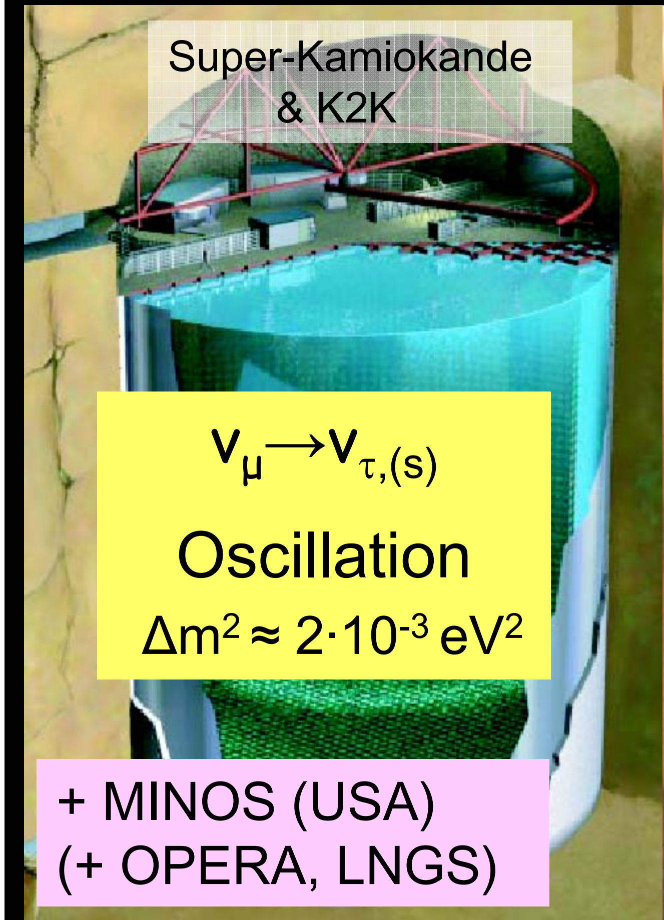
Aspects on Neutrino (Mass-) and Mixing

Caren Hagner, Universität Hamburg

- Introduction: neutrino mass and mixing
- Neutrino Oscillation (I): mu – tau mixing
    - atmospheric neutrinos
    - present neutrino beam experiments:
        - MINOS (NuMi beam: Fermilab – Soudan Mine)
        - OPERA (CNGS beam: Cern – LNGS)
- Neutrino Oscillation (II): e – mu mixing
    - solar neutrino experiments
        - short review on past experiments (SNO)
        - Borexino
    - reactor experiment: KamLand
- Neutrino Oscillation (III): Future prospects (theta13 and CPV)
    - reactor experiments: Double Chooz and Daya Bay
    - off-axis (super)beams: T2K and NovA
    - neutrinofactory and beta beams
- Neutrino Oscillation (IV): Problems?
    - LSND / MiniBoone
    - GSI anomaly
    - NuTeV anomaly
- Nature of neutrino mass: Majorana or Dirac?
    - Double beta decay

Neutrino Oscillations have been observed
→ Add Neutrino Mass & Mixing to SM

JAPAN

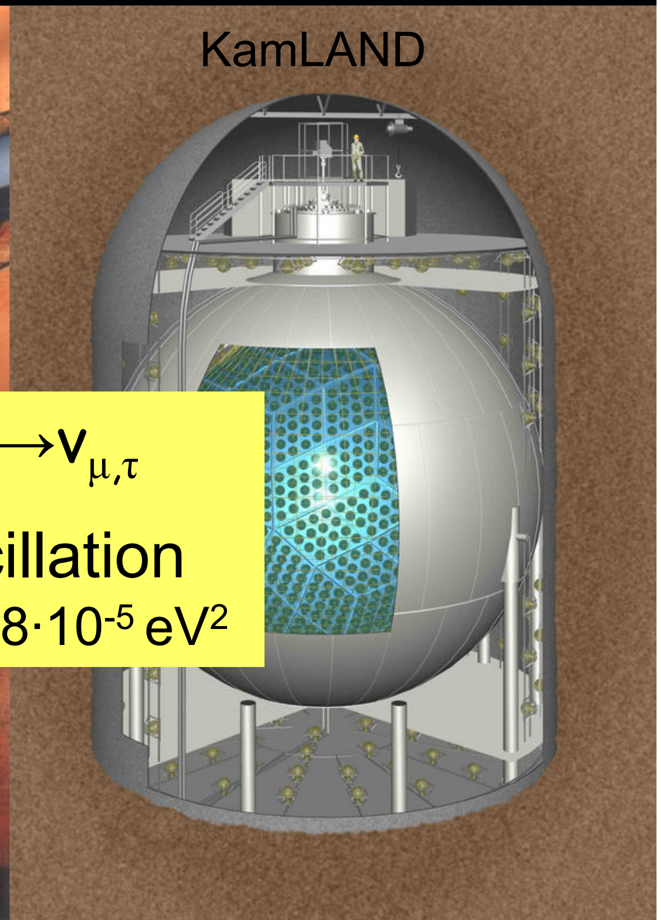


atmospheric neutrinos
accelerator neutrinos

CANADA

solar neutrinos

JAPAN



reactor neutrinos

Neutrino Oscillations (23)

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

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

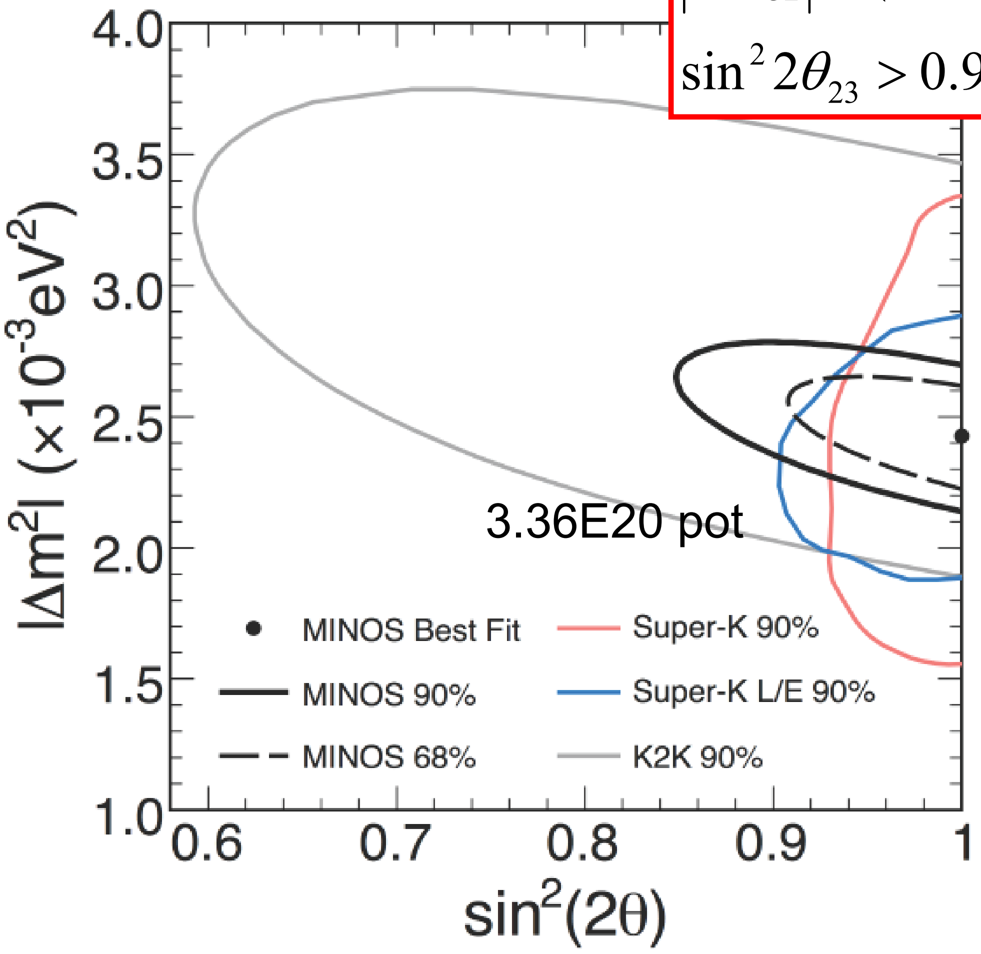
Atmospheric neutrinos & accelerator neutrinos

Last lecture: Super-Kamiokande (atm. Neutrinos) & MINOS

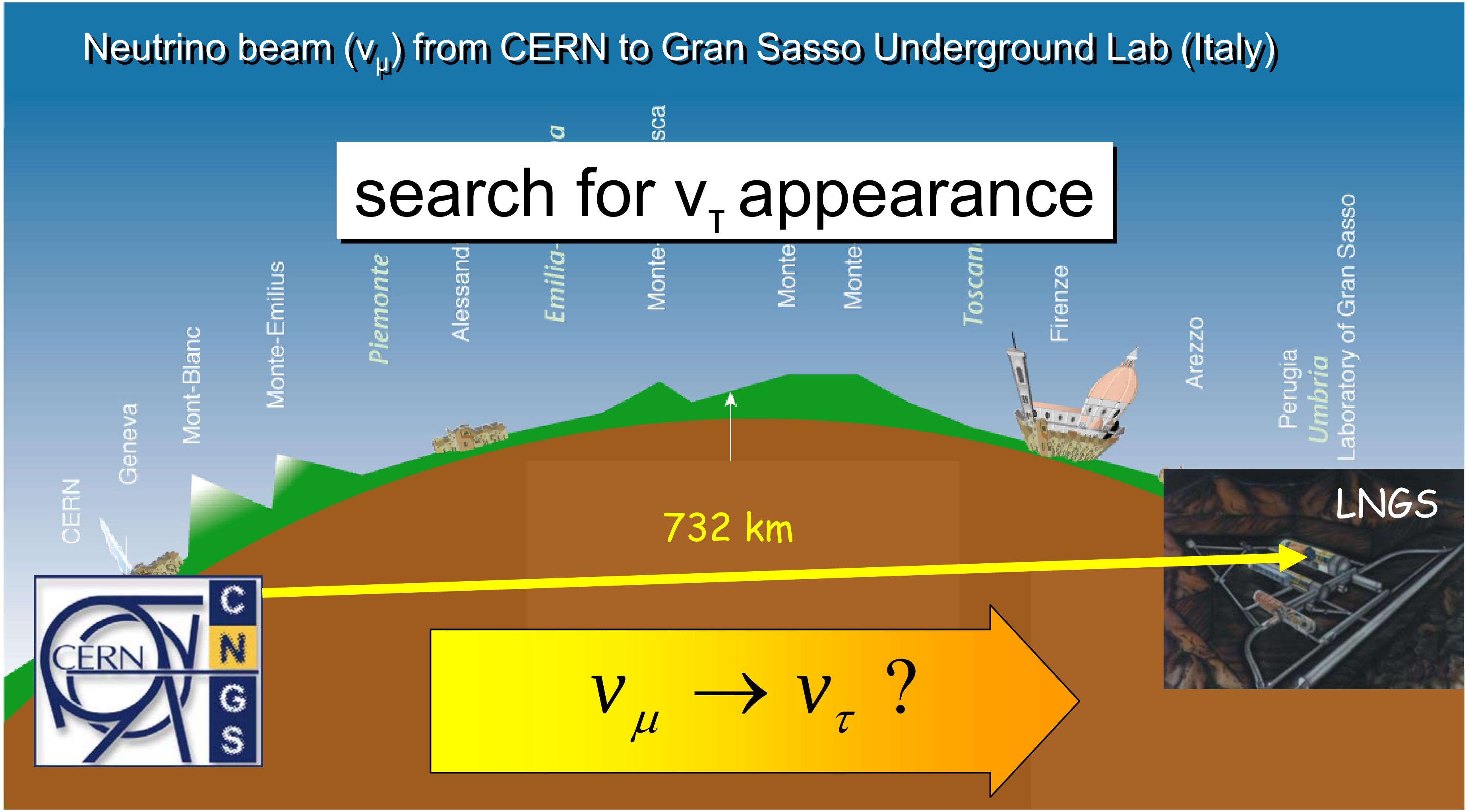
MINOS & SuperK: Allowed Regions

$$\left|\Delta m^2_{32}\right| = (2.43 \pm 0.13) \times 10^{-3}\,\mathrm{eV}^2 \quad (68\%\mathrm{CL})$$

$$\sin^2 2\theta_{23} > 0.90 \quad (90\%\mathrm{CL})$$

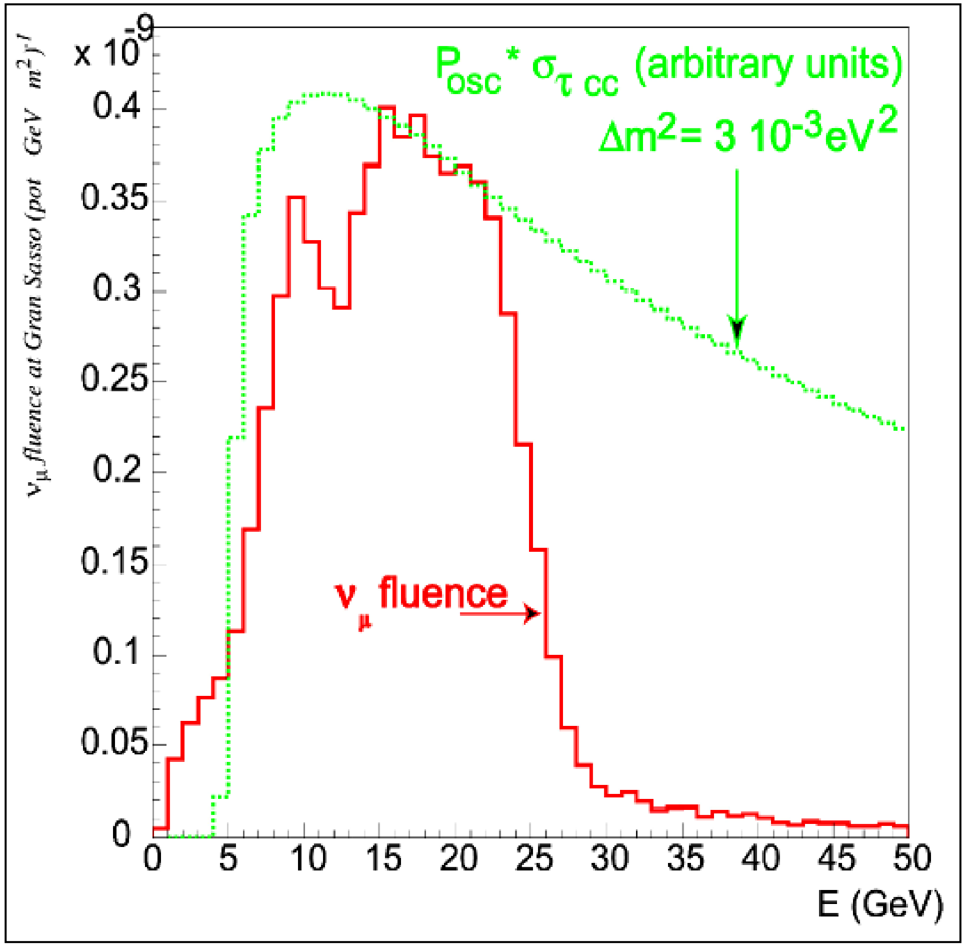


OPERA:
Oscillation Project with Emulsion tRacking Apparatus



first physics run: june-november 2008; run 2009: just started

CNGS beam ("pure" ν_μ)

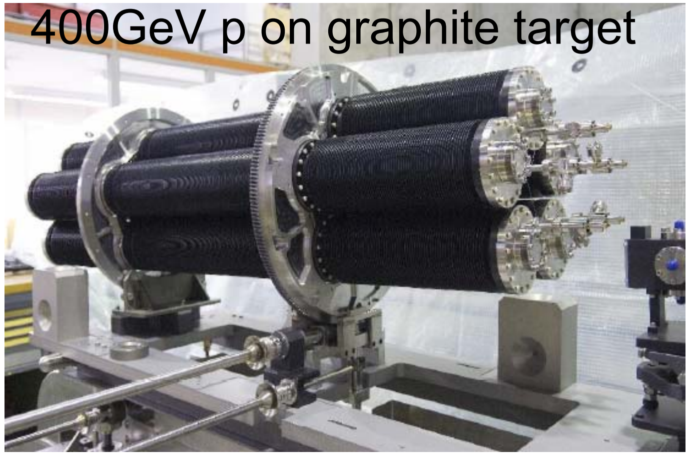


Total exposure expected: 22.5E19 pot

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

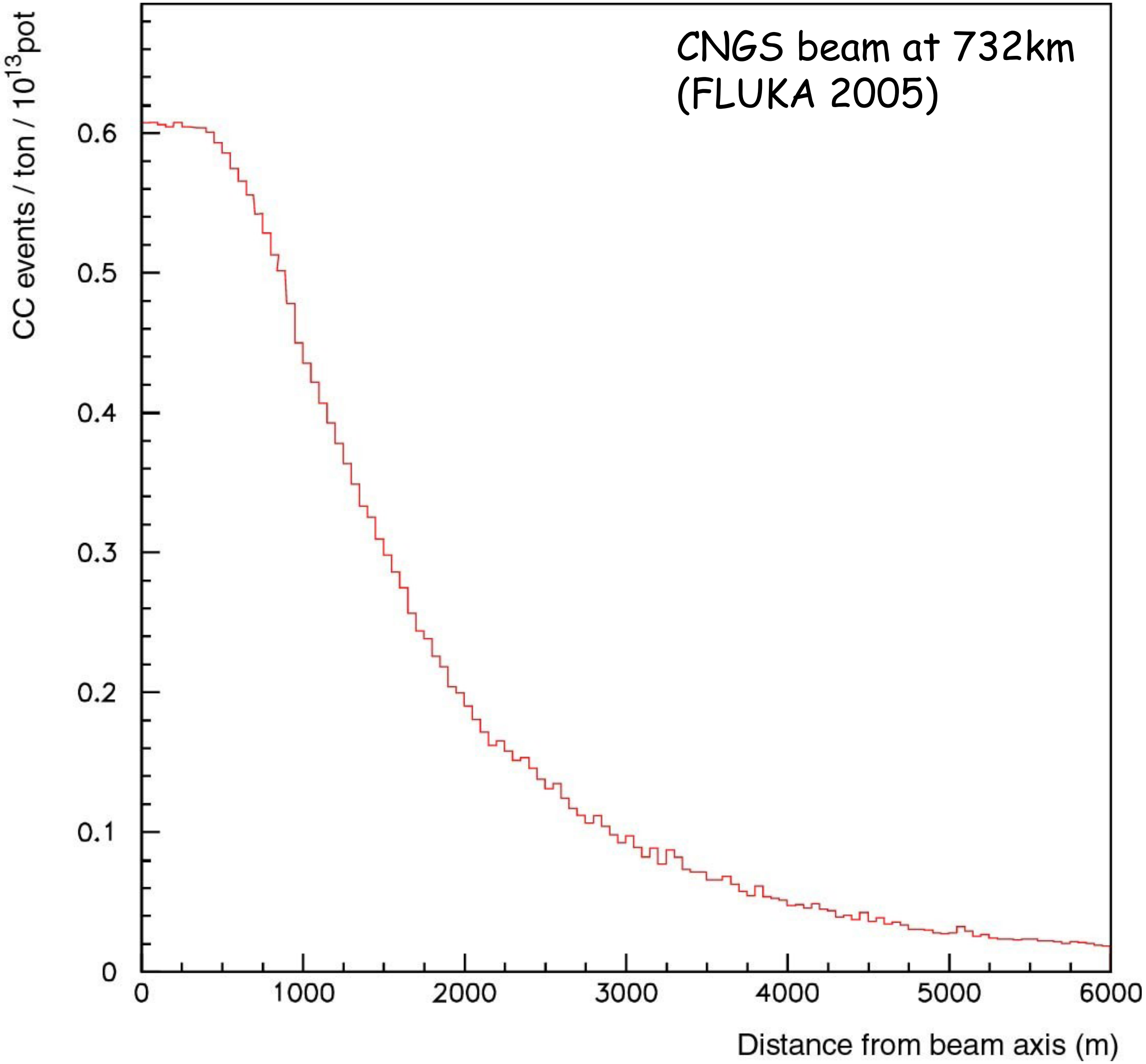
$$\bar{\nu}_\mu / \nu_\mu = 4\%$$

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

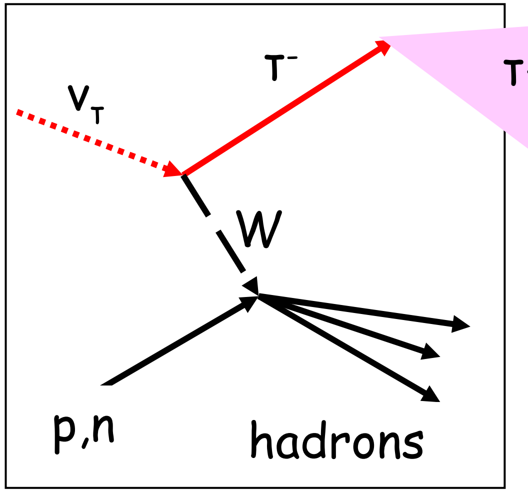


$4.5 \cdot 10^{19}$pot/year

Profile of neutrino beam @ LNGS



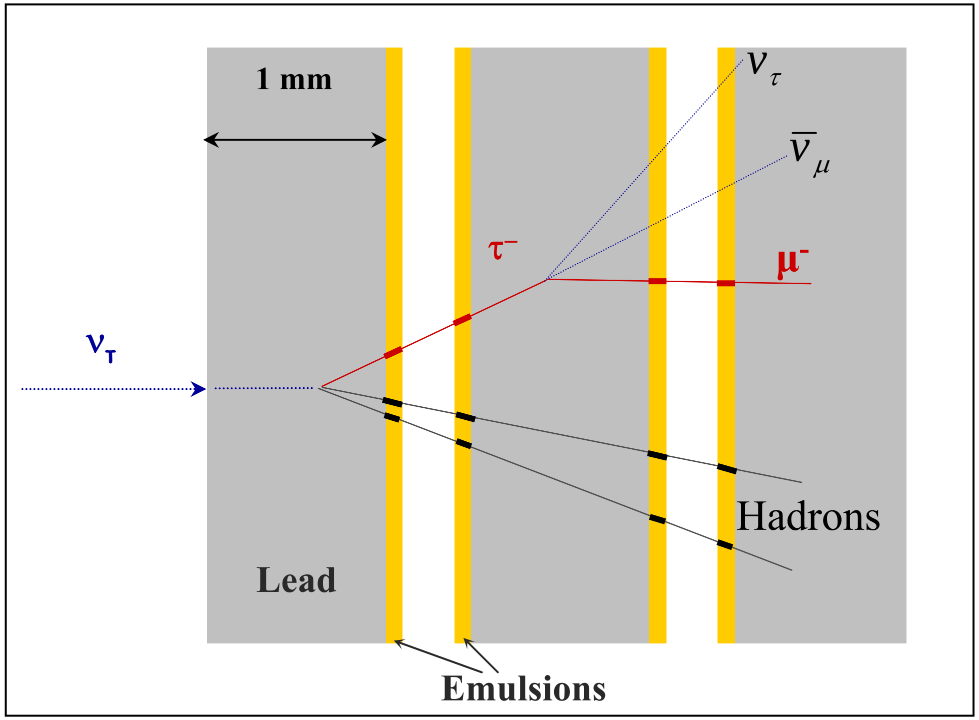
OPERA: ν_τ detection



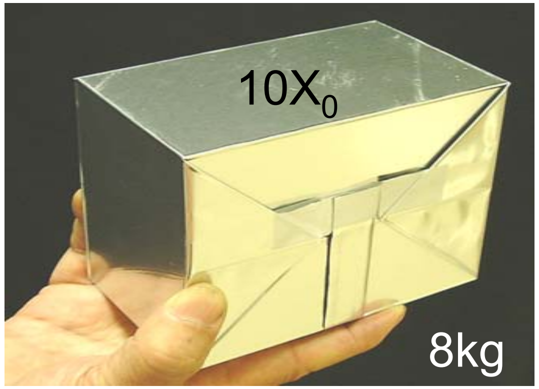
τ-decay:

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \qquad 17.4\%$$
$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \qquad 17.8\%$$
(kink)
$$\tau^- \to \text{hadron} + \nu_\tau \qquad 49.5\%$$
$$\tau^- \to \pi^-\pi^-\pi^+(n\pi^0) + \nu_\tau \qquad 15.2\%$$
(trident)

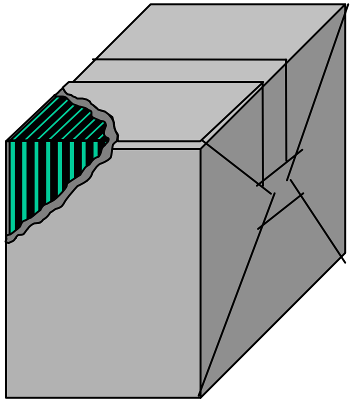
Typical topology of τ-decay:
"Kink" within 1mm from vertex

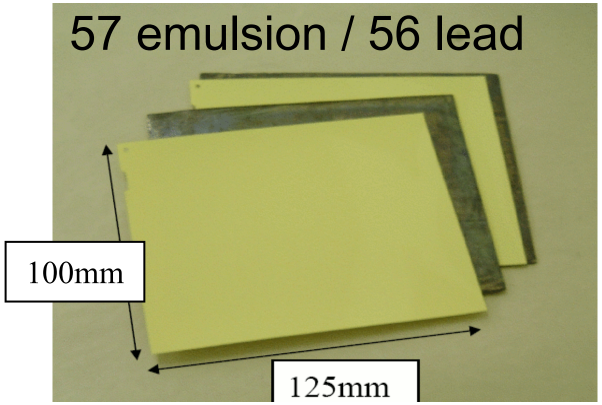


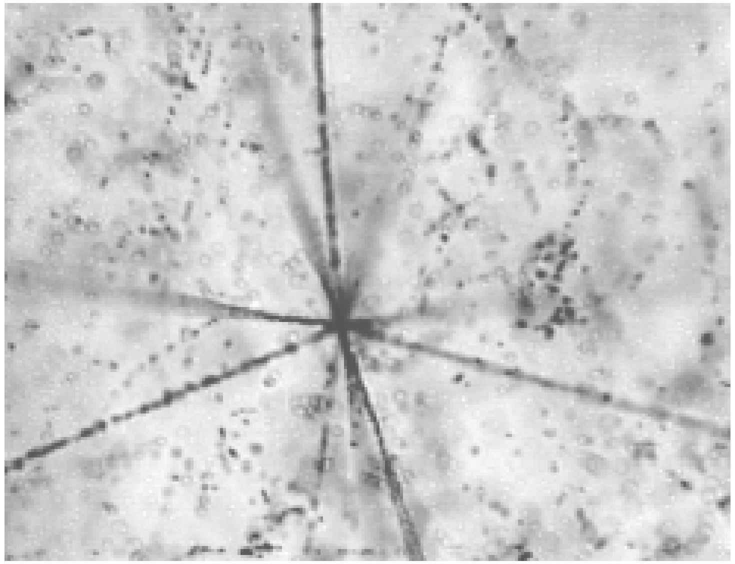
OPERA target: lead-emulsion-bricks



lead-emulsion-brick
(total ≈ 150000)

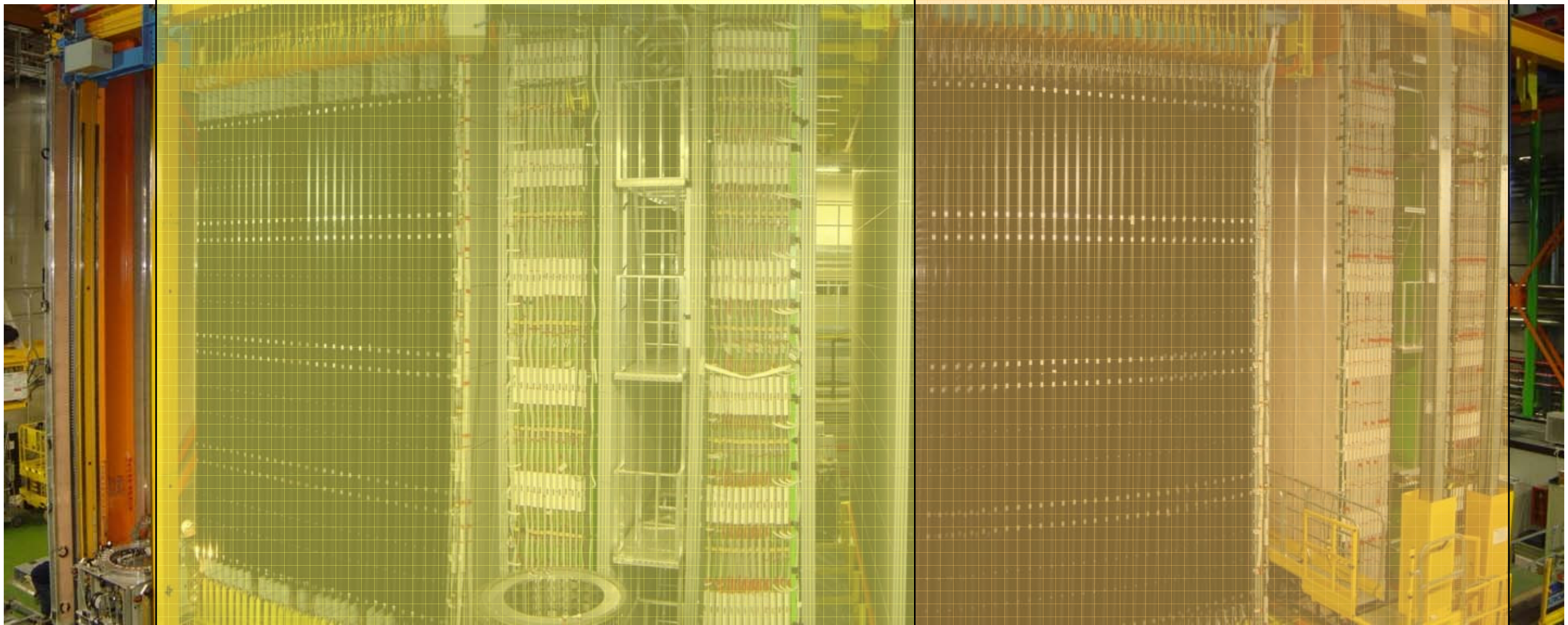






target mass:
≈1.2 kton

OPERA - Detector



Supermodule 1

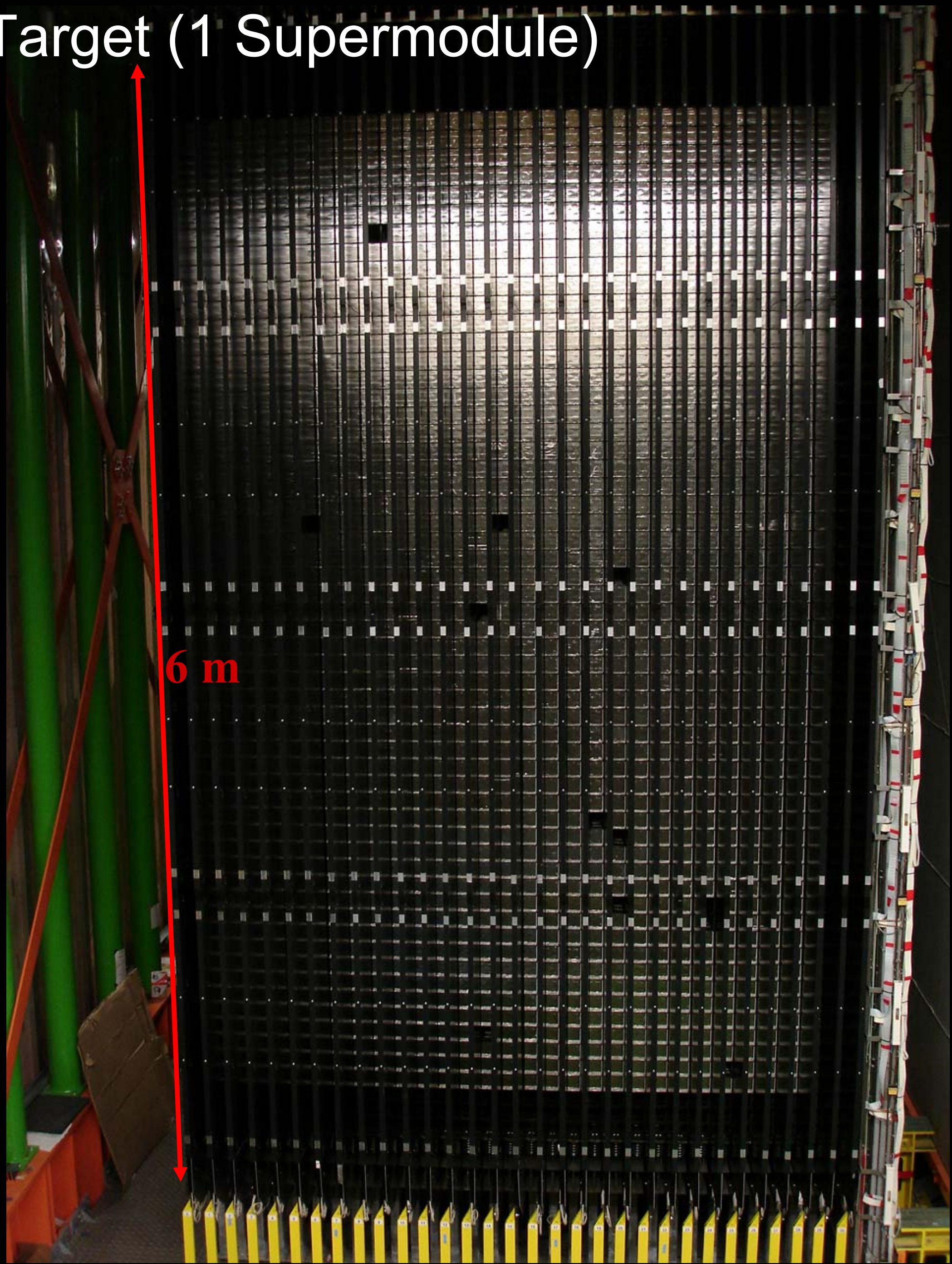
Supermodule 2

OPERA - Detector

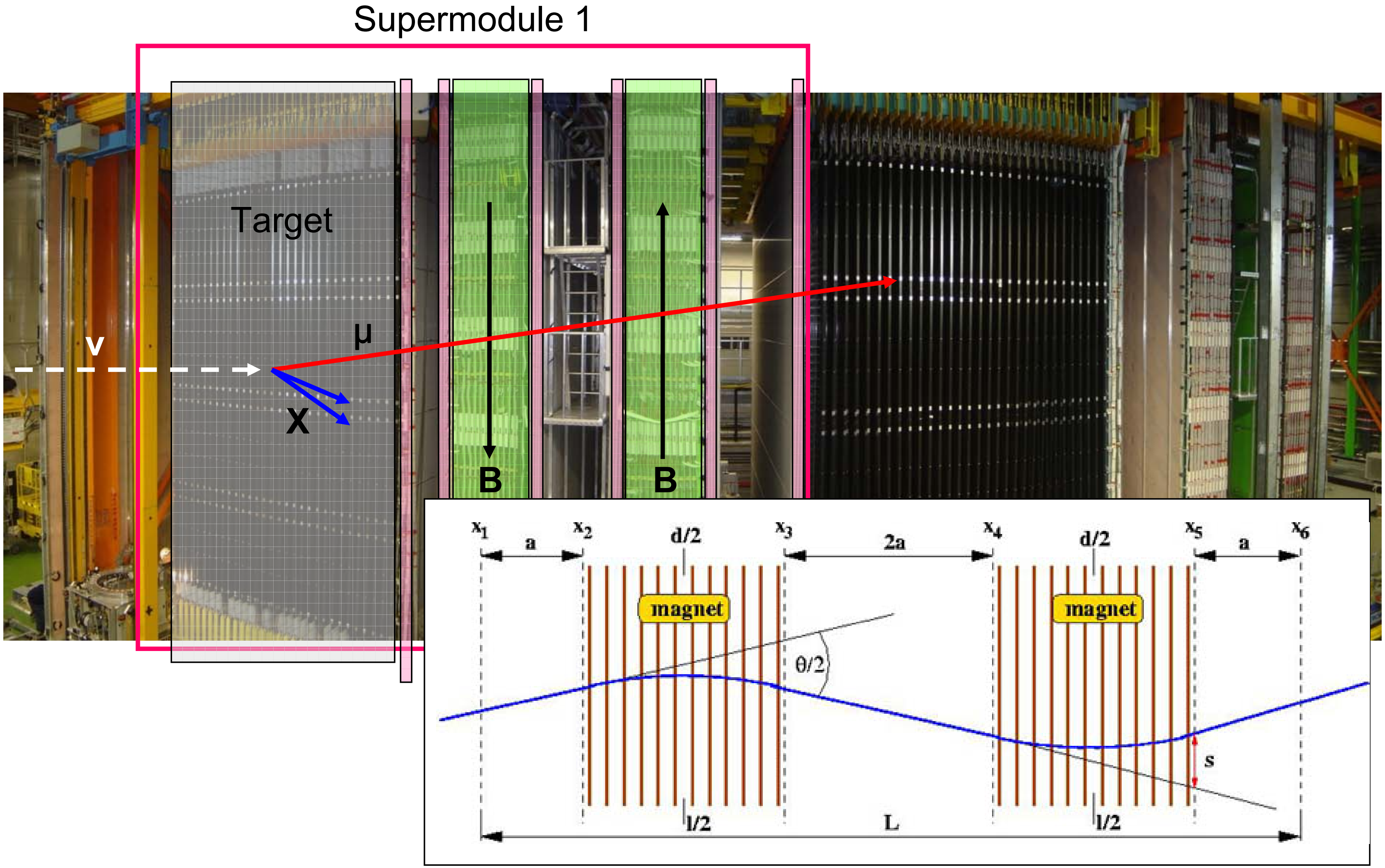
Supermodule 1

Target Region:
- Target Tracker (Scintillator)
- Lead/Emulsion Bricks (75.000 per Supermodule)

The OPERA Target (1 Supermodule)

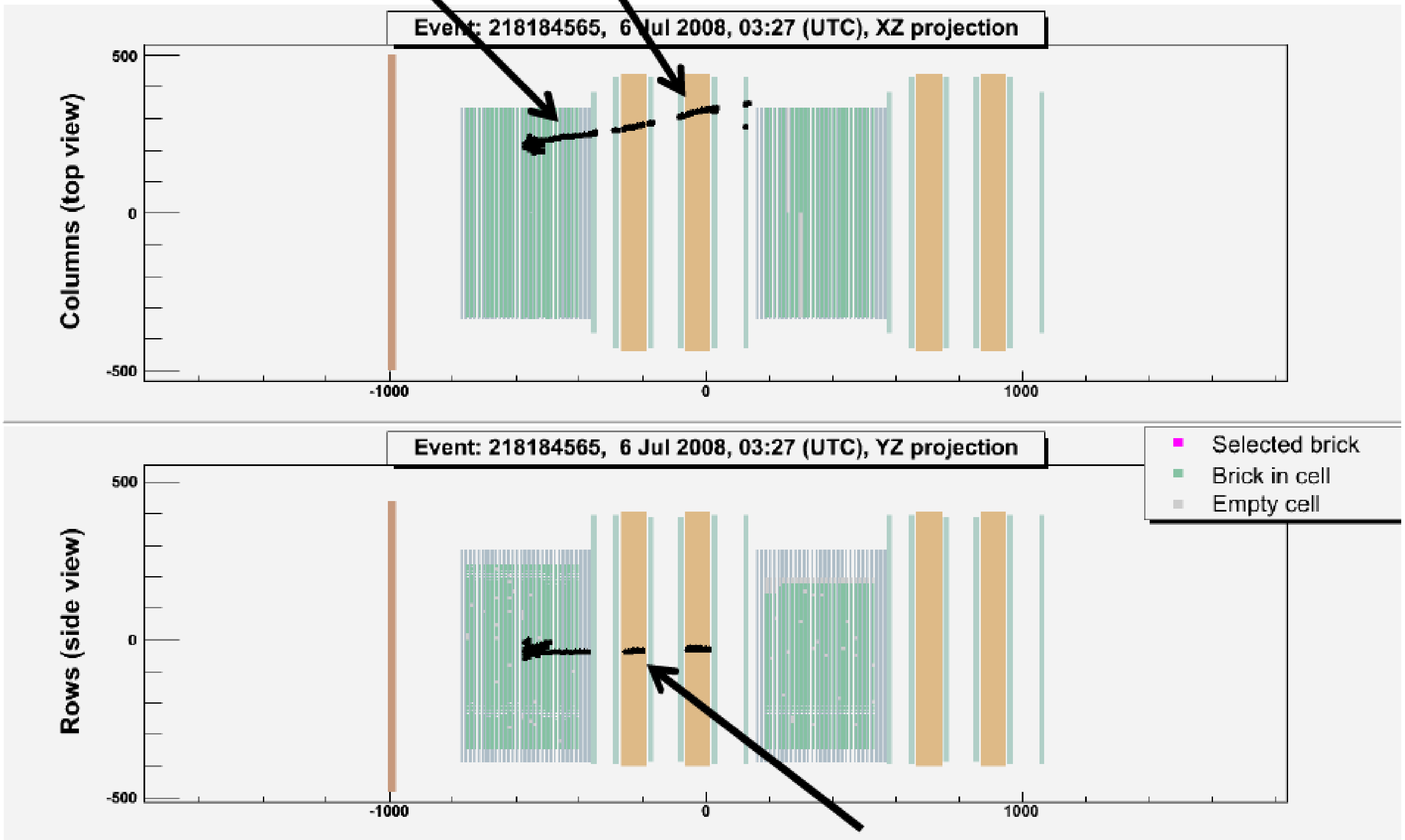


OPERA - Detector



Reconstruction (I): Myon-Spectrometer

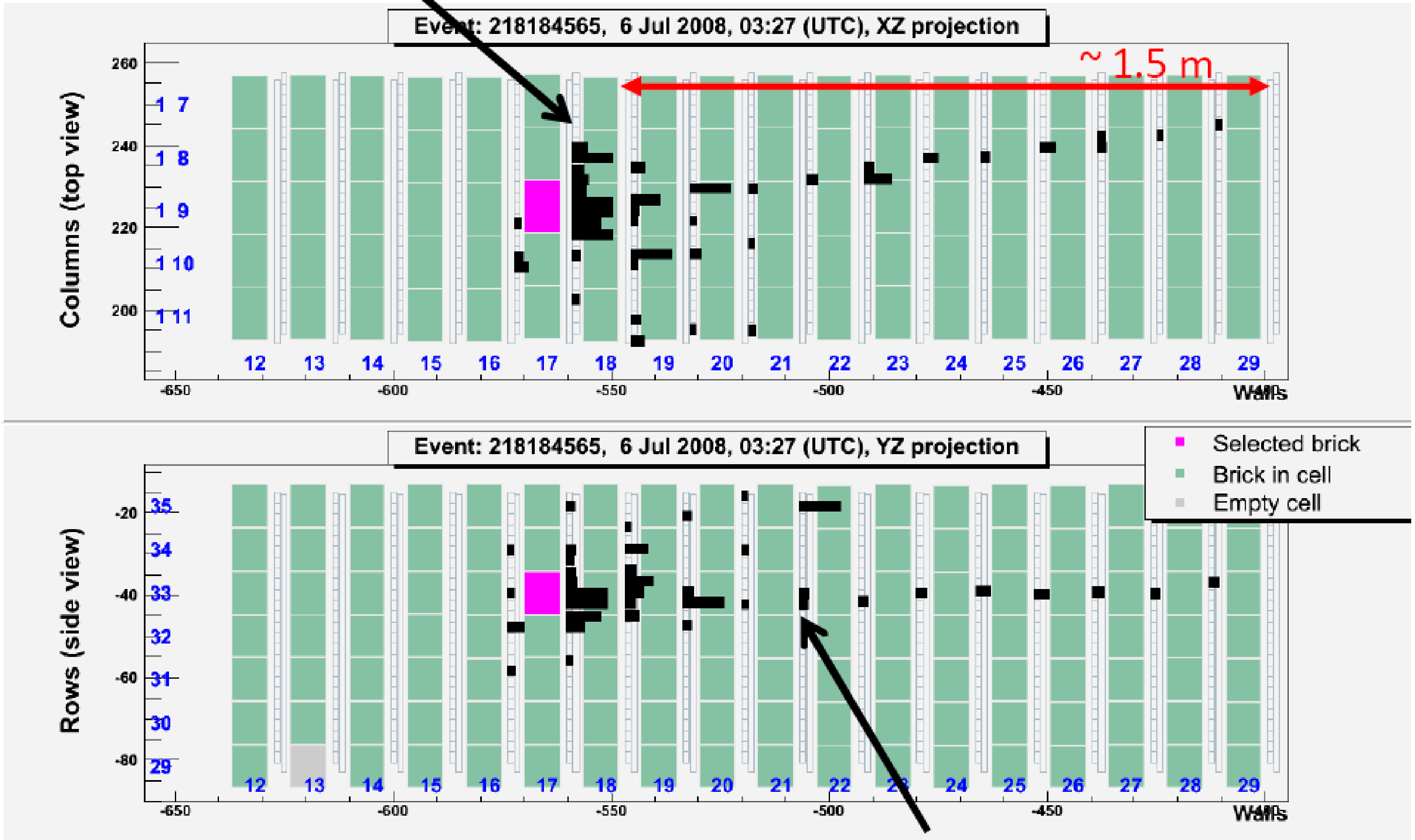
Electronic data (Target Tracker & Muon spectrometer)



Track identified as a muon (P=3.394 GeV/c)

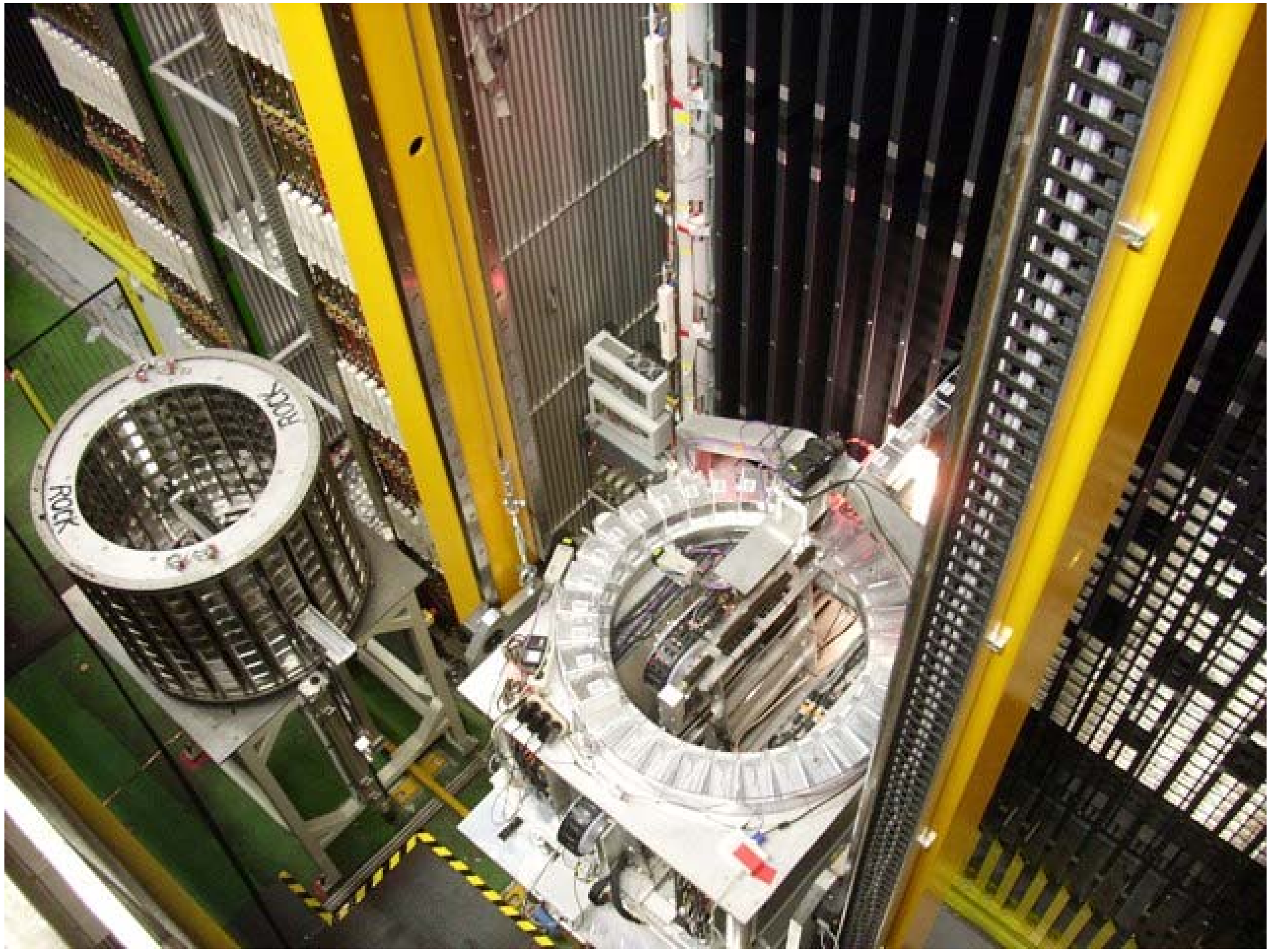
Rekonstruktion (II): Brick Finding

Electronic data (Target Tracker & Muon spectrometer)



Track identified as a muon (P=3.394 GeV/c)

OPERA – Brick Manipulating System



≈30 bricks/day are extracted

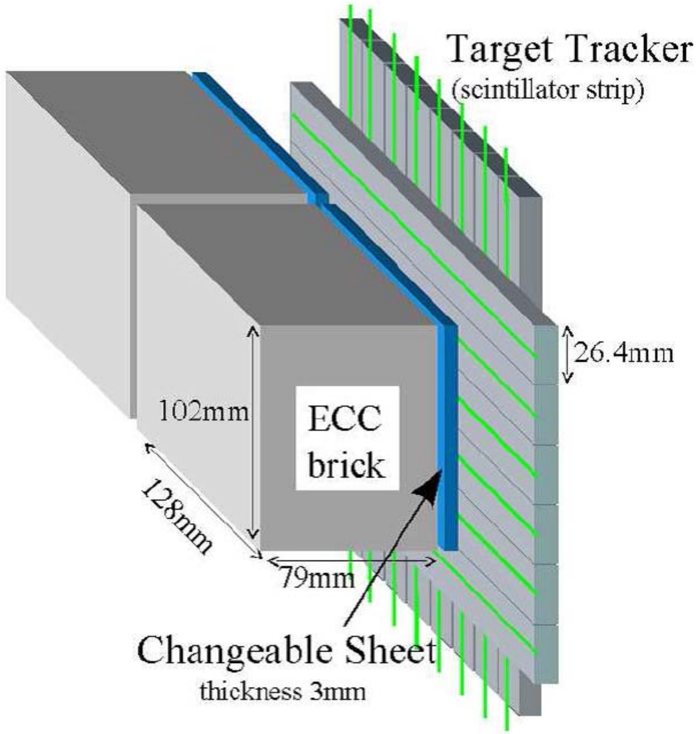
OPERA – Changeable Sheet (CS) Method

After extraction:

1.) First X-ray exposure of brick with CS

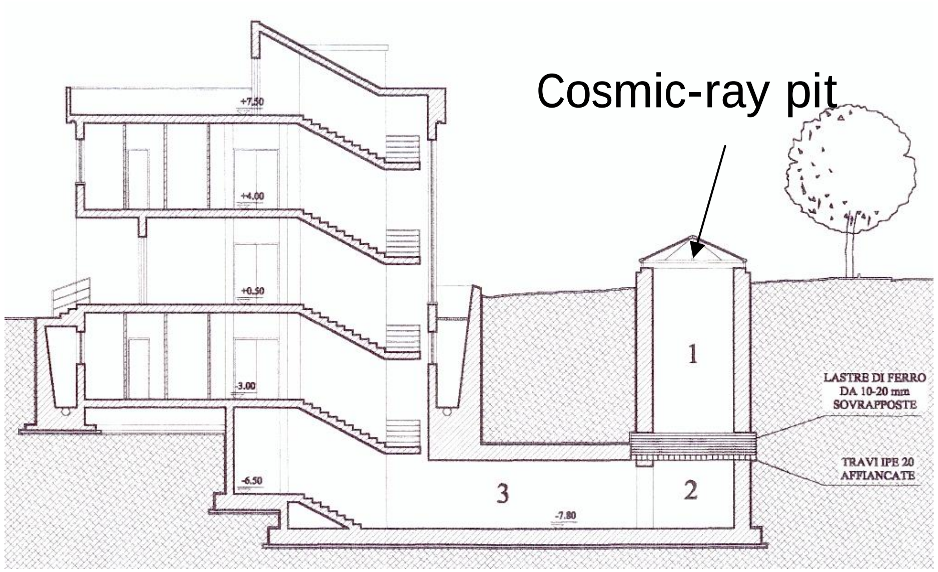
2.) CS is detached and developed underground
brick is kept in shielding box (5cm iron)

3.) If track in CS is compatible with track reconstructed by electronic detectors:
Second X-ray exposure of brick,
brick brought to surface



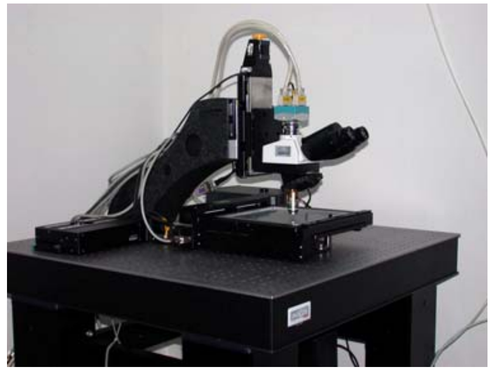
Emulsion Development @ LNGS

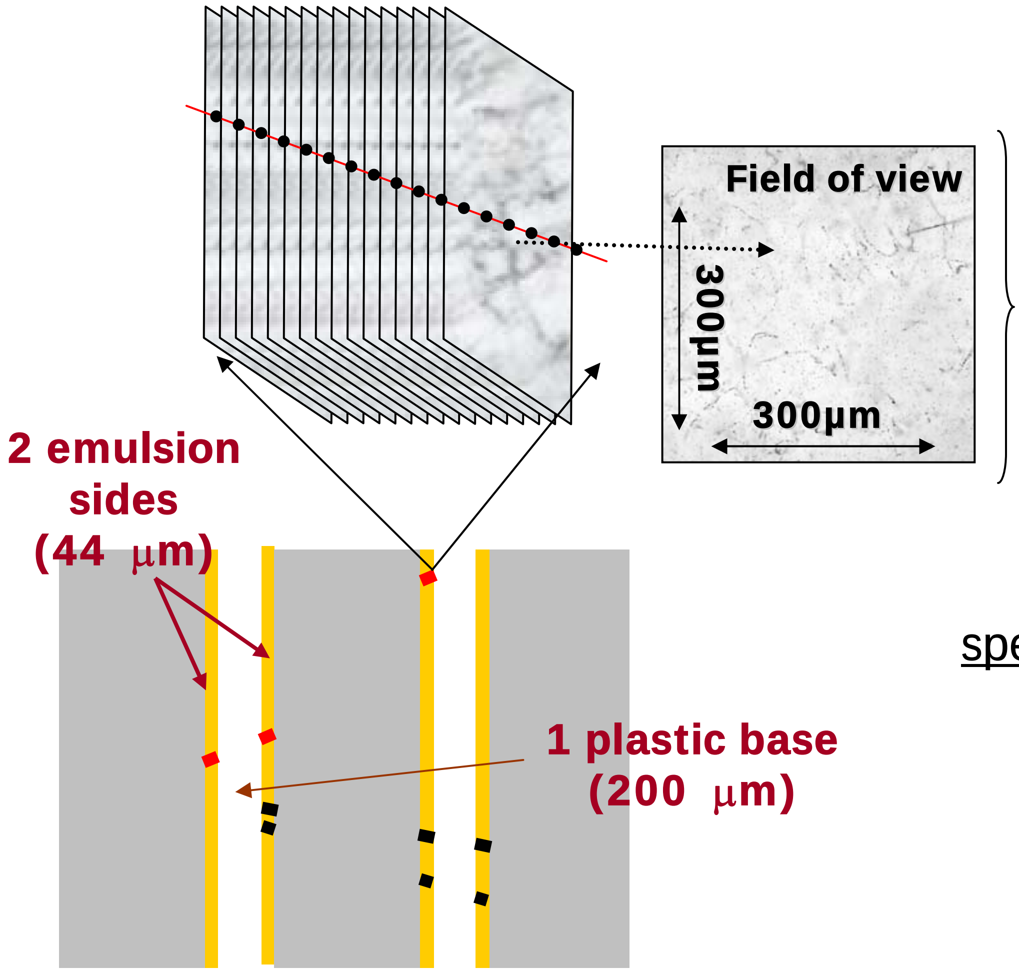
- Bricks brought to "cosmic ray pit" (@ surface), exposure 24h.
- Local alignment with cosmic myons (afterwards precision of 1-2µm).
- bricks are developed in 5 (6) automatic development lanes.
- 50 bricks/day can be developed (16h).



Scanning

≈40 automatic microscopes
in scanning labs in Europe(ESS) and Japan(S-UTS)





16 tomographic images

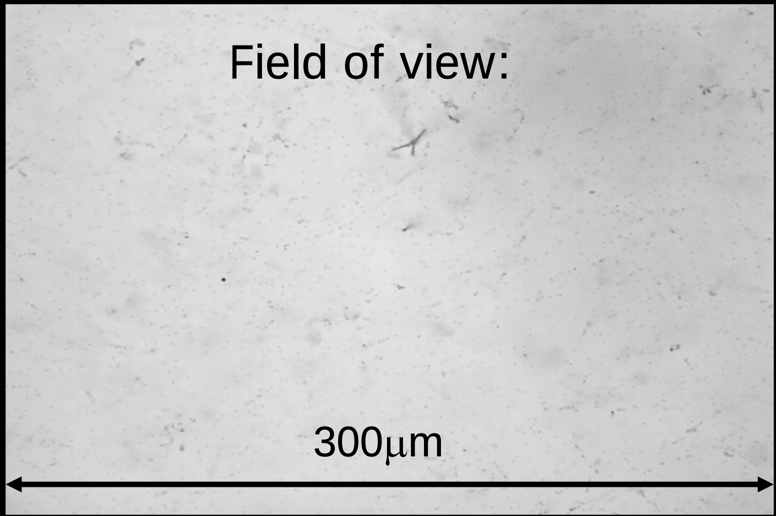
2D image processing

3D reconstruction of particle tracks

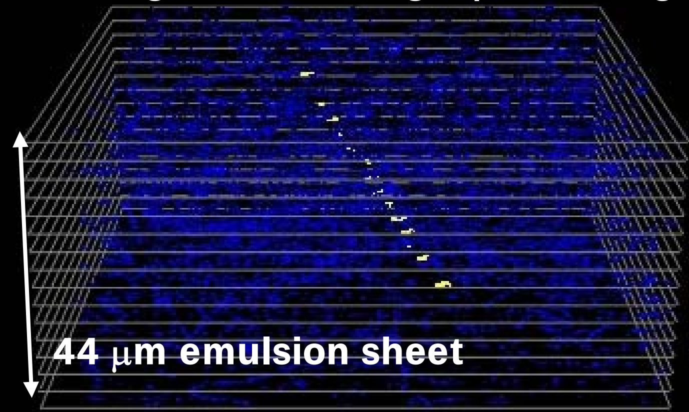
speed : 20cm²/hour/emulsion side

(1 emulsion sheet = 2 sides)

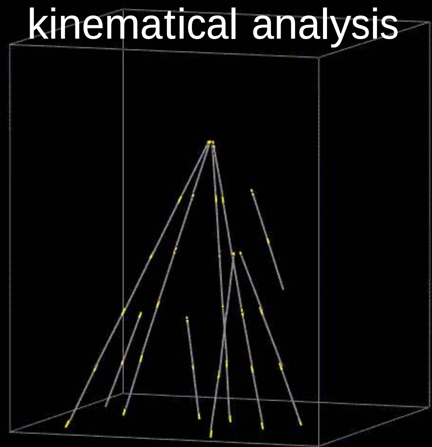
Scanning



2d image: 16 tomographic images



Vertex reconstruction &
kinematical analysis



Expected Signal

Maximal mixing, run time of 5 years @ 4.5×10^{19} pot / year

channel	Reconstruction efficiency x BR %	Signal $\Delta m^2_{23}=2.5$ eV^2	Signal $\Delta m^2_{23}=3.0$ eV^2	Back-ground
$\tau \to \mu^-$	3.74	2.9	4.2	0.17
$\tau \to e^-$	3.08	3.5	5.0	0.17
$\tau \to$h-	3.19	3.1	4.4	0.24
$\tau \to$3h	1.05	0.9	1.3	0.17
Total	11.06	10.4	14.9	0.75

for OPERA with 1.35kt (75% of proposal)

Most important background processes:

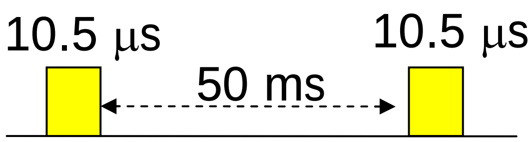
- Charm production and decay
- Hadron re-interactions in lead
- Large angle myon scattering in lead

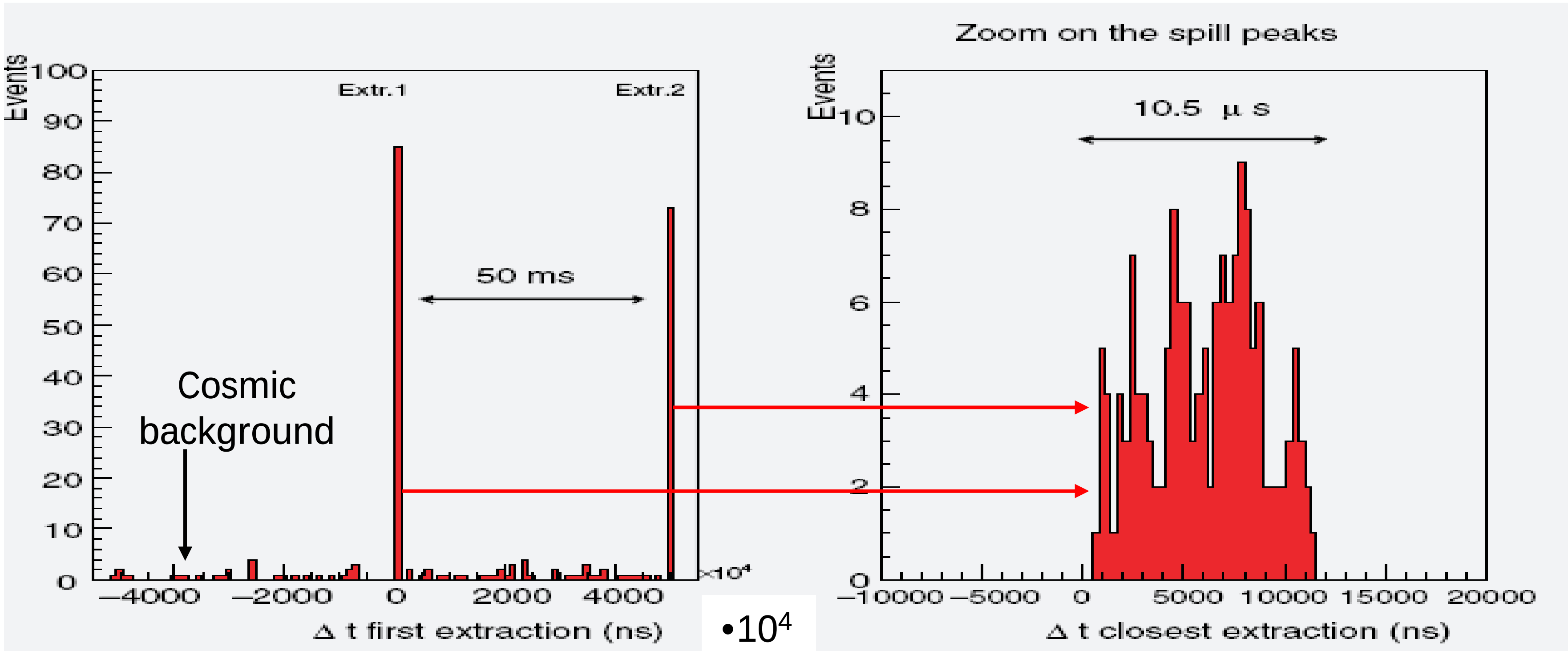
Overview expected events:

25000	ν interactions
120	ν_τ interactions
~10	identified ν_τ
<1	background

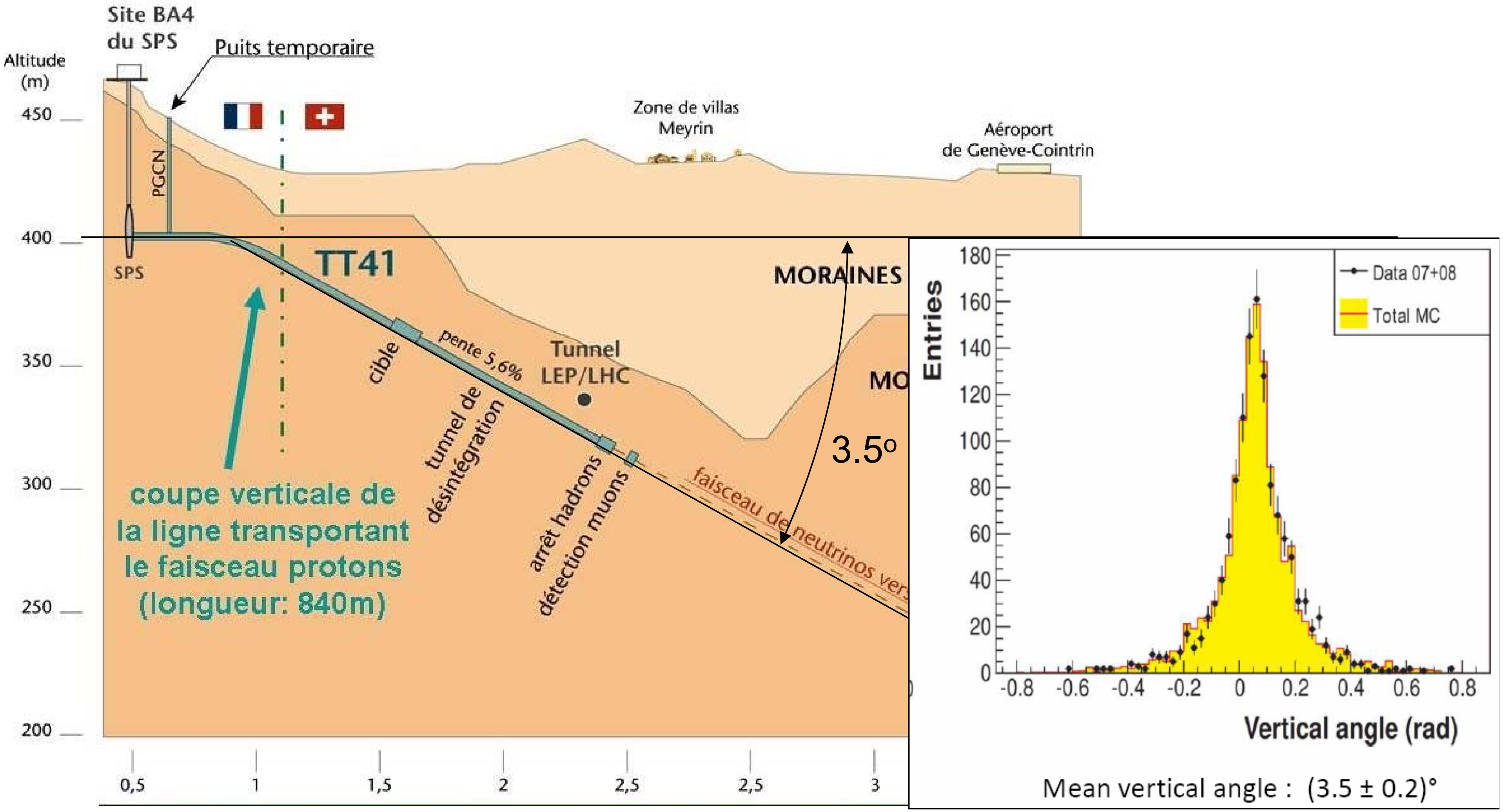
Time Synchronisation

- event selection using GPS timing information
- event timing agrees with CNGS time structure
- background $O(10^{-4})$
- accuracy 100nsec

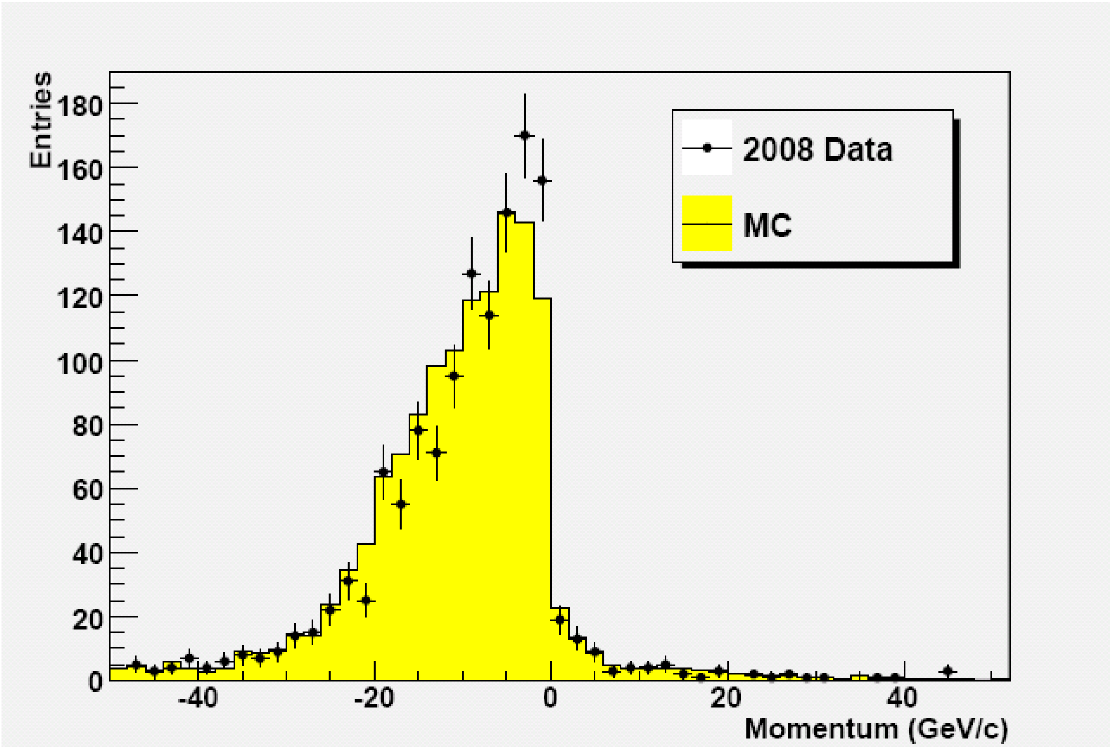




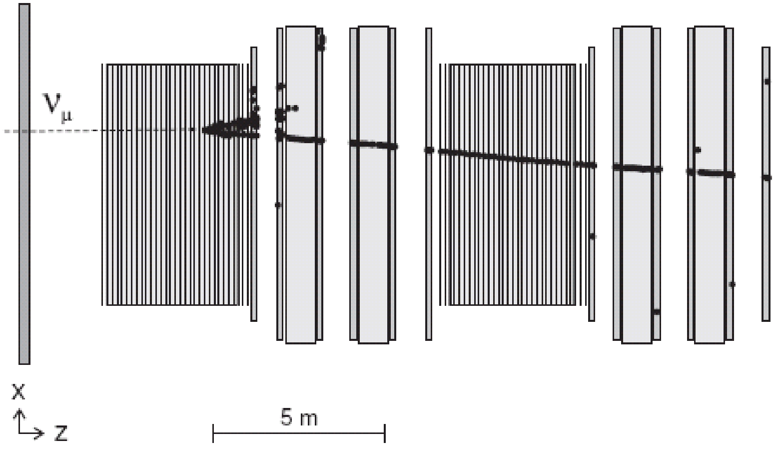
Direction of CNGS neutrino beam

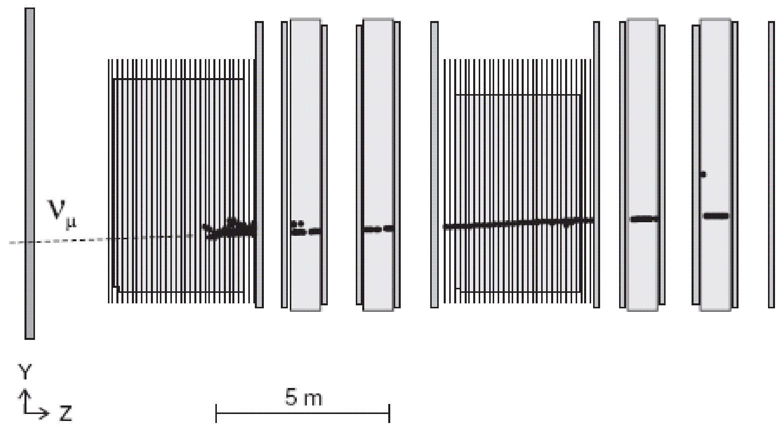


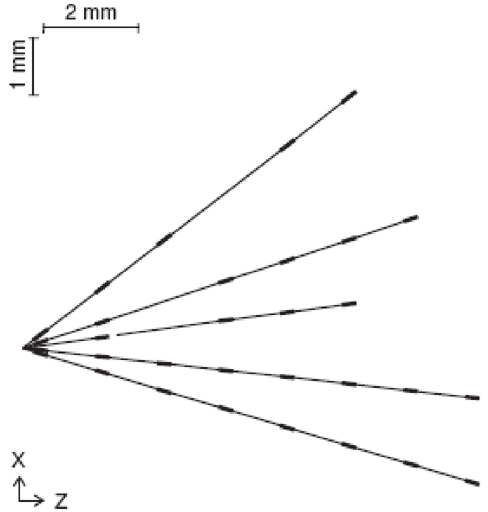
Reconstruction of μ momentum (electronic detector)

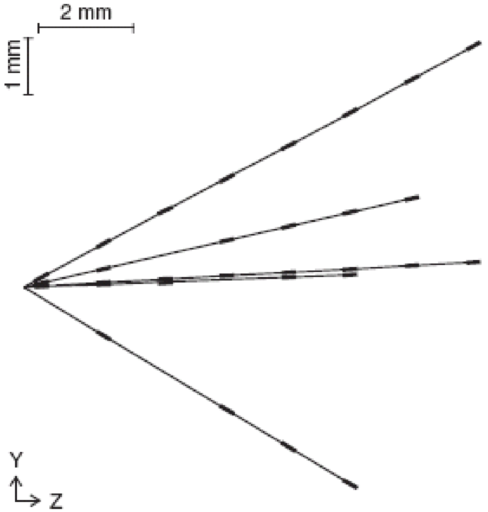


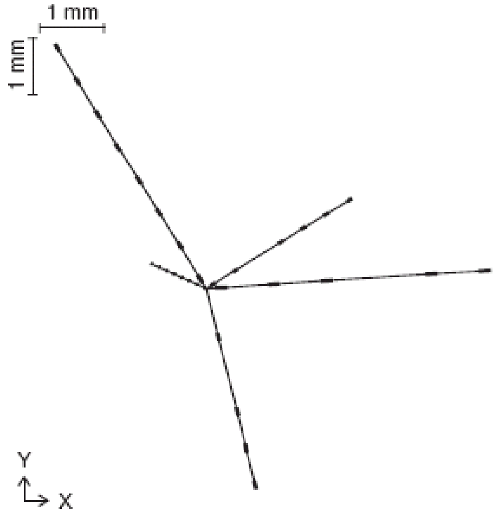
Example of real CC event:



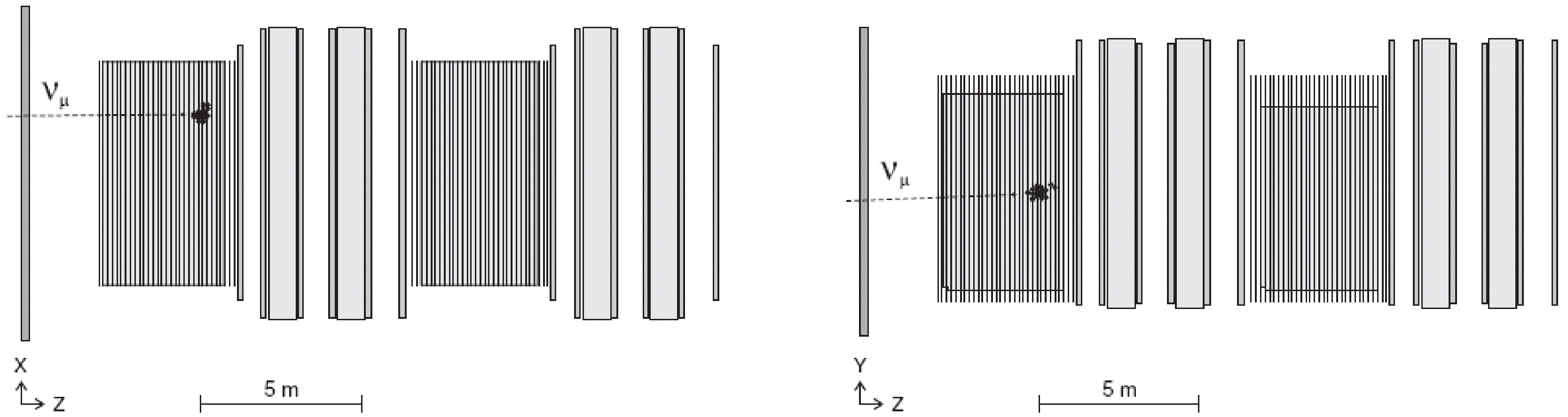


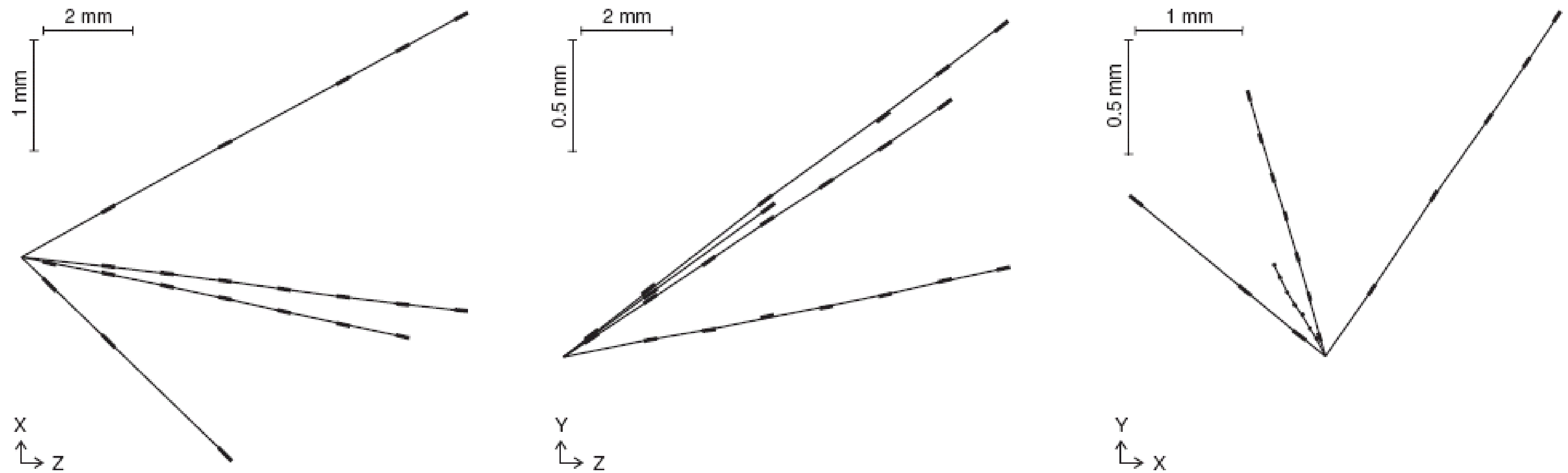




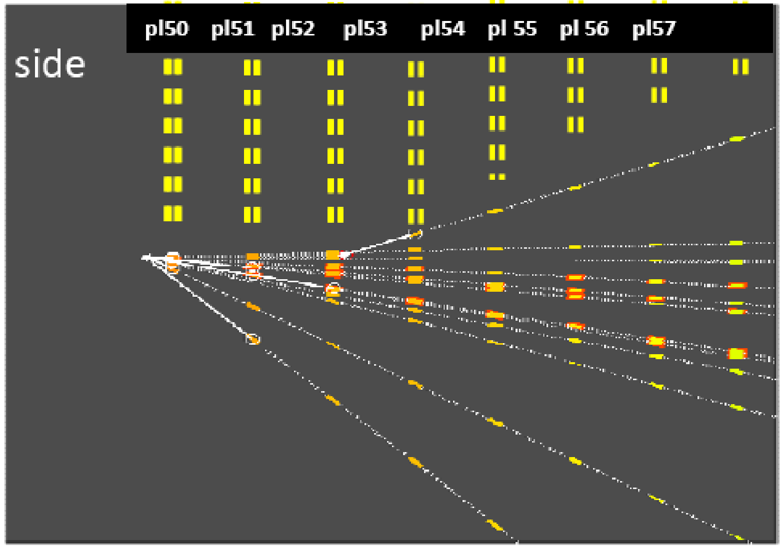


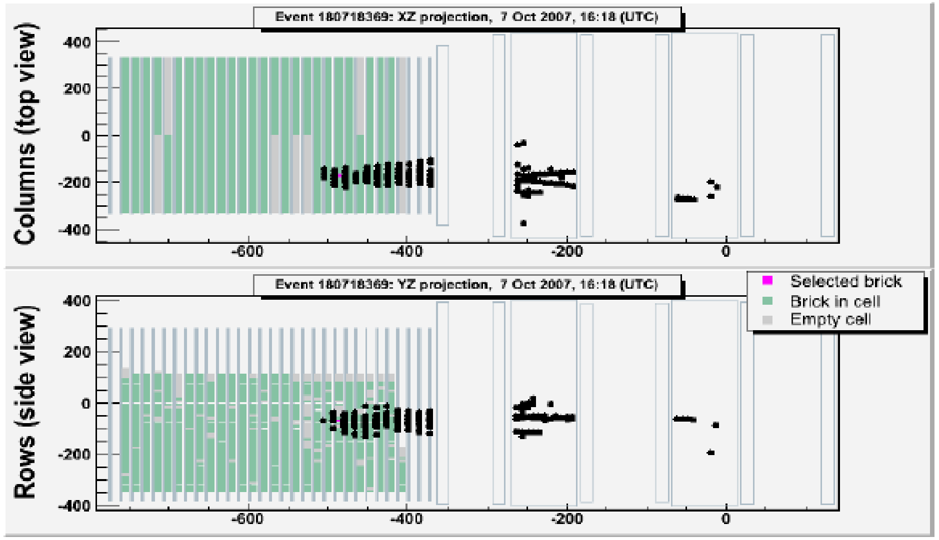
Example of real NC event:

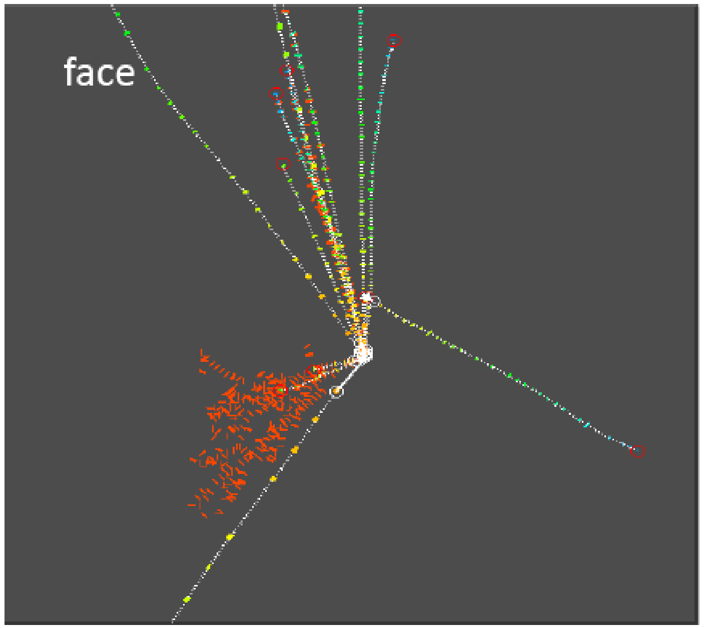




A Charm-Candidate







Clear kink topology
Two EM showers pointing to the vertex

Flight length	3247.2 µm
θ_{kink}	0.204 rad
$P_{daughter}$	3.9 (+1.7 -0.9) GeV
P_T	796 MeV

4×10^{-4} % probability for a hadron re-interaction to have a $P_T > 600$ MeV 7

OPERA summary:

- Detector (target) has been completed by July 2008
- First OPERA beam period june - november 2008:
  exposure: 1.8E19 pot, 1700 bricks with events extracted.
  Brick analysis is ongoing (≈ 450 vertices found by march09).
  First candidates for charm have been identified.

  OPERA collaboration: arXiv:0903.2973v1, accepted for publication in JINST.
  „The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment".
- Beam period 2009 just started:
  1.2E18 pot in first week.
  outlook: 3.5E19 pot from CNGS -> 3500 events in bricks expected,
  -> we may expect 2 ν_τ candidates in 2009…

OPERA is awaiting the first ν_τ- candidate

Neutrino Oscillations (12)

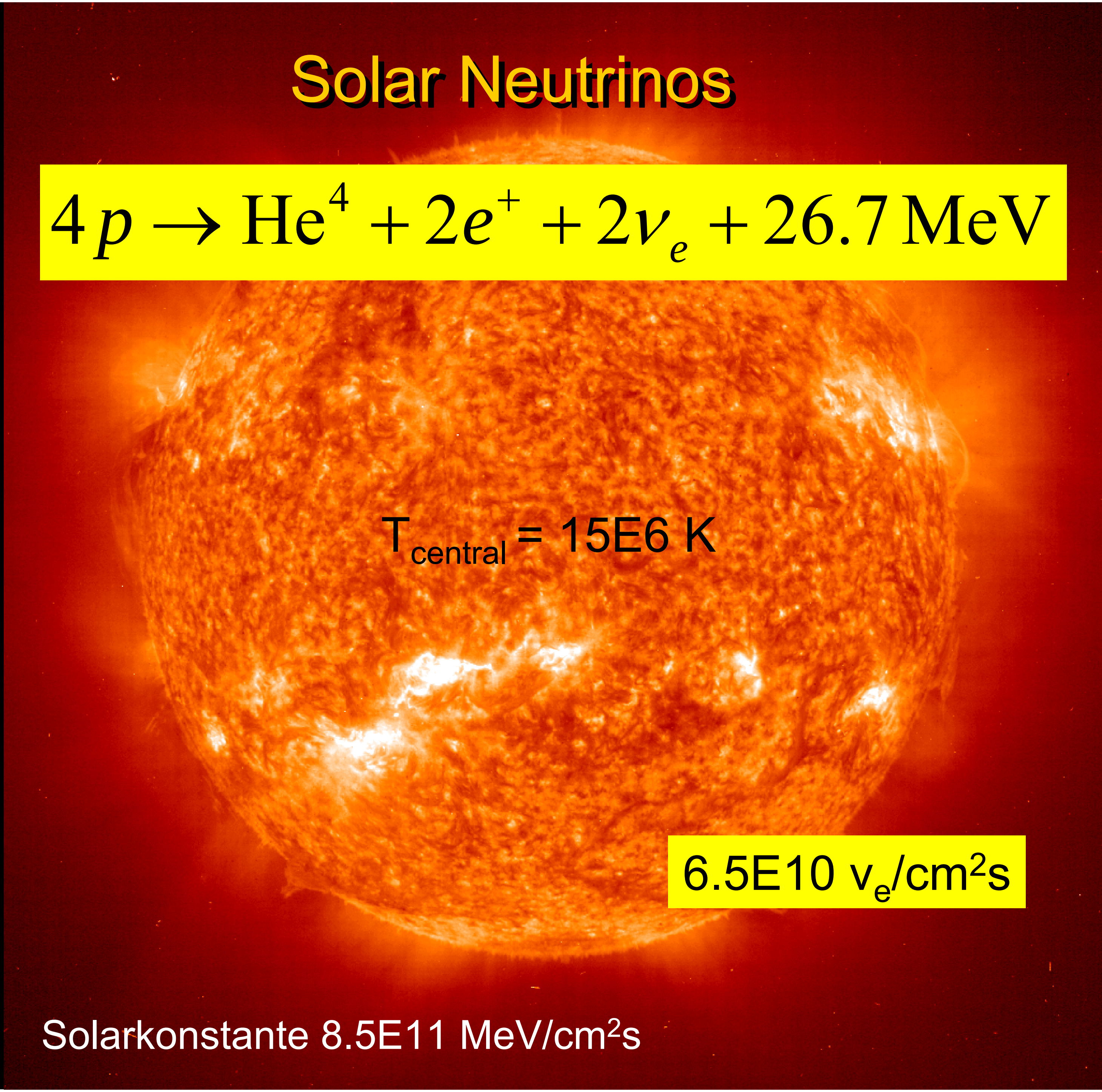
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

$\nu_e \rightarrow \nu_{\mu\tau}$ Oscillations

Solar neutrinos & Reactor neutrinos

Solar Neutrinos

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



$T_{central}$ = 15E6 K

6.5E10 ν_e/cm^2s

Solarkonstante 8.5E11 MeV/cm^2s

Energy production in stars

Hans Bethe 1939 (Nobel prize 1967)

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.*

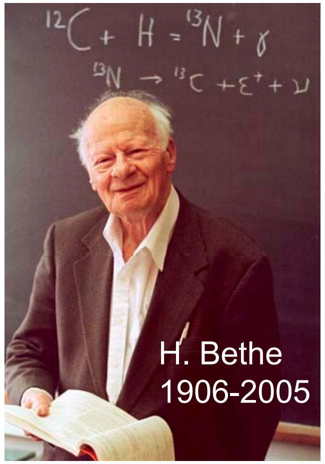
$$H+H=D+\epsilon^+. \quad (1)$$

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

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

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.



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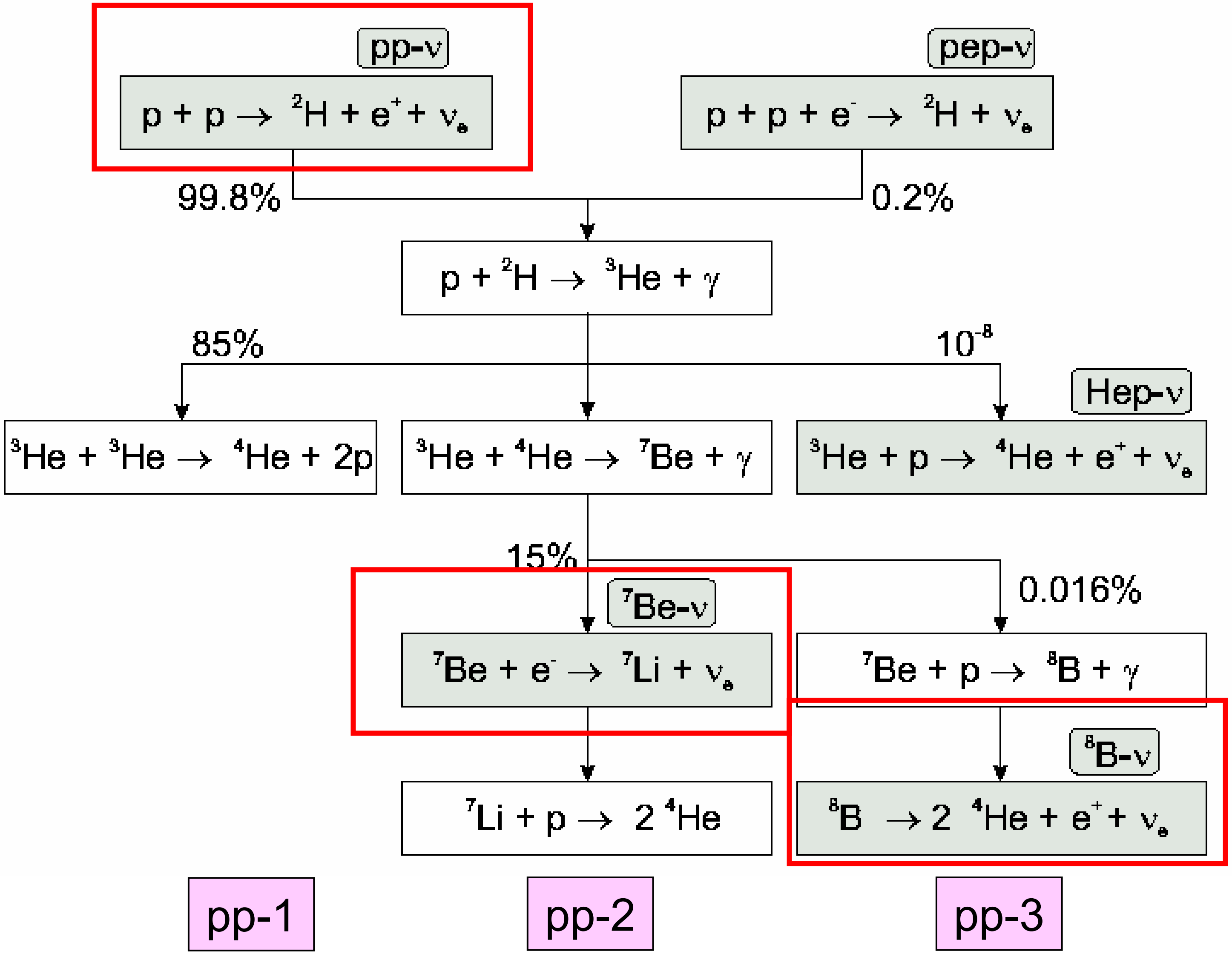
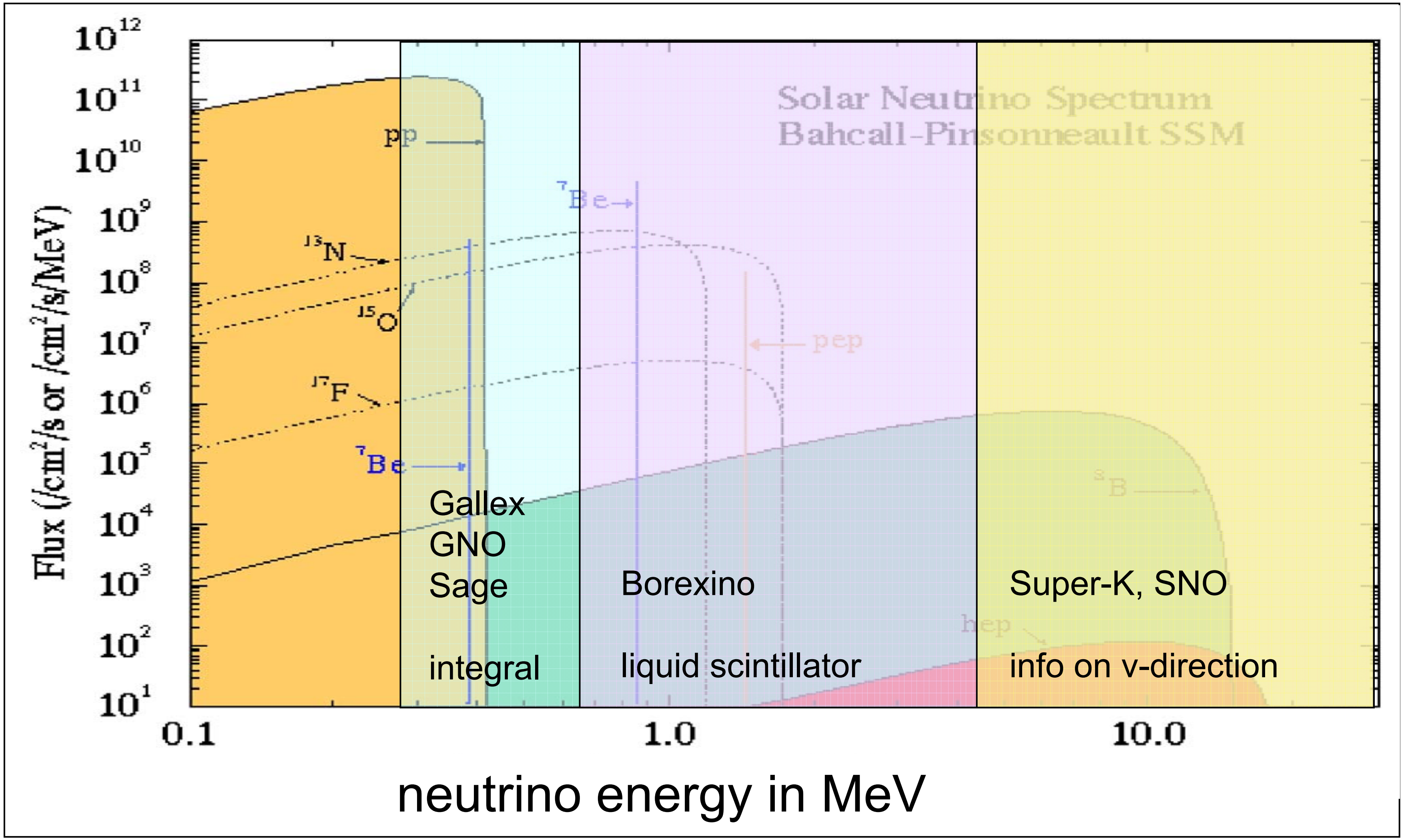
$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, \qquad N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, \\ &N^{14}+H=O^{15}+\gamma, \qquad O^{15}=N^{15}+\epsilon^+ \qquad (2) \\ &N^{15}+H=C^{12}+He^4. \end{aligned}$$

Energy production in the sun: pp cycle



Solar Neutrino Spectrum



Calculation and Measurement of the flux of 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)

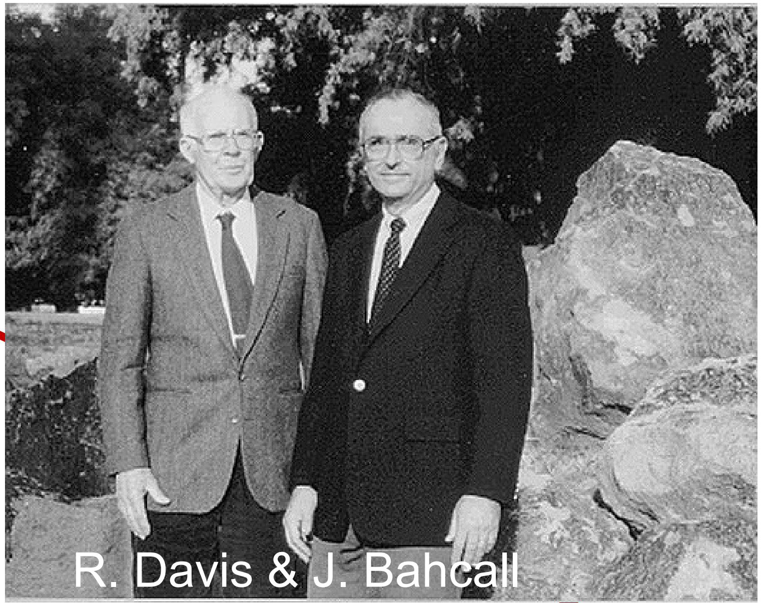
The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^-)^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These 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,

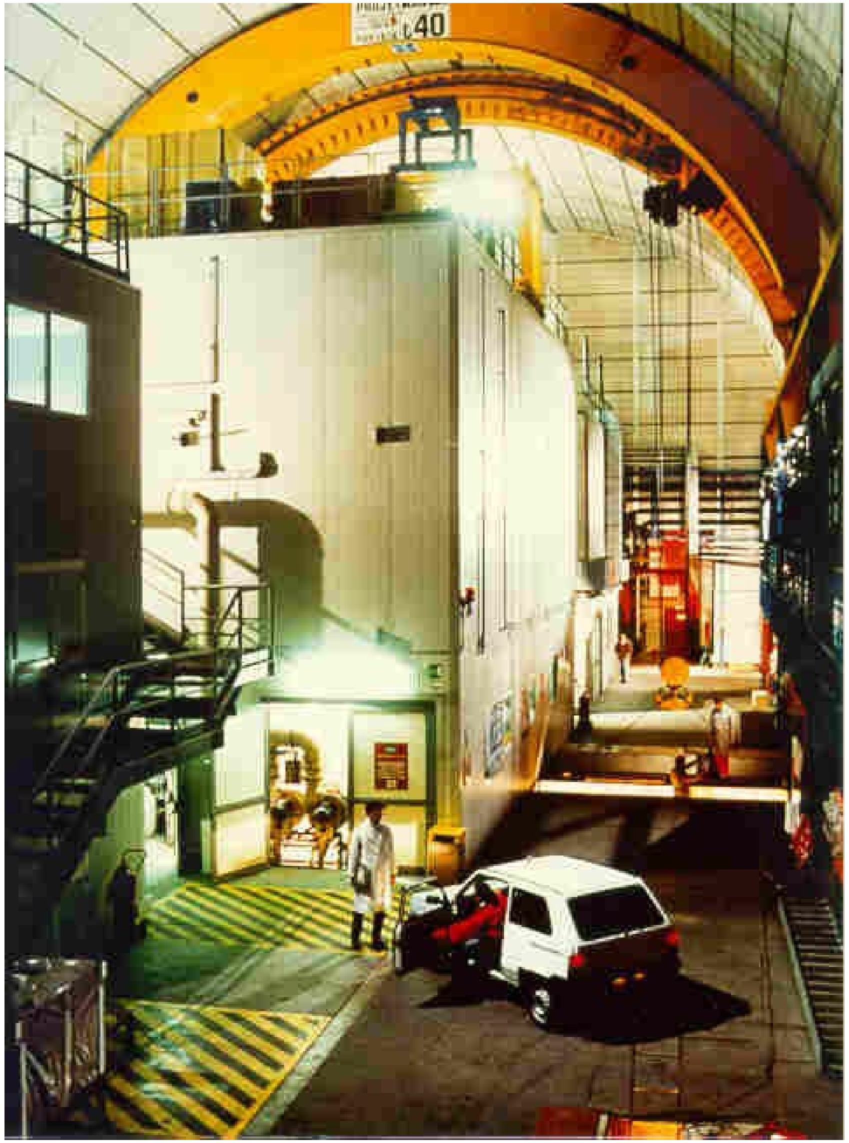
$$\sum \varphi_\nu(\text{solar})\,\sigma_{abs} = (4\pm2)\times10^{-35}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1},$$

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



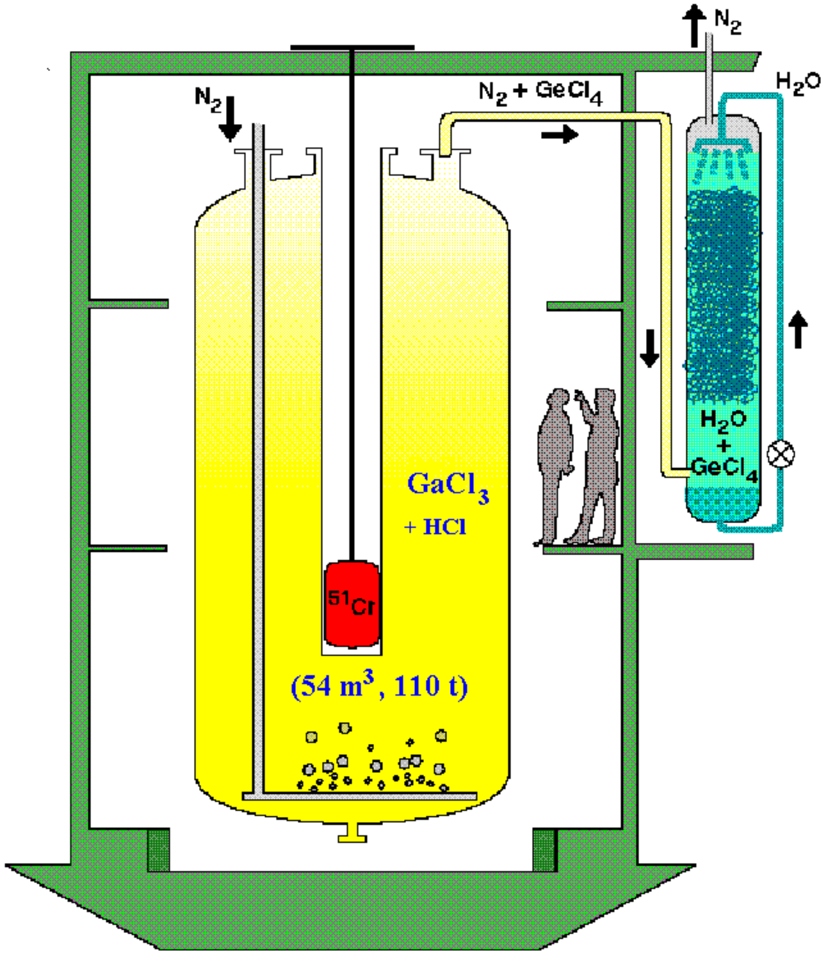
the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

GALLEX (& GNO)

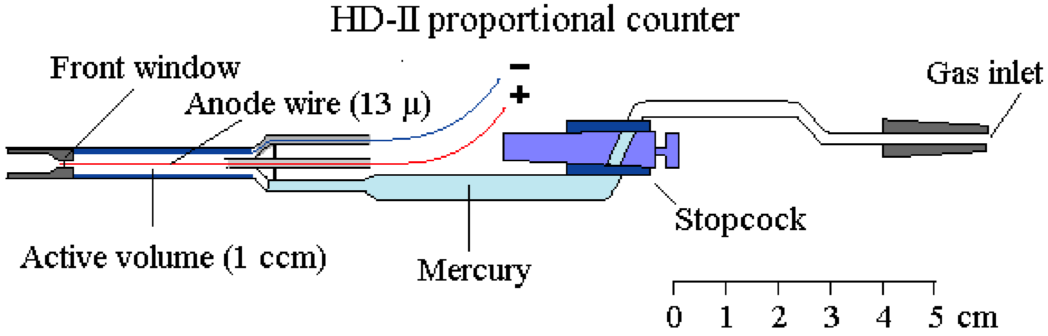


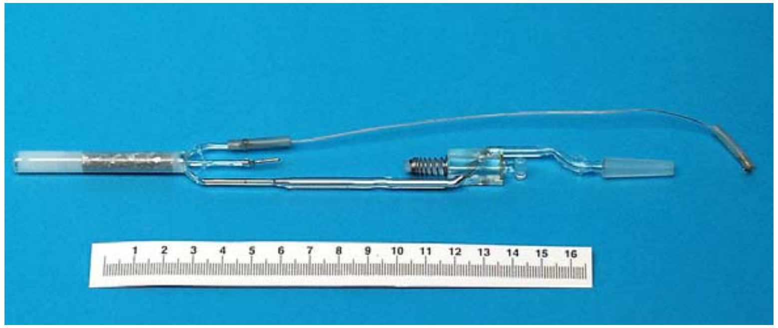
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

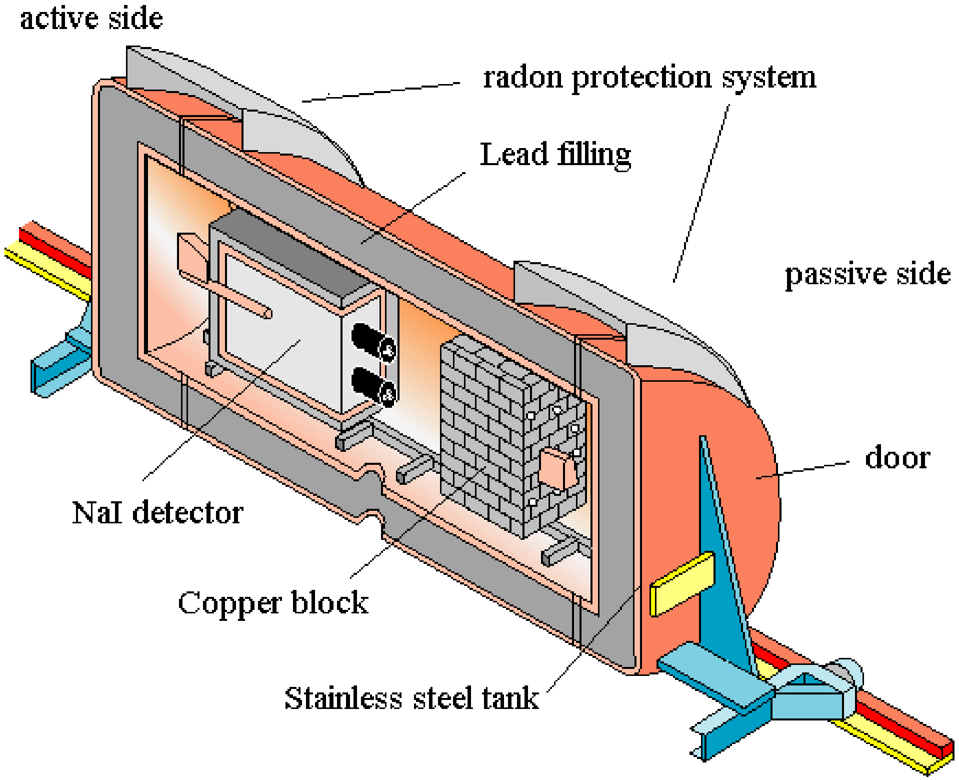
$E_\nu > 233$ keV



Ge - Counting



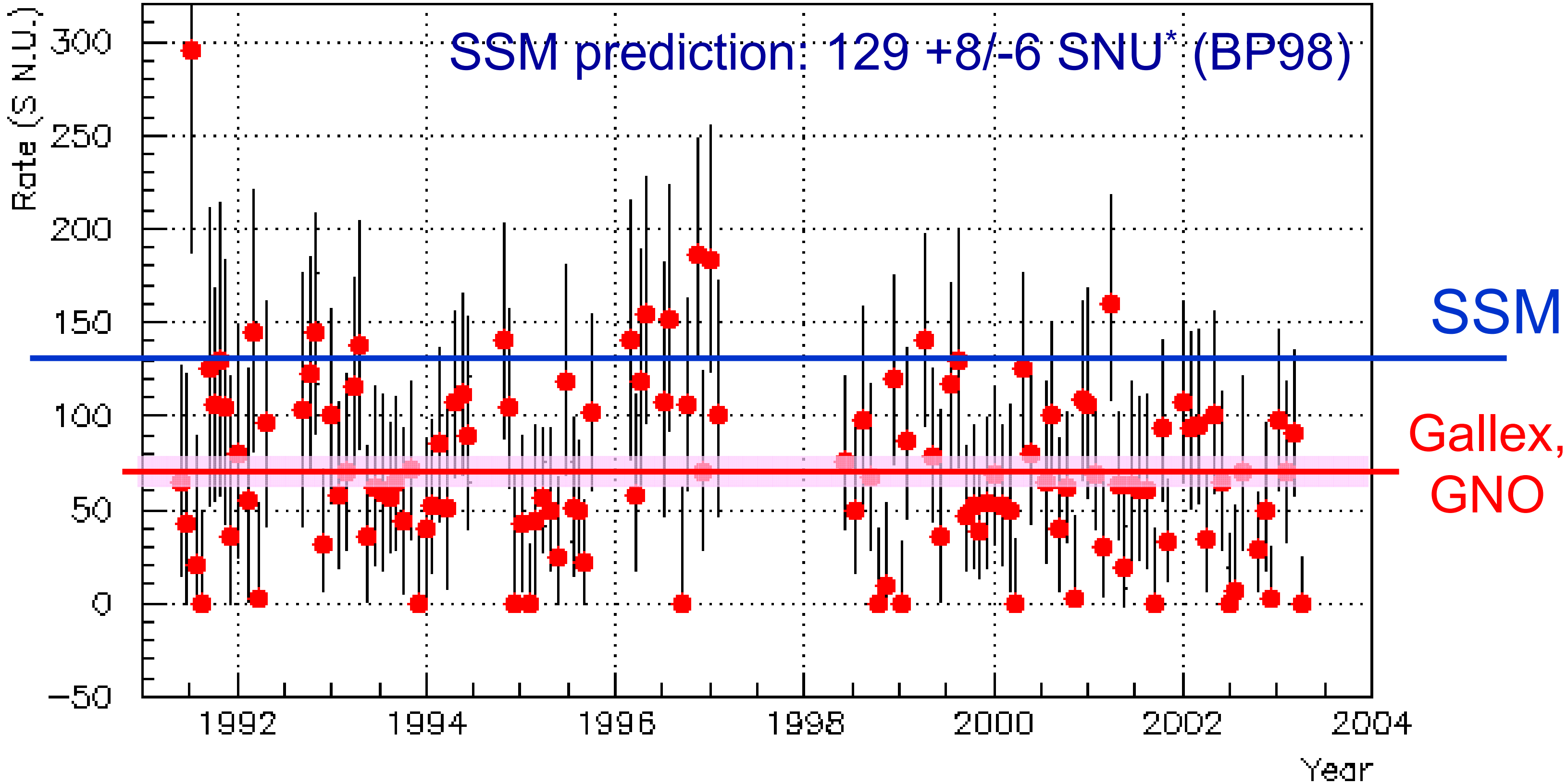




$$e^- + {}^{71}\mathrm{Ge} \rightarrow {}^{71}\mathrm{Ga} + \nu_e$$

$$T_{1/2} = 11.4\ \mathrm{d}$$

Gallex / GNO results

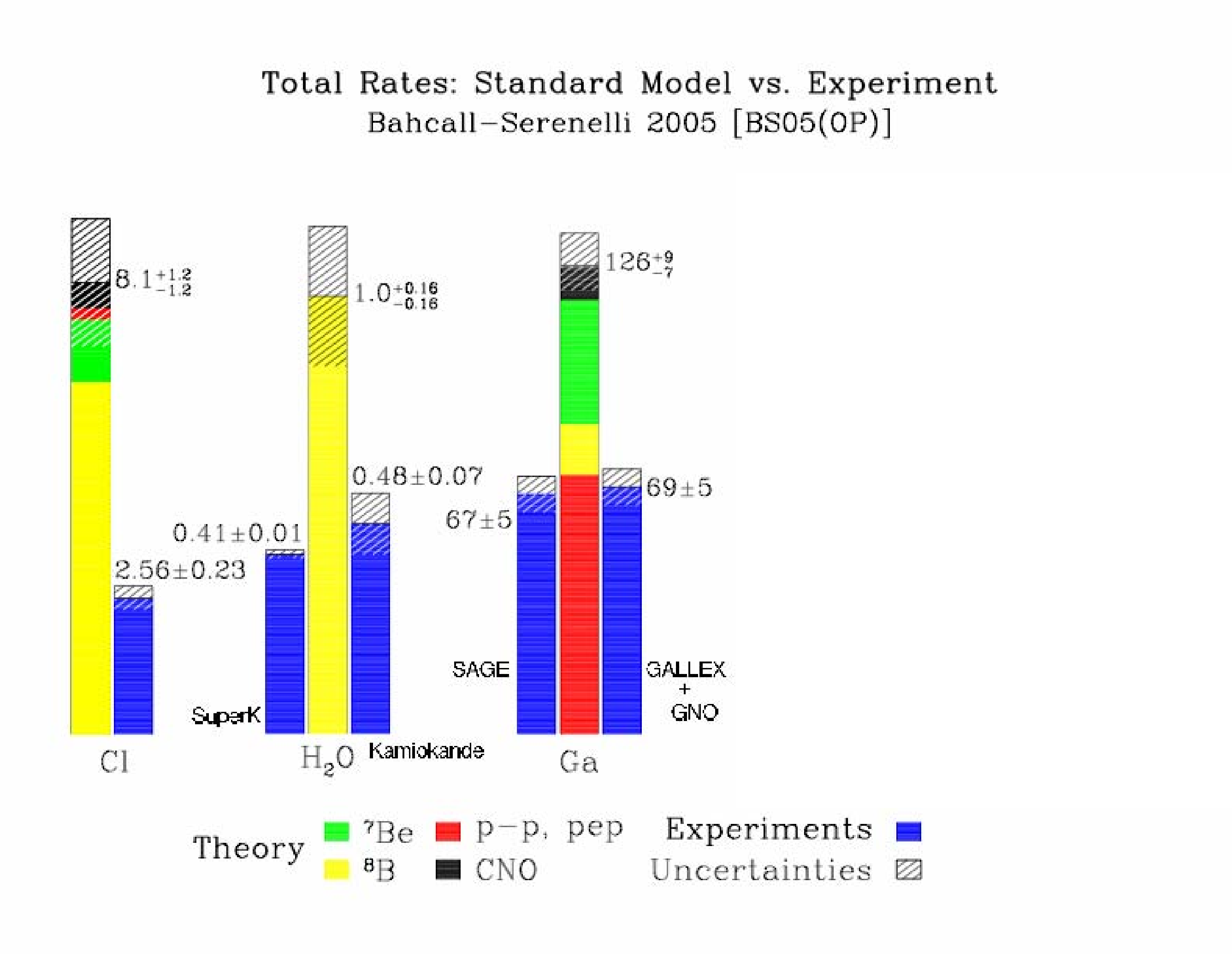


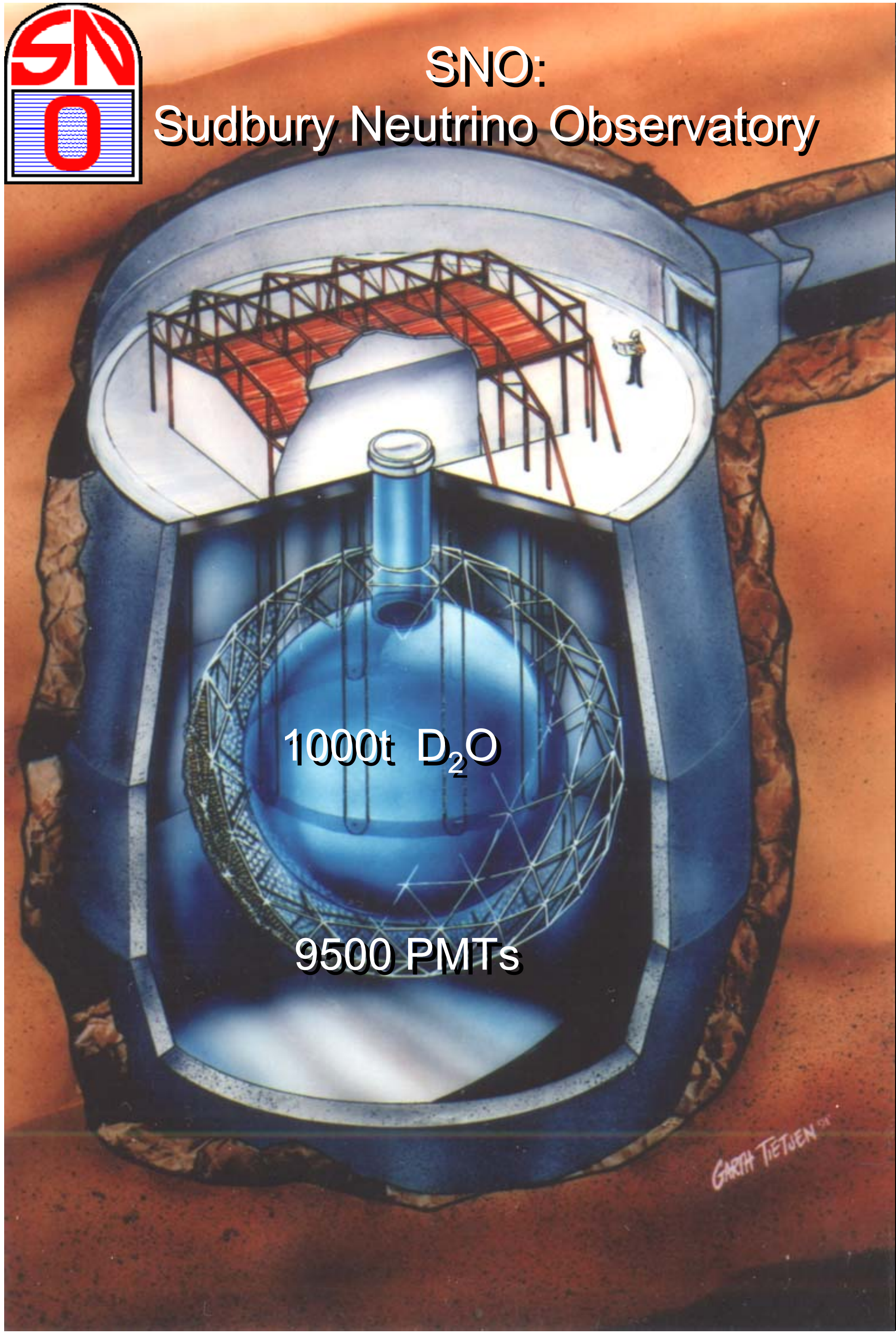
Gallex/GNO: 69.3 ± 4.1 ± 3.6 SNU

Total: GALLEX/GNO & SAGE: 68.1 ± 3.75 SNU

*) 1 SNU (solar neutrino unit) = 1 ν-capture / 10^{36} target atoms

The solar neutrino puzzle



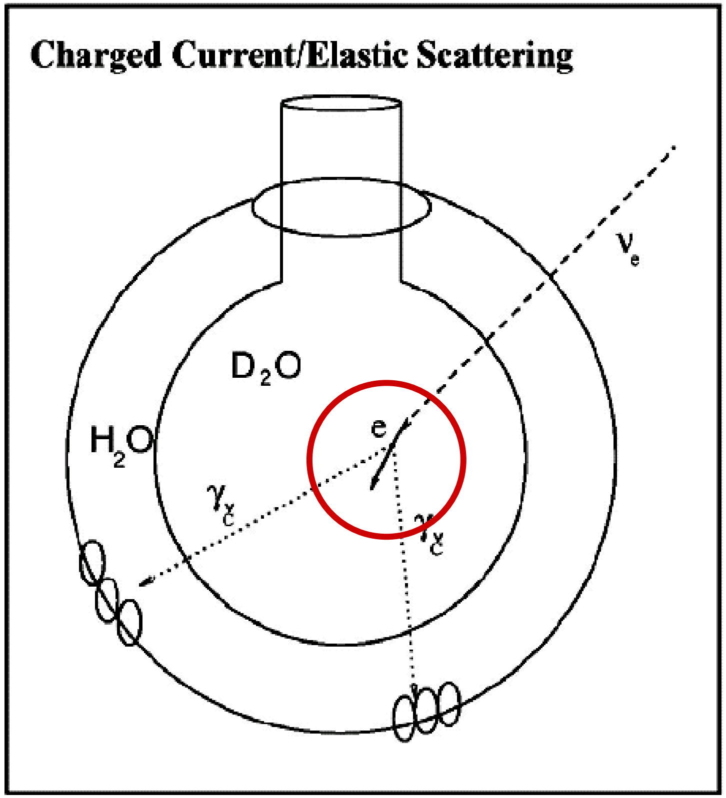

SNO:
Sudbury Neutrino Observatory
1000t D_2O
9500 PMTs
GARTH TIETJEN

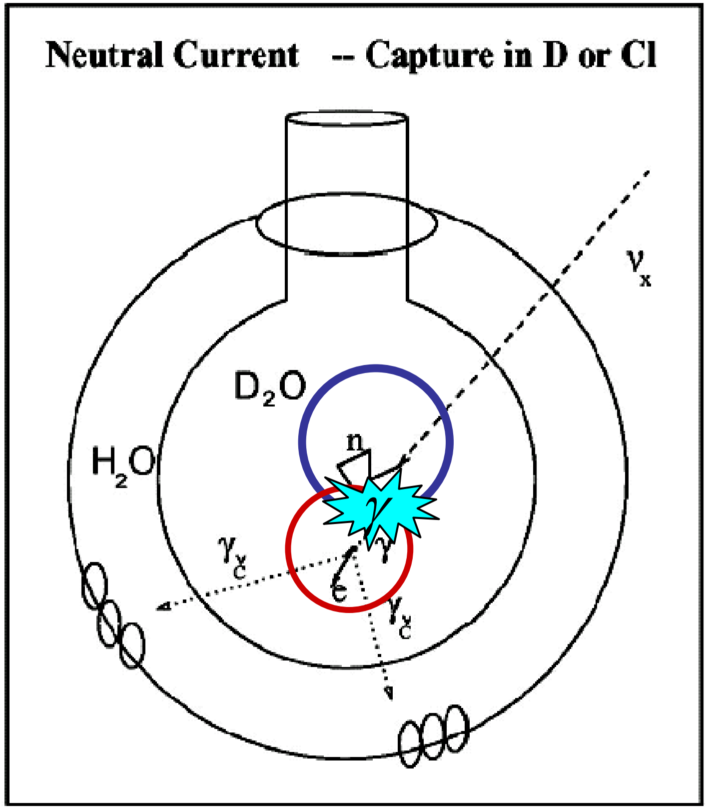

Creighton Mine (Nickel)
Sudbury, Canada


Depth 2070m

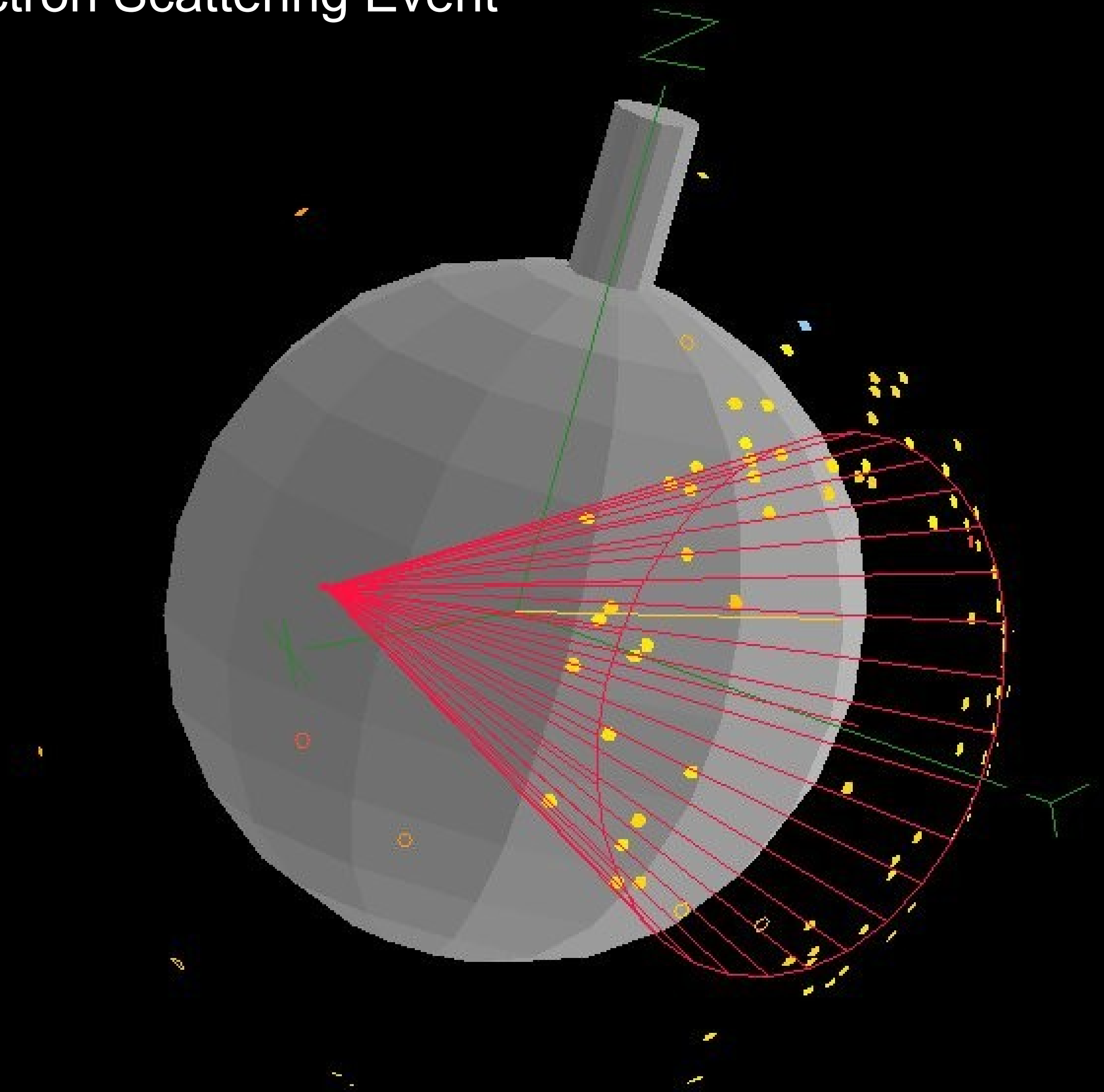
Neutrino detection in SNO

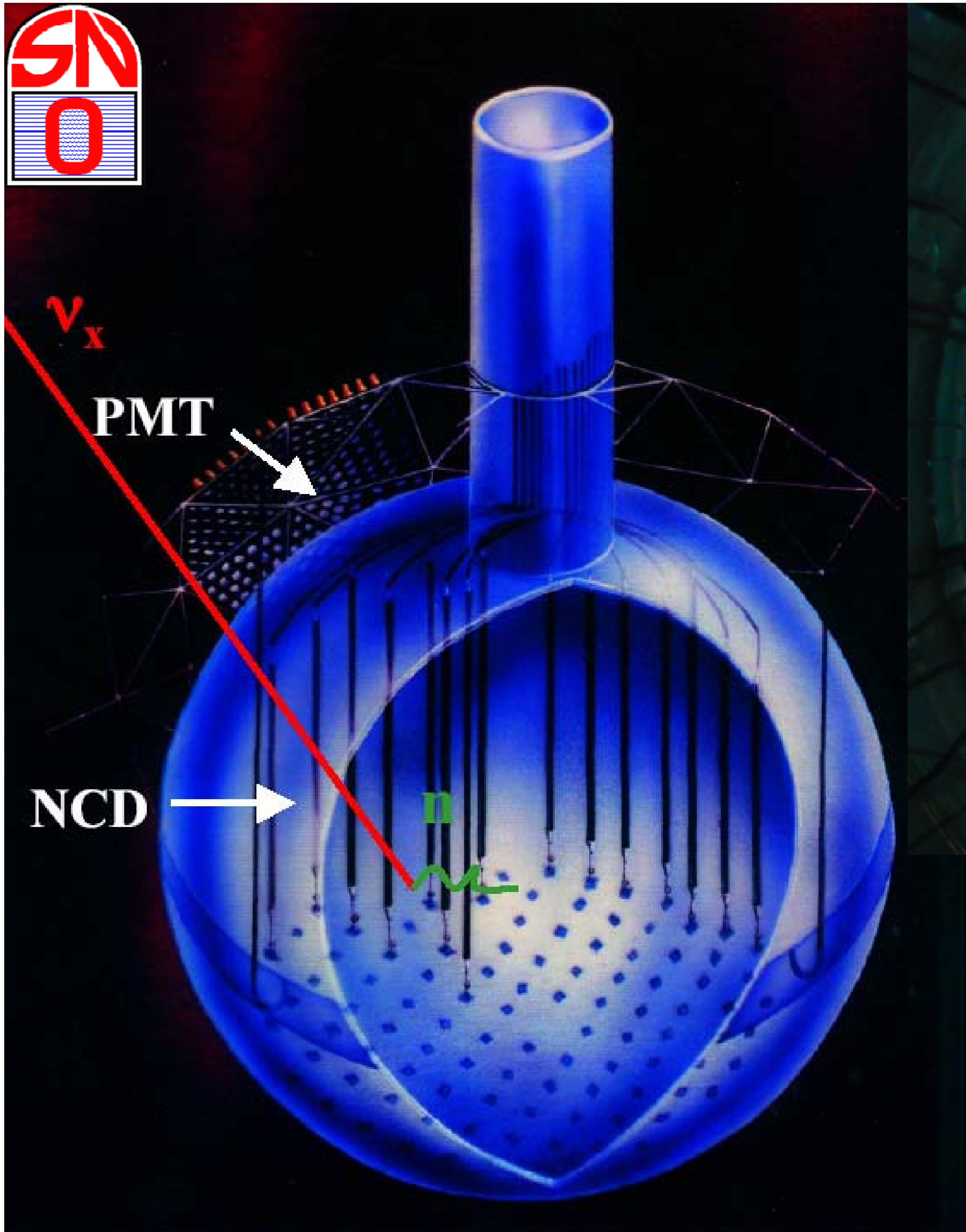
CC	$\nu_e + d \rightarrow p + p + e^-$
ES	$\nu_e + e^- \rightarrow \nu_e + e^-$
NC	$\nu_x + d \rightarrow p + n + \nu_x$

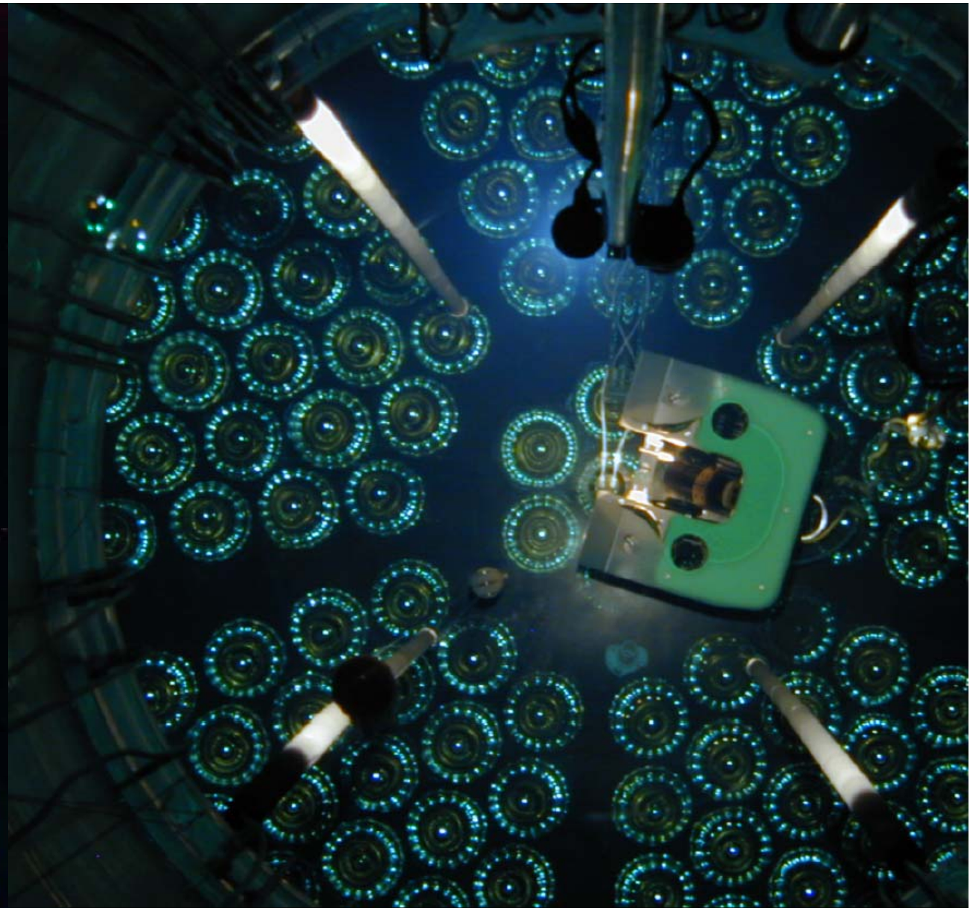




Neutrino - Electron Scattering Event







Since 2004:
Installation of ^{3}He counters
for neutron detection

SNO results

„Independent Measurement of the Total Active 8B Solar Neutrino Flux Using an Array of 3He Proportional Counters at the Sudbury Neutrino Observatory“, SNO Collaboration, PRL 101, 111301 (2008):

CC	$\nu_e + d \rightarrow p + p + e^-$
ES	$\nu_e + e^- \rightarrow \nu_e + e^-$
NC	$\nu_x + d \rightarrow p + n + \nu_x$

$$\phi_{CC}^{SNO} = 1.67^{+0.05}_{-0.04}(\text{stat})^{+0.07}_{-0.08}(\text{syst})$$

$$\phi_{ES}^{SNO} = 1.77^{+0.24}_{-0.21}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$$

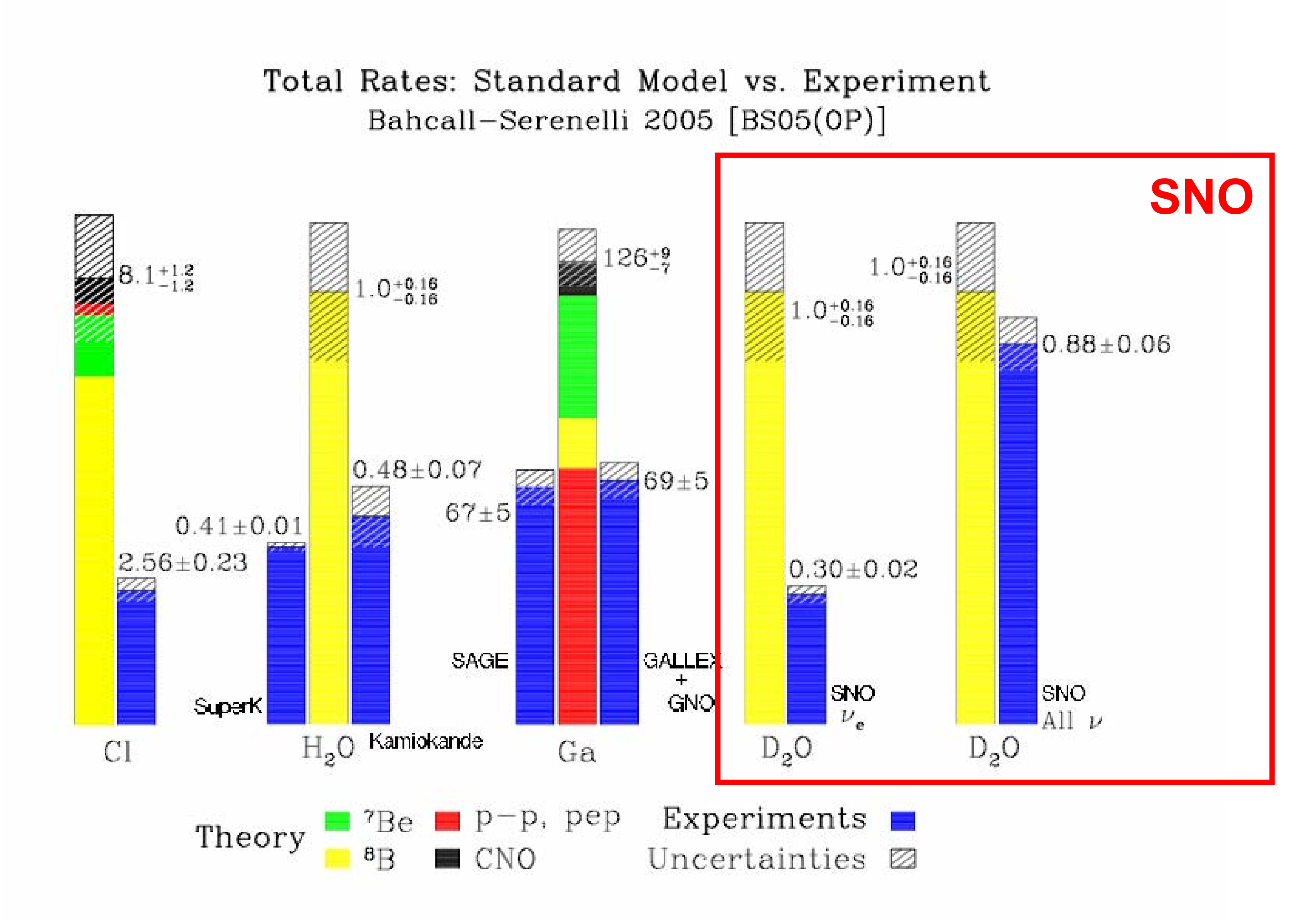
$$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst}),$$

(in units of $10^6\ \text{cm}^{-2}\,\text{s}^{-1}$)

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033(\text{total})$$

- 1/3 of solar neutrinos are detected as ν_e in SNO.
- 2/3 of solar neutrinos are detected as ν_μ or ν_τ in SNO.
- measured total neutrino flux = SSM predicted flux

Solution of the solar neutrino puzzle



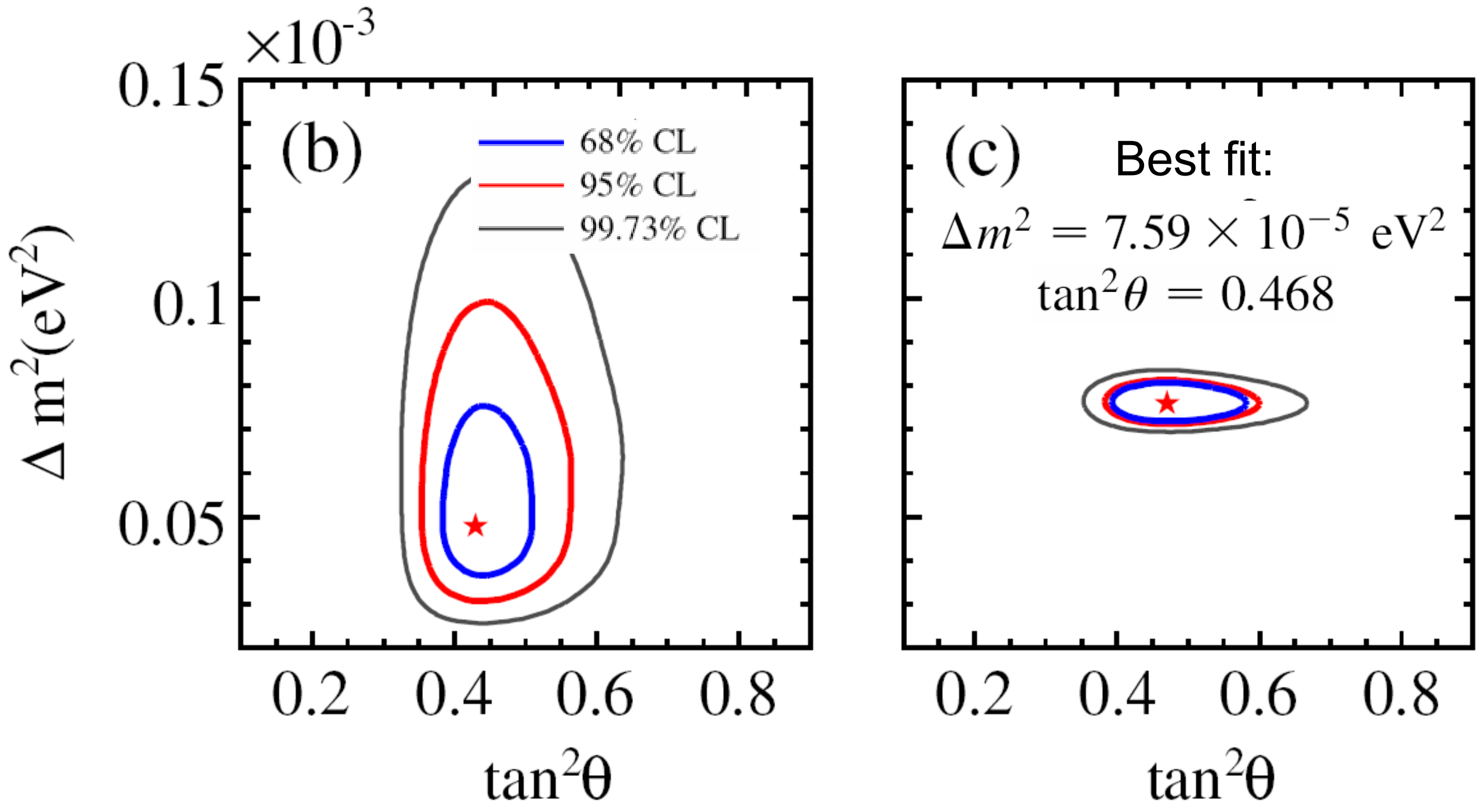
Results are compatible with:

≈ 60% of pp, ^{7}Be neutrinos and ≈ 33% of ^{8}B neutrinos arrive on earth as ν_e

Neutrino Oscillation Analysis (after SNO)

b) Global Analysis using data from SNO, SK, Cl, Ga, Borexino

c) Global Analysis using data from solar exp. & KamLand



SNO coll., PRL 101, 111301 (2008)

Explanation of results of solar neutrino experiments:

(≈60% of pp-neutrinos and ≈33% of ^{8}B neutrinos arrive on earth as ν_e)

- We assume:
  $\Delta m_{12}^2 = 8 \cdot 10^{-5} eV^2$, $\theta_{12} \approx 33^o$
- The probability of vacuum oscillations is then given by:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{12} \sin^2 \underbrace{\left(1.27 \frac{\Delta m_{12}^2 / \mathrm{eV}^2 \cdot L / \mathrm{m}}{E / \mathrm{MeV}} \right)}_{\text{Phase } \delta}$$

$$\delta = 1.27 \frac{8 \cdot 10^{-5} \cdot 1.5 \cdot 10^{11}}{\text{values of } 0.1 - 10} = 10^{7 \pm 1}$$

The phase varies over a large range!

- Therefore the survival probability for solar neutrinos (in vacuum) is:

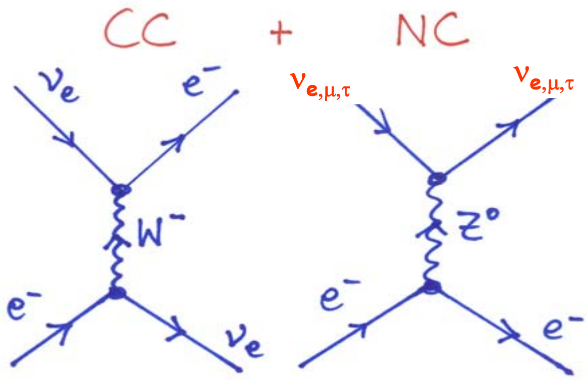
$$\langle P(\nu_e \to \nu_e) \rangle_{\text{averaging over phases}} = 1 - \tfrac{1}{2} \sin^2 2\theta_{12} \approx 0.6$$

This explains quite well the experimental results for pp-neutrinos

But this is independent of energy!
→ Therefore we need another effect to explain why only 33% of ^{8}B neutrinos arrive…

Neutrino propagation in matter – MSW (Mikheyev, Smirnov, Wolfenstein) Effect

Origin: ν_e and $\nu_{\mu,\tau}$ have different interaction with matter
(ν_e can undergo CC and NC reaction, $\nu_{\mu,\tau}$ only NC!)



Only elastic forward scattering of neutrinos is relevant

In matter: $+4E\sqrt{2}G_F N_e$

Vacuum:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta & \Delta m^2 \sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

In matter there is an additional potential in the equation of motion for ve → ve scattering (Flavor base)

Matter:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta + 2\sqrt{2}G_F N_e E & \Delta m^2 \sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

with $2\sqrt{2}G_F \underbrace{N_e}_{\frac{Y_e\rho}{m}} E = 1.53\cdot 10^{-7}\,\mathrm{eV}^2\left(\frac{Y_e\rho}{\mathrm{g/cm^3}}\cdot\frac{E}{\mathrm{MeV}}\right)$ center of Sun: $\frac{Y_e\rho}{\mathrm{g/cm^3}} \cong 100$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta+2\sqrt{2}G_F N_e E & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta-2\sqrt{2}G_F N_e E\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

can be written as:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m_m^2\cos 2\theta_m & \Delta m_m^2\sin 2\theta_m\\ \Delta m_m^2\sin 2\theta_m & \Delta m_m^2\cos 2\theta_m\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

where $\Delta m_m^2 = m_2^2 - m_1^2$ and θ_m, denote the "effective" masses and mixing angles in matter and:

$$\Delta m_m^2\cos 2\theta_m = \Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E$$
$$\Delta m_m^2\sin 2\theta_m = \Delta m^2\sin 2\theta$$

Solving these equations gives:

$$\Delta m_m^2 = \sqrt{\left(\Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E\right)^2 + \left(\Delta m^2\sin 2\theta\right)^2}$$

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\left(\frac{2\sqrt{2}G_F N_e E}{\Delta m^2} - \cos 2\theta\right)^2 + \left(\sin 2\theta\right)^2}}$$

Neutrino propagation in matter: 3 regimes

1. Quasi – vacuum: $$2\sqrt{2}G_F N_e E \ll \Delta m^2 \cos 2\theta$$ pp, ^{7}Be Neutrinos

$$\Delta m_m^2 \cong \Delta m^2, \qquad \theta_m \cong \theta$$

2. Resonance:
(Mikheyev, Smirnov 1985)

$$2\sqrt{2}G_F N_e E = \Delta m^2 \cos 2\theta$$

$$\Delta m_m^2 = \Delta m^2 \sin^2 2\theta$$

$$\theta_m = \tfrac{\pi}{4} \quad (45^\circ)$$

3. Matter dominated: $$2\sqrt{2}G_F N_e E \gg \Delta m^2 \cos 2\theta$$ ^{8}B Neutrinos

$$\Delta m_m^2 \to 2\sqrt{2}G_F N_e E$$

$$\theta_m \to \tfrac{\pi}{2} \quad (90^\circ)$$

Neutrino mixing in matter:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

and

$$\begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} = \begin{pmatrix} \cos\theta_m & -\sin\theta_m \\ \sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

^{8}B neutrinos at center of Sun:
θ_m = 73°,
with:
$\Delta m_{12}^2 = 8 \cdot 10^{-5} eV^2$,
$\theta_{12} \approx 33°$,
$Y\rho \approx 90 g/cm^3$.

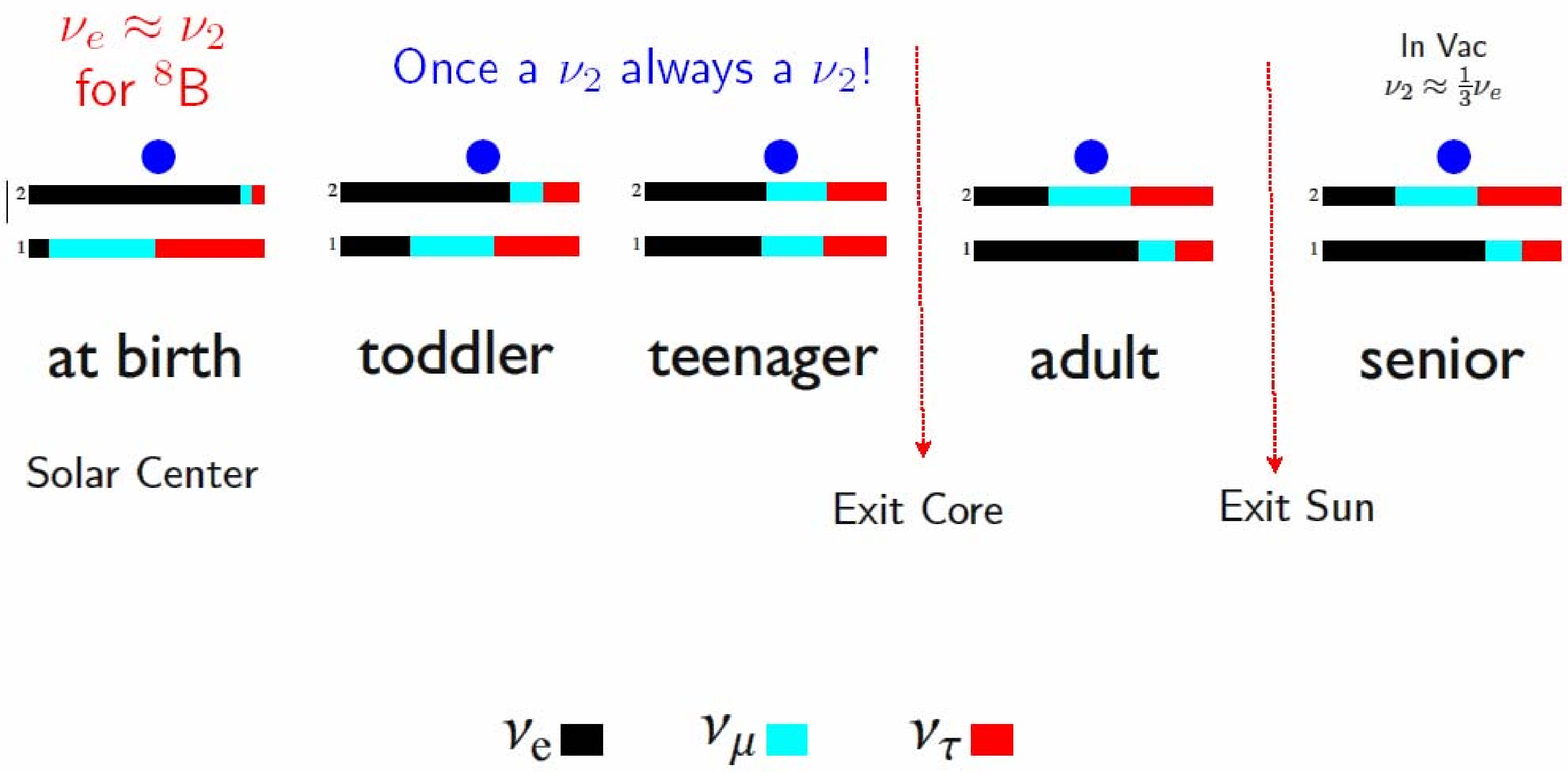
For ^{8}B neutrinos at the center of Sun:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos 73^\circ & \sin 73^\circ \\ -\sin 73^\circ & \cos 73^\circ \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

The probability that the created ν_e is in the state ν_{2m} is then given by $\sin^2(73°) = 91\%$!

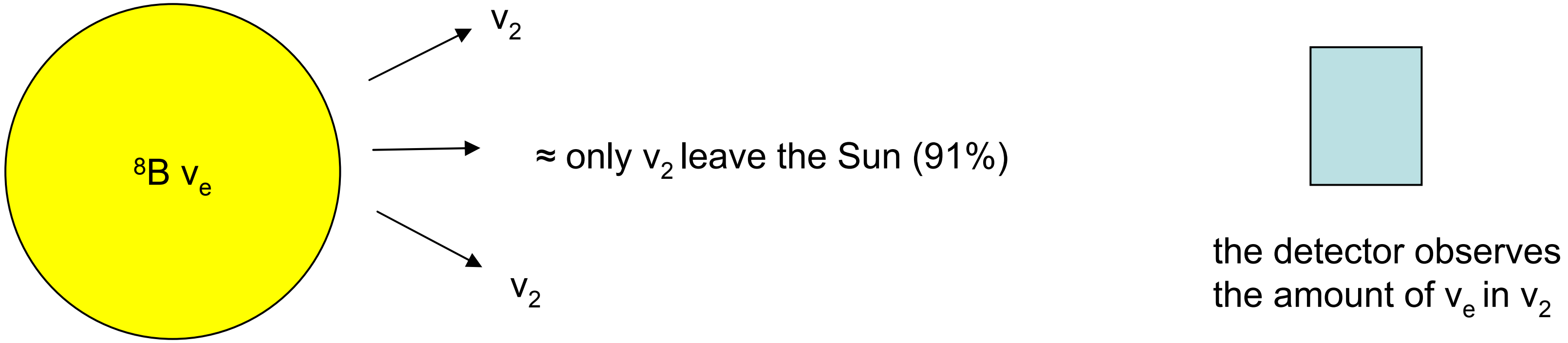
On its way through the Sun, the neutrino is with a constant probability of 91% in the state ν_{2m}.
But the composition of ν_{2m} from ν_e and ν_μ changes with the varying density.

Life of a Boron-8 Solar Neutrino:



From Stephen Parke http://boudin.fnal.gov/AcLec/AcLecParke.html (part1)

Explanation of ^{8}B solar neutrino results with matter effect



The probabilty that a ^{8}B neutrino is detected as ν_e is then given by:

$$\langle P(\nu_e \to \nu_e) \rangle_{\text{incoherent}} = f_1 \cos^2\theta + f_2 \sin^2\theta$$

where:

f_1 = probability that a neutrino leaving the Sun is in the state ν_1 = $\cos^2(73^o)$ = 0.09.

f_2 = probability that a neutrino leaving the Sun is in the state ν_2 = $\sin^2(73^o)$ = 0.91.

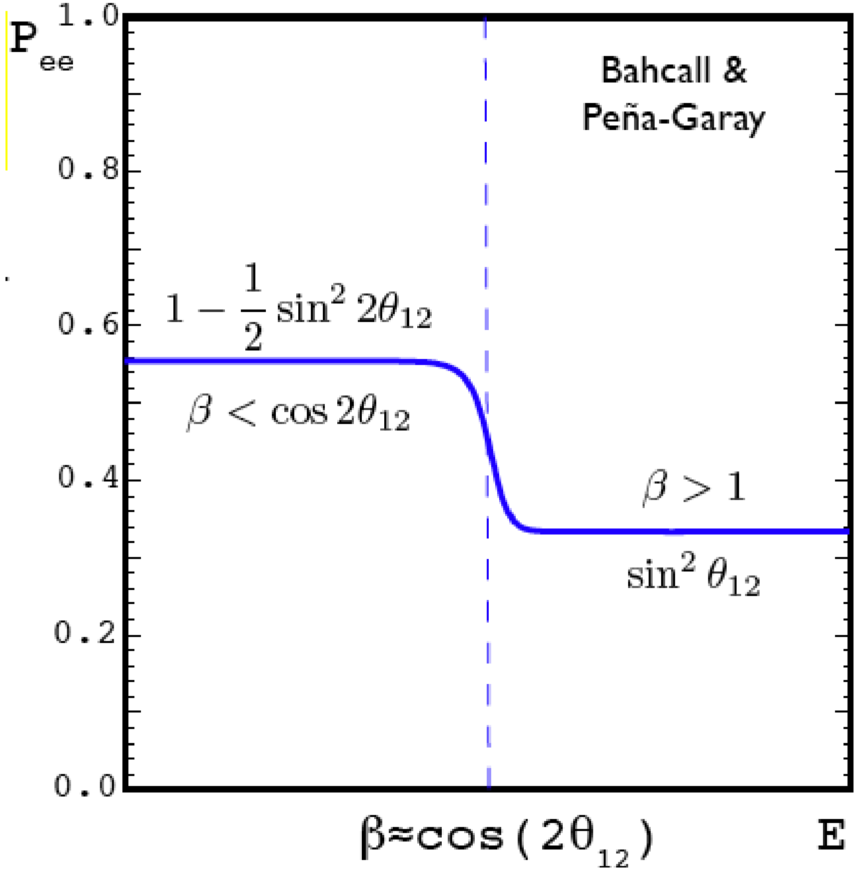
$\cos^2\theta$ = probability that ν_1 contains the state ν_e = $\cos^2(33^o)$ = 0.70.

$\sin^2\theta$ = probability that ν_2 contains the state ν_e = $\sin^2(33^o)$ = 0.30.

$$\langle P(\nu_e \to \nu_e) \rangle_{\text{incoherent}} = 0.09 \cdot 0.70 + 0.91 \cdot 0.30 = 0.336$$

This is exactly what we observe in SNO and Super-K for ^{8}B neutrinos!

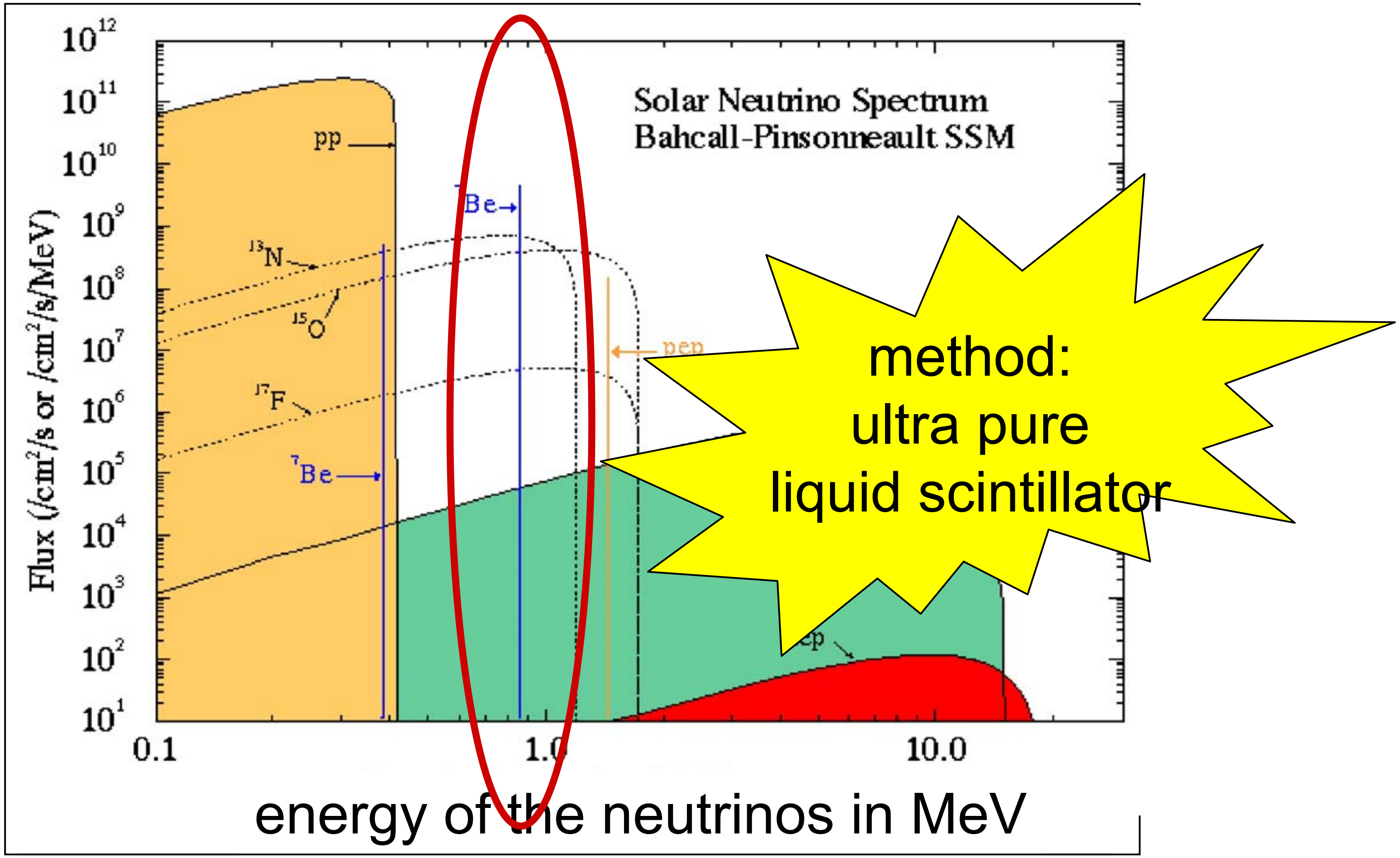
„Survival probability“ of a solar neutrino



$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2} = 0.22 \left[\frac{E}{1\ \mathrm{MeV}}\right] \left[\frac{\rho \cdot Z/A}{100\ \mathrm{g\ cm}^{-3}}\right] \left[\frac{7 \times 10^{-5}\ \mathrm{ev}^2}{\Delta m^2}\right]$$

$$E[\mathrm{MeV}] = 6.8 \times 10^6 \frac{\cos(2\theta_{12}) \Delta \mathrm{m}_{12}^2 [\mathrm{eV}^2]}{\rho [\mathrm{g/cm}^3] \mathrm{Z/A}} \simeq 1\text{–}2\ \mathrm{MeV}$$

The new generation of solar neutrino experiments

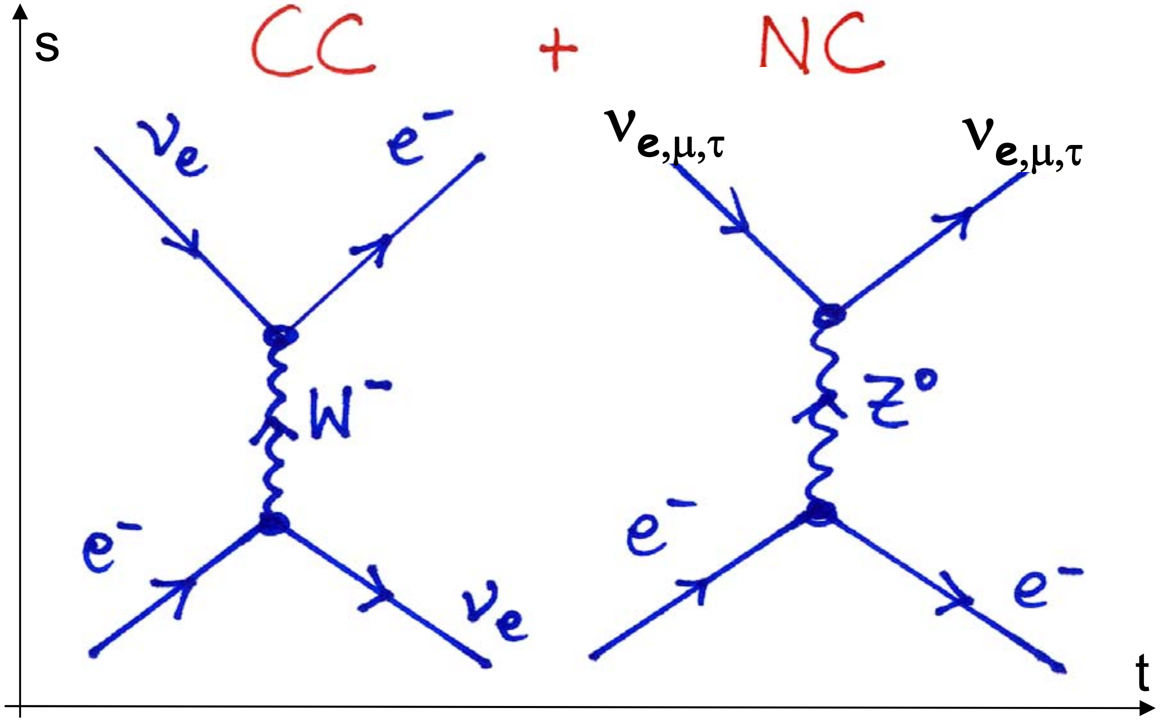


^{7}Be: E_ν = 860 keV, monoenergetic line

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

$$\nu_x + e^- \rightarrow \nu_x + e^-$$ (dominated by ν_e)

(Kinematics like Compton effect)

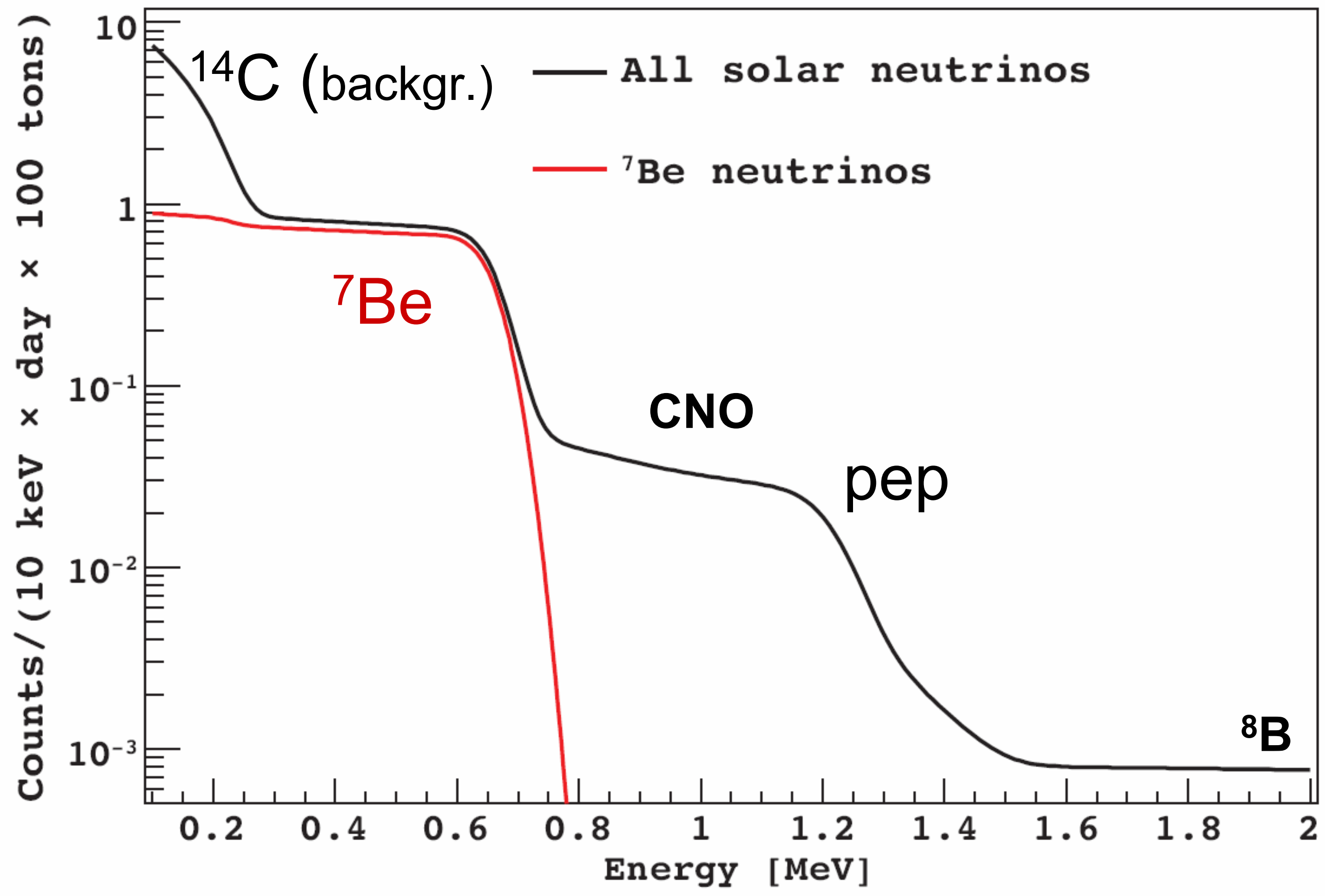


ν_e can interact via CC + NC

ν_μ and ν_τ can only interact via NC!

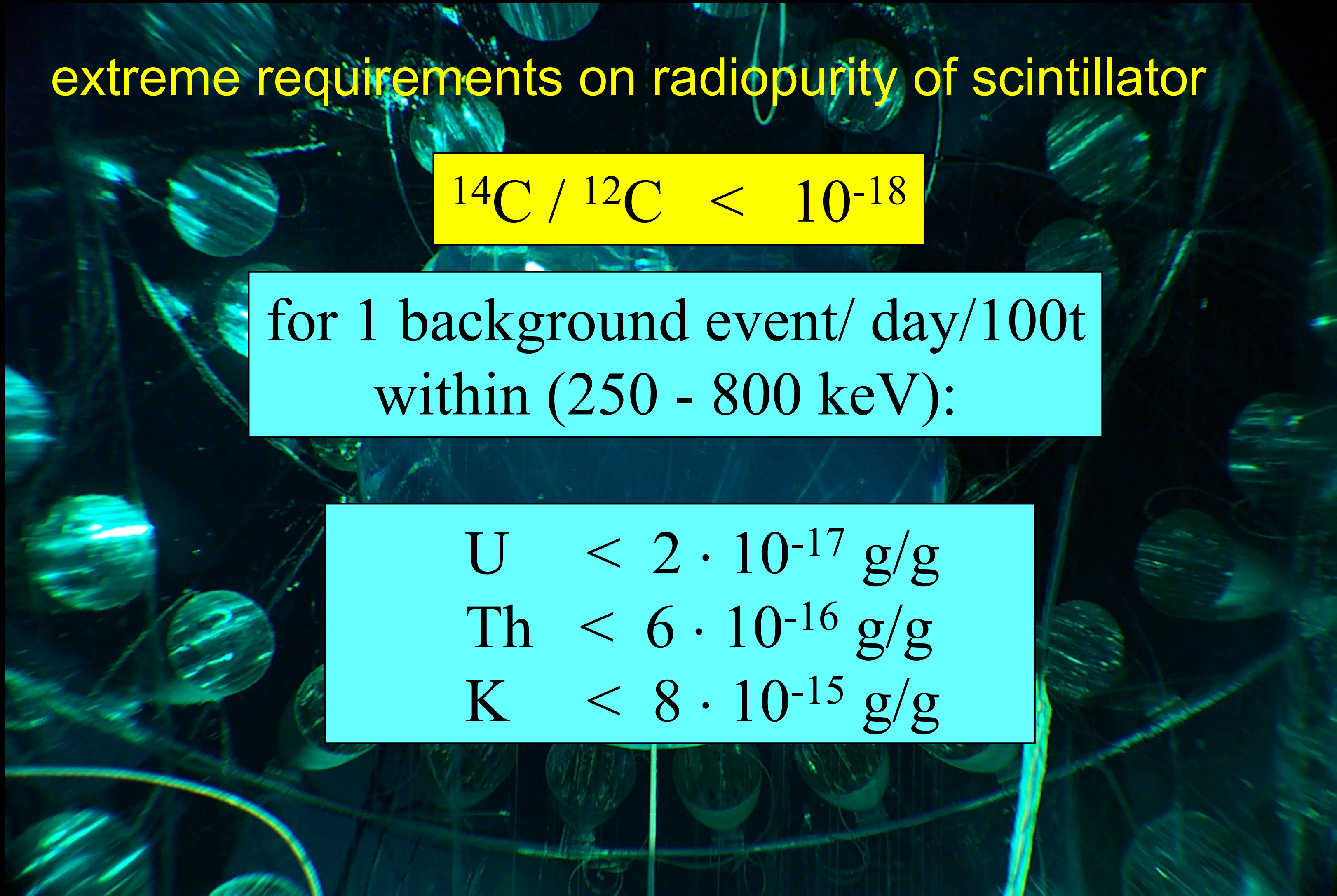
BOREXINO

Expected (electron) energy distribution:



Edge at 665 keV

Technical challenge for Borexino & KamLAND



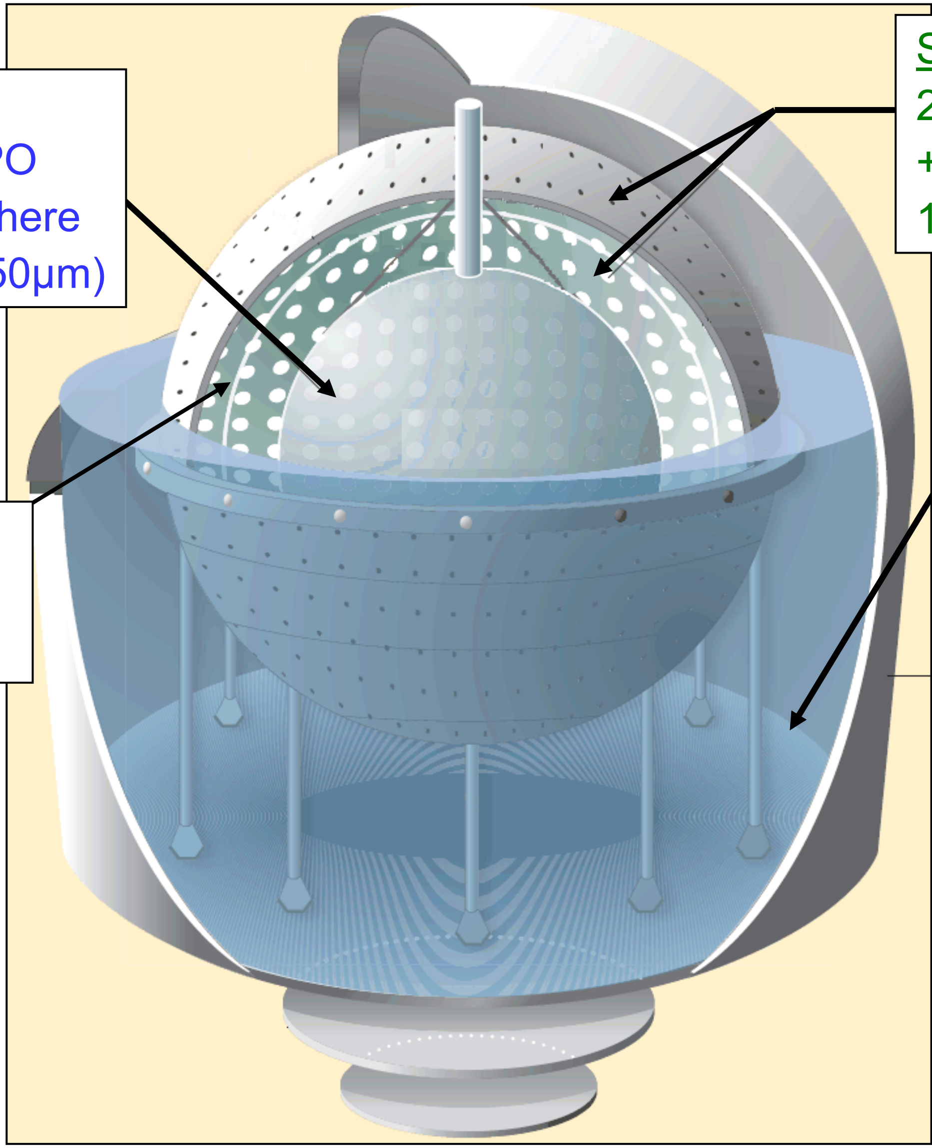
extreme requirements on radiopurity of scintillator

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

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

BOREXINO Detector



Scintillator:
300 t PC+PPO
in a nylon sphere
(thickness 150µm)

Stainless steel sphere:
2212 PMTs
+light concentrators
1350 m^3

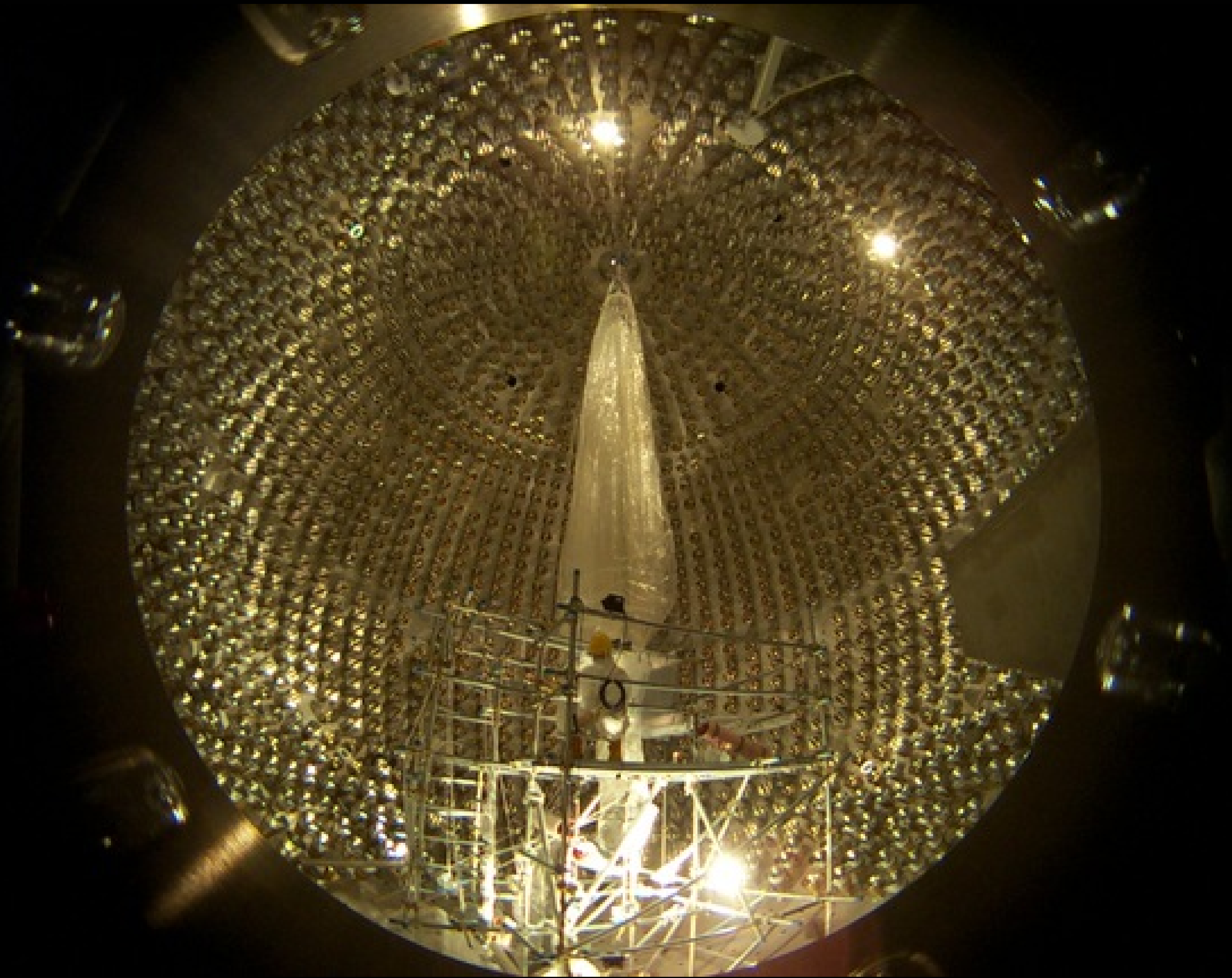
Radon barrier:
Nylon membrane at
5.50 m

Water:
γ and n shielding,
water Č detector
208 PMTs
2100 m^3

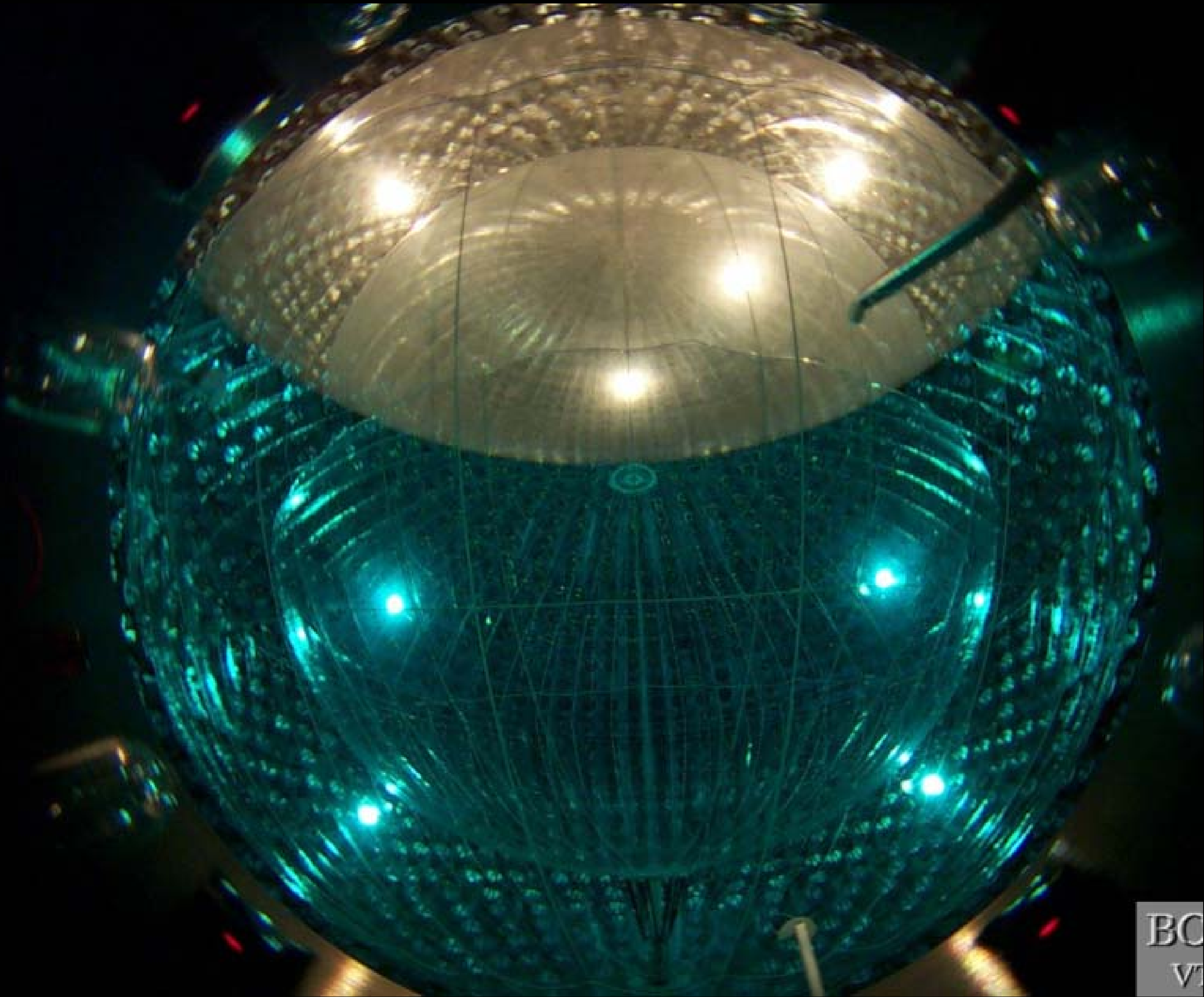
Excellent shielding against external background

Increasing purity of materials from outside to center

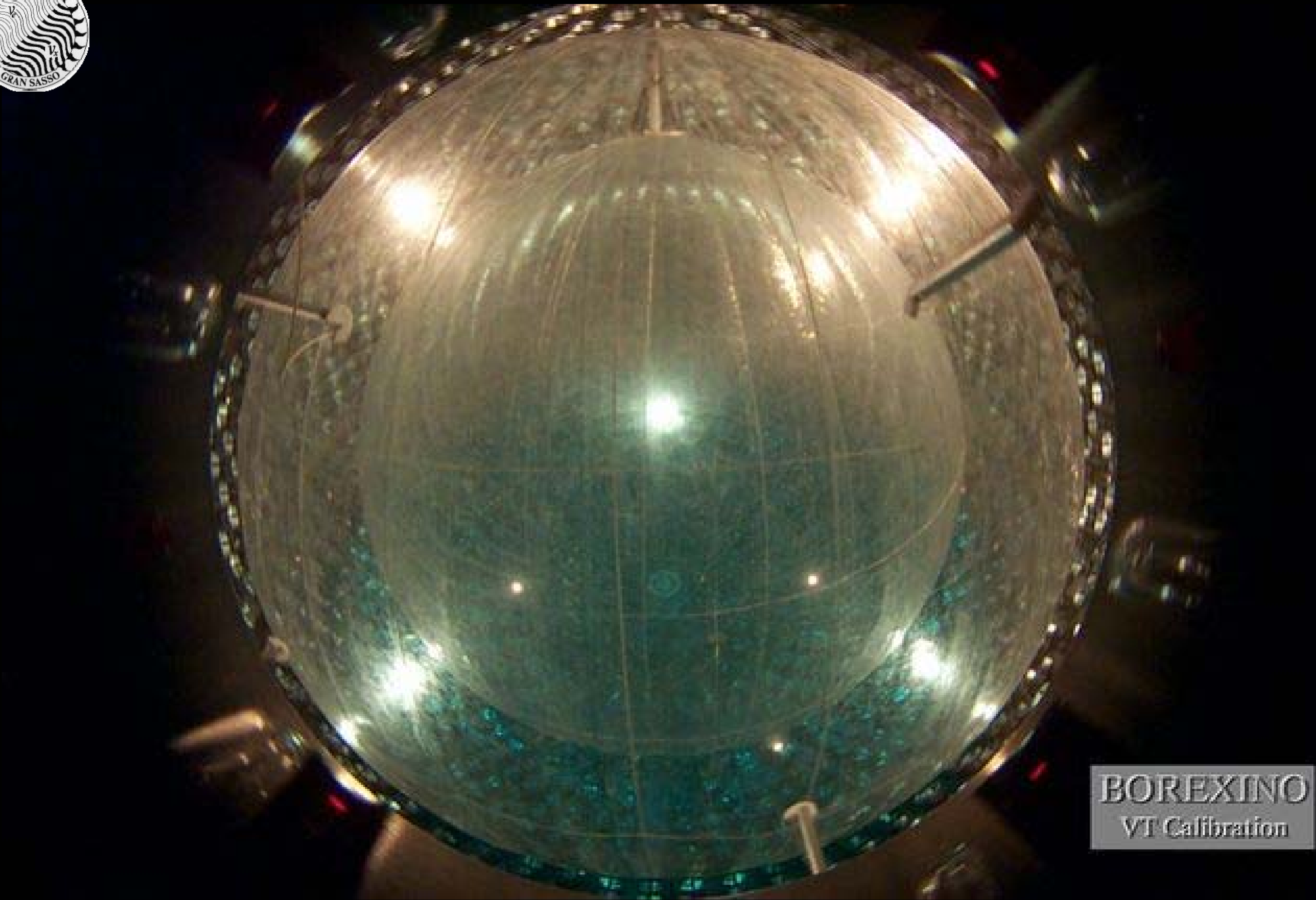
Mounting of Borexino photomultipliers with light concentrators



Installation of the 2 inner nylon spheres

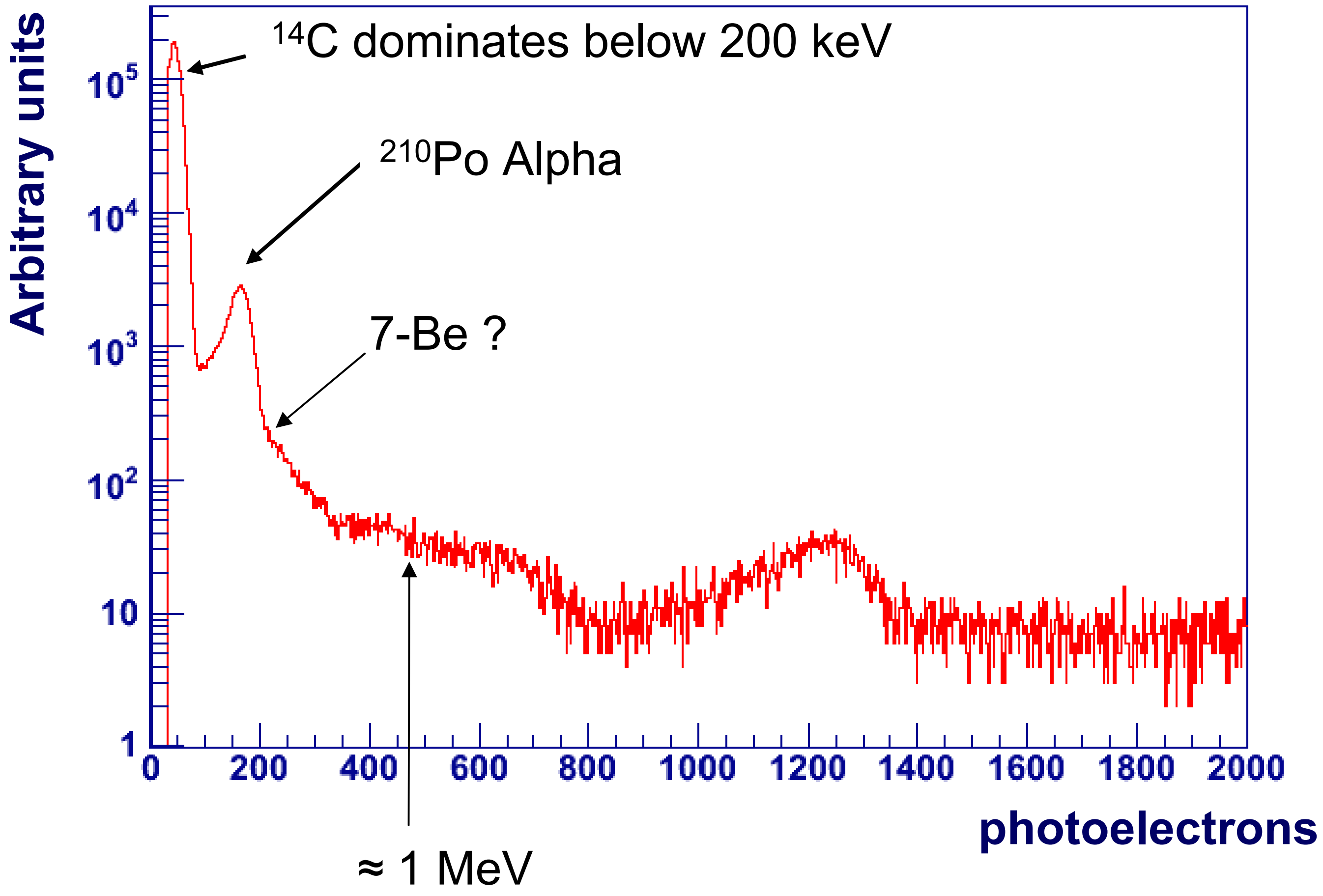


Borexino during filling phase (scintillator in upper part, ultra pure water in lower part)

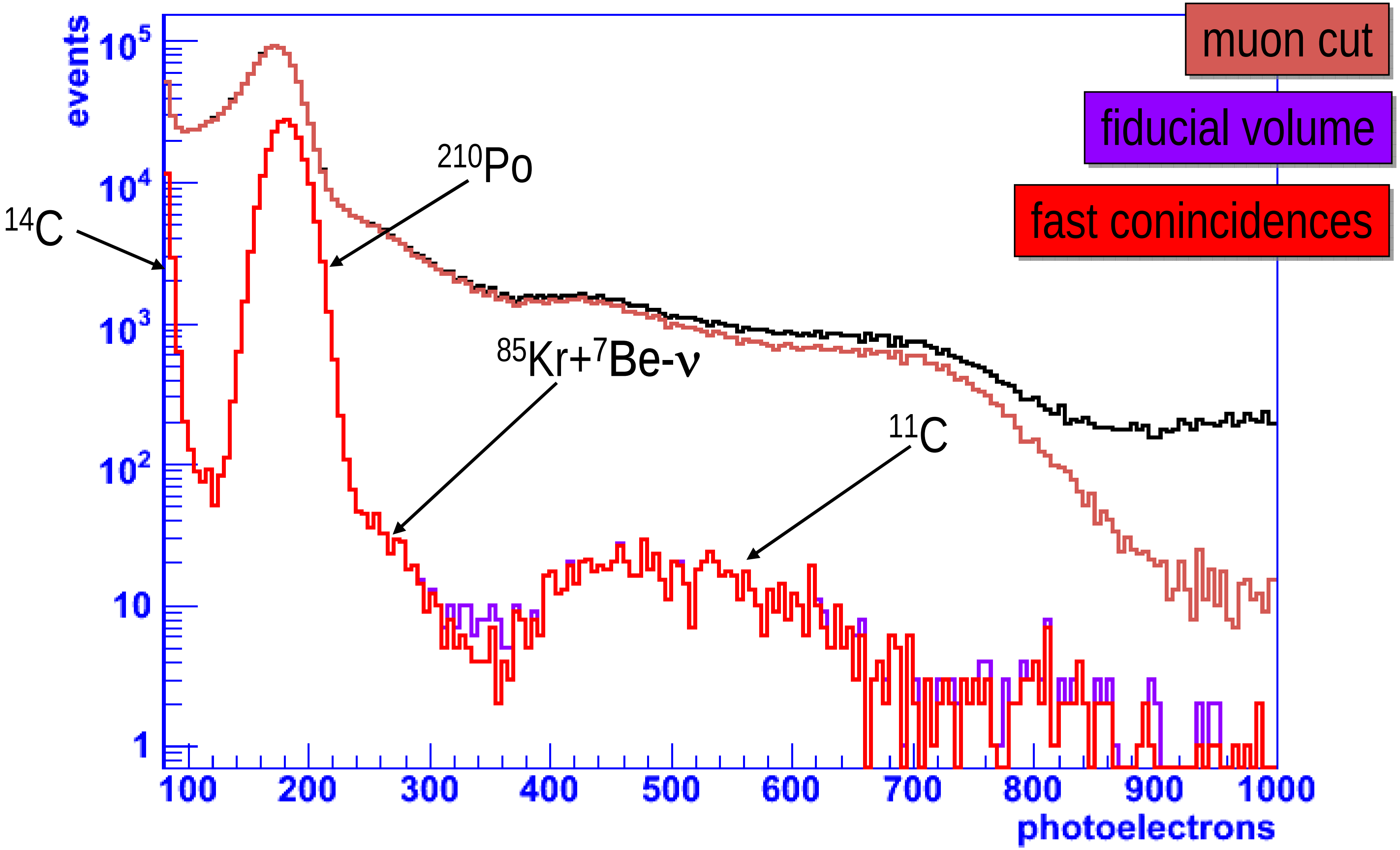


Scintillator filling completed May 15, 2007

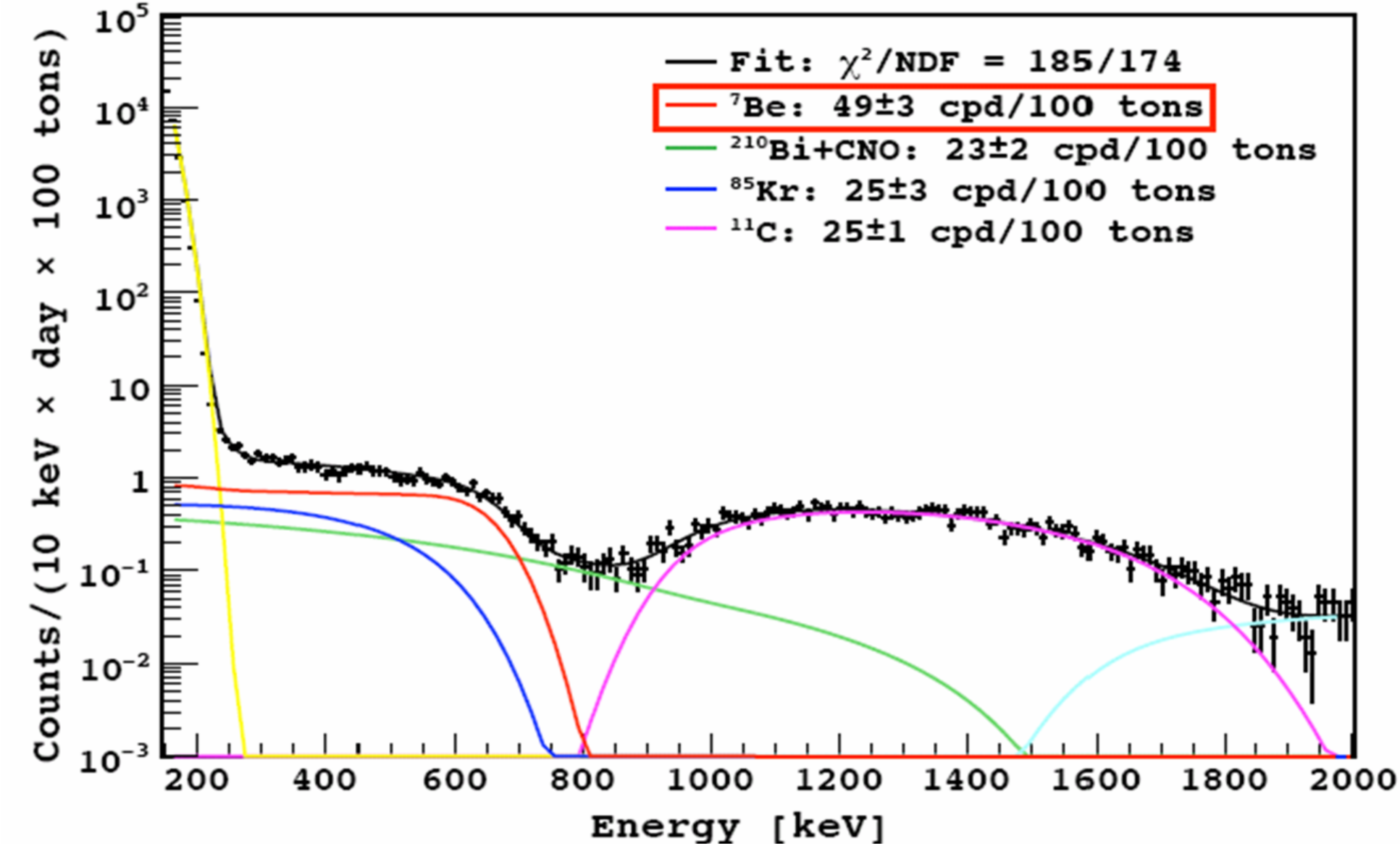
Borexino: raw data, without cuts



Borexino: Spectrum after cuts



Borexino: result



PRL 101:091302 (2008). arXiv:0805.3843

Borexino result: what does it mean?

49 ± 3stat ± 4sys cpd/100 t

Prediction of standard solar model:

No oscillation	75 ± 5	cpd/100 t
Oscillation (LMA):		
„high metalicity“	48 ± 4	cpd/100t
„low metalicity“	44 ± 4	cpd/100 t

„No-Oscillation“ is excluded from BOREXINO alone with 4 sigma.

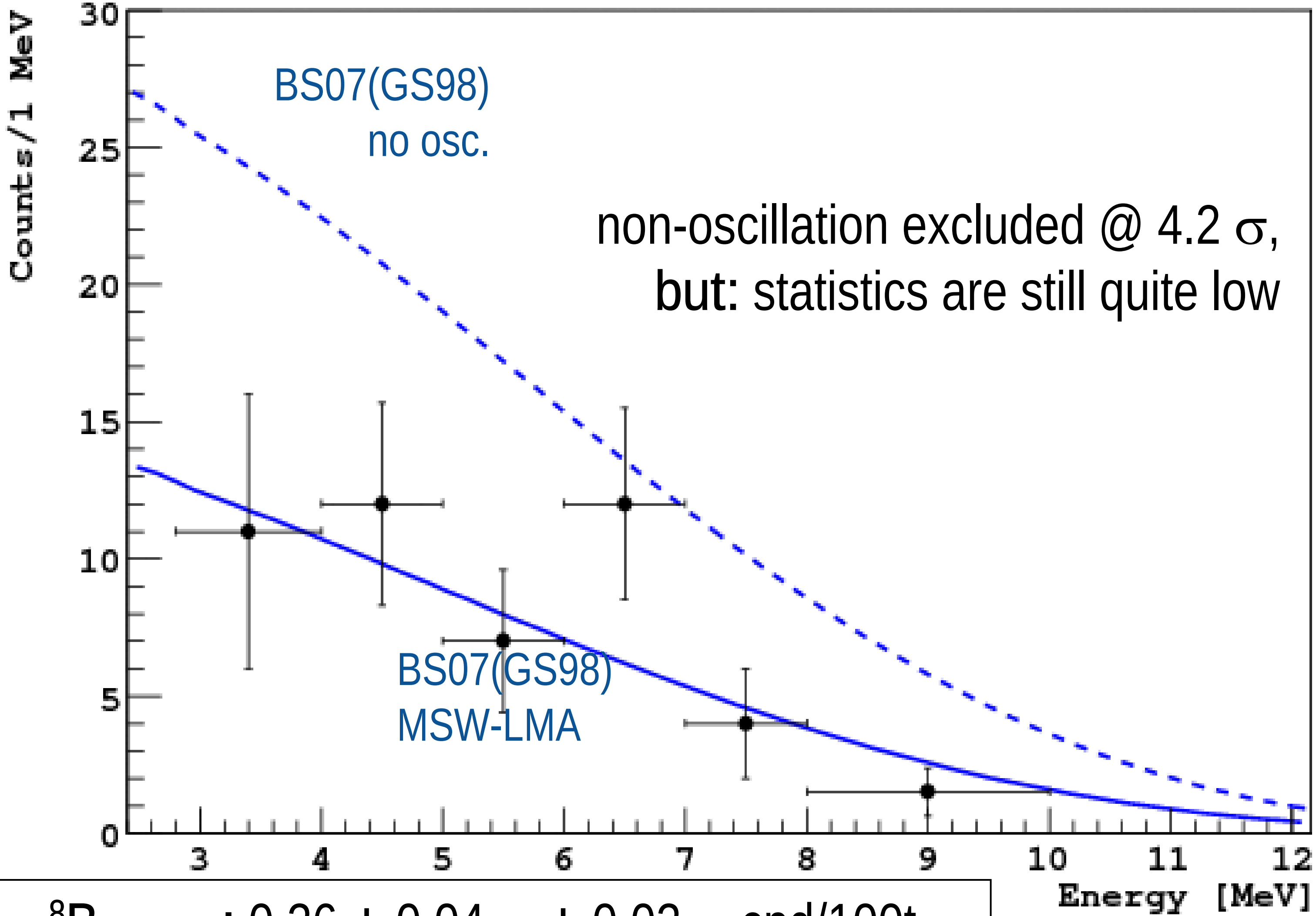
$$\phi(^7\mathrm{Be}) = (5.18 \pm 0.51) \times 10^9\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$f(^7\mathrm{Be}) = \phi(^7\mathrm{Be}) / \phi_{\mathrm{SSM}} = 1.02 \pm 0.10$$

$$f(\mathrm{pp}) = 1.005^{+0.008}_{-0.020}$$

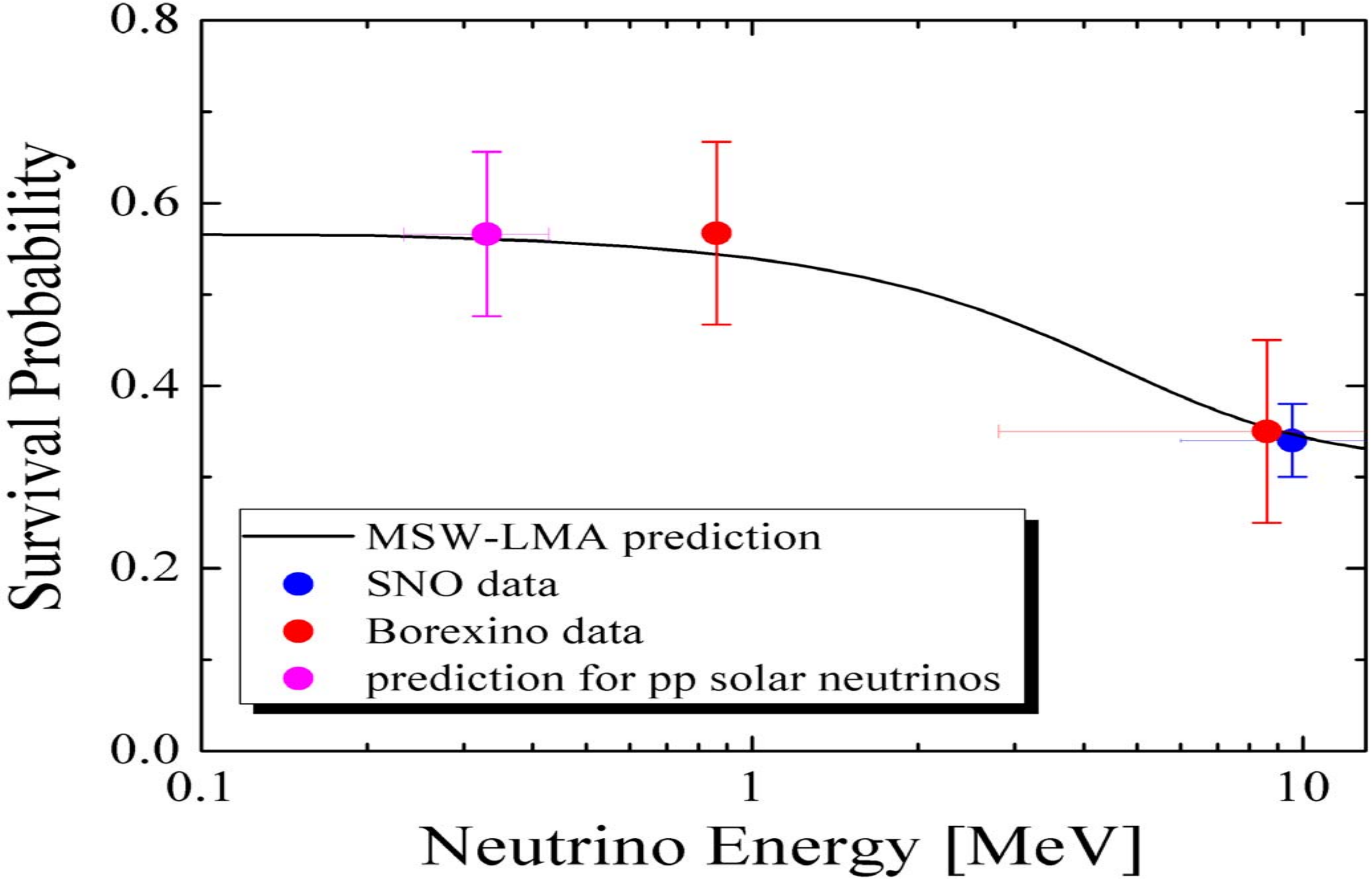
$$f_{\mathrm{CNO}} < 3.8\%$$

Borexino: New results for ^8B



$^8B_{>2.8MeV}$: $0.26 \pm 0.04_{stat} \pm 0.02_{sys}$ cpd/100t

Testing the MSW hypothesis:



Global analysis: Hints of $\theta_{13} > 0$

„Hints of θ13 > 0 from global neutrino data analysis“, Fogli, Lisi, Marrone, Palazzo, Rotunno, arxiv:0806.2649v2