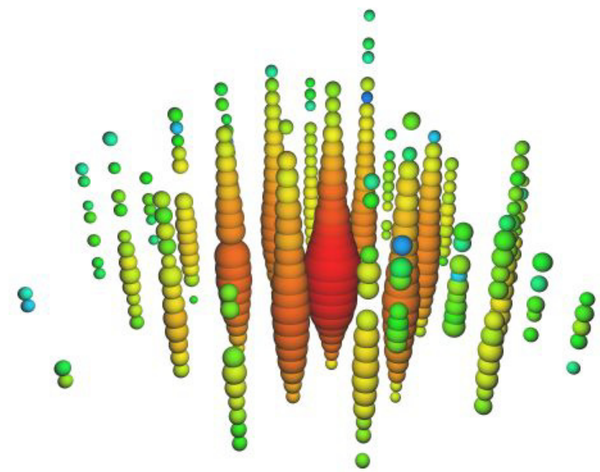
XI. Neutrino physics

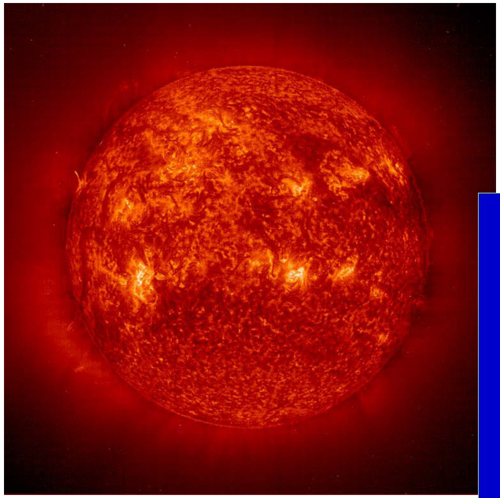
Neutrinos are perhaps the least understood SM particles due to the very small cross sections of their interactions.

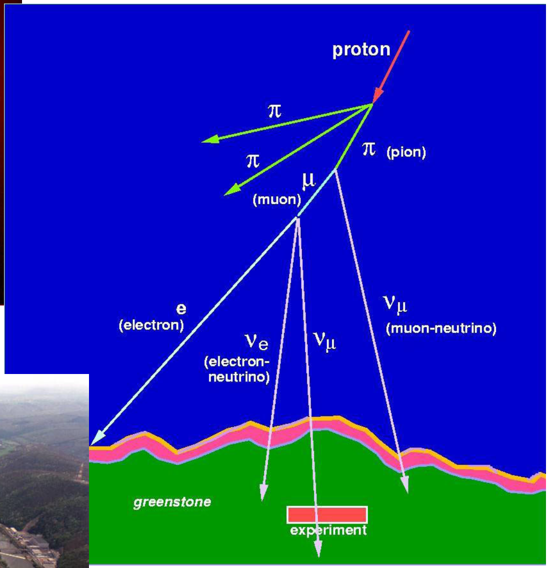
- In the Standard Model, neutrinos are massless and always left-handed, couple to weak bosons W and Z
  - However, observed neutrino oscillations prove that neutrinos do have mass
- Some open questions are:
  - What are neutrino masses and do they contribute to the Dark Matter?
  - Is neutrino its own antiparticle?
  - Do neutrinos violate CP leading to matter-antimatter asymmetry?
  - What are neutrino mixing parameters?

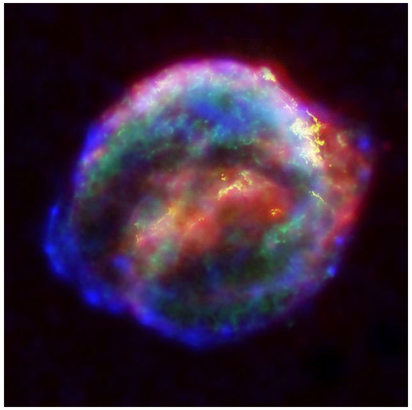


Neutrino sources:

- The Sun
- Cosmic rays (“atmospheric neutrinos”)
- Secondary accelerator beams
- Nuclear reactors
- Natural radioactivity
- Supernovae
- The Big Bang







Neutrino masses

- Idea behind experiments: if neutrinos have non-zero masses, they must be subject to *neutrino-mixing*

Recall: quark mixing in weak interactions

$$d' = d\cos\theta_C + s\sin\theta_C$$

$$s' = -d\sin\theta_C + s\cos\theta_C$$

By analogy, neutrinos can be represented as linear combinations:

$$\nu_e = \nu_1\cos\alpha + \nu_2\sin\alpha$$

$$\nu_\mu = -\nu_1\sin\alpha + \nu_2\cos\alpha \qquad (220)$$

Here ν_1 and ν_2 are *mass eigenstates* with masses m_1 and m_2 (ν_e and ν_μ are *flavor eigenstates*)

- For neutrinos, flavor eigenstates do not coincide with mass eigenstates!

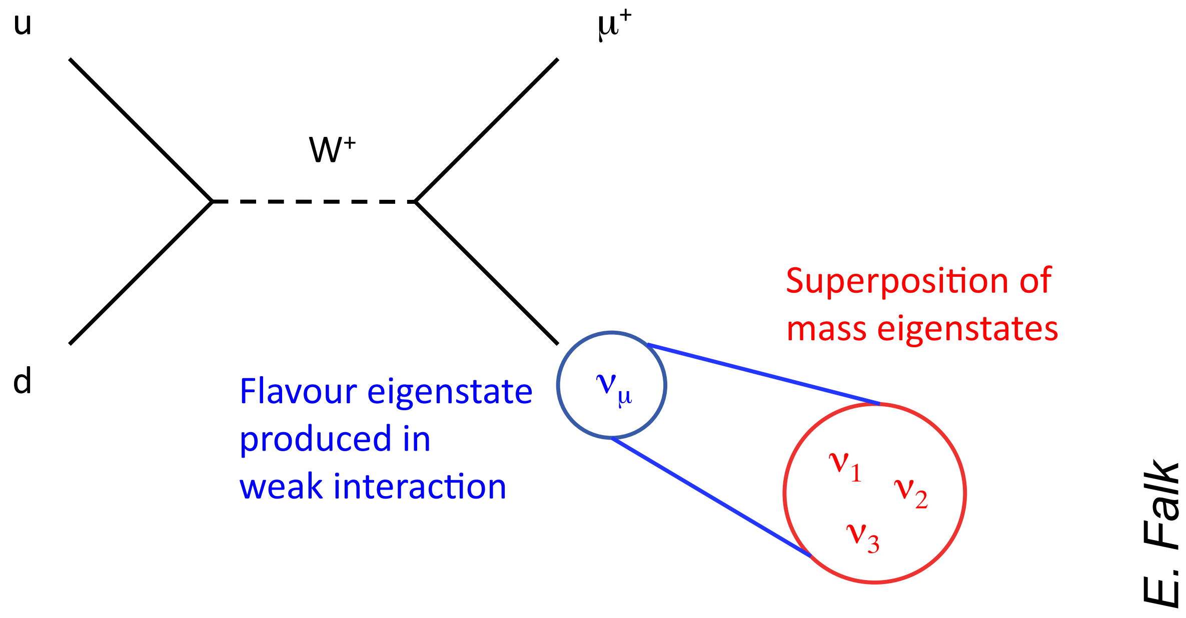


Figure 180: Flavor eigenstates of neutrinos are superpositions of three mass eigenstates

- Mixing angle α is determined from experiments that observe *neutrino oscillations*
- *Neutrino oscillation*: a beam of ν_e develops ν_μ component as it travels through space, and vice versa

In Dirac notation, the initial superposition is (for 2 eigenstates):

$$|\nu_e, \vec{p}\rangle = \cos\alpha|\nu_1, \vec{p}\rangle + \sin\alpha|\nu_2, \vec{p}\rangle \tag{221}$$

and after a period of time *t* it evolves to:

$$e^{-iE_1t}\cos\alpha|\nu_1, \vec{p}\rangle + e^{-iE_2t}\sin\alpha|\nu_2, \vec{p}\rangle \tag{222}$$

here e^{-iE_it} are oscillating time factors (recall strangeness oscillation in Section V.)

Form (222) is not a pure ν_e state anymore, but a mixture:

$$A(t)|\nu_e, \vec{p}\rangle + B(t)|\nu_\mu, \vec{p}\rangle \tag{223}$$

where the ν_μ states are, similarly to (221):

$$|\nu_\mu, \vec{p}\rangle = -\sin\alpha|\nu_1, \vec{p}\rangle + \cos\alpha|\nu_2, \vec{p}\rangle \tag{224}$$

The functions *A(t)* and *B(t)* hence are:

$$A(t) = e^{-iE_1t}\cos^2\alpha + e^{-iE_2t}\sin^2\alpha$$
$$B(t) = \sin\alpha\cos\alpha[e^{-iE_2t} - e^{-iE_1t}] \quad (225)$$

Squares of $A(t)$ and $B(t)$ are probabilities to find ν_e (respective ν_μ) in a beam of electron neutrinos ν_e:

$$P(\nu_e \to \nu_e) = |A(t)|^2 = 1 - P(\nu_e \to \nu_\mu) \quad (226)$$

$$P(\nu_e \to \nu_\mu) = |B(t)|^2 = \sin^2(2\alpha)\sin^2\frac{(E_2 - E_1)t}{2} \quad (227)$$

- If neutrinos have equal (zero) masses $\Rightarrow E_1=E_2 \Rightarrow$ no oscillations

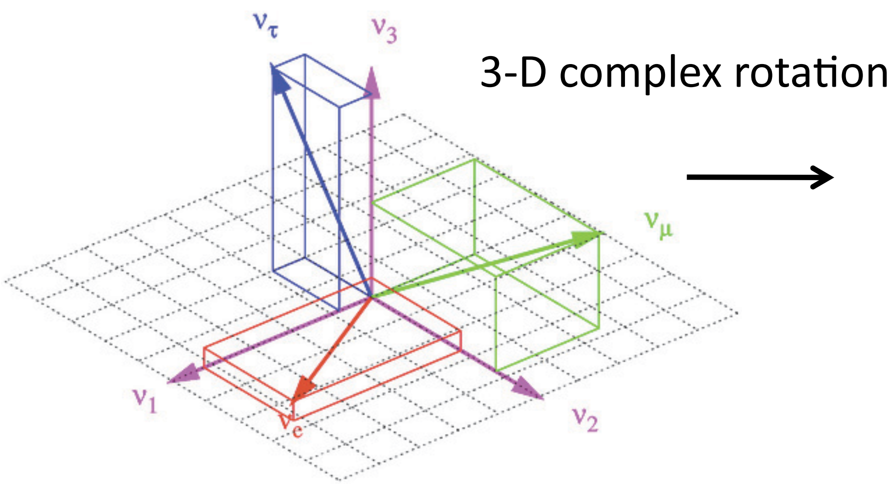
For $E >> m$ and $\Delta m_{21}^2 \equiv m_2^2 - m_1^2$, $E_2 - E_1 \cong (\Delta m_{21}^2)/(2E)$:

$$P(\nu_e \to \nu_\mu) = \sin^2(2\alpha)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad (228)$$

Here Δm^2 and α (better known as θ_{ij}) are measured, while E and L are experiment parameters

- If mass eigenstates have different masses, they travel at different speeds (assuming the energy is the same)
- Probability to detect a neutrino of a given flavor depends on the distance travelled

In general, for 3 flavors, a 3x3 matrix must be used (similarly to CKM):



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

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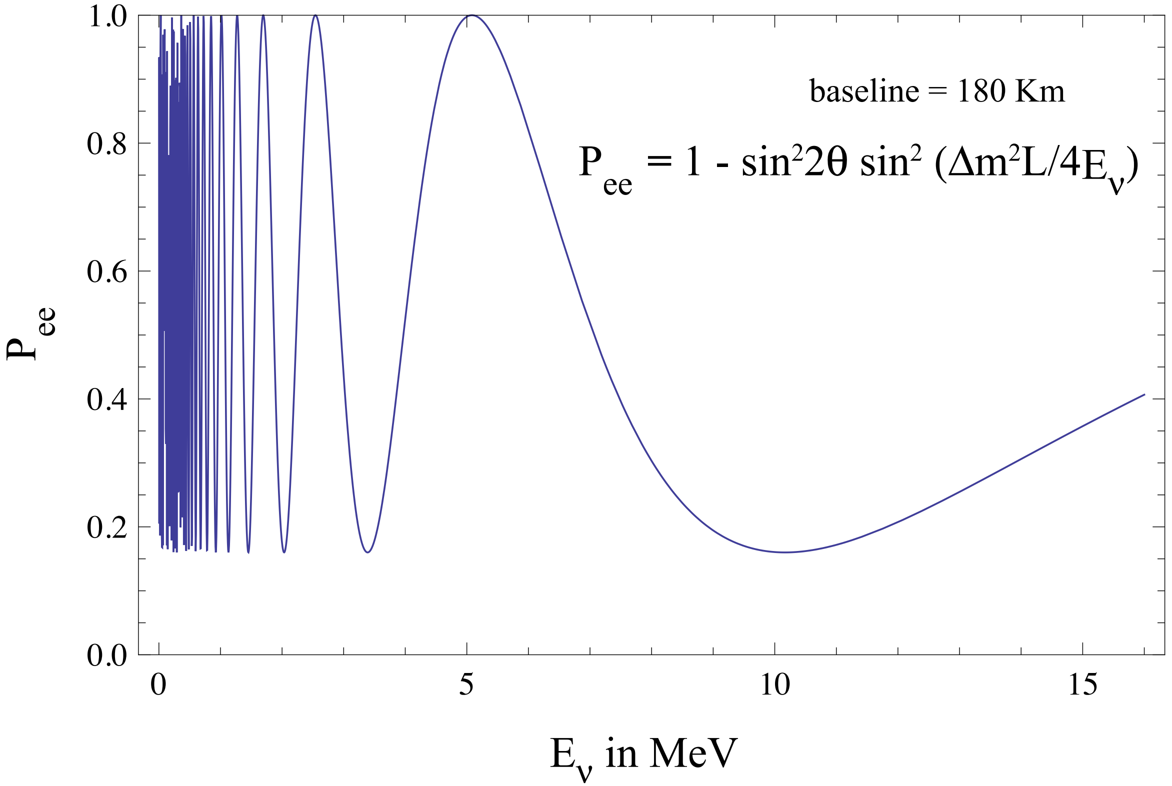
Figure 181: Flavor eigenstates are a “rotation” of mass eigenstates

- Matrix in Fig.181 is called U_{PMNS} (Pontecorvo-Maki-Nakagawa-Sakata)



$$\Delta m_{21}^2 = 7 \times 10^{-5} eV^2$$

$$\sin 2\theta = 0.84$$

Figure 182: Electron (anti)neutrino survival probability

The PMNS matrix can be decomposed into four components

- Three 2-dimensional rotation matrices, each characterised by different mixing angle
- The last one (U_{Maj}) does not correspond to oscillations

Three independent mixing angles

CP-violation phase

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\text{CP}}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\text{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U^{\text{diag}}_{\text{Maj}} \quad (229)$$

Measured from atmospheric and accelerator neutrinos

Sub-dominant oscillations, measured in reactor and accelerator experiments

Measured from Solar and reactor neutrinos

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Mass hierarchy

- As of today, we know that ν_2 has higher mass than ν_1
- We however don't know yet whether ν_3 is the heaviest or the lightest

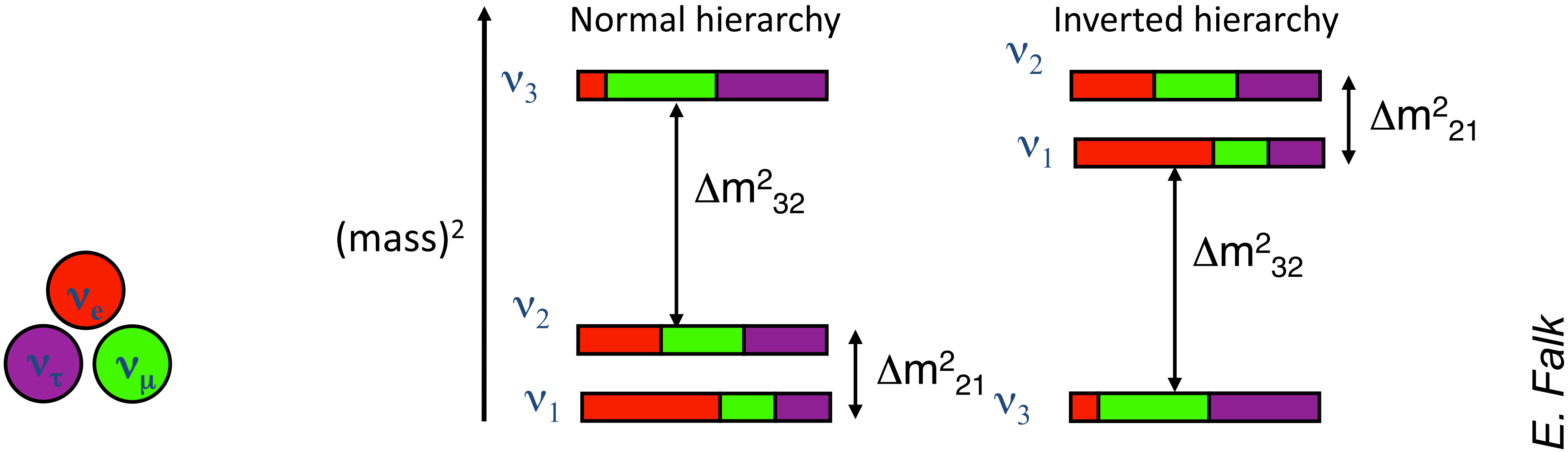


Figure 183: Two possible mass hierarchies: normal and inverted

Tests of neutrino oscillations

Methods to detect neutrino oscillations:

- Appearance search
- Disappearance test

- ν_e and ν_μ can be distinguished by their interaction with neutrons: former produce electrons and latter - muons:

$$\nu_e + n \rightarrow e^- + p$$

$$\nu_\mu + n \rightarrow \mu^- + p$$

  - Cherenkov detectors can tell electron from muon

- Time t in (227) can be determined from the distance between the detector and the source of neutrinos

Atmospheric neutrino anomaly

Was first detected in 1980's: instead of predicted $N(\nu_\mu) \approx 2N(\nu_e)$, rates of both neutrinos were approximately equal

- *Super-Kamiokande* detector: measures rates and flavours of neutrinos coming both from zenith and nadir
  - A neutrino created in cosmic rays travels ~15 km in the atmosphere $\Rightarrow$ has no time to oscillate (proven by other experiments)
  - A similar neutrino created on the other side of the Earth travels ≈13000 km $\Rightarrow$ has good chances to oscillate
  - If ratio of ν_e and ν_μ is different in two cases above $\Rightarrow$ there are oscillations $\Rightarrow$ at least one neutrino is massive.
- The detector is placed in a deep mine to reduce the background

– 50 000 m^3 of water and 13 000 photomultipliers work as the Cherenkov detector

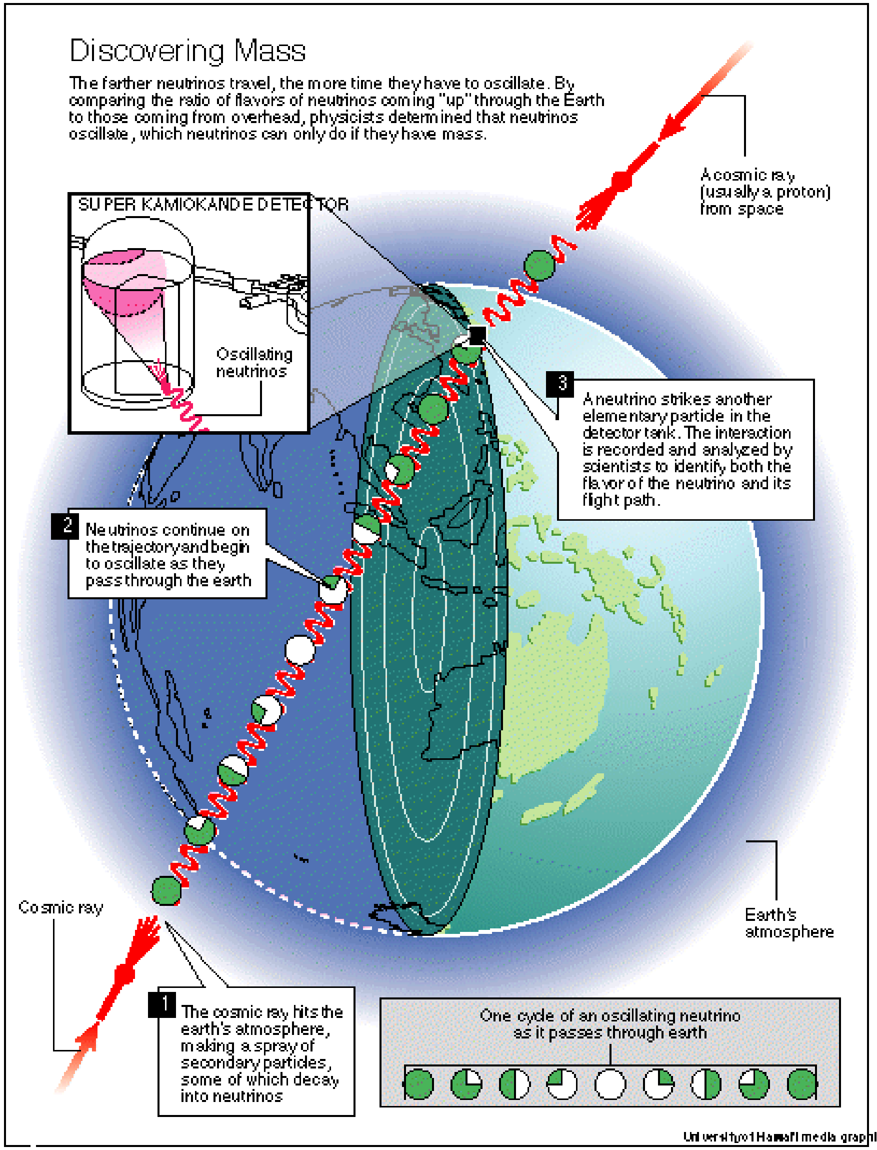


Figure 184: Neutrino oscillations through Earth seen by Super-Kamiokande

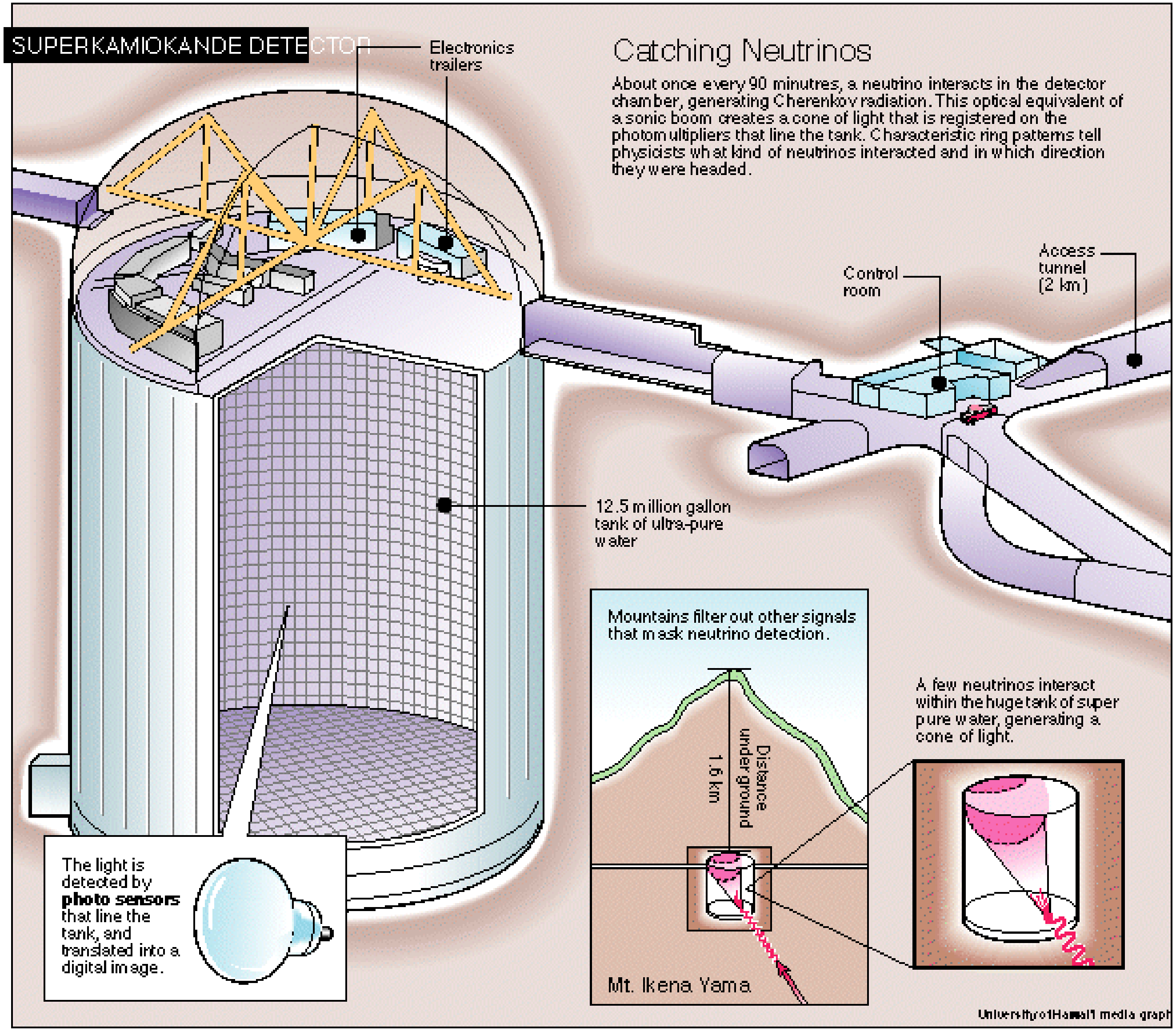


Figure 185: Schematics of the Super-Kamiokande detector

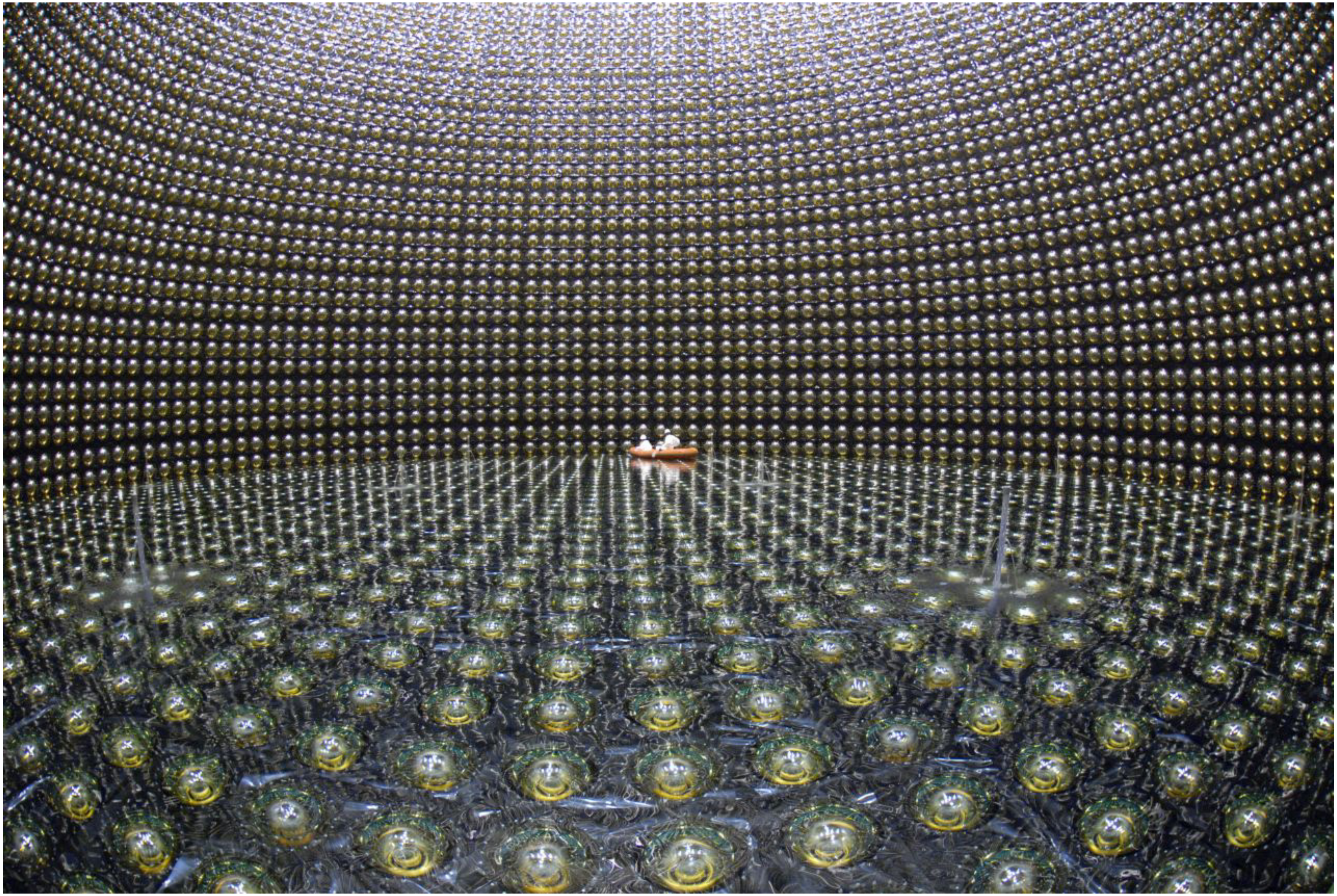


Figure 186: Interior of the Super-Kamiokande detector (April 2006, filling with water after full reconstruction)

- In 1998, the Super-Kamiokande Collaboration announced:

a) 4654 observed events – by far the largest statistical sample back then (much more data collected now)

b) data exhibit zenith angle dependence of ν_μ deficit

c) hence the "atmospheric neutrino anomaly" can only be explained by oscillations $\nu_\mu \leftrightarrow \nu_\tau$, which leads to muonic neutrino deficiency in cosmic rays.

d) the $\nu_2 \leftrightarrow \nu_3$ mixing angle and neutrino mass difference Δm from atmospheric neutrino studies are currently estimated at

$$\theta_{23} = (45 \pm 7)^\circ$$
$$\Delta m^2 = 2.4\times 10^{-3}\ eV^2 \tag{230}$$

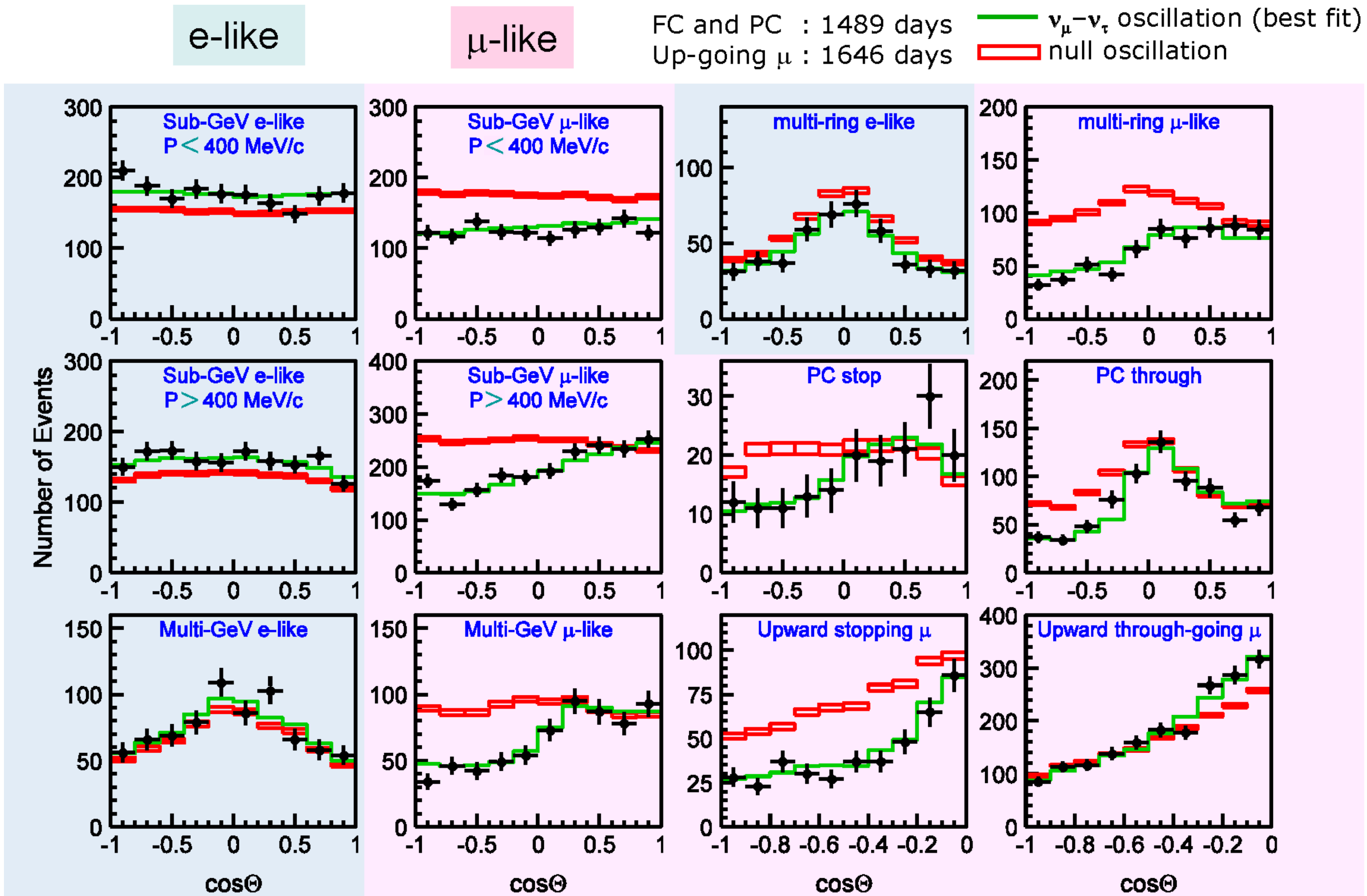


Figure 187: Zenith angle distributions, Super-Kamiokande I

Solar neutrino problem

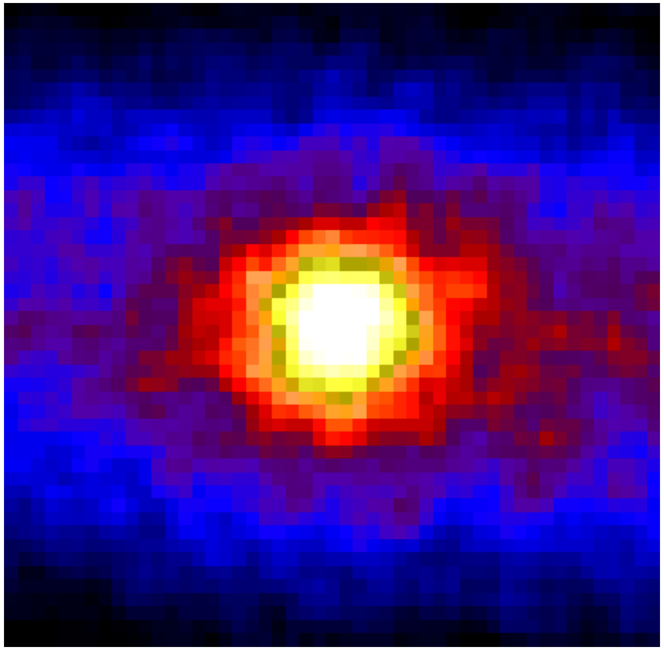


Figure 188: “Portrait” of the Sun in neutrinos (by Super-Kamiokande)

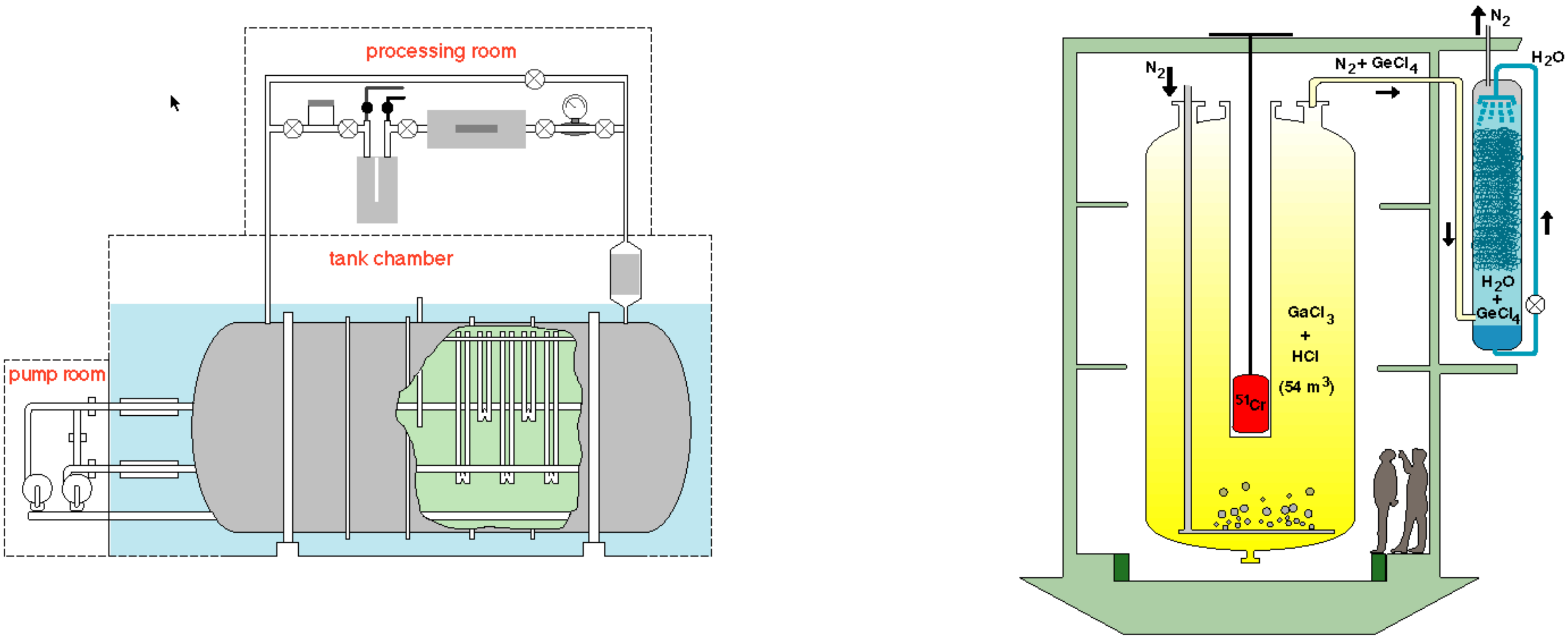
- Several methods are used to detect solar neutrinos of different energies:

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

$$\nu_e + {}^{98}Mo \rightarrow e^- + {}^{98}Tc$$

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

Experimental installations typically are tanks filled with corresponding medium and placed underground



Homestake gold mine chlorine detector (data taking in 1969-1993, USA)

GALLEX detector under the Gran Sasso mountain (Italy), data taking in1991-1997

Figure 189: Layouts of first solar neutrino detectors

Solar neutrino flux is measured in SNU ("solar neutrino unit"):

1 SNU = 1 capture / 1 second / 10^{36} target atoms

"Solar neutrino problem" (SNP):

- For the Homestake detector, predicted neutrino flux is 7.3 ± 2.3 SNU, measured 2.6 ± 0.2 SNU
- GALLEX: predicted 129 ± 8 SNU, measured 77.5 ± 8 SNU

Reactions producing solar neutrinos are:

1) $p + p \rightarrow {}^2H + e^+ + \nu_e$ $E_{\nu,max}$=0.42 MeV (85%)
2) $e^- + {}^7Be \rightarrow {}^7Li + \nu_e$ $E_{\nu,max}$=0.86 MeV (15%)
3) ${}^8B \rightarrow {}^8Be + e^+ + \nu_e$ $E_{\nu,max}$=15 MeV (0.02%)

GALLEX measures all of them, Homestake – only the last one.

- Neutrino oscillations seemed to be the most appealing explanation, although there were many other hypotheses

Sudbury Neutrino Observatory (SNO)

- A Cherenkov counter
- Used heavy water and could detect all three kinds of neutrinos
- Data taking from 1999 to 2006, upgrading to SNO+ now
- In 2001, produced the first evidence of <u>oscillations</u> in solar neutrinos, which effectively solved the SNP

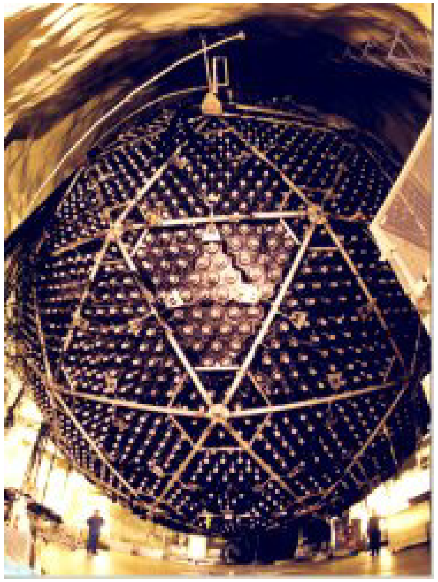


Figure 190: Sudbury Neutrino Observatory layout (2km underground)

SNO was measuring three kinds of neutrino-induced reactions:

- Charged current: $\nu_e + d \rightarrow p + p + e^-$, sensitive to ν_e, Cherenkov light is used to detect electrons
- Neutral current: $\nu_x + d \rightarrow p + n + \nu_x$, sensitive to all ν, breaks up deuterium; neutron capture produces gamma-rays which scatter detectable electrons
- Electron scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$, sensitive to all ν, but dominated by ν_e

SNO neutral current flux measurement (all neutrino flavors):

$$\frac{\phi_{tot}^{measured}}{\phi_{tot}^{expected}} = 1.01 \pm 0.12$$

Charged current (only ν_e):

$$\frac{\phi_{\nu e}^{measured}}{\phi_{\nu e}^{expected}} = 0.35 \pm 0.02$$

This confirmed that the Solar model is correct, and there <u>are</u> neutrino oscillations

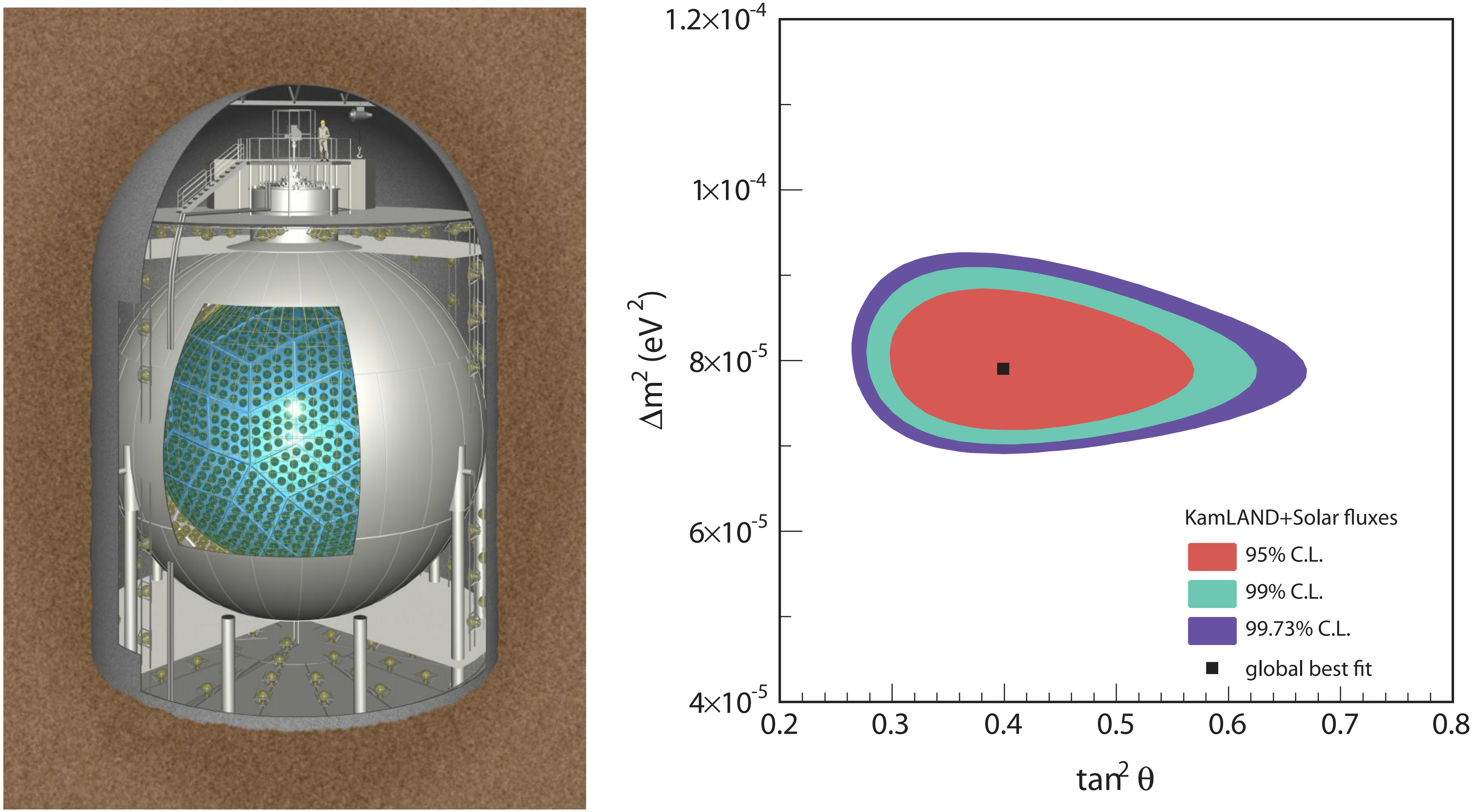


Figure 191: KamLAND detector (liquid scintillator, data taking since 2002) and the combined SNO and KamLAND (neutrinos from a reactor) fit

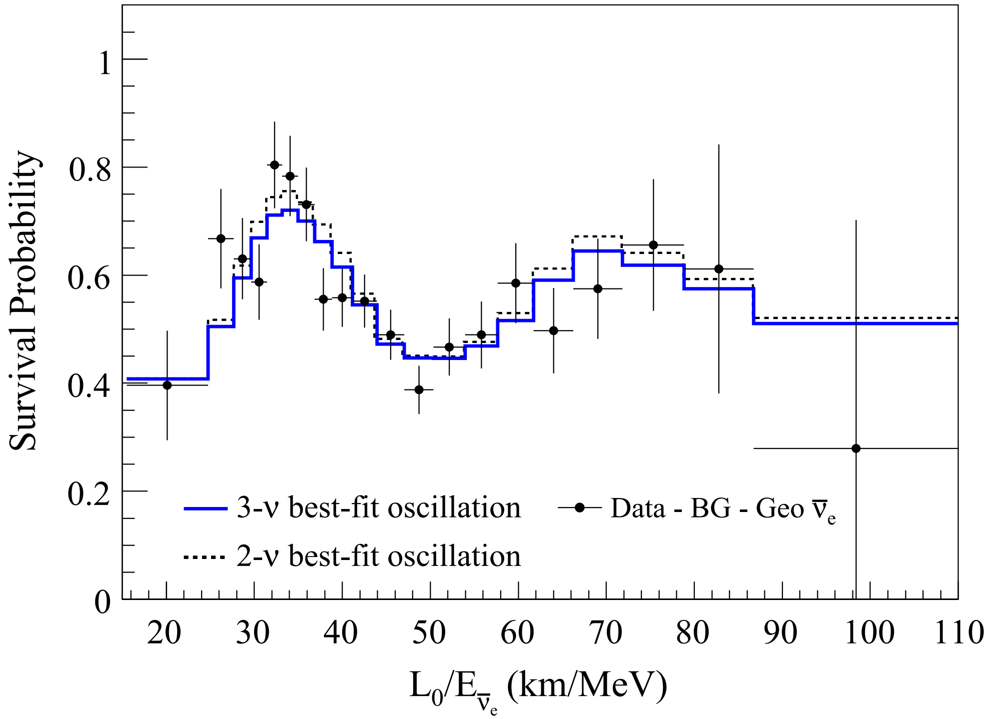


Figure 192: Electron antineutrino survival probability as measured by KamLAND. Antineutrinos from 26 reactors in the radius of 140-210 km are detected

Accelerators can create high-intensity neutrino beams and direct them towards detector installations

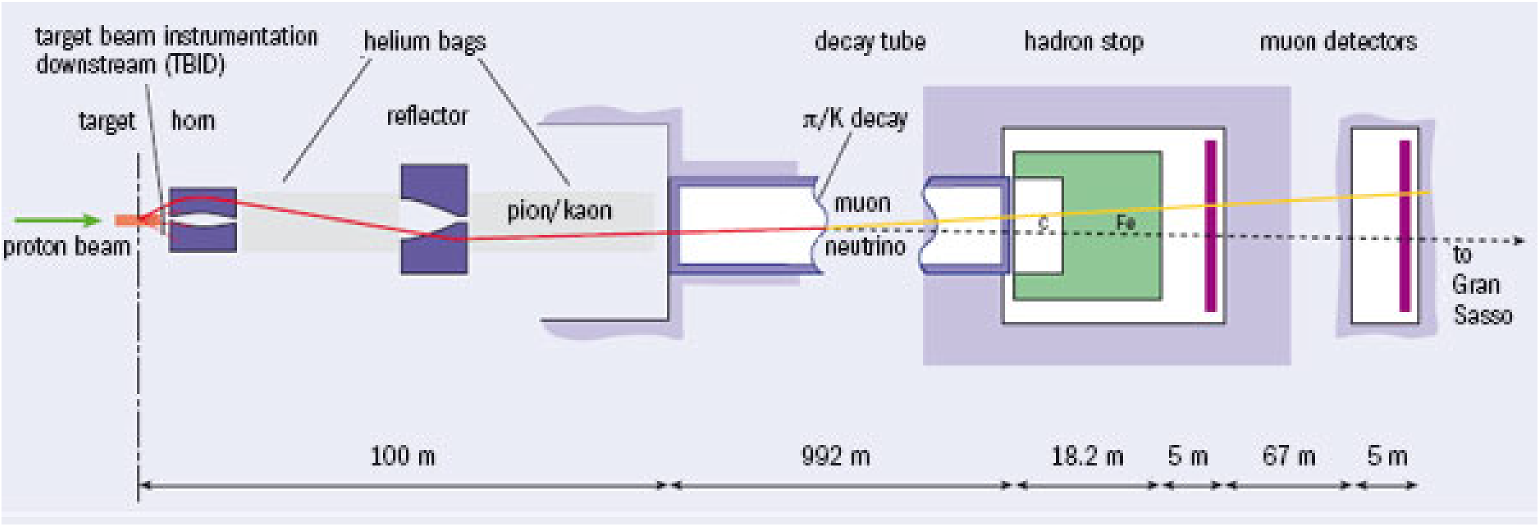


Figure 193: Scheme of the CERN to Gran Sasso (732 km away) neutrino beam

- Detector closer than 1km: short-baseline; NOMAD and CHORUS at CERN were 800 m away and found no signal
- *Long-baseline*: beam shot through Earth to a detector hundreds of kilometers away

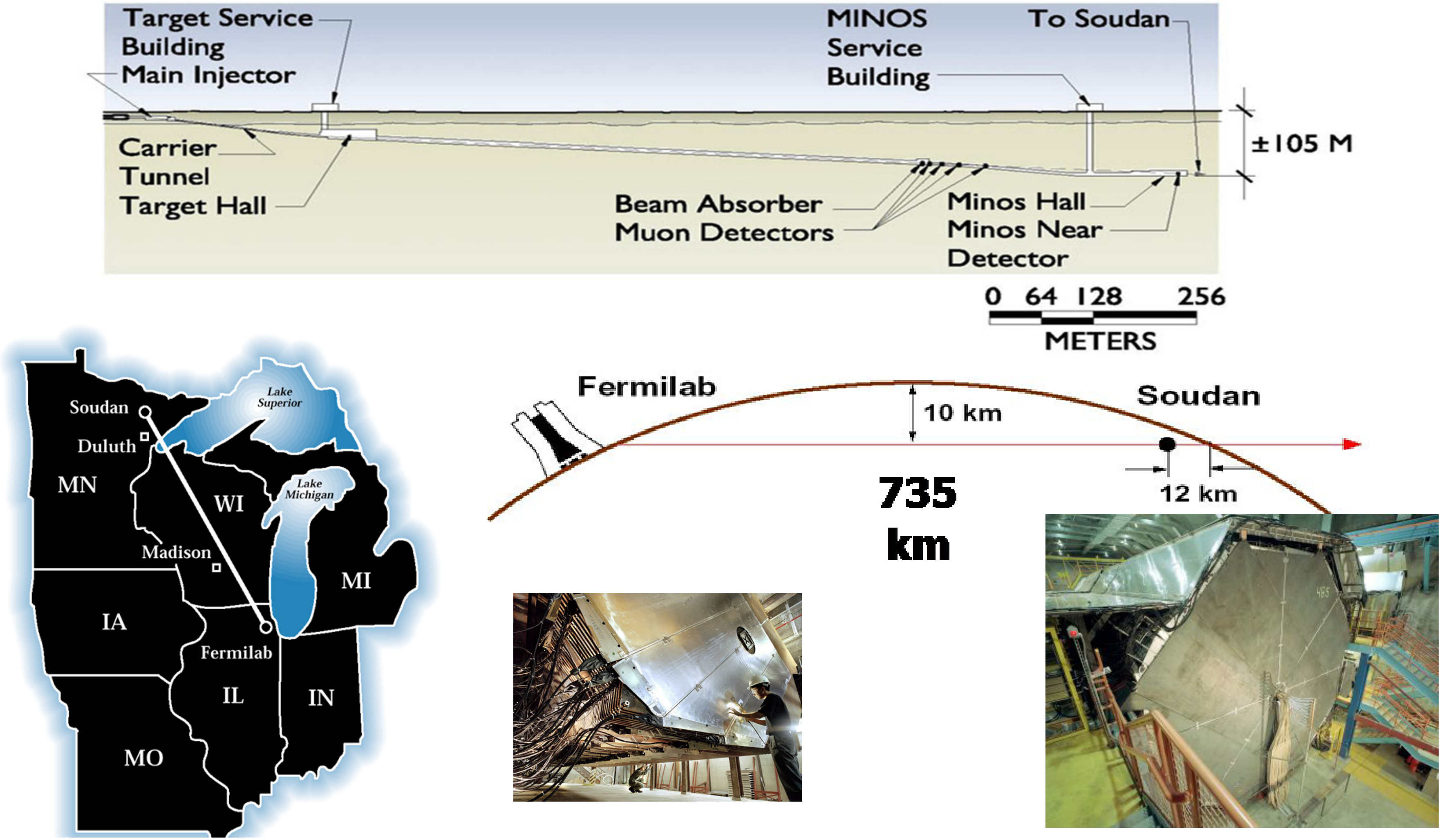
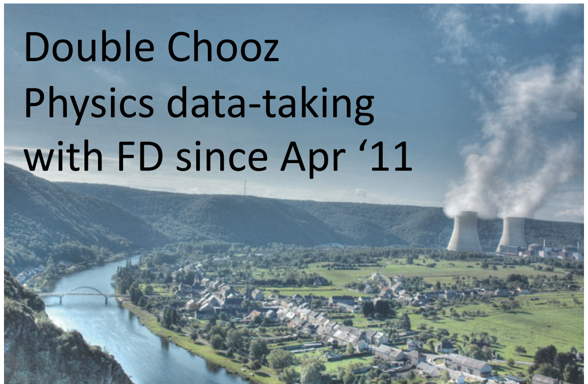


Figure 194: NuMI beam of ν_μ is shot from Fermilab (IL) to the MINOS experiment in Soudan (MN) mine 735 km away. Takes data since 2005.

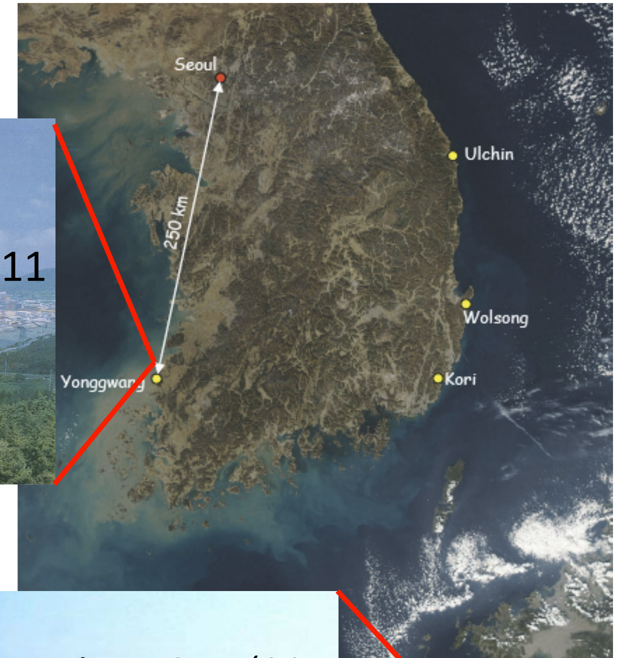
- Two detectors (near and far) are used in a disappearance experiment

New reactor experiments, focus on θ_{13}:

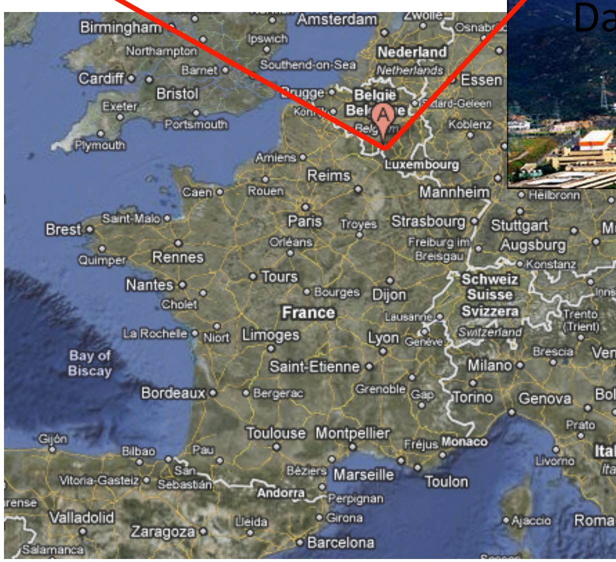


Double Chooz
Physics data-taking with FD since Apr '11

RENO
Physics data-taking with both detectors since Aug '11



Daya Bay
Data-taking with 2 of 8 detectors since Aug '11



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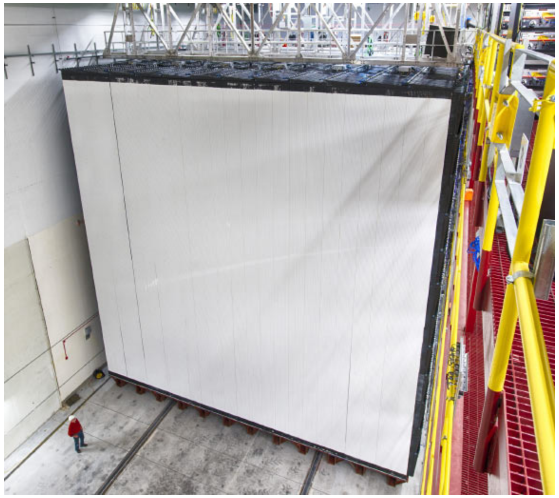
Appearance experiments

Appearance experiments are more challenging, but provide the necessary complementary measurements. Use either scintillators or Cherenkov detectors.

- OPERA - in Gran Sasso, looks for appearance of tau neutrino in muon neutrino beam, takes data since 2006
- T2K - Super-Kamiokande, appearance of electron neutrino in the beam (295 km from J-PARC), takes data since 2010

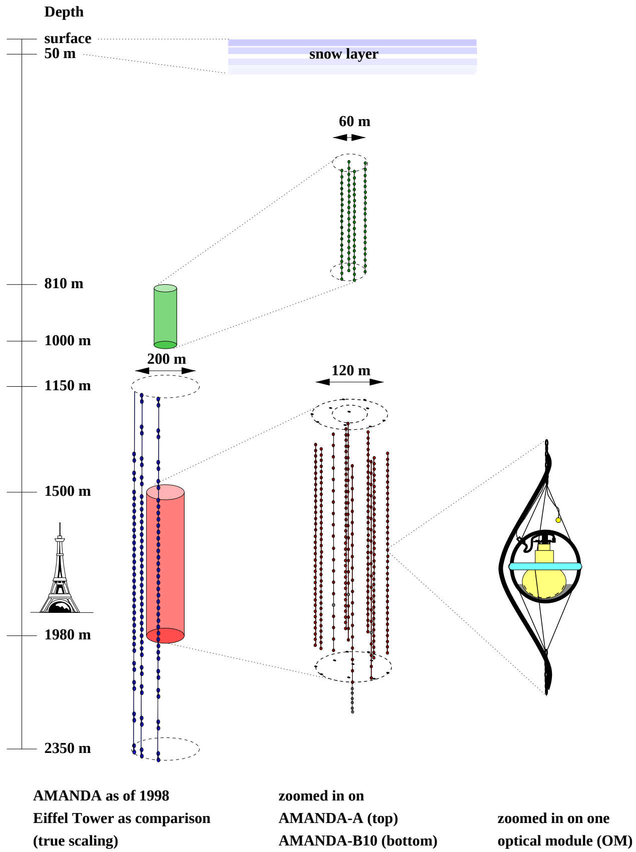


- NOνA experiment - same basic setup as NuMI/Soudan, but different detectors, ~2 degrees off the beam axis to enhance the signal (like T2K), appearance of electron neutrino. Should start taking data very soon now.

Extra-galactic neutrinos

- Detection of neutrinos from *supernovae* can provide information about neutrino mass
- Simultaneous observation of neutrinos from the SN1987a on February 23, 1987 by two experiments (IMB and Kamiokande) set the upper limit of neutrino mass at 20 eV

Figure 195: SN1987a as seen by the Hubble Space Telescope in 1994



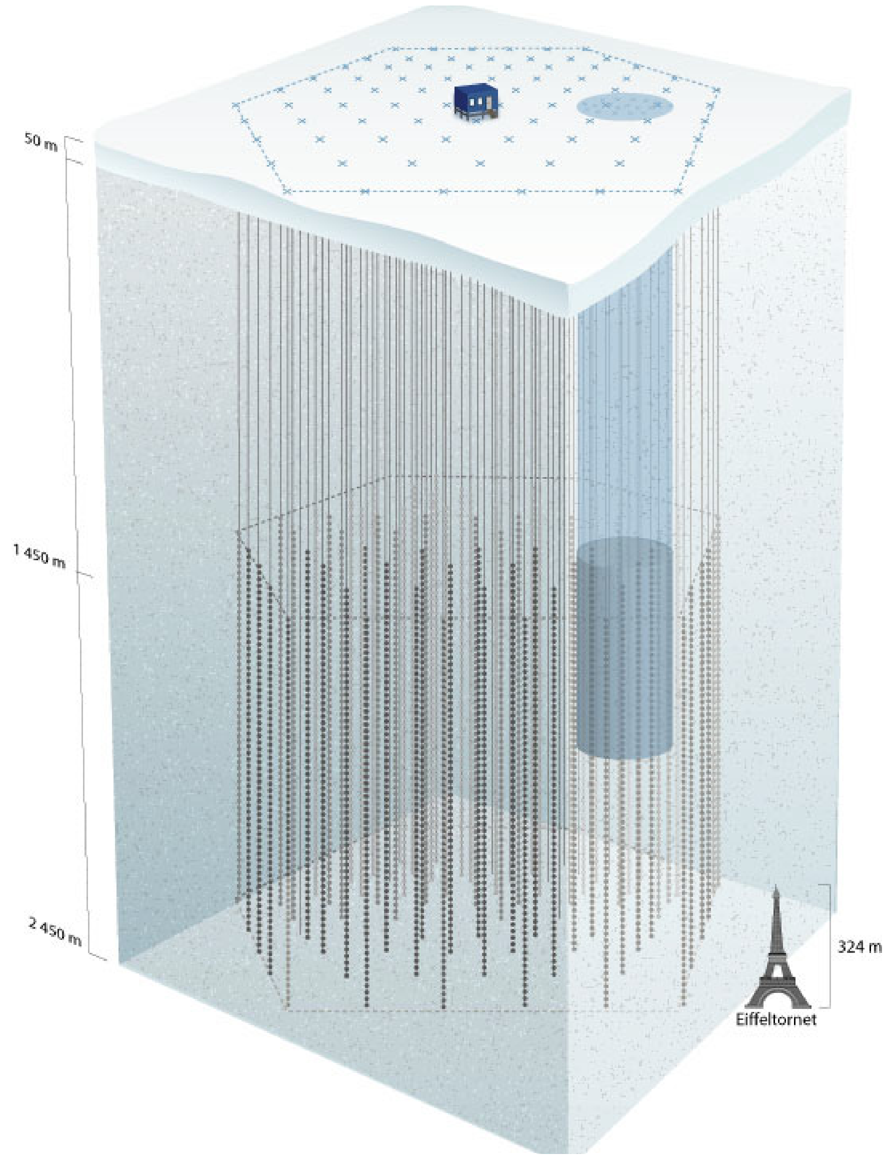


Figure 196: AMANDA (left, runs since 1996) and IceCube (right) neutrino telescopes at the South Pole. So far detected 28 candidates.

- Neutrino telescopes look for extra-Solar-system neutrinos and cover very large areas (1 cubic kilometre for IceCube)
- Located in (sometimes frozen) water bodies: lakes, seas - and consist of strings of PEMs to detect Cherenkov light
- Some other neutrino telescopes:
  - Baikal (since 1993)
  - In Mediterranean: ANTARES (since 2006), NESTOR (since 2003)
  - KM3NeT - to be constructed in Mediterranean, in 3 locations (prototype: NEMO)



Is neutrino its own antiparticle?

- Can neutrino be its own antiparticle, violating lepton number conservation?

Recap: neutrinos are always relativistic, hence left-handed (antineutrinos - right-handed); moreover, antineutrinos have opposite sign of lepton quantum numbers

Neutral particles may or may not have antiparticles:

- γ, Z^0, π^0 have no antiparticles (all are bosons)
- K^0, n have antiparticles (n is a fermion)

Neutron is a *Dirac fermion* (has an antiparticle). *Majorana fermions* have no antiparticles, but never been observed yet.

If neutrinos have mass, then right-handed neutrinos are possible:

- Dirac neutrino: ν_L, $\bar{\nu}_R$ and ν_R, $\bar{\nu}_L$
- Majorana neutrino: only ν_L and ν_R and no lepton number conservation

The so-called "see-saw mechanism" combines Dirac and Majorana terms, leading to extremely light ν_L and extremely heavy ν_R

- May explain why ν_L are so light

Majorana neutrino signature: neutrinoless *double beta decay*

- Double beta decay requires even-even nuclei; only 35 isotopes known, all with half-lifes longer that the Universe age

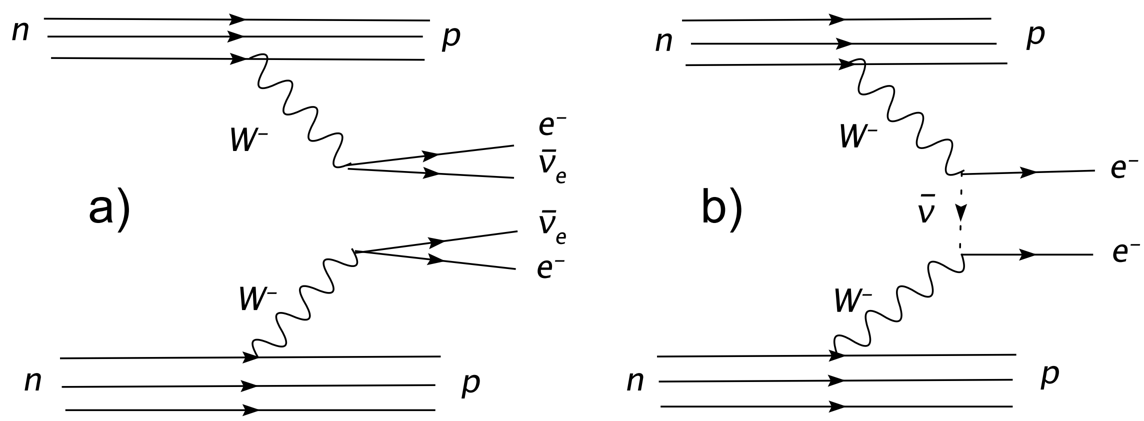
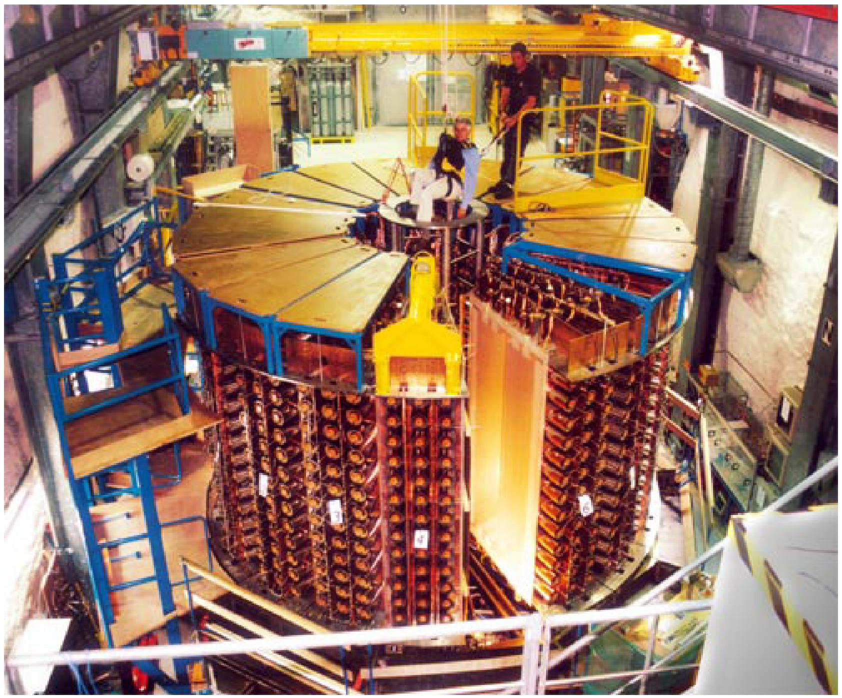


Figure 197: Process (a) is allowed for both Dirac and Majorana neutrinos; process (b) - only for Majorana

To detect a signal, one has to:

- Chose a good isotope
- Know your background (as usual in neutrino experiments)
- Get a good detector



- NEMO3 experiment is currently collecting data (in the Frejus road tunnel under Alps)
- Planned experiments: SNO+, SuperNEMO, CUORE, KamLAND-Zen
- No sign of Majorana neutrinos yet...

Summary of most recent neutrino oscillation parameters

Parameter	Best-fit value (±1σ)
Δm^2_{21} $[10^{-5} eV^2]$	7.54 ± 0.26
$\left\|\Delta m^2\right\|$ $[10^{-3} eV^2]$	2.43 ± 0.10
$sin^2\theta_{12}$	0.307 ± 0.018
$sin^2\theta_{23}$	0.386 ± 0.024
$sin^2\theta_{13}$	0.0241 ± 0.0025

Here $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$

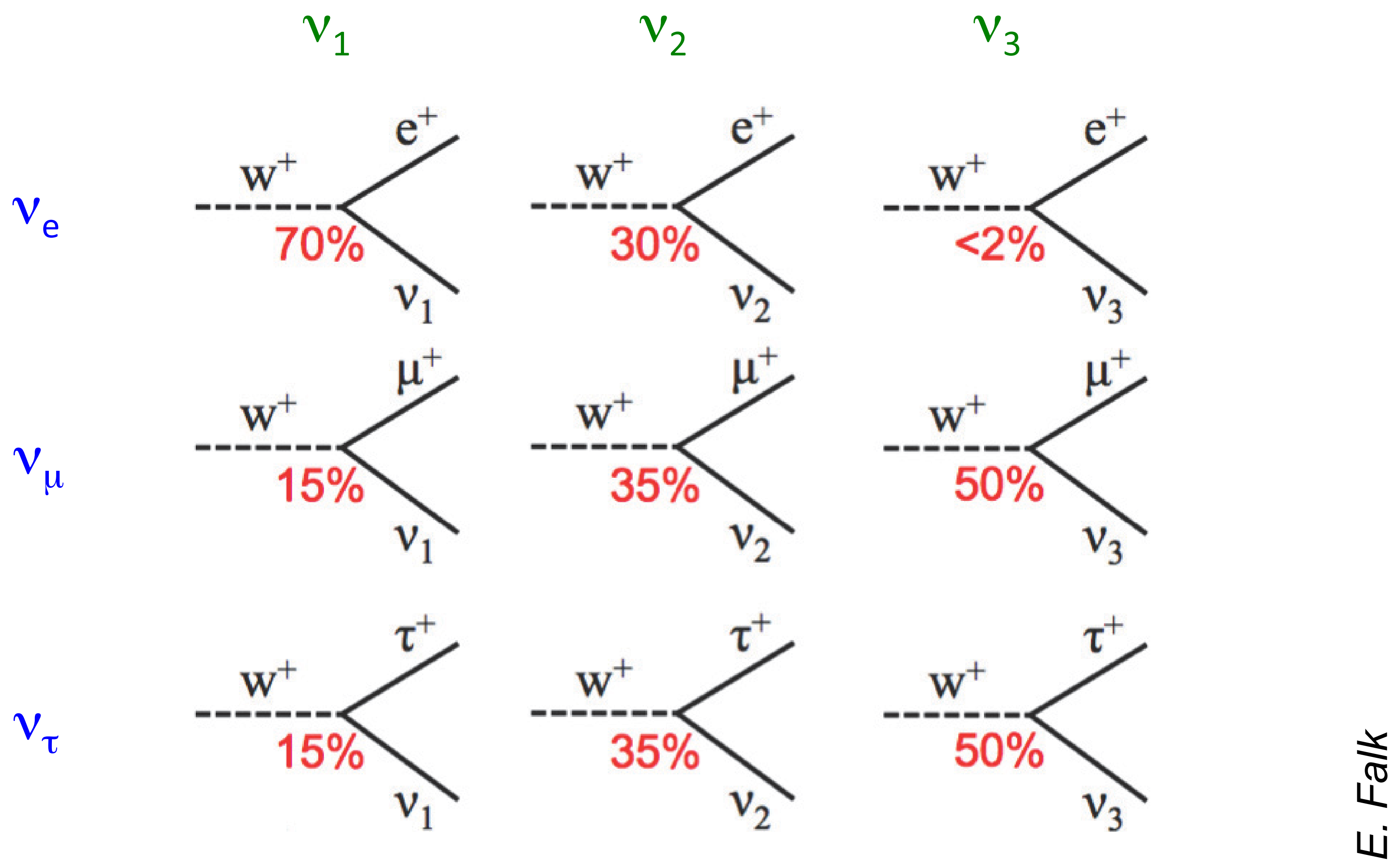


Figure 198: Summary of current knowledge about neutrino mass and flavor eigenstates