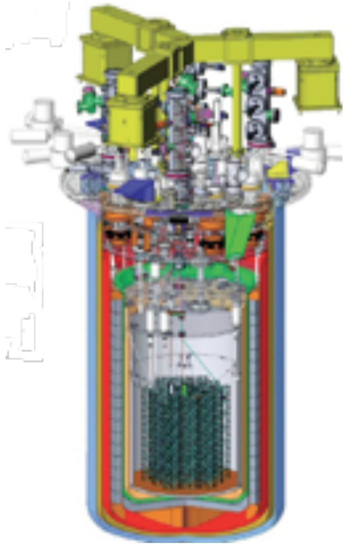
Experiments and detection methods for ββ-decay searches

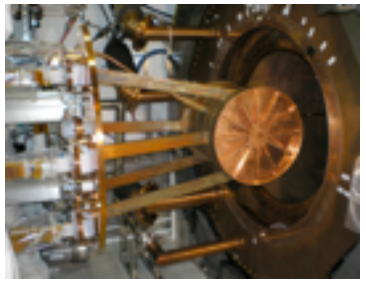


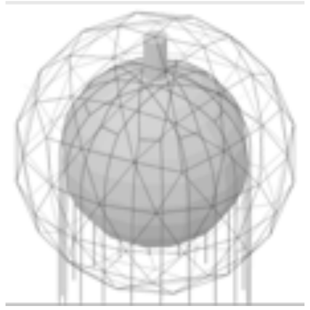
John Wilkerson

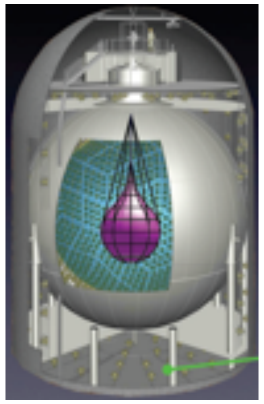
University of North Carolina
Triangle University Nuclear Laboratory
Oak Ridge National Laboratory

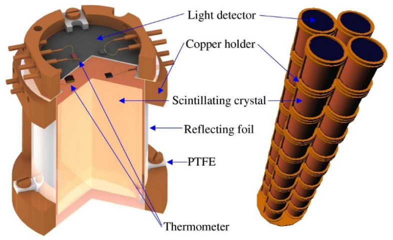
Gran Sasso Summer Institute 2014

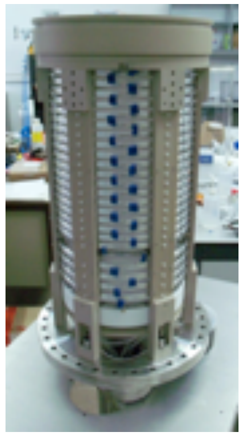
Laboratori Nazionali del Gran Sasso

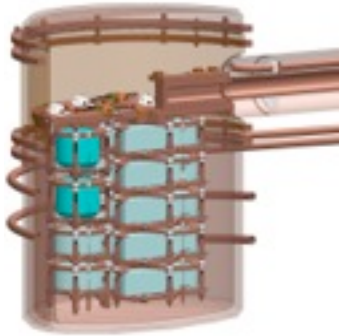












THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

TUNL

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

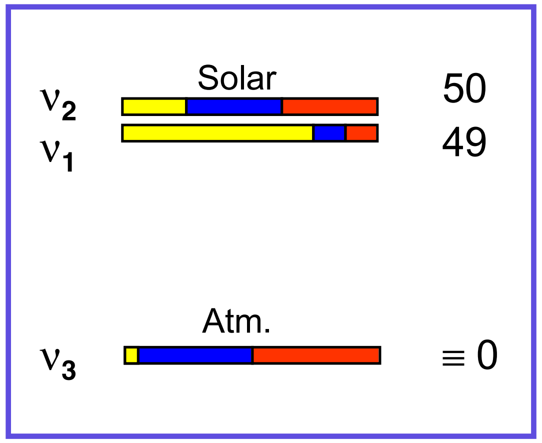
Lecture Outline

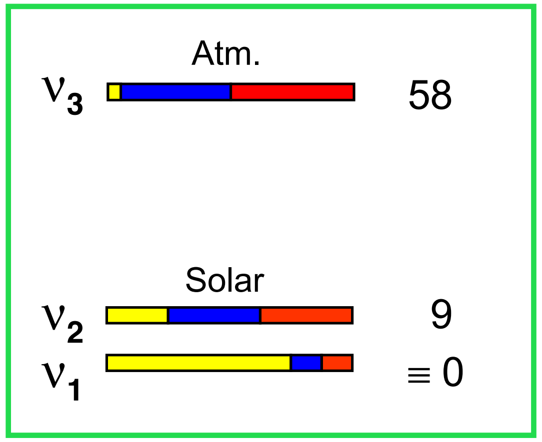
- 0νββ Sensitivity Considerations
- Backgrounds
- Experiments and Measurement Techniques

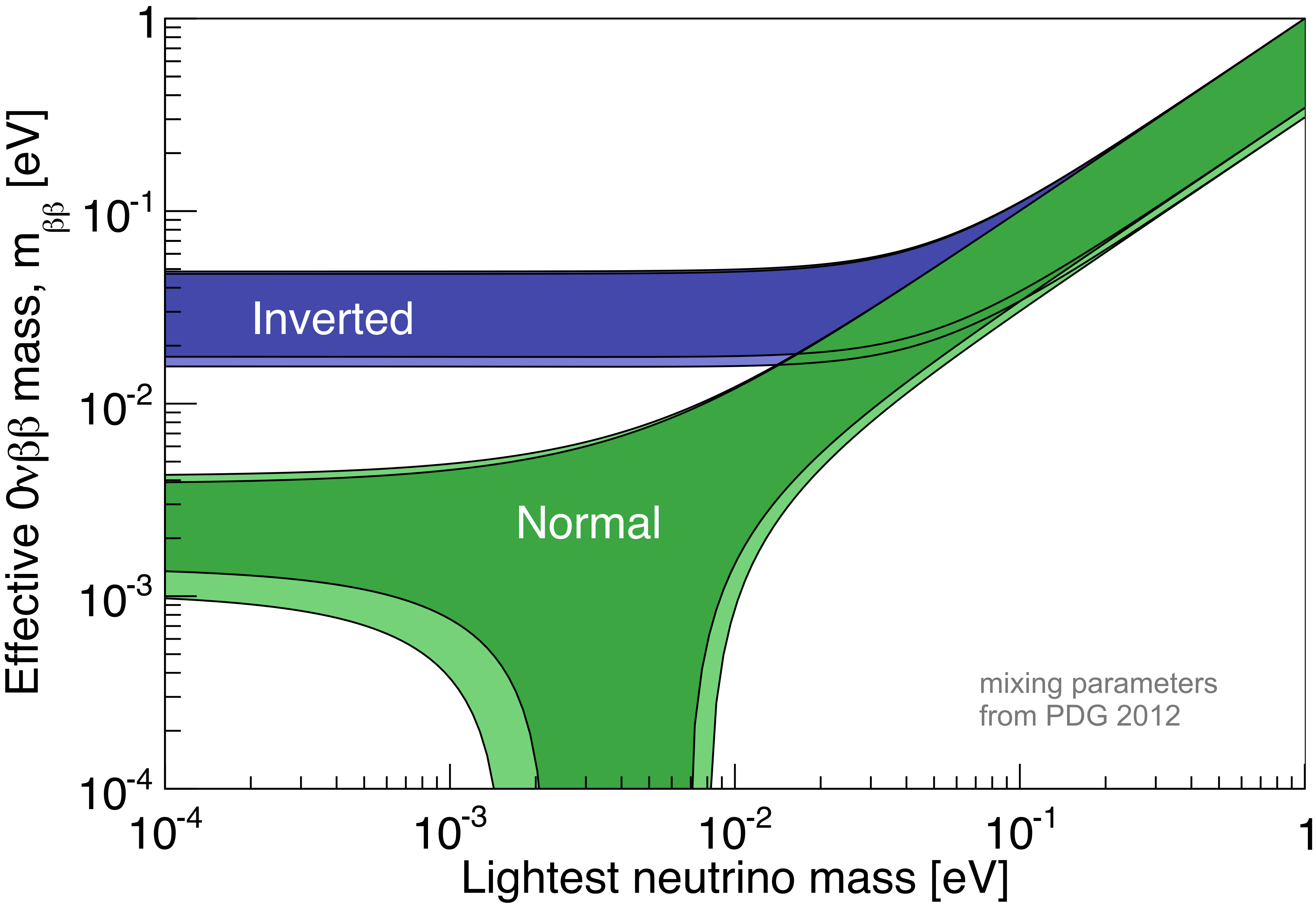
0νββ Decay and <mββ>

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$







0νββ Decay and <mββ>

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

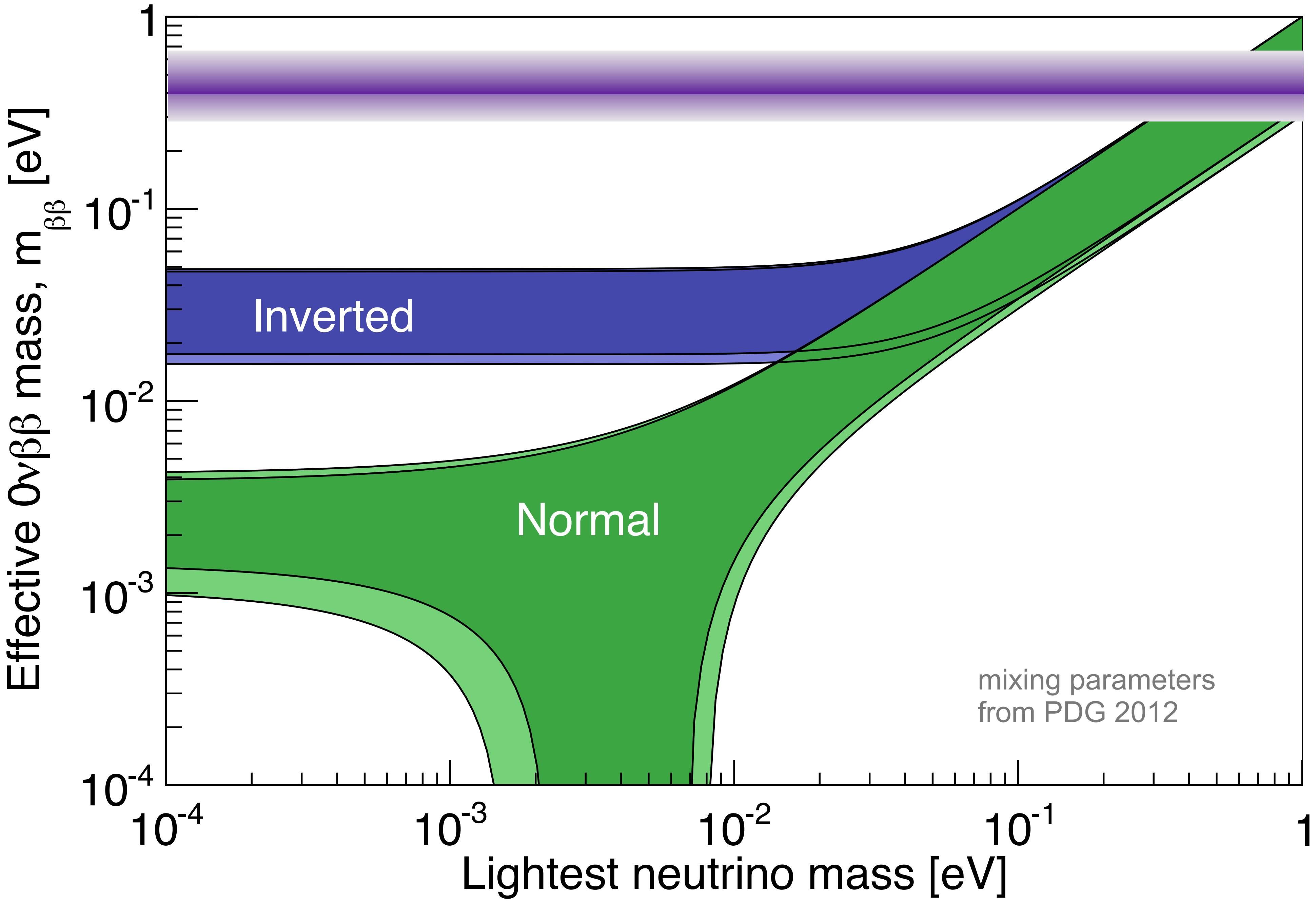
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Today →

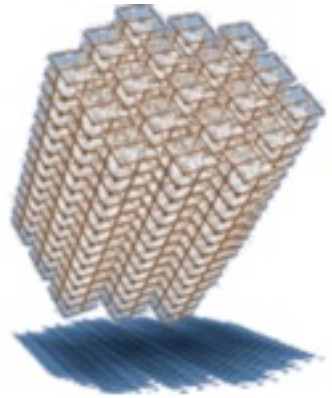
2015-2017 →

Large Scale →

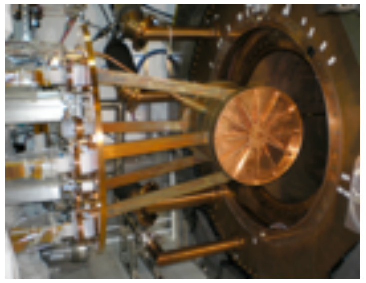


0νββ decay Experiments - Efforts Underway

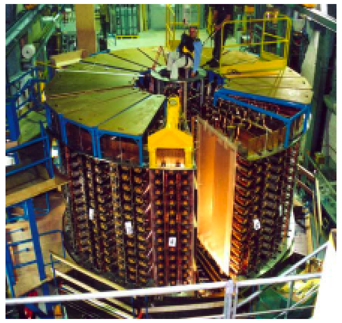
CUORE



EXO200



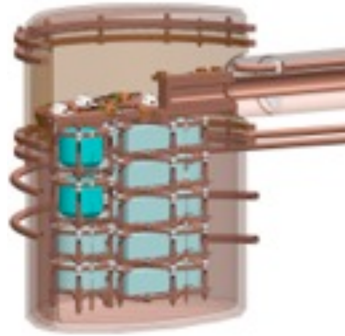
NEMO



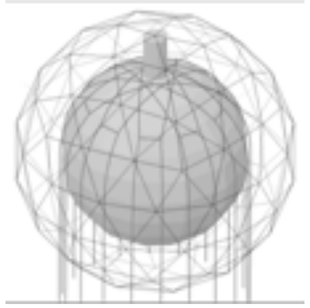
Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ tonne	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
II		Point contact Ge in LAr	30-35 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	30 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	CaMoO4 scint. bolometer	50 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
COBRA	Cd-116	CdZnTe detectors	10 kg 183 kg	R&D
CUORICINO	Te-130	TeO_2 Bolometer	10 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	380 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	Construction
EXO200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	~ tonne	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

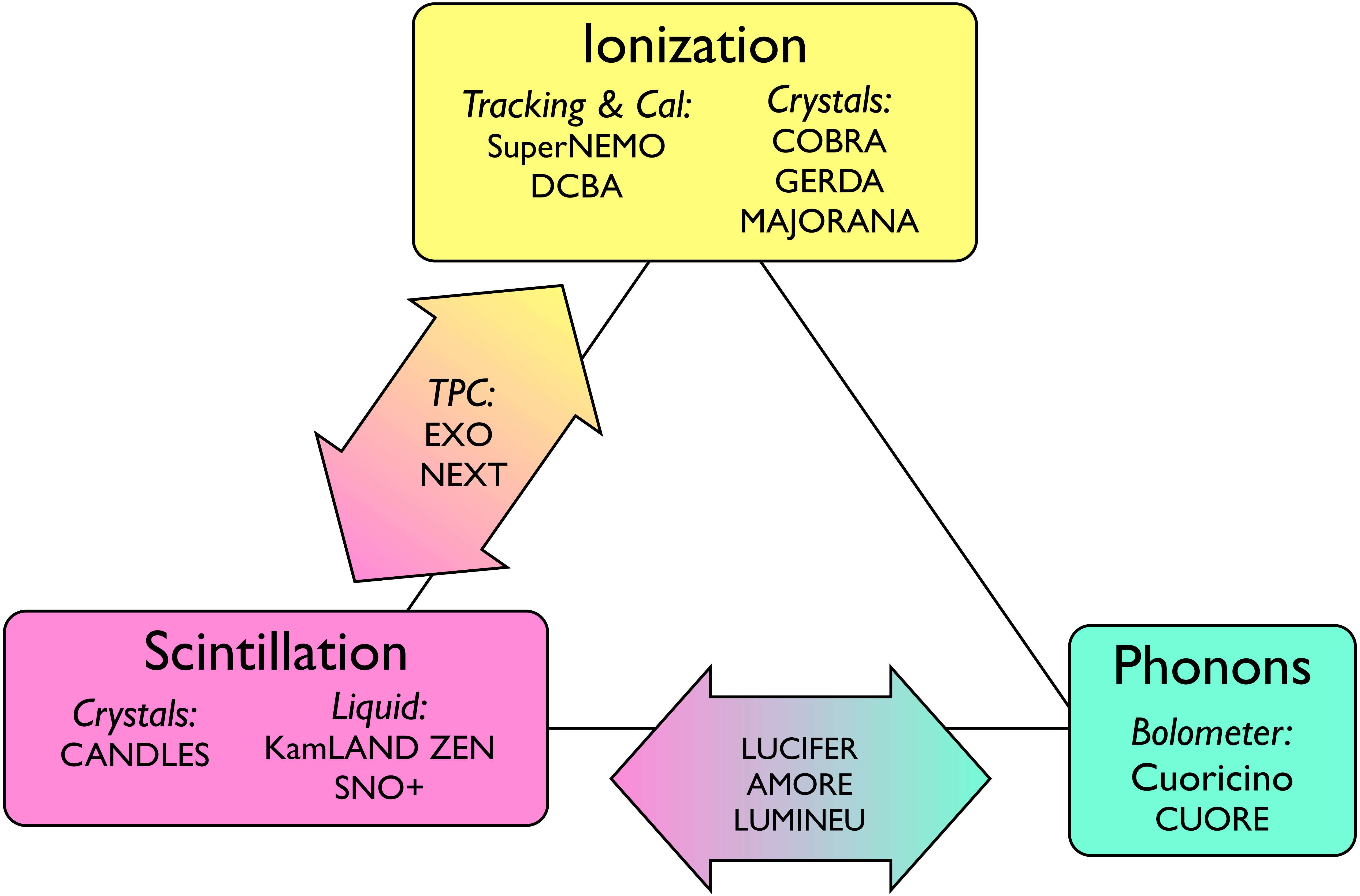
MAJORANA



SNO+



0νββ Detection Techniques



Ionization

Tracking & Cal:
SuperNEMO
DCBA

Crystals:
COBRA
GERDA
MAJORANA

TPC:
EXO
NEXT

Scintillation

Crystals:
CANDLES

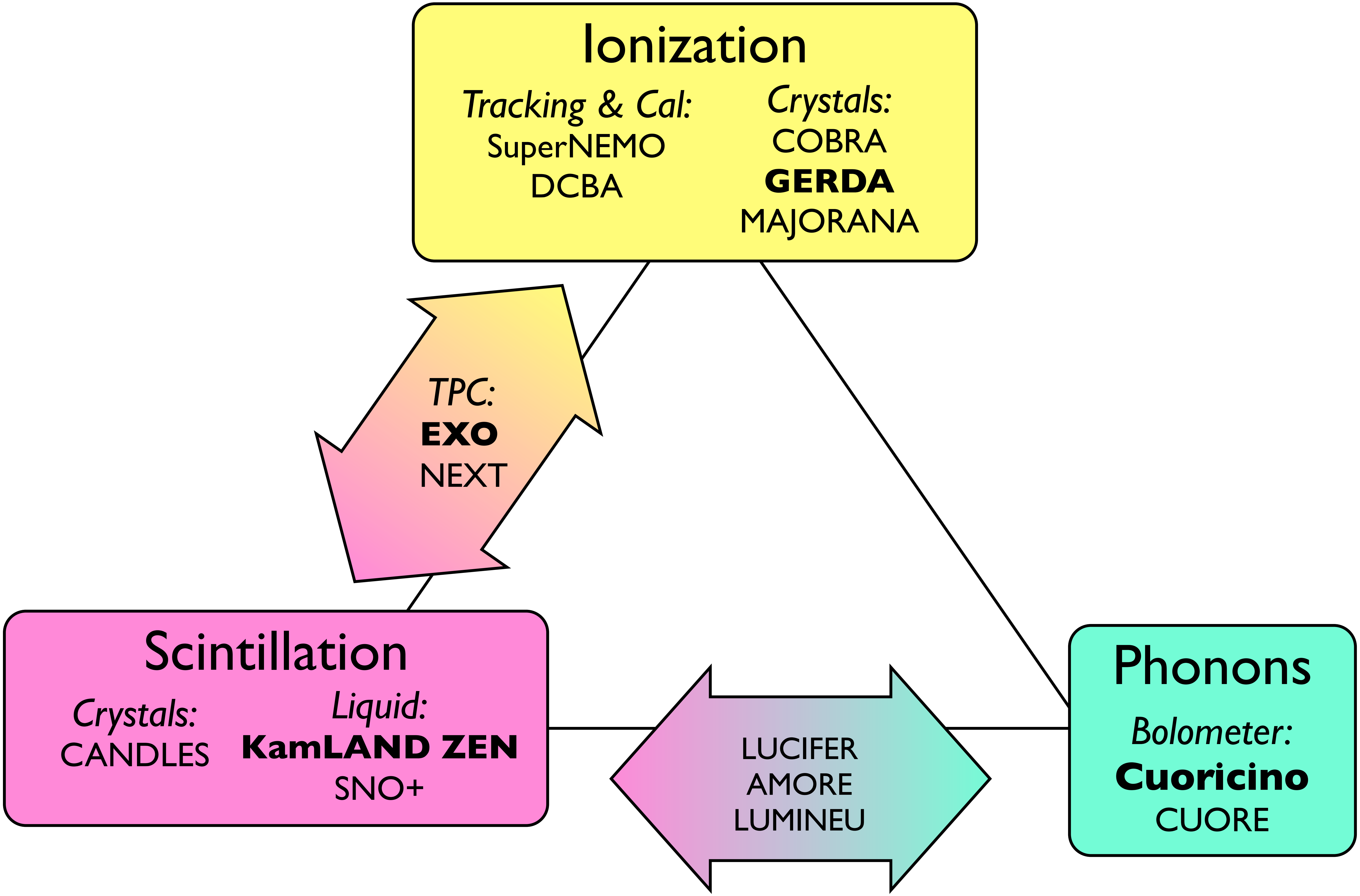
Liquid:
KamLAND ZEN
SNO+

LUCIFER
AMORE
LUMINEU

Phonons

Bolometer:
Cuoricino
CUORE

0νββ Detection Techniques



Ionization

Tracking & Cal:
SuperNEMO
DCBA

Crystals:
COBRA
GERDA
MAJORANA

TPC:
EXO
NEXT

Scintillation

Crystals:
CANDLES

Liquid:
KamLAND ZEN
SNO+

LUCIFER
AMORE
LUMINEU

Phonons

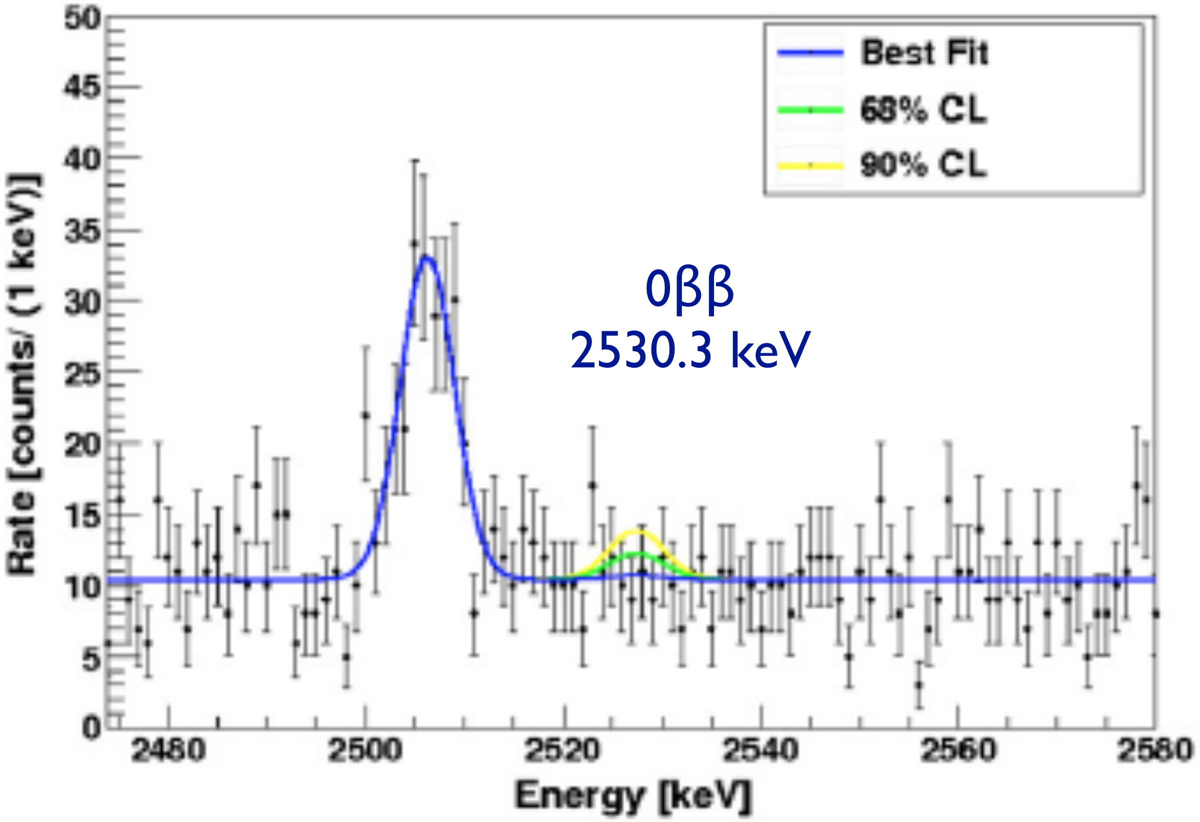
Bolometer:
Cuoricino
CUORE

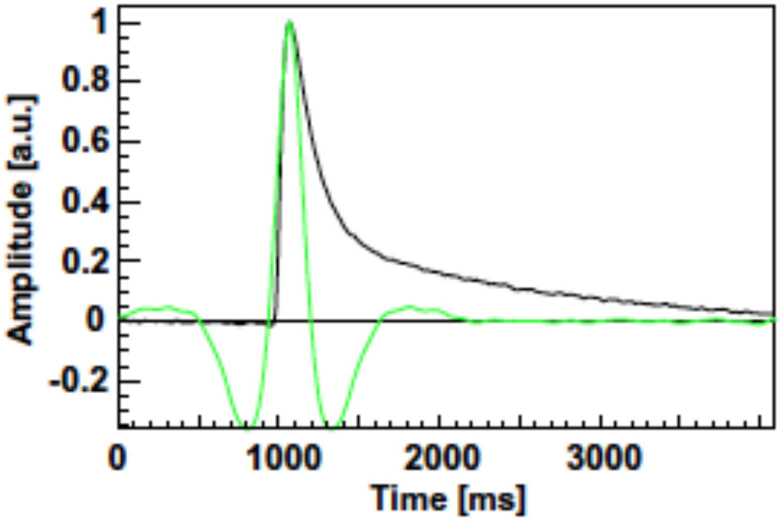
Cuoricino ^{130}Te 2003-2008

Phonons

- 11.2 kg ^{130}Te (34% nat.) bolometer (10 mK)
- Array of 62 TeO_2 crystals, 40.7 kg
- 19.75 kg - years exposure
- FWHM of 8 keV
- utilized pulse shape discrimination

$T_{1/2} > 2.8 \times 10^{24}$ y (90% CL)

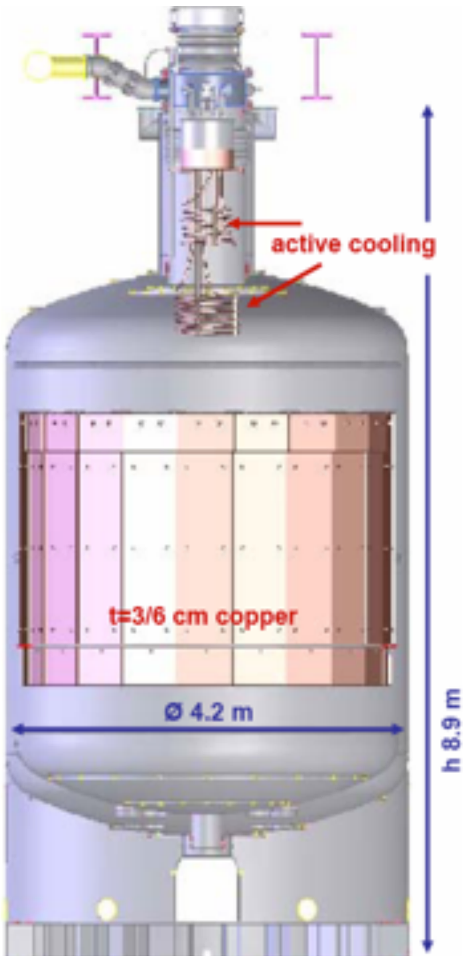




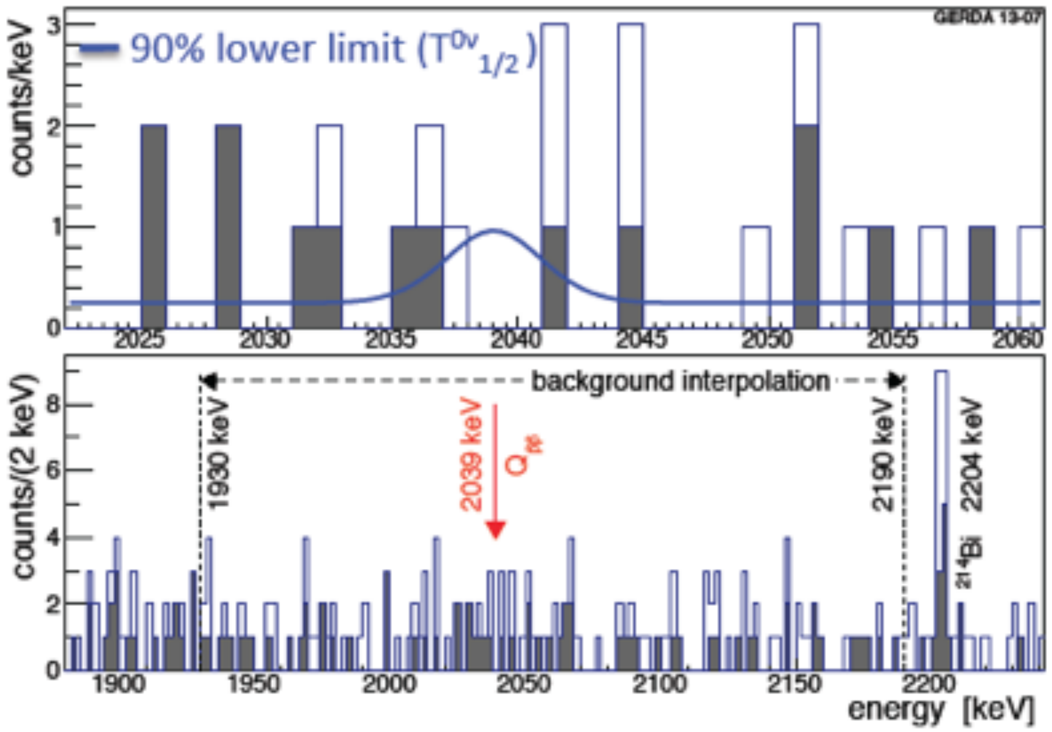
Astroparticle Physics 34 (2011) 822–831

GERDA ^{76}Ge Phase 1

Ionization



- 87% enriched ^{76}Ge detectors (crystals) in LAr
- $Q_{\beta\beta}$=2039 keV
- 14.6 kg of 86% enriched ^{76}Ge (6 p-type semi-coax detectors from H-M & IGEX). (4.8 keV FWHM @ $Q_{\beta\beta}$)
- 3 kg of 87% enriched BEGe enriched detectors (5 detectors) (3.2 keV FWHM @ $Q_{\beta\beta}$)
- Single-site, multi-site pulse shape discrimination

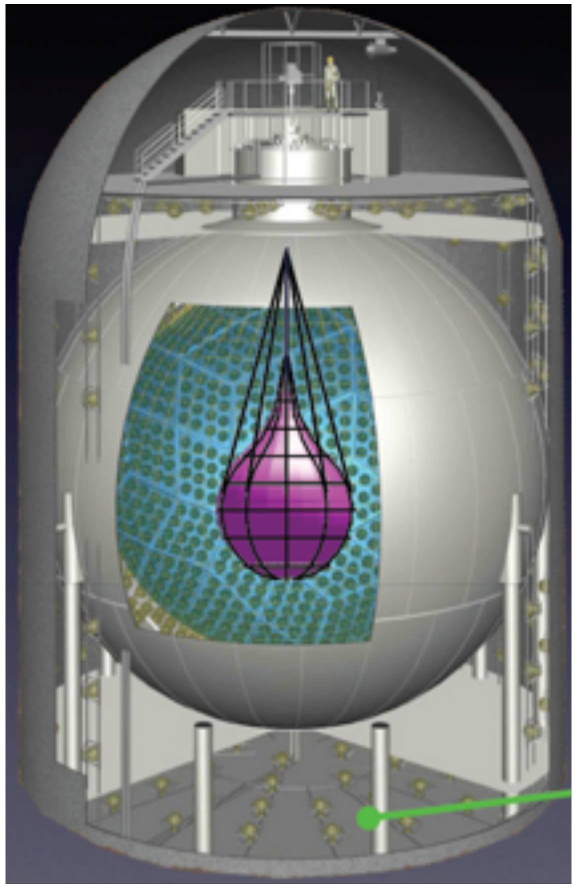


- 21.6 kg-year exposure
- Frequentist
  $T_{1/2} > 2.1 \times 10^{25}$ y (90% CL)
- Bayesian
  $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)

GERDA Collaboration, PRL 111 (2013) 122503
Eur. Phys. J. C (2014) 74:2764

KamLAND-ZEN ^{136}Xe

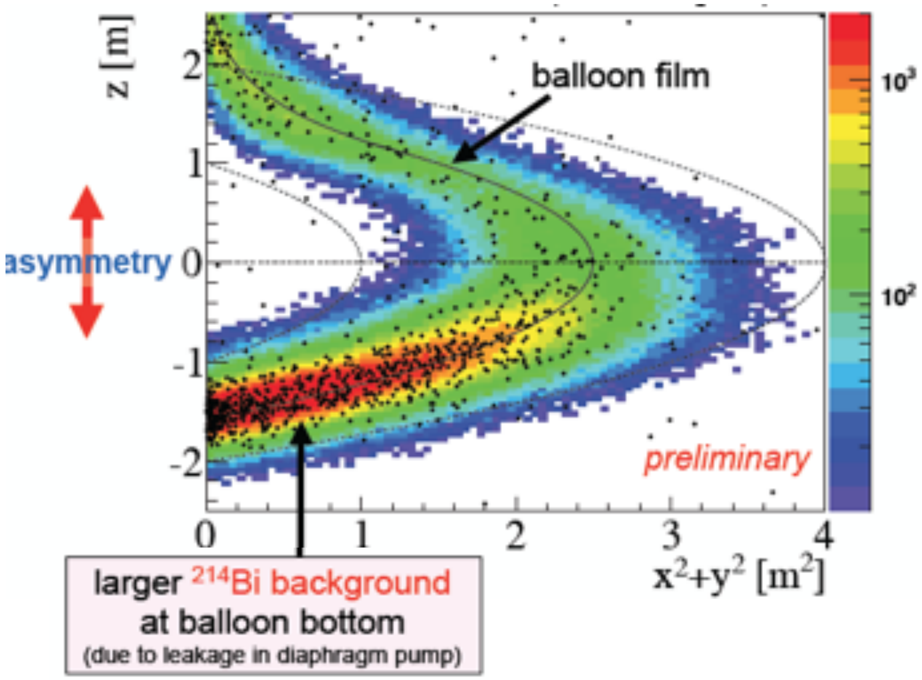
Scintillation



- Enriched Xe in liquid scintillator, ballon of R=1.5 m
- $Q_{\beta\beta}$=2457.8 keV
- Phase 1
  - 320 kg (2.44% by Xe wt.) 91.7% enriched^{136}Xe
  - 112.3 days, with 89.5 kg years exposure
  - σ_E = 4%
  - evidence for ^{110}Ag contamination

  $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)
- Phase 2
  - 384 kg (2.44% by Xe wt.) 91.7% enriched^{1}
  - 1 m fiducial cut
  - 114.8 days, with 35.6 kg years exposure
  - ^{110}Ag contamination reduced by x10
  - ROI of 400 keV

  $T_{1/2} > 1.3 \times 10^{25}$ y (90% CL)



larger ^{214}Bi background at balloon bottom (due to leakage in diaphragm pump)

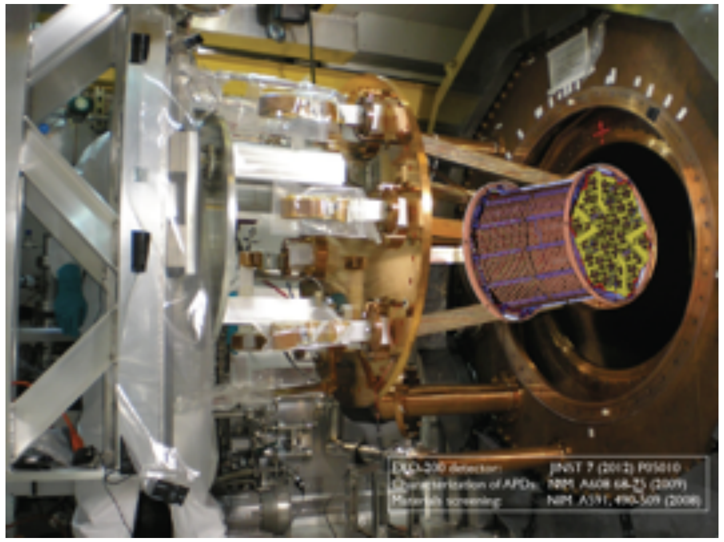
KamLAND ZEN Collaboration, Shimizu, Neutrino 2014

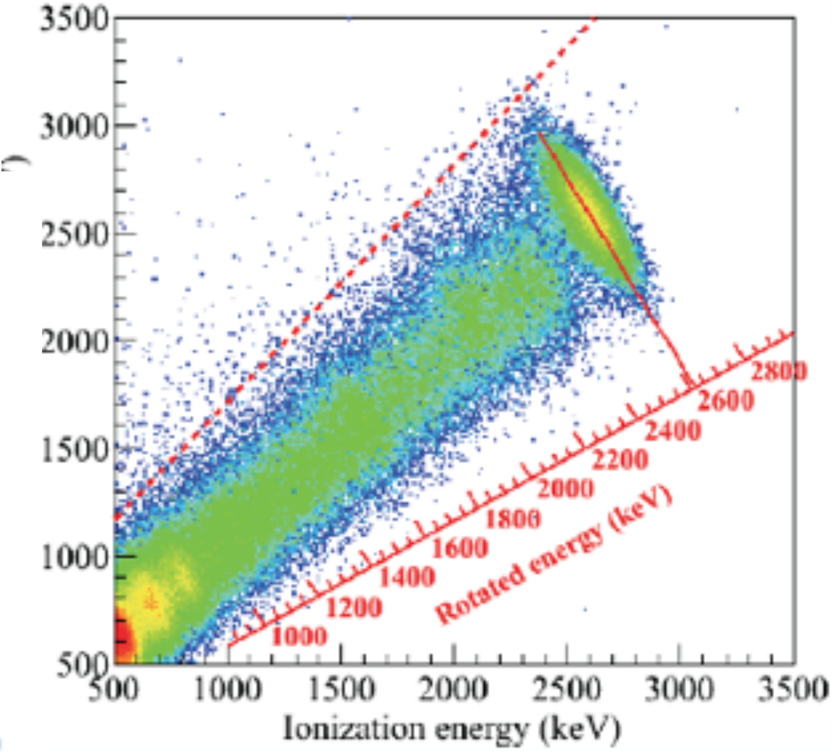
EXO-200 ^{136}Xe

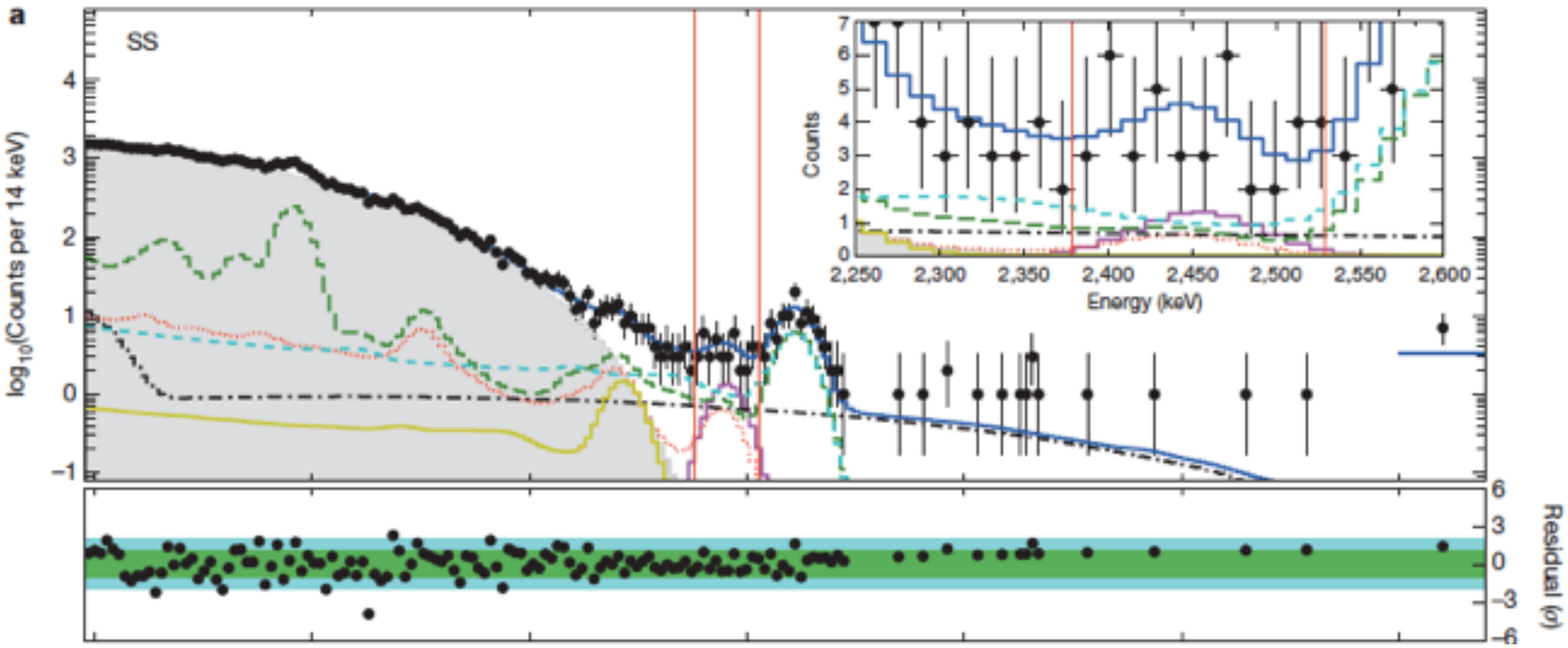
Scintillation - Ionization

- Enriched Liquid Xe in TPC
  - $Q_{\beta\beta}$=2457.8 keV
  - 200 kg of 80.6 % enriched ^{136}Xe
  - 75.6 kg fiducial volume,
  - 123.7 kg years exposure
  - Combine Scintillation-Ionization signal for improved resolution of 3.6% FWHM
  - Single site - Multisite discrimination

$T_{1/2} > 1.1 \times 10^{25}$ y (90% CL)







EXO-200 Collaboration, Nature **510** 229 (2014)

Experiments & sensitivity to 0νββ-decay

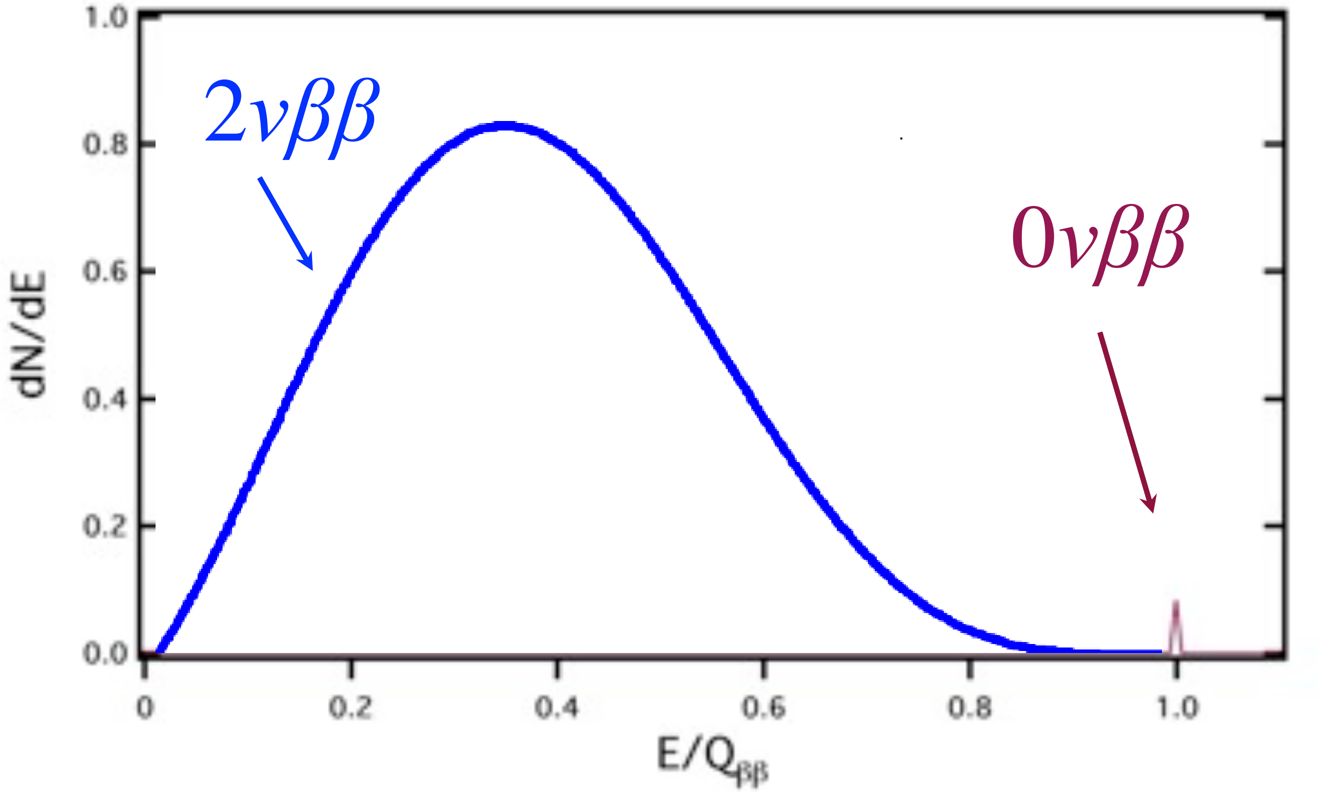
Most sensitive experiments to date using ^{76}Ge, ^{130}Te, and ^{136}Xe have attained $T_{1/2} > 10^{25}$ years

typical Source Mass · exposure times of 30 - 100 kg-years

To reach IH region requires sensitivities of

0νββ $T_{1/2} \sim 10^{27}$ - 10^{28} years

(2νββ $T_{1/2} \sim 10^{19}$ - 10^{21} years)

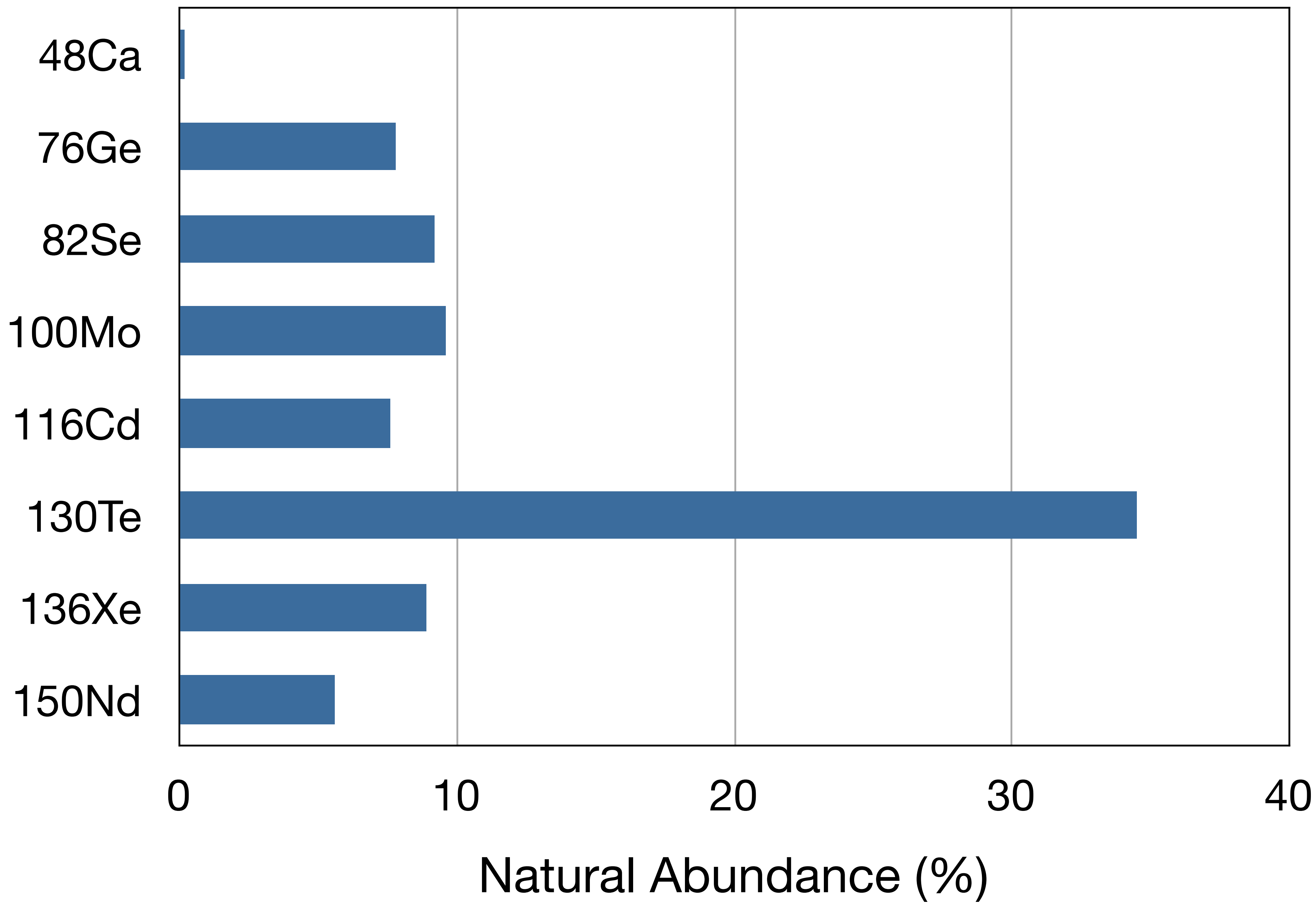


Question : Is there a “best” isotope?

Question : What’s needed to reach such small $T_{1/2}$ values?

Question : What is required for a 0νββ discovery?

0νββ Isotopes : Natural Abundances

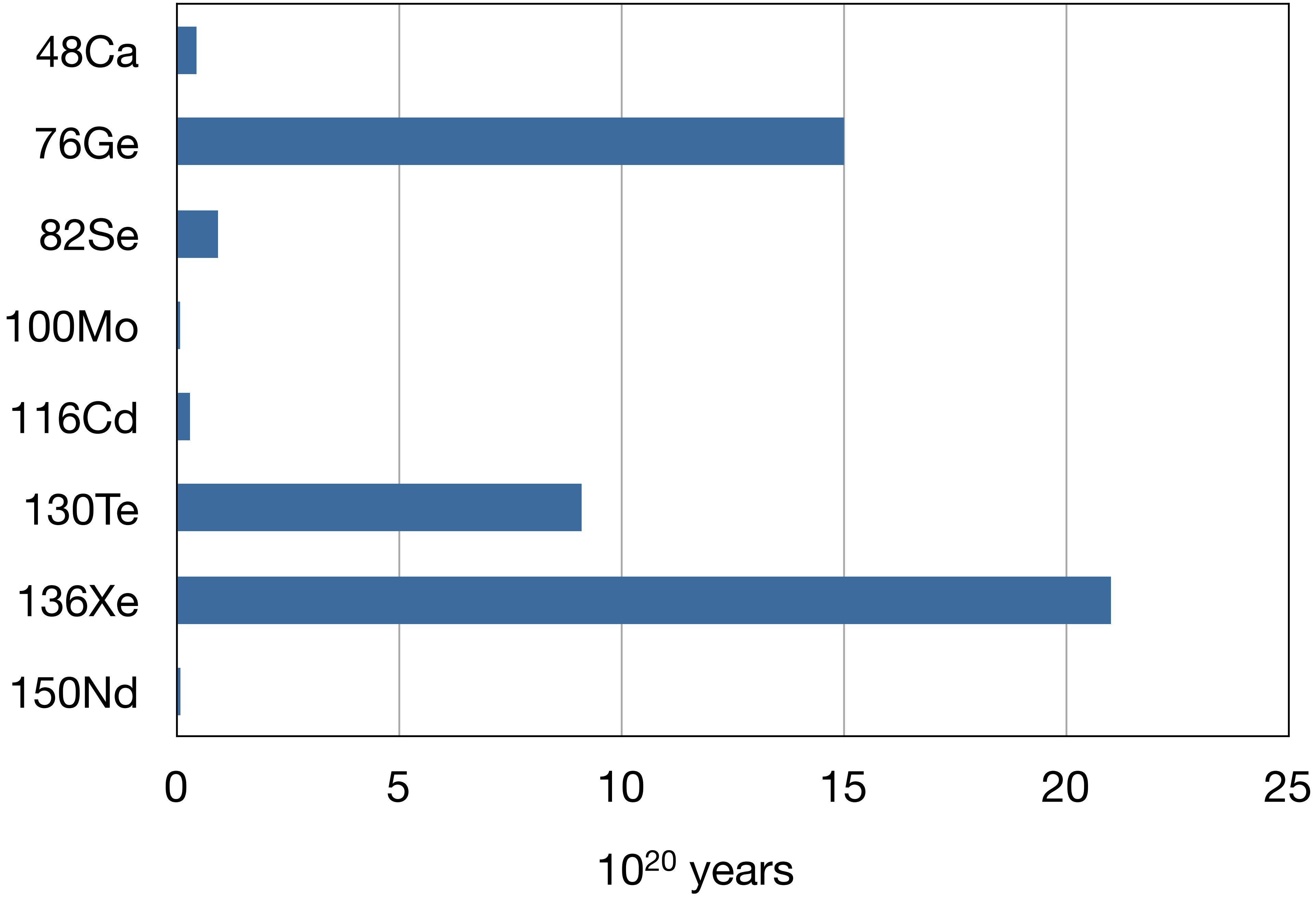


ββ Isotope	Natural Abundance
^{48}Ca	0.187
^{76}Ge	7.8
^{82}Se	9.2
^{100}Mo	9.6
^{116}Cd	7.6
^{130}Te	34.5
^{136}Xe	8.9
^{150}Nd	5.6

Clearly ^{130}Te has an advantage.

For the others, Isotopic enrichment ($s) is needed

0νββ Isotope : 2νββ $T_{1/2}$

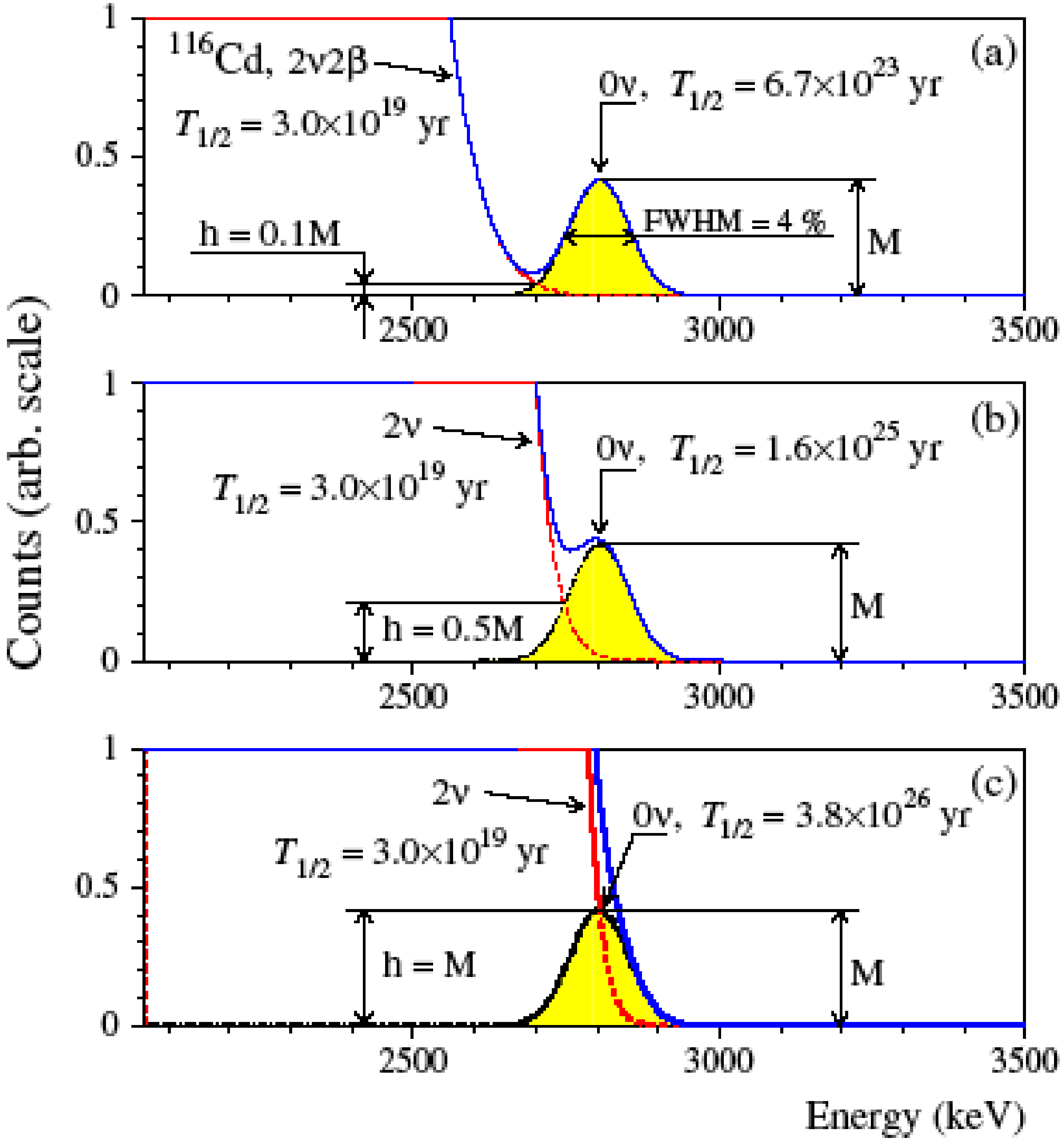


ββ Isotope	**2νββ $T_{1/2}$ 10^{20} years**
^{48}Ca	0.44
^{76}Ge	15
^{82}Se	0.92
^{100}Mo	0.07
^{116}Cd	0.29
^{130}Te	9.1
^{136}Xe	21
^{150}Nd	0.08

Longer 2νββ $T_{1/2}$ (better) ⇒ lower background rate

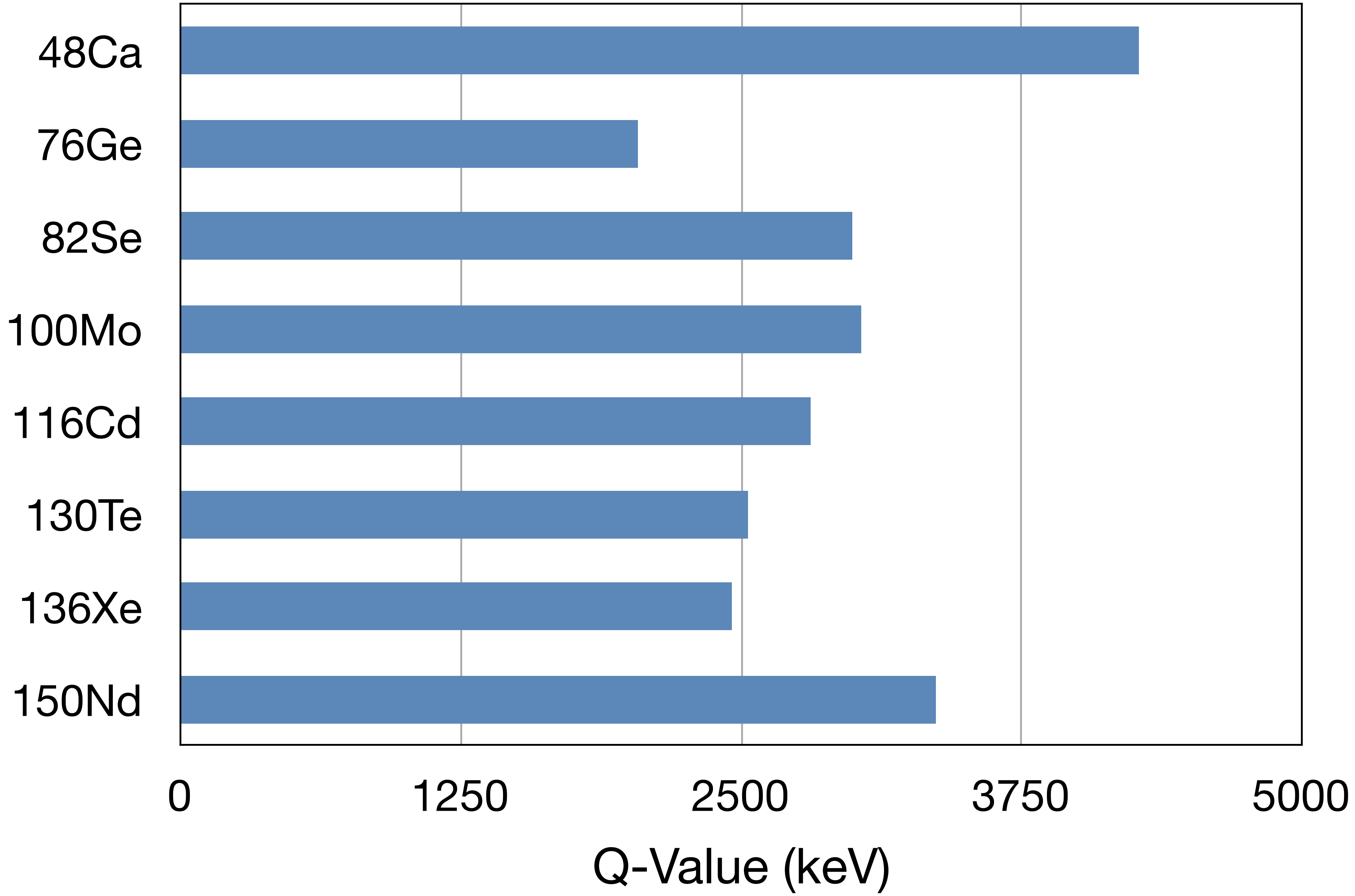
Irreducible background ⇒ minimize with good resolution

Resolution, 2νββ & Sensitivity to 0νββ



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

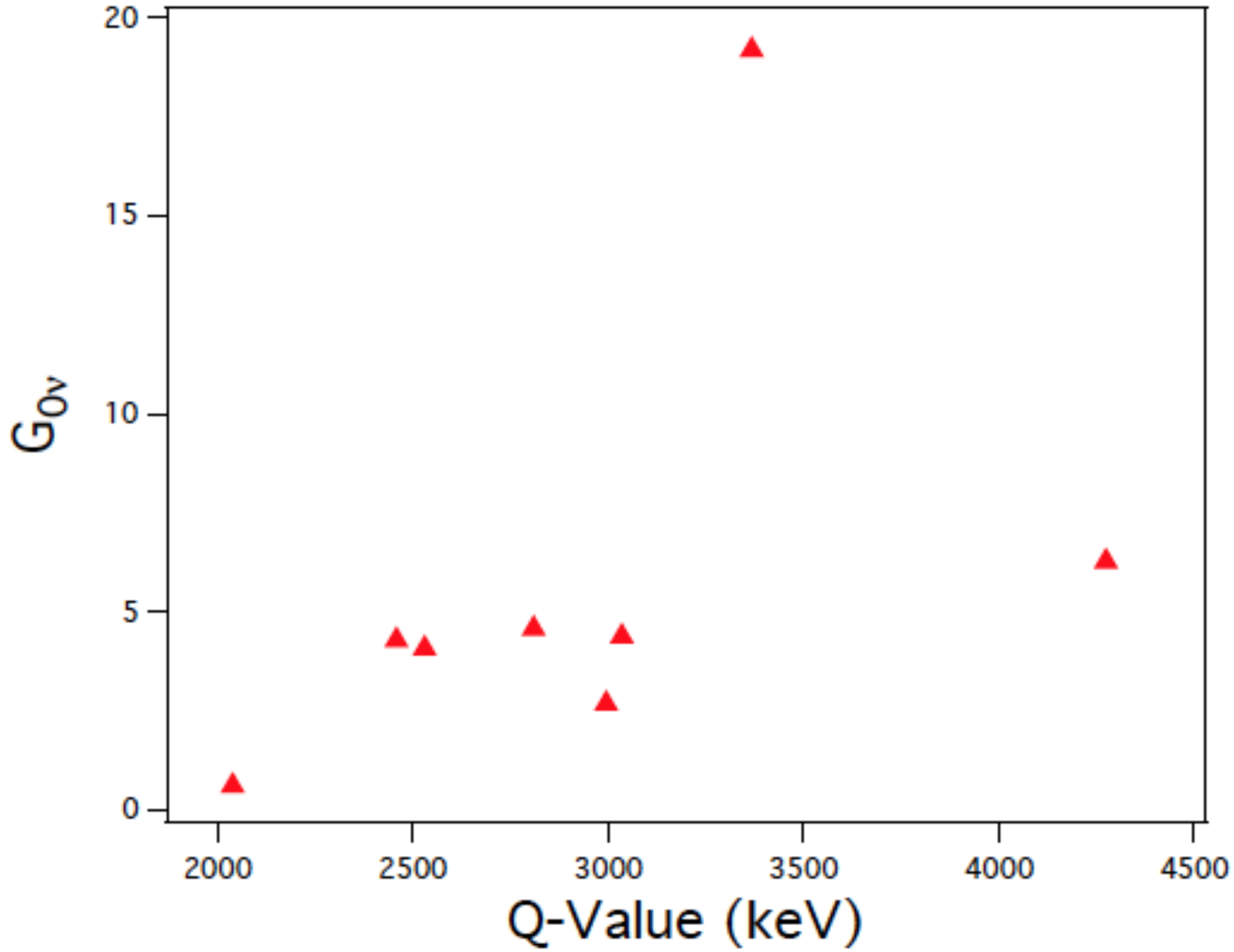
0νββ Isotopes : Q-Values



ββ Isotope	Q-Value
^{48}Ca	4273.7
^{76}Ge	2039.1
^{82}Se	2995.5
^{100}Mo	3035
^{116}Cd	2809.1
^{130}Te	2530.3
^{136}Xe	2457.8
^{150}Nd	3367.3

- Higher Q-value will result in the ββ-decay signal being above potential backgrounds.
- “*Higher Q-value means a higher rate and an easier measurement!*”

$0\nu\beta\beta$ Isotopes : $G_{0\nu}$ vs. Q-Values



$\beta\beta$ Isotope	$G_{0\nu}$	Q-Value
^{48}Ca	6.3	4273.7
^{76}Ge	0.63	2039.1
^{82}Se	2.7	2995.5
^{100}Mo	4.4	3035
^{116}Cd	4.6	2809.1
^{130}Te	4.1	2530.3
^{136}Xe	4.3	2457.8
^{150}Nd	19.2	3367.3

✓ Higher Q-value will result in the $\beta\beta$-decay signal being above potential backgrounds.

? "*Higher Q-value means a higher rate and an easier measurement!*"

Rates (sensitivity) per unit mass

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

Of the known potential 0νββ isotopes, is there an isotope that has an inherent advantage in terms of sensitivity per unit mass?

- Arguments often made related to enhanced NME, phase space, ...
- Typically phase space is expressed in activity per atom, not per unit mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

The phase space $G_{0\nu}$ is in activty per atom

$$\lambda_{0\nu}\frac{N}{M} = \frac{\ln(2)N_A}{Am_e^2} G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$$\equiv H_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

The specific phase space $H_{0\nu}$ is in activty per unit mass

Dependence on g_A and uncertainties

following Robertson, arXiv 1301.1323

Typically, the effective axial-vector coupling constant, g_A, is incorporated in the phase space factor $G_{0\nu}$, or occasionally in the nuclear matrix elements (NME) $M_{0\nu}$.

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2 \Rightarrow G_{0\nu}g_A^4\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

Kotila and Iachello, Phys. Rev. C85 034316

Calculated phase-space factors for 0νββ use the free-nucleon value g_A = 1.269, or g_A = 1.25, or g_A = 1.

Barea et al. and Ejiri have fit half-lives for 2νββ and find of g_A of about 0.8 for shell-model calculations and 0.6 for the Interacting Boson Model (IBM).

Barea, Kotila and Iachello Phys. Rev. Lett. 109 042501 (2012); Ejiri Prog. Part. Nucl. Phys. 64 249, (2010)

➡Not entirely clear what is the "correct" value (NME dependence?).

➡Assumed values of g_A can change calculated rate by ~20

Nuclear Matrix Elements

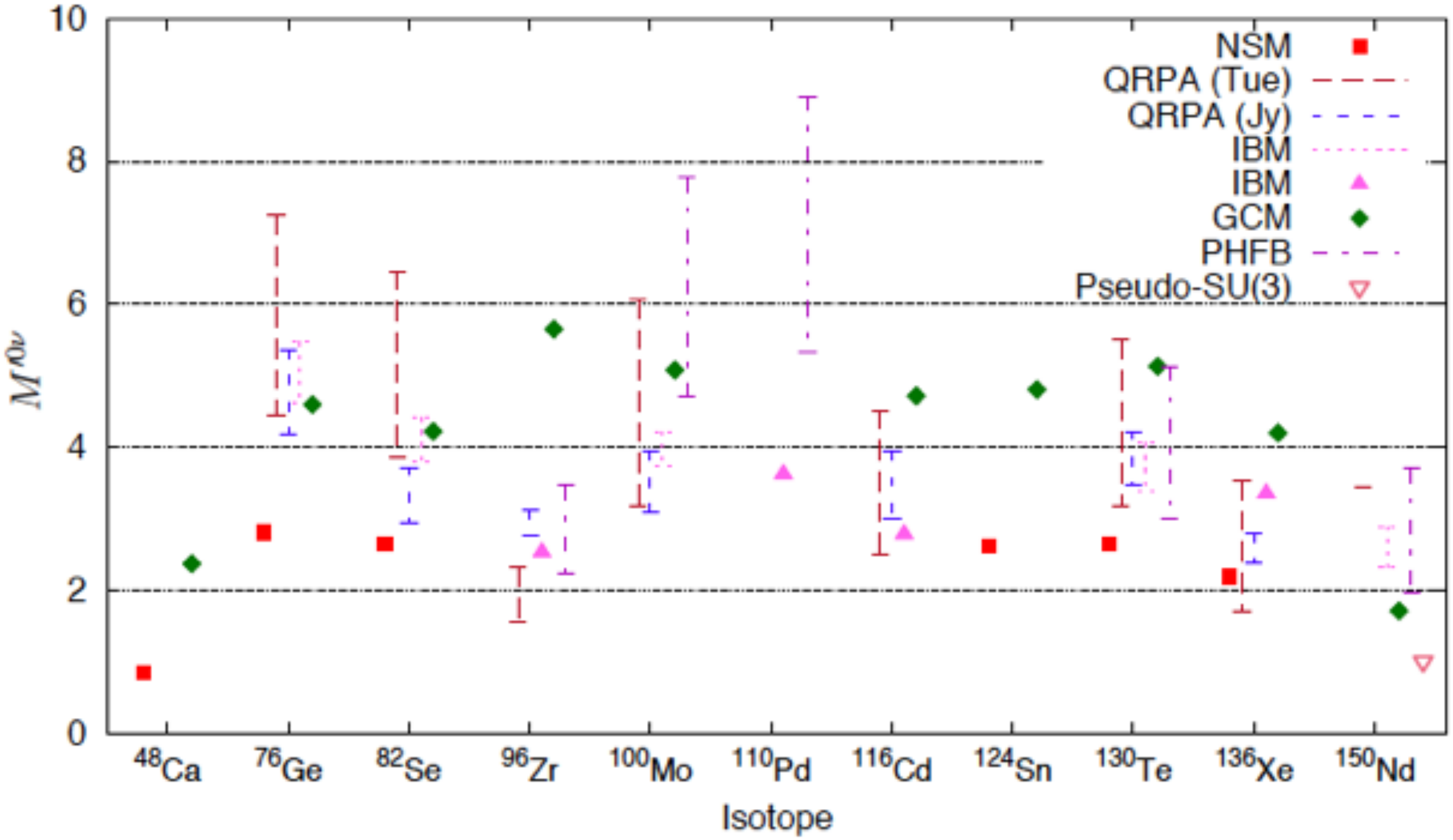
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

Extracting an effective neutrino mass requires an understanding of the nuclear matrix elements (NME) at about the 20% theoretical uncertainty level.

Recent progress NSM-QRPA:
2005 : within x 5
Present : agree within x 2-3

Agreement between methods doesn’t necessarily provide an estimate of theoretical uncertainties or of actual values.

NME are calculated using different approximate methods: Nuclear Shell Model; Quasi-random phase approximation (QRPA); Interacting Boson Model; Projected Hartree-Fock-Bogoliubov; Generating co-ordinate method extension of PHFB; Pseudo-SU(3) deformed shell model.



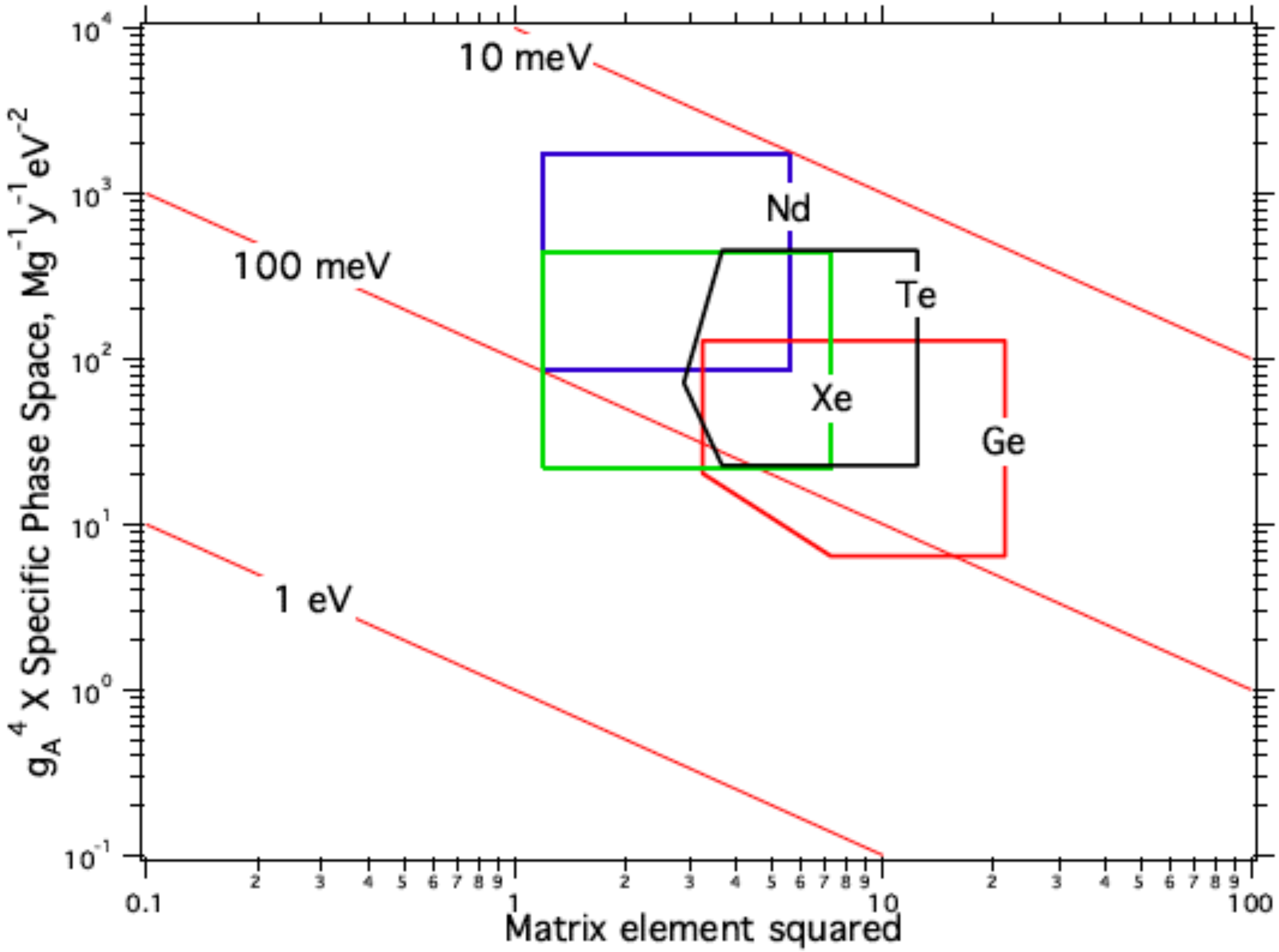
Dueck, Rodejohann & Zuber Phys. Rev. D 63 054031 (2011)
with r_0 = 1.2 fm and g_A = 1.25

Sensitivity to $\langle m_{\beta\beta} \rangle$

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

For Ge, Te, Xe, Nd

← uncertainty on NME →

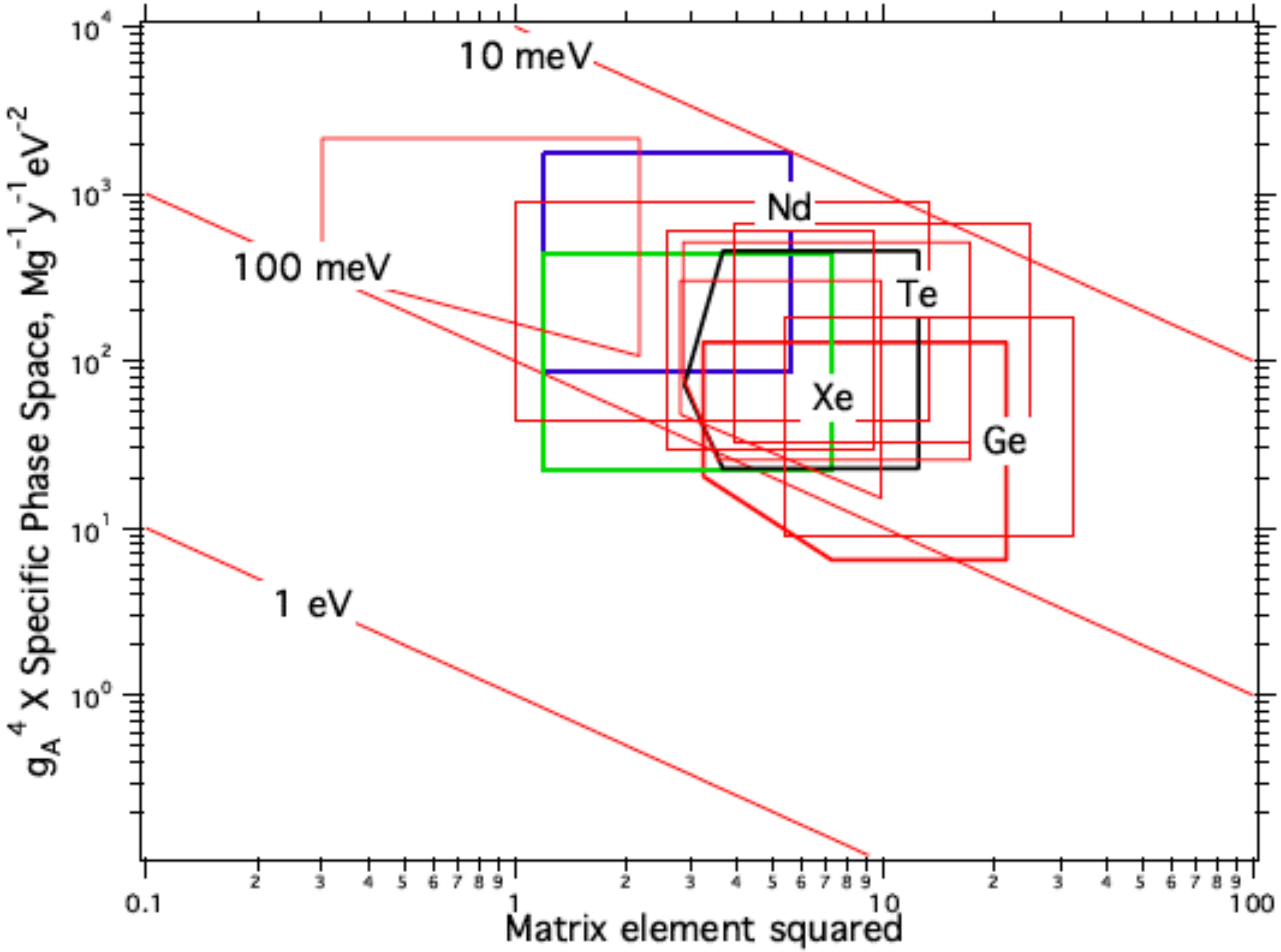


↑ uncertainty on value of g_A ↓

Sensitivity to <$m_{\beta\beta}$>

R.G.H. Robertson, MPL A **28** (2013) 1350021
(arXiv 1301.1323)

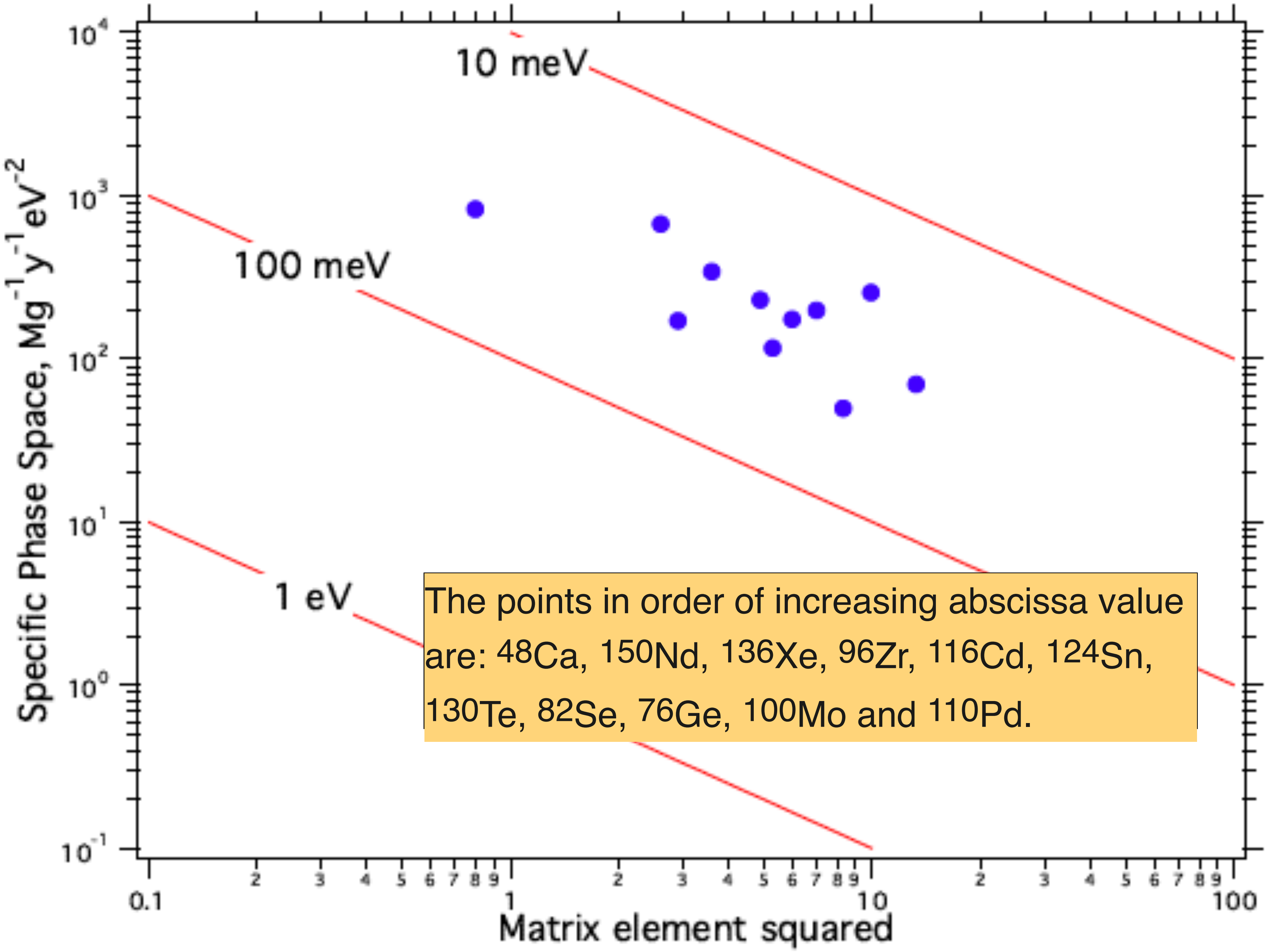
➡Based on rate per unit mass, no isotope is clearly preferred.



^{48}Ca (2.2, 2143),
^{82}Se (17, 514),
^{96}Zr (13,889),
^{100}Mo (25, 660),
^{110}Pd (33,181),
^{116}Cd (9, 597),
^{124}Sn (10, 302)
(coordinates upper right corner)

Sensitivity per unit mass of isotope

➡ Based on rate per unit mass, no isotope is clearly preferred.



The points in order of increasing abscissa value are: ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo and ^{110}Pd.

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

Inverse correlation observed between phase space and the square of the nuclear matrix element .

geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1

0νββ signals vs. $T_{1/2}$

Half life (years)	~Signal (cnts/tonne-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
$>10^{29}$	<0.05

$0\nu\beta\beta$ signals & sensitivity

Half life (years)	~Signal (cnts/tonne-year)	S:B = 1 ROI = 4 keV (cnts/keV kg year)	S:B = 1 ROI = 100 keV (cnts/keV kg year)
10^{25}	500	1.25×10^{-1}	5×10^{-3}
5×10^{26}	10	2.5×10^{-3}	1×10^{-4}
5×10^{27}	1	2.5×10^{-4}	1×10^{-5}
$>10^{29}$	<0.05	$< 1.25 \times 10^{-5}$	$< 5 \times 10^{-7}$

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

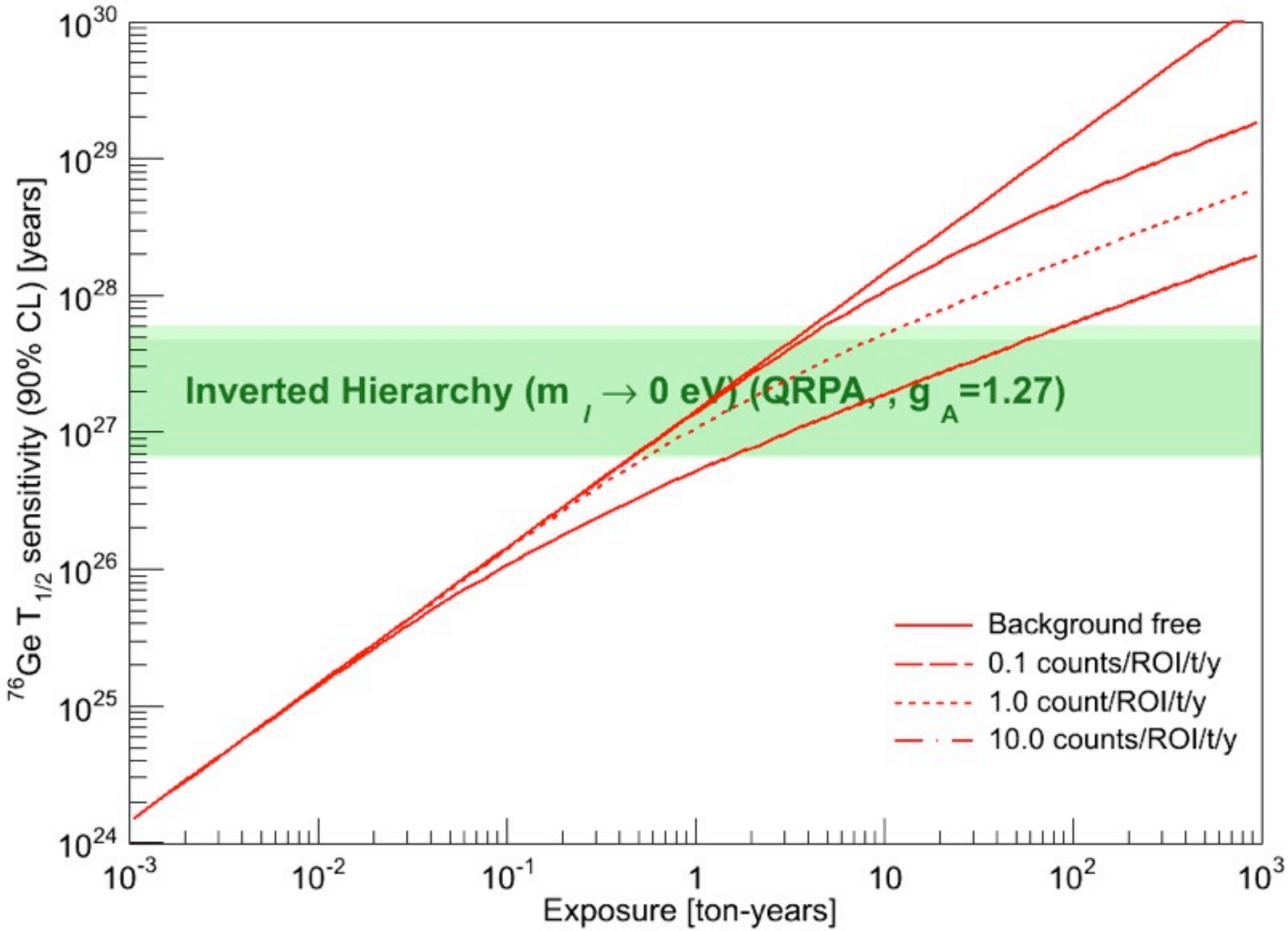
Background free

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

Background limited

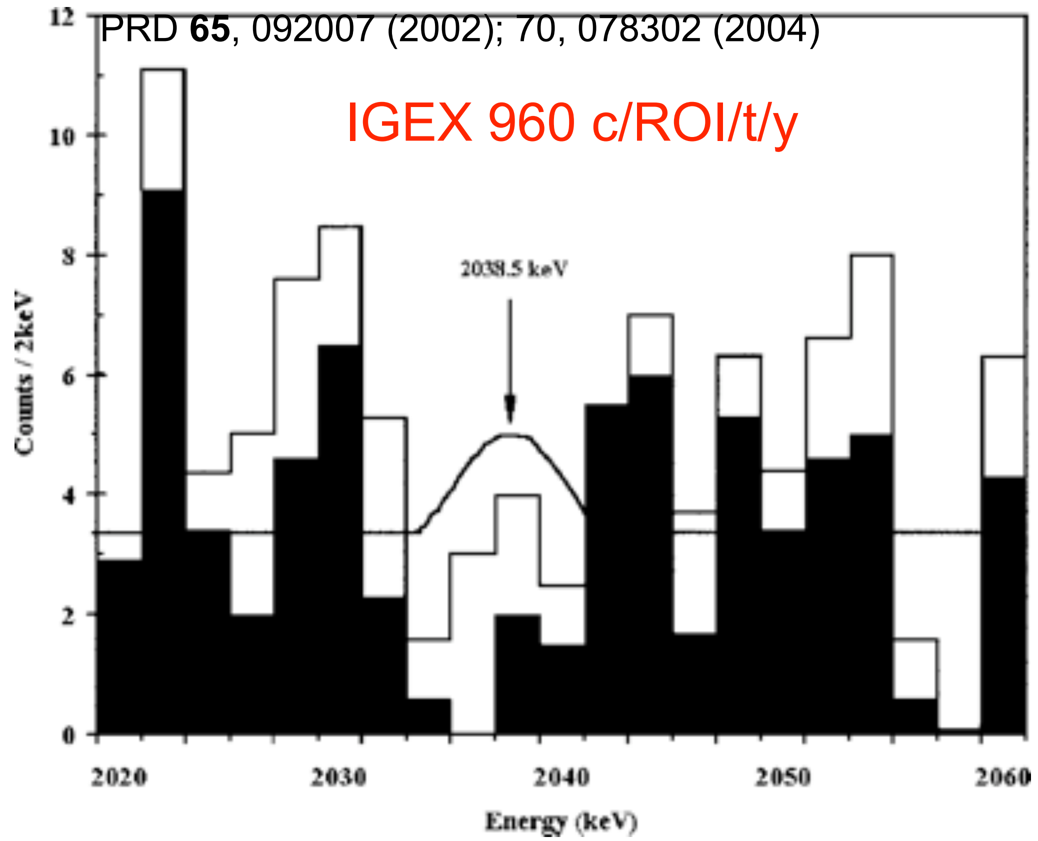
Sensitivity vs. Background (^{76}Ge)

J. Detwiler

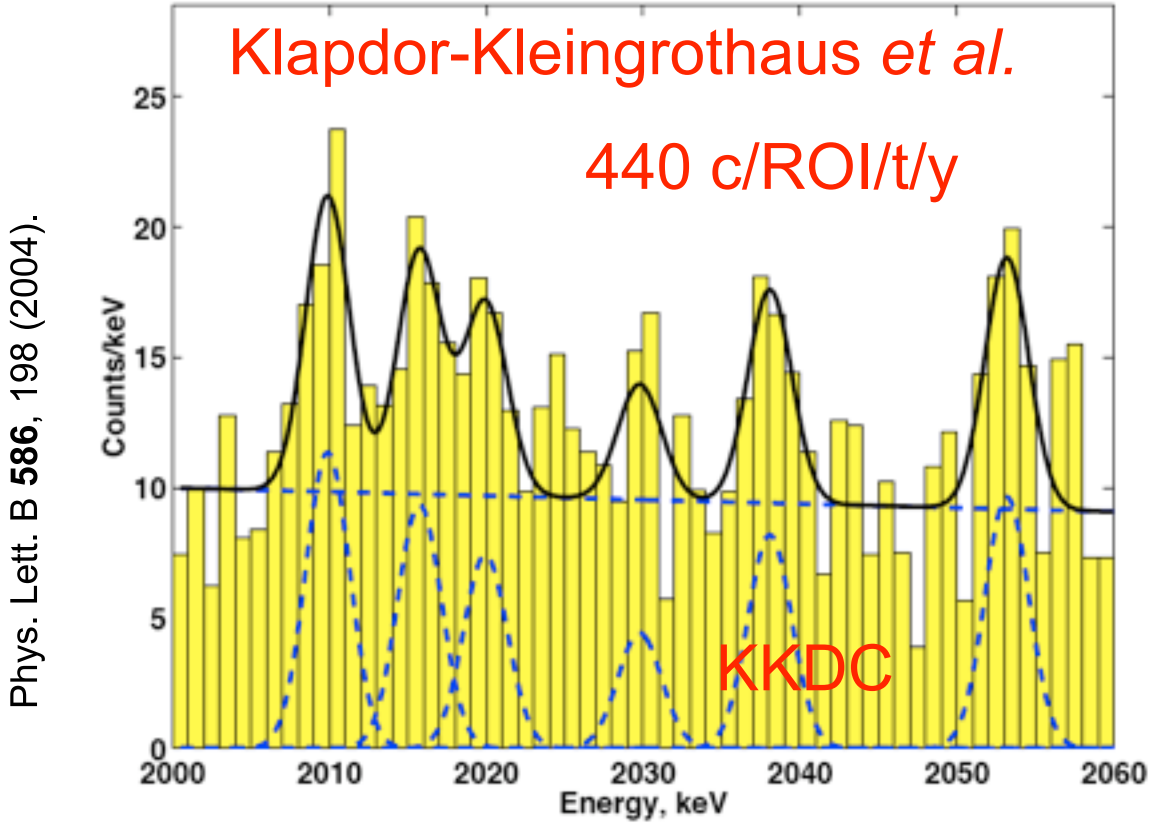


Backgrounds in recent experiments

S.R. Elliott


PRD **65**, 092007 (2002); 70, 078302 (2004)

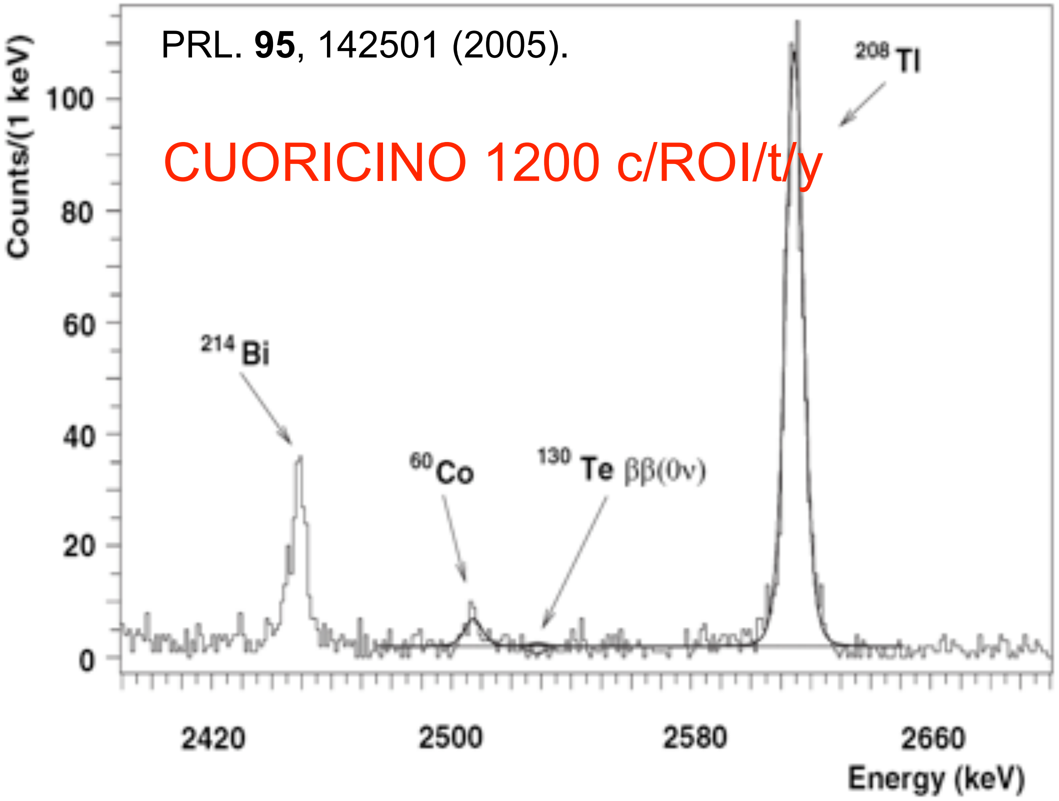
IGEX 960 c/ROI/t/y


Klapdor-Kleingrothaus *et al.*

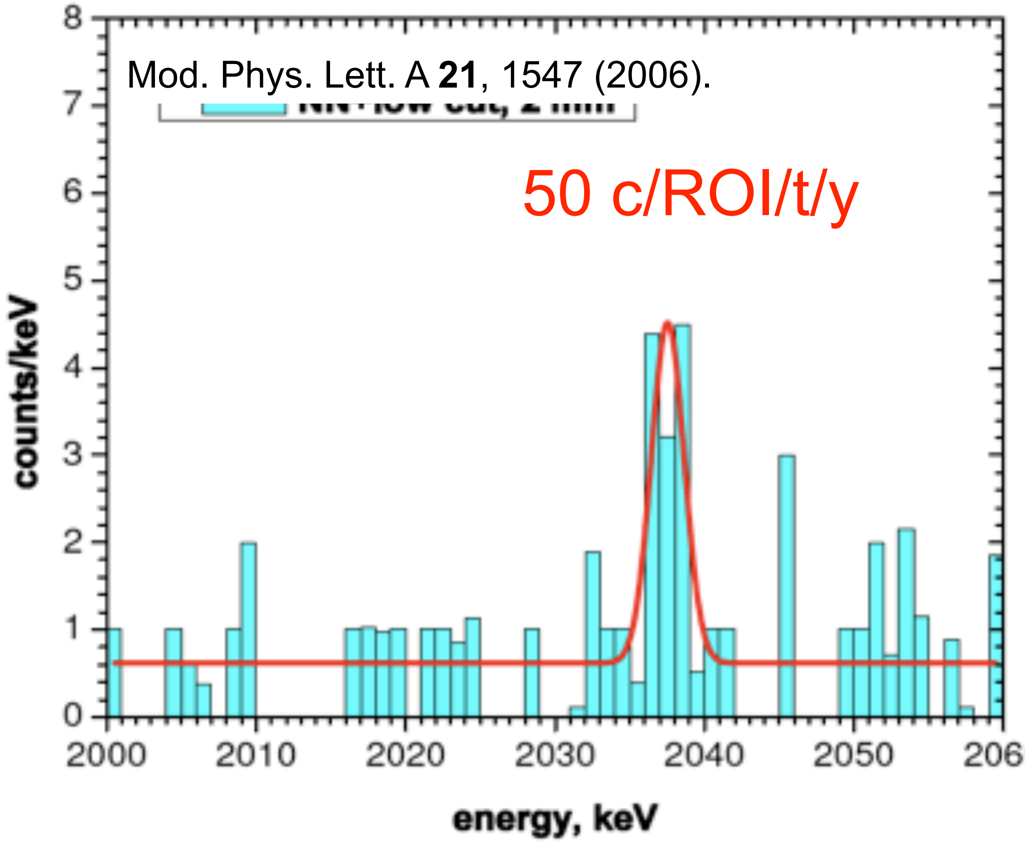
440 c/ROI/t/y

KKDC

Phys. Lett. B **586**, 198 (2004).


PRL. **95**, 142501 (2005).

CUORICINO 1200 c/ROI/t/y

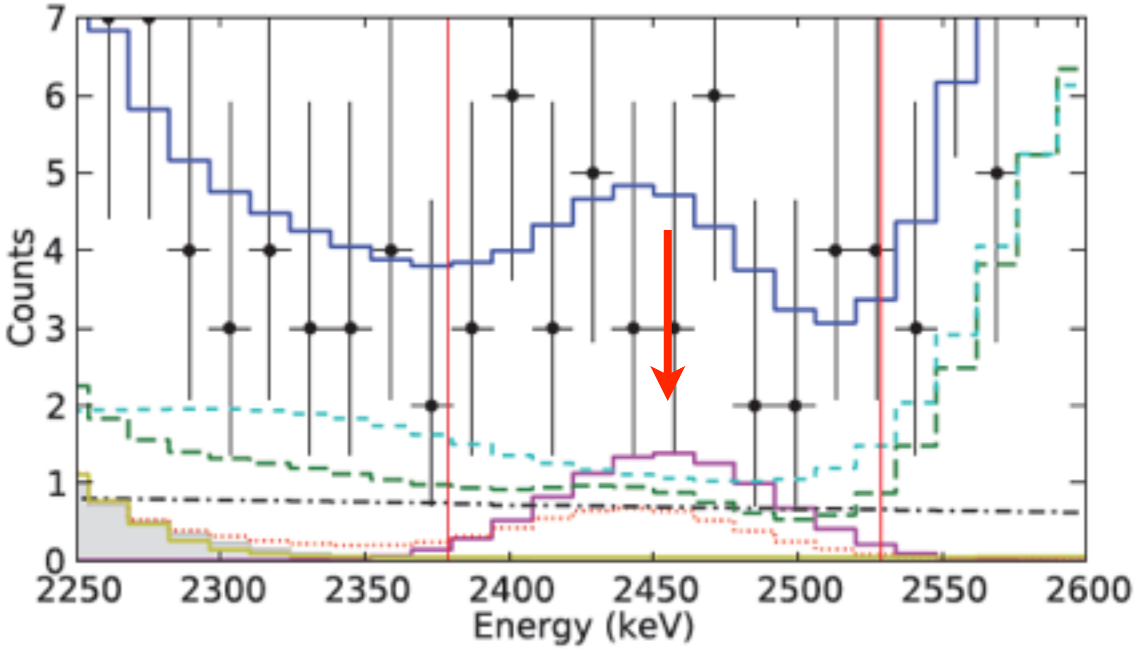

Mod. Phys. Lett. A **21**, 1547 (2006).

50 c/ROI/t/y

Backgrounds in recent experiments

$Q_{\beta\beta}$=2457.8 keV

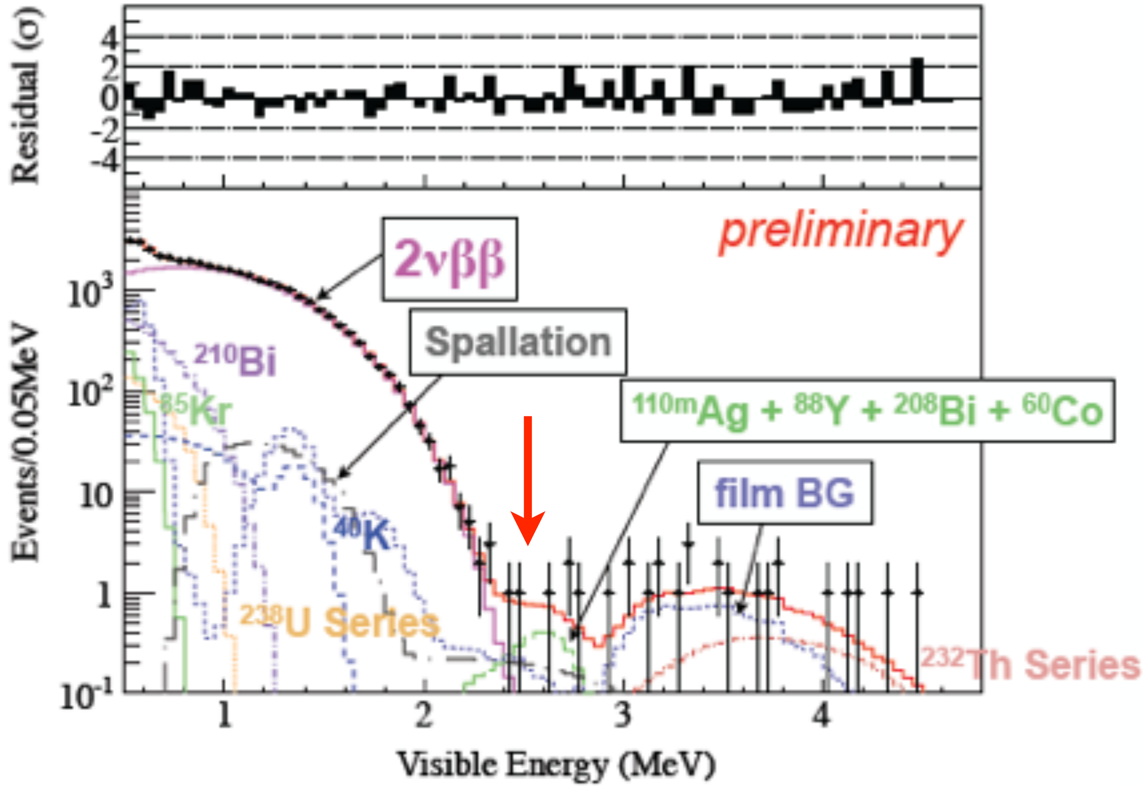
EXO-200 Collaboration, Nature **510** 229 (2014)

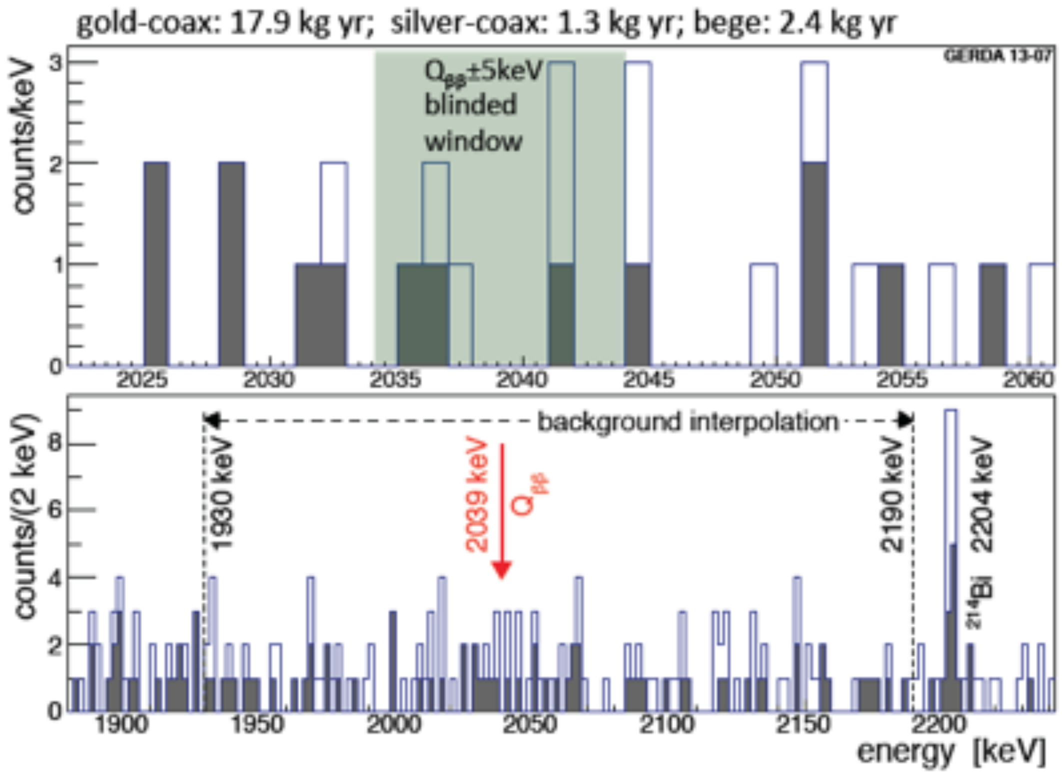


EXO-200: 132 c/ROI/t/y

KamLAND-Zen: 214 c/ROI/t(Xe)/y

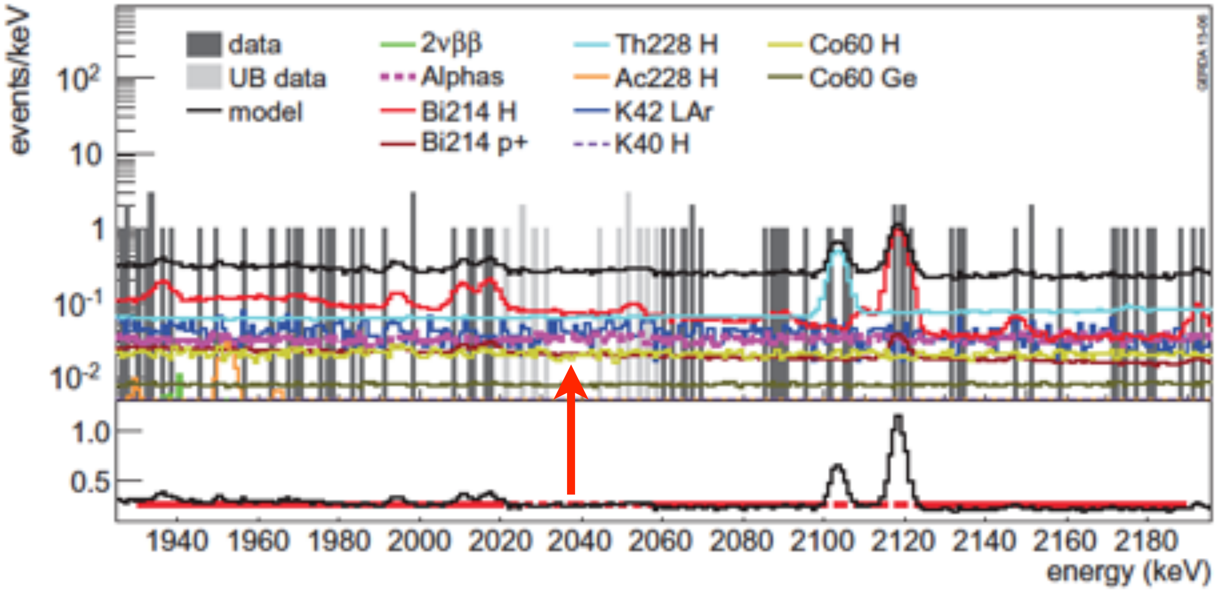
KamLAND ZEN Collaboration, Shimizu, Neutrino 2014





GERDA Phase 1: 40 c/ROI/t/y

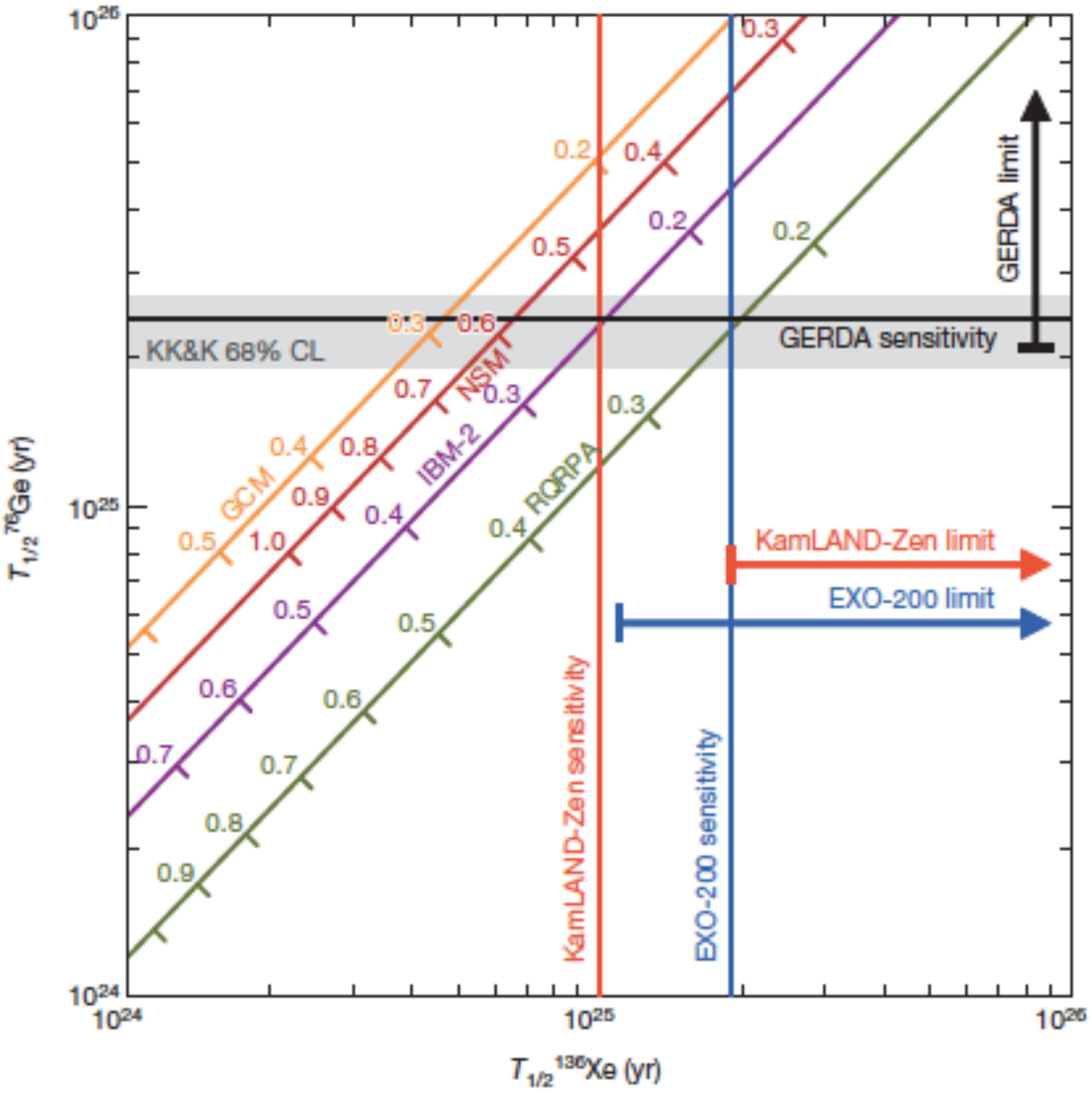
GERDA Collaboration, PRL 111 (2013) 122503
Eur. Phys. J. C (2014) 74:2764



Backgrounds in recent experiments

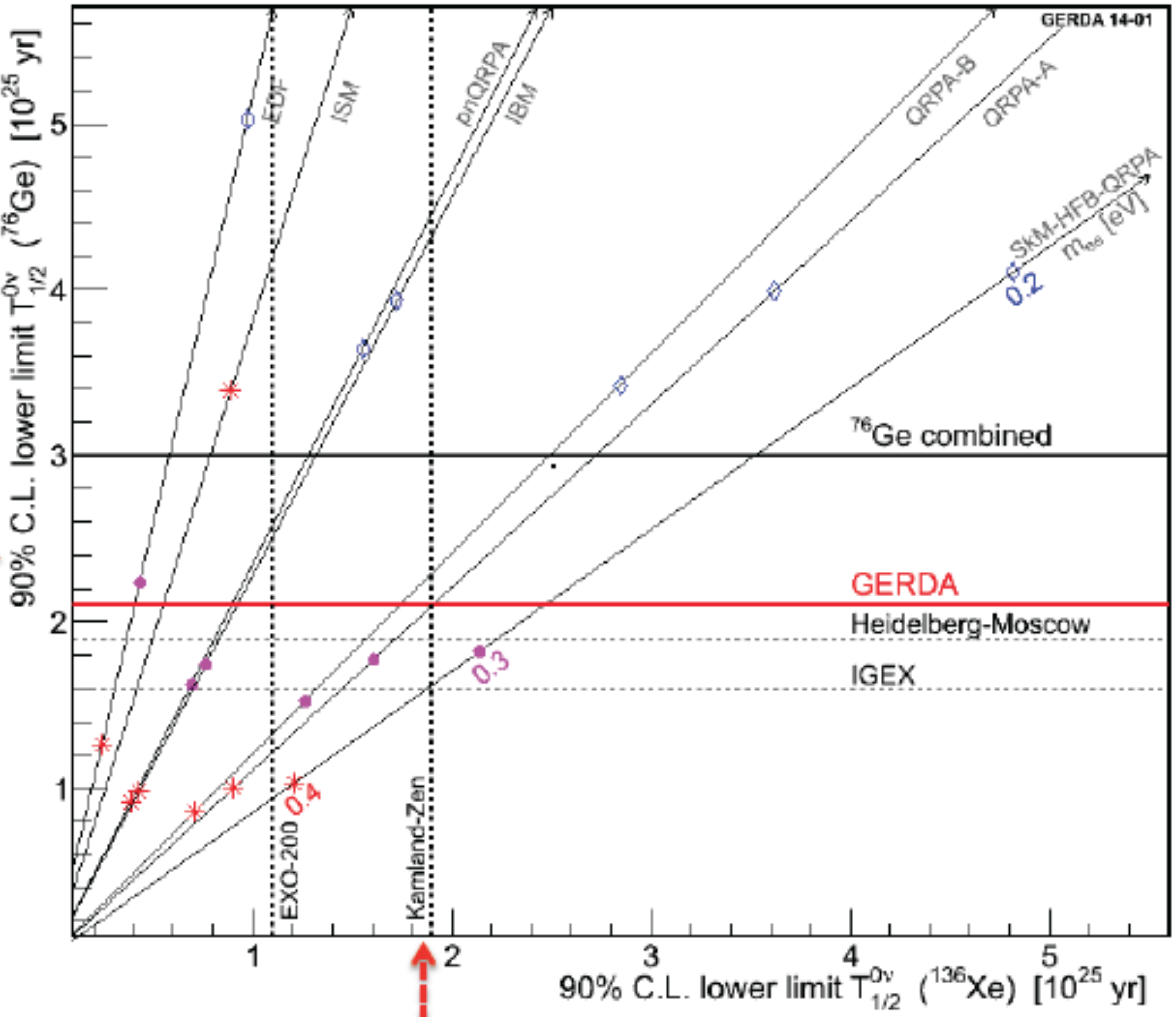
Experiment	Bkg (cnts/ROI-t-y)	Width (1 FWHM)	Bkg (ckky) (cnts/keV-kg-y)
IGEX	960 (400 with PSD)	4 keV ROI	24 (10) x 10^{-2}
Heid.-Moscow	440 (50 with PSD)	4 keV ROI	11 (1.25) x 10^{-2}
CUORICINO	1200	8 keV ROI	15 x 10^{-2}
GERDA (Phase 1)	40	4 keV ROI	1 x 10^{-2}
EXO-200	132	88 keV ROI	1.5 x 10^{-2}
KamLAND-Zen (Phase 2)	214 per t(Xe))	400 keV ROI	4 x 10^{-6}

EXO-200, KamLAND Zen, GERDA Comparison



EXO-200 Collaboration, Nature **510** 229 (2014)

EXO-200, KamLAND Zen, GERDA Comparison



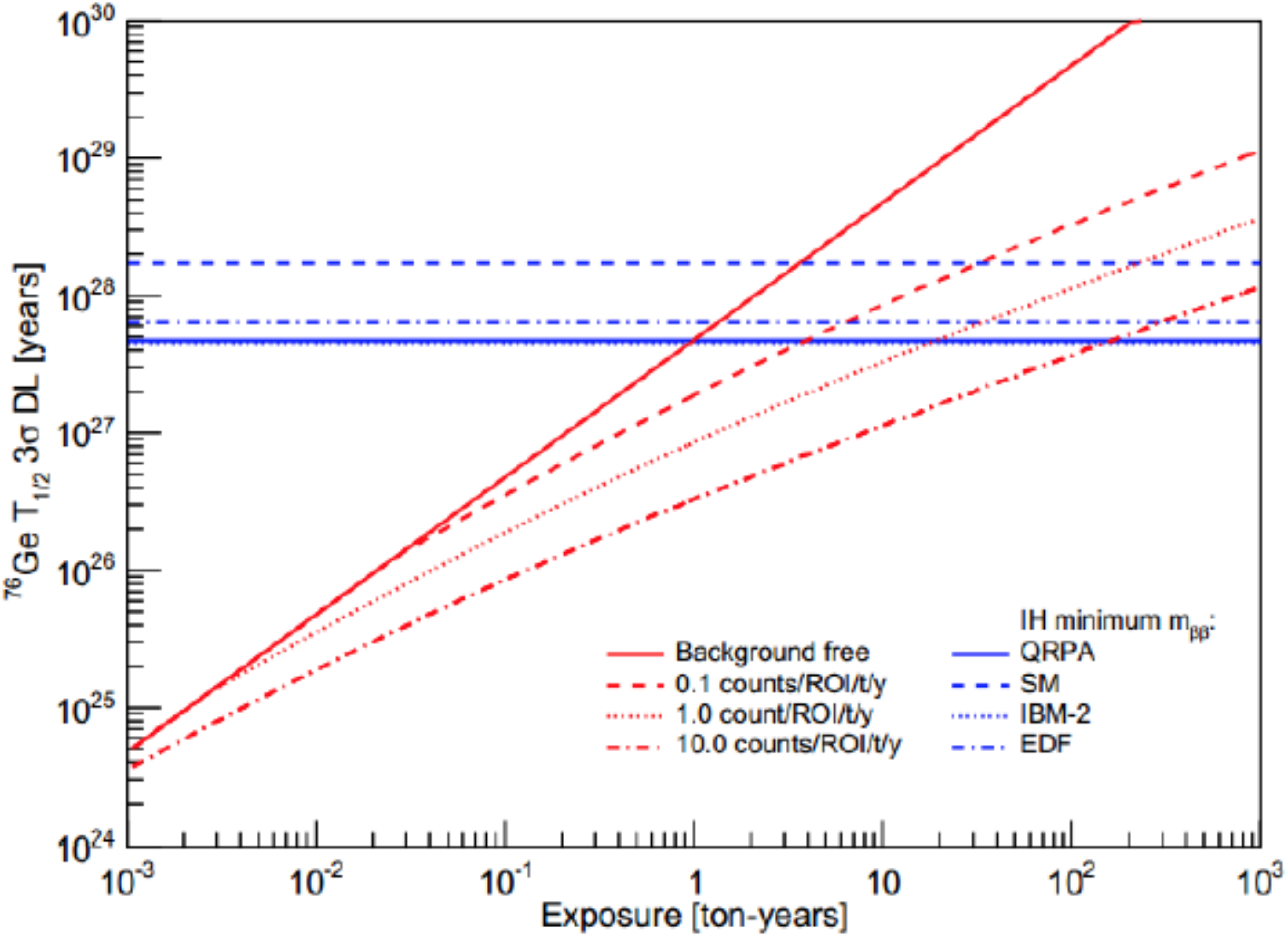
Sensitivity
GERDA Phase I

EXO sensitivity

GERDA Collaboration, Schönert, Neutrino 2014

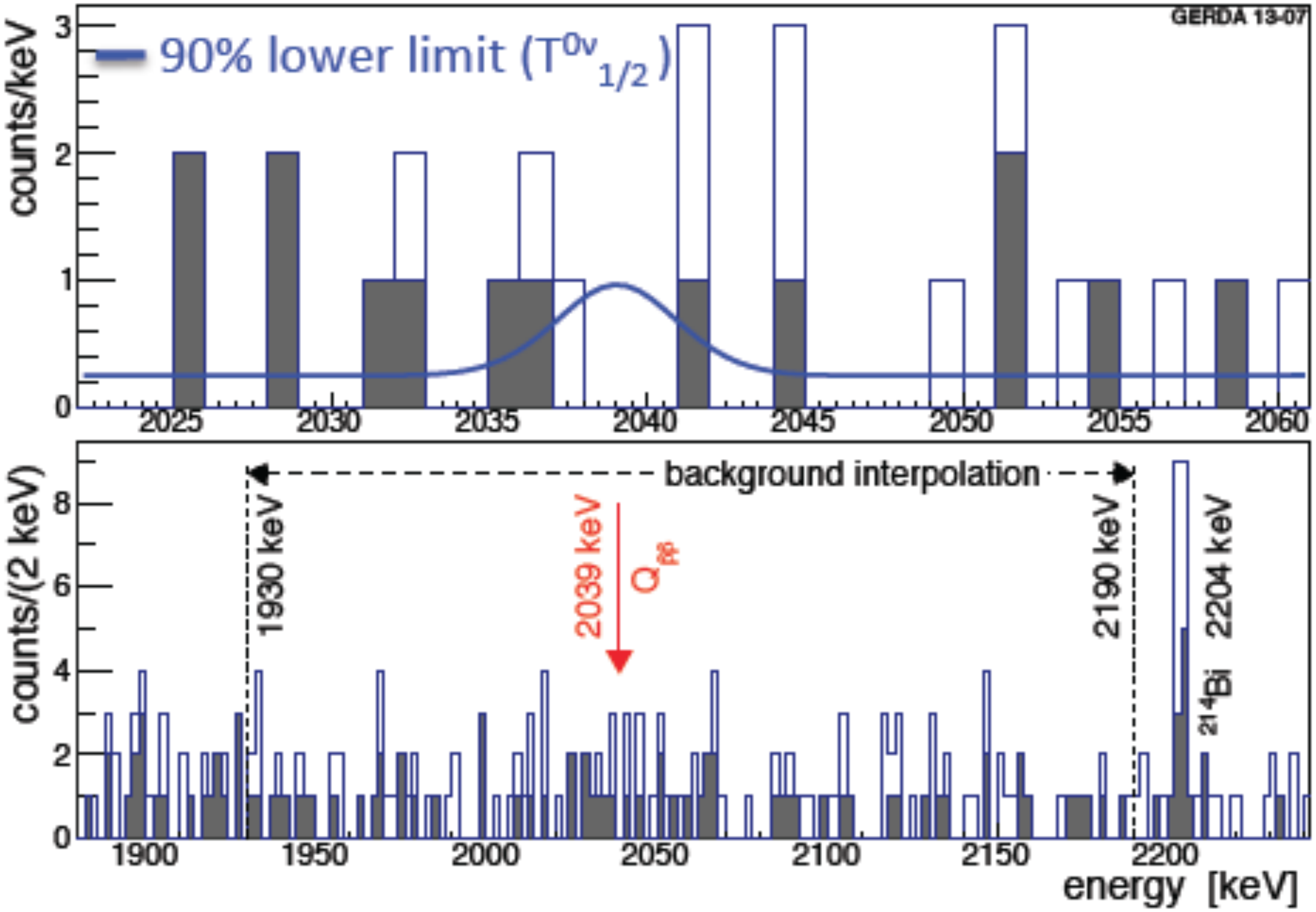
Discovery vs. Background (^{76}Ge)

J. Detwiler



What constitutes a discovery?

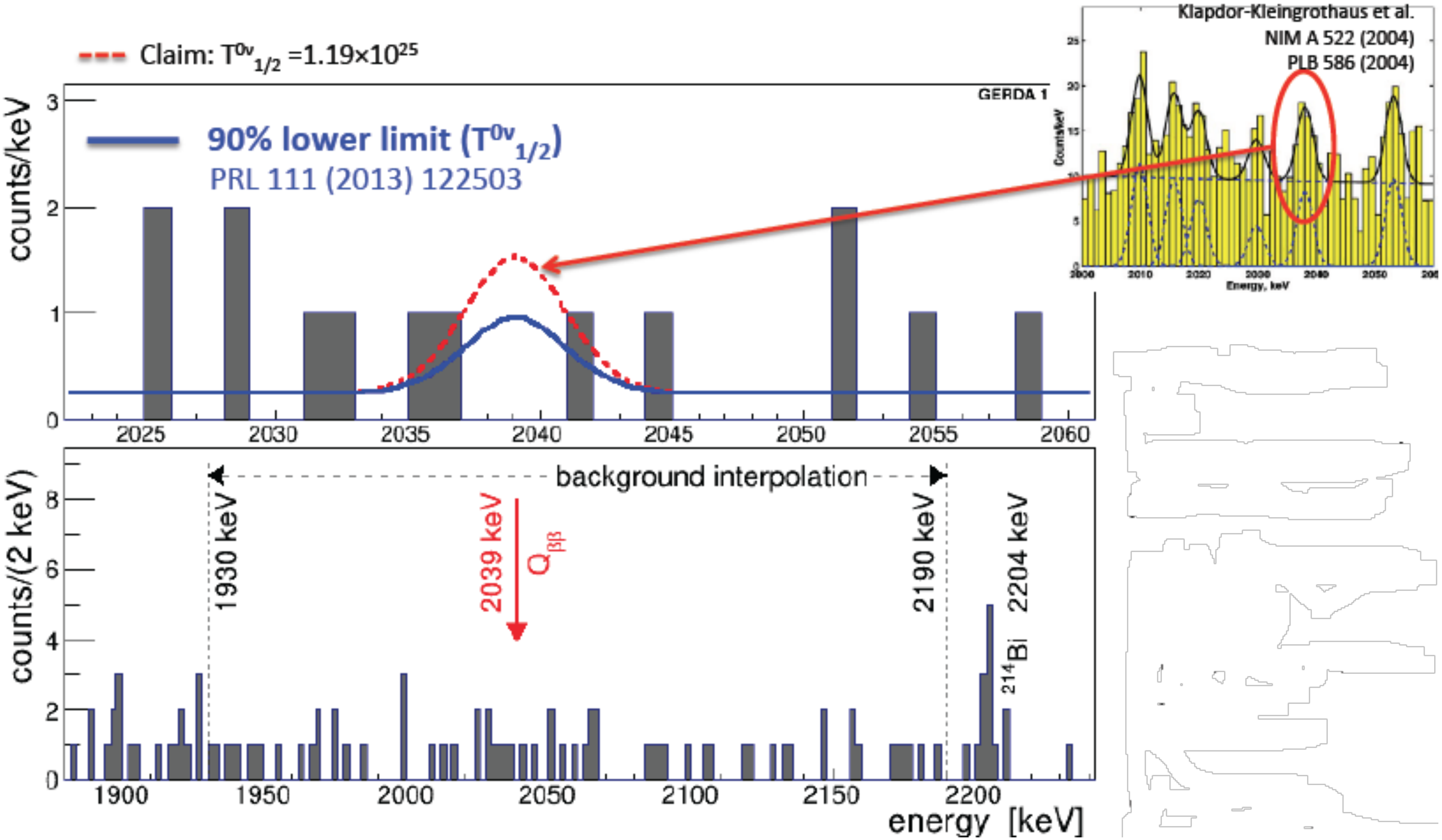
GERDA Phase I



GERDA Collaboration, Schönert, Neutrino 2014

What constitutes a discovery?

GERDA Phase I



GERDA Collaboration, Schönert, Neutrino 2014

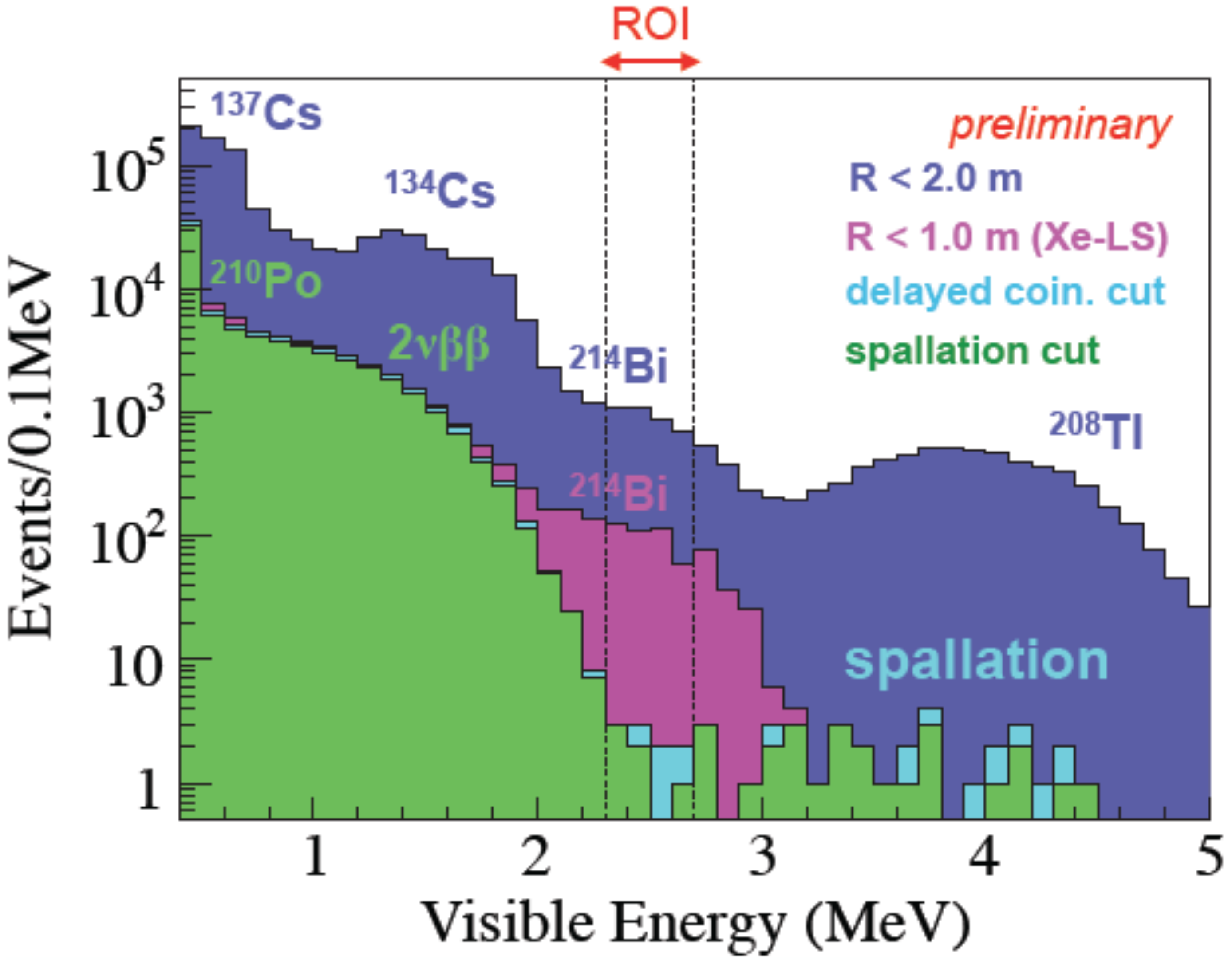
Discovery in the presence of backgrounds

KamLAND-ZEN (Neutrino 2014)

Phase 2 114.8 days

ββ isotope ^{136}Xe 90.77% enriched $Q_{\beta\beta}$ = 2458 keV

348 kg ^{136}Xe in all volume   Dec. 11, 2013 - May 1, 2014



number of event
in ROI
(2.3 < E < 2.7 MeV)

Dec. 11, 2013 - May. 1, 2014
around mini-balloon
(R < 2.0 m)
&
muon veto

3756 events

volume cut
R < 1.0 m
(V = 4.2 m^3)

413 events

delayed coincidence cut
(^{214}Bi-Po, ^{212}Bi-Po, anti-ν)

10 events

Spallation cut

6 events
(Livetime 114.8 days)

KamLAND ZEN Collaboration, Shimizu, Neutrino 2014

0νββ Large Scale Discovery Considerations

- Need large, highly efficient source mass
- Extremely low (zero?) backgrounds in the 0νββ peak region

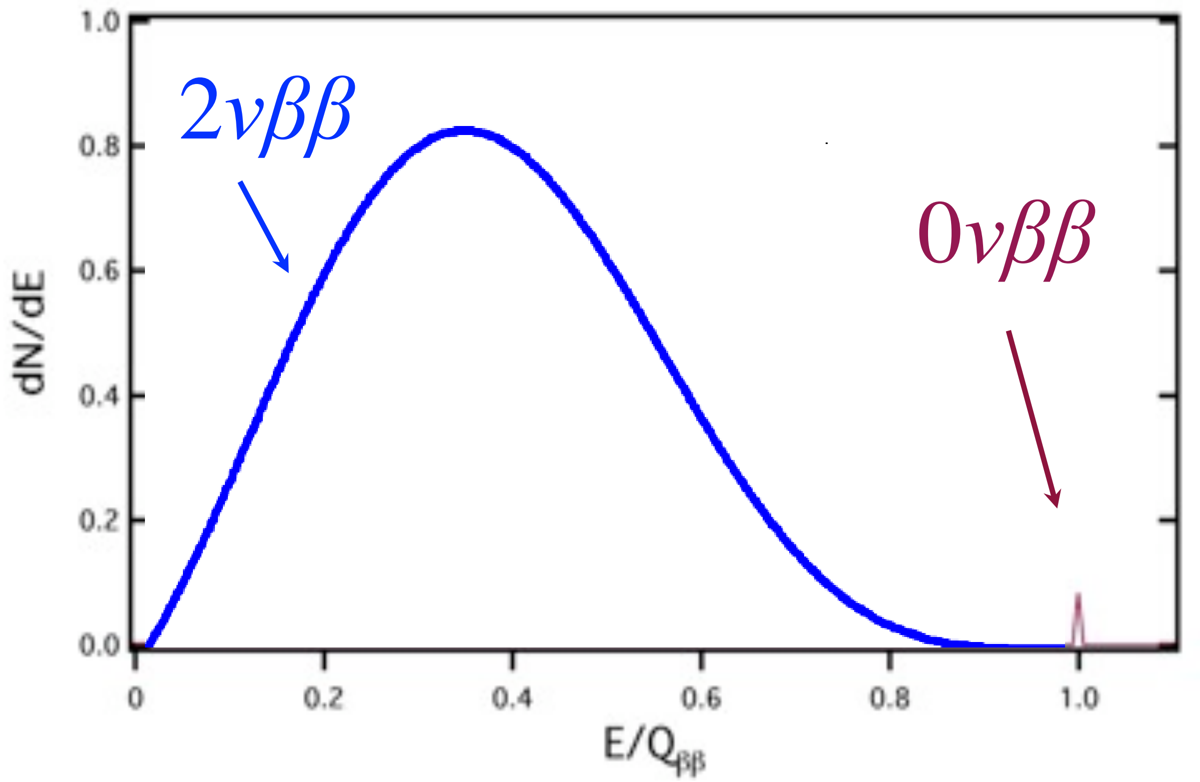
➡Signal background better than 1:1

  - For a tonne and $P_{Bkg} < 5\%$ in a year in the ROI ⇒ $5 \cdot 10^{-5}$ cnts/kg-y

Want best possible energy resolution and/or kinematical method to discriminate 0νββ from 2νββ.

➡Best possible resolution, ΔE, to minimize region of interest

  - No 2νββ at 5σ ⇒ ΔE/E < 1 %



Tonne scale experiments require backgrounds of ≤ 0.1 cts / ROI-t-y

Need independent observations from different isotopes

Discovery of 0νββ-decay

- Evidence : a combination of
  - Correct peak energy
  - Single-site or localized energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Good signal to background (3 σ discovery)
  - Full energy spectrum (backgrounds) understood.
- More direct confirmation : very difficult
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay(s)
- Convincing
  - Observe 0νββ in several different isotopes, using a variety of experimental techniques that meet the above definition of evidence

$0\nu\beta\beta$ signals, backgrounds, & sensitivity

- Expect signals of 1 count / tonne / year for half-lives of 10^{27} years ($<m_{\beta\beta}> \sim 15$ meV)
- For discovery need signal:backgrounds of better than 1:1 in region of interest.
- Region of interest directly determined by detector resolution.
- Best S:B to date is ~40 counts/tonne/year in ROI (GERDA Phase 1).

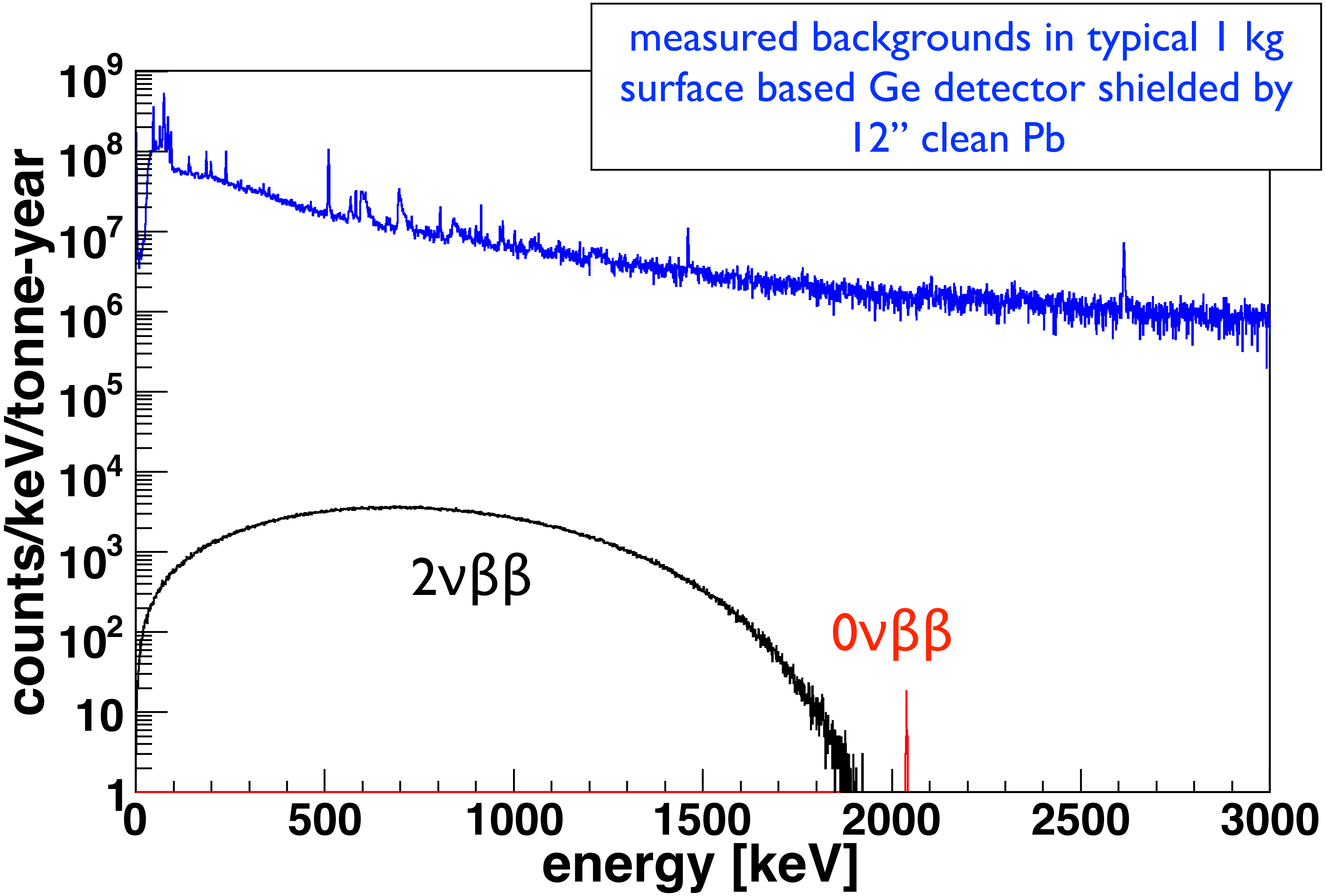
Lecture Outline

- 0νββ Sensitivity Considerations
- Backgrounds
- Experiments and Measurement Techniques

Potential contributions to the background

- Primordial, natural radioactivity in the detector and array components: U, Th, K:
- Backgrounds from cosmogenic activation while material is above ground: ββ-decay or shield specific, ^{60}Co, ^{3}H...
- Backgrounds from the surrounding environment:
  external γ, (α,n), (n,α), Rn plate-out, etc.
- μ-induced backgrounds generated at depth:
  Cu,Pb(n,n' γ), ββ-decay specific(n,n),(n,γ), direct μ
- 2 neutrino double beta decay (irreducible)
- neutrino backgrounds (negligible)

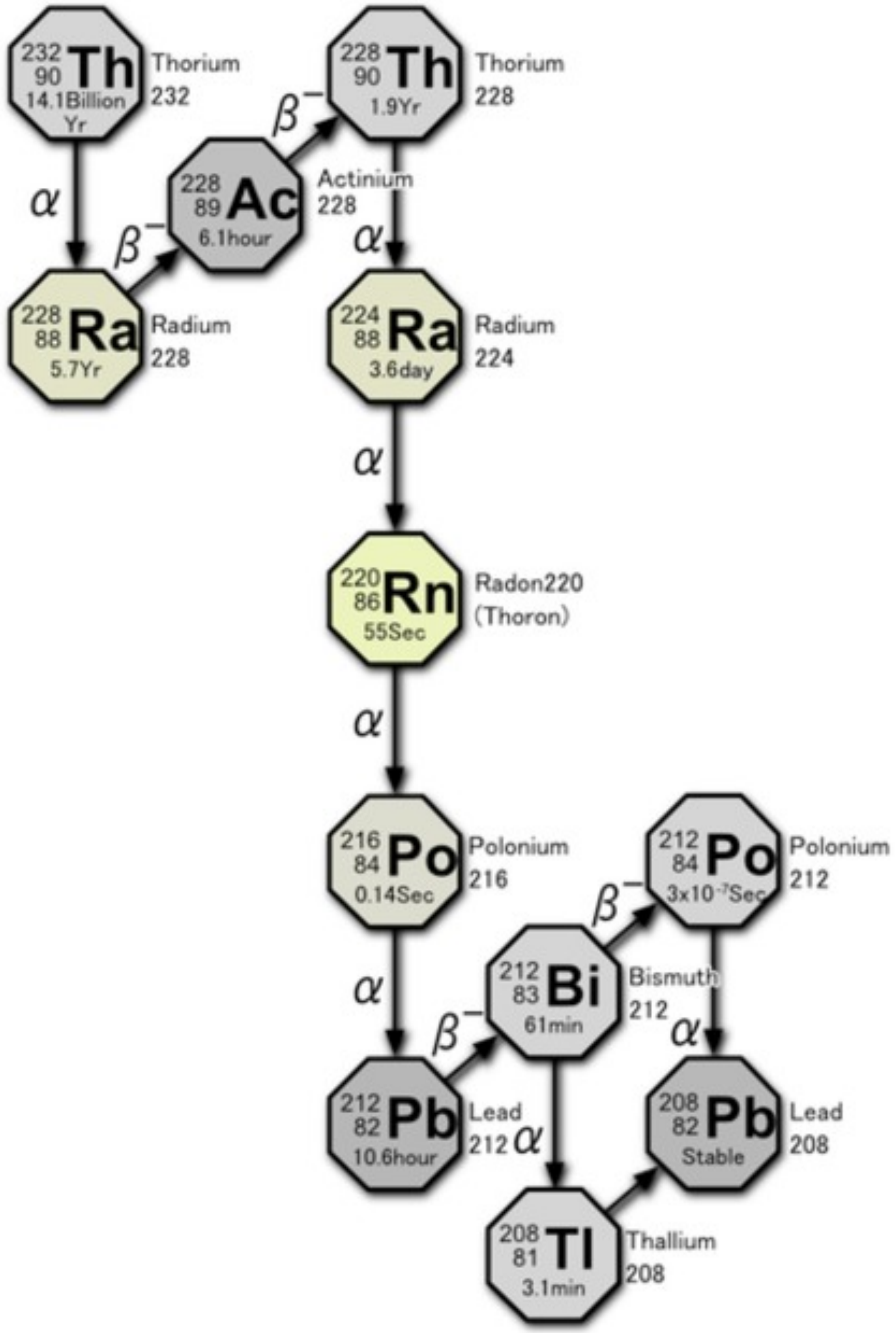
1ct/tonne-year in context - Ge example

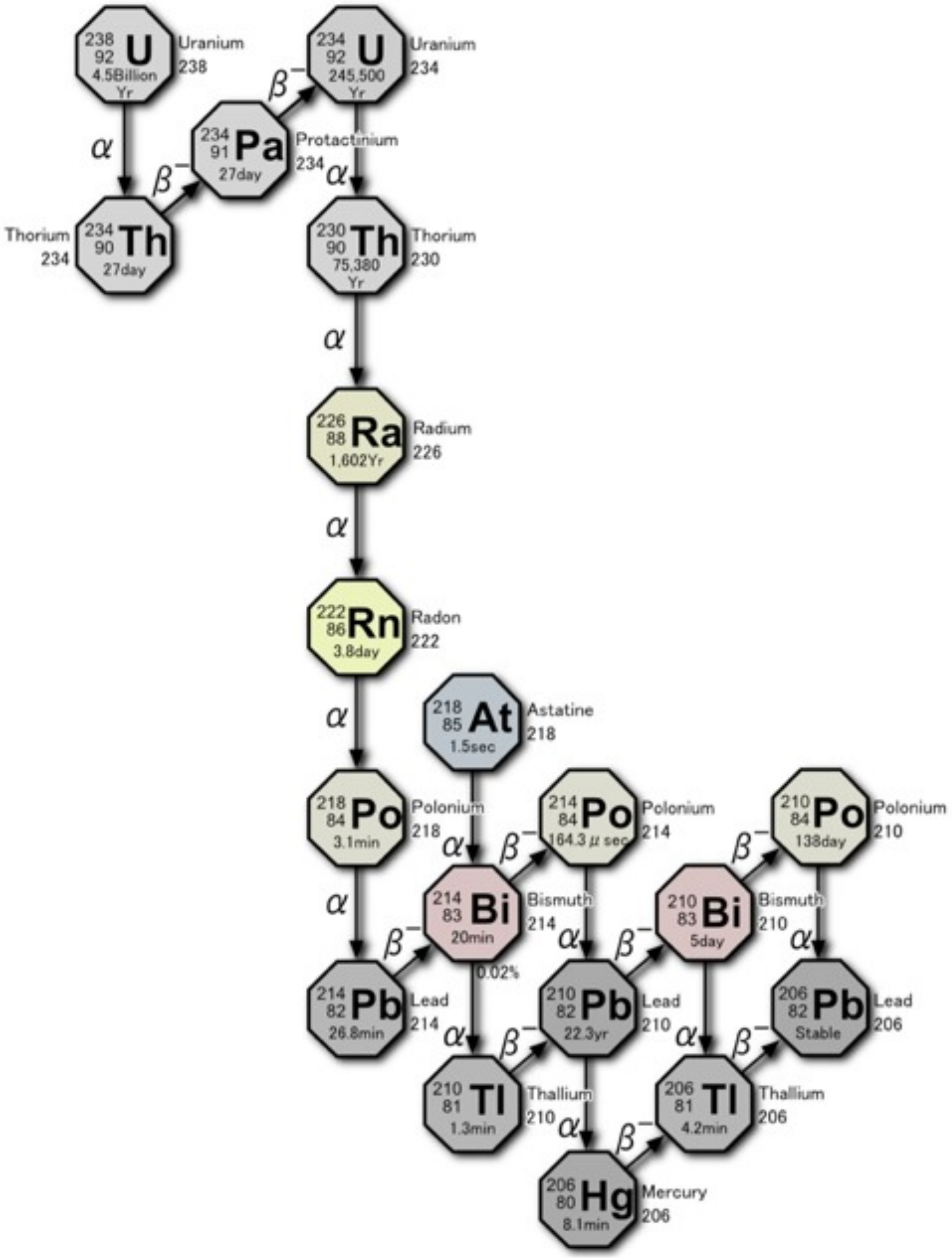


A. Schubert

For illustrative purposes 0νββ half-life chosen to be 10x current limit

Naturally occurring backgrounds





Reducing Backgrounds - Two Basic Strategies

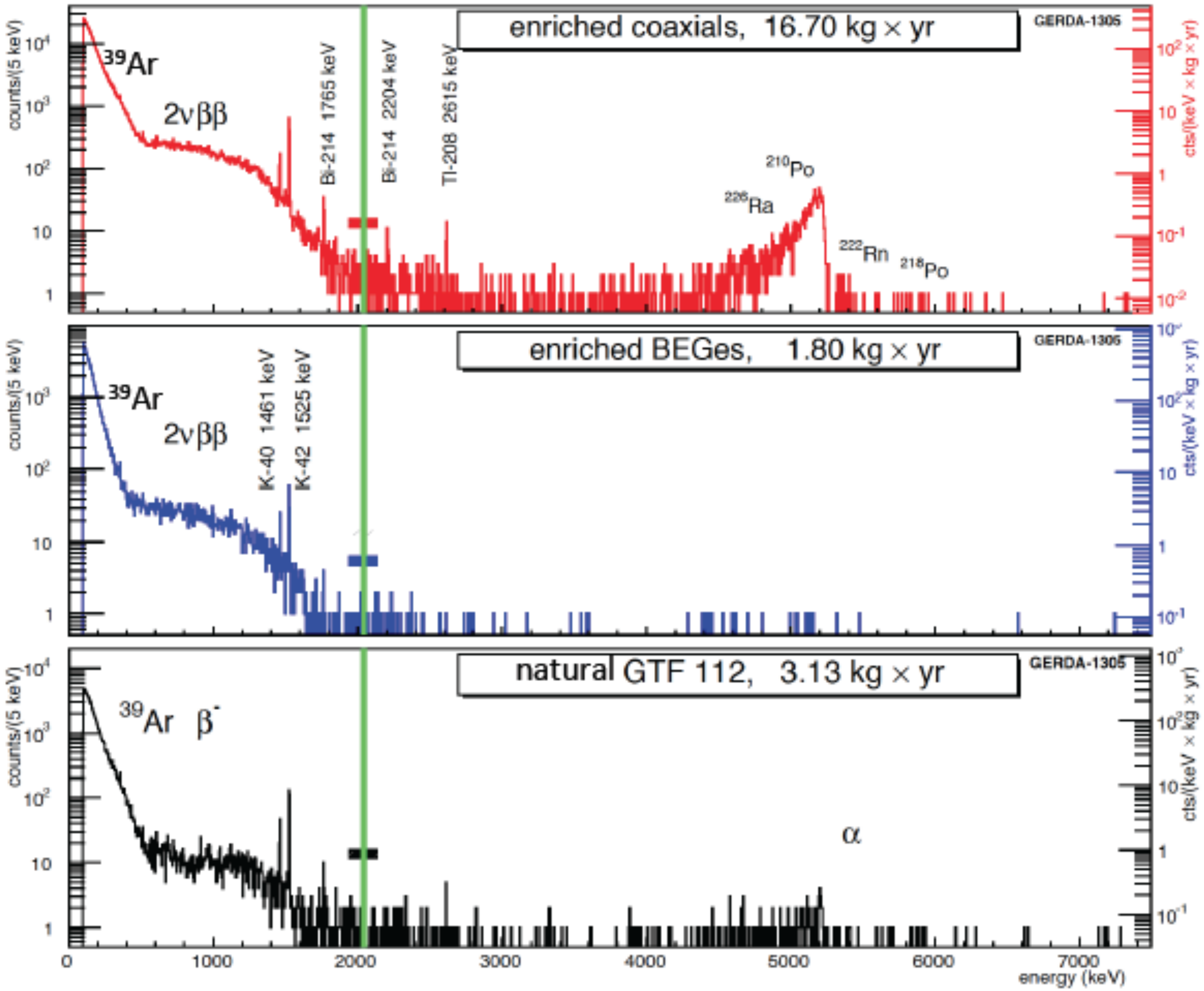
- Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non "source" materials
  - Clean passive shield
  - Fabricate ultra-clean materials underground
  - Go deep — reduced μ's & related induced activities
- Utilize background discrimination techniques

0νββ is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions

- Energy resolution
- Active veto detector
- Tracking (topology)
- Energy & Angular correlations
- Ion Identification
- Fiducial Cuts (inefficient use of isotope)
- -- Granularity [multiple detectors]
- Pulse shape discrimination (PSD)
- Segmentation
- Single Site Time Correlated events (SSTC)

GERDA Phase 1 Backgrounds

GERDA Collaboration, Phase 1, Eur. Phys. J. C (2014) **74**:2764



GERDA Phase 1 Backgrounds

GERDA Collaboration, Phase 1, Eur. Phys. J. C (2014) **74**:2764

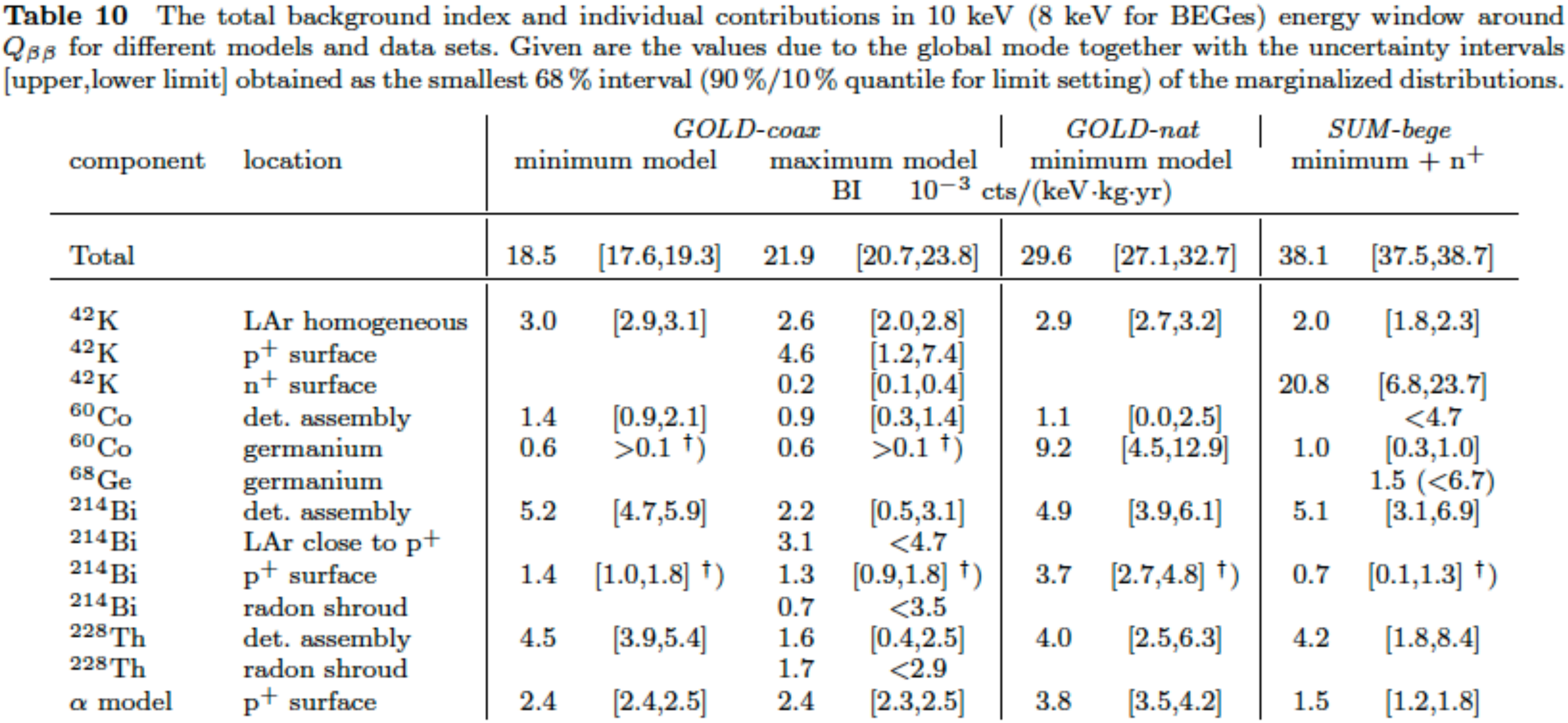
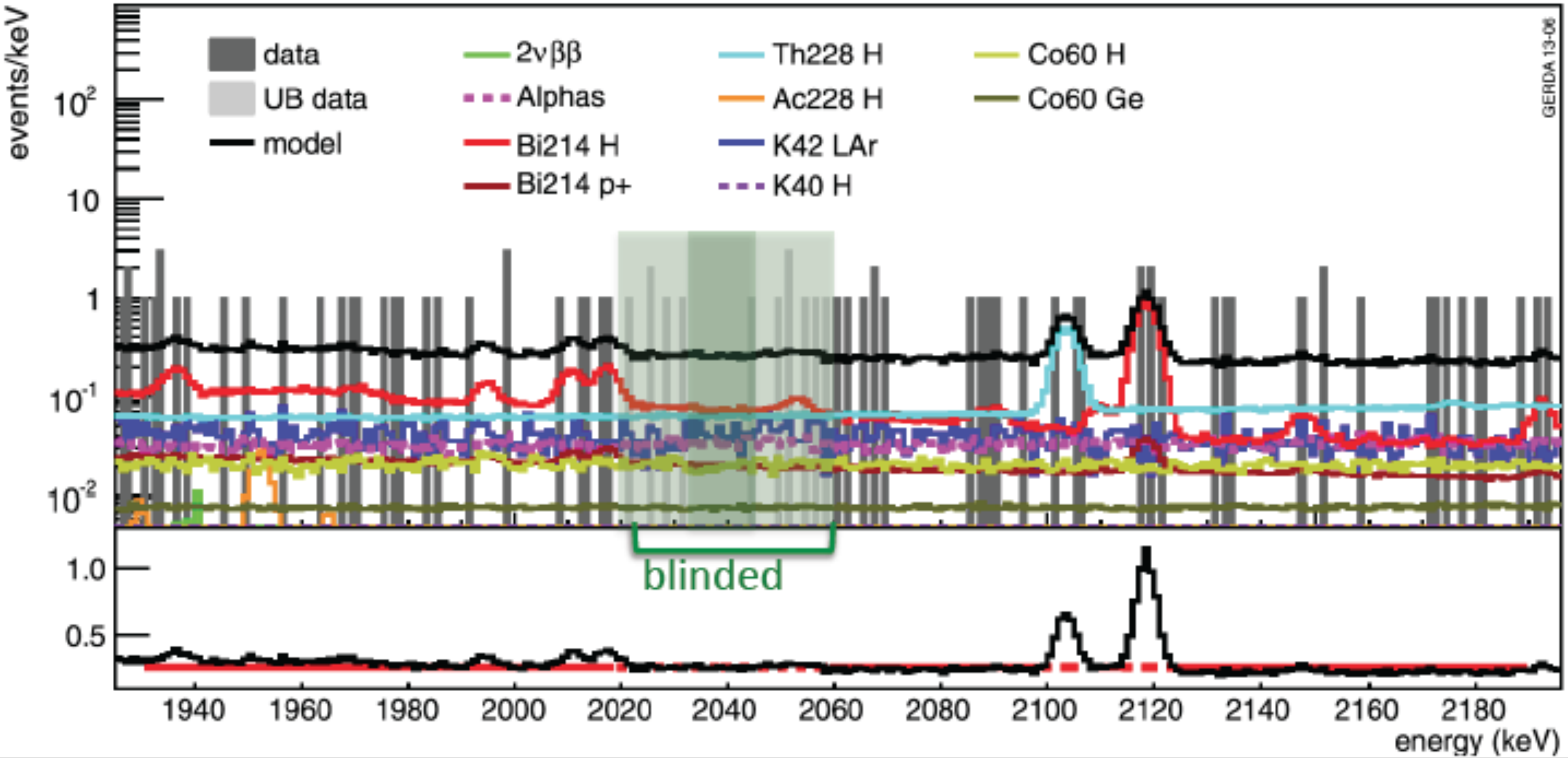


Table 10 The total background index and individual contributions in 10 keV (8 keV for BEGes) energy window around $Q_{\beta\beta}$ for different models and data sets. Given are the values due to the global mode together with the uncertainty intervals [upper,lower limit] obtained as the smallest 68 % interval (90 %/10 % quantile for limit setting) of the marginalized distributions.

component	location	*GOLD-coax*				*GOLD-nat*		*SUM-bege*	
		minimum model		maximum model		minimum model		minimum + n^+	
		BI 10^{-3} cts/(keV·kg·yr)							
Total		18.5	[17.6,19.3]	21.9	[20.7,23.8]	29.6	[27.1,32.7]	38.1	[37.5,38.7]
^{42}K	LAr homogeneous	3.0	[2.9,3.1]	2.6	[2.0,2.8]	2.9	[2.7,3.2]	2.0	[1.8,2.3]
^{42}K	p^+ surface			4.6	[1.2,7.4]				
^{42}K	n^+ surface			0.2	[0.1,0.4]			20.8	[6.8,23.7]
^{60}Co	det. assembly	1.4	[0.9,2.1]	0.9	[0.3,1.4]	1.1	[0.0,2.5]		<4.7
^{60}Co	germanium	0.6	>0.1 †)	0.6	>0.1 †)	9.2	[4.5,12.9]	1.0	[0.3,1.0]
^{68}Ge	germanium								1.5 (<6.7)
^{214}Bi	det. assembly	5.2	[4.7,5.9]	2.2	[0.5,3.1]	4.9	[3.9,6.1]	5.1	[3.1,6.9]
^{214}Bi	LAr close to p^+			3.1	<4.7				
^{214}Bi	p^+ surface	1.4	[1.0,1.8] †)	1.3	[0.9,1.8] †)	3.7	[2.7,4.8] †)	0.7	[0.1,1.3] †)
^{214}Bi	radon shroud			0.7	<3.5				
^{228}Th	det. assembly	4.5	[3.9,5.4]	1.6	[0.4,2.5]	4.0	[2.5,6.3]	4.2	[1.8,8.4]
^{228}Th	radon shroud			1.7	<2.9				
α model	p^+ surface	2.4	[2.4,2.5]	2.4	[2.3,2.5]	3.8	[3.5,4.2]	1.5	[1.2,1.8]

GERDA Phase 1

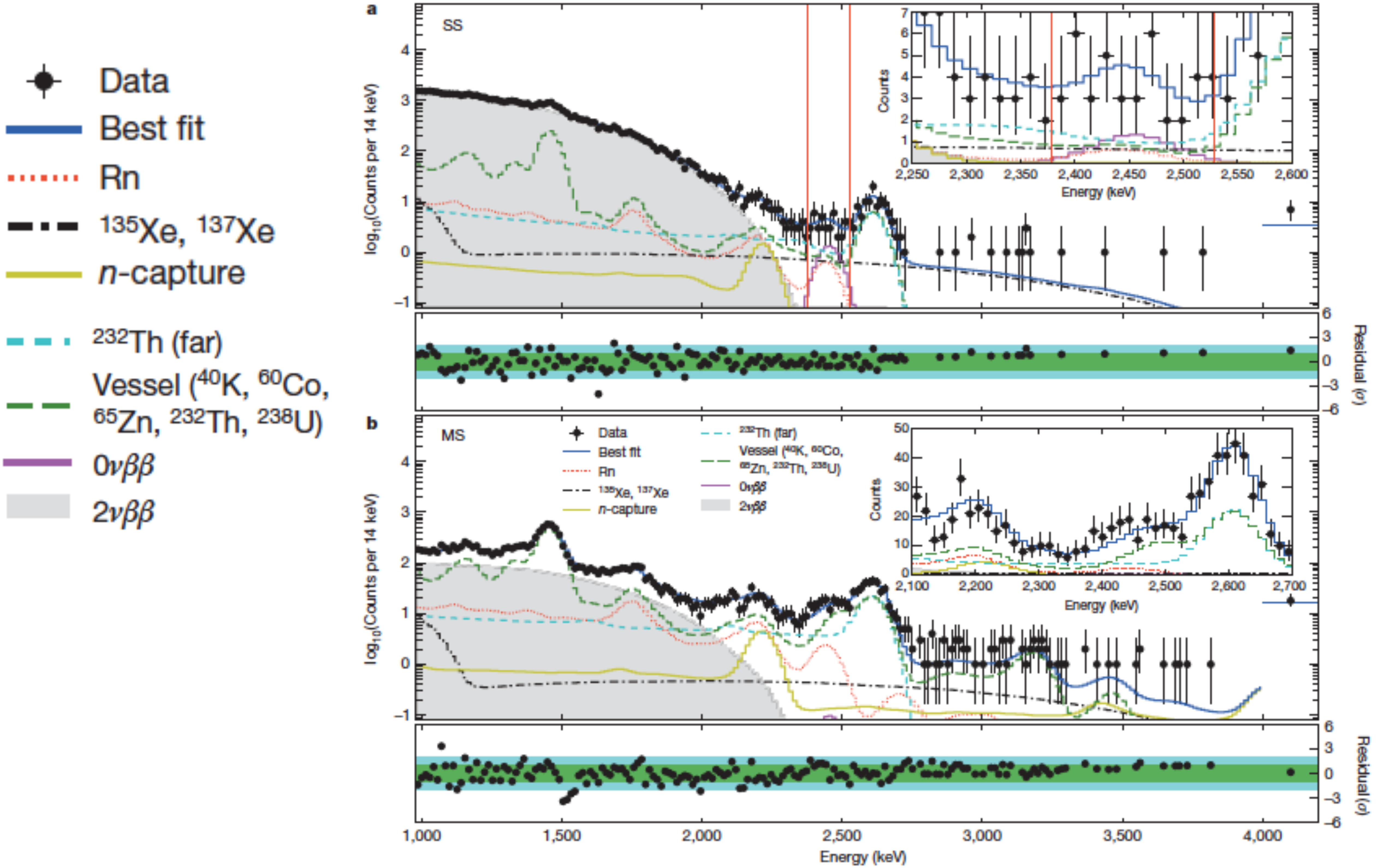


- **No background peaks** expected around $Q_{\beta\beta}$ expected
- BI at $Q_{\beta\beta}$ **(17.6-23.8) x 10^{-3} cts/(keV kg yr)** depending on assumptions for location of sources
- Spectrum can be modeled with **flat background** (red line) in 1930-2190 keV excluding known peaks at 2104 and 2119 keV
- **Statistical uncertainty** of BI from interpolation **coincides** numerically **with systematic** uncertainty from model
- Prediction for 30 keV blinded side wings: Min./Max Mod: 8.2-9.1 / 9.7-11.1 observed.: 13

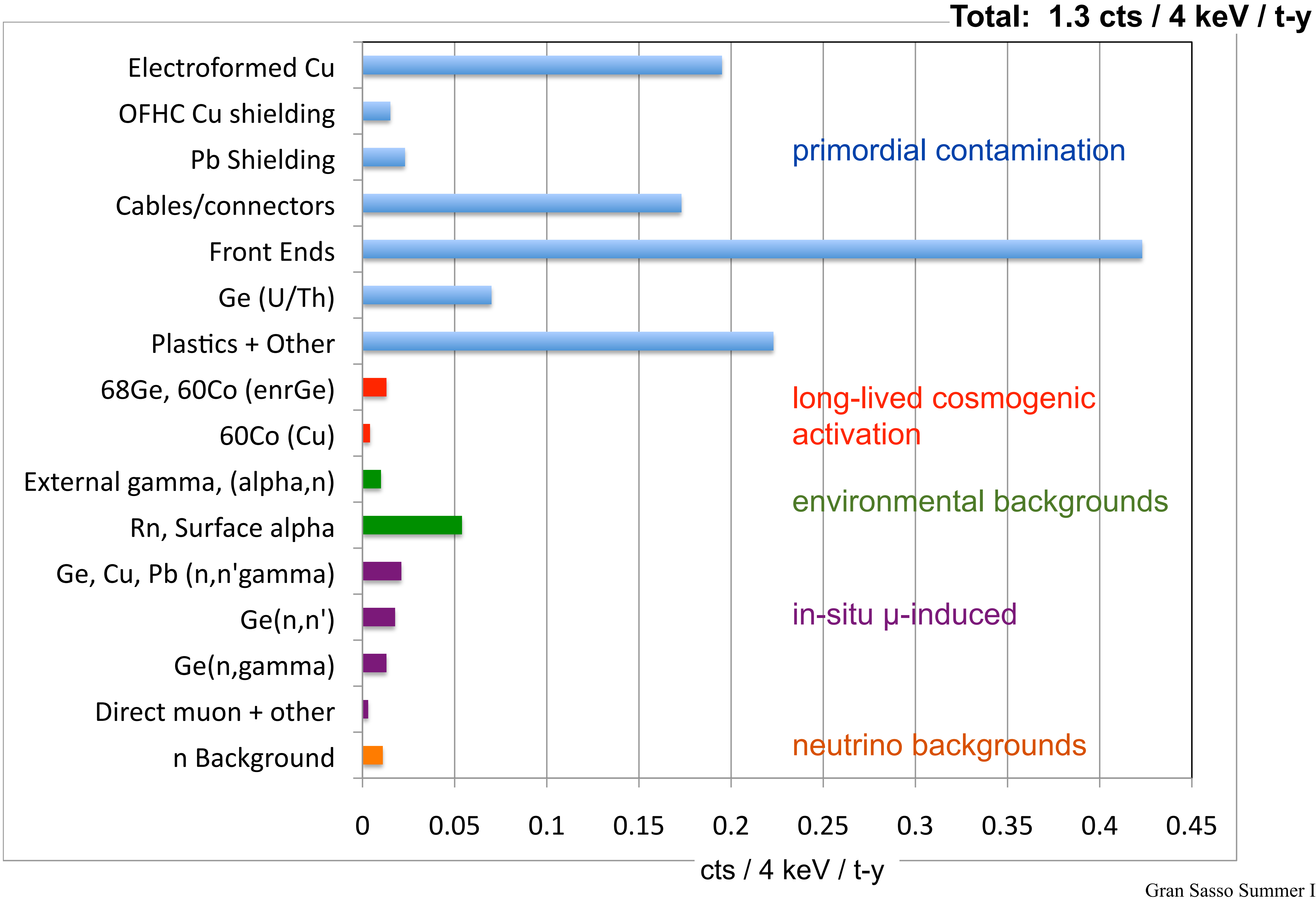
GERDA Collaboration, Schönert, Neutrino 2014

EXO-200 Backgrounds

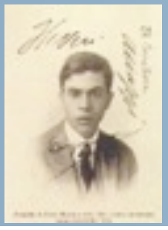
EXO-200 Collaboration, Nature **510** 229 (2014)



LSGe Background Budget Goal



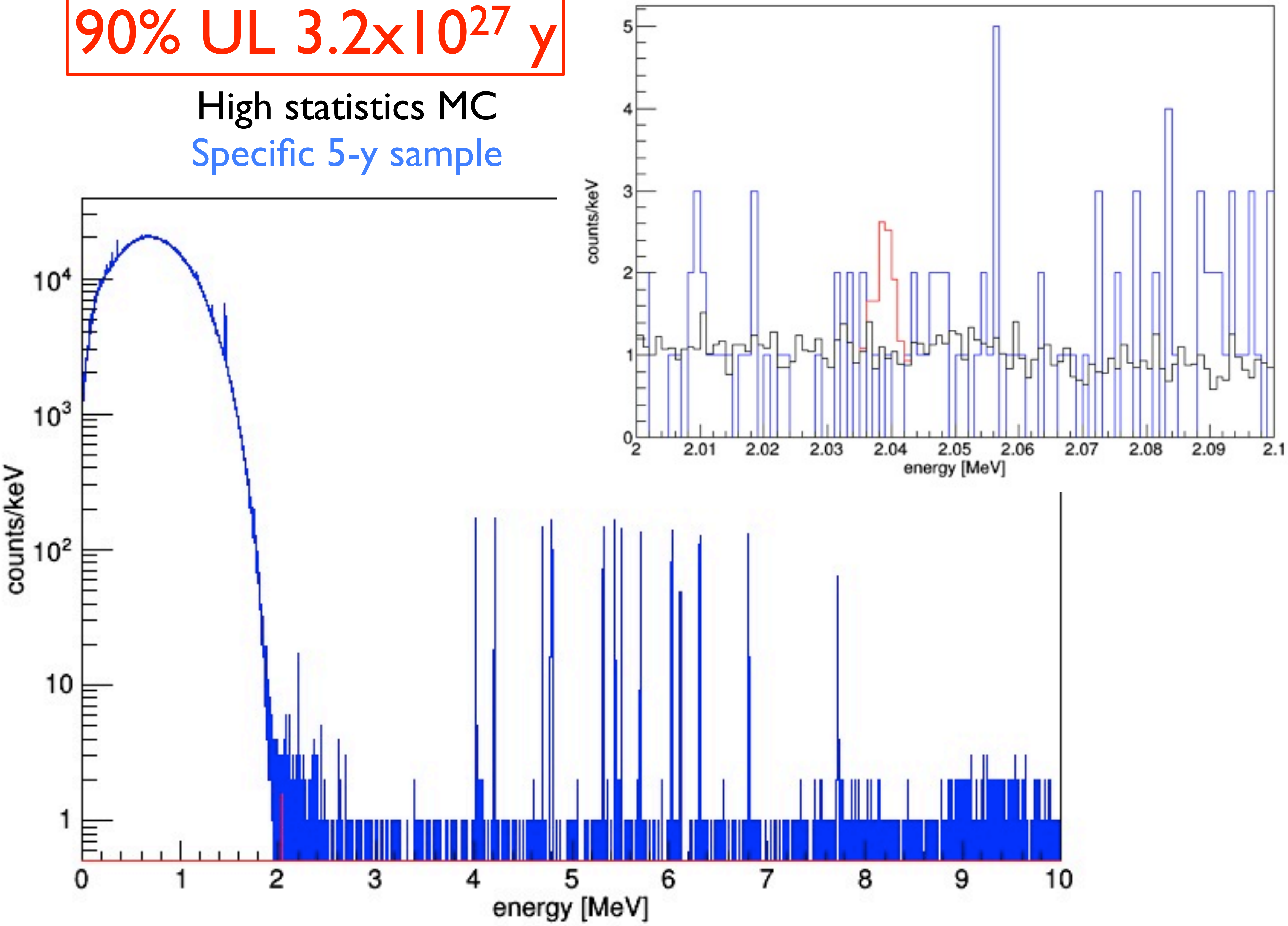
LSGe Simulated Spectrum - 5 t-y Exposure



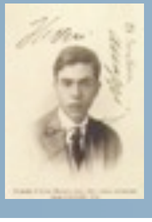
90% UL 3.2×10^{27} y

High statistics MC

Specific 5-y sample



Ultra-clean electroformed Cu

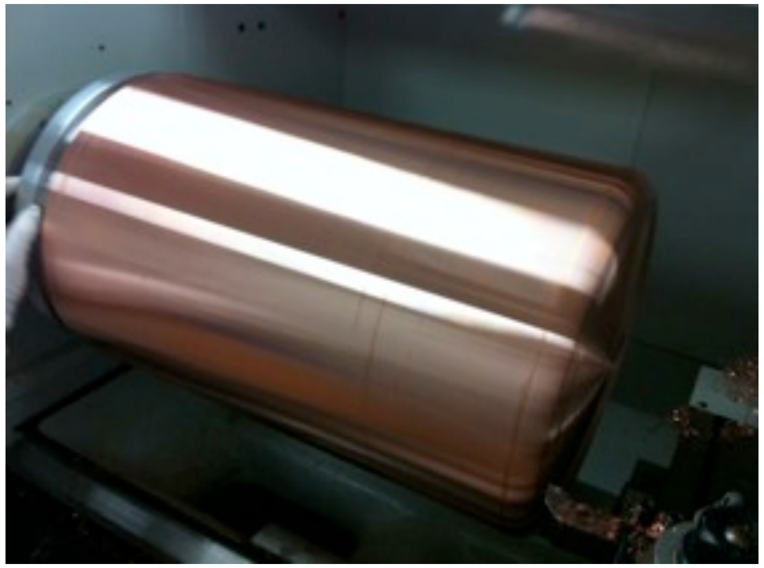


- MJD operates 10 baths at the Temporary Clean Room (TCR) facility at the 4850’ level and 6 baths at a shallow UG site at PNNL. All copper is machined at the MJD Davis campus.

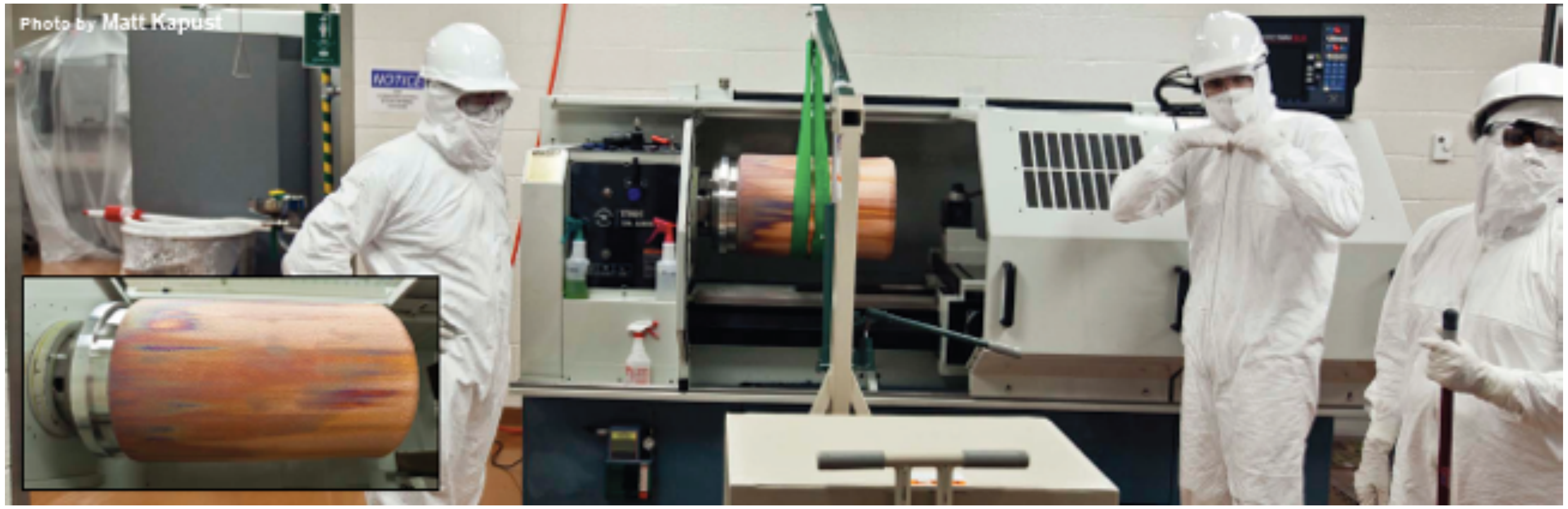
Electroforming Baths in TCR

Inspection of EF copper on mandrels

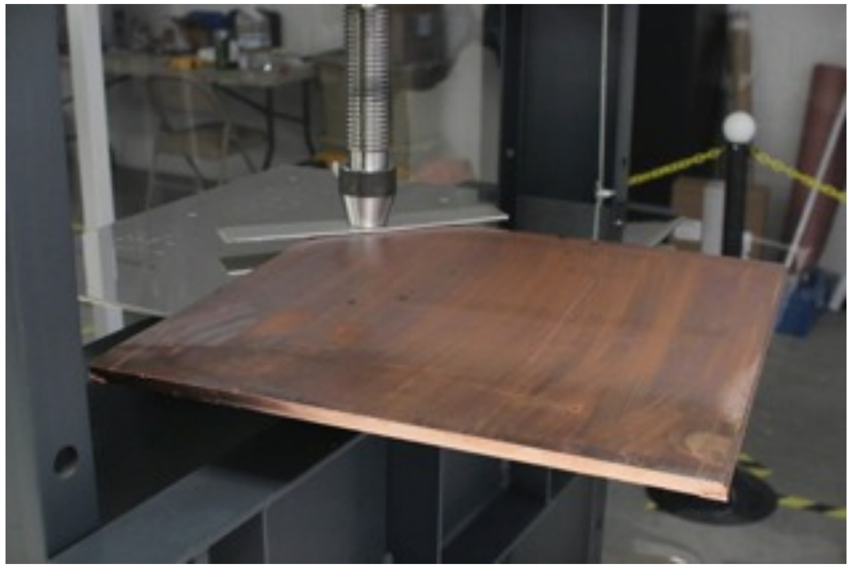
EF copper after turning on lathe



Preparing to machine electroformed copper mandrel in the clean machine shop, MJD Davis Campus, 4850’



Flattened plate



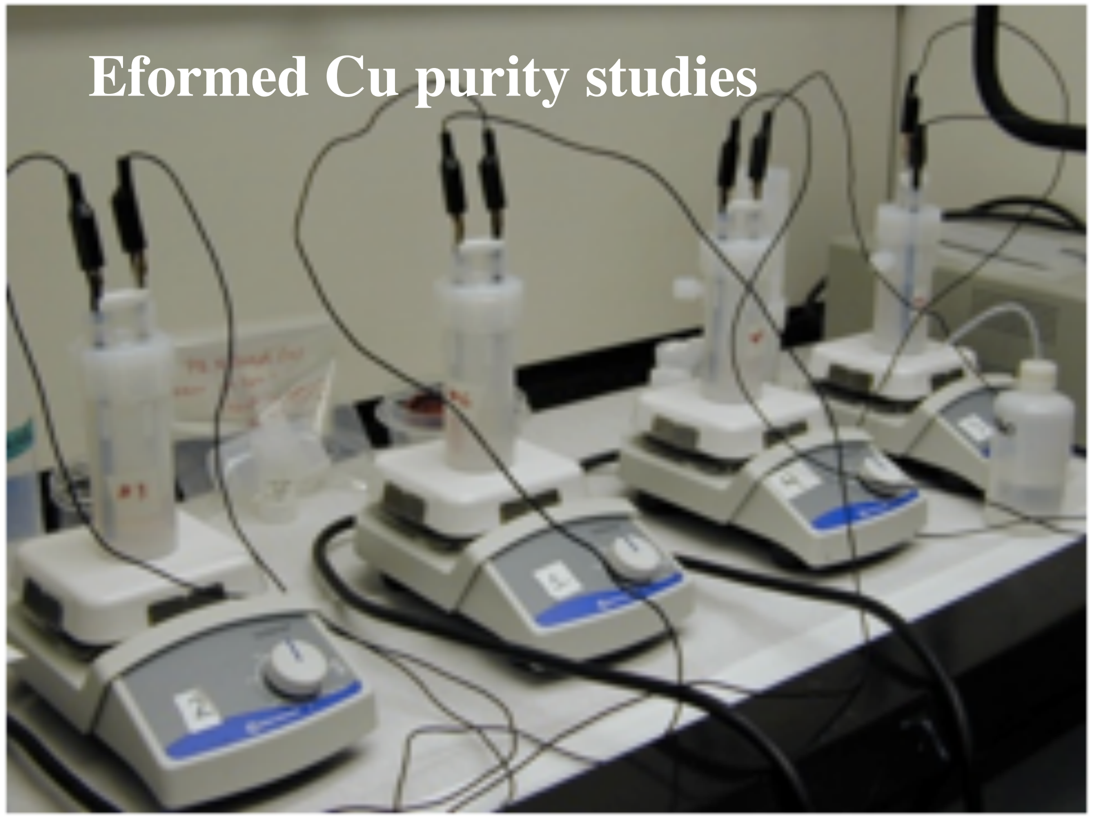
- Th decay chain 0.06 ± 0.02 μBq/kg (0.15 counts in ROI)
- U decay chain 0.17 ± 0.03 μBq/kg (0.08 counts in ROI)

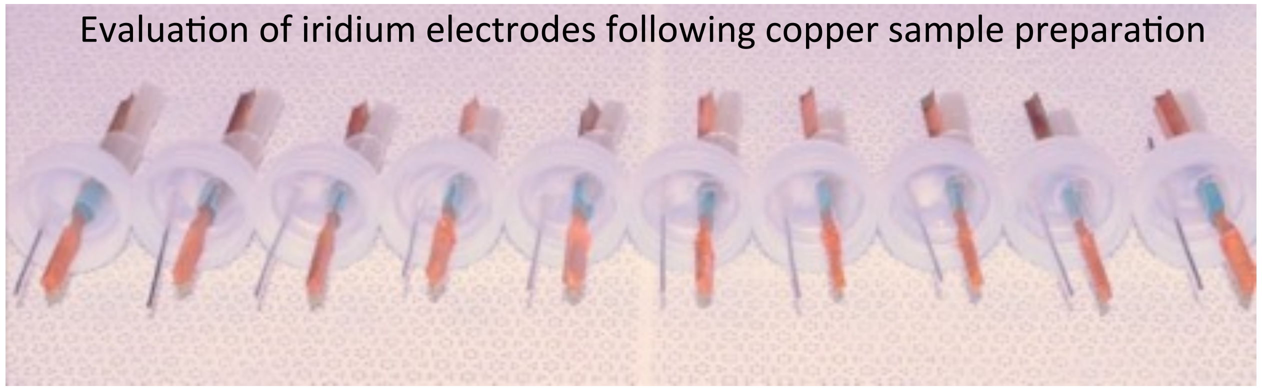
Ultra-sensitive Materials Assay

- MJD developed world's most sensitive ICP-MS based assay techniques for U and Th in Cu

  (Original Goal : <0.3 μBq/kg for U and Th)

- Current MDL (method detection limits) with iridium anode improvements
  - U decay chain 0.1 μBq ^{238}U/kg
  - Th decay chain 0.1 μBq ^{232}Th/kg
- Sensitivities with ion exchange copper sample preparation
  - U decay chain <0.10 μBq ^{238}U/kg
  - Th decay chain <0.06 μBq ^{232}Th/kg





Backgrounds & 0νββ

Next generation experiments should strive for backgrounds in the 0νββ region of interest at the level of **≤ 0.1 counts/tonne-year**.

- Requires materials with sub μBq/kg level radioimpurities.
  - Cannot achieve this sensitivity with direct radioassays
- Shielding from cosmogenic activation, even during the fabrication stage.
- "New background regime" -- background sources that could previously be ignored
  - e.g. : very weak (n,n',gamma) lines

Each experiment's susceptibility to backgrounds depends on a number of factors:

- $Q_{\beta\beta}$ of the isotope being studied
- Detector resolution
- Detection technique (Solid state, TPC, bolometer, ...)
- Detector response function to backgrounds (γ, α, β, neutron, ...)
- Construction materials and surrounding materials
- Signal to background discrimination capabilities

Lecture Outline

- 0νββ Sensitivity Considerations
- Backgrounds
- Experiments and Measurement Techniques

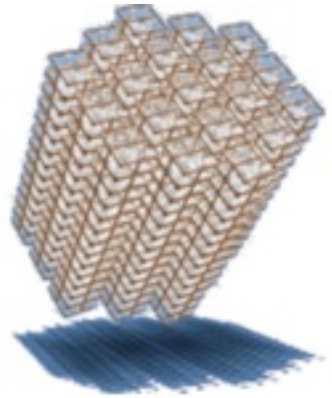
“Ideal” Experiment

- Source serves as the detector
- Elemental (enriched) source to minimize active material.
- Large $Q_{\beta\beta}$ value - faster 0 rate and also places the region of interest above many potential backgrounds.
- Relatively slow $2\nu\beta\beta$ rate helps control this irreducible background.
- Spatial resolution and timing information to reject background processes.
- Demonstrated technology at the appropriate scale.
- Direct identification of the decay progeny in coincidence with the $0\nu\beta\beta$ decay eliminates all potential backgrounds *except* $2\nu\beta\beta$.
- Full Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use $2\nu\beta\beta$)

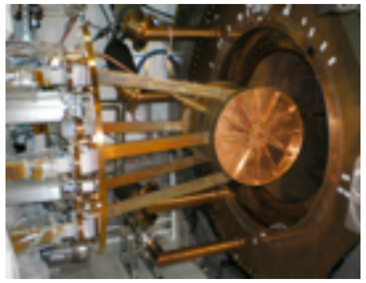
No one ideal isotope or experimental technique

0νββ decay Experiments - Efforts Underway

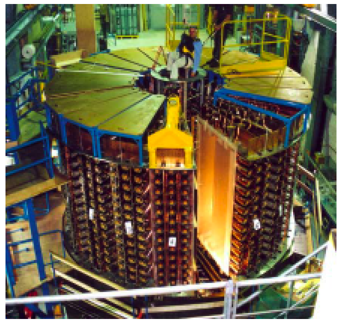
CUORE



EXO200



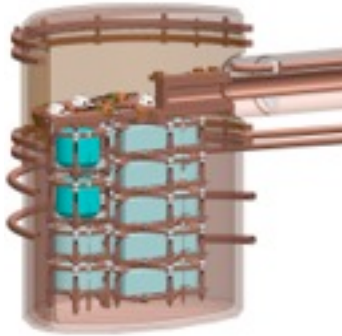
NEMO



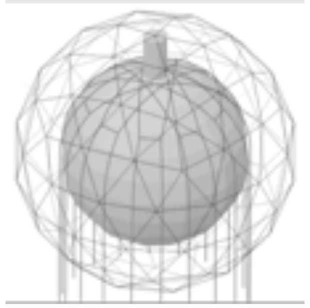
Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF$_2$ crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	^{48}CaWO$_4$ crystal scint.	~ tonne	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
II		Point contact Ge in LAr	30-35 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	30 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	CaMoO4 scint. bolometer	50 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
COBRA	Cd-116	CdZnTe detectors	10 kg 183 kg	R&D
CUORICINO	Te-130	TeO$_2$ Bolometer	10 kg	Complete
CUORE-0	Te-130	TeO$_2$ Bolometer	11 kg	Operating
CUORE	Te-130	TeO$_2$ Bolometer	206 kg	Construction
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	380 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	Construction
EXO200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	~ tonne	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

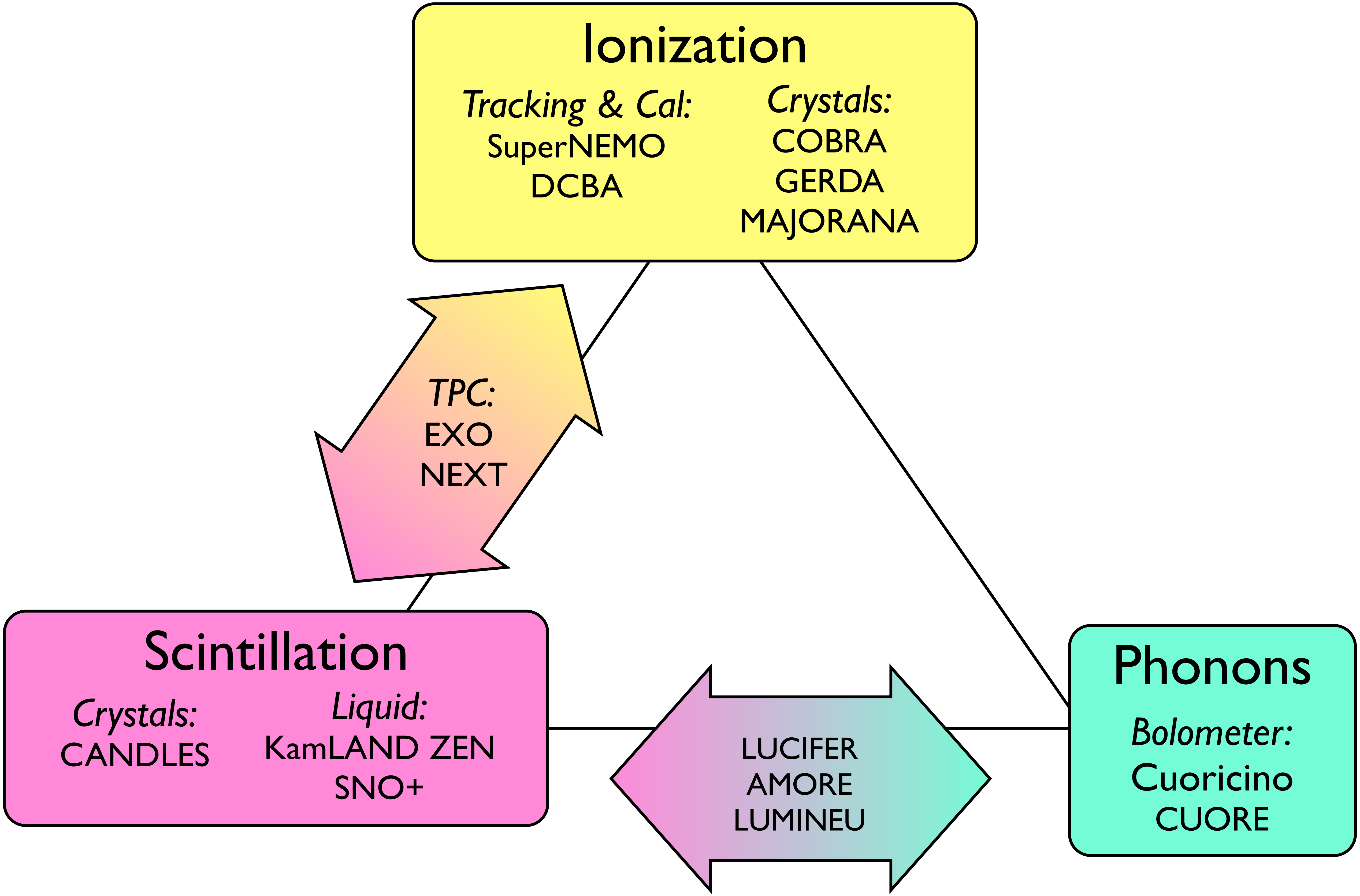
MAJORANA



SNO+



0νββ Detection Techniques



Ionization

Tracking & Cal:
SuperNEMO
DCBA

Crystals:
COBRA
GERDA
MAJORANA

TPC:
EXO
NEXT

Scintillation

Crystals:
CANDLES

Liquid:
KamLAND ZEN
SNO+

LUCIFER
AMORE
LUMINEU

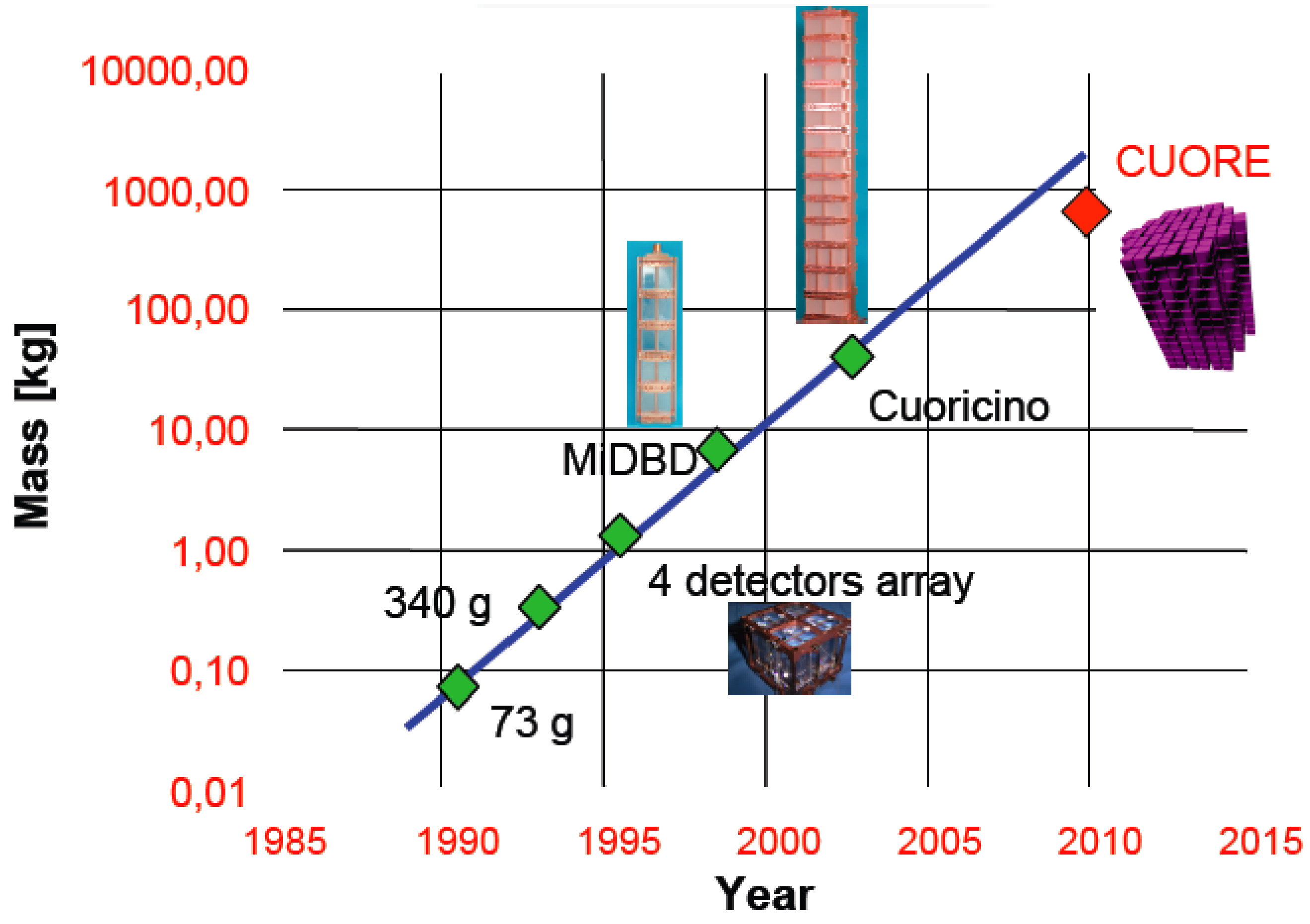
Phonons

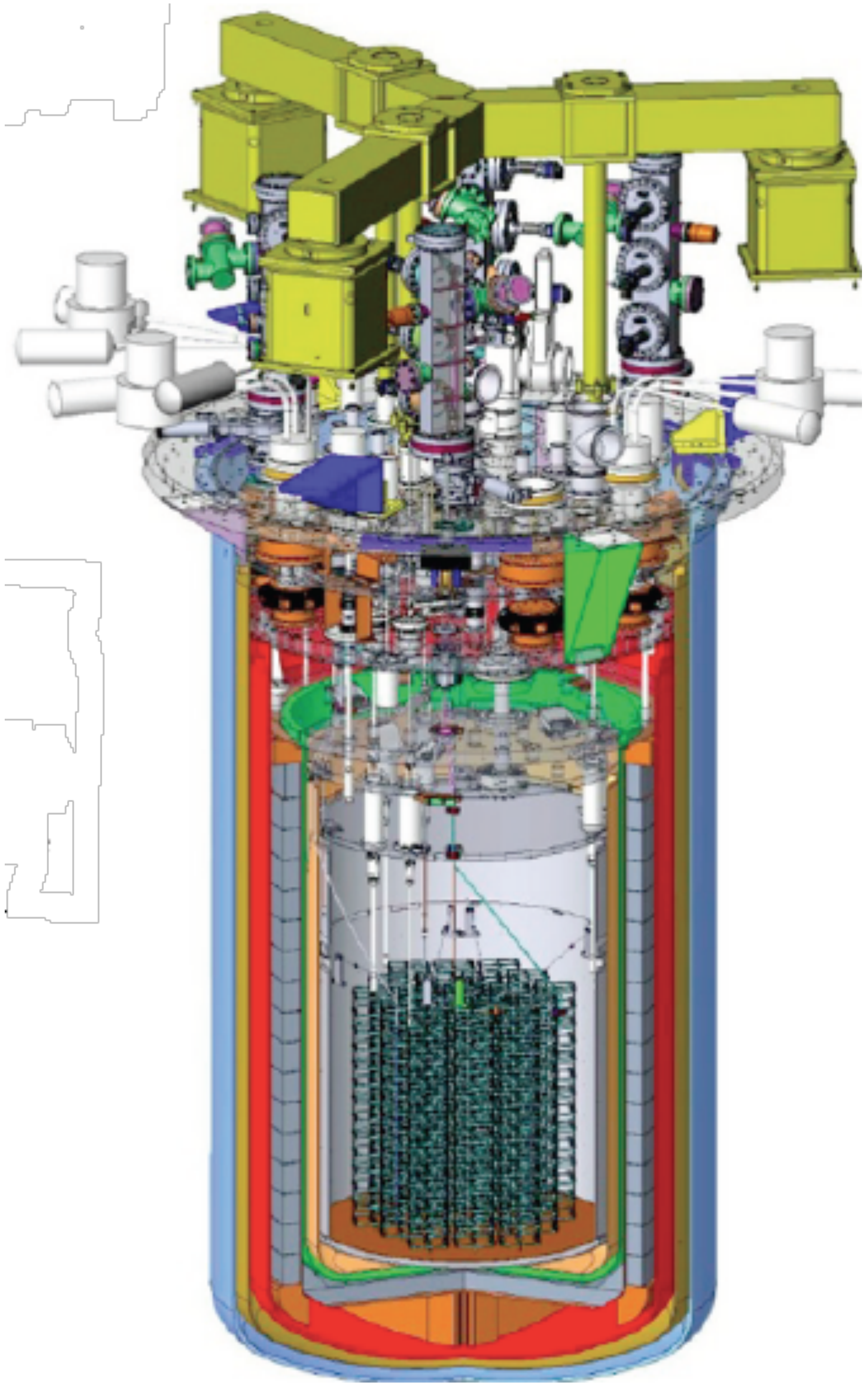
Bolometer:
Cuoricino
CUORE

CUORE ^{130}Te

Phonons

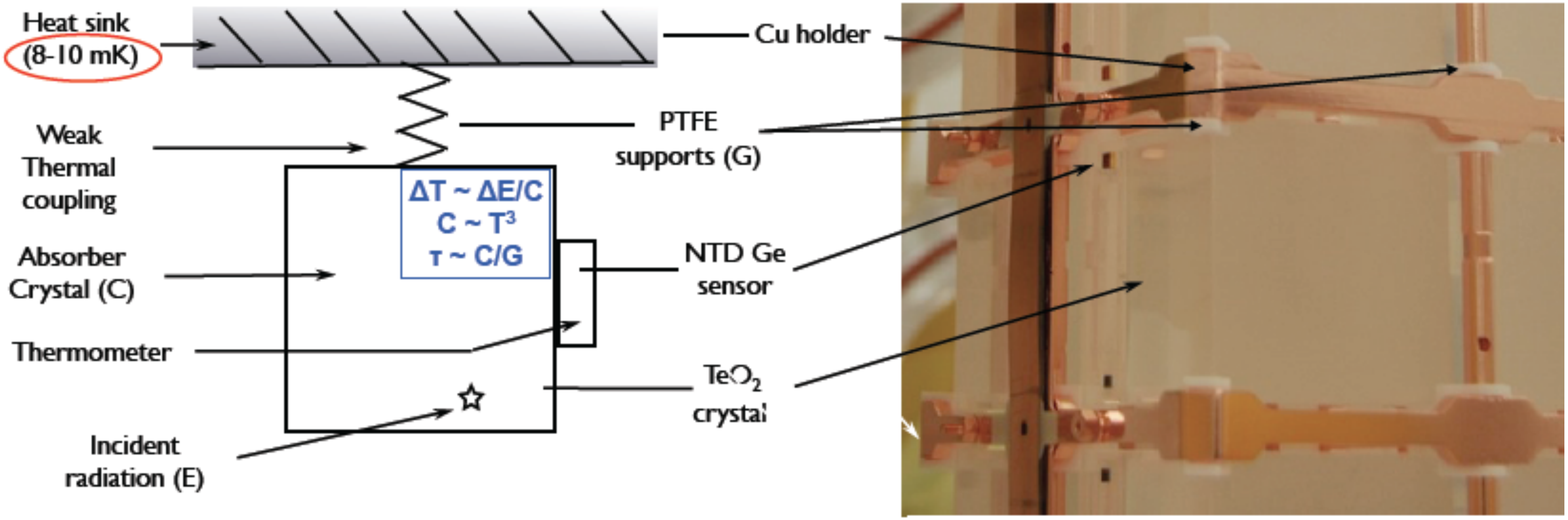
- 206 kg ^{130}Te (34% abundance) bolometer.
- Array of 988 TeO_2 crystals, 19 towers
- Builds upon success of Cuoricino and CUORE-0
- Resolution 5 keV FWHM
- Projected Sensitivity of 1.6 x 10^{26} y



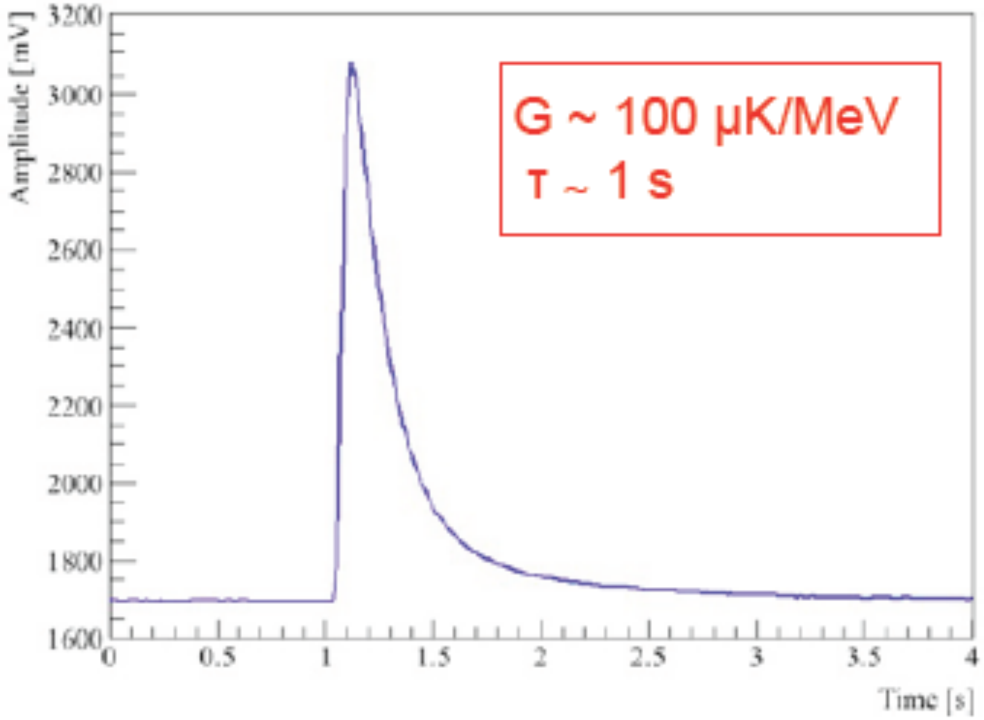


Bolometry

Phonons



$\Delta T \sim \Delta E/C$
$C \sim T^3$
$\tau \sim C/G$



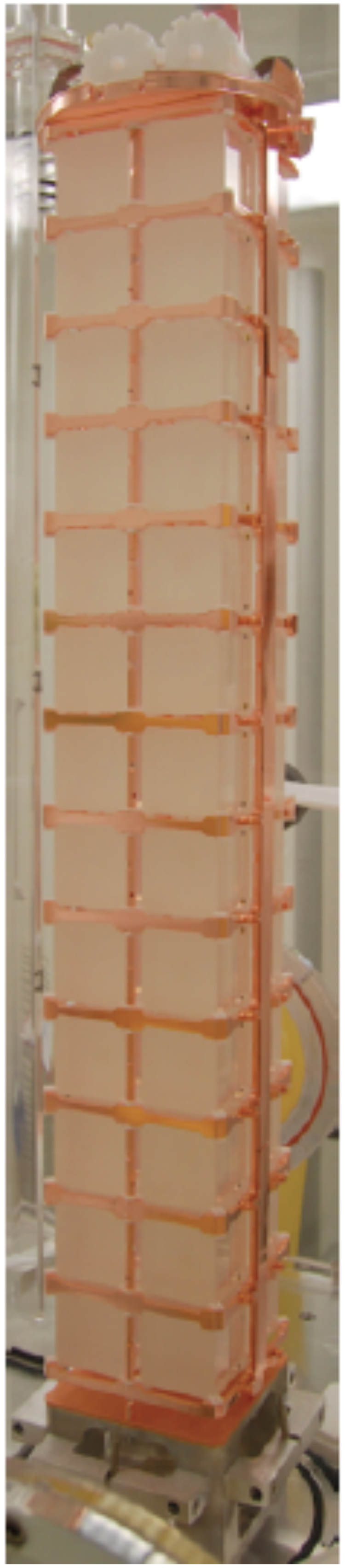
G ~ 100 μK/MeV
τ ~ 1 s

- Excellent energy resolution: $(k_B C T^2)^{1/2}$
- Calorimetric approach
- Wide choice of the absorber material
- Large mass arrays

CUORE Collaboration, Cremonesi, Neutrino 2014

CUORE-0 ^{130}Te

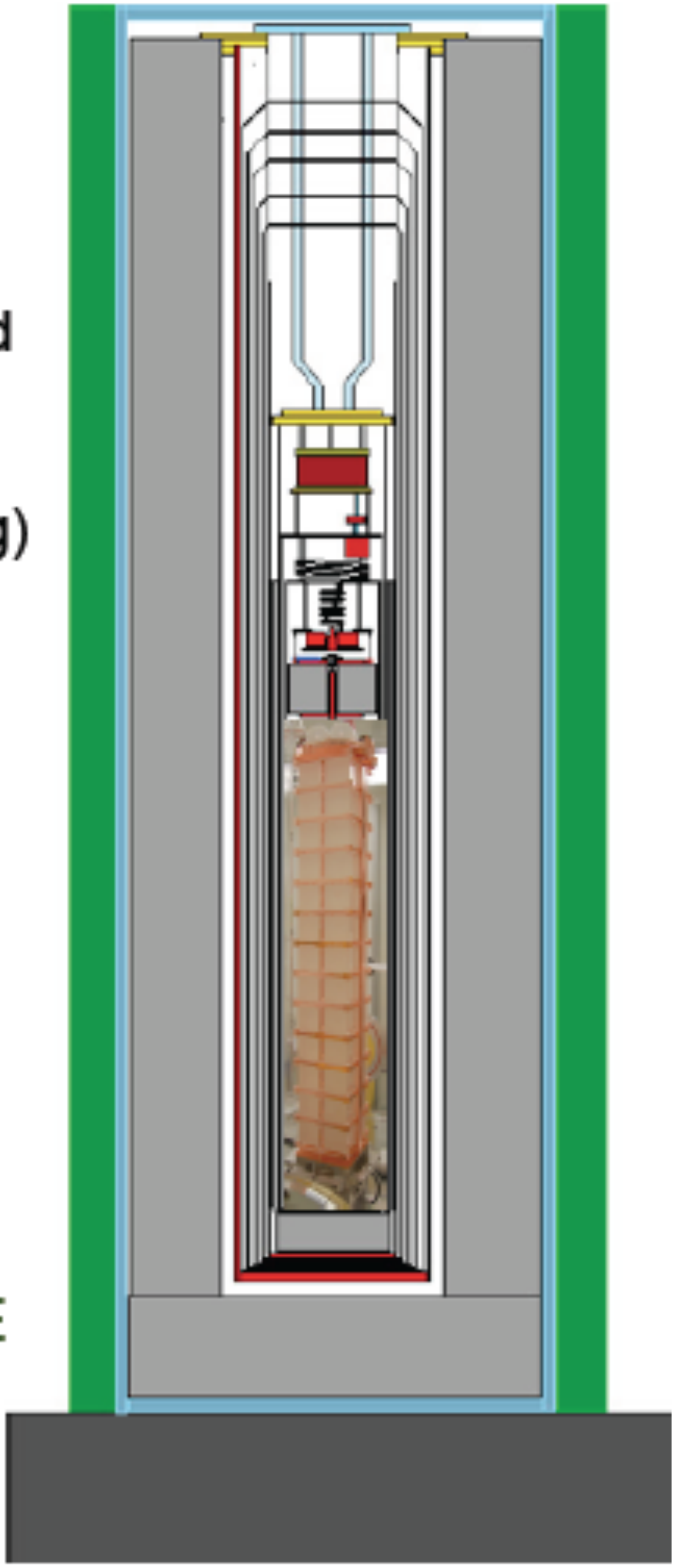
Phonons



1 CUORE tower
- $52\ TeO_2\ 5x5x5\ cm^3$ bolometers
- 13 floors of 4 crystals each
- total mass: 39 kg (11 kg of ^{130}Te)

- All detector components manufactured, cleaned and stored with same protocols defined for CUORE
- Assembled with the same procedures of CUORE:
  - dedicated class 1000 clean room (underground building)
  - all steps of the assembly (crystal gluing, mounting, cabling, bonding) performed under nitrogen inside special glove boxes.
- Operated inside the 25-year-old Cuoricino cryostat at LNGS.
- Low temperature roman lead shield

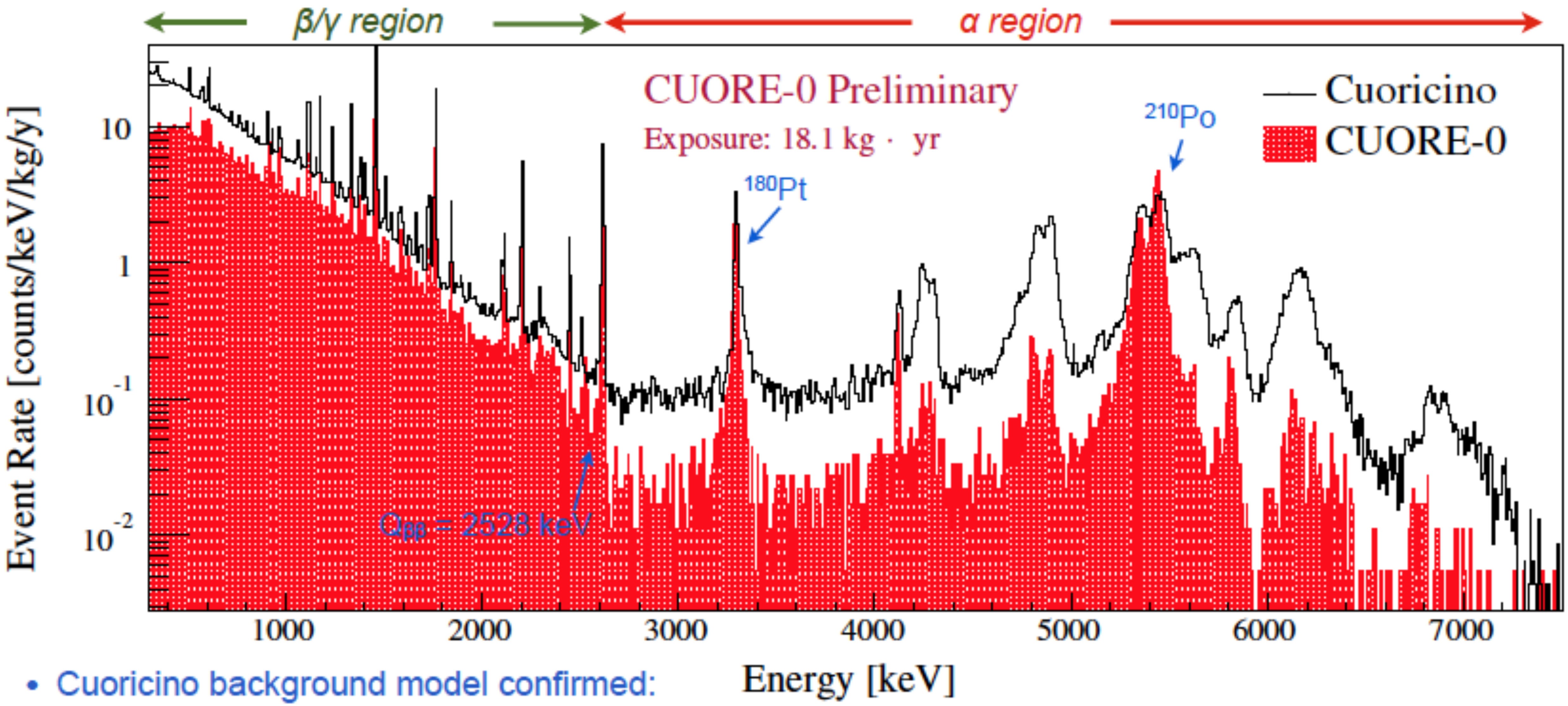
Goals:
- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Operating as independent experiment while CUORE is under construction
- Demonstrate potential for DM detection



CUORE Collaboration, Cremonesi, Neutrino 2014

CUORE-0 ^{130}Te

Phonons



- Cuoricino background model confirmed:
  - environmental gamma's from material bulk contaminations
  - surface radioactive contaminations of close materials

- Evident reduction with respect to Cuoricino
  - factor of 6 for surface contaminations
  - factor ~2.5 in the ROI

	0νββ region cnts/(keV kg y)	***2700-3900 keV***	***ε(%)***
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	**0.063 ± 0.006**	**0.020 ± 0.001**	78

CUORE Collaboration, Cremonesi, Neutrino 2014

LUCIFER

Scintillator - Phonons

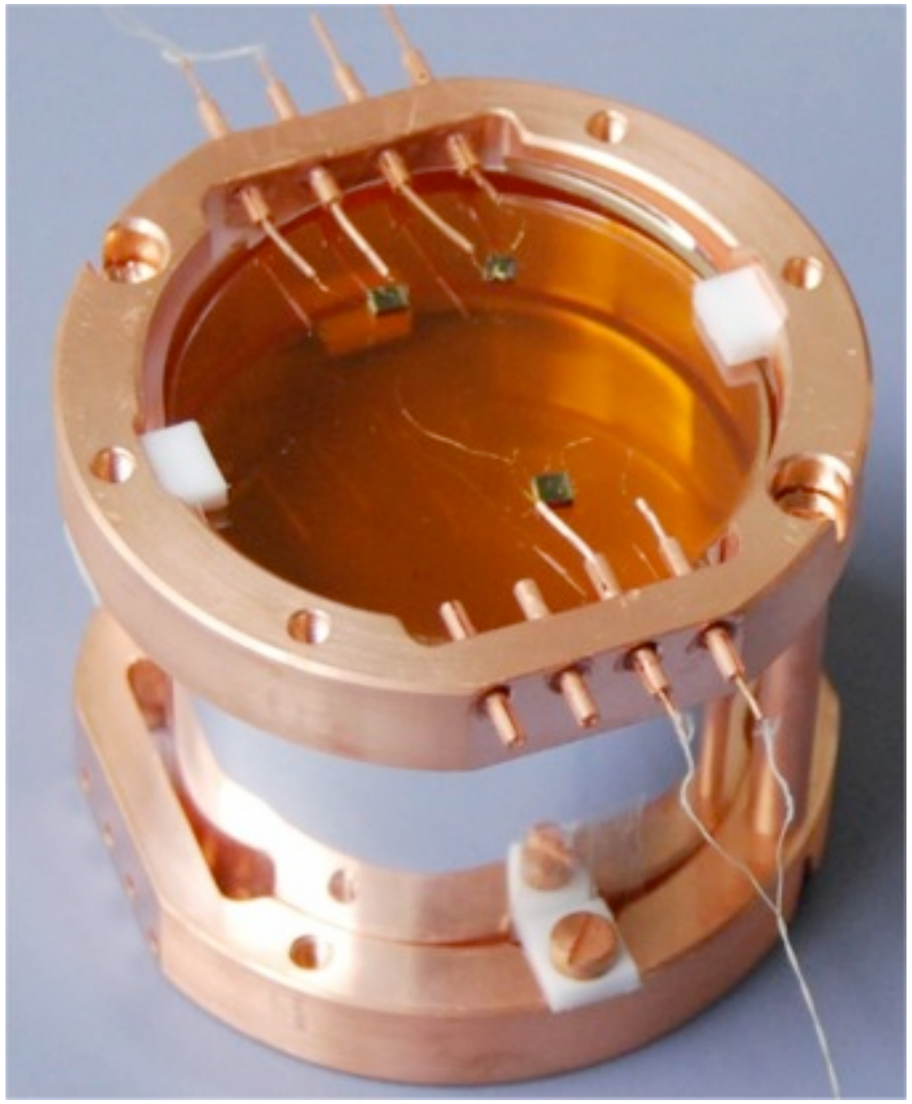
Energy resolution from bolometer, particle discrimination via scintillator light

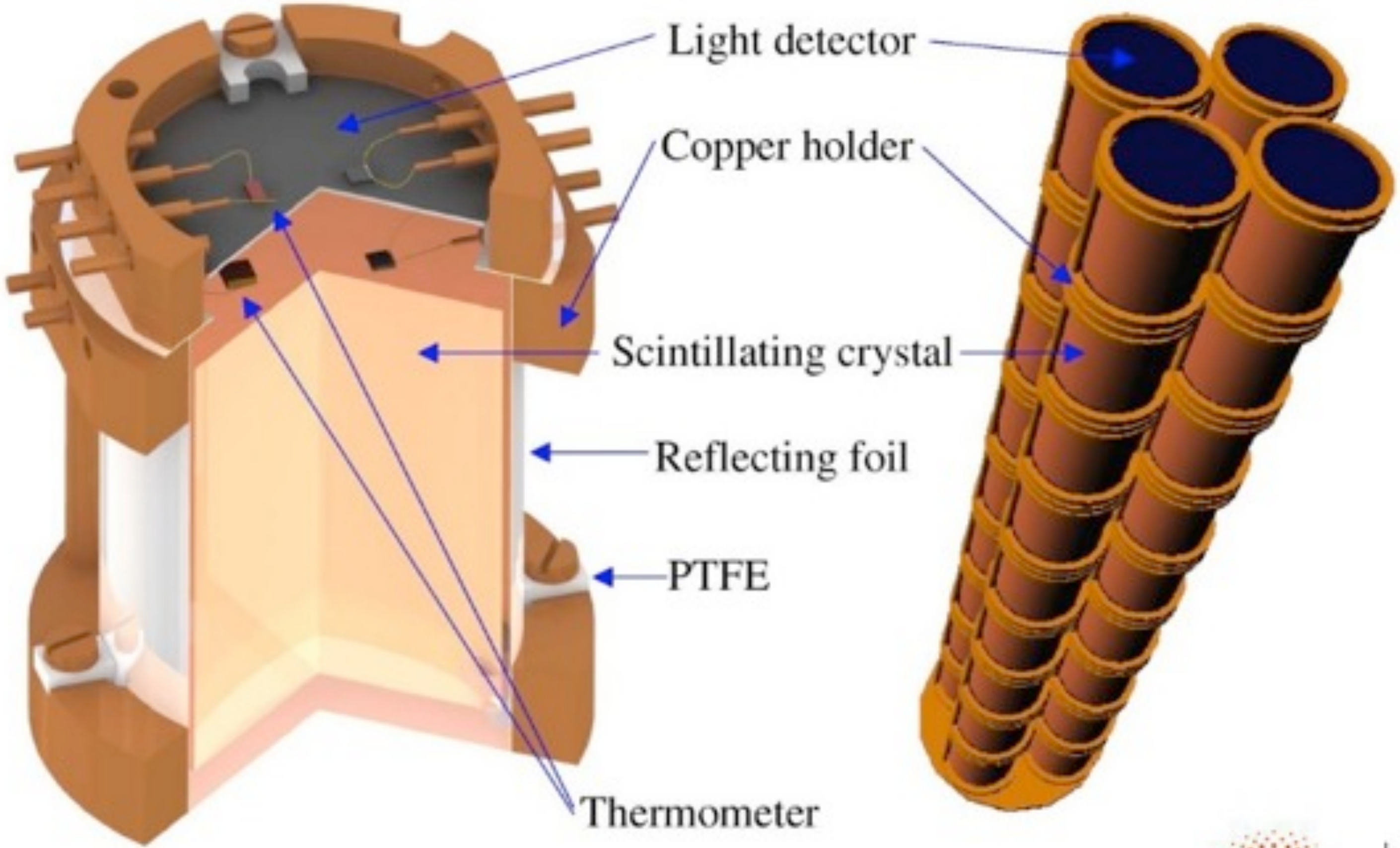
Will be composed by an array of 32 - 36 enriched (95%) Zn^{82}Se crystals.

The mass of the single detector 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





15/15 kg ^{82}Se already produced. Final *purified* batch for 02/2015. Crystal growth from Feb to July 2015

LUCIFER Collaboration, Stefano Pirro

AMoRE ^{40}Ca^{100}MoO$_4$

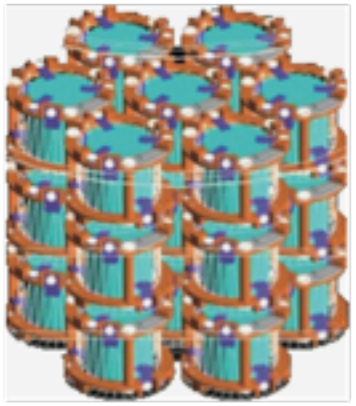
Scintillator - Phonons

Advanced Mo based Rare process Experiment) ^{40}Ca^{100}MoO$_4$

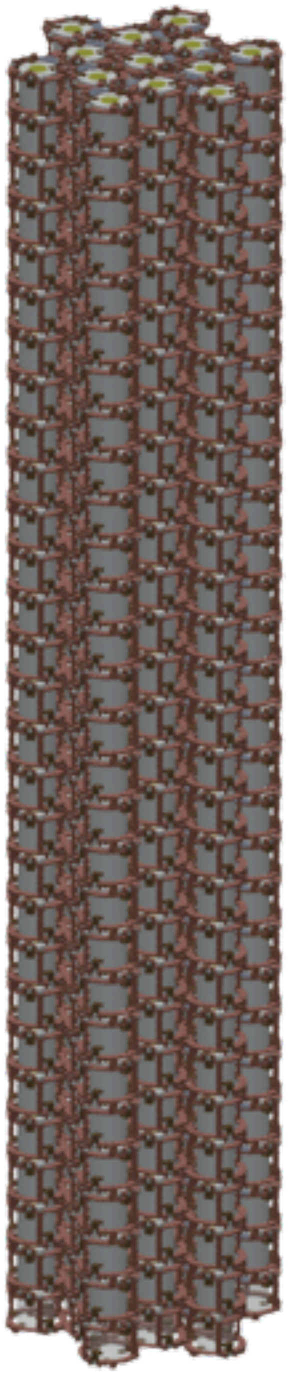
Energy resolution from bolometer, particle discrimination via scintillator light

Crystal: ^{40}Ca^{100}MoO$_4$, doubly enriched scintillating crystals
^{100}Mo enrichment > 95%, ^{48}Ca depletion > 35 times
Temperature: 10-50 mK
Energy Resolution: 5 keV @ 3 MeV
(Now ~9keV in over-ground)
Single Detector Mass: 300-500g
AMoRE is fully funded for 10-year support

	AMoRE-10	AMoRE-200
Mass	10 kg	200 kg
Background (keV kg year)$^{-1}$ For zero bkg	10^{-2}	3×10^{-4}
Sensitivity(m_{ee}) (meV)	80-250	20-50
Schedule	July 2016	2019



CMO: ~ 300g
5 layers-7 columns
<AMoRE10, 2016>



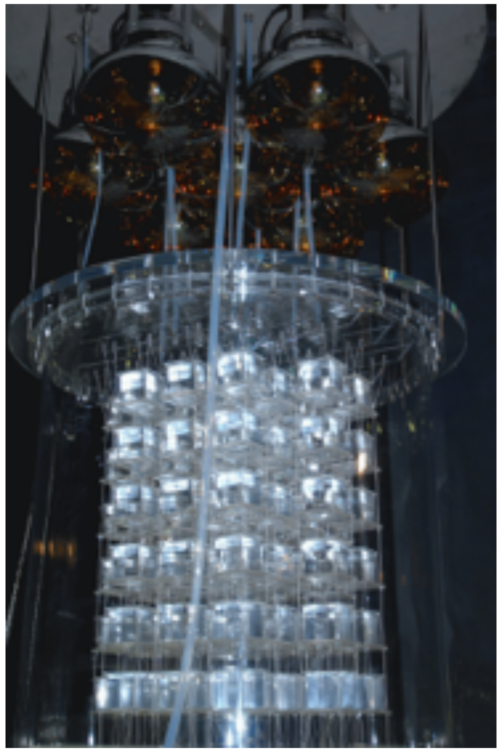
Each Cell : D=70 mm, H=80 mm.
CMO (D=50mm, H=60mm, 506g)
30 layers(2.4 m height)-13 columns
or 20 layers(1.6 m height)-19 columns
<AMoRE200, 2019>

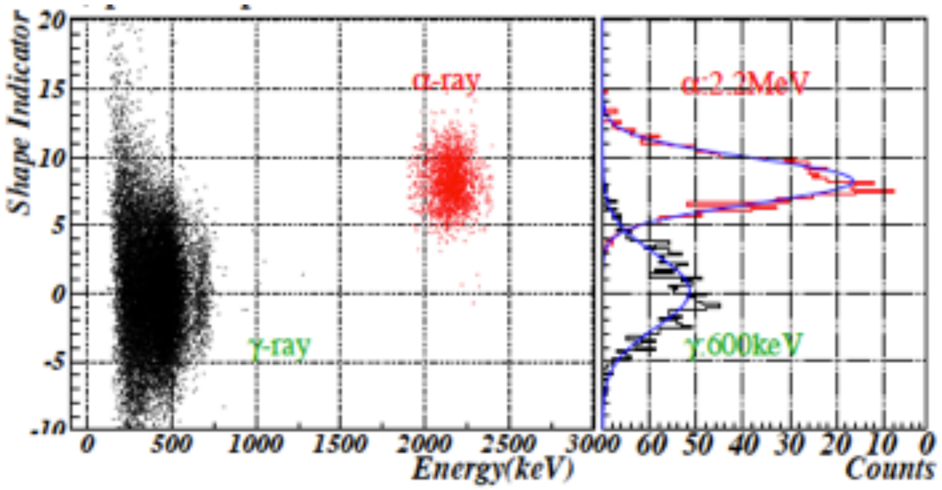
Center of Underground Physics in IBS
YangYang UG Laboratory, Korea

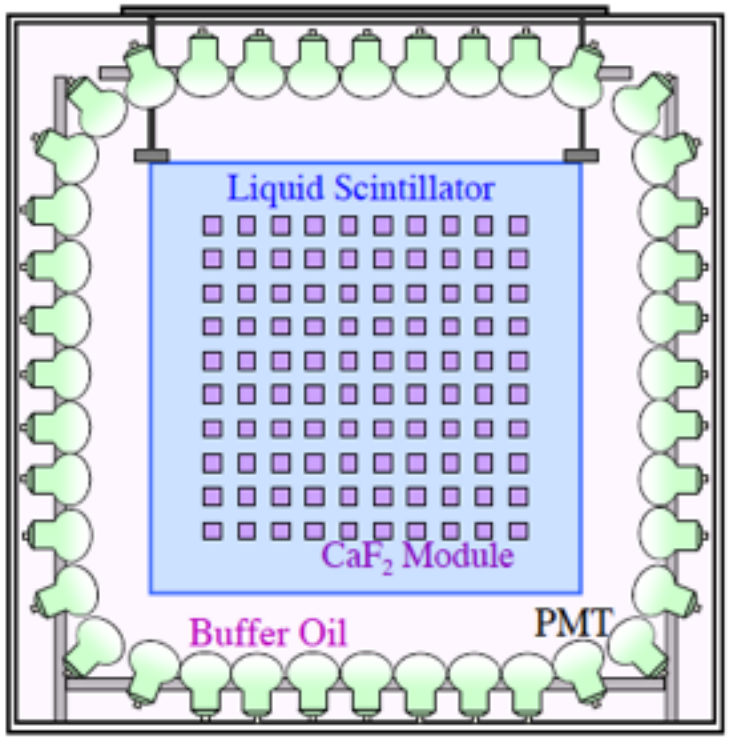
CANDLES ^{48}Ca

Scintillation

- Highest $Q_{\beta\beta}$ of 4.27 MeV
- ^{48}Ca (0.187 % abundance) scintillating CaF_2 crystals in liquid scintillator.
- CANDLES III
  - 305 kg of natural CaF_2 crystals
  - Kamioka Laboratory
- Working on enrichement scheme







CANDLES Collaboration, Saori Umehara

SNO+ ^{130}Te

Scintillation

Science : 0νββ-decay, Geoneutrinos, Solar ν

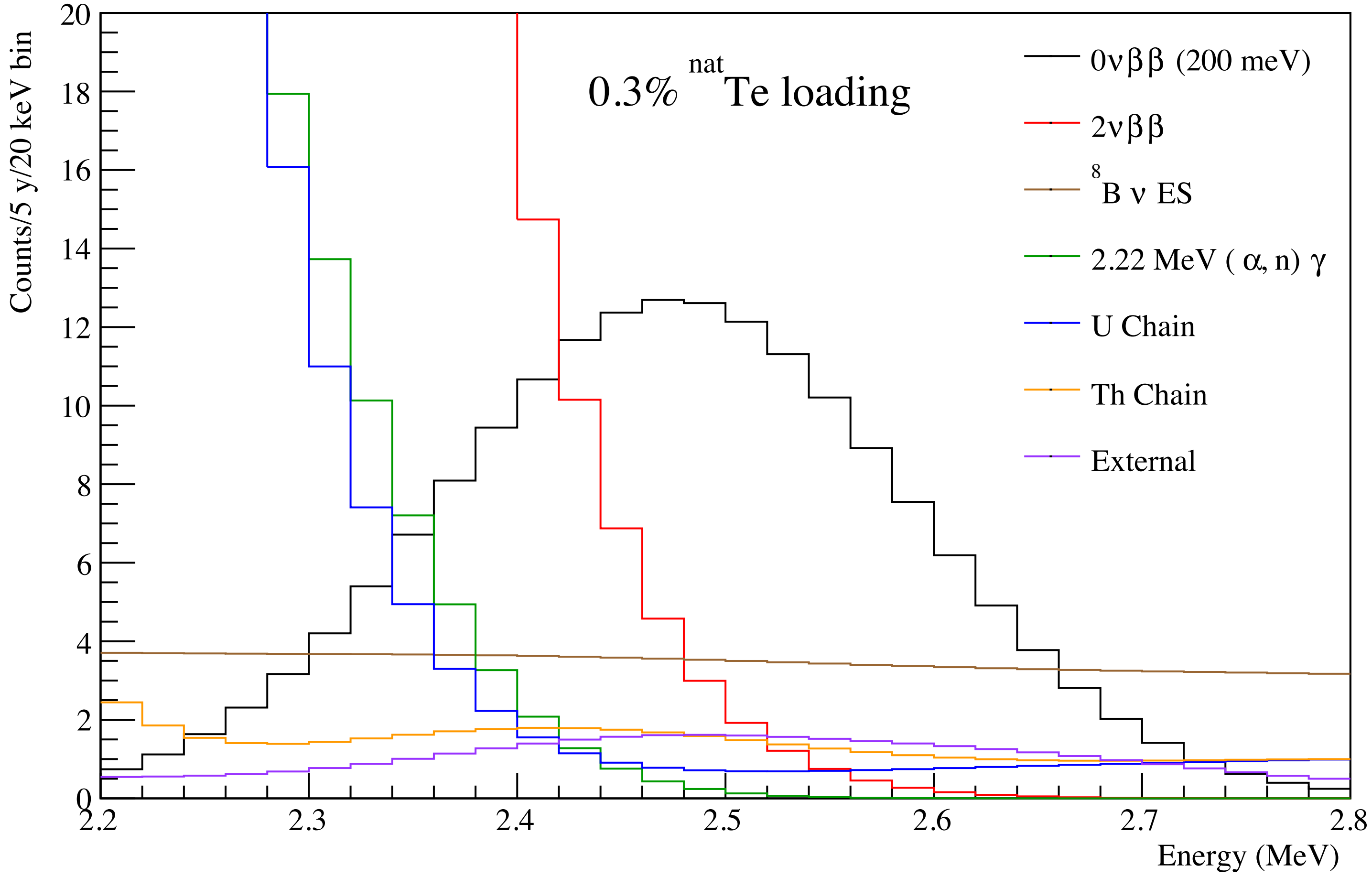
- large natural isotopic abundance 34% for ^{130}Te

  0.3% Te (by weight) in SNO+ is 2.34 tonnes of Te or **800 kg** of ^{130}Te ***isotope***…0.3% loading isn't a fundamental loading limit.

- in the energy range of the Te endpoint, the known U chain background (^{214}Bi-^{214}Po) can be rejected by factor >5,000!

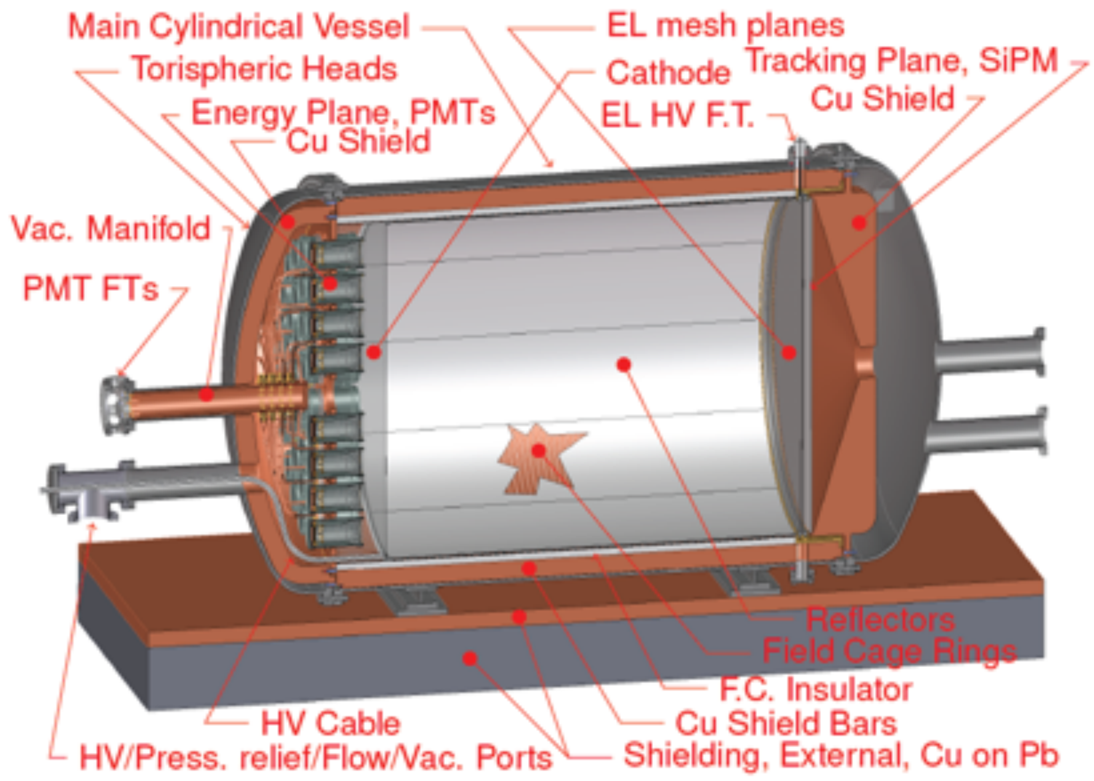
- Fiducial of 160 kg
- Resolution of 270 keV, so will have to account for 2νββ
- use asymmetric window
- successful loading of scintillator
- Water fill now, scintillator in 2015

simulation - 5 years of data



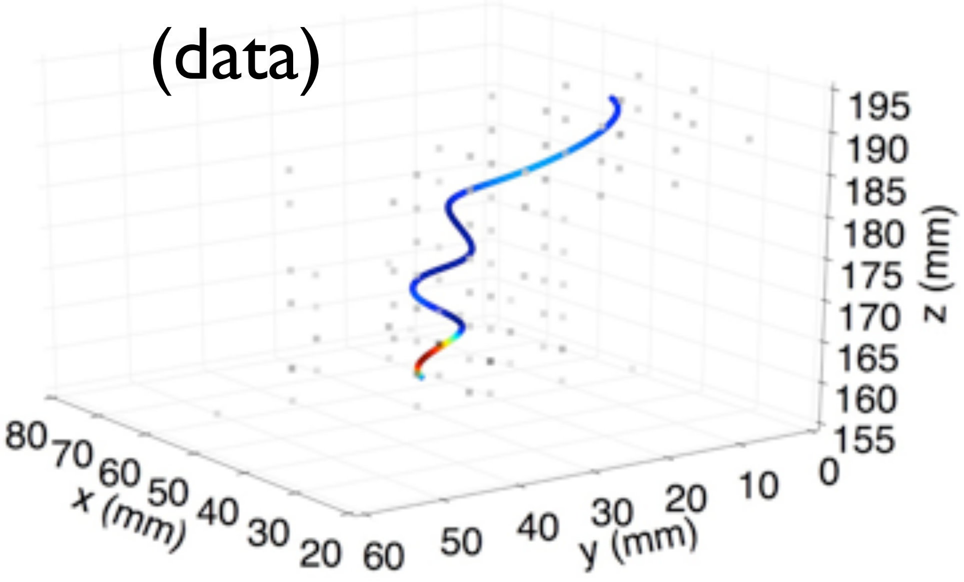
next ^{136}Xe

Scintillation - Ionization

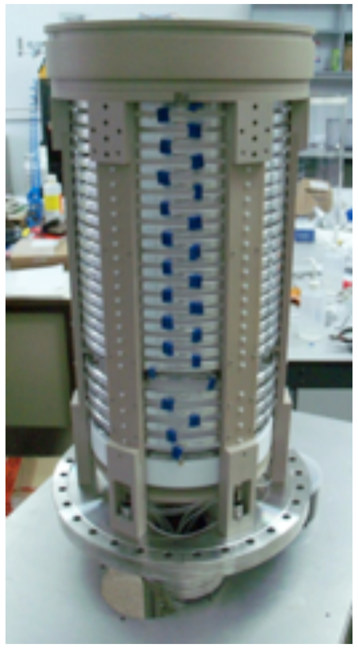


- HP^{136}Xe TPC + EL for high E- resolution + tracking capability
- 10 kg prototype in LSC in 2014
- Tonne-scale sensitivity: $m_{\beta\beta}$ < (20-50) meV

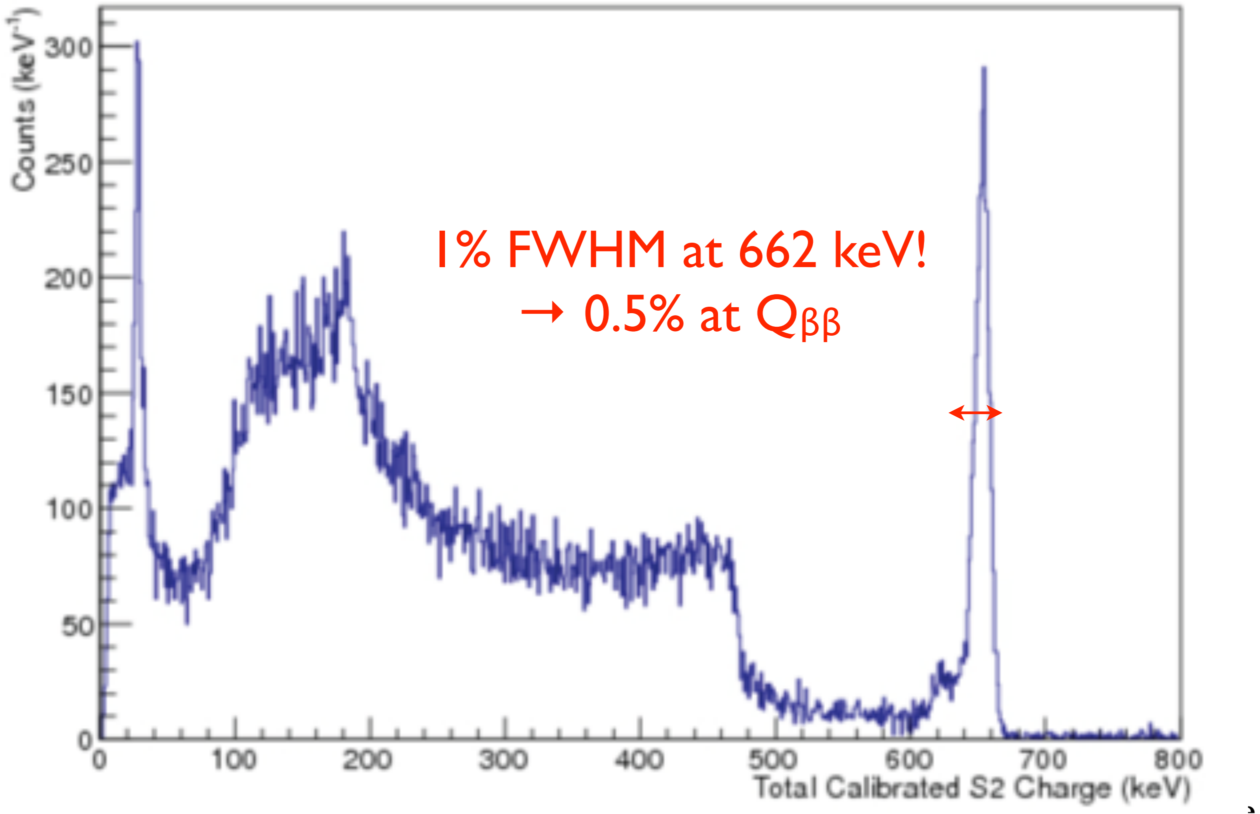
e^- scatter (data)



NEXT-DEMO



Hernando, TAUP13. arXiv:1211.4474.



1% FWHM at 662 keV!
→ 0.5% at $Q_{\beta\beta}$

SuperNEMO ^{82}Se

Ionization & Cal.

- Thin foil with tracking and calorimeter, based on successful NEMO3 detector.
- Planar and modular design: ~ 100 kg of enriched isotopes (20 modules × ~5-7 kg)
- Starting with single Demonstrator module, (7 kg of ^{82}Se) to show scalable
  - First physics results in 2015.
  - $T_{0\nu 1/2} > 6.5 \times 10^{24}$ y → $\langle m\nu \rangle < 0.20 - 0.40$ eV @ (90 % C.L.)
- SuperNEMO 40-140 meV
  - 100 kg of ^{82}Se running for 5 years
  - $T_{0\nu 1/2} > 1 \times 10^{26}$ y → $\langle m\nu \rangle < 0.04 - 0.10$ eV @ (90 % C.L.

Demonstrator (1 module):

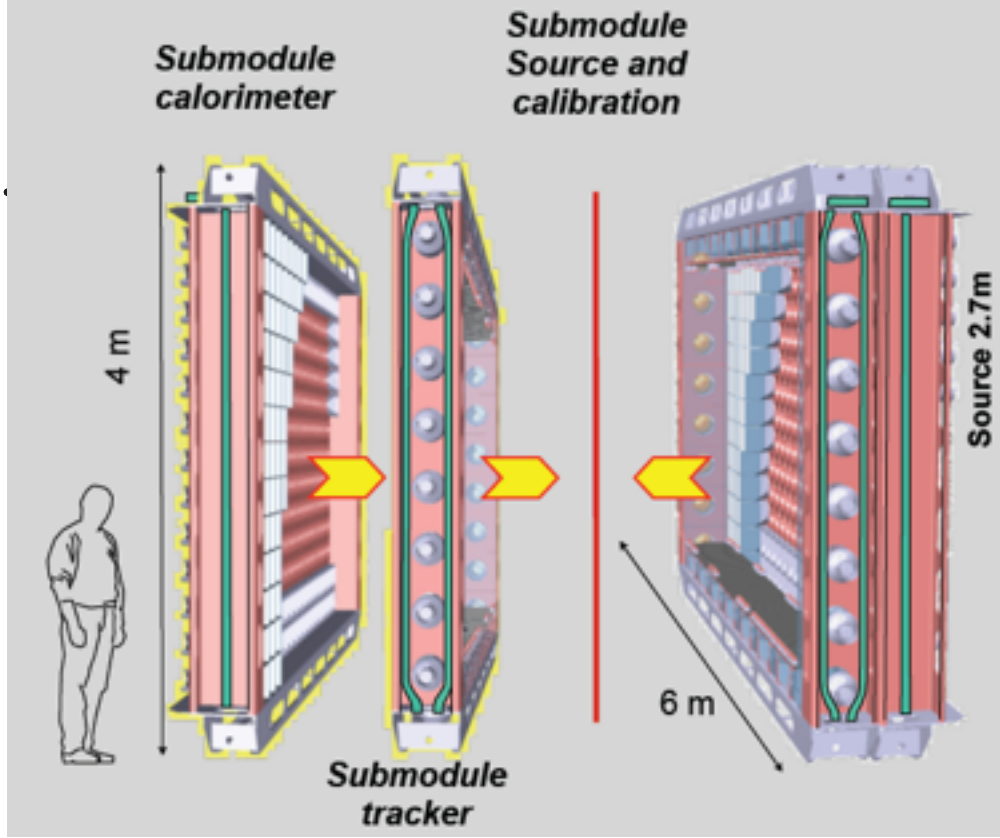
Source (40 mg/cm^2) 4 x 3 m^2

Tracking : drift chamber ~2000 cells in Geiger mode

Calorimeter: scintillators + PMTs

~550 PMTs+scint. blocks

Passive water shield

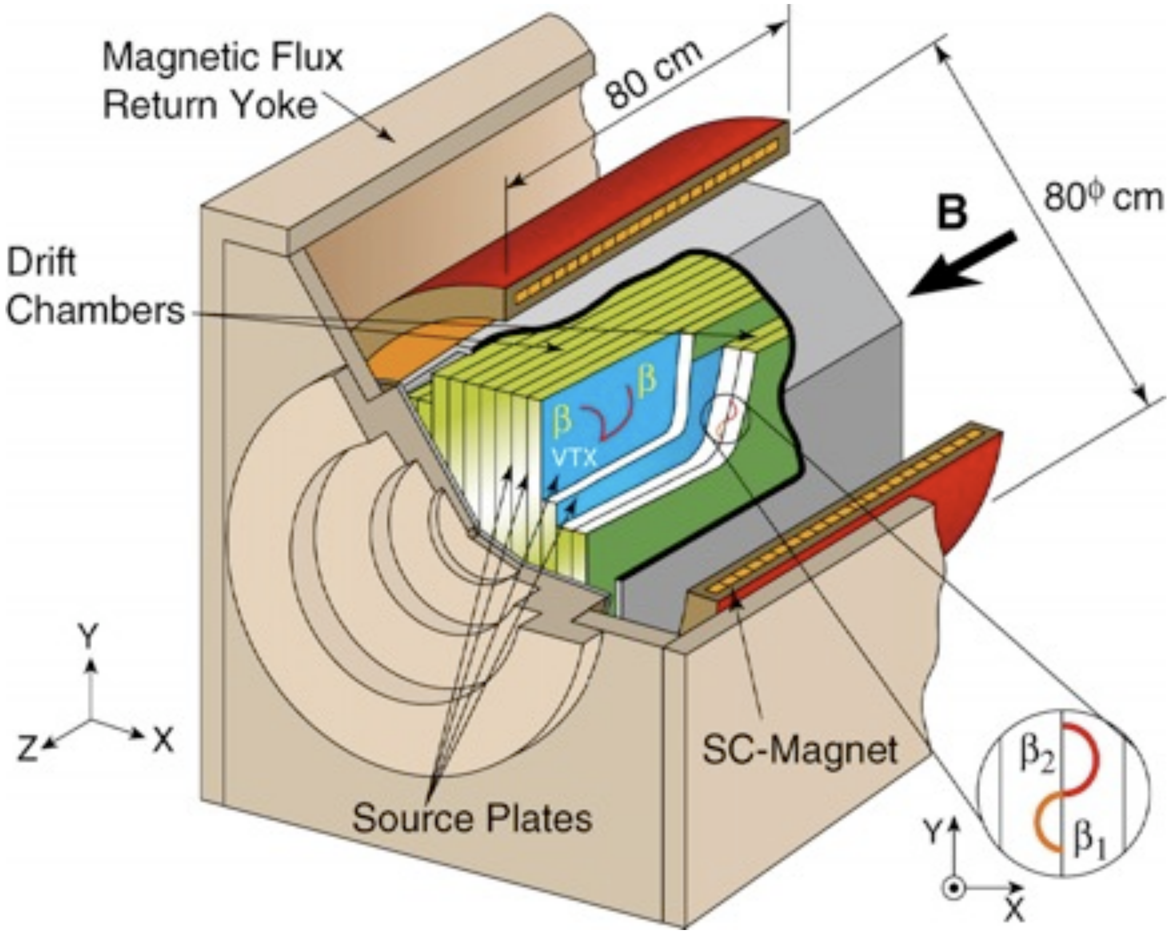


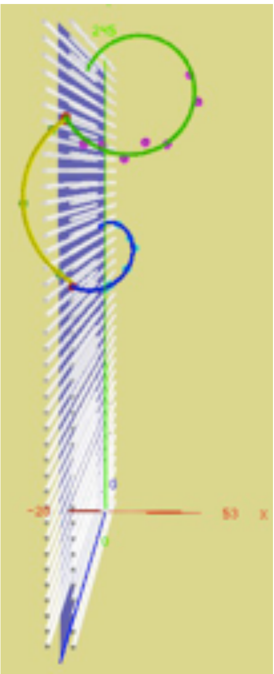
SuperNEMO Collaboration, Remoto, NOW 2014

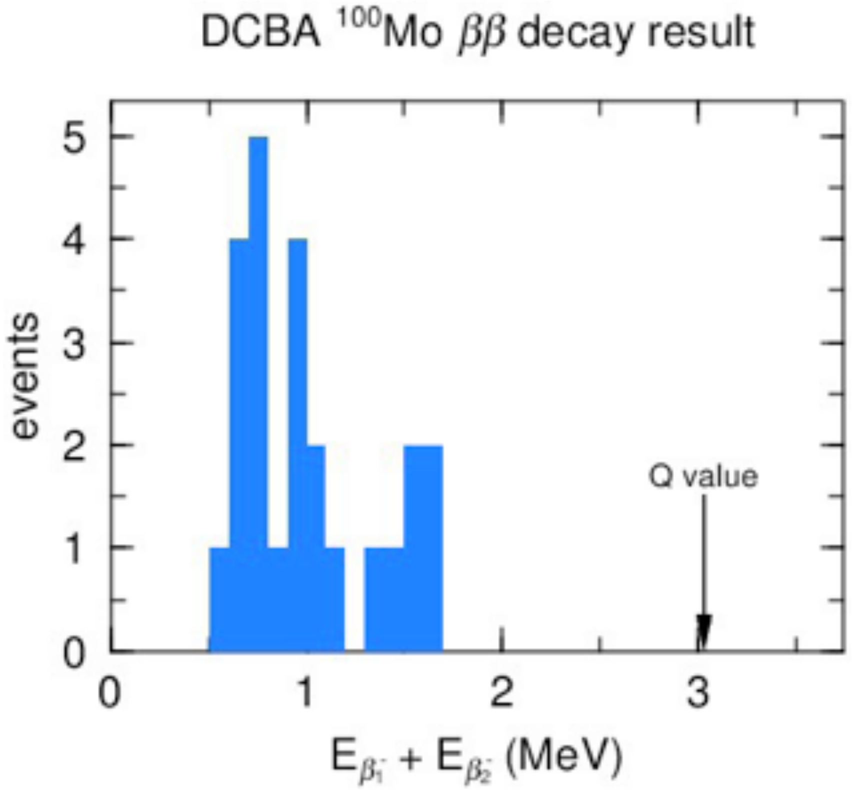
DCBA

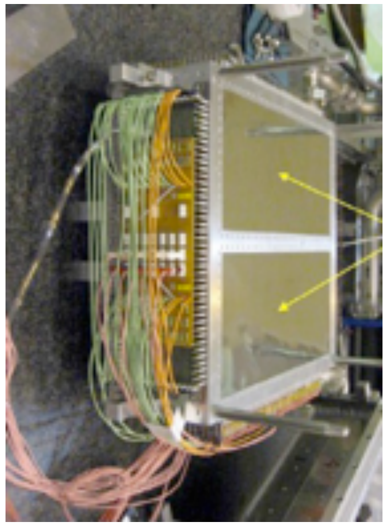
Ionization & Cal.

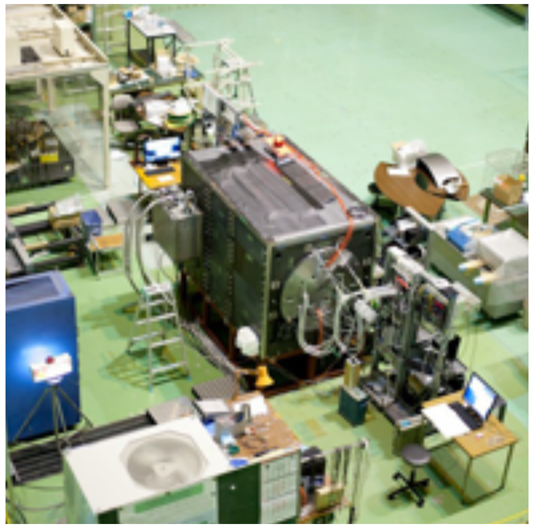
- Source plates in drift chambers with B field: unique “S” signature for ββ decay
- DCBA-T2.5 prototype at KEK with 30 g ^{nat}Mo, taking data since July 2011
- 2014: DCTA with finer pitch, higher B, switch to ^{150}Nd (Nd_2O_3)
- Future: 10s of kg ^{82}Se, ^{150}Nd









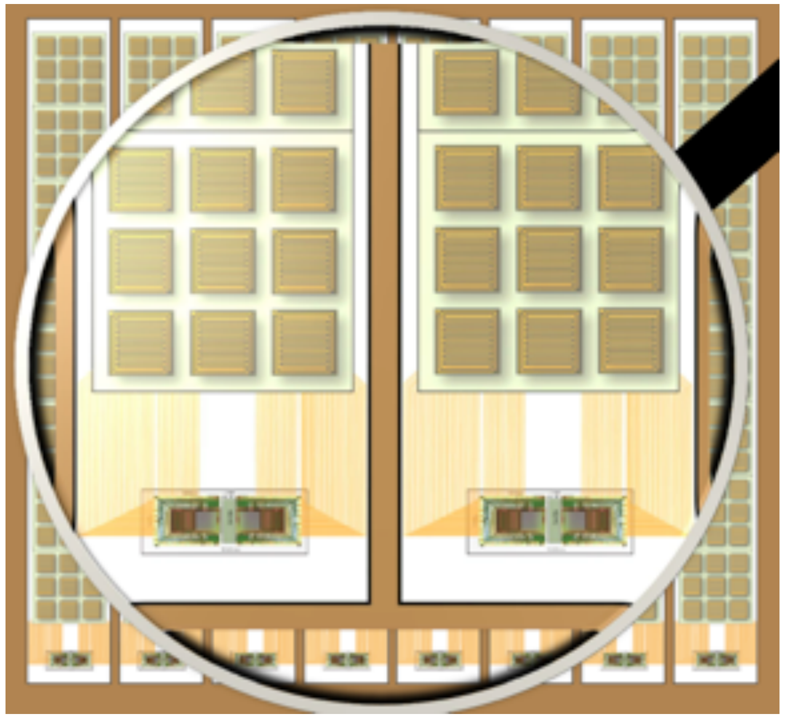


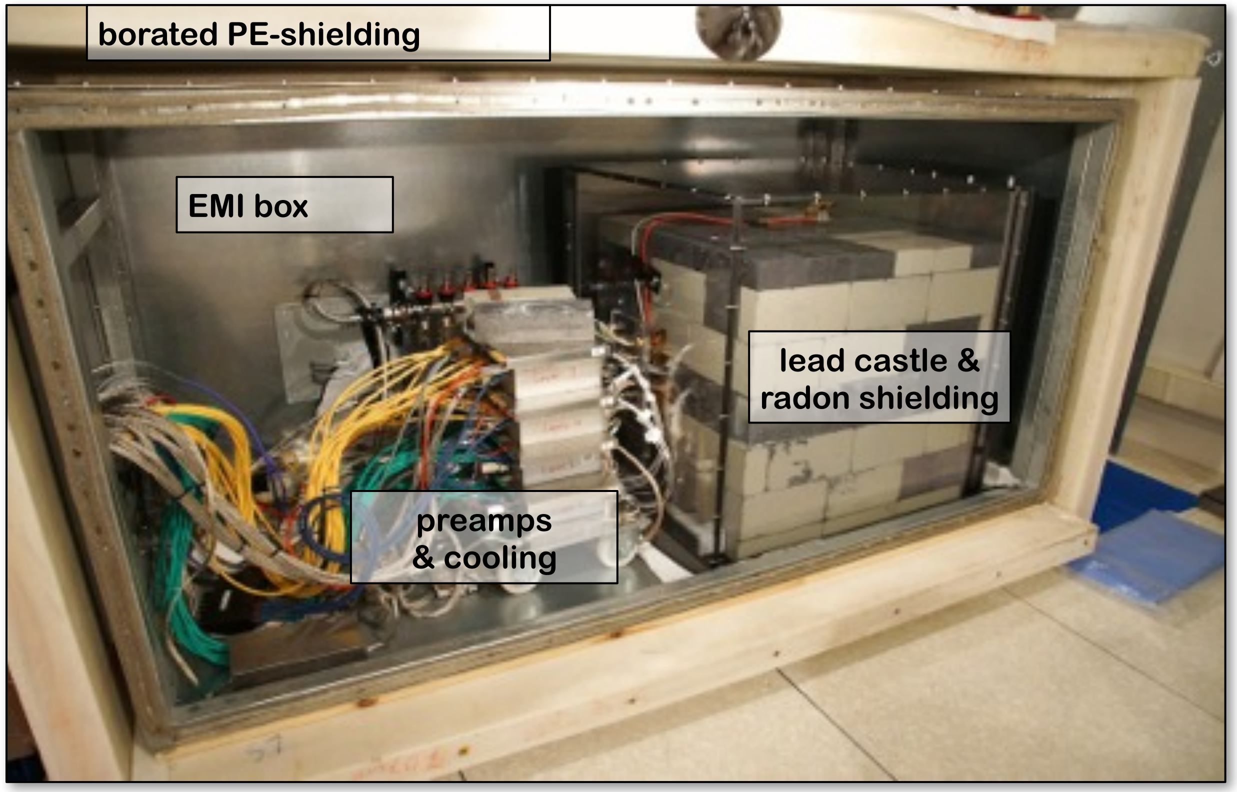
COBRA - CdZnTe

Ionization

K. Zuber, Phys. Lett. B 519,1 (2001)

- ^{116}Cd Q-value at 2813 keV, above all major gamma lines from natural chains
- Room temperature
- Semiconductor (clean)
- Good energy resolution
- Enrichment (>90%) feasible and purification as well
- Coincidences
- Pulse shape analysis
- Very modular design
- Tracking option
- Full 64 array running since Nov. 2013



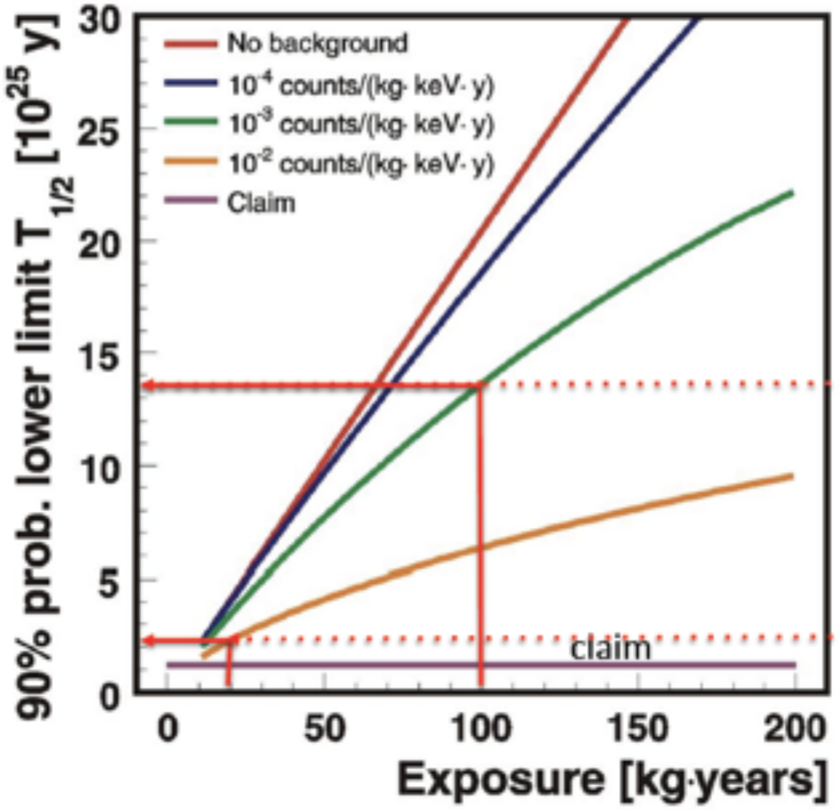


COBRA Collaboration, Kai Zuber

GERDA ^{76}Ge Phase 2

Ionization

- Increase ^{enr}Ge mass (~40 kg in total) 21 kg in form of Ge-BEGe detectors
- enhanced PSD to pinpoint ββ events (Single Site) vs residual γ events (Multi Site)
- Reduce radioactivity of Ge holders and mechanical structures
- New Ge readout electronics with closer FE devices in die for improved FWHM
- LAr as active media(active detector) and not only as passive shield
- ^{42}K bkgd: Transparent Nylon Mini Shroud (NMS) coated with WLS (instead of Cu opaque) surrounding each BEGe detector string



Goal:
'background free' operation
$T^{0\nu}_{1/2}$ scales with exposure

Phase II:
Add new enr. BEGe detectors (+20 kg)
BI ≈ 0.001 cts / (keV kg yr)
Sensitivity after 100 kg yr

Phase I:
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr)
Sensitivity after 20 kg yr

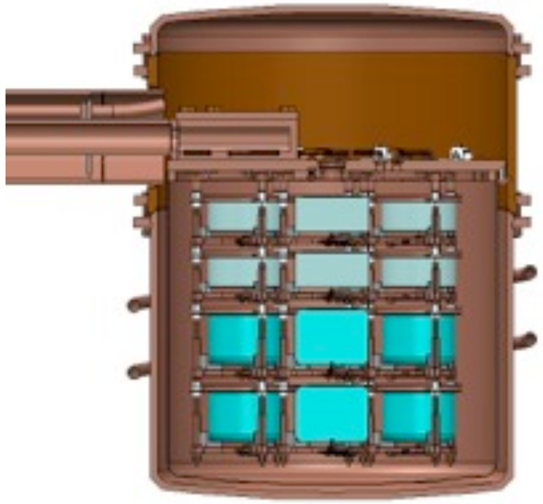
GERDA Collaboration, Cattadori, NOW 2014

The Majorana Demonstrator

Ionization

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

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

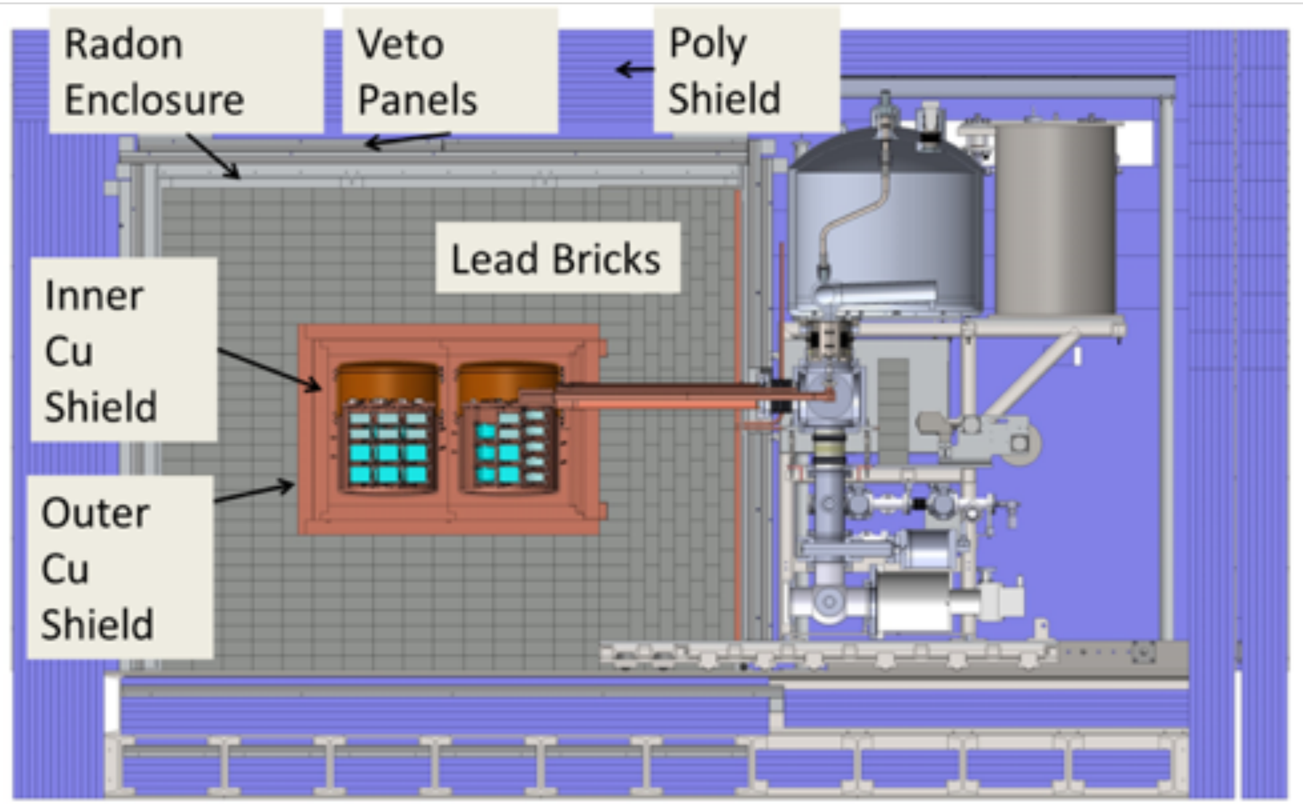


- **Located underground at 4850’ Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**

  3 counts/ROI/t/y (after analysis cuts) **Assay U.L. currently ≤ 4.1**

  scales to 1 count/ROI/t/y for a tonne experiment

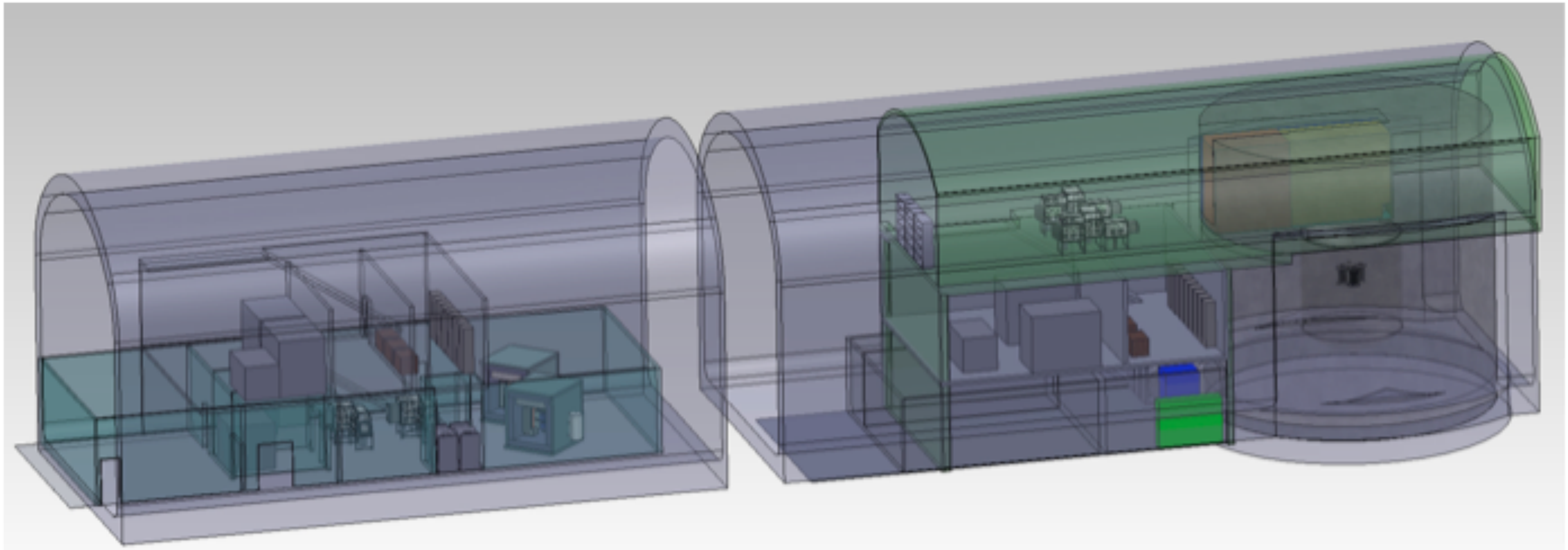
- **40-kg of Ge detectors**
  - 30 kg of 87% enriched ^{76}Ge crystals
  - 10 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- **Compact Shield**



Large-Scale ^{76}Ge 0νββ

Ionization

- MAJORANA and GERDA are working towards the establishment of a single international ^{76}Ge 0νββ collaboration
- Envision a phased, stepwise implementation;
  e.g. 250 → 500 → 1000 kg
- Moving forward predicated on *demonstration* of projected backgrounds by MJD and/or GERDA
- Anticipate down-select of best technologies, based on results of the two experiments



Compact shield

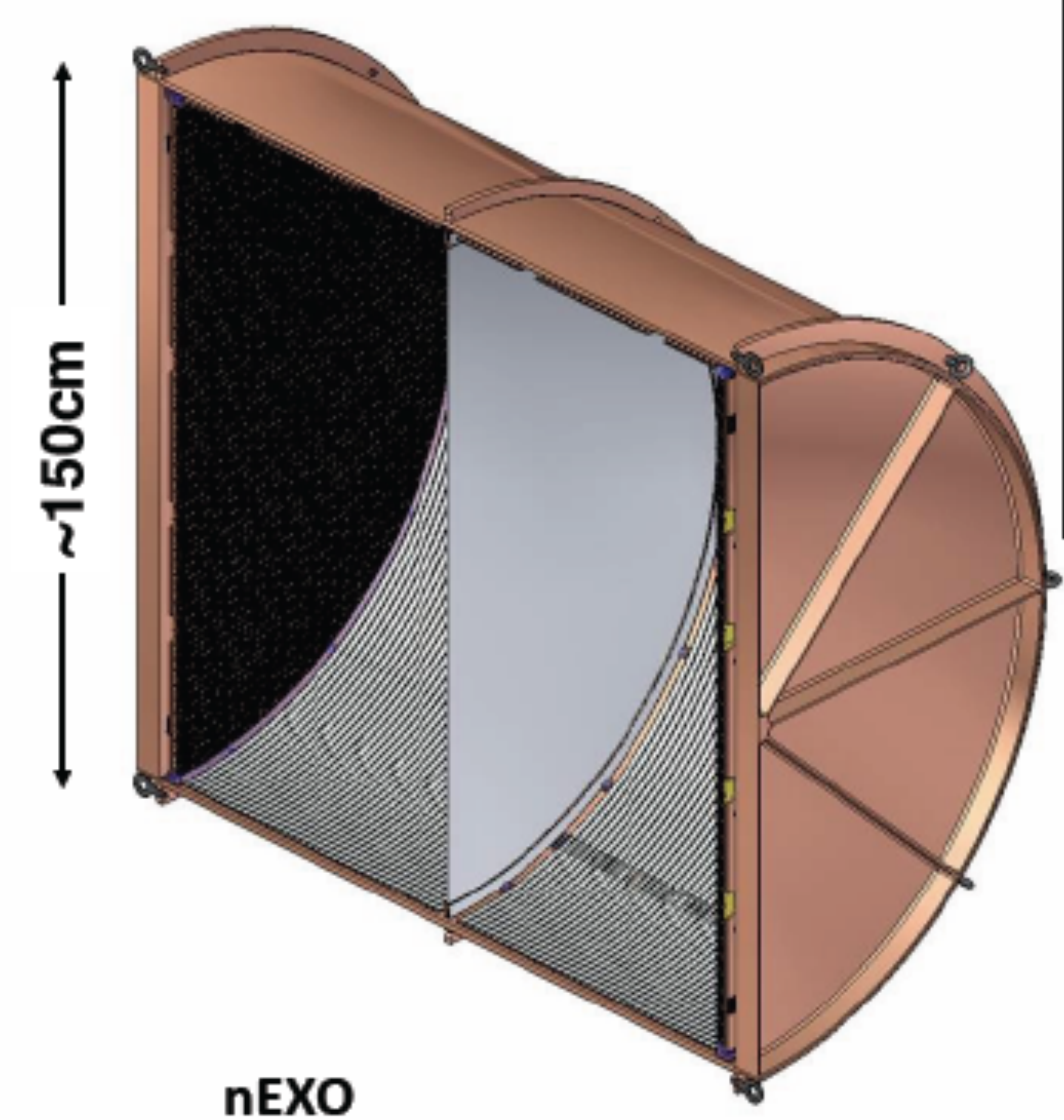
Cryogenic shield

nEXO

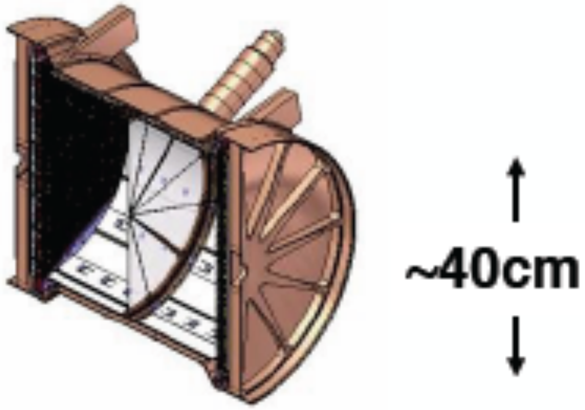
"as similar to EXO-200 as possible"

Overall Mass: 5 tonnes, 90% enriched ^{136}Xe
Time Projection Chamber (TPC)
Running Time: 10 years
Baseline energy resolution: 1.5%
Preferred site: SNOLAB Cryopit
Final $T_{1/2}$ sensitivity (90% CL): 4.1×10^{27} yrs
With barium tagging: 2.1×10^{28} yrs

Design still not finalised



nEXO

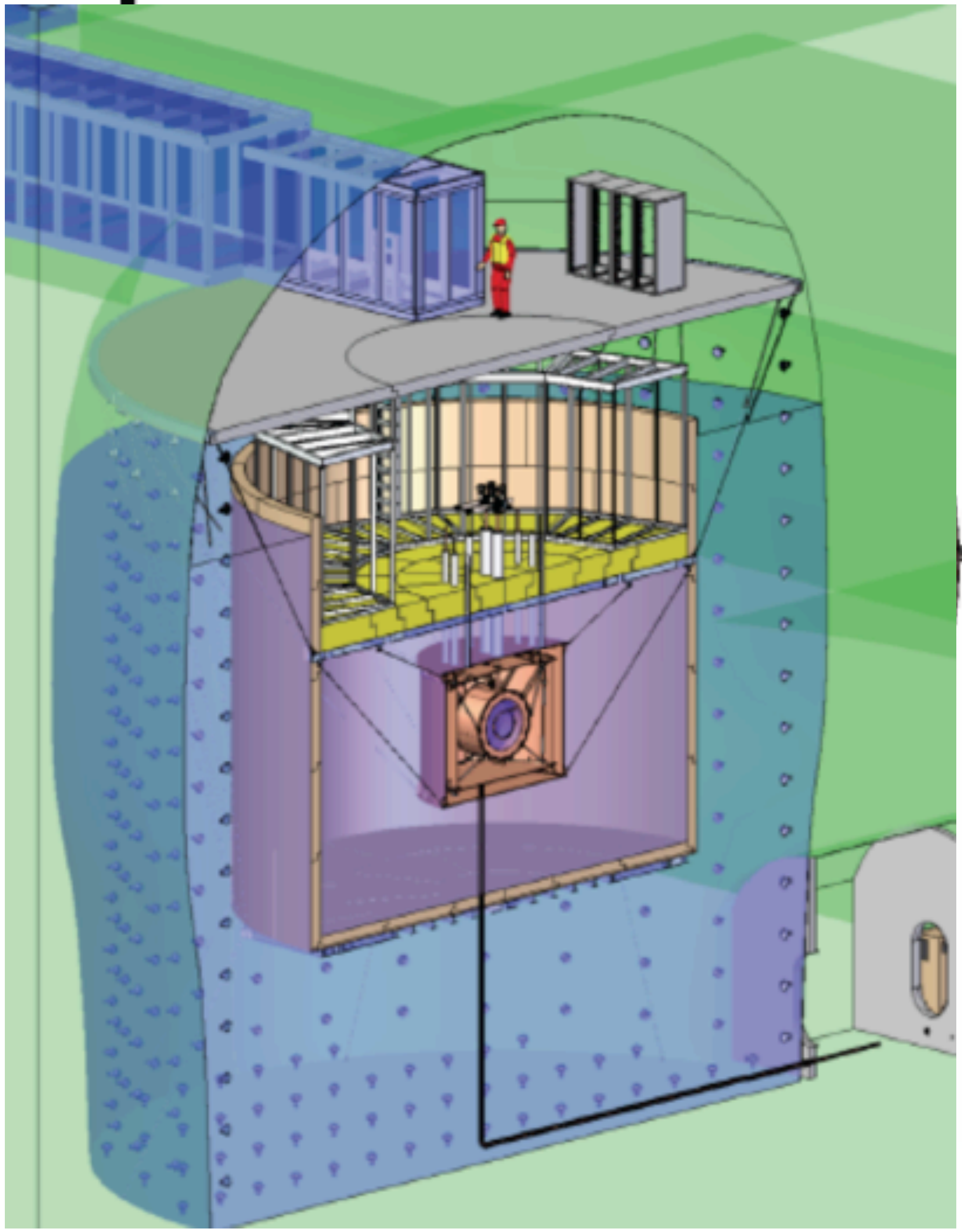


EXO-200

nEXO

Scintillation - Ionization

“as similar to EXO-200 as possible”



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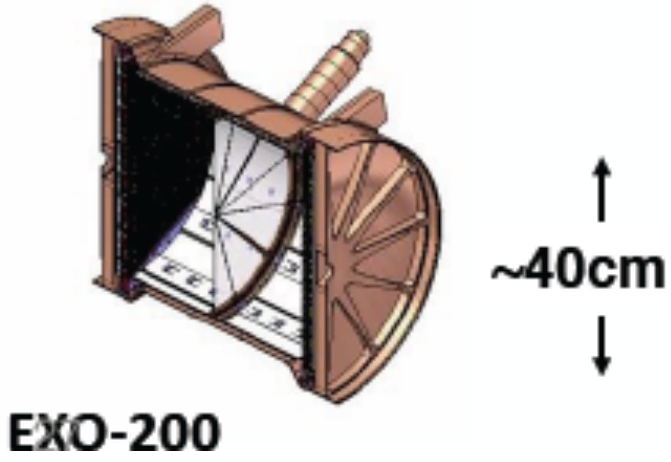

NSAC Sub-committee on ββ-decay

U.S. Nuclear Science Advisory Committee independent panel

- It is the assessment of this Subcommittee that the pursuit of neutrinoless double beta decay addresses urgent scientific questions of the highest importance, and that sufficiently sensitive second generation experiments would have excellent prospects for a major discovery. Furthermore, we recommend that DOE and NSF support this subject at a level appropriate to ensure a leadership position for the US in this next phase of discovery-caliber research.

- The Subcommittee recommends that the “current generation” experiments continue to be supported and that the collaborations continue to work to resolve remaining R&D issues in preparation for consideration of a future “second generation” experiment. New techniques that offer promise for dramatic reductions in background levels should also be supported.

- The subcommittee recommends establishing a theory task force that aims at:

  1.) developing criteria to establish and rank the quality of existing and future calculations,

  2.) identifying methods to constrain the less tested assumptions in existing approaches.

NSAC Sub-committee on ββ-decay

The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments:

1.) Discovery potential: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter mββ=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.

2.) Staging: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.

3.) Standard of proof: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.

4.) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.

5.) International Collaboration: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.

6.) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

0νββ-decay Future Prospects

- A variety of innovative experimental approaches, at the 10 - 800 kg scale, are being pursued using different 0νββ nuclei.
  - Reaching sensitivities of 10^{27} years requires reducing backgrounds to or below 1 count/tonne/year in the region of interest and larger masses.
- Towards large, tonne scale experiments.
  - With the possible exception of ^{130}Te, experiments require enriched material, which dominates the overall experimental cost.
  - Given the technical challenges and costs involved all experiments are taking a scalable approach. Discussions of tonne scale experiments, implies a phased, stepwise approach.
  - The scales and costs call for international collaborations.
  - **No technique has yet demonstrated readiness to go to the tonne scale.**
  - Interfering backgrounds could render an otherwise promising 0νββ isoptope not viable.

0νββ-decay Summary

- The observation of 0νββ-decay would demonstrate Lepton number violation and indicate that neutrinos are Majorana particles - constituting a major discovery.
  - Needs to be confirmed from *independent experiments using different isotopes* and measurement techniques.

- The primary experimental challenge is attaining unprecedented low backgrounds.

- If 0νββ-decay is observed then it opens an exquisitely sensitive window to search for physics beyond the Standard model.
  - *Measurements in different isotopes* may provide insights into the underlying lepton violating physics process(es).
  - With existing NME uncertainties, the extraction of $<m_{\beta\beta}>$ will be challenging.