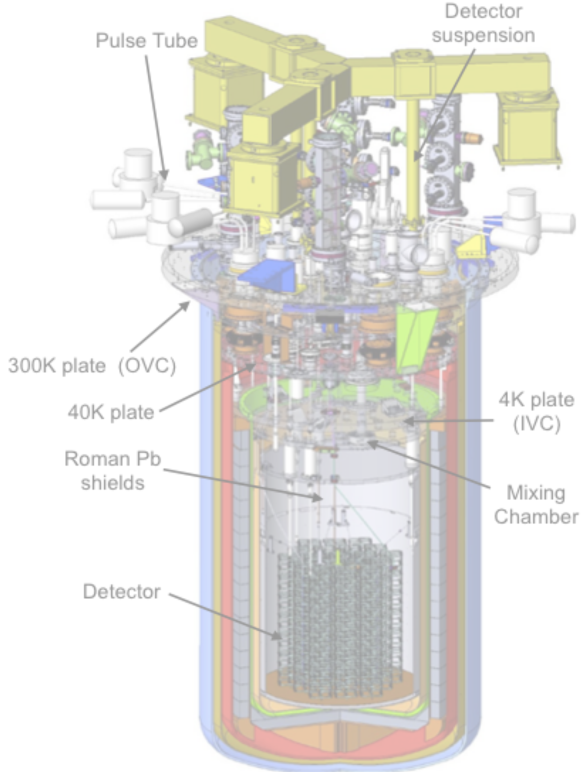
Neutrinoless ββ decay @ LNGS

compstar



Compact Stars in the QCD phase diagram V”

May 25, 2016 - LNGS, Italy

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Present knowledge about neutrinos

- neutrinos are massive fermions
- there are 3 active neutrino flavors (ν_α)
- neutrino flavor states are mixtures of mass states (ν_k)

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric / Accelerator — Reactor / Accelerator — Solar / Reactor

Measurements of neutrino parameters from:

- neutrino oscillations
- single beta decay
- cosmology
- neutrinoless double beta decay

Open questions

- What is the absolute neutrino mass scale?
- What is the neutrino mass hierarchy?

  Normal ($m1 < m2 \ll m3$) or Inverted ($m3 \ll m1 < m2$)?
- Are neutrinos Dirac or Majorana particles?
- What is the origin of neutrino masses and flavor mixing?
- Is there CP violation in the lepton sector?

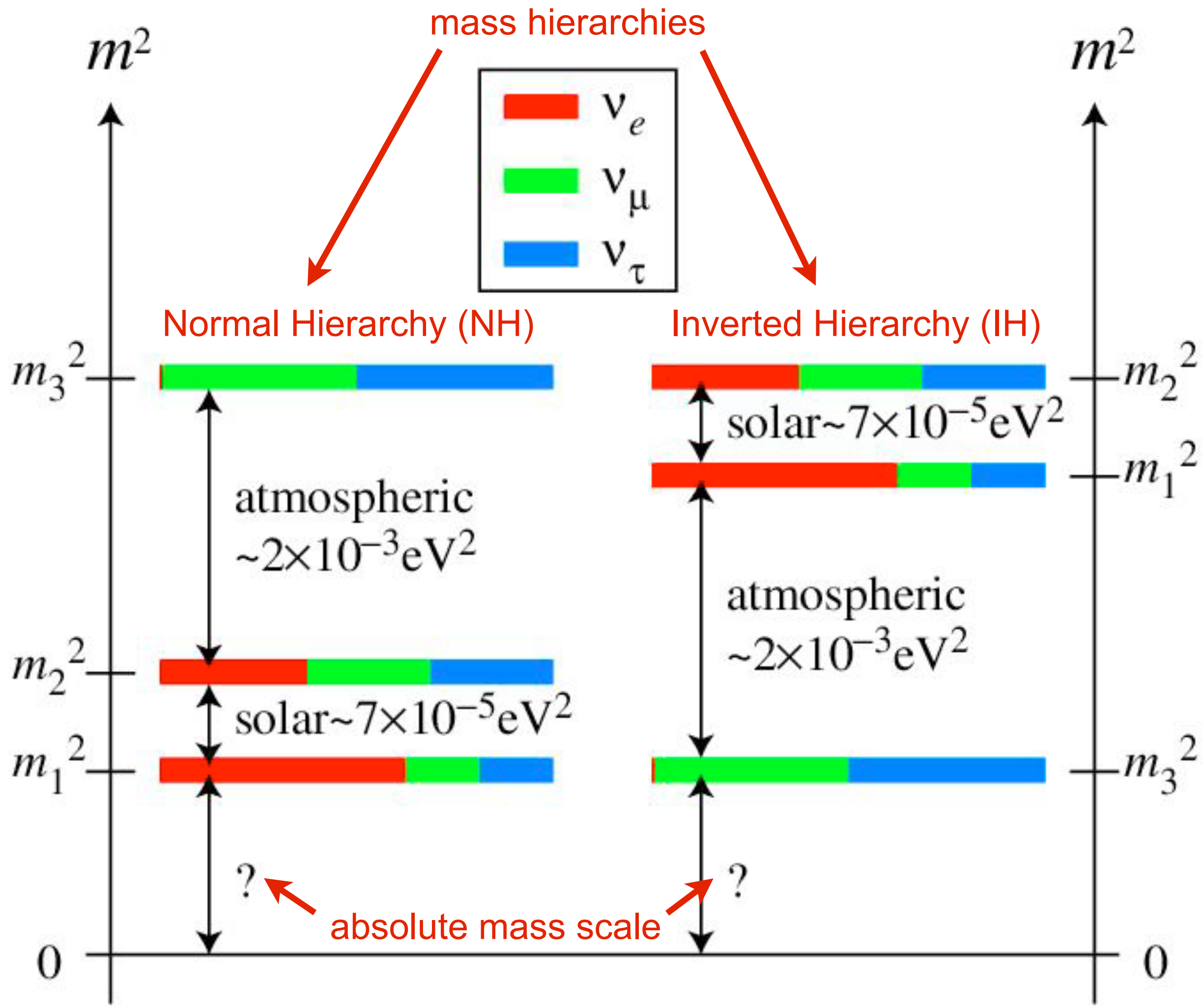
‣ Neutrinos are important probes of the Standard Model limits

‣ Neutrino masses are linked (directly or indirectly) to all the above questions

Open questions

0ν-ββ can give an answer to three of those questions:

- Dirac or Majorana nature
- absolute mass scale:
  mass of the lightest ν
- hierarchy of masses
  (m1 < m2 ≪ m3 or m3 ≪ m1 <m2)

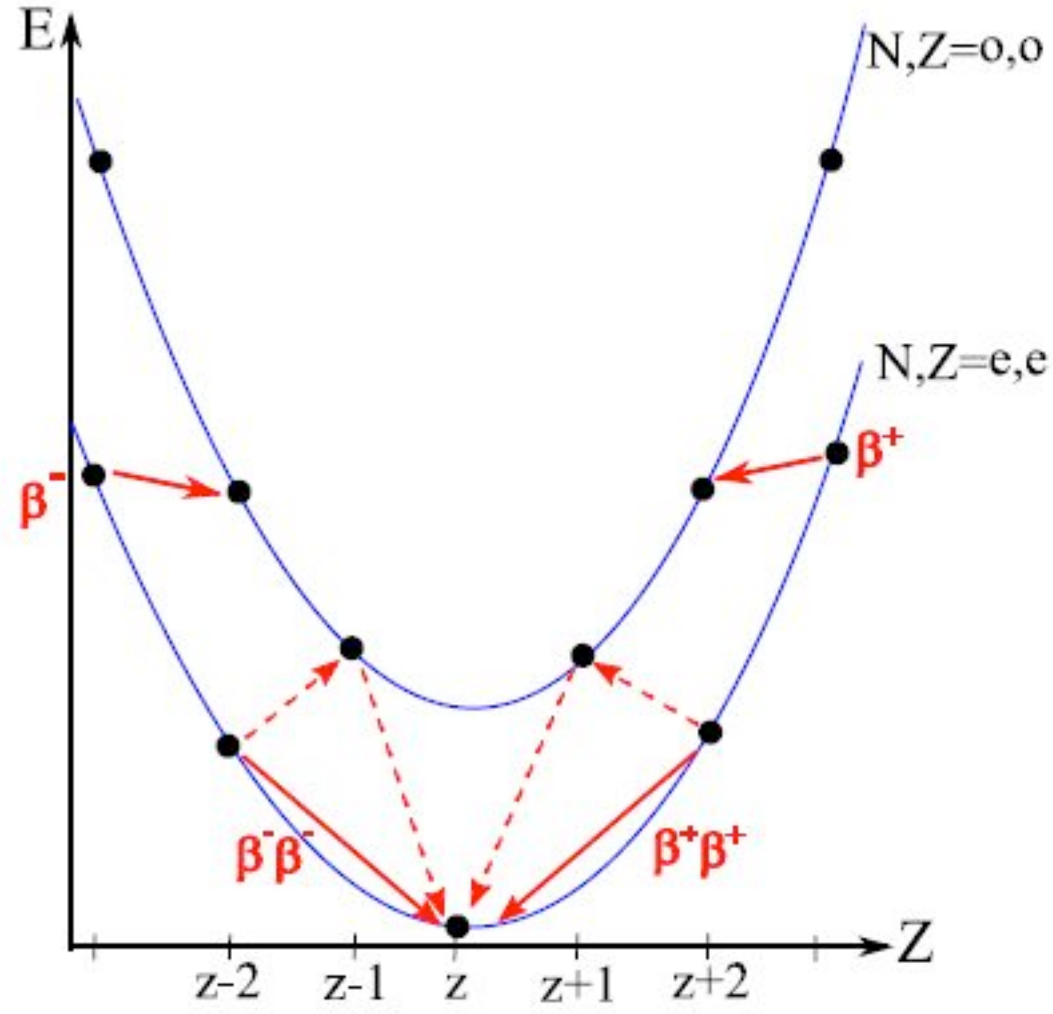


Oscillation experiments can determine the hierarchy but are blind to the other two questions

Double beta decay

Very rare nuclear decay (A,Z) → (A,Z+2) + 2e$^-$ (+?)

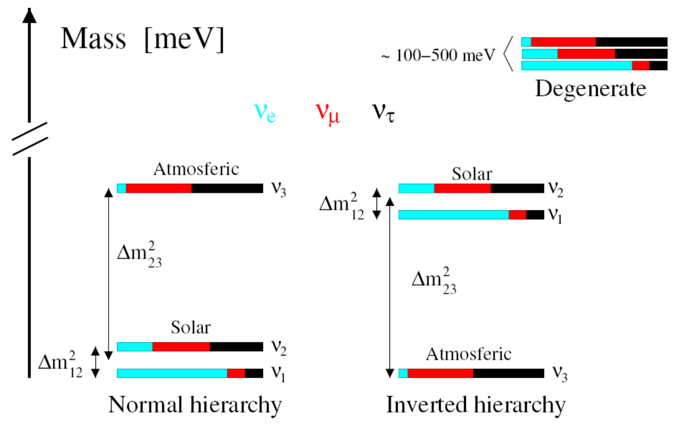
Isotope	Q-value [keV]	Isotopic abundance
^{48}Ca	4272	0,19
^{76}Ge	2039	7,8
^{82}Se	2996	9,2
^{96}Zr	3350	2,8
^{100}Mo	3034	9,6
^{116}Cd	2814	7,6
^{130}Te	2527	33,4
^{136}Xe	2459	8,9
^{150}Nd	3371	5,6

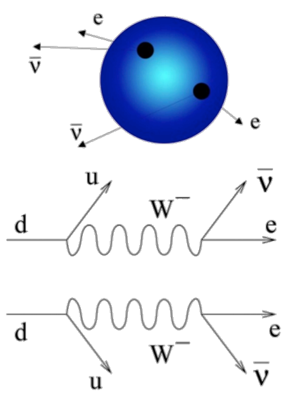


Double beta decay

0ν-DBD is a fundamental tool to determine neutrino properties

- Dirac or Majorana nature
- Absolute mass scale
- Mass hierarchy



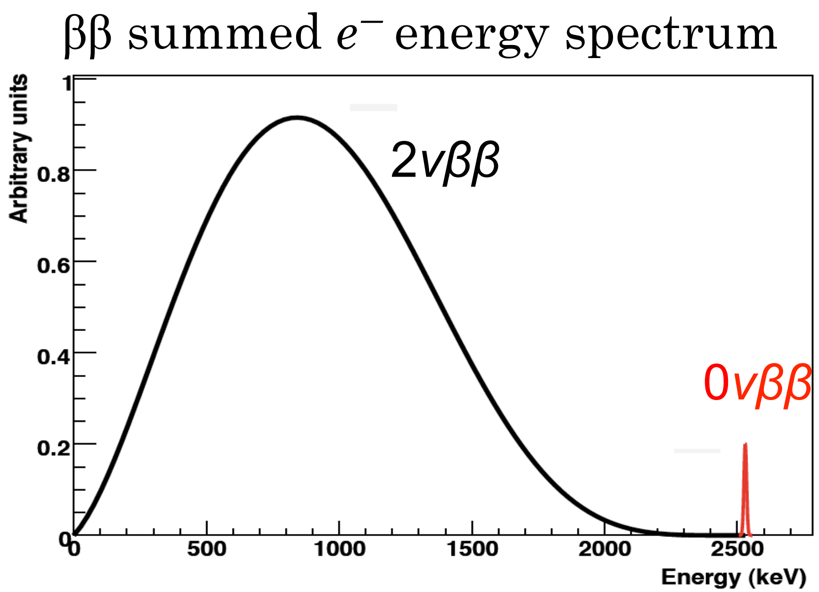


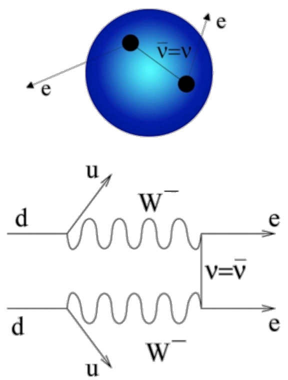
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}$$

2ν-DBD

2nd order process allowed in the SM

observed in several nuclei with $\tau^{2\nu} \sim 10^{19}$-10^{21} y





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

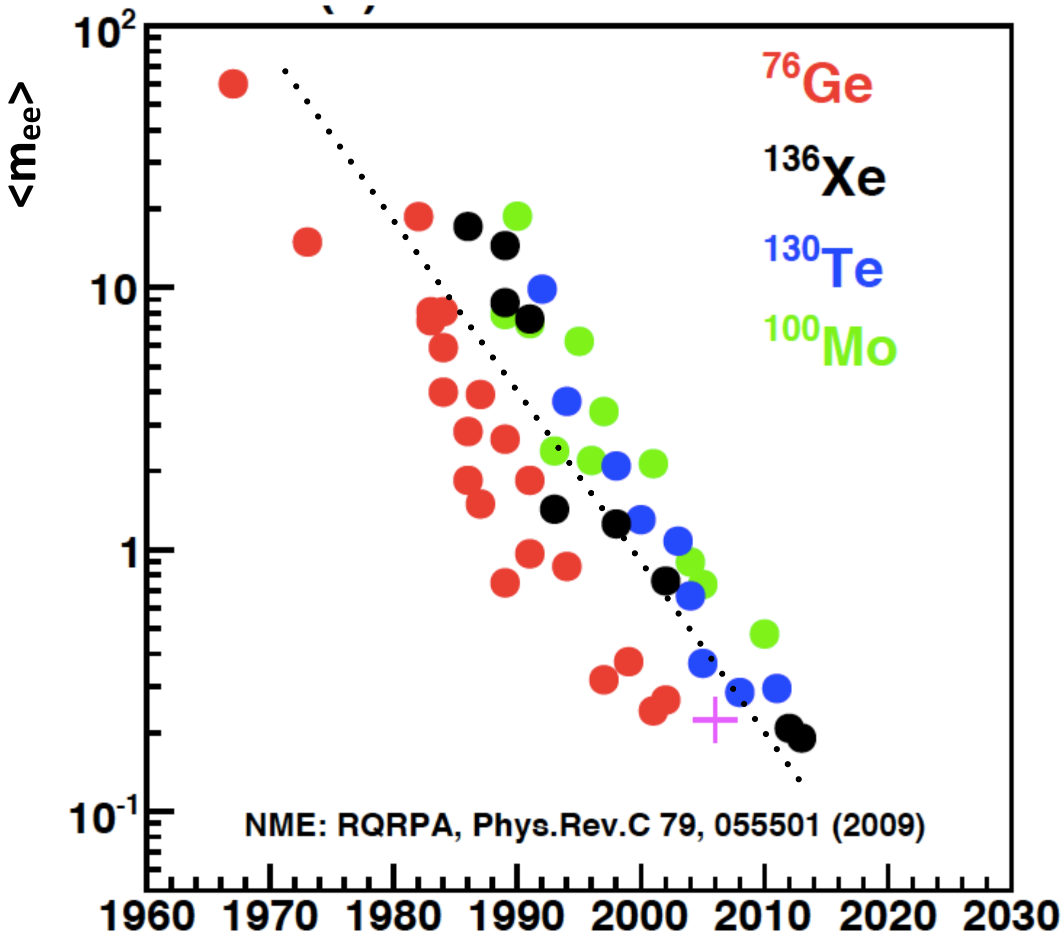
0ν-DBD (implies physics beyond SM)

lepton number violating process

$\tau^{0\nu} > 10^{24}$-10^{25} y

exists if neutrino is a Majorana particle and $m_\nu \neq 0$

A long history of 0ν-ββ experiments



An order of magnitude on the effective Majorana mass every 15 years?

0ν-ββ and Majorana mass

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}\, g_A^4\, |M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

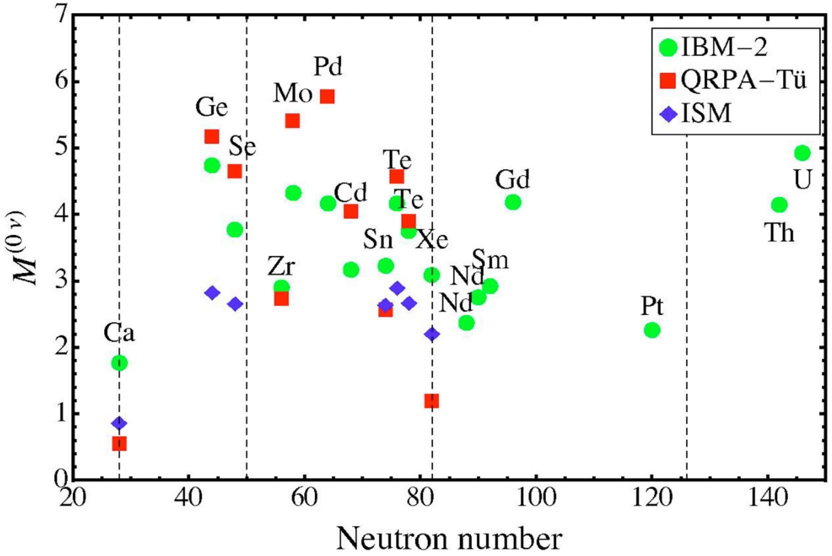
- $[T^{0\nu}_{1/2}]^{-1}$: 0νββ decay rate
- $G_{0\nu}$: Phase space factor
- g_A^4: Axial vector coupling
- $|M_{0\nu}|^2$: Nuclear matrix element
- $\langle m_{\beta\beta}\rangle^2$: Effective Majorana mass

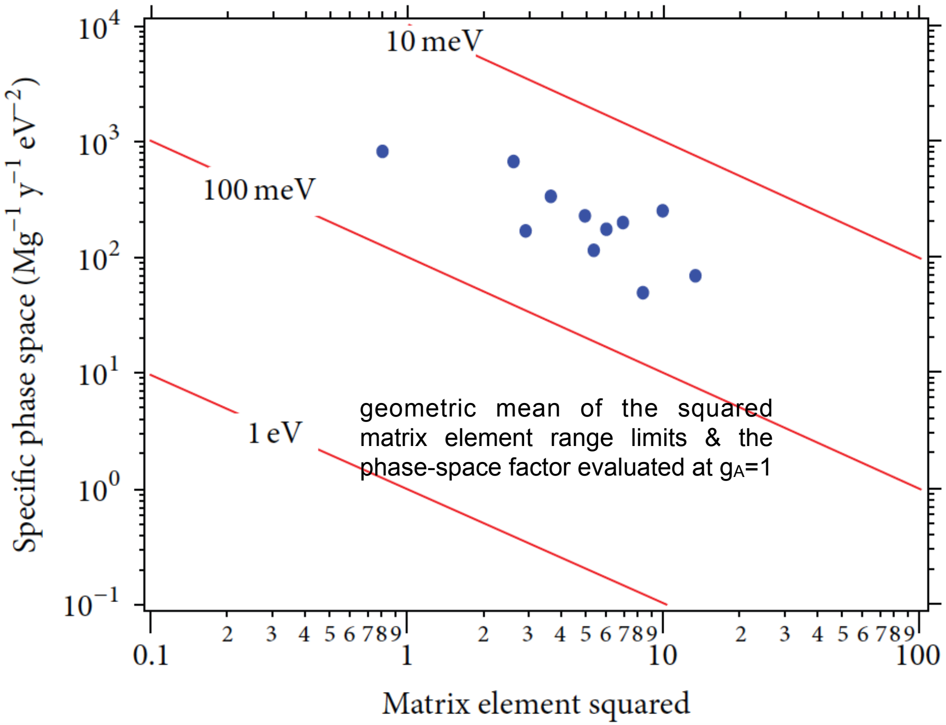
$$\langle m_{\beta\beta}\rangle = \sum_k U_{ek}^2 m_k = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

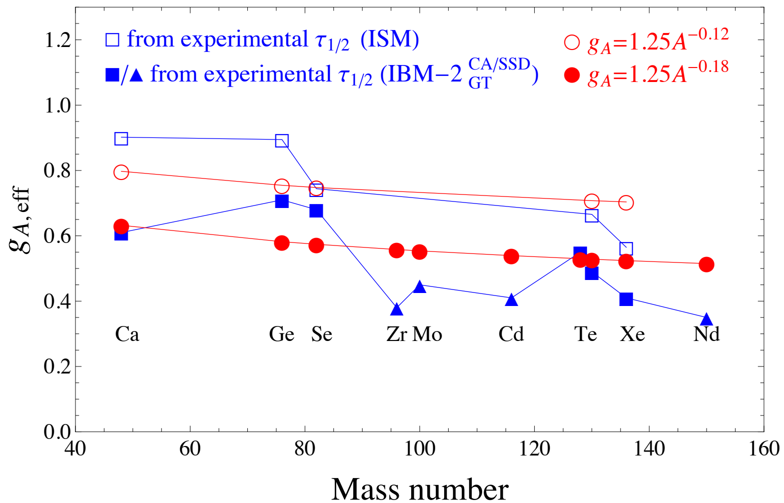
- m_k: NEUTRINO MASS EIGENVALUES
- U_{ek}: NEUTRINO MIXING MATRIX

Is there a preferred isotope?

- Nuclear matrix elements calculations are rapidly improving and today the differences between different methods (IBM, QRPA, ISM) are much smaller than in the past
- Uncertainty on g_A plays a relevant role
  factor 2 in g_A is a factor 16 in decay rate
- inverse correlation observed between phase space and square of the nuclear matrix element







Isotope choice

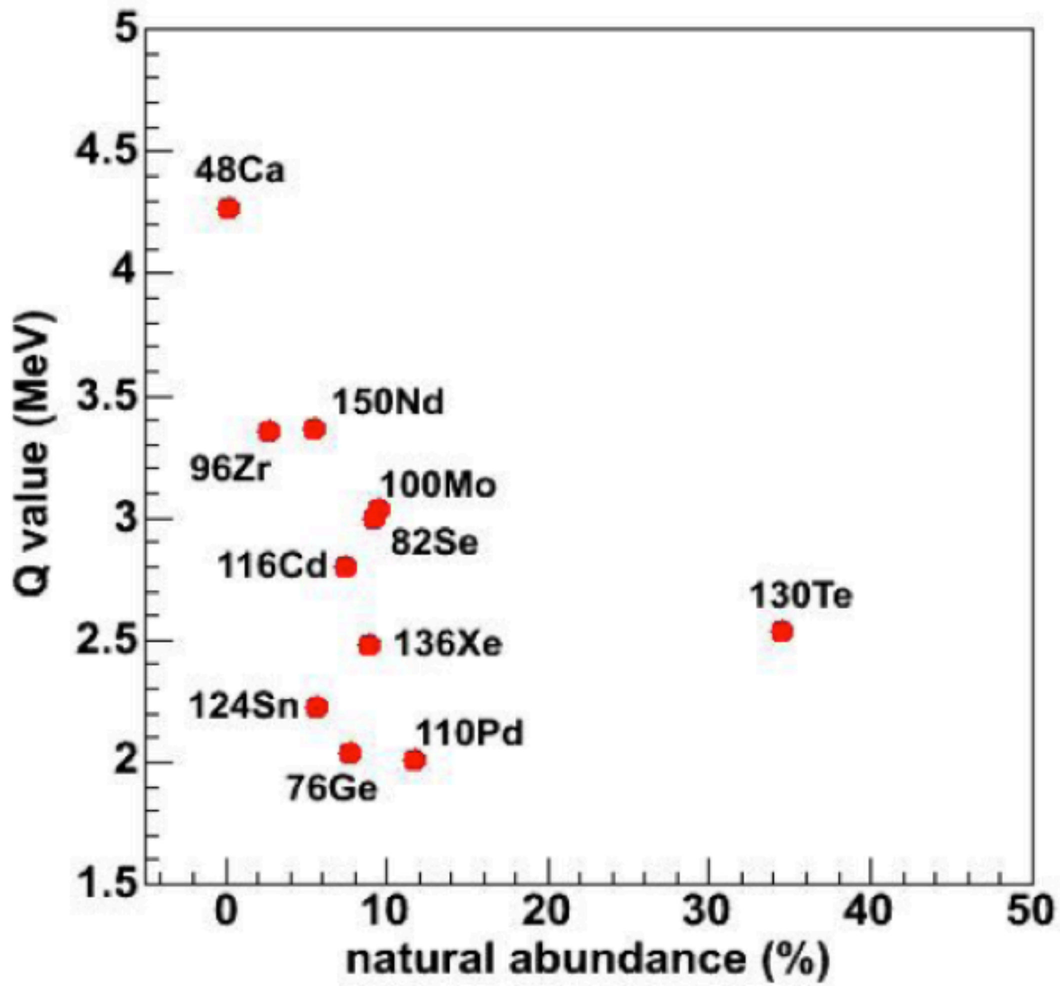
In many cases driven by the detector characteristics.

- ^{76}Ge with Germanium diodes
- ^{136}Xe with Xenon TPCs
- bolometers and scintillators have multiple choices

- Isotopic abundance as high as possible
  - money issue

- Q-value as high as possible
  - background

- 2v-DBD half-life as high as possible
  - energy resolution



Sensitivity

Half-life corresponding to the minimum detectable number of events over background at a given confidence level

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

finite background: M·T·B·ΔE >1

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} M \cdot T$$

zero background: M·T·B·ΔE ≲1

M: active detector mass [kg]

T: measurement life time [anni]

B: background in the ROI [counts keV^{-1} kg^{-1} y^{-1}]

W: molecular weight

N_A: Avogadro number

η: isotopic abundance

ε: detector efficiency

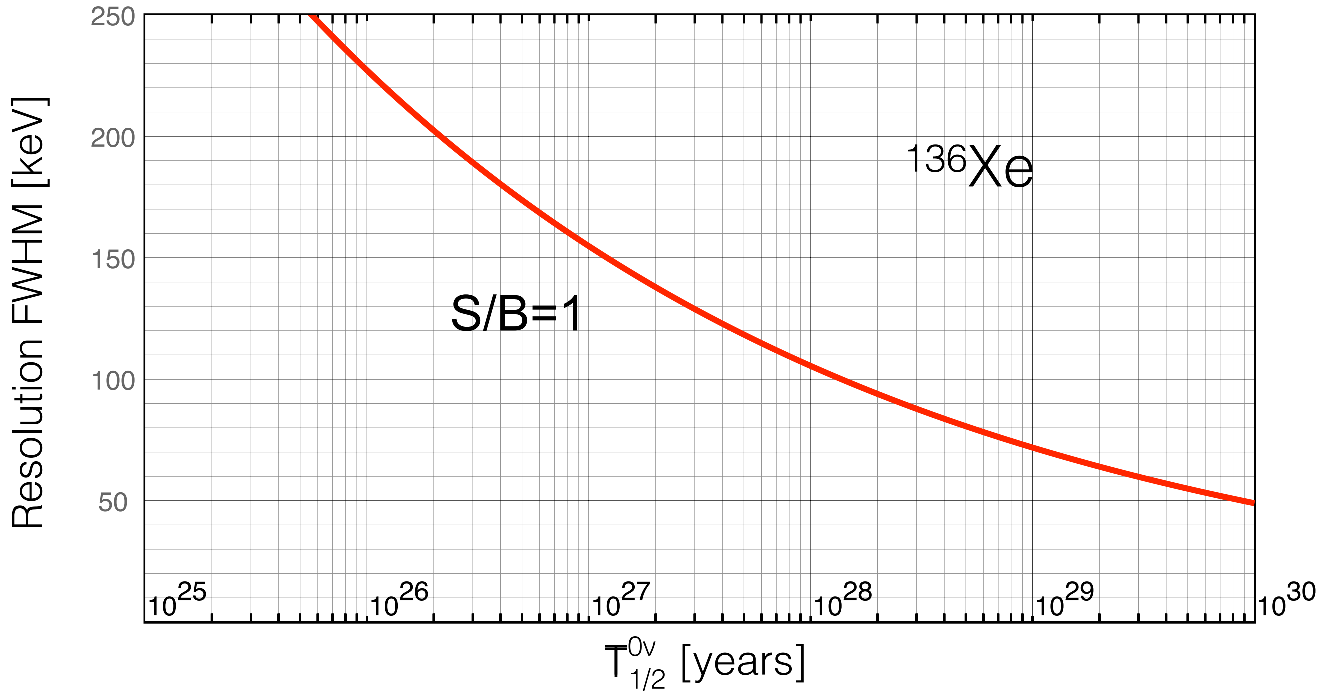
ΔE: FWHM energy resolution @ Q-value

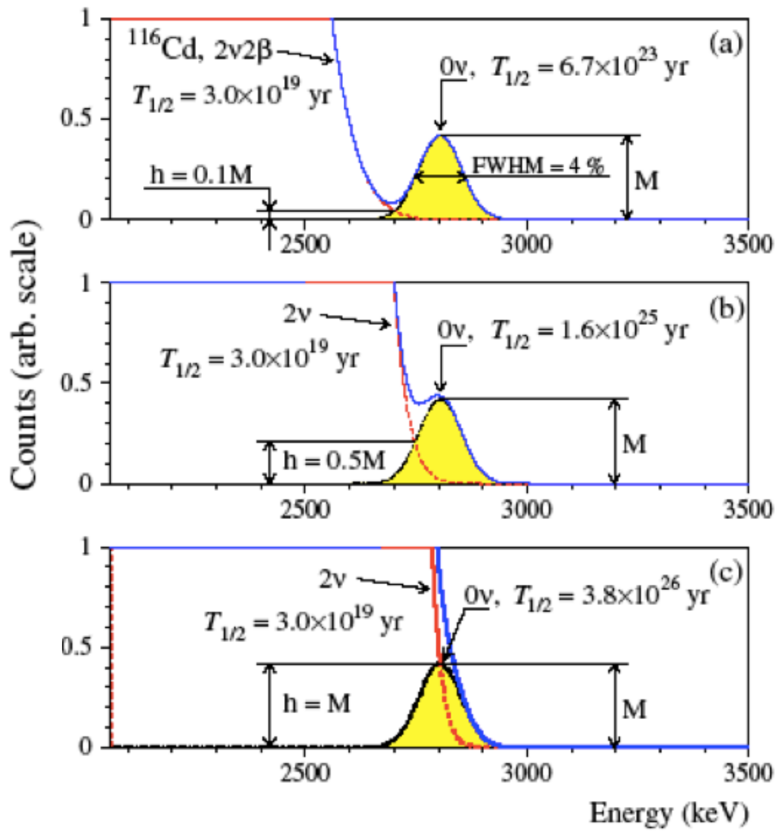
How to improve sensitivity?

- Increase measurement time
- Increase mass
- Increase isotopic abundance (enrichment)
- Improve energy resolution
- Reduce background

Irreducible background from 2ν-ββ

- The irreducible background induced by the 2ν-ββ could be mitigated just by the energy resolution
- The effect can be partially attenuated with an asymmetric ROI (but losing efficiency)





Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

$$\frac{S}{B} = \frac{m_e}{7Q\delta^6}\frac{\Gamma_{0\nu}}{\Gamma_{2\nu}} = \frac{m_e}{7Q\delta^6}\frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}$$

Neutrinoless ββ decay @ LNGS

A long history in $0\nu\beta\beta$ search

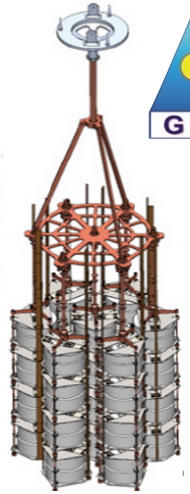
- MiDBD (^{130}Te)
- Heidelberg-Moscow (^{76}Ge)
- Cuoricino (^{130}Te)
- GERDA-I (^{76}Ge)
- CUORE-0 (^{130}Te)

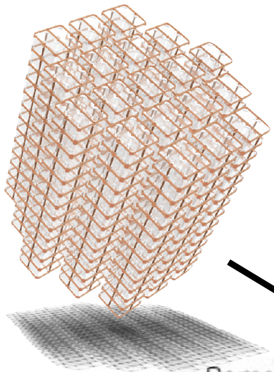
various R&D projects

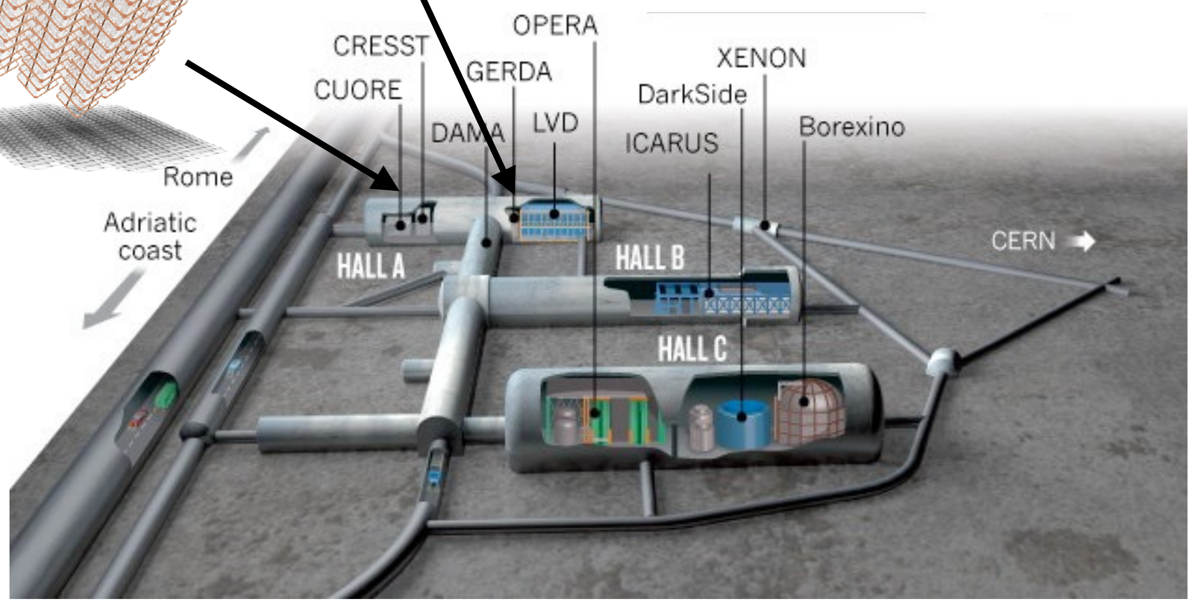
- DAMA R&D (^{116}Cd)
- Cobra (^{116}Cd)
- CUPID-0/LUCIFER (^{82}Se)

important role in the next years

- GERDA-II (^{76}Ge)
- CUORE (^{130}Te)



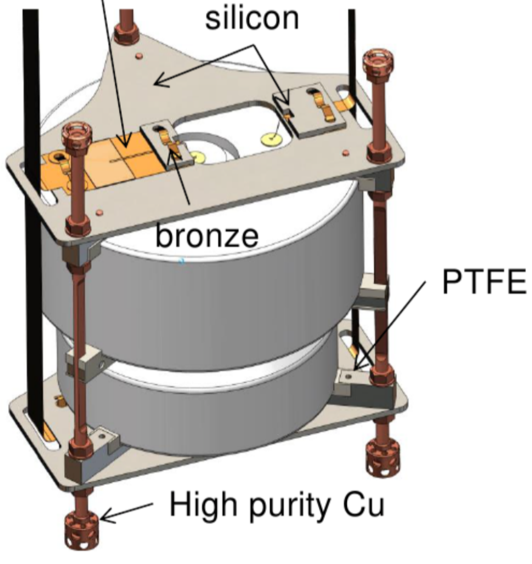


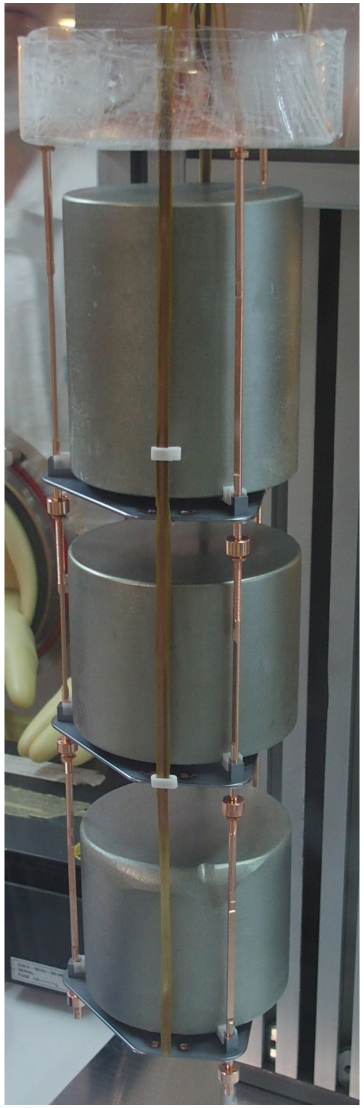


- ~3600 m.w.e. deep
- μ_S: ~$3\text{x}10^{-8}$/(s cm^2)
- γ_S: ~0.73/(s cm^2)
- neutrons: $4\text{x}10^{-6}$ n/(s cm^2)

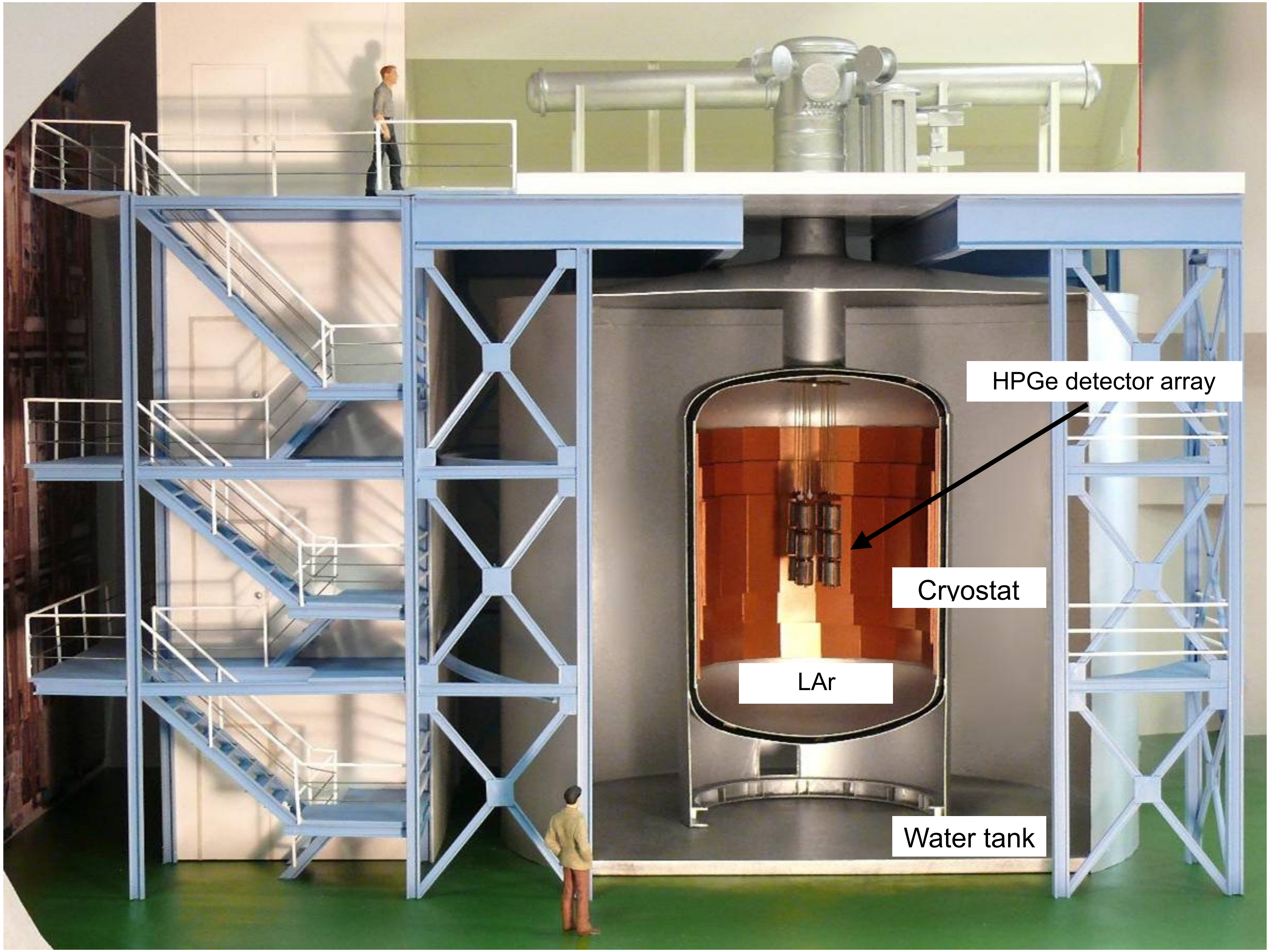
GERDA

- High purity semiconductor
- Enrichment: about 87% of ^{76}Ge
- $Q_{\beta\beta}$ value 2039 keV
- Energy resolution @ $Q_{\beta\beta}$ ~ 0.2% (FWHM)
- High detection efficiency
- Modular
- Point-like energy deposition (PSD)

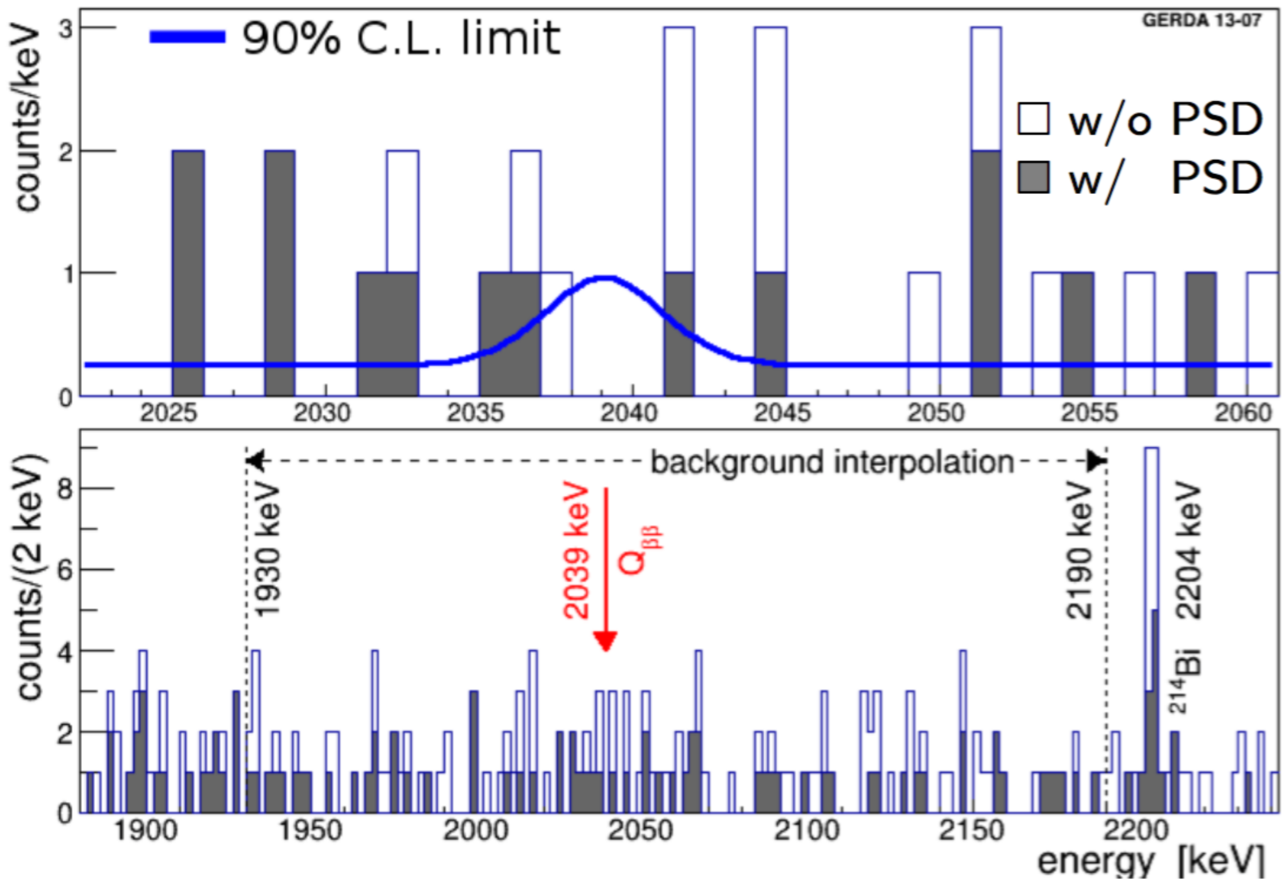




GERmanium Detector Array



GERDA Phase I results



- Exposure 21.6 kg · yr
- Blind analysis
- Detection efficiency:
  - 62% for Coax
  - 66% for BEGe
- Sensitivity $2.4 \cdot 10^{25}$ yr
- No counts in 2039 keV$\pm 1\sigma$

$T_{1/2} > 2.1 \cdot 10^{25}$ yr

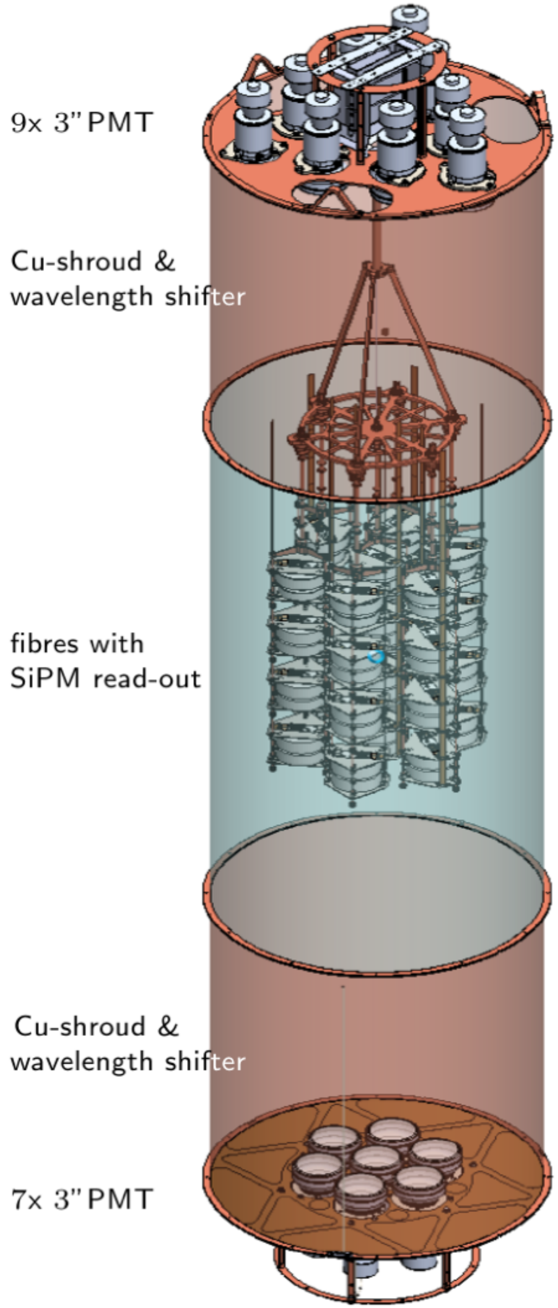
$\langle m_{\beta\beta} \rangle < 0.2-0.4$ eV (90% C.L.)

GERDA Phase II

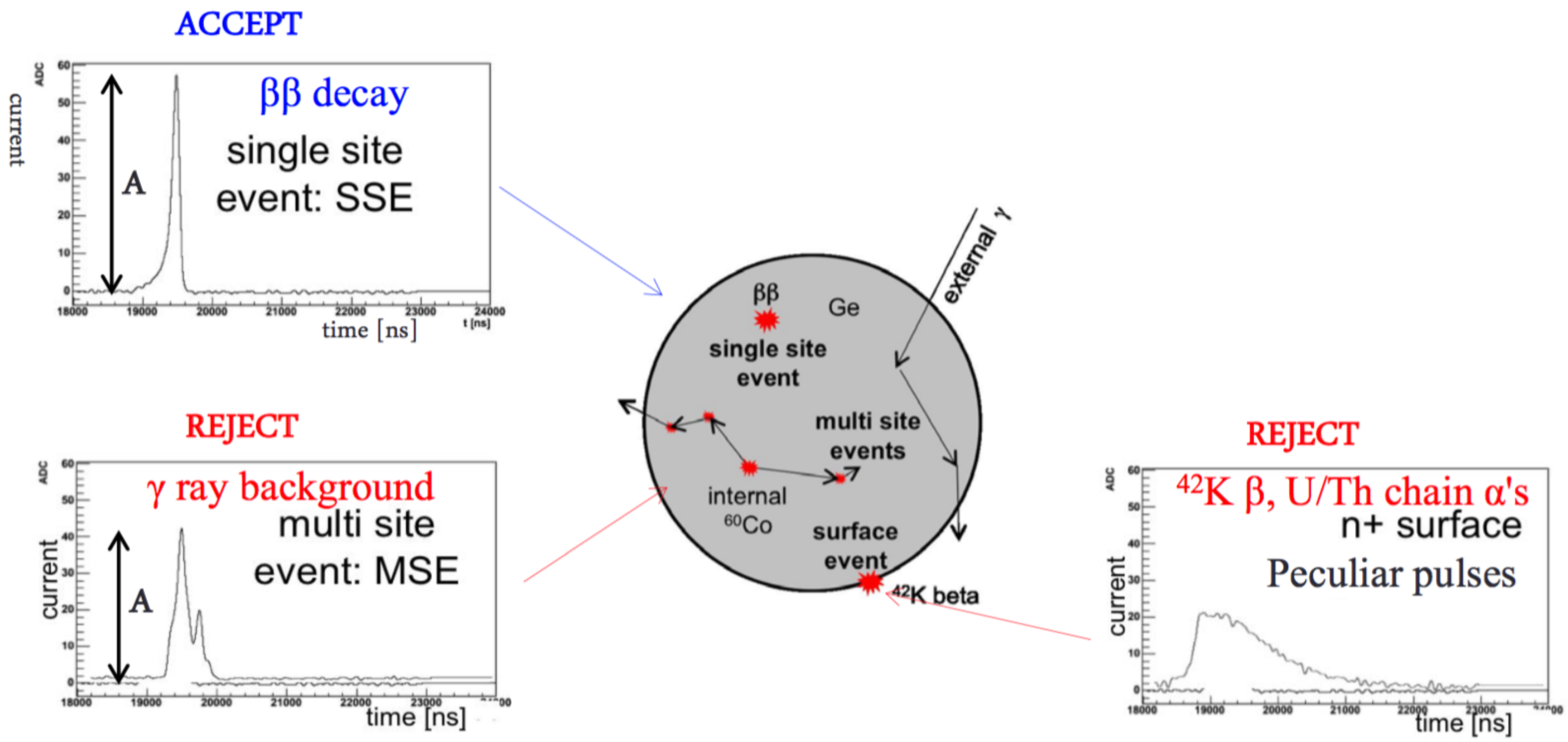
Goals:
- Sensitivity above $1 \cdot 10^{26}$ yr
- Exposure ~ 100 kg · yr
- Background index 10^{-3} cts/(keV·kg·yr)

What's new?
- 30 custom BEGe detectors (~ 20 kg)
- energy resolution ~ 3keV FWHM @ 2MeV
- pulse shape discrimination of bulk SSE against surface events (α&β) and MSE

Background veto
- LAr scintillating read–out
- better anti-coincidence



PSD



- **Anti-coincidence** with the **muon veto**
- Anti-coincidence **between detectors** (cuts MSE)
- **Active veto** using LAr scintillation (implemented in Phase II)
- **Pulse shape** discrimination (PSD)
  - MSE within one detector and surface events
  - Very efficient for the BEGe detectors
    - Accept **>90% of SSE**, while rejecting **90%** of MSE and surface events
  - Less efficient with coaxial detectors, but still doable (acc: 90%/ suppr: 50%)

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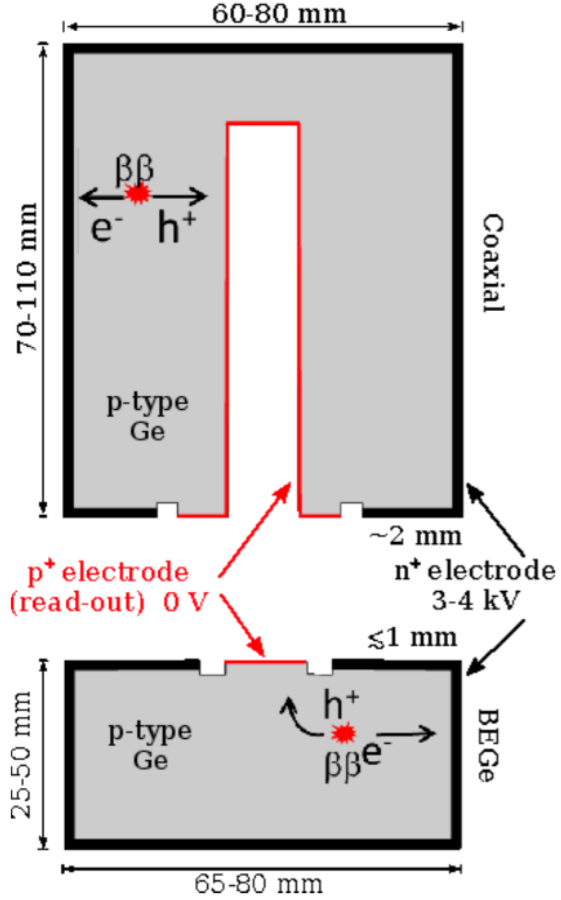
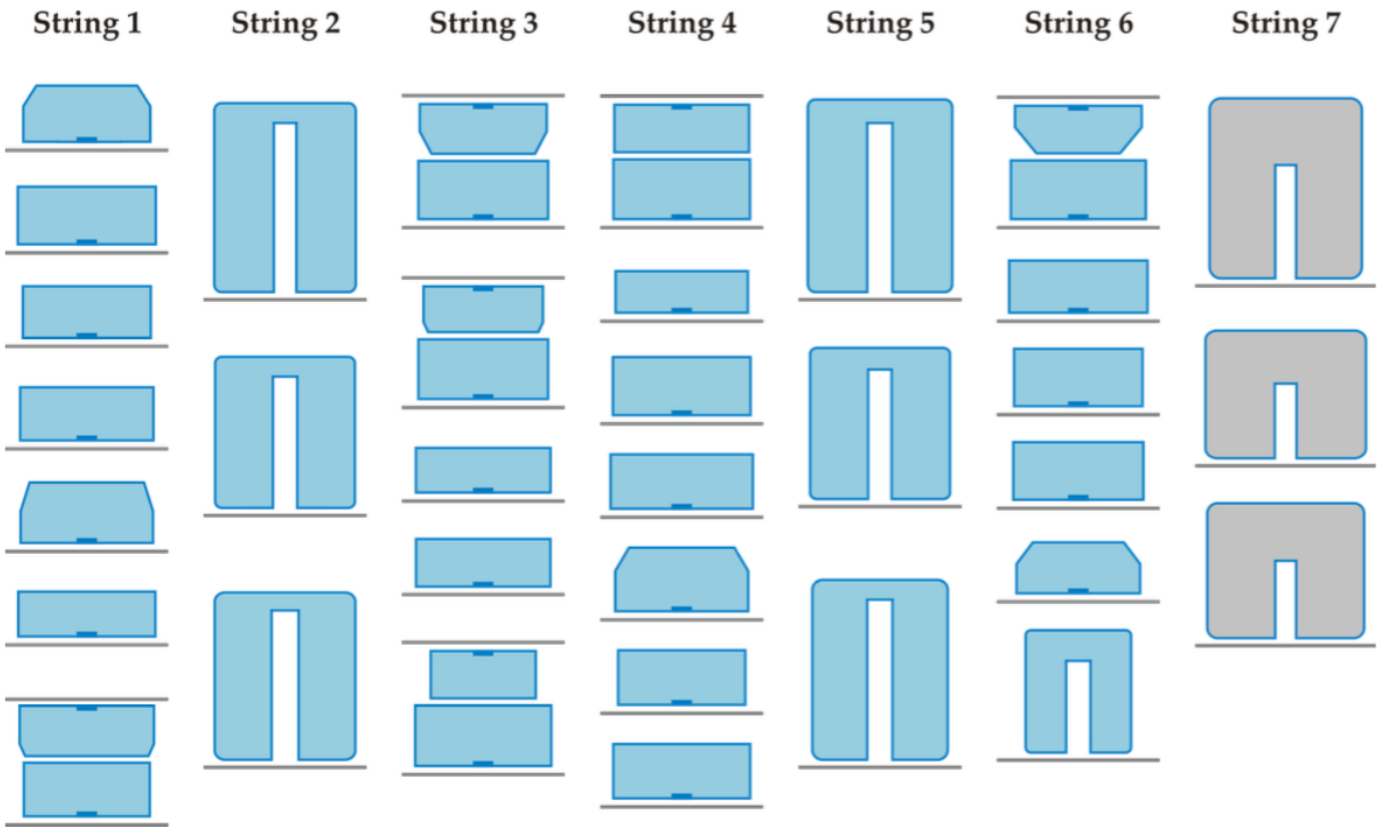
Phase II Detectors



Phase II detectors layout



Coax mass:

15.8 + 7.6 kg

$\sim$ 2 kg/det

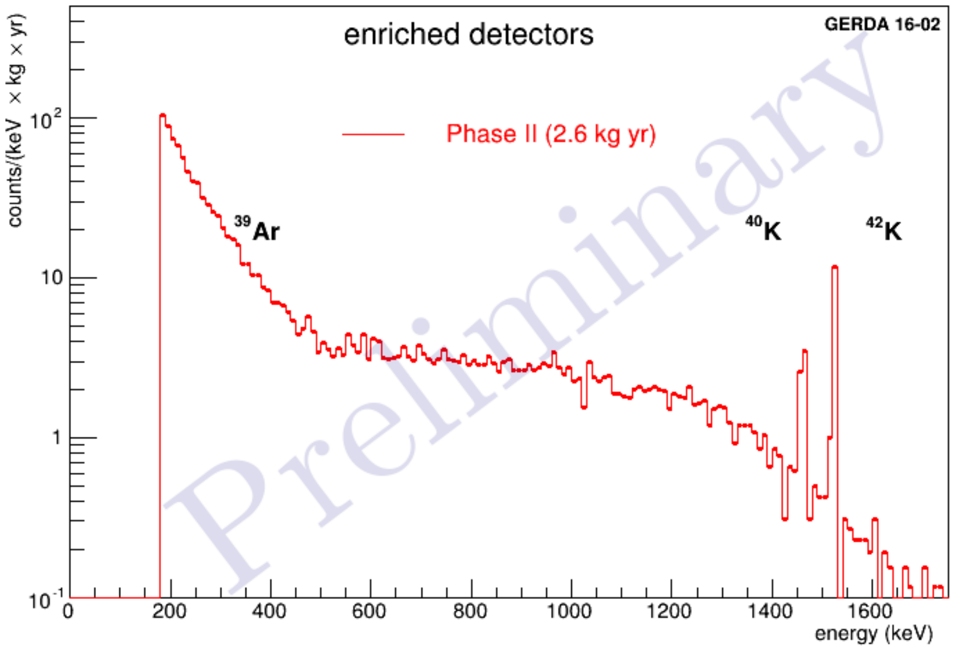
BEGe mass:

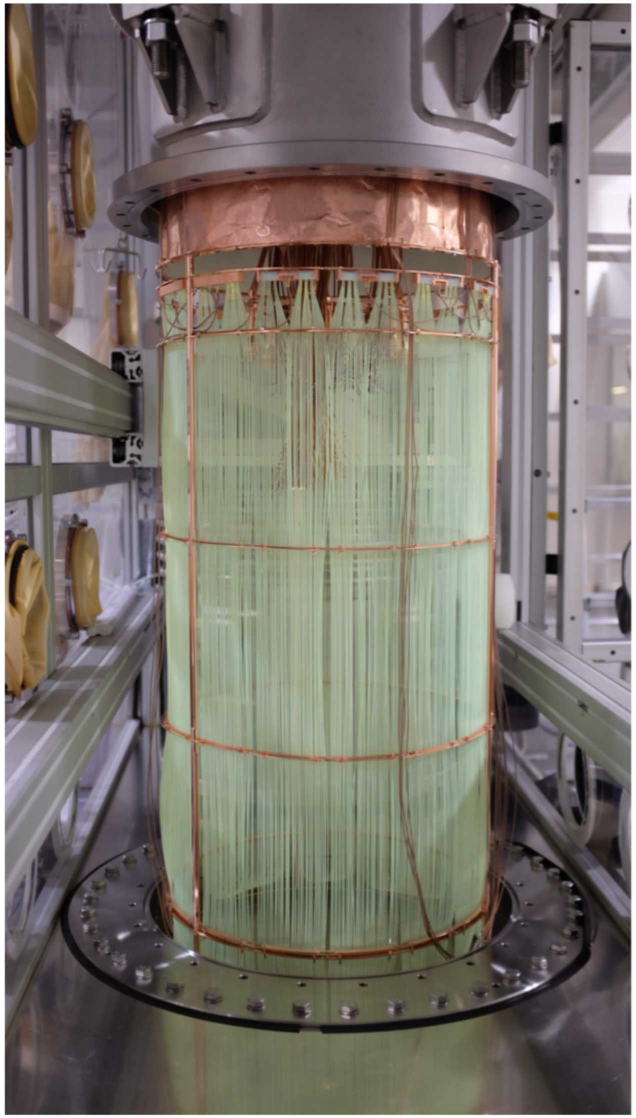
20.0 kg

$\sim$ 0.7 kg/det

Present Status

- Phase II started on December 20, 2015
- 7 strings – 40 detectors
- exposure by Feb 2016: ~ 2.6 kg · yr
- no surprises in the background spectrum

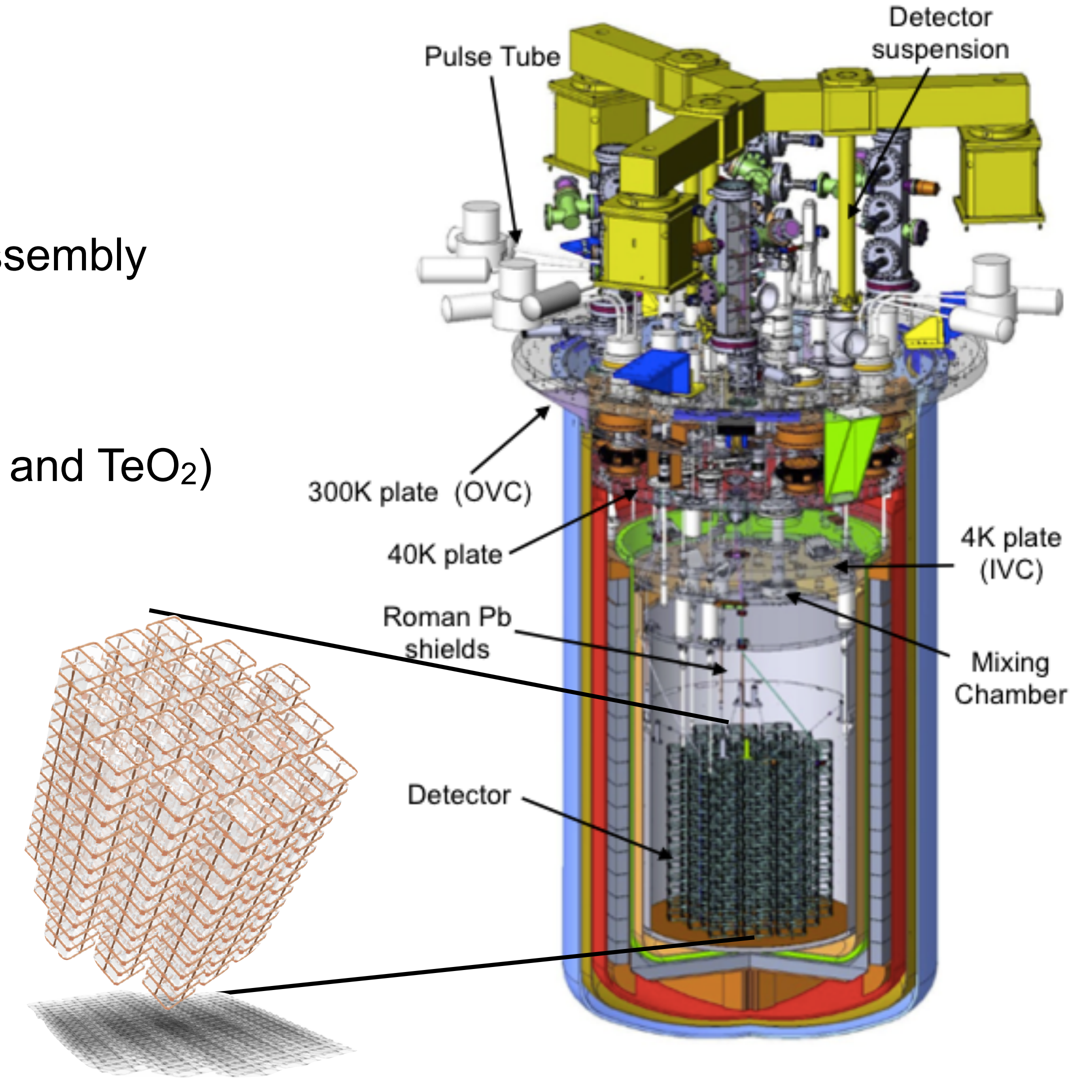




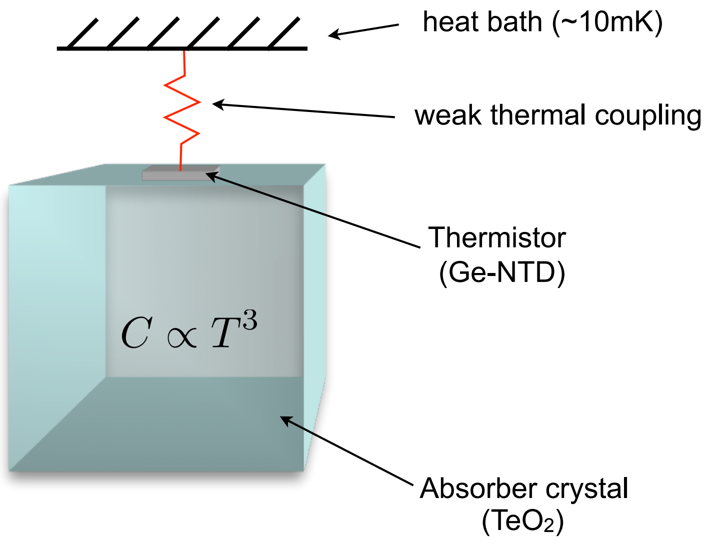
The CUORE challenge

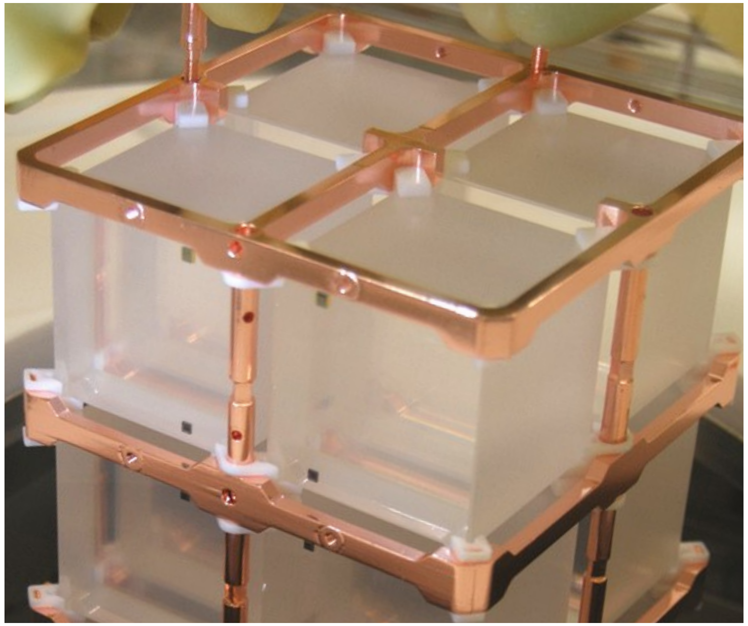
Operate a huge thermal detector array in a extremely low radioactivity and low vibrations environment

- 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
- Mass to be cooled down: ~ 15 tons (lead, copper and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- $T_{1/2}$ sensitivity (90% C.L.): ~ 9.5×10^{25} yr



Thermal detectors





- wide choice of detector materials

  low heat capacity @ T_{work}

- excellent energy resolution (~1 ‰ FWHM)

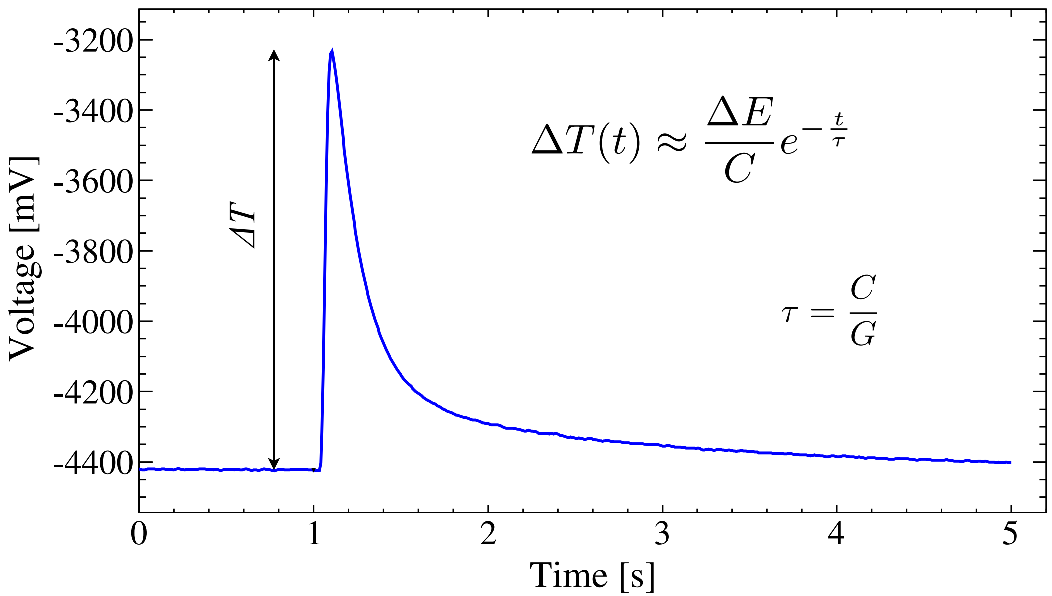
  huge number of energy carriers (phonons)

- equal detector response for different particles

  true calorimeters

- slowness

  in rare event search doesn't matter



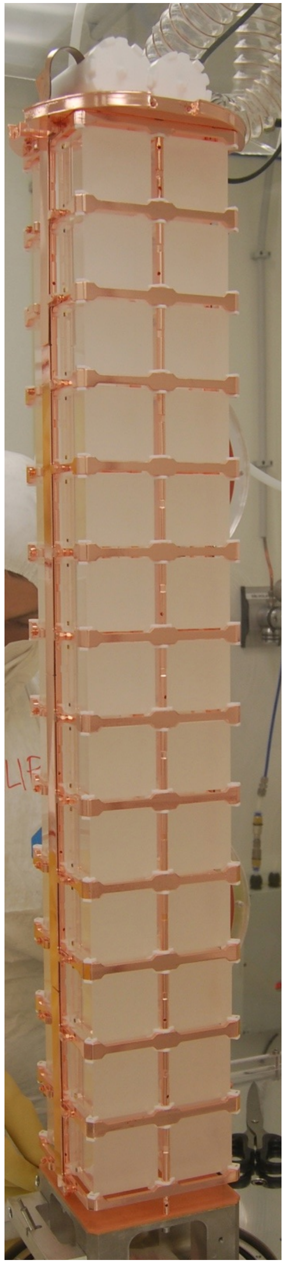
CUORE-0

CUORE-0 is the first tower produced out of the CUORE assembly line.

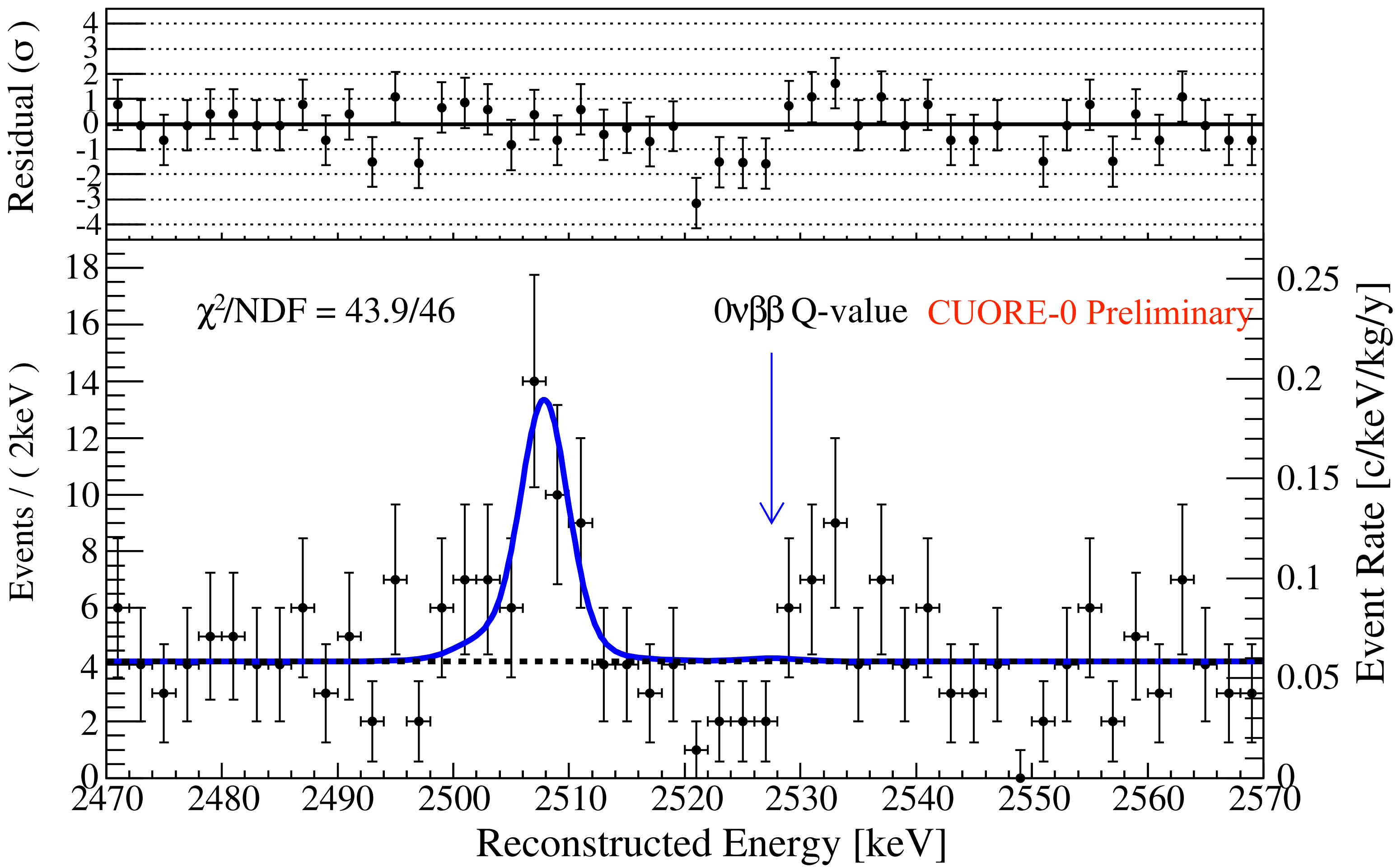
- 52 TeO_2 5x5x5 cm^3 crystals (~750 g each)
- 13 floors of 4 crystals each
- total detector mass: 39 kg TeO_2 (10.9 kg of ^{130}Te)

CUORE-0 has been taking data since March 2013 in the 25 year old Cuoricino cryostat.

- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Check of the radioactive background reduction
- Extend the physics reach beyond Cuoricino while CUORE is being assembled
- Sensitive 0vDBD experiment



CUORE-0 results



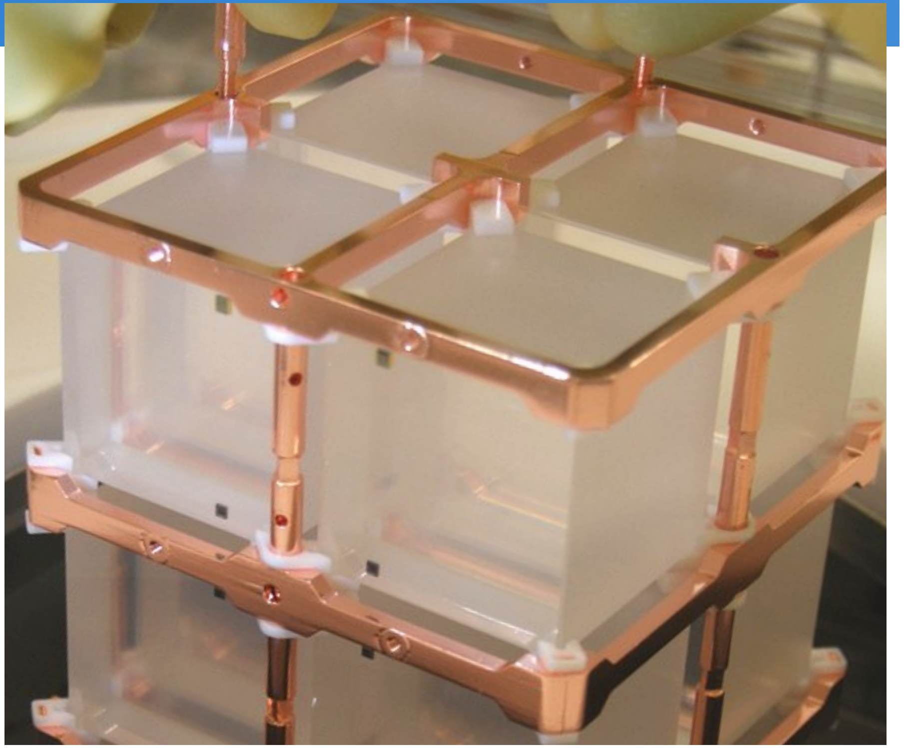
Background index: 0.058 ± 0.004 (stat.) ± 0.002 (syst.) c keV^{-1} kg^{-1} yr^{-1}

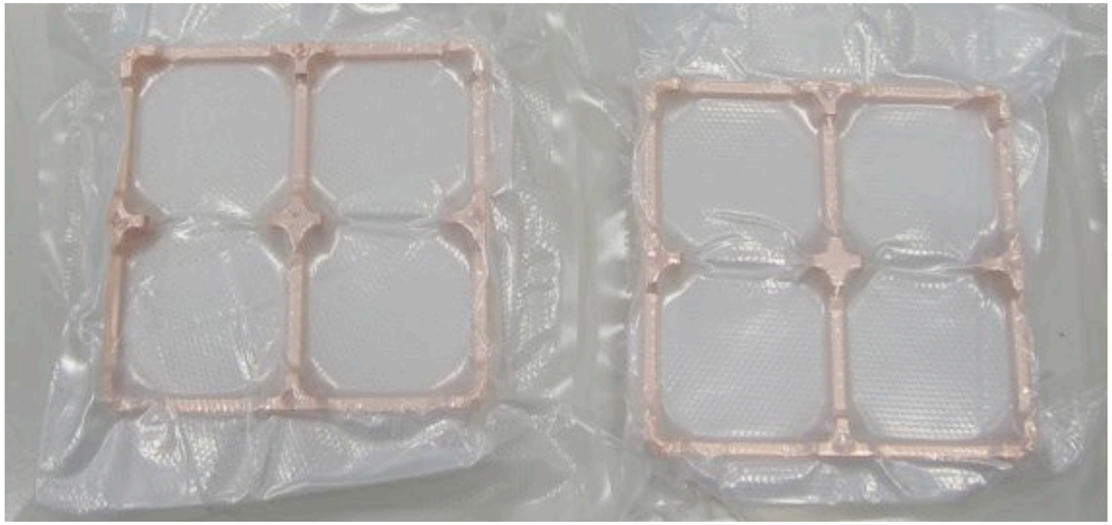
0vDBD ^{130}Te Bayesian 90% C.L. limit: $T_{1/2} > 2.7 \times 10^{24}$ yr

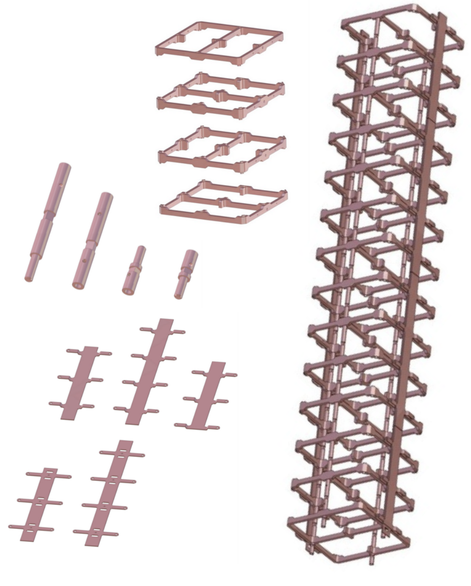
<mββ> < (270-650) meV

CUORE detectors

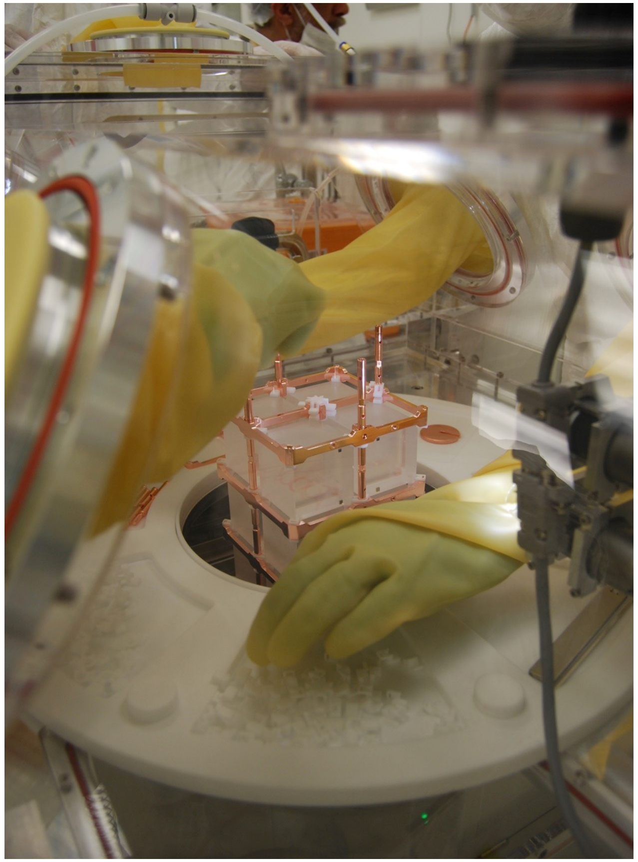
- New lighter detector design structure
- Reduced overall copper surfaces by a factor ~2
- New surface cleaning technique
- Strict production protocols for TeO_2 surface contamination
- Minimization of Rn exposure (Glove Box assembly)
- Strict material selection

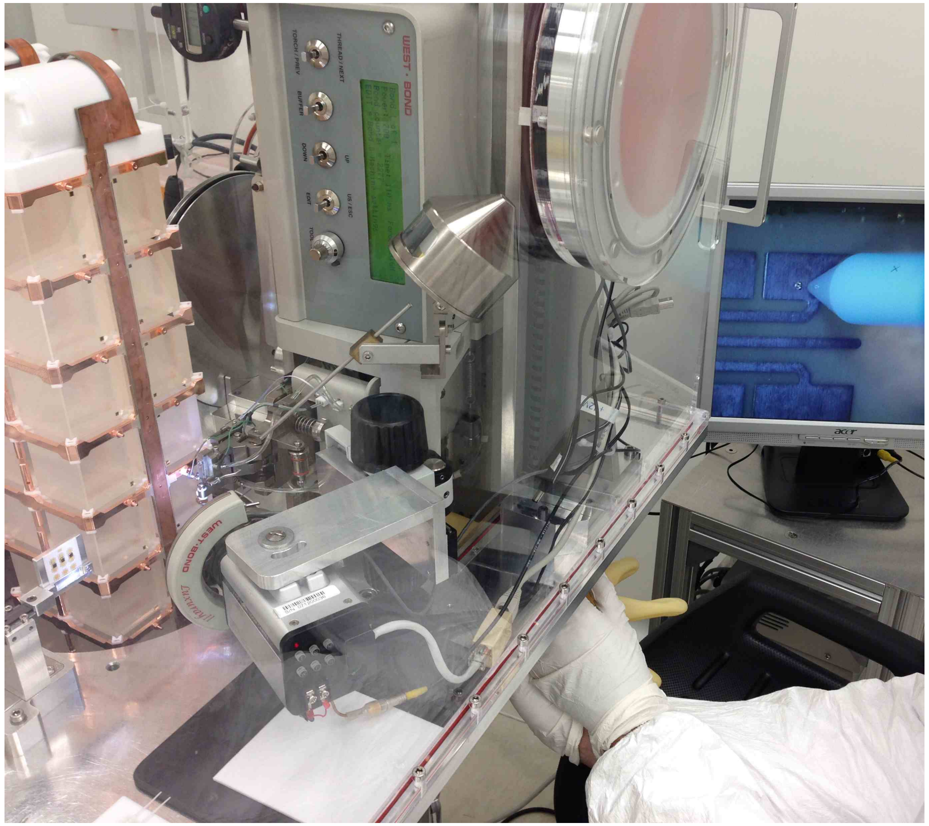


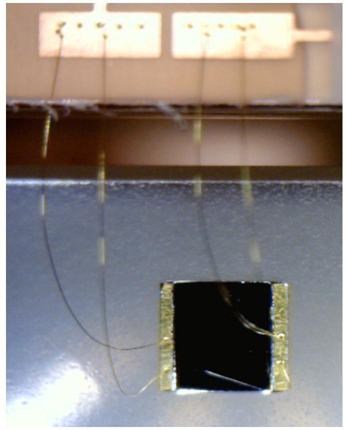


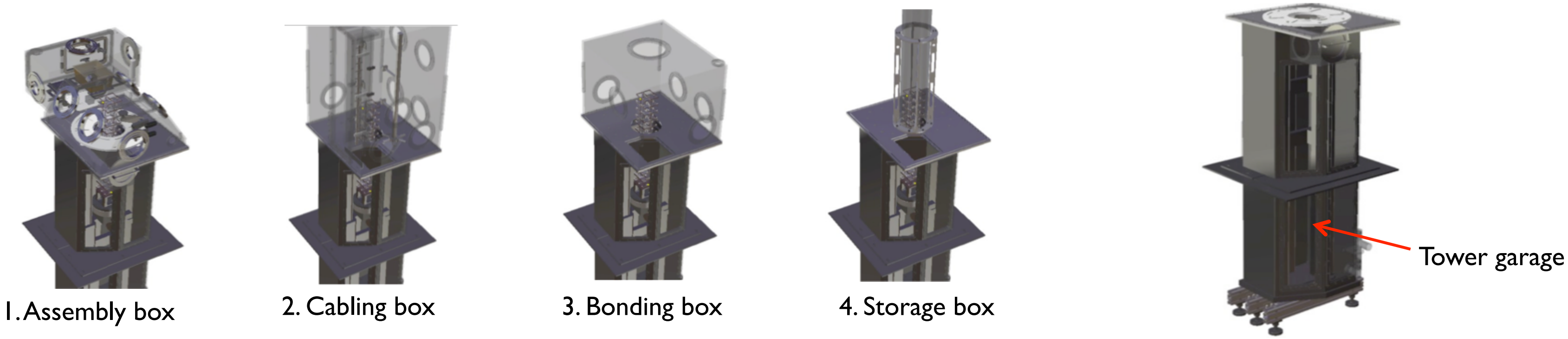


CUORE Assembly & Bonding









CUORE Towers Assembly

- Assembly of all the 19 CUORE towers completed in 2014

Assembly line improved after CUORE-0

CUORE-0

51/52 NTD connected

51/52 heaters connected

CUORE

988/988 NTD connected

988/988 heaters connected

- Also a mockup tower for the Detector installation phase and a minitower to be used during the cryostat commissioning runs were produced

Cryogenic system commissioning: phase 1

Phased commissioning adding complexity at each step

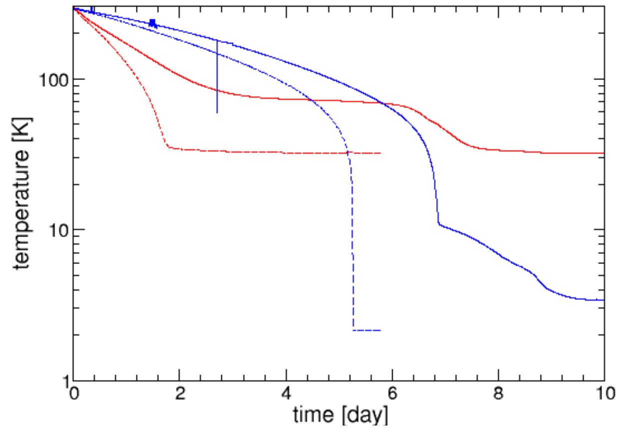
- Phase I: individual systems test
  - Outer/Inner vacuum chamber
  - Cryostat

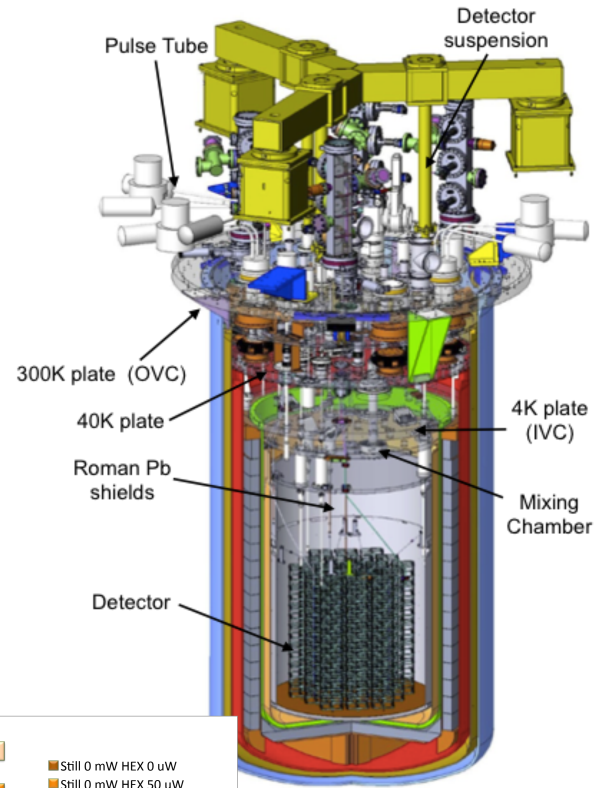
    Final temperatures:

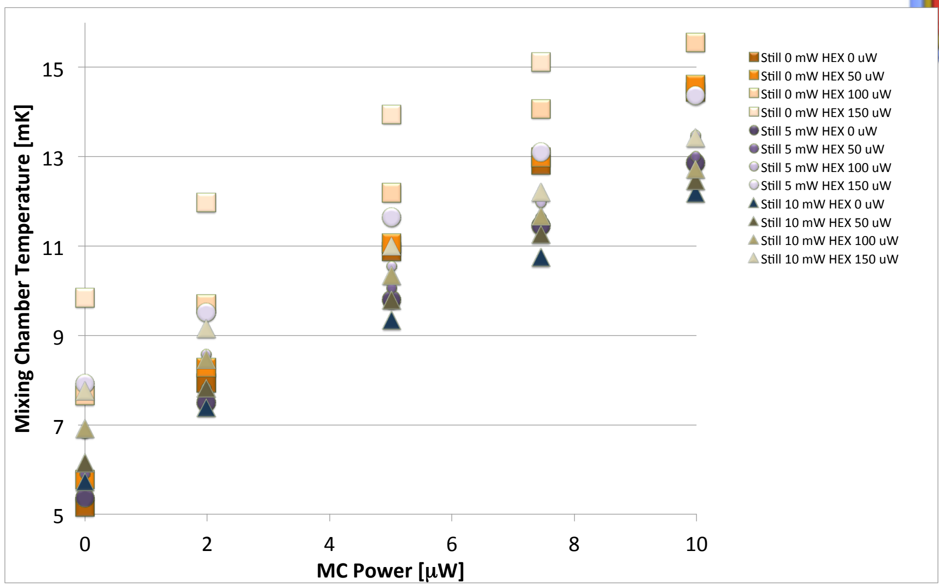
    32 K at the 40K stage

    3.3 K at the 4K stage
  - Dilution Unit

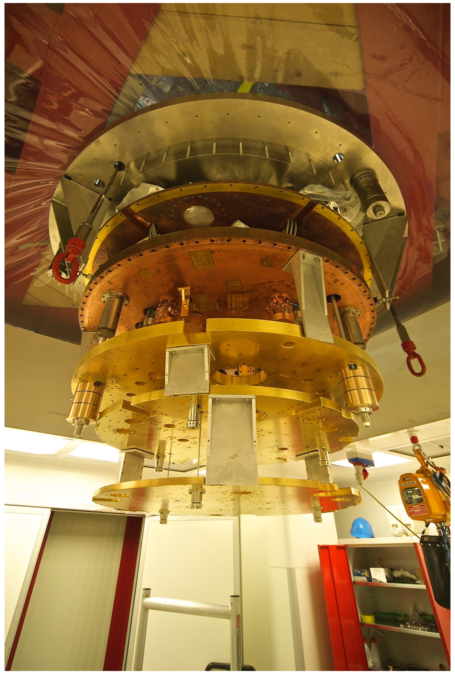
    Lowest temperature: 4.95 mK
- Phase II: system integration

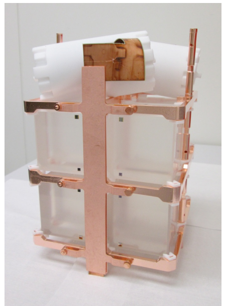






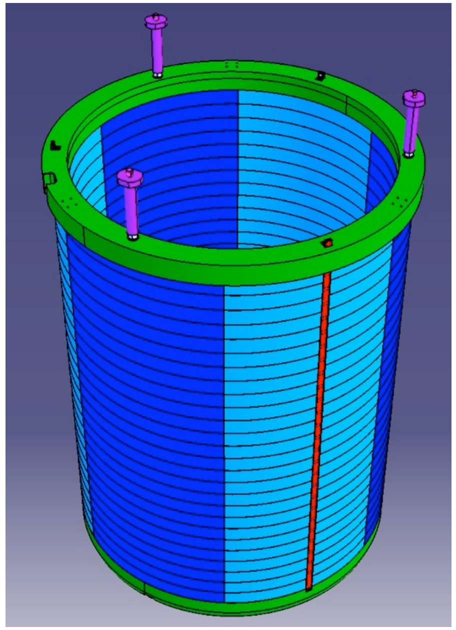
Cryogenic system commissioning: phase 2





Insertion of few TeO_2 detectors

↓



Cryostat
+
Dilution Unit

→

Wiring

→

Top Pb shield
Detector Calibration System
Towers support plate
Fast Cooling System

→

side roman Pb shield

Coldest m^3

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2
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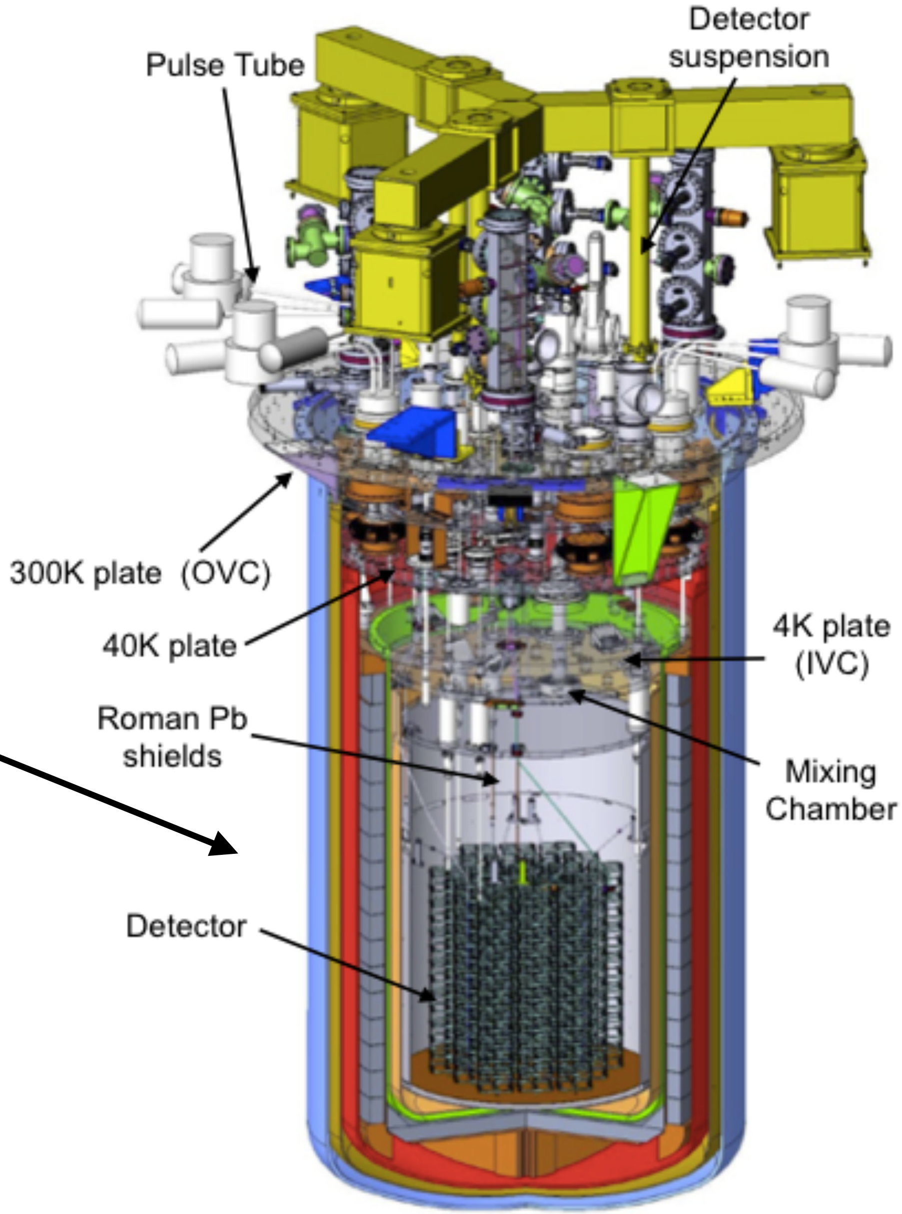
CUORE: The Coldest Heart in the Known Universe

The CUORE collaboration at the INFN Gran Sasso National Laboratory has set a world record by cooling a copper vessel with the volume of a cubic meter to a temperature of 6 milliKelvins: it is the first experiment ever to cool a mass and a volume of this size to a temperature this close to absolute zero (0 Kelvin). The cooled copper mass, weighing approx. 400 kg, was the coldest cubic meter in the universe for over 15 days.

CUORE is an international collaboration involving some 130 scientists mainly from Italy, USA, China, Spain, and France. CUORE is supported by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the Department of Energy Office of Science (Office of Nuclear Physics), the National Science Foundation, and Alfred P. Sloan Foundation in the United States.

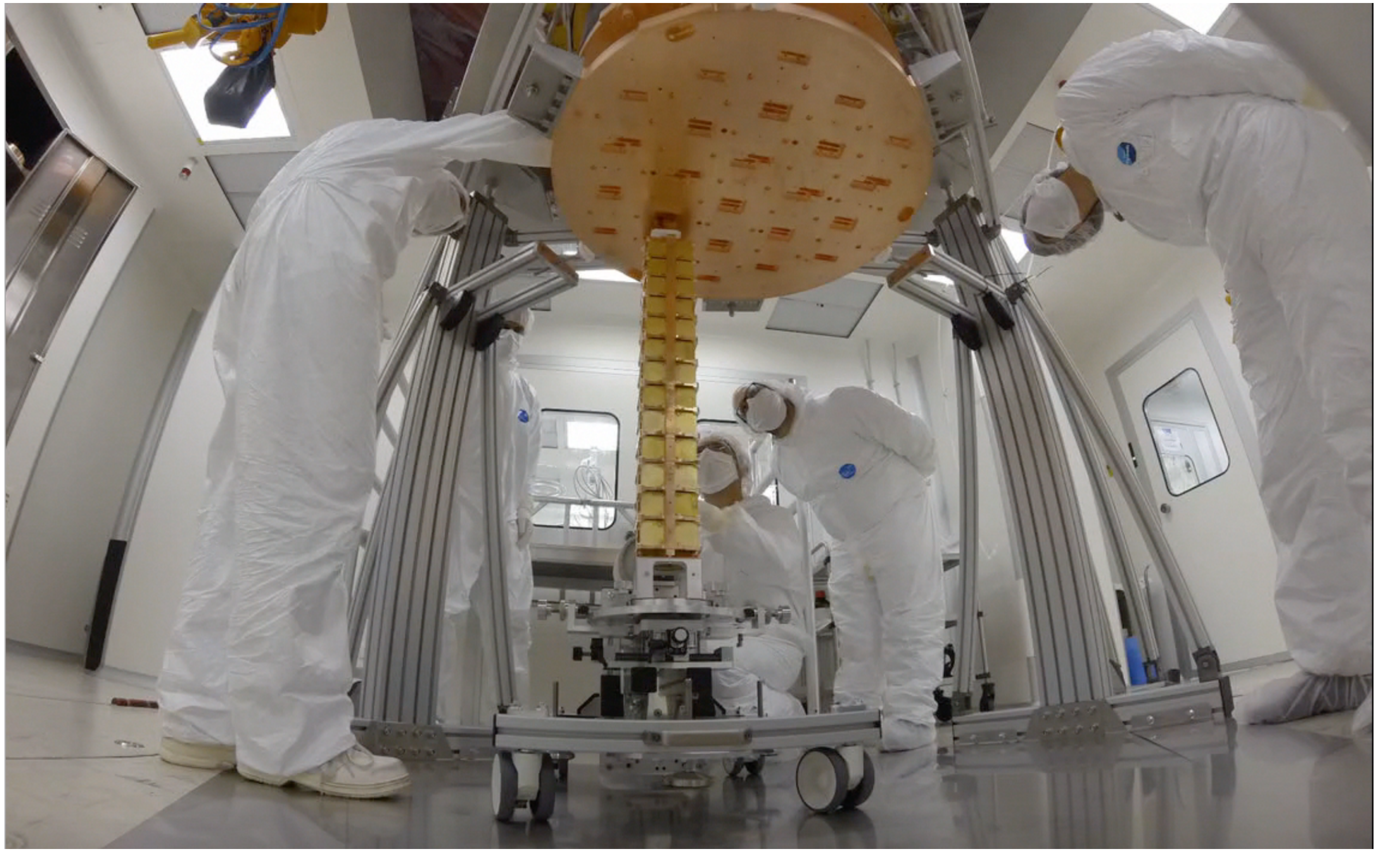
Present Status

- Commissioning is over
- Installation of all the 19 CUORE towers in the cryostat

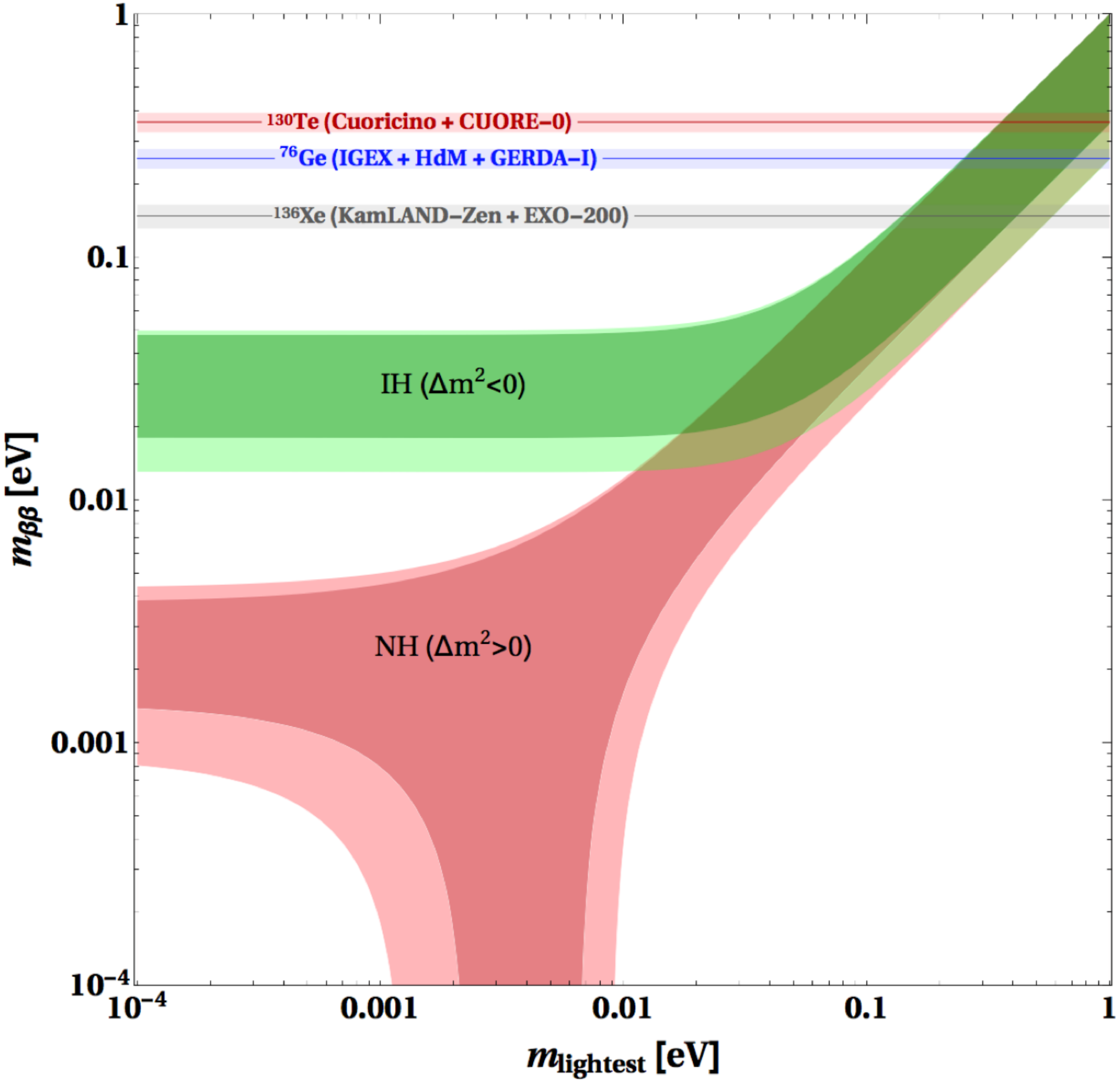


Present Status

- Detector installation phase started (to be finished by the end of August)
- cooldown foreseen for October
- operation before the end of 2016



Present limits on $m_{\beta\beta}$



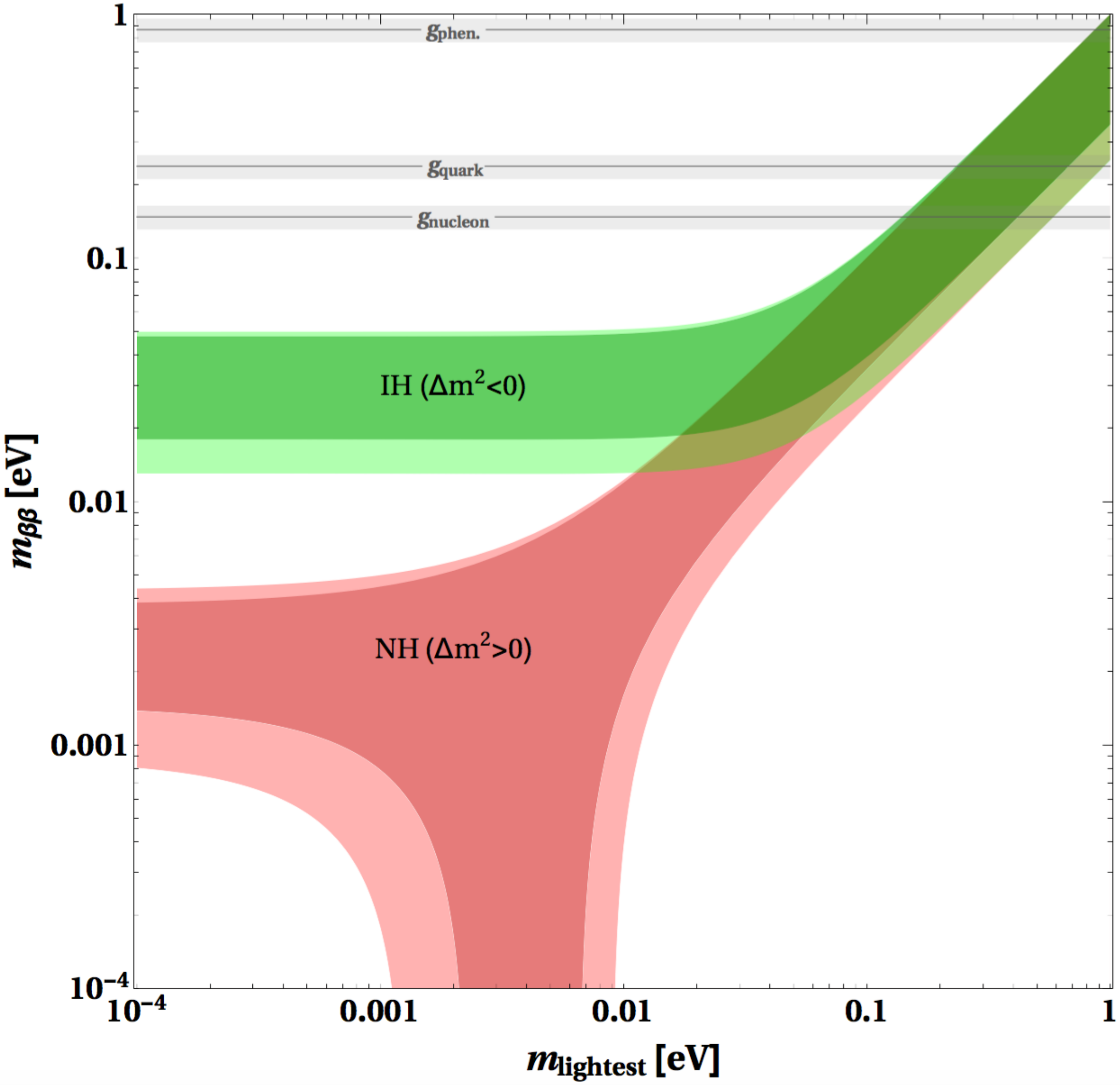
$$m_{\beta\beta} \leq \frac{m_e}{g_A^2\, \mathcal{M}_{0\nu} \sqrt{G_{0\nu}\, S_{0\nu}^{1/2}}}$$

Isotope	$S_{0\nu}^{1/2}$ (90% C. L.) [yr]	$m_{\beta\beta}^{min}$ [eV]
^{130}Te	$4.0 \cdot 10^{24}$	0.36 ± 0.03
^{76}Ge	$3.0 \cdot 10^{25}$	0.25 ± 0.02
^{136}Xe	$3.4 \cdot 10^{25}$	0.15 ± 0.02

NMEs (IBM-2): J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
PSFs: J. Kotila & F. Iachello, **Phys. Rev. C 85, 034316 (2012)**
$g_A = 1.269$

Experiment sensitivities:
^{130}Te: K. Alfonso *et al.*, **Phys. Rev. Lett. 115, 102502 (2015)**
^{76}Ge: M. Agostini *et al.*, **Phys. Rev. Lett. 111, 122503, (2013)**
^{136}Xe: A. Gando *et al.*, **Phys. Rev. Lett. 110, 062502, (2013)**

Importance of the g_A quenching



$$t_{0\nu}^{1/2} \propto \mathcal{M} = g_A^{-4} \mathcal{M}_{0\nu}^{-2}$$

$$g_A = \begin{cases} g_{A,\text{ nucleon}} & = 1.269 \\ g_{A,\text{ quark}} & = 1 \\ g_{A,\text{ phen.}} & = 1.269 \cdot A^{-0.18} \end{cases}$$

g_A	$m_{\beta\beta}^{\text{min}}$ [eV]
$g_{A,\text{ nucleon}}$	0.15 ± 0.03
$g_{A,\text{ quark}}$	0.24 ± 0.05
$g_{A,\text{ phen.}}$	0.87 ± 0.17

NMEs (IBM-2): J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
PSFs: J. Kotila & F. Iachello, **Phys. Rev. C 85, 034316 (2012)**
^{136}Xe: A. Gando *et al.*, **Phys. Rev. Lett. 110, 062502, (2013)**

Which is the level that we can reach?