Neutrino physics and dark matter

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Symposium on Physics of Elementary Interactions in the LHC Era,
Warszawa, 21-22 April, 2008

Neutrinos – introduction

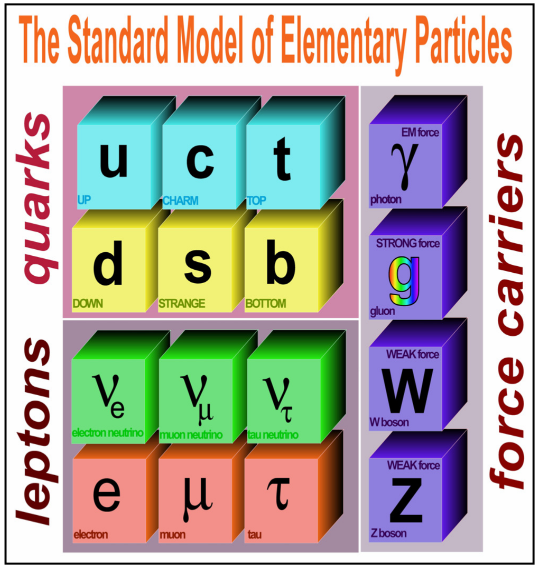
Neutrino oscillations and neutrino astrophysics

Big open questions in neutrino physics

Dark matter – WIMPS? Axions?

And ... gamma bursts,

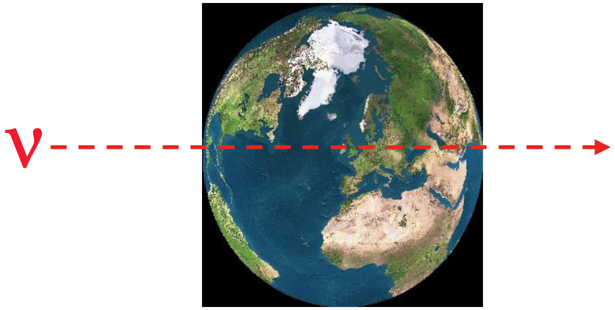
Introduction to neutrinos



Neutrinos are neutral leptons

-they intract only weakly, e.g. a mean free path for neutrino of energy 1 GeV at Earth density equals 10^6 Earth diameters,

thus 10^6 such neutrinos are needed to get one interacting in the Earth



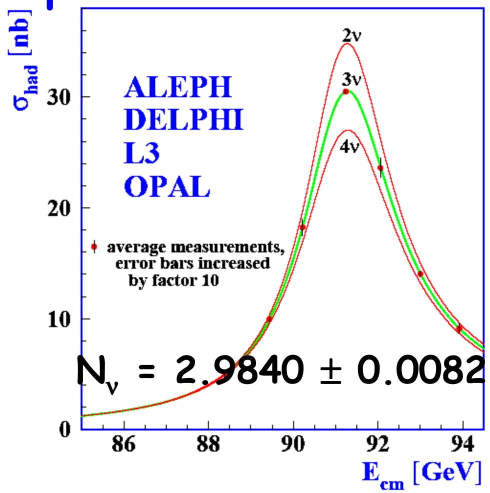
Neutrinos are the second most abundant particles in the Universe

(behind the photons) e.g. there are about 300/cm^3 relict neutrinos

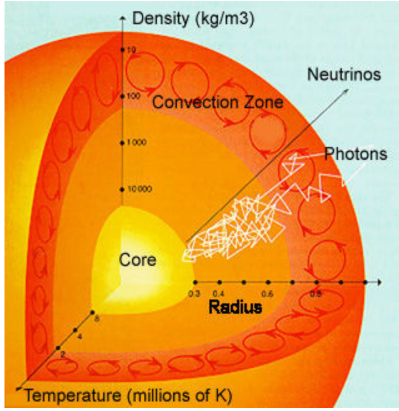
There are three flavours of neutrinos:

ν_e ν_μ ν_τ

- result from the CERN experiments at LEP



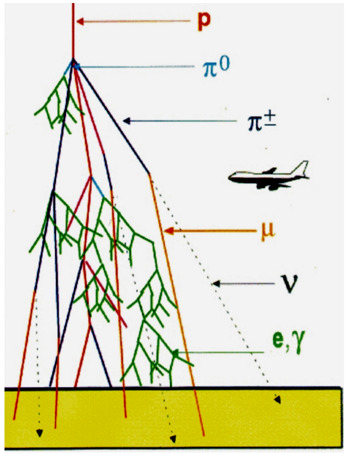
Neutrino sources



Types of neutrinos observed in experiments:

Natural: solar, atmospheric, from Supernova explosions and other astrophysical sources, geo-neutrinos

Artificial: reactor and accelerator neutrinos



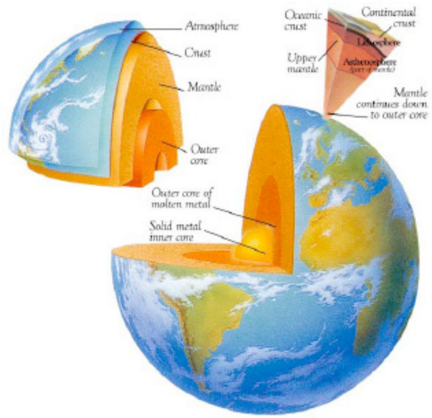
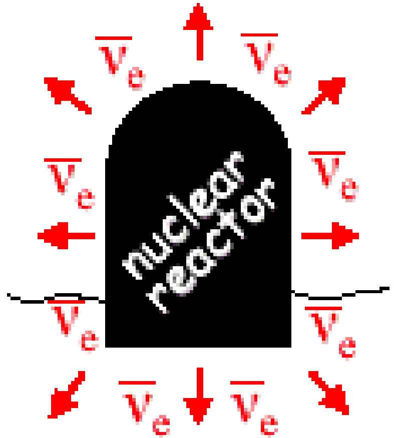
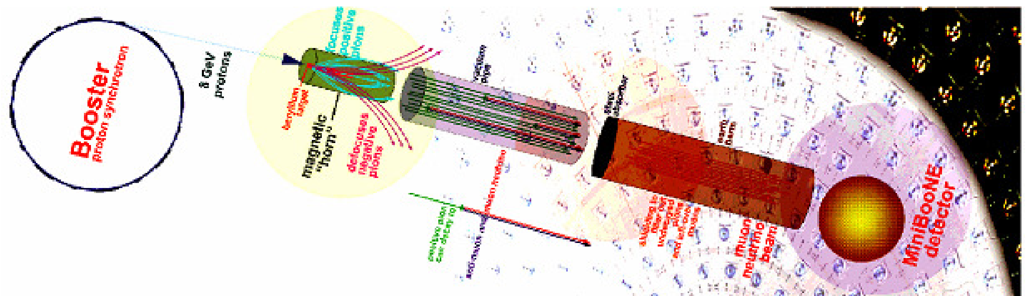


Image by Colin Rose and Dorling Kindersley



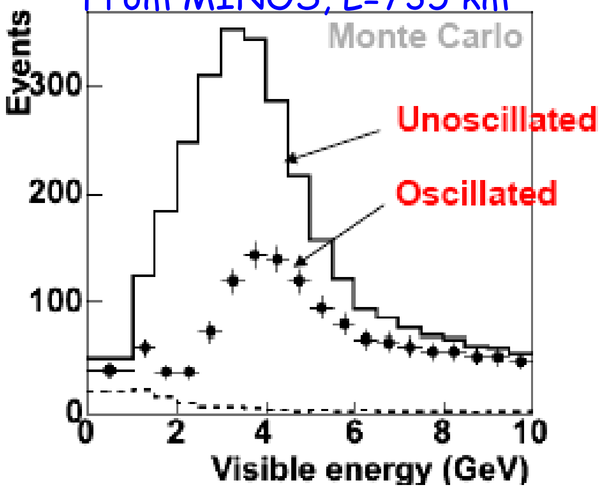


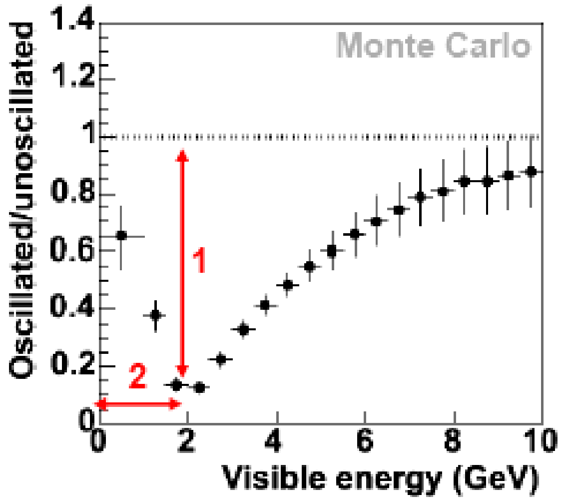
Neutrino oscillations primer

In the two-neutrino oscillation scheme with two flavour eigenstates α and β and two mass eigenstates 1 and 2, the probability that neutrino of flavour α transforms into neutrino of flavour β:

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\sin^2 2\theta}_{1} \sin^2(1.267 \underbrace{\Delta m^2}_{2} L / E)$$

From MINOS, L=735 km





Disappearance experiment:

$$P(\nu_\alpha \to \nu_\alpha) \le 1$$

Appearance experiment:

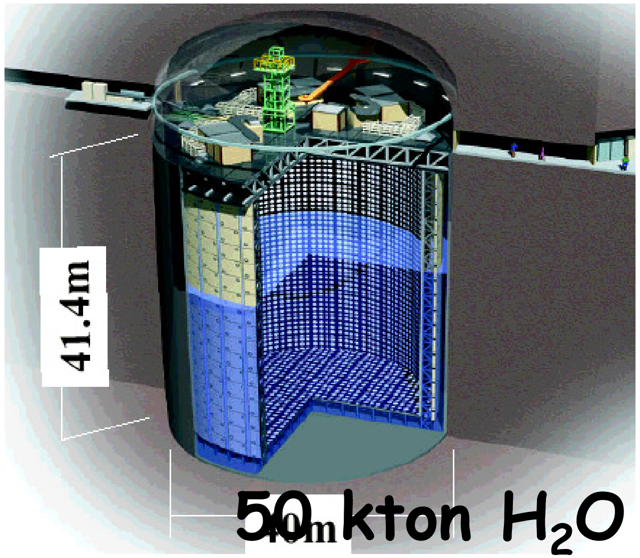
$$P(\nu_\alpha \to \nu_\beta) \ge 0$$

Matter effects: for neutrinos going through a dense matter

Neutrinos oscillate → they are massive!

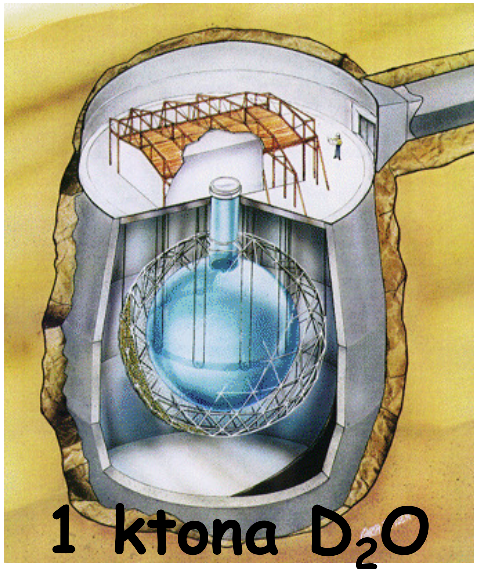
1998 - 2002 - romantic era of great discoveries

1998 SuperKamiokande – solid evidence for the ν_μ <-> ν_τ oscillations
2002 confirmed by the long base accelerator experiment K2K
2001-2002 SNO solves the 35 years old solar neutrino puzzle
by the ν_e -> $\nu_{\mu,\tau}$ transitions inside Sun
2002 KamLAND shows that reactor anti-ν_e's oscillate like solar ν_e's



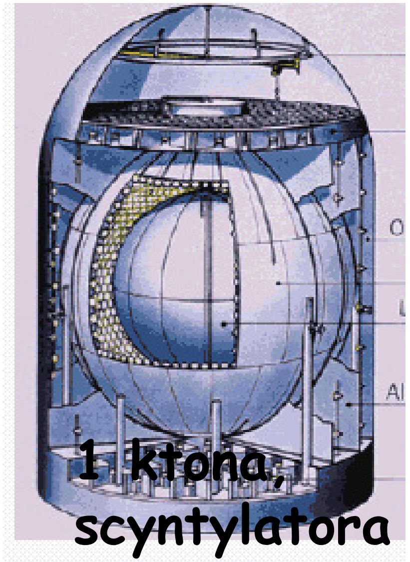
50 kton H_2O

SuperKamiokande



1 ktona D_2O

SNO



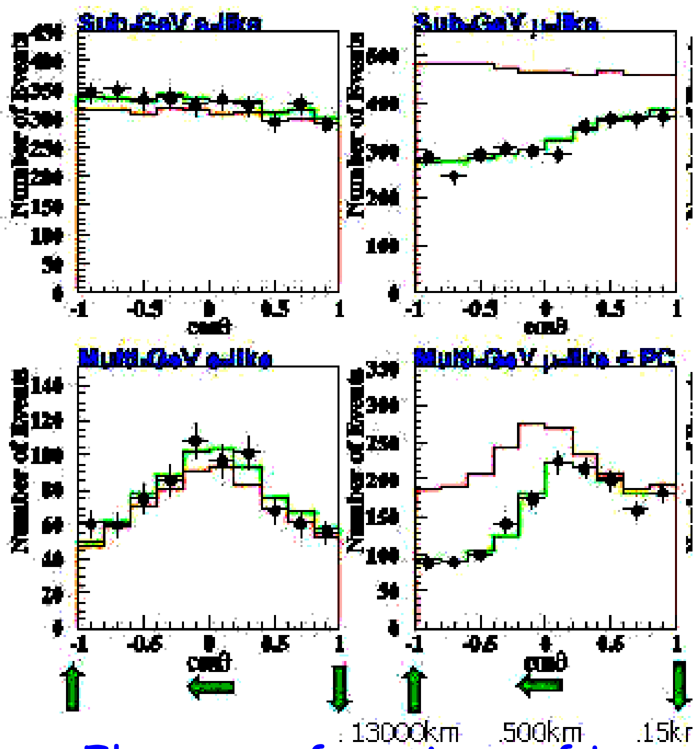
1 ktona, scyntylatora

KamLAND

How have we learned it? - 1

From the measurements of total neutrino fluxes, fluxes as functions of L, neutrino energy spectra and L/E distributions

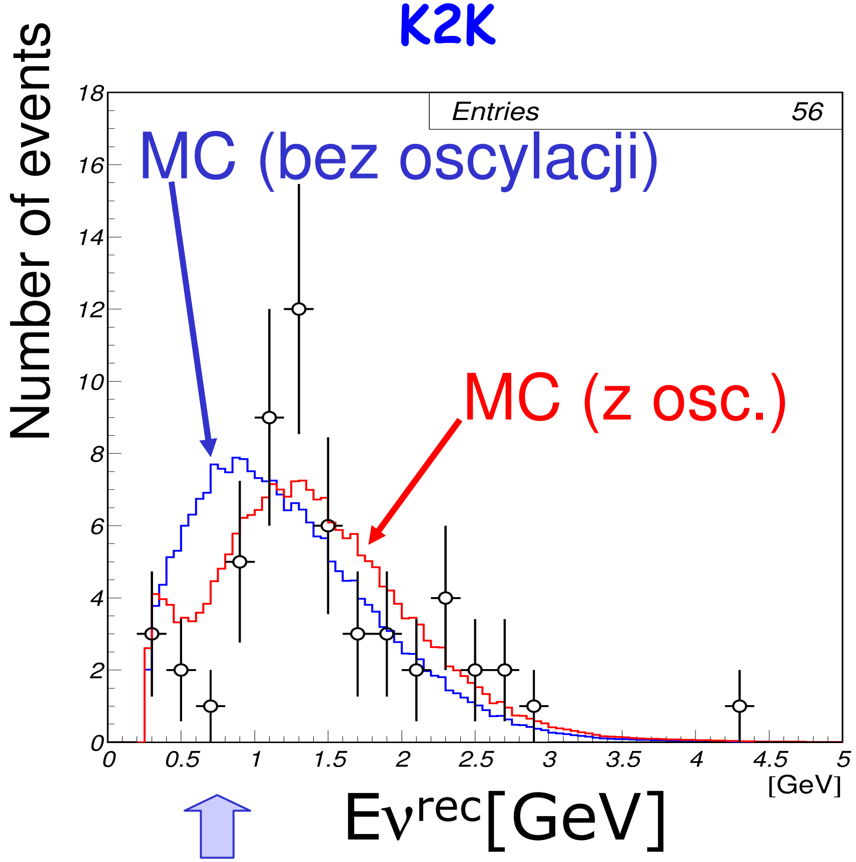
SuperKamiokande



Fluxes as functions of L

$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

K2K



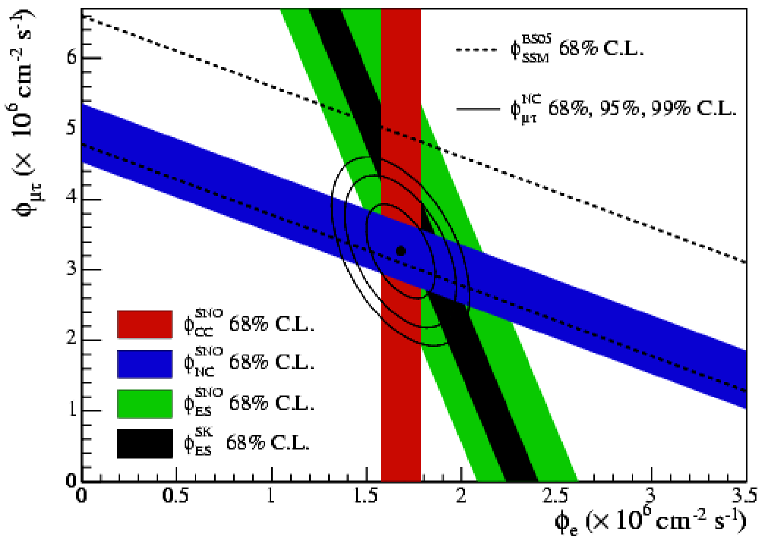
Modification of energy spectrum

Agreement with SuperKamiokande

How have we learned it? - 2

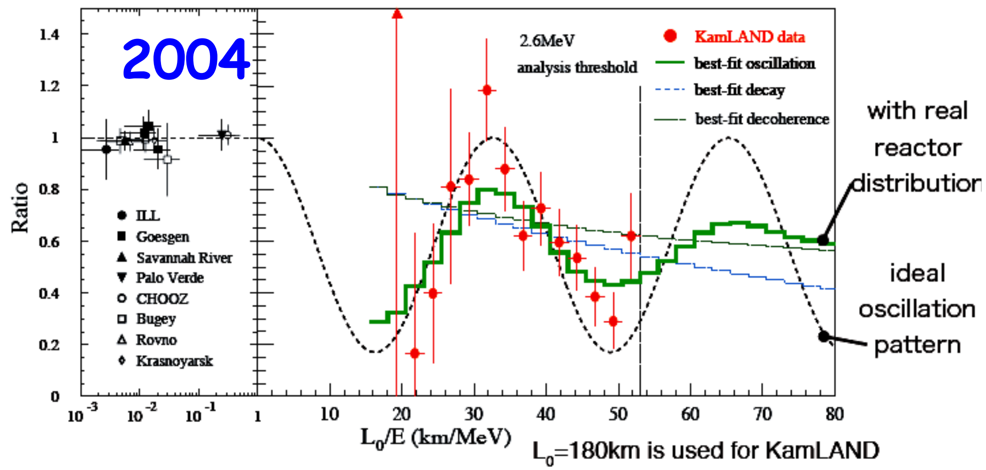
Good knowledge od fluxes and energy spectra before oscillations become visible is essential

SNO

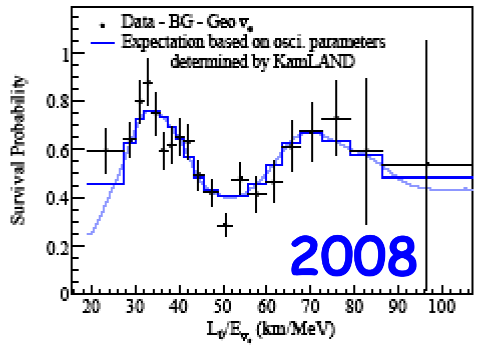


- Only ν_e's are produced in a core of Sun
- Solar neutrino puzzle: the total ν_e flux measured on the Earth is too small
- SNO measurement: the total neutrino flux ($\nu_e + \nu_\mu + \nu_\tau$) in agreement with the Solar Model → $\nu_e \rightarrow \nu_{\mu,\tau}$

KamLAND



Oscillatory behaviour of the $\overline{\nu}_e$ flux as a function of L/E



Neutrino oscillations now

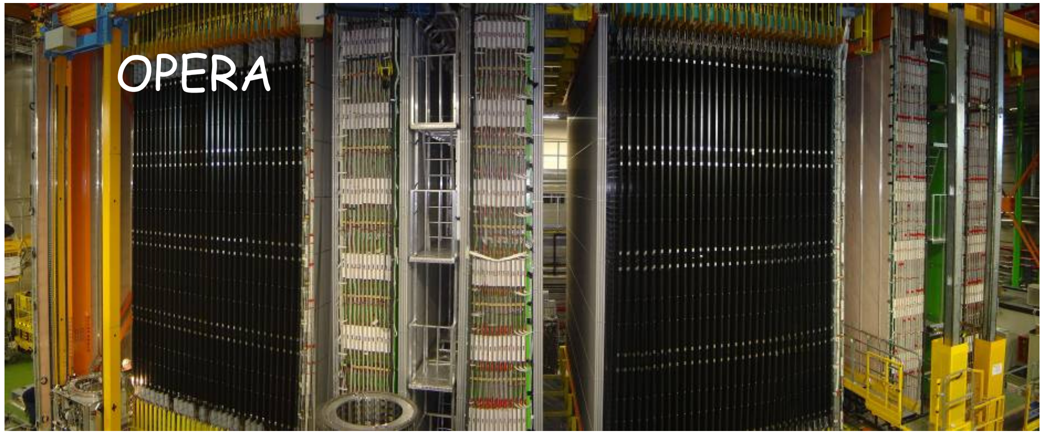
from 2003 onwards – fighting for precision

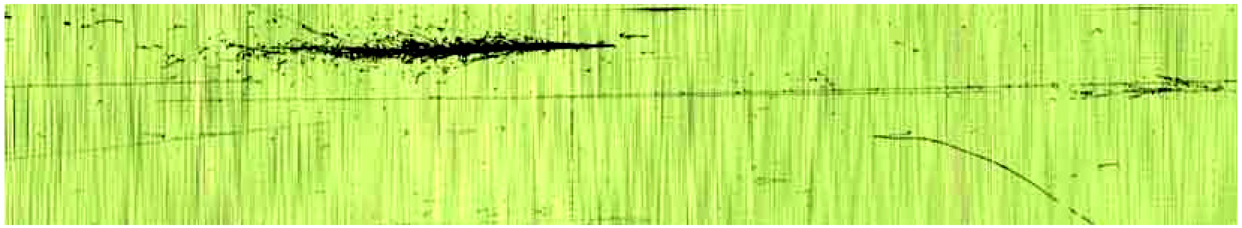
• New LongBaseLine accelerator experiments: MINOS at the NuMI ν_μ beam from FNAL to Soudan, measuring ν_μ disappearance; OPERA and ICARUS, searching for ν_τ appearance in the initial CNGS ν_μ beam from CERN to Gran Sasso,
• Medium Base Line accelerator accelerator experiment MiniBooNE at FNAL
• New solar neutrino experiment: Borexino

Detectors at the NuMI and CNGS beams

• MINOS – near and far detector, both in a form of sandwitches of magnetized iron and scintilators, running since 2005,
• OPERA – far detector with the sandwitched emulsion target (1.36 ktons) plus electronic spectrometer, test run in 2006, complete detector in June 2007,
• ICARUS - large TPC's filled with liquid Argon (600 t), start-up in a fall of 2007

MINOS

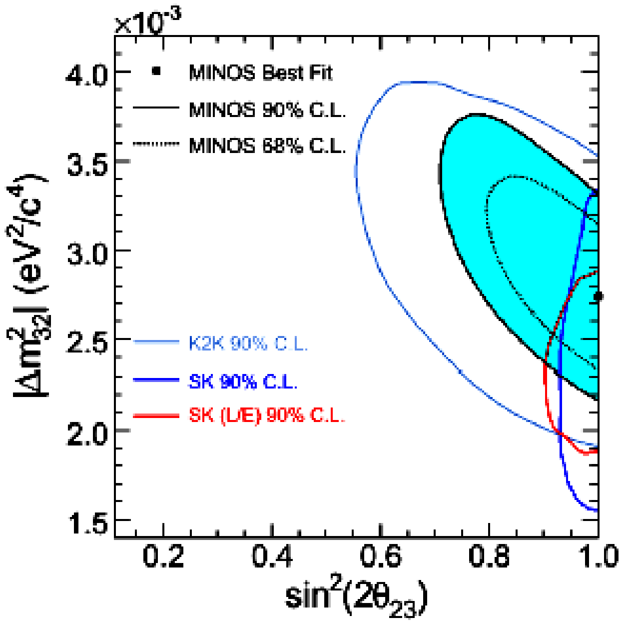




ICARUS – event from test run

Oscillations parameters

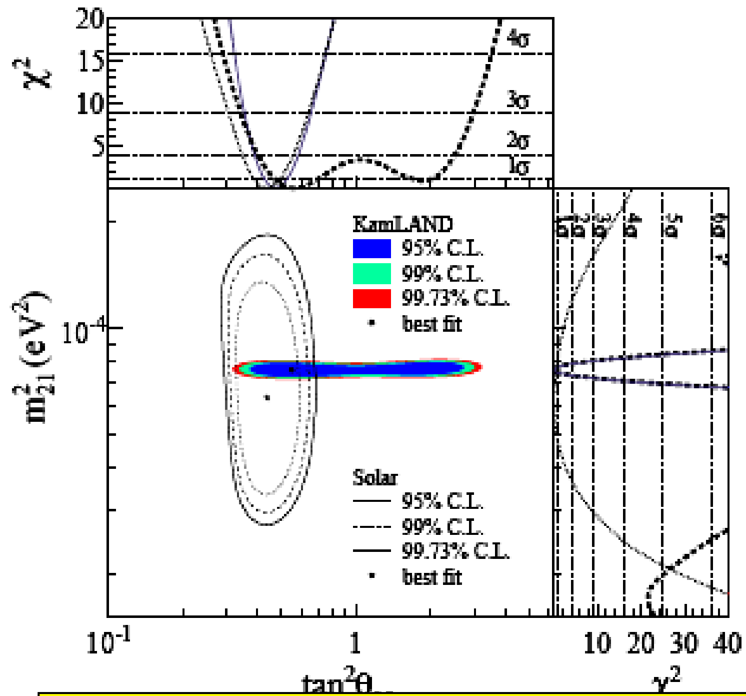
For three neutrino flavours and three mass states – there are six oscillation parameters: three mixing angles θ_{12}, θ_{23}, θ_{13}, two differences of mass squared Δm^2_{21}, Δm^2_{32} and one phase δ_{CP}



$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}(\text{stat}+\text{syst})\times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat}+\text{syst})$$

Constrained to $\sin^2(2\theta_{23}) \leq 1$



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

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

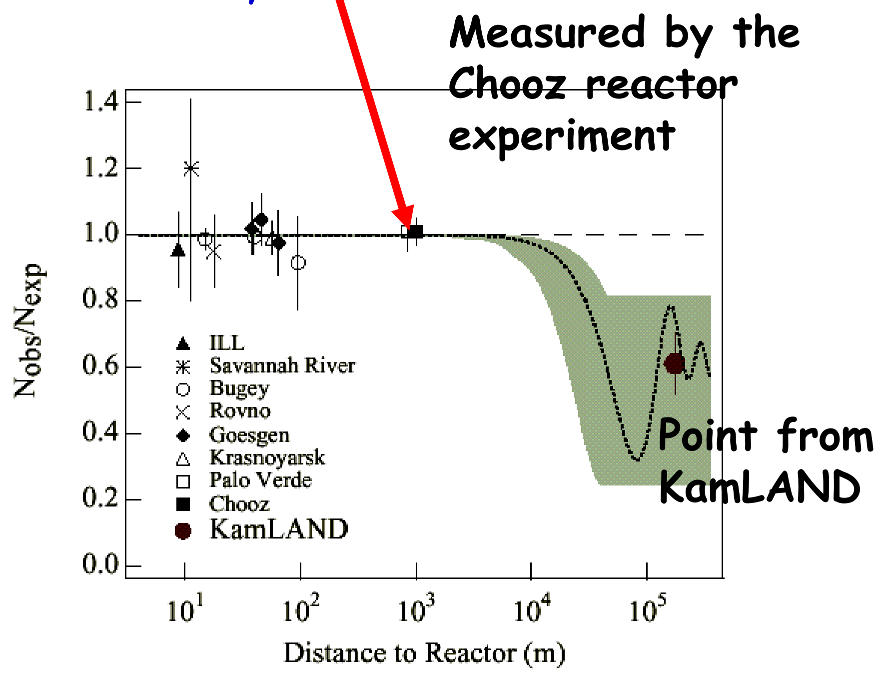
Oscillation parameters

The most probable values for the scheme with 3 ν flavours:

$\theta_{23} \approx 45^0$ (maximal mixing), $\theta_{12} \approx 34^0$ (large), $\theta_{13} < 13^0$ (small),

$|\Delta m^2_{32}| \approx 2.7 \times 10^{-3}\ eV^2$, $\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ eV^2$,

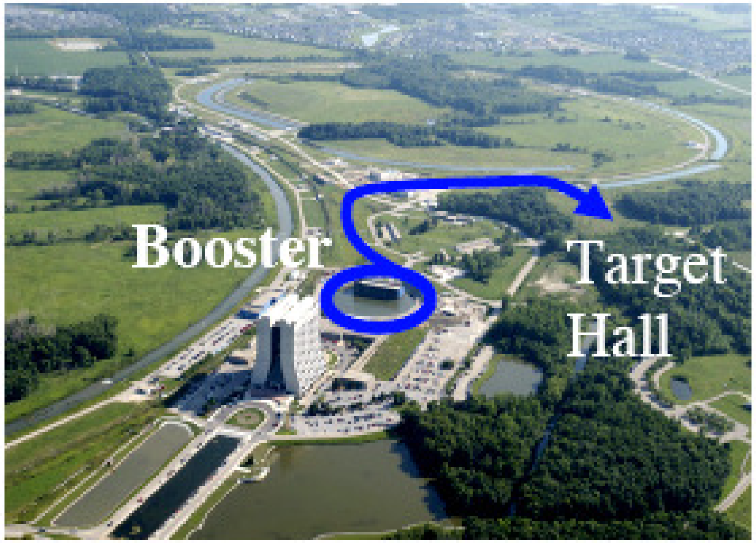
$|\Delta m^2_{31}| = |\Delta m^2_{32} - \Delta m^2_{21}|$



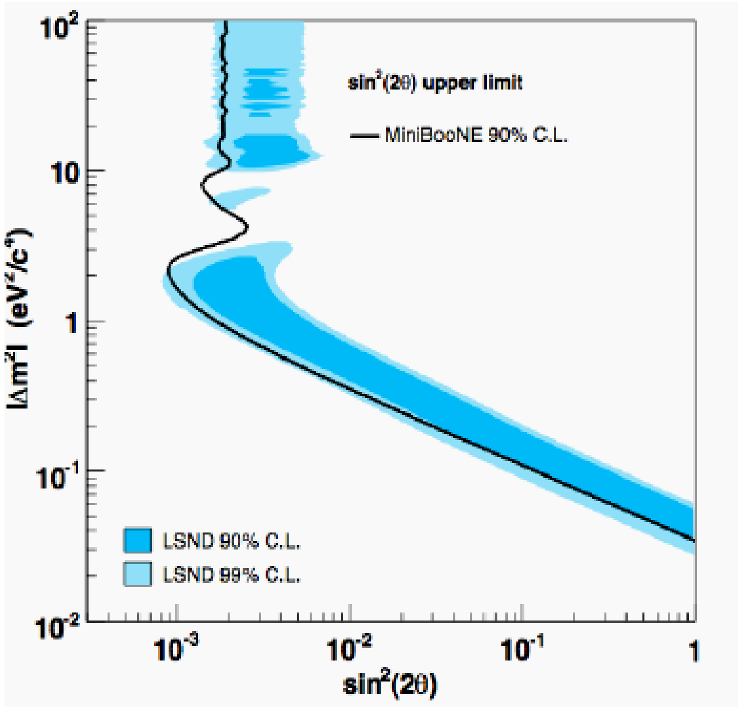
One more thing we know about oscillations

There is no need for extra ν species (sterile neutrino(s)):

It is the result of the MiniBooNE experiment, searching for the $\nu_\mu \leftrightarrow \nu_e$ oscillations for $L/E \approx 1$: L = 500 m, E ≈ 500 MeV (published in 2007), exclusion of the so called LSND effect.



Another neutrino beam at FNAL



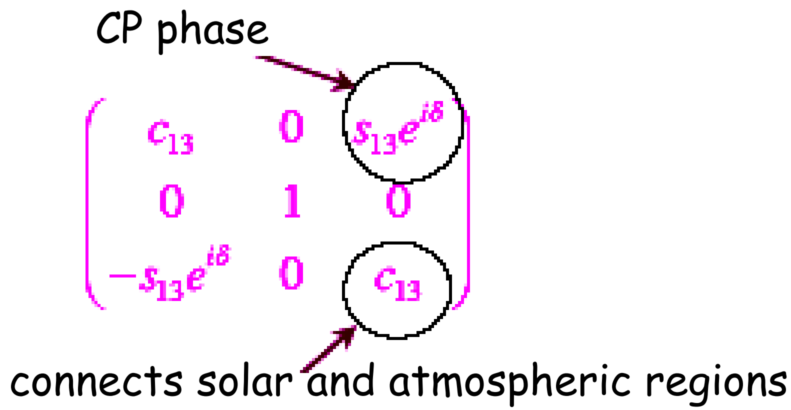
χ^2 probability equal 93% for the hypothesis of no oscillations

Neutrino oscillations - questions

How close to 45^0 is θ_{23}?

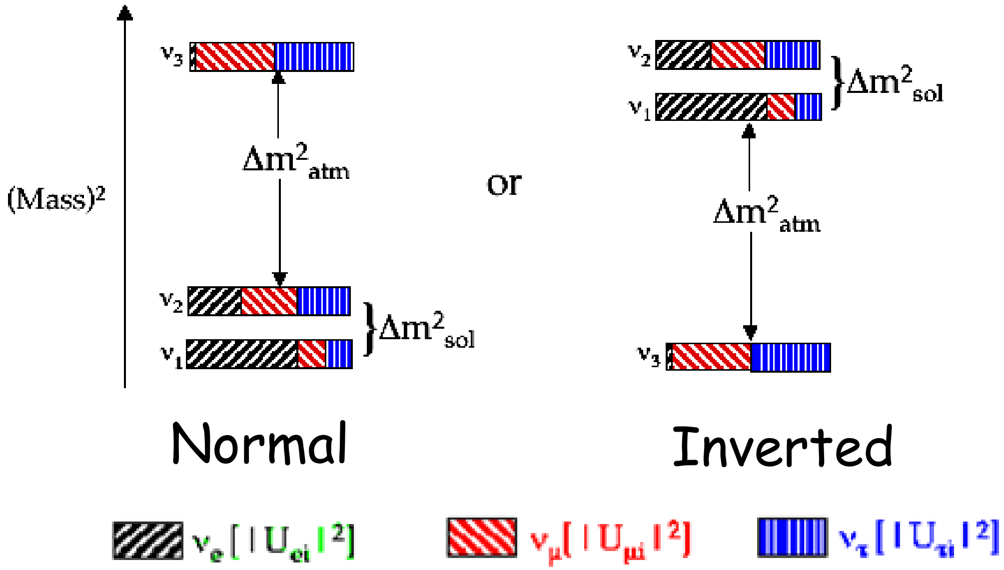
How small is θ_{13}? - first priority

Is CP violated for neutrinos?



Is there a new symmetry of Nature hidden behind the scheme of neutrino mixing?

Which is the hierarchy of neutrino masses?



How to better measure θ_{13}?

Phase I

By searching for $\nu_\mu \leftrightarrow \nu_e$ (and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$) in LBL accelerator experiments: T2K, (NOνA) – very complicated analysis because $P(\nu_\mu \to \nu_e)$ depends on all oscillation parameters (correlations + degeneracies) but due to that it offers a possibility to measure also sign of Δ^2_{32} (mass hierarchy) and δ_{CP} (if θ_{13} is not too small) – one needs, however, measurements at different distances and to use both ν_μ and $\bar{\nu}_\mu$ beams

By measuring $\bar{\nu}_e$ disappearance in the new generation reactor experiments DoubleChooz and Daya Bay with two (DCh) or eight (DB) detectors at two (DCh) or three (DB) distances from reactors to significantly reduce systematic uncertaintes related to $\bar{\nu}_e$ flux, cross section and reactor thermal power – pure measurement of θ_{13}

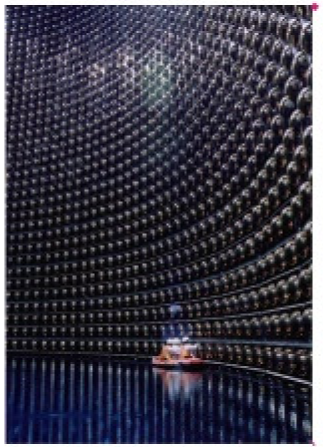
$$1 - P_{\bar{e}\bar{e}} \cong \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(\alpha^2)$$

T2K (Tokai to Kamioka) experiment

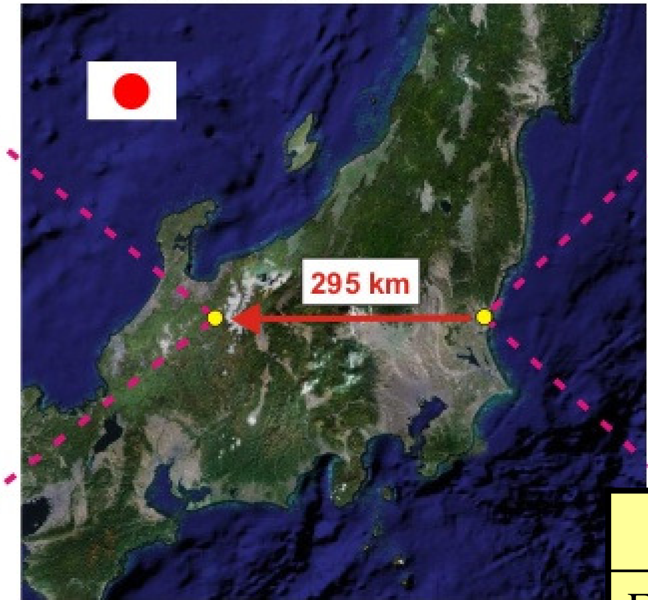
T2K (start in 2009) – very intensive neutrino beam (first superbeam) due to very intensive proton beam from the new synchrotron at JPARC, off-axis configuration of the detectors (kinematical squeezing of the neutrino energy spectrum),

ND280 near detector – a complex magnetic spectrometer,
the SuperKamiokande detector as a far detector

Super Kamiokande
50,000 tons of water
10,000 phototubes



Neutrino beam directed across Japan



Tokai accelerator complex and
location of near detector (ND280)

	T2K	K2K
E(GeV)	50 (30 @t=0)	12
Int.(10^{12}ppp)	330	6
Power(MW)	0.75	0.0052

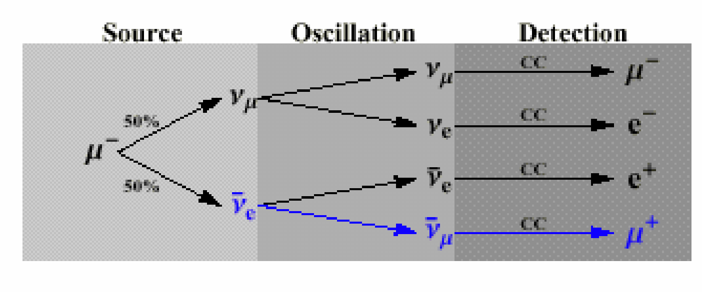
Amount of initial protons essential!

Further future of the $\nu_\mu \leftrightarrow \nu_e$ studies

Phase II:

New sources of neutrinos based on new types of accelerators

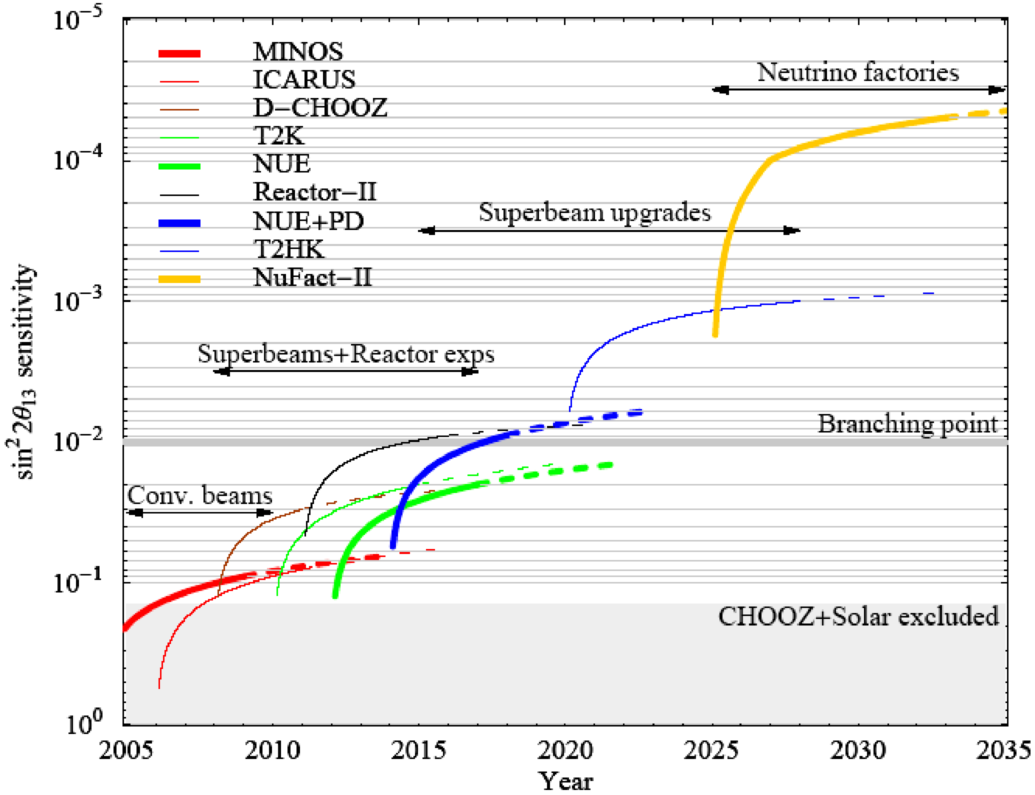
Neutrino factories



β beams - neutrinos (antineutrinos) from accelerated ^{18}Ne (^6He)

and before that still

Superbeams (ν_μ's from π, K decays) but based on proton beams of up to 4 MW power



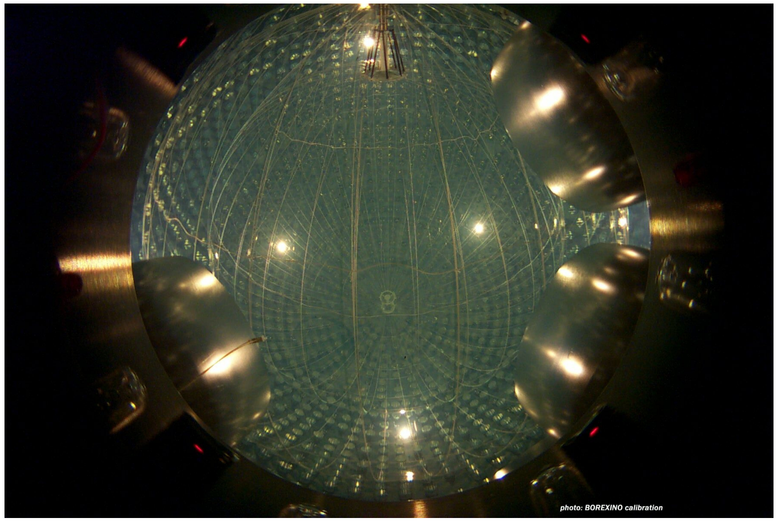
Astrophysics of low energy neutrinos

Neutrino astronomy of the Sun,

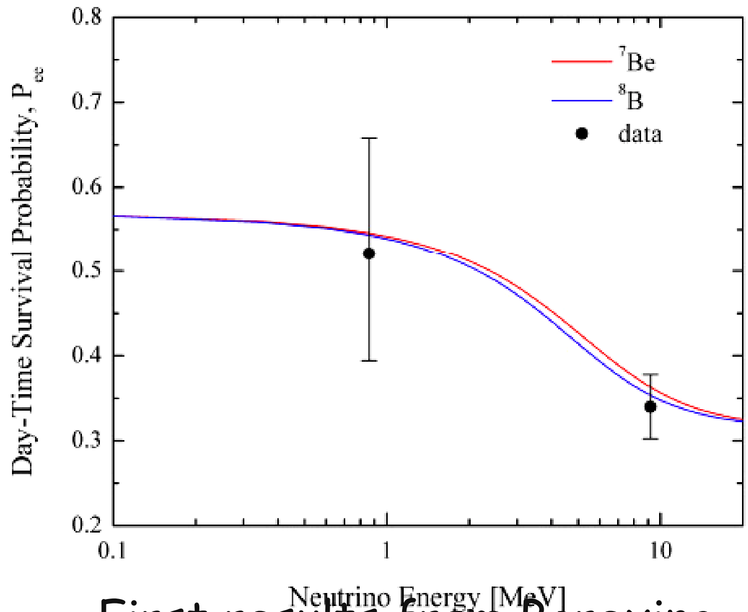
e.g. measurement of the flux of pep neutrinos and of neutrinos from the CNO cycle will be possible in the Borexino experiment (neutrino energy threshold below 0.9 MeV)

Neutrinos from SN explosions

to understand mechanism of the SN gravitational colappse



The Borexino detector filled
With scintillator – 15.05.2007

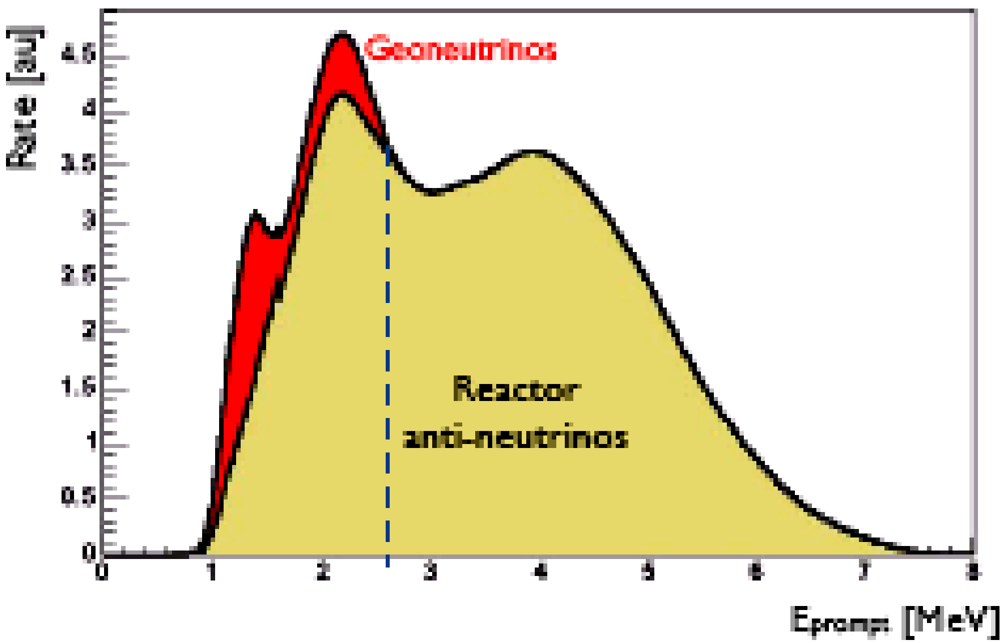


First results from Borexino

Geoneutrinos in KamLAND

• Antineutrinos from ^{238}U, ^{232}Th and ^{40}K allow to study the mechanism of heat generation inside Earth

• KamLAND is the first experiment sensible enough to measure neutrinos from U and Th decays



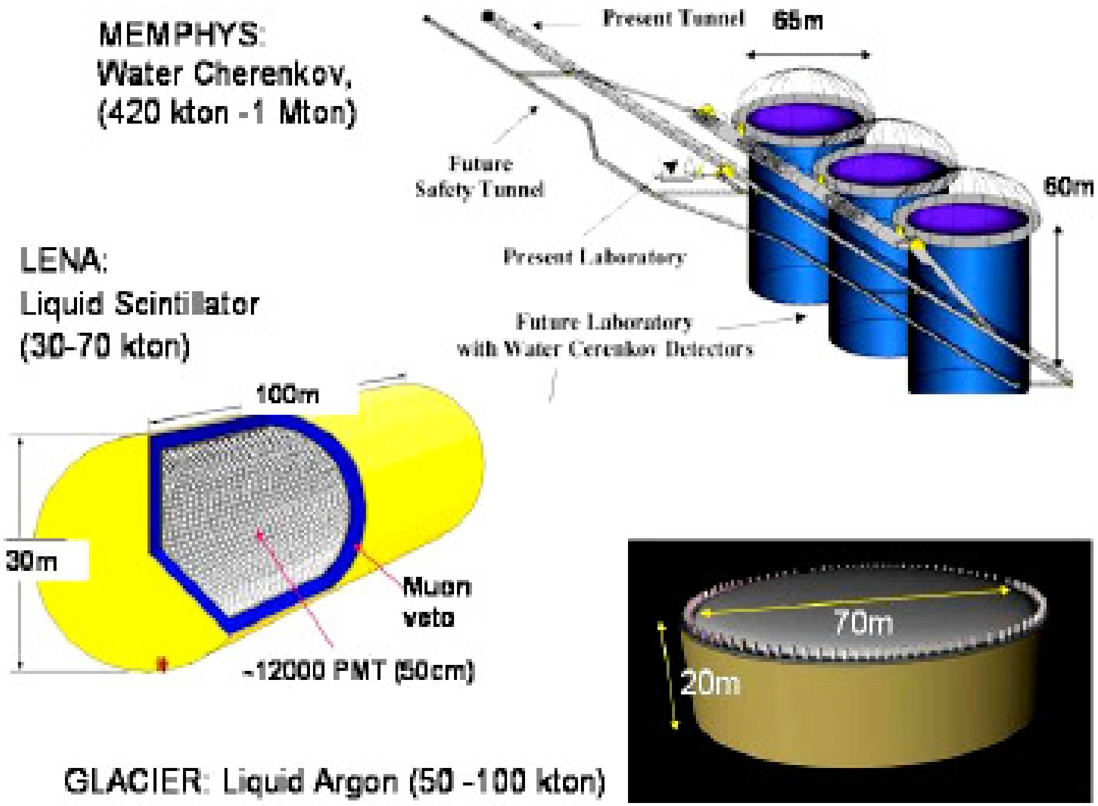
The present limit from KamLAND on a heat from radioactive decays from U and Th < 60 TW (as compared to the estimate of 31+-1 TW)

T.Araki et al., Nature 436 (2005) 467

Much better results will come from the Borexino experiment

Future of the studies of low energy neutrinos-1

Huge detectors of a total mass of 100 ktons – 1 Mton,
e.g. in the European LAGUNA project three types of the detector techniques are considered: water Cherenkov detector (MEMPHYS), liquid Argon detector (GLACIER) and scintillator detector (LENA)

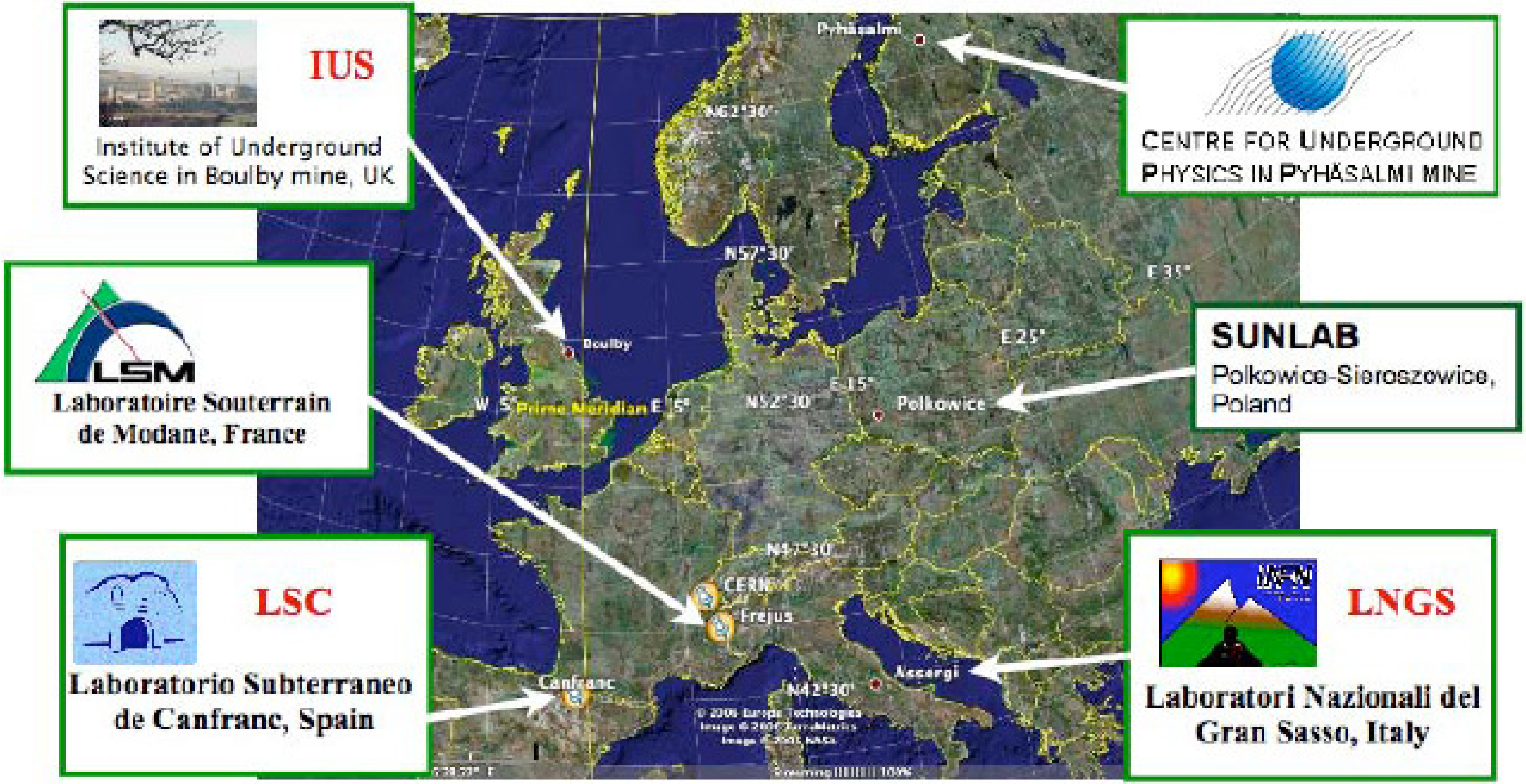


But also searches for proton decays with ~10 times higher sensitivity !!!

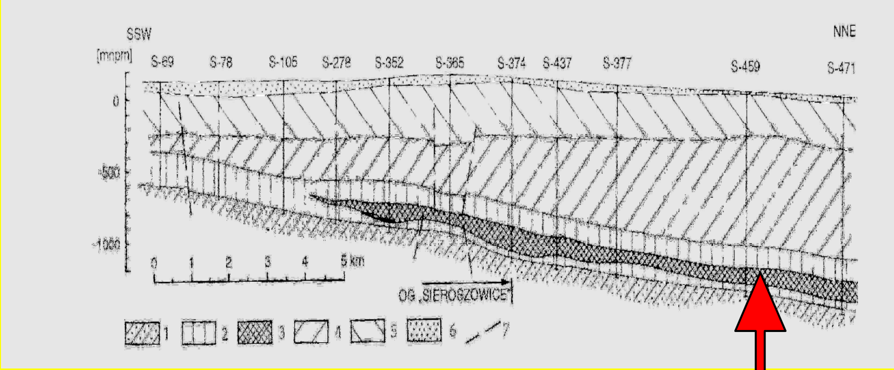
Future of the studies of low energy neutrinos-2

New underground laboratory(-ies) to host such detectors

e.g. in the European LAGUNA project feasibility studies will be performed for seven potential localizations



SUNLab – Sieroszowice Underground Laboratory?



Geological cutoff – salt

Existing big chamber in salt:

- volume: 85 x 15 x 20 m^3
- at a depth ~950 m from the surface
- very low humidity, temperature ~35^0

Measurements of the wall movements

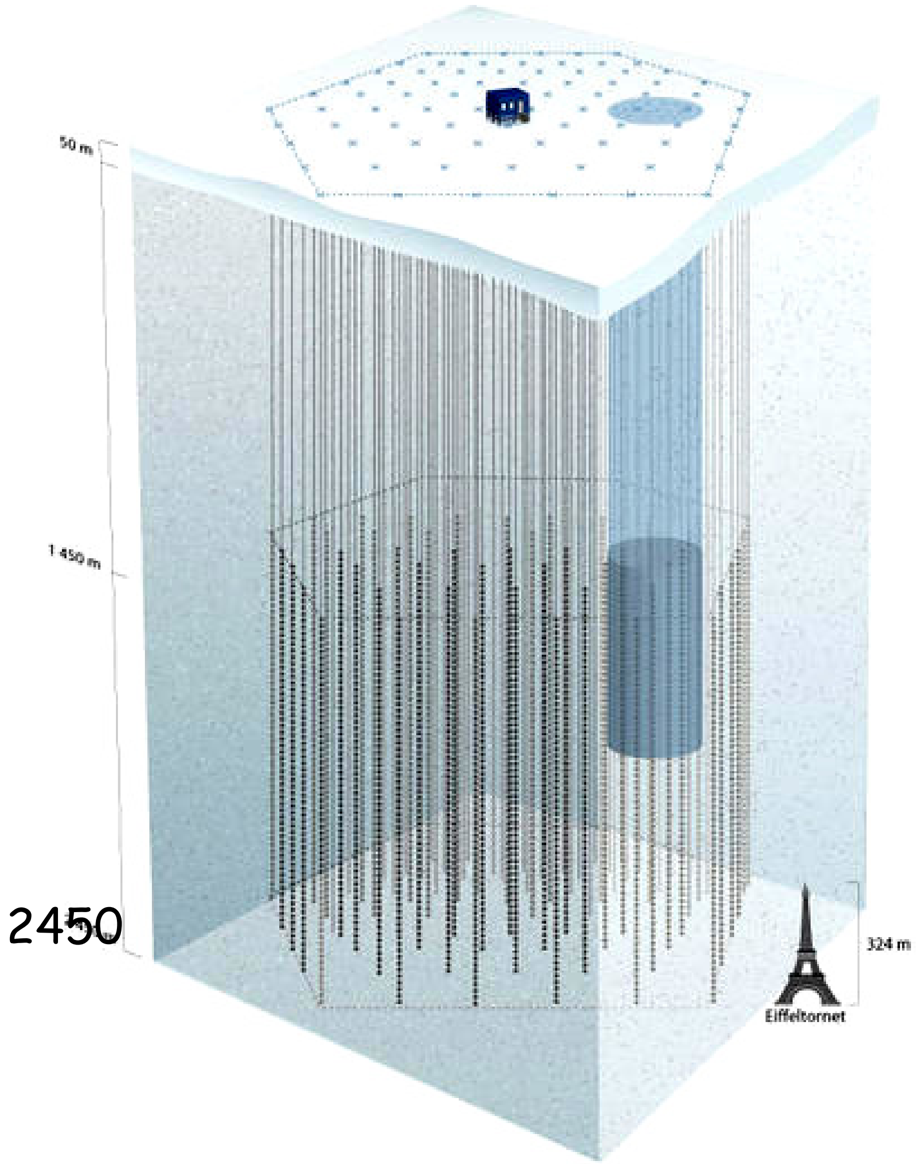
Very low background due to natural radioactivity of the rock

Very high energy neutrinos

Do they exists?
Where do they come from?

It is a part of the experimental program realized with big volume detectors **(1 km^{3}scale)**
based on a detection of Cherenkov radiation in ice
Icecube (pioneered by AMANDA)
- ν's from the northern hemiphere, energy range (10^{11} – 10^{21}) eV

or deeply in a sea water
Antares, Nestor, Nemo (pioneered by Baikal)
- ν's from the southern hemisphere



Big open questions in neutrino physics

which cannot be solved by oscillation experiments:

What are the masses of neutrinos?

Are they Majorana or Dirac particles?

Direct measurements of the ν_e mass based on the end-point of electron energy spectra in beta decays

The best measurement from the end-point of the tritium β decay (2.2 eV limit at present, 0.2 eV in a few years from the KATRIN experiment)

Cosmological limits

Resent cosmic microwave background measurements by the Wilkinson Microwave Anisotropy Probe (WMAP) together with different survey experiments give upper limits for a sum of masses of different neutrino species typically below 1 eV but they are model dependent

Measurements based on the lifetime measurements for the neutrinoless double beta decays

Potentially the most sensitive method for the mass determination but neutrino must be the Majorana particle

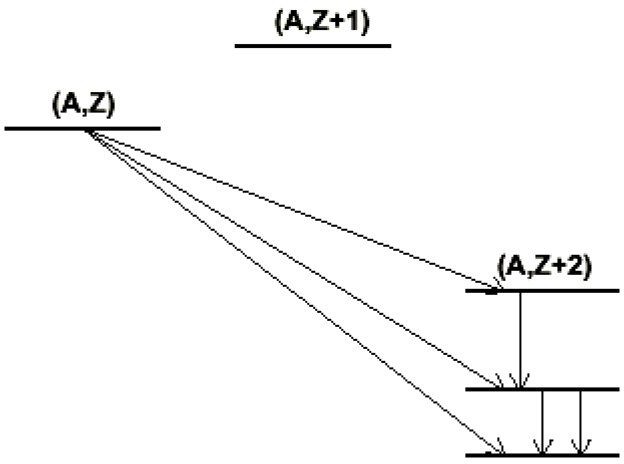
Double beta decay primer

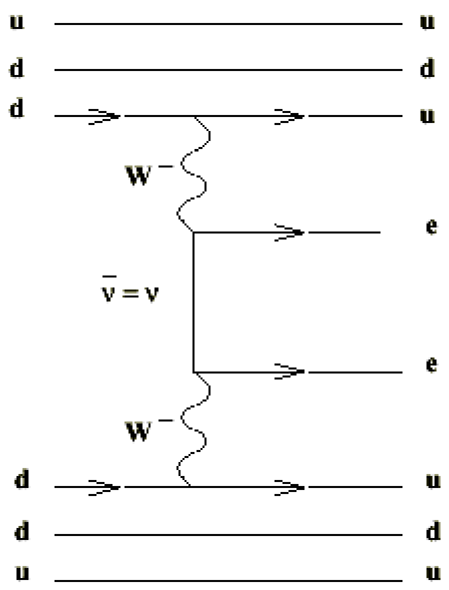
For some even-even nuclei the decay chain

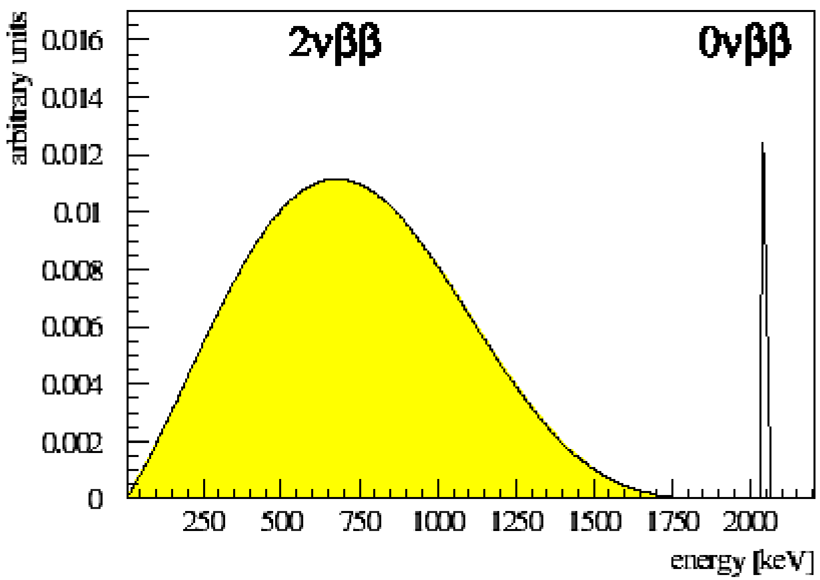
$$(A,Z) \rightarrow \quad (A,Z+1) + e^- + \overline{\nu}_e$$
$$\hookrightarrow (A,Z+2) + e^- + \overline{\nu}_e$$

is forbidden by energy conservation and one could have

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$$
$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$







Double beta decay

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_\nu \rangle^2$$

$|M^{0\nu}|^2$ The nuclear matrix element

$\langle m_\nu \rangle^2$ effective neutrino mass $\langle m_\nu \rangle = \sum_k \phi_k m_k U^2_{e,k}$

nucl-ex/0410029

Ultimate goal of experiments: sensitivity ~10 meV

Many sophisticated experiments in preparation – always important:

- background reduction
- isotopic enrichment
- good energy resolution

Isotope	$T^{0\nu}_{1/2}$ (y)	References	$\langle m_\nu \rangle$ (eV)
^{48}Ca	$> 1.4 \cdot 10^{22}$	[[77]]	$< 7.2 - 44.7$
^{76}Ge	$> 1.9 \cdot 10^{25}$	[[40]]	< 0.35
^{82}Se	$> 2.7 \cdot 10^{22}$ (68%)	[[43]]	< 5.0
^{100}Mo	$> 5.5 \cdot 10^{22}$	[[83]]	< 2.1
^{116}Cd	$> 1.7 \cdot 10^{23}$	[[89]]	< 1.7
^{128}Te	$> 7.7 \cdot 10^{24}$	[[58]]	$< 1.0 - 4.4$
^{130}Te	$> 5.5 \cdot 10^{23}$	[[85]]	$< 0.37 - 1.9$
^{134}Xe	$> 5.8 \cdot 10^{22}$	[[61]]	$< 17.0 - 27.0$
^{136}Xe	$> 1.2 \cdot 10^{24}$	[[61]]	$< 0.8 - 2.4$
^{150}Nd	$> 1.2 \cdot 10^{21}$	[[51]]	< 3.0
^{76}Ge	$(0.69 - 4.18) \cdot 10^{25}$	[[78]]	$0.24 - 0.58$
^{76}Ge	$1.19 \cdot 10^{25}$	[[78]]	0.44
^{82}Se	$> 1.4 \cdot 10^{23}$	[[82]]	$< 1.5 - 3.1$
^{100}Mo	$> 3.1 \cdot 10^{23}$	[[82]]	$< 0.8 - 1.2$
^{130}Te	$> 7.5 \cdot 10^{23}$	[[86]]	$< 0.3 - 1.6$

0νββ signal in the Moskow-Heidelberg experiment?

First announcement in 2002, new publication in 2004, based on the data collected between 1990 and 2003

Klapdor-Kleingrothaus Phys. Lett. B586 (2004) 198

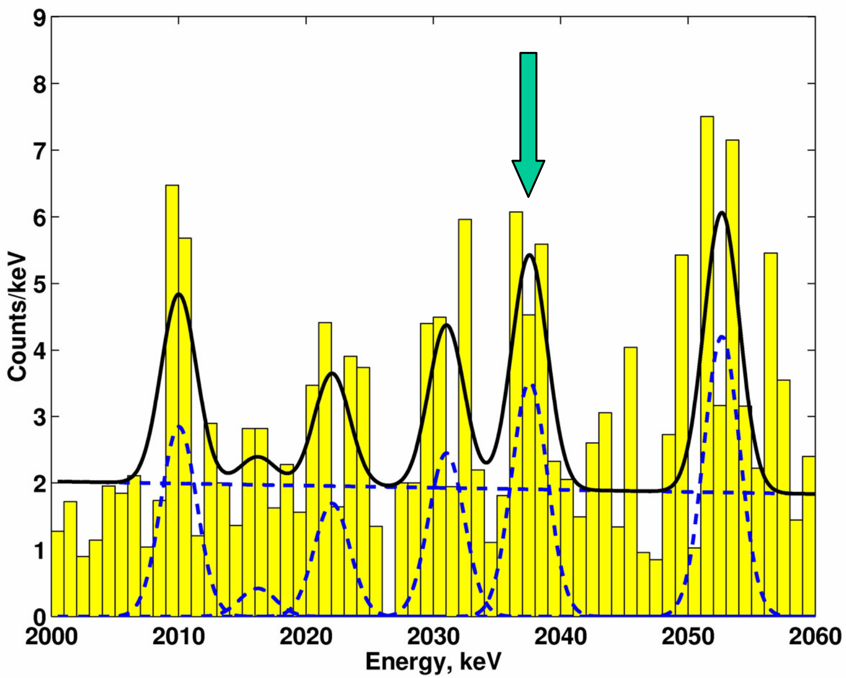


Fig. 31. The single site sum spectrum of the four detectors 2,3,4,5 for the period November 1995 to May 2003 (51.389 kg y), and its fit (see section 3), in the range 2000 - 2060 keV.

Maximum at 2039 keV

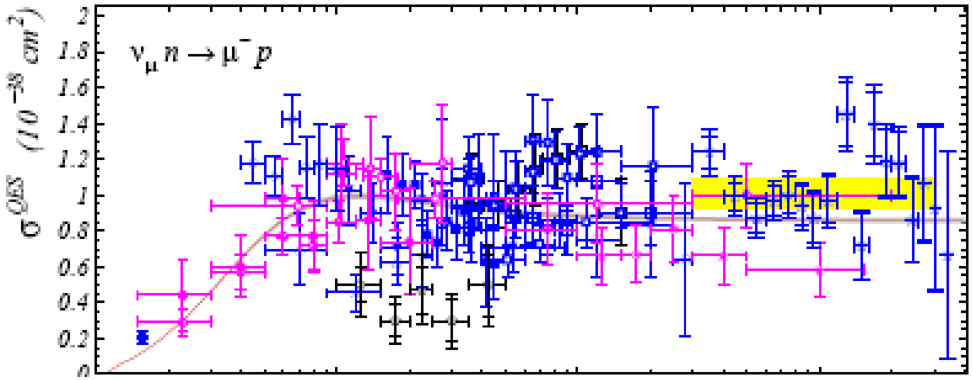
$T_{1/2} = 0.6\text{-}8.4 \times 10^{25}$lat

→ $m_\nu = 0.17\text{-}0.63$ eV

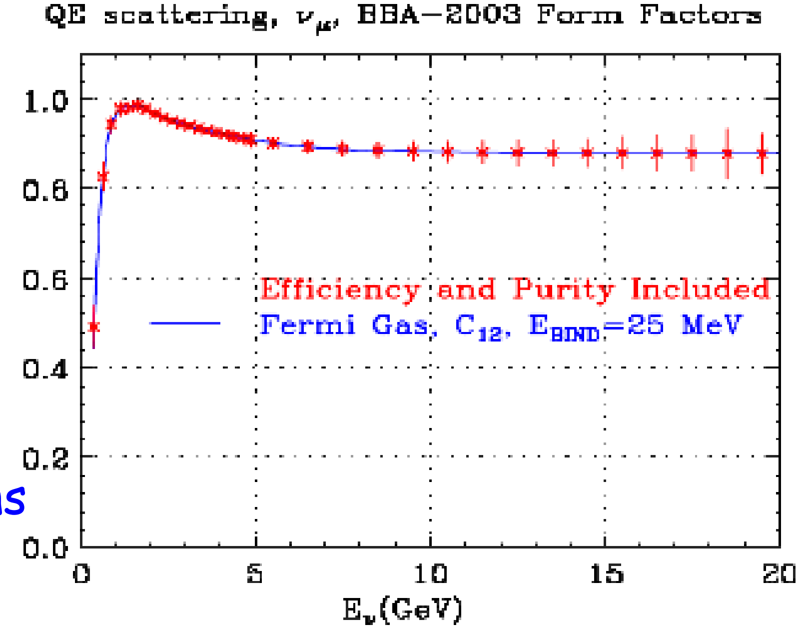
This result must be verified by another experiment, e.g. GERDA or NEMO3 should achieve the required sensitivity in a few years

Neutrino cross sections and nuclear effects

Very poor knowledge of neutrino cross sections – much better data from the MINERνA experiment in a few years



Present experimental status and simulations of the situation „after MINERνA"

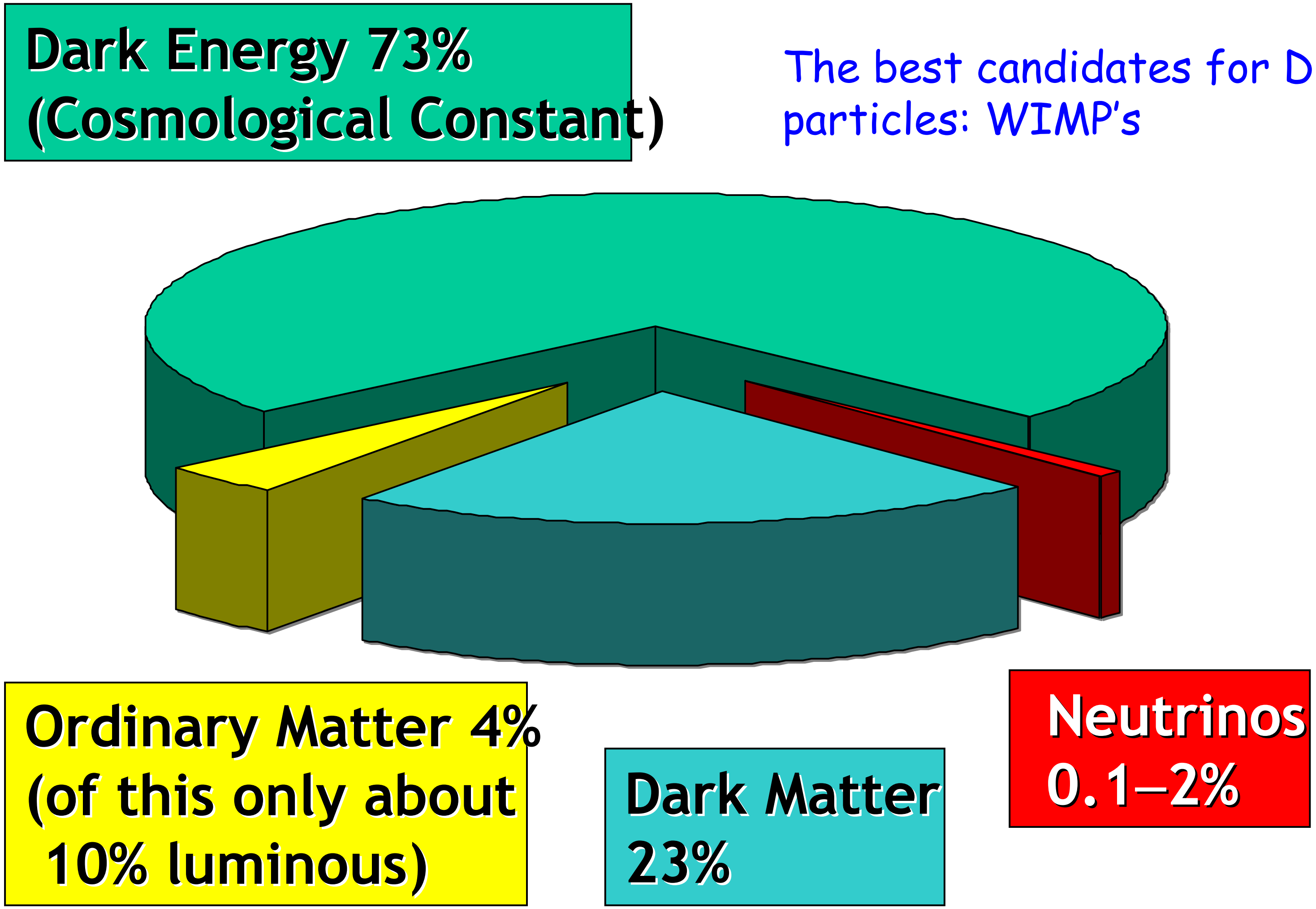


A better description of low energy neutrino interactions with nuclei are very much needed, the same for proton decay inside nucleus, a better knowledge of the nuclear matrix elements in the neutrinoless double β decays are really crucial. (Contributions from Polish theorists)

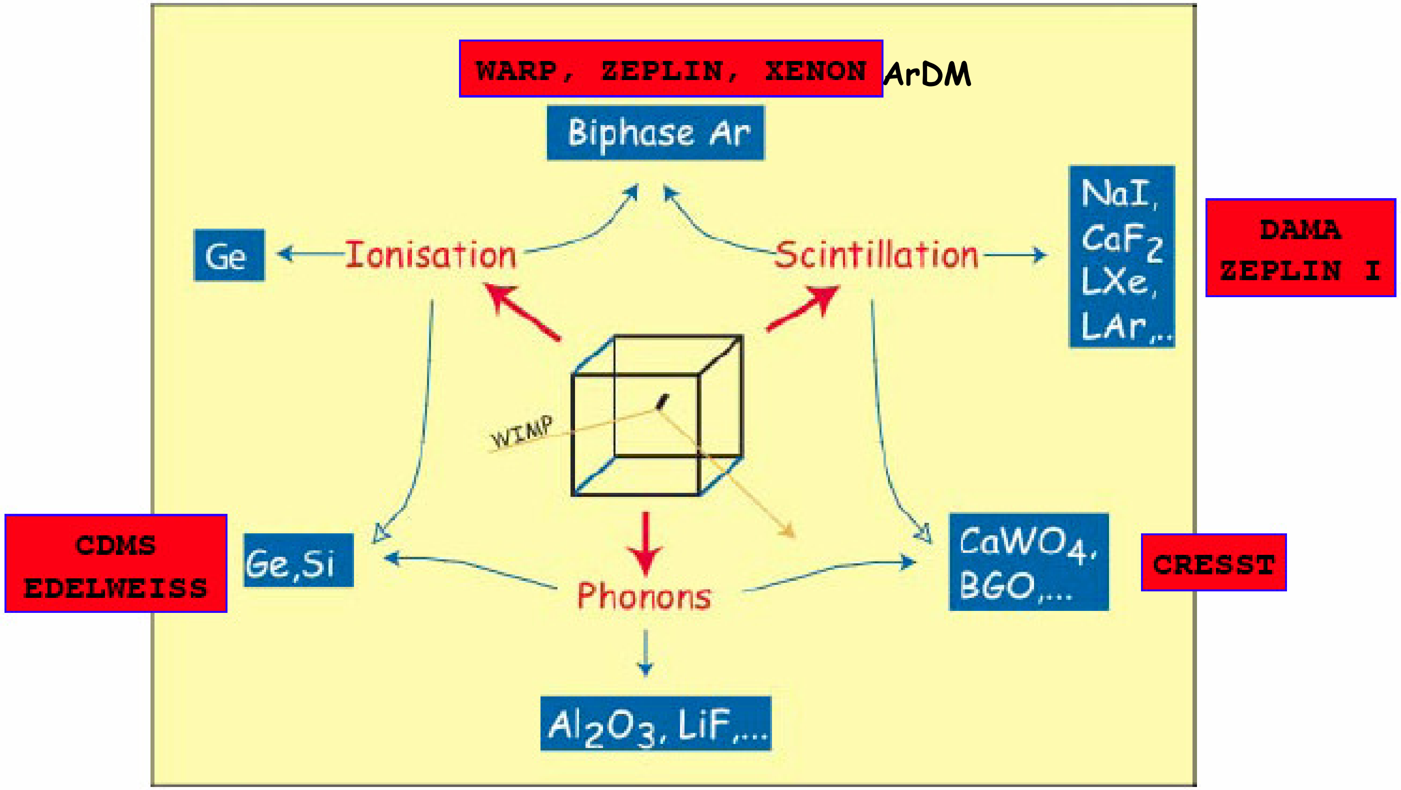
Dark Matter

Baryonic matter constitutes only ~5% of the Universe mass-energy;
About ~23% is non-baryonic, yet undetected (Dark Matter)

The best candidates for DM particles: WIMP's



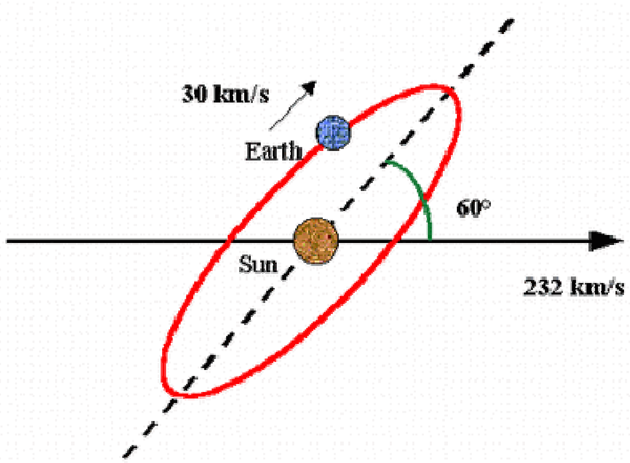
WIMP's - direct and indirect detection



Indirect detection of WIMP's, e.g. searches for neutrinos from the annihilation of WIMP's inside Earth, Sun,...

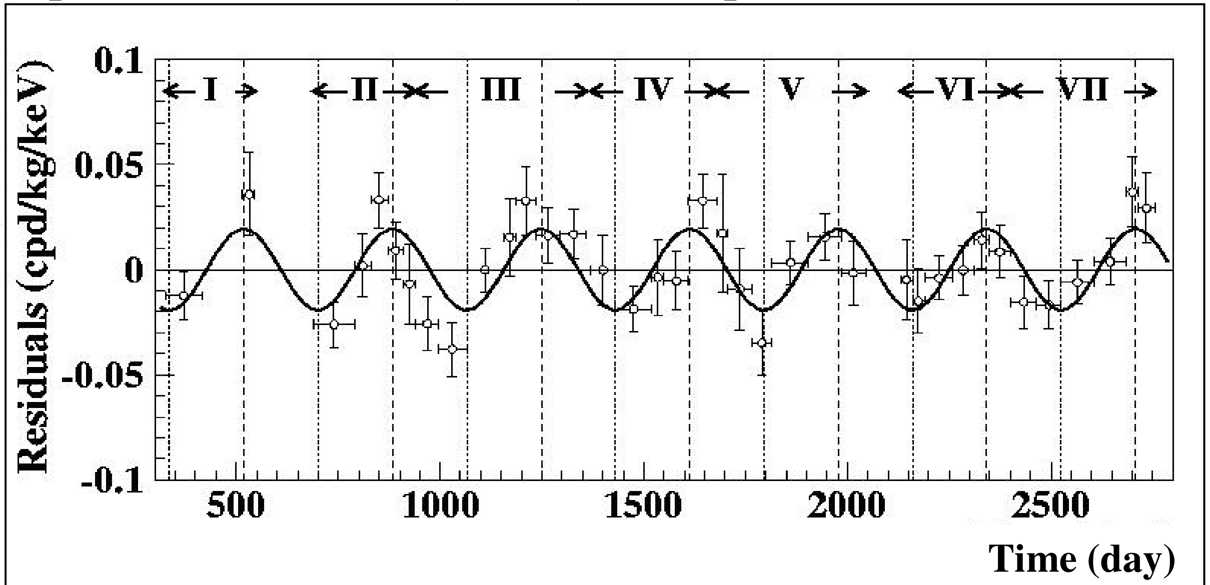
Controversy – has the DM signal been observed or not?

The DAMA experiment at Gran Sasso – claimed to observe annual modulation of signal at energies (2-6) keV



Signal maximal in June,
Minimal in December

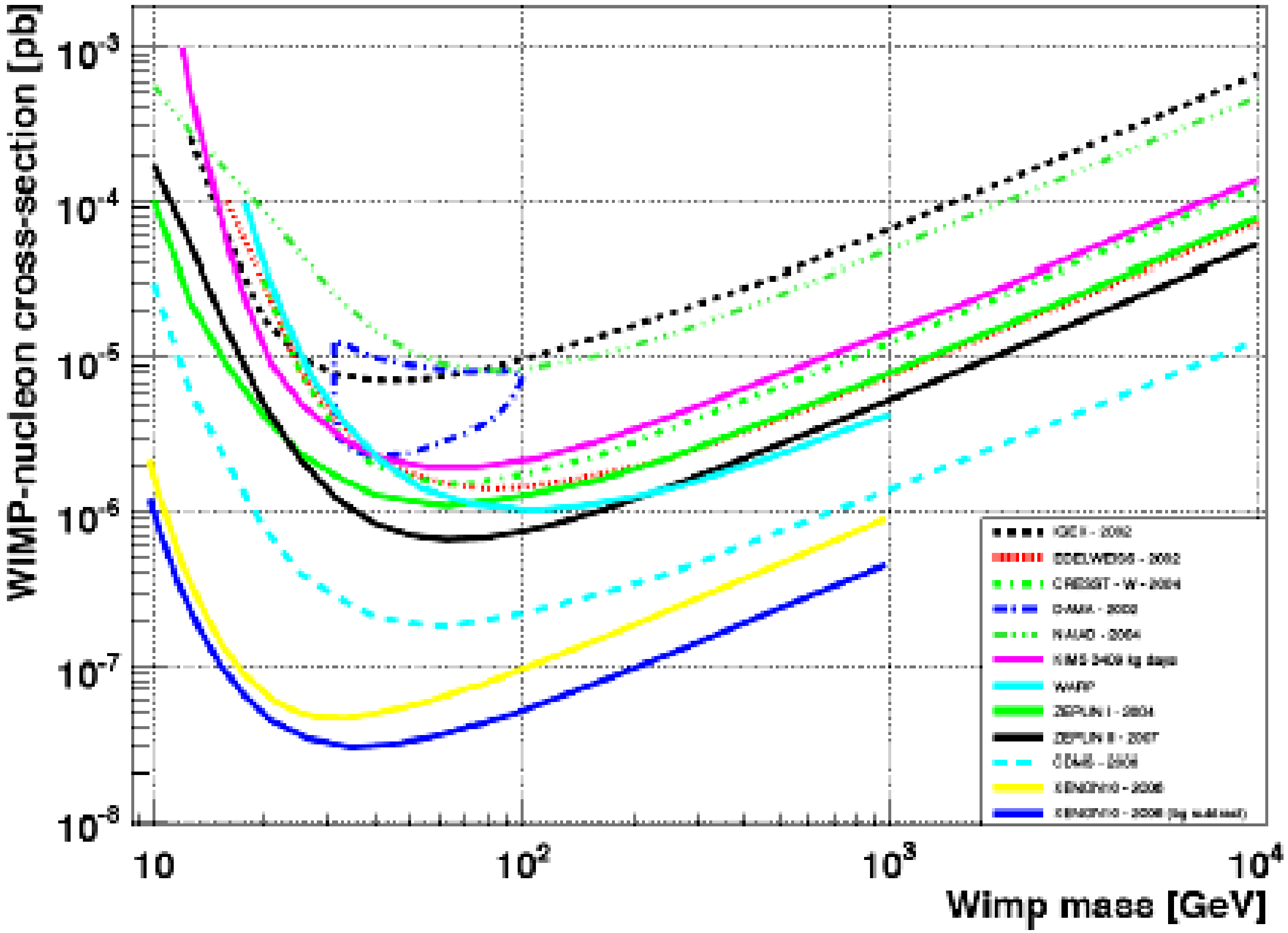
DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]



- Detector stability ?
- „Background stability“ ?

Controversy – has the DM signal been observed or not?

Other experiments exclude the parameter region of DAMA's

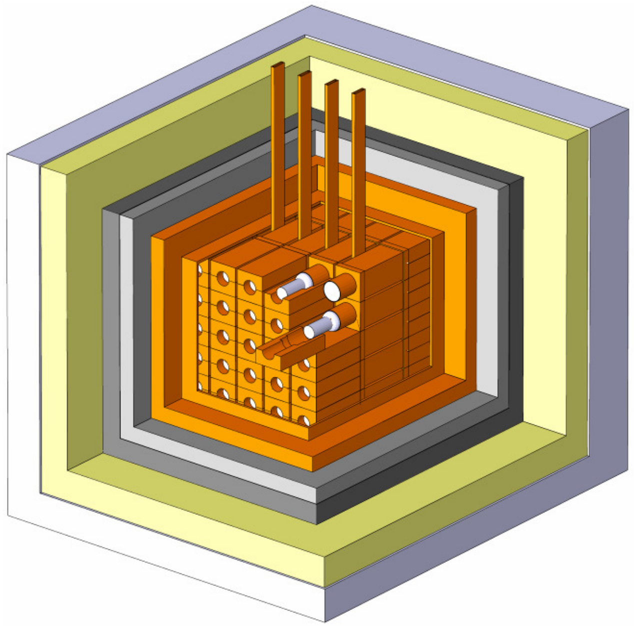


arXiv:0705.3345v1

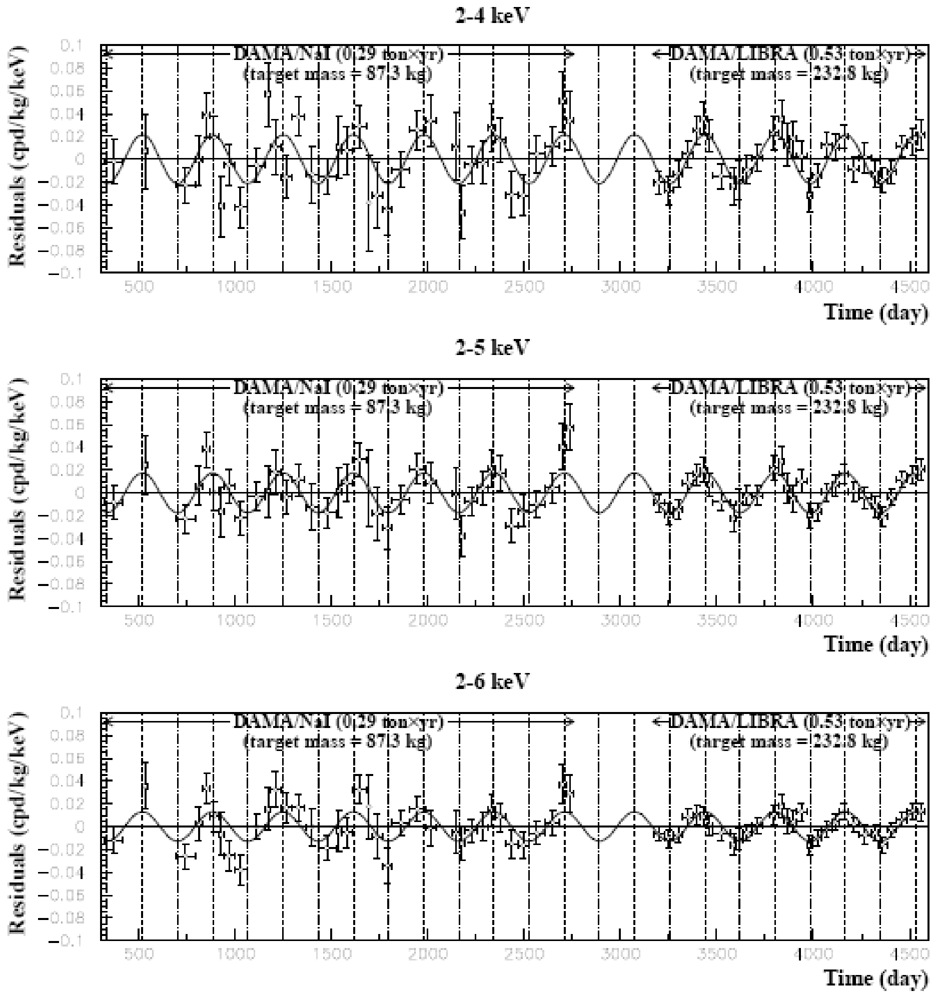
Recent results from DAMA/LIBRA

Four years of data taking, larger detector mass (250 kg of NaI)

DAMA results confirmed!



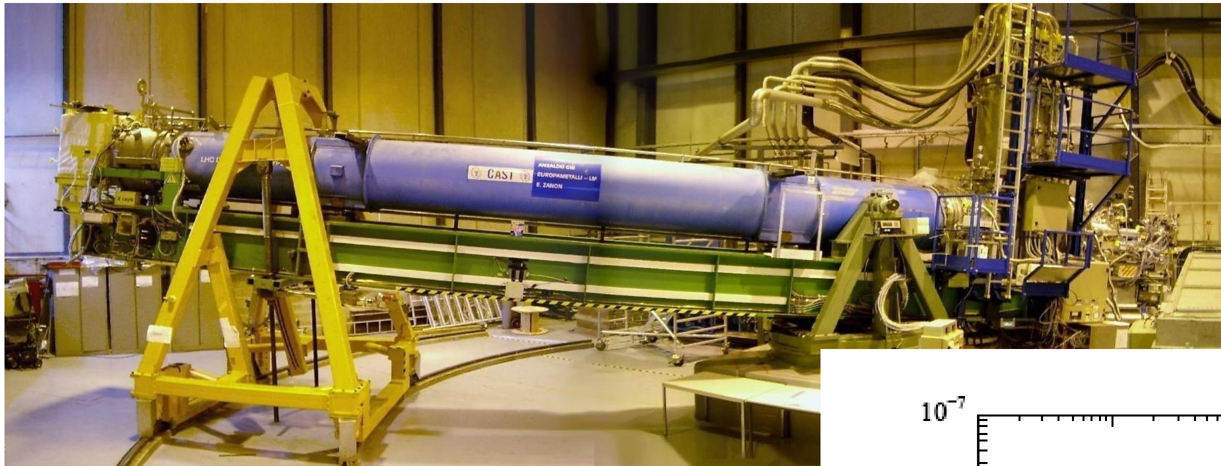
arXiv:0804.2741v1 – 17 April



LHC measurements are essential !

Axions – other candidates for DM

The CAST experiment at CERN looks for axions from Sun using the LHC prototype magnet

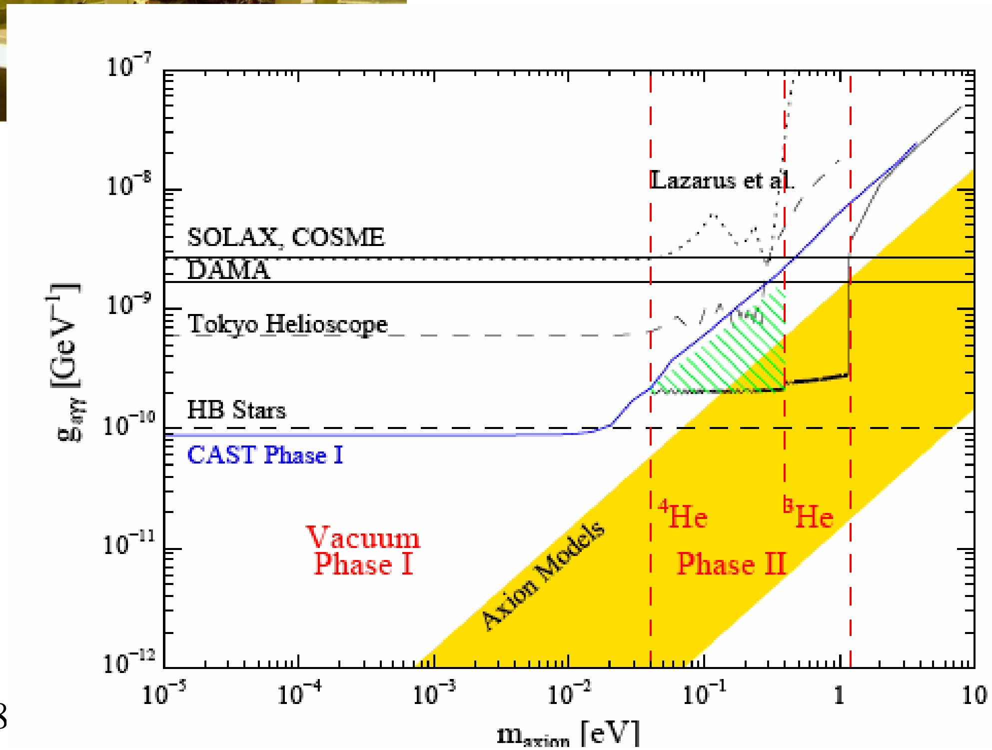


In electromagnetic field axions can produce photons via Primakoff effect

Axions were introduced to solve „strong-CP problem"
They couple to photons

$$L_{A\gamma\gamma} = g_{A\gamma\gamma}\,\mathbf{E}\cdot\mathbf{B}\ \phi_A$$

arXiv:0706.0637v1
the best exclusion limit at present



And why not to produce axions?

The OSQAR experiment at CERN – another LHC prototype magnet in use

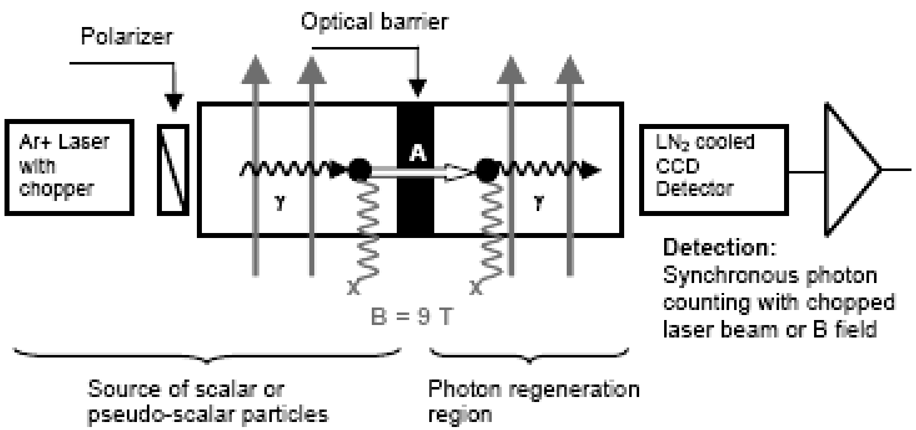
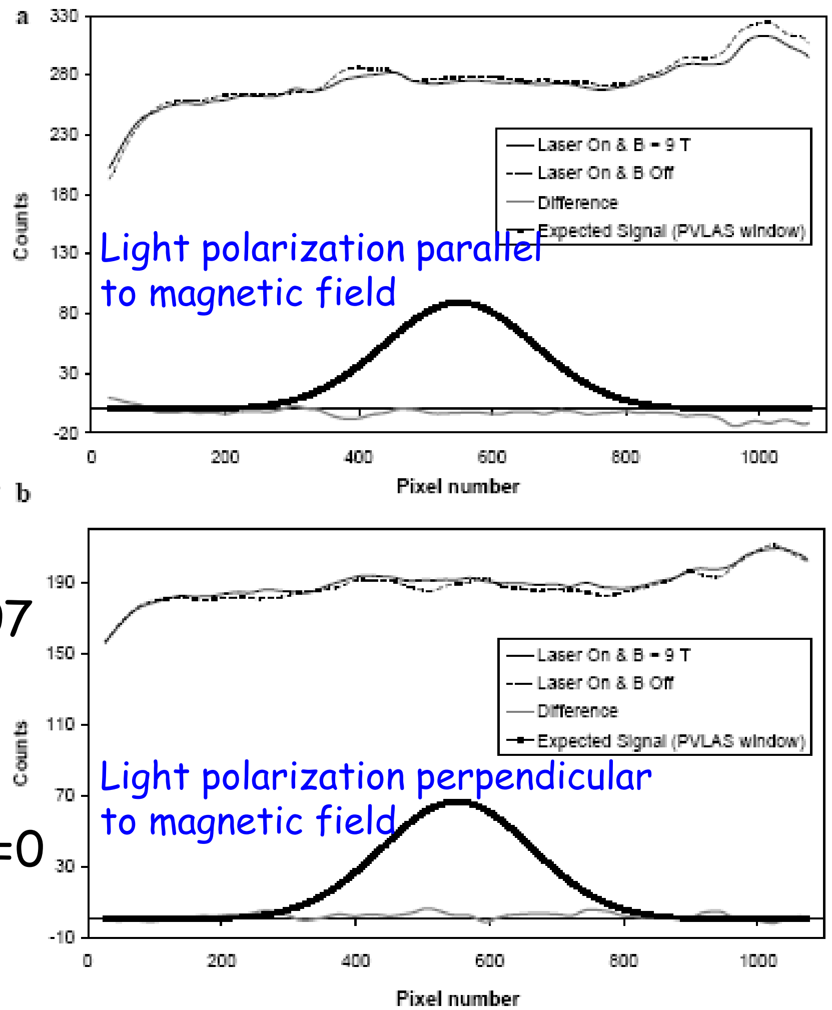


Figure 1 | Experimental set-up. Principle of the OSQAR photon regeneration experiment.



A few nights of data taking in autumn 2007

$$q \approx \frac{m_A^2}{2\omega} - (n-1)\omega$$

tuning n to realize coherence condition qL=0

→ probing various axion mass regions

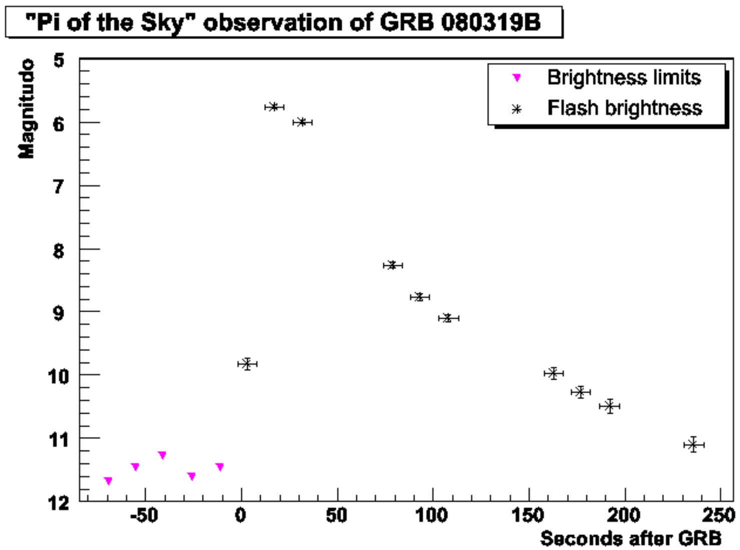
arXiv:0712.3362v1

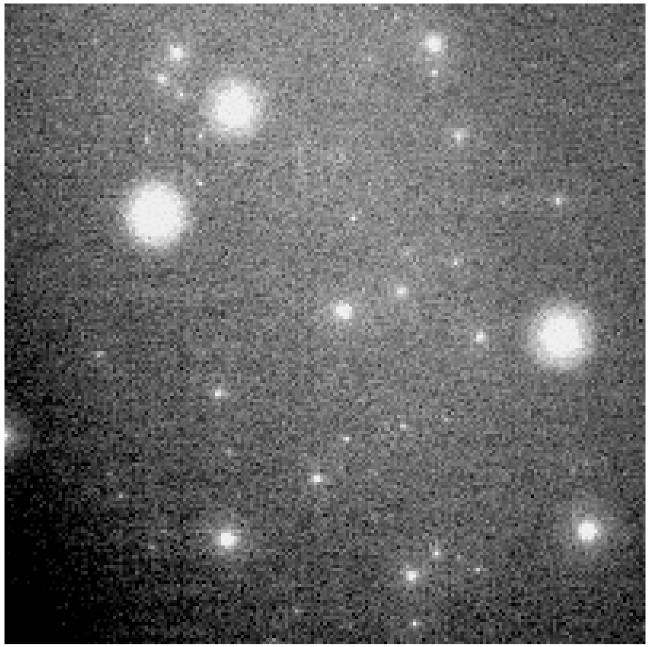
GRB's (Gamma Ray Bursts)

Intense (energy release of approximately 10^{52} ergs) and short (0.1 s – 100 s) bursts of gamma ray radiation which occur all over the sky approximately once/day in very distant galaxes

GRB 080319b – the brighest GRB ever seen, triggered and located by the Swift Burst Alert Telescope (BAT)

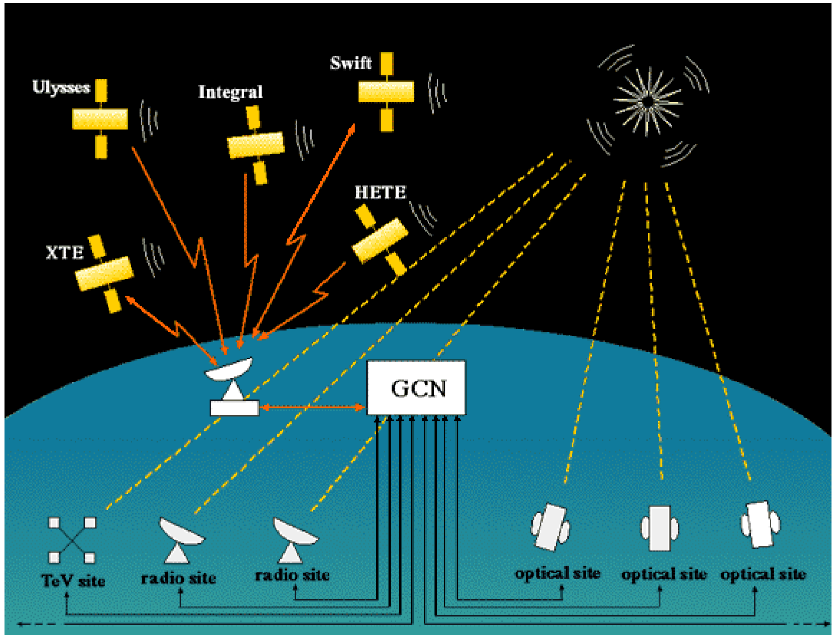
"Pi of the Sky" apparatus located at Las Campanas Observatory imaged the region of GRB 080319b (Swift trigger 306757 at 06:12:49 UT) before, during and after the GRB with 10s exposures (IR-cut filter only). Optical emission was imaged at the position given by Swift XRT.



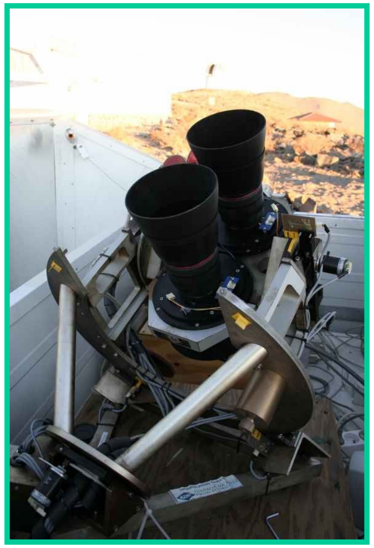


The „π of the Sky” experiment

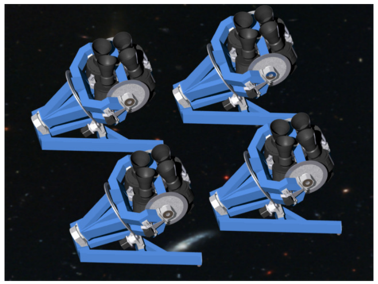
Participating institutions : Centrum Fizyki Teoretycznej PAN, Warszawa, Instytut Problemów Jądrowych, Warszawa i Świerk, Instytut Fizyki Doświadczalnej UW, Instytut Systemów Elektronicznych PW, Wydział Fizyki PW, Centrum Badań Kosmicznych PAN

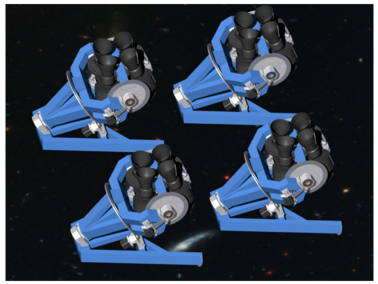


Gamma Ray Bursts Coordinates Network



Present prototype system, taking data in Chile





Full system (under construction)

Where are the Polish groups?

Neutrino physics:

SuperKamiokande (D.Kiełczewska since the very beginning), Gallex/GNO (M.Wójcik for many years),

ICARUS, T2K, MINOS Borexino, GERDA, NEMO3 and SuperNEMO (searches for neutrinoless double beta decays), LAGUNA

Dark matter searches: WARP and ArDM experiments (using Argon as the detector medium), OSQAR

„π of the Sky": an example that a good group of people can do valuable research even outside the big international collaborations

Conclusions

No doubt that the presented topics belong to the best of the XXI century physics

A nice feature is their interdisciplinary character between particle physics, astrophysics, cosmology and nuclear physics

Particle physics detectors and methodology of data analysis, introduced to astrophysics, helped to create a new branch of physics, which is the astroparticle physics

CERN is a catalyst for many activities in this field

The LHC results will be an important input for astroparticle physics

Future studies of neutrino oscillations will critically depend on the intensity of proton beams

Does the tiny neutrino mass (probably much smaller than 1 eV) reflect the existance of particles with masses unaccessible to studies at accelerators and of the yet undiscovered laws of Nature?