Neutrino physics

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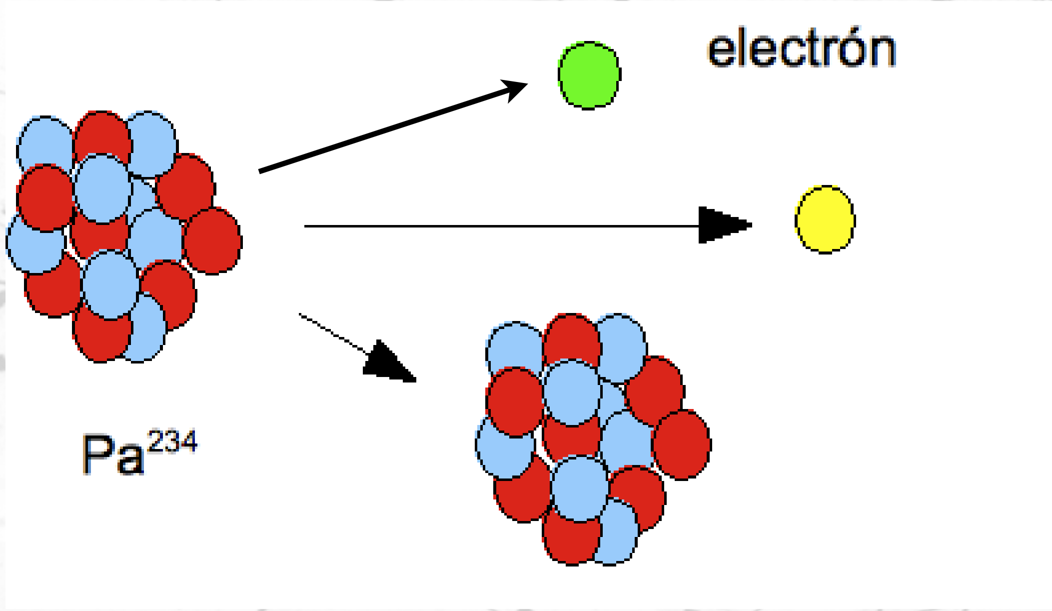
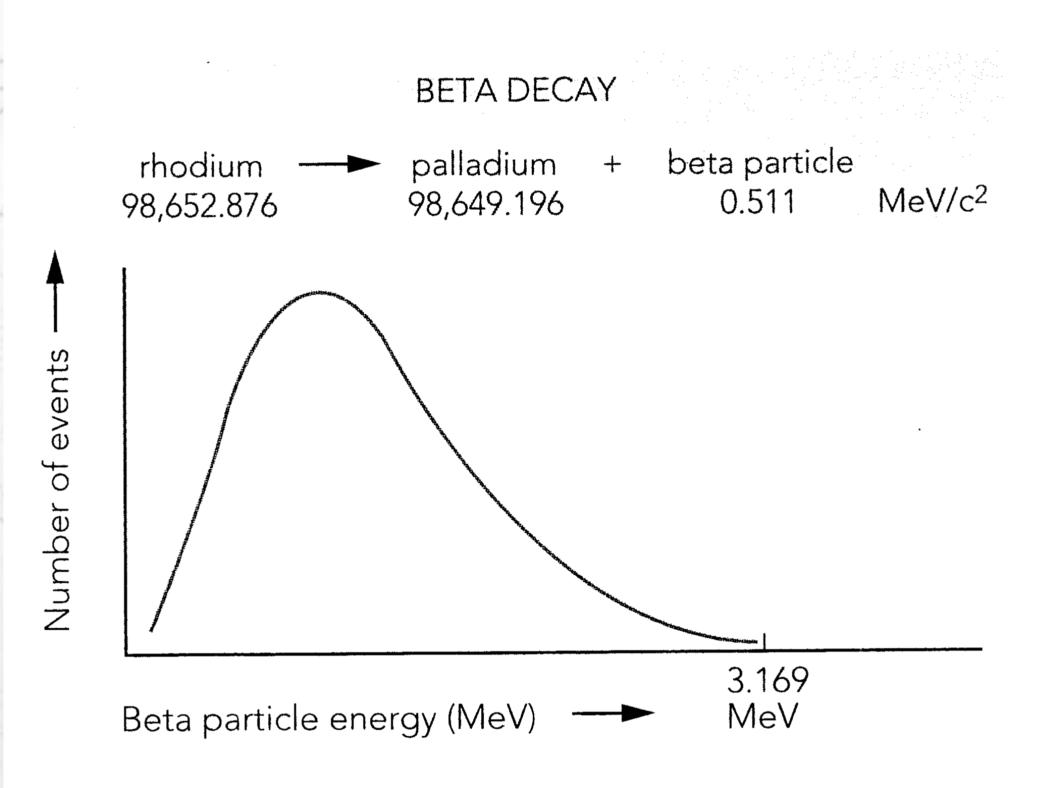
Outlook

- Neutrinos: discovery and early ideas.
- Oscillation phenomenology:
  - Solar neutrinos + Kamland
  - Atmospheric neutrinos + Long Base line experiments.
  - θ_{13} & CP violation.
- Majorana mass & $0\nu2\beta$
- Closing remarks

Neutrinos

- Neutrinos were proposed in 1931 by Pauli in a desperate attempt to understand the beta spectrum.
- The particle (first called neutron) had the following properties:
  - Neutral
  - weakly interacting
  - low mass ($<<m_e$)
  - Spin 1/2





Neutrinos

- The first experiments to determine the mass of neutrinos were proposed in 1933 by Perrin and Fermi. The idea was to investigate the endpoint of the β spectrum.
    - This is still the method used for direct search in Katrin!!!!
    - At that time, upper limits of 100 eV were achieved.
- *After the parity violation in β-decays were discovered, the two-component neutrino theory (Landau , Lee and Yang and Salam, 1957) was the first theoretical idea about neutrino masses.*
    - *The idea was simple, two neutrinos (Left-Right), one of them is "sterile" (do not interact) so it is not "needed".*

Neutrinos

- If we consider that the neutrino field has two components (L,R) the Dirac equations can be written as:

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

- Taking into account the boundaries and the fact that only one field was needed (L or R) to describe the weak interactions, it was accepted that $m_\nu = 0$.

- The "other" helicity was a "sterile": no mass & no interaction & no production mechanism → it does not exist.

- The neutrino helicity was measured in 1958 in a spectacular experiment by M. Goldhaber: neutrinos were left-handed.

Neutrinos

- From this point of view the parity violation in weak interactions was due to the fact that the neutrino mass was zero and only one neutrino helicity existed.

- This idea was changed after the Feynman, Gell-Mann, Marshak and Sudarshan proposed the V-A theory in 1958. The two component theory was not needed because the interaction was governed by the propagator and not the neutrino helicity.

- But, the simplicity of the $m_\nu = 0$ theory prevailed for years... and it was "assumed" that neutrinos were massless.

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:

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

  - And observed some (wrong) events.

As many other times these were preliminary hints that finally vanished.

- At that time only one neutrino especie was known. The only option was to have oscillations (similar to the already known K^0 system) was:

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

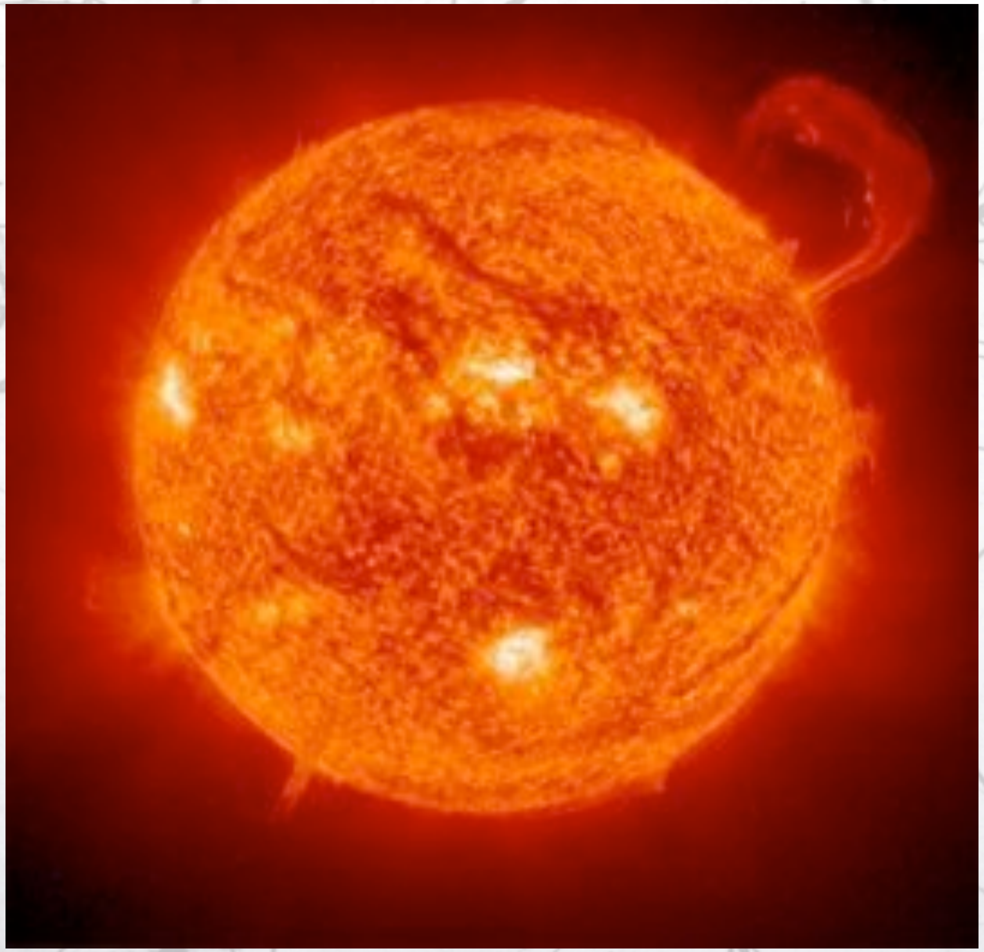
- In his model, he was already proposing that ν were a mixed system of two “Majorana particles” with different mass (ν_1,ν_2).

Neutrino oscillation

- The ν_μ was discovered at Brookhaven in 1962 by Lederman, Schwartz and Steinberger.
- At this time, Pontecorvo proposed the alternative model based on $\nu_\mu \leftrightharpoons \nu_e$ oscillations. The model "only" required that neutrinos were massive.
- Around same 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 (MeV) to produce a muon (100 MeV), so ν_μ is invisible in charged current interactions.*

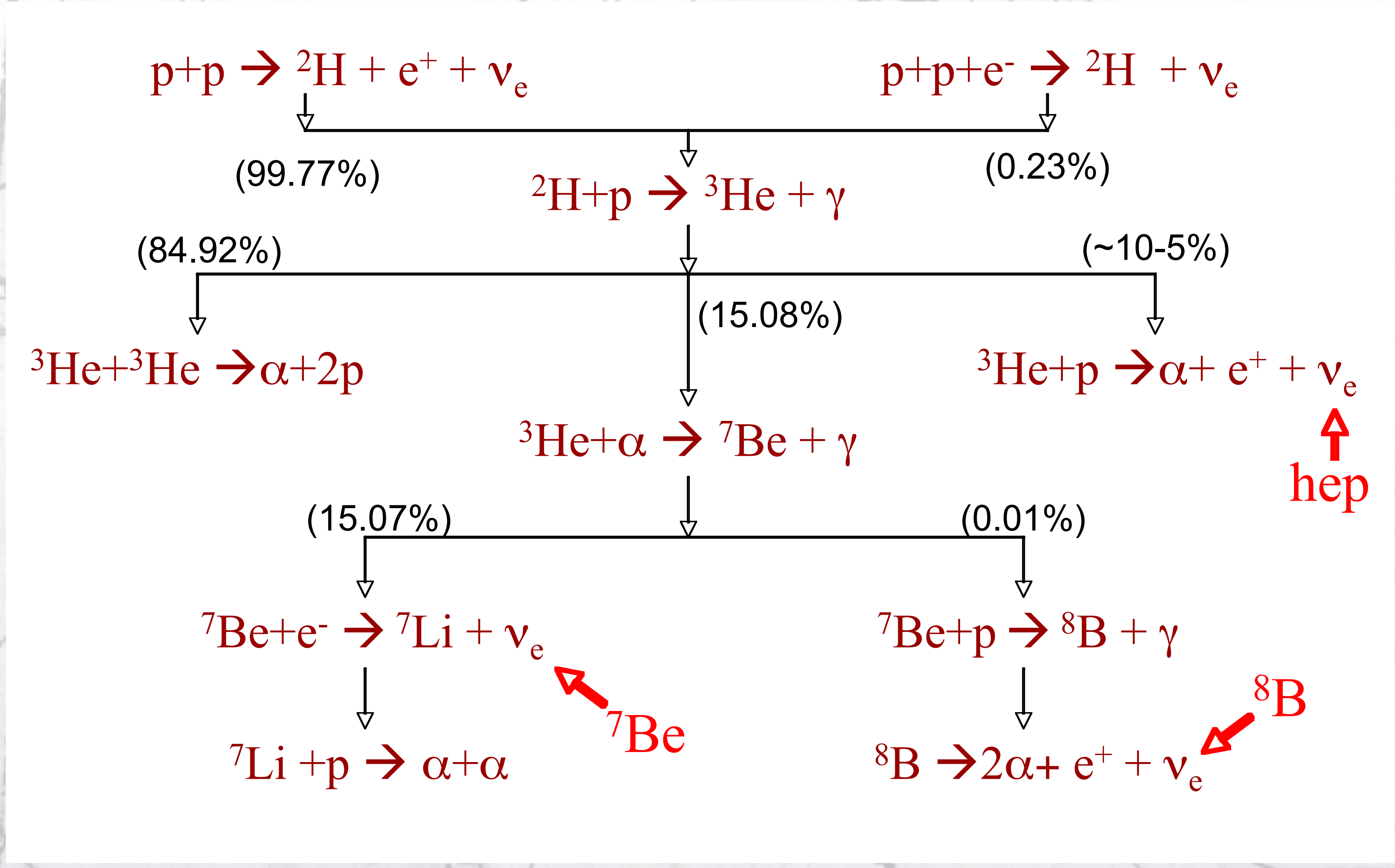
This is still the fundament of neutrino disappearance experiments

Solar neutrinos



Solar neutrinos

- The sun is a thermal fusion nuclear reactor. The sequence of reactions is known to a good level (10%). This allows to predict a relation between the neutrinos and the sun luminosity.



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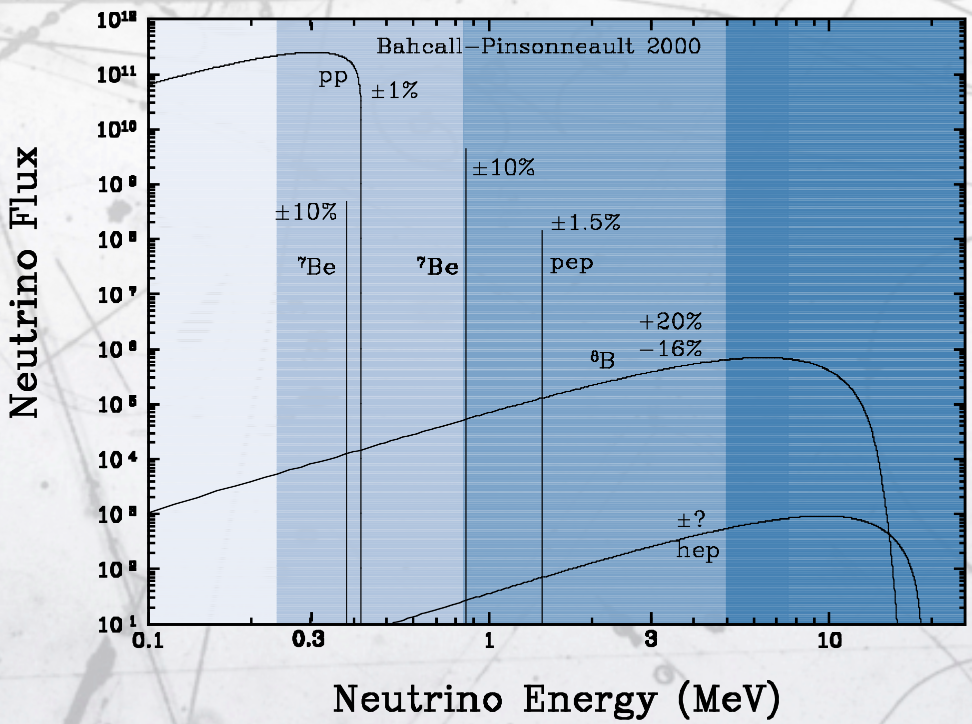
Solar neutrinos

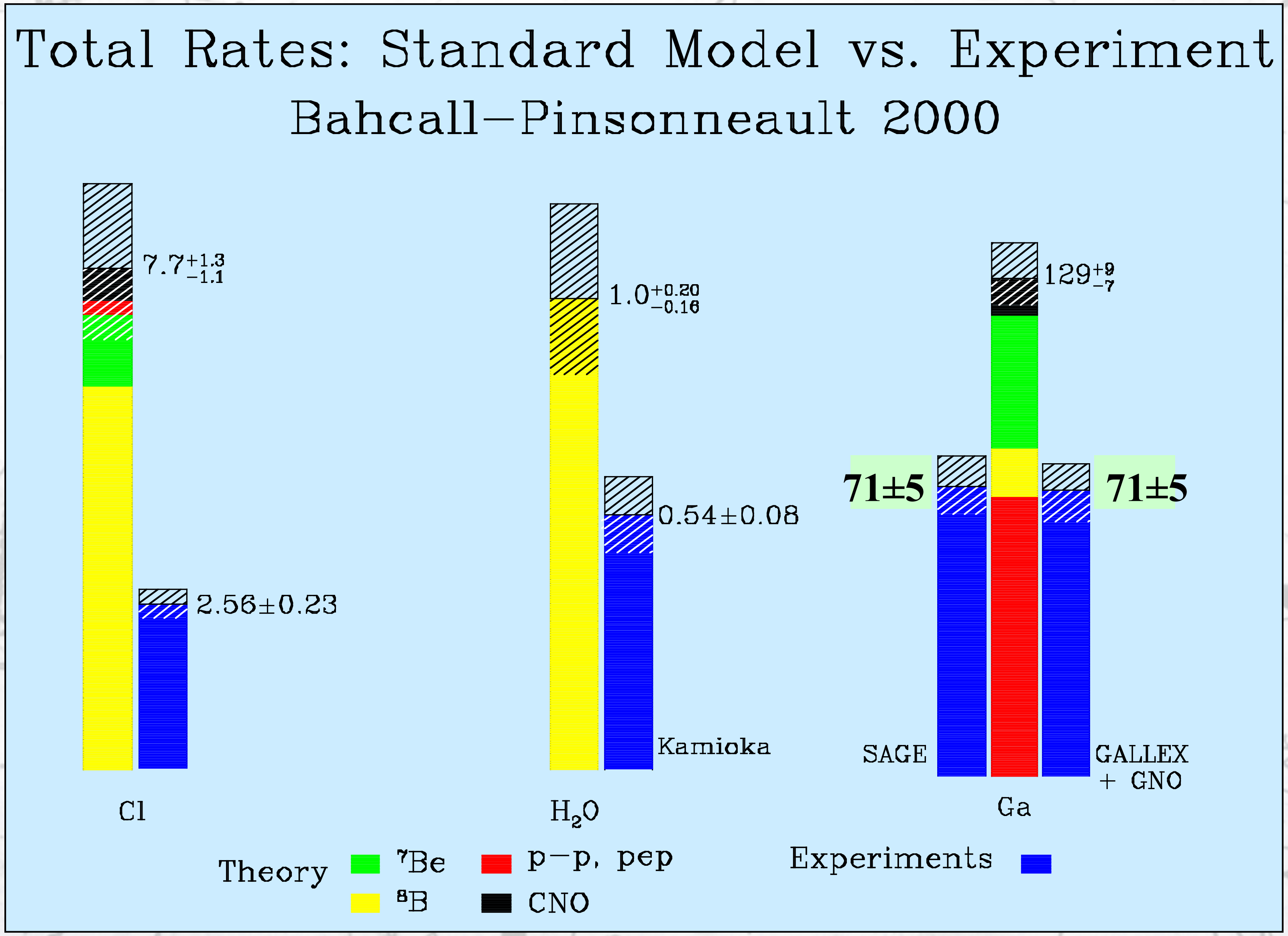
- Solar net reaction is 4p → ^{4}He 2e$^+$ 2 ν_e
- The sun releases 25.7MeV/c^2, or 4.12x10^{-12}J, per Helium nucleus produced (or ½ of that per neutrino). The solar constant is 1370Watts/m^2 at Earth's orbit. The neutrino flux should be then 1370/(2.06x10^{-12})/m^2/sec or: **6.65x10^{10}/cm^2/sec.**
- This number is known to 10% (although not uniformly along the neutrino spectrum).



Solar Neutrinos

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

Solar neutrinos



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

Solar neutrino problem

The strength of paradigms

- 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."

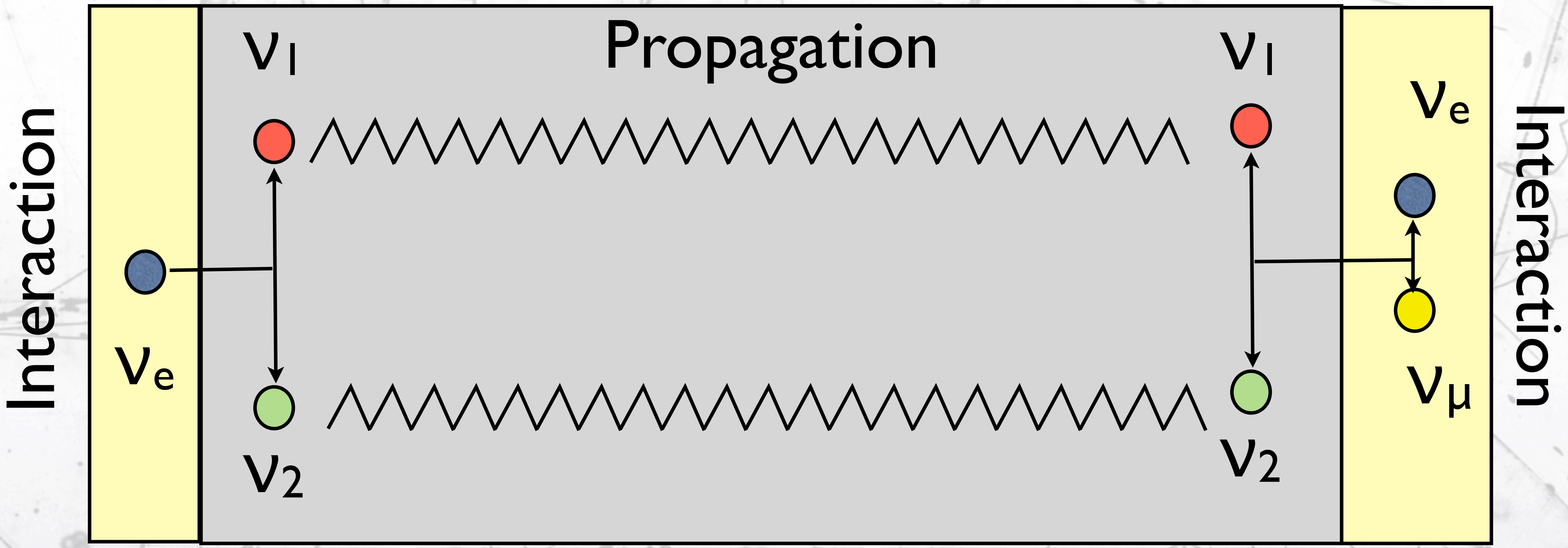
Neutrino oscillation

- 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 flavor).
    - the eigenstates of flavor 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

- Neutrinos are produced always as a flavour neutrino but they propagate in vacuum as mass eigenstates.



- 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

- 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:

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

- $m_\nu << p$:

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

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

Neutrino Oscillation

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

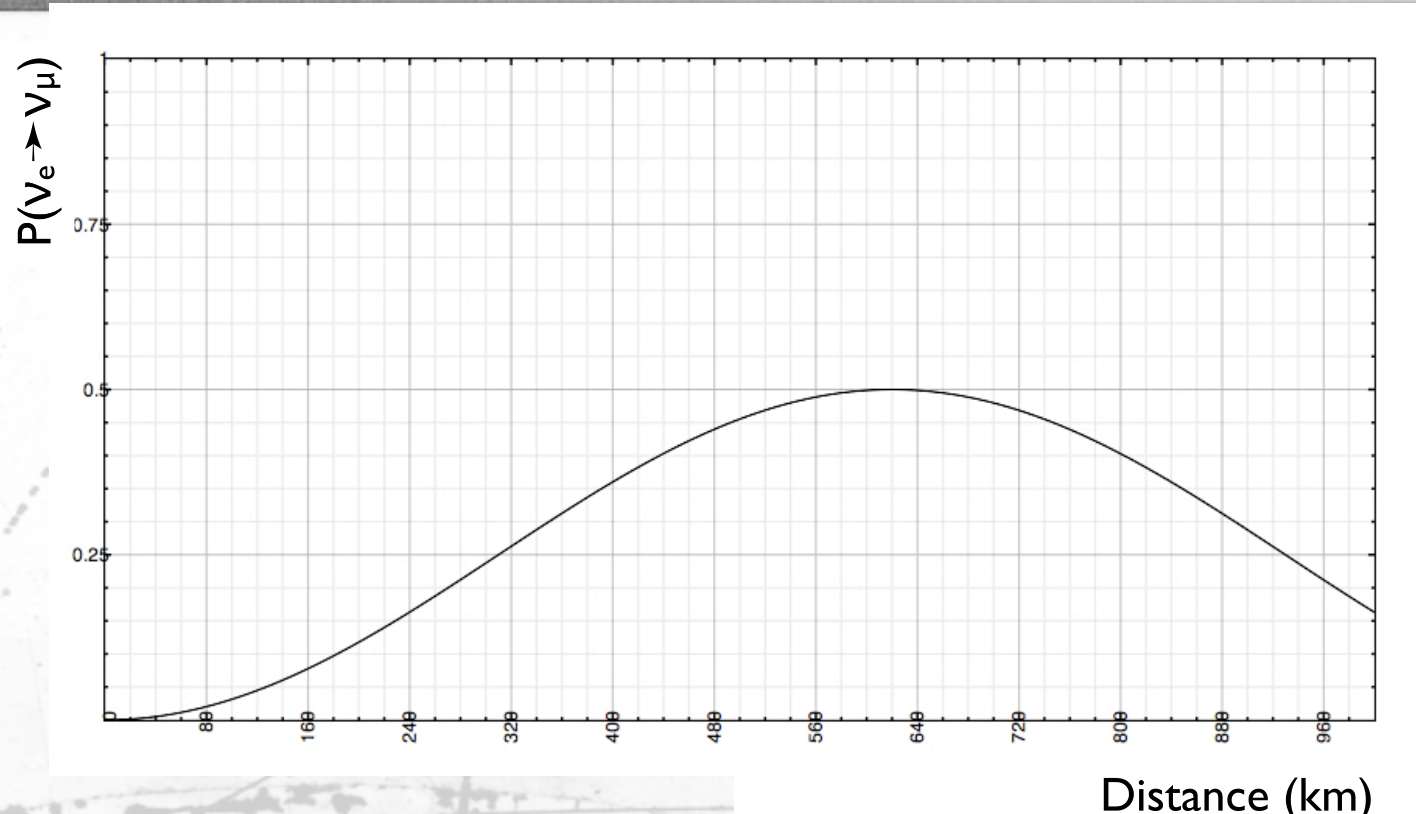
$$|\nu_e;t>= \cos\theta e^{i(p+\frac{m_1^2}{2p})\frac{t}{\hbar}}|\nu_1;0> + \sin\theta e^{i(p+\frac{m_2^2}{2p})\frac{t}{\hbar}}|\nu_2;0>=$$
$$e^{i(p+\frac{m_1^2}{2p})}(\cos\theta|\nu_1;0> + \sin\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}|\nu_2;0>)$$

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

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

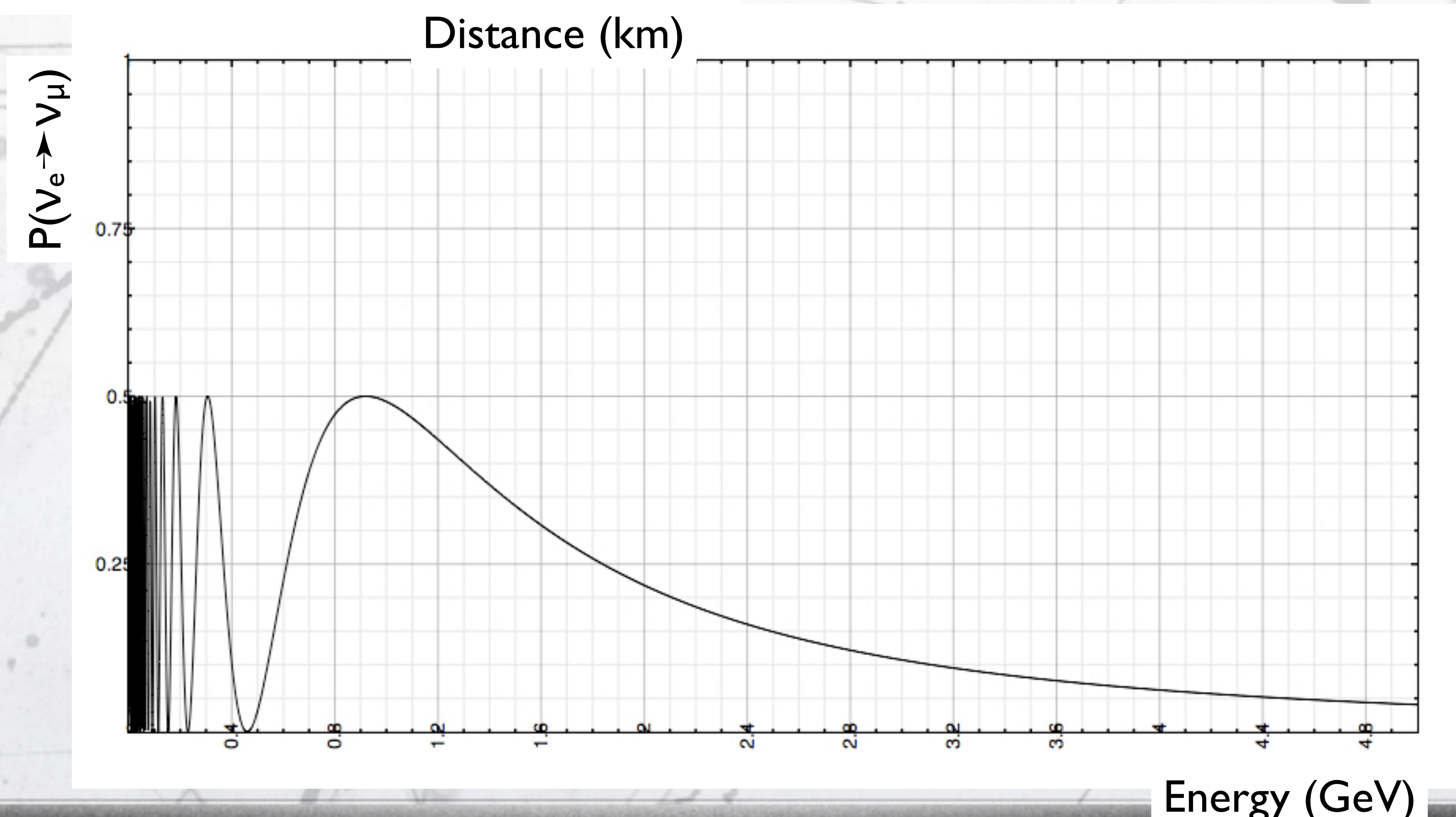
- Flavour-lepton number is not conserved!.
- Opens the possibility for flavour violation in lepton decay & production.

Neutrino Oscillation



$\theta = \pi/2$

$\Delta m^2 = 2.\mathrm{x}10^{-3}\ \mathrm{eV}^2$



Oscillations with 3 ν's

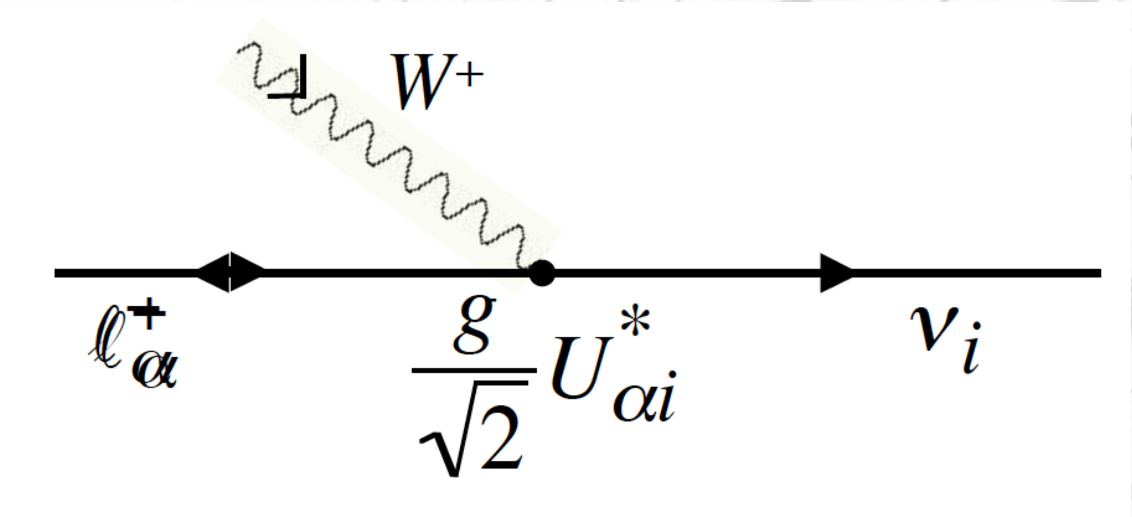
$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{21} & \sin\theta_{21} & 0 \\ -\sin\theta_{21} & \cos\theta_{21} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

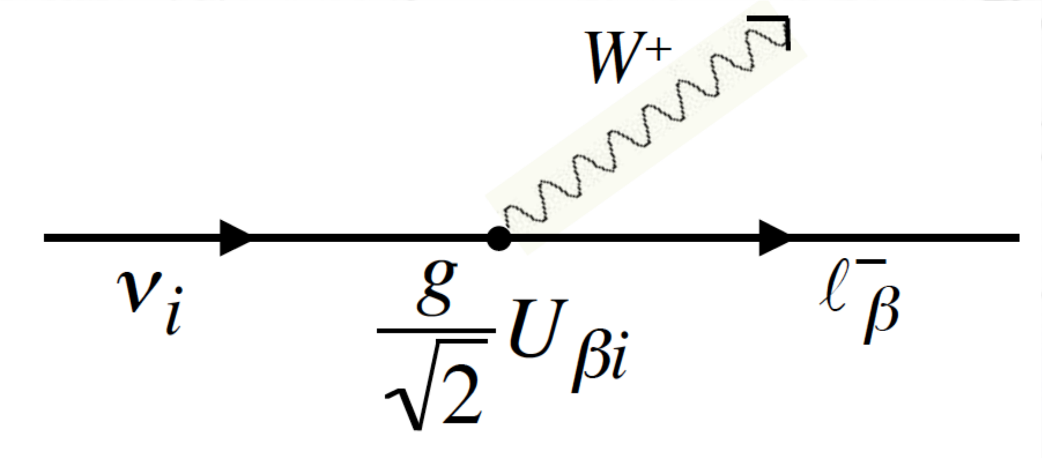
- With 3ν, there are 3 angles and 1 imaginary phase:
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2, traditionally Δm^2_{12} &Δm^2_{31}.

The meaning of U_{PMNS}

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



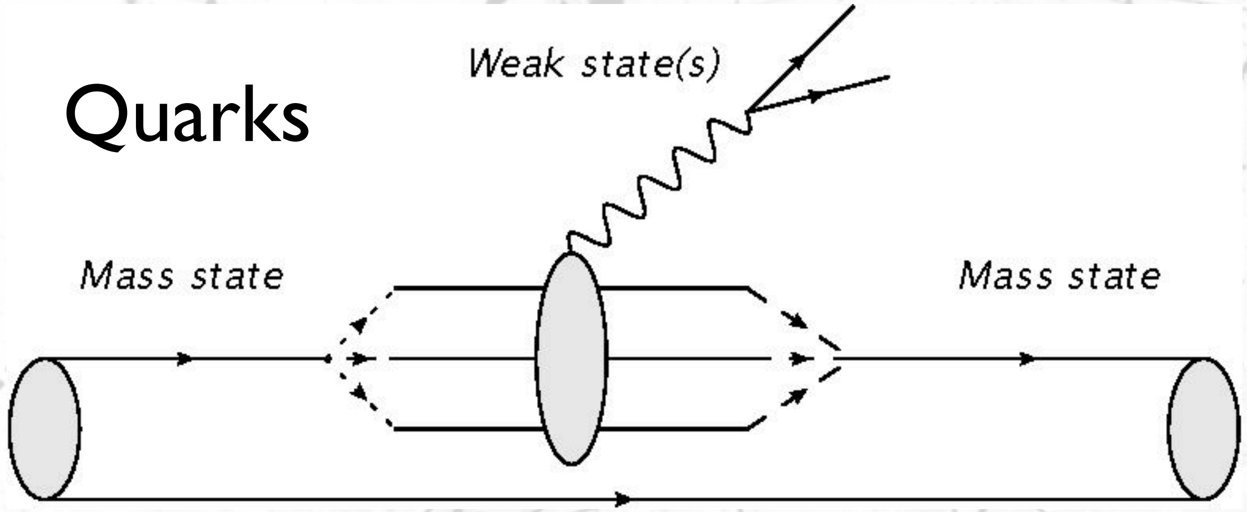
Production



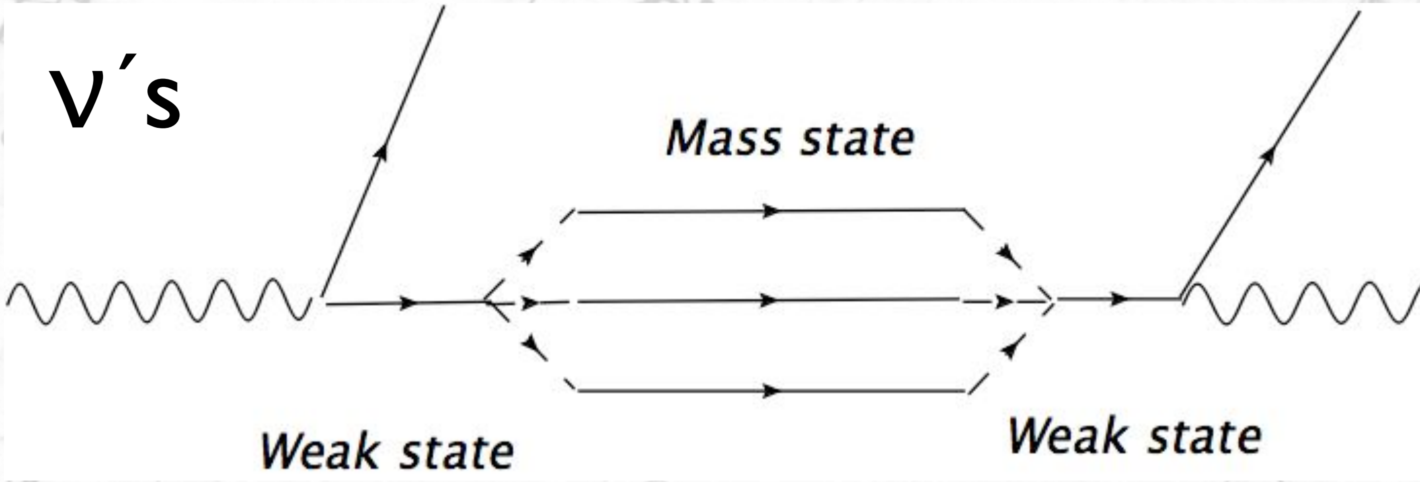
Detection

Lepton & quark mixing

Quarks



ν´s



- The mixing model is the same for quarks and neutrinos.
- Quarks & neutrinos exists in matter and vacuum as mass states.
- The neutrinos are normally identified during the interaction → as flavour state.
- The quarks are identified through it bound state (mesons), so normally as mass states.

Neutrinos in matter

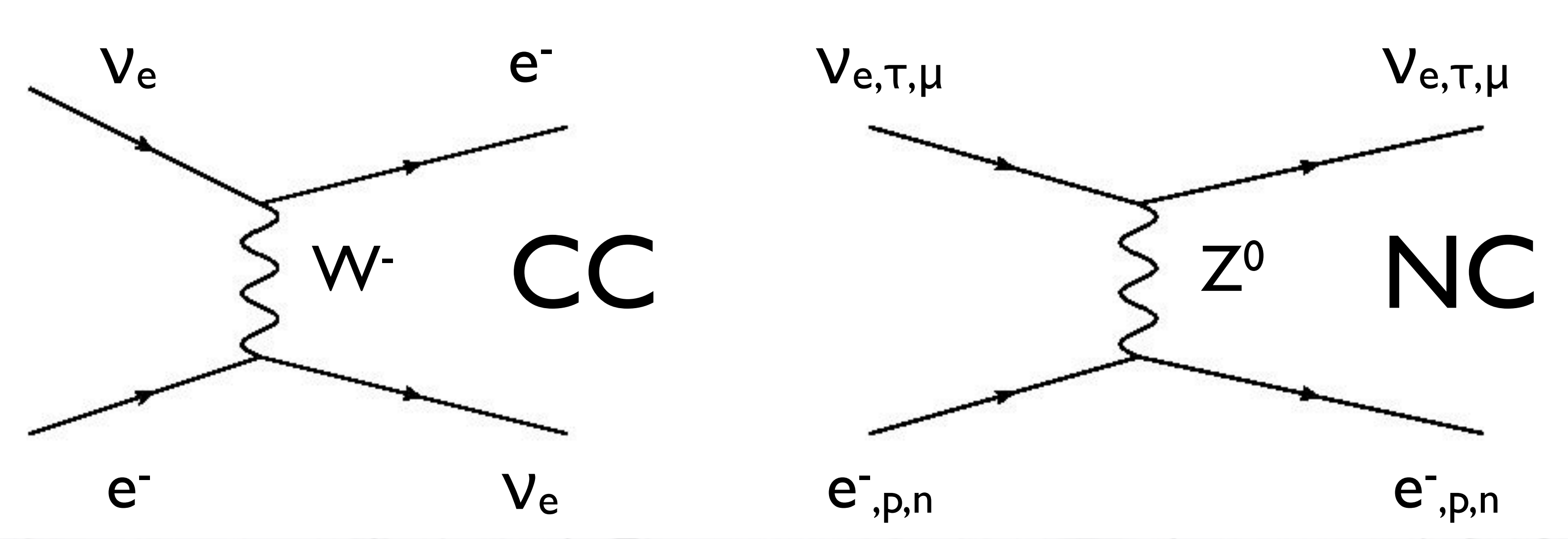
- Neutrinos can have two types of interaction with matter:
  - Incoherent inelastic (the neutrino and the target varies state and/or kinematics): $\sigma \sim 10^{-43}$ (E/MeV)^2
  - Coherent (the medium is unchanged and the scattered and un-scattered waves interfere enhancing the effect)
    - It introduces a phase in the propagation, that can be invisible if the target and neutrino do not alter their properties.
- Actually Coherent interaction is visible in neutrino oscillation due to the asymmetry induced by matter (only electrons and no muons and taus!).

Neutrinos in matter

- The Schrödinger equation of ν in matter:

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

- V_C introduces the coherent interaction (phase) depending on the neutrinos flavour:



- The NC phase is common and factorizes. The CC remains:

$$V_C = diag(\pm\sqrt{2}G_F n_e, 0, 0)$$

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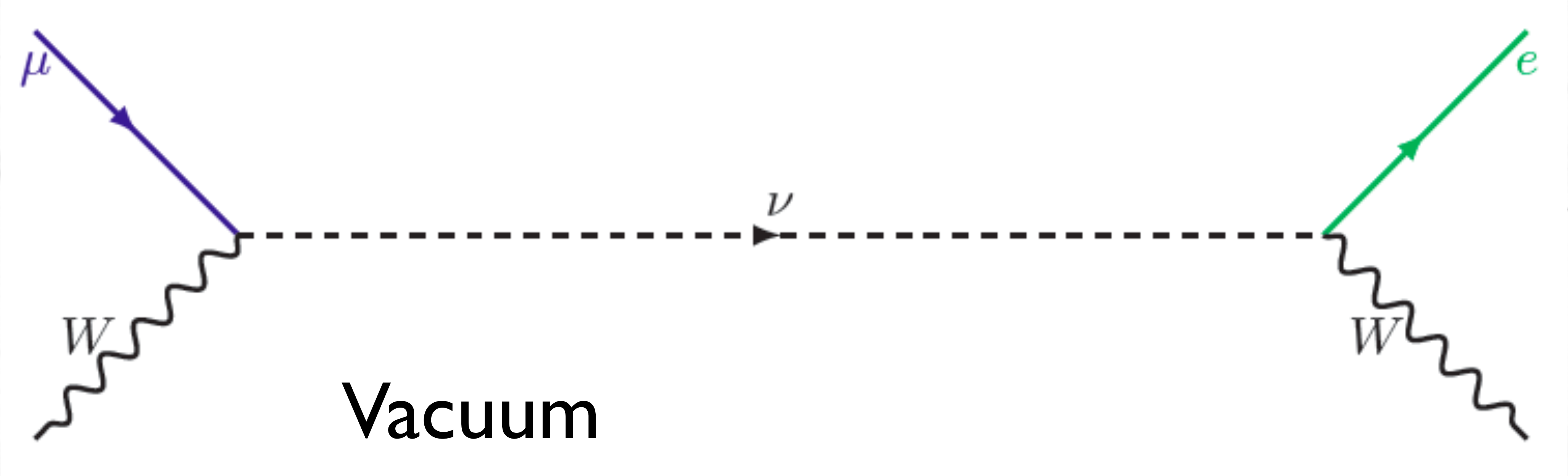
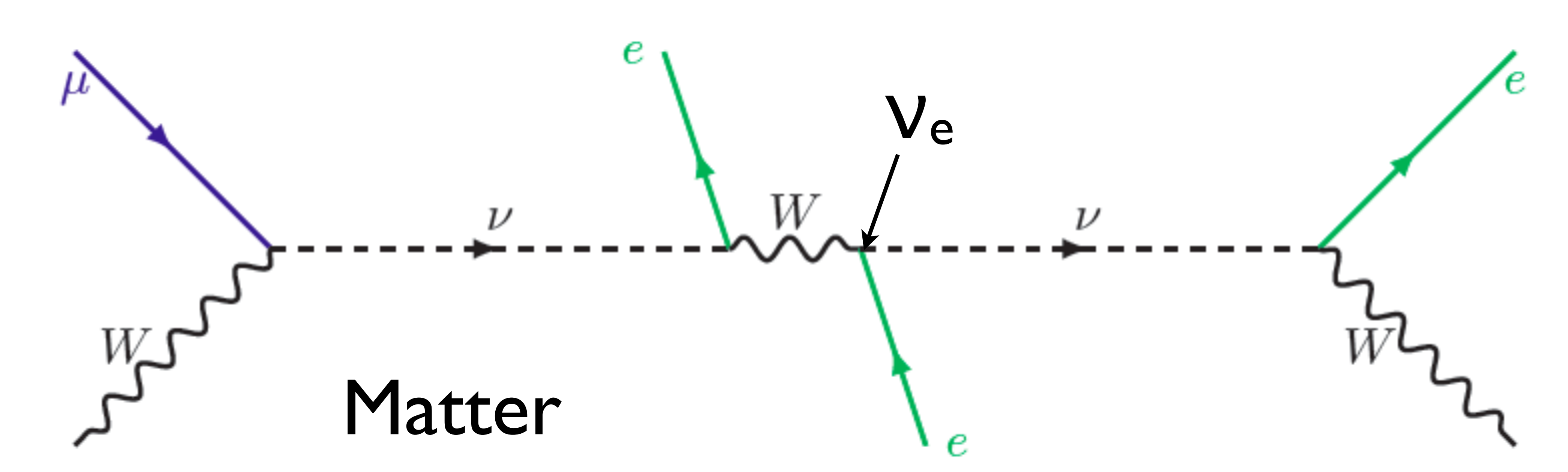
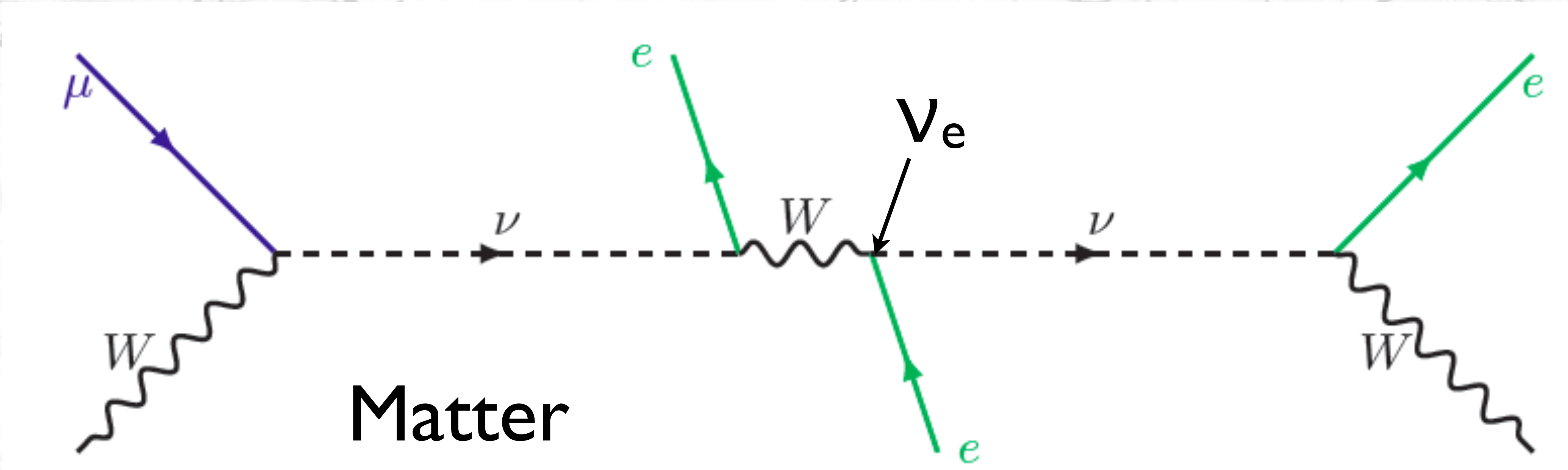
Neutrinos in matter





Neutrinos in matter



$$i\hbar\frac{\partial\nu}{\partial t} = H_{eff}\nu \qquad H_{eff} = U_{PNMS}\begin{pmatrix}\frac{m_1^2}{2E} & 0 & 0\\ 0 & \frac{m_2^2}{2E} & 0\\ 0 & 0 & \frac{m_3^2}{2E}\end{pmatrix}U^\dagger_{PNMS} \pm \sqrt{2}G_F N_e \begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

flavour states

$$i\hbar\frac{\partial\nu_i}{\partial t} = H^*_{eff}\nu_i \qquad H^*_{eff} = \begin{pmatrix}\frac{m_1^2}{2E} & 0 & 0\\ 0 & \frac{m_2^2}{2E} & 0\\ 0 & 0 & \frac{m_3^2}{2E}\end{pmatrix} \pm \sqrt{2}G_F N_e U^\dagger_{PMNS}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}U_{PMNS}$$

mass states

Neutrinos in matter

- The mass effect can be interpret as a change in the mass eigenstate and eigenvalue. It changes interference pattern & effective mixing angle. Both depend on the neutrino energy and local electron density.

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

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

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

$$V_\alpha = \pm\sqrt{2}G_F n_e$$

$$V_\beta = 0$$

$$|\nu_1 >= \cos\theta_m|\nu_\alpha > - \sin\theta_m|\nu_\beta >$$

$$|\nu_2 >= \sin\theta_m|\nu_\alpha > + \cos\theta_m|\nu_\beta >$$

Neutrinos in matter

- When $A \ll \Delta m^2 \cos(2\theta)$, the $\tan(2\theta_m)$ is like $\tan(2\theta_o)$ (vacuum oscillations).
- When $A \sim \Delta m^2 \cos(2\theta)$, the $\tan(2\theta_m)$ becomes infinite (maximal mixing) and changes sign → the proportions of 1&2 invert for α&β states ("level crossing").
- When $A \ll \Delta m^2 \cos(2\theta)$, the mixing tends to 0 but the effective mass becomes infinite → fast oscillations.

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

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

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

$$V_\alpha = \pm\sqrt{2} G_F n_e$$

$$V_\beta = 0$$

$$|\nu_1 >= \cos\theta_m |\nu_\alpha > - \sin\theta_m |\nu_\beta >$$

$$|\nu_2 >= \sin\theta_m |\nu_\alpha > + \cos\theta_m |\nu_\beta >$$

When θ_m crosses 45° we can interchange cos and sin and the proportions reverse.

Neutrinos in matter

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

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

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

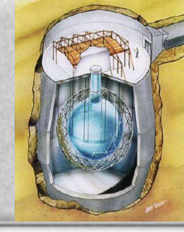
$$V_\alpha = \pm\sqrt{2}G_F n_e$$

$$V_\beta = 0$$

- There is a CP-like effect due to matter effects (no positrons in matter) → systematics for CP violation.
- The matter effect parameter is summed to Δm^2 so, it is sensitive to the sign of this difference → sensitive to hierarchy.
- It depends on the Energy of the neutrino.
- It depends on the electron density:
  - sensitive to the type of matter it crosses, so electron composition of earth for example → systematics and geophysics.

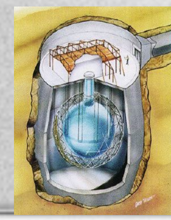
Solar Neutrinos

- Back to experiments: How to unveil the "solar neutrino" problem? It was not statistics or systematics, repeating experiments won't help. We need to:
  - measure the total neutrino flux (3 flavours) from the Sun (SNO).
  - produce a neutrino flux that is calculable. (Kamland).
- In parallel, search in the ν_μ sector for equivalent phenomena (atmospheric neutrinos & SuperKamikande).

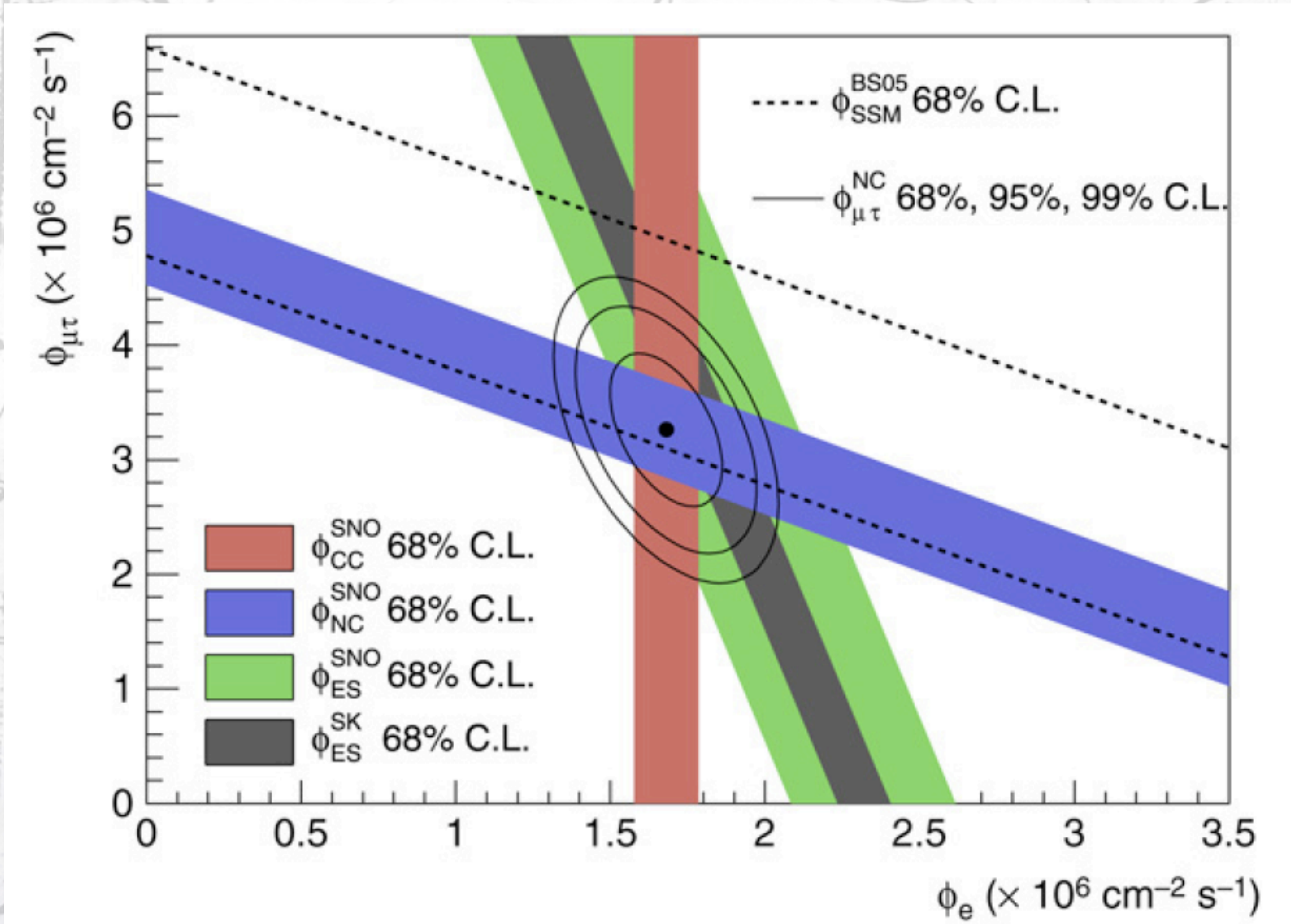


SNO

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



SNO



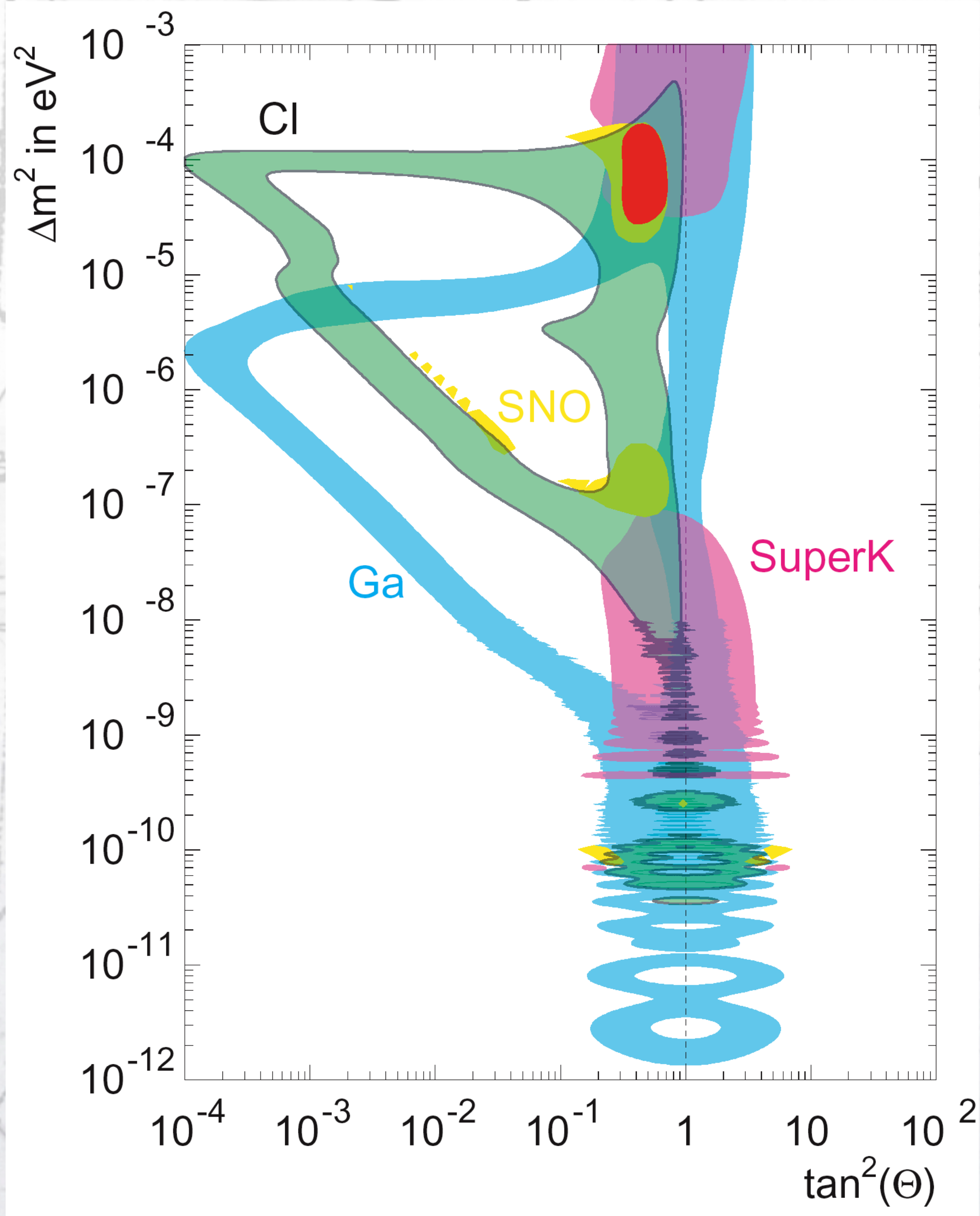
$$\Phi^{CC}_{SNO} = \left(1.68^{+0.06}_{-0.06}{}^{+0.08}_{-0.09}\right) \times 10^6\,\mathrm{cm^{-2}\,s^{-1}} \Rightarrow \frac{\Phi^{CC}_{SNO}}{\Phi_{SSM}} = 0.29 \pm 0.02,$$

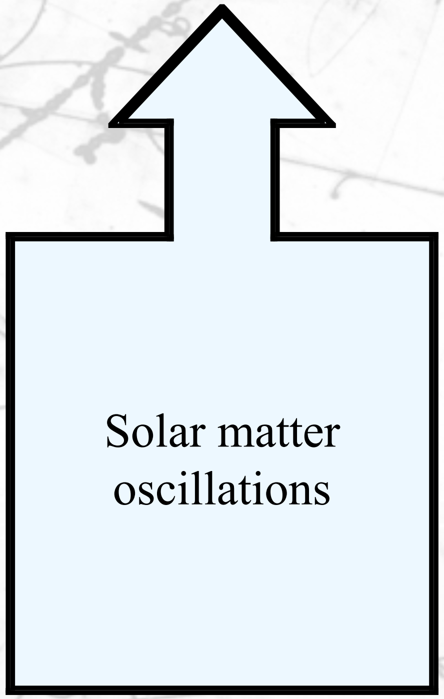
$$\Phi^{ES}_{SNO} = (2.35 \pm 0.22 \pm 0.15) \times 10^6\,\mathrm{cm^{-2}\,s^{-1}} \Rightarrow \frac{\Phi^{ES}_{SNO}}{\Phi_{SSM}} = 0.41 \pm 0.05,$$

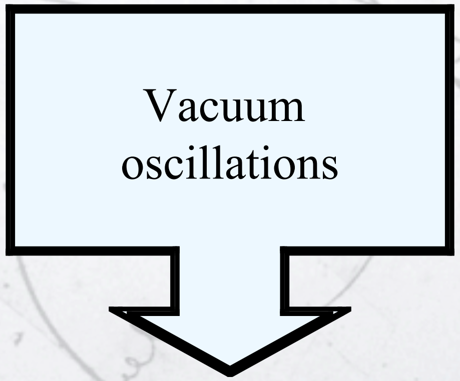
$$\Phi^{NC}_{SNO} = (4.94 \pm 0.21^{+0.38}_{-0.34}) \times 10^6\,\mathrm{cm^{-2}\,s^{-1}} \Rightarrow \frac{\Phi^{NC}_{SNO}}{\Phi_{SSM}} = 0.87 \pm 0.08.$$

Oscillation from sun

Status after first SNO data







Mikeev, Smirnov, Wolfenstein (MSW) effect

- The sun produces ν_e. The neutrino propagates in a high density matter with a radial dependency.
- In the sun, the matter hamiltonian dominates the vacuum hamiltonian. ($A >> \Delta m^2 \cos(2\theta)$).
- 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

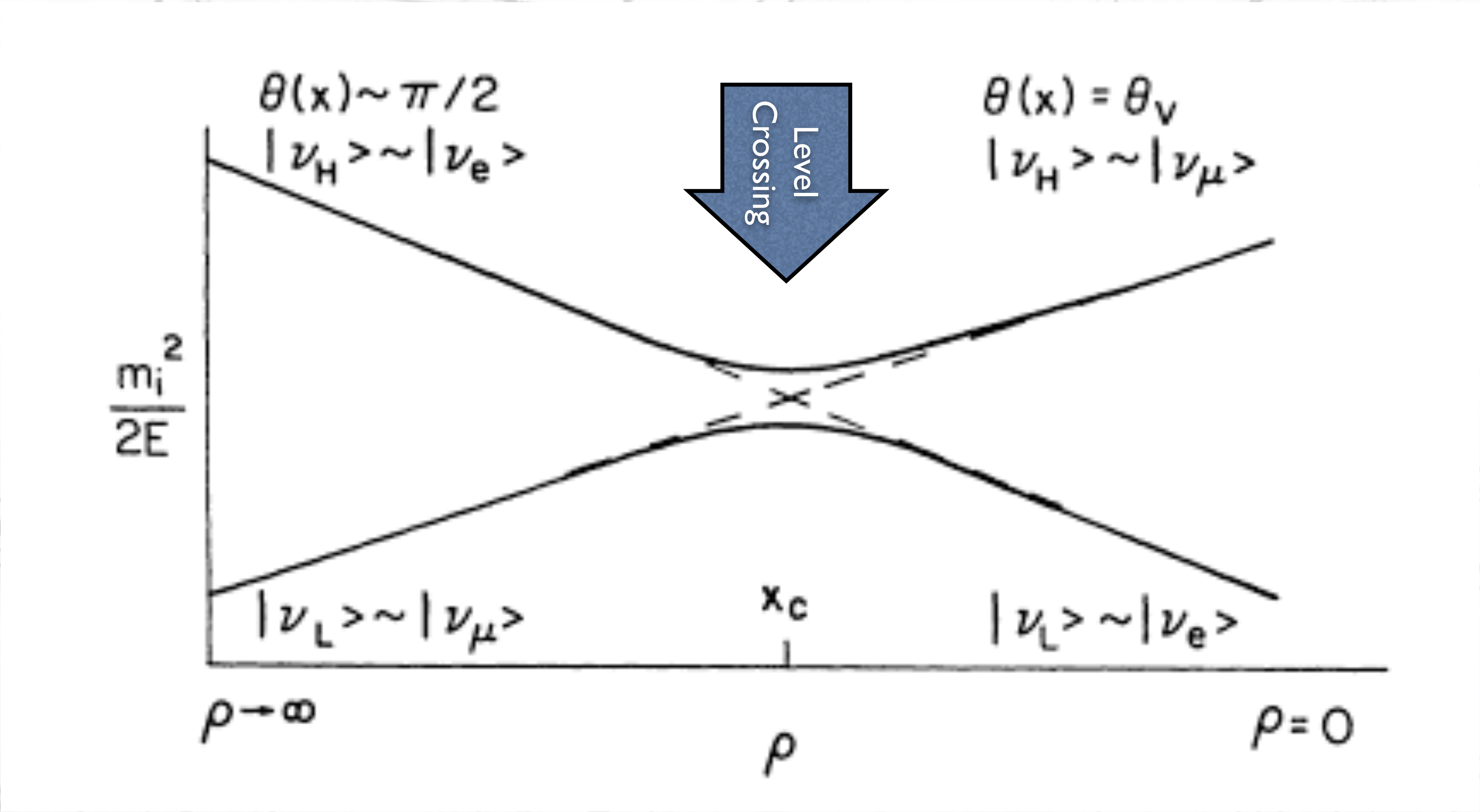
Mikeev, Smirnov, Wolfenstein (MSW) effect

- The density varies adiabatically (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)

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

- The vacuum state ν_2, propagates without interference to the Earth → no seasonal dependency.
- This effect occurs because locally the off-diagonal terms of the Hamiltonian are negligible with respect to the diagonal.

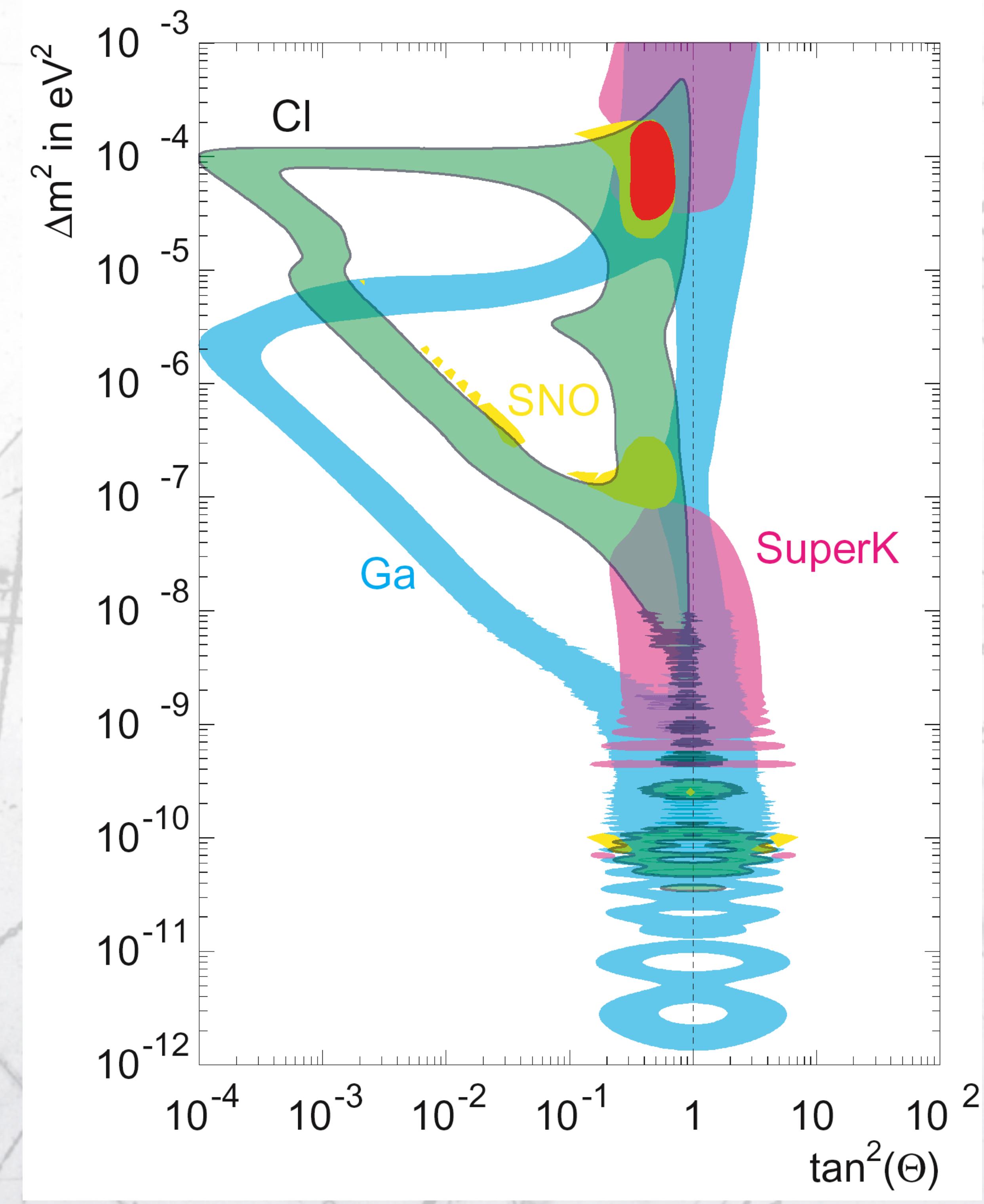
Solar neutrinos



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

Oscillation from sun

Status after first SNO data



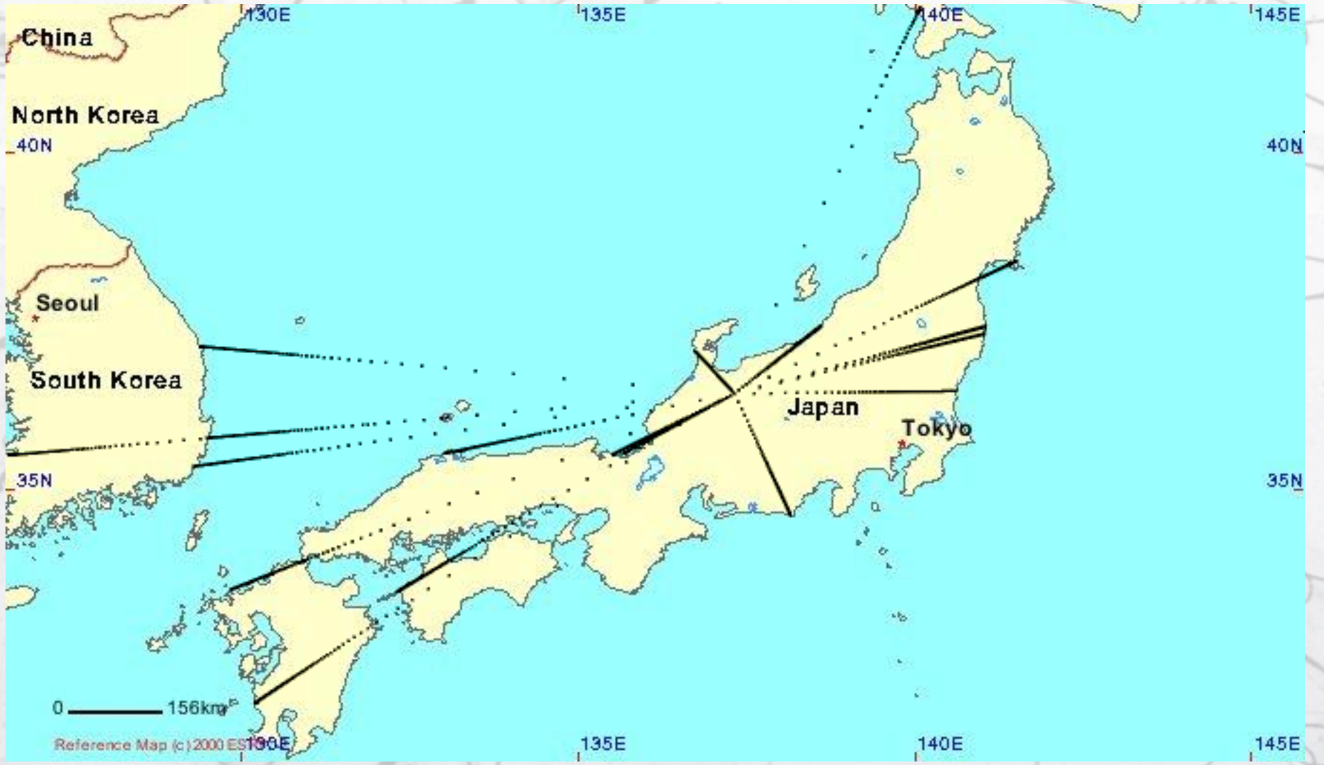
Solar matter oscillations

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

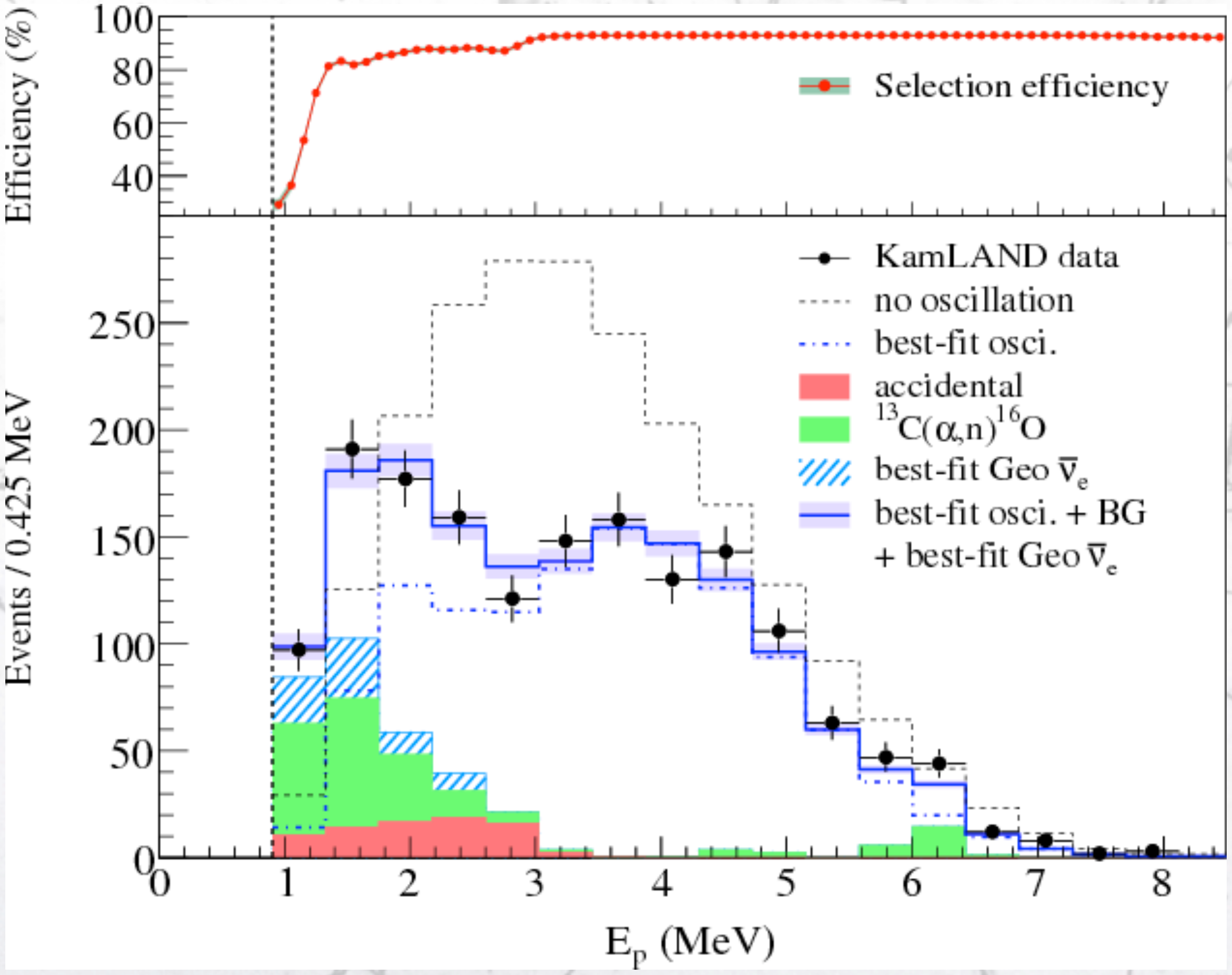
Vacuum oscillations

Kamland

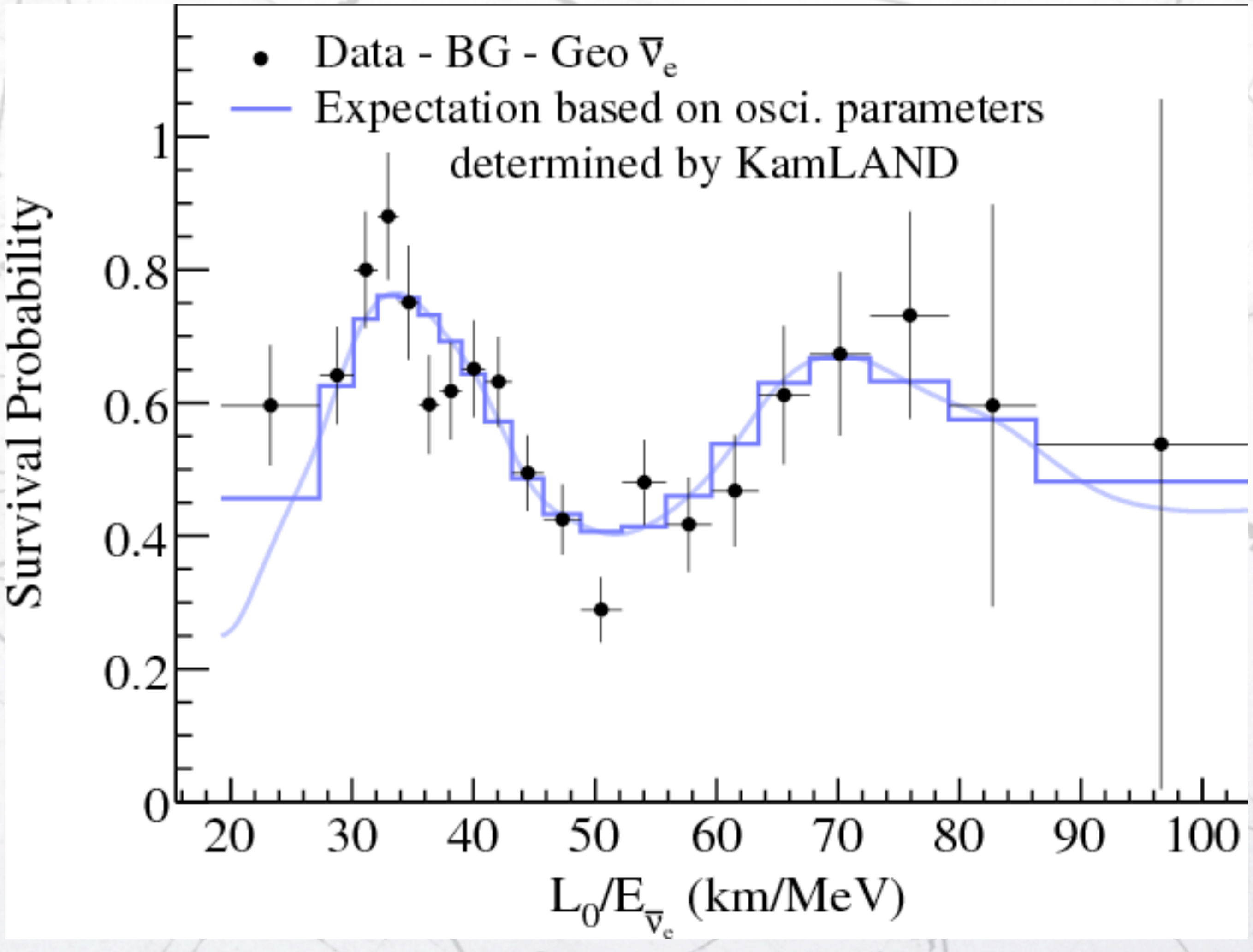
- Search for $\bar{\nu}_e$ oscillations from nuclear reactors.
- Average distance: ~180km.
- Average Energy: ~4 MeV.
- Sensitive to $\Delta m^2 \sim 10^{-4}$ eV^2



Kamland

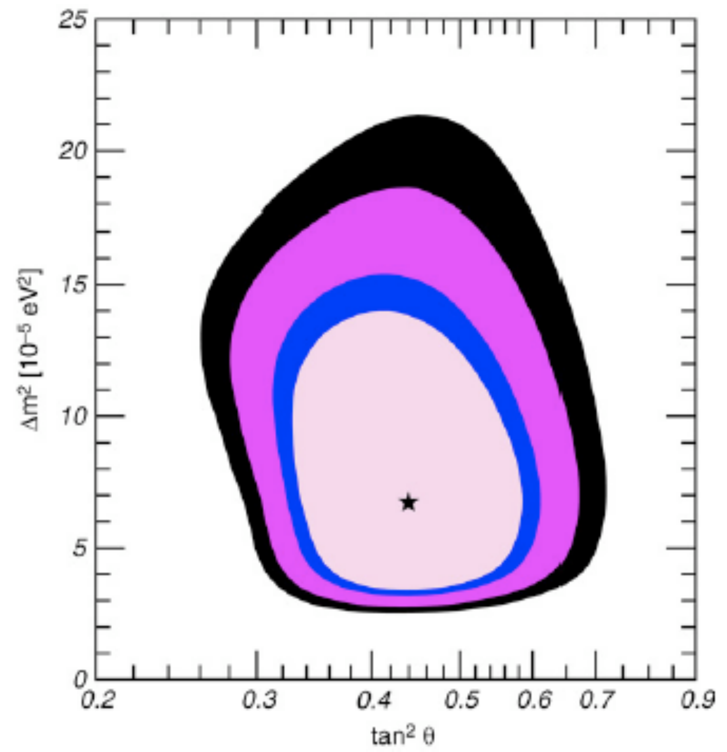


Efficiency (%)
Selection efficiency
KamLAND data
no oscillation
best-fit osci.
accidental
$^{13}C(\alpha,n)^{16}O$
best-fit Geo $\bar{\nu}_e$
best-fit osci. + BG
+ best-fit Geo $\bar{\nu}_e$
Events / 0.425 MeV
E_p (MeV)

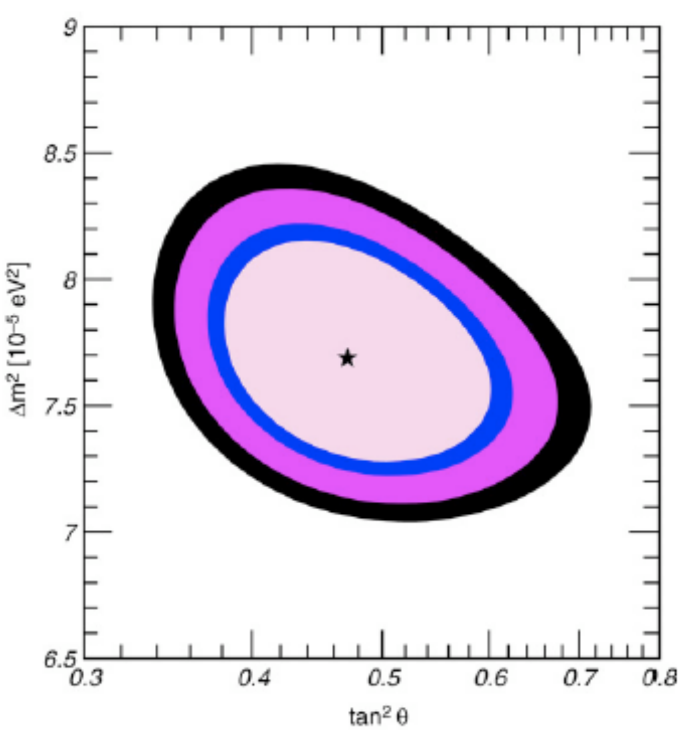


Data - BG - Geo $\bar{\nu}_e$
Expectation based on osci. parameters
determined by KamLAND
Survival Probability
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

Solar neutrinos now



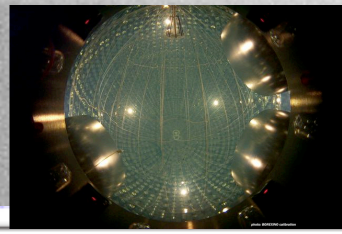
Solar

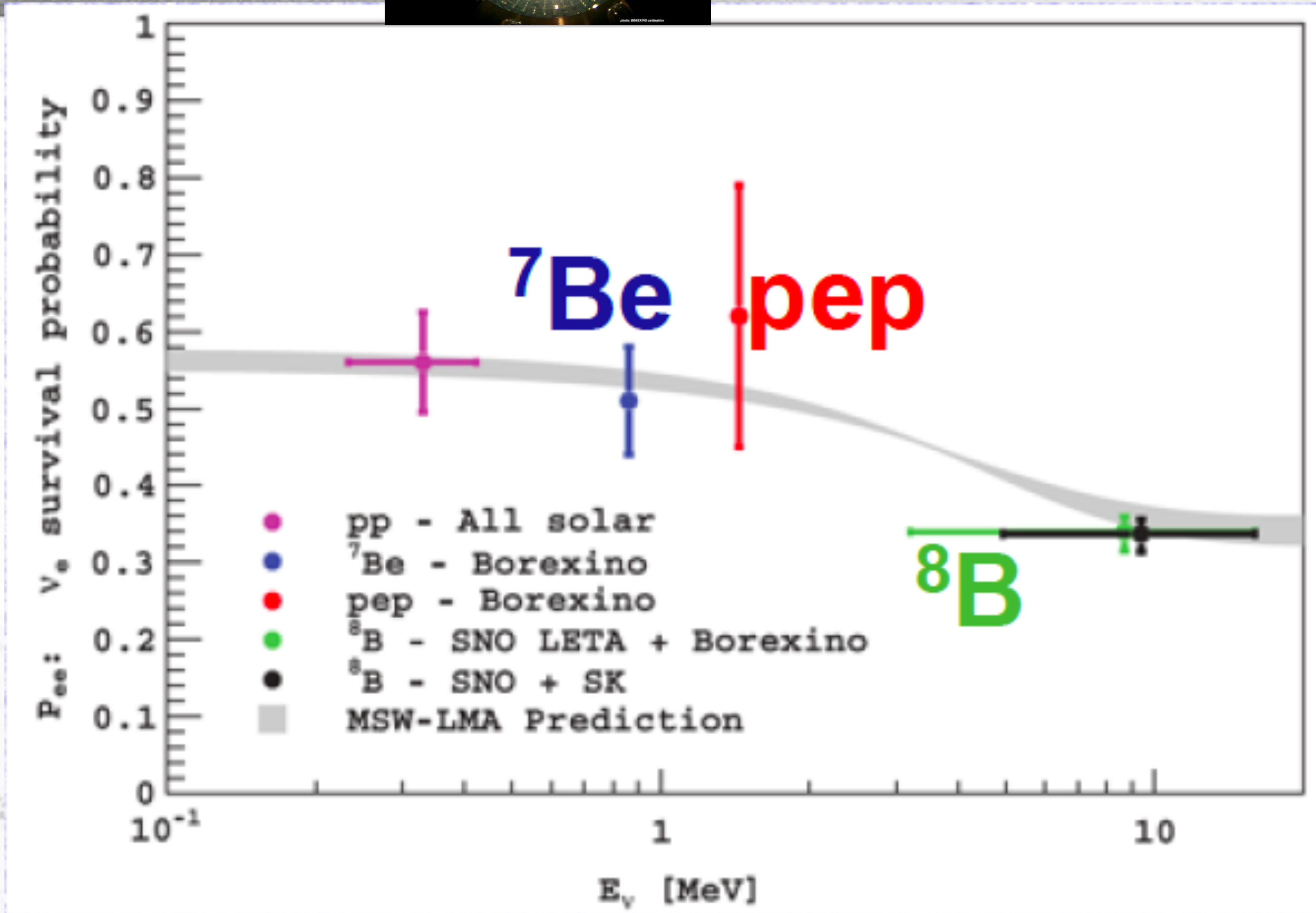


Solar
+
Kamland

- Chlorine, Gallium, SNO & SK:
  - SNO energy dependency.
  - SK day-night asymmetry.
- Kamland Δm^2:
  - $\nu \equiv \bar{\upsilon}$.
- Solar neutrinos follow the LMA → adiabatic oscillation in the sun matter.

Borexino & LMA





- 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:

$$2E_\nu\sqrt{2}G_F n_e << \Delta m^2 \cos 2\theta$$

- We should expect a transition when this happens.

$$n_e(core) \approx 3\times 10^{-31} m^{-3} \oplus \theta_{sol} \approx 30^{\rm o} \oplus \Delta m^2_{sol} \approx 8\times 10^{-5} eV^2 \rightarrow E > 1MeV$$

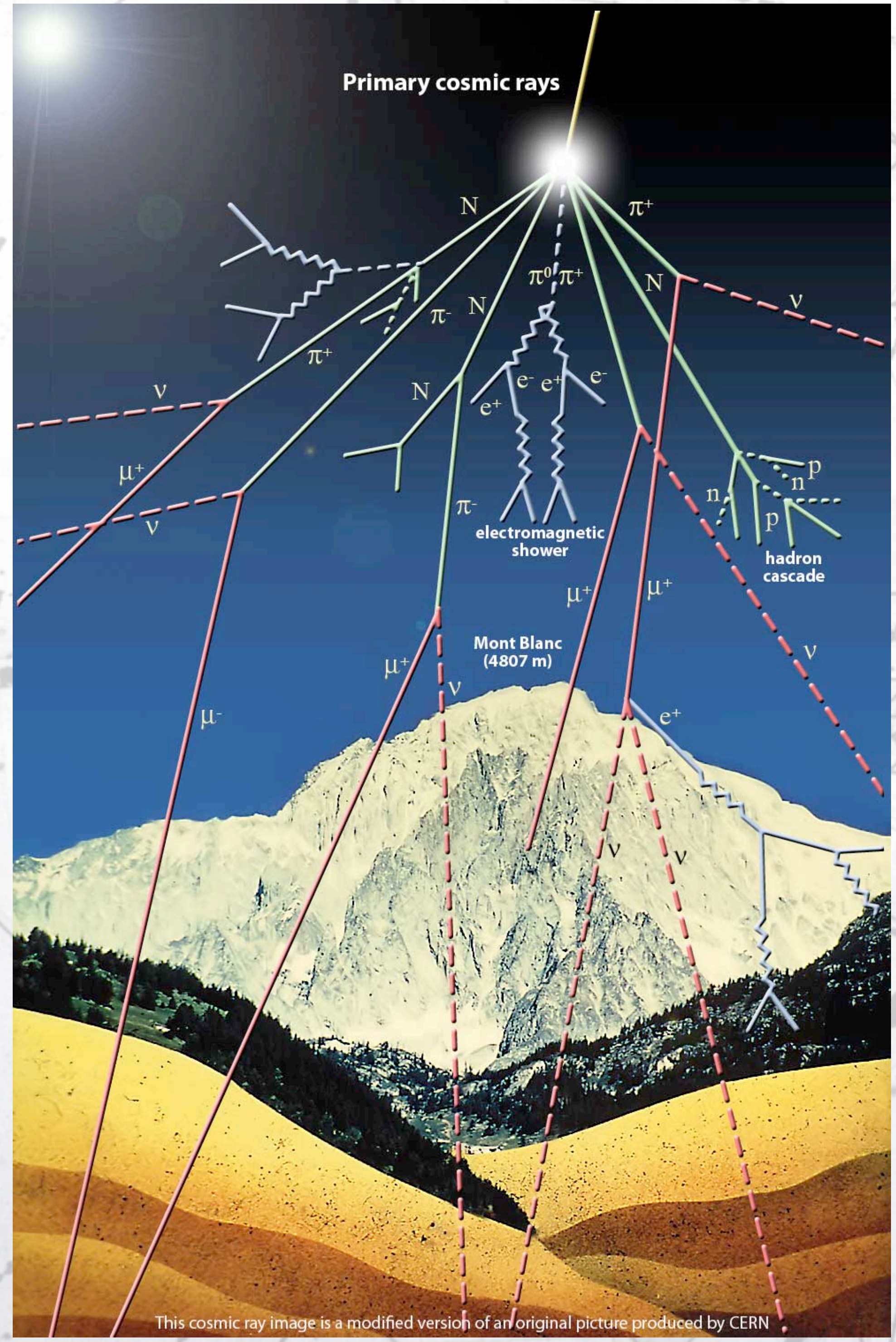
$$\mu^2_{1,2}(x) = \frac{m_1^2+m_2^2}{2} + E_\nu(V_\alpha+V_\beta) \mp \frac{1}{2}\sqrt{[\Delta m^2\cos 2\theta - A]^2 + [\Delta m^2 \sin 2\theta]^2}$$

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

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

$$V_\alpha = \pm\sqrt{2}G_F n_e$$

$$V_\beta = 0$$

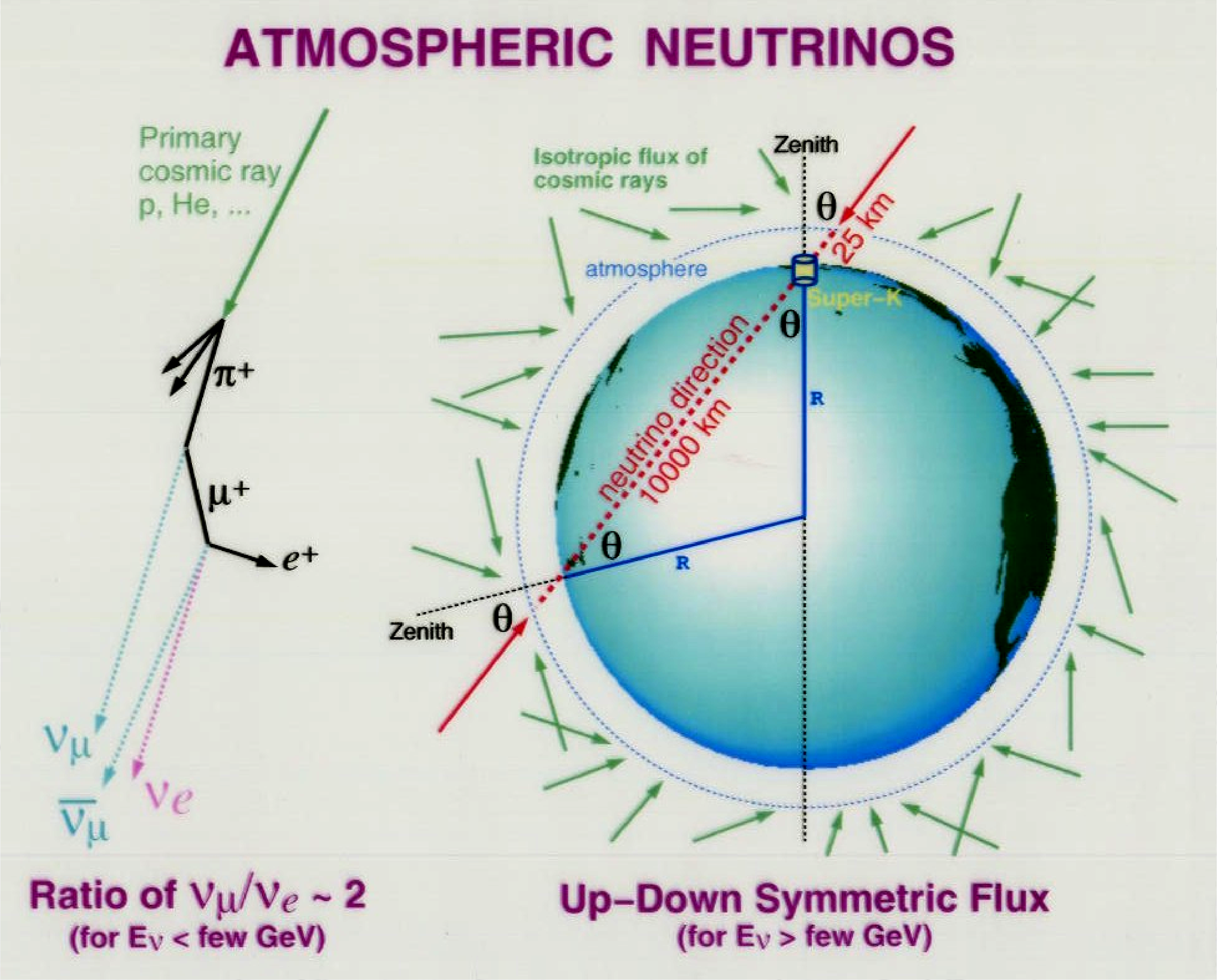


Atmospheric neutrinos

Atmospheric ν

- Up to now we have been looking at ν_e (solar) disappearance:
  - Is the ν_e oscillating to ν_μ or ν_τ ?
  - What about the ν_μ and ν_τ ? Do they also oscillate?
- Some trivialities:
  - Solar neutrinos (~MeV) do not have energy to produce μ (106 MeV) or τ(1777 MeV).
    - Only NC are possible (SNO) and NC do not distinguish between ν_μ and ν_τ
    - We need another "abundant" source of higher energy neutrinos: the atmosphere!!.

Atmospheric ν



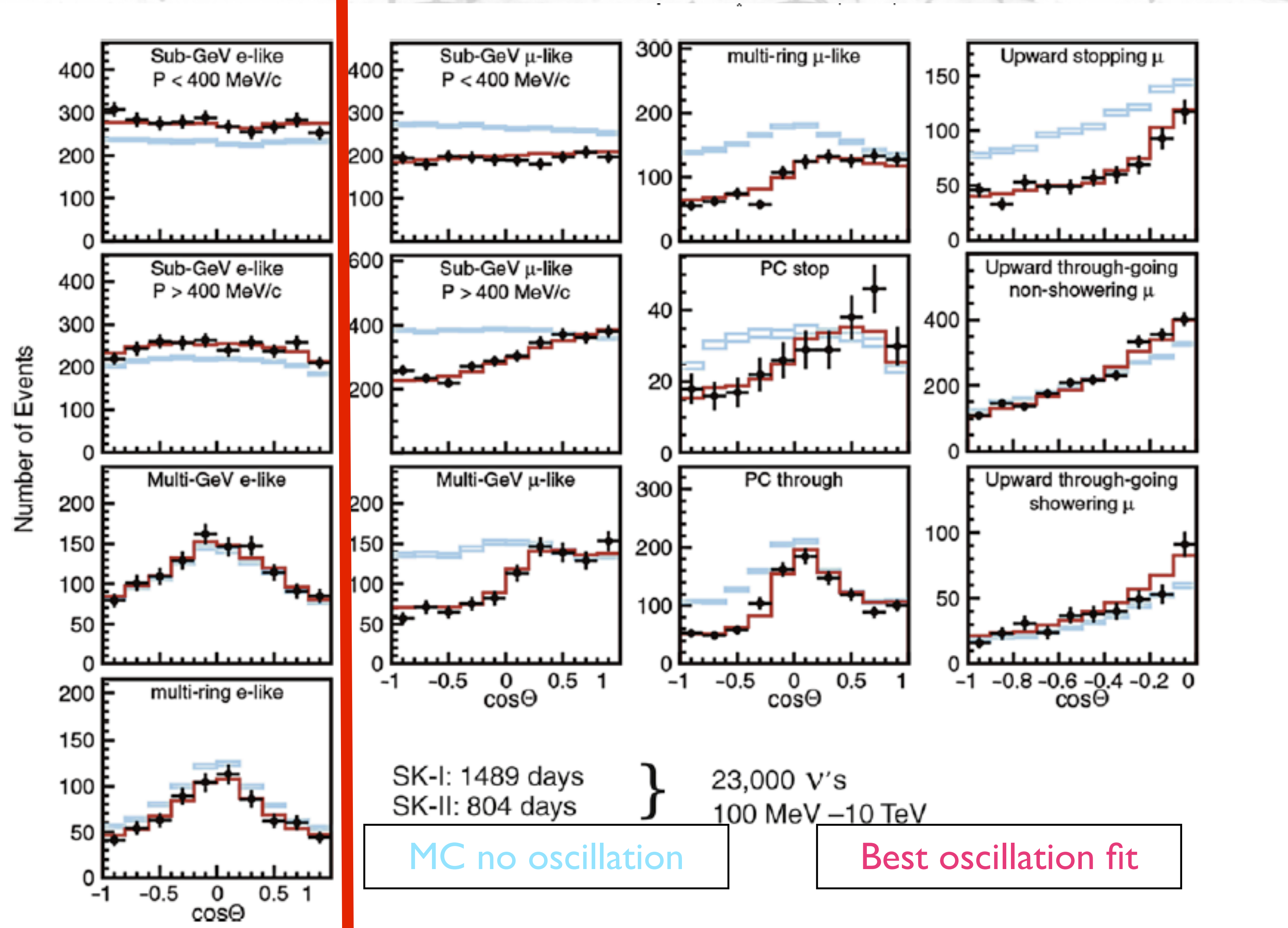
$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_e \nu_\mu$$

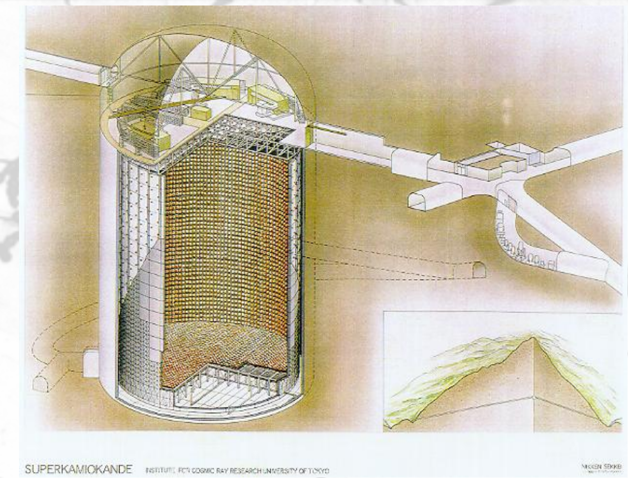
$$\frac{N_{\nu_\mu}}{N_{\nu_e}} \approx 2.0 \quad for \quad E_\nu < few\,GeV$$

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

Atmospheric ν in SK

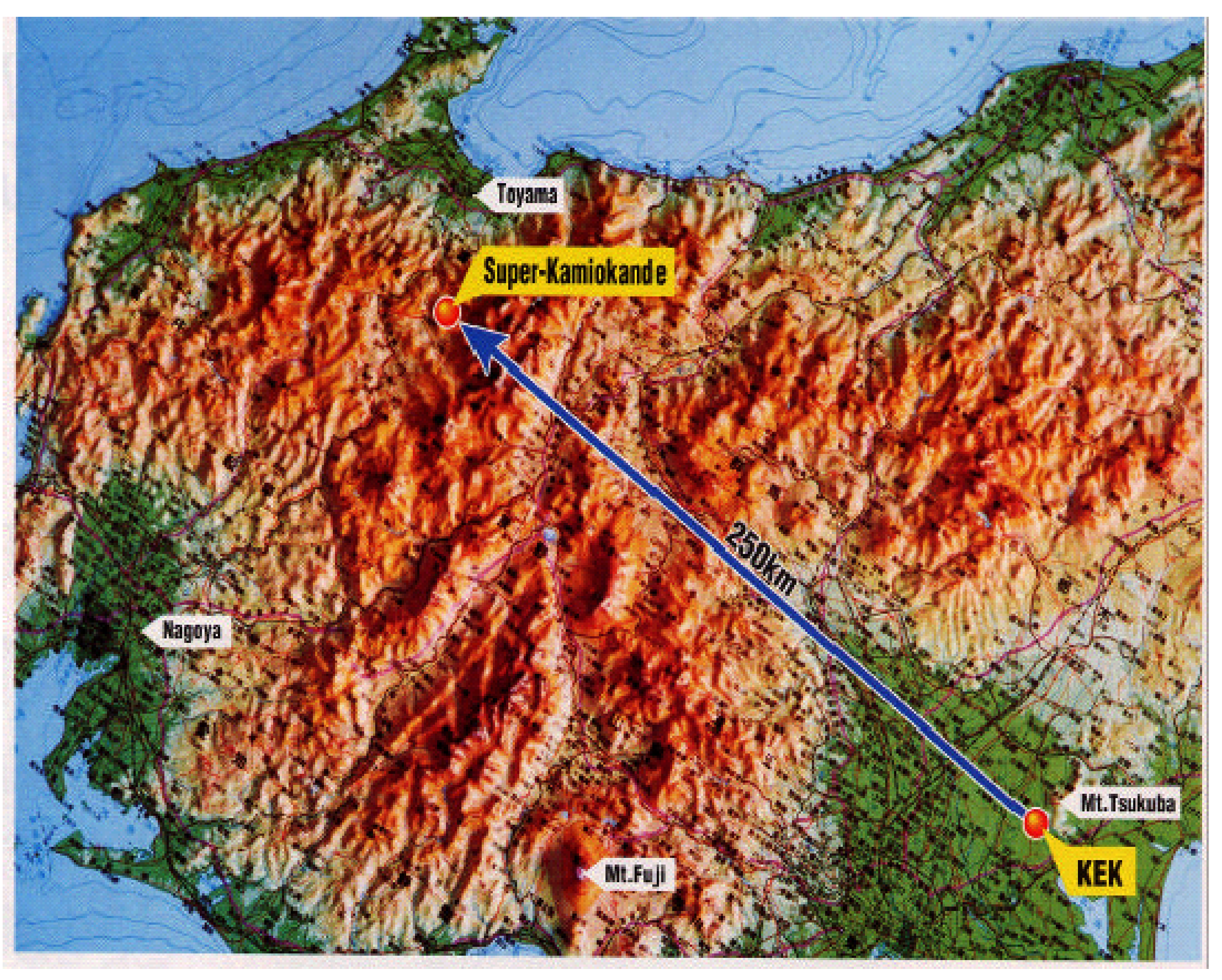
ν_e ν_μ





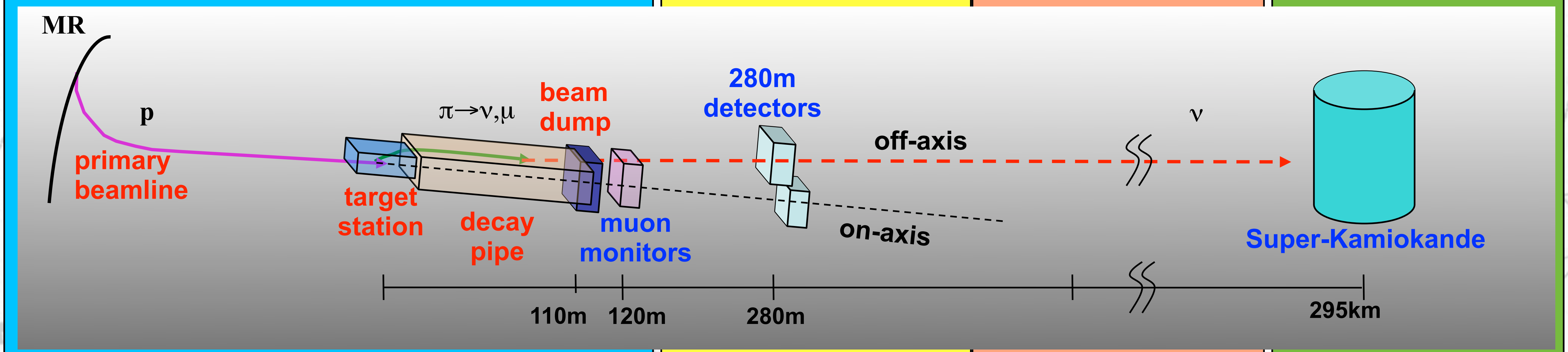
- Agreement for ν_e . The change is due to normalisation only.
- Strong distortion for ν_μ
- Distortion as function of zenith angle.
- Most probably $\nu_\mu \rightarrow \nu_\tau$

K2K: the confirmation



- 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.

Basic principle



Neutrino production

Reactors

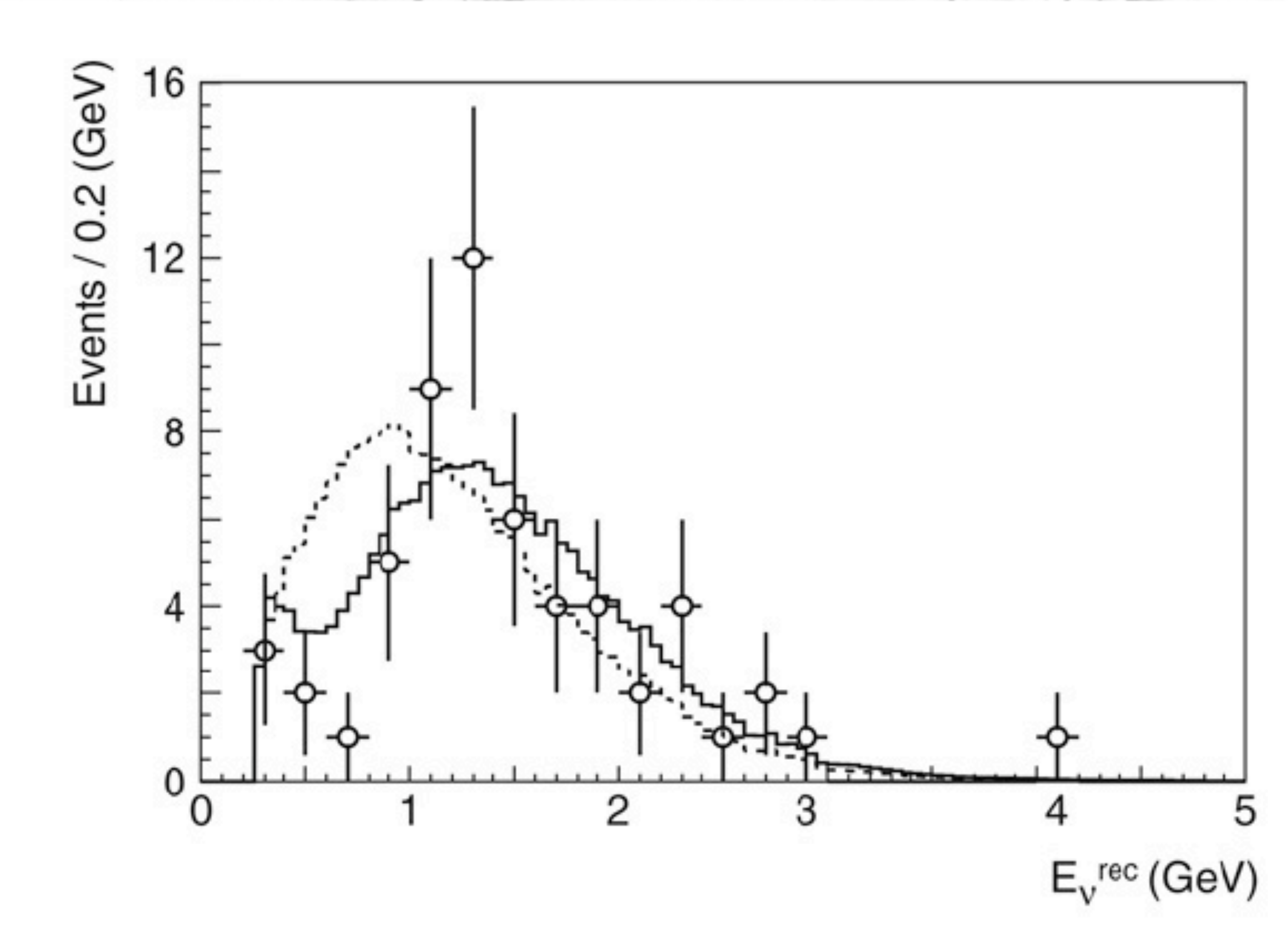
Conventional beams

Beam flux and neutrino-target cross-sections

Flight & oscillations

Far detector Particle ID

K2K, the confirmation

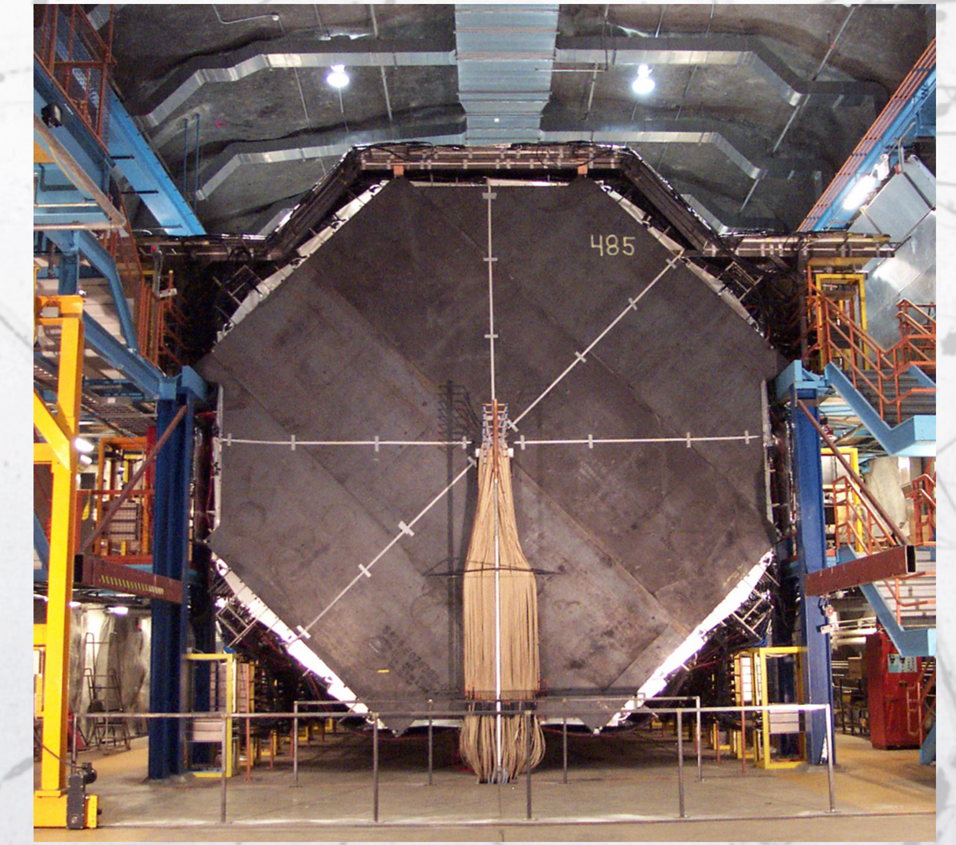


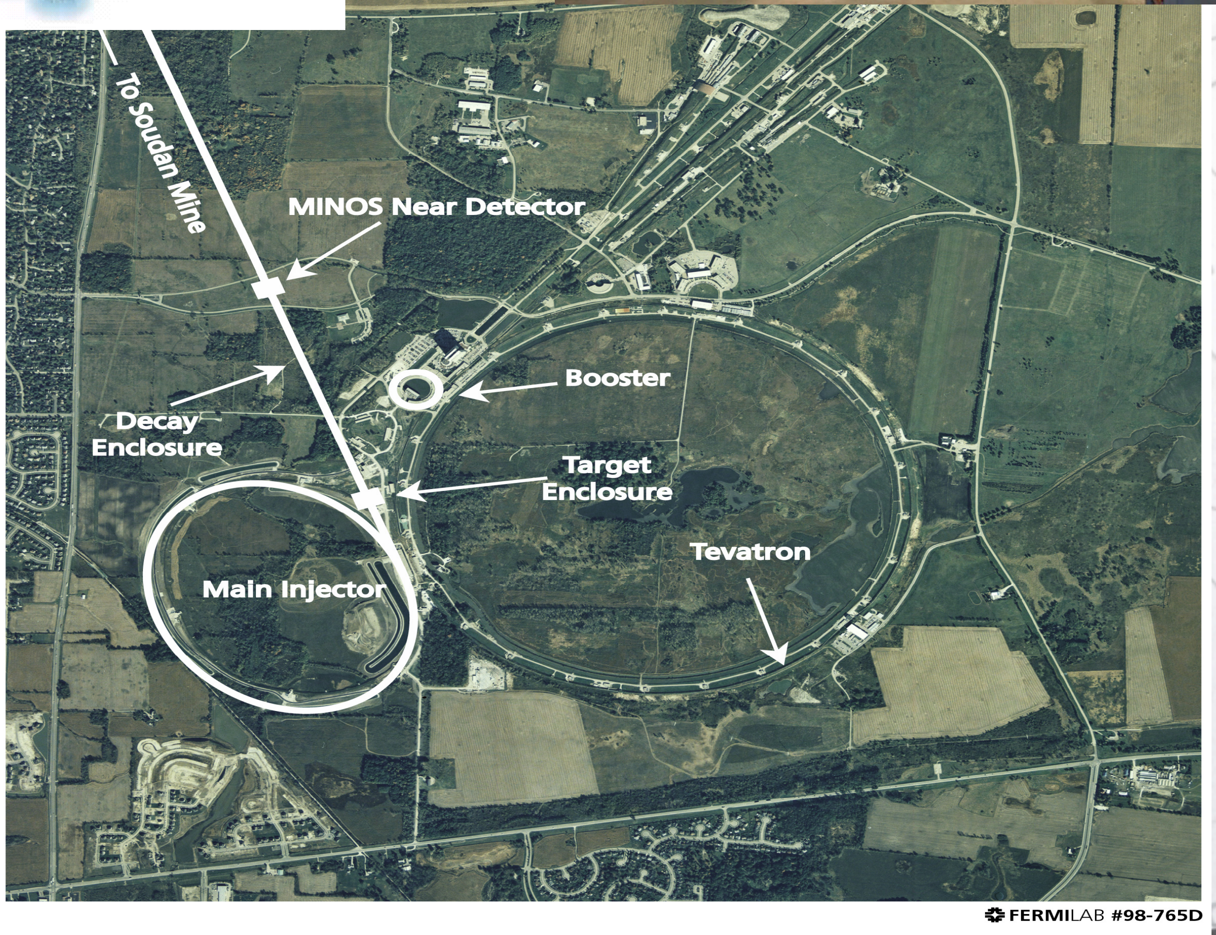
- 1st long base line experiment: prove of principle and technology.
- Deficit and spectrum distortion compatible with SK results.

Minos: precision era

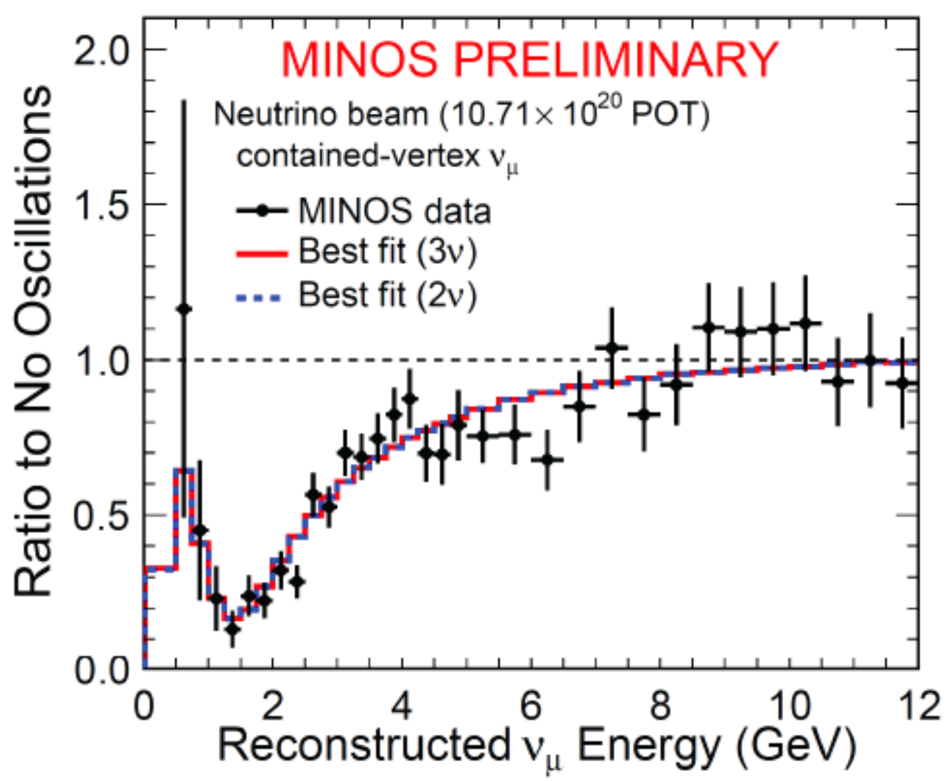
Neutrinos of several GeV produced in FNAL and detected 800 km away.

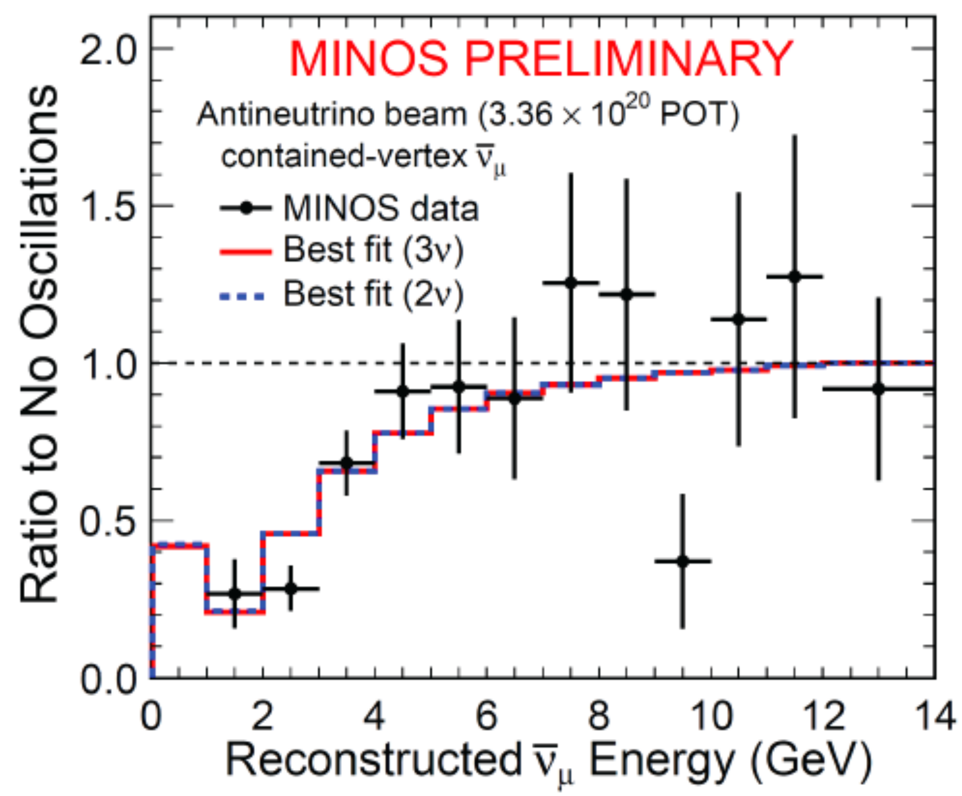
Dedicated near and far detectors.





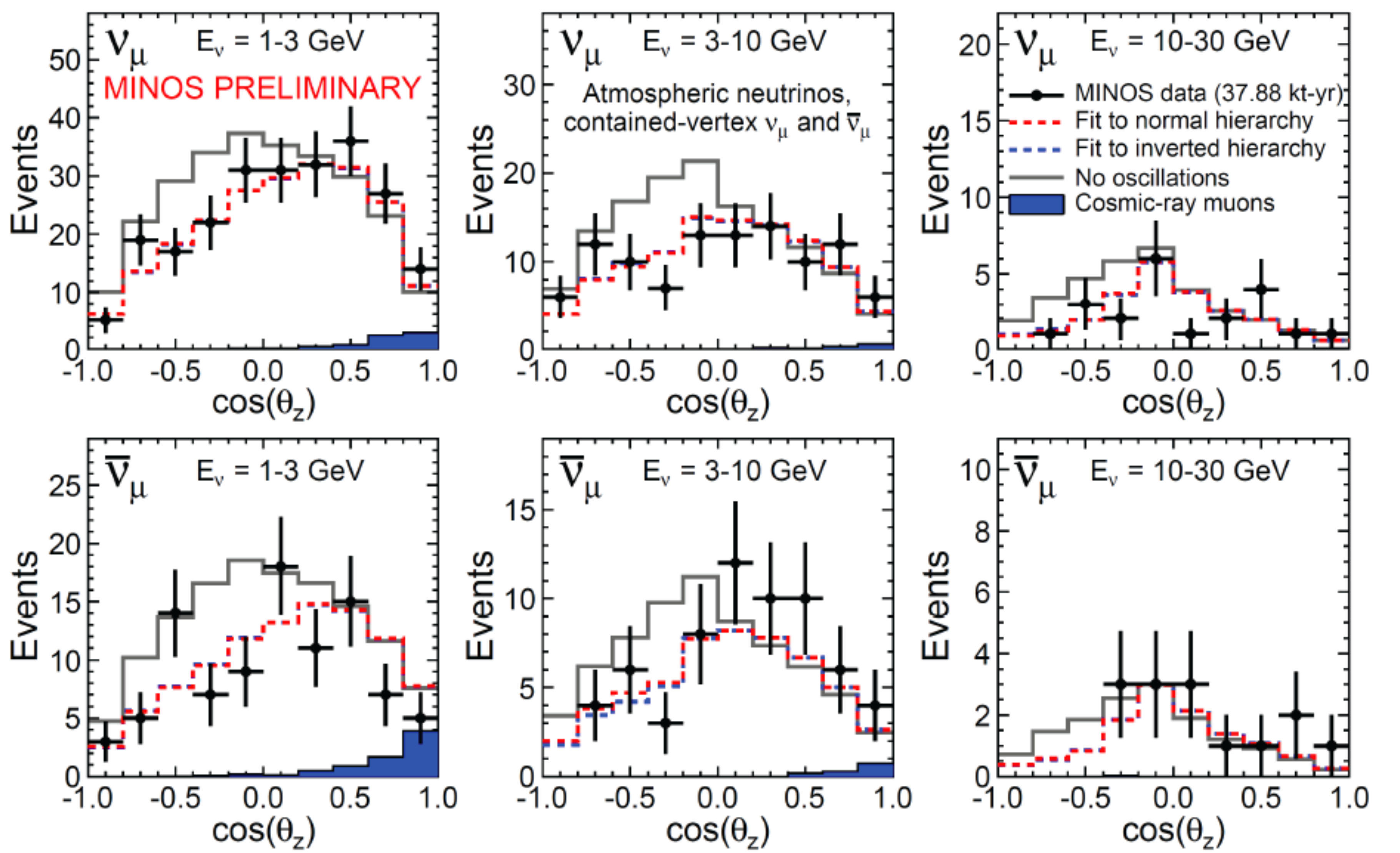
Accelerator neutrinos





- Predicted 3201 ν_μ-CC candidates and 363 $\overline{\nu}_\mu$-CC candidates
- Observed 2579 ν_μ-CC candidates and 312 $\overline{\nu}_\mu$-CC candidates
- 2ν and 3ν best fits are almost indistinguishable for beam ν's

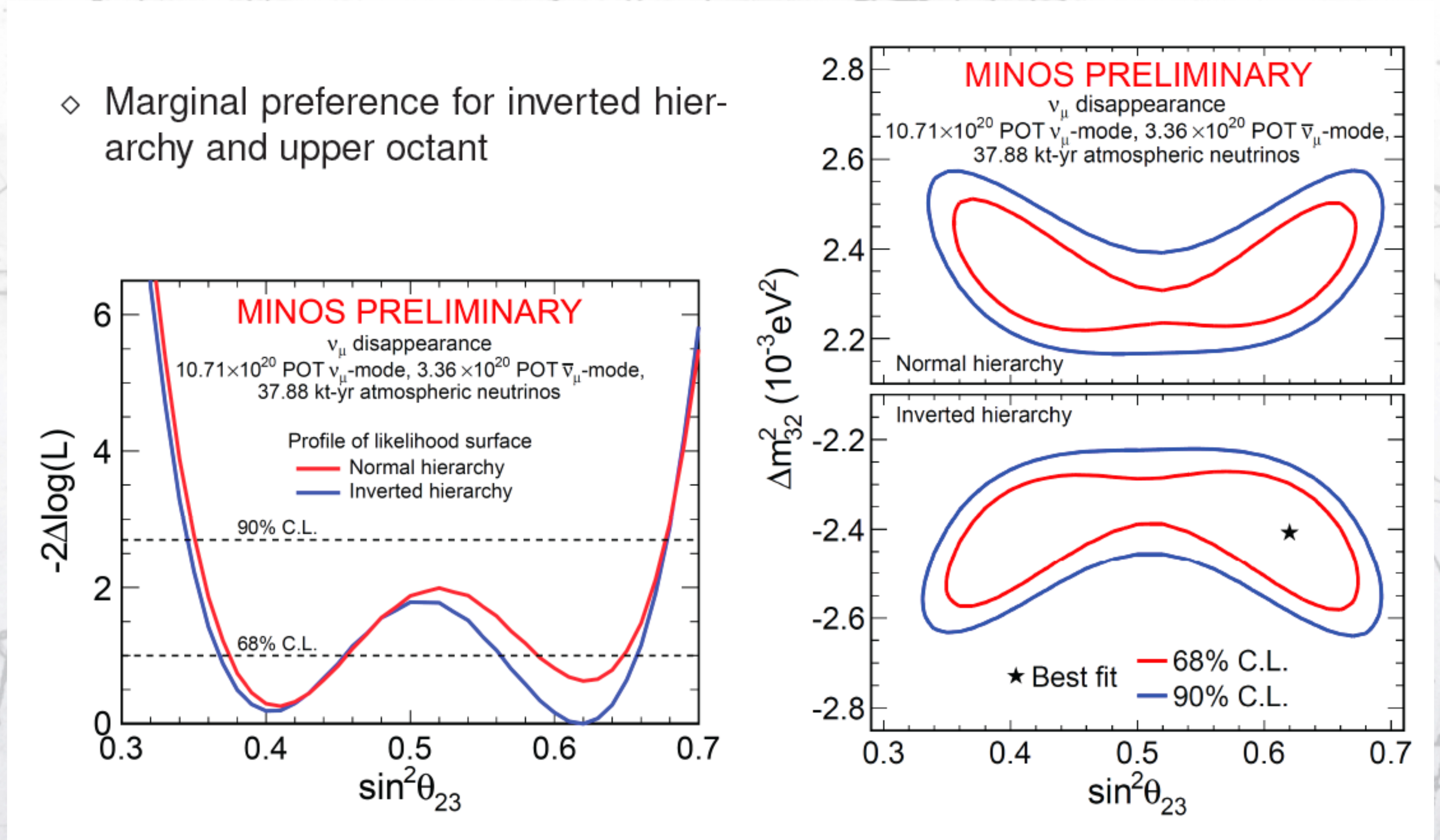
Atmospheric neutrinos @ Minos



- Predicted 1100 events, observed 905 events
- Small effects from hierarchy in the resonance region

Atmospheric neutrinos

- The combination of very long base line $\bar{\upsilon}$ *and* υ from atmospheric and long base lines from accelerators open sensitivity to other parameters. (Breaking degeneracies)



Decoupled Solar and 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.

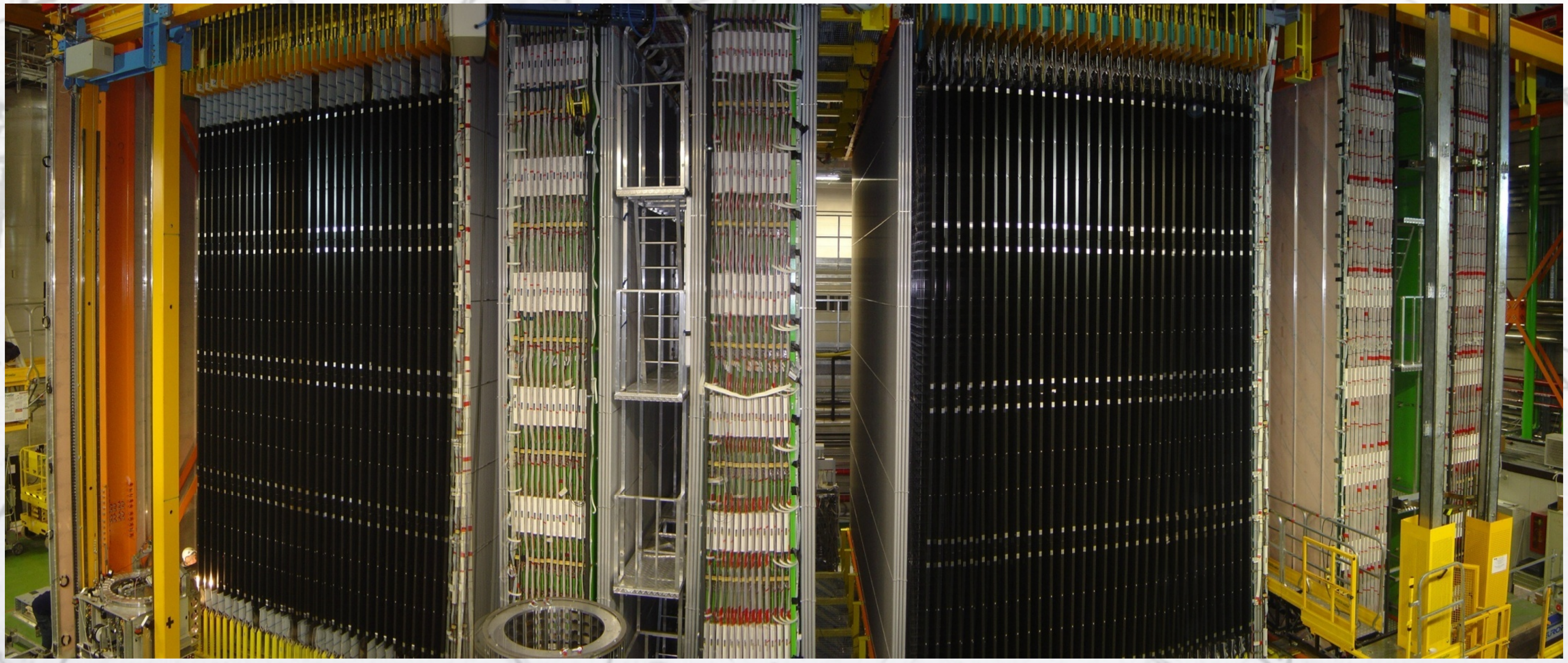
$$\frac{\Delta m^2_{23}}{\Delta m^2_{12}} \approx 30.$$

  - 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.

Decoupled Solar and 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.

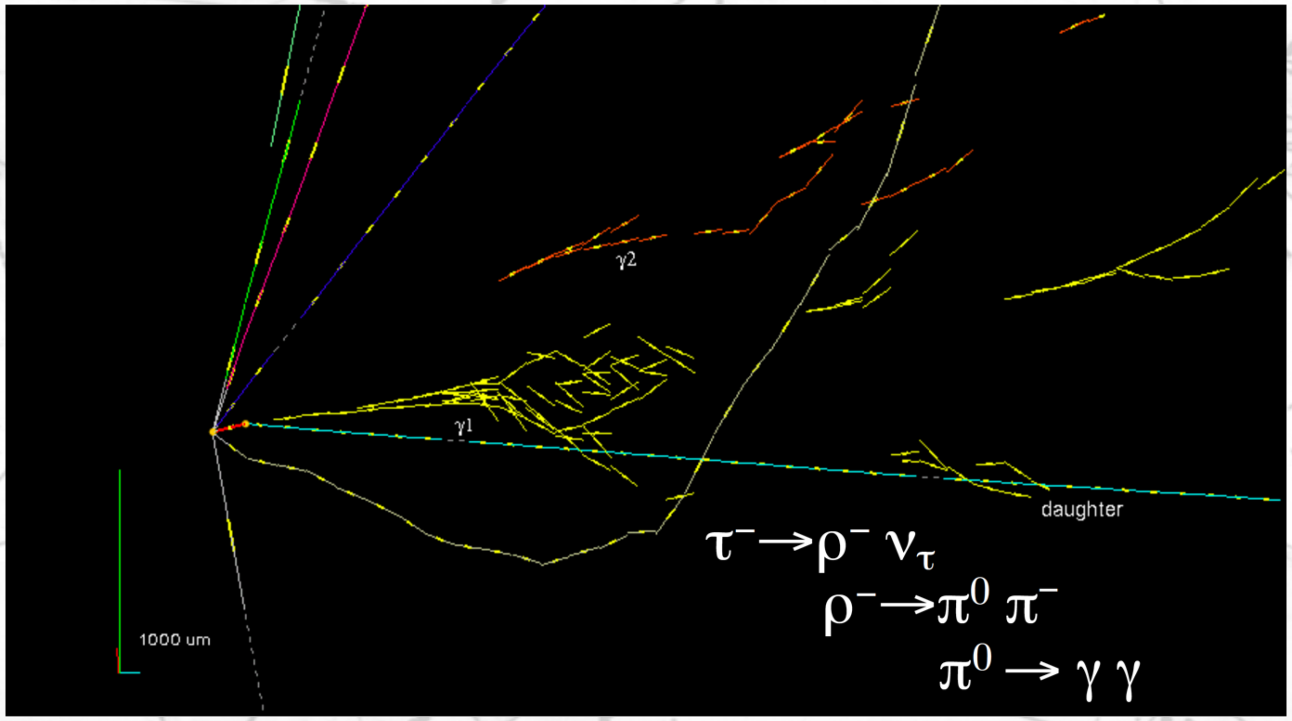
ν_τ : the final cross-check

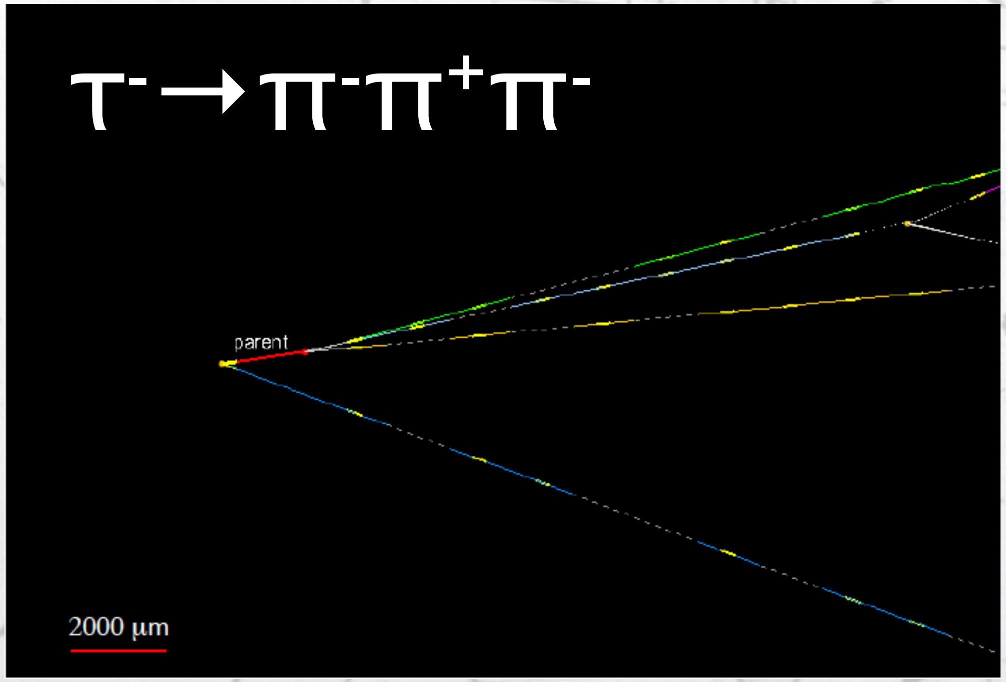


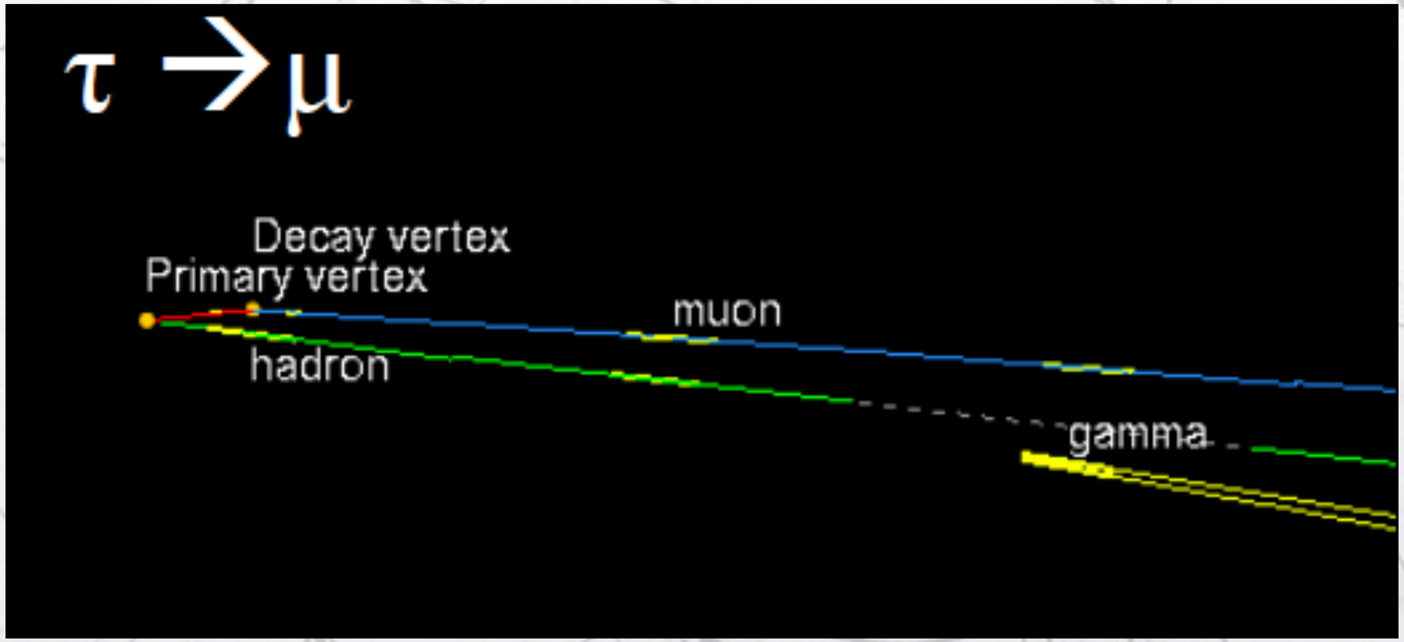
Opera: ν_τ appearance

- Intense ν_μ beam from Geneva to Gran Sasso near L'Aquila.
- Search for ν_τ at far detector.
- L = 733 km.
- Far detector uses a photographic technology (emulsions).
- Tau detection via the impact parameter from the tau time of flight.

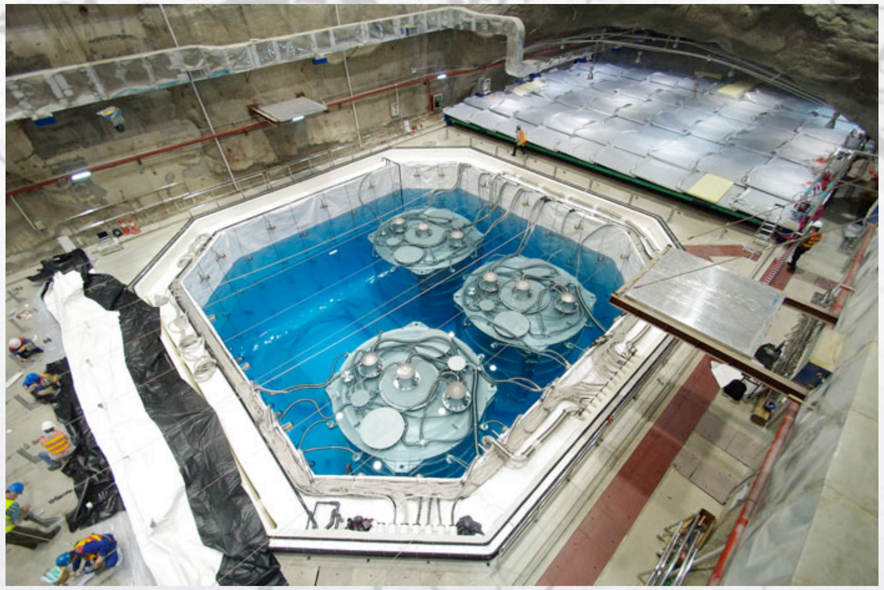
Opera: ν_τ appearance

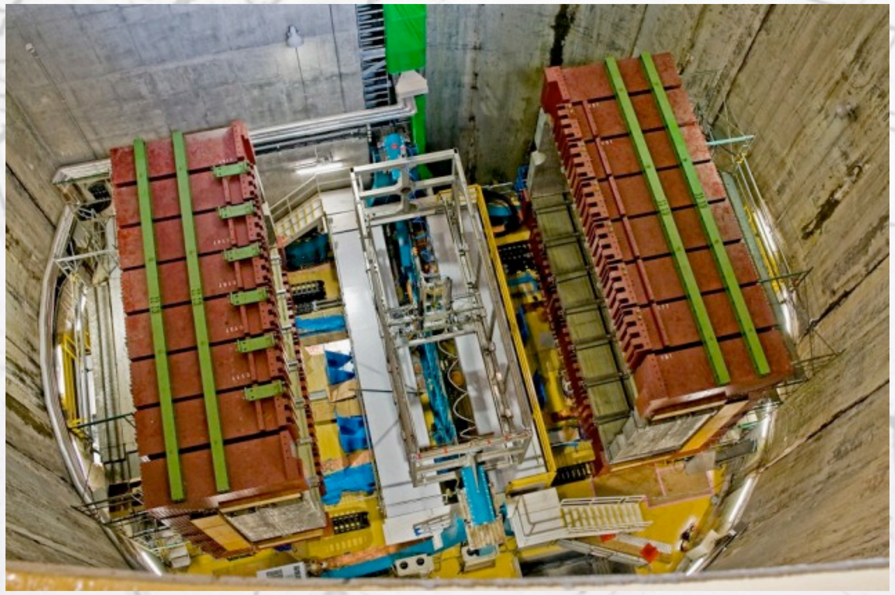


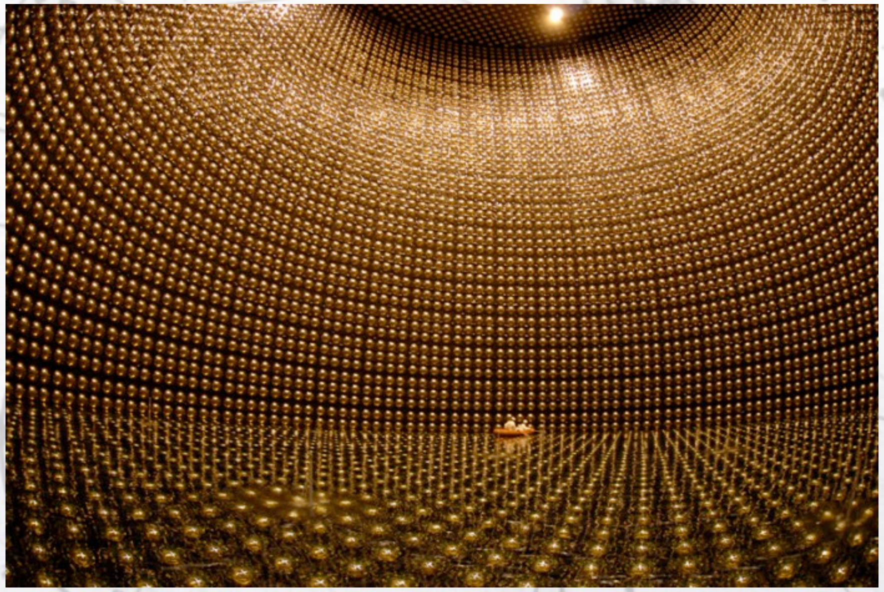




θ_{13} & δ_{CP}







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, this 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.*

Measuring θ13

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

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

No matter effects

- 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.

Degeneracies

- The uncertainties on certain parameters change the oscillation probability:
  - The value of θ_{23} is close to 45°. If larger or smaller change the sign of some of the terms (Octant).
  - The value of the CP phase changes also the probability.
  - Hierarchy changes the probability through the mass term.

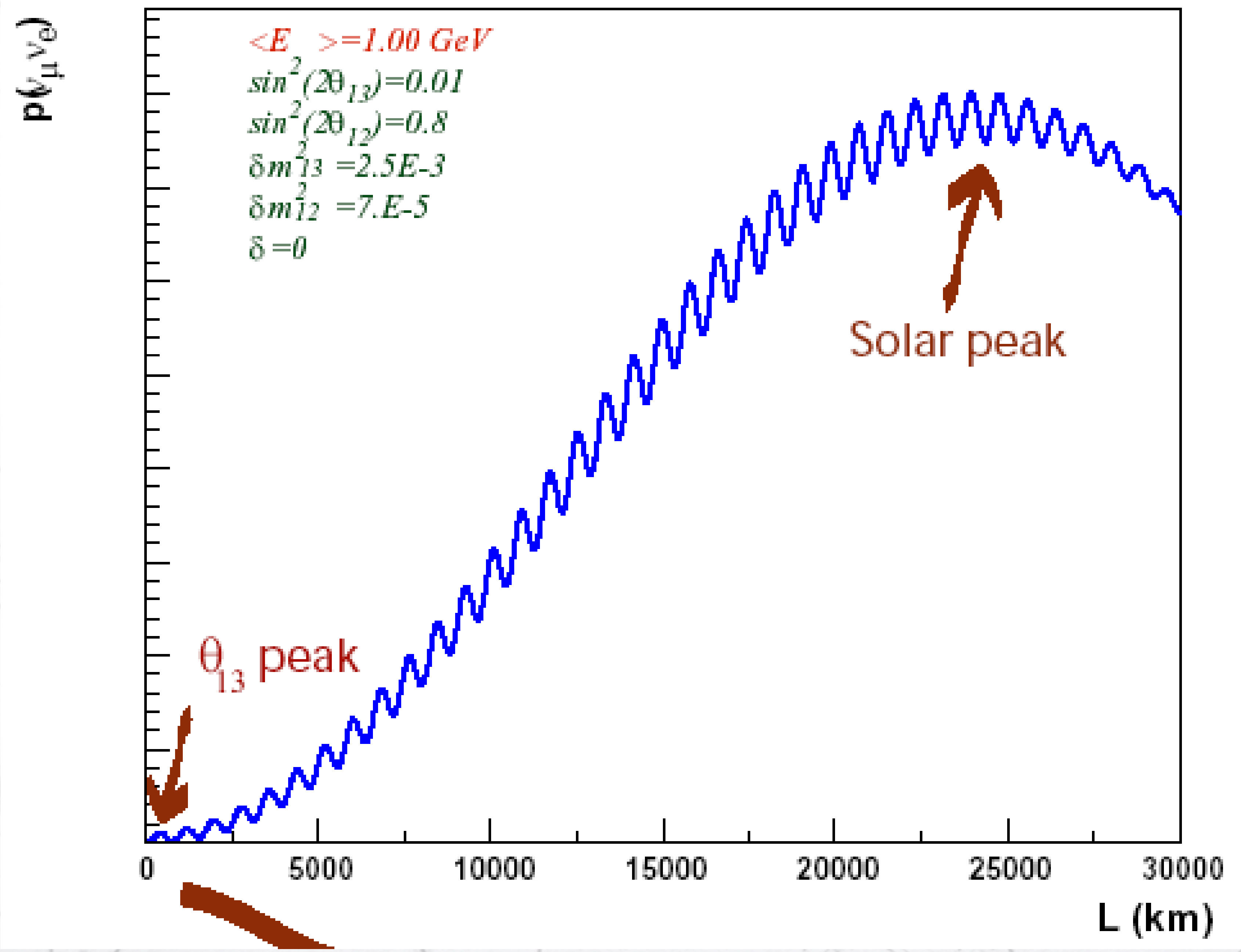
$$
\begin{aligned}
P_{\nu_\mu,\nu_e} \approx\ & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
\pm\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E} \\
-\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E} \\
+\ & \left(\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right)^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
& -8 \cos^2\theta_{23} \sin^2\theta_{13} \sin^2\theta_{23} (1 - 2\sin^2\theta_{13}) 2\sqrt{2} G_F n_e L \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E}
\end{aligned}
$$

Degeneracies

- The presence of degeneracies makes the determination of the mixing angles complicated. We need to measure the oscillation in different conditions to be able to resolve the degeneracies:
  - For different energies: first and second oscillation has different matter effects and different contributions of the mixing angles.
  - For different lengths: changes the matter effects or minimize them.
  - appearance vs disappearance: to reduce CP violation.
  - Precise measurement of the θ_{23} for the octant.
  - Observe different oscillation channels.

- This is not always possible with a single experiment:
  - L is normally fixed.
  - Change oscillation channel implies normally to be able to look for tau neutrinos.
  - It is not easy to make an electron neutrino beam with E > 500 MeV.
- This is also the origen of all the oscillation phenomenology.

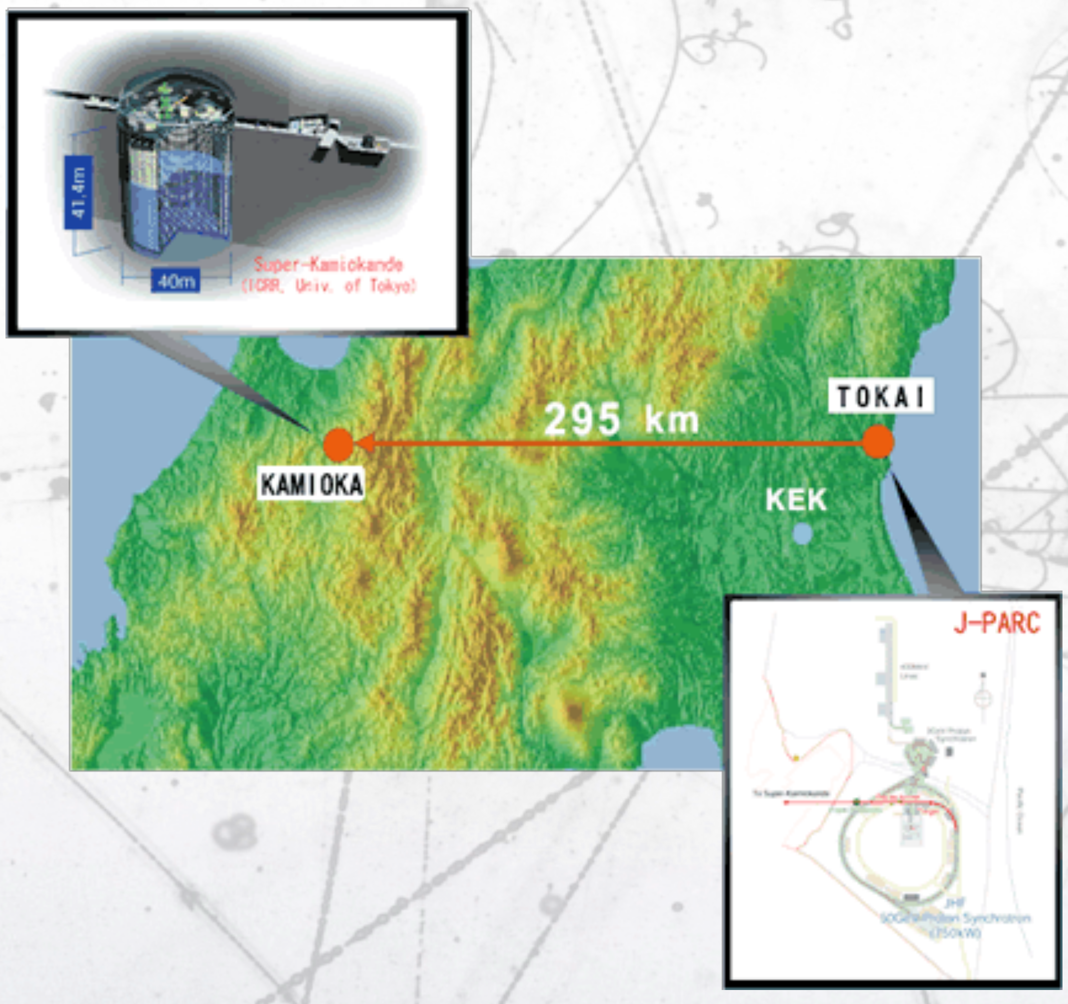
Measuring θ_{13}

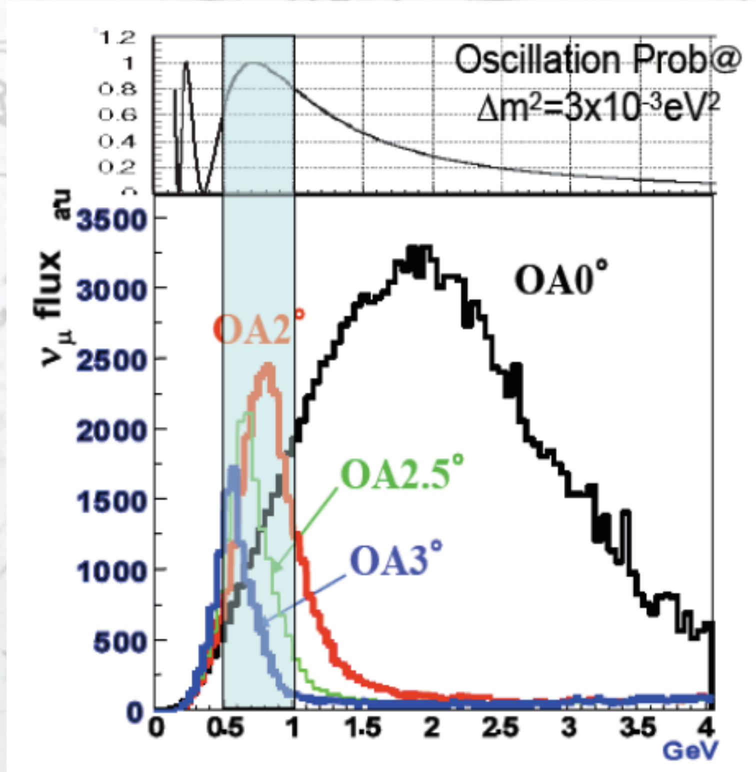


- $\nu_\mu \longrightarrow \nu_e$ compites with the Solar oscillation.
- decoupled only from the L/E value.

T2K

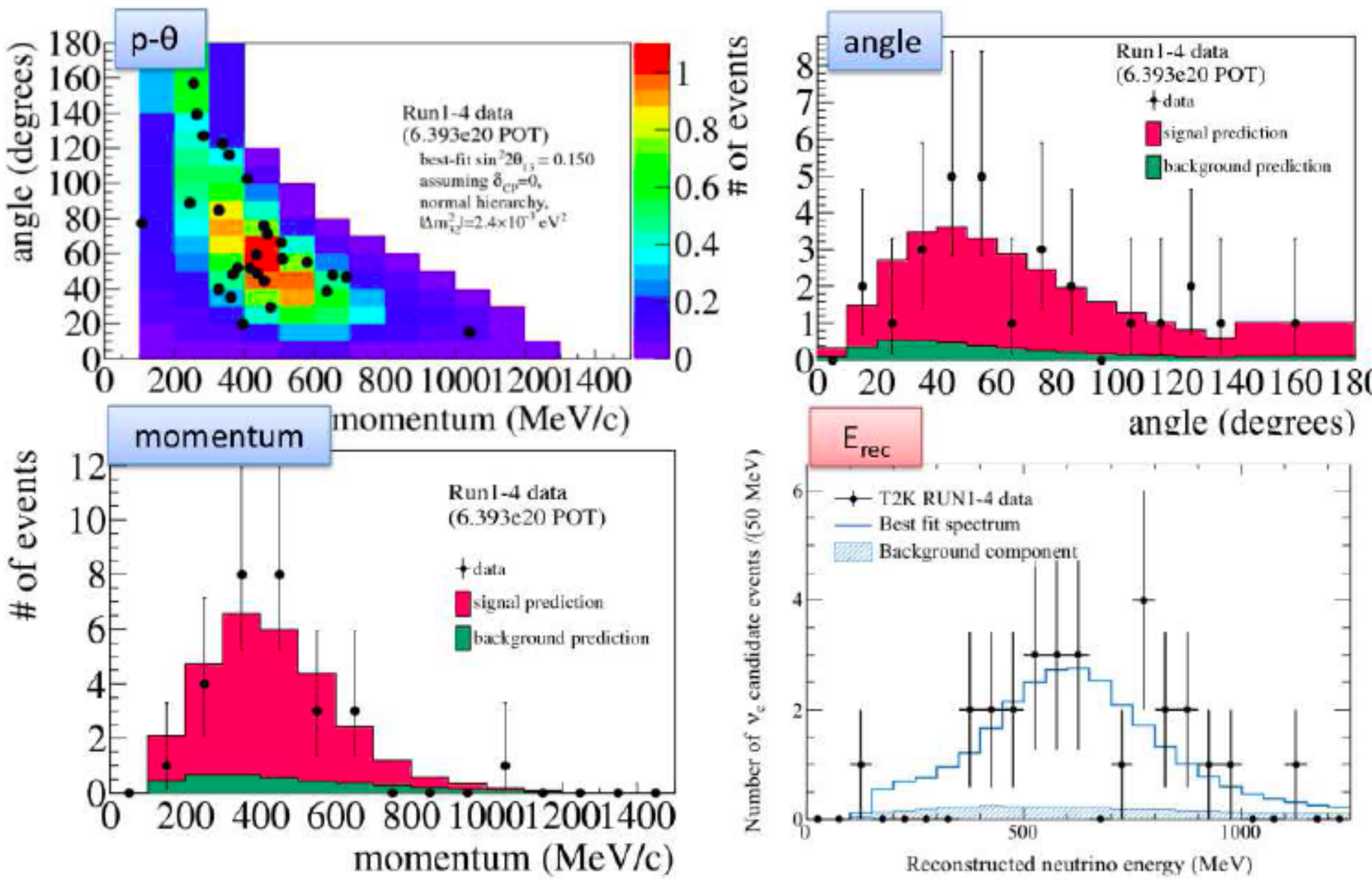
- $\nu_\mu \to \nu_e$ & $\nu_\mu \to \nu_\mu$ from high intensity accelerator.
- E_ν ~ 700 MeV.
- Oscillation distance: 295km.
- Off-axis technique → narrow energy spectrum.





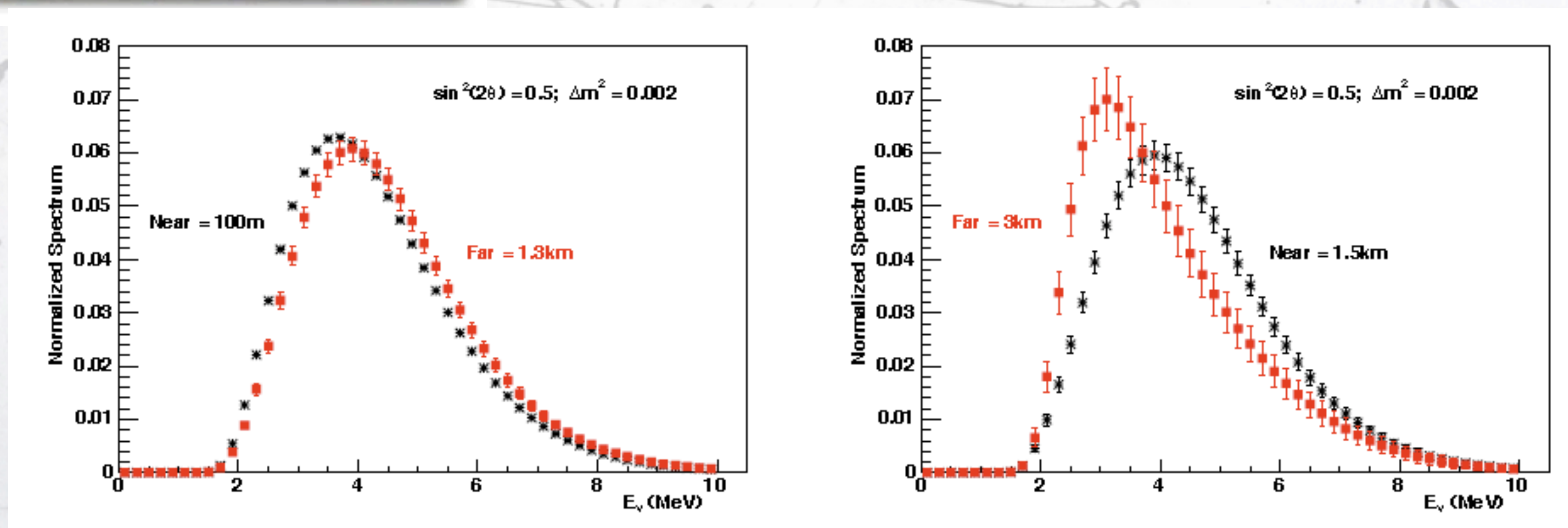
T2K

- First observation of an exclusive appearance.!!
  - Expected 20.4 ± 1.8 signal events and 4.6 ± 0.5 background events $\rightarrow 5.5\sigma$ sensitivity
  - Observed 28 ν_e candidate events

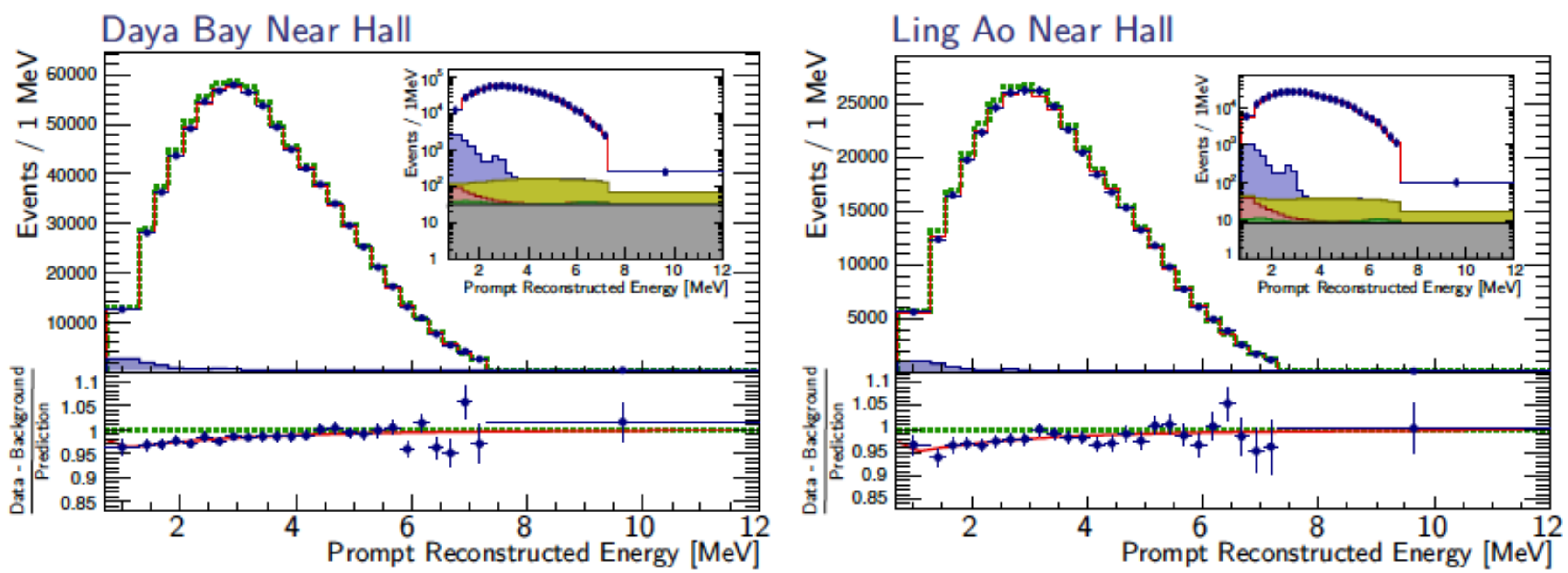


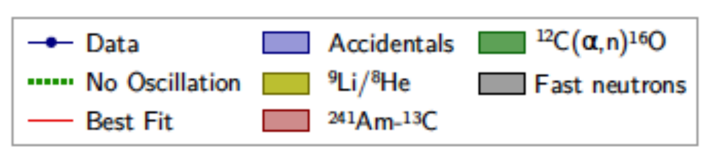
Reactors

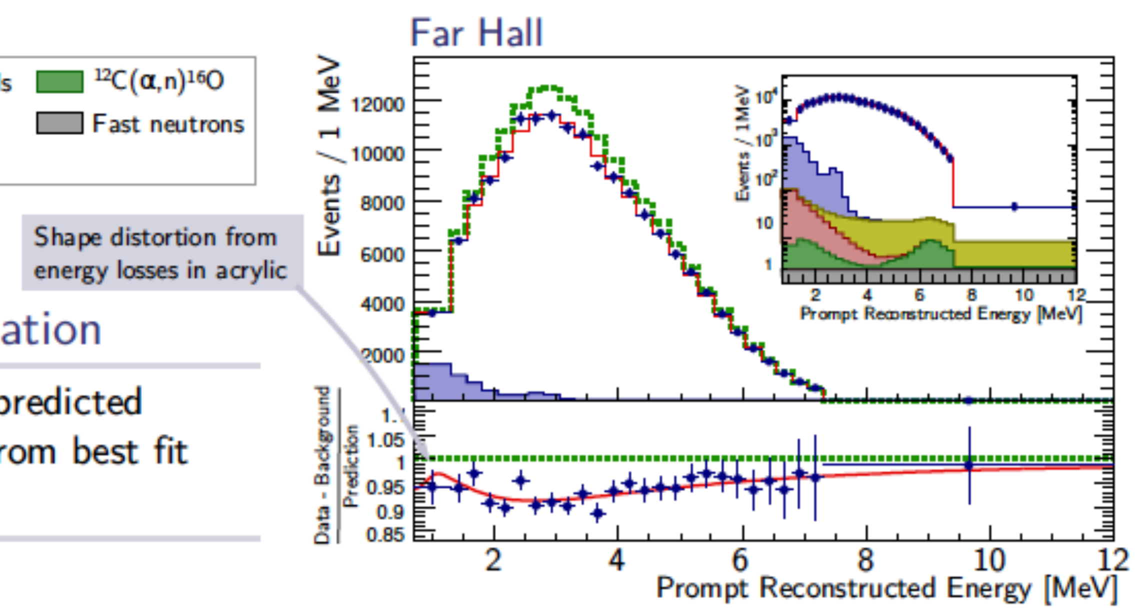
- $\bar{\nu}_e \to \bar{\nu}_e$ from nuclear reactor.
- 2 detectors for relative normalization.
- Base Line ~ 1km
- Energy ~ 3MeV
- Sensitive to θ_{13}



Reactor neutrinos





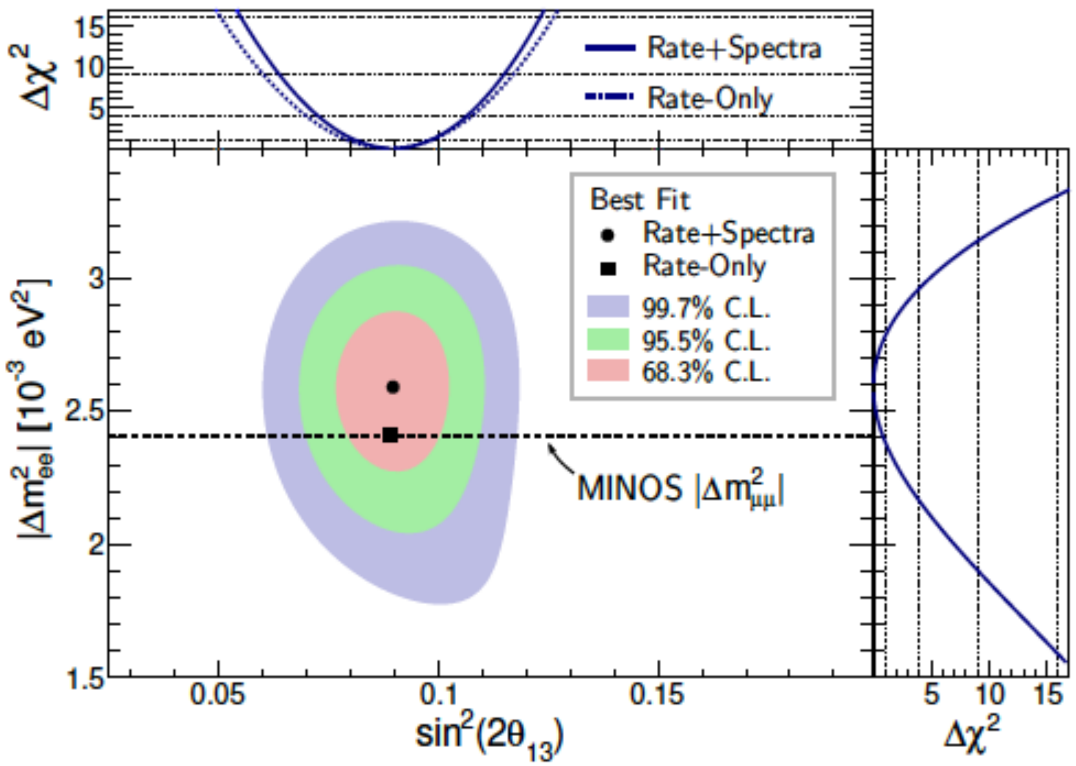


Spectral distortion consistent with oscillation

- Both background and predicted no-oscillation spectra from best fit
- Statistical errors only

Reactor neutrinos

- 1st measurement of Δm^2 associated to θ_{13}



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

$$\chi^2/N_{\text{DoF}} = 162.7/153$$

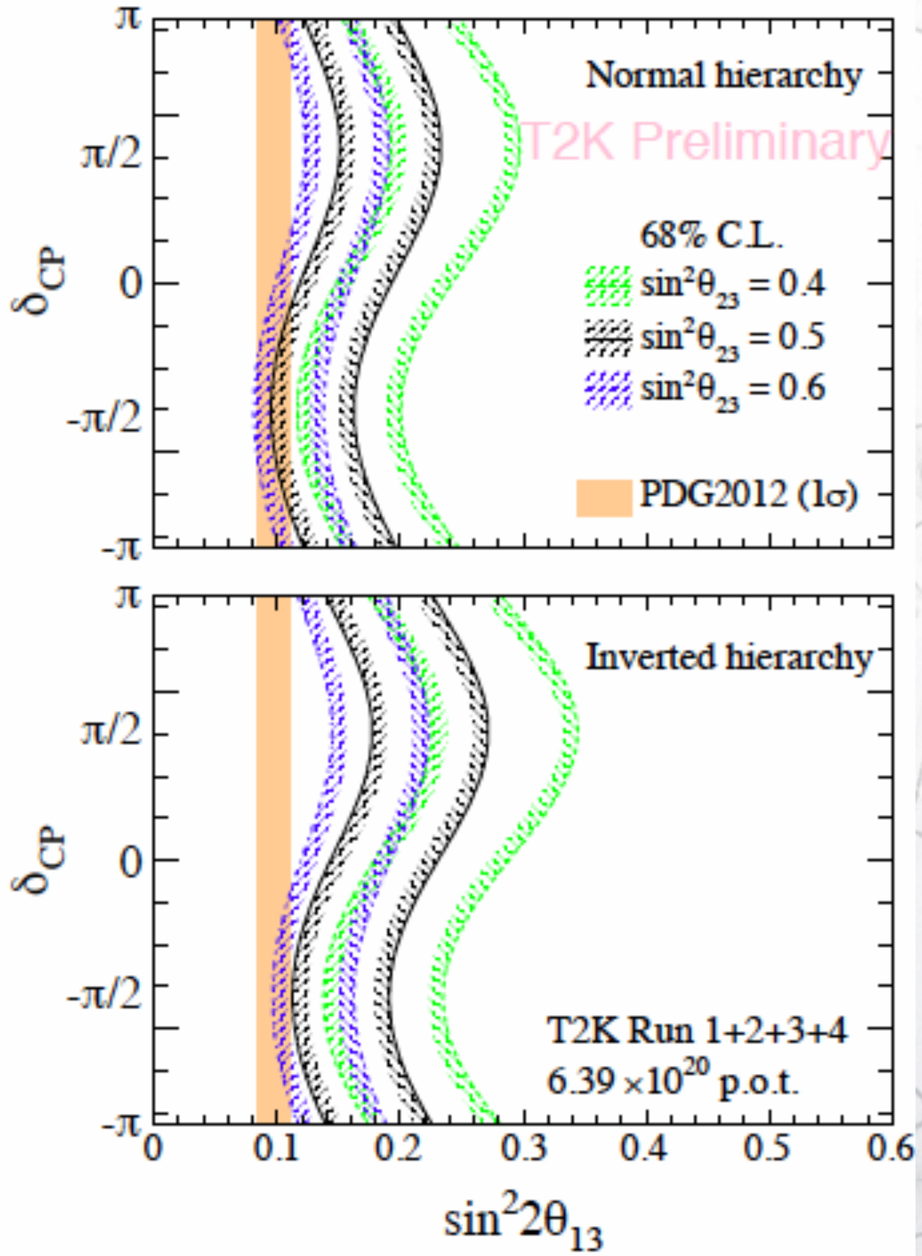
Strong confirmation of oscillation-interpretation of observed $\bar{\nu_e}$ deficit

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$ [João, NuFact2013]	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.12}_{-0.09}$

Good agreement!

- Degeneracies and δ_{CP}

  - 2013 T2K appearance results assume $\sin^2\theta_{23} = 0.5$
  - However, the $\nu_\mu \to \nu_e$ appearance sensitivity depends on the true value of $\sin^2\theta_{23}$
  - Precision measurement of $\sin^2\theta_{23}$ will be important for future $\nu_\mu \to \nu_e$ results
    - Particularly for possible δ_{CP} measurement
  - NOTE: δ_{CP} values are fixed when generating these plots, they are not 2D contours



Measuring δ_{CP}

- To measure CP we need:

Done!

  - $\theta_{13} \neq 0$.
    - *If 0, this is like a 2 neutrino mixing and the phase is cancelled.*
  - *Neutrino appearance:*
    - *If we look at disappearance only, this 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.*

Started!

EXCELENCIA SEVERO OCHOA

The usual "we know"

$$\Delta m^2_{12} = 7.58^{+0.22}_{-0.26} \times 10^{-5} eV^2$$

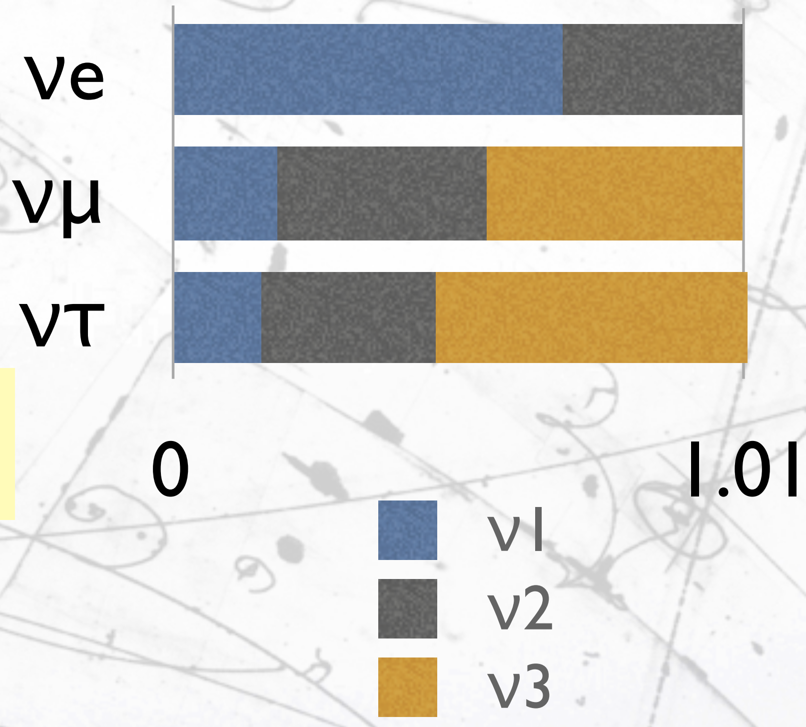
$$|\Delta m^2_{23}| = 2.35^{+0.12}_{-0.09} \times 10^{-3} eV^2$$ Sign?

$$\sin^2\theta_{12} = 0.306^{+0.018}_{-0.015}$$

$$\sin^2\theta_{23} = 0.42^{+0.08}_{-0.03}$$ Maximal? Octant?

$$\sin^2\theta_{13} = 0.021^{+0.07}_{-0.08}$$

$$\delta_{CP} \in [0^o, 360^o]$$ ≠ 0?



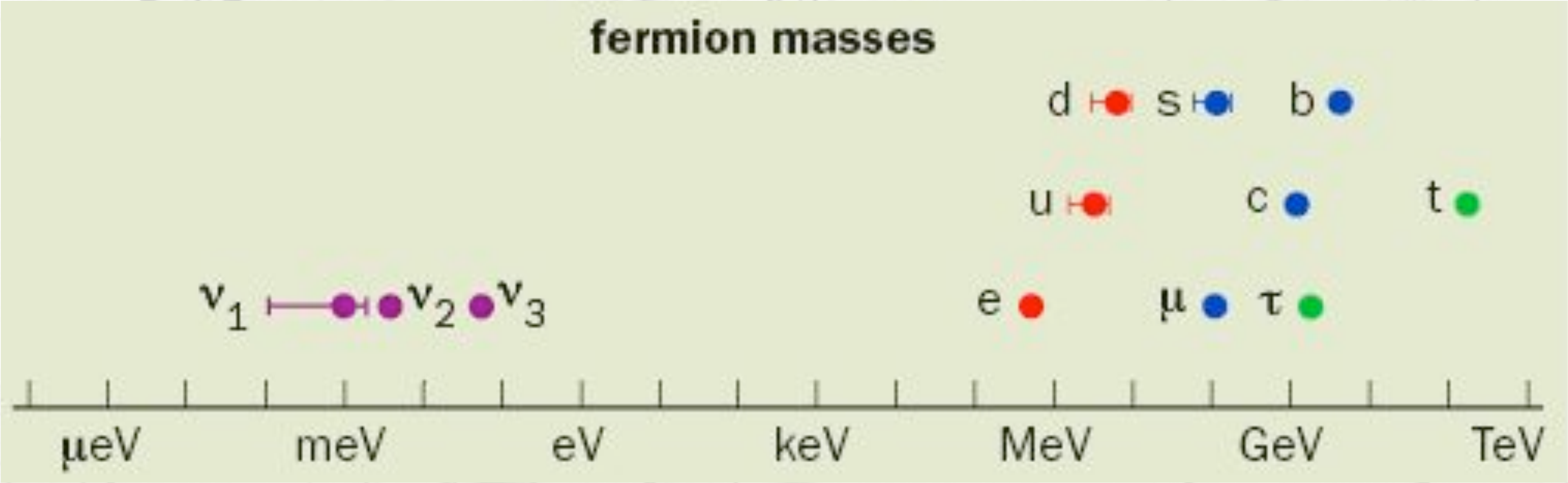
- Still a long way to go!
- Most urgent: values of δ_{CP} & absolute mass scale (hierarchy)

We have seen

θ_{12} Δm^2_{12}	$\nu_e \longrightarrow \nu_x$	SNO
θ_{13}	$\nu_\mu \longrightarrow \nu_e$	T2K
θ_{13}	$\nu_\mu \longrightarrow \nu_\tau$	OPERA & SK
θ_{12} Δm^2_{12} θ_{13}	$\nu_e \longrightarrow \nu_e$ & $\bar{\nu}_e \longrightarrow \bar{\nu}_e$	Daya Bay, RENO, Double Chooz, Kamland, SK, Borexino, Gallex, ….
θ_{12} Δm^2_{23}	$\nu_\mu \longrightarrow \nu_\mu$ & $\bar{\nu}_\mu \longrightarrow \bar{\nu}_\mu$	SK, K2K, Minos, T2K

Beyond oscillations: neutrino mass nature

Neutrino masses



- Now that the neutrinos have mass we need to understand:
  - What to do with right-handed?
  - Why the mass are so small?
- Theoretical physics 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 helicity) 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.
- 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 $\mathcal{L}_M = -m_M \bar{\nu^c_R} \nu_R + h.c.$

Majorana masses

- Majorana mass implies two new properties:
  - The neutrino is equal to its antiparticle.
  - There is no right handed, it is just the anti-particle.
- Turning the argument around!. We need an additional symmetry to forbid the Majorana term in the Lagrangian.
- How to detect them:
  - We can boost back a neutrino and find an antineutrino.
  - We can 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.

Majorana & Seesaw

- Consider that we have both Majorana (m^M) and Dirac (m^D) mass terms.

$$\mathcal{L} = -\frac{1}{2}\left(\bar{\nu}_L \bar{\nu}_R^c\right)\begin{pmatrix} m_L^M m^D \\ m^D m_R^M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

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

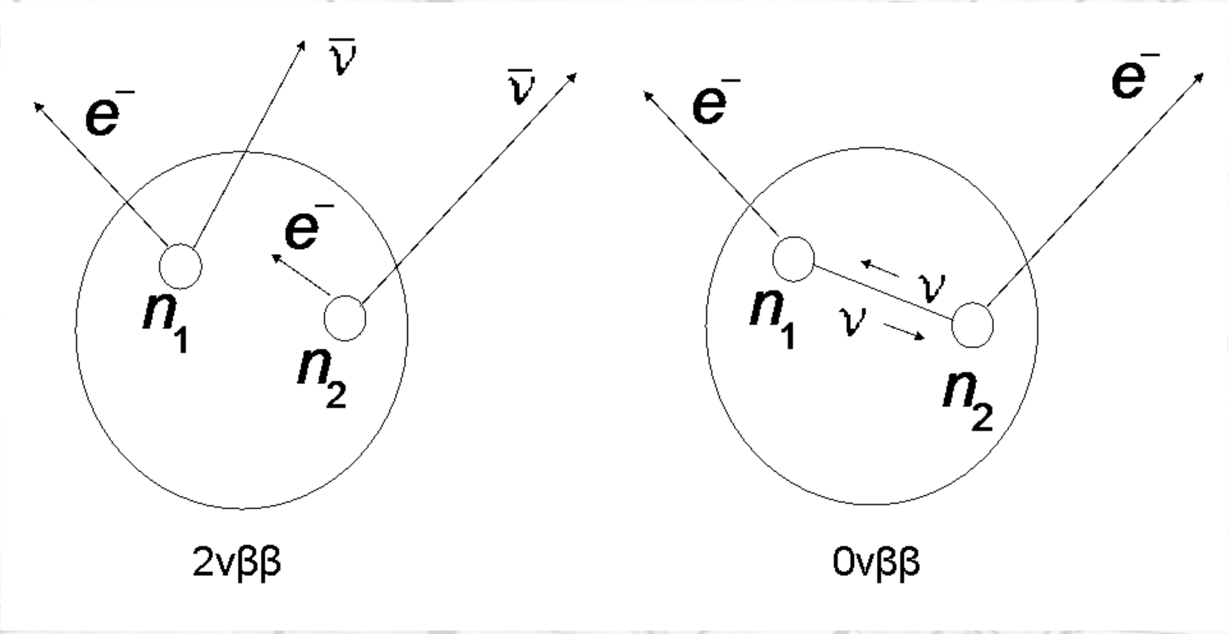
$$\lambda_\pm = \frac{1}{2}(m_L^M + m_R^M) \pm \frac{1}{2}\sqrt{(m_L^M + m_R^M)^2 - 4(m_L^M m_R^M - m^D m^D)}$$

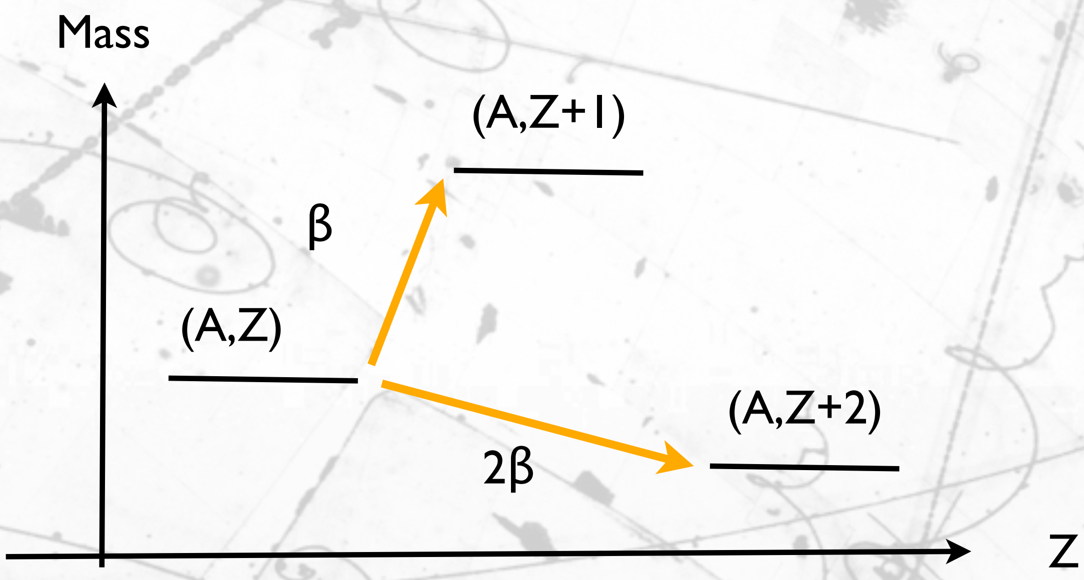
- If we assume $(m_L^M m_R^M - m^D m^D) << (m_L^M + m_R^M)^2$, then:

$$\lambda_+ = m_L^M + m_R^M$$
$$\lambda_- = \frac{(m_L^M m_R^M - m^D m^D)}{m_L^M + m_R^M}$$

- 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.

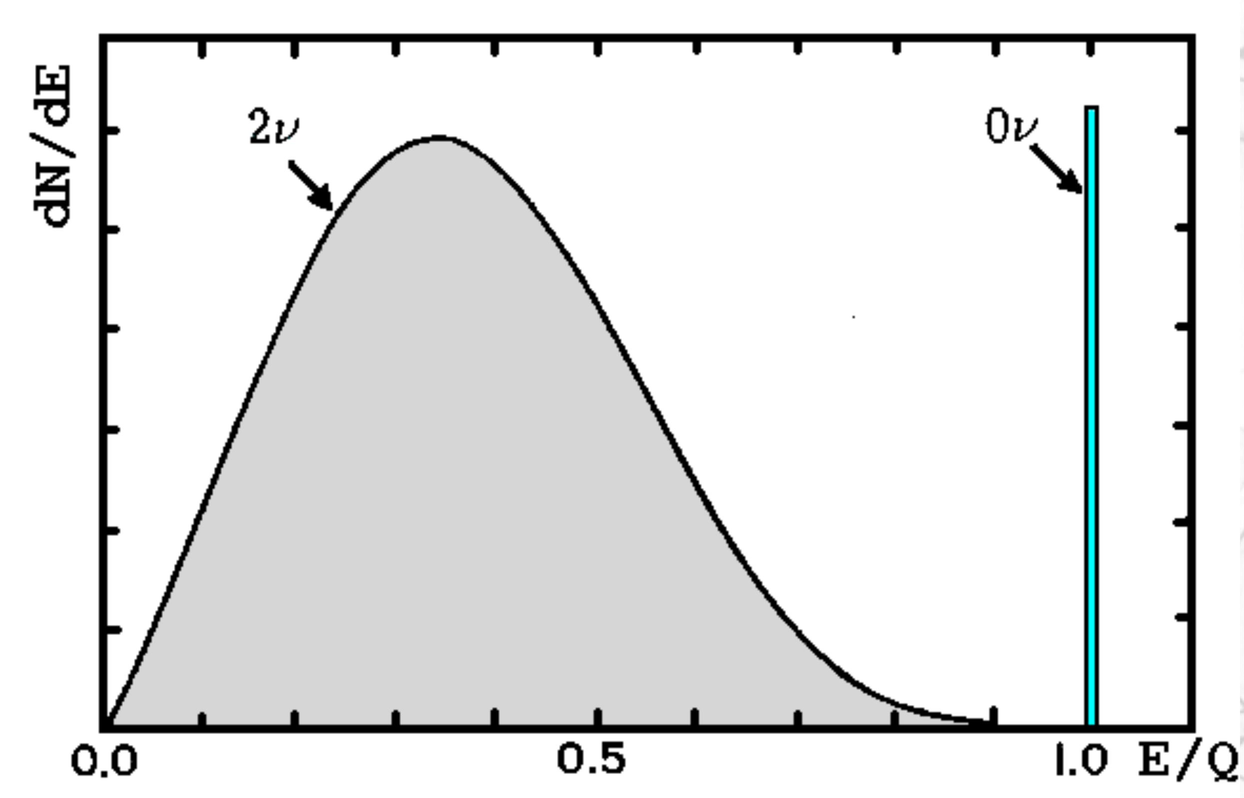
0ν2β process





- 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: $T_{1/2} >> 10^{20}$ s
- The rate of 0ν2βis proportional to a ν effective mass: kind of ν mass scale.

0ν2β process

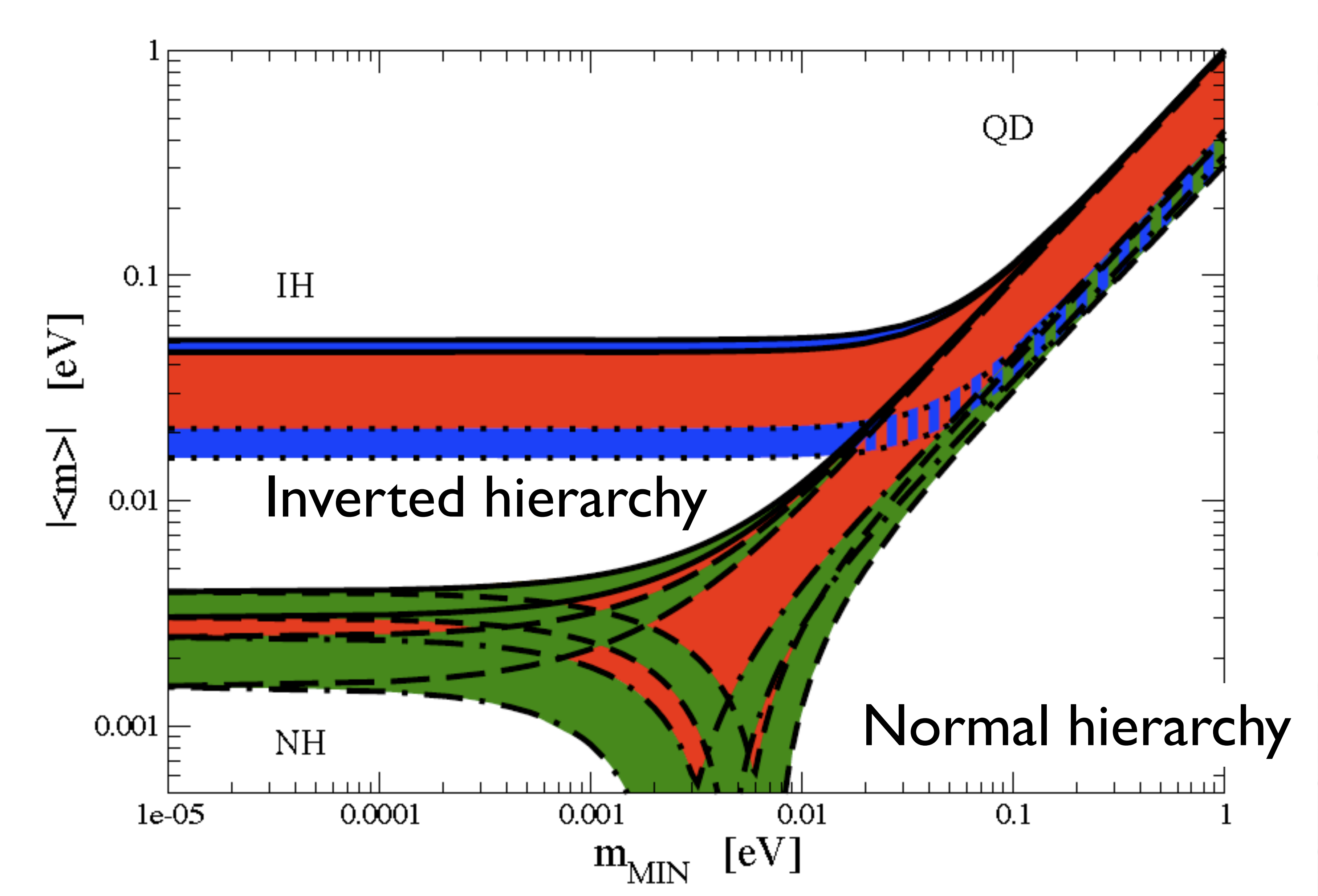


- The 0ν2β is characterized by a monochromatic 2e emission.
- The experiments are mainly low background underground high resolution calorimeters (ΔE/E ~ 0.2 %)
- New experiments try to get the advantage of the 2 electrons to reduce non 2β background from natural radioactivity: NEMO, NEXT,...

0ν2β process

The effective mass includes mixing parameters:

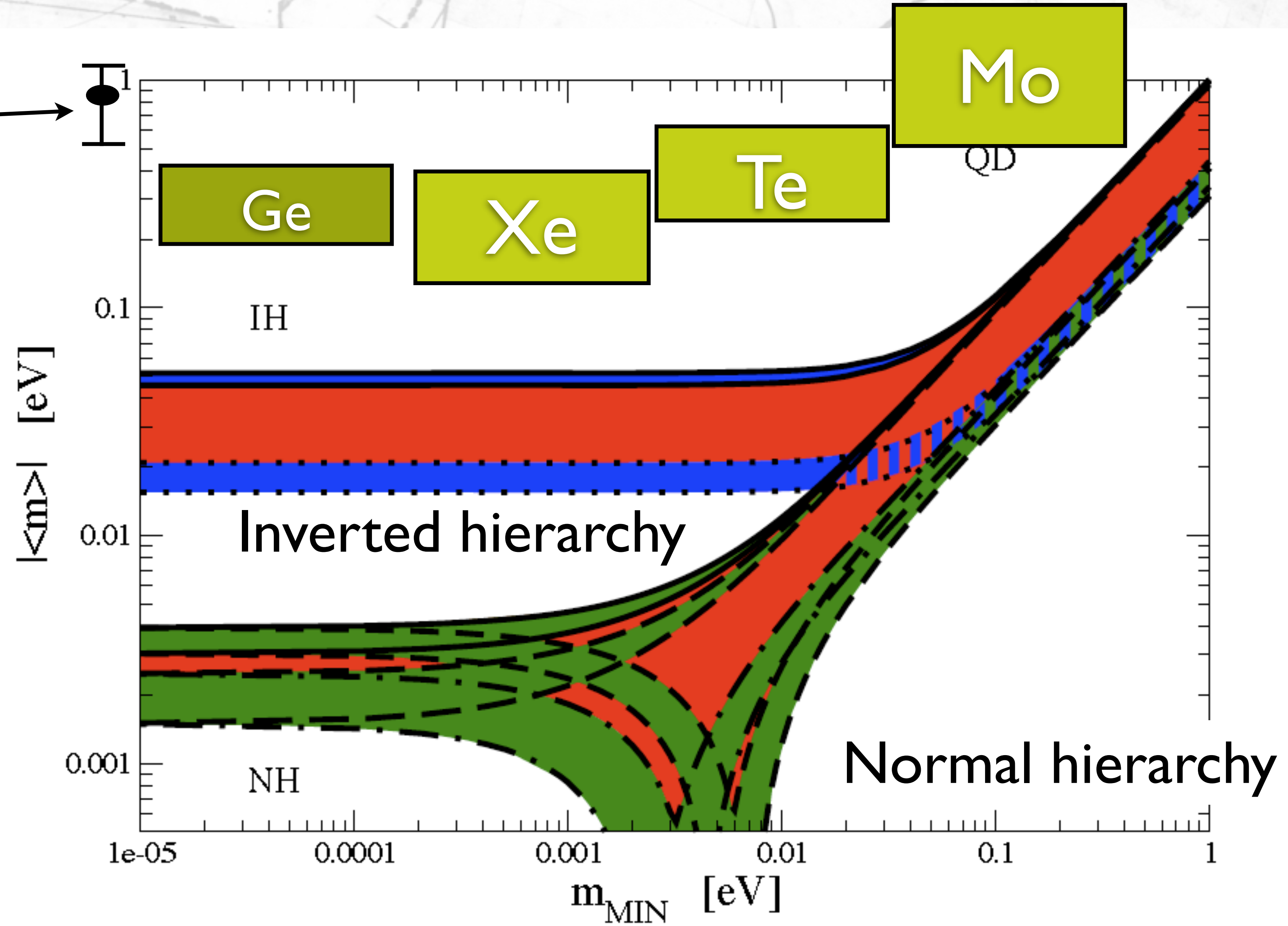
$$m_{\beta\beta} = \sum_{i=1}^{3} m_i U_{ei}^2$$



and it depends on the hierarchy.

0ν2β process

Klapdor et al. claim @ 68%CL.

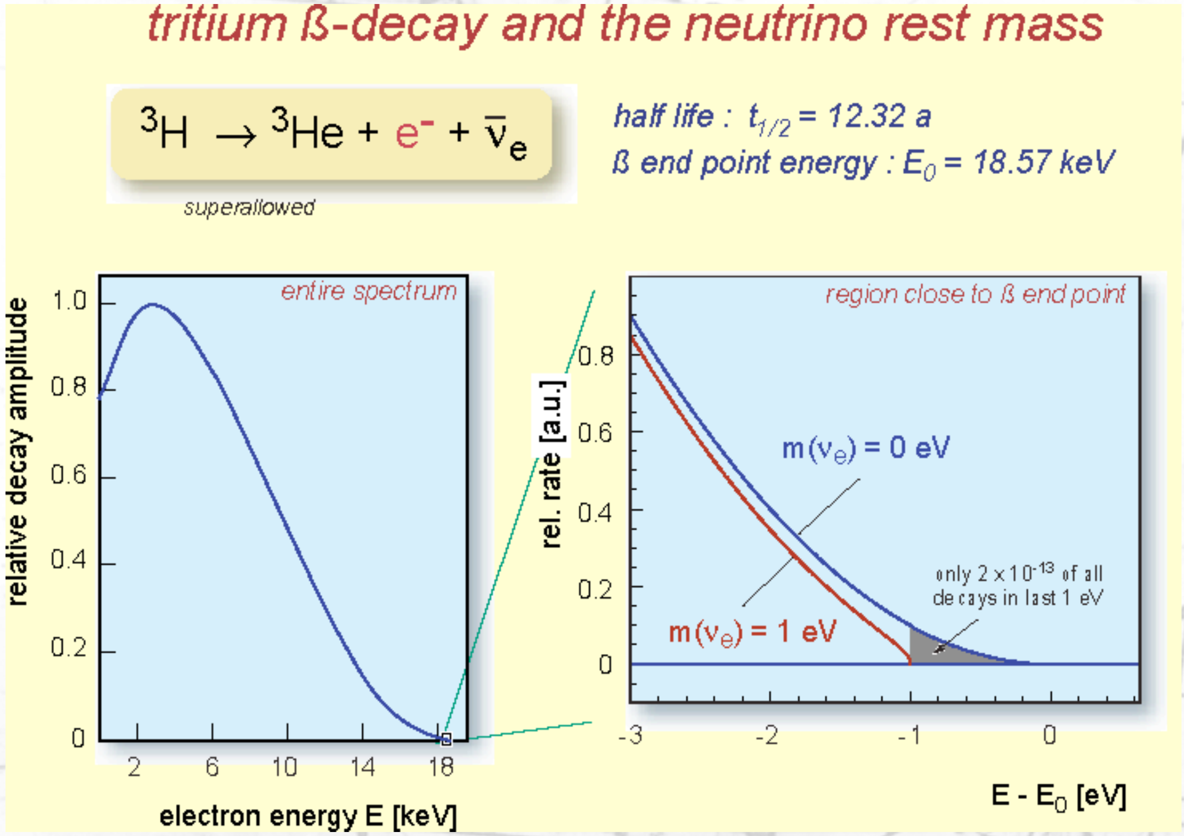


$$\langle m_{ee} \rangle^2 = \frac{1}{\tau_{1/2} \, G_{0\nu} \, |M_{0\nu}|^2}$$

XX

Limits band depending on nuclear matrix element

Katrin



- Absolute neutrino mass experiment:
  - ^{3}H β-decay end point.
  - MAC-E filter threshold spectrometer.
  - High resolution: ~0.2eV

As conclusions

- Fast development in the last 10 years. We have measured:
  - All mixing parameters but the phase.
  - mass differences and hierarchies of solar splitting.
  - solar model tested including LMA-MSW transition.
  - mass effects in neutrino propagation (solar)
  - Tested both with natural and artificial sources.
  - well established results: picture is rather complete and non-contradicting.
  - Observed disappearance but also neutrino transformation in SNO.
  - Stablished observation of appearance of different flavour. (T2K).

As conclusions

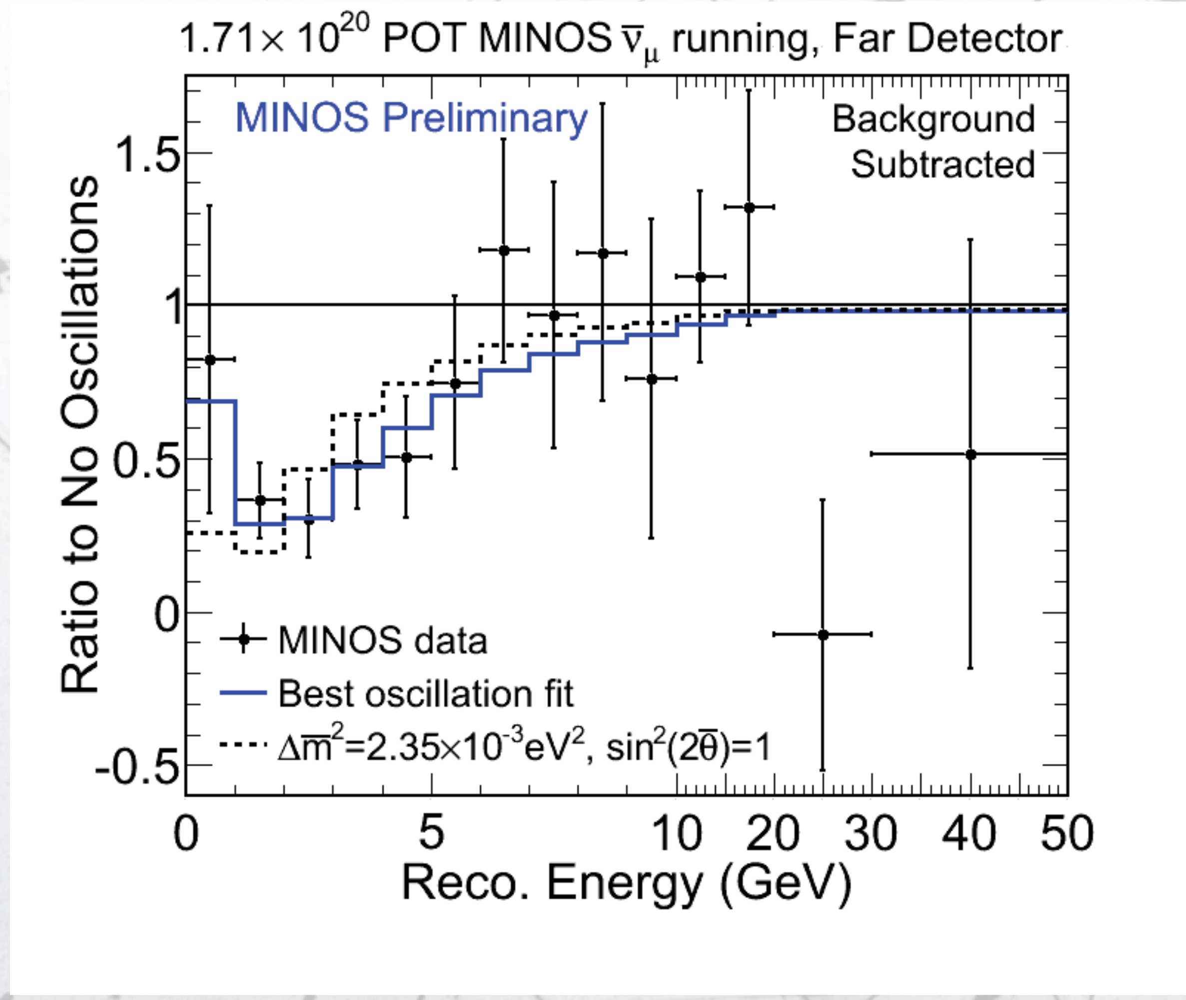
- But, it is not finished yet:
  - CP violation?
  - Mass hierarchy of atmospheric splitting.
  - Are the neutrinos Majorana or Dirac? or both?
  - Additional (sterile) neutrinos? (Not mentioned here but a recurrent subject).
- The main question is still open:
  - Why the mass is so small: “ad-hoc”, see-saw,…(we will need some external help here: LHC?,cosmology?,...)
- There is a new decade of successful neutrino physics ahead!

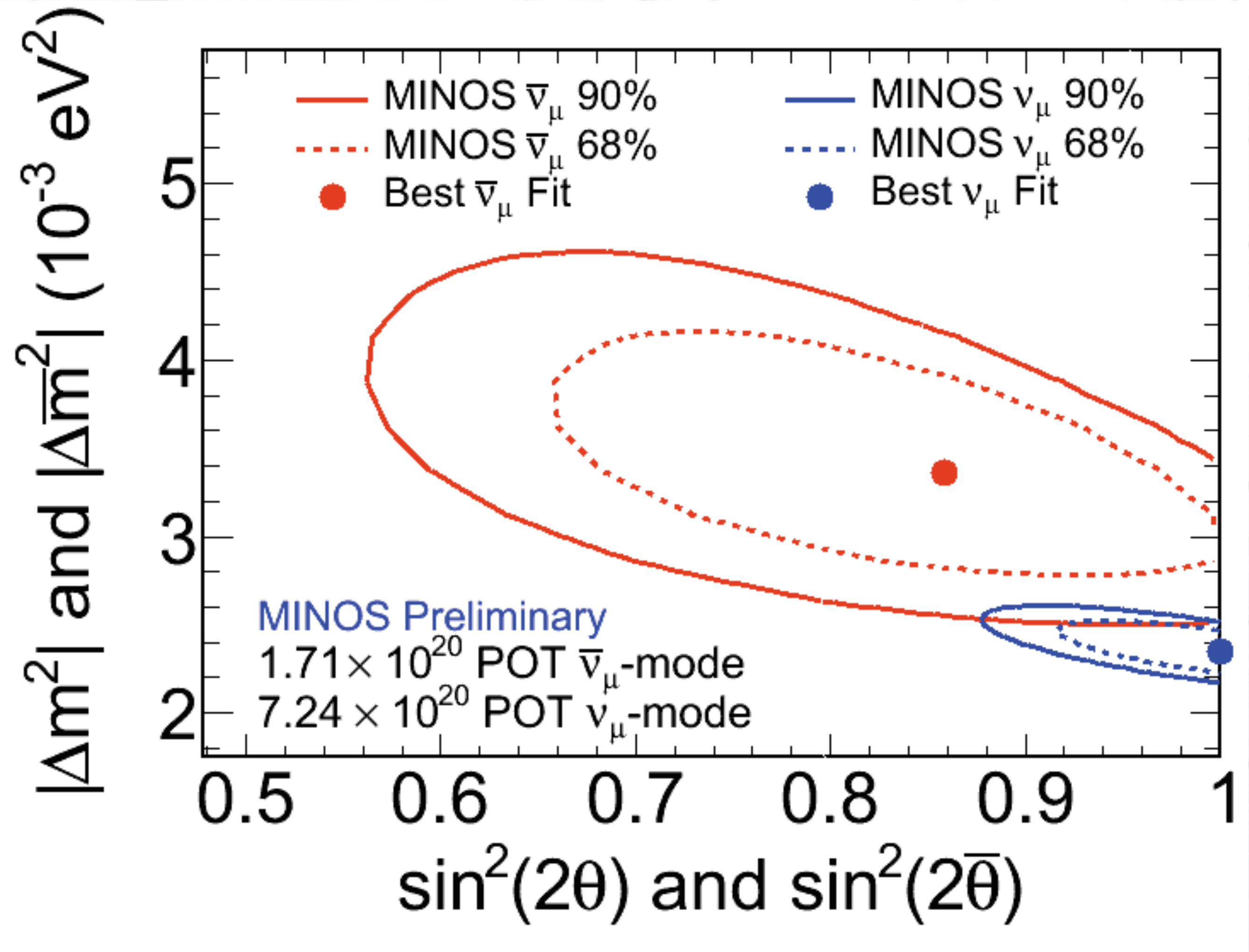
Backup slides

Minos: entering the precision era

- First anti-neutrino data for ν_μ

CPT violation?



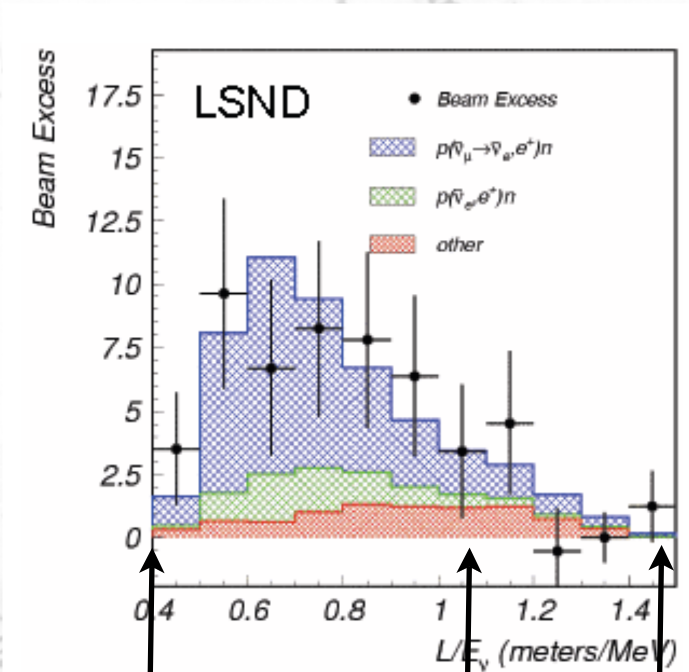


Experimental landscape

	Oscillation	Goals	Challenges
Accelerator	disappearance appearance	Θ_{23} Θ_{13} Δm^2_{13} δ sterile	Beam intensity, ν flux properties, ν-N interactions
Reactor	disappearance	Θ_{13}	ν flux properties, background
Natural	disappearance appearance	Θ_{23} Θ_{13} Δm^2_{13} δ sterile MSW SN	ν flux properties, ν-N interactions detector technology and mass

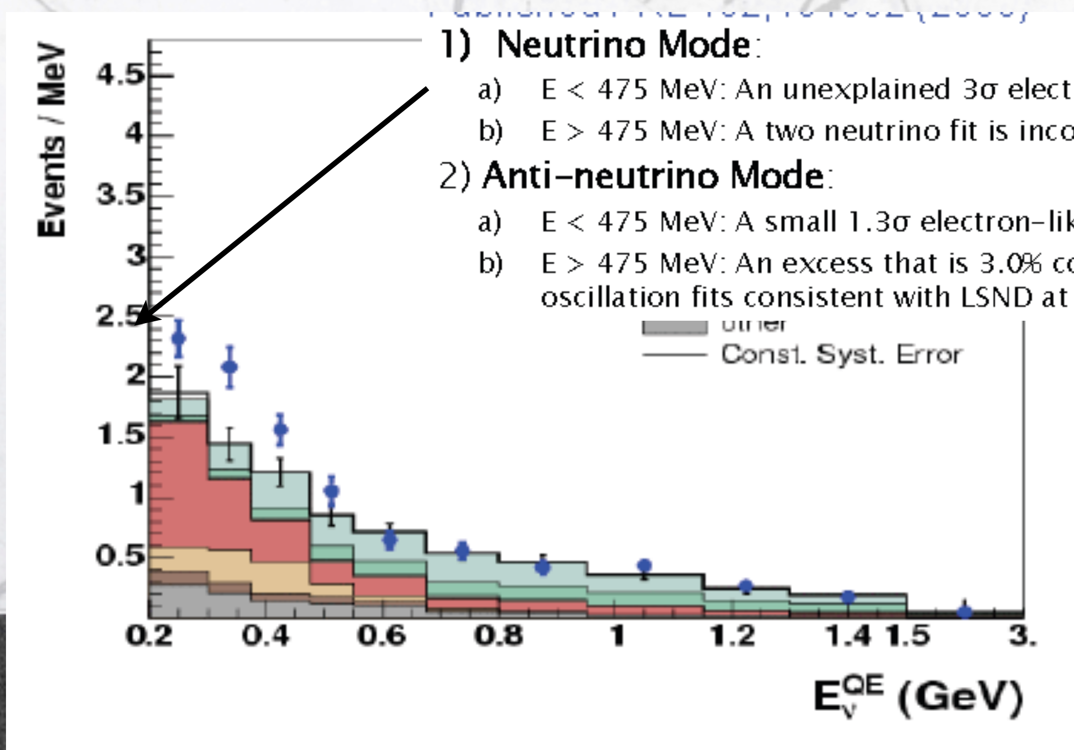
- Experiments complement among them. Main targe

MiniBoone/LSND and sterile neutrinos

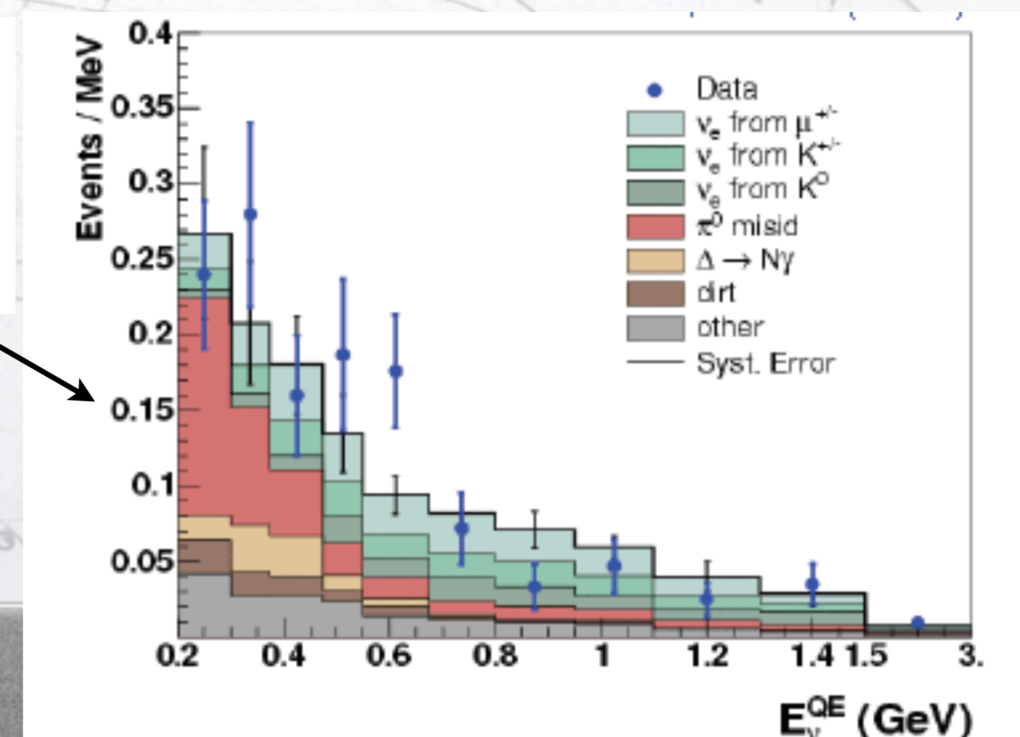


- LSND observed events compatible with the transition: $\nu_\mu \rightarrow \nu_\tau$
- This can't be fitted in the usual 3 flavour model ➔ Sterile neutrinos!.
- MiniBoone tried to check the measurement in different conditions.

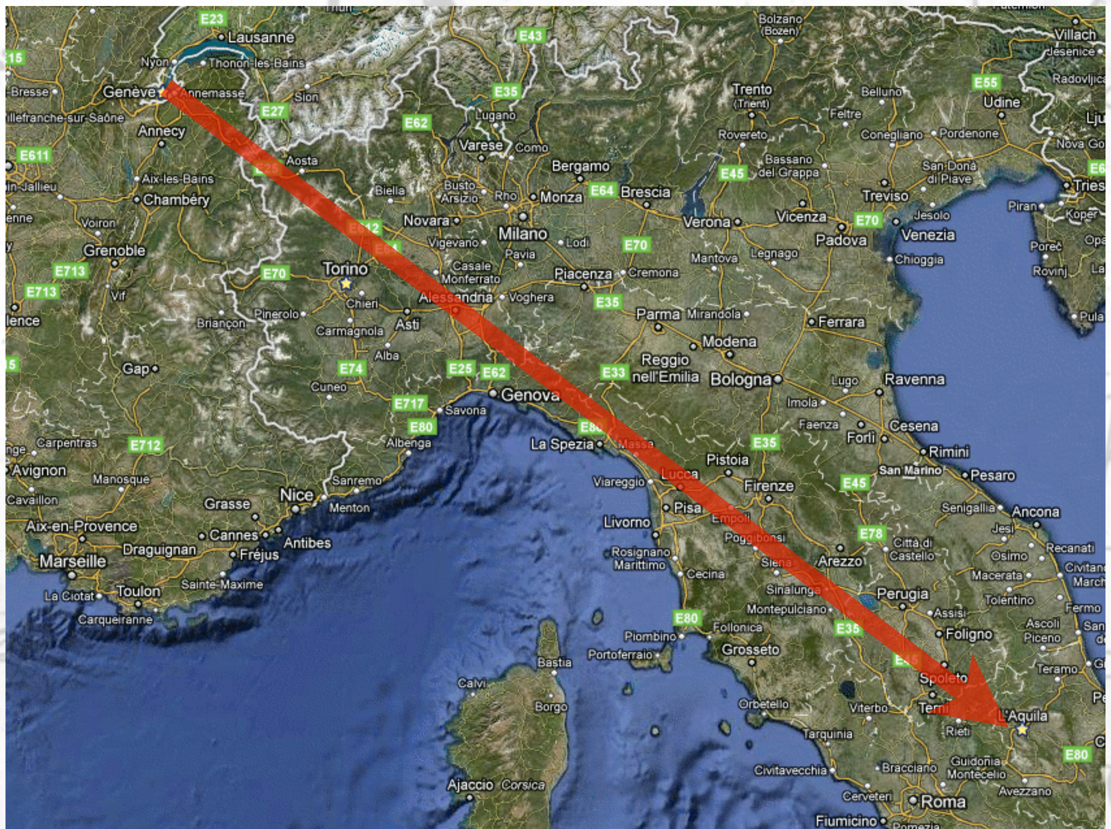
1250 475 333 Mev @ MiniBoone

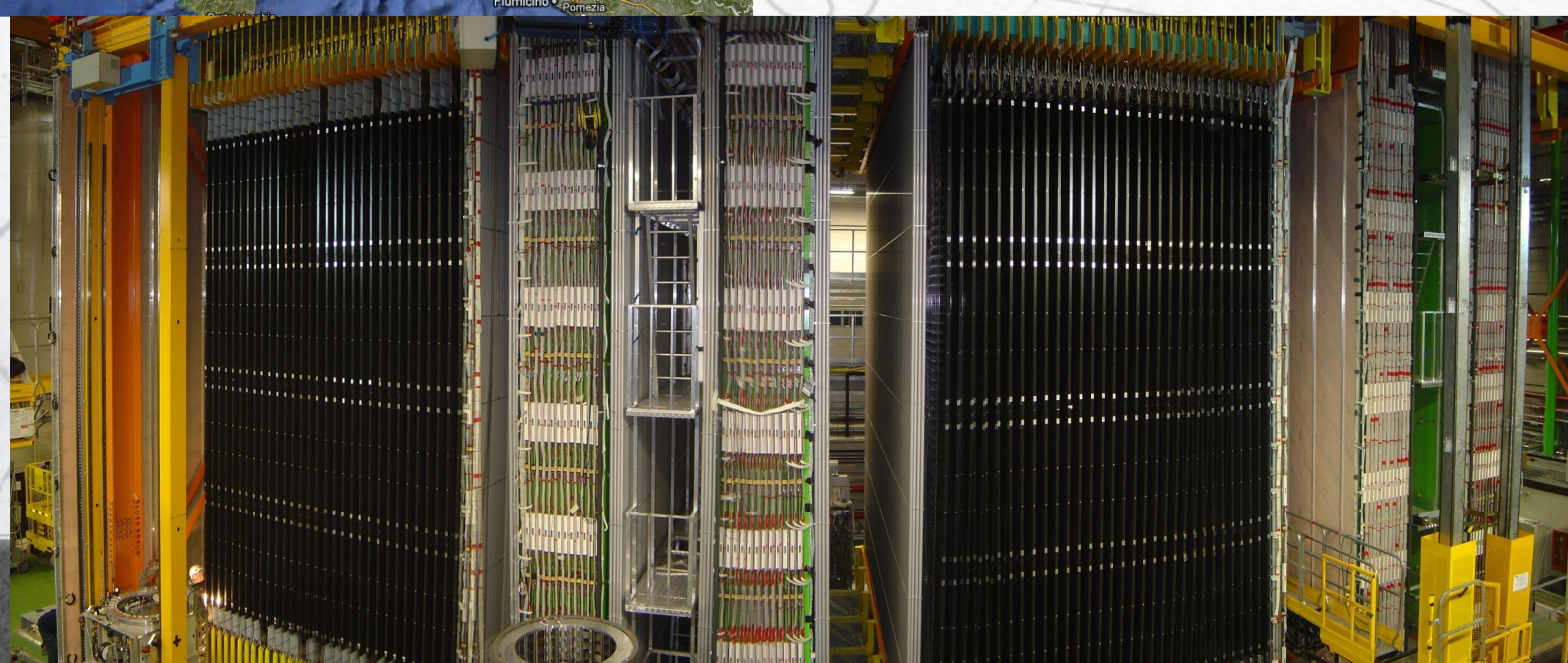


1) **Neutrino Mode**:
   a) E < 475 MeV: An unexplained 3σ electron-like excess.
   b) E > 475 MeV: A two neutrino fit is inconsistent with LSND at the 90% CL.
2) **Anti-neutrino Mode**:
   a) E < 475 MeV: A small 1.3σ electron-like excess.
   b) E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.



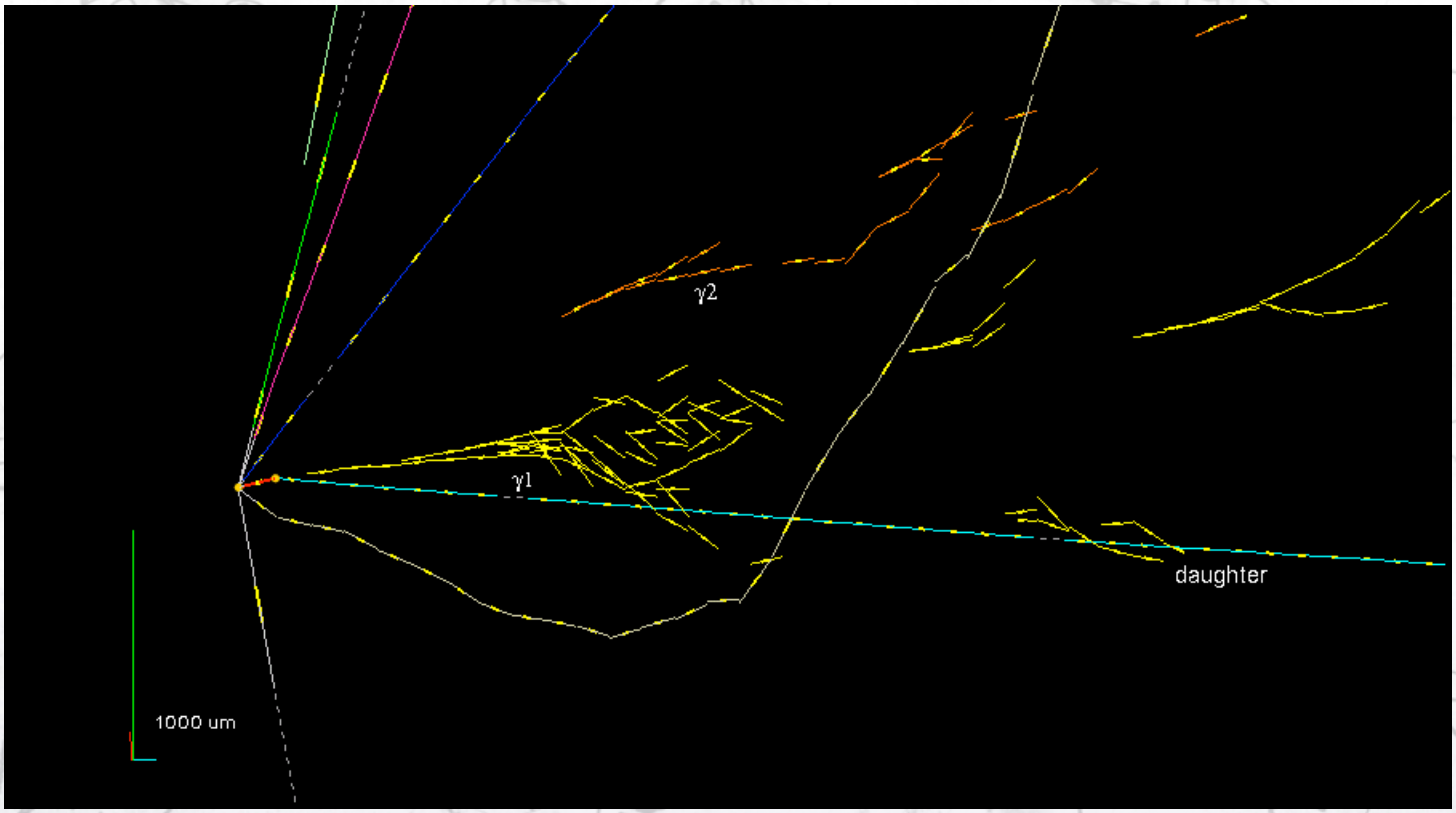
Opera: appearance confirmation





- Intense ν_μ beam from Geneva to Gran Sasso near L'Aquila.
- Search for ν_τ at far detector.
- L = 733 km.
- Far detector uses a photographic technology (emulsions).

Opera: appearance

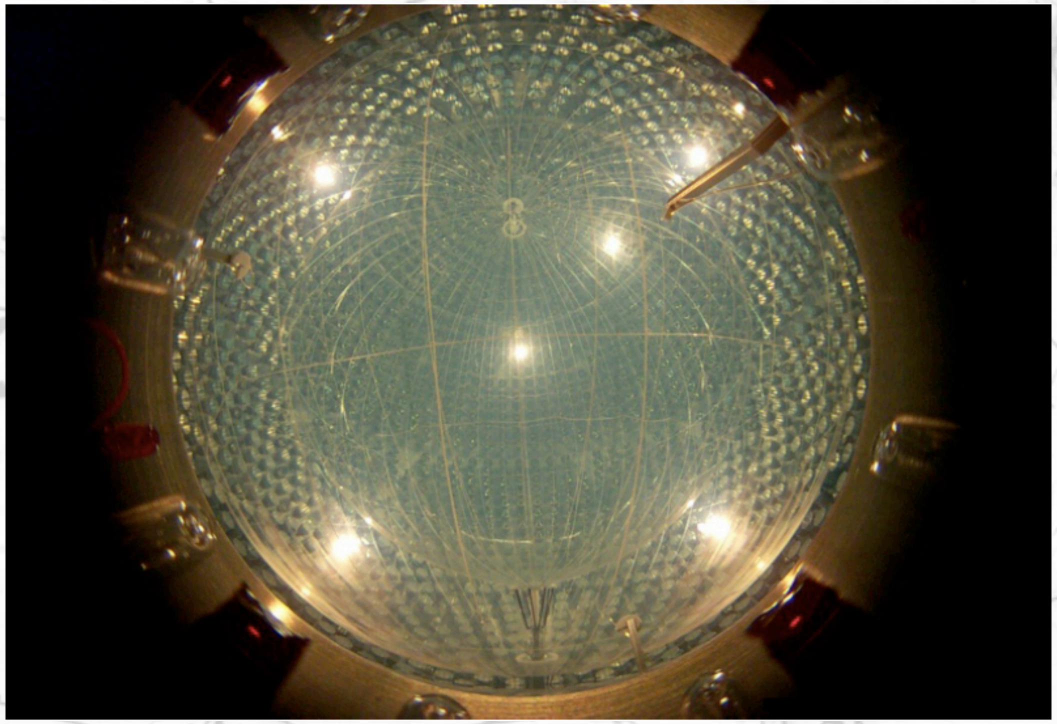


- ν_τ candidate published by OPERA last summer.
- No muon in the event. 2 gammas.
- Compatible with expectations.

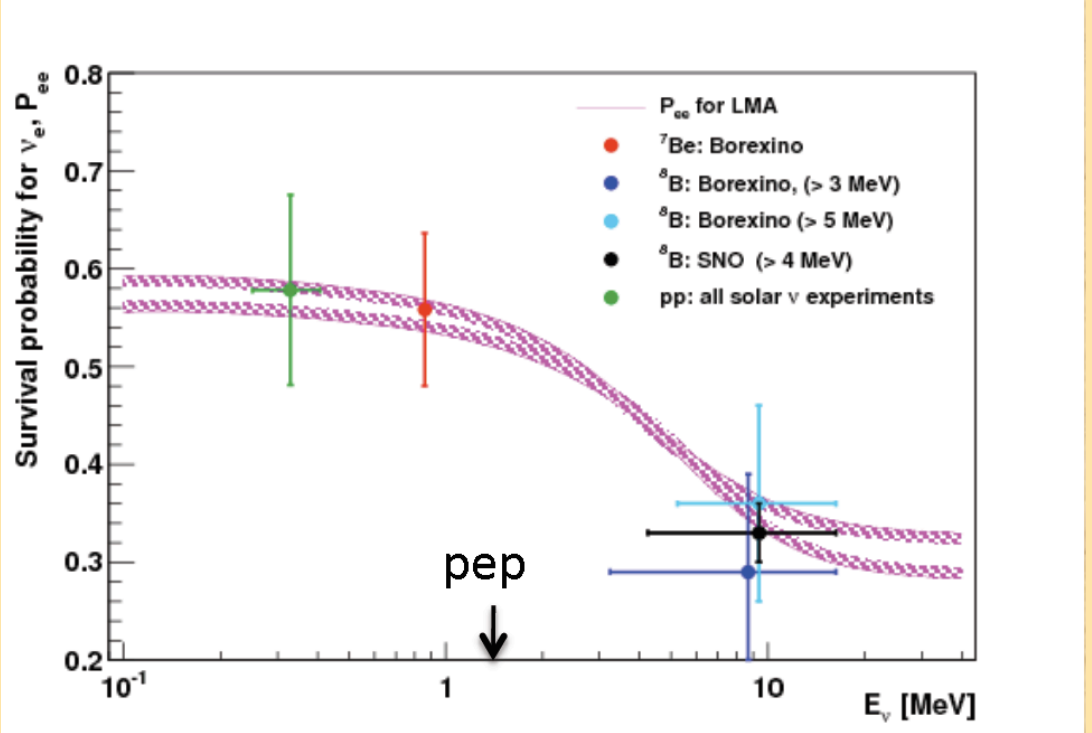
EXCELENCIA SEVERO OCHOA

Borexino: low energy

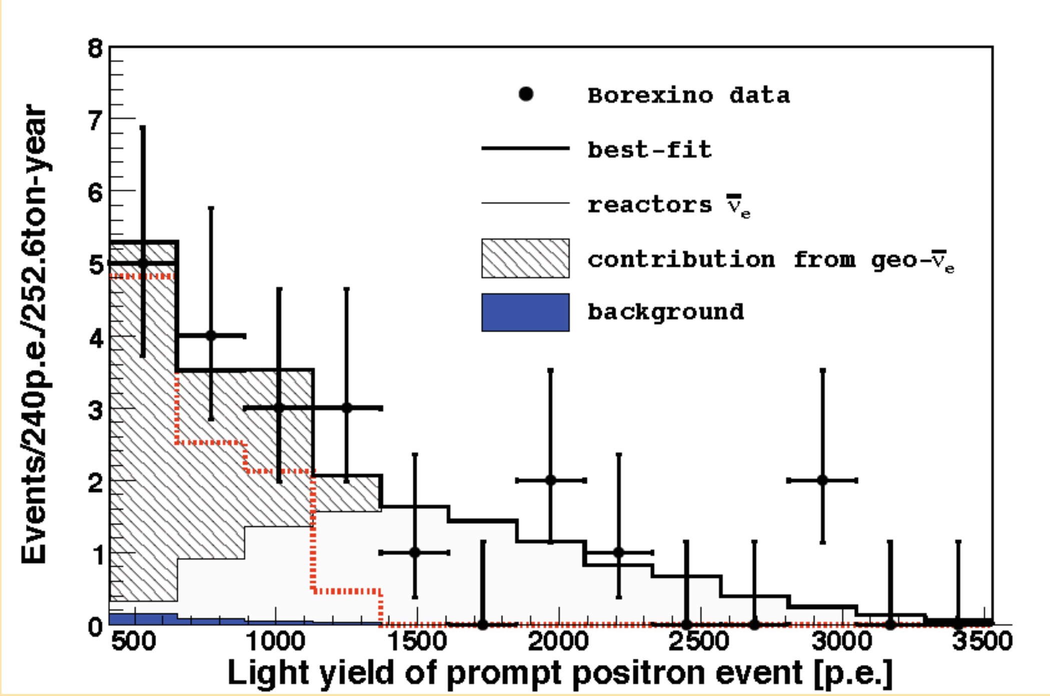
- Radiopure liquid scintillator detector.
- 60 kev threshold but dominated by radioactive background.
- excellent energy resolution (5% @ 1MeV).
- Very low background level: ~120 counts per day per 100 ton.
-



Solar MSW



Geoneutrinos



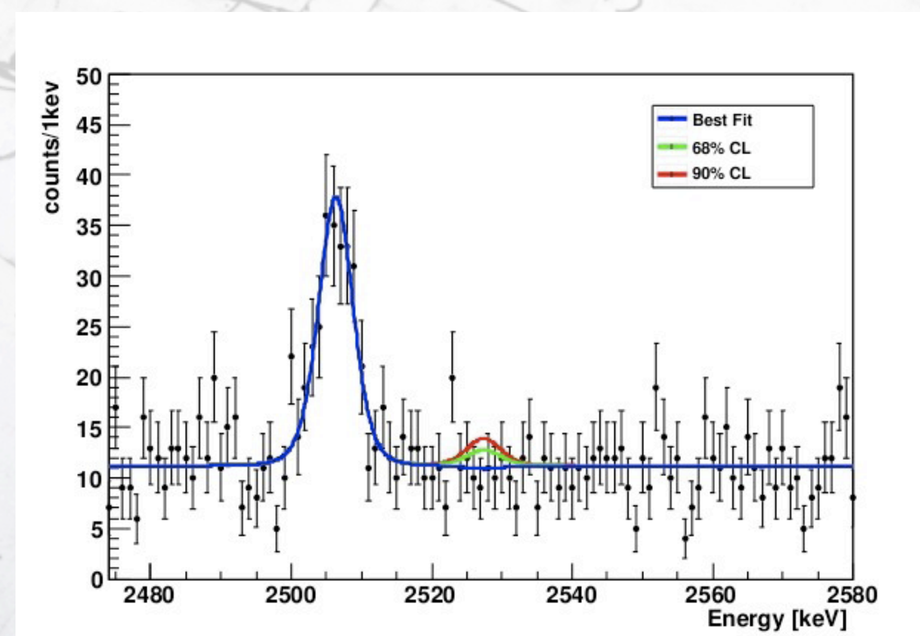
Double beta decay

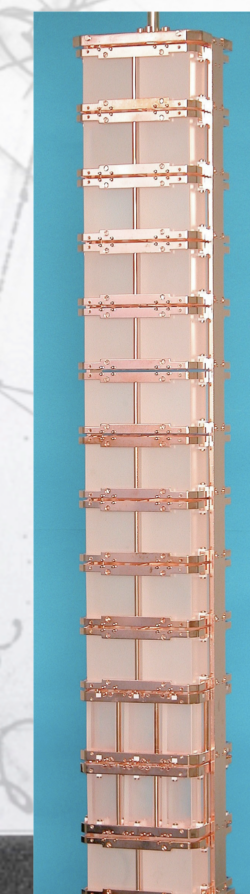
Technology	Pro's	Con's	Isotopes	Experiments
Bolometers	Excellent E resolution isotope = detector	Few isotopes Bckg handling total mass(?)	Ge, Te,	Cuore, Gerda
Calorimeters	(Very)Large mass isotope = detector	Single isotope	Xe	EXO, Kamland+ SNO++
Tracking + Calo	Topological bckg reduction many isotopes	Worse E resolution isotope != detector total mass ?	Mo, Ca, Se, Nd	NEMO/SuperNemo.
Calo tracking	Large mass Good E resolution topological bckg reduction isotope = detector	Single isotope	Xe	NEXT, EXO Gas., Cobra, DCBA,..

Bolometers

- Ge detector (Klapdor claim) in a large water tank for background reduction.
- Charge in Ge: excellent resolution: 0.2% @ 1 MeV.
- Started operation in October 2010 with ~15 kg of enriched Ge.
- Second phase with up to 100 kg.

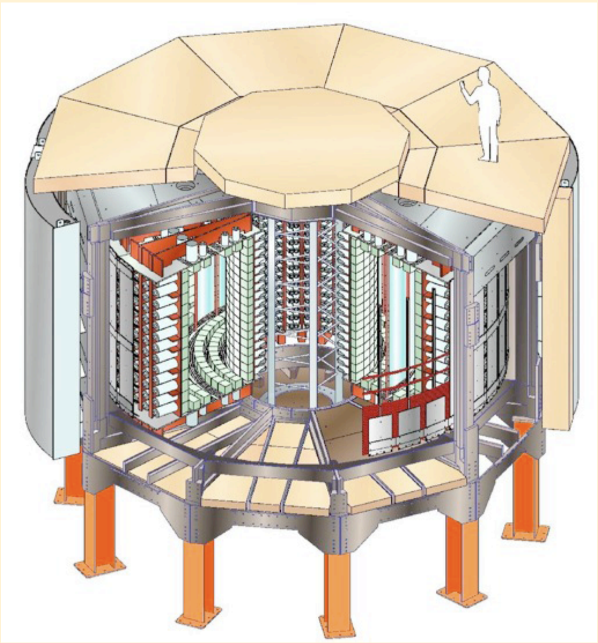
- Te bolometers: measure increase of temperature due to decay products.
- Excellent energy resolution: 0.2% FWHM @ $Q_{\beta\beta}$= 2.6 MeV.
- First run with low mass (10kg) (Cuoricino)
- Building Cuore: 200kg.

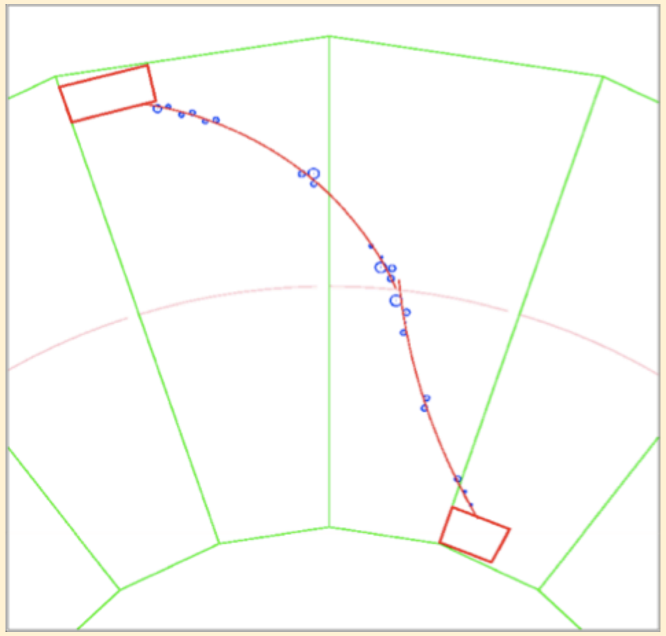




Tracking + calorimeter

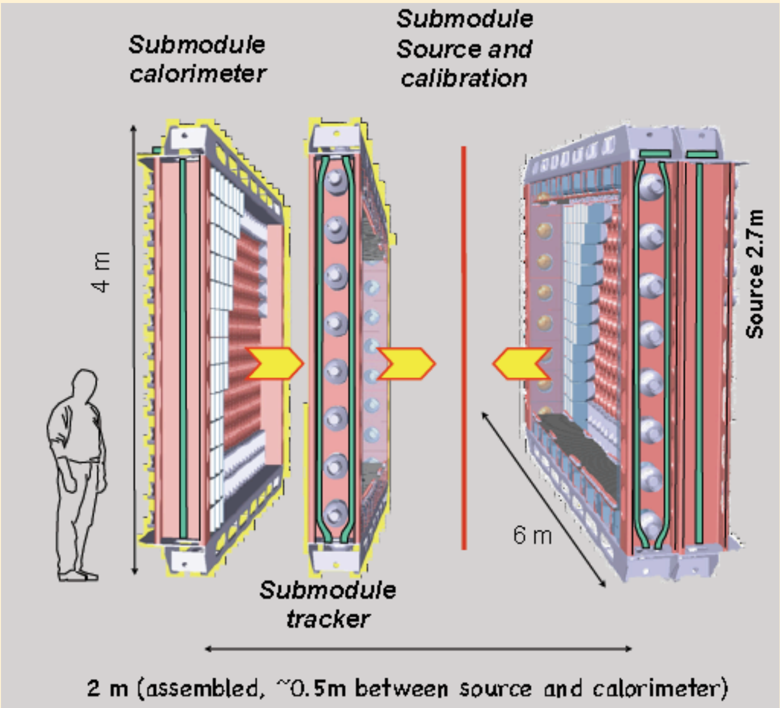
Nemo 3

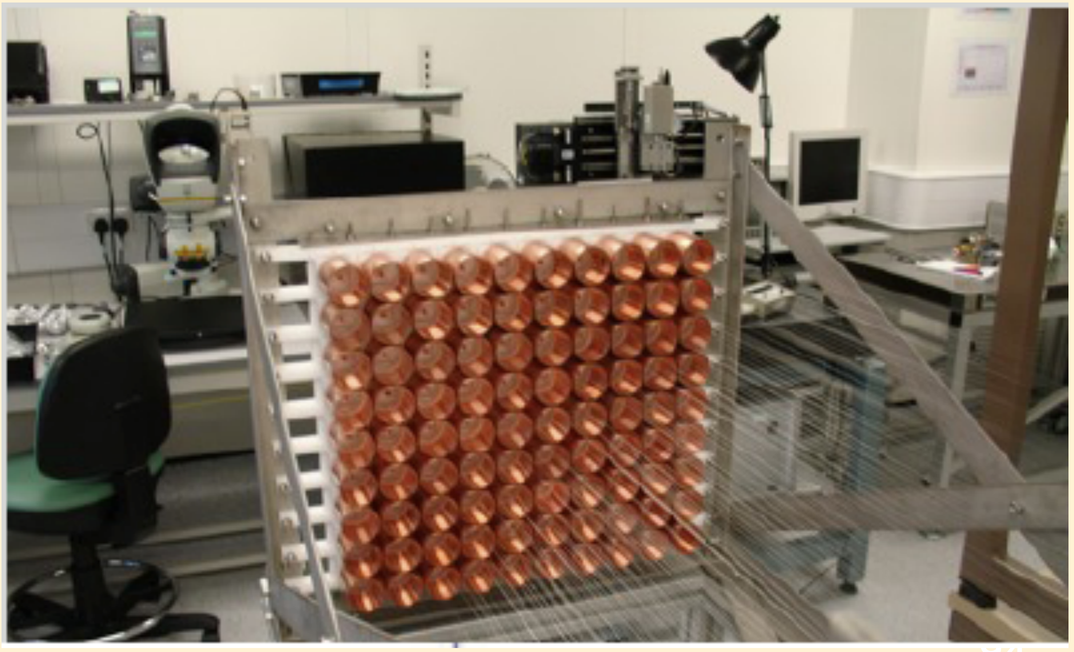




- NEMO3: stablished technology. Leading $2\beta0\nu$ measurement with Mo. $\langle m_{\nu} \rangle <$ 300-900 meV.
- Topological bckg reduction.
- SuperNemo: upgrade and more massive (~100kg) NEMO3 detector. Goal: $\langle m_{\nu} \rangle <$ 50-100 meV @ 90%CL. Change isotope to Se.
- SuperNemo first test run in 2013.

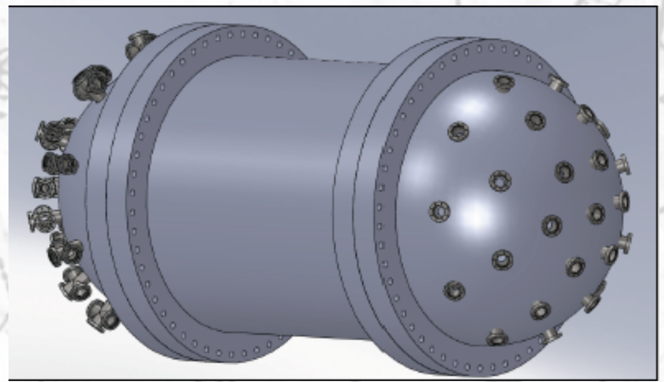
SuperNemo

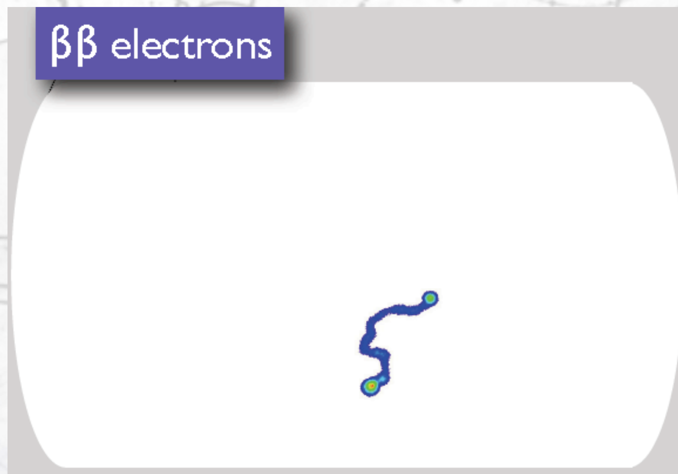




Tracking calorimeter

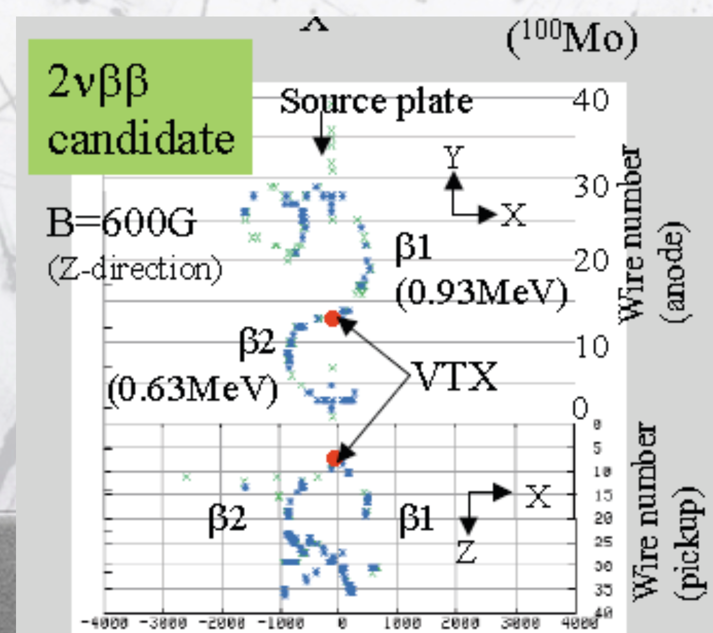
TPC

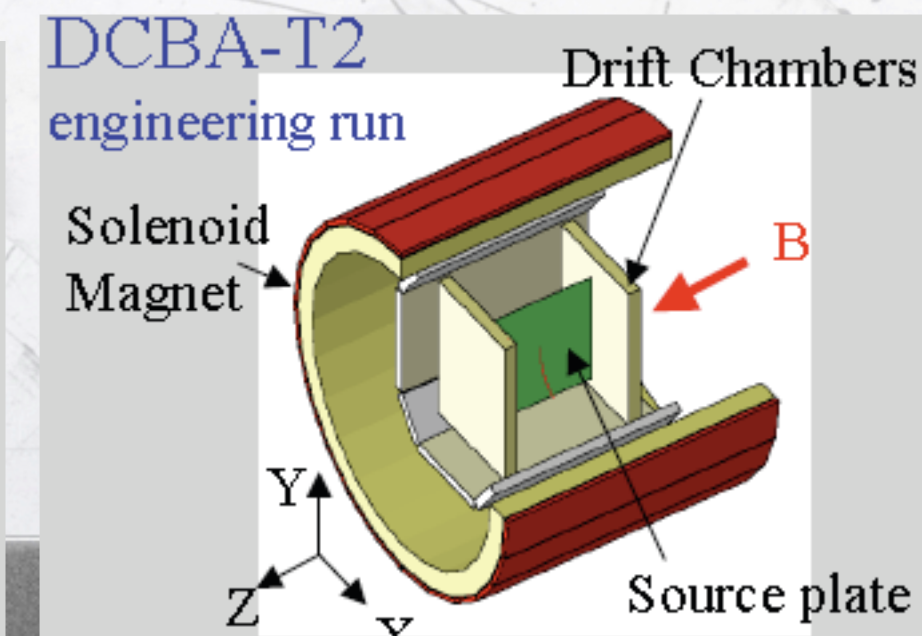




- High pressure Xenon gas TPC: tracking and energy resolution. NEXT & EXO gas. See other talks for reference.
- Energy resolution: 1%FWHM @ Xe $Q_{\beta\beta}$.
- Topological background reduction.
- Good energy resolution with electroluminiscence.

- DCBA-T2. Momentum by electron curvature.
- Foil structure like NEMO3
- topological background reduction.



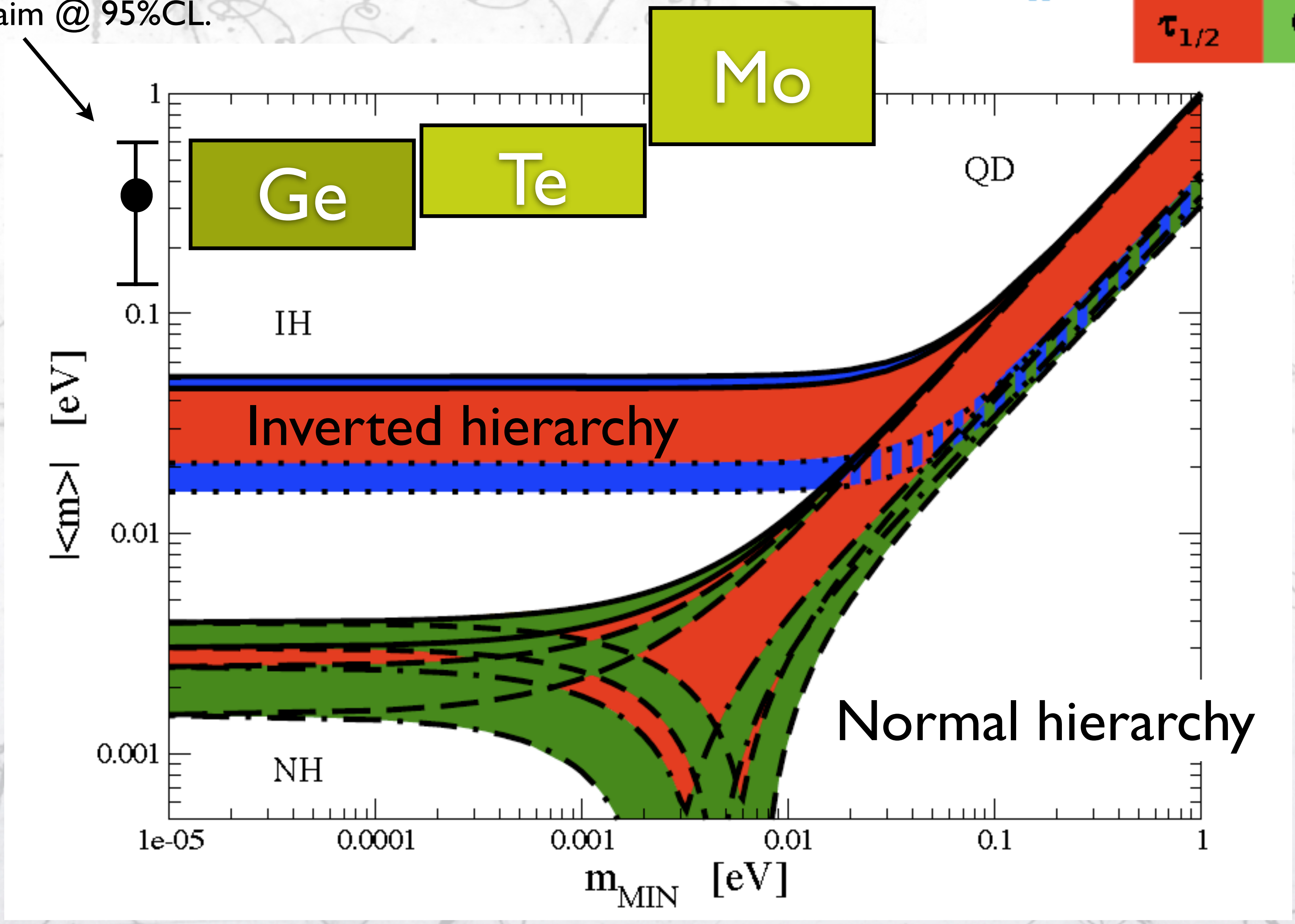


Brief introduction

Experimental situation

$$\langle m_{ee}\rangle^2 = \frac{1}{\tau_{1/2}\, G_{0\nu}\, |M_{0\nu}|^2}$$

Klapdor et al. claim @ 95%CL.



XX Lower limit band depending on nuclear matrix element

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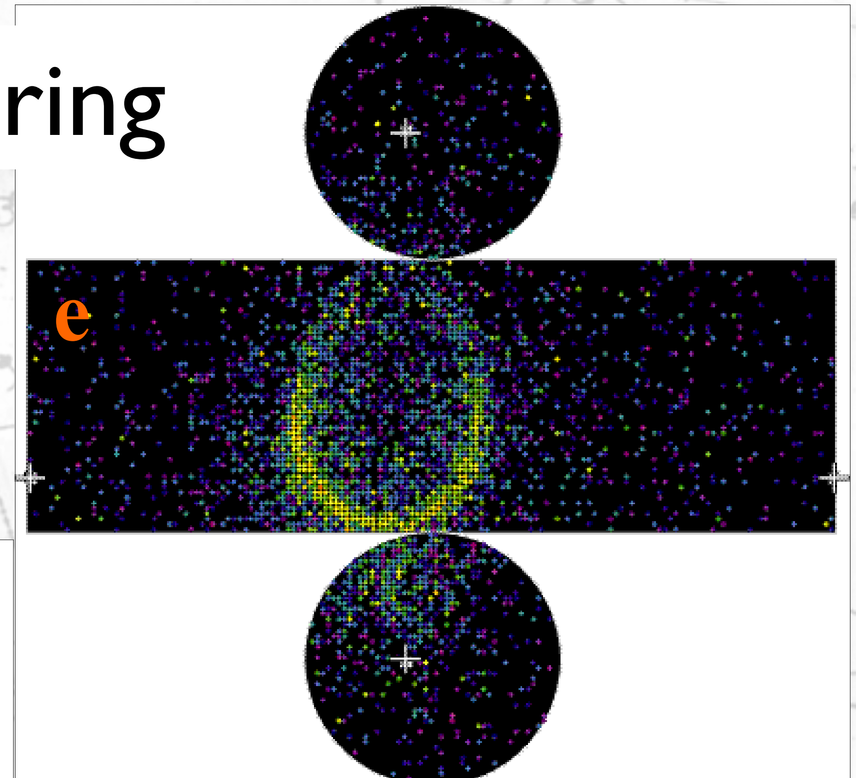
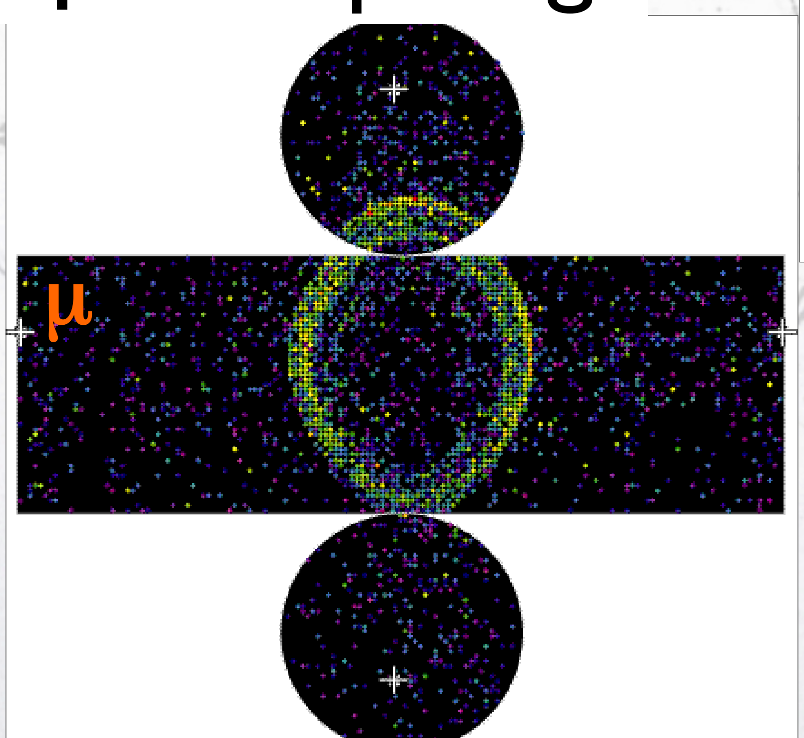
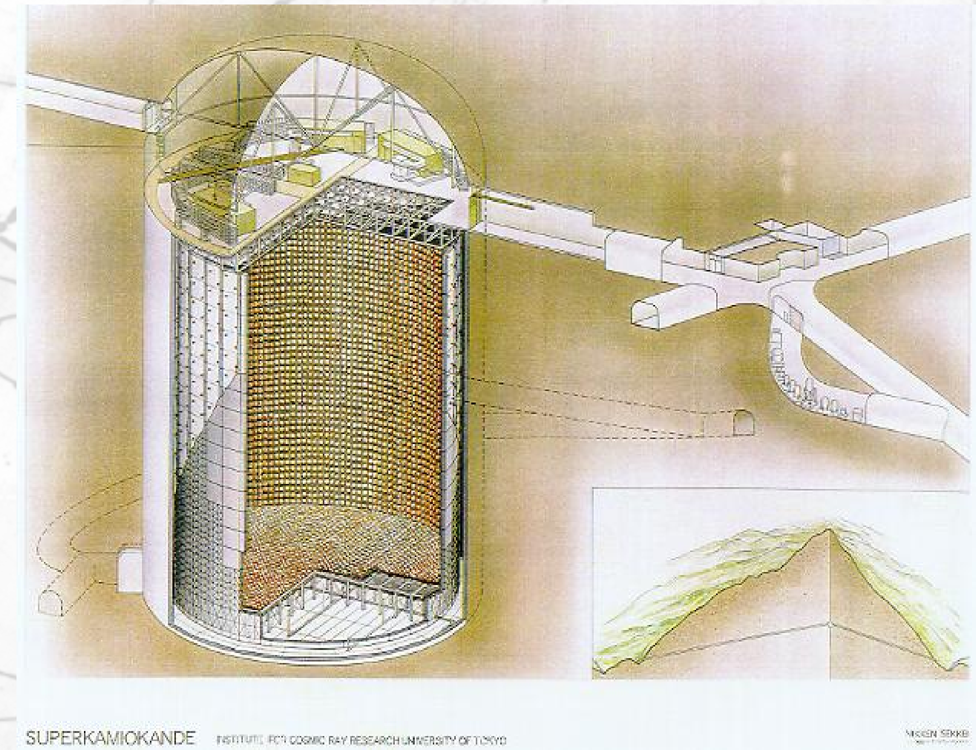
Superkamiokande

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.