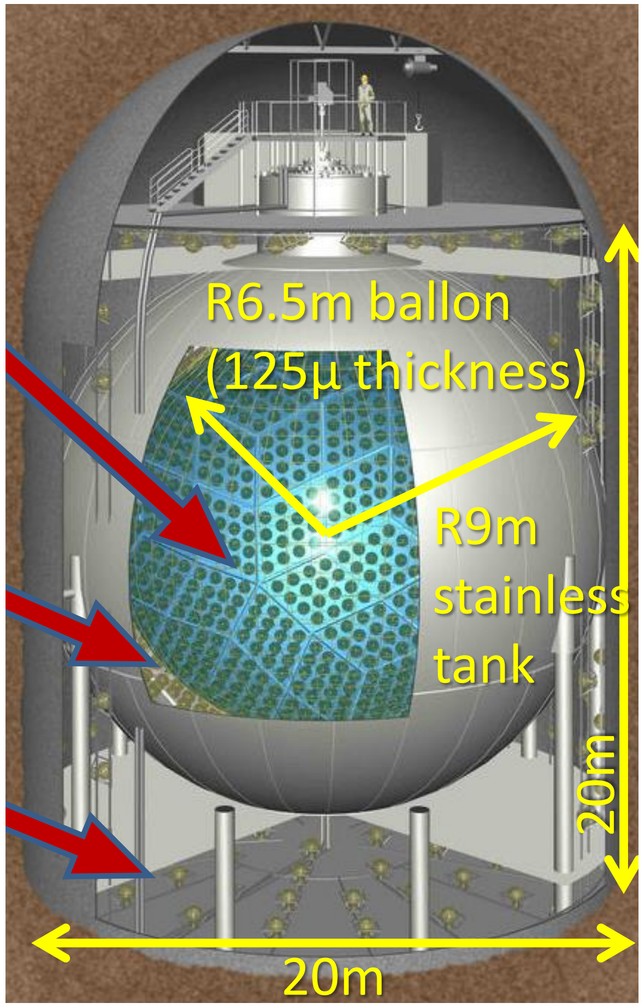
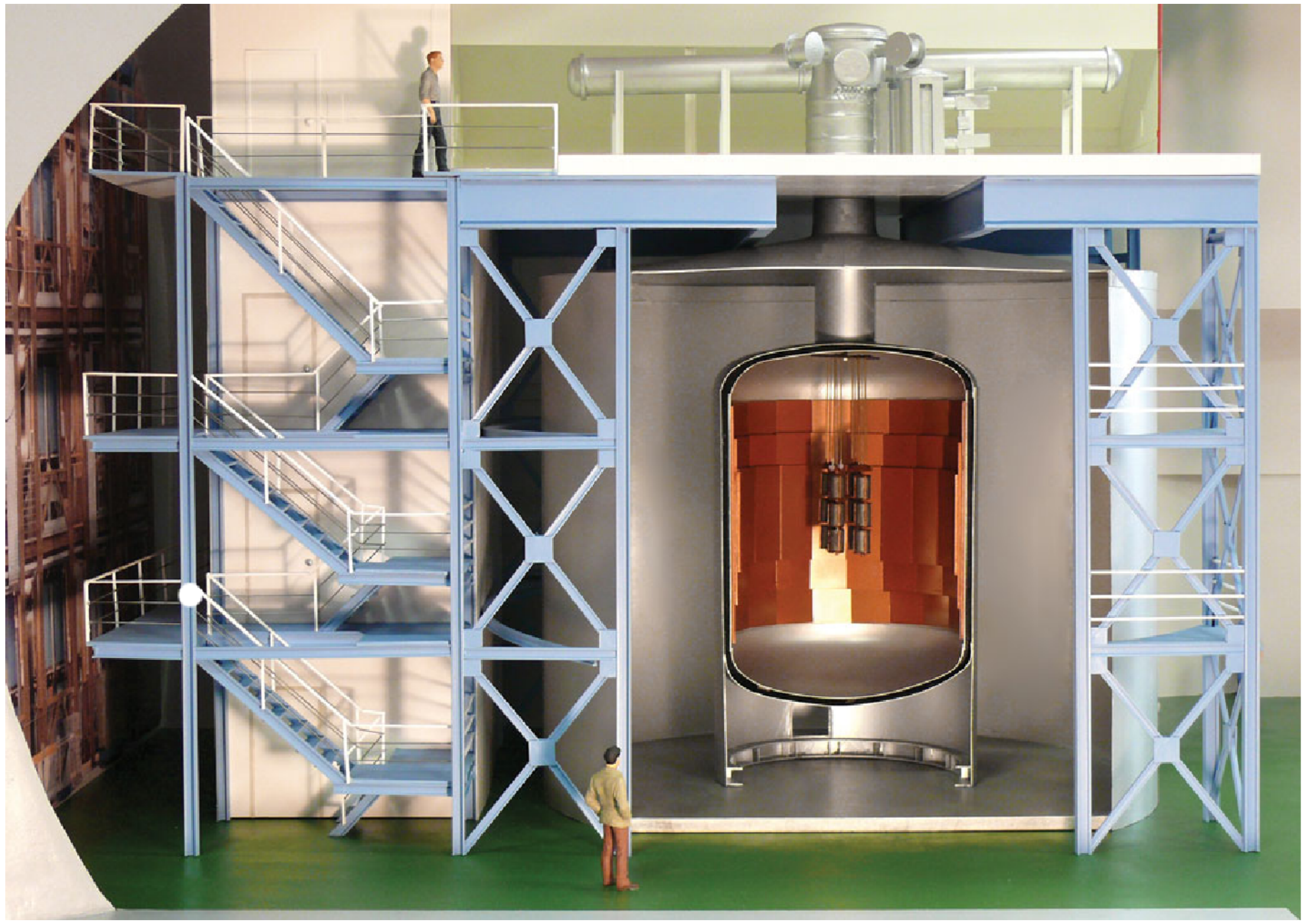
Measuring the neutrino mass

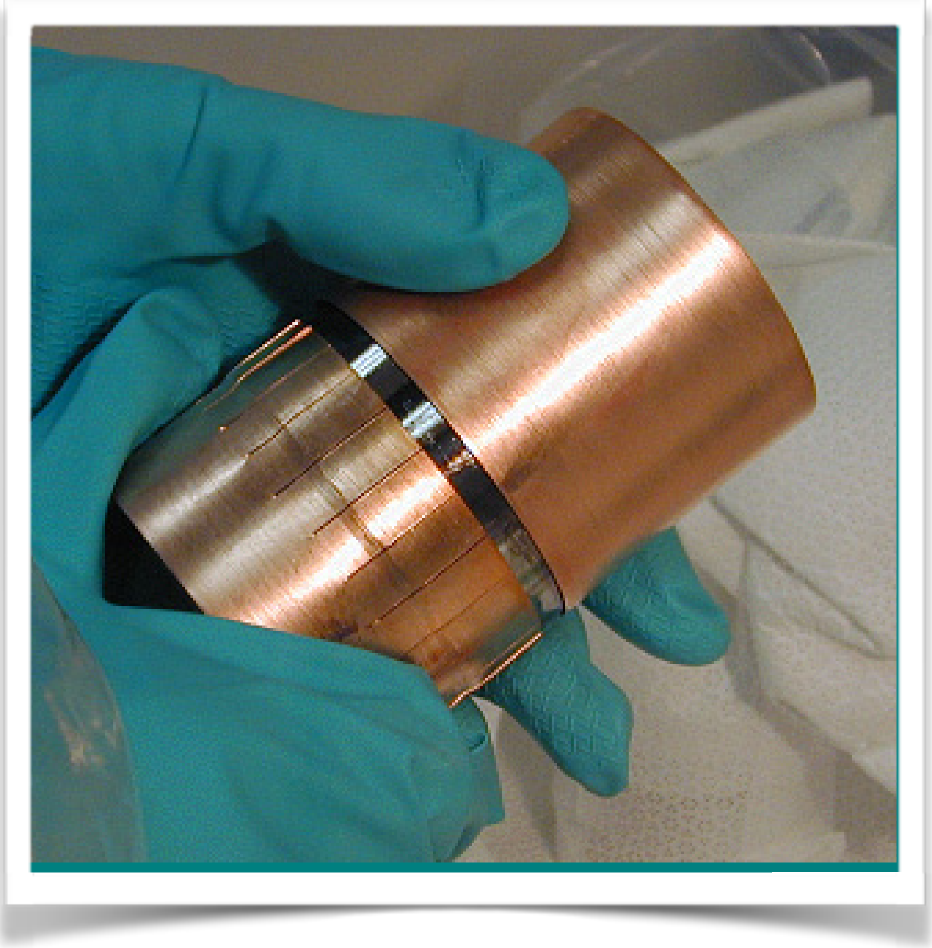
J.J. Gómez Cadenas
IFIC (CSIC & UV)

St. Andrews, INSS, 2014
Lecture 4



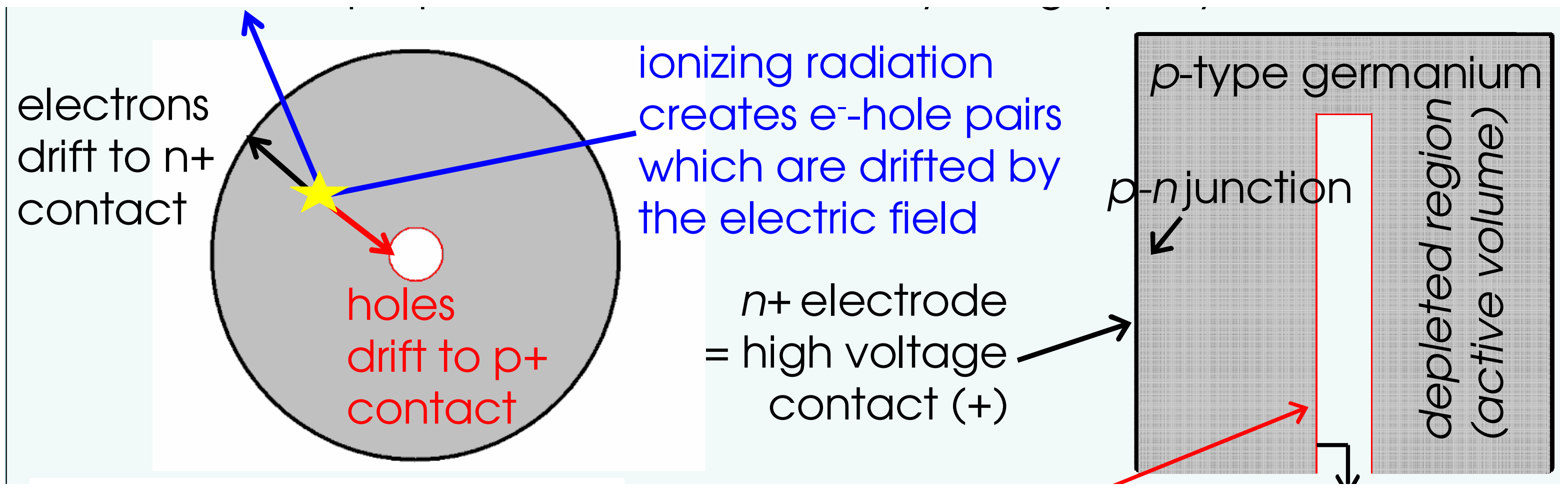


Calorimeters



High resolution experiments: Ge diodes, Te bolometers and scintillation bolometers

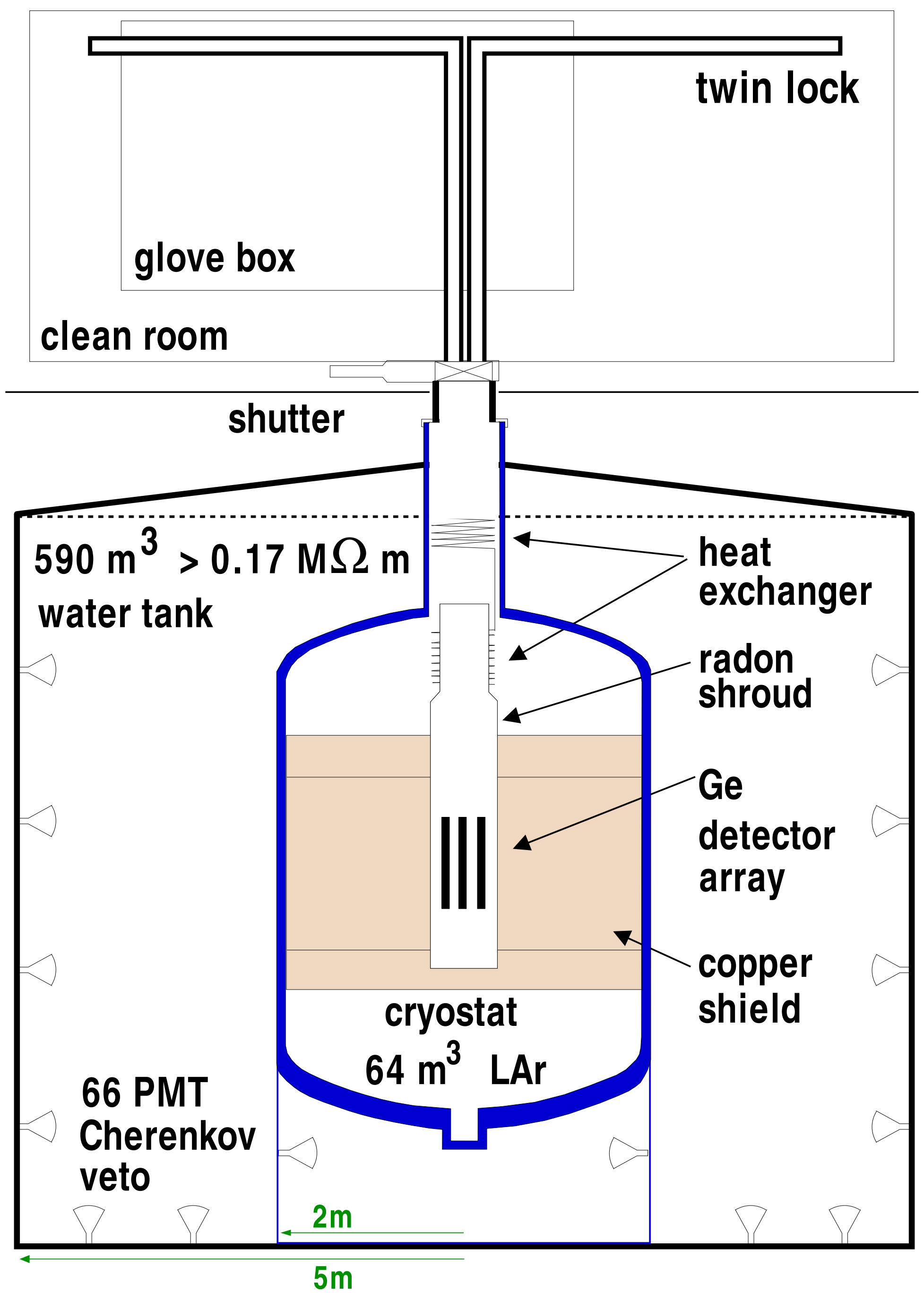
Germanium detectors



- **Ge has three desirable properties as as a detector:**
    - Is dense (therefore suitable as a calorimeter)
    - Can be manufactured with high purity (avoiding backgrounds in the material itself)
    - Is a semiconductor: very good energy resolution

Ge detectors must be cooled (~120 K) to avoid thermal excitation of electron-pair holes that would spoil energy resolution

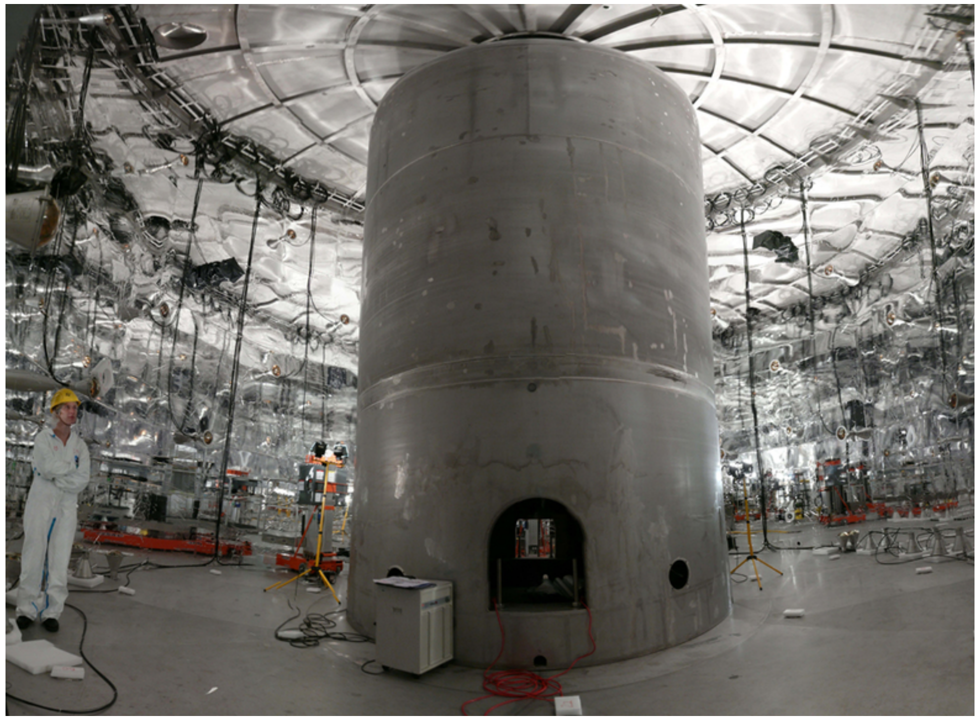
GERDA (GERmanium Detector Array)



- **Array of Ge detectors located inside a cryostat containing 64 m^3 of LAr**
  - LAr acts as coolant and as shield of external backgrounds
  - Copper shield inside (steel) cryostat (further shielding from external backgrounds)
- **Cryostat inside water tank**
  - Water shielding gammas from rocks
  - Instrumented to veto cosmic muons

GERDA

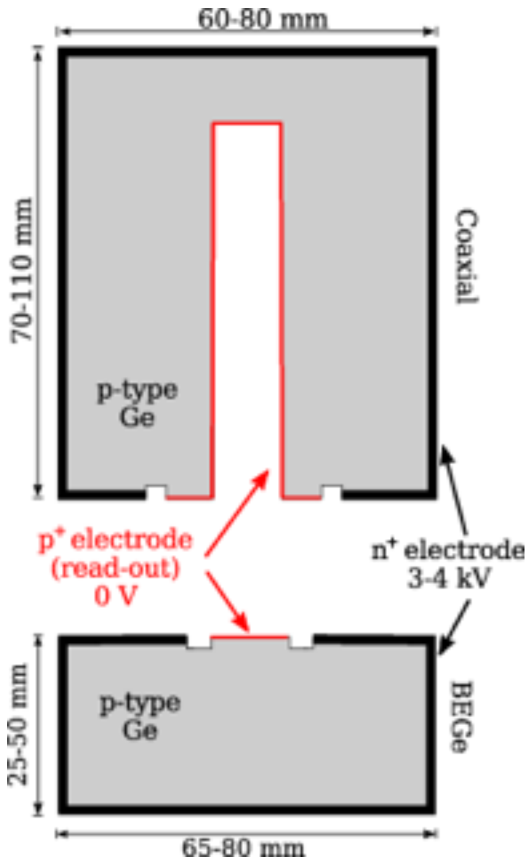
- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden
- Array of bare enriched Ge detectors in liquid argon (LAr)
- Minimal amount of material in proximity of the diodes



Experiment structure

- 590 m^3 Water Tank to absorb neutrons and veto cosmic muons
- 64 m^3 Liquid Argon (LAr) for cooling and shielding (and vetoing)
- Plastic scintillators above the cryostat to further veto cosmic

Gerda detectors

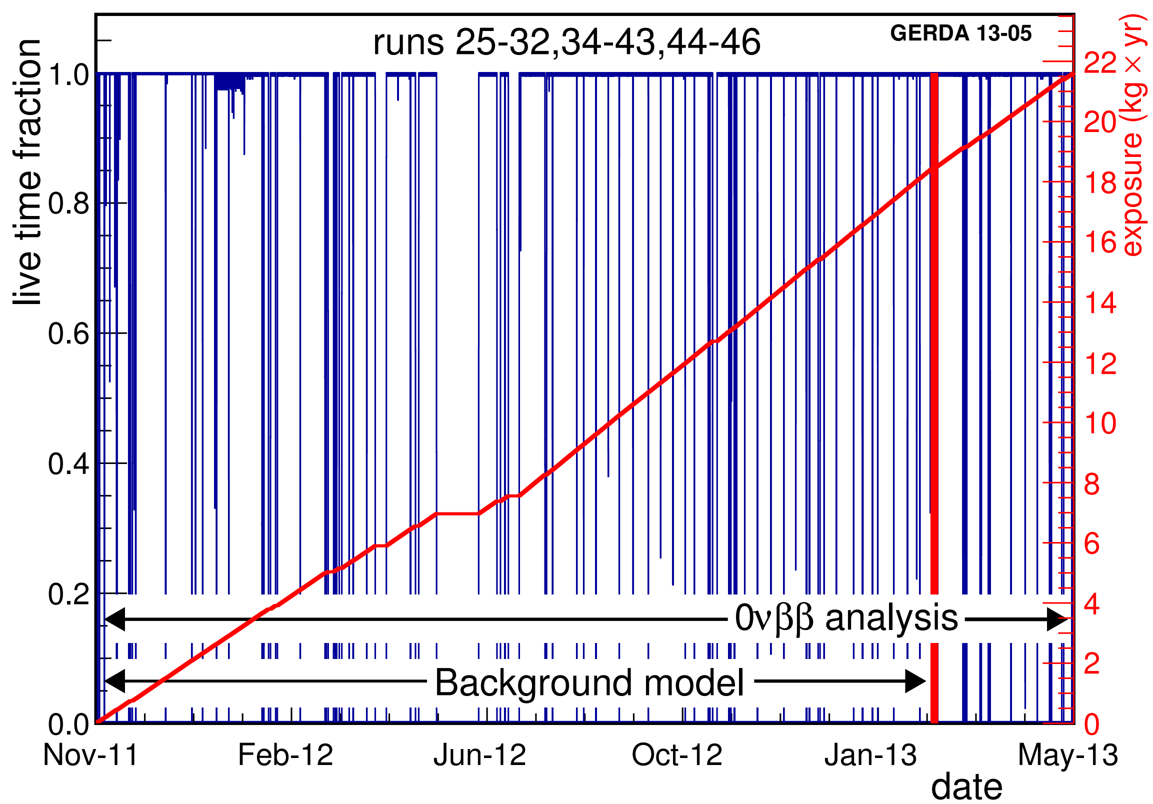


detector	FWHM [keV]	detector	FWHM [keV]
SUM-coax		*SUM-bege*	
ANG 2	5.8 (3)	GD32B	2.6 (1)
ANG 3	4.5 (1)	GD32C	2.6 (1)
ANG 4	4.9 (3)	GD32D	3.7 (5)
ANG 5	4.2 (1)	GD35B	4.0 (1)
RG 1	4.5 (3)		
RG 2	4.9 (3)		
mean coax	4.8 (2)	mean BEGe	3.2 (2)

- **Coaxial**
  - 0.2 % resolution (~5 keV @ $Q_{\beta\beta}$)
  - Reprocessed from previous experiments. Active volume 87%
  - Total enriched (useful mass): 14.7 kg
  - Deployed in strings of 3 detectors

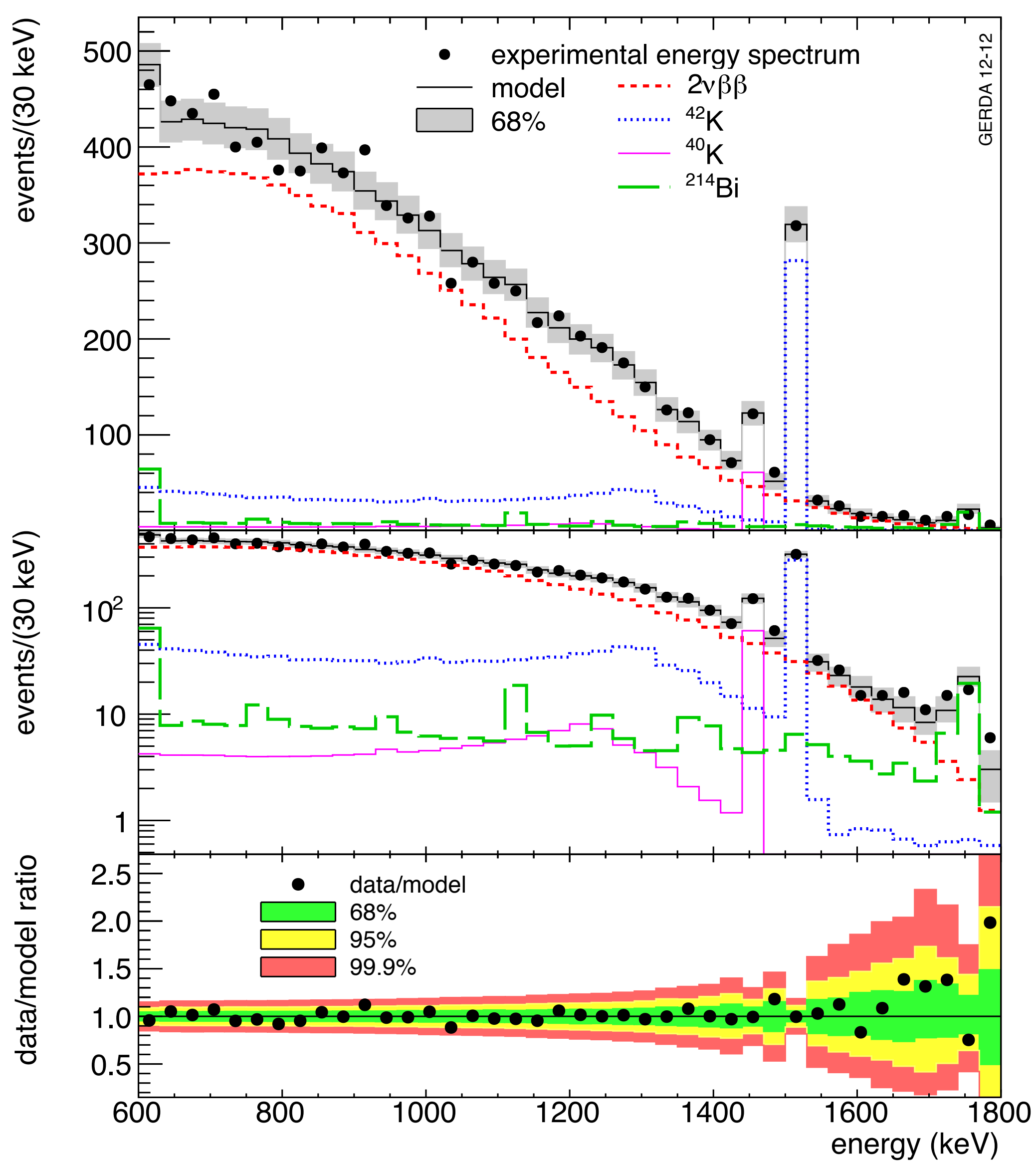
- **BEGe (Broad Energy Germanium)**
  - 0.1 % resolution at 2.6 MeV (~3 keV @ $Q_{\beta\beta}$)
  - Enhanced Pulse Shape Discrimination
  - 20 kg already produced and tested
  - 1 strings of 5 detectors inserted in Gerda. Active volume 92%

GERDA I data taking

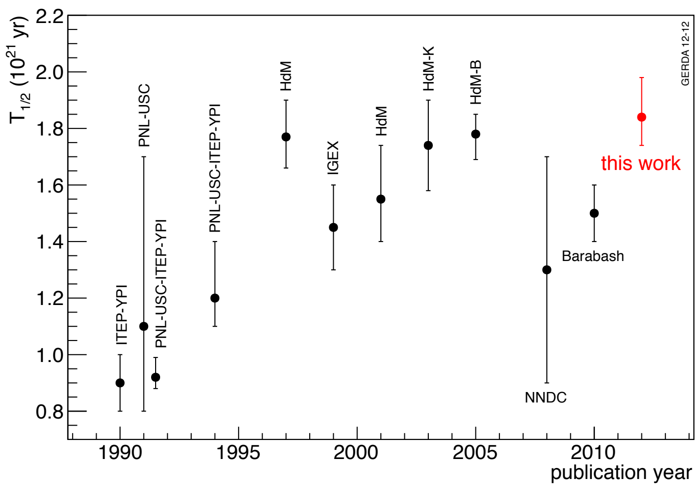


- **Total mass of detectors deployed**
  - 8 coaxial: 17. 7 kg
  - 5 BeGe: 3.6 kg.
  - Total mass: 21.3 kg
  - Not all detectors active at all times due to different deployment times and instrumental issues
- **total running time**
  - 18.6 months, duty factor 88%: 492.3 days
- **total exposure**
  - 21.6 kg x yr
  - Thus the overall “exposure efficiency” is roughly 12/18 ~ 66%

The 2ν mode



- Measured by GERDA with 5.04 kg·yr exposure
- High signal-to-background ratio: small systematic error due to background model
- $T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr
- J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110



GERDA background model

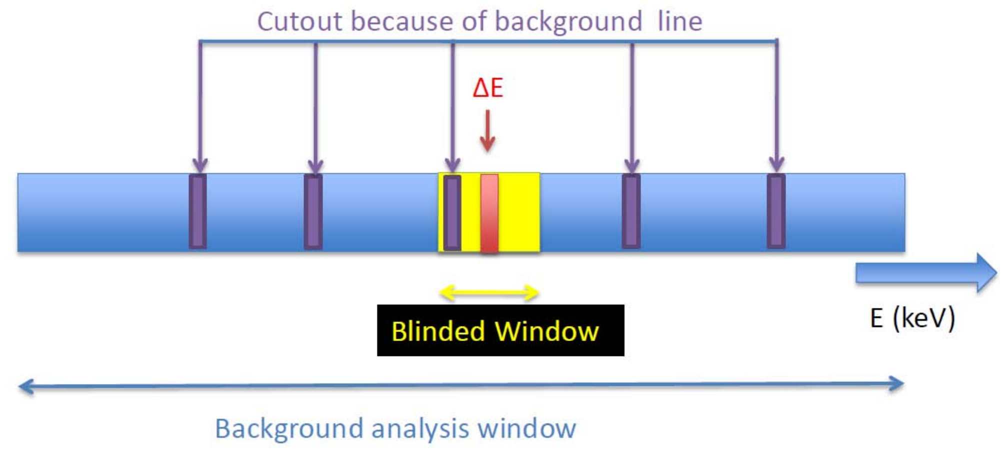


Fig. 1 Representation of energy spectra for definition of the energy windows used in the blind analysis.

- **Background sources**
- Ar42 →K42 (LAr shield)
- Contamination of bulk materials and surfaces with trace elements from the two main radioactive chains, U238 and Th232.
- Radon (Rn222)!

- The strategy is to blind out the region where the signal is expected, to avoid biases.
- Then measure the expected background in the signal region using an energy window around it.
- Construct the background model from the known activities of the materials in the detector and the environment.
- Use the known, narrow energy lines (resolution!) to normalise

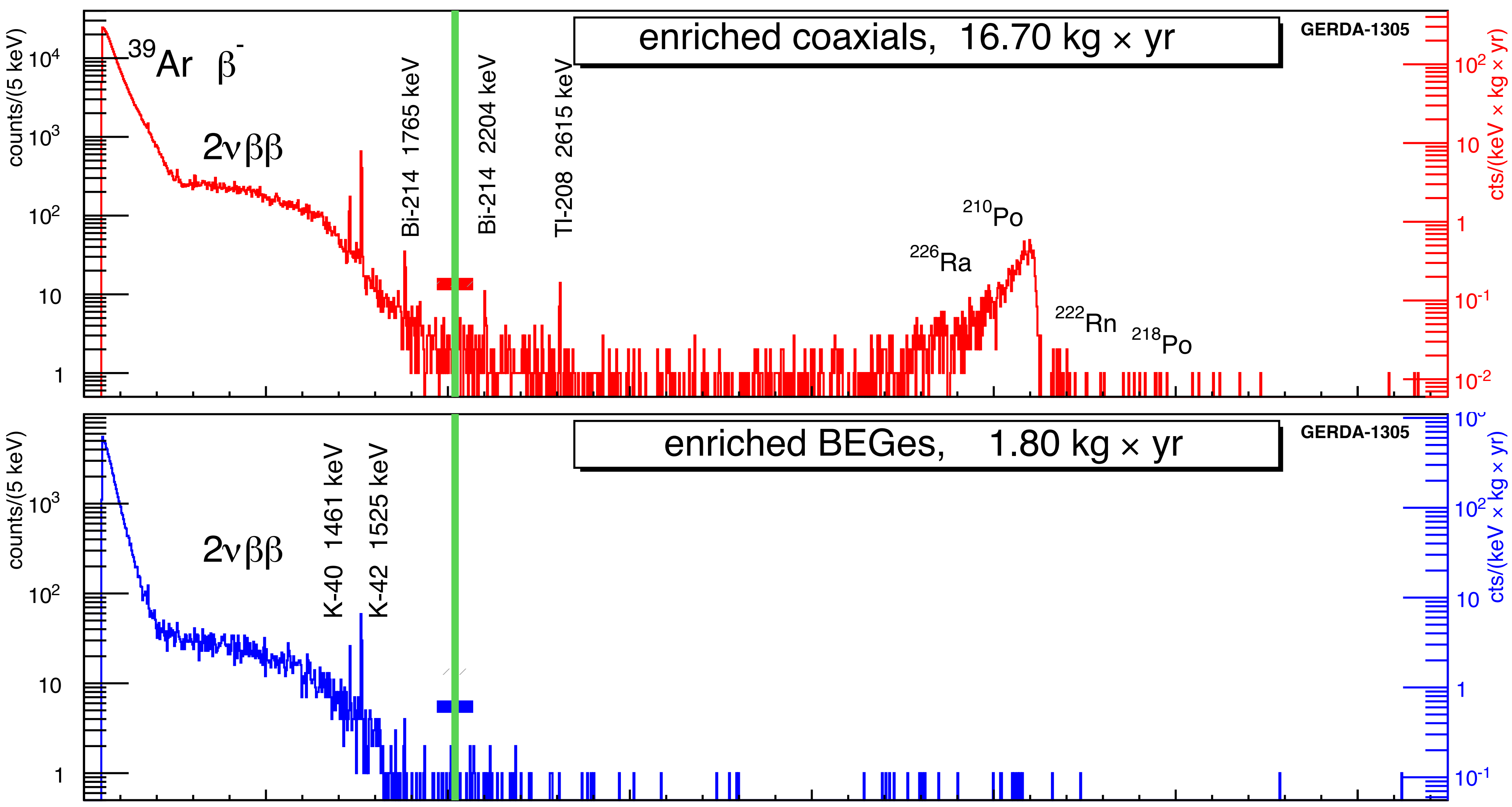
GERDA background budget

Table 2 Gamma ray screening and ^{222}Rn emanation measurement results for hardware components. The activity of the mini shroud was derived from ICP-MS measurement assuming secular equilibrium of the ^{238}U decay chain. Estimates of the BI at $Q_{\beta\beta}$ are based on efficiencies obtained by MC simulations [13, 14] of the Gerda setup.

component	units	^{40}K	^{214}Bi&^{226}Ra	^{228}Th	^{60}Co	^{222}Rn	BI 10^{-3} cts/(keV·kg·yr)
close sources: up to 2 cm from detectors							
Copper det. support	µBq/det.	< 7	< 1.3	< 1.5			< 0.2
PTFE det. support	µBq/det.	6.0 (11)	0.25 (9)	0.31 (14)			0.1
PTFE in array	µBq/det	6.5 (16)	0.9 (2)				0.1
mini shroud	µBq/det.		22 (7)				2.8
Li salt	mBq/kg		17(5)				≈ 0.003†
medium distance sources: 2 - 30 cm from detectors							
CC2 preamps	µBq/det.	600 (100)	95 (9)	50 (8)			0.8
cables and suspension	mBq/m	1.40 (25)	0.4 (2)	0.9 (2)	76 (16)		0.2
distant sources: further than 30 cm from detectors							
cryostat	mBq					54.7 (35)	< 0.7
copper of cryostat	mBq	< 784	264 (80)	216 (80)	288 (72)		] < 0.05
steel of cryostat	kBq	< 72	< 30	< 30	475		] < 0.05
lock system	mBq					2.4 (3)	< 0.03
^{228}Th calib. source	kBq			20			< 1.0

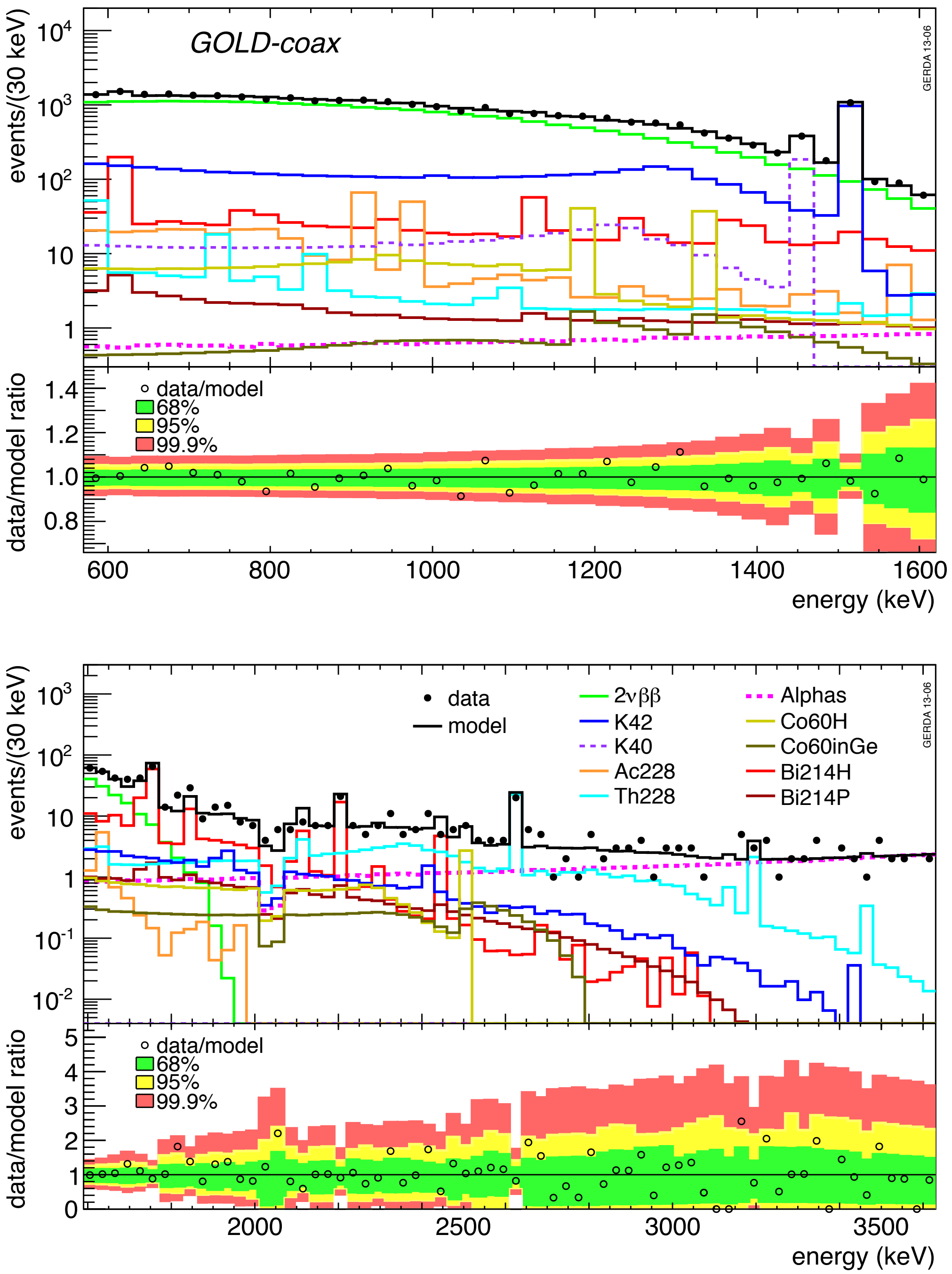
†) value derived for 1 mg of Li salt absorbed into the surface of each detector

GERDA spectrum



- Green line: Blinded signal region
- Horizontal bar: region used to measure background.

Fitting the data

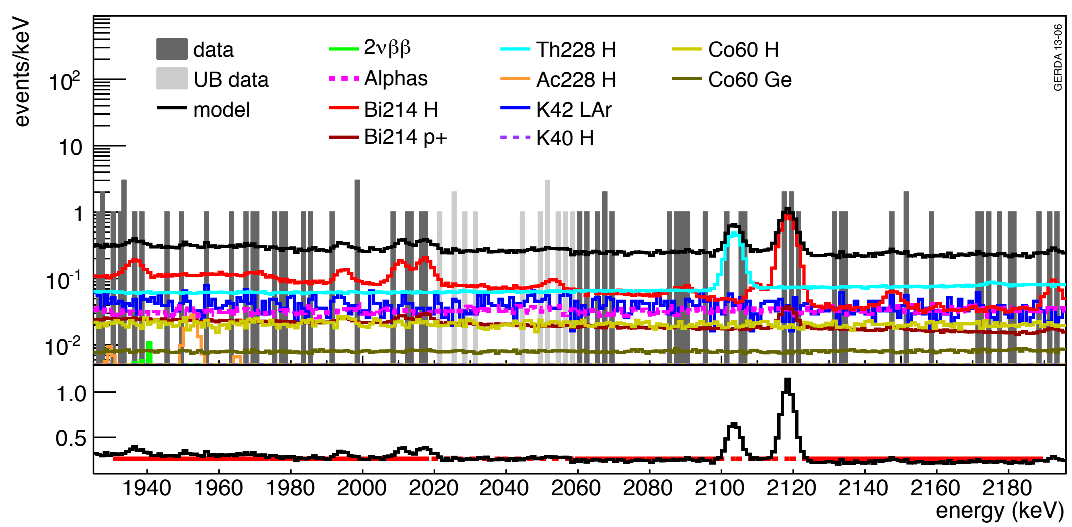


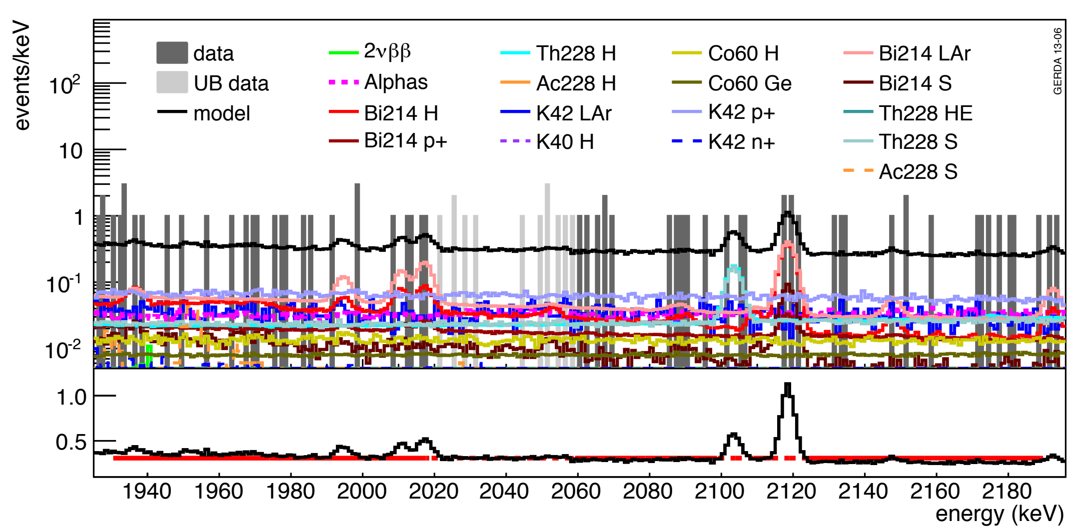
Minimum model for Golden dataset

- Only known and visible contributions considered
- Data used: 09.11.2011-03.03.2013 in order to be in time for the unblinding
- Fit range: 570-7500 keV
- No hint for any different behavior in the last 3 months of data
- Background Model published: EPJC 74 (2014) 2764
- Alternative (maximum) model constructed, including all possible backgrounds

Background prediction before PSD

- Both min and max model predict a flat bkg at $Q_{\beta\beta} \rightarrow$ unblind side-bands!
- BI predicted from bkg models and fitted from data are in agreement





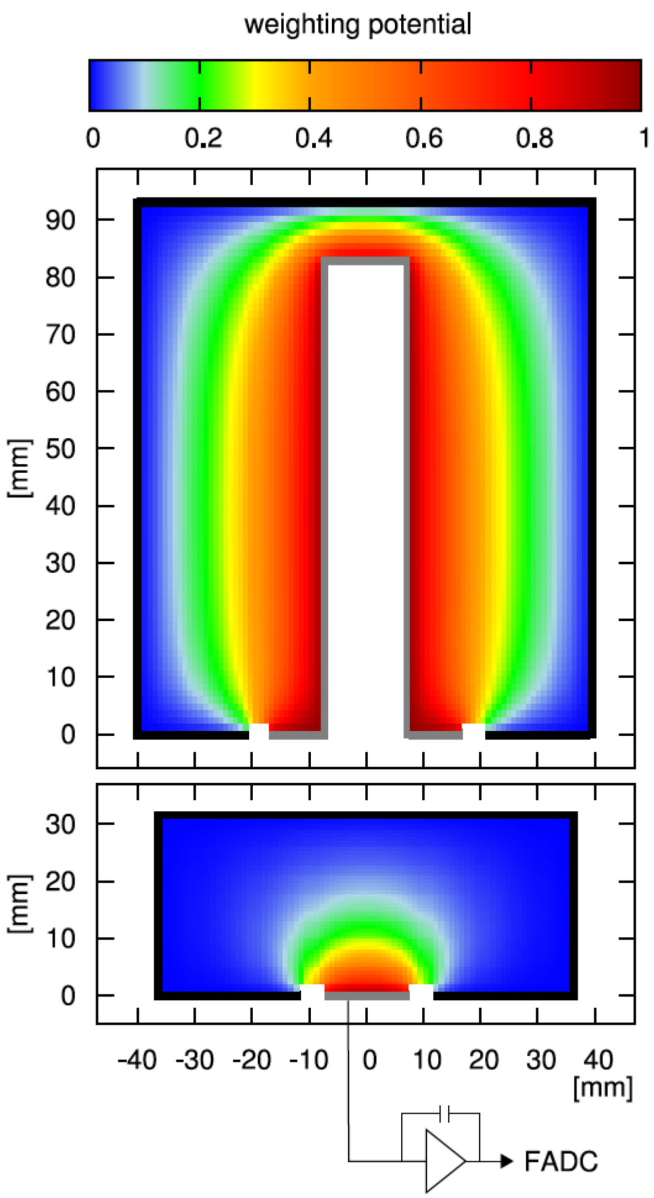
BI before PSD interpolated in the Region of Interest:

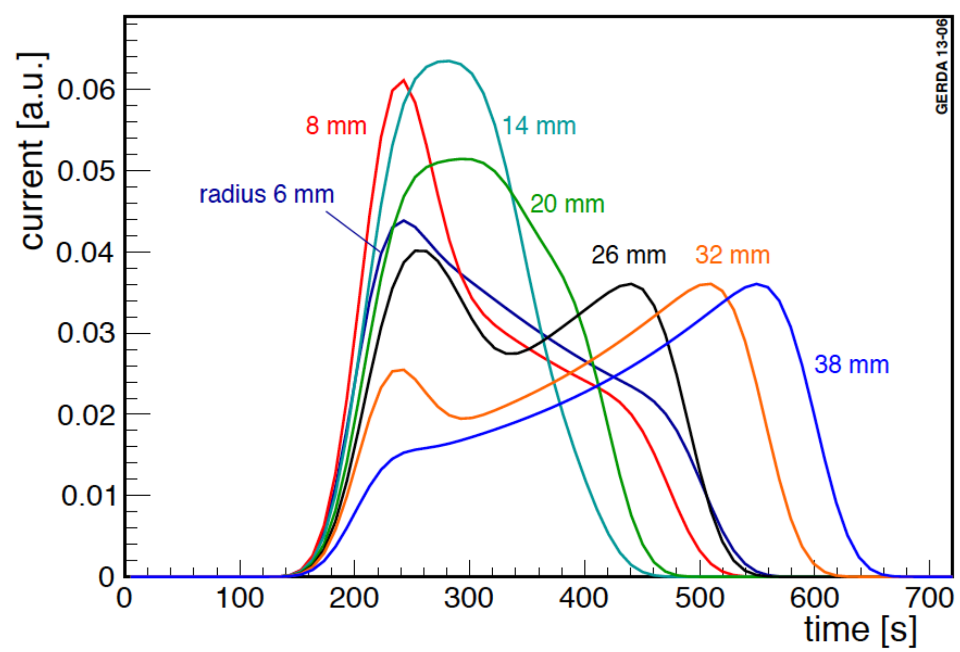
	GOLD-coax	SUM-BEGe
	BI in ROI before PSD (10 keV for coaxial, 8 keV for BEGe) [10^{-3}cts/(keV·kg·yr)]	
interpolation	17.5[15.1, 20.1]	36.1[26.4, 49.3]
minimum	18.5[17.6, 19.3]	38.1[37.5, 38.7]
maximum	21.9[20.7, 23.8]	-

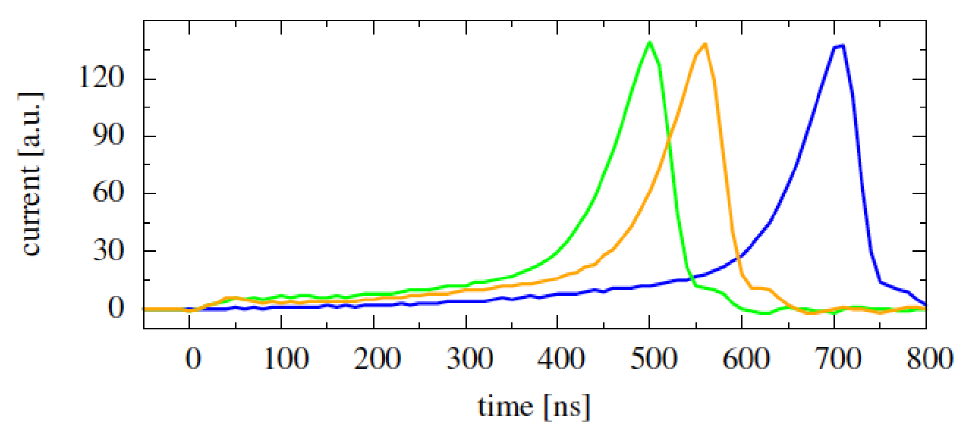
Analysis recipe: fit with Gaussian peak and flat background in the 1930-2190 keV region, excluding known gamma peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi).

Pulse Shape Discrimination

- PSD: distinguish between $(0\nu2\beta)$ signal-like events (SSE) and background-like events (MSE, p^+, n^+)
- Different PSD needed for coaxial and BEGe detectors

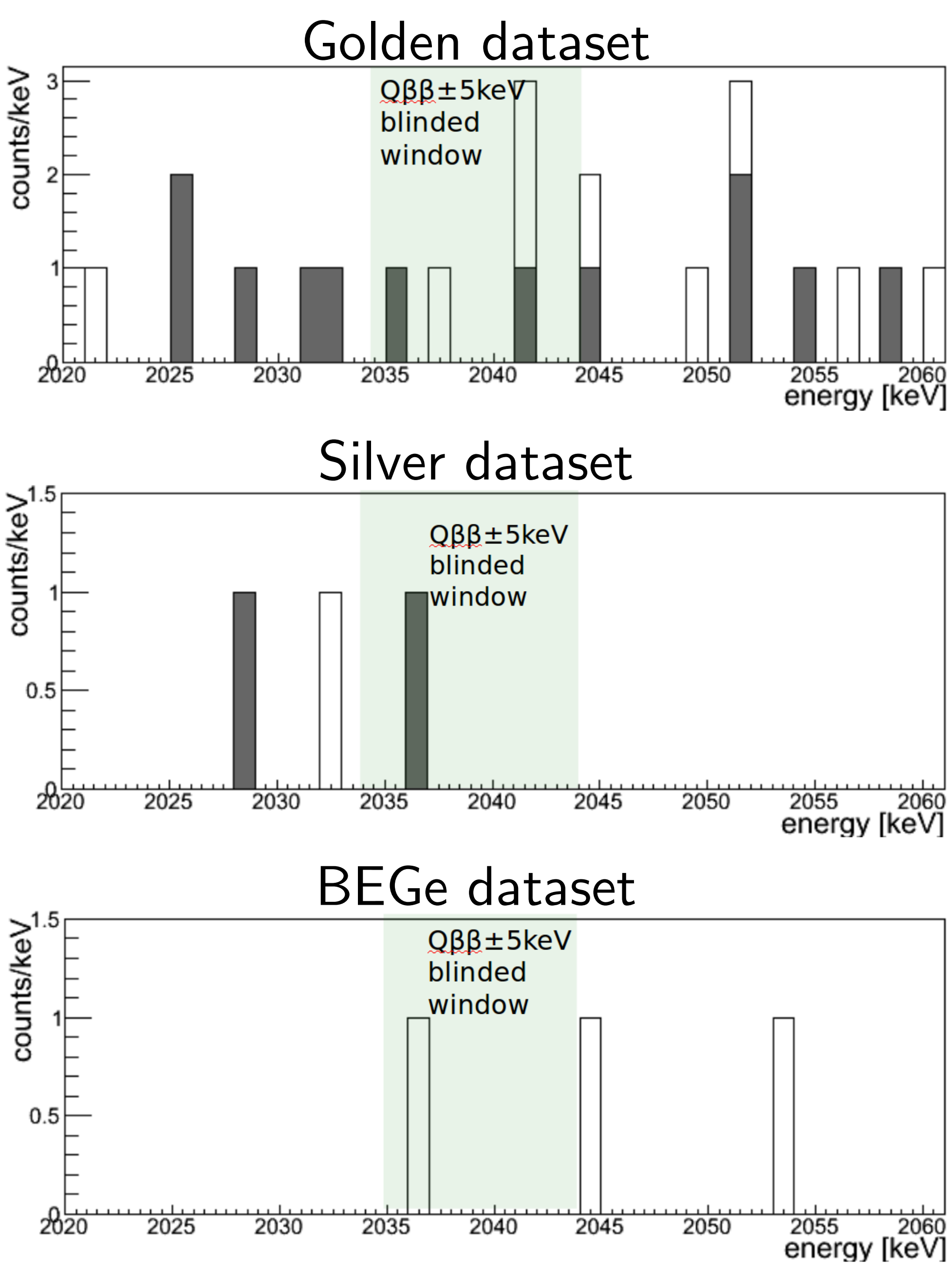






- Simulated current pulse in coaxial detector
- Simulated current pulse in BEGe

GERDA Phase I result



Profile Likelihood Method

- best fit $N^{0\nu} = 0$
- No excess of signal over bkg
- 90% C.L. lower limit:

  $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr

- Median sensitivity: $2.4 \cdot 10^{25}$ yr

Bayesian Approach

- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]$ yr^{-1}
- best fit $N^{0\nu} = 0$
- 90% credibility interval:

  $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr

- Median sensitivity: $2.0 \cdot 10^{25}$ yr

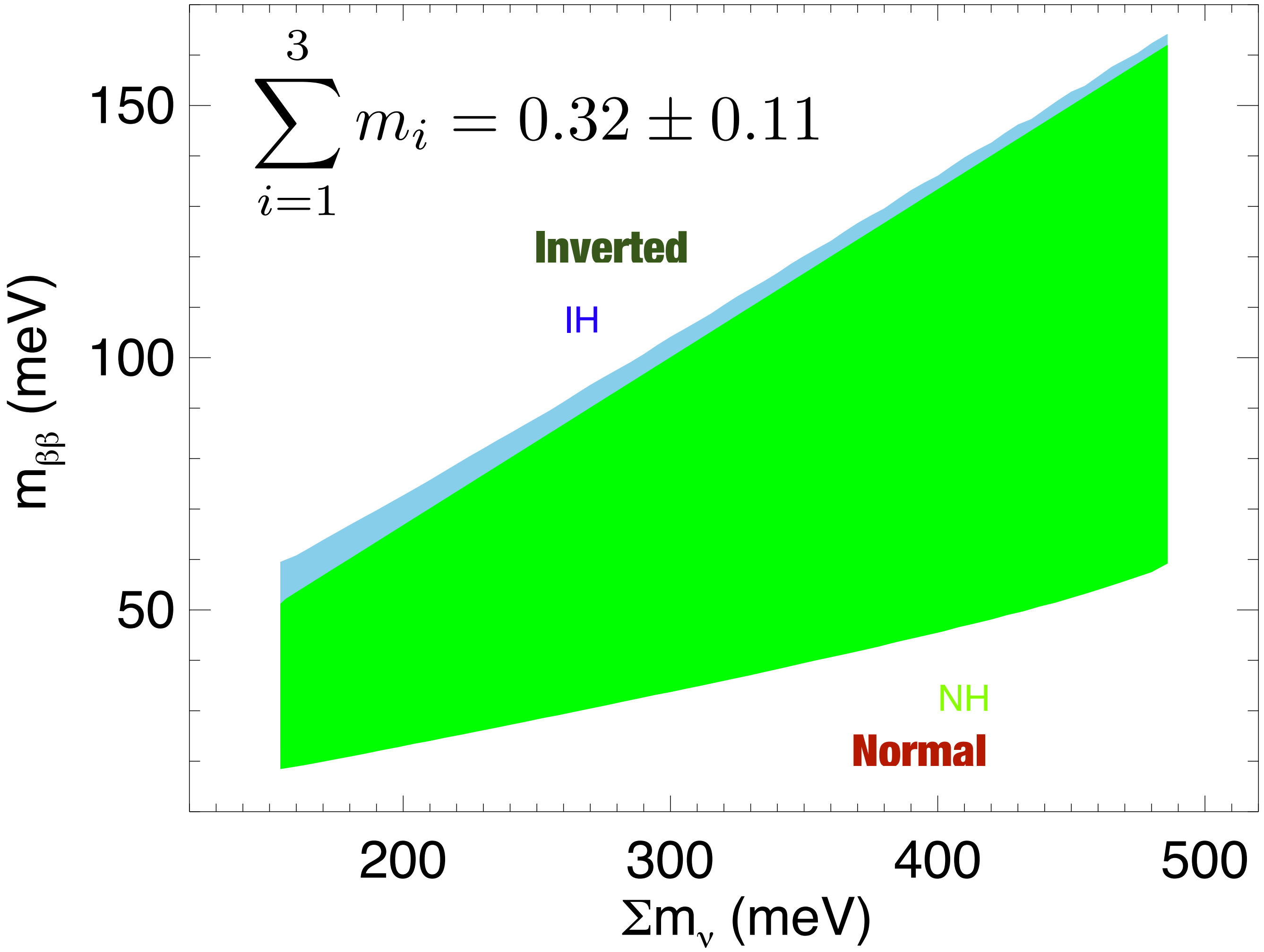
Phys. Rev. Lett. 111 (2013) 122503

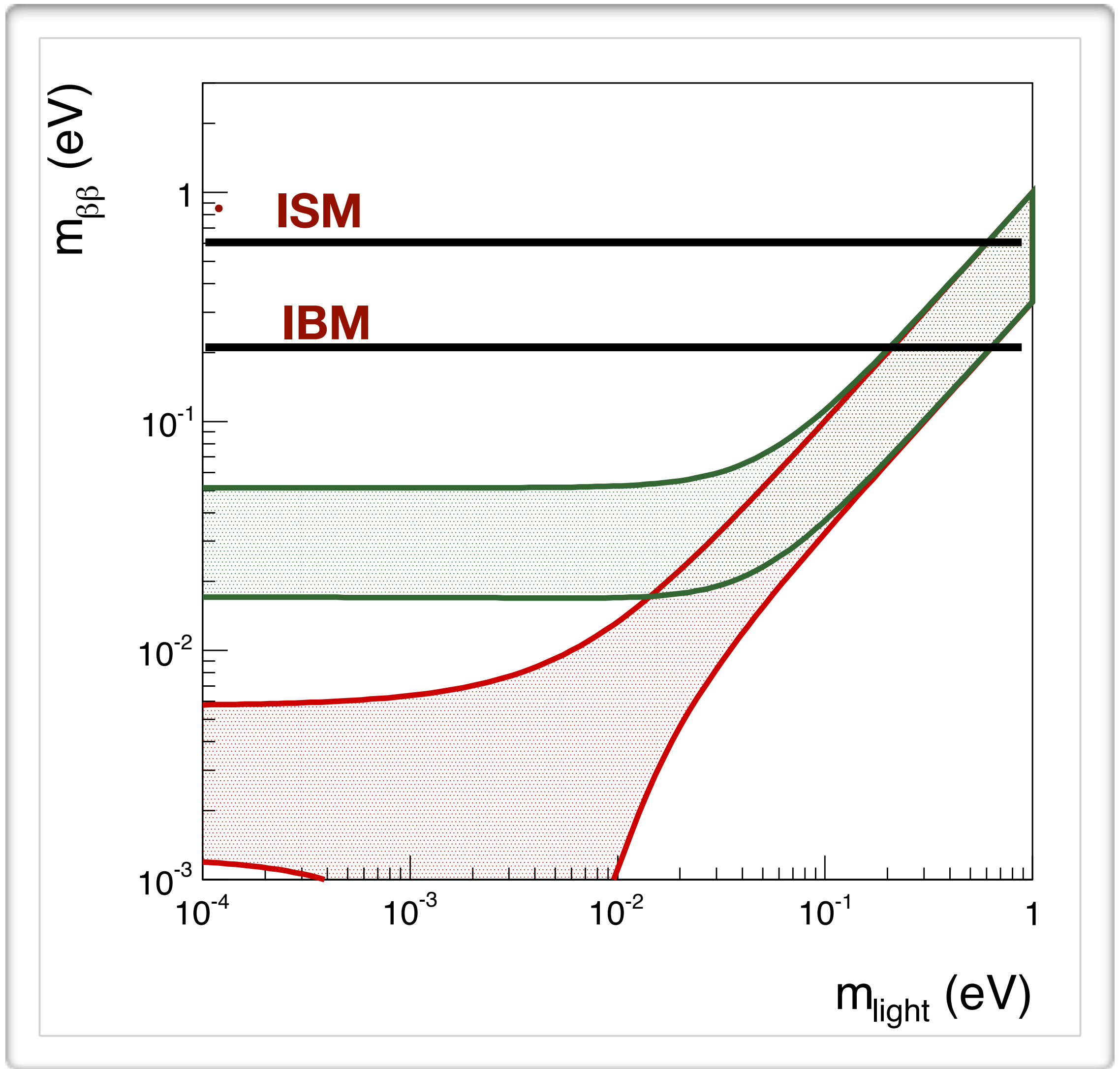
Reproducing Gerda results

- **Run example GERDAI.py in pybbsens software**
- **Input:**
- efficiency = 0.62
- ΔE = 0.02 % at 2040 MeV
- B = 1.32 x 10^{-2} ckky
- Exposure = 21.6 kg x y
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **T^{0v} = 2.2 x 10^{25} y**

- **Run example GERDAII.py in pybbsens software**
- **Input:**
- efficiency = 0.62
- ΔE = 0.01 % at 2.6 MeV
- B = 1. x 10^{-3} ckky
- Exposure: 200 kg x y
- Mass 50 kg BeGe
- Time 4 x 1.5 ~6 years
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **T^{0v} = 2.3 x 10^{26} y**

GERDA I





- **In terms of $m_{\beta\beta}$**
- ISM (worst case): **648.7 meV**; IBM2 (best case): **257.8 meV**
- **Not yet in "cosmo-region"**

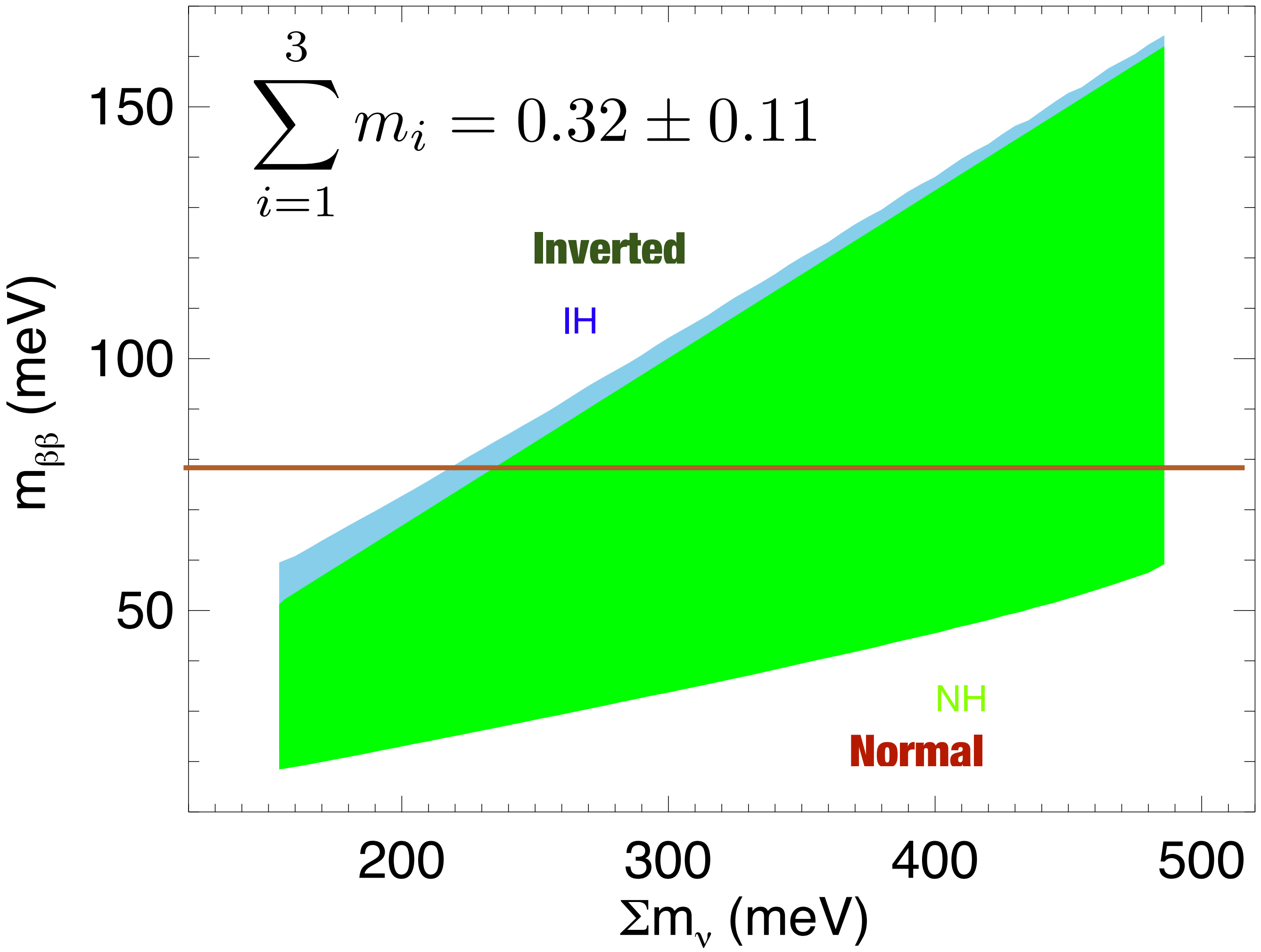
Phase II

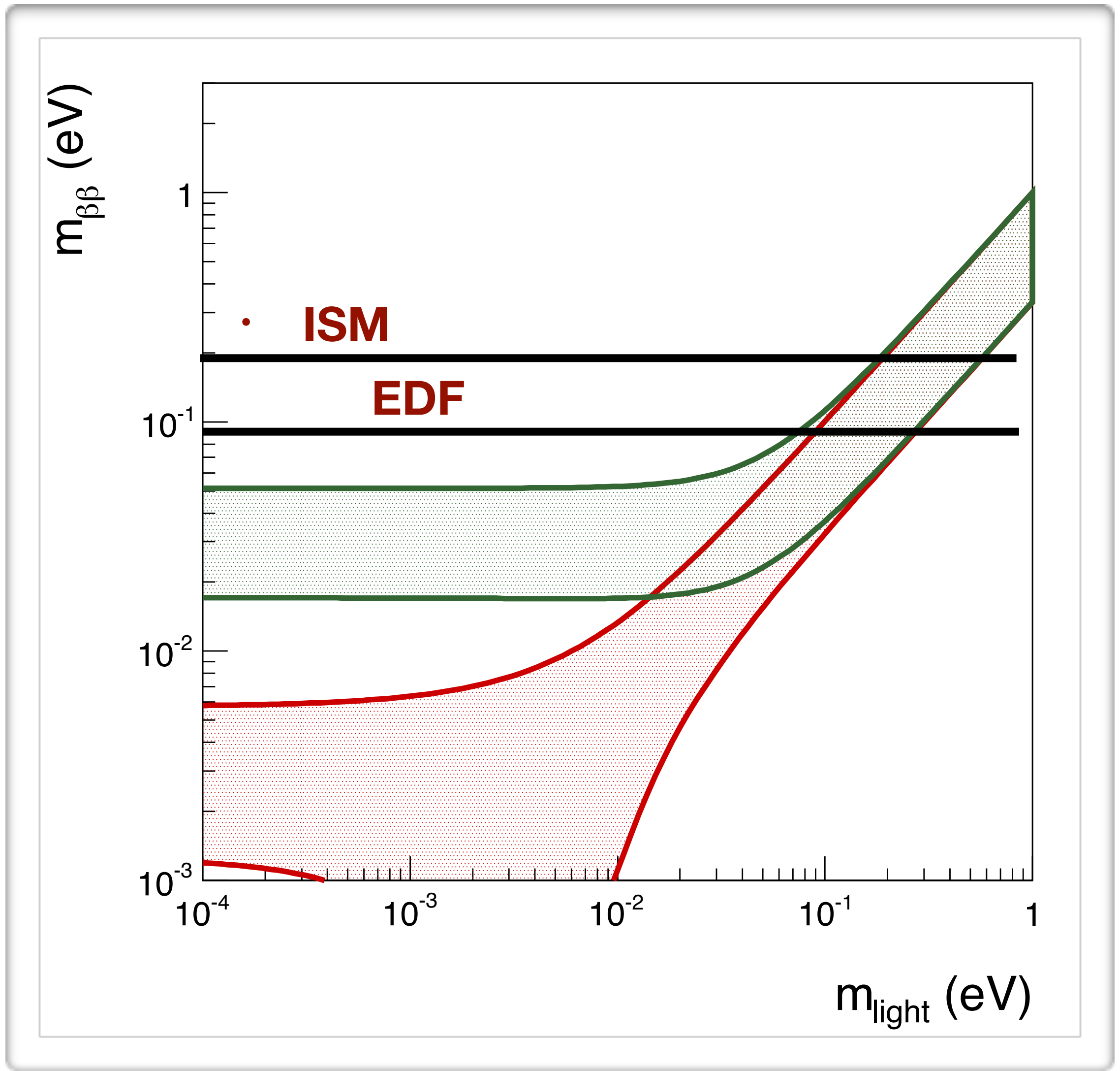
How to reach 10^{26} yr sensitivity in $T^{0\nu}_{1/2}$?

- Increase the statistics
  - More active mass (new BEGe detectors)
  - Longer data taking
- Improve energy resolution
  - Use BEGe detectors
  - Improve shaping filter
- Reduce Background
  - Cleaner cables and electronics
  - Lighter detector holders
  - Special care in crystal production
  - Reject residual background radiation
    - Improve PSD (BEGe detectors)
    - Read LAr scintillation light

- **The approach is incremental. No new technology providing an extra handle, but systematic improvement of the detector.**

GERDA II





- **In terms of $m_{\beta\beta}$**
- ISM (worst case): **200 meV**; IBM2 (best case): **80 meV**
- **Gerda II will explore a fraction of the "cosmo-region", but still "degenerate hierarchy"**

Bolometers using natural Te: CUORE

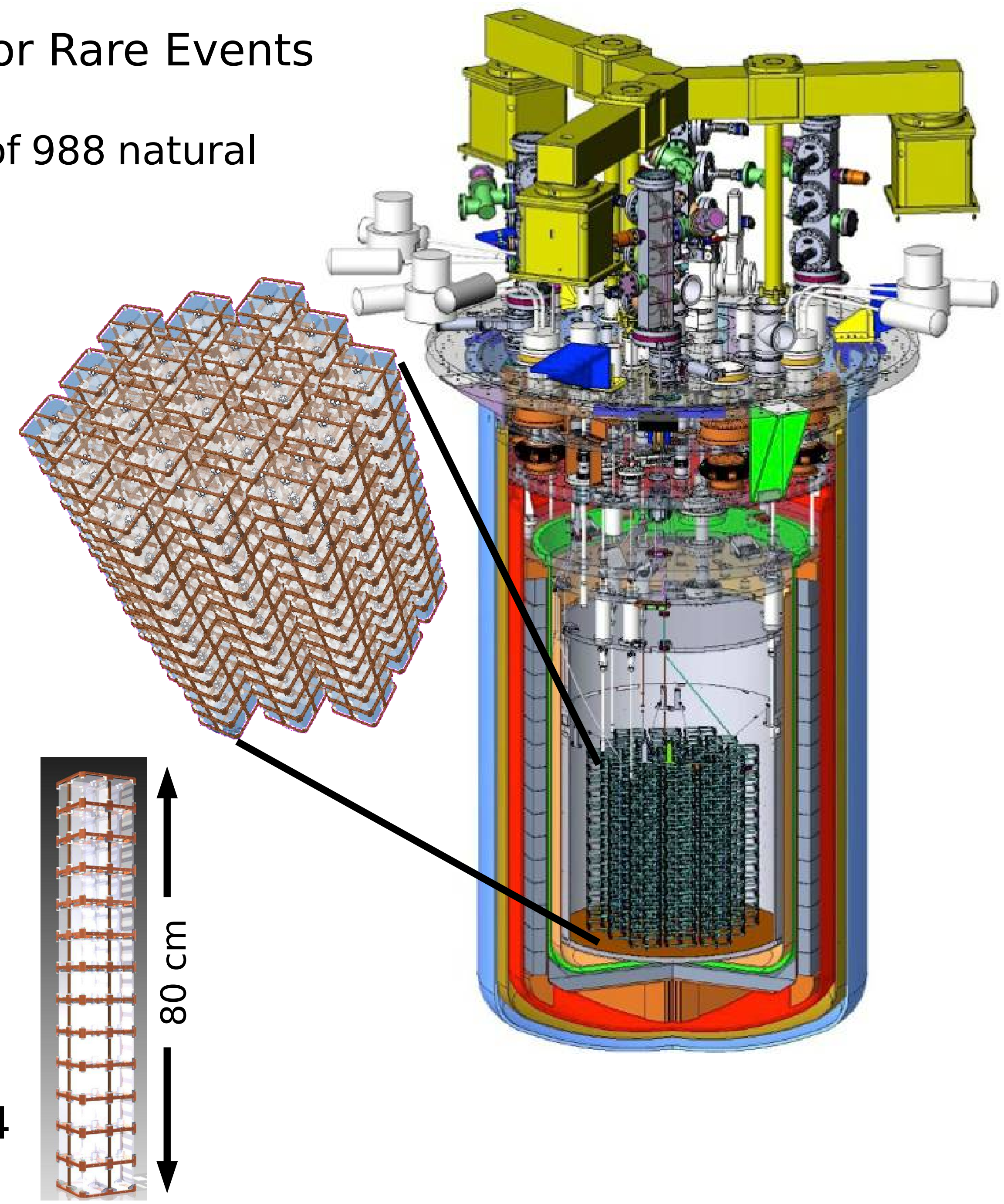
Cryogenic Underground Observatory for Rare Events

- Search for 0vDBD in ^{130}Te using an array of 988 natural TeO_2 bolometers

Detector parameters:
- ^{130}Te mass: 206 kg (~10^{27} nuclei)
- 988 TeO_2 bolometers (741 kg)
  - 19 towers
  - 52 bolometers/tower
- Single bolometer:
  - 5x5x5 cm^3 TeO_2 crystal

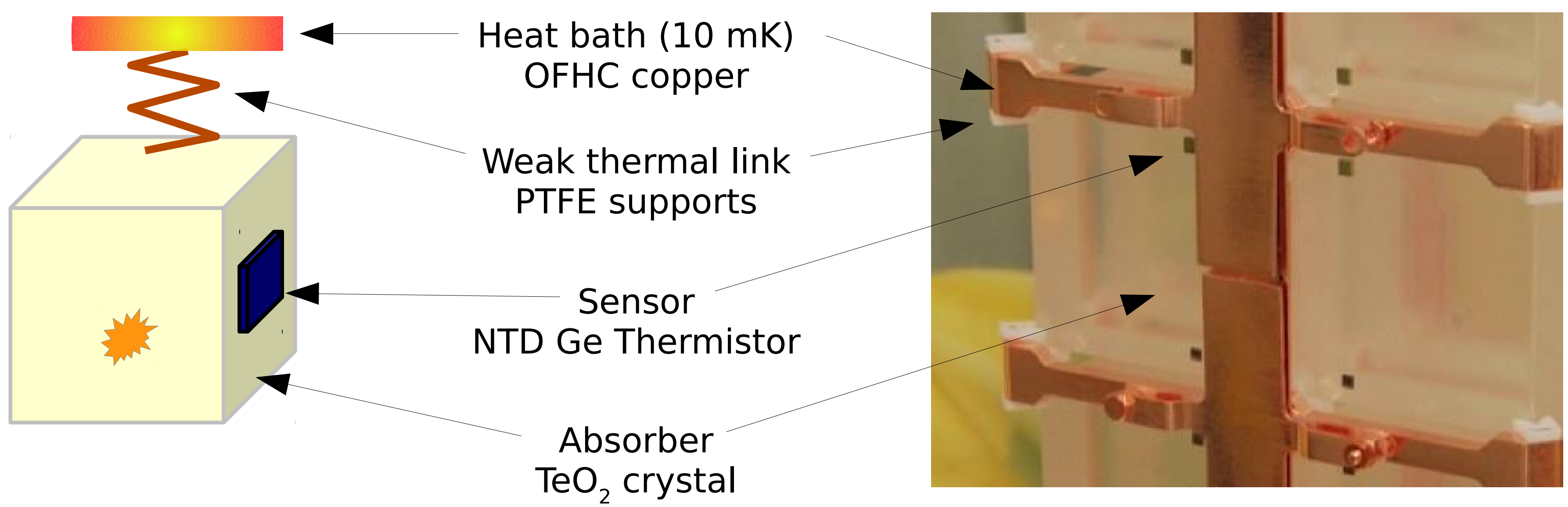
Goals:
- Resolution: 5 keV FWHM at 2.5 MeV
- Bkg: 0.01 counts/(keV kg y)

Detector cool down at the end of 2014



The Bo principle (also good for β experiments)

Energy releases produce a measurable temperature rise of the absorber crystal: $\Delta T = \frac{E}{C}$

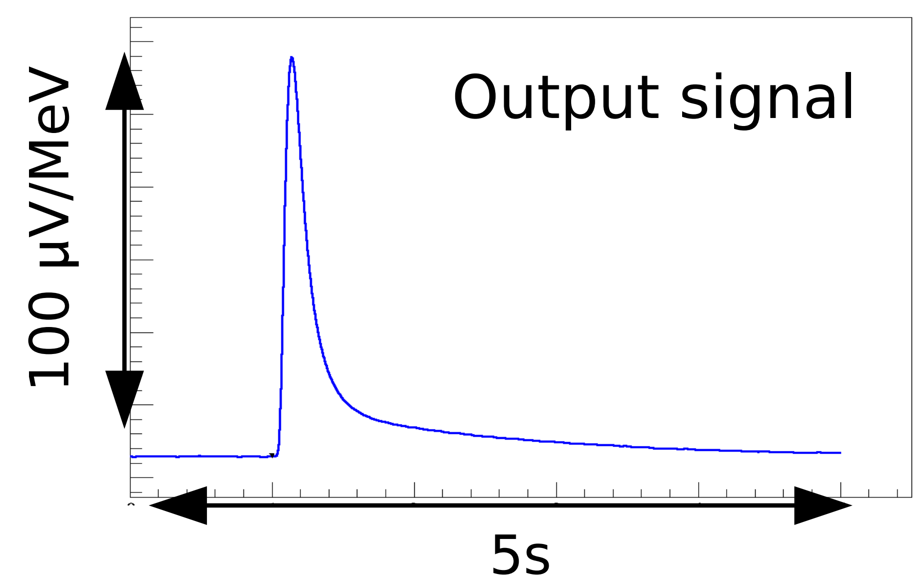


Absorber

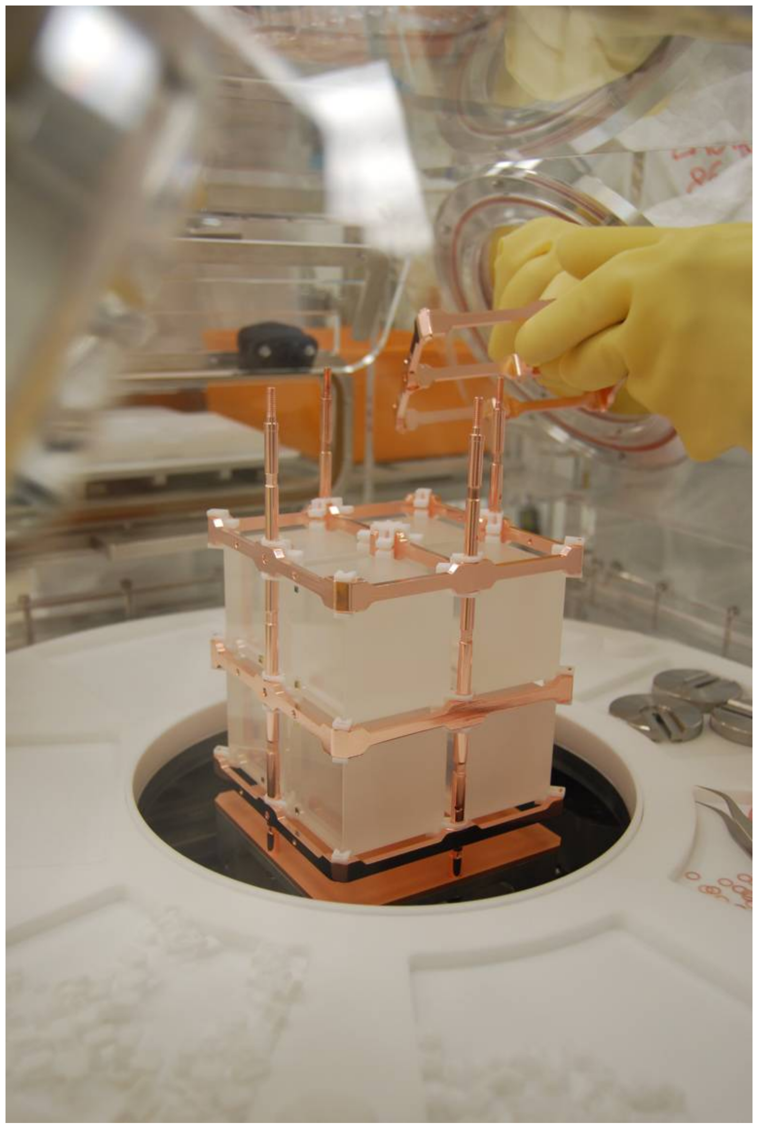
- Dimension: 5x5x5 cm3
- M ~ 0.75 kg
- C ~ 10^{-9} J/K
- ΔT/ΔE ~ 100 μK/MeV

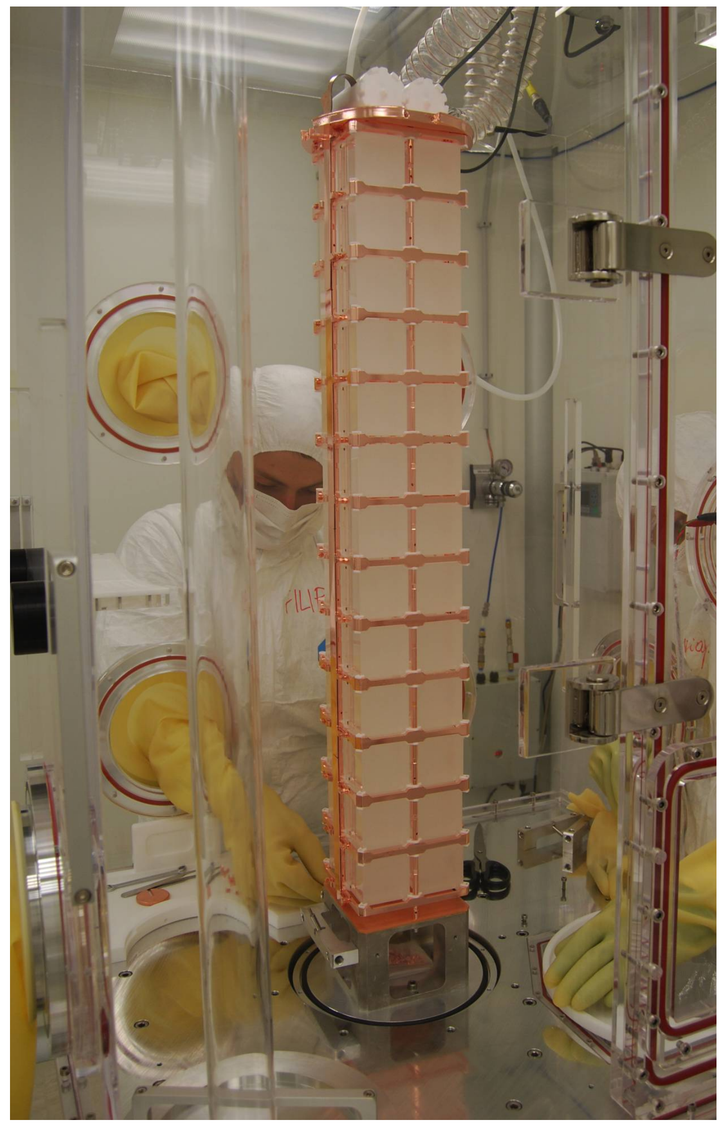
Sensor

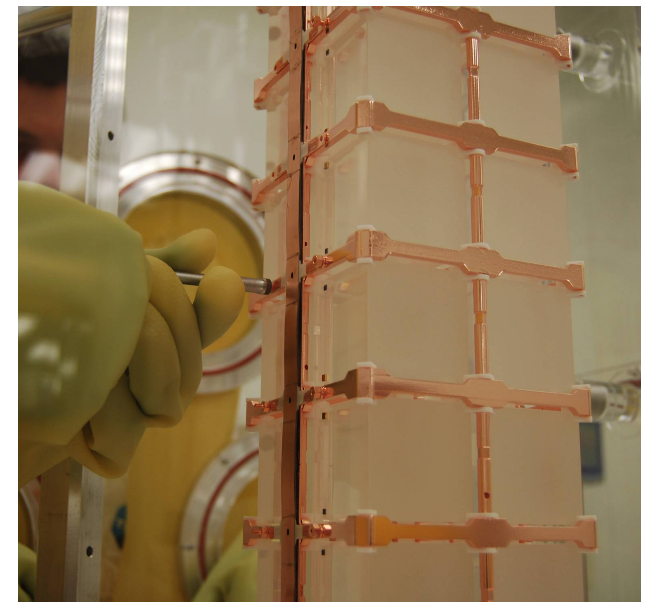
- R = R0 $\exp[(T_0/T)^{1/2}]$
- R ~ 100 MΩ
- ΔR/ΔE ~ 3 MΩ/MeV



Cuore assembly



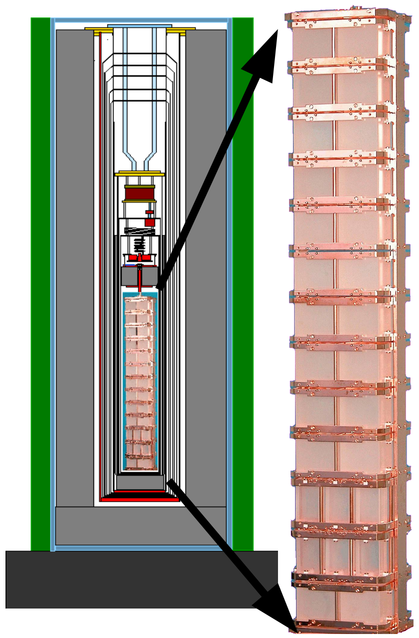




- Copper support structure
- Teflon supports
- Crystals
- Wire trays

All operations performed in glove boxes to avoid radon recontamination

Cuoricino (2003-2008)

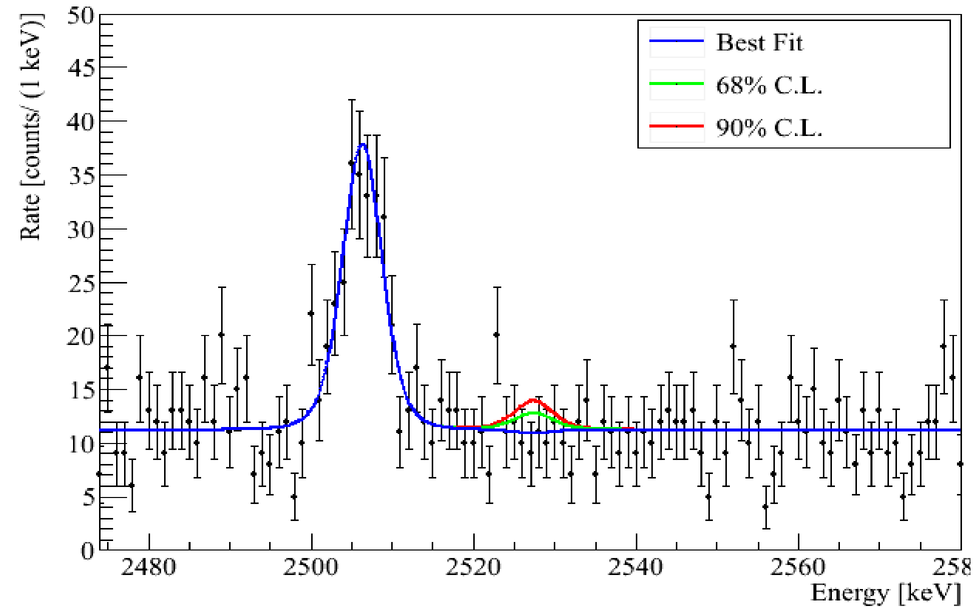


- 62 TeO_2 bolometers
- 41 kg (11.3 kg in ^{130}Te)
- Statistics: 19.75 kg y in ^{130}Te
- Resolution: 6.3 keV FWHM
- Bkg: 0.15 counts/(keV kg y) (790g crystals only)

$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\ y\ @\ 90\%\ CL$$

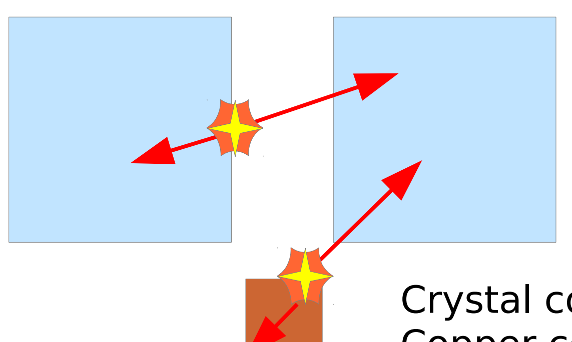
$$m_{\beta\beta} < 0.30 \div 0.71\ eV$$

Astropart. Phys. 34 (2011) 822–831

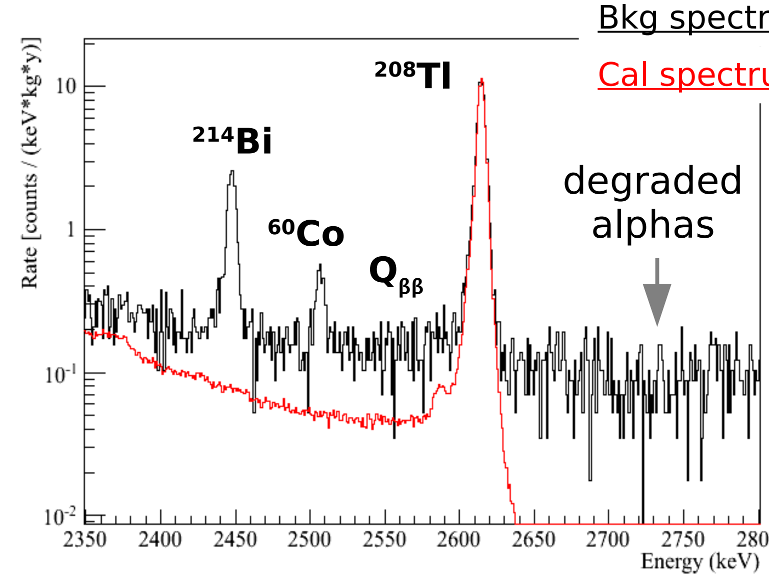


Main background contributions

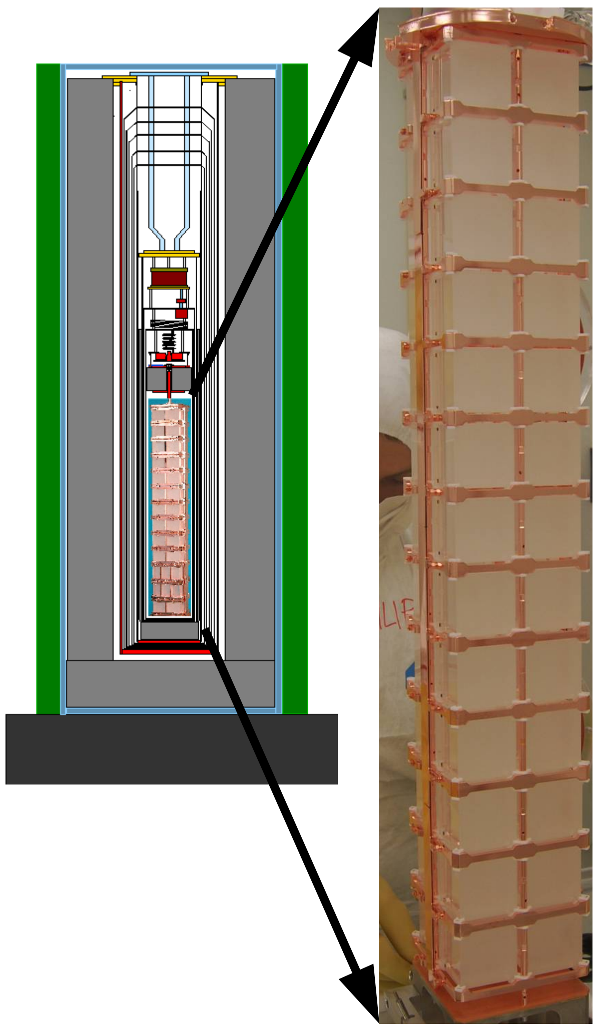
- Gammas from ^{208}Tl (^{232}Th cont. in cryostat shields): (30±10)%
- Radioactive contaminations from crystal surfaces: (10±5)%
- Radioactive contaminations from Cu holders surfaces: (50±20)%



Crystal contamination: double hit
Copper contamination: single hit



Cuore-0



- A single CUORE-like tower:
  - 52 5x5x5 cm^3 TeO_2 bolometers

- Test of the CUORE cleaning procedures
- Test of the CUORE assembly procedures
- A sensitive 0vDBD experiment

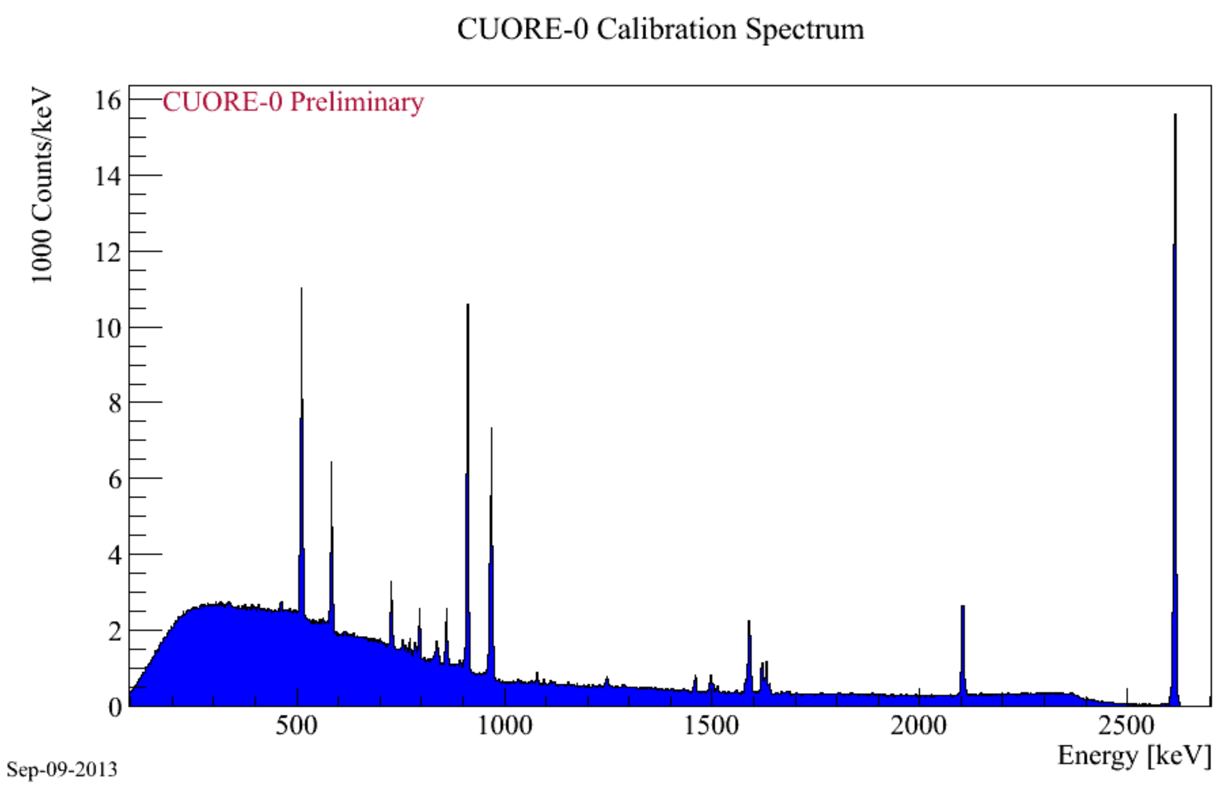
- Same detector mass as CUORICINO:
  - TeO2 mass: 39 kg
  - 130Te mass: ~11 kg

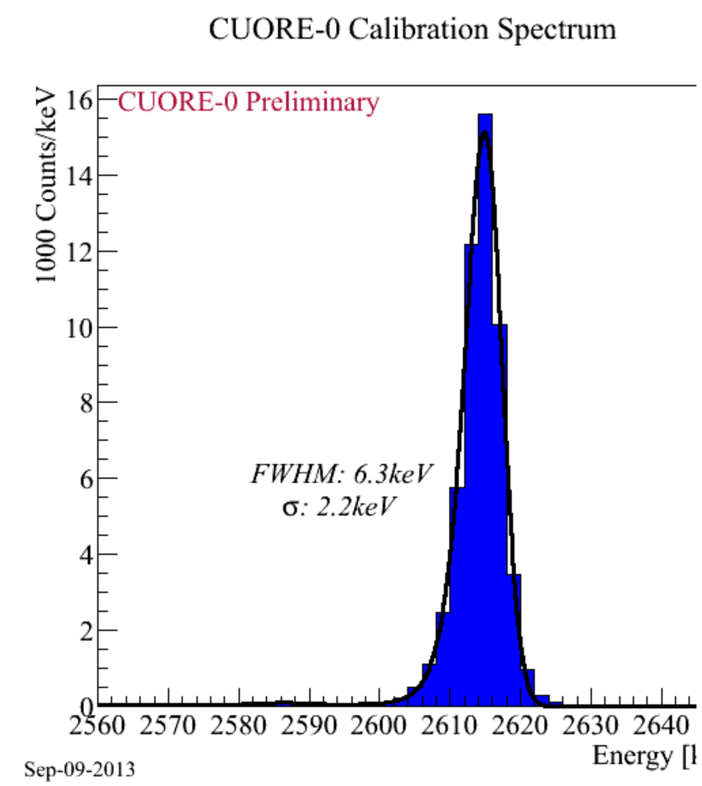
- Shielding:
  - Internal and external lead shield
  - Borated pohlyethylene shield
  - Anti radon box

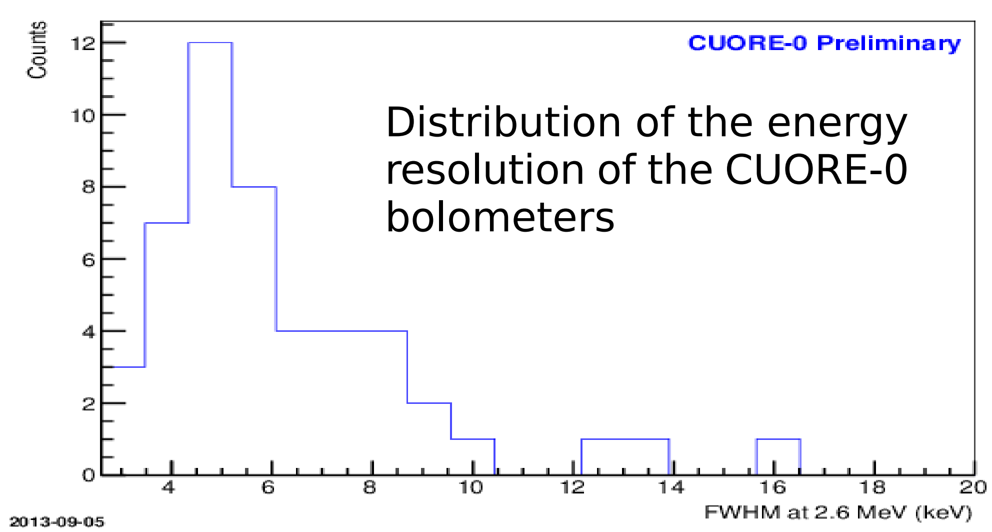
Started data taking in March 2013

Operated in the CUORICINO cryostat:
γ background not expected to change → study background due to near surface contaminations

Calibration



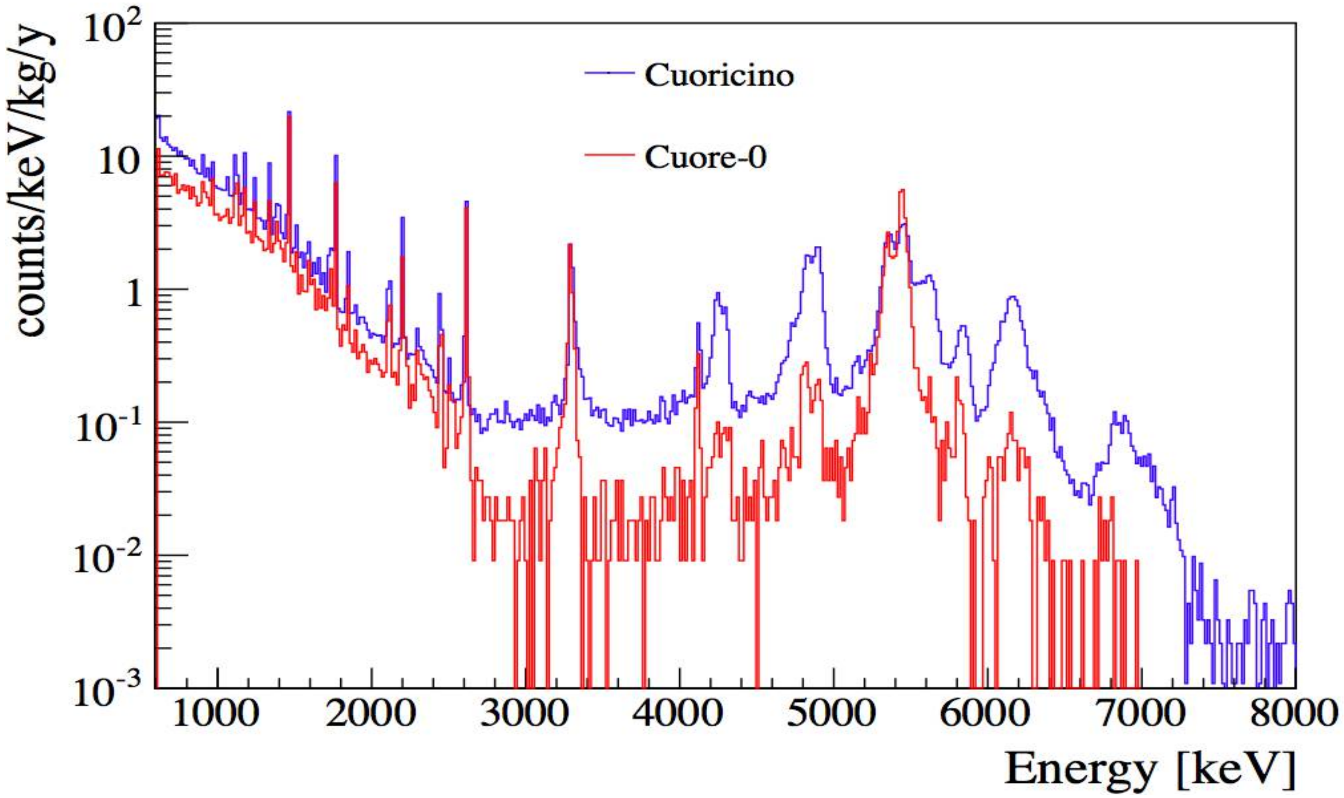


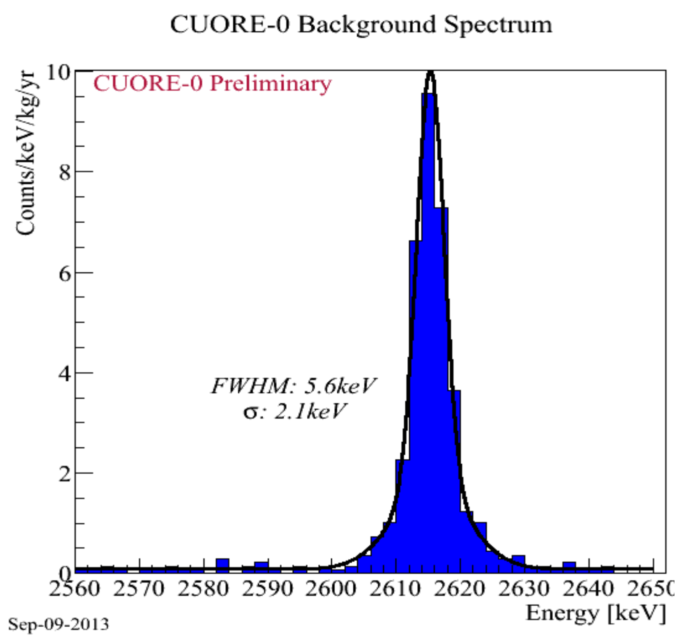


Calibration performed by inserting ^{232}Th source between the cryost and the external lead shield

Energy resolution: 6.3 keV FWHM

Background (Cuore-0)





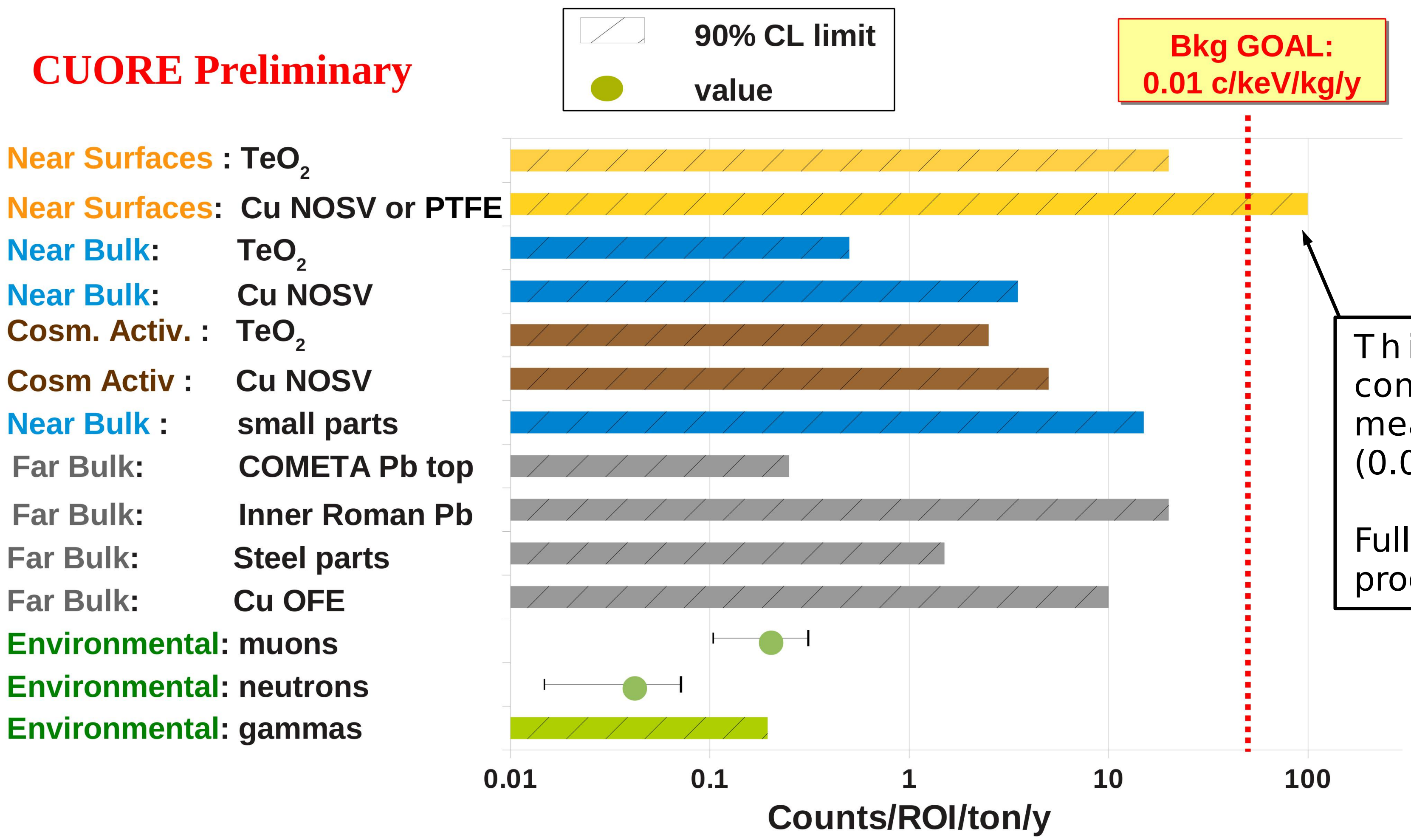
Energy resolution in bkg
5.6 keV FWHM

^{238}U γ lines reduced by a factor 2 (better radon control)
^{232}Th γ lines unchanged (originate from the cryostat)
^{238}U and ^{232}Th α lines reduced thanks to improved detector surface cleaning

Flat background	Avg flat bkg [counts/(keV kg y)]		Signal efficiency [%]
	0vDBD region	2.7 – 3.9 MeV region	(detector + cuts)
CUORICINO	0.153 ± 0.006	0.110 ± 0.001	83 ± 1
CUORE-0	0.074 ± 0.012	0.019 ± 0.002	78 ± 1

Background budget

- New cryostat with radio-pure materials: γ contributions are made negligible
- Less copper surface facing the crystals: α bkg from copper surfaces can be reduced
- More crystal surfaces facing each others: more effective anticoincidence, negligible α bkg from crystal surfaces

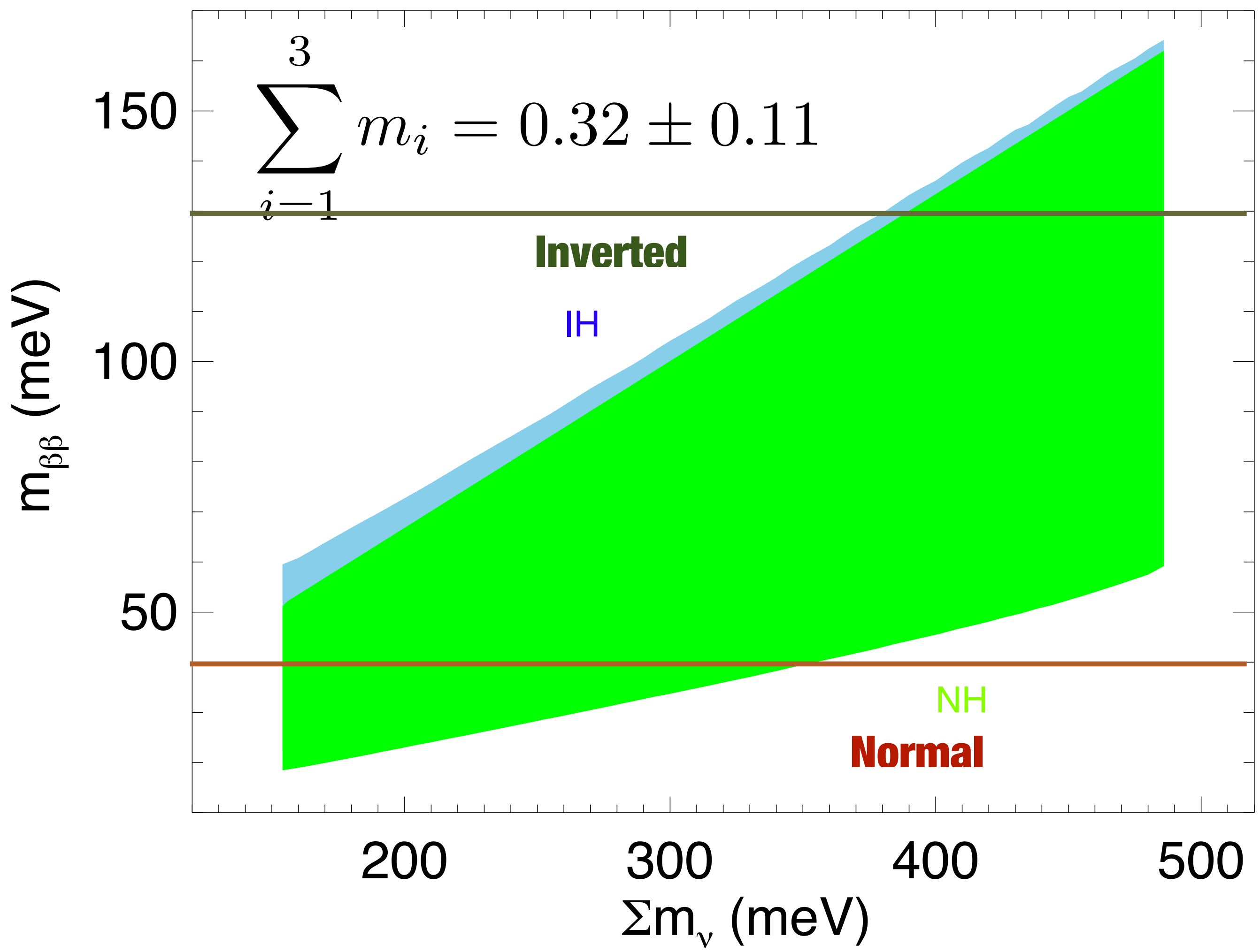


Conservative upper limits

This is the "alpha" continuum background measured in CUORE-0 (0.019 counts/(keV kg y)

Full MC simulation still in progress

Predicting CUORE results

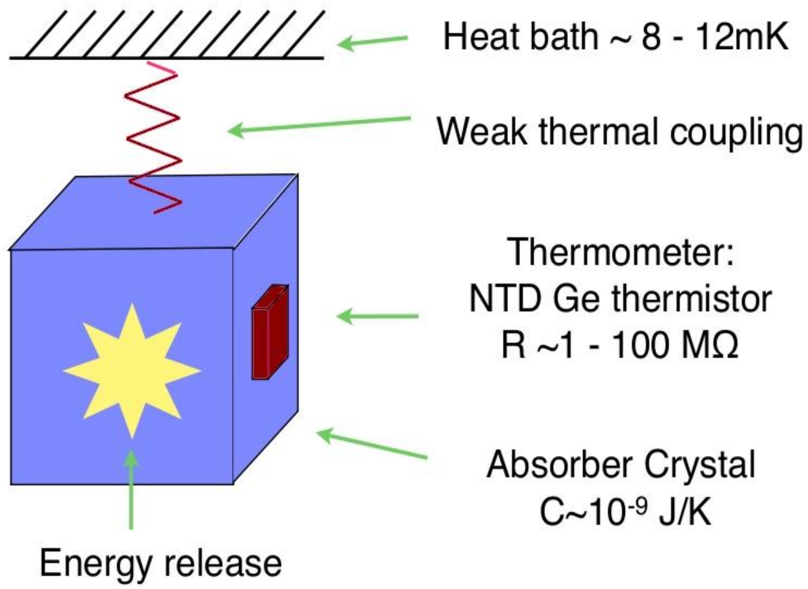


- **Run example CUORE.py in pybbsens software**
- **Input:**
- efficiency = 0.87
- ΔE = 0.02 % at 2600 MeV
- B = 1. x 10^{-2} ckky (projected)
- Exposure =1000 kg x y
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **$T^{0\nu}$ = 1 x 10^{26} y**

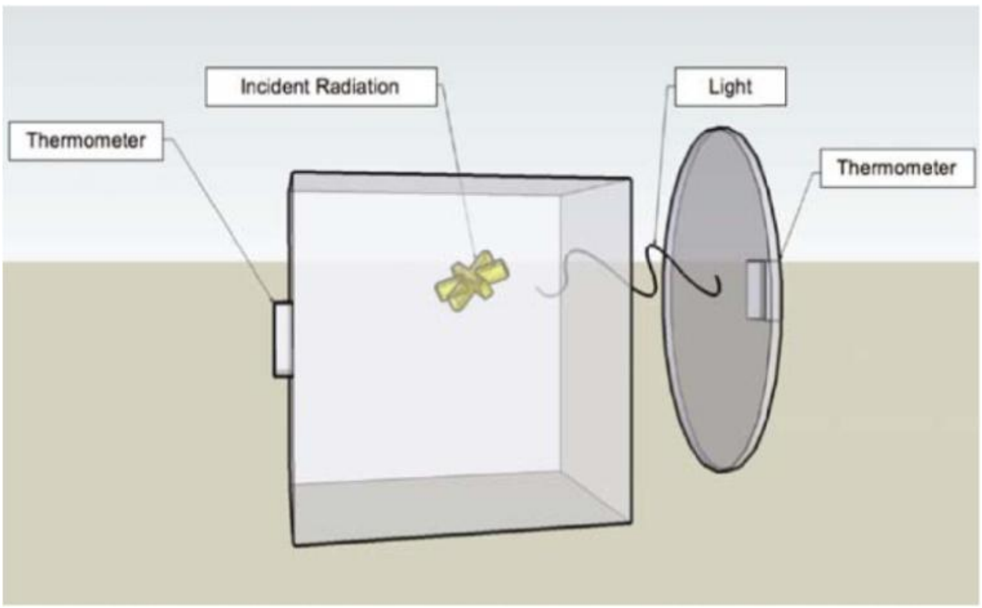
- Mass 206 kg
- Time ~5-7 years
- **$m_{\beta\beta}$ = 41-129 meV**

- **Reaches similar sensitivity on period than GERDA-I but more sensitive to $m_{\beta\beta}$.**
- **Will cover a significant fraction of the cosmo-region (depending on NME)**

Scintillating Bolometers

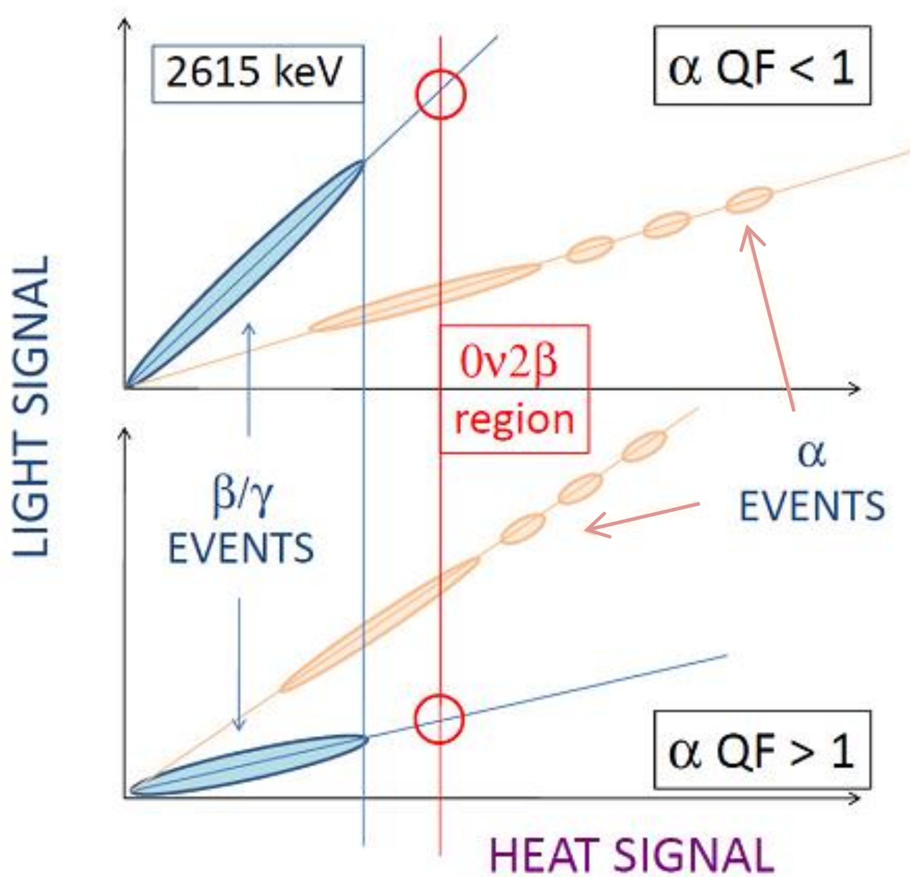


A particle interaction in the crystal causes a temperature increase.
The temperature increase can be transformed in a voltage variation by means of proper sensors.



If the crystal scintillates, a further background suppression can be achieved by means of the scintillation light read-out.
β/γ events, indeed, emit more light with respect to α events.
Therefore, we expect the two different events to lie on different bands in the light vs heat scatter plot.

The detection technique



Research Proposal (B1) LUCIFER 2009

If the crystal scintillates, a further background suppression can be achieved by means of the scintillation light read-out.

β/γ events, indeed, emit more light with respect to α events.

Therefore, we expect the two different events to lie on different bands in the light vs heat scatter plot.

→ Only β/γ background!!

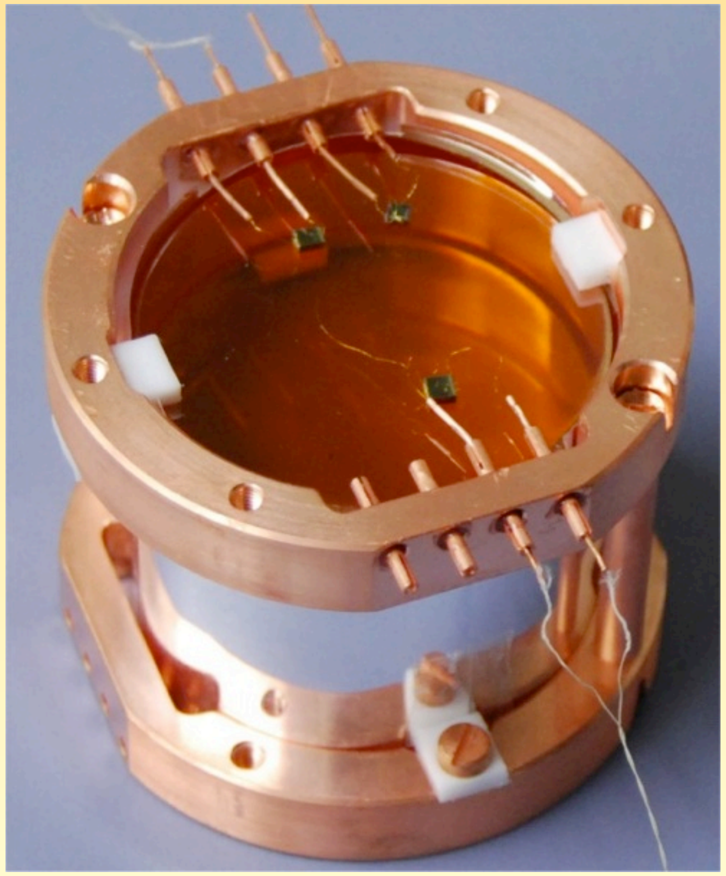
Lucifer (Lumineux)

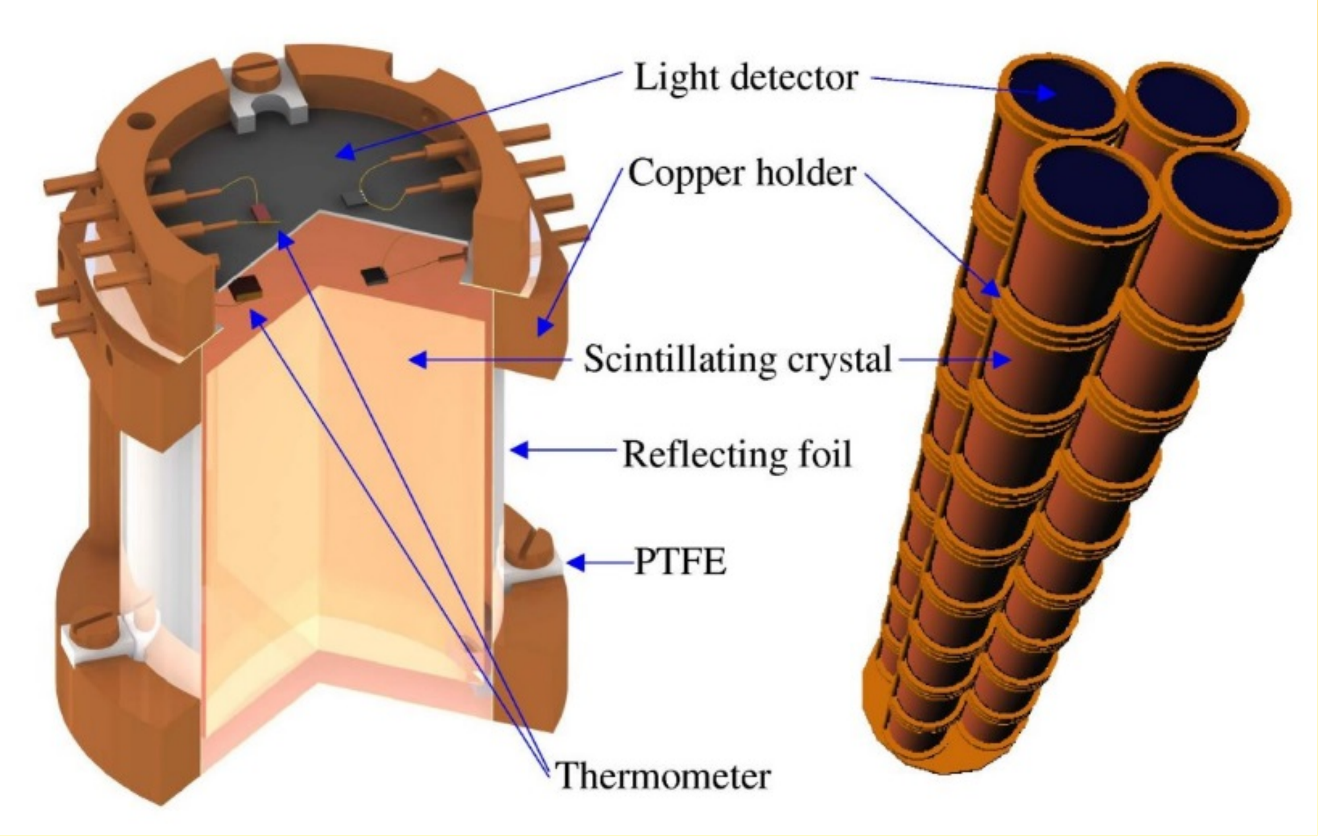
Lucifer will be composed by an array of 32÷36 enriched (95%) $Zn^{82}Se$ crystals.
The total ^{82}Se nuclei will be (6.7÷8.0) 10^{25}

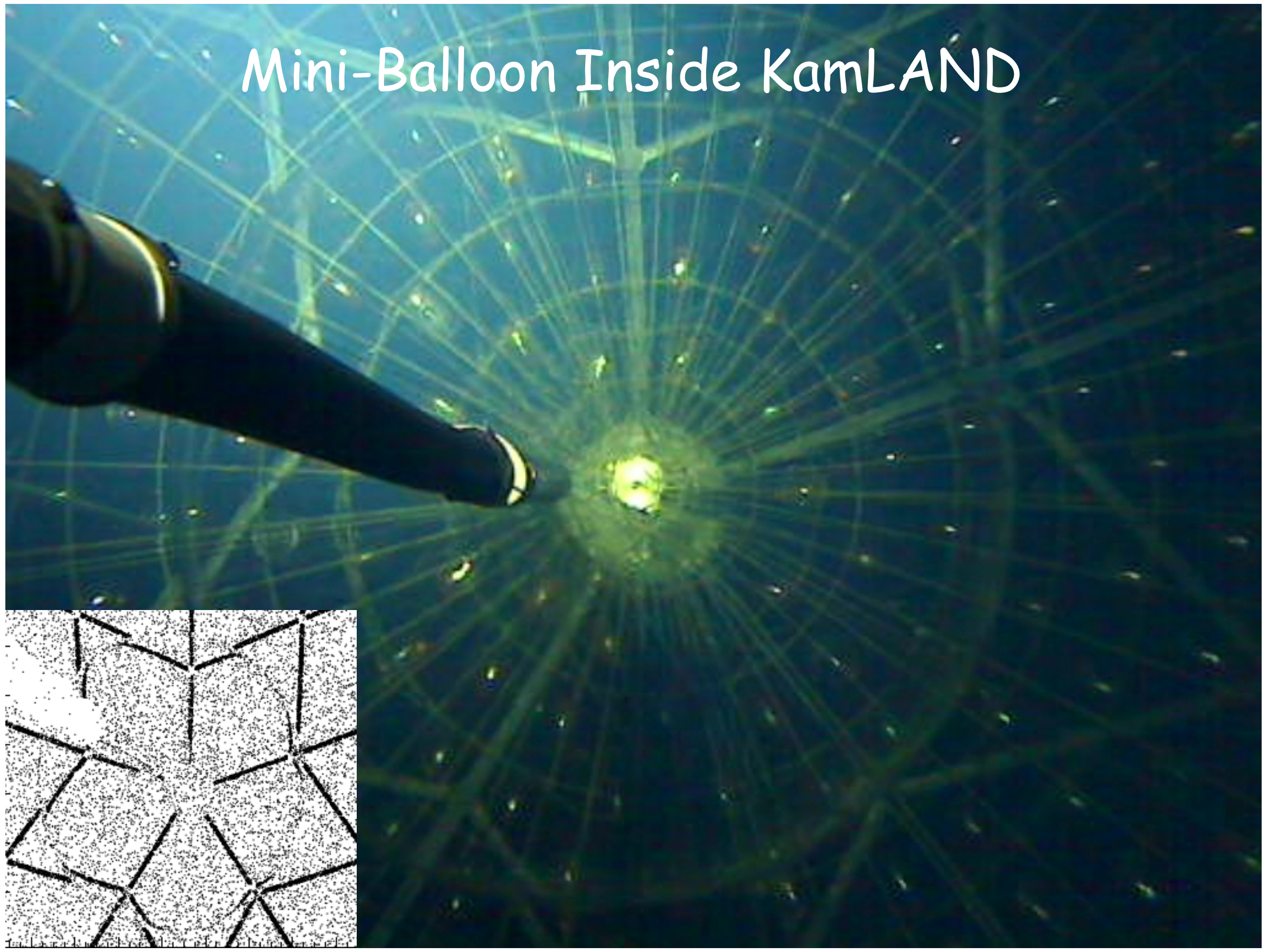
The mass of the single detector will be 460 g

The expected background in the ROI (2995 keV) is of the order of 1÷2 10^{-3} c/keV/kg/y

The energy resolution of the single detector is expected to be ~ 10÷15 keV FWHM







Low resolution, high self-shielding experiments: LS calorimeters, KamLAND-ZEN and SNO+

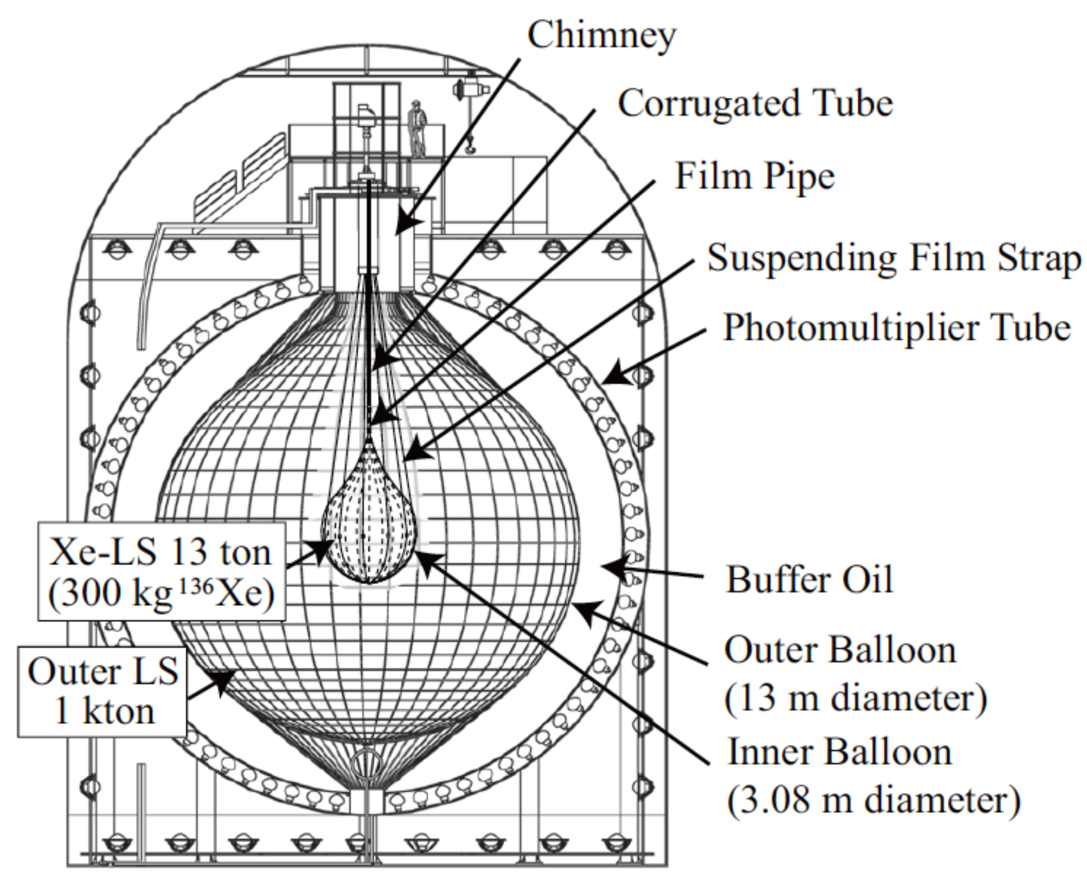
Large self-shielding calorimeters: Optimise ΔB

Basic idea: Deploy a mini-balloon full of Xe-loaded scintillator
into the middle of KamLAND

Running detector
-> relatively low cost, quick start
-> detector well understood
-> experience with balloons,
LS purification
-> ongoing antineutrino program
outside Xe mini-balloon

Large and clean
-> negligible external backgrounds
-> no escaping/invisible β/γ energy

Highly scalable
-> 100s of kg of ^{136}Xe in first phase
-> up to several tons
with larger mini-balloon



Disadvantage: energy resolution (4.0% at 2.458 MeV)

NOTICE: ΔE~10 % FWHM at Qββ (eg: factor 50-100 Ge calorimeters)

Mixing target and detector: Xe dissolved in LS

Technical challenges: Xe-loaded liquid scintillator (LS)

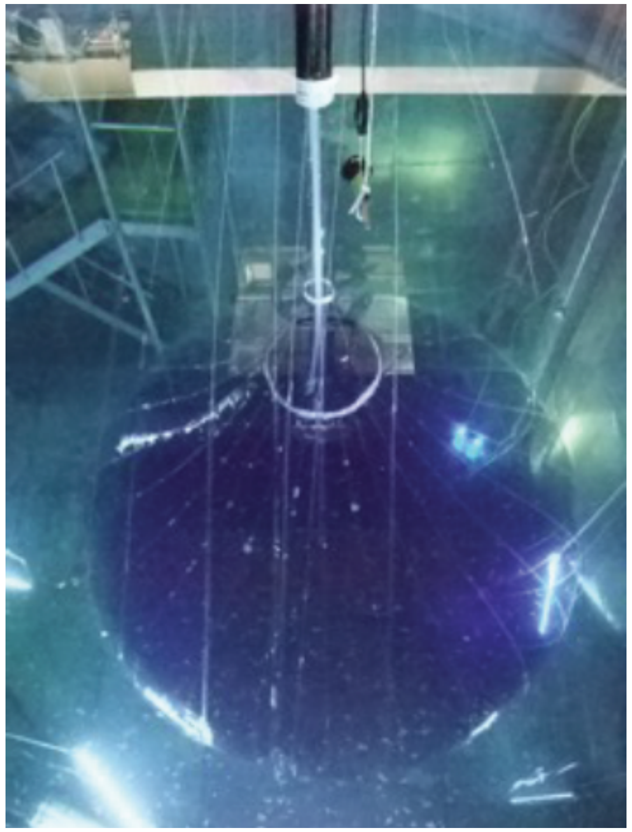
- Match light yield to existing KamLAND LS
  -> Achieved: matched to within 3%
- Similar overall density to existing KamLAND LS, for mini-balloon integrity
  -> Tuned to 0.10% higher density
- Xe loading: (2.52 ± 0.07) % by weight
- Composition:
  82% decane
  18% pseudocumene
  2.7 g/L PPO
  (2.52 ± 0.07) % Xe
- Xe is (90.93 ± 0.05)% ^{136}Xe, (8.89 ± 0.01)% ^{134}Xe
- 129 kg ^{136}Xe in the fiducial volume

Mini-Ballon

Technical challenges: Mini-Balloon

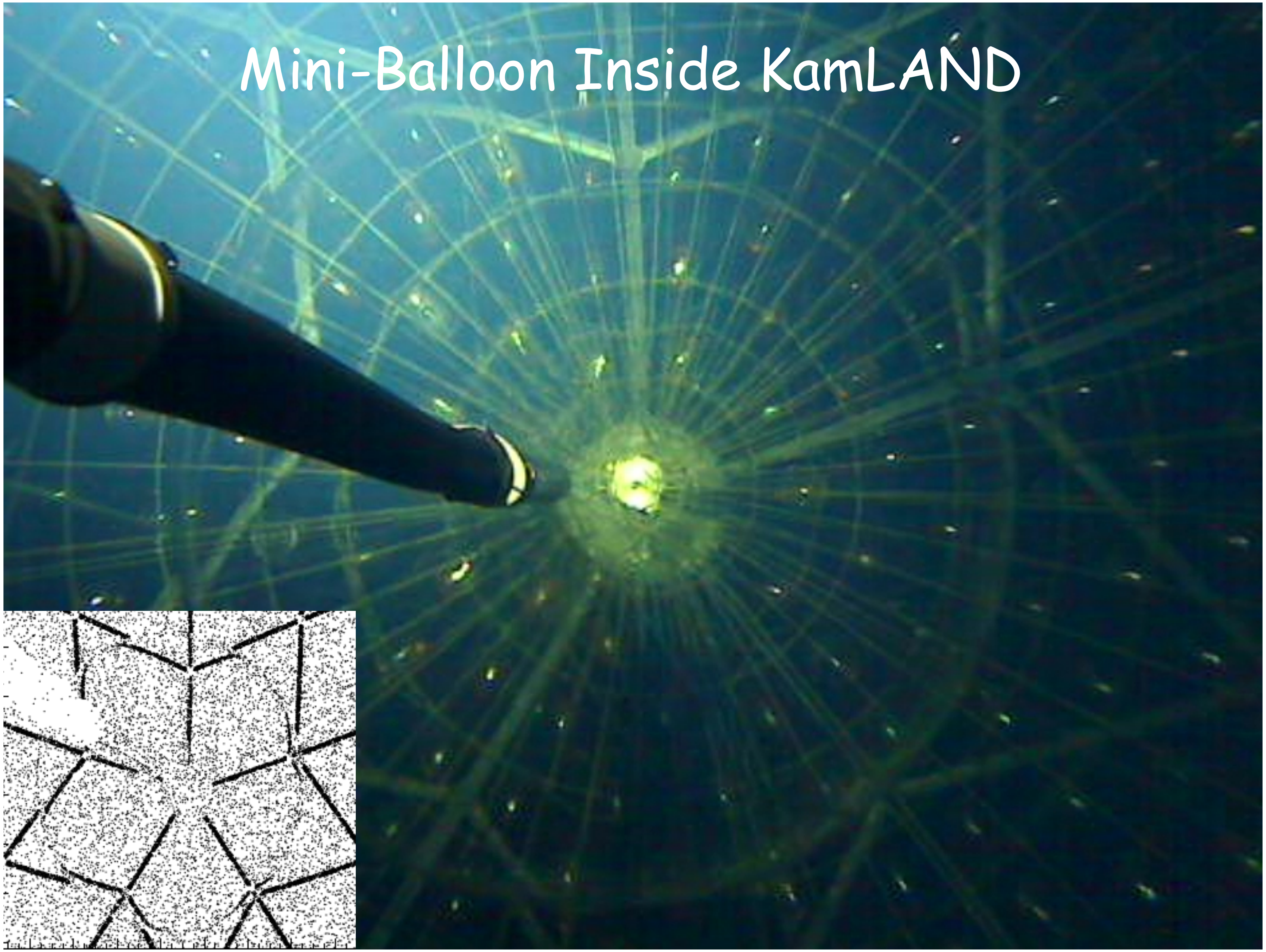
- Very thin: 25 μm nylon
- Welded seams (!)
- Must be Xe barrier
- High transparency
- Low contaminations of U, Th, K

Tests in water to establish procedures for deployment, inflation, LS replacement

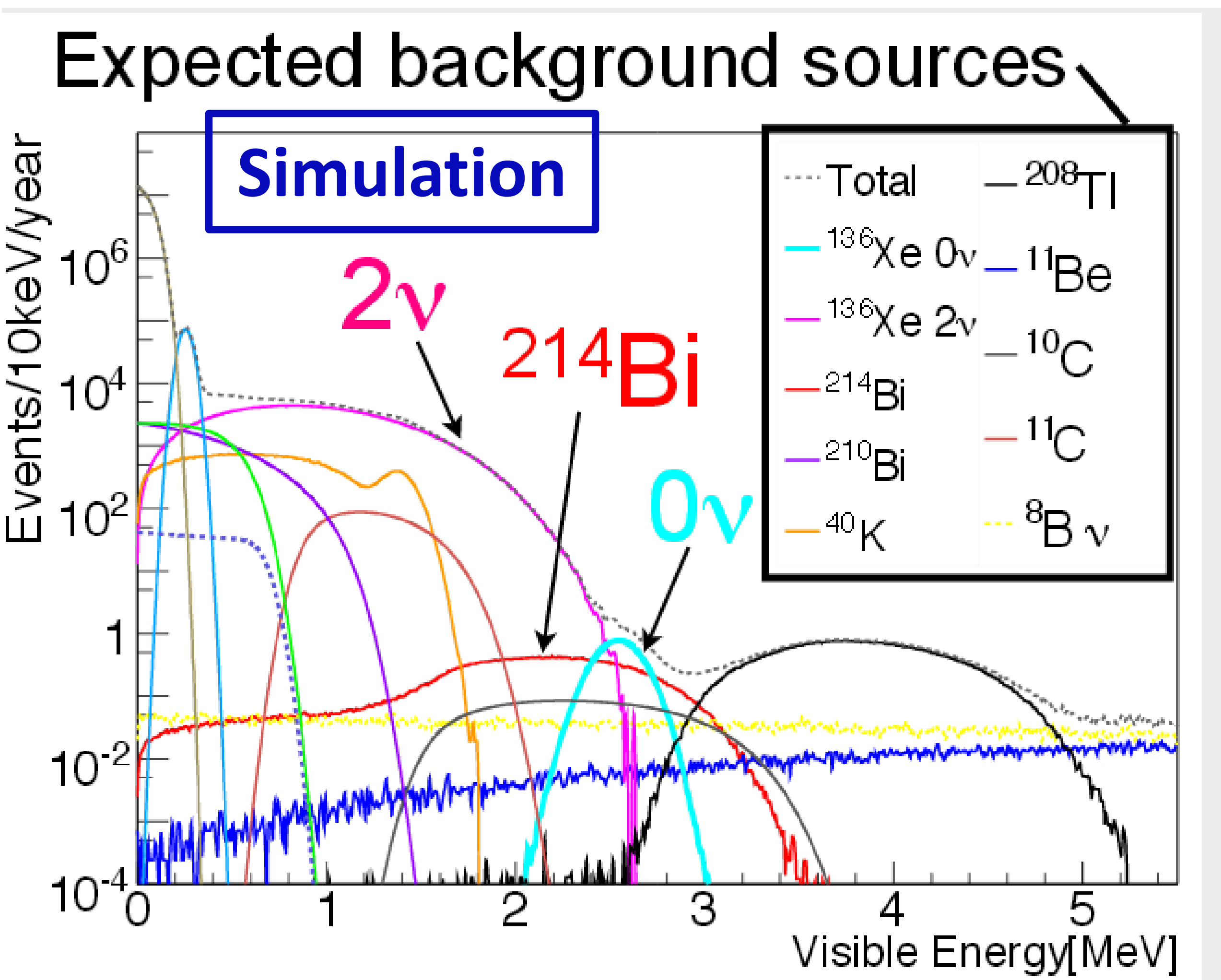


80 μm polyethylene test balloon

25 μm Nylon 6 balloon


Mini-Balloon Inside KamLAND

Signal and background



$\langle m_\nu \rangle = 150\text{meV}$, Xe:400kg

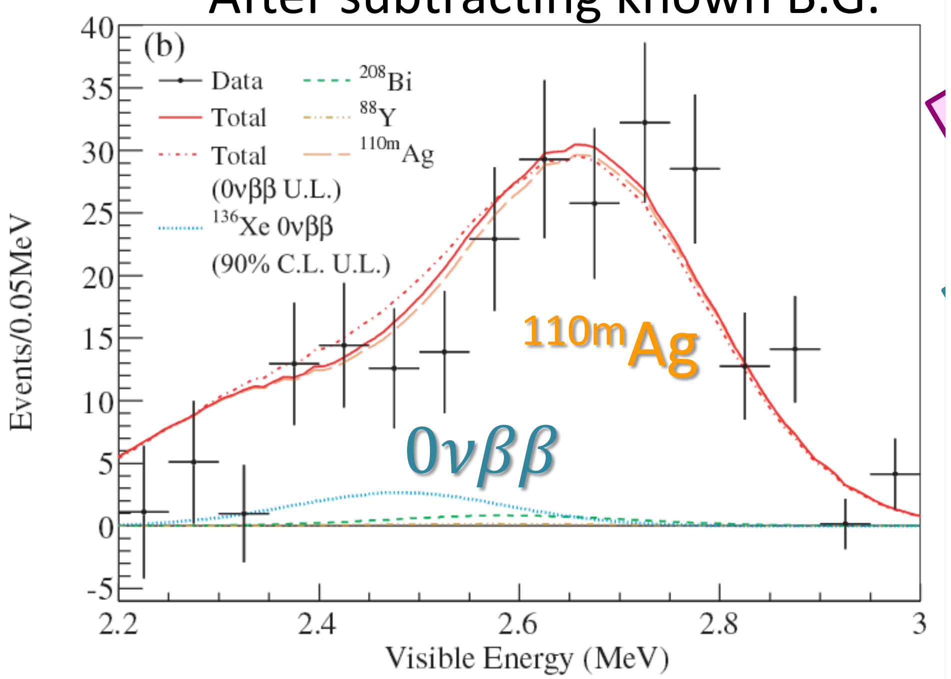
- **Understanding the background model is crucial, since the experiment is pure counting (no peaks to fit).**
- **But it is difficult to calibrate well the background model with data, precisely due to the absence of narrow peaks to calibrate.**
- **Notice that 2ν mode, Bi-214 and Tl-208 background fully overlap with signal area.**
- **Background is proportional to M_{LS} and area ballon but the signal is proportional to M_{Xe}. Thus increasing the load increases signal "for free"**

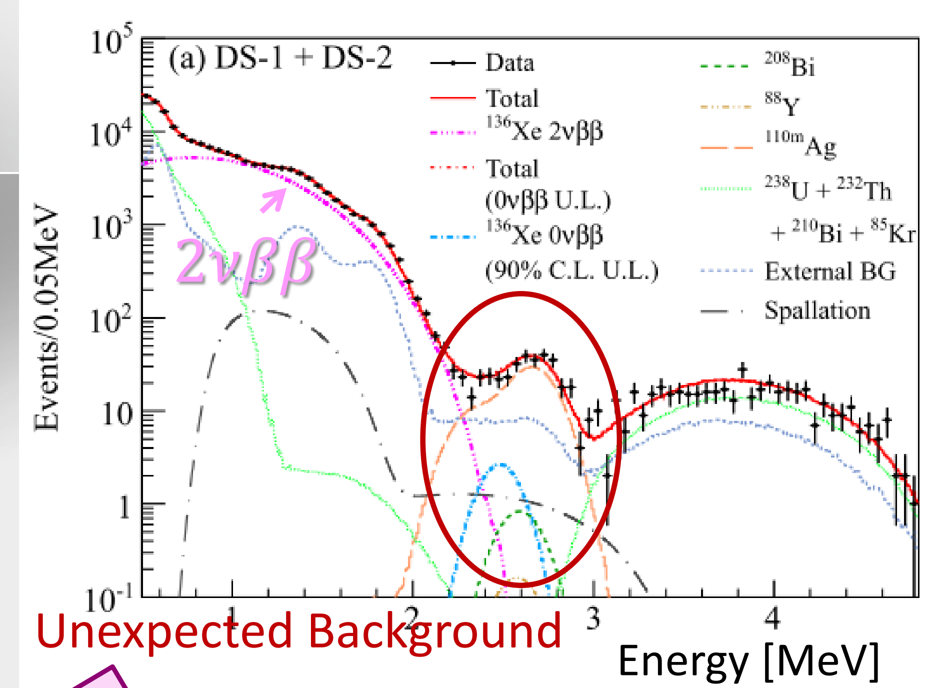
Recent results

- Event Selection

1. Fiducial Cut
2. 2ms veto after muon
3. Remove Bi-Po events
4. Anti-nu CC reaction cut
5. Vertex-time-charge test to cut noise

After subtracting known B.G.





2νββ

$$T_{1/2}^{2\nu} = 2.30 \times 10^{21}\text{year} \pm 0.02(stat.) \pm 0.14(sys.)$$

0νββ

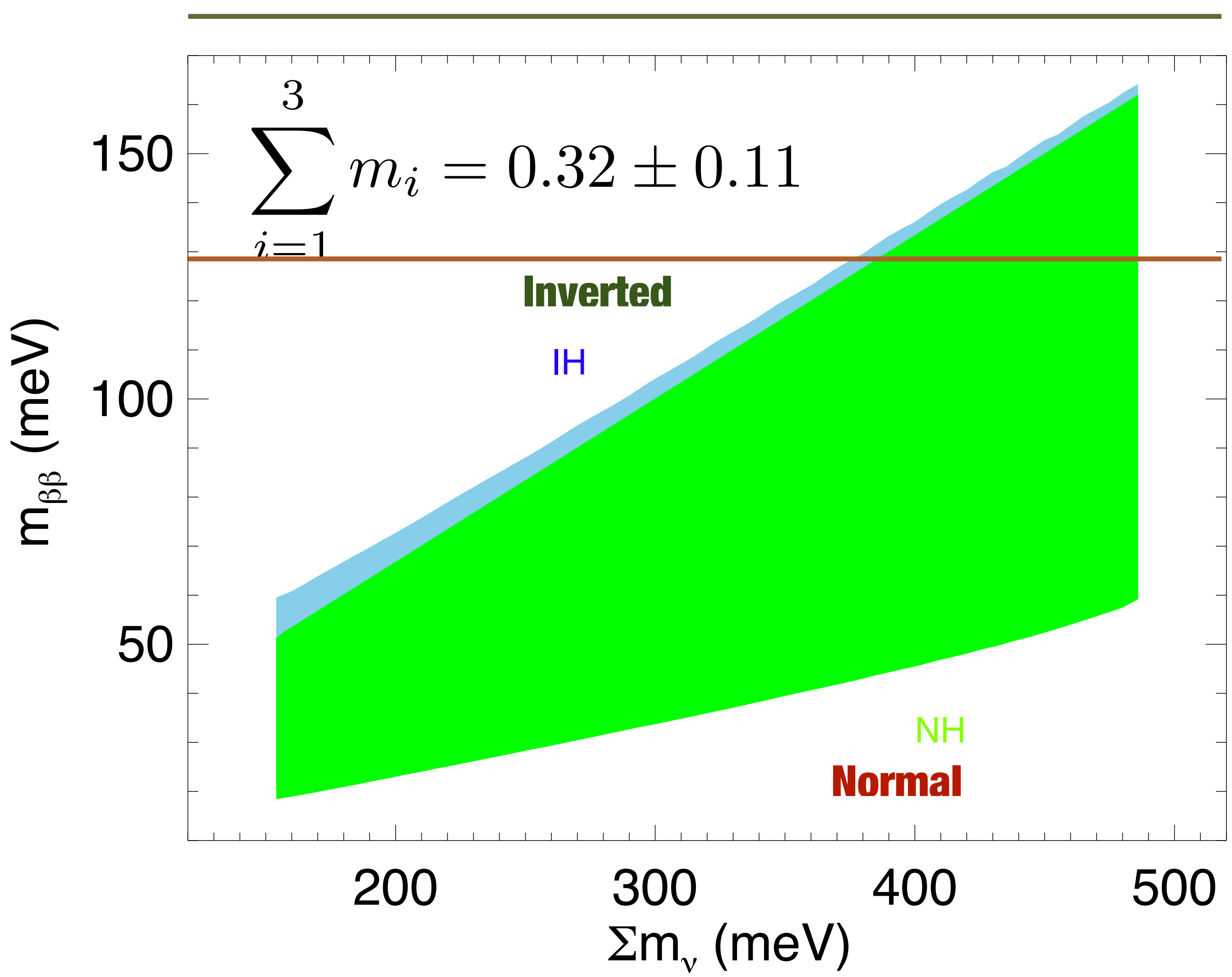
$$T_{1/2}^{0\nu} > 1.9 \times 10^{25}\text{yr} \quad \text{90\% C.L.}$$

Background

Half-life & energy spectrum fitting

→ Identified as ^{110m}Ag

Reproducing KamLAND-Zen results

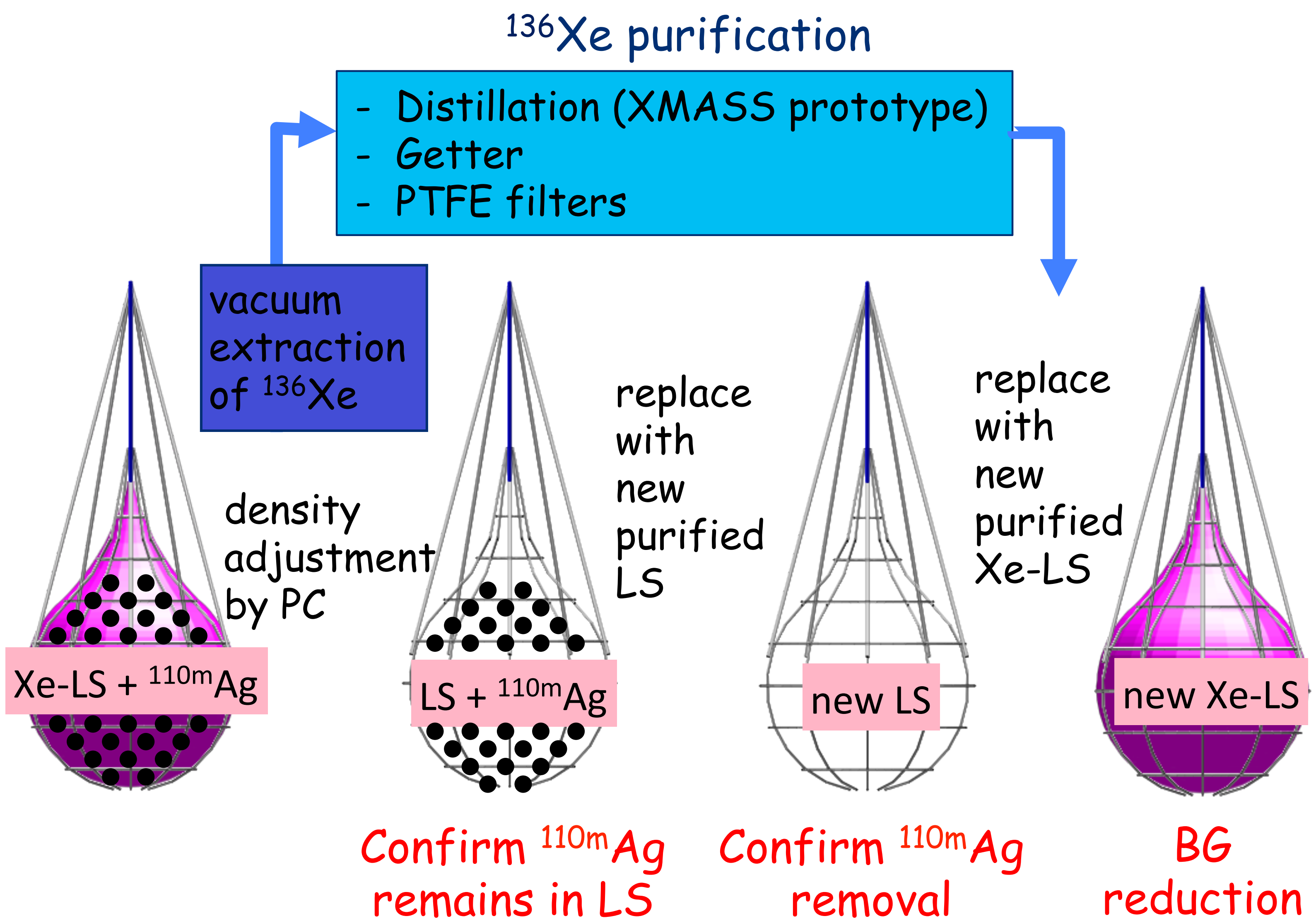


- **Run example KZEN.py in pybbsens software**
- **Input:**
- efficiency = 0.55
- ΔE = 10 % at $Q_{\beta\beta}$
- B = 6 x 10^{-4} ckky
- Exposure =89.5 kg x y
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **$T^{0\nu}$ = 2.0 x 10^{25} y**

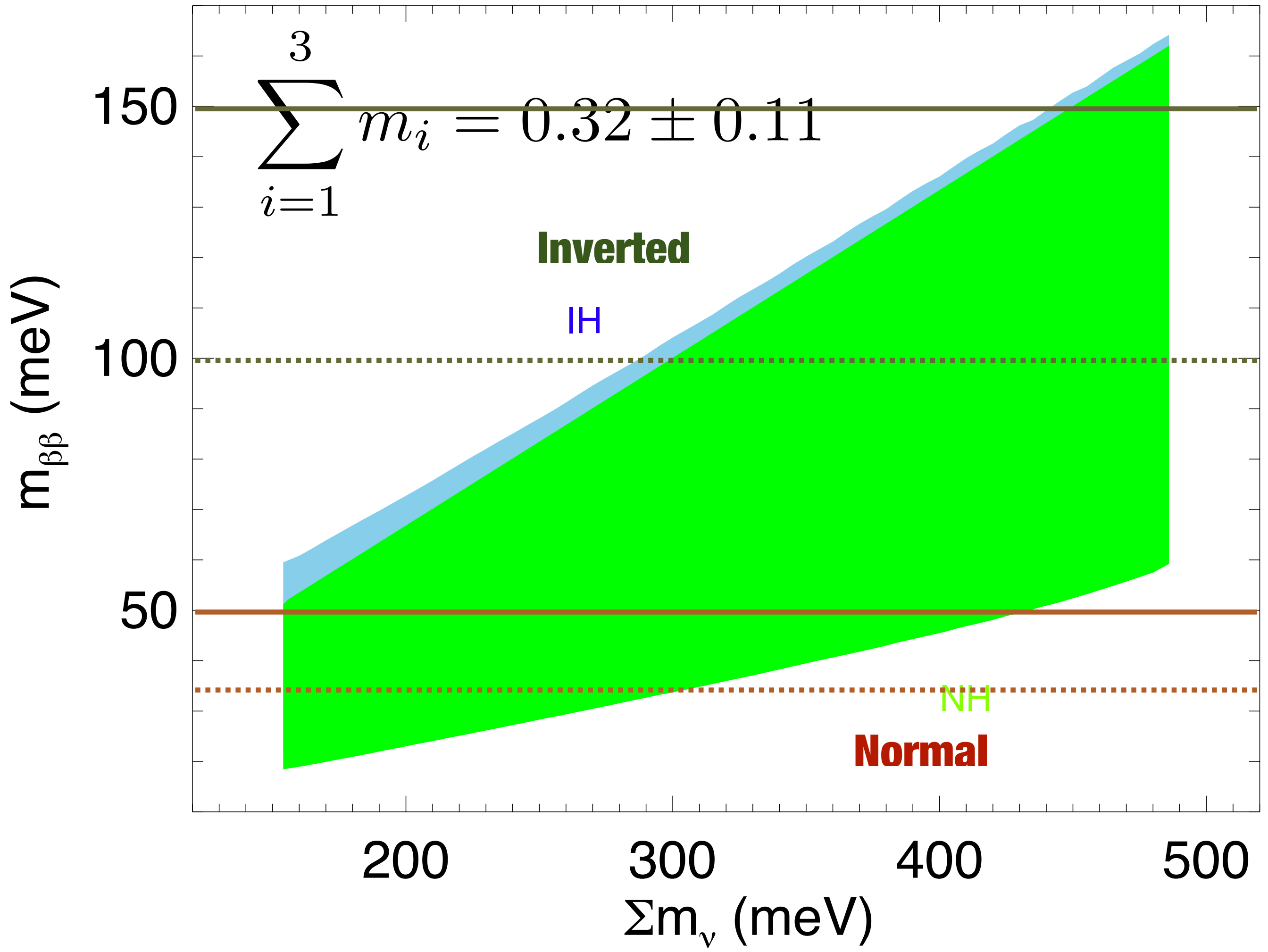
- Mass 170 kg in fiducial volume
- **$m_{\beta\beta}$ = 127-355 meV**

Current KZ run: background distillation

- Run began Nov. 2013
- ^{110m}Ag reduced by > 10x



Second phase: the 600 kg run

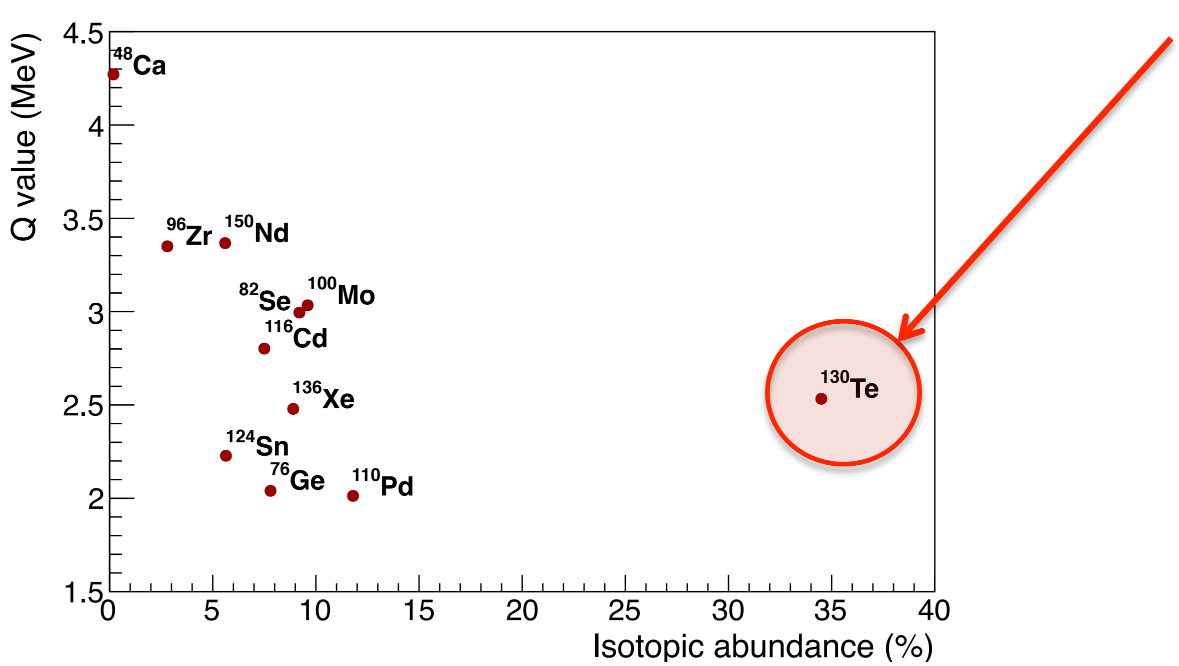


- 440 kg x 5 yr ~2200 kg x yr
- B=6 x 10^{-4} ckky ⇒
  - $T^{0\nu}$=1 x 10^{26}⇒$m_{\beta\beta}$ = 53-149 meV
- B=10^{-4} ckky ⇒
  - $T^{0\nu}$=2.7 x 10^{26}⇒$m_{\beta\beta}$ = 35-98 meV

- The second phase of KamLAND-ZEN appears to be capable of covering a very large fraction of the cosmo-region. The crucial issue is to understand the background index, which is very low and very difficult to measure.

The SNO+ approach

- **SNO+ DBD concept**: deploy element containing DBD isotope in LAB liquid scintillator
- **SNO+ isotope**: deploy 0.3% loading (~2.3 tonne) of **Te**
  - 800 kg of **^{130}Te** (160 kg in 3.5m fiducial volume)
  - Intention to increase loading once technique is demonstrated

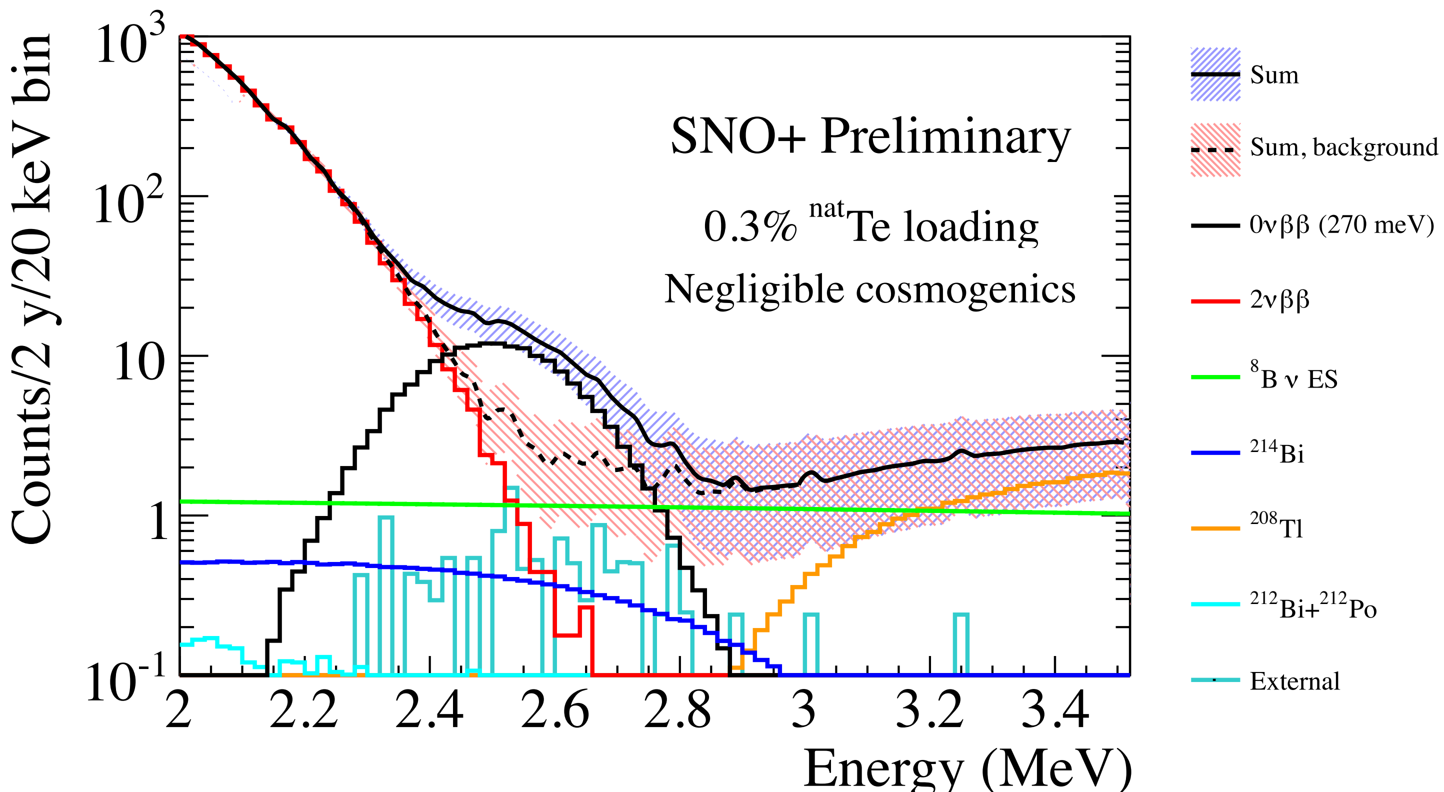


^{130}Te:

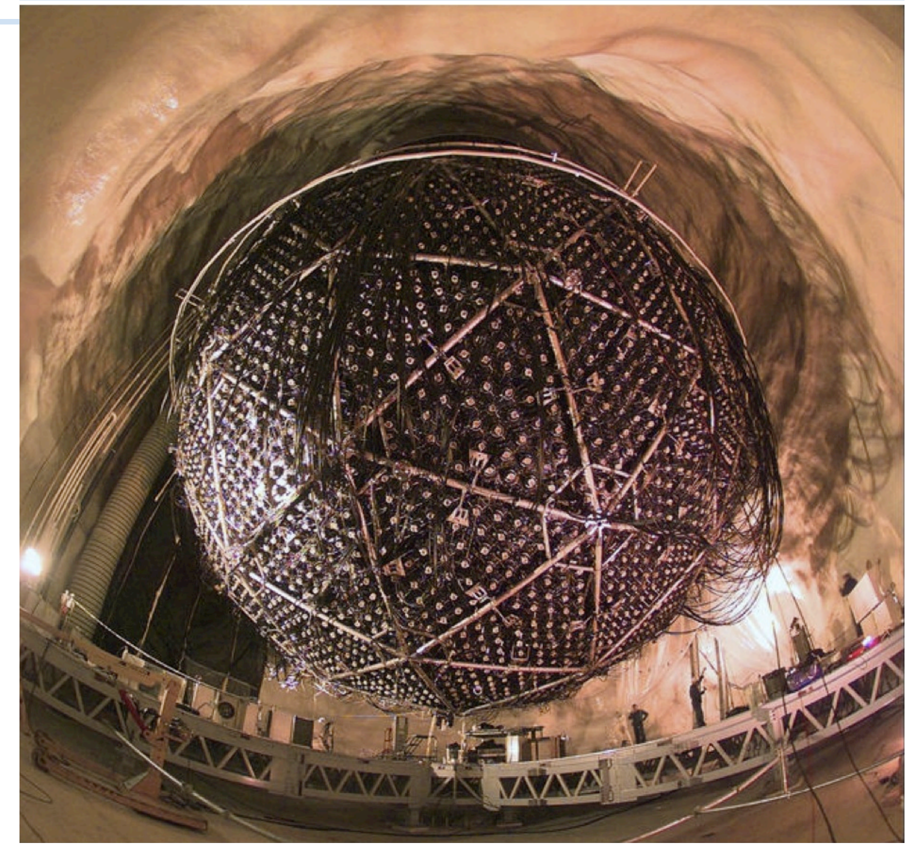
- Highest natural abundance
- $2\nu\beta\beta$ background 100 times lower than for ^{150}Nd
- Large $0\nu\beta\beta$ matrix element
- Proven ability to load in LAB LS

No need to enrich the isotope! However, total isotope mass (today) less than that of KZ

SNO+



$M^{0\nu}$,g_A from Phys. Rev. C, 87, 014315(2013)



Start run foreseen for 2014-2015