Astroparticle Physisc at LNGS

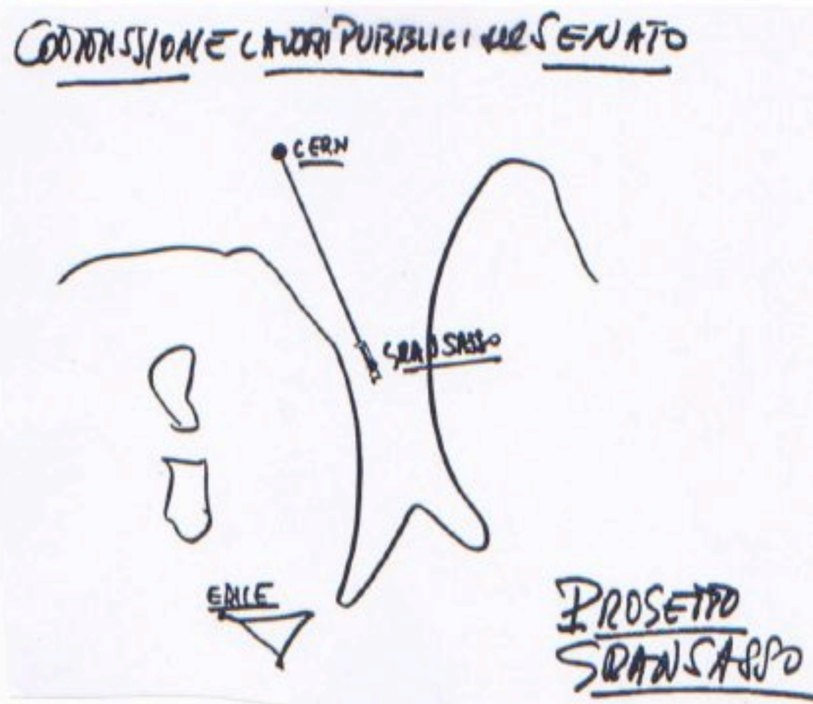
Vulcano 2014

Stefano Ragazzi – LNGS Director

Laboratori Naztionali del Gran Sasso

INTRODUCTION

The birth

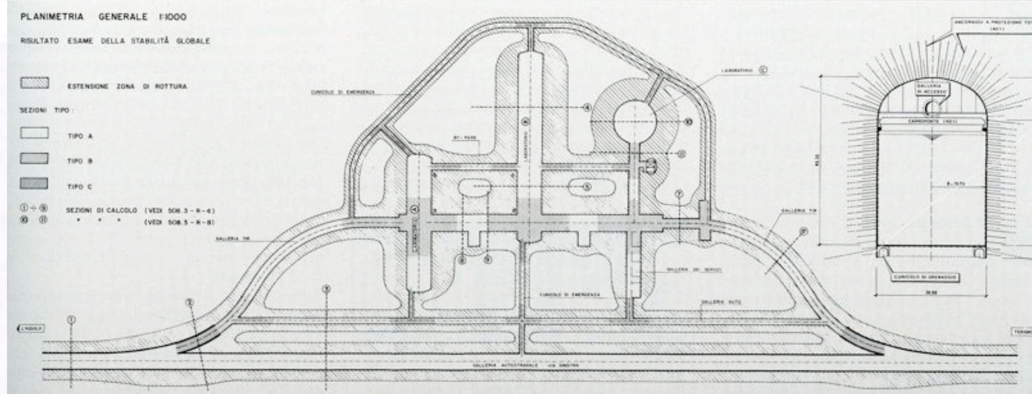


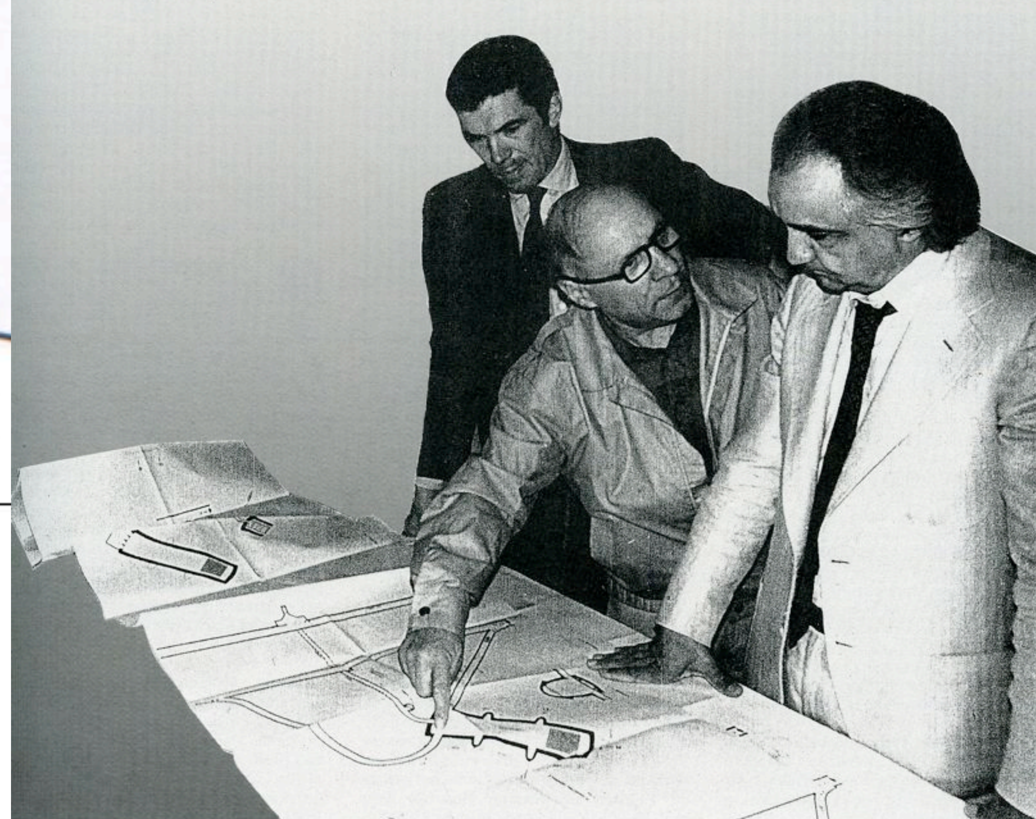
Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

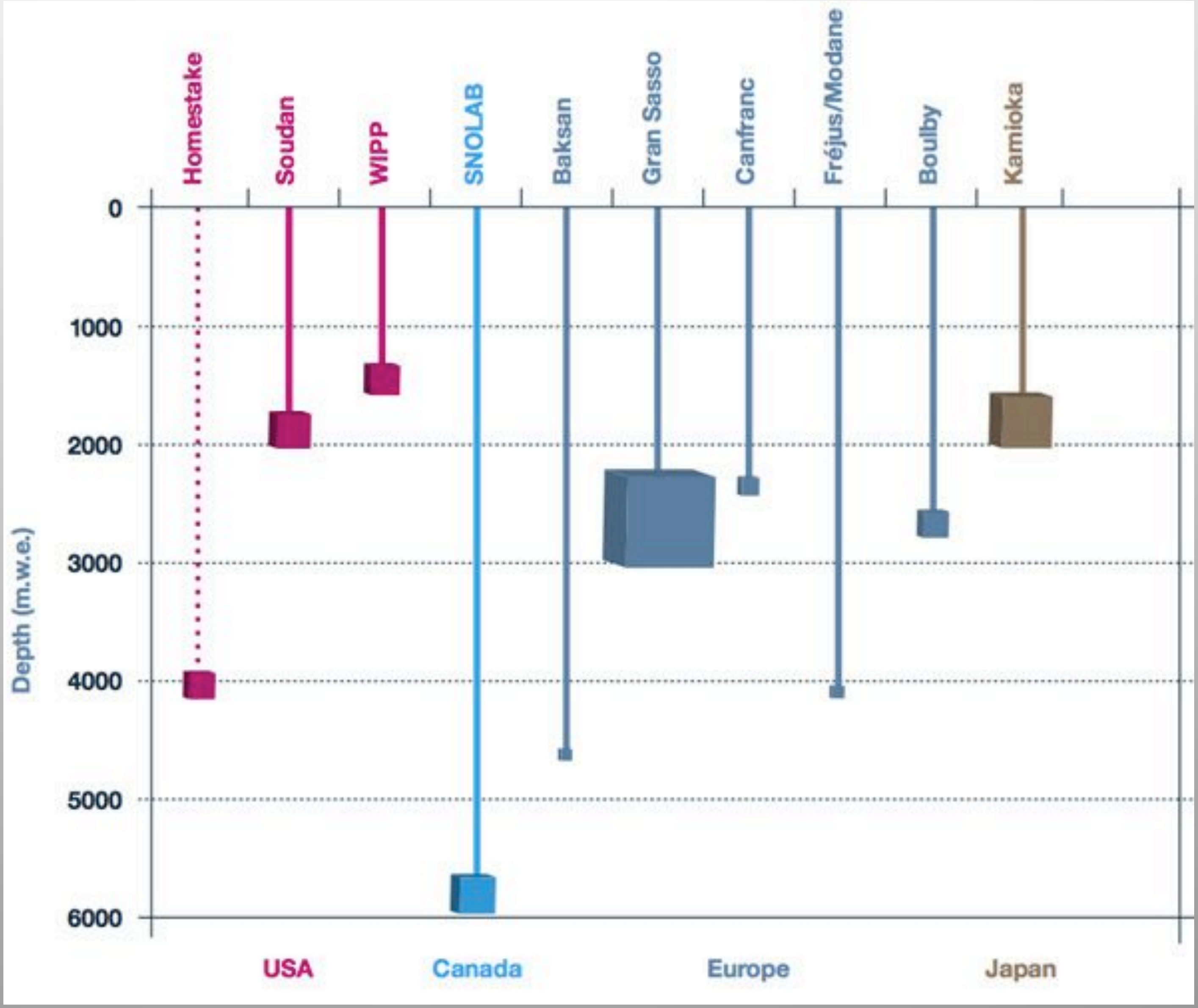
NOT only $\tau_p \neq \infty$





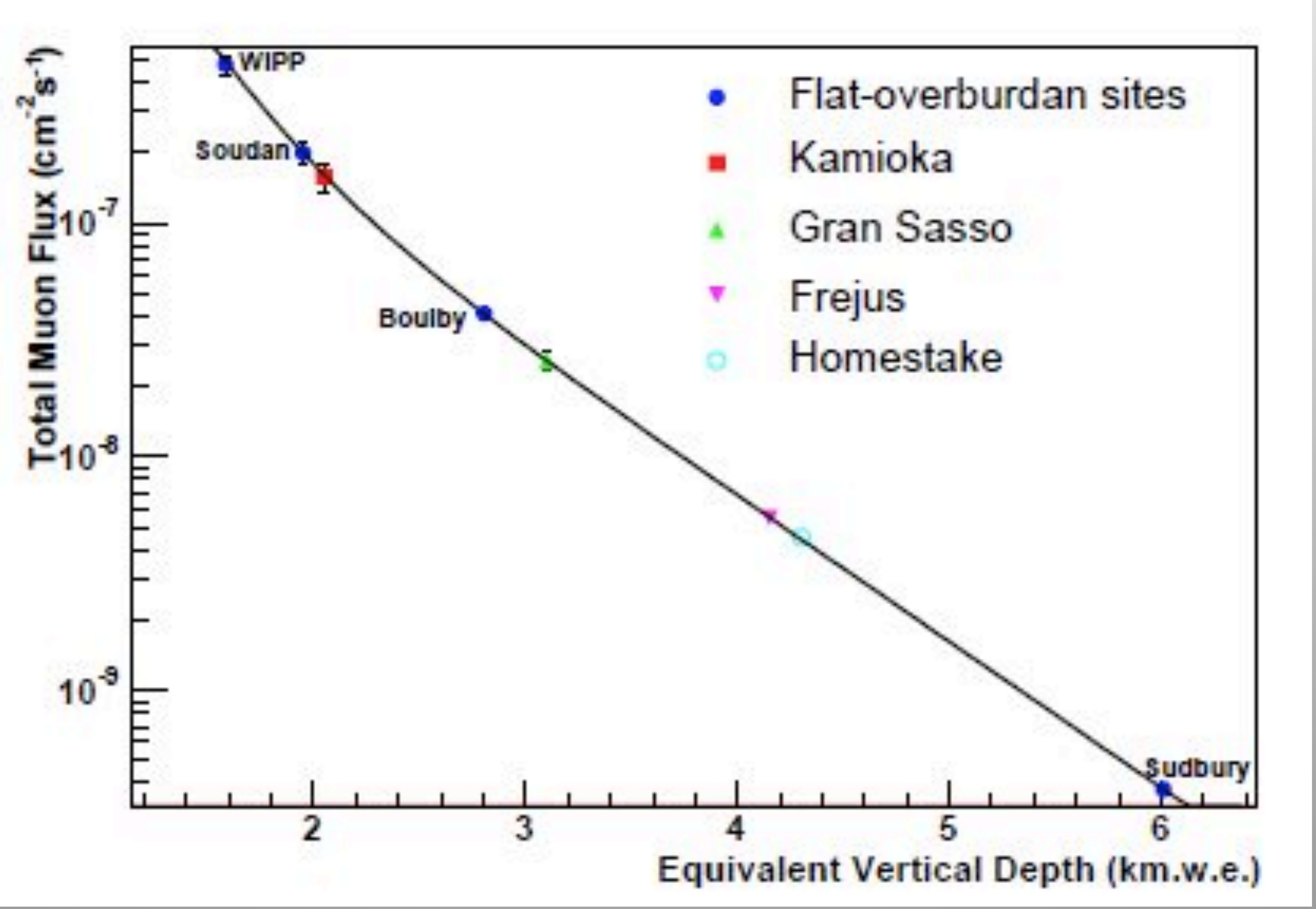
Underground Science Laboratories

- **LNGS**
  – **Largest**



Plot adapted from http://www.deepscience.org/contents/facilities.shtml

Muon Flux versus depth



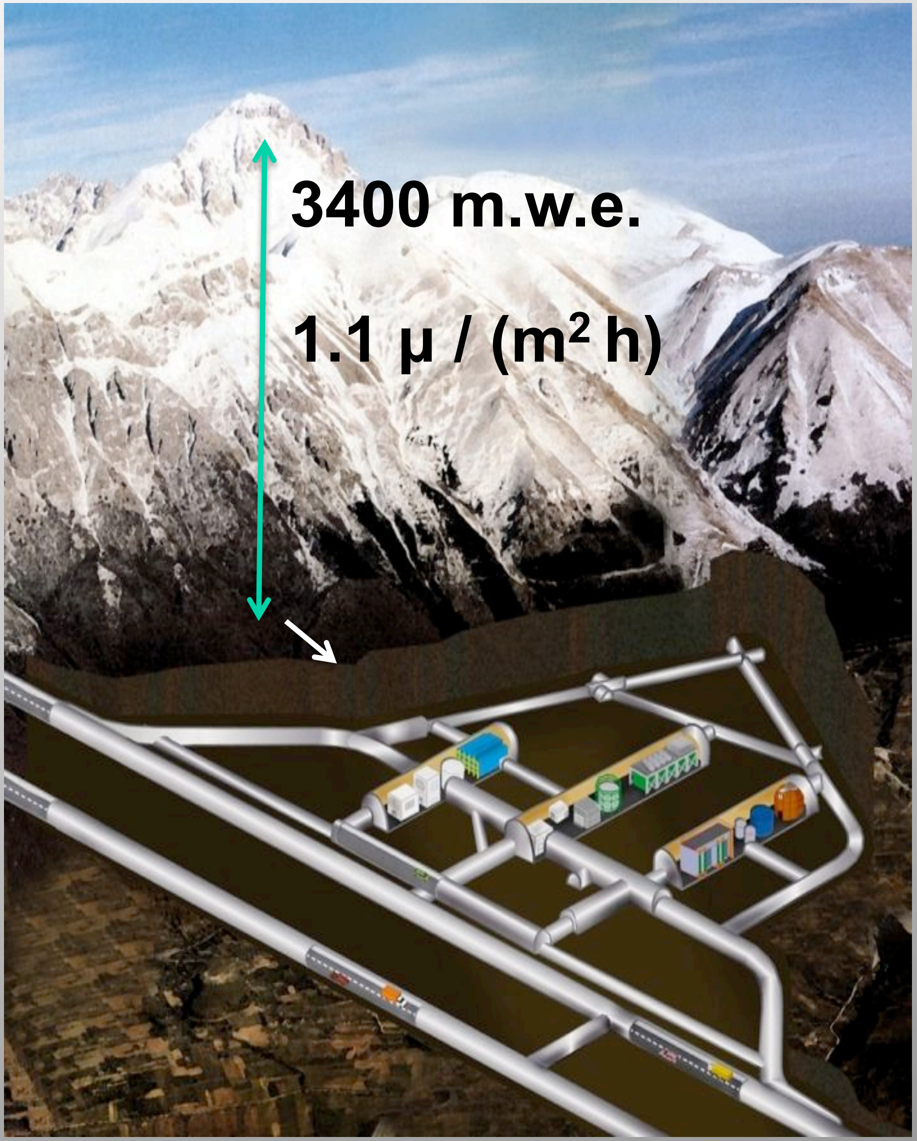
Hime and Mei, Phys.Rev. D73 (2006) 053004

The LNGS Laboratory

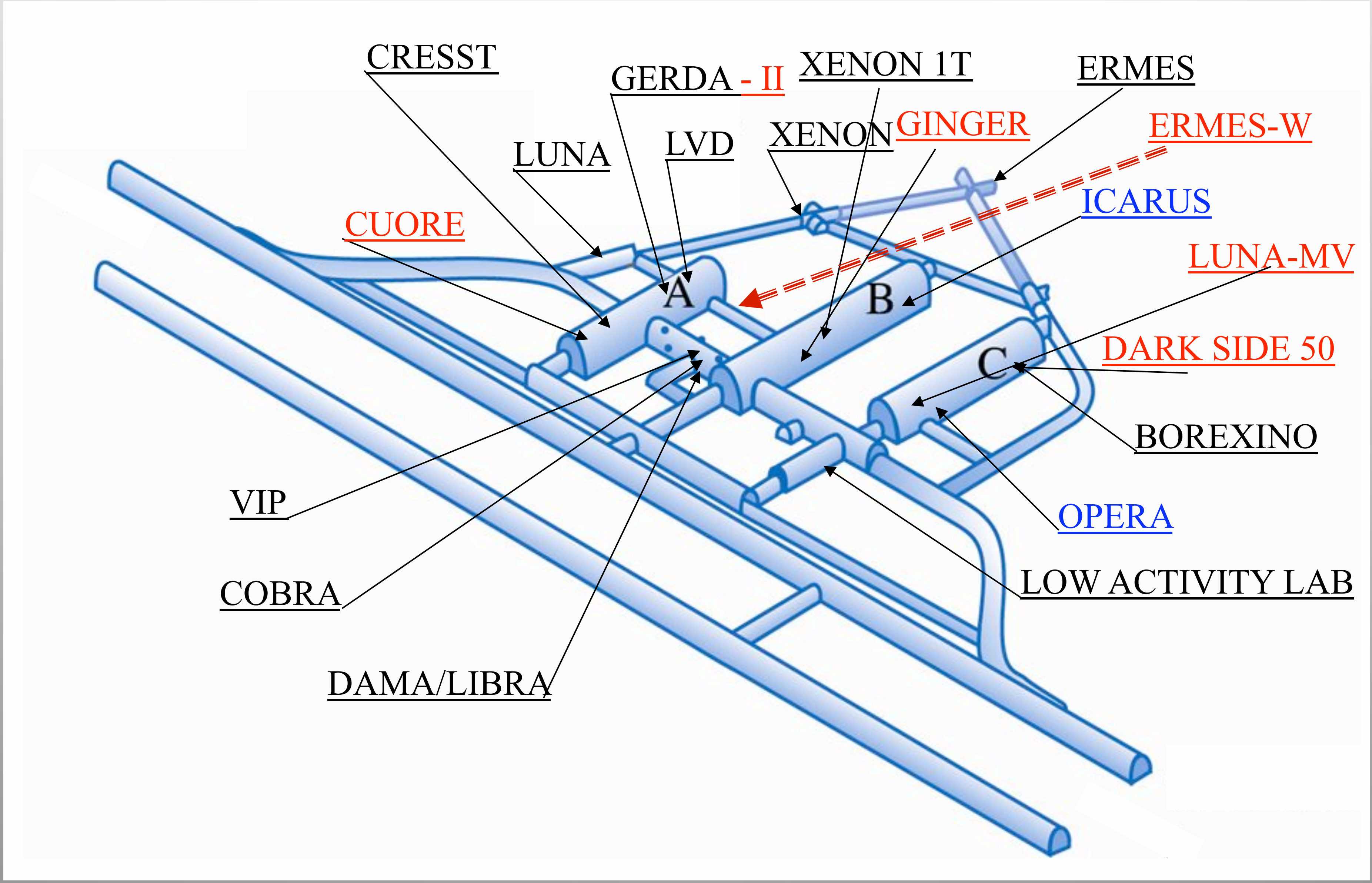
- Muon flux: 3.0 10^{-4} $m^{-2}s^{-1}$
- Neutron flux:

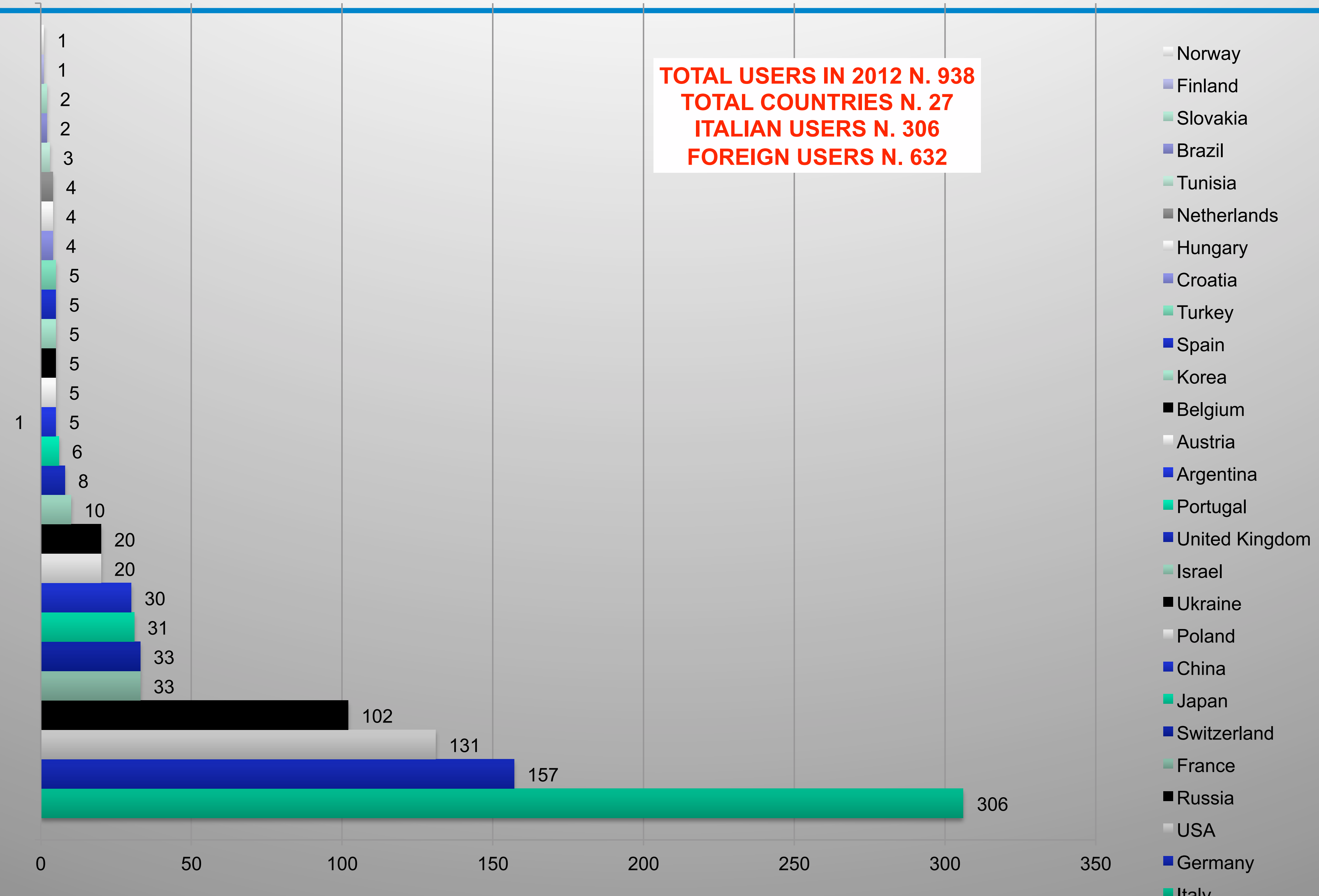
  2.92 10^{-6} $cm^{-2}s^{-1}$ (0-1 keV)

  0.86 10^{-6} $cm^{-2}s^{-1}$ (> 1 keV)
- Rn in air: 20-80 Bq m^{-3}
- Surface: 17 800 m^2
- Volume: 180 000 m^3
- Ventilation: 1 vol / 3 hours



A busy laboratory





TOTAL USERS IN 2012 N. 938
TOTAL COUNTRIES N. 27
ITALIAN USERS N. 306
FOREIGN USERS N. 632
1
1
2
2
3
4
4
4
5
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30
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102
131
157
306
0
50
100
150
200
250
300
350
Norway
Finland
Slovakia
Brazil
Tunisia
Netherlands
Hungary
Croatia
Turkey
Spain
Korea
Belgium
Austria
Argentina
Portugal
United Kingdom
Israel
Ukraine
Poland
China
Japan
Switzerland
France
Russia
USA
Germany
Italy

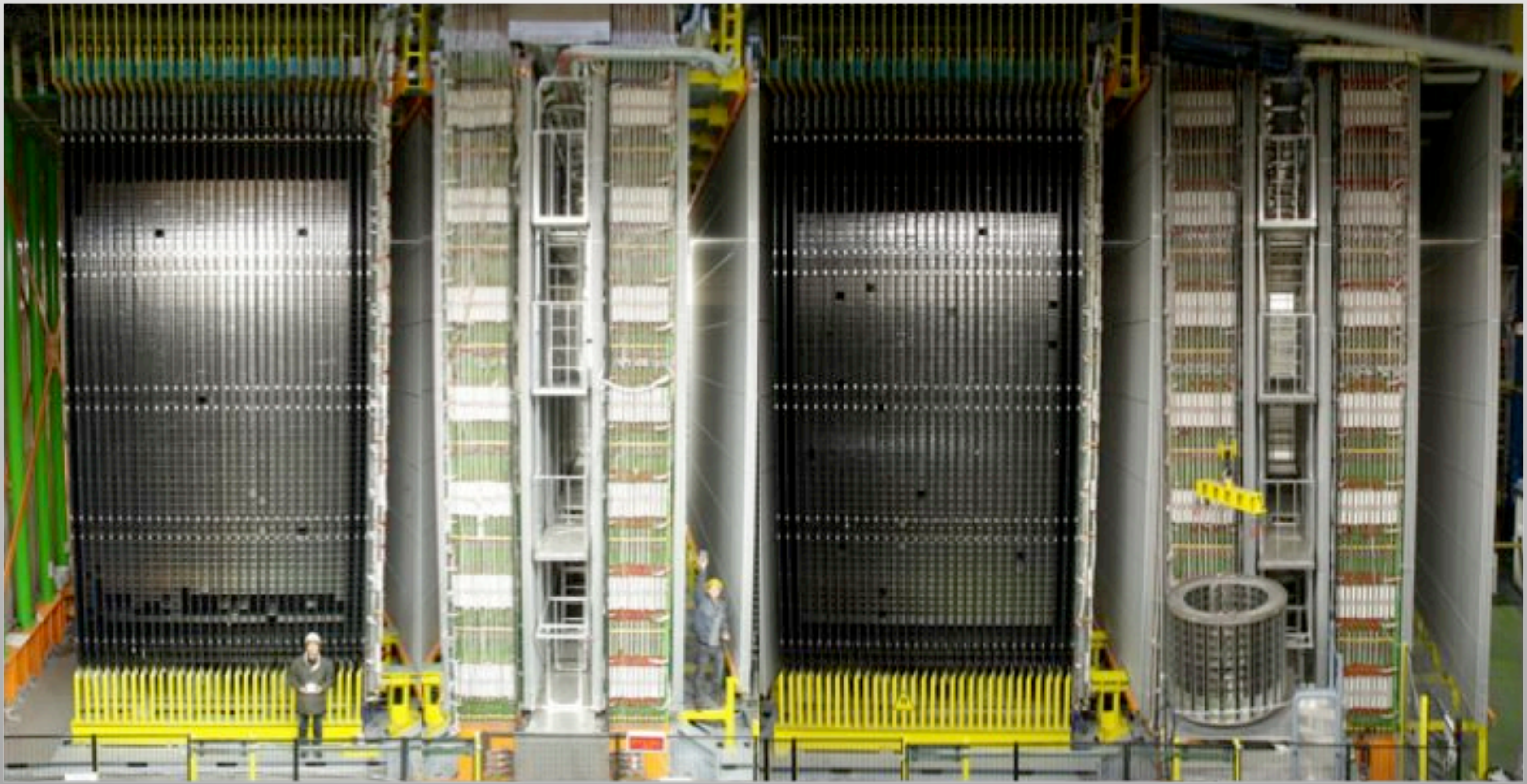
Selected topics in APP at LNGS
NOT
a comprehensive review of physics at LNGS

- High energy neutrinos
- Cosmogenic and solar neutrinos
- Neutrino properties
- Dark matter searches

HIGH-ENERGY NEUTRINOS CNGS

OPERA

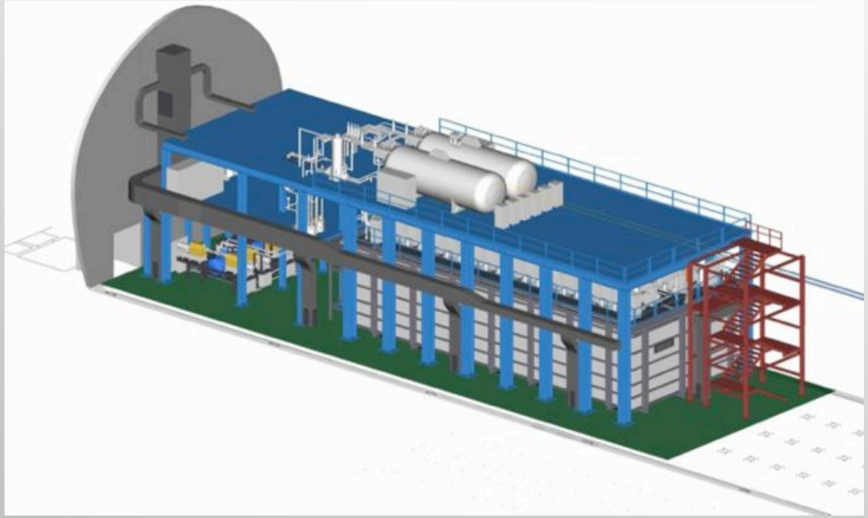
SM-1 SM-2



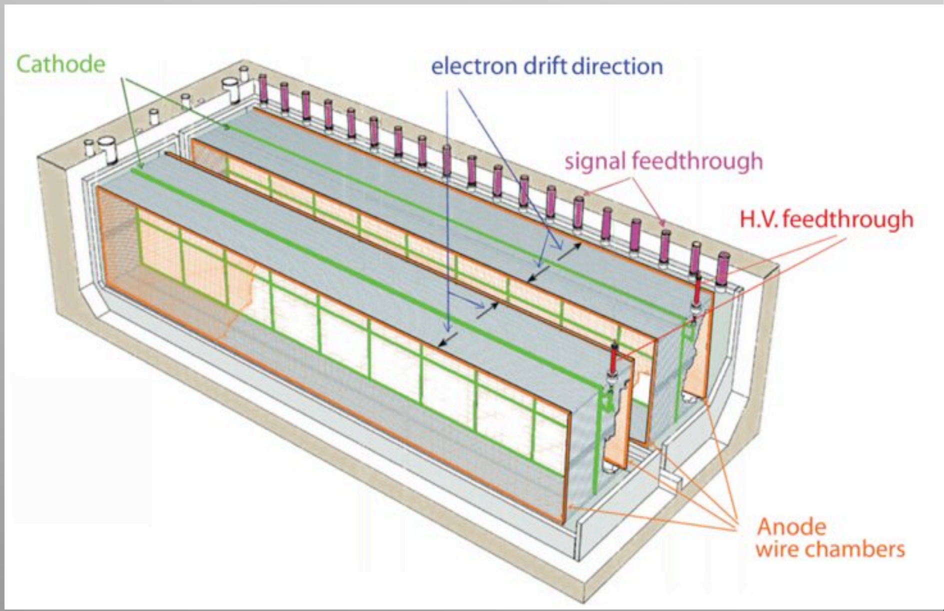
τ - appearance

See Chiara Sirignano's talk on Thursday

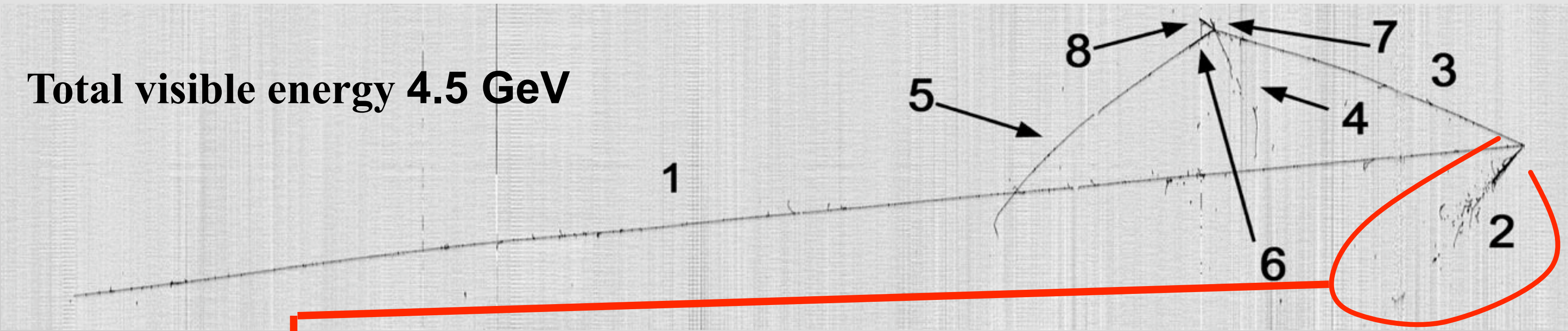
ICARUS-T600 @ LNGS

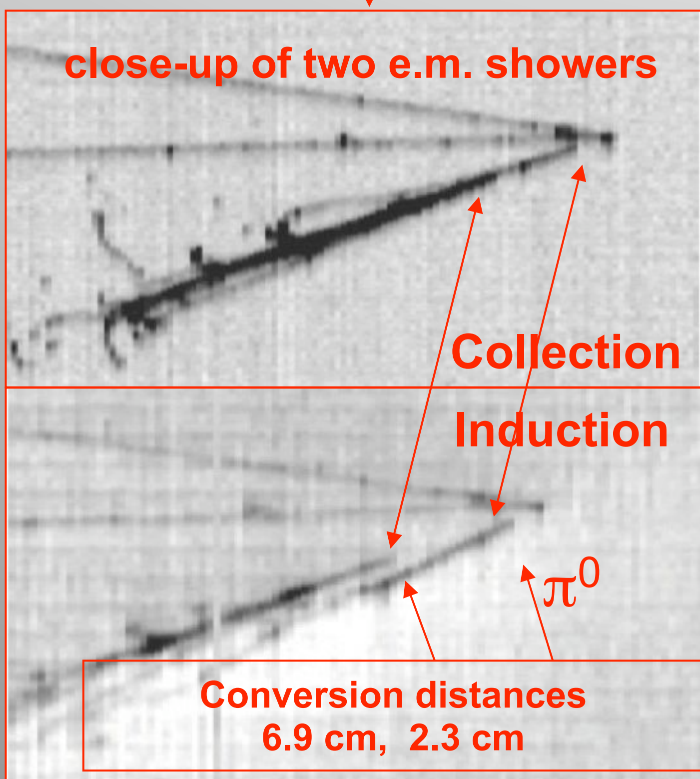


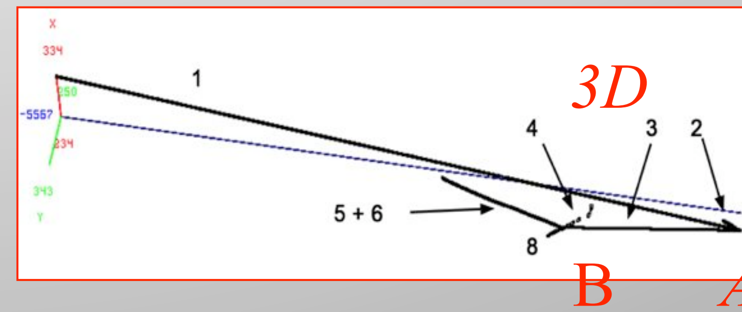
0.77 kton LAr-TPC



The LAR-TPC: the electronic bubble chamber







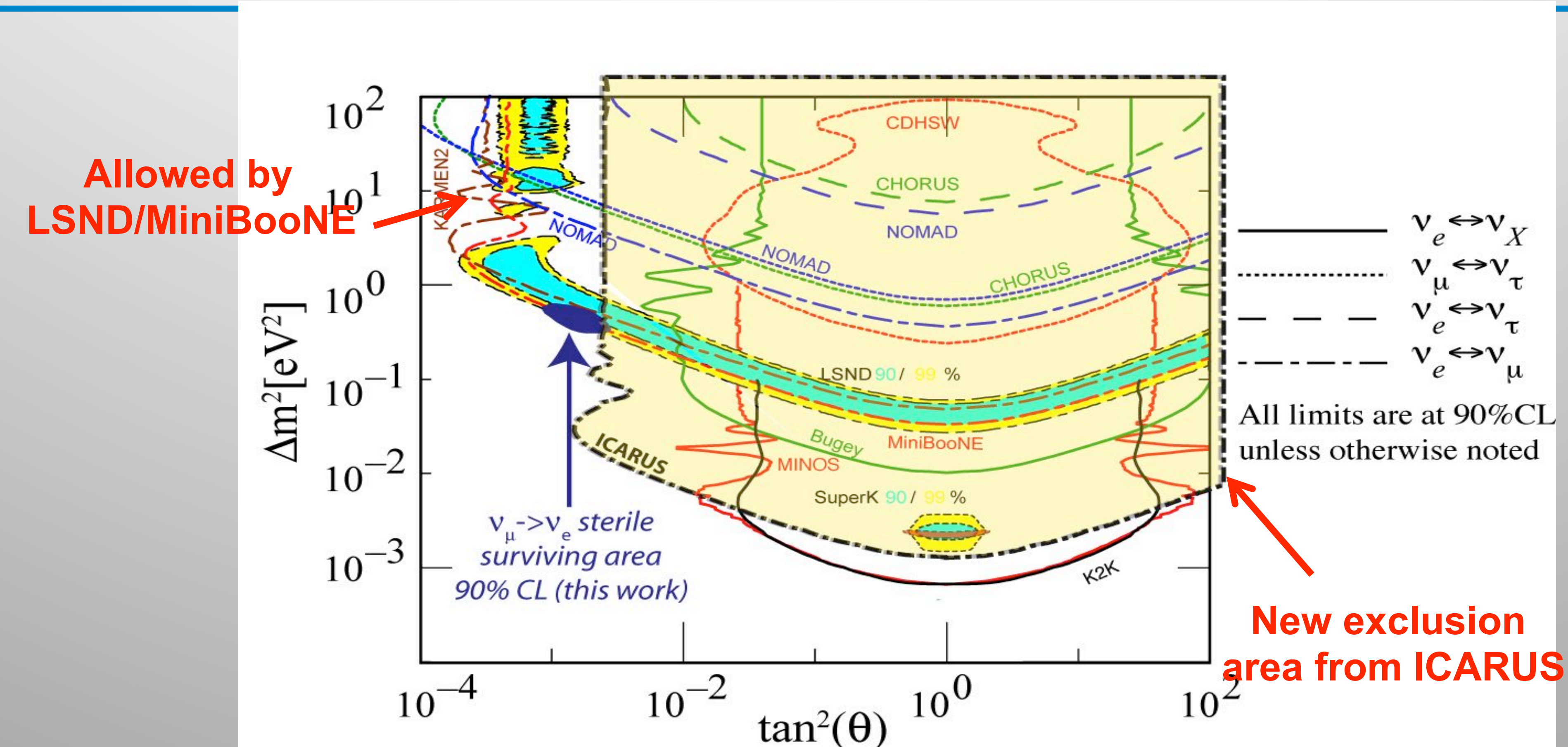
Primary vertex (A):

very long μ (1), e.m.cascades(2), π (3)

Secondary vertex (B):

longest track (5) is a μ from stopping K (6)
μ decay is observed

LSND-like exclusion



- **ICARUS result strongly limits parameters for LSND anomaly**
  - **(Δm^2–$\sin^2 2\theta$) = (0.5 eV^2-0.005)**
- **overall agreement (90 % CL) between:**
  - **ICARUS, KARMEN and "signals" of LSND and MiniBooNE**

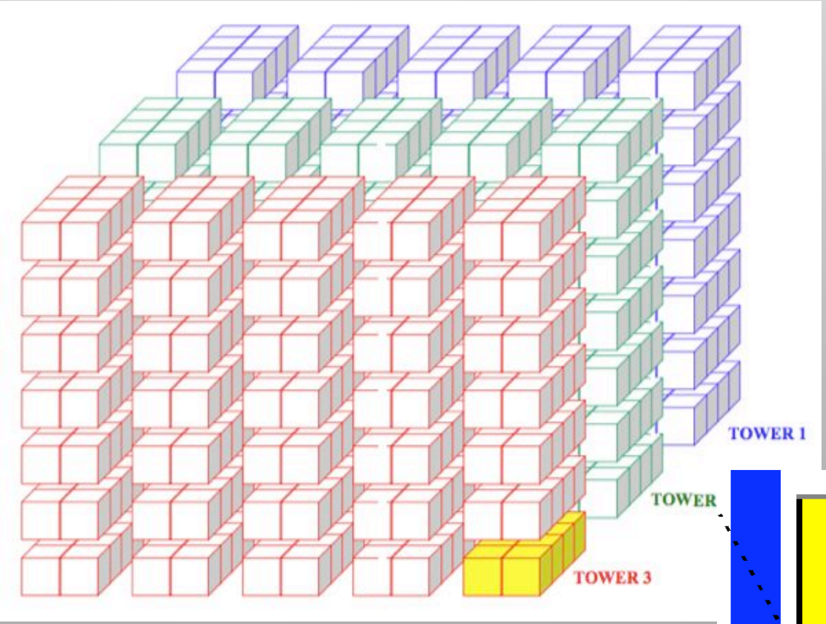
ICARUS T600 timeline

- **2010: Successful assembly and commissioning of ICARUS-T600:**
  - **May 28th : first CNGS neutrino**
  - **October: start of physics runs**
- **2011 – Dec 3rd, 2012:**
  - **T600 data-taking with CNGS beam and cosmic rays**
    - **2800 CC + 900 NC**
    - **Muons from upstream GS rock ≈ 12000 ev (≈ 8200 on TPC front face)**
    - **Intrinsic beam νe CC ≈ 26 ev**
    - **ν_μ -> ν_τ with kinematic ν_τ -selection (~2 event τ ->e) ν_μ -> ν_e (θ_{13}) from e-like CC events**
    - **excess at E < 20 GeV (~5 events CC)**
    - **Search for ν_s in LSND parameter space, studying e-like CC events at E > 10 GeV**
  - **Nov. 2011 & March 2012: bunched beam for v velocity measurement**
- **Dec.2012 – June 2013:**
  - **Data-taking with cosmic ray**
- **July 2013 - 2014**
  - **Decommissioning**
- **2015 onward**
  - **CERN**

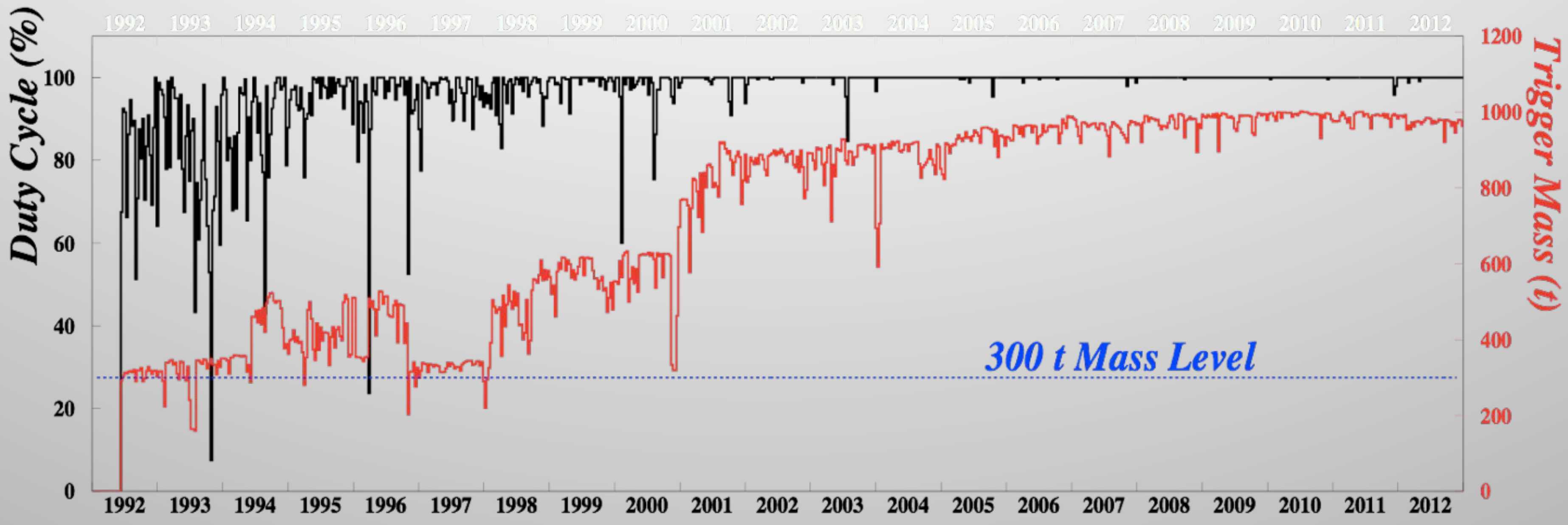
SOLAR AND COSMOGENIC NEUTRINOS

Search for ν from Core Collapse Supernovae

- LVD live since 1992.
- 90% c.l. upper limit of gravitational stellar collapses ($D \leq 20$ kpc)
  $R < 0.12$ events/year

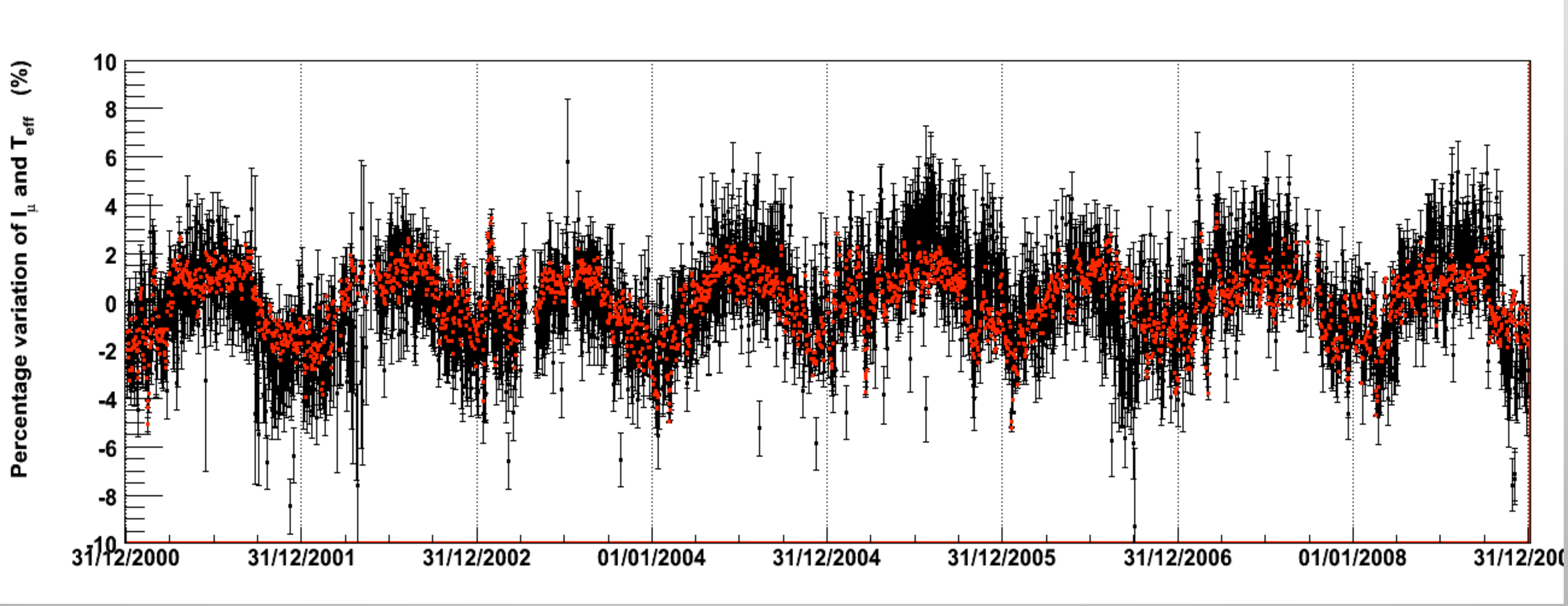


Duty factor



- **Need large mass**
  - **1 kT**
- **Need high availability**
  - **~100%**

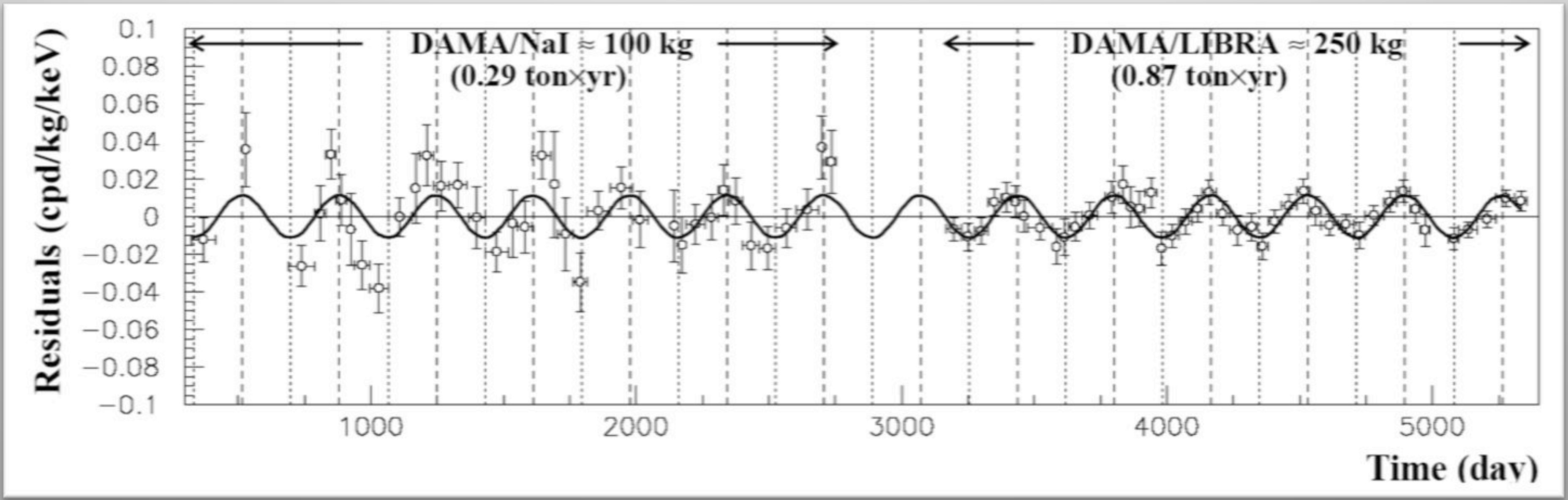
Seasonal modulation of muon flux



2001-2008.

NOT the same as

DAMA: see talk of Rita Bernabei on Tuesday



N.B. significant phase shift

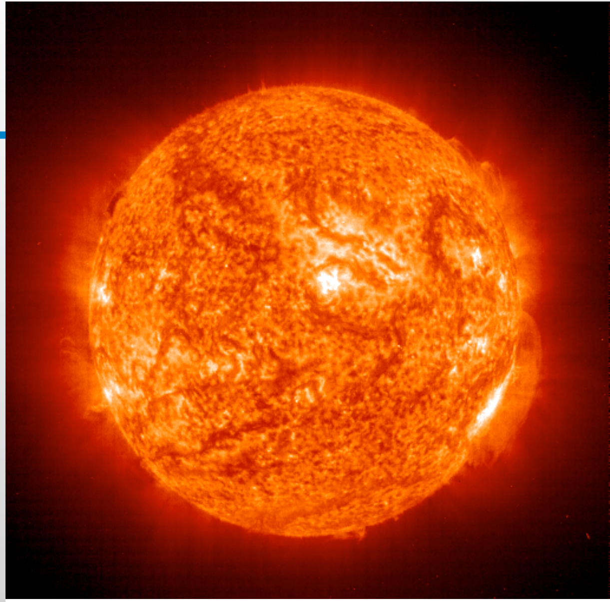
…. and for the future

Continue data taking trying to keep the experiment as much performing as it was since the past 21 years!

AND catch an SN collapse

Solar Neutrinos

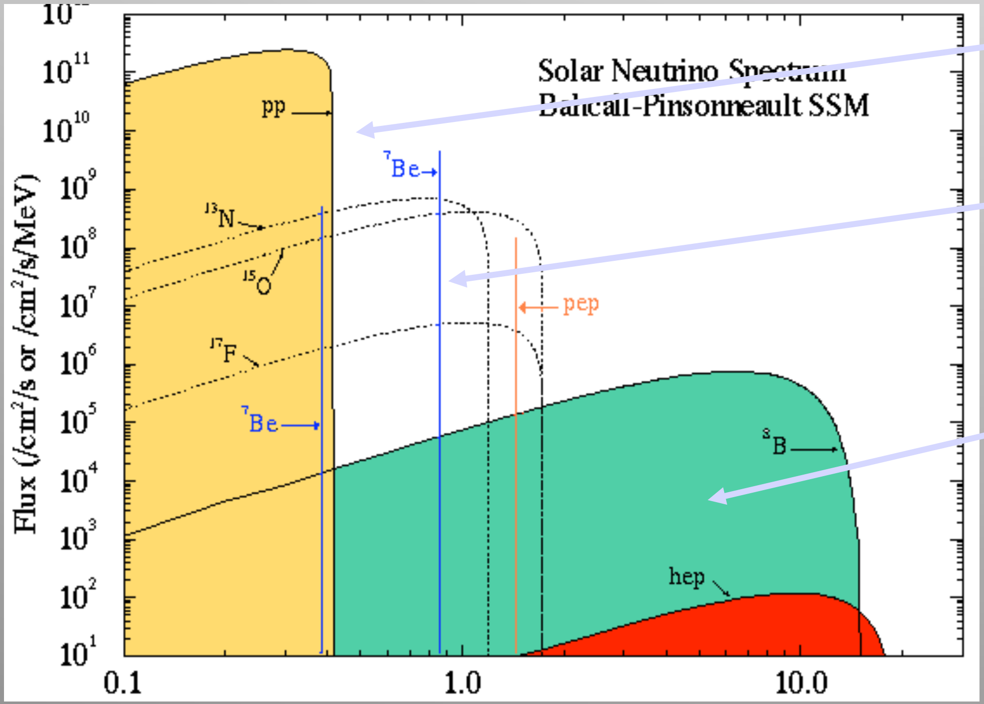
- neutrinos are produced in the sun



Of the 3 types of neutrino
  - electron, muon, tau

only electron neutrinos come from the sun

pp	$\rightarrow$	${}^2H + e^+ + \nu_e$	
${}^2H + p$	$\rightarrow$	${}^3He + \gamma$	
${}^3He + {}^3He$	$\rightarrow$	${}^4He + 2p$	85%
${}^3He + {}^4He$	$\rightarrow$	${}^7Be + \gamma$	15%
$e^- + {}^7Be$	$\rightarrow$	${}^7Li + \nu_e$	
${}^7Li + p$	$\rightarrow$	$2\,{}^4He$	
$p + {}^7Be$	$\rightarrow$	${}^8B + \gamma$	0.02%
${}^8B$	$\rightarrow$	${}^8Be^* + e^+ + \nu_e$	
${}^8Be^*$	$\rightarrow$	$2\,{}^4He$	



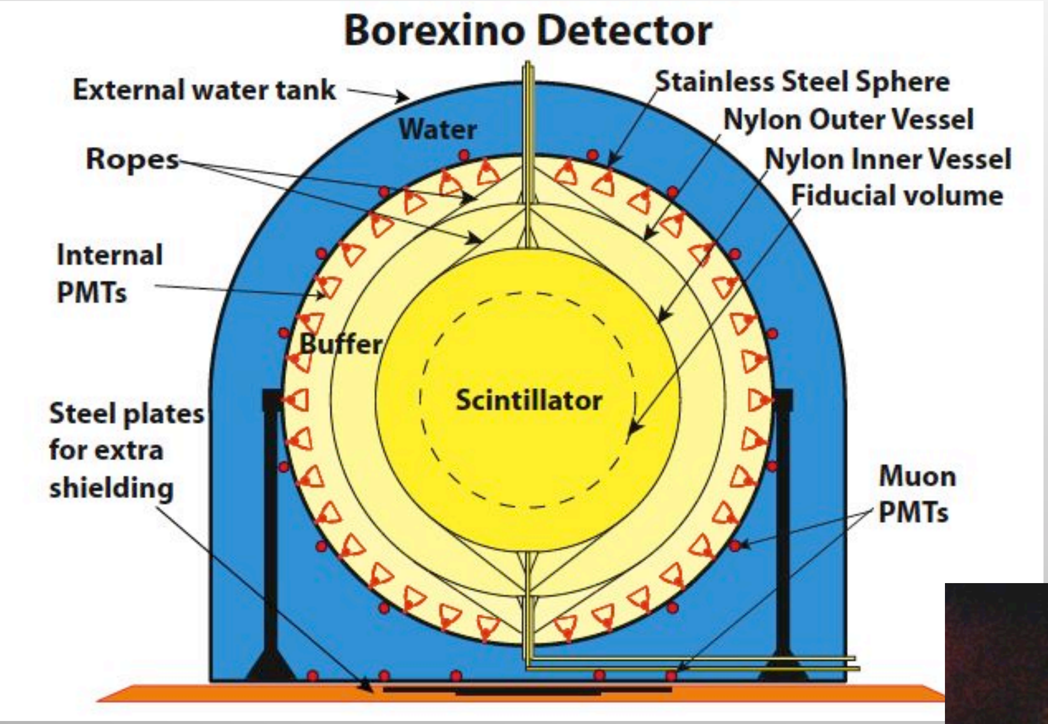
Can we detect them?

YES!

Do they all reach the earth?

Apparently NO!

Borexino



Borexino Detector
External water tank
Water
Stainless Steel Sphere
Nylon Outer Vessel
Nylon Inner Vessel
Fiducial volume
Ropes
Internal
PMTs
Buffer
Scintillator
Steel plates
for extra
shielding
Muon
PMTs

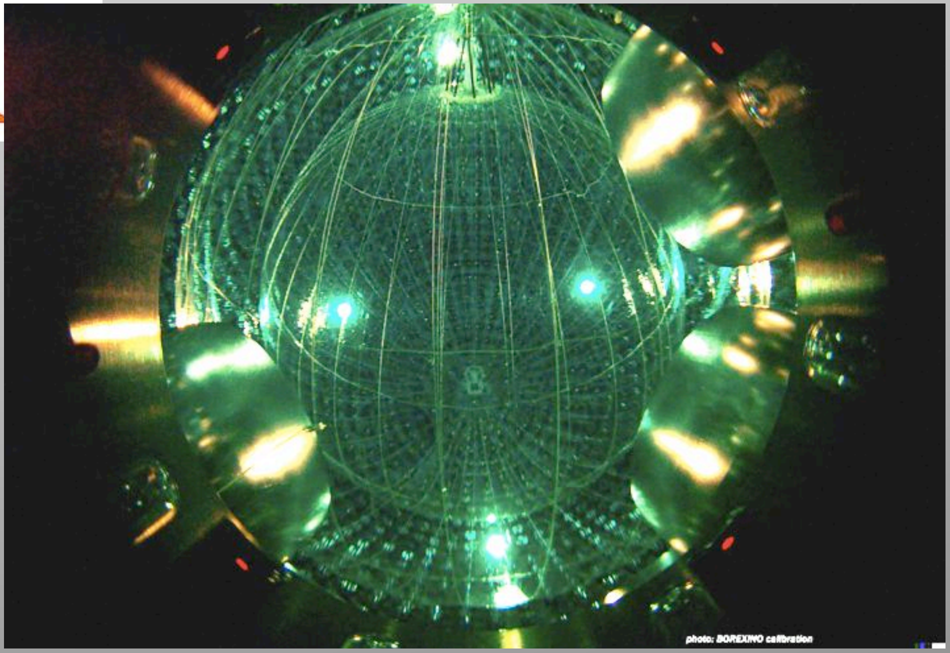
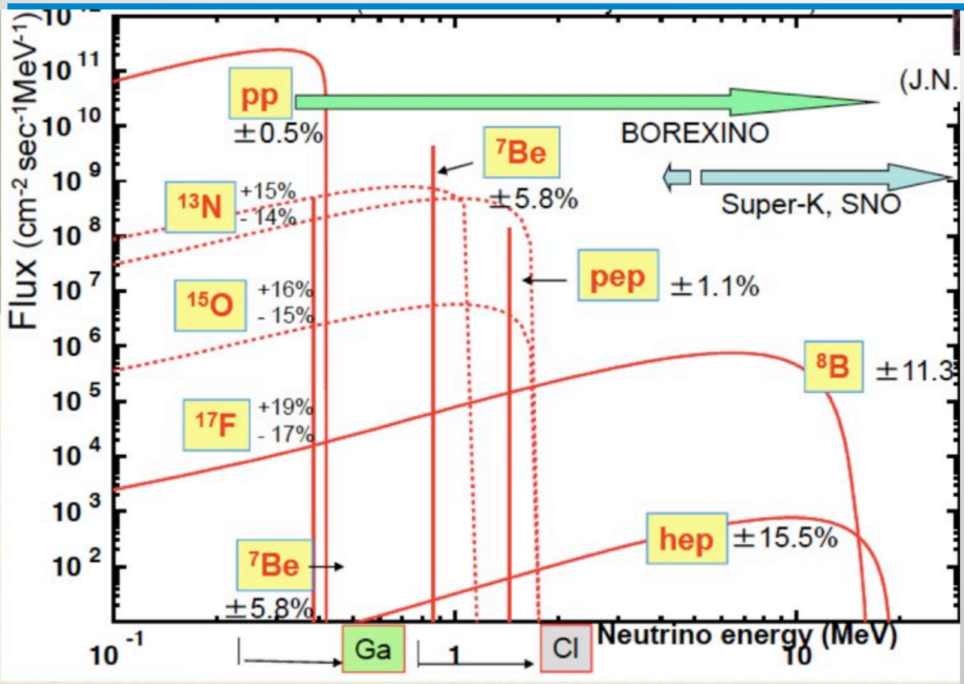
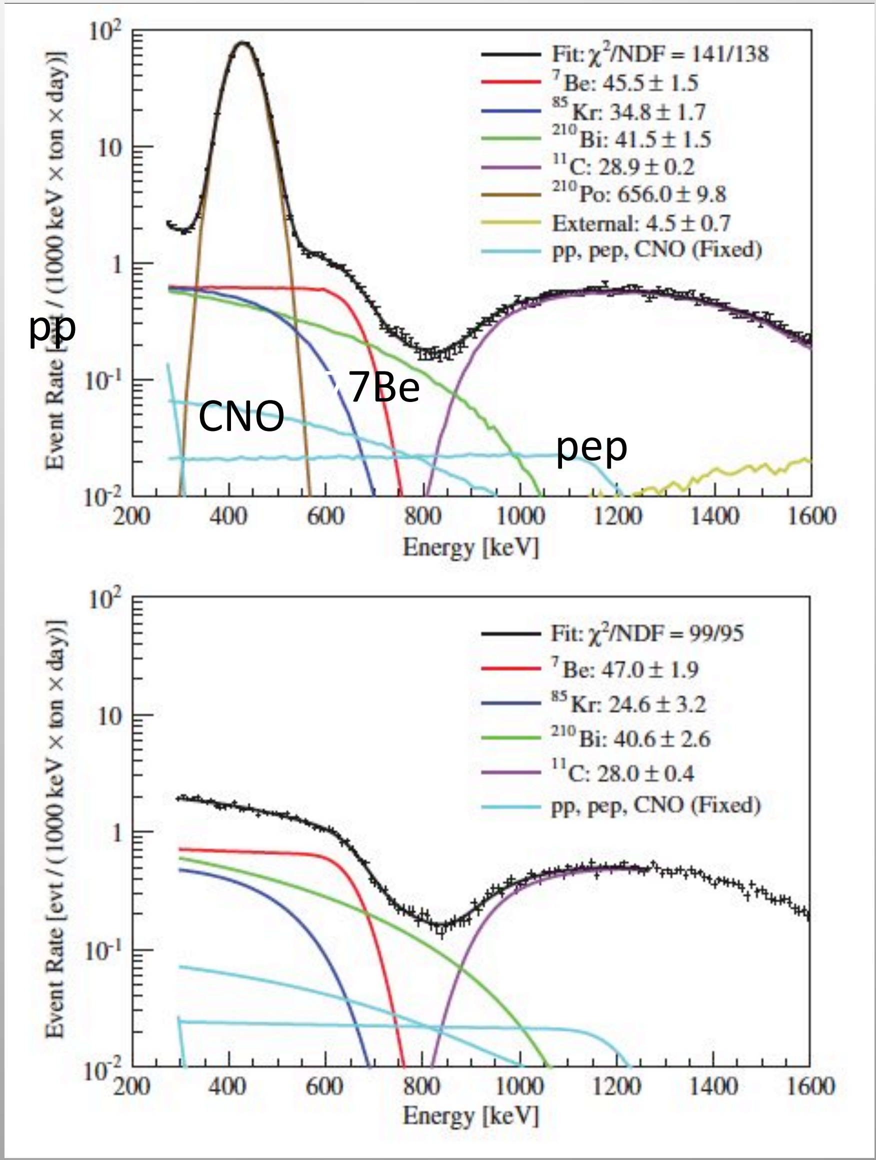


photo: BOREXINO calibration

Borexino and solar neutrinos



740.7 live days from May 2007 to May 2010

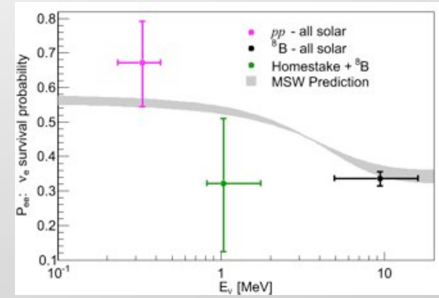


Borexino solar ν results

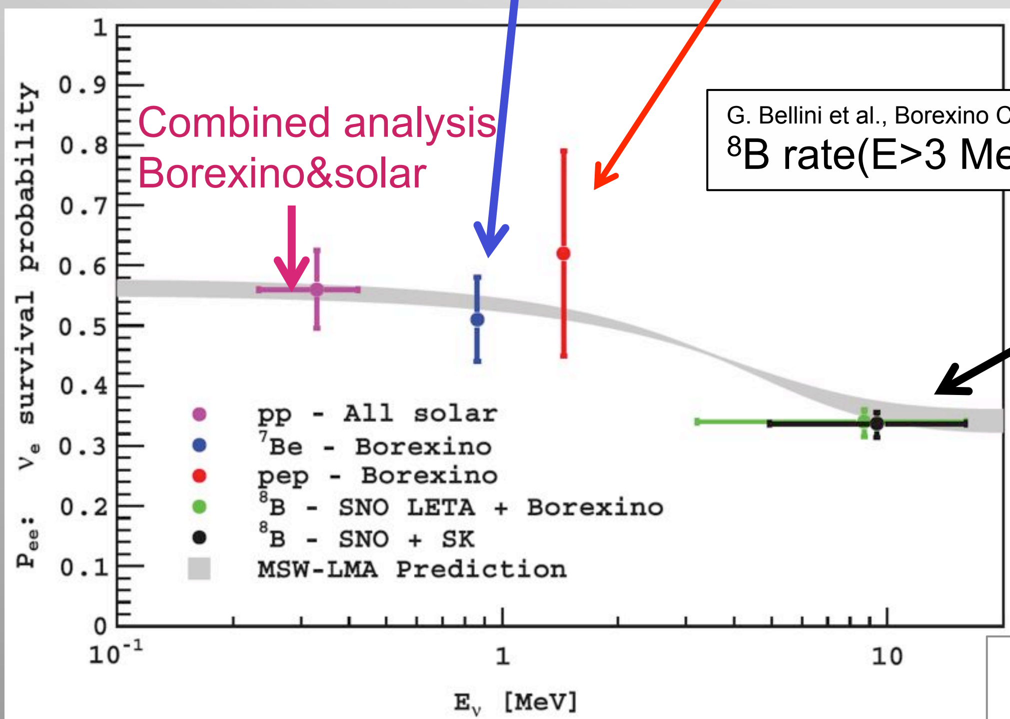
Neutrino Survival Probability $P_{ee}(E)$

G. Bellini et al., Borexino Collaboration, Phys. Rev. Lett. 108 (2012) 051302..
Pep rate= 3.1 ±0.6 (stat) ±0.3 (sys) cpd/100t

G. Bellini et al., Borexino Collaboration, Phys. Rev. Lett. 107 (2011) 141302.
^{7}Be rate(0.862 MeV)=46.0± 1.5 (stat) $^{+1.5}_{-1.6}$ (sys) cpd/100 t



Before Borexino



G. Bellini et al., Borexino Collaboration, Phys. Rev. D82 (2010) 033006.
^{8}B rate(E>3 MeV)= 0.22 ±0.04(stat) ±0.01 (sys) cpd/100t

Best upper limit on CNO n flux
CNO< 7.9 cpd/100t
Data/SSM<1.5 (with pep result)

Absence of ^{7}Be day night asymmetry
0.001 ± 0.012(stat) ± 0.007(sys)

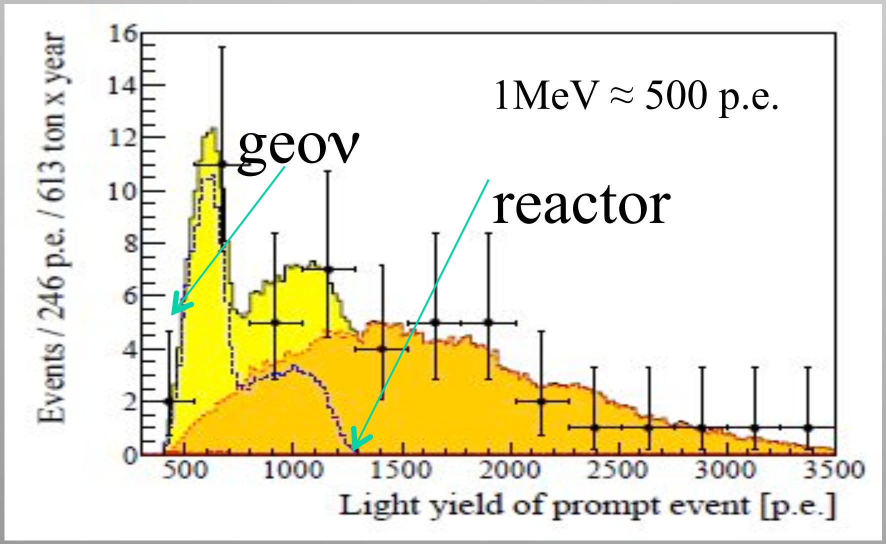
G. Bellini et al., Borexino Collaboration, Phys. Lett. B707 (2012) 22.

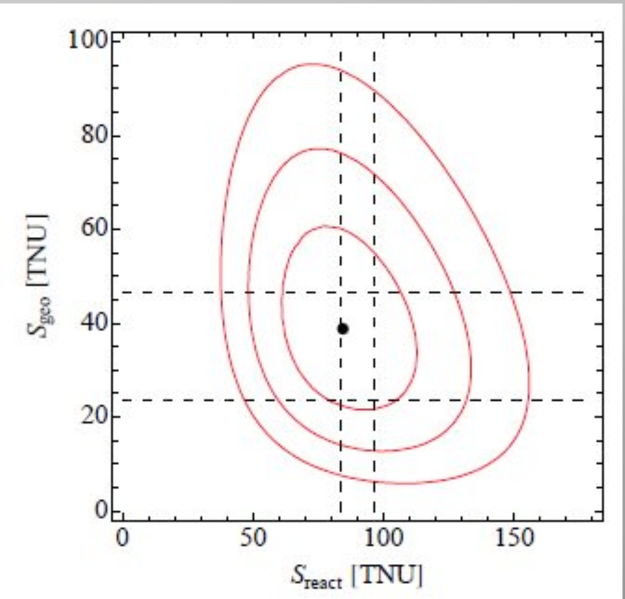
Geo Neutrinos

$N_{reactor}$ Expected with osc.	$N_{reactor}$ Expected no osc.	Others back.	N_{geo} measured	$N_{reactor}$ measured	N_{geo} measured	$N_{reactor}$ measured
events	Events	events	events	events	TNU	TNU
33.3±2.4	60.4±2.4	0.70±0.18	14.3±4.4	$31.2_{-6.1}^{+7}$	38.8±12.0	$84.5^{+19.3}_{-16.9}$

Exposure 613 ± 26 ton year
(3.69 ± 0.16) 10^{31} proton year

No signal: rejected at 4.5 σ C.L.





2.4 times data more than in Phys. Lett. B 687 (2010) 299 (Borexino Coll.)

Borexino measurements

Solar Neutrino rates (cpd/t)

- 7Be: 0.460 ± 0.023 Phys. Rev. Lett. 107 141302 (2011)
- 8B: 0.0022 ± 0.0004 Phys. Rev. D 82, 033006 (2010)
- pep: 0.031 ± 0.005 Phys. Rev,. Lett. 108, 051302 (2012)
-

Geo-neutrinos

- Total 14.3 ± 4.4 events Phys. Lett. B722, 295 (2013)

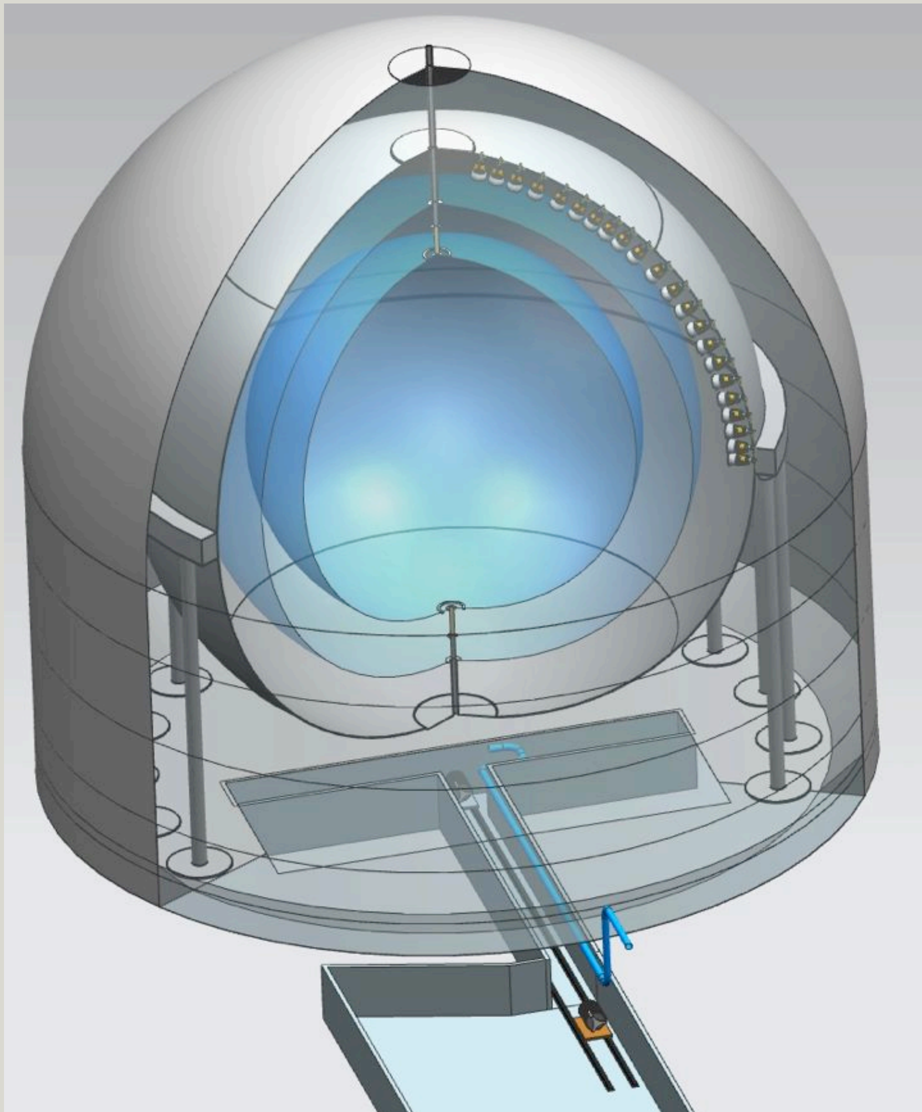
NEUTRINO PROPERTIES

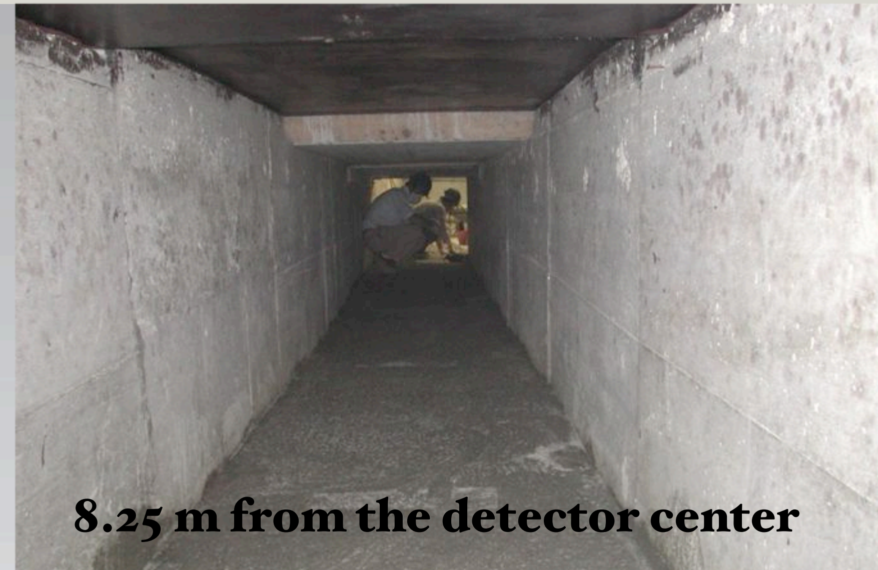
Testing LSND with SOX

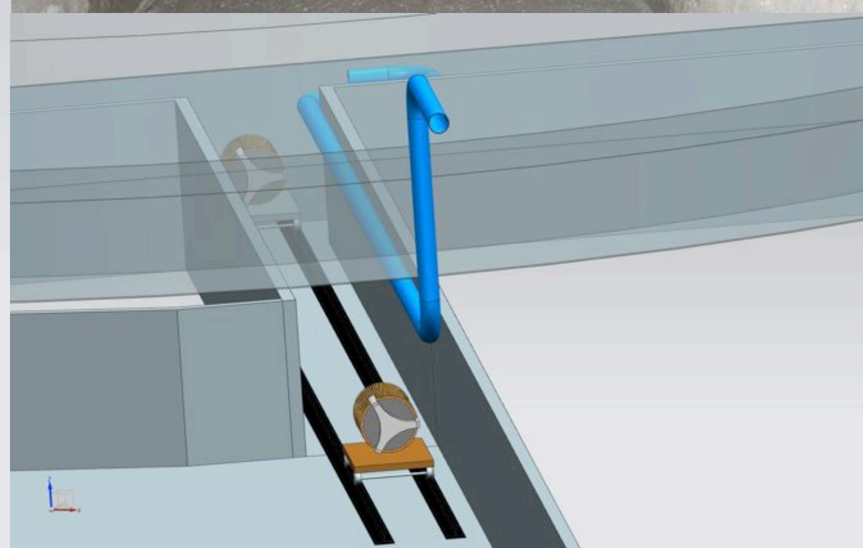
- **Science motivations:**
  - Search for **sterile neutrinos** or other **short-distance effects on P_{ee};**
  - Measurement of Weinberg angle θ_W at low energy (~ 1 MeV);
  - Improved limits of the neutrino magnetic moment;
  - Measurement of the vector g_V and axial g_A current coefficients at low energy;
- **Technology**
  - Neutrino source: **^{51}Cr**
  - Anti-neutrino source: **^{144}Ce**
- **Project:**
  - ERC advanced grant for **^{51}Cr** (M. Pallavicini INFN-Genova);
  - ERC starting grant for **^{144}Ce** (T. Lasser APC-Paris: **NEW: this project has recently moved from KamLAND/CeLAND to Borexino);**

SOX

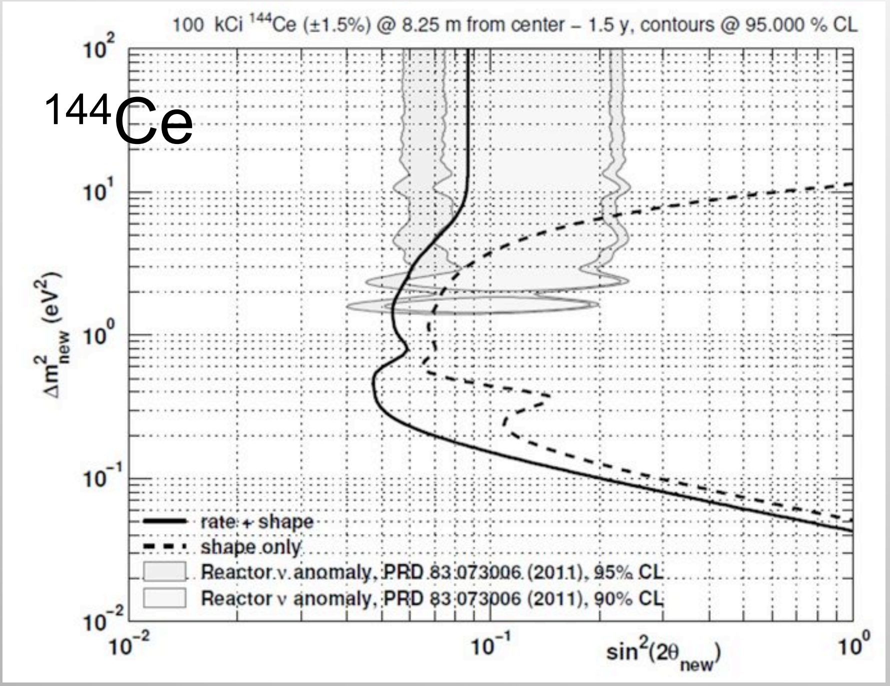
Sources located in Borexino pit

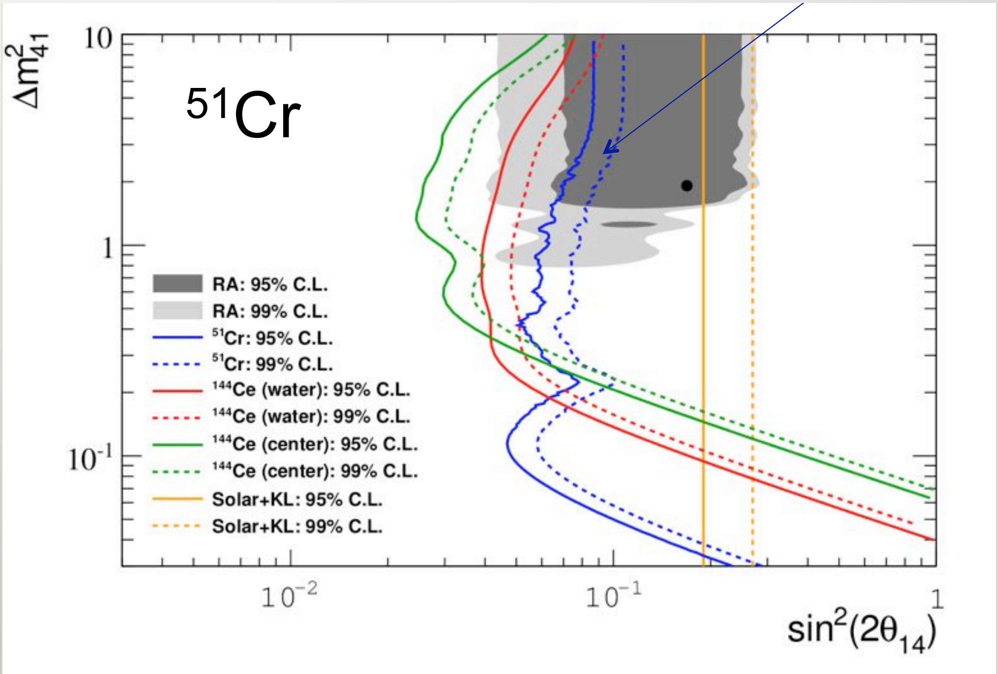






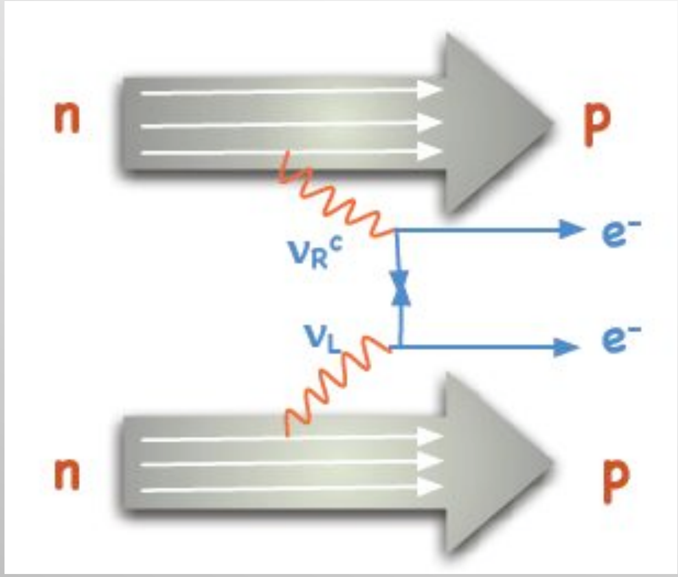
SOX sensitivity – sources in pit





- ^{51}Cr ad ^{144}Ce source measurements (in the Borexino pit) estimated for 2015: which source first? The one which will be ready first!
- DAQ with ^{51}Cr: few months
- DAQ with ^{144}Ce: 1.5 year
- Long term: after completion of the solar neutrino program, possible SOX phase C with ^{144}Ce source placed inside the detector: improved sensitivity but some HW changes required;

Introduction: 0νββ



Expected decay rate:

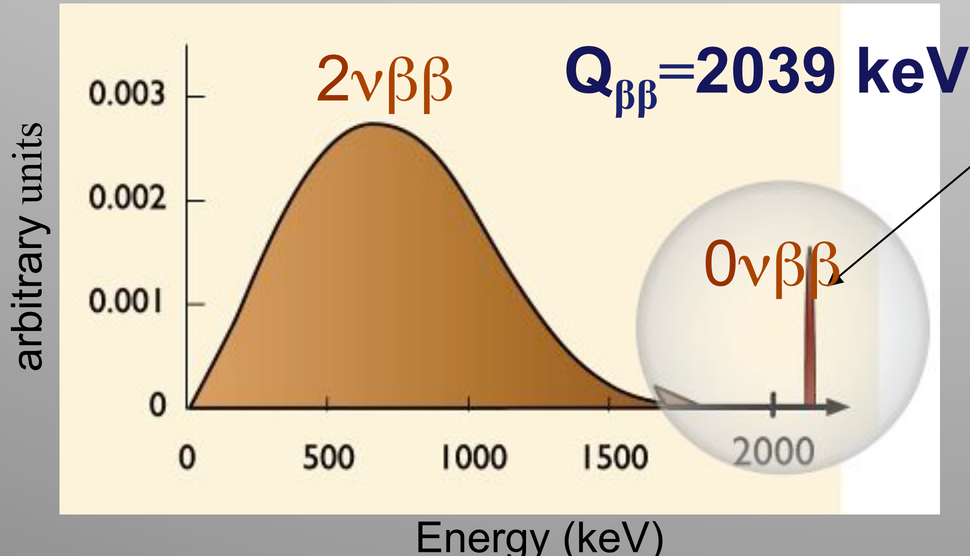
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

Phase space integral   Nuclear matrix element

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$ Effective neutrino mass

U_{ei} Elements of (complex) PMNS mixing matrix

Example ^{76}Ge



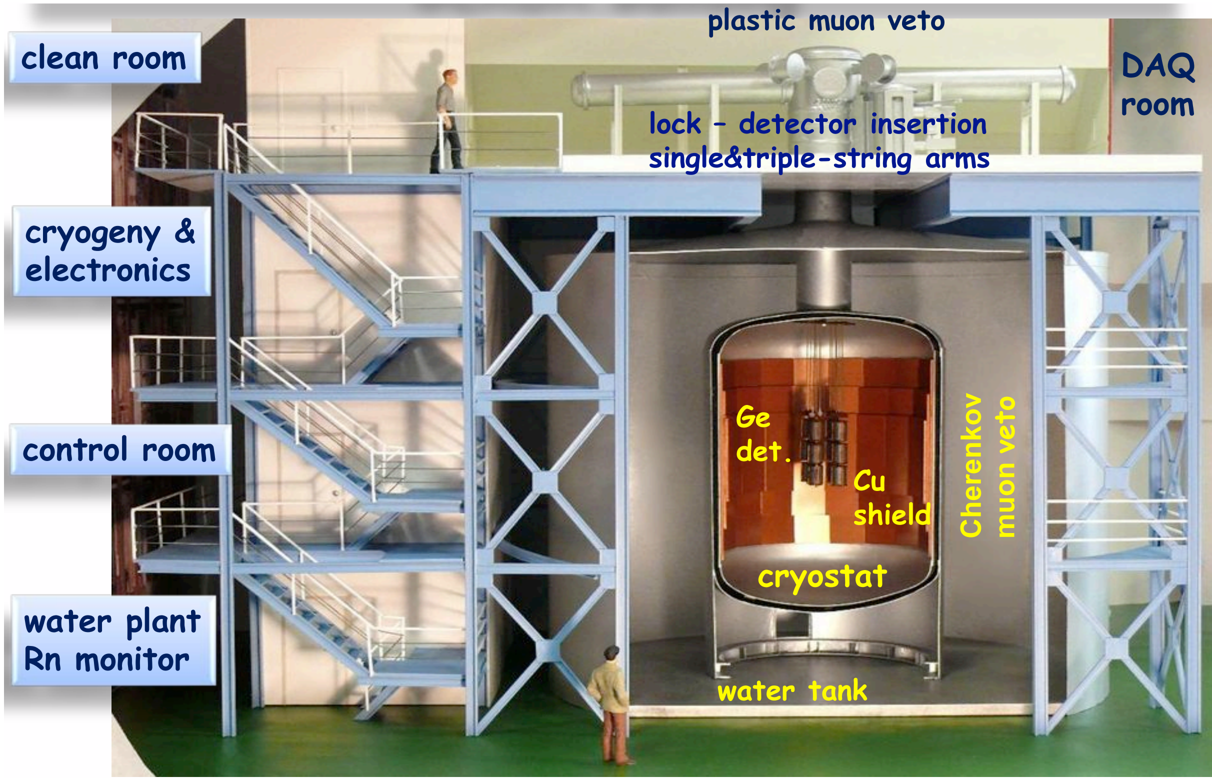
Experimental signatures:

- peak at $Q_{\beta\beta} = m(A,Z)-m(A,Z+2)-2m_e$
- two electrons from vertex

Discovery would imply:

- lepton number violation ΔL = 2
- ν's are Majorana type
- mass scale & hierarchy
- physics beyond the standard model

GERDA

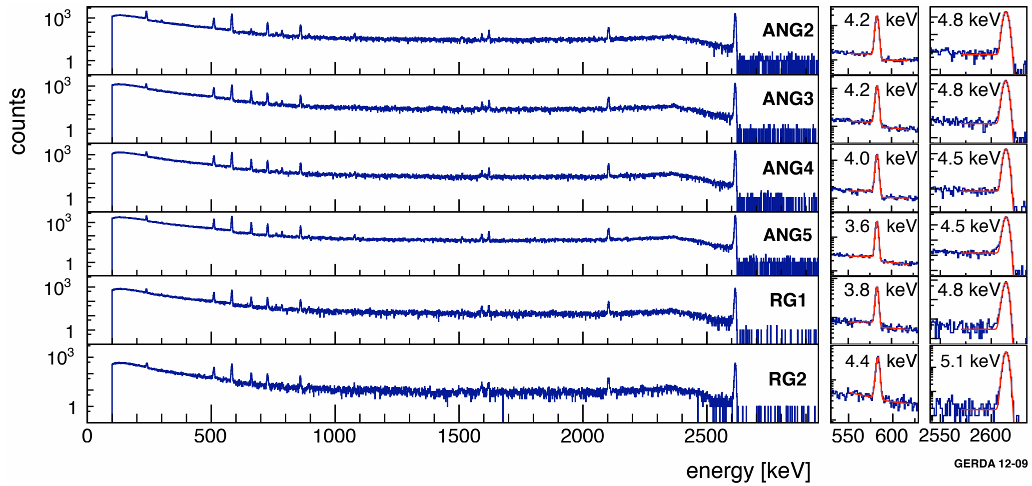


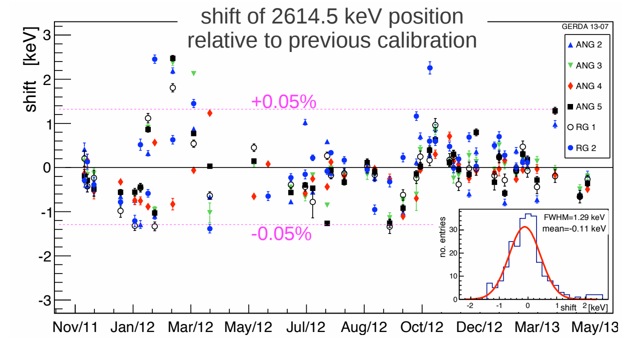
The GERDA collaboration, Eur. Phys. J. C 73 (2013)

- 3 + 1 strings
- 8 enriched Coaxial detectors: working mass 14.6 kg
  (2 of them are not working due to high leakage current)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: working mass 3.0 kg (testing Phase II concept)

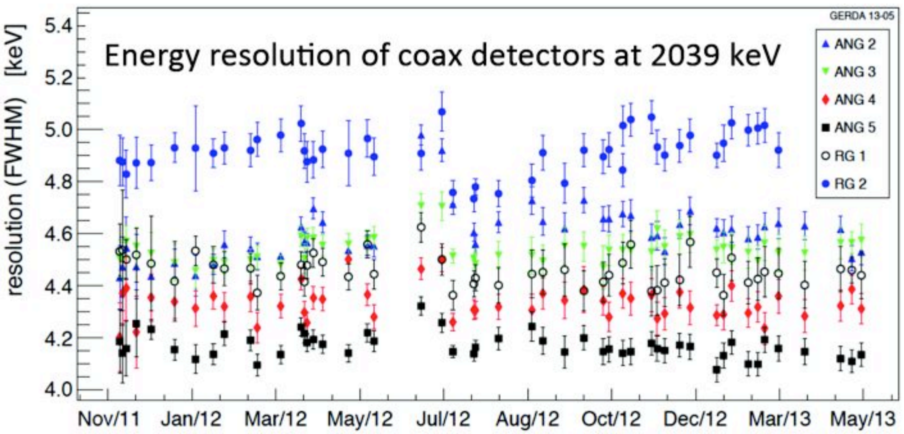
GERDA – calibration and data processing

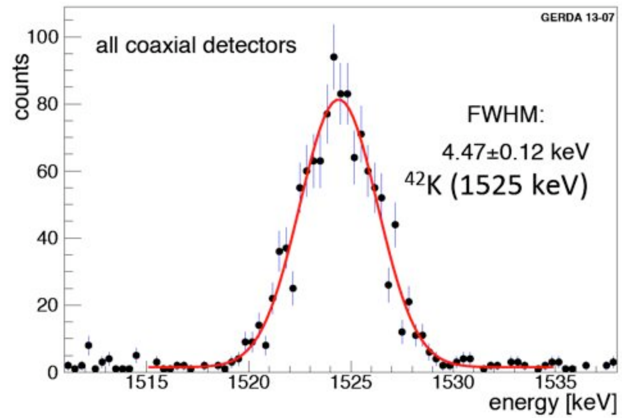
- weekly calibrated spectra with ^{228}Th sources and pulser with 0.05 Hz frequency
- data useful for monitoring of resolution and stability over time
- exposure-weighted FWHM at $Q_{\beta\beta}$ is about 4.8 keV for Coaxials (0.23%) and 3.2 keV (0.16%) for BEGes





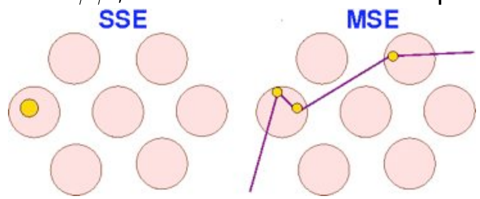
shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$





GERDA PSD

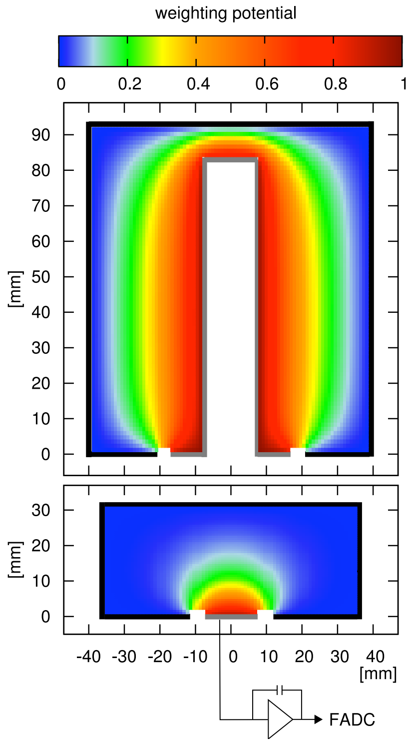
SSE: $\beta\beta$, DEP MSE: Compton

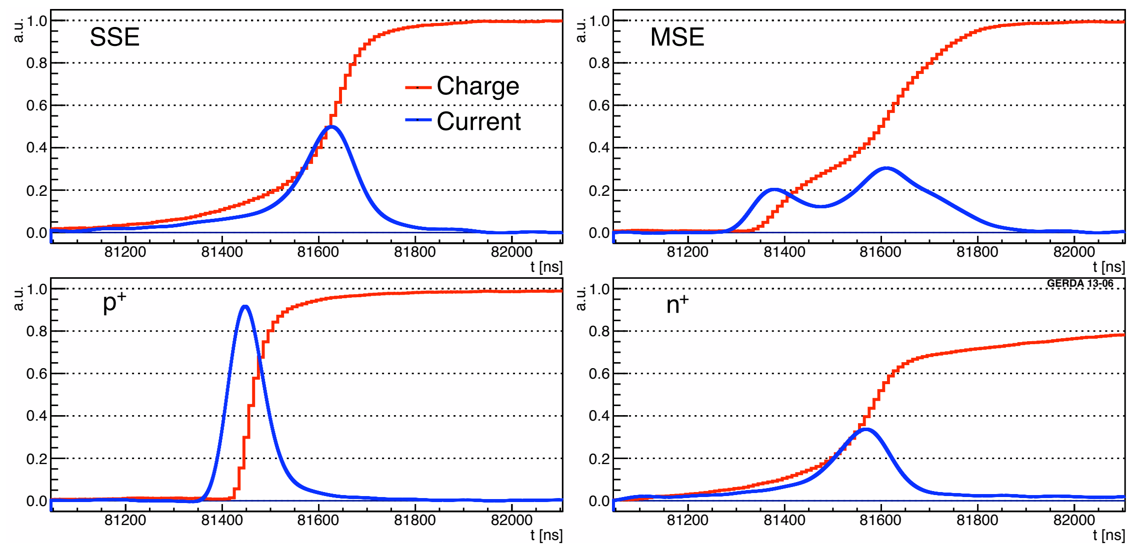


Pulse-shape analysis

e signal: single site energy deposition

γ signal: multiple site energy deposition





Current signal $= q \cdot v \cdot \Delta\Phi$
q=charge, v=velocity
(Schockley-Ramo theorem)

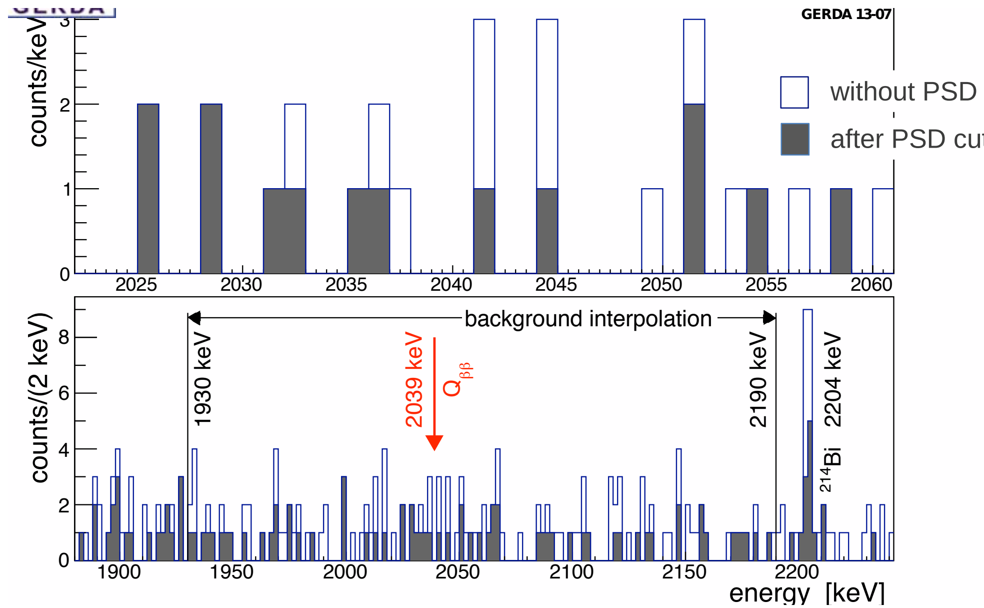
$0\nu\beta\beta$ events: 1 MeV electrons in Ge $\sim$ 1mm range one drift of electrons and holes SINGLE SITE EVENTS (SSE)

Background from γ's: MeV γ in Ge $\sim$ cm range several electron/holes drifts MULTI SITE EVENTS (MSE)

Surface events: only electron or hole drift

GERDA results

- Summed exposure: **21.6 kg yr**
- Unblinding after calibration finished, data selection frozen, analysis method fixed and PSD selection fixed
- Consider the 3 data sets separately in the analysis
- BI = 0.01 cts/(keV kg yr) after PSD
- No events in $\pm\sigma_E$ after PSD
- 3 events in $\pm 2\sigma_E$ after PSD



data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI $^{\dagger)}$	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	18 ± 2	5
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

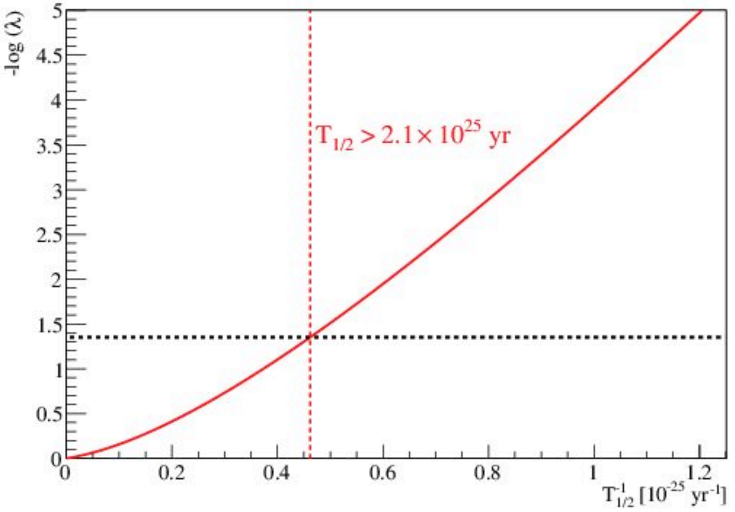
$^{\dagger)}$ in units of 10^{-3} cts/(keV·kg·yr).

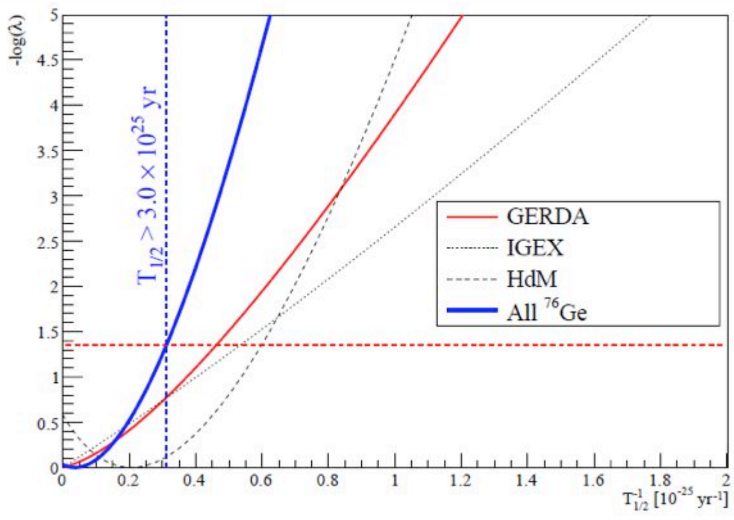
data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG 1	2041.7	27-Apr-2013 22:21	no

No peak in spectrum observed, number of events consistent with expectation from background → GERDA sets a limit on the half-life of the decay!

GERDA $0\nu\ \beta\beta$

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503



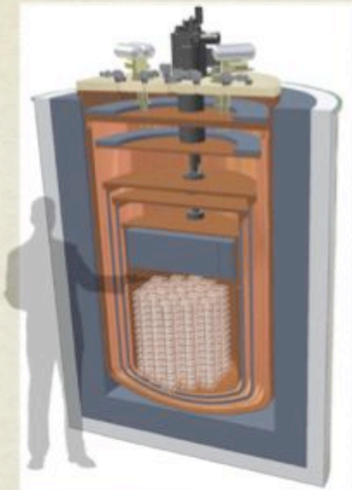


- Frequentist analysis
  Median sensitivity:
  $T^{0\nu}_{1/2} > 2.4{\cdot}10^{25}$ yr at 90% C.L.
- Maximum likelihood spectral fit
  (3 subsets, $1/T_{1/2}$ common)
- Bayesian analysis also available
  Median sensitivity:
  $T^{0\nu}_{1/2} > 2.0{\cdot}10^{25}$ yr at 90% C.L.

- **Profile likelihood result**:
  $\mathbf{T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}}$ **yr at 90% C.L.**
- **Bayesian analysis result**:
  $\mathbf{T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}}$ **yr at 90% C.I.**
- Best fit: $N^{0\nu}=0$

CUORE

Searching for neutrinoless double beta decay of ^{130}Te



200 Kg

^{130}Te

CUORE Hut

Expected 5 Years sensitivity:

$T_{1/2}$ = 2.1 x 10^{26} y, $m_{\beta\beta}$=41–95 meV

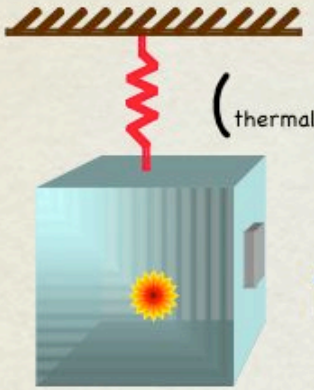
background counting rate

10^{-2} c/keV/kg/y

CUORE Principle

heat sink (T_0)

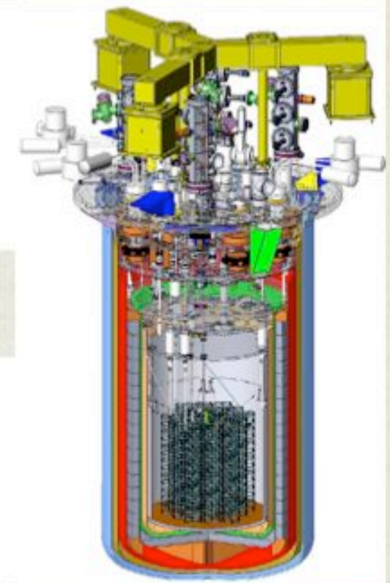
Basic Physics: $\Delta T = E/C$



(thermal conductance G)

$$C(T) = \beta \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3$$

thermometer



$\beta\beta$ atom x-tal

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau} \right)$$

$T_0 \sim 10$ mK

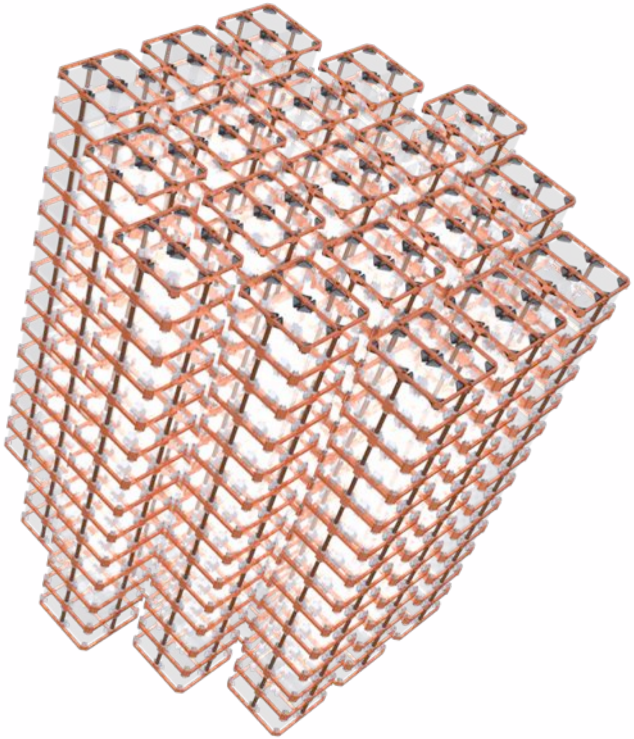
$C \sim 2$ nJ/K ~ 1 MeV/0.1 mK

$G \sim 4$ pW/mK

The CUORE challenge

- Operate a huge thermal detector array in a extremely low radioactivity and low vibrations environment

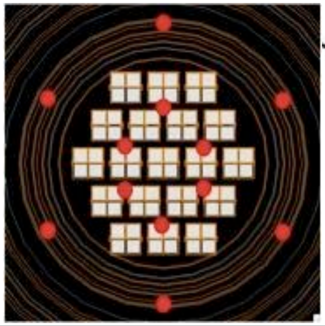
  - Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each)
  - Mass of TeO_2: 741 kg (~206 kg of ^{130}Te)
  - Energy resolution: 5 keV @ 2615 keV (FWHM)
  - Stringent radiopurity controls on materials and assembly
  - Operating temperature: ~ 10 mK
  - Background aim: 10^{-2} c/keV/kg/year

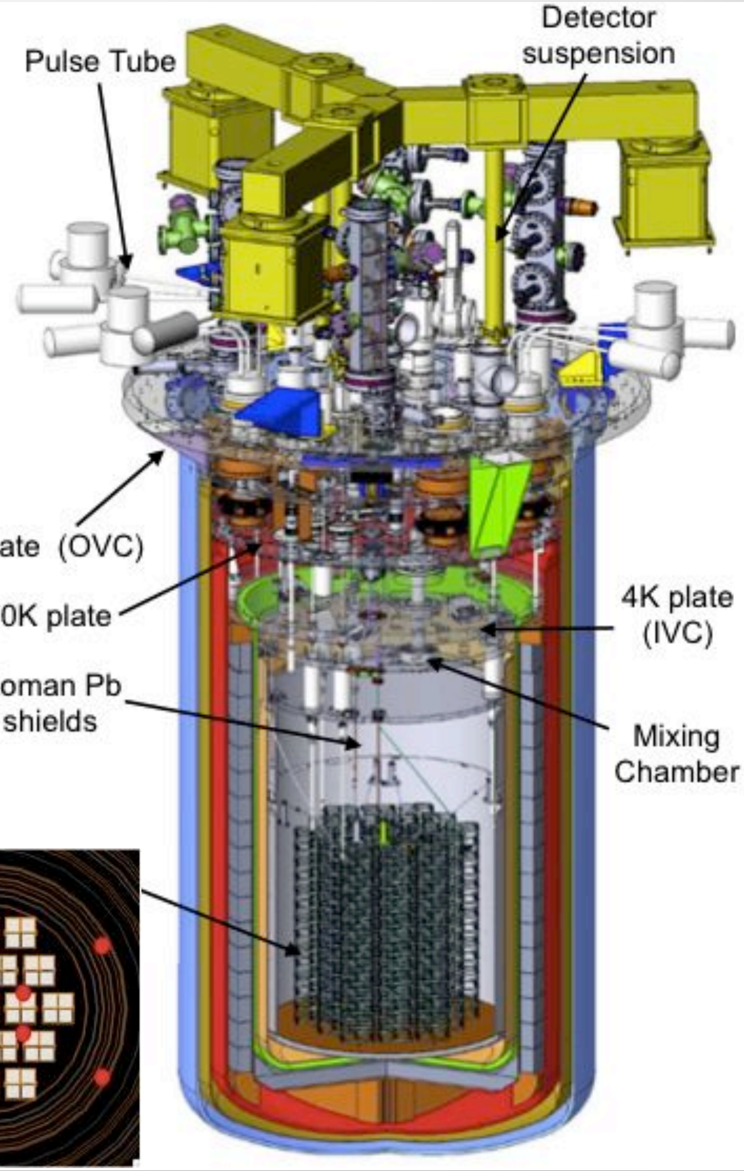


CUORE cryo system

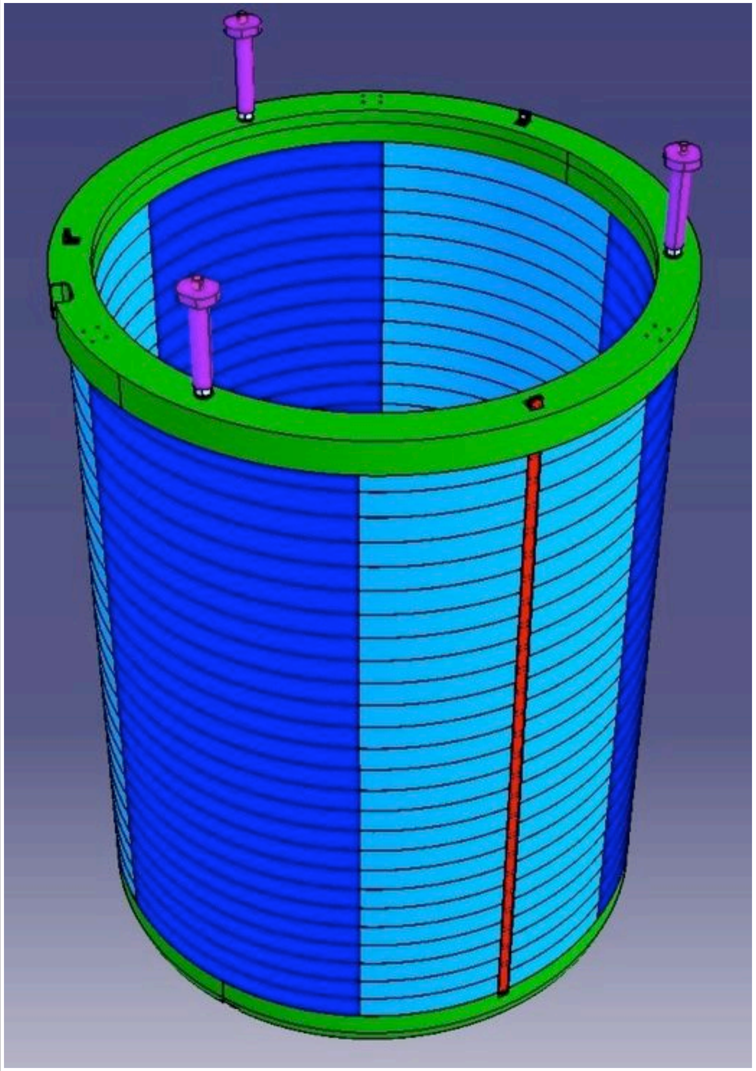
- Custom, cryogen-free dilution refrigerator
- Detector suspension independent of refrigerator apparatus
- Total mass: ~ 20 tons
- Internal Roman lead shield: 6 cm thick

- Detector Calibration System to calibrate periodically the detector deploying radioactive sources close to the array



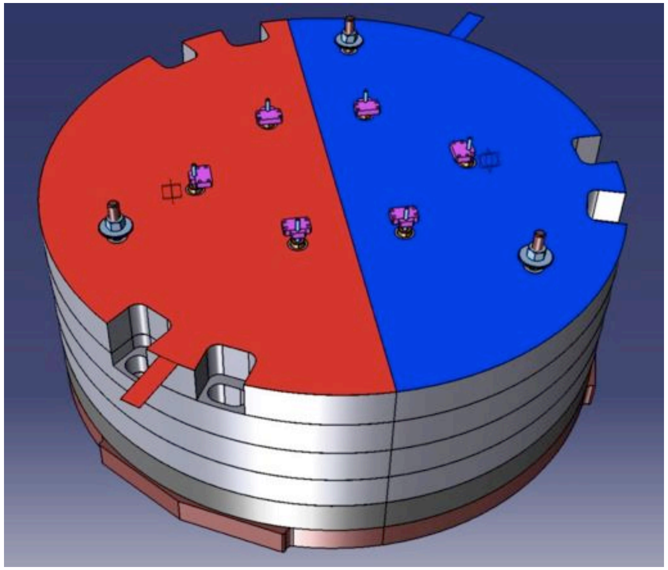


CUORE – Pb cold shielding



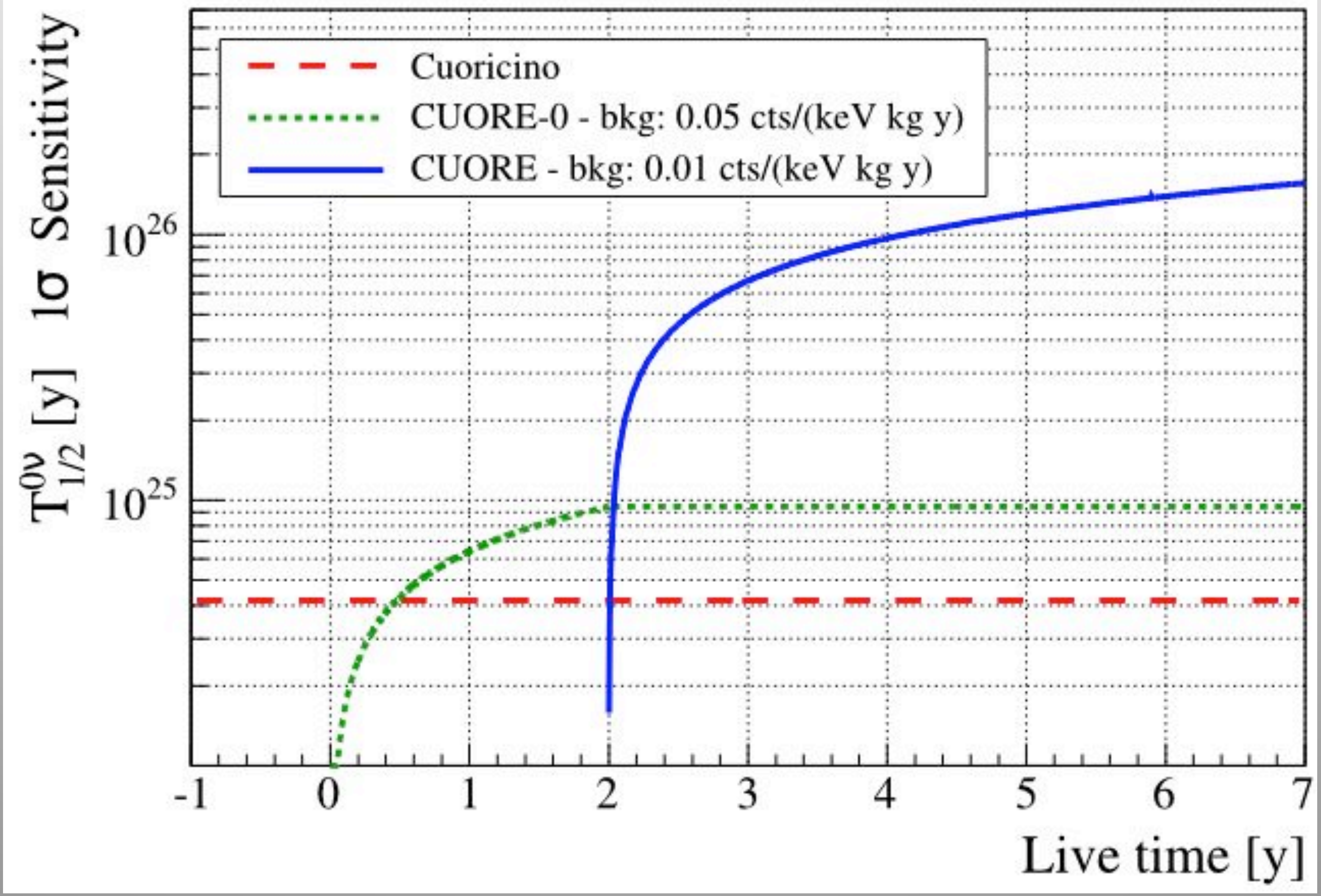
Bottom plate + 6 sector side rings
Suspended to 600 mK plate thermalized to 4K

- 2 main elements
  - side & bottom: roman Pb, 6 cm thick
  - top: 5 discs (6 cm thickness) of modern lead



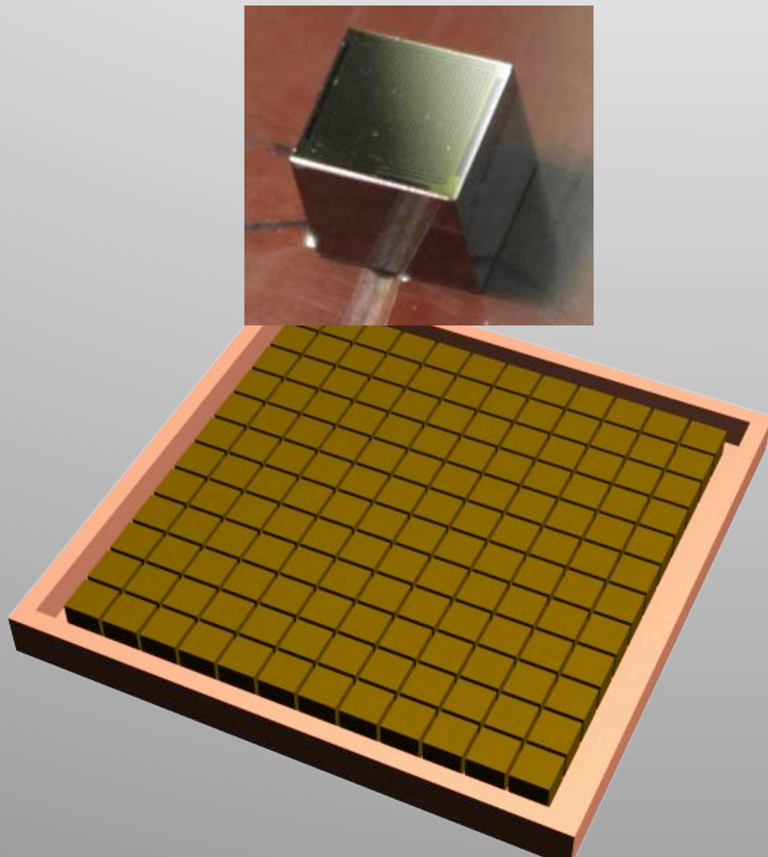
Lead discs interleaved with Cu sheets
Suspended to 300K SS plate thermalized to 50 mK

CUORE sensitivity



COBRA: The idea

Use large amount of CdZnTe Semiconductor Detectors



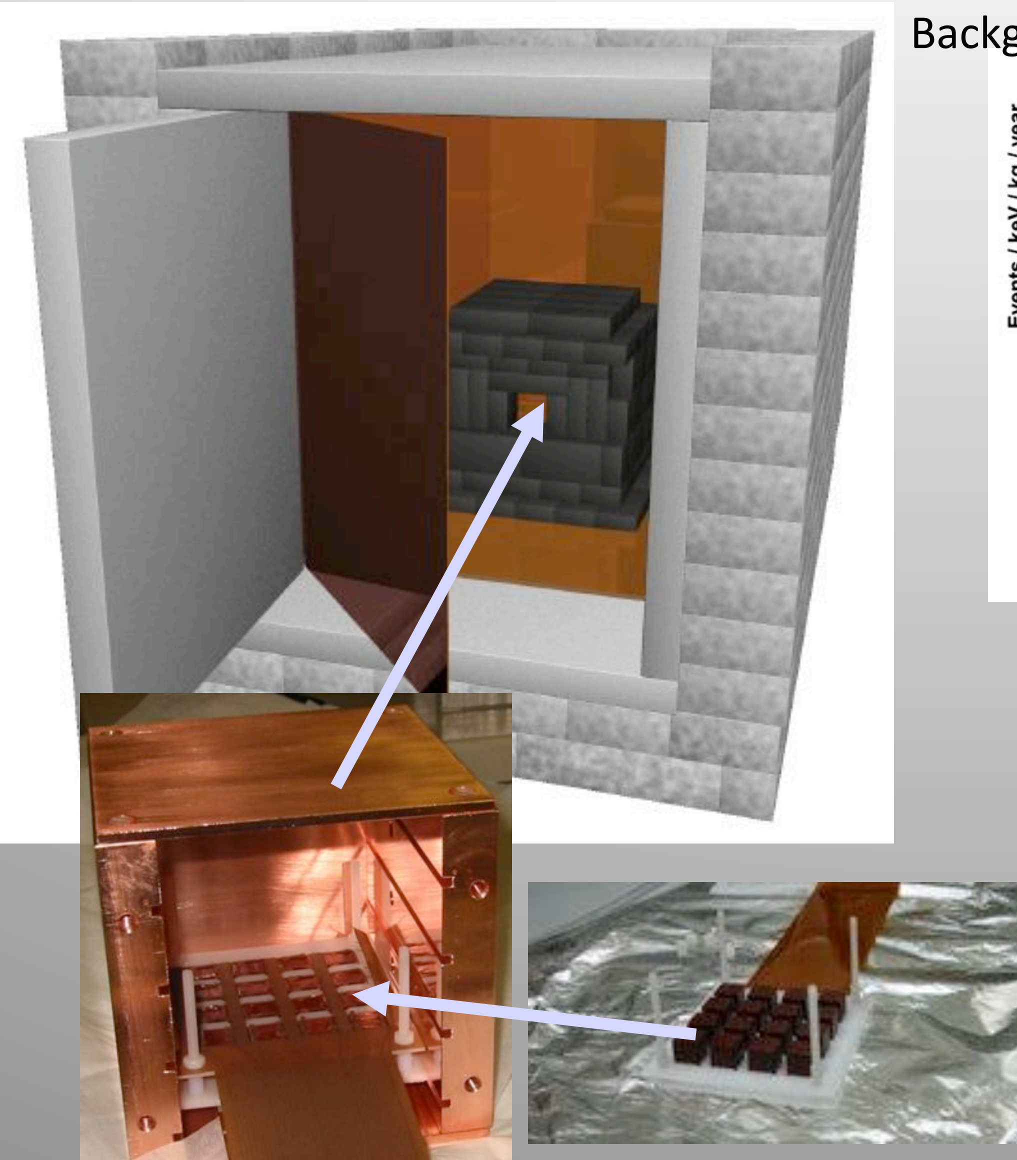
- Source = detector
- Focus on ^{116}Cd
  Q-value = 2813.50 ±0.13 keV
- Semiconductor
  Good energy resolution, clean
- Room temperature
- Modular design
  Coincidences
- Tracking/Pixelisation
  "Solid state TPC"

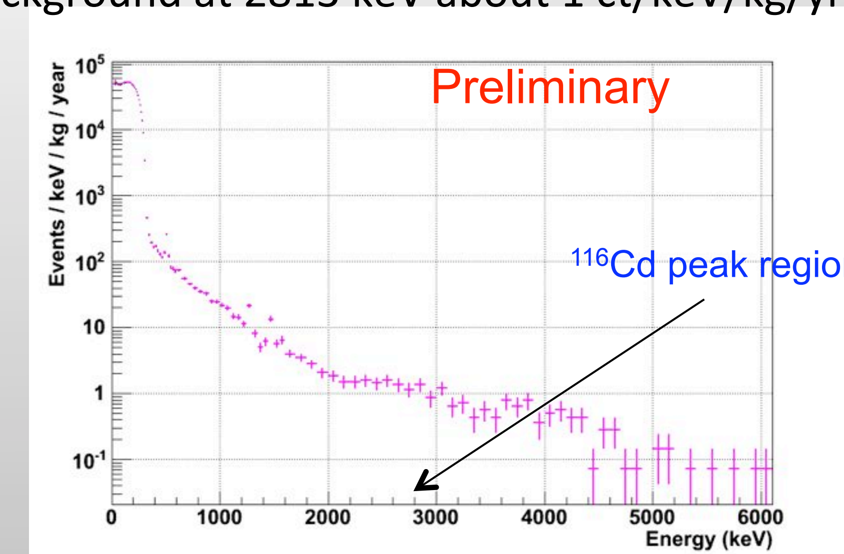
K. Zuber, Phys. Lett. B 519,1 (2001)

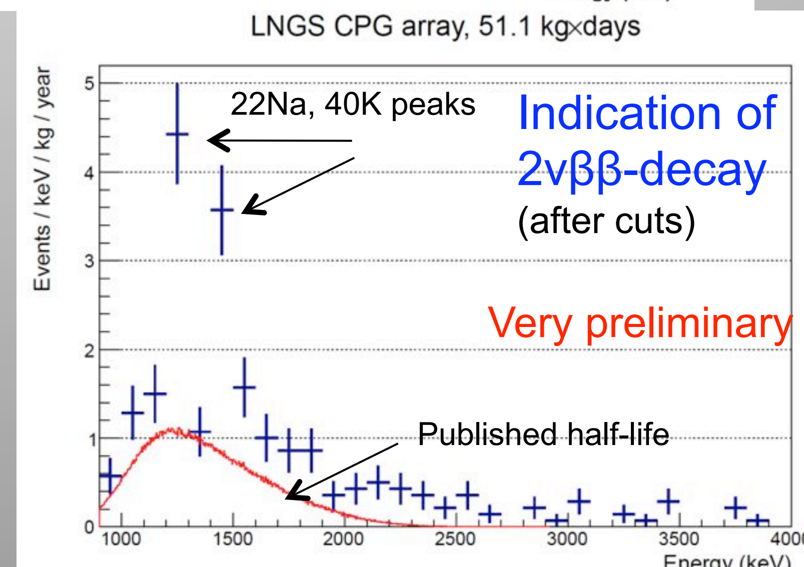
Setup at Gran Sasso Lab

Upgrade to 64 detectors soon

Current spectrum (32 detectors), 51.1 kg*days
Background at 2813 keV about 1 ct/keV/kg/yr



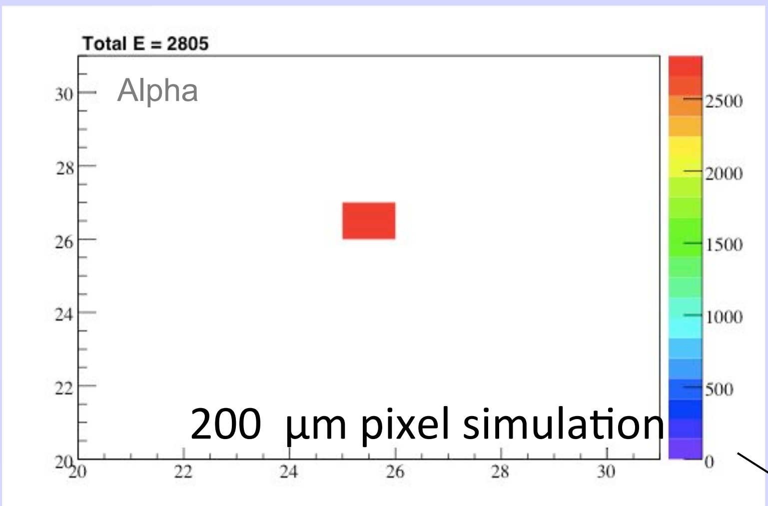


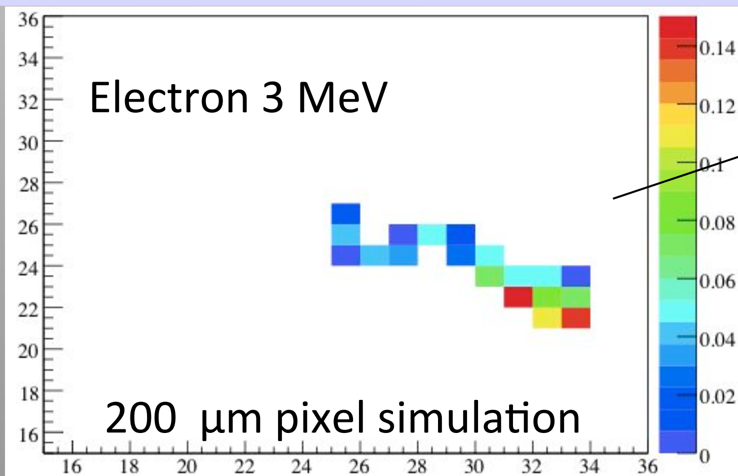


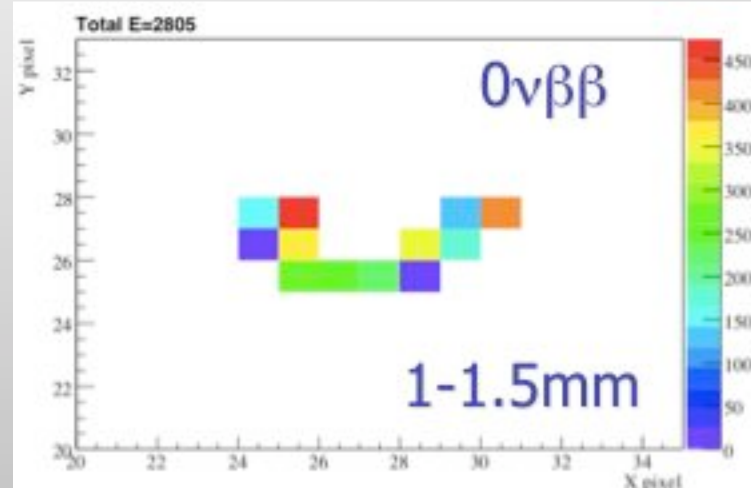
The pixel option – Semiconductor tracker

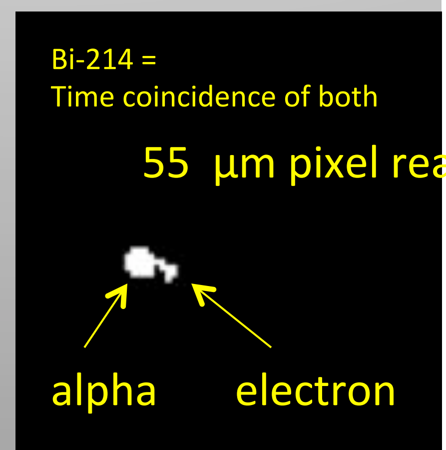
Idea: Massive background reduction by particle identification

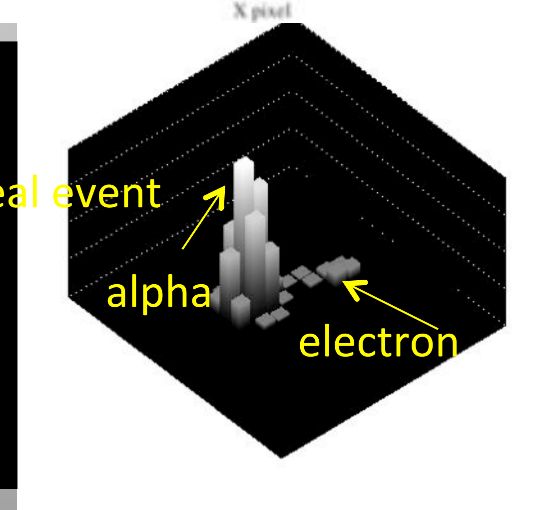
According to Monte Carlo simulation this reduce background by 2-3 orders of magnitude







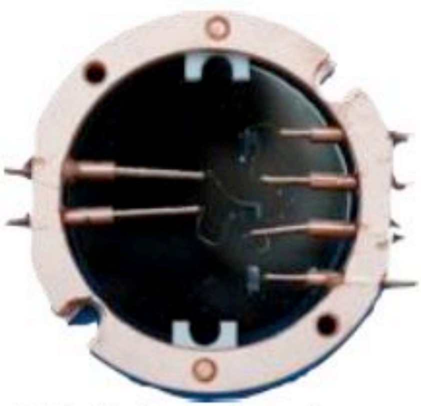


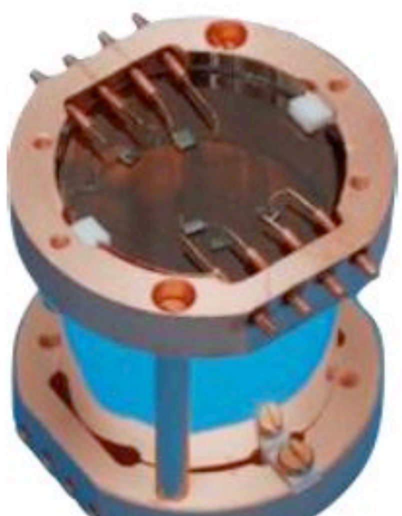


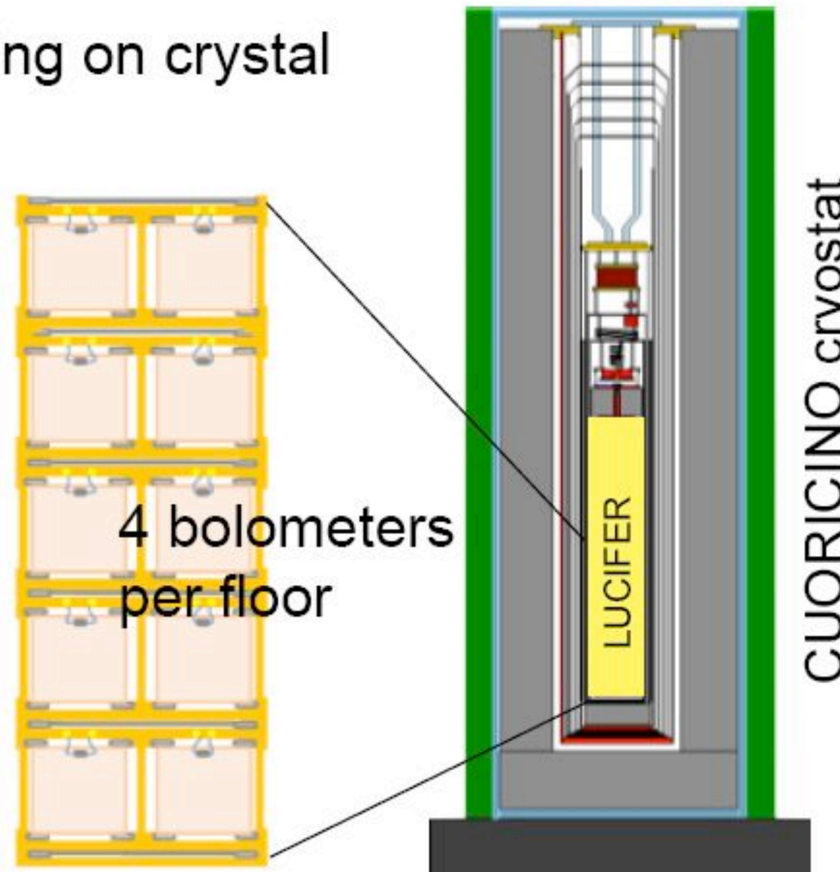
Real event!

LUCIFER

- Tower of 32-40 ZnSe scintillating bolometers at Gran Sasso, enriched in ^{82}Se , ~10 kg of ^{82}Se.
- Background free: α background identified via the scintillation signal, β/γ radioactive background below the ^{82}Se Q-value (2997 keV).
- Operation in 2015. Presently focusing on crystal growth.

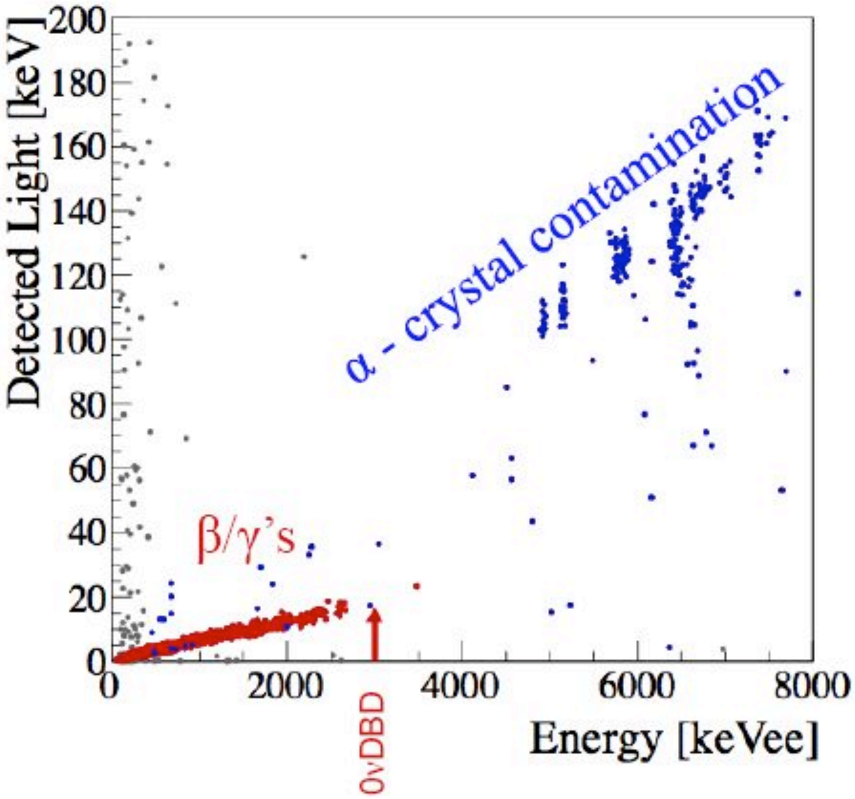

Light detector (Ge bolometer)

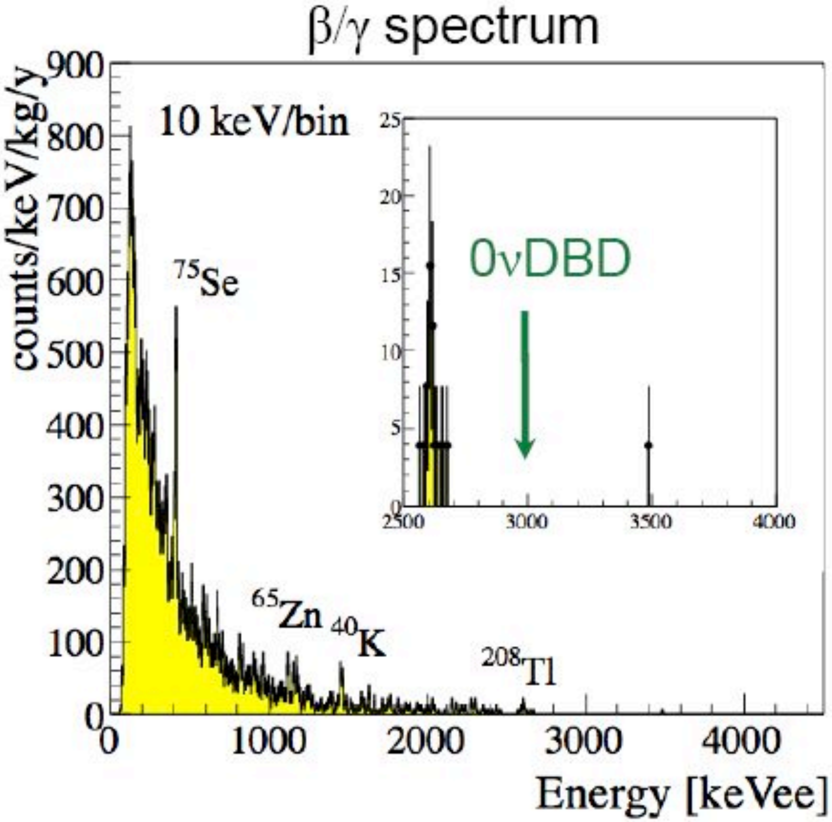
ZnSe bolometer




LUCIFER

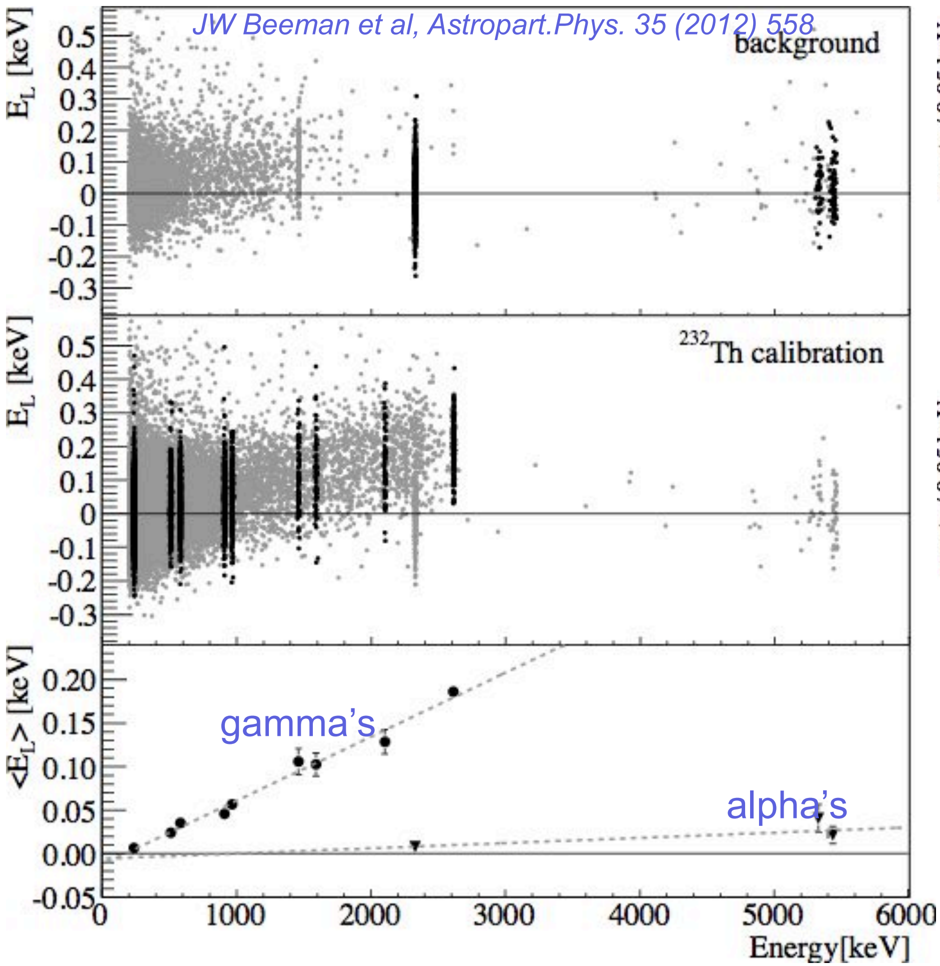
- 431g $Zn^{nat}Se$ crystal operated for 22 days.
  - ΔE@2615 keV = 13 keV FWHM
  - α background entirely identified via light pulse shape.

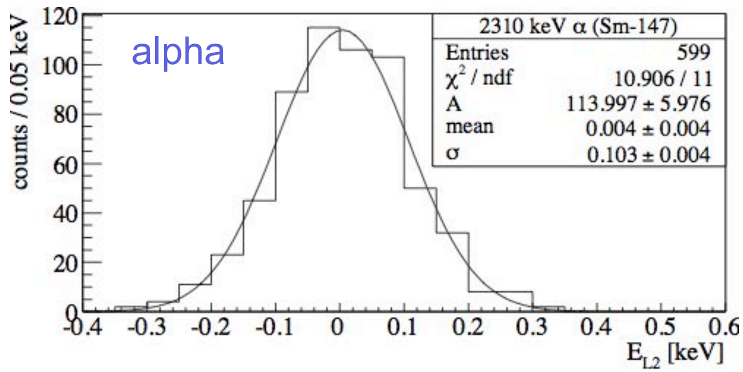


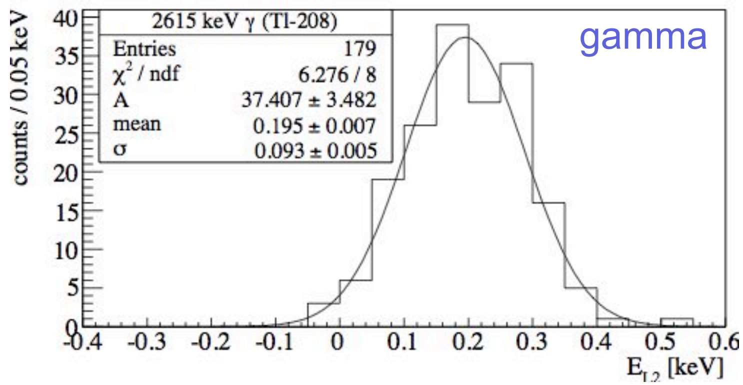


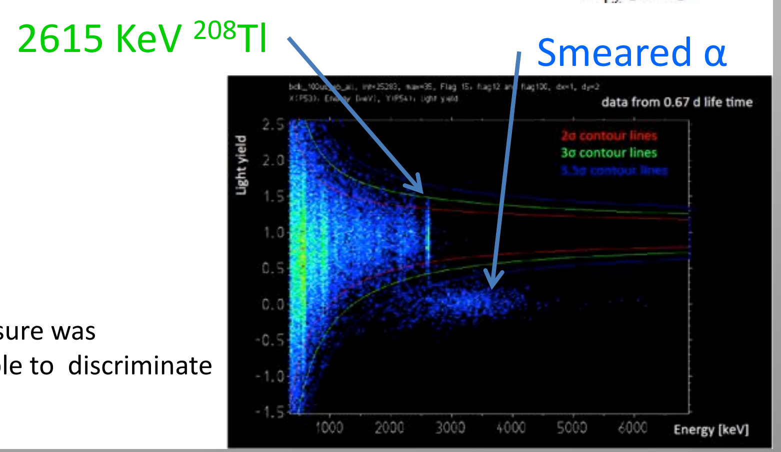
- One β/γ event above 2615 keV, in coincidence with several hits in nearby detectors (μ-spallation).
- Easily to tag via coincidence analysis in an array, or via a μ-veto.

LUCIFER









195 eV from a 2615 keV gamma, ~zero light from alpha's (117 gr crystal)

98 eV from a 2615 keV gamma, (CUORE crystal) **ArXiv :1403.5528**

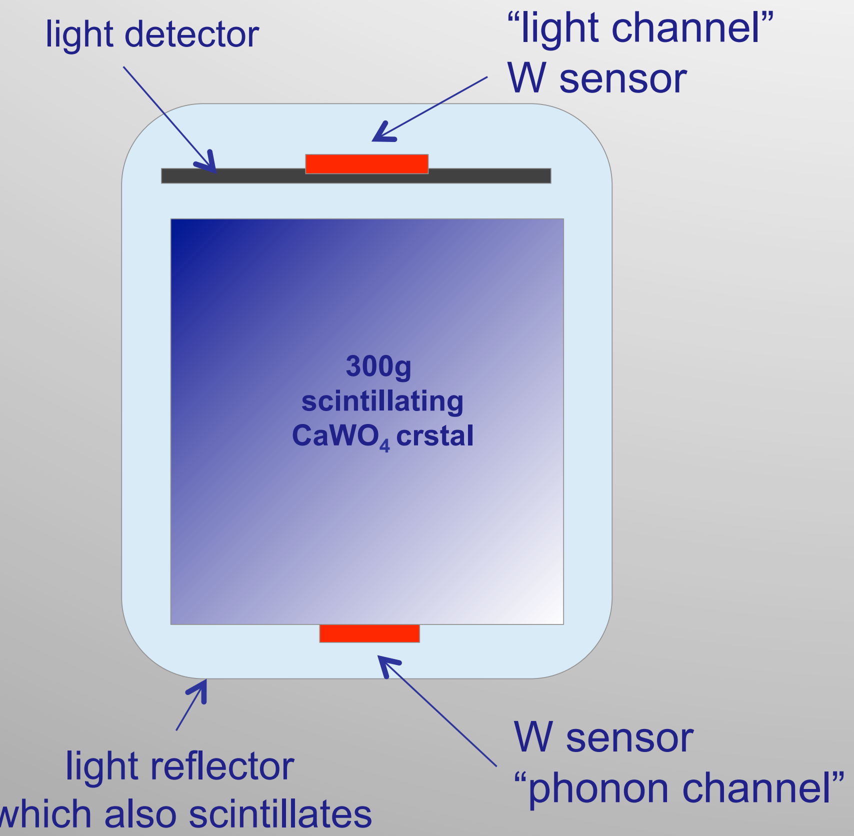
Measure obtained by using a 305 g TeO_2 with a "CRESST" light detector. This measure was performed in Collaboration with the MPI Munich. It clearly shows that it is possible to discriminate alpha particles at a level > 3 σ using the Cherenkov emission.

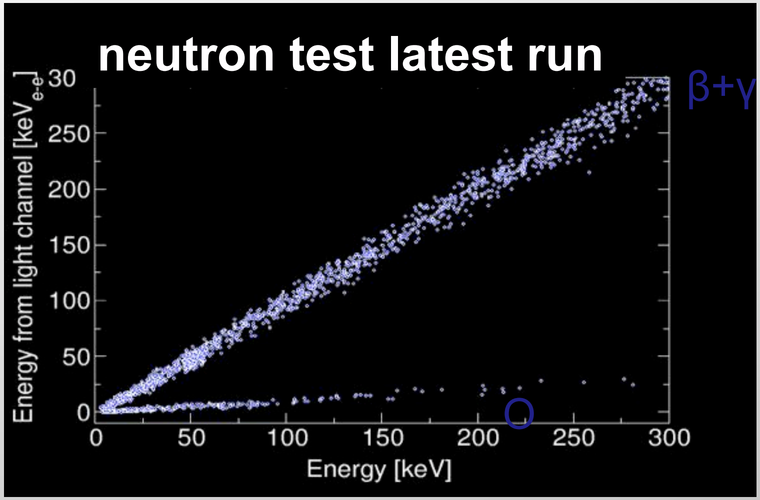
DARK MATTER SEARCHES

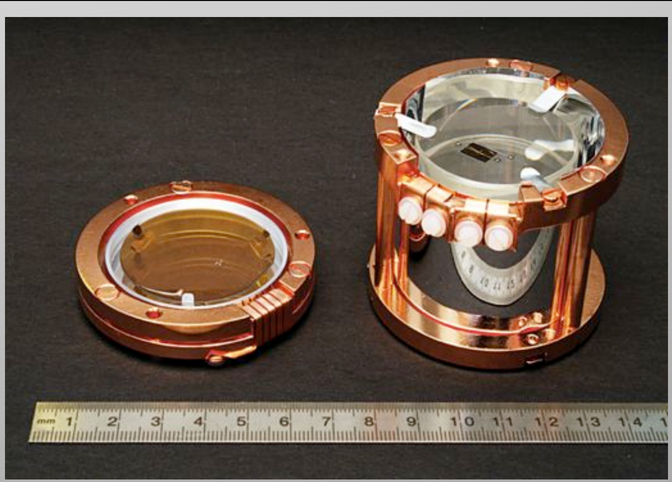
Dark Matter @ LNGS

- **DAMA/LIBRA**
  - see R. Bernabei talk on Tuesday
- **XENON family**
  - See M. Messina talk on Tuesday
- **CRESST**
- **DarkSide**

CRESST-II





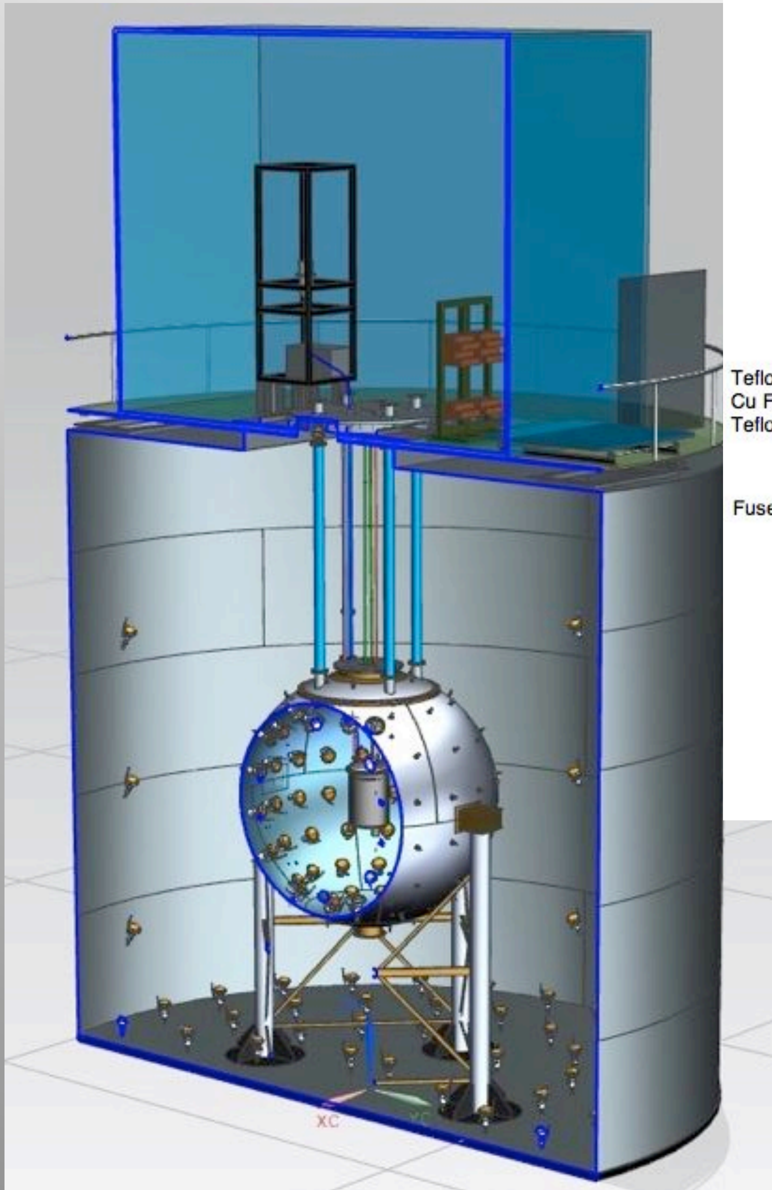


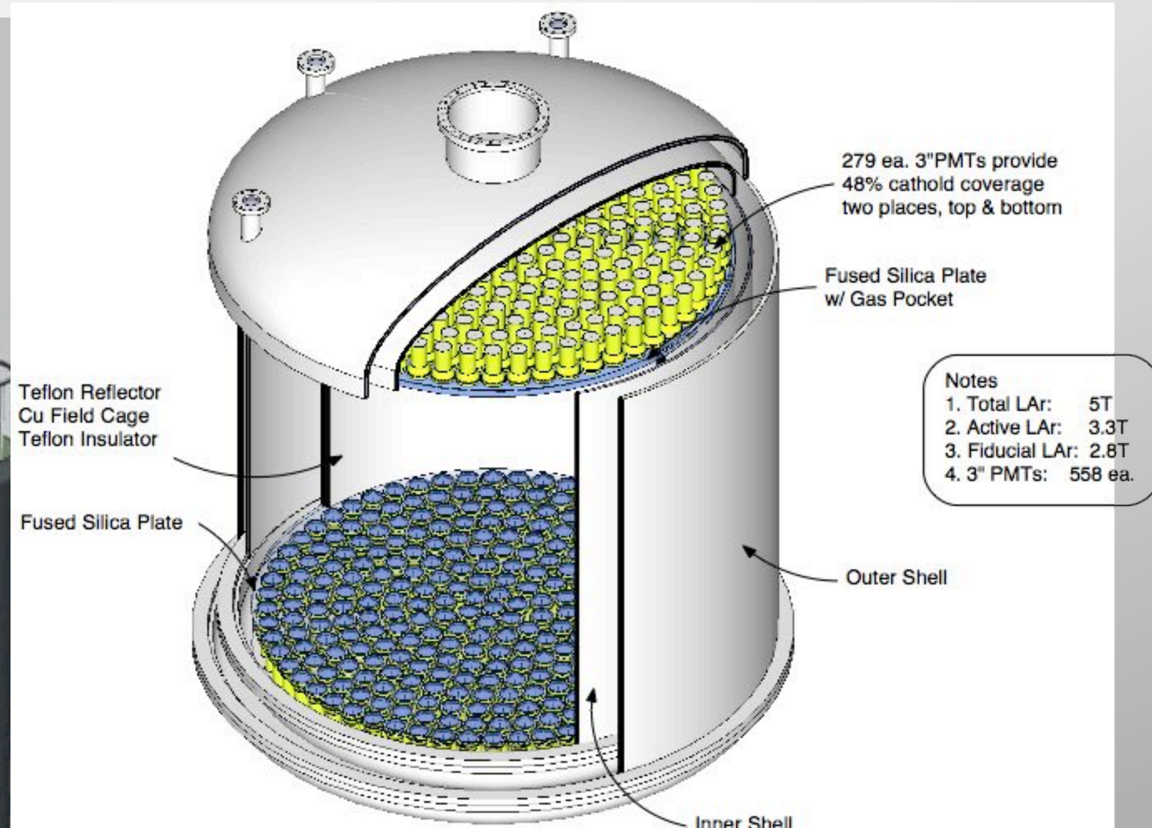
→ phonon channel provides precise measurement of deposited energy

→ Light channel distinguishes types of interaction

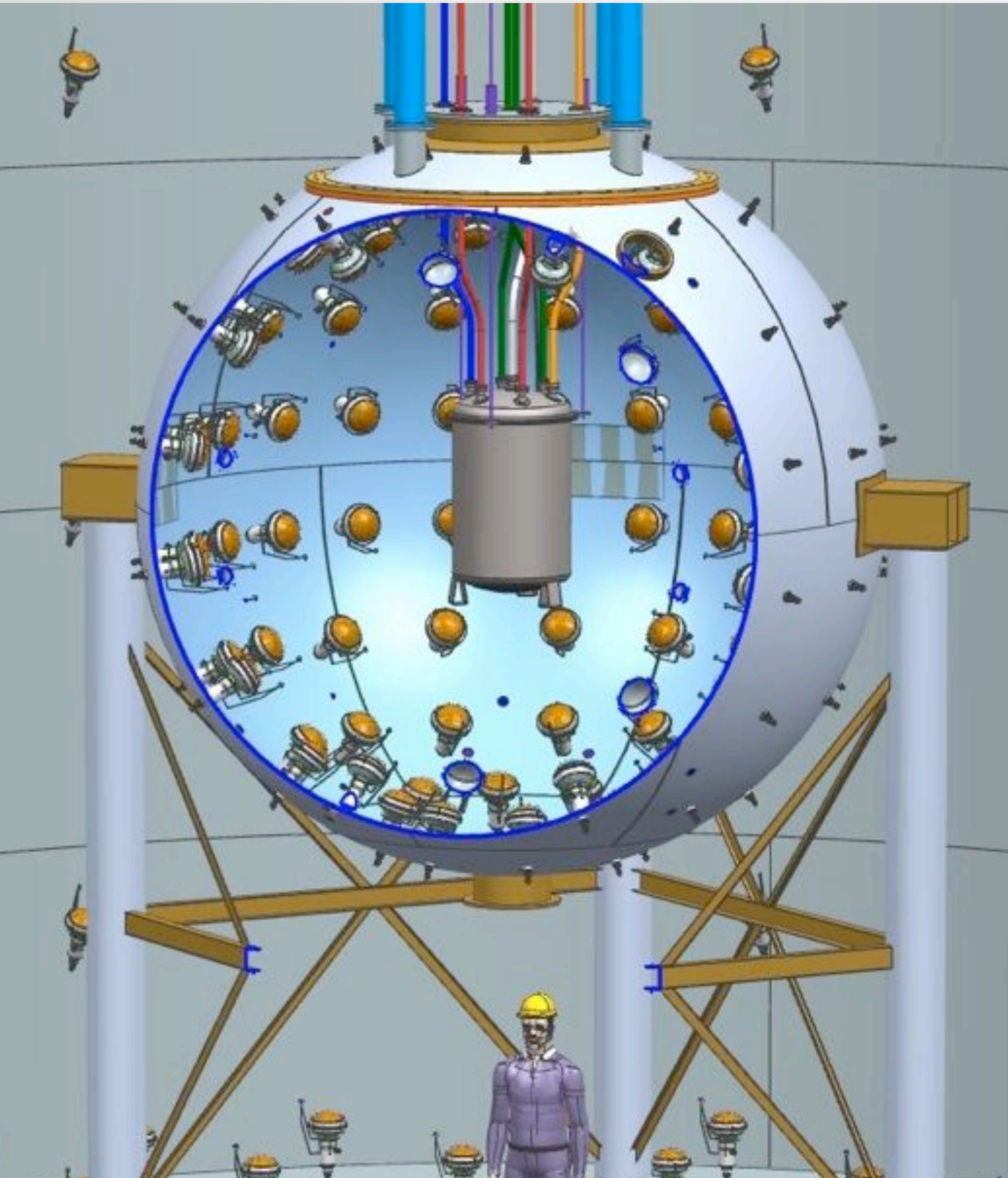
→ Types of recoiling nuclei distinguished by different slopes in light energy plane

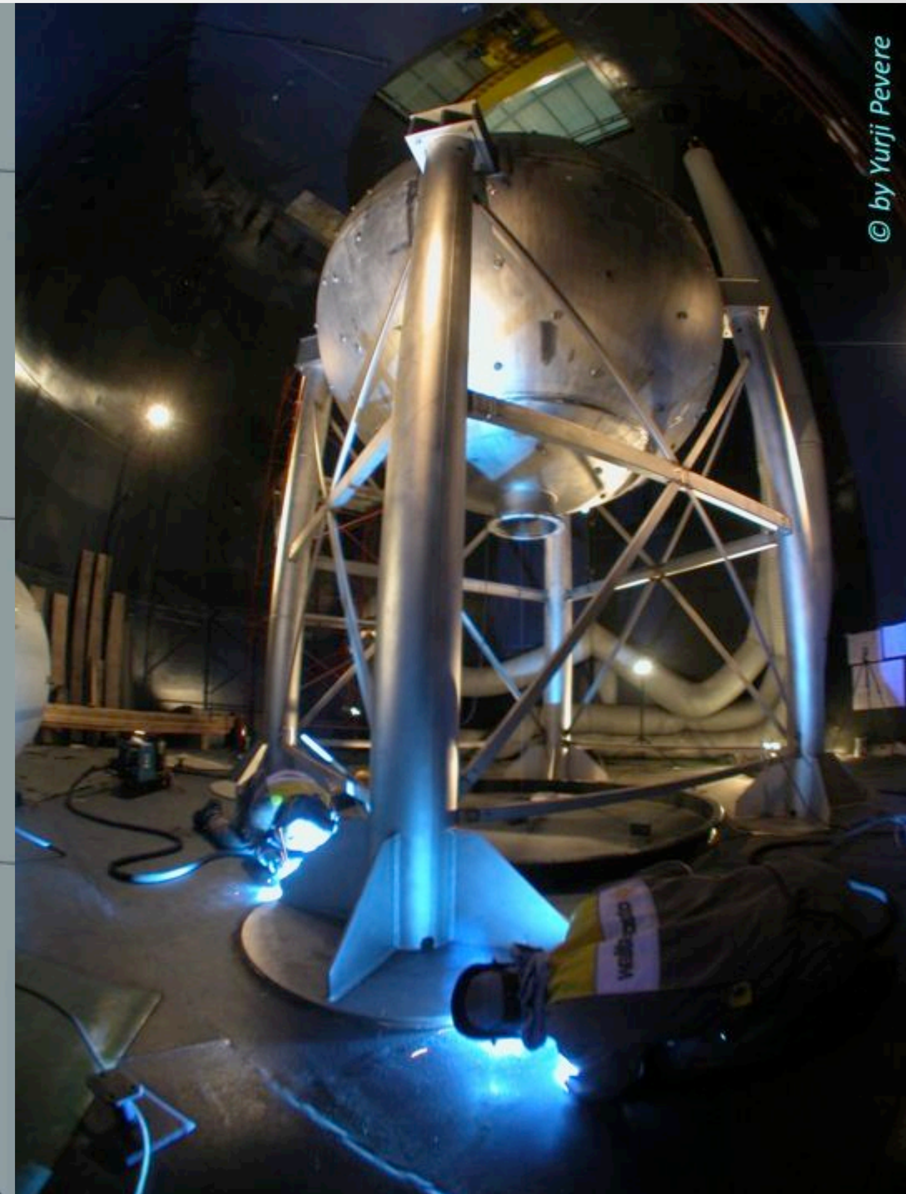
Darkside (LAr Dark Matter Search)





Darkside inner chambers





Darkside key features

- **Pulse shape Discrimination**
  - **Primary Scintillation**
- **Ionization/scintillation Ratio**
- **Sub-cm Spatial Resolution**
- **Underground argon**
- **Active neutron veto** (Boron loaded LSD)
- **Active muon veto** (Water Cherenkov)
- **Sensitivity to high-mass WIMPS**

DarkSide program @ LNGS

Scalable technology for a two-phase TPC in LAr

- ✓ **DarkSide-10** (DS-10)
  - 10 kg active mass
  - Operated in 2012 @ LNGS
  - Technical prototype for larger TPC
- ✓ **DarkSide-50** (DS-50)
  - 50 kg active mass
  - Built inside CTF Water Tank with active neutron veto
  - Launch technology for next generation detectors
  - In operation since Nov 2013
  - Expected WIMP sensitivity 10^{-45} cm^2 with UAr
- ✓ **DarkSide-G2**
  - 3600 kg fiducial
  - Can be built inside present DS-50 neutron veto
  - Expected sensitivity 10^{-47} cm^2

New NaI DM experiments

2 LOI

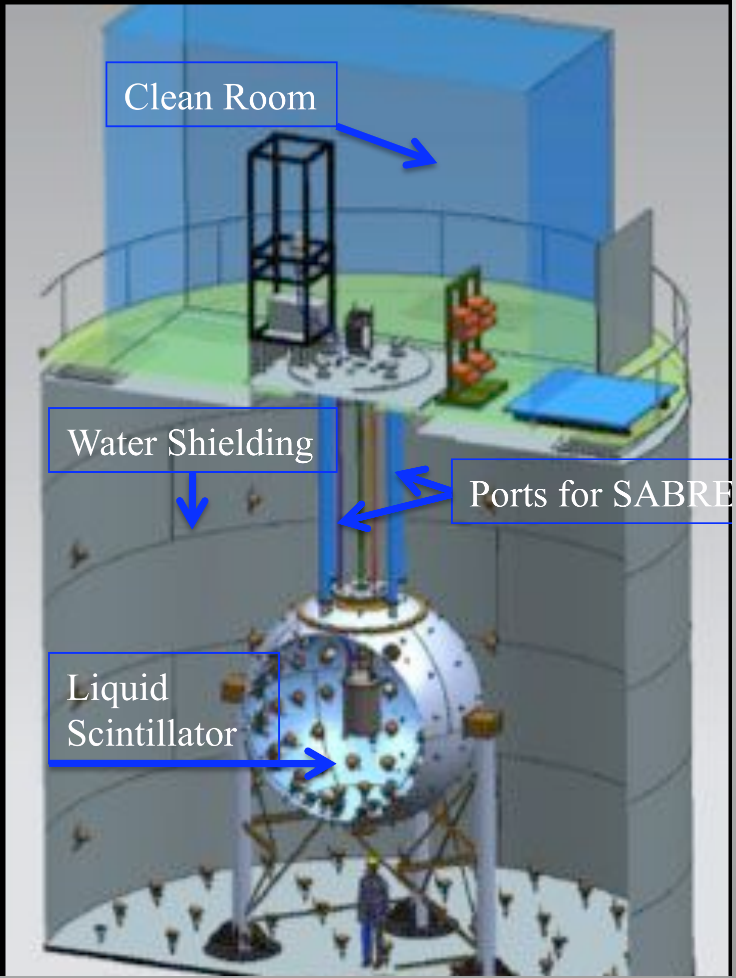
- Sabre
  - initially take advantage of Darkside
- DM-Ice 250
  - Initally take advantage of Xenon-100

Sabre

DarkSide Liquid Scintillator Neutron Veto

Darkside L.S. Veto is Operating.

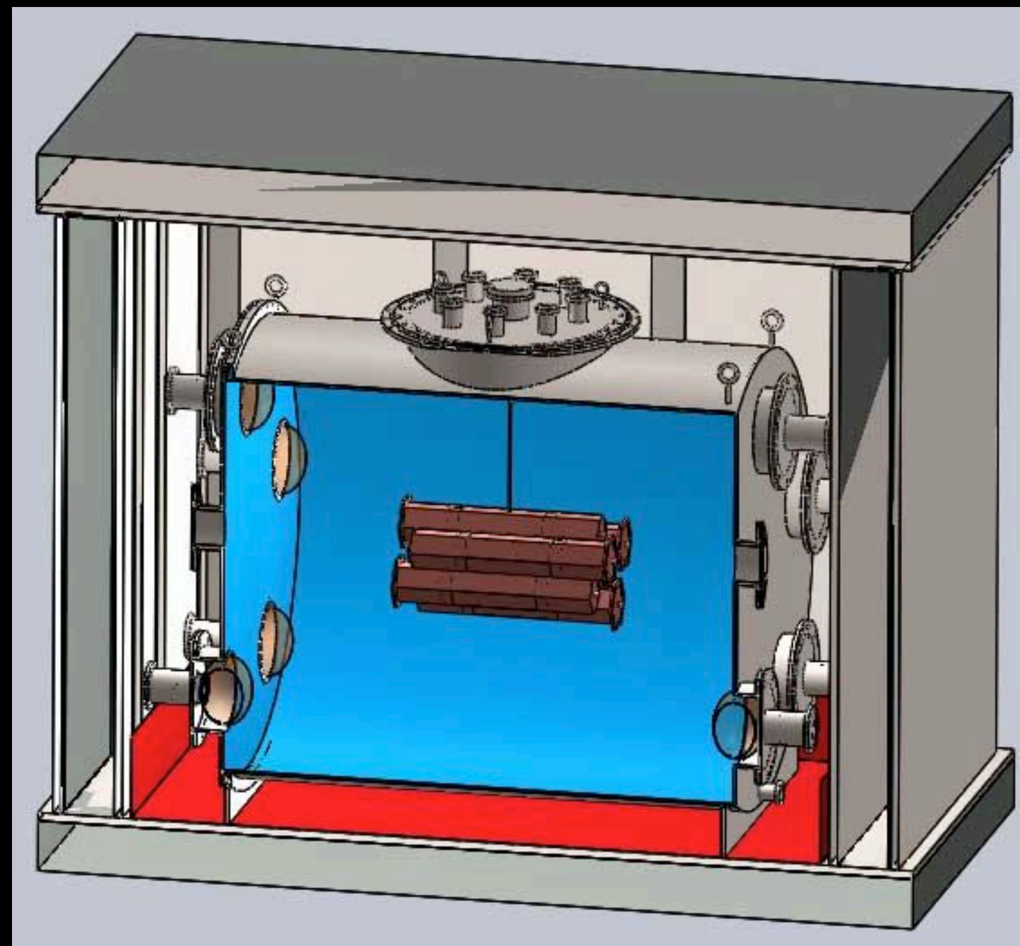
- 4 m diameter sphere
- ~30 tons of PC + TMB
- 110 high QE PMTs
- Light-yield ~0.52 p.e./keV with same Lumirror reflector used for SABRE.
- Shielded by >3-4 m of water
- NaI(Tl) 1-kg detector radio-purity tests start Summer 2014.
- Use of 3 ports for 70-kg SABRE to be decided by schedules of SABRE and large Darkside G2 detector.



Sabre

SABRE Veto Detector for 50-60 kg NaI(Tl)

- Sufficient NaI(Tl) mass
  - Bkgnd < 0.4 cpd/kg/keV
- Cylinder: 1.5 m x 1.5 m
- LAB scintillator: 2 tons
- PMTs: Ten 8-inch Ham.
- Reflector: Lumirror
- L.Y.: 0.22 p.e./keV
- Shielding: 25cm steel.
  - Small footprint.
- Portable: LNGS, SNOLab, Australia?
- Funded by NSF.
  - In construction.



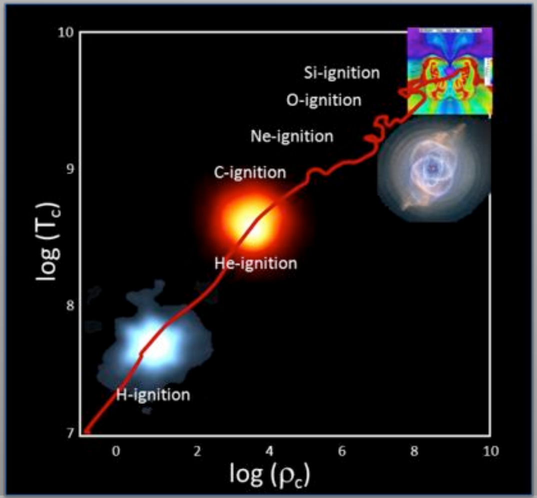
NUCLEAR ASTROPHYSICS

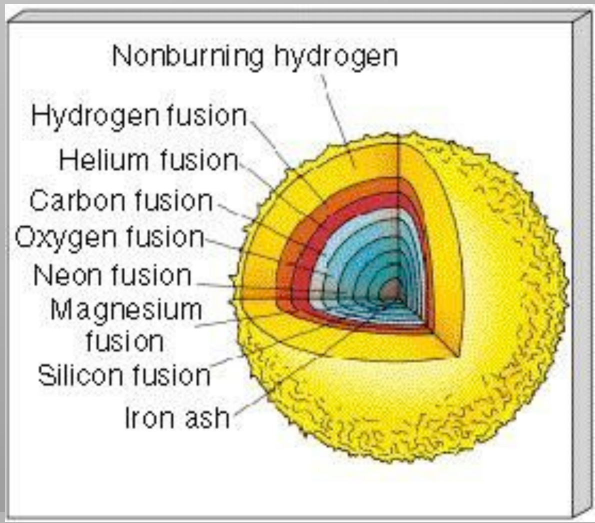
The LUNA experiment

nuclear fusion reaction cross sections

- Key parameters to model stars
  - chemical composition, opacity…
  - reactions cross sections
  - Many reactions need high precision data

C. Broggini talk today





Summary

- **The Scientific Programme at Gran Sasso is**
  - **World-leading**
  - **Addresses important astroparticle topics**
  - **Neutrino physics**
    - **neutrino oscillations**
    - **solar physics**
    - **double beta decay**
    - **cosmogenic & geo neutrinos**
  - **Dark Matter**
  - ***And more…***
    - *Foundations of physics*
    - *Environment and health Physics*
- **A national lab & international asset**