Ettore Majorana meets his shadow (III)

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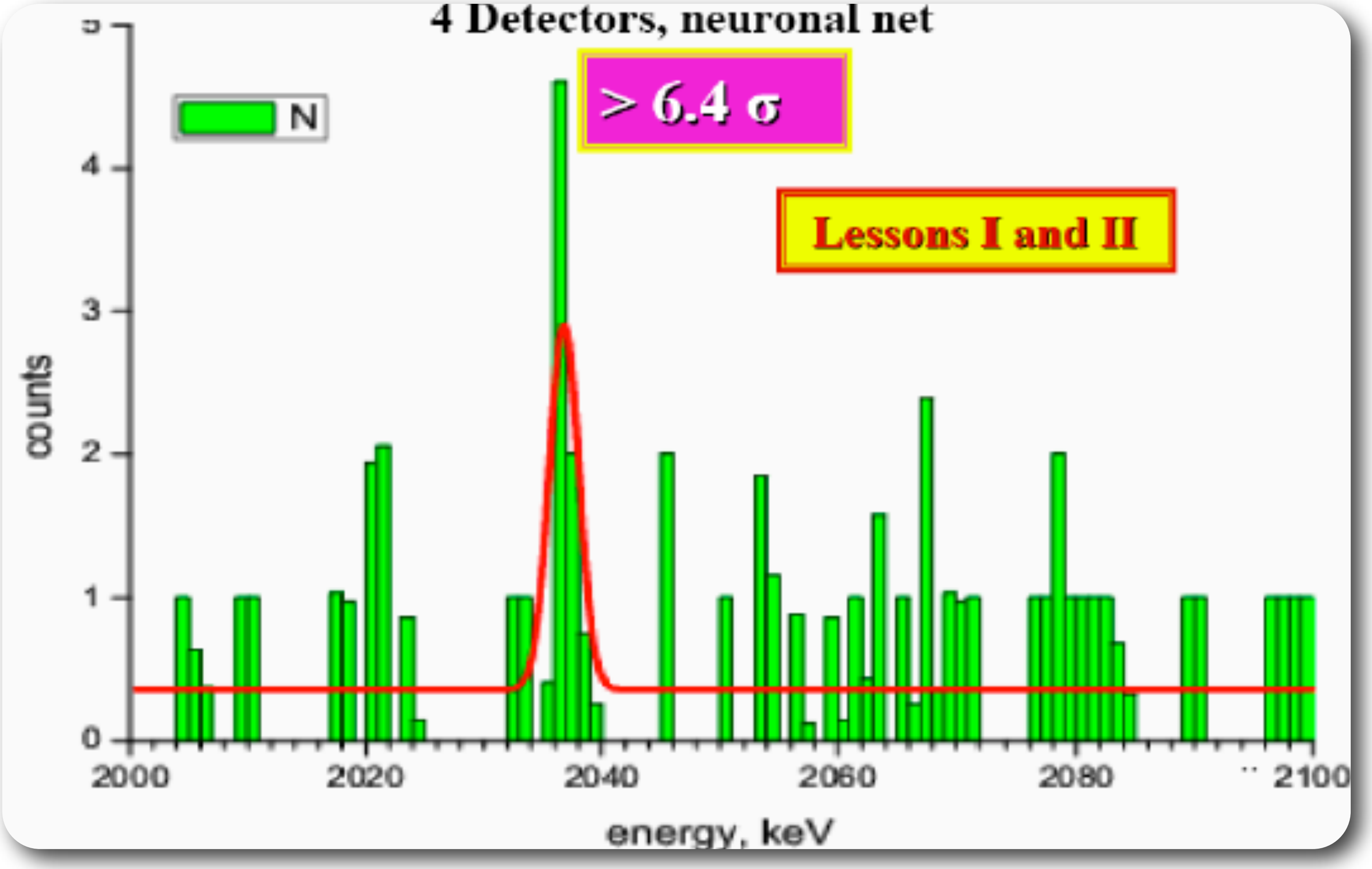
DBD Game

- Discovery: Free trip to Stockholm
- Not Discovery: What exactly did you do in the last 20 years?

Discovery?



Not Discovery

Heidelberg-Moscow experiment:

- 35 kg·yr exposure
- $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr
- $m_{\beta\beta} < 0.35$ eV (0.3 – 1.24 eV)

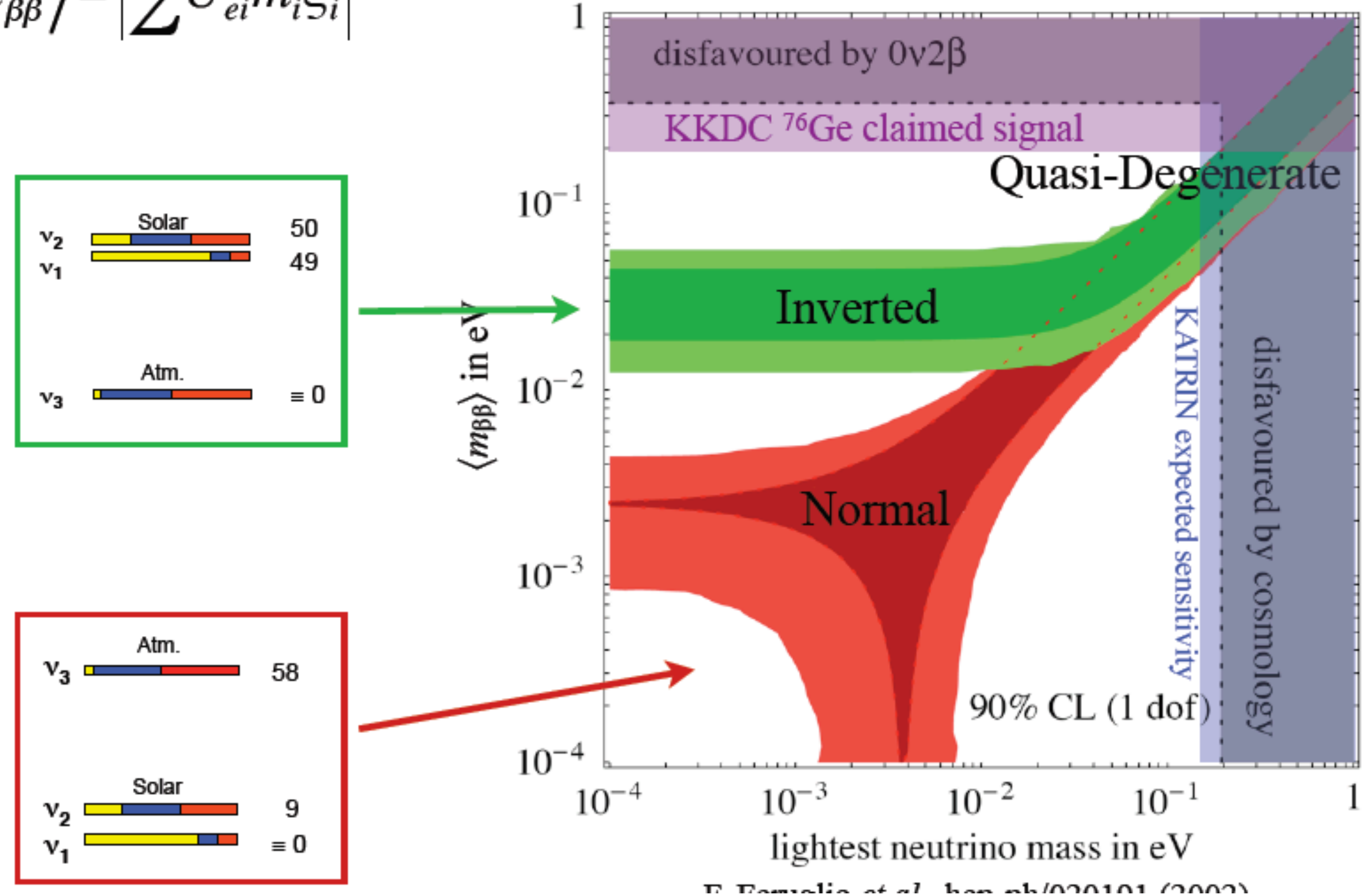
- 6.4σ significance
- $T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr
- $m_{\beta\beta} = (0.32 \pm 0.03)$ eV
- With NME uncertainties: $m_{\beta\beta} = (0.1 – 0.9)$ eV

Or discovery?

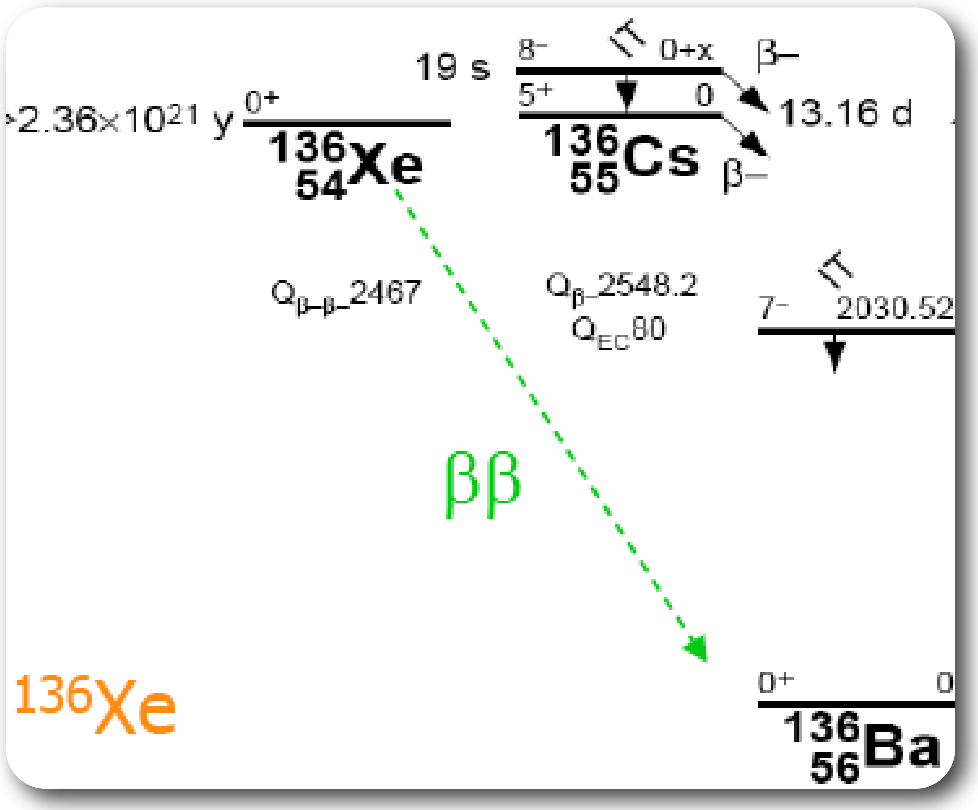
bb0nu sensitivity to mbb

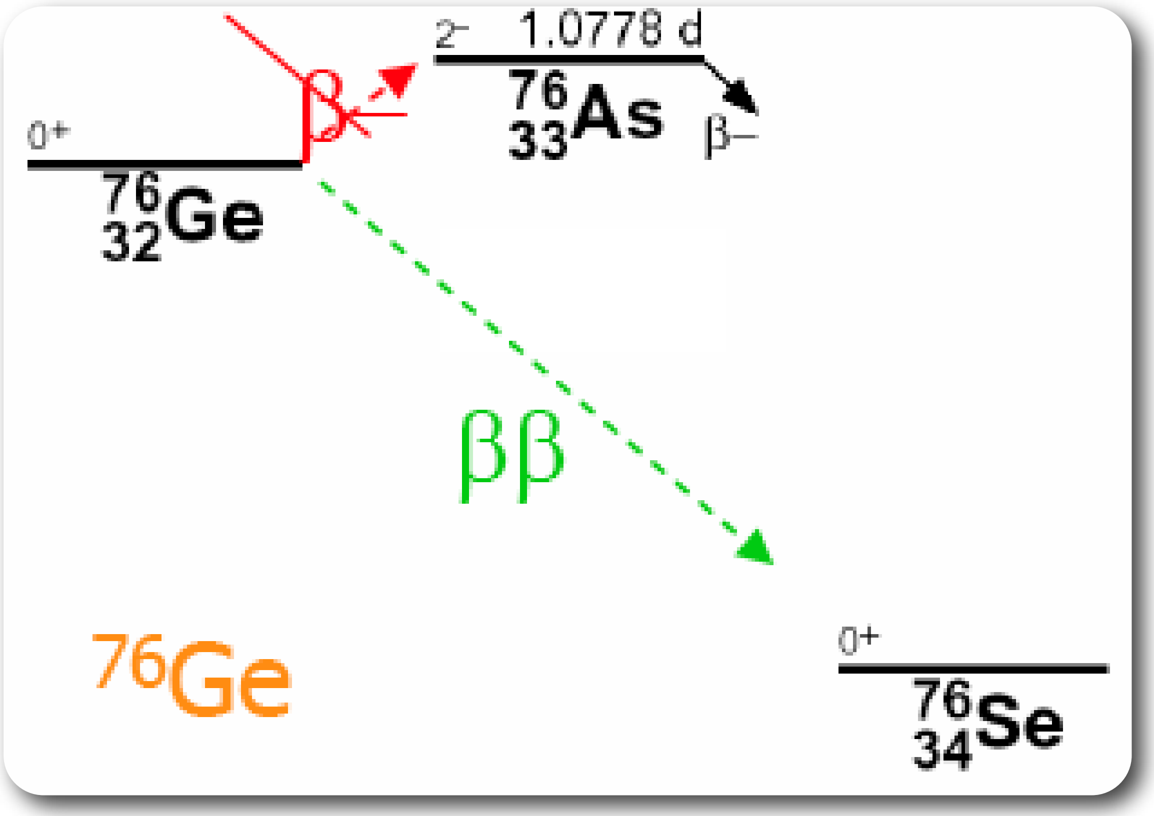
$0\nu\beta\beta$ limits for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd
^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

$$\langle m_{\beta\beta} \rangle = \left| \sum U_{ei}^2 m_i \xi_i \right|$$



DBD Lifetime





$$T_{\beta\beta 2\nu} \sim 10^{18} - 10^{20}\, y$$

$$T_{\beta\beta 0\nu} \sim 10^{26} - 10^{27}\, y$$

Germanium: 8 events per ton year for a period of 10^{27} y

Why DBD experiments are difficult

a) terrestrial radioactivity

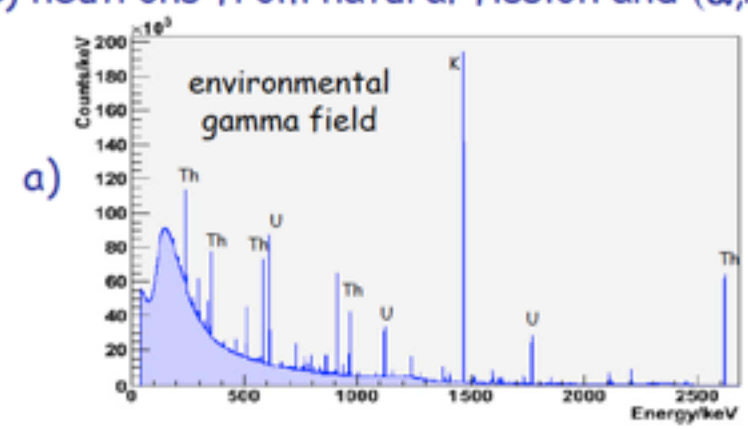
b) radio-impurities in detector and shield material:
primordial, anthropogenic, cosmogenic

c) Rn and its progenies

d) cosmic rays secondaries:
muons, neutrons

e) neutrons from natural fission and (α,n) reactions

illustrated by Ge-spectroscopy



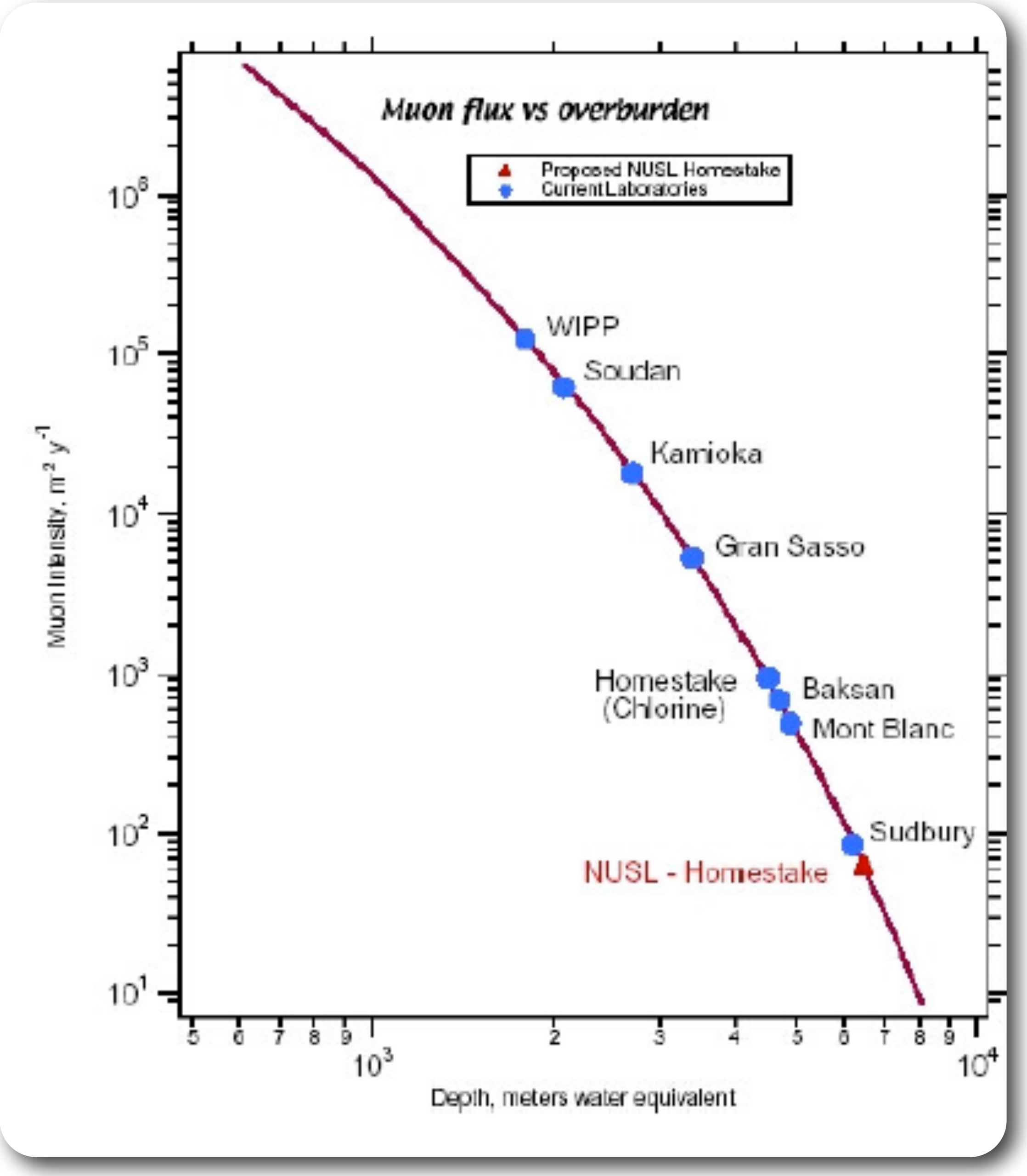
	concentration [Bq/kg]		
rock	^{238}U	^{232}Th	^{40}K
granite	60	80	1000
limestone	30	7	90

G.H., Int. student workshop on ν-less ββ-decay, LNGS, 11.11.10

Very long lifetime

- Uranium and Thorium are weakly radioactive, with a lifetime of the order of 10^9 y
- Exploring bbonu implies lifetimes of the order of 10^{25} y.
- Truly, a needle in a haystack.

Why DBD experiments are underground



Muon flux

- Experiments who want to register one or two events of signal and no background per year, cannot live with high muon flux
- Underground is also quiet and controlled working conditions

Measuring Tbb

$$T_{1/2}^{-1} \propto a \cdot \varepsilon \cdot M \cdot t$$

Background free

$$T_{1/2}^{-1} \propto a \cdot \varepsilon \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

Background dominated

a: isotopic abundance
ε: efficiency
M: source mass
t: time
ΔE: energy resolution
B: background $(\text{keV yr kg})^{-1}$

DBD is all about optimizing this parameters

Ingredients for the ultimate neutrinoless double beta experiment

Plot Credits: Michel Sorel

Isotopes

	Q (MeV)	Abund.(%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

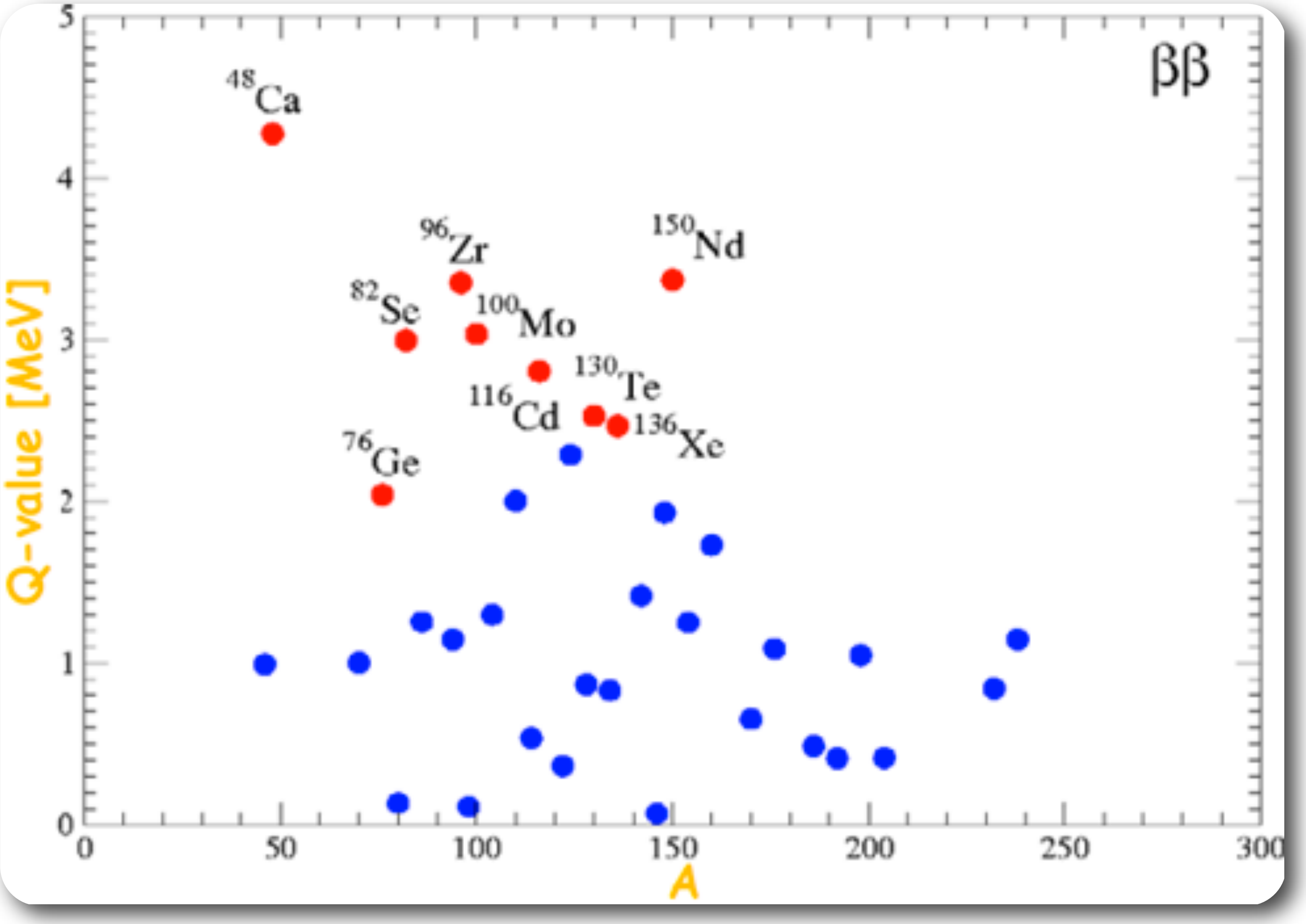
Abundance:

- Worse case is Ca-48
- Best case is Te-130 (only practical for a “natural element experiment)

Enrichment

- Most experiments need to operate with the element enriched at > 80% in the isotope.
- Easiest isotope to enrich: Xe-136.
- Difficult: Ca-48, Nd-150

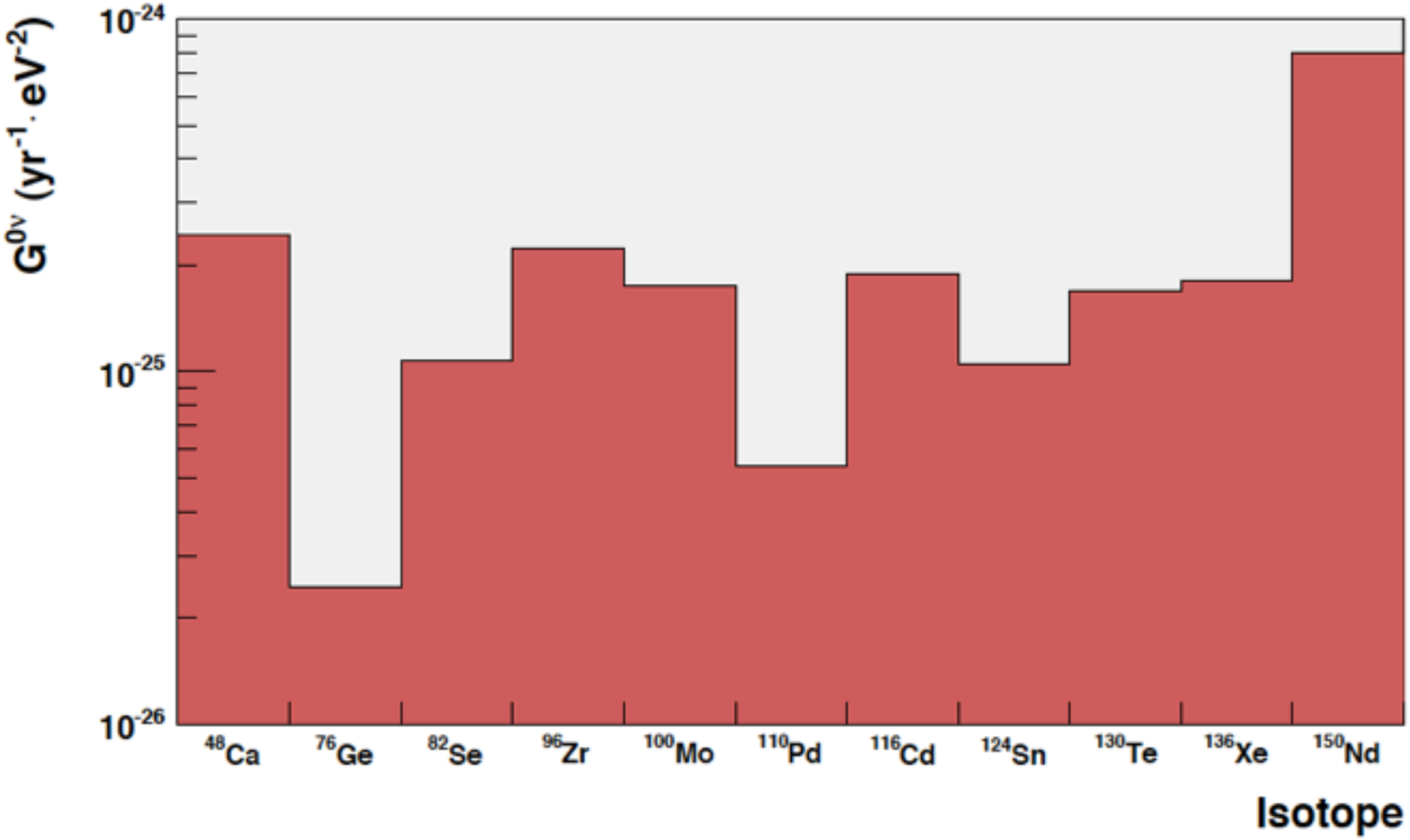
Isotopes



Q-value:
The highest the Q value the better for backgrounds (both bb2nu and natural radioactivity)

- Worse case is Ge-76
- Best cases Ca-48 and Nd-150
- Most others about the same

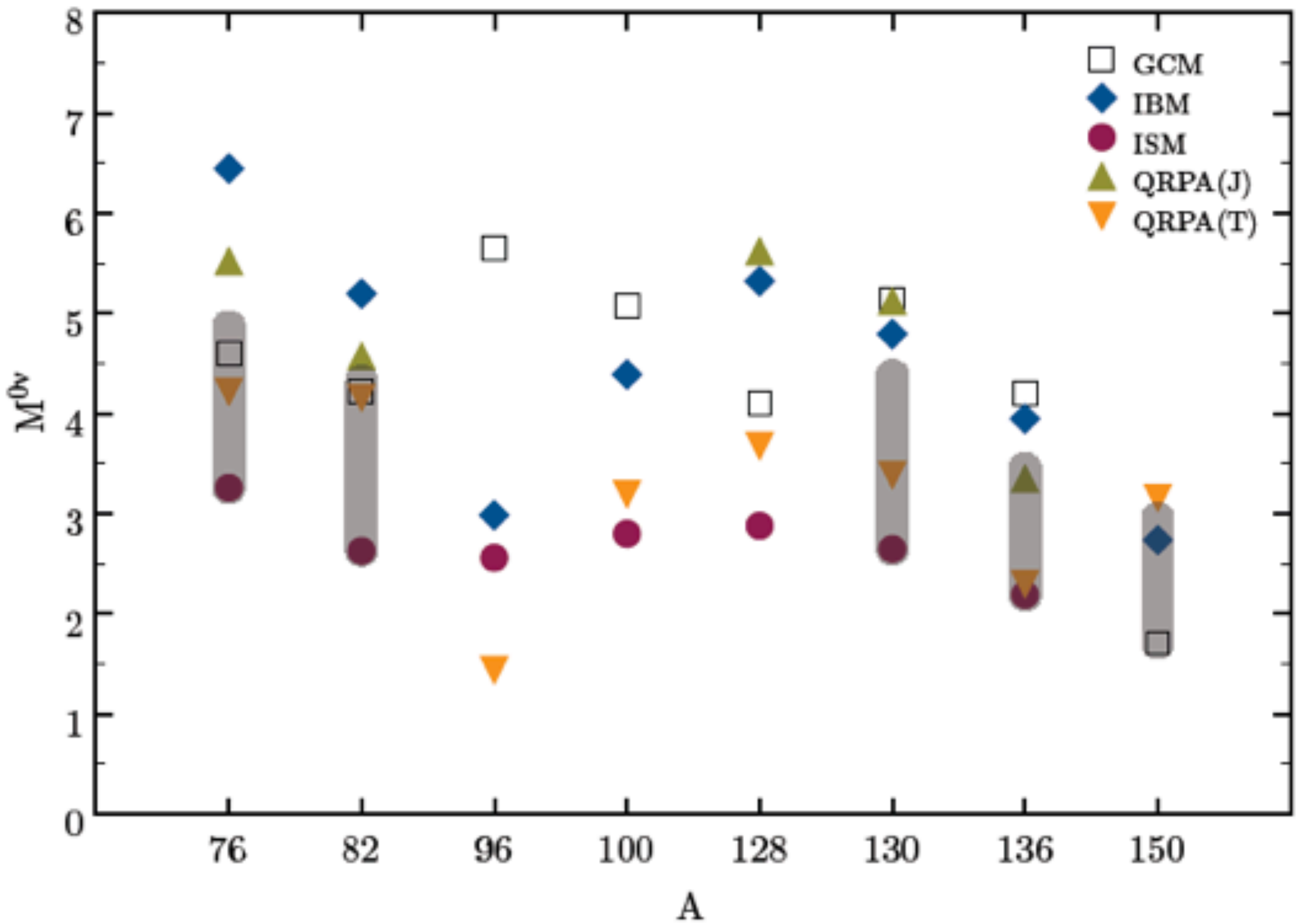
Isotopes



Phase space must be as high as possible.

- Best case: Nd-150
- Worse case: Ge-76
- All others: about the same

Isotopes



NME must be as high as possible.

- Best case: Ge-76
- Worse case: Nd-150
- According to PMR: all quite close

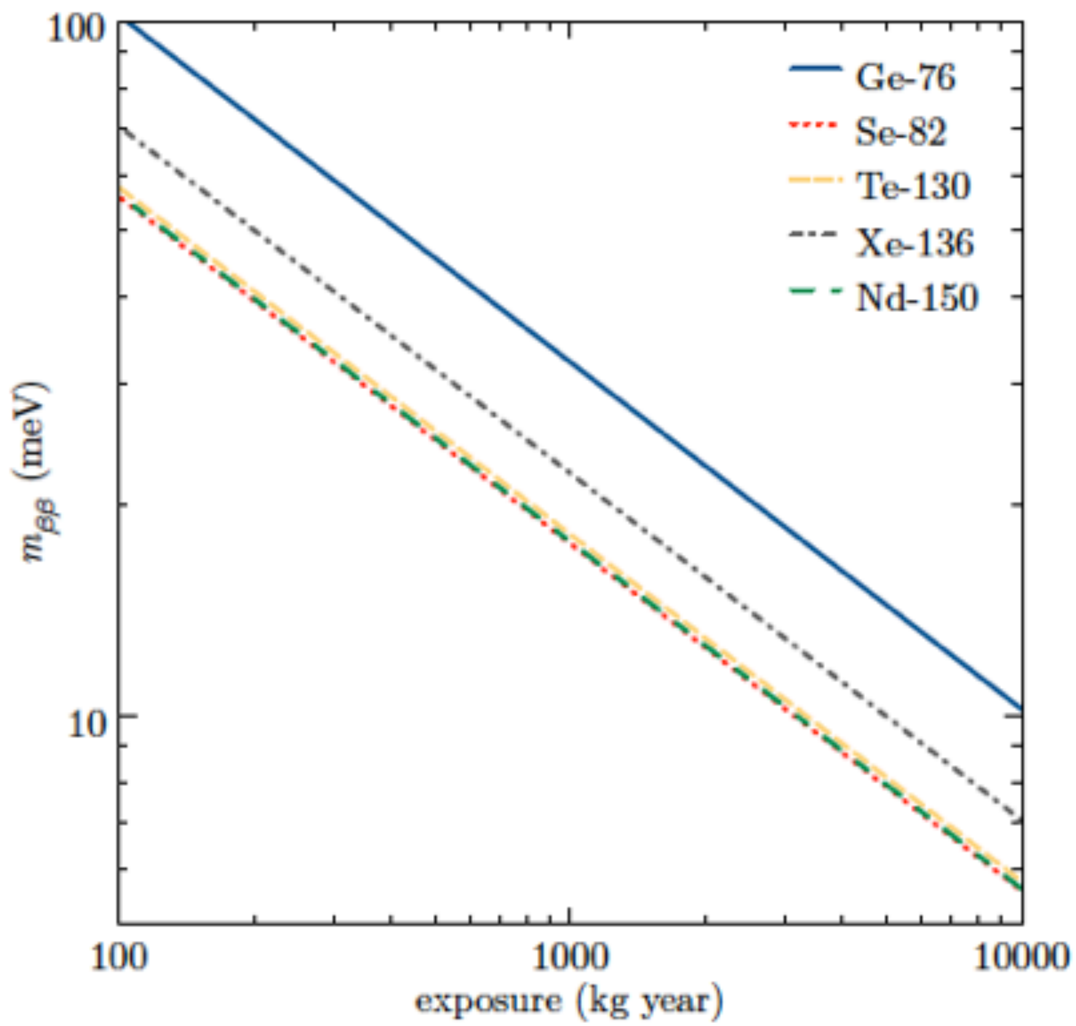
Isotopes

Isotope	W (g/mol)	$Q_{\beta\beta}$ (keV)	$\lvert M_{0\nu}\rvert$	$\lvert G_{0\nu}\rvert^{-1}$ (10^{25} y eV^2)	$T^{0\nu}_{1/2}(m_{\beta\beta} = 50$ meV) (10^{27} y)	$N_{0\nu}/N_{0\nu}$(Ge)
^{76}Ge	75.9	2039	4.07	4.09	0.95	1.0
^{82}Se	81.9	2996	3.48	0.93	0.26	3.3
^{130}Te	129.9	2528	3.63	0.59	0.18	3.1
^{136}Xe	135.9	2458	2.82	0.55	0.25	2.1
^{150}Nd	149.9	3368	2.33	0.13	0.15	3.3

Absolute rate (in this case relative to Ge-76)

- Worse case: Ge-76
- Next-to-worse: Xe-136
- All others: about the same (50 % better than Xe-136, 3 times better than Ge-76)

Isotopes



Sensitivity to $m_{\beta\beta}$

- for ***ideal*** experiments based on different isotopes

Isotopes

So what is the best isotope?

Mass

$$T_{1/2}^{-1} \propto a \cdot \varepsilon \cdot M \cdot t$$

$$T_{1/2}^{-1} \propto a \cdot \varepsilon \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

- ΔE is the resolution. At best constant when you increase the mass
- B is the background rate in *c/(kev·kg·year)*. To keep it constant one needs to decrease the counts/kg (since the mass increases). **Very difficult**.

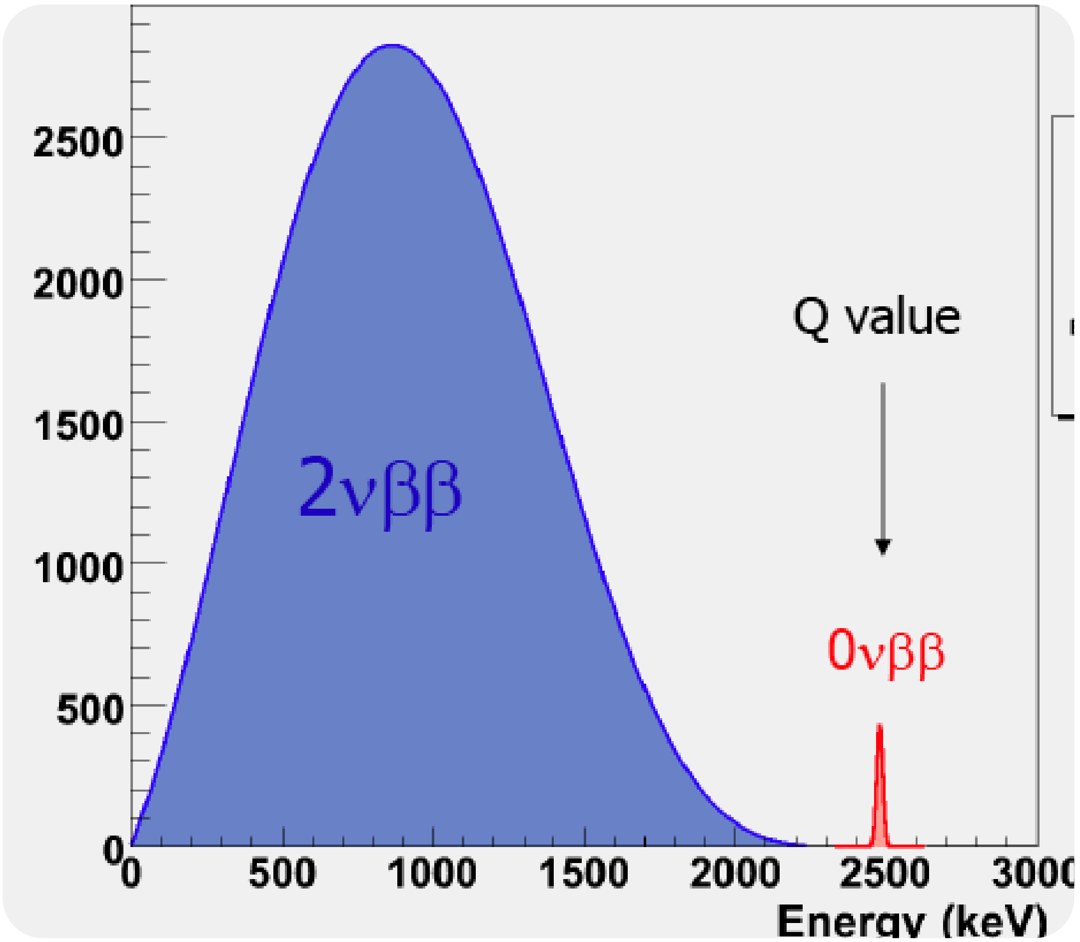
Background free

- Accumulate as much mass as possible. Also, improve linearly with mass (in period)
- It is very difficult to make a background free experiment (but we will try)

Background dominated

- Only worth to improve M (in or to be exact M·t) if you can keep the product ΔE·B constant.

Resolution

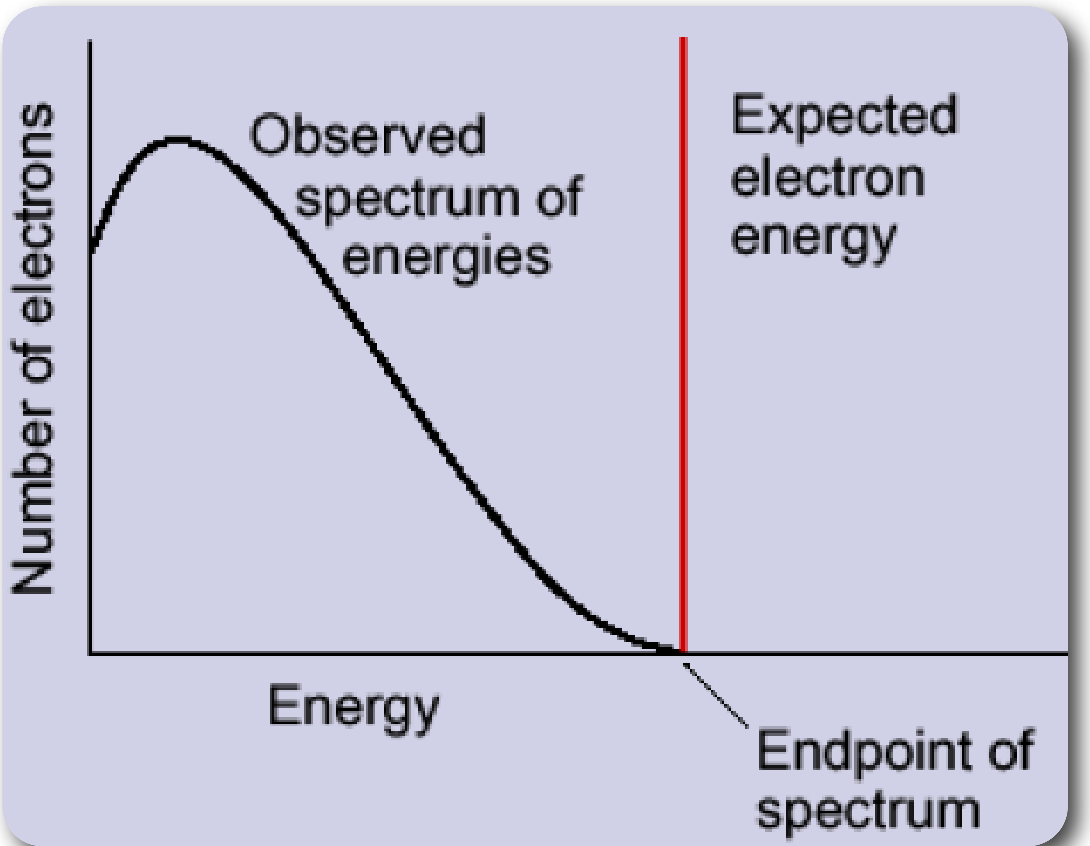


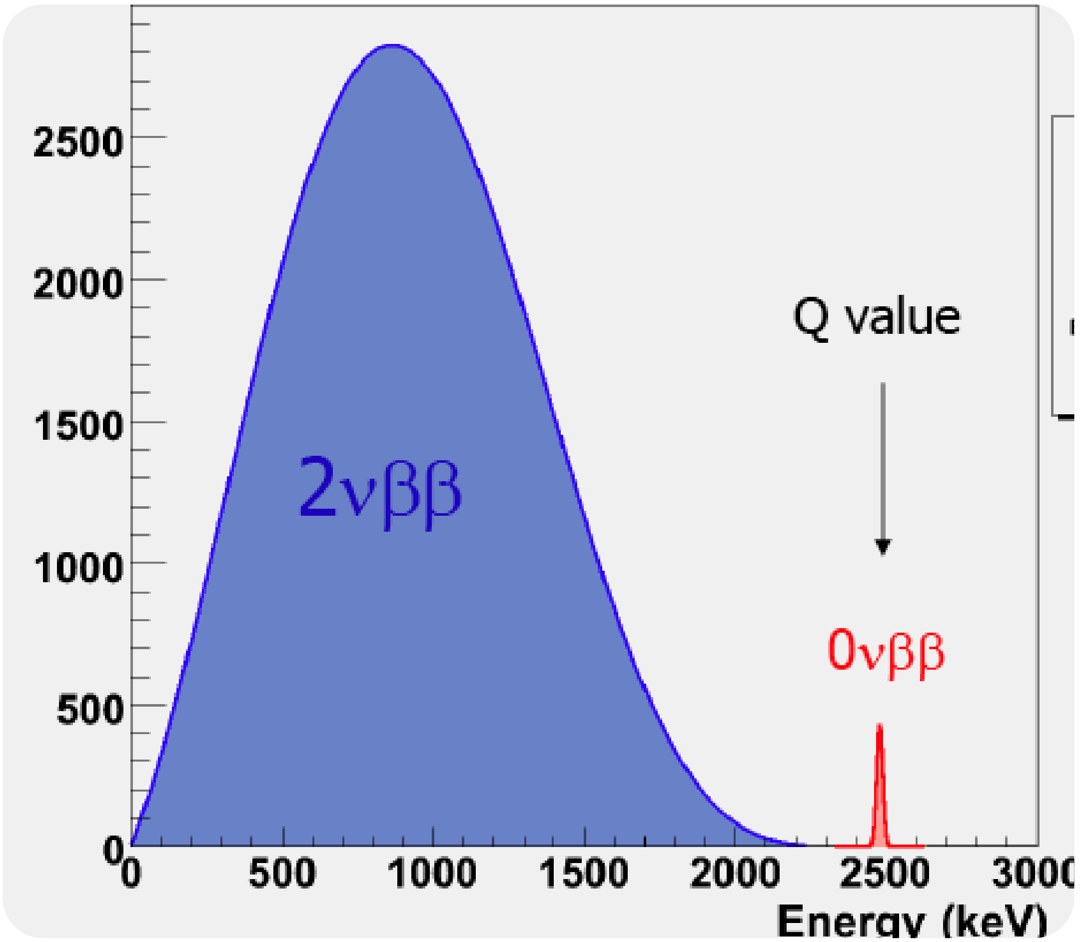
Ideal detector

Good detector (3% FWHM resolution)

Easy, right?

Resolution





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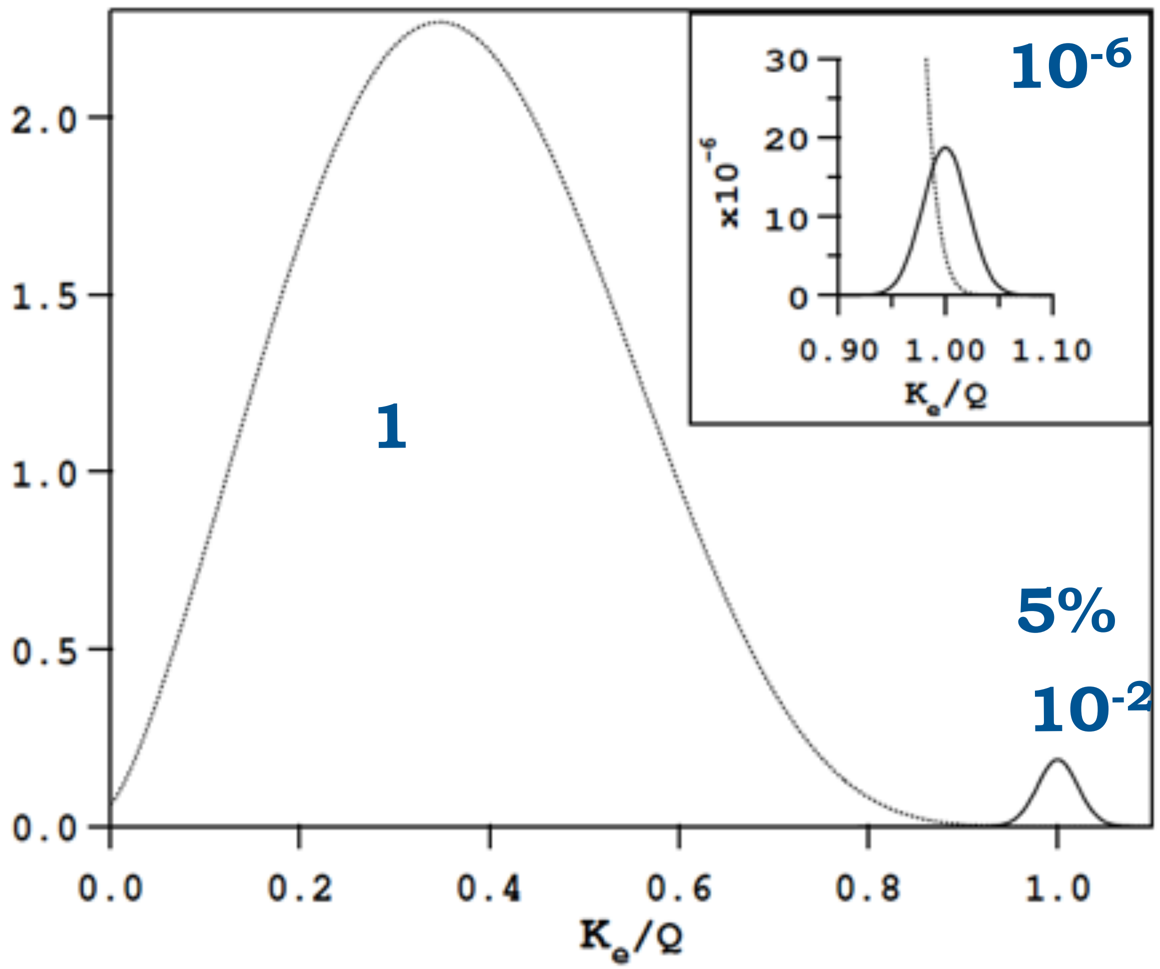
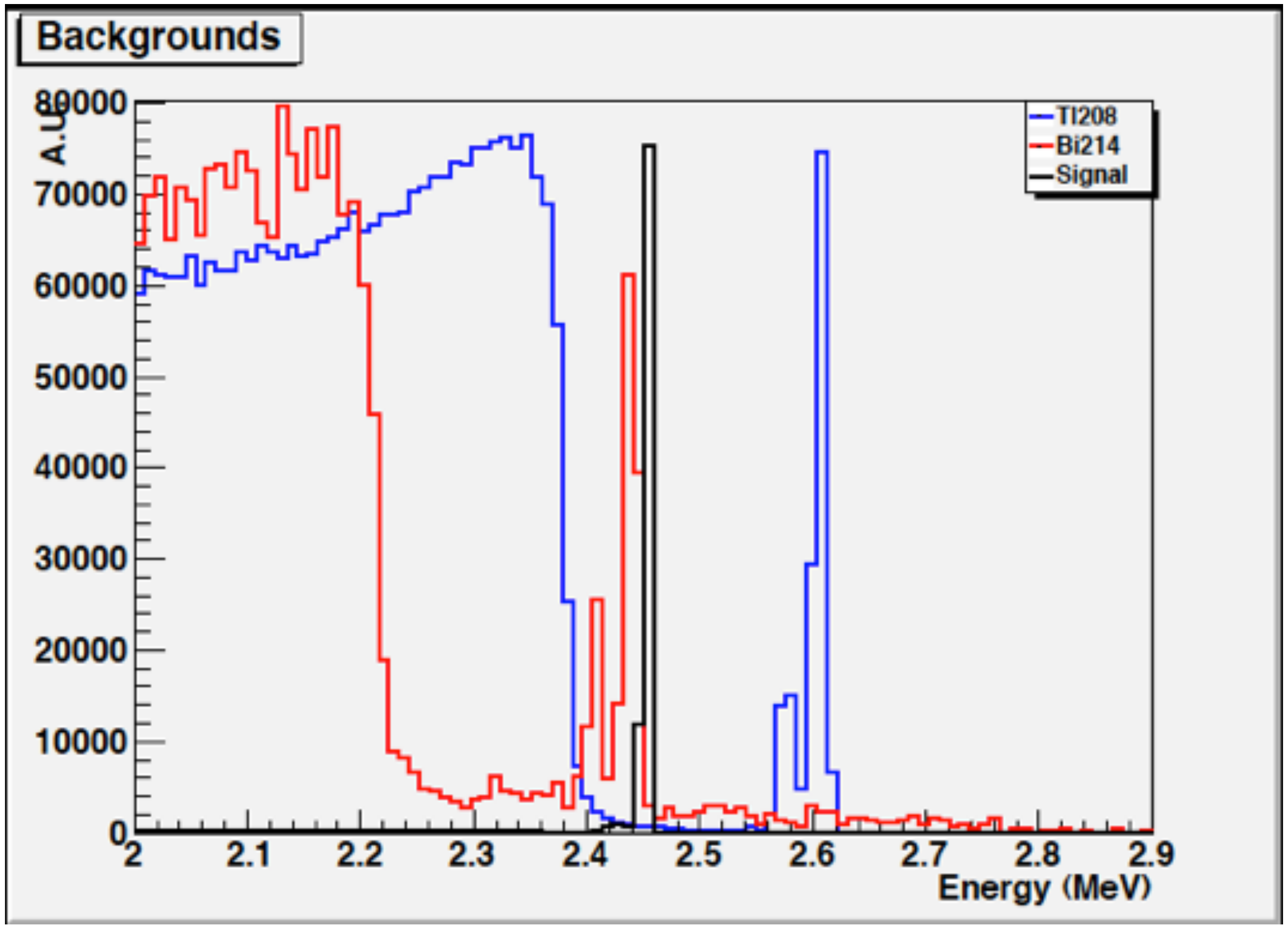


- In fact, very difficult.
- bb0nu (typically) 10^{18}-10^{19}
- Next generation bb0nu: 10^{26} -->7 orders of magnitude bb2nu
- Need better resolution than 5% to eliminate bb2nu

The Xenon landscape & resolution

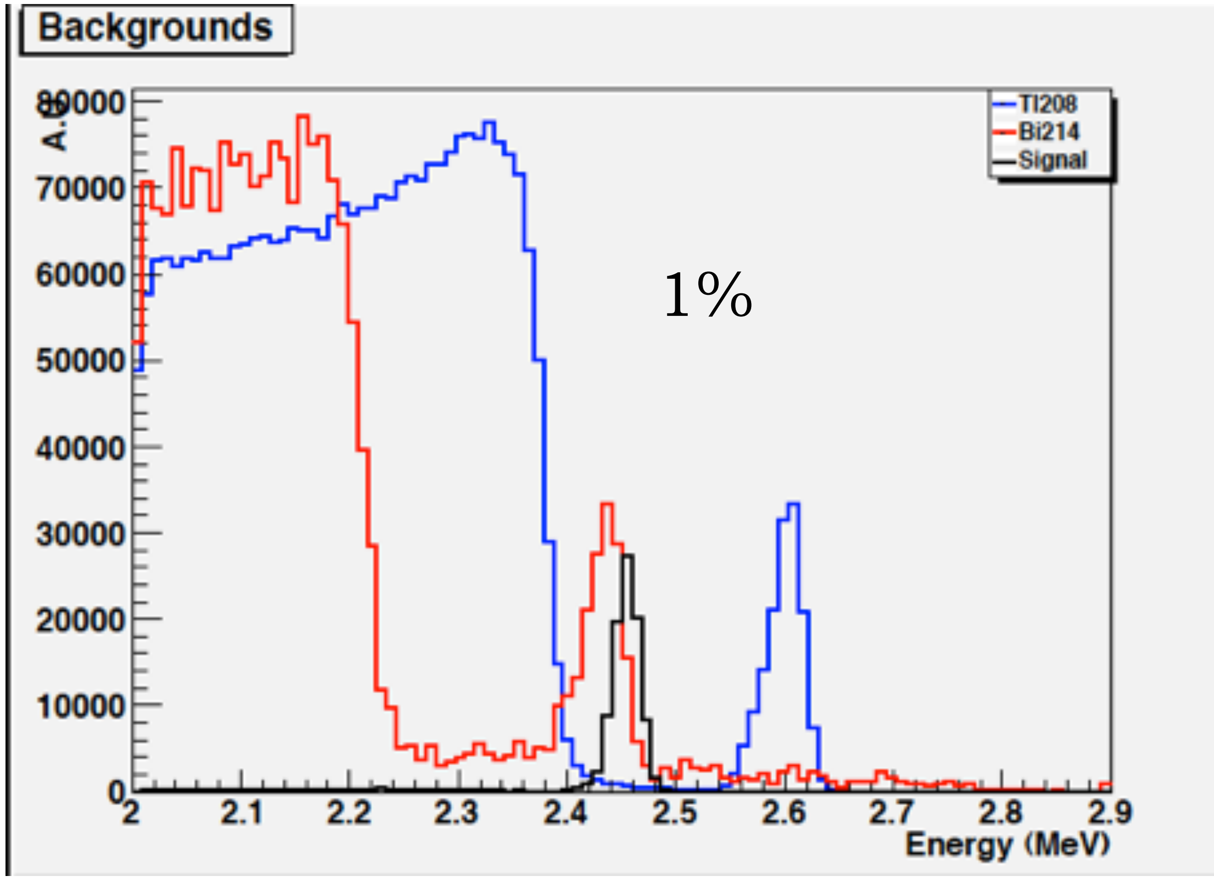


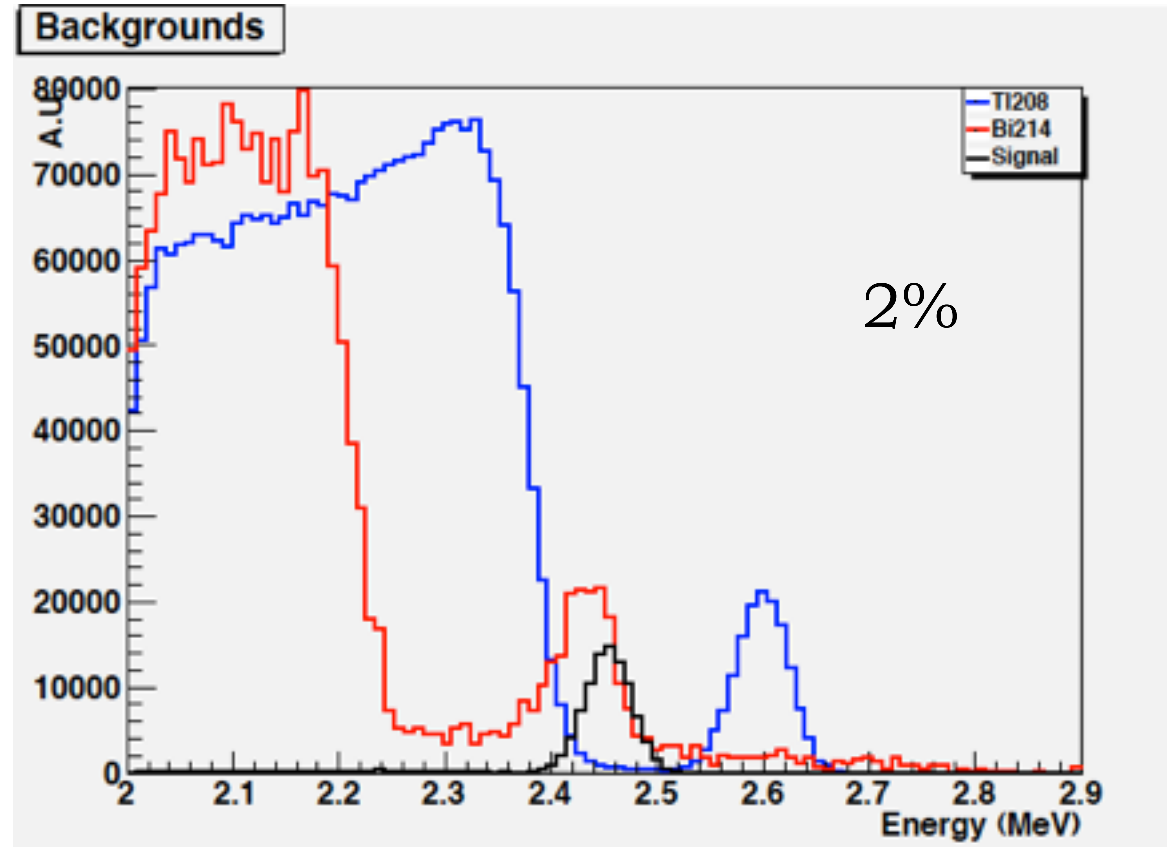
Black: signal with 0.2% resolution (as seen by a Ge calorimeter)

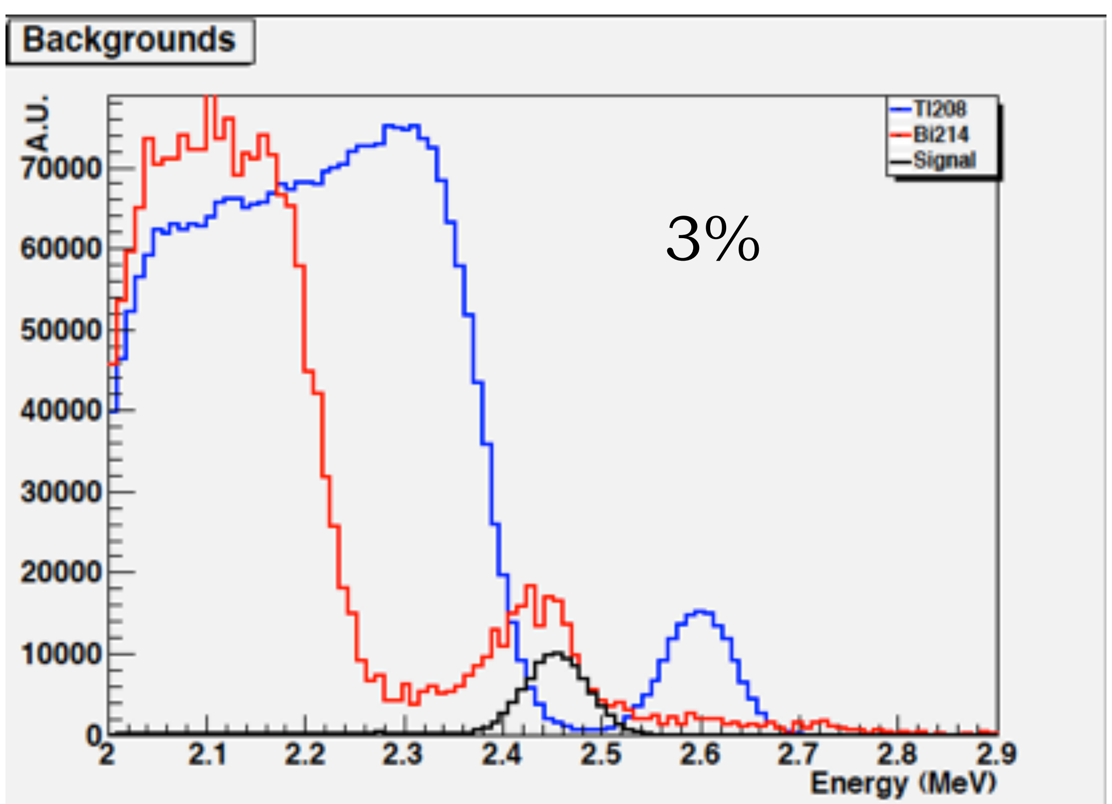
Red: Bi-214

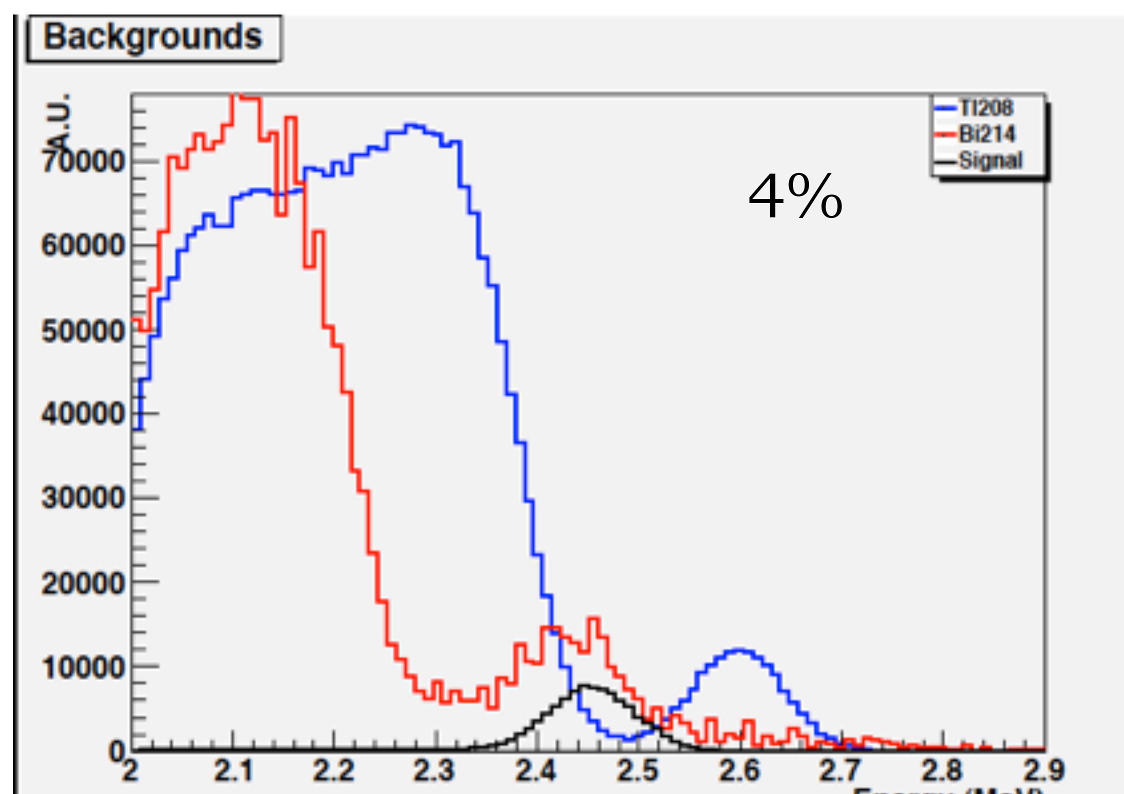
Blue: Tl-208

The Xenon landscape & resolution

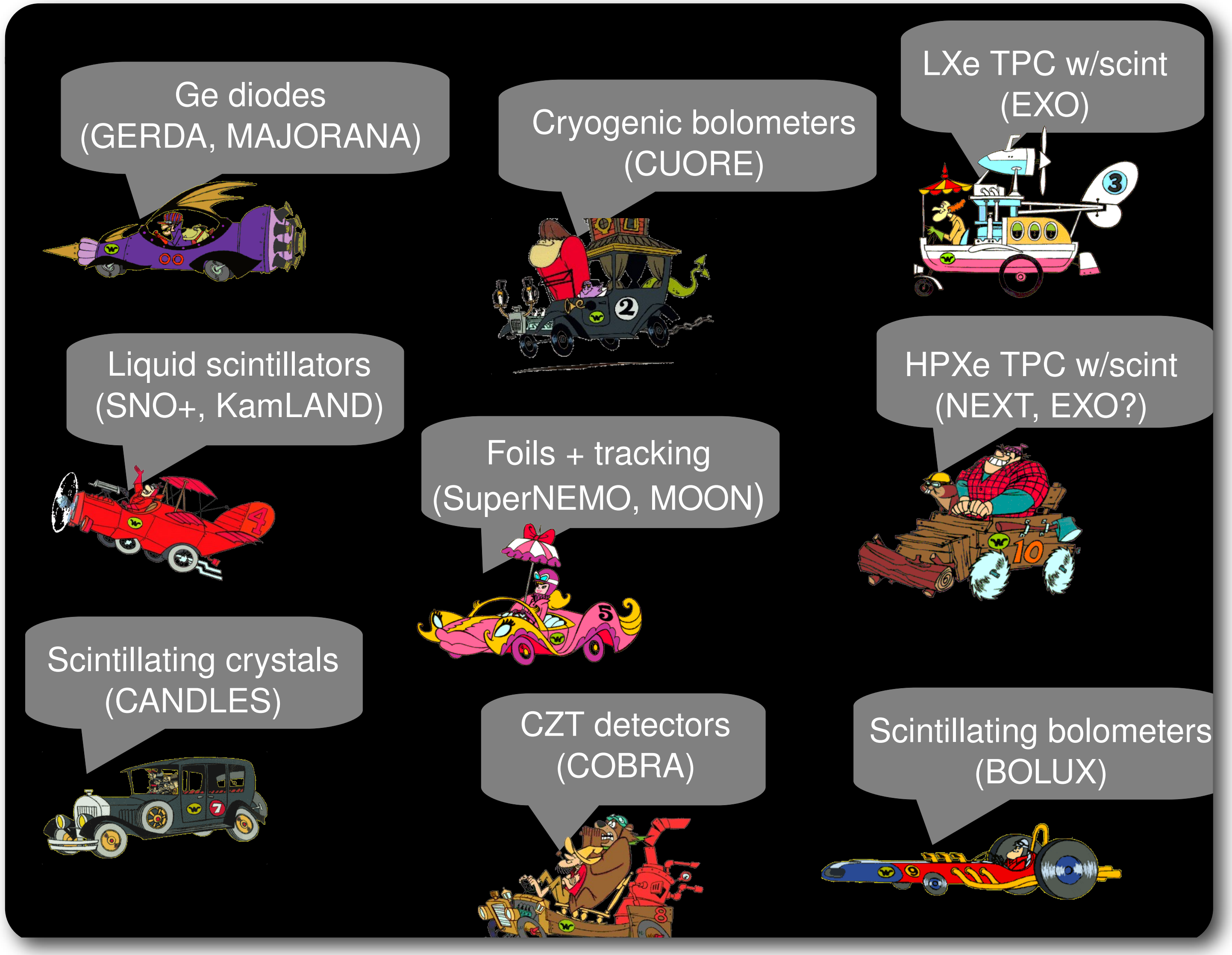








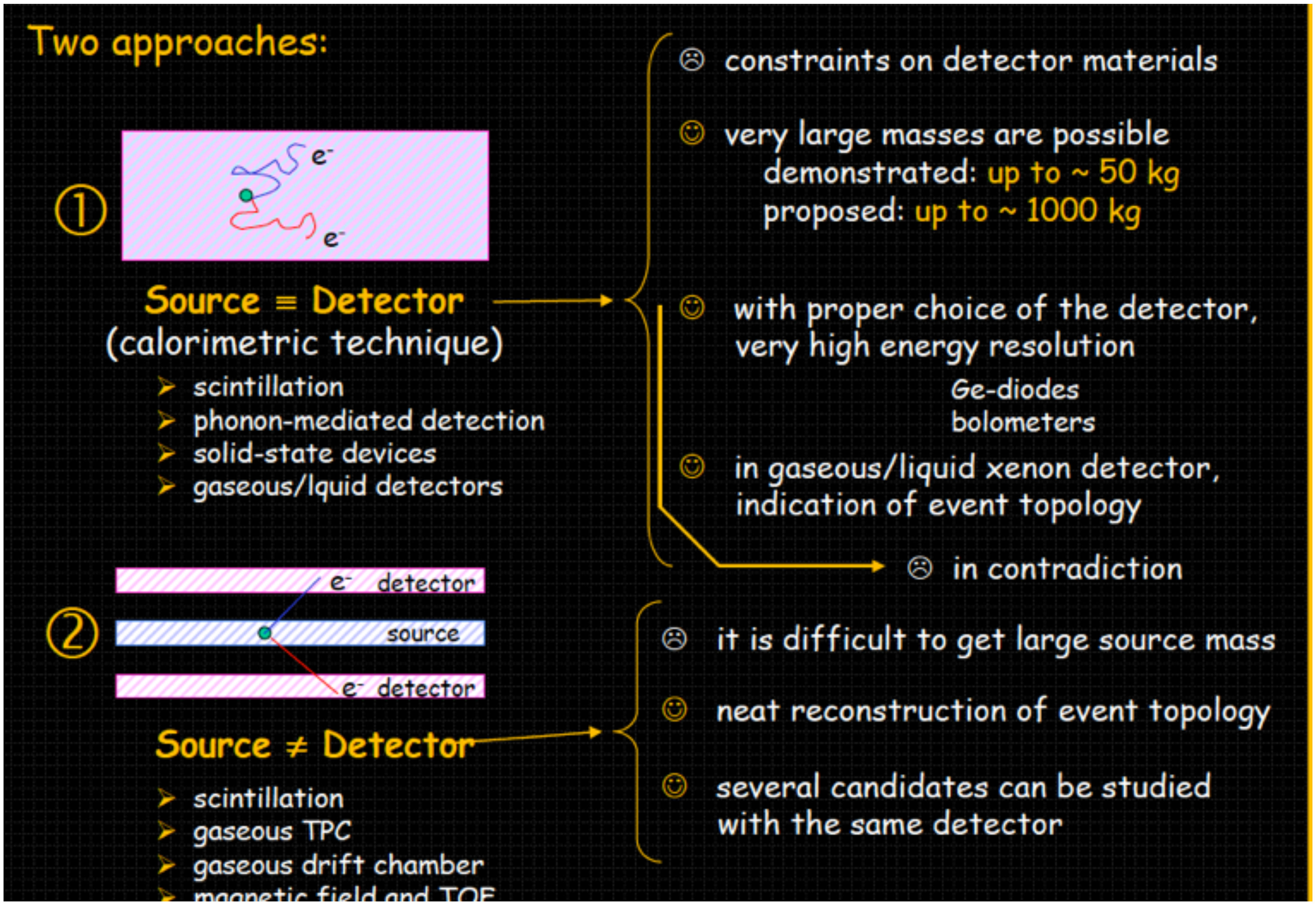
Background rate



Plot Credits: Michel Sorel

Depends on the technology

Experimental approaches



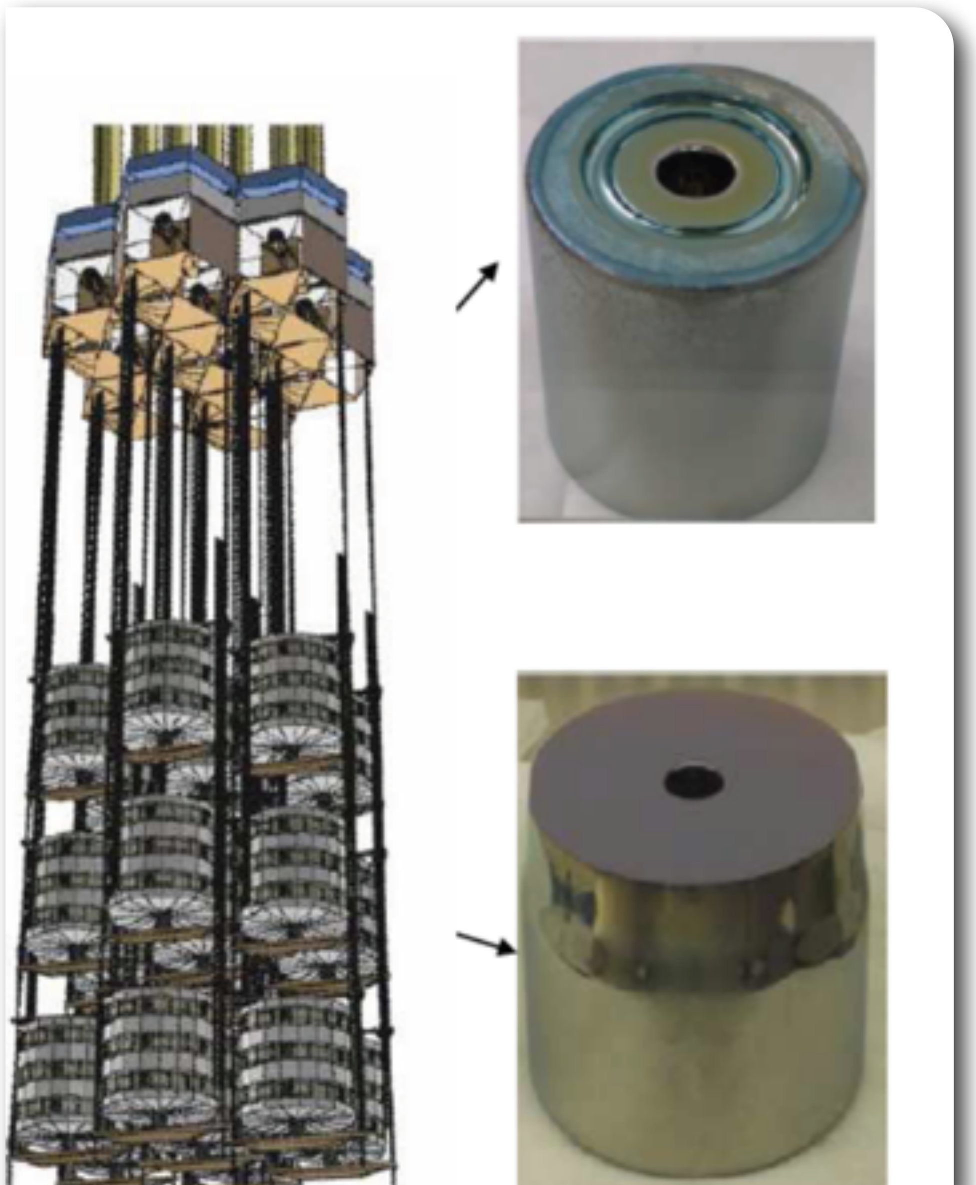
Borrowed from A. Giuliani

DBD Triathlon

- Be there first
- Minimize background
- Maximize mass

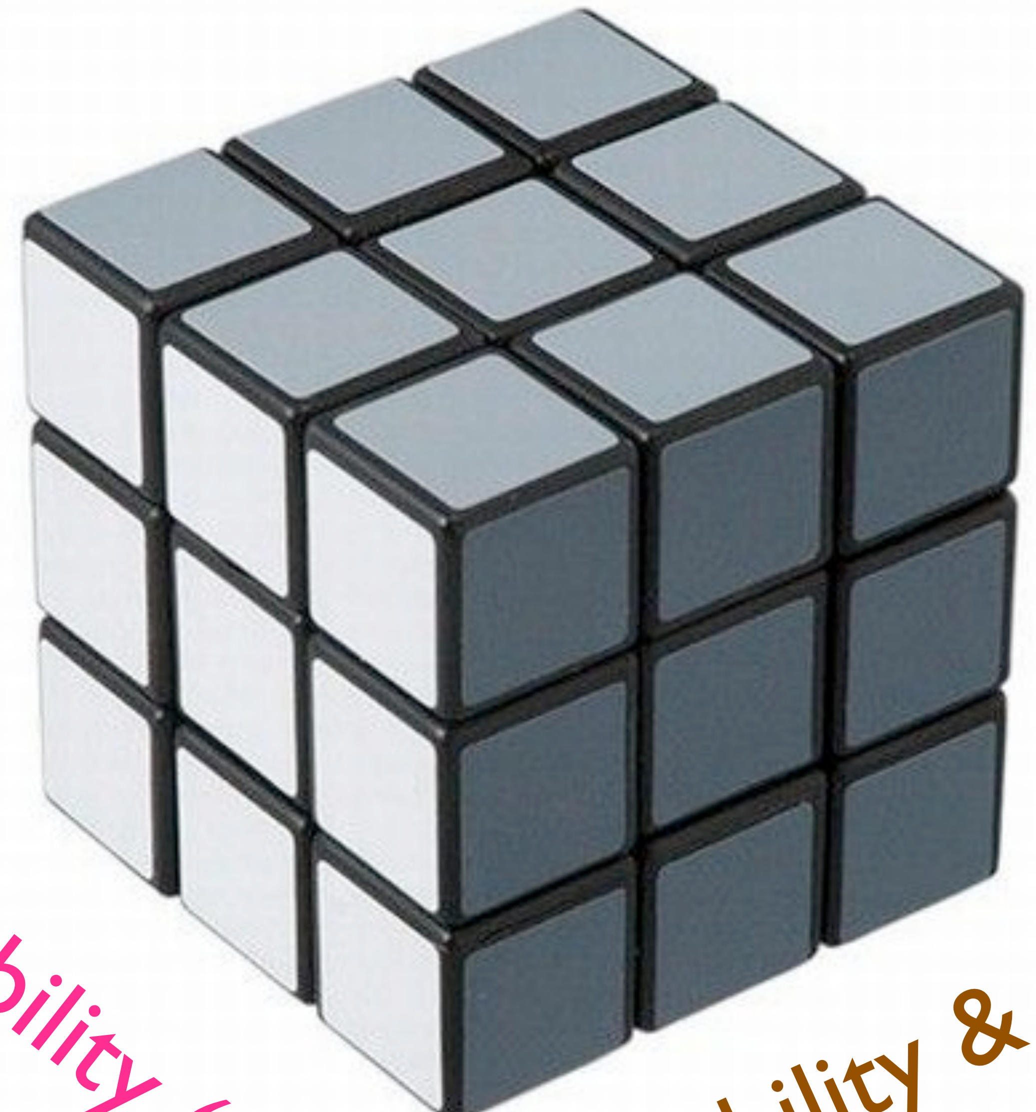
DBD Rubik's cube

Gerda



- Naked Ge-76 diodes immersed in LAr.
- Excellent resolution of 0.15% FWHM at Qbb
- High efficiency (~80%)
- PHASE-I 18 kg of Ge-76 (enriched at 85%) from the Heidelberg-Moscow and IGEX experiments -->background rate 10^{-2} ckky
- PHASE-II 40 kg of Ge-76 -->b~10^{-3} ckky

Gerda's cube



10^{-2} -10^{-3} ckky

background

35-100 kg

scalability (mass, cost)

feasibility & t0

RUNNING!

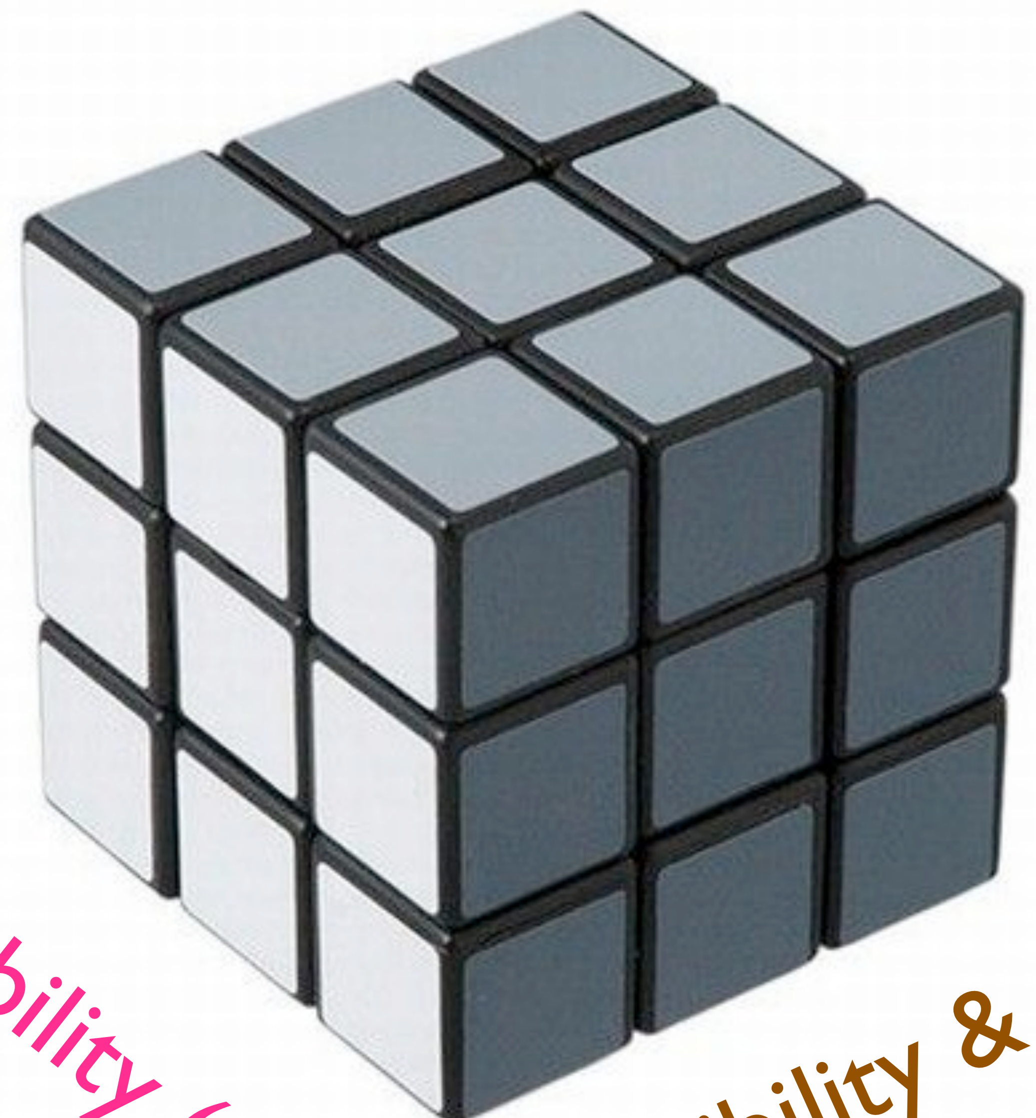
Background in Gerda Phase II

The 2007 Europhysics Conference on High Energy Physics IOP Publishing
Journal of Physics: Conference Series **110** (2008) 082010 doi:10.1088/1742-6596/110/8/082010

Table 1. Estimate of the background level expected in the GERDA experiment for a simplified Phase II setup at the present level of R&D.

Detector part	Contribution $[10^{-4}$ counts/(kg·keV·y)]
Germanium detector (cosmogenic ^{68}Ge)	10.8
Germanium detector (cosmogenic ^{60}Co)	0.3
Germanium detector (bulk)	3.0
Germanium detector (surface)	3.5
Cabling	7.6
Copper holder	3.4
Electronics	3.5
Cryogenic liquid	0.1
Infrastructure	2.9
Muons and neutrons	2.0
Total	37.1

Gerda's cube



background

scalability (mass, cost)

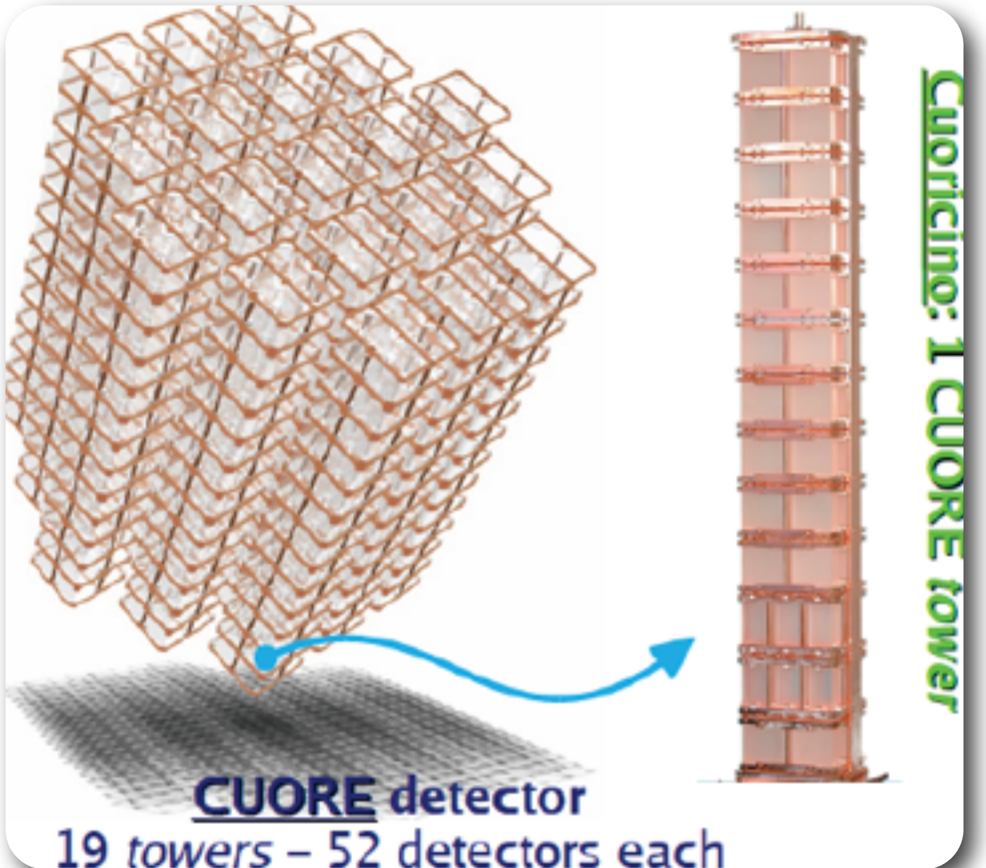
feasibility & t0

10^{-2} -10^{-3} ckky

35-100 kg

RUNNING!

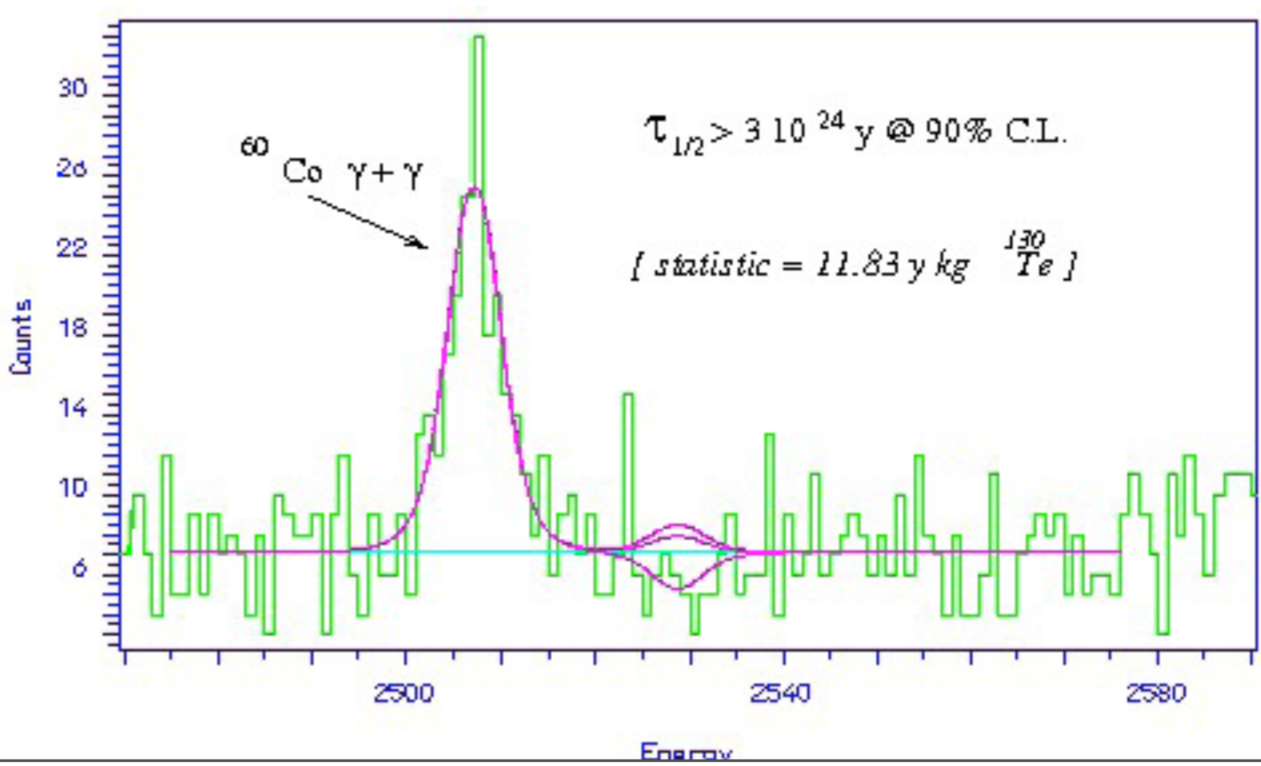
Cuore



- TeO2 bolometers (shielded by lead).
- Excellent resolution of 0.2% FWHM at Qbb (2530 keV)
- High efficiency (~80%)
- 800 kg of natural Te (34% Te-130) 200 kg of isotope

Cuoricino --> b= 0.18 ckky (kg of detector)

MC calculations -->b=10^{-2} ckky



Cuore backgrounds

- 1) 2615 keV ^{208}Tl line. Due to the contamination between the inner Roman lead shield and the external lead shield (cryostat). Contributes 30%. Thicker Roman lead shield is needed combined with a better cryostat design. CUORE projects that the background due to ^{208}Tl will be< 10^{-3} ckky.
- (2) Degraded alpha particles. They produce a flat background in the energy region above the ^{208}Tl line. Their contribution to the background is 70%. These alpha particles are coming from U and Th crystal surface contamination (20±10)% and from Cu surface contamination (50 ± 10)%. The contamination can be controlled with proper surface treatments (including chemical etching and polishing with clean powders). Measured contamination projected on CUORE is < 3 x 10^{-3} ckky.
- (3) Flat background in the 3−4 MeV region. It is believed to be due to the surface contamination of the inert part of the detector. In this region measured contamination projected on CUORE is 2 - 4 x 10^{-2} ckky.
- Thus, background model suggests 10-2 ckky

CUORE's cube

background

scalability (mass, cost)

feasibility & t0

$4x10^{-2}$ - 10^{-3} ckky

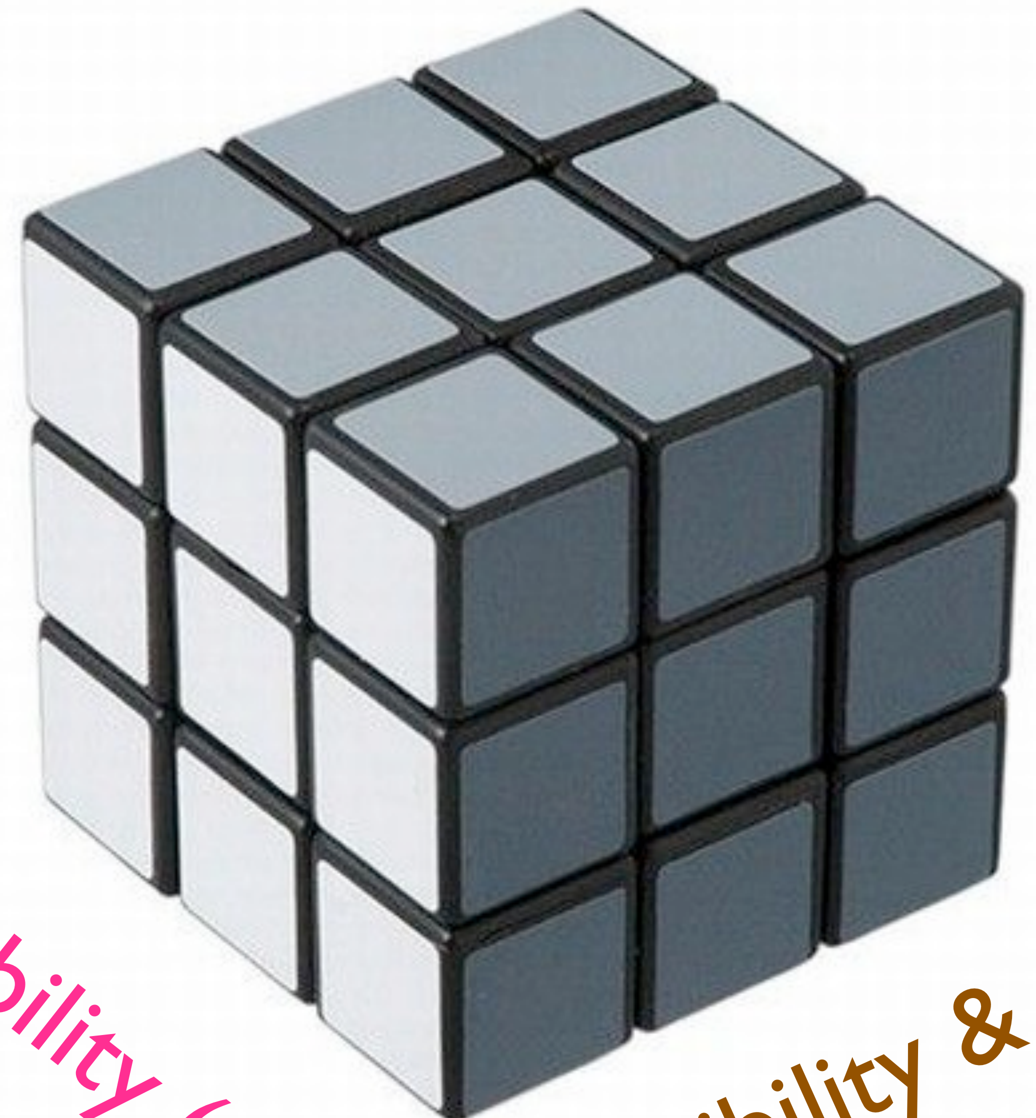
200-400 kg

Cuoricino, Cuore0 starts in 2011, full CUORE in 2014

Kamland-ZEN cube

~(2-5) x10^{-4}
ckky

background



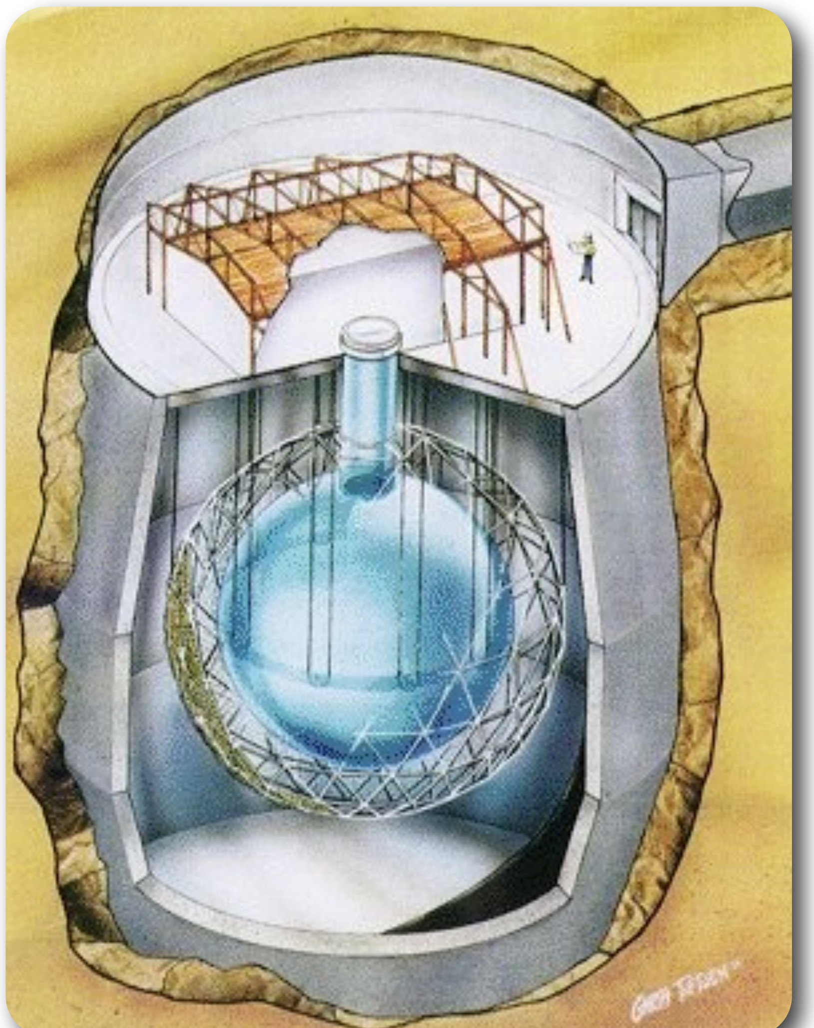
scalability (mass, cost)

feasibility & t0

350-1000 kg

R&D on radiopure balloon
liquid scintillator
readout electronics
starts in 2012? 2013?

SNO+



- Nd dissolved in liquid scintillator.
- No inner ballon, thus lower efficiency (~50%)
- Natural Nd (5.6% abundance of Nd-150).
- 780 tons of liquid scintillator, at 0.1% loading of Nd (43.6 kg of isotope).
- Poor resolution (about 6% at Qbb)
- b~10^{-3} ckky (?)

SNO+ backgrounds

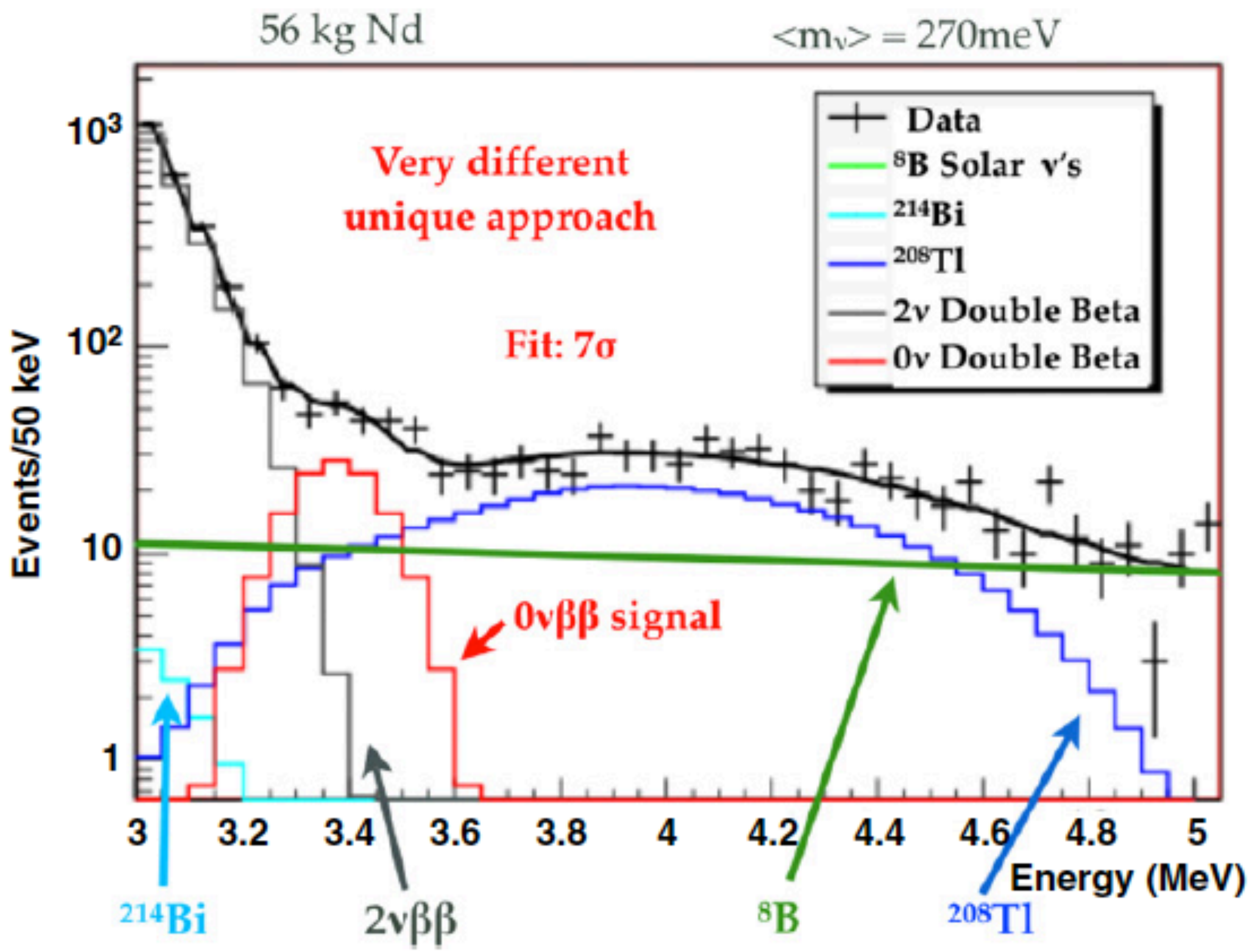


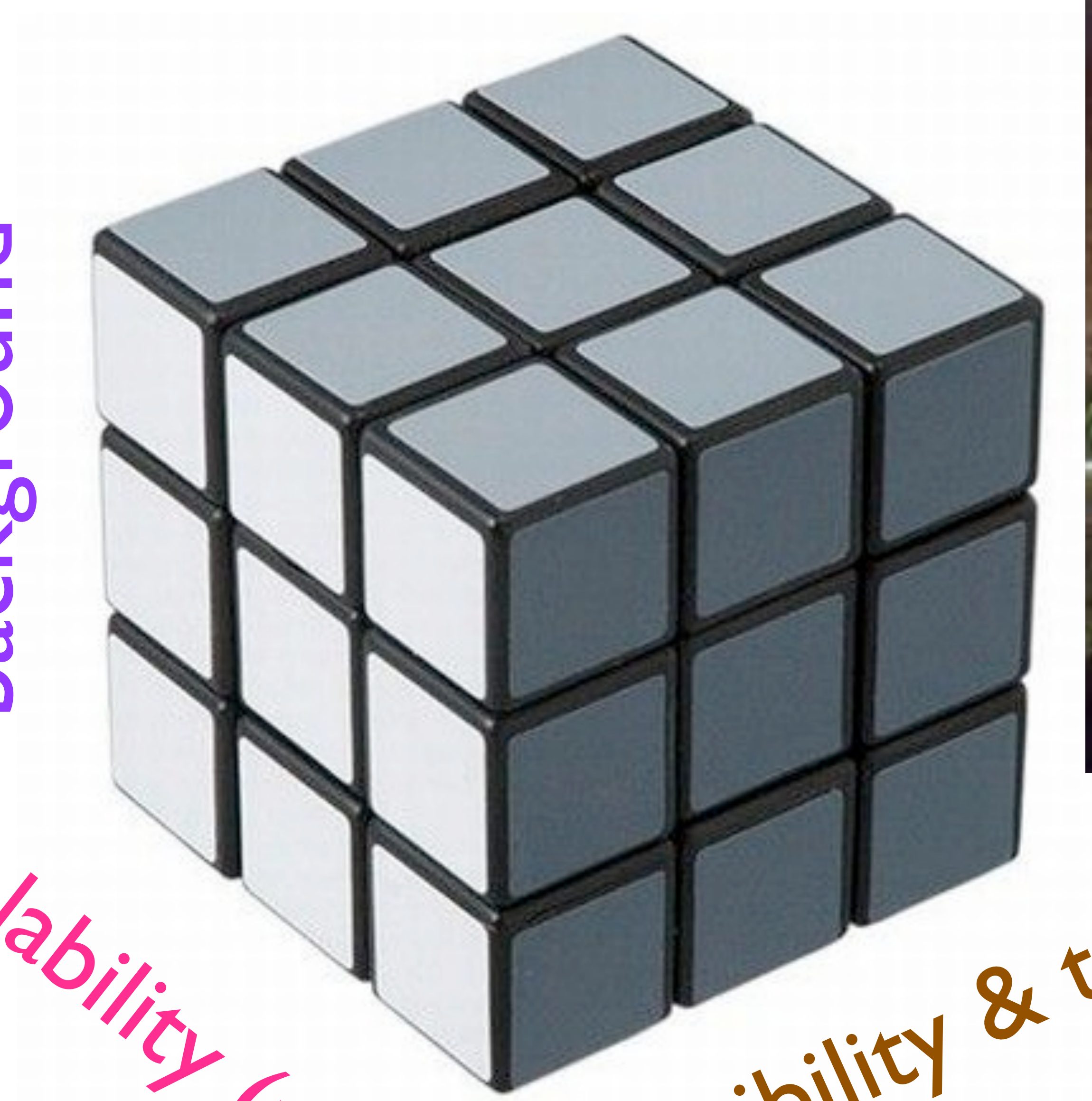
Fig. 2. Simulated SNO+ energy neutrino spectrum around Nd endpoint.

Backgrounds dominated by Tl-208, B-8 neutrinos and bb2nu

SNO+ cube

~10^{-3} ckky

background



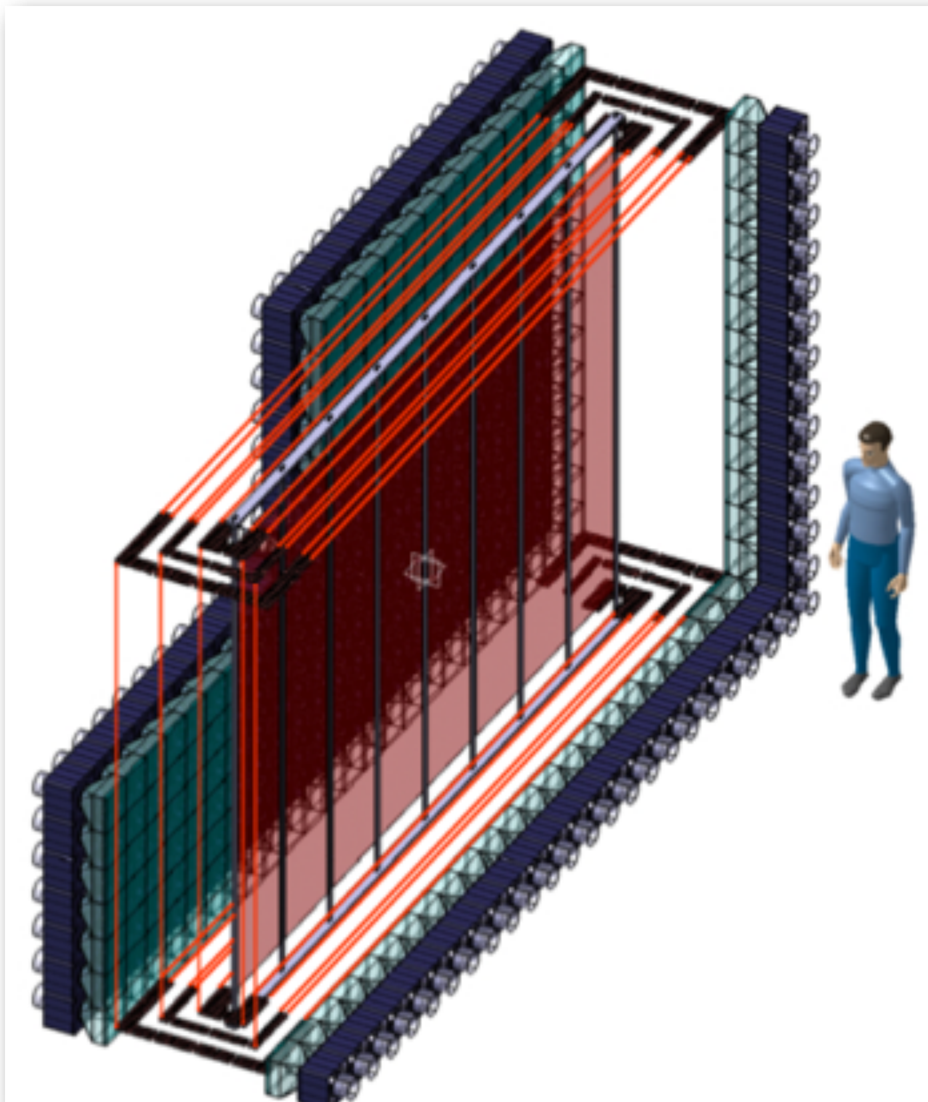
scalability (mass, cost)

feasibility & t0

50-500? kg
(enrichment?)

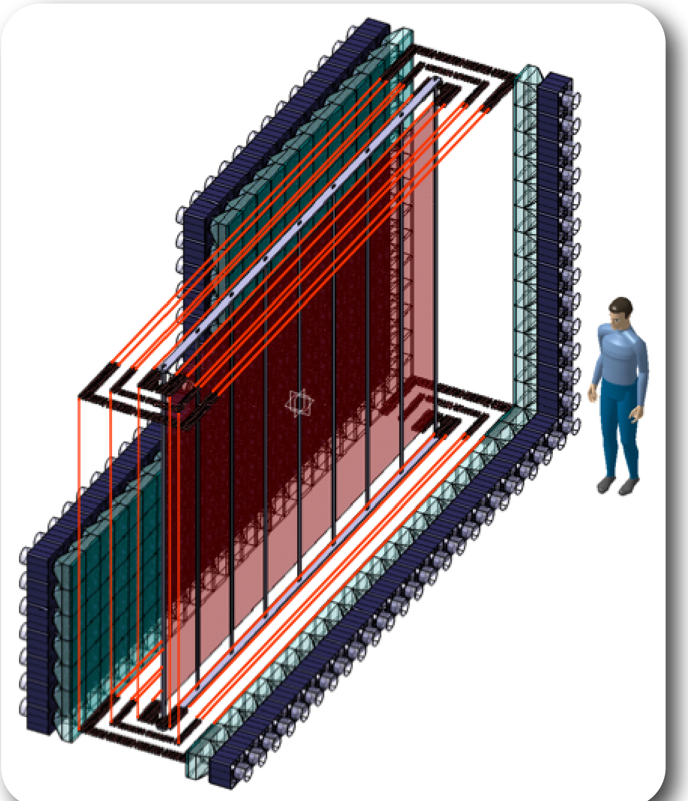
starts in 2012?

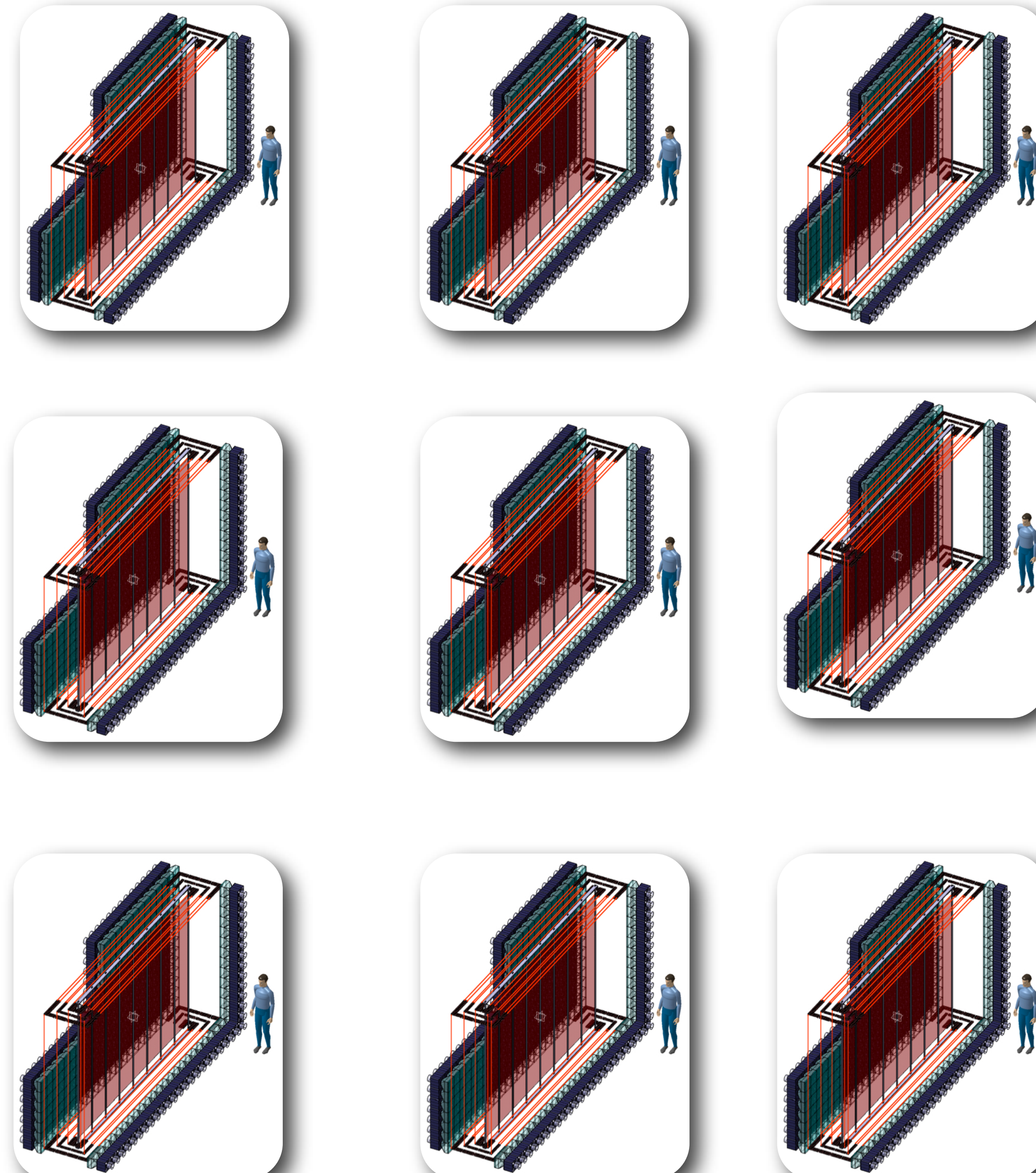
Super Nemo



- Modules of Se-82 (or other)
- Mediocre efficiency (~30%)
- Mediocre resolution (~4% at Qbb) and topological signature.
- b~10^{-4} ckky (background model from MC calculations)
- Background model assumes extreme radiopurity of target sheets.
- Radon degassing difficult to prevent (no gas recirculation through cold traps)
- Very hard to scale (each module is 5-7 kg of isotope)
- Hard to shield from external backgrounds (many modules...)

Scaling Super Nemo





Modular detectors must
be duplicated (20 for 100 kg)

Price & effort scales linearly

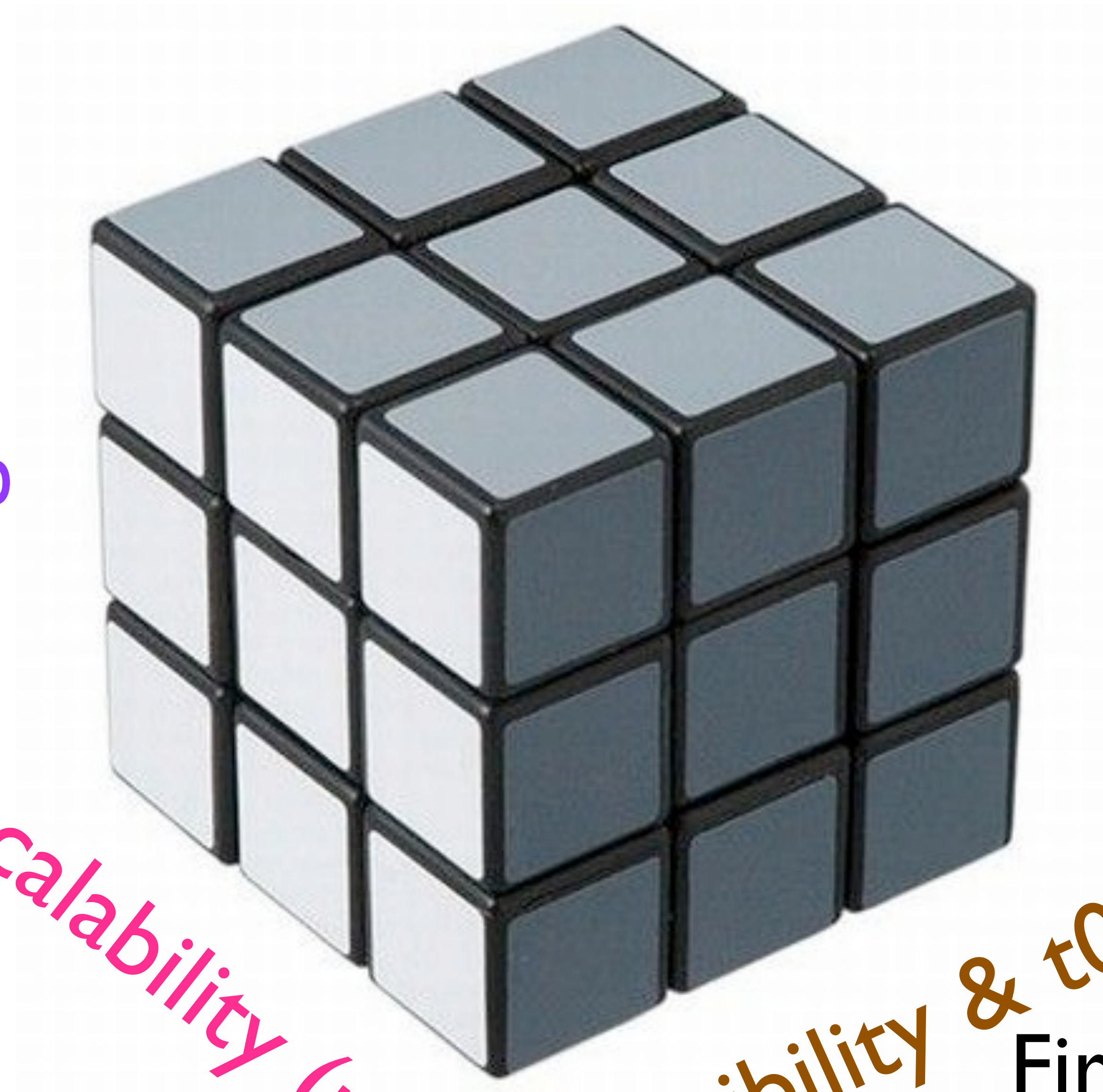
Backgrounds (proportional
to surfaces) scale linearly

Room, maintenance, construction

Cost!

Super Nemo cube

~10^{-4} ckky



25-100 kg

First module starts in 2014?
20 modules?
Underground lab?