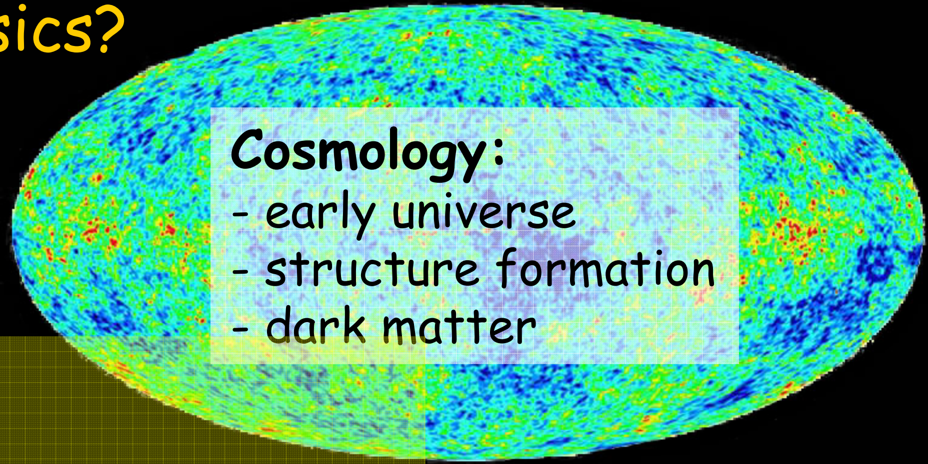
Neutrino Physics

Caren Hagner, Universität Hamburg

Part 1:
- What are neutrinos?
- Neutrino interactions, sources and detectors
- Majorana neutrinos
- Neutrino mass and mixing
- Neutrino oscillations
- Oscillations of atmospheric neutrinos (SuperK)

Part 2:
- Neutrino beams:
  Oscillation of accelerator neutrinos (OPERA)
- Solar neutrinos:
  Oscillation of solar neutrinos
  (Homestake, SNO)
- KamLAND reactor neutrino experiment

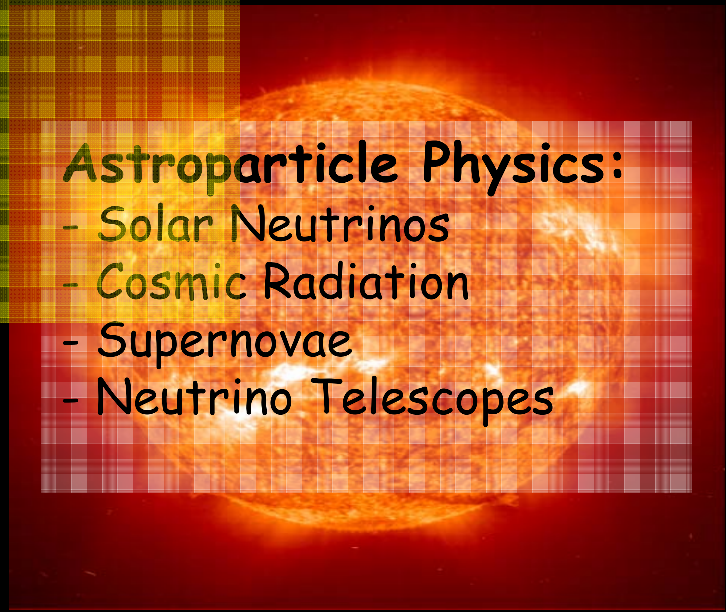
Why are we doing Neutrino Physics?



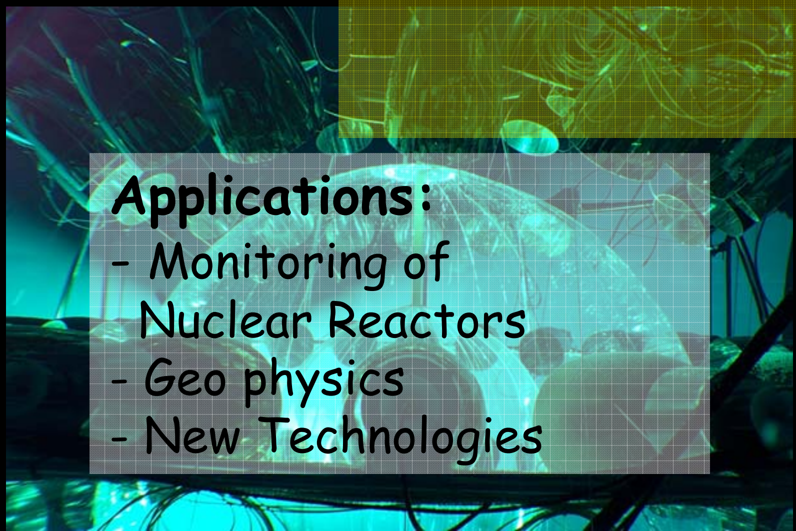
Cosmology:
- early universe
- structure formation
- dark matter

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

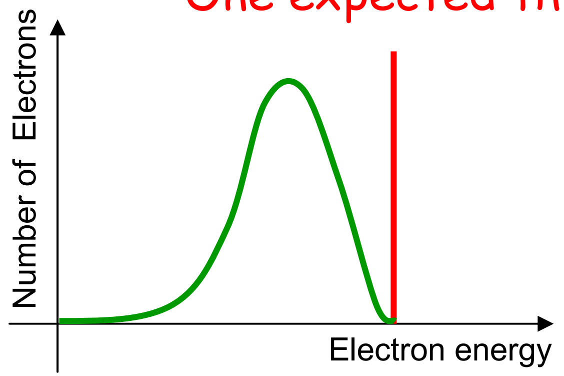
Wolfgang Pauli postulates the Neutrino (1930)

Energy spectrum of electrons from β-decay

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

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

One expected this

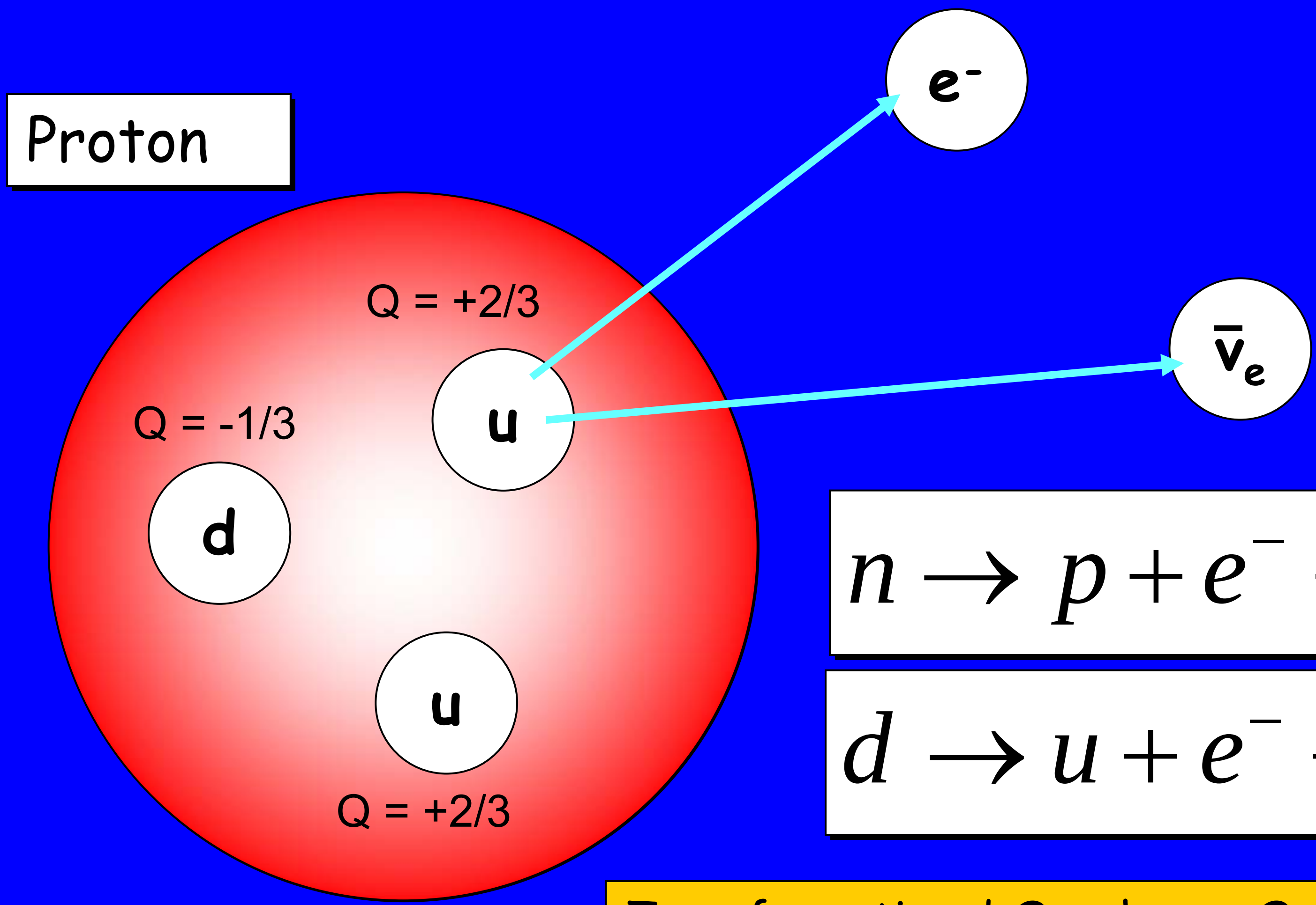


But this was observed!

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

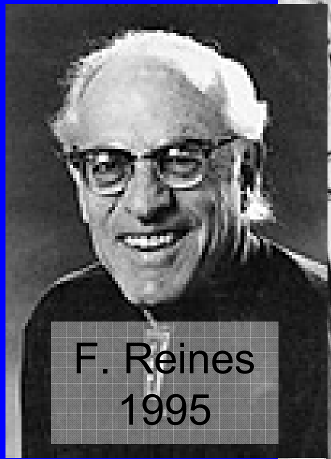


$$n \rightarrow p + e^- + \bar{\nu}_e$$

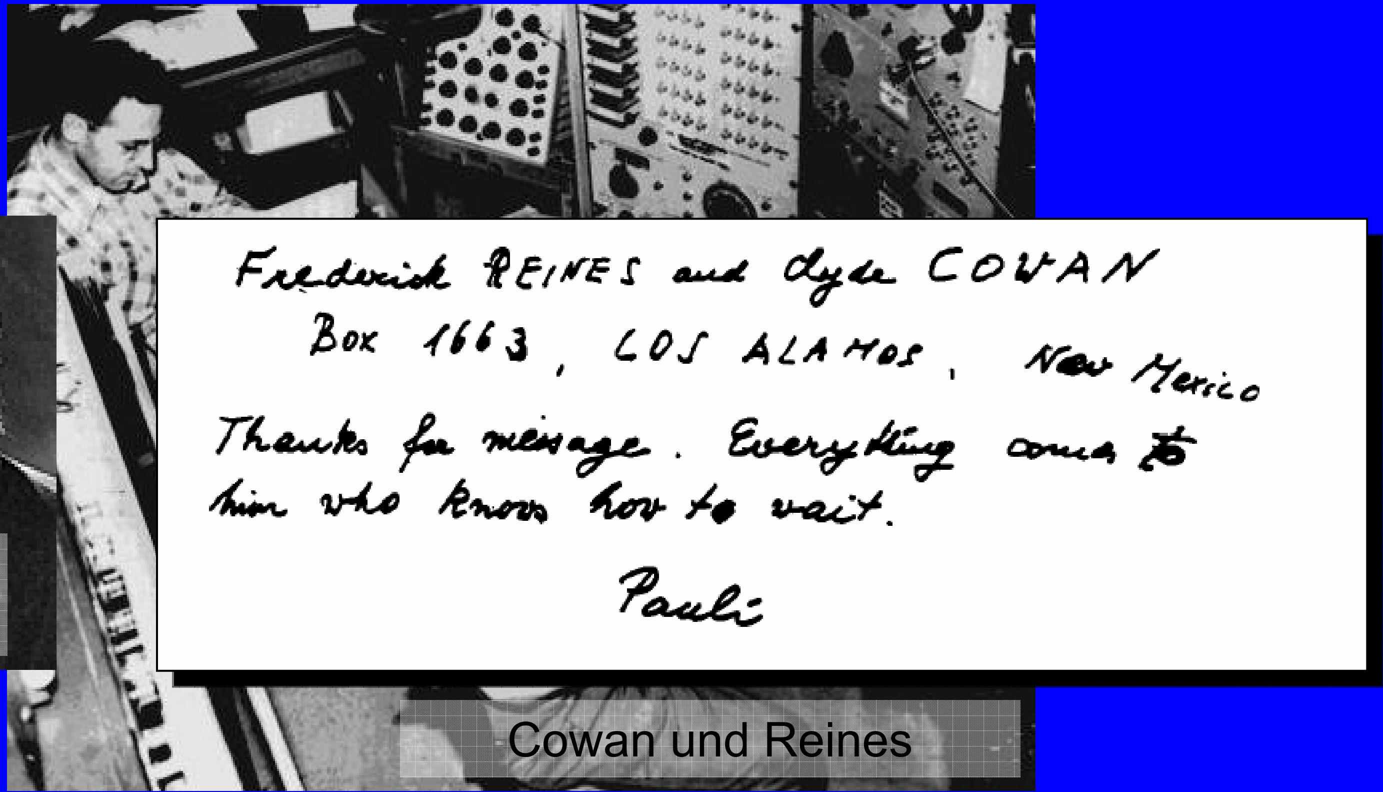
$$d \rightarrow u + e^- + \bar{\nu}_e$$

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

First Detection of a Neutrino: 1956



F. Reines 1995



Cowan und Reines

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

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

Pauli

- Neutrino source: Nuclear reactor
- Detection Method: $\bar{\nu}_e + p \rightarrow e^+ + n$
- 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

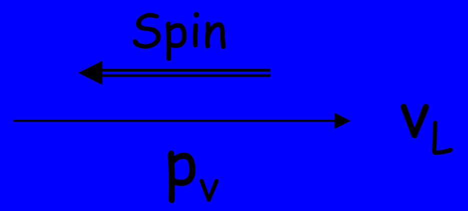
Leptons:

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 ½
- In the Standard Model:
  massless, stable, always left handed!

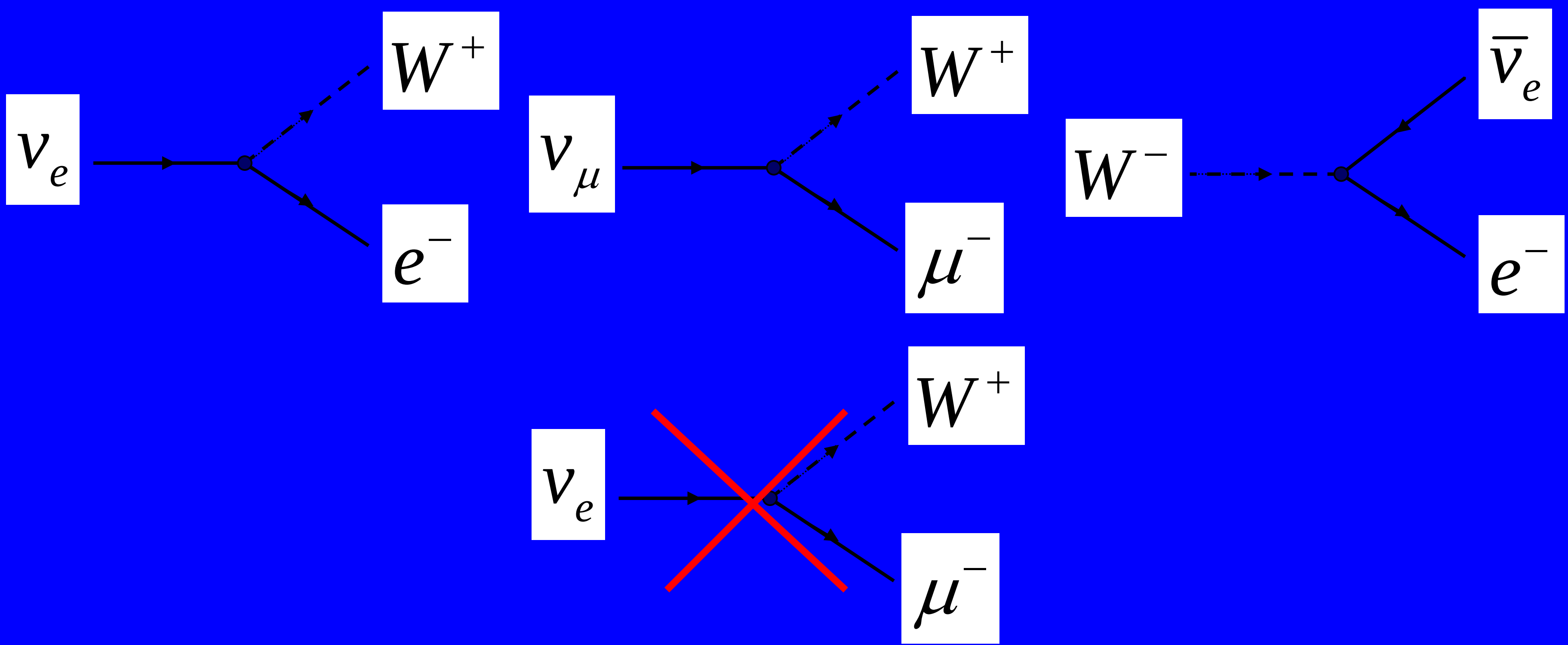


- **BUT:** Today we know that neutrinos have mass
  0.05 meV < m_ν < 2 eV
  Standard Model must be extended!
- Are Neutrinos and Anti-Neutrinos identical?
- many other properties are still unknown:
  sterile neutrinos?, CP-violation?, neutrino decay?, magnetic moment?...

How Neutrinos interact

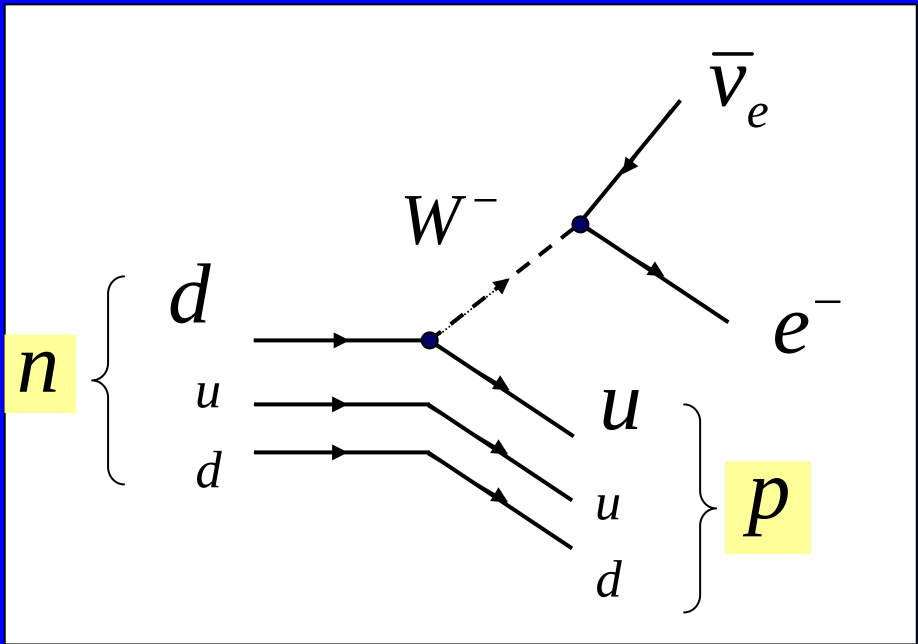
- The weak interaction

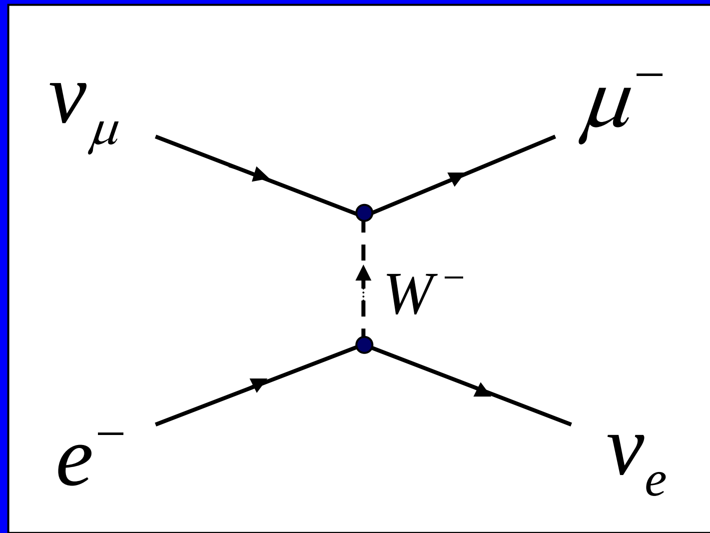
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

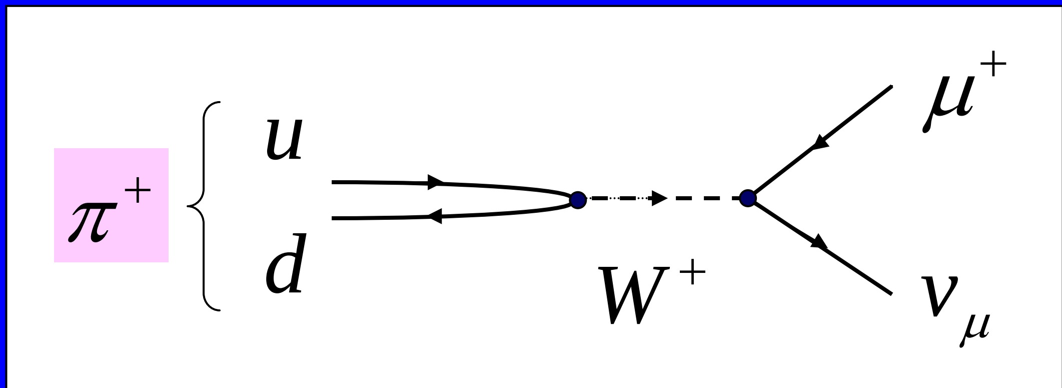


Charged Current

- Exchange of a W Boson:

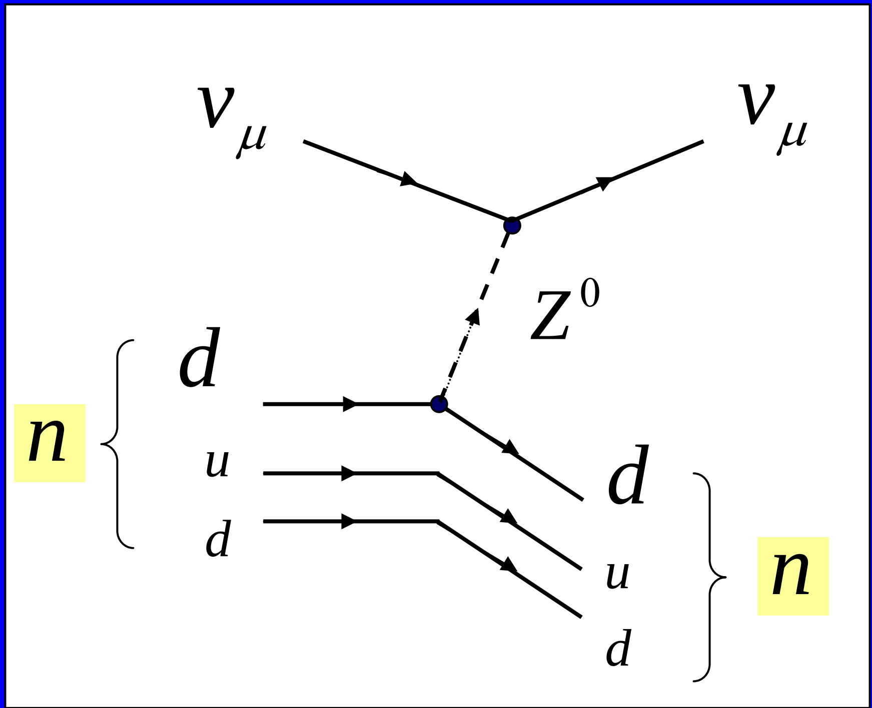


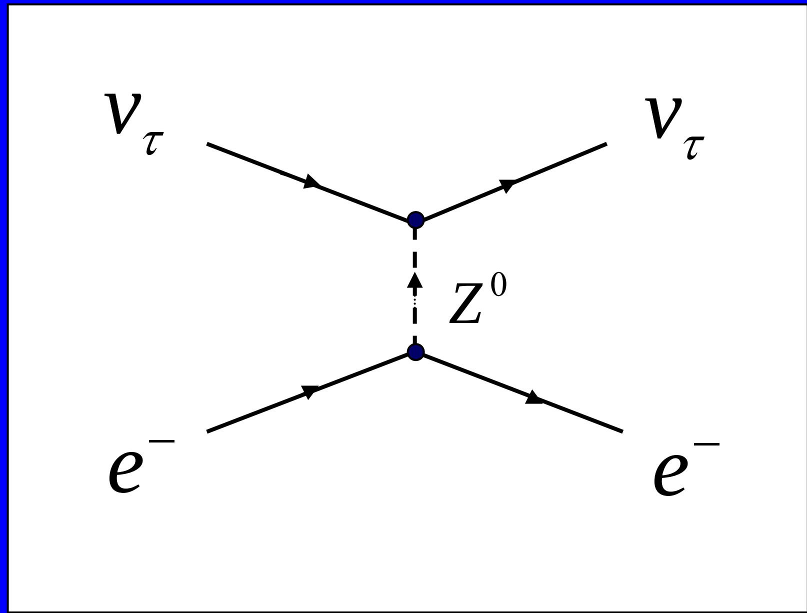




Neutral Current

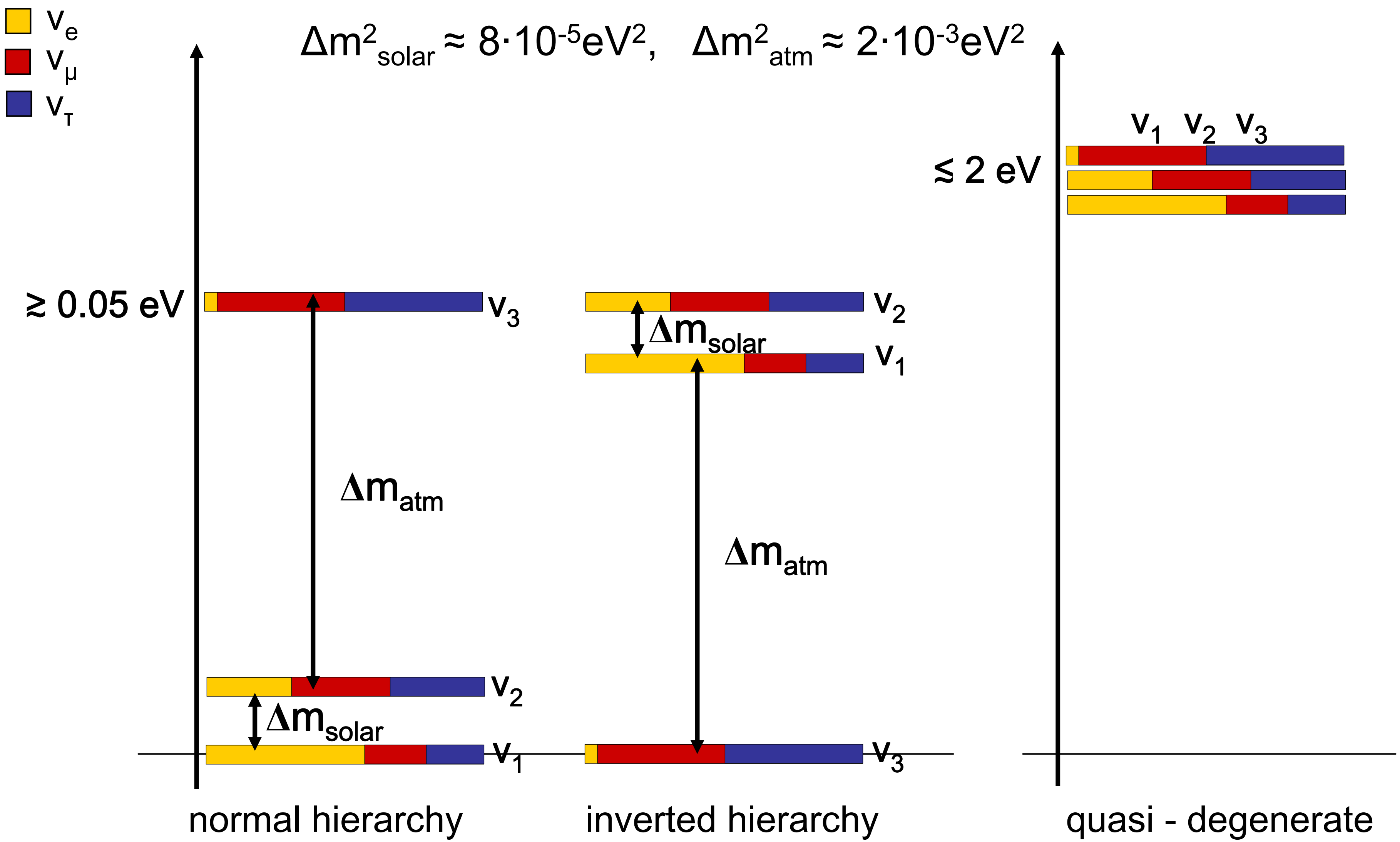
- Exchange of a Z^0 Boson:





What do we know about neutrino masses?

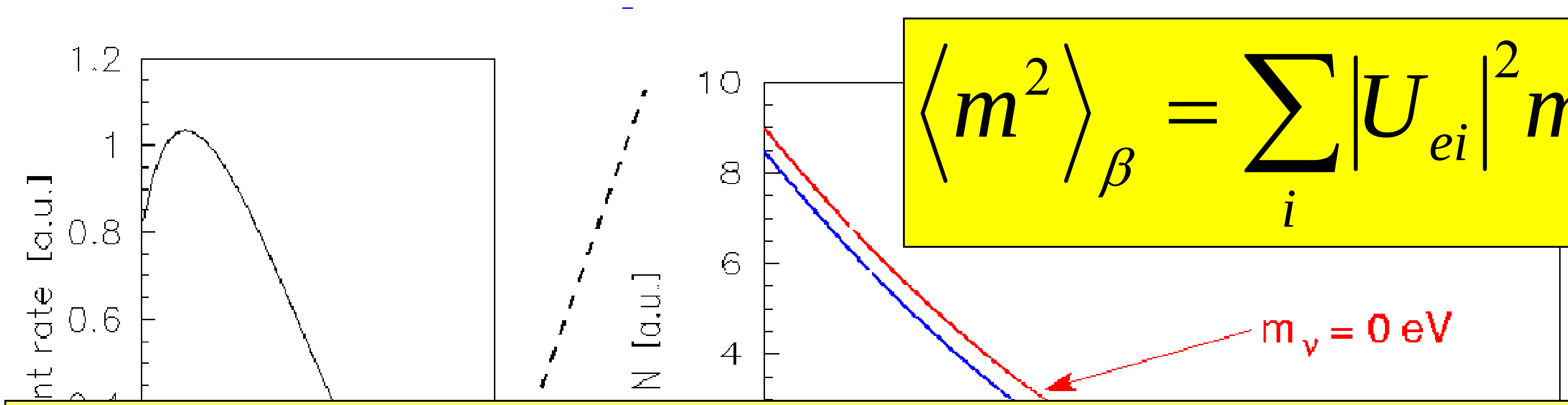
$\Delta m^2_{solar} \approx 8 \cdot 10^{-5} eV^2$, $\Delta m^2_{atm} \approx 2 \cdot 10^{-3} eV^2$



Tritium β-Decay: Mainz/Troitsk

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \mathrm{e}^{-} + \overline{\nu}_{e}$$ E_0 = 18.6 keV

$$dN/dE = K \times F(E,Z) \times p \times E_{tot} \times (E_0 - E_e) \times [\,(E_0 - E_e)^2 - \mathbf{m_\nu^2}\,]^{1/2}$$



$$\langle m^2 \rangle_\beta = \sum_i |U_{ei}|^2 m_i^2$$

Mainz Data (1998,1999,2001)

$$\langle m^2 \rangle_\beta = -1.2 \pm 2.2 \pm 2.1\ \mathrm{eV}^2 \quad \Rightarrow \quad \langle m \rangle_\beta < 2.2\mathrm{eV}\ (95\%\mathrm{CL})$$

KATRIN: delivery of vacuum vessel (2008)

goal:

$$\langle m \rangle_\beta < 0.20 \text{ eV}$$

Are Neutrinos Majorana Particles?

Because neutrinos carry no electric charge (and no color charge), there is the possibility:

particle ≡ anti-particle

Majorana particle

particle ψ

anti-particle (charge conjugate field): $\psi^c = C\overline{\psi}^T$

for a Majorana particle: $\psi_M^c = \pm\psi_M$

But what about experiments?

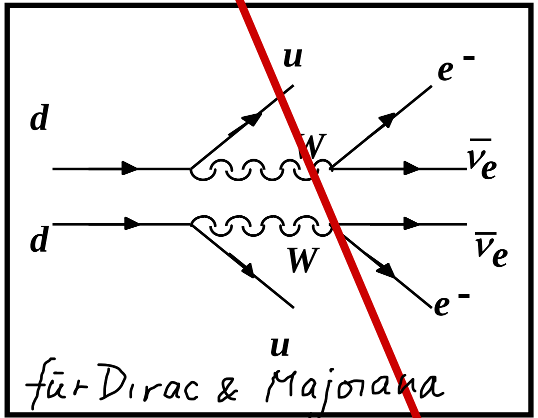
Neutrinos (solar): $\nu_{eL} + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^-$ observed!

Anti-neutrinos(reactor): $\nu_{eR} + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^-$ not observed!

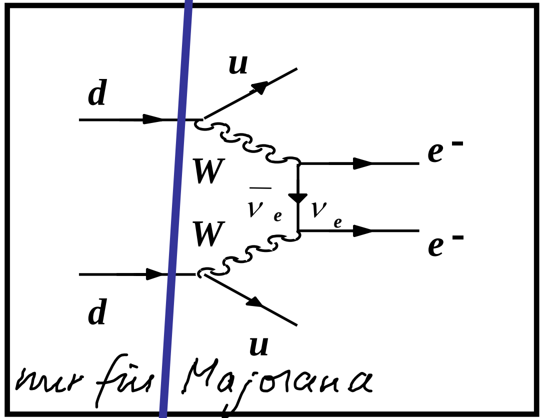
There are two different states per flavor
but the difference could be due to left-handed and right-handed states!

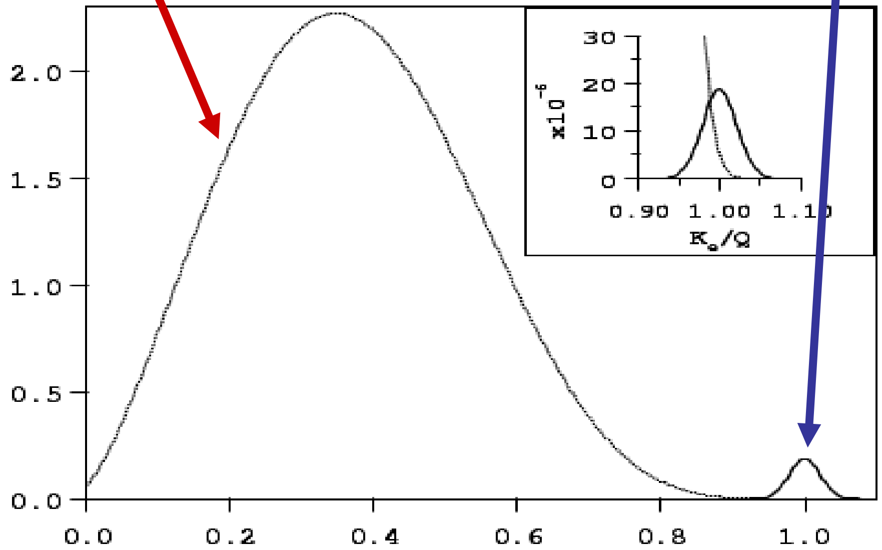
2ν and 0ν double beta - decay

2ν - ββ decay 1987 erstmals beobachtet



0ν - ββ decay





Sum energy of electrons (E/Q)

0ν Doppel-Beta experiments: results

$$\langle m \rangle_{\beta\beta} < 0.35\,\mathrm{eV}\ \ (90\%\ \mathrm{CL})$$

Heidelberg-Moskau Collaboration, Eur.Phys.J. A12 (2001) 147
IGEX Collaboration, hep-ex/0202026, Phys. Rev. C59 (1999) 2108

Isotope	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu \rangle$ (eV)
^{48}Ca	$> 9.5 \times 10^{21} (76\%)$	< 8.3
^{76}Ge	$> 1.9 \times 10^{25}$ HM-K	< 0.35
	$> 1.6 \times 10^{25}$ IGEX	$< 0.33 - 1.35$
^{82}Se	$> 2.7 \times 10^{22} (68\%)$	< 5
^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
^{116}Cd	$> 7 \times 10^{22}$	< 2.6
^{128}Te	$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$
^{130}Te	$> 2.1 \times 10^{23}$	$< 0.85 - 2.1$
^{136}Xe	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
^{150}Nd	$> 1.2 \times 10^{21}$	< 3

all 90%CL

Heidelberg-Moskau Experiment (HDM)

5 Ge-Detektoren
(angereichert mit ^{76}Ge)

„Die Detektoren zerfallen!"

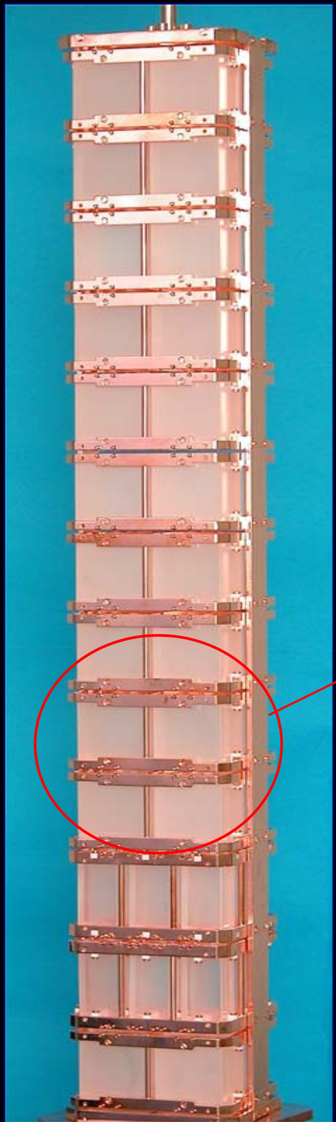
CUORICINO → CUORE

2ν double beta with ^{130}Te (Q=2529 keV)

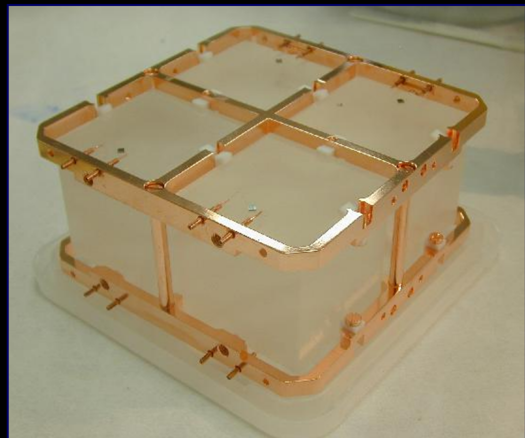
18 crystals 3x3x6 cm3 + 44 crystals 5x5x5 cm3
40.7 kg of TeO_2 → 750 kg TeO_2
↳ 203 kg ^{130}Te

from 2003-2008

search for 0ν double beta:
$T_{1/2}^{0\nu}$ (^{130}Te) > 7.5 x 10^{23} y
$\langle m_\nu \rangle$ < 0.3 - 1. 6 eV



2 modules, 9 detector each,
crystal dimension 3x3x6 cm^3
crystal mass 330 g
9 x 2 x 0.33 = 5.94 kg of TeO_2



11 modules, 4 detector each,
crystal dimension 5x5x5 cm^3
crystal mass 790 g
4 x 11 x 0.79 = 34.76 kg of TeO_2

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%

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

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

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

Leptons vs Quarks

Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

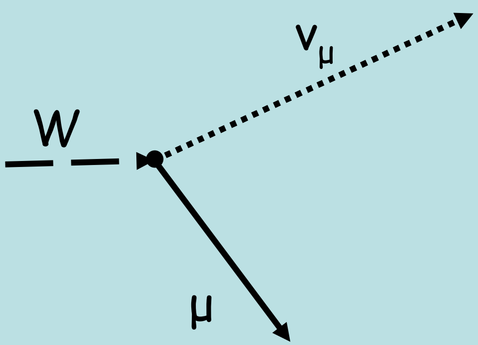
Neutrino Oscillations

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

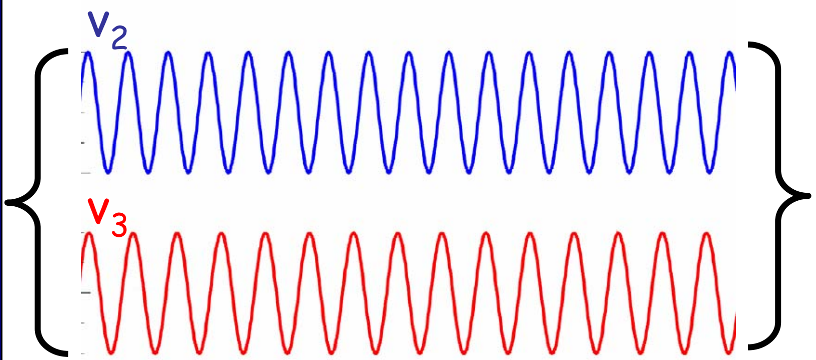
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2, ν_3 with m_2, m_3

source creates flavor-eigenstates



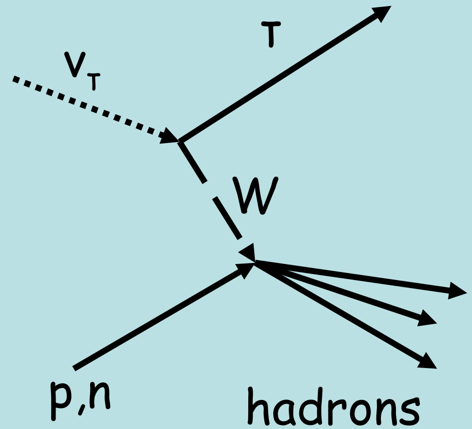
propagation determined by mass-eigenstates



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

slightly different frequencies
→ phase difference changes

detector sees flavor-eigenstates



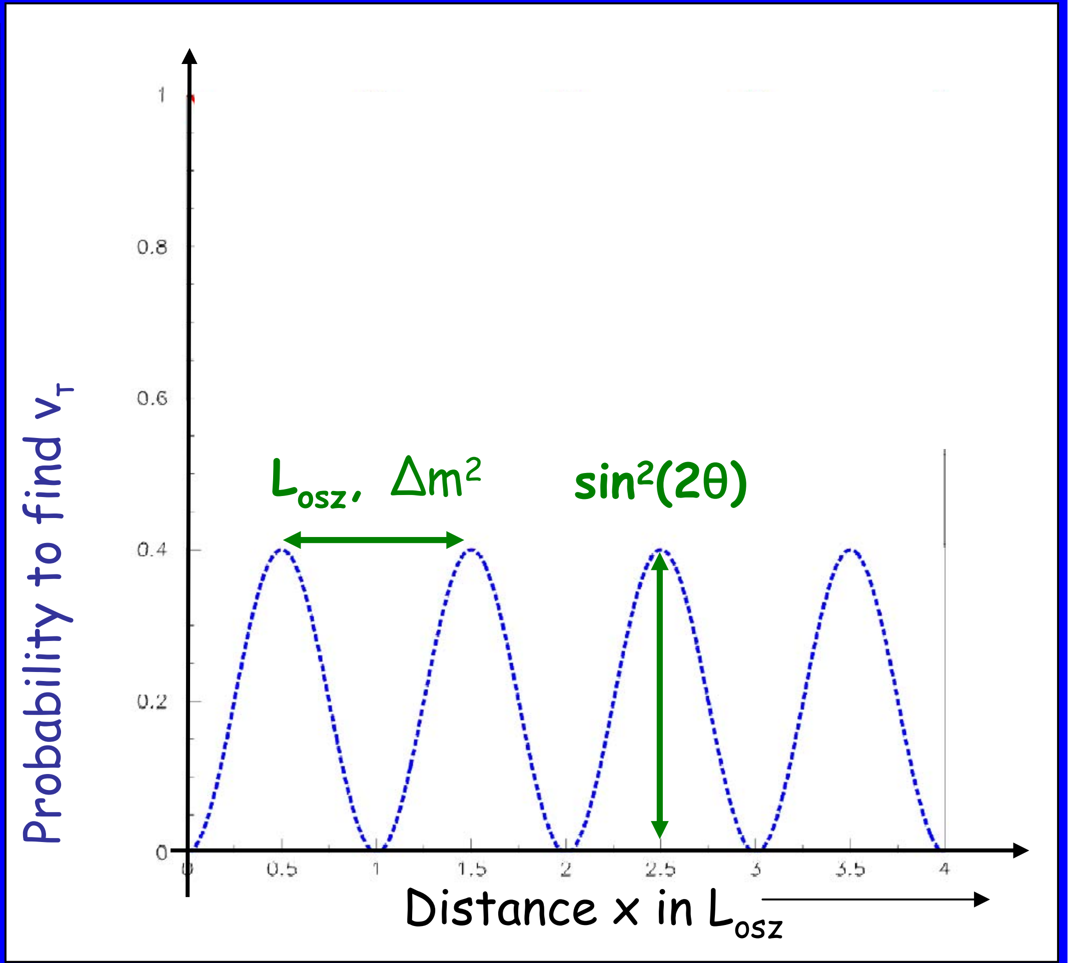
2 Flavor Neutrino Oscillations

<u>Oscillation probability</u>

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

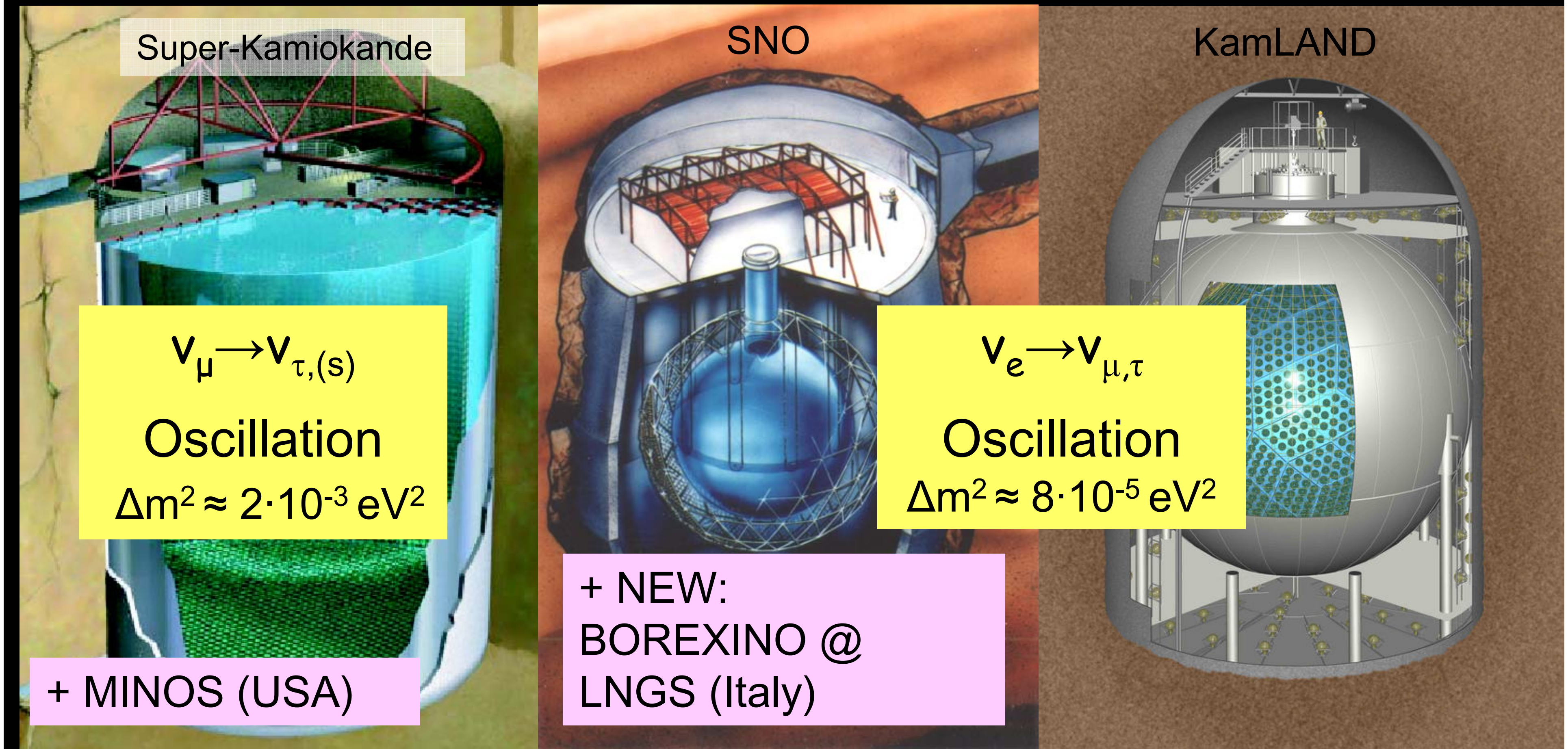
$$L_{osz}(\text{in km}) = \frac{2.48 \cdot E(\text{in GeV})}{\Delta m^2(\text{in eV}^2)}$$

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



Neutrino Oscillations were observed
→ Neutrinos have mass!

JAPAN | CANADA | JAPAN



atmospheric neutrinos
accelerator neutrinos

solar neutrinos

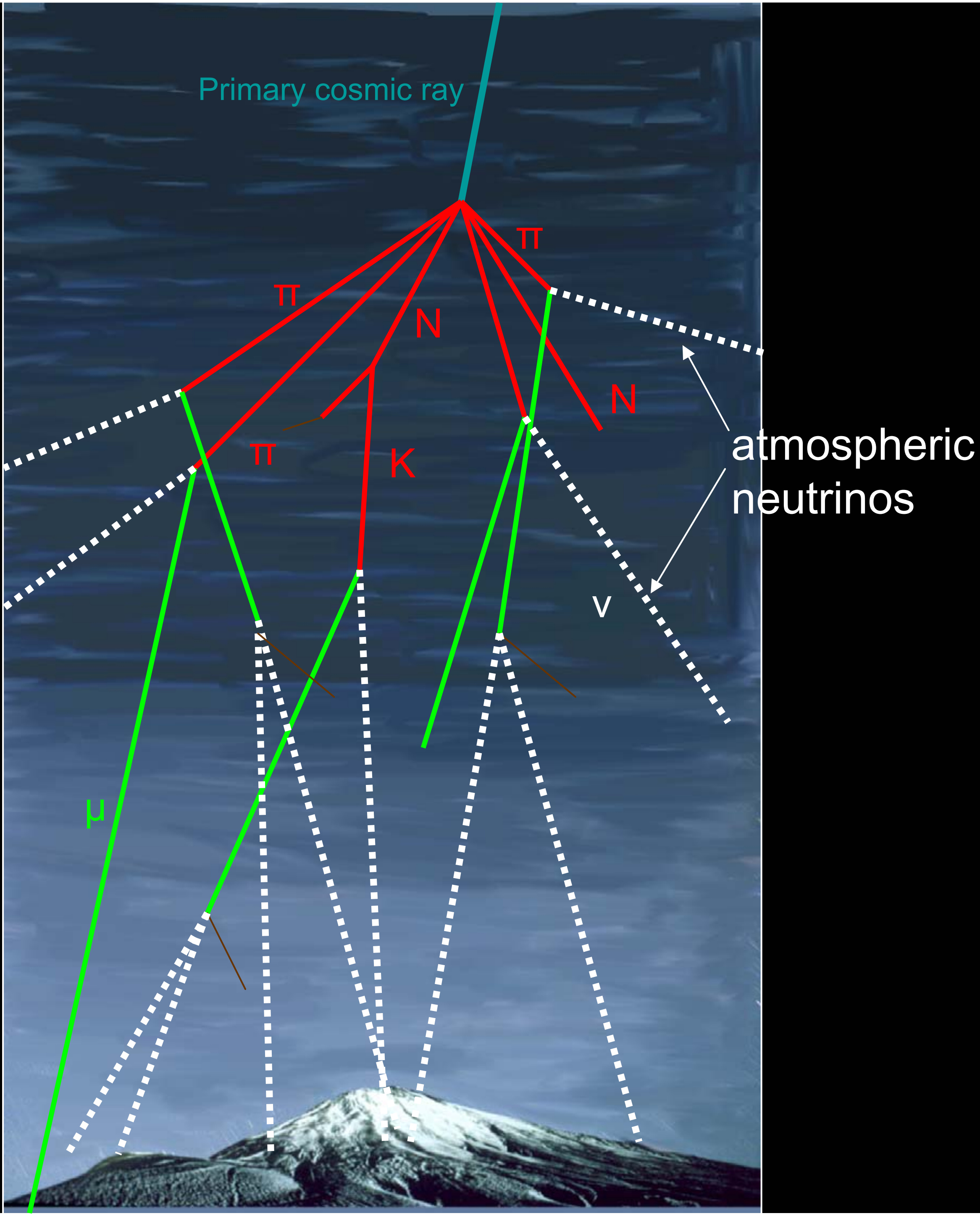
reactor neutrinos

Let us first look how muon neutrinos oscillate

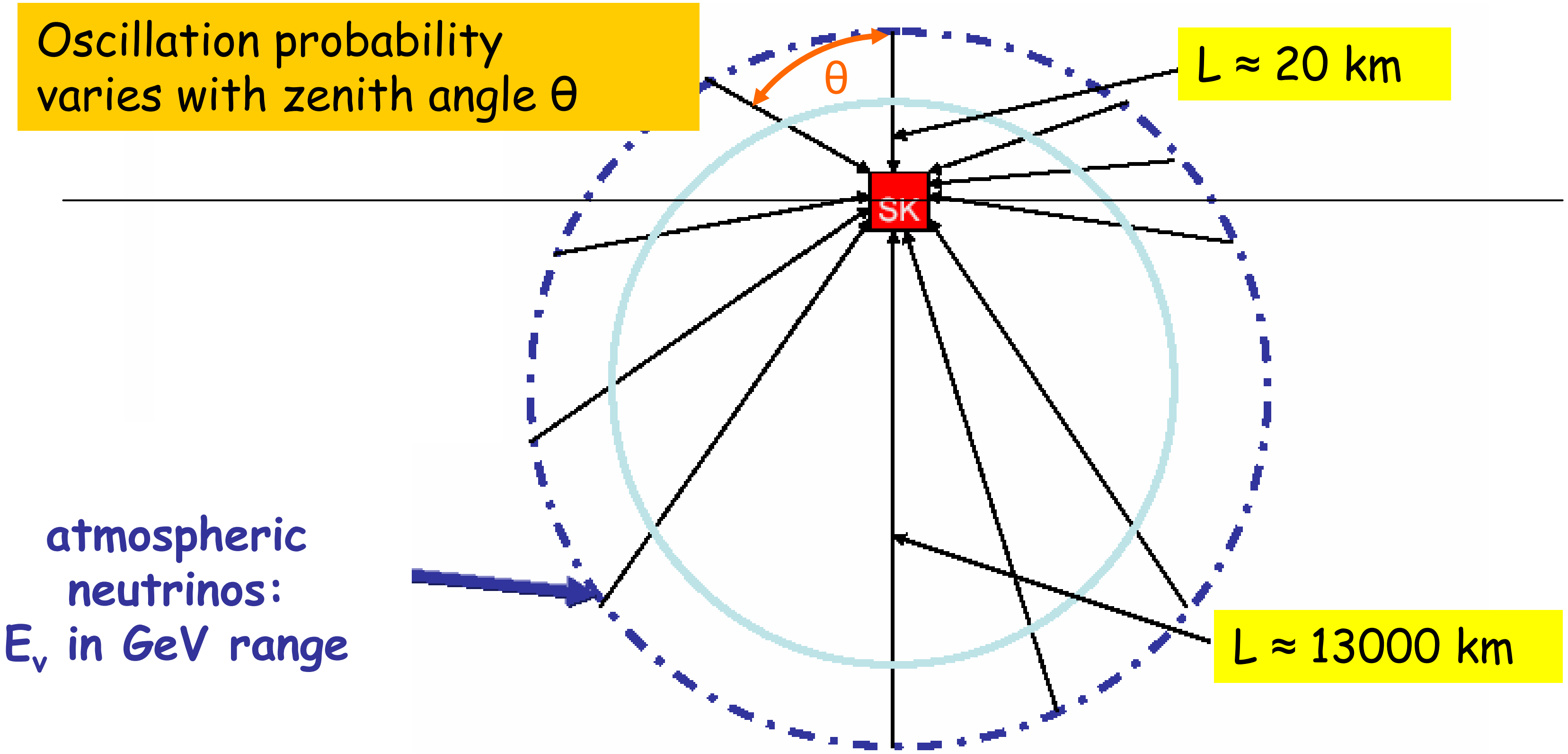
- Sources of muon neutrinos are:
  The atmosphere (comic rays)
  Neutrino beams at particle accelerators

- These neutrinos have energies of a few GeV

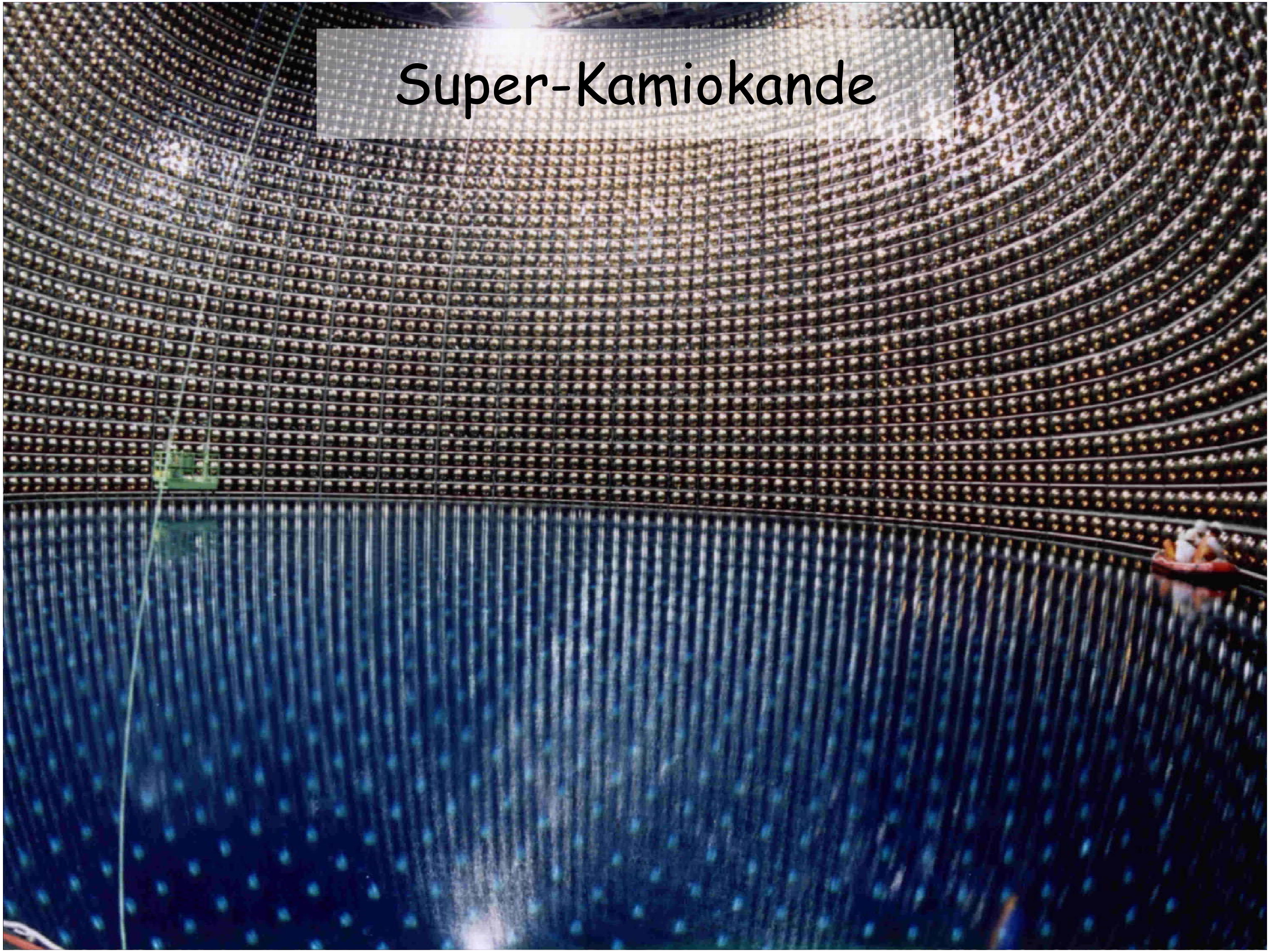
- Detection with methods of high energy particle physics
  (Water Cherenkov)

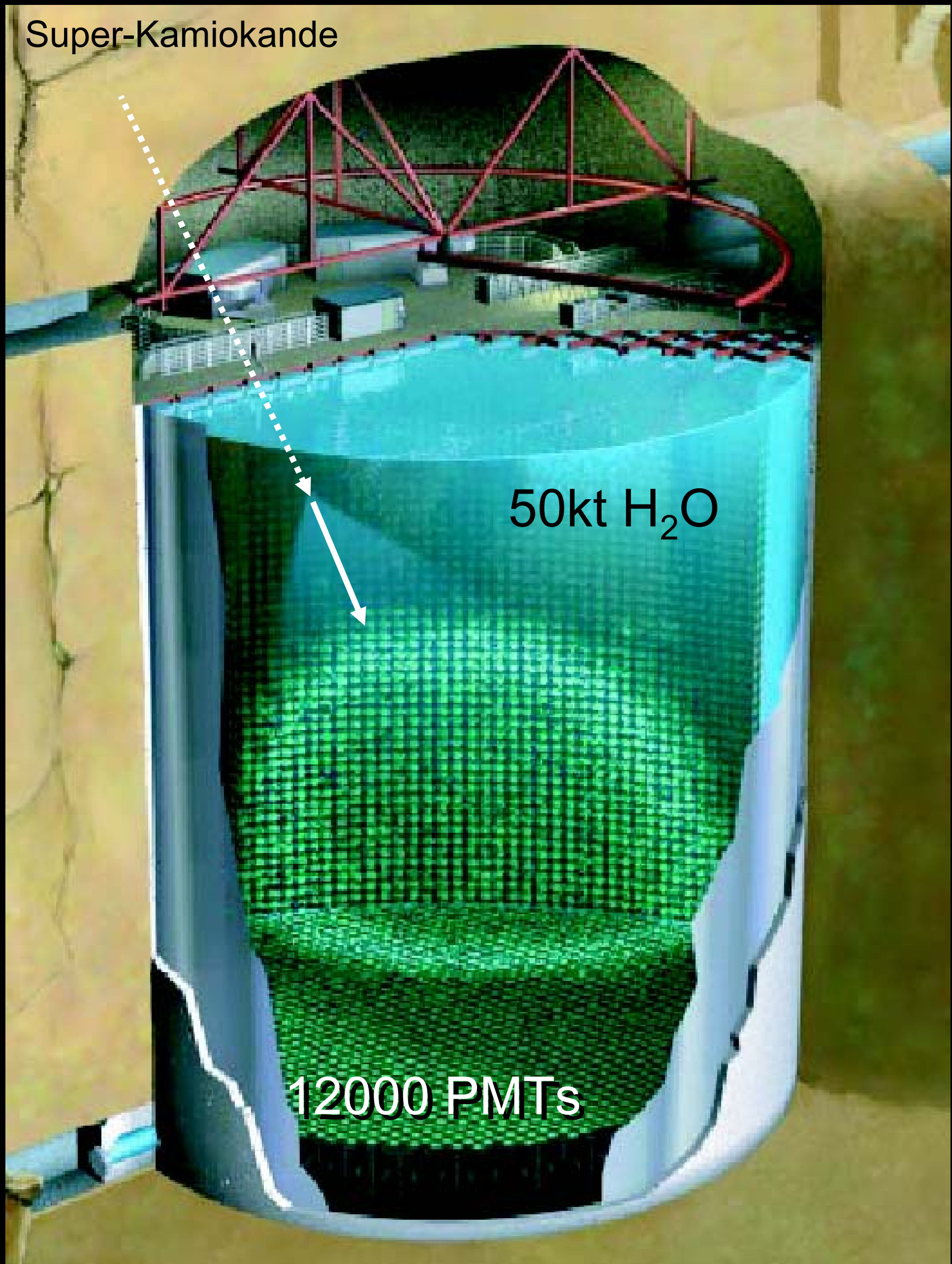

Primary cosmic ray
π
π
N
π
K
N
π
μ
ν
atmospheric
neutrinos

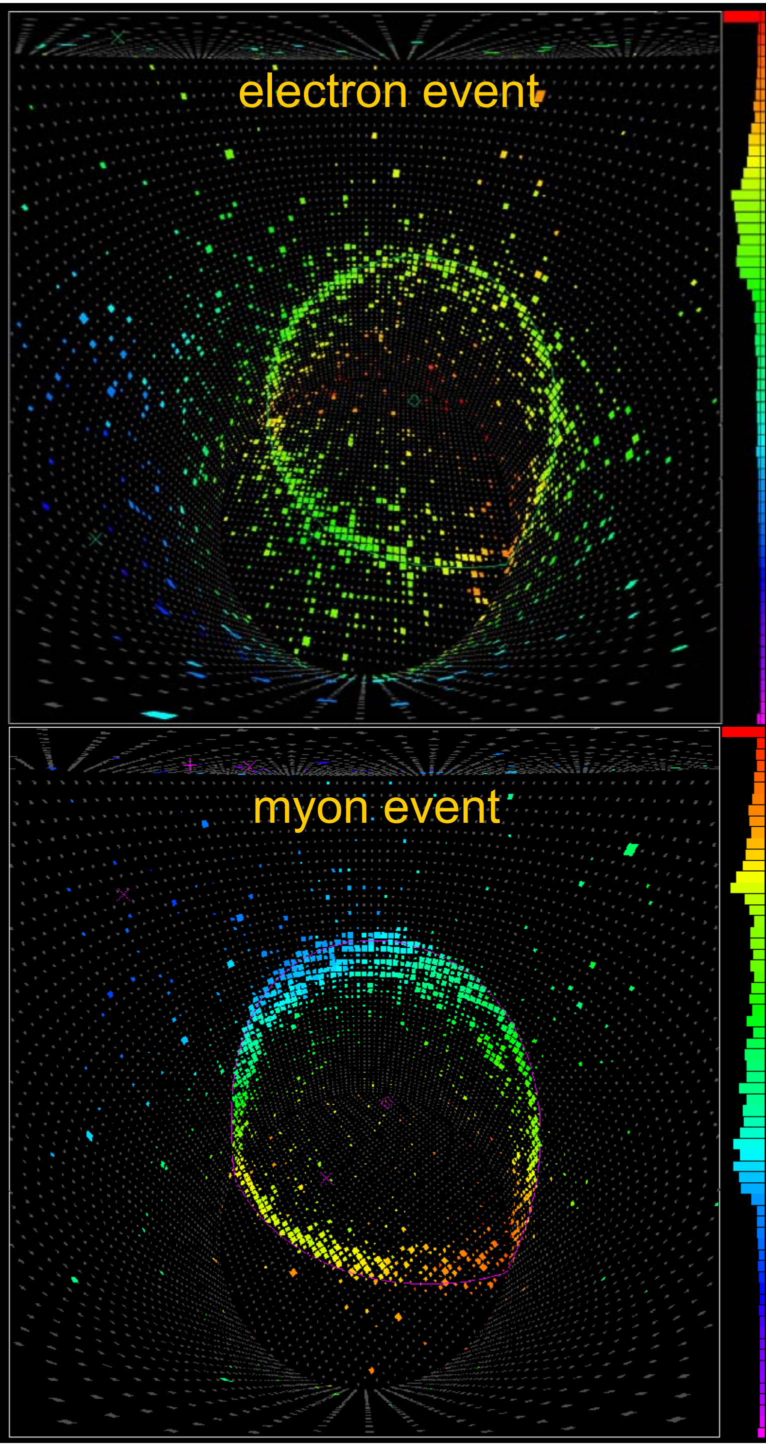
Oscillation of atmospheric neutrinos (1998)



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

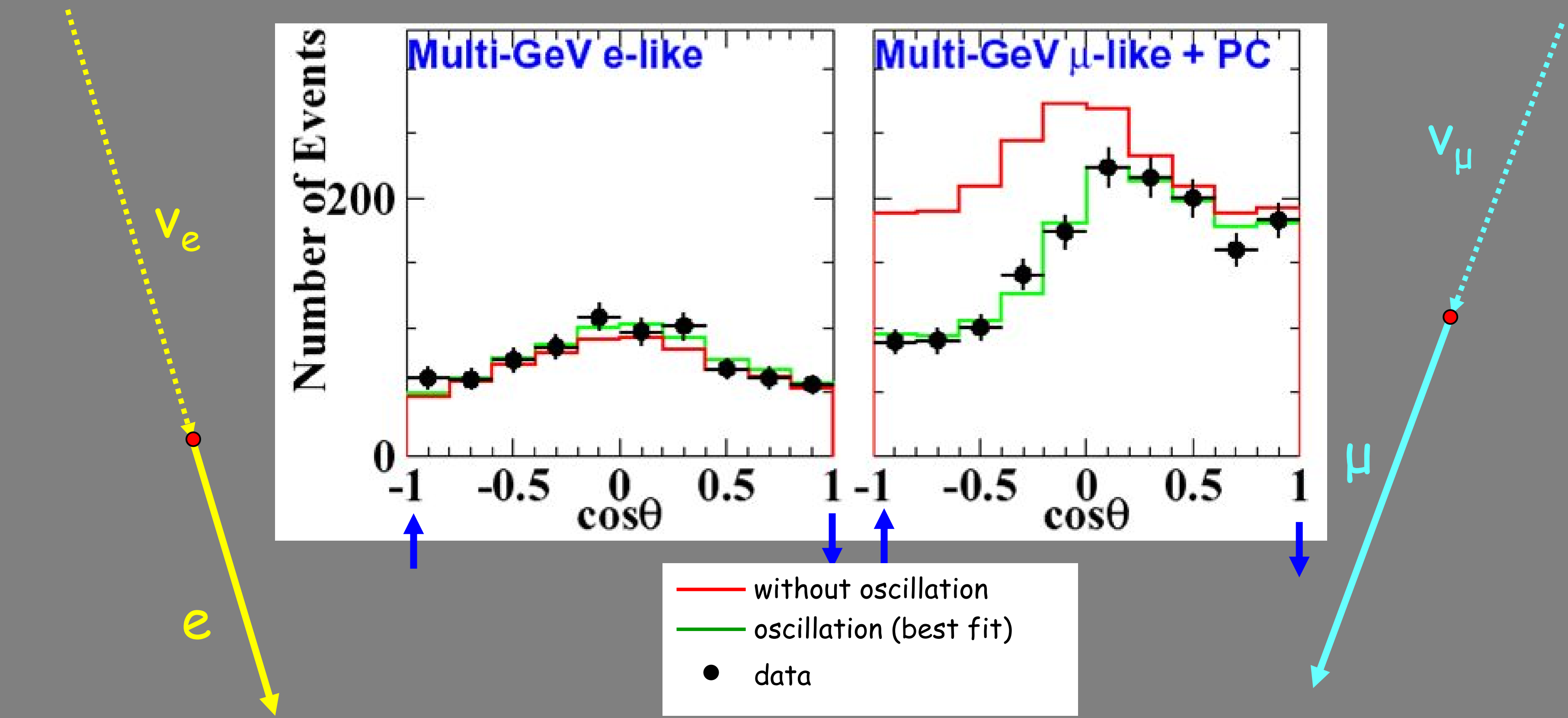

Super-Kamiokande


Super-Kamiokande
50kt H_2O
12000 PMTs


electron event
myon event

SuperK - atmospheric neutrinos

e-like events | μ-like events

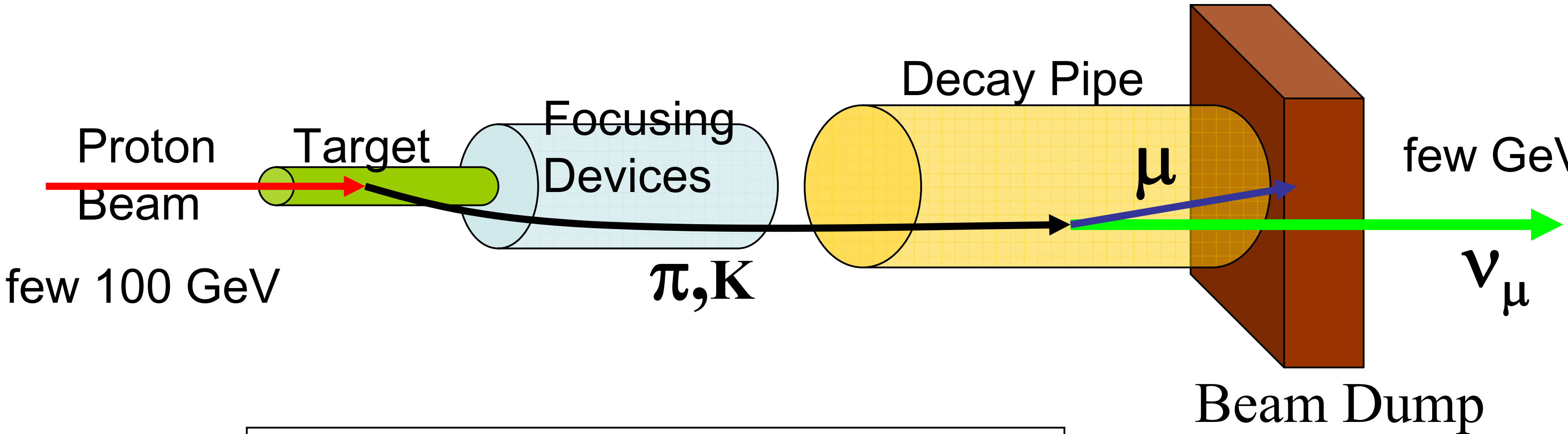


Full SK-I data set, 90% CL (PRD71 (2005) 112005):

$\sin^2 2\theta > 0.92$

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

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



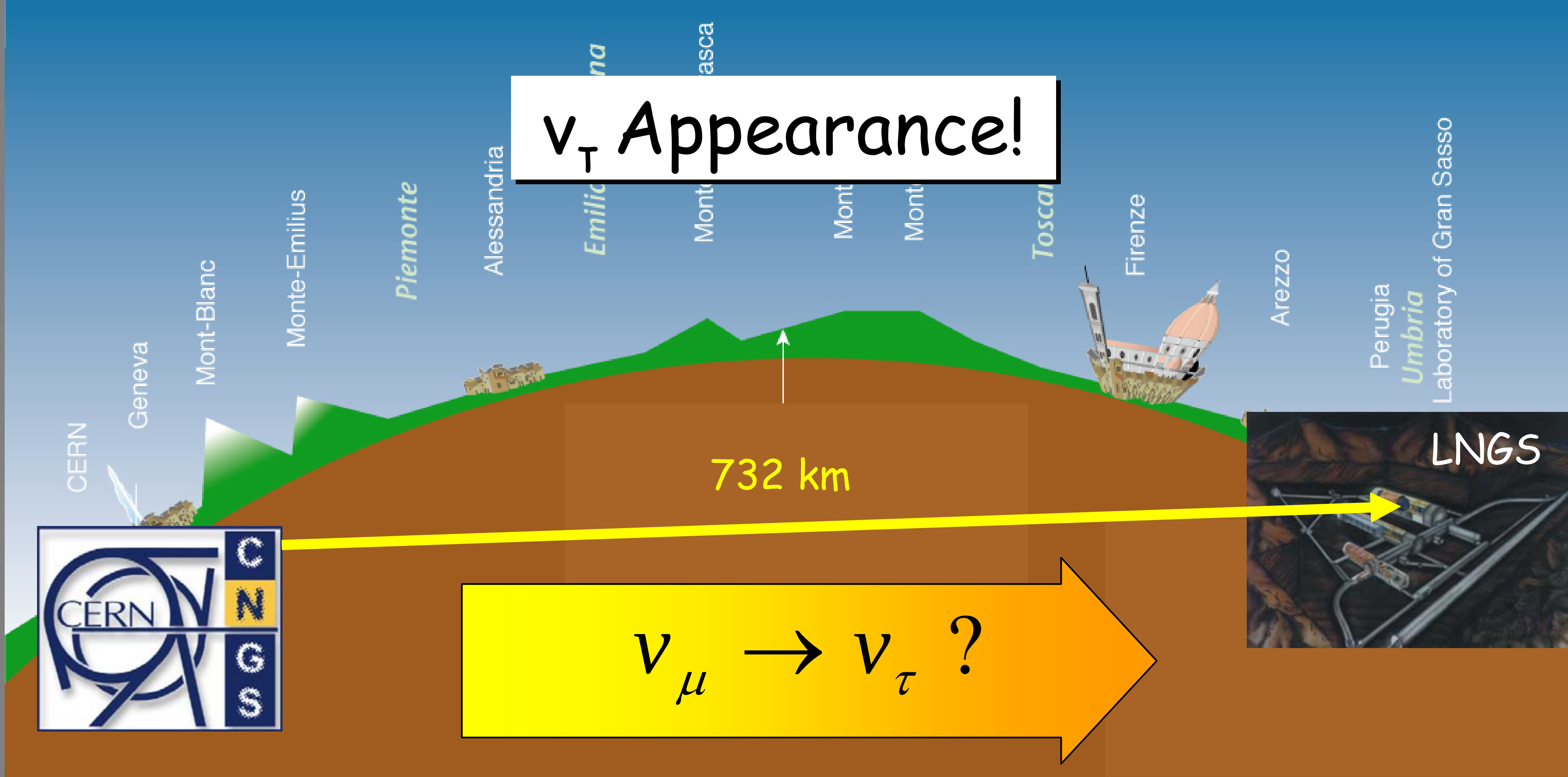
Beam composition (typical example):

- 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

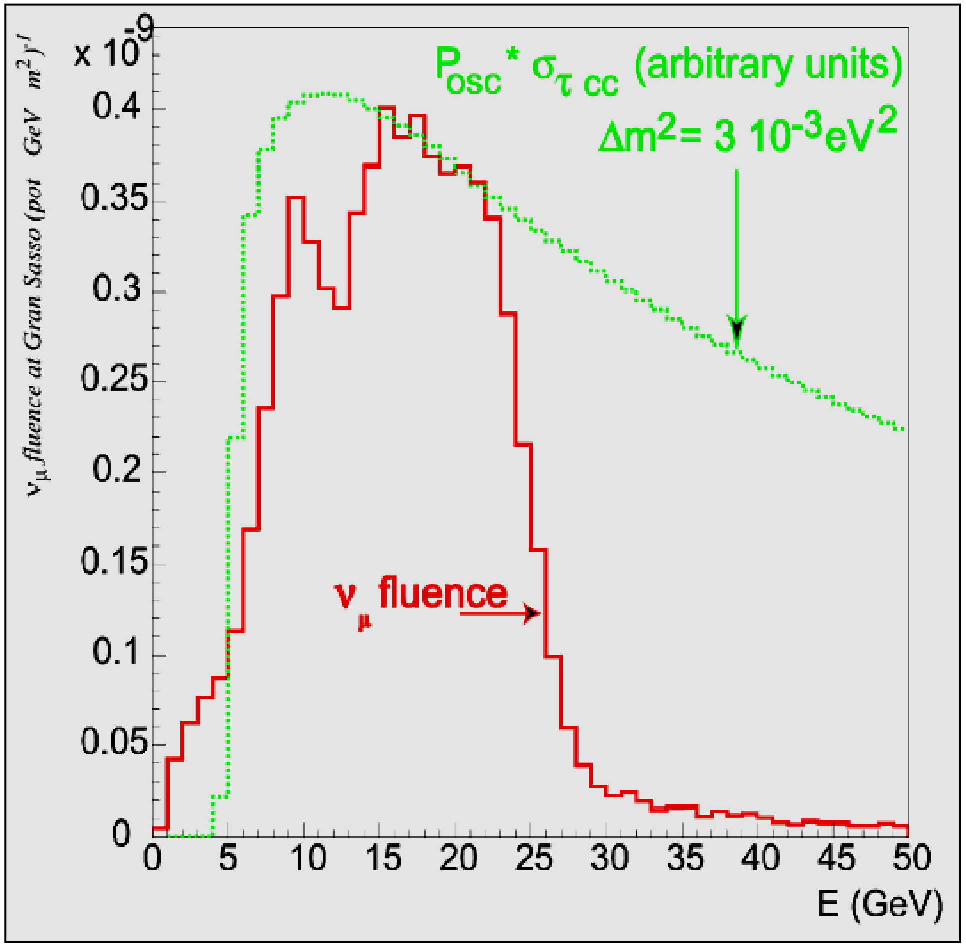
OPERA

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



Started in june 2008, running…

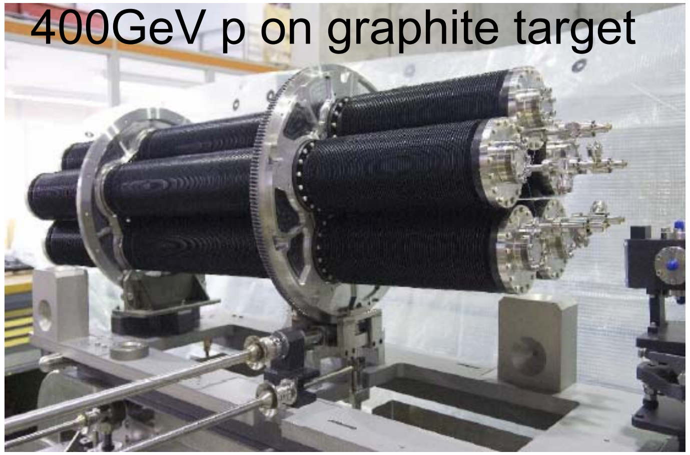
OPERA: CNGS beam



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

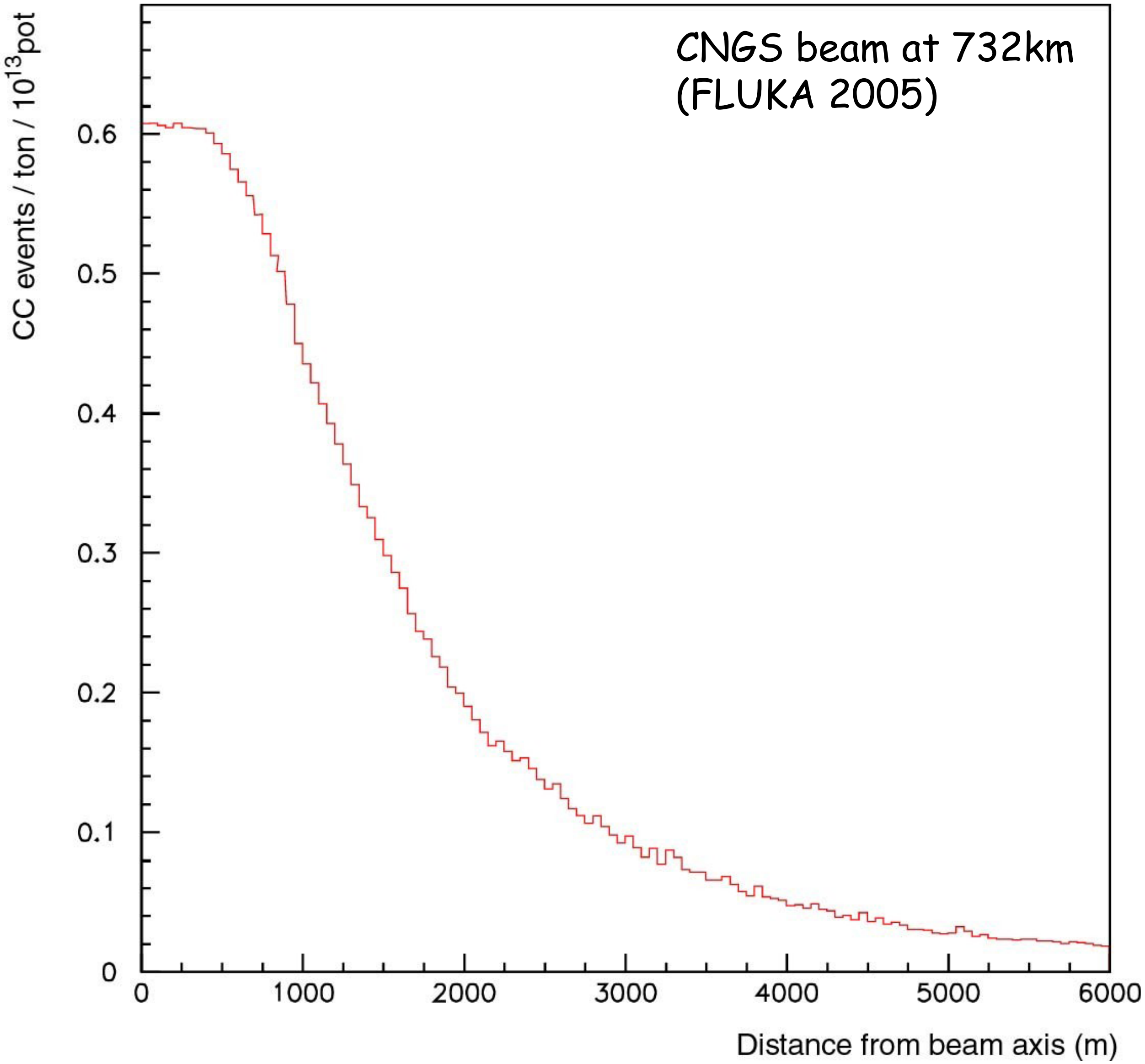
$$\bar{\nu}_\mu / \nu_\mu = 4\%$$

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

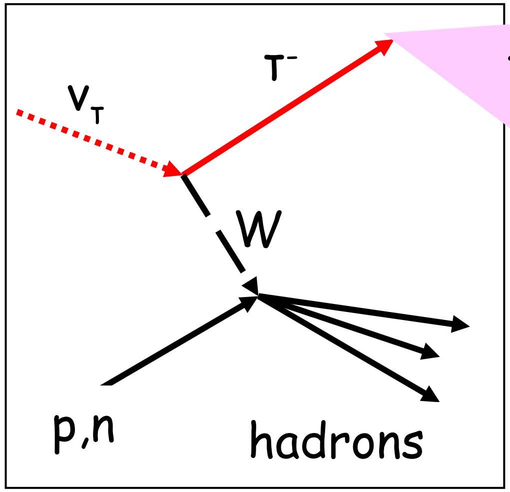


$4.5 \cdot 10^{19}$pot/year

Querschnitt des Neutrinostrahls



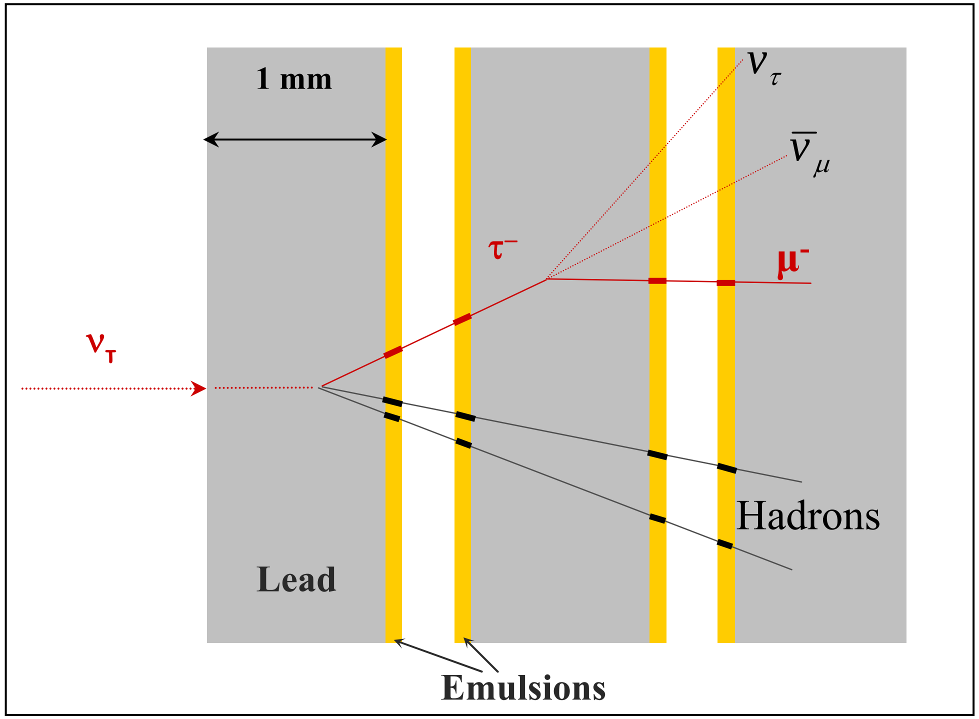
OPERA: Detection of ν_τ



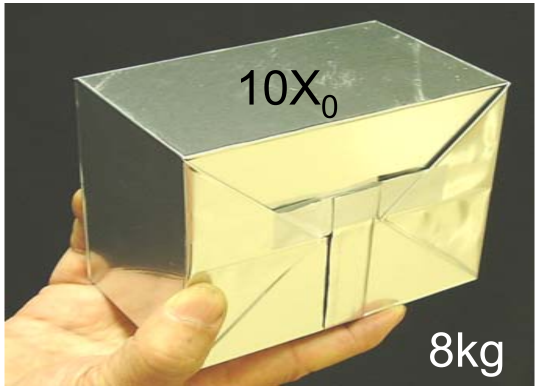
τ-decay:

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

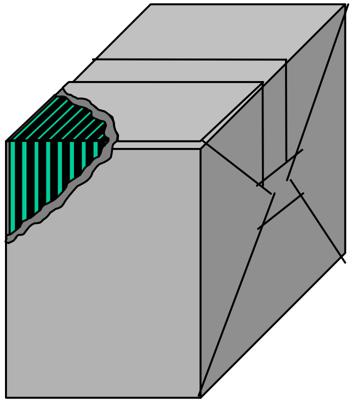
Typical topology of τ-decay:
"Kink" within 1mm from vertex

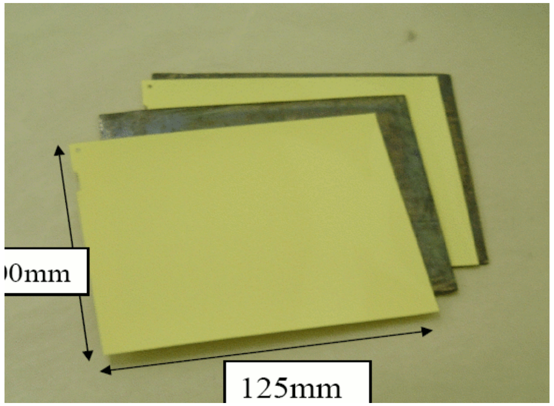


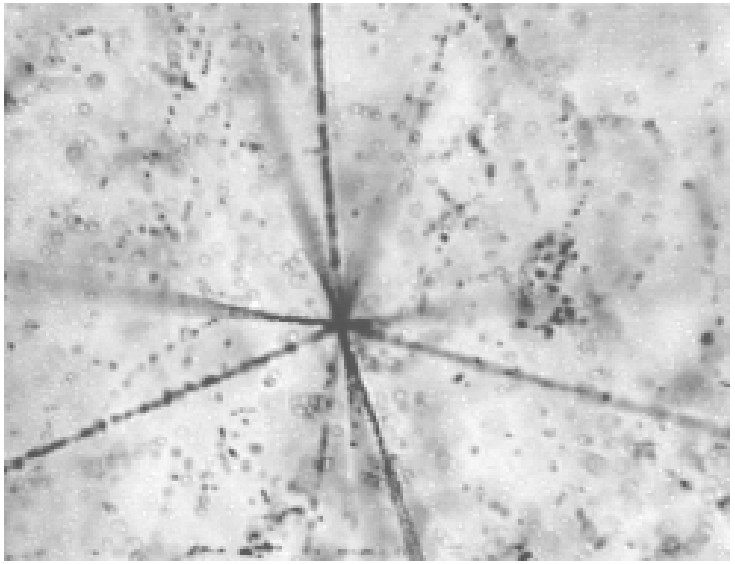
OPERA Target: Lead/Emulsion Bricks



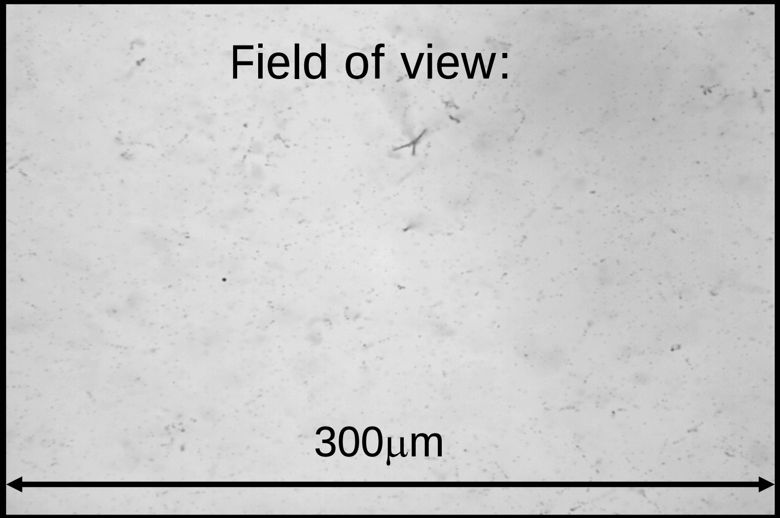
Lead/Emulsion Brick
(total ≈ 200000)



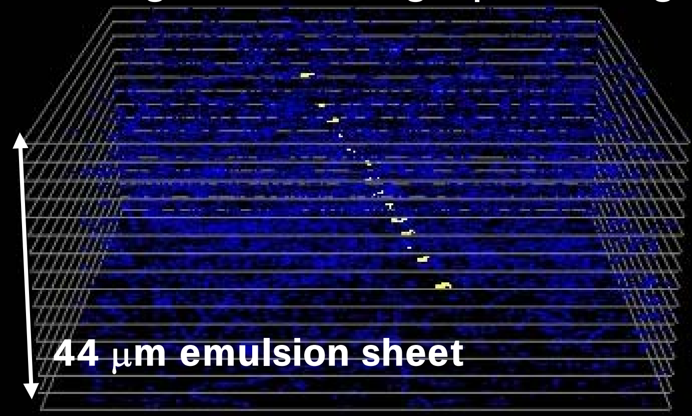




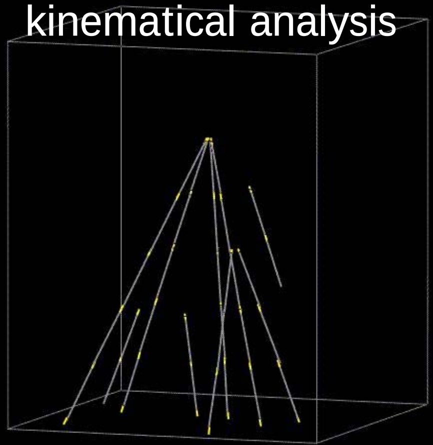
Scanning



2d image: 16 tomographic images



Vertex reconstruction &
kinematical analysis

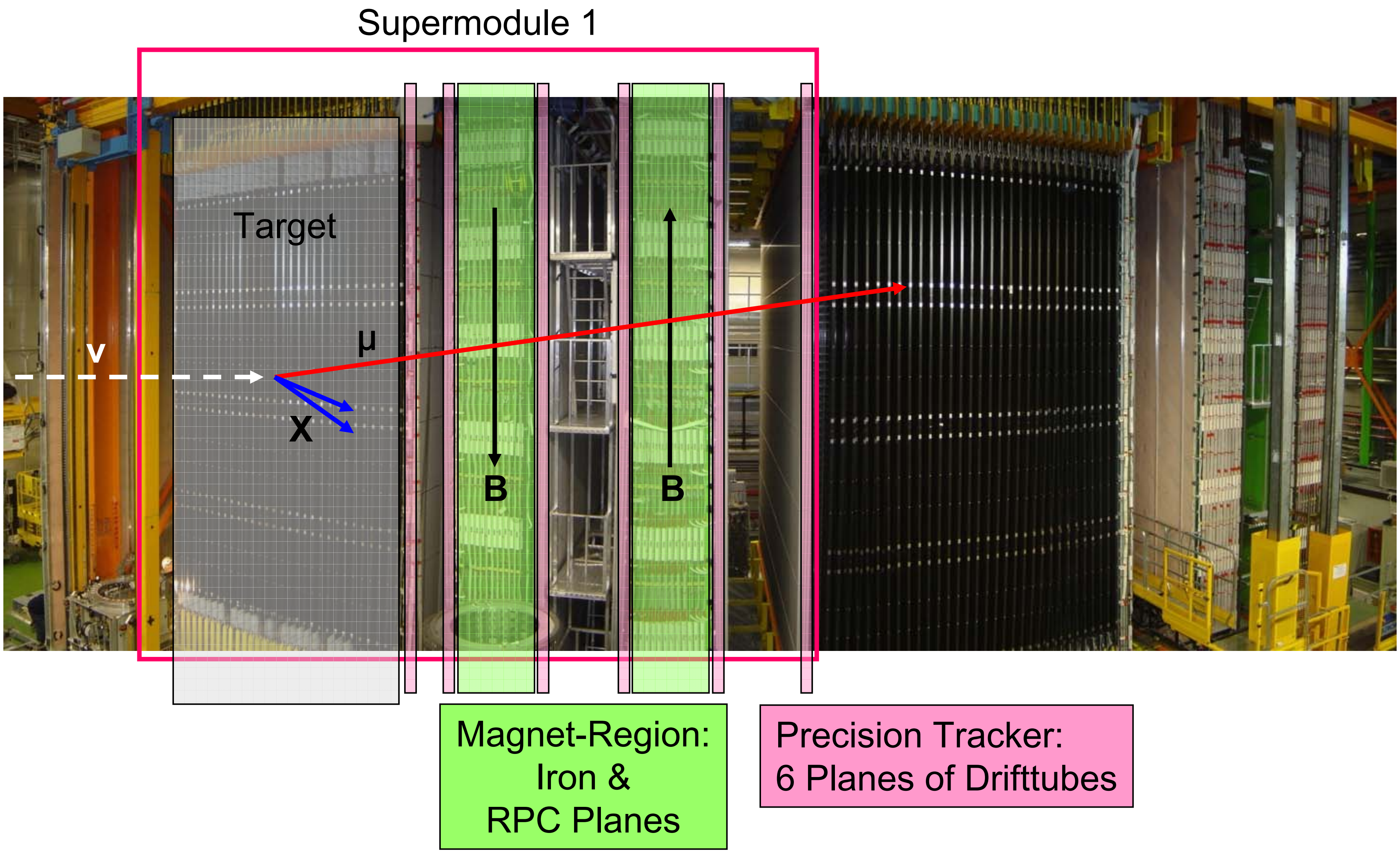


OPERA - Detector

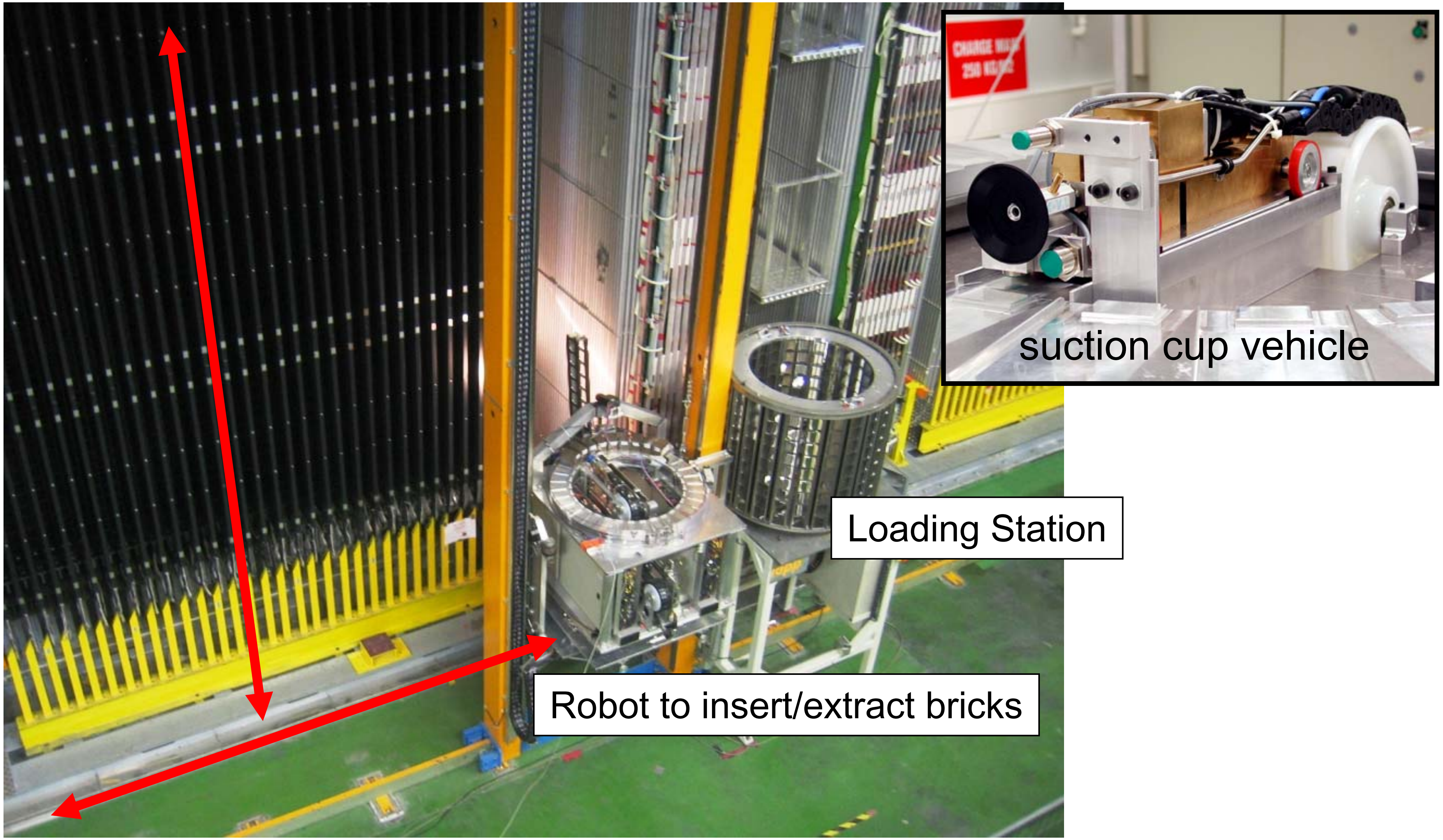
Supermodule 1

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

OPERA - Detector



OPERA – Brick Manipulating System



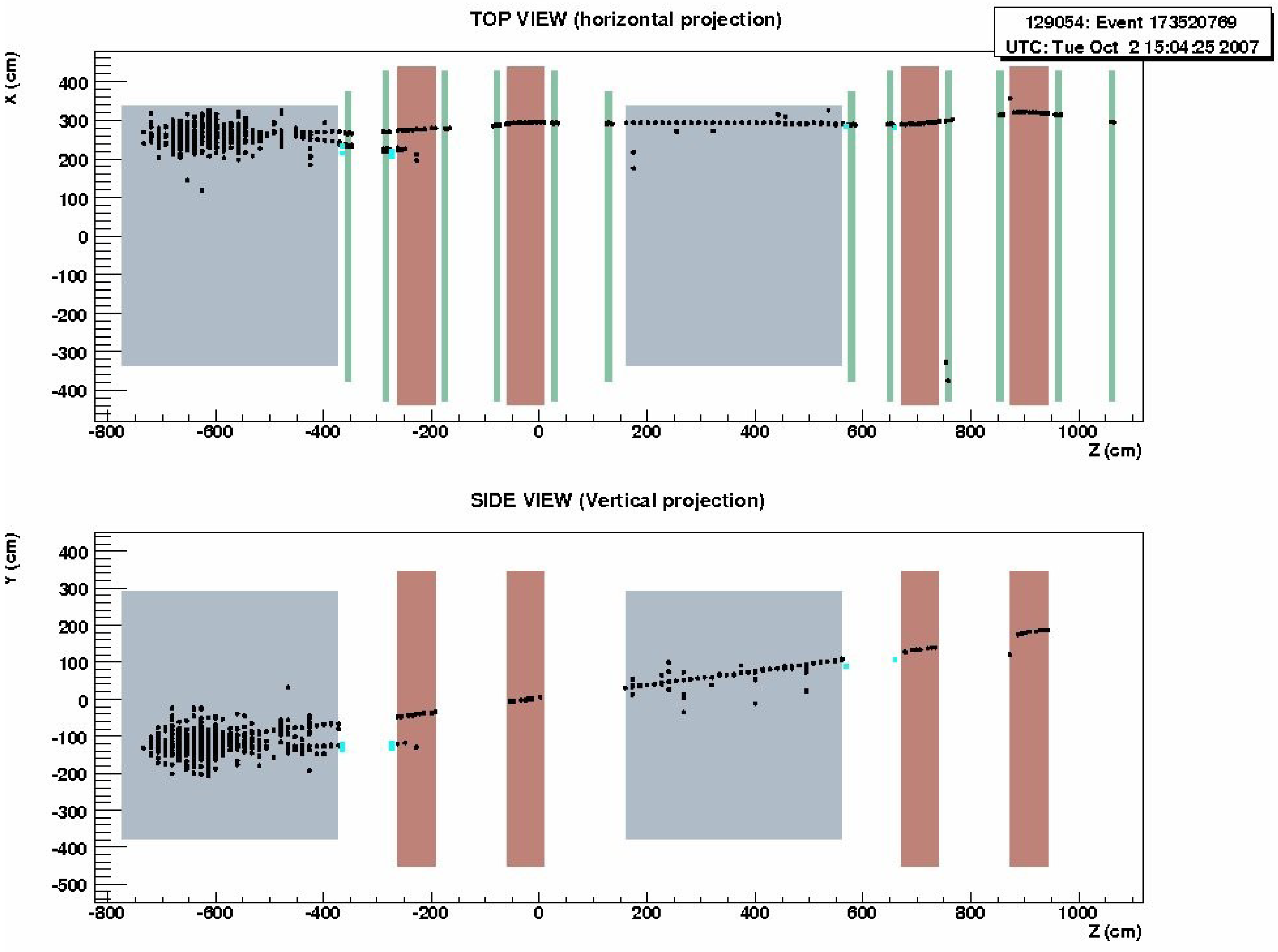
OPERA Sensitivity

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

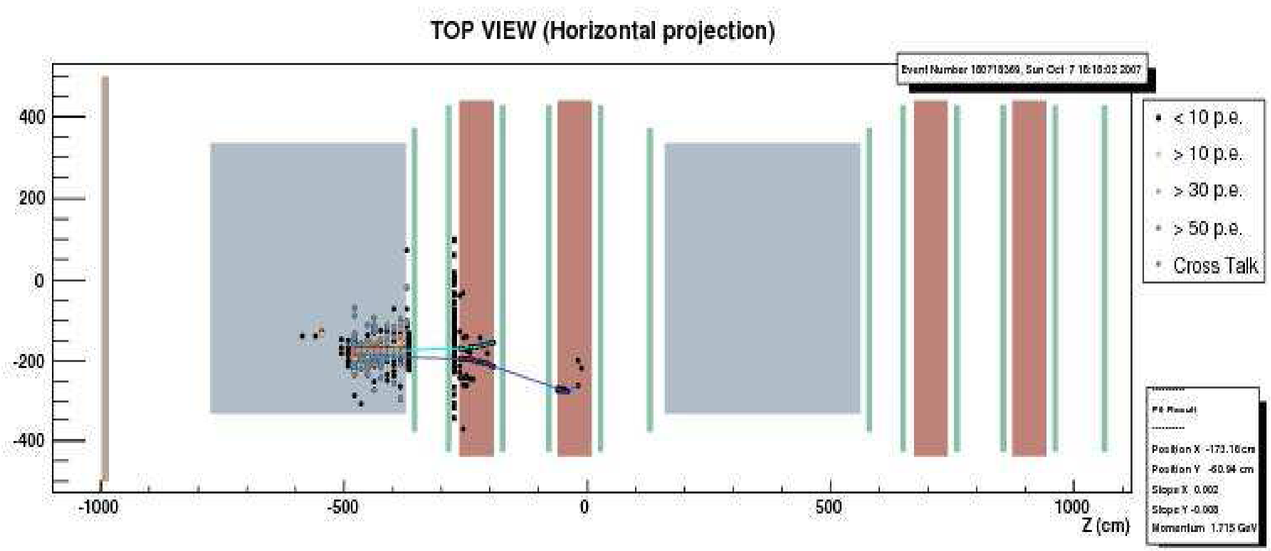
	$\Delta m^2=1.9\text{x}10^{-3}$eV^2	$\Delta m^2=2.4\text{x}10^{-3}$eV^2	$\Delta m^2=3.0\text{x}10^{3}$eV^2	BKGD
ν_τ in OPERA	6.6	10.5	16.4	0.7

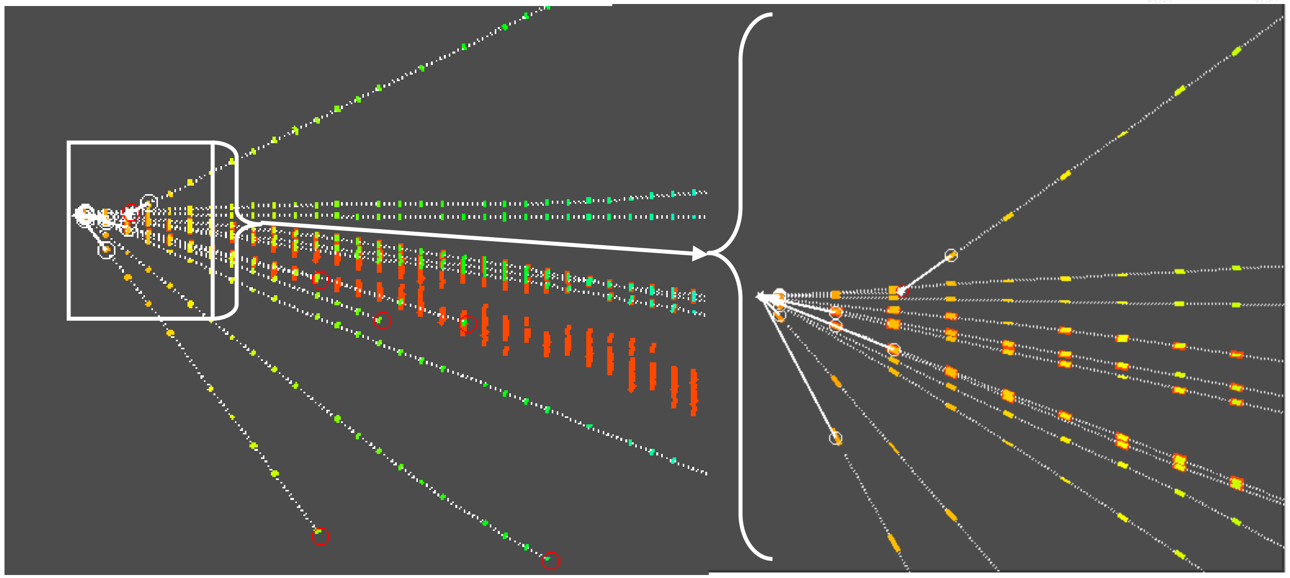
exposure: 5 years @ 4.5 x10^{19} pot / year

OPERA Event (ν_μ CC)



Event 180718369



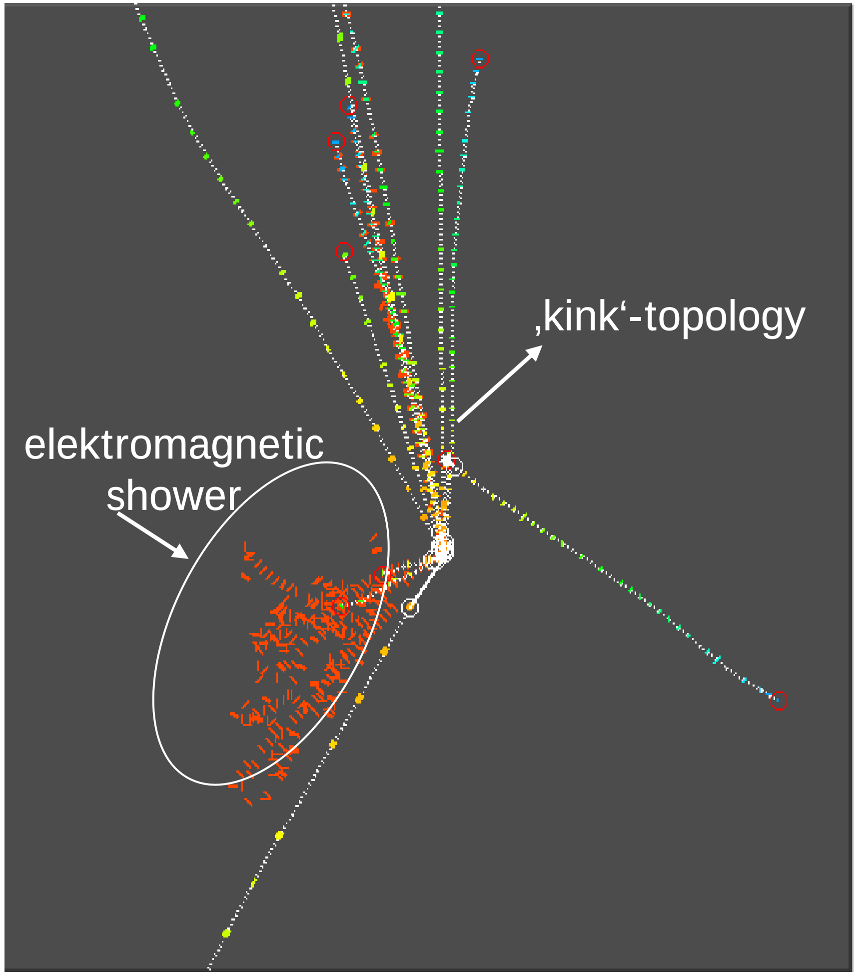


Charm-Candidate

Secondary Vertex:

- daughter momentum = $3.9^{+1.7}_{-0.9}$ GeV
- kink angle = 0.204 rad
- flight length = 3247 μm
- PT = 796 MeV
- PT_{MIN} = 606 MeV (90% C.L.)

Kink probably from decaying D-Meson (contains c-quark).



OPERA summary

- Experiment running since June 2008
- Detector is working fine (Charm candidates identified)
- Brick analysis is ongoing
- In total ~10 identified tau-neutrino events expected
- So far no tau-neutrino has been found (0.6 expected)

OPERA is awaiting its first tau-neutrino!

Now we look at electron neutrinos

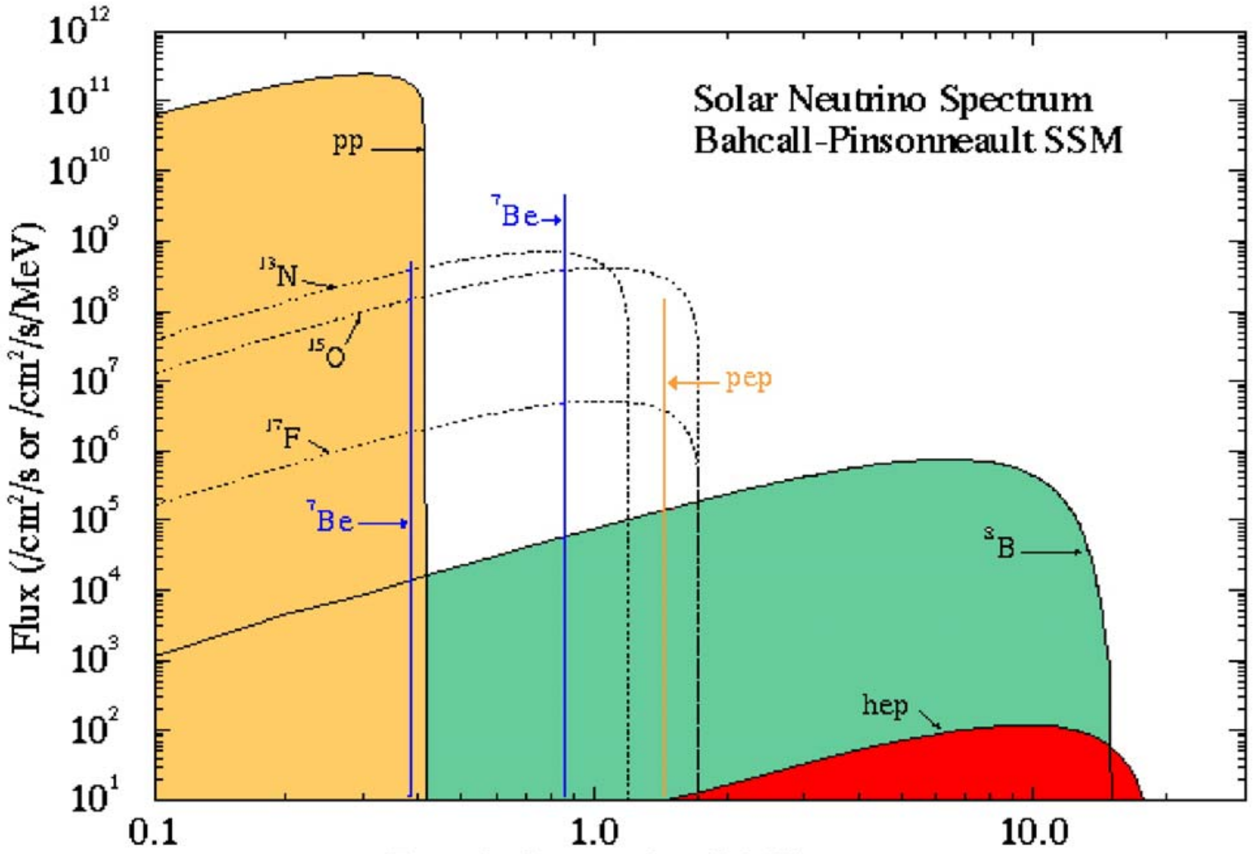
- Electron neutrino sources are:
  The Sun (neutrinos)
  Nuclear reactors (anti-neutrinos)

- These neutrinos have energies of a few MeV

- completely different detection techniques necessary!

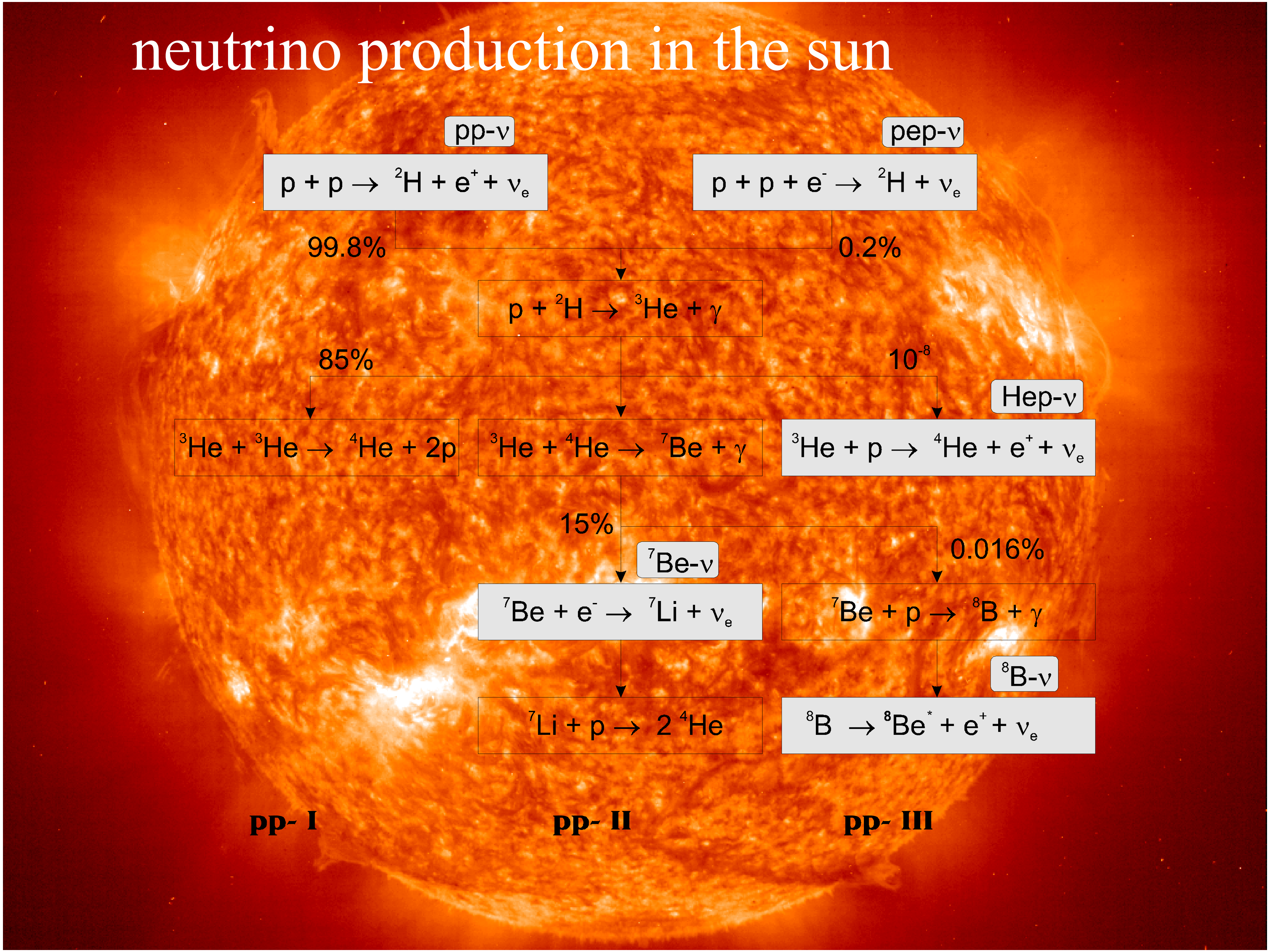
Solar Neutrinos ($E_\nu \approx$ MeV)

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



energy of the neutrinos in MeV

neutrino production in the sun



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 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

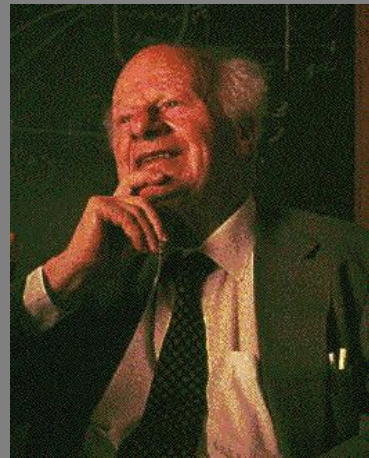
$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \quad (2)$$

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



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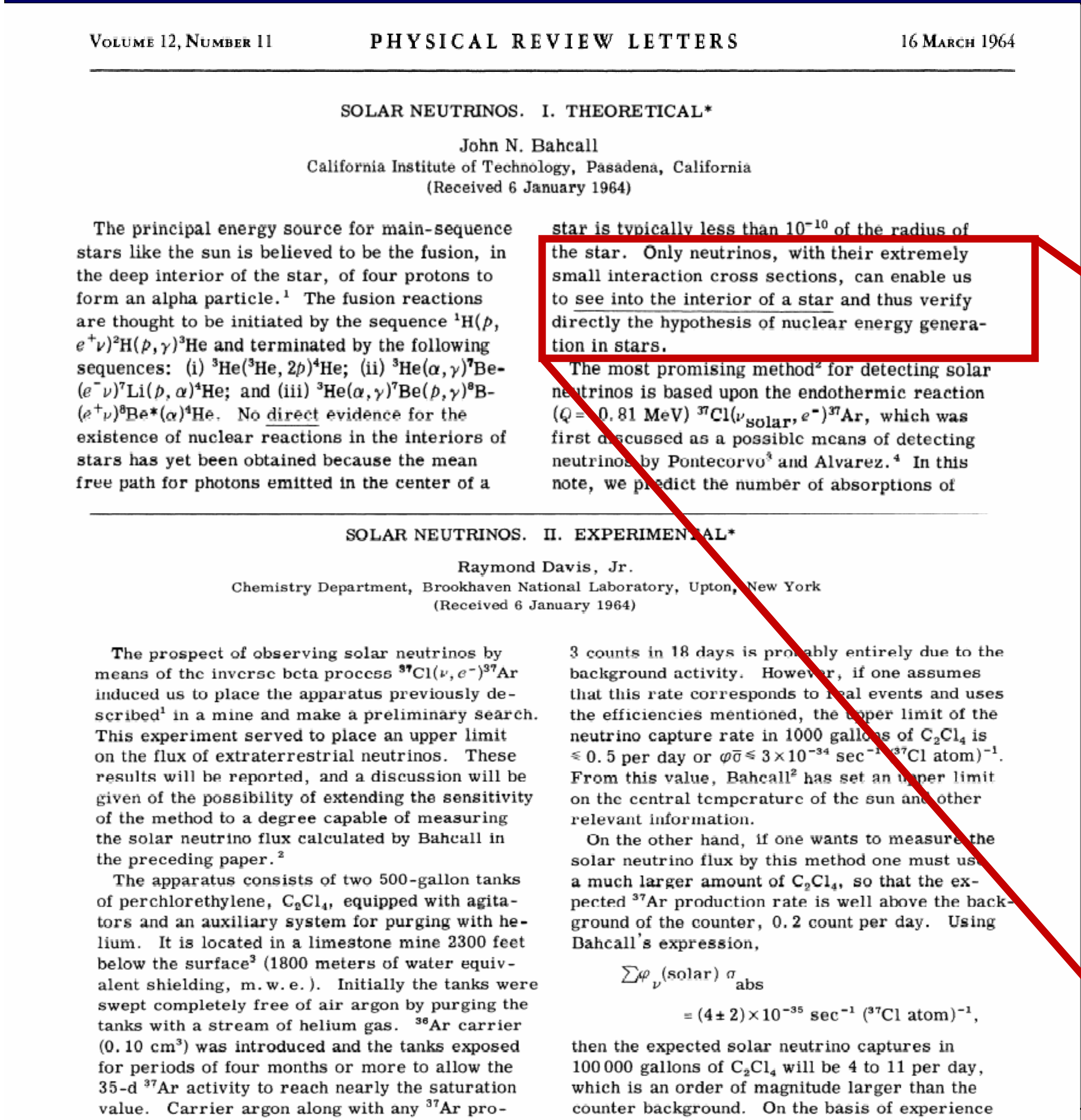
Solar Neutrinos

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]

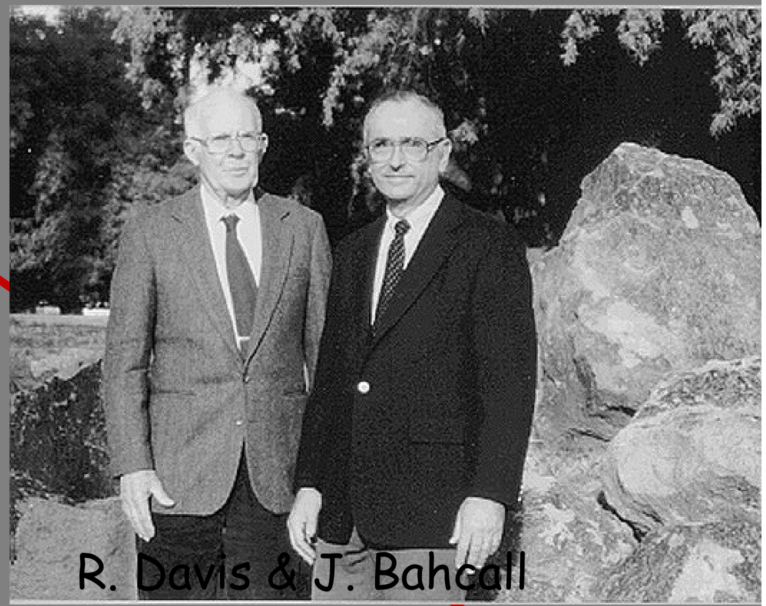
The apparatus consists of two 500-gallon tanks of perchlorethylene, C_2Cl_4, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 2300 feet below the surface[3] (1800 meters of water equivalent shielding, m.w.e.). Initially the tanks were swept completely 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-

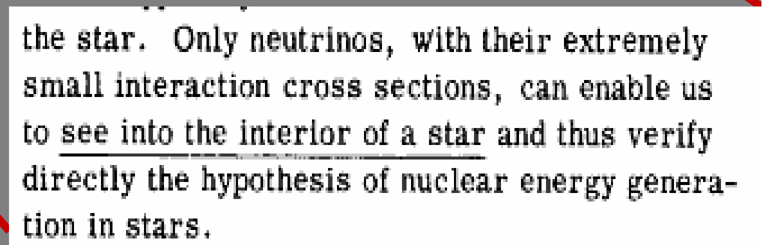
3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \le 3\times10^{-34}$ 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

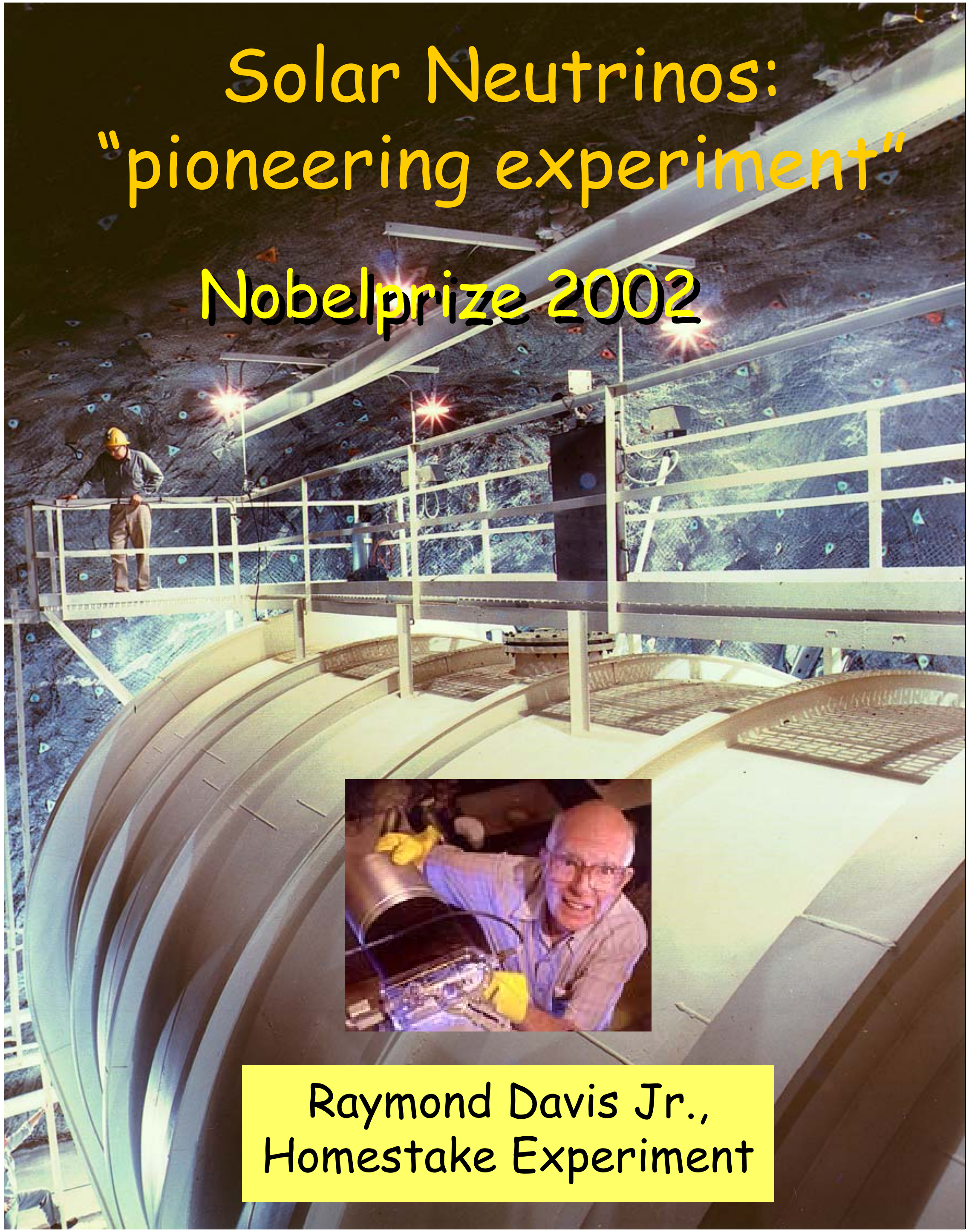




the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

Solar Neutrinos: "pioneering experiment"

Nobelprize 2002



Raymond Davis Jr.,
Homestake Experiment

Since≈1970

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

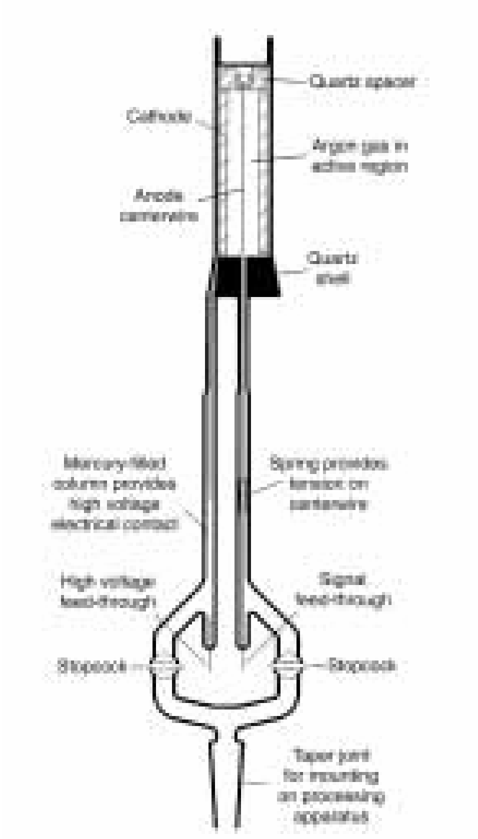
$E_\nu > 814$ keV

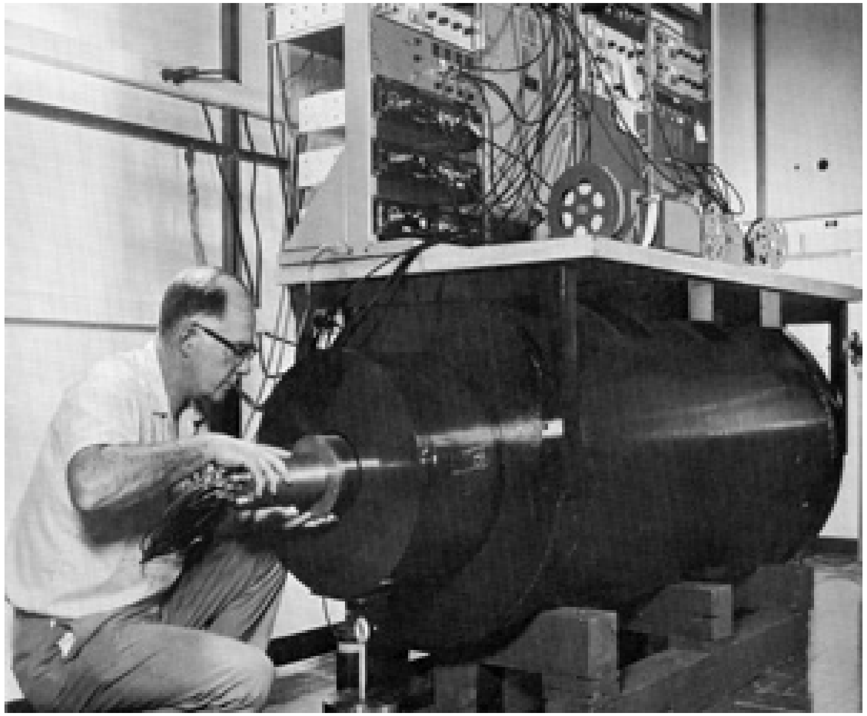
$R_{exp} = 0.34 \times \mathrm{SSM}$

Ar – Counting:

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

$T_{1/2}$ = 35 Tage





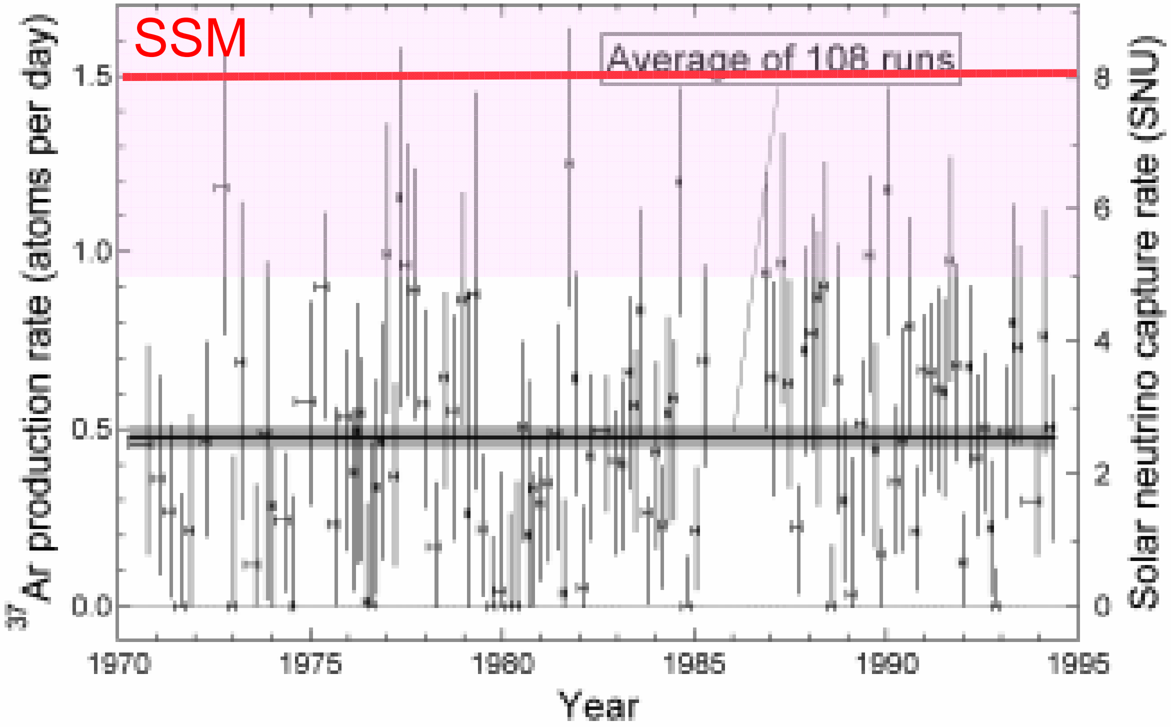
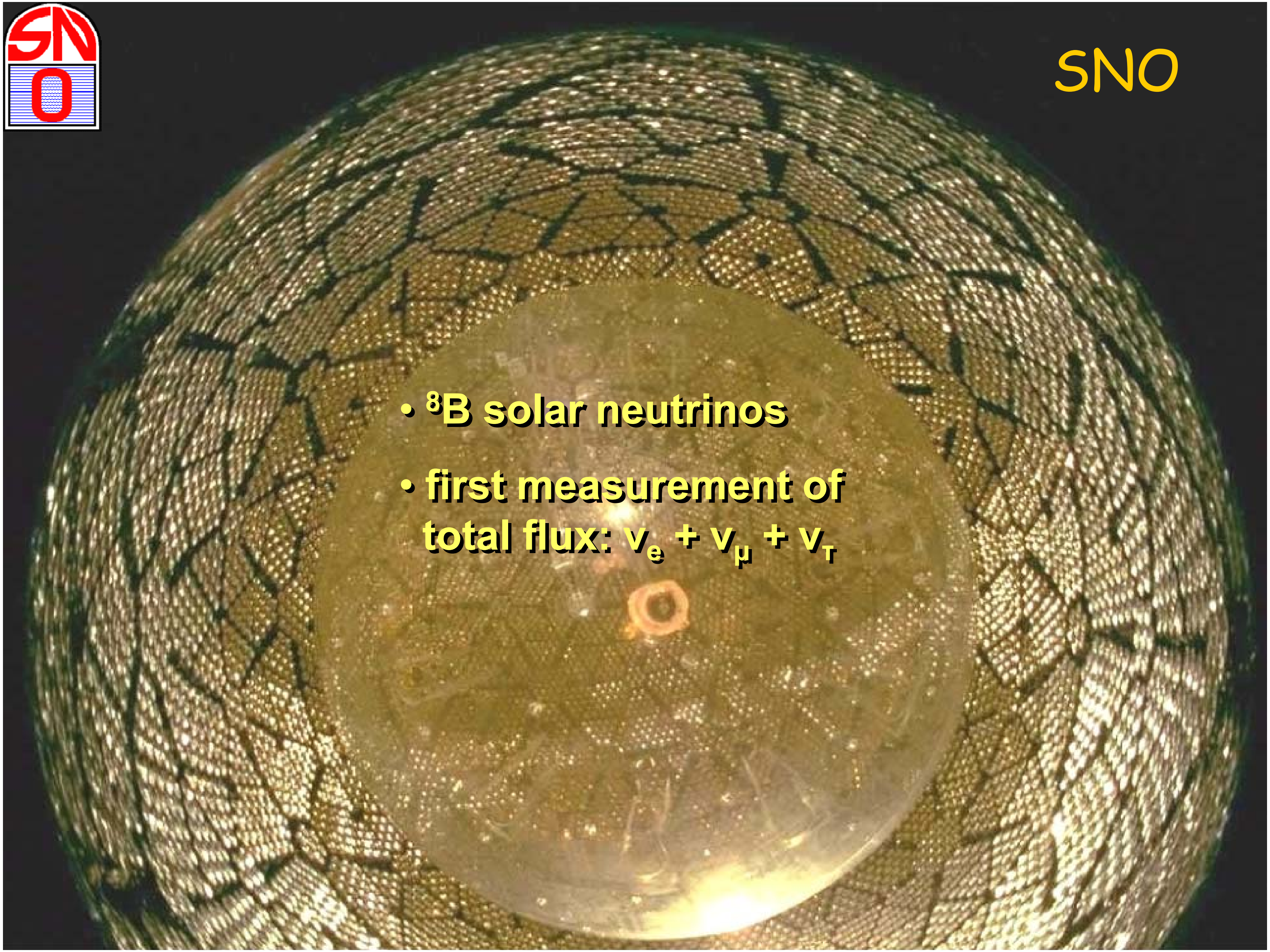
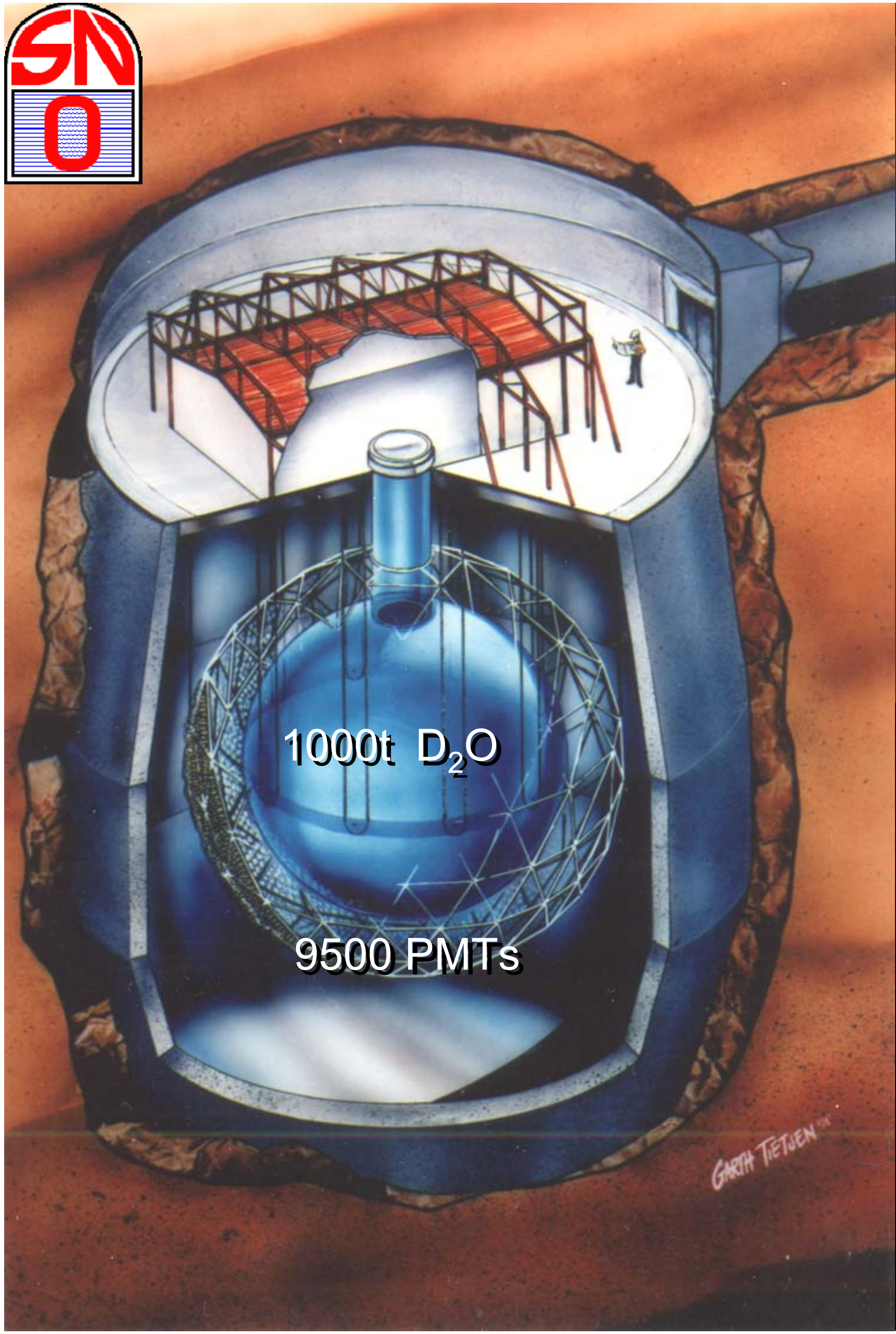


Figure 15. A summary of all of the runs made at Homestake after implementation of rise-time counting. Background has been subtracted. Over a period of 25 years, 2200 atoms of ^{37}Ar were detected, corresponding to an average solar neutrino flux of 2.56 SNU. The gap in 1986 occurred when both perchloroethylene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


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

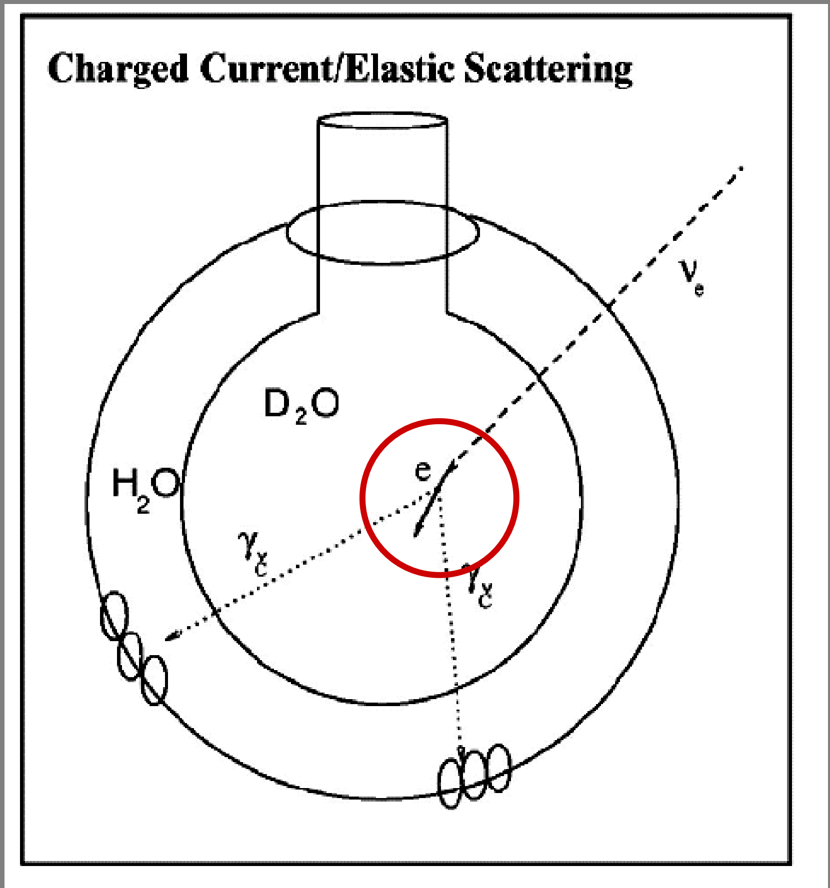

Depth 2070m

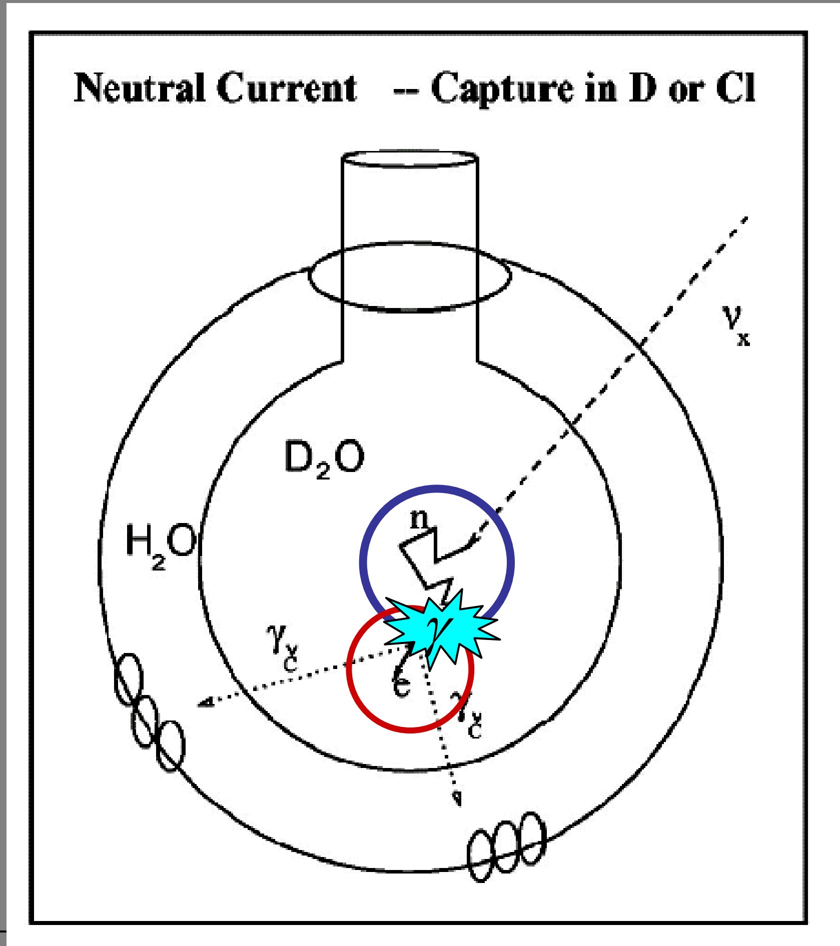
Neutrino detection in SNO

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

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

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





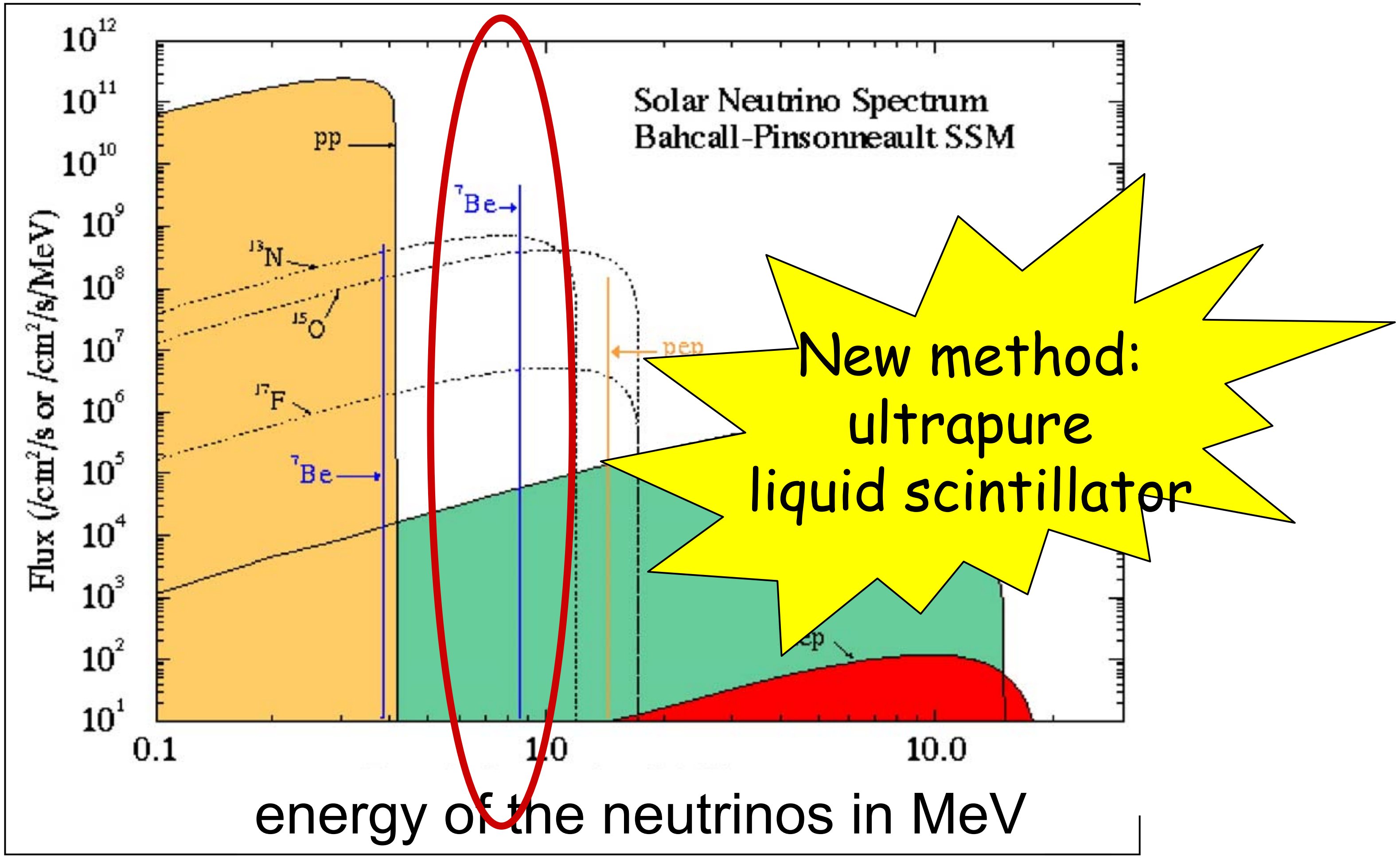
SNO Result (salt-phase)

(PRL 92, 181301, 2004)

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

- 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)

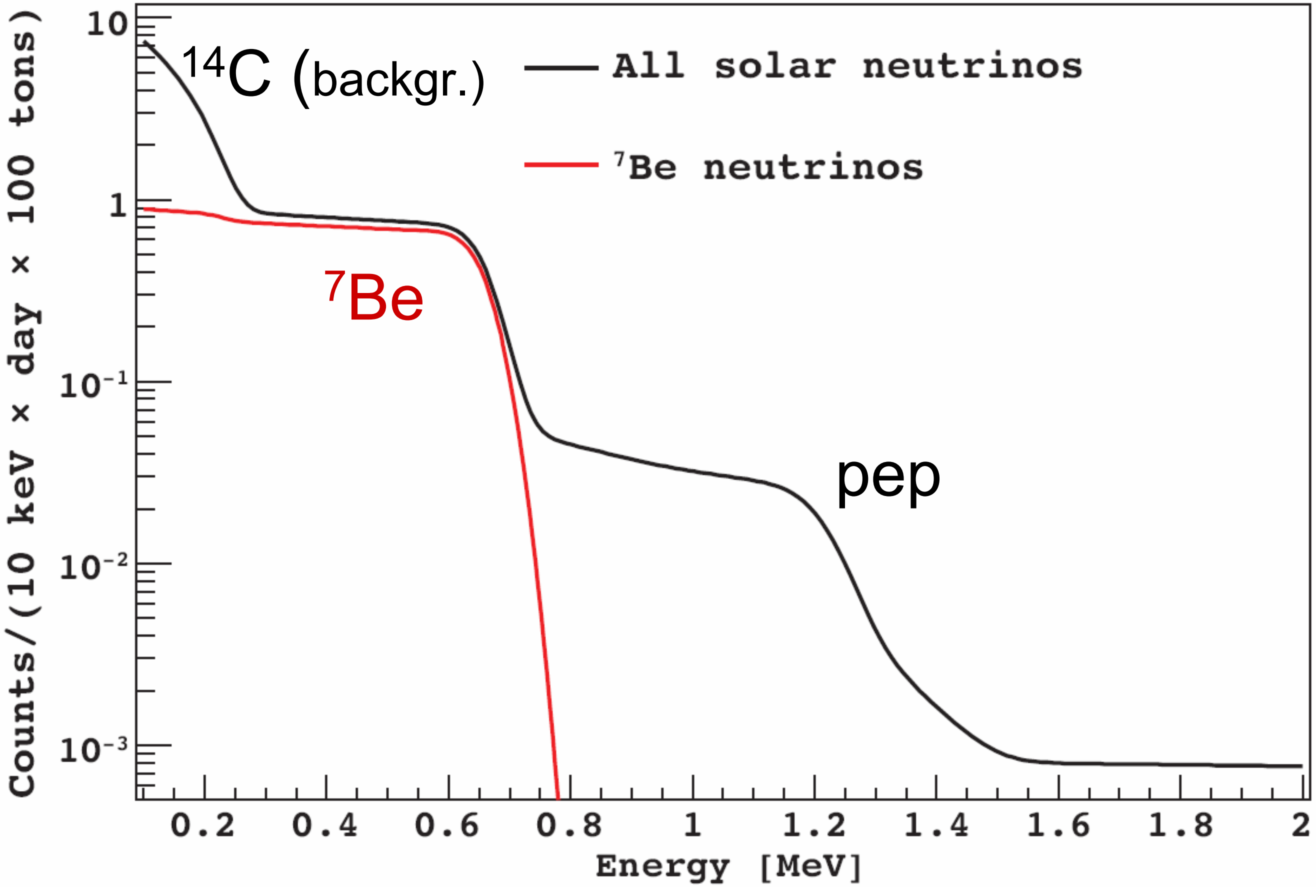
New Generation of Solar Neutrino Experiments



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

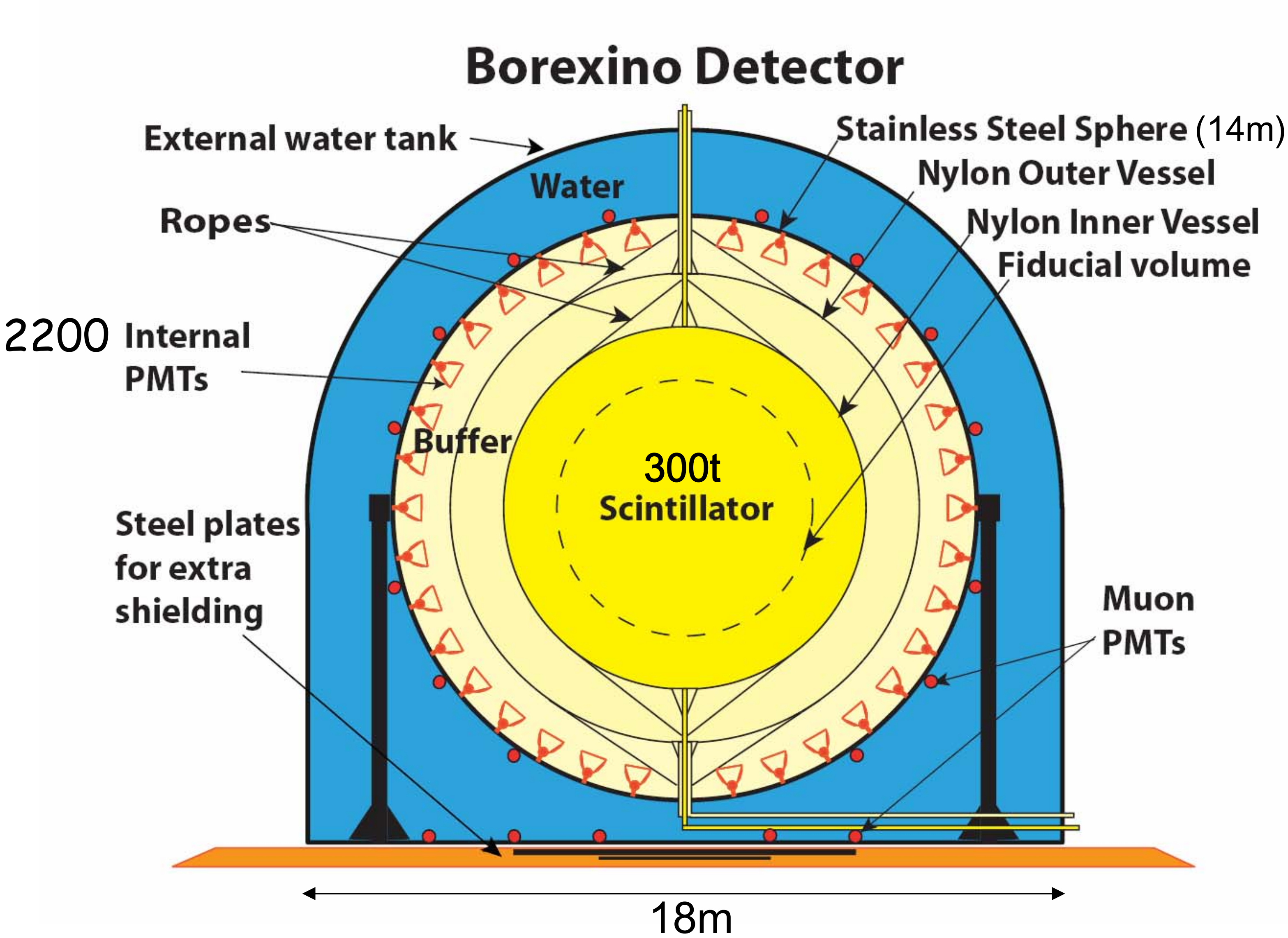
BOREXINO

Expected (electron) energy distribution:



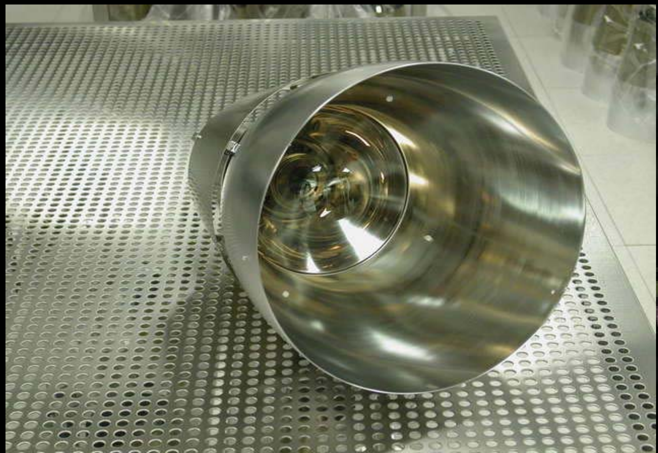
Edge at 665 keV

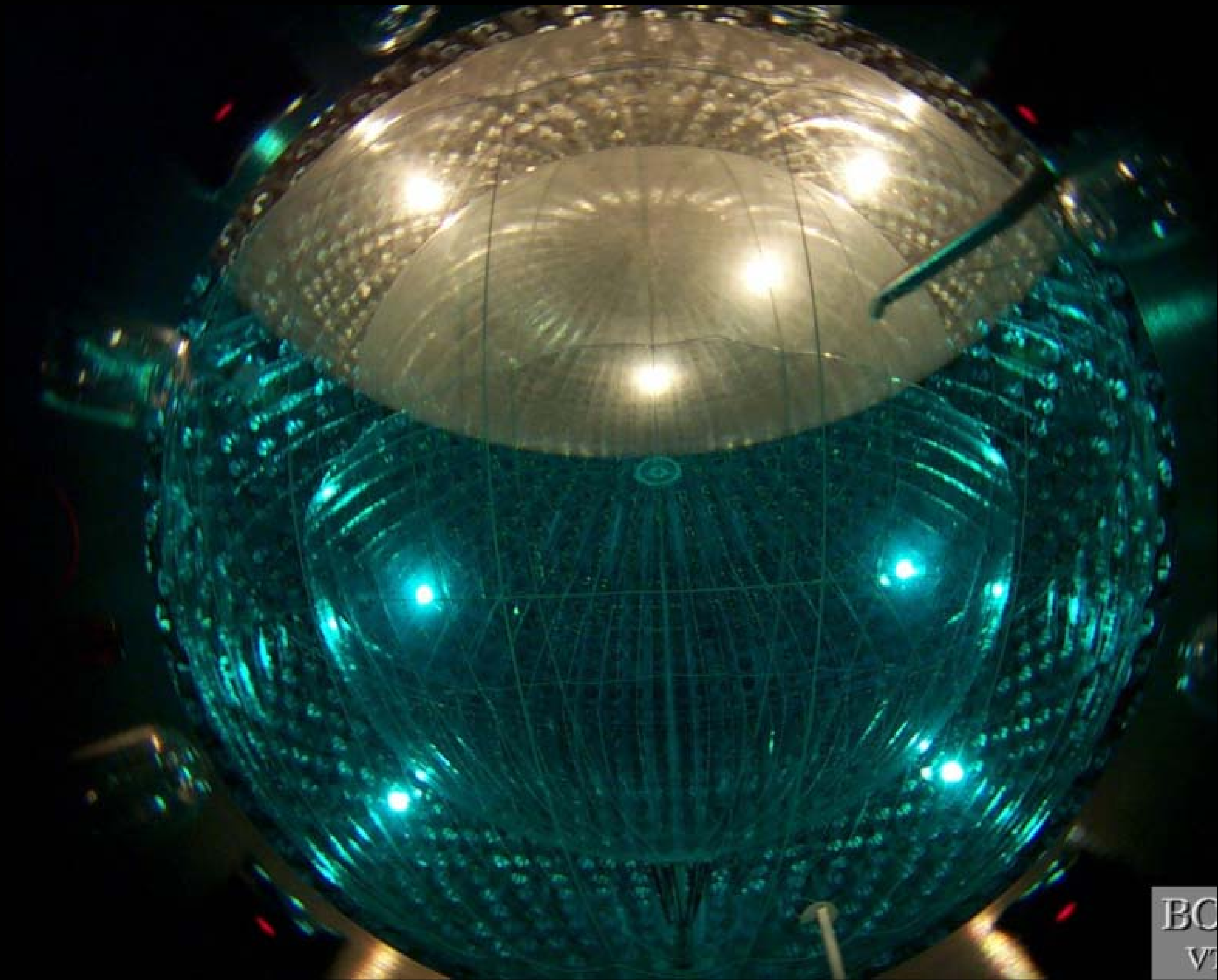
BOREXINO @ LNGS



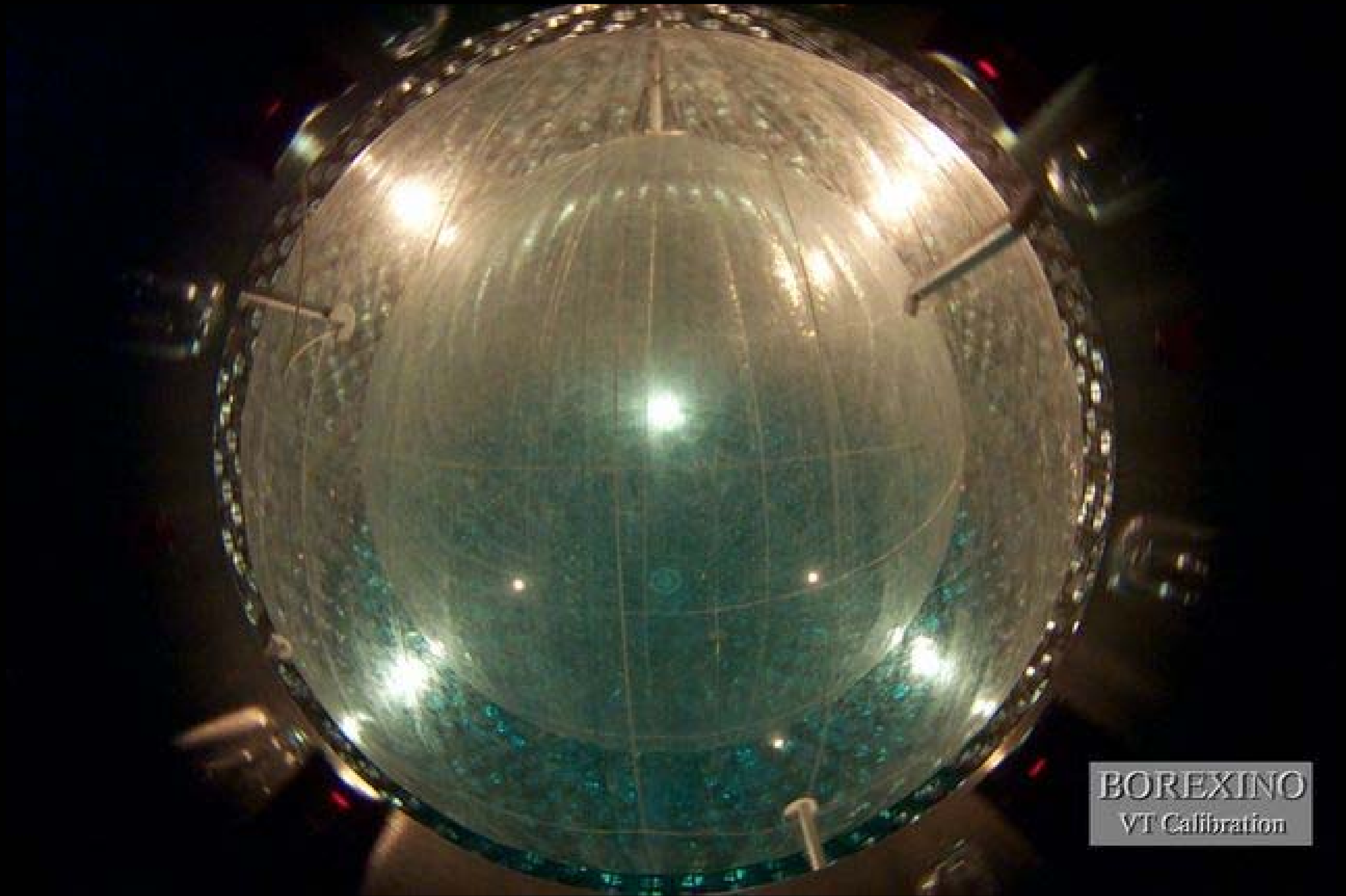
CTF (Borexino)

Photomultipliers and light concentrators in Borexino



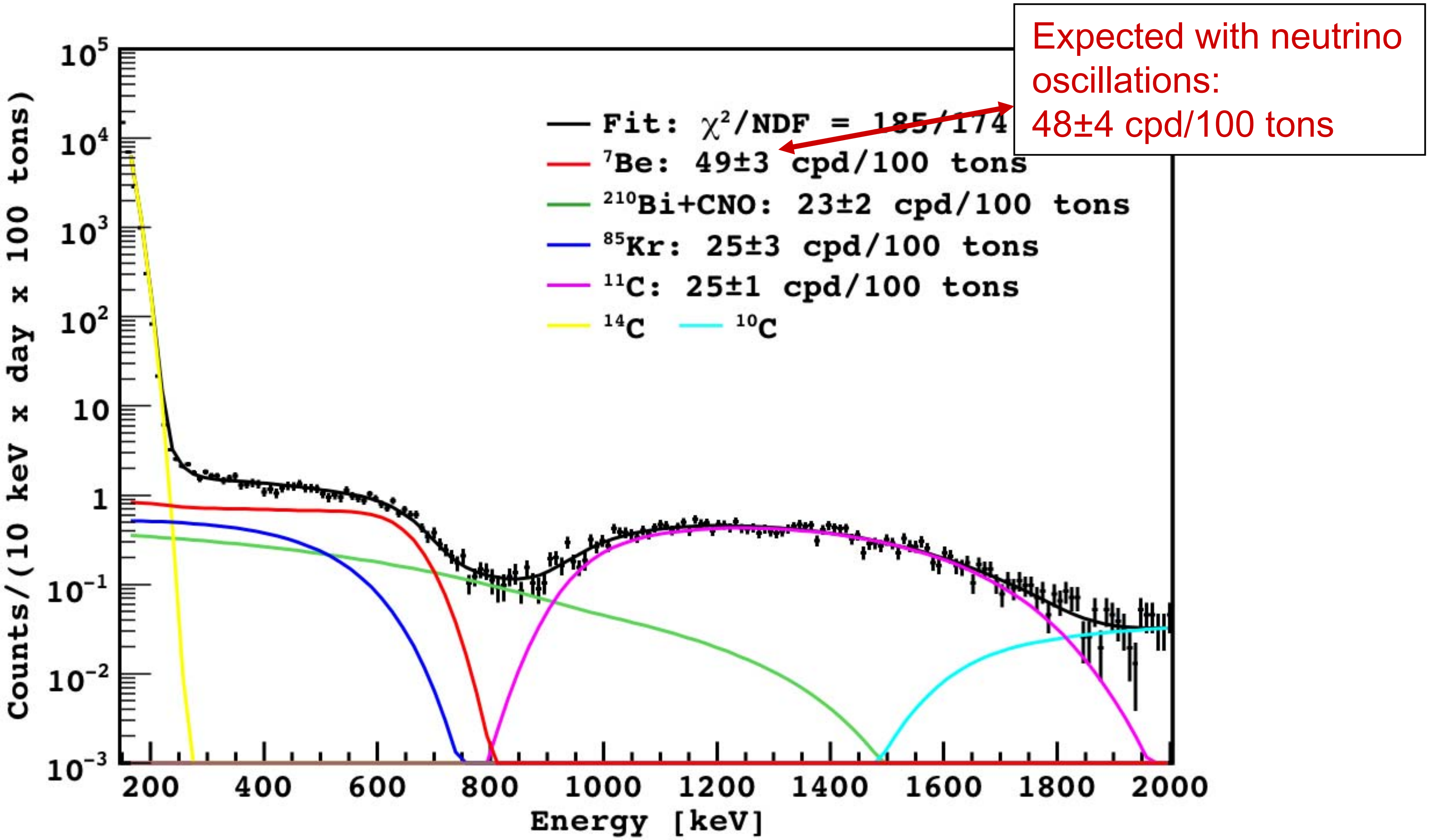


Borexino during filling (on top scintillator, lower part water)

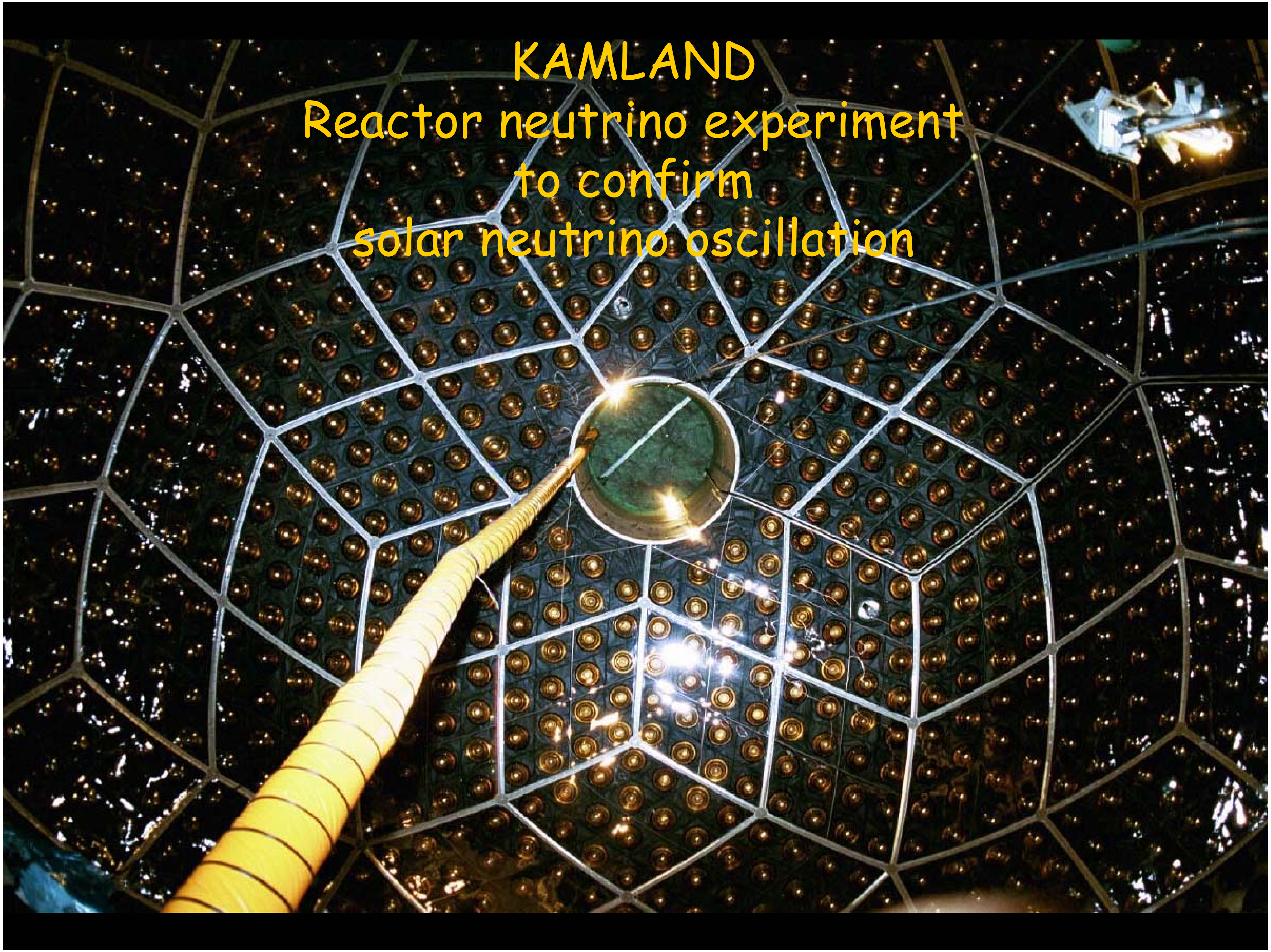


Scintillator filling completed May 15, 2007

Recent BOREXINO Result (May 2008)

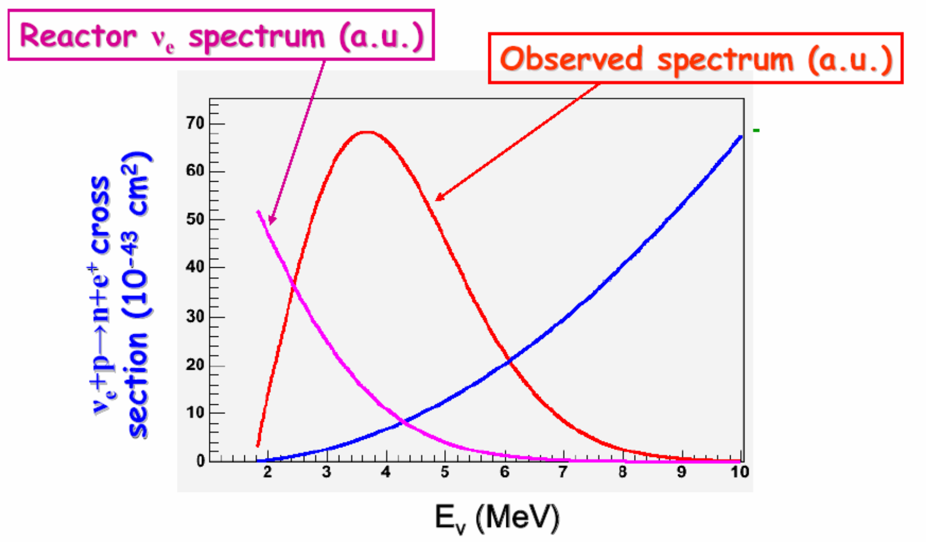


PRL 101:091302 (2008). arXiv:0805.3843:
"New results on solar neutrino fluxes from 192 days of Borexino data"


KAMLAND
Reactor neutrino experiment
to confirm
solar neutrino oscillation

KAMLAND

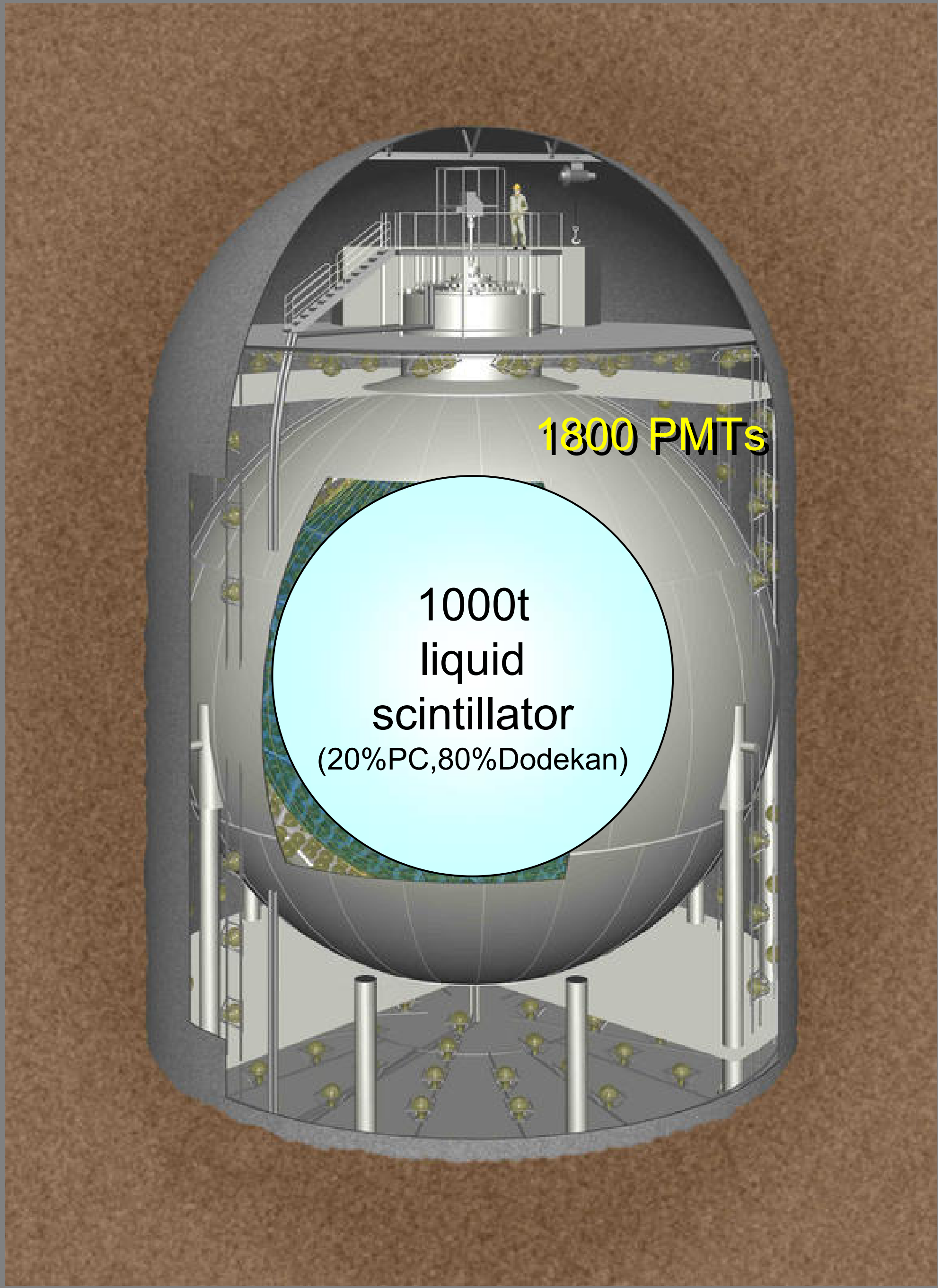
reactor neutrinos = $\bar{\nu}_e$



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

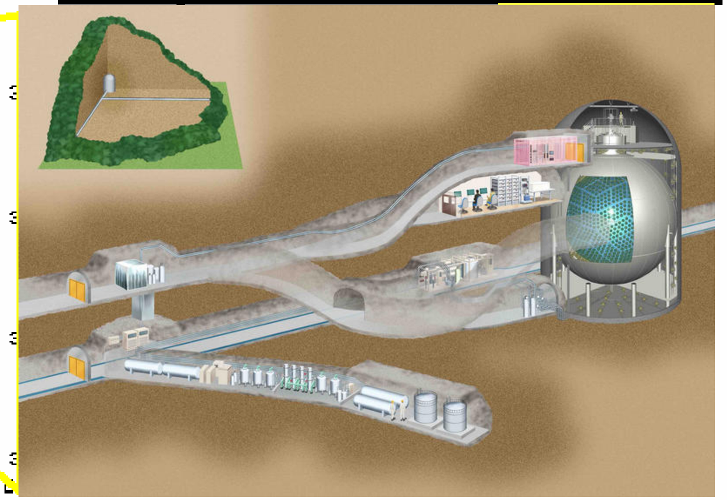
prompt signal
E_ν – 0.77MeV

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

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

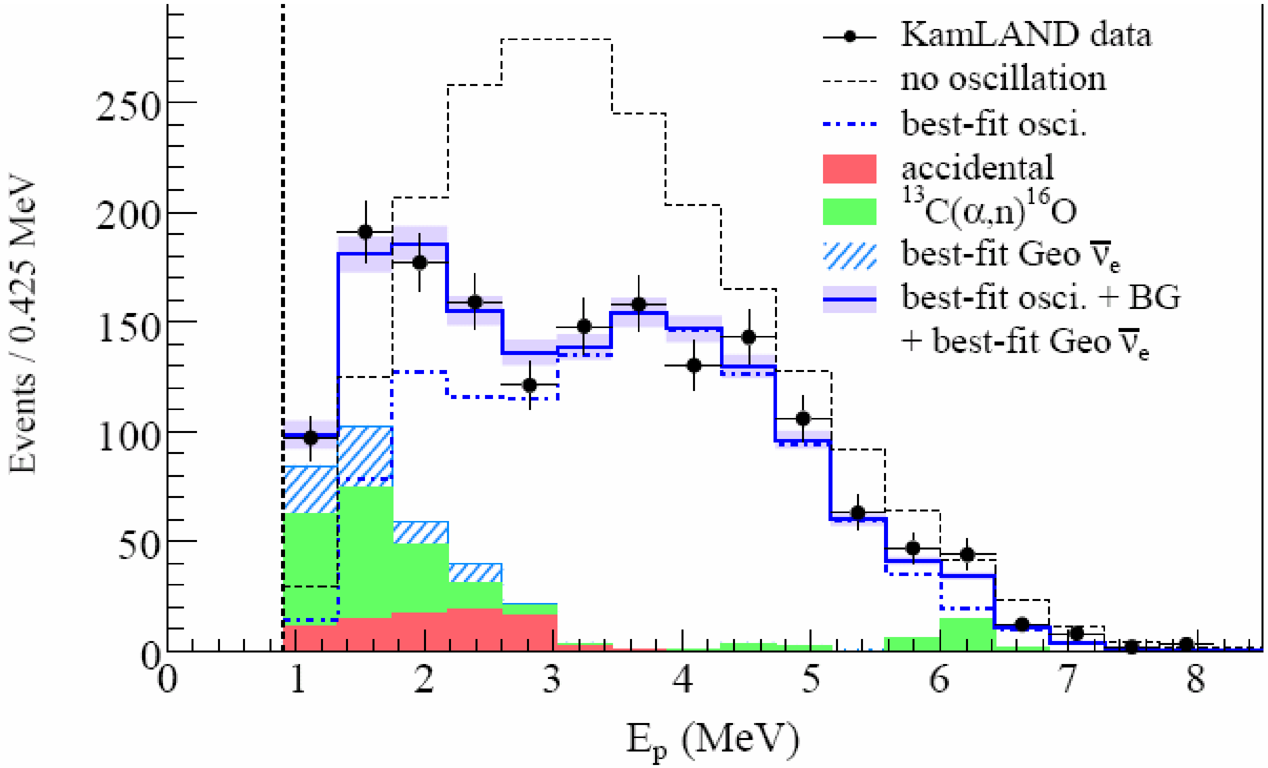
E (Reactor ν) ≈ 4MeV
Δm^2 (solar ν) = $8 \cdot 10^{-5} eV^2$

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

Test possible!

KamLAND result (2008)

prompt event energy spectrum of anti-ν_e candidates



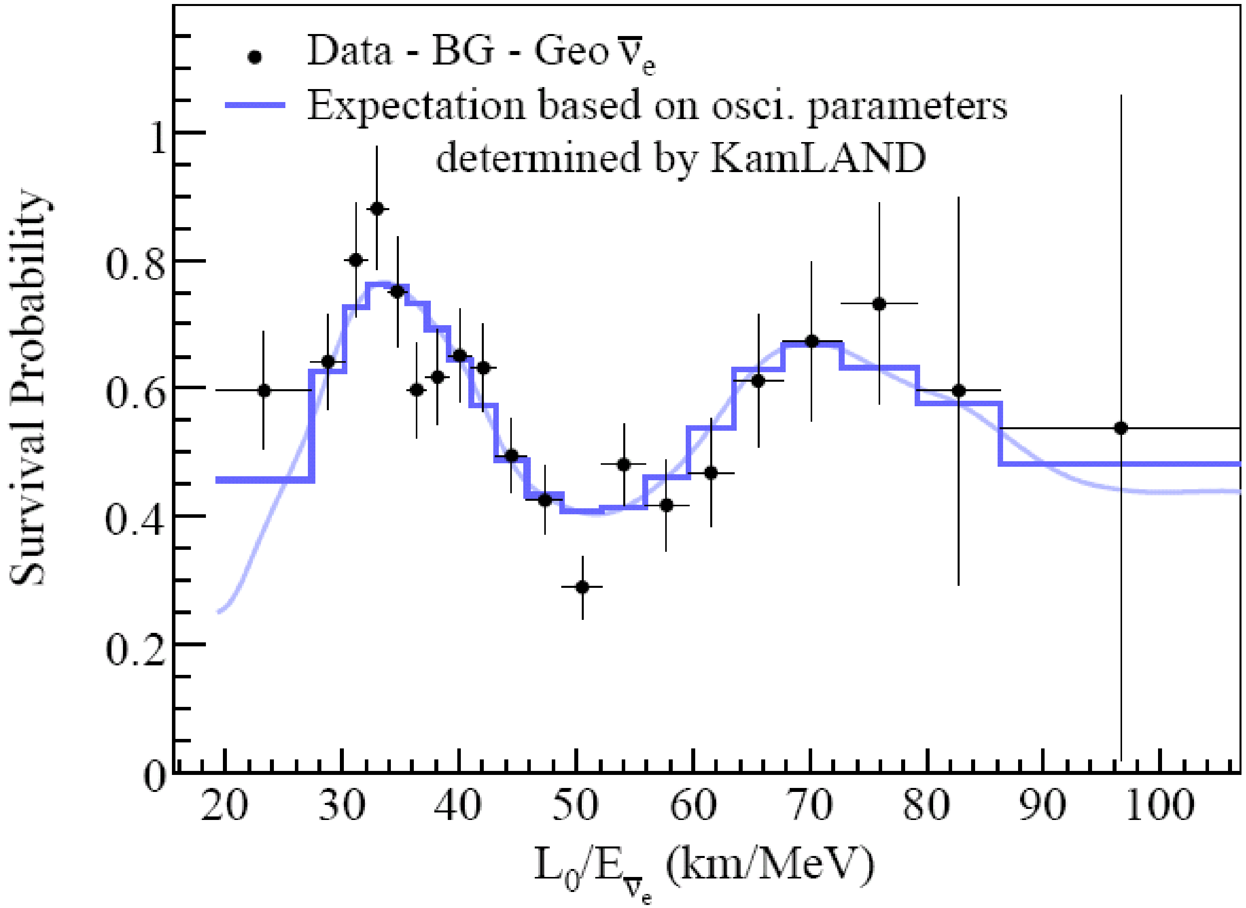
best fit: $$\Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(\text{stat})^{+0.15}_{-0.15}(\text{syst}) \times 10^{-5}\ \text{eV}^2$$

$$\tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(\text{stat})^{+0.10}_{-0.06}(\text{syst})$$

„Precision Measurement of Neutrino Oscillation Parameters with KamLAND“, Phys.Rev.Lett.100:221803,2008

KamLAND result (2008)

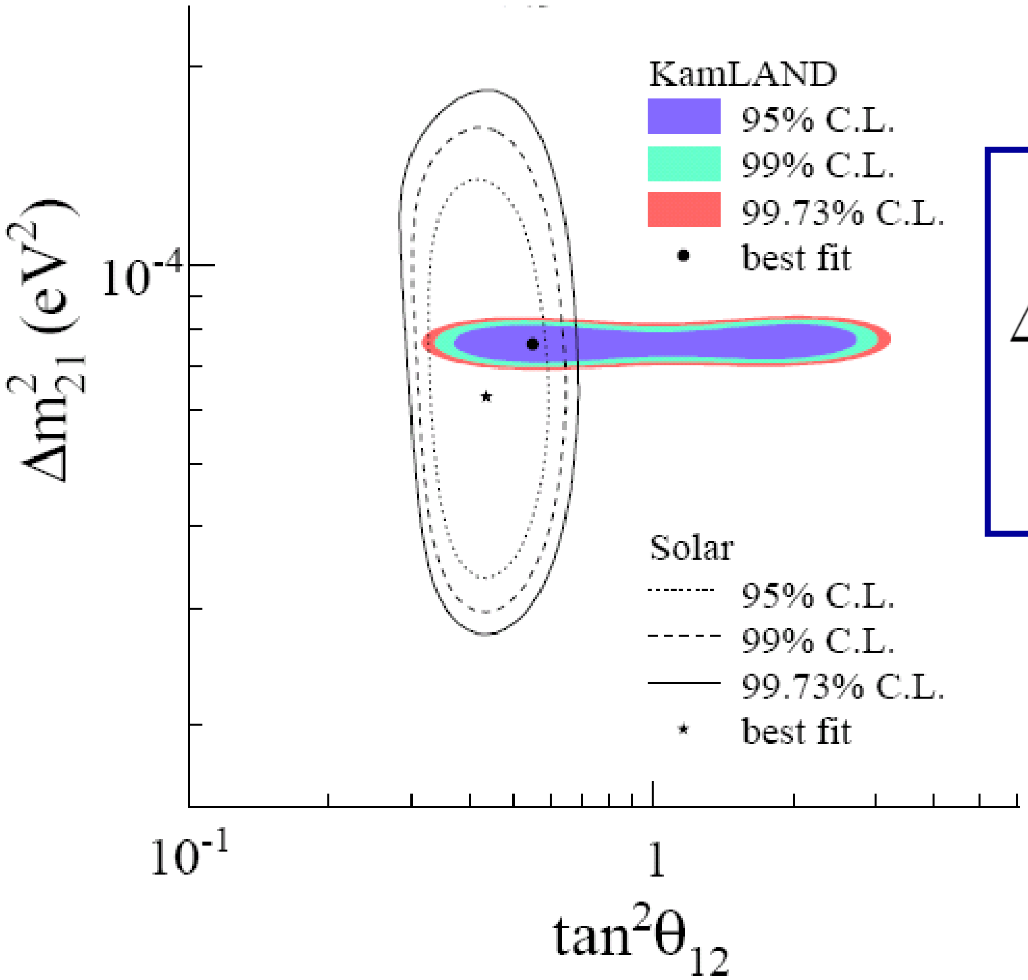
„Precision Measurement of Neutrino Oscillation Parameters with KamLAND", Phys.Rev.Lett.100:221803,2008



L_0 is the „effective" baseline = flux-weighted average of distance = 180km

KamLAND result (2008)

„Precision Measurement of Neutrino Oscillation Parameters with KamLAND“, Phys.Rev.Lett.100:221803,2008



KamLAND + solar:

$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

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 some of you!