LNGS program

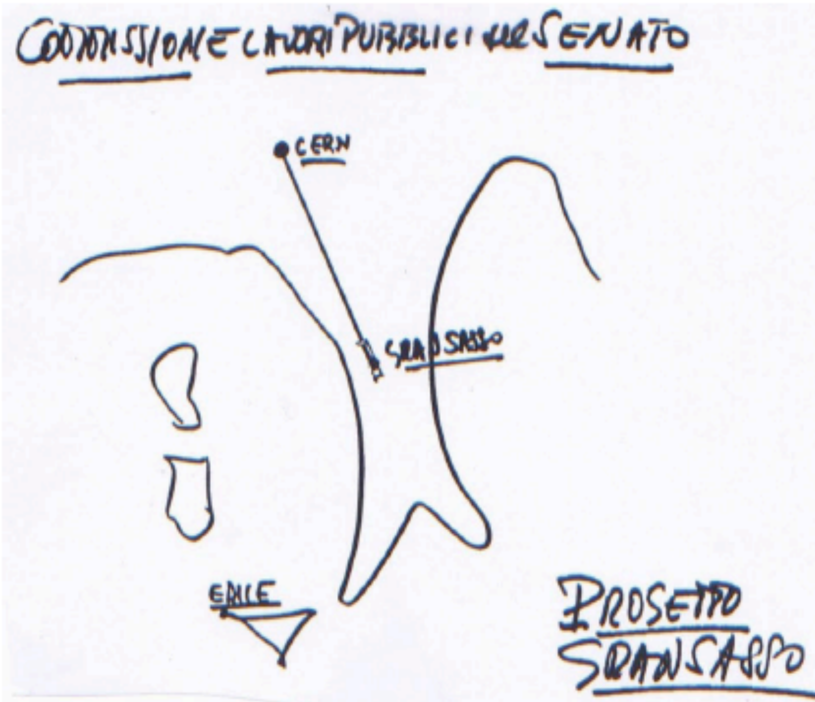
Neutrino Telescopes
Venezia, March 2015

Stefano Ragazzi – LNGS Director

Laboratori Nazionali del Gran Sasso

INTRODUCTION

The birth

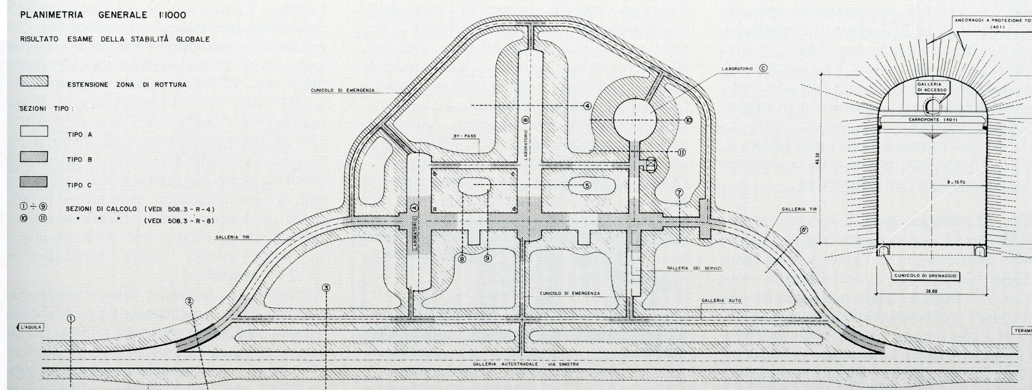


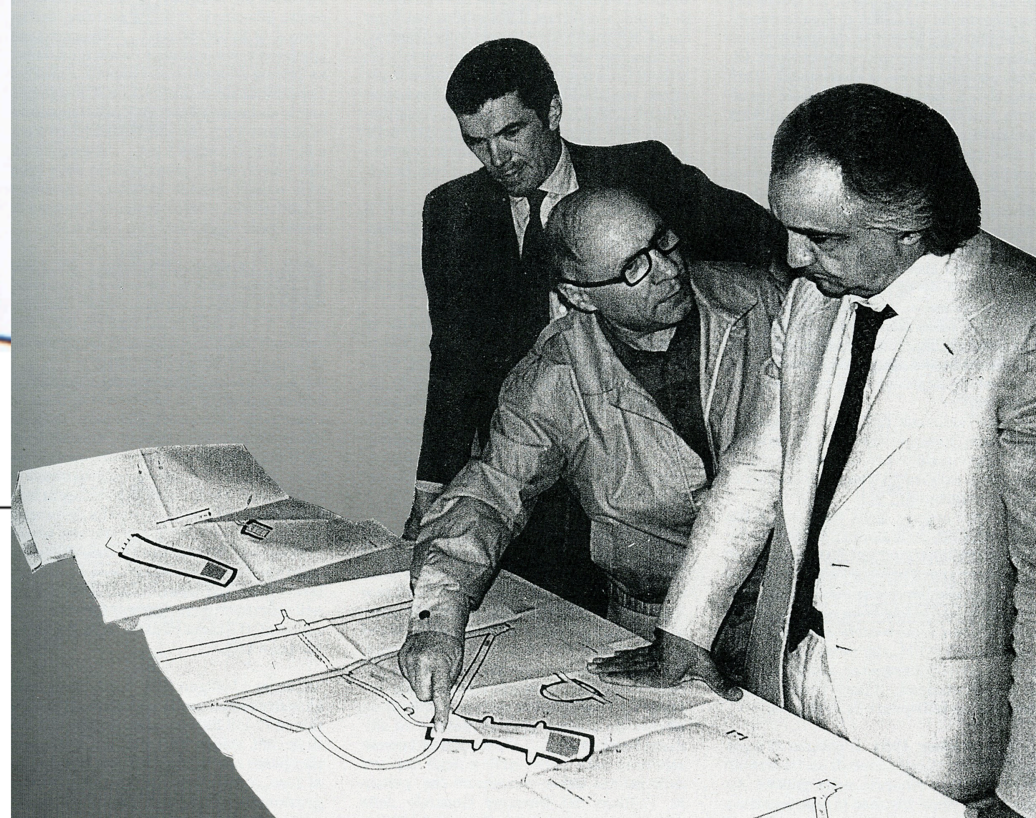
Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

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.

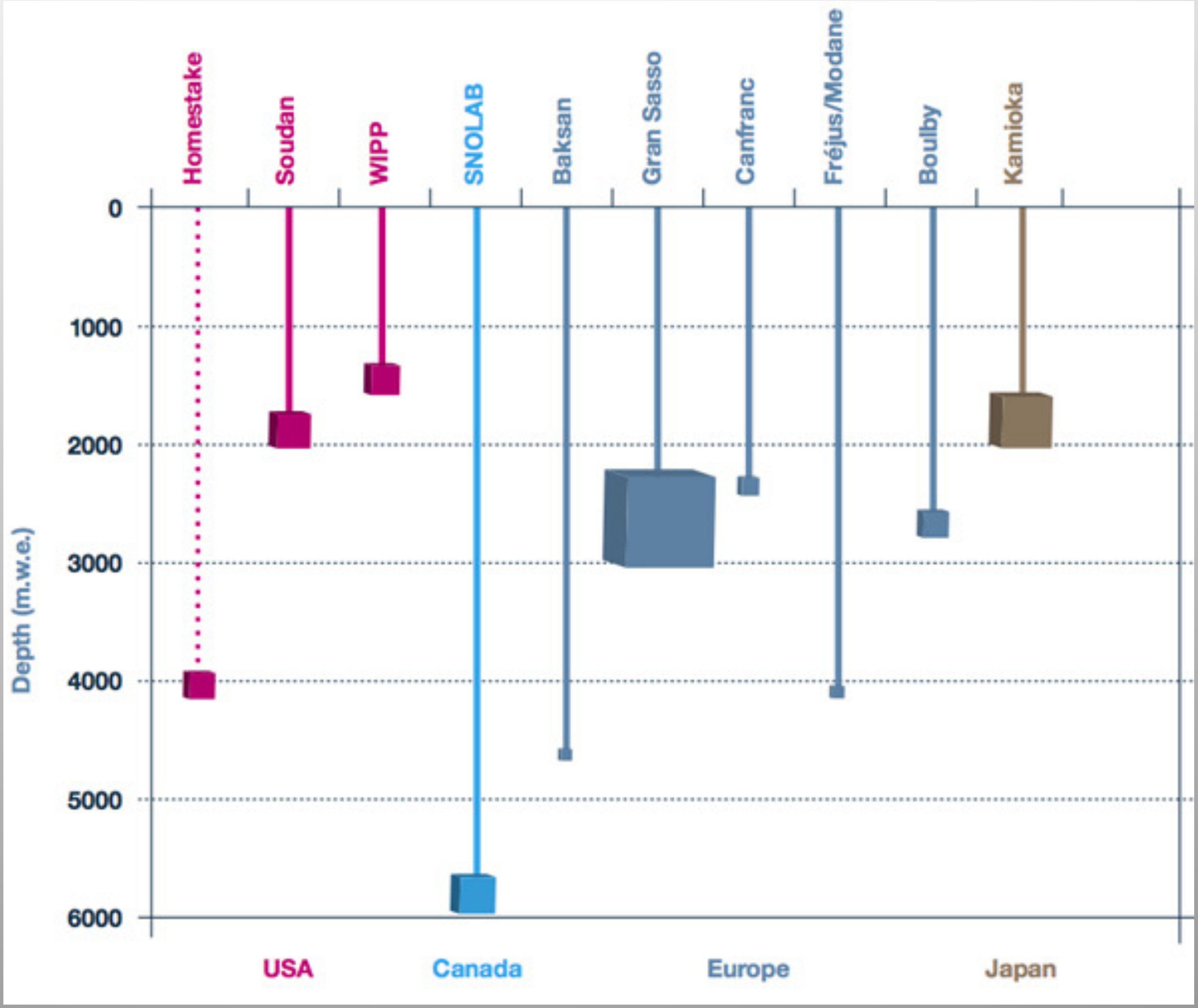
NOT only $\tau_p \neq \infty$





Underground Science Laboratories

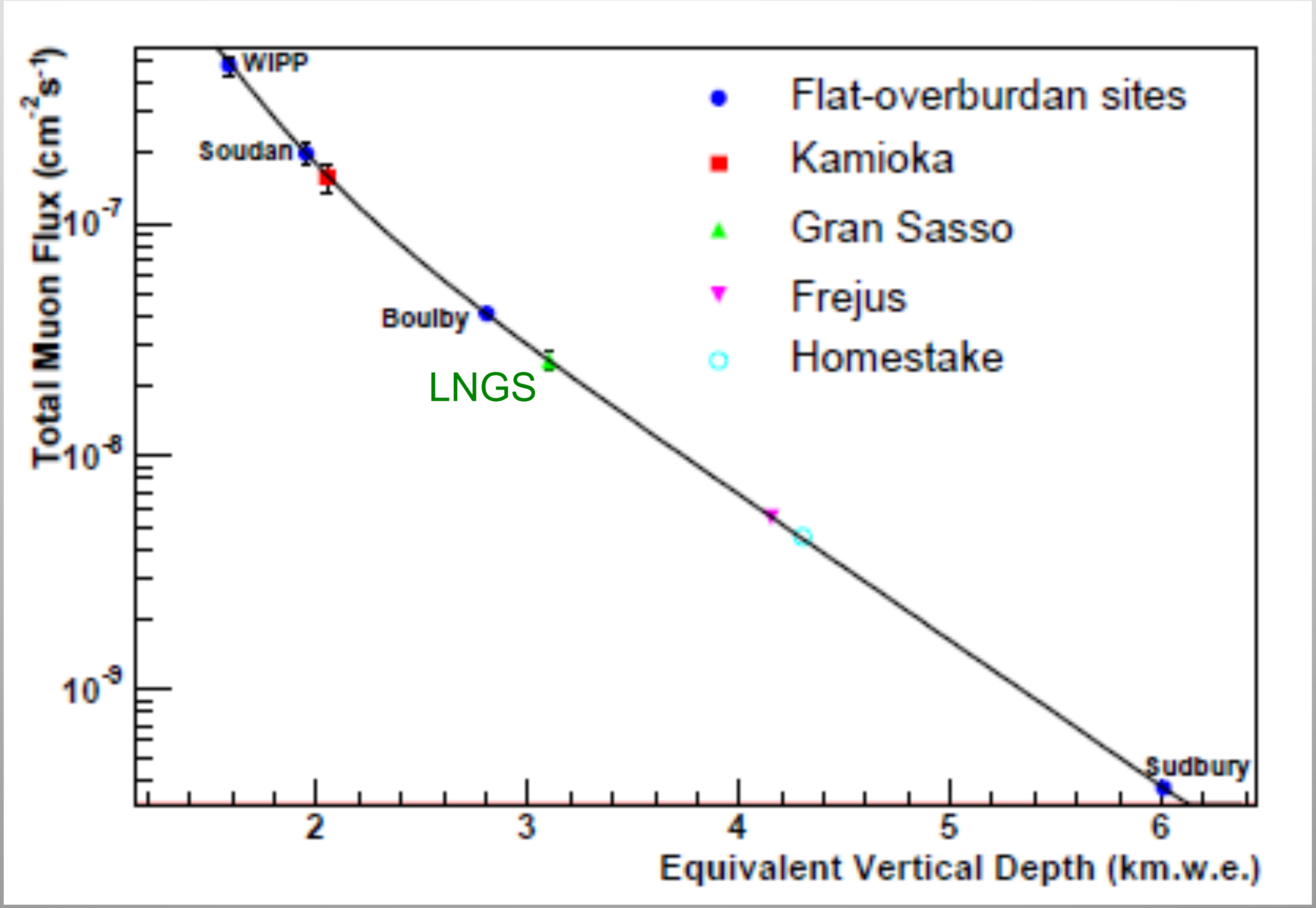
- **LNGS**
  - Largest
  - Easy access



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

Muon Flux versus depth

LNGS: 10^{-6} wrt surface



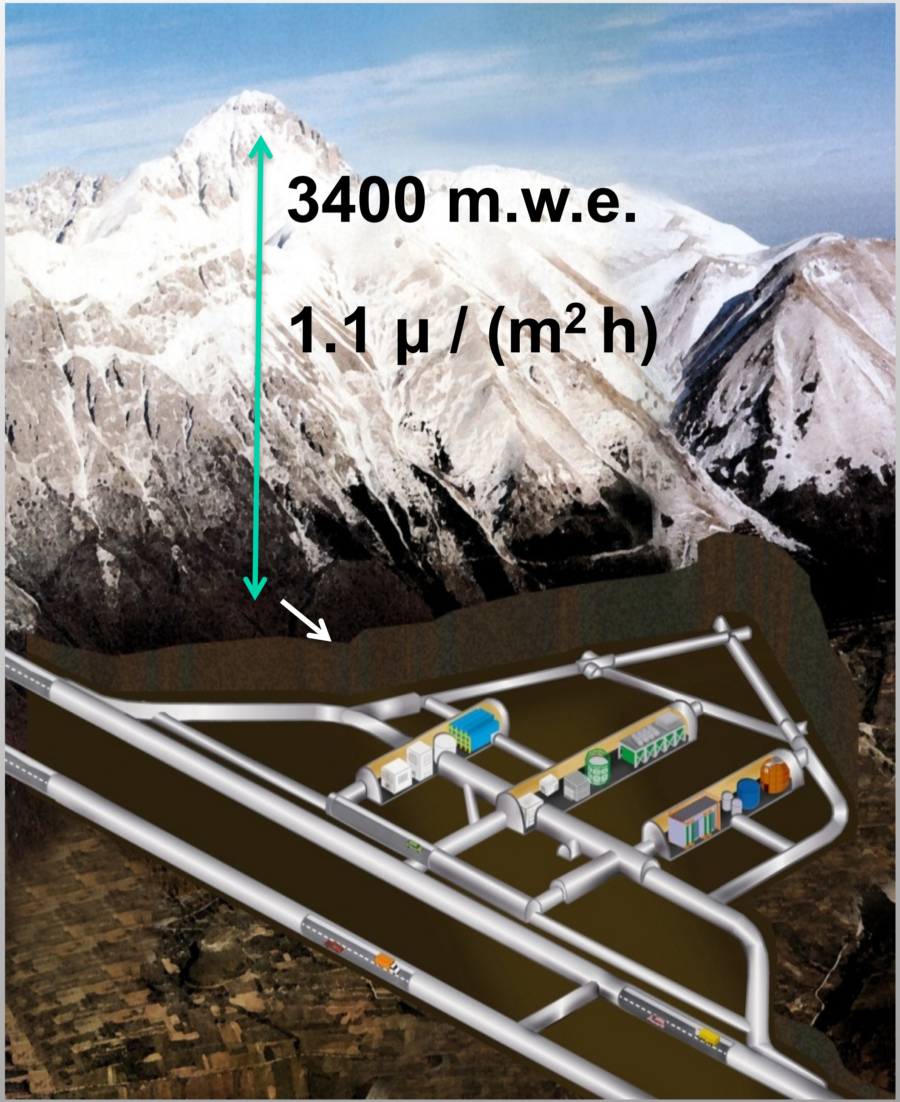
Hime and Mei, Phys.Rev. D73 (2006) 053004

The LNGS Laboratory

- 42.46°N 13.57°E
- Muon flux: $3.0\ 10^{-4}\ m^{-2}s^{-1}$
- Neutron flux:

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

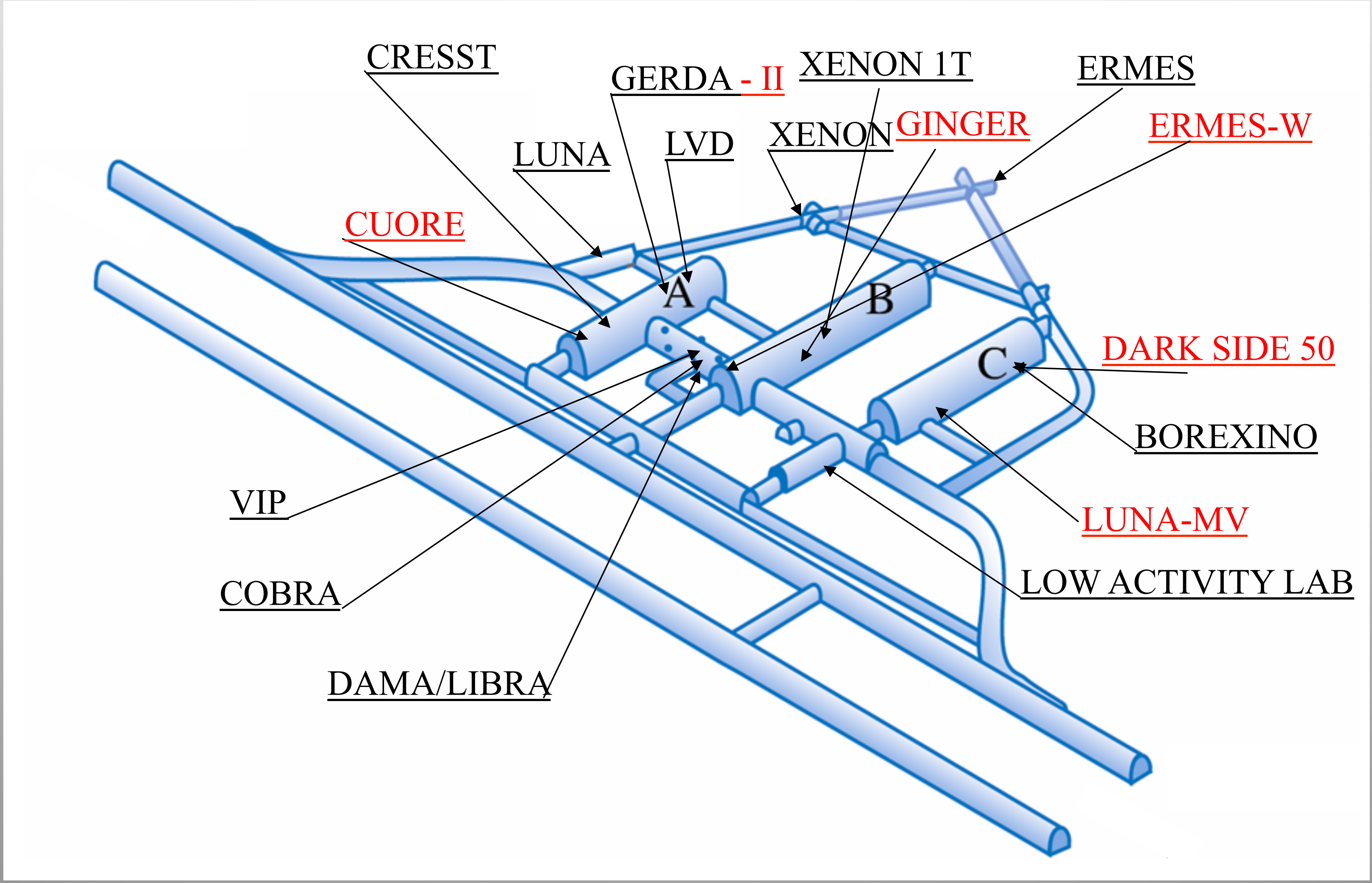
  $0.86\ 10^{-6}\ cm^{-2}s^{-1}$ (> 1 keV)
- Rn in air: 20-80 Bq m^{-3}
- Surface: 17 800 m^2
- Volume: 180 000 m^3
- Ventilation: 1 vol / 3.5 hours



Virtual tour

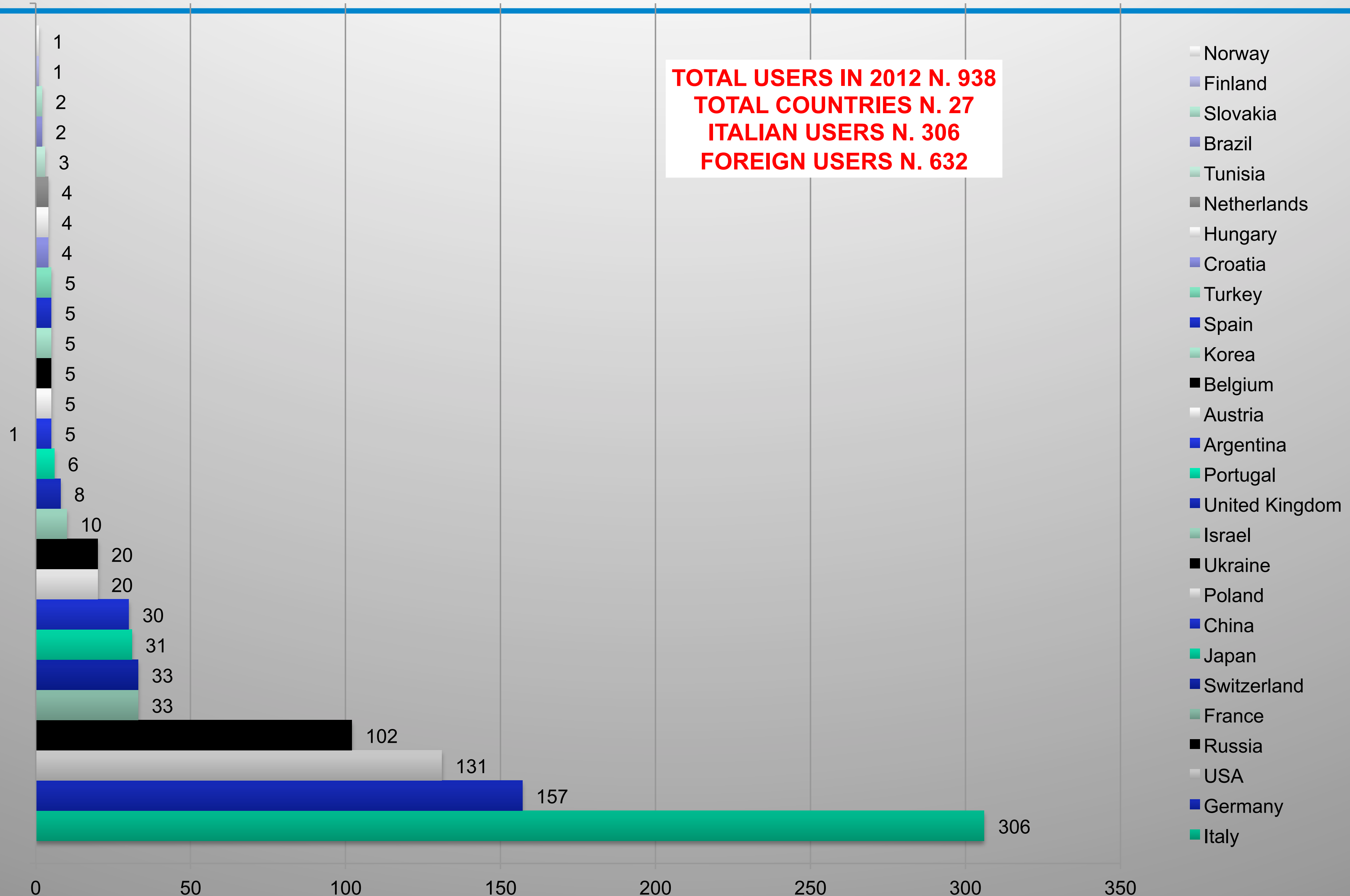
- **From Google Street View**
- www.google.it/maps/@42.4538978,13.5746863,3a,75y,266.25h,74.88t/data=!3m5!1e1!3m3!1sU33rehgjcSpsBNVVJXXT_w!2e0!3e5

A busy laboratory



Busy people

- **102 Staff**
  - Research
  - Administration
  - Operation
  - Safety & Environment
  - Mechanics design & workshop
  - Electronics Laboratory
  - Chemistry Laboratory
  - Trace radioactivity measurements
- **> 900 users**
- **~ 220 daily presence**


TOTAL USERS IN 2012 N. 938
TOTAL COUNTRIES N. 27
ITALIAN USERS N. 306
FOREIGN USERS N. 632
Norway 1
Finland 1
Slovakia 2
Brazil 2
Tunisia 3
Netherlands 4
Hungary 4
Croatia 4
Turkey 5
Spain 5
Korea 5
Belgium 5
Austria 5
Argentina 5
Portugal 6
United Kingdom 8
Israel 10
Ukraine 20
Poland 20
China 30
Japan 31
Switzerland 33
France 33
Russia 102
USA 131
Germany 157
Italy 306
1
0
50
100
150
200
250
300
350

LNGS main topics

Selected topics

NOT

a comprehensive review of Physics at LNGS

Core activities in the LNGS program

- Neutrino Astrophysics
- Neutrino Physics
- Dark Matter searches
- Astro-Nuclear Physics

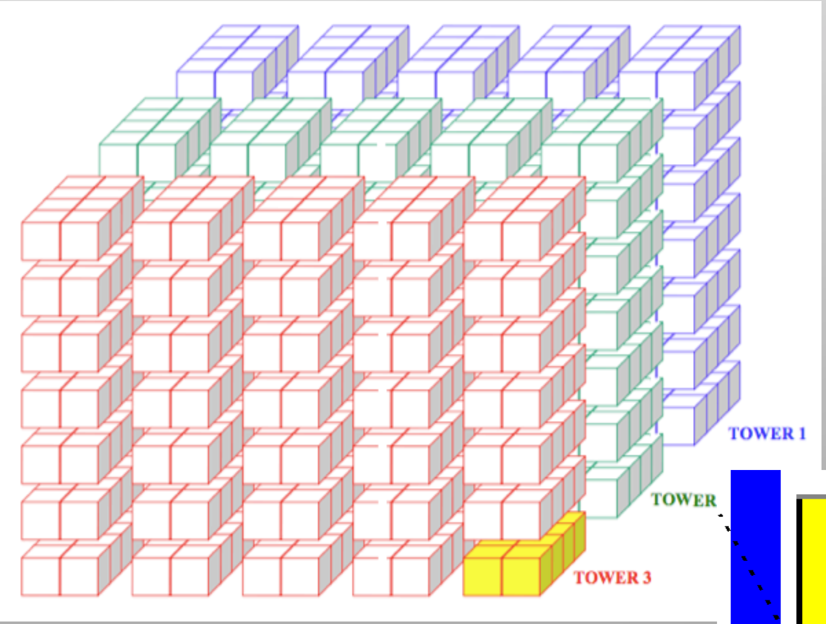
COSMOGENIC AND SOLAR NEUTRINOS

Men in pits or wells sometimes see the stars…
Aristotle

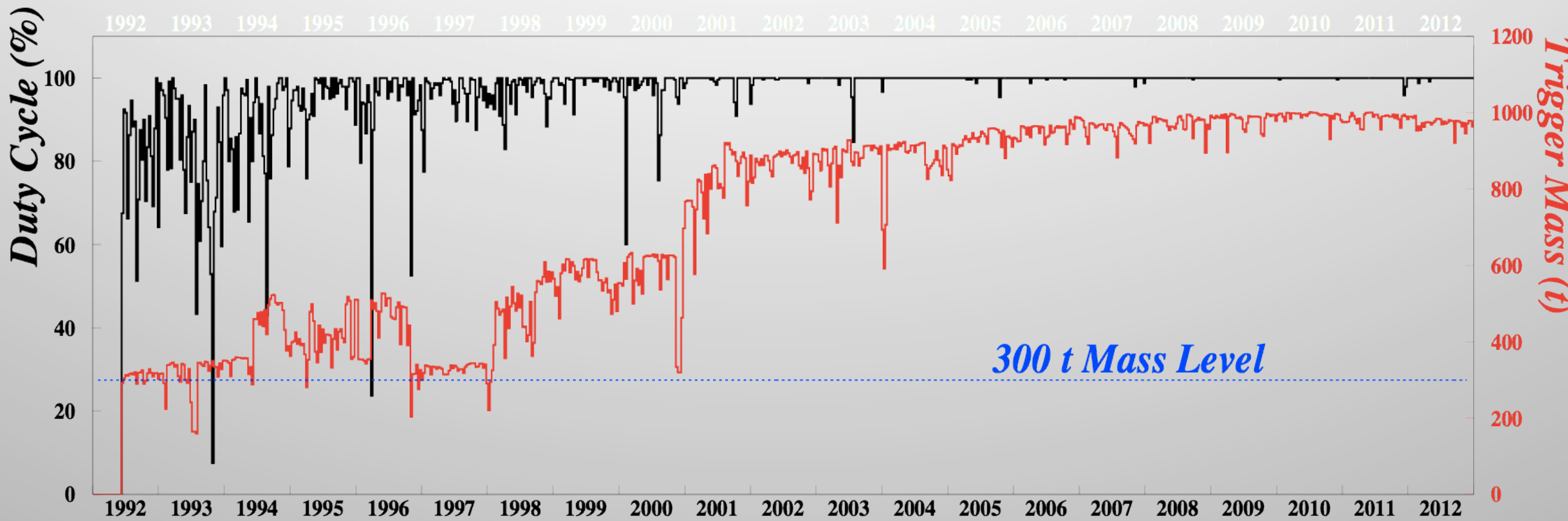
LVD

Search for ν from Core Collapse Supernovae

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



Duty factor



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

…. and for the future

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

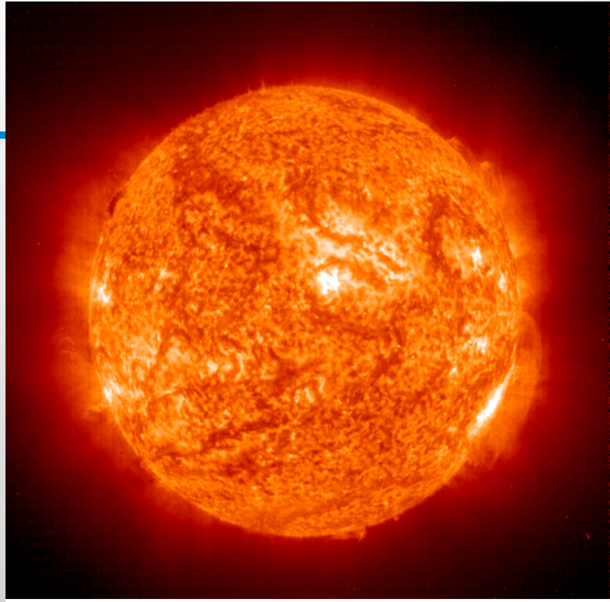
AND catch an SN collapse

Solar Neutrinos

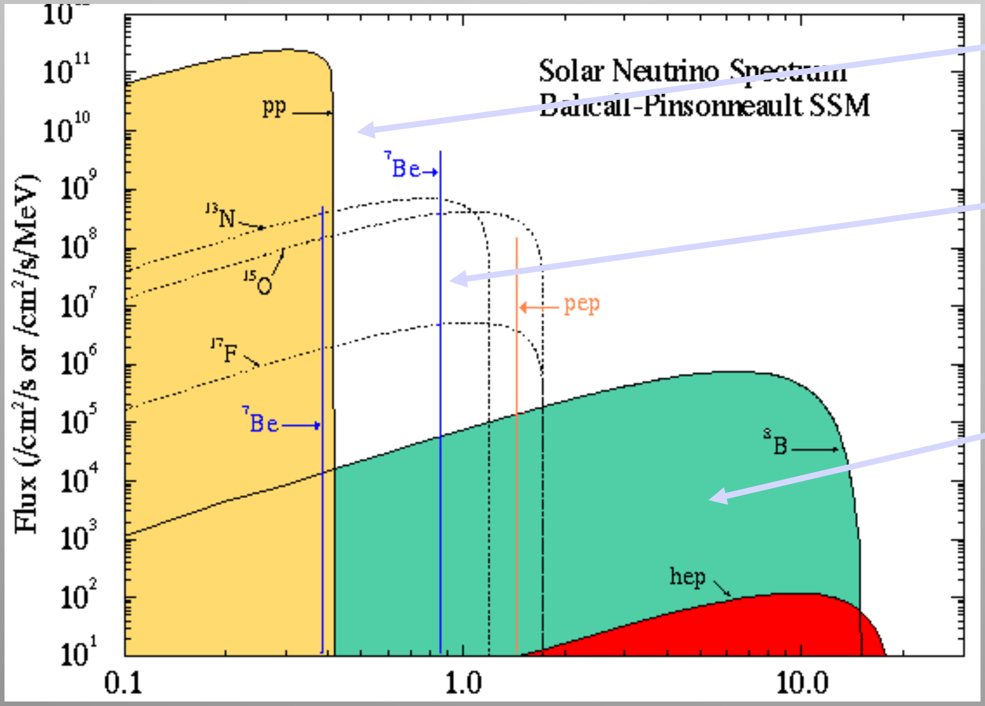
- Sun is a precious source of neutrinos
  - studied on the Earth: ~10^{10} cm^{-2}s^{-1}

Sun Astrophysics

Neutrino Physics



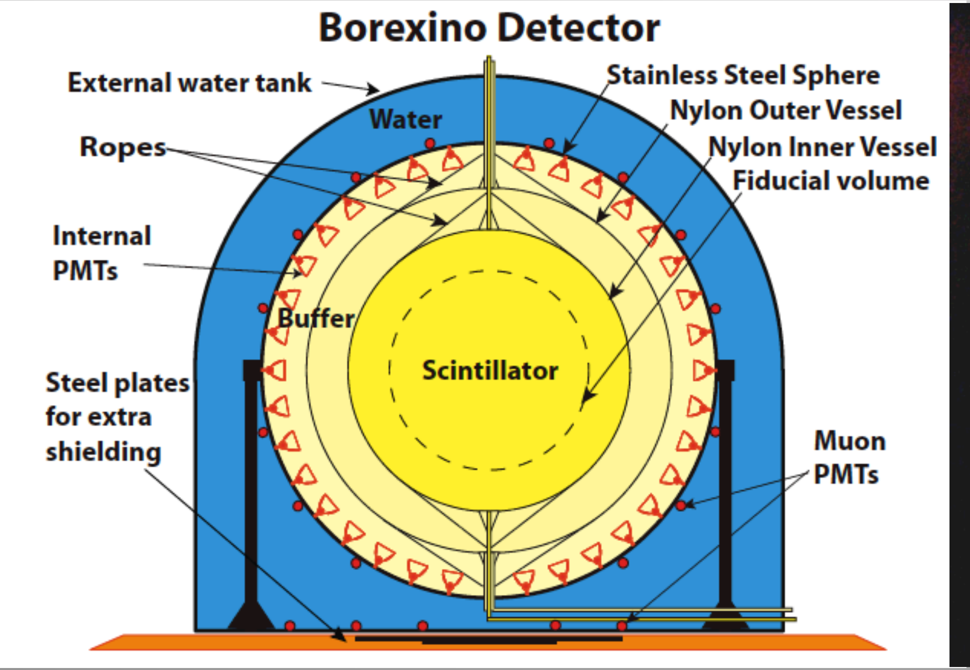
pp	$\rightarrow$	$^2H + e^+ + \nu_e$	
$^2H + p$	$\rightarrow$	$^3He + \gamma$	
$^3He + {}^3He$	$\rightarrow$	$^4He + 2p$	85%
$^3He + {}^4He$	$\rightarrow$	$^7Be + \gamma$	15%
$e^- + {}^7Be$	$\rightarrow$	$^7Li + \nu_e$	
$^7Li + p$	$\rightarrow$	$2\,{}^4He$	
$p + {}^7Be$	$\rightarrow$	$^8B + \gamma$	0.02%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

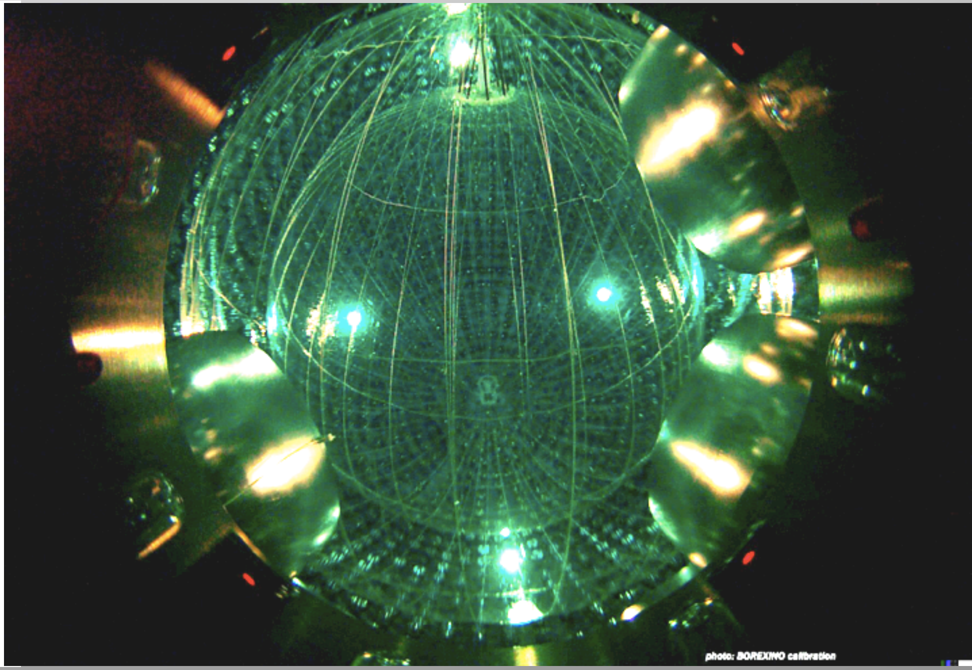


Borexino

"A remarkable detector called Borexino has operated for the past seven years…"

Wick Haxton Nature v.512 p.378, 28 August 2014



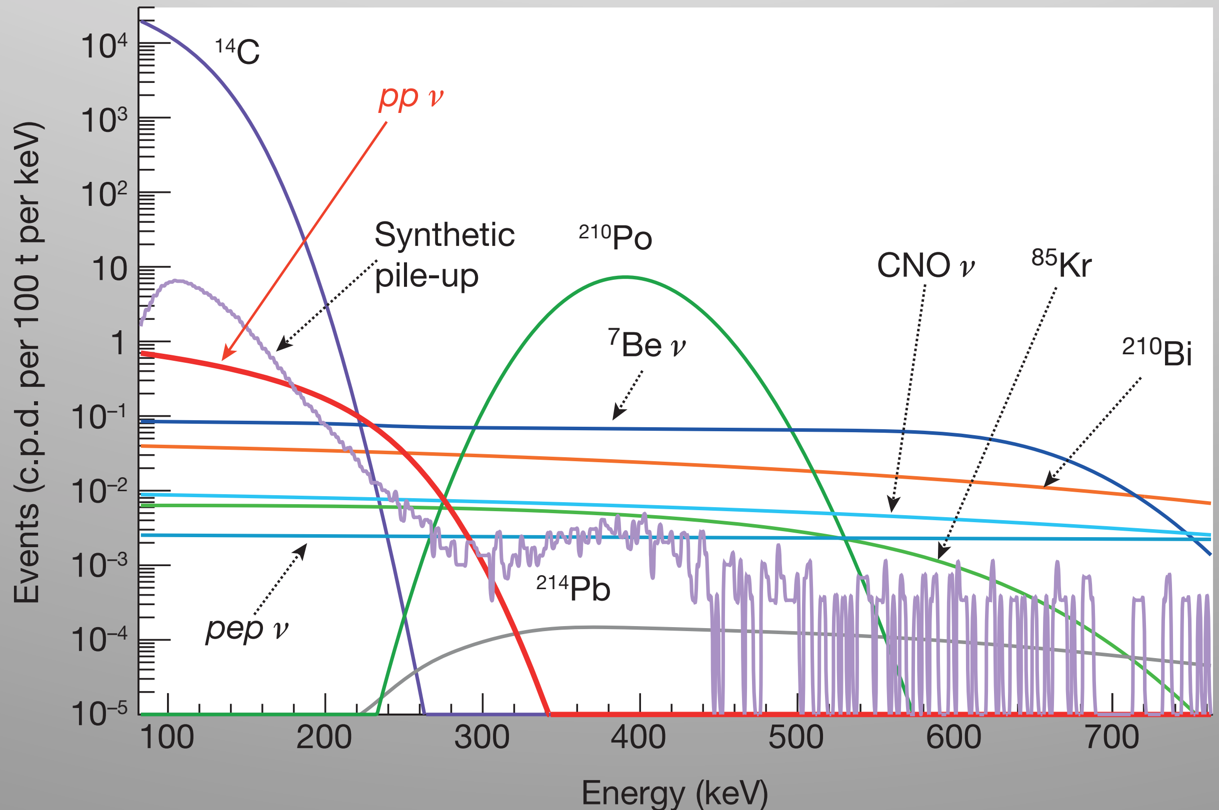


Borexino @ LNGS

Borexino

Physics World: 2014 top ten achevments of the year …

- To the Borexino collaboration, for being the first to detect neutrinos from the main nuclear reaction that powers the Sun

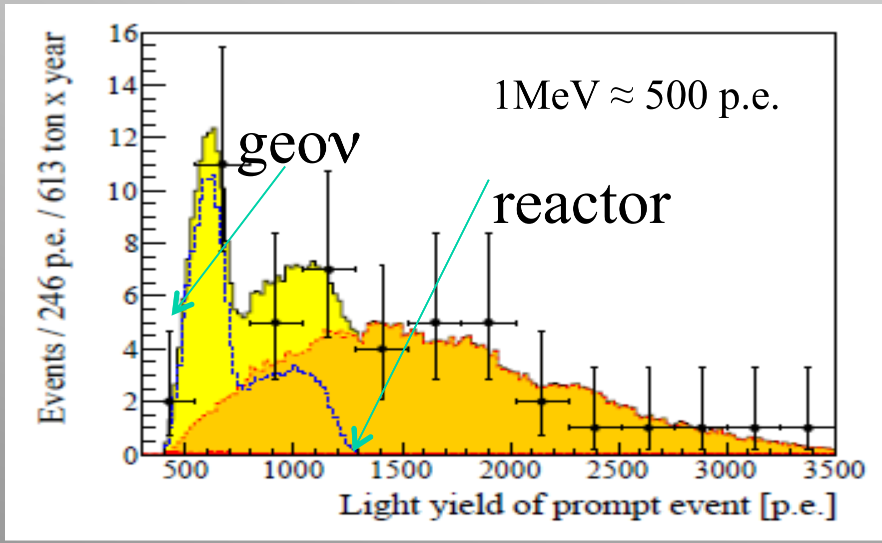


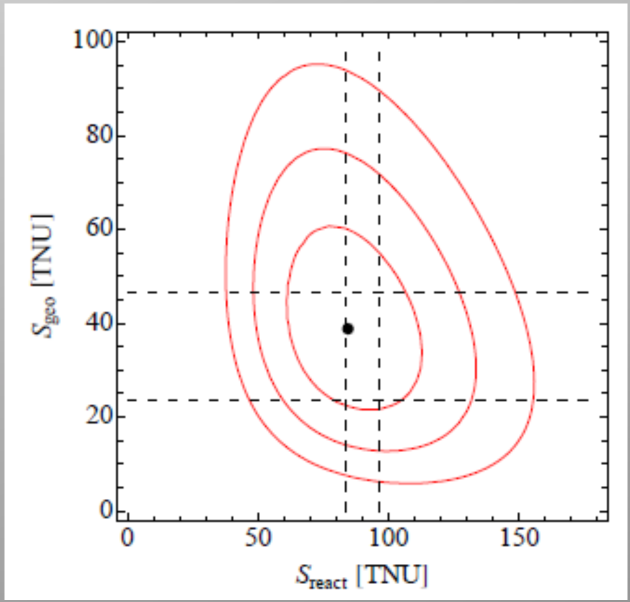
Geo Neutrinos

$N_{reactor}$ 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)
• pp:	1.44 ± 0.13 ± 0.10	Nature 512, 383 (2014)

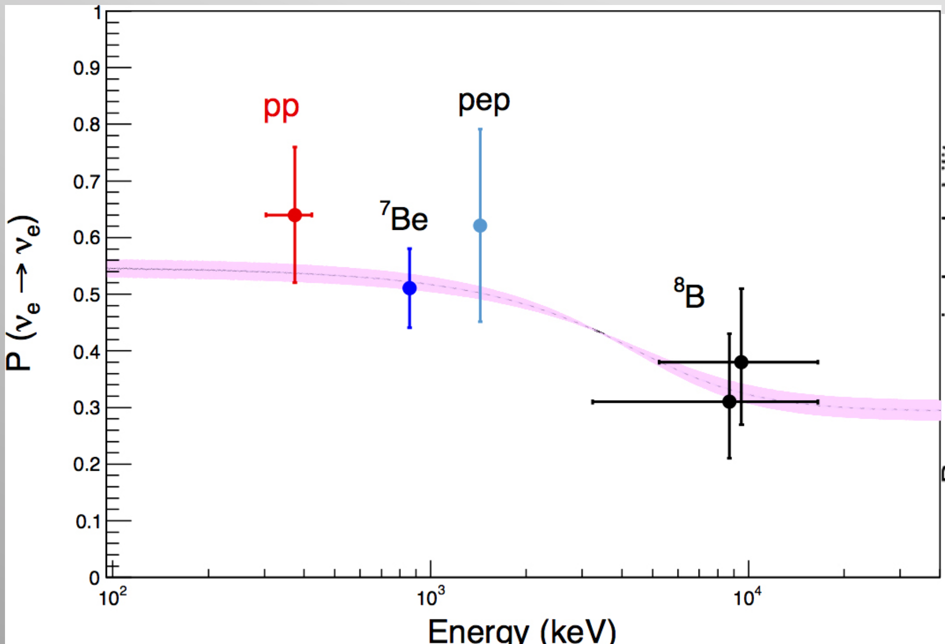
Geo-neutrinos

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

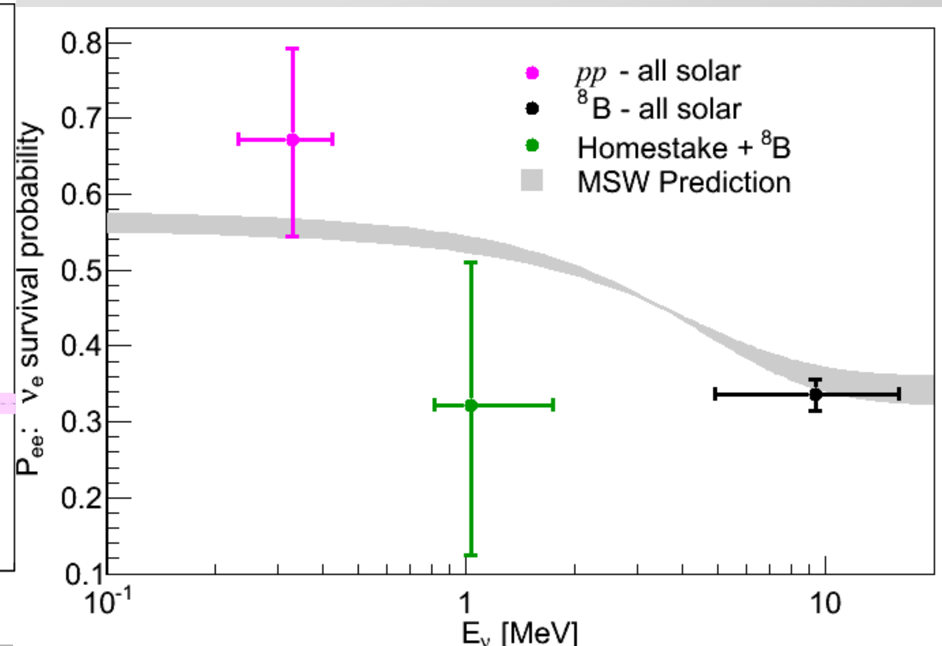
Borexino solar ν results

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

Borexino

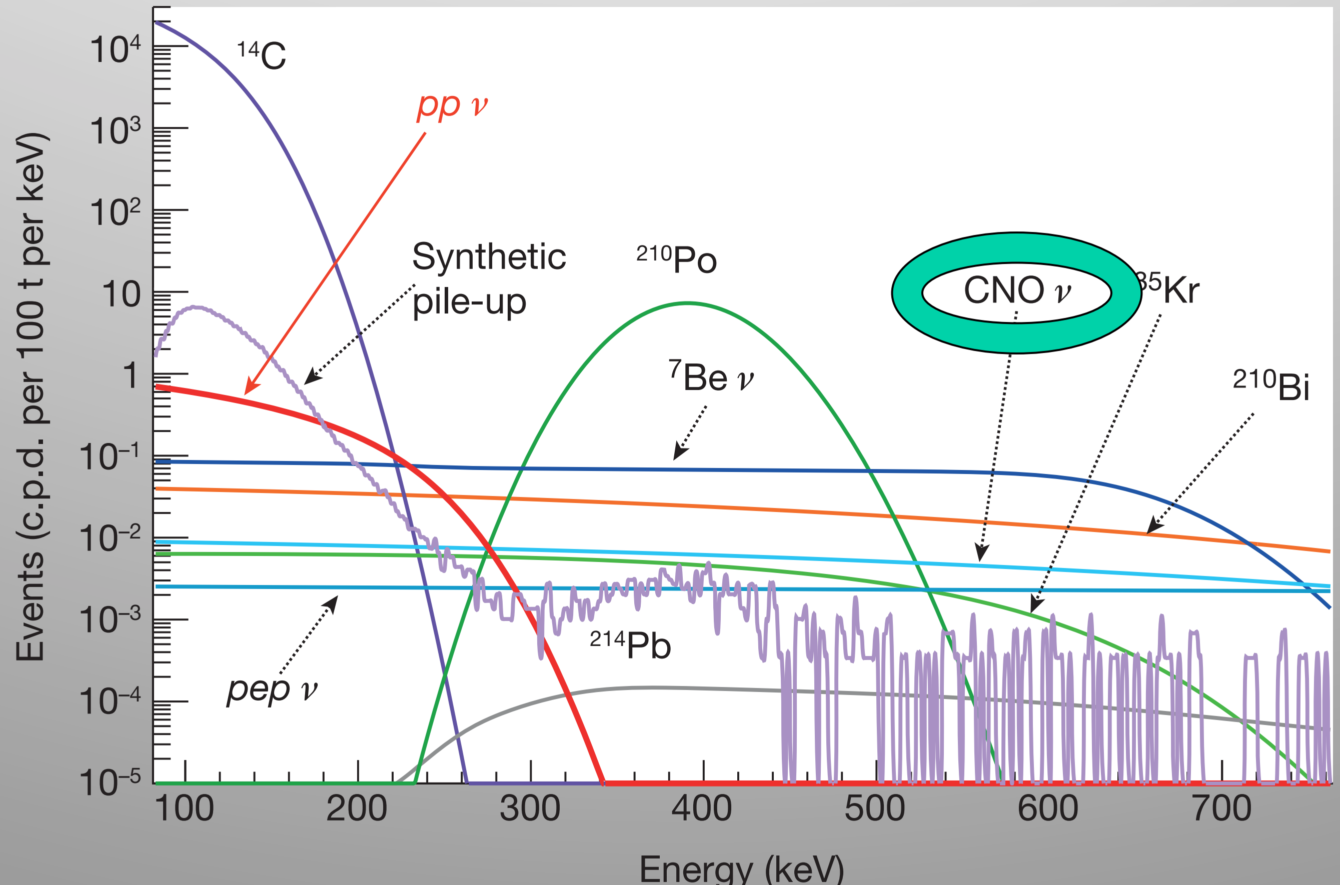


Rest of the world, combined



Borexino: next challenge

- CNO ν rate is a fraction of beta rate from ^{210}Bi
- ^{210}Bi rate monitored by ^{210}Po α rate
  - provided that rates are stable



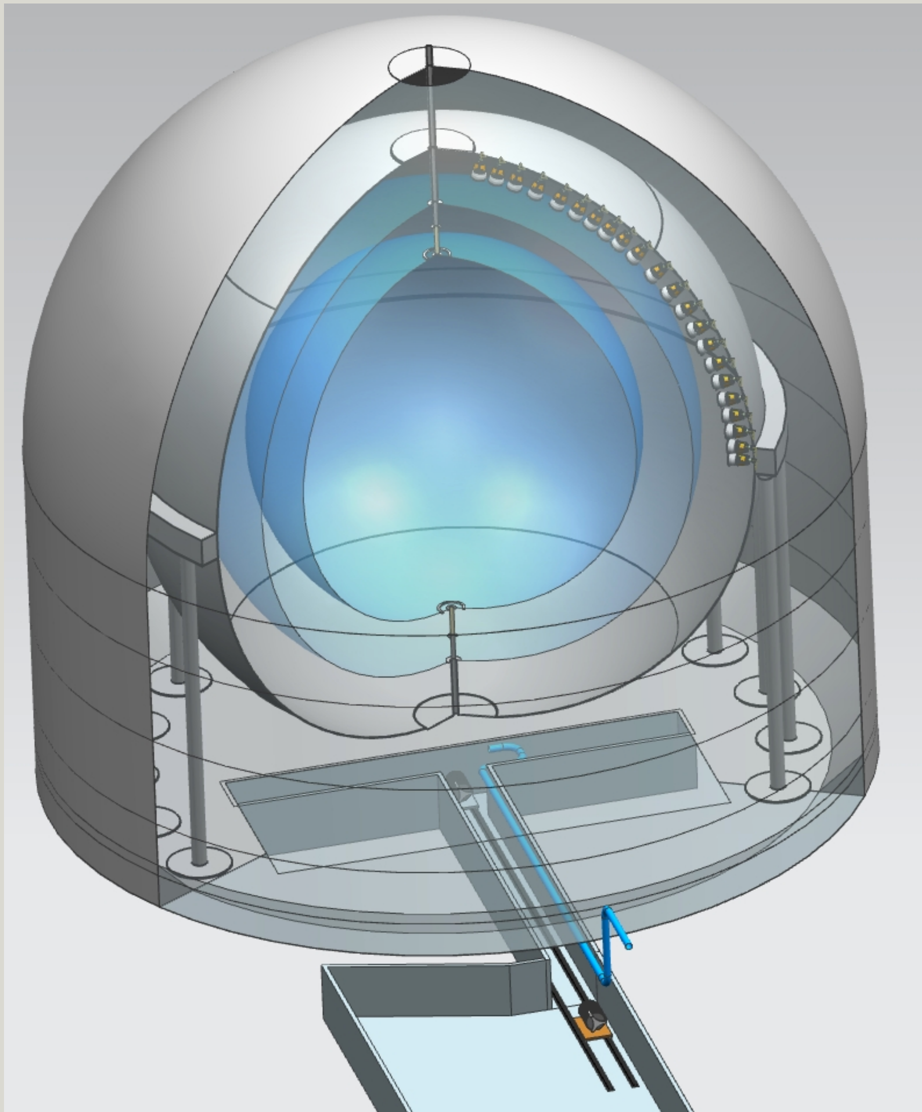
NEUTRINO PROPERTIES

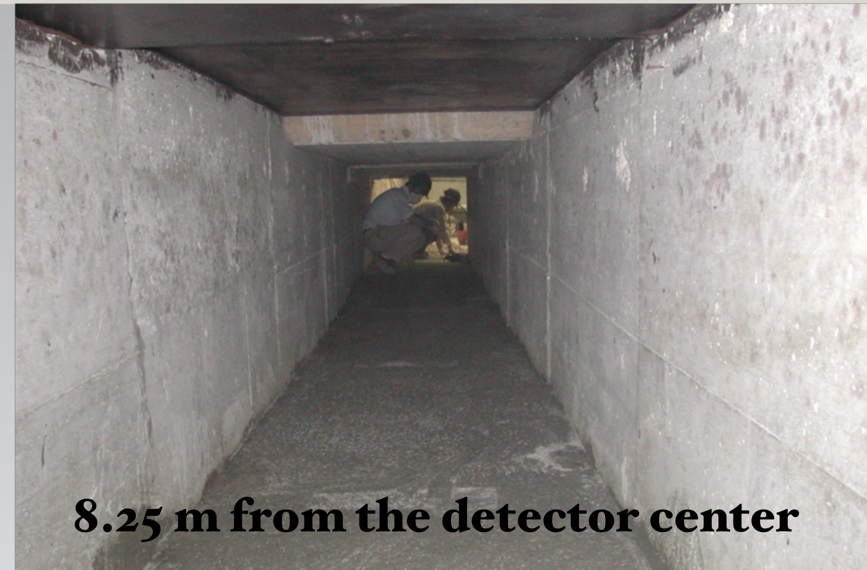
Testing LSND with SOX

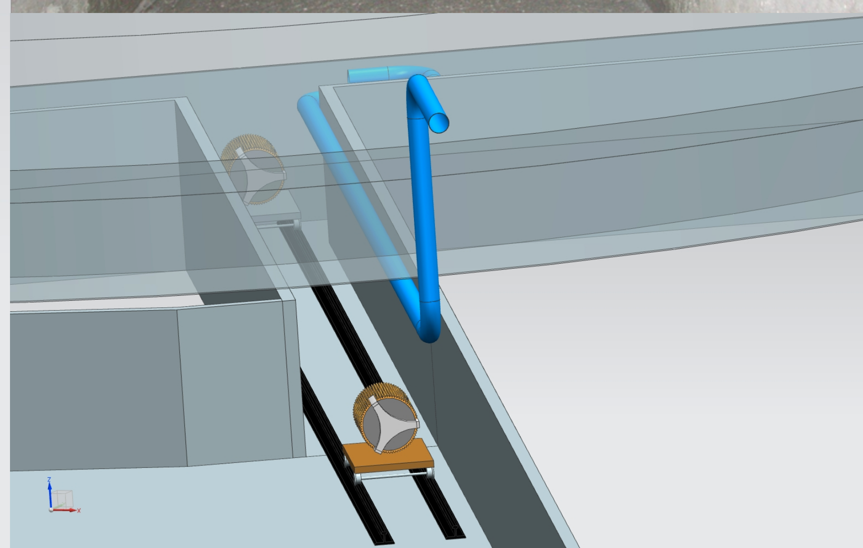
- **Science motivations:**
  - Search for **sterile neutrinos** or other **short-distance effects on P_{ee};**
  - Measurement of Weinberg angle θ_W at low energy (~ 1 MeV);
  - Improved limits of the neutrino magnetic moment;
  - Measurement of the vector g_V and axial g_A current coefficients at low 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

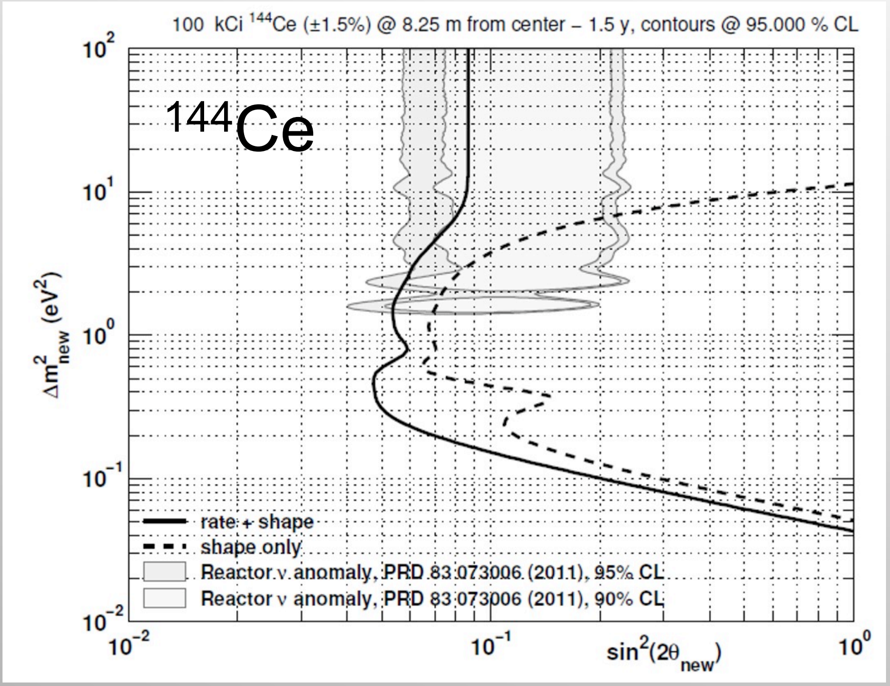
Sources located in Borexino pit

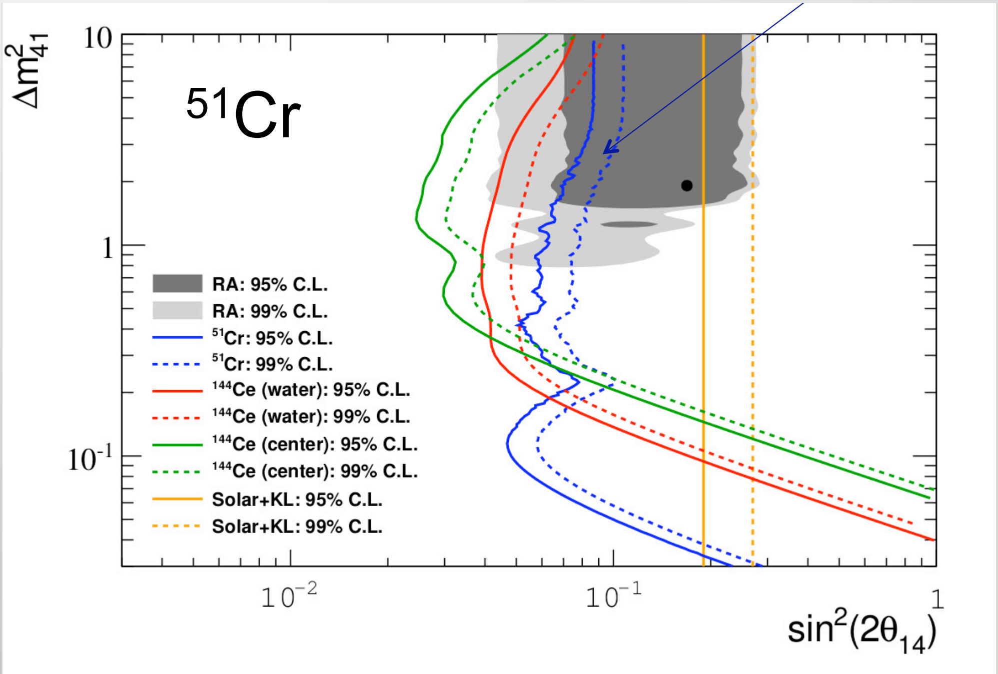






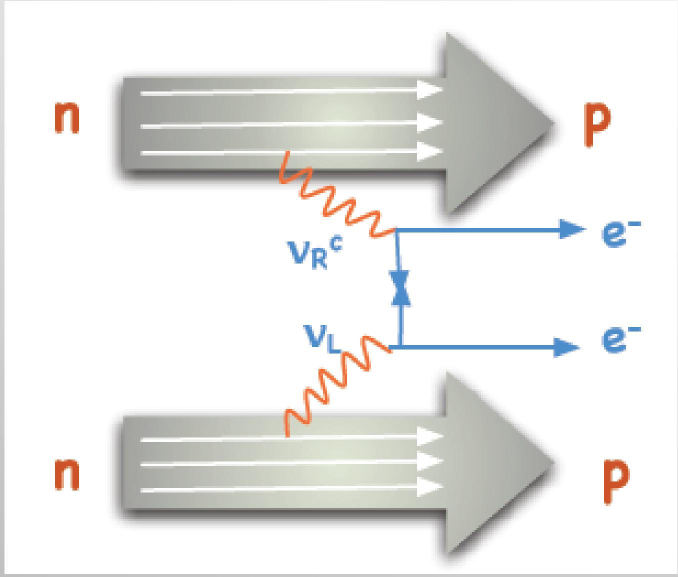
SOX sensitivity – sources in pit





Start with 1.5 y run, beginning fall 2016, with 100 kCi ^{144}Ce source

Introduction: 0νββ



Expected decay rate:

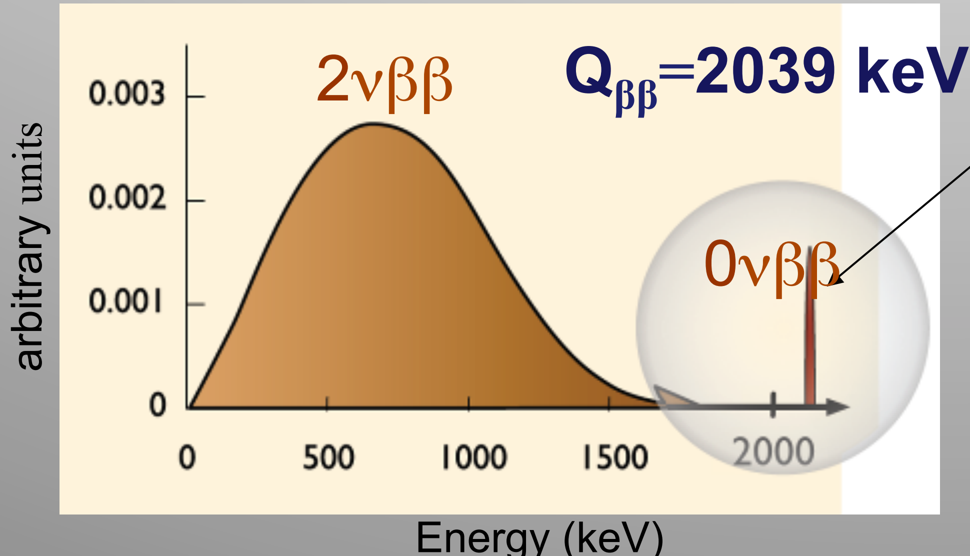
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \,\langle m_{ee}\rangle^2$$

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

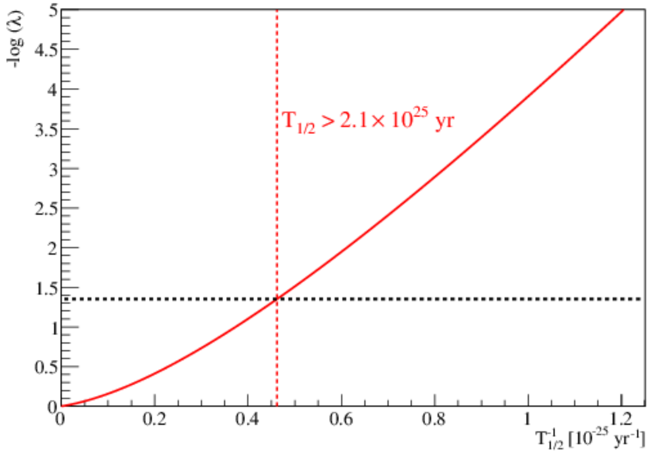
GERDA

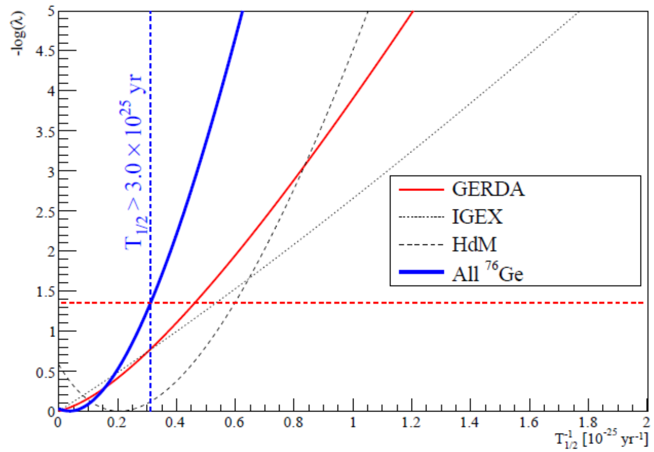
The GERDA collaboration, Eur. Phys. J. C 73 (2013)

- 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 $0\nu\ \beta\beta$

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





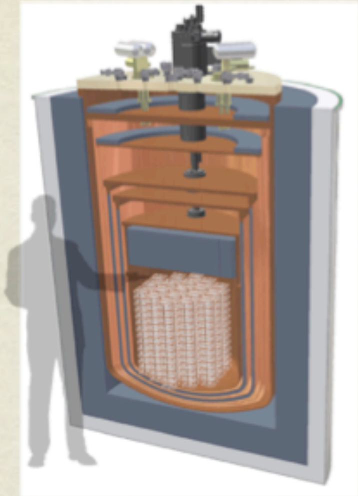
- Frequentist analysis
  Median sensitivity:
  $T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr at 90% C.L.
- Maximum likelihood spectral fit
  (3 subsets, $1/T_{1/2}$ common)
- Bayesian analysis also available
  Median sensitivity:
  $T^{0\nu}_{1/2} > 2.0 \cdot 10^{25}$ yr at 90% C.L.

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

Now preparing for phase-II
More from C.Macolino at this conference

CUORE

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



CUORE Hut

200 Kg

^{130}Te

Expected 5 Years sensitivity:

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

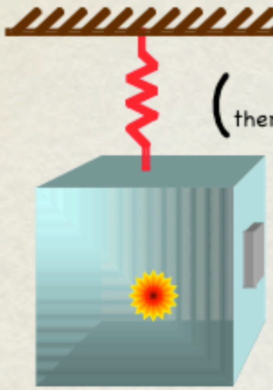
background counting rate

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

CUORE Principle

heat sink (T_0)

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



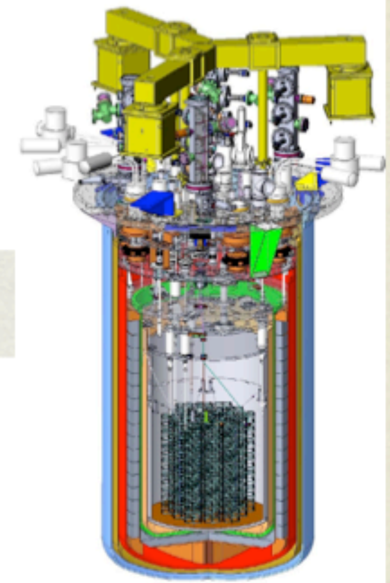
(thermal conductance G)

thermometer

$\beta\beta$ atom x-tal

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

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



$T_0 \sim 10$ mK

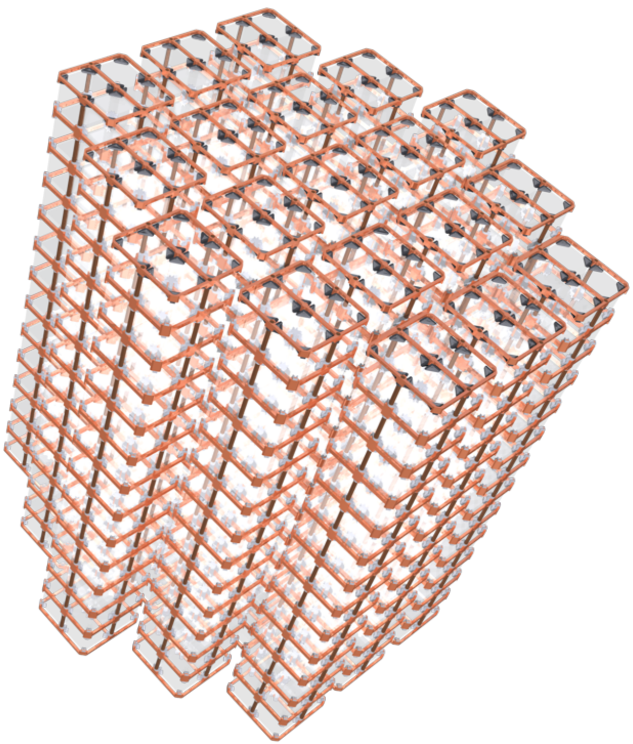
$C \sim 2$ nJ/K ~ 1 MeV/0.1 mK

$G \sim 4$ pW/mK

The CUORE challenge

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

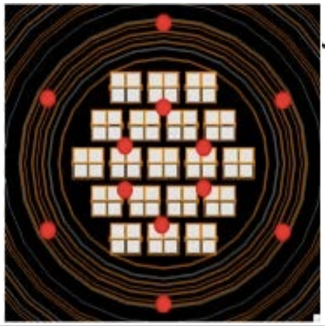
  - Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each)
  - Mass of TeO_2: 741 kg (~206 kg of ^{130}Te)
  - Energy resolution: 5 keV @ 2615 keV (FWHM)
  - Stringent radiopurity controls on materials and assembly
  - Operating temperature: ~ 10 mK
  - Background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

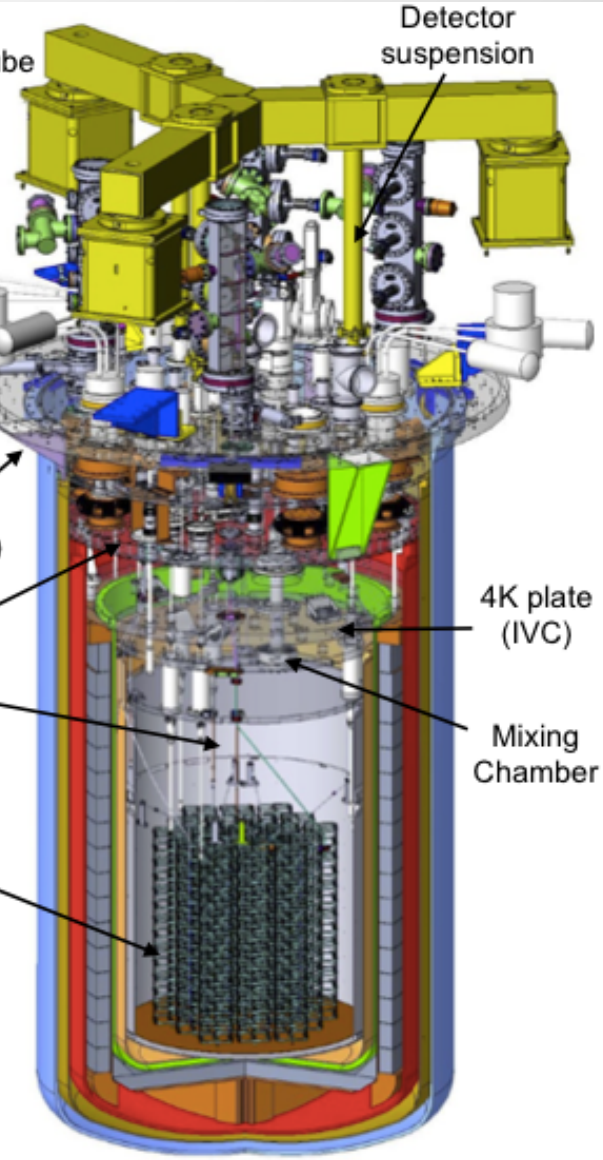


CUORE cryo system

- 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



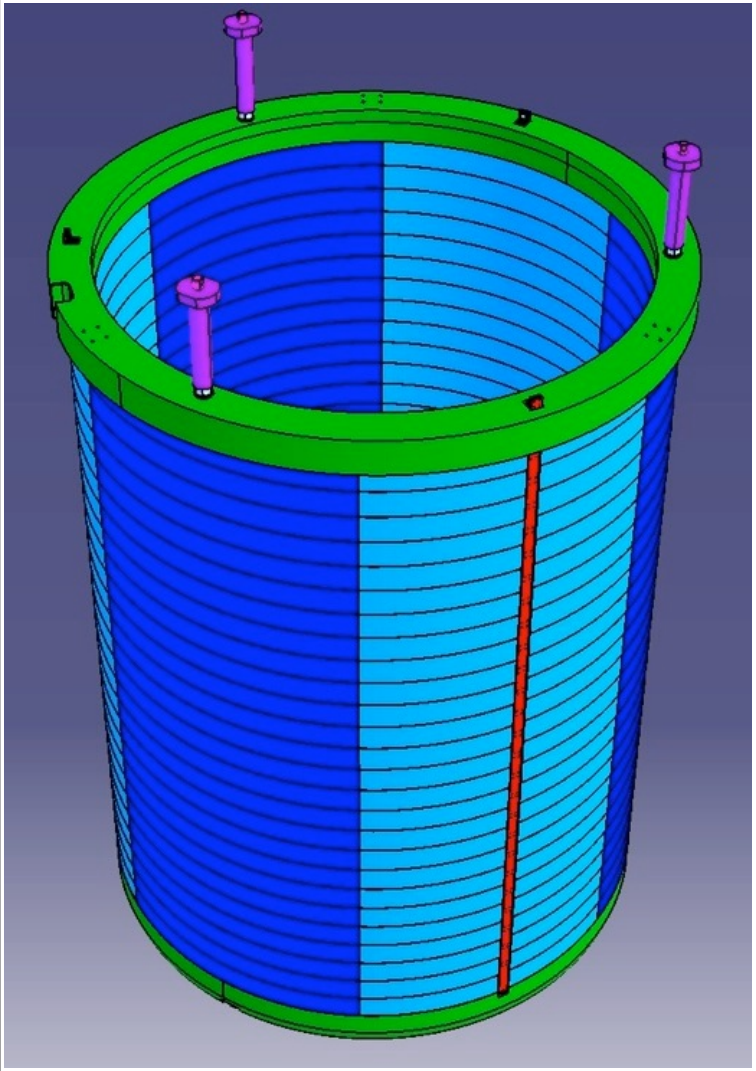


COLD!!!

September 2014
large cryostat
reached 6 mK

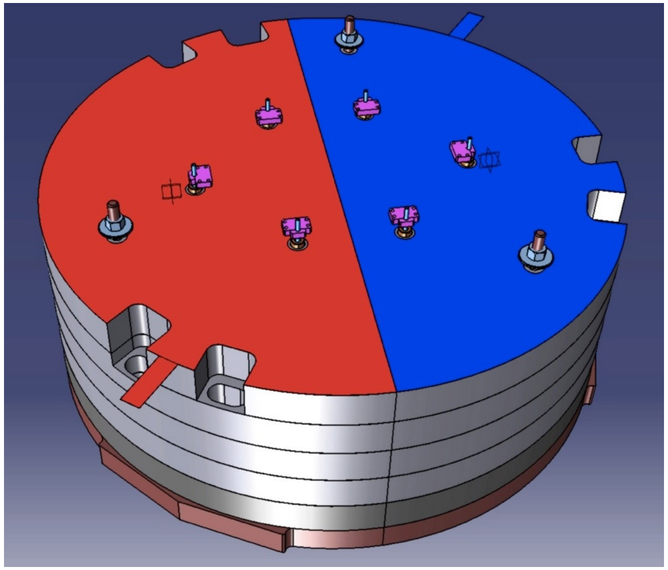
COLDEST m^3 in the
Universe!

CUORE – Pb cold shielding



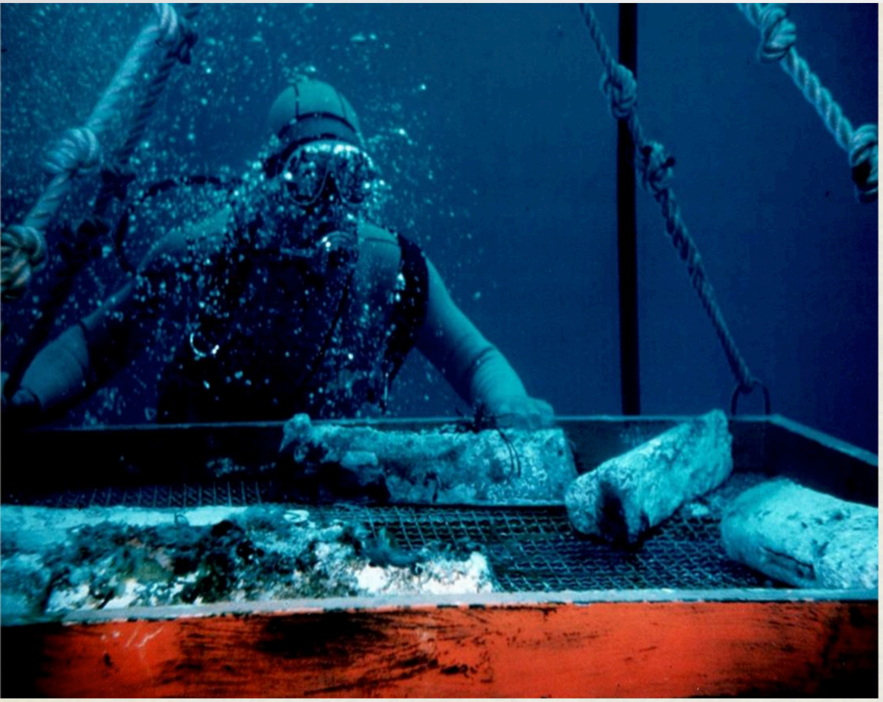
Bottom plate + 6 sector side rings
Suspended to 600 mK plate thermalized to 4K

- 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

(Physics and Archaeology)



A couple of hundred ingots

for the CUORE shielding

^{210}Pb free (22.3 y half-life)

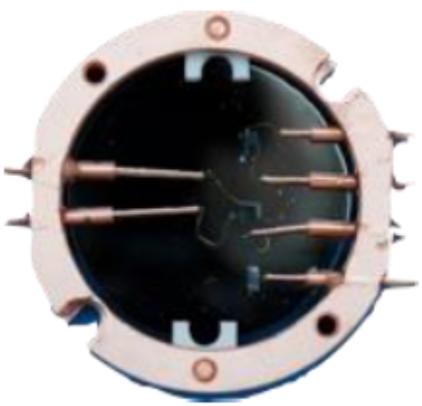
2000 y shielded by sea water

CUORE

More about CUORE in Maura Pavan talk at this conference

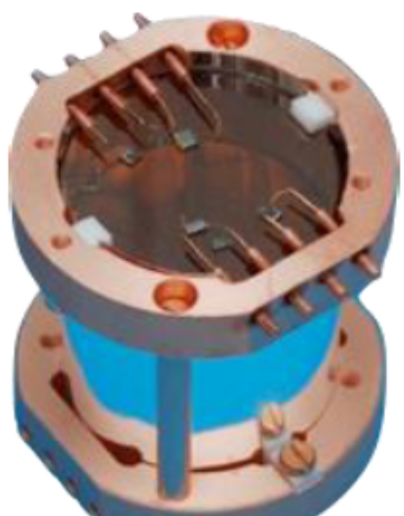
LUCIFER

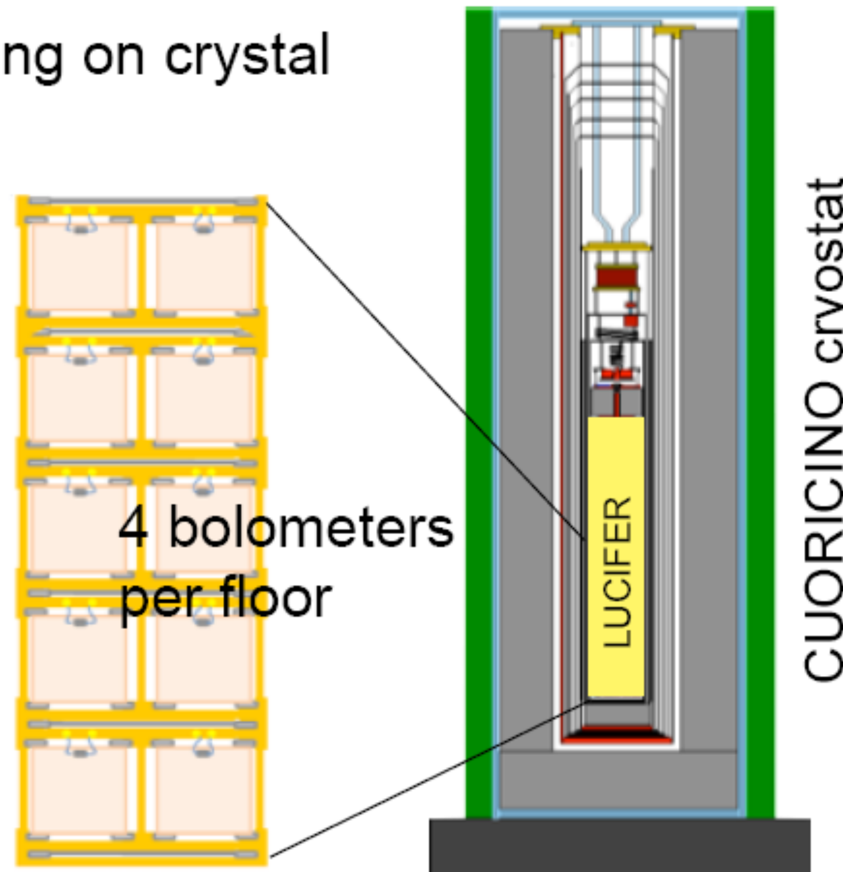
- Tower of 32-40 ZnSe scintillating bolometers at Gran Sasso, enriched in ^{82}Se , ~10 kg of ^{82}Se.
- Background free: α background identified via the scintillation signal, β/γ radioactive background below the ^{82}Se Q-value (2997 keV).
- Operation in 2015. Presently focusing on crystal growth.



Light detector (Ge bolometer)

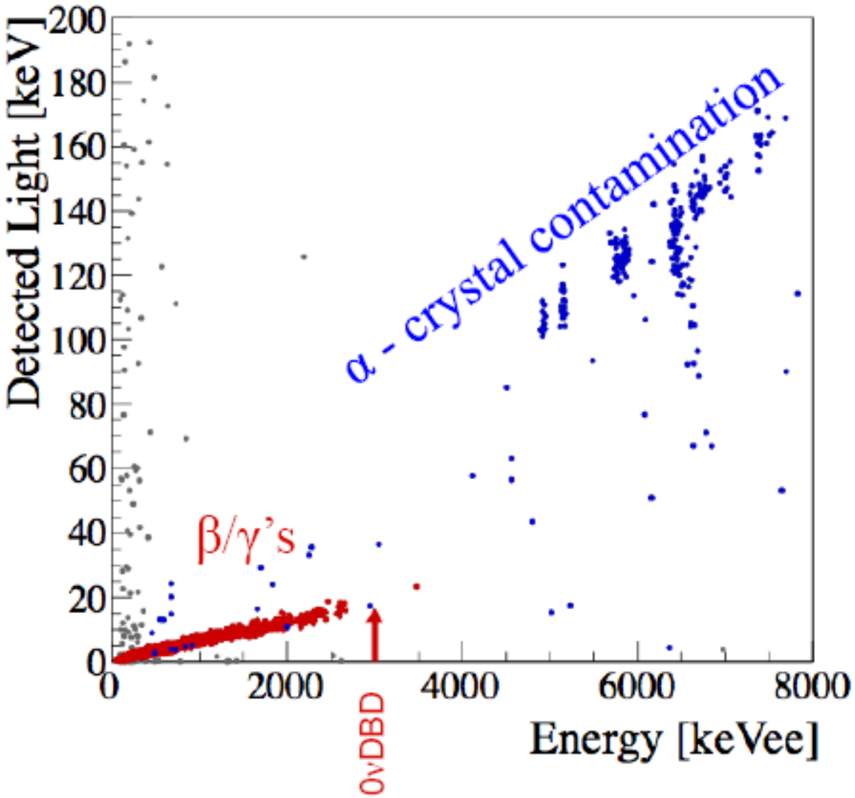
ZnSe bolometer

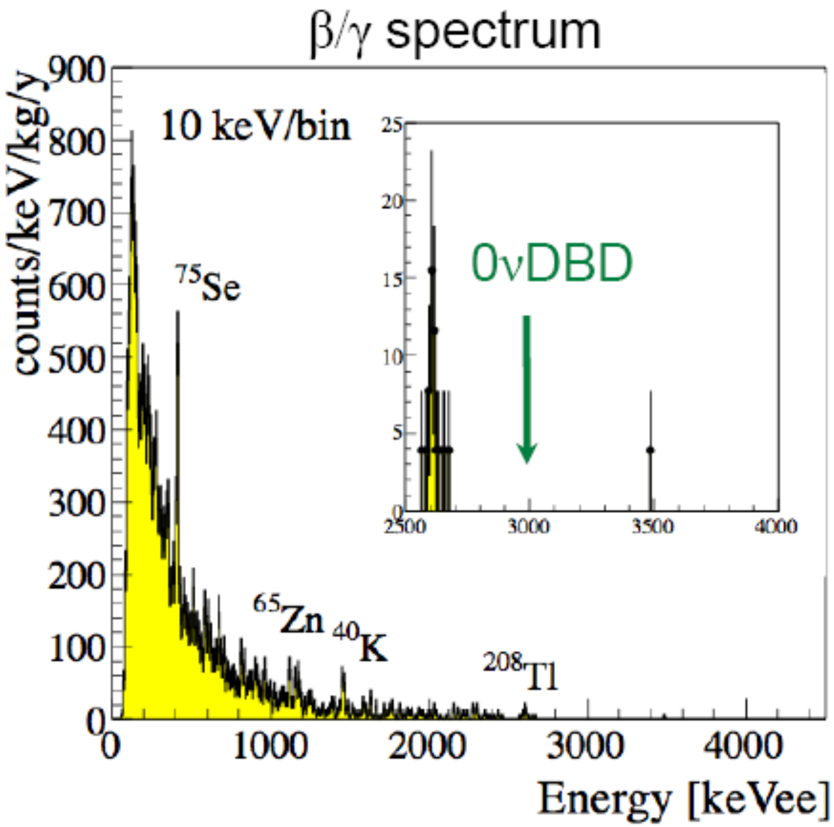




LUCIFER

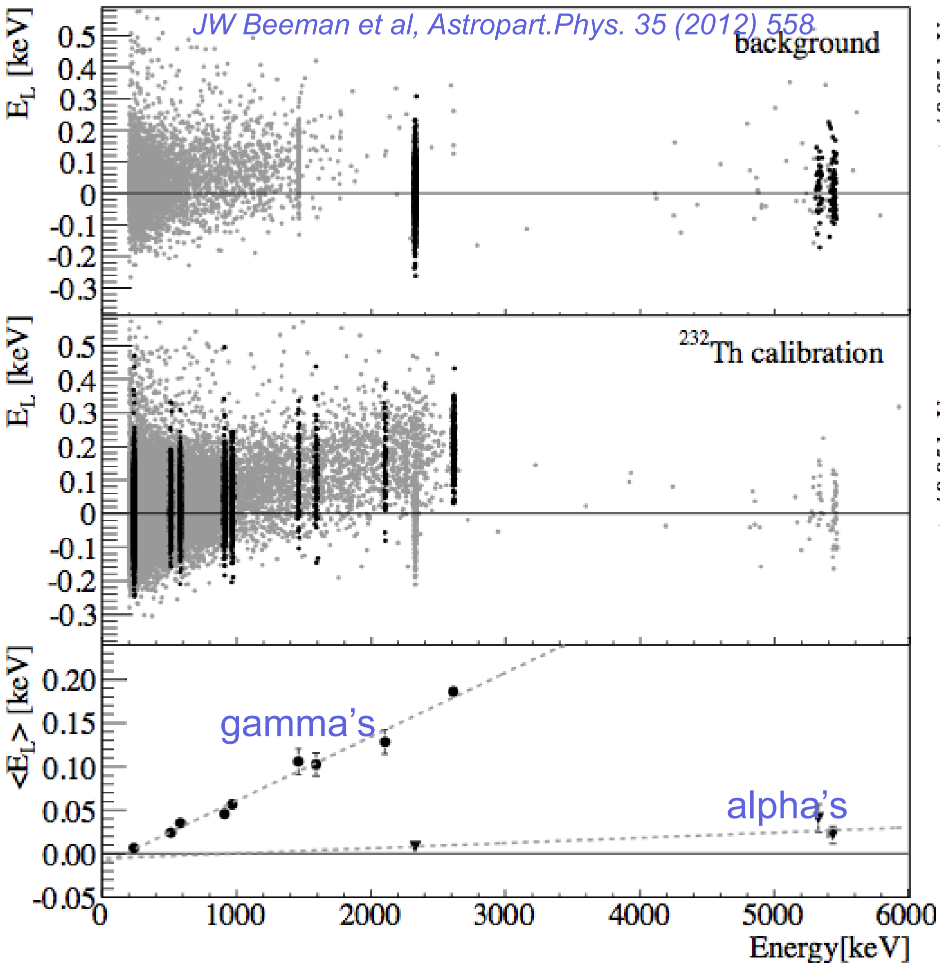
- 431g $Zn^{nat}Se$ crystal operated for 22 days.
  - ΔE@2615 keV = 13 keV FWHM
  - α background entirely identified via light pulse shape.

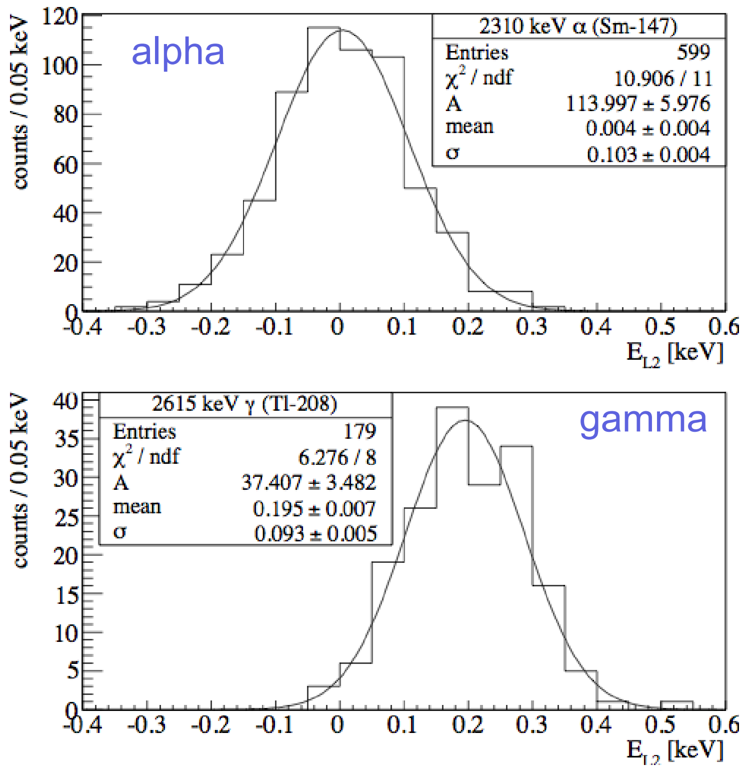




- One β/γ event above 2615 keV, in coincidence with several hits in nearby detectors (μ-spallation).
- Easily to tag via coincidence analysis in an array, or via a μ-veto.

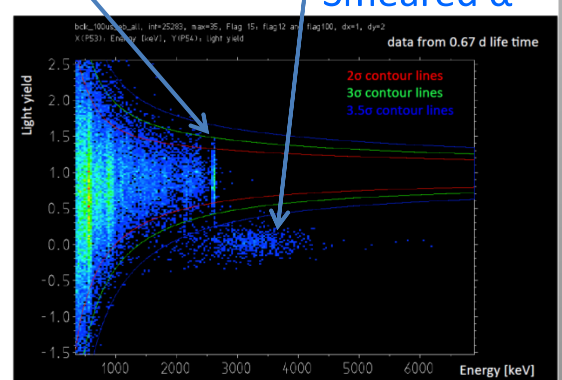
LUCIFER





2615 KeV ^{208}Tl

Smeared α



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.

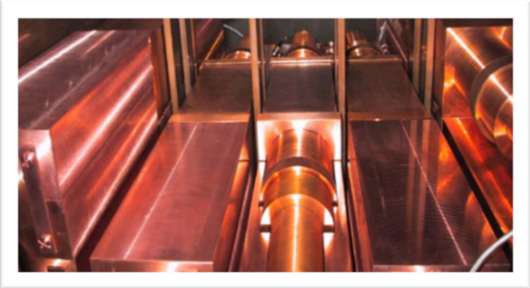
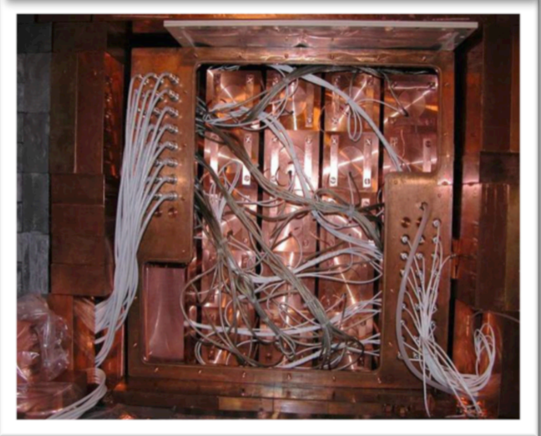
DARK MATTER SEARCHES

Dark Matter @ LNGS

- DAMA/LIBRA
- CRESST
- XENON family
- DarkSide

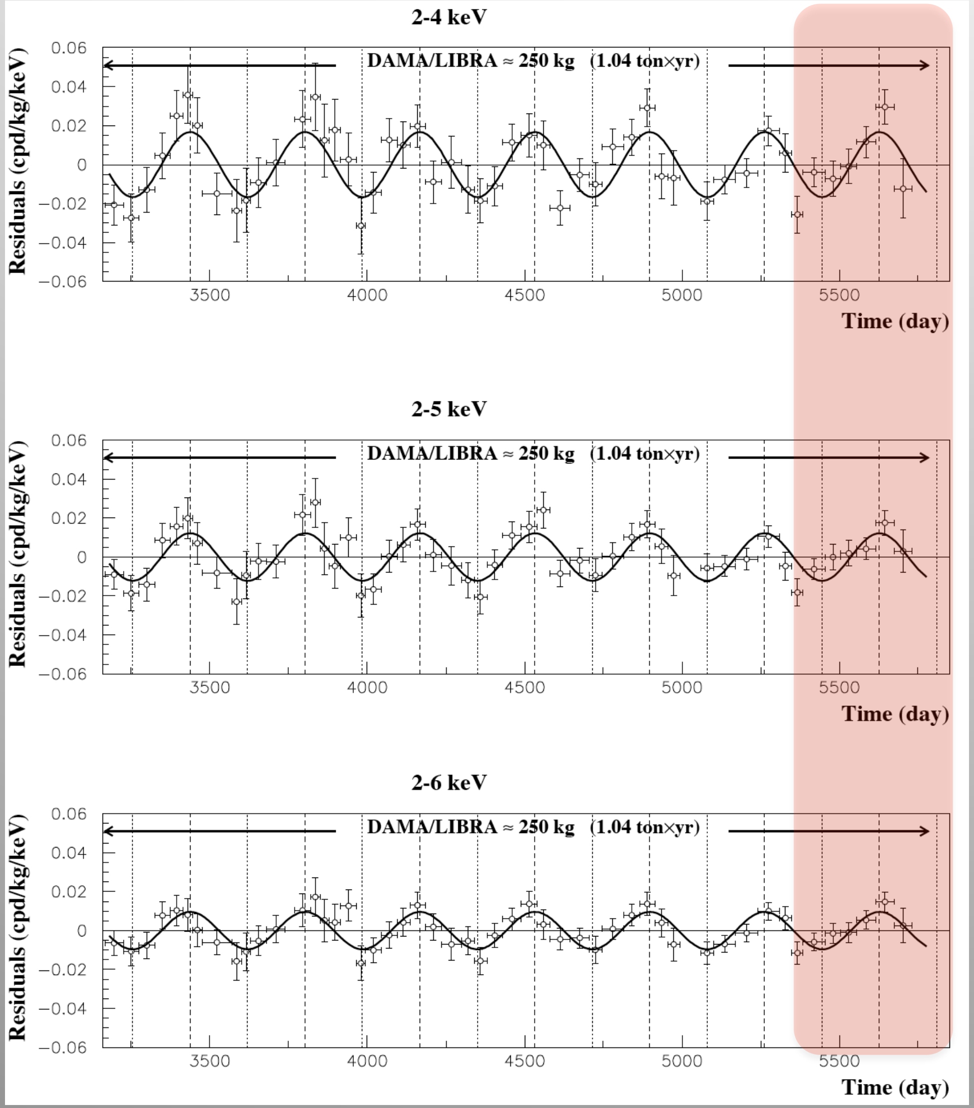
DAMA/LIBRA

- **Ultrapure Na(Tl)**
  - **Residual contamination**
    - **^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g**


DAMA/LIBRA

Analysis of residuals of single-hit events



A: modulation amplitude

2-4 keV

A=(0.0167±0.0022) cpd/kg/keV

χ^2/dof = 52.3/49 **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=111.2/50 ⇒ P(A=0) = 1.5×10^{-6}

2-5 keV

A=(0.0122±0.0016) cpd/kg/keV

χ^2/dof = 41.4/49 **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=98.5/50⇒ P(A=0) = 5.2×10^{-5}

2-6 keV

A=(0.0096±0.0013) cpd/kg/keV

χ^2/dof = 29.3/49 **7.4 σ C.L.**

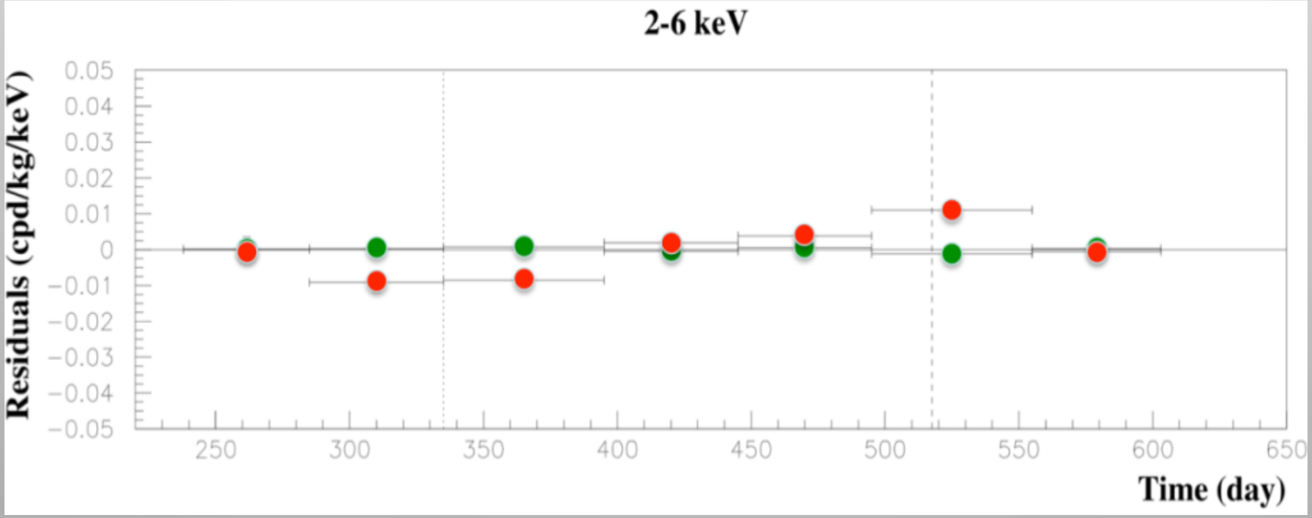
Absence of modulation? No

χ^2/dof=83.1/50 ⇒ P(A=0) = 2.2×10^{-3}

DAMA/LIBRA – annual modulation

Comparison between **single hit residual rate (red points)** and
multiple hit residual rate (green points);
A=-(0.0006±0.0004) cpd/kg/keV

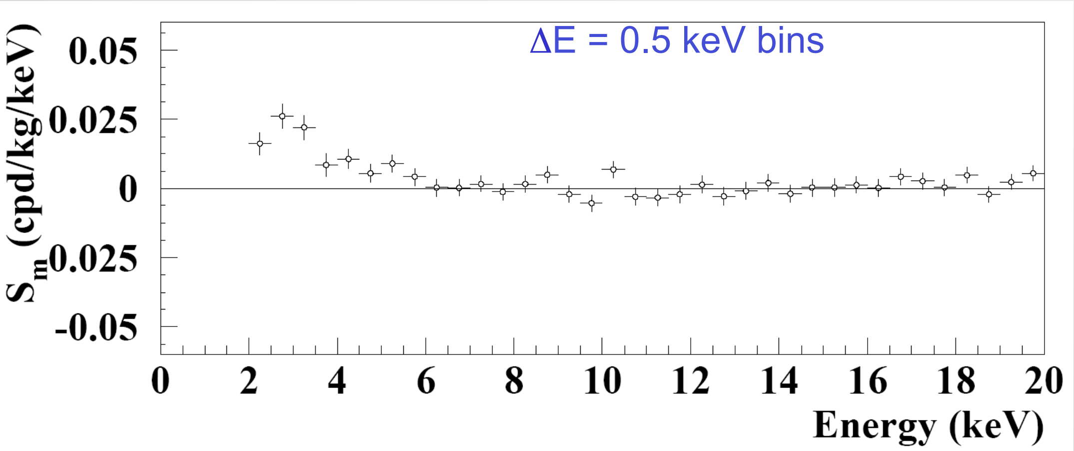
Multiple hits events = Dark Matter particle "switched off"

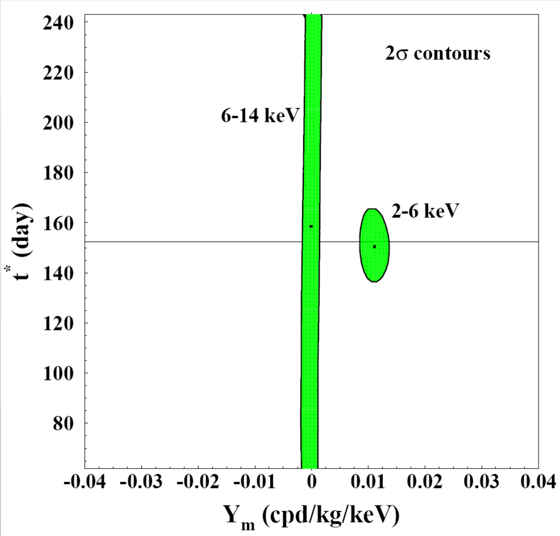


Dama annual modulation analysis

$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$ *T=2π/ω=1* yr and *t_0= 152.5* day

$R(t) = S_0 + Y_m \cos[\omega(t - t^*)]$





- **No modulation above 6 keV**
- **No modulation in the whole energy spectrum**
- **No modulation in the 2-6 keV multiple-hit events**

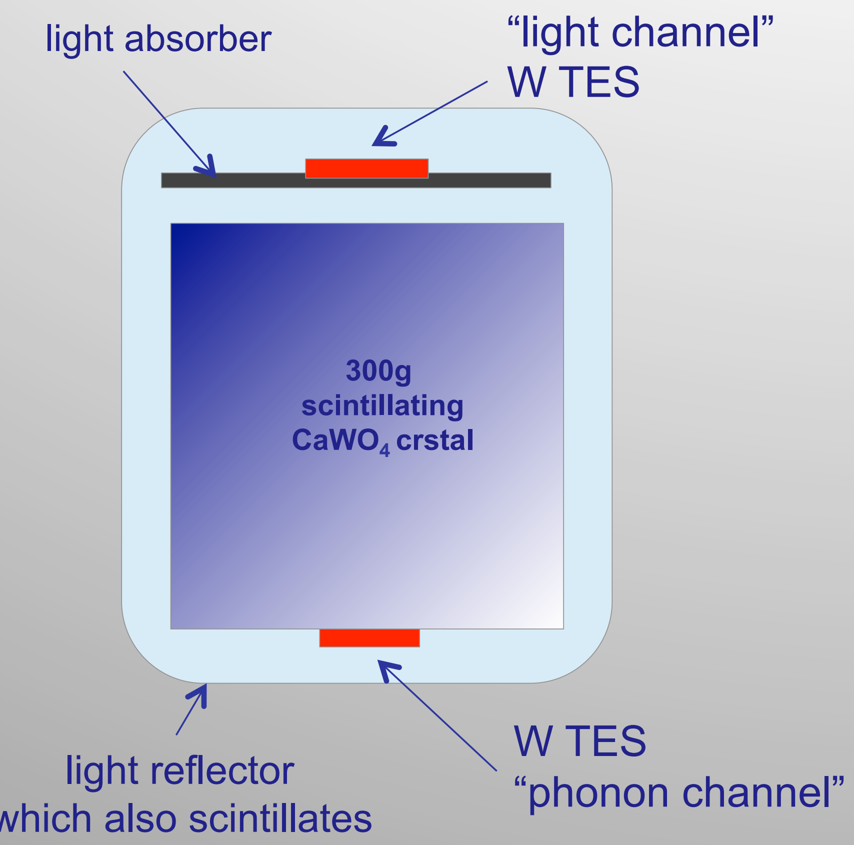
Systematics or other processes do not explain quantitatively the measured modulation amplitude and simultaneously satisfy the signal characteristics.

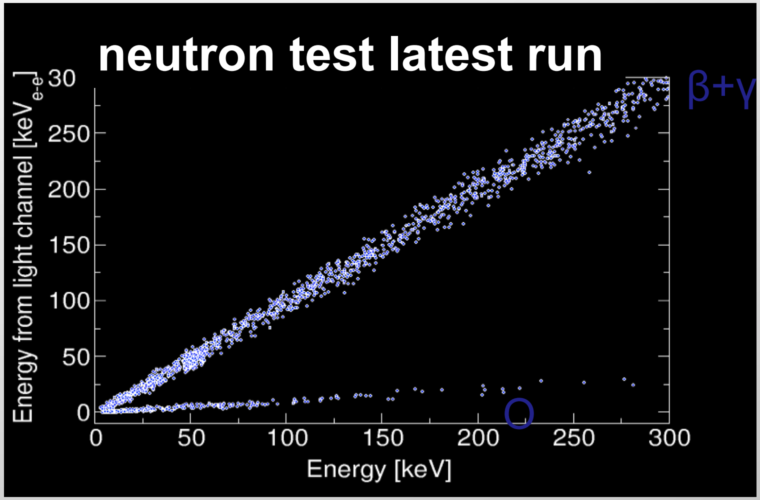
- **DAMA/LIBRA - phase 1 concluded:**
  the data of the last annual cycle will be released soon
- **New investigations on other rare processes in progress**

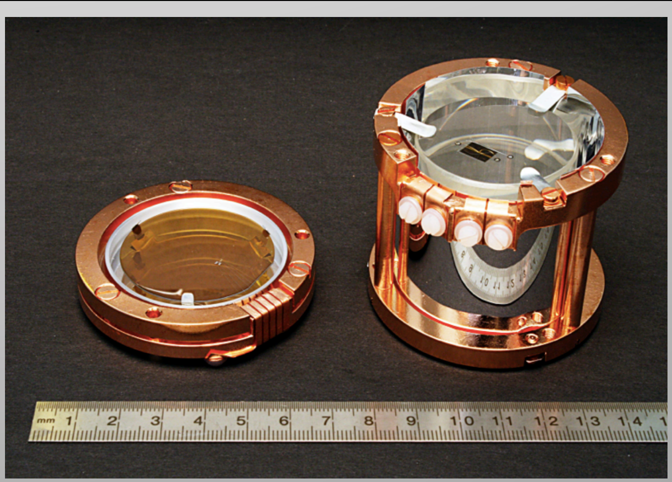
DAMA/NaI (7 years) + DAMA/LIBRA (6 years) Total exposure: 425428 kg×day = 1.17 ton×yr

EPJC 56(2008)333, EPJC 67(2010)39

CRESST-II







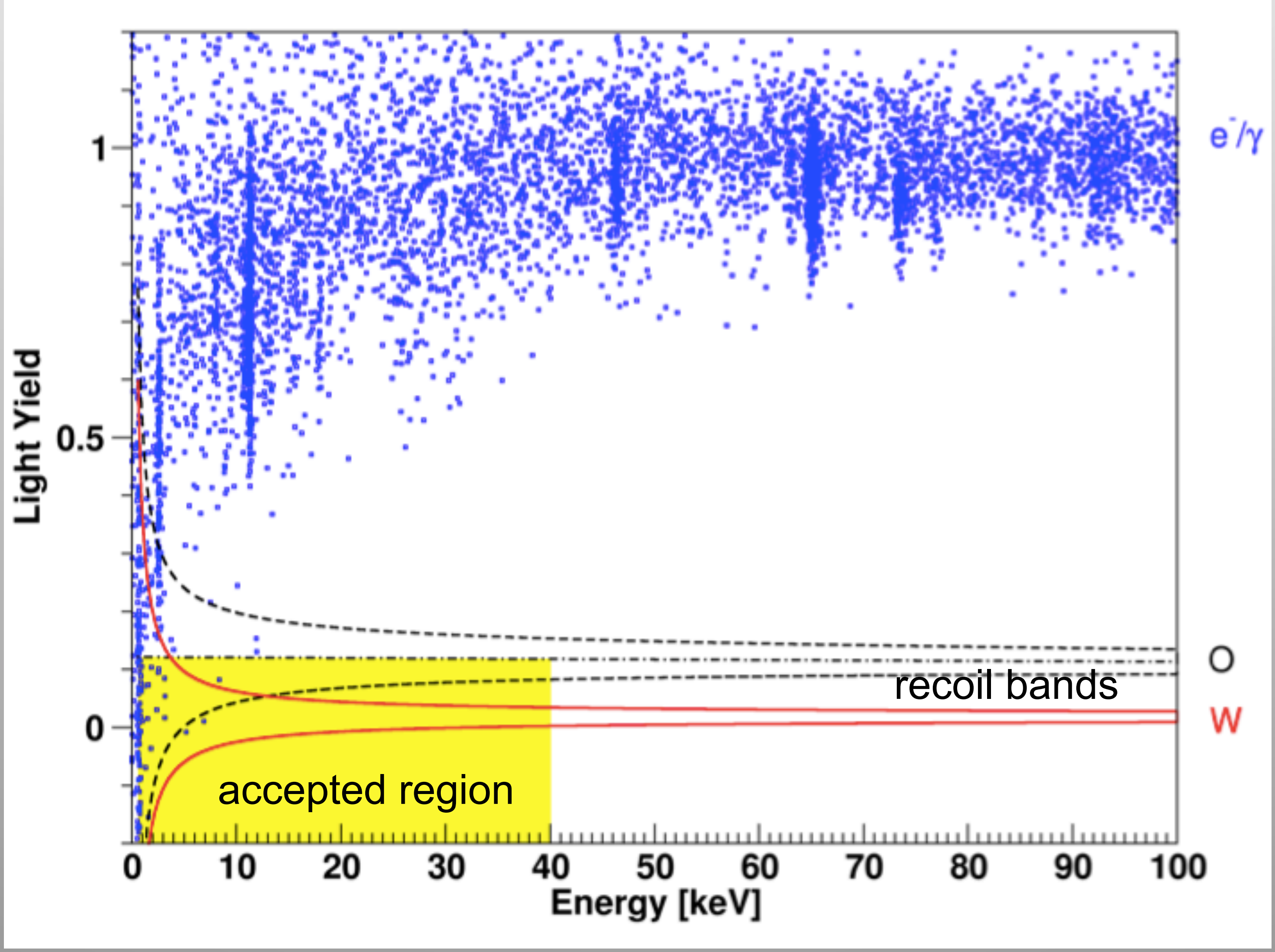
→ phonon channel provides precise measurement of deposited energy

→ Light channel distinguishes types of interaction

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

CRESST-II

energy/LY discrimination

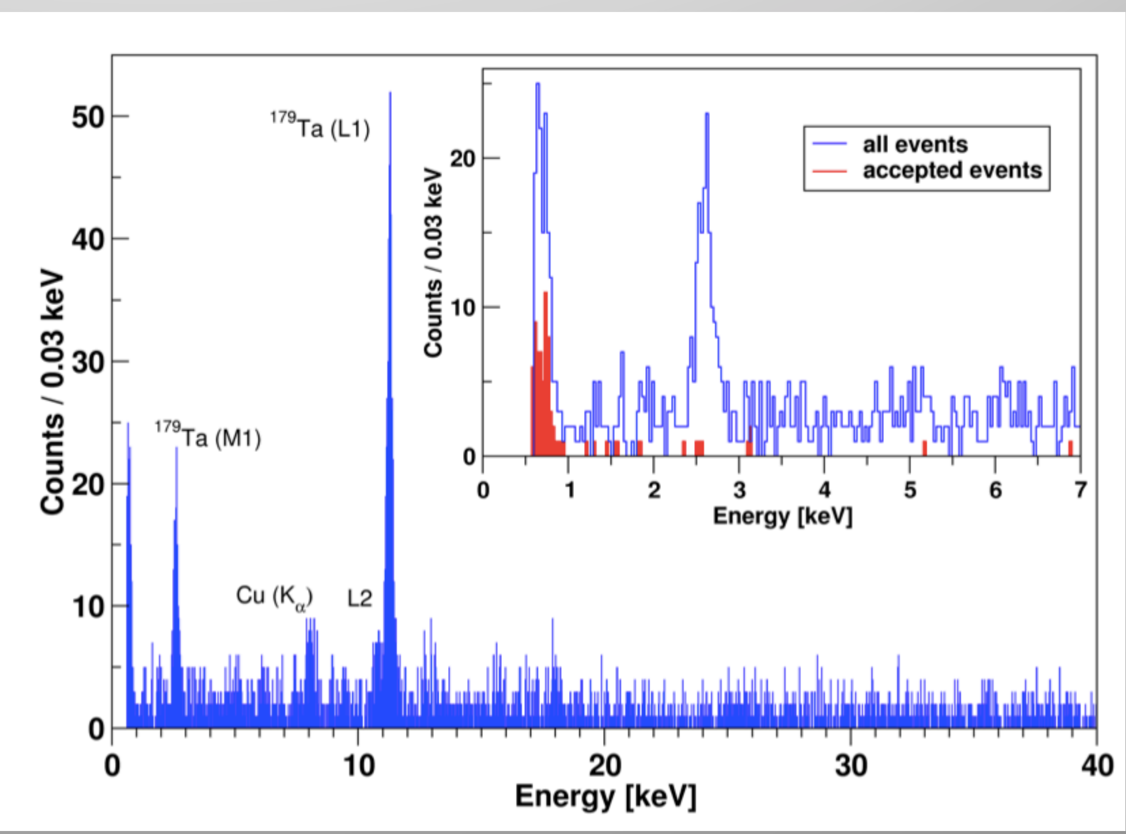


CRESST - II

- single upgraded detector module: new fully scintillating design (metal holding clamps replaced by $CaWO_4$ sticks)
- fully-efficient active discrimination of Pb recoils
- low-theshold analysis

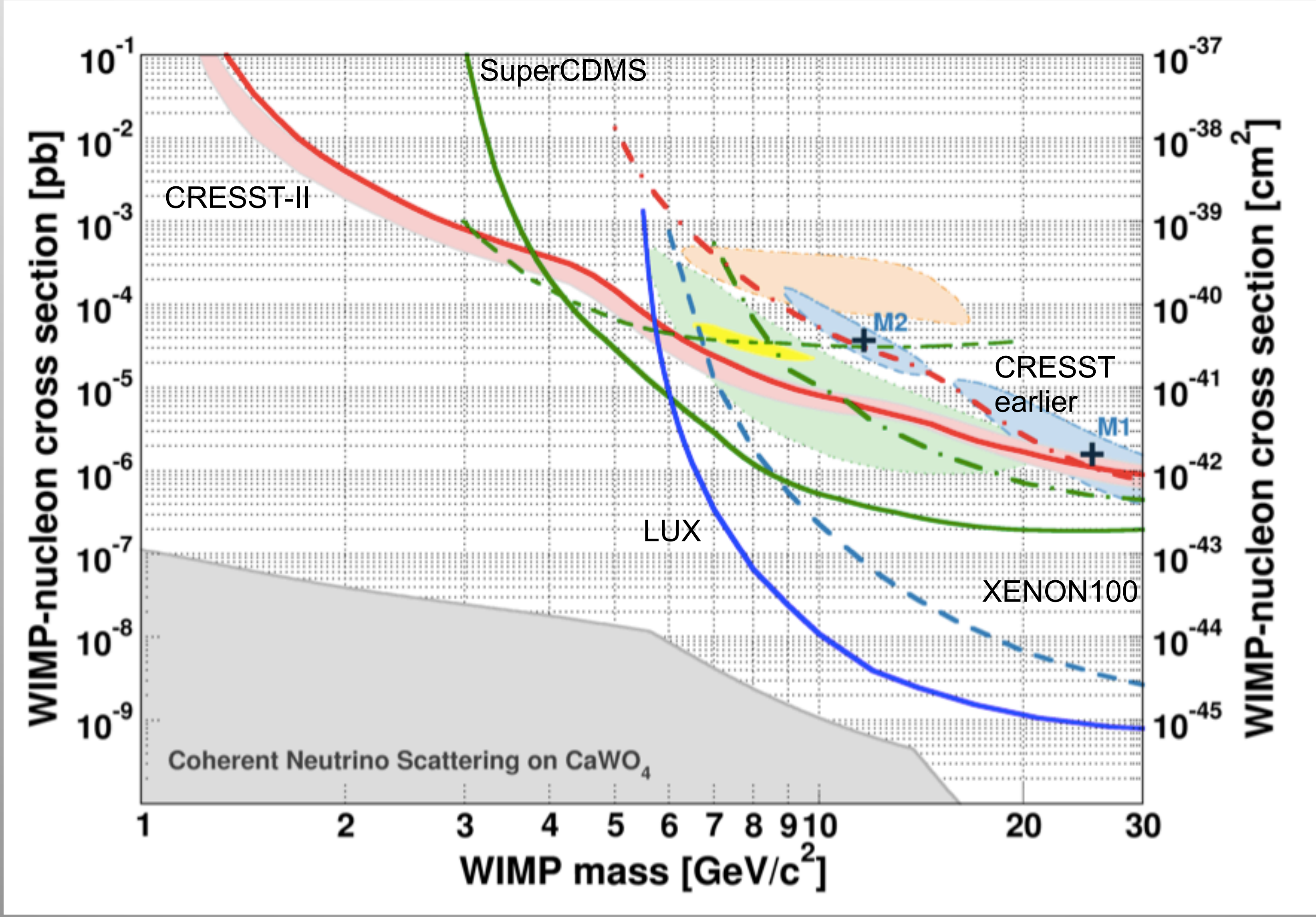
29.35 kg day live in 2013

- Blue: all events
- Red: accepted region events



CRESST-II result

spin independent (~A^2) WIMP-nucleon scattering

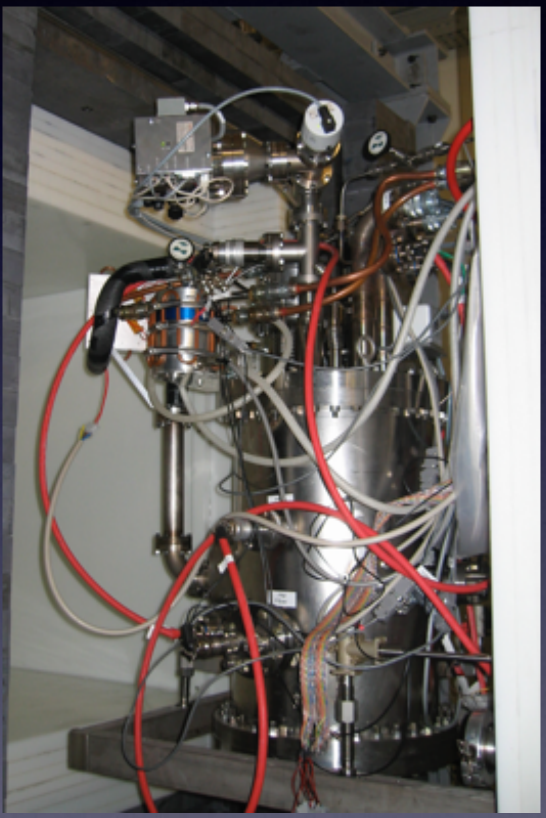


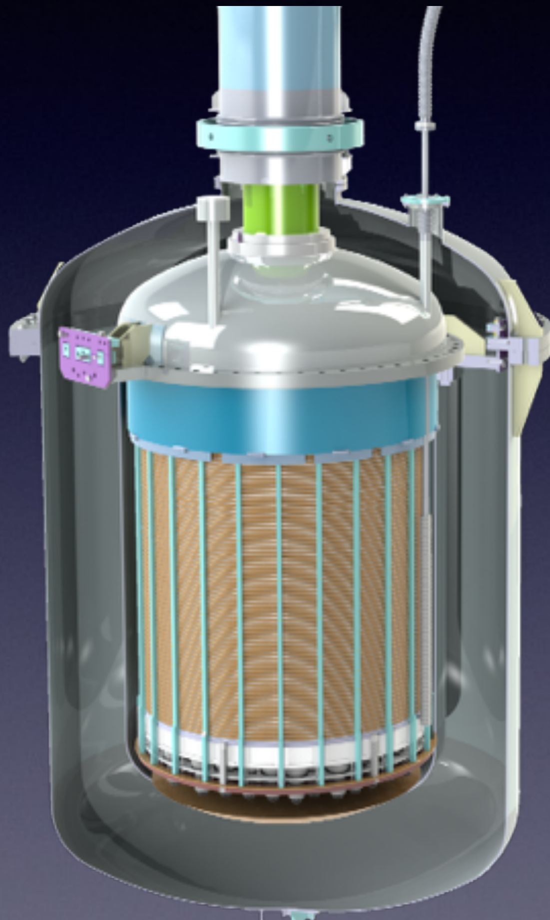
The XENON DM program

2005 - 2007

2008-2015

2012- 2017





XENON10

15 cm drift TPC - 25 kg

XENON100

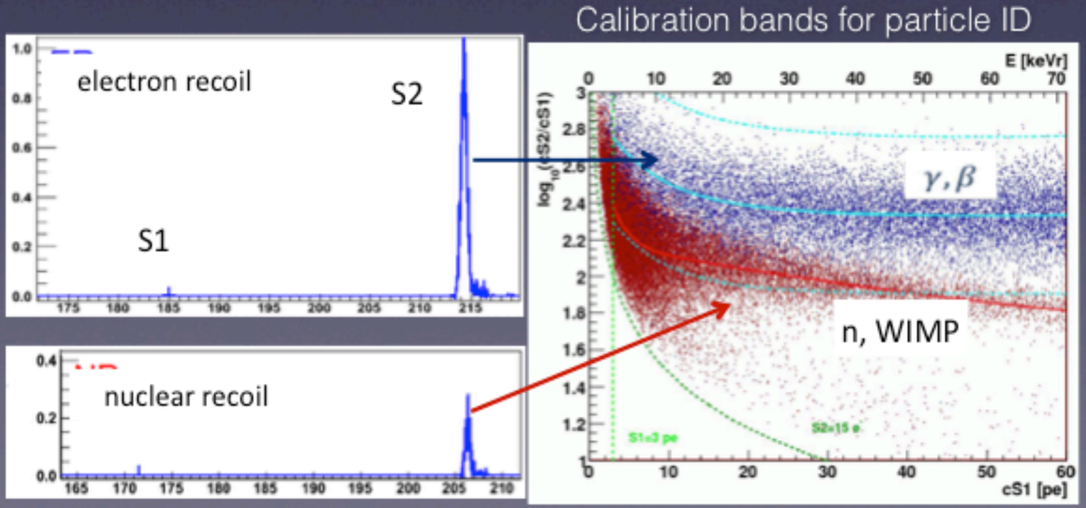
30 cm drift TPC - 161 kg

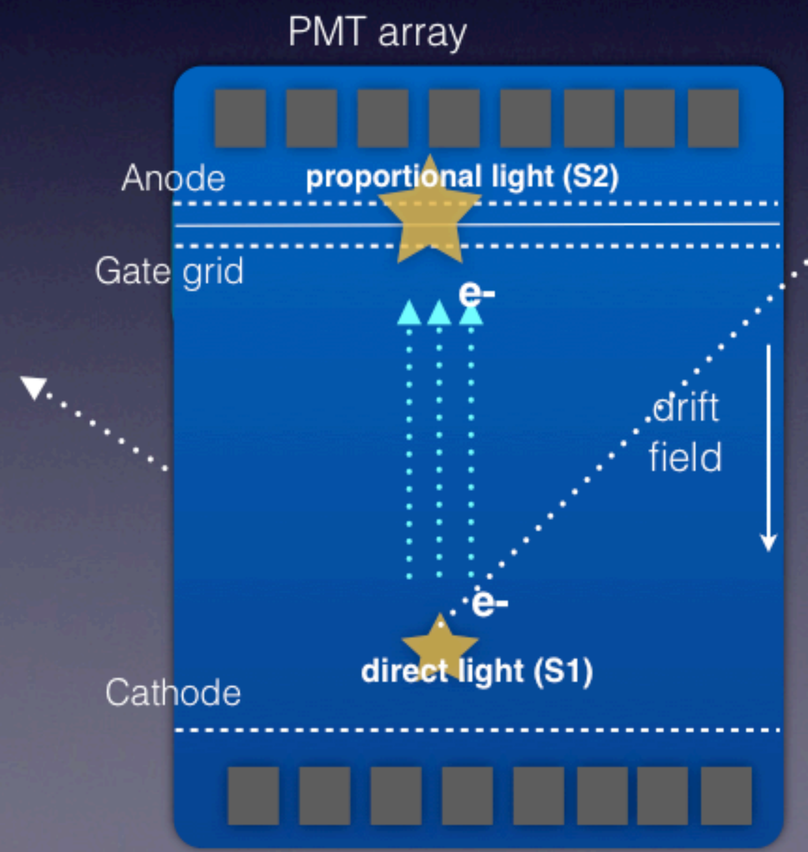
XENON1T

100 cm drift TPC - 3300 kg

Double phase Xenon TPC

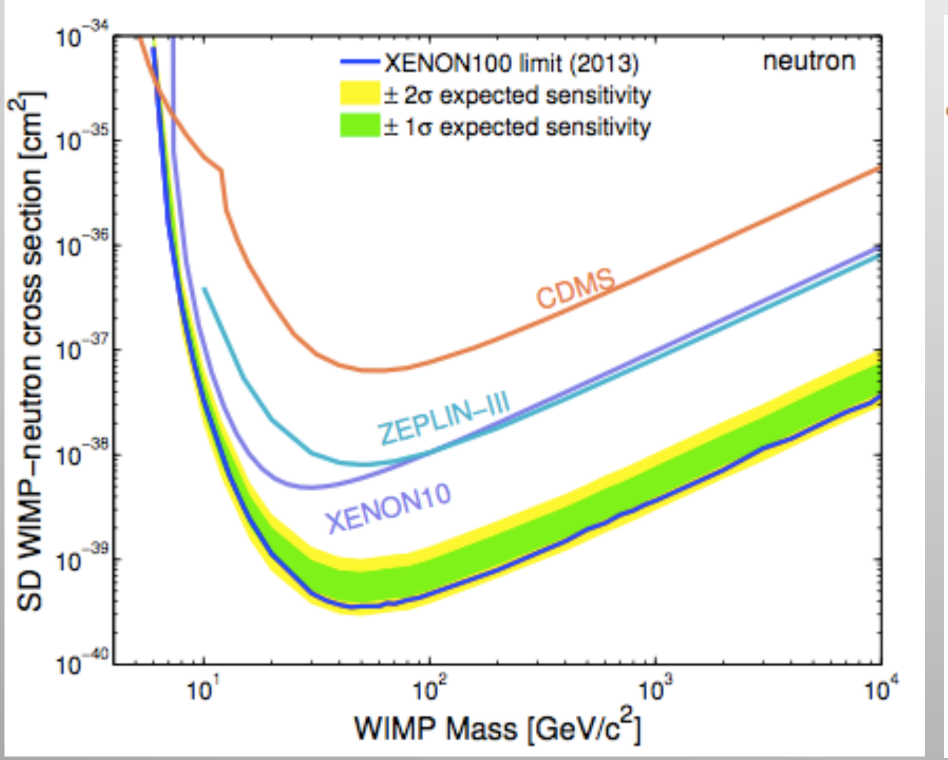
- Particle interaction in the active volume produces prompt scintillation (S1) and ionization electrons
- Electrons which reach the liquid/gas interface are extracted, accelerated in the gas gap and detected as proportional light (S2)
- PMTs in liquid and gas detect S1 and S2
- Charge/light depends on dE/dx: $(S2/S1)_{WIMP} \ll (S2/S1)_{gamma}$
- 3D-position sensitive detector with particle ID

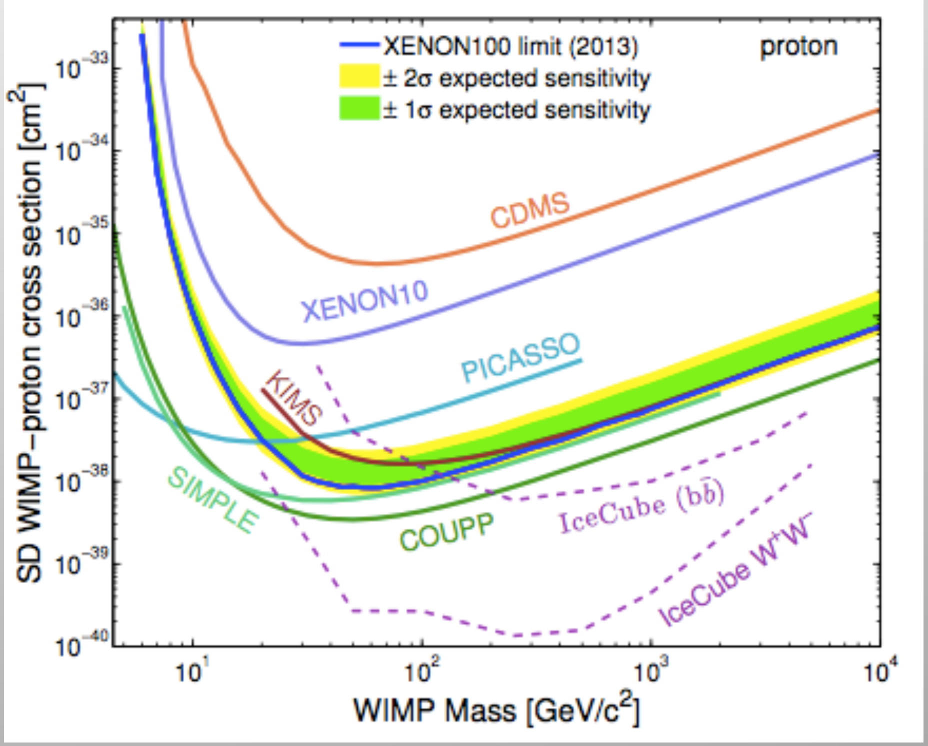




XENON100 SD results

Bkg 5.3×10^{-3} kg^{-1}d^{-1} before S1/S2 disceimination



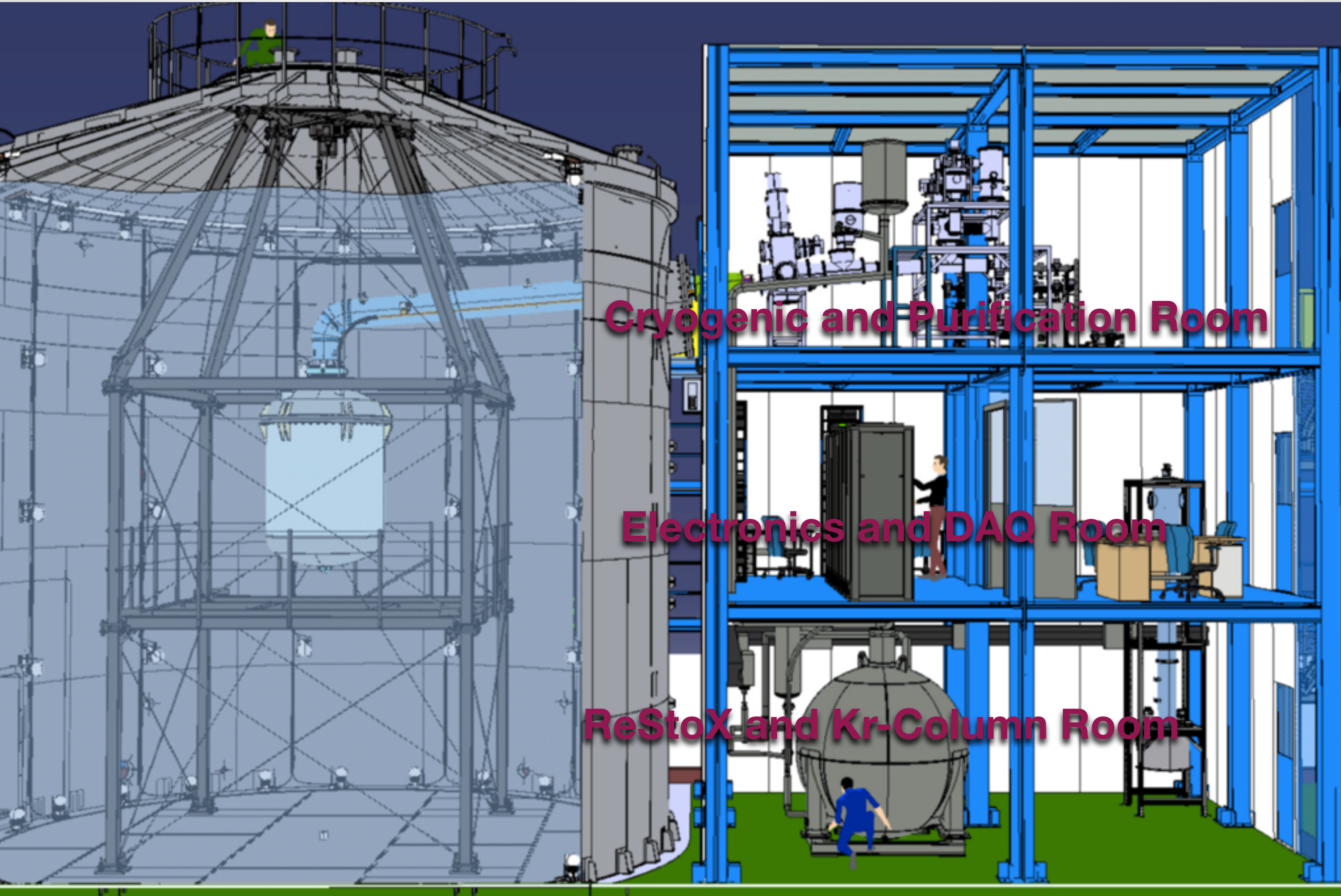


SI < 2×10^{-45} cm^2 for M=55 GeV

XENON1T

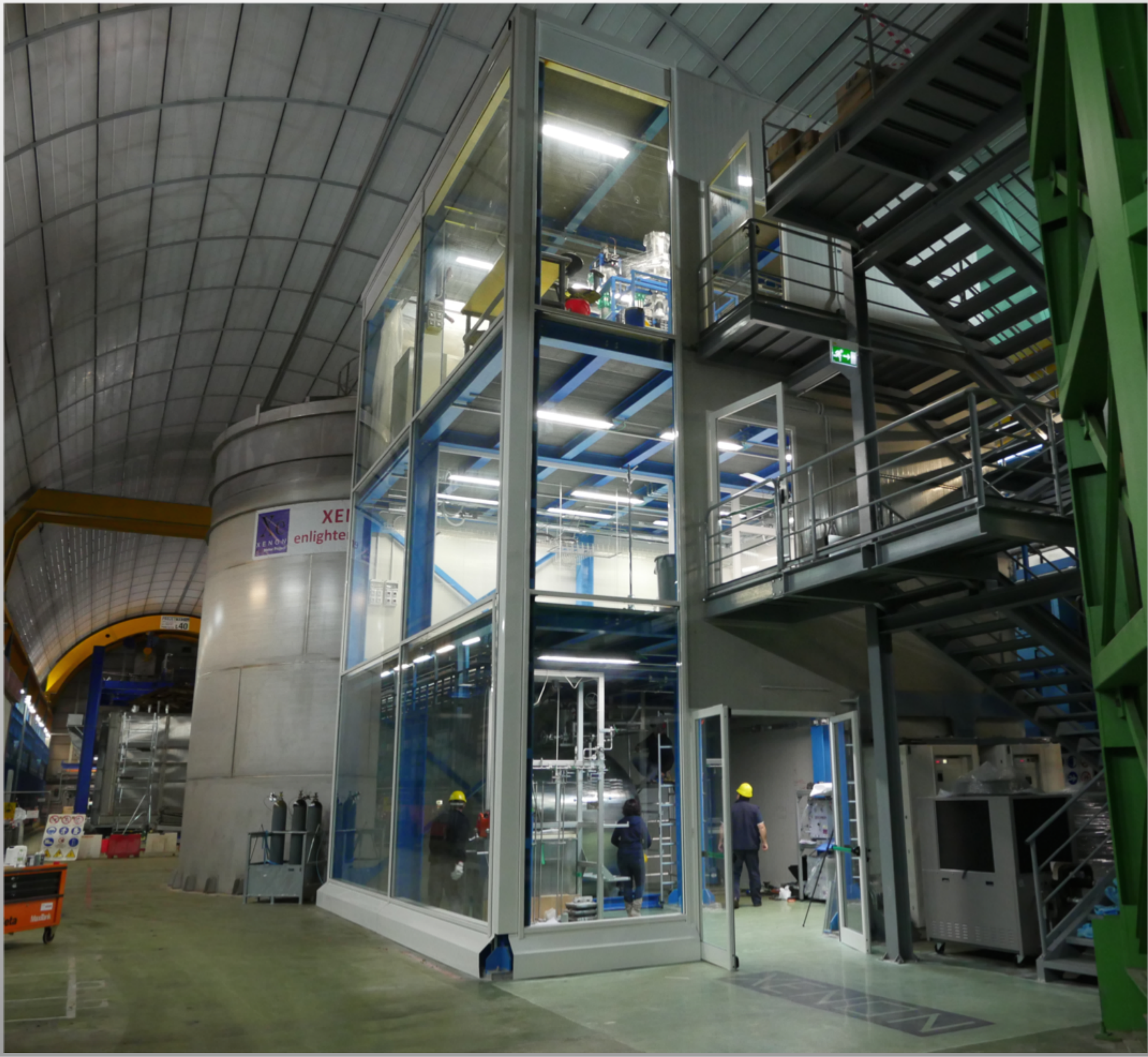
- Two-phase TPC with 1 meter drift and ~1 m diameter electrodes exploiting ~3.3 tonnes of Xe
- Experiment designed to enable a fast upgrade to a larger diameter TPC exploiting ~7 tonnes of Xe
- Schedule: under construction at LNGS started fall 2013
- Science Goal: $2x10^{-47}$ cm^2 with 2 ton-years of data or by 2017
- Funded with 50% of capital cost covered by NSF and the rest from Europe and Israel.

XENON1T Systems



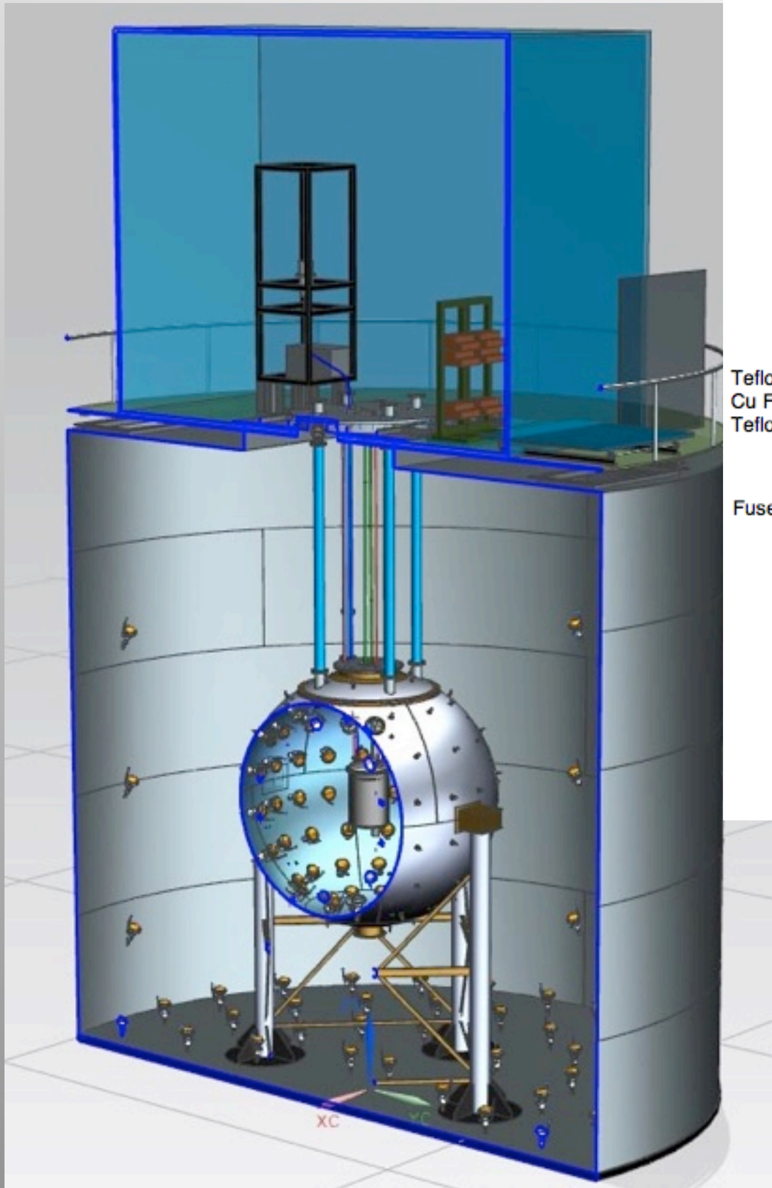
XENON1T

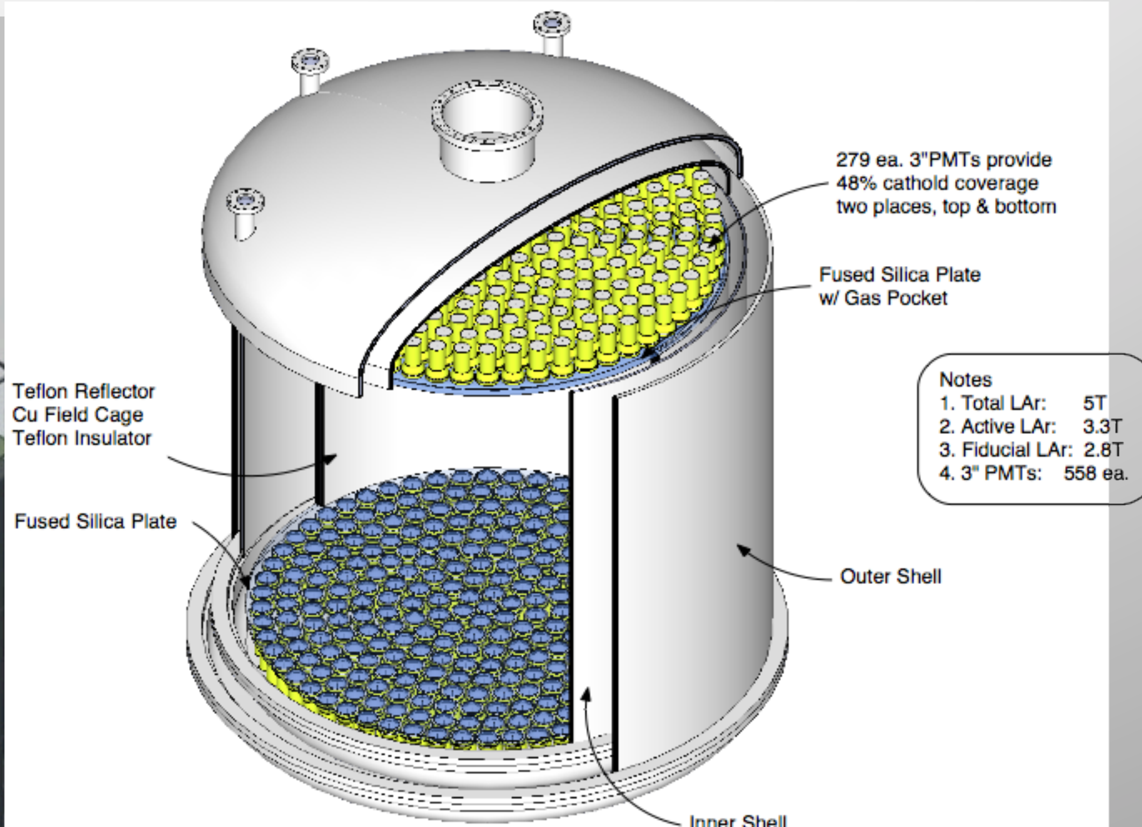
HALL-B
Sep. 2014



Data in late
summer 2015

Darkside (LAr Dark Matter Search)

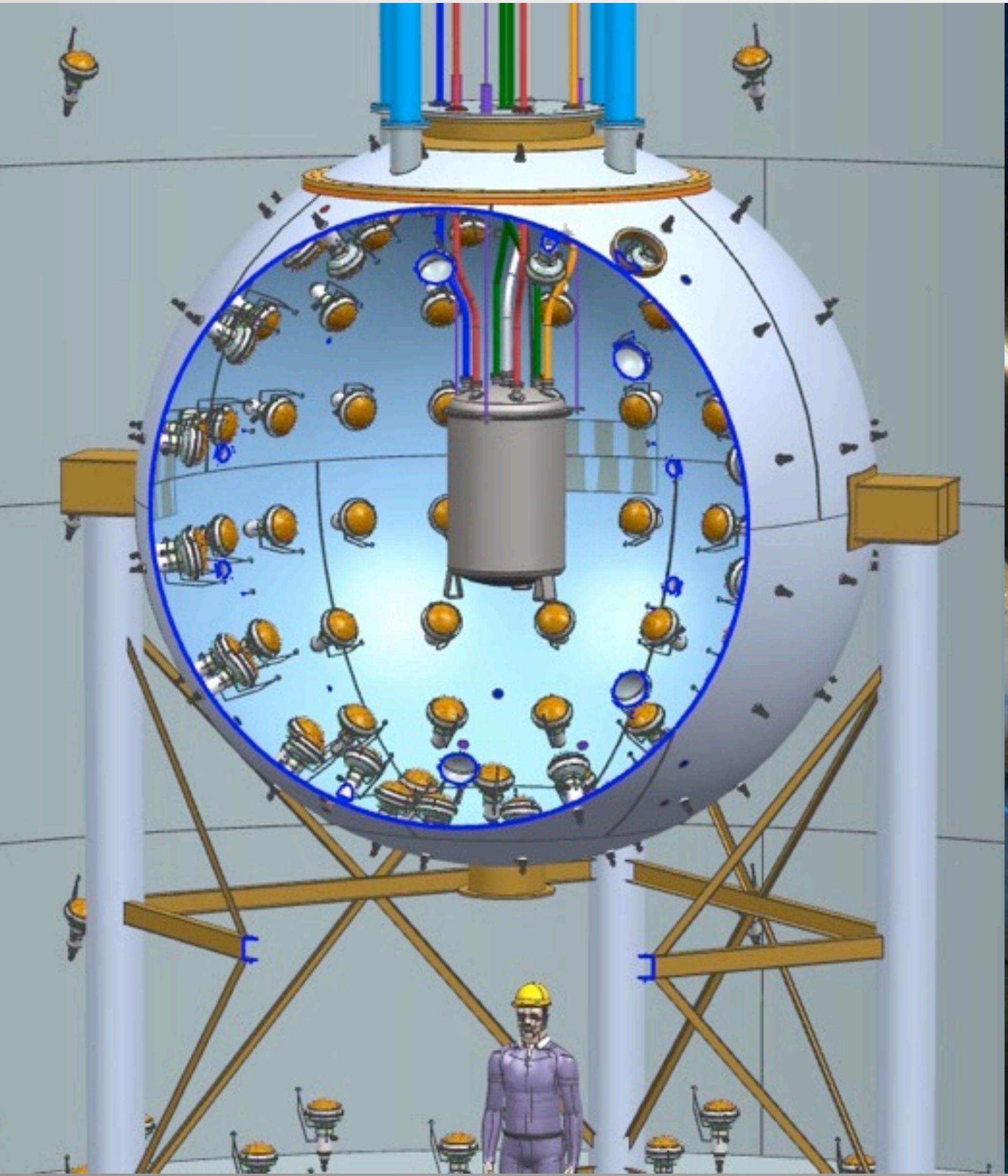


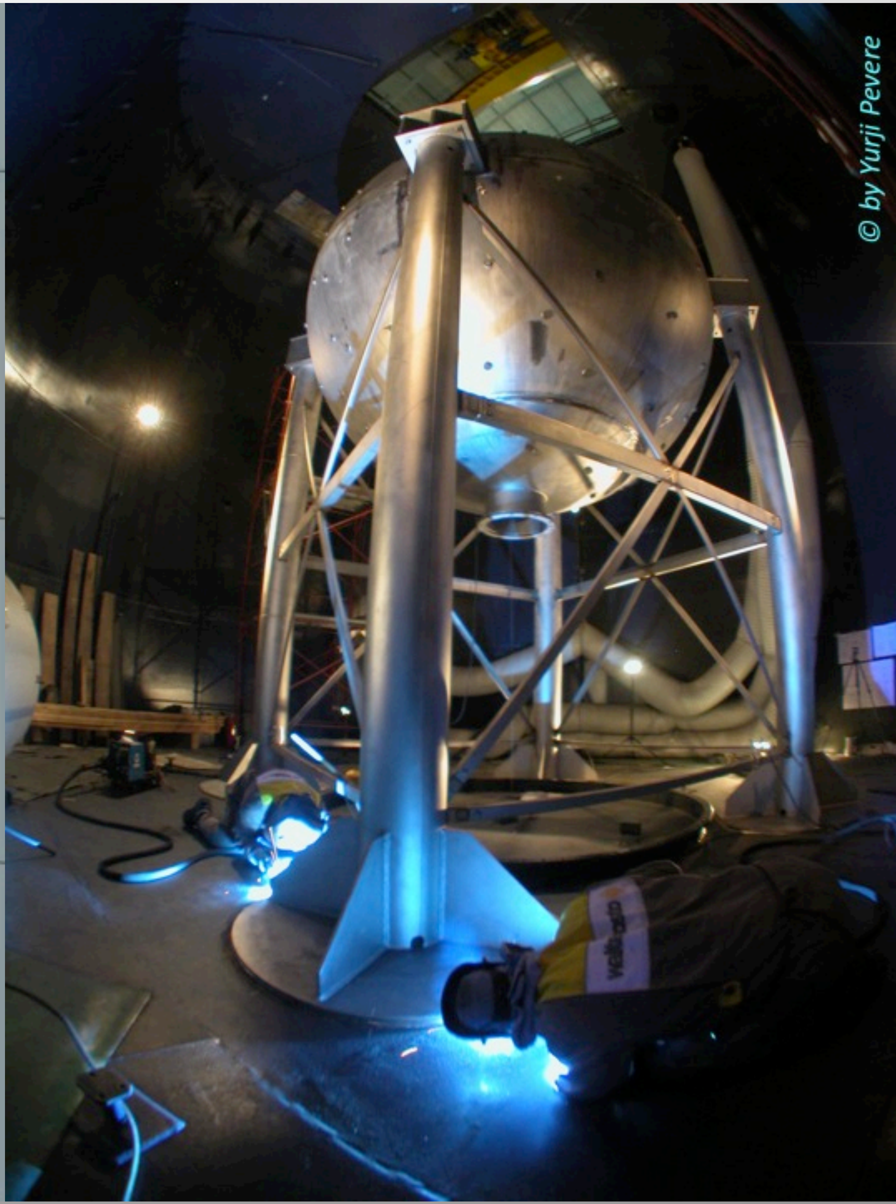


Darkside key features

- Pulse Shape Discrimination on 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 inner chambers





DarkSide program @ LNGS

Scalable technology for a two-phase TPC in LAr

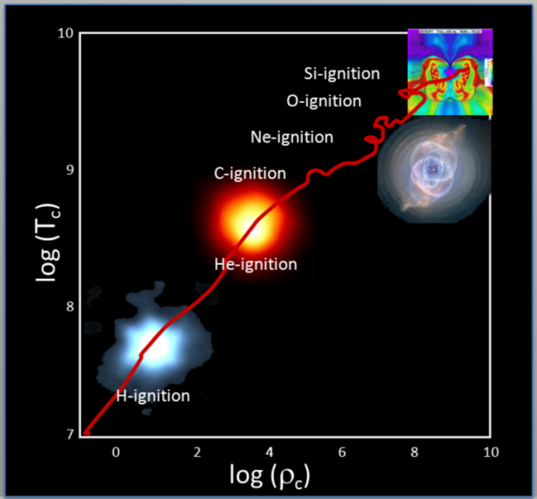
- ✓ **DarkSide-10** (DS-10)
  - 10 kg active mass
  - Operated in 2012 @ LNGS
  - Technical prototype for larger TPC
- ✓ **DarkSide-50** (DS-50)
  - 50 kg active mass
  - Built inside CTF Water Tank with active neutron veto
  - Launch technology for next generation detectors
  - In operation since Nov 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~~

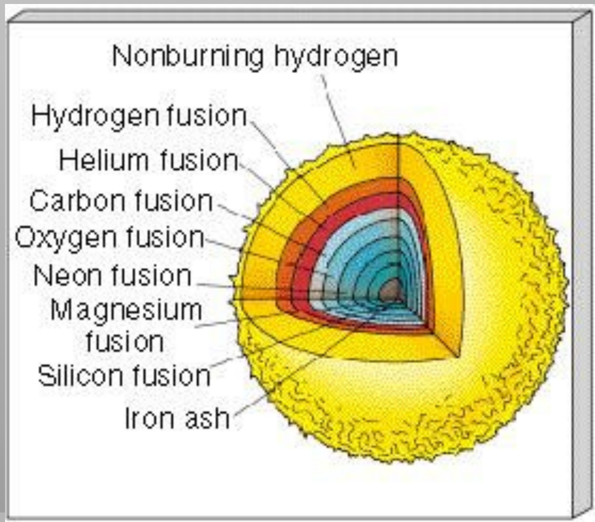
NUCLEAR ASTROPHYSICS

The LUNA experiment

nuclear fusion reaction cross sections

- Stars powered by nuclear reactions
- Key parameters to model stars
  - chemical composition, opacity…
  - reactions cross sections
    - determine the origin of elements
    - stellar evolution and dynamics
  - Many reactions need high precision data.



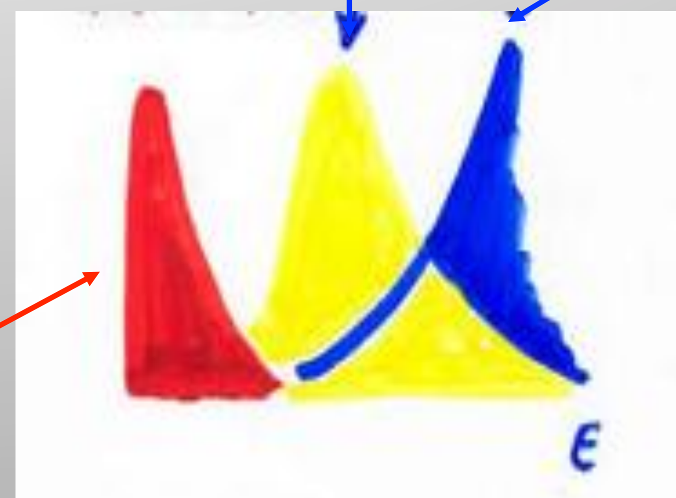


From Sun to novae and beyond

- Stellar Energy+Nucleosynthesis
- Hydrogen Burning
- $\sigma(E_{star})$ with $E_{star} << E_{Coulomb}$

$$\sigma(E) = S(E)\, e^{-2\pi\eta}\, E^{-1}$$

$$2\pi\eta = 31.29\, Z_1 Z_2 \sqrt{\mu/E}$$



$$\text{Reaction Rate(star)} \approx \int \Phi(E)\, \sigma(E)\, dE$$

LUNA astrophysical motivation

- **Solar neutrinos:**
  - $^{3}He(^{3}He,2p)^{4}He$, $^{3}He(^{4}He,\gamma)^{7}Be$, $^{14}N(p,\gamma)^{15}O$
- **Age of globular cluster:**
  - $^{14}N(p,\gamma)^{15}O$
- **Light nuclei nucleosynthesis**
    - ($^{17}/^{18}O$ abundances, ^{19}F production, ^{26}Mg excess,...):
  - $^{15}N(p,\gamma)^{16}O$, $^{17}N(p,\gamma)^{18}O$, $^{25}Mg(p,\gamma)^{26}Al$
- **Big Bang Nucleosynthesis:**
  - $^{2}H(\alpha,\gamma)^{6}Li$, $^{3}He(^{4}He,\gamma)^{7}Be$, $^{2}H(p,\gamma)^{3}He$
- **Next:**
- **Light nuclei nucleosynthesis:**
  - $^{17}O(p,\alpha)^{14}N$, $^{22}Ne(p,\gamma)^{23}Na$, $^{23}Na(p,\gamma)^{24}Mg$, $^{18}O(p,\gamma)^{19}F$, $^{18}O(p,\alpha)^{15}N$
- **He burning and stellar evolution:**
  - $^{12}C(\alpha,\gamma)^{16}O$
- **s process nucleosynthesis:**
  - $^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$

LUNA MV

- **Higher energy machine**
  - 3.5 MV single ended positive ion accelerator
  - Mainly devoted to He-burning in stars
  - Relevant at higher temperatures than H-burning

$^{12}C(\alpha,g)^{16}O$ the most important reaction of nuclear astrophysics: production of the elements heavier than A=16, star evolution from He burning to the explosive phase (core collapse and thermonuclear SN) and ratio C/O

Sources of the neutrons responsible for the S-process: 50% of the elements beyond Iron

$^{13}C(\alpha,n)^{16}O$: isotopes with A≥90 during AGB phase of low mass stars

$^{22}Ne(\alpha,n)^{25}Mg$: isotopes with A‹90 during He and C burning in massive stars

(α,γ) on **^{3}He, ^{14}N, ^{15}N, ^{18}O……**

LUNA MV Project

- **C-beam upgrade**
  - ^{12}C-^{12}C fusion
  - More precise measurement of C-α reactions

- **Accelerator funded**
- **Accelerator construction tendered**

LNGS plans - precision

- **Borexino**
  - Fully exploit its remarkable capabilities
    - What next to SOX?
- **LUNA-MV**
  - It is a long-term measurements plan

LNGS plans - discovery

- **Neutrino Physics**
  - Support run of 2nd generation $\beta\beta$ experiments
  - Attract 3rd generation $\beta\beta$ experiments
    - **Invest in strategic facilities**
- **Dark Matter searches**
  - Test the puzzling DAMA result
    - Encourage and support new NaI experiment
  - Full support to run of 2nd generation: XENON1T
  - Attract 3rd generation DM experiments
    - Crystals: synergies with R&D for $\beta\beta$
    - *Facility for noble gas(es)?*