DOUBLE BETA DECAY: NON-^{136}XE EXPERIMENTS

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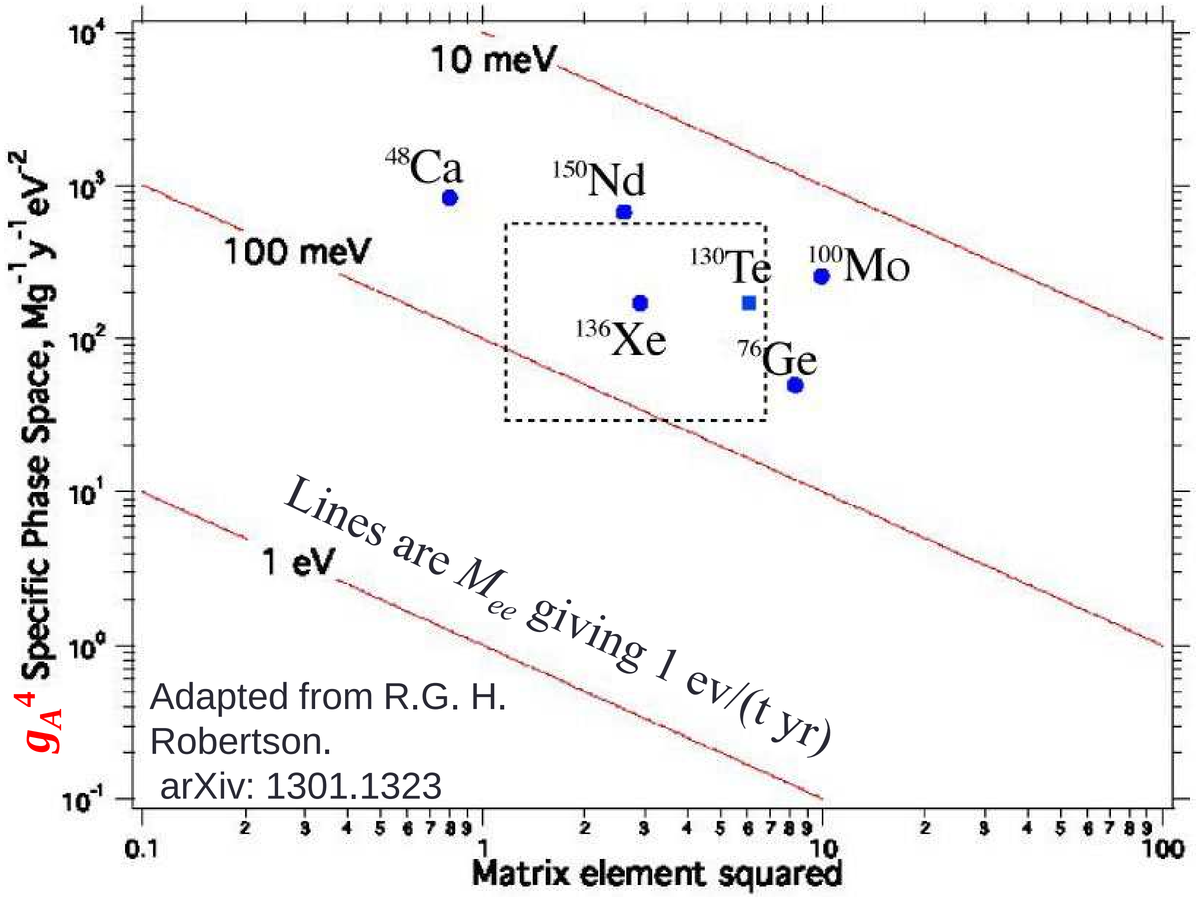
Thanks to: A. Bettini, M. Chen, O. Cremonesi, S. Elliott, F. Piquemal, S. Umehara

Many $0\nu2\beta$ candidates…



- Many different **candidate isotopes** available
  - no clear **"golden candidate"**
    - Similar specific rates (within a factor of two)
  - ^{76}Ge important also for historical reasons
- Choice on **practical** grounds
  - "Easy" **enrichment**
  - Energy **resolution**
  - $T_{1/2}$ of **2**ν decay
  - **Scalability**/modularity
  - **Cost**

Exposures of many **10's of kg·yr** achieved with ^{76}Ge, ^{130}Te, ^{100}Mo (and ^{136}Xe of course) → scale up to 100's kg·yr

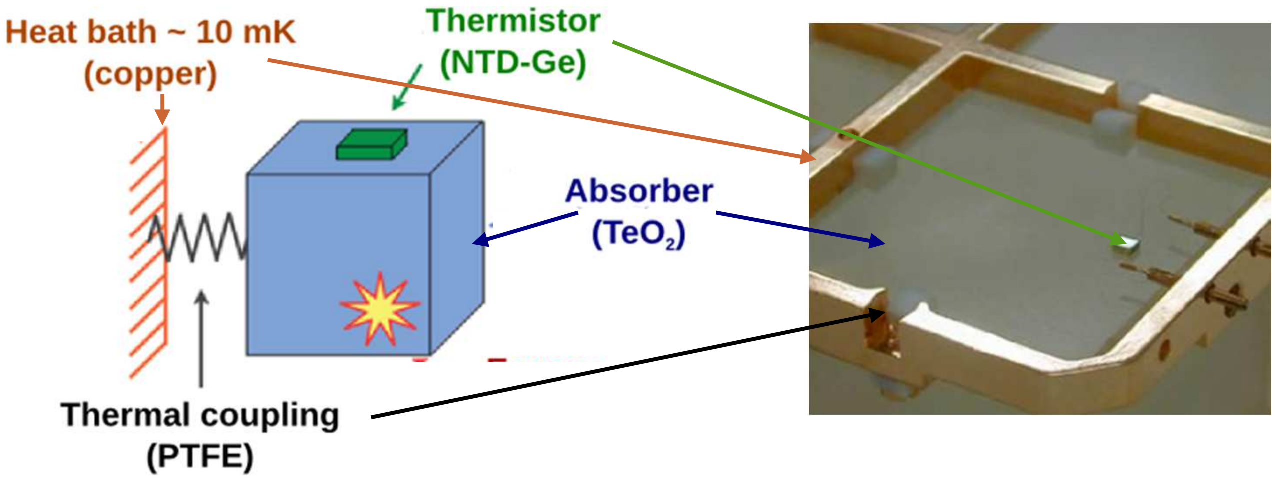
Inventory of the present non-Xe $0\nu 2\beta$ projects (data taking, construction, R&D)

Experiment	Isotope	Lab	Status	Talk in par. session
GERDA	^{76}Ge	LNGS	Phase I completed Migration to Phase II	B. Schwingenheuer, B. Majorovits (Mo)
CUORE0 / CUORE	^{130}Te	LNGS	Data taking / Construction	M. Vignati, K. Han (We)
MJD	^{76}Ge	SURF	Construction	M. Green (Mo)
SNO+	^{130}Te	SNOLAB	R&D / Construction	S. Biller (We)
SuperNEMO demonstrator	^{82}Se (or others)	LSM	R&D / Construction	M. Bongrand (Th)
Candles	^{48}Ca	Kamioka	R&D / Construction	S. Umehara (Th)
COBRA	^{116}Cd	LNGS	R&D	B. Wonsak (Mo)
Lucifer	^{82}Se	LNGS	R&D	
DCBA	many	[Japan]	R&D	H. Kakuno (Th)
AMoRe	^{100}Mo	[Korea]	R&D	Y.-H. Kim (We)
MOON	^{100}Mo	[Japan]	R&D	

CUORE0 and CUORE (^{130}Te)

- **Bolometric technique**
  - Technology demonstrated by MiDBD (1997-2001,1.8 kg) and CUORICINO (2003-2009, 11.3 kg) at LNGS
  - CUORICINO **final result** (19.7 kg yr)

$T_{1/2}^{0\nu} > 2.8 \cdot 10^{24}$ yr



- From CUORICINO to **CUORE**
  - Sensitivity x **~35**
  - CUORE0 as first step (**one tower**) → **operating** in the old CUORICINO cryostat since **March 2013**

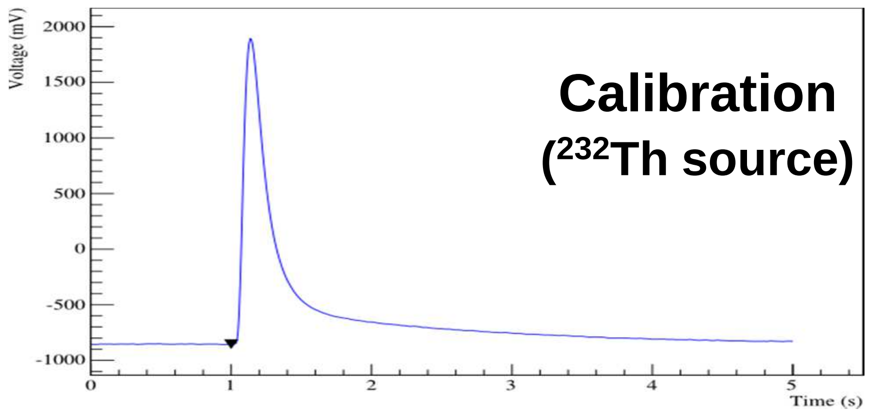
988 TeO_2 5x5x5 cm^3 crystals (750 g each)
Detector Mass: 741 kg TeO_2
^{130}Te mass (natural i.a.) : 206 kg of ^{130}Te

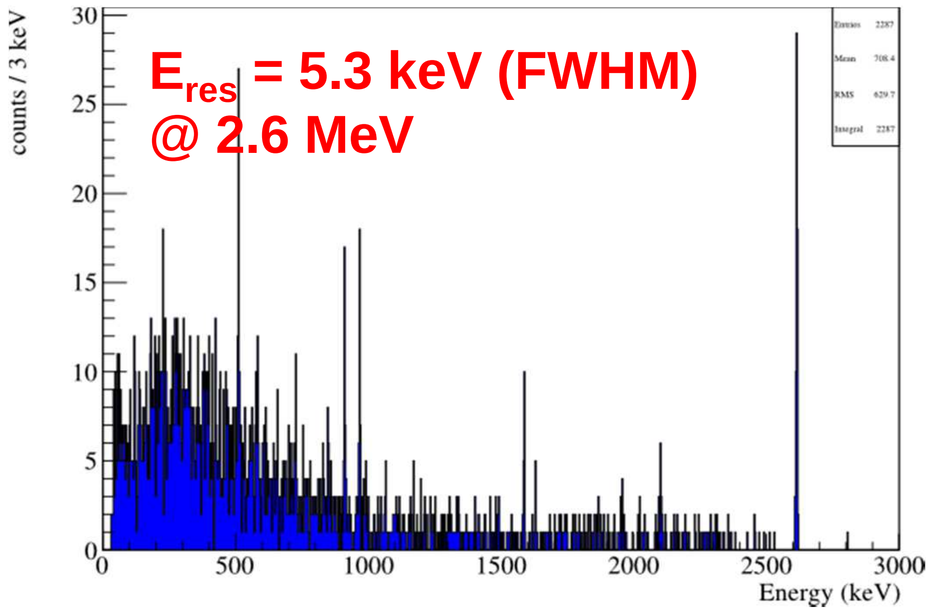
Array: 19 towers, each with 52 crystals each

Background goal: 0.01 cts/(keV ·kg of TeO_2 · yr)

CUORE0 and CUORE (^{130}Te)

- **Successfully tested** and defined the CUORE **assembly procedures**
- Demonstrated that **a complete CUORE tower** can be assembled in **less than 4 weeks**
- **51 detectors alive** (out of 52)



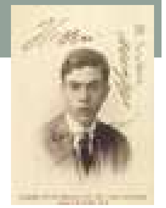


- **CUORE** is **under construction**
- CUORE **cool down** foreseen **by end 2014**

Talks by M. Vignati, K. Han (Sep 11)

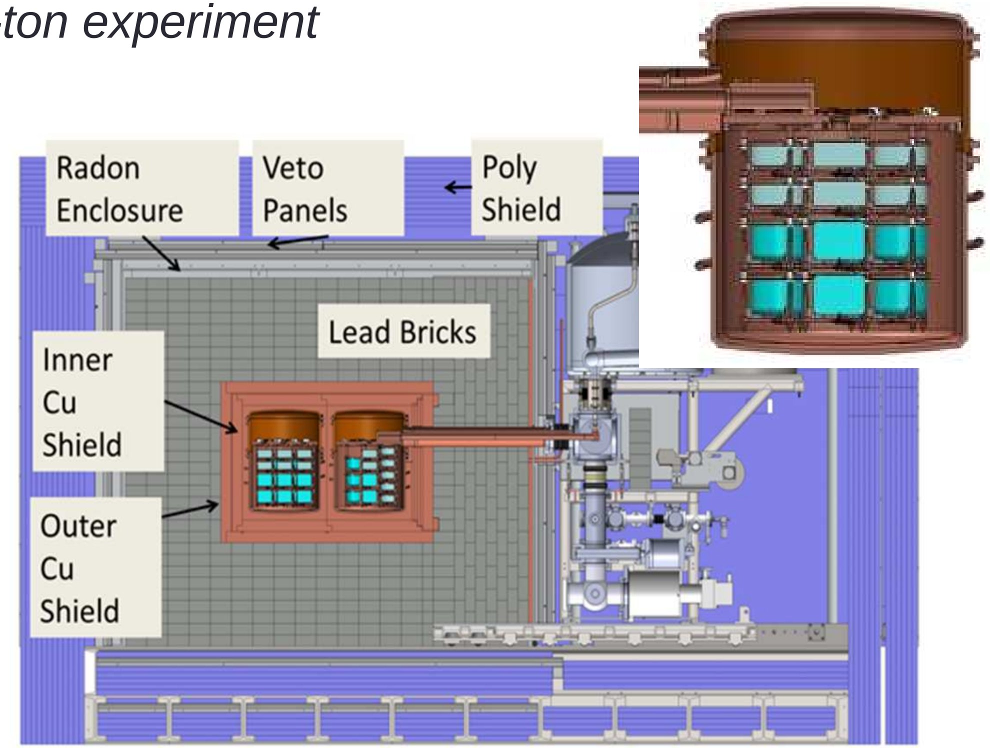
	CUORE-0	CUORE
Assumption:	2 yr, 0.05 cts/(keV kg yr)	5 yr, 0.01 cts/(keV kg yr)
$T_{1/2}$ (90% CL)	**5.9×10^{24} yr**	**9.5×10^{25} yr**

Majorana Demonstrator (MJD) (^{76}Ge)



Goals: - Demonstrate **backgrounds low enough** to justify building a **ton-scale** exp.
- Establish feasibility to construct & field modular arrays of Ge detectors.

- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  3 counts/(ROI ton yr) (after analysis cuts)
  scales to 1 count/(ROI ton yr) for a 1-ton experiment
- **40-kg of Ge detectors**
  - 30 kg of 86% enriched ^{76}Ge crystals
  - 10 kg of ^{nat}Ge
  - Detector : P-type, point-contact.
- **2 independent cryostats**
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
- **Compact Shield**
  - low-background passive Cu and Pb shield with active muon veto



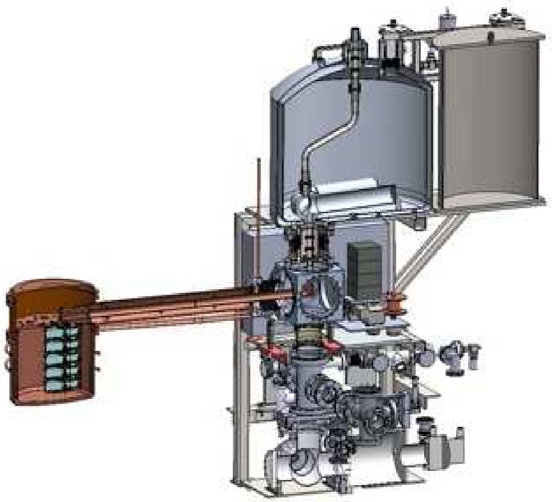
Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics, with additional contributions from international collaborators.

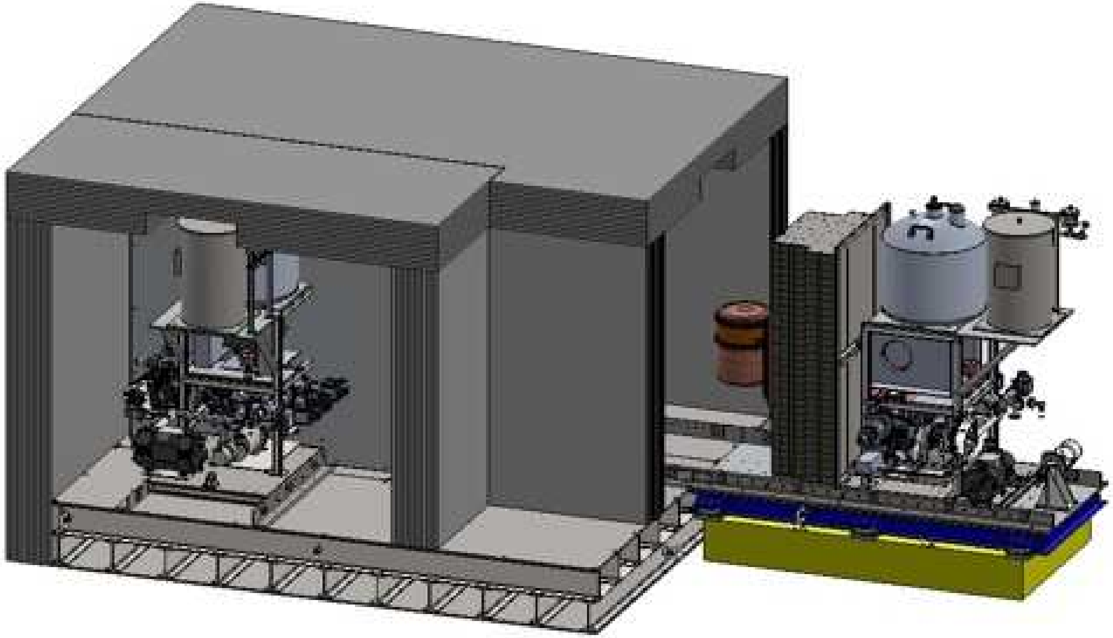
Majorana Demonstrator Schedule

- **Three Steps**
  - Prototype Cryostat* (2 strings, ^{nat}Ge)
  - Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge)
  - Cryostat 2 (7 strings ^{enr}Ge)

Commissioning dates (Estimated)

- **(~ NOW)**
- **(Early 2014)**
- **(Late 2014)**

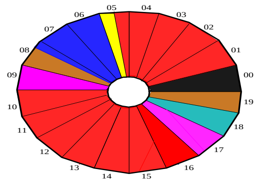




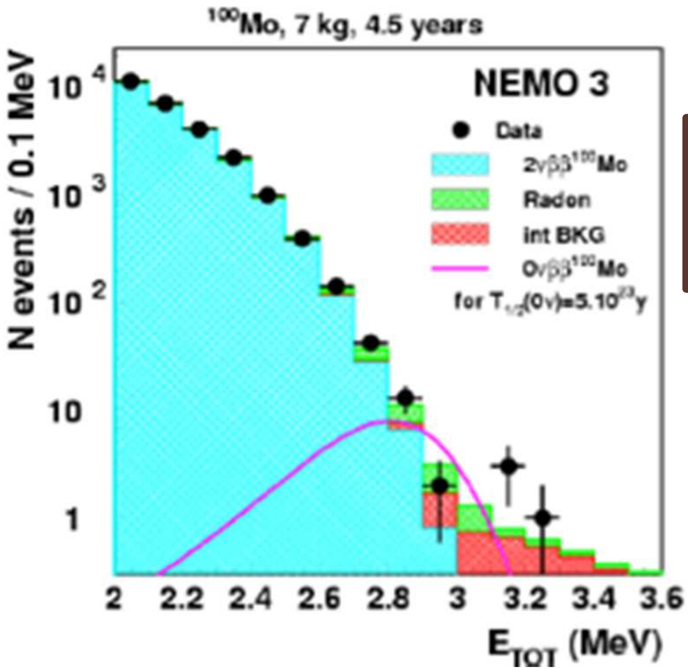
*Same design as Cryos 1 & 2, but fabricated using OFHC Cu (non-electroformed) components.

Talk by M. Green (Sep 9)

Recent results from NEMO3 (^{100}Mo)



- **Tracking detector**: drift chambers (6180 Geiger cells)
  - σ_t = 5 mm, σ_z = 1 cm (vertex)
- **Calorimeter** (1940 plastic scintillators and PMTs)
  - Energy resolution: **FWHM=8% (3 MeV)**
- Background level at $Q_{\beta\beta}$ [2.8 – 3.2 MeV] : **1.2 10^{-3} cts/(keV kg yr)**
- **Multi-isotope** (7 measured at the same time)
- Running at **LSM** (2003 - 2011)



Preliminary result

^{100}Mo $T_{1/2}$ ($\beta\beta0\nu$) > 1.0 10^{24} yr (90% C.L.)

$\langle m_\nu \rangle$ < 0.31– 0.79 eV

[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

Precise measurements of $2\nu2\beta$ decay of 7 isotopes (also to excited states)

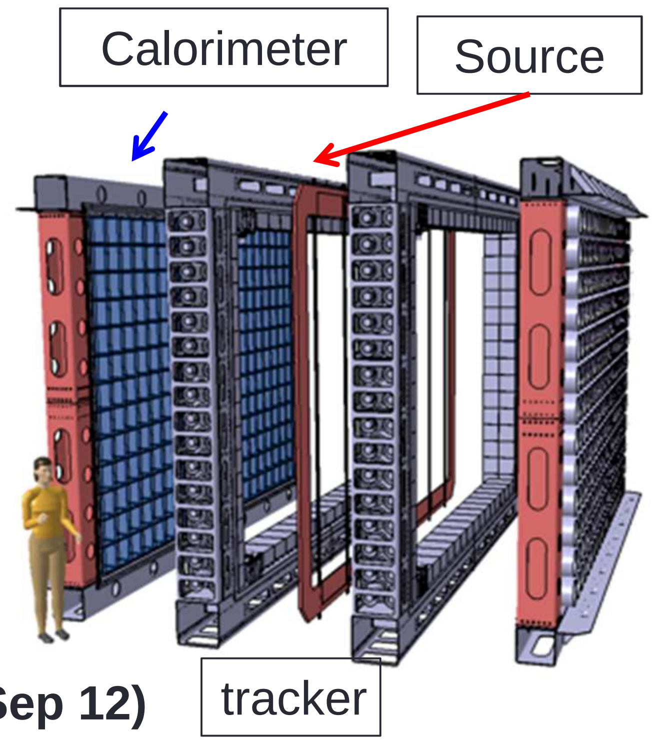
Limits on Majoron and V+A decay modes

See talk by M. Bongrand (Sep 12)

SuperNEMO demonstrator (^{82}Se, or ^{150}Nd, or ^{48}Ca)

- **Tracking detector**: technology demostrated in NEMO3
- **SuperNEMO**: 100 kg of ^{82}Se in 20 modules at **LSM**
- First, a "**demonstrator**", **1 module, 7 kg** of **^{82}Se**
  - Construction at **LSM** from end 2013 (commissioning: 2014)

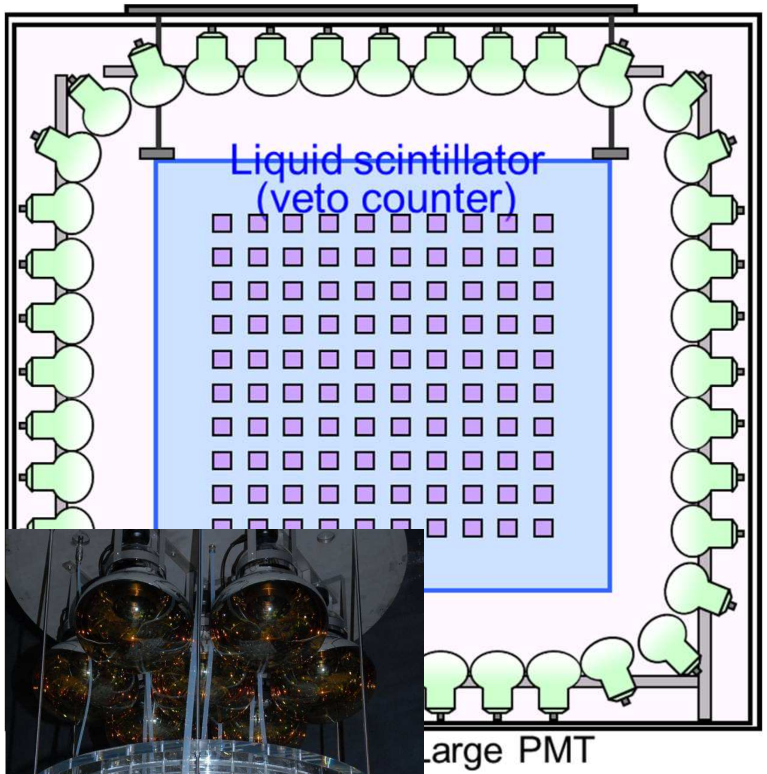
> - Modular detector with 3 main components :
>   - Central source foil frame : 7 kg of isotope
>   - Tracking : 2 000 drift chambers
>   - Calorimeter : 712 scintillators+ PMTs
> - Shielded by iron (300 tons) and water

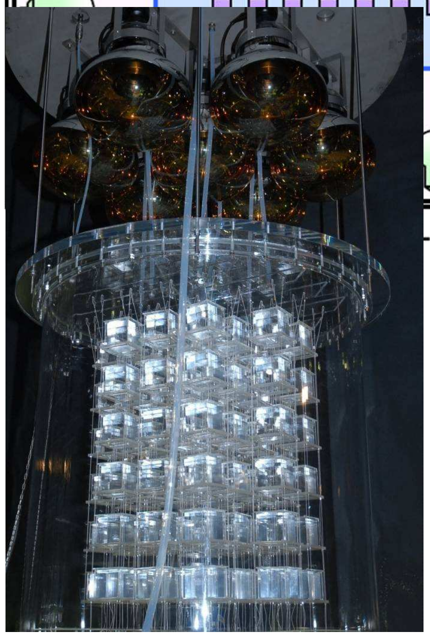


- Very stringent requirements for ^{208}Tl, ^{222}Rn and ^{214}Bi contaminations
- Resolution: **4% @ 3 MeV FWHM**
- Expected to be **background-free** for 7 kg of ^{82}Se and 2 years of data taking

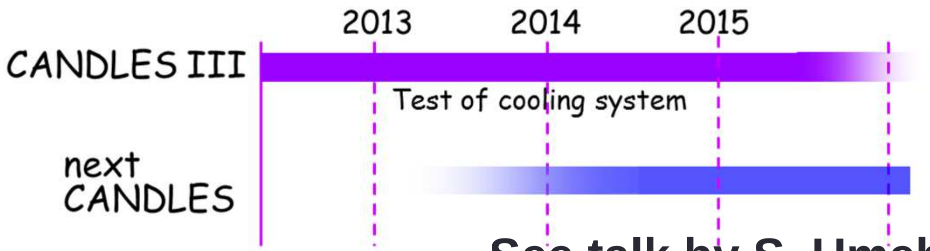
See talk by M. Bongrand (Sep 12)

CANDLES (^{48}Ca)





- **CANDLES System**
  - For ^{48}Ca ($Q_{\beta\beta}$=4.3MeV, but 0.187%)
  - CaF_2 detector and 4π active shield
  - Enriched ^{48}Ca
- **CANDLES III** at Kamioka Lab.
  - 96 CaF_2 (305 kg, 0.187%^{48}Ca) + liquid scintillator
  - **Data taking** and background studies from Spring 2013
  - Sensitivity of 0.5 eV
- R&D for **^{48}Ca enrichment**
  - CANDLES IV & V
  - Not funded yet



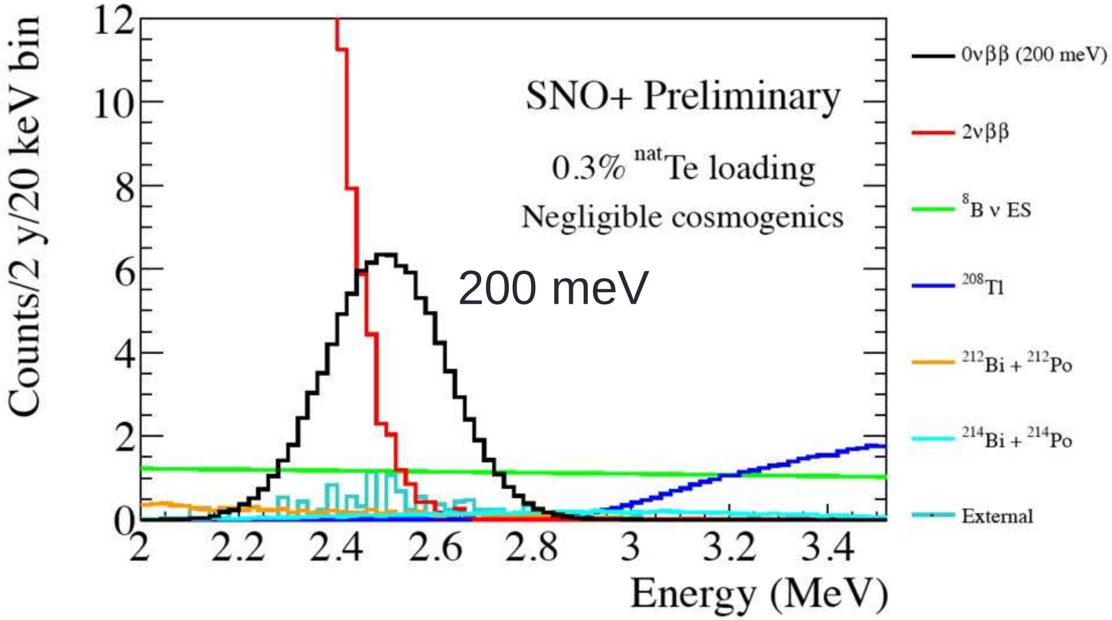
See talk by S. Umehara (Sep 12)

SNO+ (^{130}Te)

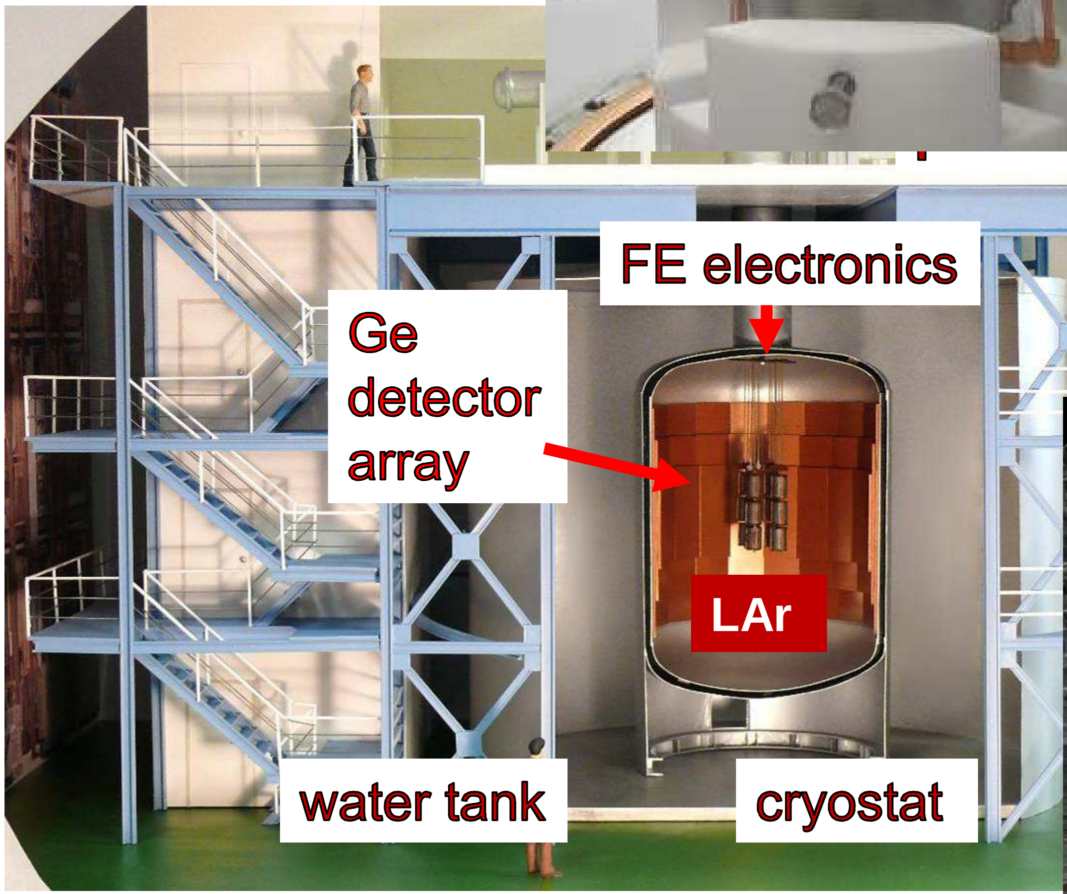
- Infrastructures from the SNO experiment: **D_2O → liquid scintillator**
  - Preparation ongong at SNOLAB
  - Many physics goals, priority given to double beta decay
- SNO+ isotope: 0.3% **loading** (2.3 tons) of **Te**
  - 800 kg of ^{130}Te in the fiducial volume (3.5 m radius)
- Milestones
  - Mid-2014: fill detector with (purified) scintillator
  - Early 2015: load with Te

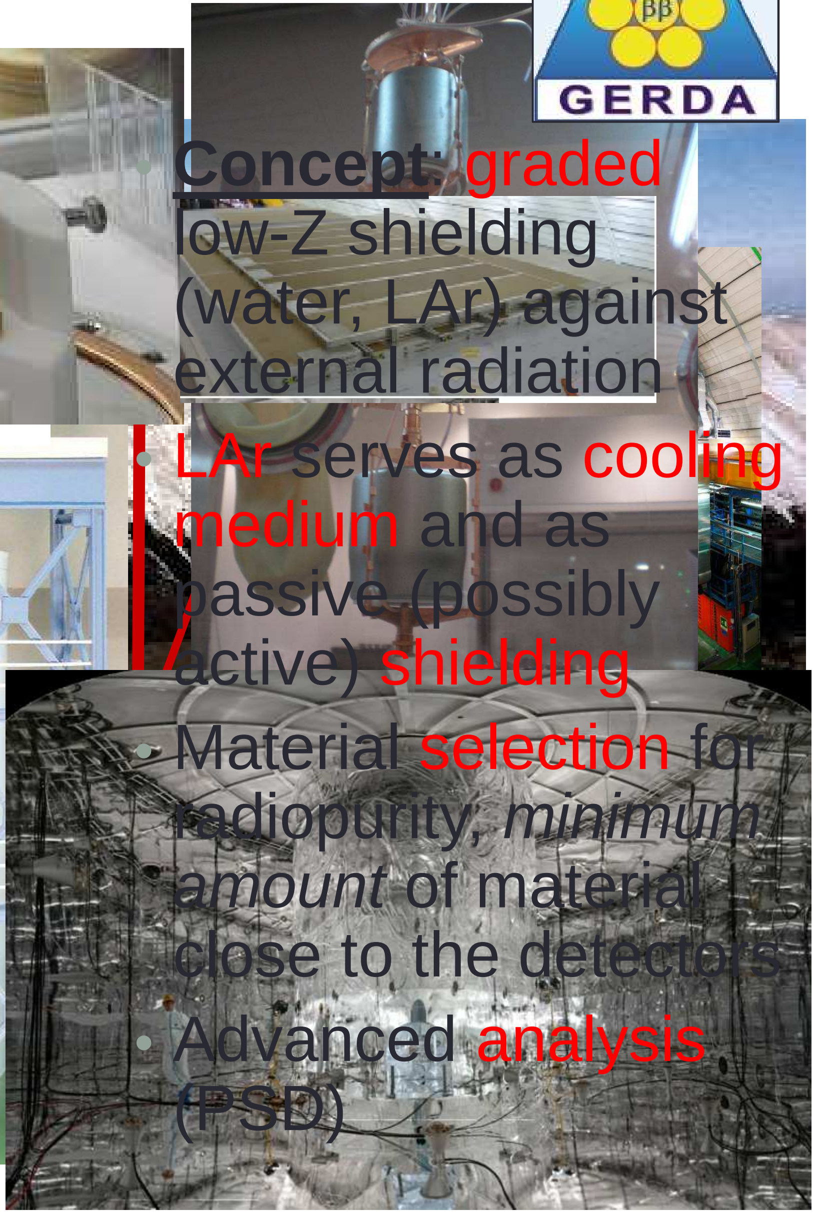
See talk by S. Biller (Sep 11)

2 years, 3.5 m fiducial radius, σ = 4%



GERDA (^{76}Ge)

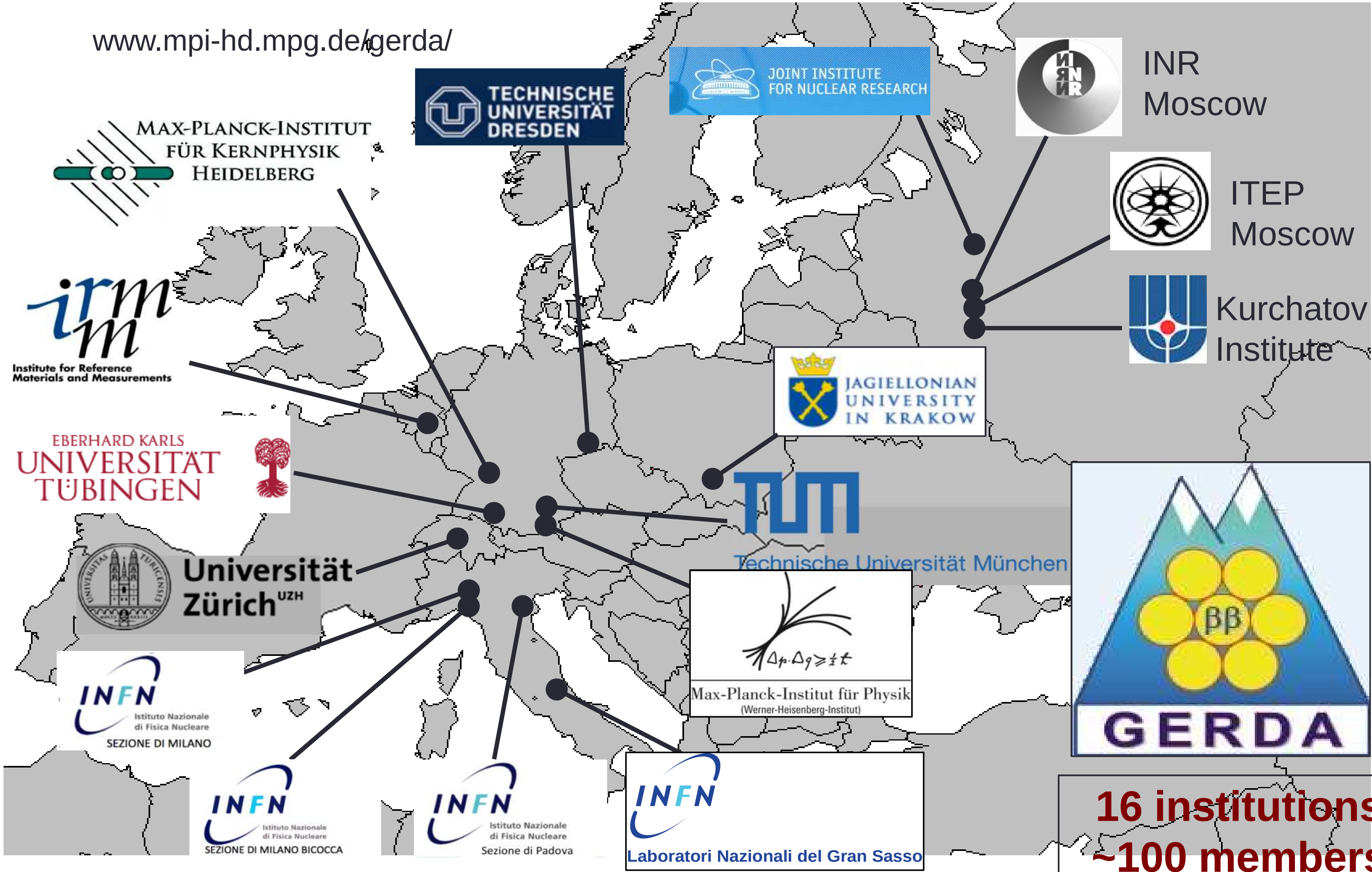




- **Concept:** graded low-Z shielding (water, LAr) against external radiation
- LAr serves as cooling medium and as passive (possibly active) shielding
- Material selection for radiopurity, *minimum amount* of material close to the detectors
- Advanced analysis (PSD)

GERDA: the Collaboration

www.mpi-hd.mpg.de/gerda/



16 institutions
~100 members

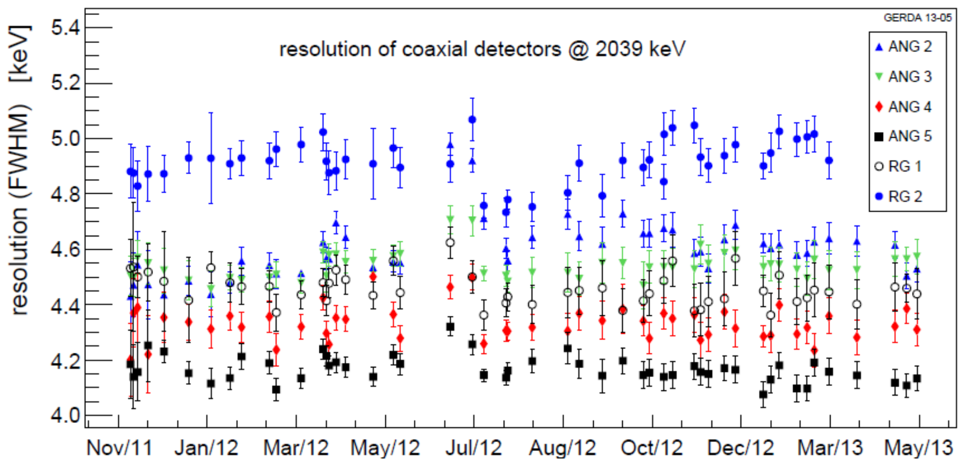
GERDA data taking

- Total exposure: **21.6 kg yr** (diodes) between Nov 2011 and May 2013 (492.3 live days, 88.1% duty factor)
  - Weekly calibration with **^{228}Th source,** stability monitor with **test pulses** (0.05 Hz)
- Used for analysis: 6 ^{enr}Ge coaxial detectors (4 from HdM + 2 from IGEX), 14.6 kg; 4 ^{enr}Ge Phase II BEGe detectors (deployed in June 2012), 3.0 kg
  - Data from three other deployed detectors (two coaxial and one BEGe) not used in analysis because of high LC or instabilities

- Energy reconstruction
  - Offline, using semi-gaussian filter (fast and robust)
  - Resolution can be improved by **~10%** by dedicated optimized filters
    - See poster by G. Benato et al.

Resolution FWHM at $Q_{\beta\beta}$=2039 keV

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)

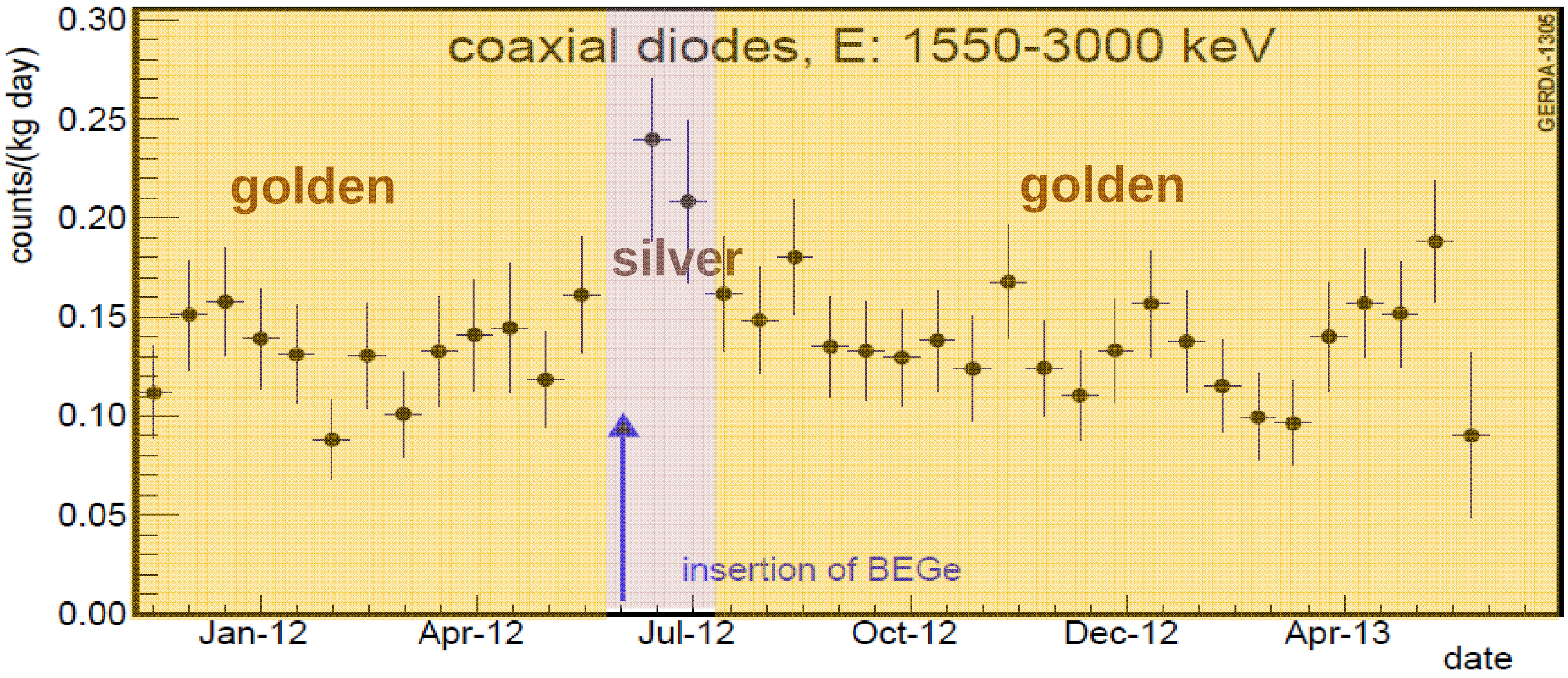


Position of the 2614 keV line from ^{208}Tl between successive calibrations **stable** (Δ = **0.5 keV** rms)

The GERDA datasets

arXiv: 1306.5084v1

- Data are *not "homogeneous"* throughout the entire data taking
  - Higher background observed for the coaxial detectors for ~**20 days** after the deployment of BEGes (*silver dataset*). All the rest: *golden dataset*
  - BEGe detectors have better energy resolution than coaxials



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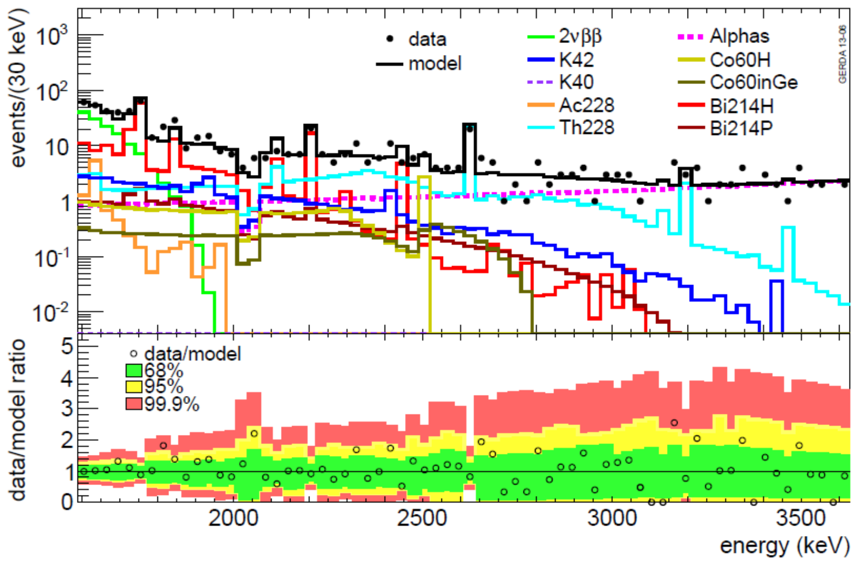
- **Analysis strategy:**
  - **All data are taken**, but not summed up (separate analysis)
    - Maximizes information, avoids "worse data" to spoil better ones
    - Three datasets used ("golden coax", "silver coax", "BEGes"), with independent backgrounds and resolutions
  - **Blind analysis** (new in the field of $0\nu 2\beta$ search)
    - Events in a 40 keV range around $Q_{\beta\beta}$ (energy & waveforms) are not made available for the analysis
    - Develop and validate the background model and the PSD cuts **before** the unblinding (all parameters frozen prior to unblinding)

arXiv: 1306.5084v1

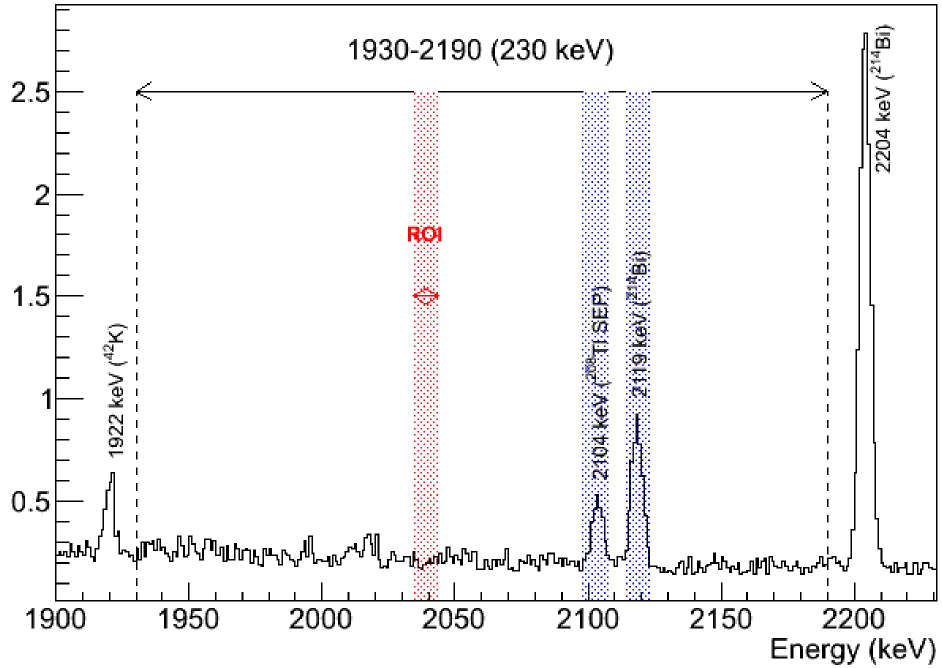
Identification of background components



- The model predicts a **flat background** around $Q_{\beta\beta}$
- No intense γ-lines expected around the $Q_{\beta\beta}$

→ spectra can be **fitted with a flat background** apart from lines 2104 keV and 2119 keV

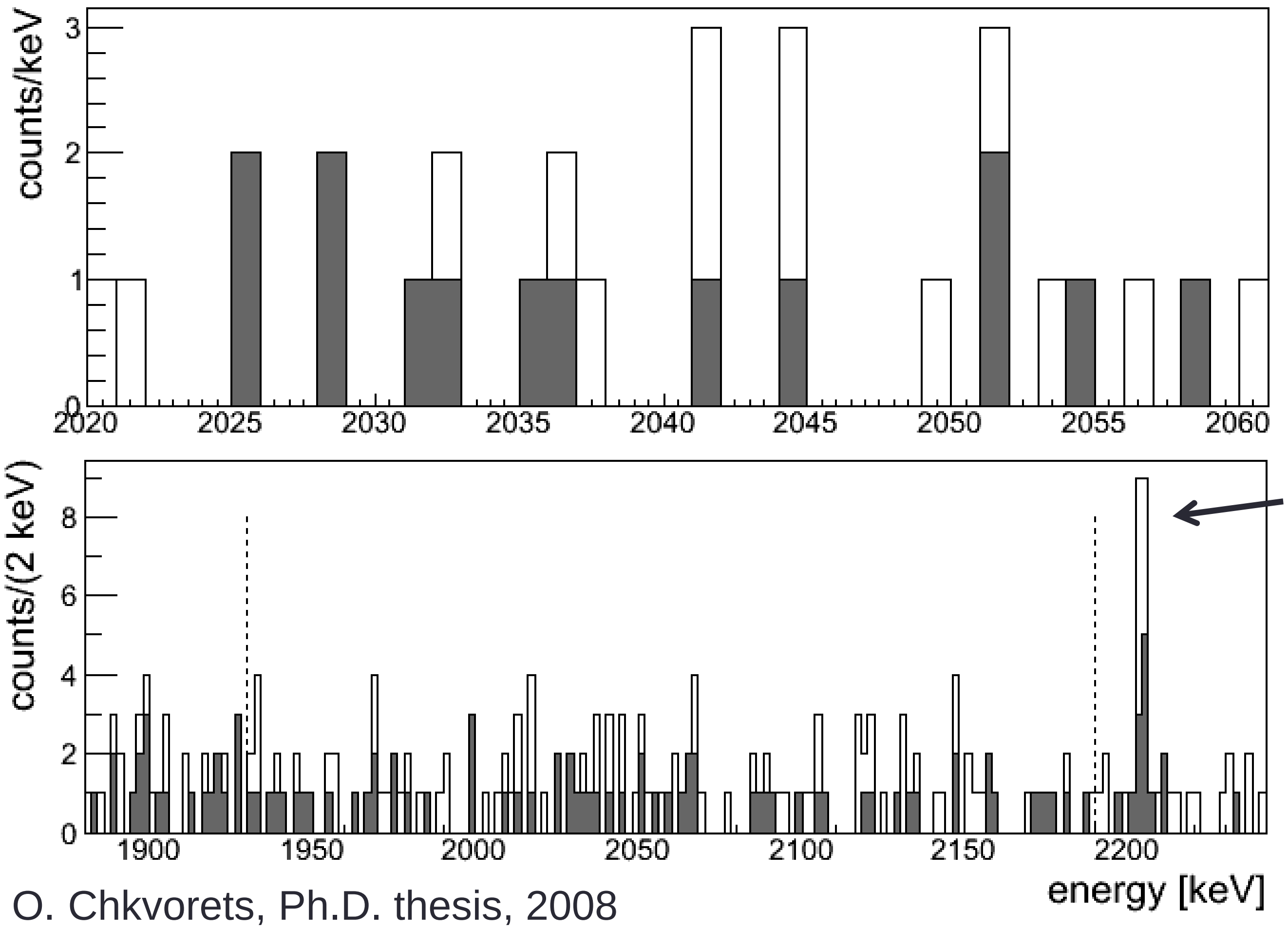
- **Contributors at $Q_{\beta\beta}$ (for coax)**:
  - γ emitters (close): ^{214}Bi, ^{208}Tl (2/3)
  - surface contaminations: ^{42}K, and α (1/3)
- α contamination from ^{210}Po
  - ^{210}Po decaying away ($t_{1/2}$=138 d)
  - Large differences among detectors



After the unblinding… the spectra

arXiv: 1307.4720
accepted by PRL

- Sum spectrum, **21.6 kg·yr**
  - Note: Real analysis uses the three dataset spectra *separately*



Without PSD

With PSD

2204 keV from ^{214}Bi

~ 18 cts w/o PSD
→ 0.83 cts/(kg·yr)
~ 9 cts w/ PSD

HdM w/o PSD [1]:
(8.1±0.5) cts/(kg·yr)

[1] O. Chkvorets, Ph.D. thesis, 2008

The events

arXiv: 1307.4720
accepted by PRL

Table 1: List of all events within $Q_{\beta\beta} \pm 5$ keV

data set	detector	energy [keV]	date	PSD passed	ANN	A/E	Cut Threshold
golden	ANG 5	2041.8	18-Nov-2011 22:52	no	0.344		0.366
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes	0.518		0.366
golden	RG 2	2041.3	16-Dec-2012 00:09	yes	0.682		0.364
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no		0.750	0.965÷1.070
golden	RG 1	2035.5	29-Jan-2013 03:35	yes	0.713		0.372
golden	ANG 3	2037.4	02-Mar-2013 08:08	no	0.205		0.345
golden	RG 1	2041.7	27-Apr-2013 22:21	no	0.369		0.372

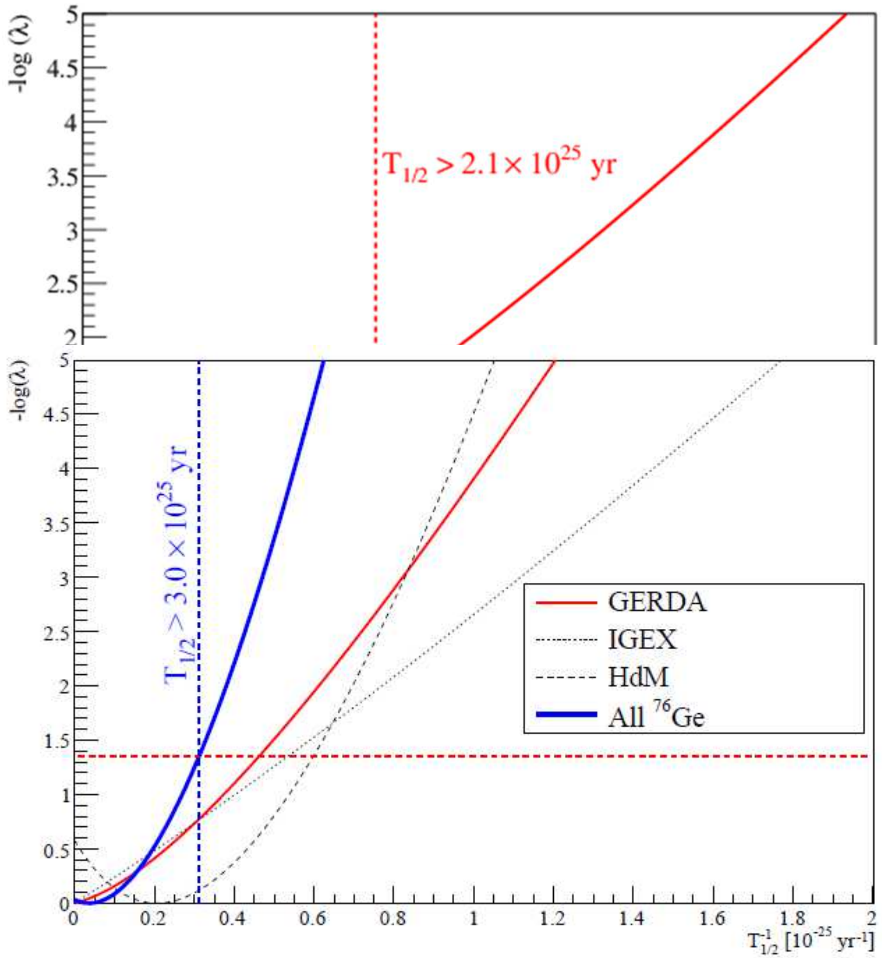
data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI †)	cts	Expected from background only
without PSD						
golden	17.9	0.688 ± 0.031	76	18 ± 2	5	3.3
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1	0.8
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1	1.0
with PSD						
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2	2.0
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1	0.4
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0	0.1

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

The analysis

arXiv: 1307.4720
accepted by PRL

- Baseline analysis with a frequentist approach (profile likelihood)
  - Maximum likelihood spectral fit (3 datasets, common $1/T_{1/2}$)
  - Bayesian version also available



Gerda only

Best fit: $N^{0\nu} = 0$

$N^{0\nu} < 3.5$ cts @ 90% C.L.

$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr @ 90% CL

MC Median sensitivity (for no signal):
$T_{1/2}^{0\nu} > 2.4 \times 10^{25}$ yr @ 90% C.L.

GERDA+HdM [1] +IGEX [2]

Best fit: $N^{0\nu} = 0$

$T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr @ 90% CL

[1] Eur. Phys. J. A 12, 147 (2001)
[2] Phys. Rev. D 65, 092007 (2002),
Phys. Rev. D 70 078302 (2004)

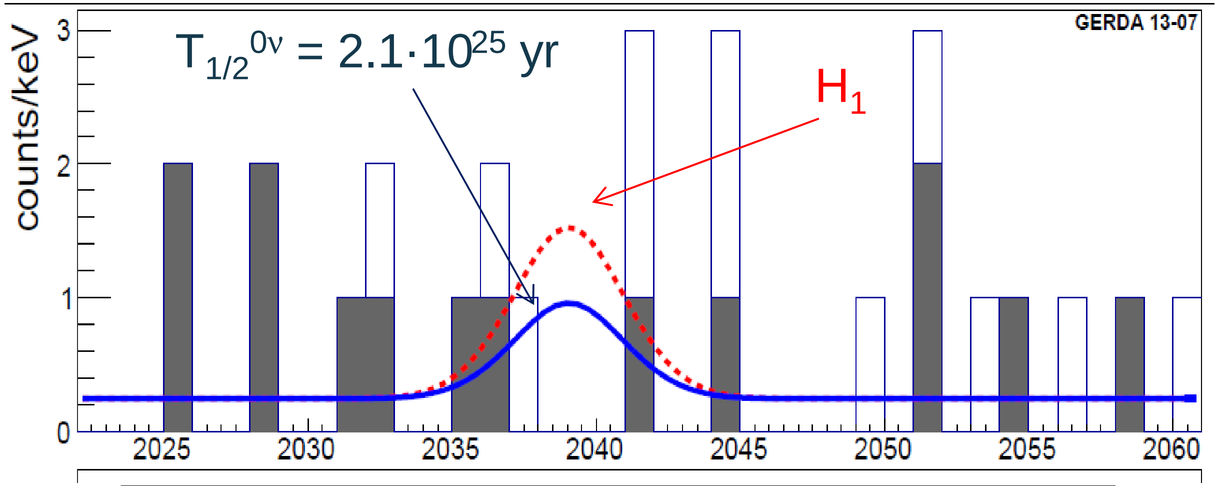
Comparison with Phys. Lett. B 586 198 (2004) claim

- Compare **two hypotheses**
  - **H_1**: $T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr (*) vs. **H_0**: background only

Expected Signal (w/ PSD): (5.9 ± 1.4) cts in ±2σ

Expected Bckgd (w/ PSD): (2.0 ± 0.3) cts in ±2σ

Observed: **3.0** in ±2σ (0 in ±1σ)



Claim strongly disfavoured

GERDA only:

Profile likelihood:

$P(N^{0\nu}=0|H_1)=0.01$

Bayes factor

$P(H_1)/P(H_0)=0.024$

GERDA+HdM+IGEX:

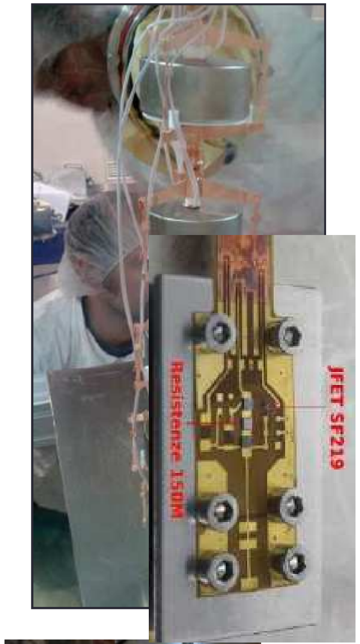
Bayes factor

$P(H_1)/P(H_0)=0.0002$

(*) $T_{1/2}^{0\nu}$ from Mod. Phys. Lett. A 21 (2006) 1547 **not** considered because of the **inconsistencies** (= missing efficiency factors, *problem in the conversion from counts to $T_{1/2}^{0\nu}$*) pointed out in Ann. Phys. 525 (2013) 269 → see also talk by B. Schwingenheuer, Sep. 9

Transition to GERDA Phase II … ongoing

- **Increase mass**: up to additional 30 enriched BEGe detectors (**~ 20 kg**)
  - already produced by Canberra Olen and completely tested at Hades (Belgium)
  - first BEGe sample already tested in the data chain of the Phase I
    - No anomalies found with internal and surface background (very low ^{210}Po)
- **Suppress background** by **factor >** 10 with respect to Phase I
  - New front end readout in close proximity (2 cm) to detectors, and new front end cabling
  - New HV and signal cabling with improved radiopurity and Rn emanation
  - PSA discrimination with the BEGe's
  - **Liquid argon veto instrumentation**
- Start **commissioning** in **Fall 2013 – Spring 2014**



See talk by B. Majorovits (Sep 9)

Conclusions

- **No** theoretical "**golden isotope**" for the $0\nu 2\beta$ decay
  - Other parameters (energy resolution, background, scalability, cost) can well compensate for a smaller NME or a lower Q-value
- **Many** experimental and R&D programs ongoing, with different candidate isotopes: **100's kg·yr** scale
  - GERDA completed Phase I (→ transition fo Phase II)
  - CUORE0 started, other experiments are being built
  - New results from NEMO3
- **GERDA** at LNGS collected **21.6 kg·yr** of exposure
  - Background 10^{-2} counts/(keV·kg·yr), after PSD
  - **Blind** analysis**, no positive signal** at $Q_{\beta\beta}$
  - $T_{1/2}$ **> 2.1 x 10^{25} yr** @ 90% CL (GERDA alone), **> 3.0 x 10^{25} yr** (with other Ge experiments)
  - **Claim** from **Phys. Lett. B 586 (2004) 198** strongly **disvafoured**, in a model–independent way (comparison of $T_{1/2}$)