BERKELEY LAB

LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Low-Background Challenges and Solutions in $0\nu\beta\beta$ Experiments with Discrete Detectors

Alan Poon

Institute for Nuclear & Particle Astrophysics

Nuclear Science Division

BERKELEY LAB

LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

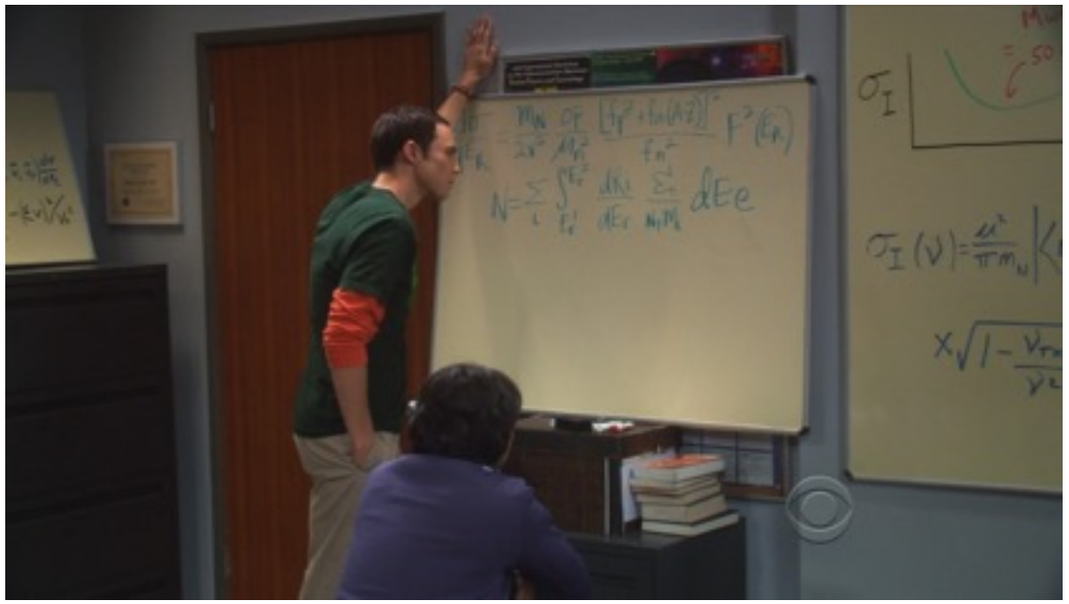
Low-Background Challenges and Solutions in $0\nu\beta\beta$ Experiments with Discreet Detectors

Alan Poon

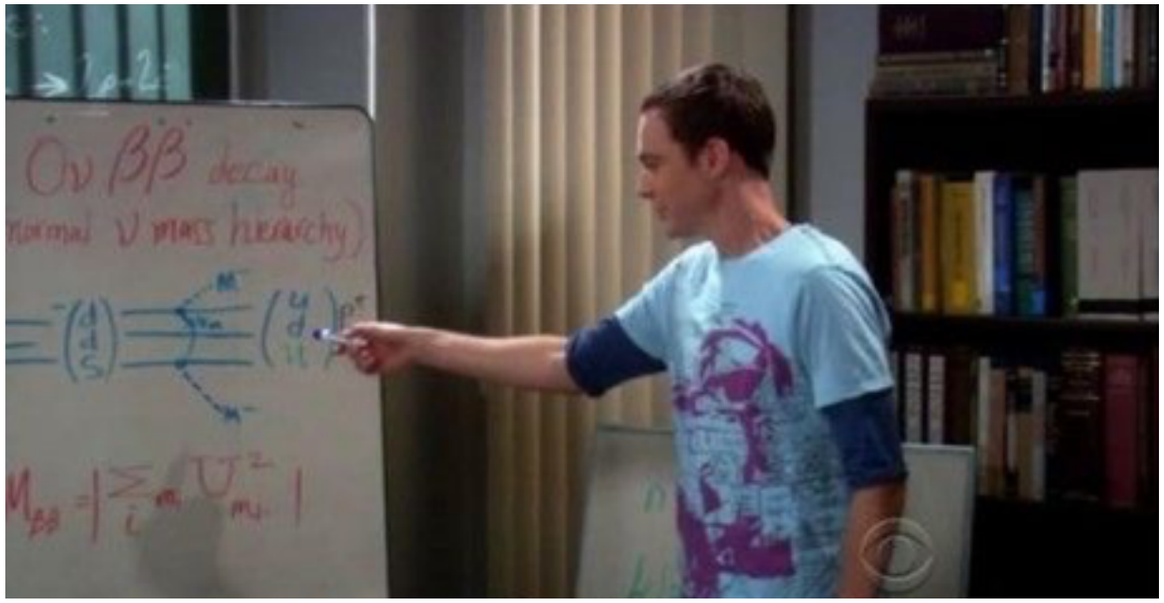
Institute for Nuclear & Particle Astrophysics

Nuclear Science Division

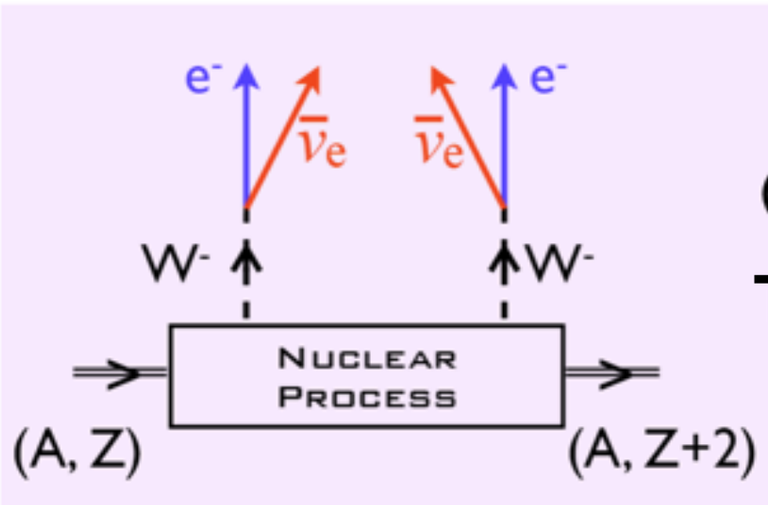
Outline



- **Introduction**
  - $0\nu\beta\beta$, Majorana ν…and all that
- **$0\nu\beta\beta$ decay experiments with discrete detectors**
  - Design considerations
  - Backgrounds
- **Challenges and solutions**
  - Ex.: Cosmogenic activation
  - Ex.: Electronics fabrication
  - Ex.: Rn background
- **Summary**



Is neutrino its own antiparticle?

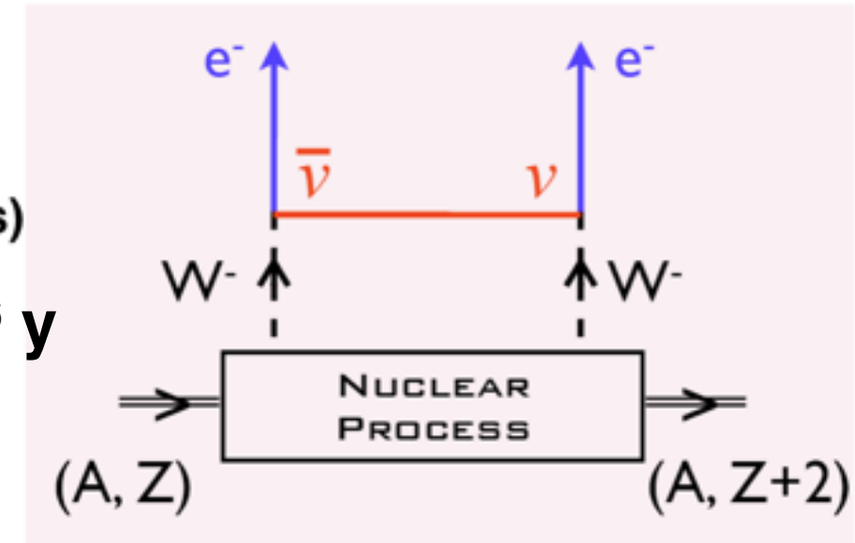


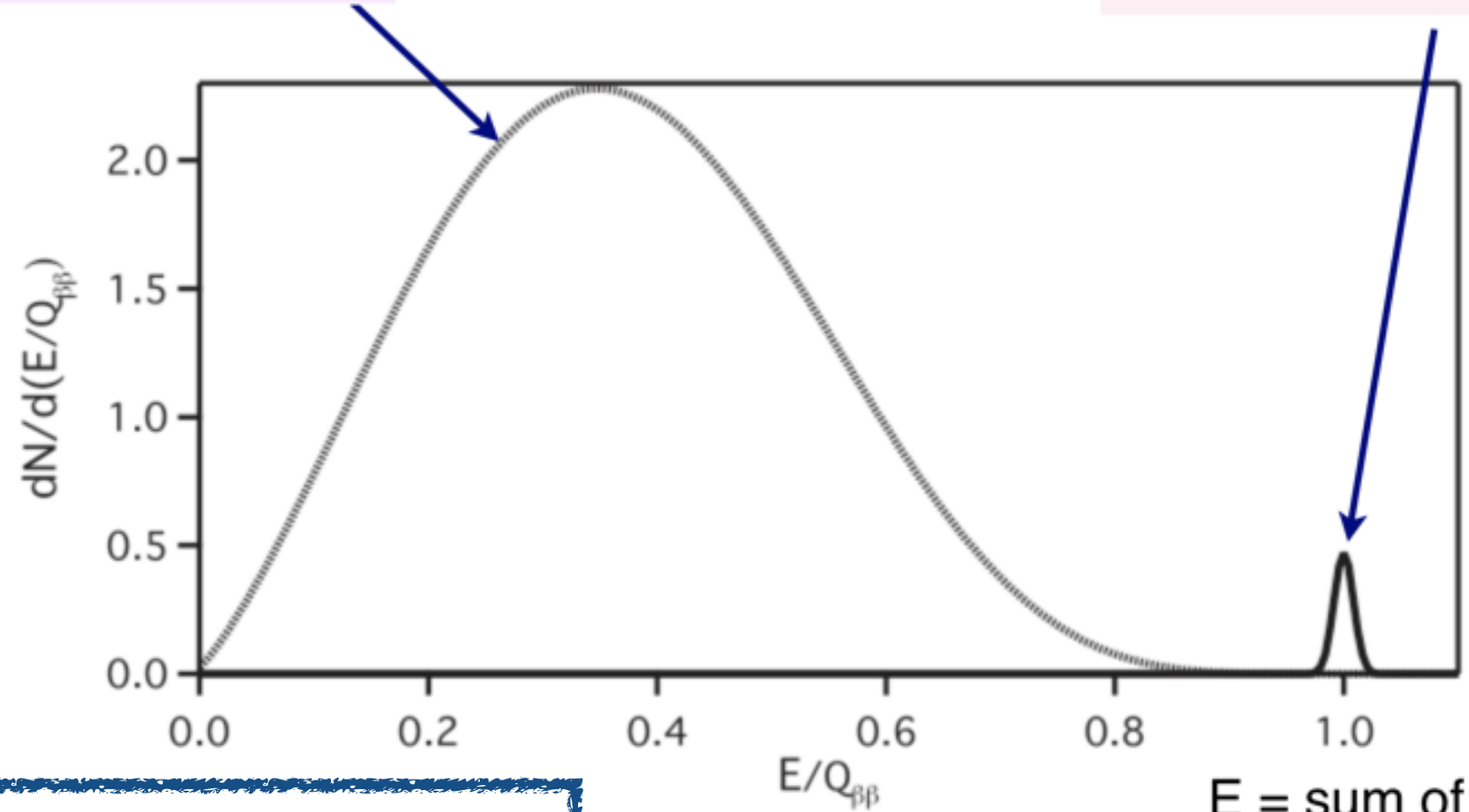
$2\nu\beta\beta$
(background)

$T_{1/2} \sim 10^{20}$ y

$0\nu\beta\beta$
(new physics)

$T_{1/2} > 10^{26}$ y

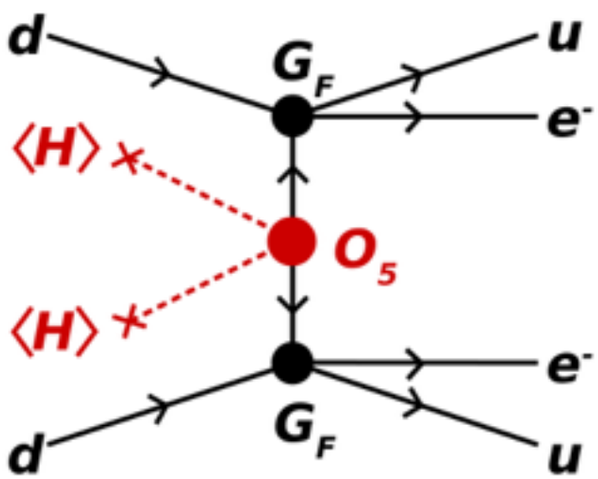




E = sum of electron energy

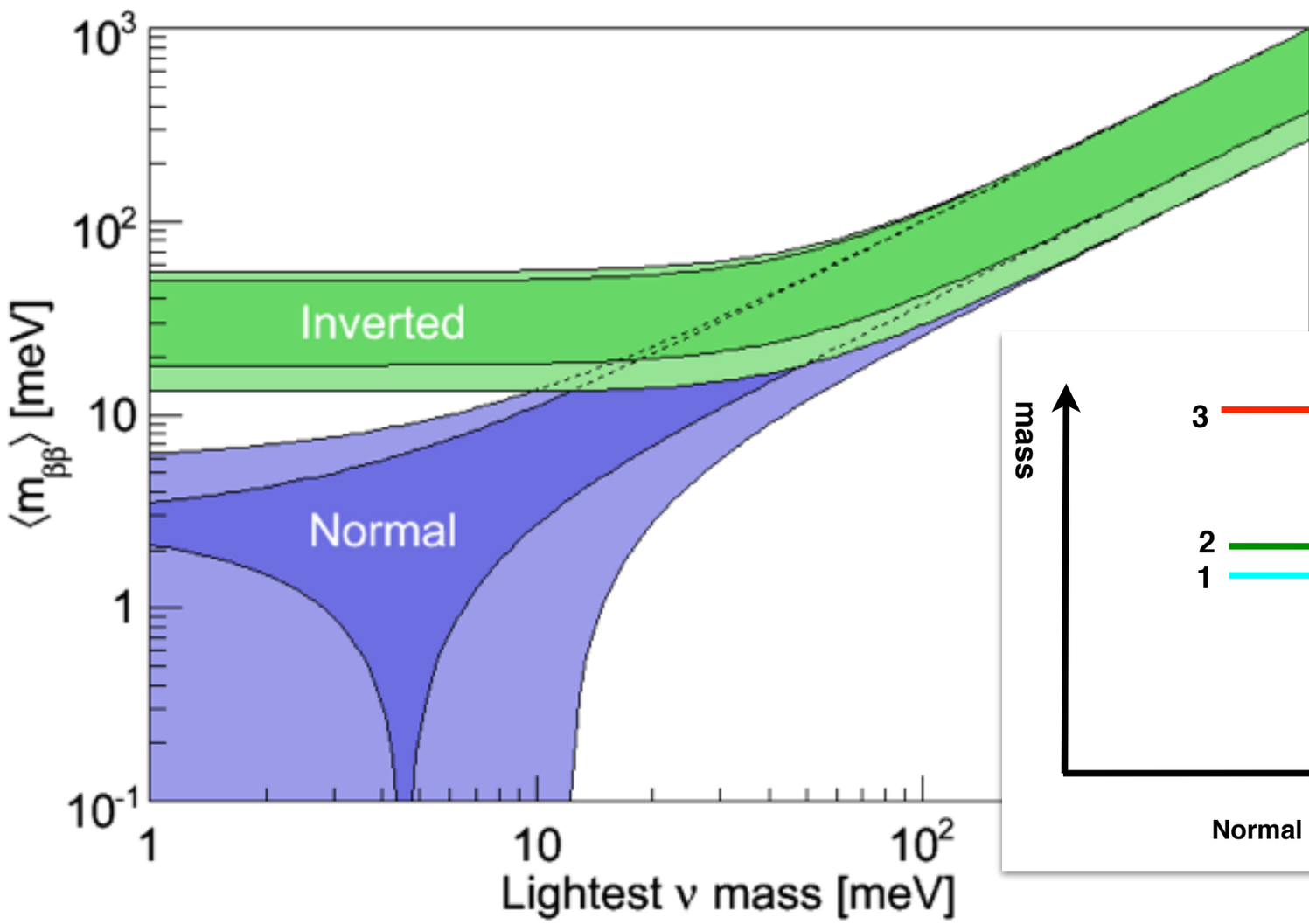
Energy resolution is key!

“Vanilla” light-Majorana mass mechanism

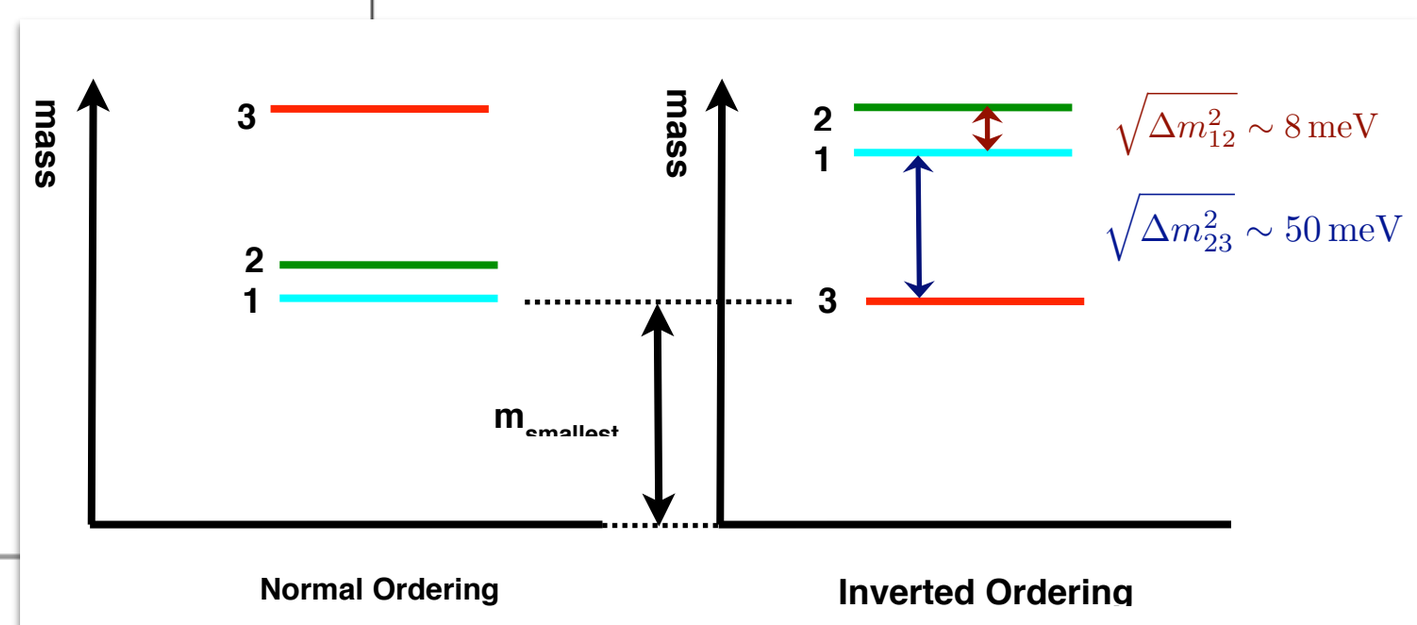


$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2$$

form factor — *nuclear matrix element* — *effective Majorana mass*



$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



Sensitivity

$$T_{1/2}(0\nu) \propto \sqrt{\frac{b\,\Delta E}{M\,T}}$$

Need:

- low background (b⬇)
- high detector energy resolution (ΔE⬇)
- large mass of ββ decaying isotope (M⬆)
- patience - count for a long time (T⬆)

Experimental background target

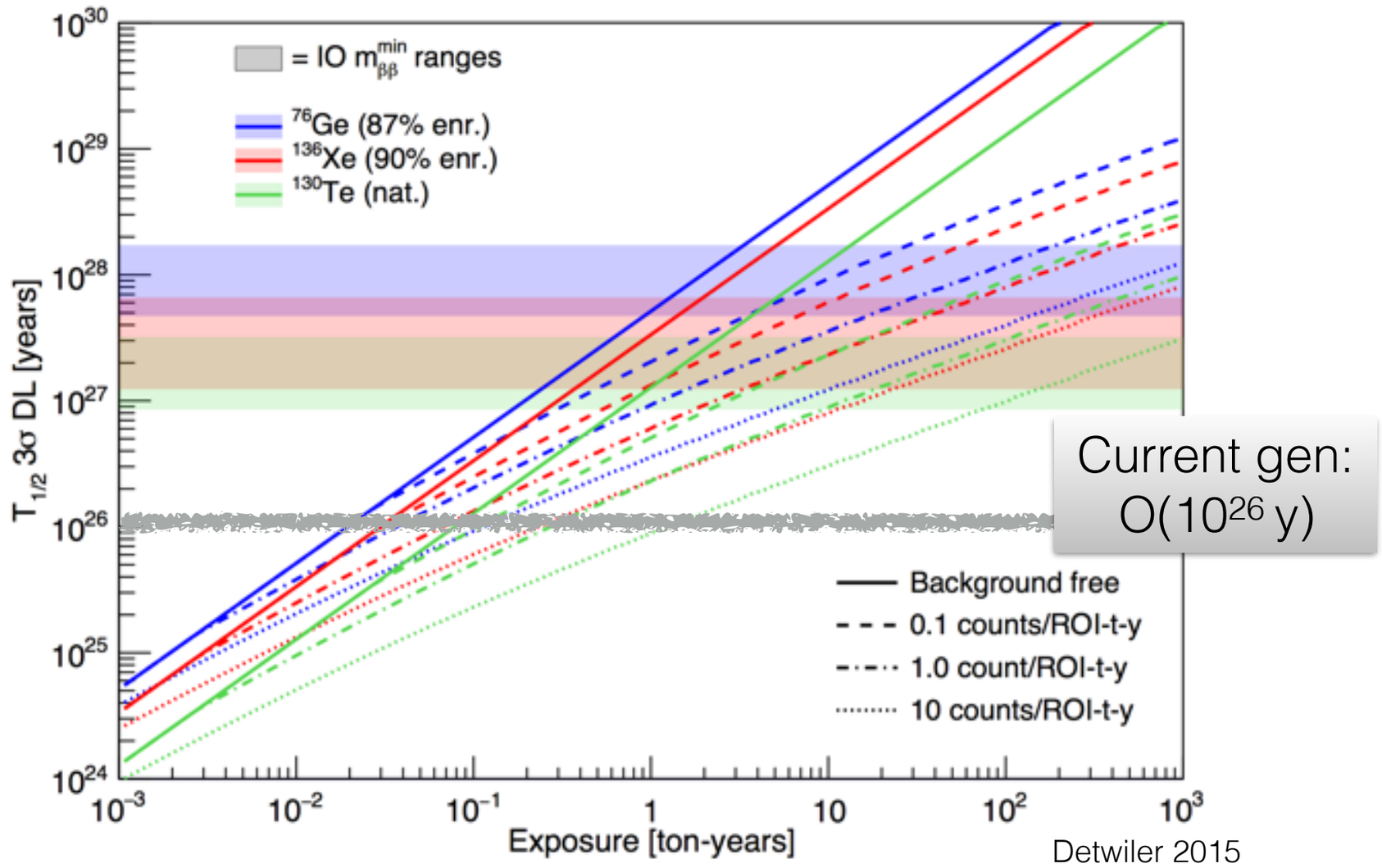
- Signal expected in real-time experiments

Type of experiment	Signal	Detection (*Background*) rate
SNO **Solar neutrino experiment (1998-2006)**	Cherenkov light from e^-	~15 events t^{-1} d^{-1}
LUX **WIMP search**	Scintillation light and ionization from nuclear recoils	(*~15 events t^{-1} d^{-1}*)
Future ^{76}Ge **neutrinoless double beta decay search**	e^- in Ge diode detectors	(*~0.1 event t^{-1} y^{-1}*)

- The SNO heavy water D_2O was purified to have ~10^{-15} (g ^{232}Th)/(g D_2O). The KamLAND liquid scintillator was purified to even higher purity.

Next-Generation 0νββ Experiments

$T_{1/2}$ (0ν)	Signal rate [cts/(ton-Ge y)]
10^{25} y	500
5×10^{26}	10
5×10^{27}	1
$> 10^{29}$	< 0.05

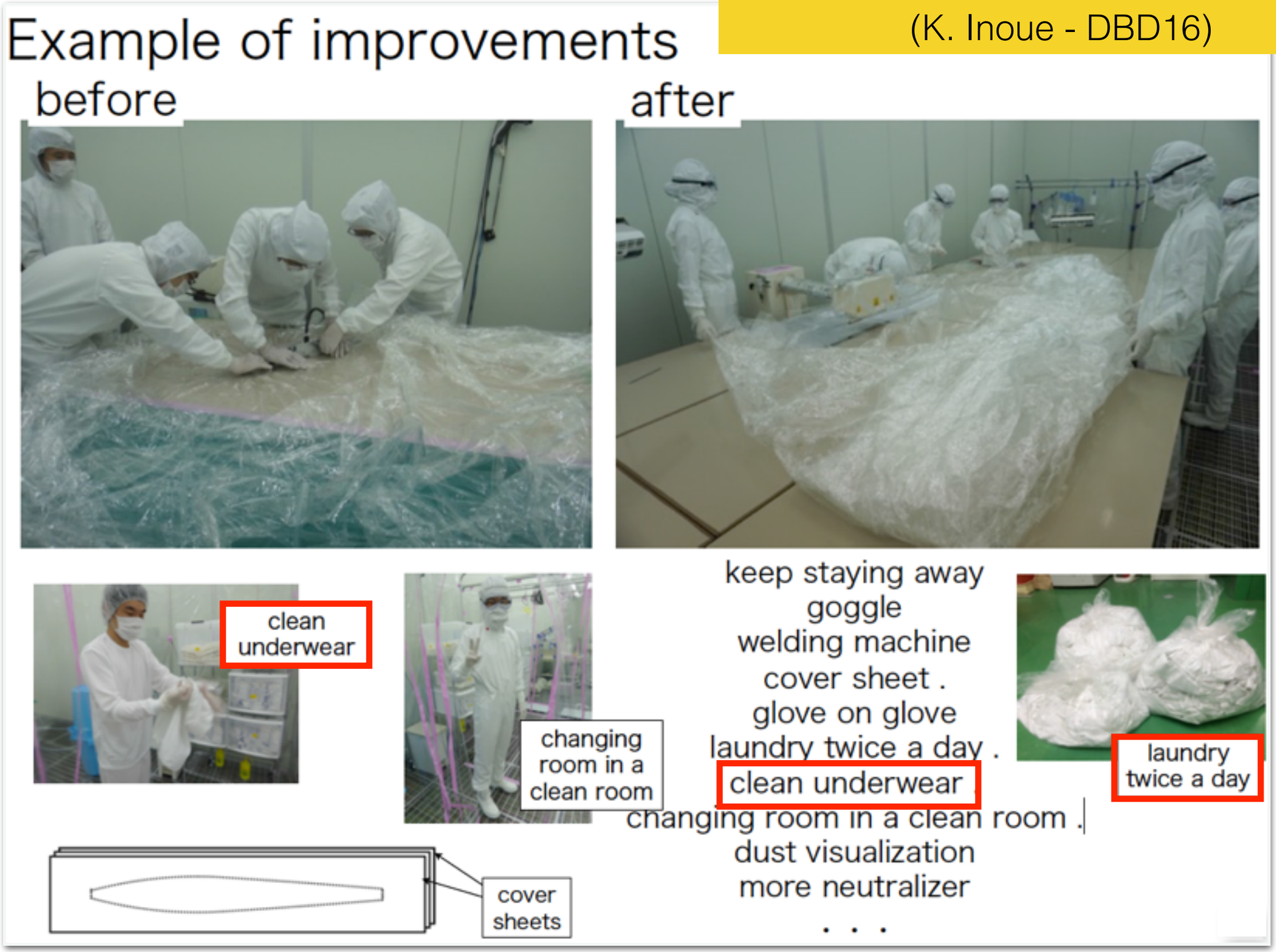


Detwiler 2015

- low background *$b \sim 0.1$ count/(ton-Ge yr) in ROI*

Keeping it clean

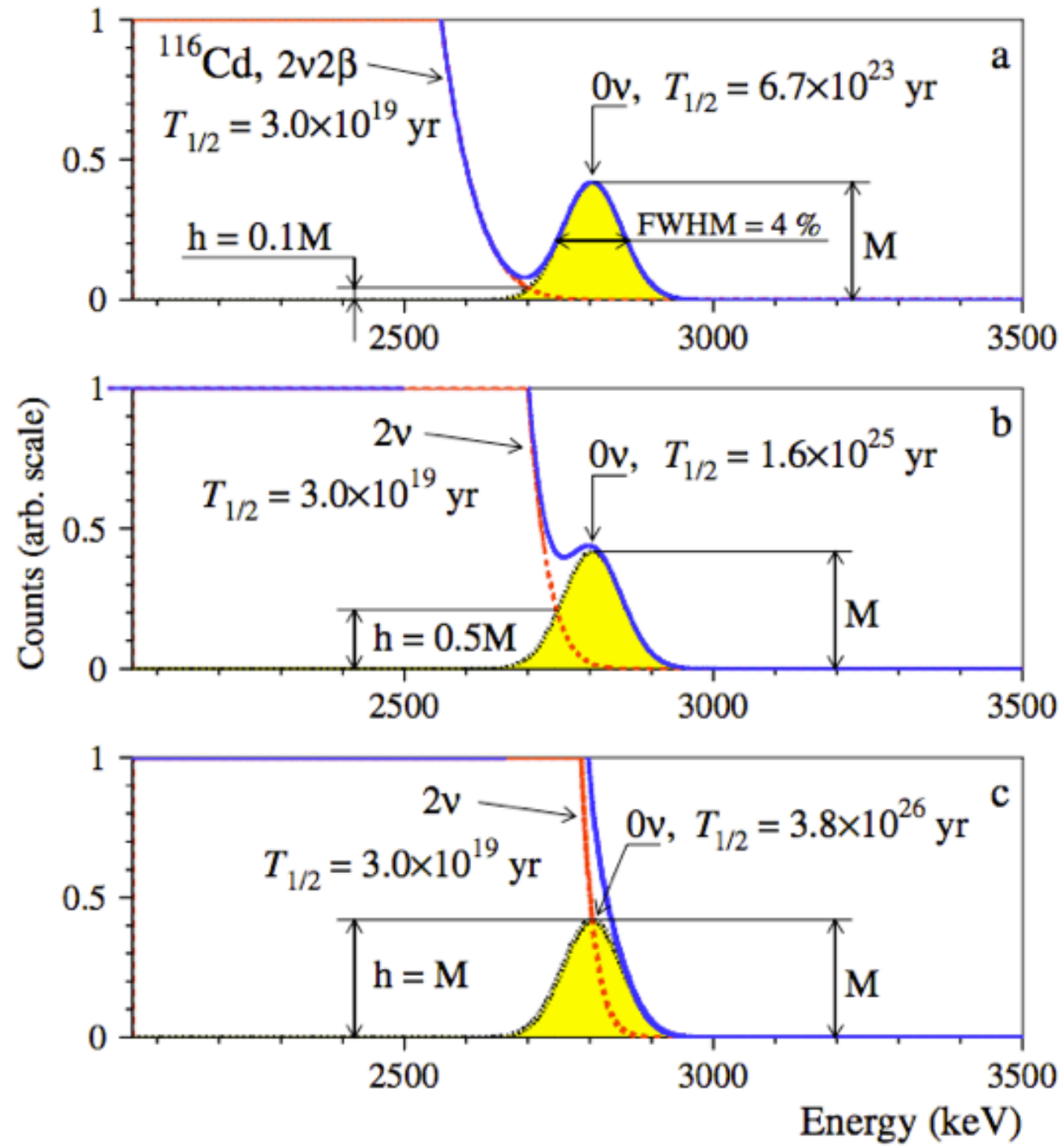
KamLAND-ZEN
clean balloon construction
(K. Inoue - DBD16)



Energy resolution ΔE and $2\nu\beta\beta$ background

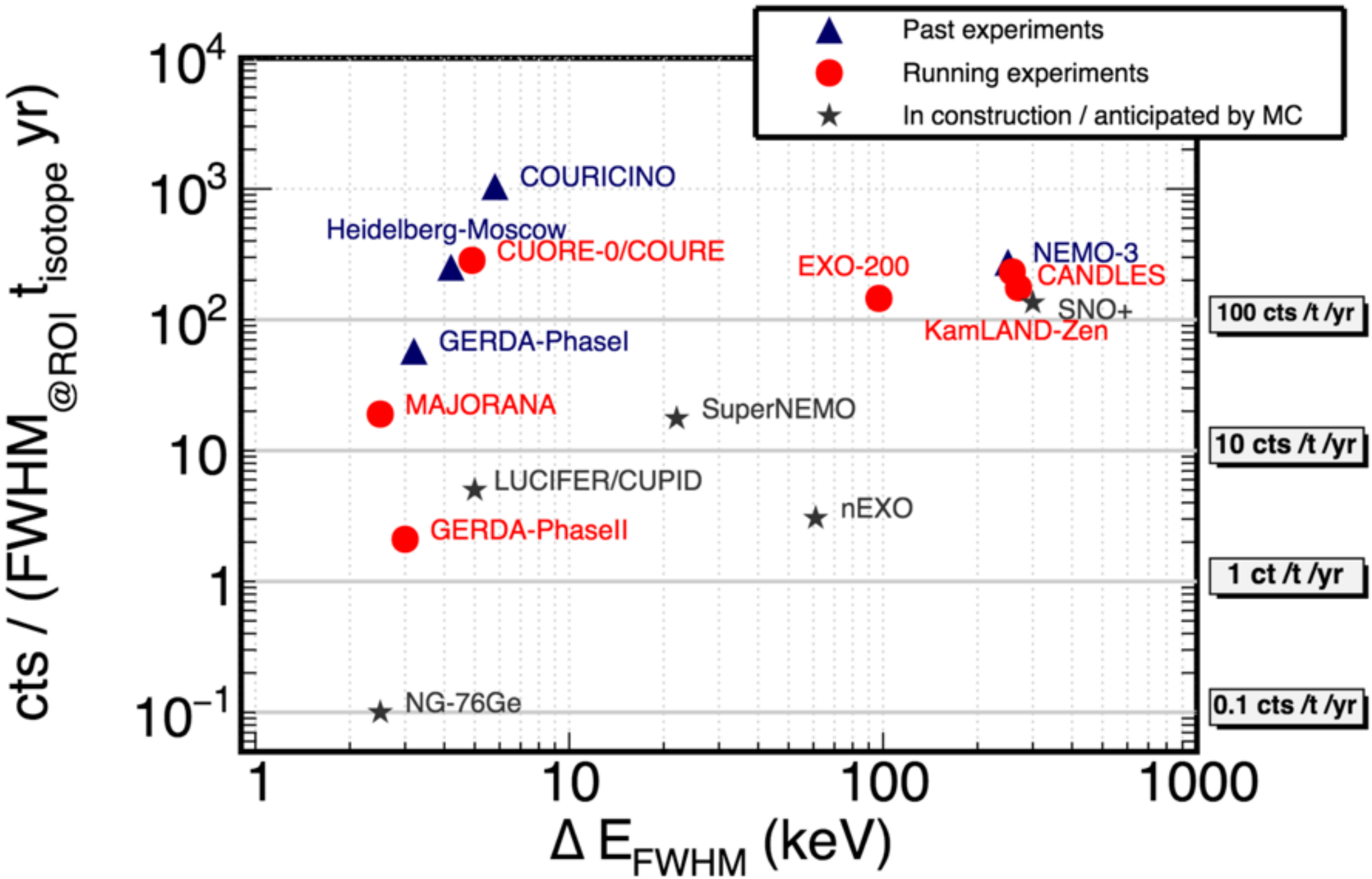
Isotope	$T_{1/2}$ (2ν) [10^{21} y]	
^{48}Ca	$(4.4^{+0.5}_{-0.4} \pm 0.4) \times 10^{-2}$	(NEMO-3)
^{76}Ge	$1.84^{+0.14}_{-0.10}$	(GERDA)
^{82}Se	$(9.6 \pm 0.3 \pm 1.0) \times 10^{-2}$	(NEMO-3)
^{96}Zr	$(2.35 \pm 0.14 \pm 0.16) \times 10^{-2}$	(NEMO-3)
^{100}Mo	$(0.57^{+0.13}_{-0.09} \pm 0.08) \times 10^{-2}$	(NEMO-3)
^{116}Cd	$(2.8 \pm 0.1 \pm 0.3) \times 10^{-2}$	(NEMO-3)
^{130}Te	$0.70 \pm 0.09 \pm 0.11$	(NEMO-3)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059$	(EXO-200)
	$2.38 \pm 0.02 \pm 0.14$	(KamLAND-Z)
^{150}Nd	$(9.11^{+0.25}_{-0.22} \pm 0.63) \times 10^{-3}$	(NEMO-3)

K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014)



Avignone et al., NJP 7 (2005) 6

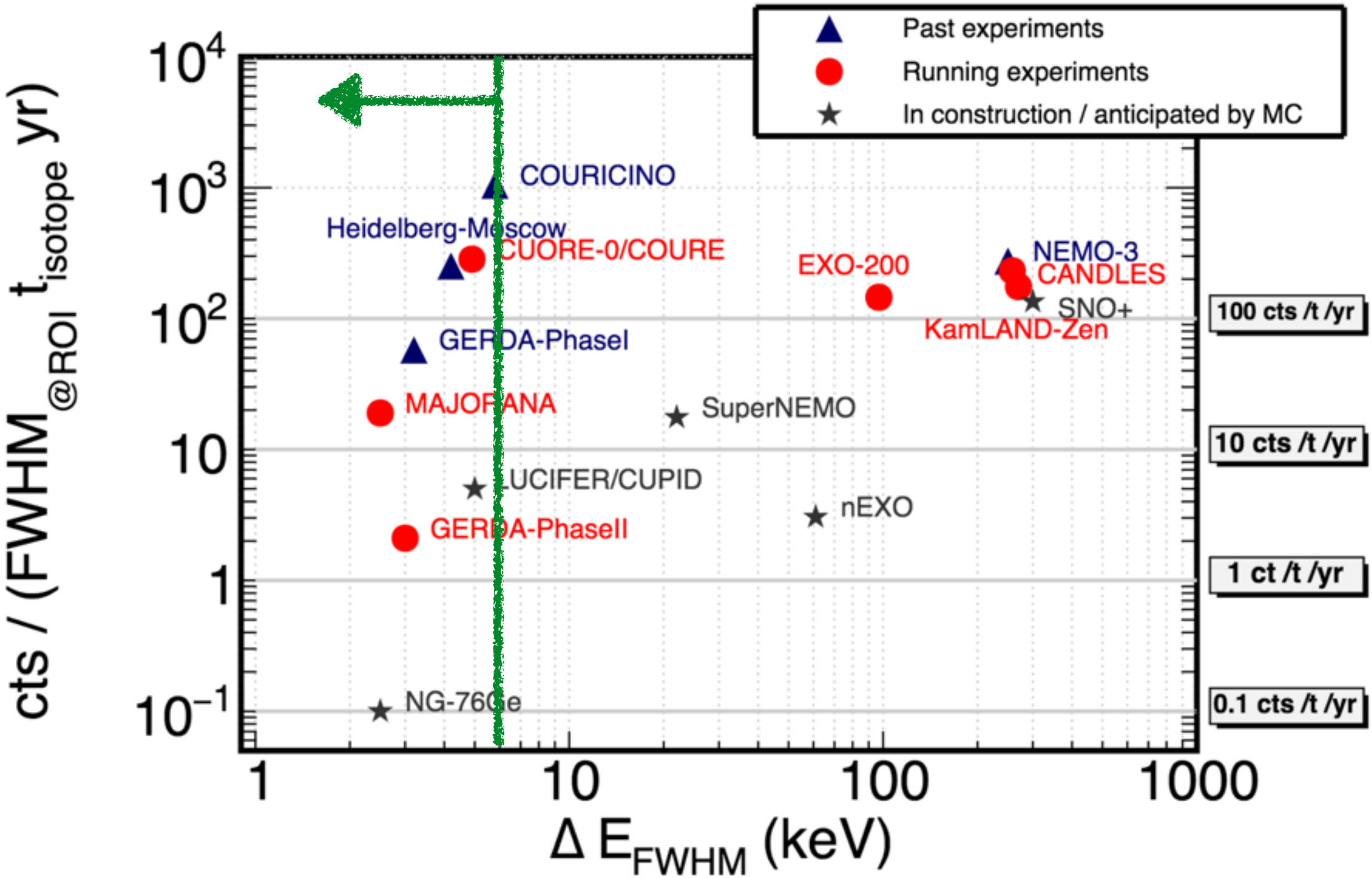
Background Comparison



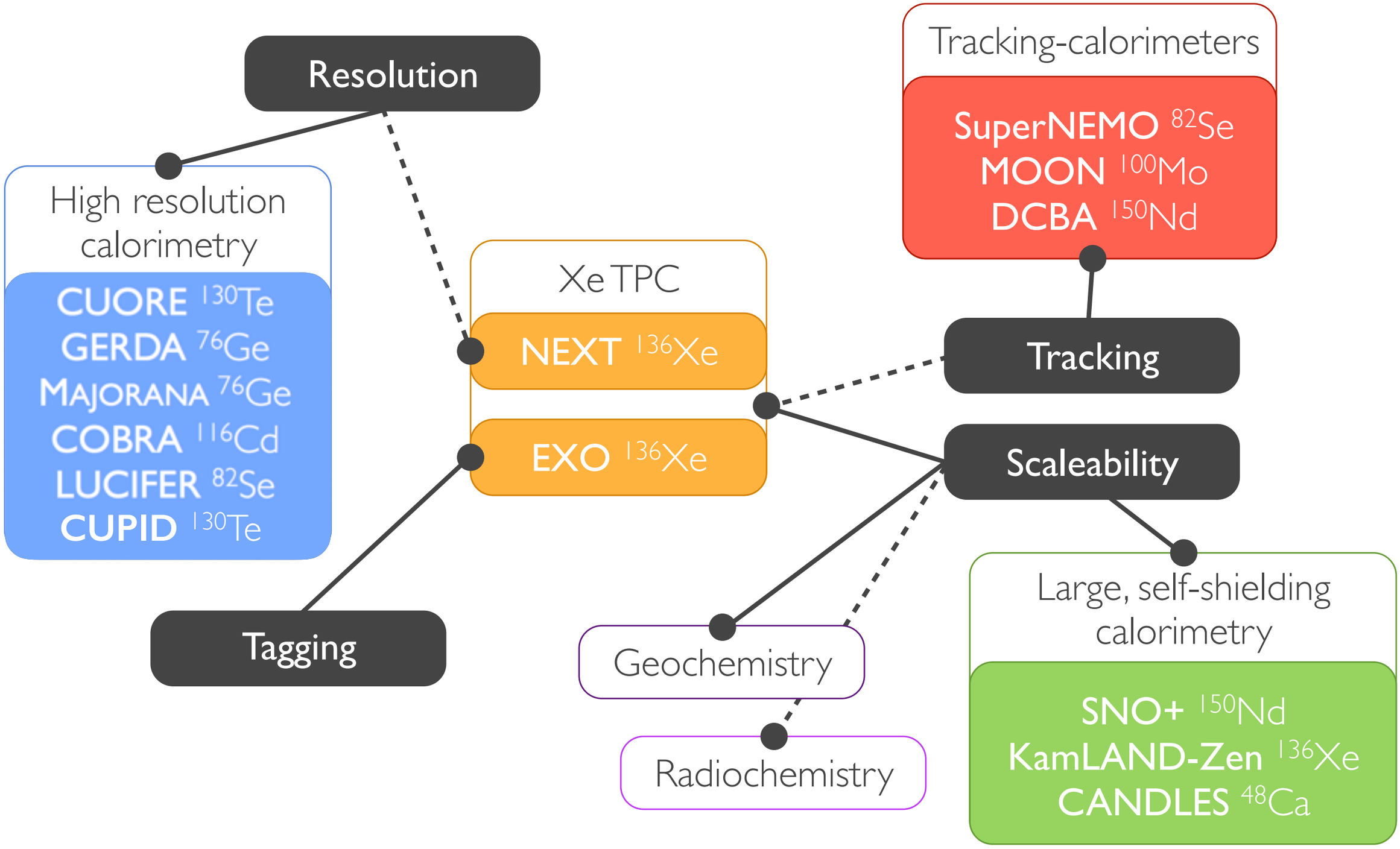
Background Comparison

source = detector
discrete detectors

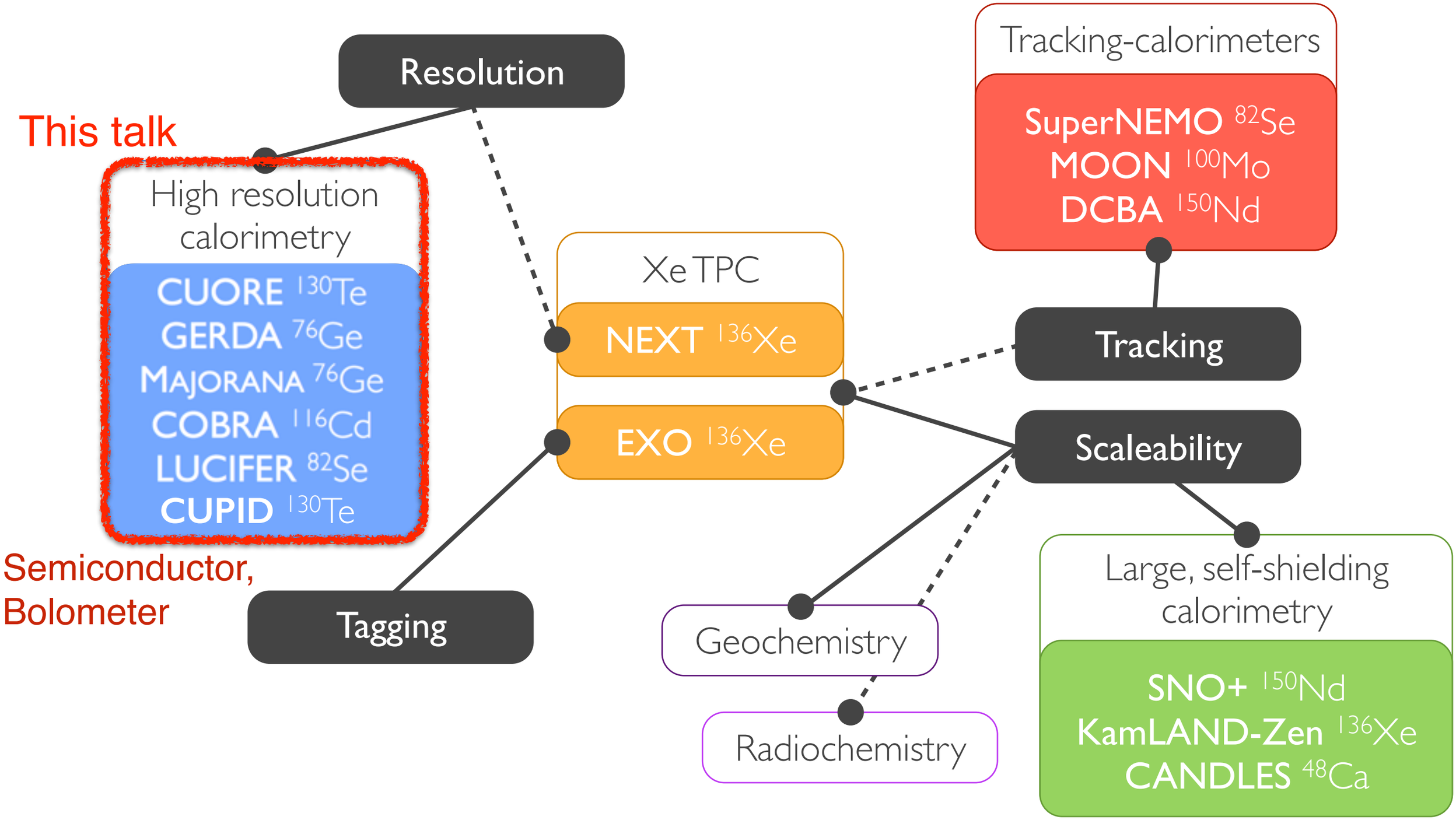
Best energy resolution



Detector Technology



Detector Technology



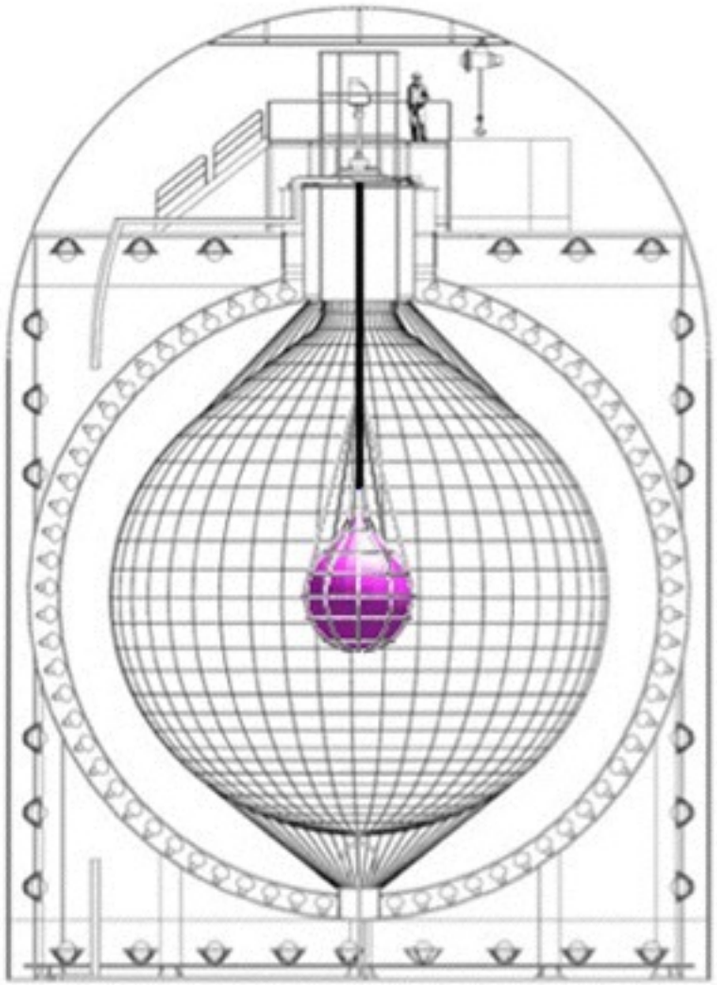
Discrete detectors

- Pros:
  - high detection efficiency (source = detector)
  - (usually) high energy resolution
  - scaling of 0νββ rate as systematic check (install detectors with different levels of isotope enrichment)
  - use neighboring detectors as veto (“granularity cut”)
- Cons:
  - extreme care in handling necessary
  - impossible / difficult to purify during operation
  - per-unit-mass detector cost could be high: isotopic enrichment + detector fabrication + material loss during fabrication

The ALARA principle

- Choose radiopure materials
- Keep hot stuff away from active detector volume

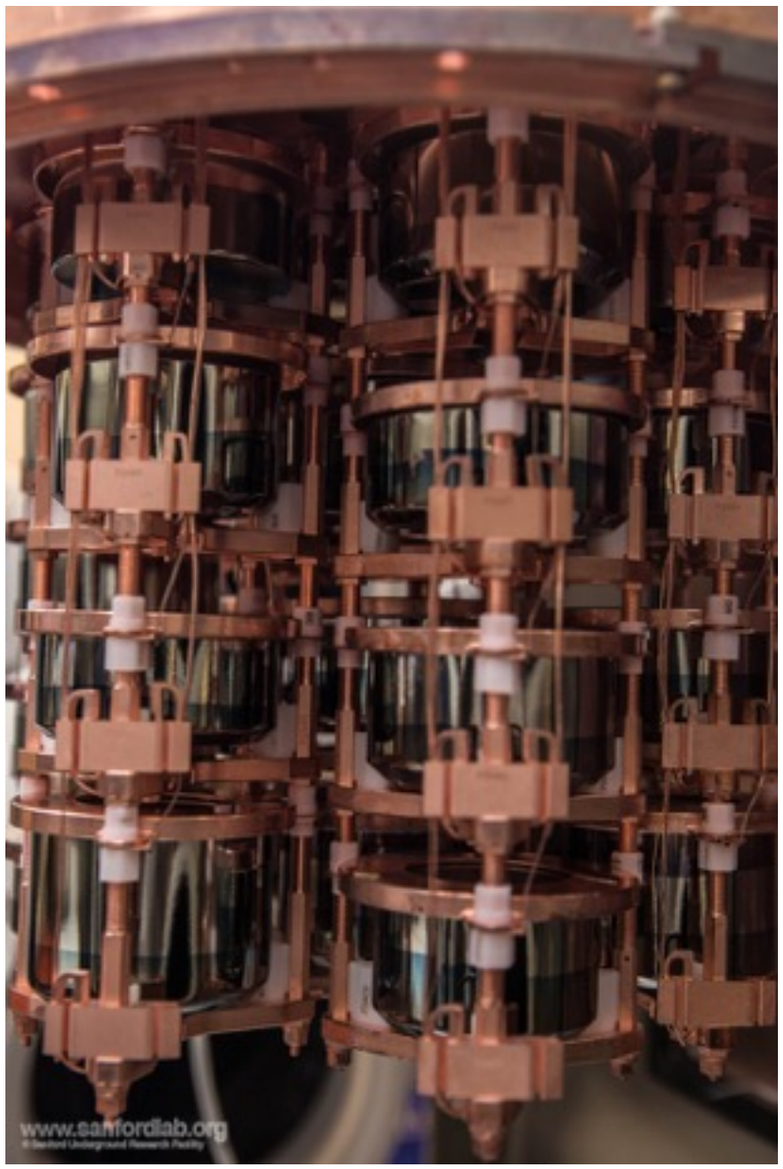
Homogeneous, self shielding, fiducial volume cut

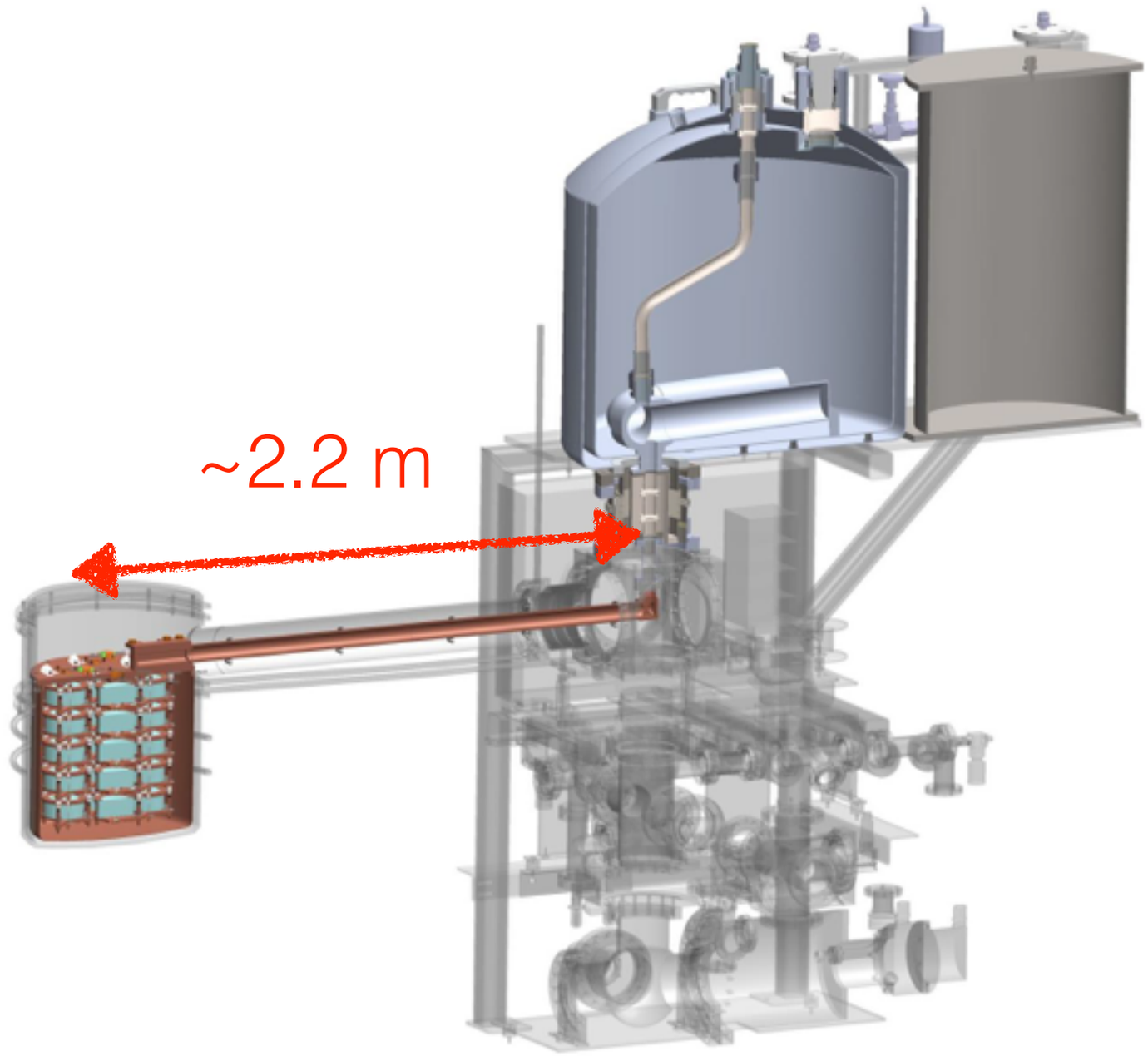


Ex: KamLAND-ZEN

The ALARA principle

- Choose radiopure materials
- Keep hot stuff away from active detector volume





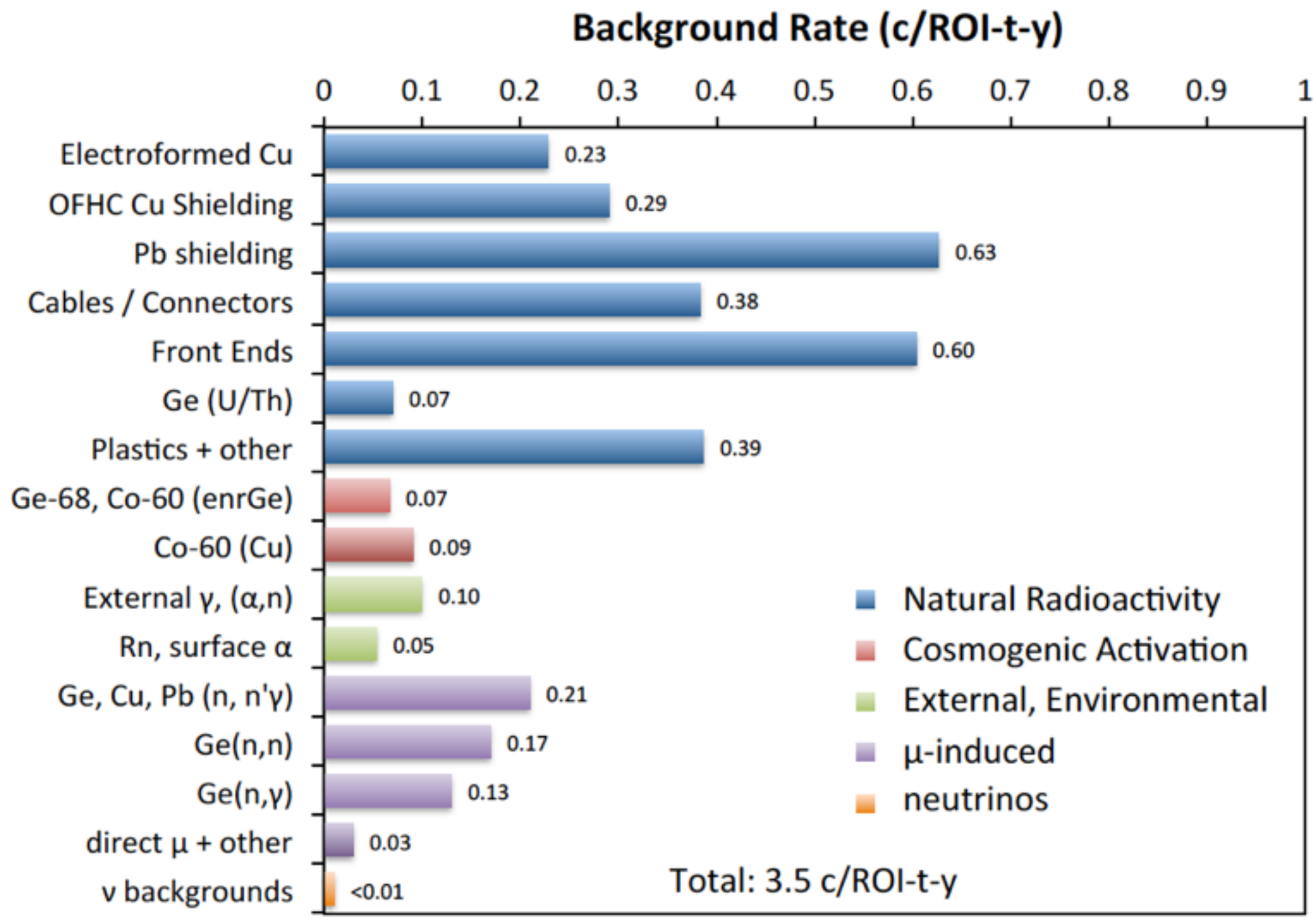
Ex: MAJORANA DEMONSTRATOR (^{76}Ge): Ge detectors in vacuum

The ALARA principle

- MAJORANA DEMONSTRATOR background budget:

Based on achieved assays of materials
When UL, use UL as the contribution

MJD goal: 3 cts / 4 keV / t-y
(scale to 1 cts / 4 keV / t-y in large-scaleGe)

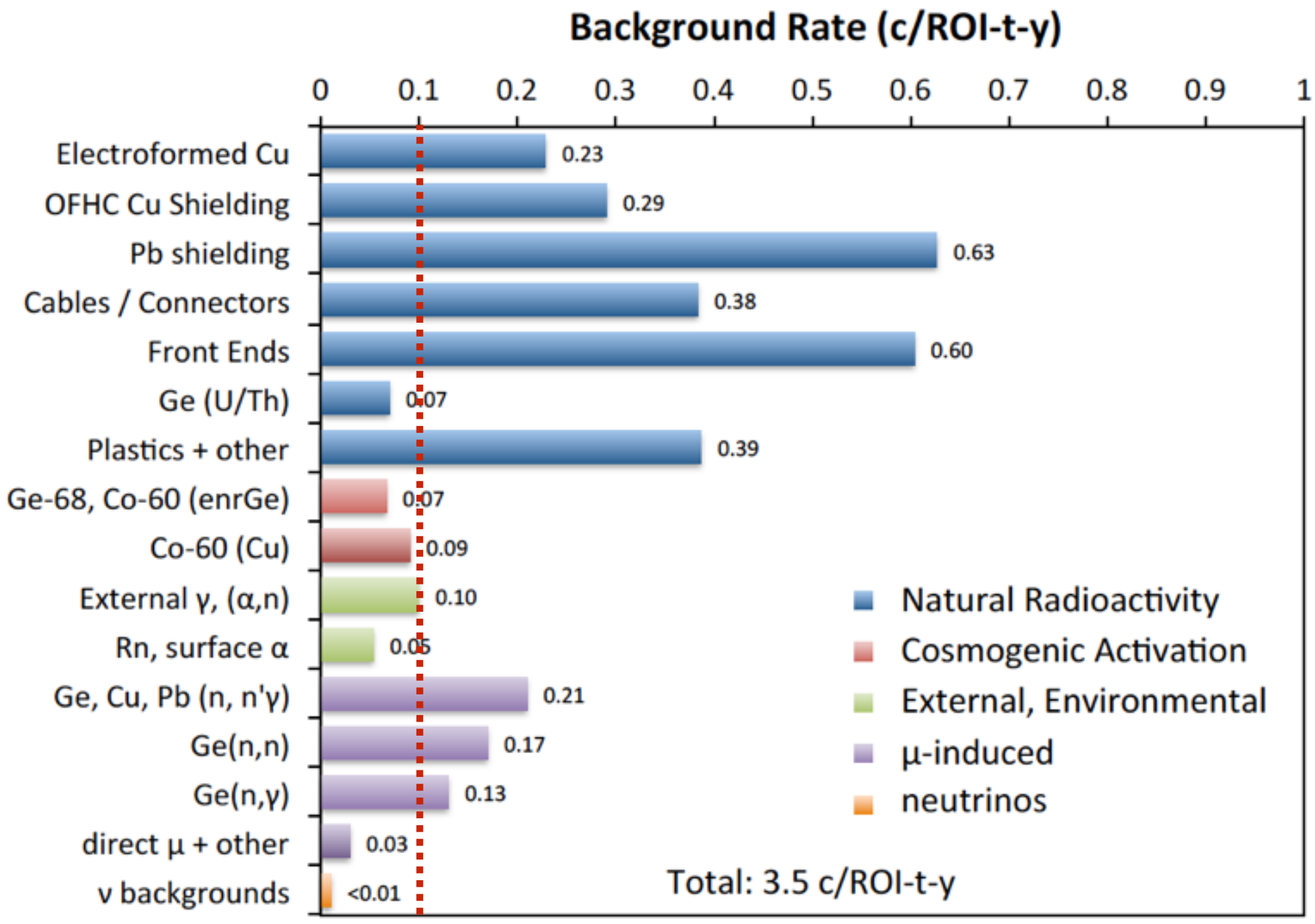


The ALARA principle

- MAJORANA DEMONSTRATOR background budget:

Based on achieved assays of materials
When UL, use UL as the contribution

MJD goal: 3 cts / 4 keV / t-y
(scale to 1 cts / 4 keV / t-y in large-scaleGe)



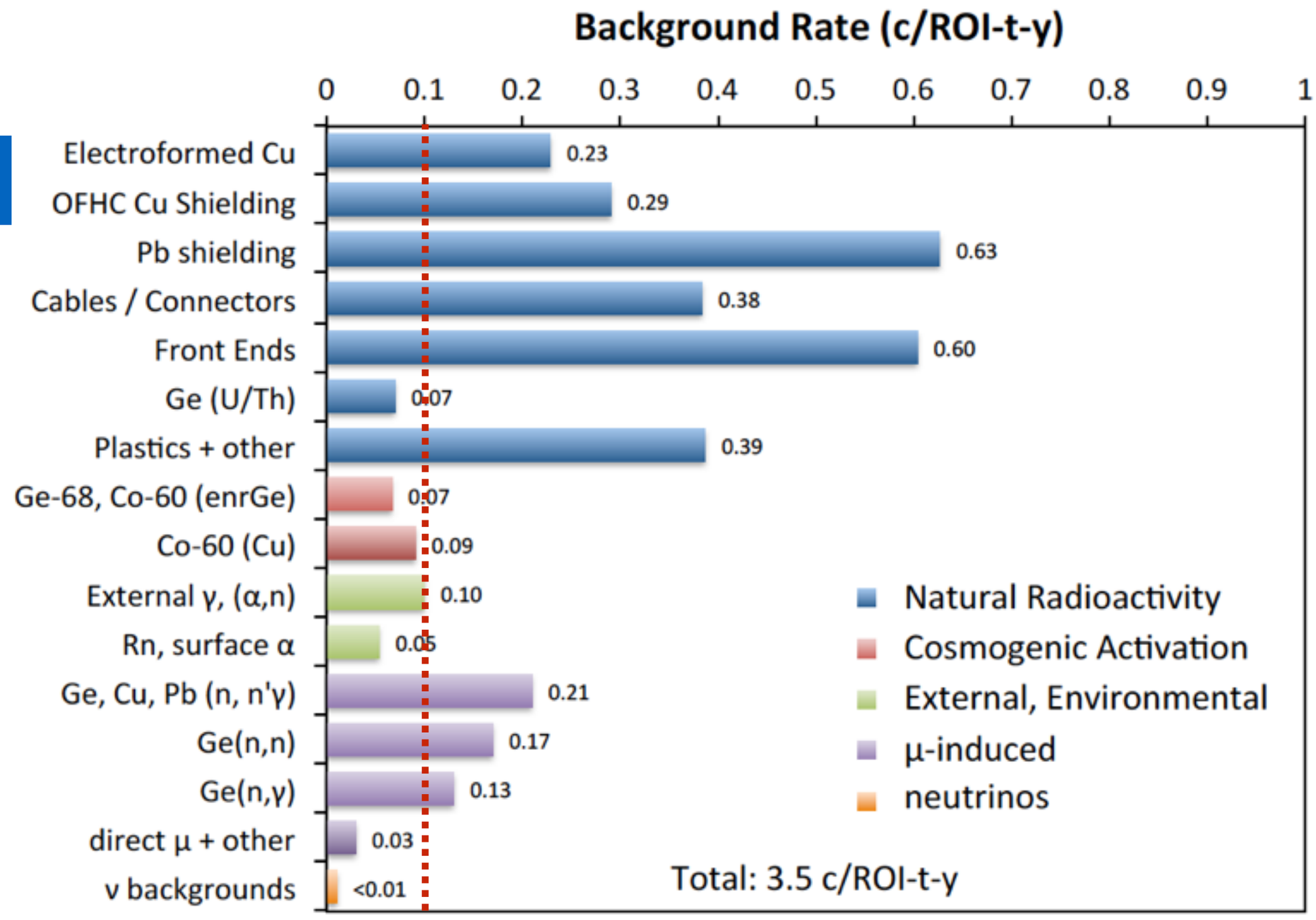
The ALARA principle

- MAJORANA DEMONSTRATOR background budget:

Based on achieved assays of materials
When UL, use UL as the contribution

MJD goal: 3 cts / 4 keV / t-y
(scale to 1 cts / 4 keV / t-y in large-scaleGe)

- cleaner materials
- active veto



The ALARA principle

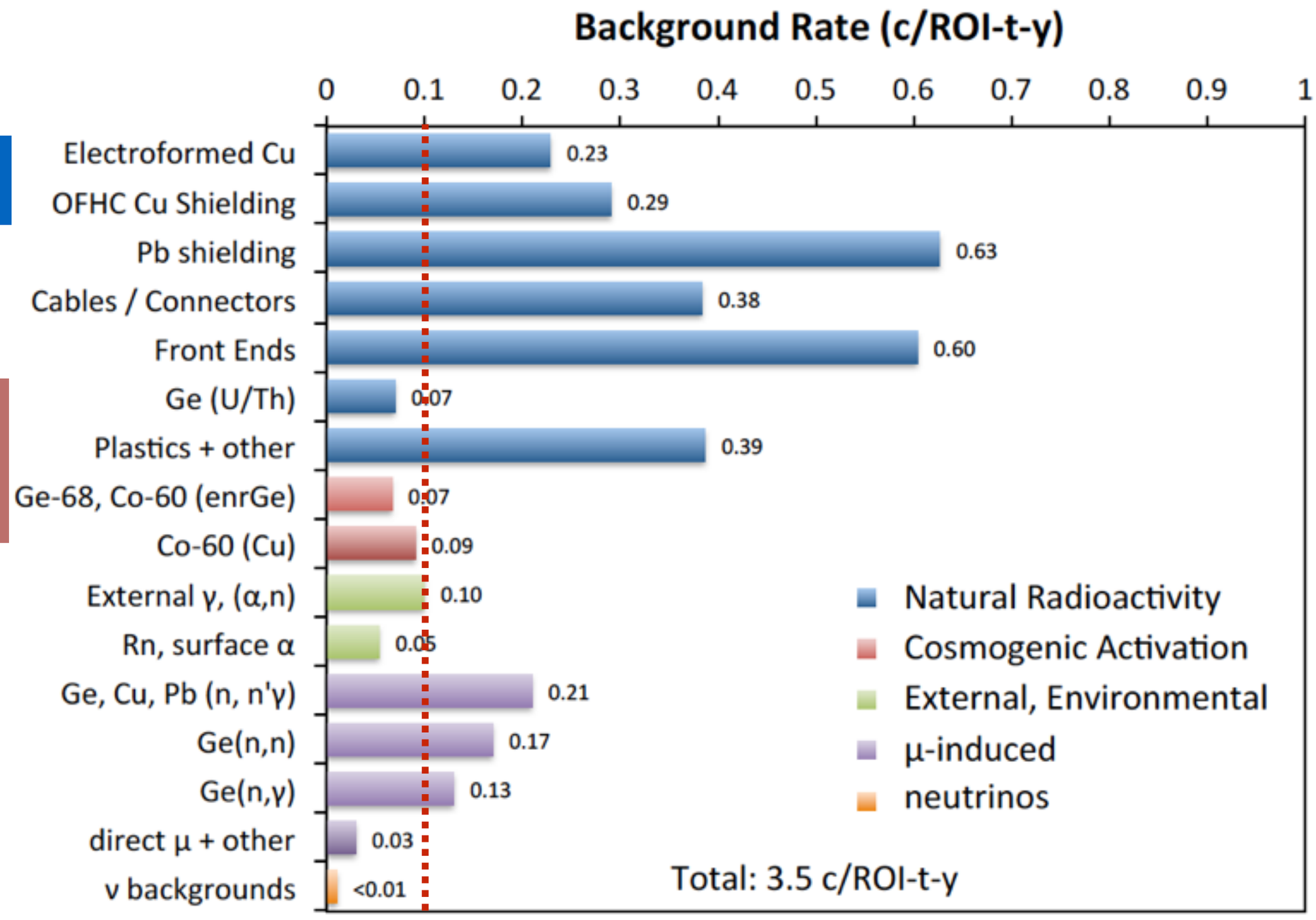
- MAJORANA DEMONSTRATOR background budget:

Based on achieved assays of materials
When UL, use UL as the contribution

MJD goal: 3 cts / 4 keV / t-y
(scale to 1 cts / 4 keV / t-y in large-scaleGe)

- cleaner materials
- active veto

- reduce exposure to cosmic-ray
- underground production



The ALARA principle

- MAJORANA DEMONSTRATOR background budget:

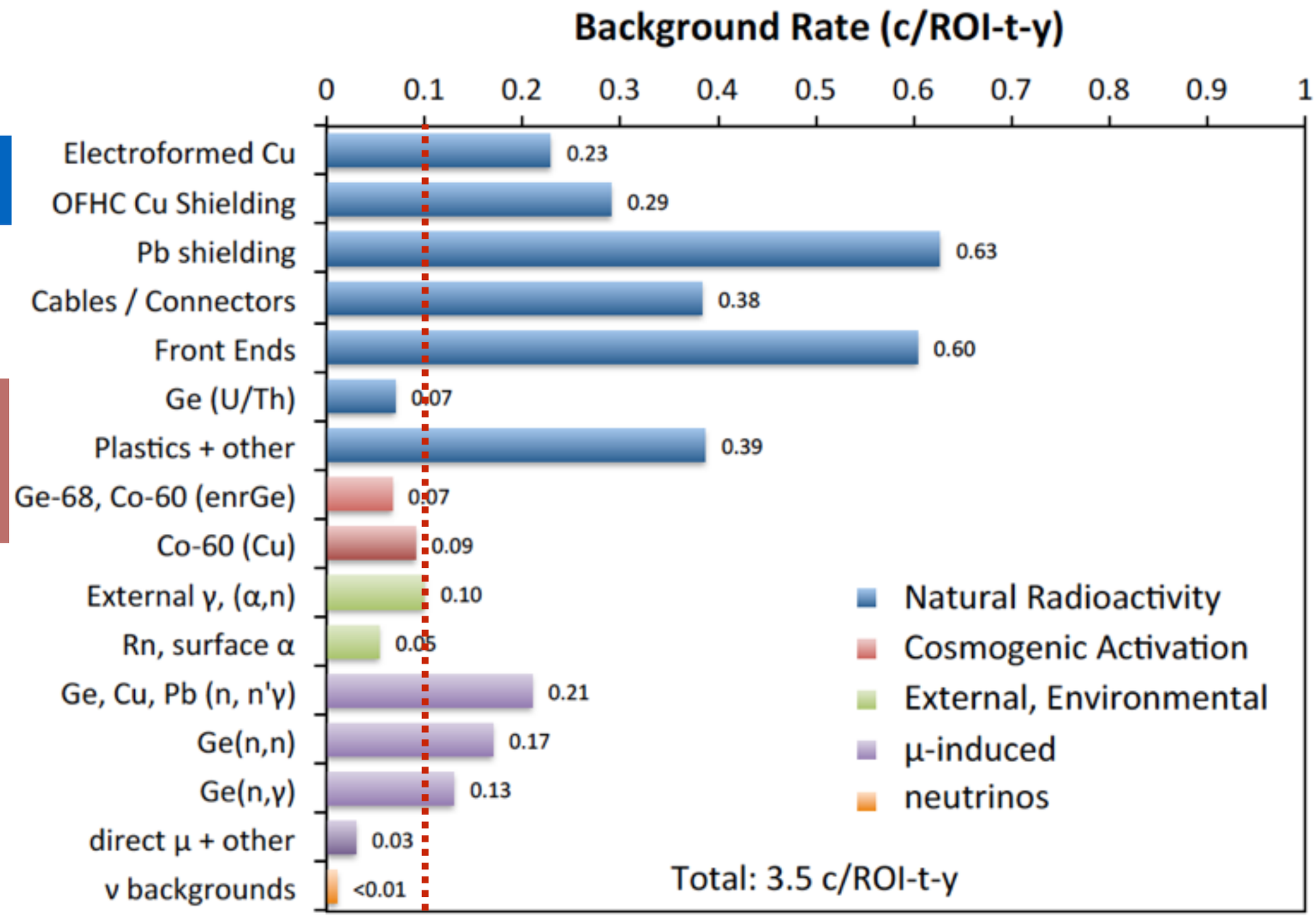
Based on achieved assays of materials
When UL, use UL as the contribution

MJD goal: 3 cts / 4 keV / t-y
(scale to 1 cts / 4 keV / t-y in large-scaleGe)

- cleaner materials
- active veto

- reduce exposure to cosmic-ray
- underground production

- better shielding
- Rn control



The ALARA principle

- MAJORANA DEMONSTRATOR background budget:

Based on achieved assays of materials
When UL, use UL as the contribution

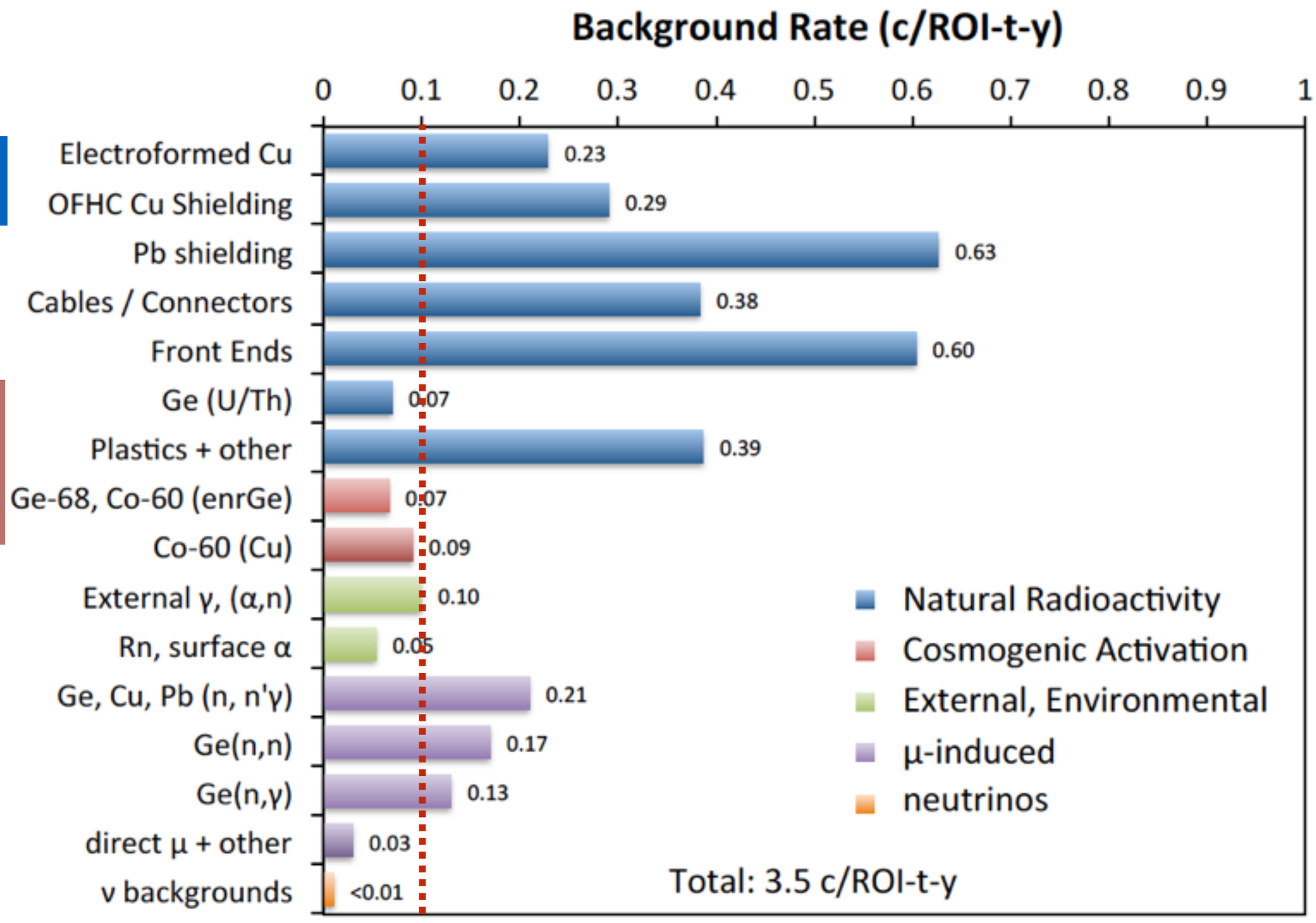
MJD goal: 3 cts / 4 keV / t-y
(scale to 1 cts / 4 keV / t-y in large-scaleGe)

- cleaner materials
- active veto

- reduce exposure to cosmic-ray
- underground production

- better shielding
- Rn control

- deeper lab
- better shielding



Example:

- Cosmogenic activation

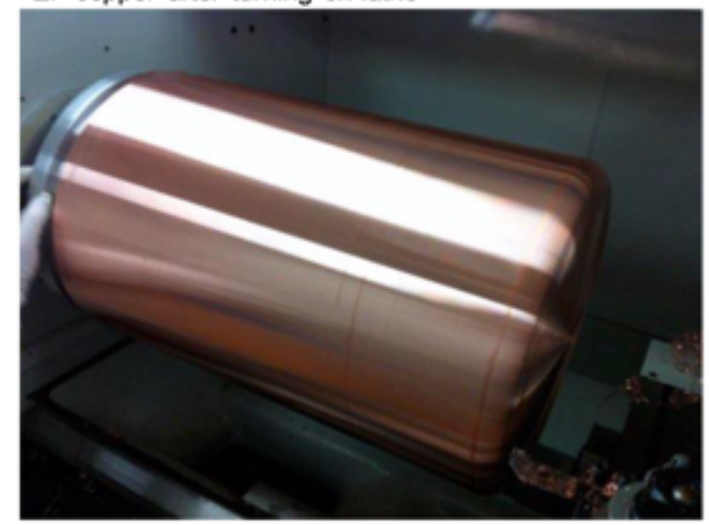
MJD Electroformed Cu

- MAJORANA operated 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 was machined at the Davis campus.
- The electroforming of copper for the DEMONSTRATOR successfully completed in May 2015.
  - 2474 kg of electroformed copper on the mandrels
  - 2104 kg after initial machining,
  - 1196 kg that will be installed in the DEMONSTRATOR.

Electroforming Baths in TCR

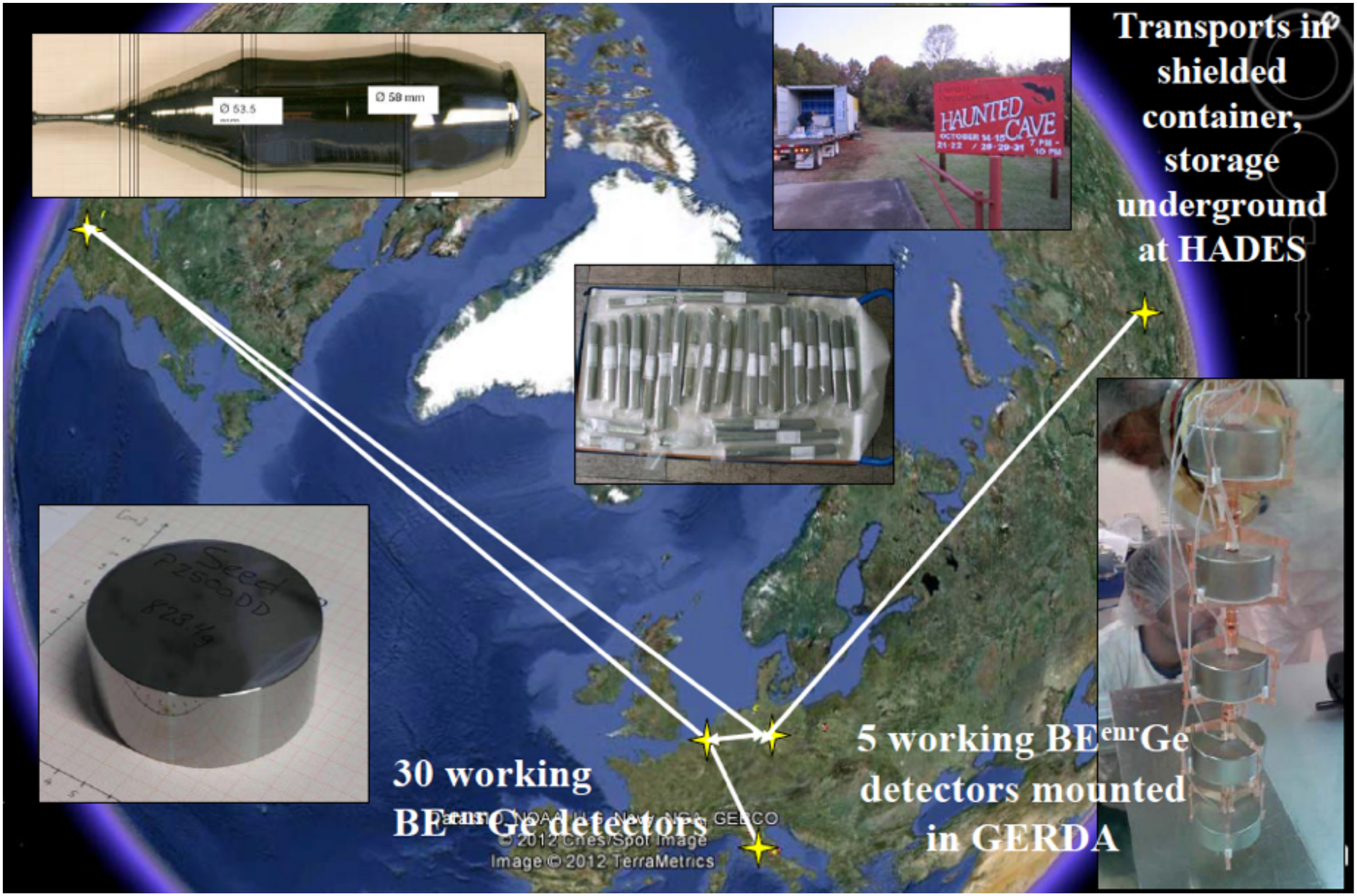
Inspection of EF copper on mandrels

EF copper after turning on lathe



- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

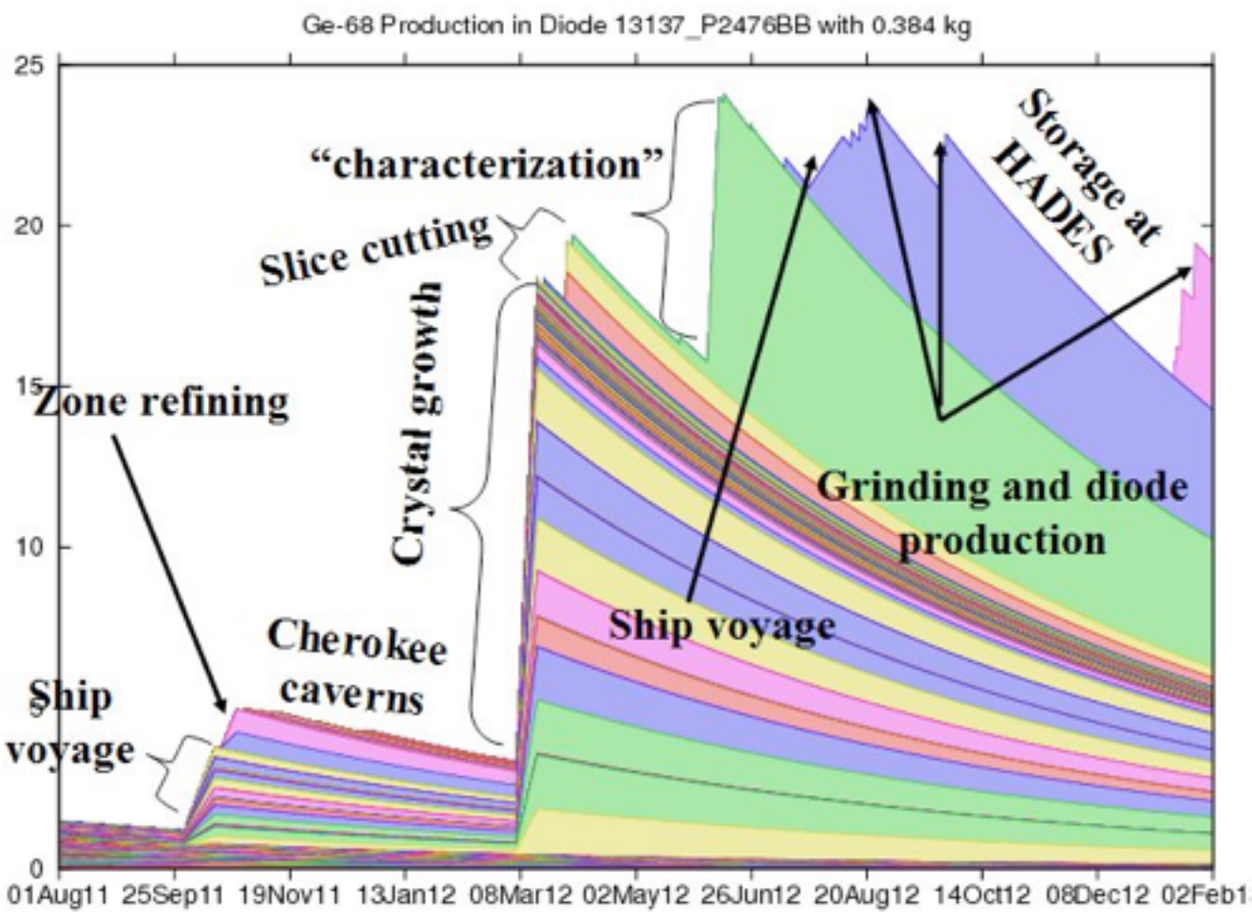
Material transport (GERDA)



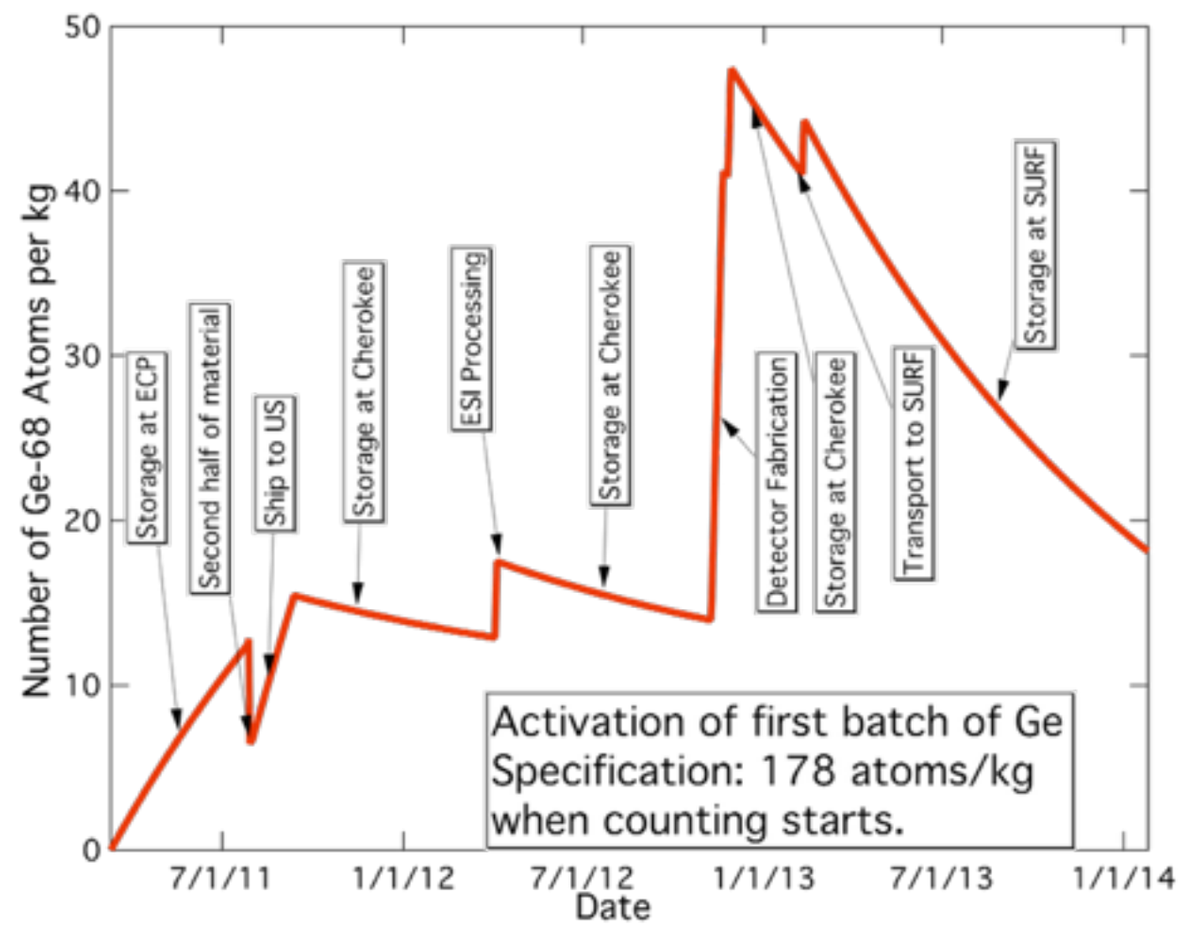
Majorovits 2014

Cosmogenic backgrounds

GERDA



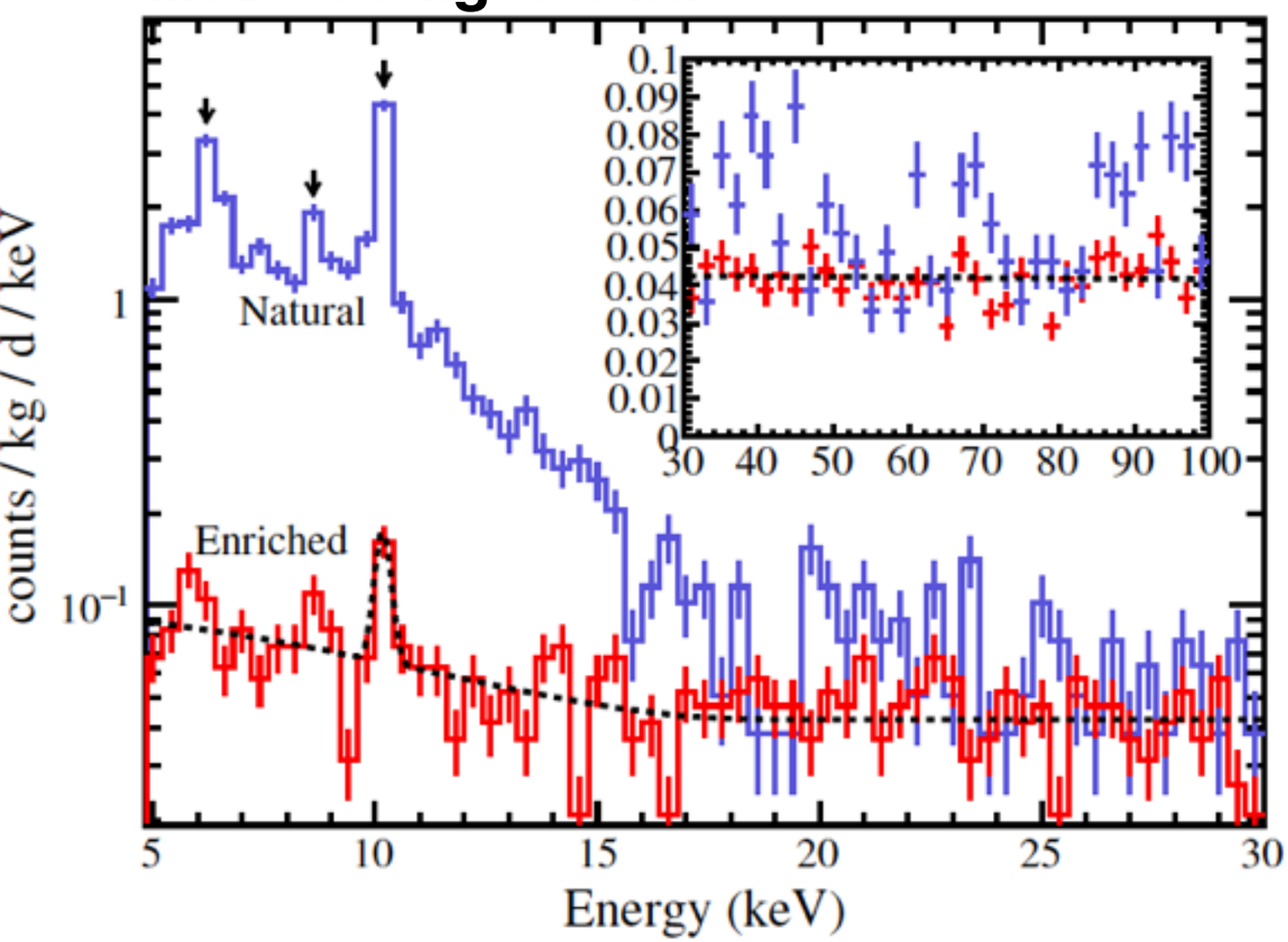
MAJORANA DEMONSTRATOR

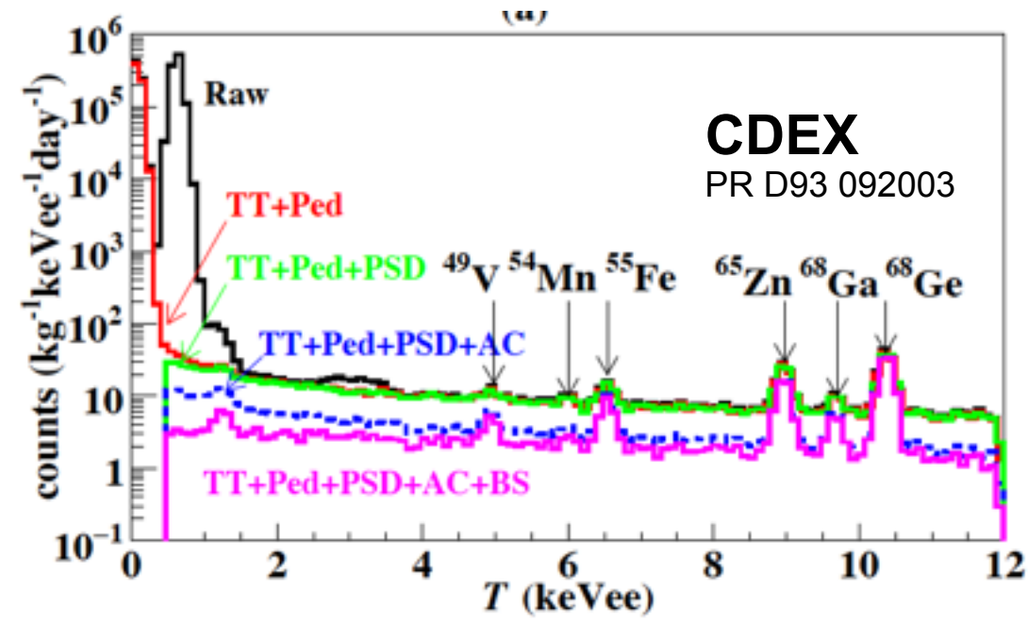


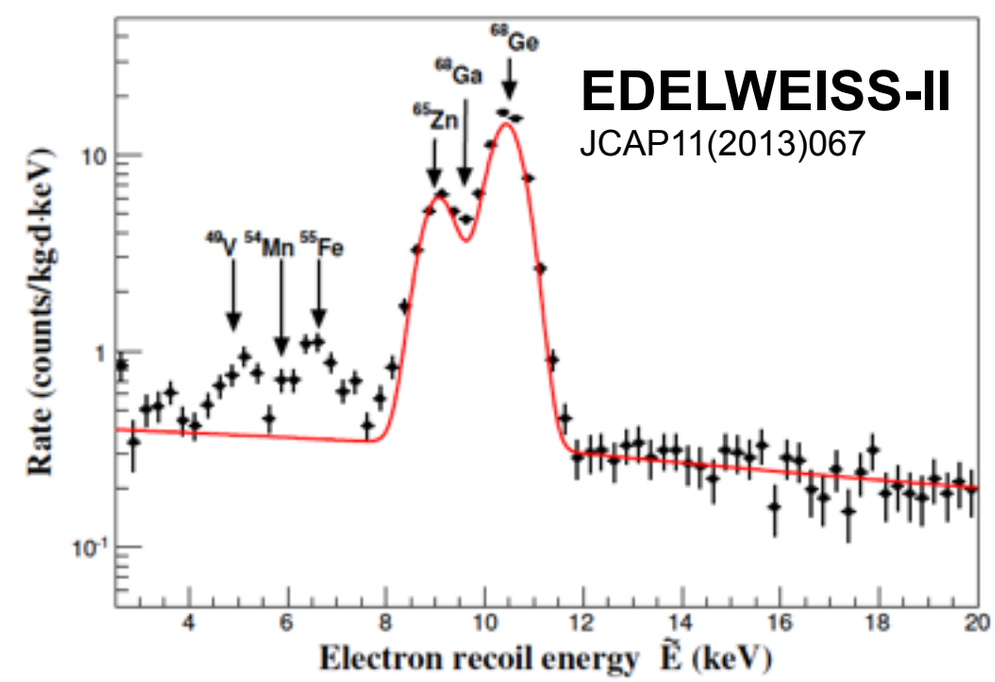
- Avoid re-growing crystal, re-work detectors (no shielding)
- Minimize transport (long exposure with some / no shielding)

Cosmogenic backgrounds at low energy

MJD 478 kg-d data







Low background in low-energy regime - extended low-energy physics program to search for physics beyond the Standard Model.

Pseudo-scale coupling results - MJD

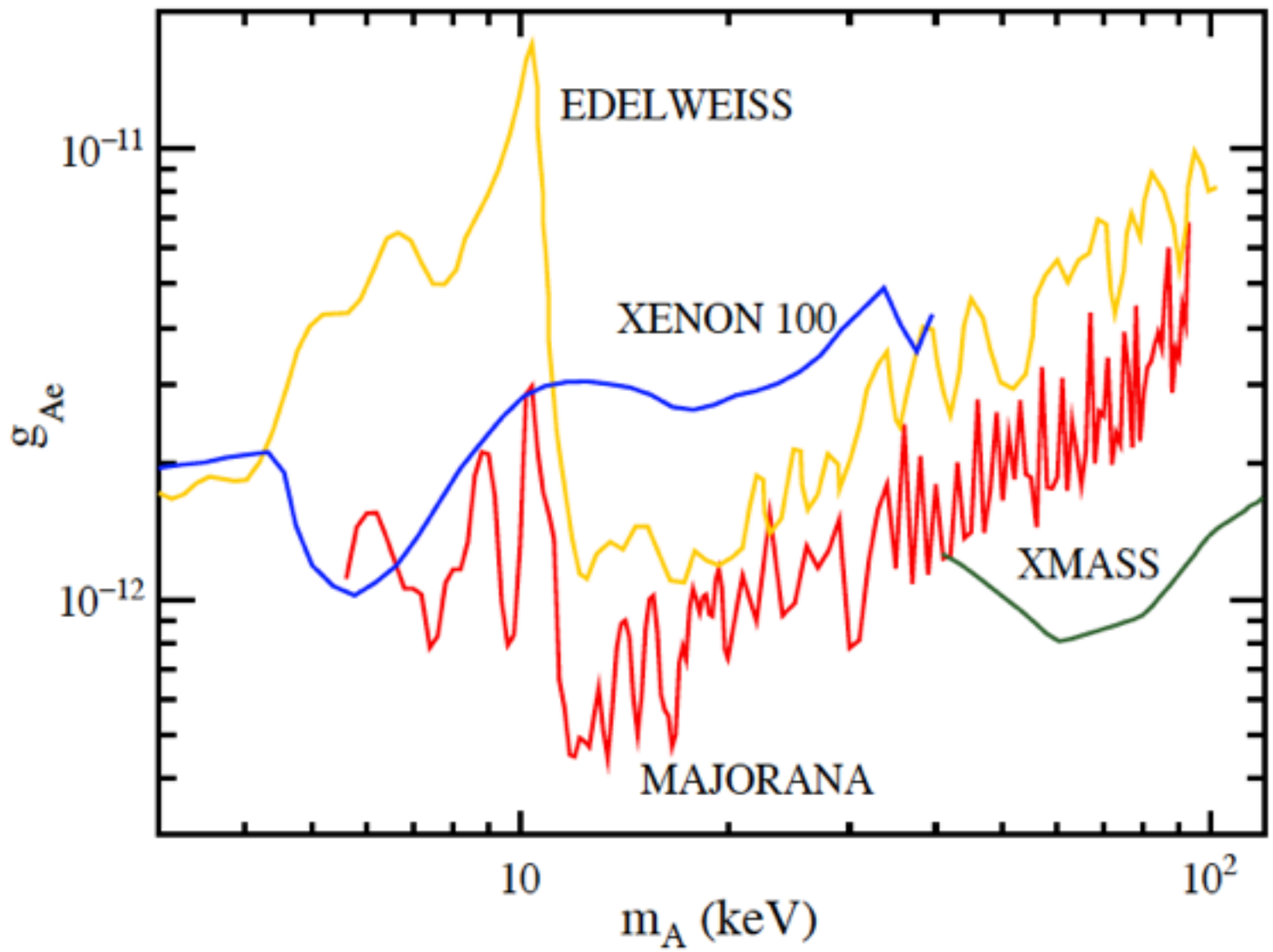


FIG. 2. (Color online) The 90% UL on the pseudoscalar axion-like particle dark mater coupling from the MAJORANA DEMONSTRATOR (red) compared to EDELWEISS [30] (orange), XMASS [38] (green), and XENON [34] (blue). Recent results by LUX have not yet been published [39], and new results from CDEX [40] are available on the arXiv [40].

Example:

- Clean materials near/in the active volume

Radiopurity of typical electronics components

500 MΩ SMD resistor used by GERDA

Size	Th-234 [uBq/pc]	Ra-226 [uBq/pc]	Th-228 [uBq/pc]	K-40 [uBq/pc]	Pb-210 [uBq/pc]
0603 0.48 mm^3/pc 1.33 mg	4 ± 2	1.9 ± 0.3	0.6 ± 0.2	10 ± 4	46 ±5
0402 0.153 mm^3/pc 0.6 mg/pc	2 ± 1	0.7 ± 0.1	0.2 ± 0.1	< 2.6	32 ± 3

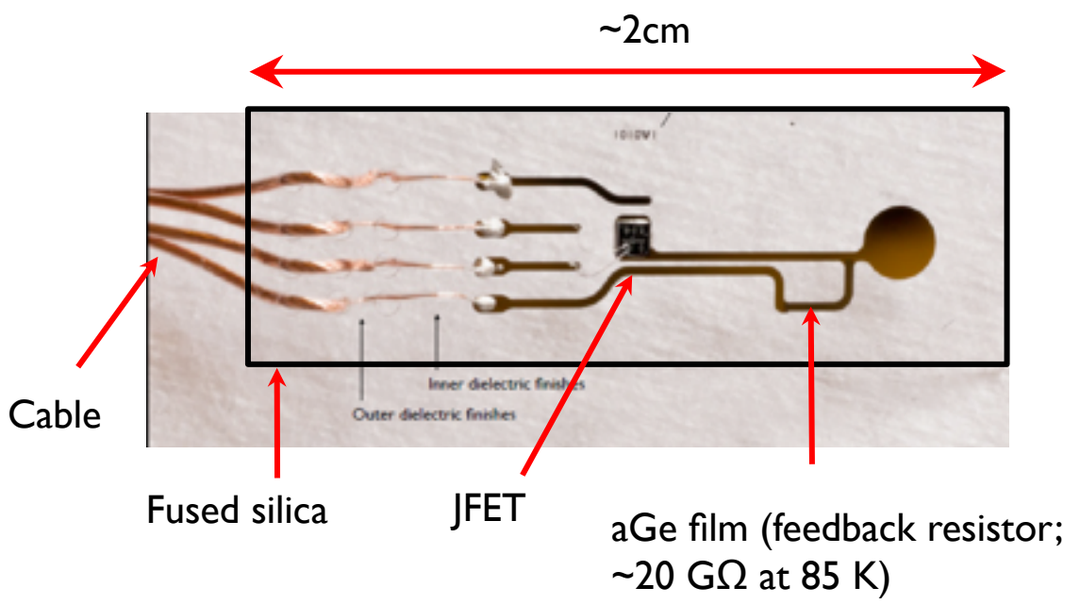
Cattadori, LRT 2015

1 μBq ≈ 0.1 / day

Low-Background Electronics Development

Current state-of-the-art: MJD low-mass front-end

P. Barton *et al.*, *Low-noise low-mass front end electronics for low-background physics experiments using germanium detectors.* IEEE Nucl. Sci. Symp. Conf. Rec. **2011**, 1976 (2011).



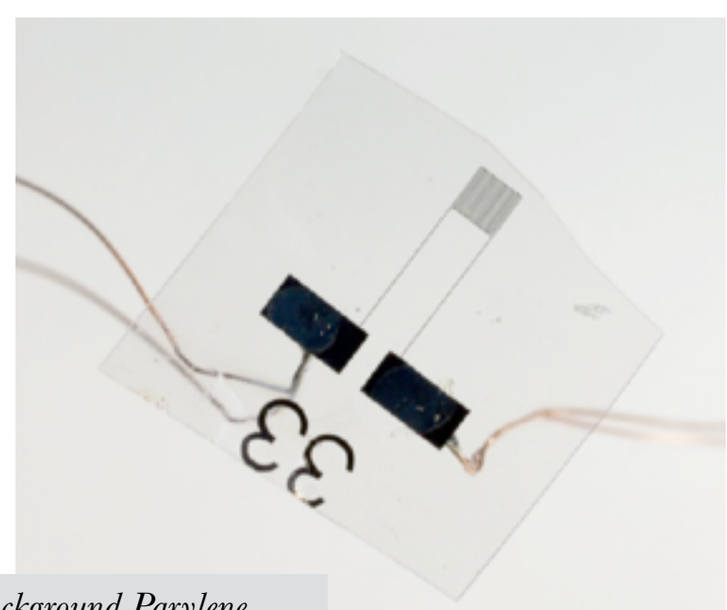
- Background: < 1 count/t/y in 4-keV ROI

Component	Material	Purity (g / g)		Counts / ROI / t / y		Ref.
		^{232}Th	^{238}U	^{232}Th	^{238}U	
Substrate	Fused silica	101×10^{-12}	284×10^{-12}	0.0259	0.0616	MJ ICP-MS
Resistor	a-Ge	5×10^{-9}	5×10^{-9}	0.0001	0.0001	MJ ICP-MS
Traces	Au	$47(1)\times10^{-9}$	$2.0(0.3)\times10^{-9}$	0.0421	0.0015	MJ ICP-MS
Traces	Ti	$<400\times10^{-12}$	$<100\times10^{-12}$	~0	~0	MJ ICP-MS
FET	FET die	$<2\times10^{-9}$	$<141\times10^{-12}$	<0.0107	<0.0006	MJ ICP-MS
Bonding wire	Al	$91(2)\times10^{-9}$	$9.0(0.4)\times10^{-12}$	0.0004	~0	MJ ICP-MS
Epoxy	Silver epoxy	$<70\times10^{-9}$	$<10\times10^{-9}$	<0.0685	<0.0082	MJ gamma
Total				<0.1476	<0.0720	

Full board assays: ~2-3x higher in background

Example of a future concept: Low-mass low-background flexible circuitry

Thermal sensor on a flexible parylene substrate

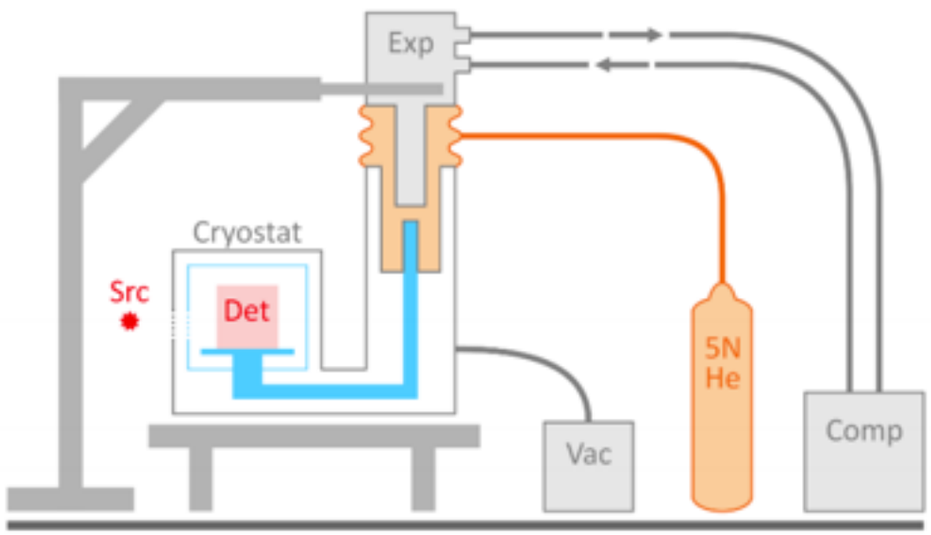


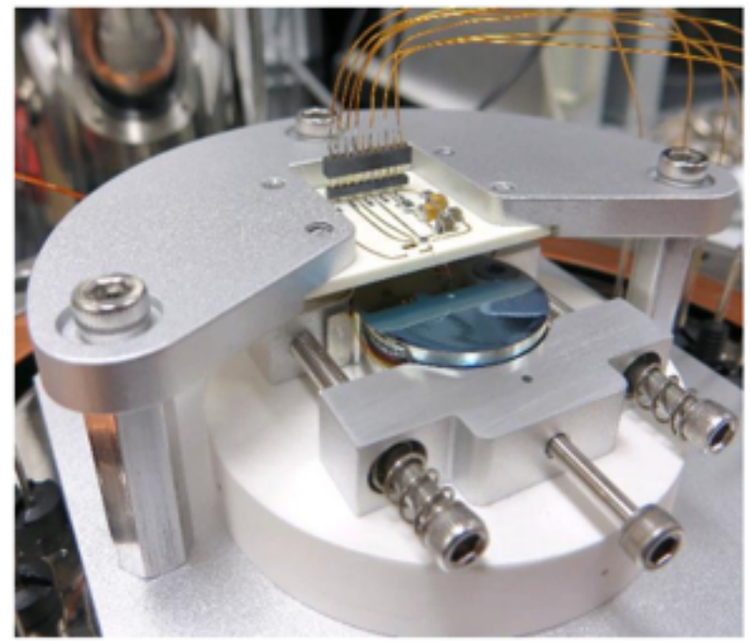
A. Dhar *et al.*, *A Low-Background Parylene Temperature Sensor*, JINST **10** P12002 (2015).

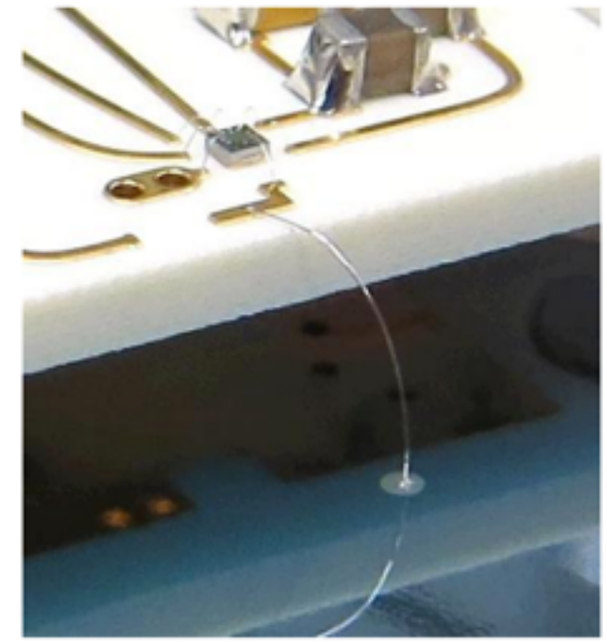
- **Technologies for future experiments:**
  - More signal readout circuitry (amplification) as close to the detector as possible [ASICs]
  - Flexibility of the form factor in these circuits [flexible substrate]
  - Ultra-low background material development
  - Ability to run at very low temperature (hence lower thermal noise)

Low-Background Electronics Development

The First: Mechanically Cooled, Wirebonded PPC HPGe, with CMOS Front End







Atmospheric Pressure He Gas

Provides ultra-low vibration thermal link using standard GM cycle (10 – 80 K)

→ Eliminates all vibrations

Ultra-Low Capacitance

Smaller point contact (0.26 pF) enabled by wire bonding

→ Ultra-Low Electronic Noise

Preamp-on-a-Chip

CMOS ASIC for SDD

4 electrons-rms noise

→ Better than JFET at low temperatures

Low temperature and **low capacitance** of CMOS and Ge.
Result: lowest noise HPGe detector: **39 eV-FWHM** at 40 K.

P. Barton *et al.*, *Ultra-low noise mechanically cooled germanium detector*. Nucl. Instr. Meth A **812**, 17 (2016).

cf. MJD front-end: 85 eV-FWHM at 80K
MJD full module: ~150-180 eV FWHM

Coaxial Cables - MJD

- For discrete detector systems, very likely that special production runs are required. MJD contracted Axon' in France to make the "picocoax" cable
- Additional testing, cleaning in ultrasonic bath and drying between production steps (conductor prep, inner dielectric extrusion, shielding, jacket extrusion).

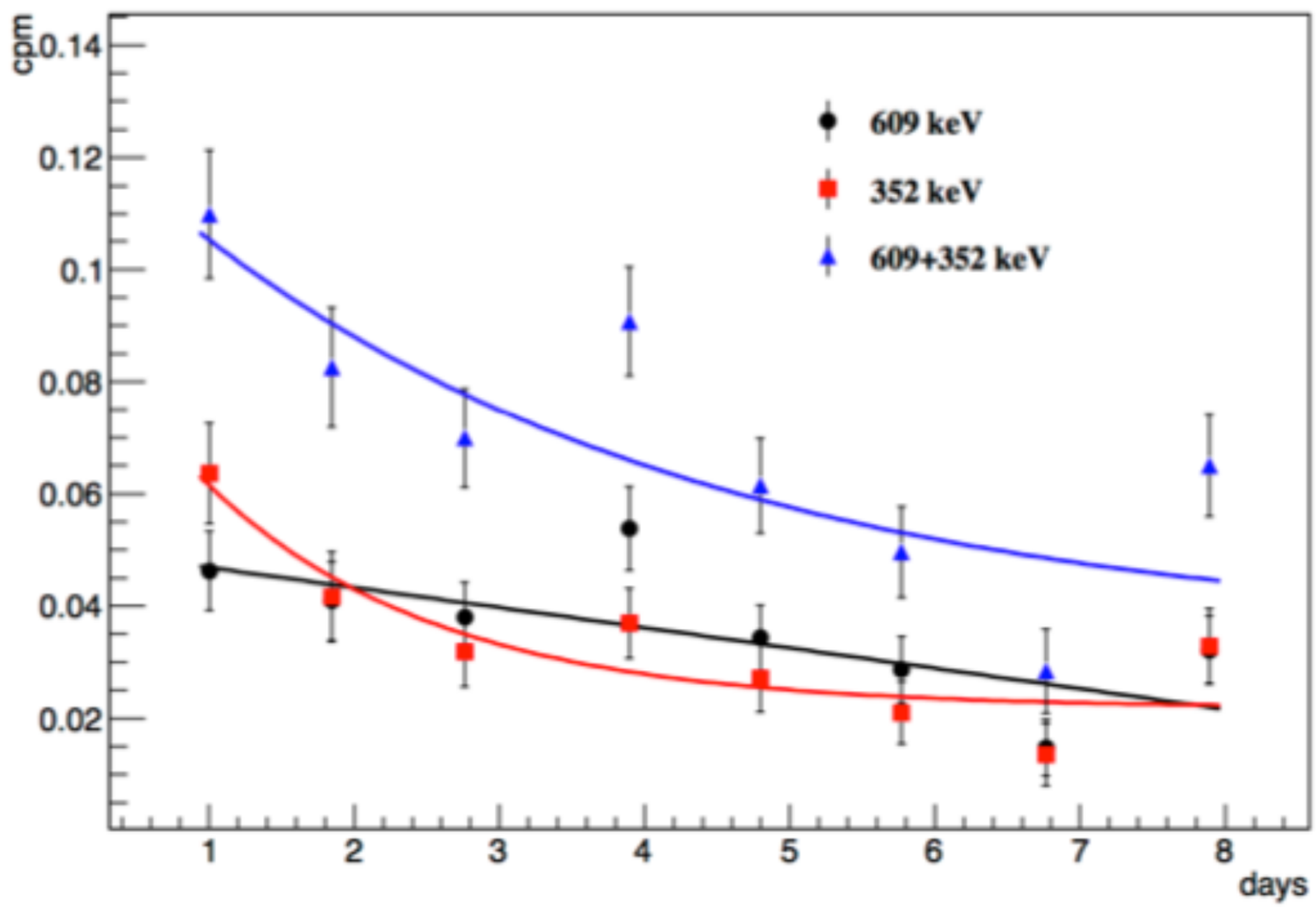
Goal: << 1 c/ROI/t/y

HV Cable	Technique	Th (c/ROI/t/y)	U (c/ROI/t/y)
Projection	Simulation & assay	<0.02	<0.06
Axon' - Run 1 (QA issue at factory - no cleaning steps)	ICPMS	1.1	16.5
Axon' - Run 2	ICPMS & Gamma	<0.004	<0.081

Site visits for quality assurance is essential

Coaxial Cables - MJD

- The cables were stored in dry N_2 environment until they were being used.
- Room ^{222}Rn can stick to the outer jacket if not stored properly



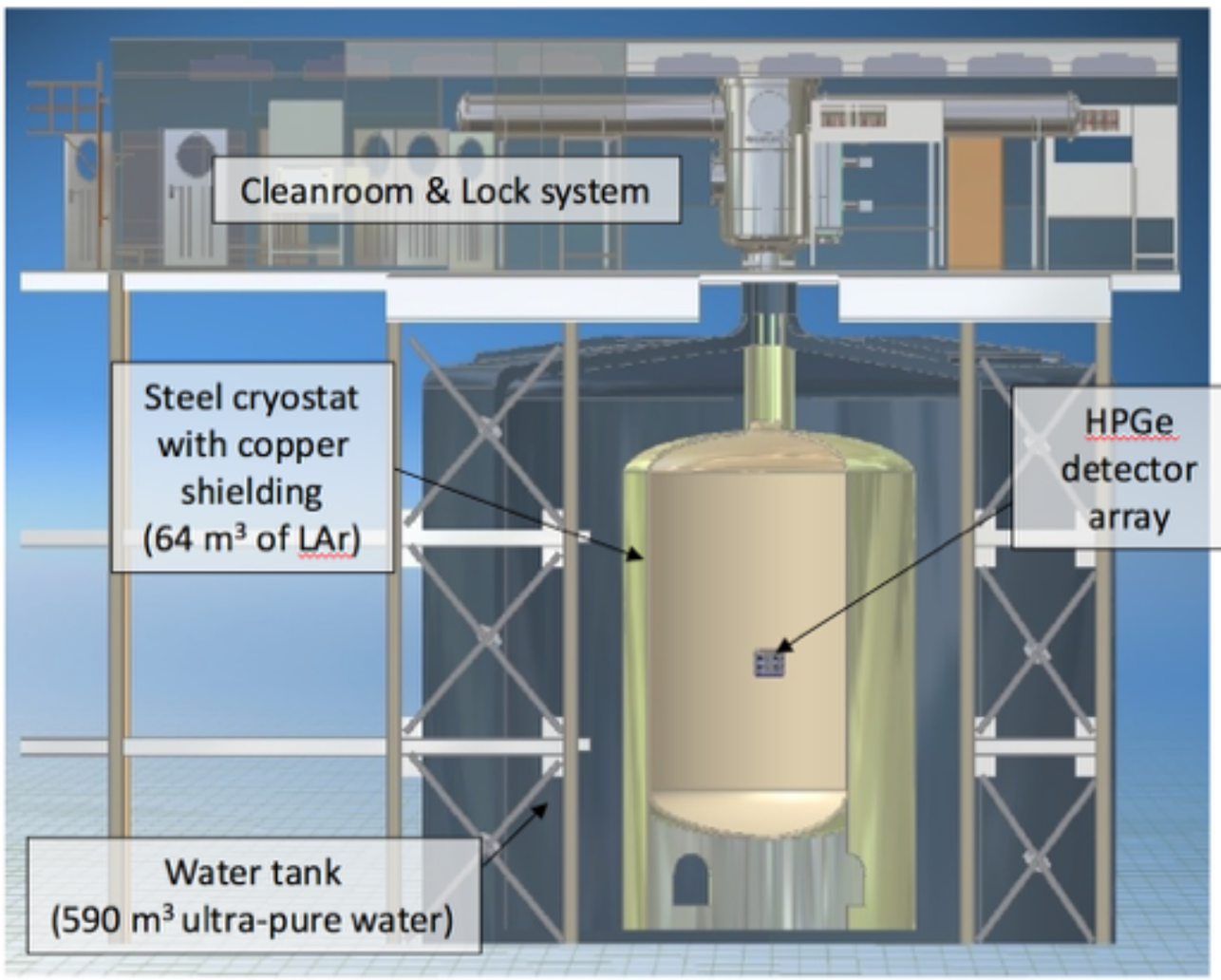
Proper clean storage of components is essential

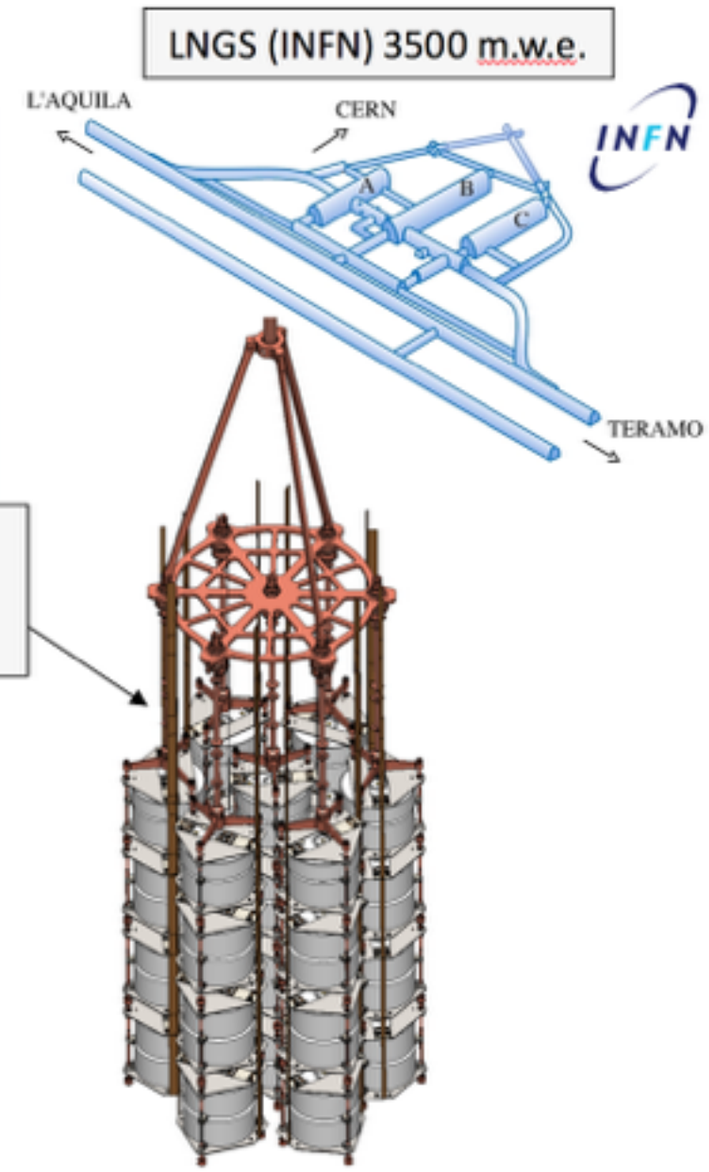
Example:

- Background rejection

Active Veto

- **Reject**:
  - backgrounds intrinsic to the detectors and
  - external backgrounds - cosmic rays and the veto itself

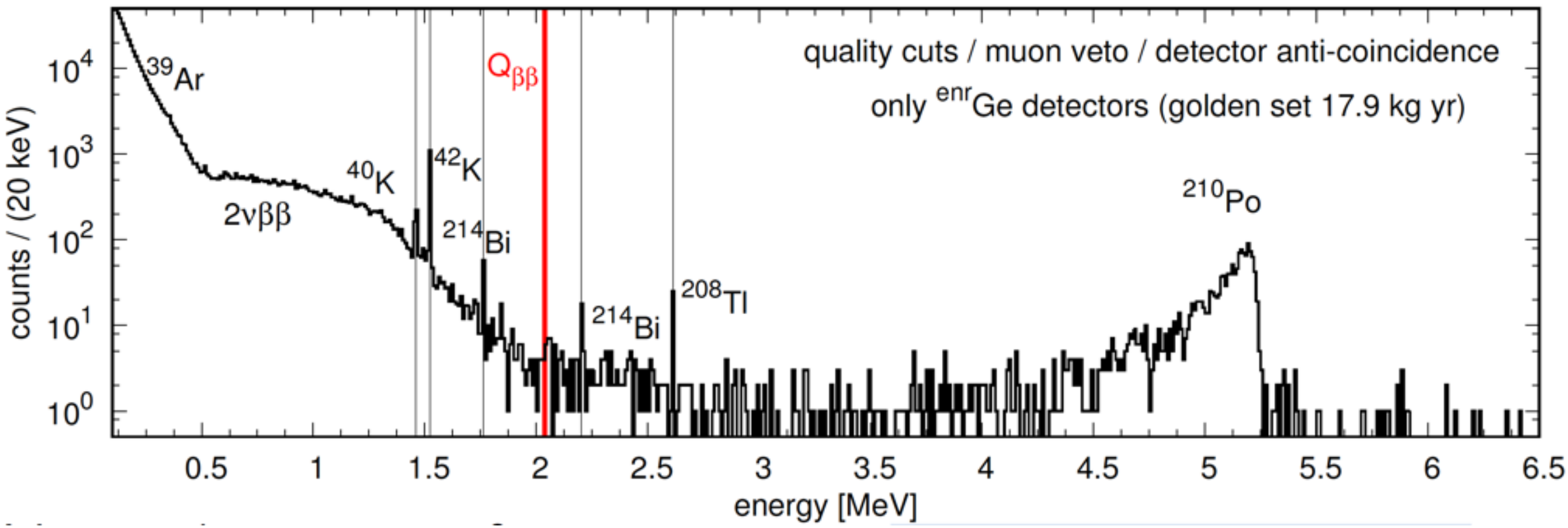




Ex: GERDA (^{76}Ge): Ge detectors immersed in LAr

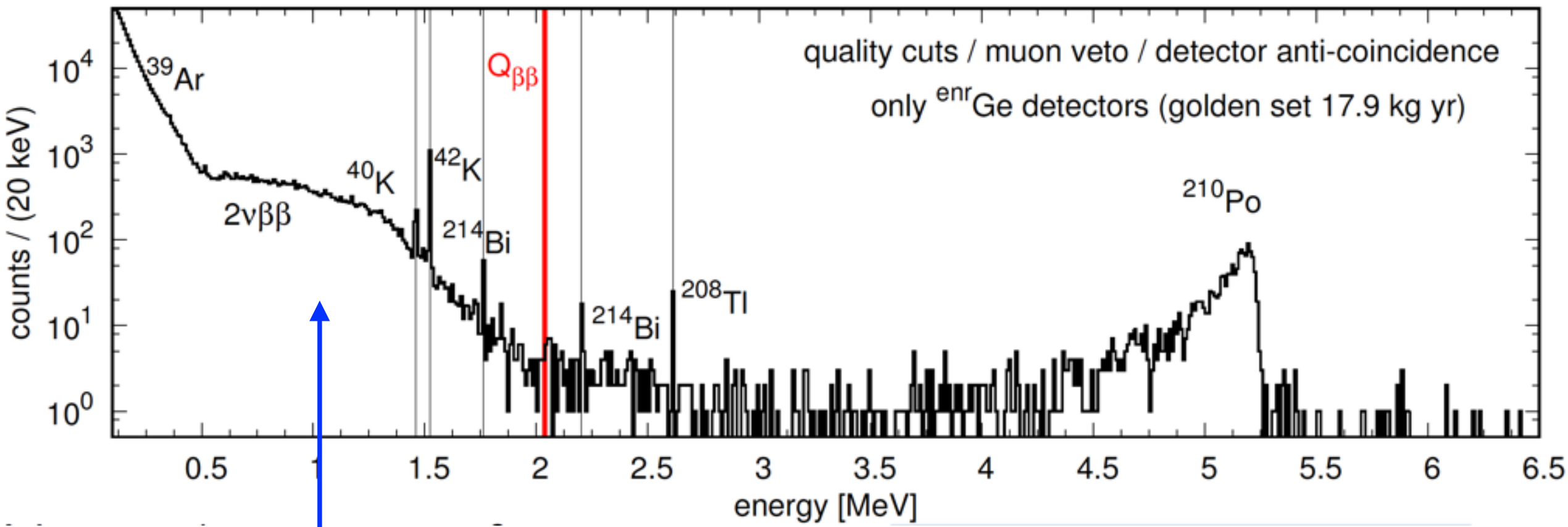
GERDA-I background

Main spectral components in Phase I



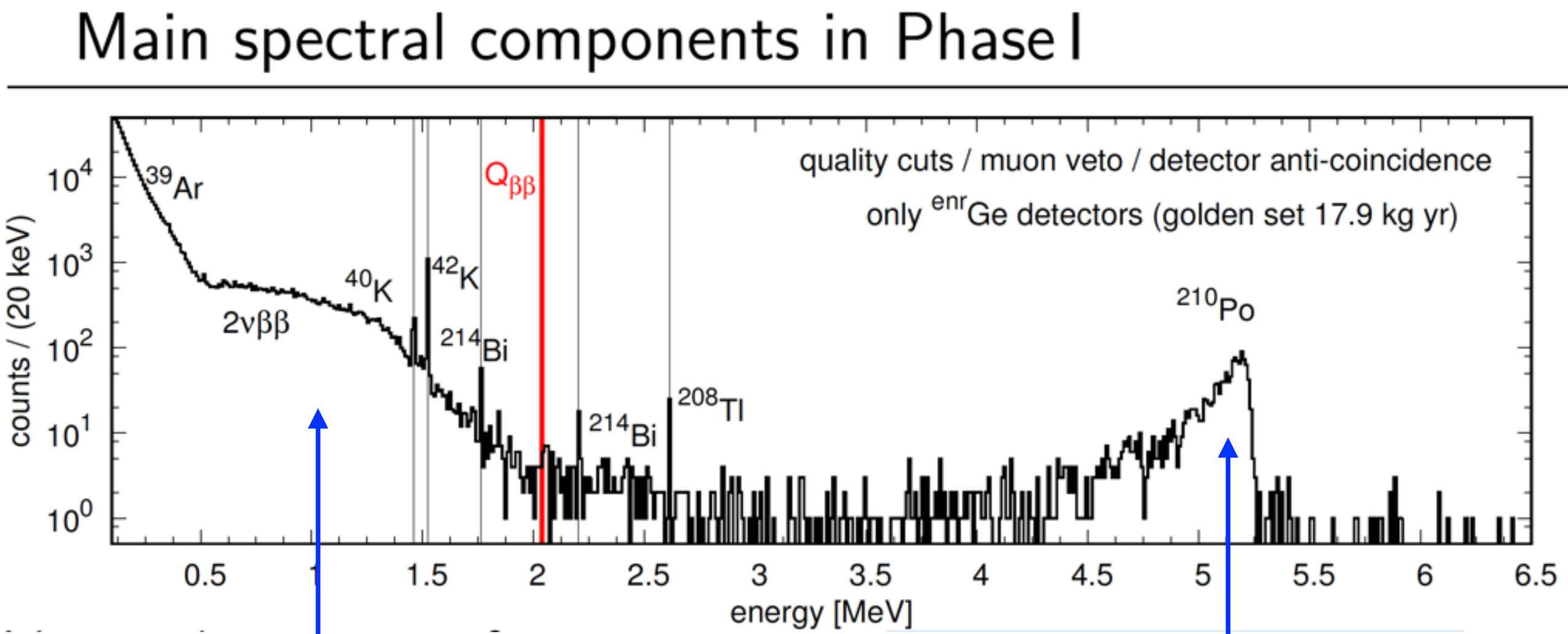
GERDA-I background

Main spectral components in Phase I



Detector intrinsic

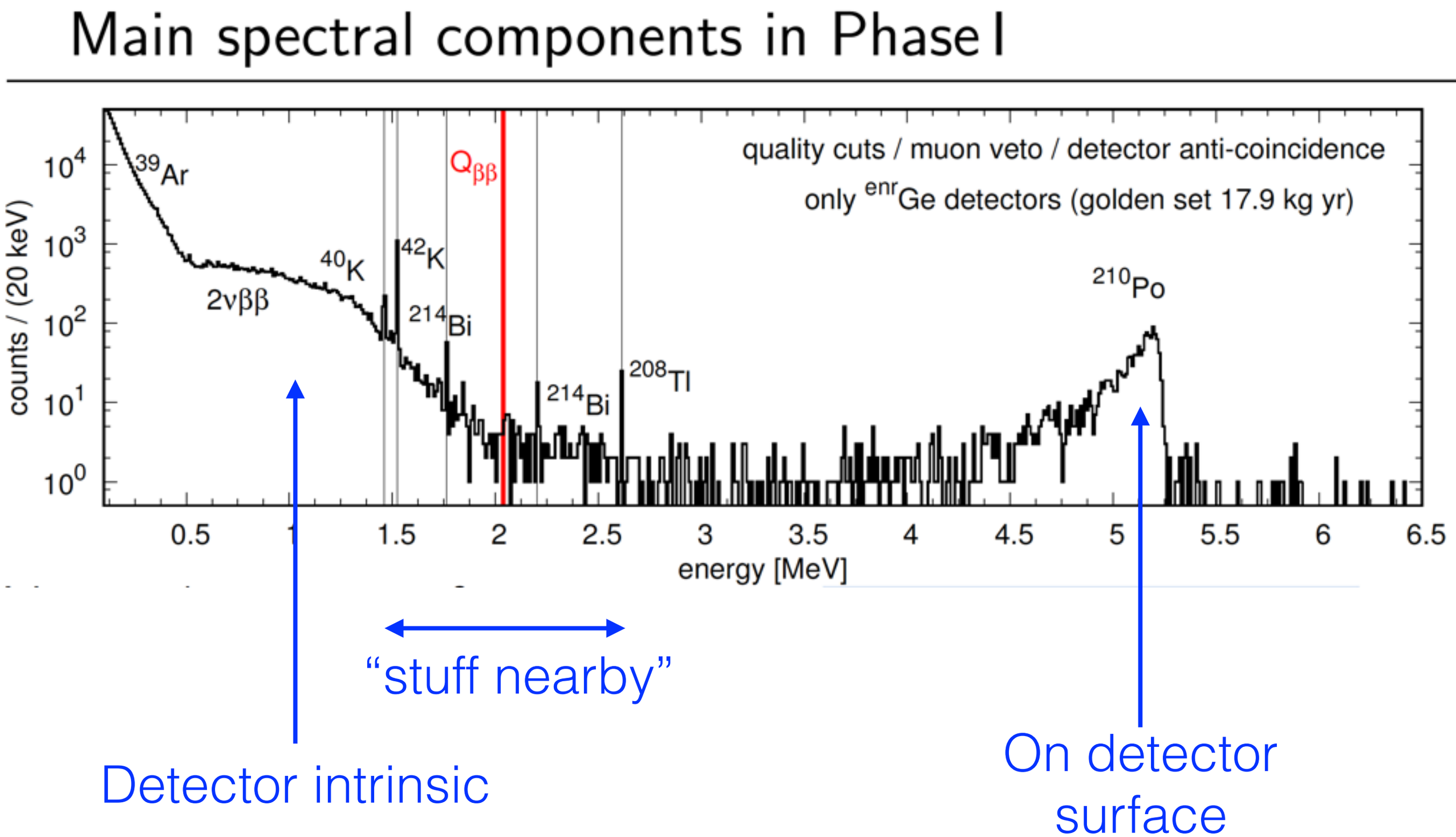
GERDA-I background



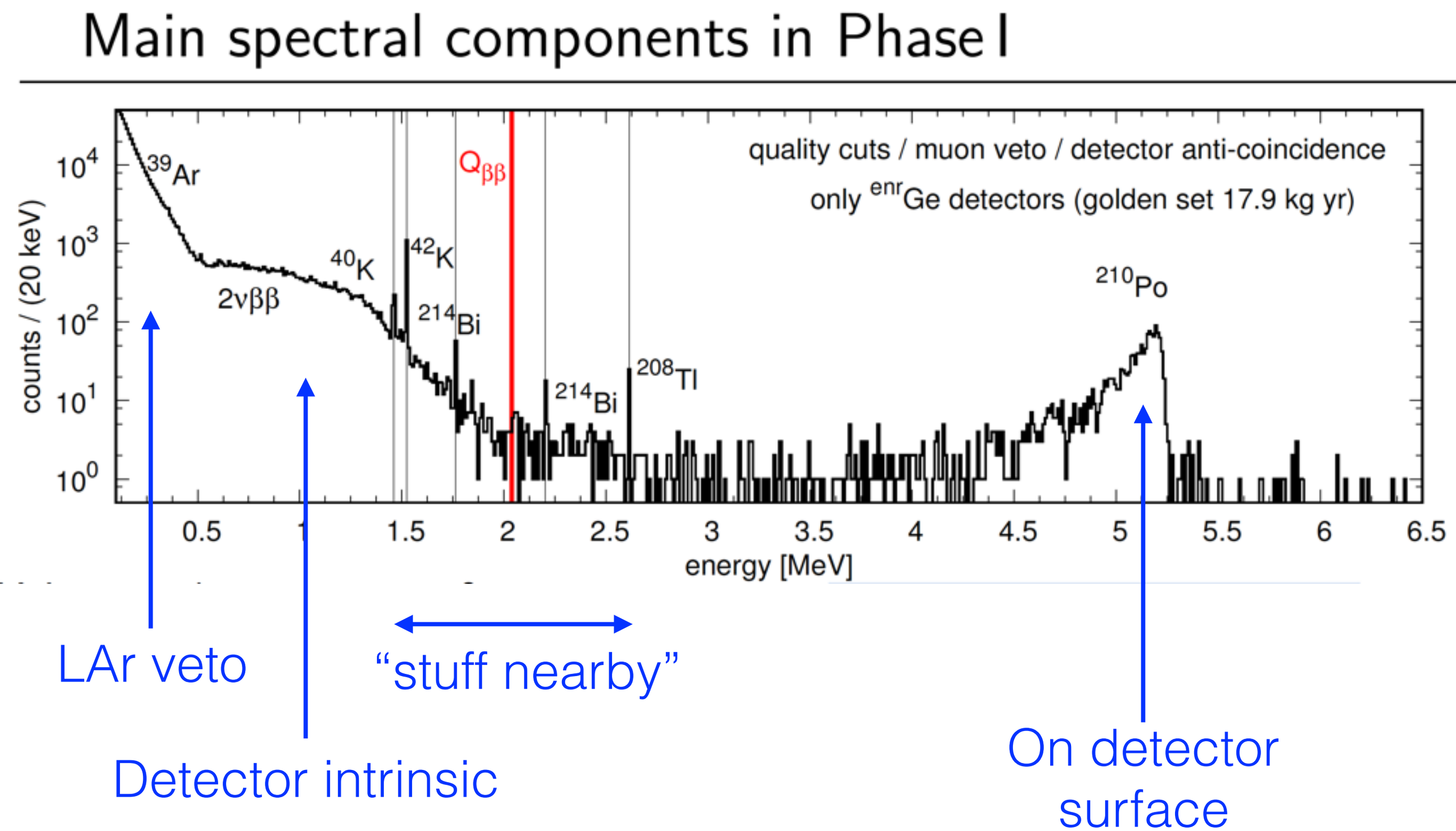
Detector intrinsic

On detector surface

GERDA-I background

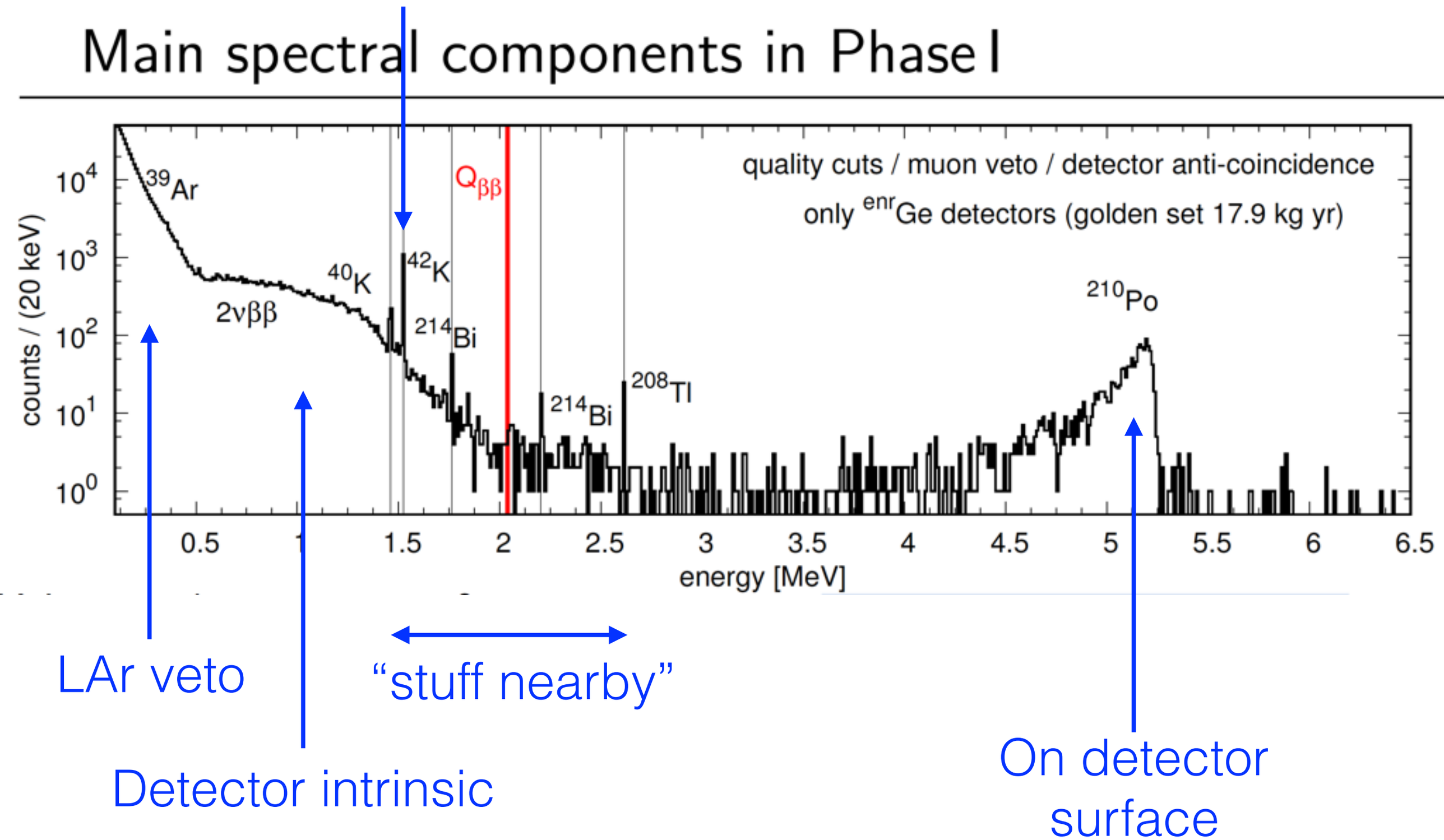


GERDA-I background

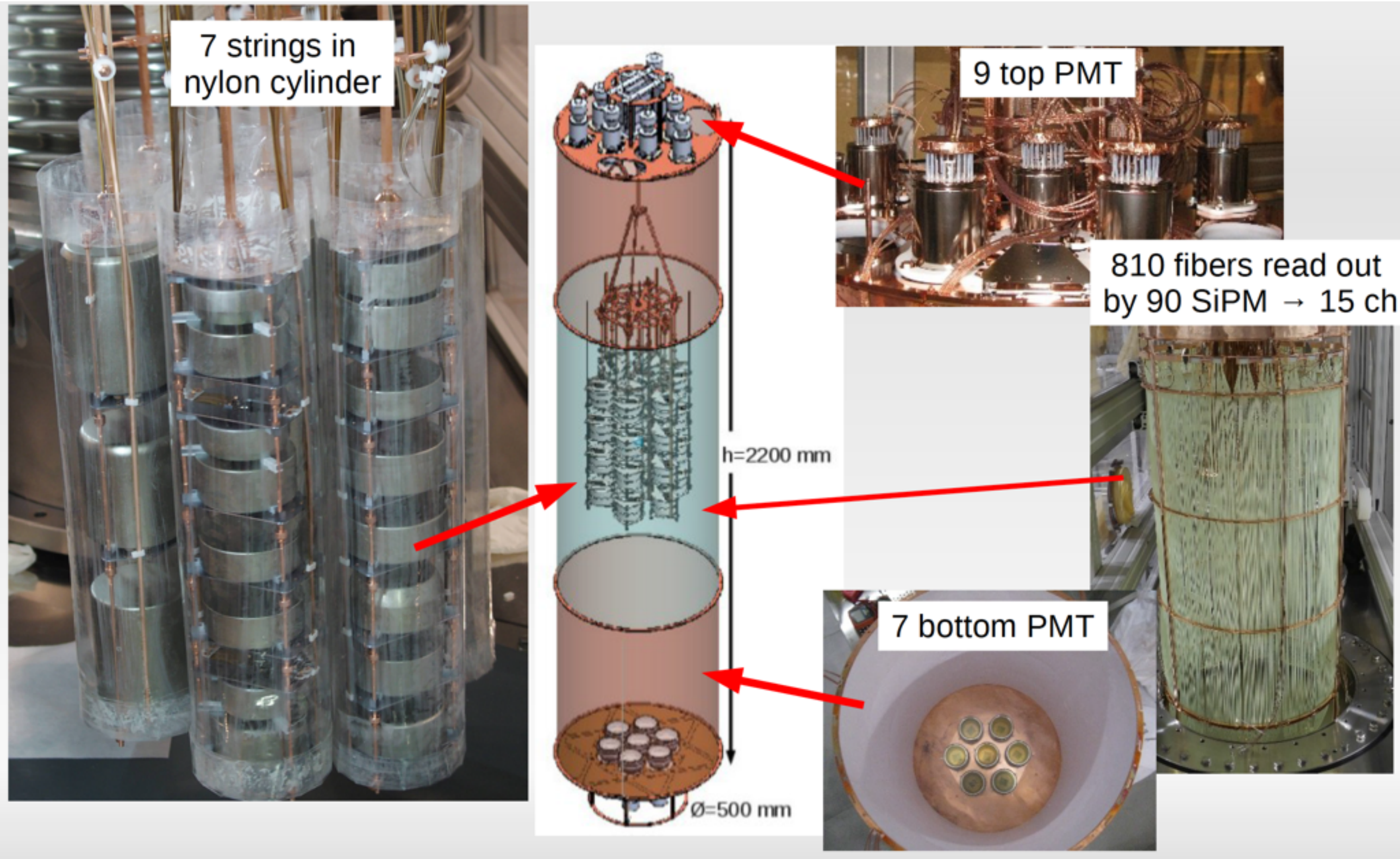


GERDA-I background

$^{42}Ar\ (t_{1/2}=33y) \xrightarrow{\beta} {}^{42}K(t_{1/2}=12.3h,\ Q=3.5MeV)$

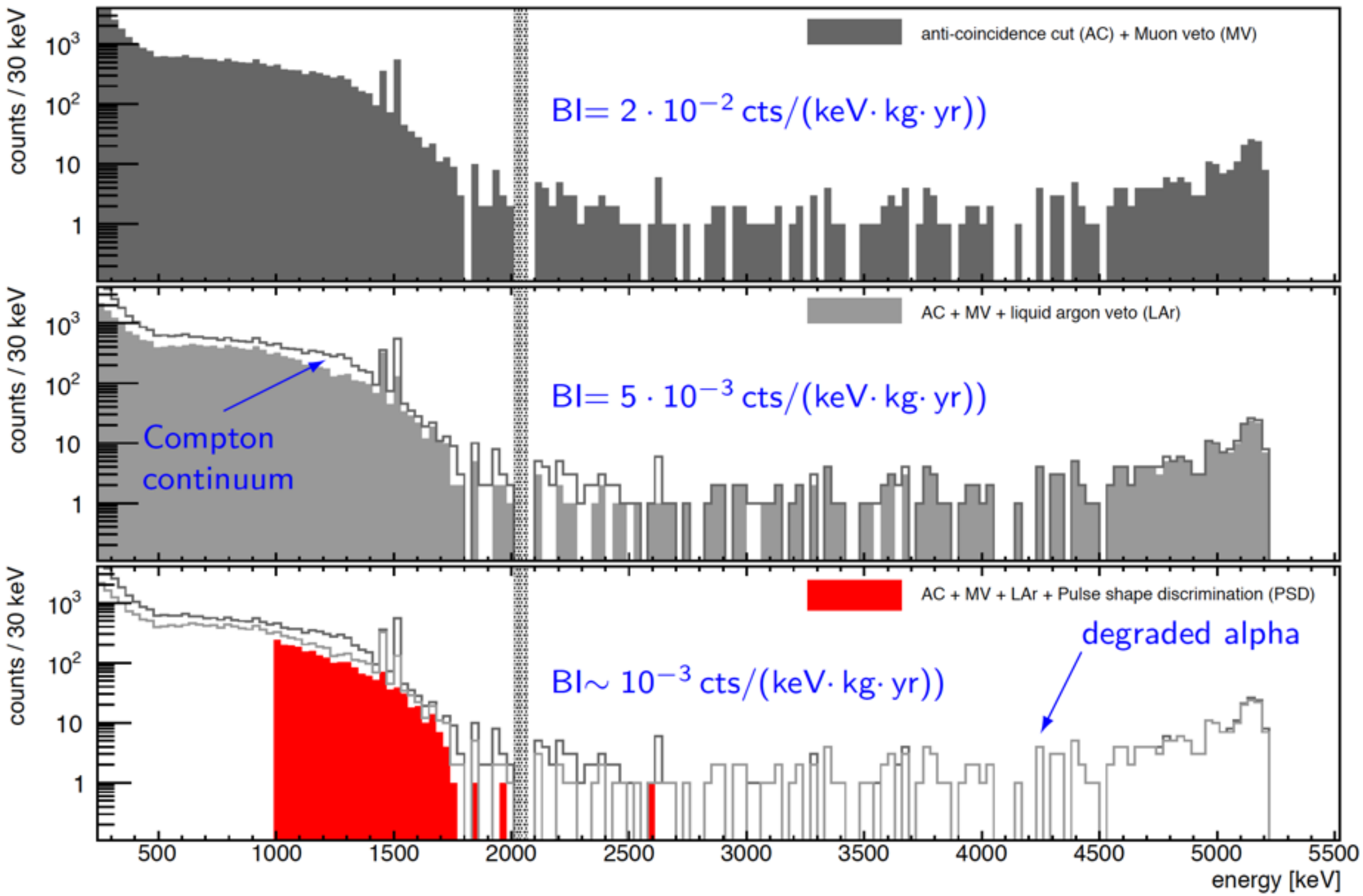


GERDA-II implementation of LAr veto

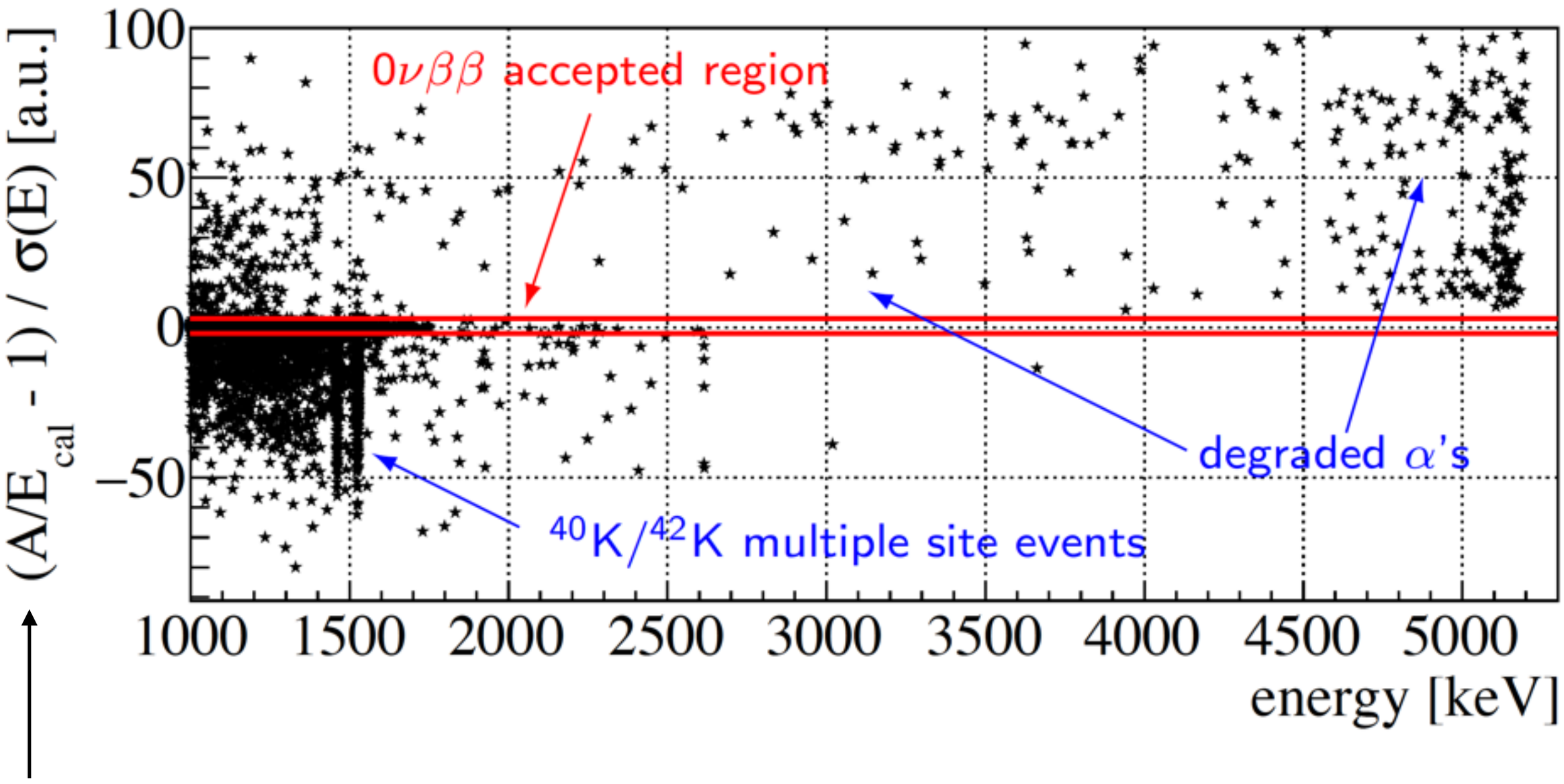


Agostini (Neutrino-2016)

GERDA background rejection



GERDA background rejection

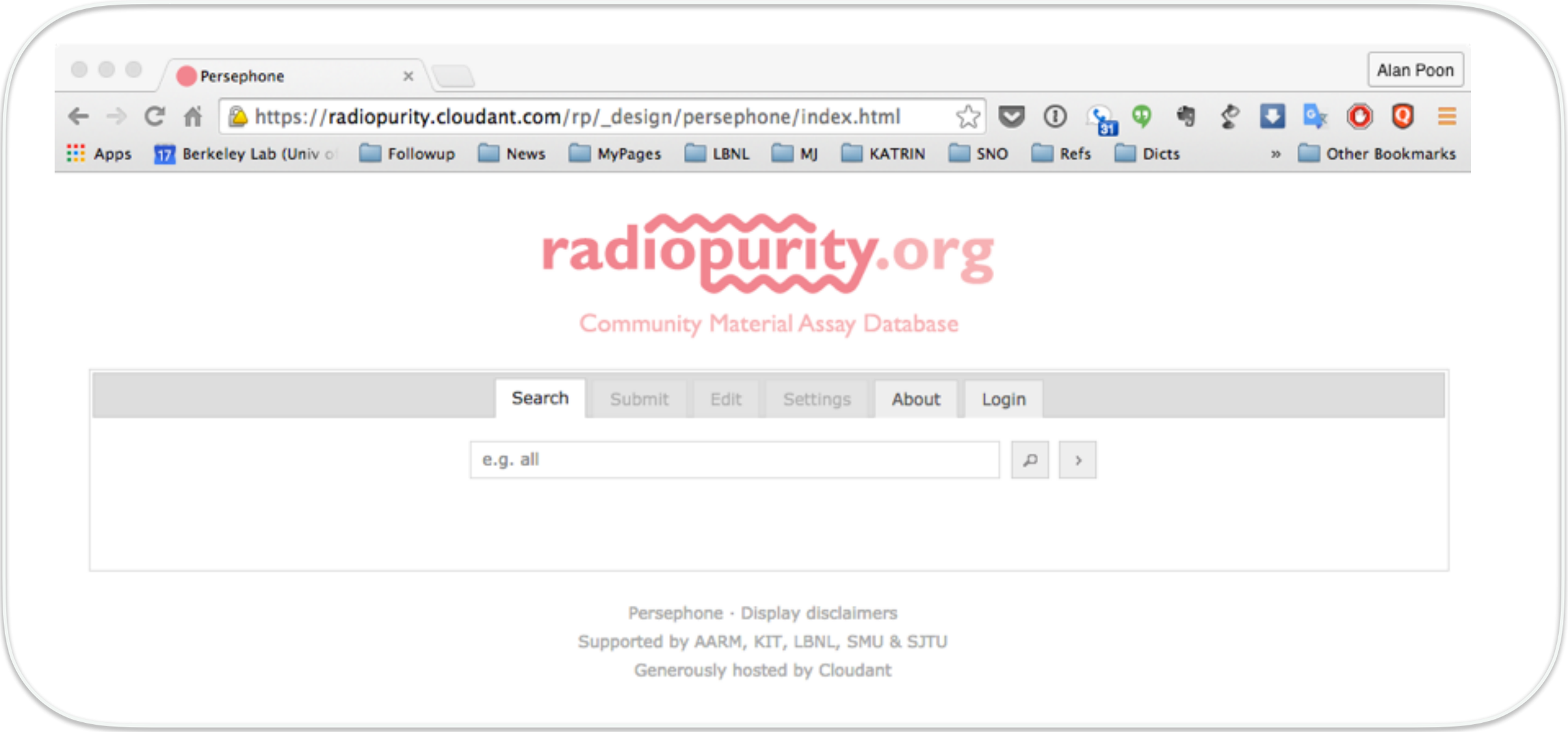


A/E: Detector pulse-shape discrimination parameter

Summary

- The DM and ββ R&D topics have a lot in common, even though the energy regimes of their signal region of interest are different.
- Similar background sources:
  - cosmic-ray
  - material impurities
  - Rn and other environmental radiation
  - contamination from handling, processing, and storage
- ββ community has achieved a background index of O(1 ct/t/y/ROI). Efforts to get to 0.1 ct/t/y/ROI underway.
- Opportunities to share resources and collaborate (example: radiopurity.org).

radiopurity.org



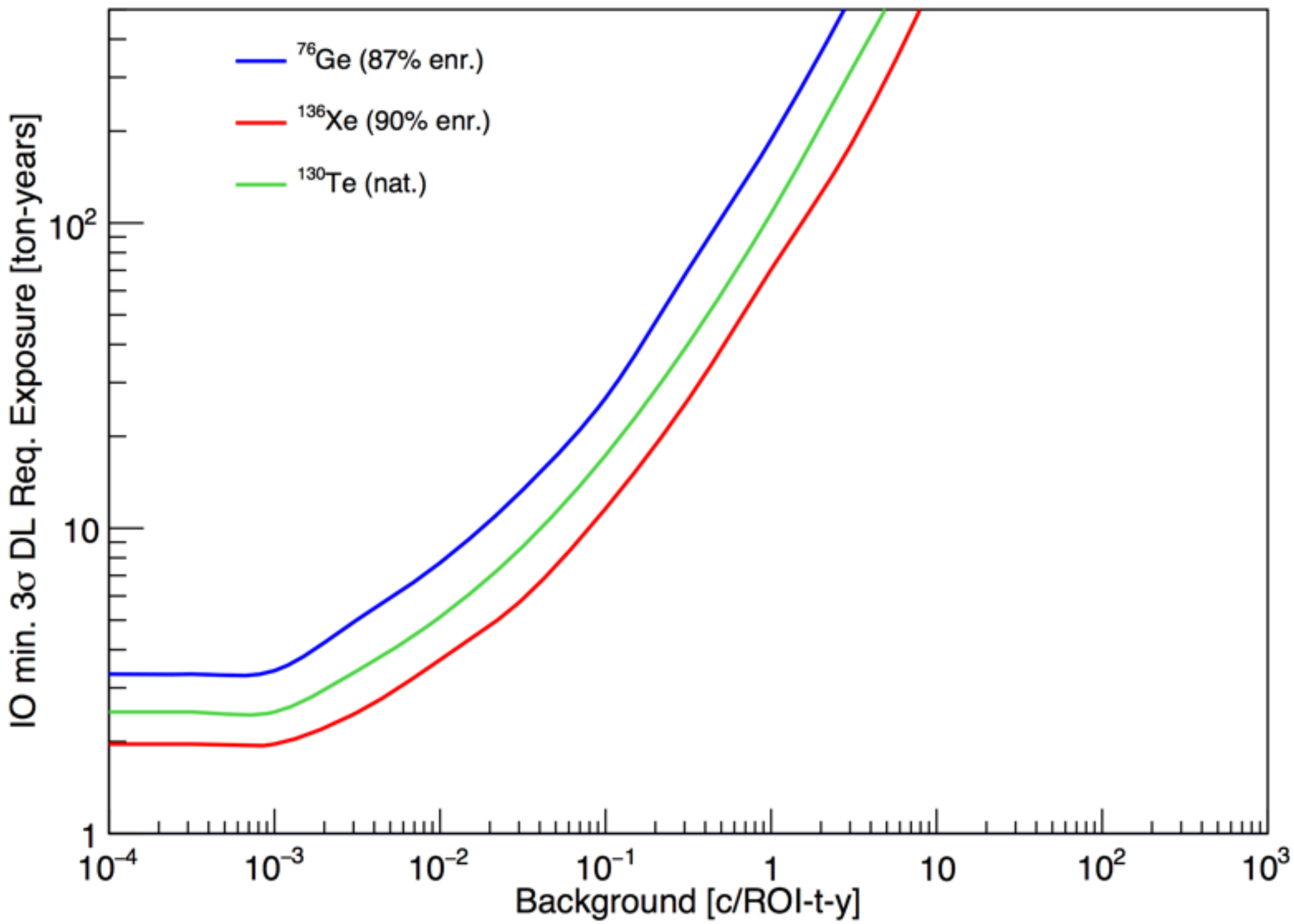
A project adopted by the international low-background community

Data from European ILIAS database incorporated

Experiments are adding their radioassay results to this database

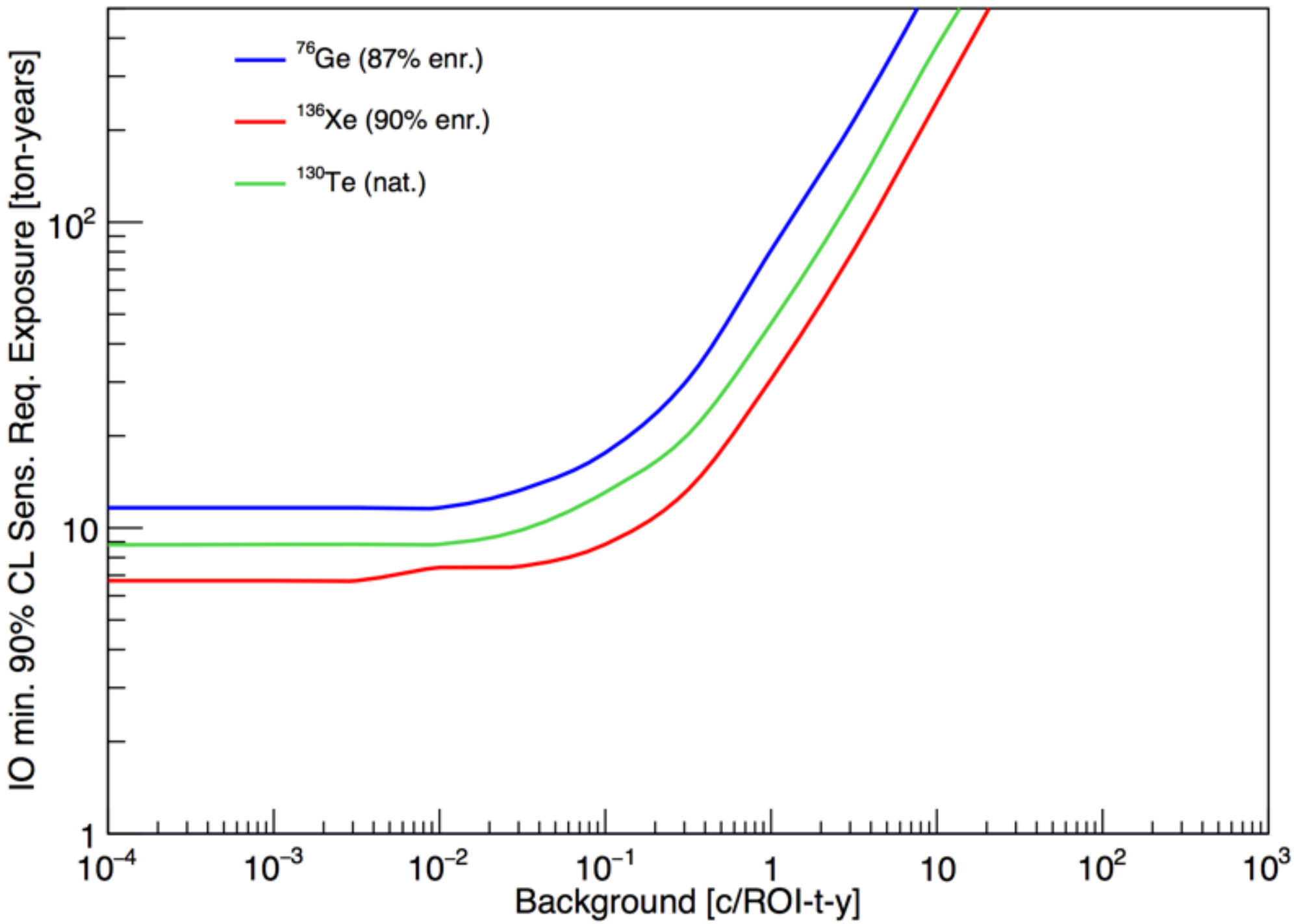
J.C. Loach *et al.*, *A Database for Storing the Results of Material Radio-purity Measurements*
Nucl. Instr. Meth. A839 (2016) 6-11

3-sigma discovery vs background



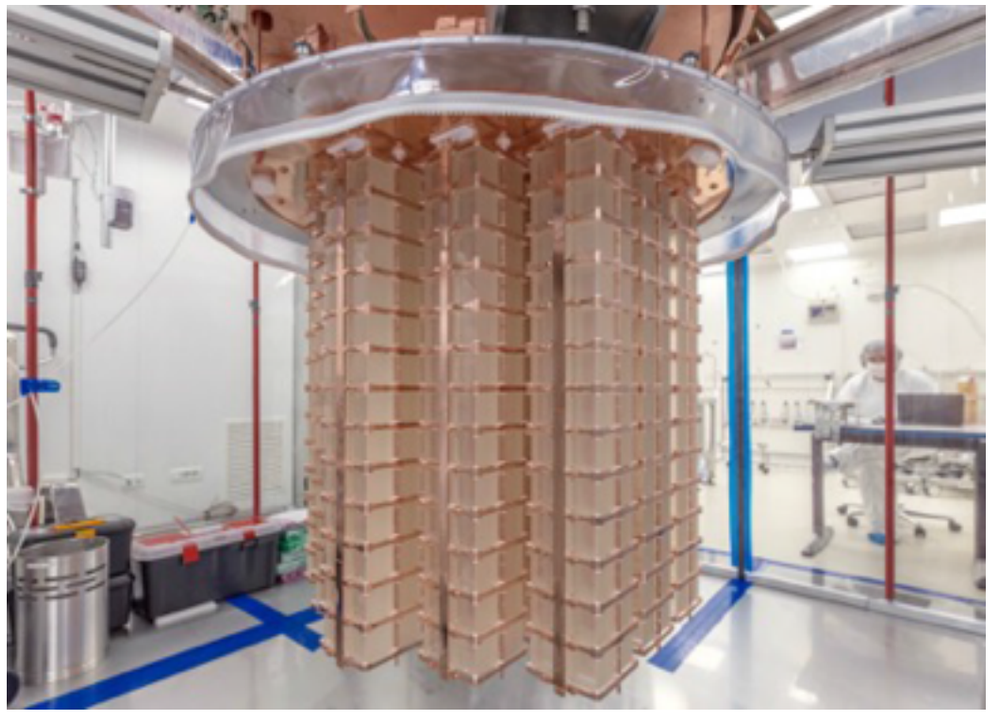
Detwiler 2015

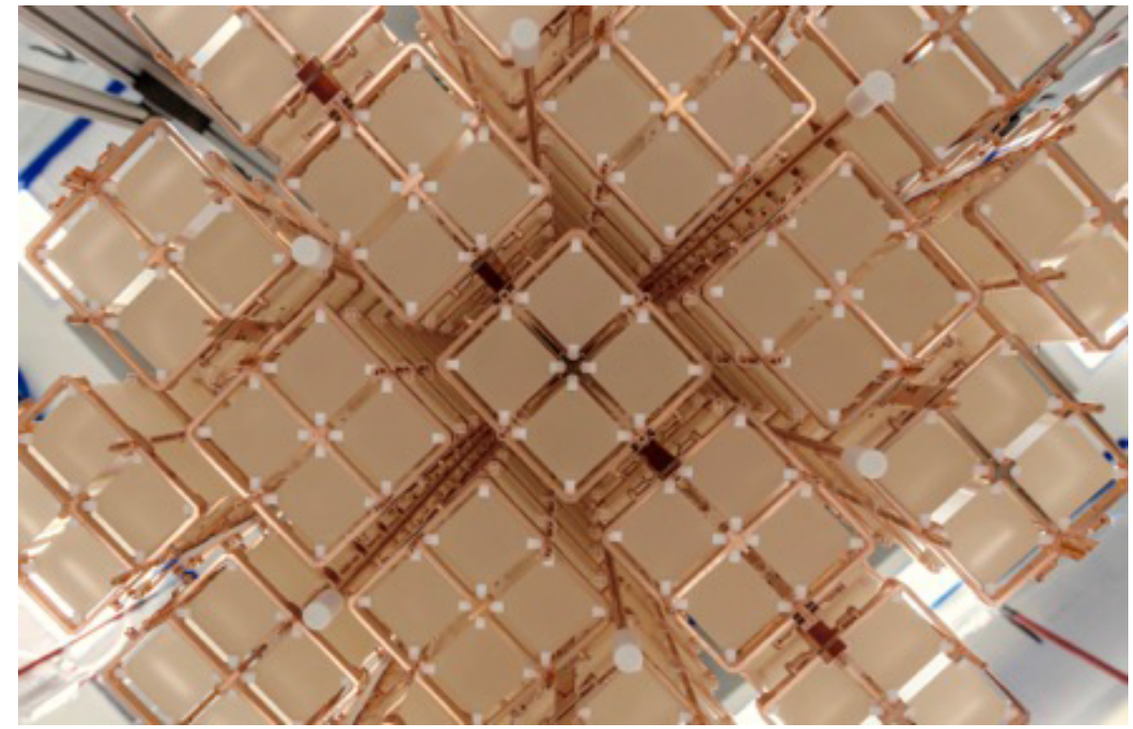
90% CL sensitivity vs background

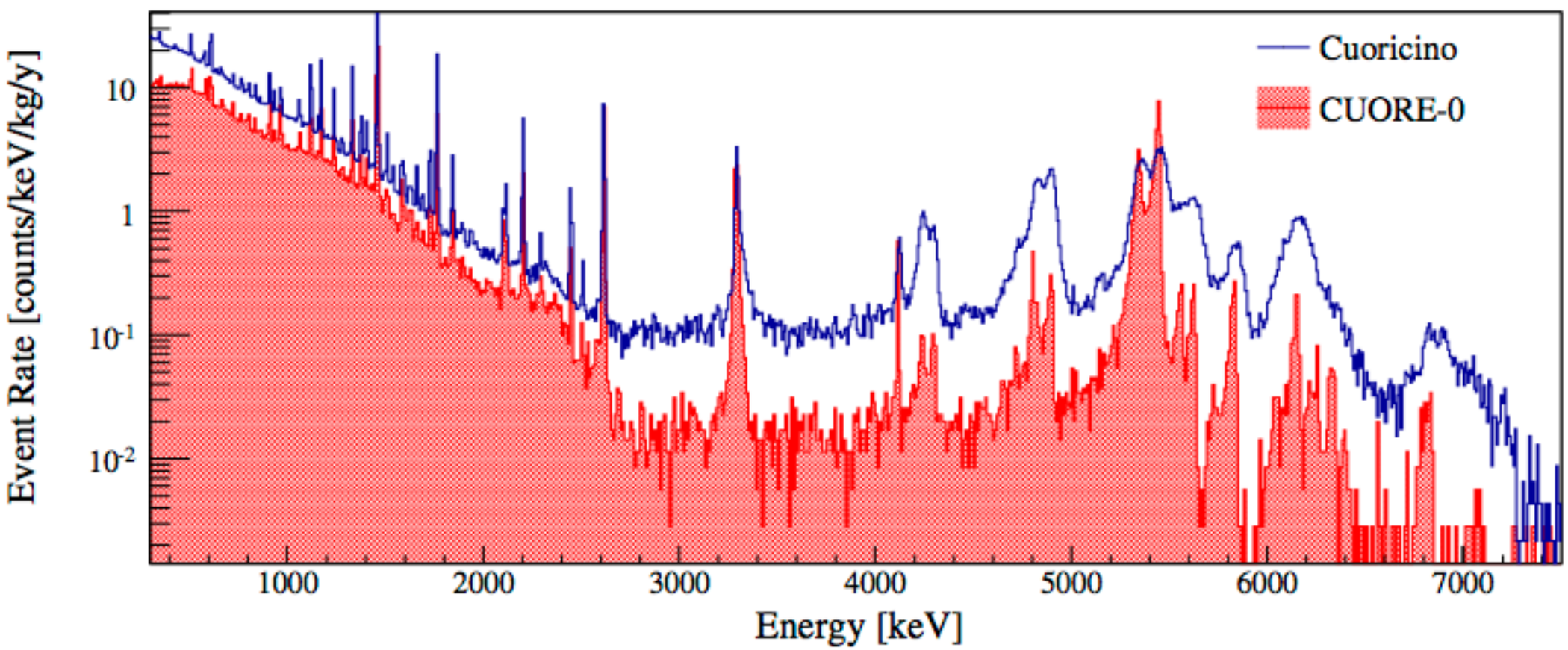


Detwiler 2015

CUORE (^{130}Te bolometers) and beyond

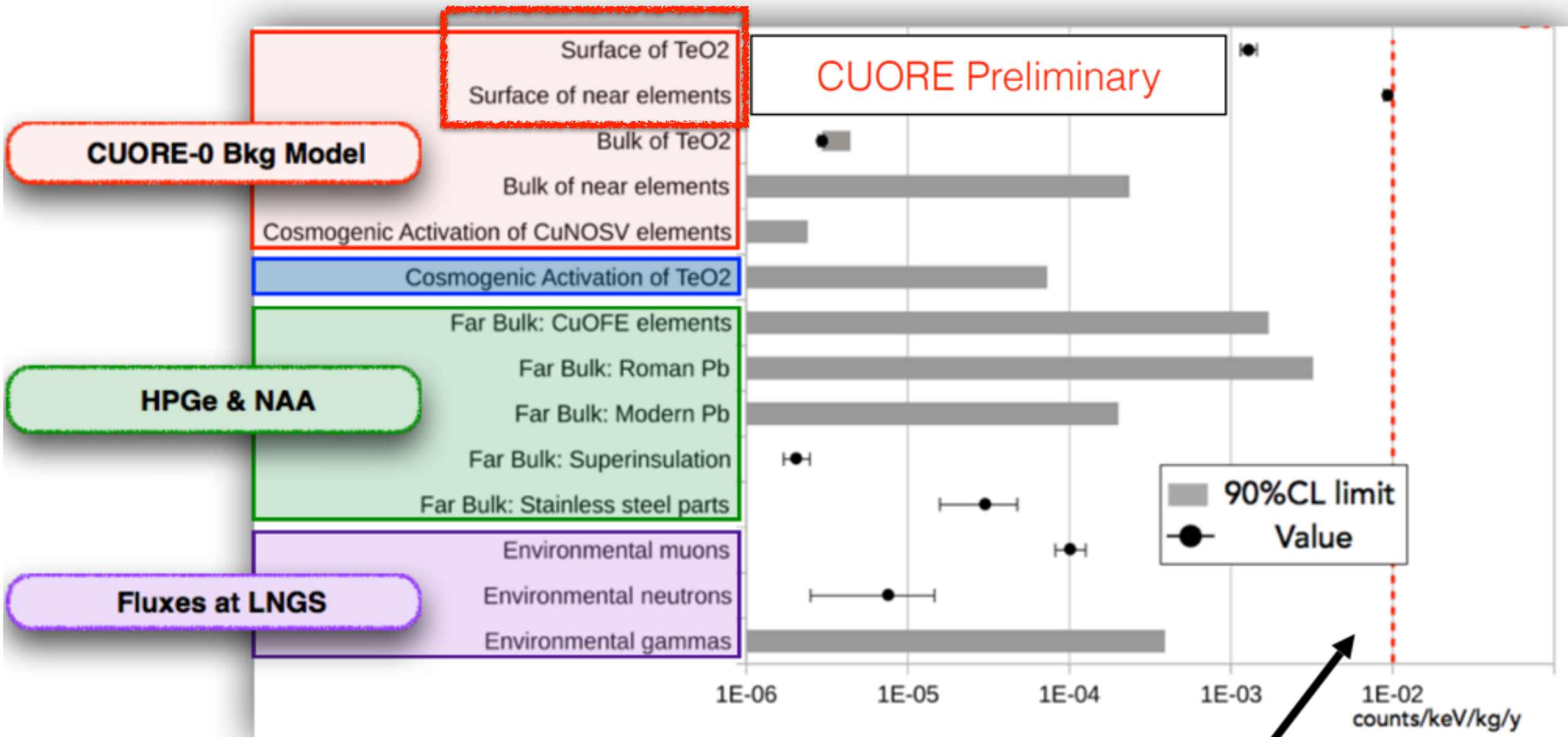






CUORE ^{130}Te and beyond

near or on detector

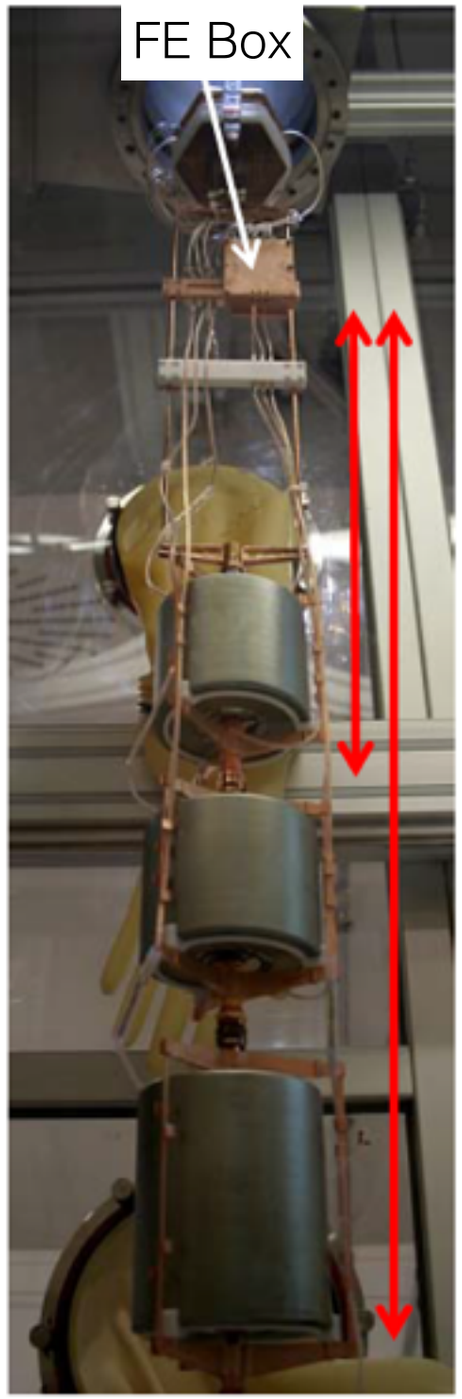


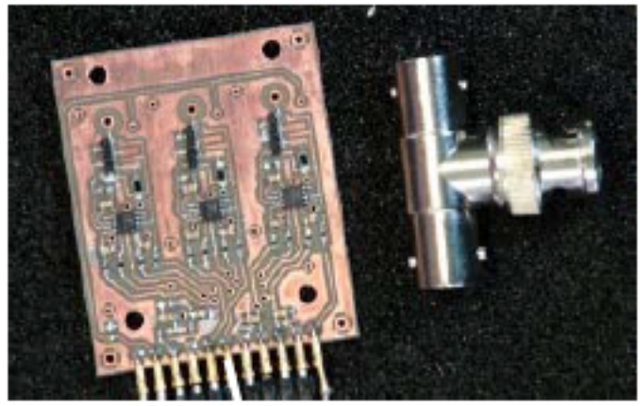
Next-Gen: rejection via Cherenkov or scintillation light

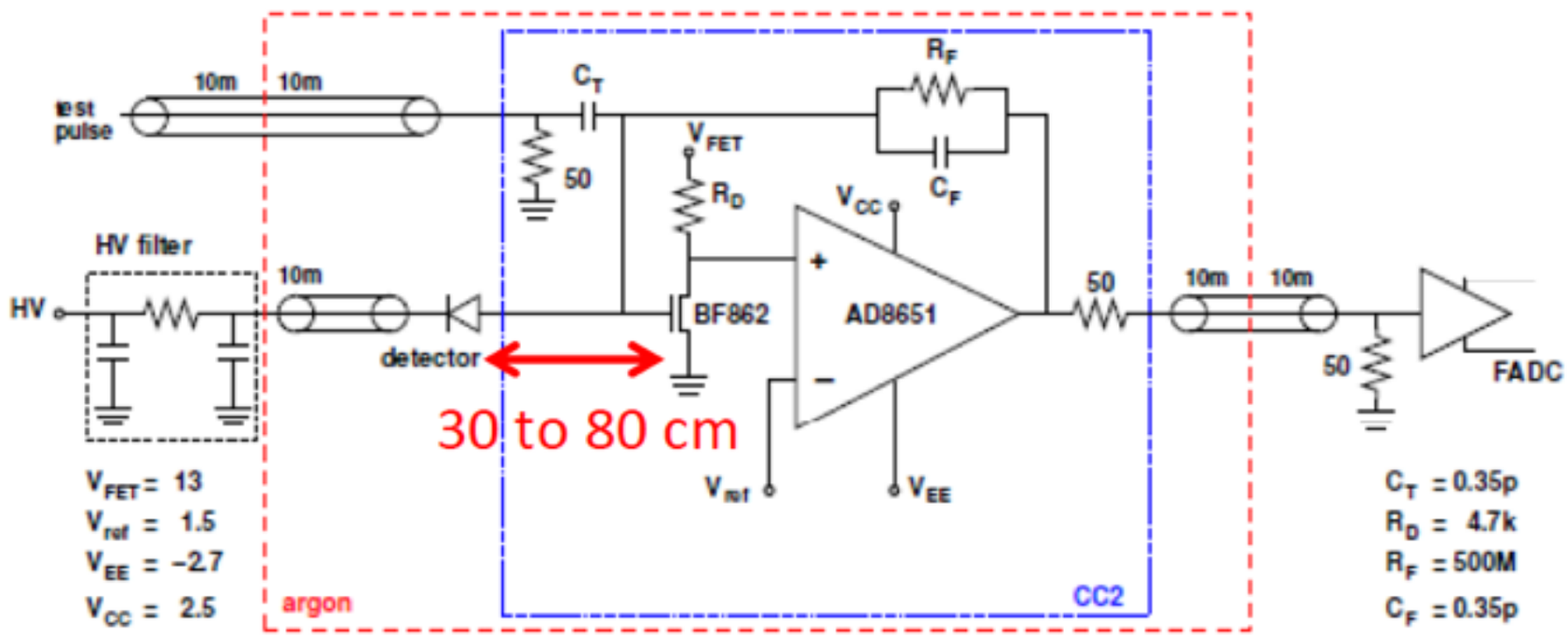
CUORE goal: 0.01 counts/keV/kg/yr

The ALARA principle

- Choose radiopure materials
- Keep hot stuff away from active detector volume







Ex: GERDA - Phase I

Cattadori, LRT 2015

The ALARA principle

- GERDA Phase-I background results:

Eur. Phys. J. C (2014) 74:2764

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

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

[a] Value derived for 1 mg of Li salt absorbed into the surface of each detector

close

far

Hard to shield components close to the detectors (e.g. front-end electronics and cables)

Coaxial Cables - GERDA

- GERDA Phase-1

^{228}Th: 1.1±0.5 mBq/kg
^{238}U < 59 mBq/kg
Cu/PTFE 1 mm OD
linear density = 2.7 g/m

Table 3 Cables deployed in the 1-string and 3-string locks.

cable	ref.	type	1-string	3-string
Habia SM50	[66]	50 Ω, coaxial	15	24
SAMI RG178	[67]	HV (4 kV), coaxial	4	-
Teledyne Reynolds 167-2896	[68]	HV (18 kV), coaxial	-	10
Teledyne Reynolds 167-2896	[68]	HV (5 kV), unshielded	1	2
total number			20	38

[arXiv:1212.4067v1]

Construction:

Conductor	Silver plated high strength copper alloy (1x0,16)	0,16
Dielectric	Solid PTFE	0,52
Braid	Silver plated copper (0,06)	0,85
Jacket	FEP, Brown-transparent	1,00
Weight	2,7 kg/km	
Temperature rating (°C)	-55 / +200°C	
Order reference	**30000-050-00**	

Over an order of magnitude too radioactive for MJD

Coaxial Cables - GERDA

- GERDA Phase-1

^{228}Th: 1.1±0.5 mBq/kg
^{238}U < 59 mBq/kg
Cu/PTFE 1 mm OD
linear density = 2.7 g/m

Table 3 Cables deployed in the 1-string and 3-string locks.

cable	ref.	type	1-string	3-string
Habia SM50	[66]	50 Ω, coaxial	15	24
SAMI RG178	[67]	HV (4 kV), coaxial	4	-
Teledyne Reynolds 167-2896	[68]	HV (18 kV), coaxial	-	10
Teledyne Reynolds 167-2896	[68]	HV (5 kV), unshielded	1	2
total number			20	38

[arXiv:1212.4067v1]

Construction:

Conductor	Silver plated high strength copper alloy (1x0,16)	0,16
Dielectric	Solid PTFE	0,52
Braid	Silver plated copper (0,06)	0,85
Jacket	FEP, Brown-transparent	1,00
Weight	2,7 kg/km	
Temperature rating (°C)	-55 / +200°C	
Order reference	**30000-050-00**	

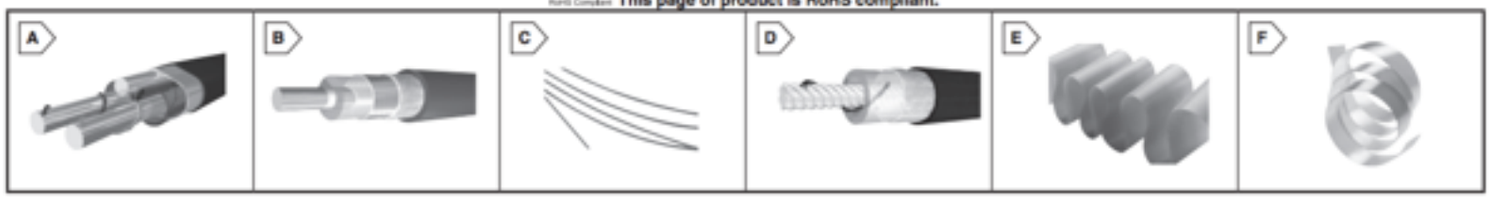
Over an order of magnitude too radioactive for MJD

- Silver-plated Cu is likely hot
- Scaling to a HV cable (5 kV DC rating) means even higher activity

Other commercial options?

Coaxial, Ribbon and Multi-Conductor Cables

This page of product is RoHS compliant.



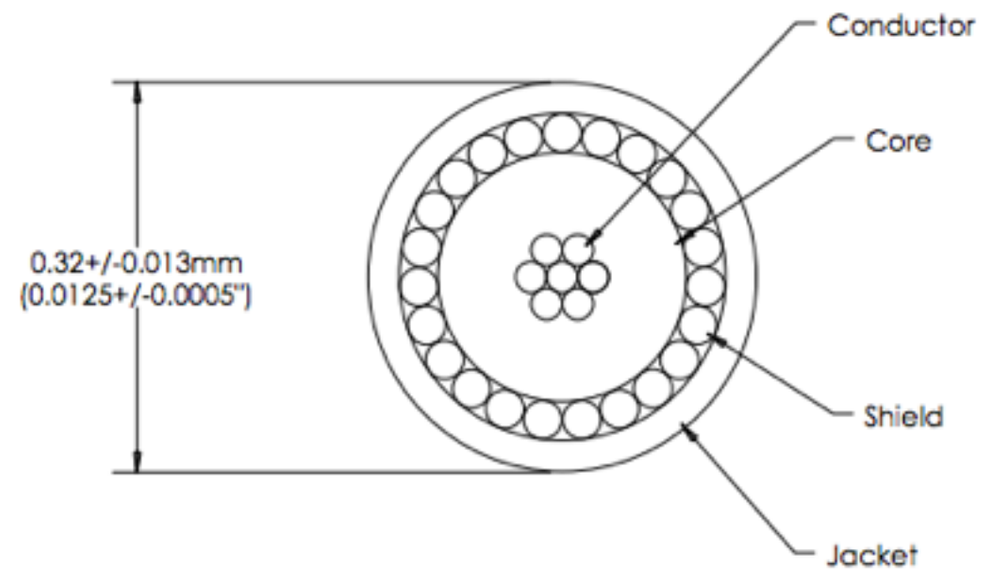
TEMP-FLEX a molex company **COAXIAL CABLES**

For quantities greater than listed, call for quote.

MOUSER STOCK NO.	Temp-Flex Part No.	Fig.	Nominal OD (in.)	Signal Conductors	Braid Shield	Color	Price Per Ft. 1	10	25	50
Twinax Cable • Capacitance: 14.5pF/ft. • Differential Impedance: 100+/-5 Ohms										
538-100TX-08	100TX-08	A	0.049+/-0.005	32AWG	44AWG	1-Blue, 1-Green	2.12	1.99	1.83	1.53
Flexible Microwave Coaxial Cables • Capacitance: 29.0pF/ft. (95pF/ft.) • Impedance: 50+/-1 Ohms										
538-141SC-1901	141SC-1901	B	0.157+/-0.005	19AWG	40AWG	Blue	11.56	10.87	9.96	8.37
538-047SC-2901	047SC-2901	B	0.056+/-0.003	29AWG	46AWG	Blue	4.49	4.22	3.87	3.25
Microminiature Coaxial Cable • Capacitance: 30pF/ft. Nominal • Impedance: 50+/-2 Ohms										
538-086SC-2401	086SC-2401	B	0.101+/-0.005	24AWG	40AWG	Blue	7.40	6.96	6.38	5.36
538-50MCX-37	50MCX-37	C	0.125+/-0.005	42AWG	48AWG	Blue	2.55	2.39	2.20	1.85
High Speed Data Cables • Capacitance: 30pF/ft. Nominal • Impedance: 50+/-2 Ohms										
538-50CX-41	50CX-41	D	0.071	30AWG, 7/38	40AWG	Black	2.81	2.64	2.42	2.04
538-50CX-42	50CX-42	D	0.100	26AWG, 7/34	38AWG	Black	3.64	3.42	3.14	2.63

TEMP-FLEX a molex company **FLAT FEP RIBBON CABLES**

Mouser catalogue



TEMP-FLEX a molex company

Enlarge

Mouser Part #:	538-50MCX-37
Manufacturer Part #:	50MCX-37
Manufacturer:	Temp-Flex
Description:	Coaxial Cables 42AWG PFA, 50 OHM MICRO COAX, PER FT

Learn more about Temp-Flex 50MCX-37

Page 1,389, Mouser Online Catalog
Page 1,389, PDF Catalog Page
Data Sheet

Radiopurity concerns:

- dye in the jacket
- silver-plated copper alloy in braid and central conductor

It became clear that we needed to do a special production run

Coaxial Cables - MJD

- FEP and PFA
  - have high dielectric strength (Dupont: 260 kV/mm)
  - are radiopure

Cu

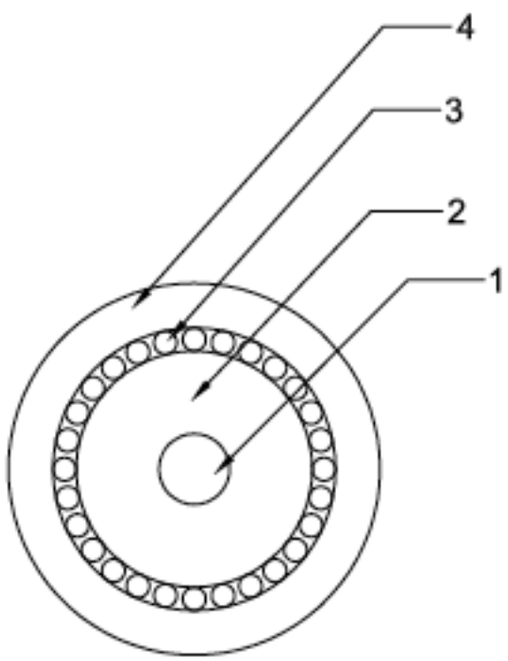
dielectric

Sample	Lab	Reported in pg/g				Reported in μBq/kg			
		^{232}Th	± 1σ	^{238}U	± 1σ	^{232}Th	± 1σ	^{238}U	± 1σ
Cu conductor wire (signal, CFW)	LBNL	<30	-	<50	-	<120	-	<620	-
Cu conductor wire (high voltage, CFW)	LBNL	<30	-	180	50	<120	-	2200	620
Cu wire 50AWG (uncleaned, MWS[1])	LBNL	120	20	73	28	490	80	910	350
Cu wire 50AWG (cleaned, MWS)	LBNL	30	30	42	10	120	120	520	120
PFA416[2]	PNNL	2.60	**	0.89	**	10.66	**	11.09	**
PFA340A[3]	PNNL	3.28	**	1.90	**	13.45	**	23.57	**
FEP 106	PNNL	0.11	**	1.96	**	0.43	**	24.36	**
FEP NP20	PNNL	0.99	**	0.61	**	4.05	**	7.60	**
FEPTE 9494	PNNL	4.03	**	0.71	**	16.52	**	8.75	**

- The radiopurity of the Cu drives the background budget:
  - reduce OD of central conductor
  - reduce OD of inner dielectric
  - helical shield (instead of braid)

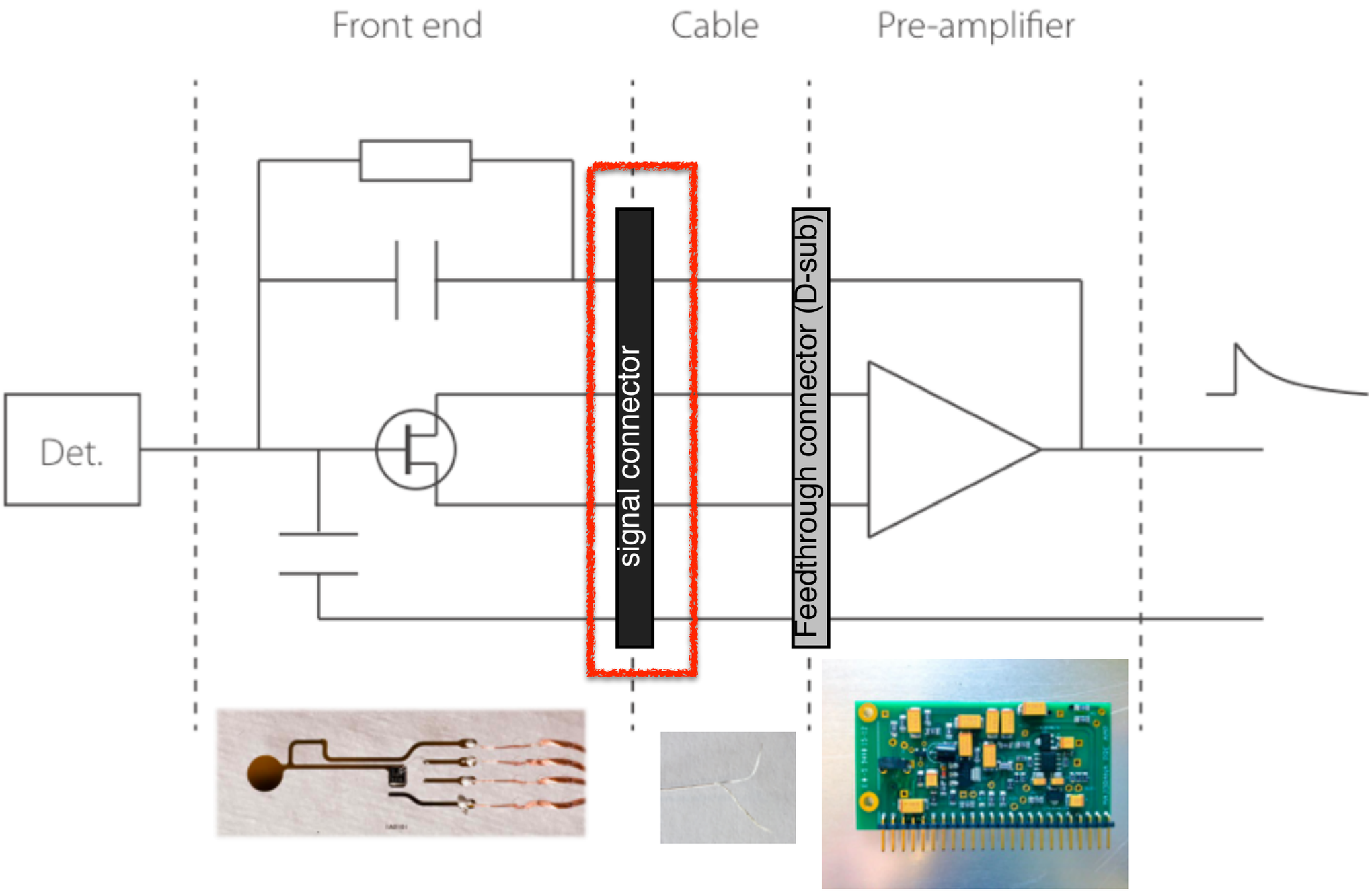
Coaxial Cables - MJD

- Contracted Axon' in France to make the "picocoax" cable



		Material	Signal	HV
1	central conductor	Bare Cu	0.0762 mm ϕ	0.152 mm ϕ
2	inner dielectric	FEP / PFA	0.254 mm ϕ	0.77 mm ϕ
3	helical shield	Bare Cu	AWG50	AWG50
4	jacket	FEP / PFA	0.4 mm ϕ	1.2 mm ϕ
Linear mass density			0.4 g/m	3 g/m

Making connectors



Technical Issue: Plug Design

- Cable connection: solder to tiny pins
- Pins are held in vespel housing that also provides strain relief
- Press-fit, keyed shell interface for ease of assembly in the glove box
- Vacuum tests indicate no significant virtual leaks.
- BeCu contact is too radioactive for MJD (~10 cts/t/y). Iterative prototyping to establish reliable connection during thermal cycling.
- Full body ICPMS indicates the connectors are sufficiently clean for MJD

Solder

- "Typical clean solder":

Grouping	Name	Isotope	Amount	Isotope	Amount		
SuperCDMS	Solder paster, Alpha WS-820	Th-232	5.28 mBq/kg	U-238	5.615 mBq/kg	...	×
ILIAS UKDM	Solder, SnCu	Th-232	1 ppb	U-238	5 ppb	...	×
ILIAS UKDM	Silfos (Ag, Cu, Sn solder)	Th-232	0.05 ppb	U-238	0.05 ppb	...	×
ILIAS UKDM	Silver solder	Th-232	0.072 ppb	U-238	0.1 ppb	...	×

- Low background ideas:
  - Roman Pb
  - Source clean solder (e.g. SnAg), use abietic acid as flux.

PCB in low-background experiment

S. Nisi *, A. Di Vacri, M.L. Di Vacri, A. Stramenga, M. Laubenstein

Laboratori Nazionali del Gran Sasso, INFN, S. S. 17/bis km 18+910, I-67010 Assergi (AQ), Italy

Applied Radiation and Isotopes 67 (2009) 828–832

Sample	^{40}K (mBq kg^{-1})	^{232}Th (mBq kg^{-1})	^{238}U (mBq kg^{-1})
PEN			
γ-spectroscopy	510±20	136±3	242±3 (^{226}Ra) 236±68 (^{234m}Pa)
ICP-MS	370±50	110±10	200±30
KAPTON® HN DuPont			
γ-spectroscopy	<5.4	1.4±0.7	14±1 (^{226}Ra) <27 (^{234m}Pa)
ICP-MS	7±3	0.65±0.08	17±2
CuFlon®			
γ-spectroscopy	48±15	<1.9	<0.84 (^{226}Ra) <132 (^{234m}Pa)
ICP-MS	6−2/+9	0.28−0.03/+0.04	0.36−0.04/+0.07

- CuFlon is cleaner than Kapton in U and Th, but it's much worse in ^{40}K

Processing PCBs

- Once selected the proper raw material →Important not to spoil its radiopurity by PCB process.
- Avoid finishing protective layers (soldermasks etc.)
- Minimize Cu deposition
- **Gold finishing required for bonding (typically <1 um) introduces significant U contaminations. Minimize golded surfaces (in GERDA few mm^2/detector)**

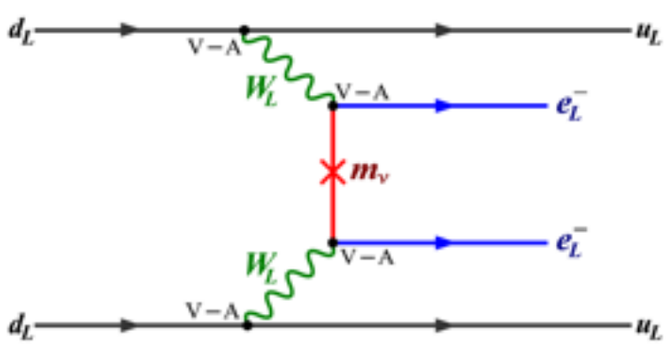
				Solfor		Fosfor		Cleaning		PreAu		Micro Etching		Gold		Nickel
39	K	ppb		2000		4900		6100		Saturate		96000		32000000		38000
208	Pb	ppb	<	0,3		0,7		11		28		17		2	<	10
232	Th	ppb	<	0,03		0,05	<	0,03		1		0,04		1,7	<	0,3
238	U	ppb		0,13		22		0,8		5,8		0,81		7,7	<	0,3

Cattadori, LRT 2015

Do other mechanisms tell us anything about (light) m(ν)?

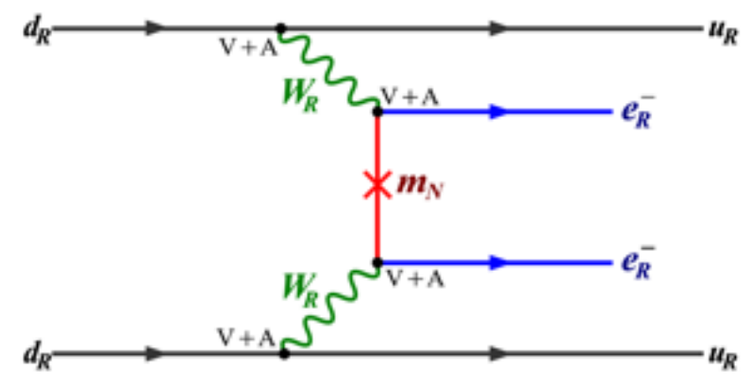
"Vanilla" mass mechanism

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} \left| U_{ei}^2 m_i \right|$$

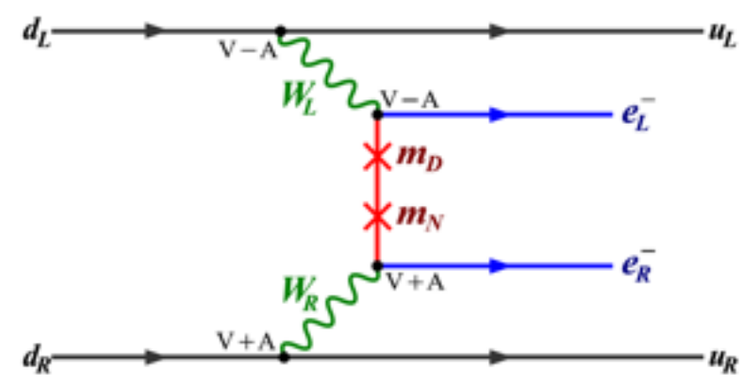


L-R symmetric model

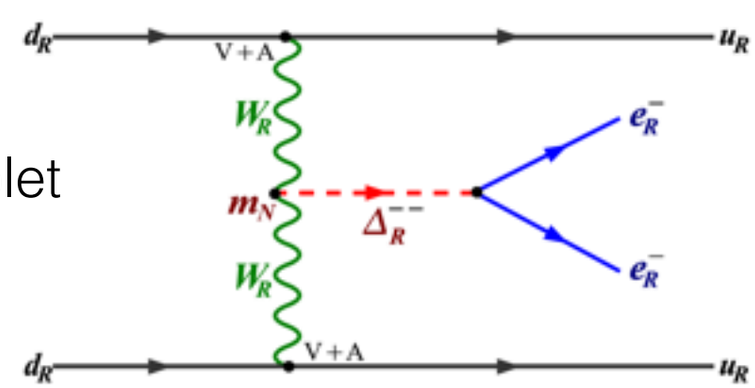
Heavy neutrino exchange



L-R mixing



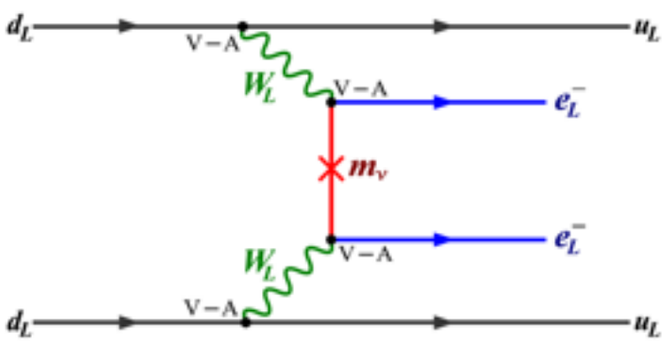
Doubly-charged Higgs triplet exchange



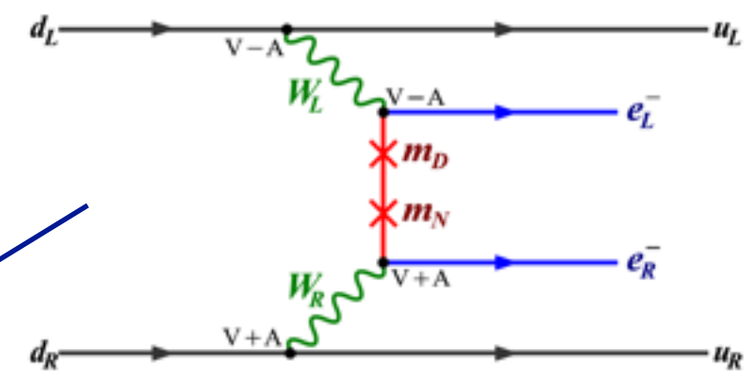
0νββ half-life may not yield any direct information about the neutrino mass.

How to disentangle different ($0\nu\beta\beta$) mechanisms?

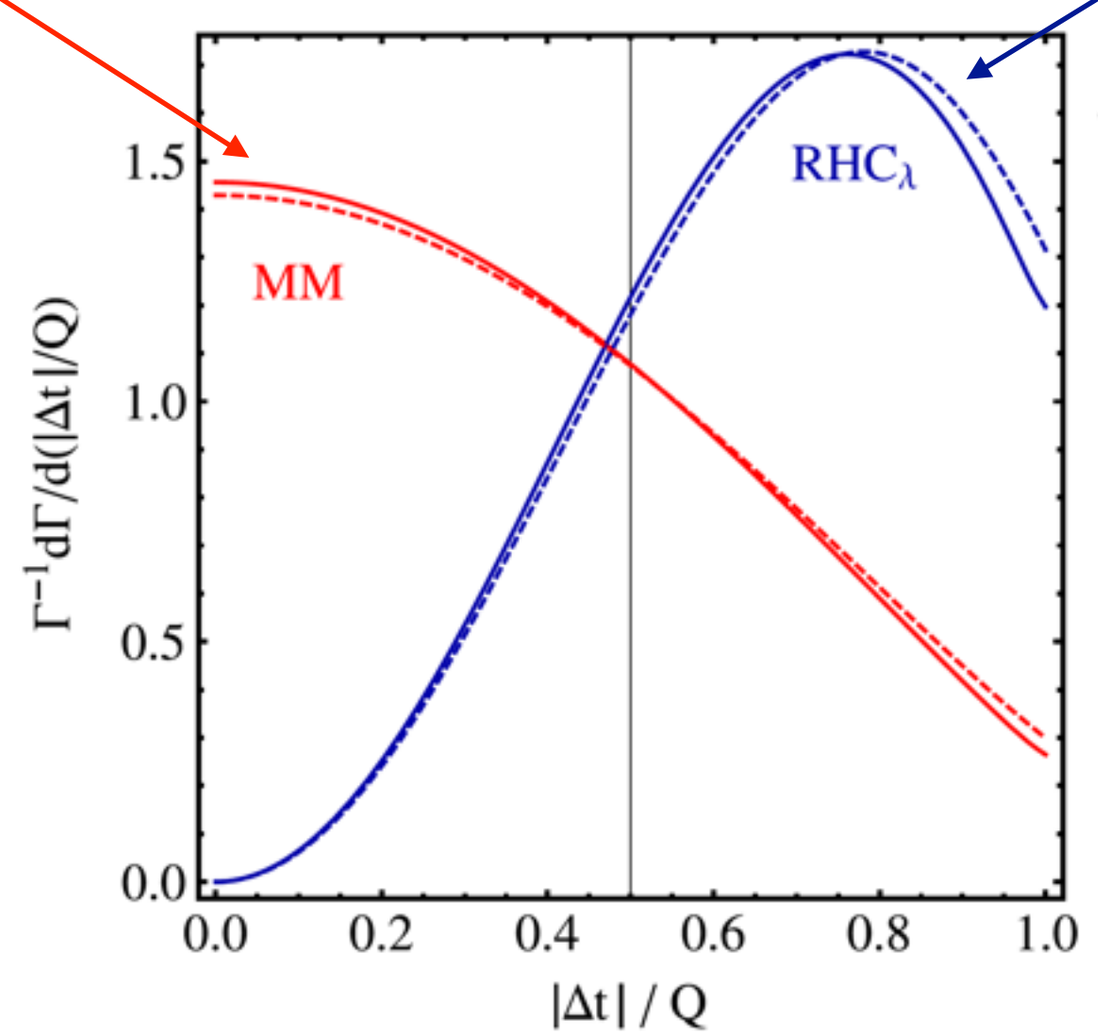
- Exploit energy and angular distributions



mass mechanism



right-handed current



$|\Delta t| = |T_{e1} - T_{e2}|$

Fig. 2 (Color online) Normalised $0\nu\beta\beta$ decay distribution with respect to the electron energy difference in the MM (*red*) and RHC$_\lambda$ mechanism (*blue*) for the isotopes ^{82}Se (*solid curves*) and ^{150}Nd (*dashed curves*) [SuperNEMO, Eur. Phys. J. C 70 (2010) 927]

How to disentangle different ($0\nu\beta\beta$) mechanisms?

- Exploit differences in different isotopes

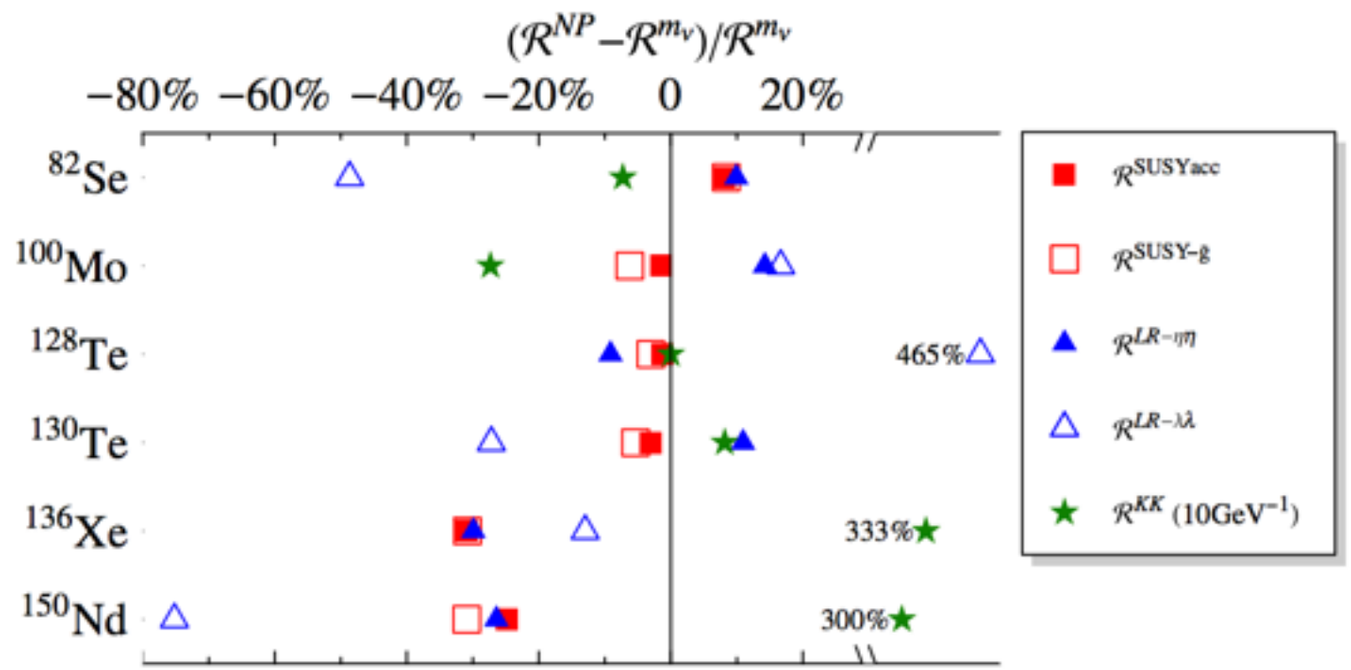


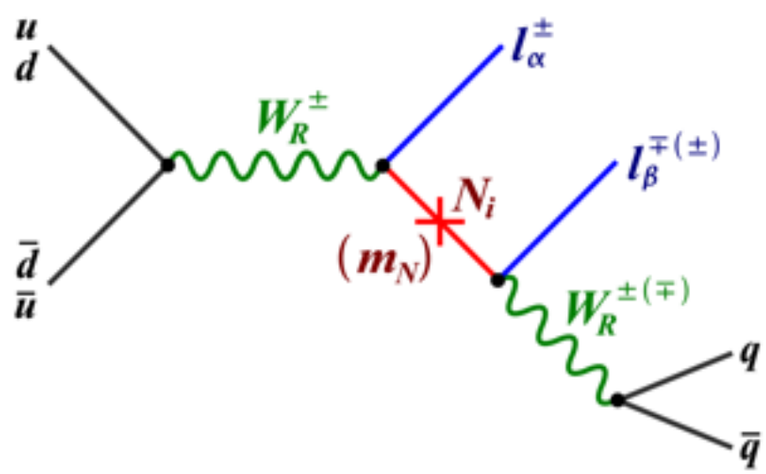
FIG. 1 (color online). Relative deviations of half-life ratios $\mathcal{R}^{NP}(^AX)$, normalized to the half-life of ^{76}Ge, compared to the ratio in the mass mechanism $\mathcal{R}^{m_\nu}(^AX)$. Deppisch et al., Phys. Rev. Lett. 98, 232501 (2

- Exploit differences in $0\nu\beta^+\beta^+$ / $0\nu\beta^+$EC
- Exploit differences in first-excited and ground state transitions

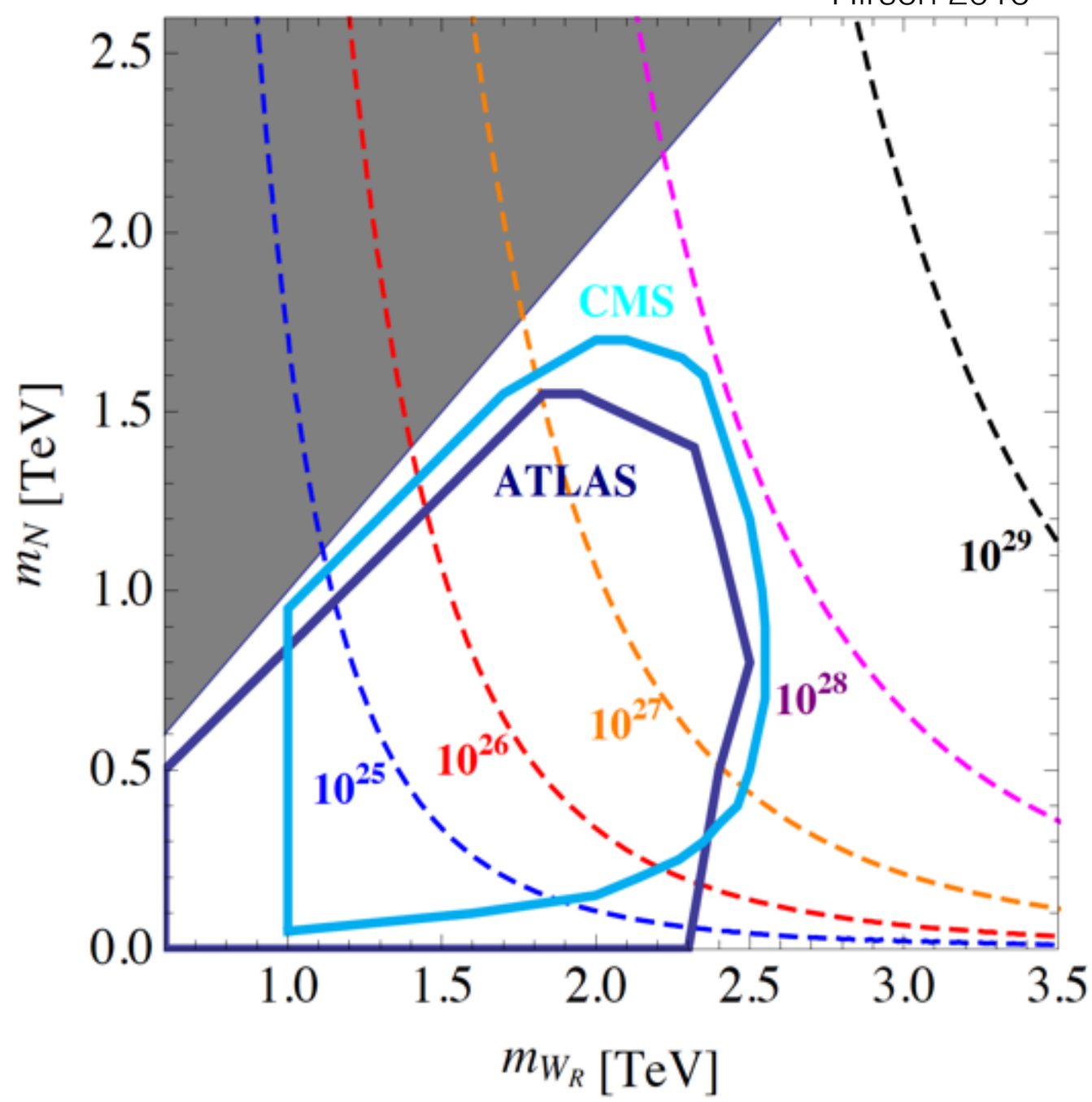
Problem: Need statistics

Complementarity to LHC / heavy flavor physics

- LNV via heavy right-handed neutrino exchange can be probed via $l^{\pm}l^{\pm} + 2j$



Hirsch 2016

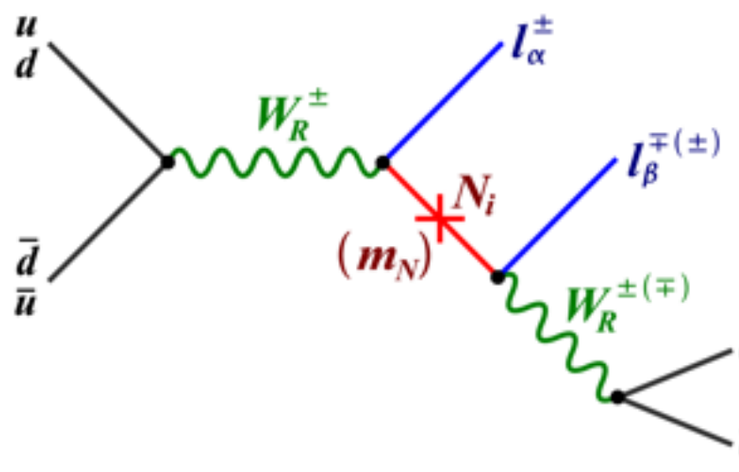


Same sign: $l^{\pm}l^{\pm} + 2j$

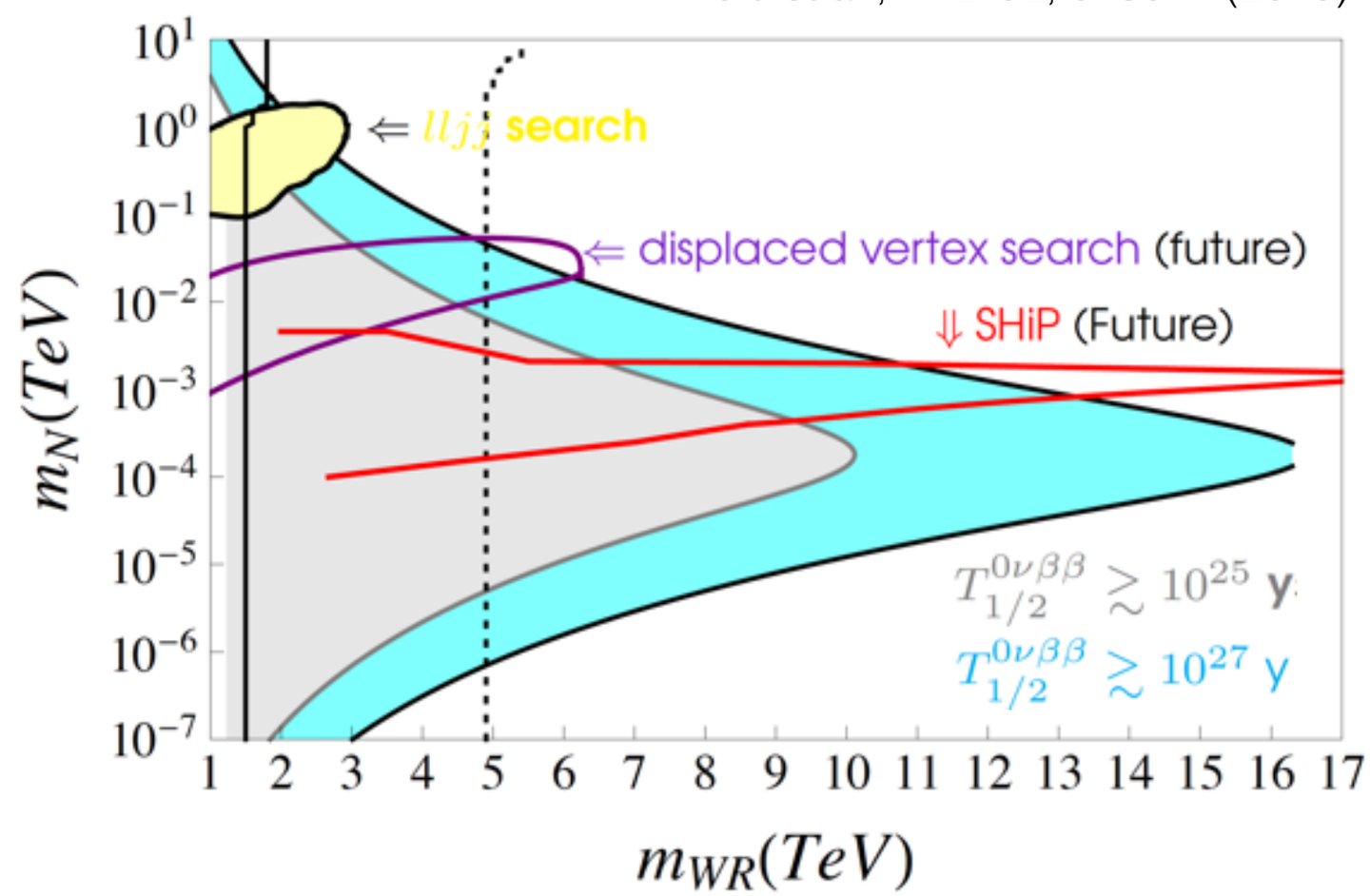
Non-observation gives stringent limits on short-range W_R mechanisms

Complementarity to LHC physics

- LNV via heavy right-handed neutrino exchange can be probed via $l^{\pm}l^{\pm} + 2j$



Helo et al., PRD 92, 073017 (2015)



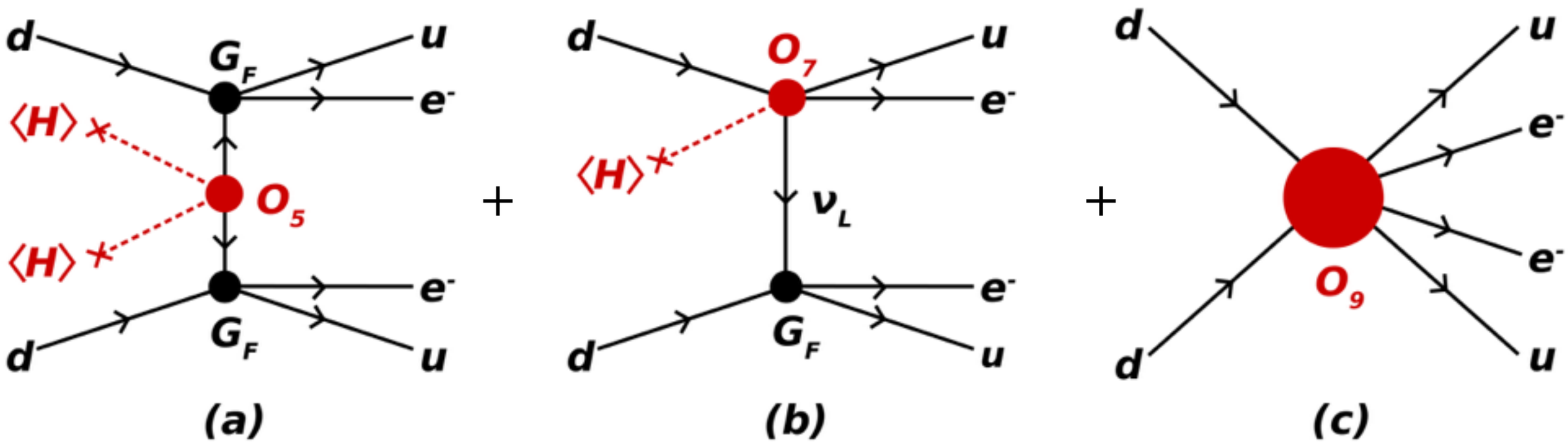
Same sign: $l^{\pm}l^{\pm} + 2j$

Non-observation gives stringent limits on short-range WR mechanisms

What are the possibilities inside the black box?

$$\Delta L = 2$$

GUT scale / seesaw **LHC energy**



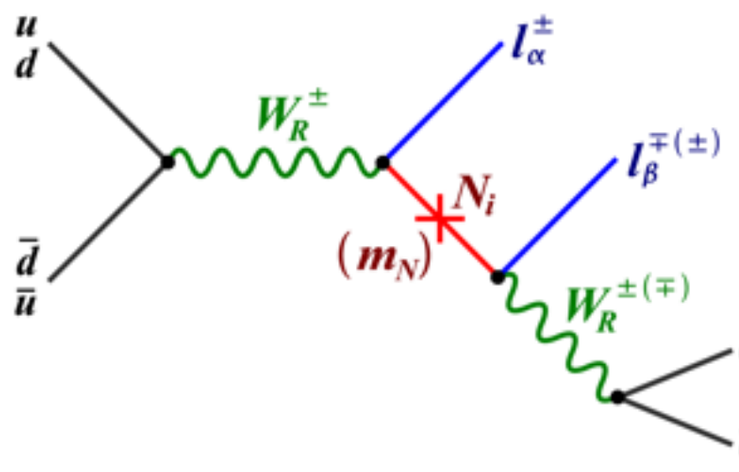
Mass mechanism “Long-range” “Short-range”

$0\nu\beta\beta$ allows us to probe the GUT scale

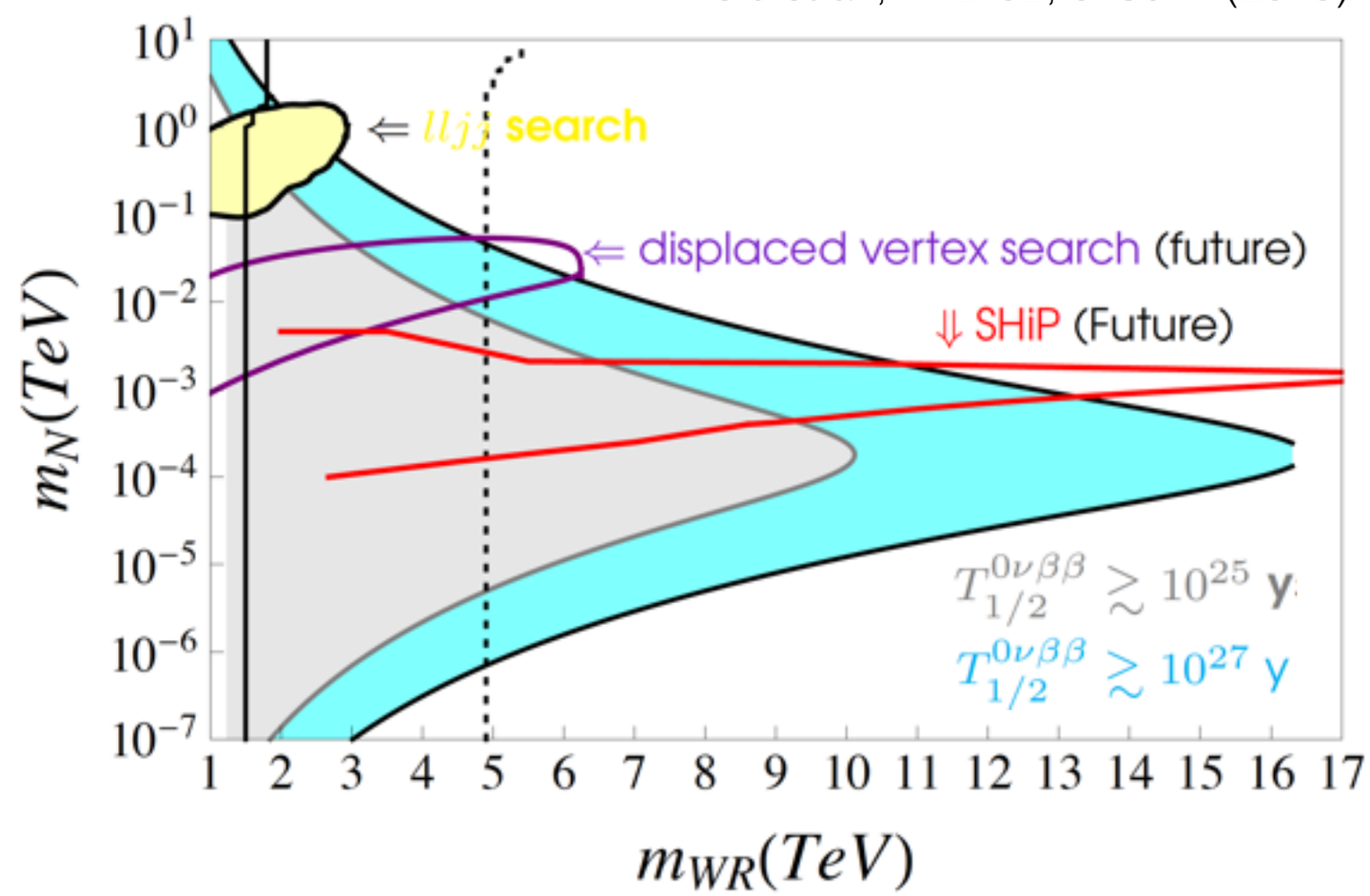
Graphics from Hirsch 2016

Complementarity to LHC physics

- LNV via heavy right-handed neutrino exchange can be probed via $l^{\pm}l^{\pm} + 2j$



Helo et al., PRD 92, 073017 (2015)



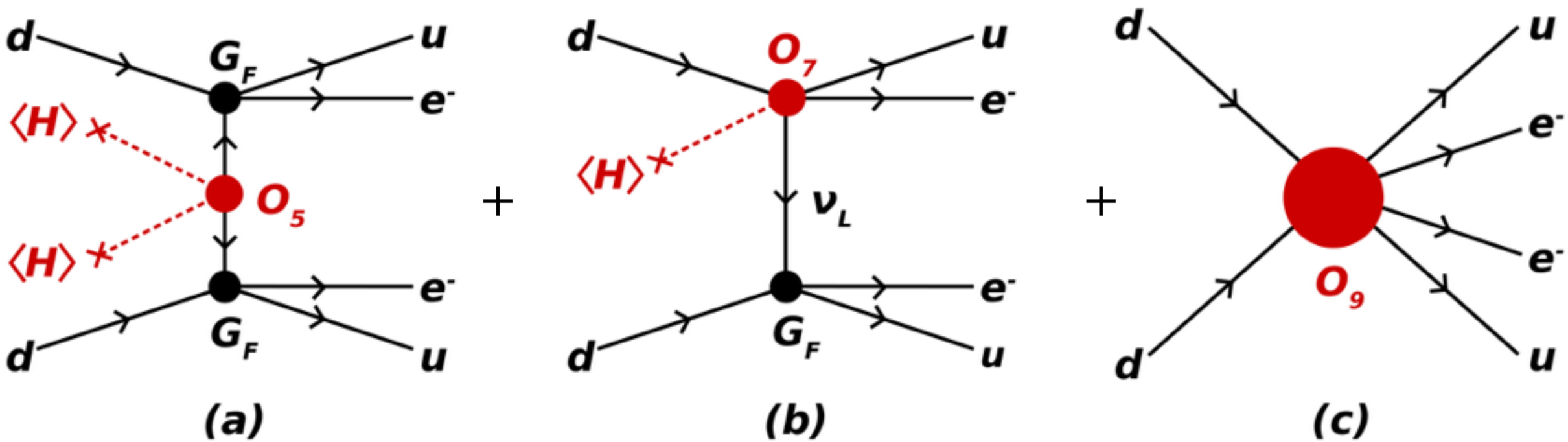
Same sign: $l^{\pm}l^{\pm} + 2j$

Non-observation gives stringent limits on short-range WR mechanisms

What are the possibilities inside the black box?

$$\Delta L = 2$$

GUT scale / seesaw **LHC energy**



Mass mechanism “Long-range” “Short-range”

$0\nu\beta\beta$ allows us to probe the GUT scale

Graphics from Hirsch 2016