Neutrino Physics

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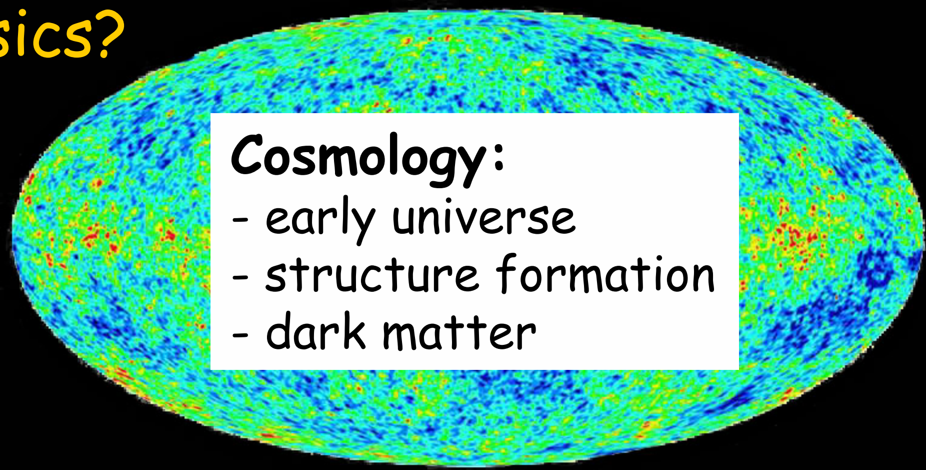
Part 1:
- What are neutrinos?
- Neutrino interactions, sources and detectors
- Neutrino oscillations
- Oscillations of atmospheric neutrinos
- Neutrino beams
- Oscillation of accelerator neutrinos

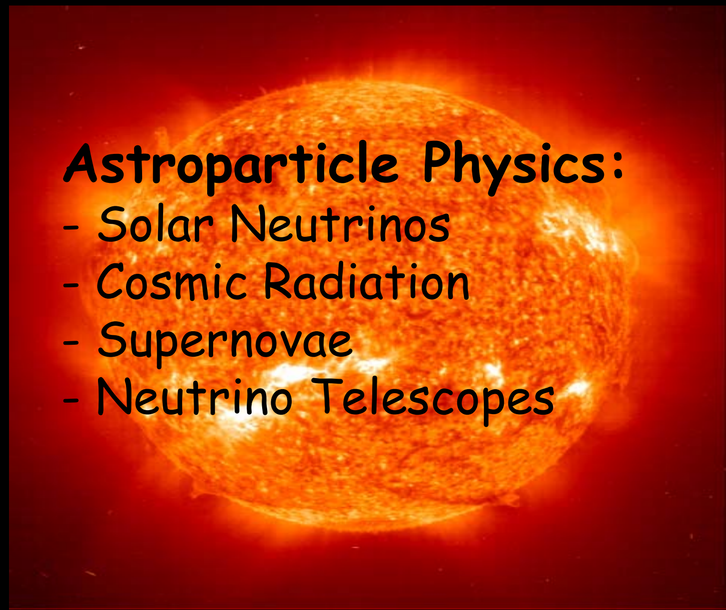
Part 2:
- Solar neutrinos
- Oscillation of solar neutrinos
- KamLAND reactor neutrino experiment
- Future solar neutrino experiments

Why are we doing Neutrino Physics?



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

Neutrino Physics



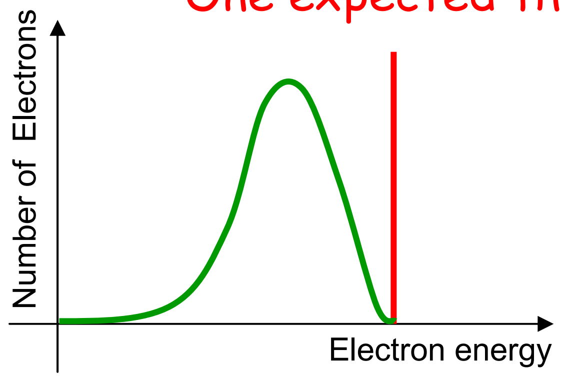
Wolfgang Pauli postulates the Neutrino (1930)

Energy spectrum of electrons from β-decay

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

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

One expected this



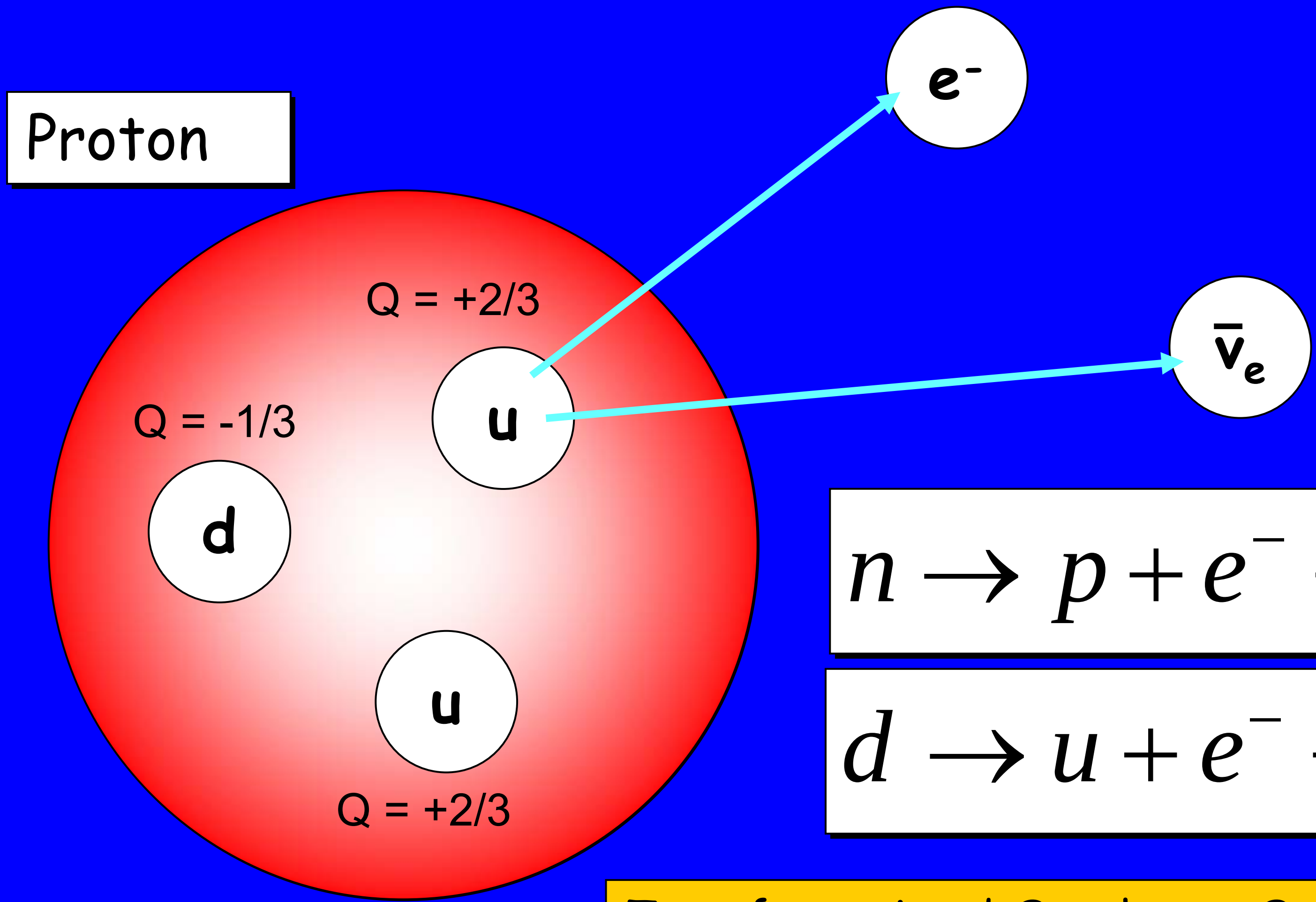
But this was observed!

Solution:
The Neutrino

1922 Assistant at Universität Hamburg

1924 Habilitation in Hamburg (Discovery of the Exclusion Principle)

Decay of the Neutron - Birth of a Neutrino

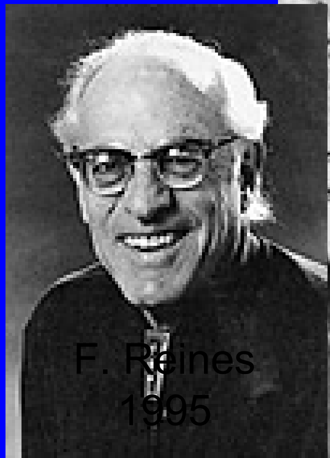


$$n \rightarrow p + e^- + \bar{\nu}_e$$

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

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

First Detection of a Neutrino: 1956



F. Reines
1995

Fredrick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

Cowan und Reines

- Neutrino source: Nuclear reactor
- Detection Method: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Detector: Scintillator, PMT's

Neutrino History

- 1930: neutrino postulated by Pauli
  (massless, neutral)
- 1956: neutrino ν_e detected by
  Reines and Cowan (Nobel prize 1995)
- 1962: Discovery of ν_μ at AGS in Brookhaven by
  Ledermann, Schwartz and Steinberger
  (Nobel prize 1988)
- 1975: neutrino ν_τ postulated after τ lepton was discovered
  by M. Perl et al.
- 2000: First direct detection of ν_τ by the DONUT experiment
  (Fermilab)

- ~ 1995: LEP measurement of Z^0 decay width:
  $\rightarrow$ 3 active neutrino flavors (m_ν < 80 GeV):
  $N_\nu = 3.00 \pm 0.06$
  ν_e, ν_μ, ν_τ

Fundamental Particles

Quarks:

u c t

d s b

Leptons:

ν_e ν_μ ν_τ

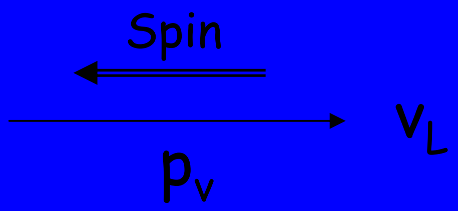
e^- μ^- τ^-

Interactions by exchange of bosons:

Graviton Photon Gluon W,Z

Neutrino Properties

- Neutral
- Fermions with Spin $\frac{1}{2}$
- In the Standard Model:
  massless, stable, always left handed!

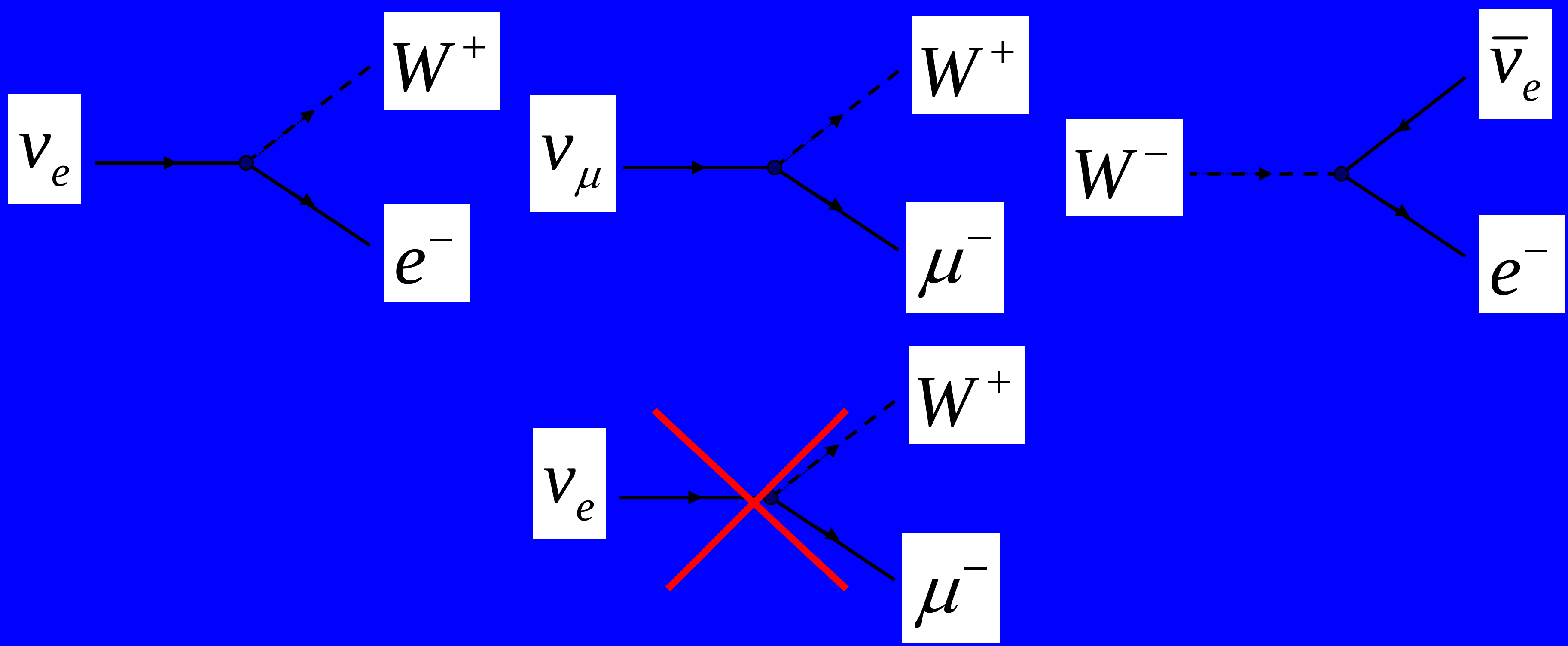


- **BUT:** Today we know that neutrinos have mass
  $0.05\ \mathrm{meV} < m_\nu < 2\ \mathrm{eV}$
  Standard Model must be extended!
- Are Neutrinos and Anti-Neutrinos identical?
- many other properties are still unknown:
  sterile neutrinos?, CP-violation?, neutrino decay?,
  magnetic moment?...

How Neutrinos interact

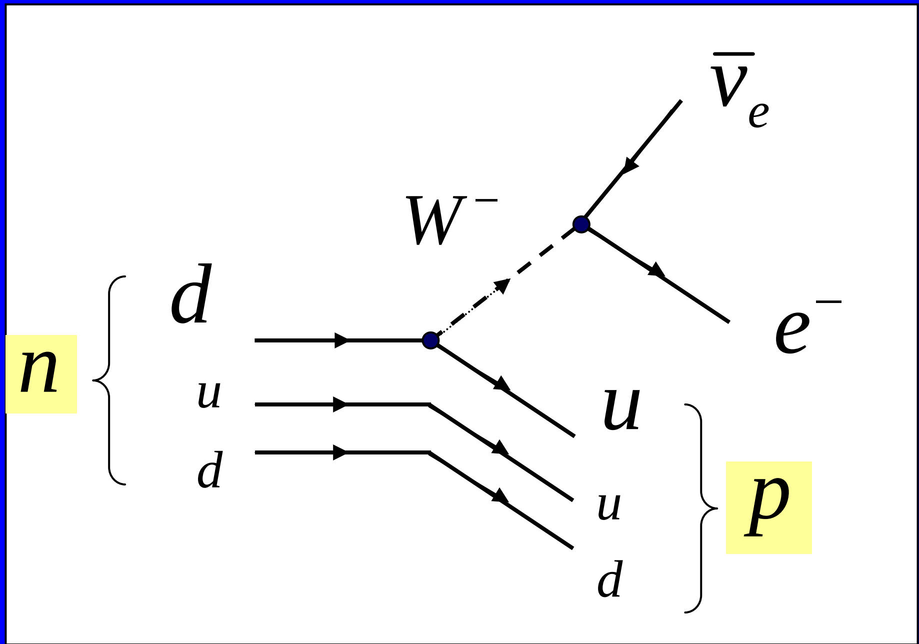
- The weak interaction

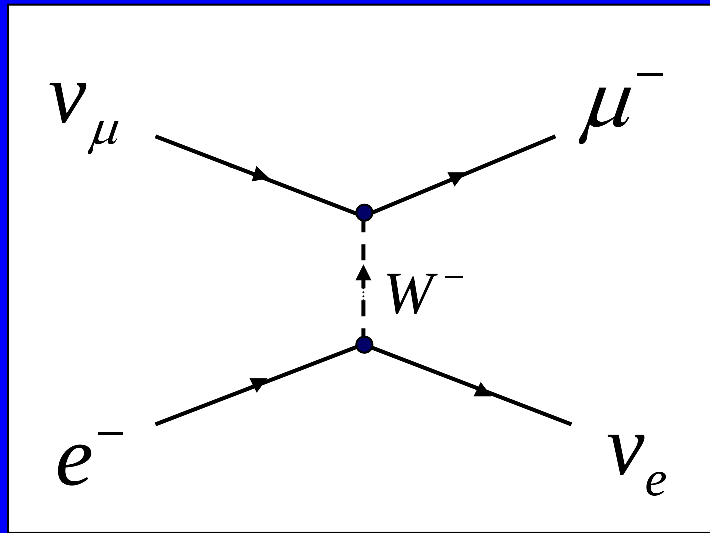
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

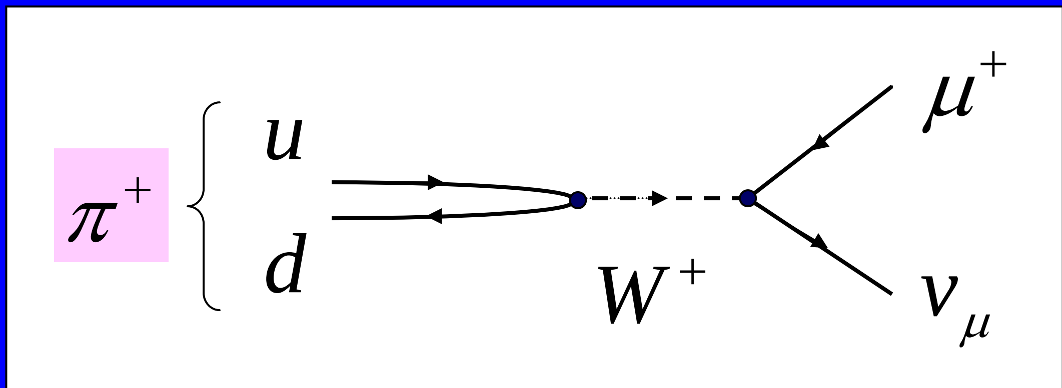


Charged Current

- Exchange of a W Boson:

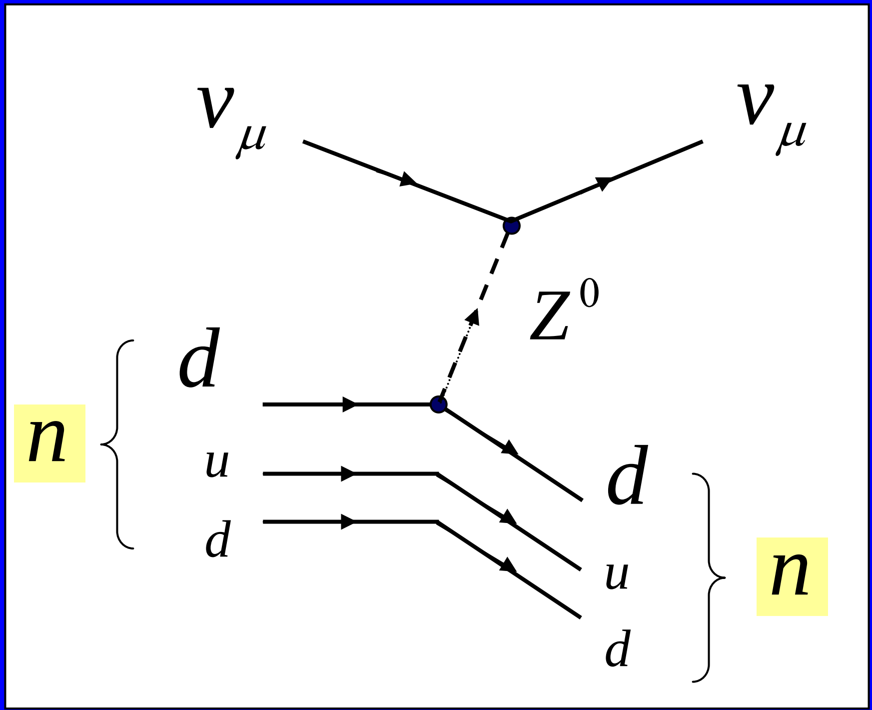


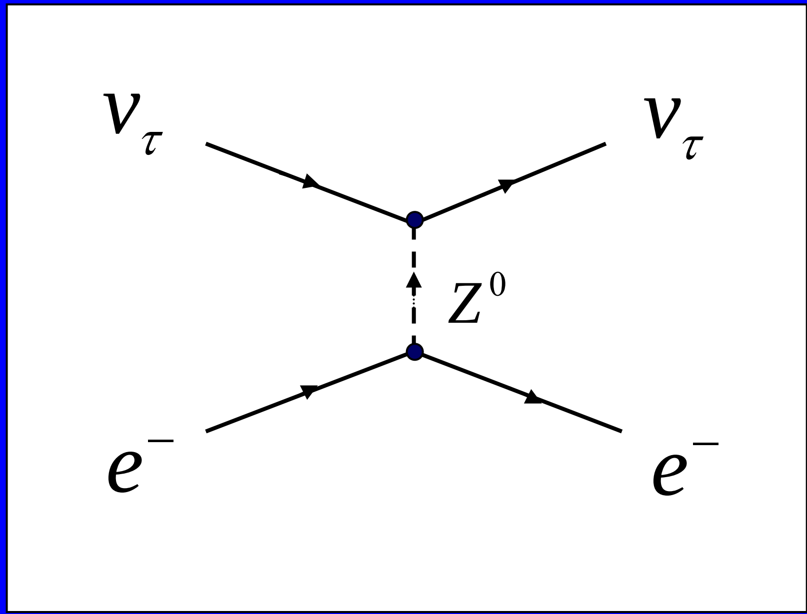




Neutral Current

- Exchange of a Z^0 Boson:





Sources of Neutrinos

- Nuclear Reactors (Energy ~ MeV, Anti-ν_e)
  β-decay of neutron rich fission fragments
- Neutrino Beams (Energy ~ 1 – 100 GeV, ν_μ):
  from decaying pions
- Solar Neutrinos (Energy ~ MeV, ν_e):
  from thermonuclear fusion reactions
- Atmospheric Neutrinos (Energy ~ 1 – 100 GeV):
  from decaying pions and muons (cosmic radiation)
- Neutrinos from Supernovae (Energy 10-30 MeV):
  emitted after gravitational collapse of a star
- Cosmic Neutrino Background (Energy 10^{-4}eV = 1.9K)

Neutrino Detection

- Problem: Weak(!) Interaction
  cross sections are of order $10^{-40}cm^2$

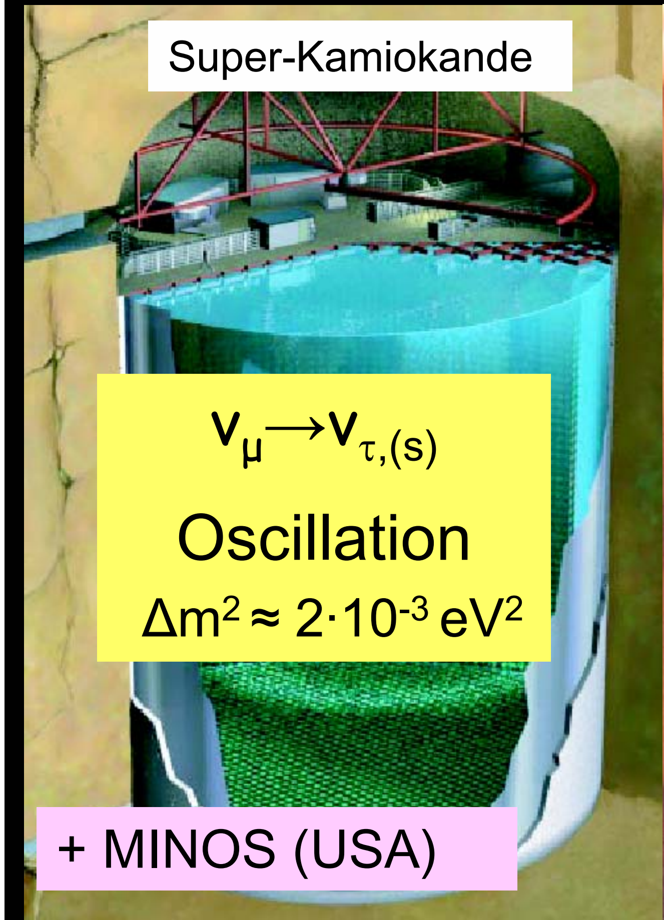
- Huge detectors needed:
  10 ton scintillator (near nuclear reactors)
  1000 ton scintillator (200 km from nuclear reactors)
  2 kton Pb/emulsion (for ν_τ detection)
  50 kton water (for solar, atmospheric, supernova ν's)
  1 Mton water (precision neutrino physics, CP-violation)
  1 km^3 water or ice (high energy neutrino astronomy)

- Detectors must be shielded against cosmic radiation:
  deep underground (1000 – 5000 mwe)
  deep underwater (2000 – 4000m)

Gran Sasso Unterground Lab LNGS

Neutrino Oscillations were observed
→ Neutrinos have mass!

JAPAN

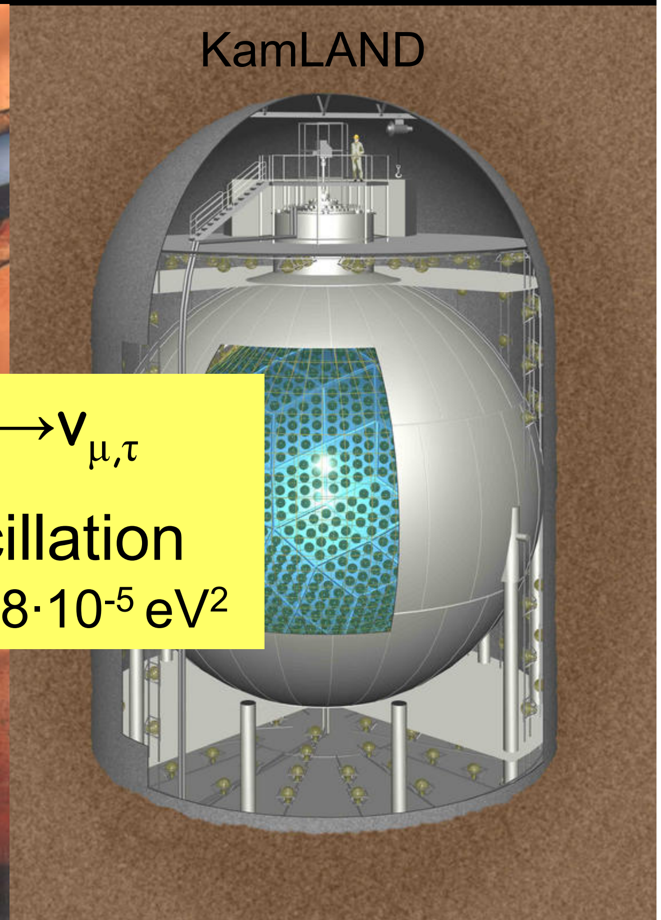


atmospheric neutrinos
accelerator neutrinos

CANADA

solar neutrinos

JAPAN



reactor neutrinos

Neutrino Oscillations
are a consequence of

neutrino mass and mixing

Quark and Lepton Mixing:

Eigenstates of weak interaction ≠ Eigenstates of mass

Neutrino - Mixing

mass eigenstates

$\sum \nu_1, \nu_2, \nu_3$ $\sum \nu_1, \nu_2, \nu_3$ $\sum \nu_1, \nu_2, \nu_3$

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

$\sum d, s, b$ $\sum d, s, b$ $\sum d, s, b$

mass eigenstates

Quark - Mixing

Quark-Mixing

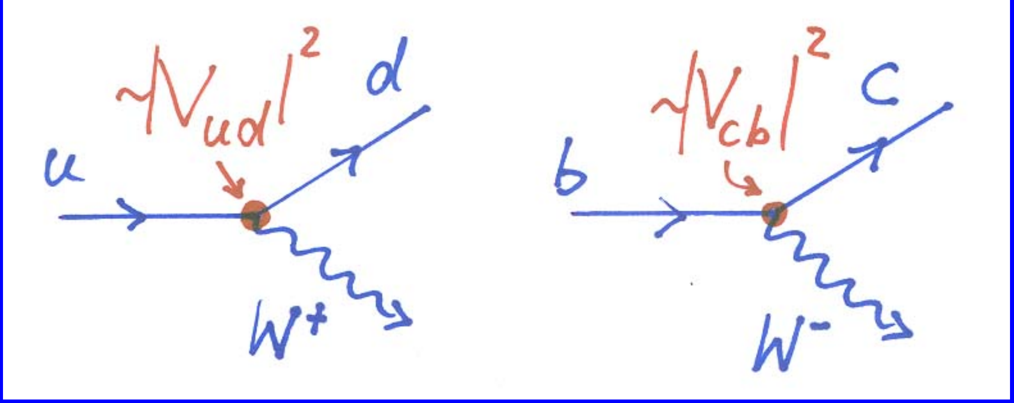
$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

Cabbibo-Kobayashi-Maskawa (CKM) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \boxed{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- 3 mixing angles
- 1 phase: $e^{i\delta}$
  CP-violation

BELLE,
BABAR,
CLEO,...



in precision measurement phase

Neutrino mass and mixing

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

Flavor-Eigenstates ν_e,ν_μ,ν_τ ≠ 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: $|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$

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 $\theta_{23} \approx 45°$:

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

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

Parametrization of Neutrino Mixing

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

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

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

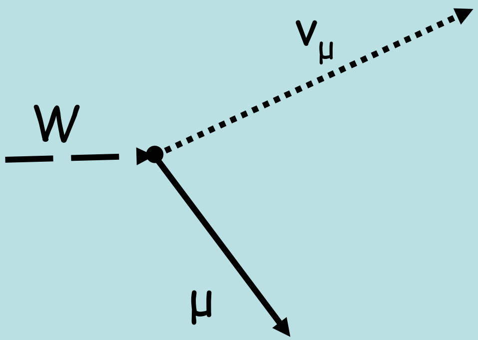
Neutrino Oscillations

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

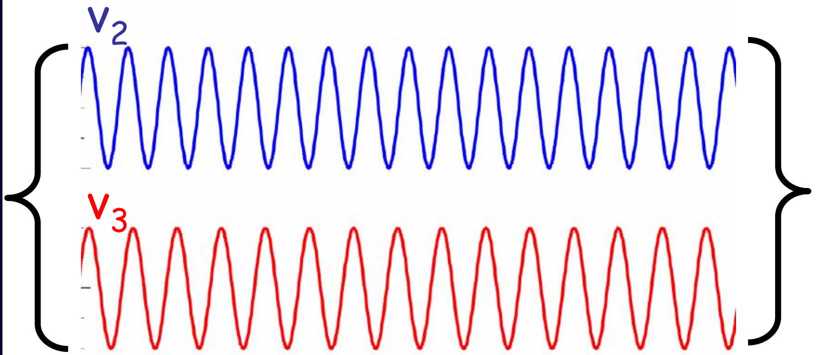
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2, ν_3 with m_2, m_3

source creates flavor-eigenstates



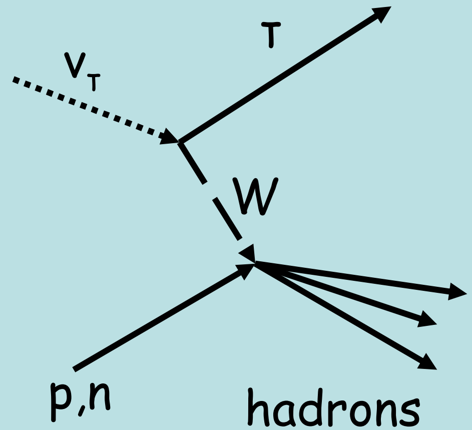
propagation determined by mass-eigenstates



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

slightly different frequencies
→ phase difference changes

detector sees flavor-eigenstates



2 Flavor Neutrino Oscillations

Oscillation probability

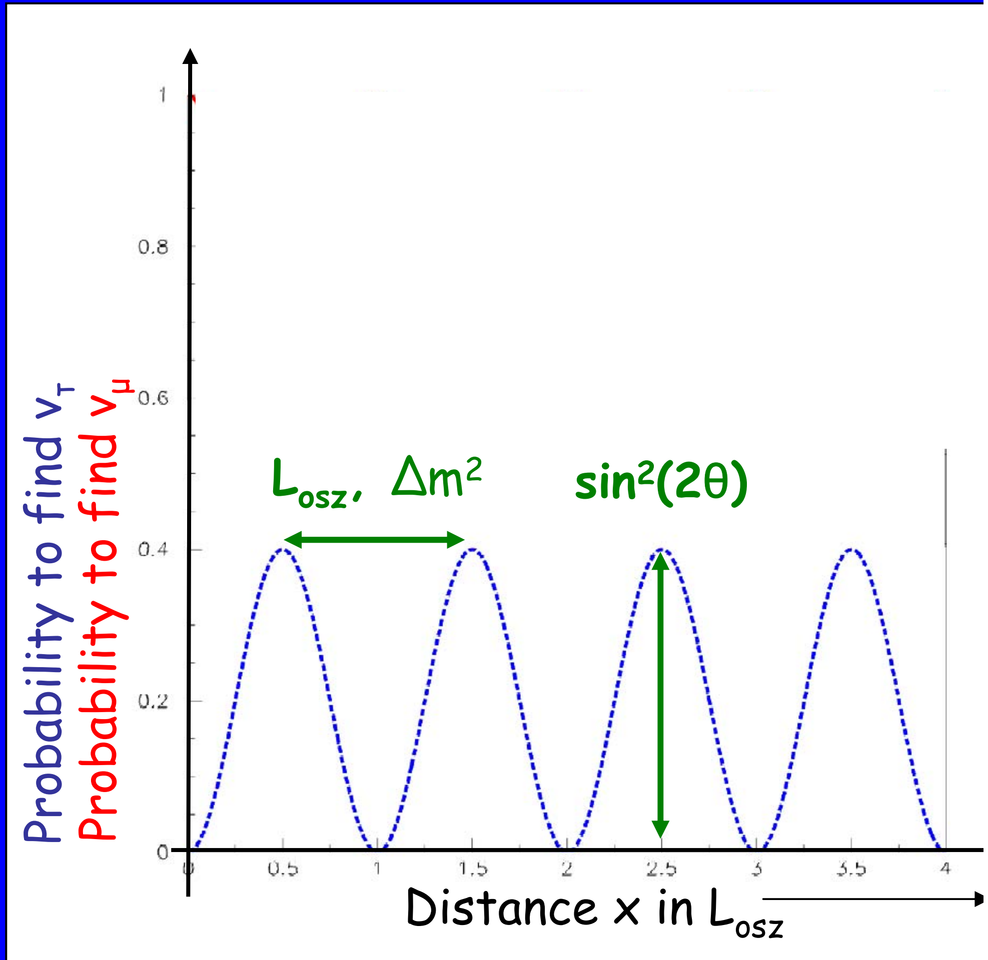
$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

Survival probability

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

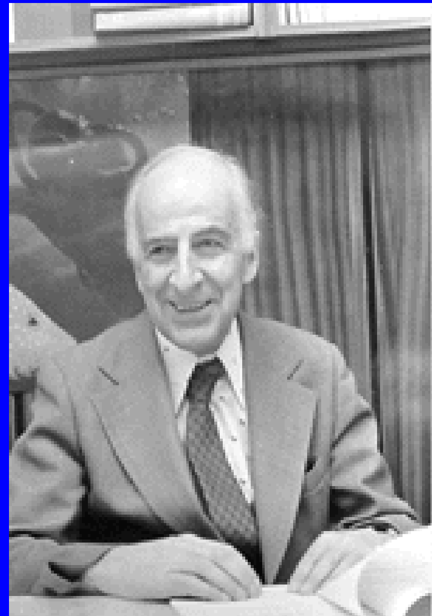
$$L_{osz}(\text{in km}) = \frac{2.48 \cdot E(\text{in GeV})}{\Delta m^2(\text{in eV}^2)}$$

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



Historical Remark

- 1957-58: B. Pontecorvo proposed neutrino oscillations (because only ν_e was known, he thought of $\nu \leftrightarrow$ anti-ν)
- 1962 Maki, Nakagawa, Sakata described the 2 flavor mixing and discussed neutrino flavor transition
- 1967 full discussion of 2 flavor mixing, possibility of solar neutrino oscillations, question of sterile neutrinos by B. Pontecorvo



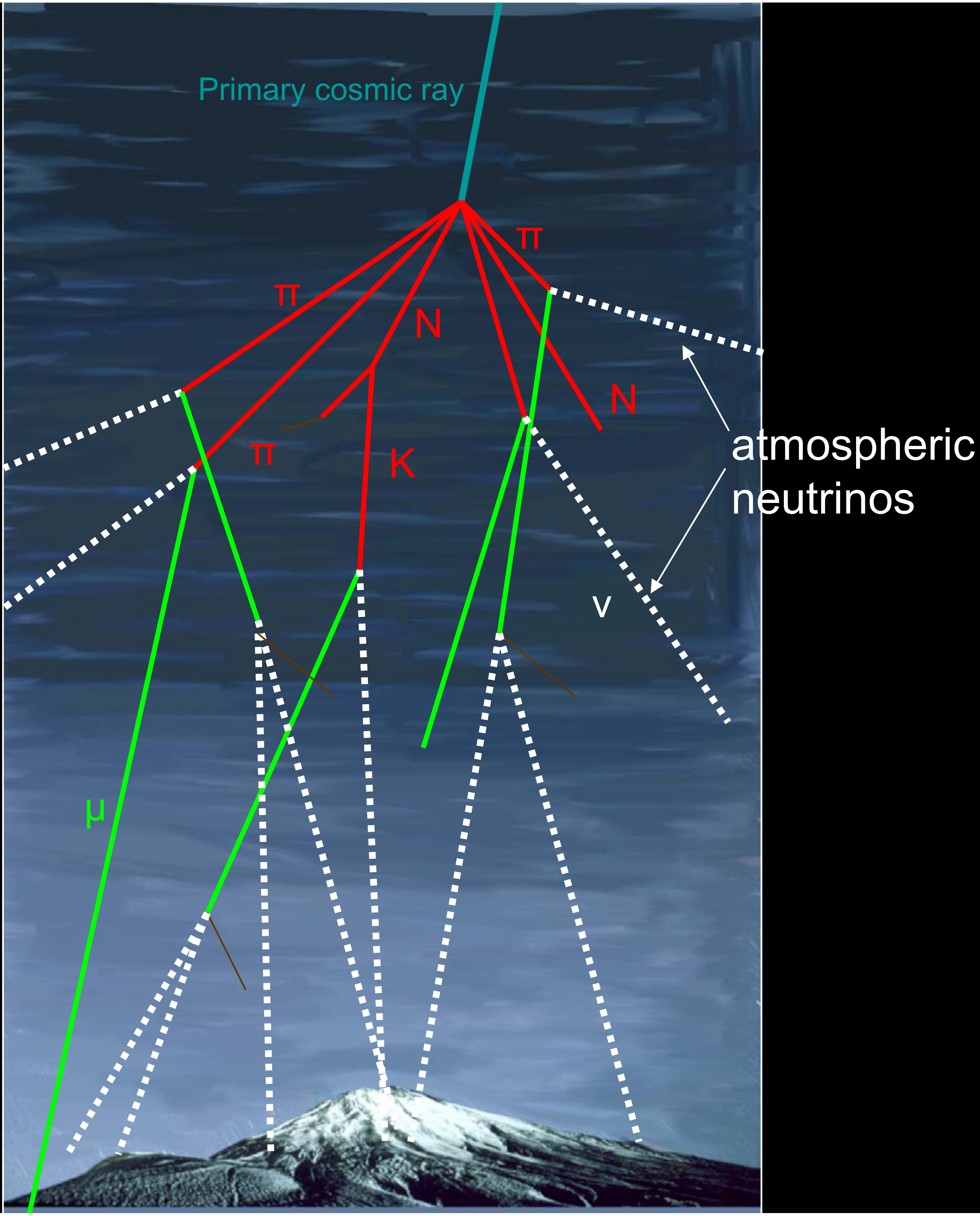
B. Pontecorvo

Neutrino Oscillations (23)

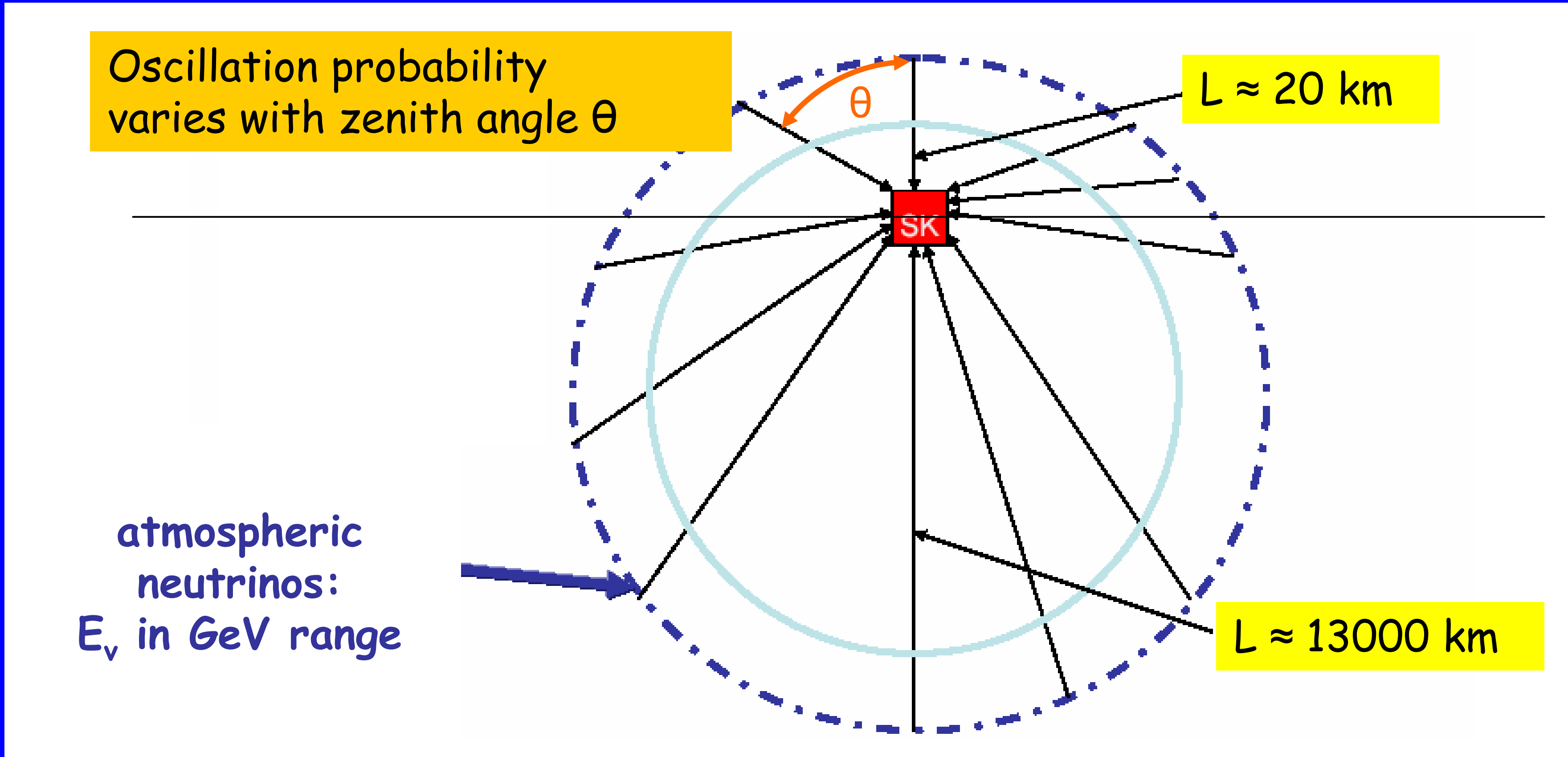
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\nu_\mu \rightarrow \nu_\tau$ Oscillations

Atmospheric neutrinos & accelerator neutrinos


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

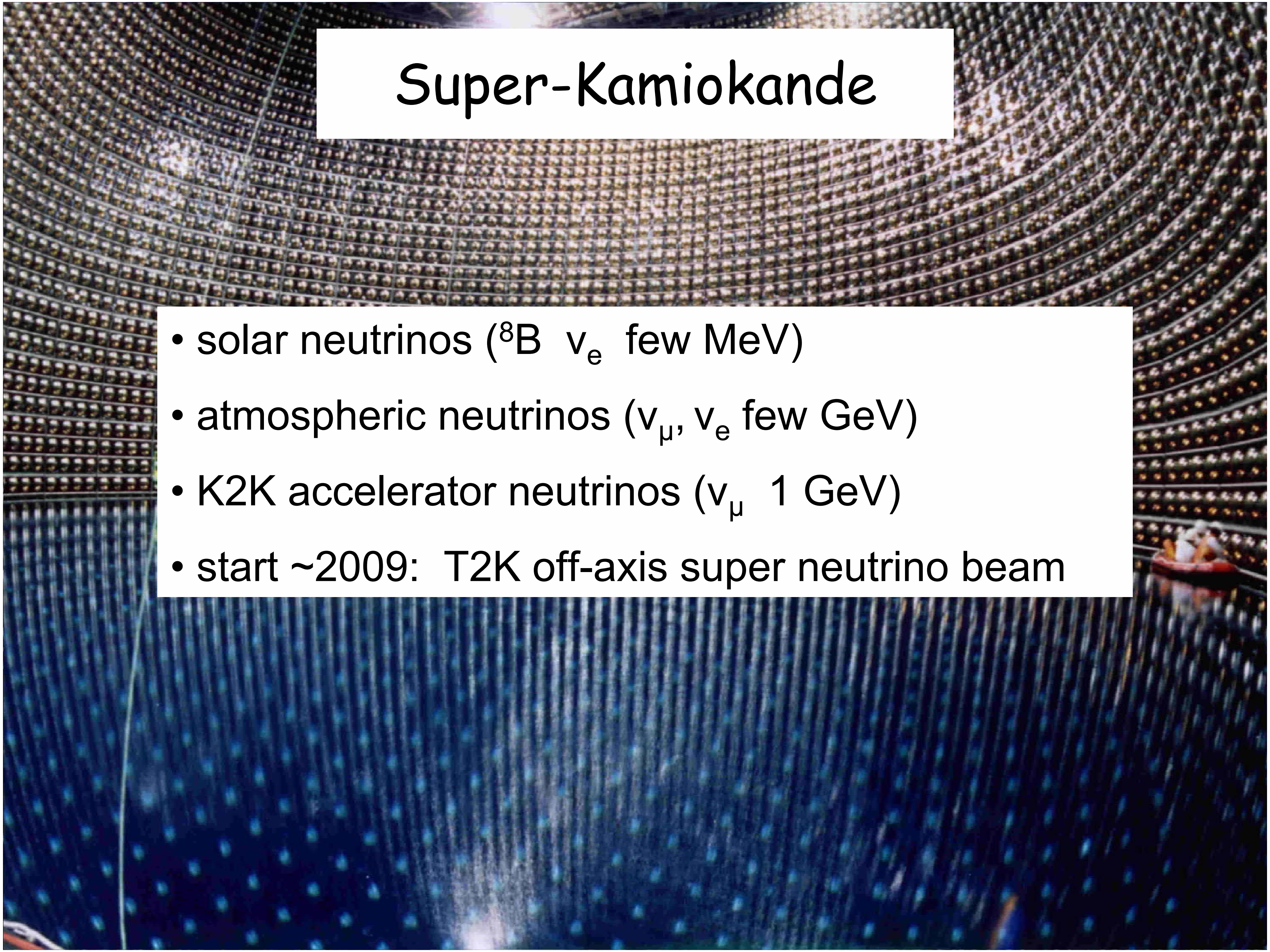
Oscillation of atmospheric neutrinos

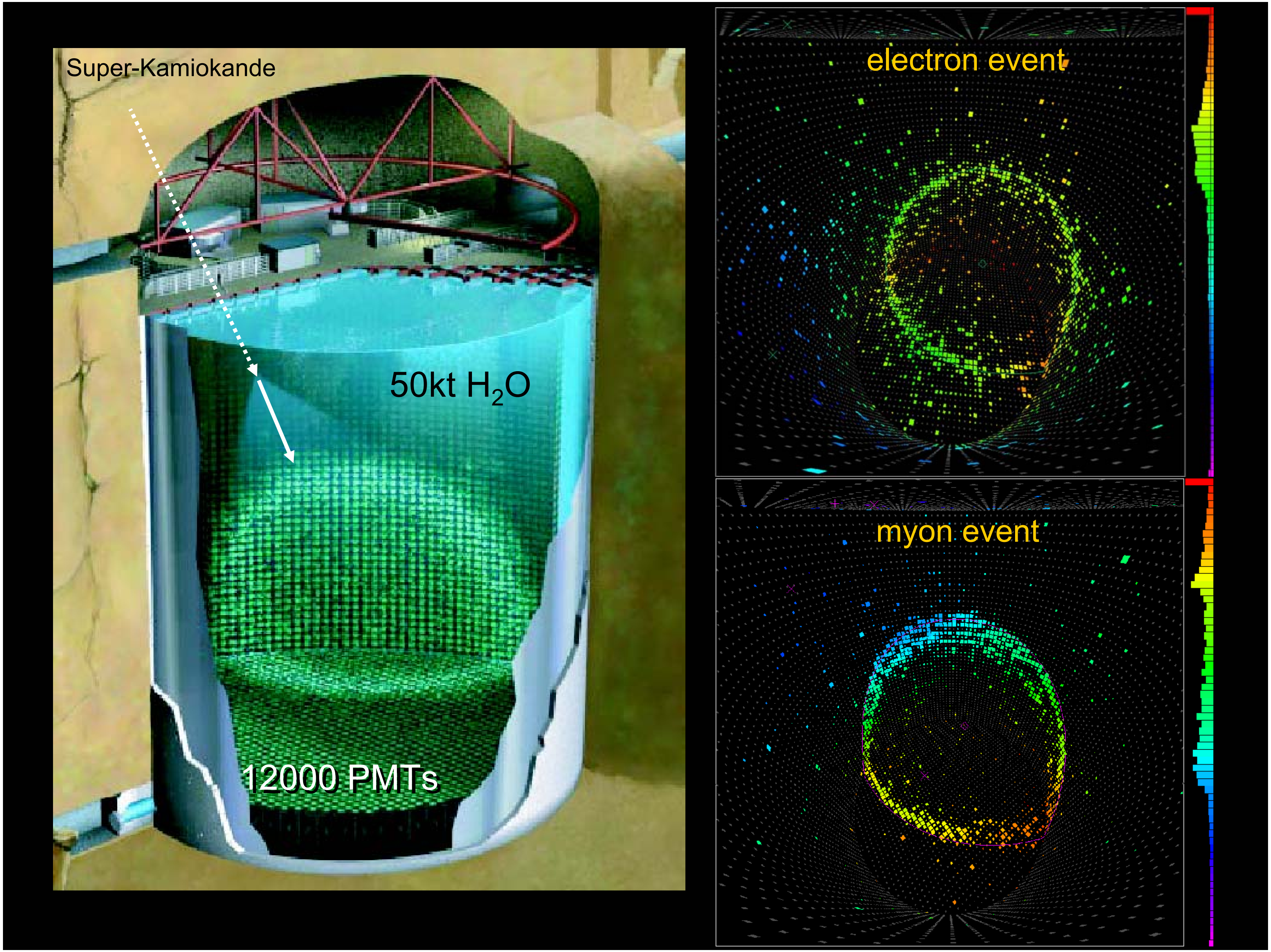


$$P(\nu_\mu \to \nu_x) = \sin^2 2\theta_{atm} \sin^2\left(\frac{1.27\Delta m^2_{atm}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

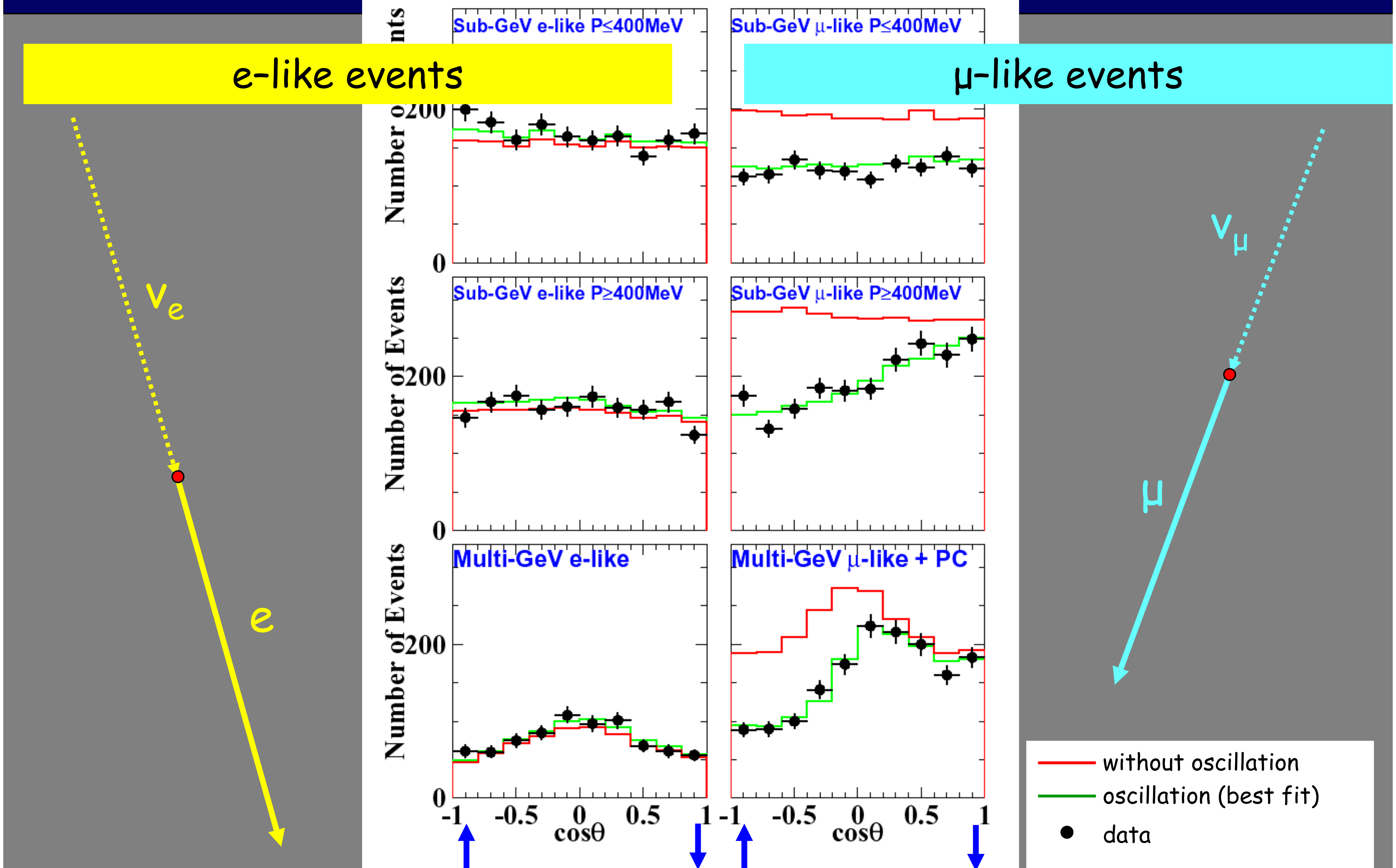
Super-Kamiokande

- solar neutrinos (^8B ν_e few MeV)
- atmospheric neutrinos (ν_μ, ν_e few GeV)
- K2K accelerator neutrinos (ν_μ 1 GeV)
- start ~2009: T2K off-axis super neutrino beam

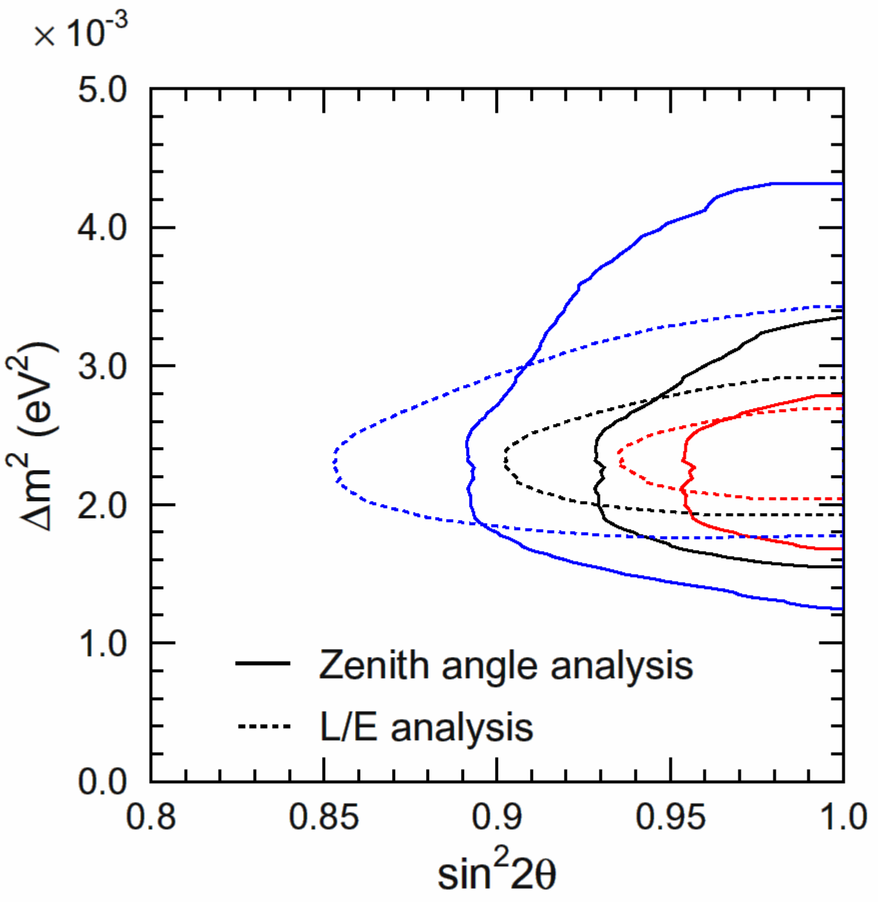



Super-Kamiokande
50kt H_2O
12000 PMTs
electron event
myon event

SuperK - atmospheric neutrinos



Atmospheric Neutrino Results

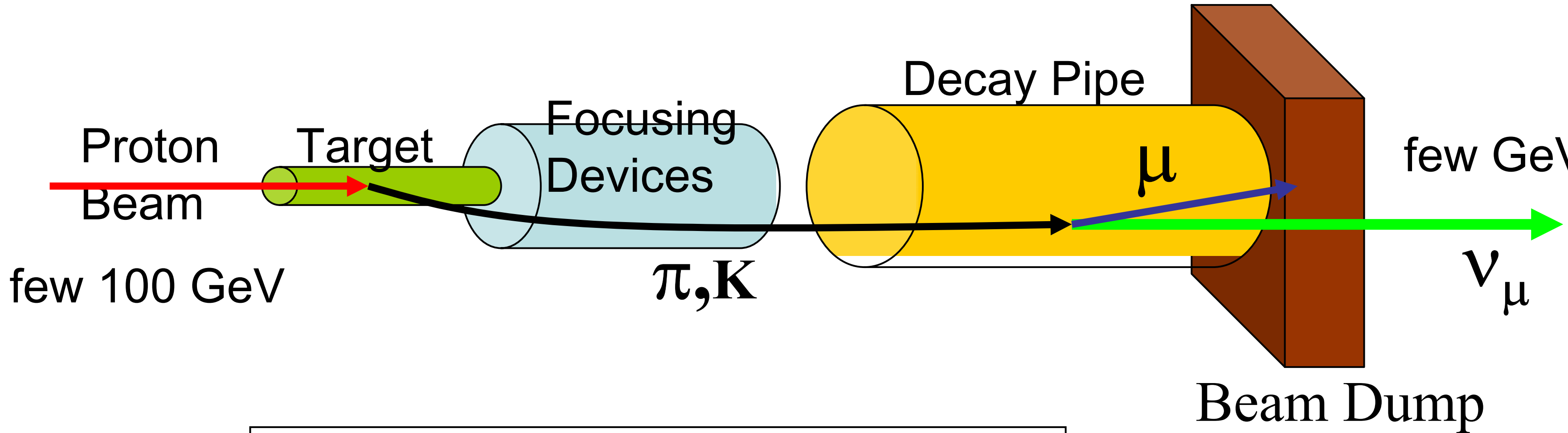


L/E Analysis
(PRL93 (2004) 101801),
Best Fit:
$\sin^2 2\theta = 1.02$
$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2

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

$\sin^2 2\theta > 0.92$
$1.5 \cdot 10^{-3}$ eV$^2 < \Delta m^2 < 3.4 \cdot 10^{-3}$ eV^2

How to make Neutrino beams



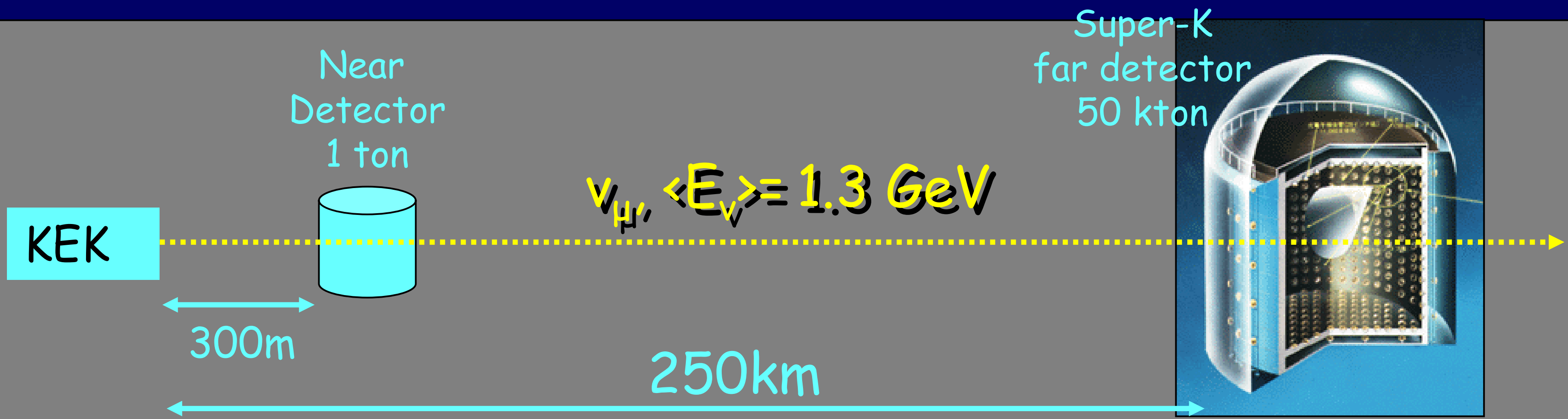
Beam composition (typical example):

• dominantly ν_μ

• contamination from
$\bar{\nu}_\mu$ (≈6%), ν_e (≈0.7%), $\bar{\nu}_e$ (≈0.2%)

• $\nu_\tau \lesssim 10^{-6}$

K2K accelerator experiment



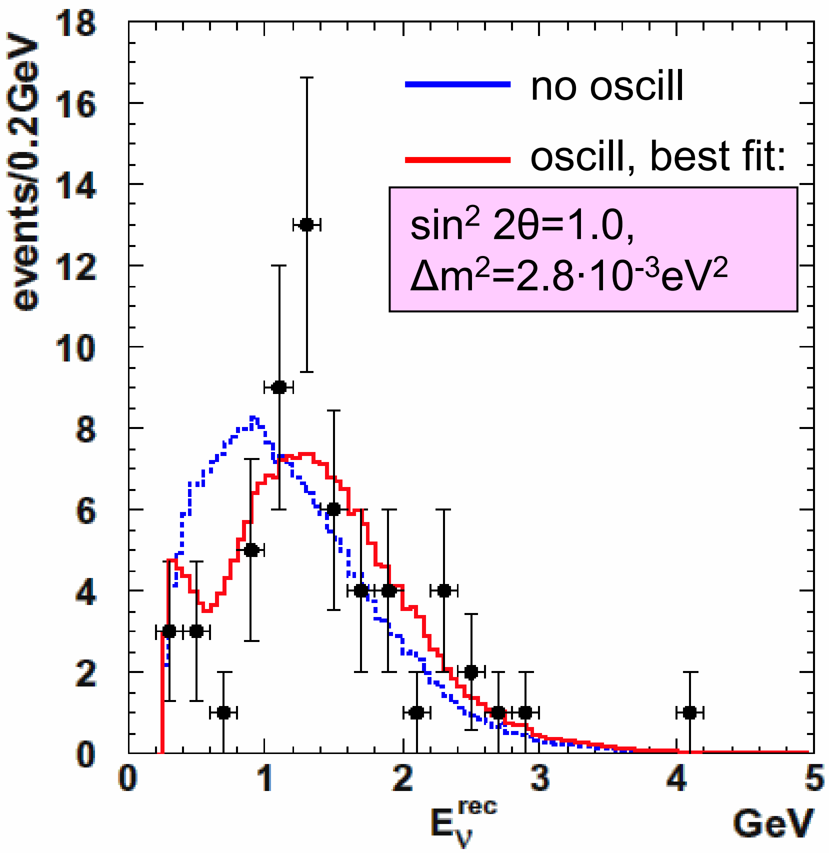
Goal: 1.0×10^{20} POT
= 200 neutrino events in SK

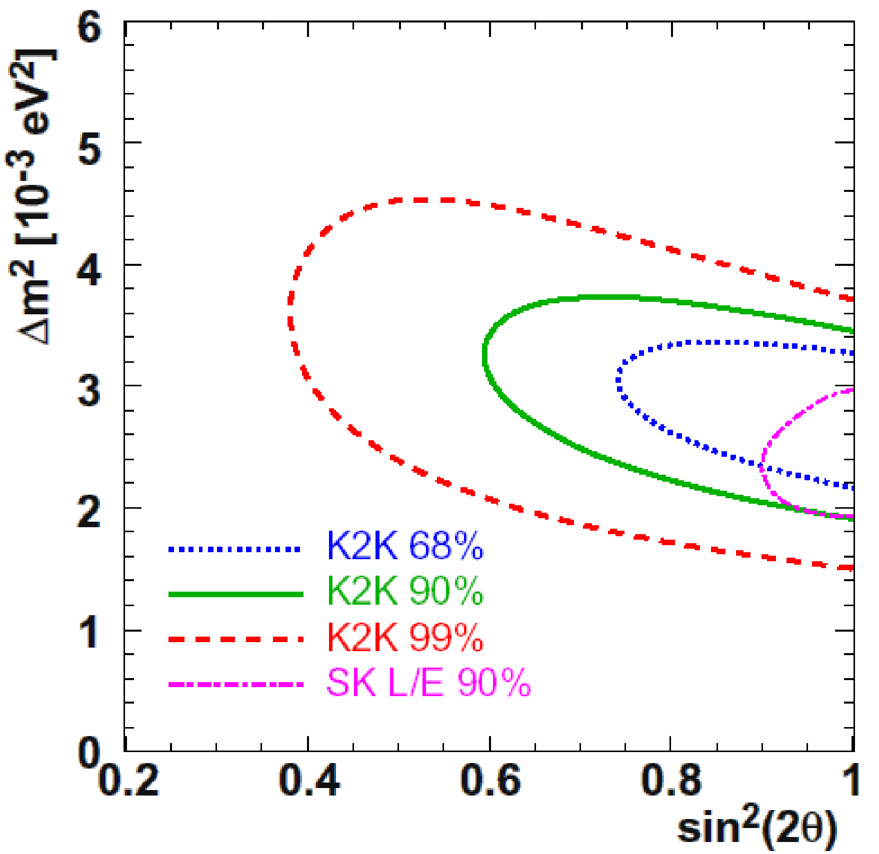
$$L_{osz}(\text{in km}) = \frac{2.48 \cdot E(\text{in GeV})}{\Delta m^2(\text{in eV}^2)}$$

Data (06/1999 – 02/2004):
$8.9\cdot10^{19}$ POT
events in "Far Detector" : 108
expected without oscillation: $150.9^{+11.6}_{-10.0}$

Probability for no oscillation: <0.01%
Neutrino oscillation confirmed with 3.9σ!

K2K Results





"Measurement of Neutrino Oscillation by the K2K Experiment"
The K2K collaboration, M. H. Ahn et al, hep-ex/0606032, Phys. Rev. D **74**, 072003 (2006)

Today: Two Long Baseline Experiments

- MINOS (running since 2005)
  Neutrinobeam (NuMI) from Fermilab to Soudan Mine
  L = 735 km, E = 3.5 GeV
  Goal: reach better precision on Δm_{23}^2, θ_{23}

- OPERA (starting, first CNGS beam August 2006)
  Neutrinobeam (CNGS) from Cern to Gran Sasso Lab
  L = 732 km, E = 17 GeV
  Goal: direct detection of ν_τ

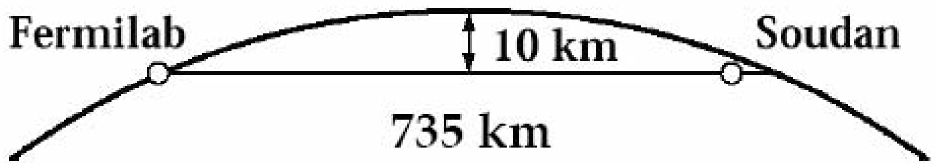
The MINOS Experiment

A large detector at Soudan

A smaller detector at Fermilab

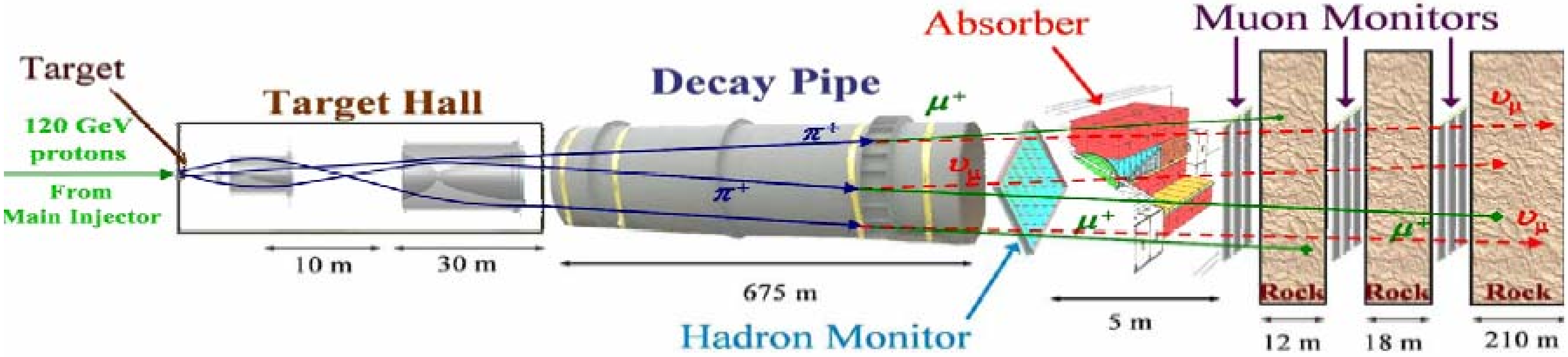
Measure the beam and neutrino energy spectrum near the source

> See how it differs far away



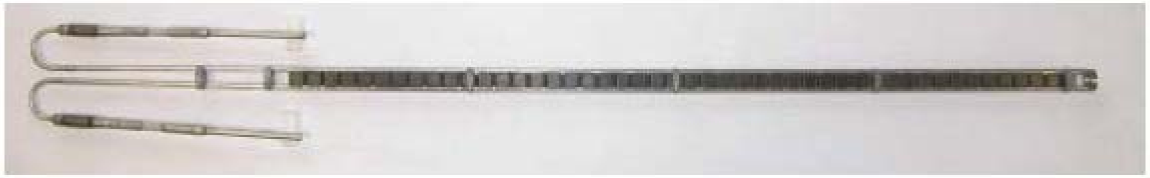
(Jeff Nelson @ Neutrino2006)

The NuMI beamline



Water-cooled segmented graphite target

- 47 2.0 cm segments; total length of 95.4 cm



2 parabolic horns carrying

- Up to 200 kA current provides up to 3T fields
- Target can be positioned up to 2.5m upstream of the first horn to change beam energy

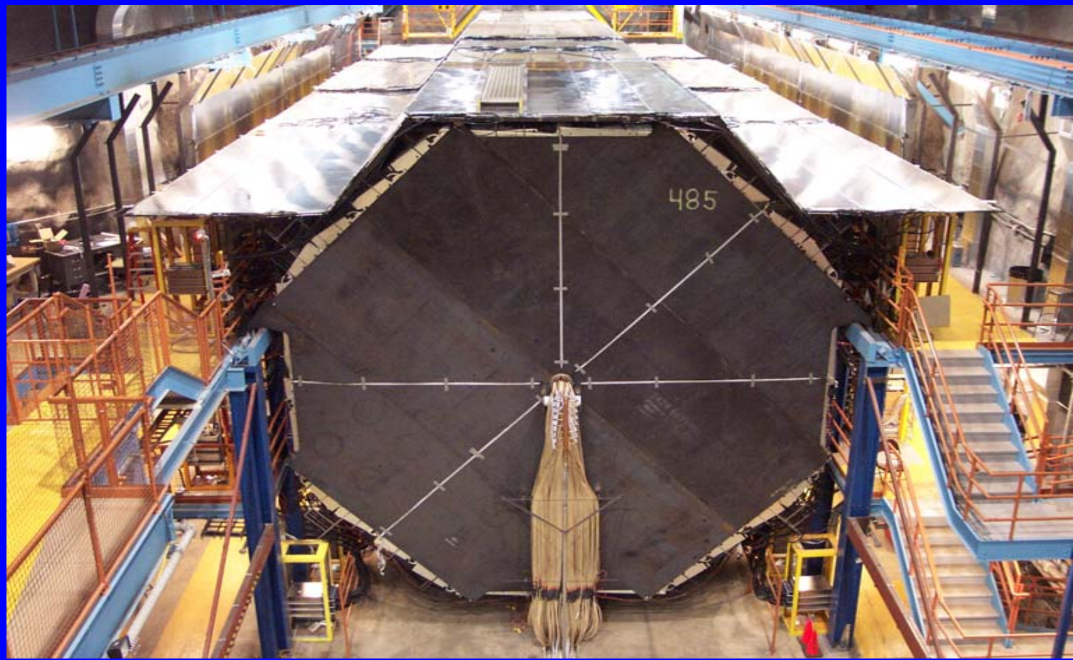
(Jeff Nelson @ Neutrino2006)

MINOS Detectors

Near Detector

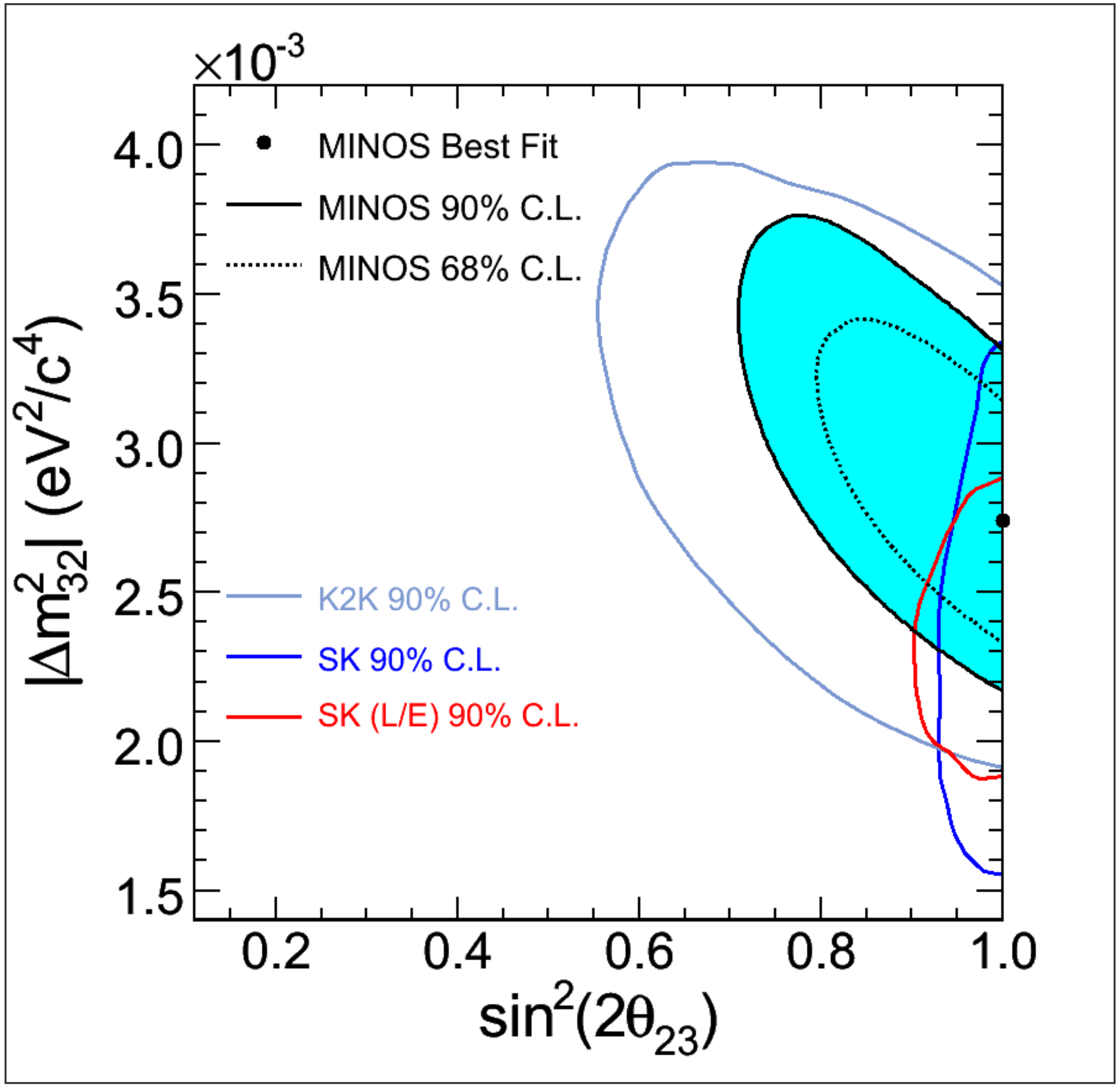
1 kton, 4×5×15m
282 steel,
153 scintillator planes

Far Detector



5.4 ktons, 8×8×30m
484 steel/scintillator planes

MINOS: Allowed Regions

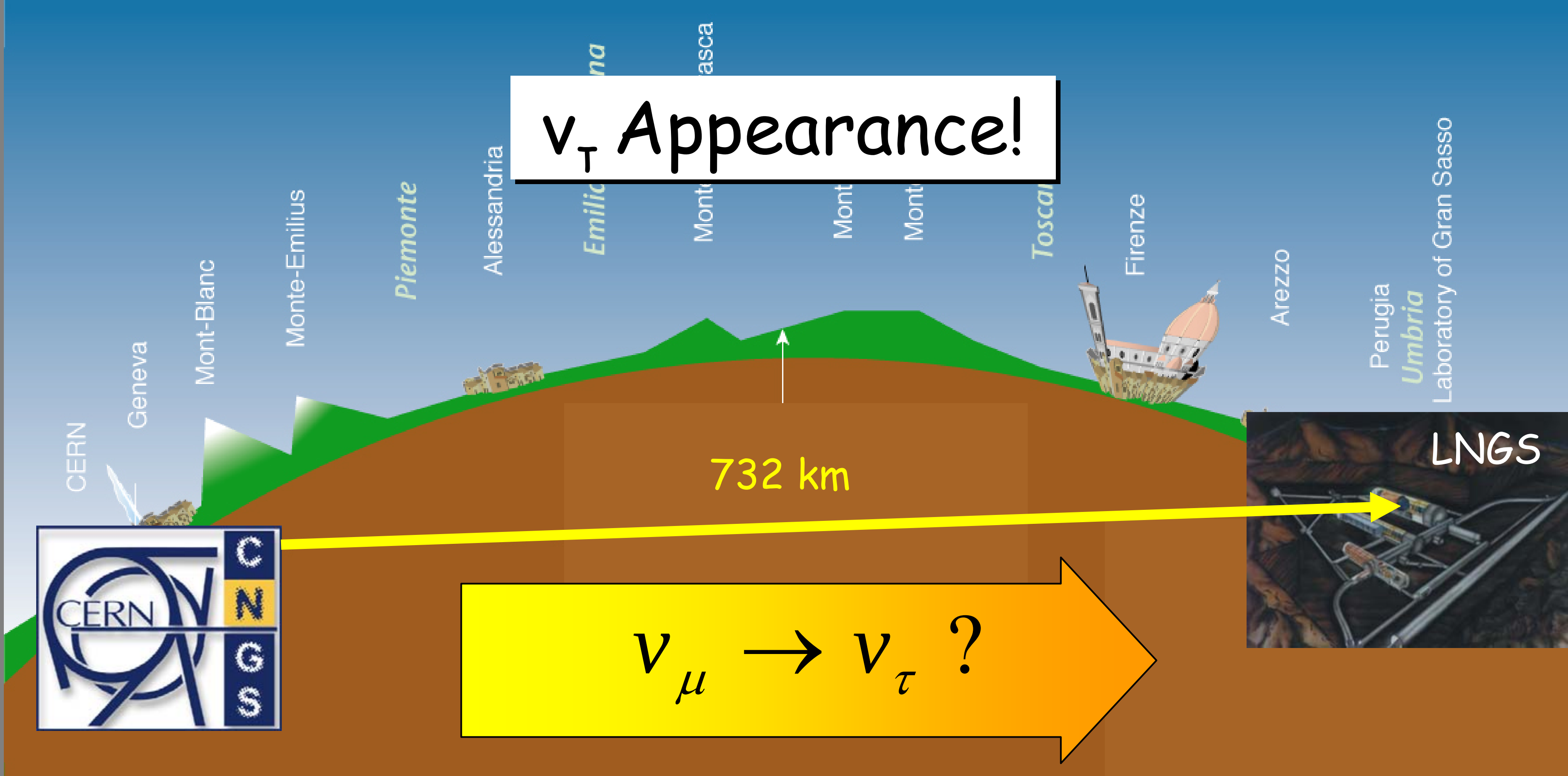


$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

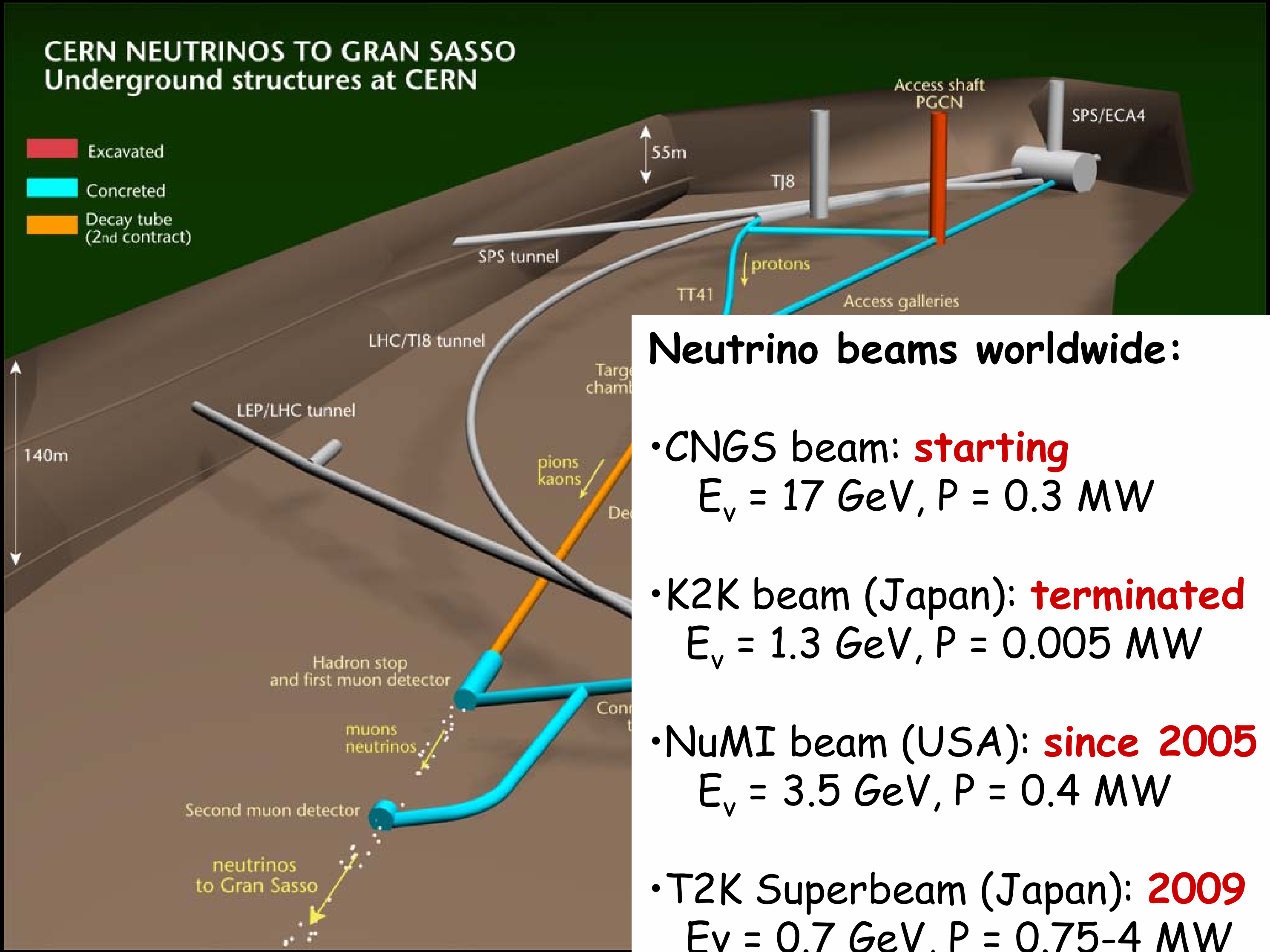
OPERA

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



First test beam in August 2006, Start in 2008

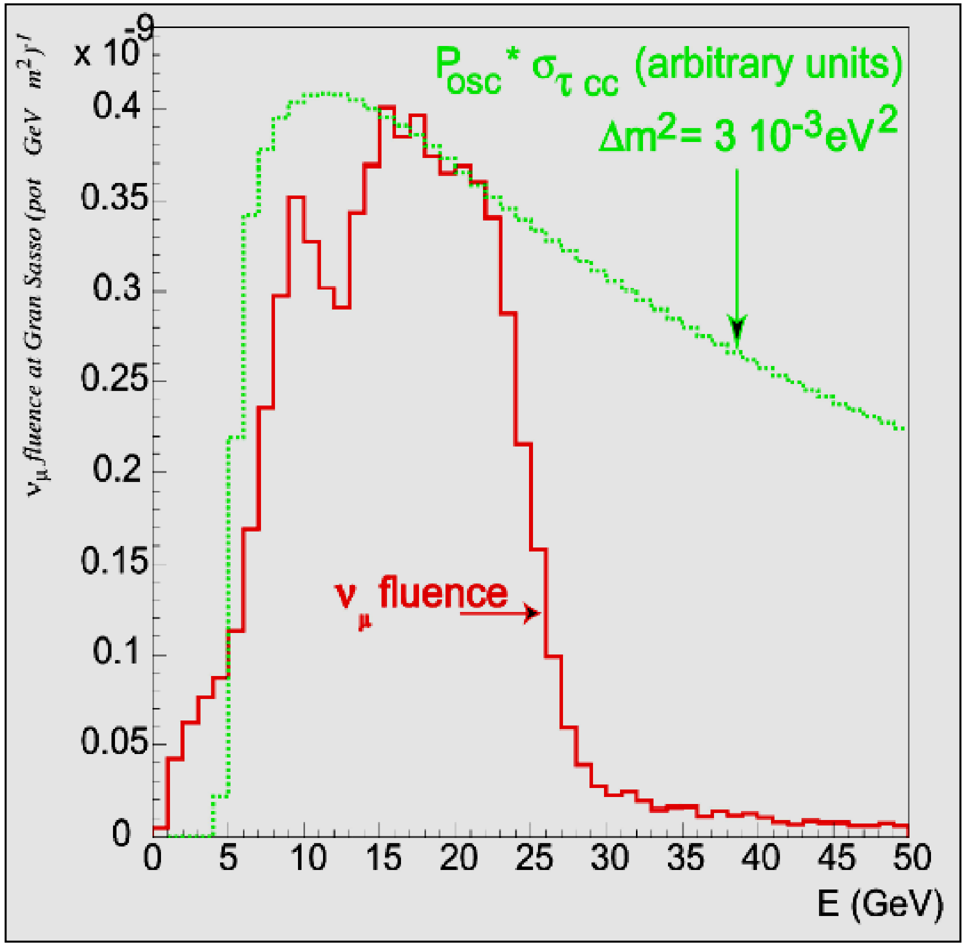
CNGS Neutrino Beam



Neutrino beams worldwide:

- CNGS beam: **starting**
  E_ν = 17 GeV, P = 0.3 MW
- K2K beam (Japan): **terminated**
  E_ν = 1.3 GeV, P = 0.005 MW
- NuMI beam (USA): **since 2005**
  E_ν = 3.5 GeV, P = 0.4 MW
- T2K Superbeam (Japan): **2009**
  Ev = 0.7 GeV, P = 0.75-4 MW

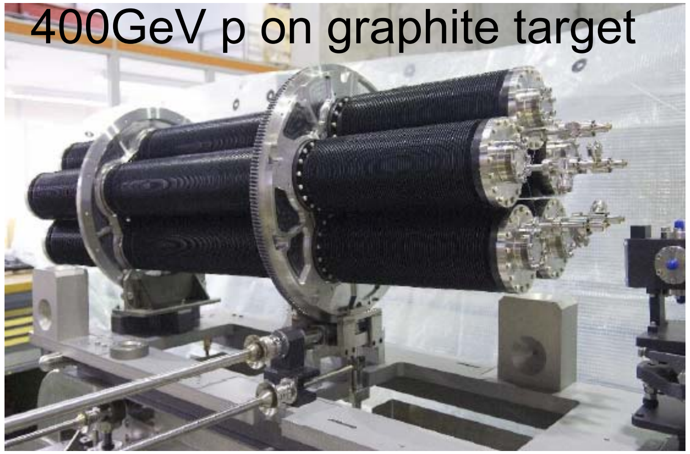
OPERA: CNGS beam



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

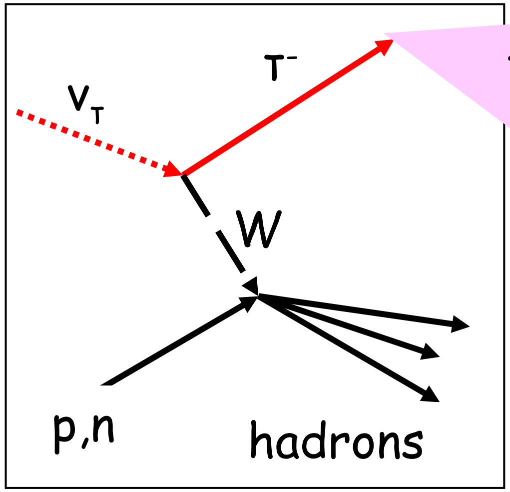
$$\bar{\nu}_\mu / \nu_\mu = 4\%$$

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



4.5·10^{19}pot/year

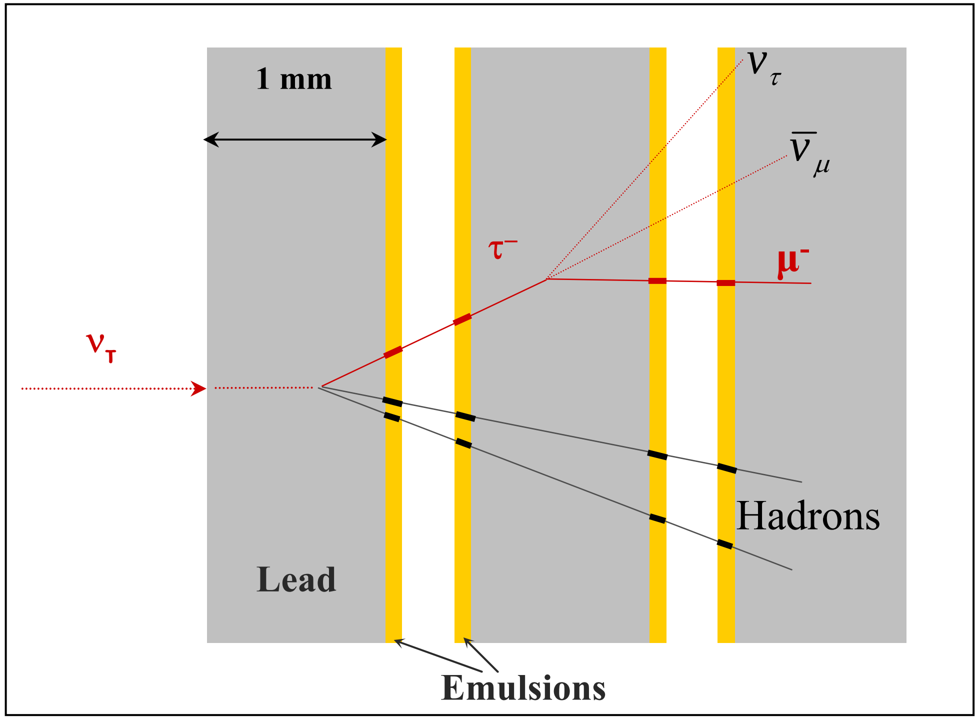
OPERA: Detection of ν_τ



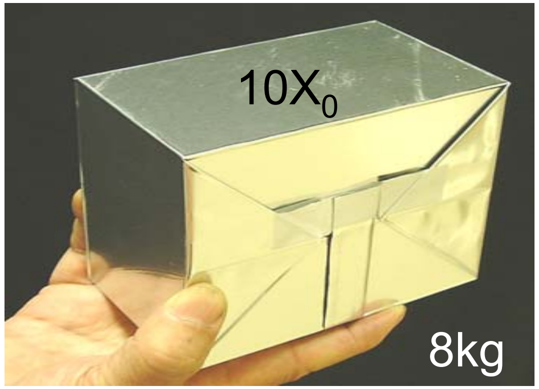
τ-decay:

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

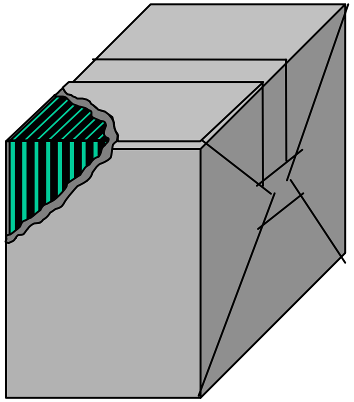
Typical topology of τ-decay:
"Kink" within 1mm from vertex

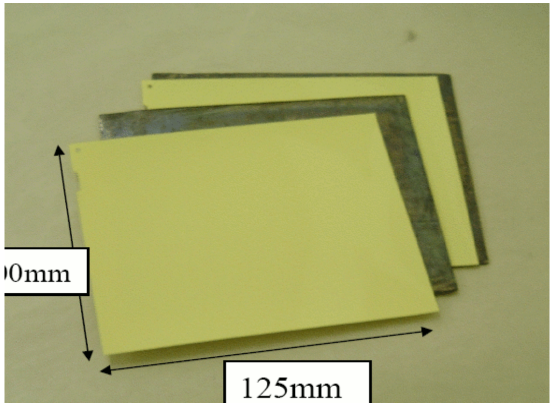


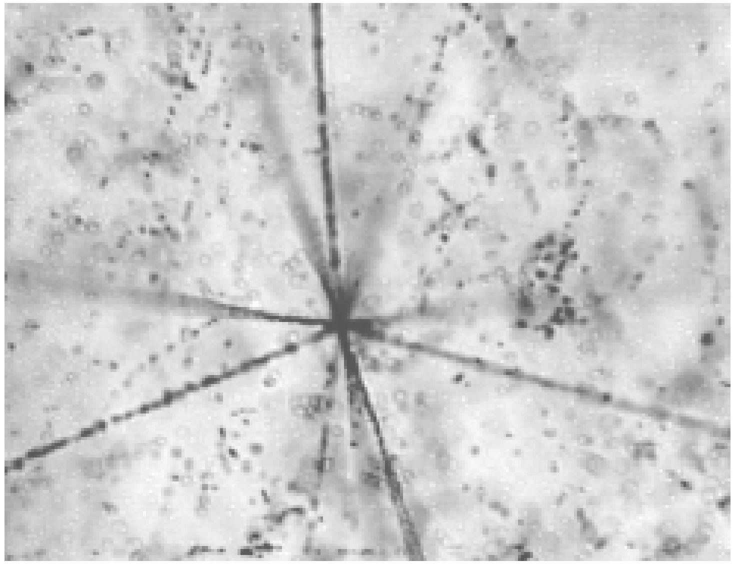
OPERA Target: Lead/Emulsion Bricks



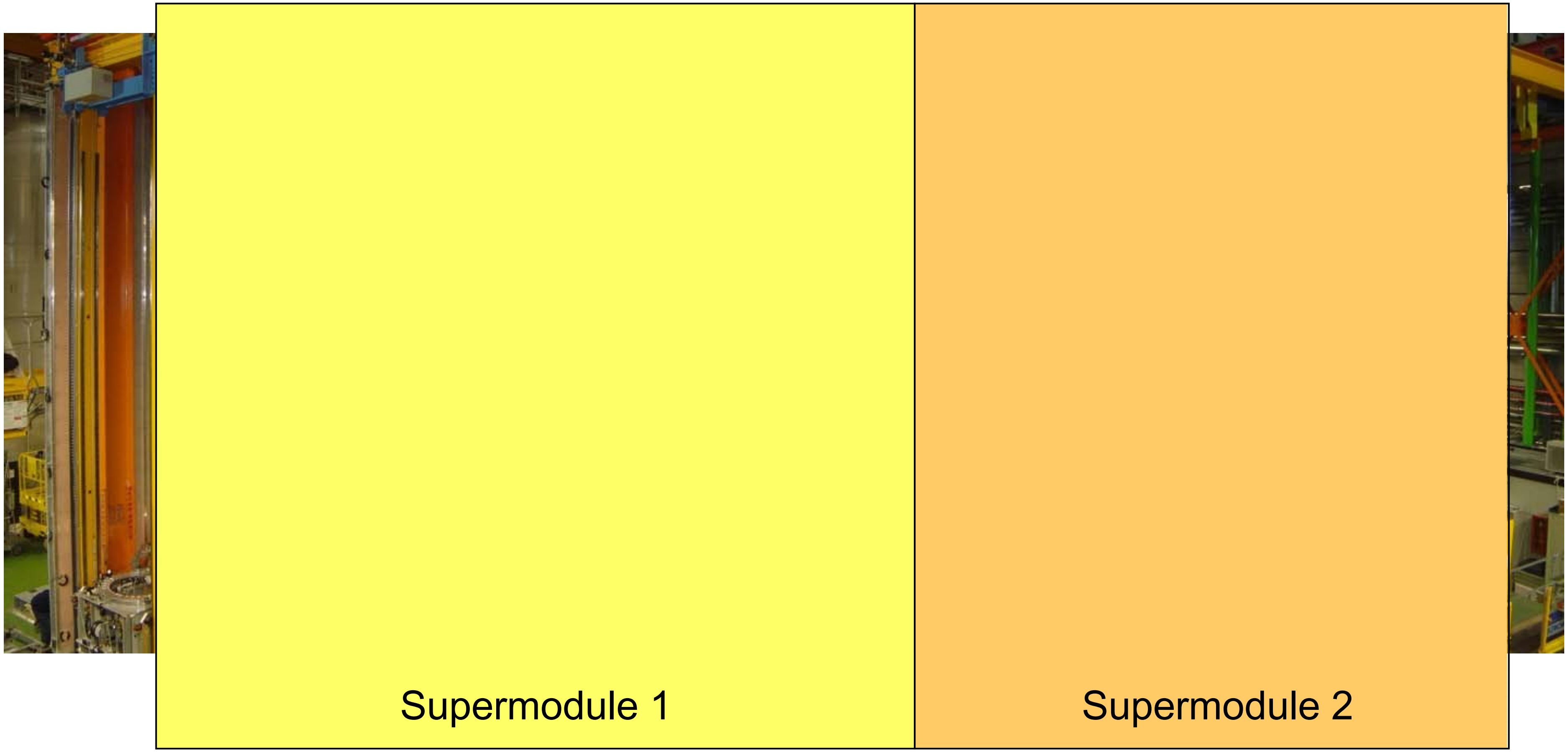
Lead/Emulsion Brick
(total ≈ 200000)







OPERA - Detector



Supermodule 1

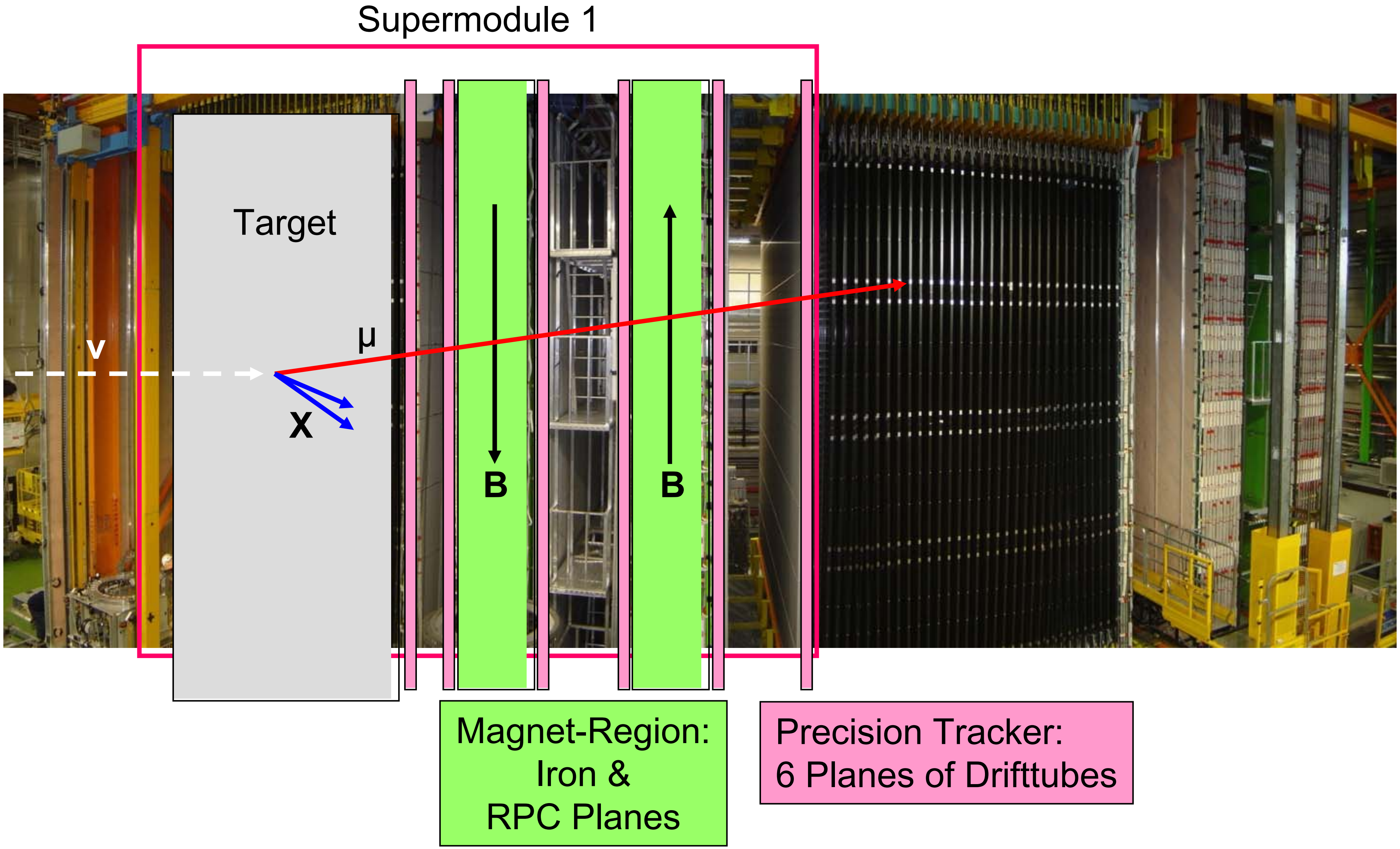
Supermodule 2

OPERA - Detector

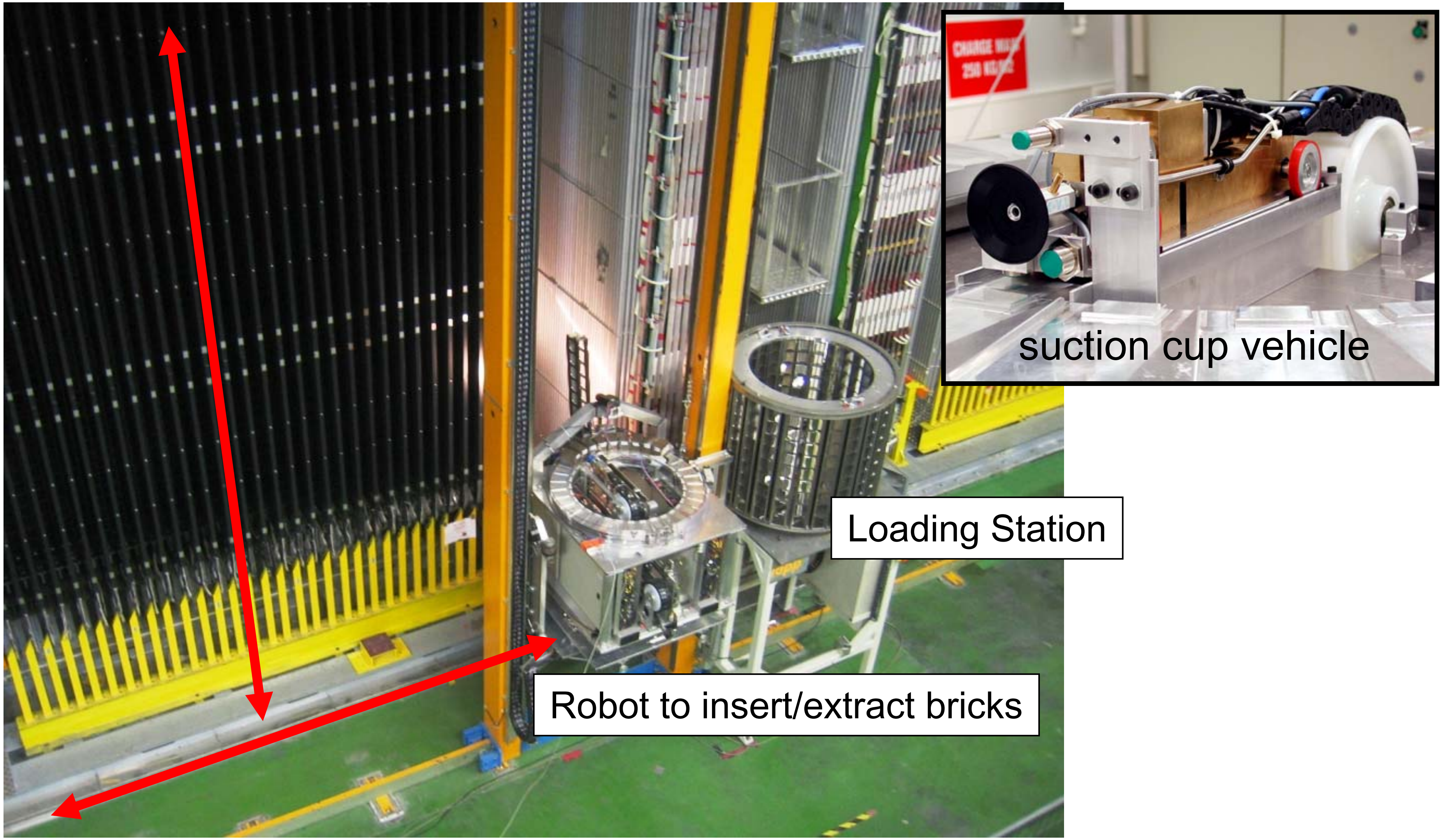
Supermodule 1

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

OPERA - Detector

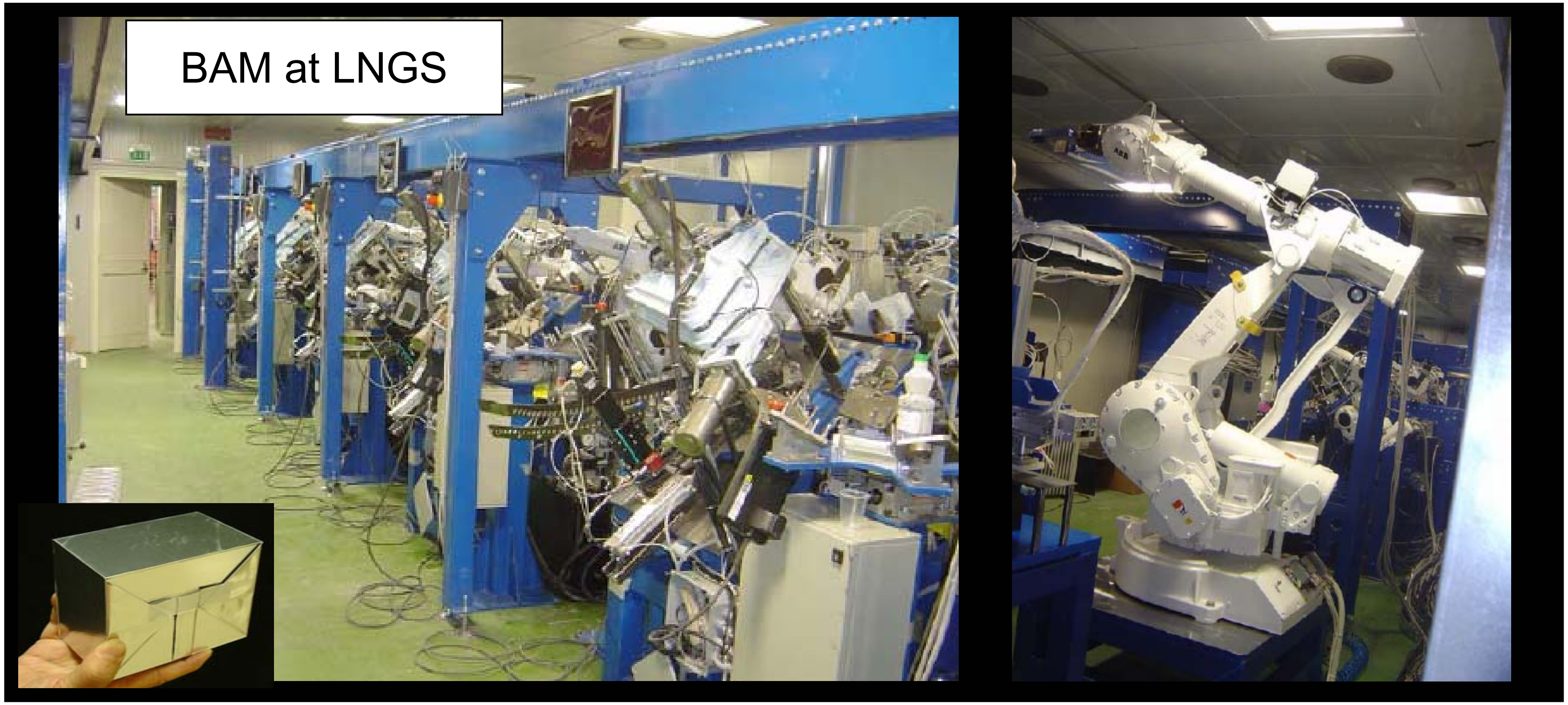


OPERA – Brick Manipulating System



OPERA – Brick Assembly Machine

- Lead/Emulsion bricks are assembled underground in GS
- Darkroom
- 5 robotized parallel stations



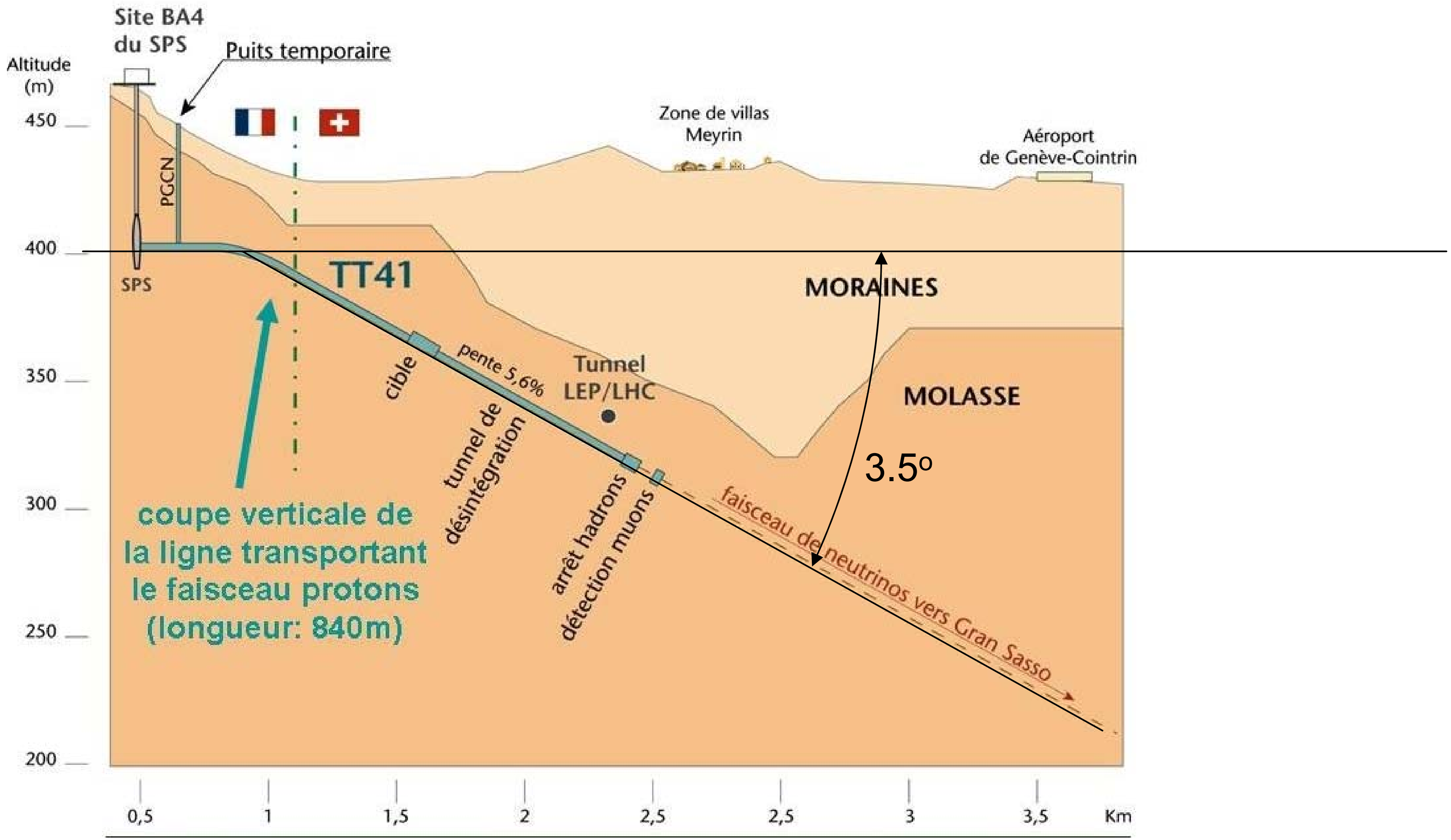
OPERA Sensitivity

OPERA: 6200 ν_μ CC+NC /year
19 ν_τ CC/year (for $\Delta m^2=2\cdot10^{-3}$ eV^2)

	$\Delta m^2=1.9\times10^{-3}eV^2$	$\Delta m^2=2.4\times10^{-3}eV^2$	$\Delta m^2=3.0\times10^{3}eV^2$	BKGD
ν_τ in OPERA	6.6	10.5	16.4	0.7

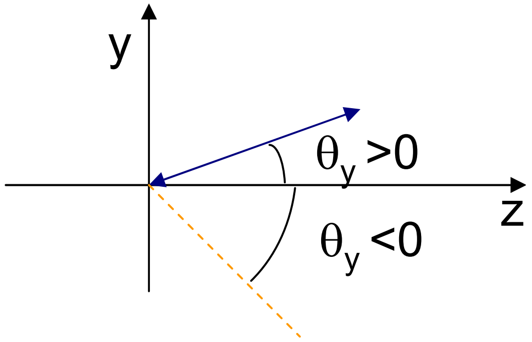
exposure: 5 years @ 4.5 $\times10^{19}$ pot / year

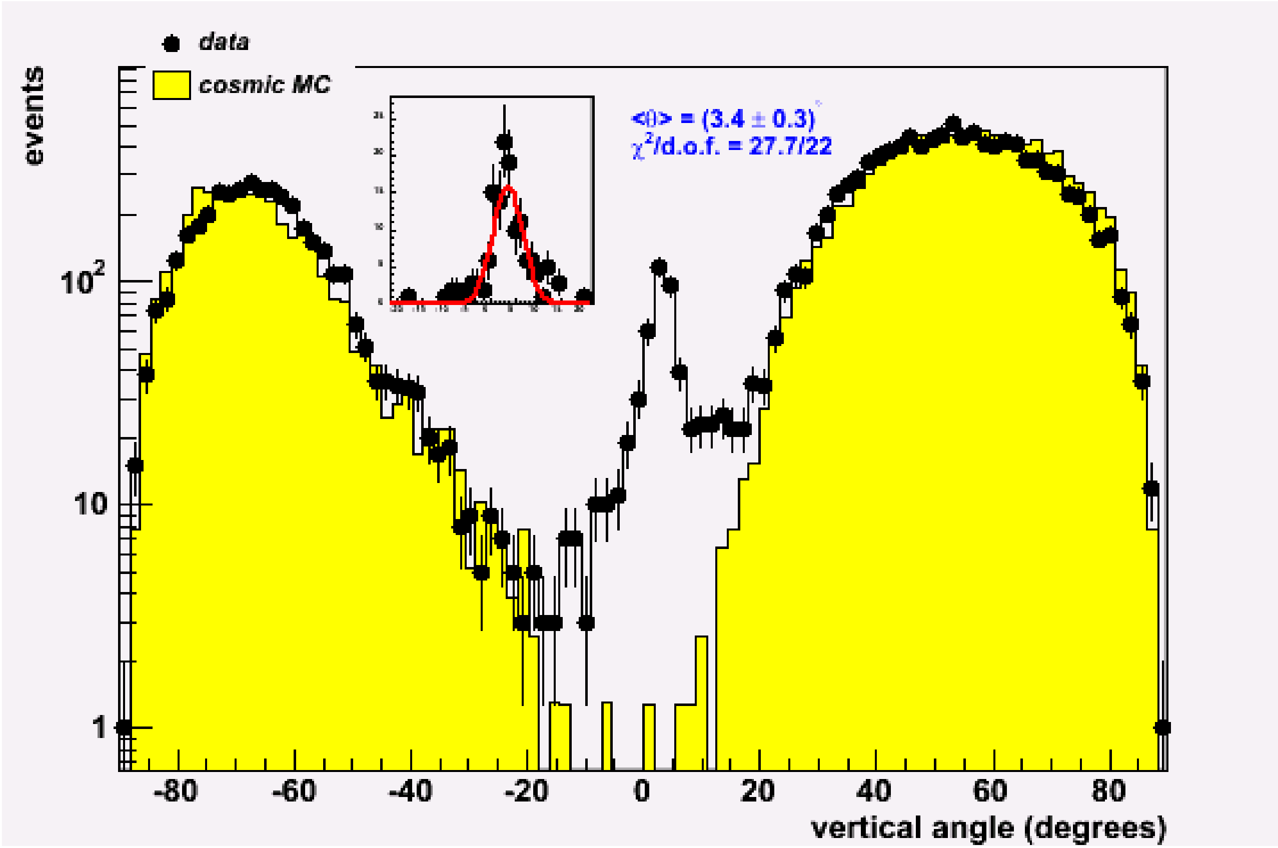
Direction of CNGS neutrino beam



CNGS beam direction measurement

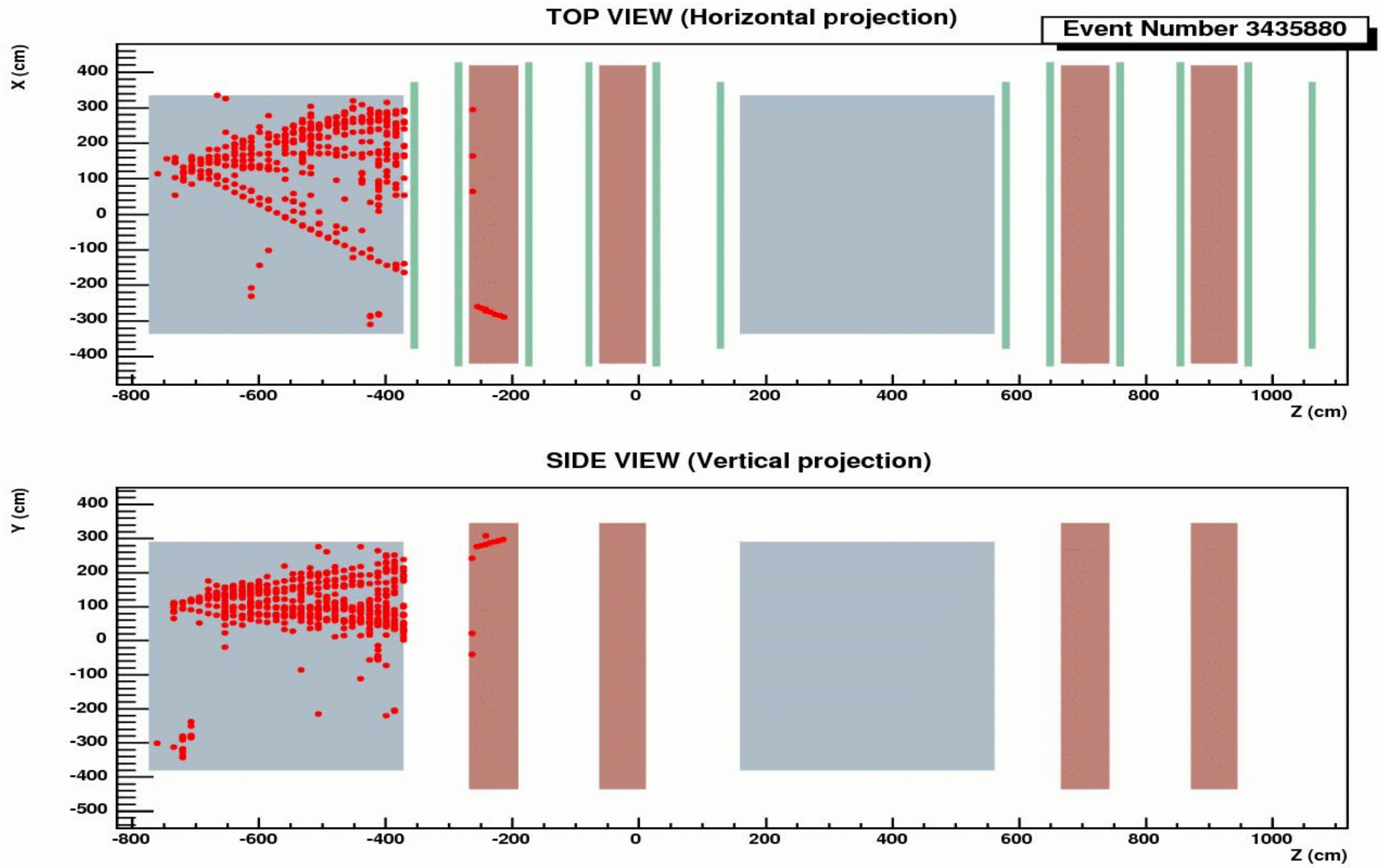
μ zenith angle



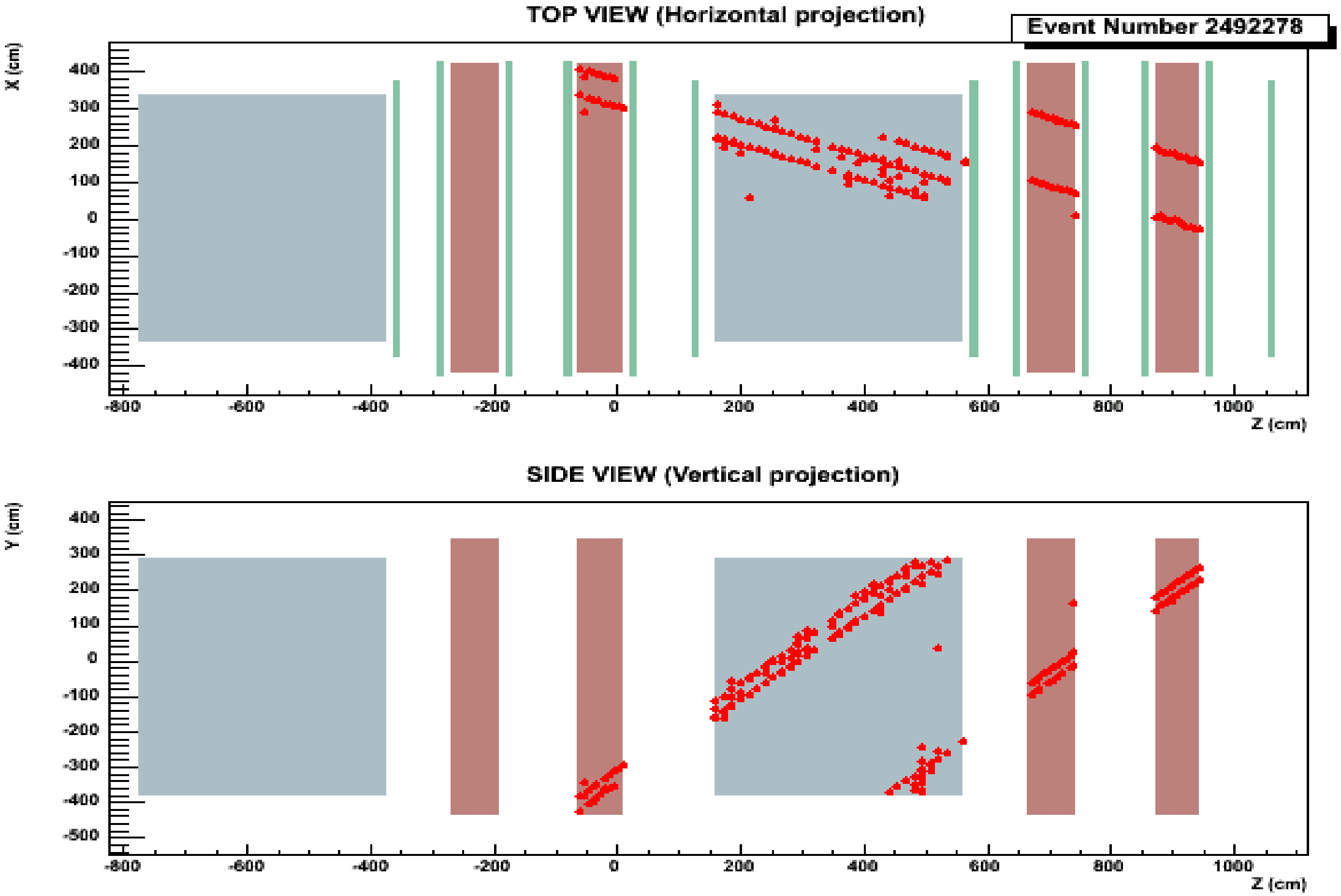


August06 testrun result:
$\langle\theta\rangle = 3.4 \pm 0.3$ degrees

ν_{CC} in Target Tracker (real event)



μ bundle (cosmics) (real event)



Neutrino Physics Part 2

Neutrino Oscillations (12)

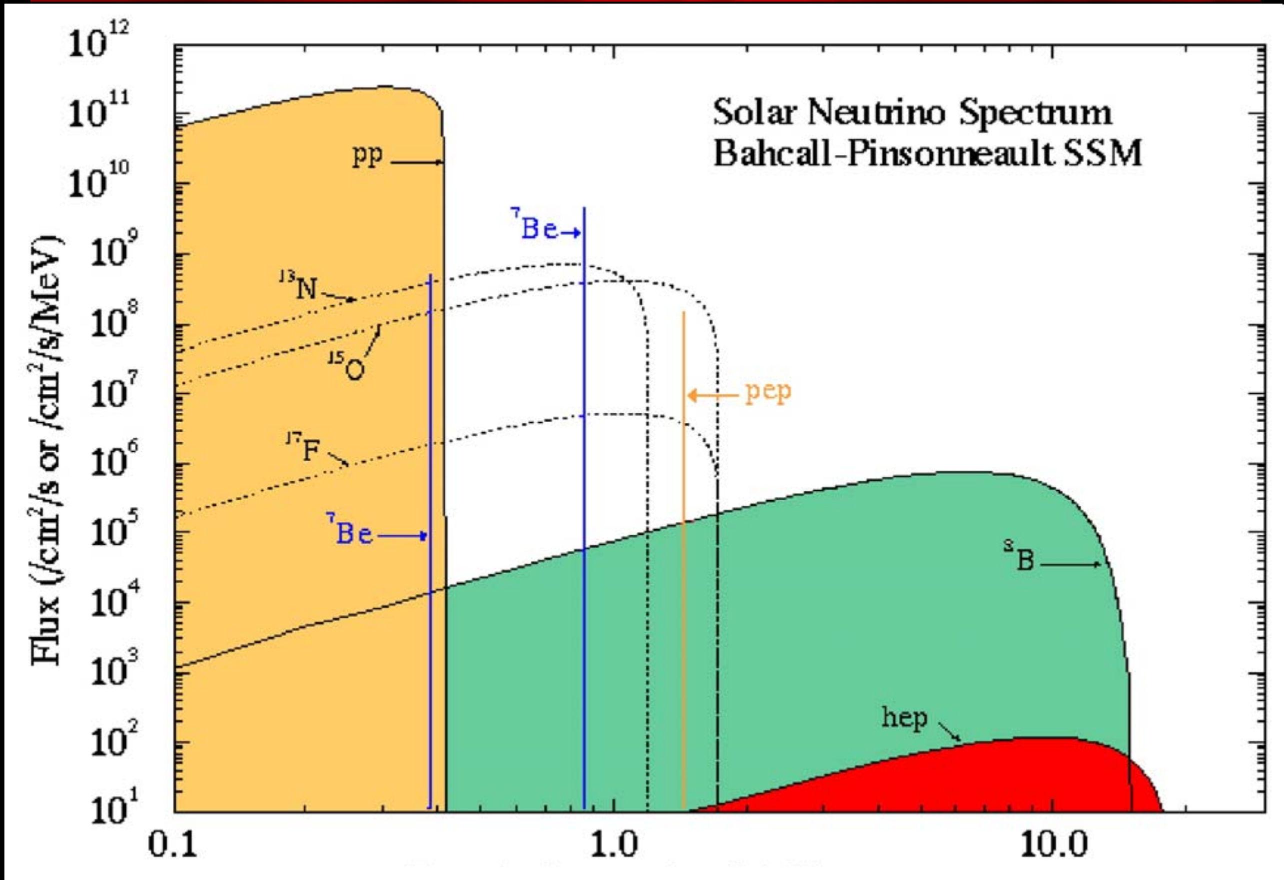
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

$\nu_e \rightarrow \nu_{\mu,\tau}$ Oscillations: θ_{12}, Δm^2_{12}

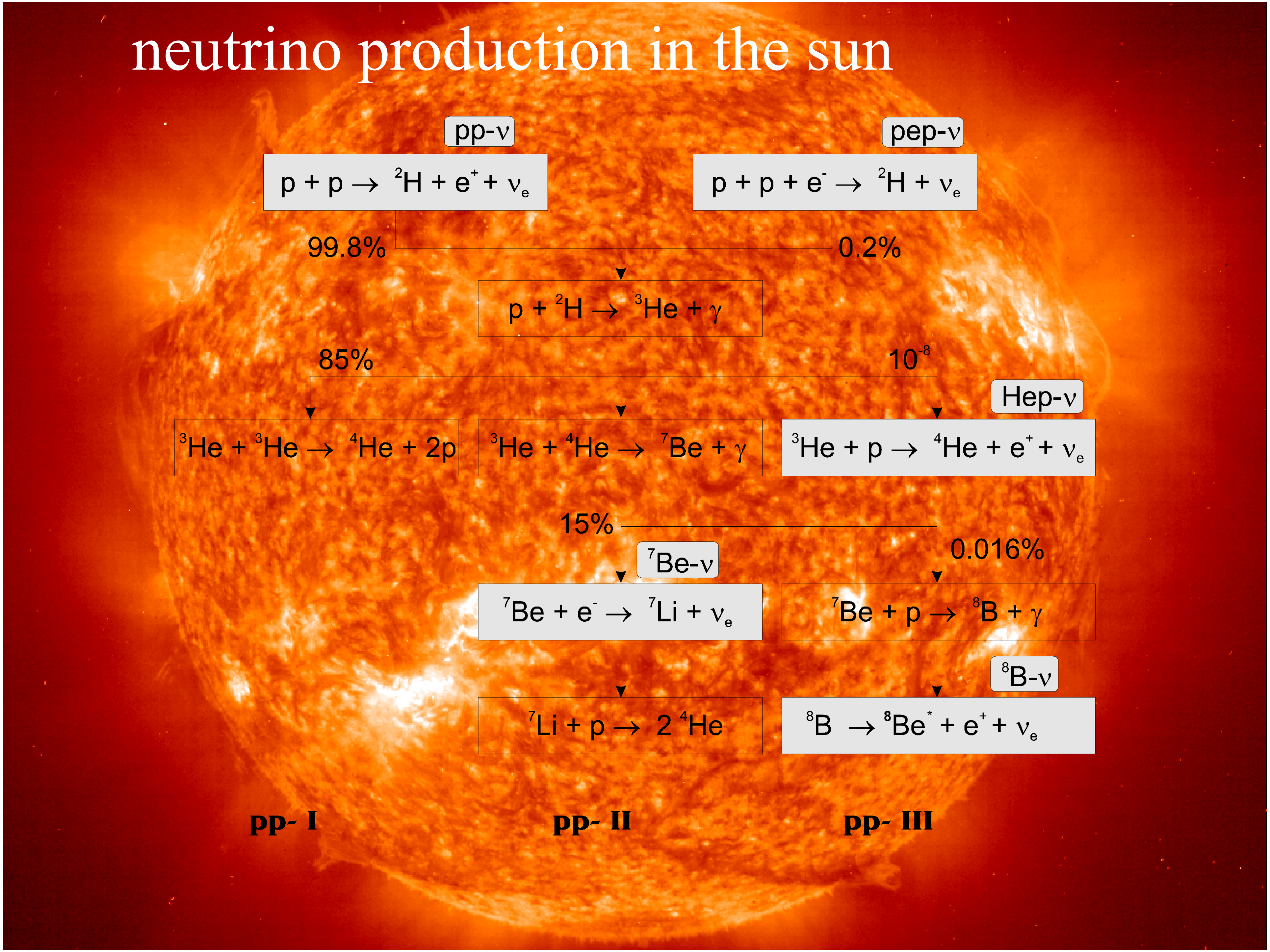
Solar Neutrinos + Reactor Neutrinos

Solar Neutrinos

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



energy of the neutrinos in MeV


neutrino production in the sun
pp-ν
$p + p \rightarrow {}^2H + e^+ + \nu_e$
pep-ν
$p + p + e^- \rightarrow {}^2H + \nu_e$
99.8%
0.2%
$p + {}^2H \rightarrow {}^3He + \gamma$
85%
10^{-8}
Hep-ν
${}^3He + {}^3He \rightarrow {}^4He + 2p$
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$
15%
0.016%
${}^7Be$-ν
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
${}^7Be + p \rightarrow {}^8B + \gamma$
${}^8B$-ν
${}^7Li + p \rightarrow 2\,{}^4He$
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
pp- I
pp- II
pp- III

Energy Production in Stars

Bethe 1939

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and tw electrons can occur essentially only in two ways The first mechanism starts with the combinatio of two protons to form a deuteron with positro emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1$$

The deuteron is then transformed into He^4 b further capture of protons; these captures occu very rapidly compared with process (1). Th second mechanism uses carbon and nitrogen a catalysts, according to the chain reaction

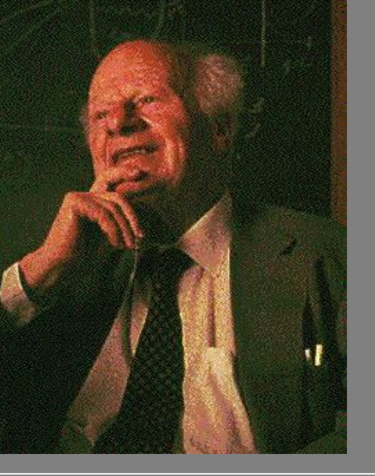
$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \quad (2$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

pp chain

CNO cycle



The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \quad (2)$$

Solar Neutrinos

Bahcall, Davis 1964

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^1H(p, e^+\nu)^2H(p,\gamma)^3He$ and terminated by the following sequences: (i) $^3He(^3He, 2p)^4He$; (ii) $^3He(\alpha,\gamma)^7Be(e^-\nu)^7Li(p,\alpha)^4He$; and (iii) $^3He(\alpha,\gamma)^7Be(p,\gamma)^8B(e^+\nu)^8Be^*(\alpha)^4He$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = 0.81$ MeV) $^{37}Cl(\nu_{solar}, e^-)^{37}Ar$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^-)^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These results will be reported, and a discussion will be given of the possibility of extending the sensitivity of the method to a degree capable of measuring the solar neutrino flux calculated by Bahcall in the preceding paper.[2]

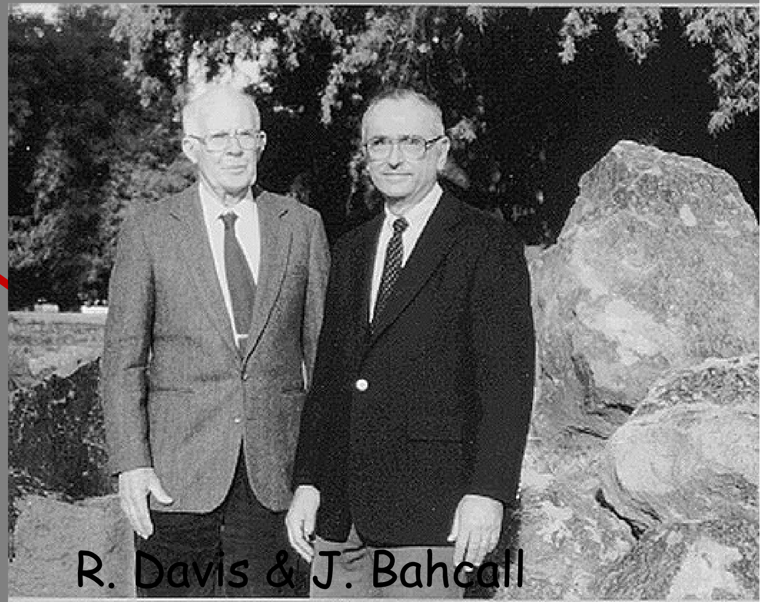
The apparatus consists of two 500-gallon tanks of perchlorethylene, C_2Cl_4, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 2300 feet below the surface[3] (1800 meters of water equivalent shielding, m.w.e.). Initially the tanks were swept completely free of air argon by purging the tanks with a stream of helium gas. ^{36}Ar carrier (0.10 cm^3) was introduced and the tanks exposed for periods of four months or more to allow the 35-d ^{37}Ar activity to reach nearly the saturation value. Carrier argon along with any ^{37}Ar pro-

3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3\times10^{-34}$ sec^{-1} (^{37}Cl atom)$^{-1}$. From this value, Bahcall[2] has set an upper limit on the central temperature of the sun and other relevant information.

On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

$$\sum \varphi_\nu(\text{solar})\,\sigma_{abs} = (4\pm2)\times10^{-35}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1},$$

then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background. On the basis of experience



the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

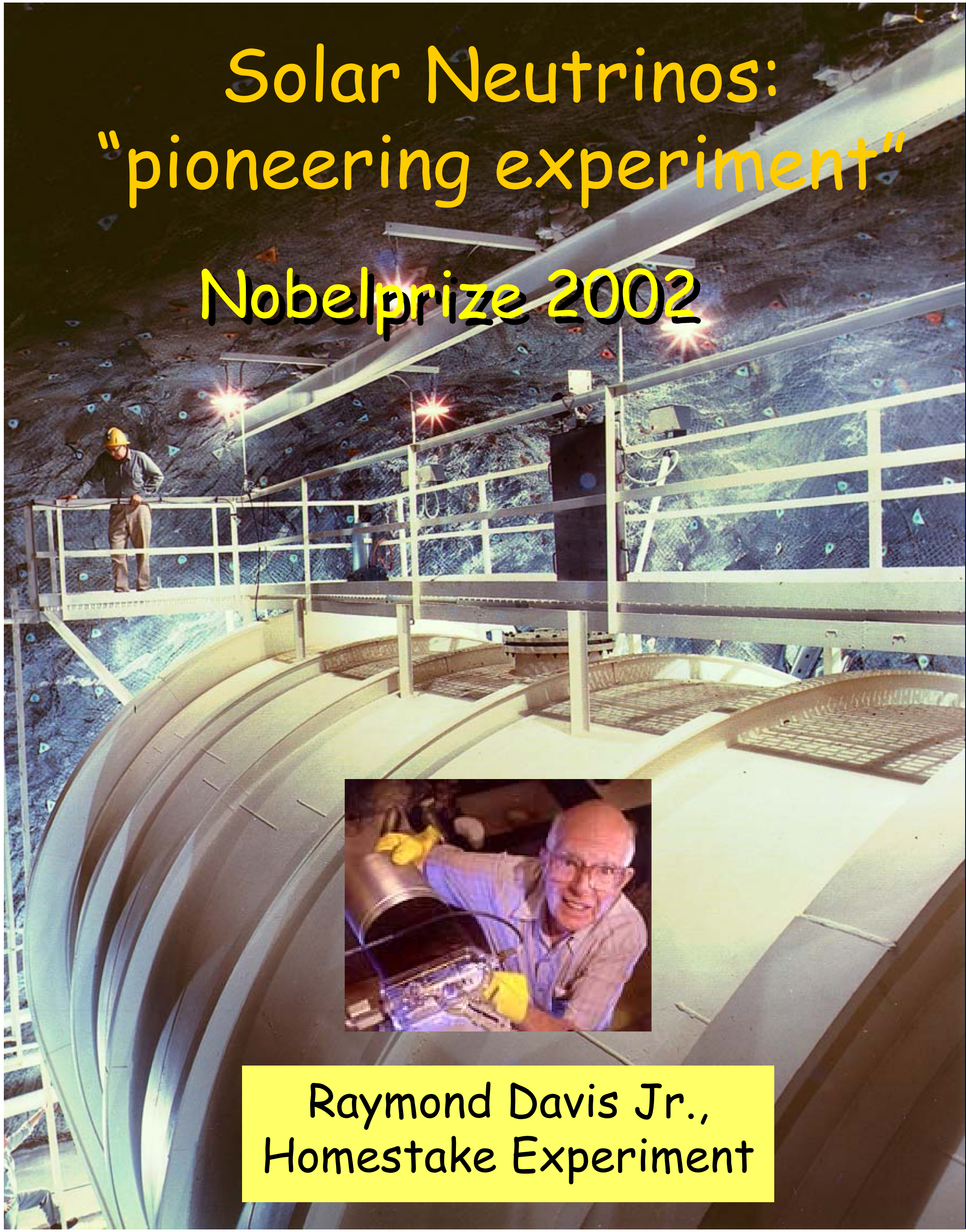
First generation of experiments

dissapearance of ν_e!

solar neutrino puzzle

Solar Neutrinos:
"pioneering experiment"

Nobelprize 2002



Raymond Davis Jr.,
Homestake Experiment

Since≈1970

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

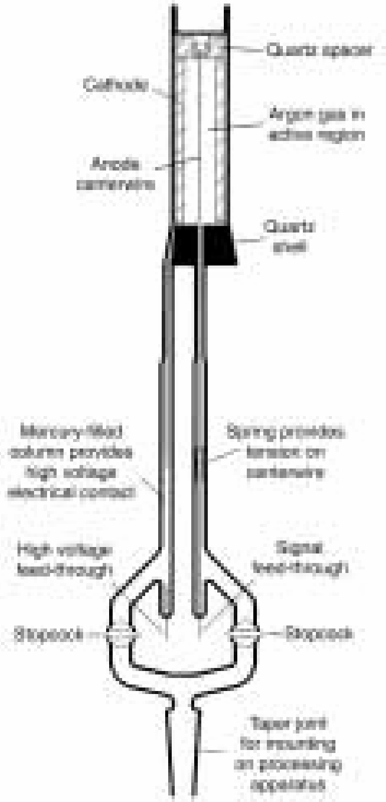
$E_\nu > 814$ keV

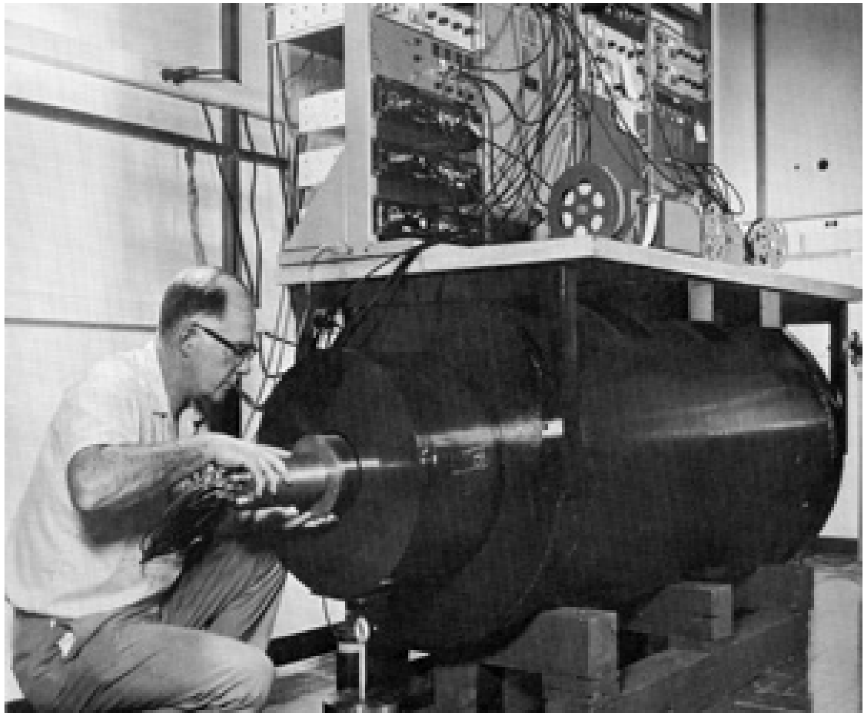
$R_{exp} = 0.34 \times$ SSM

Ar – Counting:

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

$T_{1/2}$ = 35 Tage





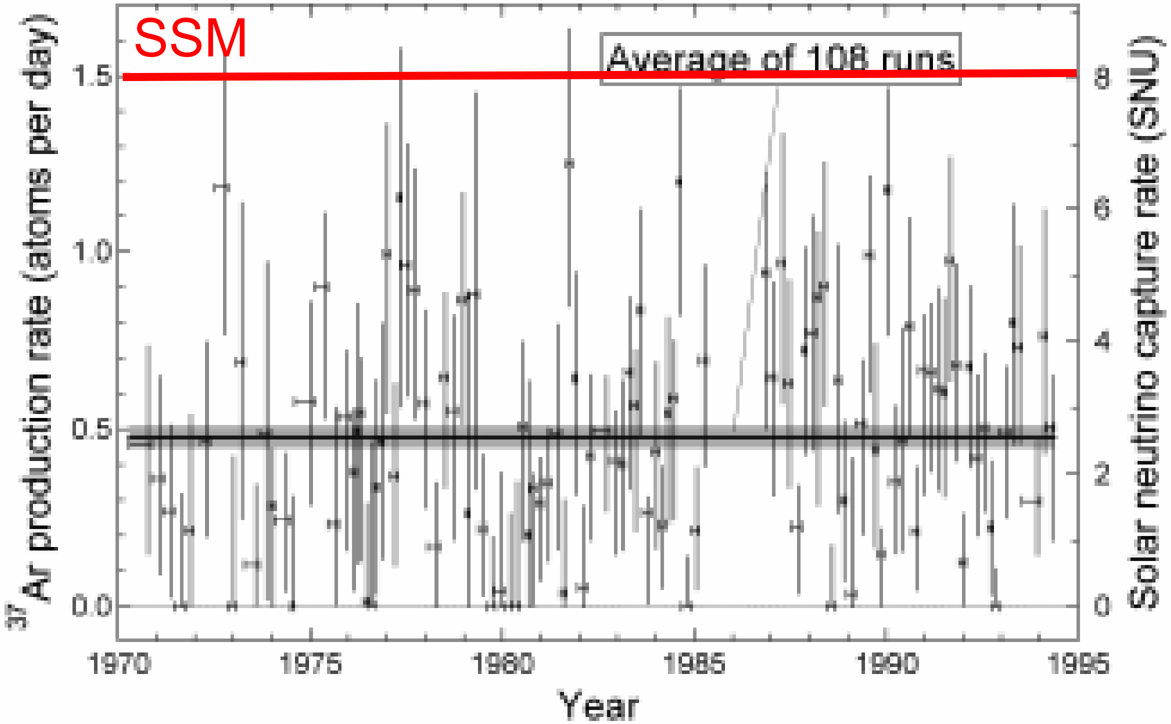


Figure 15. A summary of all of the runs made at Homestake after implementation of rise-time counting. Background has been subtracted. Over a period of 25 years, 2200 atoms of ^{37}Ar were detected, corresponding to an average solar neutrino flux of 2.56 SNU. The gap in 1986 occurred when both perchloroethylene circulation pumps failed. Based on data from Cleveland *et al.* (1998).

Бруно Понтекорво

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31 April 6/10 1972

Davis & Bahcall (1964)

Prof. J.N.Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

B.Pontecorvo

B.Pontecorvo

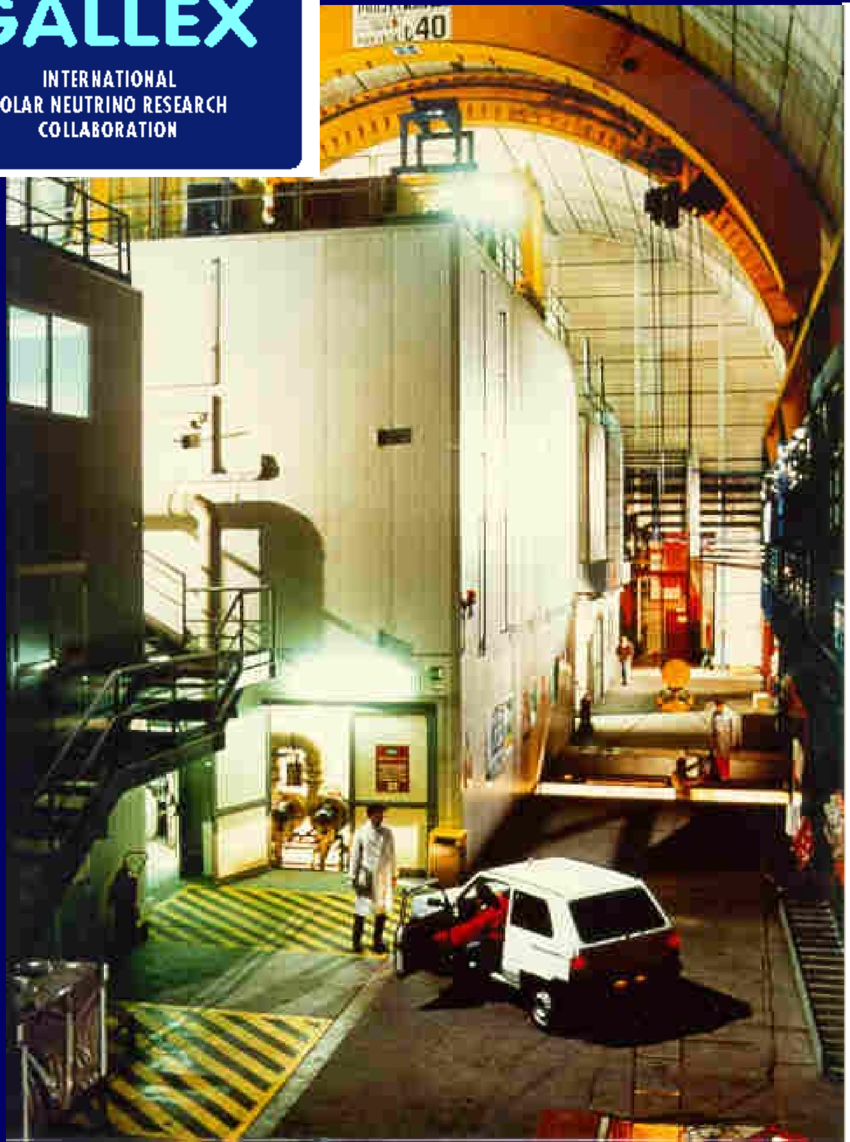
GALLEX

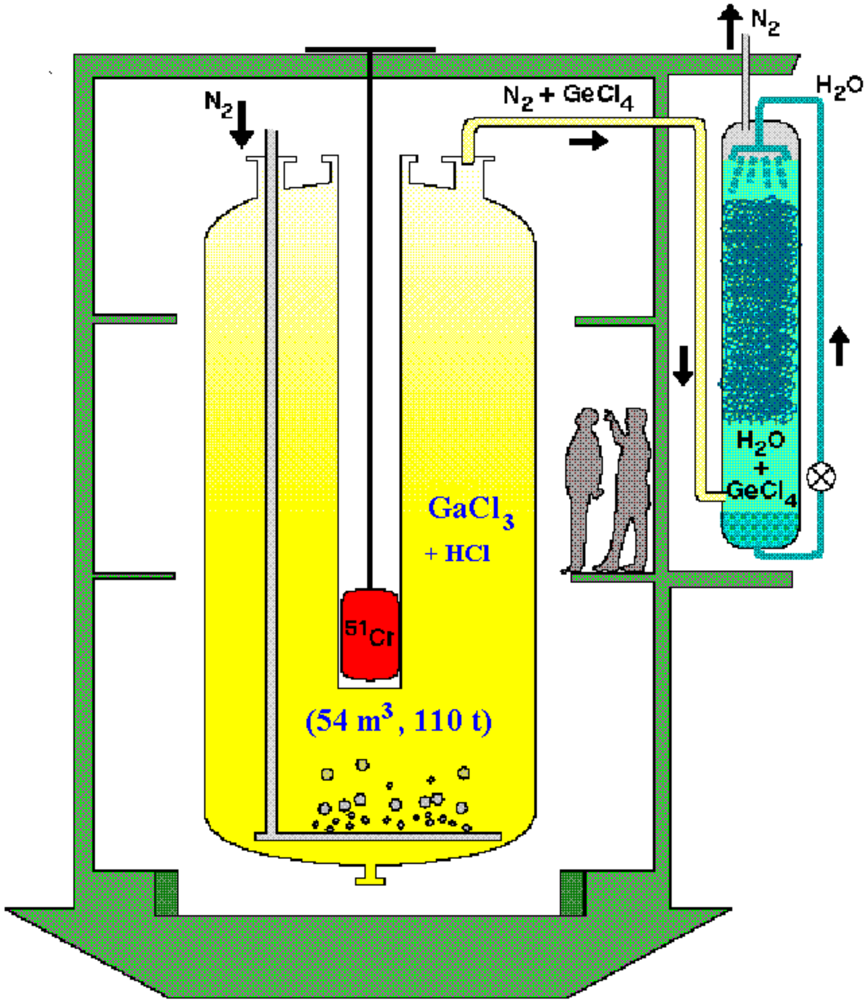
INTERNATIONAL SOLAR NEUTRINO RESEARCH COLLABORATION

Gallium Experiment at Gran Sasso

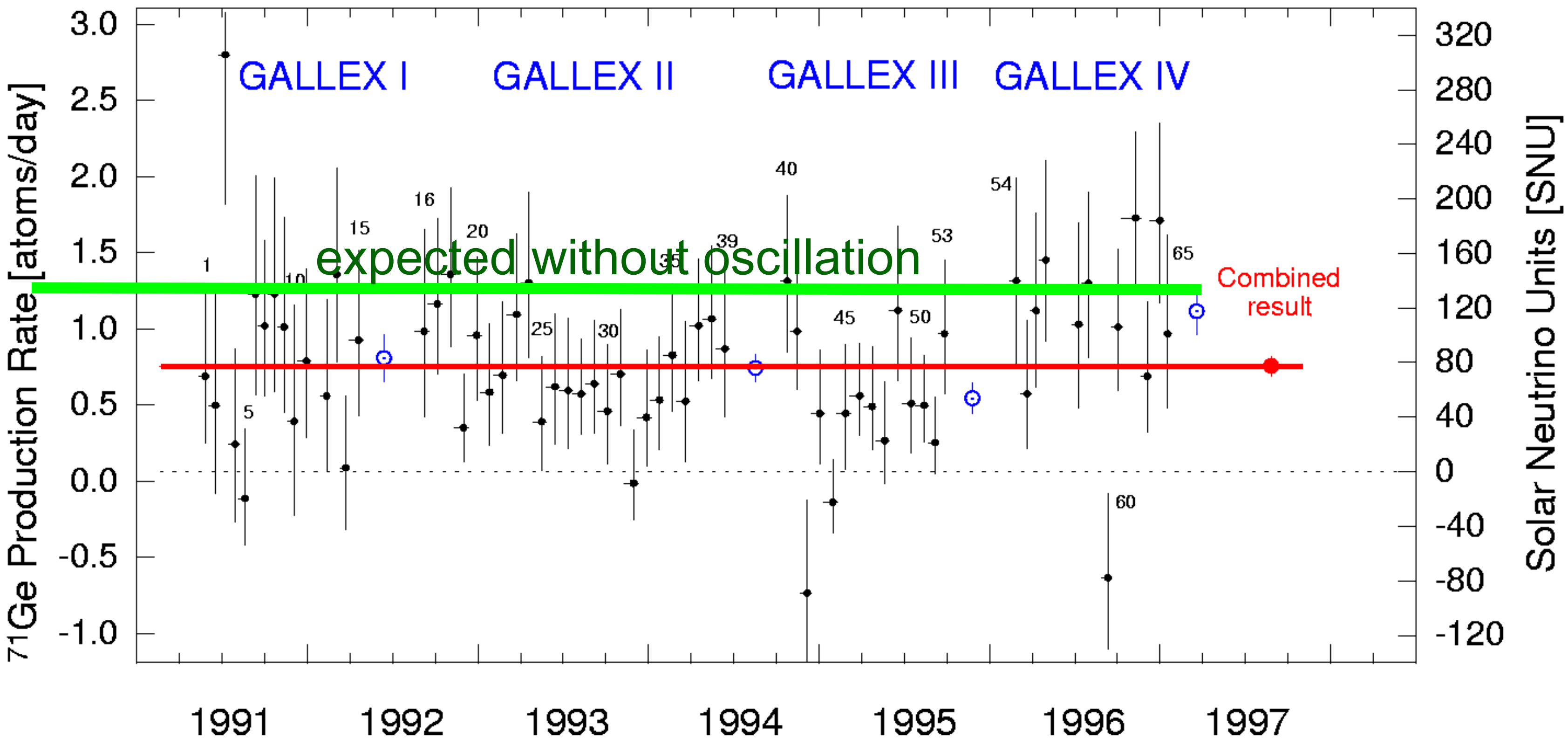
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

$E_\nu > 233$ keV





GALLEX Results



GALLEX

INTERNATIONAL
SOLAR NEUTRINO RESEARCH
COLLABORATION

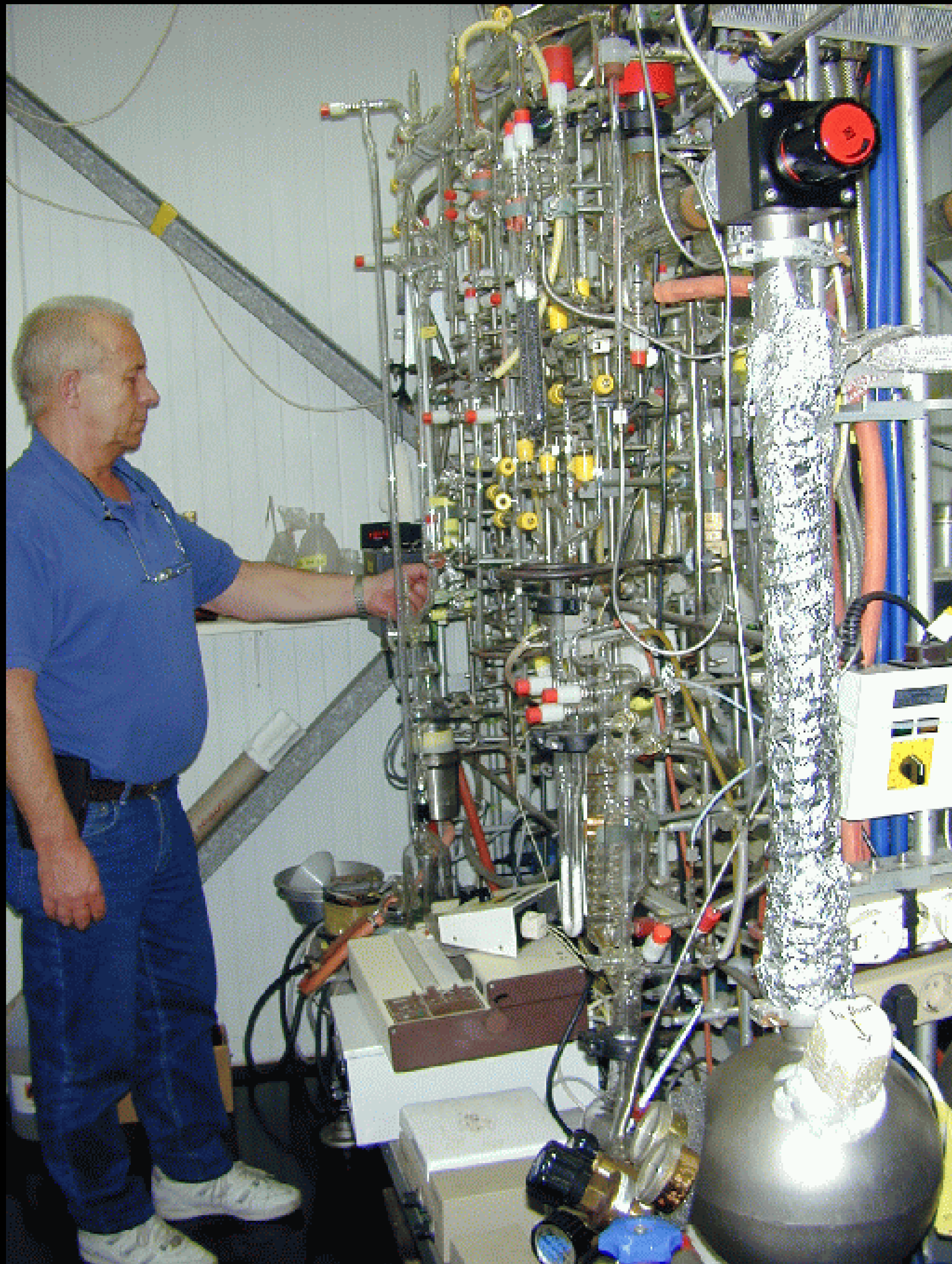
Extraction of ^{71}Ge (as $GeCl_4$) in GALLEX

GALLEX

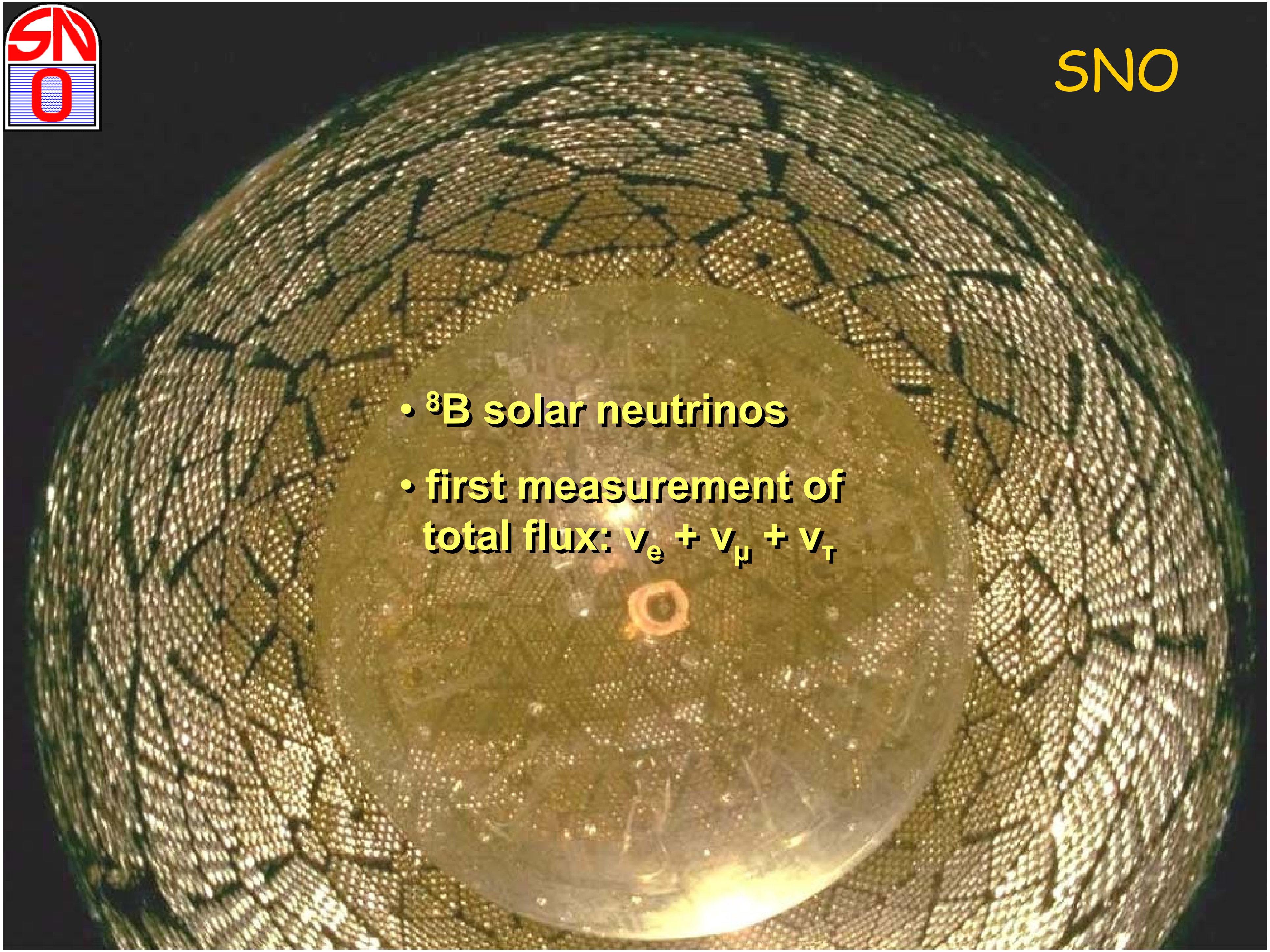
Gallium Experiment at Gran Sasso

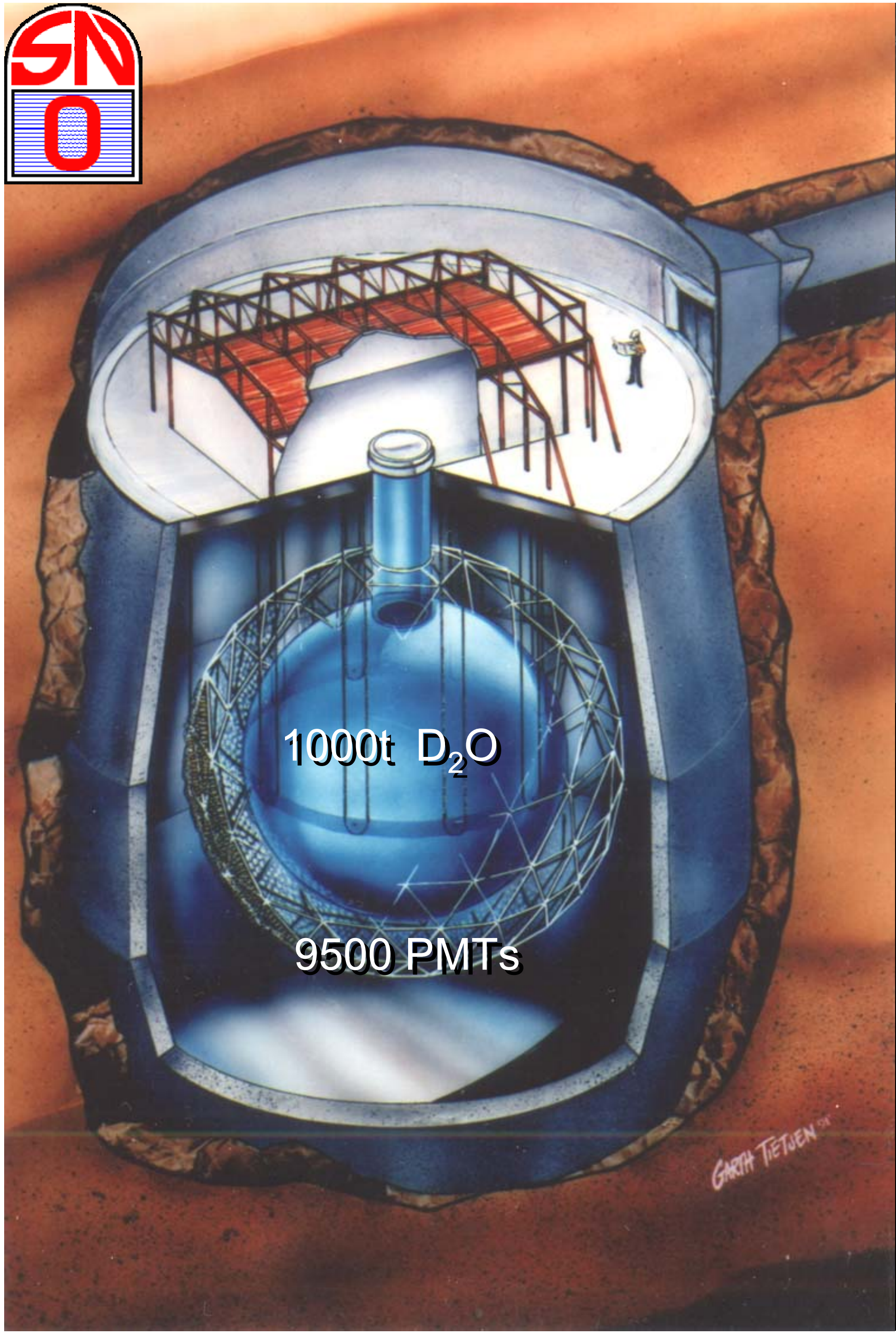
INTERNATIONAL
SOLAR NEUTRINO RESEARCH
COLLABORATION

Conversin to GeH_4



SNO


• ^{8}B solar neutrinos
• first measurement of total flux: $\nu_e + \nu_\mu + \nu_\tau$


1000t D_2O
9500 PMTs
GARTH TIETJEN


Creighton Mine (Nickel)
Sudbury, Canada

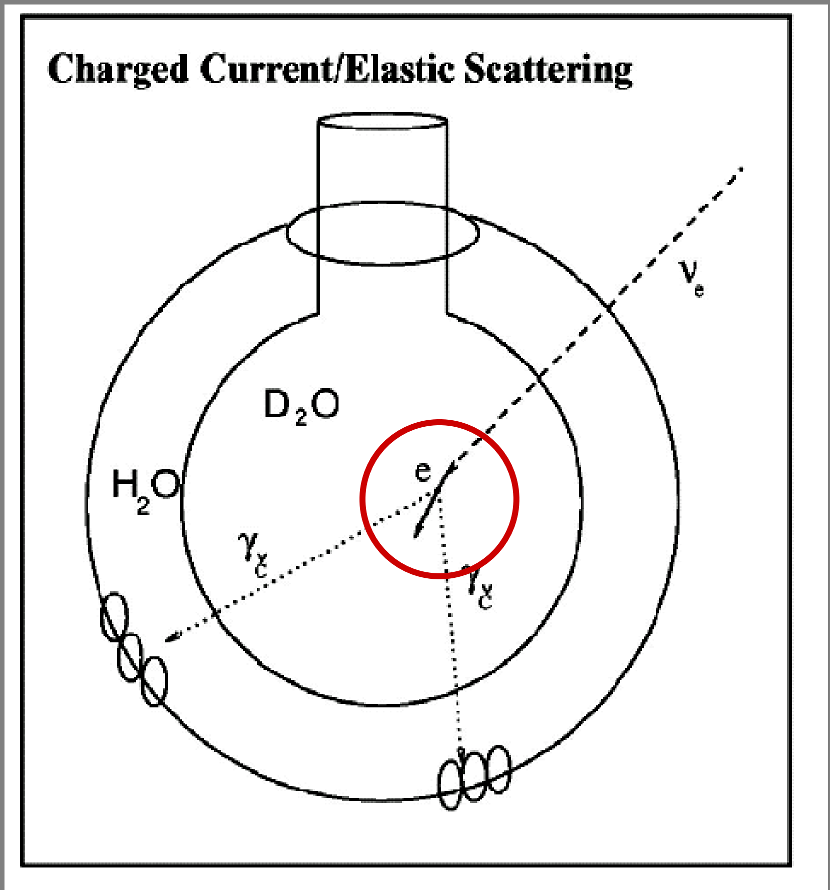

Depth 2070m

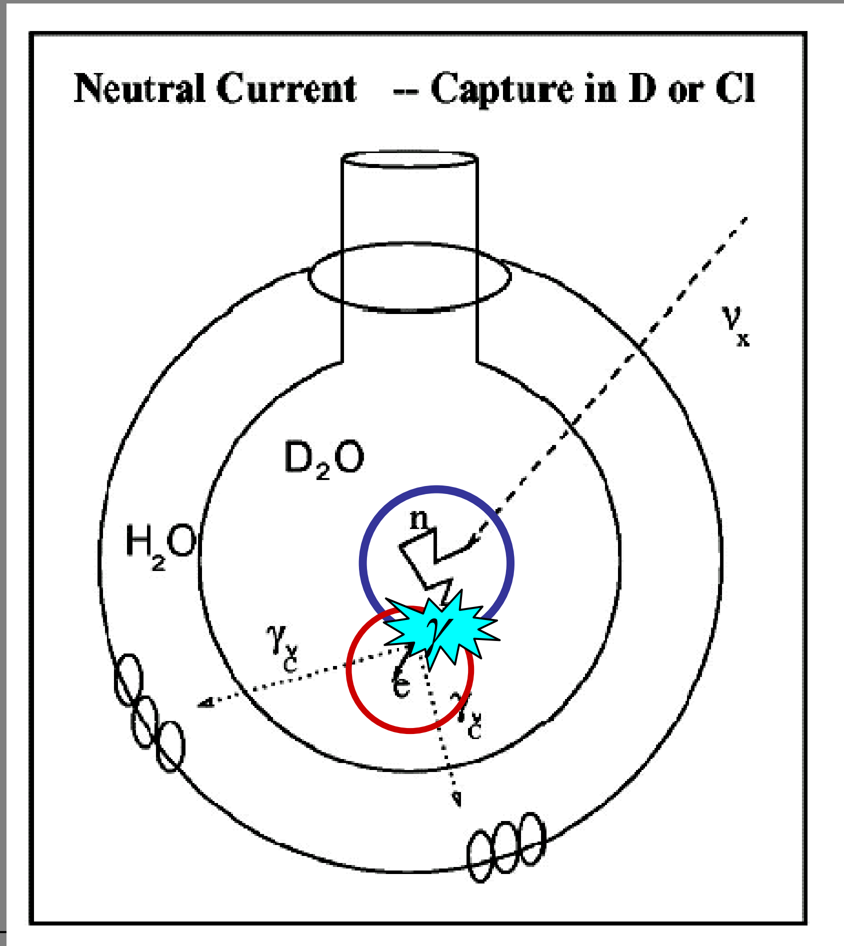
Neutrino detection in SNO

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

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

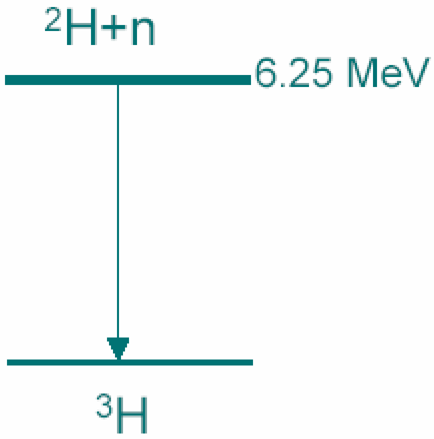
NC $\nu_x + d \rightarrow p + n + \nu_x$

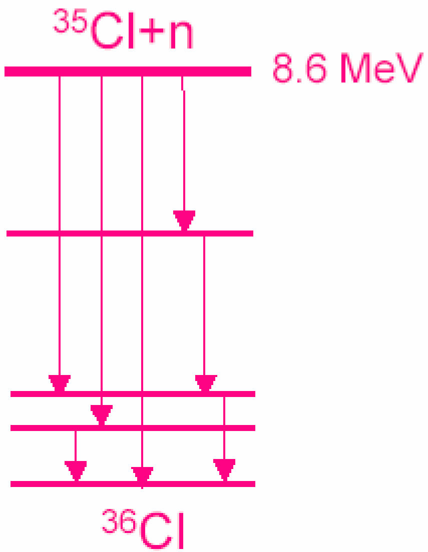




Neutron detction in SNO

Phase I (D_2O) Nov. 99 - May 01	**Phase II (salt)** July 01 - Sep. 03
n captures on $^{2}H(n, \gamma)^{3}H$ σ = 0.0005 b Observe 6.25 MeV γ PMT array readout Good CC	2 t NaCl. n captures on $^{35}Cl(n, \gamma)^{36}Cl$ σ = 44 b Observe multiple γ's PMT array readout Enhanced NC



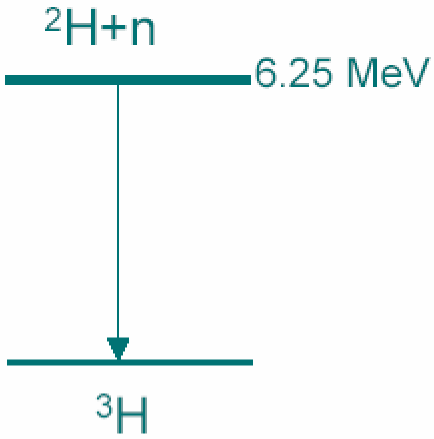


Neutron detction in SNO

Phase I (D_2O)

Nov. 99 - May 01

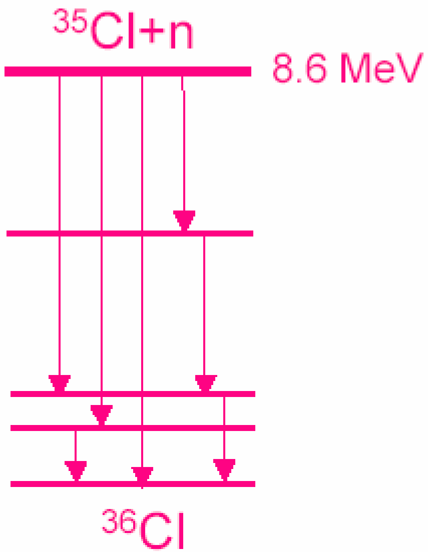
n captures on
$^2H(n, \gamma)^3H$
$\sigma = 0.0005$ b
Observe 6.25 MeV γ
PMT array readout
Good CC



Phase II (salt)

July 01 - Sep. 03

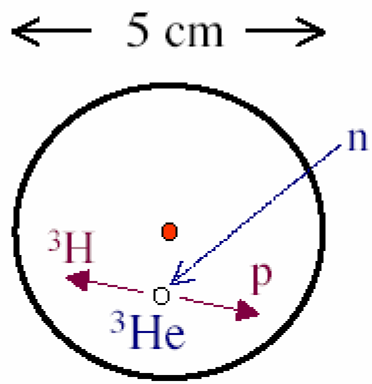
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
$\sigma = 44$ b
Observe multiple γ's
PMT array readout
Enhanced NC



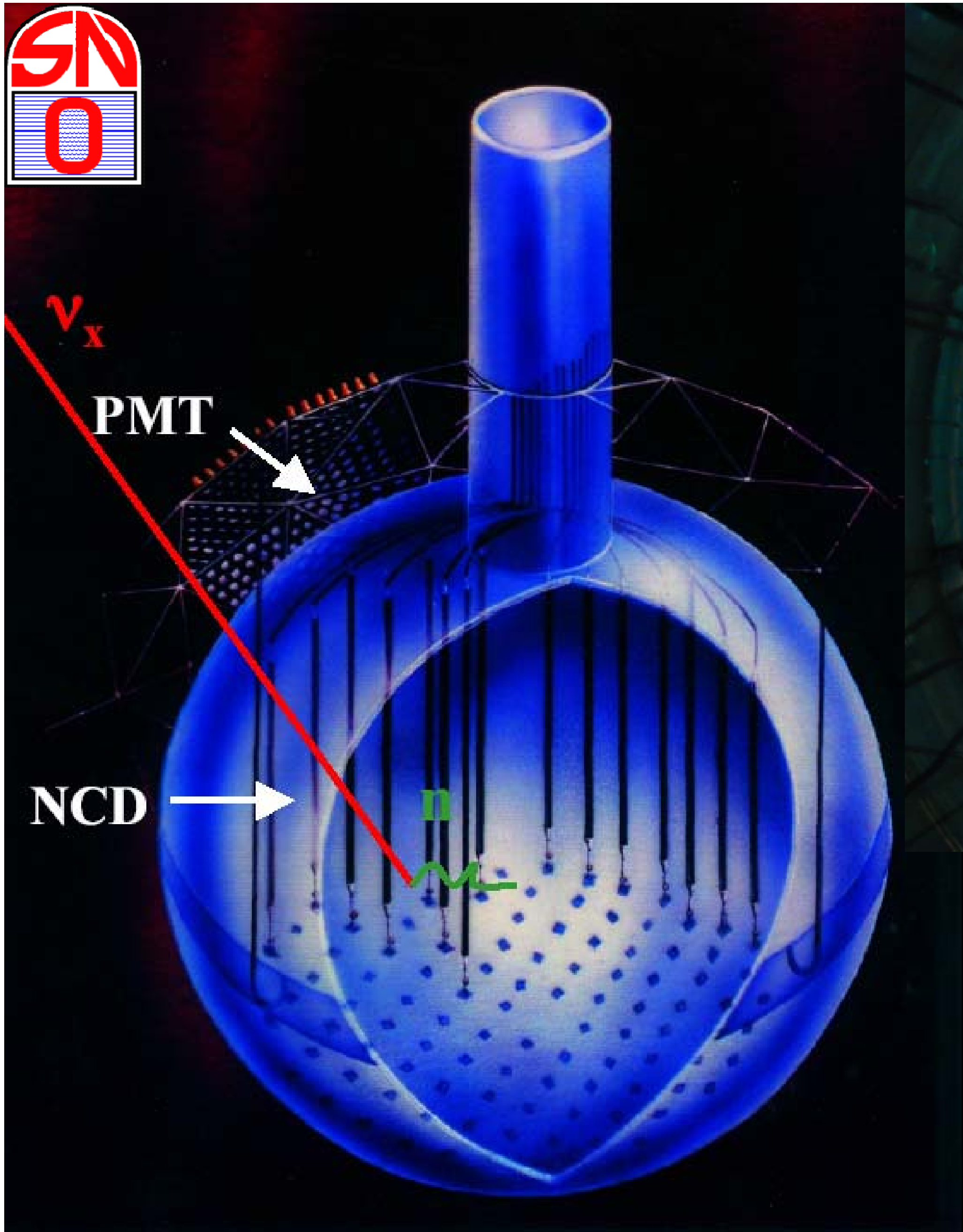
Phase III (^3He)

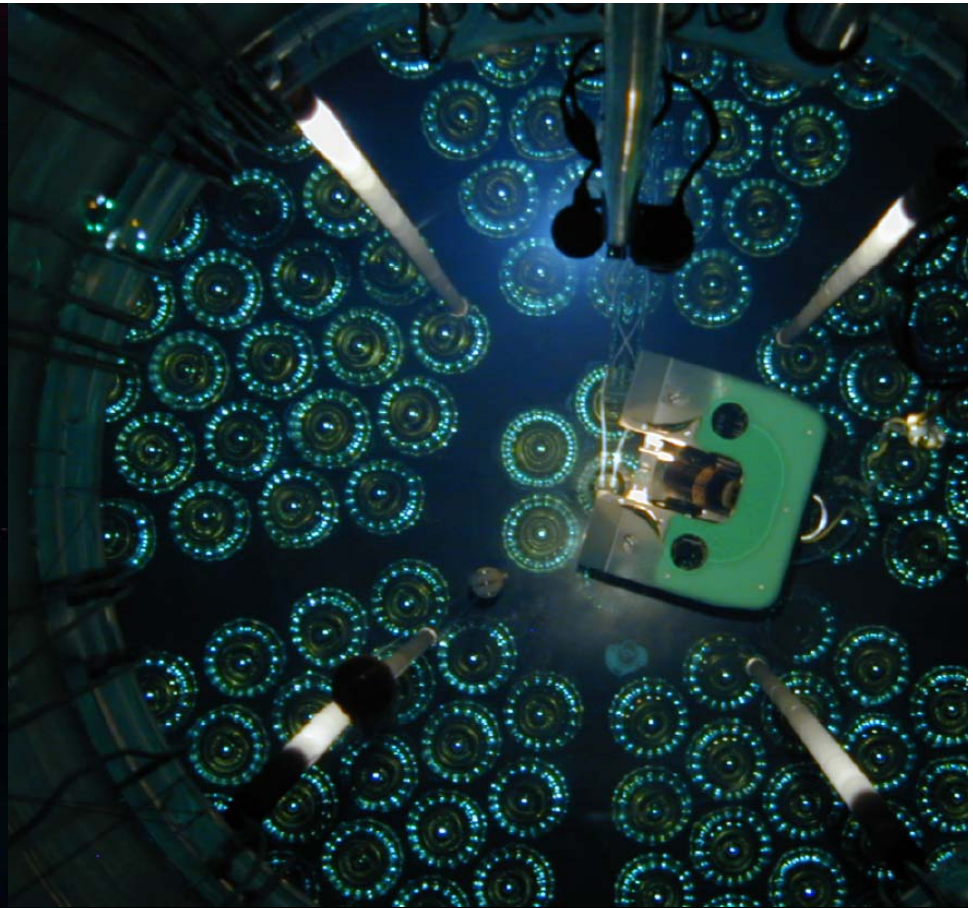
Summer 04 - Dec. 06

40 proportional counters
$^3He(n, p)^3H$
$\sigma = 5330$ b
Observe p and ^3H
PC independent readout
Event by Event Det.



$$n + {}^3He \rightarrow p + {}^3H$$


ν_x
PMT
NCD
n



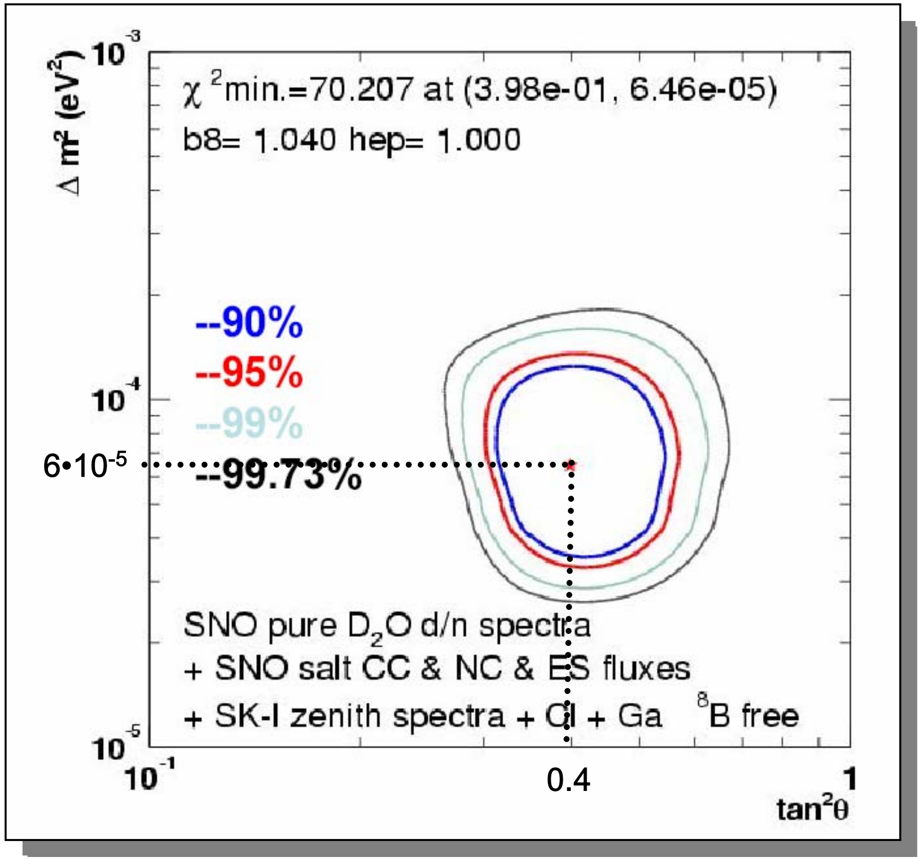
SNO Result (salt-phase)
(PRL 92, 181301, 2004)

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

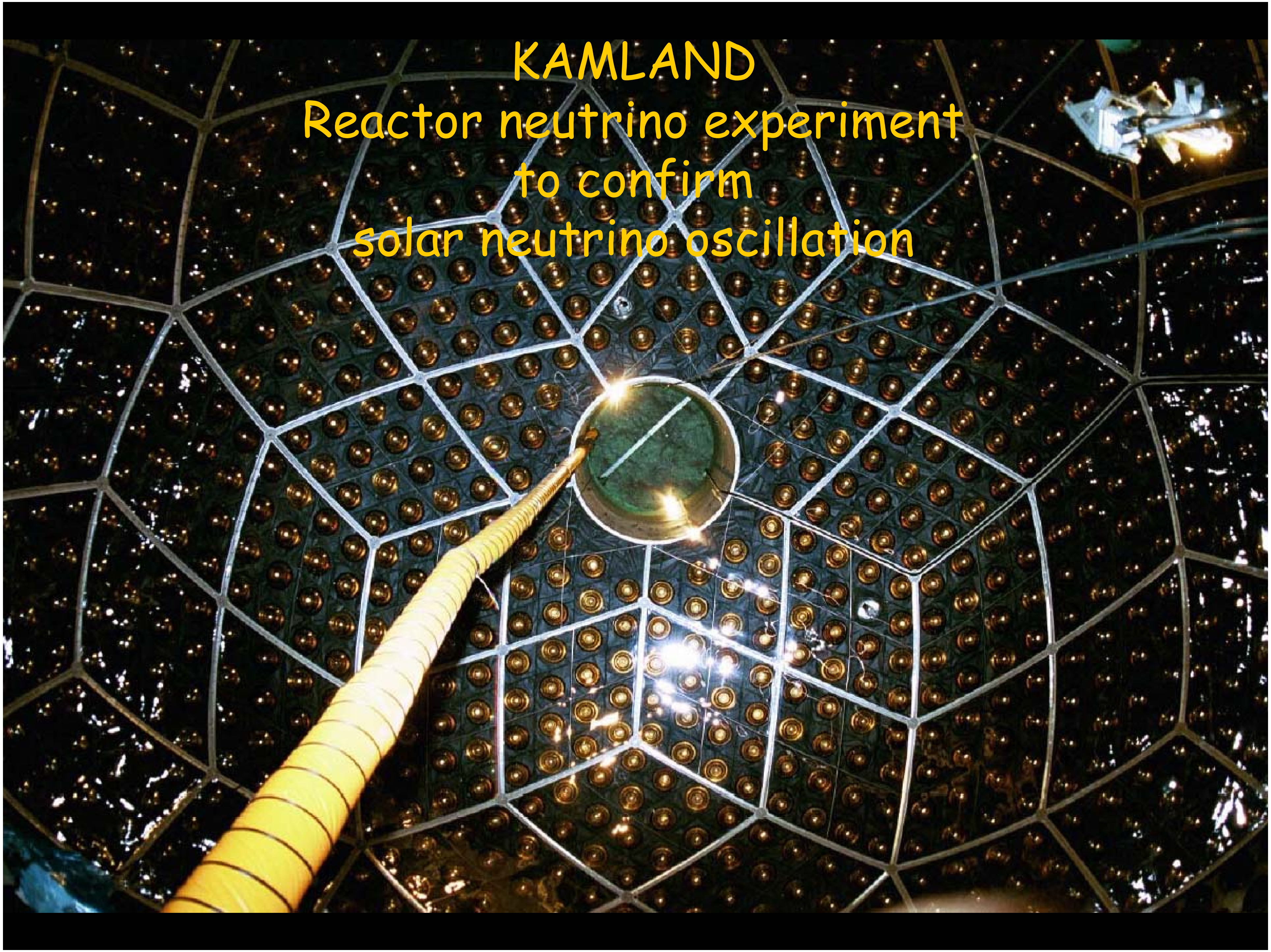
- 1/3 of solar ν_e arrive as ν_e on Earth
- 2/3 of solar ν_e arrive as ν_μ or ν_τ .
- Measured total flux = Predicted flux (Standard Solar Model)

Oscillation analysis of SNO (+ all solar neutrino experiments)

(Oscillation analysis: Matter effects, due to high density of electrons in the Sun, are important!)

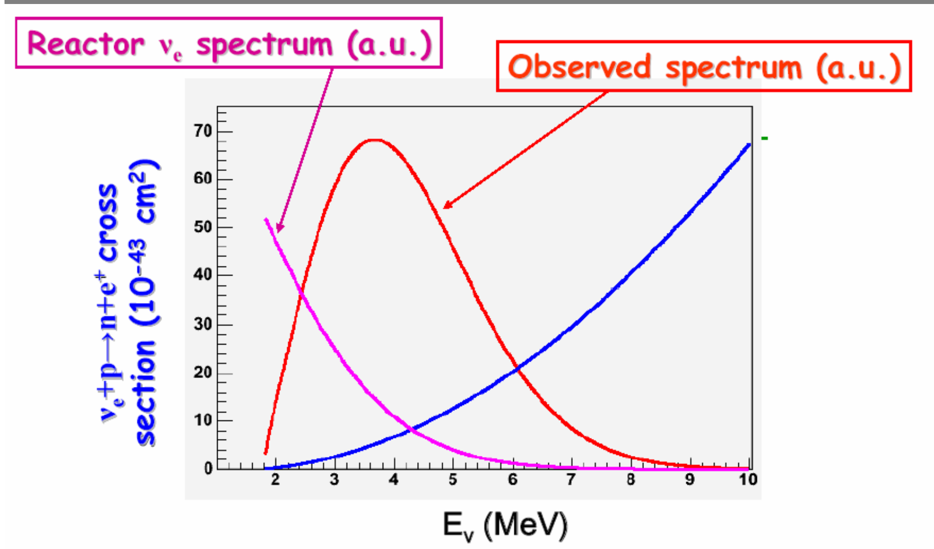


KAMLAND
Reactor neutrino experiment
to confirm
solar neutrino oscillation



KAMLAND

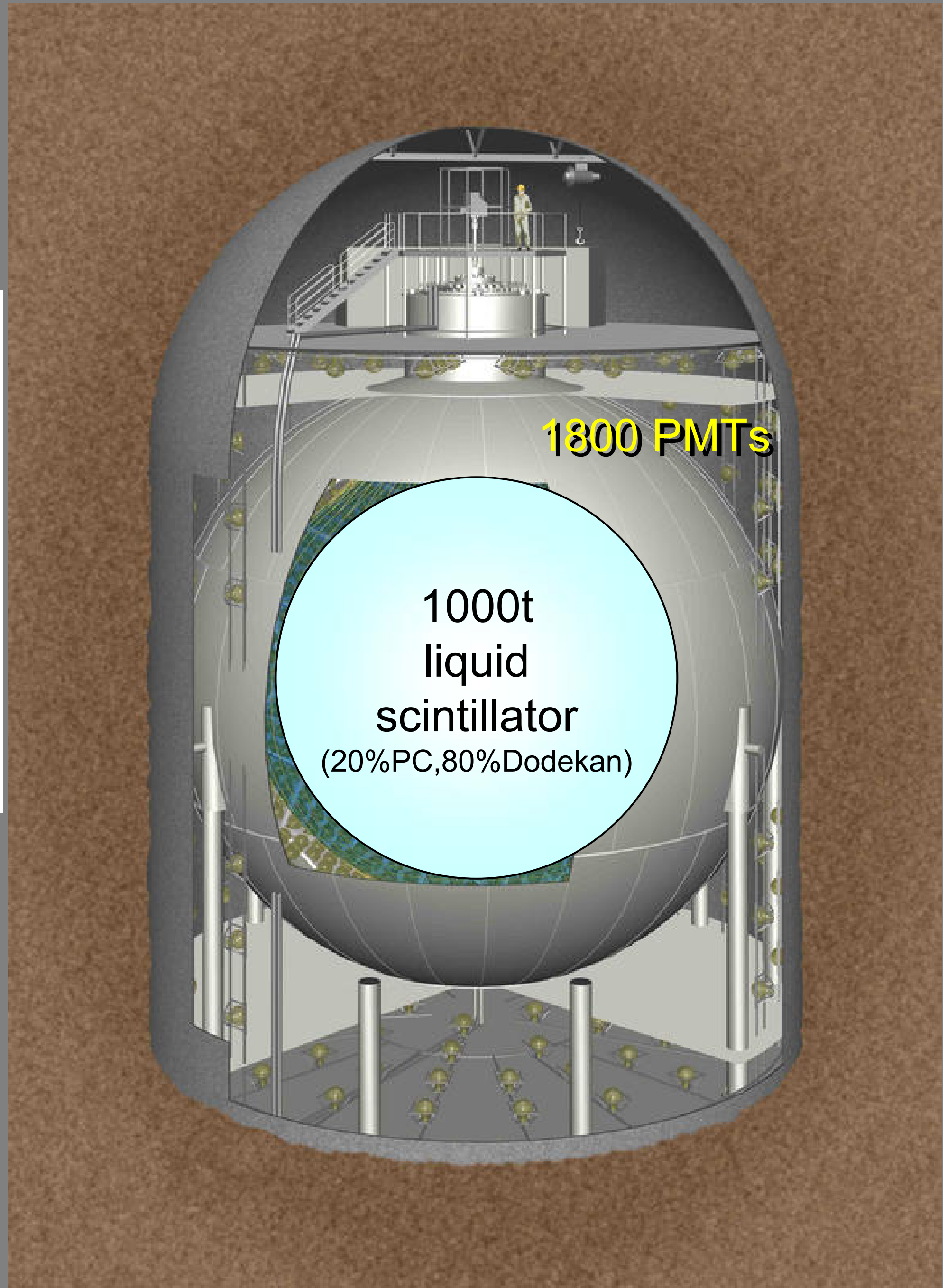
reactor neutrinos = $\bar{\nu}_e$



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

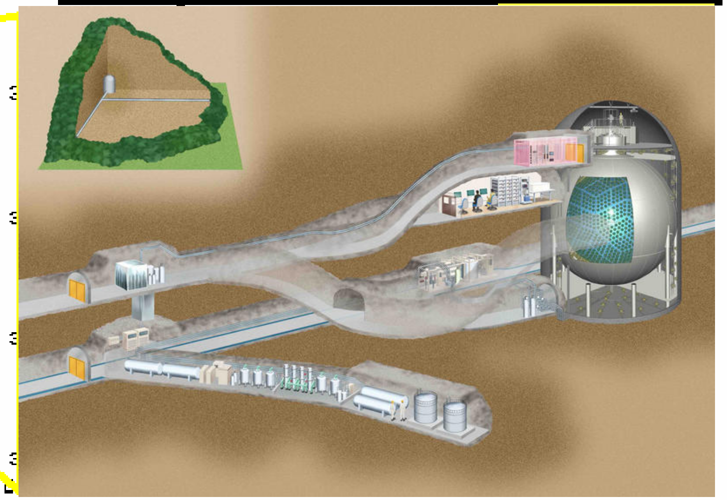
prompt signal
E_ν – 0.77MeV

delayed signal
$n + p \rightarrow d + \gamma(2.2\mathrm{MeV})$



Average distance
of reactors from KamLAND:
175km

	Site	Dist (km)	Rate noosc* (yr^{-1} kt^{-1})
Japan	Kashiwazaki	160	254.0
	Ohi	179	114.3
	Takahama	191	74.3
	Tsuruga	138	62.5
	Hamaoka	214	62.0
	Mihama	146	62.0
	Sika	88	55.2
	Fukushima1	349	31.1
	Fukushima2	345	29.5
	Tokai2	295	10.1
	Onagawa	431	9.3
	Simane	401	6.3
	Ikata	561	5.1
	Genkai	755	4.8
	Sendai	830	2.1
	Tomari	783	1.4



Test of solar Neutrino-Oscillations with Reactor Neutrinos

Average distance of japanese nuclear reactors
from KamLAND detector:
175km

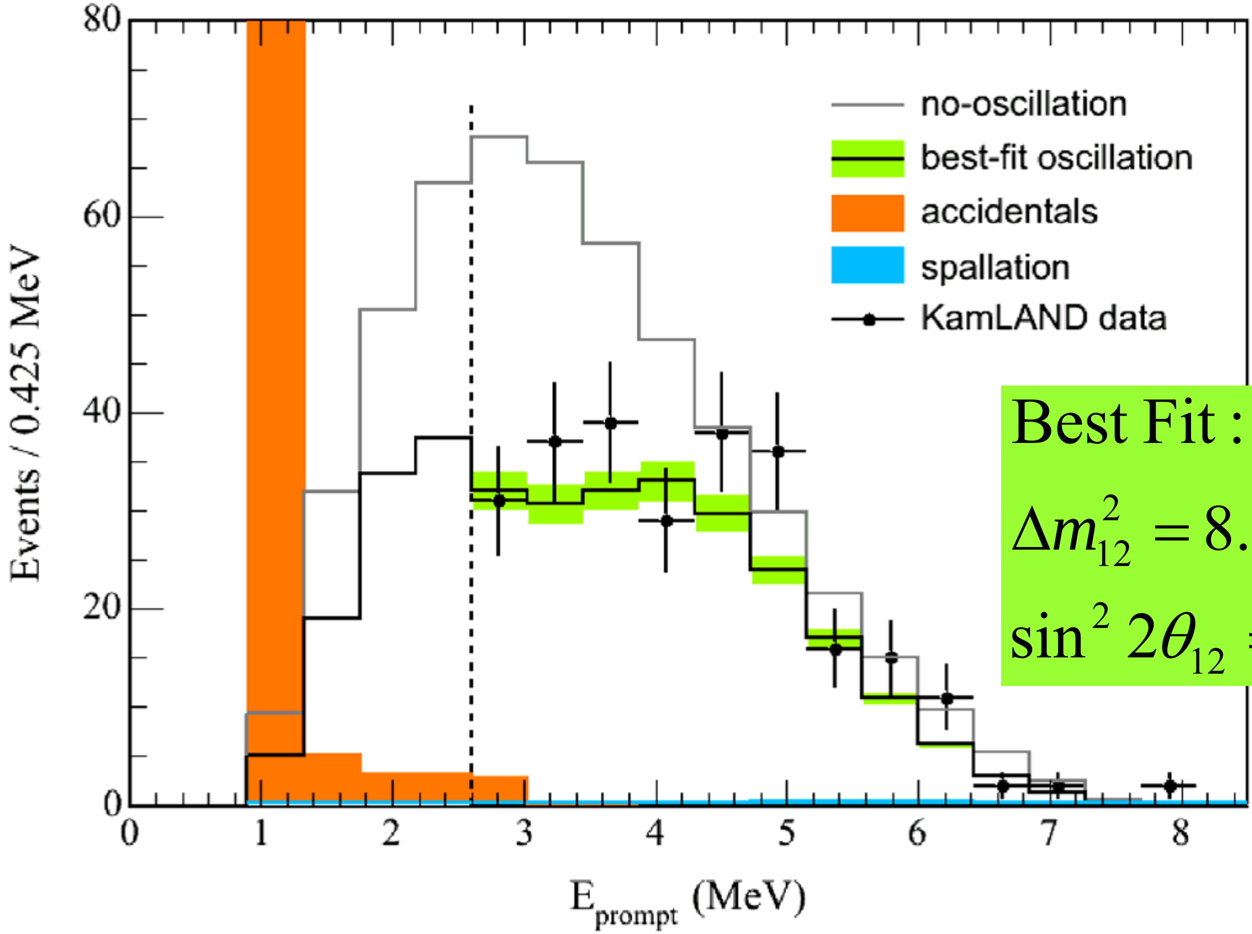
$$L_{osz}^{vac}[\mathrm{m}] = \frac{2.48 \cdot E_\nu[\mathrm{MeV}]}{\Delta \mathrm{m}^2[\mathrm{eV}^2]}$$

E (Reactor ν) ≈ 4MeV
Δm^2 (solar ν) = $8 \cdot 10^{-5} eV^2$

$$L_{osz} \approx \frac{2.5 \cdot 4}{8 \cdot 10^{-5}} \mathrm{m} = 125 \mathrm{km}$$

Test possible!

KamLAND Ergebnis (hep-ex/0406035)



Best Fit :

$$\Delta m_{12}^2 = 8.3 \times 10^{-5}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{12} = 0.83$$

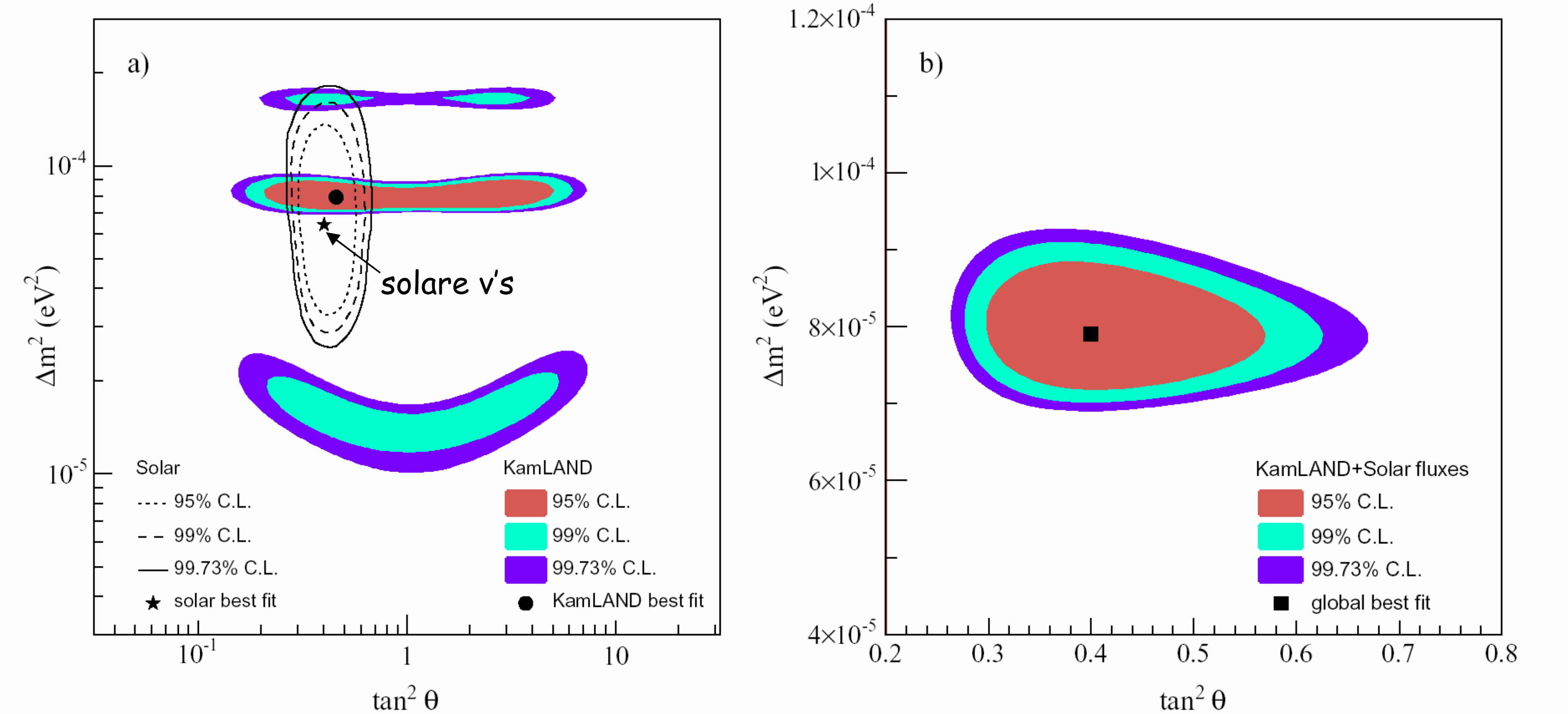
„First evidence of deformation in energy spectrum for reactor neutrinos“

Solar-ν & KamLAND: Δm^2_{12} and θ_{12}

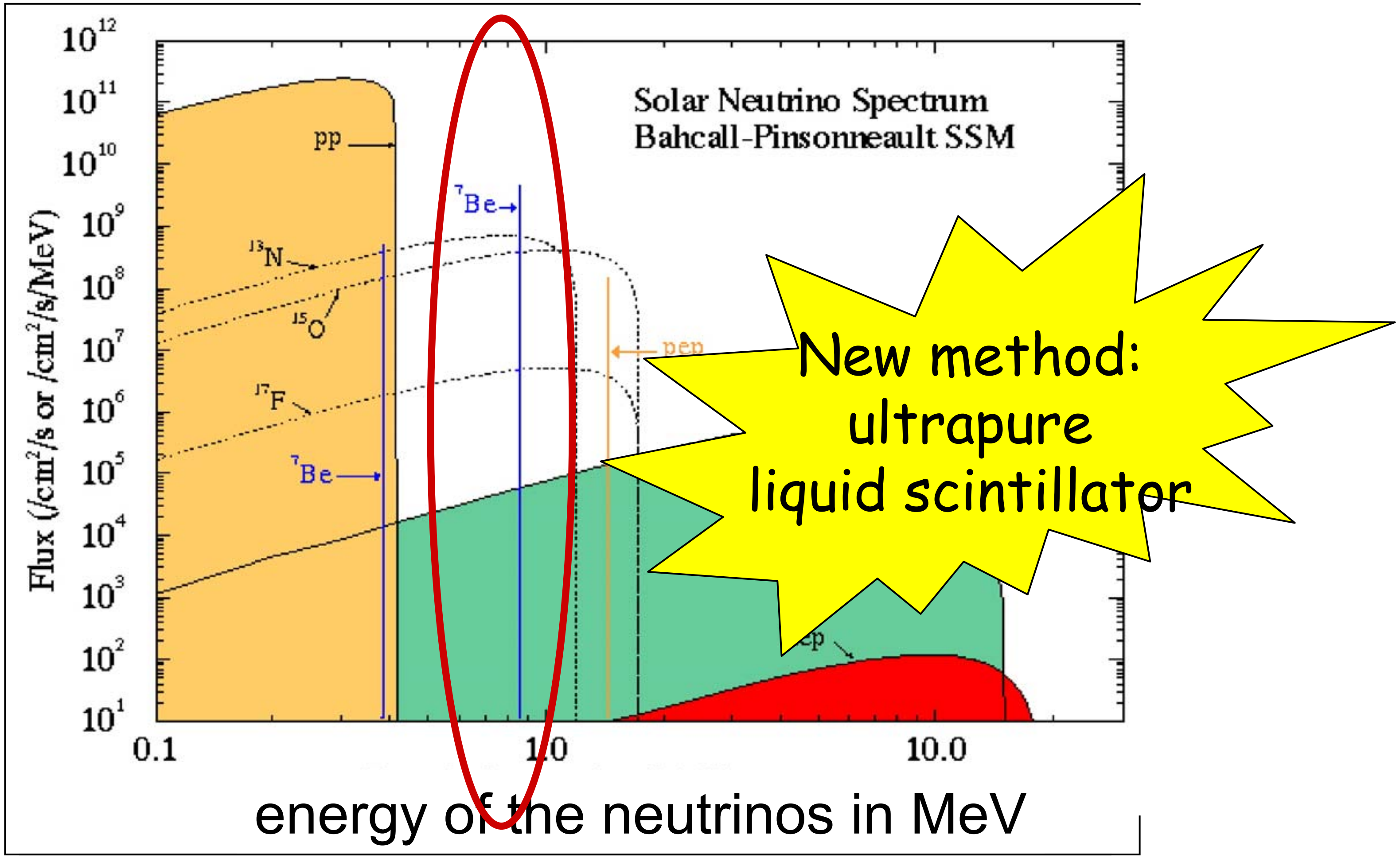
$\tan^2\theta_{12} = 0.40^{+0.10}_{-0.07}$, $\Delta m^2_{12} = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV^2 (1σ)

($\theta_{12} \approx 33^\circ \pm 5^\circ$)

$\theta_{12} + \theta_C = 45^\circ$?

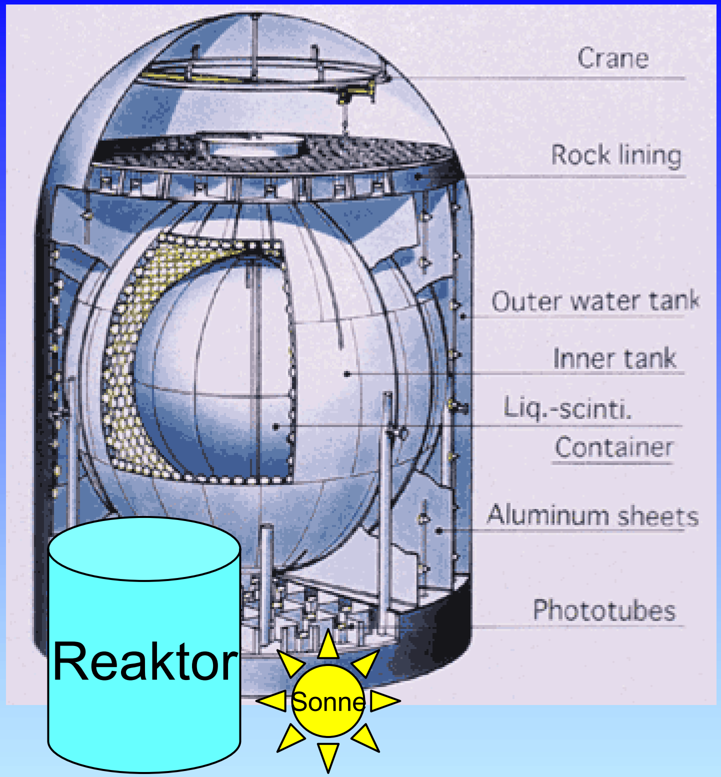


New Generation of Solar Neutrino Experiments



^{7}Be: E_ν = 860 keV, monoenergetic line

Kamland



- 1000t liquid scintillator
- $\langle L_{reaktor} \rangle$ = 175 km
- Kamioka Mine: 2700mwe

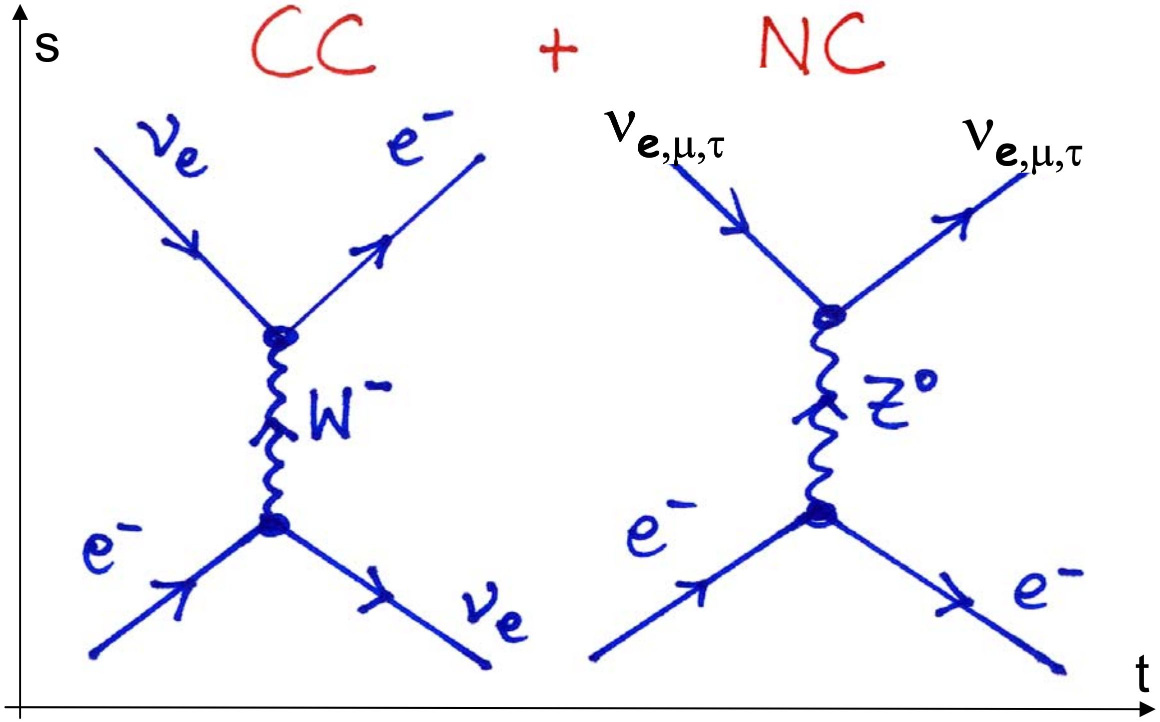
Borexino

- 300t liquid scintillator
  $\langle L_{reaktor} \rangle$ = 800 km
- Gran Sasso: 3600mwe

Detection of solar neutrinos in BOREXINO: Elastic neutrino – electron scattering

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(dominated by } \nu_e\text{)}$$

(Kinematics like Compton effect)

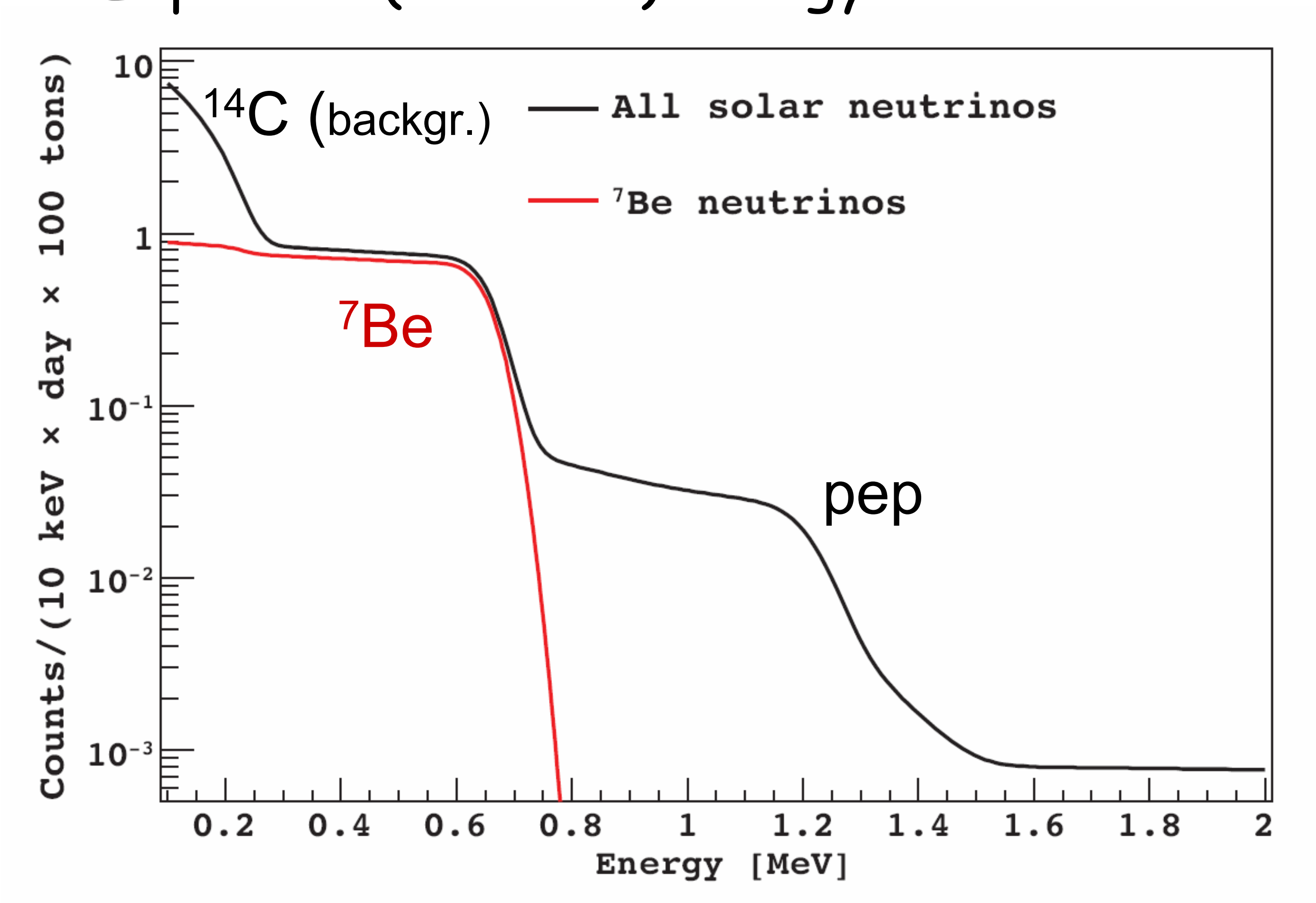


ν_e can interact via CC + NC

ν_μ and ν_τ can only interact via NC!

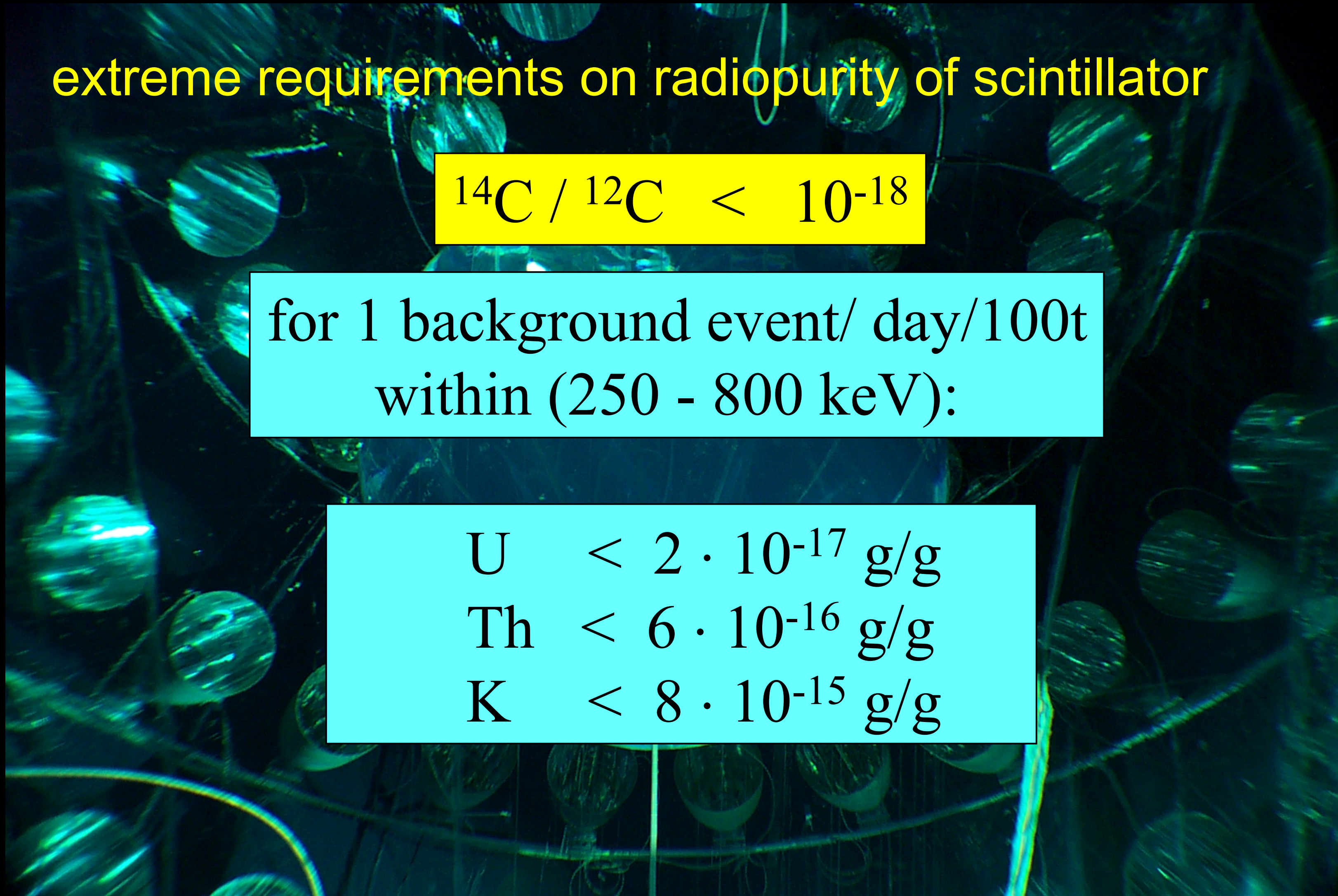
BOREXINO

Expected (electron) energy distribution:



Edge at 665 keV

Technical challenge for Borexino & KamLAND



extreme requirements on radiopurity of scintillator

$^{14}C \,/\, ^{12}C \;<\; 10^{-18}$

for 1 background event/ day/100t within (250 - 800 keV):

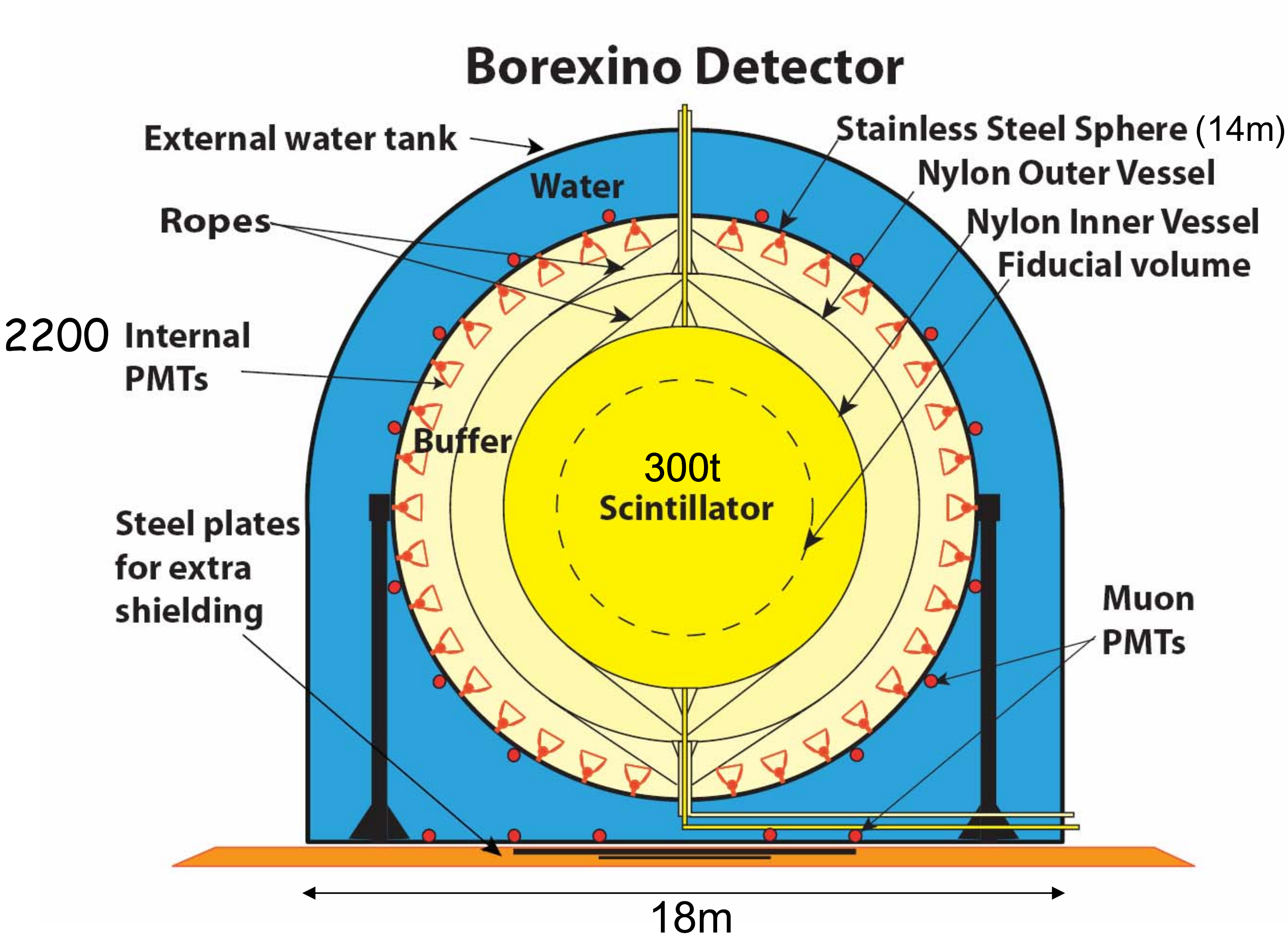
$U \;<\; 2 \cdot 10^{-17}$ g/g

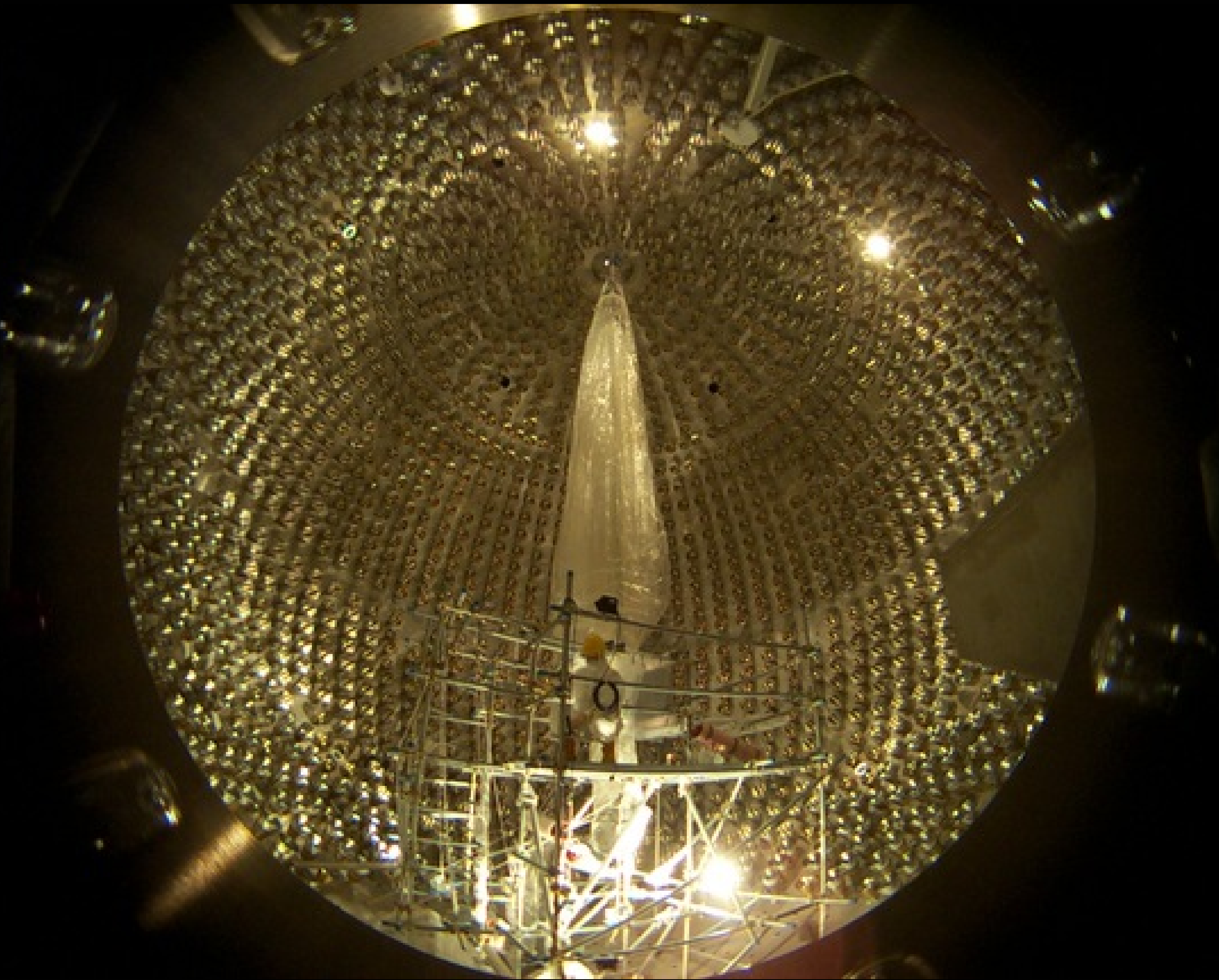
$Th \;<\; 6 \cdot 10^{-16}$ g/g

$K \;<\; 8 \cdot 10^{-15}$ g/g

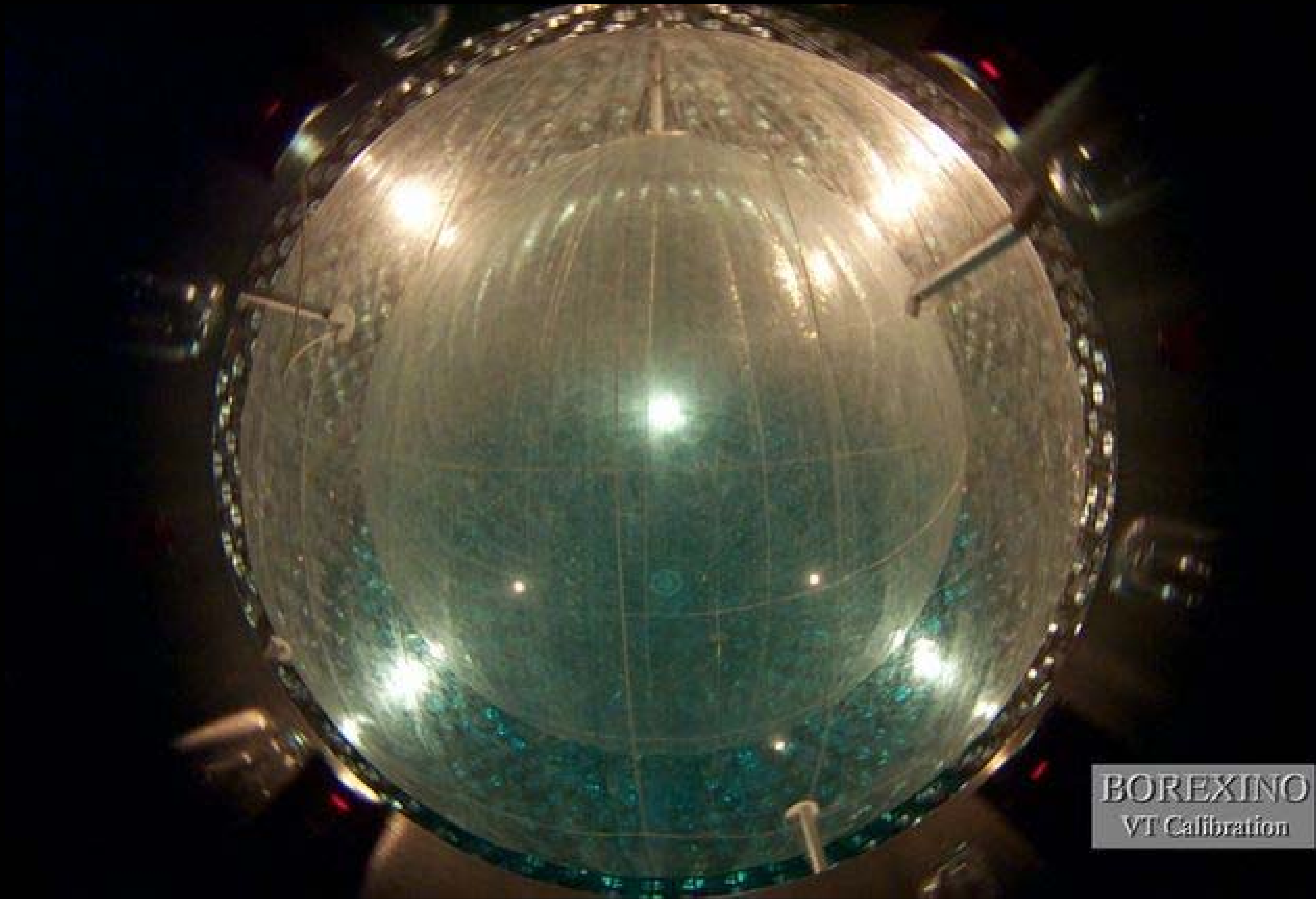
CTF (Borexino)

BOREXINO @ LNGS



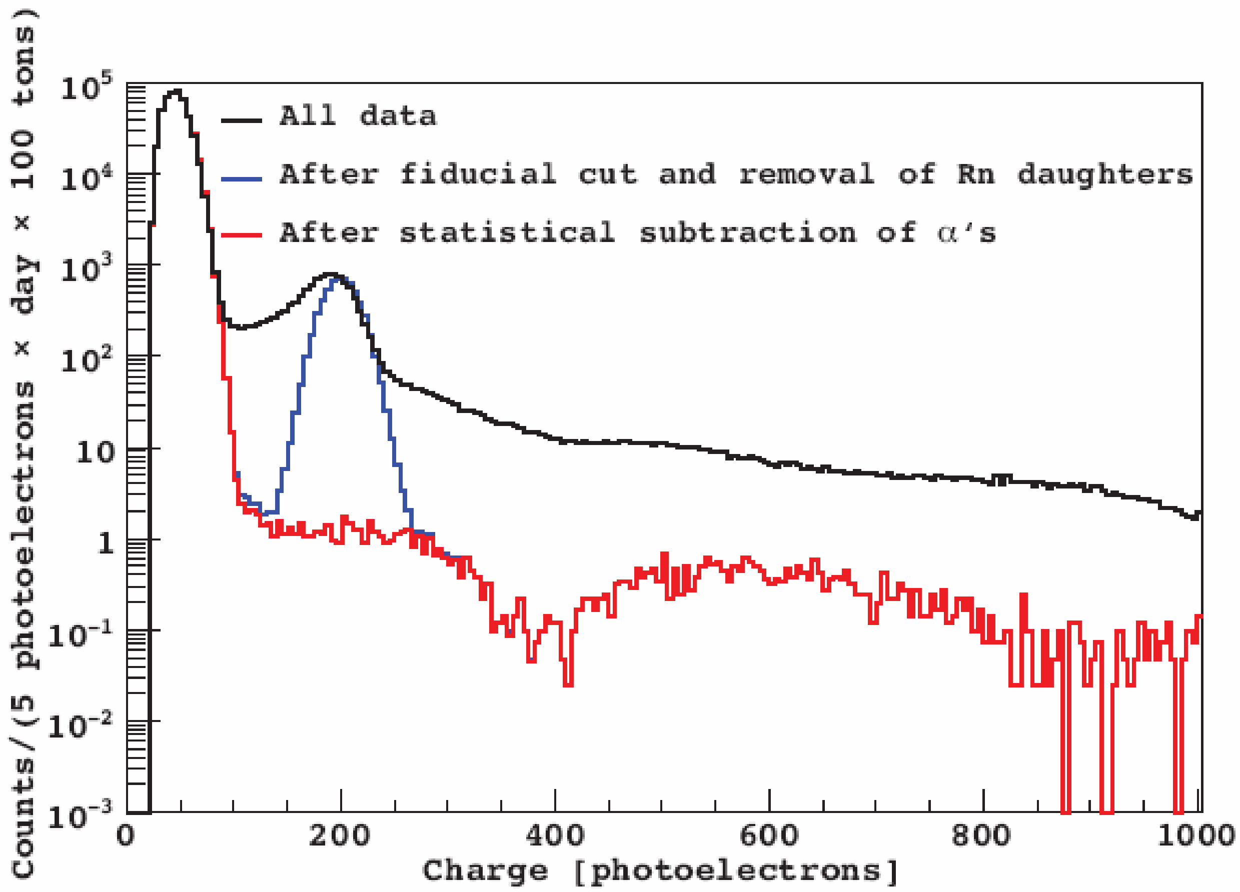


Installation of the 2 inner nylon spheres



Scintillator filling completed May 15, 2007

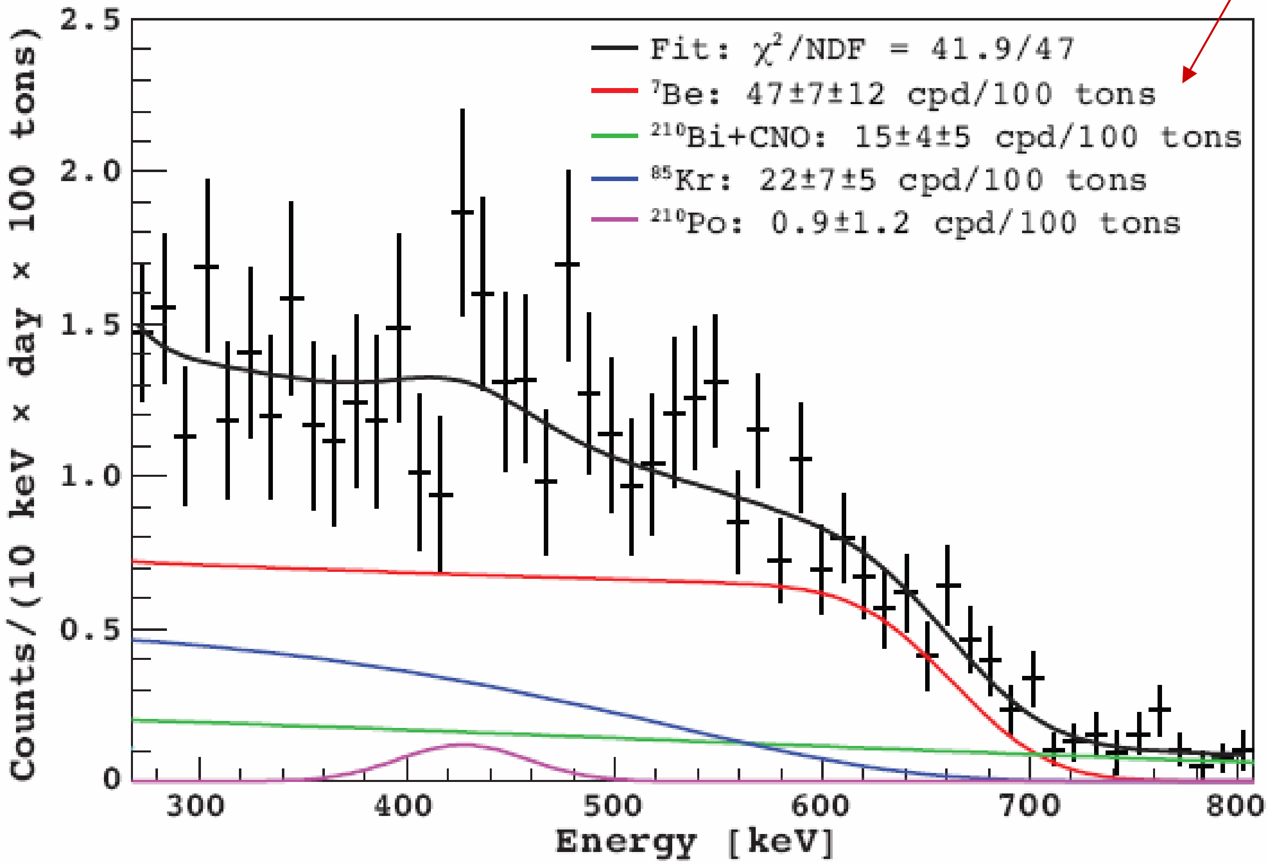
BOREXINO



All data
After fiducial cut and removal of Rn daughters
After statistical subtraction of α's
Counts/(5 photoelectrons × day × 100 tons)
Charge [photoelectrons]
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
0
200
400
600
800
1000

NEW! First BOREXINO Result

Expected for oscillation 49±4 cpd/100 tons



arXiv:0708.2251v1: "First real time detection of ^{7}Be solar neutrinos by Borexino" , 16.8.07 (submitted to PRLB)

Summary

- 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?
- The third mixing angle must be measured
- 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 you!