INFN Istituto Nazionale di Fisica Nucleare

LNGS

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Neutrinoless double beta decay searches at the Gran Sasso National Laboratory

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INFN LNGS

LNGS, October 24th 2015

Outline

- Neutrino physics and neutrinoless double beta decay
- $0\nu\beta\beta$ sensitivity considerations
- Experiments and measurement techniques
- Experiments at Gran Sasso National Laboratory

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- **Neutrino physics and neutrinoless double beta decay**
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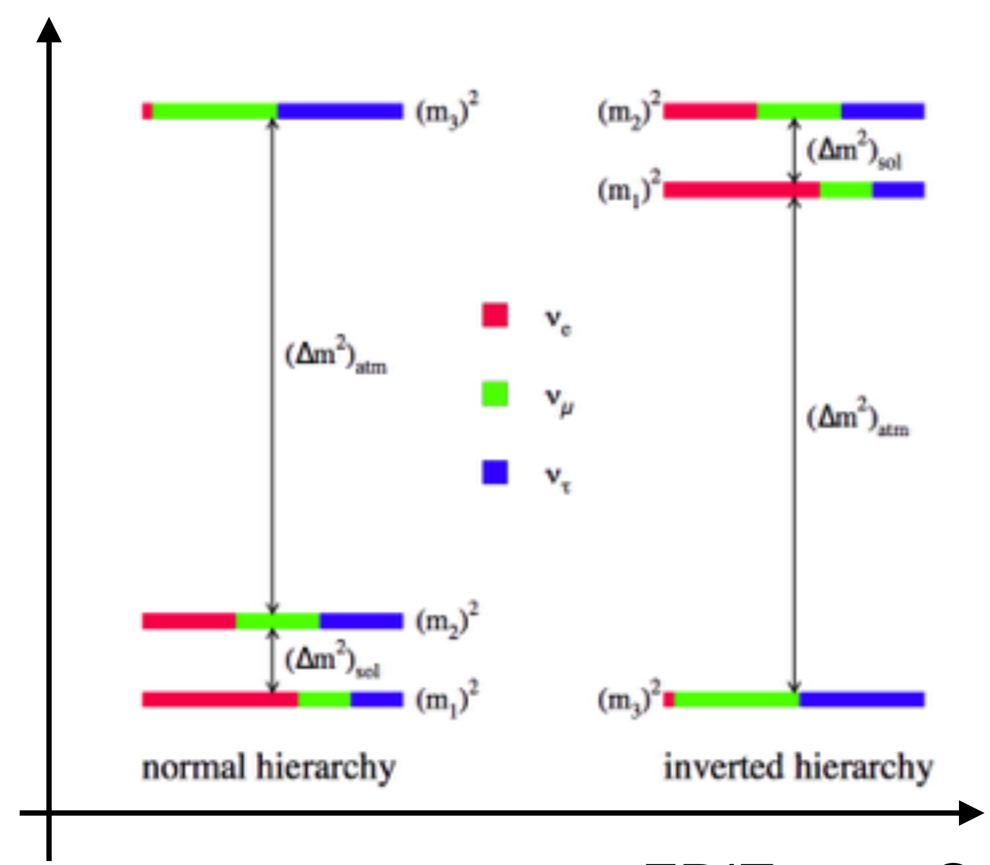
Neutrino physics

- What we do know:
  - Oscillates -> it has mass
  - Flavour mixing described by PMNS matrix U
  - Absolute values of square difference of mass eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{aligned} \Delta m^2_{21} &= (7.59 \pm 0.21) \times 10^{-5}\,\mathrm{eV}^2 \\ |\Delta m^2_{23}| &= 2.38^{+0.20}_{-0.16} \times 10^{-3}\,\mathrm{eV}^2 \end{aligned}$$

- What we do not know
  - absolute mass scale
  - mass hierarchy
  - Dirac or Majorana particle

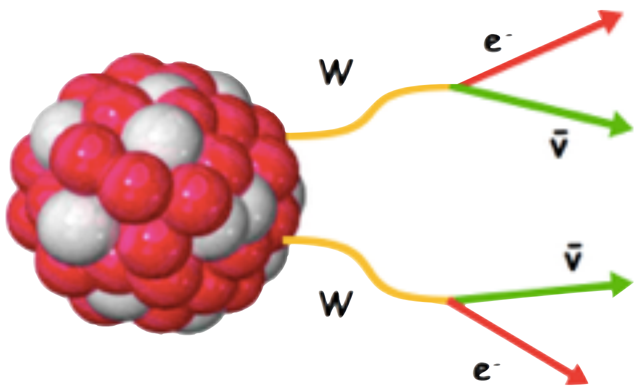


Double beta decay

- In a number of even-even nuclei, β-decay is energetically forbidden, while double-beta decay, from a nucleus of (A,Z) to (A,Z+2), is energetically allowed (^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd)

2νββ

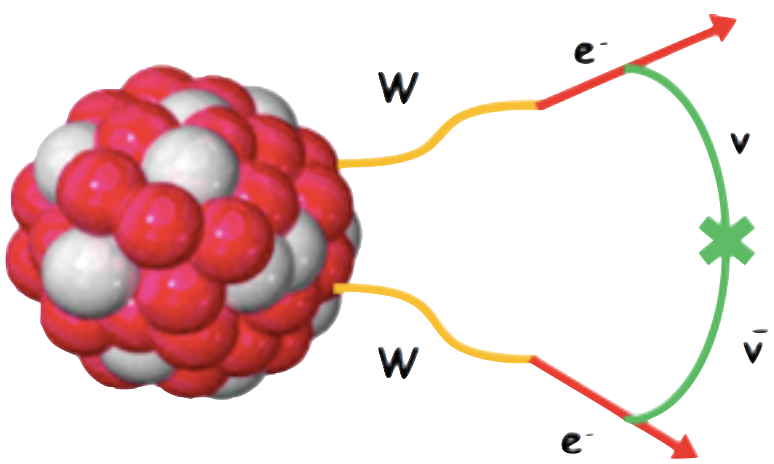
- Second order SM weak process
- Rarest decay ever observed: $T_{1/2} \sim 10^{19}$ - 10^{21} y



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

0νββ

- Not allowed by the Standard Model (ΔL=2)
- Decay never observed: $T_{1/2} > 10^{23}$ - 10^{25} y
- Possible only if neutrinos are Majorana particles



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

Neutrinoless double beta decay and the neutrino mass

Decay rate:

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

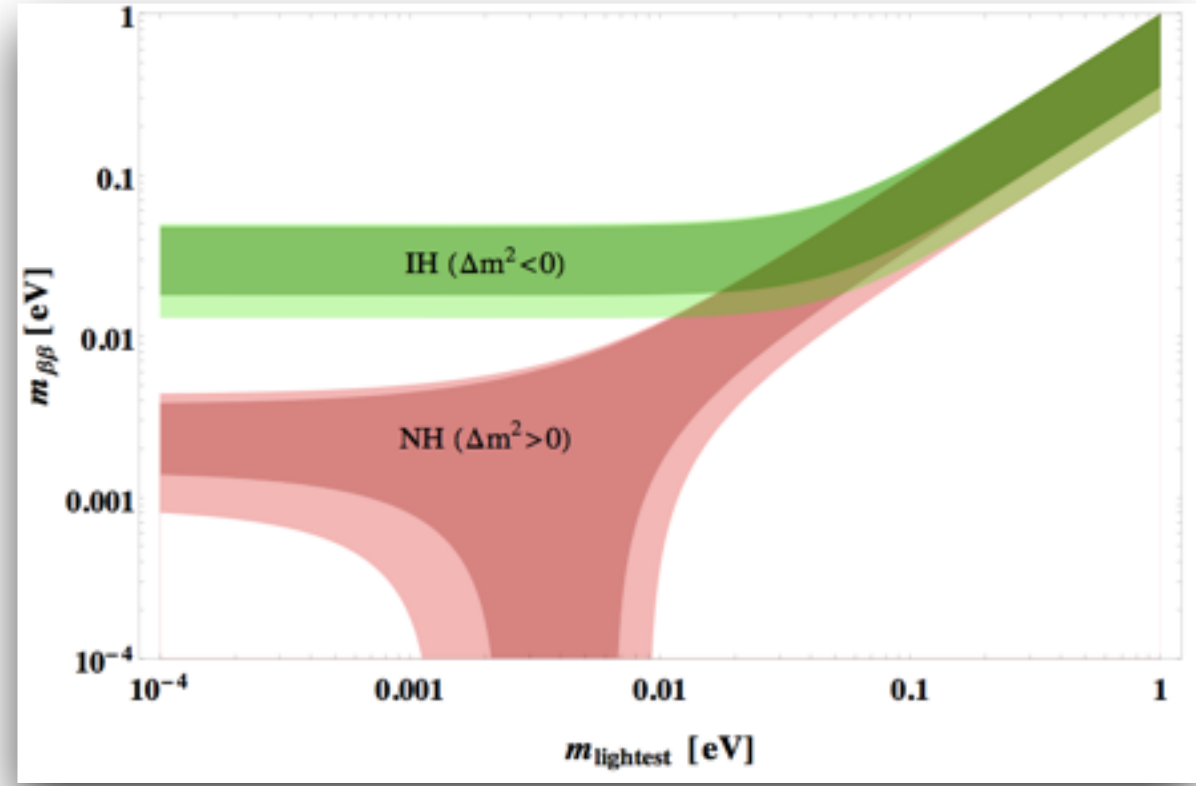
Phase space factor — **Nuclear matrix element** — **Effective neutrino mass**

$$m_{\beta\beta} = |\sum_i m_{\nu_i} U^2_{ei}|$$

$$m_{\beta\beta} = \cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}$$

The observation of 0νββ:

- proof of the Majorana nature of neutrinos
- constraints on neutrino mass hierarchy



Neutrinoless double beta decay and the neutrino mass

Decay rate:

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Phase space factor

Nuclear matrix element

Effective neutrino mass

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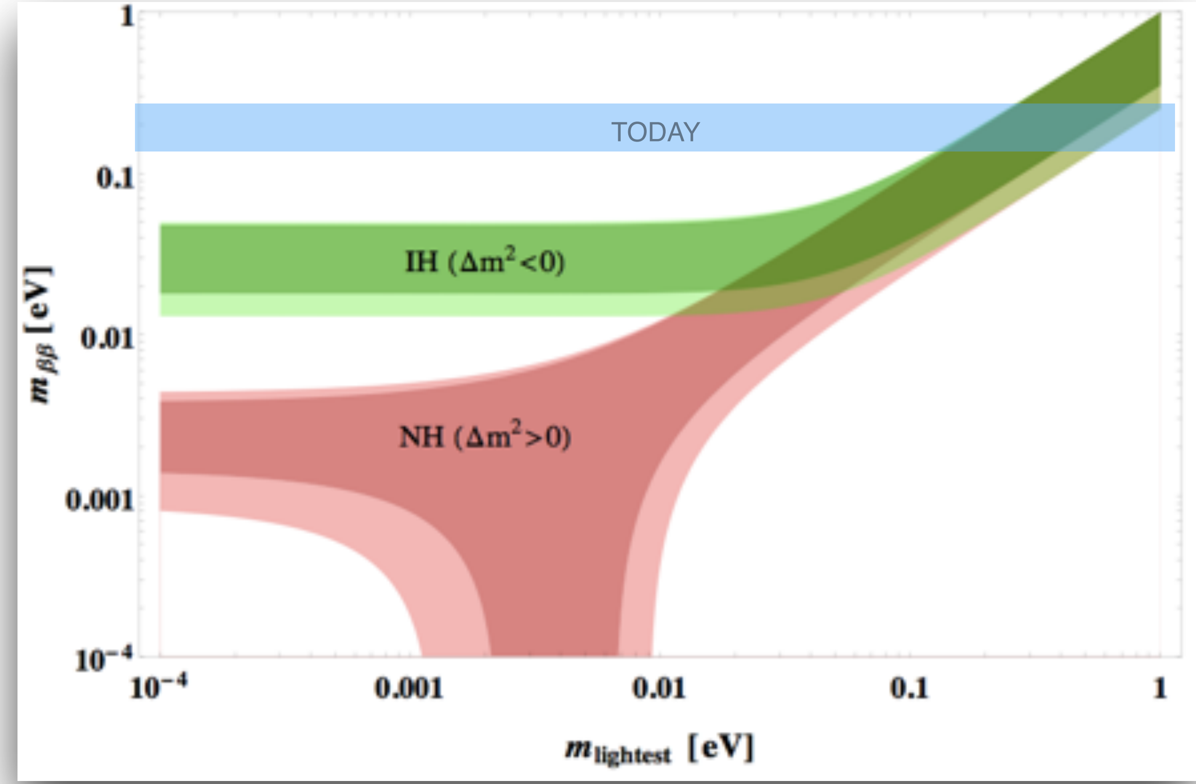
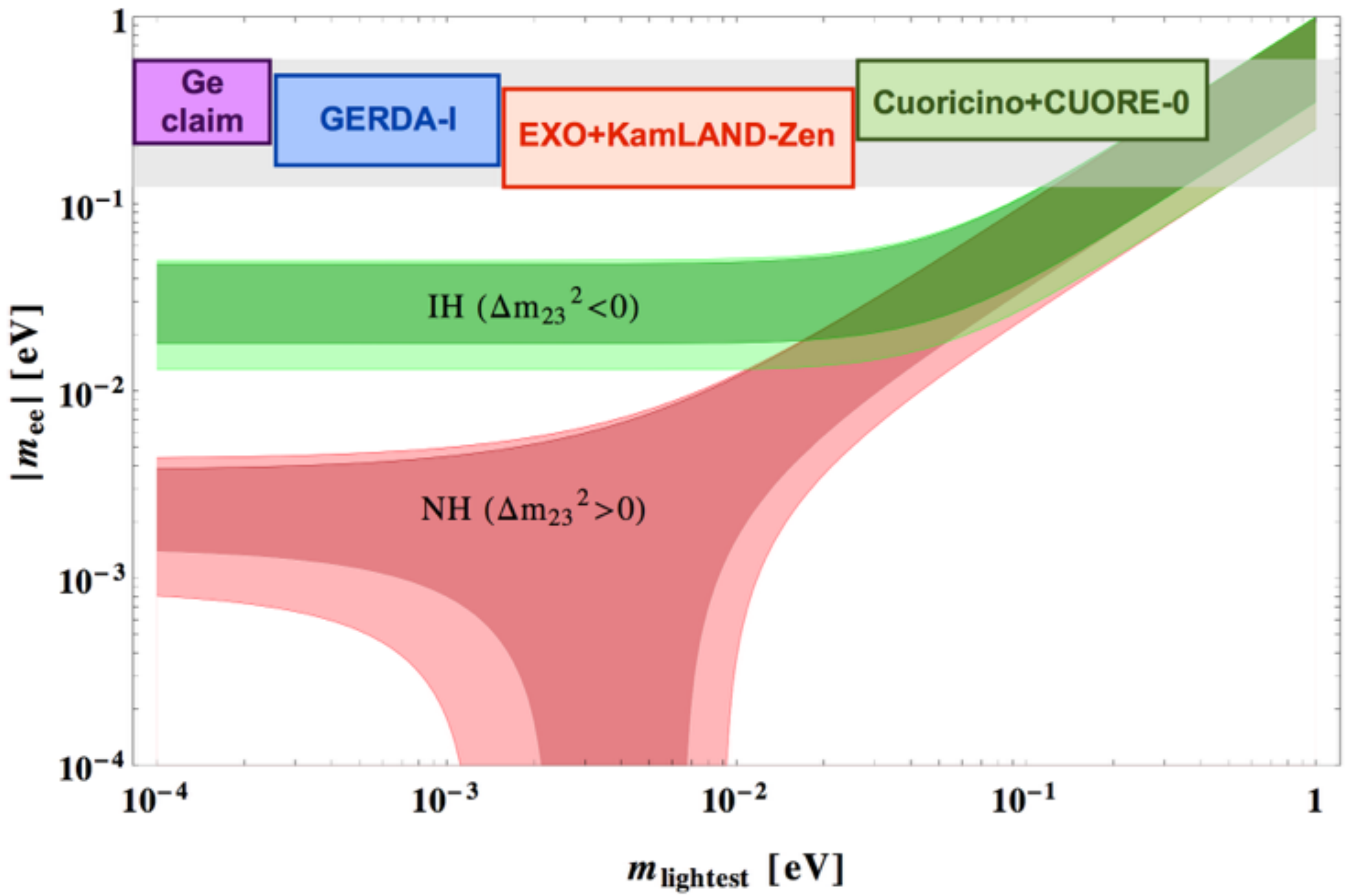
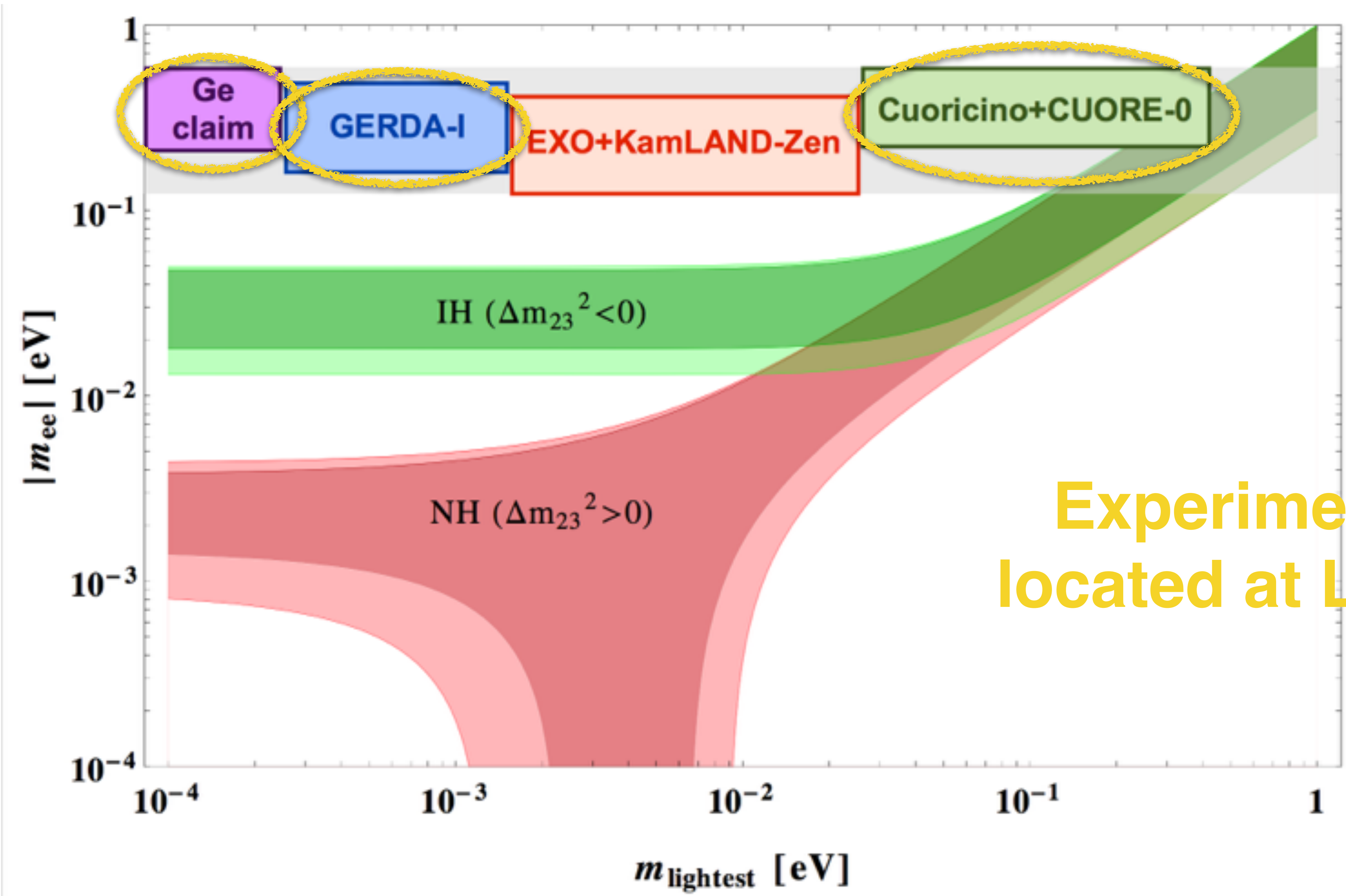


0νββ at LNGS



Ge claim
GERDA-I
EXO+KamLAND-Zen
Cuoricino+CUORE-0
IH ($\Delta m_{23}^2<0$)
NH ($\Delta m_{23}^2>0$)
$|m_{ee}|$ [eV]
$m_{lightest}$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

0νββ at LNGS



Experiments located at LNGS

Outline

- Neutrino physics and neutrinoless double beta decay.
- **0nubb sensitivity considerations**
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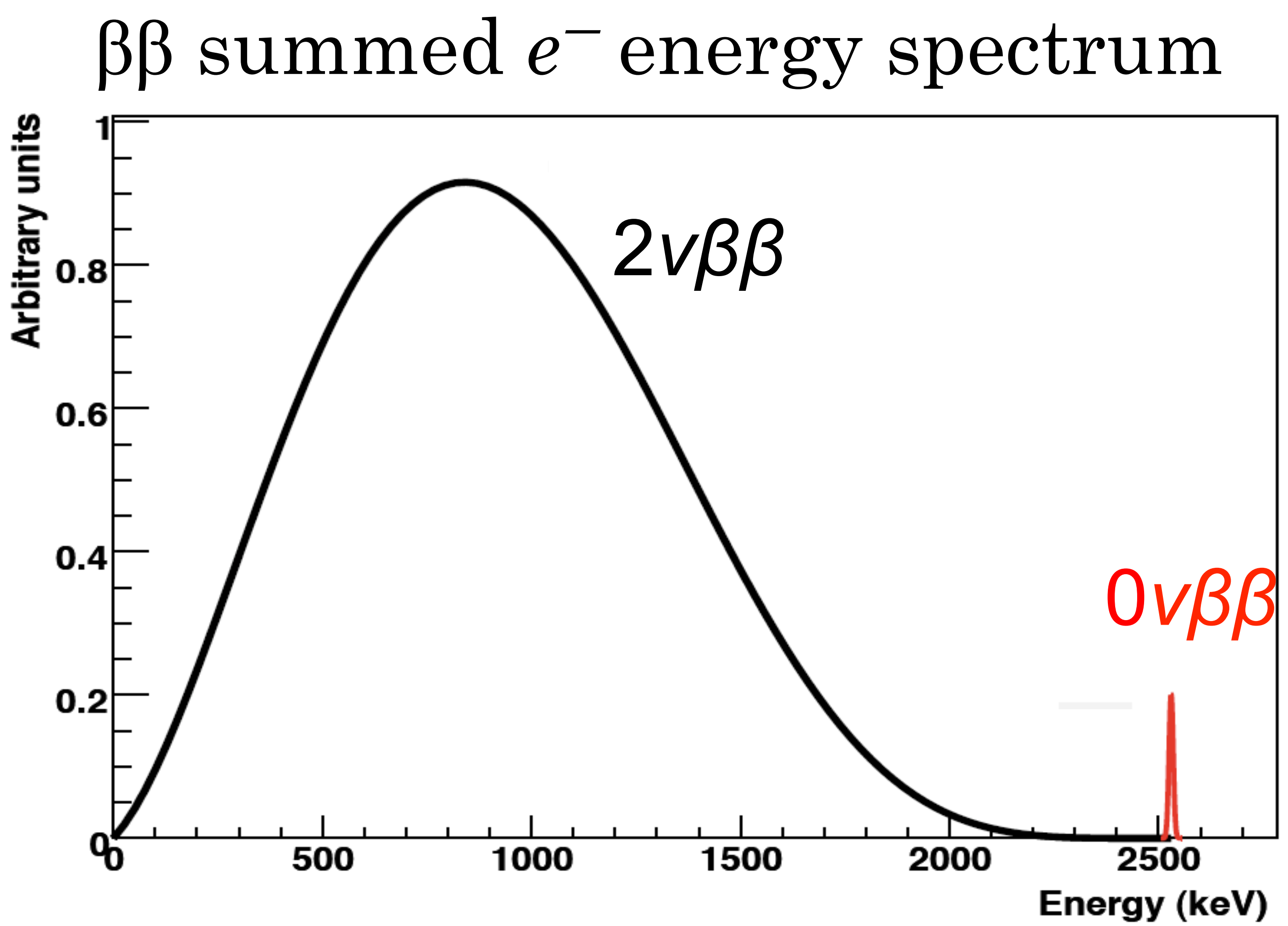
Experimental signature



- Measurement of the kinetic energy of the decay products (~MeV).
- It is a monochromatic peak at the Q-value of the nuclear transition.

$0\nu\beta\beta$ Sensitivity

$S_{0\nu\beta\beta}$: half-life corresponding to the minimum number of detectable signals above background at a given C.L.

$$S_{0\nu\beta\beta} \propto \eta \cdot \epsilon \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

M = detector mass [kg]

T = live time [y]

ε = detection efficiency

B = bkg in ROI [counts/keV/kg/y]

ΔE = energy resolution @ ROI

η = isotopic abundance

0νββ Sensitivity

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The isotope source range 10-500 kg depending on the technique

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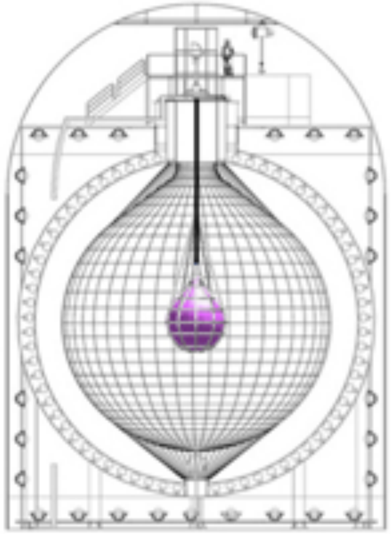

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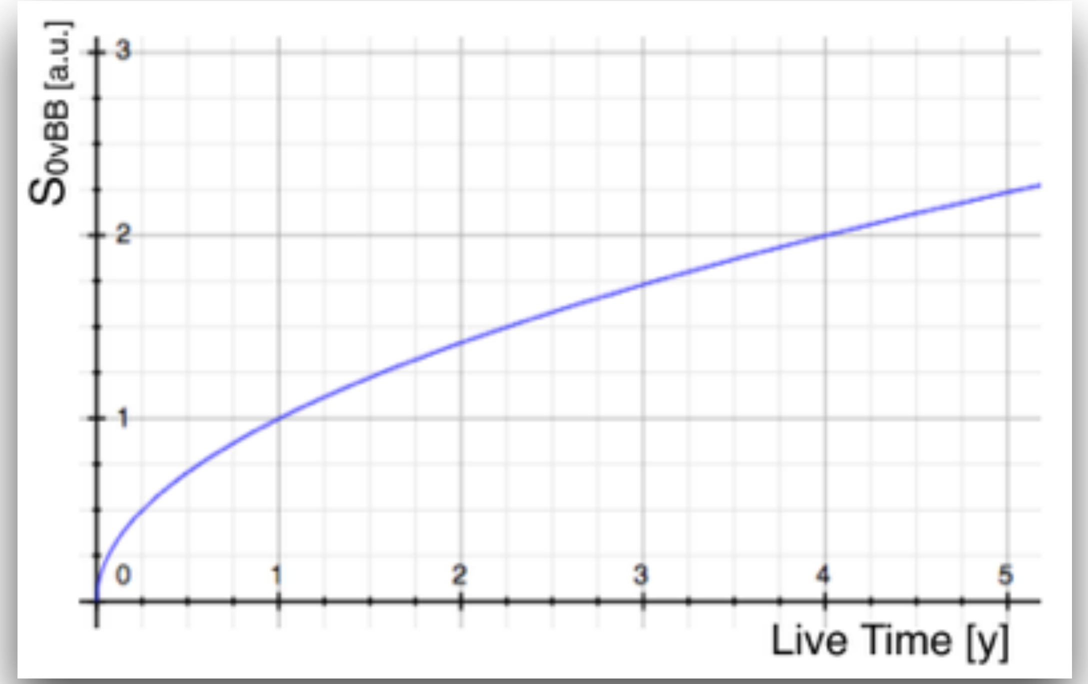
Time scale O(5-10)y



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Maximise the fiducial volume in order to have a larger number of ββ nuclei under observation

0νββ Sensitivity

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Rejection of any spurious event in the Region of Interest:

- underground location for detector operation to shield cosmic rays;
- only selected radio-pure materials;
- shielding against local environmental radioactivity.

0νββ Sensitivity

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$$S_{0\nu\beta\beta} \propto \eta \cdot \epsilon \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

Higher ΔE → Lower bkg
- narrower ROI
- better identification of bkg components
  → rejection of 2νββ "irreducible" bkg

M = detector mass [kg]

T = live time [y]

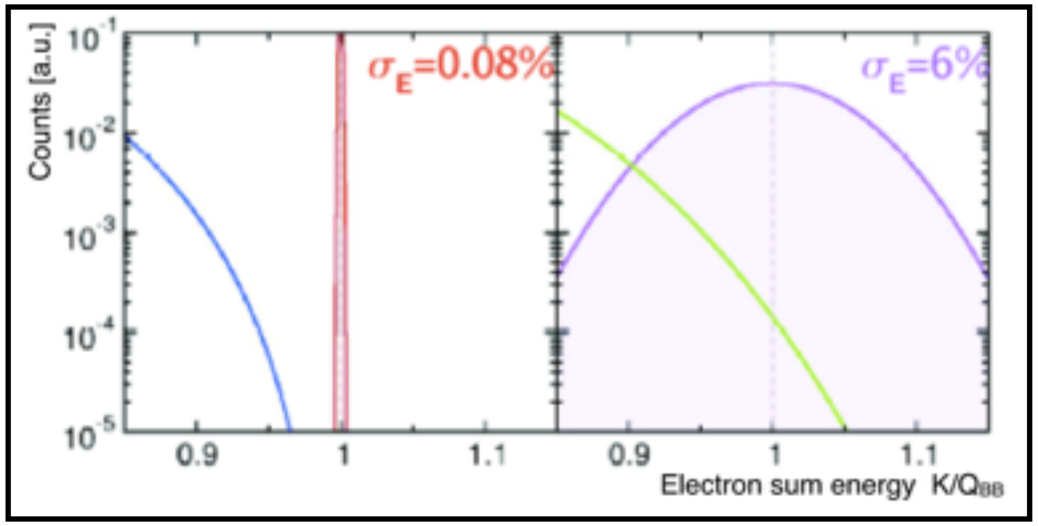
ε = detection efficiency

B = bkg in ROI [counts/keV/kg/y]

ΔE = energy resolution @ ROI

η = isotopic abundance

Energy spectrum of 2vDBD and 0vDBD



0νββ Sensitivity

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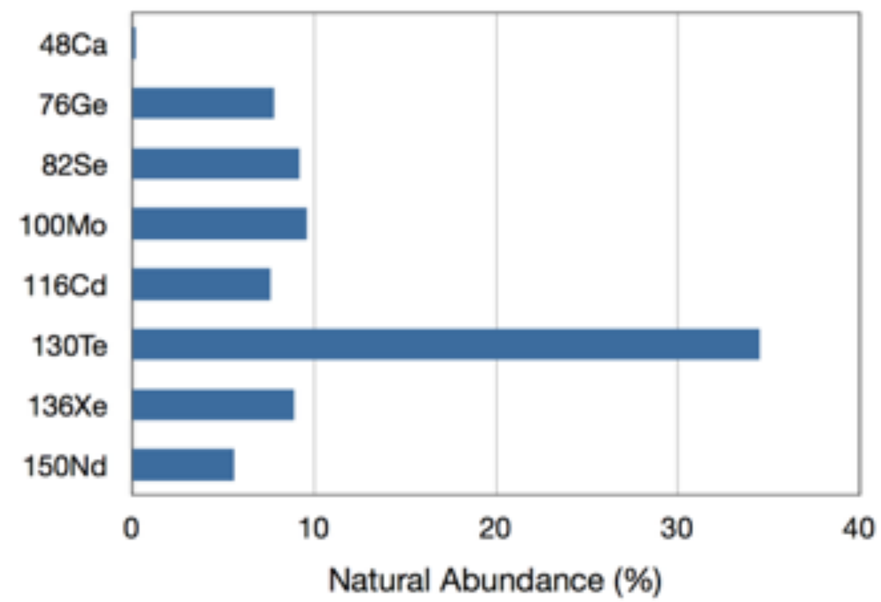
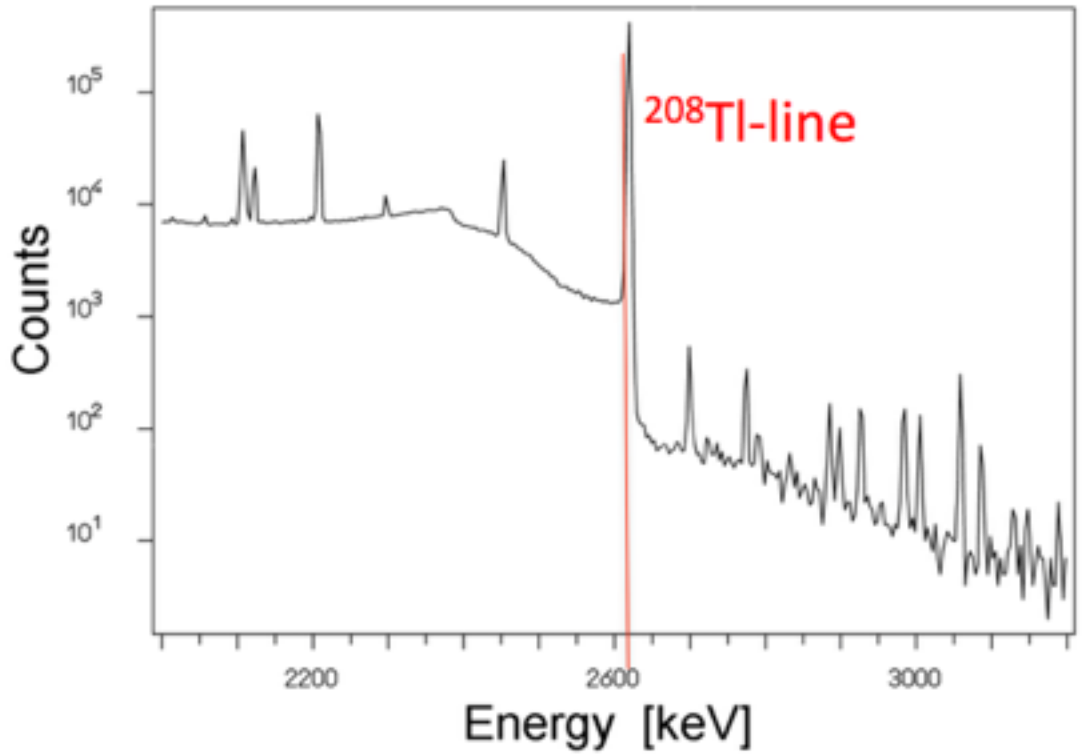


ISOTOPE	Nat. I.A.	[$]/g
^{76}Ge	7.61%	~80
^{82}Se	8.73%	~80
^{100}Mo	9.63%	~80
^{116}Cd	7.49%	~180
^{130}Te	34.08%	~20
^{136}Xe	8.87%	~5-10
^{150}Nd	5.6%	>200

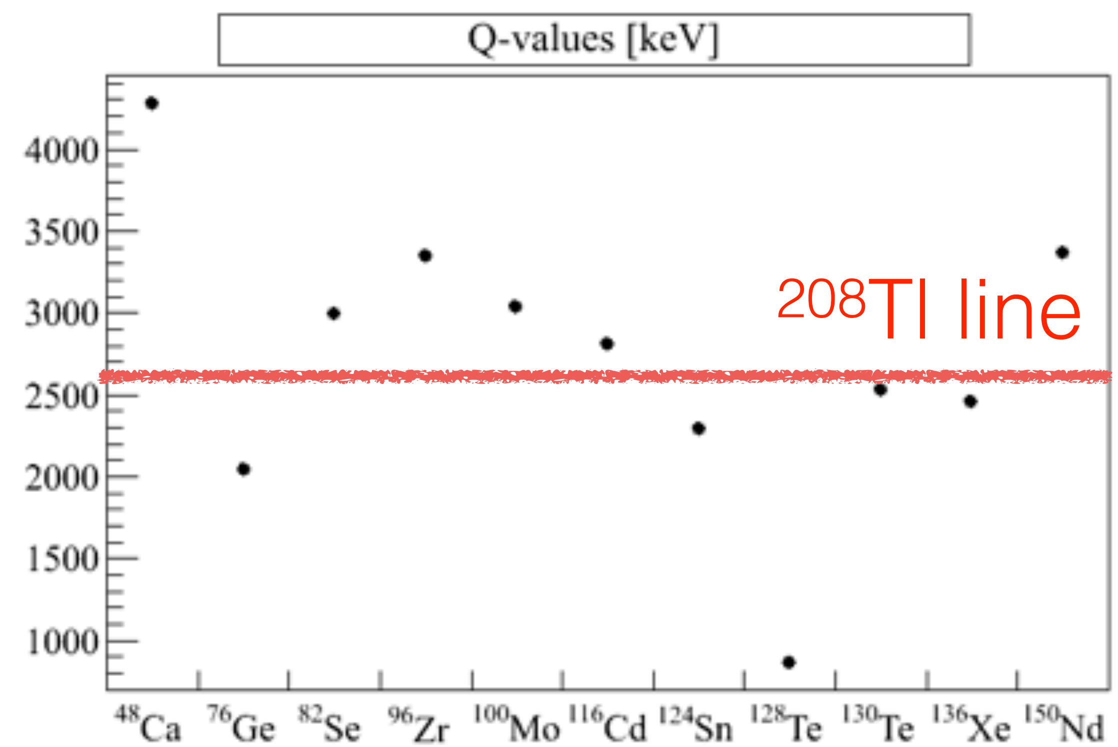
adapted from
A. Barabash J. Phys. G: Nucl. Part. Phys. 39 (2012) 085103

Background VS 0νββ isotopes

Environmental "underground" HPGE bck:
^{238}U and ^{232}Th trace contaminations



Higher Q-value will result in the ββ-decay signal being above potential backgrounds from natural radioactivity.



- Natural radioactivity extends to >10MeV
  - β/γ up to 2.6 MeV (^{208}Tl) high intensity line
  - α particles 4-10 MeV (^{238}U and ^{232}Th)
- ββ searches must be performed in low bkg regio
  - at the Compton-edge of 2.6 MeV
  - above β/γ natural radioactivity

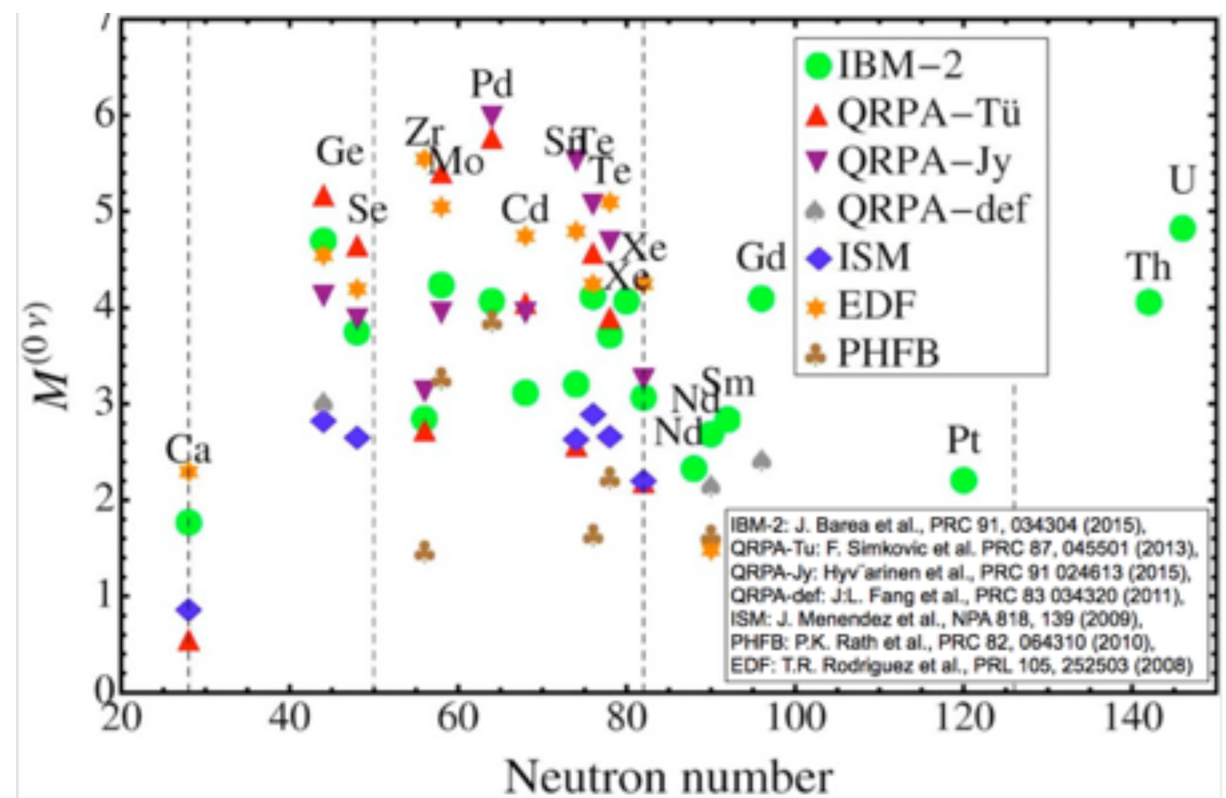
Nuclear Matrix elements

Decay rate:

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Phase space factor — **Nuclear matrix element** — **Effective neutrino mass**

From O. Cremonesi talk @ TAUP2015



- Extracting the effective neutrino mass requires an understanding of the nuclear matrix elements (NME)
- NME are calculated using different approximate methods: Nuclear Shell Model; Quasi-random phase approximation (QRPA); Interacting Boson Model (IBM); Projected Hartree-Fock- Bogoliubov (PHFB).

Recent years progress: different models agree x 2-3

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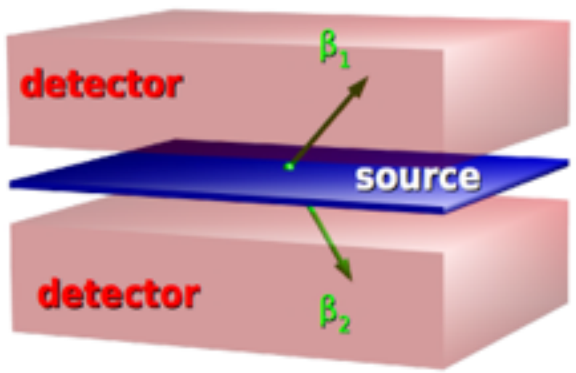
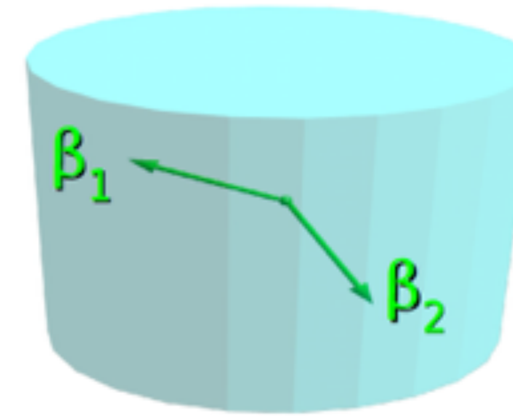
0νββ experimental approaches



Detector ≠ source

Tracker

Detector = source

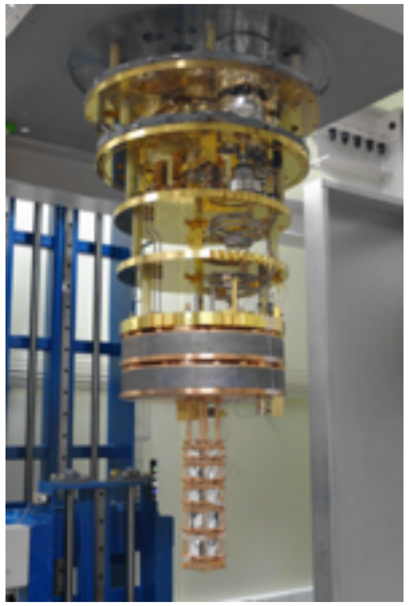


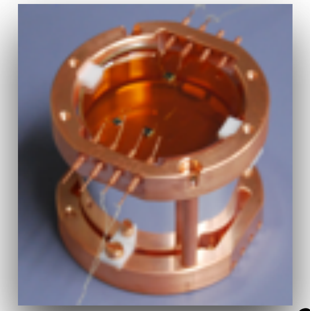
Bolometers,
Semiconductors,
Liquid Scintillators

PROs:
Particle Identification
Event topology reconstruction

PROs:
Large mass
High detection efficiency
Good energy resolution

$0\nu\beta\beta$ methods





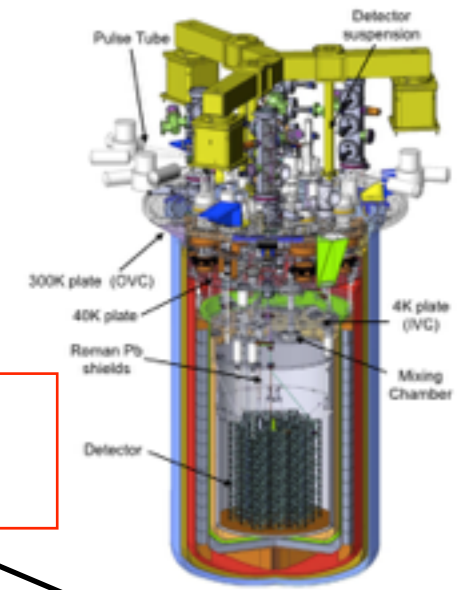
LUCIFER ^{82}Se
AMORE ^{100}Mo
LUMINEU ^{100}Mo

Scintillating bolometers

CUORE ^{130}Te

Bolometers

Phonons



Scintillation

Liquid

Crystals

Ionization

Tracker

Crystals

KamLAND-Zen ^{136}Xe
SNO+ ^{130}Te

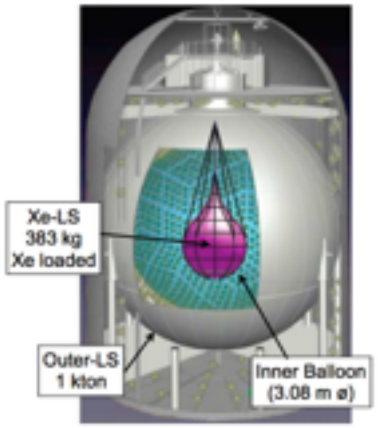
CANDLES ^{48}Ca

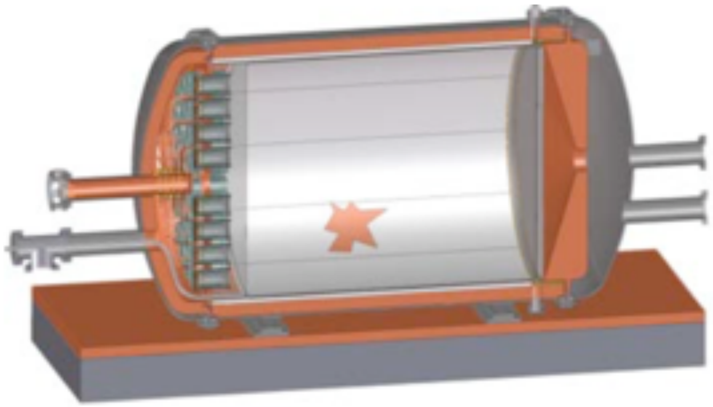
TPC

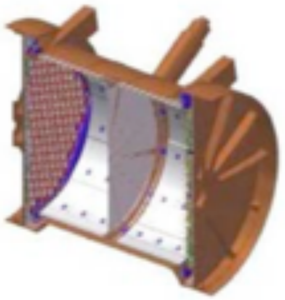
EXO200,nEXO,NEXT
^{136}Xe

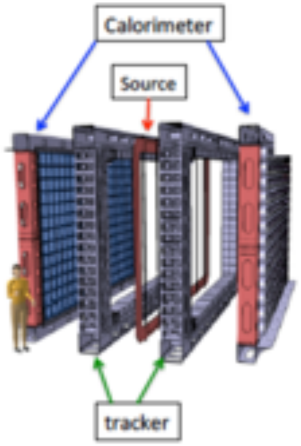
SuperNEMO
^{82}Se

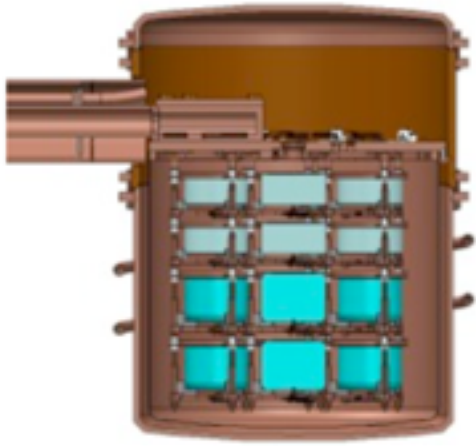
Majorana/Gerda
^{76}Ge





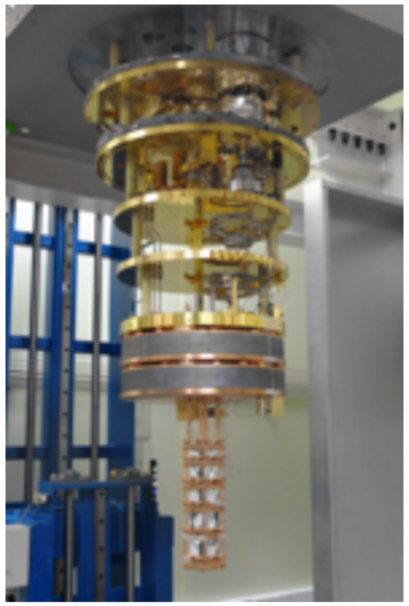






0νββ methods

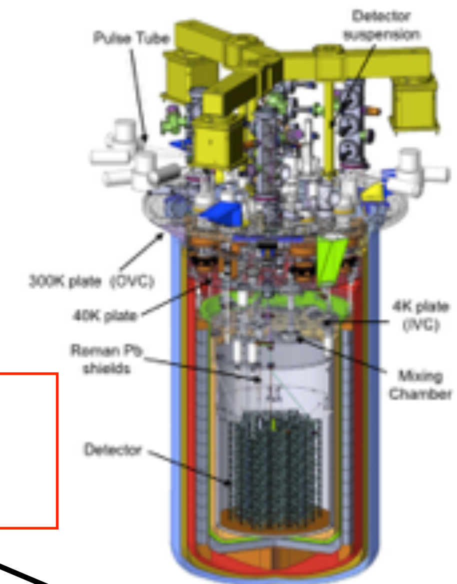
@LNGS




LUCIFER ^{82}Se
AMORE ^{100}Mo
LUMINEU ^{100}Mo
Scintillating bolometers

CUORE ^{130}Te
Bolometers

Phonons



Scintillation

Liquid

Crystals

Ionization

Tracker

Crystals

KamLAND-Zen ^{136}Xe
SNO+ ^{130}Te

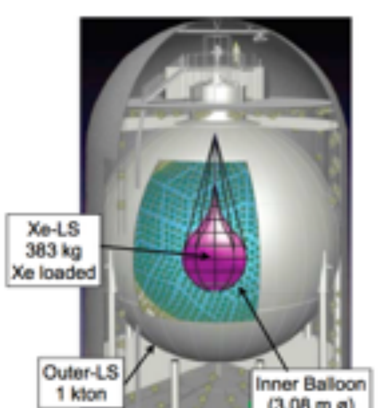
CANDLES ^{48}Ca

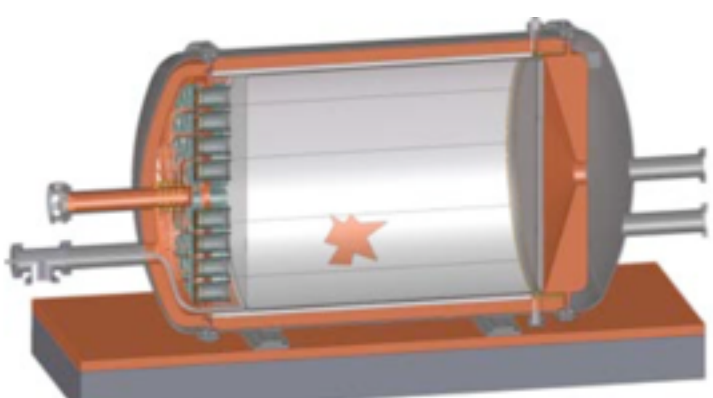
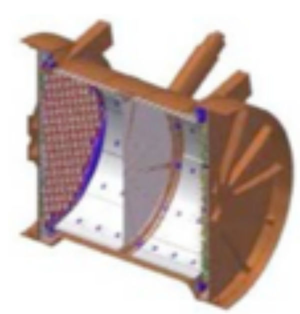
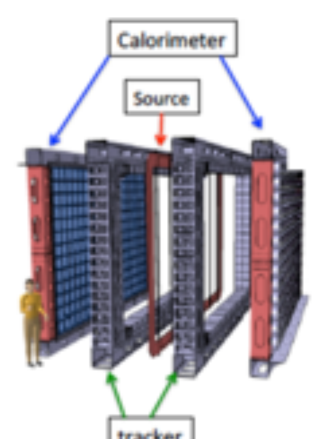
TPC

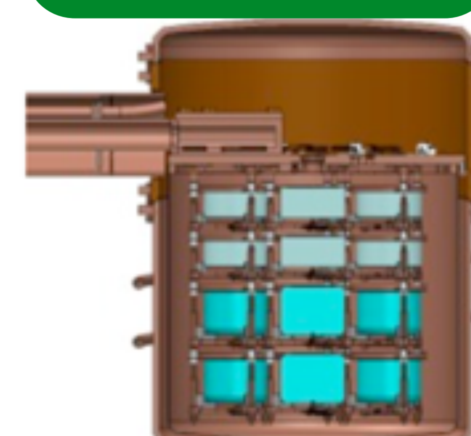
EXO200,nEXO,NEXT
^{136}Xe

SuperNEMO
^{82}Se

Majorana/Gerda
^{76}Ge





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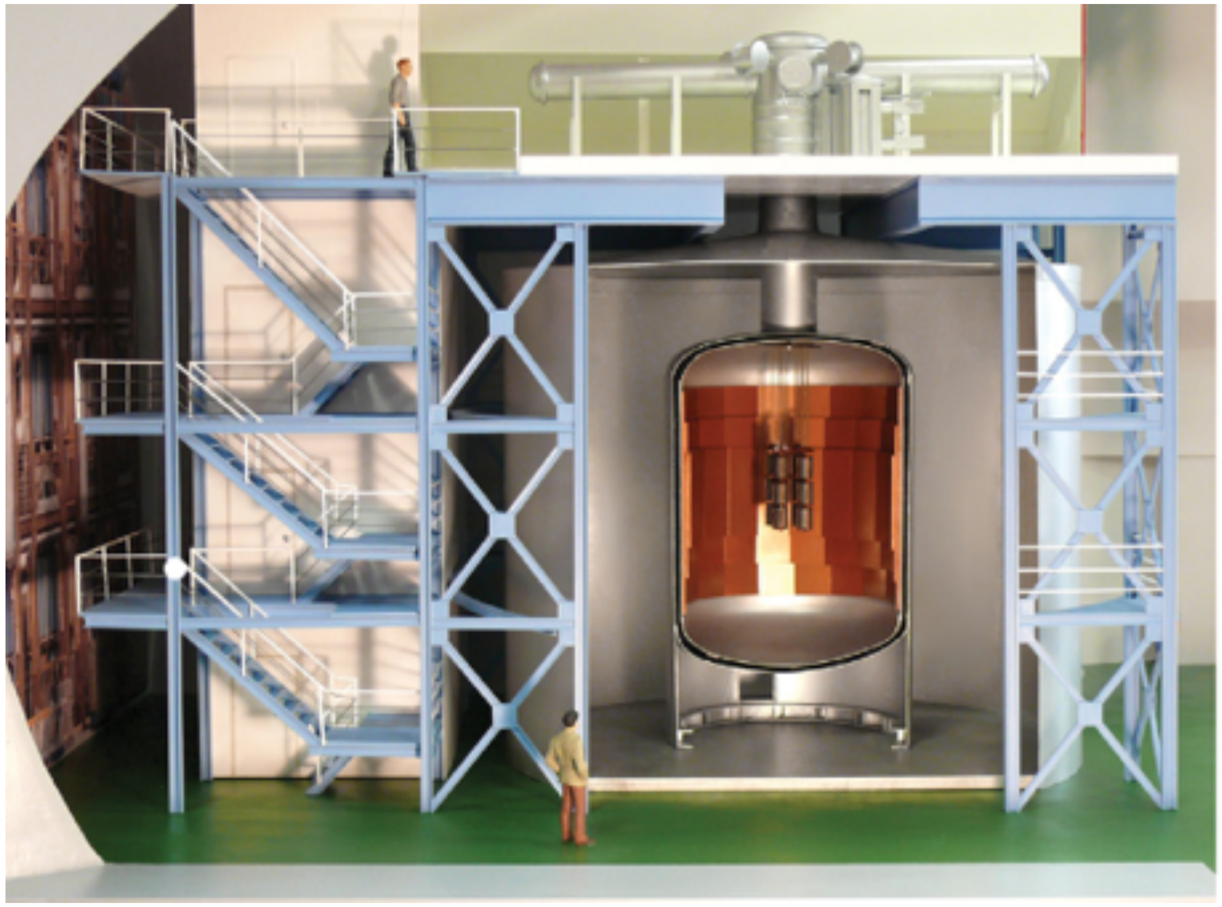
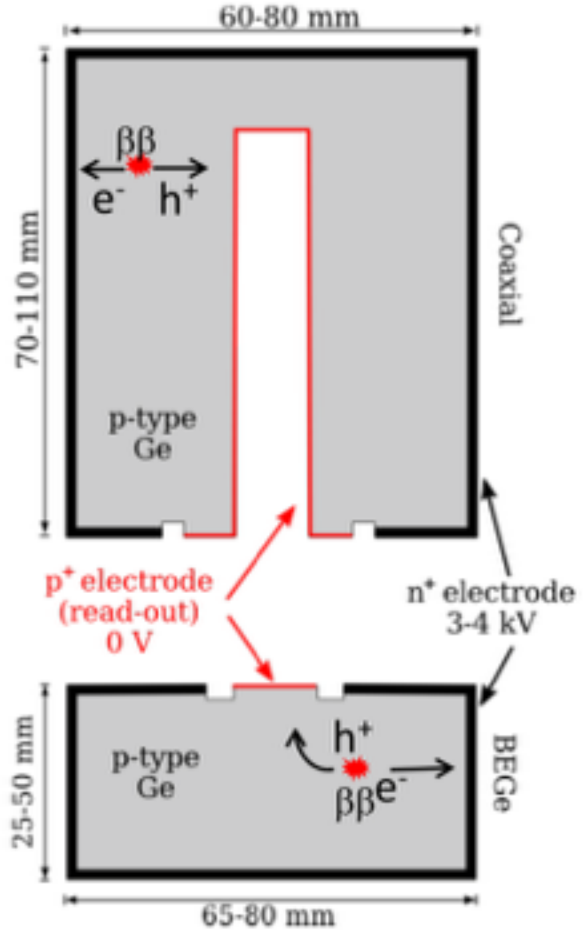
GERDA

GERmanium Detector Array



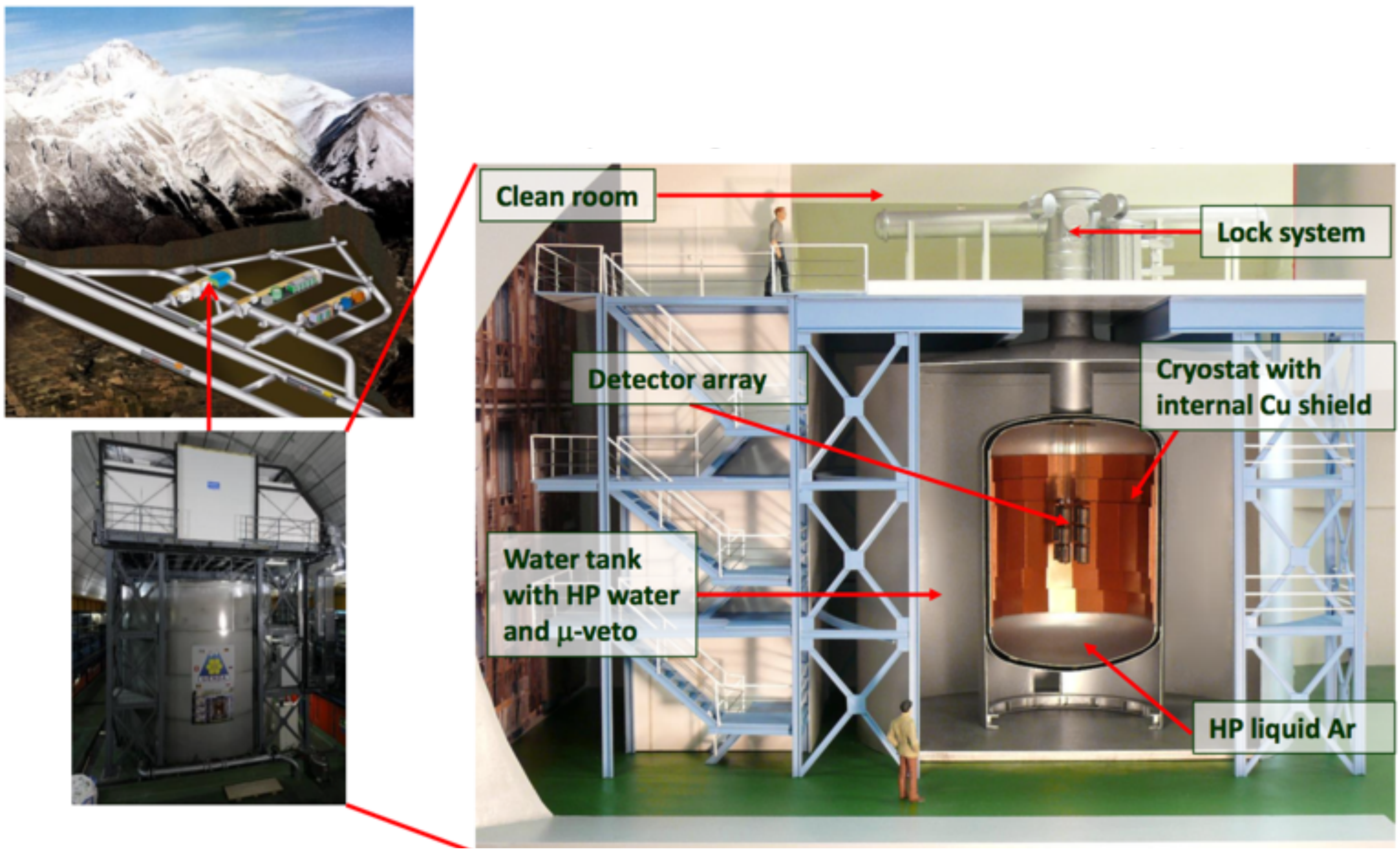
- Located in Hall A at LNGS
- HPGe detectors enriched in ^{76}Ge detectors
- established detector technology -> industrial support
- excellent energy resolution (~0.1% @ Q-value, 2039 keV)
- high detection efficiency (source = detector)



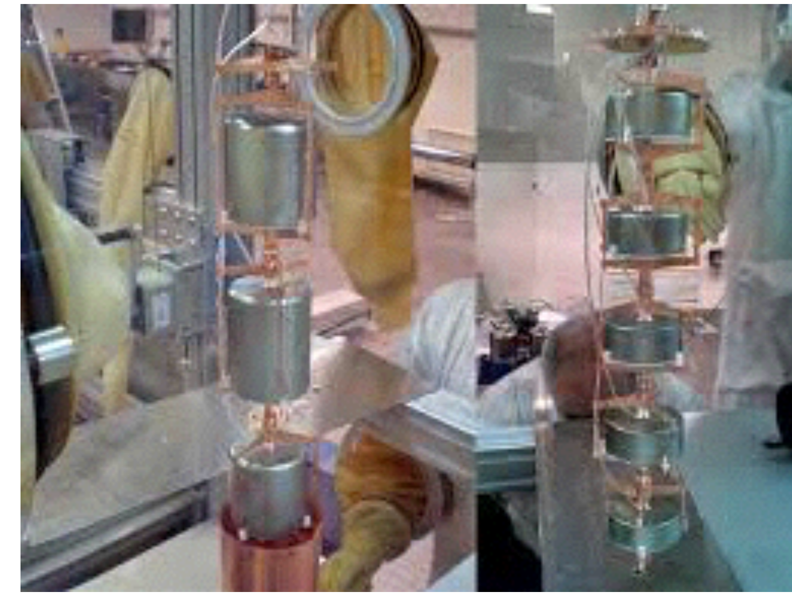
GERDA at LNGS

Experiment structure:

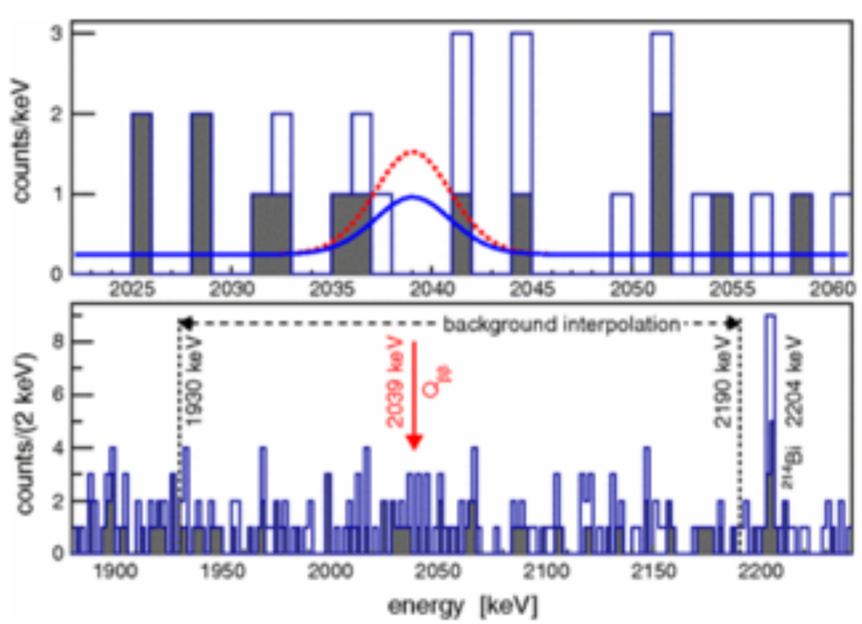
- 590m^3 Water Tank to absorb neutrons and veto cosmin muons
- 64 m^3 Liquid Argon for cooling the bare HPGe detectors and shielding
- Plastic scintillators above the cryostat to further veto cosmic muons



GERDA phase 1



- Enriched ^{76}Ge detectors, operated in Liquid Argon
- Q-value=2039keV
- 14.6 kg of 86% enriched ^{76}Ge (4.8 keV FWHM)
- 3kg of 87% enriched BEGe enriched detectors (3.2 keV FWHM)
- Pulse shape discrimination based on single-site and multi-site events

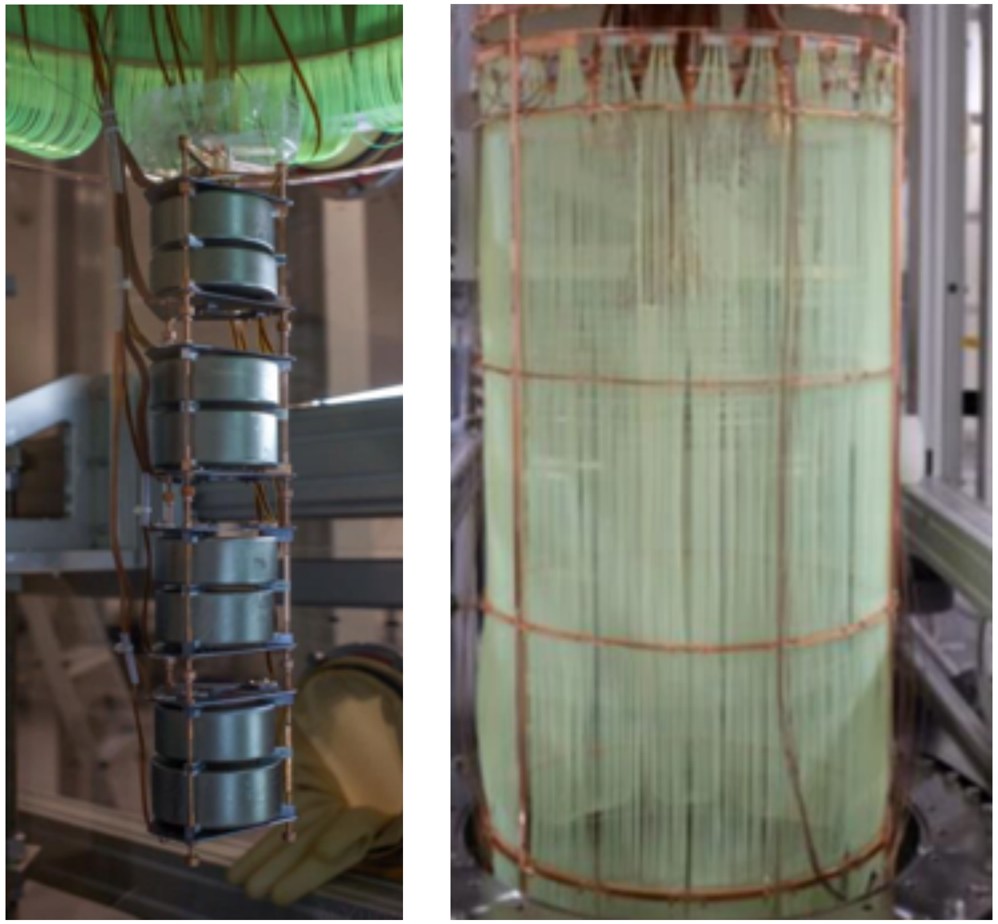


Data taking 2011-2013
21.8 kg·yr ^{76}Ge exposure
Limit on half life of ^{76}Ge:
$T_{0\nu} > 2.1 \times 10^{25}$ yr

GERDA Coll., PRL 111 (2013) 1225030

GERDA phase 2

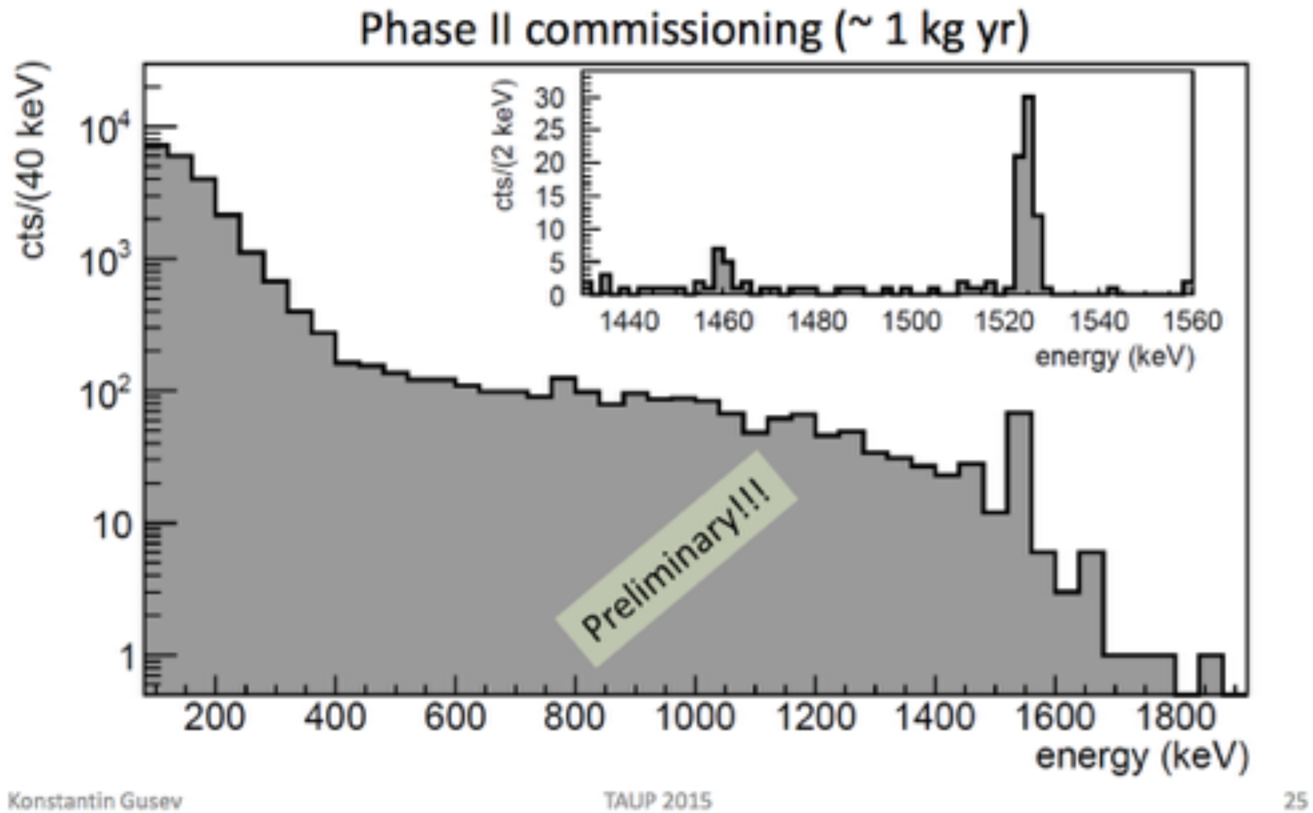
- Increase target mass: 18kg + 20 kg
- Reduce background (factor ~10) wrt GERDA-1
    - new HV and signal cables
    - new FrontEnd electronics
    - improve PSD to distinguish multi-site from single-site events
    - LAr veto instrumentation



From K. Gusev talk @ TAUP2015

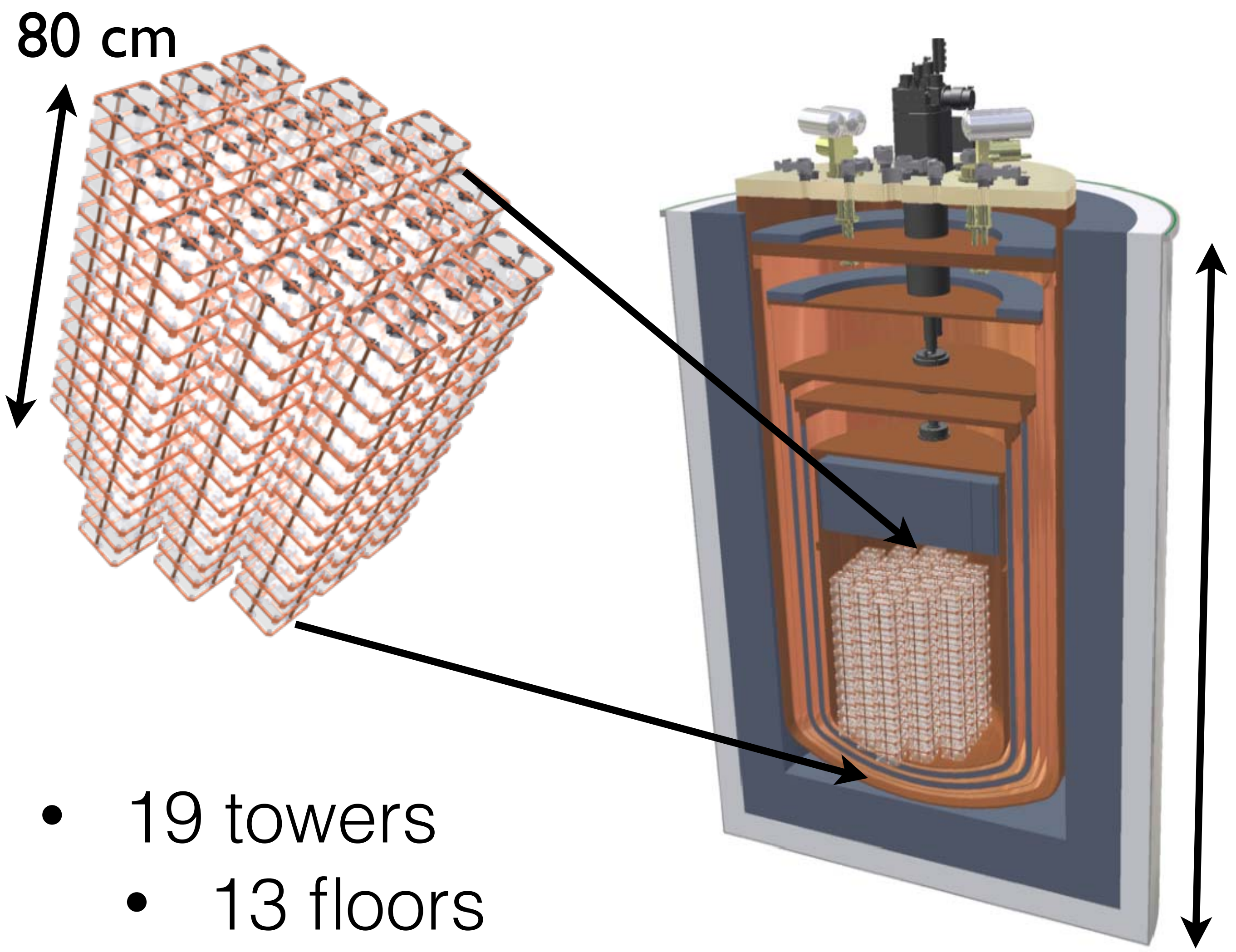
Goals:
- background < 0.001 counts/(keV kg y)
- sensitivity after 4 years: $T_{0\nu} > 1.5 \times 10^{26}$ yr

Commissioning ongoing!!



CUORE

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

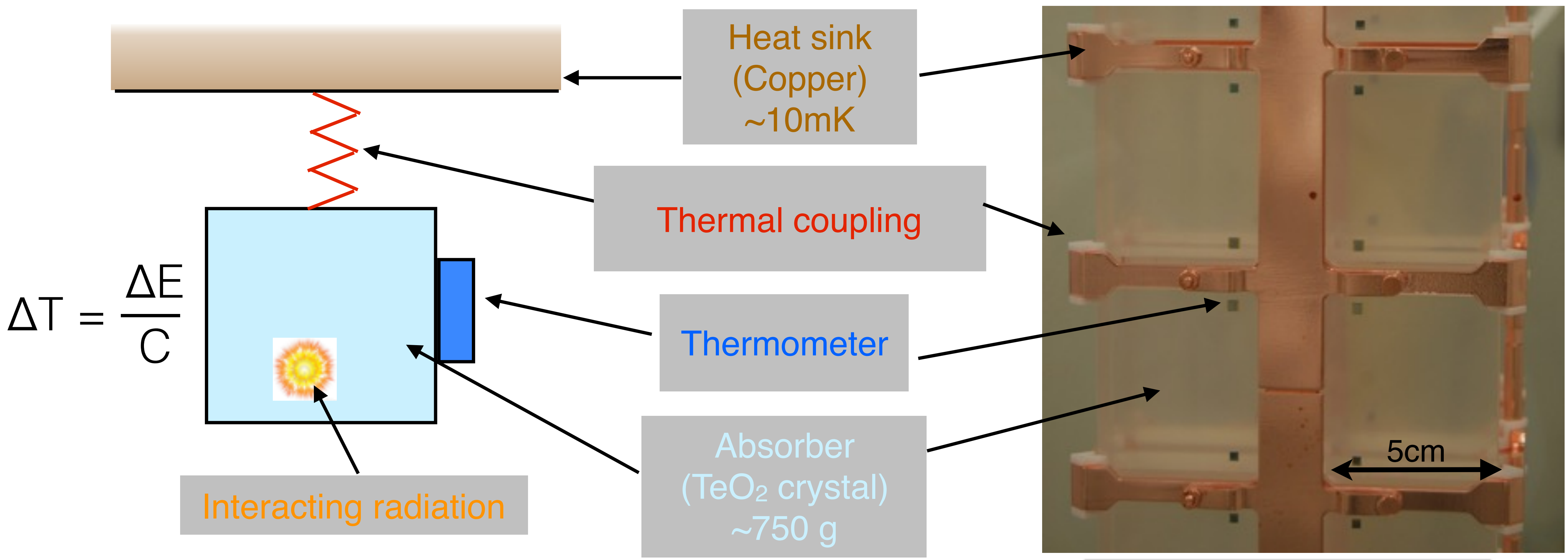


- 19 towers
  - 13 floors
    - 4 crystals

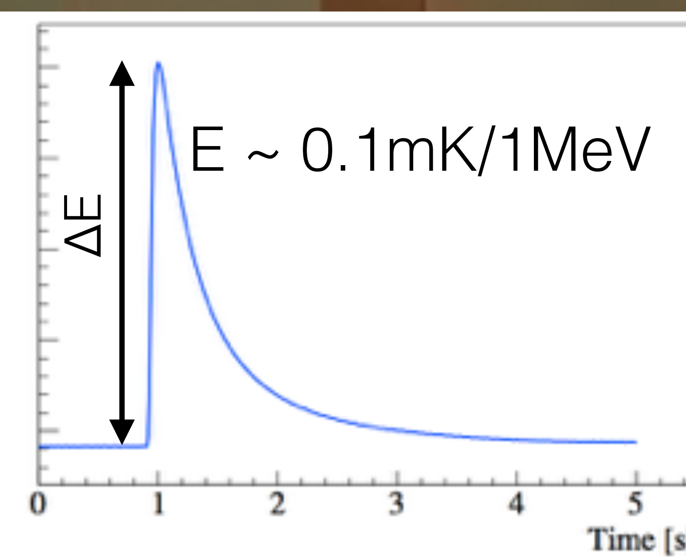
- Tightly packed array of **988 bolometric detectors**
- M = 741 kg of TeO_2 (206 kg ^{130}Te) to look for **$0\nu\beta\beta$ of ^{130}Te** and other rare processes.
- **Excellent energy resolution** of bolometers (goal: FWHM @ $Q_{\beta\beta}$: 5keV @ ~2528 keV)
- Extremely **low radioactivity** environment (goal: 0.01 c/keV/kg/y)
- Complex **cryogenic** set-up

CUORE bolometers

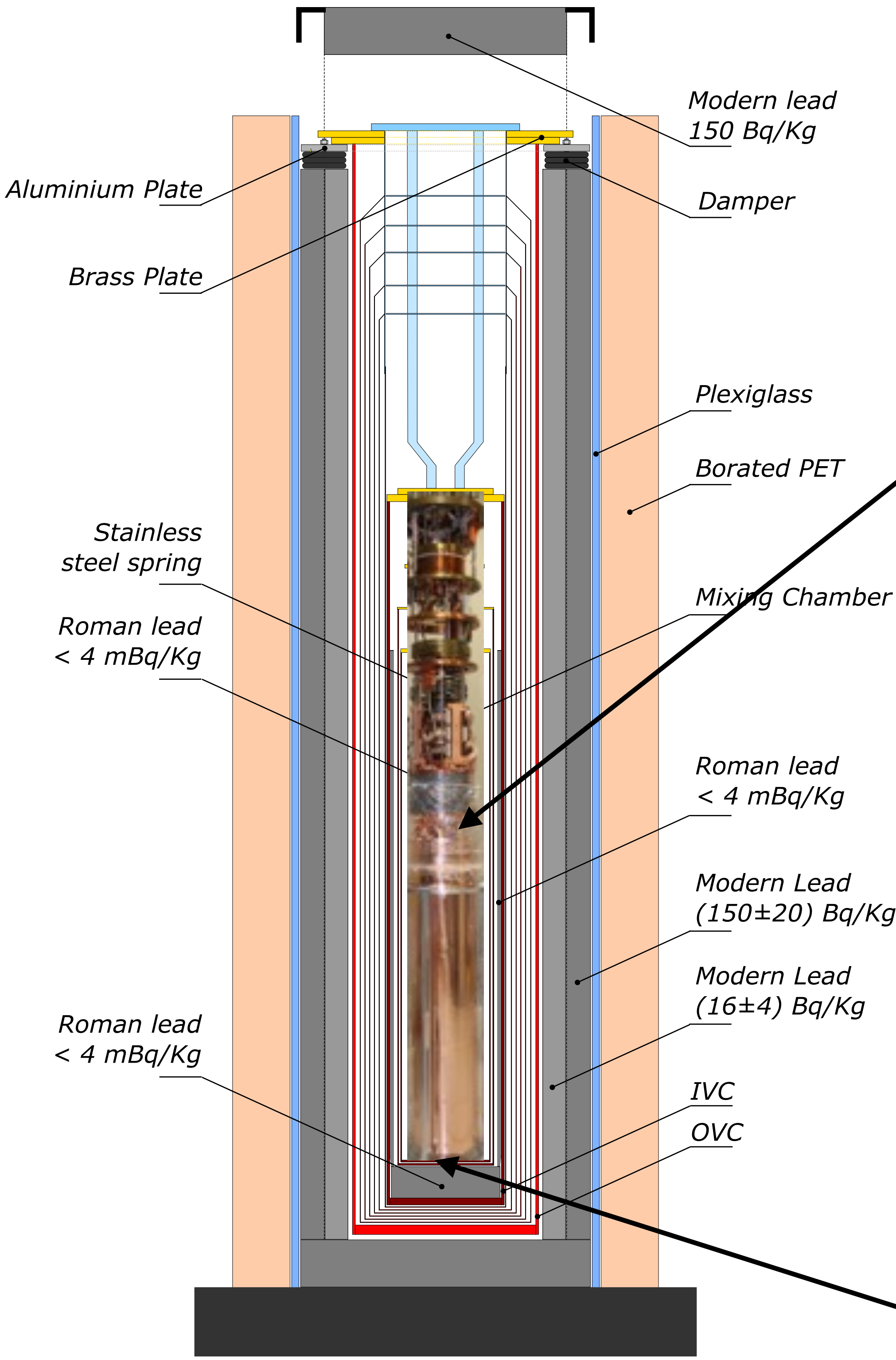
- **Bolometer:** a particle detector that measures the energy deposited by incident radiation based on the temperature change



- $^{nat}TeO_2$ crystals: low heat capacitance
- Resolution @ Q-value (2528 keV): ΔE = 5keV FWHM



CUORE-0



One CUORE-like tower of 13 floors, 4 crystals each

52 TeO_2 crystals, 750g each

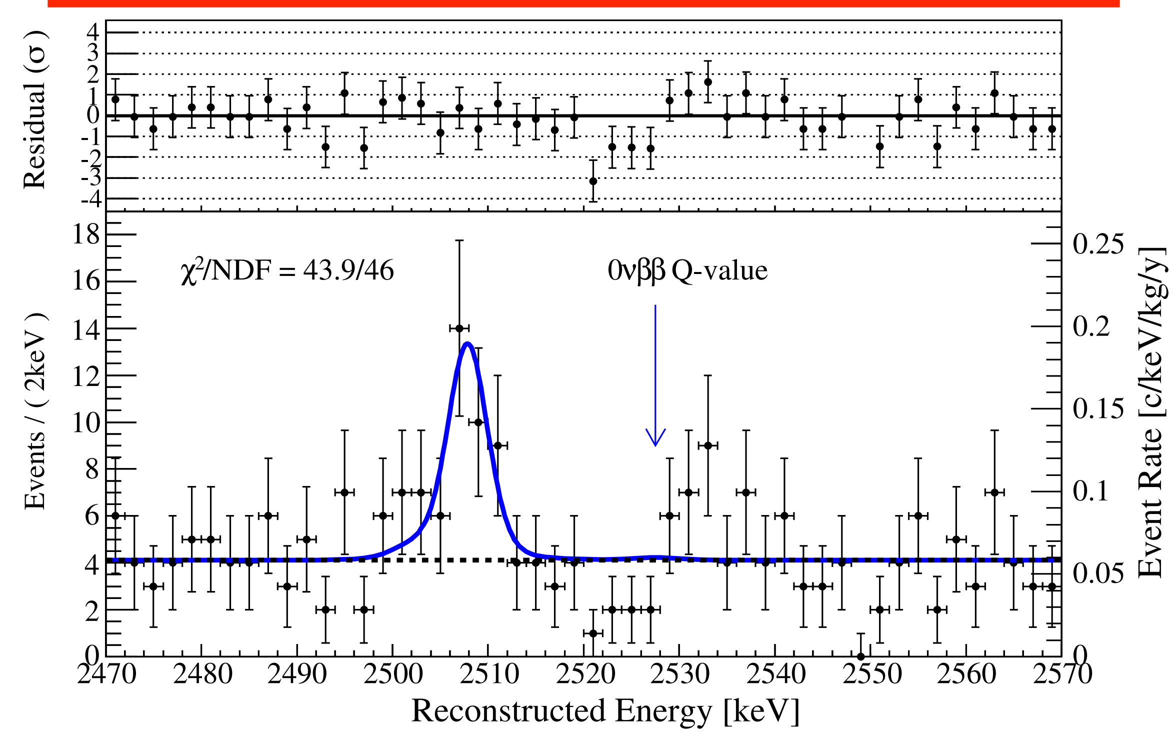
detector mass: ~39kg of TeO_2

(~11kg of ^{130}Te)

Operated from Apr 2013 to April 2015 (9.8 kg·yr ^{130}Te):

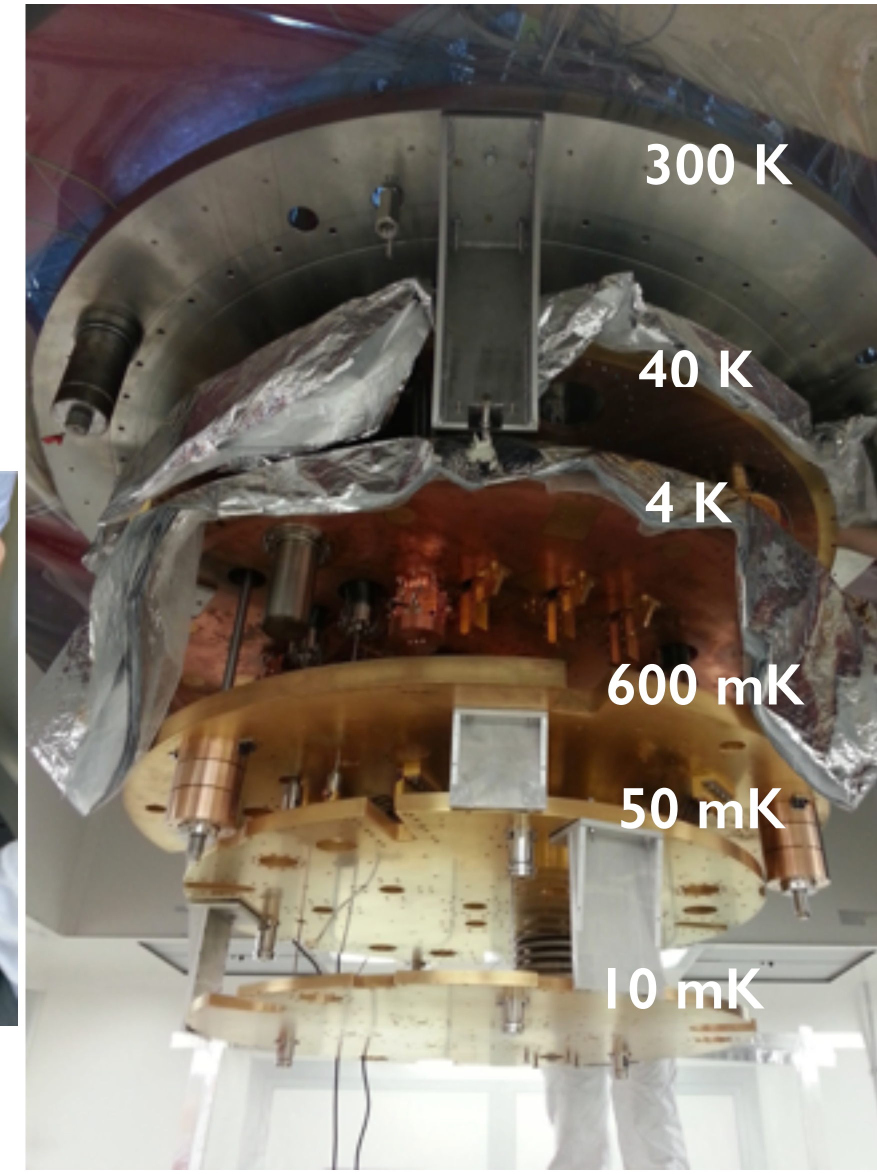
$T_{0\nu} > 4.0 \times 10^{24}$ yr

$m_{\beta\beta}$ < (270-650) meV



Phys. Rev. Lett. 115, 102502

CUORE status



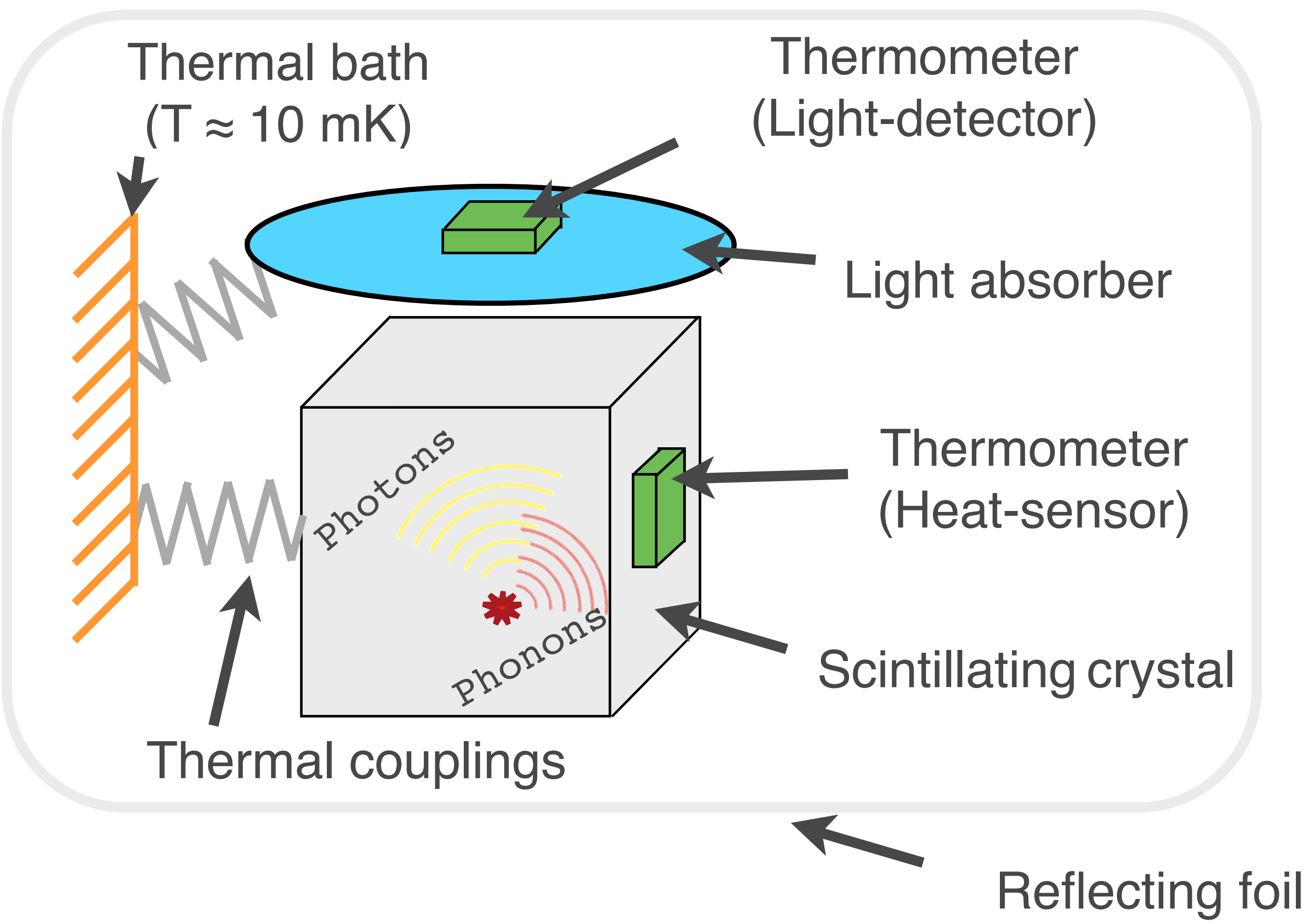
- Assembly of all the 19 CUORE towers has been completed
- Cryogenic system fully assembled, commissioning ongoing
- September 2014: it reached ~6 mK in stable conditions.
- The completion of the cryogenic system commissioning is close and will be followed by the detector installation

Scintillating bolometers

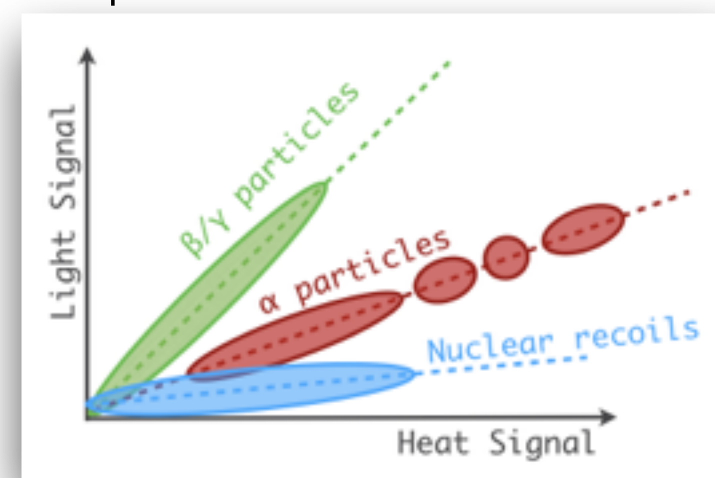
When a bolometer is also an *efficient scintillator*, at low temperatures, a fraction of the deposited energy is converted into scintillation photons (*light*) while the remaining is transformed into phonons (*heat*).

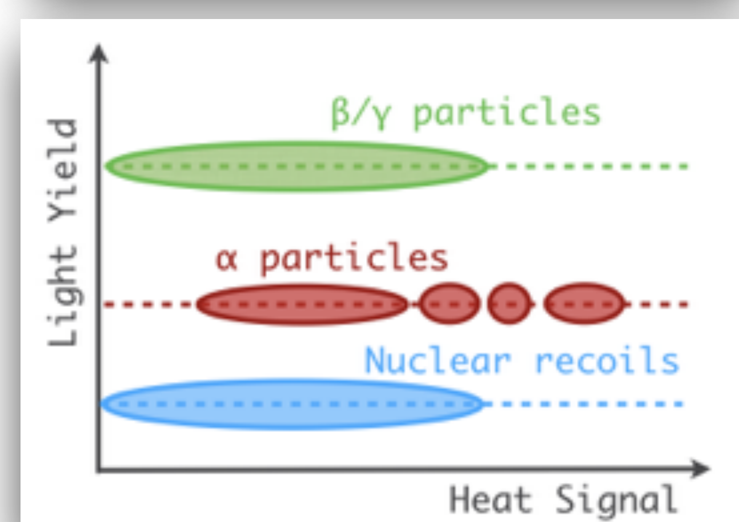
The simultaneous read-out of **HEAT** and **LIGHT** allows particle identification

Experimental set-up:



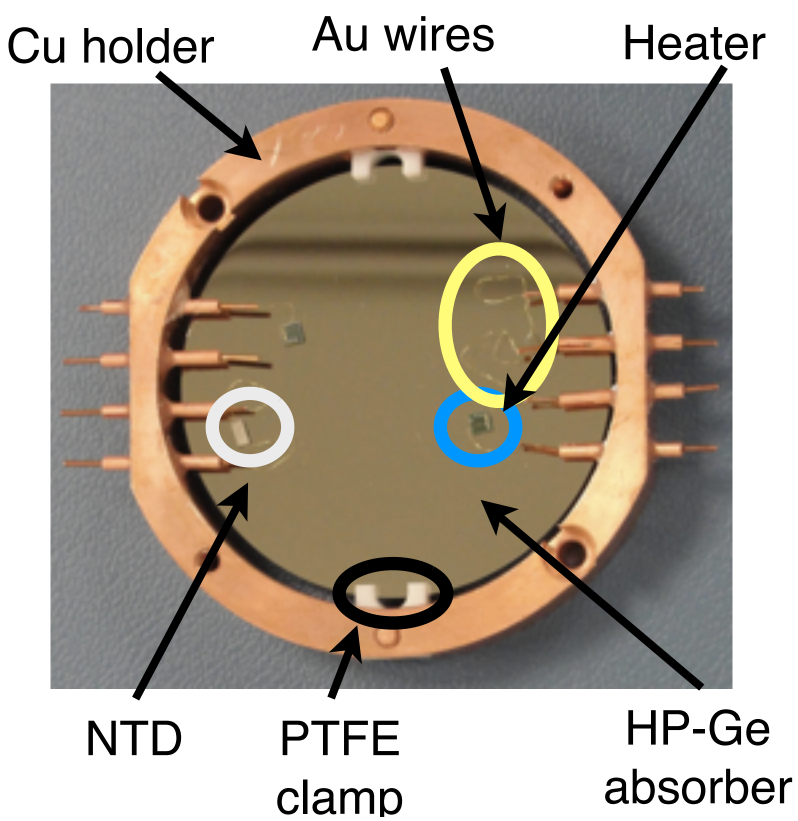
From L. Pattavina talk @ TAUP2015





Light Yield = ratio detected light signal and energy deposited in the main absorber

Light Detectors (LD)



Light signal:
- ➜ few keV/MeV
- ➜ is isotropic

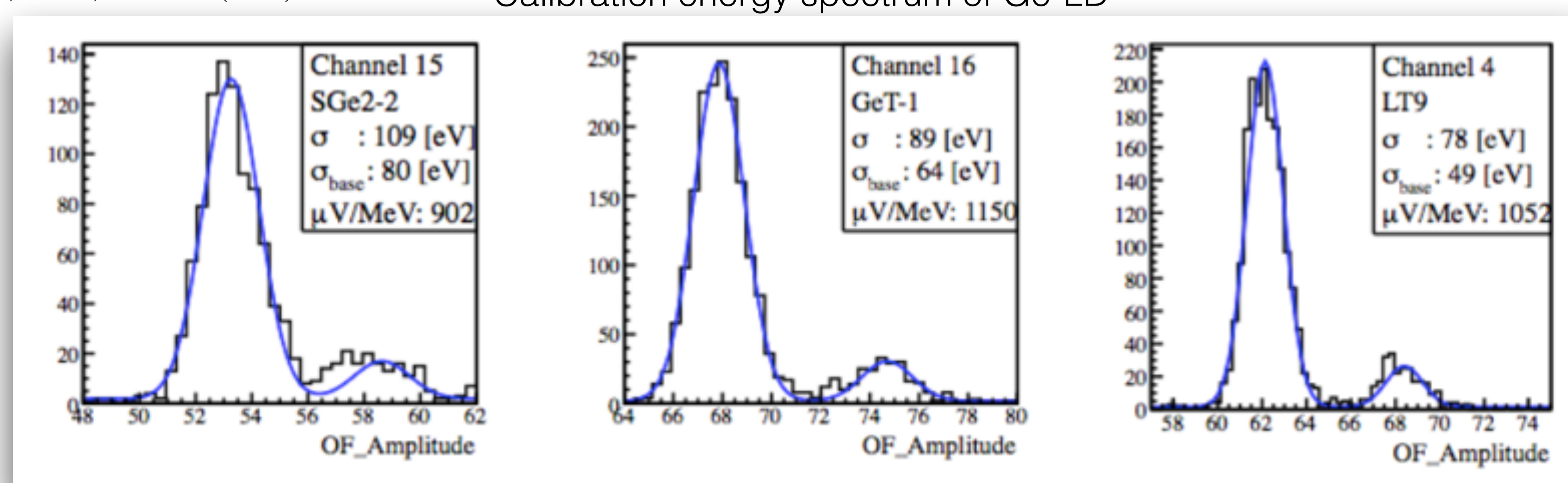
Light detector:

	PMT	Bolometer
➜ quantum efficiency	✘	✔
➜ energy resolution	✘	✔
➜ intrinsic radio-purity	✘	✔
➜ must work @ low T	✘	✔
➜ energy threshold	✔	✘

LD are characterized by means of ^{55}Fe X-ray (5.9 keV and 6.5 keV)
Baseline energy resolution <70 eV>

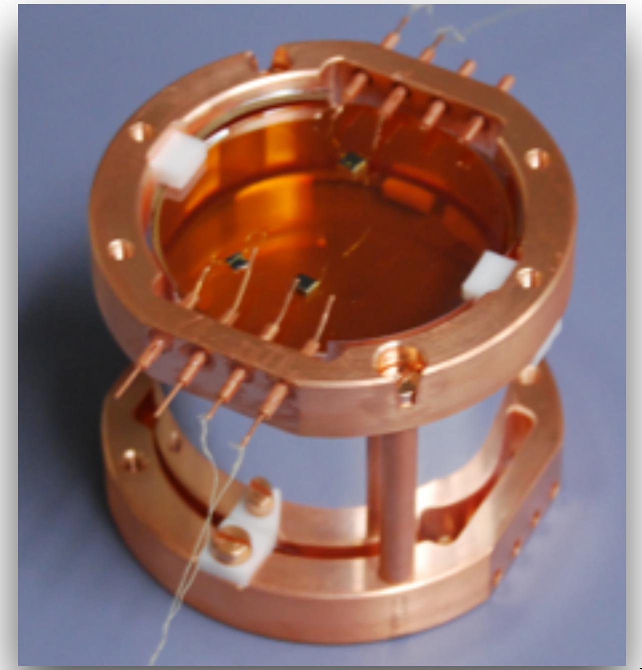
J.W. Beeman et al., *JINST*, **8** P07021 (2013)

Calibration energy spectrum of Ge-LD

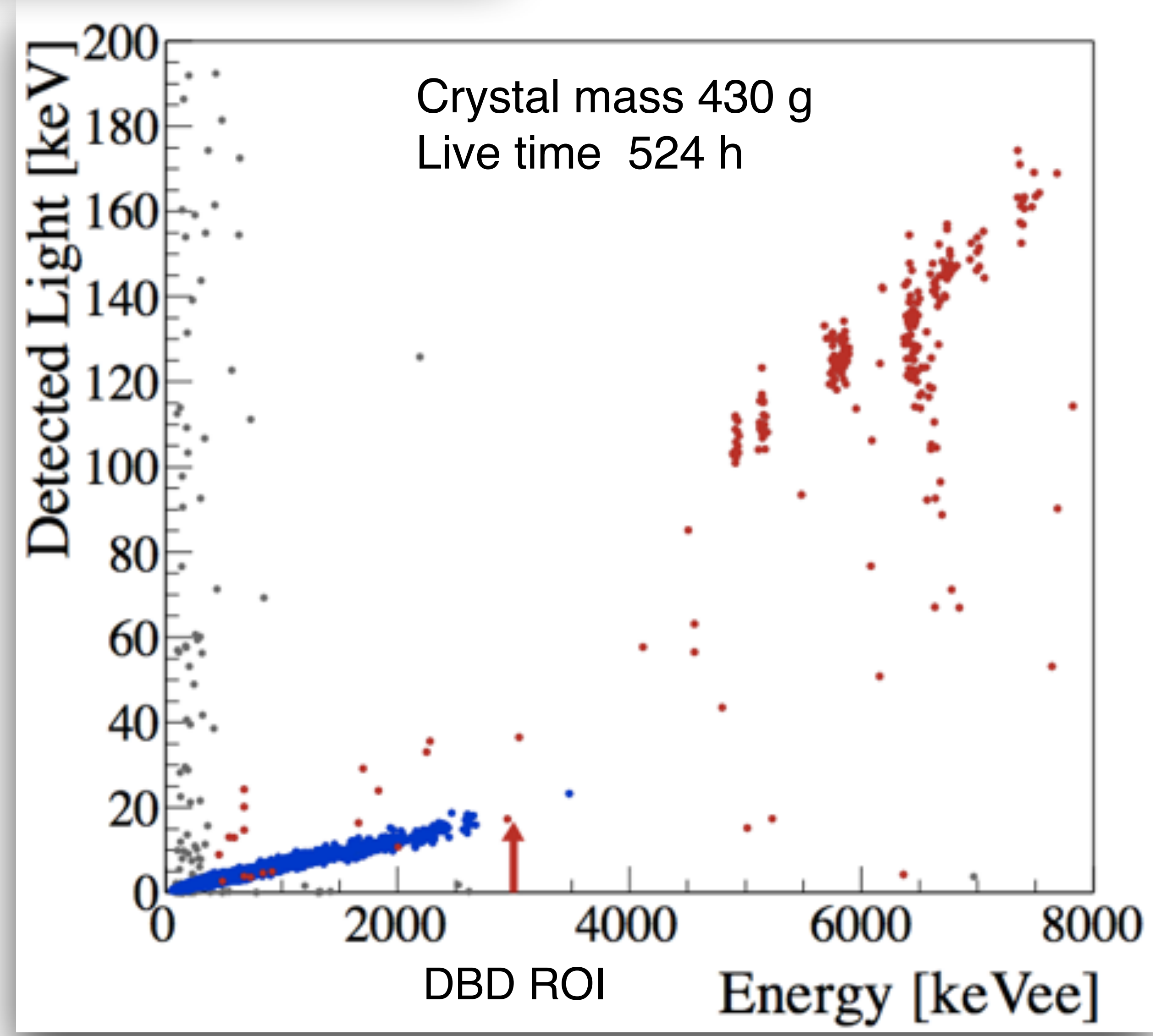


ZnSe crystal

Low Background measurement

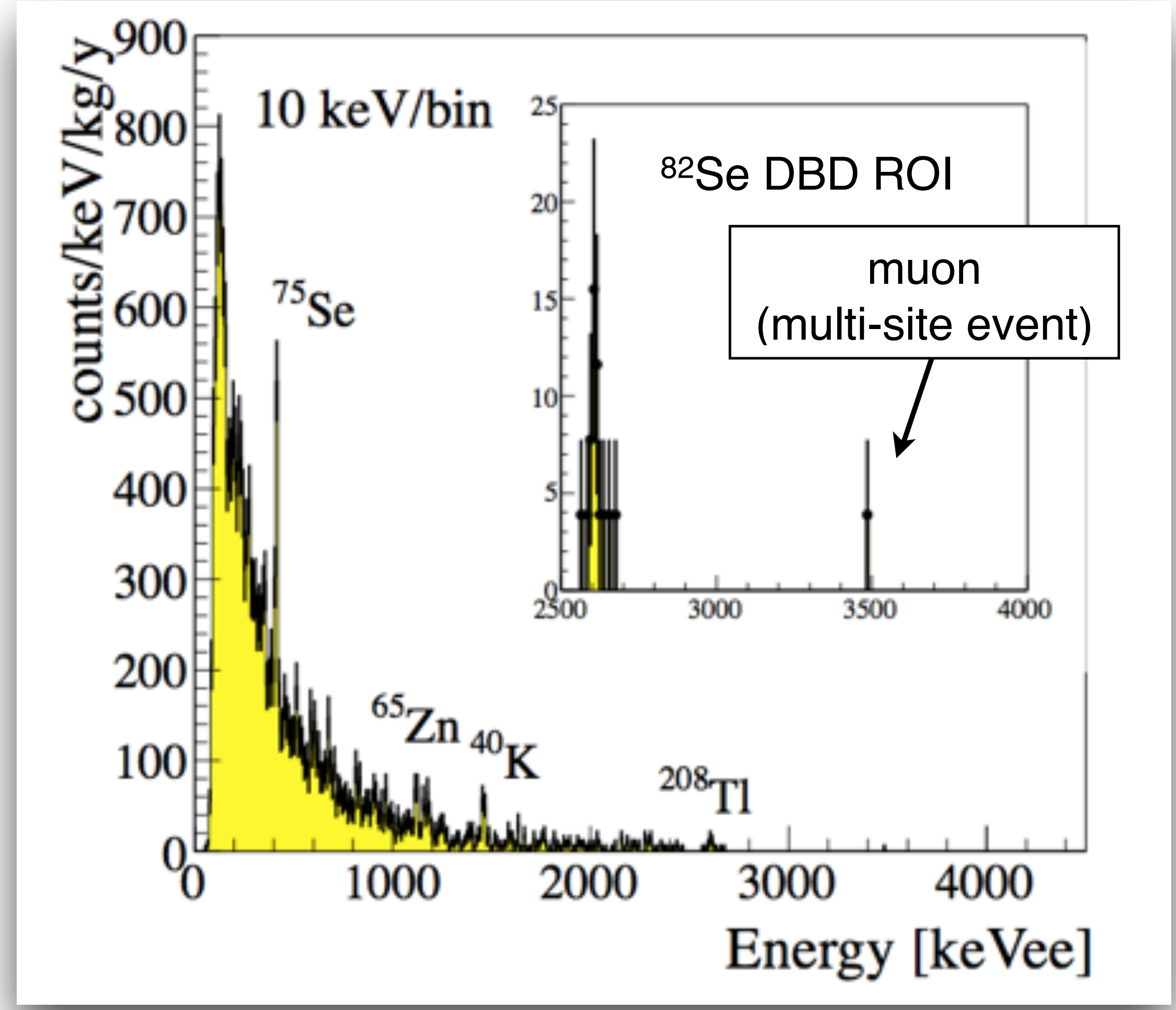


J W Beeman *et al* 2013 *JINST* **8** P05021



82Se Q-value: 2996 keV

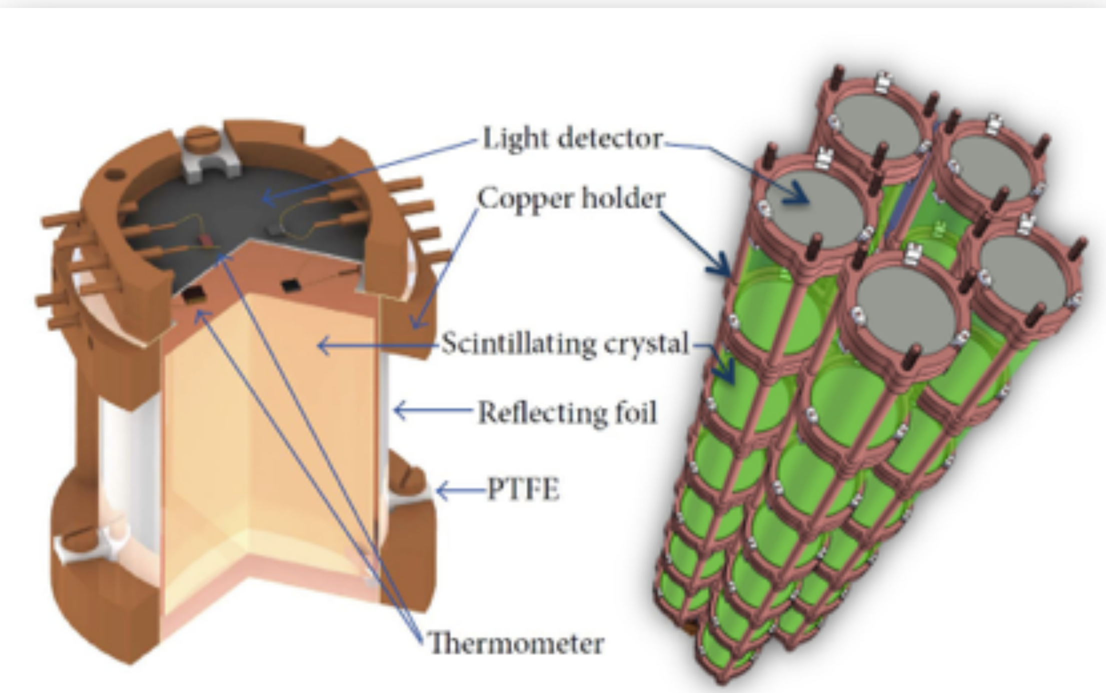
β/γ events selection



- Cosmogenic activation ^{75}Se and ^{65}Zn
- Natural radioactivity: ^{40}K, ^{232}Th & ^{238}U
- **No β/γ events in the ROI!!**

LUCIFER

Low-background **U**nderground
Cryogenics **I**nstallation **F**or **E**lusive **R**ates



- 30 enriched detectors @ >95% level
- detector mass 17 kg of $Zn^{82}Se$
- expected bkg @ ROI 10^{-3} c/keV/kg/y
- FWHM @ ROI: 10 keV

- LUCIFER is funded by a ERC Advanced Grant (3.3M€) for 6 years, March 2010 - March 2016
- Demonstrator array of enriched scintillating bolometers
- LUCIFER investigates $0\nu\beta\beta$ of ^{82}Se in $Zn^{82}Se$ crystals
- Total isotope mass: ~15 kg
- Background index @ ROI ≤ 10^{-3} c/keV/kg/y

Crystal	Live time (y)	Half-life sensitivity (10^{26} y)	$\langle m_\nu \rangle^*$ (meV)
ZnSe	5	0.6	65–194
	10	1.2	46–138

Enriched crystal production is ongoing!!

General overview

Experiment	Isotope	Technique	Mass ββ(0v) isotope	Status
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
NEMO3	100Mo/82Se	Foils with tracking	6.9/0.9 kg	Complete
GERDA I	76Ge	Ge diodes in LAr	15 kg	Complete
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	30+35 kg	Commissioning
Majorana D	76Ge	Point contact Ge	30 kg	Commissioning
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.3% natTe suspended in Scint	55 kg	Construction
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	Construction
1TGe (GERDA+MJ)	76Ge	Best technology from GERDA and MAJORANA	~ tonne	R&D
CUPID	-	Hybrid Bolometers	~ tonne	R&D
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

O. Cremonesi - September 10, 2015 - TAUP 2015, Turin, Italy

Summary

- Double-beta decay physics is an excellent probe for new physics: neutrino mass hierarchy, Majorana particles,…
- A wide variety of techniques is available, no one is the perfect one.
- Large mass detector and extremely low background are needed for a sensitive DBD investigation.
- LNGS is a forefront underground lab for DBD physics:
  - different experimental techniques
  - different isotopes under investigation