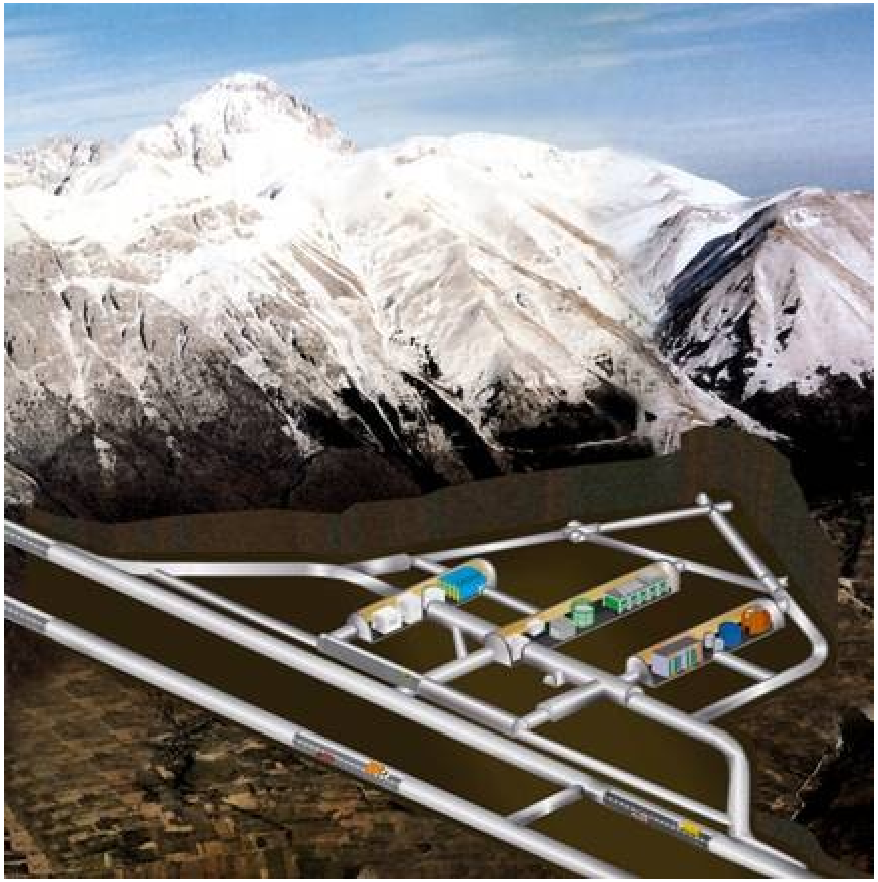
Gran Sasso National Laboratory

INFN
Laboratori Nazionali del Gran Sasso

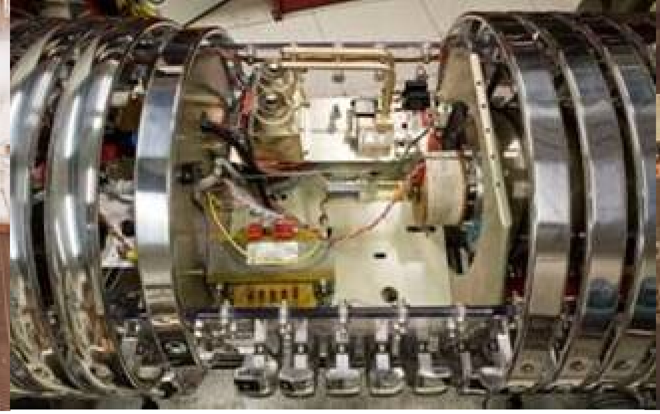
Gran Sasso National Laboratory

Research activities

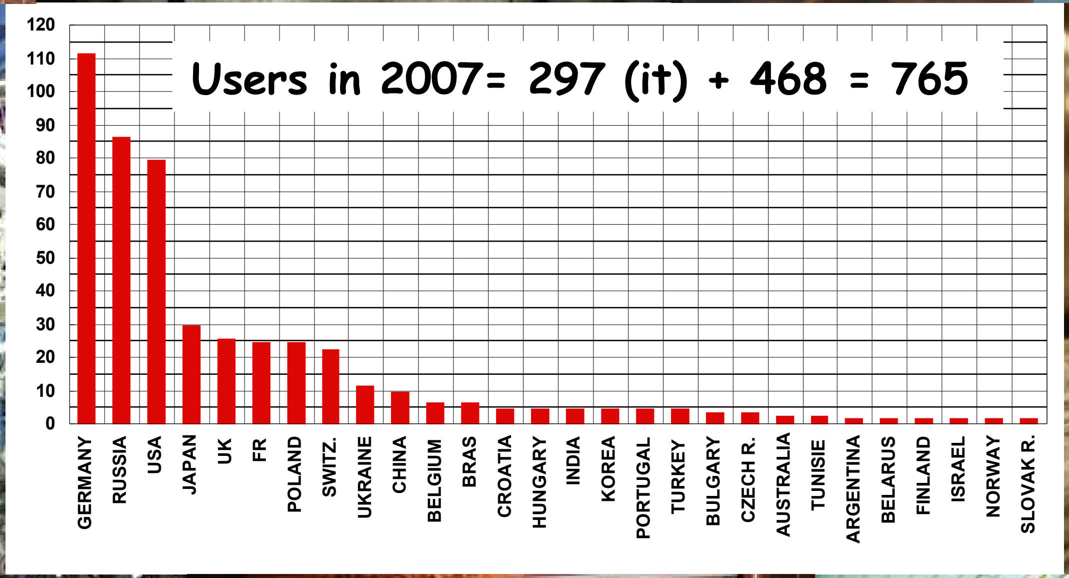
- Neutrino physics (OPERA, BOREXINO, ICARUS, LVD, GERDA, CUORE,COBRA)
- Dark matter (DAMA/LIBRA, WARP, XENON, CRESST)
- Nuclear reactions of astrophysics interest (LUNA)
- Fundamental Physics (VIP)
- Geophysics (ERMES, GIGS)
- Biology



- Opening: 1987
- 1400 m rock coverage
- Muon flux = $3.0 \times 10^{-4}\ s^{-1}\ m^{-2}$
- Experimental Area = 3 halls for about 17300 m^2
- Access: horizontal through the express way tunnel




Users in 2007= 297 (it) + 468 = 765
120
110
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GERMANY
RUSSIA
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BRAS
CROATIA
HUNGARY
INDIA
KOREA
PORTUGAL
TURKEY
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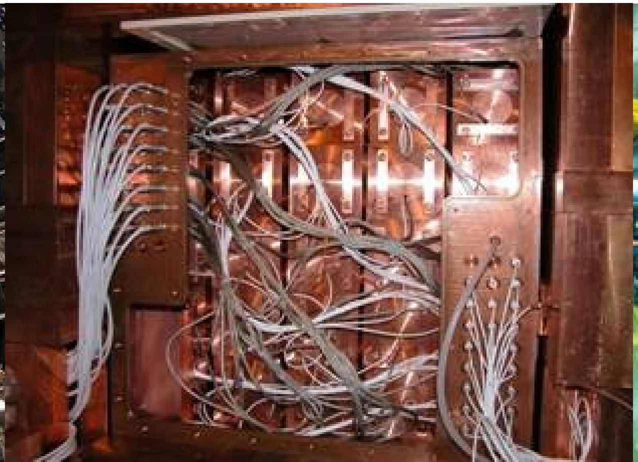
ISRAEL
NORWAY
SLOVAK R.

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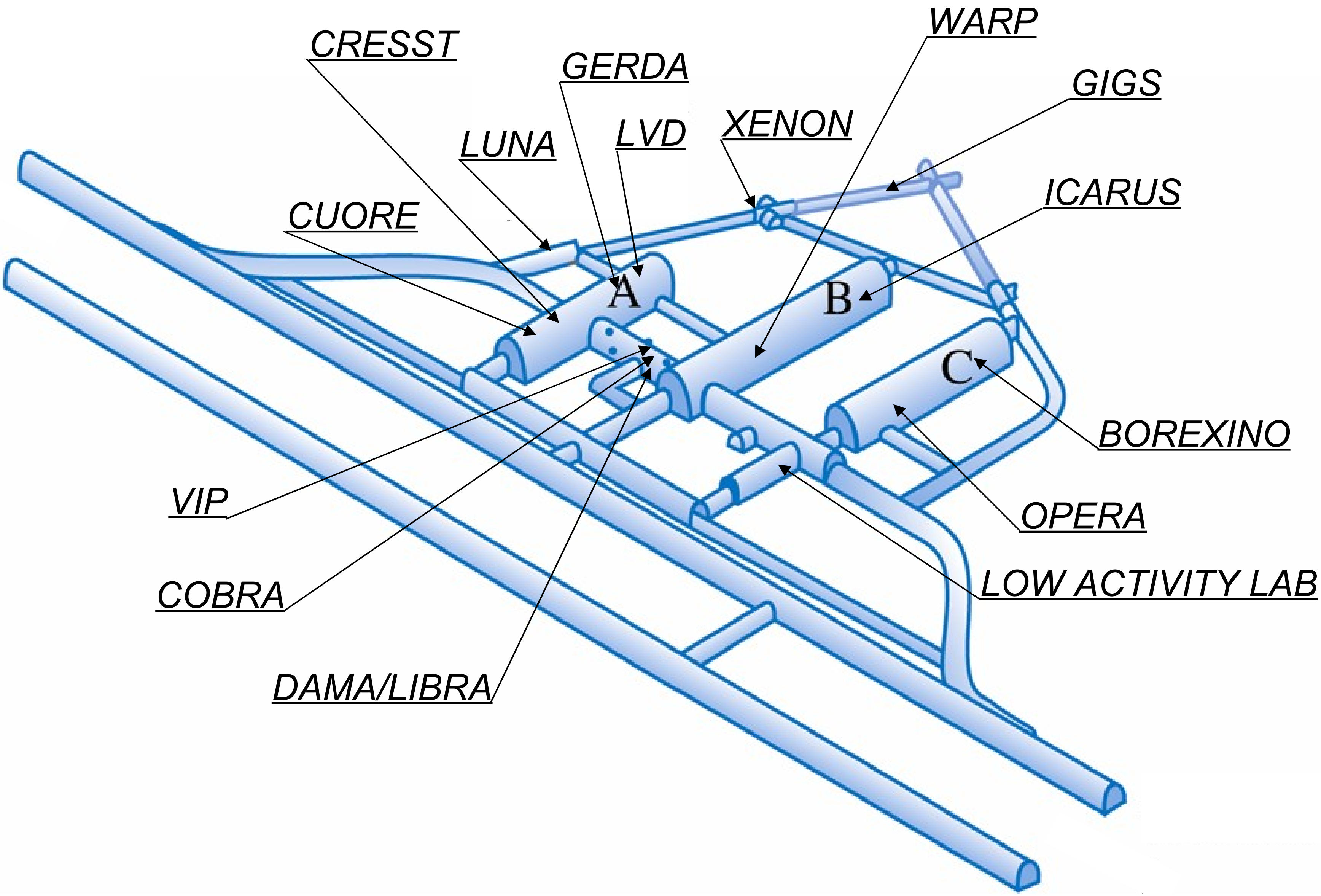
OCCUPANCY



CRESST
GERDA
WARP
GIGS
LUNA
LVD
XENON
ICARUS
CUORE
A
B
C
BOREXINO
OPERA
LOW ACTIVITY LAB
VIP
COBRA
DAMA/LIBRA

Physics at LNGS

The inventory of Universe and the dark matter

DAMA/LIBRA
CRESST
WARP
XENON

LBL - CNGS

OPERA
Icarus T600

Properties of neutrinos and their role in cosmic evolution

$2\beta0\nu$

CUORICINO
CUORE
GERDA
COBRA

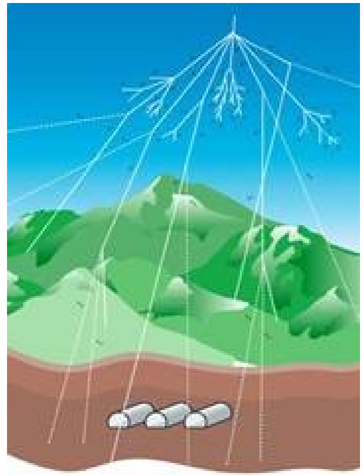
What about the interior of the Sun and the Earth

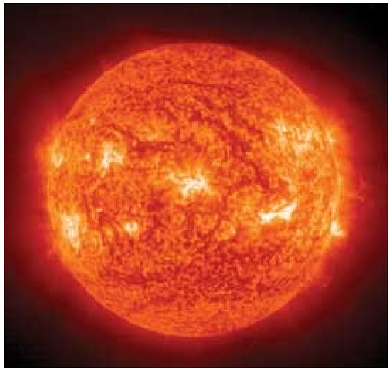
BOREXINO

LVD

What about the supernova explosions

Neutrino Physics



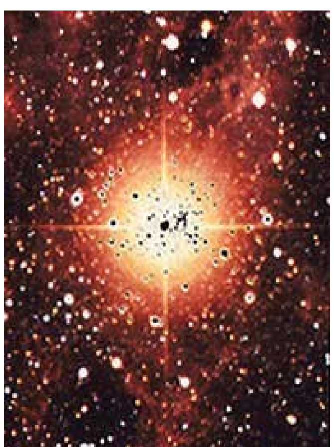


Atmospheric neutrinos
Source: CR interaction
Flavour: all
Energy: 100 MeV – 10^6 GeV
(MACRO- ~ OPERA-ICARUS)

Solar Neutrinos
Source: thermonuclear Reaction
Flavour: electron
Energy: 0.1 – 18.8 MeV
(Borexino-Icarus-GNO)

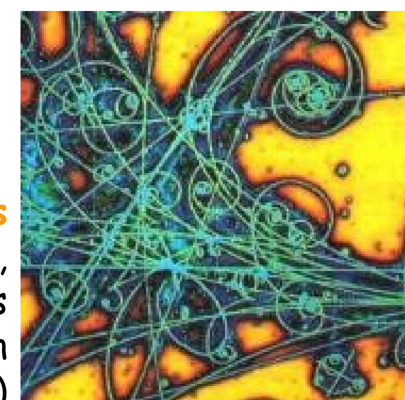
Double Beta Decay
Source: radioactive decay
Flavour: electron
Energy: MeV
(CRESST-GERDA-CUORE)

Geo-Neutrinos
Source: radioactive decay
Flavour: electron
Energy: MeV
(Borexino)



Supernova Neutrinos
Source: Star collapse
Flavour: all
Energy: several tenth of MeV
(~ Borexino-LVD-ICARUS)

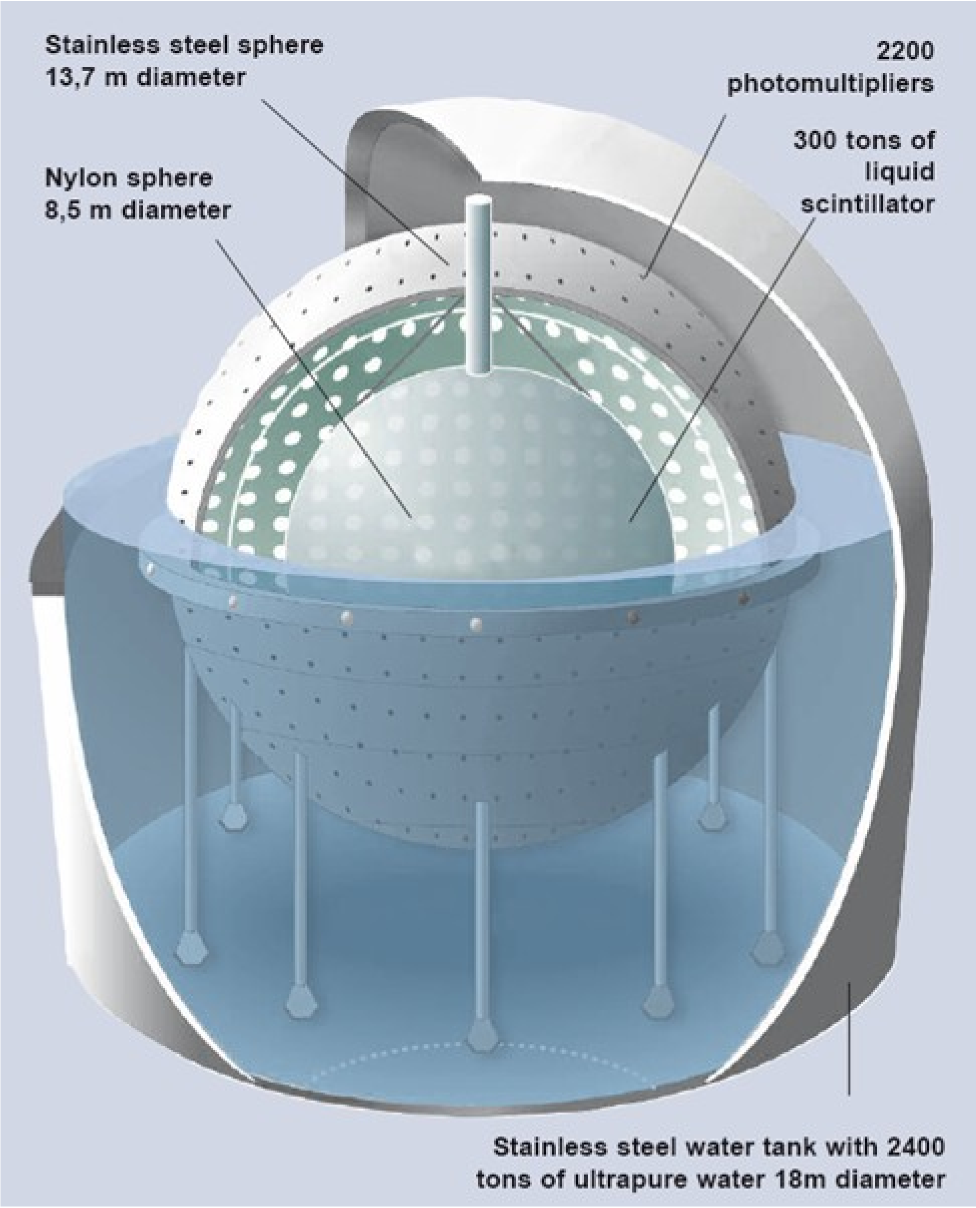
Man made Neutrinos
Source: nuclear reactors, Particle accelerators
Flavour: electron e muon
(Icarus-OPERA)



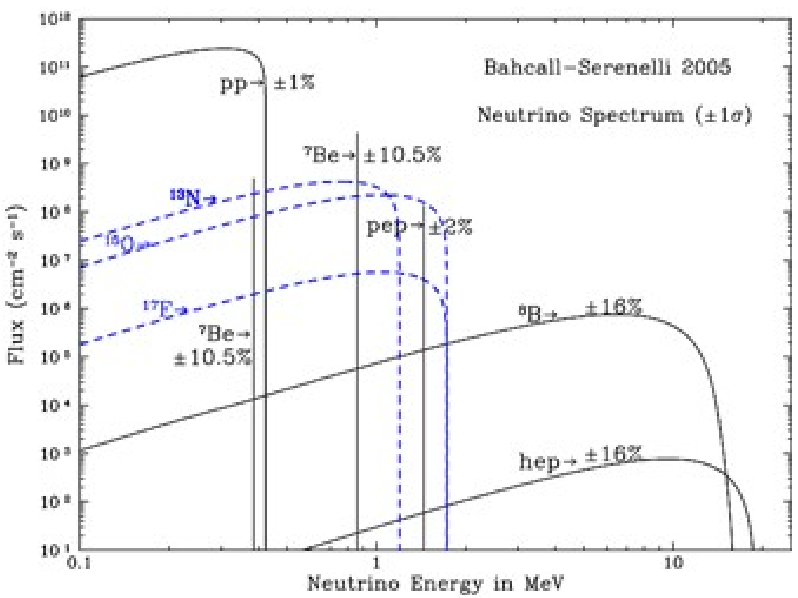
BOREXINO: a real time detector for solar neutrinos

BOREXINO: a real time detector for solar neutrinos

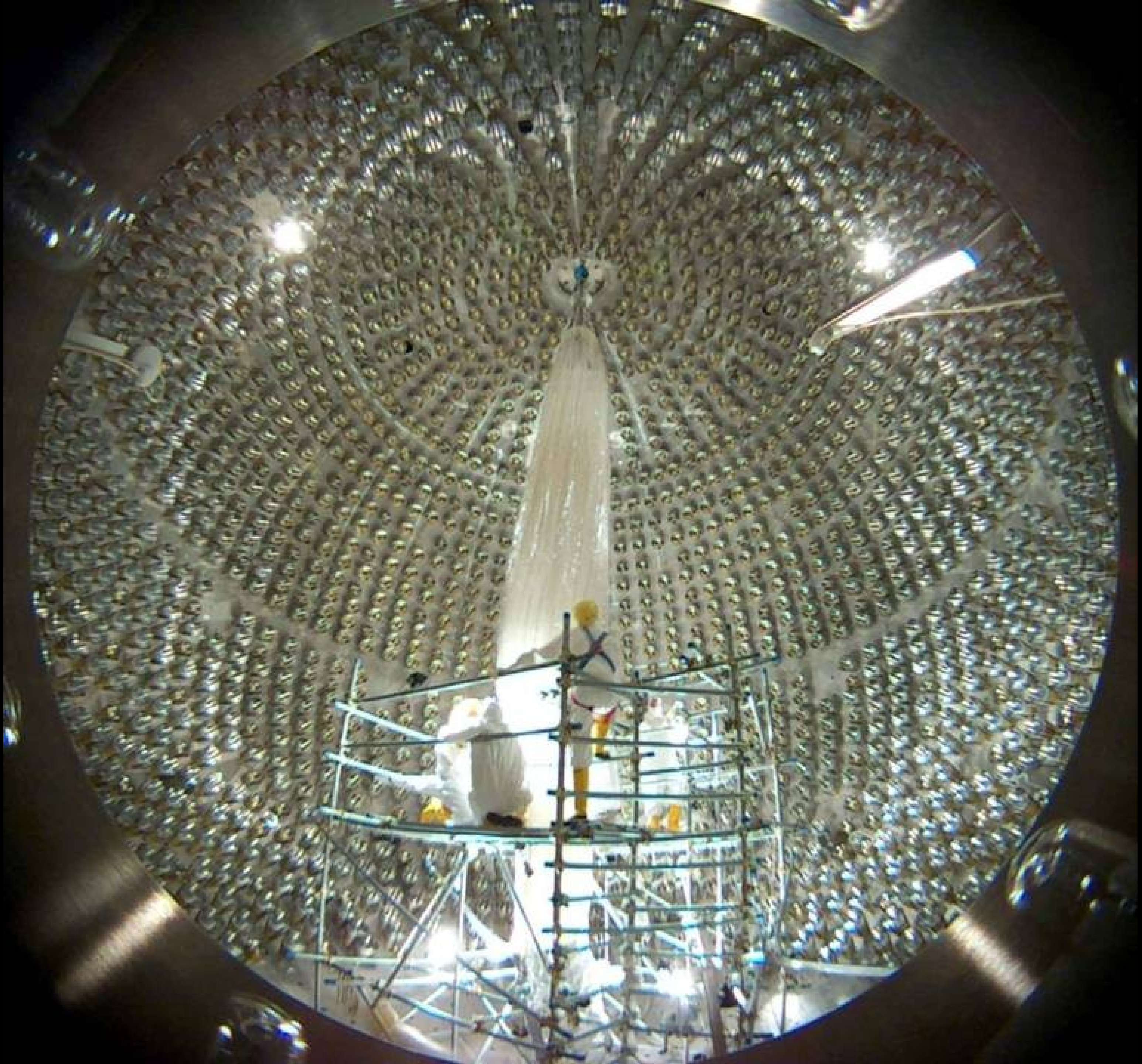
300 tons liquid scintillator in a nylon bag
2200 photomultipliers
2500 tons ultrapure water
Energy threshold 0.25 MeV
Real time neutrino (all flavours) detector
Measure mono-energetic (0.86 MeV)
^{7}Be neutrino flux through the detection of ν_e.
40 ev/d if SSM



The sun is a source of neutrinos (fusion of hydrogen nuclei is accompanied by a continuos emission of neutrinos): 60 Billions ν each second per cm².



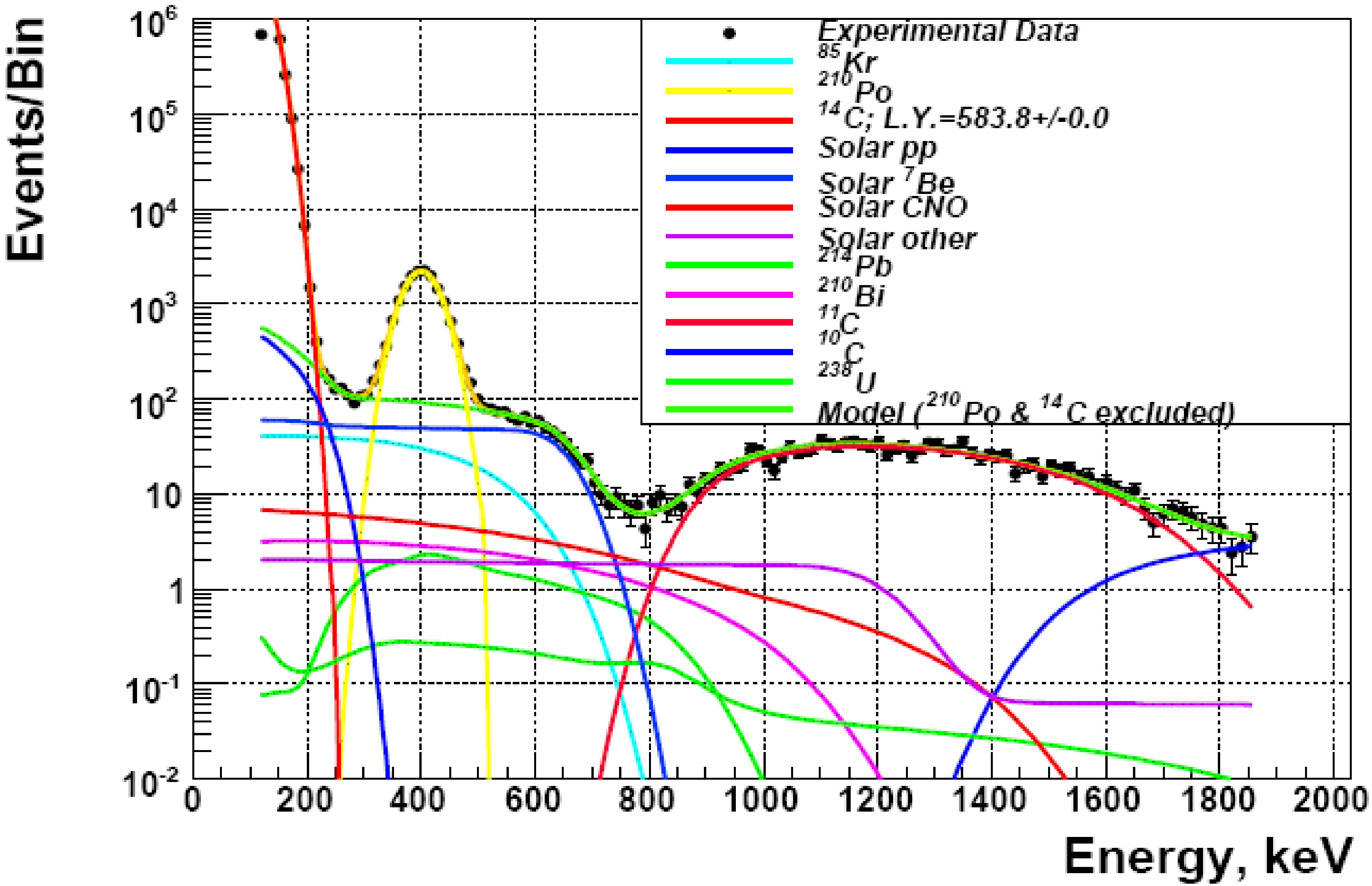
The detector is working since May 2007.



Records in the radiopurity achieved by Borexino

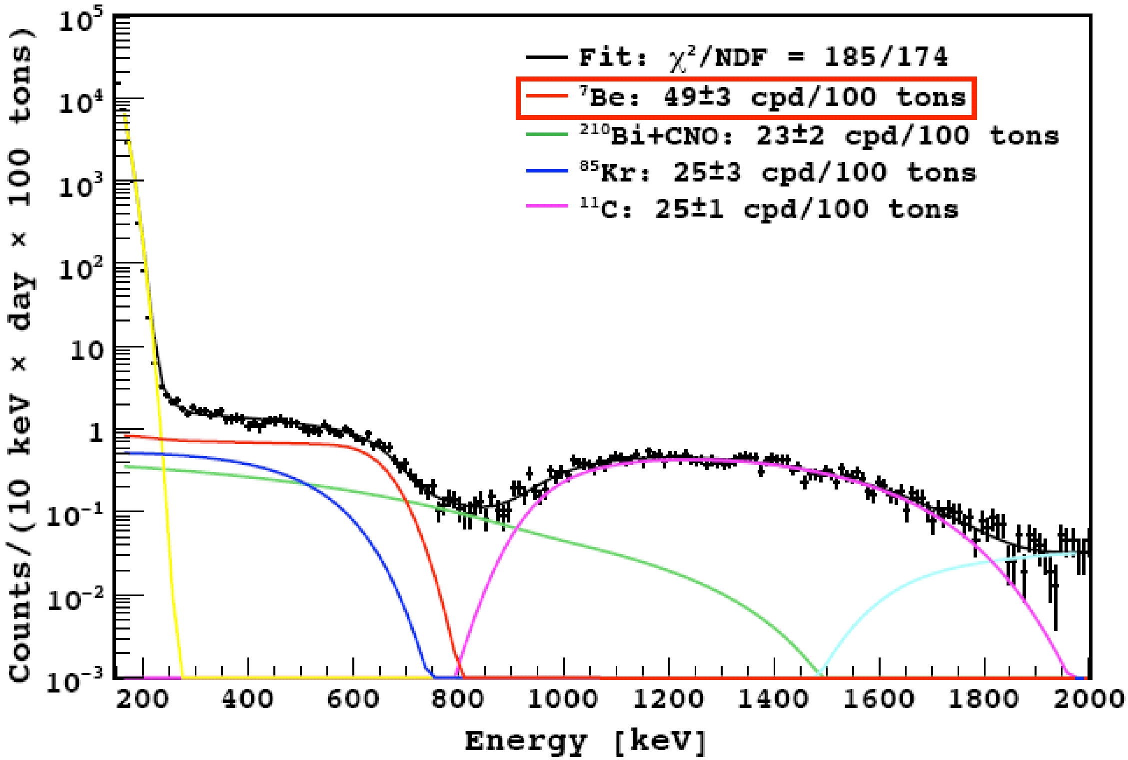
	Material	Typical conc.	Borexino level in the scintillator
^{14}C	scintillator	$^{14}C/^{12}C<10^{-12}$	
$^{238}U, ^{232}Th$ equiv.	- Hall C dust	~1 ppm	
	- stainless. steel	~1 ppb	
	- nylon	~1 ppt	$\sim 10^{-5}$ ppt
K_{nat}	Hall C dust	~1 ppm	
^{222}Rn	- external air.	~20 Bq/m^3	
	- air underground	~40-100 Bq/m^3	
^{85}Kr			
^{39}Ar	in N_2 for stripping	~1.1 Bq/m^3	
		~13 mBq/m^3	
- ^{222}Rn	LNGS - Hall C water	~50 Bq/m^3	
- $^{238}U, ^{232}Th$ equiv.		$\sim 10^{-10}$ g/g	

The measured energy spectrum: May07 - Oct08



The measurement of the ^{7}Be flux

$R_{7Be} = 49 \pm 3_{stat} \pm 4_{sys}$ cpd/100 tons

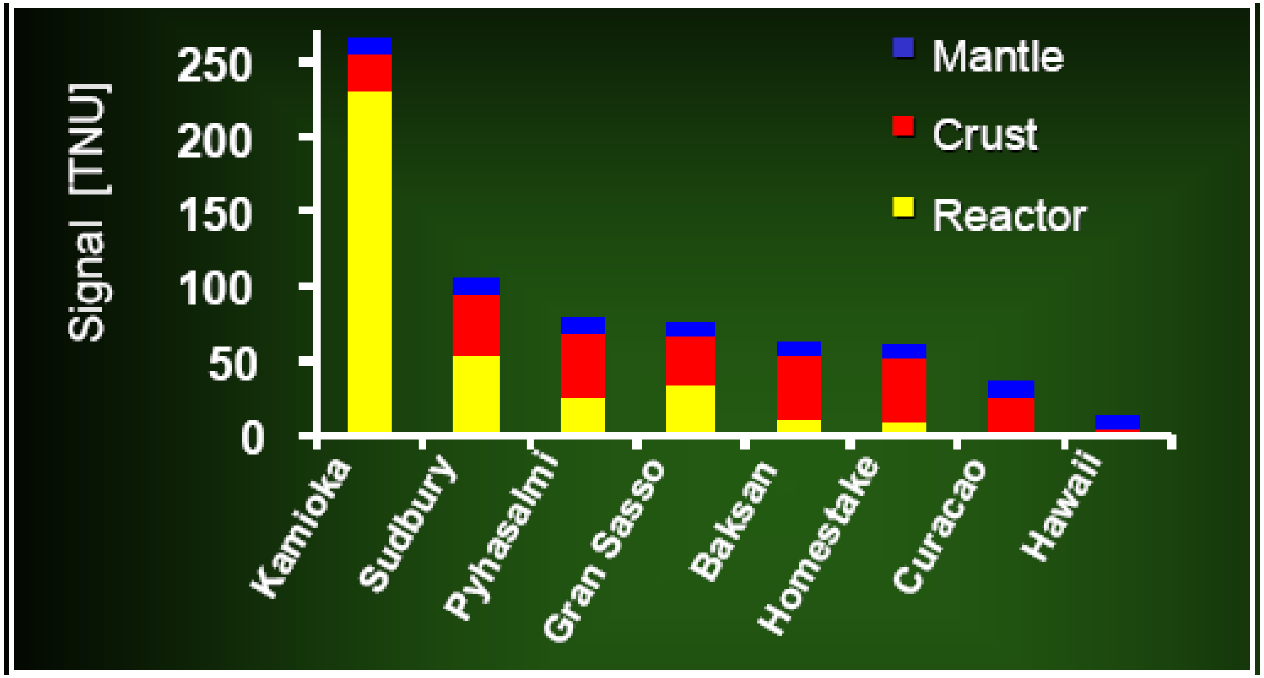


Borexino Collaboration PRL 101 (2008):
192 days of live time

	Expected rate (cpd/100 t)
No oscillation	75 ± 4
BPS07(GS98) HighZ	48 ± 4
BPS07(AGS05) LowZ	44 ± 4

No-oscillation hypothesis
rejected at 4s level

Observation of geoneutrinos



The main sources of anti-ν for Borexino are:

1)Geo-neutrinos

2)Distant reactors

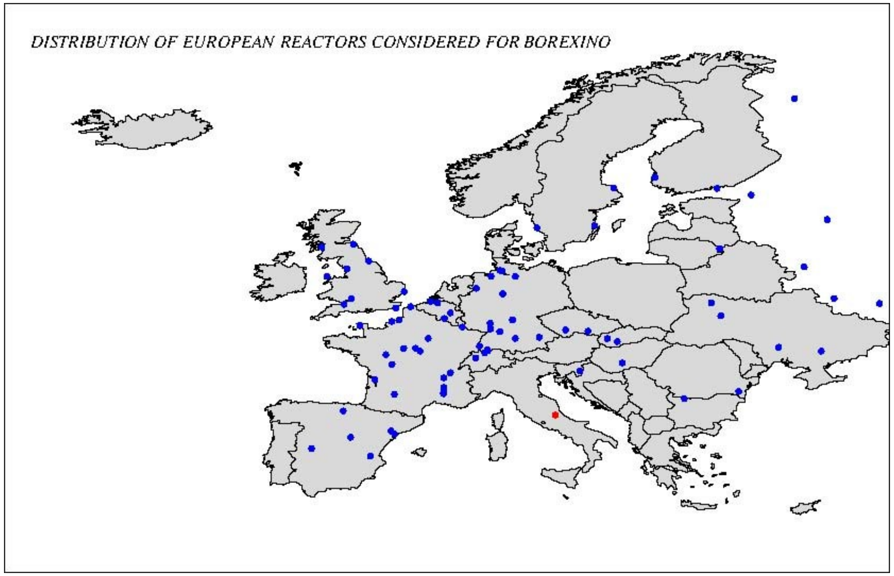
For reactors we have considered:

a) 194(Europe) + 245(World) power stations

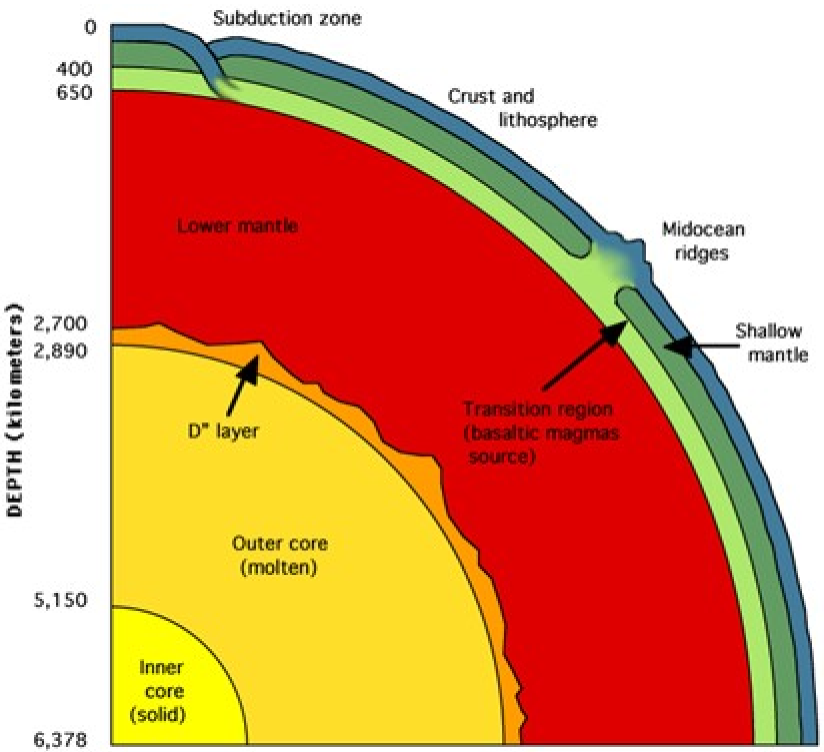
For practical purposes:

-**the effective distance from Borexino is ~1000 km**

- $\phi_{\nu} \sim 10^5$ cm^{-2} s^{-1}



Earth shines in antineutrinos: flux ~ $10^6\ cm^{-2}\ s^{-1}$



The main long-lived radioactive elements within the Earth

^{238}**U**, ^{232}**Th**, and ^{40}**K**

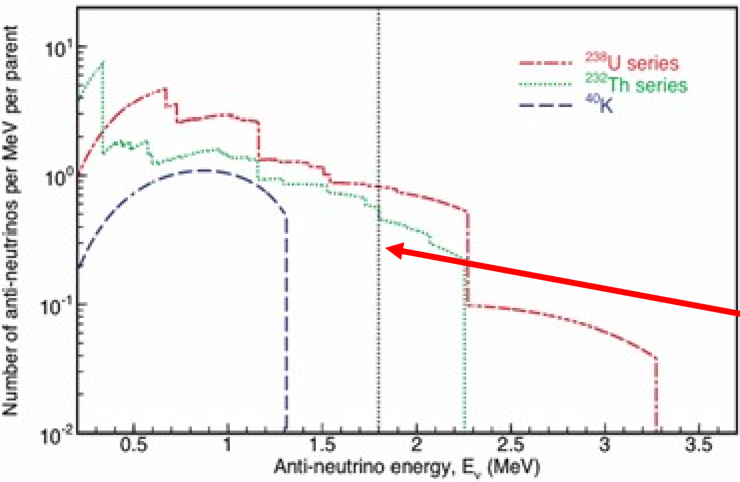
- absolute Bulk Silicate Earth (BSE) abundances varies within 10% based on the model;
- ratios of BSE element abundances more stable in different calculations:

Th/U = 3.9

K/U = 1.14×10^4

concentration for ^{238}U

upper continental crust:	2.5 ppm
middle continental crust:	1.6 ppm
lower continental crust:	0.63 ppm
oceanic crust:	0.1 ppm
upper mantle:	6.5 ppb
core	NOTHING
BSE (primordial mantle)	20 ppb



^{238}U, ^{232}Th, ^{40}K chains ($T_{1/2}$ = (4.47, 14.0, 1.28) × 10^9 years):

$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 8e^- + 6$ anti-neutrinos + 51.7 MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4$ anti-neutrinos + 42.8 MeV

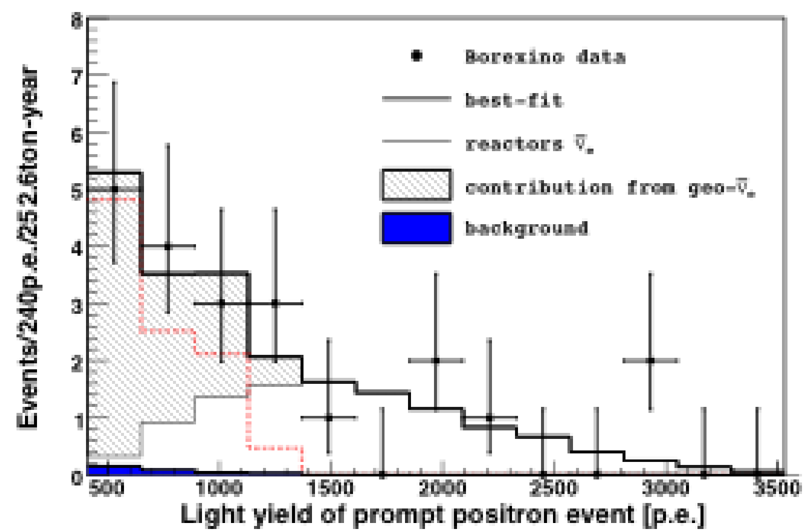
$^{40}K \rightarrow {}^{40}Ca + e^- + 1$ anti-neutrino + 1.32 MeV

1.8 MeV = thr. for inverse β-decay reaction

In Borexino electron anti-n's are detected by the inverse-beta decay reaction:

anti-ν + p -> e^+ + n (E_{th}= 1.806 MeV)

- Data set: from Dec 2007 to Dec 2009
- Total live time: 537.2 live days
- Muon veto: 2s after each detected muon removed (~10% reduction of live time)
- Fiducial exposure after muon cuts and including detection efficiency: **252.6 ton-year**
- **21 anti-ν candidates selected**

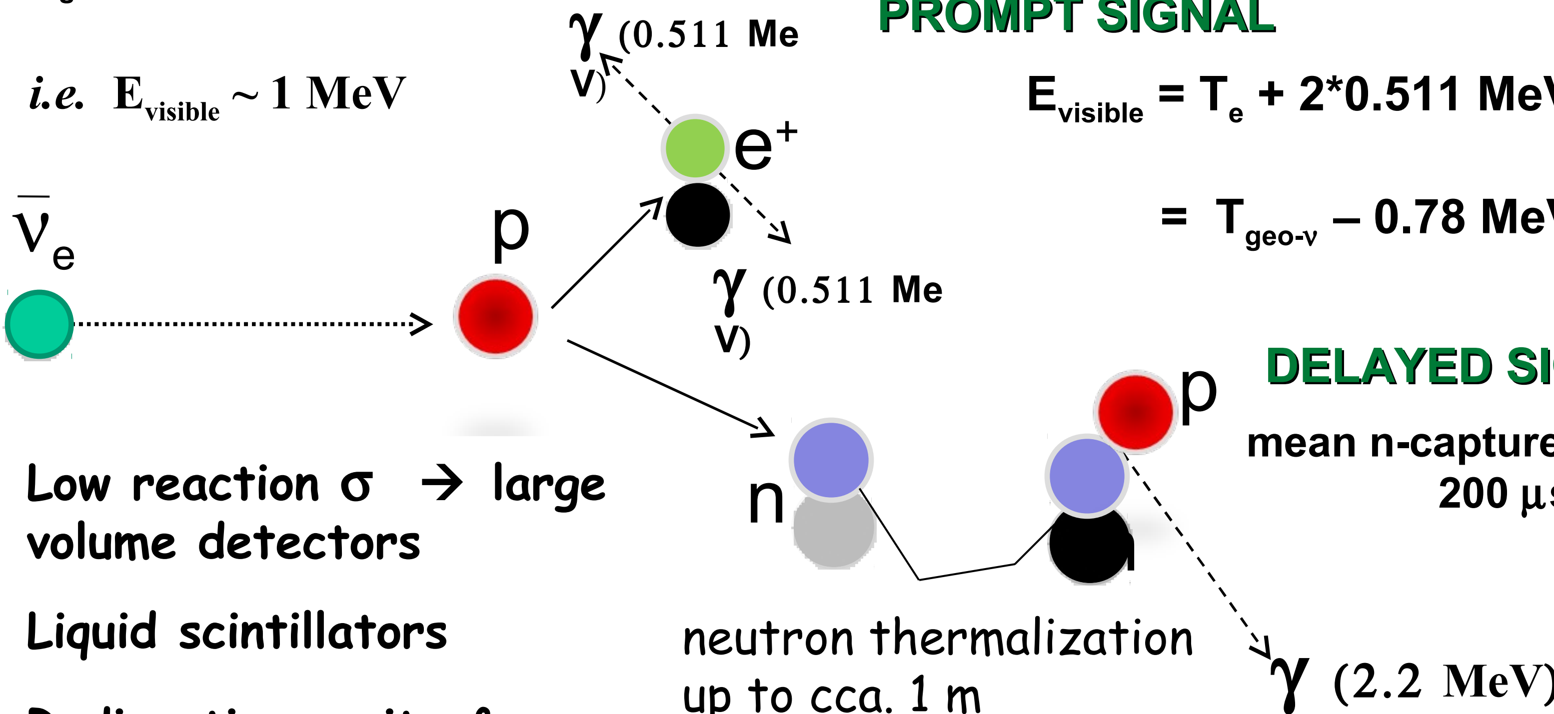


Detecting geo-ν: inverse b-decay

Energy threshold of

$T_{geo\text{-}\nu} = 1.8$ MeV

i.e. $E_{visible} \sim 1$ MeV



PROMPT SIGNAL

$E_{visible} = T_e + 2*0.511$ MeV =

$= T_{geo\text{-}\nu} - 0.78$ MeV

DELAYED SIGNAL

mean n-capture time on p
200 μs

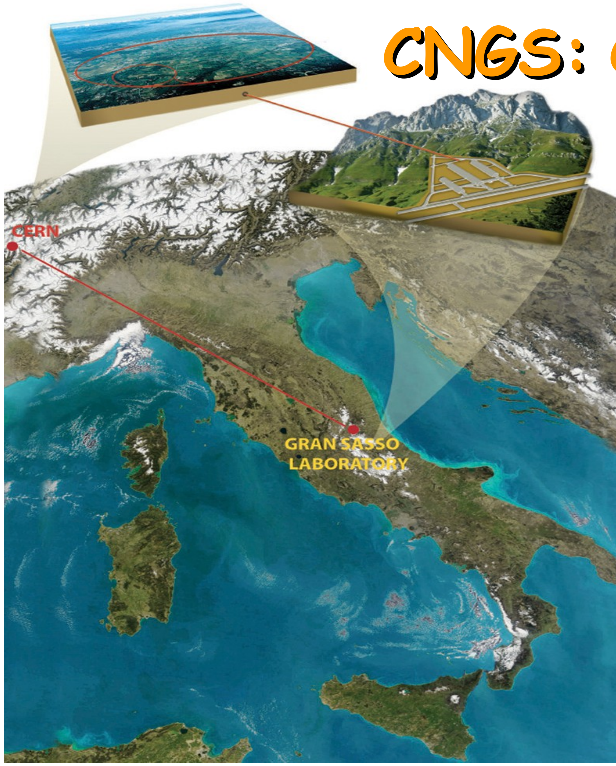
Low reaction σ → large volume detectors

Liquid scintillators

Radioactive purity & underground labs

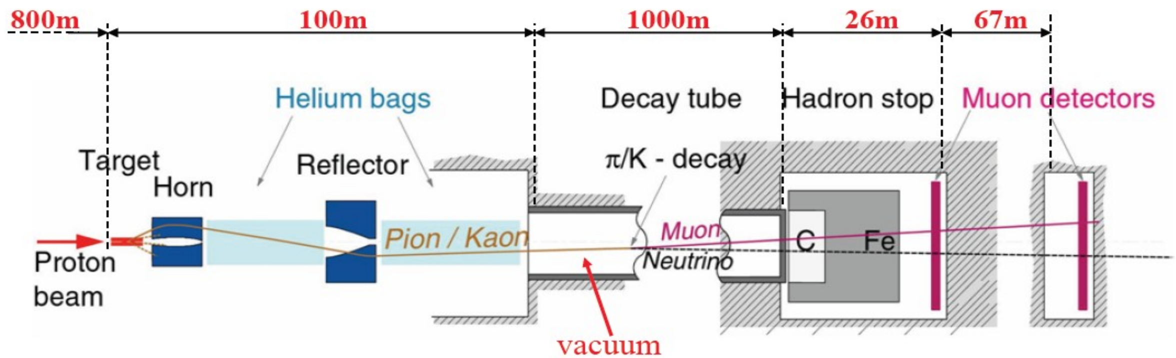
CNGS: CERN Neutrino to Gran Sasso

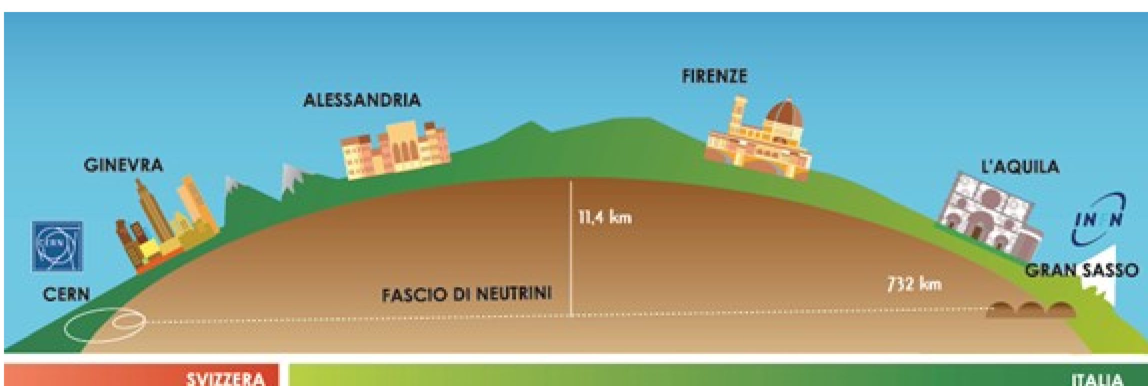
The goal: understand the nature and characteristics of neutrino - prove definitely the neutrino oscillations



Project INFN-CERN: approved in 1999, started in 2006

ν_μ beam produced at CERN and detected at LNGS (L= 730 km)

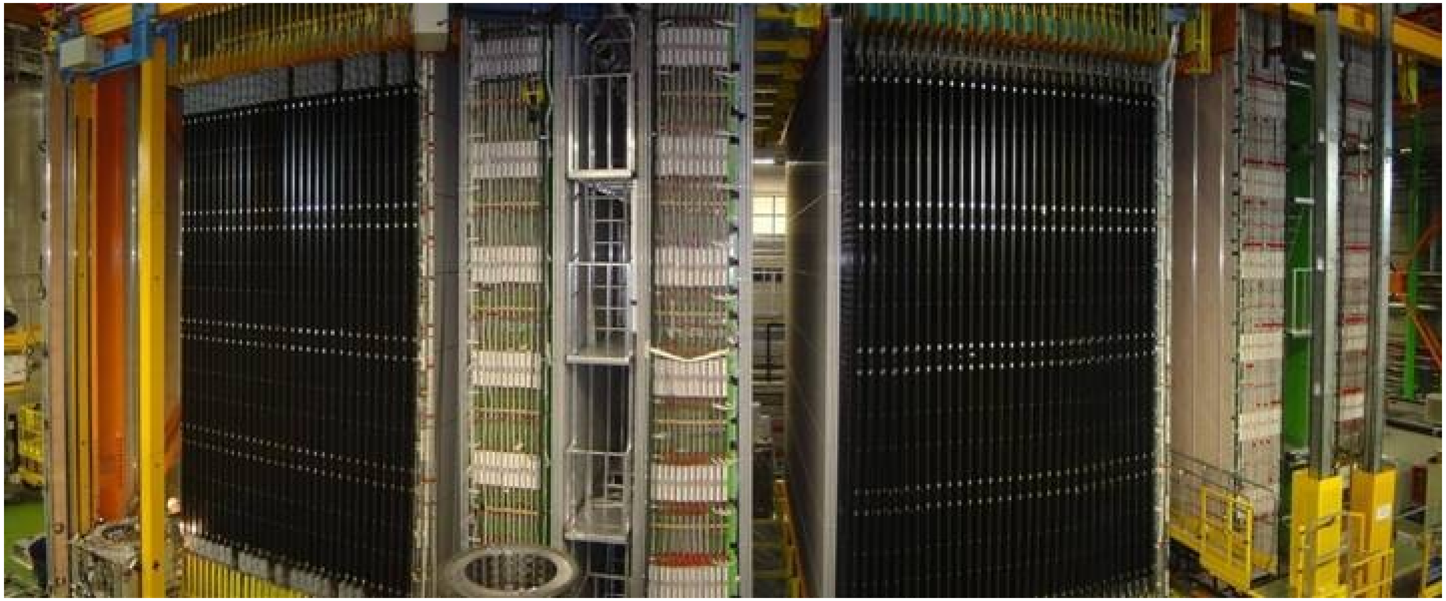




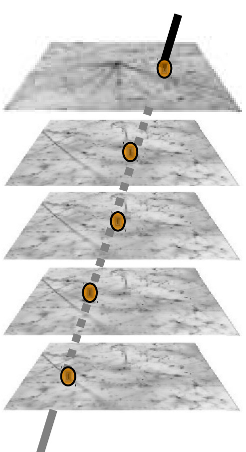
OPERA experiment

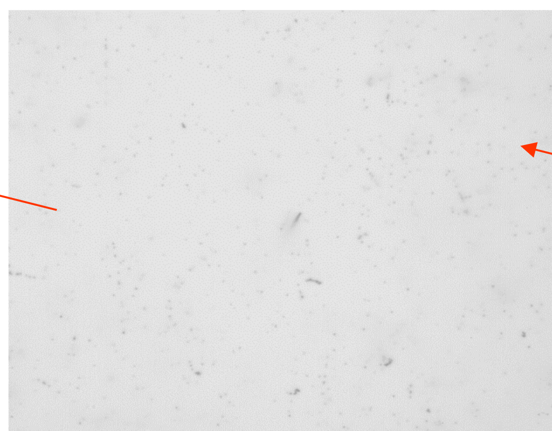
Oscillation Project with Emulsion-tRacking Apparatus

OPERA is a hybrid detector designed for the observation of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations through τ appearance induced by CNGS oscillated neutrinos.

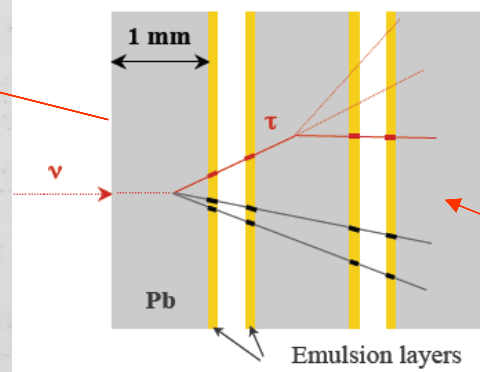


Observation of the decay topology of τ in "photographic" emulsion.

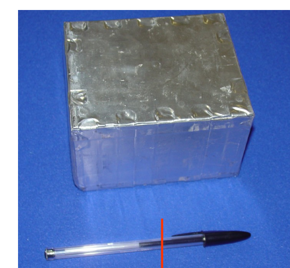


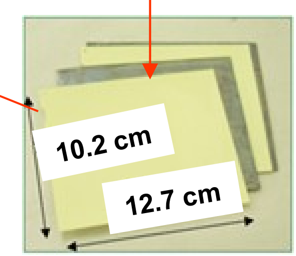


Brick interaction



57 emulsion layers interleaved with 56 lead sheets.



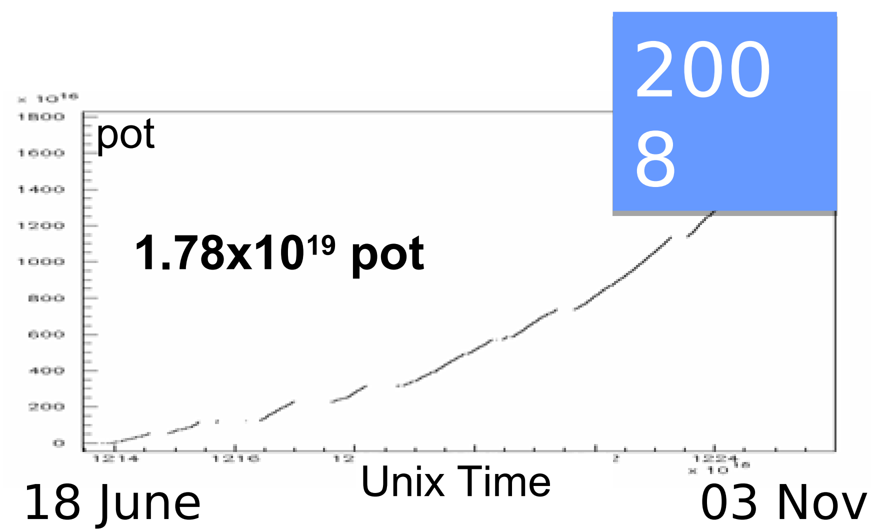


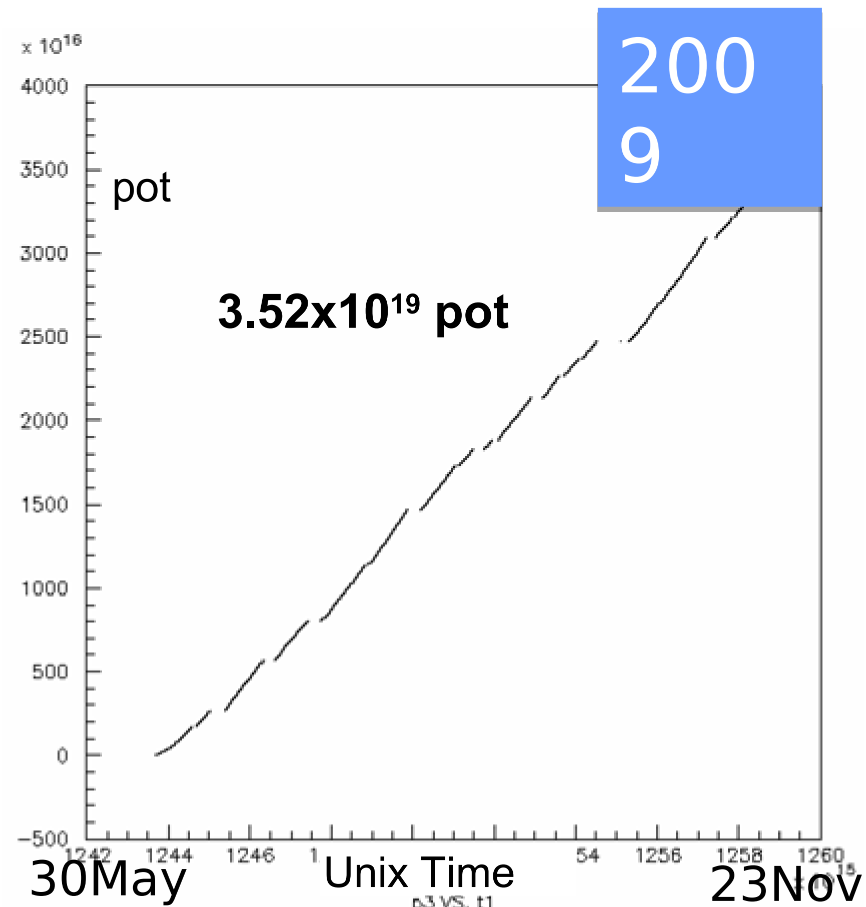
Status of data taking

2006	0.076×10^{19} pot	0 int.	Commissioning
2007	0.082×10^{19} pot	38 int.	Commissioning
2008	**1.78×10^{19} pot**	**1698 int.**	First physics run
2009	**3.52×10^{19} pot**	**3500 int.** preliminary	Second physics run

Until now, 5.30×10^{19} pot

2÷3 τ are expected





GOAL : ν_τ appearance detection from conventional ν_μ beam.

OPERA is successfully operating on the CNGS beam

-First physics run in 2008: ~900 interactions located

-physics run in 2009: 475 up to now , analysis on going

-The ability to detect τ is proven and its efficiency is being evaluated from charm detection.

ν_τ CC-interaction is expected soon. But, **2÷3 τ are expected to be detected** in the analysis of 2008-09 runs (if oscillation parameters are **$\Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$)**

OPERA is aimed at collecting 22.5 x 10^{19} p.o.t

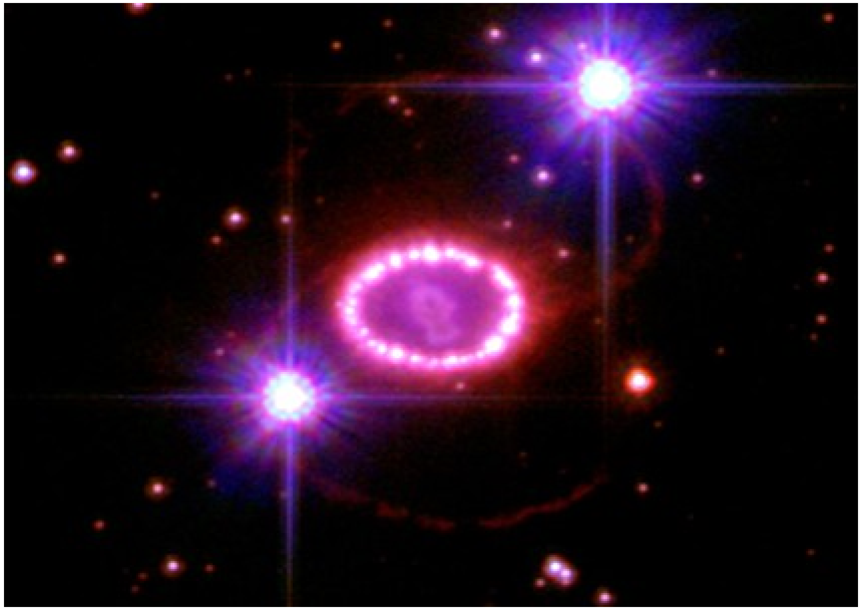
Large Volume Detector

- 1000 billions ν in 20 s from the SuperNova core.
- Measurement of neutrinos energy spectra and time evolution provides important information on ν physics and on SN evolution.
- Neutrino signal detectable only from SN in our Galaxy or Magellanic Clouds

1000 tons liquid scintillator in 3 towers

300 ν from a SN in the center of Galaxy (8.5 kpc)

Running since 1992



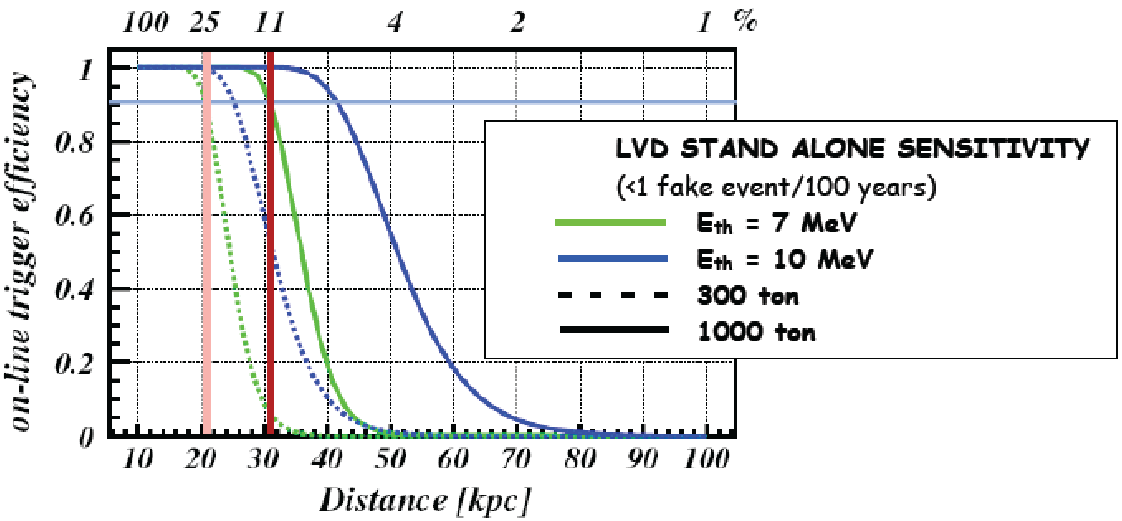
SN1987A

Early warning of neutrino burst important for astronomical observations with different messengers (Gravitational Waves)

SNEWS = Supernova Early Warning System

LVD, SNO, SuperK

in future: Kamland, BOREXINO



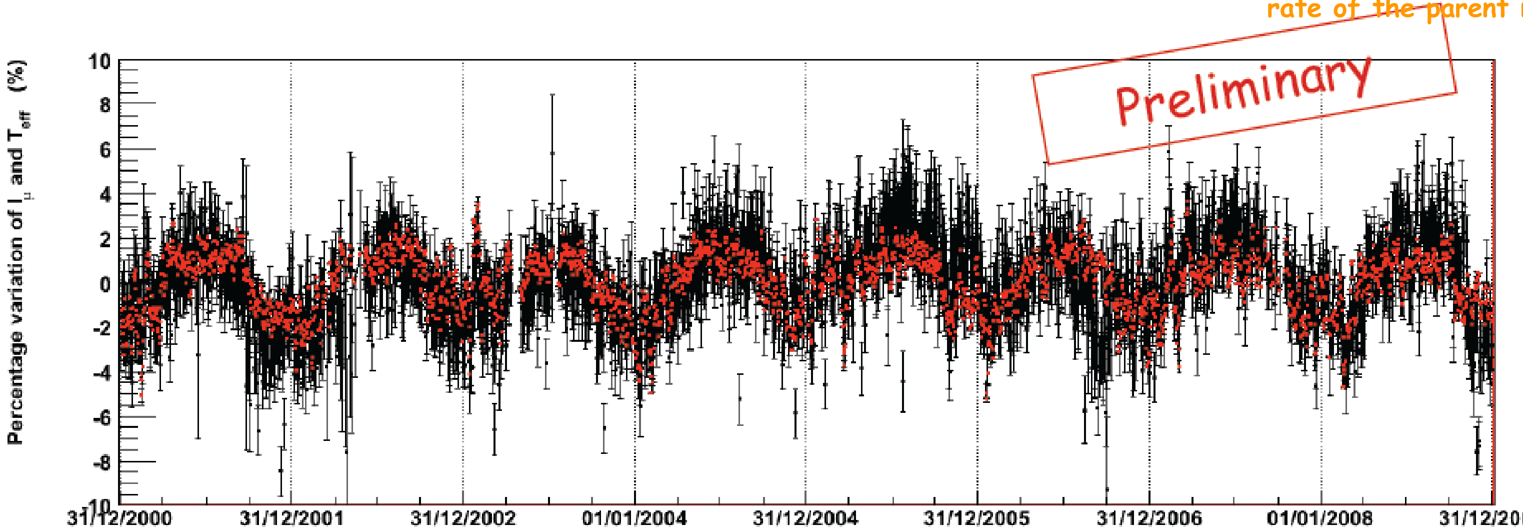
Search for neutrino bursts from Core Collapse Supernovae.

LVD is observing the Galaxy since 1992. The resulting 90% c.l. upper limit to the rate of gravitational stellar collapses at distances ($D \leq 20$ kpc), is:

$R < 0.15$ events/year

It is well known that the flux of cosmic muons underground is related to the temperature of the Earth atmosphere (the higher the temperature, the higher the muon ux underground) because the change in the air density implies a variation in the decay and interaction rate of the parent mesons.

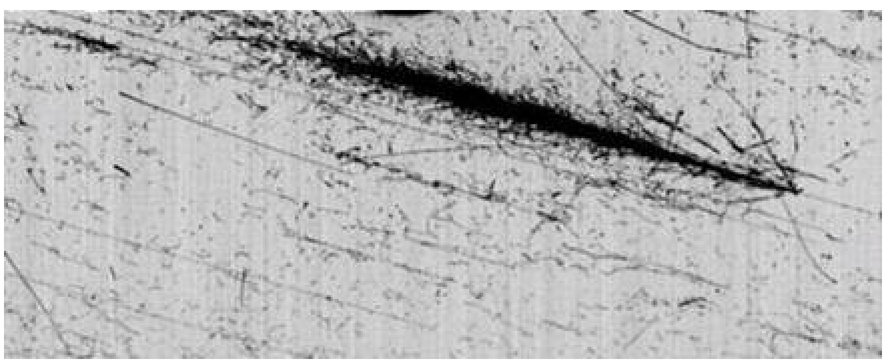
Analysis of the seasonal modulation of the cosmic muon flux in the LVD detector during 2001-2008.



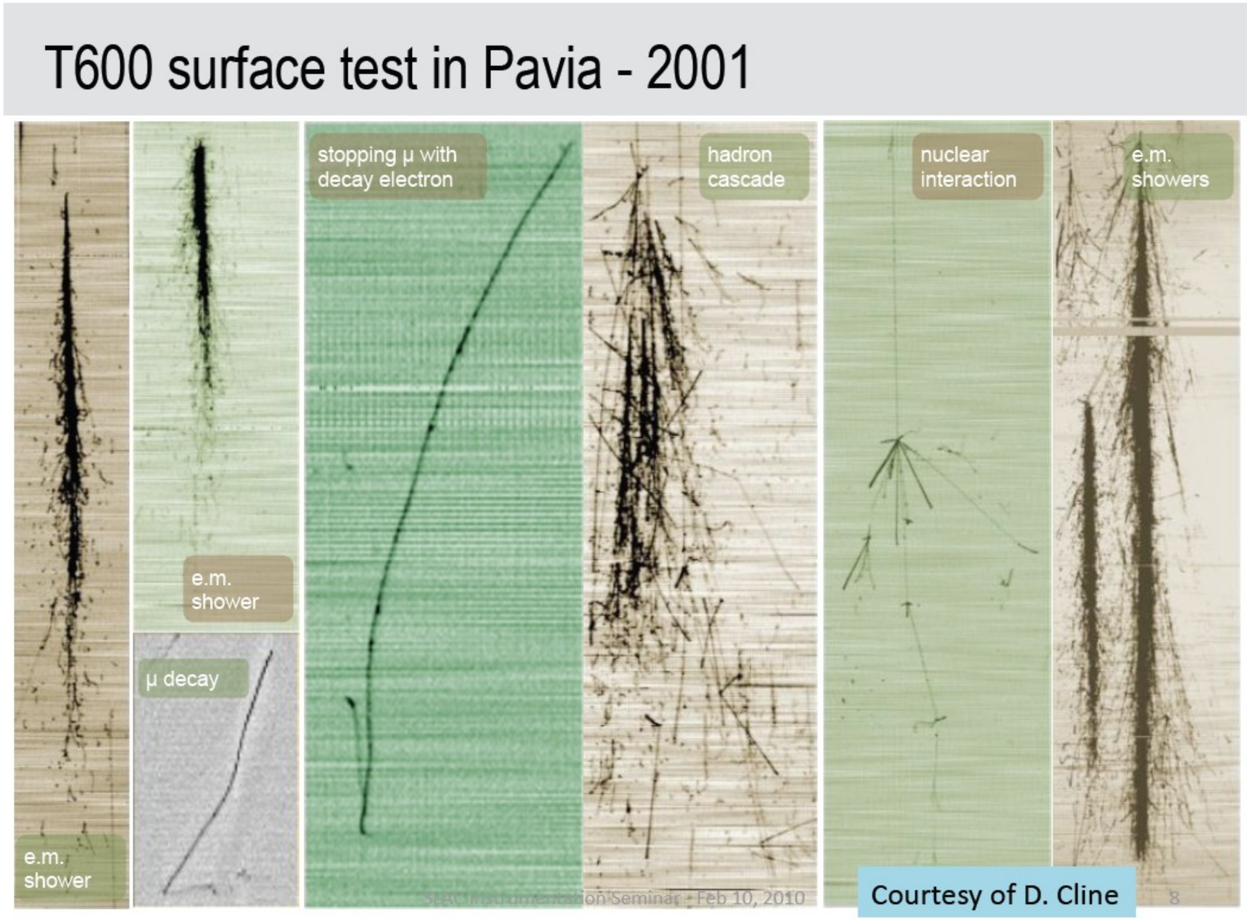
Fractional variation of the muon intensity (black) and effective temperature (red)

Imaging Cosmic And Rare Underground Signals

The ICARUS T600 detector is a multi-purpose detector that opens up unique opportunities to look for phenomena beyond the Standard Model through the study of atmospheric, solar and supernovae neutrinos, nucleon decay searches and neutrinos from the CERN to Gran Sasso beam.

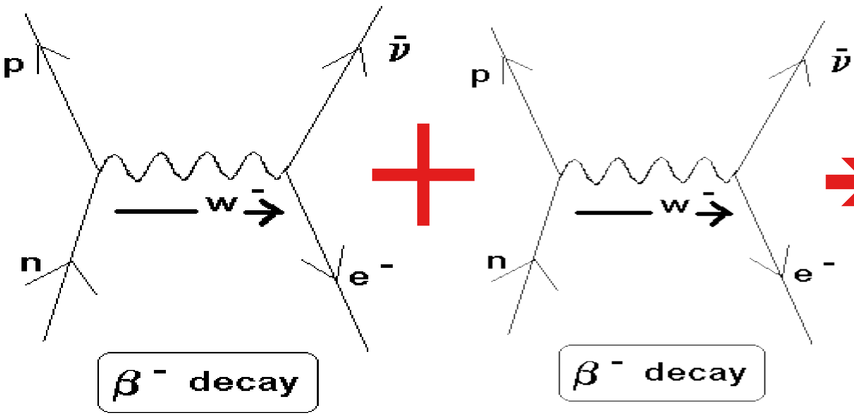


The experimental technique of the ICARUS T600 detector is based on the use of Time Projection Chambers (TPC) in liquid argon. The detector consists of two identical semi-modules, each hosting 300 tons of liquid argon 'observed' by two TPCs and 20 photomultipliers. This kind of detector is able to produce high granularity 3D reconstruction of recorded events as well as high precision measurements over large sensitive volumes.

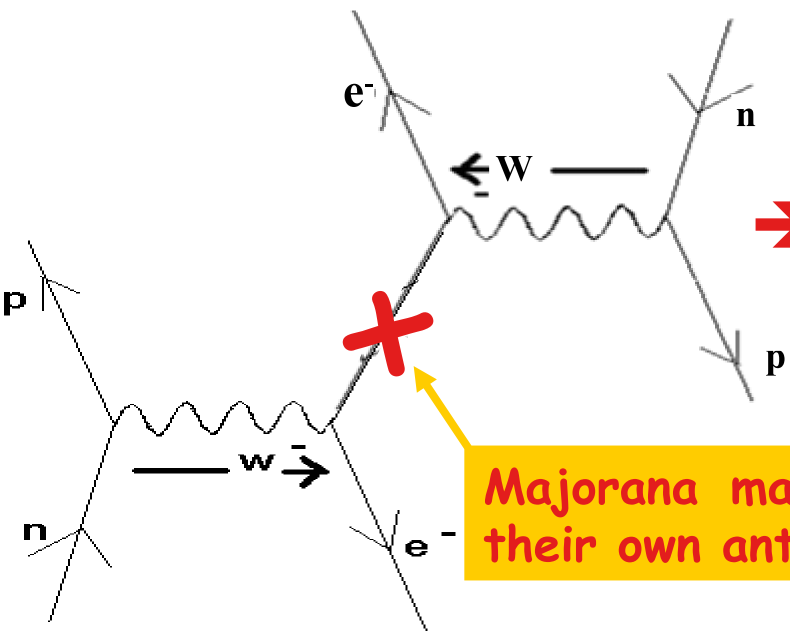


The cryogenic plant has been completed and almost completely tested. The electronic read out of the 54000 TPC wires has been positioned on the top of the detector, connected and tested. Actually both the cryostats are being evacuated before they can be cooled down and filled with liquid argon. The residual pressure is of the order of 10^{-5} mbar. The detector will be probably filled during the next month.

Double Beta Decay



→ 2 neutrinos plus 2 electrons

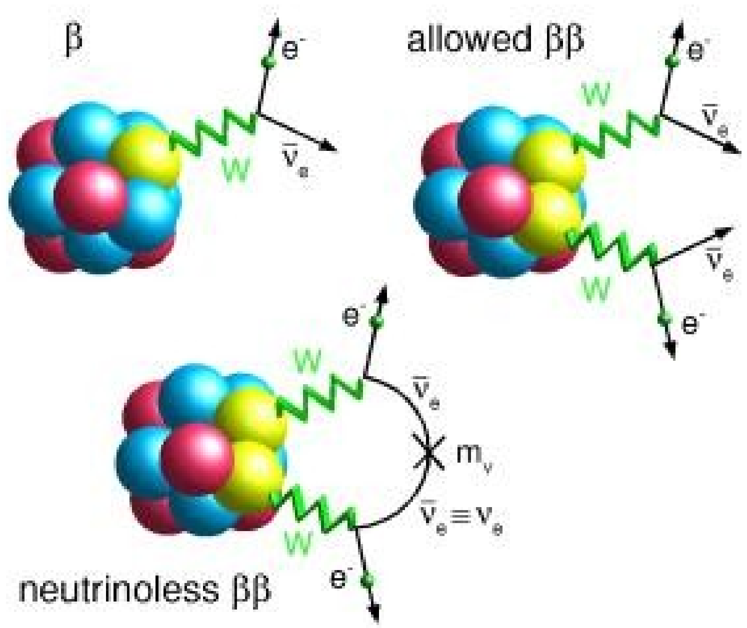


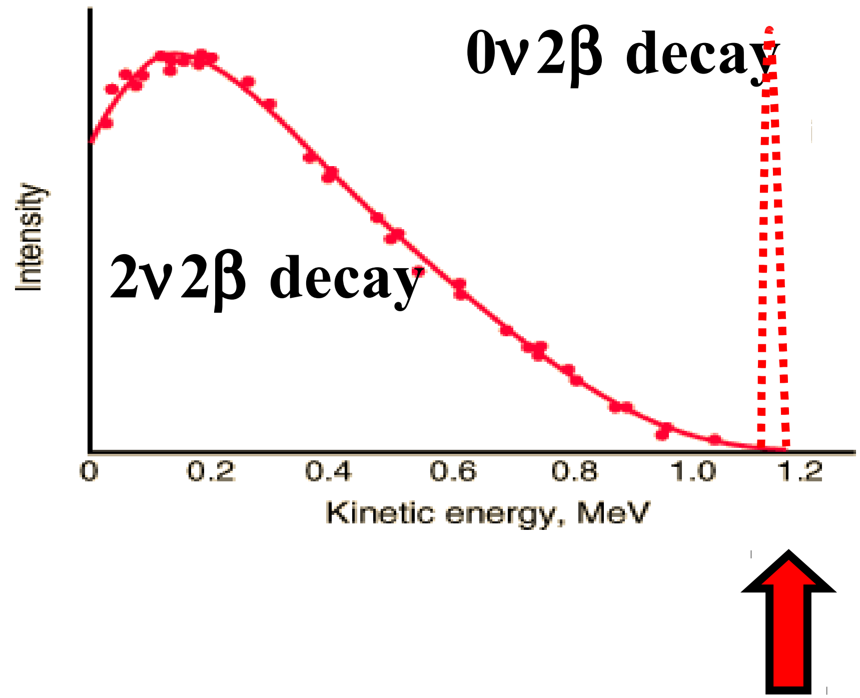
→no neutrinos just 2 electrons

Majorana mass ←→ ν's are their own antiparticles

$0\nu\beta\beta$ Decay Kinematics

$2\nu 2\beta$ decay of ^{76}Ge observed: $\tau = 1.5 \times 10^{21}$ y





Majorana ν → $0\nu 2\beta$ decay

warning:

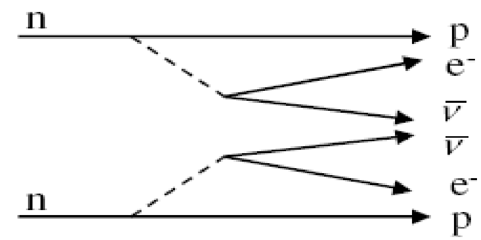
other lepton number violating processes...

- **signal at known Q-value**
- **$2\nu\beta\beta$ background (resolution)**
- **nuclear backgrounds**

Double Beta Decay Candidates

Candidate	Q(MeV)	Abund(%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

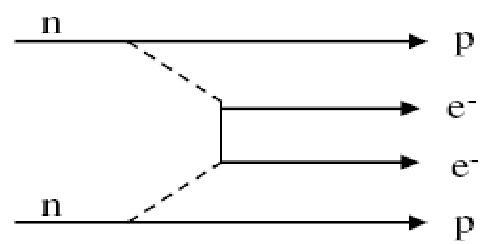
$2\nu\beta\beta$ decay



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

$T_{1/2} \sim 10^{21}y$

$0\nu\beta\beta$ decay



$(Z,A) \rightarrow (Z+2,A) + 2e^-$

$T_{1/2} > 10^{25}y$

GERmanium Detector Array

The aim of the GERDA experiment is to study ββ decay without neutrinos from ^{76}**Ge**. GERDA experiment will be equipped with semiconductor detectors enriched with ^{76}**Ge** working in a cryogenic environment.

GERmanium Detector Array

The GERDA construction in Hall A is almost completed

Going to start commissioning in late Spring 2010 → immersion of ^{nat}Ge detectors and then of ^{enr}Ge

In parallel: R&D ongoing to define the best solutions (detectors, electronics, etc.) for the Phase II

GERDA goal

phase	I	II	"III"
detector [kg]	17.9 existing	~25 more	ton-scale
exposure[kg·year]	30	100	>1000
bg [counts/(keV·kg·year)]	10^{-2}	10^{-3}	10^{-4}
limit on $T_{1/2}$ [10^{25} year](90%C.L.)	2	15	>280
limit on $m_{\beta\beta}$ [eV]*	0.27	0.13	<0.03

Phase-I fact

Claim of evidence
signal: 28.75±6.86 events
bg level: 0.11 counts/ keV·kg·year
H.V.Klapdor-Kleingrothaus, et al.,
Phys. Lett. B 586 (2004) 198-212

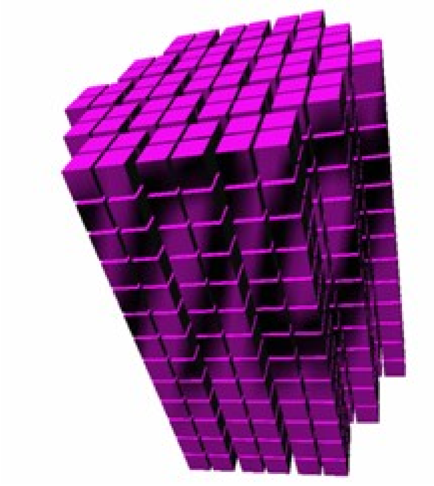
If claim true, phase-I will see:
signal: 13 events
bg: 3 events

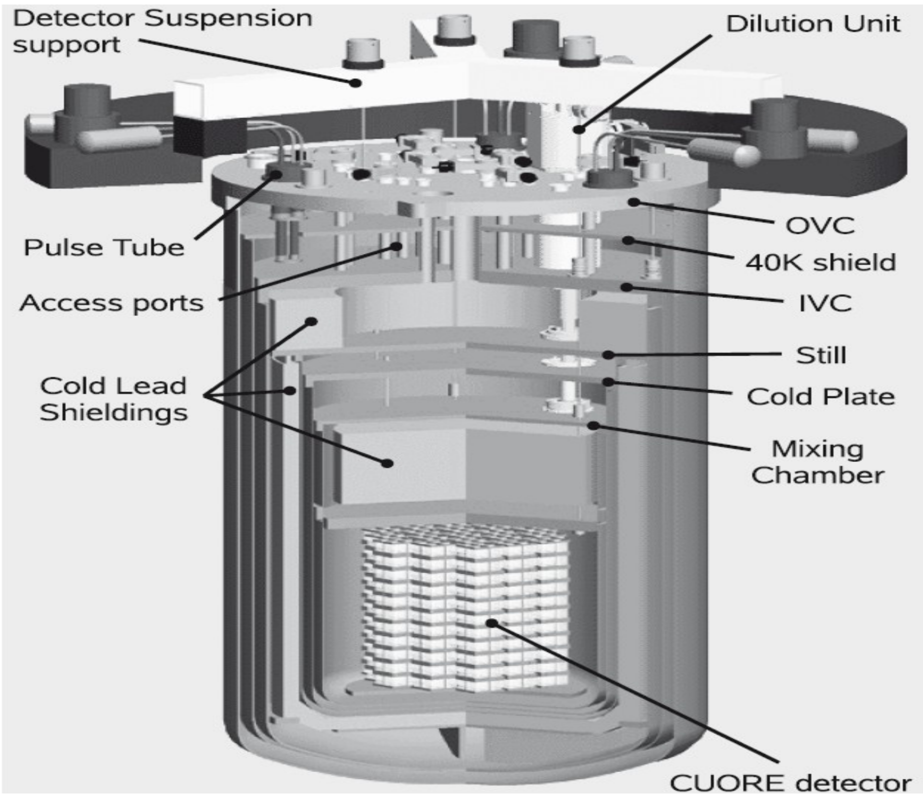
in 10keV window at 2MeV
assume 4keV FWHM at 2MeV

*Assuming $<M^{0\nu}>=3.92$
(Erratum: Nucl. Phys. A766 (2006) 107)

The CUORE experiment

The CUORE experiment is able to detect ββ decay of ^{130}Te by using cryogenic detectors made of TeO_2 crystals. The prototype CUORICINO, already installed at LNGS, demonstrated the feasibility of the large scale detector CUORE that will start the operation in 2011.

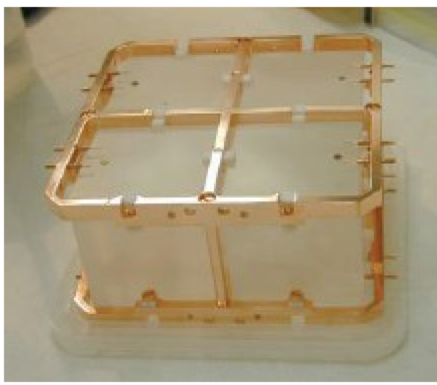


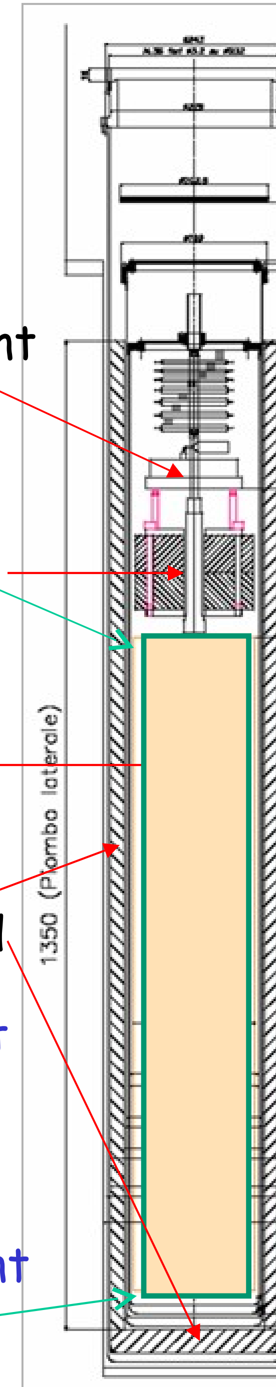


The CUORICINO set-up

CUORICINO = tower of 13 modules,
11 modules x 4 detector (790 g) each
2 modules x 9 detector (340 g) each

M = ~ 41 kg ⇒ ~ 5 x 10^{25} ^{130}Te nuclides



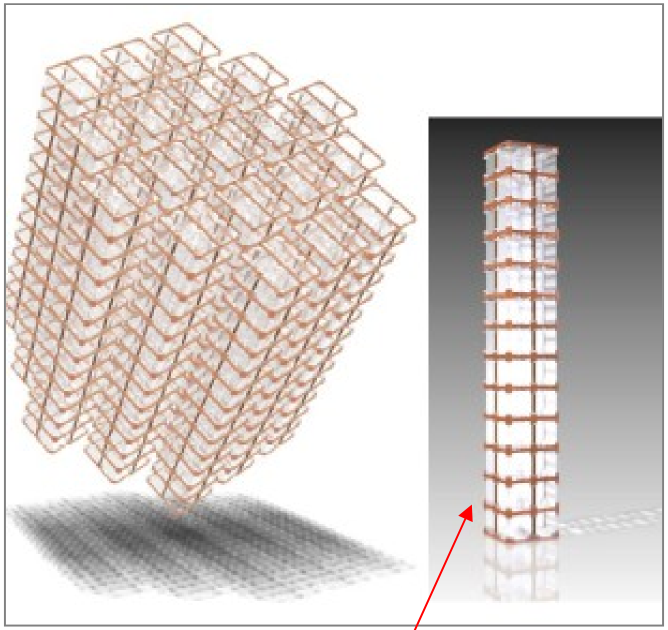


Same cryostat
and similar
structure
as previous
pilot experiment

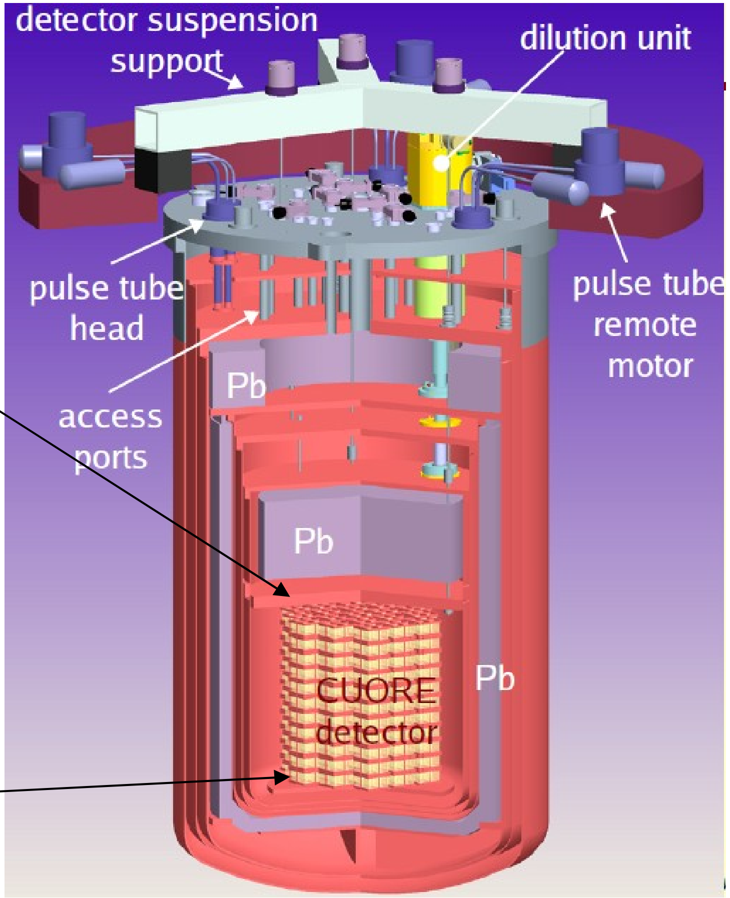
From CUORICINO to CUORE
(Cryogenic Underground Observatory for Rare Events)

CUORE = closely packed array of 988 detectors
19 towers - 13 modules/tower - 4 detectors/module
M = 741 kg $\Rightarrow$ ~ 10^{27} ^{130}Te nuclides

Compact structure, ideal for active shielding



Each tower is a CUORICINO-like detector



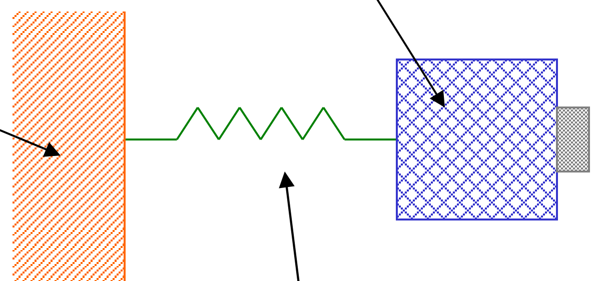
Custom dilution refrigerator

The bolometric technique for ^{130}Te: detector concepts

Te dominates in mass the compound
Excellent mechanical and thermal properties

Energy absorber
TeO_2 crystal
$C \cong 2$ nJ/K $\cong$ 1 MeV / 0.1 mK

Heat sink
$T \cong 10$ mK



Thermometer
NTD Ge-thermistor
$R \cong$ 100 MΩ
$dR/dT \cong$ 100 kΩ/mK

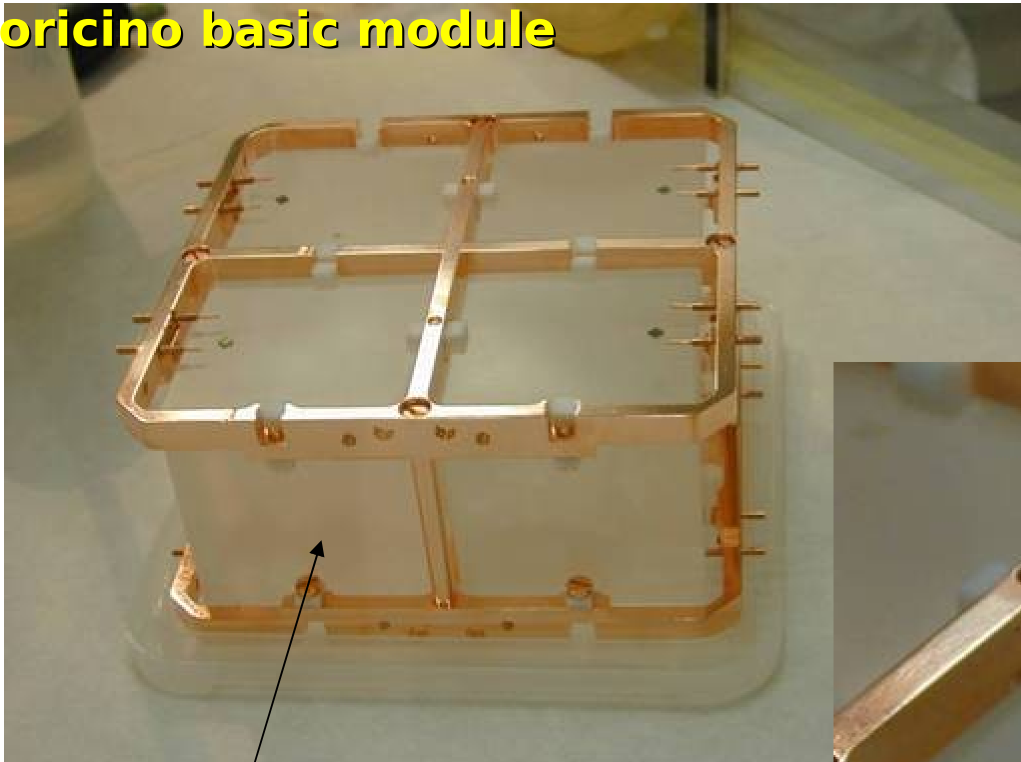
Thermal coupling
$G \cong 4$ nW / K = 4 pW / mK

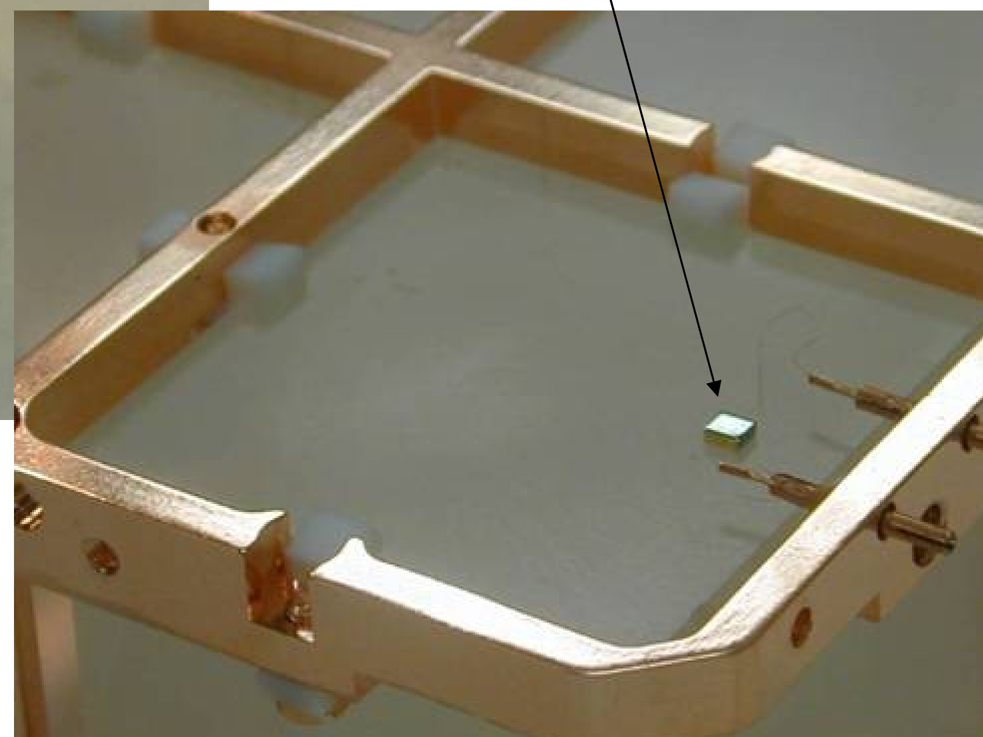
- Temperature signal: $DT = E/C \cong 0.1$ mK for $E = 1$ MeV
- Bias: $I \cong 0.1$ nA $\Rightarrow$ Joule power $\cong 1$ pW $\Rightarrow$ Temperature rise $\cong 0.25$ mK
- Voltage signal: $DV = I \times dR/dT \times DT \Rightarrow DV = 1$ mV for $E = 1$ MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s
- Noise over signal bandwidth (a few Hz): $V_{rms} = 0.2\ \mu V$

In real life signal about a factor 2 - 3 smaller

Energy resolution (FWHM): $\cong$ 1 keV

A physical realization of bolometers for DBD





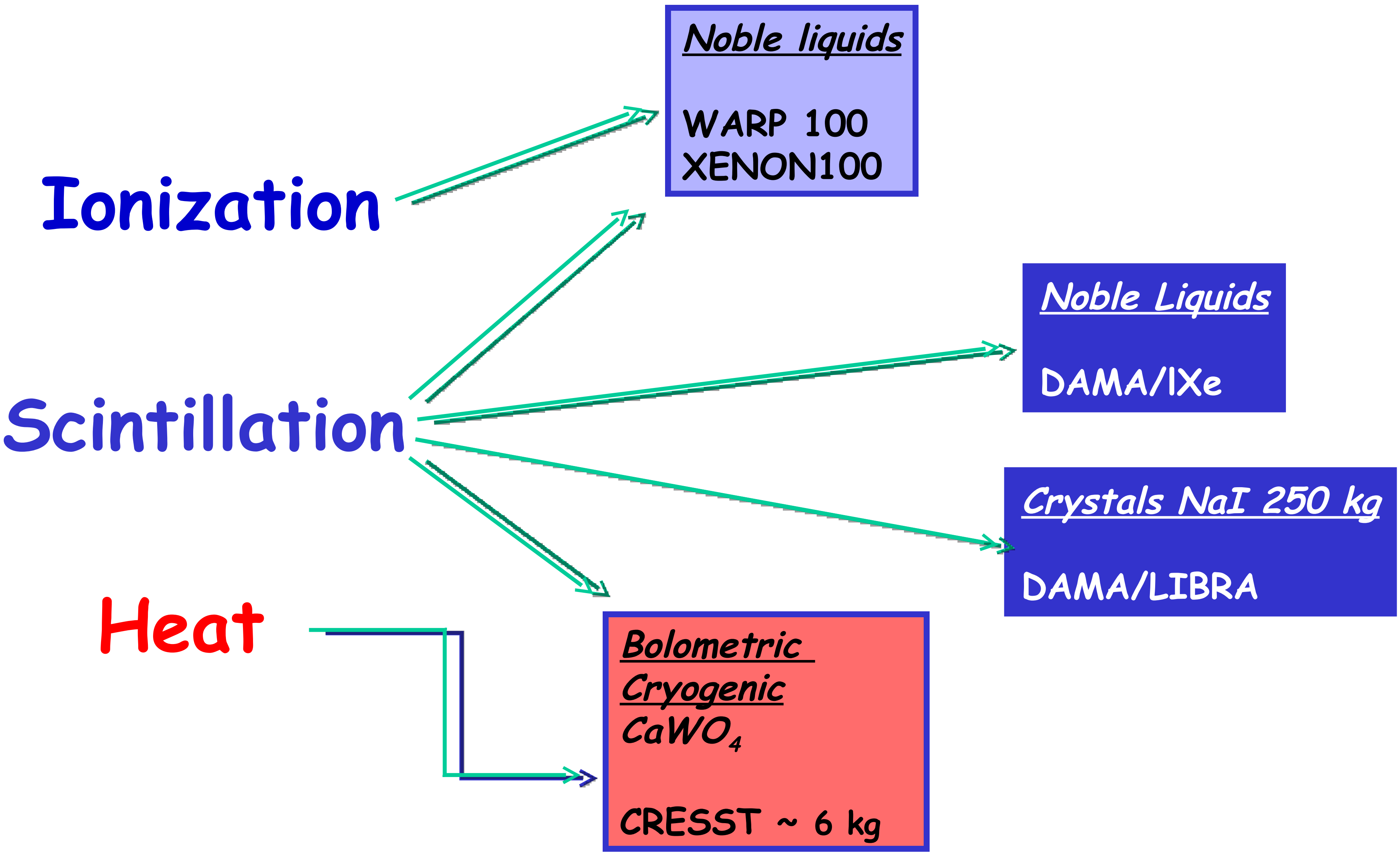
Thermometer
(doped Ge chip)

Energy absorber
single TeO_2 crystal
- 790 g
- 5 x 5 x 5 cm

DARK MATTER

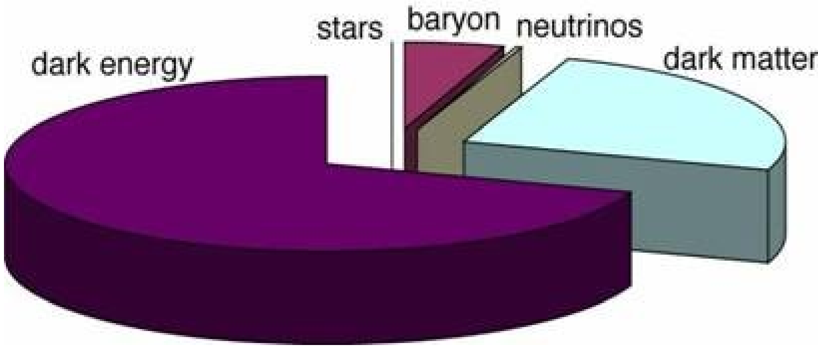
Dark matter

Different methods and techniques towards a "smoking gun" signature



Dark Matter

The velocity with which cloud of gas rotate around galaxies indicates that the mass of the galaxies themselves is greater, (around 10 times), than the visible mass of the stars they contain. The matter that can be observed through traditional instruments is only few per cent of all the energy contained in the Universe. More than 90% of the Universe does not emit light [is DARK (energy and matter)].



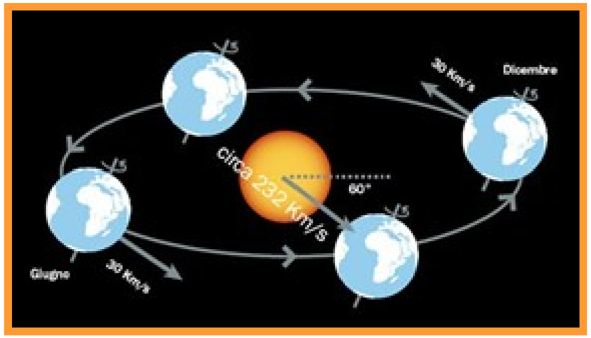
- Stars and galaxies are only 0.1%
- Neutrinos are ~0.1-10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~25%
- Dark Energy ~70%
- Anti-Matter 0%

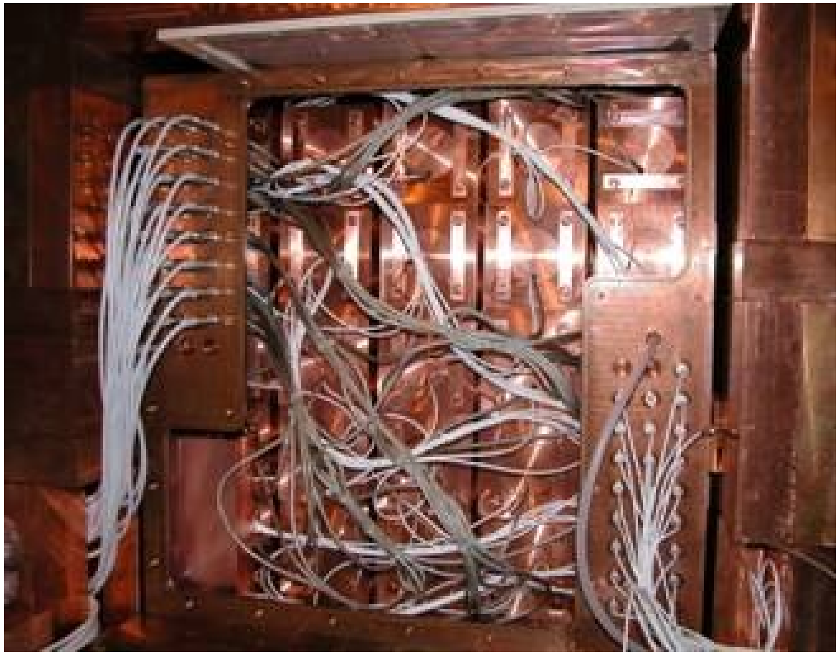
WIMP (Weakly Interacting massive Particles) is a possible candidate as fundamental particle of the Dark Matter

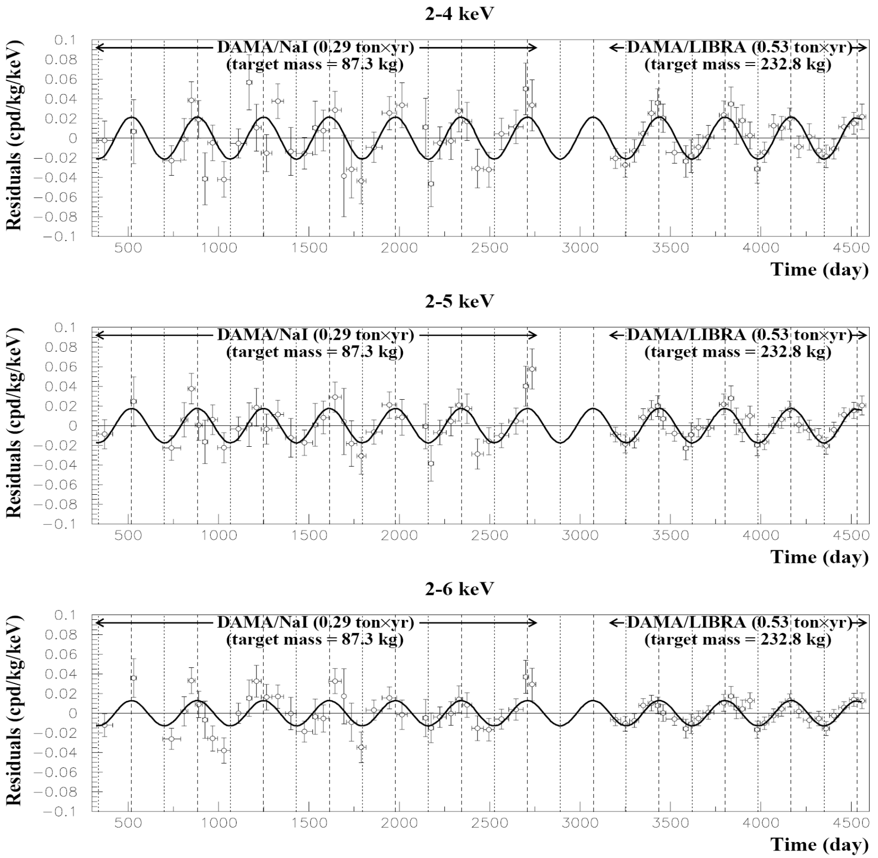
WIMPs should be produced in the Big Bang. They should be heavy (50, 100 times the proton mass) and without electric charge.

DArk MAtter search

DAMA's aim is to detect dark matter particle (WIMP) looking for the so called **"annual modulation"**. WIMPs (Weakly Interacting Massive Particle) detection through the flash of light produced by a Iodine nucleus recoiling after having been hit by a WIMP.
Since march 2003, the new upgraded apparatus DAMA/LIBRA is working.







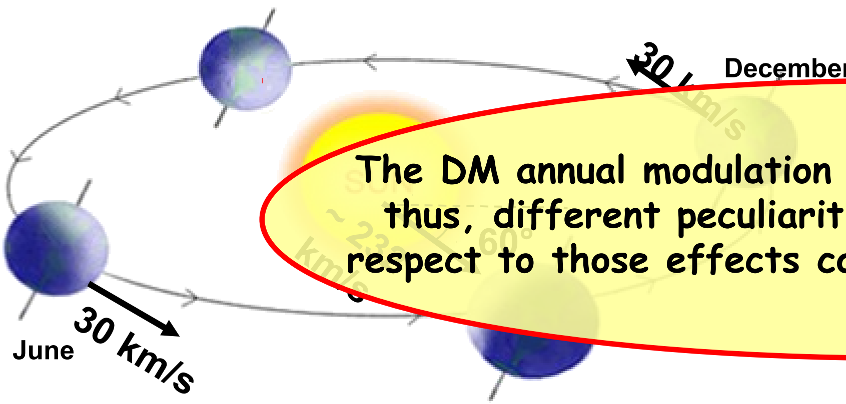
DAMA experiment, up to the 2003, employed **100 kg** of sodium iodine cristals NaI(Tl), since 2003 to now, the detector is working by using **250 kg** of **NaI**.

It is the only available experiment sensitive to the annual modulation.

The DM annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

As a consequence of its annual revolution around the Sun, which is moving in the Galaxy, the Earth should be crossed by a larger flux of Dark Matter particles around 2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around 2 December (when the two velocities are subtracted).

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2[nd] June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

The DM annual modulation effect has different origins and, thus, different peculiarities (e.g. mainly the phase) with respect to those effects connected instead with the seasons

Expected rate in given energy bin changes because of the annual motion of the Earth around the Sun moving in the Galaxy

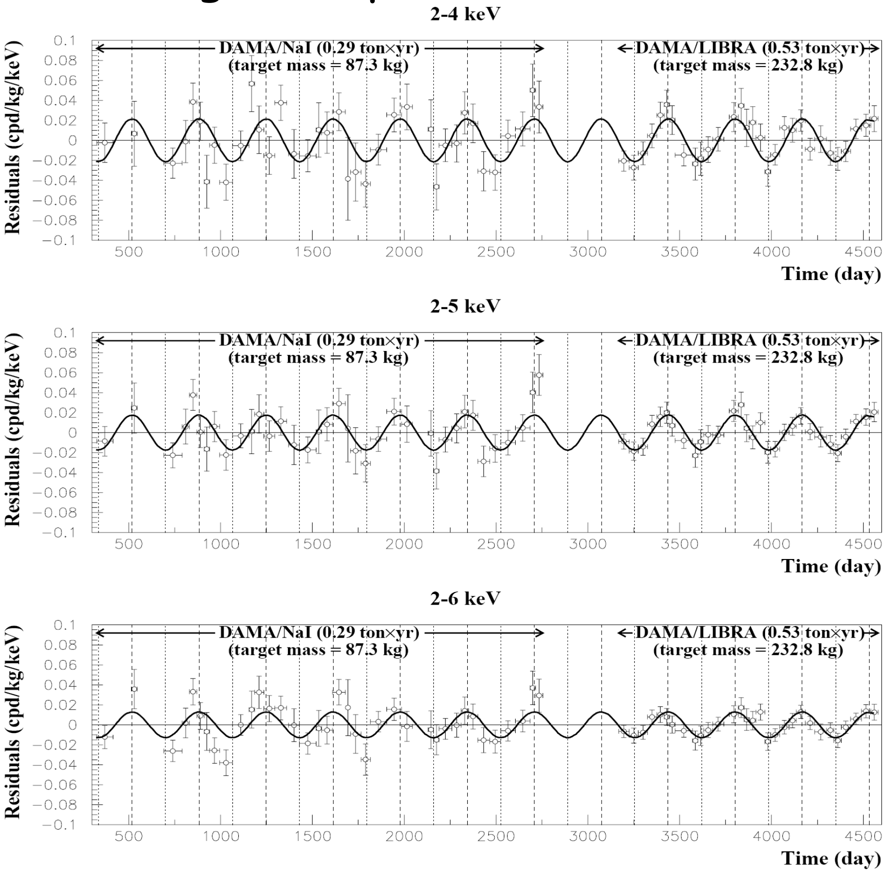
Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

To mimic this signature, systematics and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

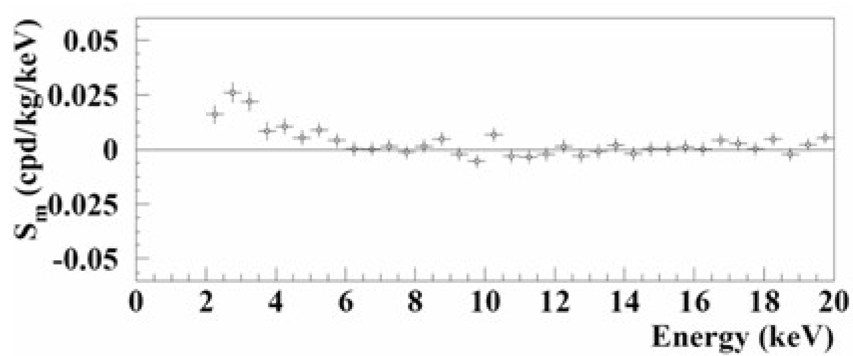
DArk MAtter search

DAMA/NaI (7 years) + DAMA/LIBRA (6 years). Total exposure: 1.17 ton×yr (the largest exposure ever collected in this field)



The modulation is present only in the low energy **2÷6 keV** range and not in other higher energy regions, consistently with expectation for the Dark Matter signal.

- **No modulation above 6 keV**



DAMA/LIBRA: Status and perspectives

Status

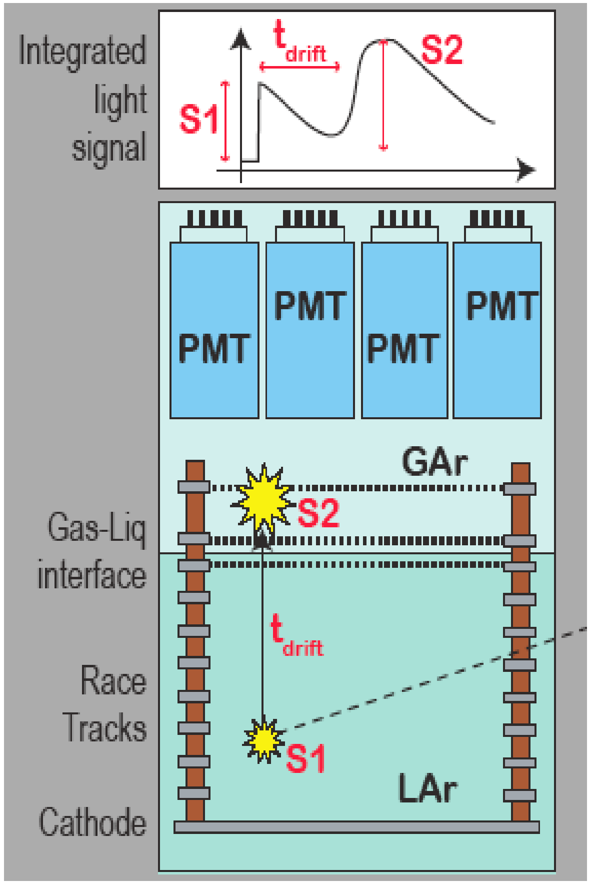
- First data release on April 2008
- First upgrading on September 2008
- New data release in February 2010
- In data taking
- New higher Q.E. PMTs under construction

Perspectives

- Next foreseen upgrading → substitution of all the PMTs with higher Q.E. ones
- Achieve an extremely large exposure to achieve a very large C.L. and to investigate with very high sensitivity the related astrophysics, nuclear and particle Physics scenario and second order effects as regards DM as well as many rare processes in ^{23}Na and ^{127}I

Wimp ARgon Programme

Dark Matter can be detected by collecting and analyzing the scintillation light produced by the interaction between WIMP and particular materials, Liquid Argon (-186 °C) in the case of WARP.



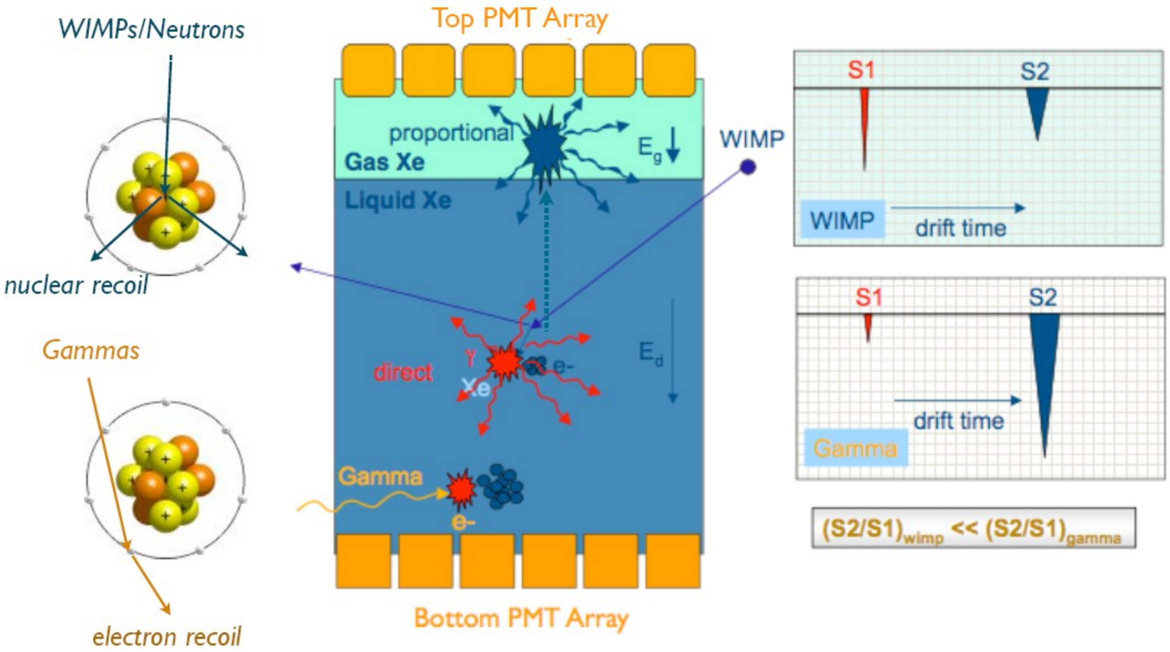
- 140 kg (100 l) active target
- Complete neutron shield
- 4π active neutron veto (9 tons Liquid Argon, 300 PMTs)
- 3D Event localization and definition of fiducial volume for surface background rejection
- detection threshold of < 20 KeV_{ion}

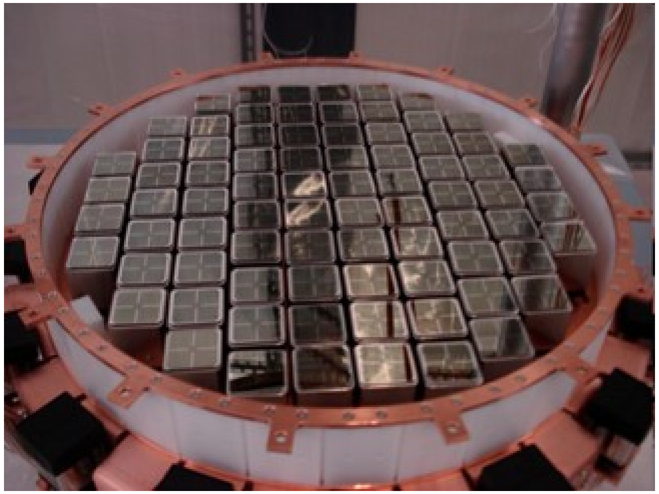
The WArP 100l detector is installed in the hall B of the Gran Sasso laboratory and is actually being filled with liquid argon.

WARP-100: 100 l of Liquid Argon TPC with an intense electric field applied. The detector measures simultaneously the scintillation and the ionization produced by radiation in pure Ar, to discriminates signal from background.

XENON 10 - 100 experiment

XENON100 is a new dark matter search experiment, aiming to increase the fiducial liquid xenon target mass to 100 kg with a 100 times reduction in background rate, compared to the XENON10 experiment.

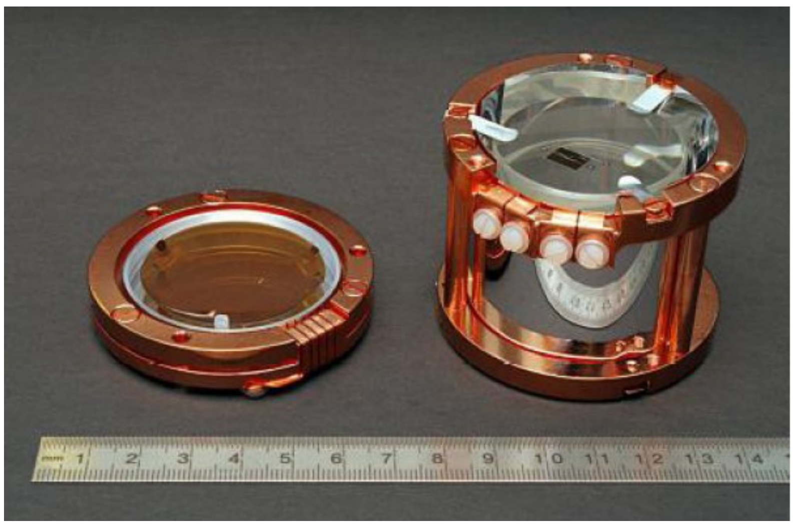


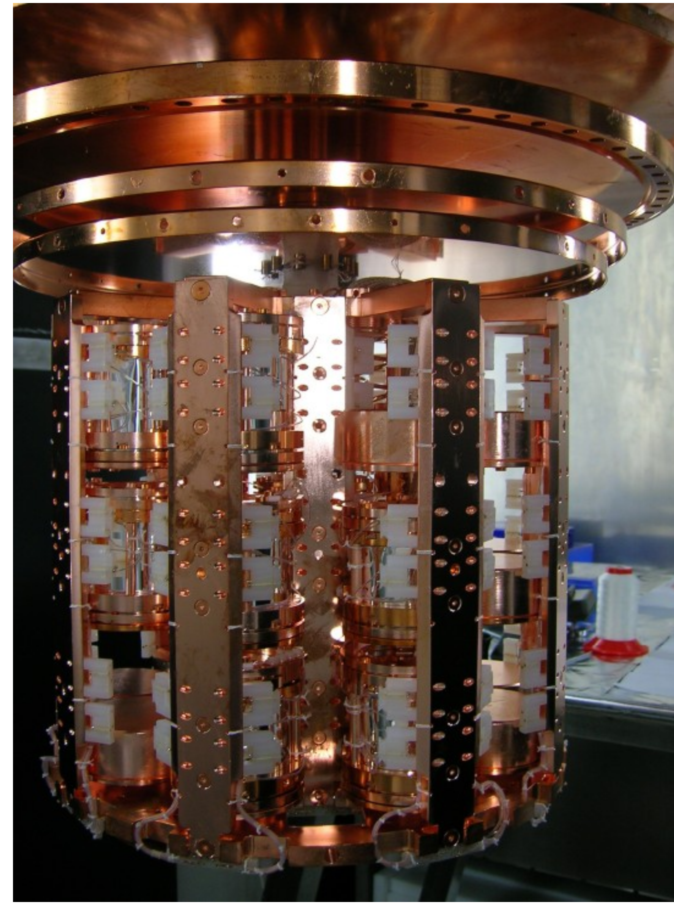


It is a position-sensitive XeTPC, with the sensitive LXe volume viewed by two arrays of total 178 photomultiplier tubes (PMTs), to detect simultaneously the primary scintillation signal (S1) and the ionization signal via the proportional scintillation mechanism (S2).

Cryogenic Rare Event Search with Superconducting Thermometers

The CRESST experiment is able to detect the interaction between WIMP and traditional matter by measuring the temperature increase (very tiny) induced by the energy deposition inside a crystal. The hearth of the detector is cooled up to 15 mK over the absolute zero. In the CRESST first phase, 260 g of Sapphire crystals were used.
Presently, the experimental performances have been upgraded by using 300 g of $CaWO_4$ crystals.



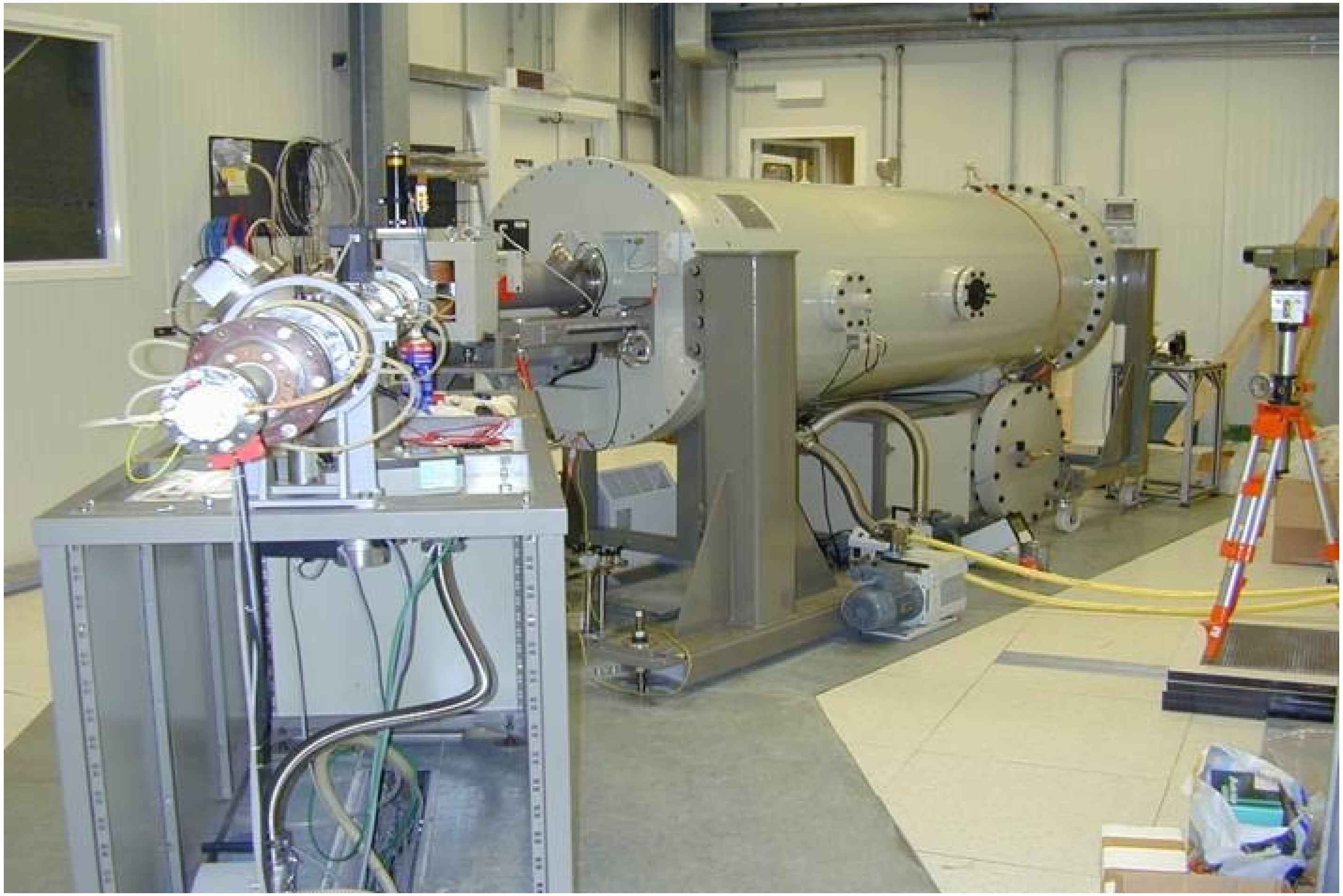


Combined mesurements

Phonon channel: Scintillating $CaWO_4$-crystal (300g, height=40mm) as target with W-TES on top

Light channel: SOS (Silicon on Sapphire) crystal (=40mm) with W-TES on top

Laboratory for Underground Nuclear Astrophysics



400 kV Accelerator : $E_{beam} \approx 50 - 400$ keV

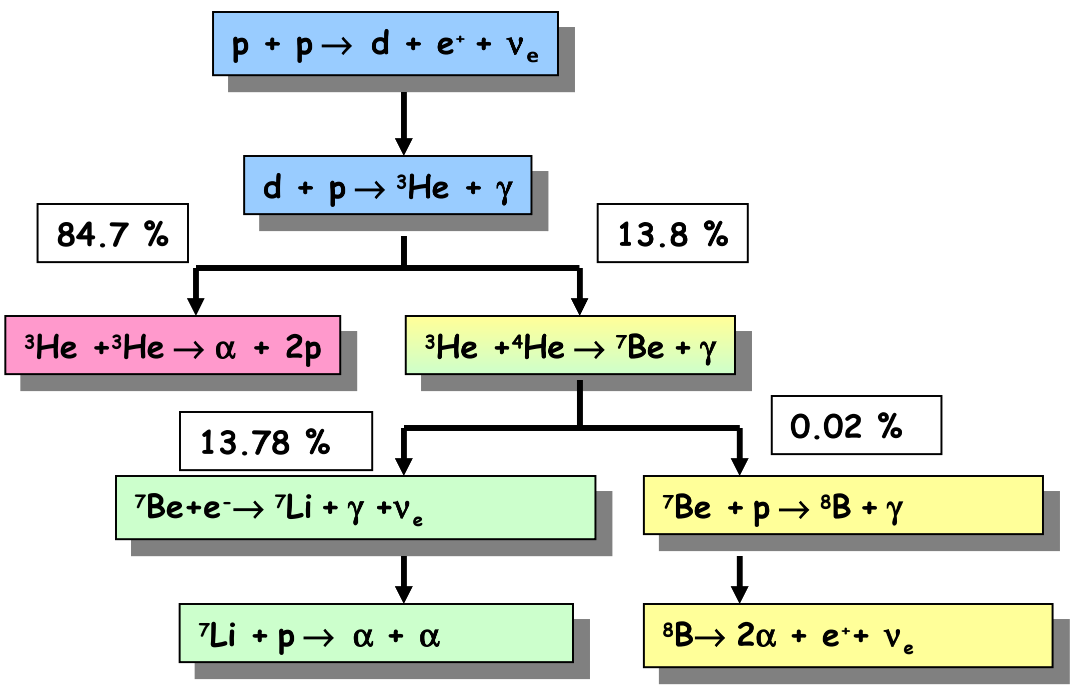
$I_{max} \approx 500\ \mu A$ protons $I_{max} \approx 250\ \mu A$ alphas

Energy spread ≈ 70 eV Long term stability ≈ 5eV/h

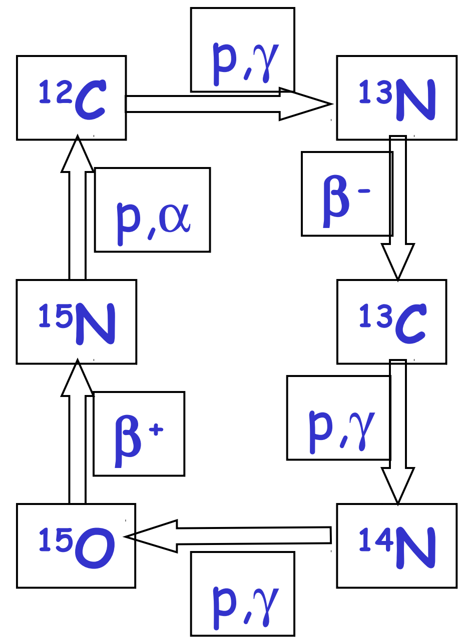
Hydrogen burning

produces energy for most of the life of the stars

pp chain



CNO cycle



$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$