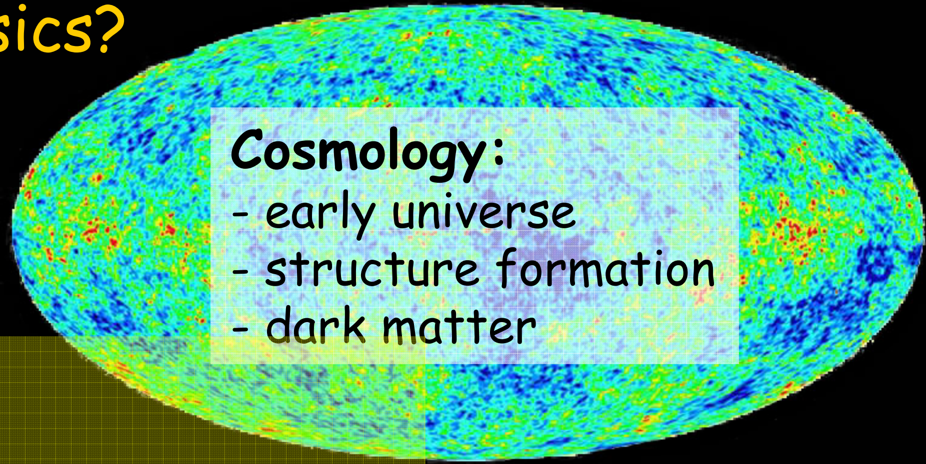
Neutrino Physics

Caren Hagner, Universität Hamburg

- What are neutrinos?
- Neutrino mass and mixing
- Neutrino oscillations
- Oscillations of atmospheric neutrinos (SuperK)
- Neutrino beams:
  Oscillation of accelerator neutrinos (OPERA)
- Solar neutrinos:
  Oscillation of solar neutrinos
  (Homestake, SNO, Borexino)
- KamLAND reactor neutrino experiment
- Summary
- Outlook: Majorana neutrinos

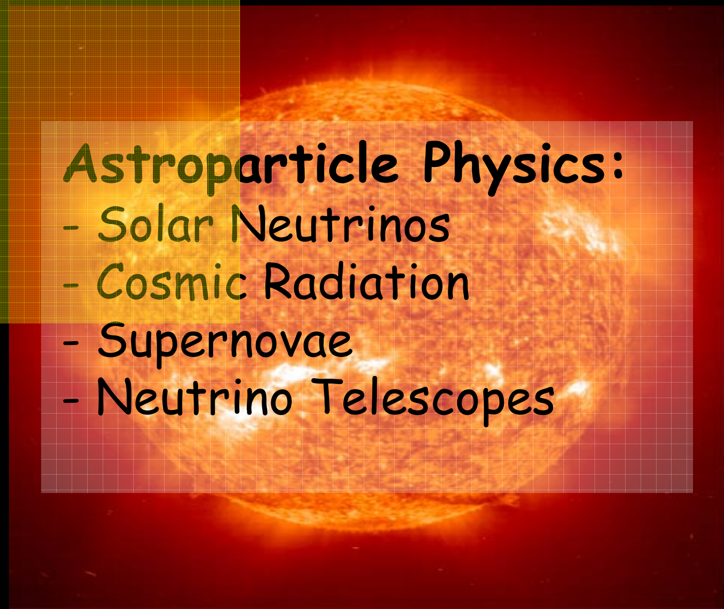
Why are we doing Neutrino Physics?



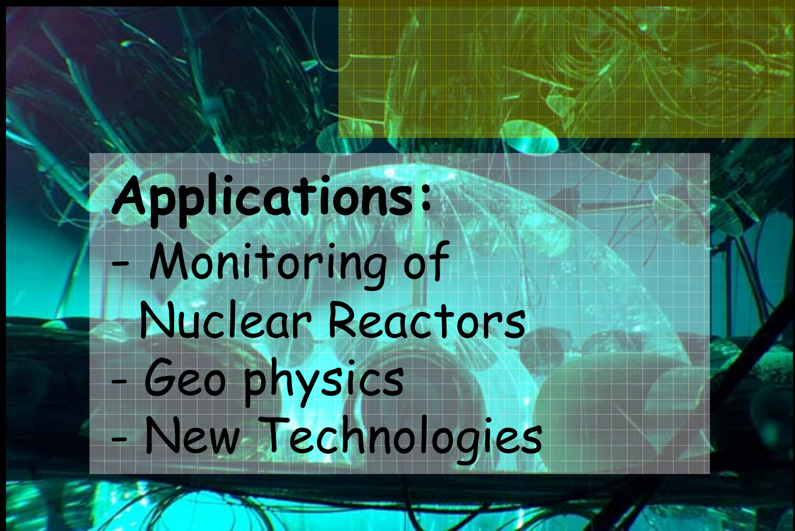
Cosmology:
- early universe
- structure formation
- dark matter

Elementary Particle Physics:
- Mass?
- Matter – antimatter symmetry
- Physics beyond the Standard Model

Neutrino Physics



Astroparticle Physics:
- Solar Neutrinos
- Cosmic Radiation
- Supernovae
- Neutrino Telescopes



Applications:
- Monitoring of Nuclear Reactors
- Geo physics
- New Technologies

Fundamental Particles

Quarks:

u	c	t
d	s	b

Leptons:

ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

Interactions by exchange of bosons: Graviton, Photon, Gluon, W,Z

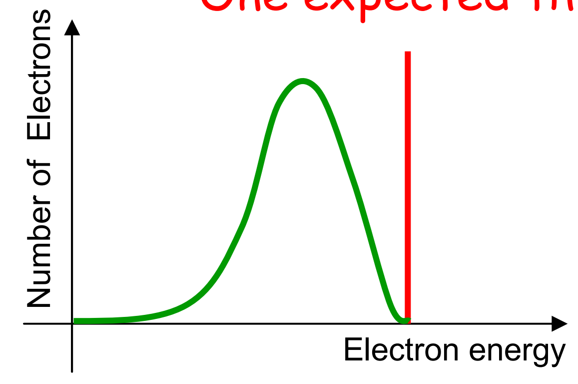
Wolfgang Pauli postulates the Neutrino (1930)

Energy spectrum of electrons from β-decay

$$n \rightarrow p + e^{-}$$

$$E_{electron} = m_n c^2 - m_p c^2$$

One expected this



But this was observed!

Solution:
The Neutrino

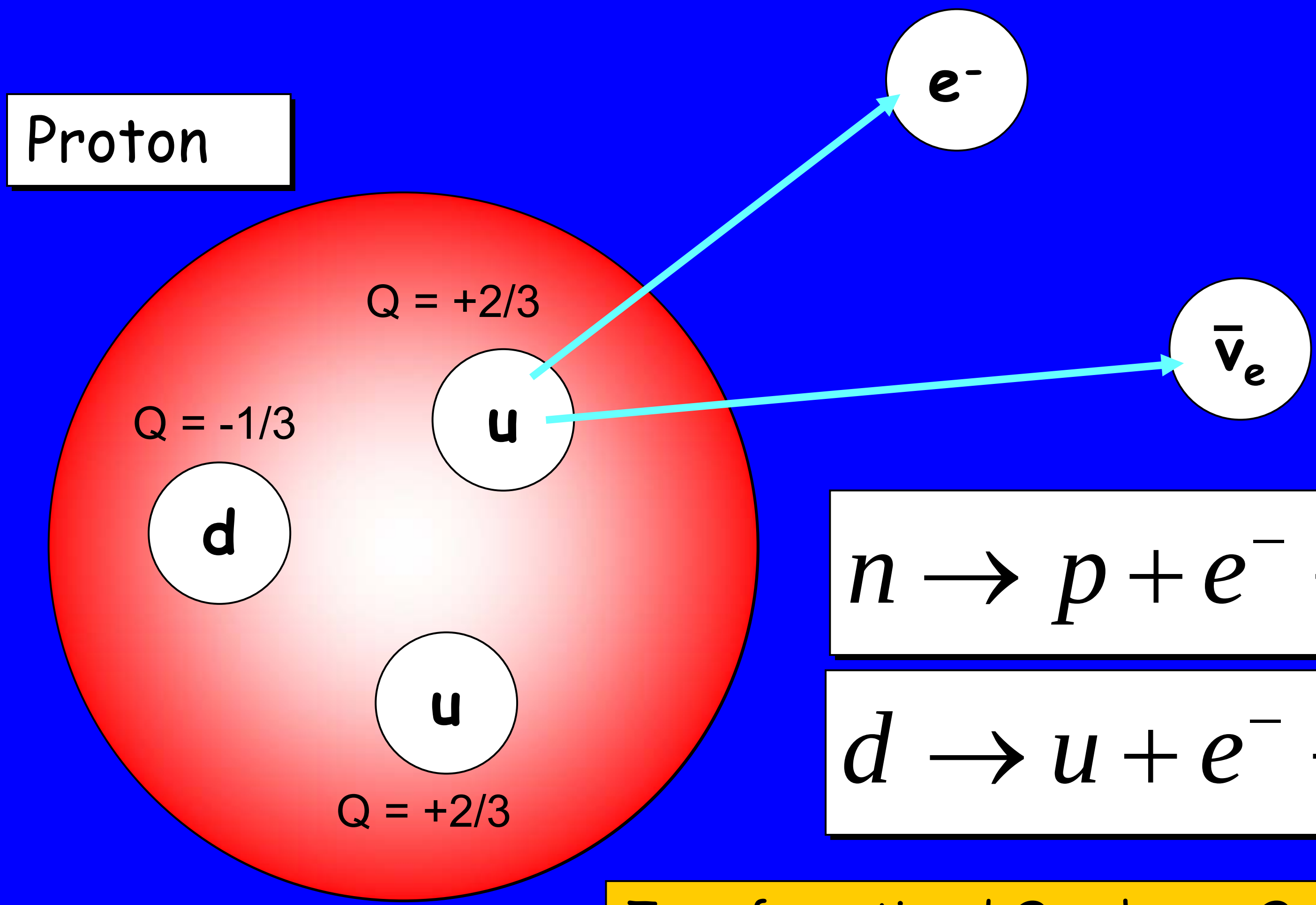
Wolfgang Pauli in Hamburg (1955)

1925 Kopenhagen

1922 Assistant at Universität Hamburg

1924 Habilitation in Hamburg (Discovery of the Exclusion Principle)

Decay of the Neutron - Birth of a Neutrino



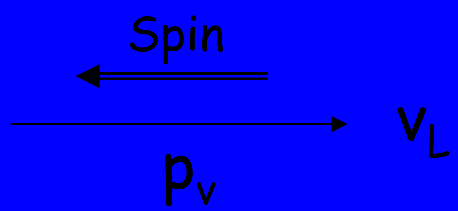
$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$d \rightarrow u + e^- + \bar{\nu}_e$$

Transformation d-Quark → u-Quark:
Electroweak Interaction!

Neutrino Properties

- Neutral
- Fermions with Spin ½
- In the Standard Model:
  massless, stable, always left handed!

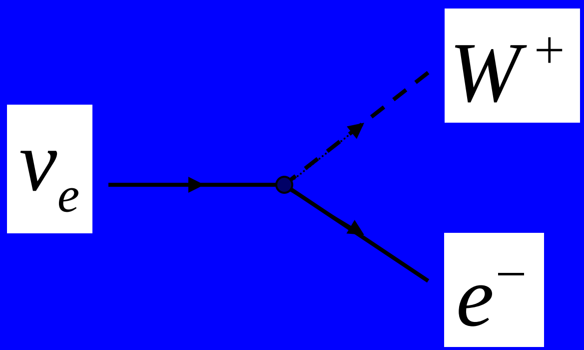


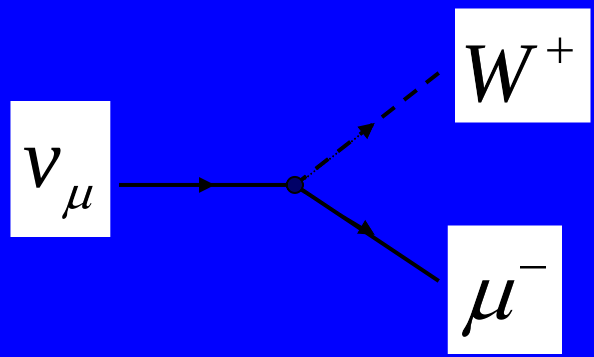
- **BUT:** Today we know that neutrinos have mass
  0.05 meV < m_ν < 2 eV
  Standard Model must be extended!

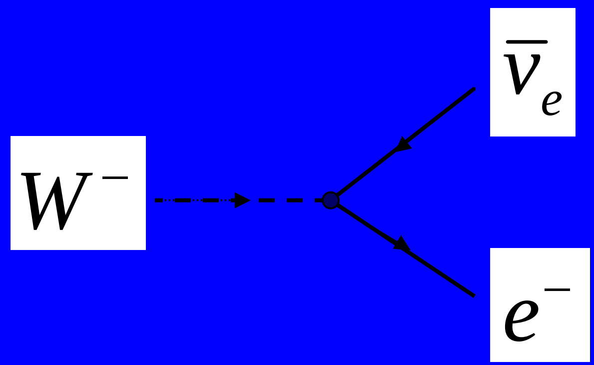
How Neutrinos interact

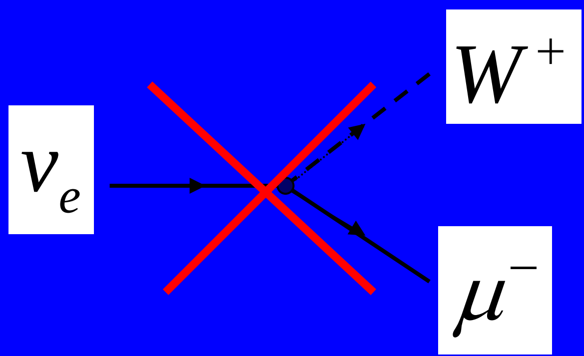
- The weak interaction

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$



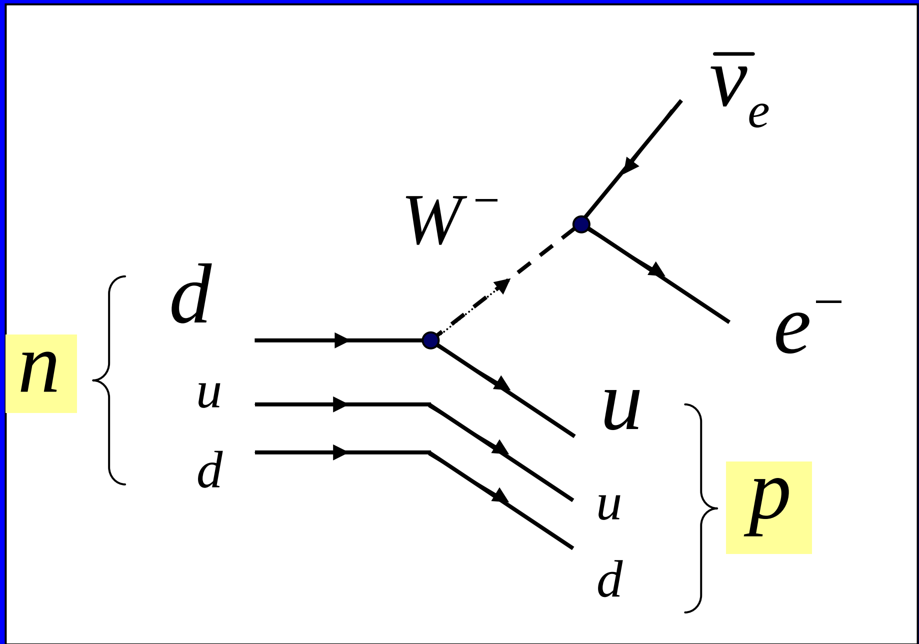


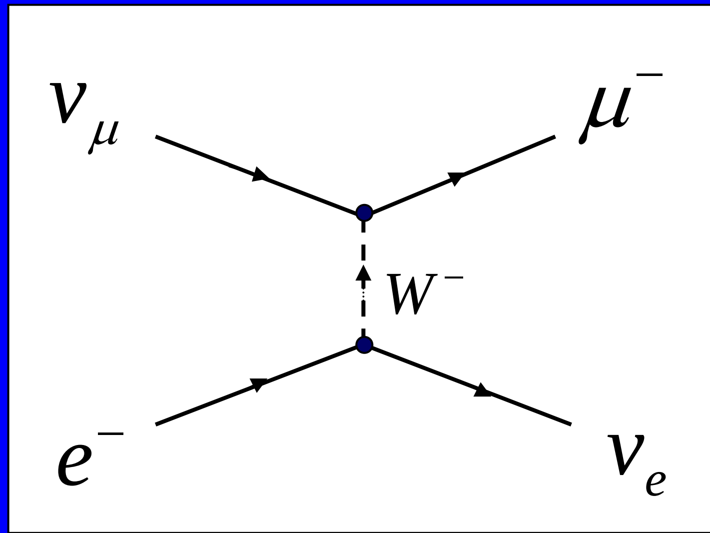


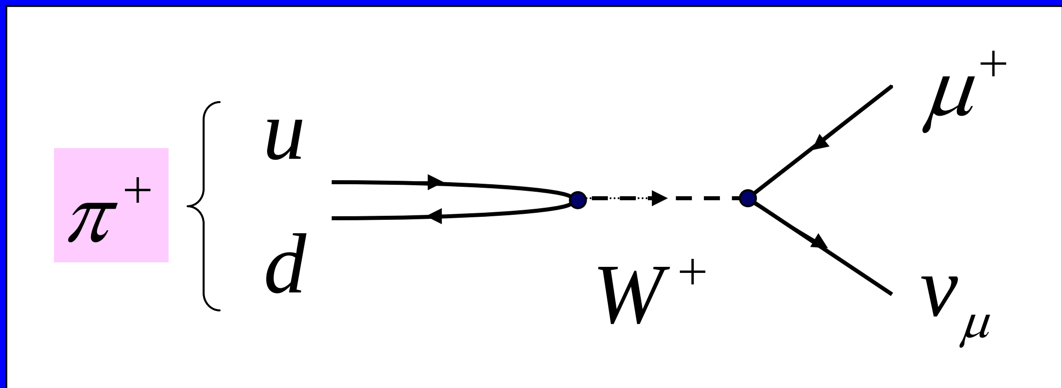


Charged Current

- Exchange of a W Boson:

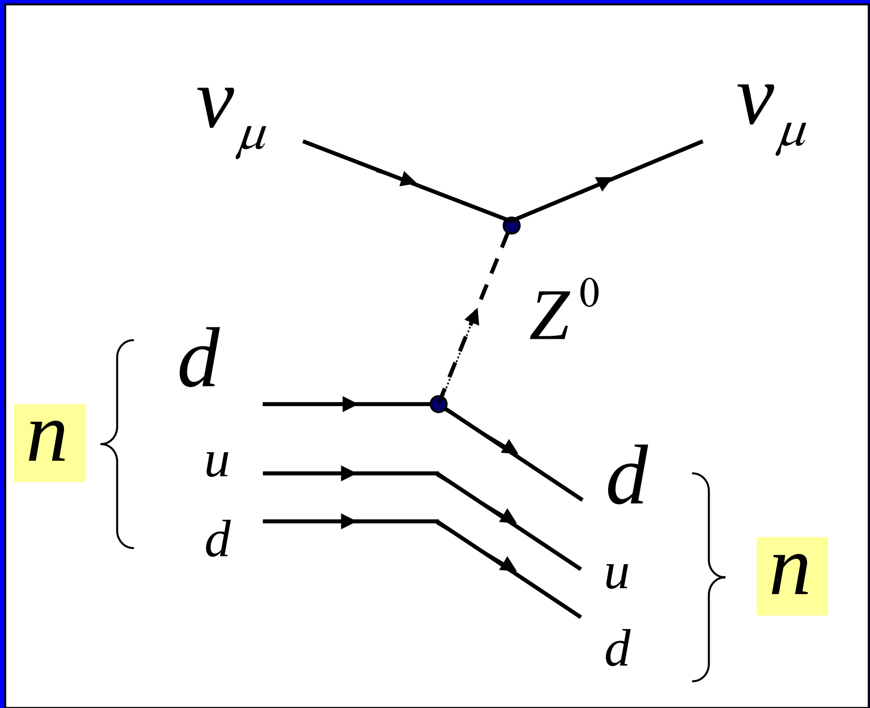


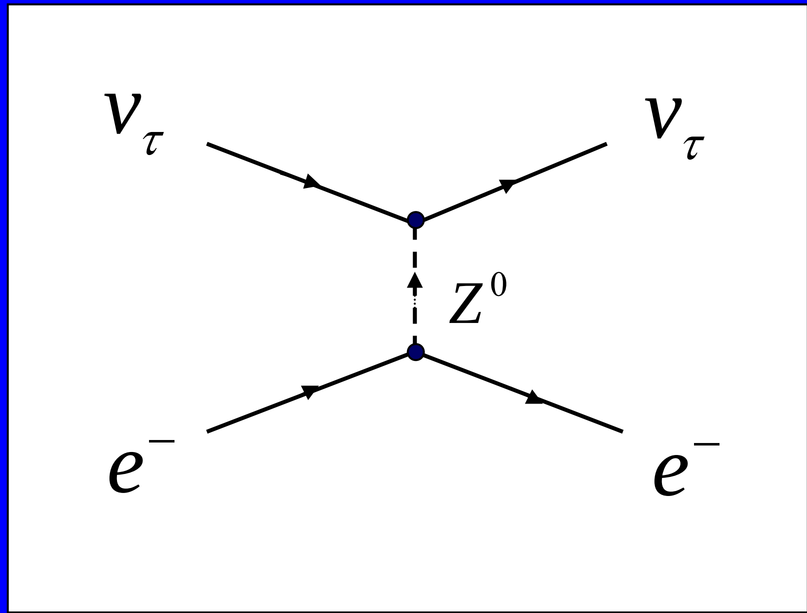




Neutral Current

- Exchange of a Z^0 Boson:





Neutrino mass and mixing

3 massive neutrinos: ν_1, ν_2, ν_3 with masses: m_1, m_2, m_3

Flavor-Eigenstates $\nu_e, \nu_\mu, \nu_\tau \neq$ Mass-Eigenstates

Neutrino mixing!

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

Example: $\left|\nu_e\right\rangle = U_{e1}\left|\nu_1\right\rangle + U_{e2}\left|\nu_2\right\rangle + U_{e3}\left|\nu_3\right\rangle$

Parametrisation of Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:
- 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- 1 Dirac-phase (CP violating): δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Mixing for 2 Flavors

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_\mu\rangle = \cos\theta_{23}|\nu_2\rangle + \sin\theta_{23}|\nu_3\rangle$$

The probability that ν_μ has mass m_2 is $\cos^2\theta_{23}$

mixing angle → probability to have a certain mass

Today we know that $\theta_{23} \approx 45°$:

$$|\nu_\mu\rangle = \tfrac{1}{\sqrt{2}}\left(|\nu_2\rangle + |\nu_3\rangle\right) \qquad |\nu_\tau\rangle = \tfrac{1}{\sqrt{2}}\left(-|\nu_2\rangle + |\nu_3\rangle\right)$$

e.g. probability that ν_μ has mass m_2: 50%

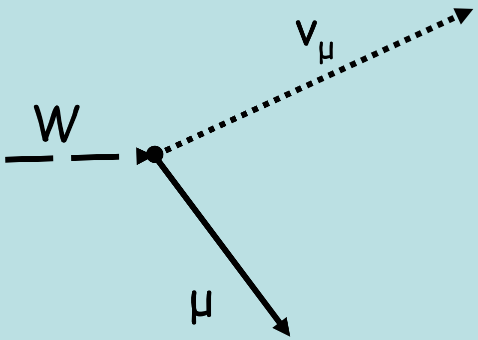
Neutrino Oscillations

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

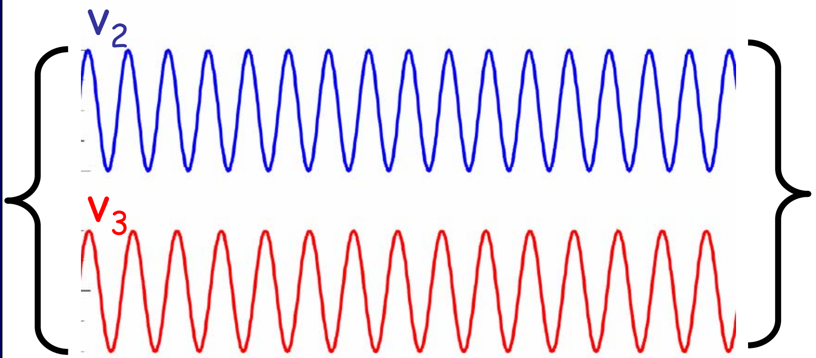
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2,ν_3 with m_2, m_3

source creates flavor-eigenstates



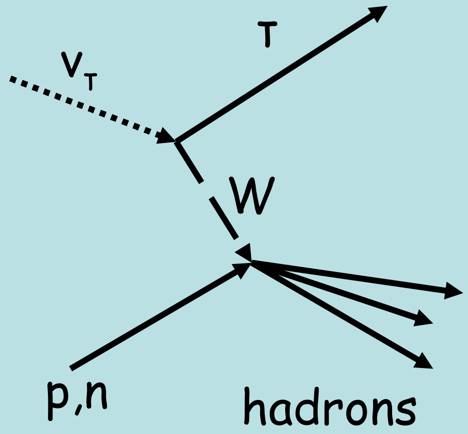
propagation determined by mass-eigenstates



$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

slightly different frequencies
→ phase difference changes

detector sees flavor-eigenstates



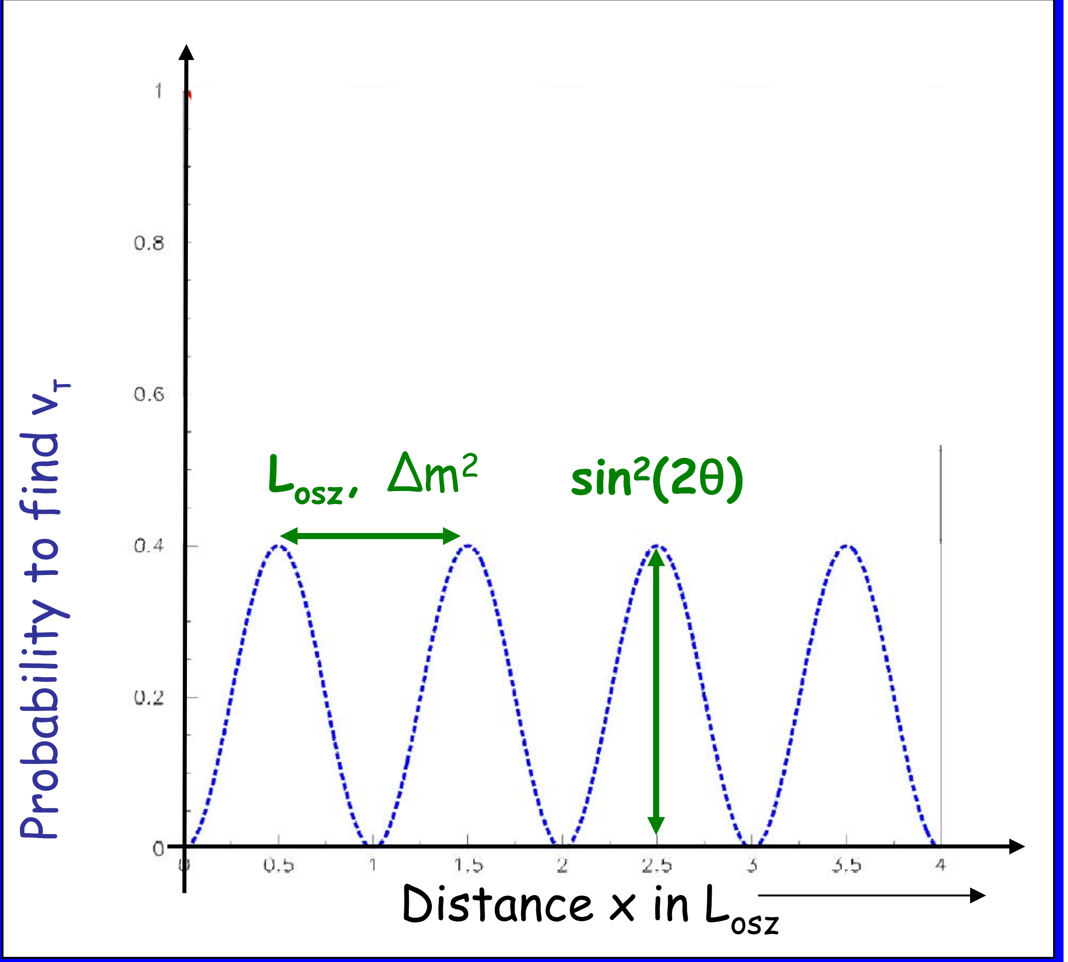
2 Flavor Neutrino Oscillations

<u>Oscillation probability</u>

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

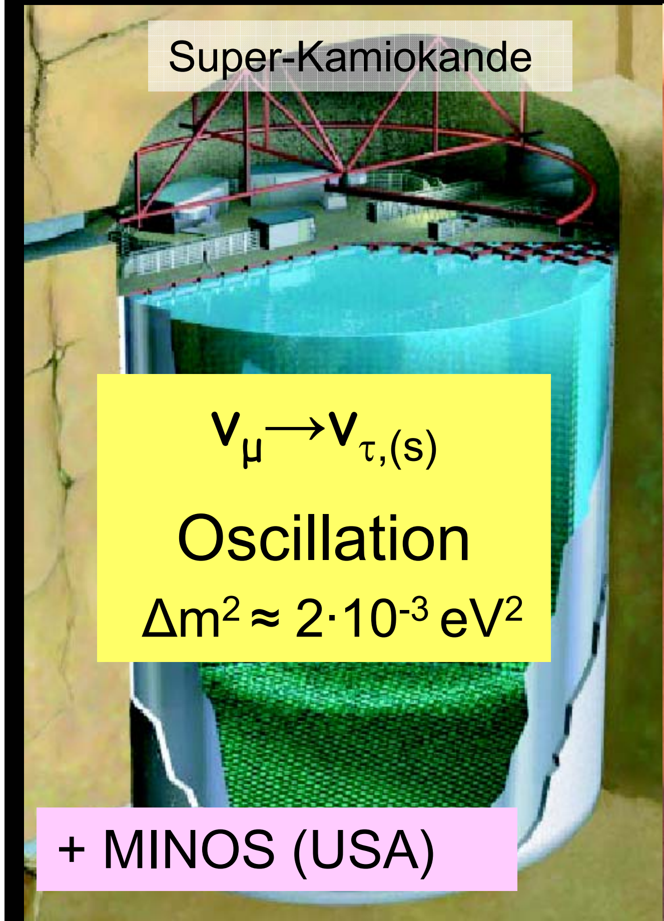
$$L_{osz}(\text{in km}) = \frac{2.48 \cdot E(\text{in GeV})}{\Delta m^2(\text{in eV}^2)}$$

$$\Delta m^2 = m_2^2 - m_3^2$$



Neutrino Oscillations were observed
→ Neutrinos have mass!

JAPAN



$\nu_\mu \longrightarrow \nu_{\tau,(s)}$

Oscillation

$\Delta m^2 \approx 2 \cdot 10^{-3}\ eV^2$

+ MINOS (USA)

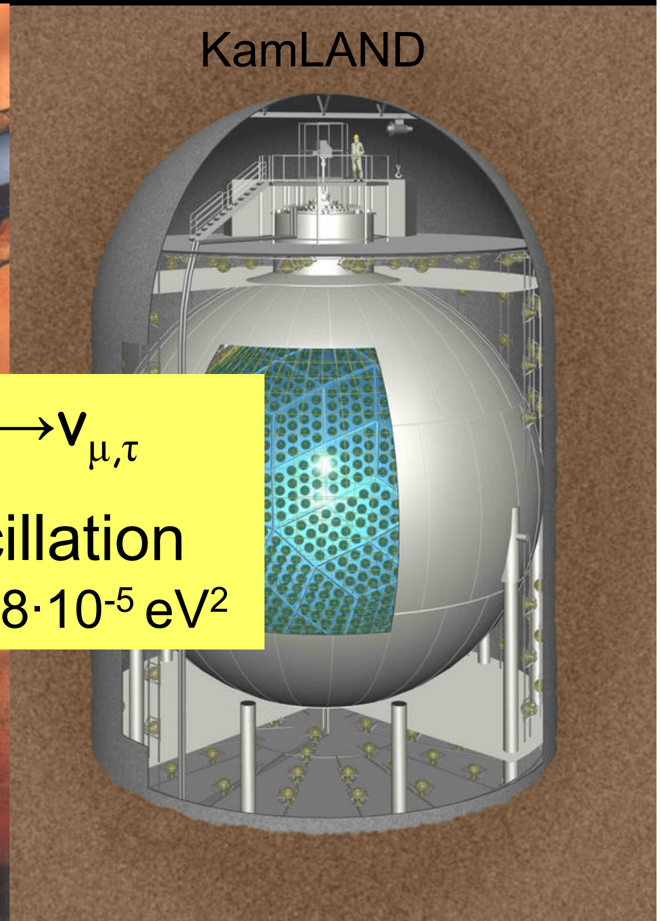
atmospheric neutrinos
accelerator neutrinos

CANADA

+ NEW:
BOREXINO @
LNGS (Italy)

solar neutrinos

JAPAN



$\nu_e \longrightarrow \nu_{\mu,\tau}$

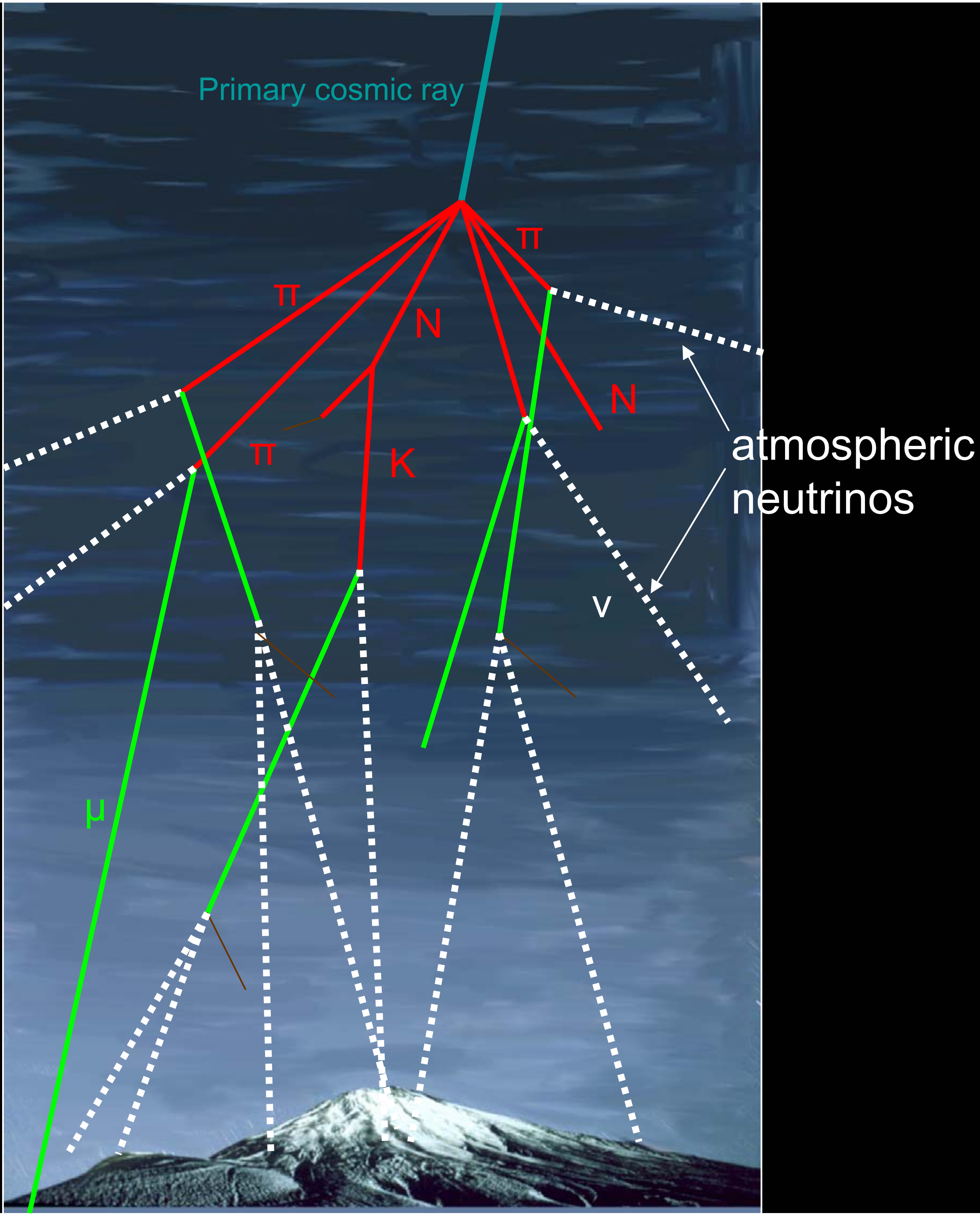
Oscillation

$\Delta m^2 \approx 8 \cdot 10^{-5}\ eV^2$

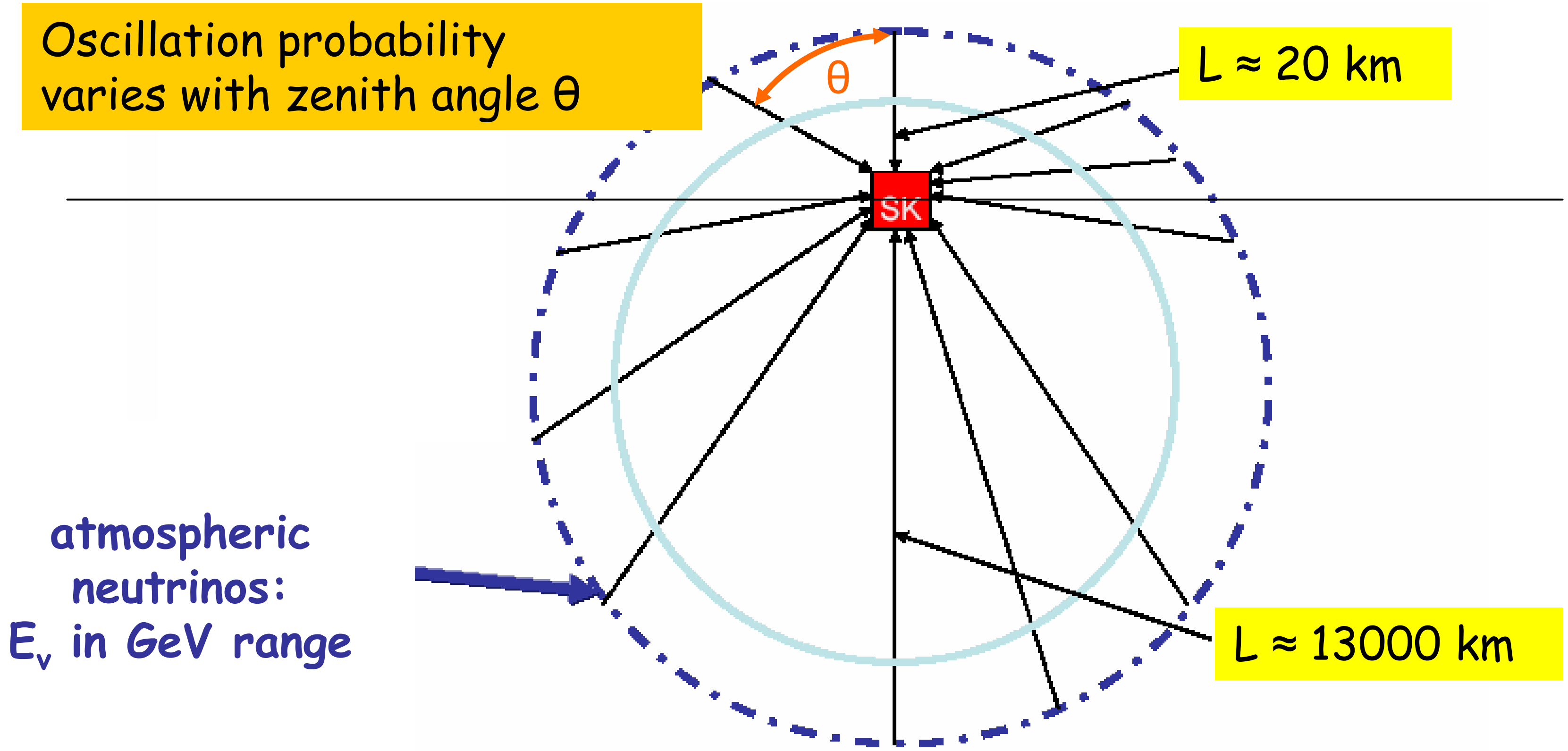
reactor neutrinos

Let us first look how muon neutrinos oscillate

- Sources of muon neutrinos are:
  The atmosphere (comic rays)
  Neutrino beams at particle accelerators
- These neutrinos have energies of a few GeV
- Detection methods:
  Water Cherenkov, Plastic Scintillators,
  Drift Tubes, Fotographic emulsions

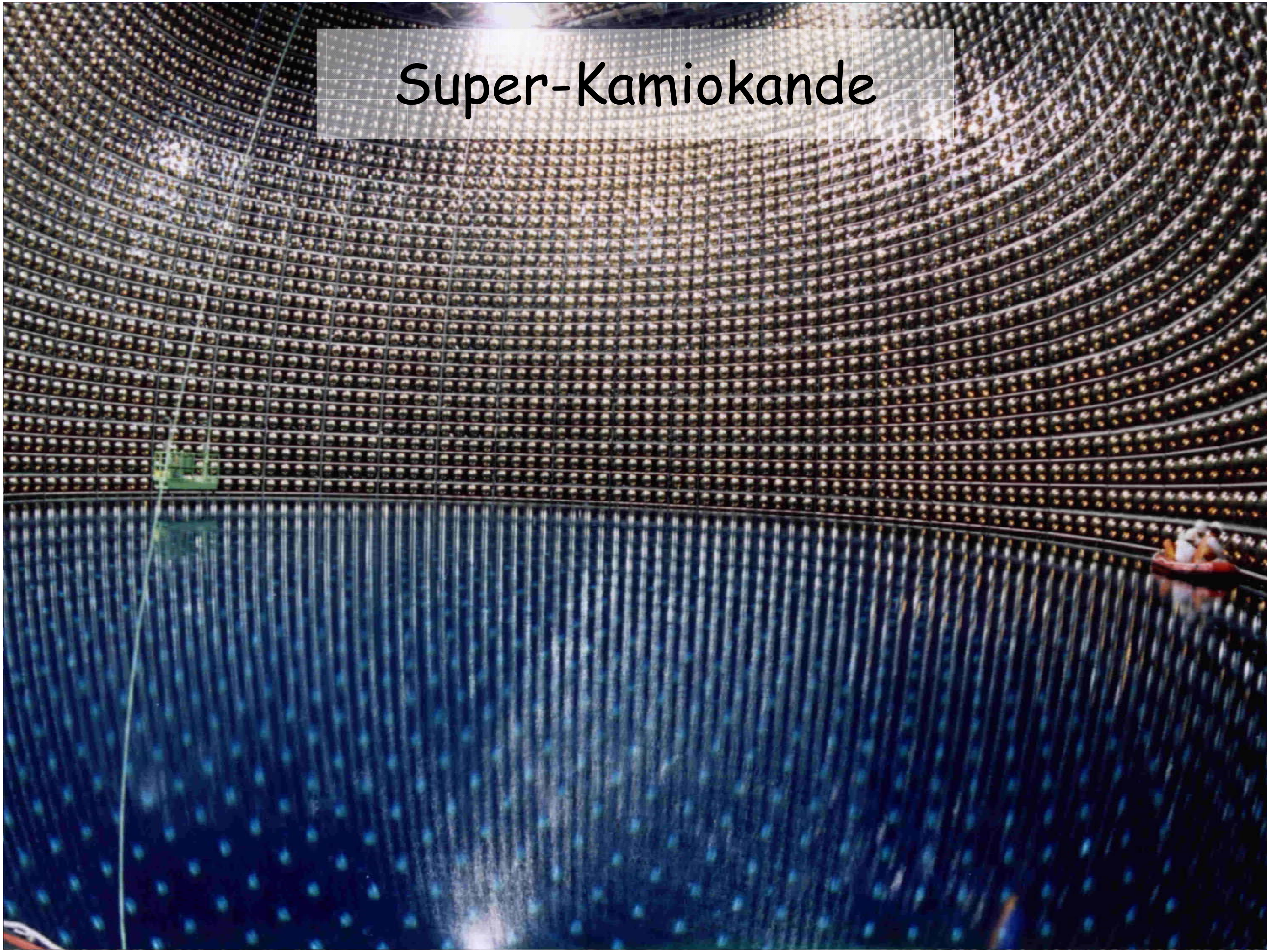

Primary cosmic ray
π
π
N
N
π
K
atmospheric
neutrinos
ν
μ

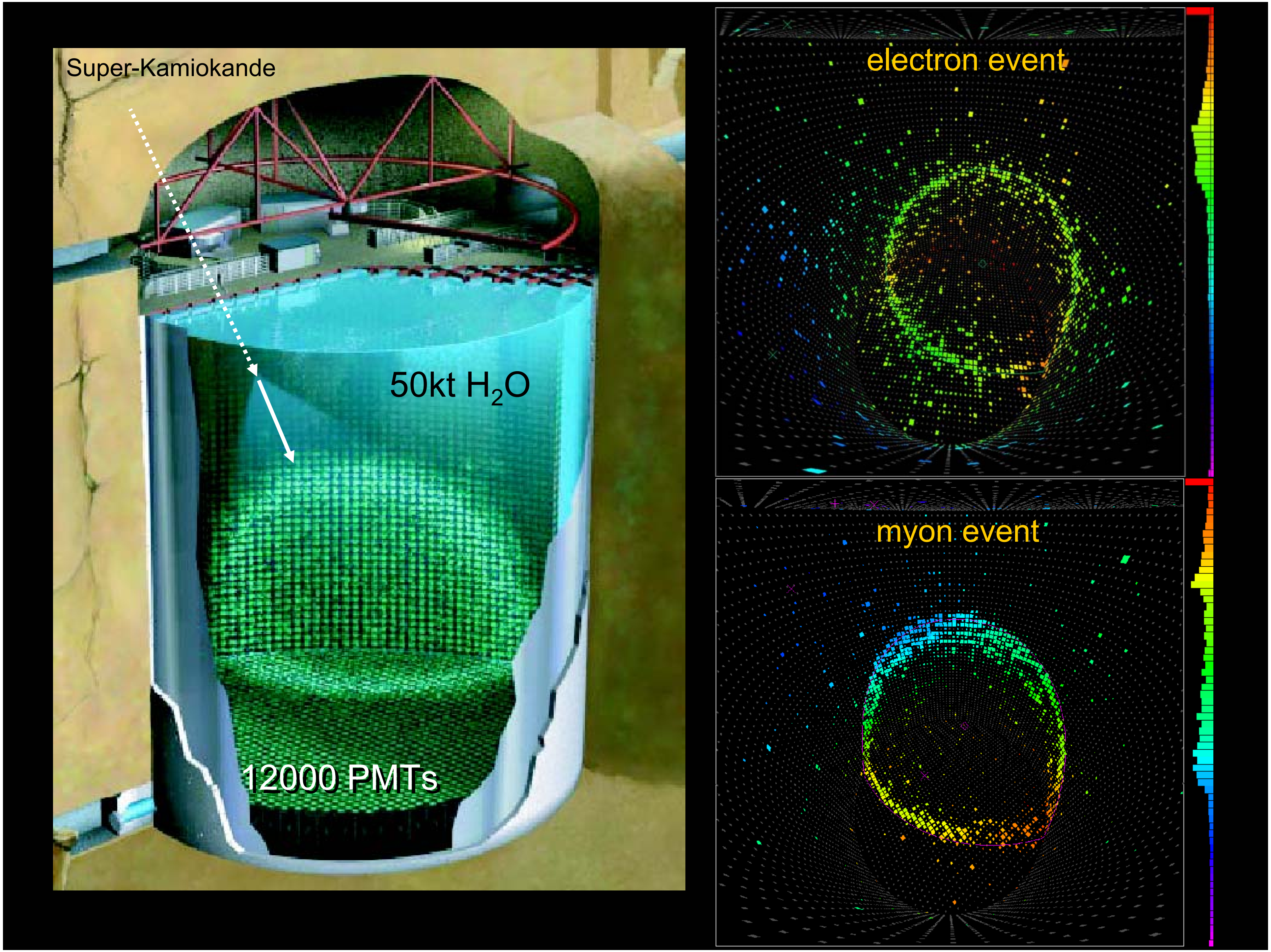
Oscillation of atmospheric neutrinos (1998)



$$P(\nu_\mu \to \nu_x) = \sin^2 2\theta_{atm} \sin^2\left(\frac{1.27\Delta m^2_{atm}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Super-Kamiokande

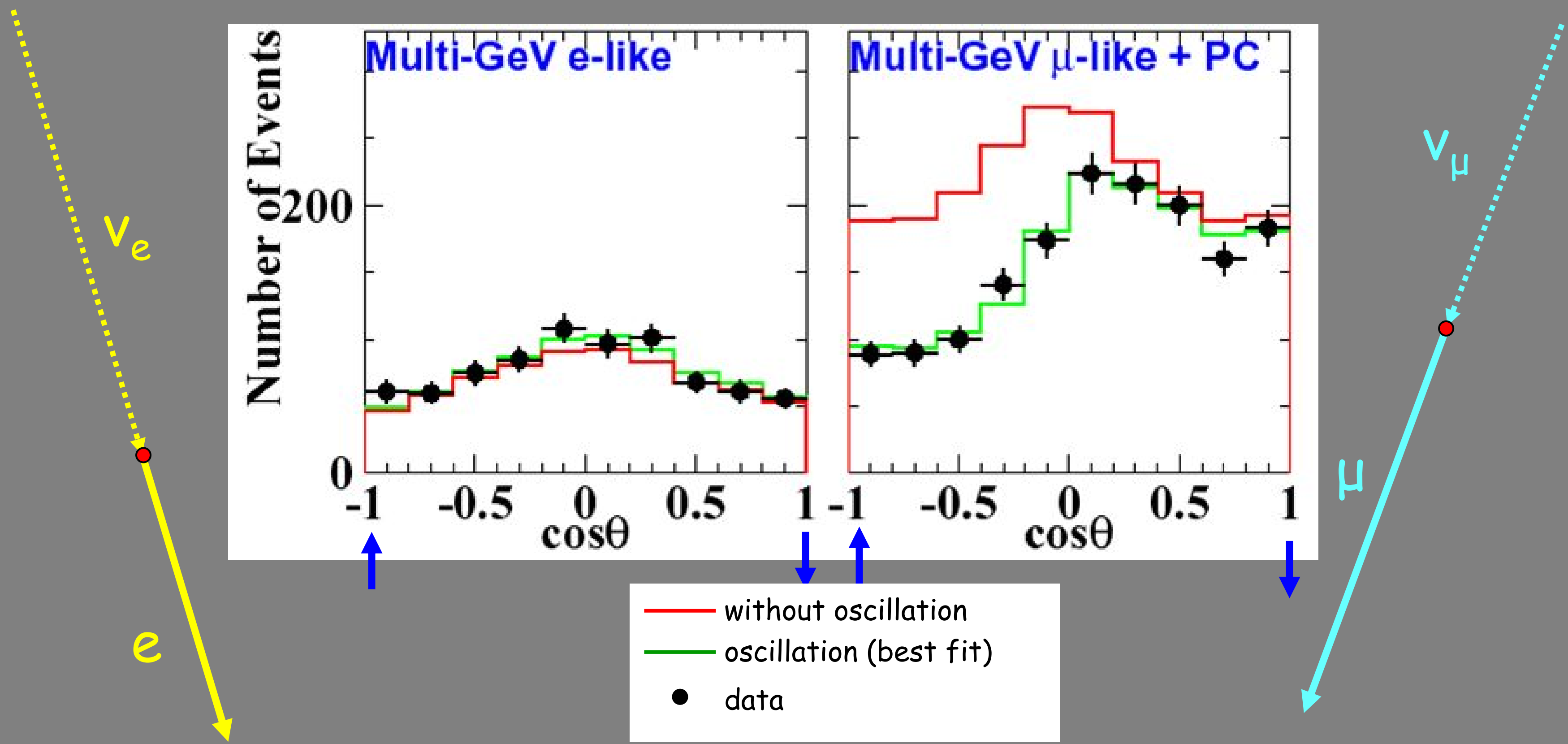



Super-Kamiokande
50kt H_2O
12000 PMTs
electron event
myon event

SuperK – atmospheric neutrinos

e–like events

μ–like events

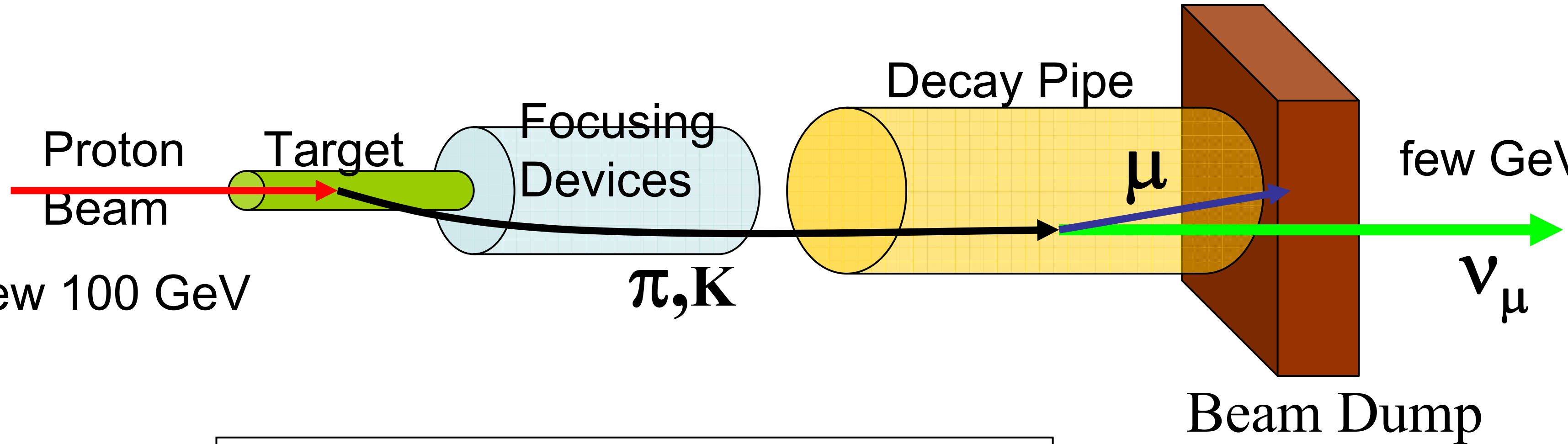


Full SK-I data set, 90% CL (PRD71 (2005) 112005):

$$\sin^2 2\theta > 0.92$$

$$\mathbf{1.5 \cdot 10^{-3}\ eV^2 < \Delta m^2 < 3.4 \cdot 10^{-3}\ eV^2}$$

How to make Neutrino beams ($E_\nu \approx$ 1GeV-100GeV)



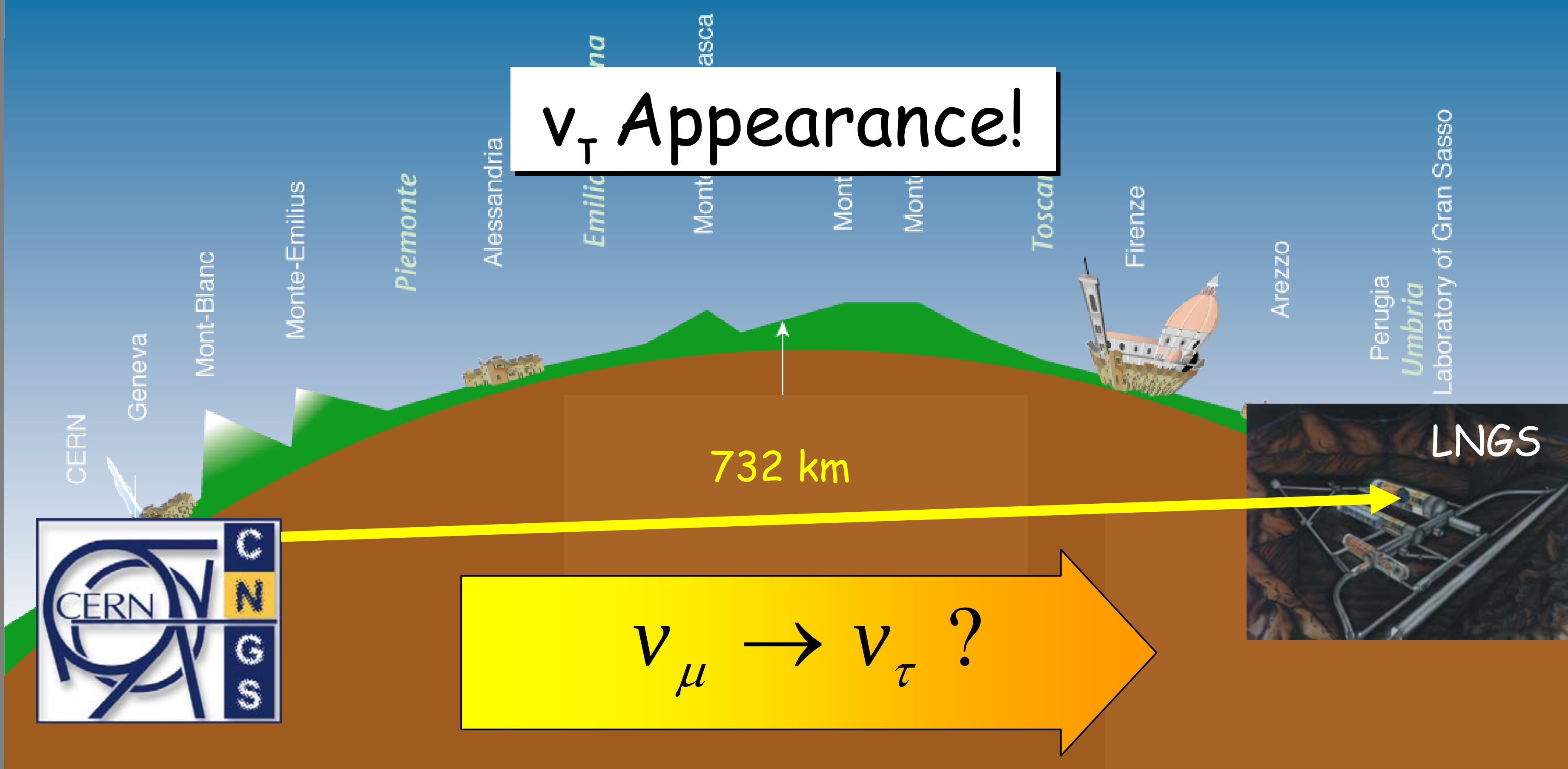
Beam composition (typical example):

- dominantly ν_μ
- contamination from
  $\bar{\nu}_\mu$ (≈6%), ν_e (≈0.7%), $\bar{\nu}_e$ (≈0.2%)
- $\nu_\tau \lesssim 10^{-6}$

Caren Hagner, Universität Hamburg

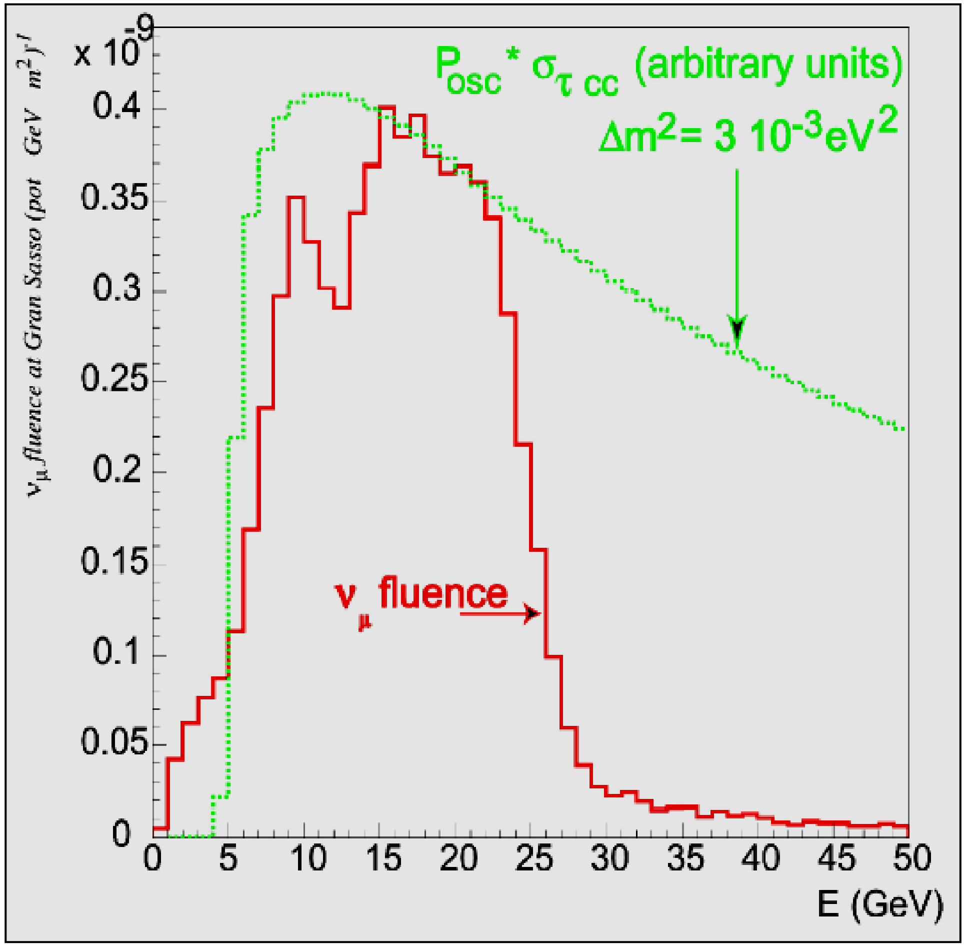
OPERA

Neutrino beam (ν_μ) from CERN to Gran Sasso Underground Lab (Italy)



Started in june 2008, running…

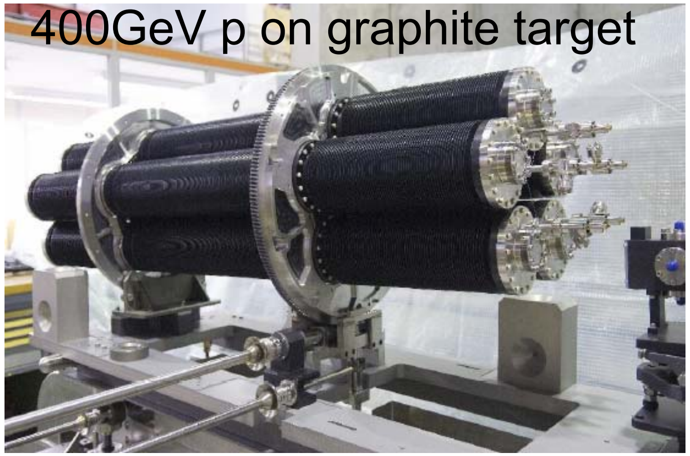
OPERA: CNGS beam



$$\langle E_\nu \rangle = 17\text{GeV}$$

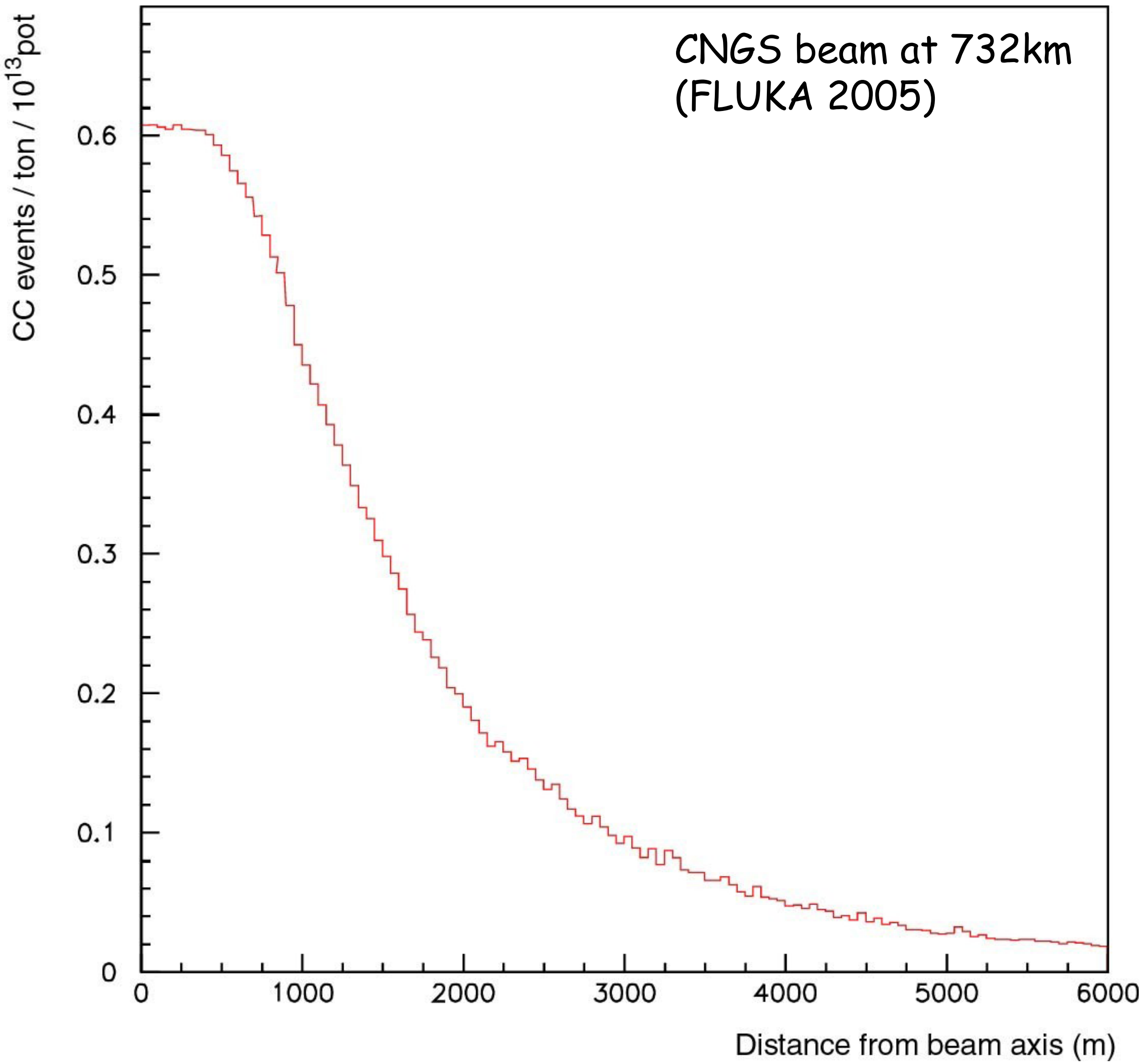
$$\bar{\nu}_\mu / \nu_\mu = 4\%$$

$$(\bar{\nu}_e + \nu_e)/\nu_\mu = 0.87\%$$

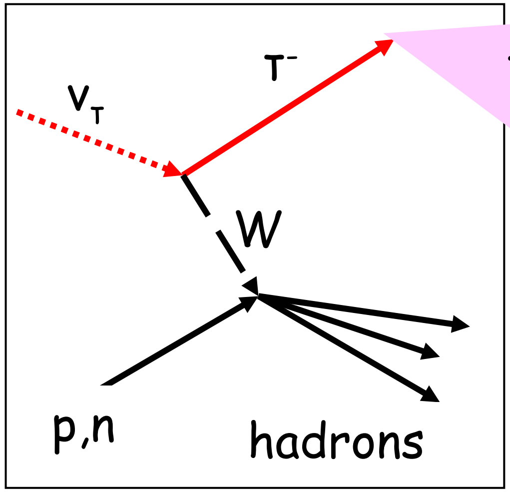


4.5·10^{19}pot/year

Querschnitt des Neutrinostrahls



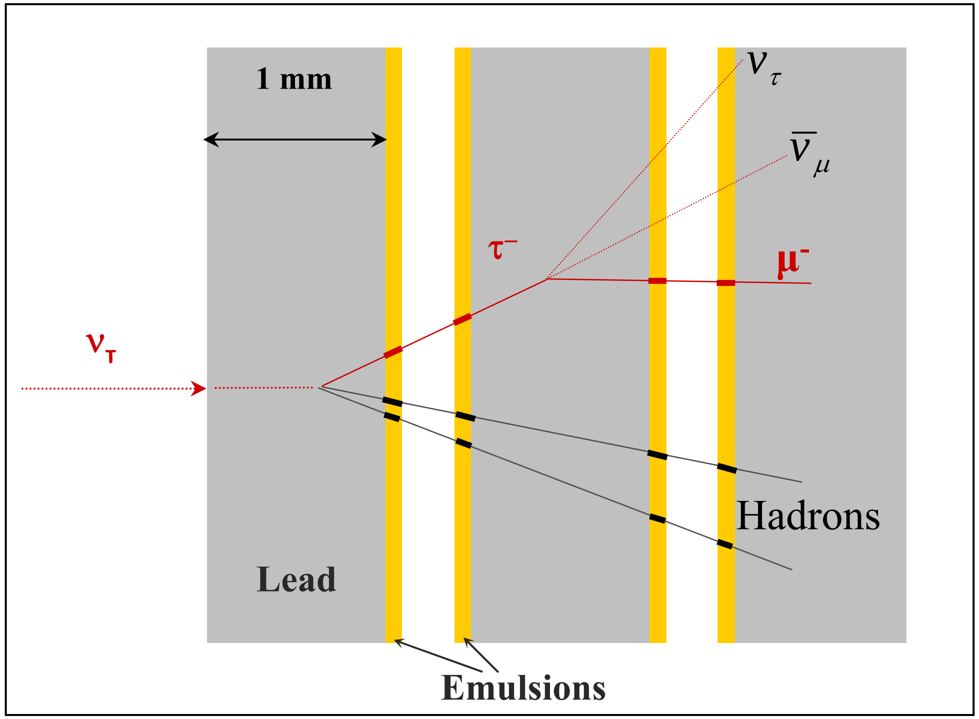
OPERA: Detection of ν_τ



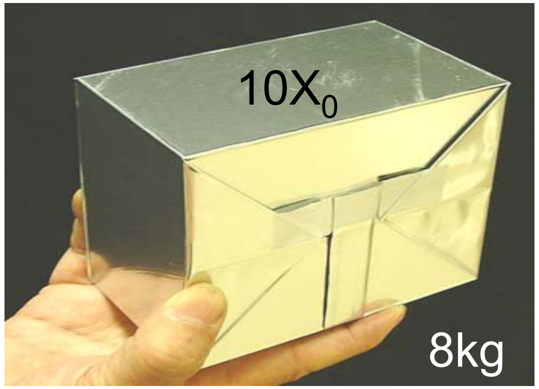
τ-decay:

$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$	18%
$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$	18%
$\tau^- \rightarrow \pi^- (n\pi^0) + \nu_\tau$	48%
$\tau^- \rightarrow \pi^- \pi^- \pi^+ (n\pi^0) + \nu_\tau$	15%

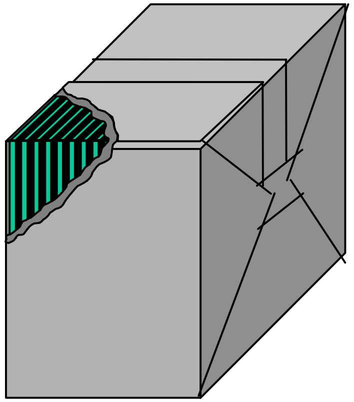
Typical topology of τ-decay:
"**Kink**" within 1mm from vertex

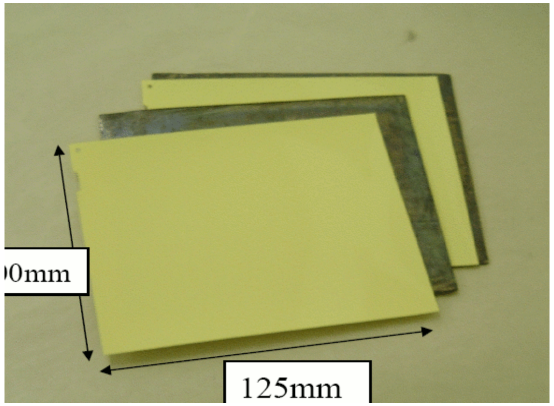


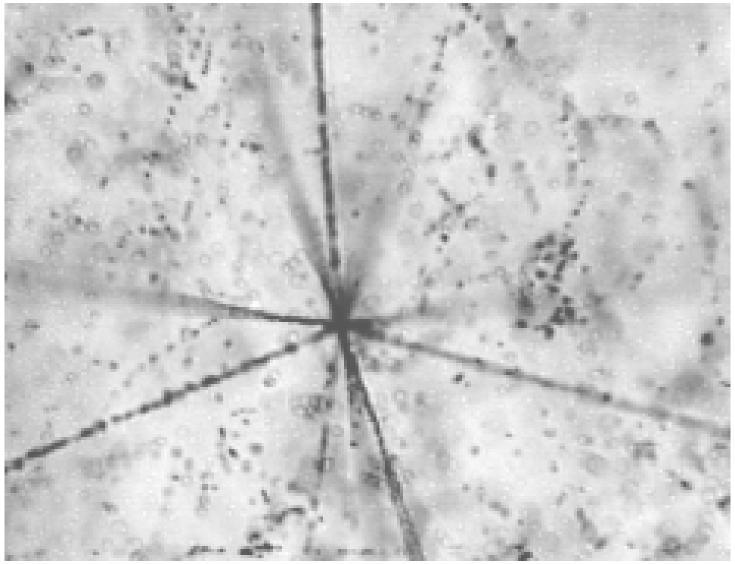
OPERA Target: Lead/Emulsion Bricks



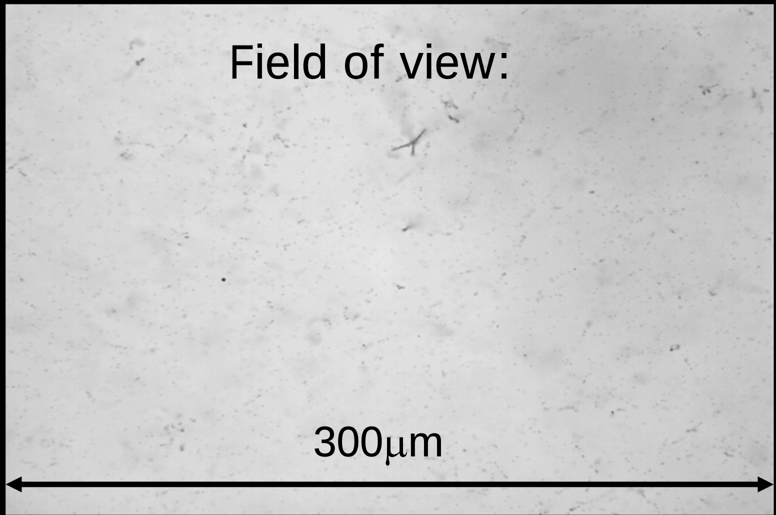
Lead/Emulsion Brick
(total ≈ 200000)



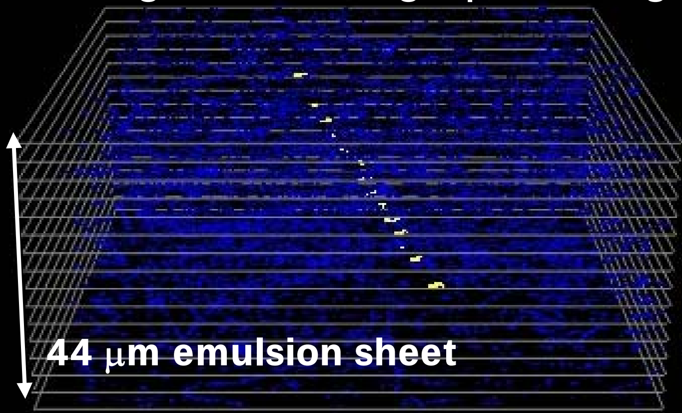




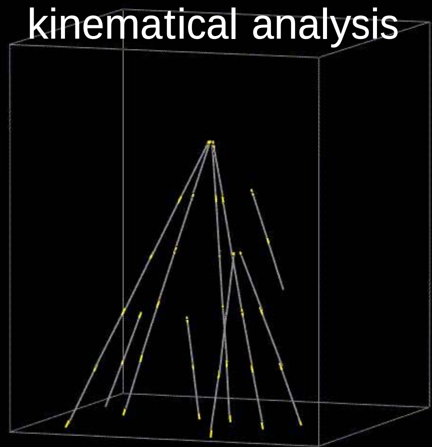
Scanning



2d image: 16 tomographic images



Vertex reconstruction &
kinematical analysis

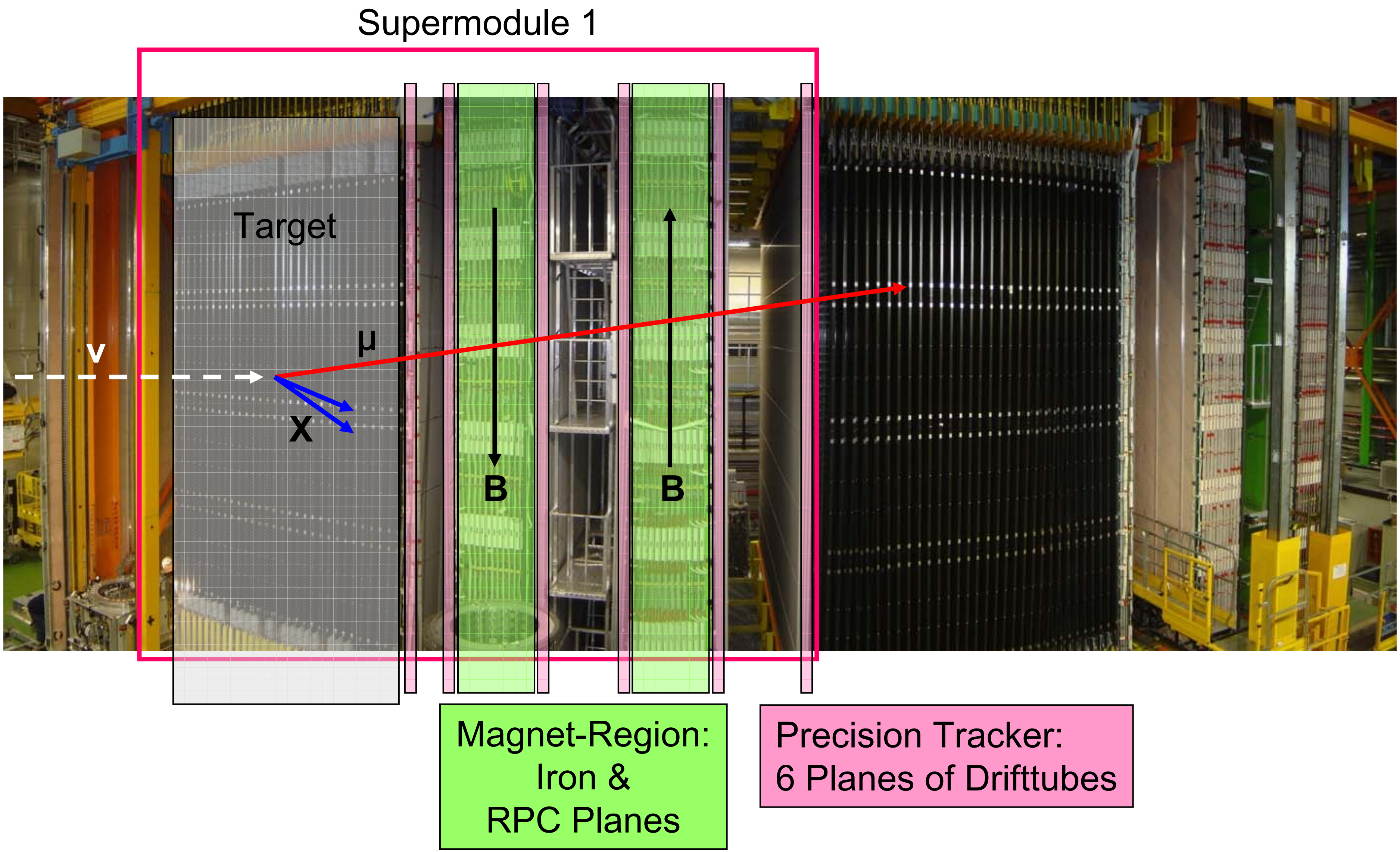


OPERA - Detector

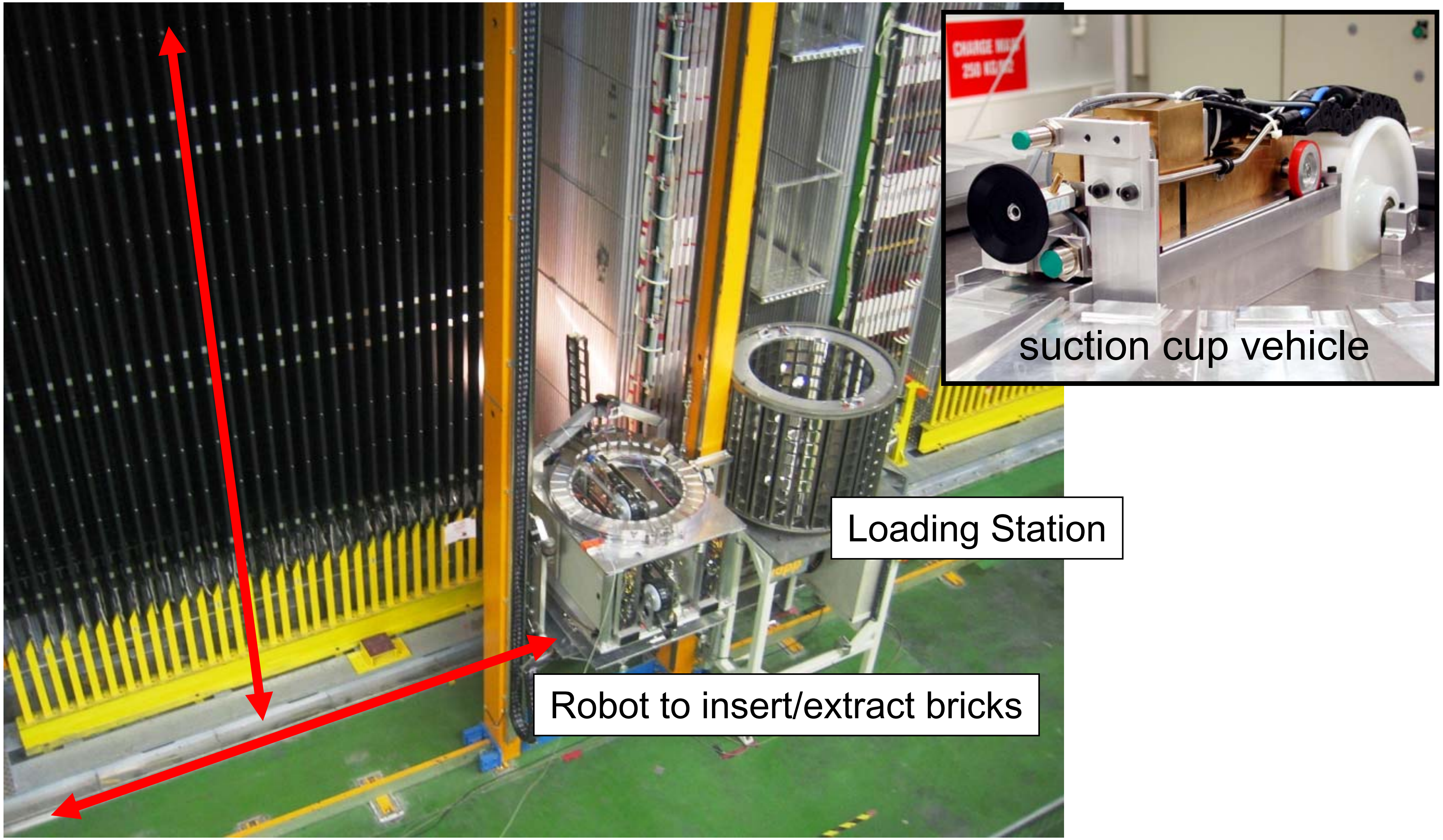
Supermodule 1

Target Region:
- Target Tracker (Scintillator)
- Lead/Emulsion Bricks (100.000 per Supermodule)

OPERA - Detector



OPERA – Brick Manipulating System



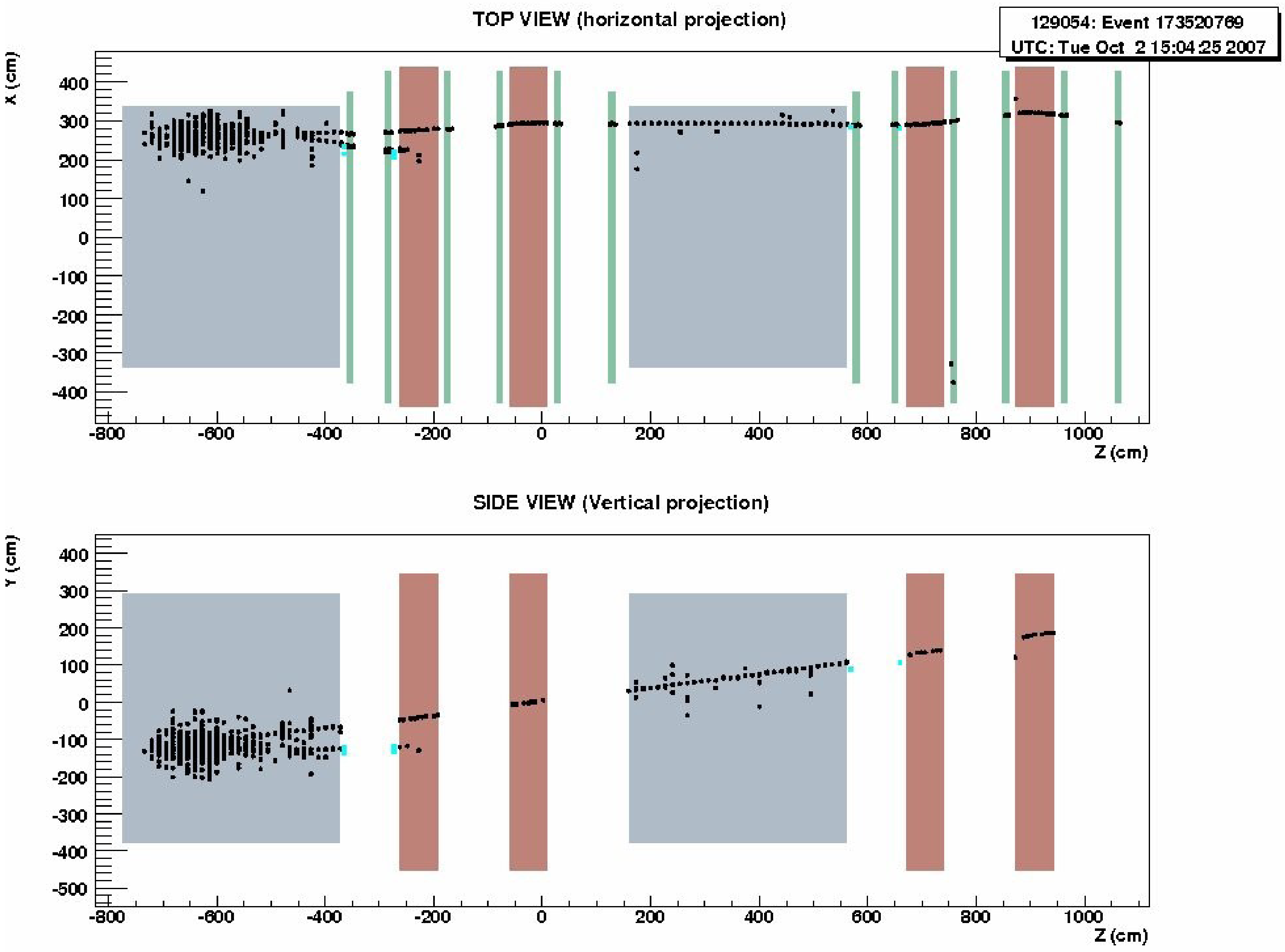
OPERA Sensitivity

OPERA: 6200 ν_μ CC+NC /year
19 ν_τ CC/year (for $\Delta m^2 = 2 \cdot 10^{-3}$ eV^2)

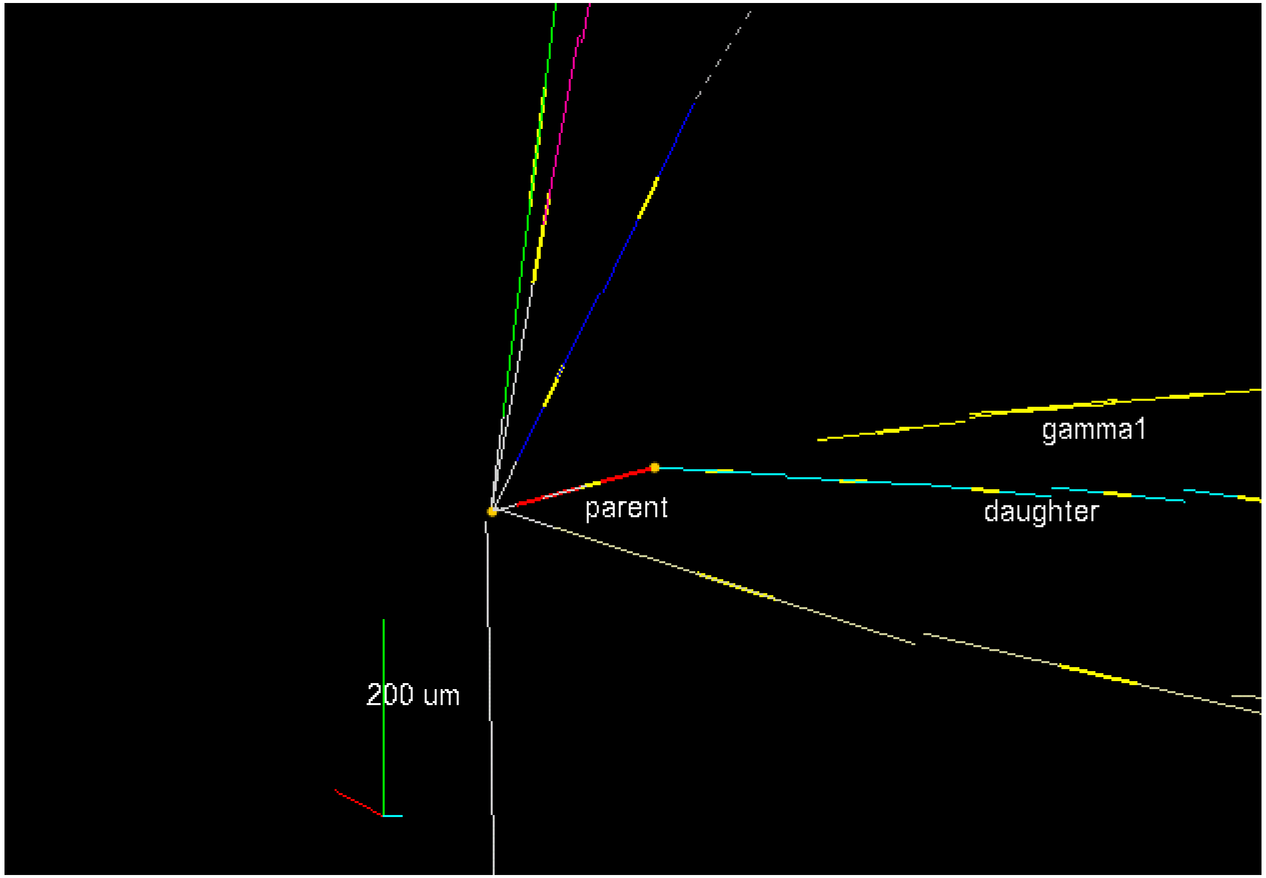
	$\Delta m^2 = 1.9 \times 10^{-3} eV^2$	$\Delta m^2 = 2.4 \times 10^{-3} eV^2$	$\Delta m^2 = 3.0 \times 10^{3} eV^2$	BKGD
ν_τ in OPERA	6.6	10.5	16.4	0.7

exposure: 5 years @ 4.5 x10^{19} pot / year

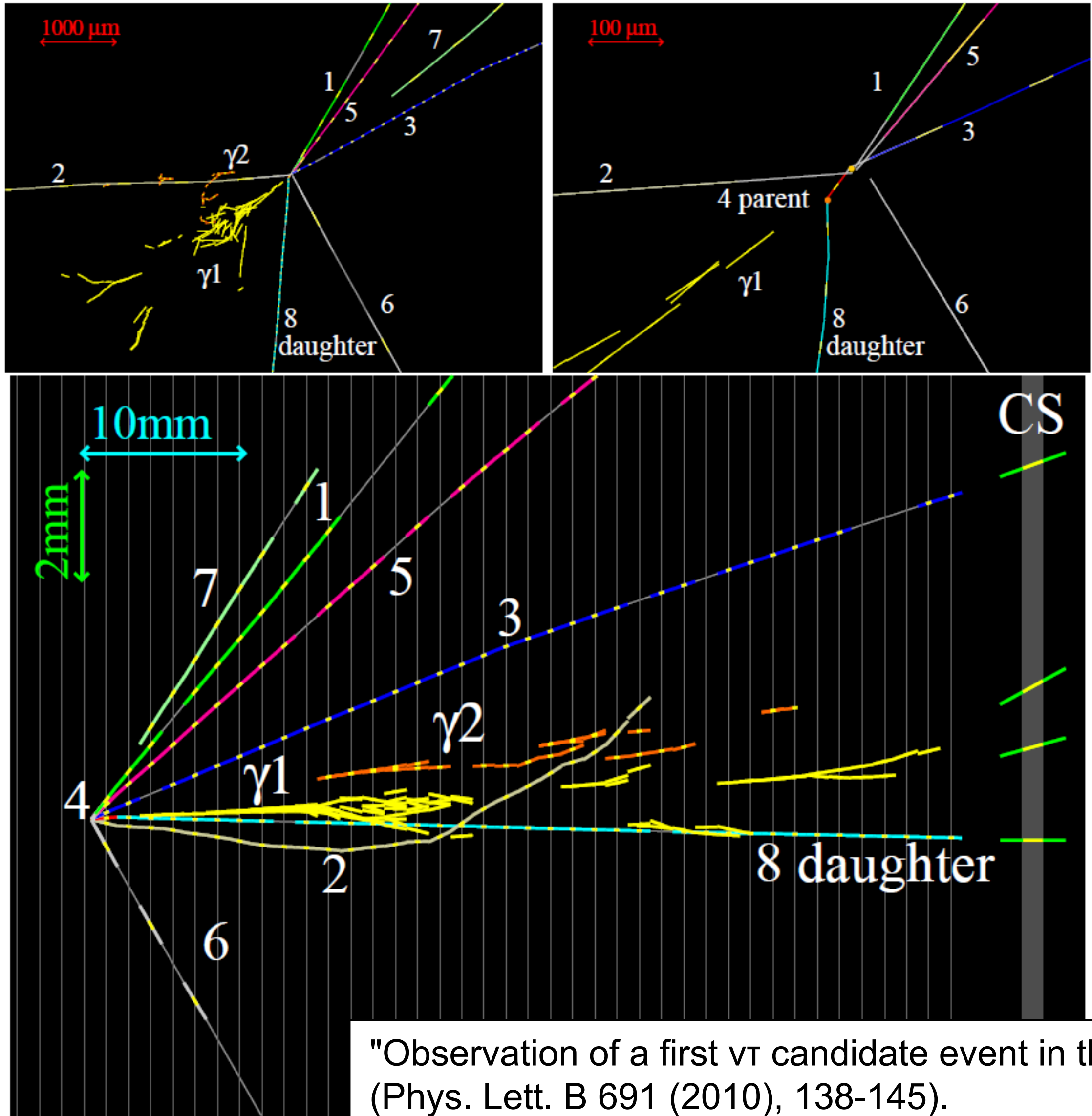
OPERA Event (ν_μ CC)



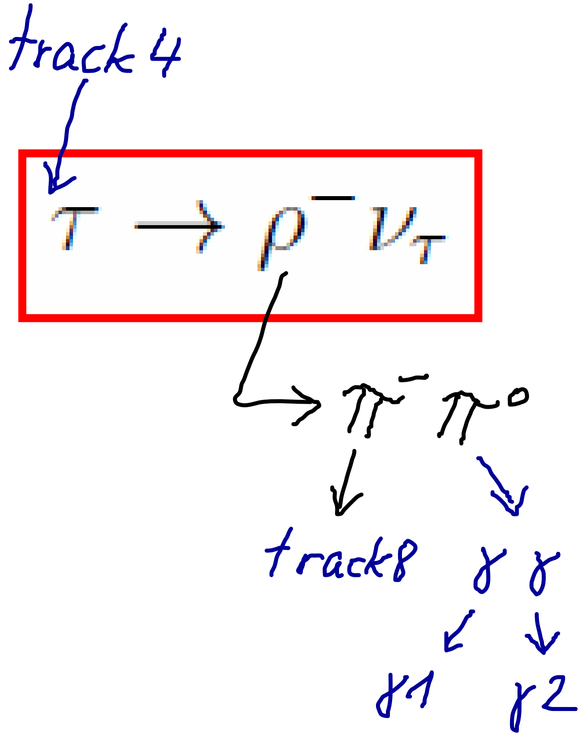
May 2010: OPERA finds 1st ν_τ Event!



OPERA 1st ν_τ Event



Track 4: Kink after 1335µm daughter track 8



"Observation of a first ντ candidate event in the OPERA experiment in the CNGS beam" (Phys. Lett. B 691 (2010), 138-145).

Now we look at electron neutrinos

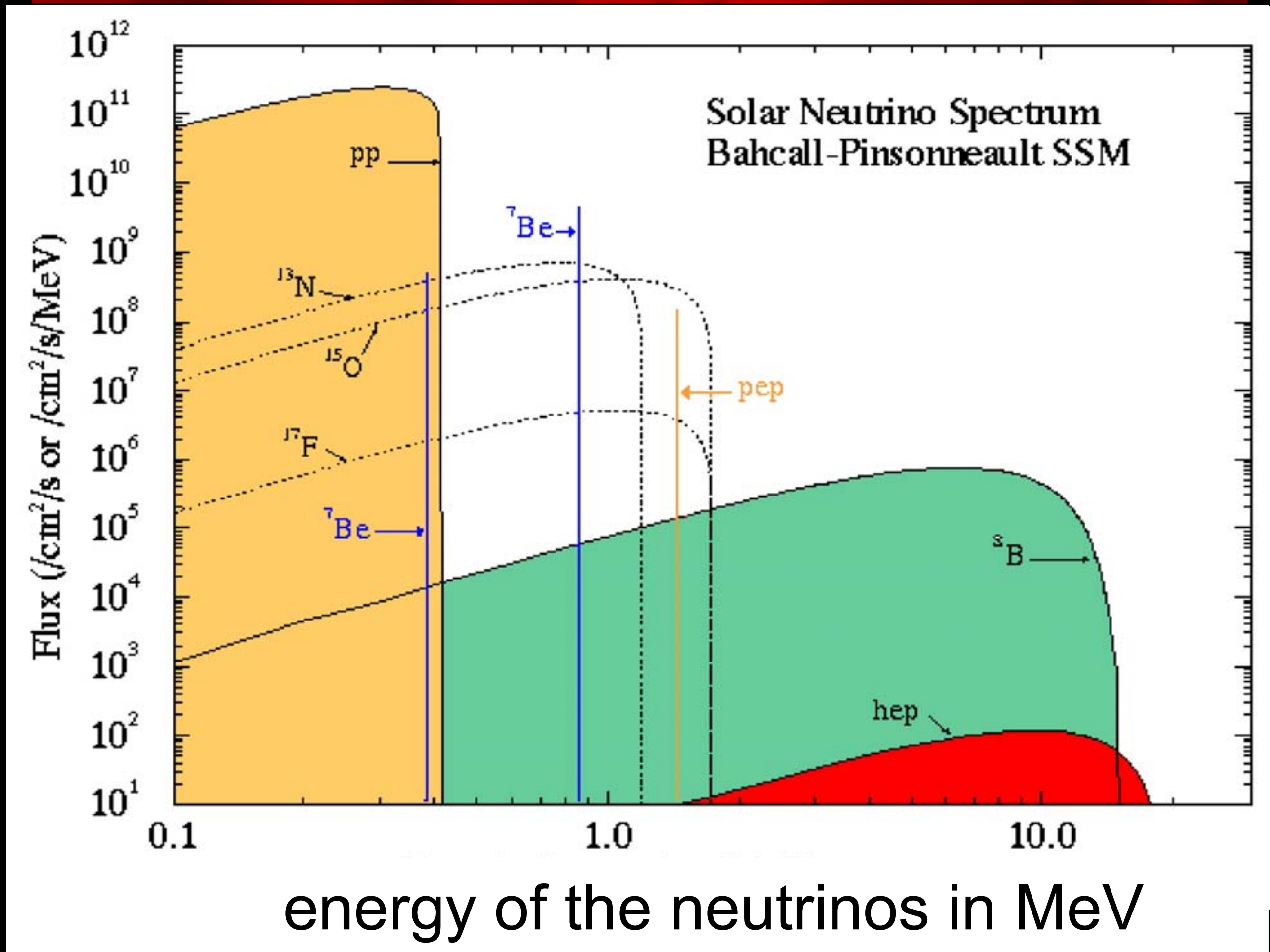
- Electron neutrino sources are:
  The Sun (neutrinos)
  Nuclear reactors (anti-neutrinos)

- These neutrinos have energies of a few MeV

- completely different detection techniques necessary!

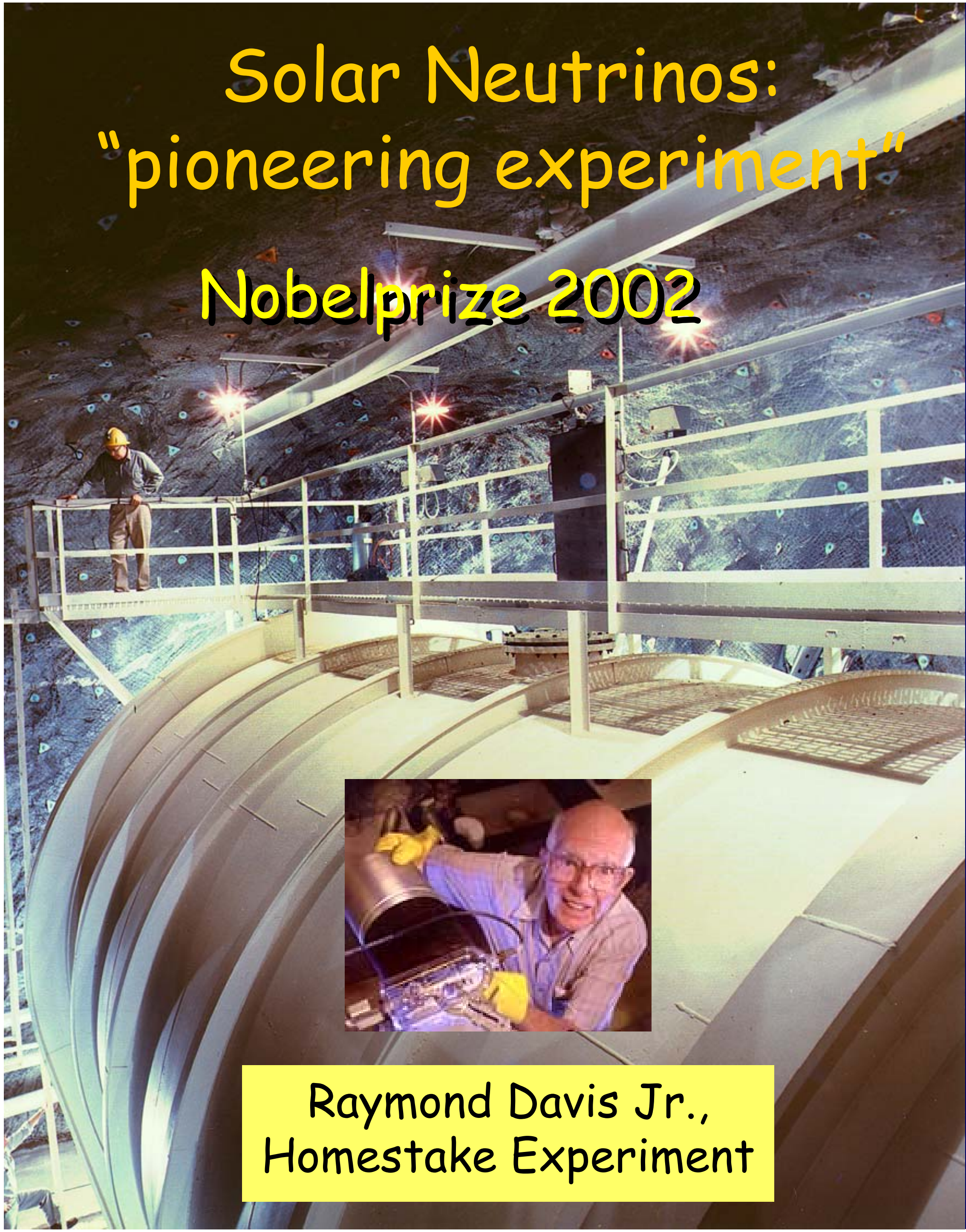
Solar Neutrinos ($E_\nu \approx$ MeV)

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



Solar Neutrinos: "pioneering experiment"

Nobelprize 2002



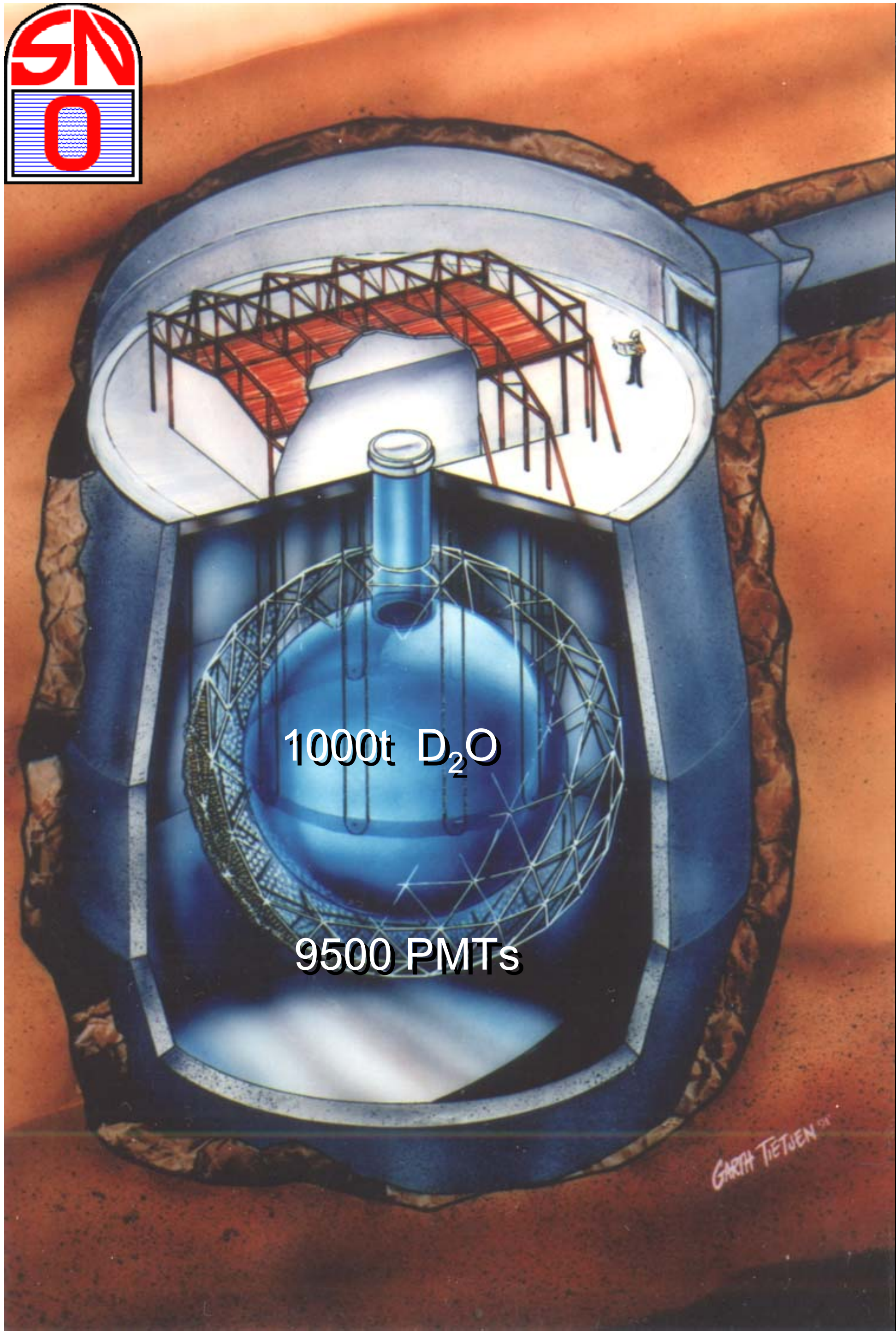
Raymond Davis Jr., Homestake Experiment

Since≈1970

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

E_ν > 814 keV

R_{exp} = 0.34 × SSM


1000t D_2O
9500 PMTs


Creighton Mine (Nickel)
Sudbury, Canada

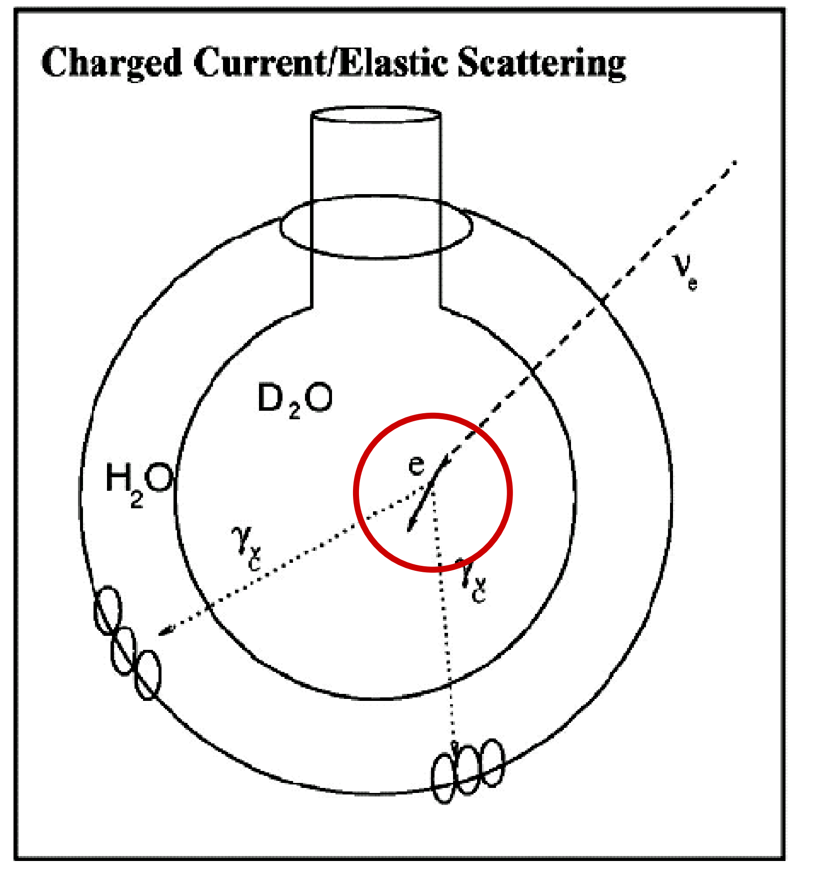

Depth 2070m

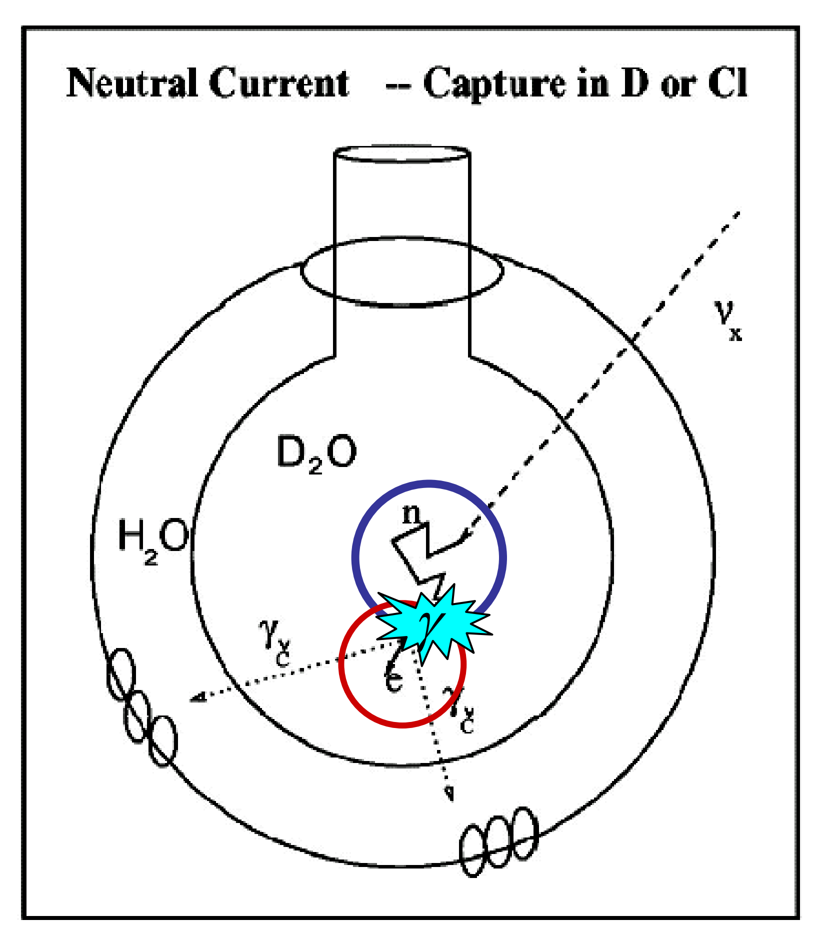
Neutrino detection in SNO

CC $\nu_e + d \rightarrow p + p + e^-$

ES $\nu_e + e^- \rightarrow \nu_e + e^-$

NC $\nu_x + d \rightarrow p + n + \nu_x$





SNO Result (salt-phase)

(PRL 92, 181301, 2004)

$$\phi(^8B)_{meas} = (0.88 \pm 0.04\,(exp) \pm 0.23\,(th)\,)\ \phi(^8B)_{SSM}$$

- 1/3 of solar ν_e arrive as ν_e on Earth
- 2/3 of solar ν_e arrive as ν_μ or ν_τ .
- Measured total flux = Predicted flux
  (Standard Solar Model)

Parametrisation of Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

- 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- 1 Dirac-phase (CP violating): δ

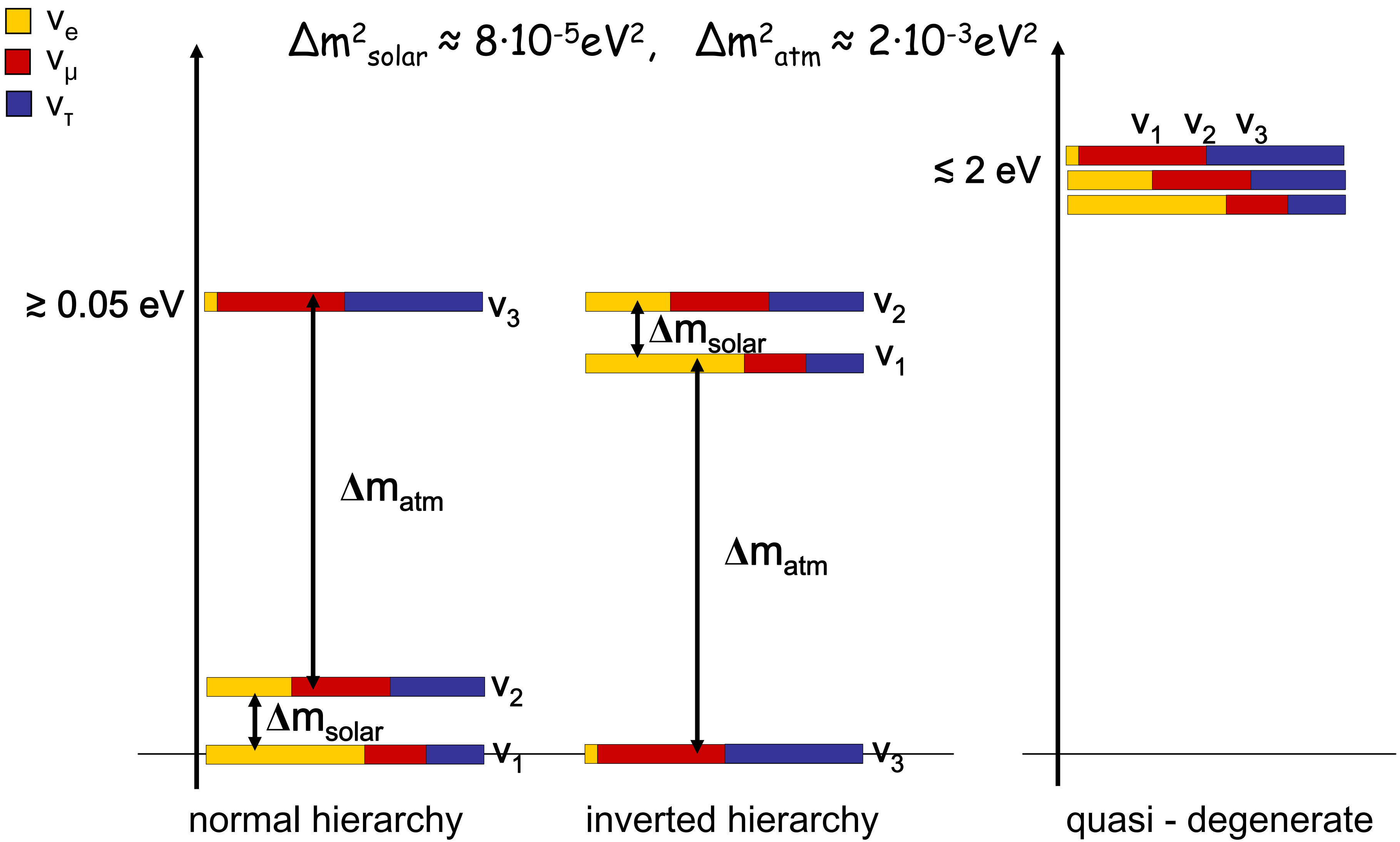
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{atm} | θ_{13}, δ | θ_{sol}

Θ_{23}: 34° - 58° | θ_{13}<13°, δ ? | θ_{12}: 29° - 39°

What do we know about neutrino masses?

$$\Delta m^2_{solar} \approx 8\cdot 10^{-5} eV^2, \quad \Delta m^2_{atm} \approx 2\cdot 10^{-3} eV^2$$



Summary of Neutrino Oscillations

- Neutrino Oscillations have been observed with solar, atmospheric, reactor and accelerator neutrinos.
- Neutrinos have mass!
  The absolute neutrino mass has not yet been measured, allowed range: 0.05 eV < m_ν < 2 eV
- Neutrino mixing exists and is very different from quark mixing. Why?
- Measurements of third mixing angle have been started
- Is there CP-violation for neutrinos?
- Is the neutrino a Majorana particle?
  Search for neutrinoless Double-Beta Decay (Evidence?)

Many interesting results expected in next years
Many questions still waiting to be solved by some of you!