Neutrino oscillation experiments

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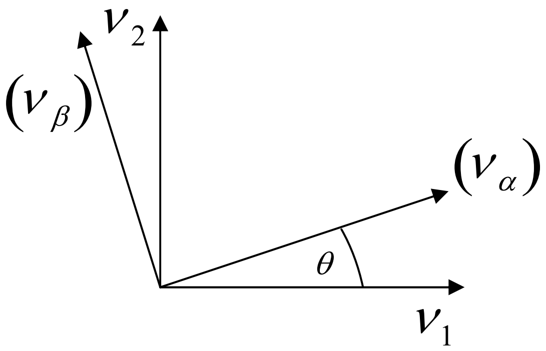
- **Basics of neutrino oscillations**
- **How to measure neutrino oscillations? (results from solar neutrino experiments)**
- **Examples of experiments (three liquid based detection techniques)**
- **Future – new undergorund laboratory for the next generation detector.**

Kielce, 06.12.2008

Oscillation of two neutrino flavours in vacuum:

$$\begin{pmatrix} |\nu_\alpha\rangle \\ |\nu_\beta\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$



in *t=0* there are only neutrinos ν_α

$$|\nu(t)\rangle = e^{i\bar{p}\cdot\bar{x}}\left(\cos\theta\cdot e^{-iE_1t}|\nu_1\rangle + \sin\theta\cdot e^{-iE_2t}|\nu_2\rangle\right) \longrightarrow$$ evolution of state

$$P(\nu_\alpha \to \nu_\alpha) = \left|\langle\nu_\alpha|\nu(t)\rangle\right|^2$$

probability to find, after time *t*, neutrinos ν_β (in *t=0* there are <u>only</u> neutrinos ν_α)

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4p} t\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

(only one approximation: $m << p \Rightarrow E_i \approx p + \frac{m_i^2}{2p}$)

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{E_\nu}\right)$$

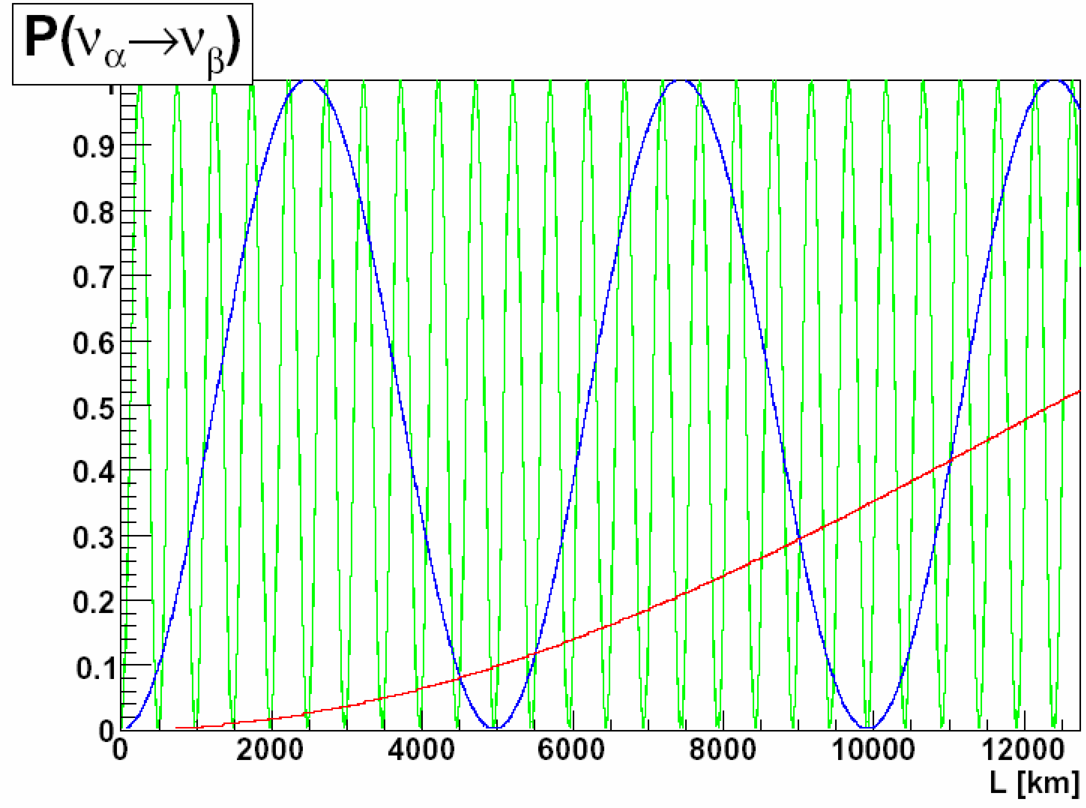
$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \times \Delta m^2\left[eV^2\right] \times L[km]}{E_\nu\left[GeV\right]}\right)$$

$\downarrow$

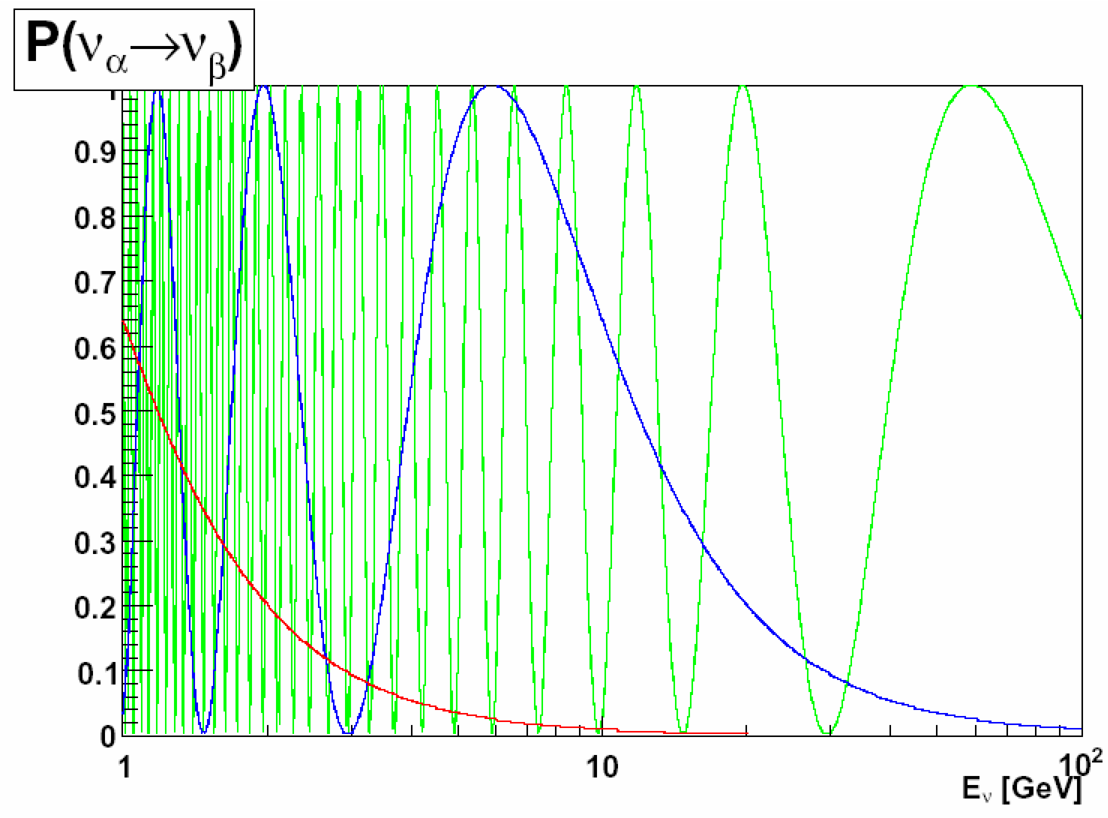
does not depend on:

→ sign Δm^2

→ change $\theta \leftrightarrow \frac{\pi}{2} - \theta$



$E_\nu = 20\text{GeV}$, $\theta = 45^0$: $\Delta m^2 = 10^{-3}$ 10^{-2} 10^{-1} eV^2



L = 732km, $\theta = 45^0$: $\Delta m^2 = 10^{-3}$ 10^{-2} 10^{-1} eV^2

Sensitivity to neutrino oscillations:

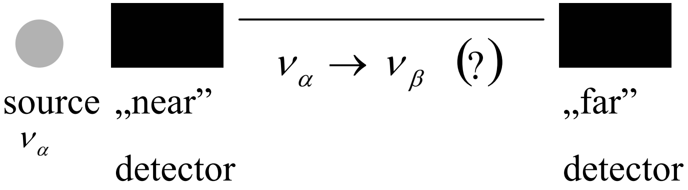
$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \times \Delta m^2\left[eV^2\right] \times L\left[km\right]}{E_\nu\left[GeV\right]}\right)$$

	E_ν(MeV)	L(m)	$\Delta m^2(eV^2)$
Supernovae	**<100**	**$>10^{19}$**	**$10^{-19} – 10^{-20}$**
Solar	**<14**	**10^{11}**	**10^{-10}**
Atmospheric	**>100**	**$10^4 - 10^7$**	**10^{-4}**
Reactor	**<10**	**$<10^6$**	**10^{-5}**
Accelerator **(short baseline)**	**>100**	**10^3**	**10^{-1}**
Accelerator **(long baseline)**	**>100**	**$<10^6$**	**10^{-3}**

(thanks to E.Rondio and D.Kiełczewska)

Neutrino oscillations: two types of experiments with a neutrino beam

DISAPPERANCE



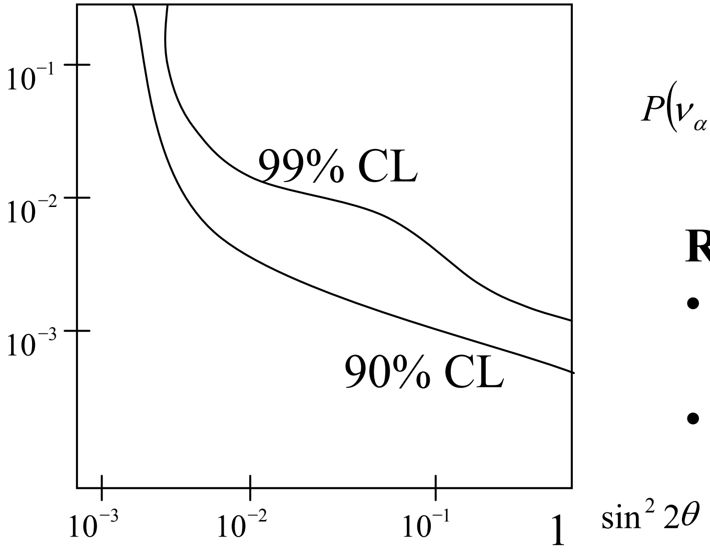
Measurement of ν_α flux

$$P(\nu_\alpha \rightarrow \nu_\beta) = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27\frac{\Delta m^2 \cdot L}{E}\right)$$

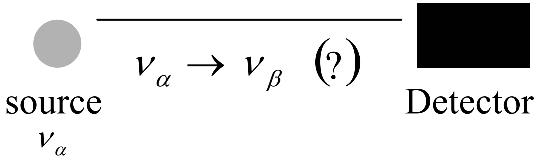
Requirements:

- 2 neutrino detectors,
- precise measurement of flux

RESULT



APPERANCE



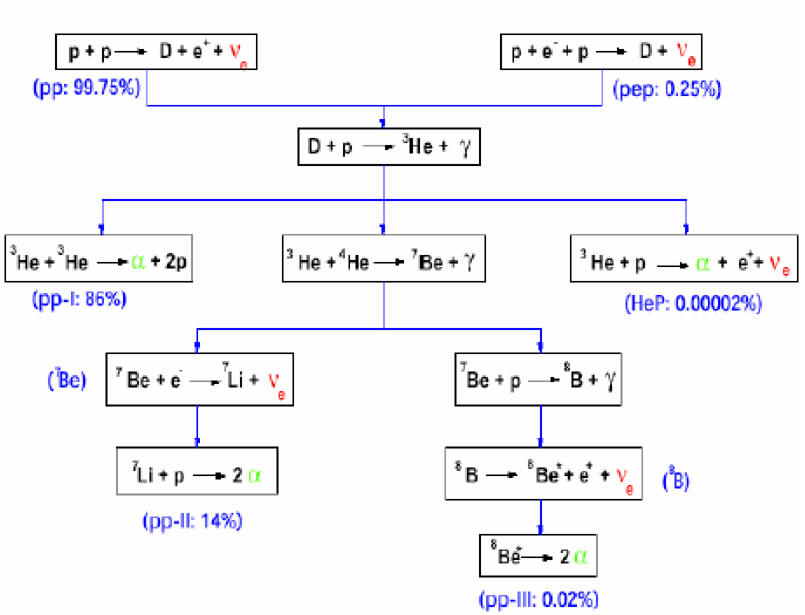
Detection of rare events $\nu_\beta \neq \nu_\alpha$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2\left(1.27\frac{\Delta m^2 \cdot L}{E}\right)$$

Requirements:

- precise knowledge of ν_β admixture in beam
- background

Do we observe neutrino oscillations? (Solar neutrinos)



$p + p \rightarrow D + e^+ + \nu_e$ (pp: 99.75%)

$p + e^- + p \rightarrow D + \nu_e$ (pep: 0.25%)

$D + p \rightarrow {}^3He + \gamma$

${}^3He + {}^3He \rightarrow \alpha + 2p$ (pp-I: 86%)

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^3He + p \rightarrow \alpha + e^+ + \nu_e$ (HeP: 0.00002%)

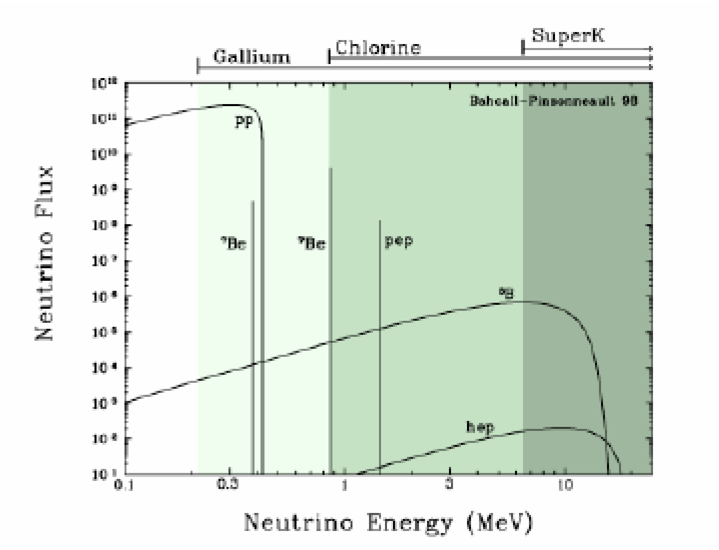
(${}^7Be$) ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow 2\alpha$ (pp-II: 14%)

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$ (${}^8B$)

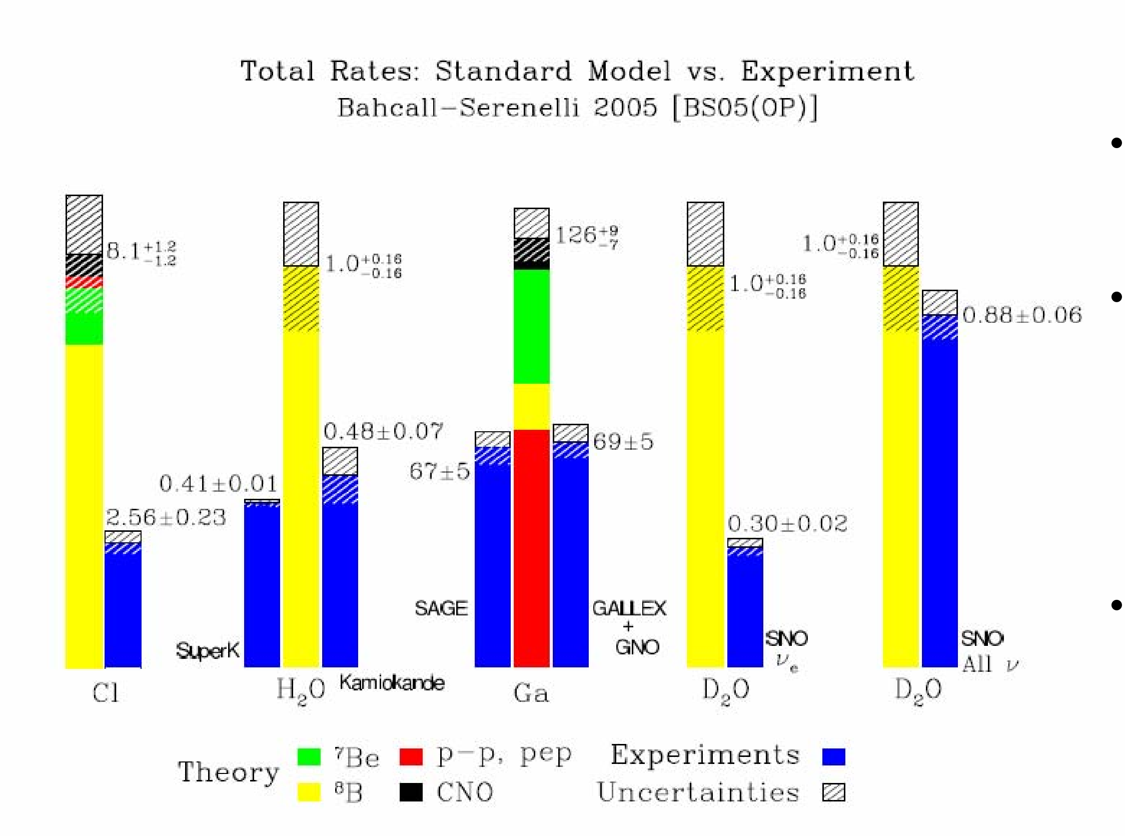
${}^8Be^* \rightarrow 2\alpha$ (pp-III: 0.02%)



Standard Solar Model (Bahcall):

- energy production in the Sun core in the chain of thermonuclear reactions,
- thermal and hydrostatic equillibrium,
- several observables: total emtted power, surface temperature, …

Measured flux of solar neutrinos vs Standard Solar Model predictions



- **SNO was able to observe ALL neutrino flavours, NOT ONLY ν_e,**
- **Only electron neutrinos are produced in the Sun, therefore ν_e have to change (oscillate) i.e. flavour states are combinations of mass states,**
- **Oscillation parameters:**
  $\theta_{12} \approx 34^0$,
  $\Delta m_{21} \approx 7.6 \cdot 10^{-5}$ eV^2

[in SNU (Solar Neutrino Units): 1 SNU = 1 interaction / (10^{36} target atoms • 1s)]

Neutrino Properties. Current Picture.

Last decade dominated by neutrino oscillation discovery – SK, 1998
then MACRO, SOUDAN2, GALLEX+SAGE, SNO, K2K, MINOS,KamLAND…

Atmospheric (SK)
Accelerators (K2K,Minos)

Reactors ((D-)CHOOZ)
Accelerators (JPARC,Nova)

Solar (SNO, SK)
Reactors (KamLAND)

DBD exprts

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$\theta_{23} \approx 45°$

$\theta_{13} < 13°(3\sigma)$
δ_{CP} – Dirac phases

$\theta_{12} \approx 34°$

α,β – Majorana phases

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.6	7.3–8.1	7.1–8.3
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.4	2.1–2.7	2.0–2.8
$\sin^2\theta_{12}$	0.32	0.28–0.37	0.26–0.40
$\sin^2\theta_{23}$	0.50	0.38–0.63	0.34–0.67
$\sin^2\theta_{13}$	0.007	≤ 0.033	≤ 0.050

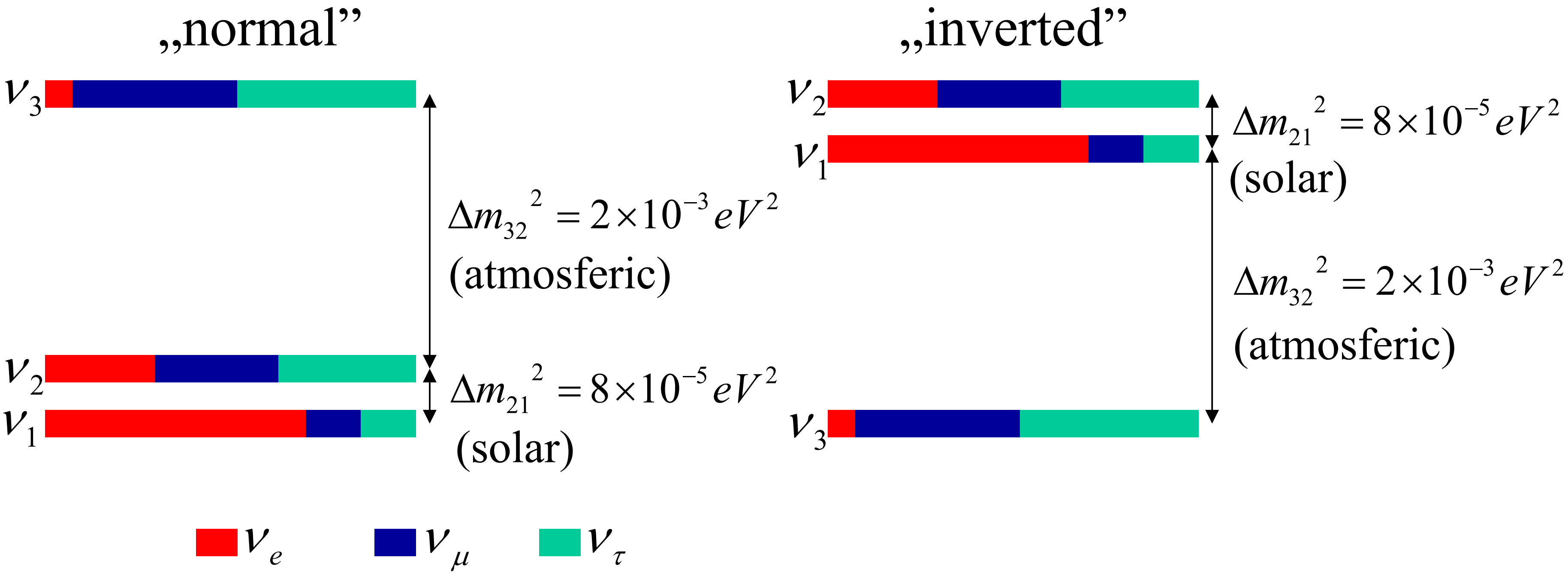
From Tritium beta decay

$$m_{\overline{\nu}_e} < 2.3\ \mathrm{eV}$$

From cosmology

$$\sum m_{\nu_i} < 1\ \mathrm{eV}$$

2 mass schemes for neutrinos:



„normal”

ν_3

ν_2

ν_1

$\Delta m_{32}{}^2 = 2\times10^{-3}\,eV^2$ (atmosferic)

$\Delta m_{21}{}^2 = 8\times10^{-5}\,eV^2$ (solar)

„inverted”

ν_2

ν_1

ν_3

$\Delta m_{21}{}^2 = 8\times10^{-5}\,eV^2$ (solar)

$\Delta m_{32}{}^2 = 2\times10^{-3}\,eV^2$ (atmosferic)

🟥 ν_e 🟦 ν_μ 🟩 ν_τ

sign $\Delta m_{23}{}^2$ is not known $\Leftrightarrow$ we do not know which mass scheme is realized in Nature

$\Delta m_{32}{}^2 > 0 \rightarrow$ „normal” mass scheme

$\Delta m_{32}{}^2 < 0 \rightarrow$ „inverted” mass scheme

Neutrino oscillation experiments: three detection techniques

- Water Cerenkov detector (Super-Kamiokande, see E.Rondio talk)
- Liquid scintillator detector (Borexino, Kamland,…)
- Liquid argon detector (ICARUS)

Future: next generation detectors and the new undergound laboratory in Europe

The LAGUNA (Large Apparatus for Grand Unification and Neutrino Astrophysics) project:

Design Study in the framework FP7 with the main goal:

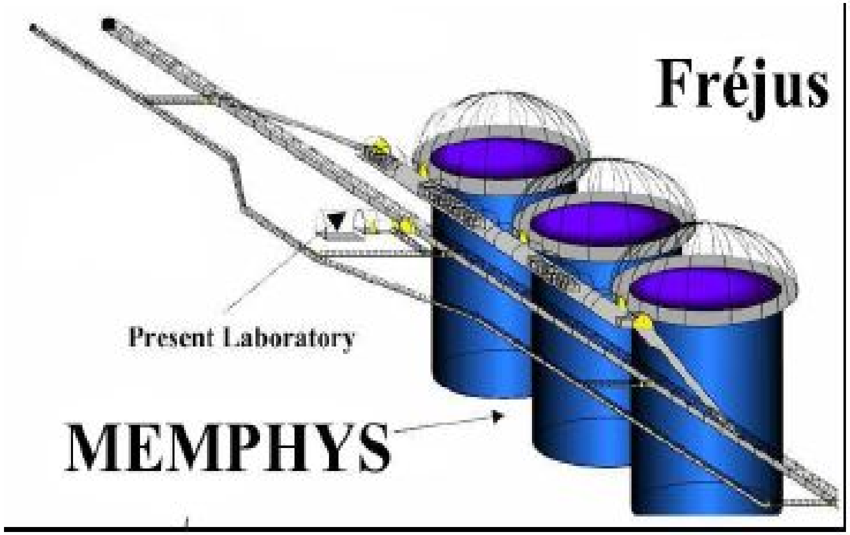
- studies of possible localizations (in Europe) of a new underground laboratory able to host a new generation, very massive (10^5-10^6 tons) liquid (liquid argon, water, liquid scintillator) detector for neutrino astrophysics and proton decay.

Several Polish participating institutions.

Localization in Poland (Sieroszowice) considered within LAGUNA project.

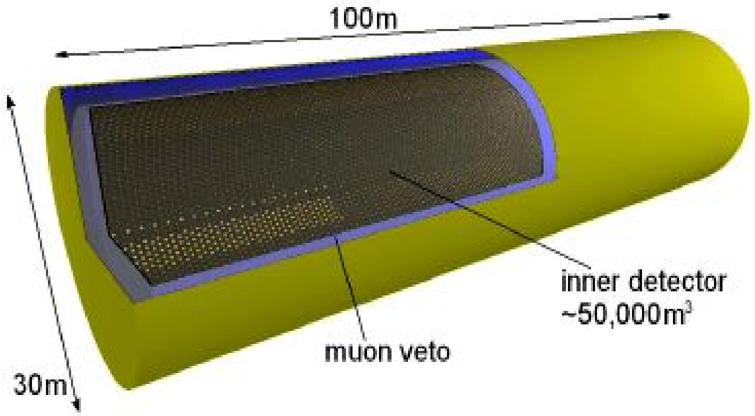
MEMPHYS (water Cerenkov)

- extrapolation of Super-Kamiokande detector
- 3-5 tanks in shafts 65m diameter and 65m height
- ~81000 12’’ PMTs (30% surface coverage) or 20’’ PMTs (40% coverage)
- possibility of introducing $GdCl_3$ (decrease of background by tagging neutrons from inverse beta decay)

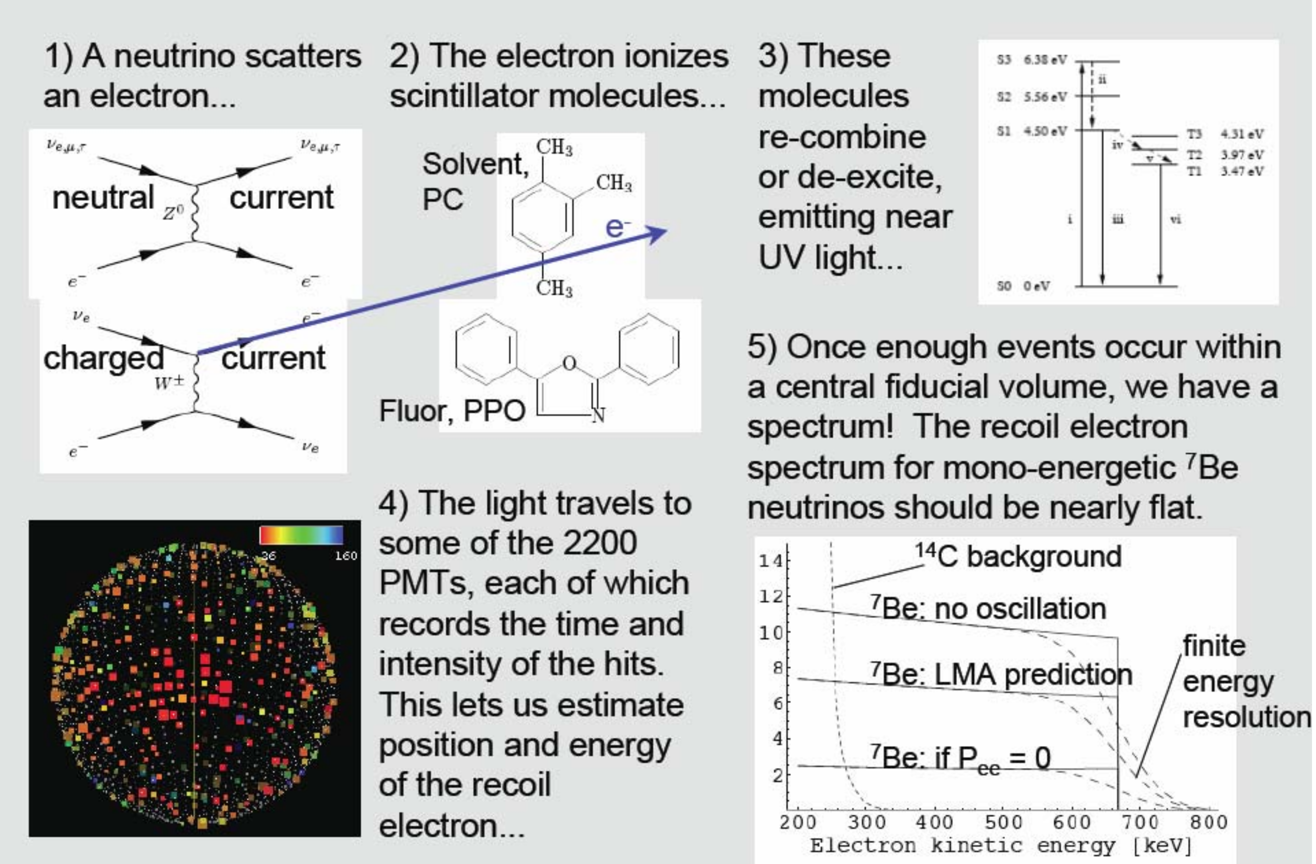


LENA (liquid scintillator)

- one cylindrical tank
- inner volume contains about 50000m^3 of liquid scintillator
- scintillation light detected by 12000 20’’ PMTs (30% surface coverage)
- outer part (muon veto) filled with water
- technology used in KamLAND and Borexino detectors



Liquid scintillator (Borexino detector):



1) A neutrino scatters an electron...

2) The electron ionizes scintillator molecules...

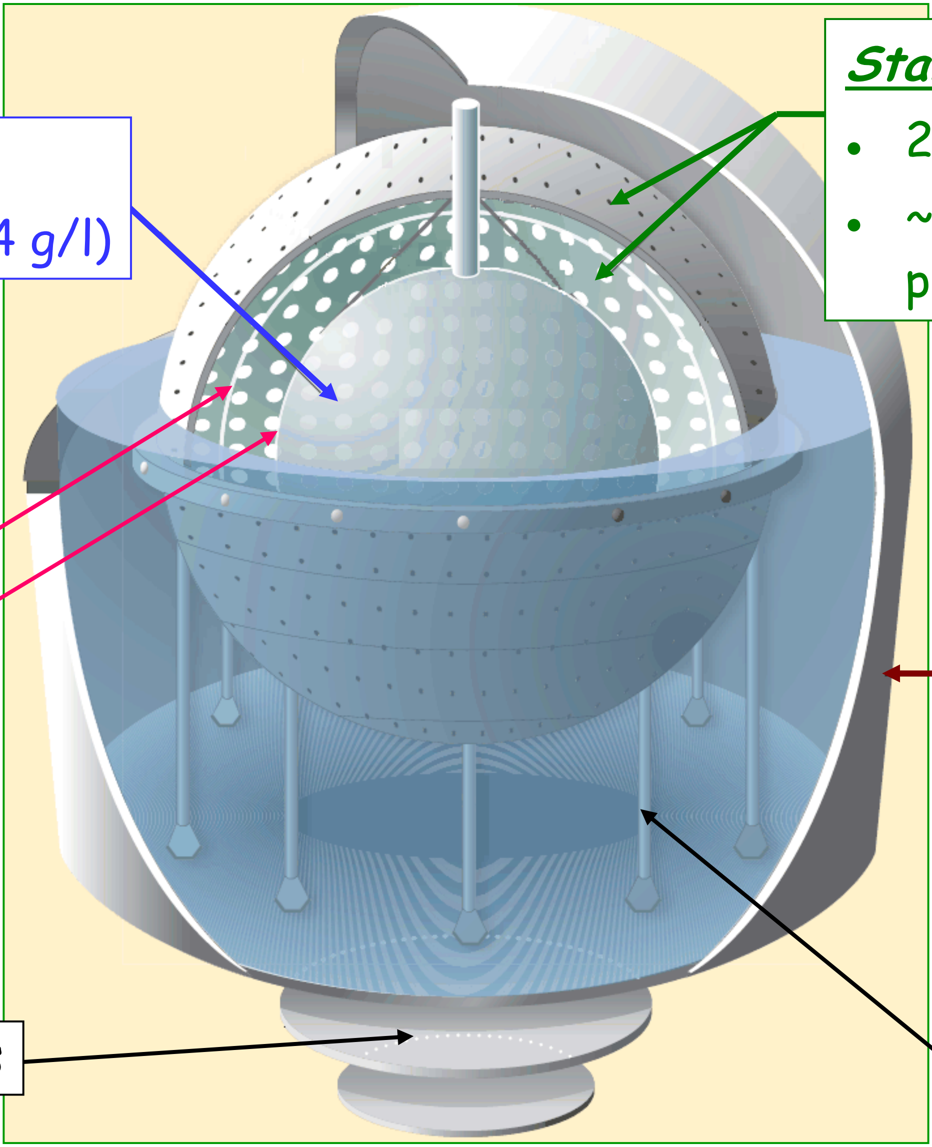
3) These molecules re-combine or de-excite, emitting near UV light...

4) The light travels to some of the 2200 PMTs, each of which records the time and intensity of the hits. This lets us estimate position and energy of the recoil electron...

5) Once enough events occur within a central fiducial volume, we have a spectrum! The recoil electron spectrum for mono-energetic ^{7}Be neutrinos should be nearly flat.

- **very low energy threshold,**
- **measurement of position and energy, no direction of neutrino**

Borexino detector



Scintillator:

270 t PC+PPO (1.4 g/l)

Stainless Steel Sphere:

- 2212 PMTs
- ~ 1000 m^3 buffer of pc+dmp (light queched)

Nylon vessels:

(125 μm thick)

Inner: 4.25 m

Outer: 5.50 m

(radon barrier)

Water Tank:

γ and n shield

μ water Č detector

208 PMTs in water

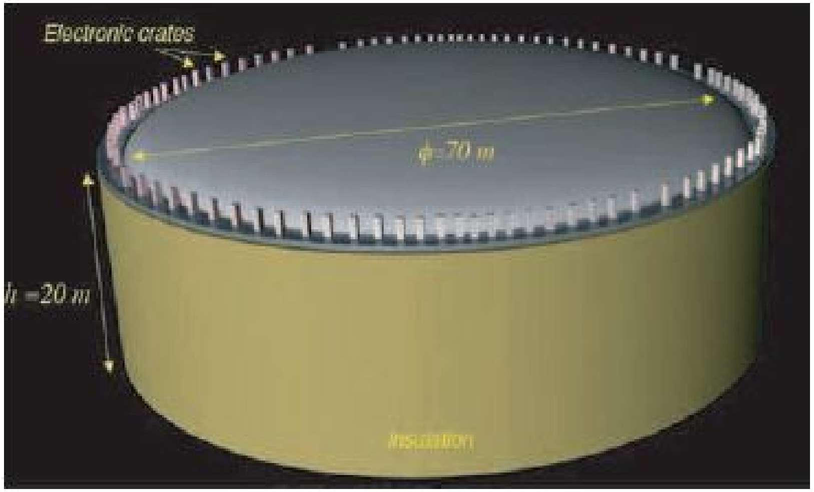
2100 m^3

Carbon steel plates

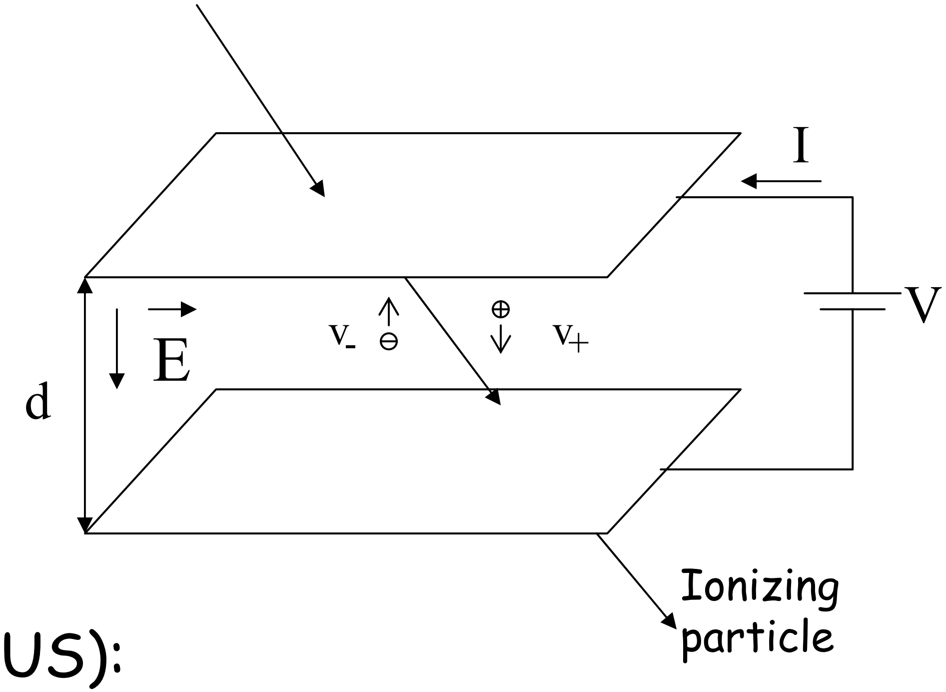
20 legs

GLACIER (liquid argon)

- liquid argon (LAr) Time Projection Chamber
- 3D reconstruction of events using information provided by ionization in LAr and light (scintillation and Cherenkov) readout by PTMs
- bi-phase mode (drifting electrons from liquid phase are extracted into gas phase and amplified)
- technology developed by the ICARUS experiment



Signals in LAr (non-multiplying medium)



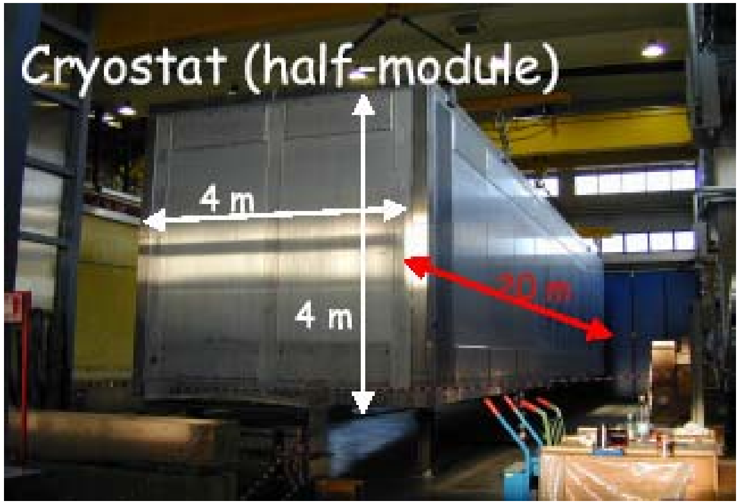
In LAr (ICARUS):

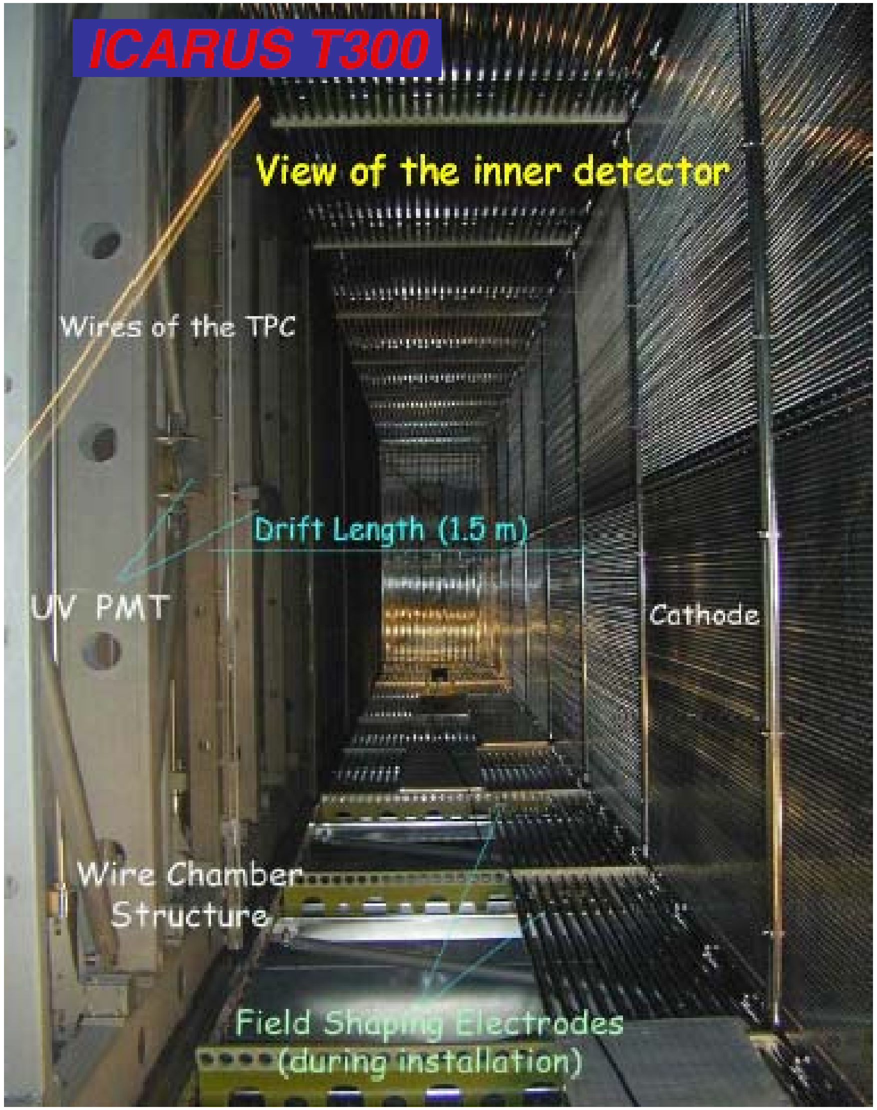
- ~ 8800 electron + ion pairs /1 mm track, for MIP
- 8800 → 5500 pairs/mm (local recombination)
- v_e^- ~ 1600 m/s @ E = 500 V/cm
- e^- drift time: ~0.6 x d[m] ms
- dE/dx ~ 2.12 MeV/cm for MIP

ICARUS T600: some numbers

- **The instrumented volume: 340.35m^3, 476.5 t of LAr, with maximum drift length = 1.5m**
- **Inner detector: two T300 Time Projection Chambers (TPC)**
- **Each TPC: 3 parallel wire planes, 3mm apart, oriented at 60^o with respect to each other, wire pitch = 3mm**
- **Total number of wires: 53 248**
- **Nominal voltage = 75kV, electric field of 500V/cm**
- **Photomulipliers**
- **LAr purity monitor system**

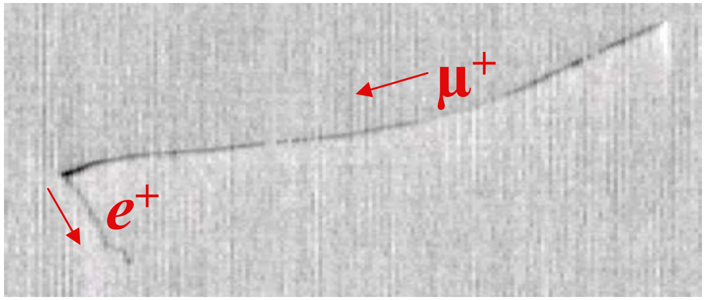
ICARUS Detector

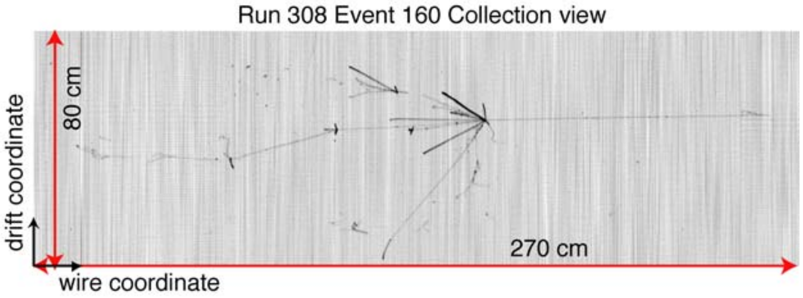


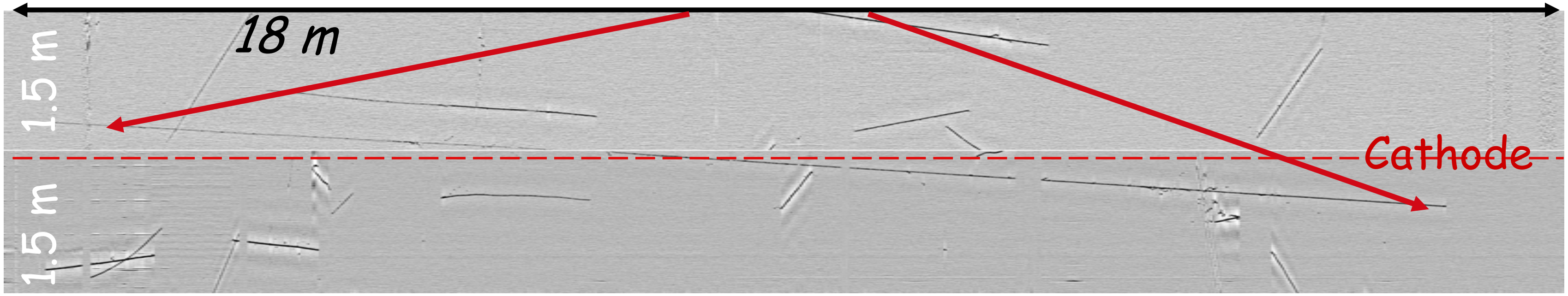


ICARUS test run: results

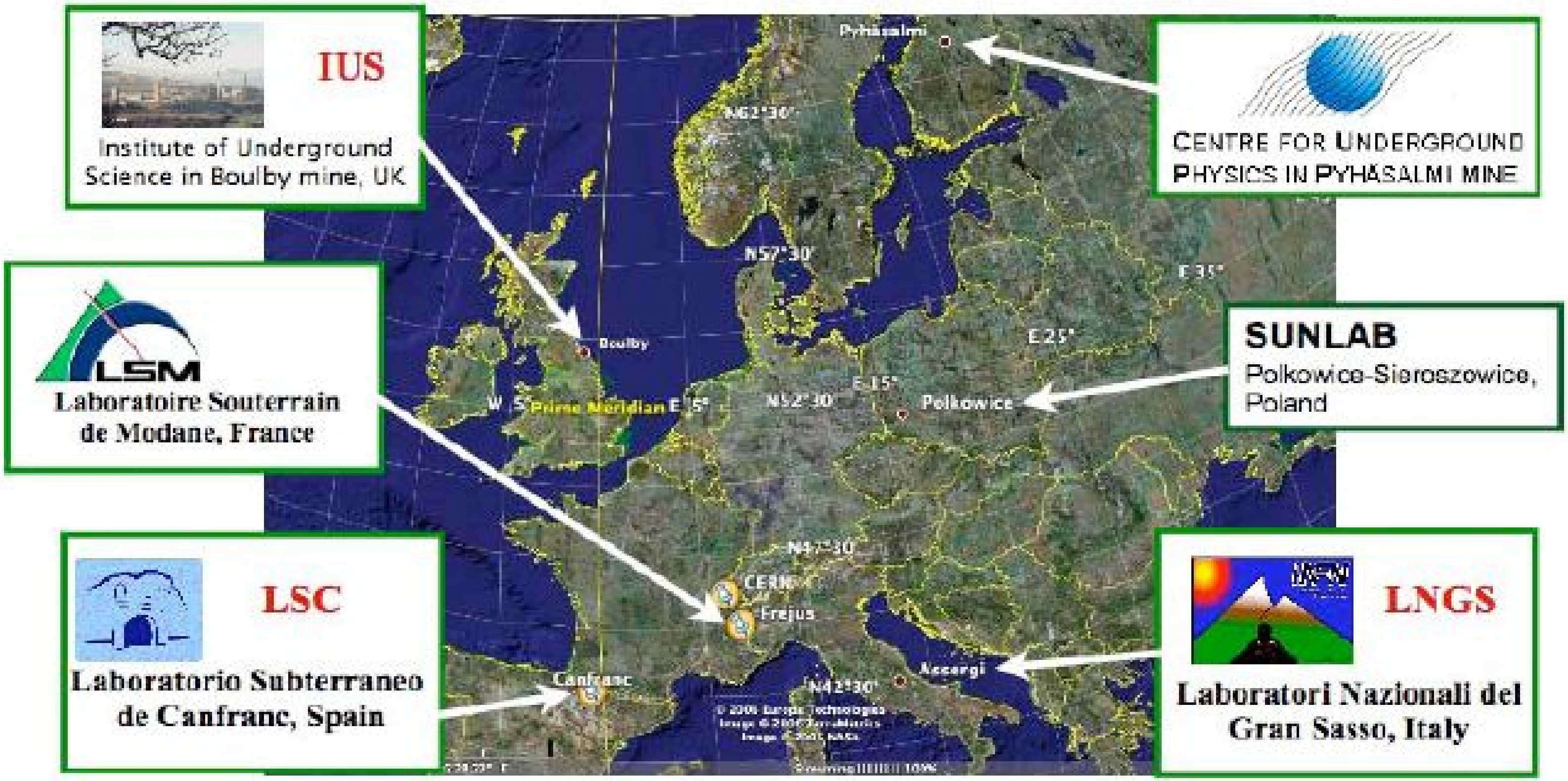
- 2001: successful test of the T300 module in Pavia (100 days of data taking, ~29000 triggers on tape, different topologies: long (up 18 m !) muon tracks, hadronic and EM interactions, muon bundles,…







Underground sites considered within the LAGUNA project



IUS
Institute of Underground Science in Boulby mine, UK

CENTRE FOR UNDERGROUND PHYSICS IN PYHÄSALMI MINE

LSM
Laboratoire Souterrain de Modane, France

SUNLAB
Polkowice-Sieroszowice, Poland

LSC
Laboratorio Subterraneo de Canfranc, Spain

LNGS
Laboratori Nazionali del Gran Sasso, Italy

(Also SLANIC in Romania)

Sieroszowice: some info and pictures

- KGHM S.A., copper mine with big (100x15x20m) salt caverns (too small to host next generation detector!) 950m underground, salt layer about 70m thick
- Extremely low natural radioactivity background (in-situ measurements J.Dorda, D.Malczewski, JK)