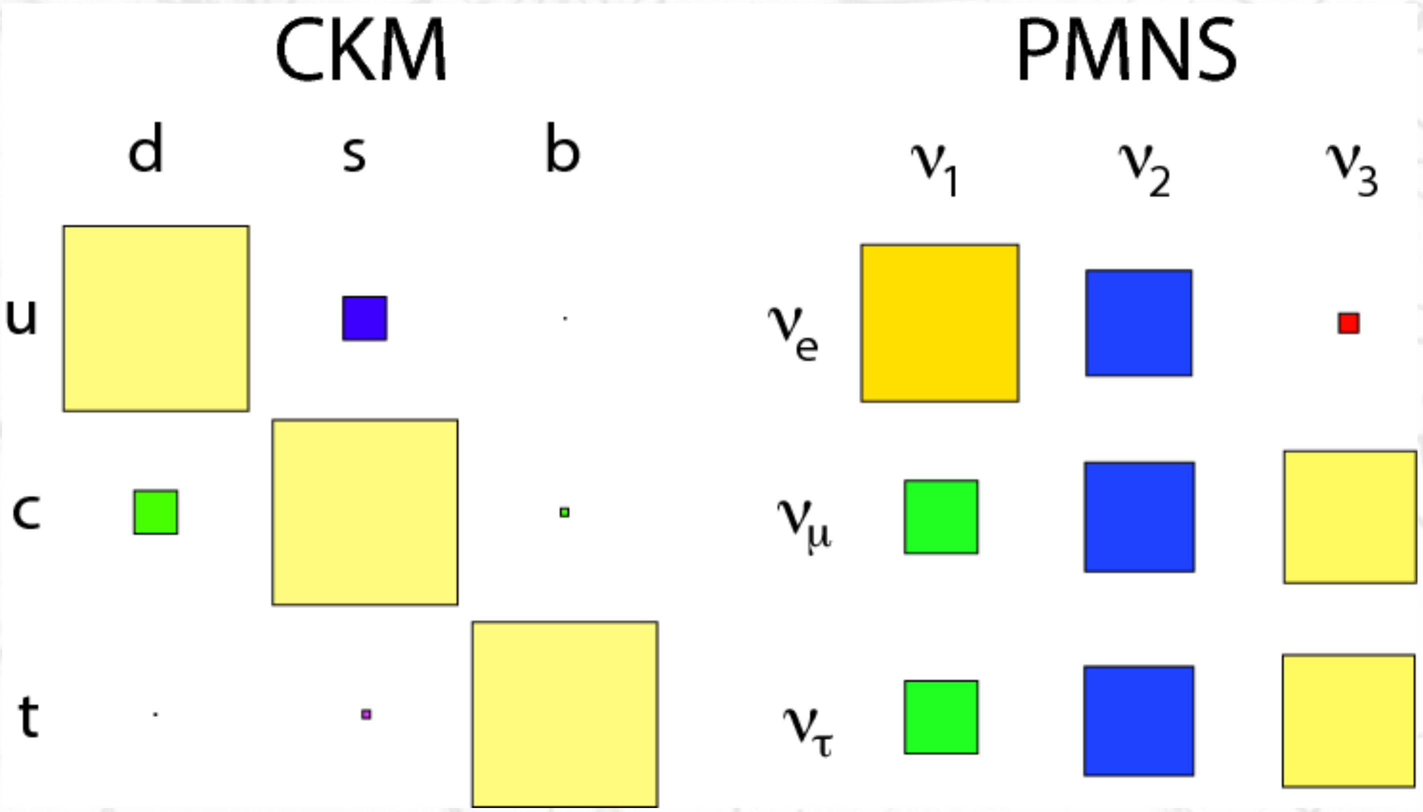
$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \approx\ & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E}\left(1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right) \\
& + 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{23}s_{13}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
& \mp 8c_{13}^2 C_{12} C_{s3} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
& + 4s_{12}c_{13}(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta) \sin\frac{\Delta m_{21}^2 L}{4E} \\
& \mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{21}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2)
\end{aligned}
$$

PNMS matrix

- This is the matrix as 2014 (mainly unchanged)

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 0.82 \pm 0.01 & 0.54 \pm 0.02 & -0.15 \pm 0.03 \\ -0.35 \pm 0.06 & 0.70 \pm 0.06 & 0.62 \pm 0.06 \\ 0.44 \pm 0.06 & -0.45 \pm 0.06 & 0.77 \pm 0.06 \end{bmatrix}$$

- Quark and neutrino mixing matrices are very different.



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Unitarity

- Is the PNMS a unitary matrix ?
- We know there is only 3 active neutrinos (LEP).
- But, neutrinos can mixed with"sterile" neutrinos.
- How could we know ?:
  - neutrinos oscillate with a Δm^2 that is not the solar or the atmospheric one.
  - Two signatures:
    - neutrino flavour disappearance with large Δm^2 : missing neutrinos!
    - **neutrino flavour transition with large Δm^2 : unexpected neutrinos!.**

Sterile neutrinos has cosmological (number of light particles) and gravitationally (dark matter) signatures.

Sterile neutrinos

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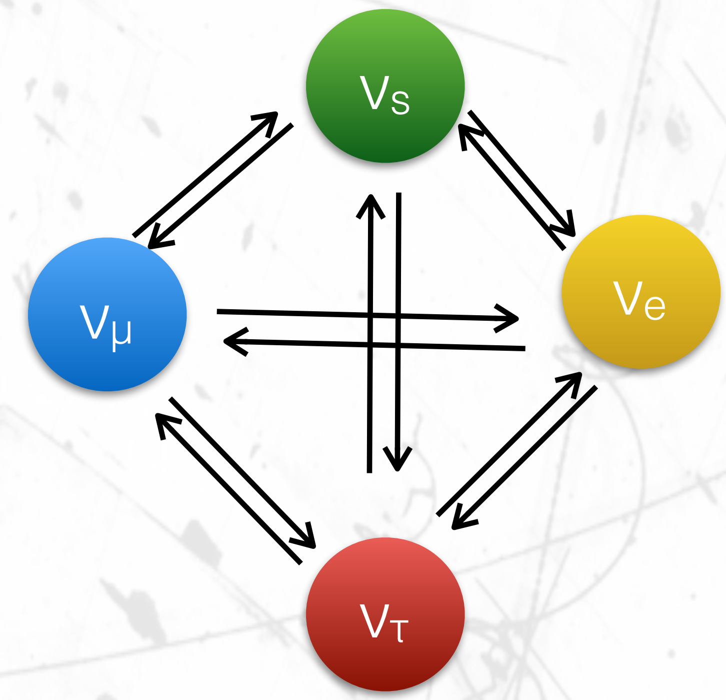
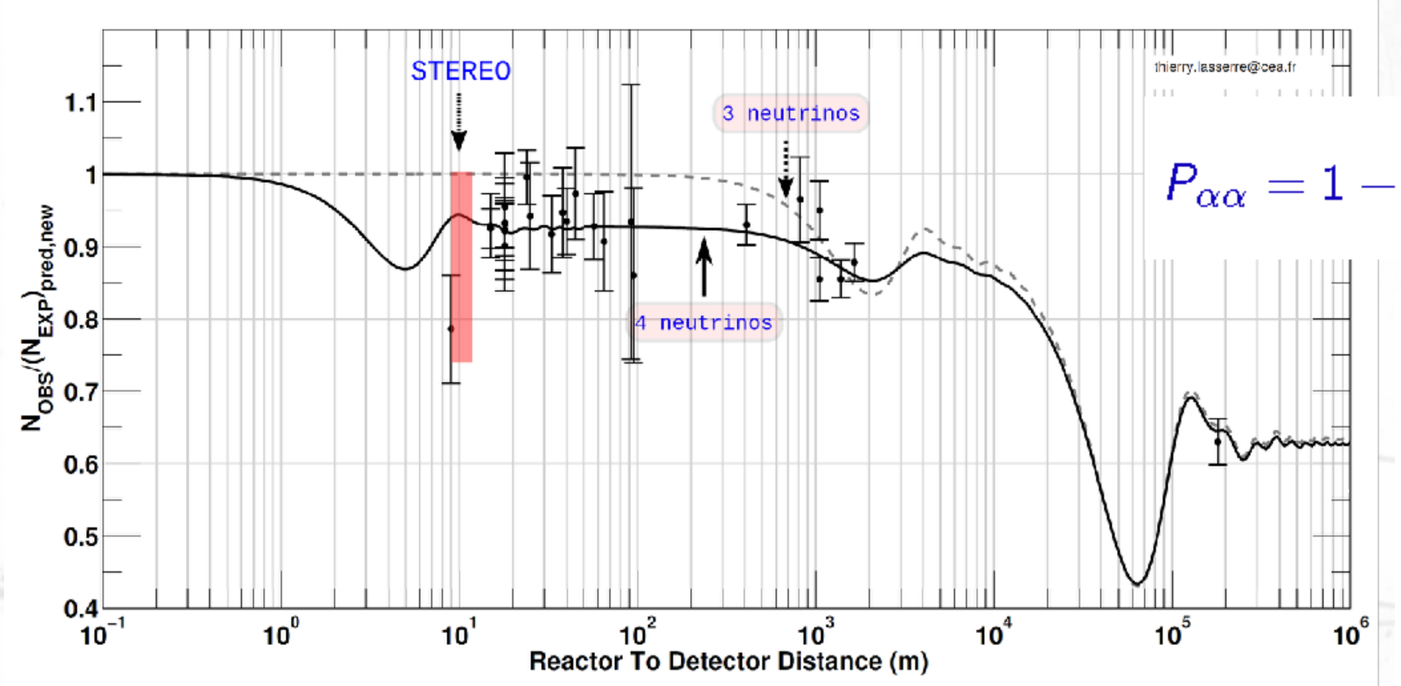
- Observation can be interpreted as a **neutrino oscillation** with a Δm^2 different from solar and atmospheric splitting.
- This is possible if there are **more than 3 neutrinos**.
- LEP demonstrated the existence of **3 active neutrinos:**
  - neutrinos that interact through weak interactions.
- The only option is a "weird" concept (sterile neutrino):
  - a **neutrino that interacts only through gravitation.**
- There might be 1 or 2 additional sterile neutrinos.
- They could be the origin of dark matter but already **cosmology** limits the neutrinos to around 3:
  - in cosmology a "neutrino" is basically a weakly interaction low mass particle.



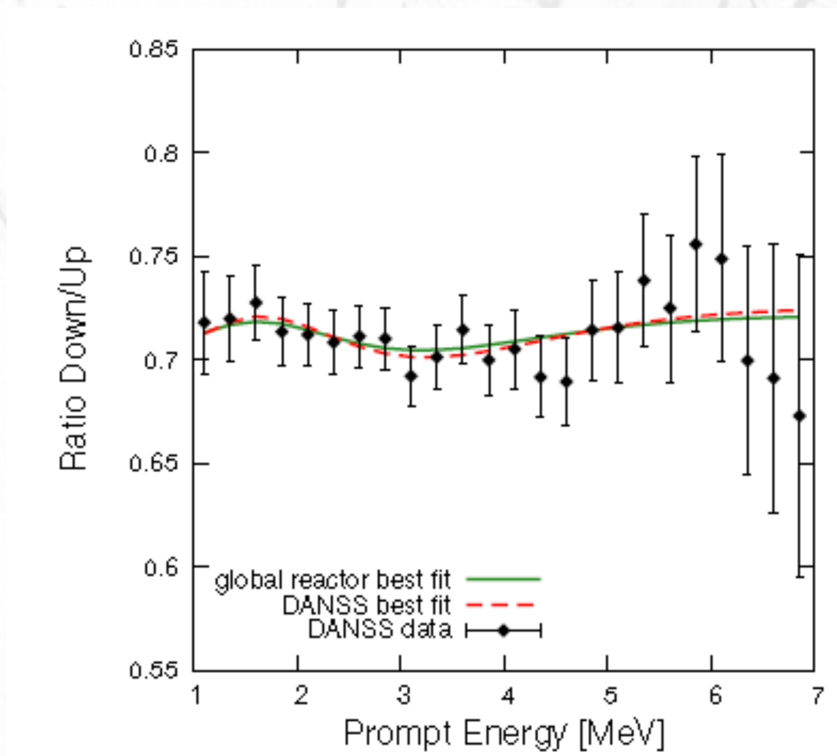
Actually right-handed neutrinos are sterile!

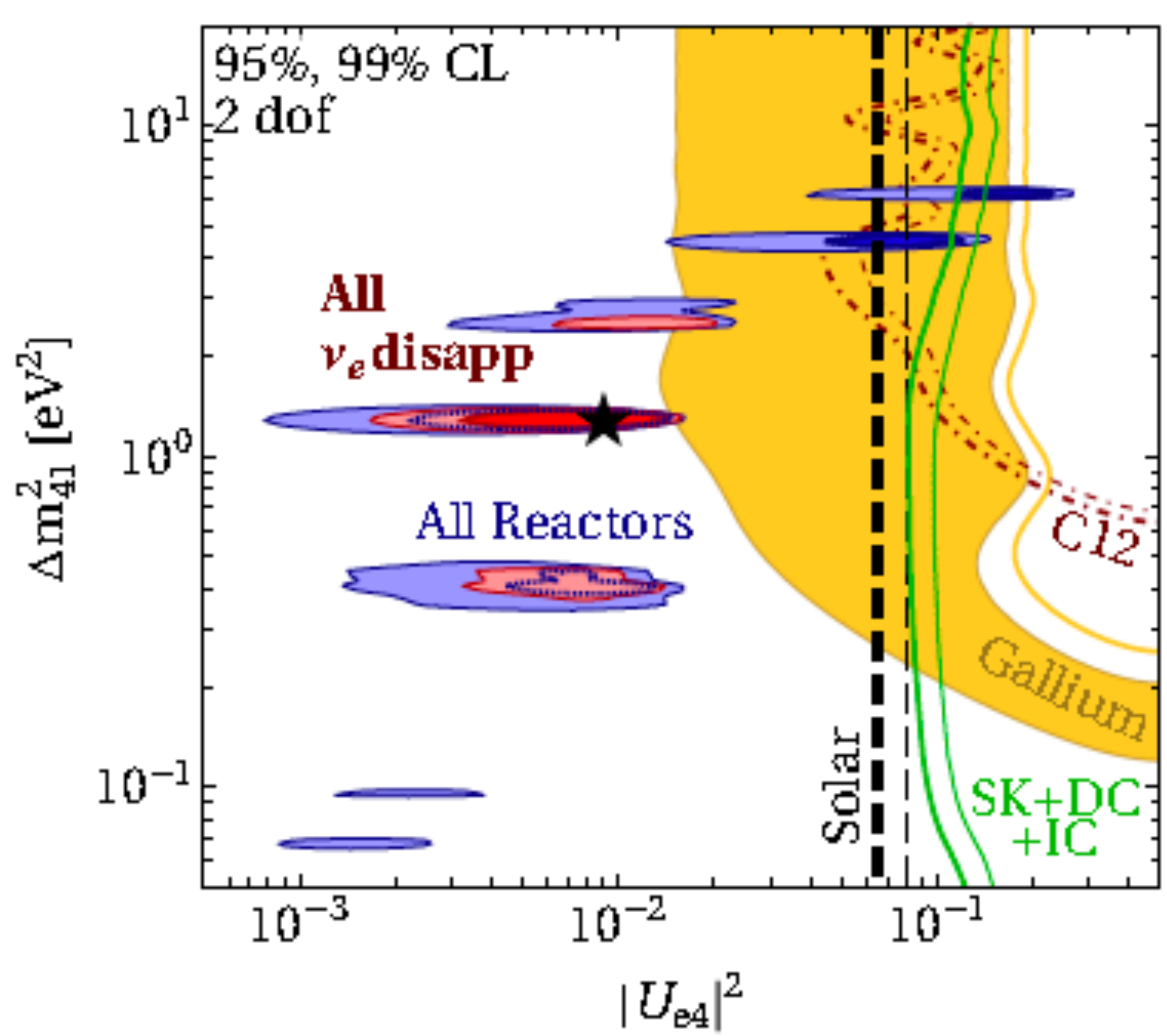
Sterile neutrinos

- Electron neutrino disappearance in reactors.



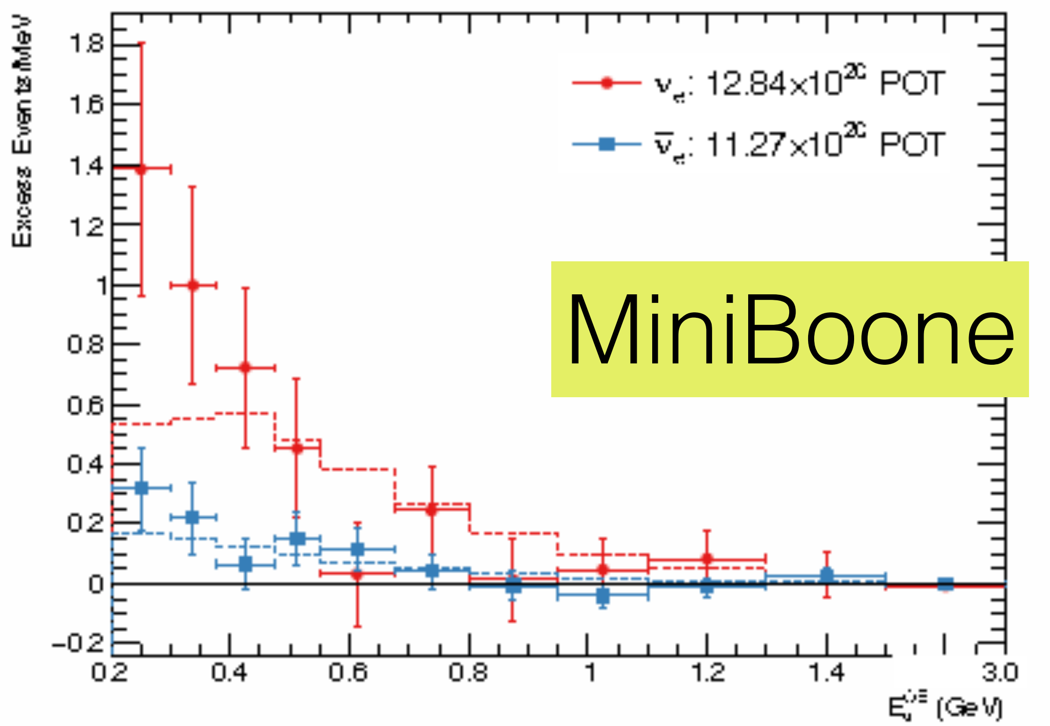
$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

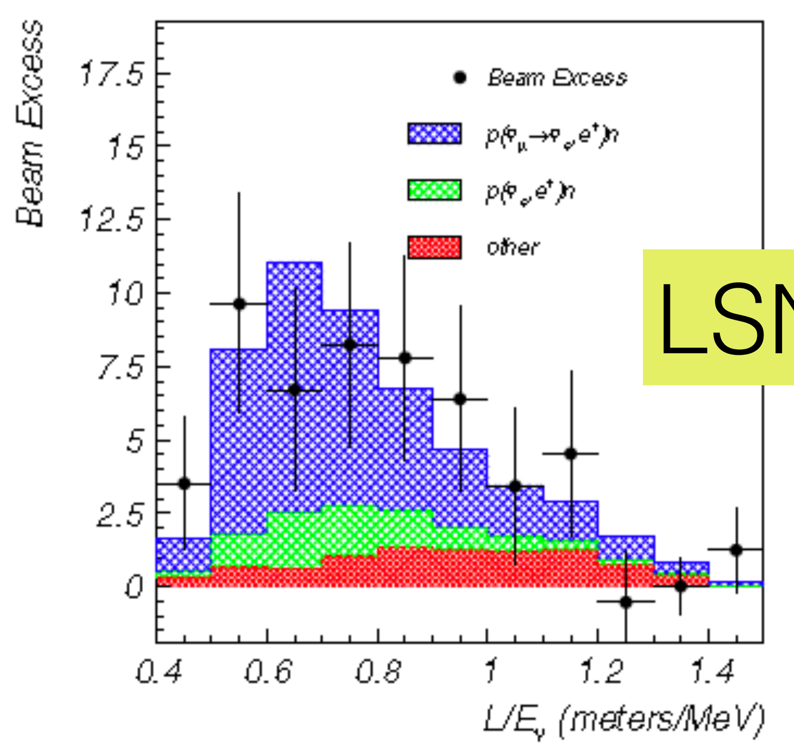




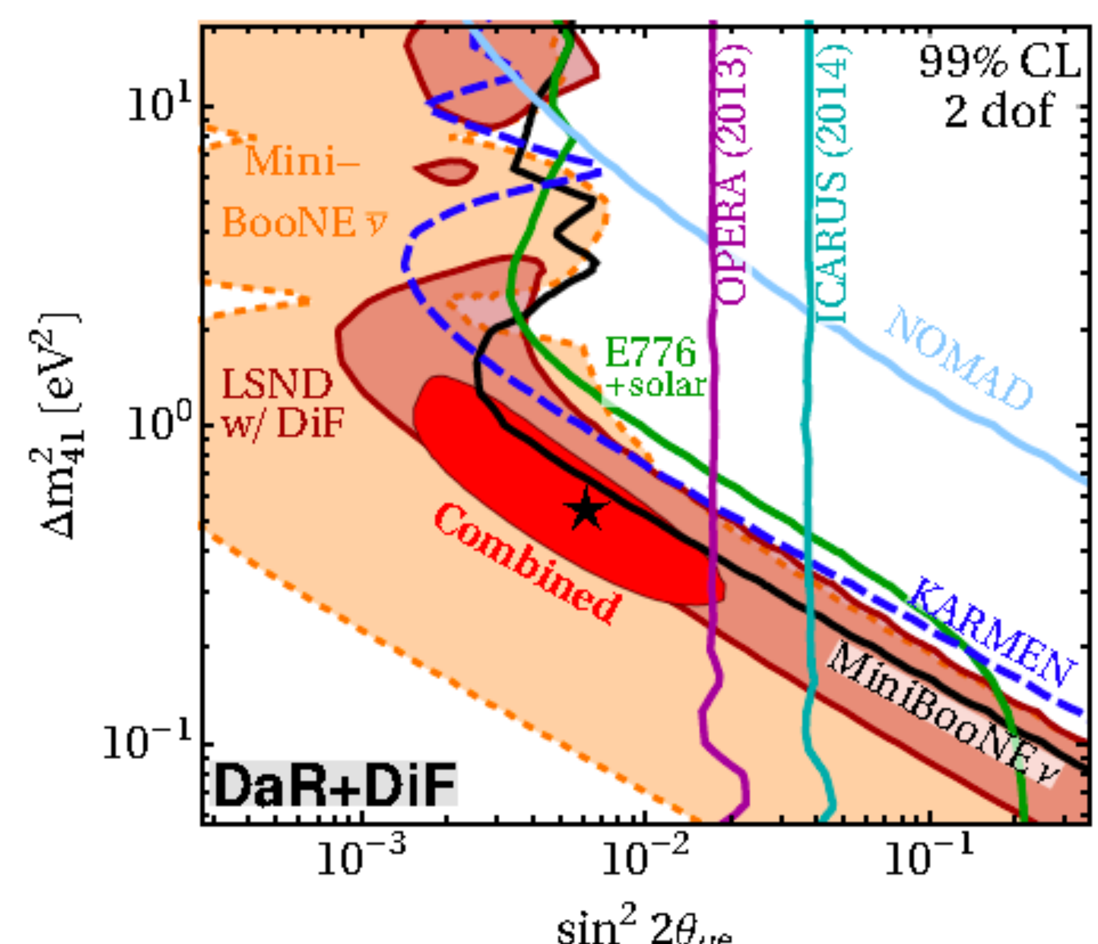
Sterile neutrinos

- $\nu_\mu \rightarrow \nu_e$ transition in neutrino accelerators.





$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$



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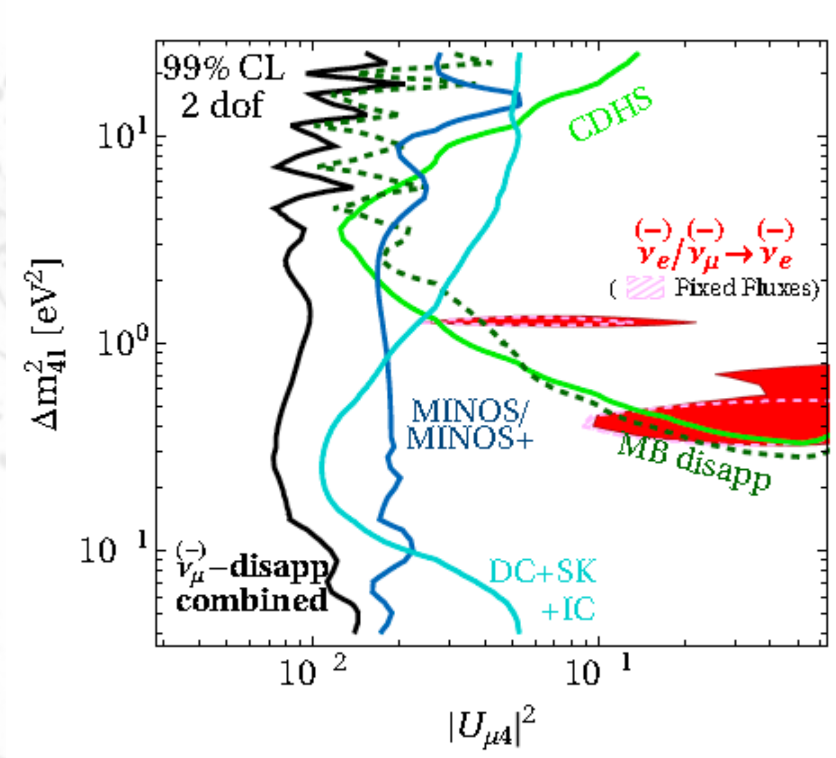
sterile neutrinos

- Can they be reconciled ?

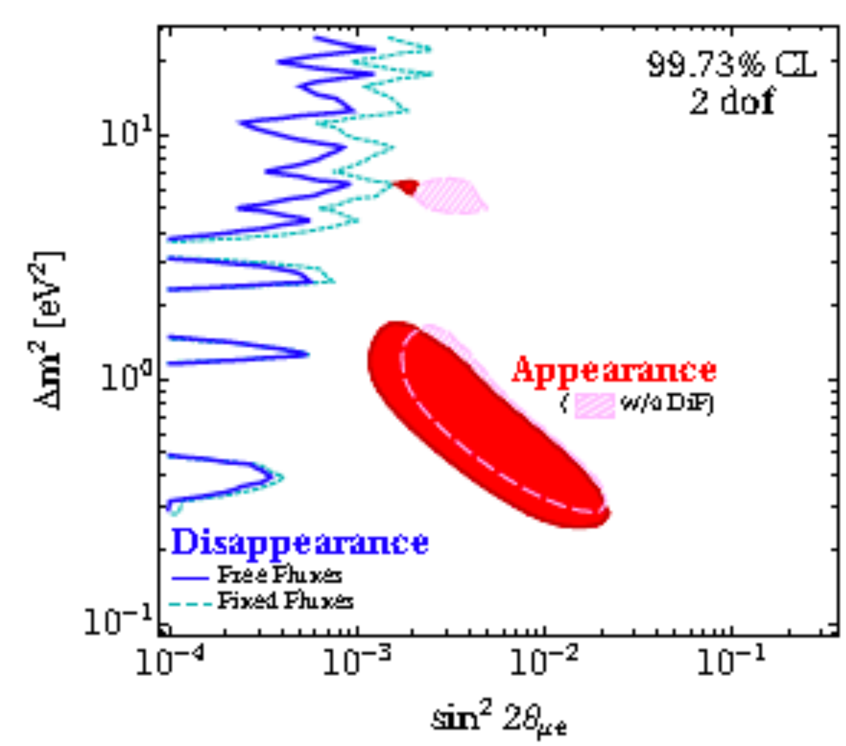
$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$



no evidence in
ν_μ disappearance



Probability of app. and diss. < 10^{-6}

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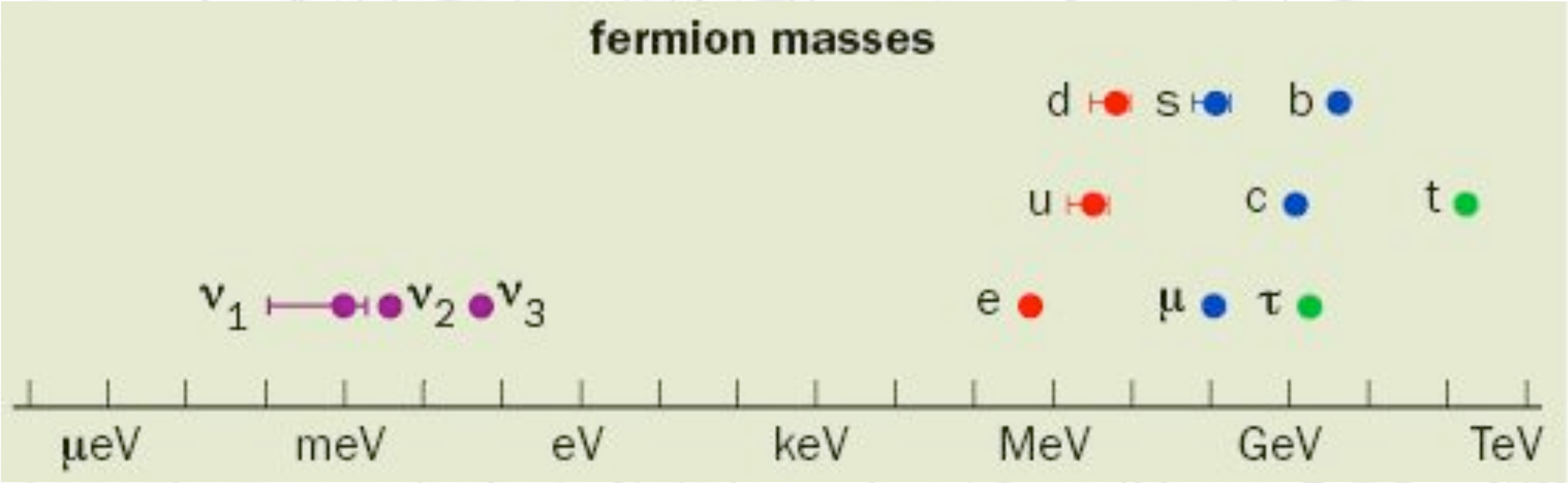
Neutrino masses



- Now that the neutrinos have mass we need to understand:
  - What to do with right-handed (sterile) neutrinos ?
  - Why the masses are so small?
- Theoretical models tend to relate both concepts…

Majorana masses

- If neutrinos have mass, then the right-handed neutrino "has to exists". After 60 years, we go back to the problem that there is a type of neutrino (Right chirality) that is sterile (does not interact).

- Theory proposed an alternative: Majorana mass. In this case the **neutrino is the same as its antiparticle,** so the right handed neutrino is just the anti-particle.

No sterile is needed:
LH⇔neutrino, RH ⇔antineutrino

- This is only possible for neutrinos because it is the only neutral fundamental lepton in the SM.

- We can write the mass term (Lorentz invariant) in two ways (or both):

Dirac $\mathcal{L}_D = -m_D \bar{\nu}_L \nu_R + h.c.$

Majorana $\mathcal{L}_M = -m_M \bar{\nu_R^c} \nu_R + h.c.$

Interactions of Majorana

- The Dirac neutrino NC interactions are given by:

$$< \nu_f^D \mid \overline{\psi^D}\gamma_\mu(1+\gamma_5)\psi^D \mid \nu_f^D >= \overline{u_f}\gamma_\mu(1+\gamma_5)u_i$$

V-A

- In the Majorana case:

$$\overline{\psi^M}\gamma_\mu\psi^M = \overline{(\psi^M)^c}\gamma_\mu(\psi^M)^c = -\overline{\psi^M}\gamma_\mu\psi^M$$

- Giving

$$< \nu_f^M \mid \overline{\psi^M}\gamma_\mu(1+\gamma_5)\psi^M \mid \nu_f^M >= \overline{u_f}\gamma_\mu\gamma_5 u_i - \overline{v_f}\gamma_\mu\gamma_5 v_i$$

~2A

- Given the Majorana term:

$$\psi^M = \sum_{\vec{p},s}\sqrt{\frac{M}{E_{\vec{p}}V}}(f_{\vec{p},s}u_{\vec{p},s}e^{ipx} + f_{\vec{p},s}v_{\vec{p},s}e^{-ipx})$$

- Unfortunately, the two are almost **indistinguishable**.

$\sigma_{2A} = \sigma_{(V-A)}$

Majorana & Seesaw

$$\mathcal{L} = -\frac{1}{2}\left(\bar{\nu}_L \bar{\nu}^c_R\right)\begin{pmatrix} m^M_L & m^D \\ m^D & m^M_R \end{pmatrix}\begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix} + h.c.$$

- When we diagonalise the matrix we obtain the following eigenvalues:

$$\lambda_\pm = \frac{1}{2}(m^M_L + m^M_R) \pm \frac{1}{2}\sqrt{(m^M_L + m^M_R)^2 - 4(m^M_L m^M_R - m^D m^D)}$$

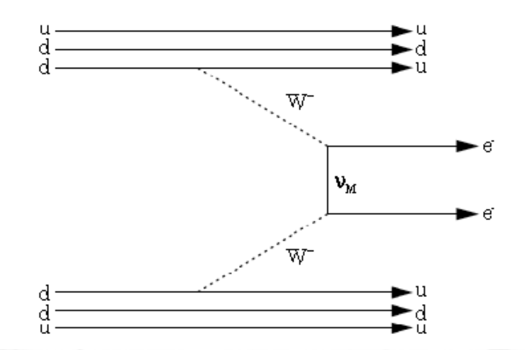
- If we assume $(m_L^M m_R^M - m^D m^D) << (m_L^M + m_R^M)^2$, then:

$$\lambda_+ = m^M_L + m^M_R$$
$$\lambda_- = \frac{(m^M_L m^M_R - m^D m^D)}{m^M_L + m^M_R}$$

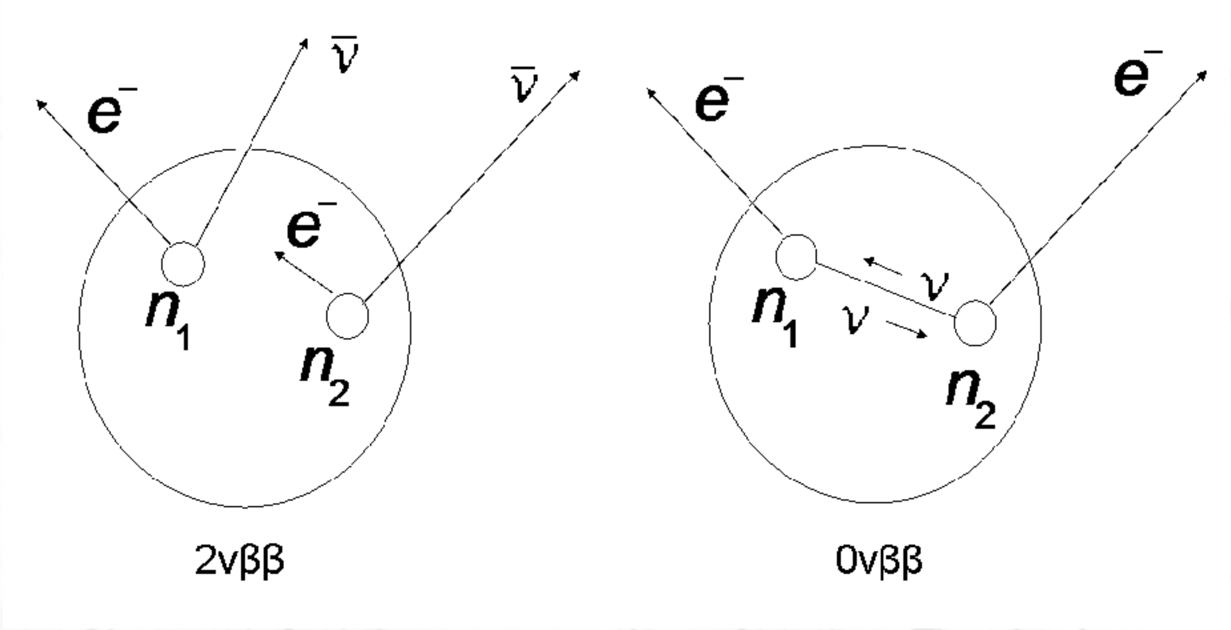
- And, $\lambda_+ >> \lambda_-$. Tuning the values of m_R^M we can generate the λ_- as small as needed since m_R^M is basically a free parameter.

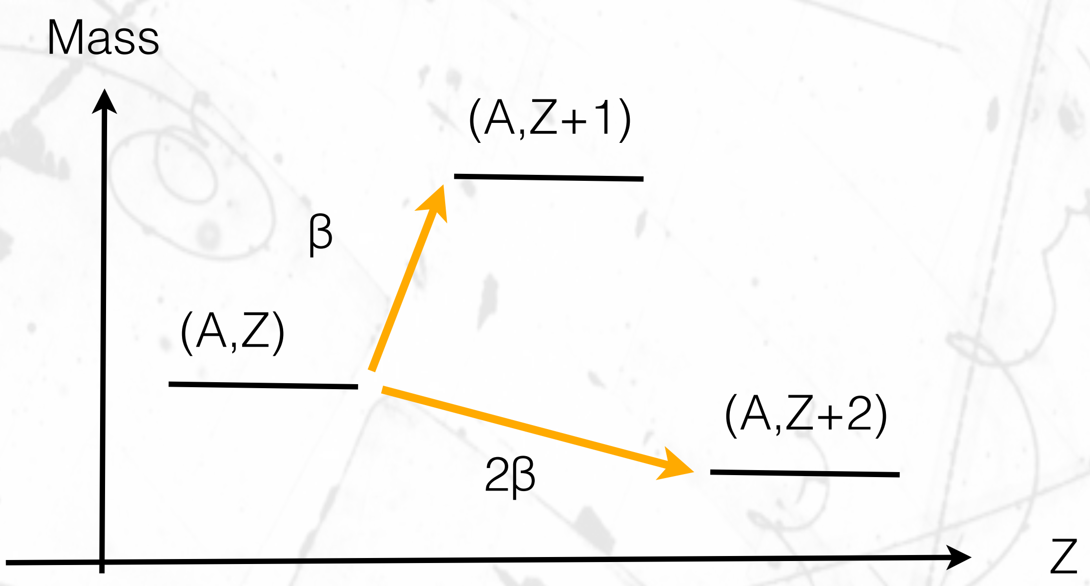
Majorana masses

- Majorana mass implies two new properties:
  - The neutrino is equal to its antiparticle.
  - There is no right handed (if no See-Saw), it is just the anti-particle
- Nothing (symmetry,…) prevents us to write a Majorana term in the Lagrangian:
  - We need an additional symmetry to forbid the Majorana term.
  - Whatever we discover will be very relevant to the SM: new symmetry or a Majorana.
- How to detect Majorana's:
  - Look for a process where the neutrino-antineutrino cancels in a loop or propagator: neutrino-less double beta decay, or any $\Delta L=2$ process.



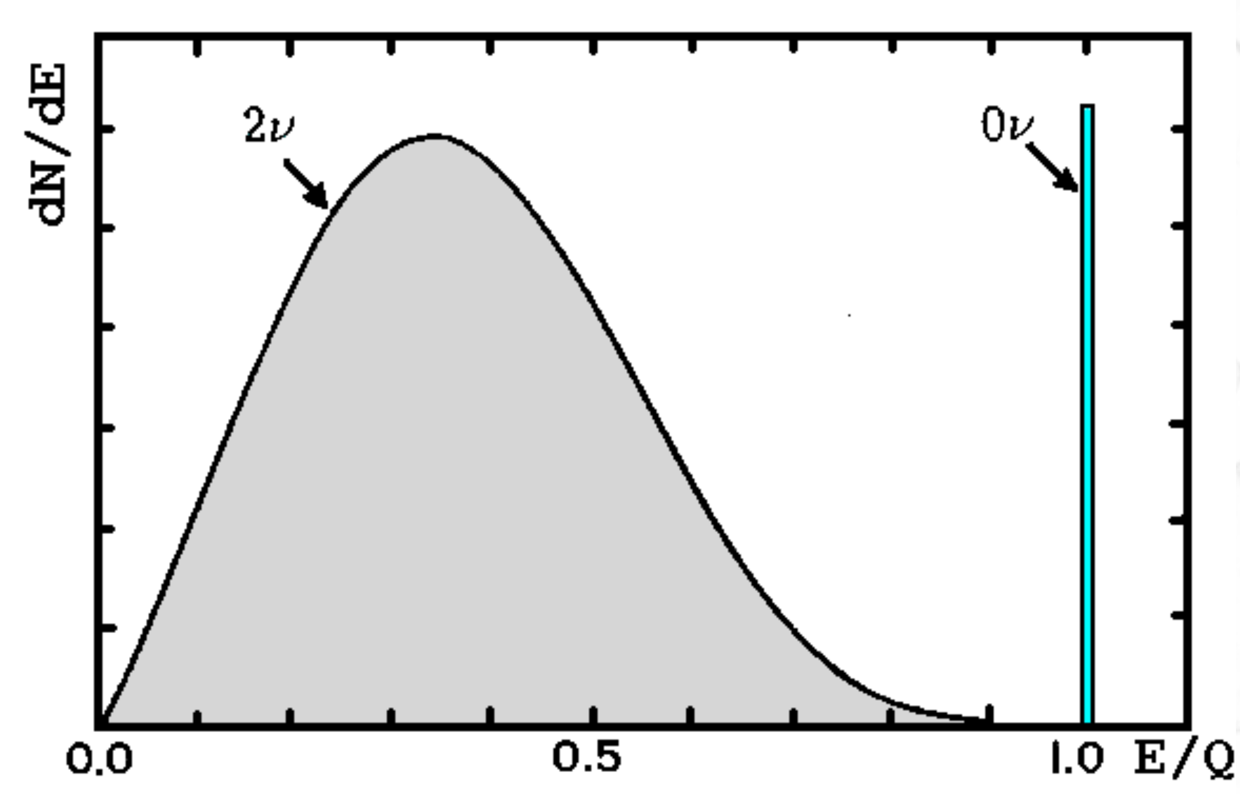
0ν2β process





- The 2ν2β has been measured for several isotopes.
- The 0ν2β has been search in many of them ("almost") without success.
- Experimentally is complex, both processes are rare: $T_{½} >> 10^{20}$ s
- The rate of 0ν2βis proportional to a ν effective mass: kind of ν mass scale.

0ν2β process



- The 0ν2β is characterised by a monochromatic 2e emission.
- The experiments are mainly low background underground high resolution calorimeters (ΔE/E ~ 0.2 %)
- New experiments try to get the advantage of the 2 electrons to reduce non 2β background from natural radioactivity: NEMO, NEXT,...

0ν2β process

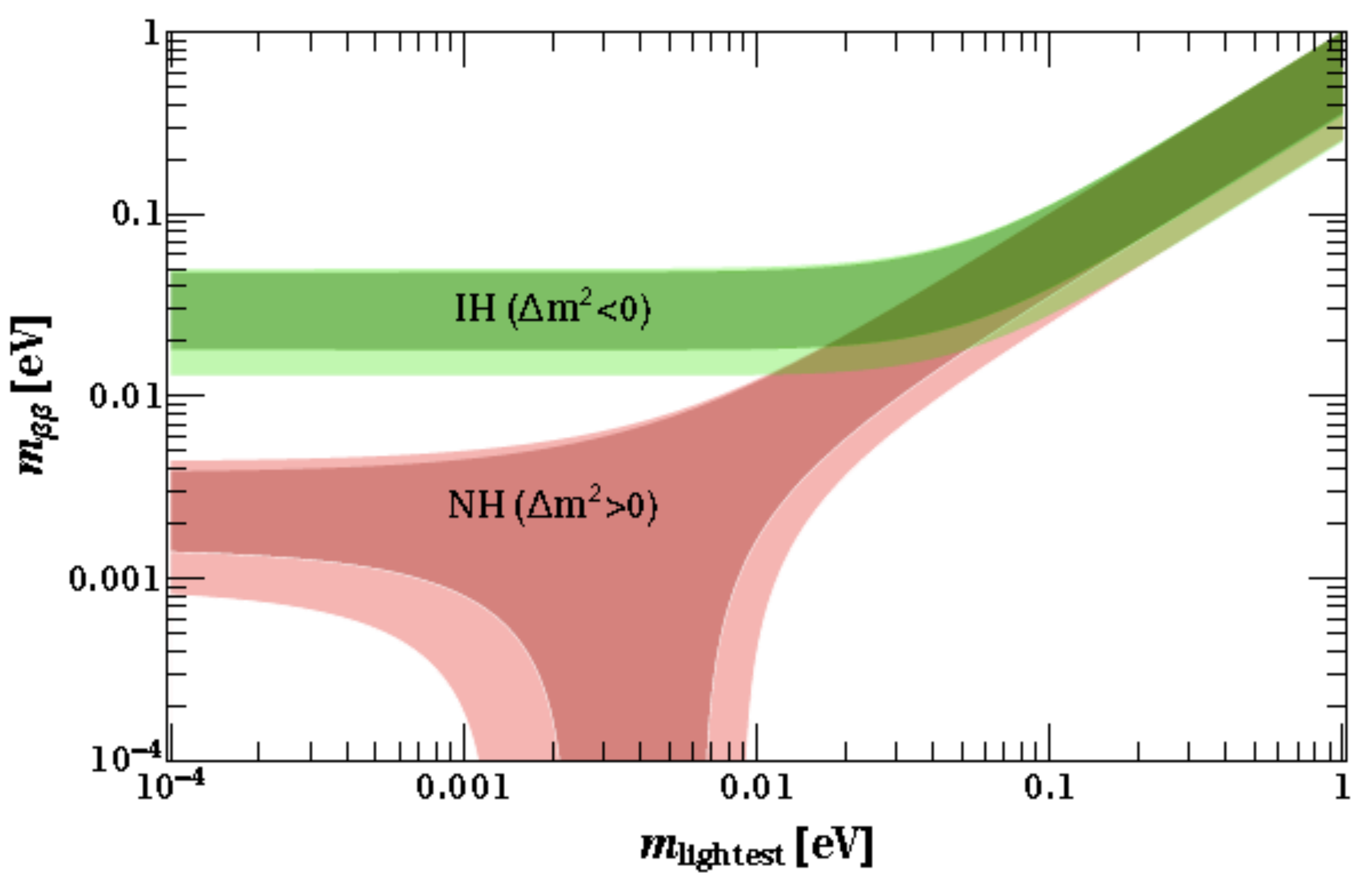
- The lifetime is computed as

$$t^2_{1/2} = G_{0\nu}|\mathcal{M}|^2 \left|\frac{1}{m_e}\sum_{k=1,2,3} U^2_{ek} m_k\right|^2 = G_{0\nu}|\mathcal{M}|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

- Where $|\mathcal{M}|$ is the nuclear matrix element and $G_{0\nu}$ is the phase space factor.

$m_{\beta\beta}$ is basically the lifetime

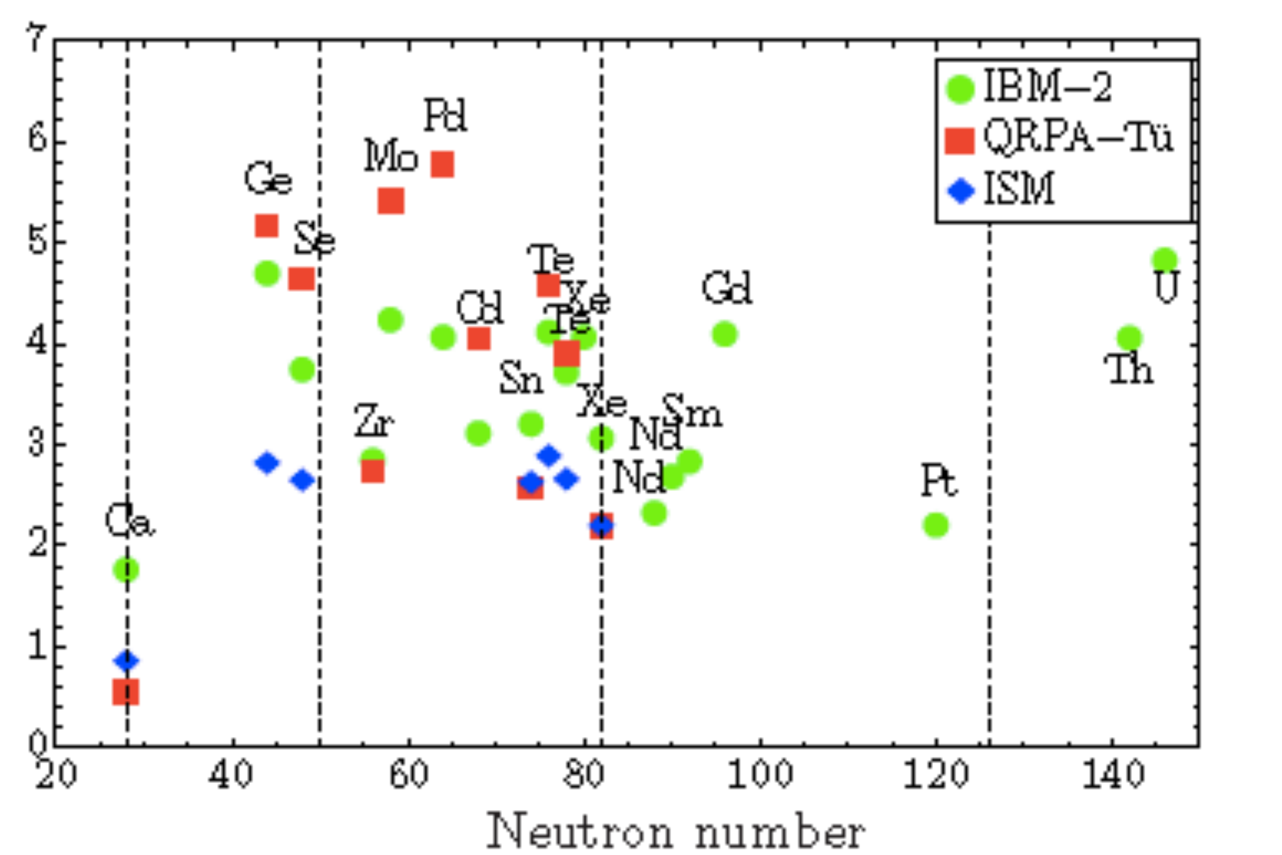
Hierarchy has a profound effect on the feasibility of the experiments.



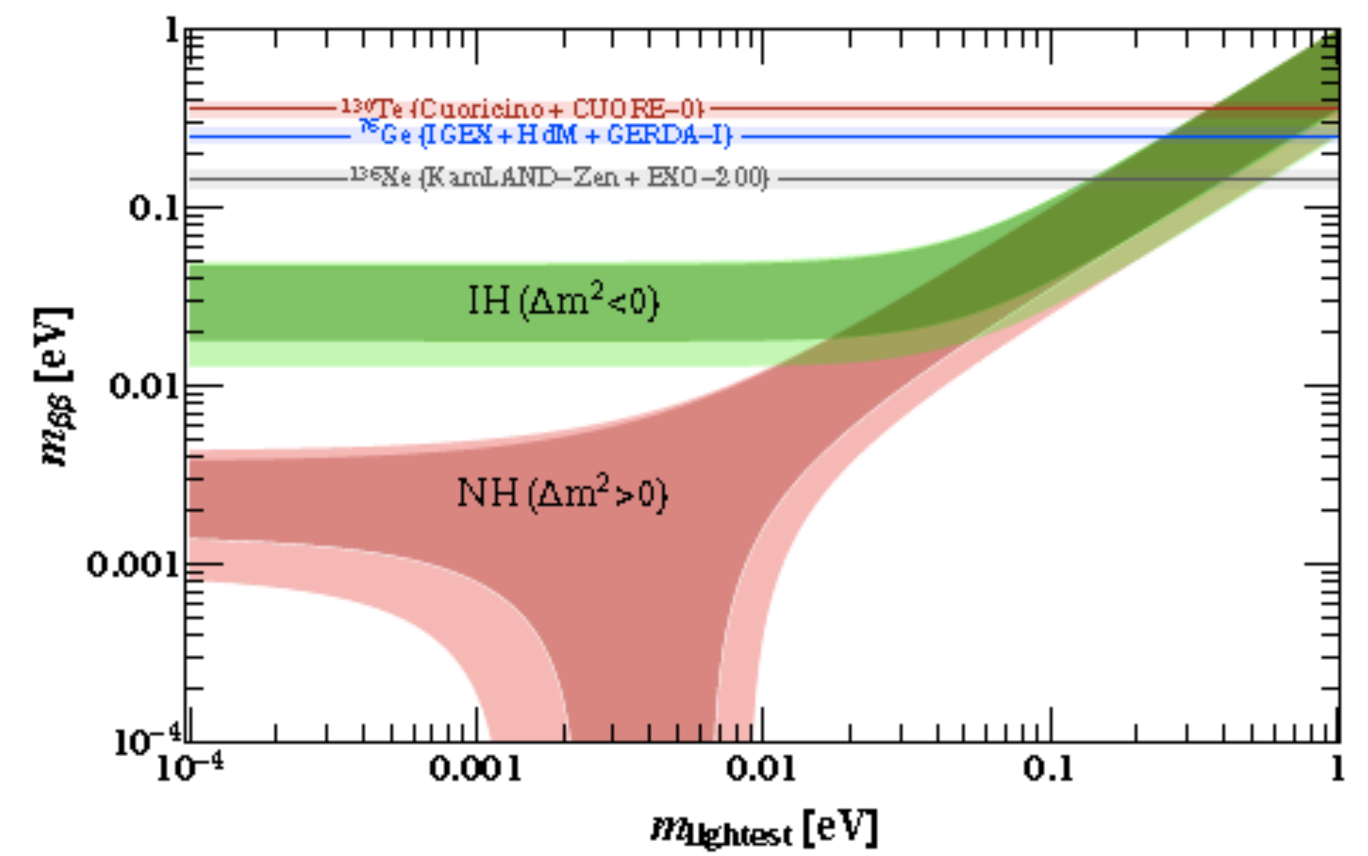
0ν2β & Nuclear physics

- Tested with several isotopes with different experimental setups: ^{136}Xe, ^{130}Te, ^{76}Ge.

- Lifetime limits larger that 10^{25} years!



Interpretation is limited by our knowledge of nuclear physics.



No positive sign yet!, still far from inverse hierarchy band

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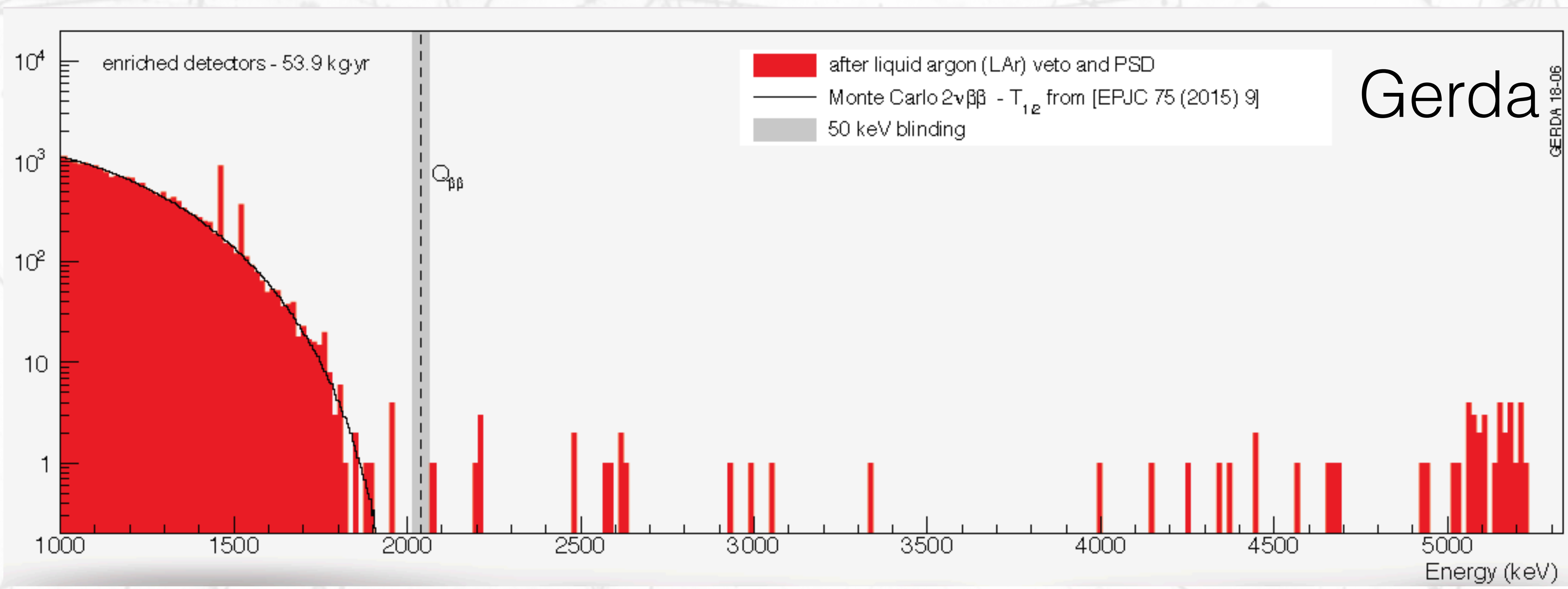
0v2β Challenges

- Low background (b) (<1 count/year) and large mass (M)

$$T_{1/2}^{0\nu}(90\%\ \mathrm{C.L.}) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times \Delta E}}$$

- High energy resolution (ΔE) to reduce background in signal region. (2v2β is always present).



$0\nu 2\beta$ results

- Best limits, so far.

Isotope, mass	$Q_{\beta\beta}$, keV	b x ΔE x M, counts/yr	$T_{1/2}$, yr	$\langle m_\nu \rangle$, eV	Experiment, technique
^{76}Ge, 40kg	**2039**	**0.07**	**$> 0.9 \times 10^{26}$**	**< 0.11-0.25**	**GERDA, HPGe**
^{82}Se, 5kg	2998	0.4	$> 2.4 \times 10^{24}$	< 0.38-0.77	CUPID-0, scintillating bolometers
^{100}Mo, 7kg	3034	1.5	$> 1.1 \times 10^{24}$	< 0.33-0.62	NEMO-3, tracko-calo
^{130}Te, 200kg	2528	21	$> 1.5 \times 10^{25}$	< 0.13-0.50	CUORE, bolometers
^{136}Xe, 380kg	**2458**	**1**	**$> 1.07 \times 10^{26}$**	**< 0.06-0.16**	**KamLAND-Zen, doped LS**

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Absolute ν mass

- Oscillation experiments provide the mass difference between the different ν mass eigenstates.

- Which is the absolute neutrino mass ?

  - **direct** measurements: end point of β spectrum.

  - **cosmology**

  - **2β0ν** provides a measurement if neutrinos are Majorana.

  - **Time of Flight** in LBL.

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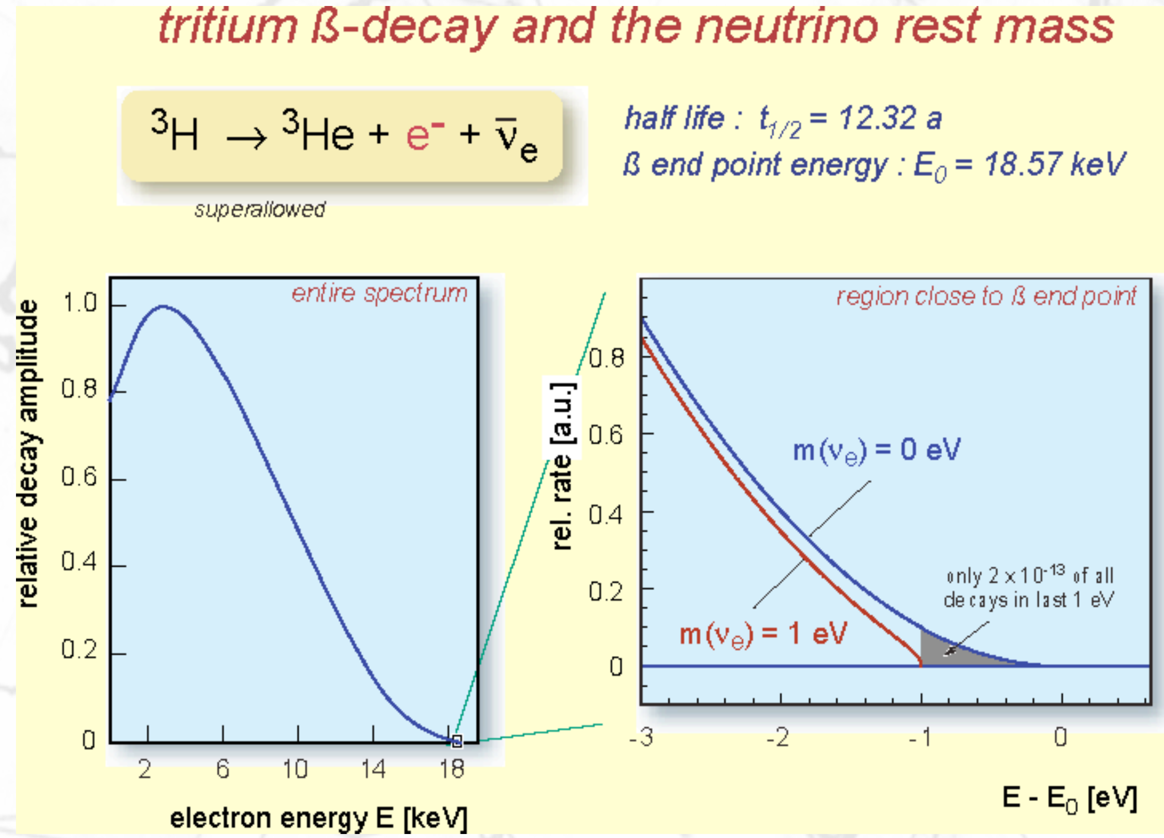
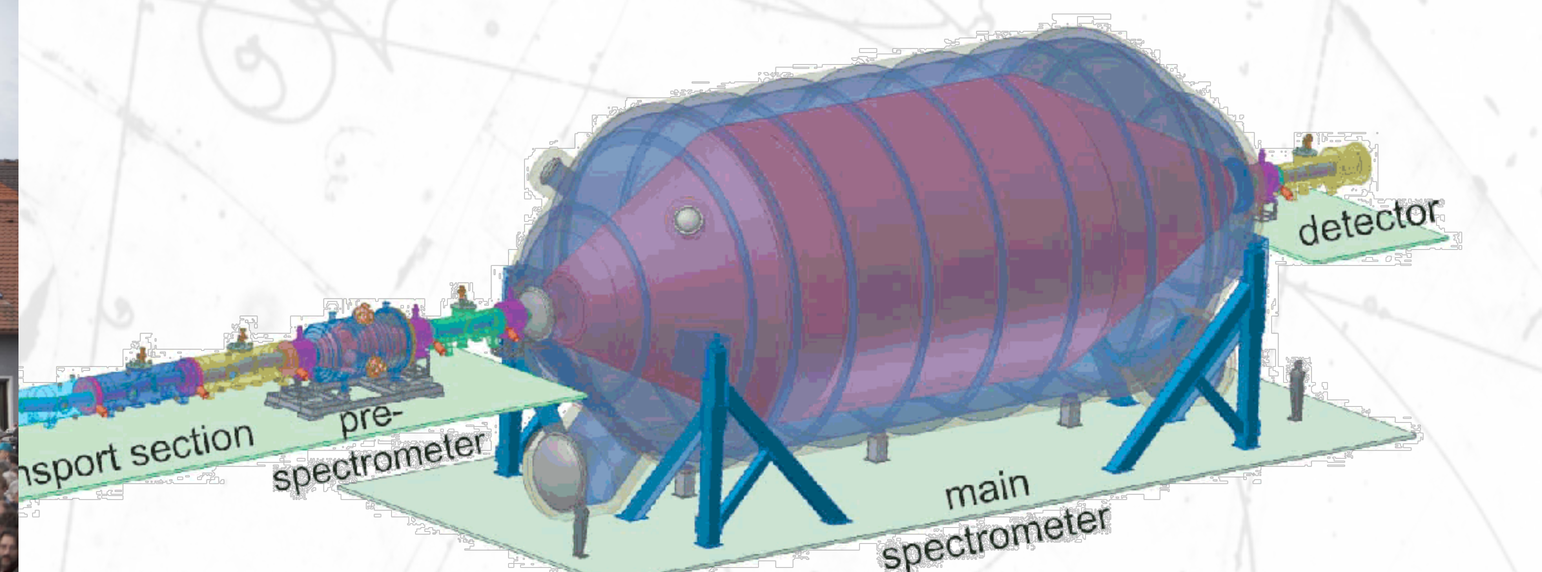
Katrin

- Absolute neutrino mass experiment:
  - **^3H β-decay end point.**
  - **MAC-E filter threshold spectrometer.**
  - **Extremely high resolution: ~0.2eV** equivalent to the mass to measure.



The experiments



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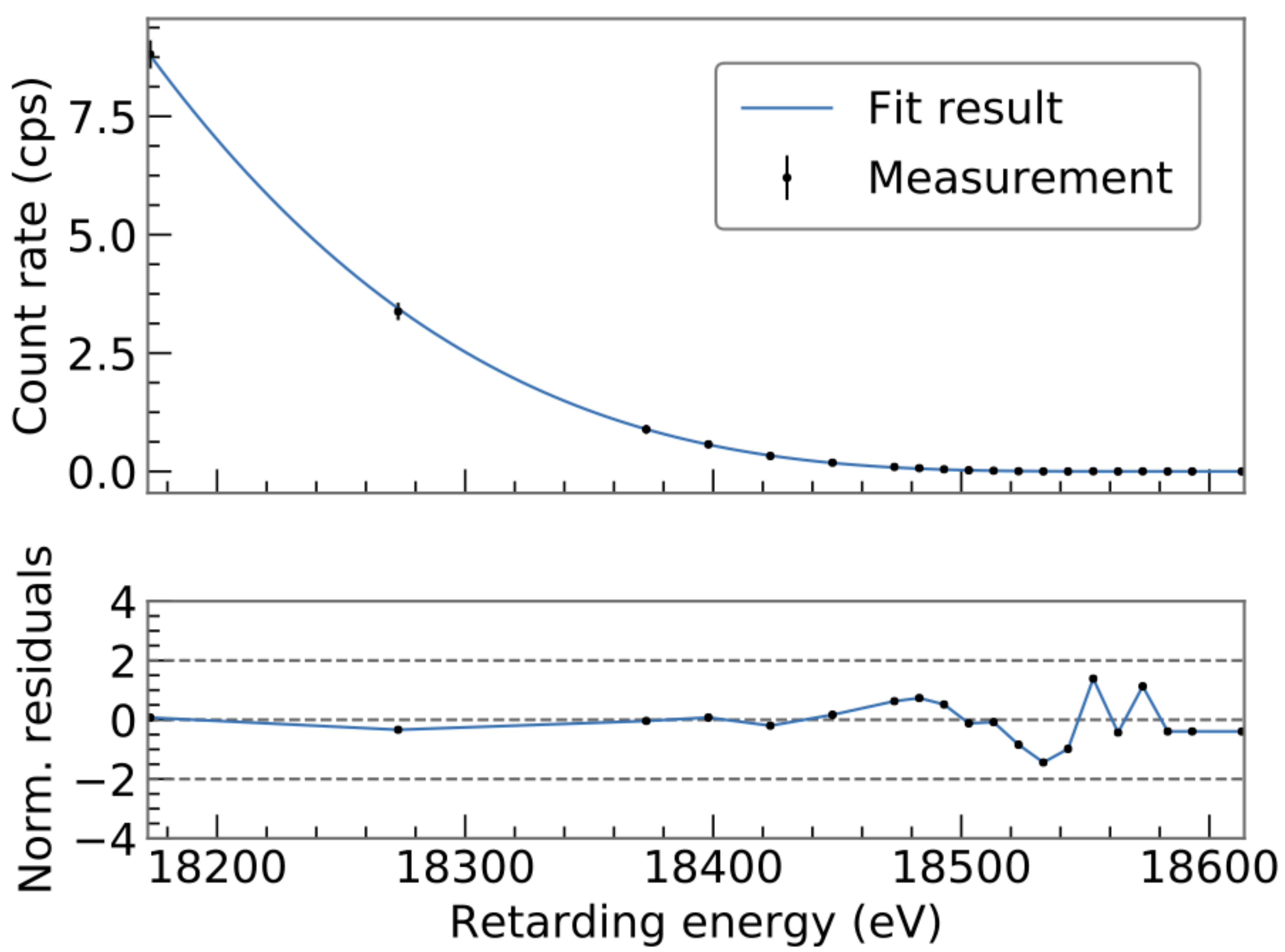
Katrin

- After many years of development. First measurements!



neutrinos as messengers

Neutrinos are excellent messengers

Neutrinos are neutral (not sensitive to magnetic fields), weakly interacting particles produced in violent phenomena in the Universe..

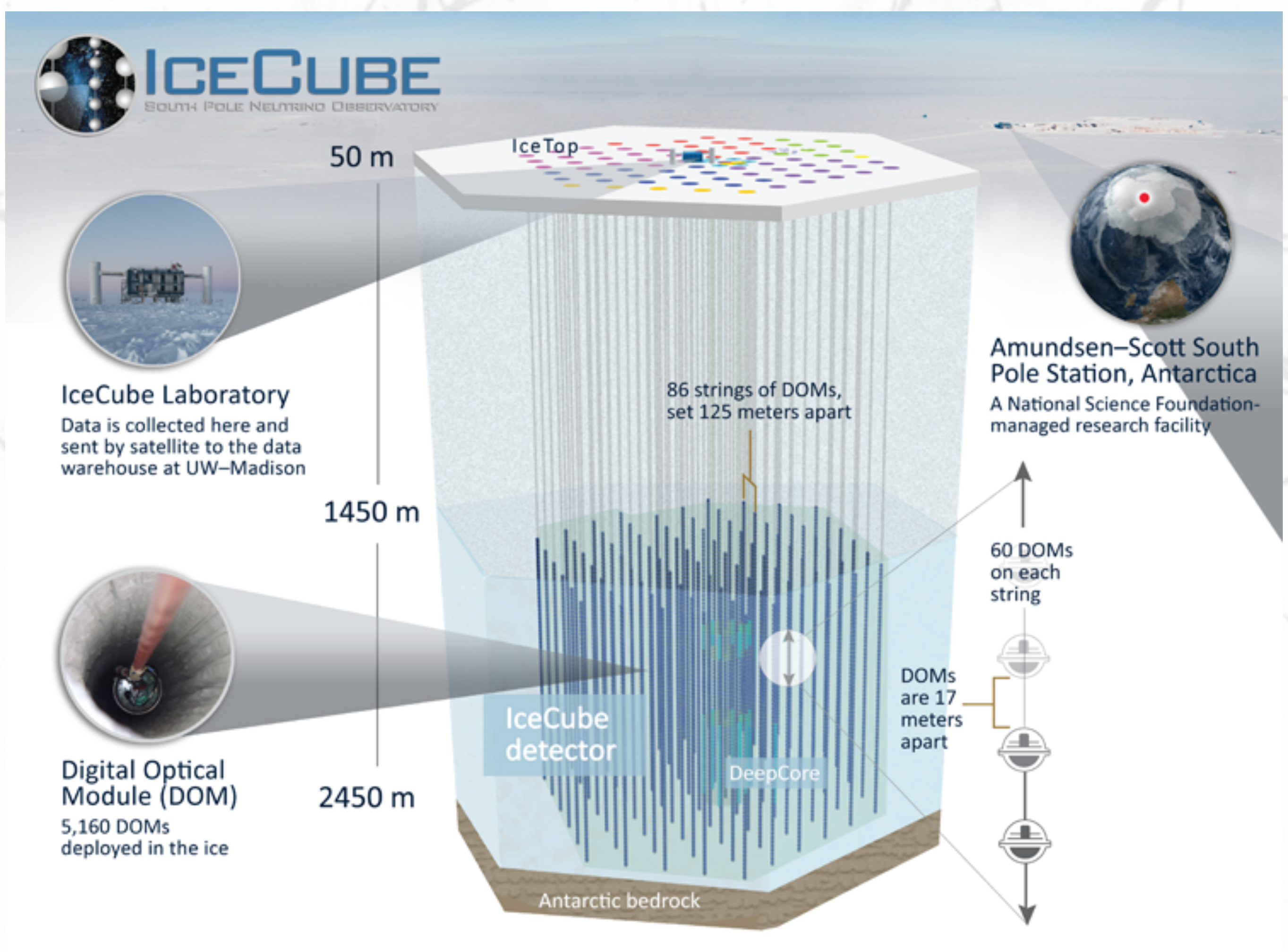
Photons are also neutral but they interaction with the photon radiation background.

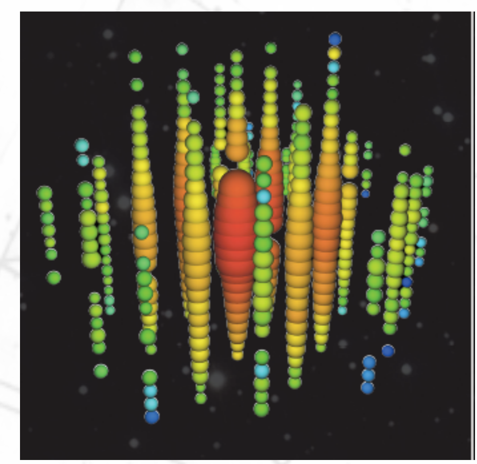
but they are difficult to detect.

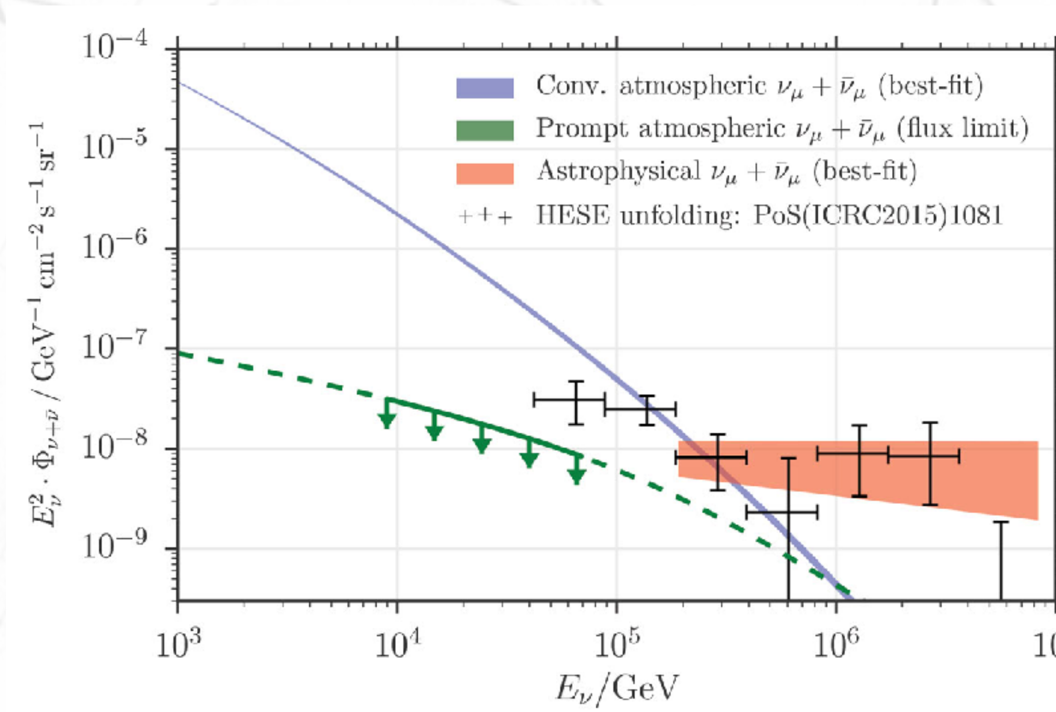
IceCube

- Cerenkov detector at the south pole.
- ~ 1 km^3 volume = 15000 x SuperKamiokandes.

- Large volume ⇔ large energy
  - large mass for stopping ν
  - large energy containment.

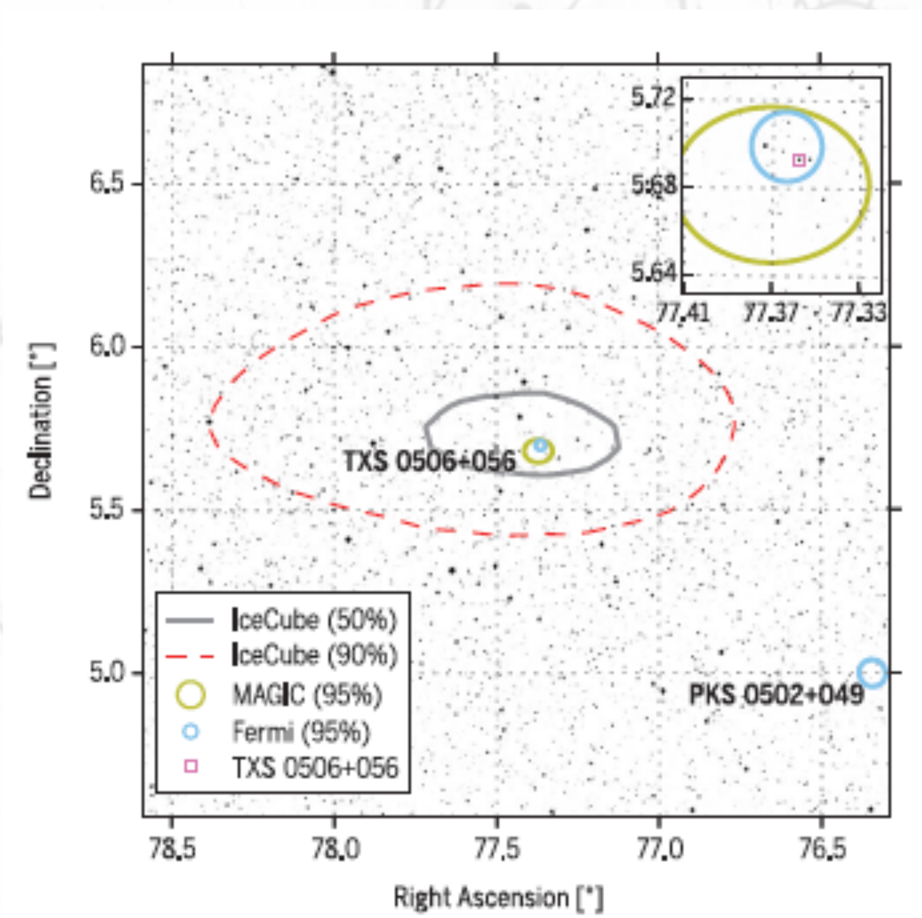


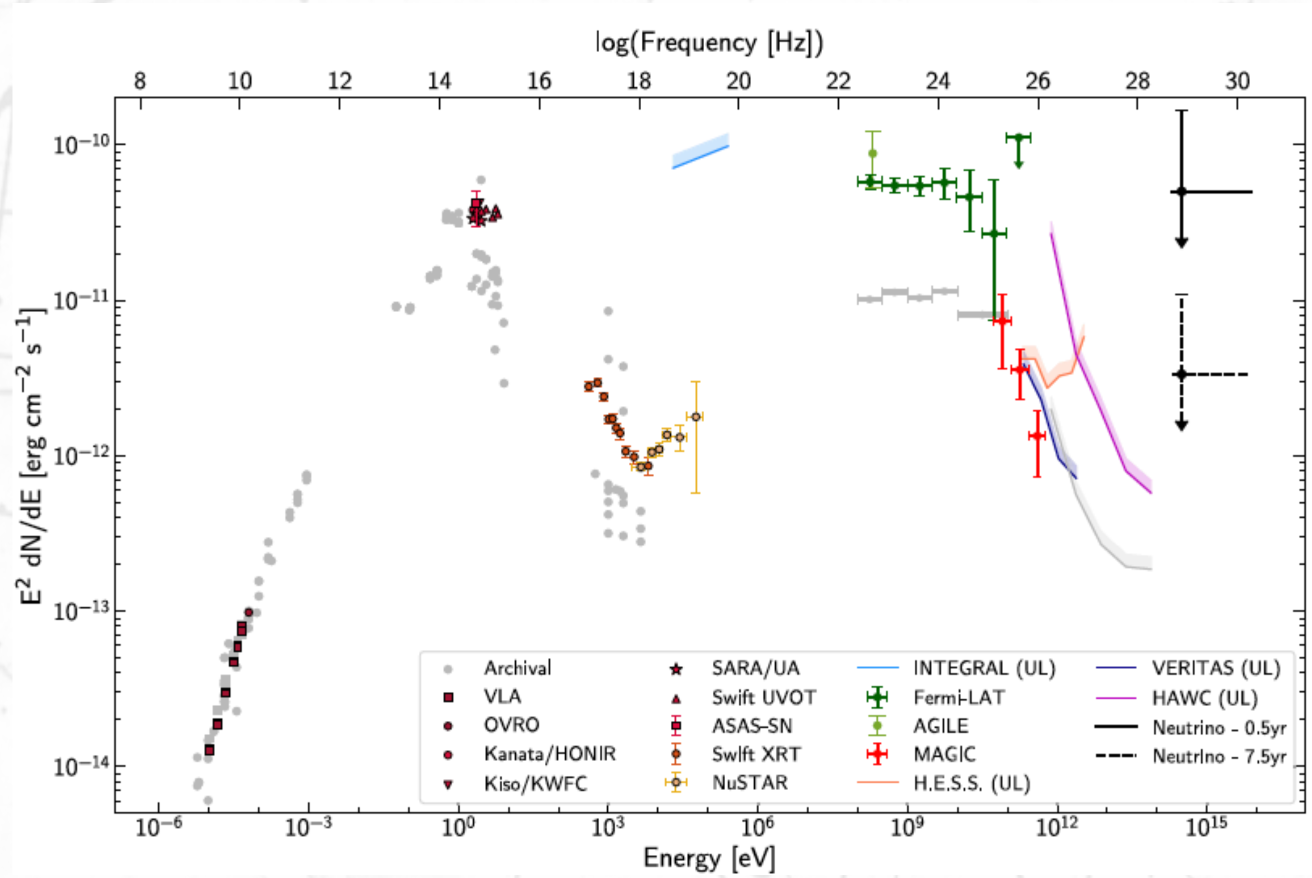




IceCube

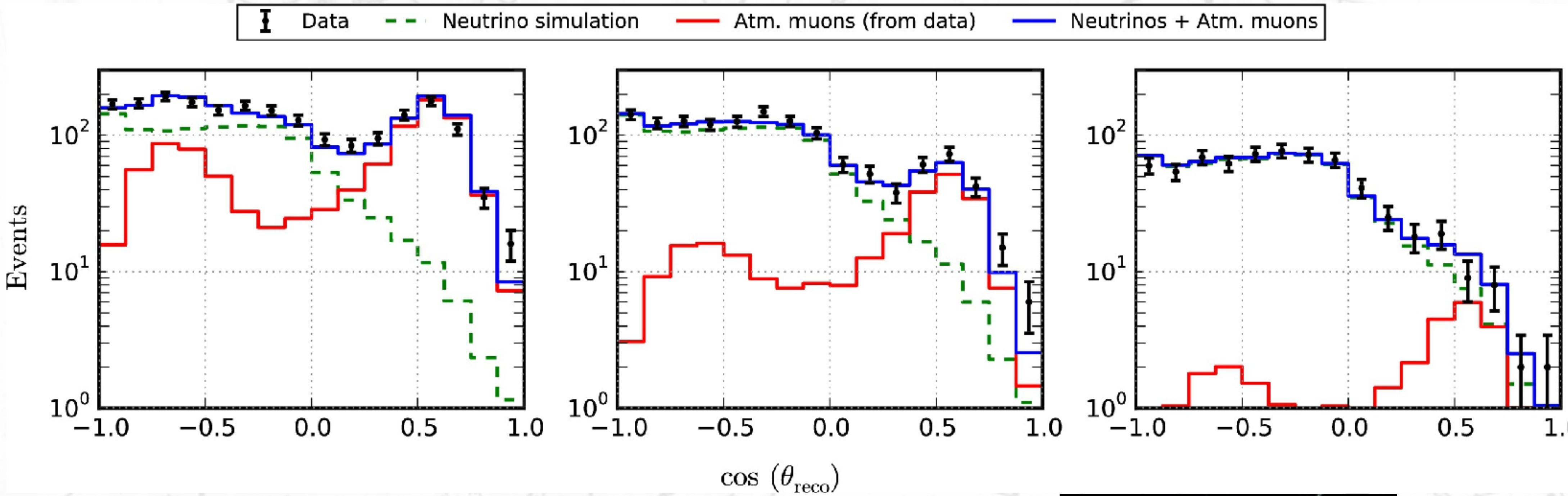
- Recent observation of a flaring blazar* with a combined signal in photons and neutrinos.
- Beginning of the multi-messenger era: gravitational waves, gammas, neutrinos.

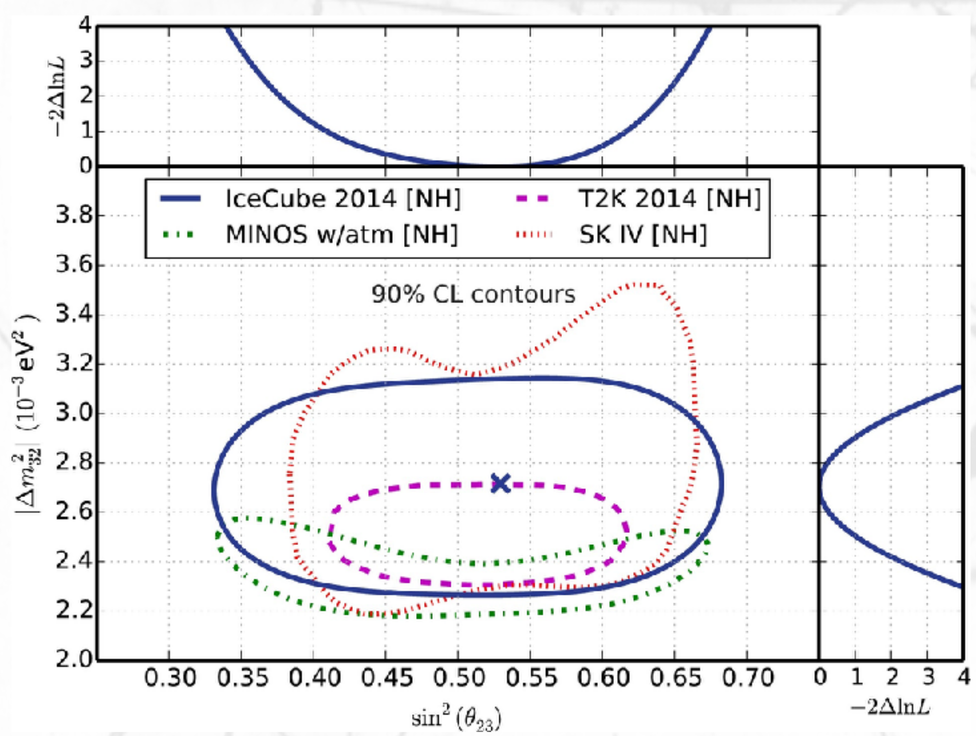




* blazar is a black hole in the center of a galaxy.

IceCube





- IceCube is also able to do oscillation physics with atmospheric neutrinos:

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neutrinos & Cosmology

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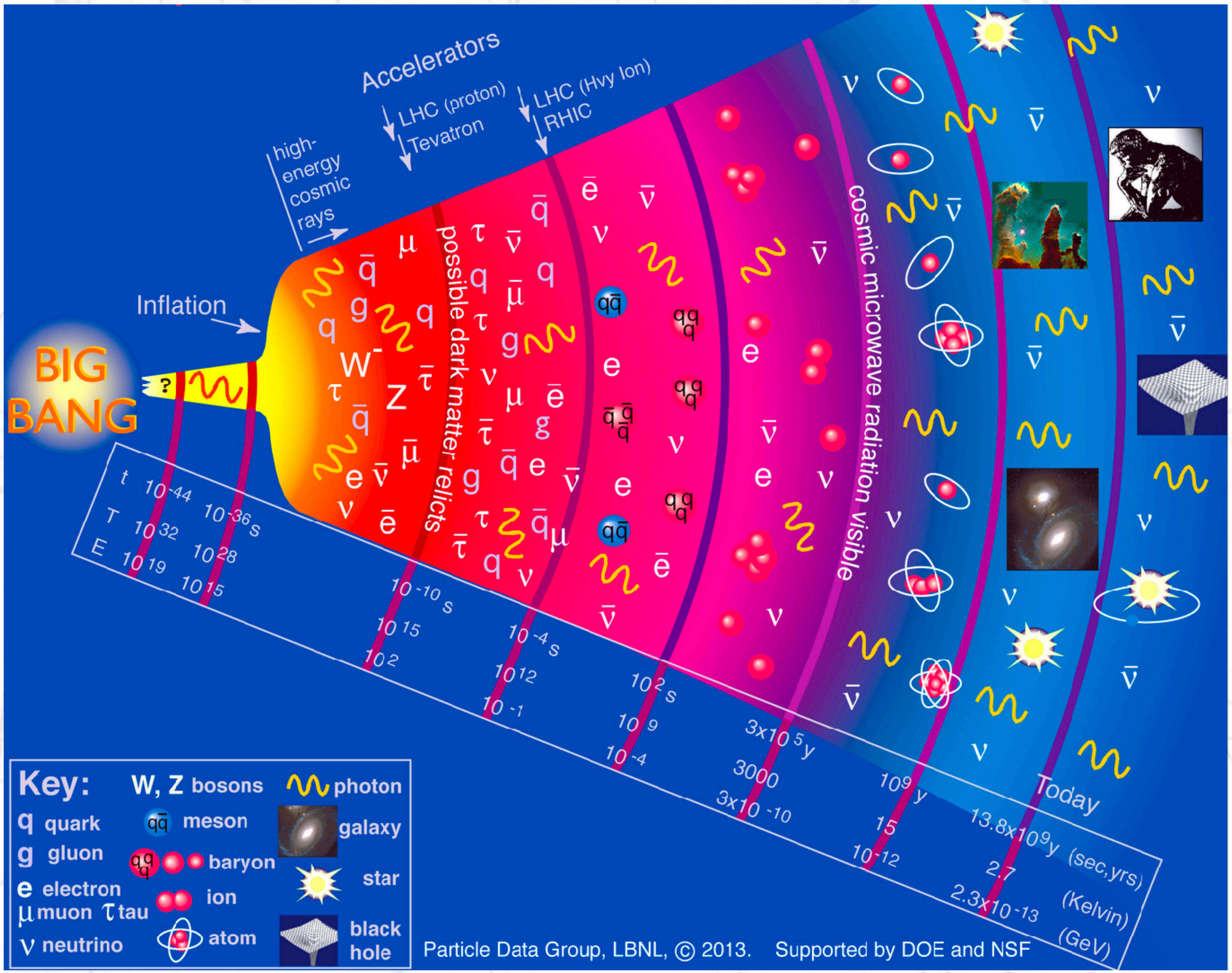

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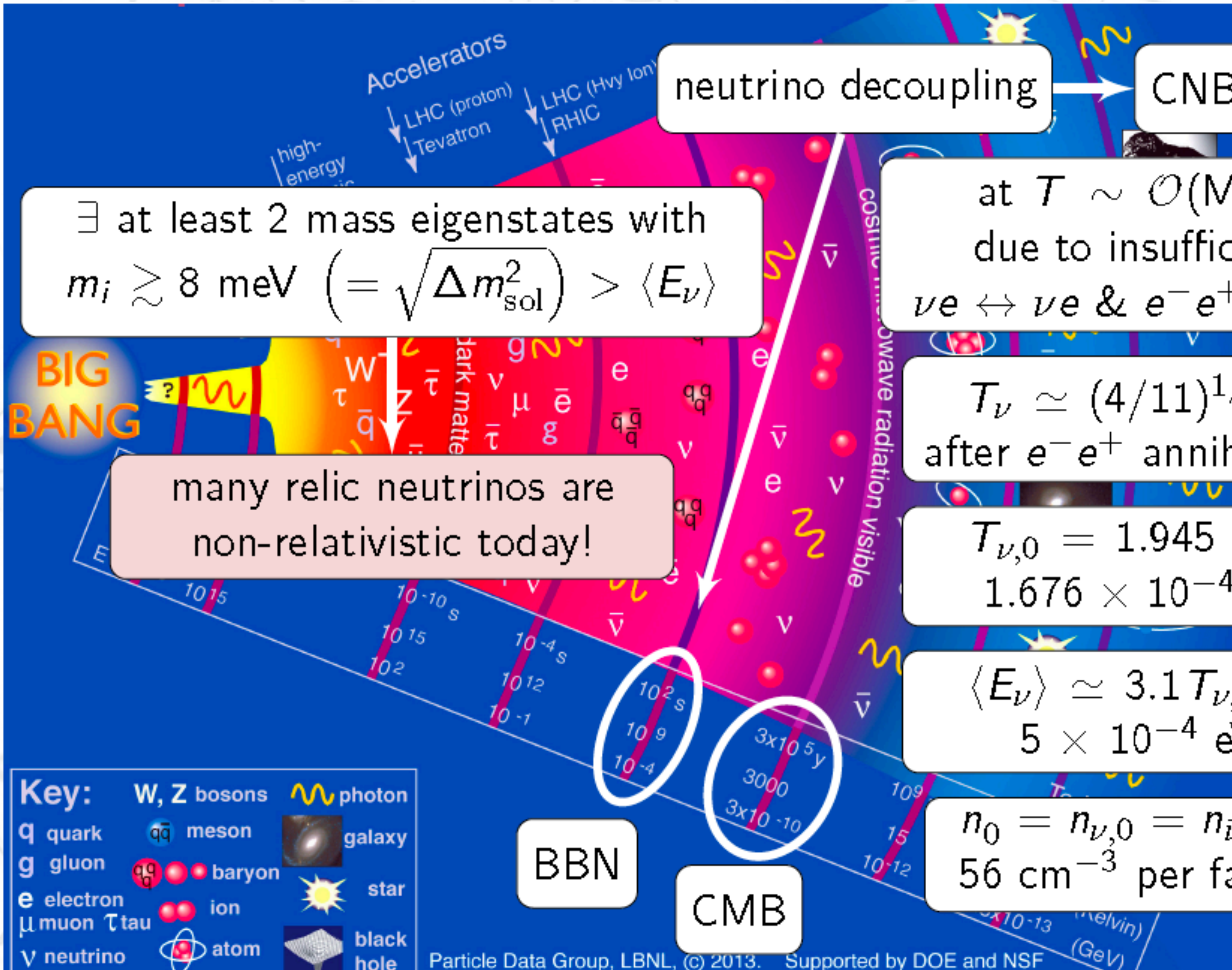

neutrino decoupling → CNB

∃ at least 2 mass eigenstates with $m_i \gtrsim 8$ meV $\left(= \sqrt{\Delta m^2_{\rm sol}}\right) > \langle E_\nu \rangle$

many relic neutrinos are non-relativistic today!

at $T \sim \mathcal{O}$(MeV) due to insufficient $\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

$T_\nu \simeq (4/11)^{1/3} T_\gamma$ after $e^- e^+$ annihilation

$T_{\nu,0} = 1.945$ K $\simeq 1.676 \times 10^{-4}$ eV

$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq 5 \times 10^{-4}$ eV

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq 56$ cm^{-3} per family

BBN

CMB

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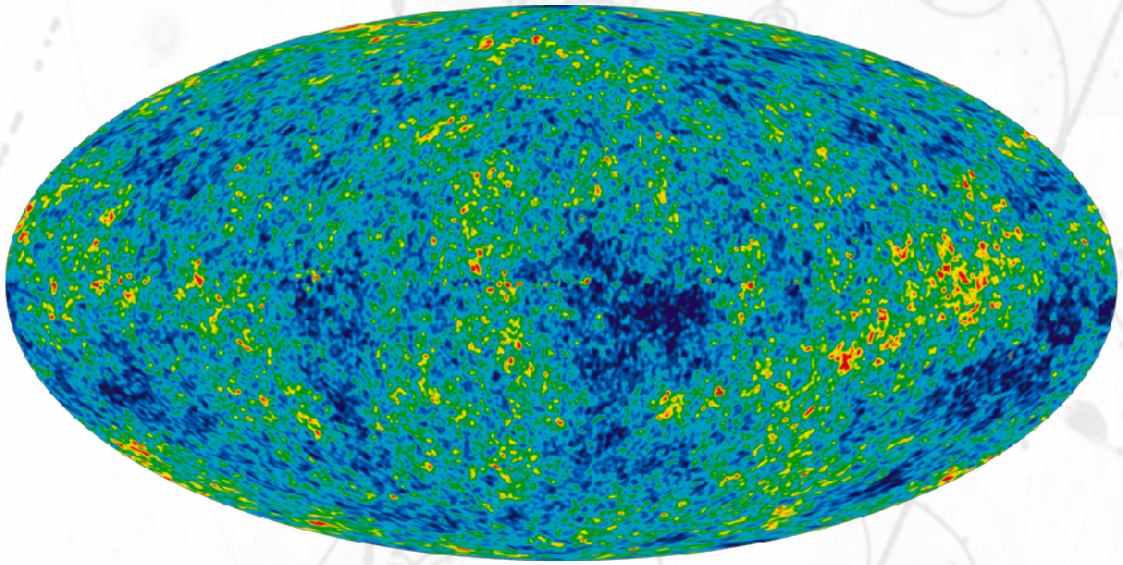
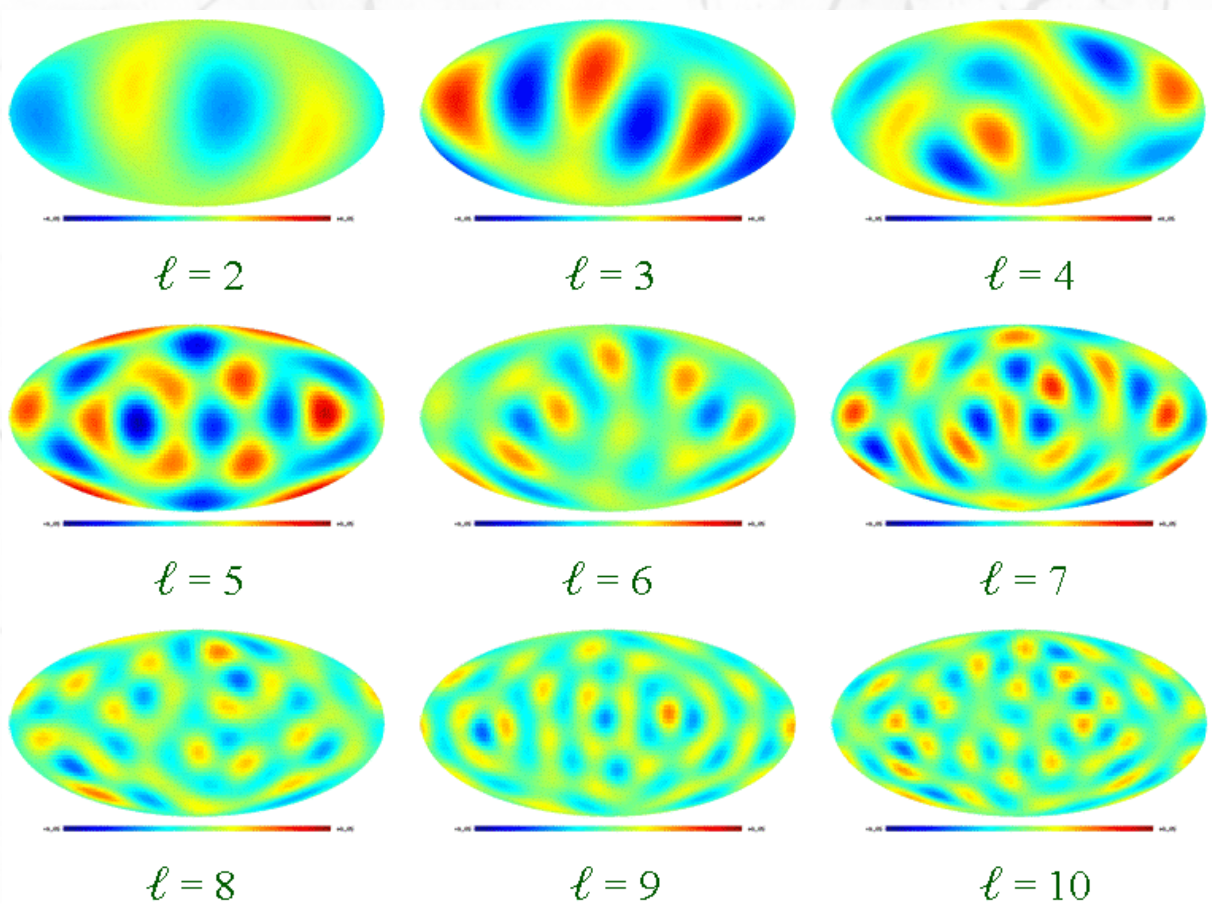
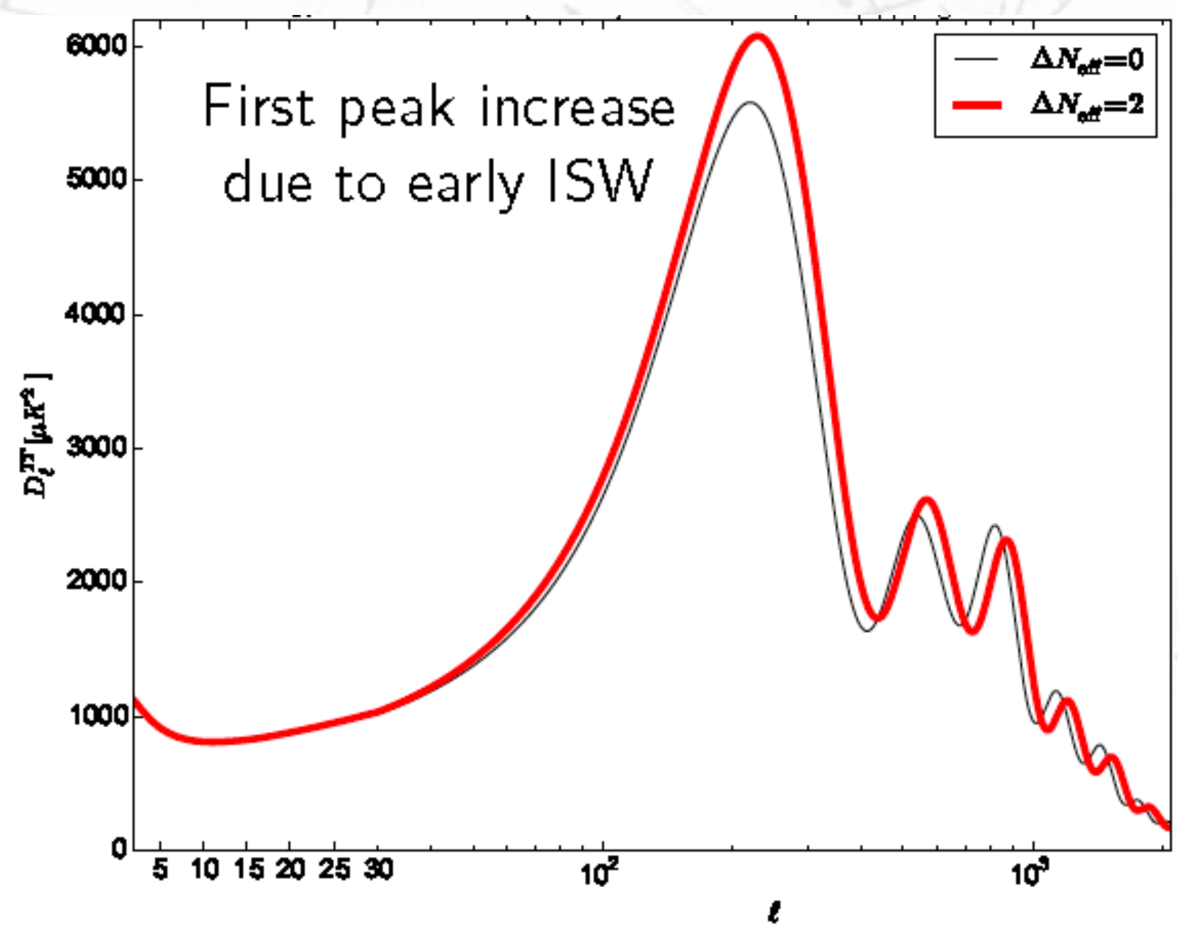


$$\frac{\delta T}{T_0} = \sum_{lm} \alpha_{lm} Y_{lm}(\theta, \phi)$$





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Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma = \left[1 + 0.2271 N_{\text{eff}}\right]\rho_\gamma$$

ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\text{eff}} \to$ all the radiation contribution not given by photons

In the SM, this is only neutrinos!

Observations: $N_{\text{eff}} \simeq 3.0 \pm 0.2$ [Planck 2018]
Indirect probe of cosmic neutrino background!

$\gg 10\sigma$!

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- Neutrino eigenstates with a mass $m_i \ll 0.57$ eV become non-relativistic after photon decoupling.
  - There is a transition as function of the neutrino energy and mass.
- This leads to several contributions to the CMB temperature and polarisation:
  1. the neutrino density increases the total non-relativistic density at late time universe evolutions, $\omega_m = \omega_b + \omega_c + \omega_\nu$
  2. the relativistic-non-relativistic transition affects the ratio between pressure and energy.
  3. the neutrino mass affects the CMB gravitational weak lensing.
  4. low energy neutrinos become non-relativistic earlier and photons feel this through the gravitational effects altering the CMB spectra.

Depending on the information (and measurements) used:

$\Sigma m_\nu < 0.14$ eV $\Sigma m_\nu < 0.68$ eV @ 95%C.L.

Future measurements might get the neutrino mass

As conclusions

- Fast development in the last 20 years. We have measured:
  - mixing parameters.
  - mass differences and hierarchies.
  - solar model tested.
  - mass effects in neutrino propagation.
  - Tested with natural and artificial sources.
  - well established results. Entering the time of global fitting like recent non-zero indications for θ_{13}
  - Observed disappearance but also neutrino transformation in SNO.
  - Starting to measure neutrino properties in the cosmos.
  - Using neutrinos as messengers from beyond the galaxy.

As conclusions

- But, it is not finished yet:
  - CP violation?
  - Mass hierarchy of atmospheric oscillations.
  - Are the neutrinos Majorana or Dirac? or both?
  - Why the mass is so small: “ad-hoc”, see-saw,… (we will need some external help here: LHC?,cosmology?,...)
  - Additional (sterile) neutrinos?
  - neutrinos as extraterrestrial messemngers
  - Precision!!! Experiments are not limited by statistics anymore, understanding and controlling all aspects of the measurement is critical:
    - Cross-sections, flux, etc…
  - Cosmology will provide surprises. Testing properties of neutrinos both in the cosmos and earth will open new level of understanding of our universe.
- There are few decades of successful neutrino physics ahead!

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Additional material