Universität Zürich UZH

invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Neutrinoless double beta decay

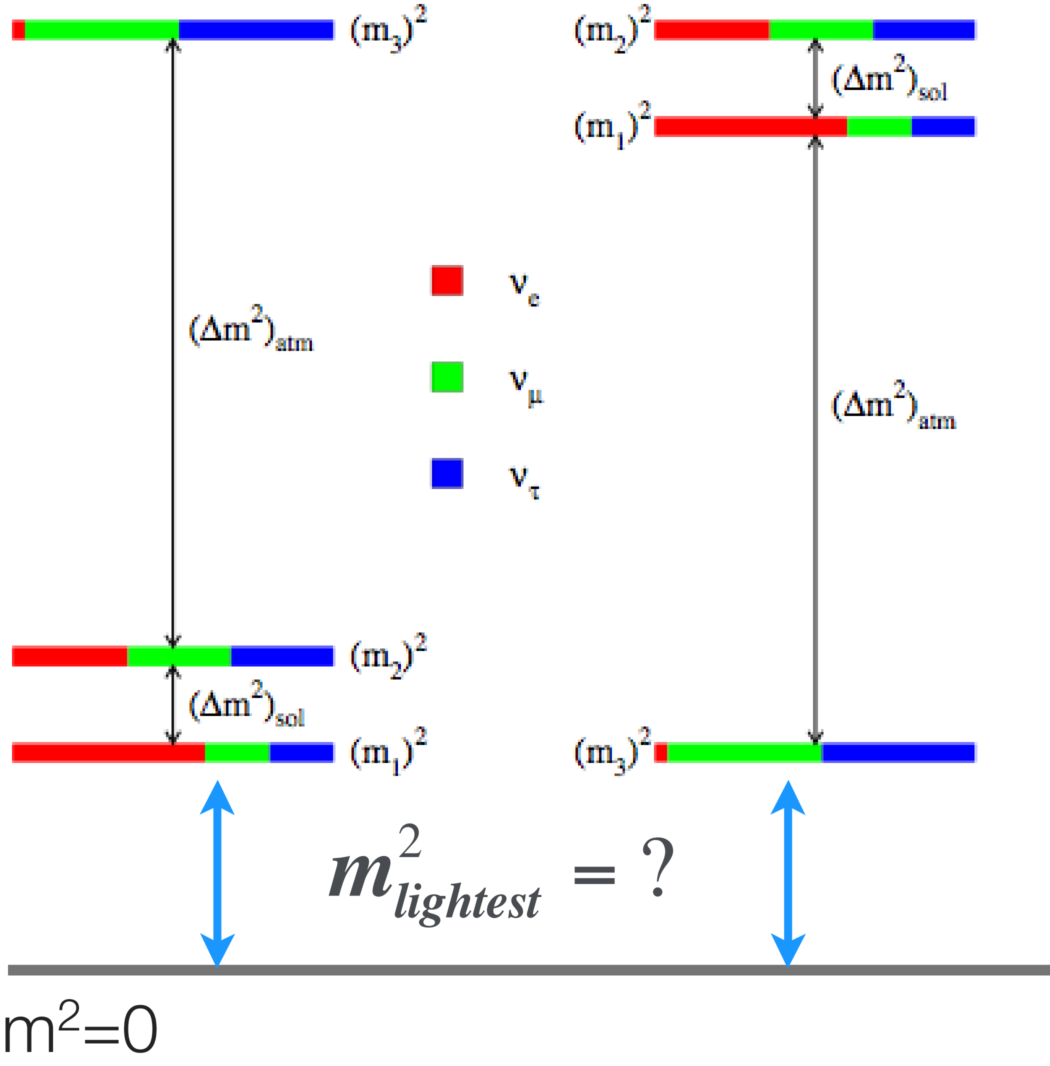
GERDA

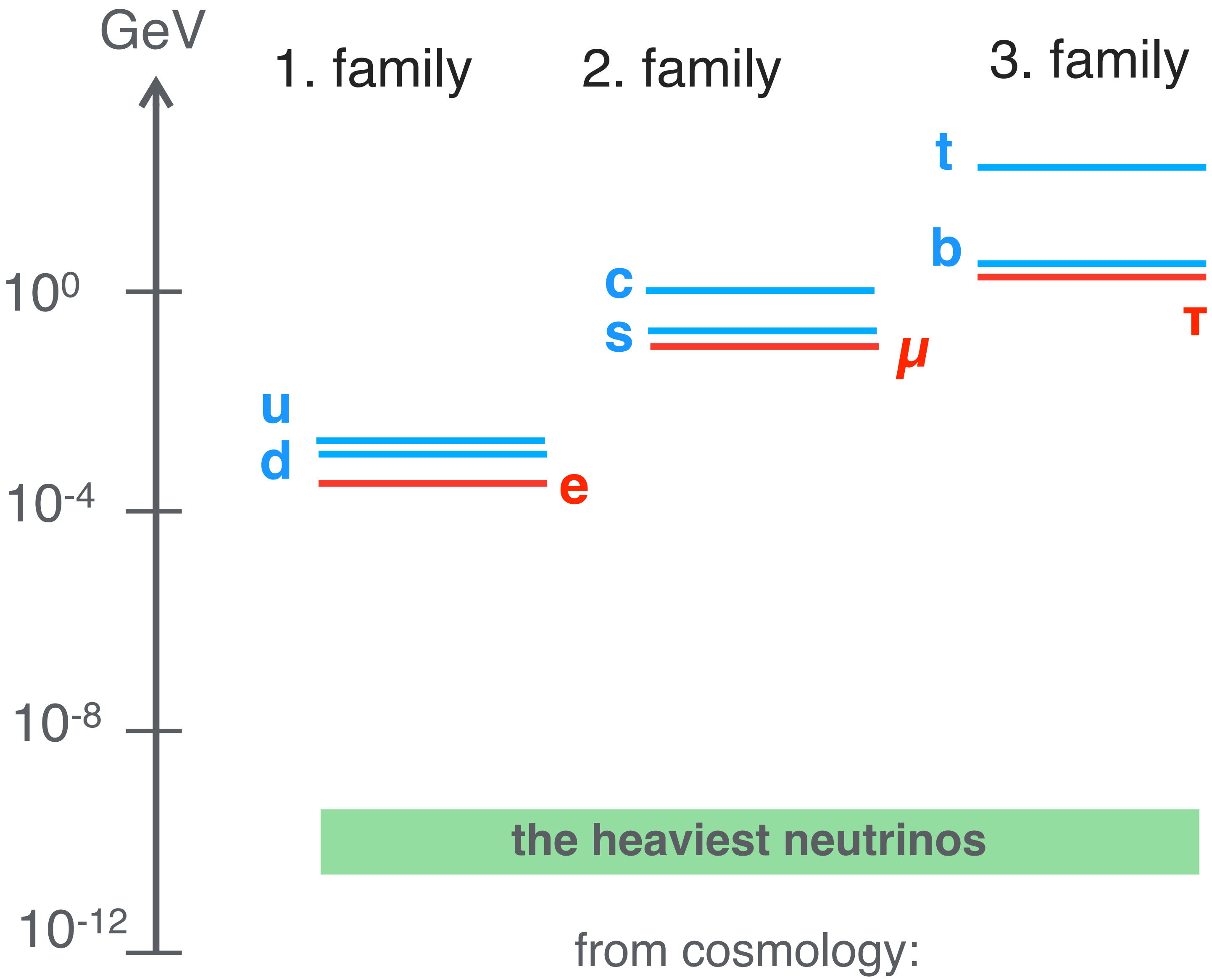
Laura Baudis
University of Zurich

CHIPP plenary meeting
Château de Bossey, July 1, 2015

Some open questions in neutrino physics

- What is the nature of neutrinos: Dirac or Majorana particles?
- What are their masses: absolute scale and ordering?



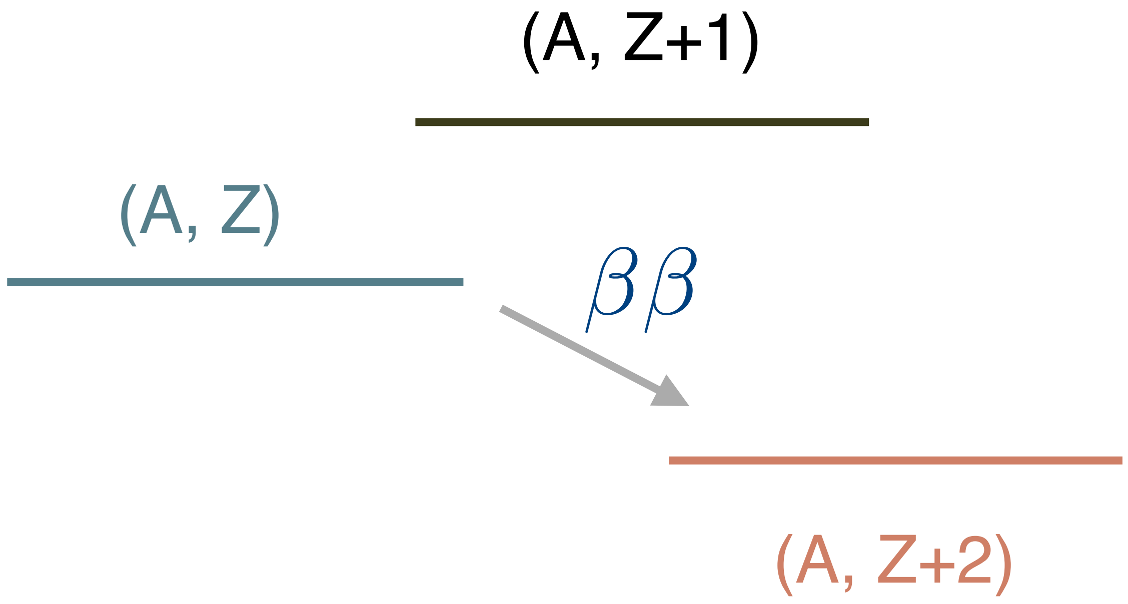


from cosmology:

$$\Sigma_i m_i \lesssim 200\,\mathrm{meV}$$

Double beta decay

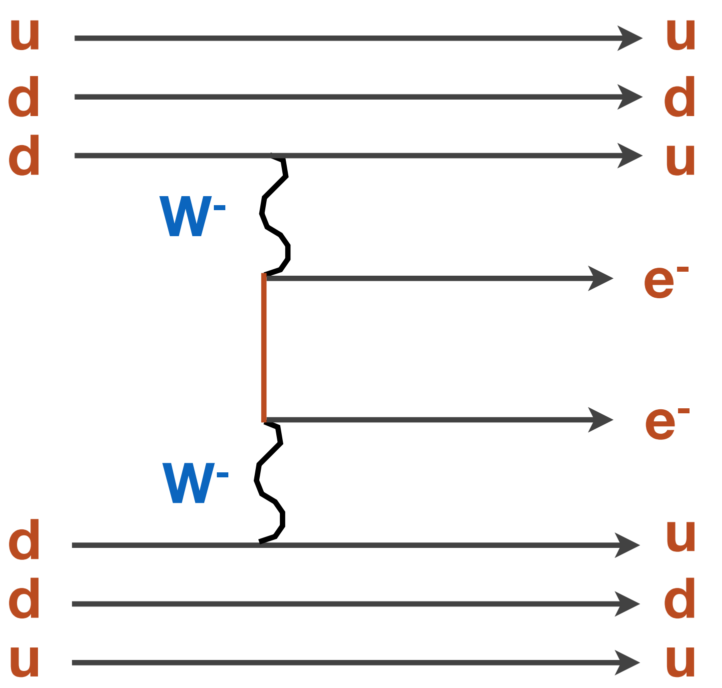
- A second-order process that can only be detected if first order beta decay is energetically forbidden
- Proposed in 1935 by Maria Goeppert-Mayer
- Observed in 11 nuclei, $T_{1/2} > 10^{18}$ y; ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U



Neutrinoless double beta decay

- Extremely rare process, $T_{1/2} > 10^{22}$ y
- Proposed in 1937 by Ettore Majorana; not yet observed
- **Requires massive Majorana neutrinos & lepton number violation***

In an atomic nucleus:



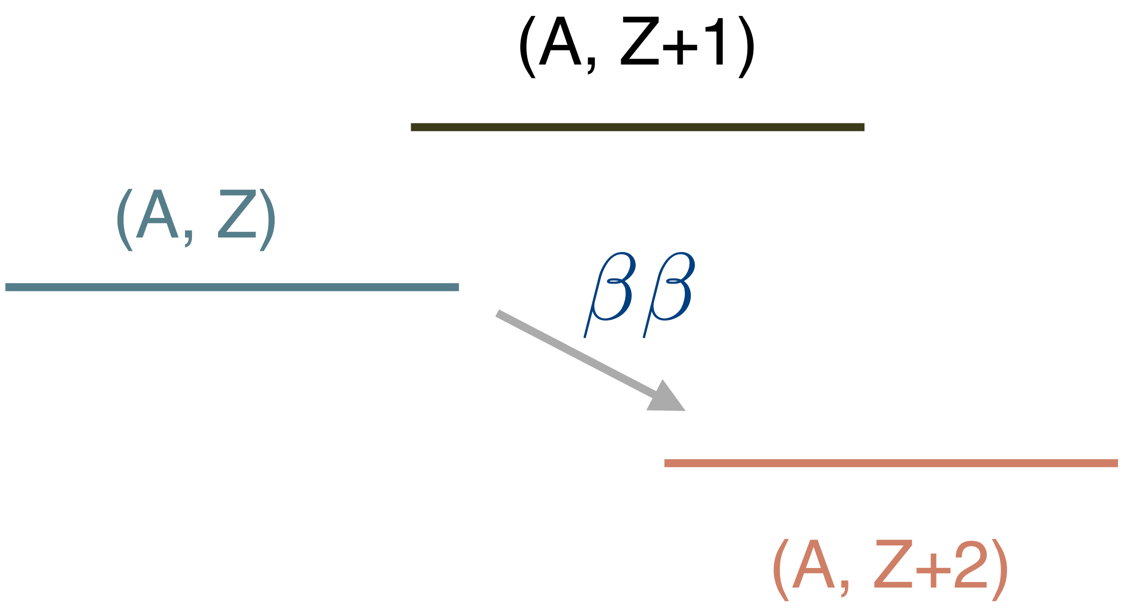
L = 0

L = 2

* In the simplest interpretation -> light neutrinos and SM interactions
* New mechanism with heavy particles in general subdominant because of smaller NME

Which nuclei can decay via $0\nu\beta\beta$?

- Even-even nuclei
- Natural abundance is low (except ^{130}Te)
- Must use enriched material

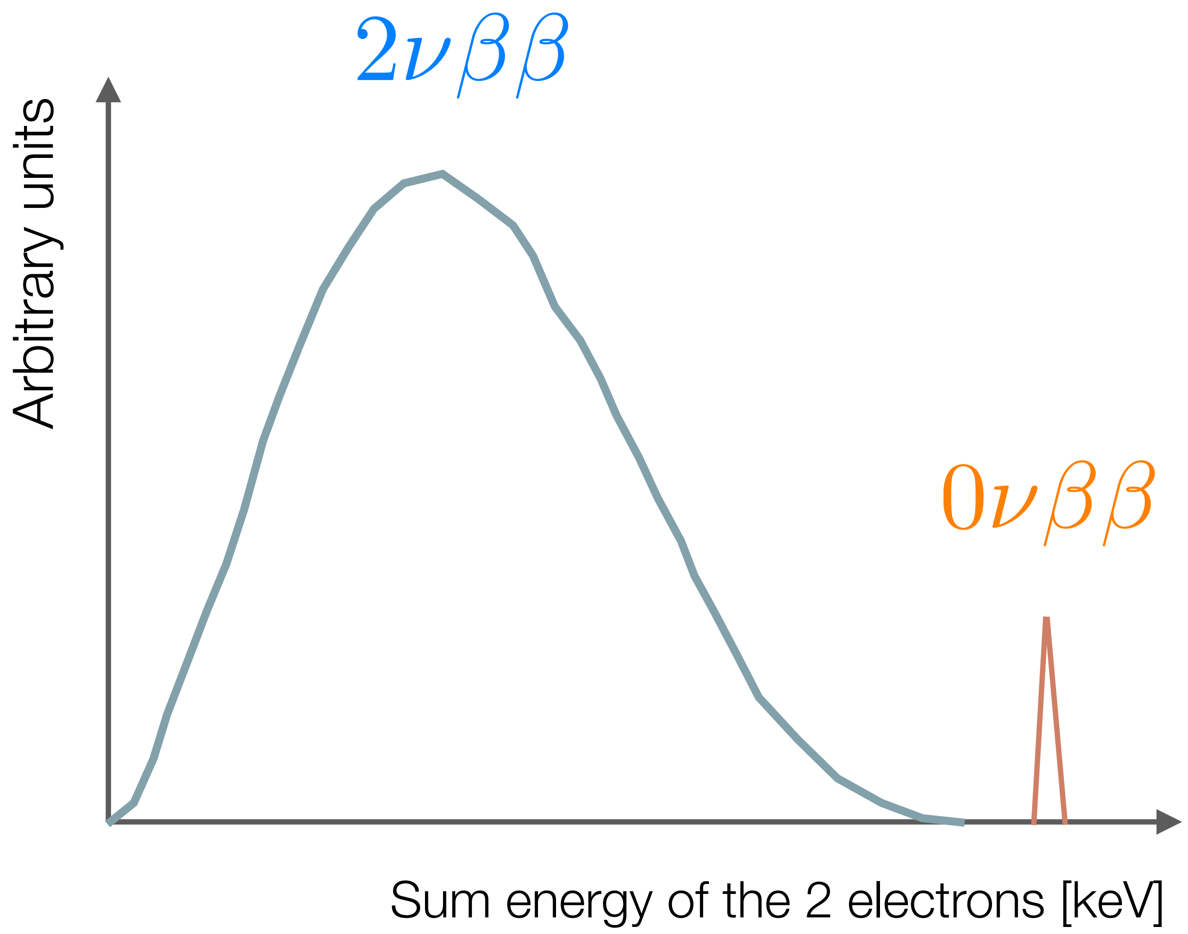


Candidate*	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	**2.04**	**7.8**
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	34.5
^{136}Xe -> ^{136}Ba	**2.479**	**8.9**
^{150}Nd -> ^{150}Sm	3.367	5.6

* Q-value > 2 MeV

How do we look for the decay?

- Observe the 2 final-state electrons
- Expect a sharp “peak” at the Q-value of the decay
- *Excellent energy resolution is essential for a discovery experiment*



$$Q = E_{\mathrm{e}1} + E_{\mathrm{e}2} - 2m_{\mathrm{e}}$$

What is the observable decay rate?

Phase space factor

Axial-vector cc

NME

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|m\beta\beta|^2}{m_e^2}$$

Can be calculated: ~ Q^5

Difficult: factor 2-3

- with the **effective Majorana neutrino mass:**

$$|m_{\beta\beta}| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i(\alpha_1 - \alpha_2)} + U_{e3}^2 m_3 e^{i(-\alpha_1 - 2\delta)}|$$

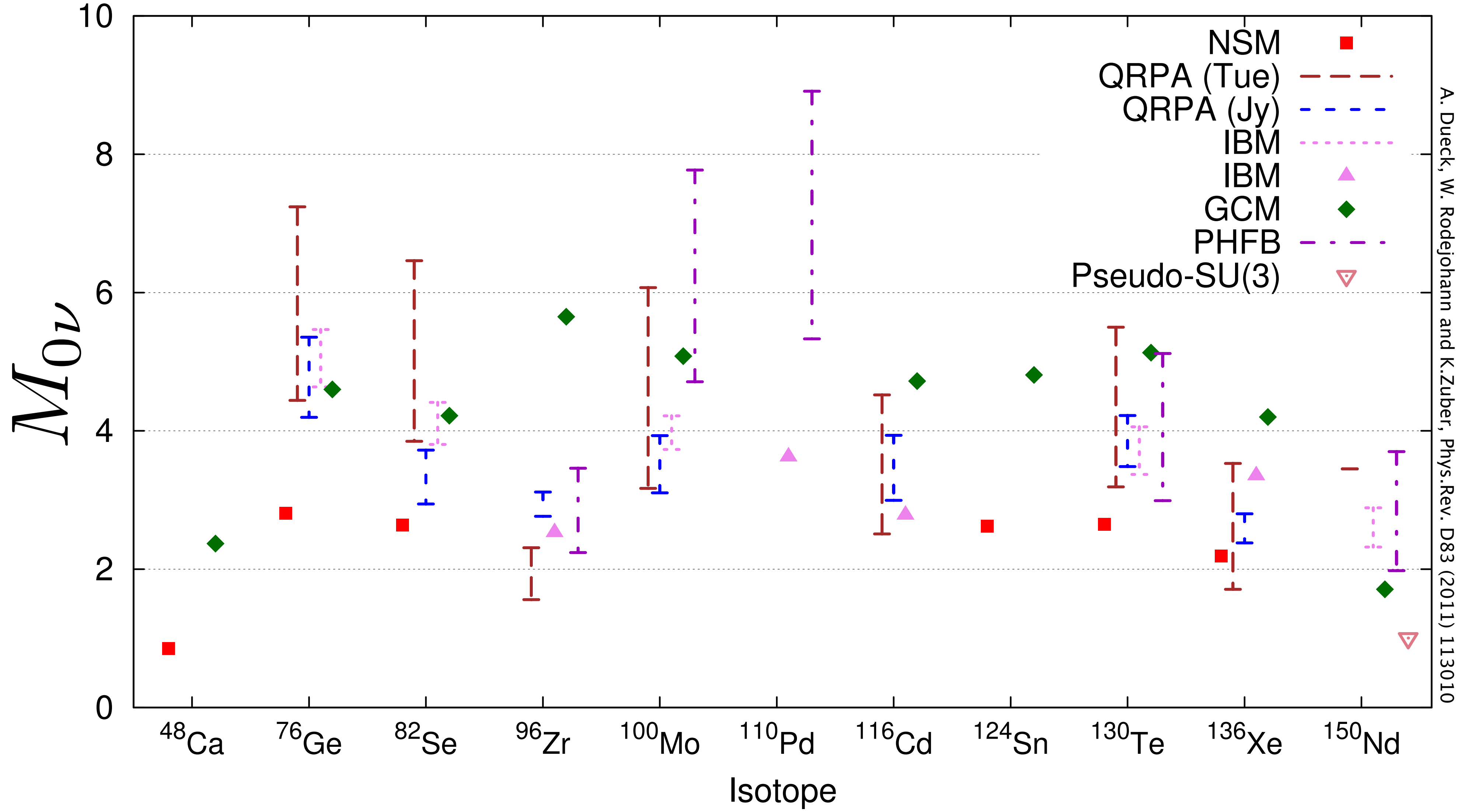
➡ a coherent sum over mass eigenstates with potentially CP violating phases

➡ = a mixture of m_1, m_2, m_3, proportional to the U_{ei}^2, with α_1,α_2 = Majorana CPV phases

- U_{ei} = matrix elements of the PMNS-Matrix, m_i = eigenvalues of the neutrino mass matrix

Matrix elements for $0\nu\beta\beta$

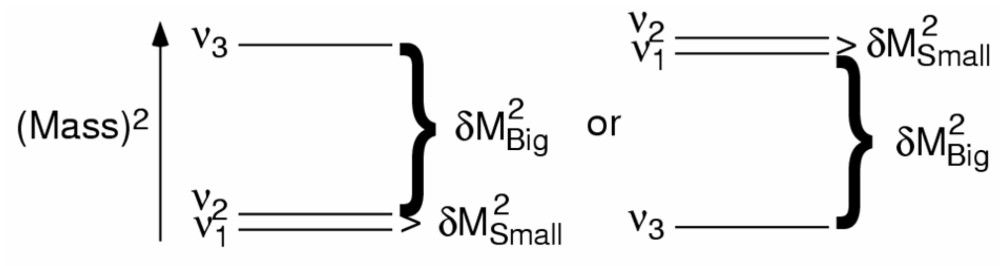
- Past years: improved agreement among the various methods
- Still spread by a factor 2-3 => **uncertainty of ~ 4 - 10 in $T_{1/2}$**



A. Dueck, W. Rodejohann and K.Zuber, Phys.Rev. D83 (2011) 113010

Effective Majorana neutrino mass

normal

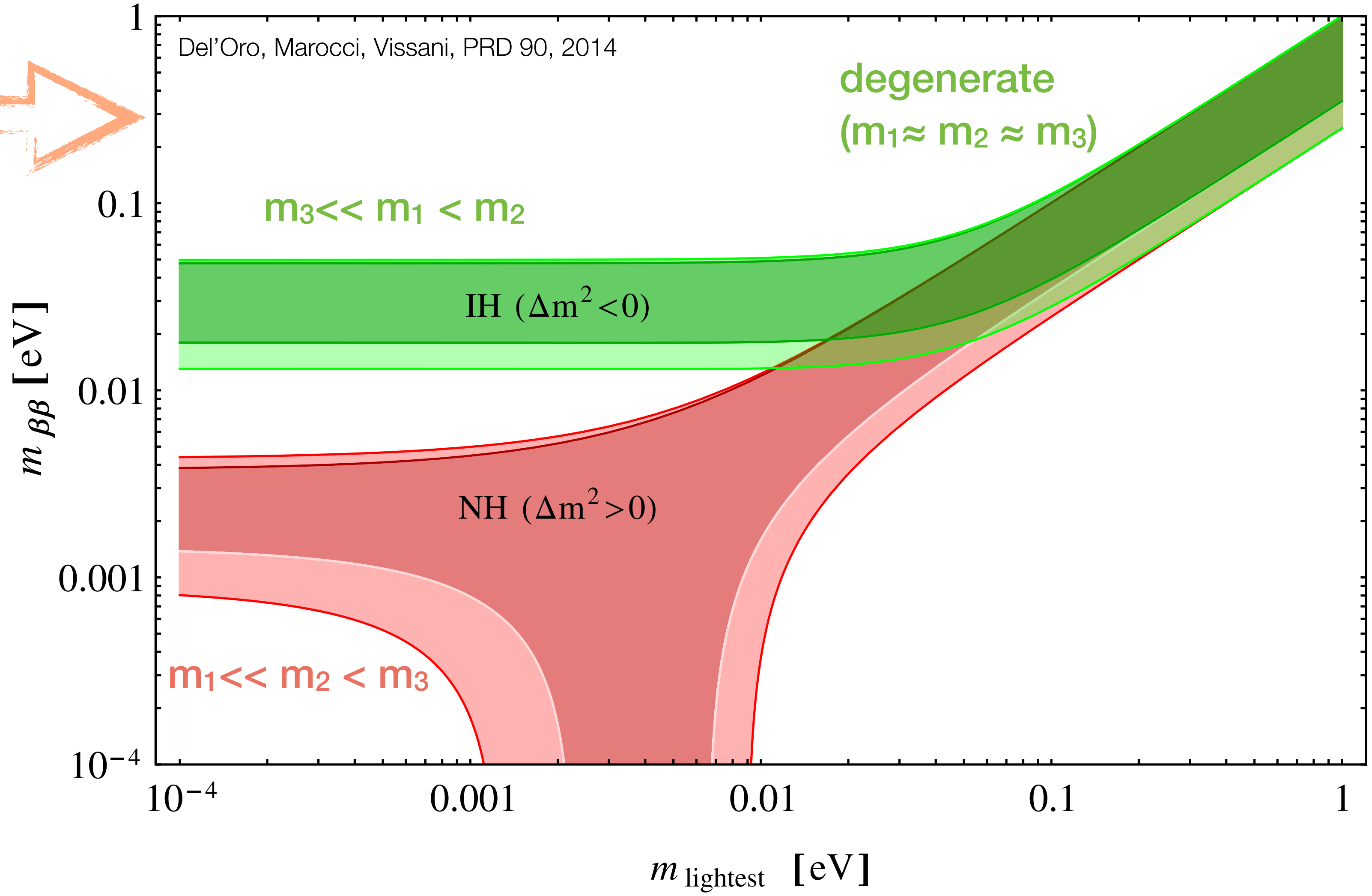


inverted

current sensitivities

$T_{1/2} \sim 10^{27}$ yr

$T_{1/2} \sim 10^{29}$ yr



Del'Oro, Marocci, Vissani, PRD 90, 2014

0.1- 1 counts/(y kg)

0.5 - 5 counts/(y t)

0.1-1 counts/(y 100 t)

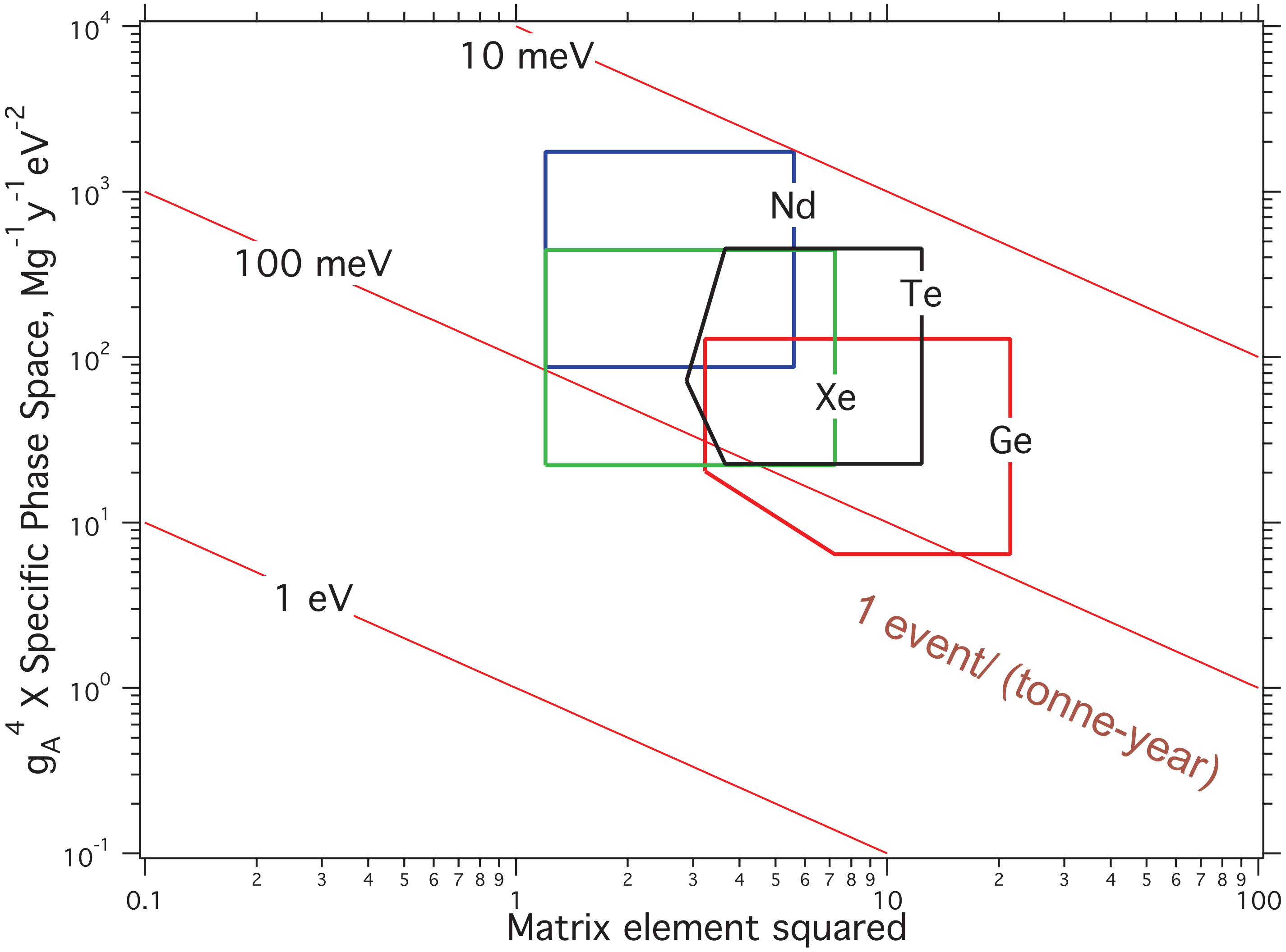
Isotopes and sensitivity to $0\nu\beta\beta$

Isotopes have comparable sensitivities in terms of rates per unit mass

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|m\beta\beta|^2}{m_e^2}$$

$$g_A^4 \ln(2) \frac{N_A}{A m_e^2} G^{0\nu}$$

$|M|^2$ uncertainty



g_A^4 uncertainty

effective value for the axial vector coupling constant g_A: ~ 0.6 - 1.269 (free nucleon value)

R. G. H. Robertson, Mod. Phys. Lett. A28 (2013) 1350021

Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}$ with a sensitivity (for non-zero background)

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

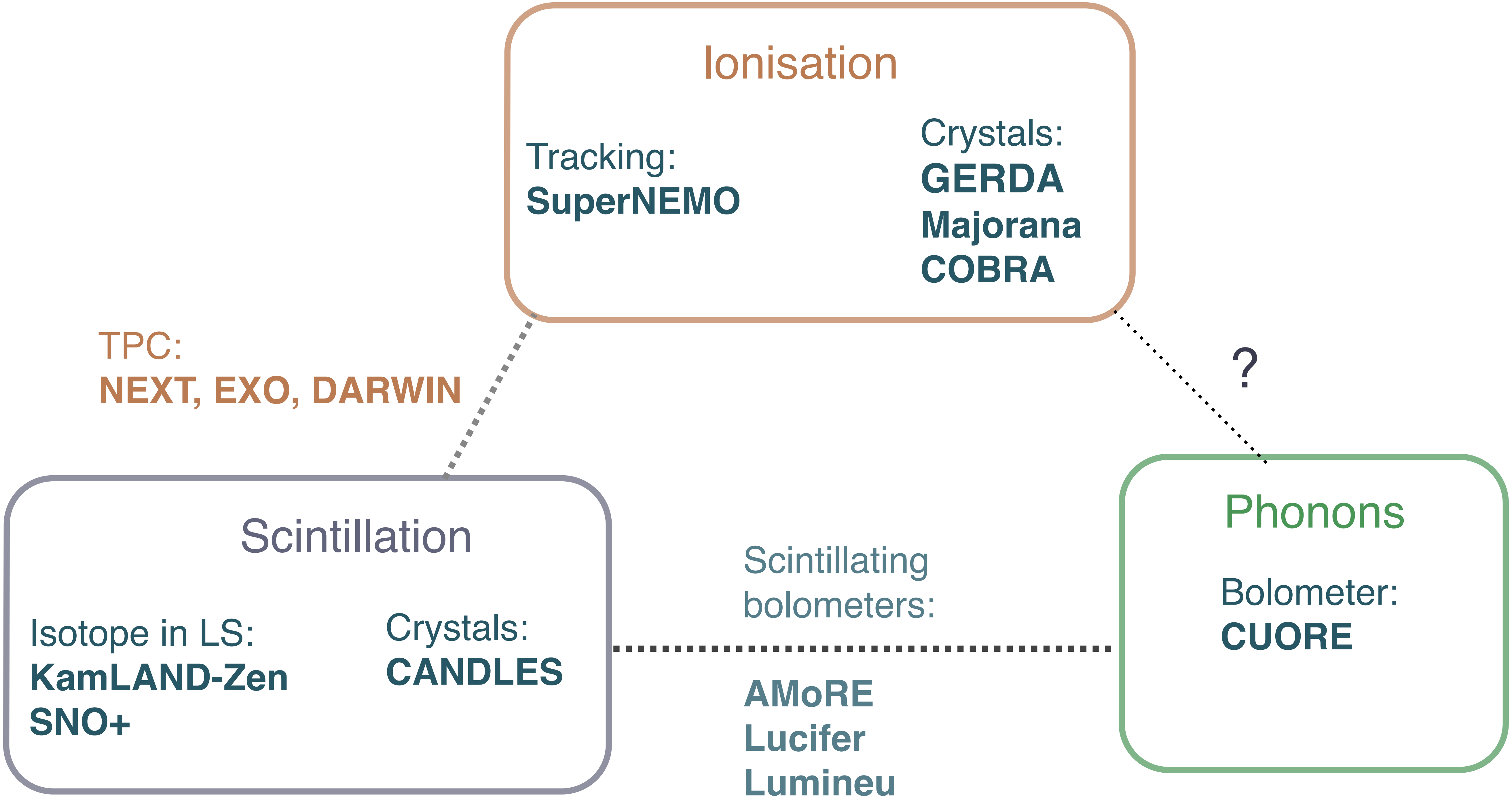
Minimal requirements:

large detector masses
high isotopic abundance
ultra-low background noise
excellent energy resolution

Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

Experimental techniques



Ionisation

Tracking:
SuperNEMO

Crystals:
GERDA
Majorana
COBRA

TPC:
NEXT, EXO, DARWIN

?

Scintillation

Isotope in LS:
KamLAND-Zen
SNO+

Crystals:
CANDLES

Scintillating bolometers:
AMoRE
Lucifer
Lumineu

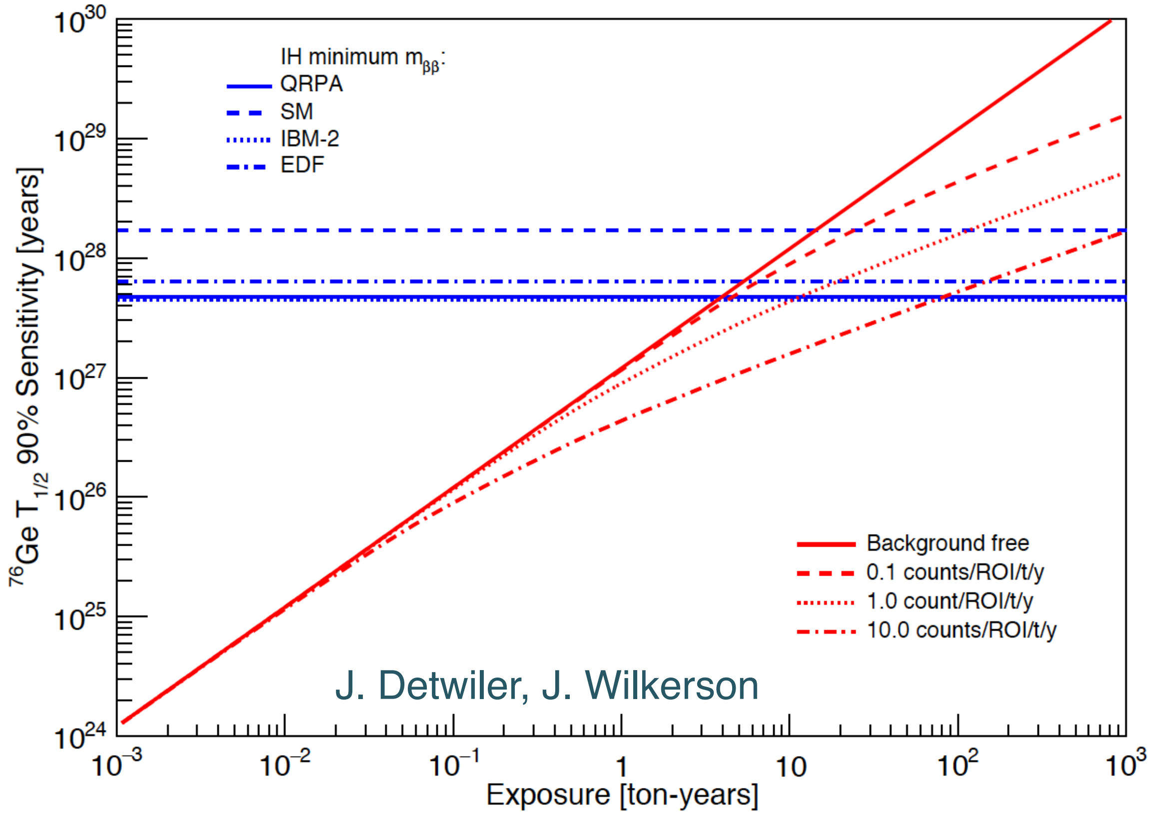
Phonons

Bolometer:
CUORE

Backgrounds

- Muon induced backgrounds
- Natural radioactivity: ^{238}U, ^{232}Th, ^{40}K, Radon, (alpha,n), (n,gamma) etc
- Anthropogenic radioactivity: ^{110m}Ag, ^{207}Bi, etc
- Cosmogenic activation of detector components: ^{60}Co, ^{42}Ar, ^{68}Ge, etc
- ^{8}B solar neutrinos
- 2 neutrino double beta decay

Ge sensitivity with/without backgrounds

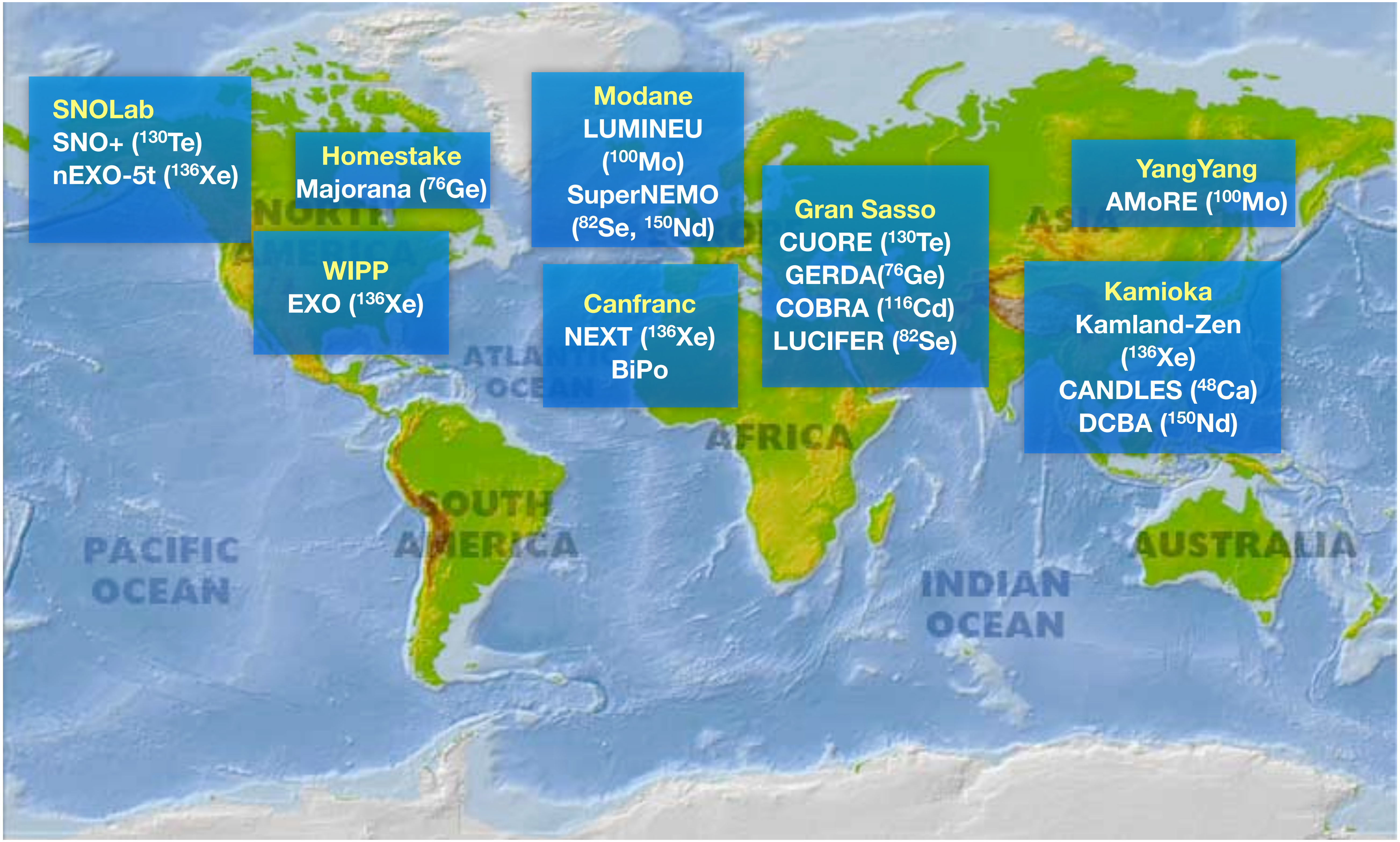


J. Detwiler, J. Wilkerson

Background reduction

- Ultra-pure materials
- Energy resolution
- Event topology
- Pulse shape discrimination
- Particle identification

Double beta experiments in underground labs



SNOLab
SNO+ (^{130}Te)
nEXO-5t (^{136}Xe)

Homestake
Majorana (^{76}Ge)

WIPP
EXO (^{136}Xe)

Modane
LUMINEU (^{100}Mo)
SuperNEMO (^{82}Se, ^{150}Nd)

Canfranc
NEXT (^{136}Xe)
BiPo

Gran Sasso
CUORE (^{130}Te)
GERDA(^{76}Ge)
COBRA (^{116}Cd)
LUCIFER (^{82}Se)

YangYang
AMoRE (^{100}Mo)

Kamioka
Kamland-Zen (^{136}Xe)
CANDLES (^{48}Ca)
DCBA (^{150}Nd)

Overview of (selected) experiments

Experiment	Isotope	Isotopic mass	Start of operation
CUORE-0 CUORE	^{130}Te	11 kg 210 kg	2013 (running) 2015
EXO-200 nEXO	^{136}Xe	200 kg 5 t	2011 2018 (?)
GERDA phase I GERDA phase II	^{76}Ge	17 kg 40 kg	2011 2015
KamLAND-Zen	^{136}Xe	300 kg	2012 (running)
Majorana	^{76}Ge	30 kg	2015
NEXT	^{136}Xe	100 kg	2016
SNO+	^{130}Te	800 kg	2016
SuperNEMO	^{82}Se	7 kg	2016

The GERDA experiment at the Gran Sasso Lab

HPGe detectors, enriched to ~86% in ^{76}Ge

Liquid argon as cooling medium and shielding

(U/Th in LAr < 7x10^{-4} µBq/kg)

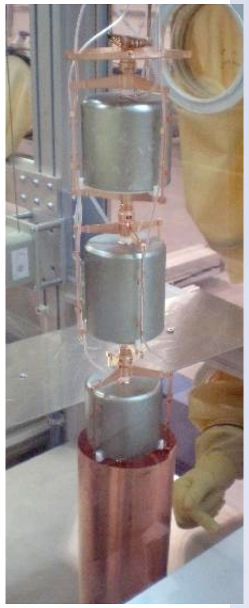
A minimal amount of surrounding materials

Phase I (2011-2014)

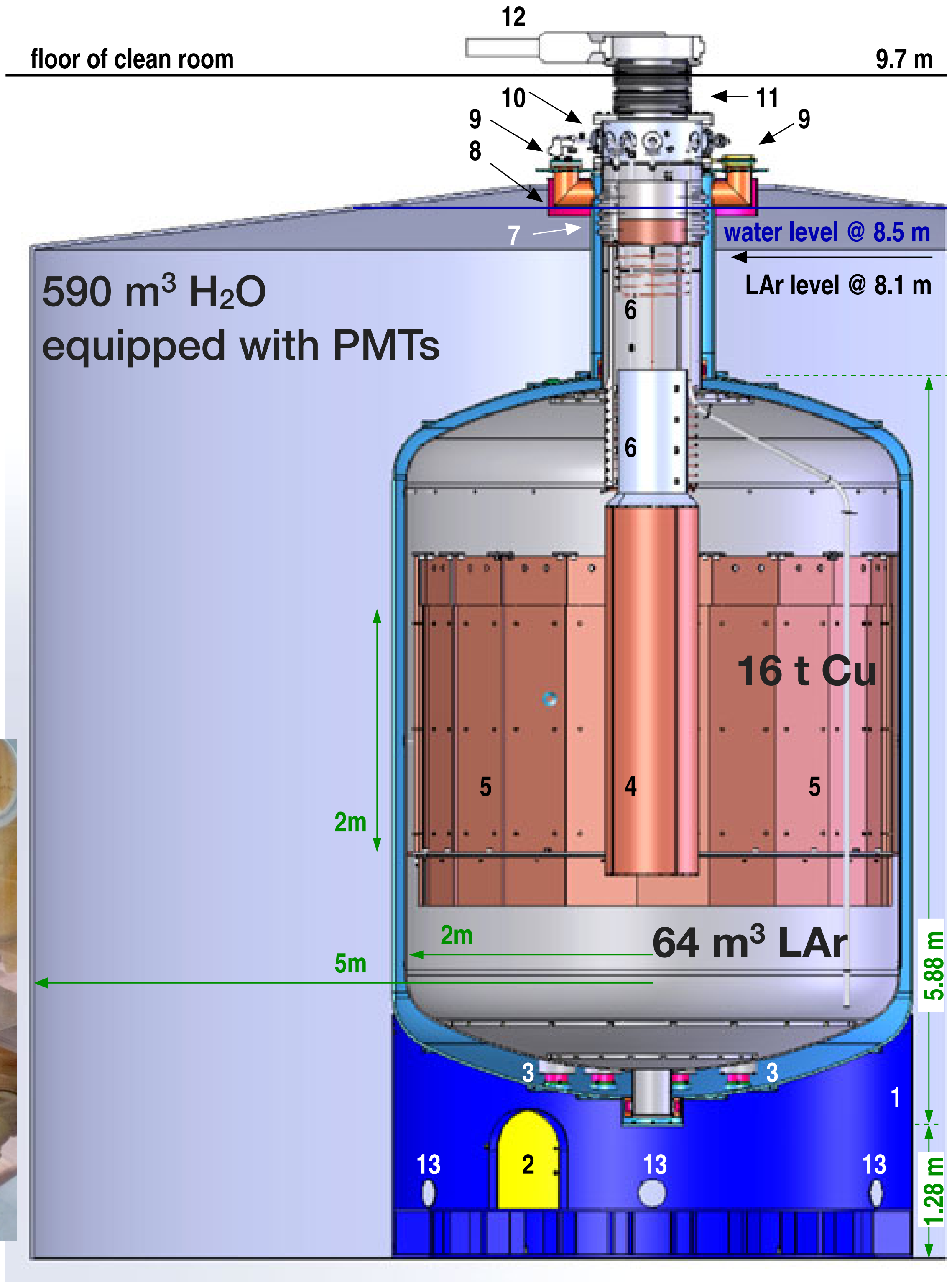
~18 kg HPGe detectors

Phase II (to start in summer 2015)

+ 20.5 kg HPGe detectors

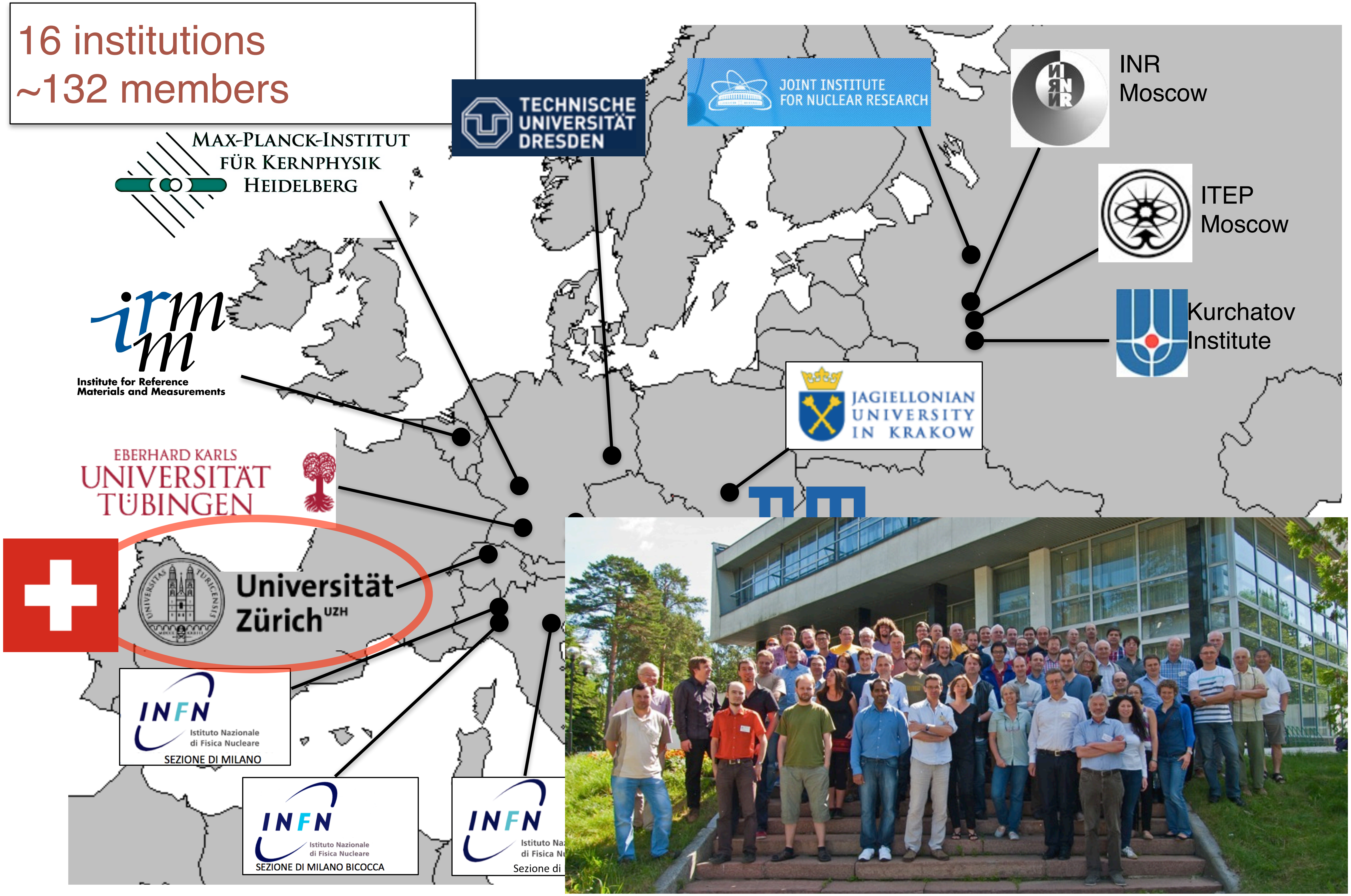


Eur. Phys. J. C (2013) 73:2330



The GERDA collaboration

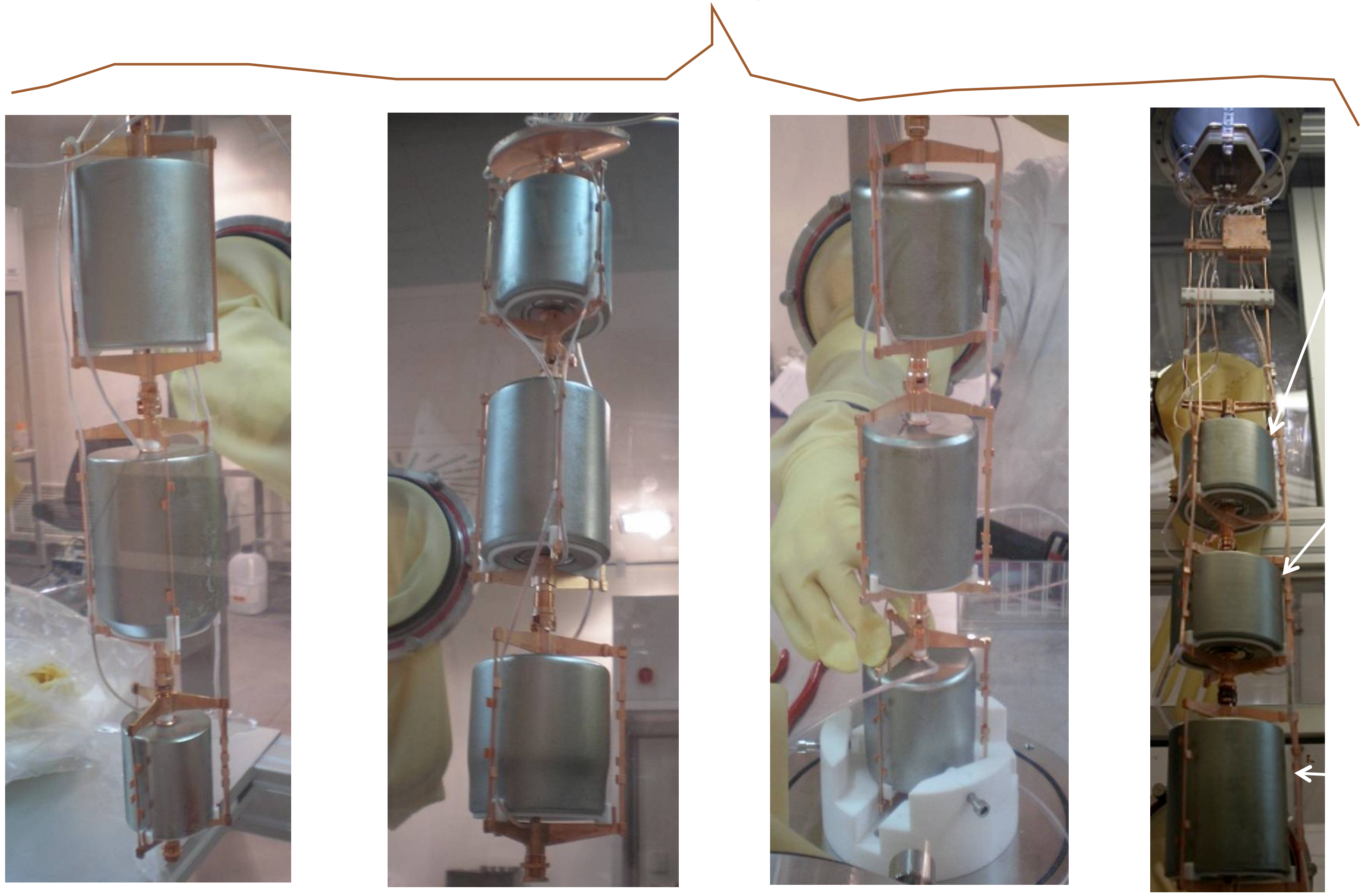
16 institutions
~132 members



The GERDA detectors in Phase I

- From HdM & IGEX experiments: total mass = 17.7 kg
  - ➡ HdM: ANG1, ANG2, ANG3, ANG4, ANG5; IGEX: RG1, RG2, RG3
  - ➡ Isotopically enriched in ^{76}Ge: 86%

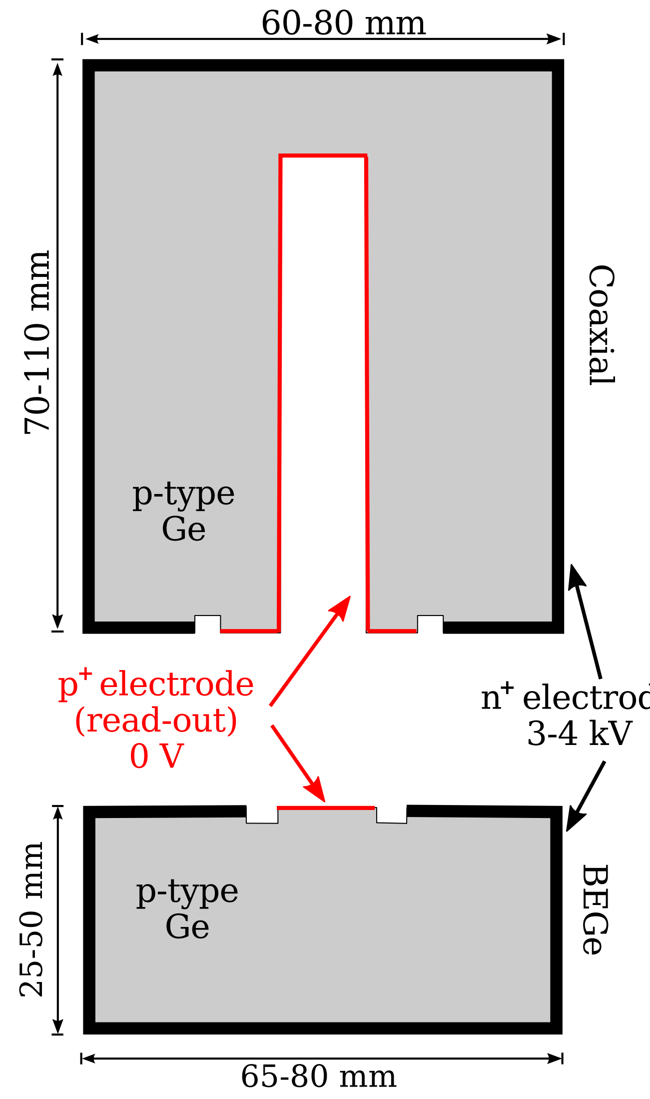
- Two ^{76}Ge detectors turned off because of high leakage current
- In addition, natural Ge detectors from Genius-TF
- Also, 5 phase II, enriched BEGe detectors added later on = 3.63 kg



Semi-coaxial HPGe

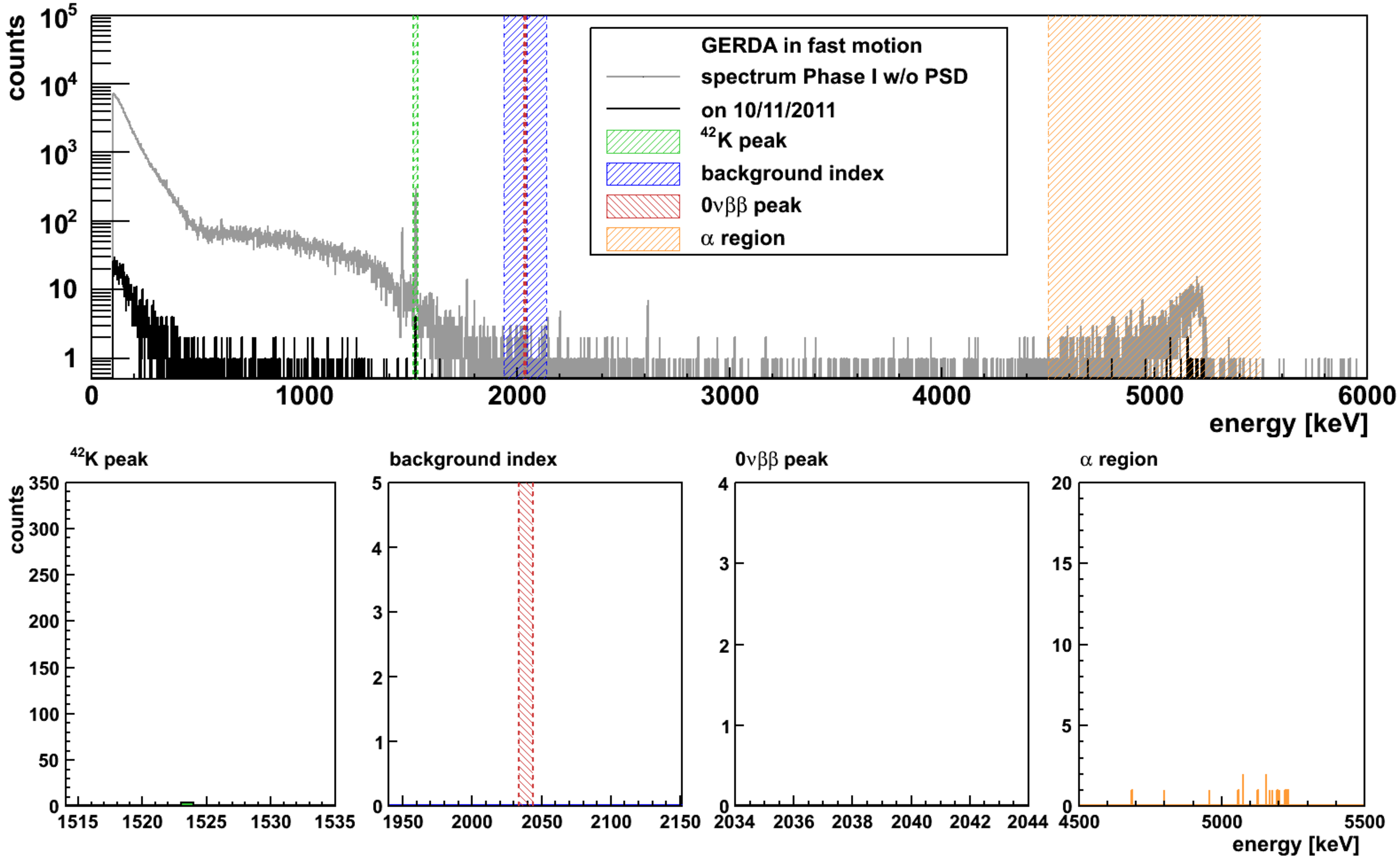
BEGe detectors

- Coaxial, p-type, 2.4‰ FWHM at Q_{bb}



- Broad energy germanium (BEGe): p-type,1.6‰ FWHM at Qbb

GERDA Phase I



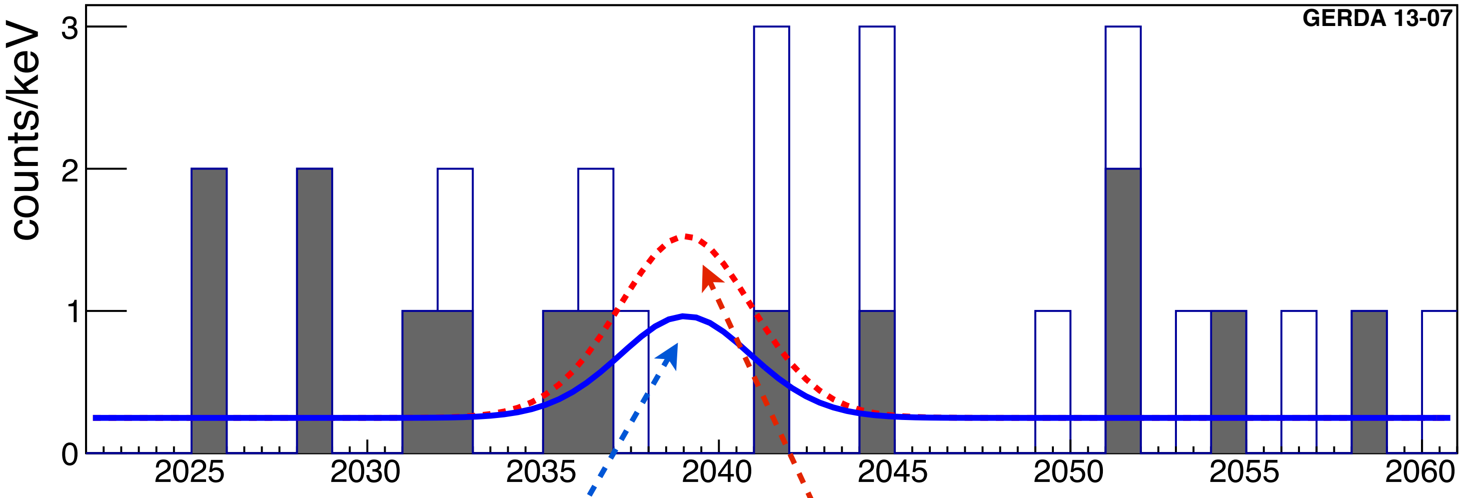
Total exposure used in neutrinoless double beta analysis: 21.6 kg yr

Background level: 0.011(2) events/(keV kg y)

Background model: EPJC 74, 2014

Phase I result: no sign for $0\nu\beta\beta$

PRL 111, 2013



“Claim”, PLB586 (2004)

$T^{0\nu}_{1/2} = 1.19 \times 10^{25}\,\mathrm{yr}$

GERDA lower limit from PL fit of the 3 data sets, with constant term for background (3 parameters for the 3 data sets) and Gaussian term for signal: *best fit is $N_{signal} = 0$*

$$T^{0\nu}_{1/2} > \; 2.1 \times 10^{25}\,\mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

- the limit on the half life corresponds to $N_{signal} < 3.5$ counts

- Observed and predicted number of background events in the energy region $Q_{\beta\beta} \pm 5$ keV

	Observed	Predicted background
No PSD	7	5.1
PSD	**3**	**2.5**

- 5.9 ± 1.4 events are expected for “claim”, and 2.0±0.3 BG events

Claim of evidence for 0vbb-decay:
signal: 28.8 ± 6.9 events
BG level: 0.11 counts/(keV kg yr)
HVKK et al., PLB 586 (2004) 198-212

Comparison with Xe experiments

- No indication for a peak at Q = 2039 keV in GERDA phase I data
- A model-independent test of the signal claim by part of the HdM collaboration
- **Combined with HdM and IGEX:**

$$T_{1/2}^{0\nu} > \; 3 \times 10^{25}\,\mathrm{yr}\;(90\%\,\mathrm{C.L.})$$

- This yields an upper limit on the effective Majorana neutrino mass in the range:

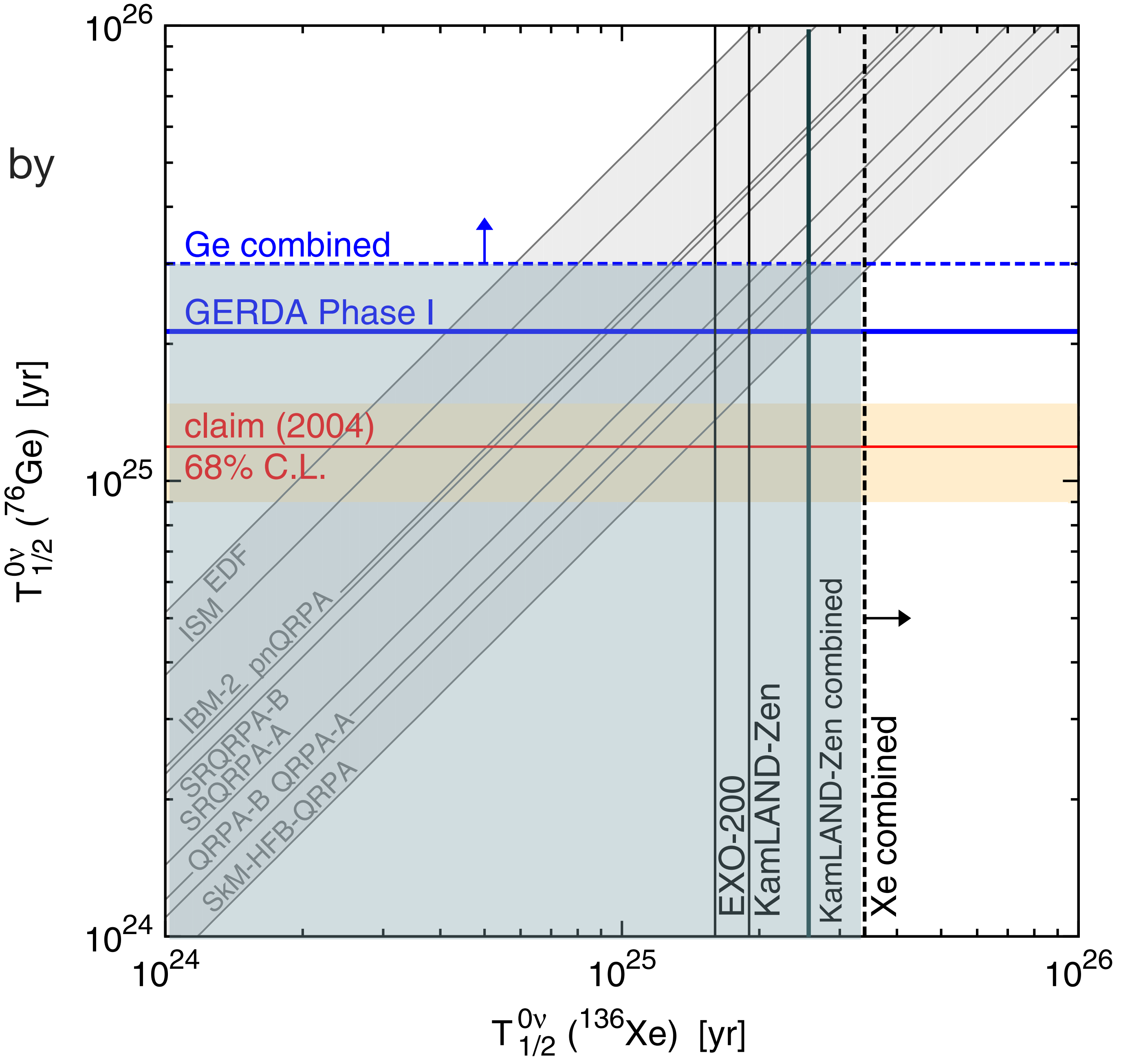
$$m_{\beta\beta} < 0.2 - 0.4\,\mathrm{eV}$$

- **EXO:**

$$m_{\beta\beta} < 0.19 - 0.45\,\mathrm{eV}$$

- **KamLAND-Zen:**

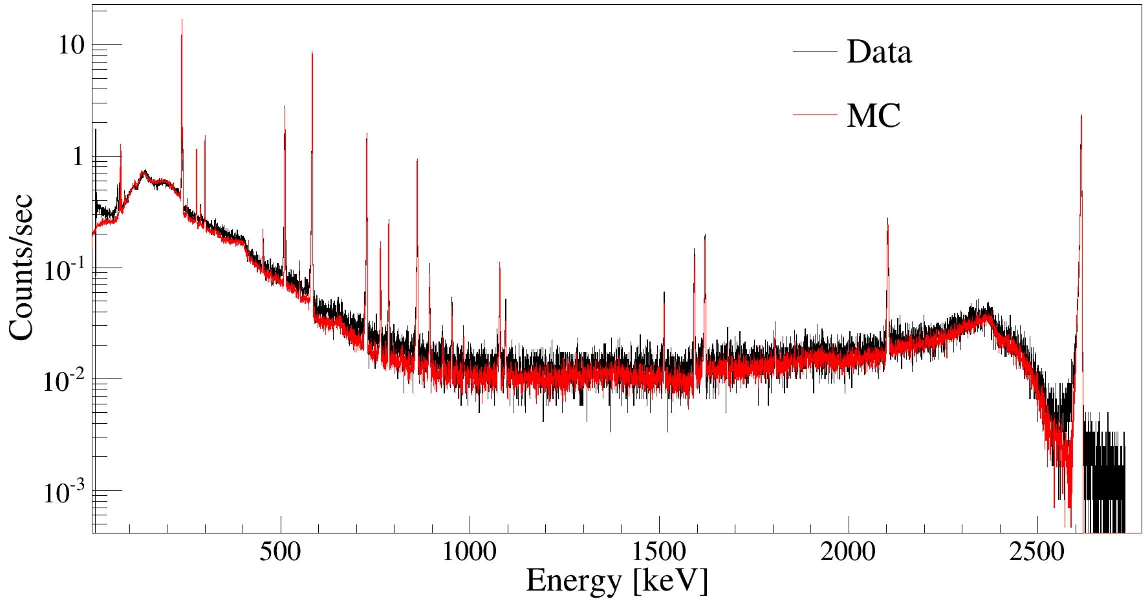
$$m_{\beta\beta} < 0.14 - 0.28\,\mathrm{eV}$$

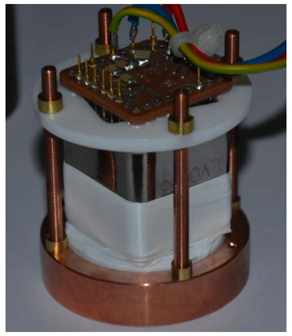


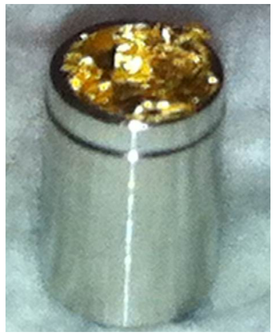
GERDA Phase II

GERDA collaboration, Eur. Phys. J. C75 (2015) 2, 39

- 30 (20.5 kg) new ^{enr}BEGe detectors procured, tested and stored at LNGS (UZH part of the ^{enr}BEGe team)
- New calibration systems and low-neutron emission ^{228}Th sources (UZH; sources in collaboration with PSI)
- 8.2 x 10^{-7} n/(s Bq) measured with LiI detector at LNGS (factor 7 reduction compared to a commercial source)



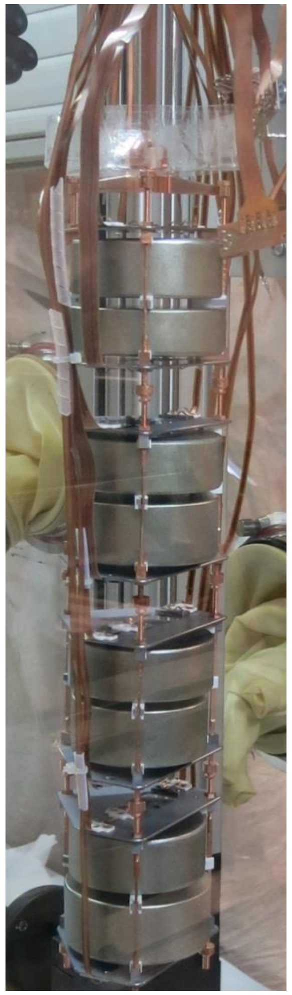


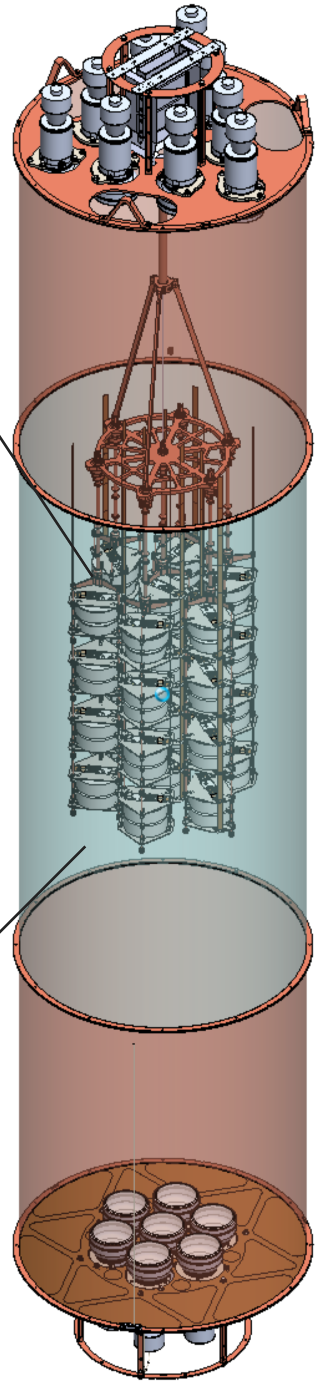


Source	Activity [kBq]
9854	$24.21^{+0.05}_{-0.06}$
9855	$34.20^{+0.06}_{-0.07}$
9856	$30.75^{+0.08}_{-0.05}$
9857	$41.28^{+0.08}_{-0.07}$

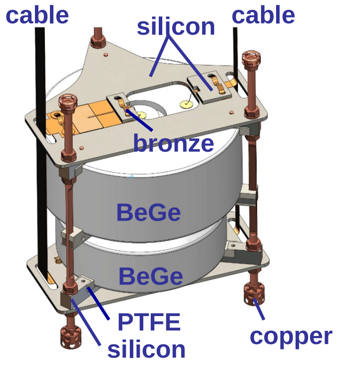
Phase II

4 strings /w BEGe det
+3 strings coaxial det





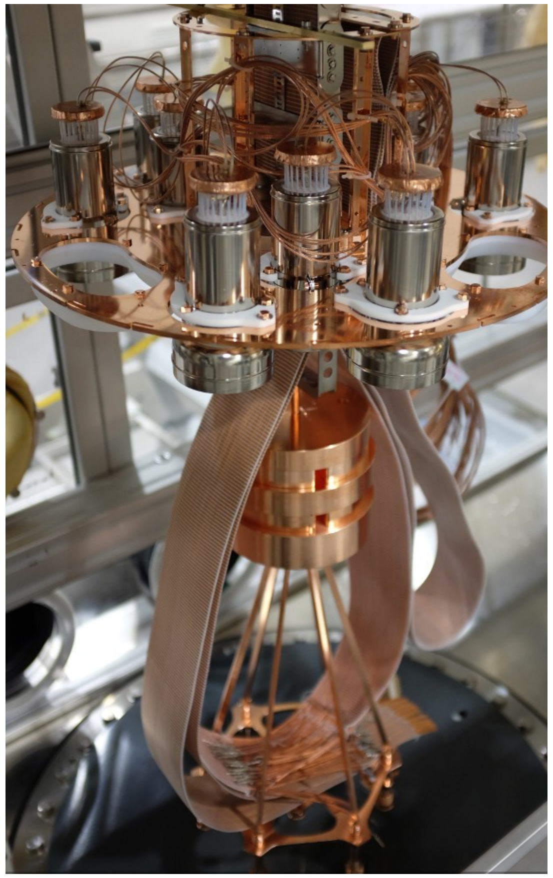
Ø = 0.49 m
h = 2.6 m

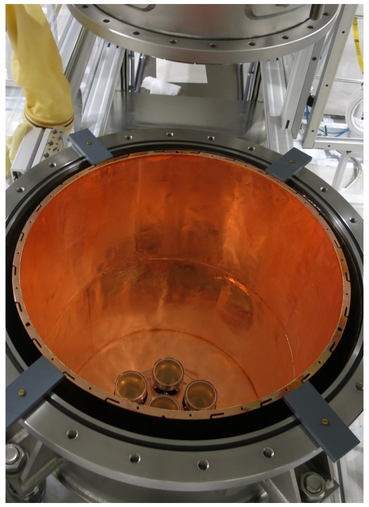
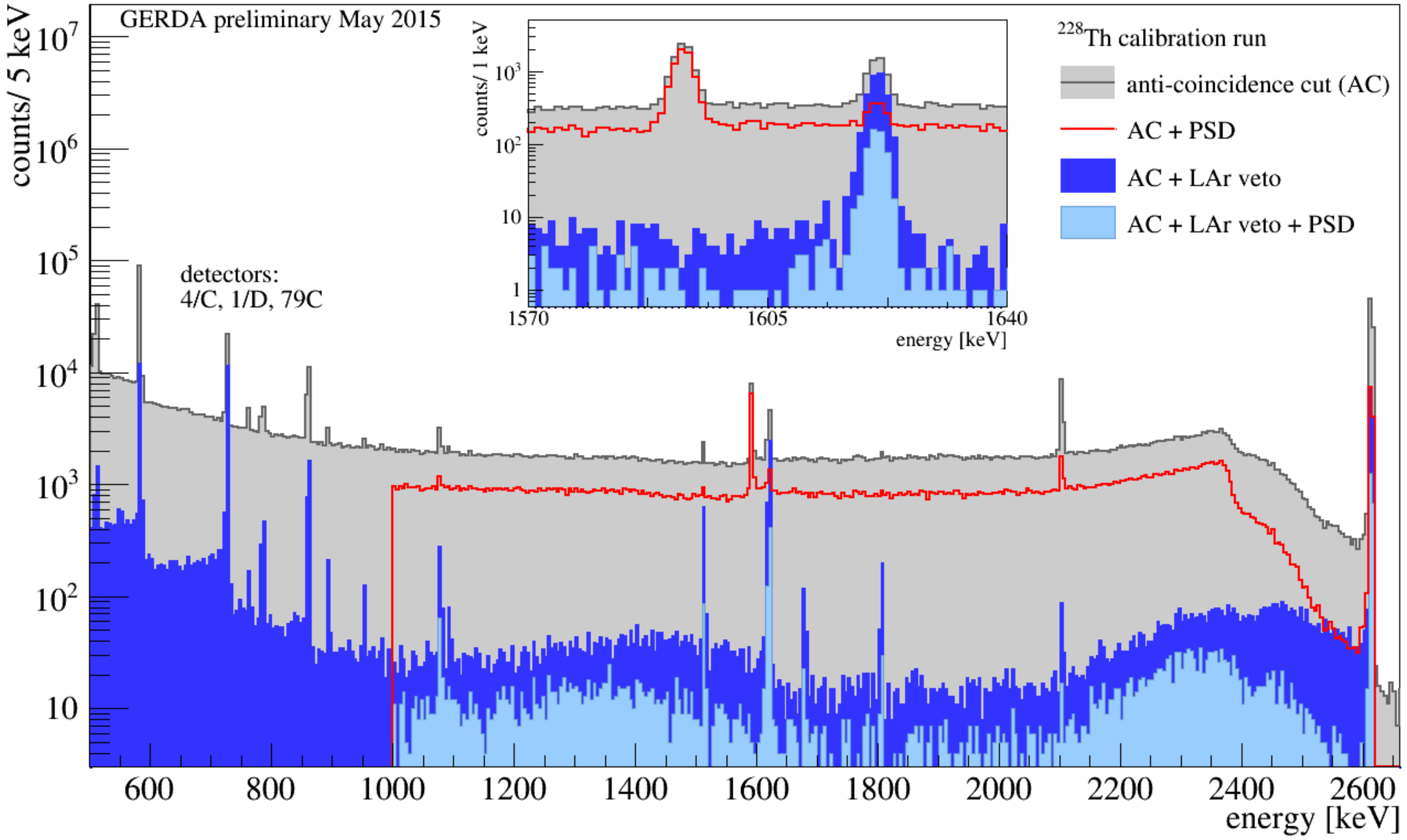


GERDA Phase II

- Liquid argon light instrumentation for active veto installed and tested (UZH: wavelength shifting of LAr light from VUV to blue region, arXiv:)
- 16 3-inch PMTs; scintillation fibers and SiPM readout

Commissioning data



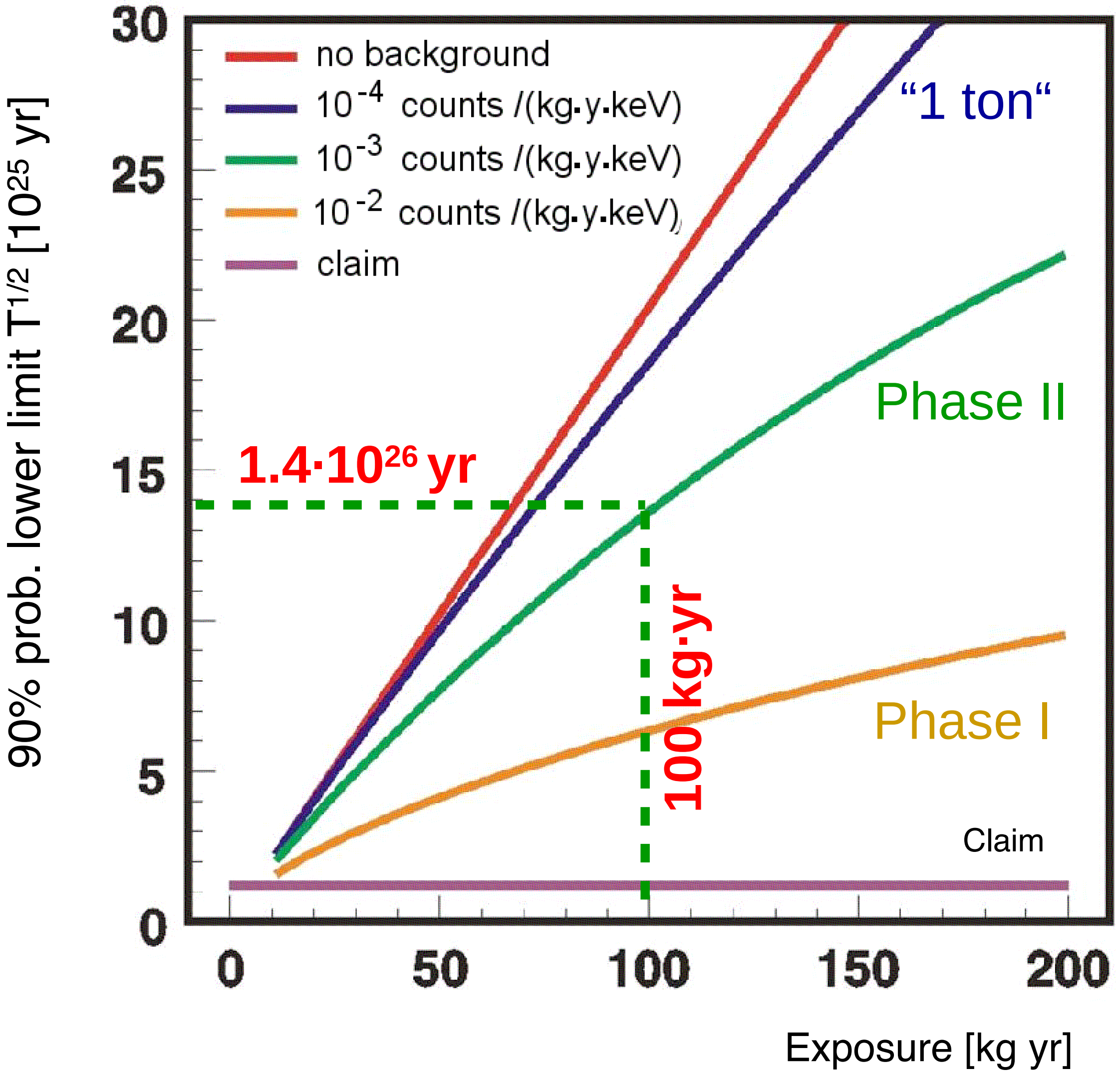
Background reduction (at Q_{bb}) by LAr veto (recently demonstrated):

- factor ~400 for ^{228}Th

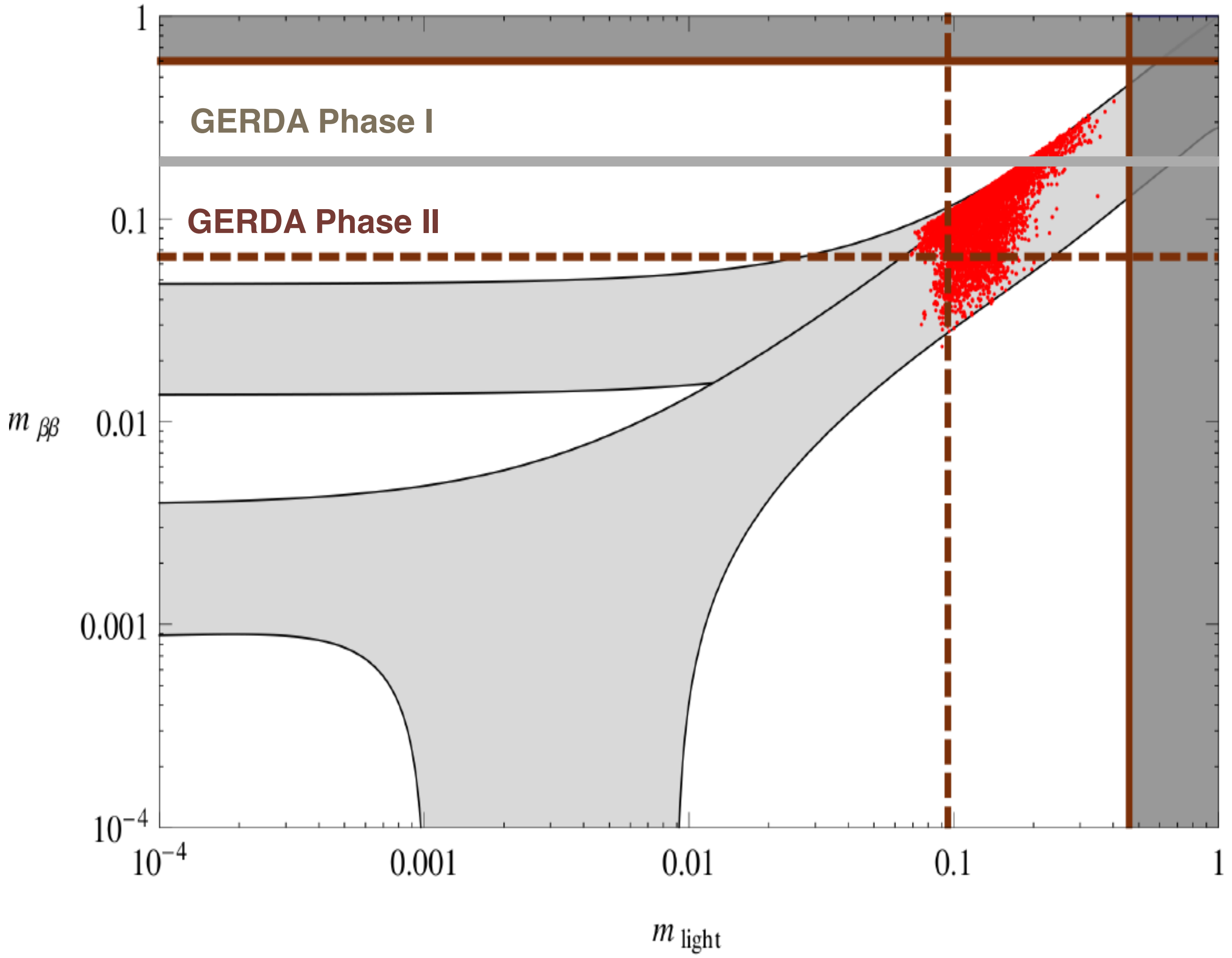
- factor >10^3 for ^{42}K (^{42}Ar decay in LAr)

Outlook for GERDA Phase II

- Background goal of ≤ 10^{-3} events/(keV kg yr) is feasible
- Explore $T_{1/2}$ values in the 10^{26} yr range, probe the degenerate mass region
- Ton-scale experiment (in collaboration with Majorana in the US) under discussion



Alonso, Gavela, Isidori,Maiani, JHEP 1311 (2013) 187
Blankenburg,Isidori, Jones-Perez, EPJC 72 (2012) 2126



Theory: neutrino mixing and masses from a minimum principle

Outlook for GERDA Phase II

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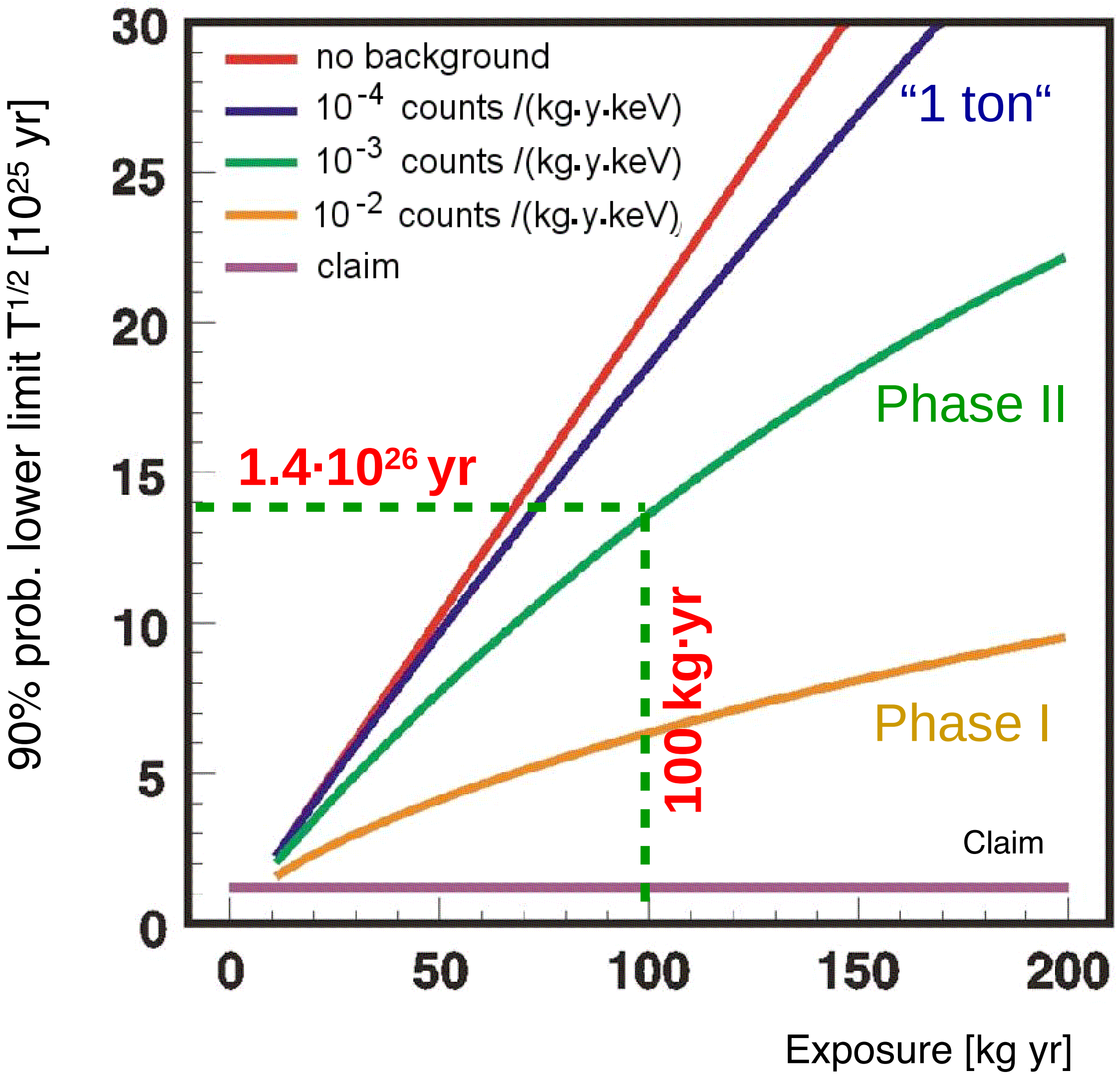
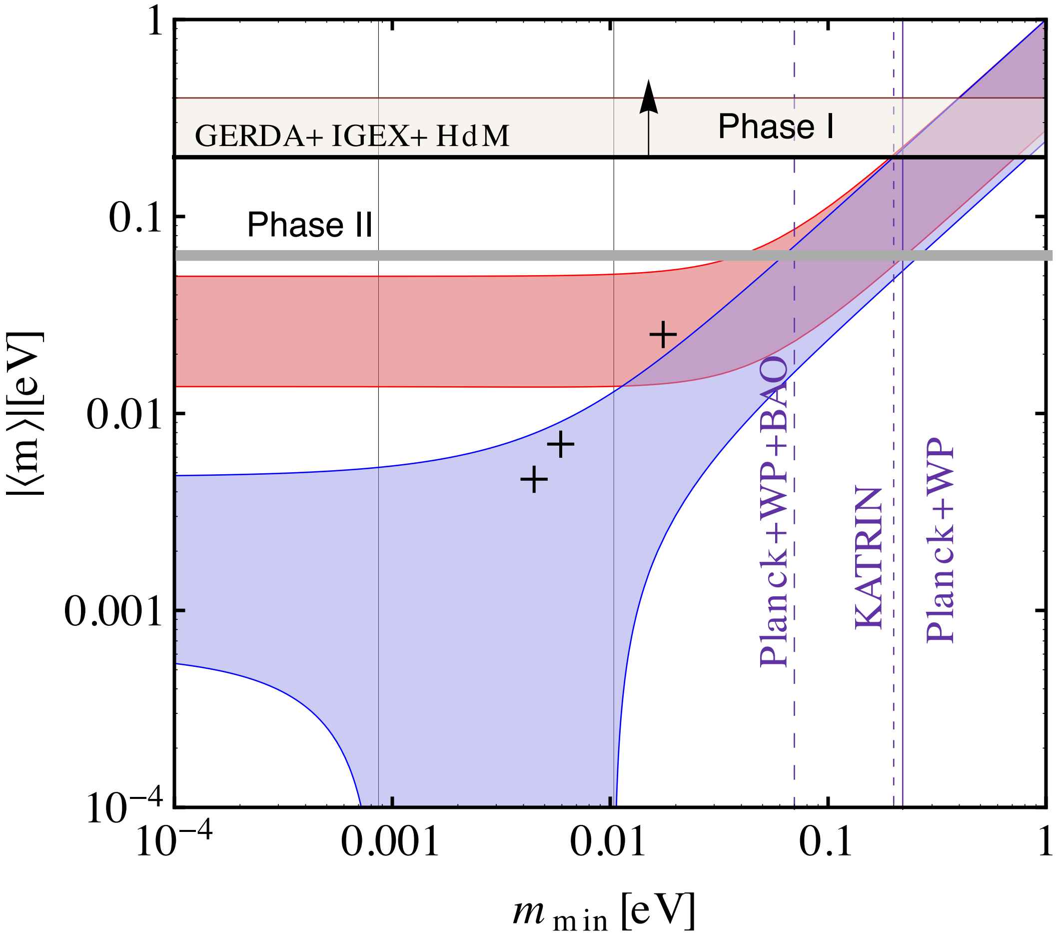


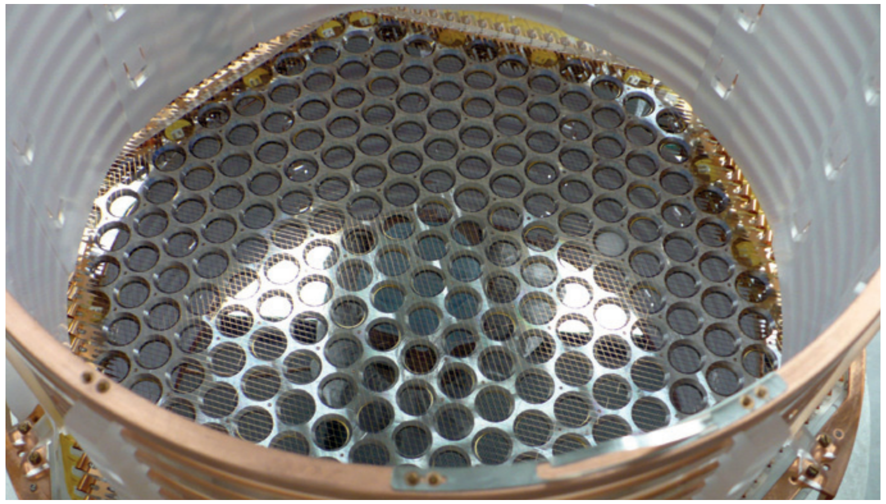
Girardi, Meroni, Petcov, Spinrath, JHEP, arXiv: 1312.1966

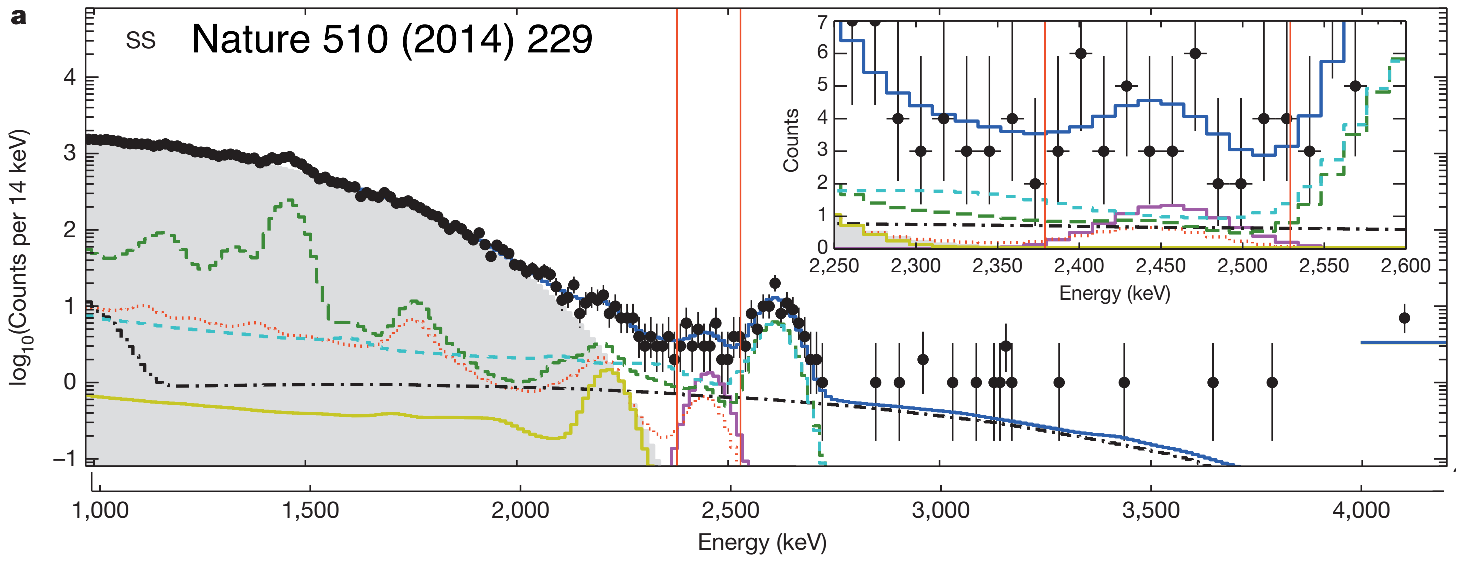


Theory: with discrete flavour symmetry (T'), which reproduces the observed neutrino mixing, and predicts the values of the absolute neutrino mass scale and of the Dirac and Majorana phases

Liquid xenon TPC: EXO and nEXO

- Dual-phase time projection chamber
- 110 kg LXe (80.6% ^{136}Xe) in active volume
- After WIPP accident: ongoing cleanup/repair effort; cooling & filling LXe TPC in summer 2015, data taking in fall 2015
- nEXO: 5 tonnes enriched LXe
- Proposed location SNOLAB cryopit





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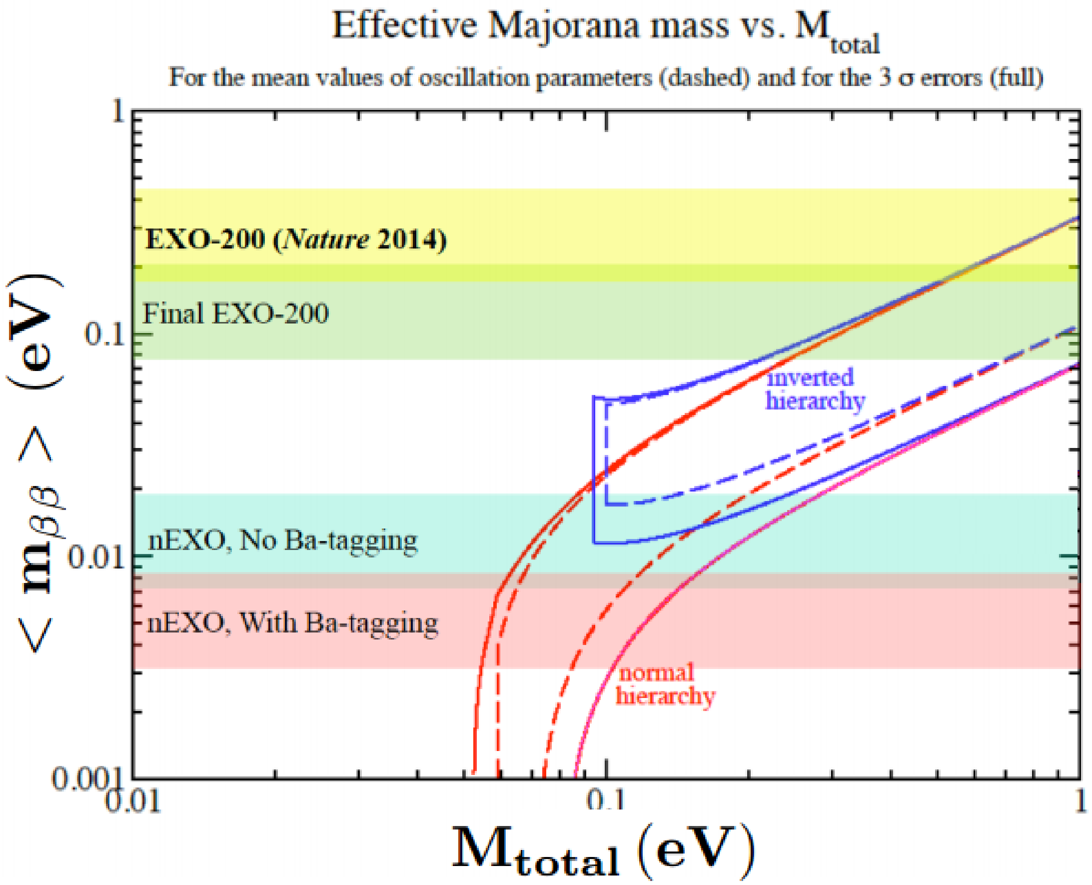
$$m_{\beta\beta} < 0.19 - 0.45\,\mathrm{eV}$$

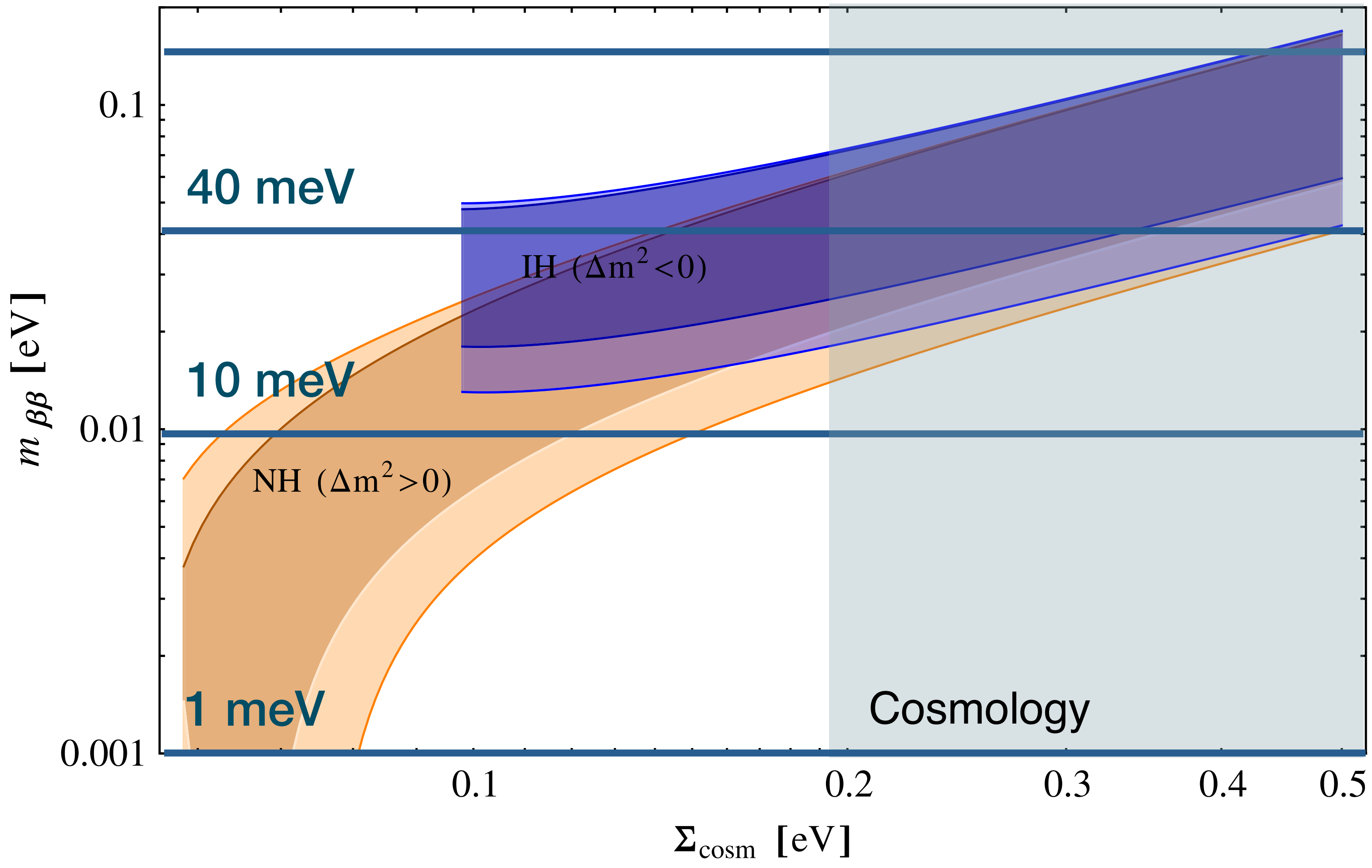

Effective Majorana mass vs. M_{total}

For the mean values of oscillation parameters (dashed) and for the 3 σ errors (full)

Outlook double beta decay

- **Ton-scale experiments are required to explore the inverted mass hierarchy scale**
- Several technologies are moving towards this scale with ultra-low backgrounds
- Experiments at the 10-100 ton scale are required to explore the *normal mass hierarchy scale*

Del'Oro, Marocci, Vissani, PRD 90, 2014



Current reach

Experiments in construction

Future experiments (ton-scale)

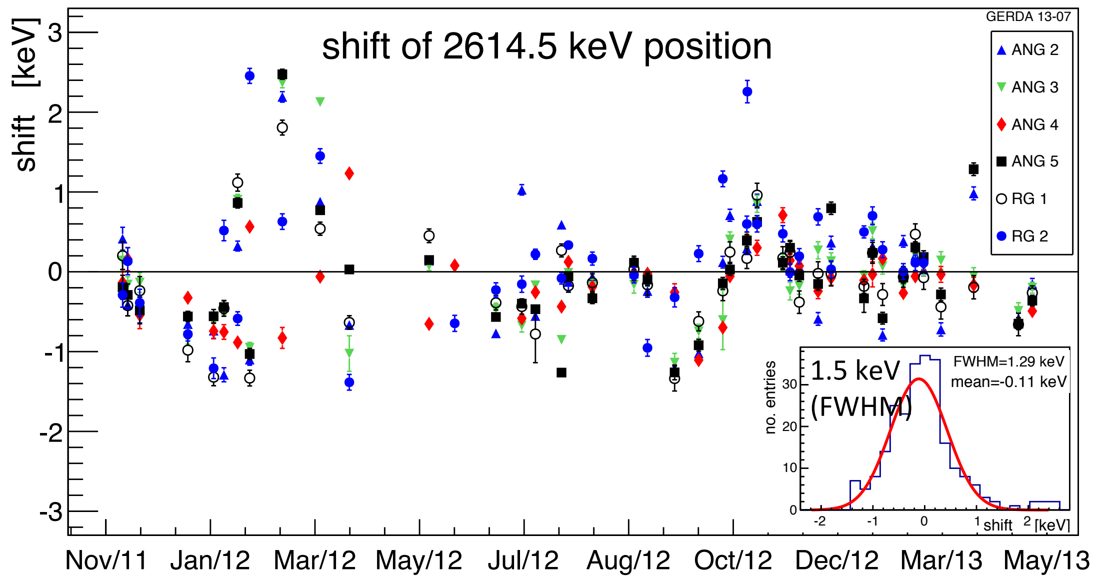
0.1-1 counts/(y 100 ton)

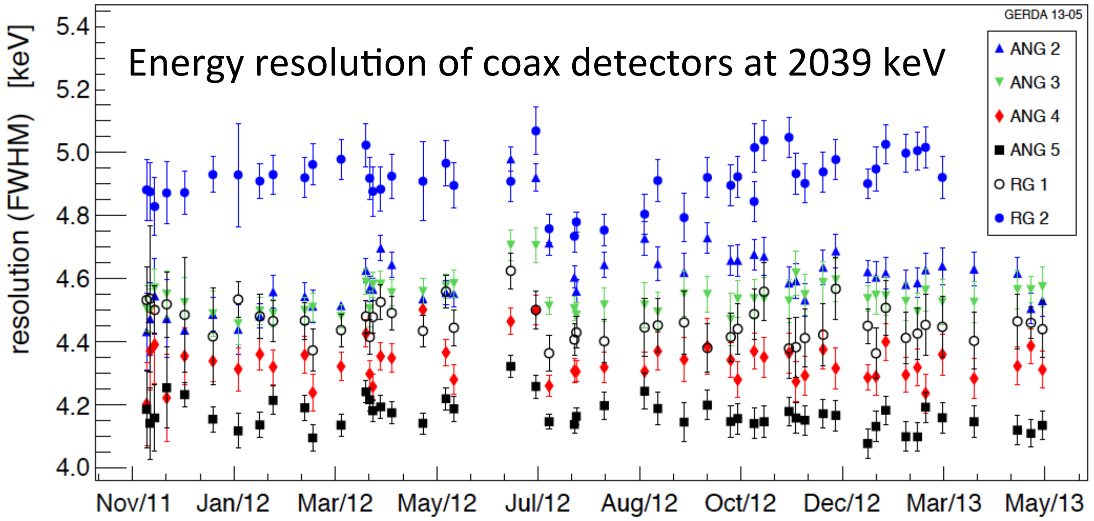
GERDA papers in 2015

- **2nbb decay of ^{76}Ge into excited states with GERDA phase I**, *GERDA collaboration, arXiv:1506.03120*
- **Enhancement of Light Yield and Stability of Radio-Pure Tetraphenyl-Butadiene Based Coatings for VUV Light Detection in Cryogenic Environments**, *L. Baudis et al., arXiv:1503.05349 ((lead author UZH PhD student)*
- **Improvement of the energy resolution via an optimized digital signal processing in GERDA Phase I,** *GERDA collaboration, Eur. Phys. J. C75 (2015) 6, 255 (lead author UZH PhD student)*
- **Results on bb decay with emission of two neutrinos or Majorons in ^{76}Ge in Phase I of GERDA**, *GERDA collaboration, arXiv:1501.02345*
- **Production, characterization and operation of ^{76}Ge enriched BEGe detectors in GERDA,** *GERDA collaboration Eur. Phys.J. C75 (2015) 2, 39*

The end

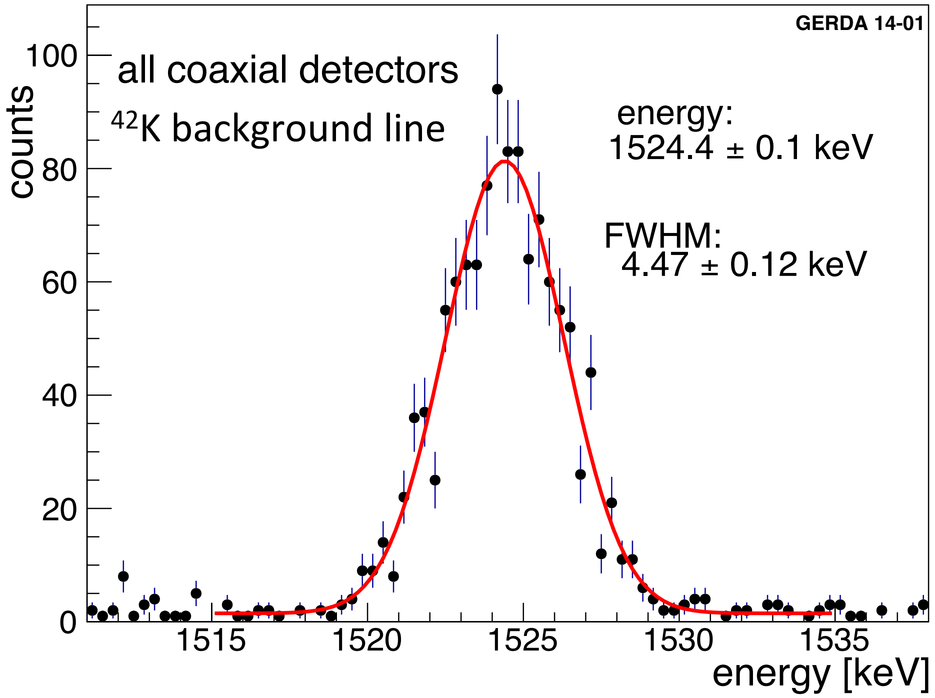
Calibration stability of GERDA detectors

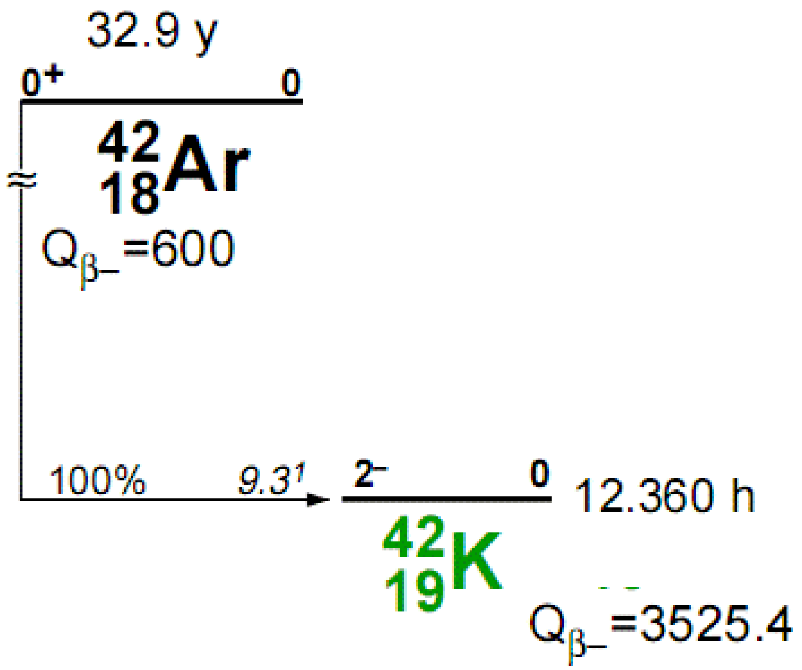




Mean energy resolution at Q=2039 keV:
Coaxial: 4.8 keV (FWHM)
BEGe: 3.2 keV (FWHM)

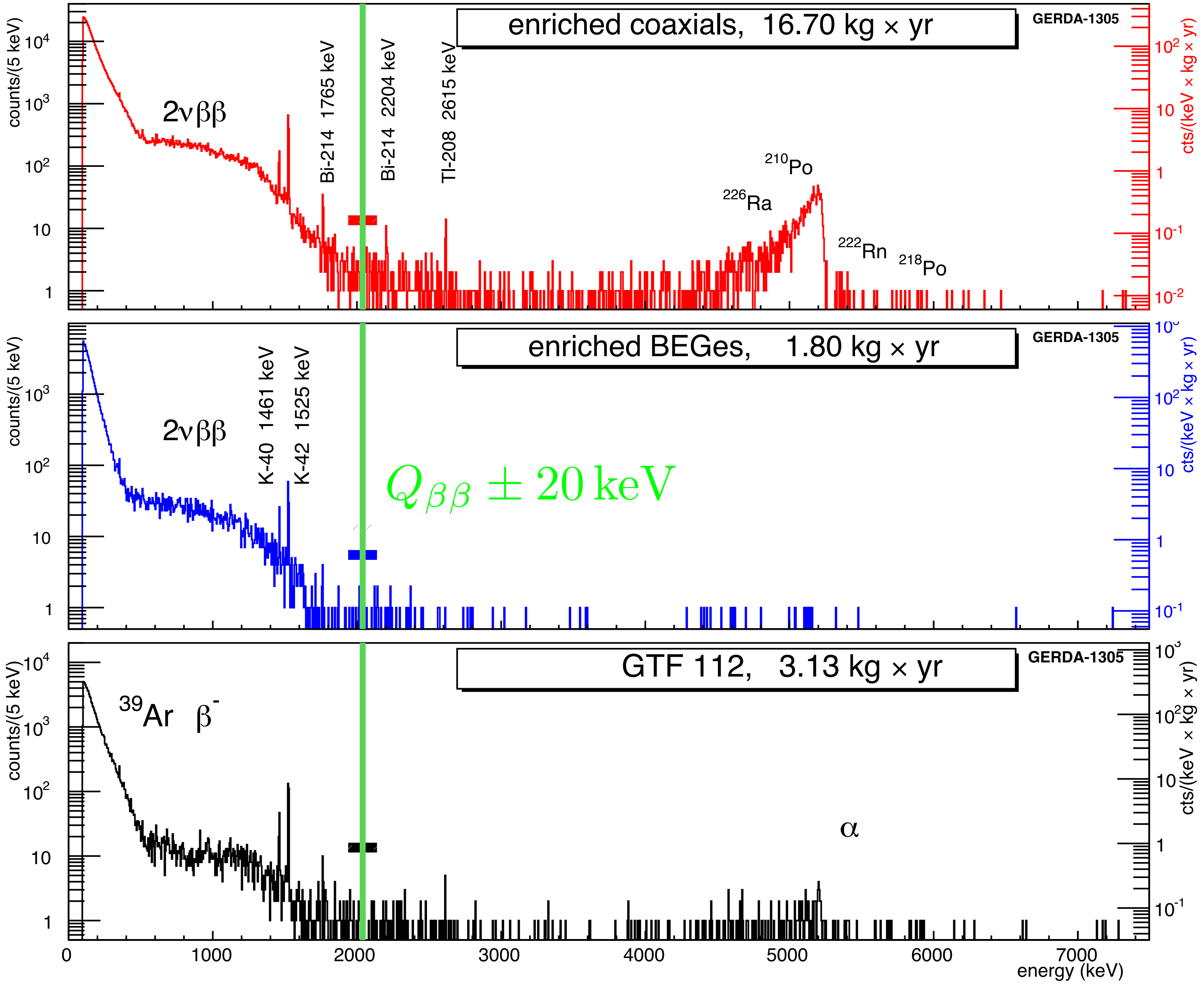
^{42}K background line - summing all runs





The background in GERDA Phase I

Eur. Phys. J. C 74, 2014

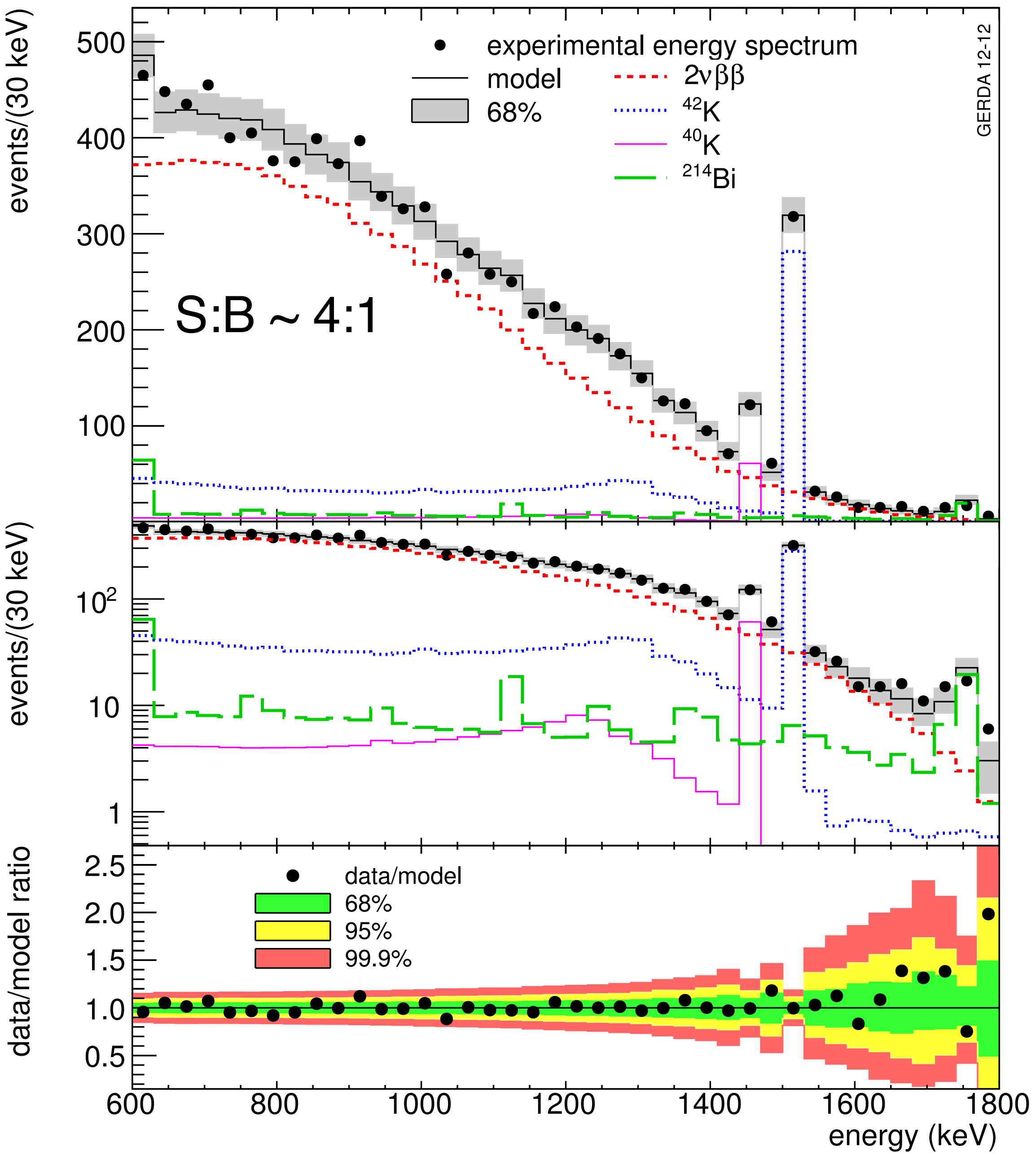


Main sources considered in the background model

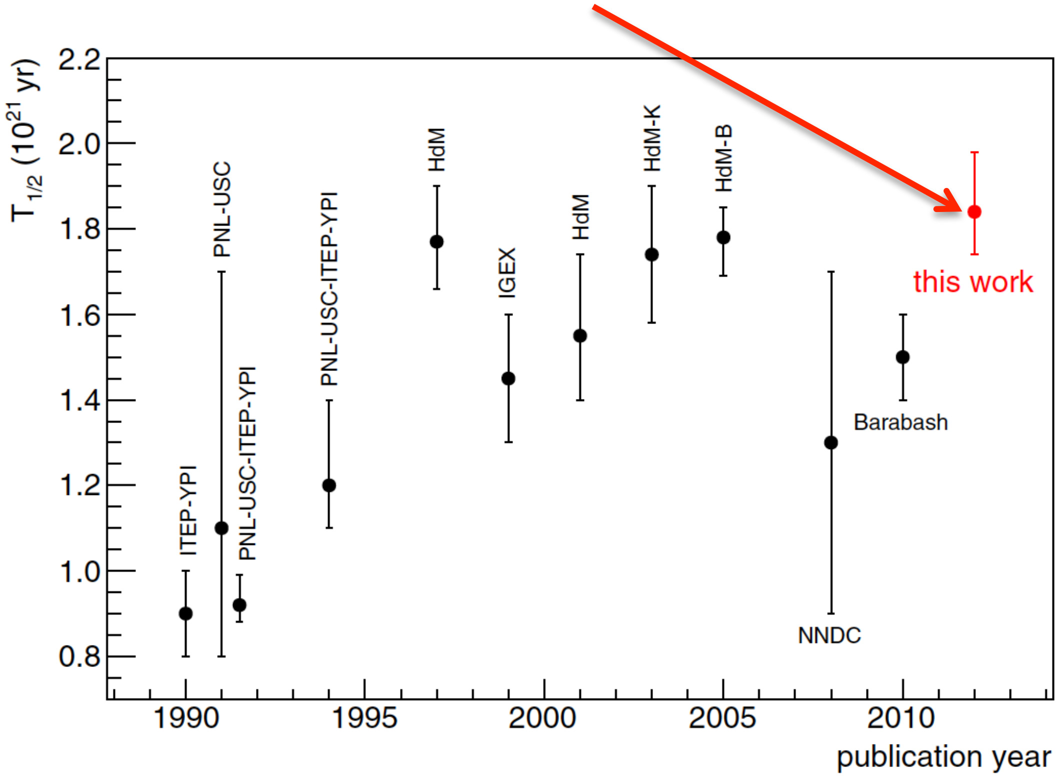
source	location
^{210}Po ^{226}Ra chain ^{222}Rn chain	p^+ surface p^+ surface LAr in bore hole
^{214}Bi and ^{214}Pb	n^+ surface mini-shroud detector assembly p^+ surface radon shroud LAr close to p^+ surface
^{208}Tl and ^{212}Bi	detector assembly radon shroud heat exchanger
^{228}Ac	detector assembly radon shroud
^{42}K	homogeneous in LAr n^+ surface p^+ surface
^{60}Co	detectors detector assembly
$2\nu\beta\beta$	detectors
^{40}K	detector assembly

Half life of the 2-neutrino decay mode

Journal of Physics G 40, 2013



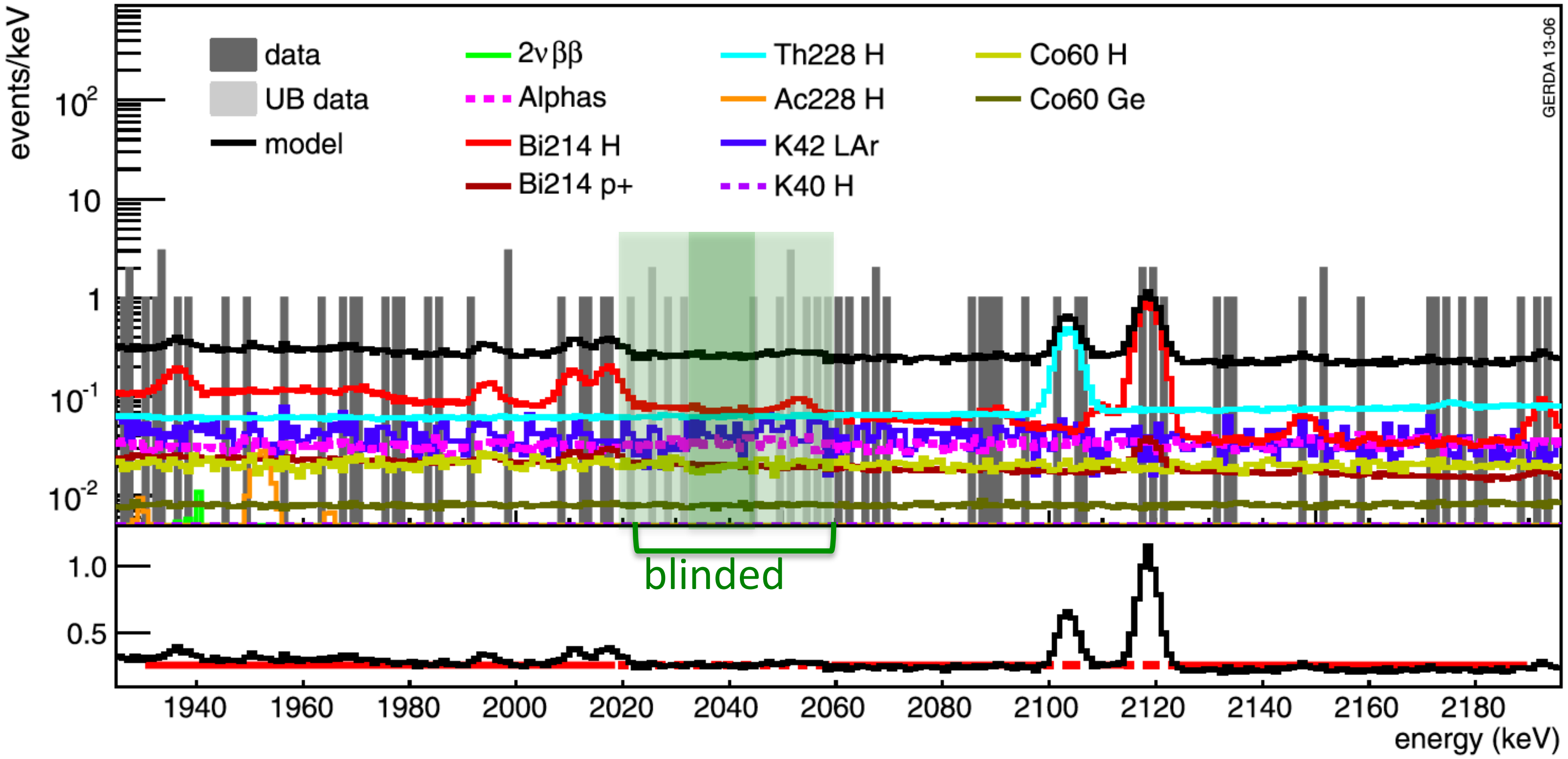
After only 5.04 kg yr exposure:
$T^{2\nu}_{1/2}(^{76}\text{Ge}) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr



Item	Uncertainty on $T^{2\nu}_{1/2}$ (%)
Non-identified background components	+5.3
Energy spectra from ^{42}K, ^{40}K and ^{214}Bi	±2.1
Shape of the $2\nu\beta\beta$ decay spectrum	±1
Subtotal fit model	$^{+5.8}_{-2.3}$
Precision of the Monte Carlo geometry model	±1
Accuracy of the Monte Carlo tracking	±2
Subtotal Monte Carlo	±2.2
Data acquisition and selection	±0.5
Grand total	$^{+6.2}_{-3.3}$

Background in the ROI for the double beta decay

- No background peaks expected at Q_{bb}
- Consistent with a *flat background* in the energy region: 1930 keV - 2190 keV
- Dominated by close sources, mainly ^{42}K, ^{214}Bi, ^{228}Th, ^{60}Co and alphas from ^{226}Ra chain



Background level interpolated into the region of interest (before PSD):

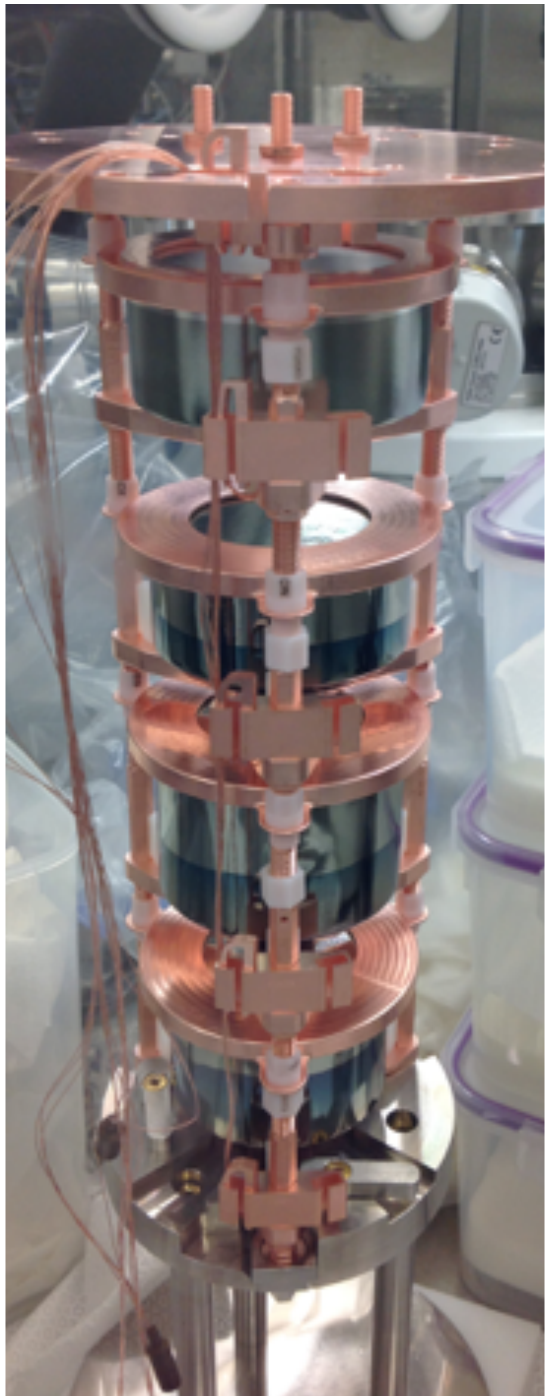
$$(1.75^{+0.26}_{-0.24}) \cdot 10^{-2}\,\mathrm{events/(keV\,kg\,yr)}$$

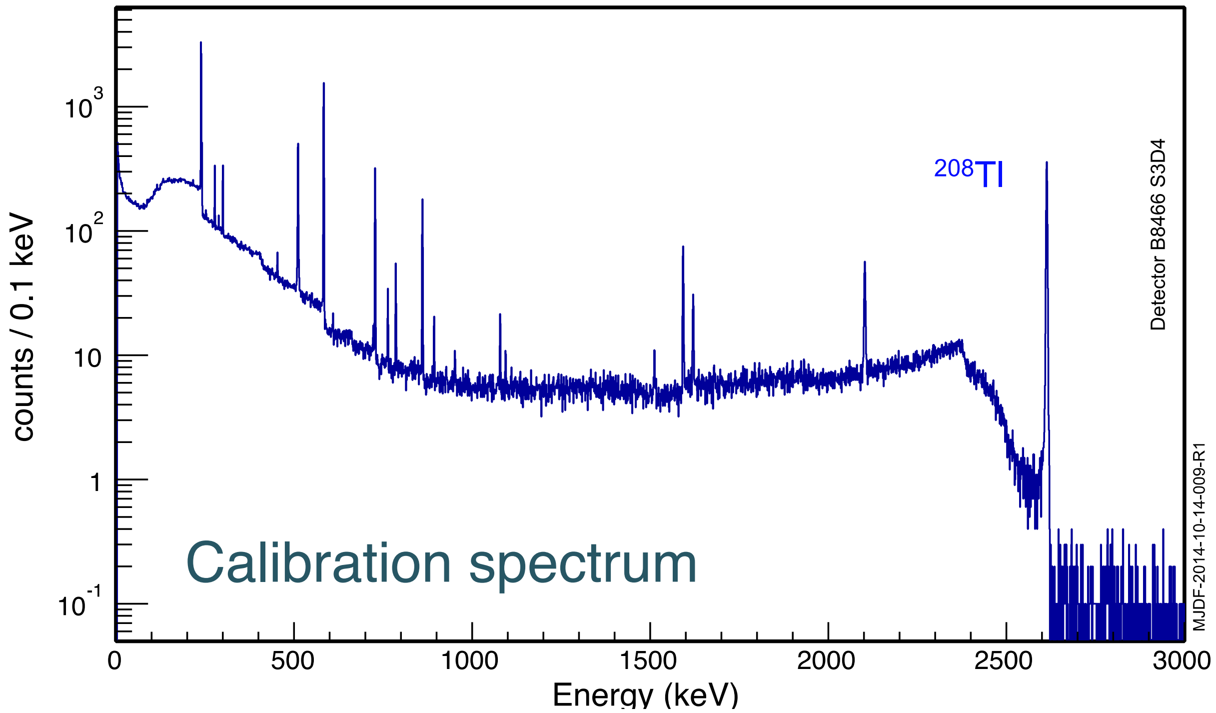
Coaxial

$$(3.6^{+1.3}_{-1.0}) \cdot 10^{-2}\,\mathrm{events/(keV\,kg\,yr)}$$

BEGe

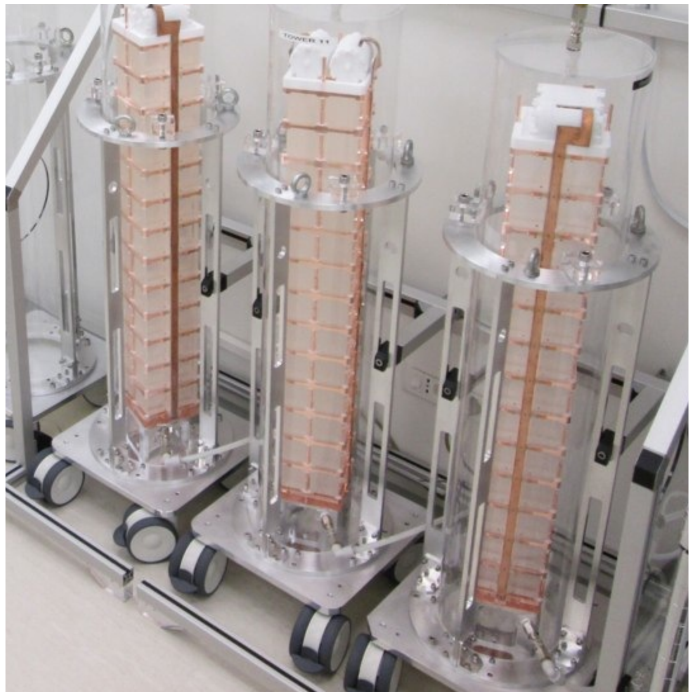
HPGe diodes: Majorana demonstrator



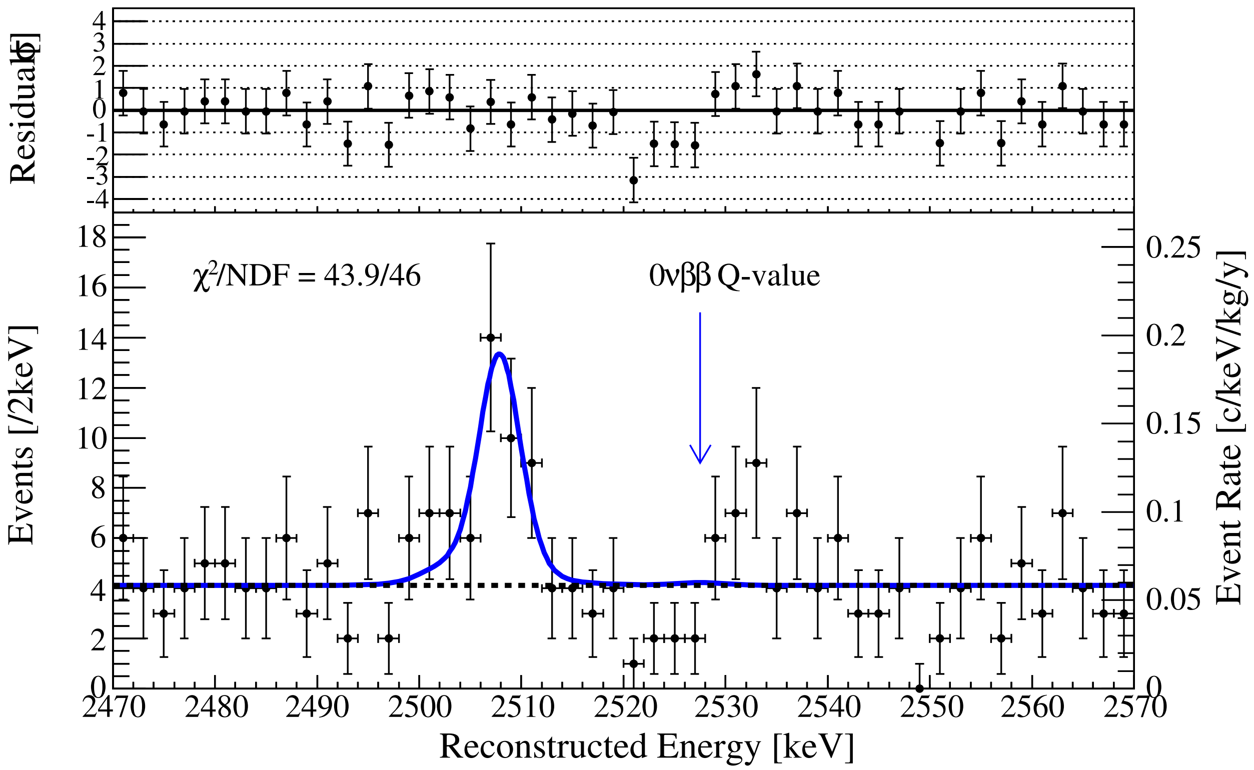


- 29 kg enriched Ge detectors (87%)
- A prototype module was installed and is taking data since July 2014
- Module 1 (~1/2) of enriched detectors to start operation summer 2015
- Assembly of strings for module 2 is proceeding well
- Completion and starting of operation by end of 2015
- **Explore $T_{1/2}$ values in the 10^{26} yr range**

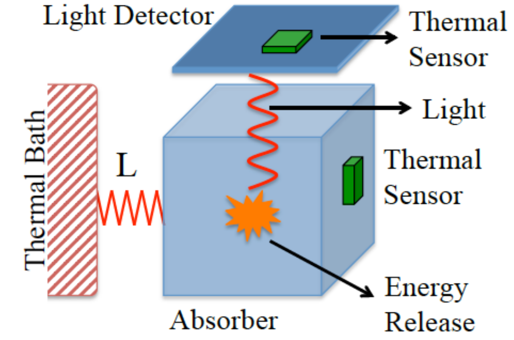
TeO_2 bolometers: CUORE



arXiv: 1504.2454

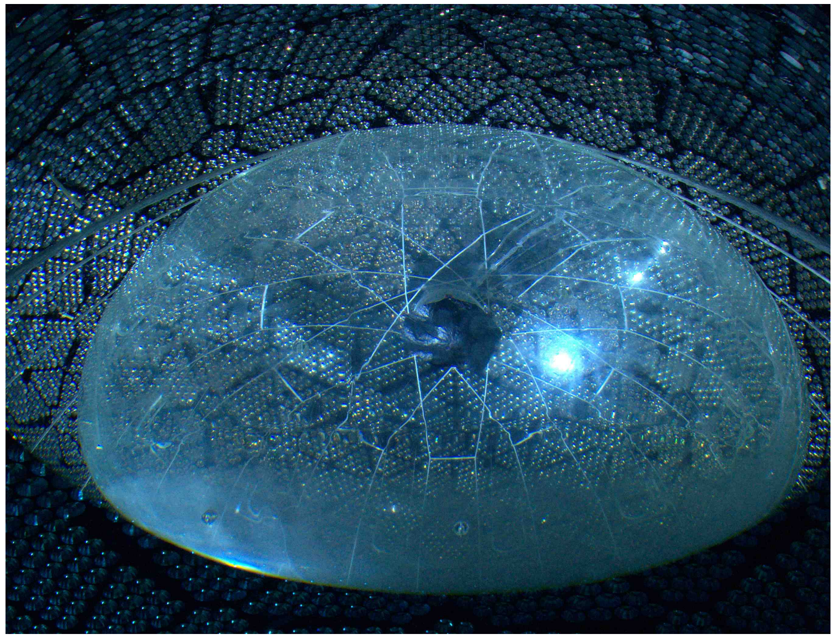


- CUORE-0: array of 52 crystals; 9.8 kg-yr exposure, FWHM = 5.1 keV
- **Recent results: $T_{1/2} > 2.7 \times 10^{24}$ y (90% CL); $T_{1/2} > 2.7 \times 10^{24}$ y (90% CL) combined with Cuoricino**
- CUORE: all 988 crystals (206 kg ^{130}Te) built and assembled in towers
- Cryostat commissioning underway; detector installation in 2015
- Next step: CUPID = CUORE detectors + light read-out for alpha suppression

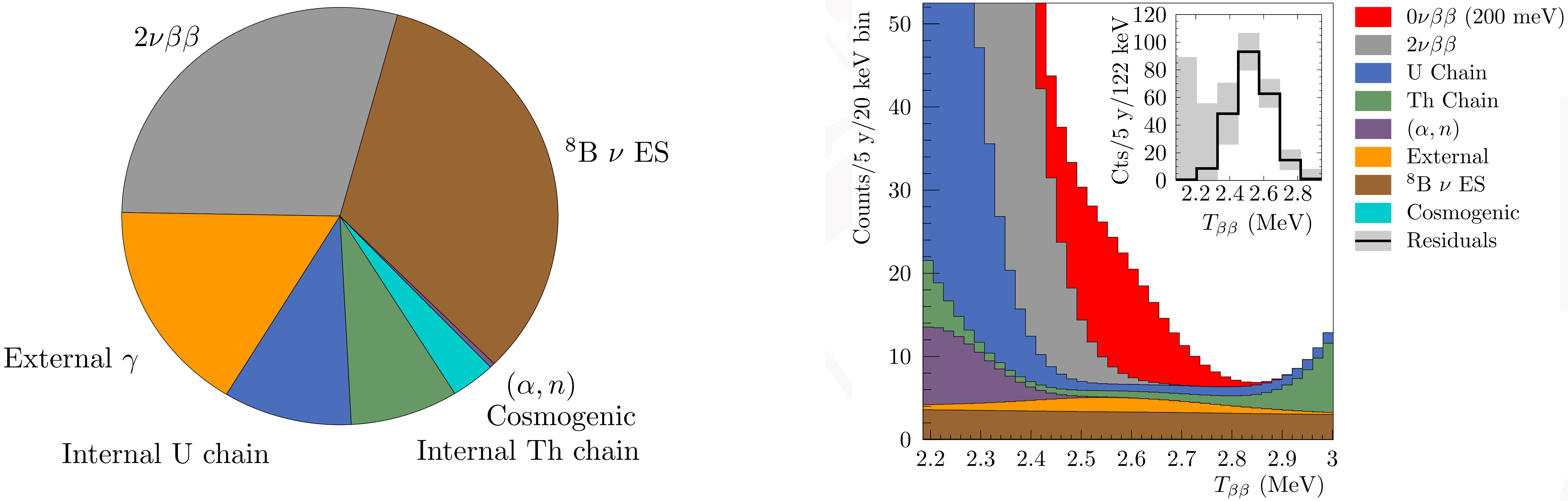


^{130}Te in liquid scintillator: SNO+

- First phase: 0.3% natural Te (~ 800 kg ^{130}Te)
- Detector and cavity being filled with water
- Start LS fill in 2016
- Load 0.3% Te in 2017
- Then upgrade PMTs and 3% load with the goal to cover the inverted hierarchy scenario

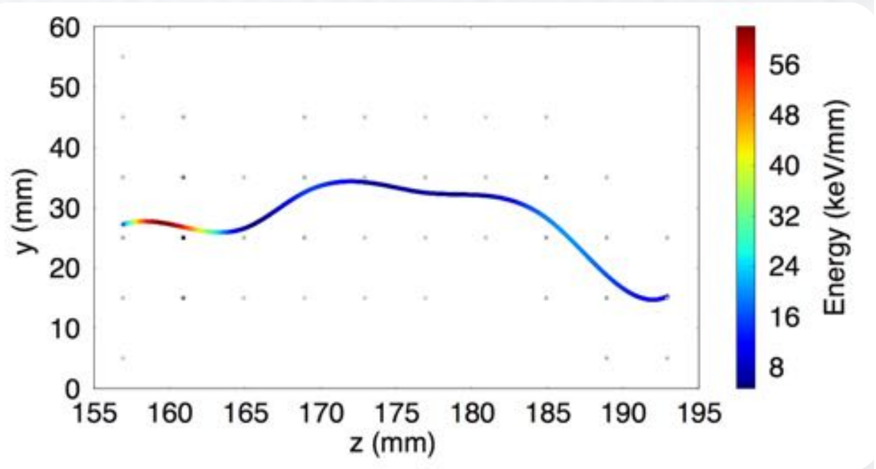


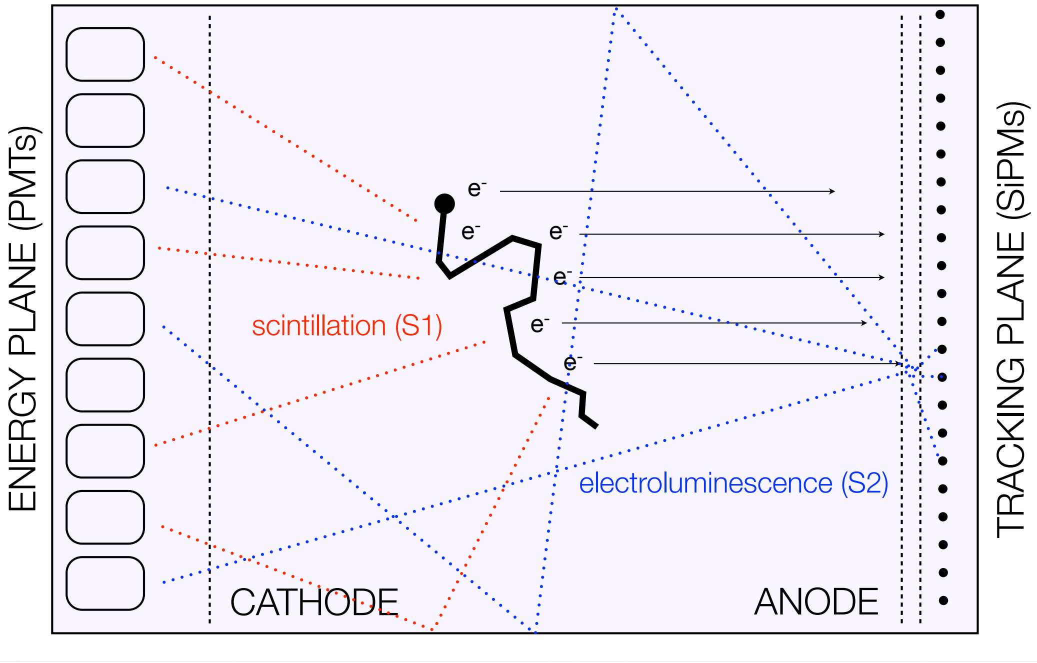
Expected backgrounds in SNO+



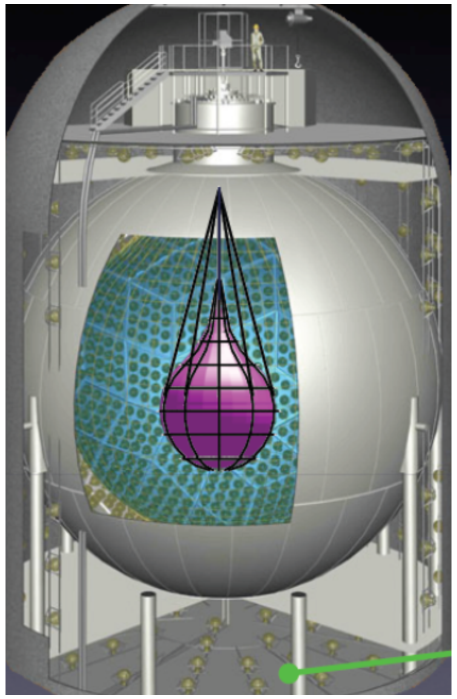
High pressure xenon TPC: NEXT

- NEXT-100: 100 kg ^{136}Xe (90% enriched) HP Xe TPC
- Tracking capabilities and < 1% (FWHM) resolution
- Under construction (vessel, sensors, gas system etc)
- Installation and commissioning at LSC by 2017: **explore the effective Majorana mass to 100 meV**
- 10 kg prototype in deployment at LSC (validate bg model)





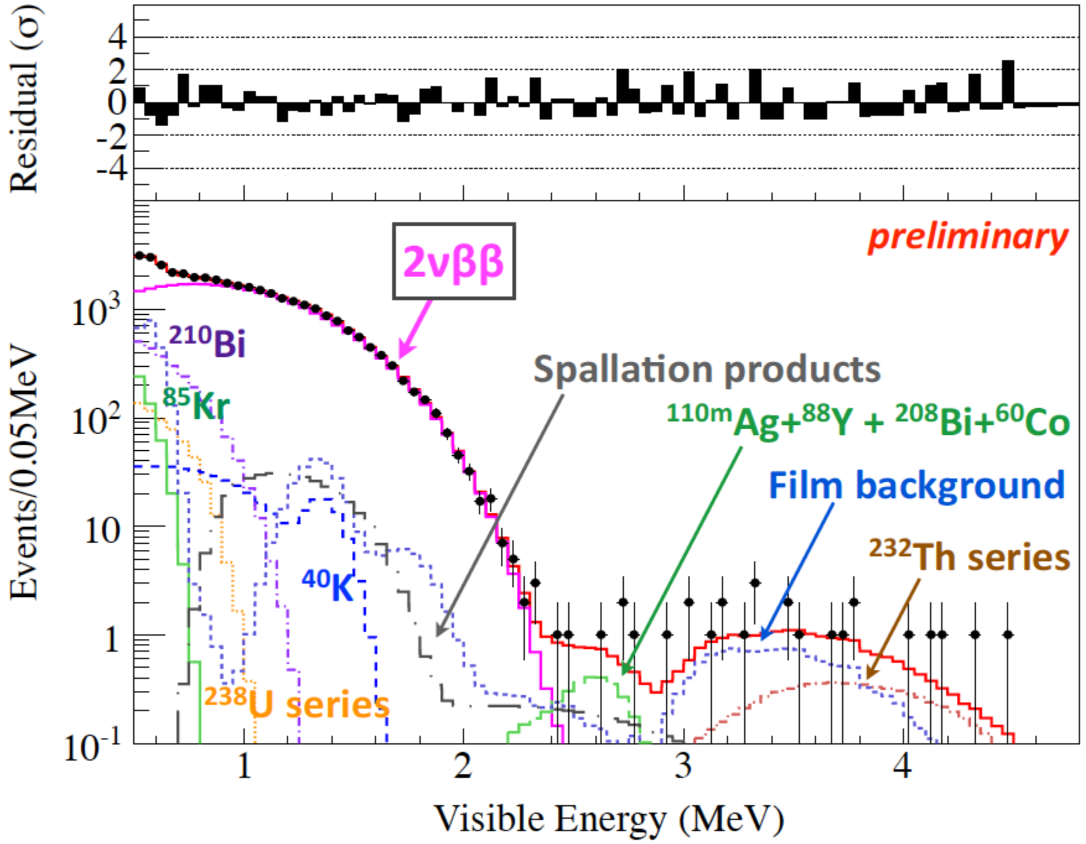
^{136}Xe in liquid scintillator: KamLAND-Zen



- Mini-balloon with ^{136}Xe-loaded LS in KamLAND
- Phase 1+2 (179 kg + 383 kg):
- **$T_{1/2} > 2.6 \times 10^{25}$ y (90% CL)**

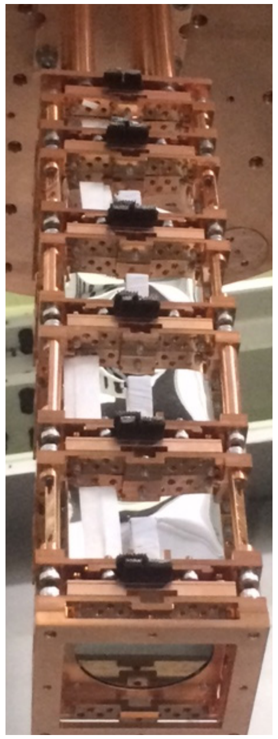
$$m_{\beta\beta} < 0.14 - 0.28\,\mathrm{eV}$$

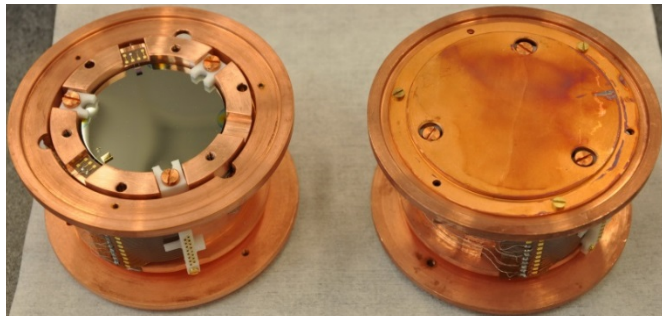
- Next phase: new mini-balloon construction in summer 2015
- Larger LS volume: 600-800 kg ^{136}Xe
- Lower backgrounds
- **Sensitivity: 2×10^{26} yr after 2 years exposure**
- Goal: cover the inverted hierarchy region

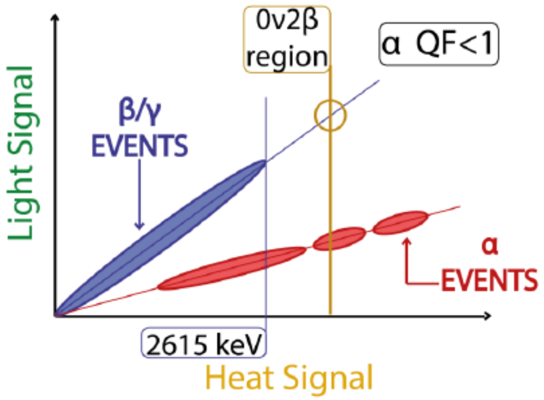


Scintillating bolometers: AMoRE/LUMINEU/LUCIFER

- Measure both heat and light: particle discrimination and background rejection
- AMoRE: $^{40}Ca^{100}MoO_4$ in 3 stages 1.5-10-200 kg of crystals
- LUMINEU: $Zn^{100}MoO_4$ 1 kg - 10 kg (LUCINEU)

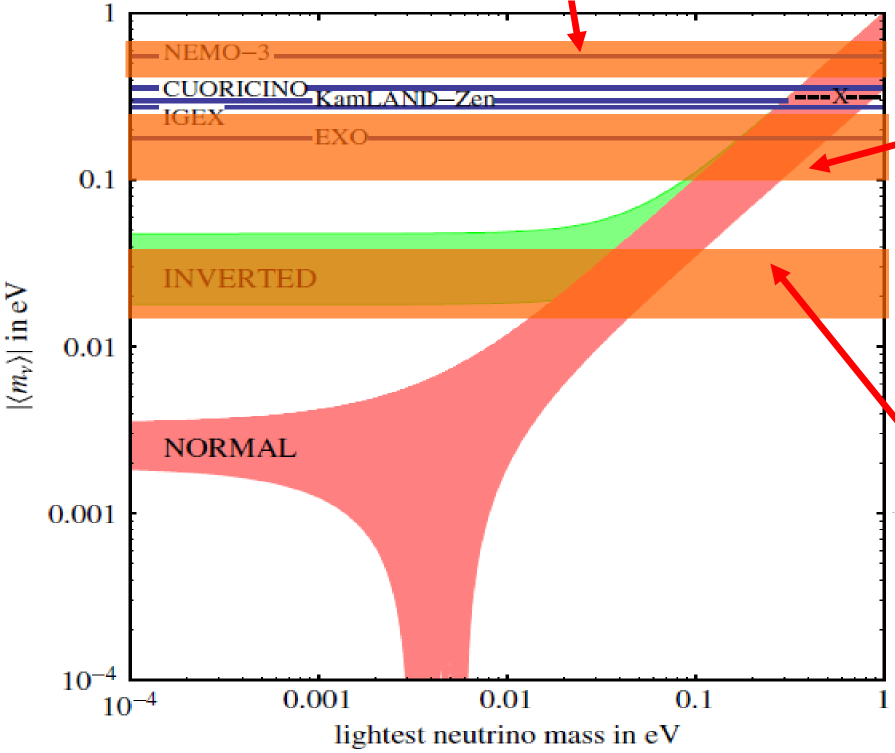




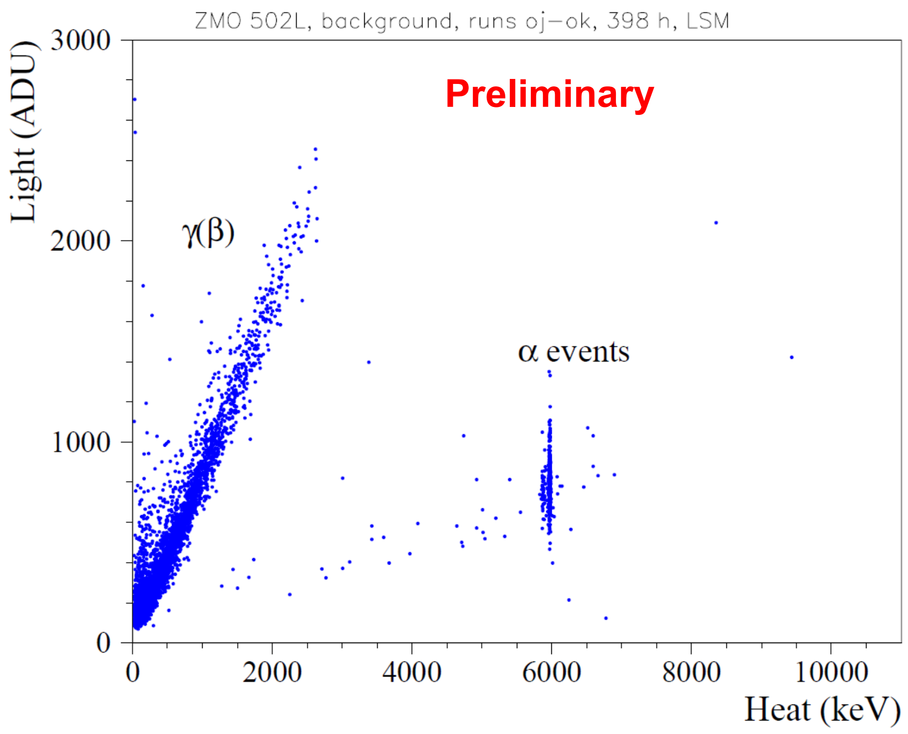


AMoRE-pilot (Now)
1.5 kg of $^{40}Ca^{100}MoO_4$
(2015~)

AMoRE-10
10 kg of $^{40}Ca^{100}MoO_4$
(2016~2018)



AMoRE-200
(2018~2022)



Tracking: SuperNEMO

- Separate tracker, calorimeter and source
- Sources: ^{82}Se (^{150}Nd, ^{48}Ca), 100 kg
- **Aim: $T_{1/2} > 10^{26}$ yr**
- Demonstrator: 7 kg ^{82}Se, $T_{1/2} > 6.6 \times 10^{24}$ yr
- Status: in assembly, first demonstrator module in 2016