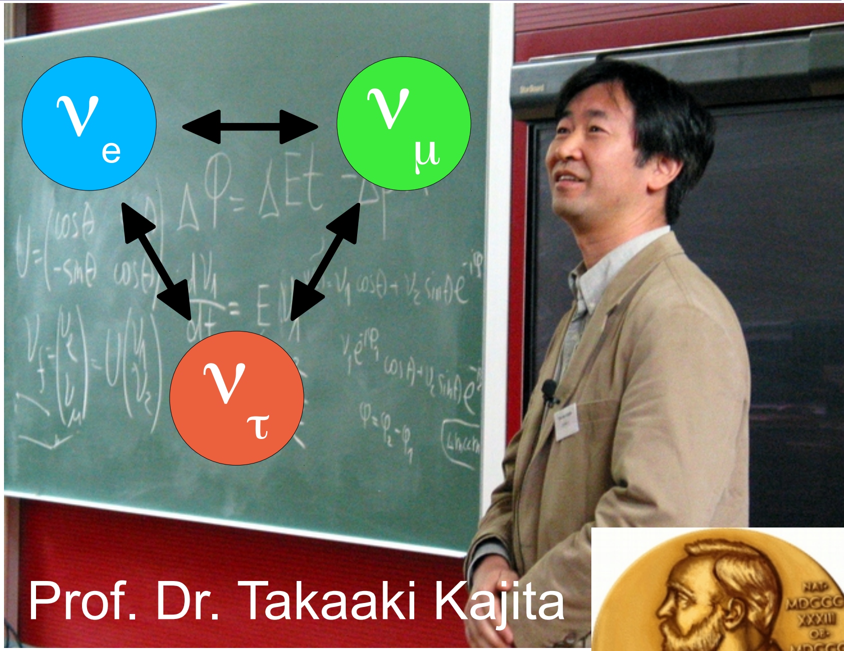
Neutrino physics: experiments

The dark side of the Universe, ISAPP, MPIK Heidelberg, May 29/30, 2019

Christian Weinheimer

Institut für Kernphysik, Westfälische Wilhelms-Universität Münster
weinheimer@uni-muenster.de



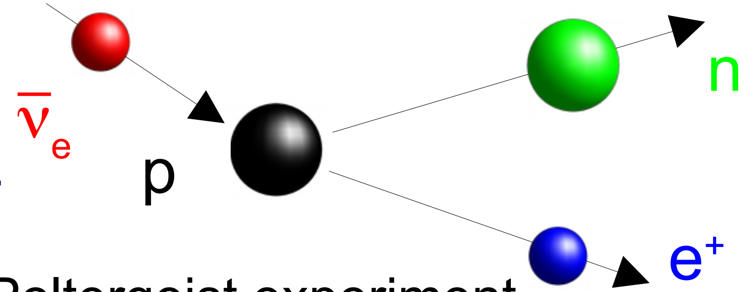
A reminder: Neutrinos
in the Standard Model of Particle Physics

Neutrino oscillations:
experiments with atmospheric,
solar, accelerator and reactor neutrinos

Neutrino masses:
- cosmology and astrophysics
- neutrinoless double β decay
- direct neutrino mass experiments

Search for sterile neutrinos
Coherent neutrino nucleus elastic scattering

Experimental proof of neutrinos



1956: Cowan and Reines: Poltergeist experiment

strong $\bar{\nu}_e$ source: nuclear power reactor:

6 $\bar{\nu}_e$ / fission (from fission products), E_ν < 9 MeV

energy gain / fission: 200 MeV

1 GW thermal power $\Rightarrow$ $2 \cdot 10^{20}$ ν/s

Detection reaction: inverse β decay: $\bar{\nu}_e + p \rightarrow n + e^+$ (threshold: 1.8 MeV)

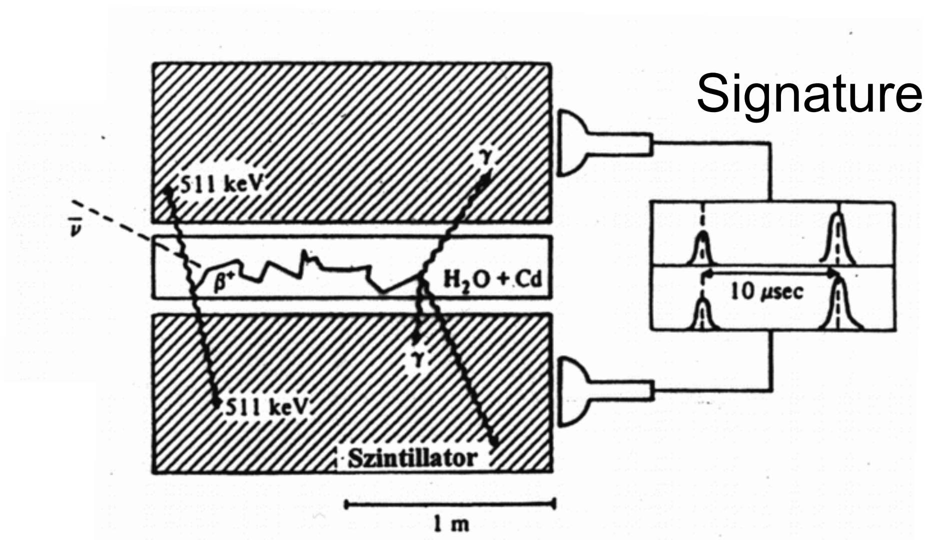


figure: Schmitz: Neutrinophysics, Teubner

Signature: a) n: thermalisation by elastic scattering, capture on Cd $\Rightarrow \gamma$'s

b) e^+: annihilation $\Rightarrow 2\,\gamma$'s (511 keV)

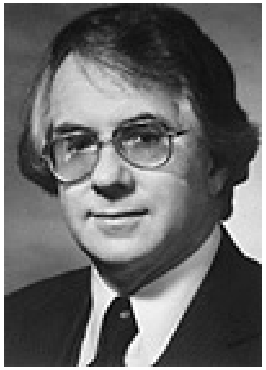
$\Rightarrow$ spatial and time-delayed coincidence (nearly background free)

measured cross section:

$(1.1 \pm 0.3) \cdot 10^{-43}$ cm^2

(in good agreement with Fermi`s theory for V-A)

ν's in the electroweak Standard Model: U(1)⊗SU(2)



S. Glashow

S. Weinberg

A. Salam

12 fundamental fermions

6 left-handed weak isospin dublets:

Leptonen $\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L$ $\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L$ $\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$ pure weak isospin dublets

Quarks $\begin{pmatrix}u\\ d\end{pmatrix}_L$ $\begin{pmatrix}c\\ s\end{pmatrix}_L$ $\begin{pmatrix}t\\ b\end{pmatrix}_L$ weak isospin dublets

9 right-handed weak isospin singulets:

$e^-_R, \mu^-_R, \tau^-_R, u_R, d_R, c_R, s_R, t_R, b_R$ (no ν_R in SM)

$$\Psi_L = P_L\Psi \quad \Psi_R = P_R\Psi \quad P_L = 1/2(1-\gamma_5) \quad P_R = 1/2(1+\gamma_5)$$

massive leptons in charged weak currents (CC):
- lepton:

$P(H = \pm 1) = (1 \pm (-v/c))/2$
$\Rightarrow P_{Long} = -v/c$

- anti lepton:

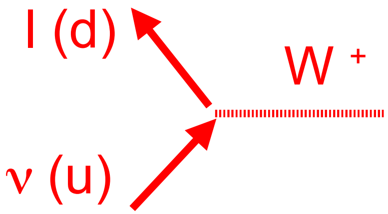
$P(H = \pm 1) = (1 \pm v/c)/2$
$\Rightarrow P_{Long} = v/c$

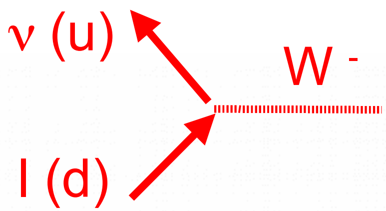
For massless particles (ν in SM):

Ψ_L, Ψ_R^c have helicity $H = -1$ $\quad \overleftarrow{\sigma}\ \vec{p}$

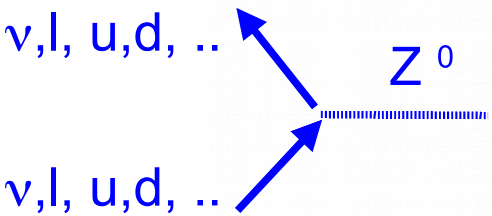
Ψ_R, Ψ_L^c have helicity $H = +1$ $\quad \overrightarrow{\sigma}\ \vec{p}$

Lagrangian: Interaction part

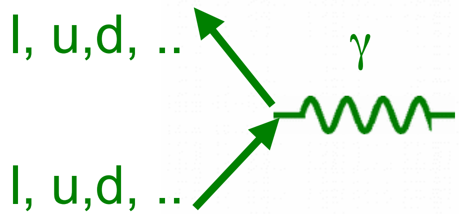




$$\mathcal{L} = \underbrace{\frac{g}{\sqrt{2}}\left(J^-_\mu W^{+\mu} + J^+_\mu W^{-\mu}\right)}_{\text{weak charged current (CC)}}$$



$$+ \underbrace{\frac{g}{\cos\theta_W}\left(J^3_\mu - \sin^2\theta_W\, J^{e.m.}_\mu\right) Z^{o\mu}}_{\text{weak neutral current (NC)}}$$



$$+ \underbrace{g \sin\theta_W\, J^{e.m.}_\mu A^\mu}_{\text{em neutral current}} \quad \ldots$$

coupling to electromagnetic current $J_\mu^{e.m.}$ as in QED: $g \sin\theta_W = e$

$\theta_W = 28.7°$ ⇒ coupling of weak interaction ≈ coupling of em. interaction,

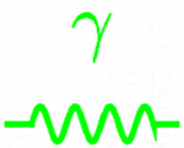
but there is a term „m_W^2" (m_Z^2) in the denominator of the propagator, see later

WWU MÜNSTER

Weakness of weak interaction

Difference ν versus electron scattering

Remember photon propagator:



$$\frac{g_\alpha^{\ \beta}}{q^2} \rightarrow \frac{1}{Q^2}$$

But W propagator:

$$\frac{i \cdot g_\alpha^{\ \beta} - \frac{q_\alpha \cdot q^\beta}{M_W^2}}{q^2 - M_W^2} \overset{q^2 \ll M_W^2}{\rightarrow} \frac{-i \cdot g_\alpha^{\ \beta}}{M_W^2} = \text{const.}$$

$\Rightarrow$ **weak cross section increases linearly with s,**

but is much smaller due to $1/M_W^4$ ($M_W \approx 80$ GeV)

ν cross sections

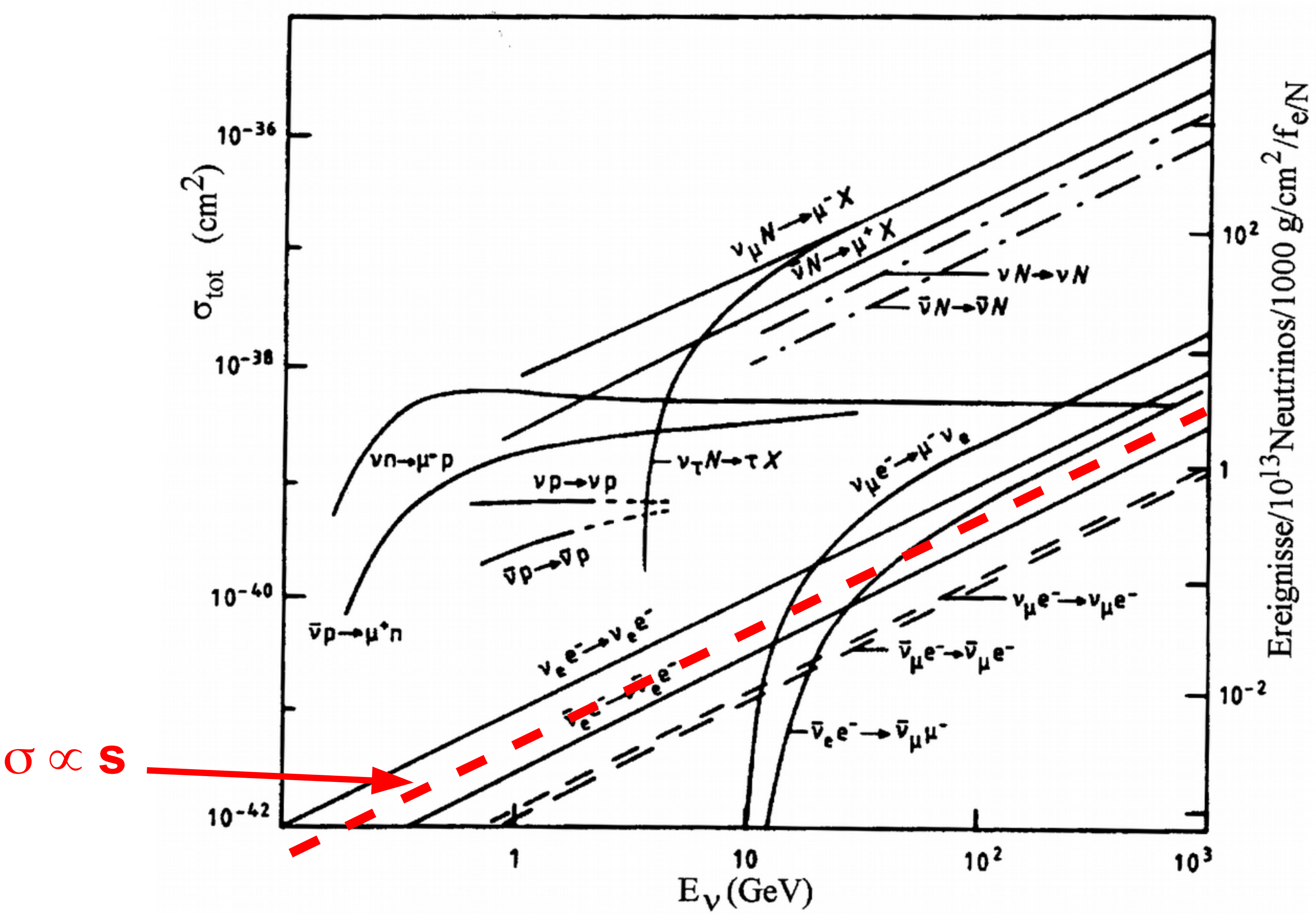


figure: Schmitz: Neutrinophysics, Teubner

ν-fermion scattering cross sections: $\sigma \propto s = m_f^2 + 2E_\nu m_f \Rightarrow s \propto E_\nu$

LEP: determination of number of neutrino generations

LEP:

$e^- + e^+ \rightarrow Z^0\,(\gamma) \rightarrow$

visible:
- $e^- + e^+$,
- $\mu^- + \mu^+$,
- $\tau^- + \tau^+$,
- $u + \bar{u}$,
- $d + \bar{d}$,
- $s + \bar{s}$,
- $c + c$,
- $b + \bar{b}$,

invisible:
- $\nu_e + \bar{\nu}_e$,
- $\nu_\mu + \bar{\nu}_\mu$,
- $\nu_\tau + \bar{\nu}_\tau$,
- ????

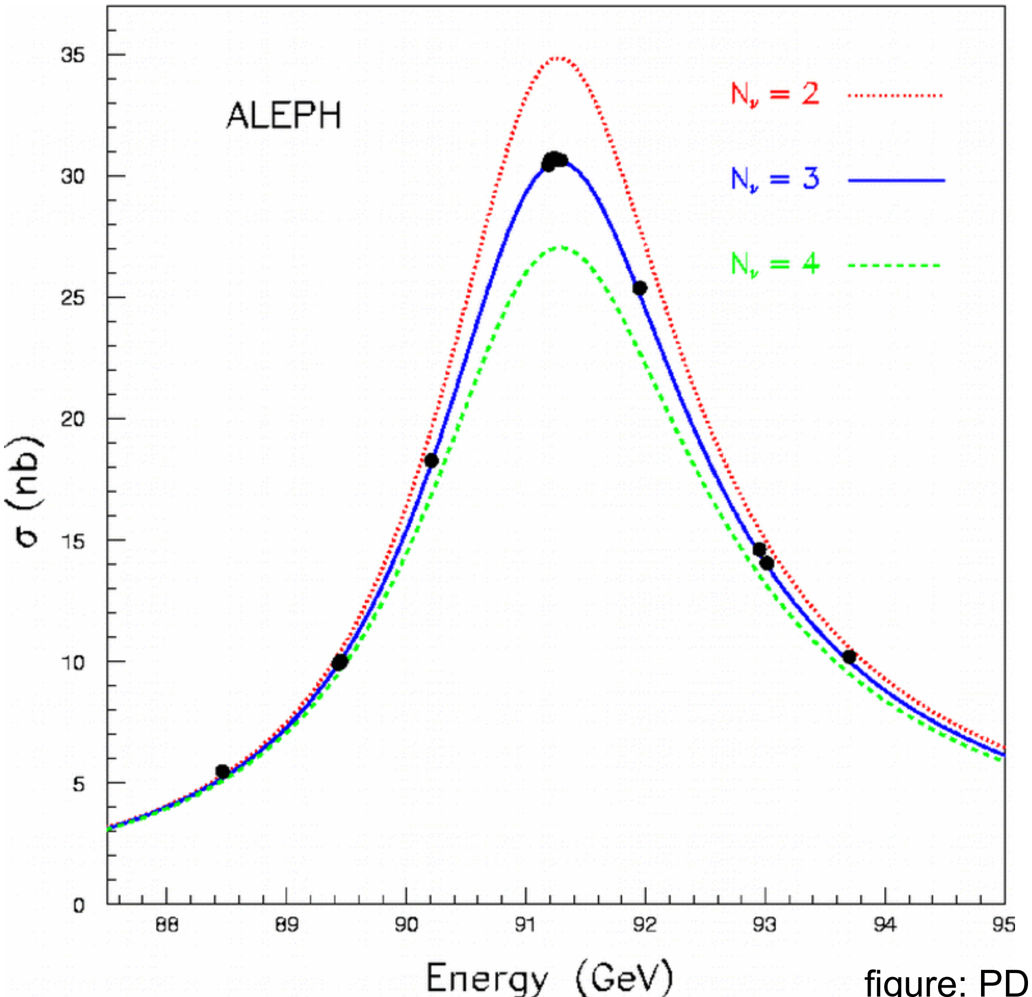


figure: PDG

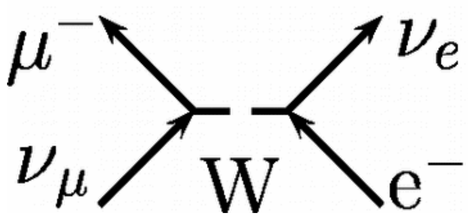
Exp: full width: $\Gamma = 2495(2)$ MeV

invisible width: $\Gamma_{invisible} = 499(2)$ MeV

ν partial width $\Gamma_\nu = 167.1$ MeV $\Rightarrow N_\nu = 2.99$

Angular distribution of neutrino-fermion scattering

Neutrino-fermion scattering:

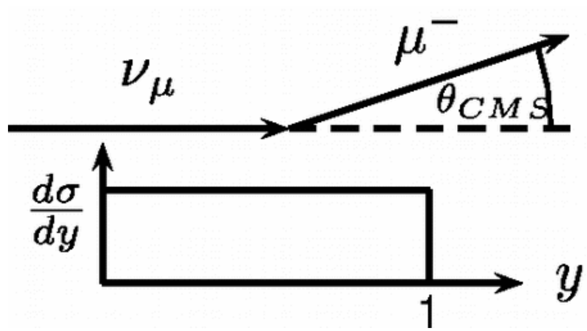


$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2} \cdot s \qquad (q^2 \ll M_W^2)$$

no angular dependence:

$$(\nu_\mu e^- \to \mu^- \nu_e)$$

$$\begin{array}{cc} \nu_\mu & e^- \\ \rightarrow & \leftarrow \\ \Leftarrow & \Rightarrow \end{array} \qquad J = 0$$

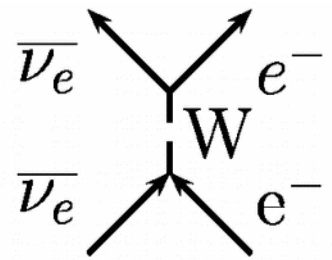


$$y = \frac{1 - \cos(\theta_{CMS})}{2}$$

y distribution is flat for νl scattering !

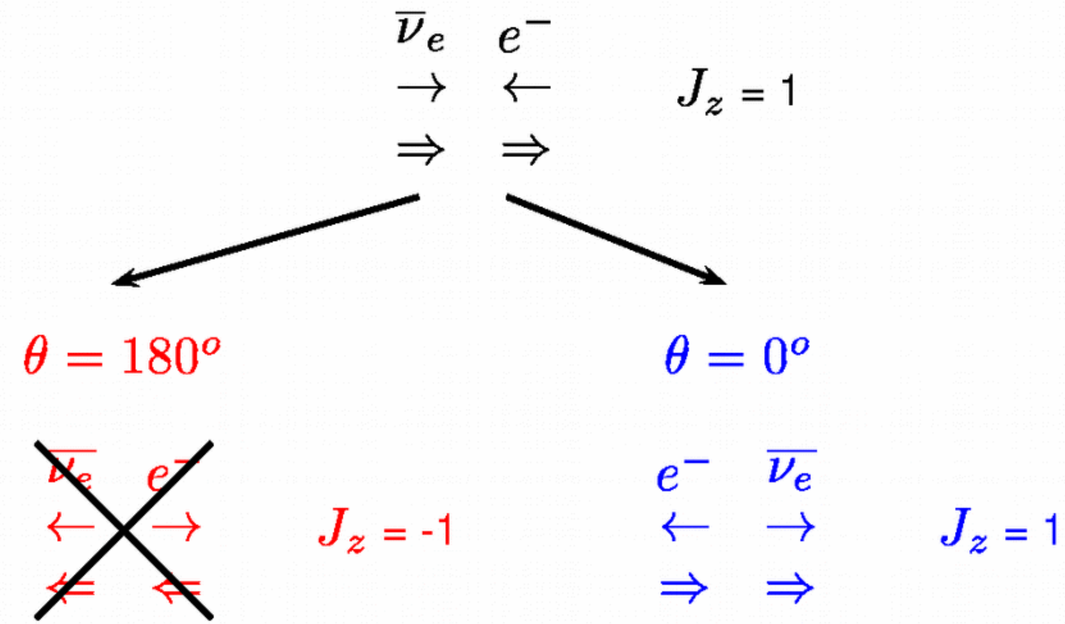
Angular distribution of antineutrino-fermion scattering

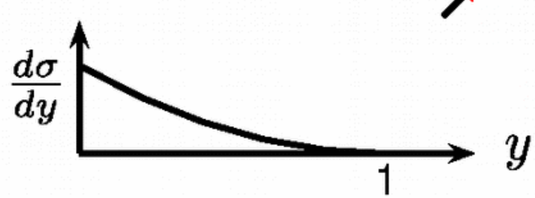
Antineutrino-fermion scattering (neglect NC):



$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2} \cdot s \cdot (1-y)^2$$

angular dependence:





y- distribution $\Rightarrow \sigma_{\overline{\nu}l} = 1/3 \cdot \sigma_{\nu l}$

y distribution is not flat for $\overline{\nu}$l scattering !

Deep inelastic (anti)neutrino-nucleon scattering

Average: $\langle (1-y)^2 \rangle = 1/3$

$\Rightarrow$ expect: $\sigma^{\nu l} = 3\sigma^{\bar{\nu} l}$ and $\sigma^{\nu N} = 3\sigma^{\bar{\nu} N}$

Experiment:

$\sigma^{\nu l} = 3\sigma^{\bar{\nu} l}$, but $\sigma^{\nu N} \approx 2\sigma^{\bar{\nu} N} < 3\sigma^{\bar{\nu} N}$

From helicity arguements we deduce for the y distribution and for σ_{tot}:

$\bar{\nu}\, q = \nu\, \bar{q}$ and $\nu\, q = \bar{\nu}\, \bar{q}$

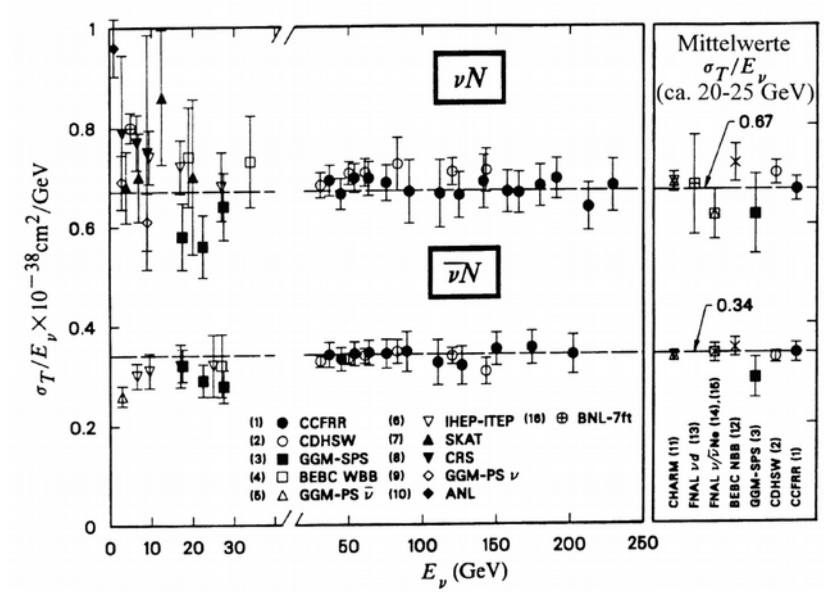
$$\frac{d^2\sigma^{\nu N}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi}\left(q(x) + (1-y)^2 \bar{q}(x)\right)$$

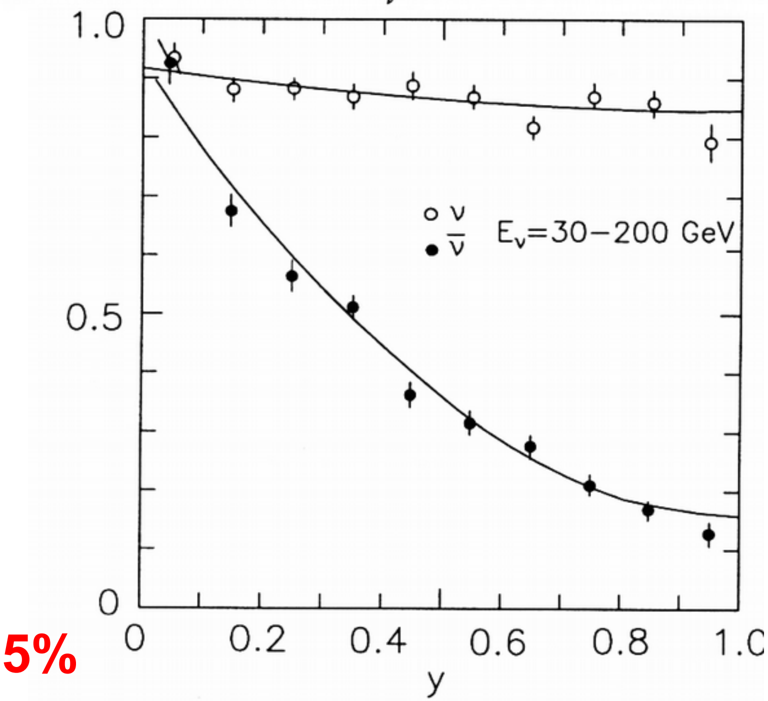
$$\frac{d^2\sigma^{\bar{\nu} N}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi}\left(\bar{q}(x) + (1-y)^2 q(x)\right)$$

with $q(x) = x\,(u(x) + d(x) + s(x) + ...)$

with $\bar{q}(x) = x\,\left(\bar{u}(x) + \bar{d}(x) + \bar{s}(x) + ...\right)$

$\Rightarrow$ Sea quark fraction $\bar{q}(x)$ in nucleon is about 15%





figures: Perkins: Introduction to High Energy Physics, Cambridge

Neutrino sources and energy spectra

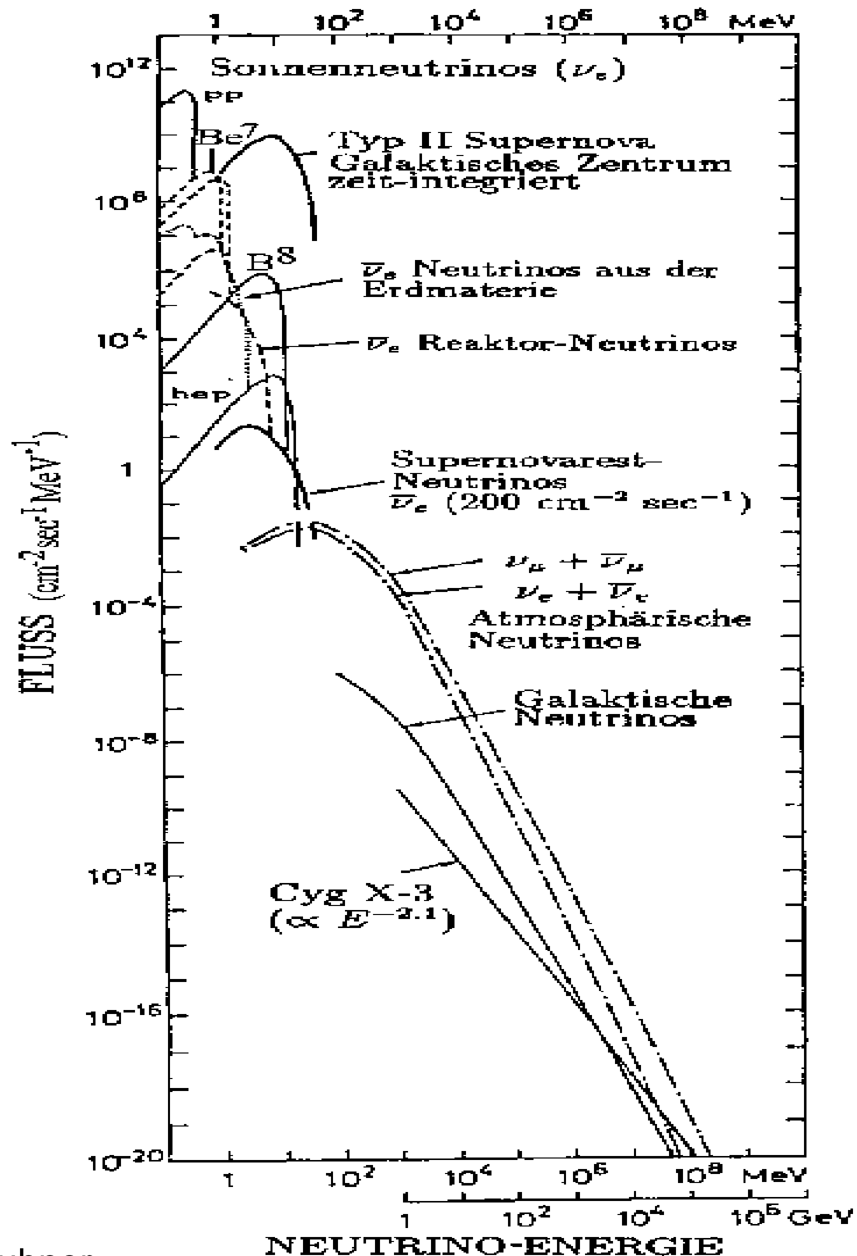


figure: Schmitz: Neutrinophysics, Teubner

Summary of neutrinos in the Standard Model of particle physics

- ν's are left-handed,
  charged fermions in CC reactions ($W^{+/-}$ exchange) are also left-handed
  charged fermion coupling to the Z^0 is more complicated
  (since the Z^0 is a superposition of the „hypercharge photon B“ and the W^3)

- ν's are massless,
  since there is no right-handed neutrino to construct a „Dirac mass term“

$$\mathcal{L} = - m \overline{\Psi}_L \Psi_R - m \overline{\Psi}_R \Psi_L$$

- ν's have very small cross section (due to the large masses of W and Z)

Neutrino physics: experiments

The dark side of the Universe, ISAPP, MPIK Heidelberg, May 29/30, 2019

Christian Weinheimer

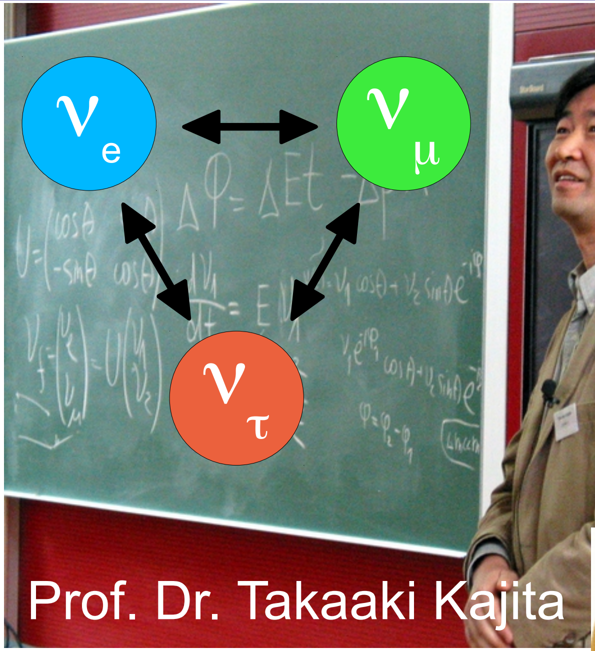
Institut für Kernphysik, Westfälische Wilhelms-Universität Münster
weinheimer@uni-muenster.de

A reminder: Neutrinos
in the Standard Model of Particle Physics

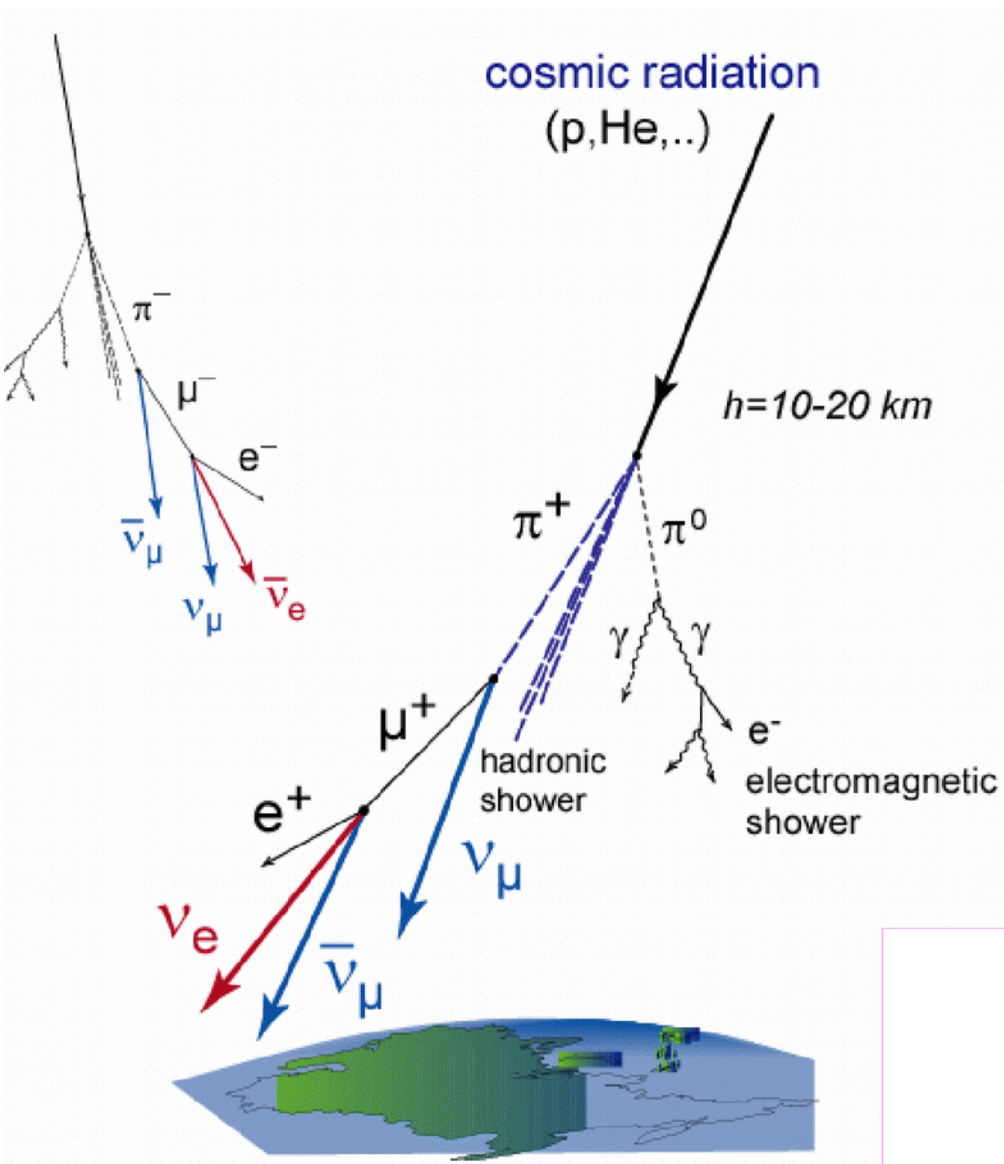
Neutrino oscillations:
experiments with atmospheric,
solar, accelerator and reactor neutrinos

Neutrino masses:
- cosmology and astrophysics
- neutrinoless double β decay
- direct neutrino mass experiments

Search for sterile neutrinos
Coherent neutrino nucleus elastic scattering

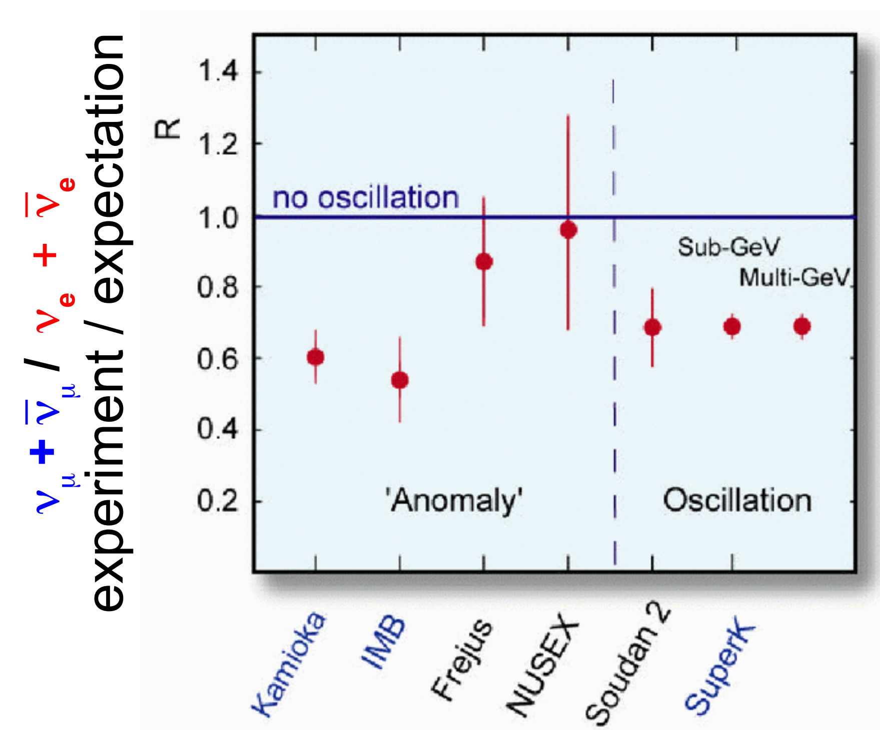


Atmospheric neutrino anomaly: too few muon neutrinos



Interaction of cosmic rays (p,α, ..)
in outer atmosphere: $\Rightarrow \pi^{\pm}$, $K^{\pm}$,...

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\rightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$
$$\rightarrow e^{-} + \nu_{\mu} + \bar{\nu}_{e}$$
$$\Rightarrow \quad \nu_{\mu} + \bar{\nu}_{\mu} \,/\, \nu_{e} + \bar{\nu}_{e} \geq \mathbf{2}$$



Kamioka Nucleon Decay Experiment: KamiokaNDE (II)

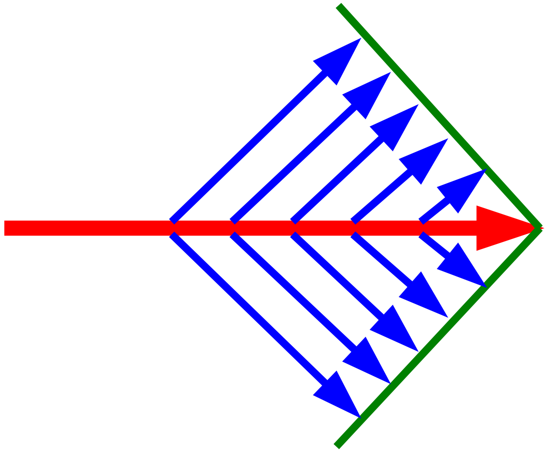
3000 t water Cherenov detector to search for proton decay (→ GUT)

16m high, 16m diameter
1000 38cm PMTs at the surface

If a charged particle moves faster than speed of light in the medium, polarisation does not follow:

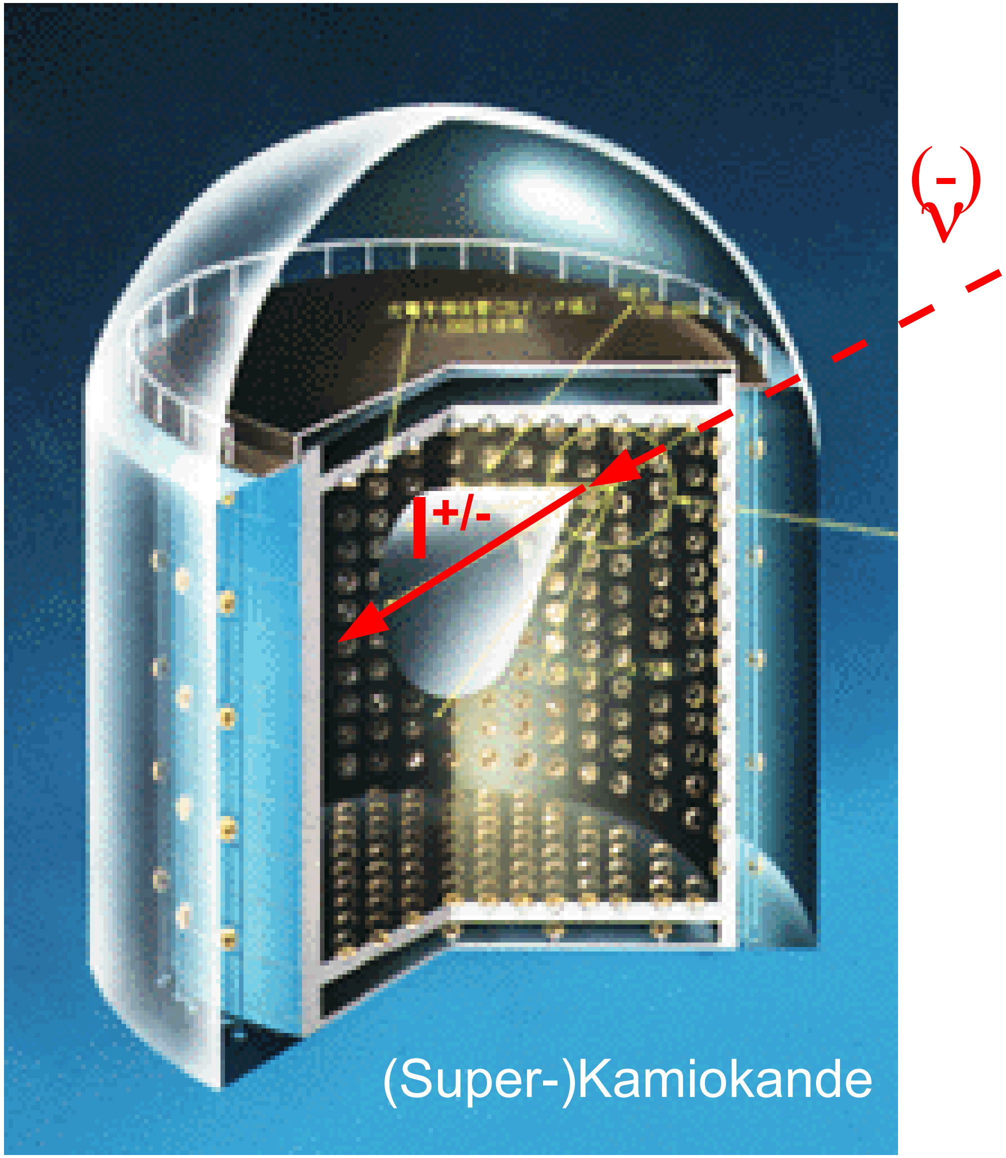
→ Emission of Cherenkov-light into a cone:

$\cos\theta = 1/\beta n$
(→ 42^o for H_20 assuming β=v/c → 1)



→ ring structure at wall covered by PMTs

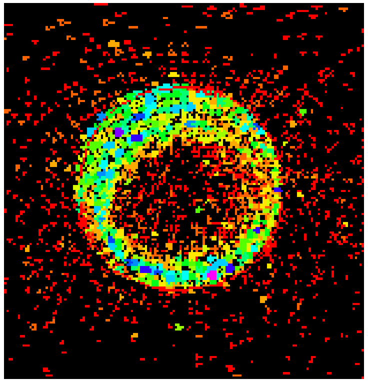
Atmospheric neutrinos in a water Cherenkov detector



Cherenkov cone gives:

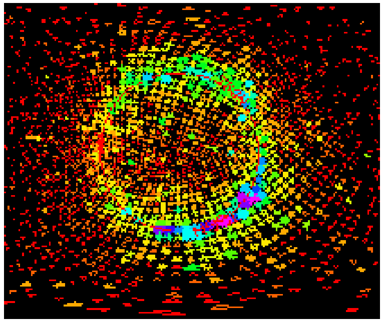
- energy
- direction
- electron/muon differentiation:

muons: sharp ring



electrons: washed-out ring

(multiple scattering, em shower)



Physics results of KamiokaNDE II

No observation of proton decay → main mission failed

but KamiokaNDE II performed extremely well, e.g.

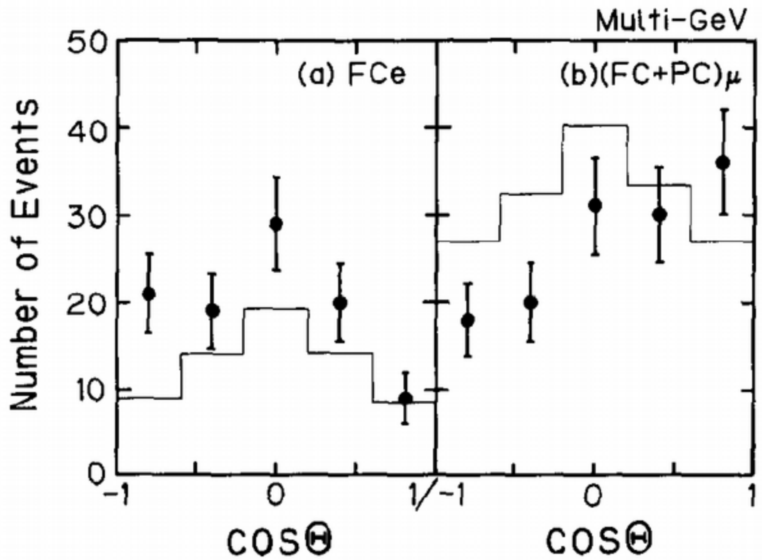
- Discovery (together with IMB) of neutrinos from SN1987a

  → Nobel prize 2002 to Masatoshi Koshiba

- confirmation of nuclear burning in the sun
  by observing solar neutrinos

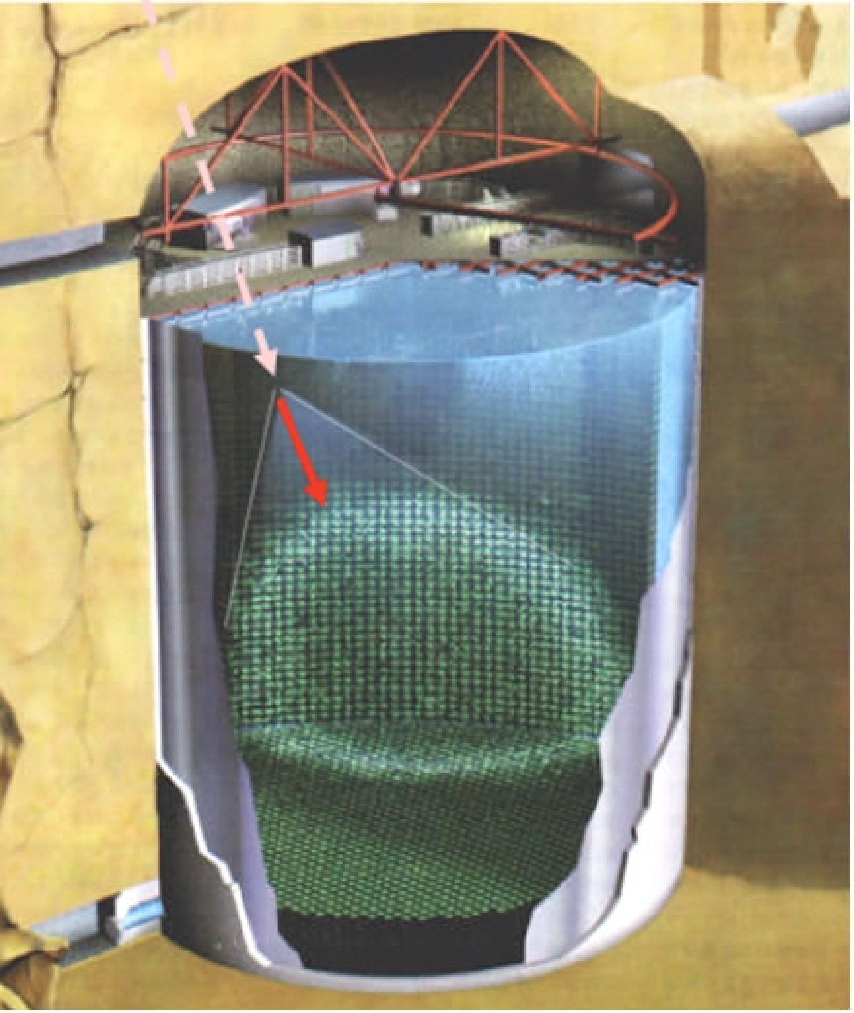
- atmospheric neutrino anomaly:
  wrong muon neutrinos/electron neutrino ratio
  & wrong angular distribution

  Y. Fukuda et al., Phys. Lett. B 335 (1994) 237



→ decision to build Super-Kamiokande

Super-Kamiokande: Start of data taking in April 1996



water Cherenkov detector

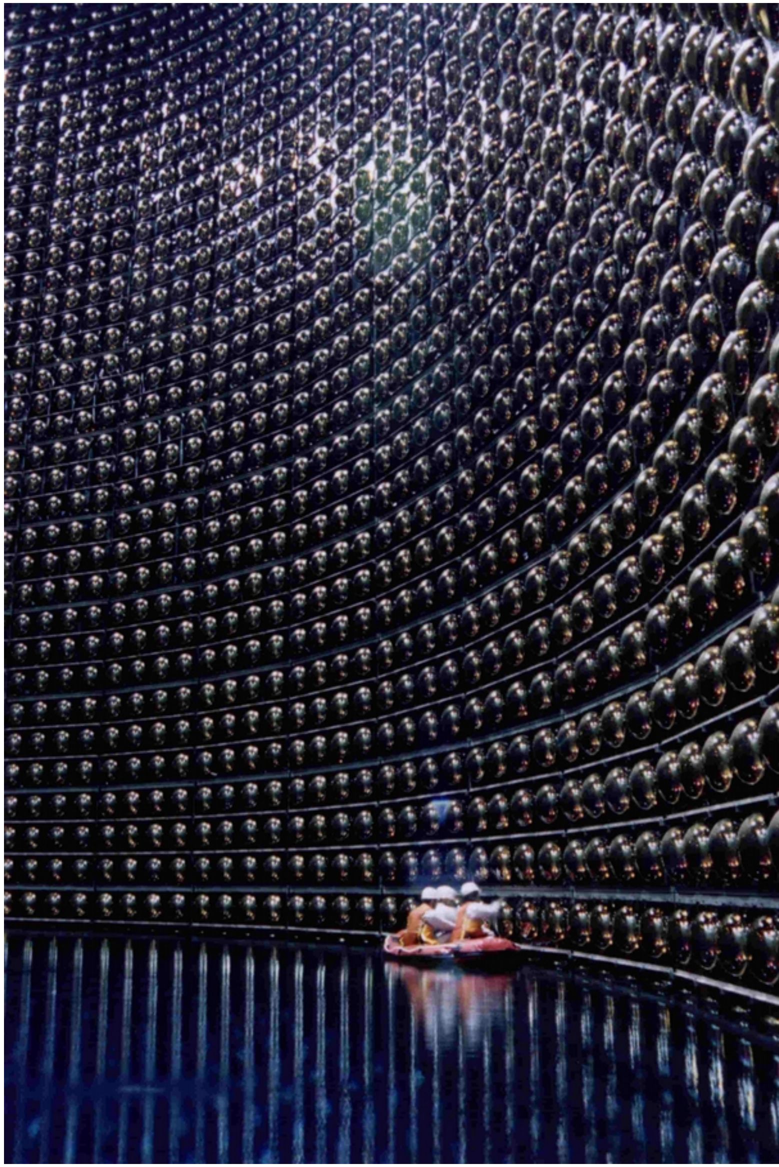
H_2O: 50 000 t

40 m high,

40 m ⌀

11146 PMTs
a 50 cm ⌀

1 km overburden
in Kamioka Mine,
Japan



Super-Kamiokande's first result at Int. Conf. Neutrino 1998 at Takayama

@Takayama 1998

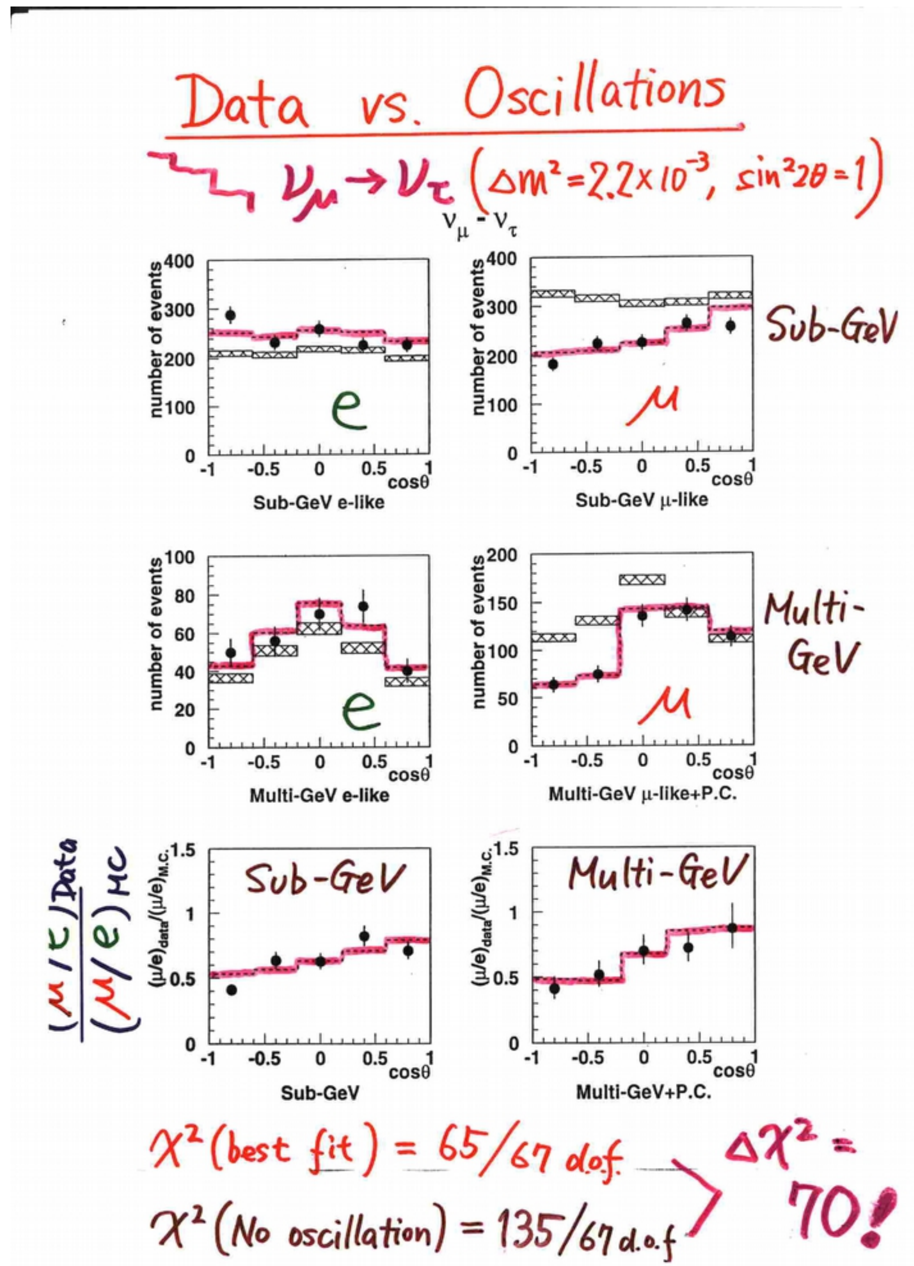
Atmospheric neutrino results from Super-Kamiokande & Kamiokande

— Evidence for ν_μ oscillations —

T. Kajita

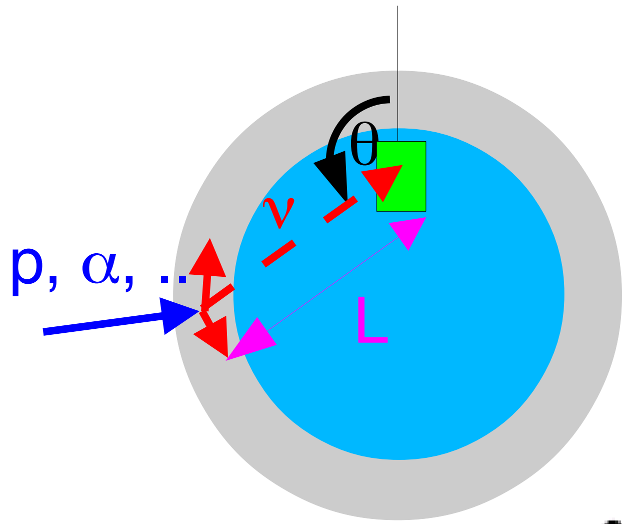
Kamioka observatory, Univ. of Tokyo

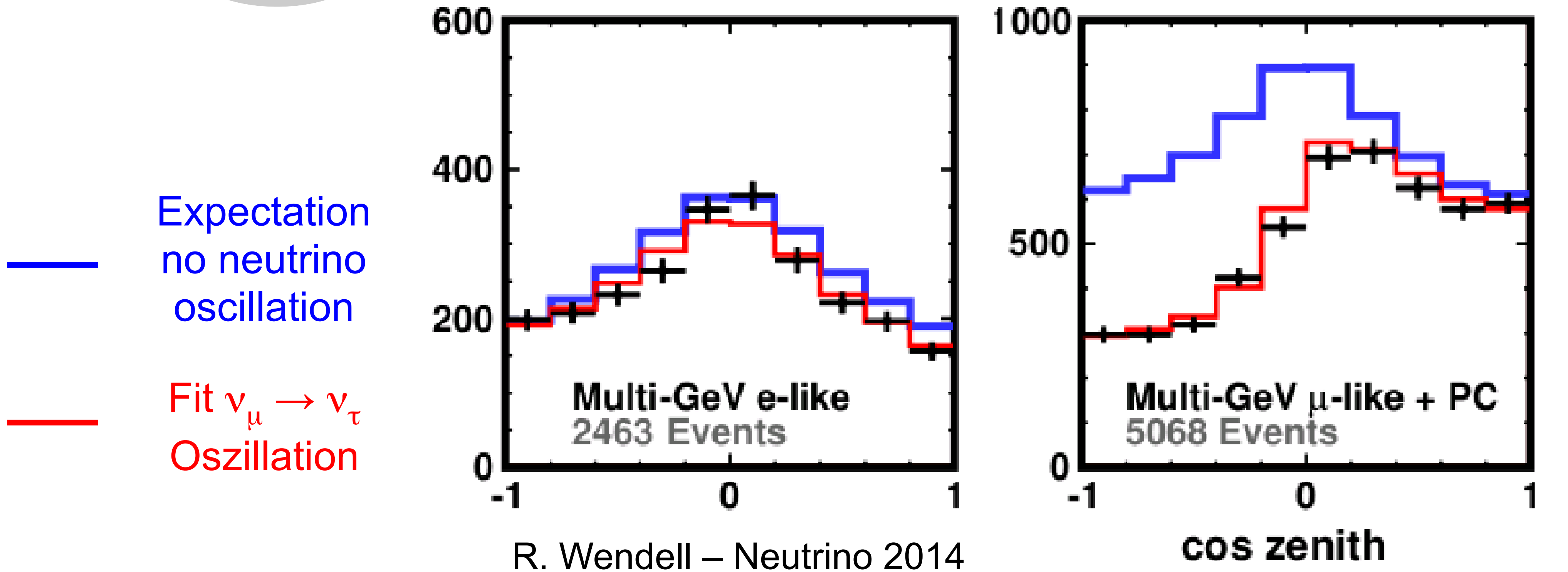
for the {Kamiokande / Super-Kamiokande} Collaborations



Nobel prize 2015 to Takaaki Kajita

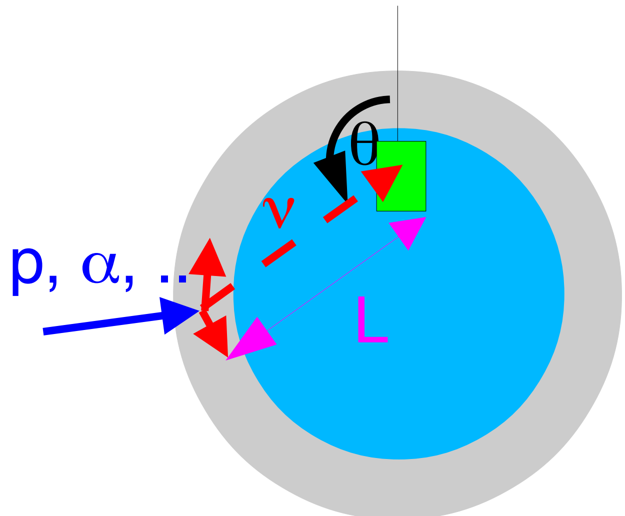
Angular distribution of ν_e and ν_μ at SK





R. Wendell – Neutrino 2014

Angular distribution of ν_e and ν_μ at SK



⇒ Clear deficit of muon neutrinos coming from below, (i.e. muon neutrino which travelled a long distance)

Measurement is compatible to neutrino oscillation:

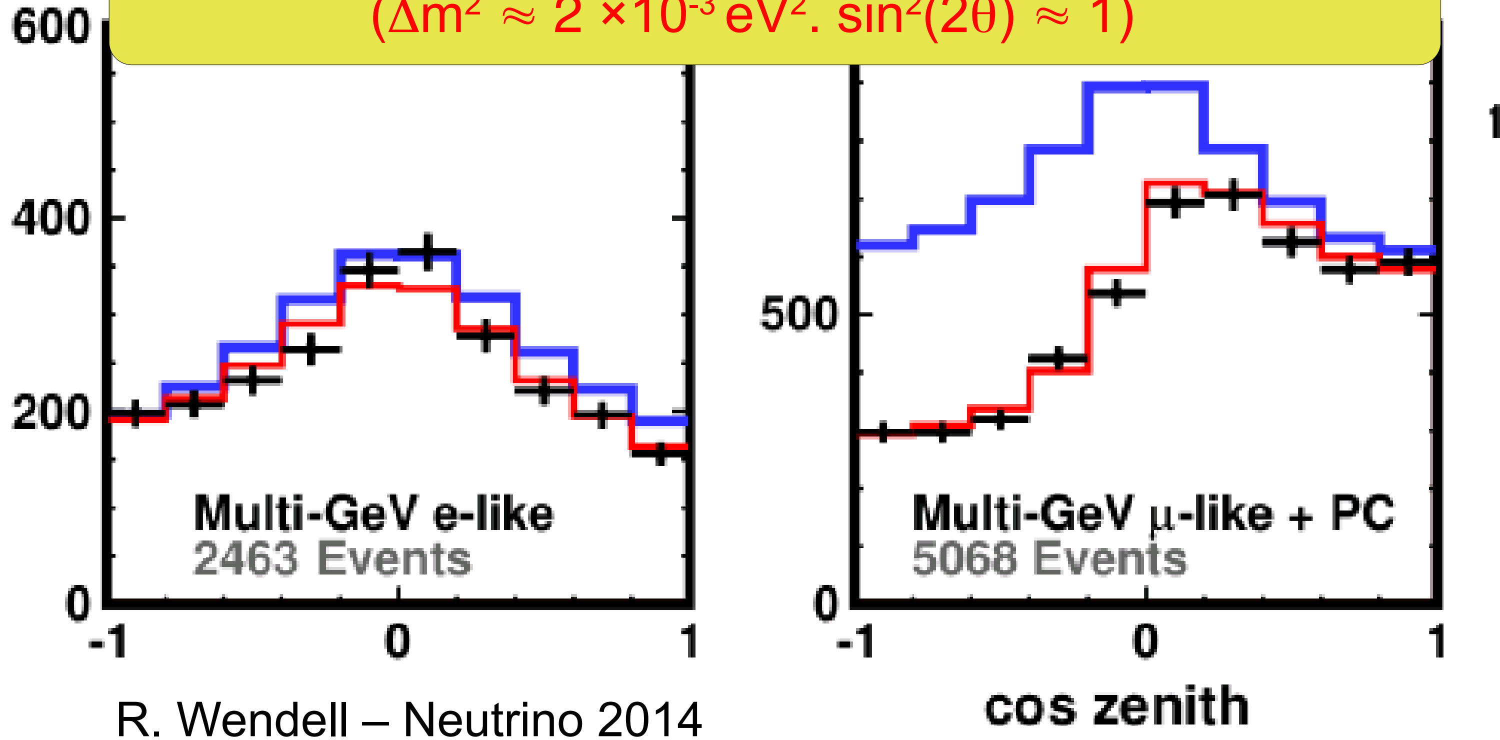
$\nu_\mu \rightarrow \nu_\tau$ (detector is nearly blind for ν_τ)

„Neutrino oscillation“ with parameters

($\Delta m^2 \approx 2 \times 10^{-3}\,\text{eV}^2$. $\sin^2(2\theta) \approx 1$)

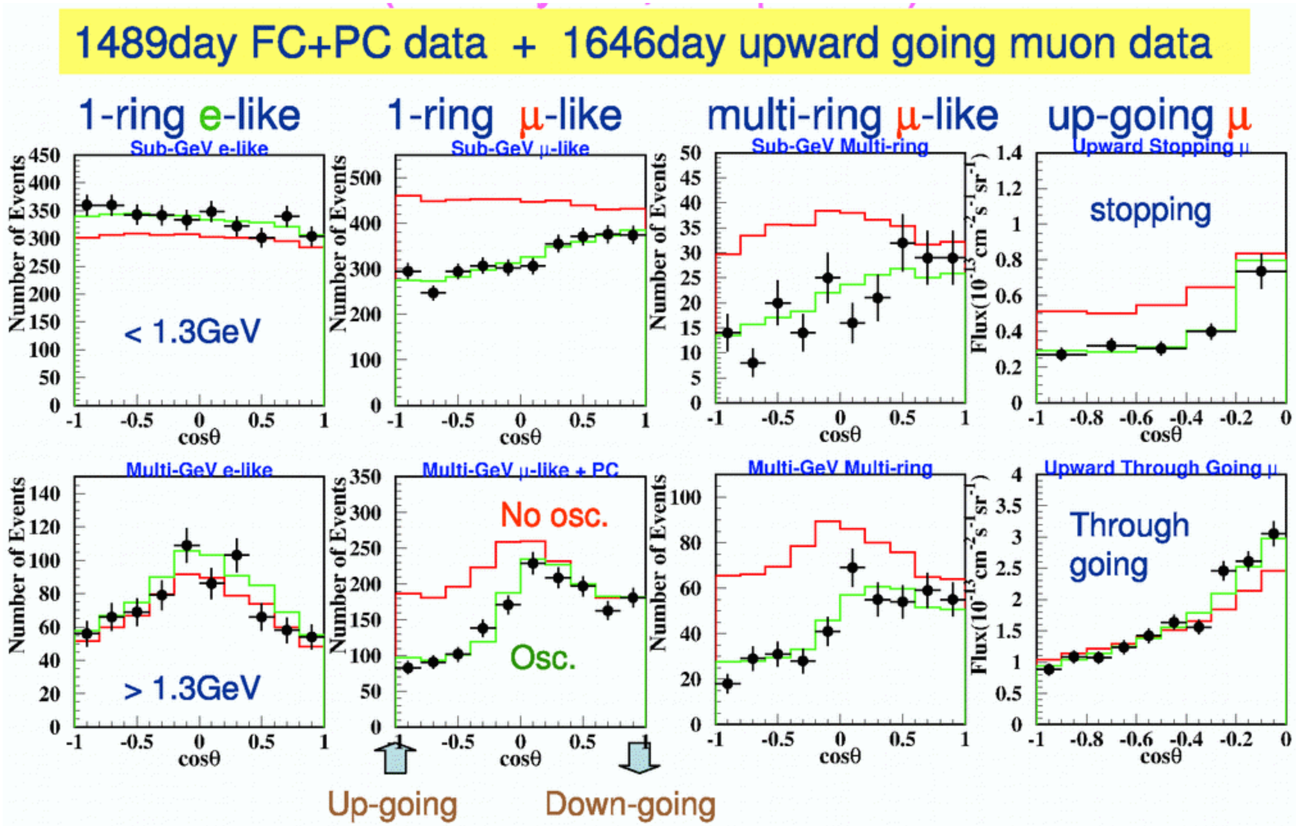
Expectation no neutrino oscillation

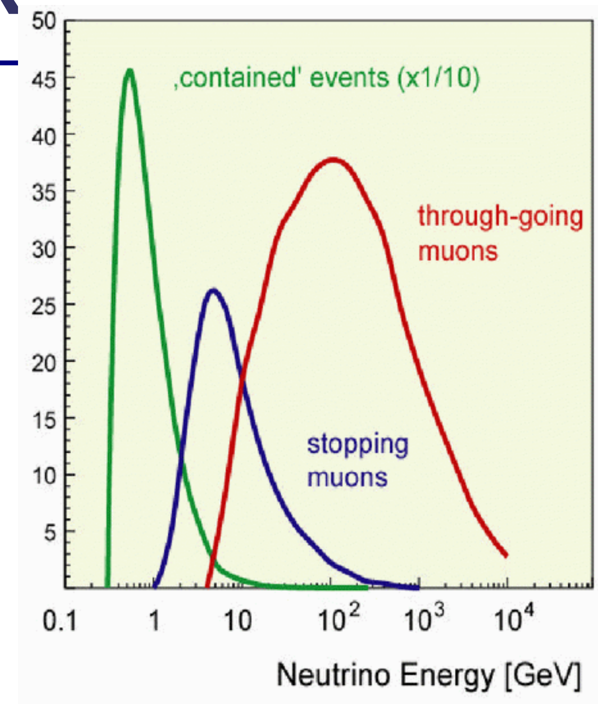
Fit $\nu_\mu \rightarrow \nu_\tau$ Oszillation

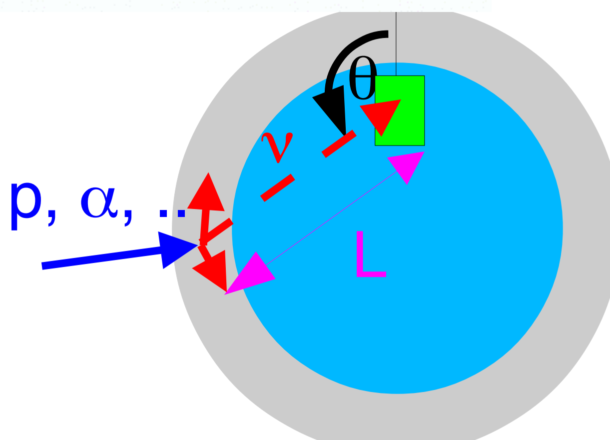


R. Wendell – Neutrino 2014

Angular distribution of ν_e and ν_μ at SK

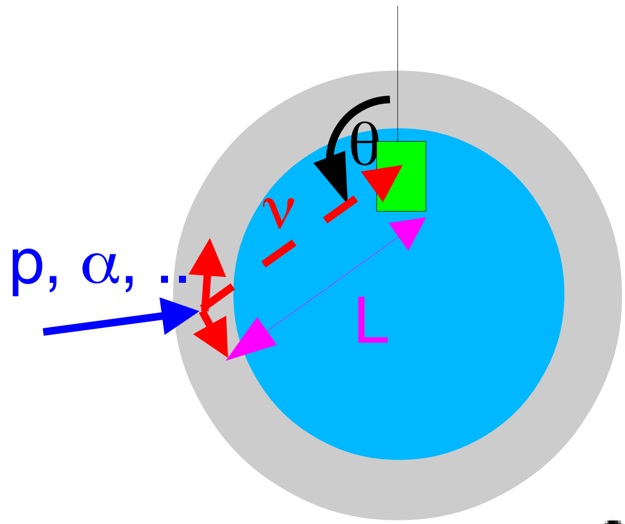






All data sets and analyses (FC, PC, up-going μ, NC enhanced): compatible with $\nu_\mu \rightarrow \nu_\tau$ oscillation ($\Delta m^2 \approx 2 \times 10^{-3}\,eV^2$, $\sin^2(2\theta) \approx 1$)

Angular distribution of ν_e and ν_μ at SK

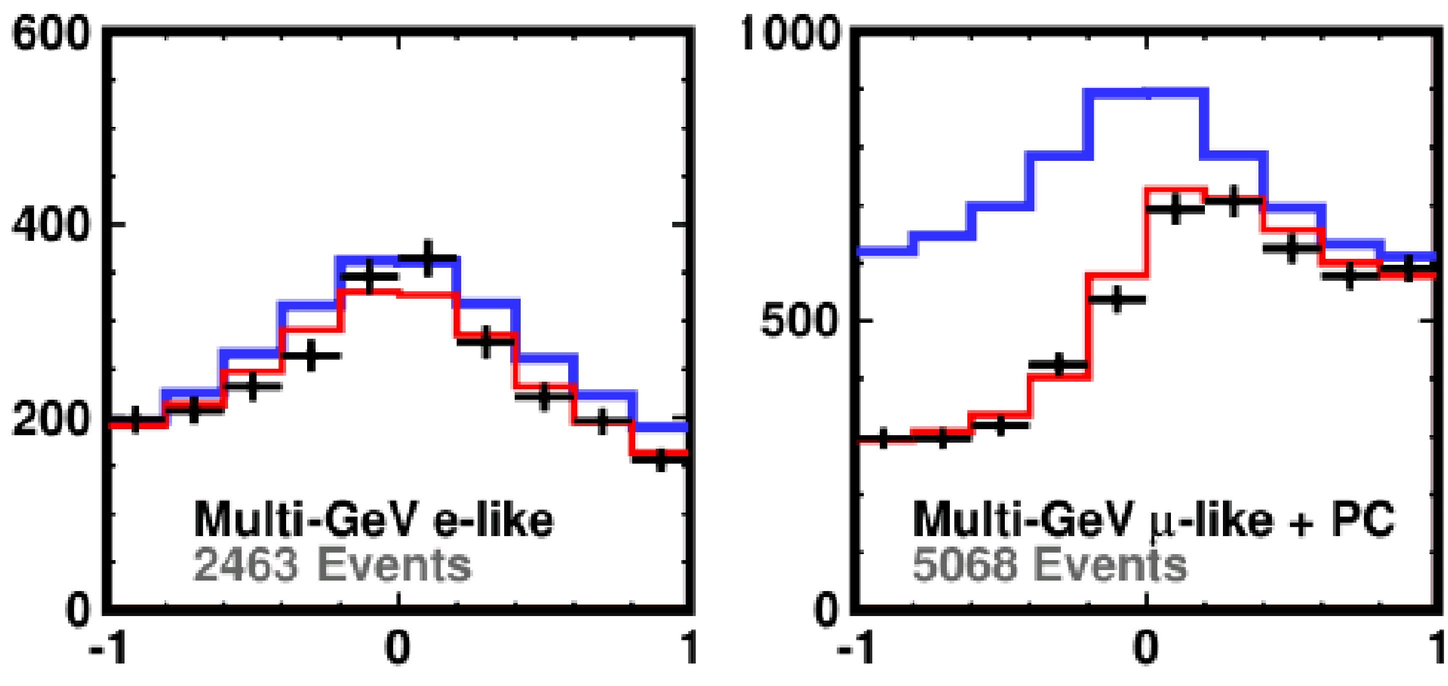


Question to think about:

What is the connection of the expected multi-GeV angular distributions of atmospheric neutrinos with the red sky at sun rise or sun set ?

Expectation no neutrino oscillation

Fit $\nu_\mu \rightarrow \nu_\tau$ Oszillation



R. Wendell – Neutrino 2014

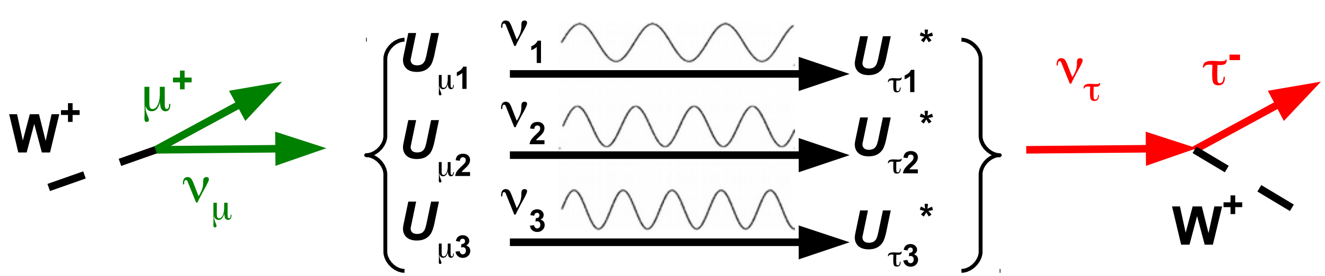
Neutrino (vacuum) oscillations

1) non-trivial unitary ν mixing matrix *U* between neutrino flavour states (ν_e, ν_μ, ν_τ) and mass states (ν_1 ν_2 ν_3):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 states mixing

2) a flavour state propagates as a coherent sum of mass states $m(\nu_i)$ if the $m(\nu_i)$ differ ⇒ neutrino oscillation



Triple slit experiment

creation of a ν_μ via weak interaction

propagation as coherent superposition of mass states

detection of a ν_τ via weak interaction

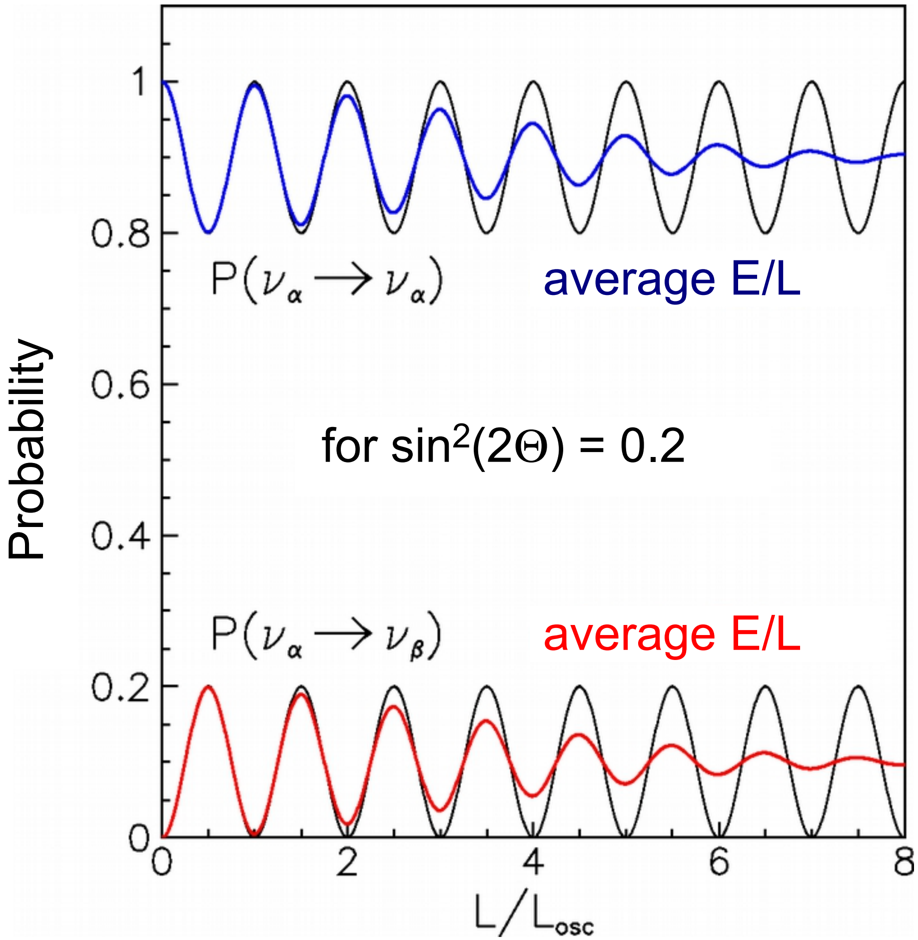
$$\mathbf{P}(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\alpha i}\, e^{-iE_i t}\, U^*_{\beta i} \right|^2 = \underbrace{\sin^2(2\theta) \cdot \sin^2 \frac{|m_2^2 - m_1^2| \cdot L}{4E}}_{\text{2 flavor mixing}}$$

Formula is correct, but correct derivation needs wave packages or QFT (see E. Akhmedov)

Neutrino (vacuum) oscillations

2 Flavor case:

$\sin^2(2\Theta)$



$\sin^2(2\Theta)$

Probability for an oscillation from ν_α to ν_β (and back) for an amplitude value of $\sin^2(2\theta) = 0.2$ in units of the oscillation length L_{osc}.

The colored curves take into account that we don't have sharp values for E and L, but that these are smeared out over a certain distribution.

3 Flavor mixing:

General oscillation formula

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\beta i} \exp^{-i(E_i t)} U^*_{\alpha i} \right|^2$$

Atmospheric neutrinos: really neutrino oscillation ?

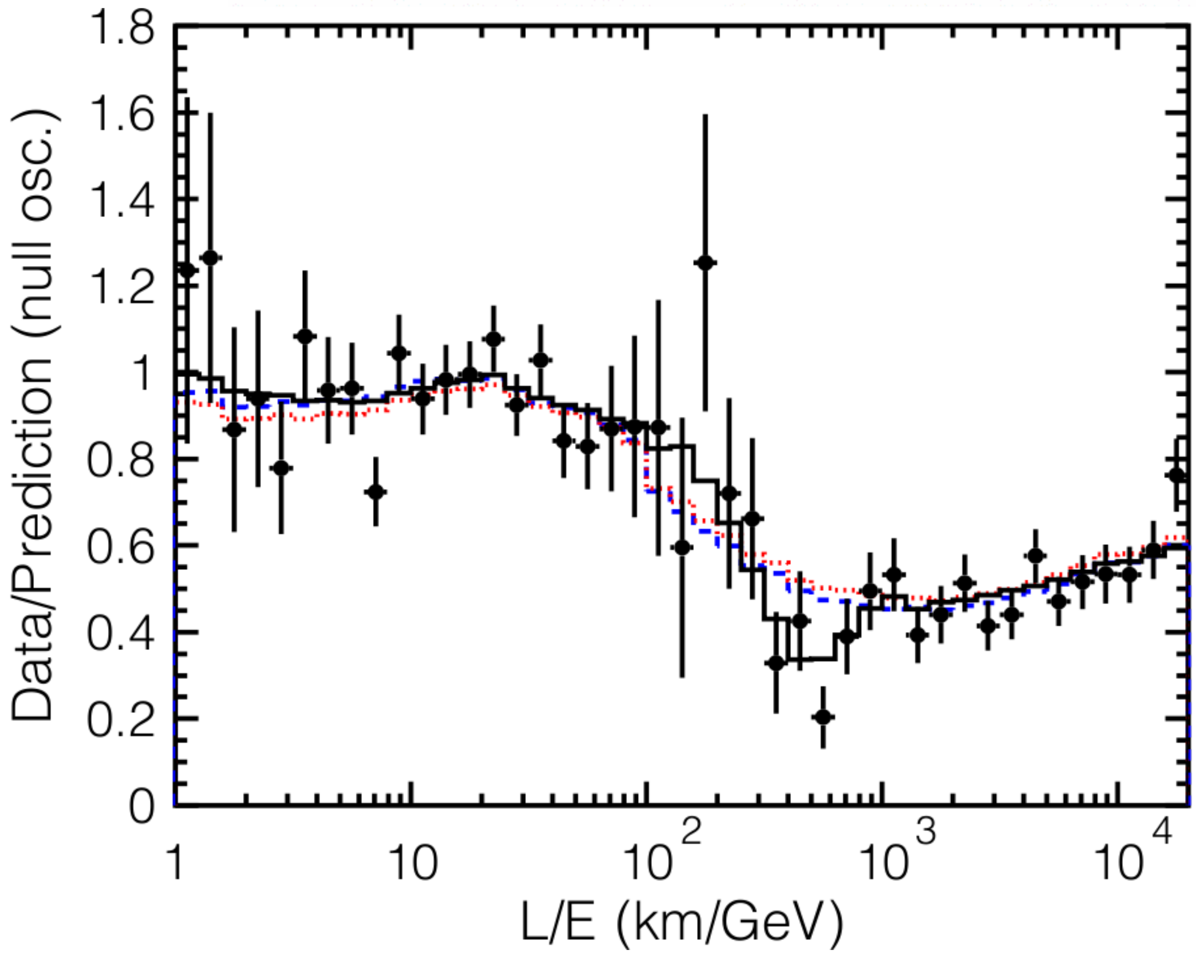
Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \times \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E}))$

here black

here blue



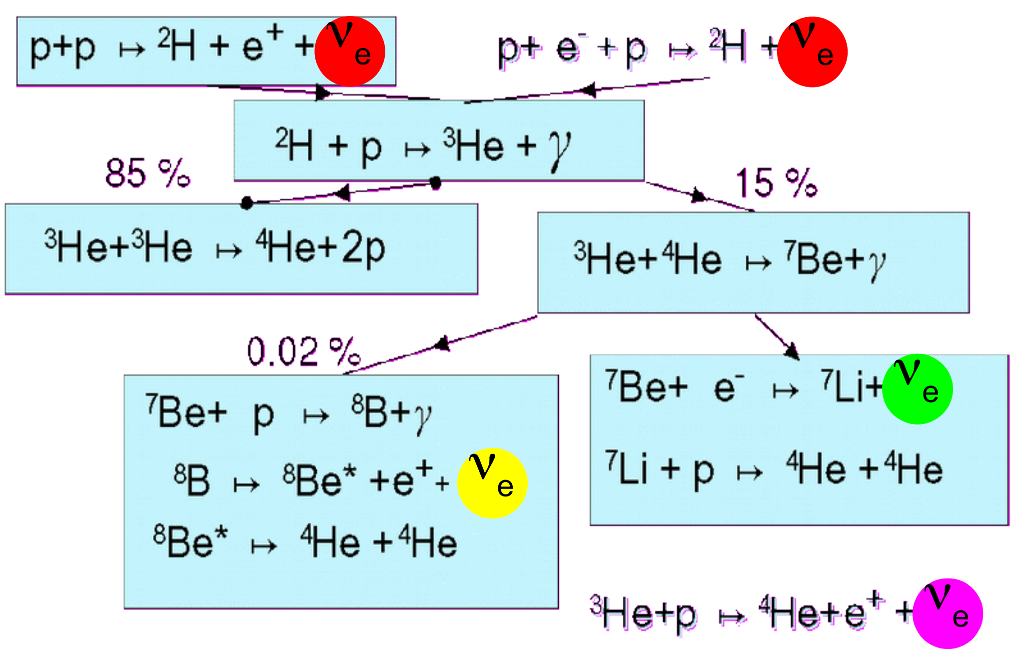
Y. Ashie et al. (Super Kamiokande) Phys.Rev.Lett.93:101801,2004

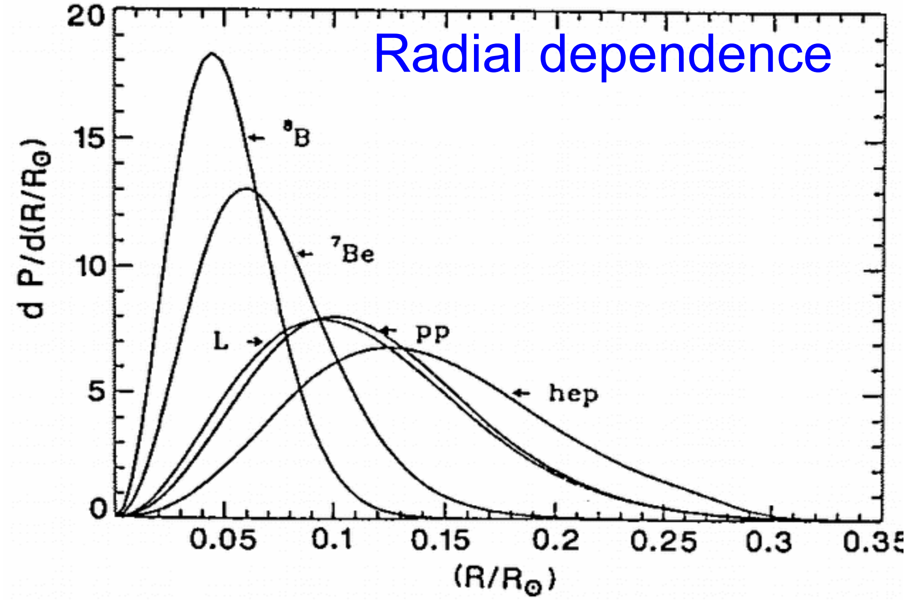
Neutrinos from the sun

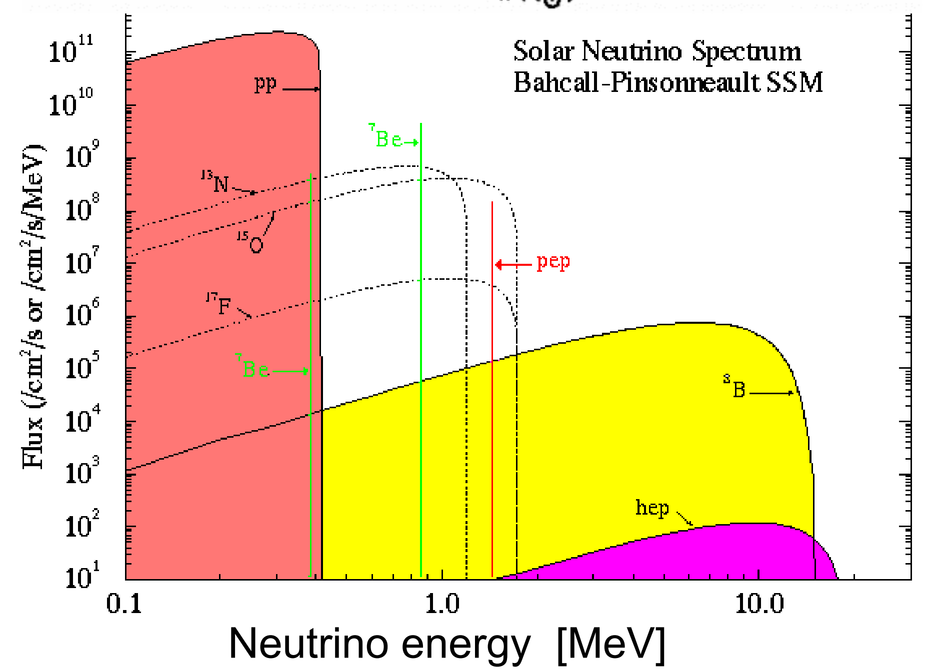
Nuclear fusion in sun core:

$4\,p \rightarrow {}^4He + 2e^+ + 2\nu_e$ (+ 26.7 MeV)

more correct:







on earth surface:

65 billion of neutrinos per s and cm²

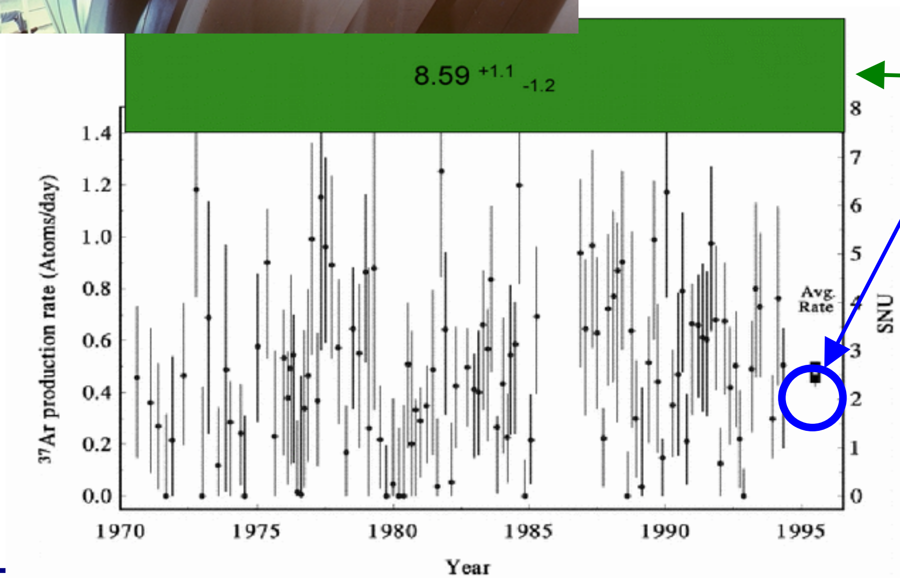
The Homestake experiment by Ray Davis

380 000 l
perchloro-ethylene
in the Homestake Mine

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Bubbling out of the ^{37}Ar (0.5 atoms/d)
and radiochemical detection

Nobel award 2002



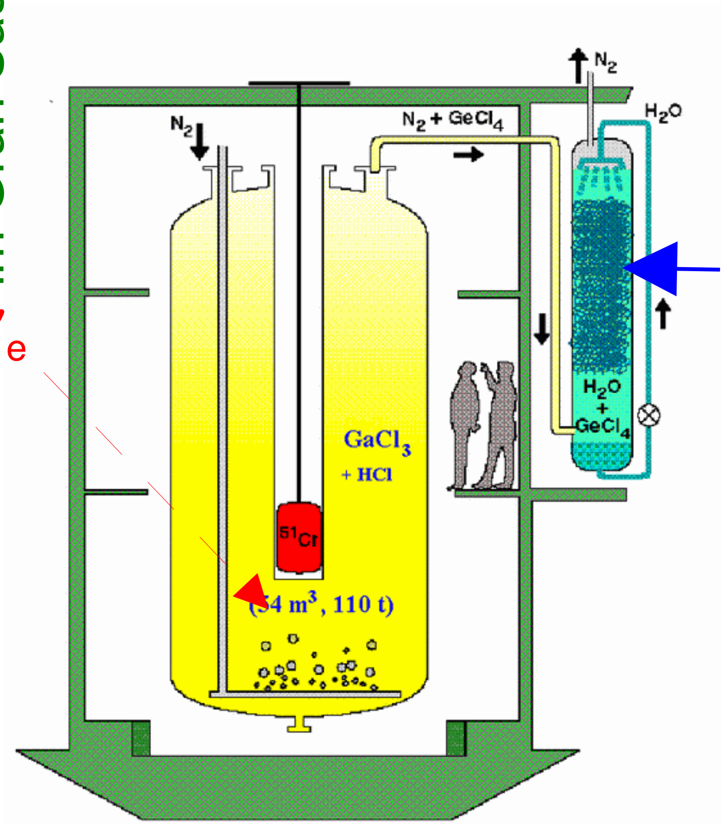
Result is only 30% of expectation

- Is the experiment wrong ?
- Is the theory of the sun wrong ?
- Do the neutrino behave differenctly ?

GALLEX and other gallium experiments

- GALLEX (later GNO), SAGE):
  Inverse β decay of solar ν_e on Gallium (^{71}Ga) (110 t)

GALLEX ν_e im Gran Sasso



$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

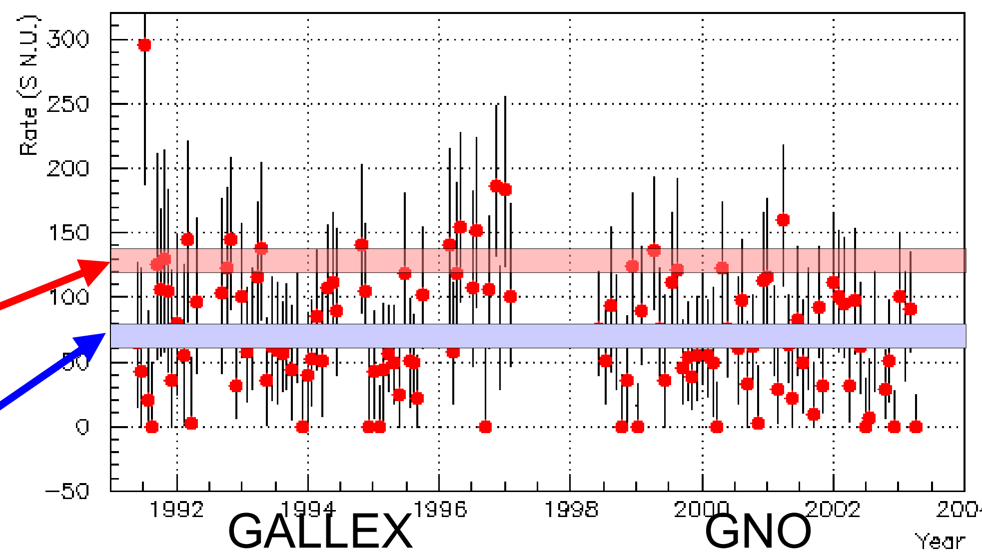
sensitive to pp neutrinos

radiochemical detection of ^{71}Ge:

1) Chemical separation of ^{71}Ge
2) Detection of decay back to ^{71}Ga

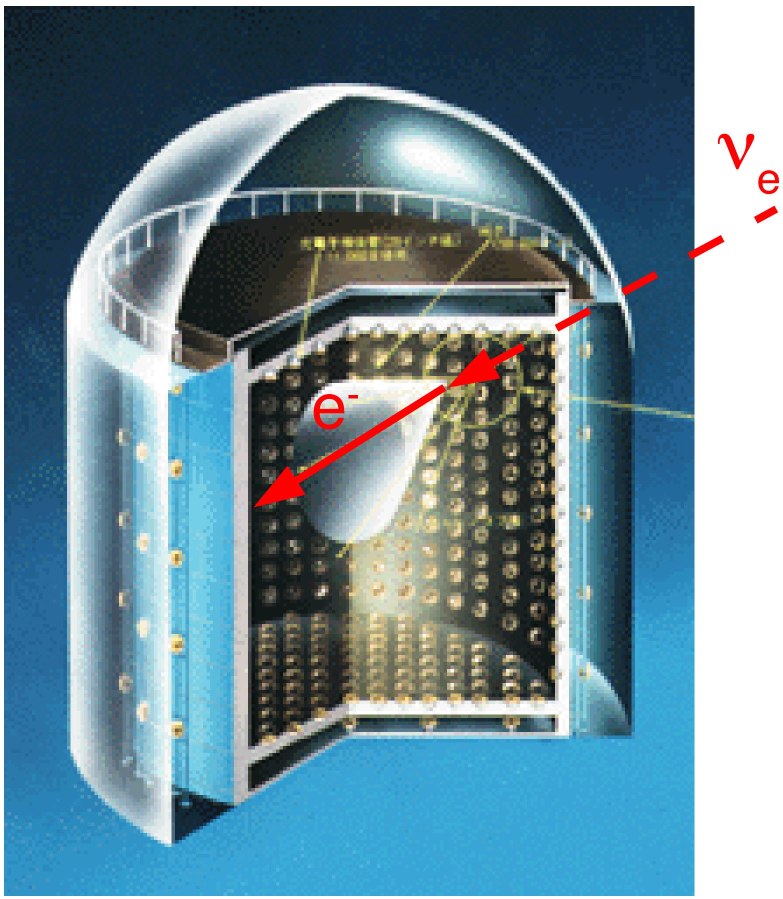
Detection efficiency ≈ 90 % (checked with ν source)

SSM(BP)	128 $^{+9}_{-7}$	SNU
GALLEX	77.5 ± 6.2 $^{+4.3}_{-4.7}$	SNU
GNO	62.9 ± 5.4 ± 2.5	SNU
SAGE	69.1 $^{+4.3}_{-4.2}$	SNU



Solar neutrinos at Super-Kamiokande

Different to atmospheric neutrinos: $\nu_e + e^- \rightarrow e^- + \nu_e$ (elastic $\nu_e e^-$ scattering)



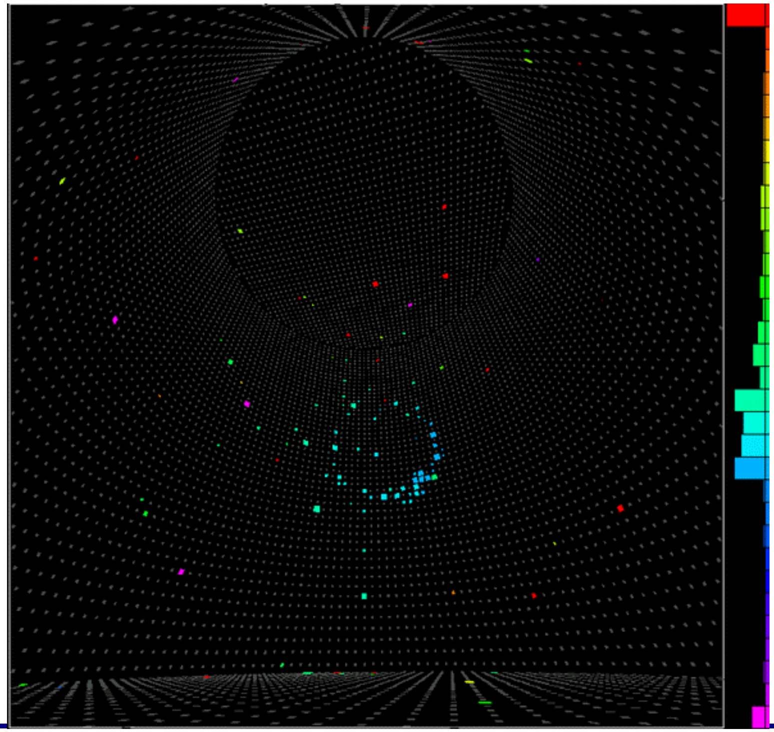
Detection of neutrinos:

ν_e creates an e^-

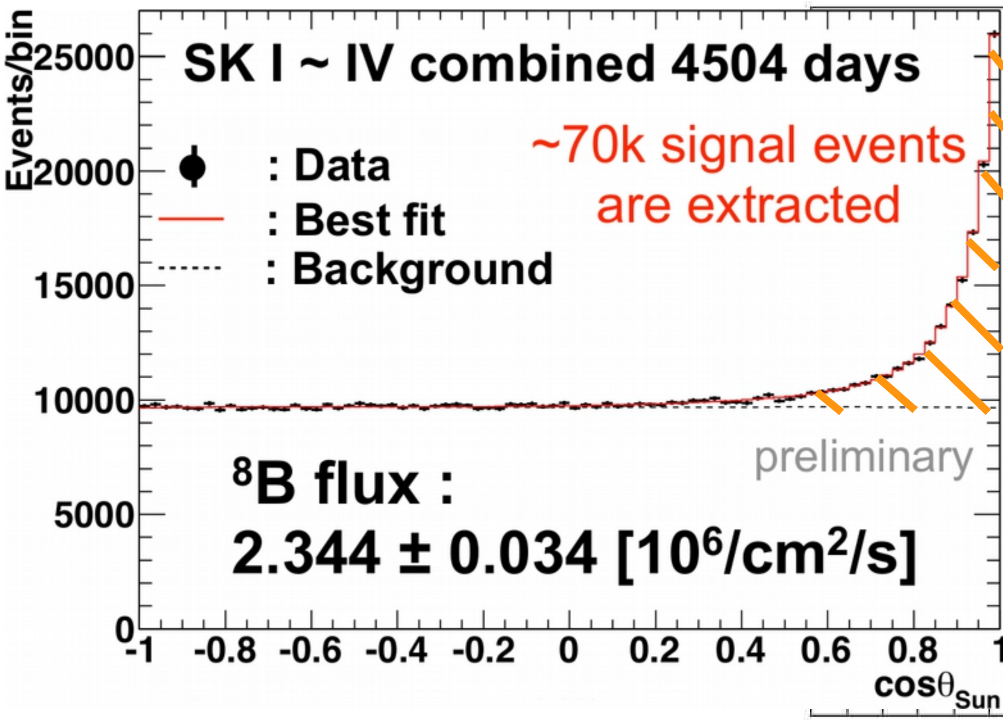
$v(e^-) > c/n$

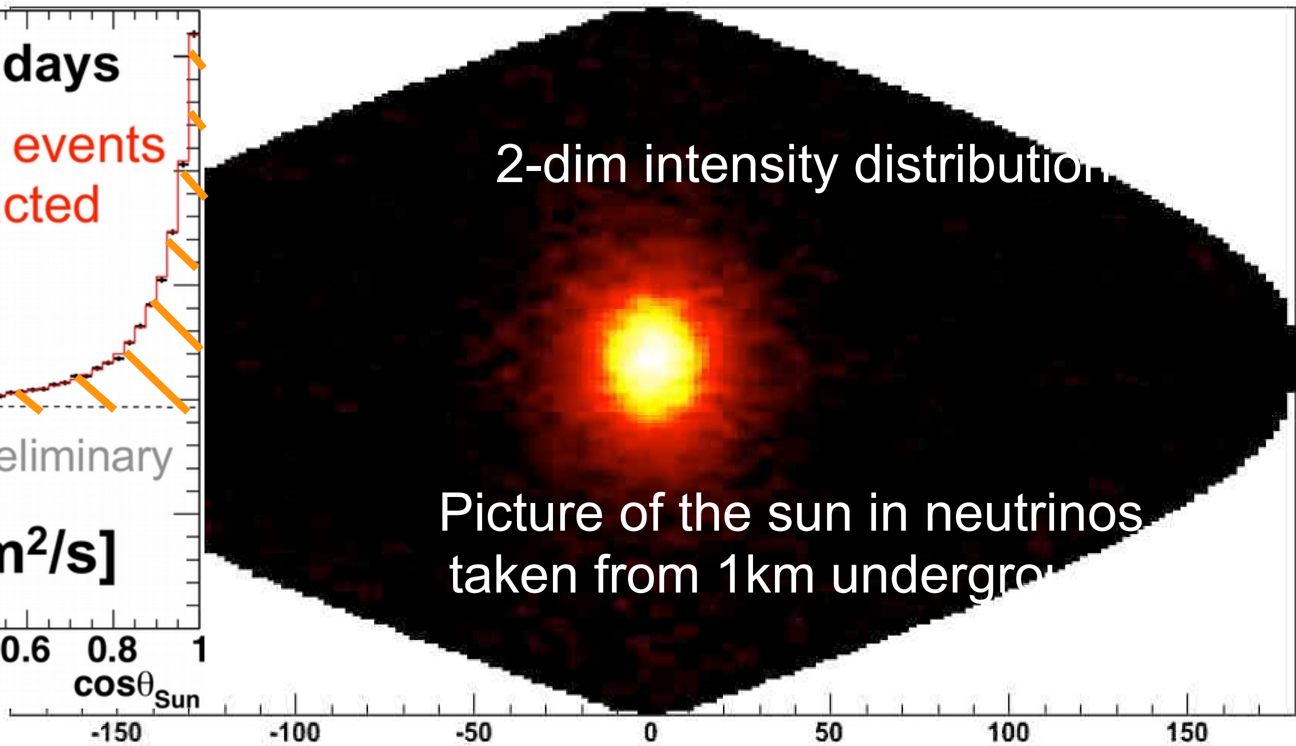
Cherenkov cone:

$\Rightarrow$ direction and energy



Determination of signal: angular distribution





Y. Koshio – Neutrino 2014

⇒ ν_e are really coming from the sun

(first direct proof of nuclear fusion in the core of the sun by Kamiokande in 1990)

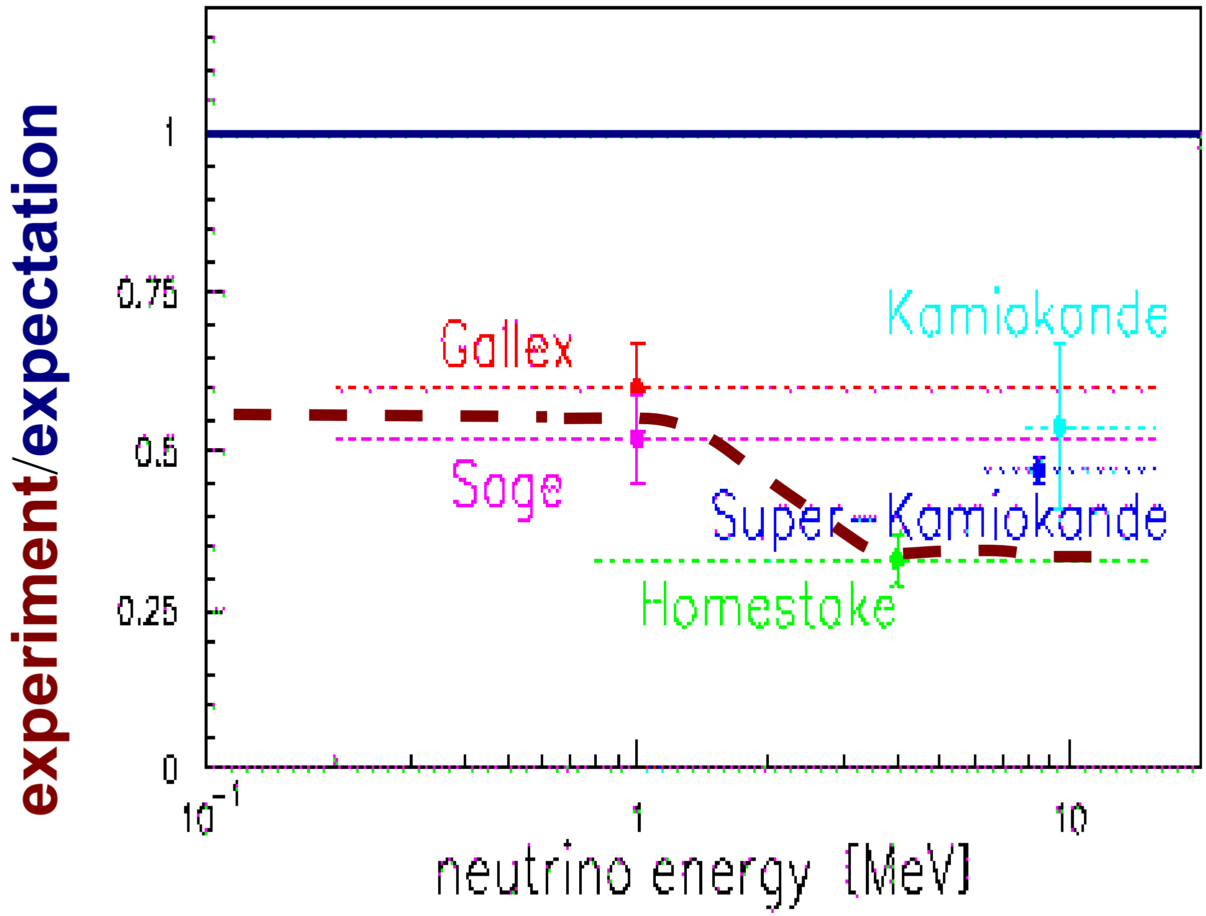
but there are too few: $\#\nu_{measured} / \#\nu_{expected} = 0.45$ (0.34 considering NC: $\nu_{\mu\tau} + e^- \rightarrow \nu_{\mu\tau} + e^-$)

Solar neutrino puzzle

Solar neutrino deficit:

Expectation from nuclear fusion: $4\,p \rightarrow {}^4He + 2e^+ + 2\nu_e$ (+ 26.7 MeV)

$\Rightarrow$ know ν_e rate from solar luminosity



Neutrino vacuum oscillation and solar neutrino problem

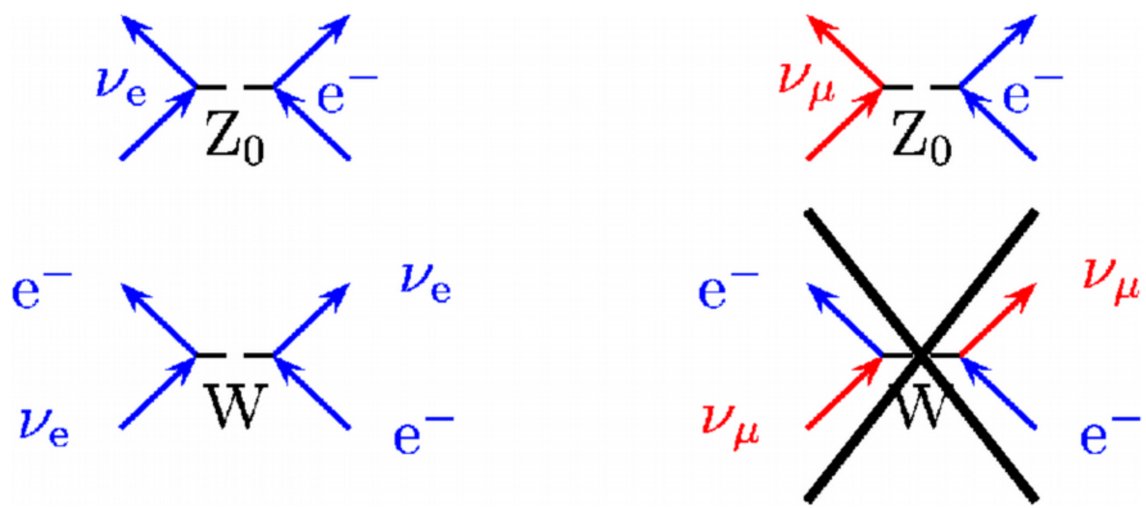
Strong reduction observed at chlorine experiment ($\approx$1/3 < 1/2)

$\Rightarrow$ distance sun-earth = $1.44 \cdot 10^{11}$ m $\approx \lambda_{osc}$, with $E_\nu \approx 10$ MeV

$\Rightarrow$ $\Delta m^2 = 10^{-10}\,eV^2$ ($\Rightarrow$ fine-tuning problem)

Solution: matter enhanced oscillation/ matter-enhanced flavor transitions (MSW effect, Mirkheyev-Smirnov-Wolfenstein)

Coherent forward scattering of ν on e^-



$\Rightarrow$ Different refraction index for ν_e and ν_μ

$\Rightarrow$ Different phase difference during propagation

$\Rightarrow$ Neutrino oscillation

Matter-enhanced neutrino oscillation: MSW effect

We want to desribe the MSW effect by adding a matter term to the Hamiltonian of the neutrino in vacuum:

$$\mathcal{H} = \sqrt{p^2 + m^2} \approx \underbrace{p}_{=:\,\mathcal{H}_0} + \underbrace{\frac{m^2}{2p}}_{=:\,\mathcal{H}_i}$$

We add now for the electron neutrino ν_e an additional term $\mathcal{H}_{CC}$, which describes the interaction of the electron neutrinos with the electrons possessing a density N_e:

$$\mathcal{H}_{CC} = \sqrt{2} G_F N_e .$$

When adding the normal Hamiltionian $\mathcal{H}$ to the additional Hamiltionian $\mathcal{H}_{CC}$ we have to consider that the former is usually written for neutrino mass eigenstates, the latter acts on neutrino flavour eigenstates.
We therefore use the unitary transformations:

$$U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \quad \text{bzw.} \quad U^{-1} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} .$$

Matter-enhanced neutrino oscillation: MSW effect

The part $\mathcal{H}_0$ does not play a role in our considerations and will be omitted in the following calculations:

$$
\begin{aligned}
\mathcal{H}_{tot} &= \underbrace{(\mathcal{H}_0)}_{\text{irrelevant for our consideration}} + \mathcal{H}_i + \mathcal{H}_{CC} \\
&= \underbrace{\begin{pmatrix} \frac{m_1^2}{2p} & 0 \\ 0 & \frac{m_2^2}{2p} \end{pmatrix}}_{H_i \text{ in mass basis}} + U^{-1} \underbrace{\begin{pmatrix} \sqrt{2} G_F N_e & 0 \\ 0 & 0 \end{pmatrix}}_{H_{CC} \text{ in flavour basis}} U \\
&= \begin{pmatrix} \frac{m_1^2}{2p} & 0 \\ 0 & \frac{m_2^2}{2p} \end{pmatrix} + \sqrt{2} G_F N_e \begin{pmatrix} \cos^2\theta & -\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \sin^2\theta \end{pmatrix} \\
&=: \begin{pmatrix} \frac{m_{1m}^2}{2p} & 0 \\ 0 & \frac{m_{2m}^2}{2p} \end{pmatrix} \quad \text{(by diagonalisation)}
\end{aligned}
$$

Thus the effective Hamiltonian $\mathcal{H}_{tot}$, can be described by effective neutrino masses in matter m_{1m} und m_{2m}. But $\mathcal{H}_{tot}$ is not anymore diagnoal in the neutrino mass basis. Therefore, the vacuum mass eigenstates ν_1 und ν_2 are not anymore eigenstates of the Hamiltionian in matter.
Therefore, in matter transitions $\nu_1 \leftrightarrow \nu_2$ can happen, analogously to the flavour transitions $\nu_e \leftrightarrow \nu_\mu$ in case of vacuum neutrino oscillations.

Matter-enhanced neutrino oscillation: MSW effect

Let us evalulate the modificed mass eigenvalues by diagonalisation:

$$0 = \det \left[\mathcal{H}_{tot} - \begin{pmatrix} \frac{m_m^2}{2p} & 0 \\ 0 & \frac{m_m^2}{2p} \end{pmatrix} \right] \qquad | \cdot 2p$$

$$\Rightarrow \qquad 0 = \det \begin{pmatrix} m_1^2 + A\cos^2\theta - m_m^2 & -A\cos\theta\sin\theta \\ -A\cos\theta\sin\theta & m_2^2 + A\sin^2\theta - m_m^2 \end{pmatrix} .$$

This defines a quadratic equation in m_m^2, which we solve introducing the usual abbreviations:

$$\begin{aligned} A &:= 2p\sqrt{2}G_F N_e \sim N_e \geq 0 \\ \Delta &:= m_2^2 - m_1^2 \\ \Sigma &:= m_2^2 + m_1^2. \end{aligned}$$

$$m_{1,2m}^2 = \frac{1}{2}\left(\Sigma + A \mp \Delta \sqrt{\left(\frac{A}{\Delta} - \cos(2\theta)\right)^2 + \sin^2(2\theta)} \right).$$

Matter-enhanced neutrino oscillation: MSW effect

Let us disuss various scenarios:

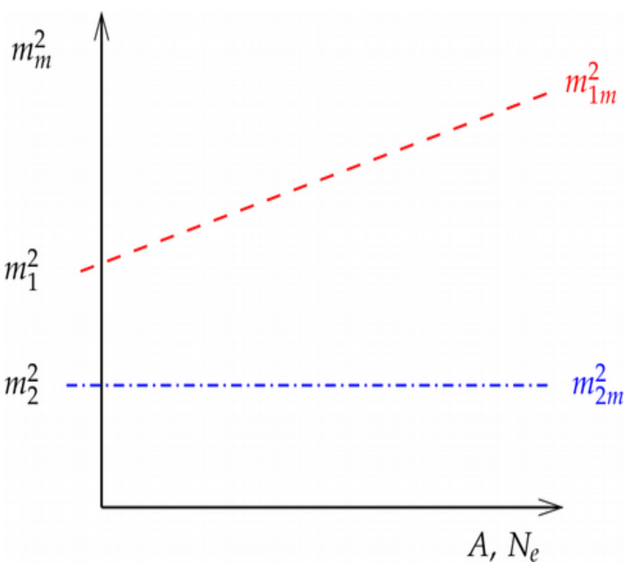
- Let $A = 0$ (vanishing electron density) corresponding to the vacuum case. The *matter mass eigenstates* are indeed the same as in the pure vacuum case:

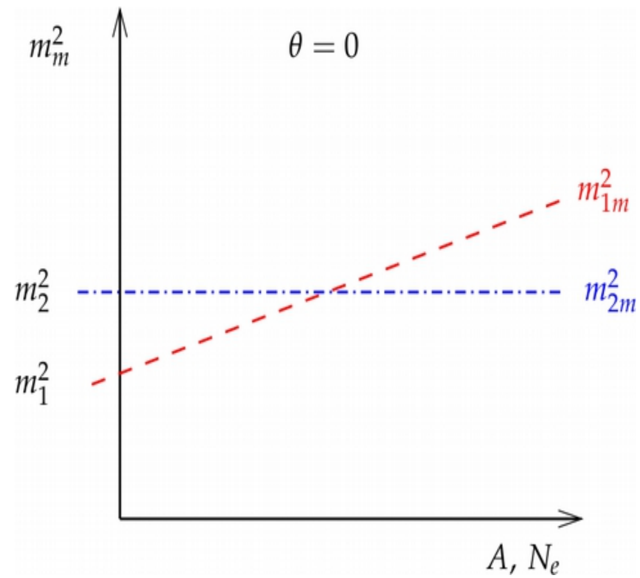
$$m^2_{1,2m} \;=\; \frac{1}{2}(\Sigma \mp \Delta) = \begin{cases} m_1^2 \\ m_2^2 \end{cases}$$

- Let us assume true matter $A \neq 0$, but no mixing $\theta = 0$ yet. One *matter mass eigenstate* has a constant mass, the square mass of the other *matter mass eigenstate* depends on the electron density:

$$m^2_{1,2m} \;=\; \frac{1}{2}(\Sigma + A \mp (A - \Delta)) = \begin{cases} \frac{1}{2}(\Sigma + \Delta) & = m_2^2 \\ \frac{1}{2}(\Sigma - \Delta + 2A) & = m_1^2 + A \end{cases} \qquad (1.25)$$

There are two cases depending on the mass hierarchy:





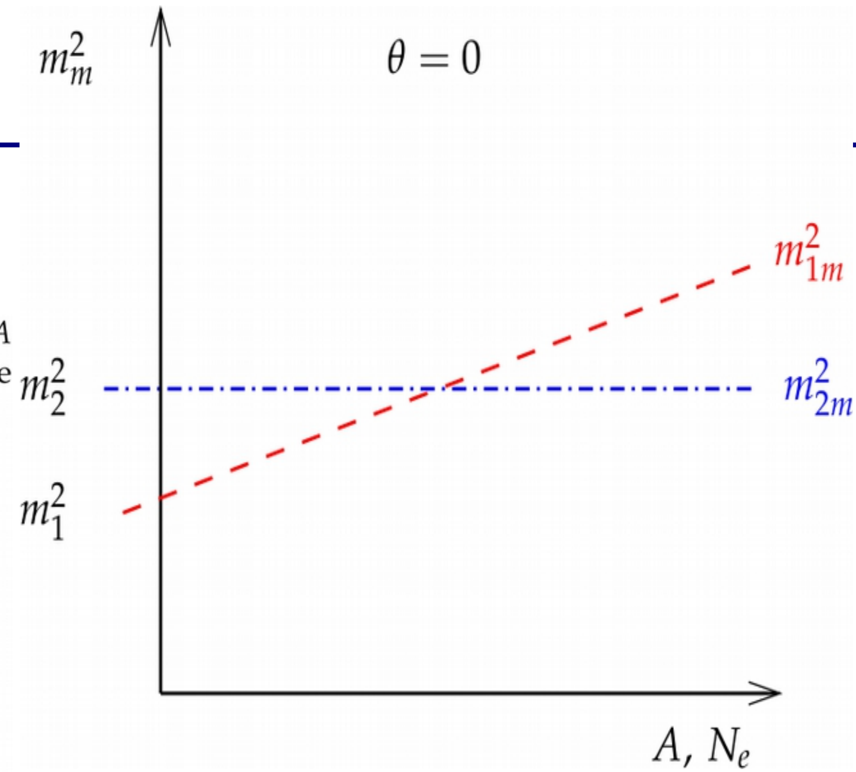
- An interesting new effect can happen for $m_2^2 > m_1^2$ if the matter density $\propto A$ varies in the right range and non-zero mixing ($\theta \neq 0$). The difference term in the square root can not vanish, but gets minimal at

$$A = A^* = \Delta \cdot \cos(2\theta)$$

The difference in m_m^2 at this minimal distance becomes:

$$\Delta m_m^2 = m_{2m}^2 - m_{1m}^2 = \Delta \cdot \sin(2\theta)$$

Both *matter mass eigenstates* can not cross.



Principle of matter enhanced neutrino oscillation

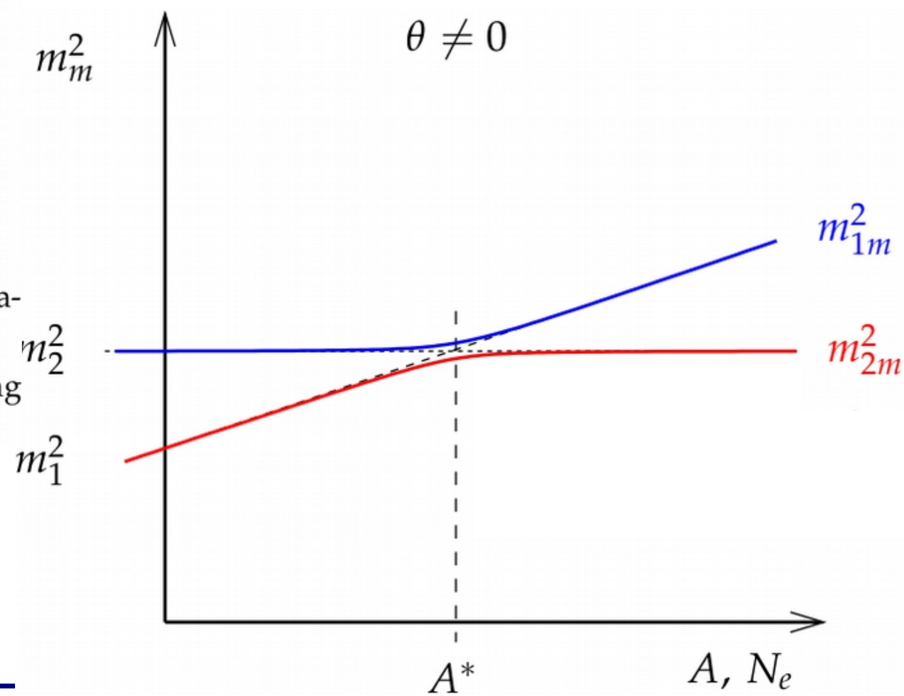
Let $\theta =: \varepsilon > 0$ with $\cos\theta = \cos\varepsilon \approx 1$ and $\sin\theta \approx \theta = \varepsilon$:

$$\nu_e = \nu_1 - \varepsilon\nu_2$$
$$\nu_\mu = \nu_2 + \varepsilon\nu_1$$

Consider a ν_e created at $A > A^*$ running towards smaller A.

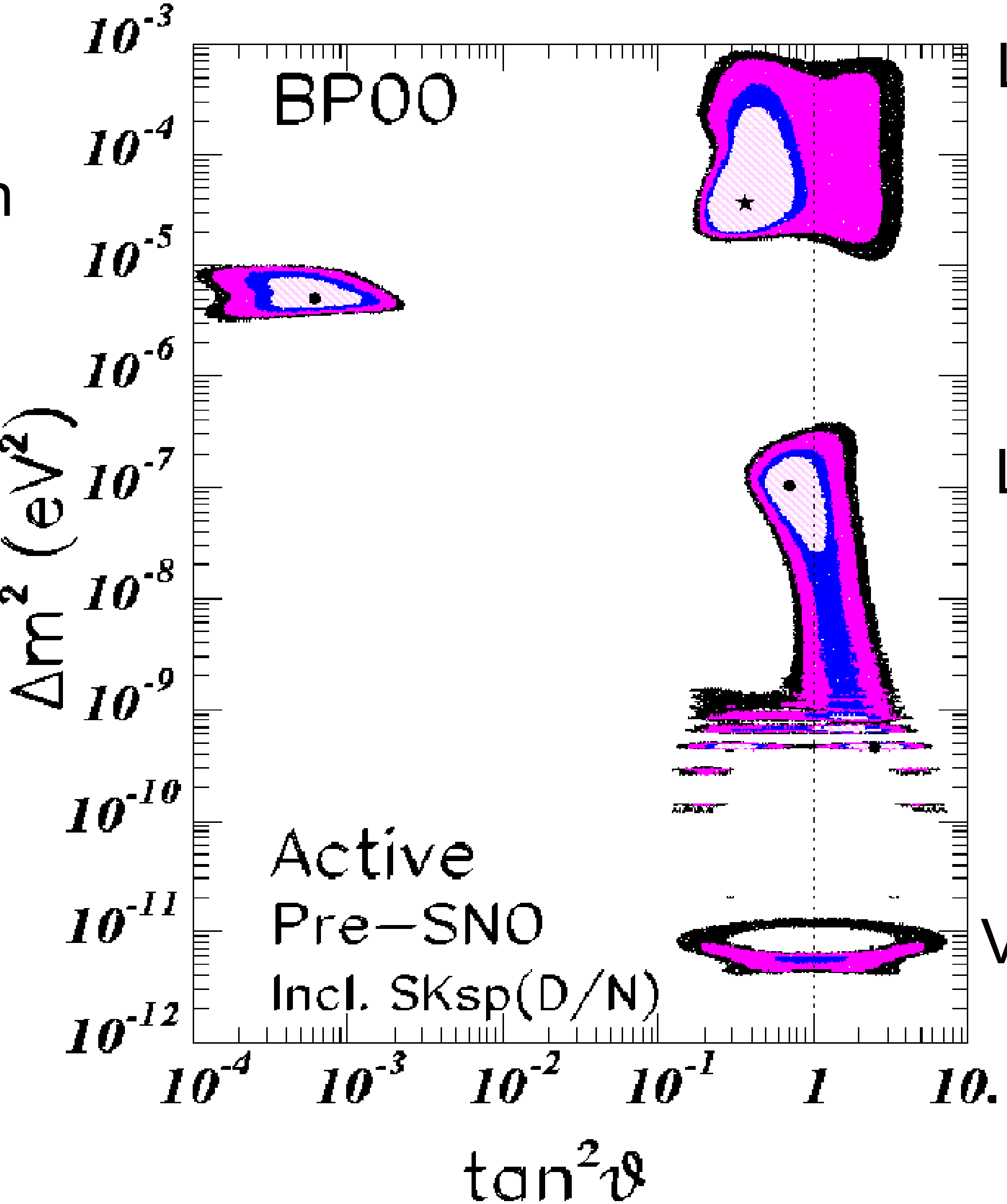
At $A = A^*$ the neutrino follows under adiabatic conditions the matter mass eigenvalue curve and arrives at $A = 0$ (vacuum) being in the mass eigenstate $\nu_2 \approx \nu_\mu$.

Thus, nearly a full transformation $\nu_e \rightarrow \nu_\mu$ has happend albeit a nearly vanishing vacuum mixing angle $\theta \approx 0$.



MSW effect and vacuum oscillation solutions for solar neutrinos

Small Mixing Angle solution (SMA)

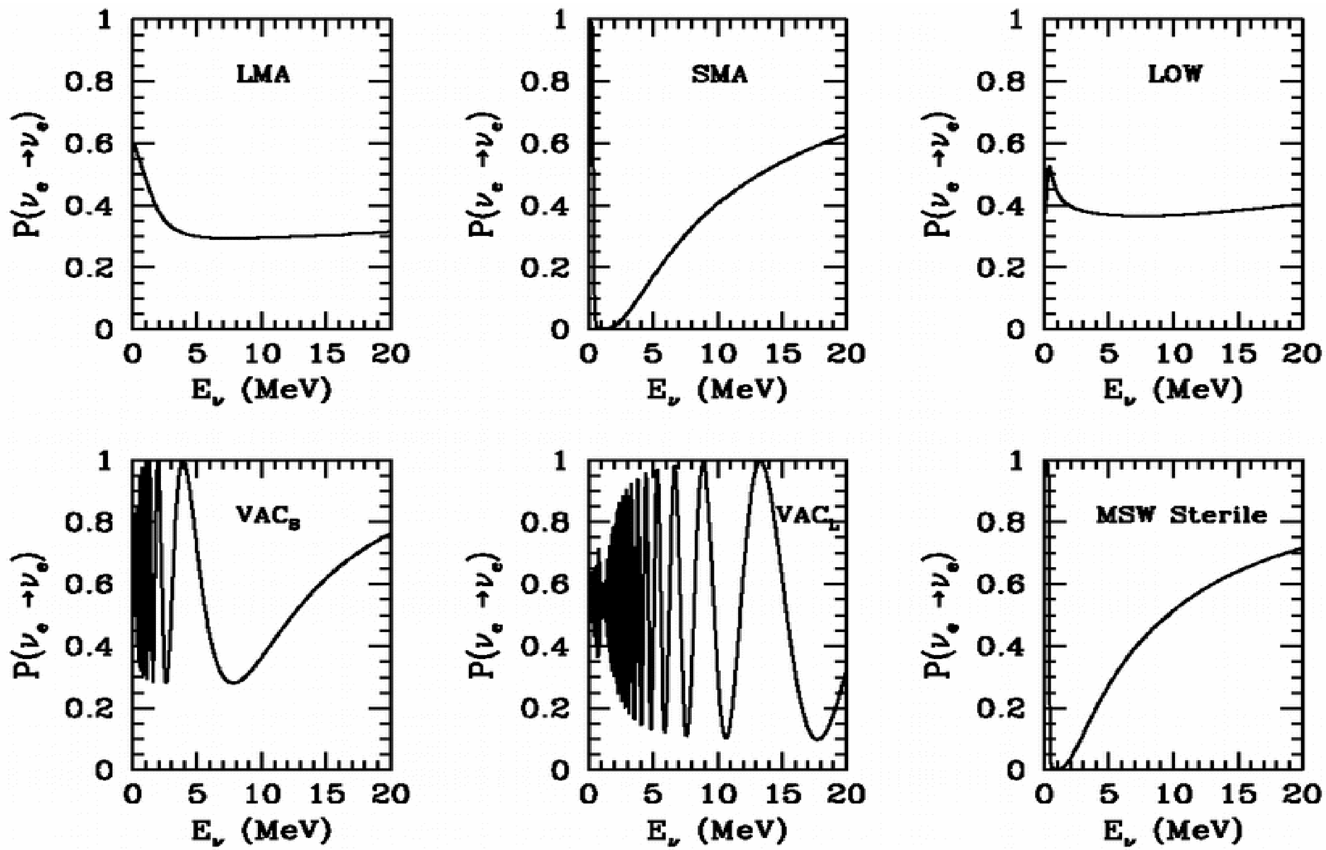


Large Mixing Angle solution (LMA)

LOW solution (LOW)

Vacuum Oscillation solution (VO)

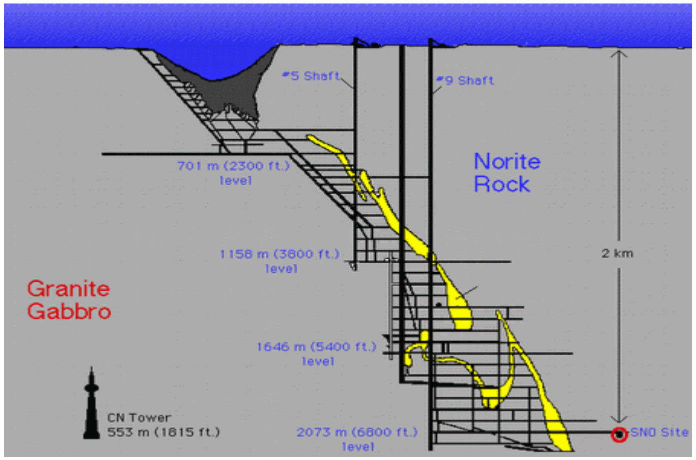
Solar neutrino experiments of 3rd generation



Requirements:

- real time (day/night asymmetry, length variation) } Borexino
- spectral information
- flavour information, proof: $\nu_e \rightarrow \nu_x$ } SNO

The Sudbury Neutrino Observatory SNO



Creighton Mine: 2 km deep underground in Sudbury, Ontario, Canada

1000 t D_2O

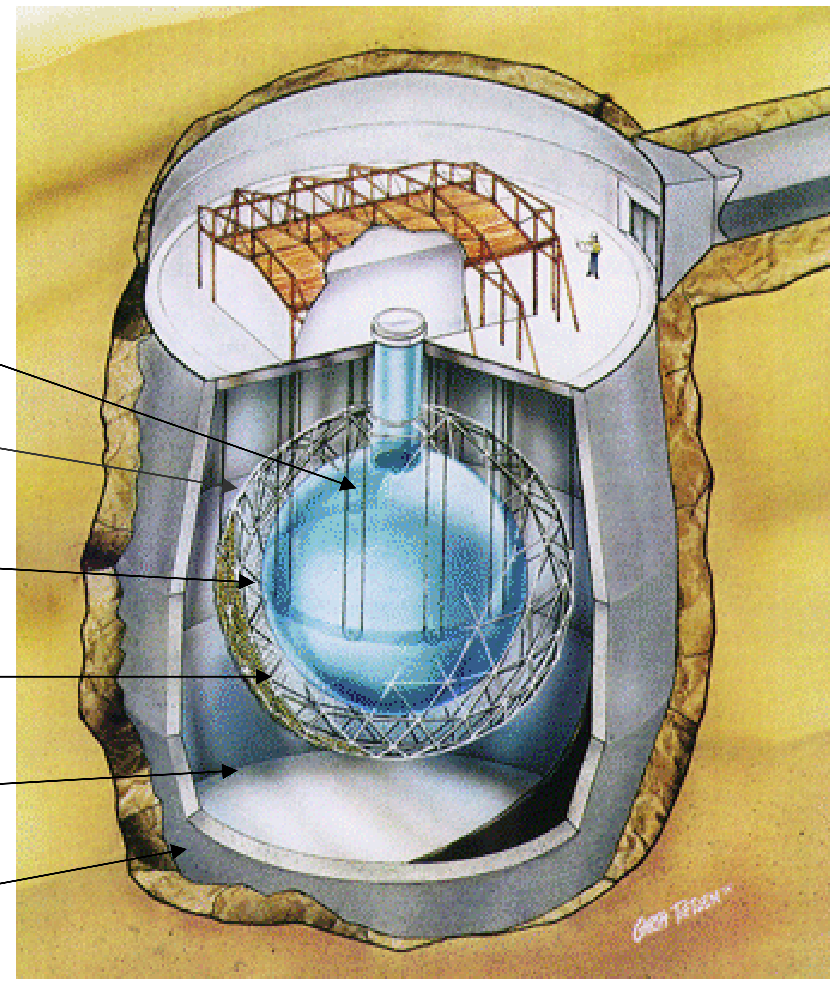
support structure for 9500 light detectors (photomultipliers)

12 m diameter acrylic vessel

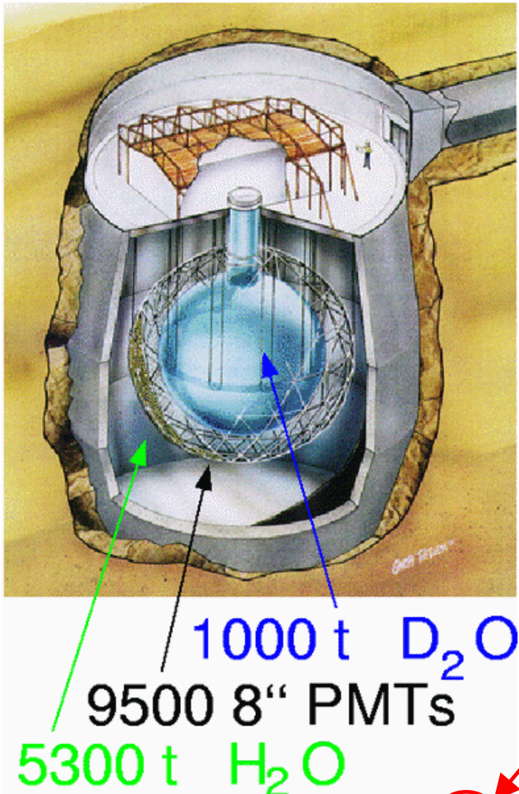
1700 t inner shielding, H_2O

5300 t outer shielding, H_2O

Urylon sealing



Solar ν fluxes from the Sudbury Neutrino Observatory SNO



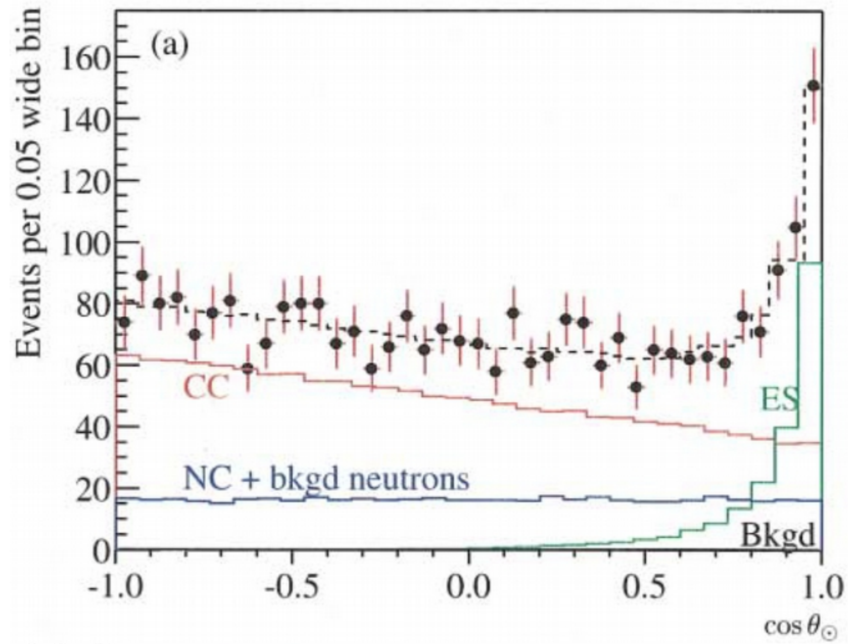
Cherenkov

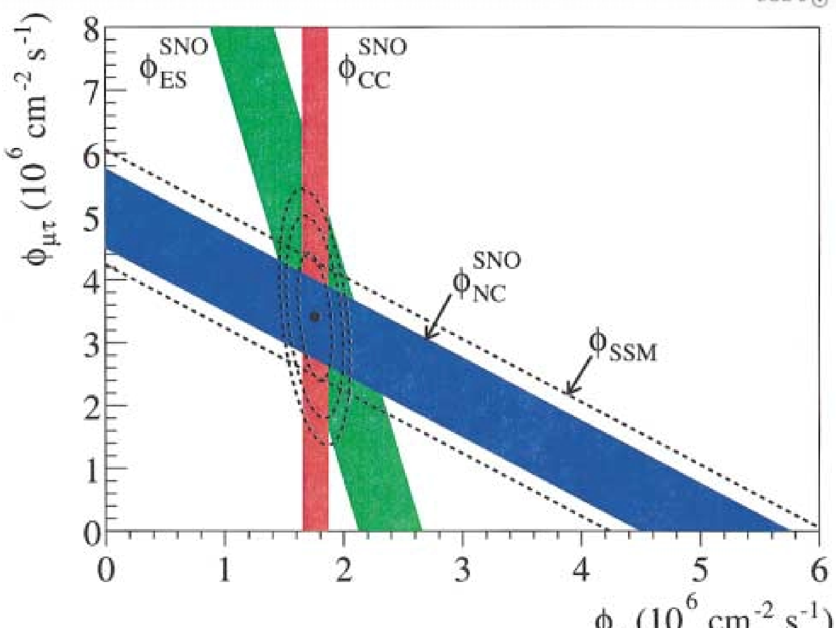
		sensitive to
ES	$\nu_x + e^- \rightarrow \nu_x + e^-$	ν_e (ν_μ, ν_τ)
CC	$\nu_e + d \rightarrow p + p + e^-$	ν_e
NC	$\nu_x + d \rightarrow p + n + \nu_x$	ν_e , ν_μ, ν_τ

Clear finding: NC > ES > CC

⇒ excistence of ν_μ, ν_τ

⇒ ν oscillation & $m(\nu_i) \neq 0$





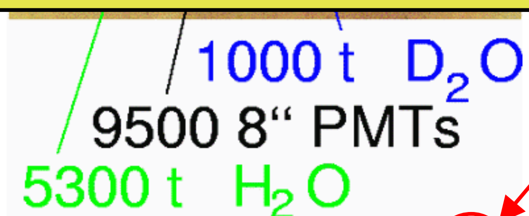
SNO PRL 89 (2002) 011301

Solar ν fluxes from the Sudbury Neutrino Observatory SNO

Question to think about:

The lightest nucleus, deuterium, consisting of one proton and one neutron has spin 1

Why do the SNO measurements confirm S(d) = 1 ?



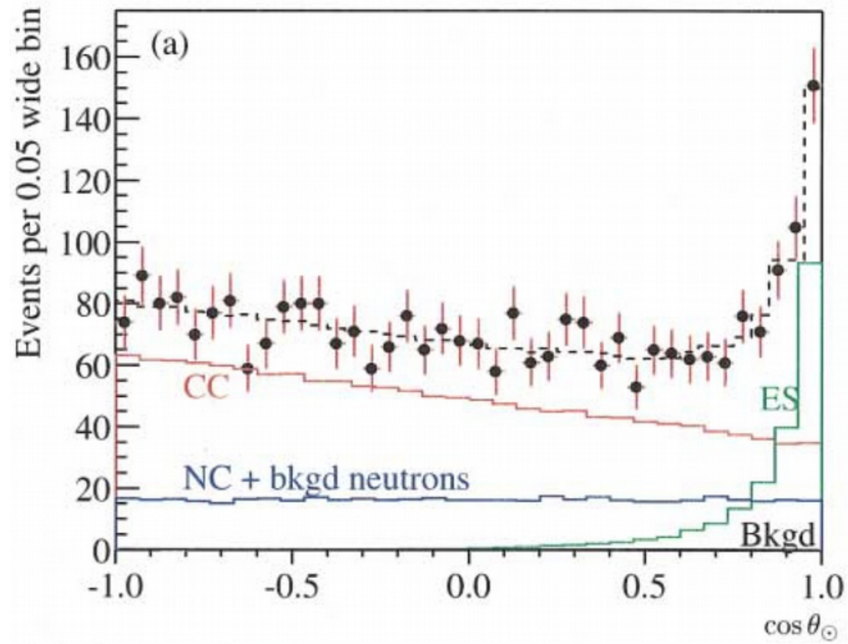
Cherenkov

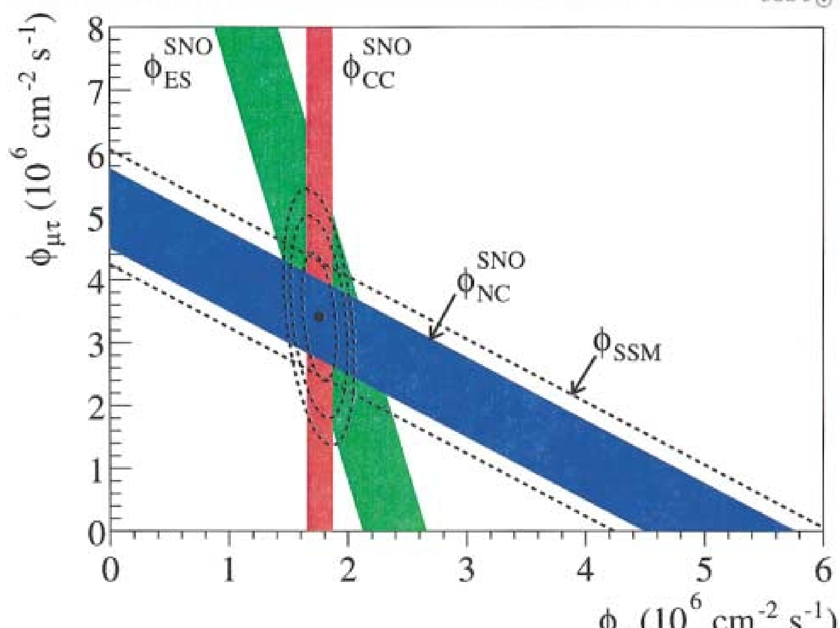
		sensitive to
ES	$\nu_x + e^- \to \nu_x + e^-$	$\nu_e\ (\nu_\mu, \nu_\tau)$
CC	$\nu_e + d \to p + p + e^-$	ν_e
NC	$\nu_x + d \to p + n + \nu_x$	ν_e, ν_μ, ν_τ

Clear finding: NC > ES > CC

$\Rightarrow$ excistence of ν_μ, ν_τ

$\Rightarrow$ ν oscillation & $m(\nu_i) \neq 0$



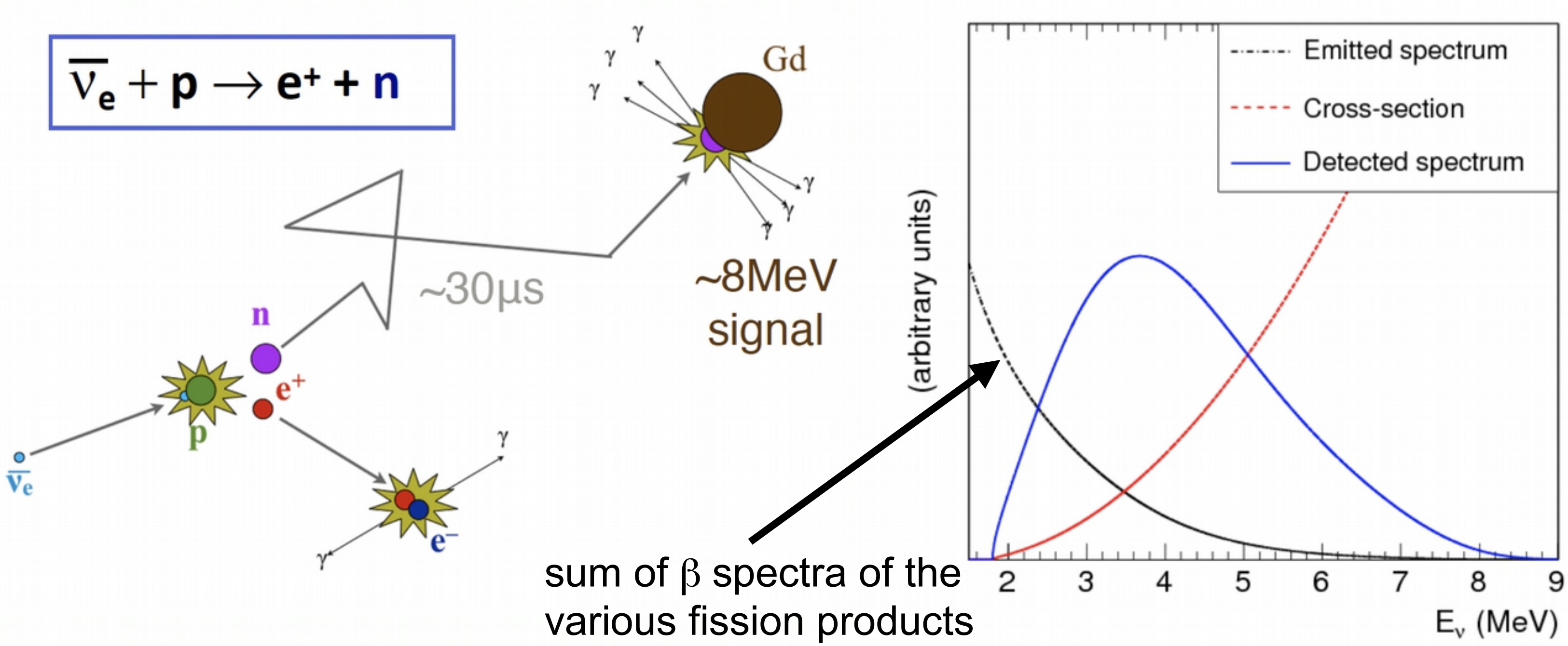


SNO PRL 89 (2002) 011301

Reactor $\bar{\nu}_e$ experiments

Inverse β decay: $$\bar{\nu}_e + p \longrightarrow e^+ + n - 1.80\ MeV$$

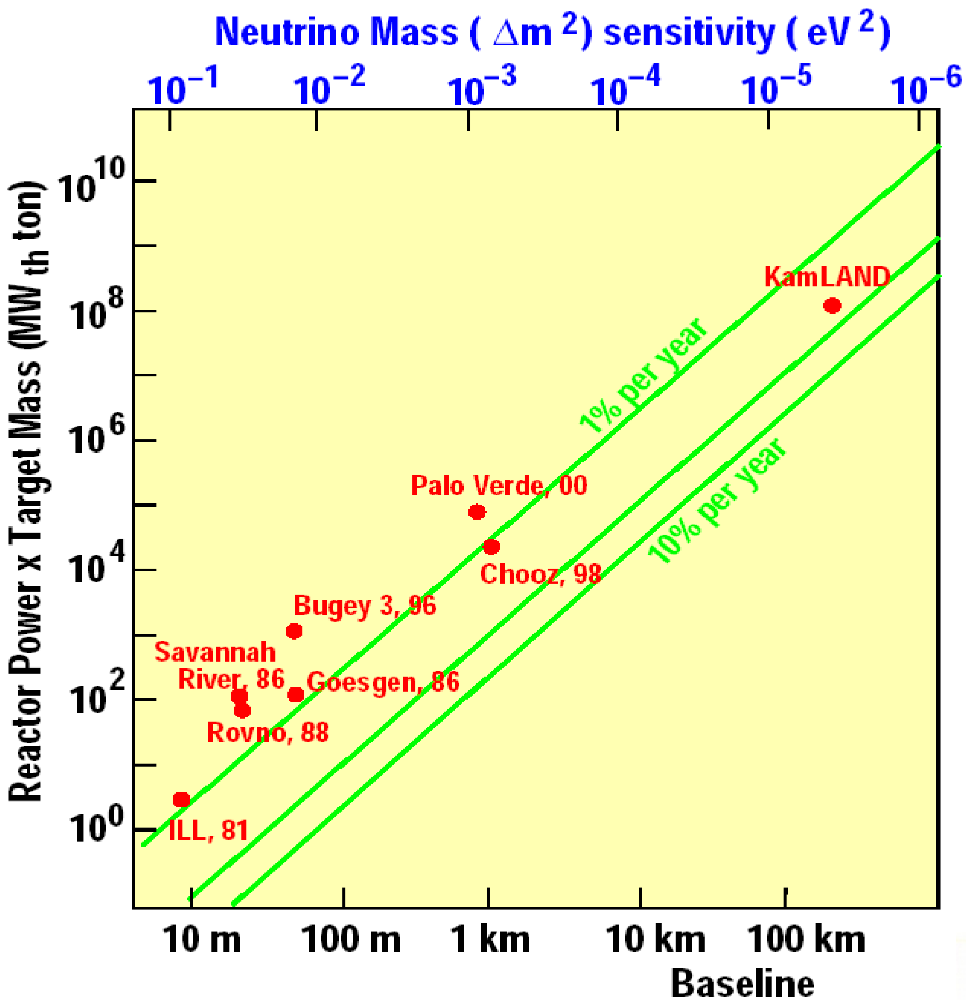
- Antineutrinos are detected via the Inverse Beta Decay (IBD) reaction:



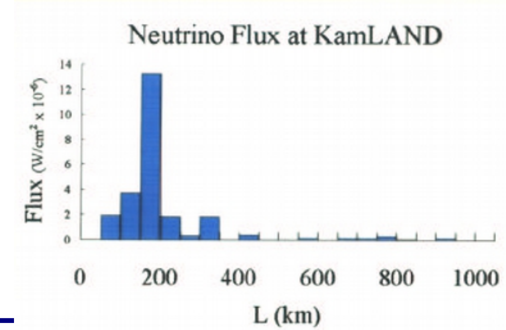
– Coincidence between positron and neutron signals allows for **powerful background rejection**

– Energy of positron preserves information about energy of incoming $\bar{\nu}_e$

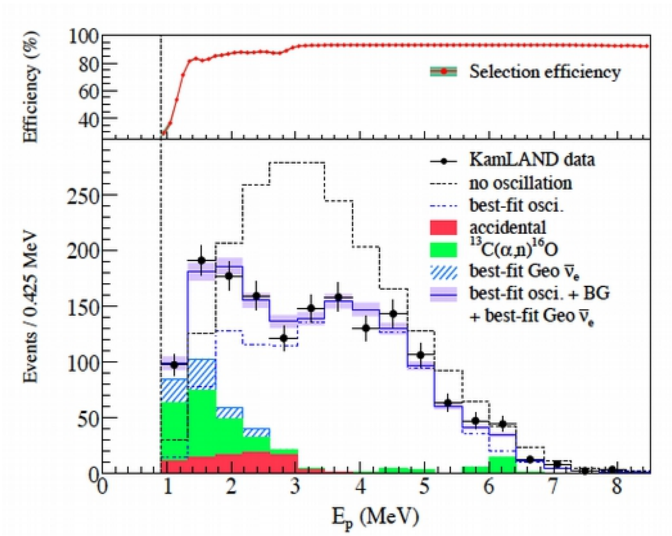
Use all japanise and corean nuclear reactors for KamLAND

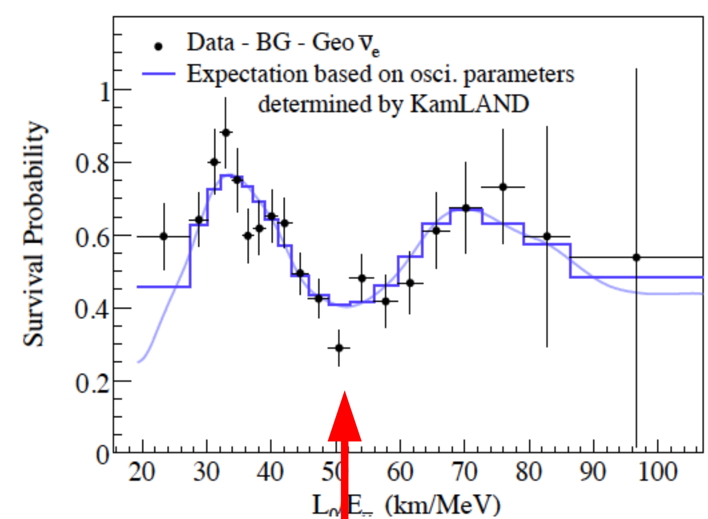


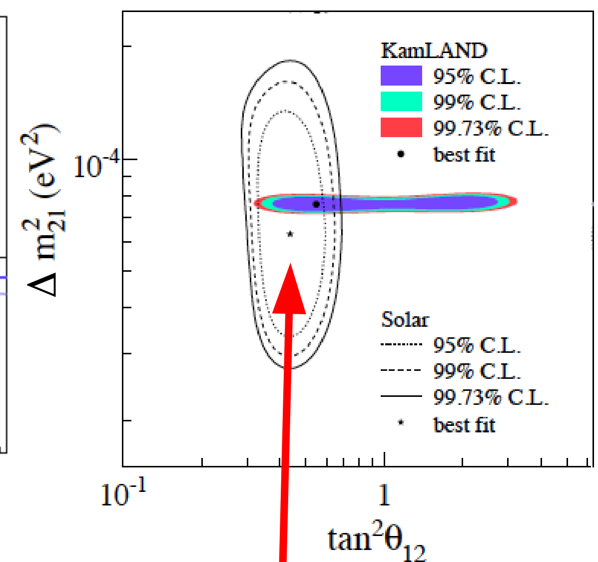
Japanese and Korean reactors

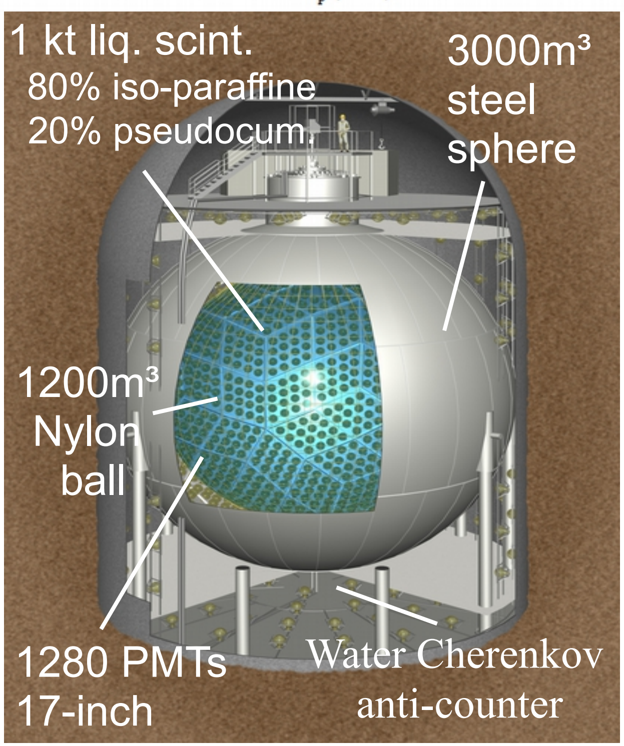


Long baseline reactor neutrinos: KamLAND at Kamioka mine: <L> = 180 km







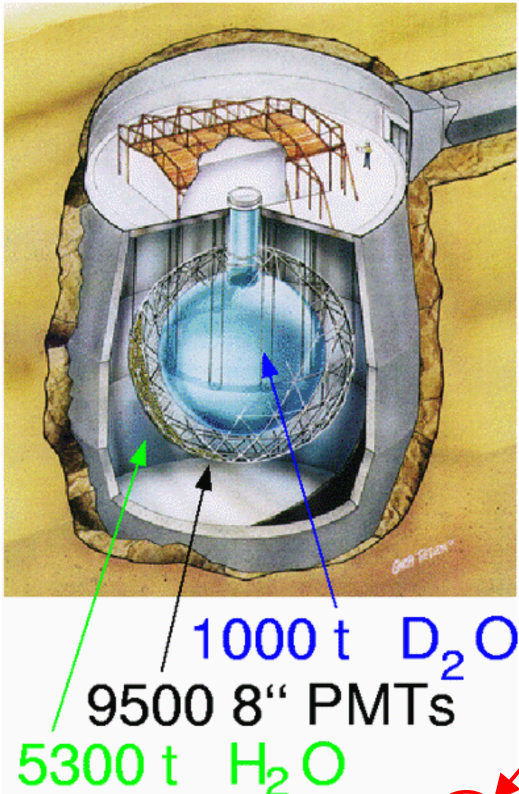


L/E plot shows oscillation
& agreement with solar neutrinos
⇒ no other neutrino flavour conversion possible
→ really neutrino oscillation

some tension in mixing angle: $\Theta_{13} \neq 0$?

S. Abe et al, arXiv.0801.4589 (2008)

Solar ν fluxes from the Sudbury Neutrino Observatory SNO



Cherenkov

		sensitive to
ES	$\nu_x + e^- \rightarrow \nu_x + e^-$	ν_e (ν_μ, ν_τ)
CC	$\nu_e + d \rightarrow p + p + e^-$	ν_e
NC	$\nu_x + d \rightarrow p + n + \nu_x$	ν_e , ν_μ, ν_τ

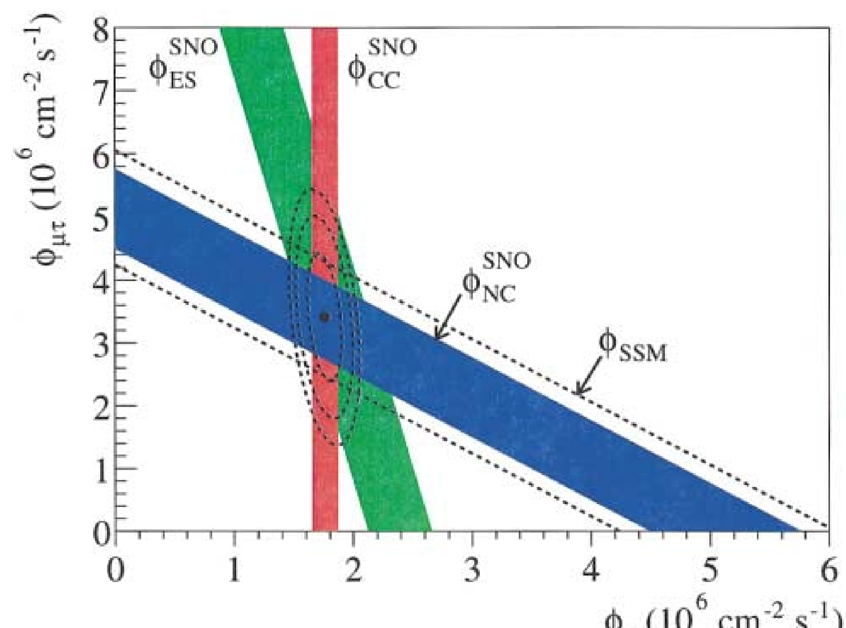
Clear finding: NC > ES > CC

⇒ excistence of ν_μ, ν_τ

⇒ ν oscillation & $m(\nu_i) \neq 0$

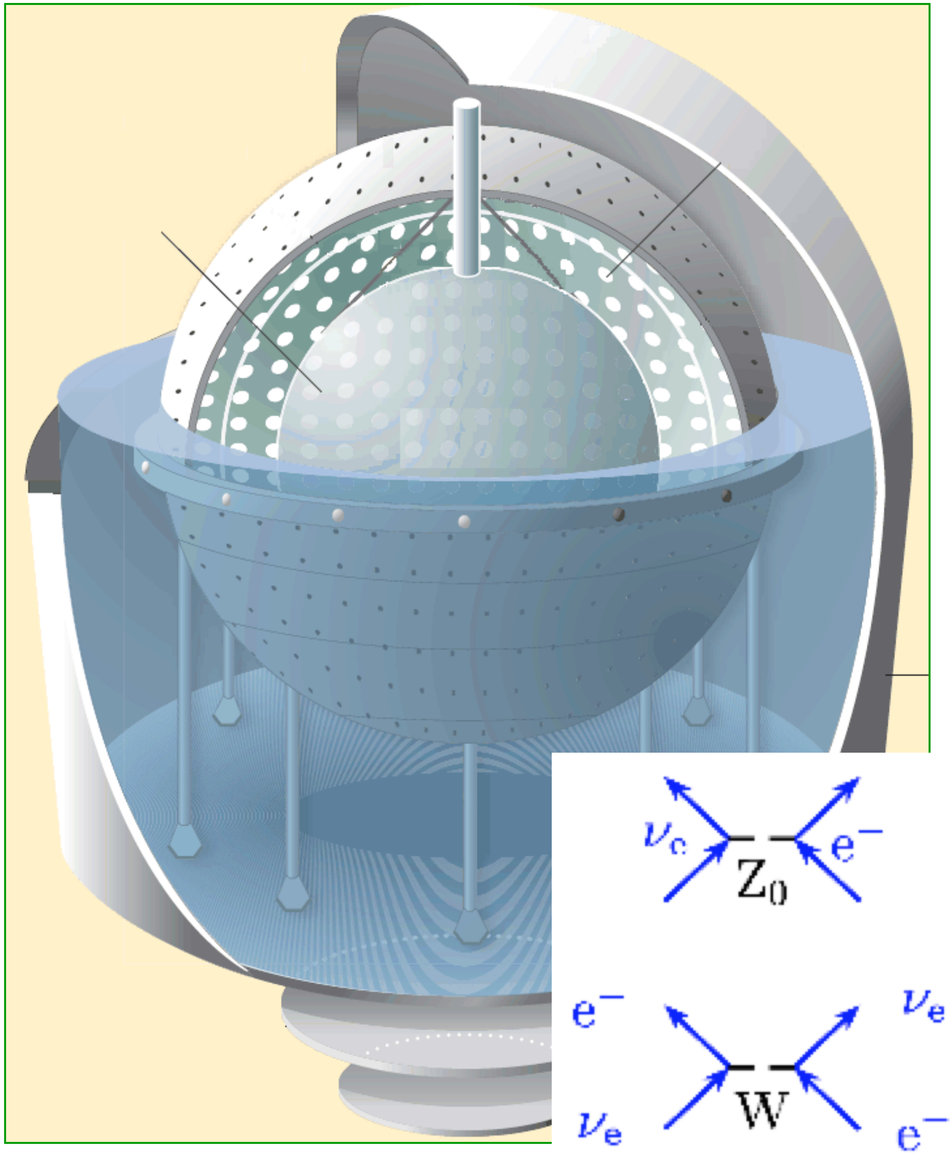
Nobel prize 2015
to Arthur B. McDonald

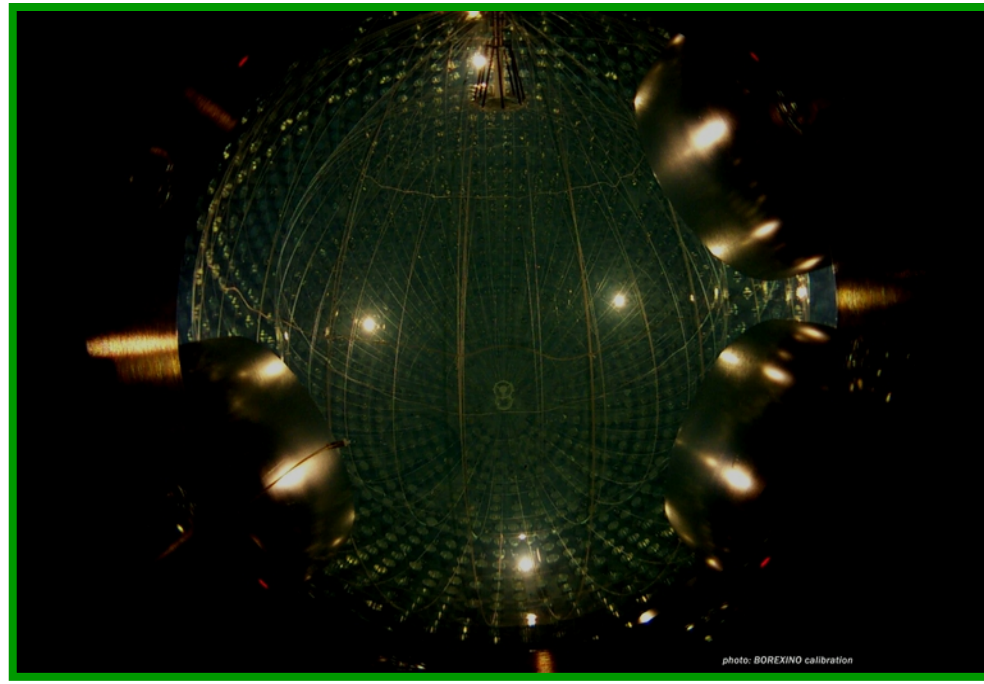
(and because of solar ^8B ν_e/ν_x = 1/3
Nobel prize 2002 to R. Davis)



SNO PRL 89 (2002) 011301

BOREXINO



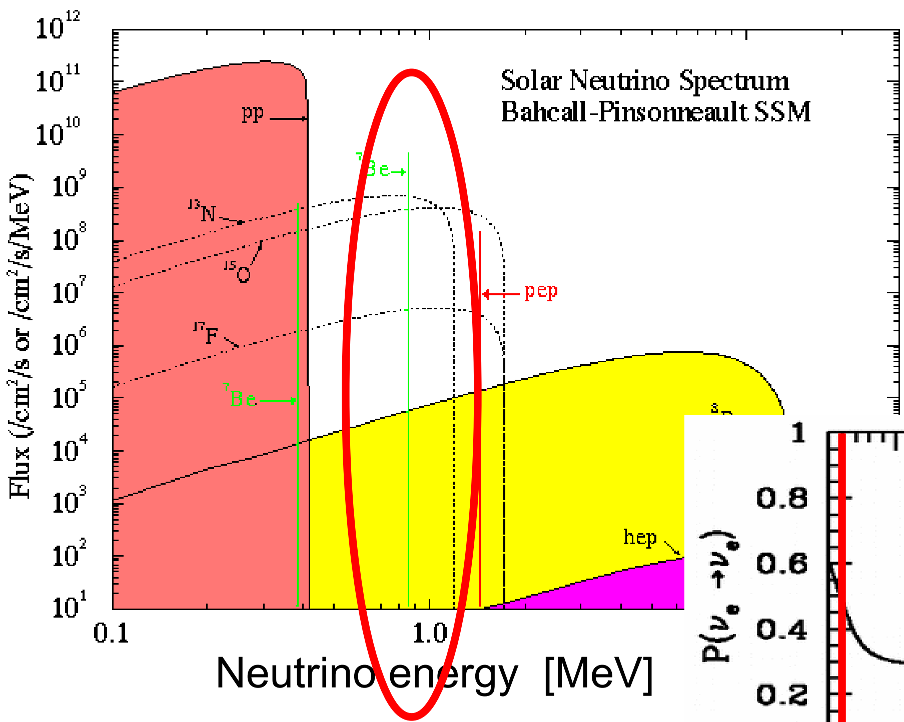


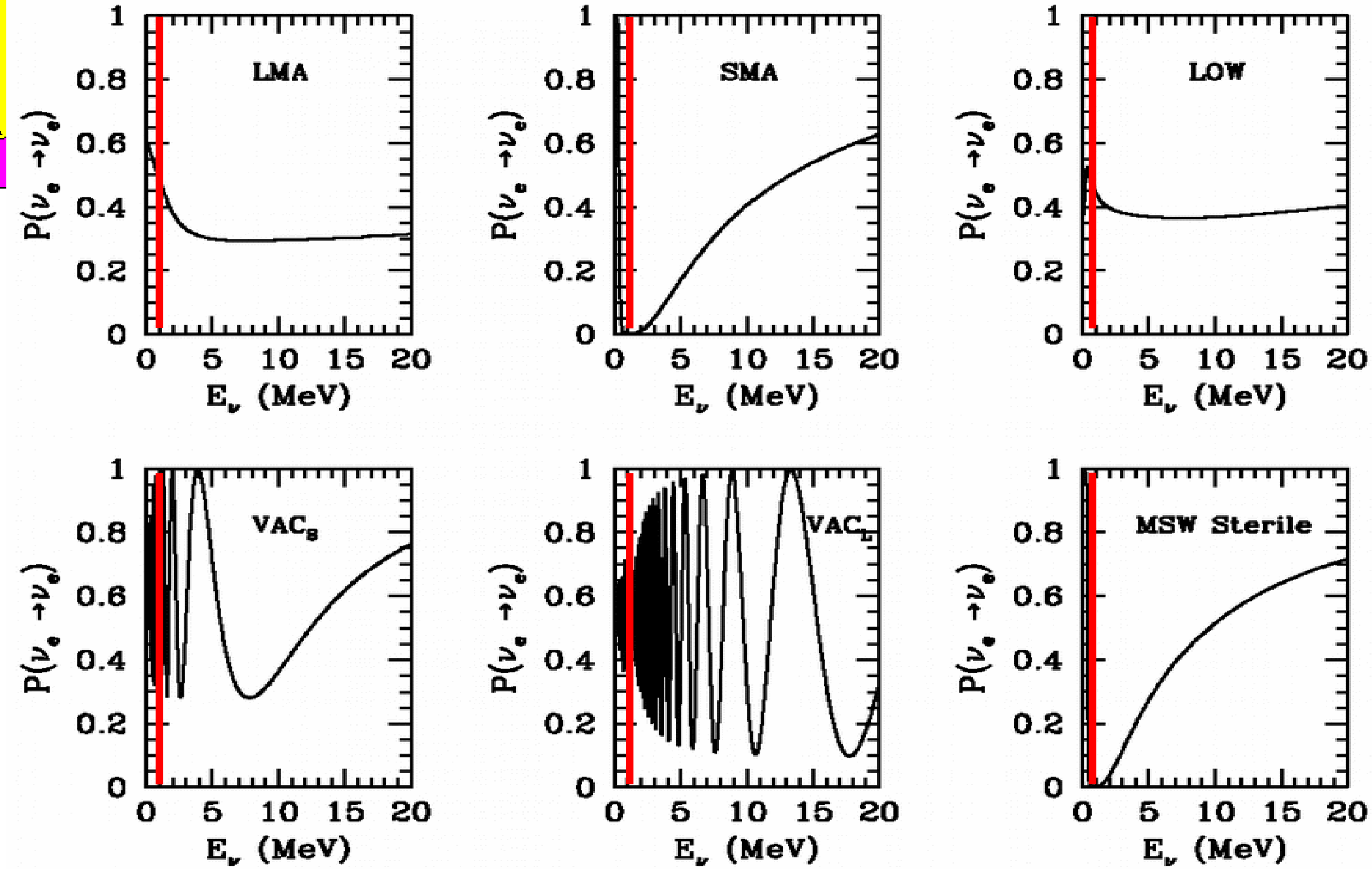
ultraclean liquid scintillator (300t) looked at by 2212 photomultipliers in a water shield

looking for „ν Compton“ scattering

located in Gran Sasso underground lab

Borexino looks for the „Compton-edge“ of the monoenergetic ^{7}Be neutrinos





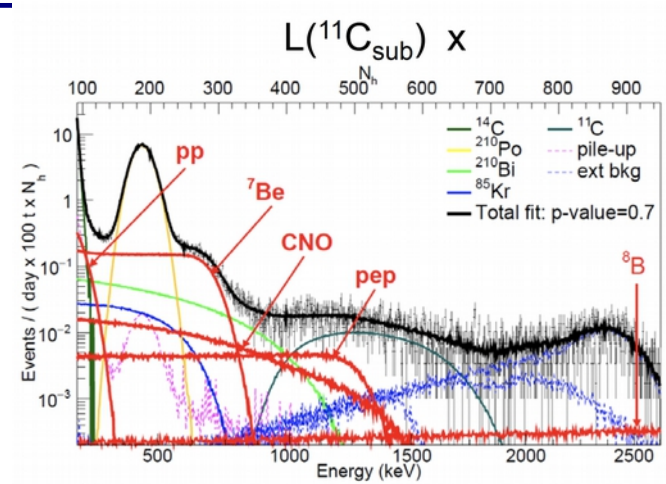
BOREXINO results

expectation for „no oscillation“:

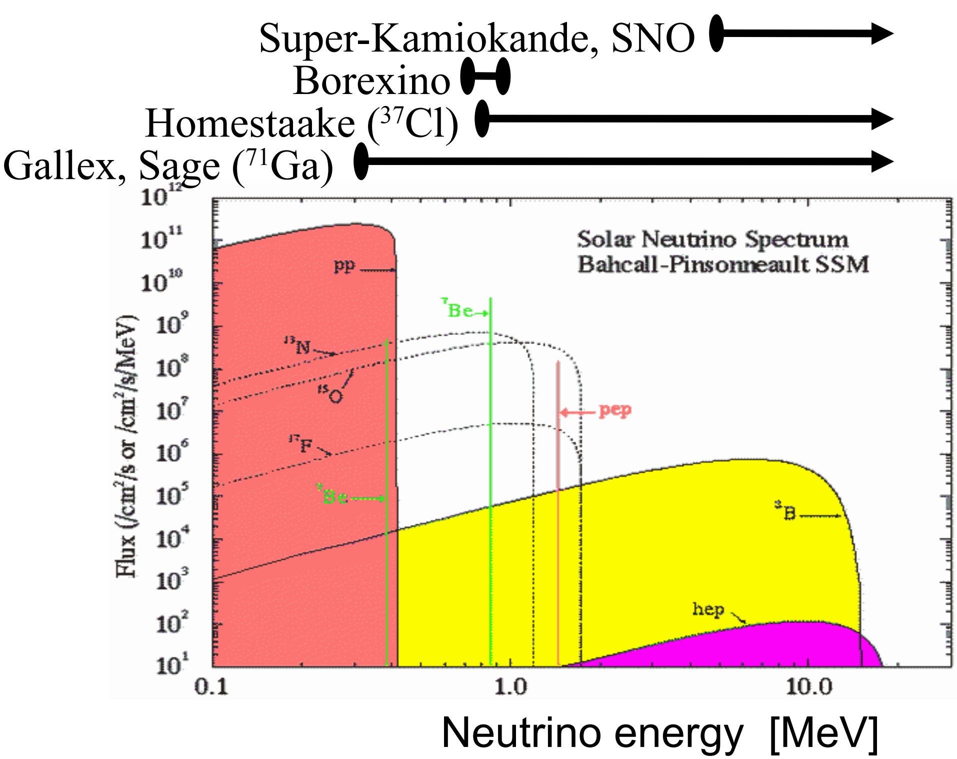
74 ± 5 cpd/100 t

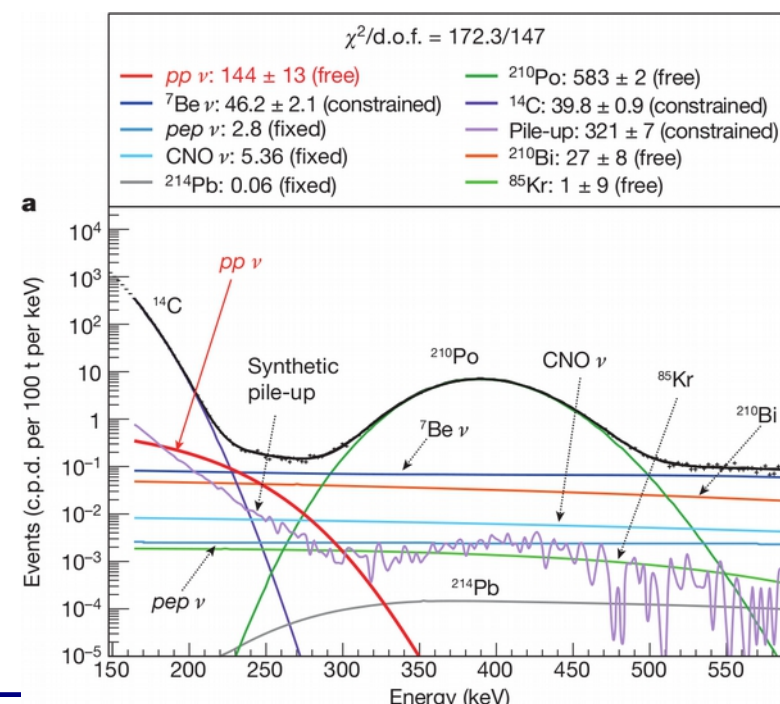
measured (arXiv:1104.1816):

$46 \pm 1.5\ ^{+1.6}_{-1.5}$ cpd/100 t



very low background & understanding it
→ even pp neutrinos by understanding ^{14}C spectrum and its pile-up

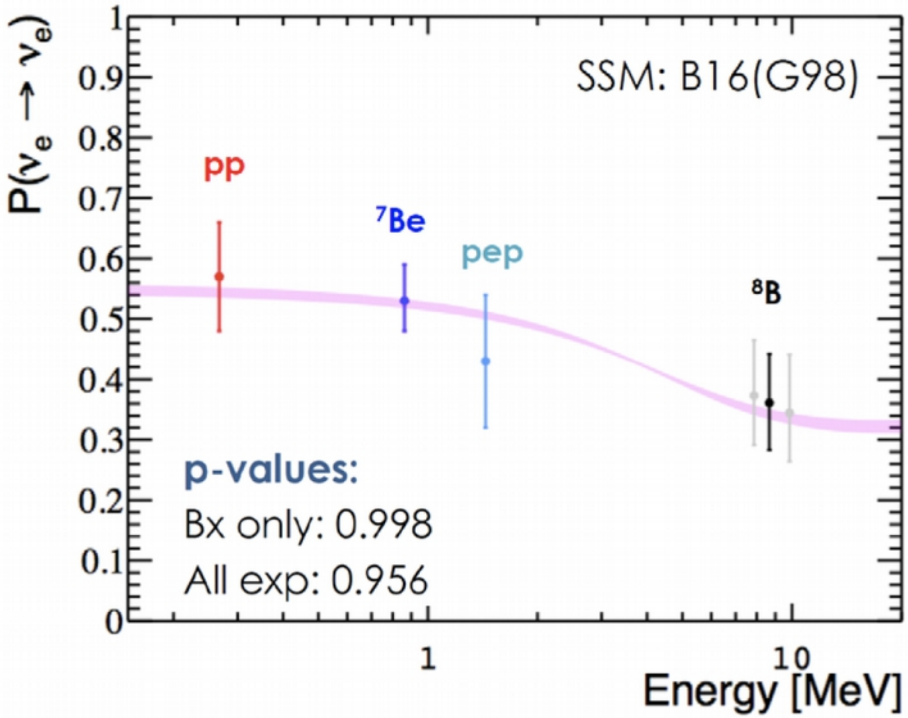




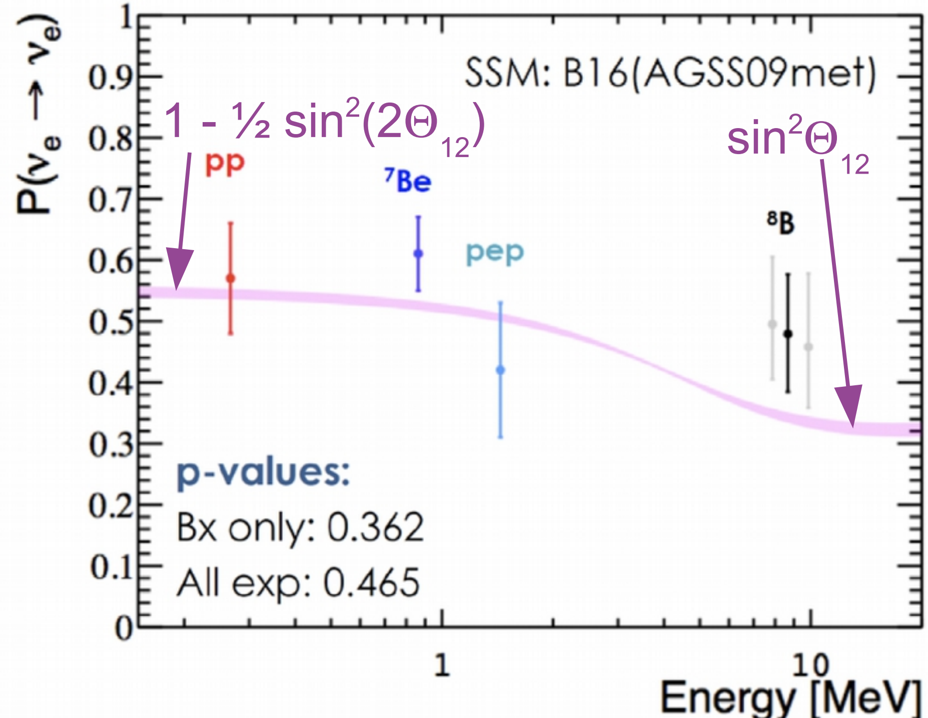
Nature 512 (2014) 13702

Full neutrino spectrum of pp-chain by real-time experiment BOREXEINO

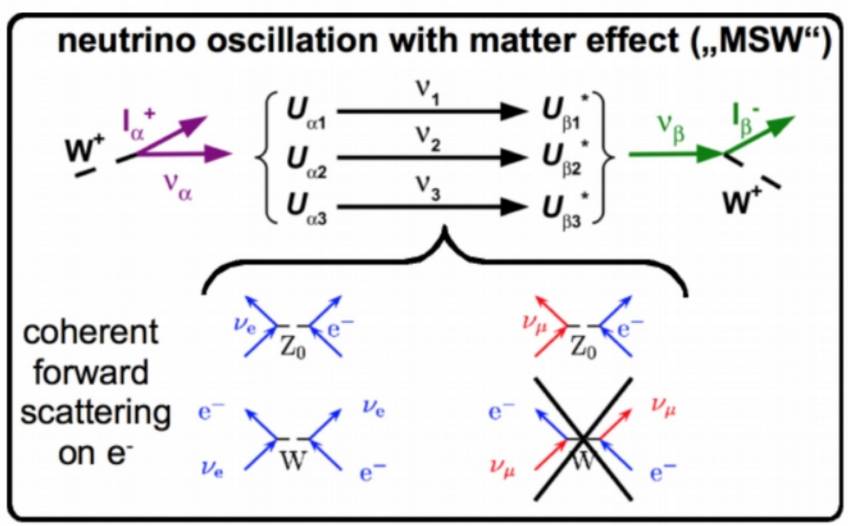
High metallicity SSM



Low metallicity SSM



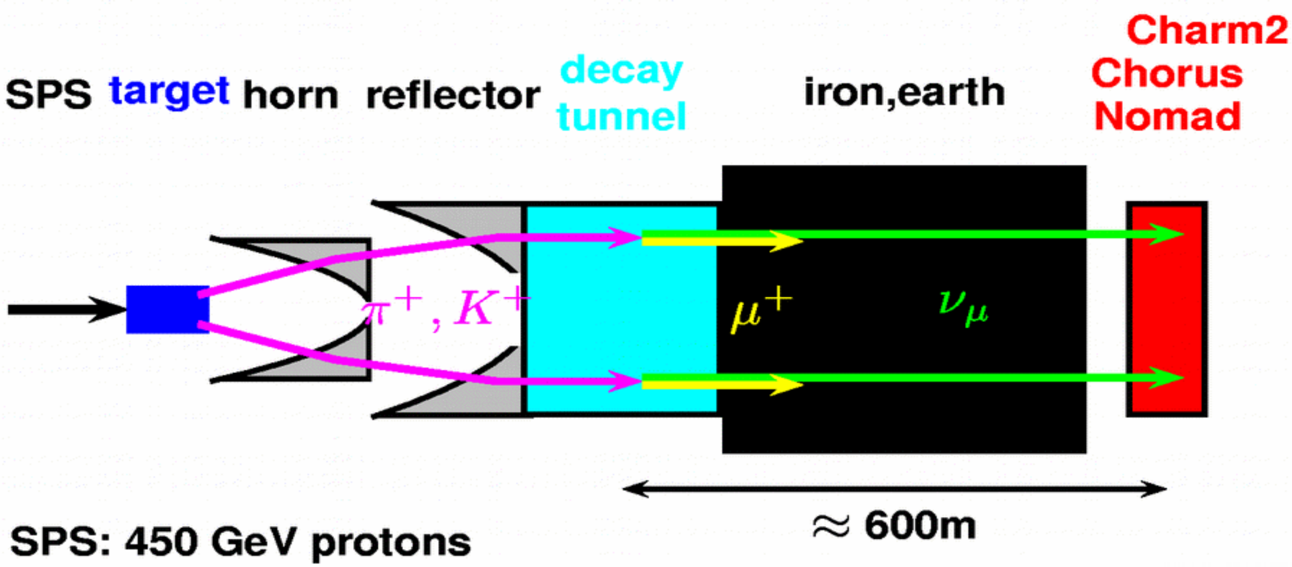
matter enh. osc.



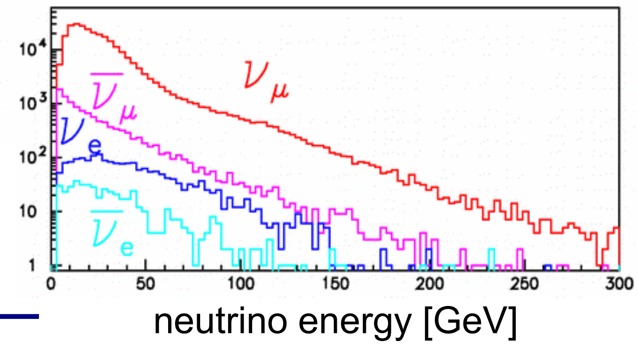
Typical accelerator neutrino beam

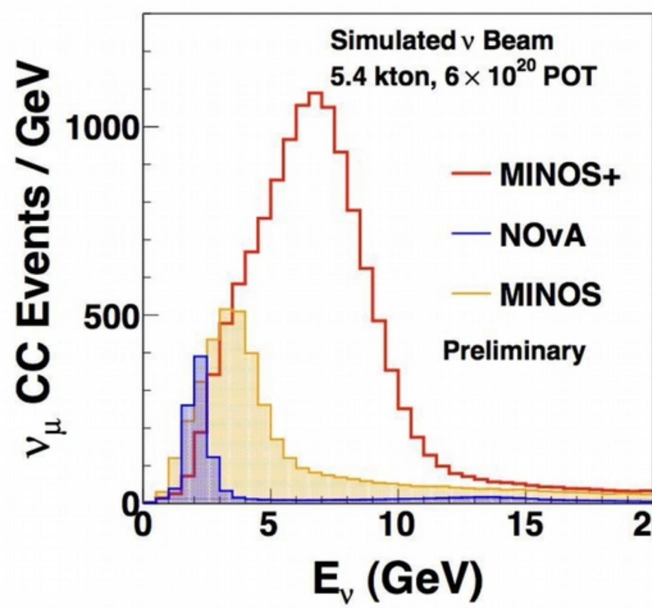
CERN Wide energy Band Beam (WBB)

$\pi^+ \to \nu_\mu + \mu^+, \quad K^+ \to \nu_\mu + \mu^+, \quad K^+ \to \pi^0 \nu_\mu + \mu^+, \quad K^+ \to \pi^0 \nu_e + e^+$

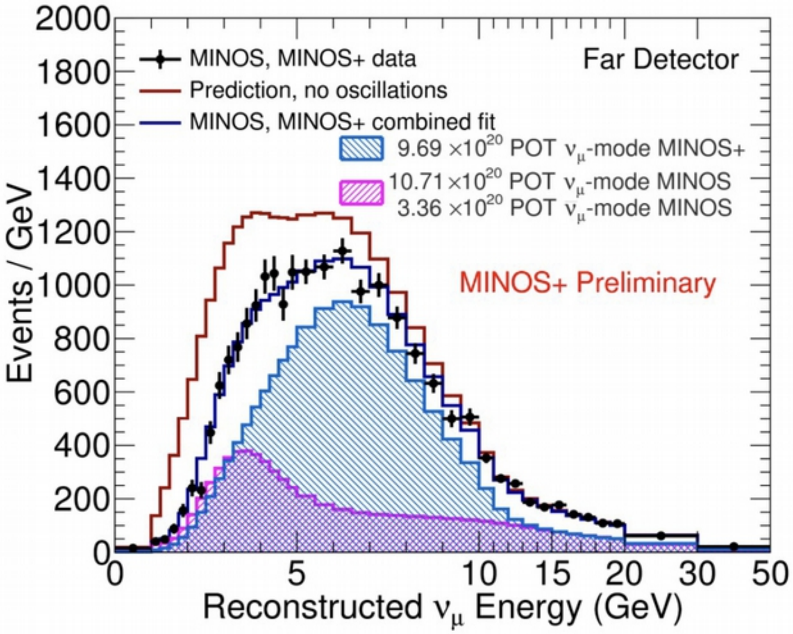


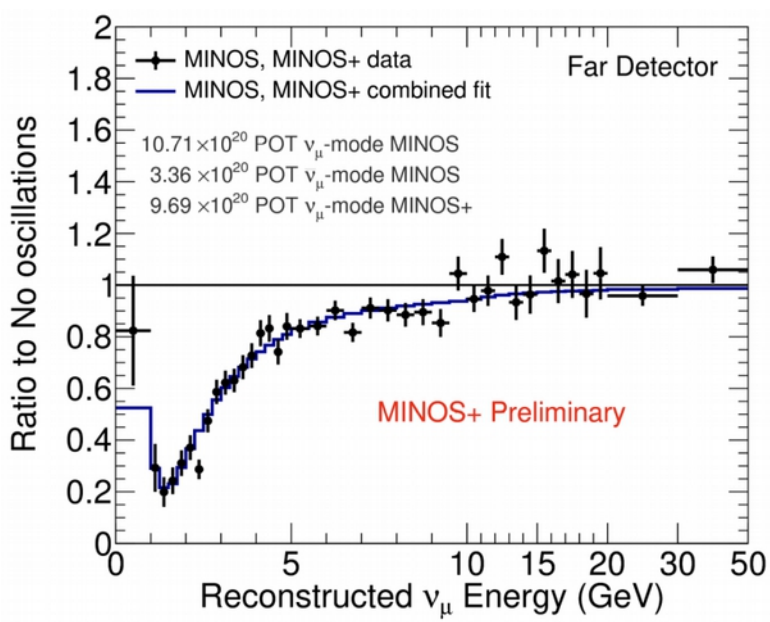
- CERN SPS: 450 GeV protons
- 2 extractions of 10^{13} protons on Be-target every 14.4 sec
- Neutrino flux at Chorus and Nomad detectors per extraction: $2.5 \cdot 10^{10}/m^2$
- $\nu_\mu : \bar{\nu_\mu} : \nu_e : \bar{\nu_e}$ = 1 : 0.056 : 0.007 : 0.002
- ν_τ-fraction: 10^{-7}
- Mean ν_μ-energy: 26 GeV



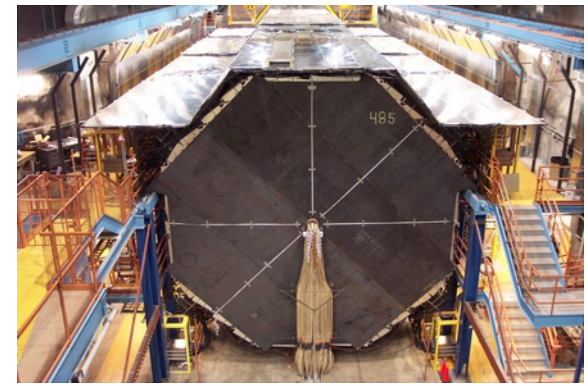


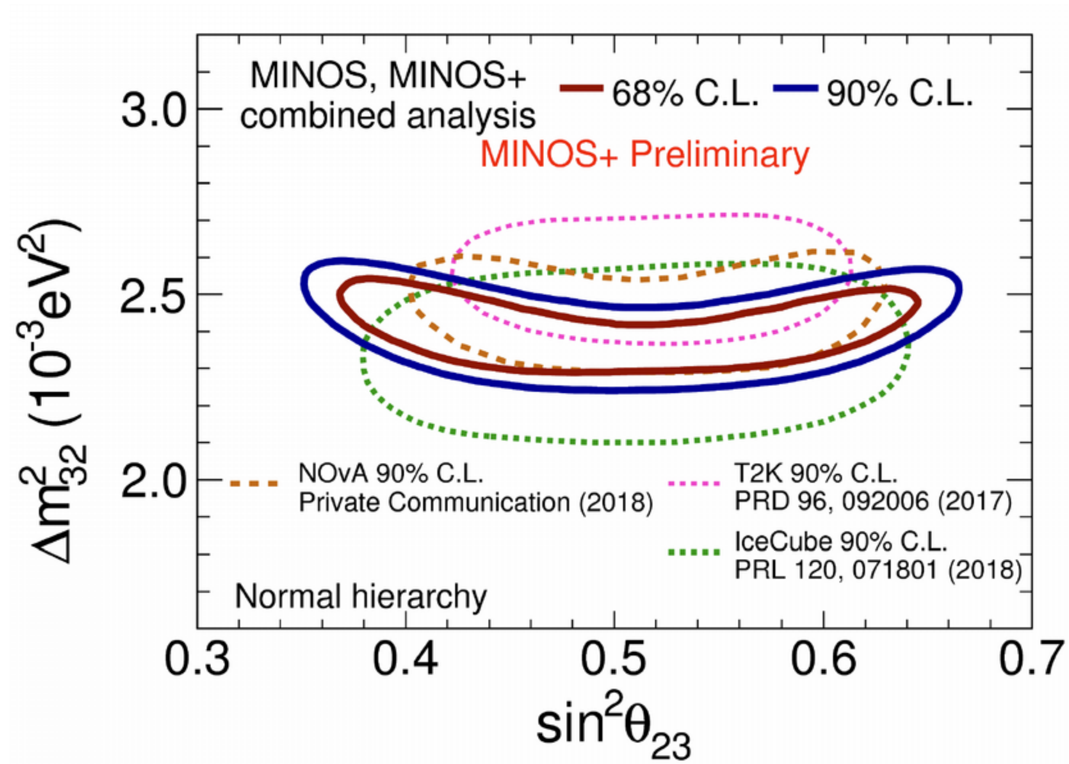
Confirmation of $\nu_\mu \rightarrow \nu_\mu$ disappearance by oscillation: long baseline experiments: MINOS



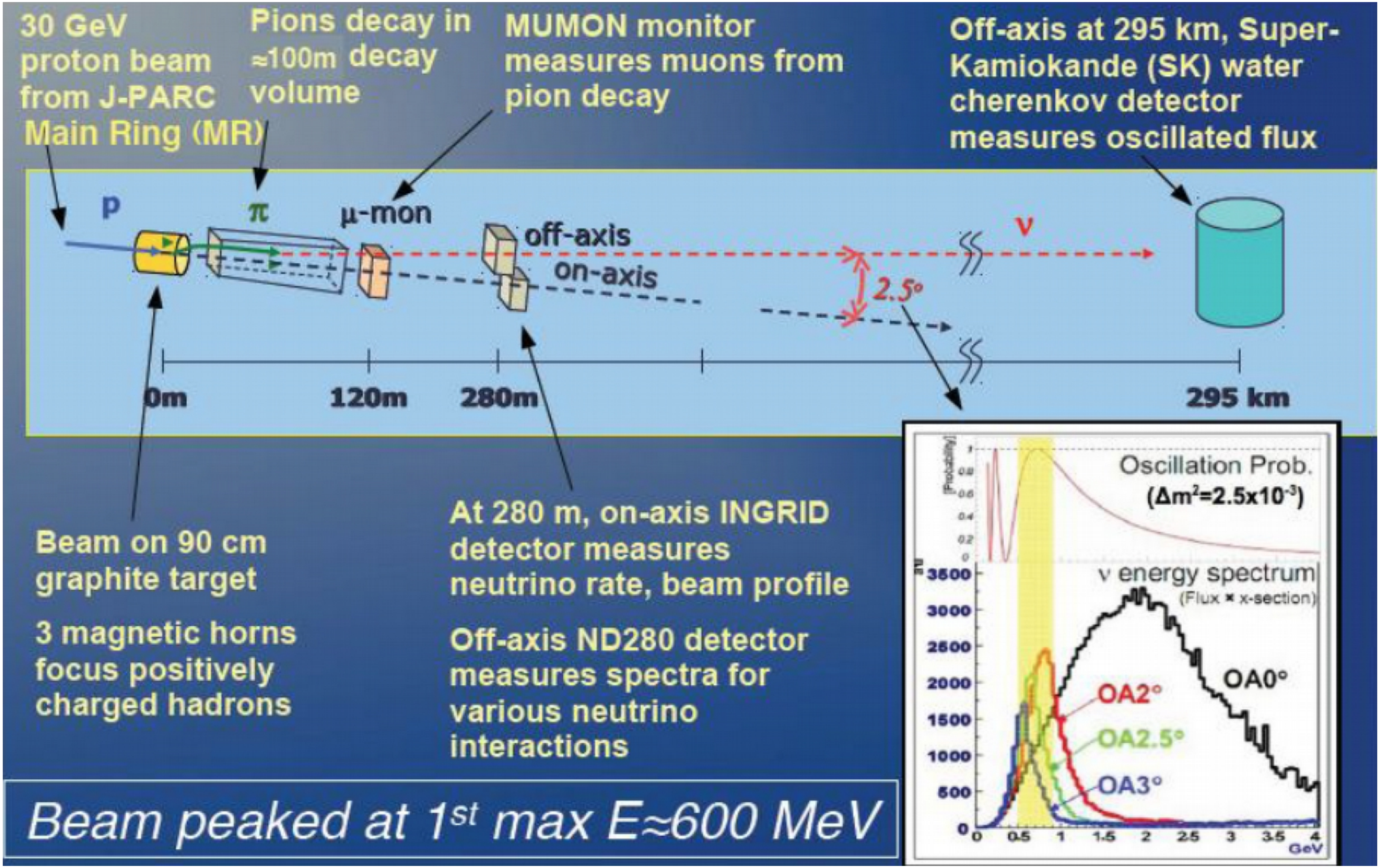


from A. Aurisano, Neutrino 2018



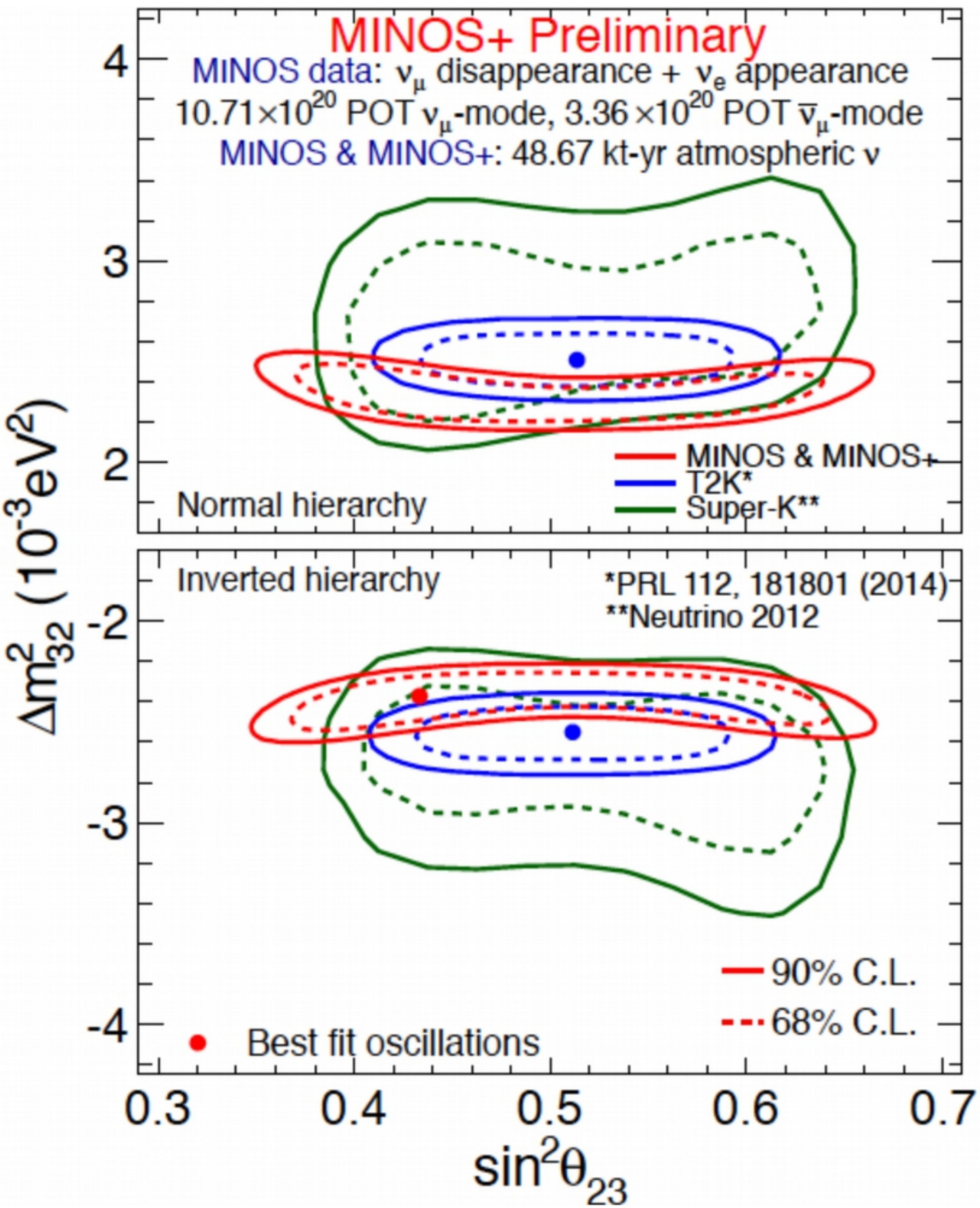


T2K: J-PARC to Super Kamiokande, 232 km off-axis beam → monoenergetic



from Dave Wark

Confirmation by accelerator experiments: MINOS, T2K, OPERA



Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$$

$$0.36 < \sin^2\theta_{23} < 0.65 \ (90\%\ \mathrm{C.L.})$$

Normal Hierarchy

$$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$$

$$0.37 < \sin^2\theta_{23} < 0.64 \ (90\%\ \mathrm{C.L.})$$

- **Most precise measurement of $|\Delta m^2_{32}|$**
- Consistent with maximal mixing

A. Sousa – Neutrino 2014

3 flavor mixing, $\theta_{13} \neq 0$ → CP-violation in lepton sector possible

3 flavor oscillation (without matter effects):

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\alpha i}\, e^{-iE_i t}\, U^*_{\beta i} \right|^2$$

Reactor neutrino disappearance:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{atm} L}{4E} - \cos^4(\theta_{13}) \sin^2(2\Theta_{solar}) \sin^2 \frac{\Delta m^2_{solar} L}{4E}$$

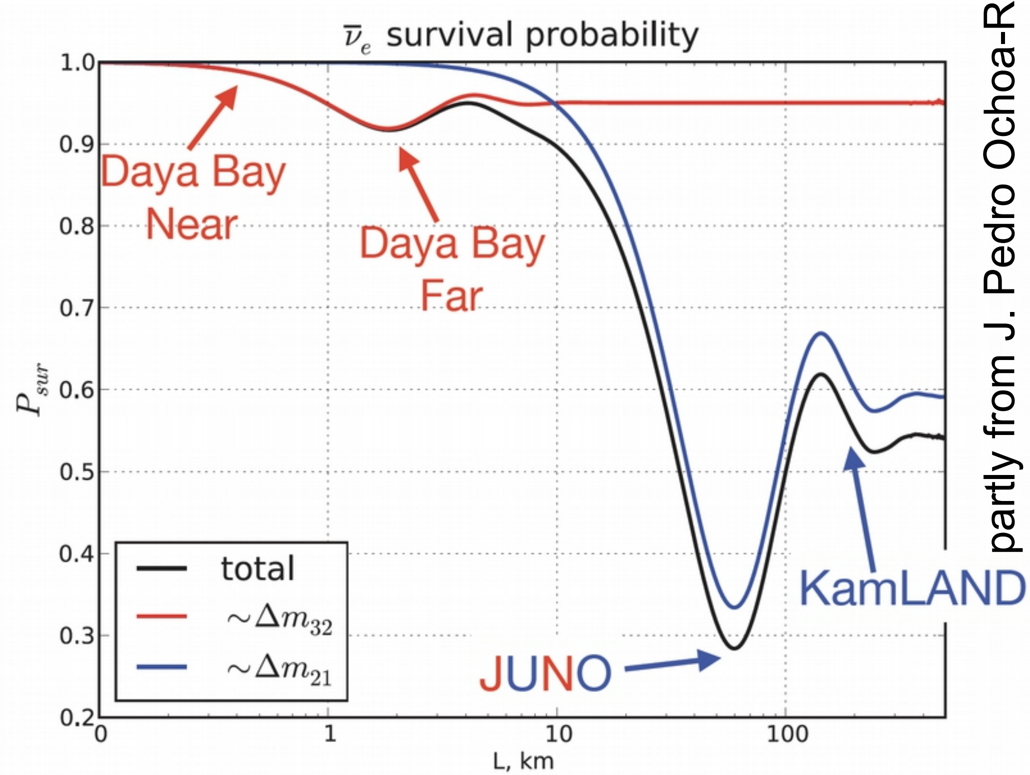
$\Delta m^2_{13} \approx \Delta m^2_{atm} \approx \Delta m^2_{23}$

$\Delta m^2_{12} = \Delta m^2_{solar}$

$\theta_{13} \neq 0$ ⇒ **CP violation in lepton sector possible**

Keys to a precise measurement:

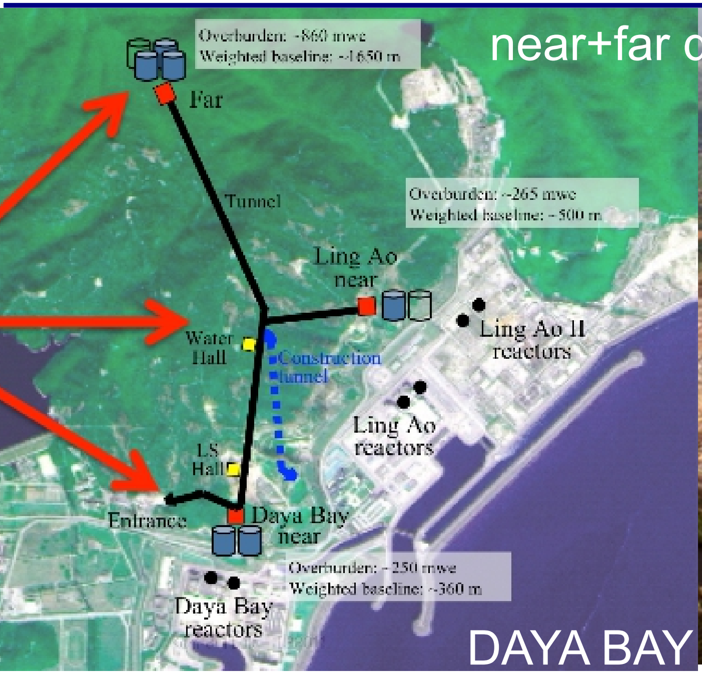
- High-statistics
- Suppressing backgrounds
- **Keeping systematics under control**
  - Relative near/far measurement
  - Make detectors as similar as possible (design, construction & calibration)

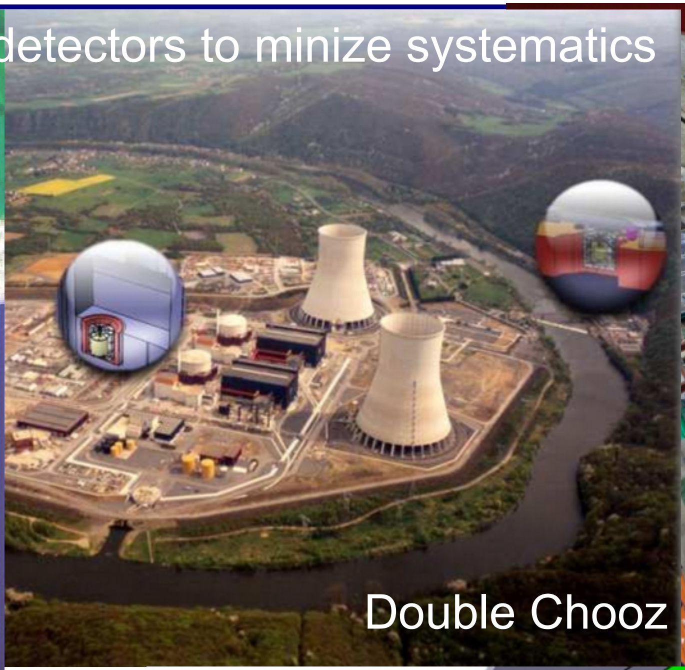


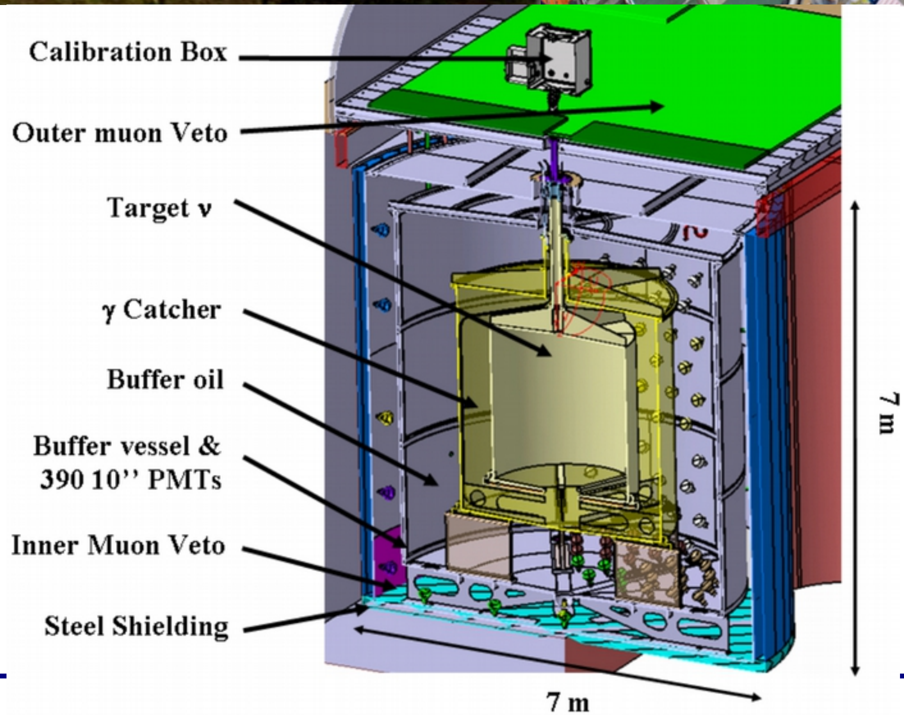
partly from J. Pedro Ochoa-Ricoux, Neutrino 2018

DAYA BAY, Double Chooz, (RENO):
$$\bar{\nu}_e + p \rightarrow n + e^+$$

near+far detectors to minize systematics



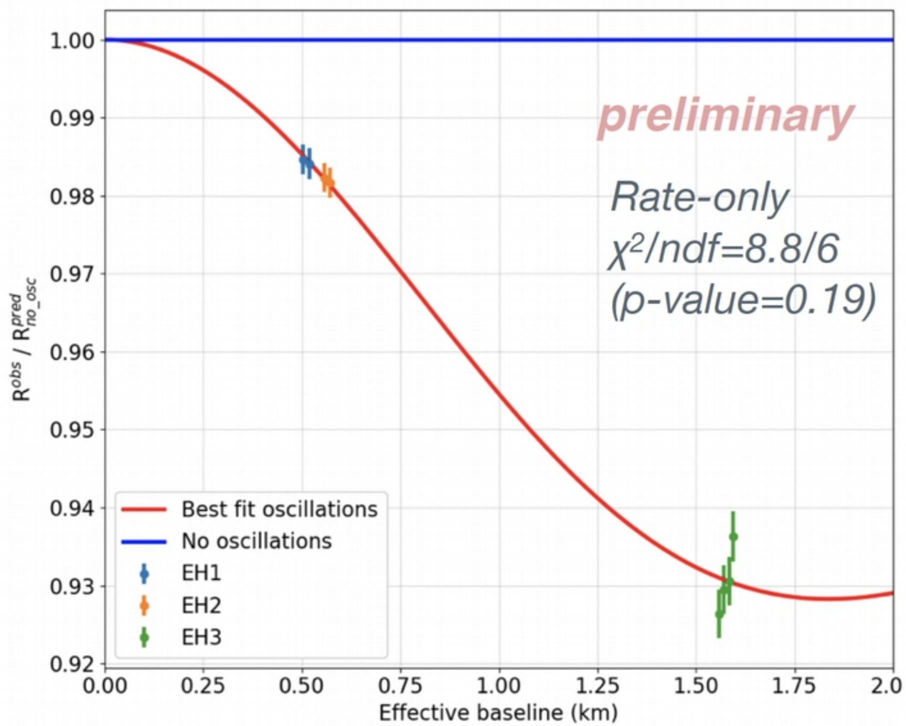


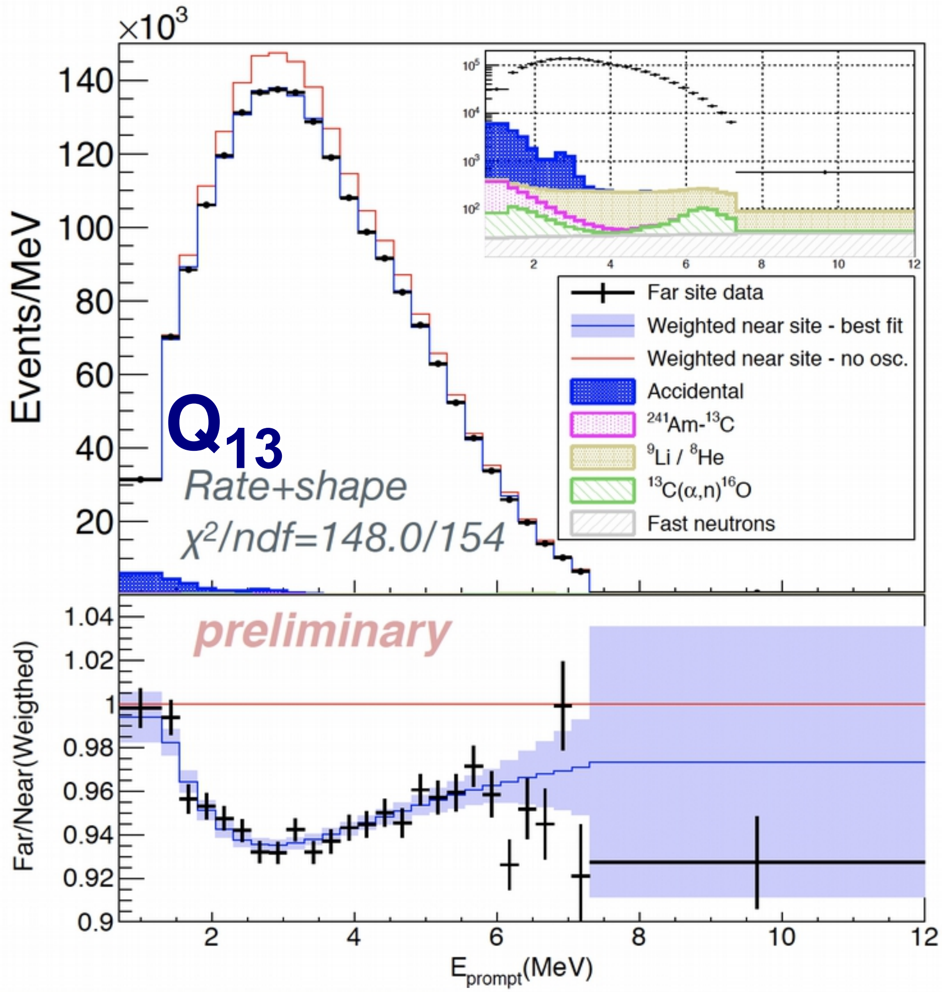


Similar detector concept
first by
Double Chooz

DAYA BAY results: precise determination of Θ_{13}

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis:





from J. Pedro Ochoa-Ricoux, Neutrino 2018

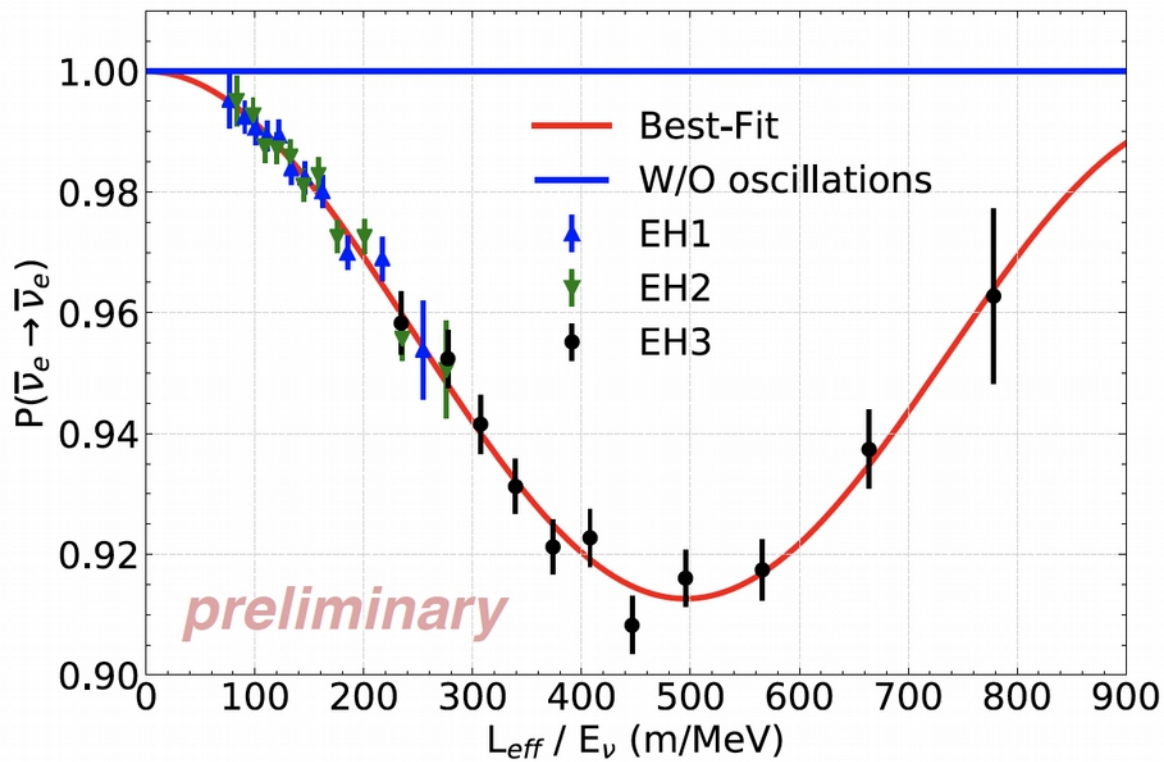
results with 1958 days →

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

$\Theta_{13} = 8.5°$

DAYA BAY oscillation curve & neutrino flux



- Previous measurement of the absolute reactor $\overline{\nu}_e$ flux compared to the Huber+Mueller expectation:

$R_{data/pred} = 0.946 \pm 0.020$ (exp.) ← systematics-dominated from absolute detection efficiency

results with 1230 days →

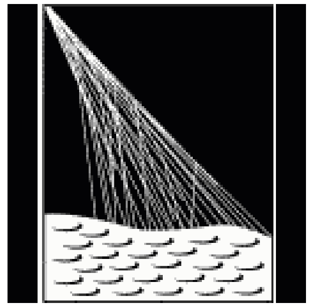
$$R_{data/pred} = 0.952 \pm 0.014(\text{exp.}) \pm 0.023(\text{model})$$

$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43}\ \text{cm}^2/\text{fission}$$

from J. Pedro Ochoa-Ricoux, Neutrino 2018

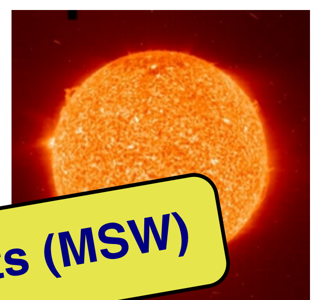
Positive results from ν oscillation experiments

atmospheric neutrinos
(Kamiokande, Super-Kamiokande, IceCube, ANTARES)



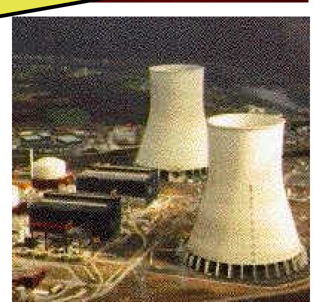
accelerator neutrinos
(K2K, T2K, MINOS, OPERA, MiniBoone)

solar neutrinos
(Homestake, Gallex, Sage, Super-Kamiokande, SNO, Borexino)



Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ, Daya Bay, Double CHOOZ, RENO, ...)



⇒ non-trivial ν-mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

$0.37 < \sin^2(\theta_{23}) < 0.63$ maximal!

$0.26 < \sin^2(\theta_{12}) < 0.36$ large !

$0.018 < \sin^2(\theta_{13}) < 0.030$ 8.5°

$7.0\ 10^{-5}\ \mathrm{eV}^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ \mathrm{eV}^2$

$2.2\ 10^{-3}\ \mathrm{eV}^2 < |\Delta m_{13}^2| < 2.6\ 10^{-3}\ \mathrm{eV}^2$

⇒ $m(\nu_j) \neq 0$, but unknown

additional sterile neutrinos ?