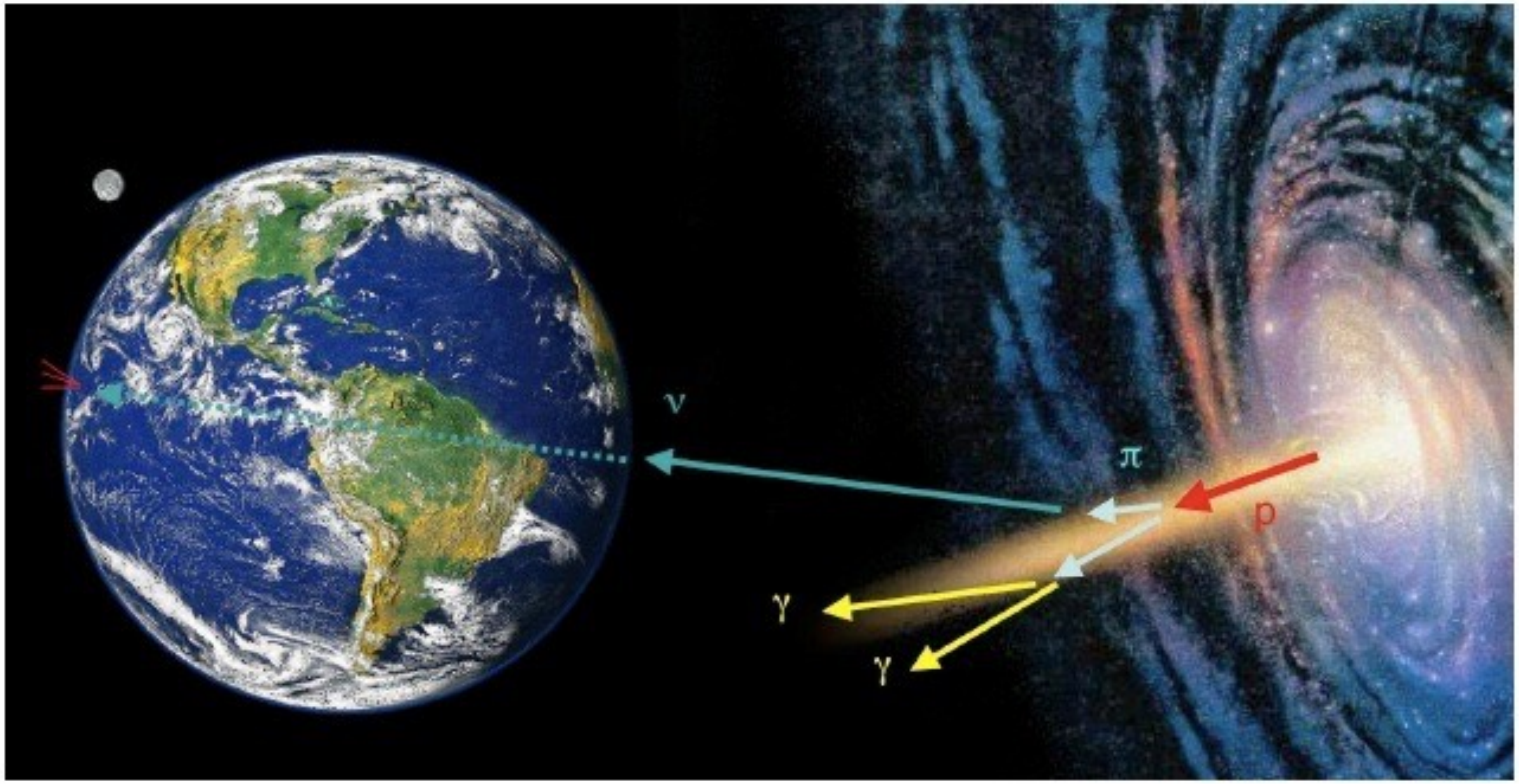
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



12. Neutrinos I - Introduction & The Discovery of Oscillations

02.07.2018

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Neutrinos: Time Line I

- 1931 W. Pauli postulates the existence of the neutrino in β decay
- 1934 E. Fermi presents a theory of the π decay (incl. neutrino)
- 1959 Discovery of ν_e (Reines and Cowan; Nobel prize 1995)
- 1962 Discovery of ν_μ
- 1968 First measurement of solar neutrinos (ν_e): less than 50% of the expected intensity („Solar Neutrino Problem“)
- 1987 Kamiokande and IMB (nucleon decay experiments) detect neutrinos from SN 1987a
- 1988 Kamiokande sees only 60% of the expected atmospheric ν_μ flux
  - 2002 Nobel prize for Koshiba and Davis for solar neutrino and Kamiokande measurements
- 1990 LEP experiments prove the existence of exactly 3 generations of light neutrinos
- 1998 Super-Kamiokande shows evidence for neutrino oscillations (ν_μ), -> neutrinos have finite mass

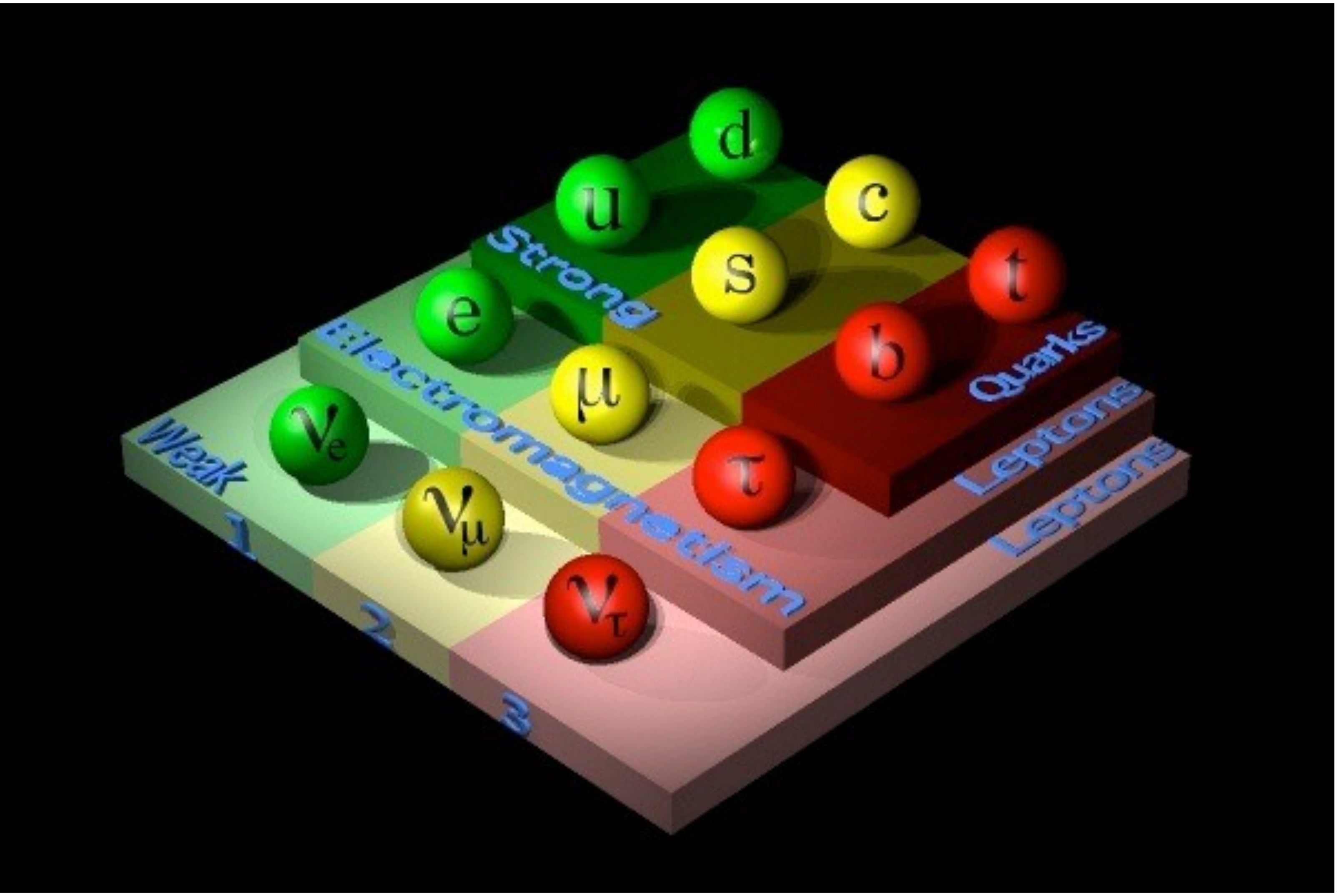
Neutrinos: Time Line II

- 2000 explicit confirmation and observation of ν_τ
- 2001 Confirmation of solar ν_e deficit and definite proof of neutrino oscillations into other flavors by SNO
  - 2015 Nobel prize for Kajita and MacDonald for SuperK / SNO discoveries
- 2011 First evidence for non-zero Θ_{13} by T2K & MINOS
- 2012 Observation of cosmic PeV neutrinos by IceCube
- 2016 First indication for possible CP violation in the neutrino sector by T2K

Introduction:

Neutrino Sorces, Interactions & Properties

Neutrinos: General Properties



- 3 known families of elementary particles:
  - 3 neutrinos as partners of the charged leptons
  - In the “simple” Standard Model neutrinos are massless
  - Experimental bounds of neutrino masses:
    $M(\nu_e) < 2$ eV
    $M(\nu_\mu) < 0.19$ MeV
    $M(\nu_\tau) < 18.2$ MeV

Neutrino Sources

- **Solar neutrinos**
  (get produced in the fusion reaction in the sun), ca 2×10^{38} /s,
  flux on earth ~ 7×10^{10} cm^{-2}s^{-1}
- **Cosmic neutrino background**
  freeze out ~ 1s after the Big Bang,
  temperature ~ 1.9 K, <E> ~ 5×10^{-4} eV, ~ 330/cm^3
- **Cosmic neutrino sources**
  supernova explosions, active galaxies, GRBs...
- **Atmospheric neutrinos**
  produced in cosmic ray air showers
- **Geo neutrinos**
  radioactive decay in earth, total power ~ 20 TW, flux ~ 10^7 cm^{-2}s^{-1}
- **Man made neutrinos**
  reactor neutrinos (MeV energies), accelerator neutrinos (MeV -> GeV)

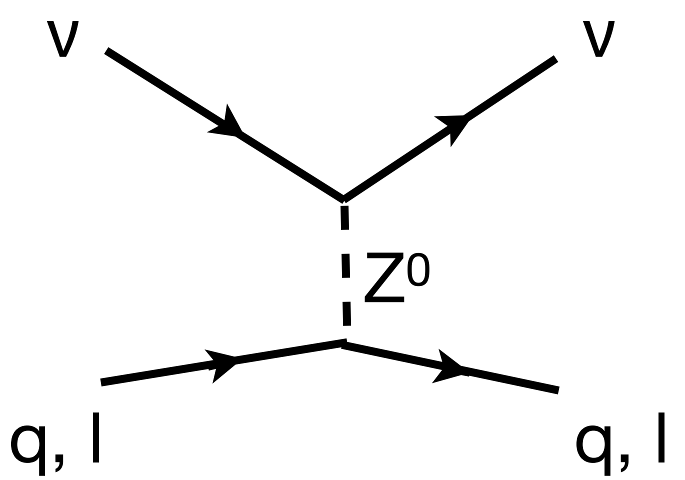
Neutrinos: General Properties

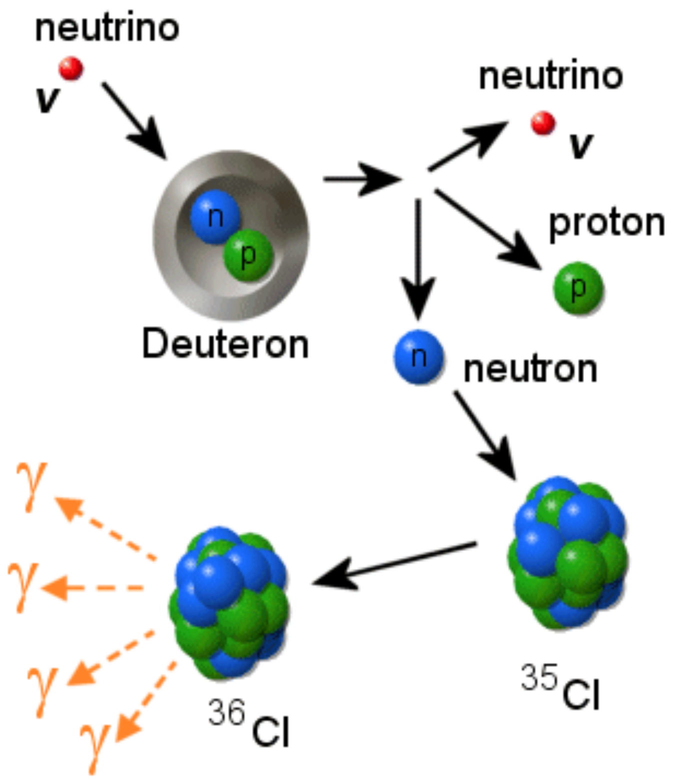
- Neutrinos are special: they only interact via the weak interaction
    - Maximum parity violation of the weak interaction enforces:
      Neutrinos are always left-handed (helicity -1)
      Anti-Neutrinos are always right-handed (helicity +1)

- Possible consequence:
    - Neutrinos may be their own anti-particles, so-called Majorana particles
        - A neutrino would then be a left-handed Majorana neutrino, an anti-neutrino a right-handed Majorana neutrino
        - ▸ The differentiation between Majorana and Dirac neutrinos is only possible for massive neutrinos

Neutrinos: Interaction with Matter

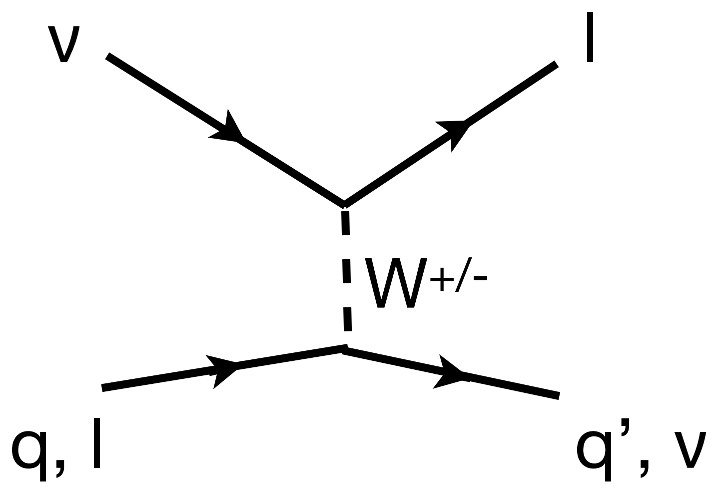
- Neutral current

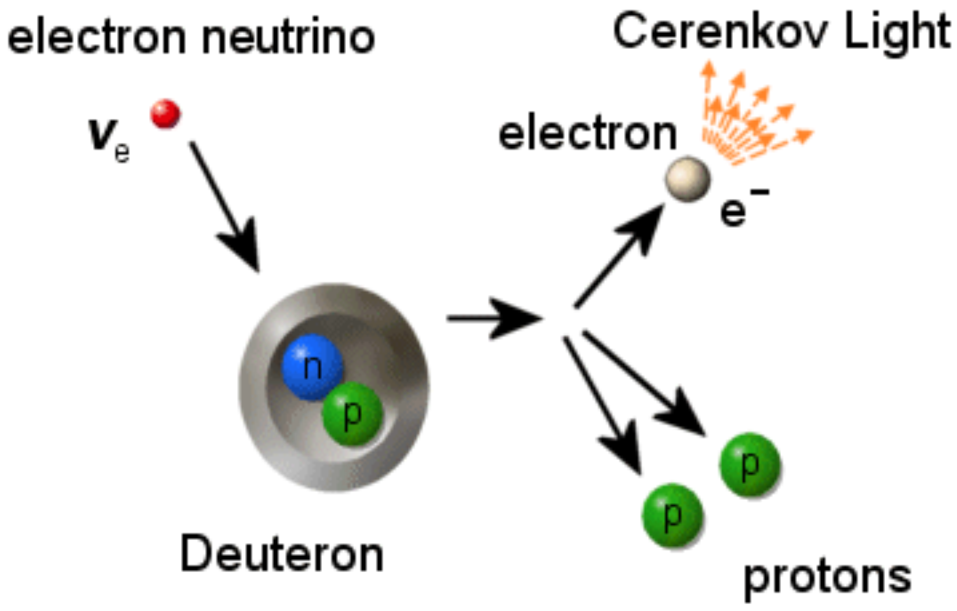




SNO

- Charged current

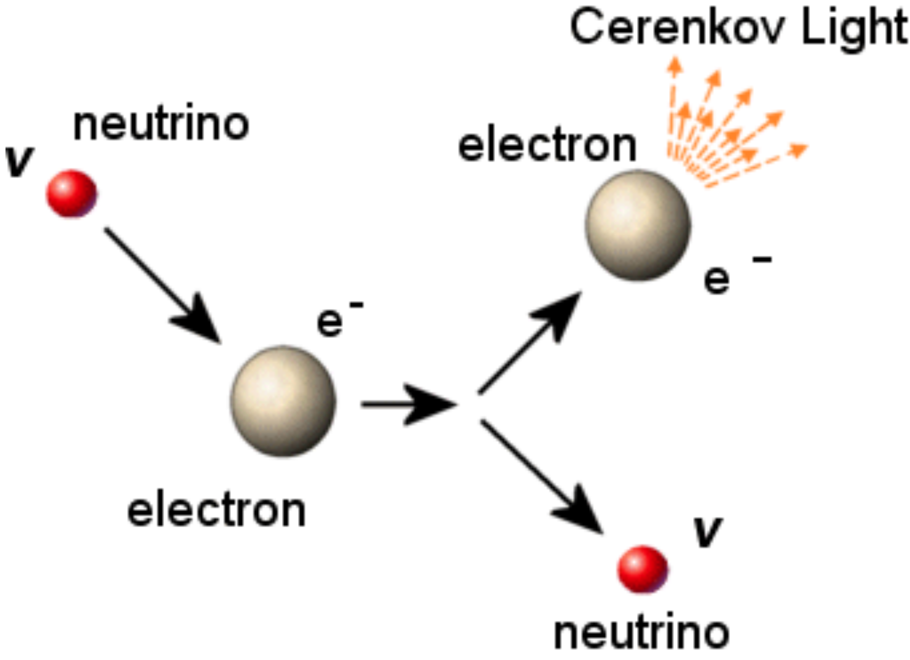




SNO

Neutrino - Elektron Scattering

- Special Case:
  - For ν_μ and ν_τ this process only works via the neutral current
  - For ν_e both neutral and charged current contributes



SNO

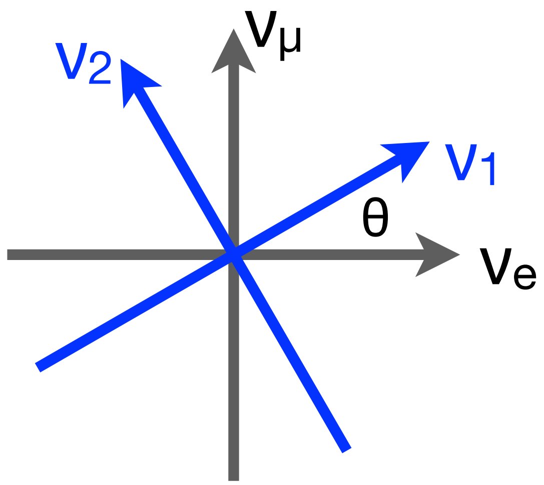
- Cross sections
  - $\nu_\mu e$: ~ 1.5 x 10^{-42} cm^2 E_ν/GeV
  - $\nu_e e$: ~ 10 x 10^{-42} cm^2 E_ν/GeV

▸ ~ three orders of magnitude smaller than neutrino-nucleon scattering

In general: neutrino cross sections are proportional to the neutrino energy!

Neutrino Oscillations: Basic Conditions

- Neutrinos have to have mass to be able to oscillate!
  - Mass eigenstates are not the same as flavor eigenstates



- Example: A world with two neutrino types:
  - The eigenstates of the weak interaction ν_μ und ν_e are not identical to the mass eigenstates ν_1 und ν_2

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

  - The eigenstates of the weak interaction ν_μ und ν_e (which we can observe and identify) are mixes of the mass eigenstates:

$$|\nu_\mu\rangle = -sin\theta\ |\nu_1\rangle + cos\theta\ |\nu_2\rangle$$

$$|\nu_e\rangle = cos\theta\ |\nu_1\rangle + sin\theta\ |\nu_2\rangle$$

Neutrino Oscillations: Two Neutrinos

- The time evolution in vacuum is given by the mass eigenstates (Schrödinger Eq):

$$|\nu_\mu(t)\rangle \;=\; -sin\theta\,(|\nu_1\rangle\; e^{-iE_1t}) \;+\; cos\theta\,(|\nu_2\rangle\; e^{-iE_2t})$$

$$E_i \;=\; \sqrt{p^2+m_i^2} \;\approx\; p + \frac{m_i^2}{2p} \;\approx\; E + \frac{m_i^2}{2E}$$

  - If the two mass eigenstates have different masses the relative composition changes over time, a ν_μ can transform into a ν_e!
  - The oscillation property is:

$$P(\nu_\mu \rightarrow \nu_e) \;=\; |\,\langle \nu_e | \nu_\mu(t)\rangle\,|^2$$

  - The transition probability as a function of distance and neutrino energy is:

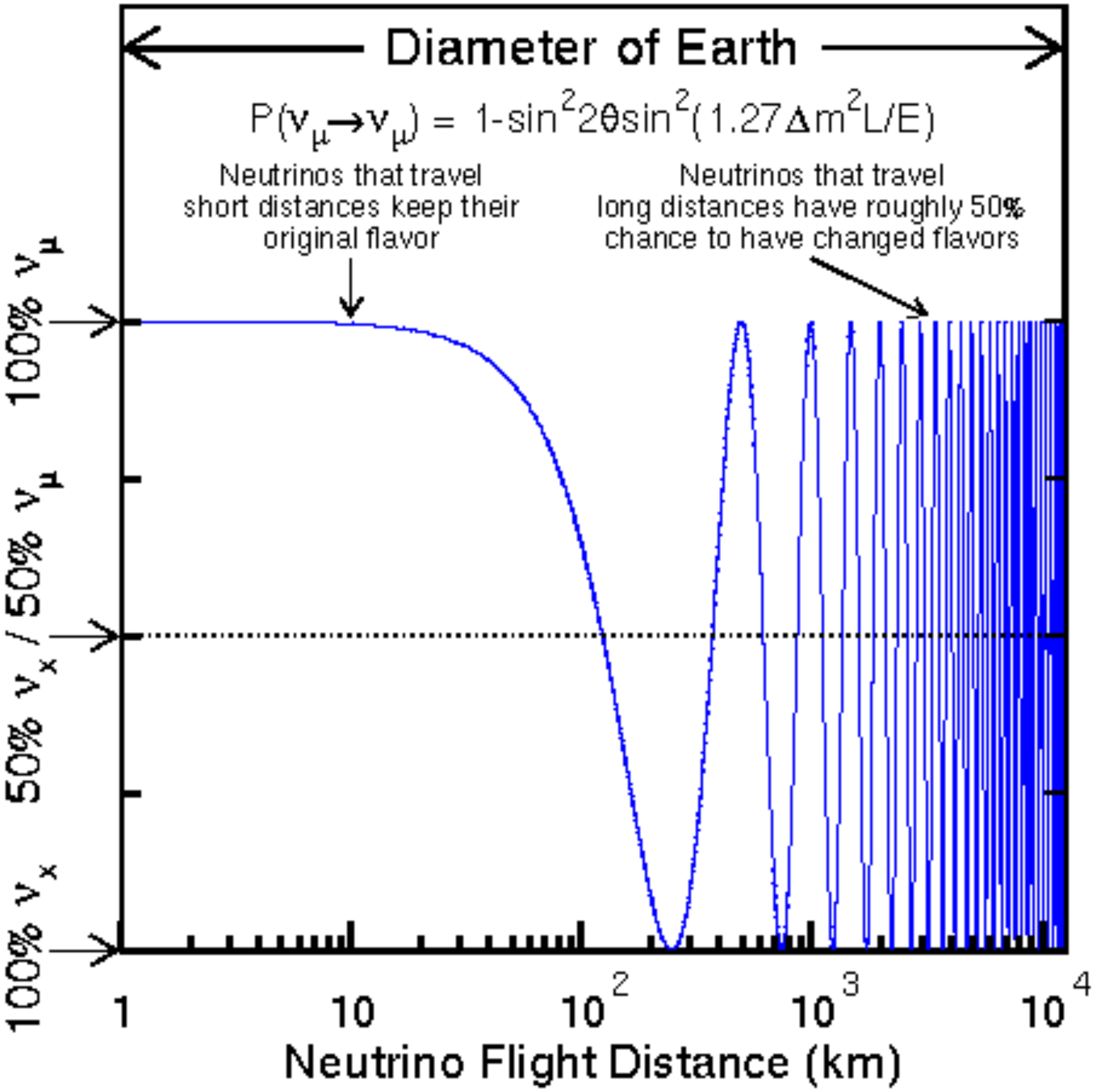
$$P(\nu_\mu \leftrightarrow \nu_e) \;=\; sin^2 2\theta\, sin^2\left(\frac{\Delta m^2 L}{4E}\right) \;=\; sin^2 2\theta\, sin^2\left(1.27\,\frac{\Delta m^2}{\mathrm{eV}^2}\,\frac{L/\mathrm{m}}{E/MeV}\right)$$

$$\Delta m^2 \;=\; m_1^2 - m_2^2$$

Neutrino Oscillations

- Neutrino oscillations as a function of distance

$$\Delta m^2 = 0.005\,\mathrm{eV}^2\ ,\ sin^2 2\theta = 1\ ,\ E = 1\,\mathrm{GeV}$$



Oscillation length:

$$L_{osc} = \frac{4\pi \cdot E}{\Delta m^2}$$

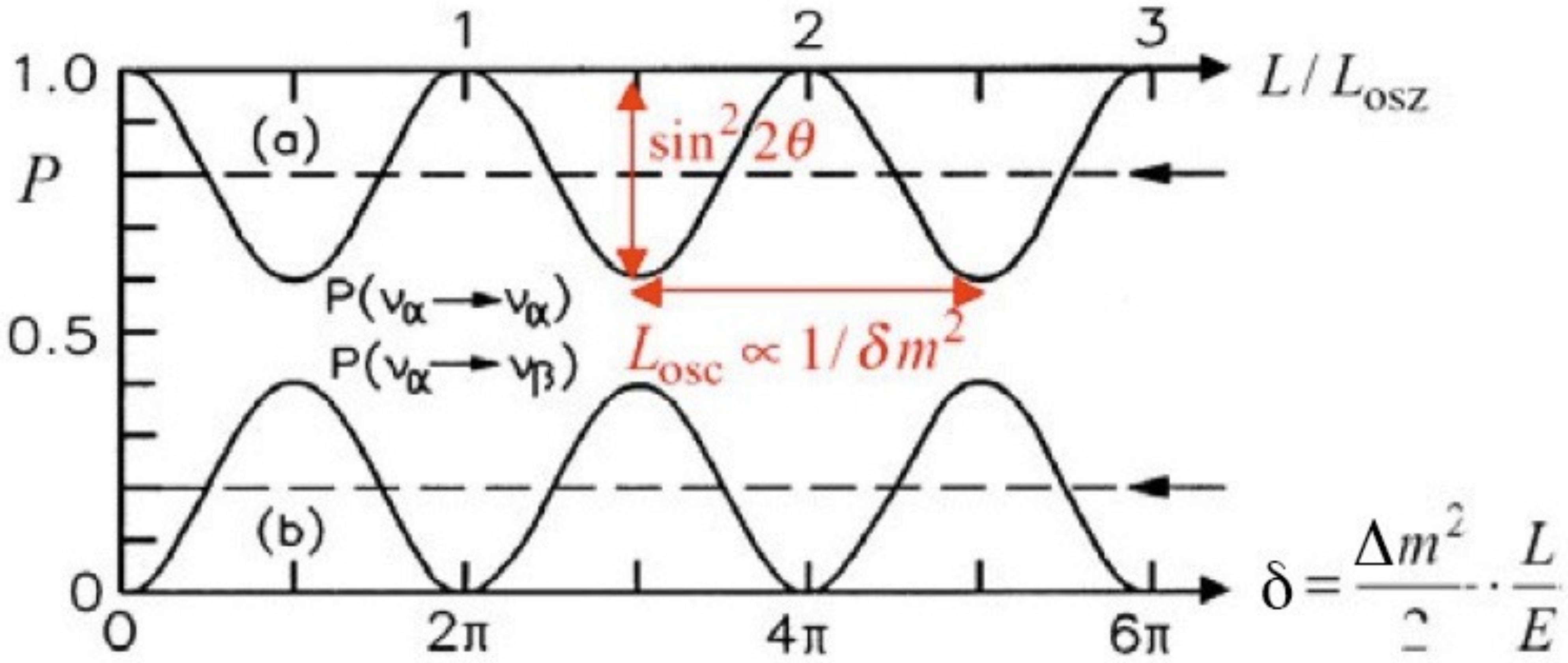
$$L_{osc}/m = \frac{2{,}5 \cdot E/MeV}{\Delta m^2/eV}$$

here:

$L_{osc} = 500$ km

Neutrino Oscillations

- The influence of the mixing angle:



- ▸ The mixing angle determines the amplitude (the maximum level of transformation), the mass difference determines the speed of the oscillation

Neutrino Oscillations: General Case

- n flavor eigenstates $|\nu_\alpha\rangle \text{ mit } \alpha = e,\, \mu,\, \tau,\, ...$
- n mass eigenstats $|\nu_i\rangle \text{ mit } i = 1,\, 2,\, 3,\, ...$

- The states are coupled via a unitary n x n mixing matrix:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}\, |\nu_i\rangle$$

- $(n-1)^2$ independent parameters of the mixing matrix:
  - n(n-1)/2 mixing angles
  - (n-1)(n-2)/2 CP violating phases

- For n = 3:
  - 3 mixing angles: $\theta_{12},\, \theta_{23},\, \theta_{13}$
  - 1 phase

General description of the 3-ν case

- Described by a 3 x 3 matrix (Pontecorvo-Maki-Nakagawa-Sakata-Matrix PMNS):
  - 3 angels and one CP violating phase
- analogous to the CKM matrix in the quark case

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

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & \boxed{s_{13}e^{-i\delta}} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

CP violation
connected to Θ13

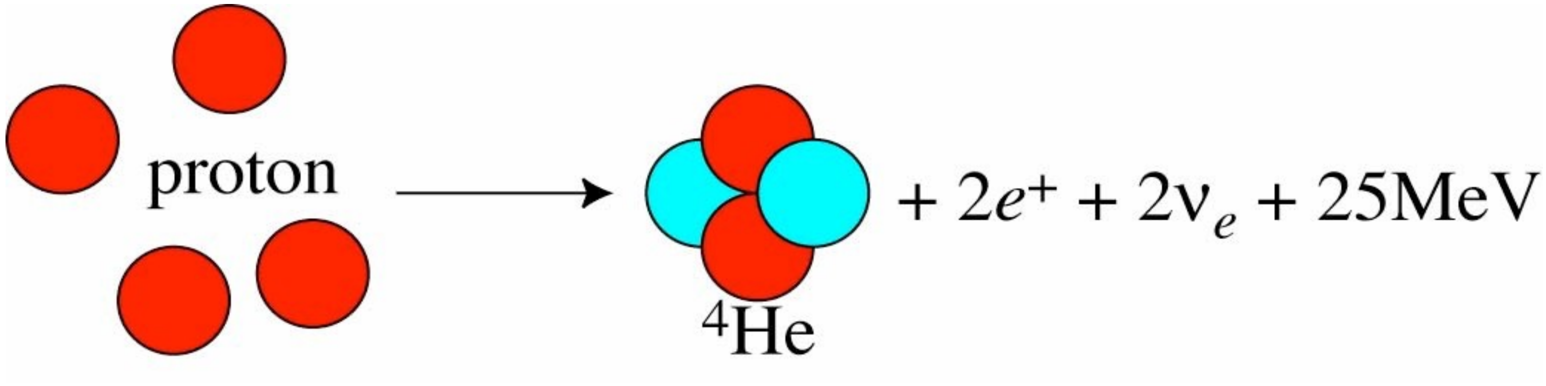
Detectors for Highly Energetic Neutrinos

- Small cross section of neutrinos: Large detector masses!
- Rare neutrino events: Good shielding from background processes:
    - Suppression of natural radioactivity: high purity
    - Shielding from cosmic muons
- Example: Kamiokande, Super-Kamiokande (Kamioka Nucleon Decay Experiment)
    - Search for proton decay with 3000 t of highly pure water (since 1983)
    - cosmic, atmospheric and solar neutrinos (since 1985)
        - 1987: 11 neutrinos from SN1987A observed
    - Upgrade to Super-K completed in 1996
        - 50 000 t highly pure water, 32 000 t active, 18 000 t as veto
        - 11 200 PMTs (50 cm diameter)

Neutrinos from the Sun

Fusion in the Sun

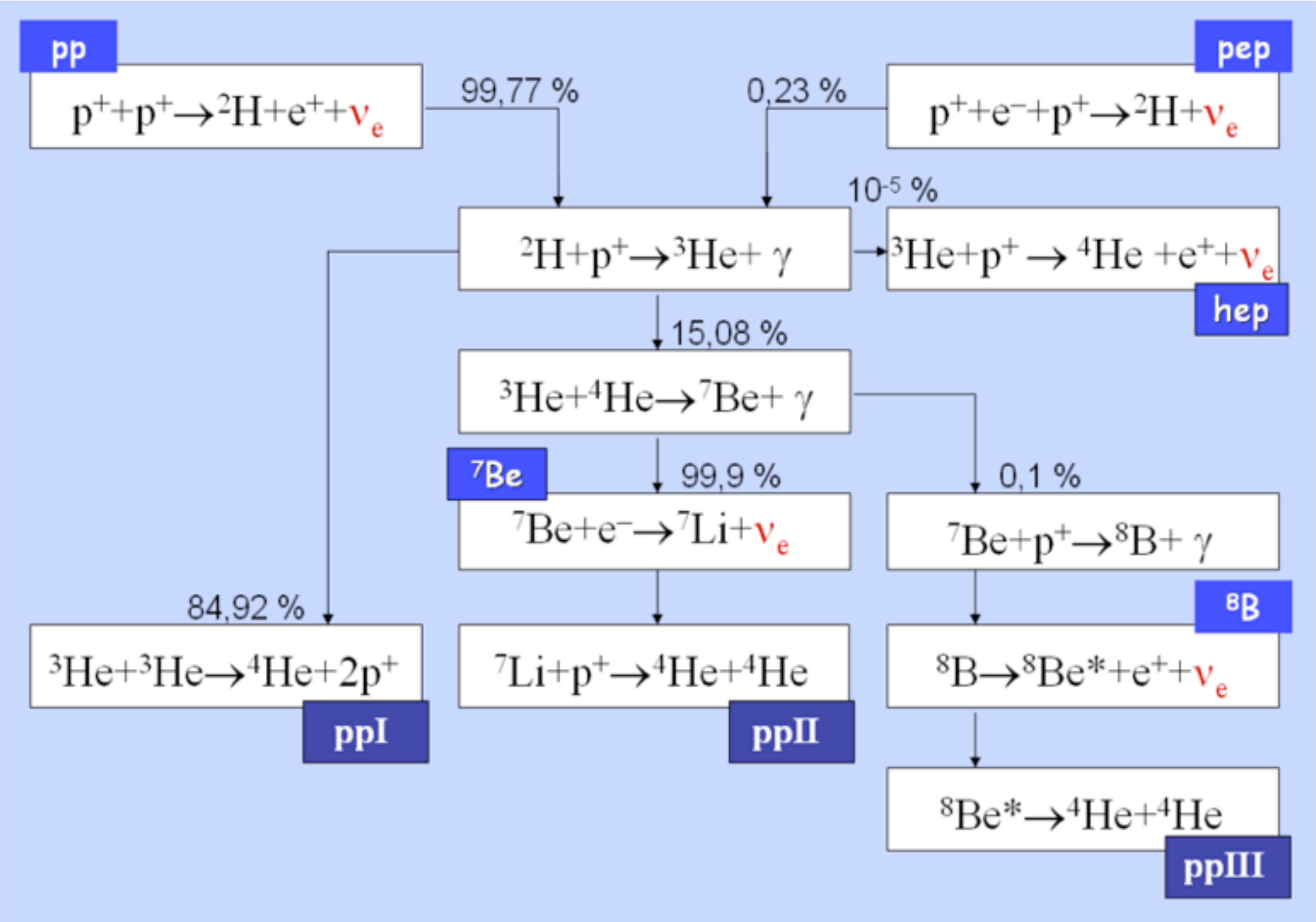
- Fusion reaction in the sun:



- … and the corresponding estimate of the neutrino production:

$$\Phi_\nu = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7 \cdot 10^{10}\,\text{sec}^{-1}\,\text{cm}^{-2}$$

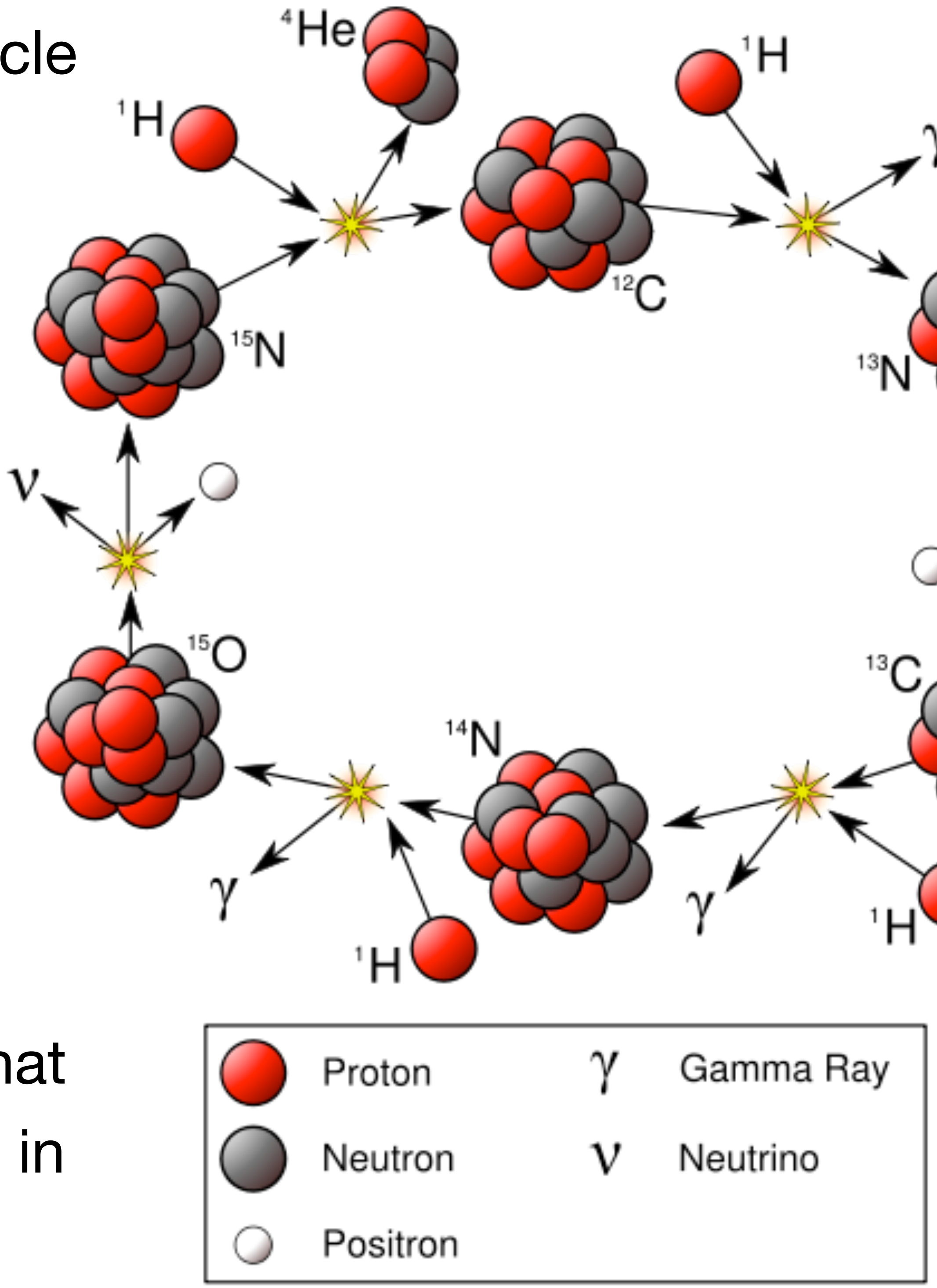
Fusion in the Sun: pp Chain



Fusion in the Sun: CNO Cycle

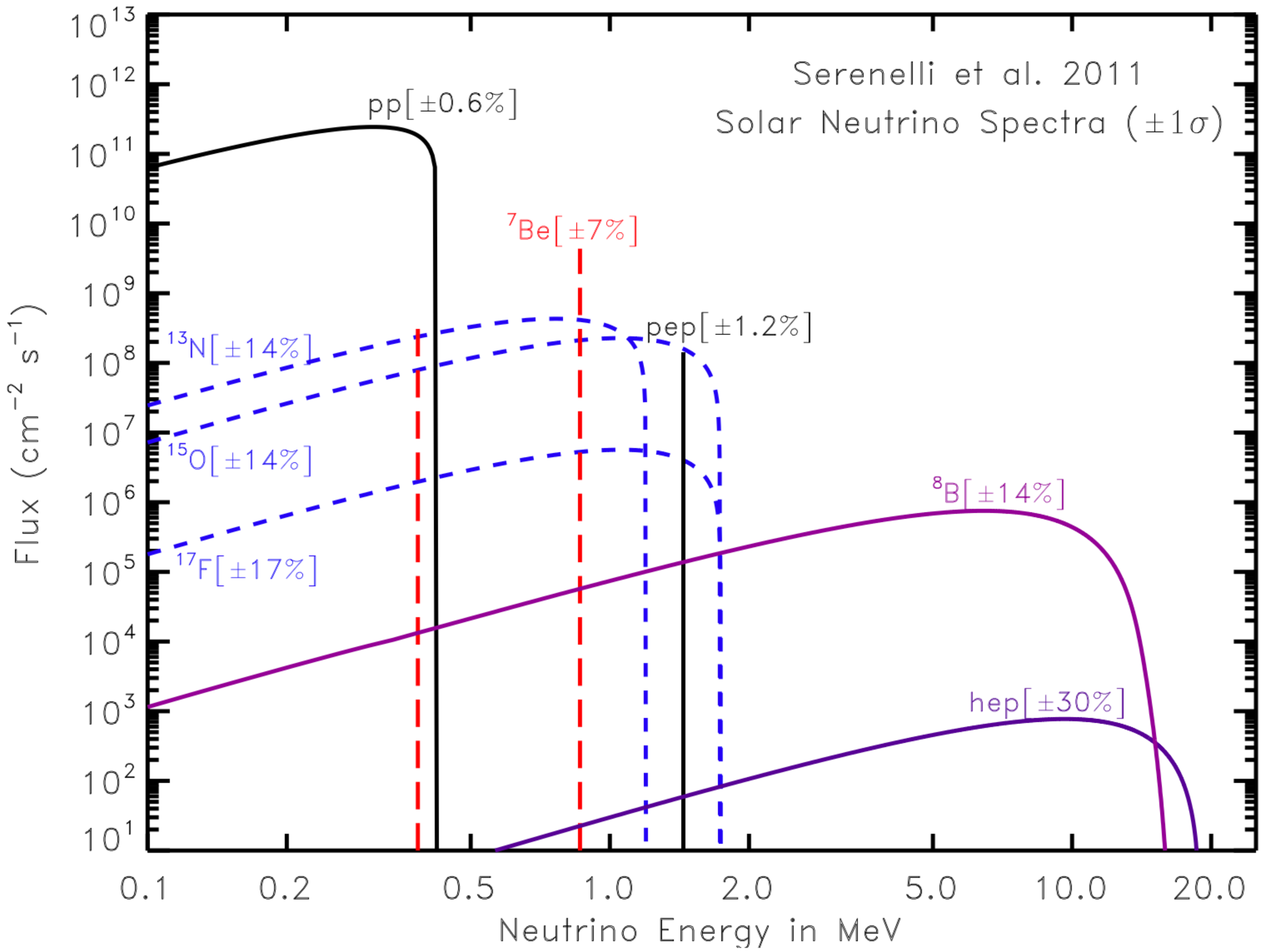
- … also called the Bethe - Weizsäcker cycle

$$
\begin{array}{llll}
{}^{12}_{6}\mathrm{C} + {}_{1}\mathrm{H} & \rightarrow & {}^{13}_{7}\mathrm{N} + \gamma & + 1.95\ \mathrm{MeV} \\
{}^{13}_{7}\mathrm{N} & \rightarrow & {}^{13}_{6}\mathrm{C} + e^{+} + \nu_e & + 2.22\ \mathrm{MeV} \\
{}^{13}_{6}\mathrm{C} + {}_{1}\mathrm{H} & \rightarrow & {}^{14}_{7}\mathrm{N} + \gamma & + 7.54\ \mathrm{MeV} \\
{}^{14}_{7}\mathrm{N} + {}_{1}\mathrm{H} & \rightarrow & {}^{15}_{8}\mathrm{O} + \gamma & + 7.35\ \mathrm{MeV} \\
{}^{15}_{8}\mathrm{O} & \rightarrow & {}^{15}_{7}\mathrm{N} + e^{+} + \nu_e & + 2.75\ \mathrm{MeV} \\
{}^{15}_{7}\mathrm{N} + {}_{1}\mathrm{H} & \rightarrow & {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} & + 4.96\ \mathrm{MeV}
\end{array}
$$

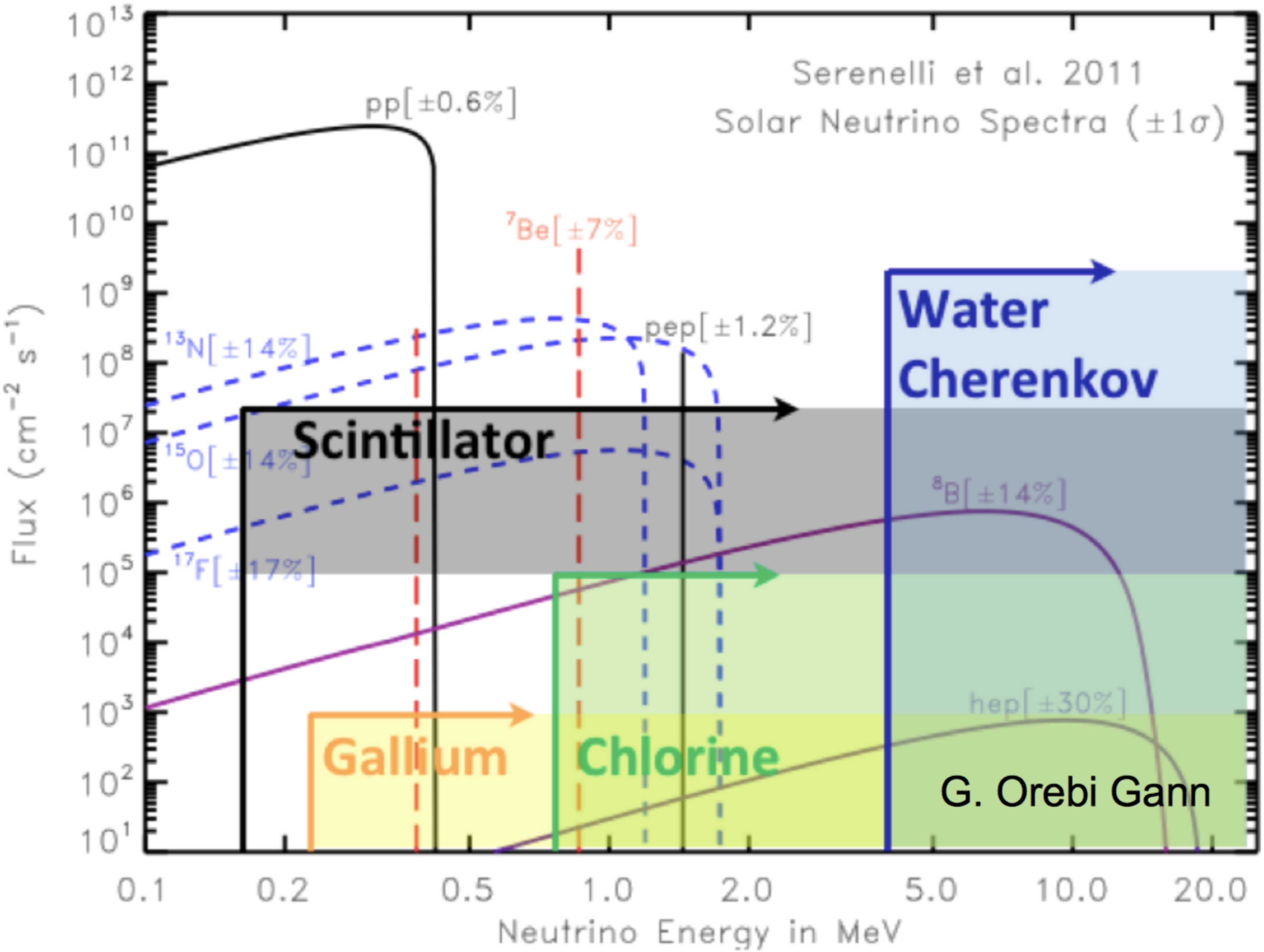


- The relative weight of pp and CNO depends on the temperature, and with that on the mass of the star: CNO dominates in heavy stars
- In the sun: 98.3% pp, 1.7% CNO

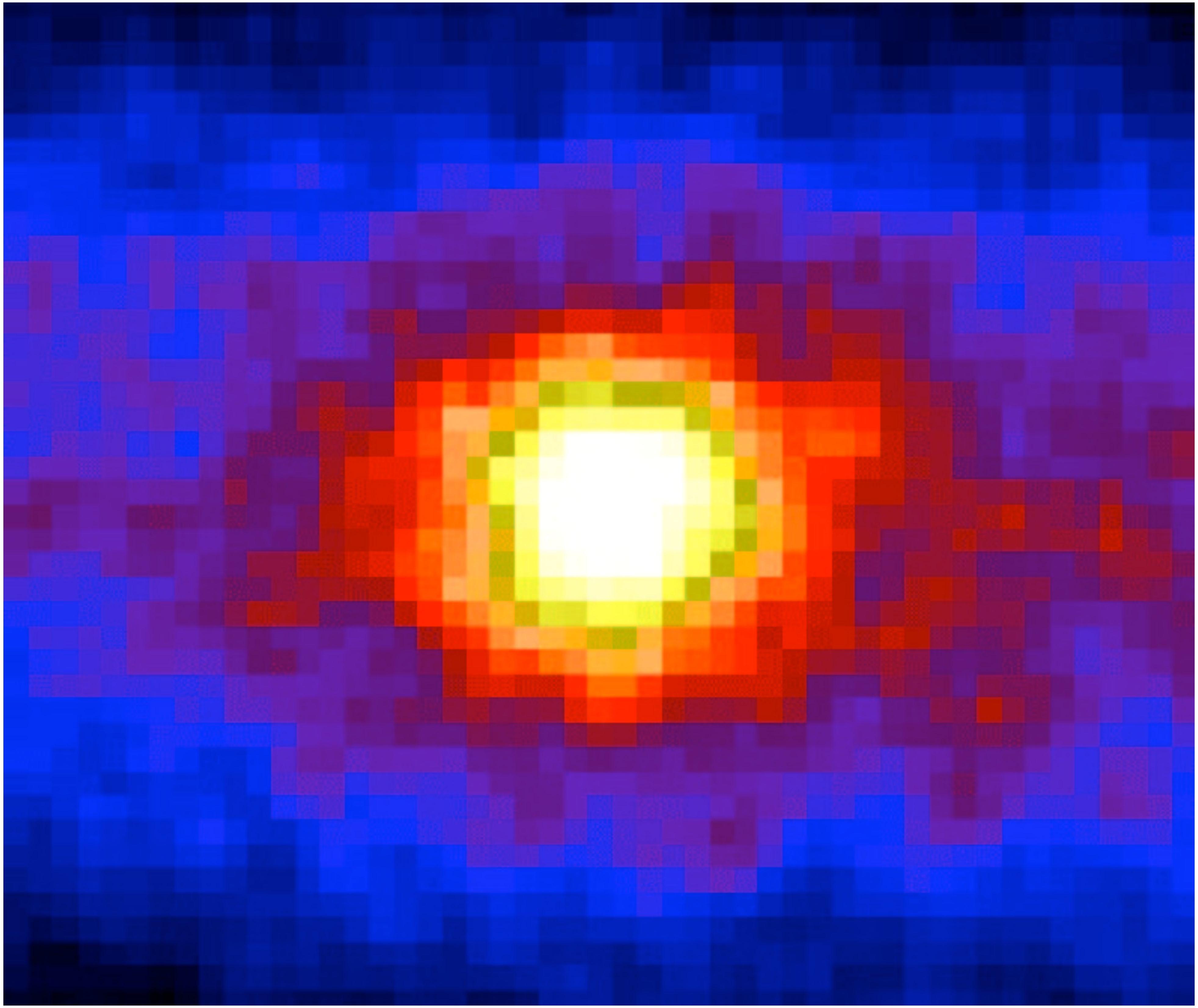
The Solar Neutrino Spectrum



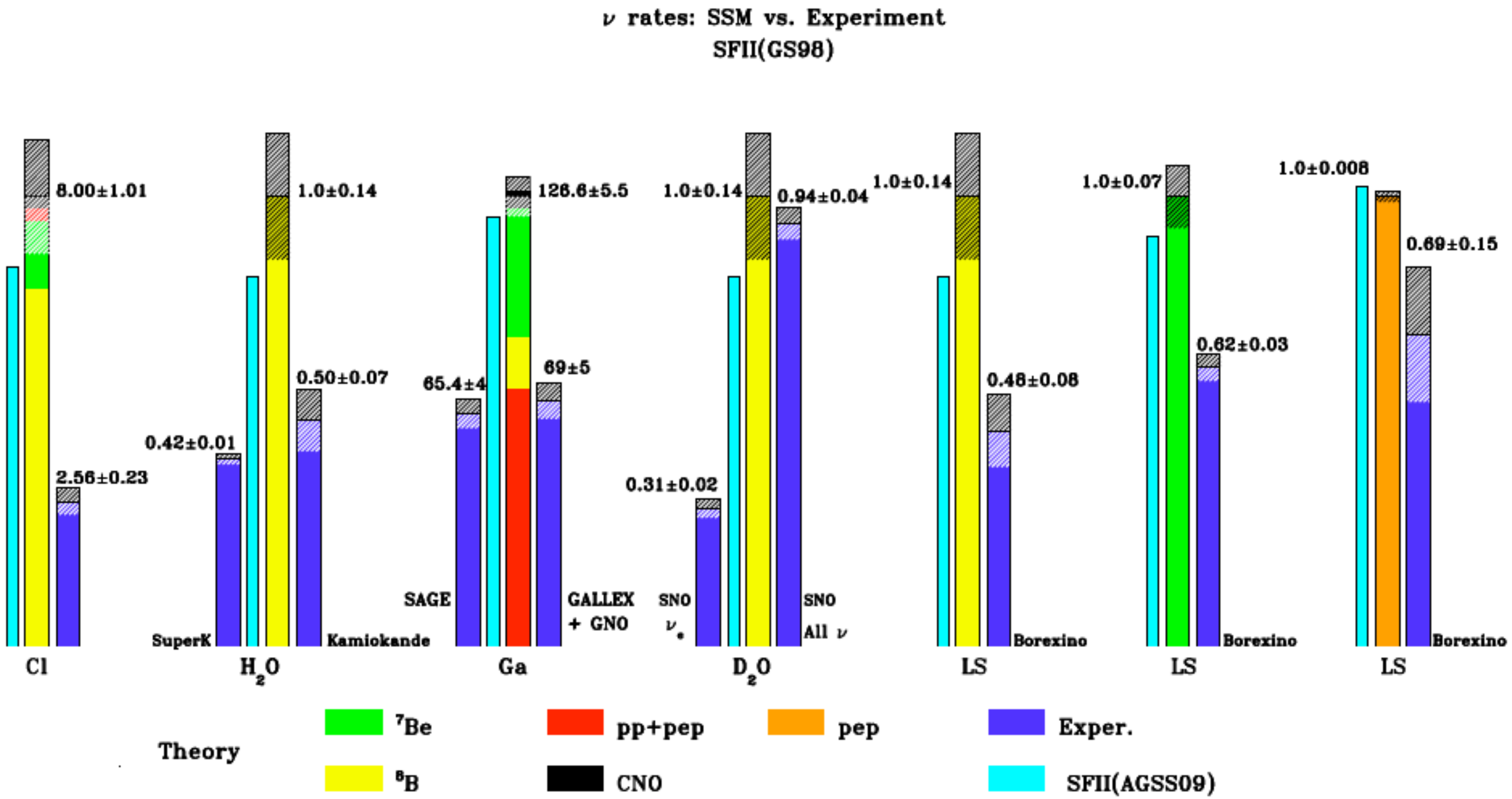
… and how to measure it



The Sun - Seen in Neutrinos (SuperK Experiment)



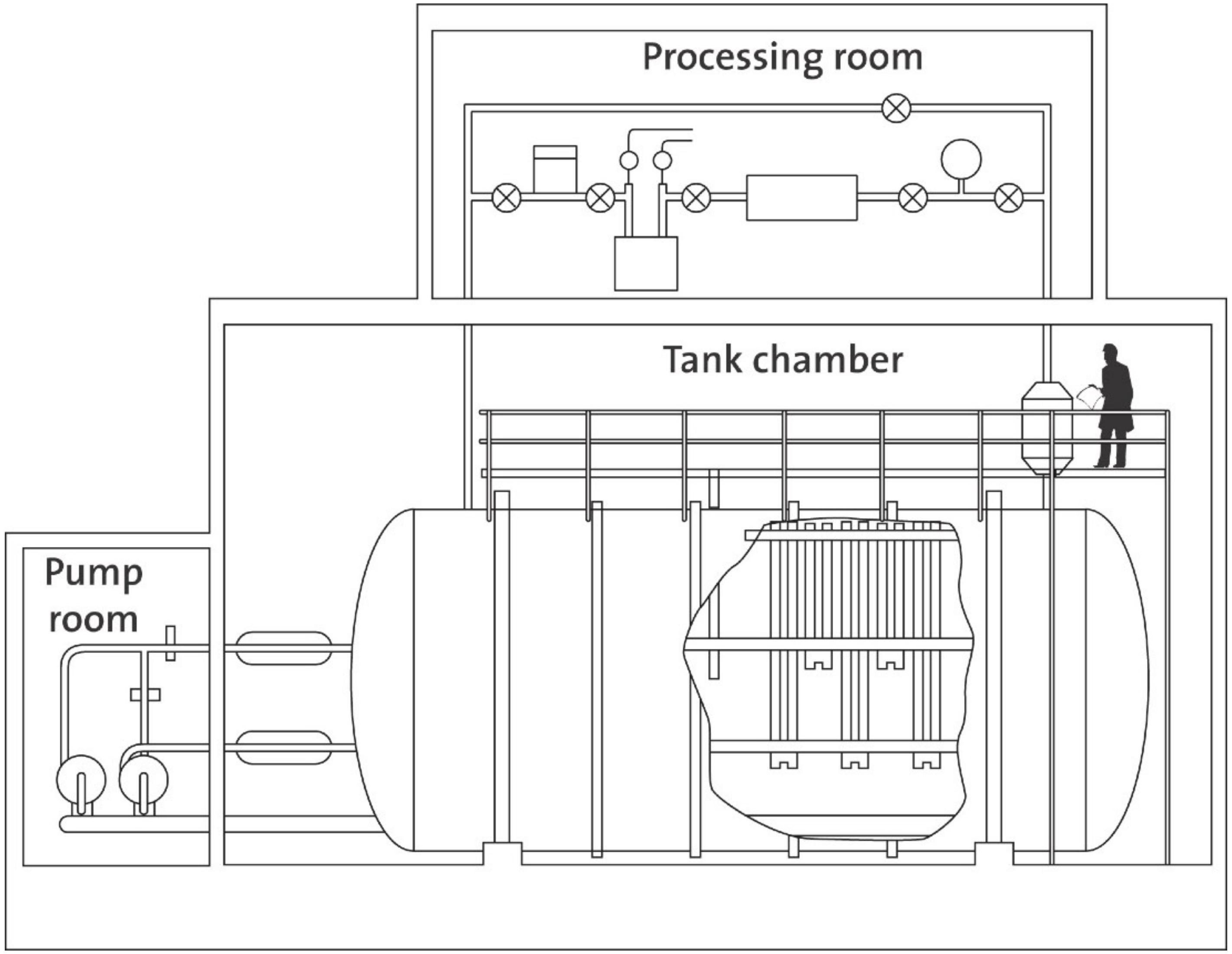
The Solar Neutrino Puzzle: Indication of Oscillations



- To few neutrinos observed by a variety of different experiments - primarily sensitive to ^{8}B neutrinos (pp chain, highest energy)

Pioneering Experiment: Homestake

- First experiments in the Homestake mine with Chlorine



- A tank of 615 t of C_2Cl_4, 2.2×10^{30} atoms of ^{37}Cl

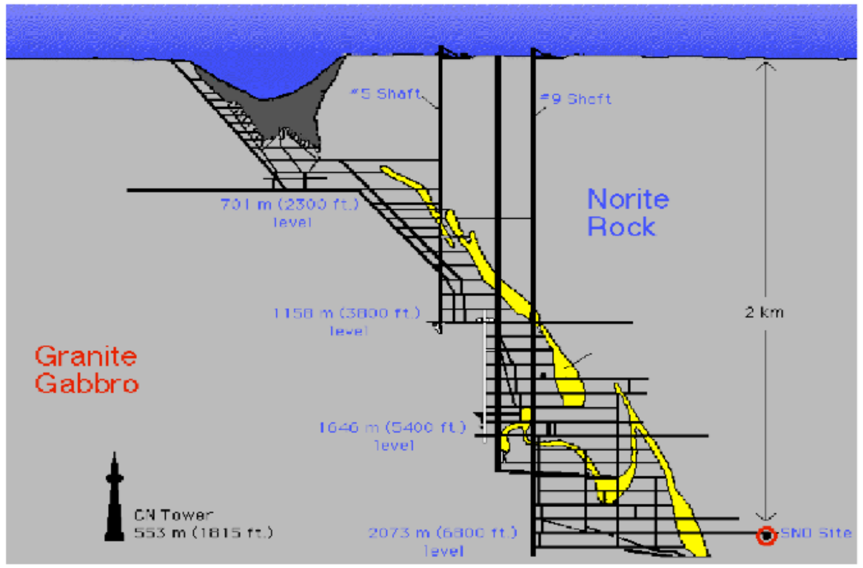
$$\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

threshold 0.81 MeV, ~ 1 atom/day

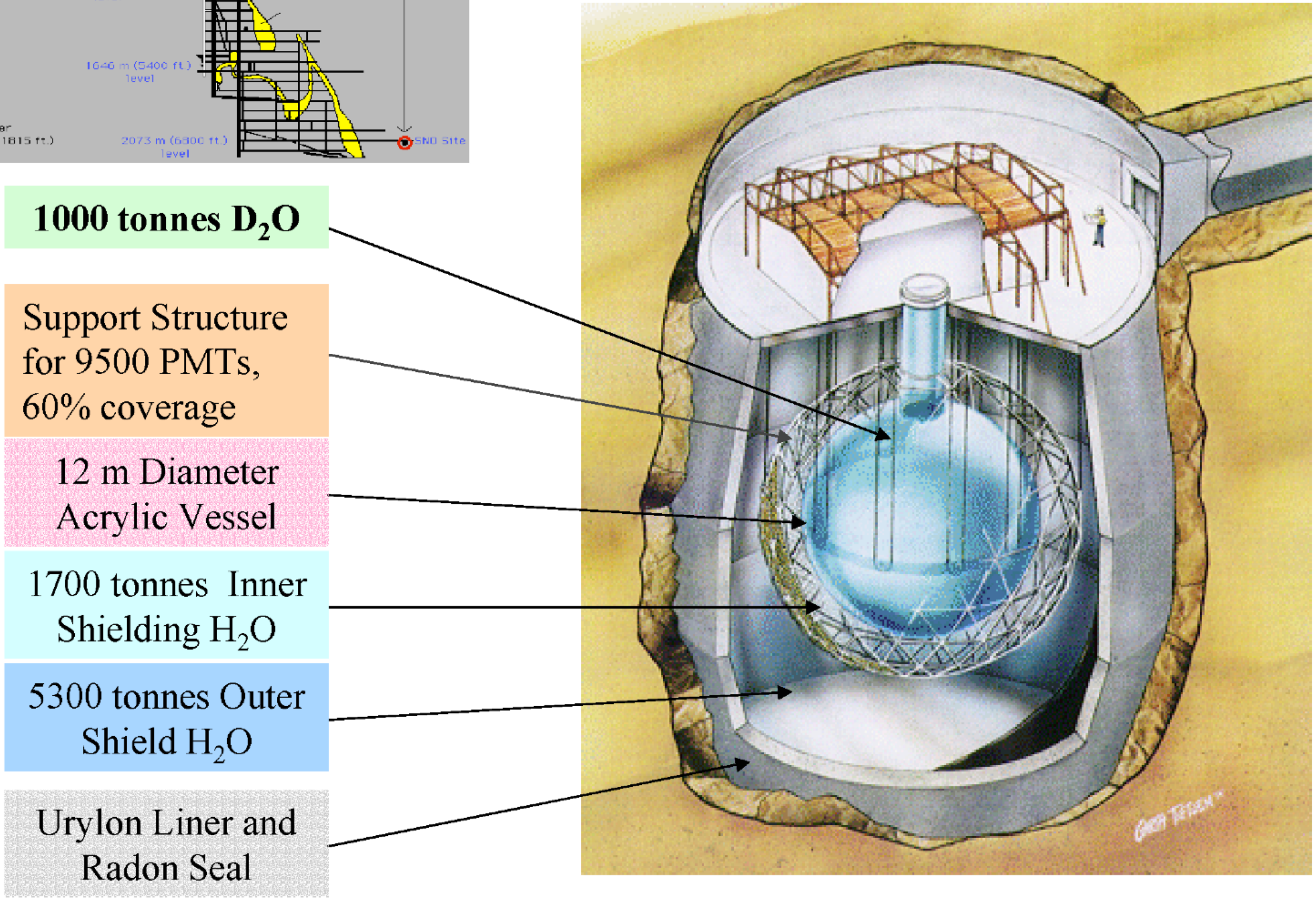
^{37}Ar atoms filtered out of target liquid and counted by observing decay

- Nobel prize to Ray Davis in 2002 (together with Koshiba for SN Neutrinos; Giacconi for cosmic X-ray sources)

Providing Confirmation: SNO



Sudbury Neutrino Observatory



1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

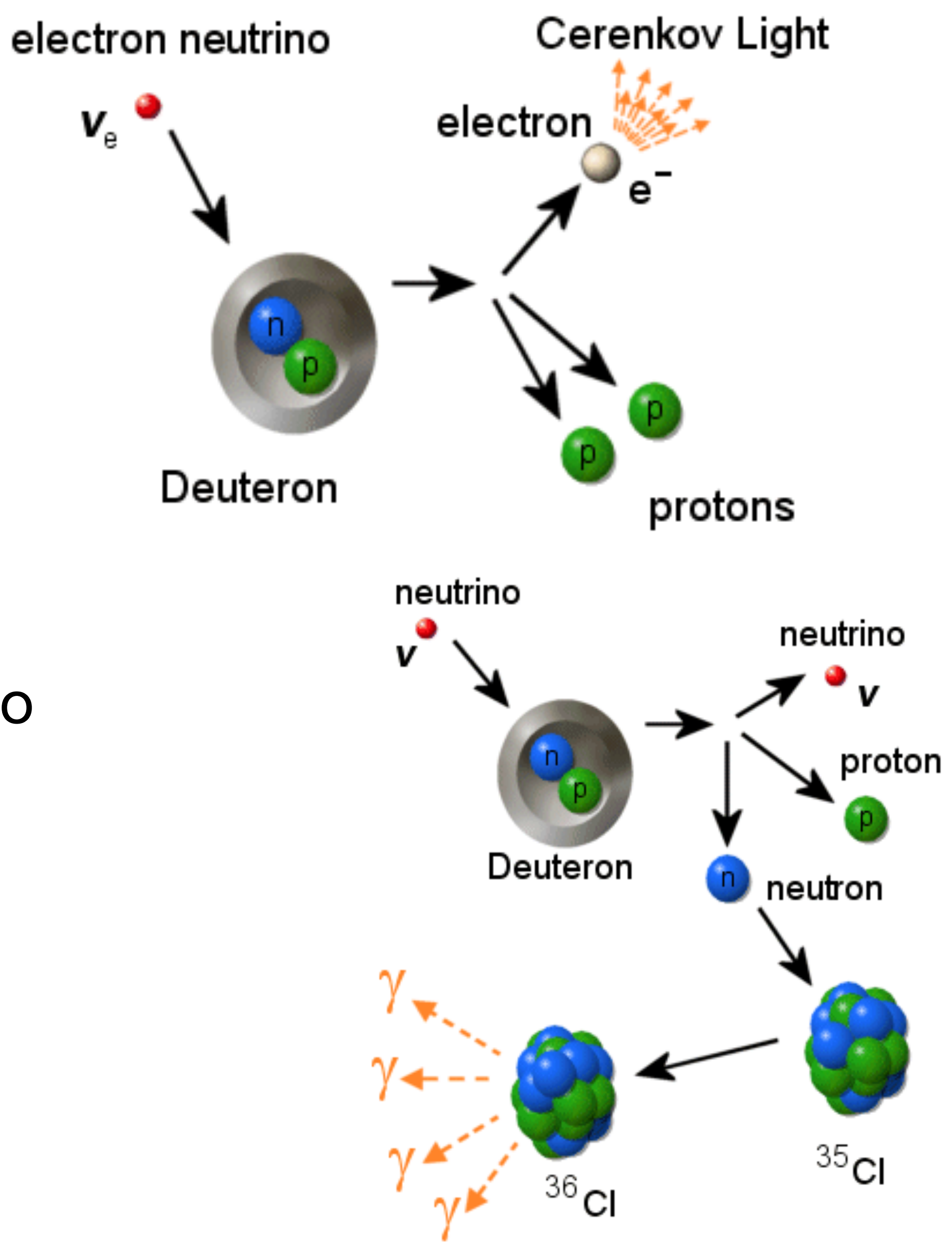
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

Providing Confirmation: SNO

- Two key measurements:
  - The flux of electron neutrinos via charged current interactions on deuterium
- The total flux of neutrinos via neutral current interactions on deuterium
  - Required the addition of salt (NaCl) to the water to detect the neutron via neutron capture on ^{35}Cl



Observation: Flux of electron neutrinos ~ 1/3 of expected flux, but total flux matches expectation!

Nobel prize 2015 to Art MacDonald

Understanding the Observations

- Averaging over the size of the source (solar core), which is larger than the oscillatio length, washes out the oscillation signal

Reminder: Length of one oscillation period:

$$L_{osc} = \frac{4\pi E}{\Delta m^2} \hat{=} \frac{2{,}5 \cdot E/\text{MeV}}{\Delta m^2/\text{eV}^2}$$

for 1 MeV and the solar oscillation parameters ($\Delta m^2 = 8 \times 10^{-5}$ eV^2): 32 km

For vacuum oscillations this would result in a survival probability for electron neutrinos of

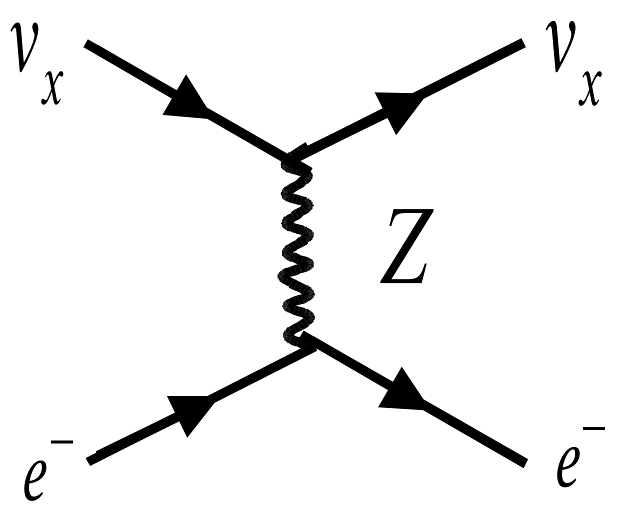
$$P_{ee} = 1 - \frac{1}{2}\sin^2(2\theta) \Rightarrow \text{Always} > 0{,}5\,!$$

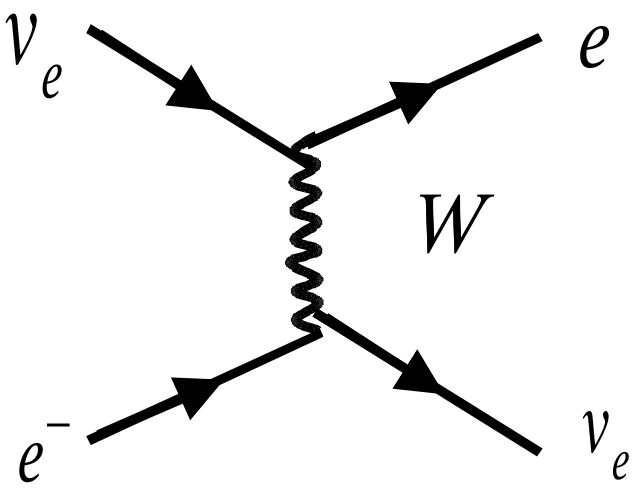
$$(\text{for } \theta = 34^\circ: \sim 0{,}6)$$

- How can the rate of electron neutrinos be lower than 50% of the expected rate?

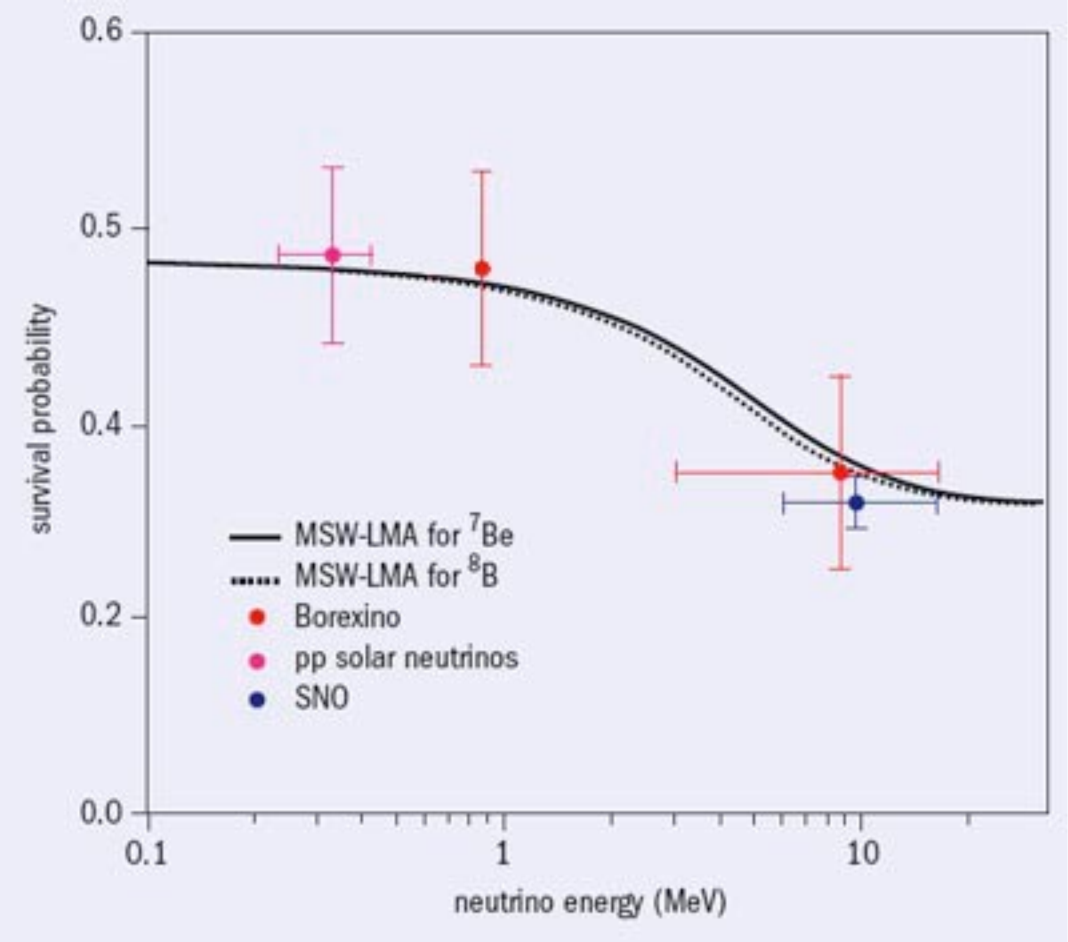
Neutrinos in Matter

- Electron neutrinos have additional reaction possibilities in matter:



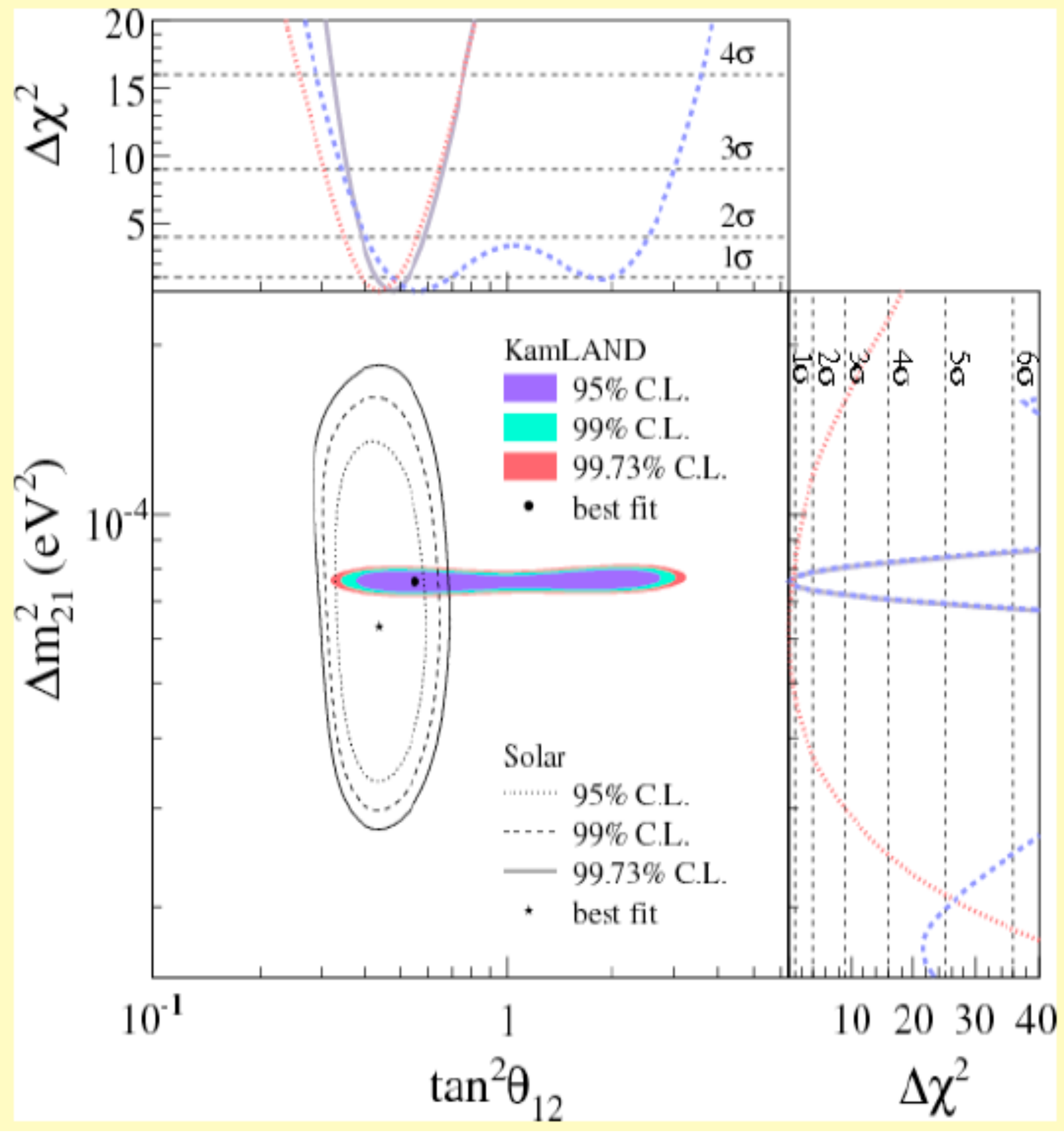


- Elastic forward scattering - introduces an change in effective mass (energy dependent!), and thus changed oscillation patterns - electron neutrinos further suppressed by interaction in matter in the sun: MSW (Mikheyev, Smirnov, Wolfenstein) effect



Solar Neutrino Oscillations: Parameters

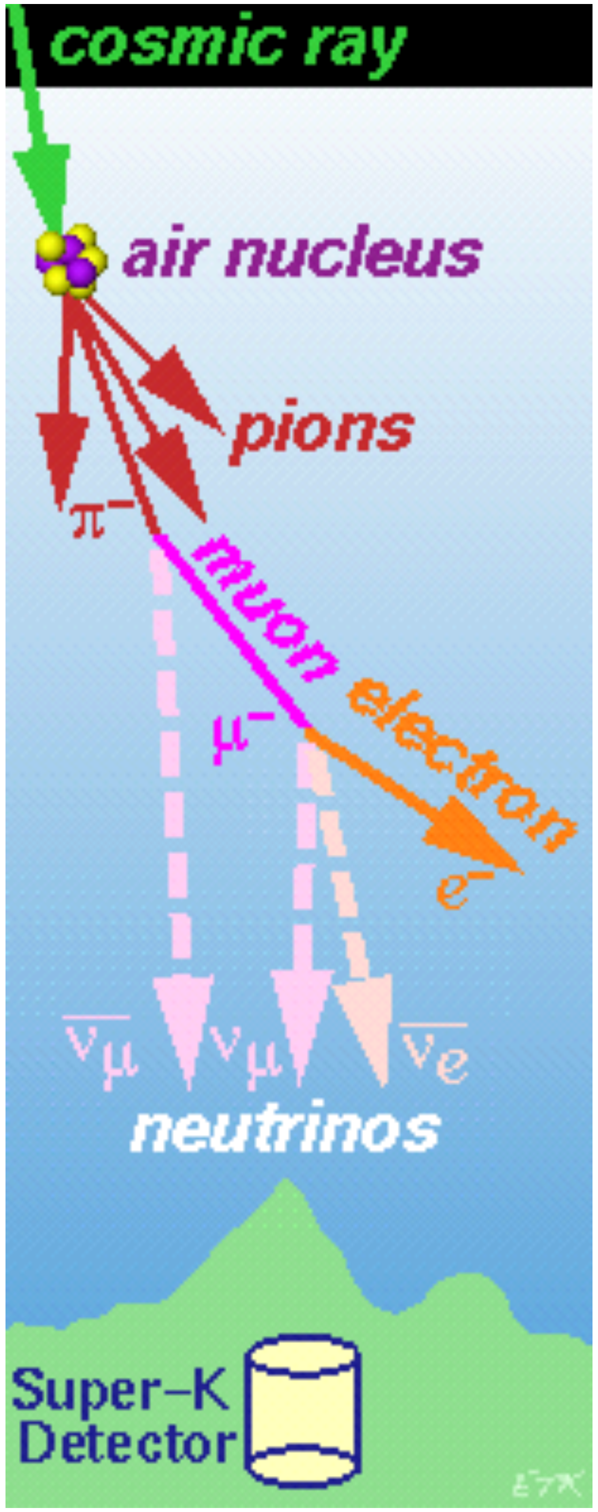
- Determined also with the help of reactor experiments - discussed in more detail next week



$$\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5} eV^2 \qquad \theta = 33.9^{+2.4}_{-2.2} \text{ deg}$$

Atmospheric Neutrinos

Atmospheric Neutrinos



- Atmospheric neutrinos are produced in air showers via pion / kaon decay and via muon decay:

$$\pi^-, K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

- Muon life time: $c\tau_\mu \approx 660\,\mathrm{m}$
- The measurement (no charge identification possible):

$$\frac{\mu}{e} \equiv \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$$

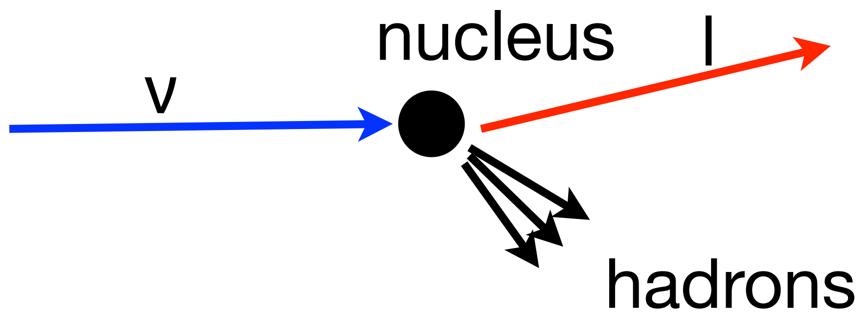
- If all muons decay (for low energies):

$$\frac{\mu}{e} \approx 2$$

- For high energies: $\frac{\mu}{e} > 2$

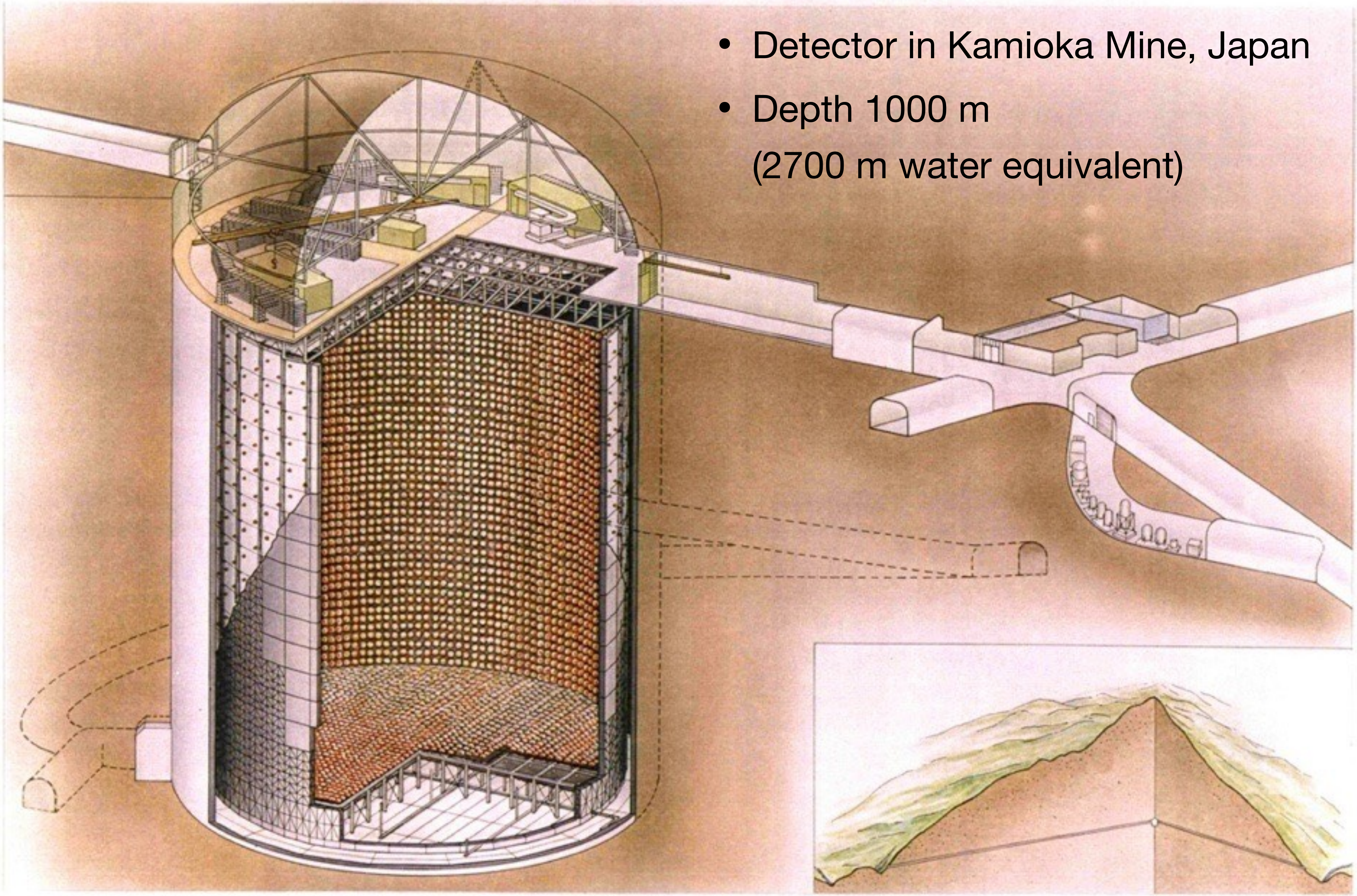
Super-Kamiokande Measurement Principle

- Neutrinos produce their corresponding leptons via charged current interaction



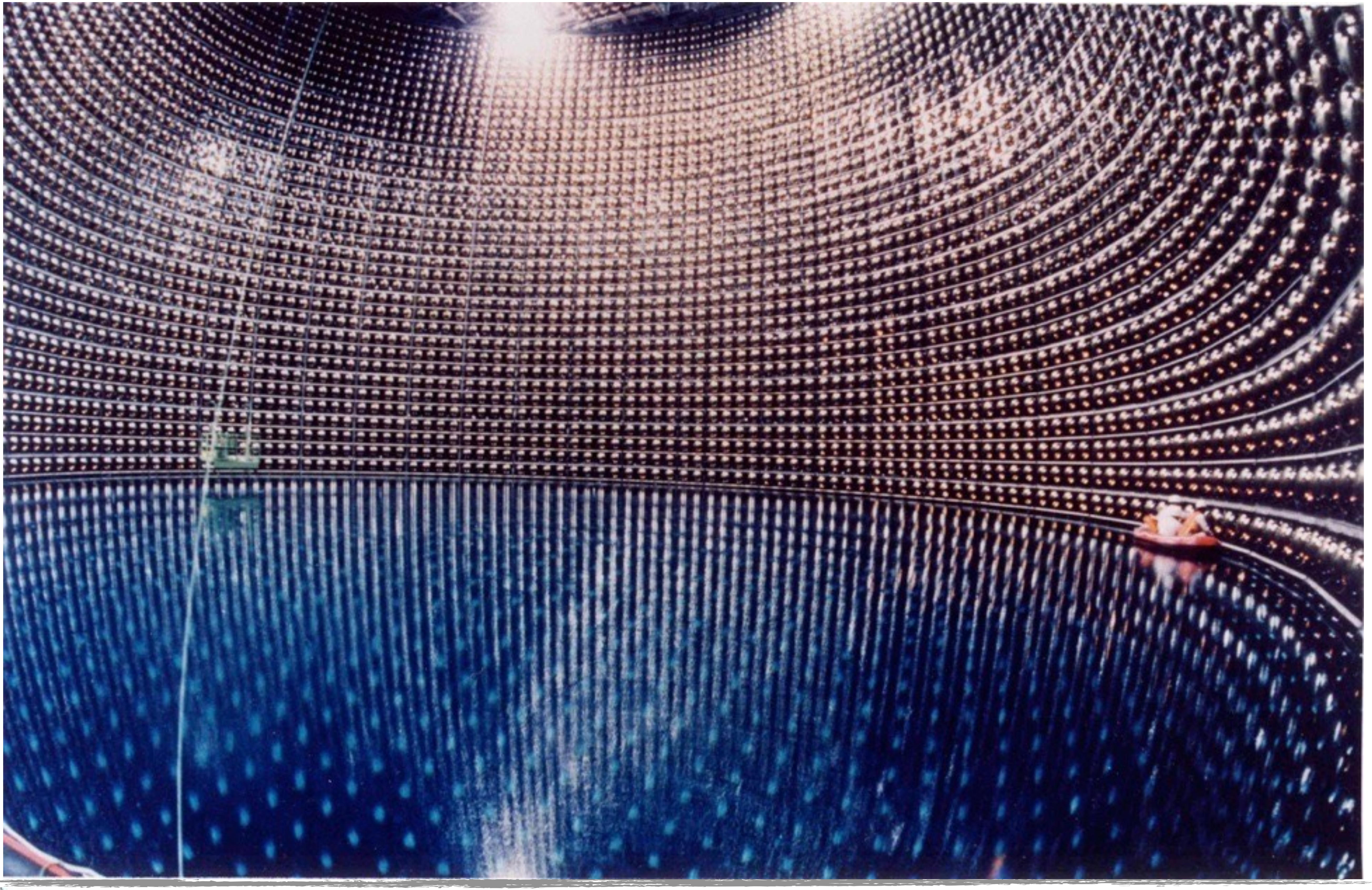
  - High energy threshold for τ - production due to high mass (1.777 GeV), thus only detection of electrons and muons
- Production of Cherenkov light of charged leptons in water (index of refraction 1.33)
  - Detection of Cherenkov light:
    - Light distribution enables particle identification (μ or e)
    - Amount of light enables measurement of track length, with that also energy and direction determination of the original neutrino

Super-Kamiokande

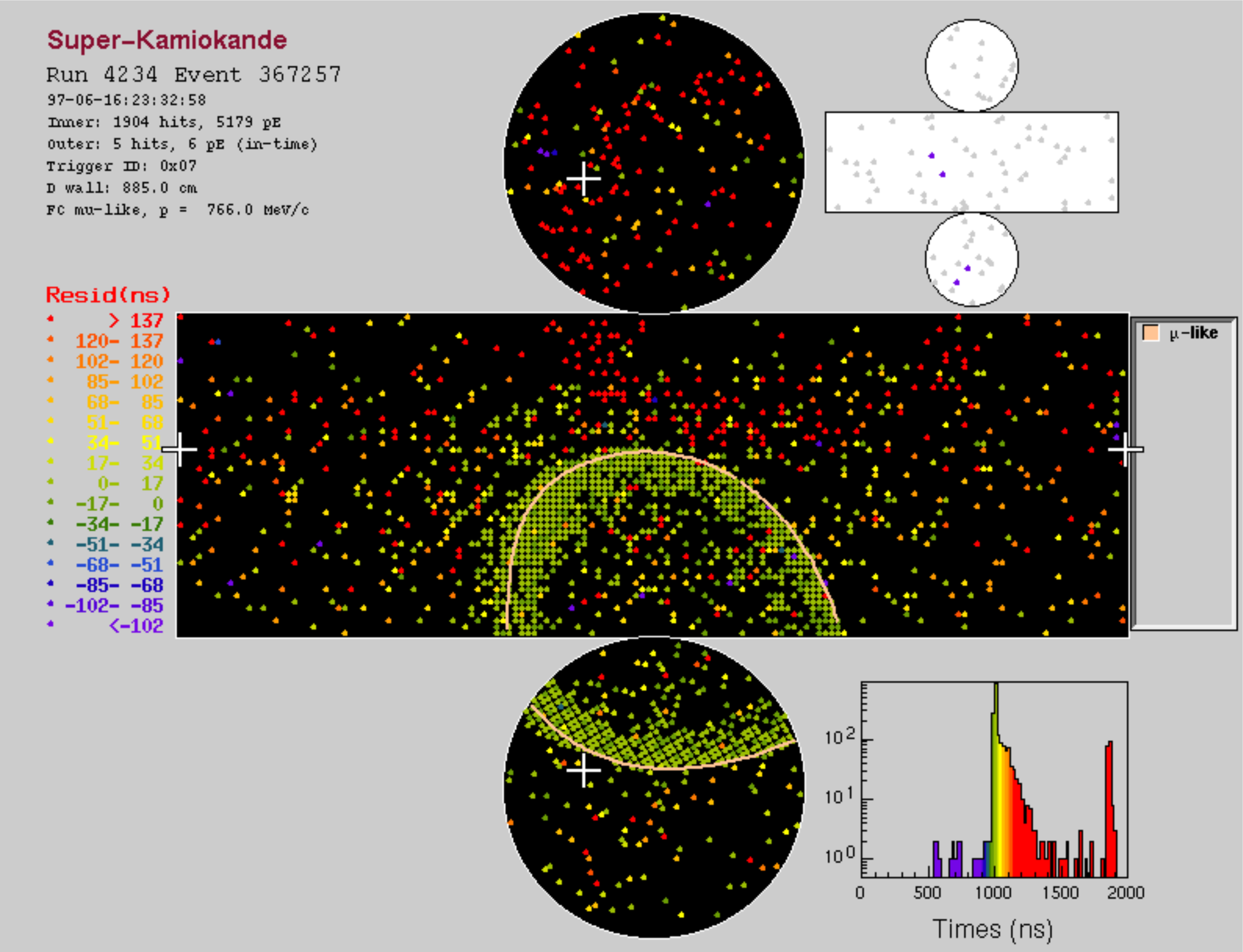


- Detector in Kamioka Mine, Japan
- Depth 1000 m
  (2700 m water equivalent)

Super-Kamiokande



Super-Kamiokande Measurements



Super-Kamiokande

Run 4234 Event 367257

97-06-16:23:32:58

Inner: 1904 hits, 5179 pE

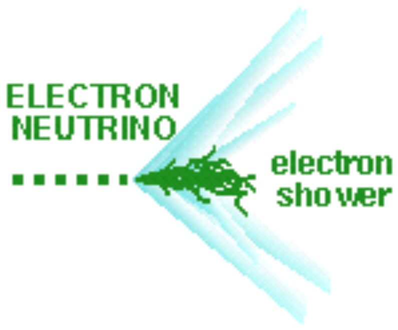
Outer: 5 hits, 6 pE (in-time)

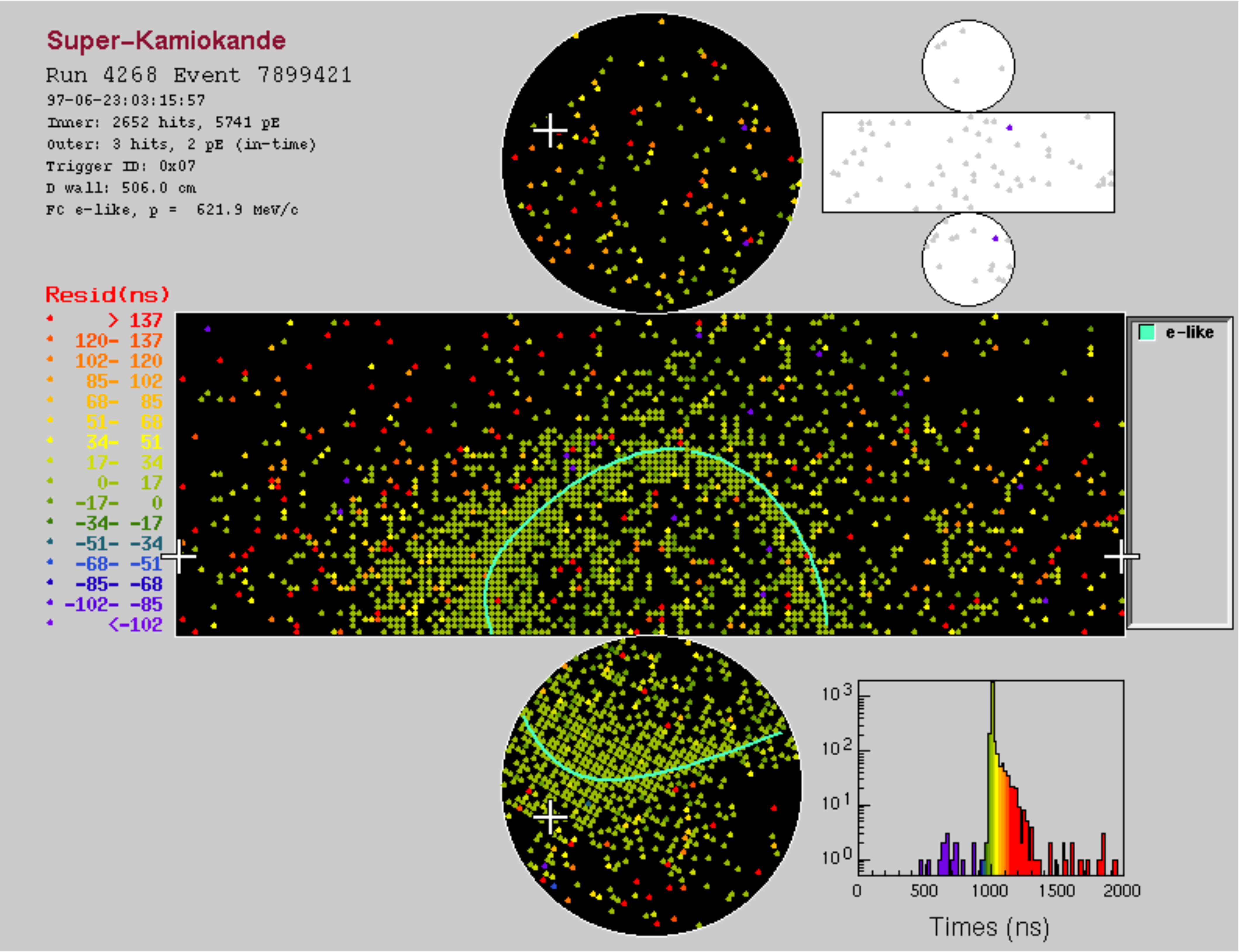
Trigger ID: 0x07

D wall: 885.0 cm

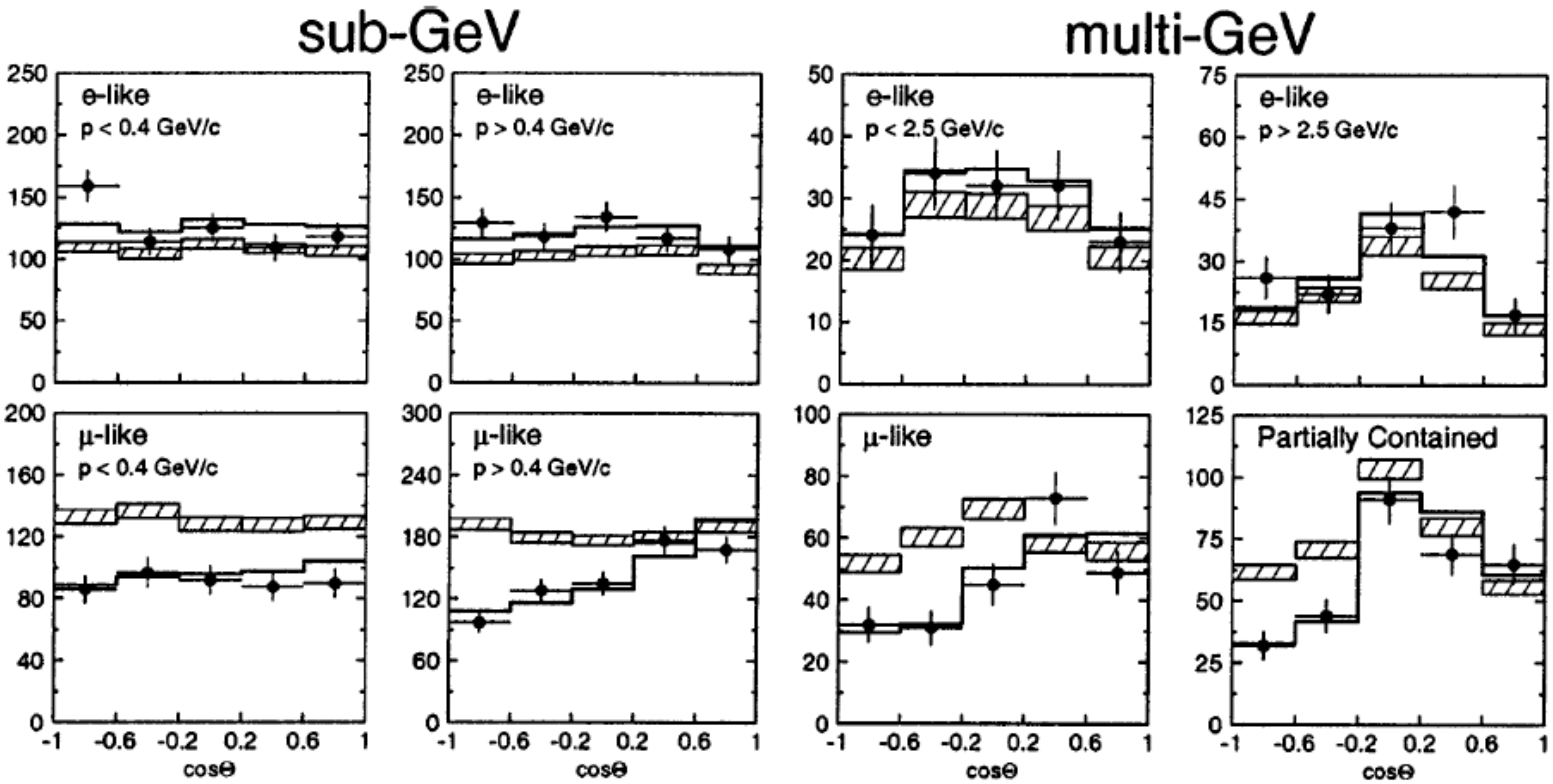
FC mu-like, p = 766.0 MeV/c

Super-Kamiokande Measurements




Super–Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p = 621.9 MeV/c

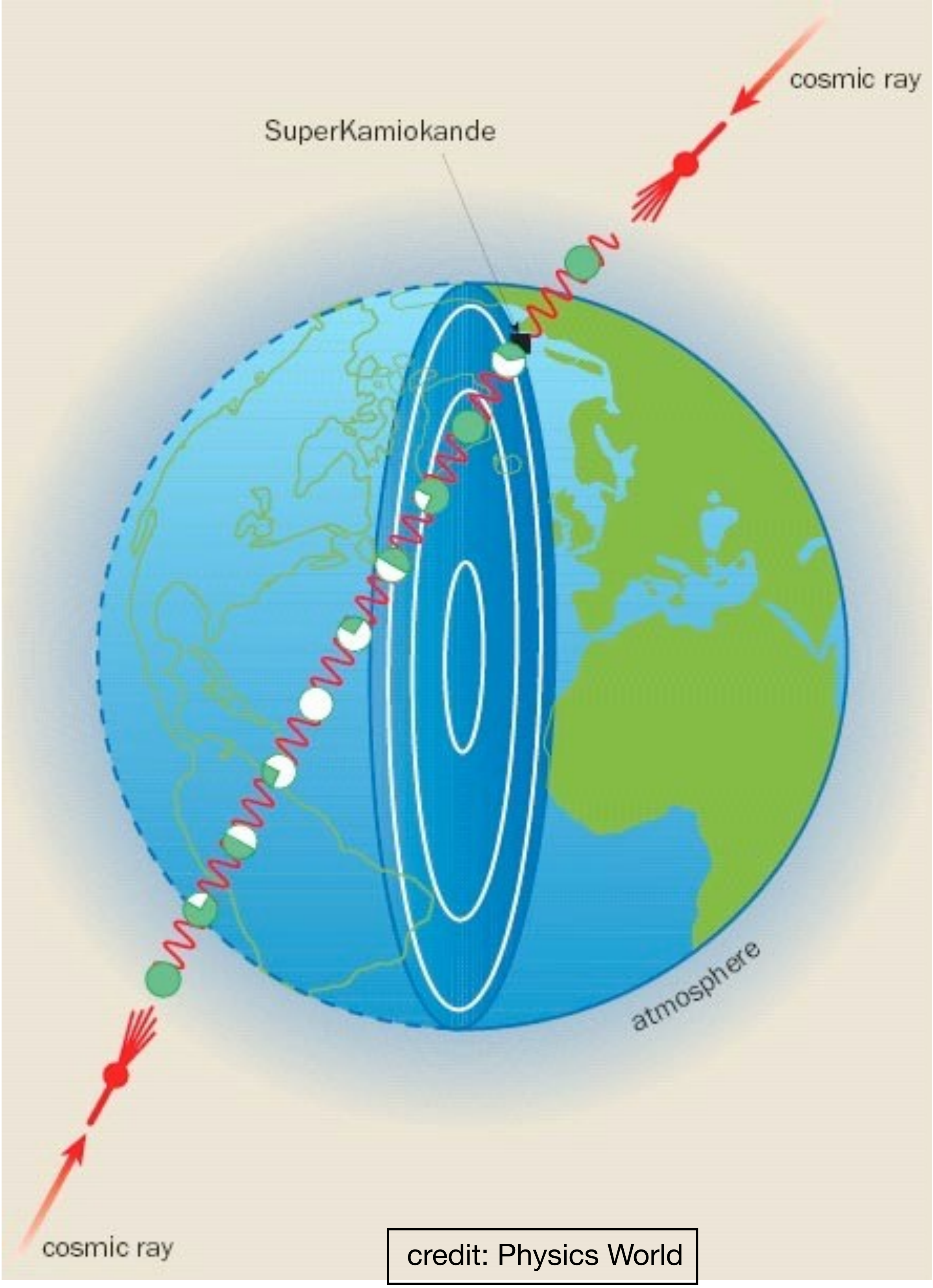
Oscillation of Atmospheric Neutrinos



Phys.Rev.Lett. 81, 1562 (1998)

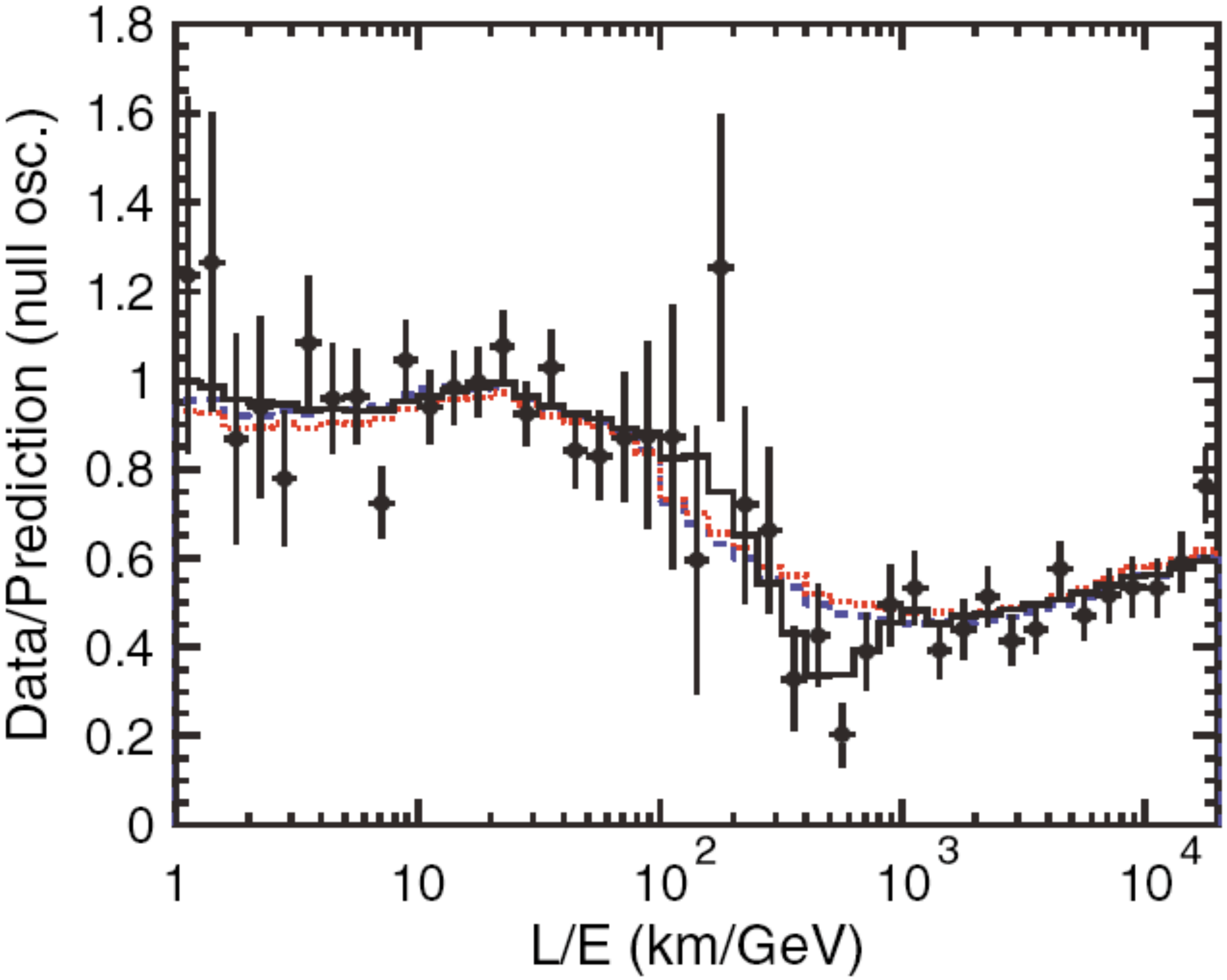
- Deficit of muon neutrinos observed, electron neutrinos match expectations
- Dependence of discrepancy with zenith angle

Oscillation of Atmospheric Neutrinos



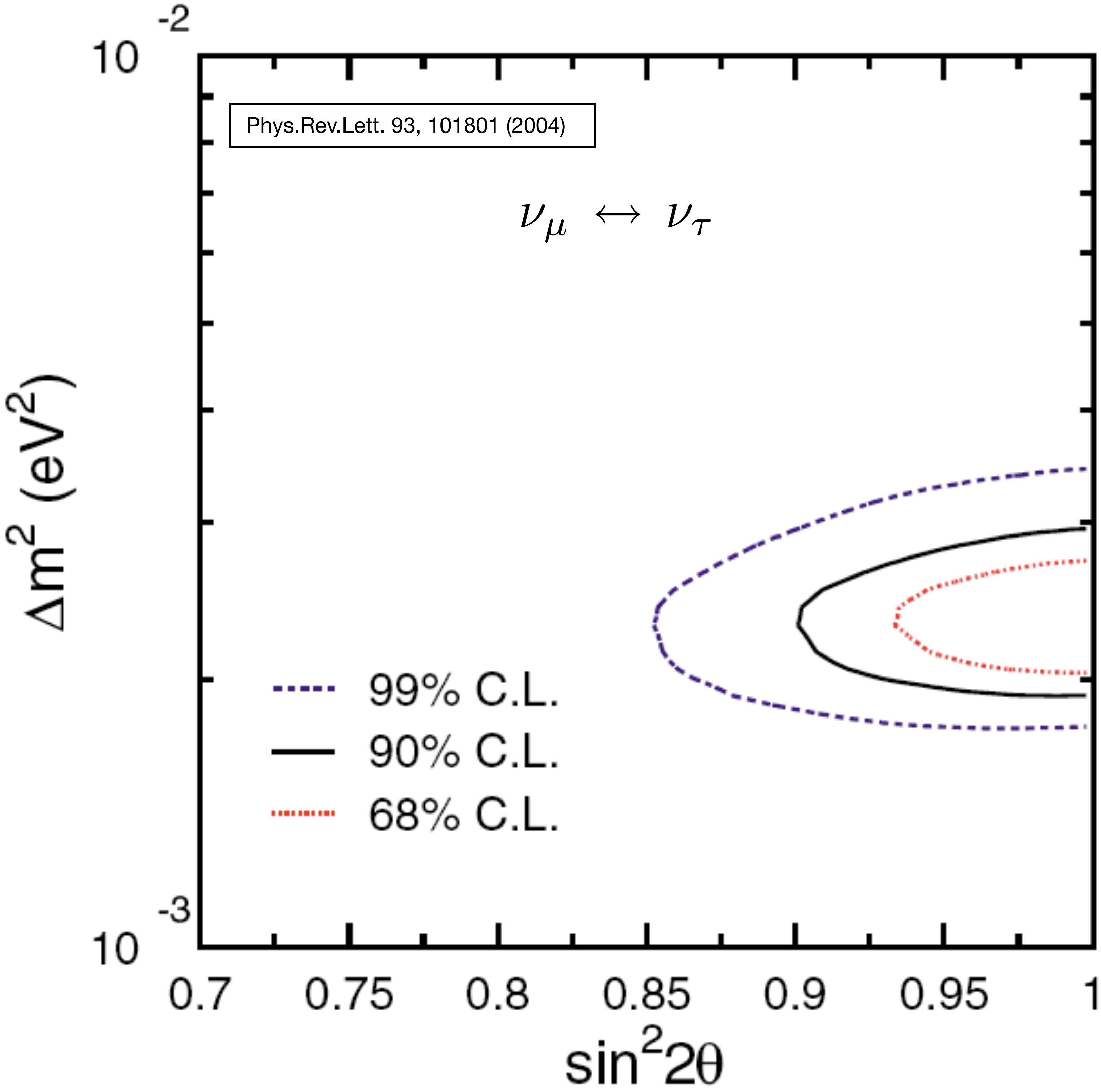
credit: Physics World

- Interpretation: On the way through earth muon neutrinos transform into tau neutrinos



Phys.Rev.Lett. 93, 101801 (2004)

Oscillation of Atmospheric Neutrinos: Result



- Best value for oscillation parameters

$$\Delta m^2 = 2.4 \times 10^{-3} \mathrm{eV}^2$$

$$sin^2 2\theta = 1.0$$

- Maximum mixing
- oscillation length ~ 1000 km E_ν/GeV

Neutrino Oscillations: Overall Picture

Neutrino Oscillations - Status

- Two distinct types of oscillations (with quite different mass splittings) have been observed:
  - Solar - disappearance of ν_e, $\Delta m^2 \sim 7.6 \times 10^{-5}$ eV^2
  - Atmospheric - disappearance of ν_μ, $\Delta m^2 \sim 2.4 \times 10^{-3}$ eV^2
- Choice of convention: small splitting between ν_1 and ν_2, big between ν_1/ν_2 and ν_3
- The data tell us: mixing between ν_1 and ν_3 is small
  - In solar oscillations, we observe $\nu_1 \rightarrow \nu_2$ oscillations, ν_1 has to have a big ν_e component
  - In atmospheric oscillations, we observe $\nu_2 \rightarrow \nu_3$, with maximal mixing: ν_3 is (almost) a 50-50 mixture of ν_τ and ν_μ

solar/
reactor

$$U_{\text{MNS}} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

atmospheric/
accelerator

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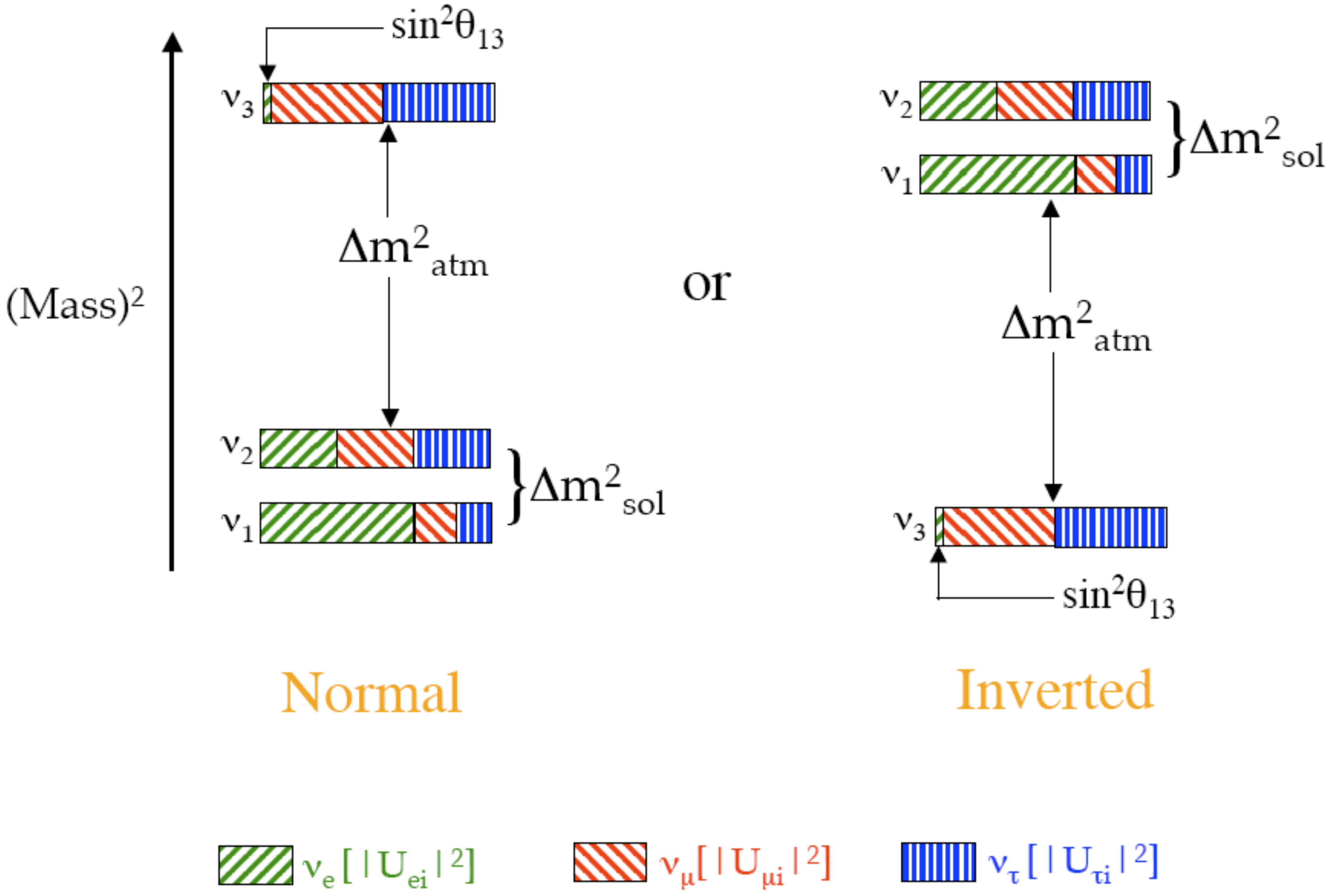
Neutrino-Oscillations: The Resulting Picture



$\Delta m^2_{sol} \sim 7.6 \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2_{atm} \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$

One neutrino has to have a mass of at least ~ 0.05 eV!

Solar and atmospheric oscillations probe two of the three mixing angles - the 3rd (smallest) needs “laboratory” experiments

- Absolute masses and hierarchy not known yet! Two possible arrangements...

Summary

- Neutrinos are the lightest particles in the Standard Models
- Neutrinos have mass: they oscillate - There are (at least) three different mass eigenstates, that are not identical with the flavor eigenstates

- Neutrino oscillations have been observed with atmospheric and solar Neutrinos
  - We see one small and one large mass difference
  - Maximal mixing for atmospheric neutrinos, smaller mixing angle for solar
  - Matter effects explain observed rate of electron neutrinos from the sun
  - At least one neutrino has to have a mass of more than 50 meV

Next (and final) Lecture: 9.07., “Neutrinos II”, F. Simon