Sense And Sensitivity of DBD Experiments

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IFIC

Neutrino Telescopes, Venice, 2011

Credits

Sense and sensitivity of double beta decay experiments

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With thanks to many colleagues, in particular M. Mezzetto and A. Bettini

Sensitivity

Double Beta Decay

ββ2ν: two simultaneous β decays

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^- + \overline{\nu}_{e_1} + \overline{\nu}_{e_2}$$

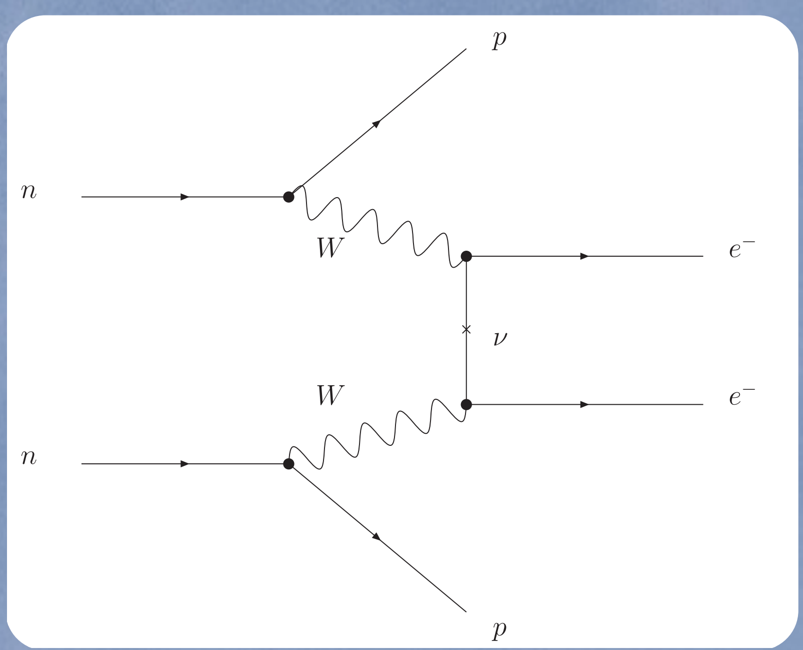
$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

ββ0ν: requires massive Majorana neutrinos. Non-SM process.

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^- \cancel{+ \overline{\nu}_{e_1} + \overline{\nu}_{e_2}}$$

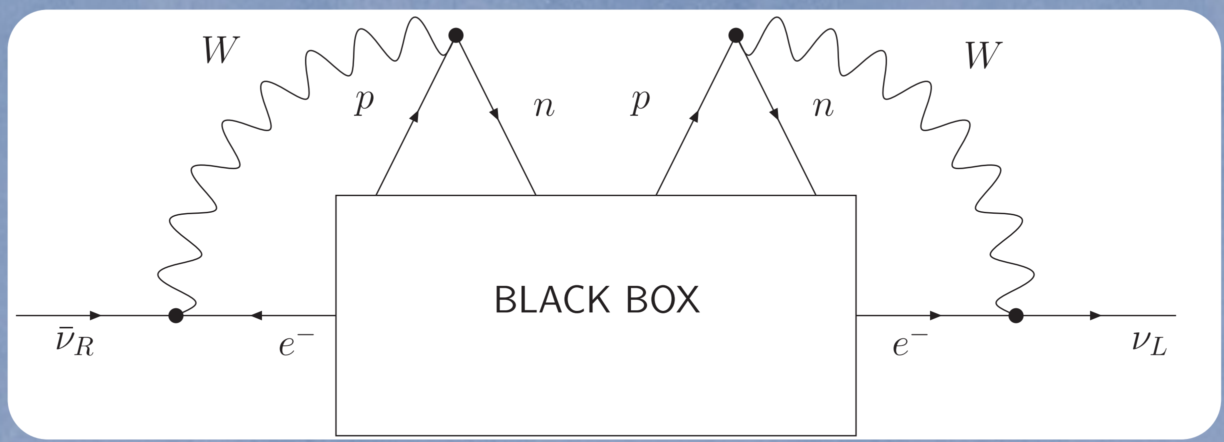
$$(\Delta L = 2)$$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$



Exchange of light Majorana neutrinos

Other mechanisms are possible, but all of them imply a Majorana neutrino mass.

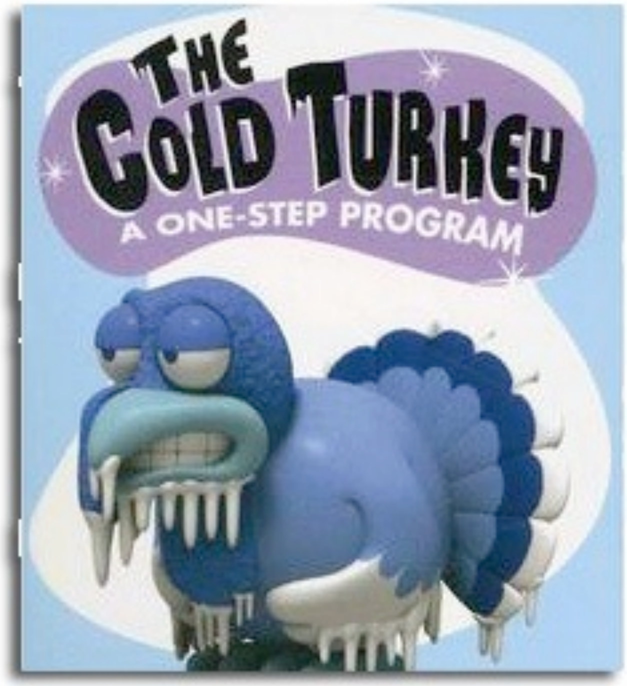


DBD Game

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

Sensitivity

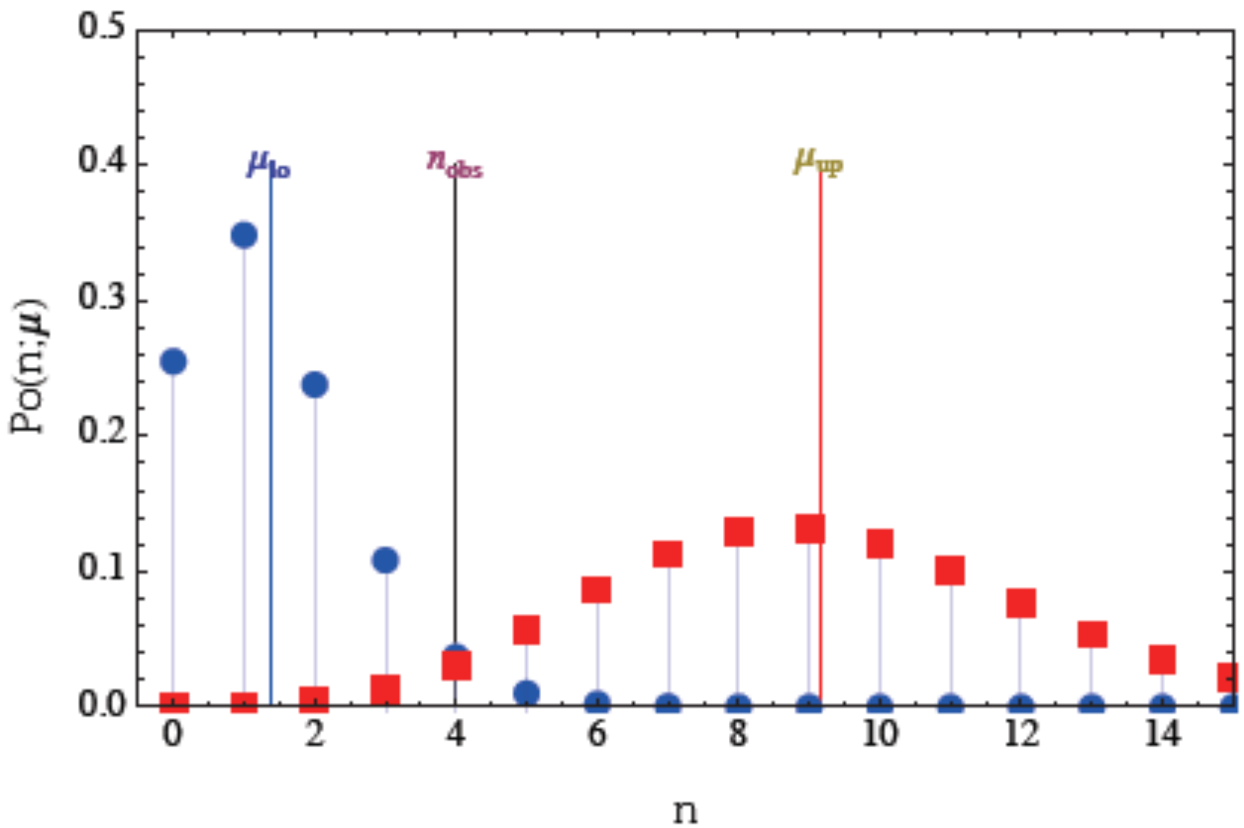
- A perverse way of expressing "cold turkey"
- Experiments who have not yet run try to convince funding agencies that they have a physics case by assuming failure in finding the signal!
- If the signal depends of some physics parameter, mbb, failure can be translated in a bound on the parameter (for DBD experiment an upper bound in mbb)
- The experiment who expects the lowest bound in mbb is the "best"



Describing DBD experiments

$$Po(n;\mu+b)=\frac{(\mu+b)^n}{n!}e^{-(\mu+b)}$$

Where mu is the true value of the signal (unknown) and b the expected background (known)



Example: An experiments observes 4 events (and expects b=0)

$$Po(n;\mu_{lo}=1.37)$$

90% of the blue dots are below n=4 (lower limit at 90% CL)

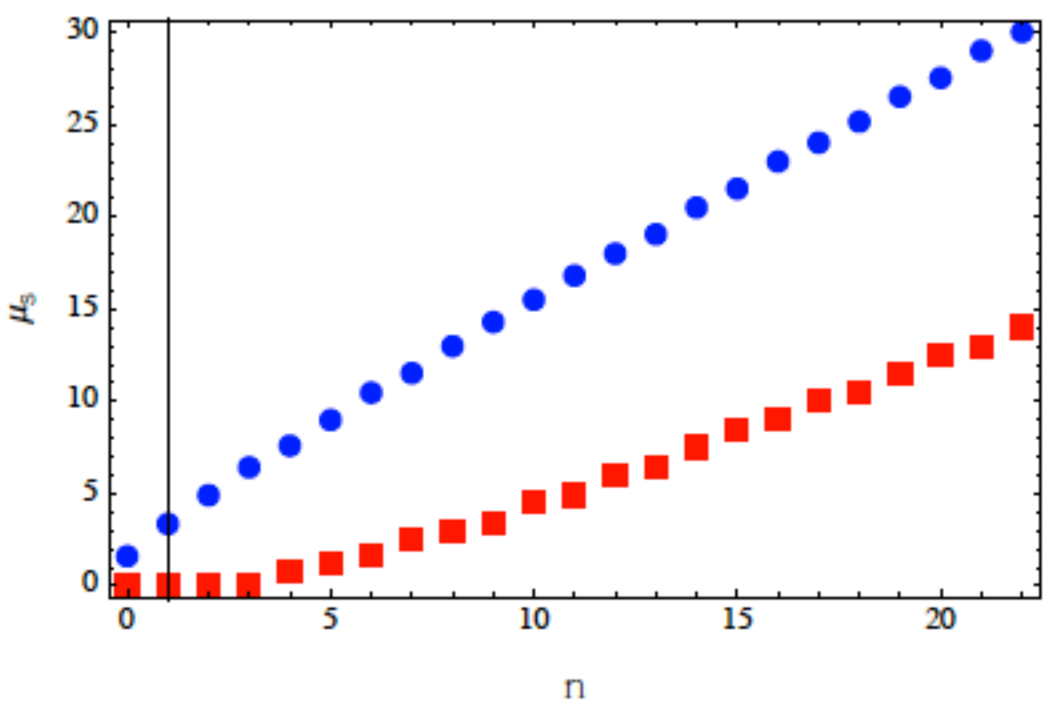
$$Po(n;\mu_{up}=9.15)$$

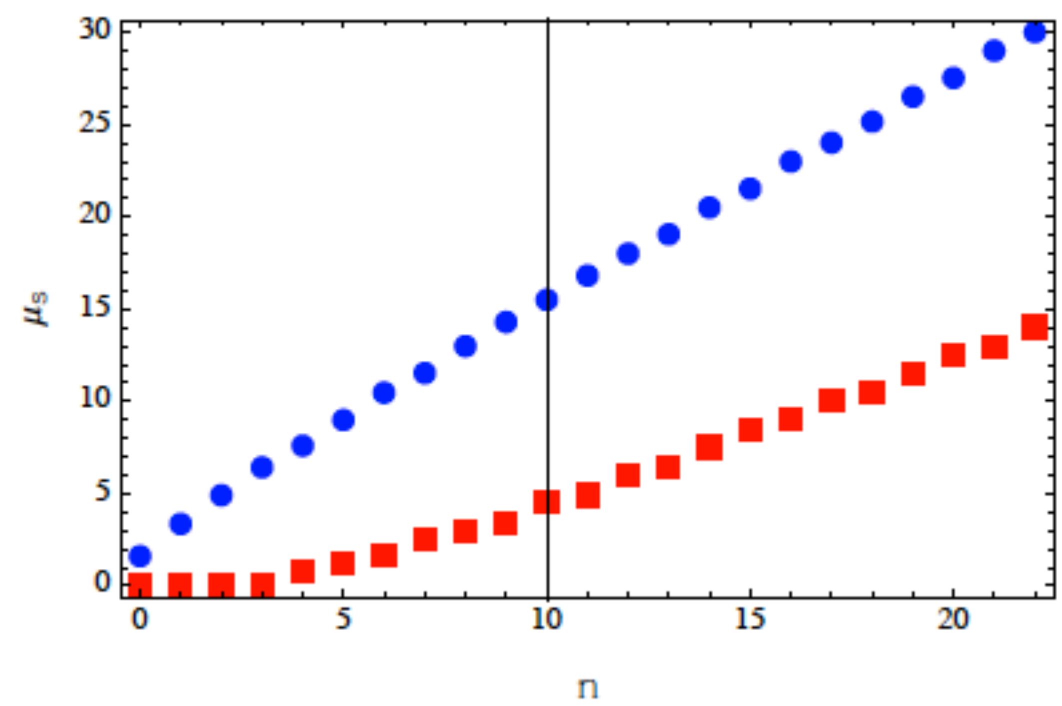
90% of the red dots are above n=4 (upper limit at 90% CL)

CONFIDENCE BELTS

$$\sum_{n=n_1}^{n_2} \frac{(\mu_{lo}+b)^n}{n!} e^{-(\mu_{lo}+b)} \geq CL$$

For a given value of b construct belts for all possible values of mu (example, b=1)





Construct horizontal: read vertical

The Unified Approach

$$\sum_{n=n_1}^{n_2} \frac{(\mu_{lo}+b)^n}{n!} e^{-(\mu_{lo}+b)} \geq CL$$

Acceptance interval constrained by equation but not fully specified by it.

Unified approach (a.k.a Feldman & Cousins)

ordering principle based on likelihood ratio

Given an expected background b and an observation n, F&C provides mu_up and mu_low.

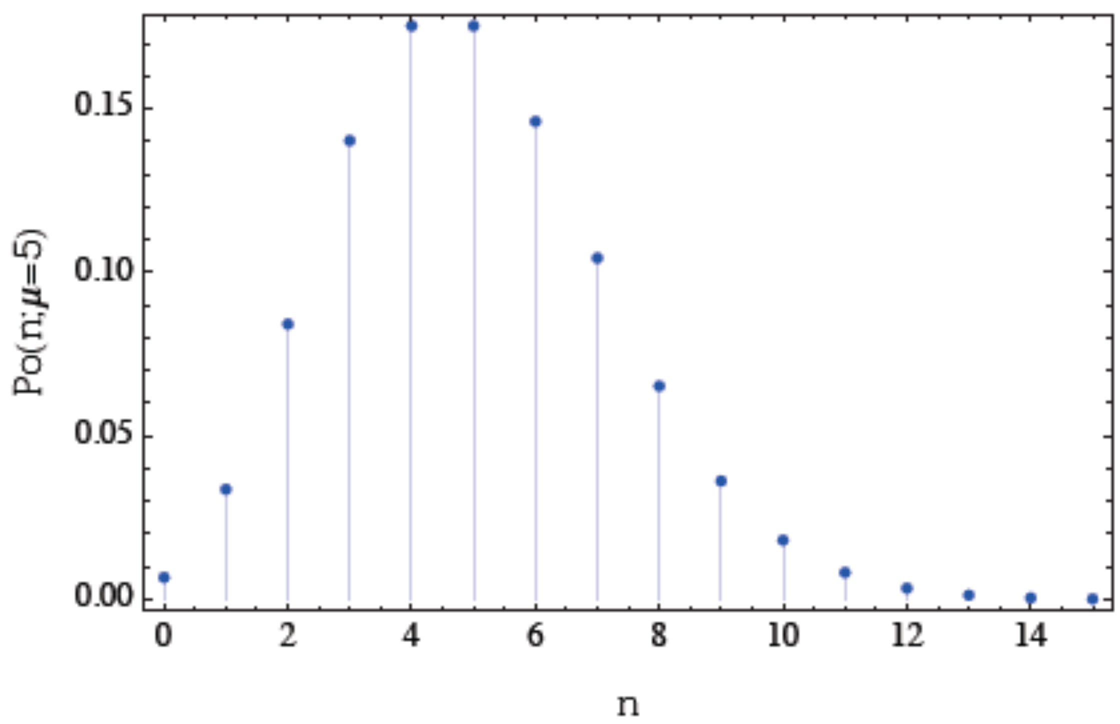
What is Sensitivity of an experiment with background b?

Average upper limit that would be obtained by an ensemble of identical replicas of such experiment, all of them expecting the same background and no true signal

Given an expected background b F&C can be used to compute the Sensitivity of a given experiment.

Sensitivity of an experiment with background

In the example:
1) Compute the upper limit using F&C for each "experiment" (defined by n=0, 1, 2... defined by U(n;b)
2) Multiply by the probability of each experiment defined by Po(n;mu)



$$S(b)=\sum_{n=0}^{\infty}Po(n;b)U(n;b)$$

$$S(5)=\sum_{n=0}^{\infty}Po(n;5)U(n;5)=4.99\times0.175+3.66\times0.175+...=5.17$$

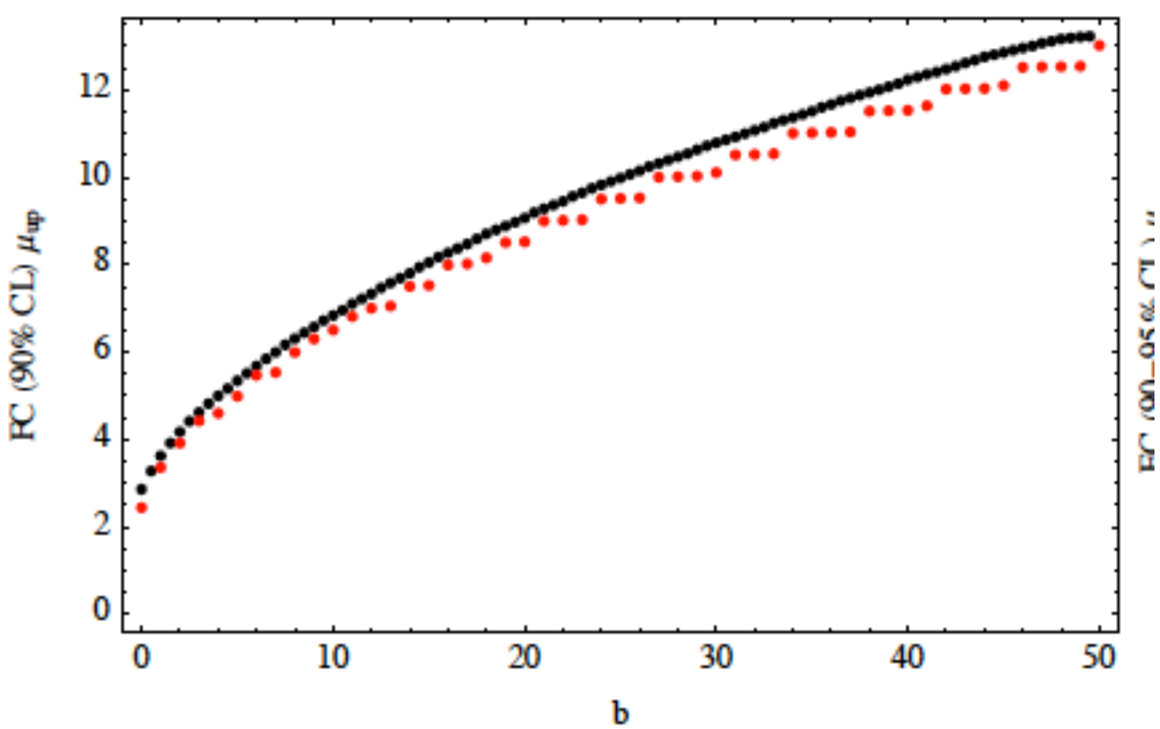
Example: Ensemble of experiments with b=5, mu=0

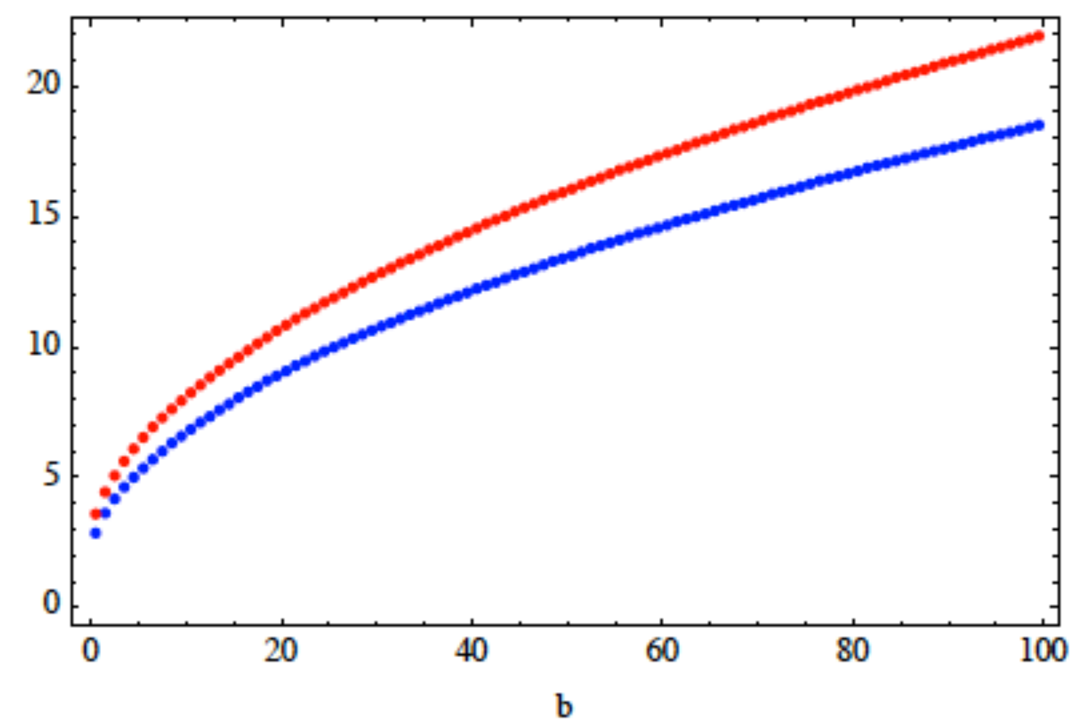
Sensitivity of an experiment with background

Experiments can be described in terms of three numbers:
Efficiency, background rate and resolution
Then, run their sensitivity as a function of total exposure (Mt)

$S(b) \sim \sqrt{b} \Rightarrow$ for large n

$S(b) \sim 90\%$ and 95% CL



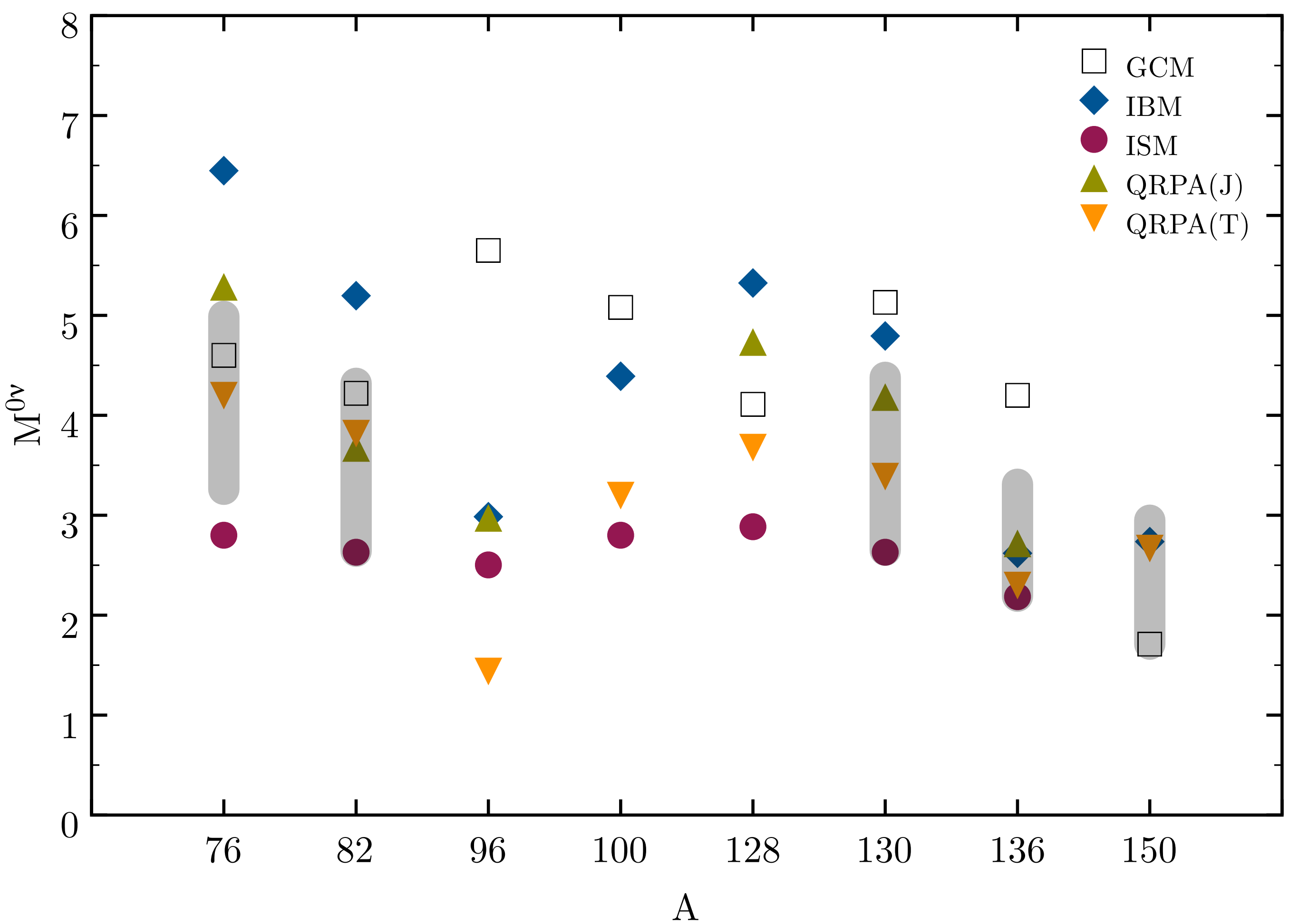


$$m_{\beta\beta} = K_2\sqrt{\frac{b^{1/2}}{\varepsilon M t}} \longrightarrow b = c \cdot Mt \cdot \Delta E \longrightarrow m_{\beta\beta} = K_2 \sqrt{1/\varepsilon} \left(\frac{c\,\Delta E}{Mt}\right)^{1/4}$$

From period to mbb

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$



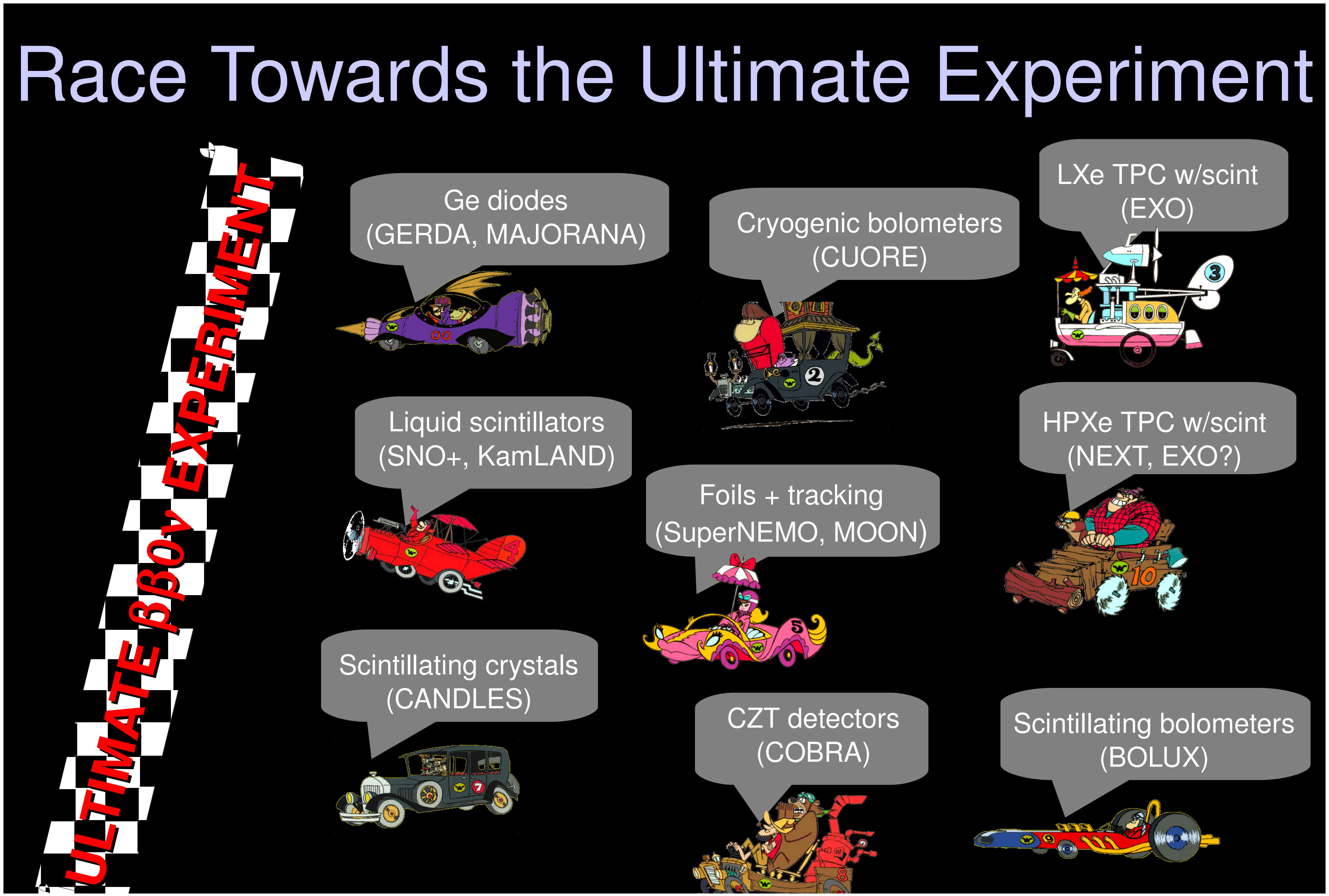
- Each one of the major methods has some advantages and drawbacks, whose effect in the values of the NME can be explored.
- ISM calculations: full treatment of the nuclear correlations, while their drawback is that they may underestimate the NMEs due to the limited number of orbits in the affordable valence spaces. It has been estimated in that the effect can be of the order of 25%.
- On the contrary, the RPA variants, the GCM and the IBM, are prone to underestimate the multipole correlations in one or another way. As it is well established that these correlations tend to diminish the NME's, they should tend to overestimate them.
- Why not use a a physics-motivated range (PMR) of theoretical values for the most important isotopes?

Sensitivity for DBD: a proposal

- Agree on the use of a common procedure to evaluate CL. We propose a very simple approach based in F&C, others are possible.
- We argue that reaching an agreement on the use of a PMR set for sensitivity calculations will be good to compare experiments in a more rational way.
- We have tried a particular implementation, but surely a much more sophisticated set can be worked out by locking the experts of the different NME's models in a room, and not releasing them until they submit a proposal for PMR.

Sense

Many experiments & proposals in the market

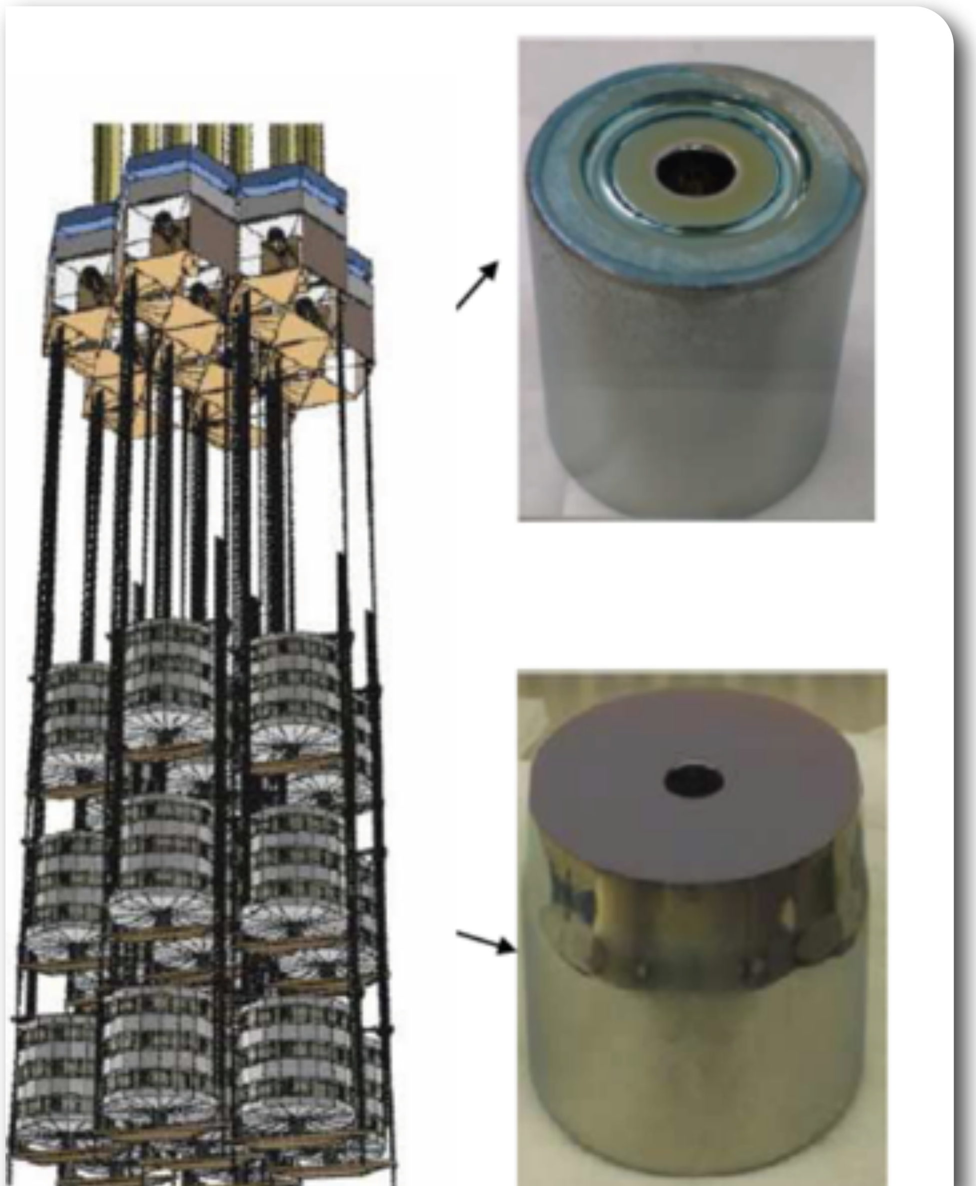


DBD Triathlon

- 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 for Phase I is b=10^{-2} ckky
- PHASE-II 40 kg of Ge-76

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

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

background

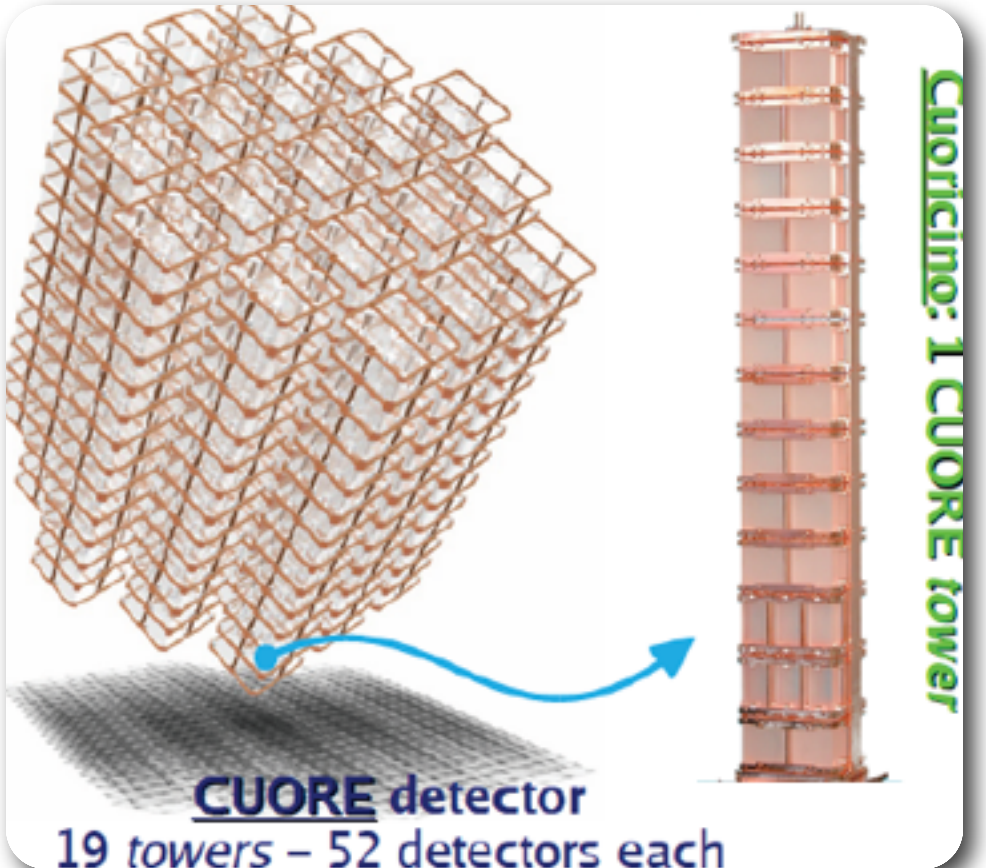
scalability (mass, cost)

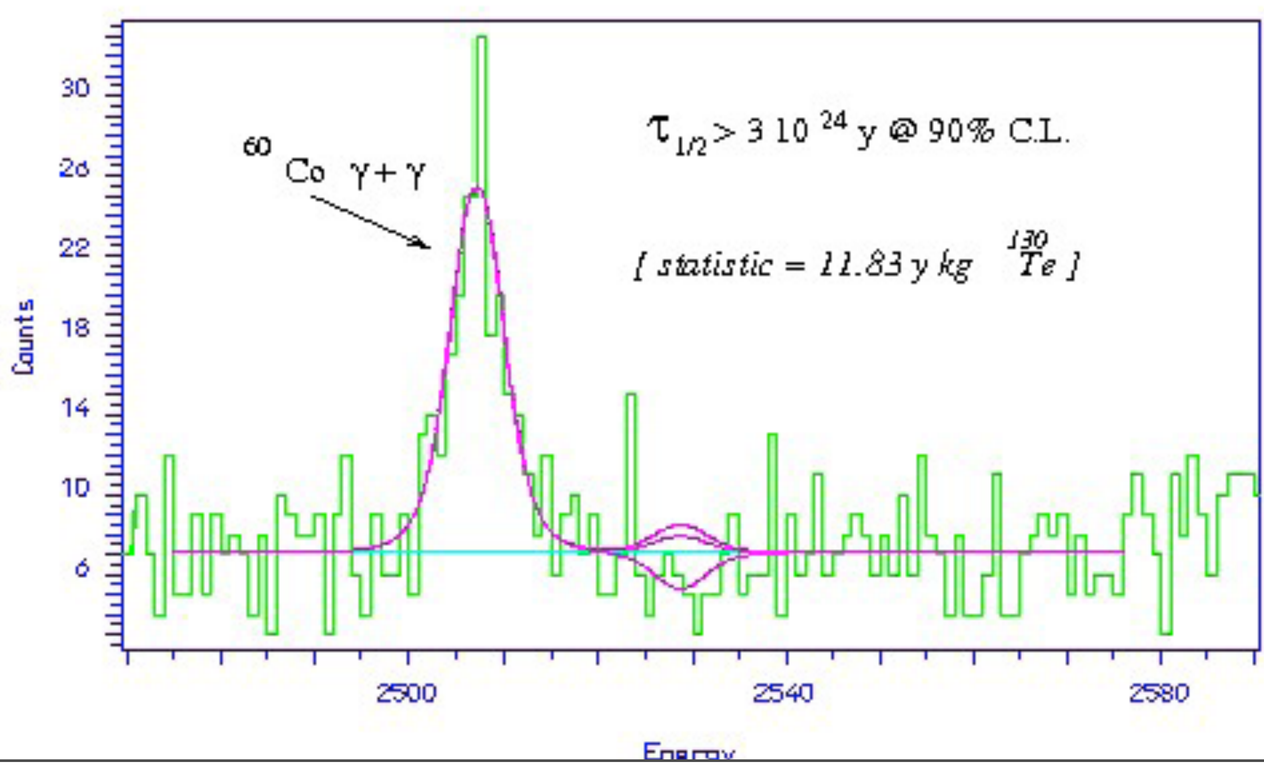
feasibility & t0

35-100 kg

built: running (2011)

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)

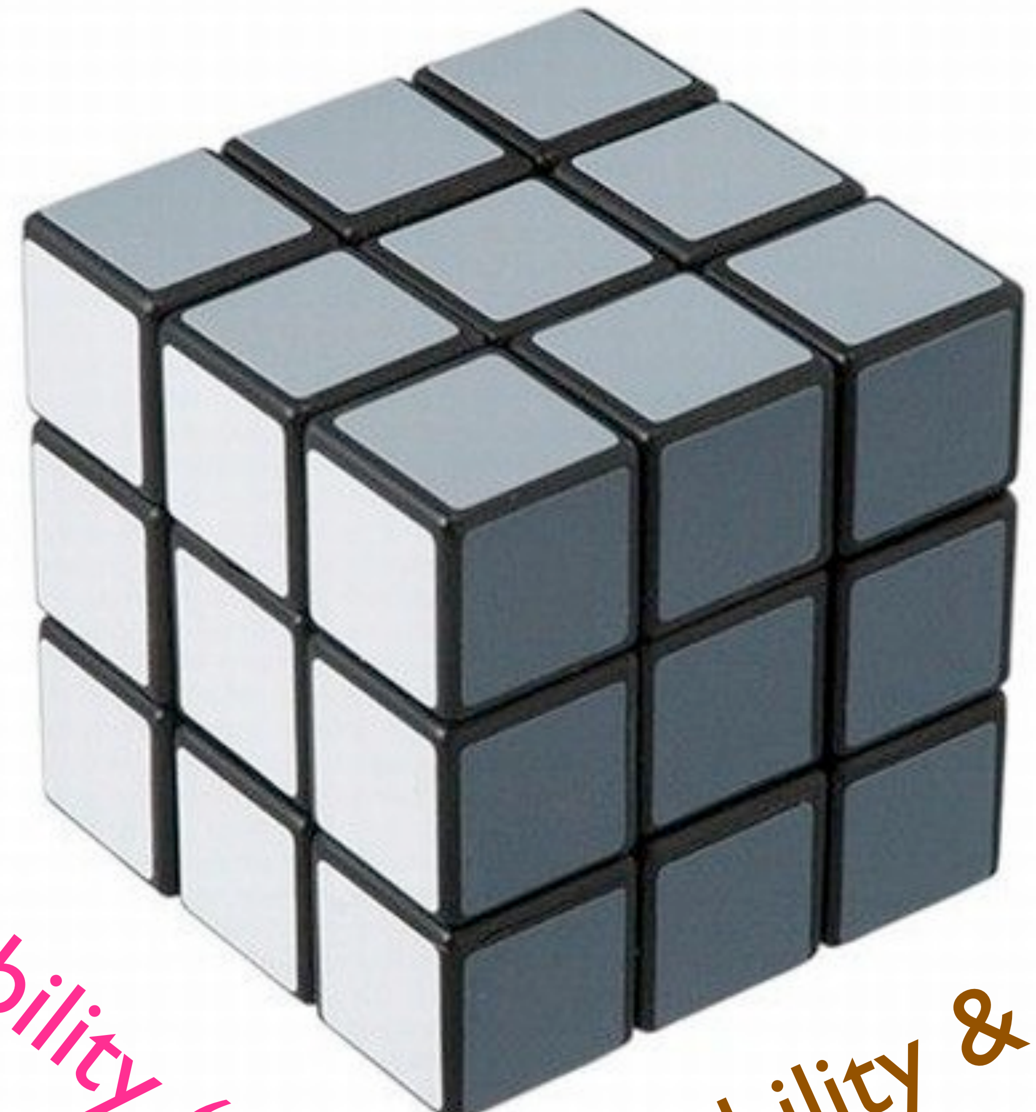
Cuore backgrounds

- 1) 2615 keV ^{208}Tl line. Due to the contamination between the inner Roman lead shield and the external lead shield (cryostat). 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. 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.
- All the above per kg of detector.

CUORE's cube

$4x10^{-2}$ -10^{-3} ckky
(kg detector)

background



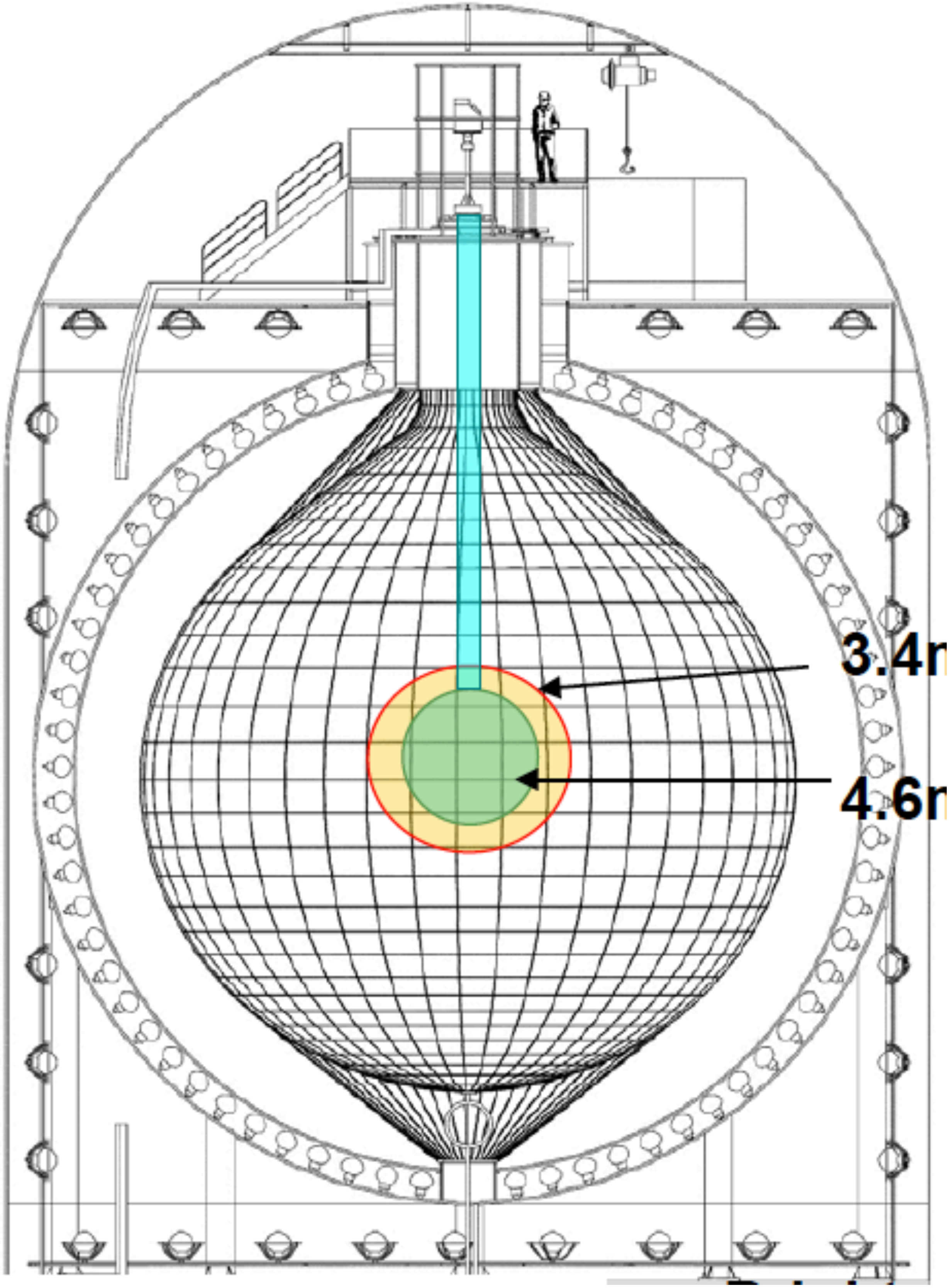
scalability (mass, cost)

feasibility & t0

200-400 kg

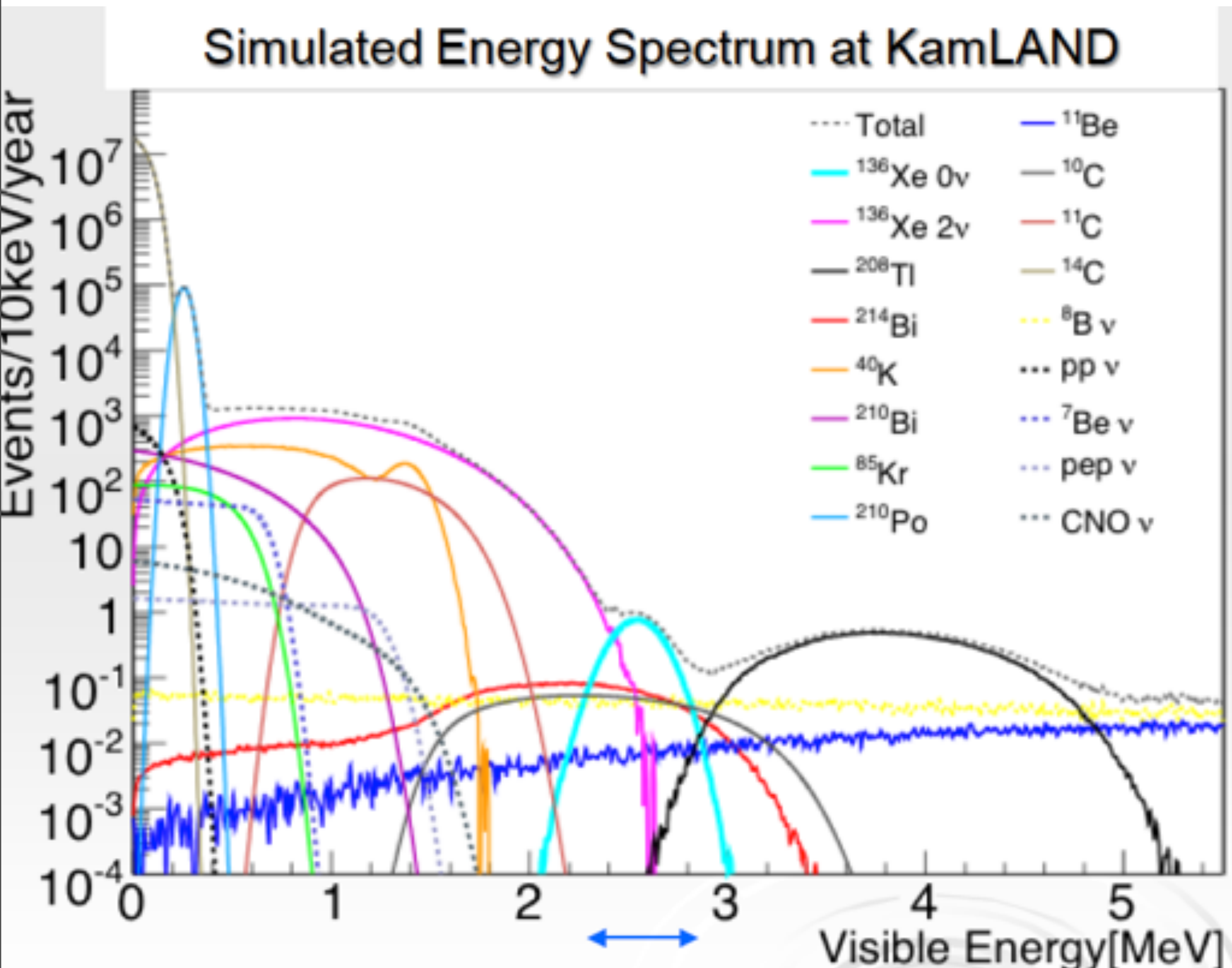
Cuoricino, Cuore0 starts in 2011, full CUORE in 2014

Kamland-Zen



- Xenon dissolved in ultra-pure liquid scintillator.
- Very radiopure balloon of 2 m radius.
- High efficiency (~80%)
- Phase I 400 kg of Xenon.
- PHASE-II 1 ton of Xenon.
- Poor resolution (about 10% at Qbb).
- Liquid scintillator purity is good but still far from that of Borexino...

Background model



Summary of BG and signal in signal region

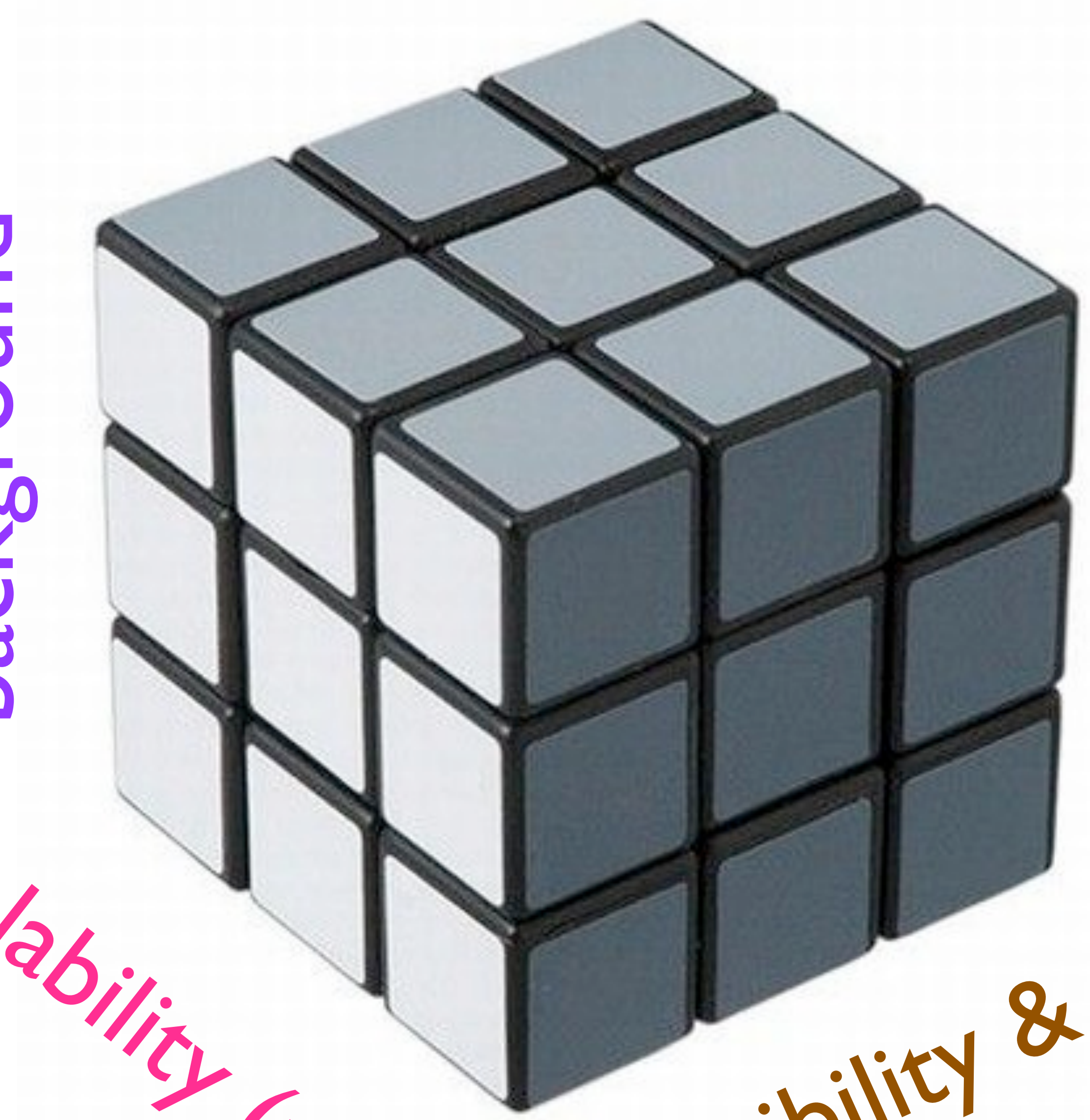
^{136}Xe 2ν	^{208}Tl	^{214}Bi	^{10}C	^{11}Be	^{8}B	Total	^{136}Xe 0ν
2.08 ±0.15	1.86×10^{-2} $\pm0.13\times10^{-2}$	2.40 ±0.01	3.09 ±0.01	0.26 ±0.01	1.52 ±0.03	9.35 ±0.23	18.08 ±0.02

[events/year]

- Purely MC studies.
- Backgrounds can increase sizably if bb2nu for Xenon is faster than 10^{22} y
- Aggressive assumptions for tagging capabilities (90% 10C, 60% 214Bi)
- Assumes extreme radiopurity of both scintillator and balloon (10^{-12} g/g in U and Th).
- Changing the assumptions about bb2nu and using latest measurement for Xe Qbb may change b by a factor 2 to 5.
- Radiopurity of liquid scintillator may increase the background level by a factor 10

Kamland-ZEN cube

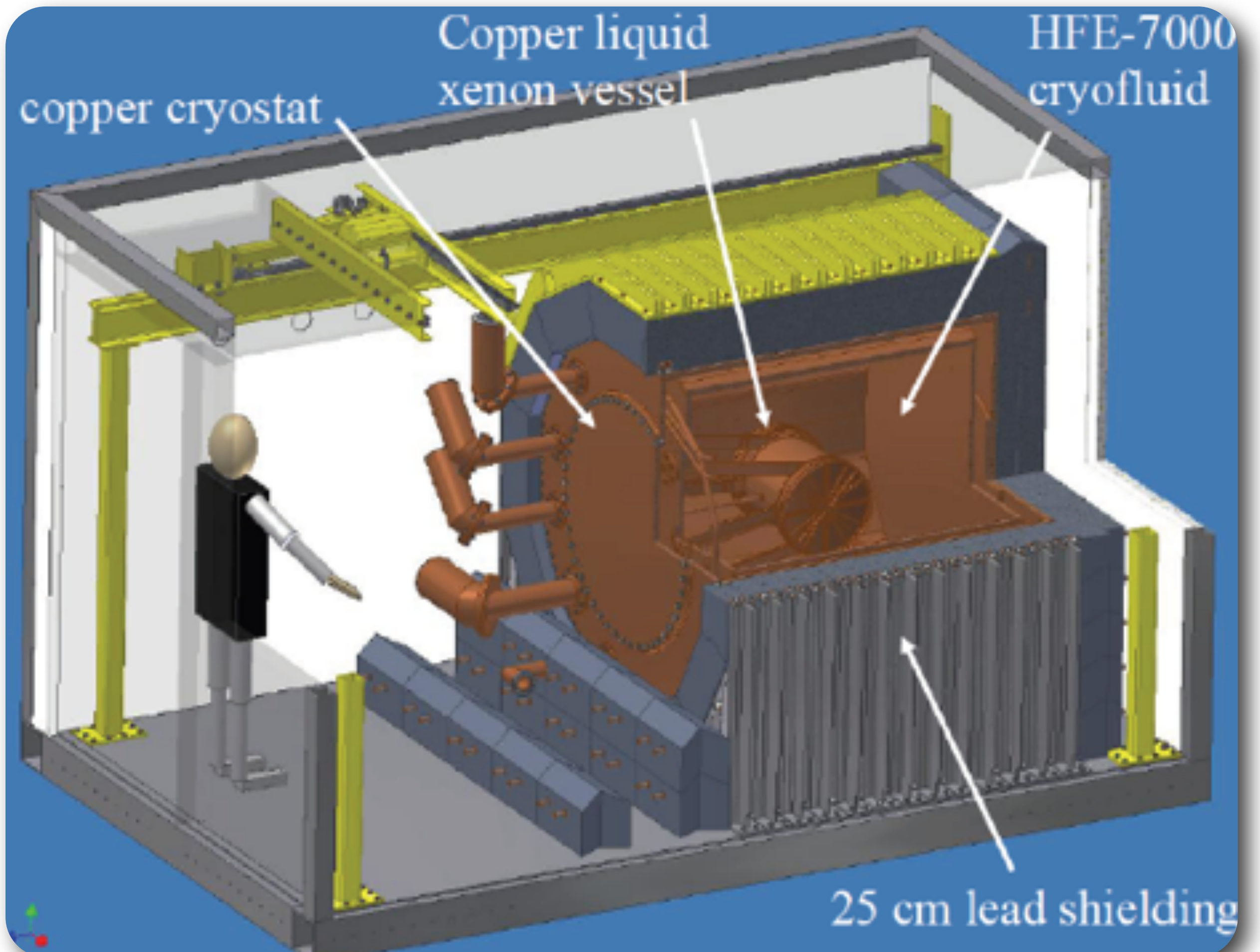
$\sim 5\text{x } 10^{-3}$-- $5\text{x}10^{-4}$
ckky



350-1000 kg

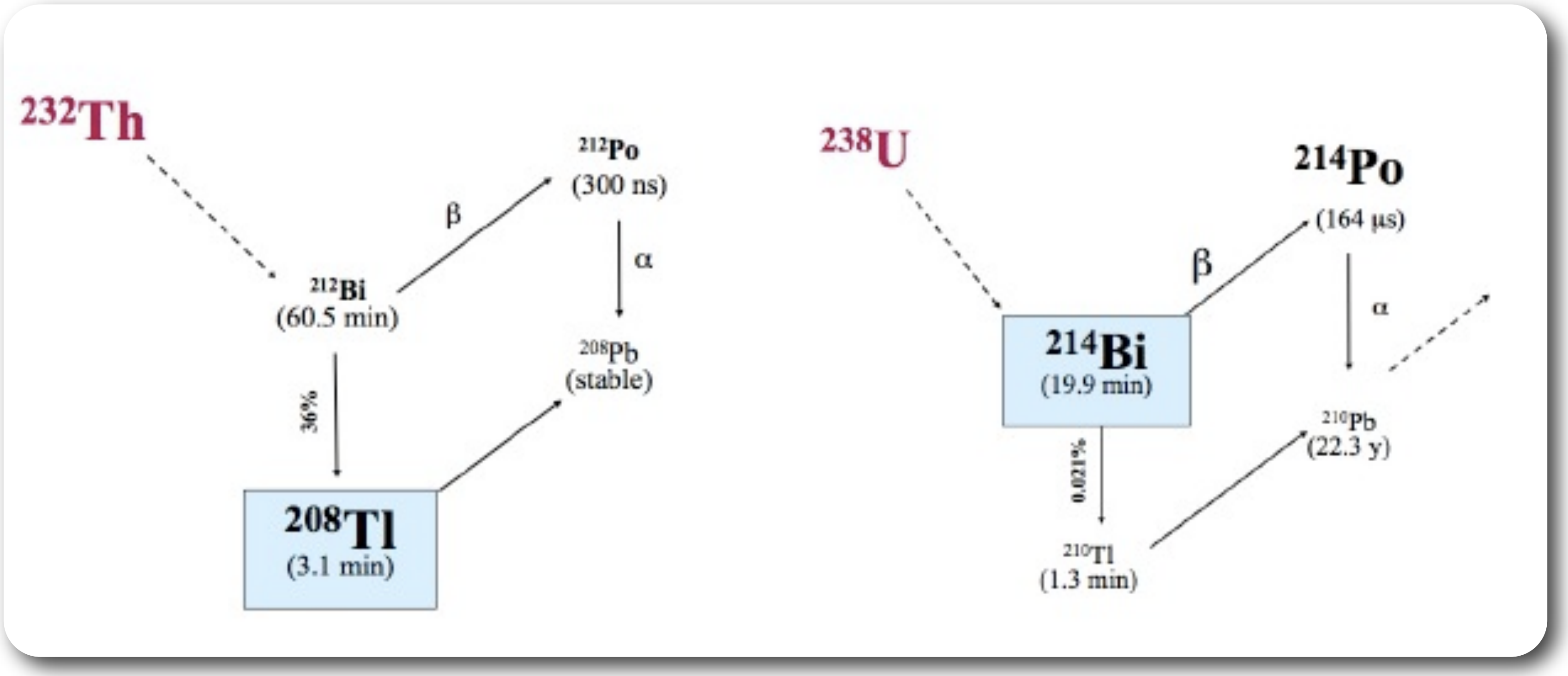
Starts in 2011

EXO-200



- 200 kg of liquid Xenon (enrichment at 80%)
- High efficiency (~70%)
- Better resolution than Kamlan-ZEN and SNO+, but still relatively poor (about 4% at Qbb), however excellent self shielding.

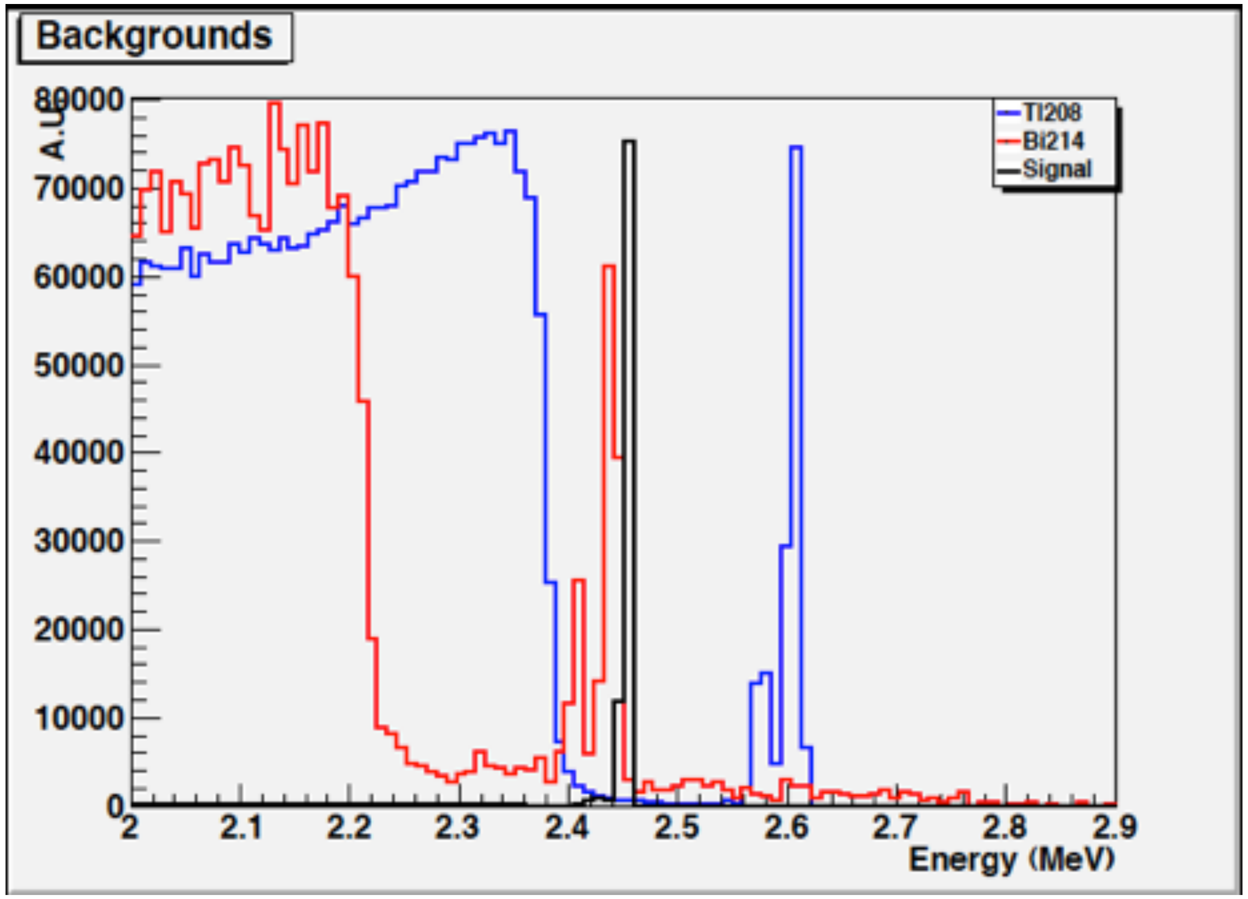
Backgrounds for EXO (and for NEXT)



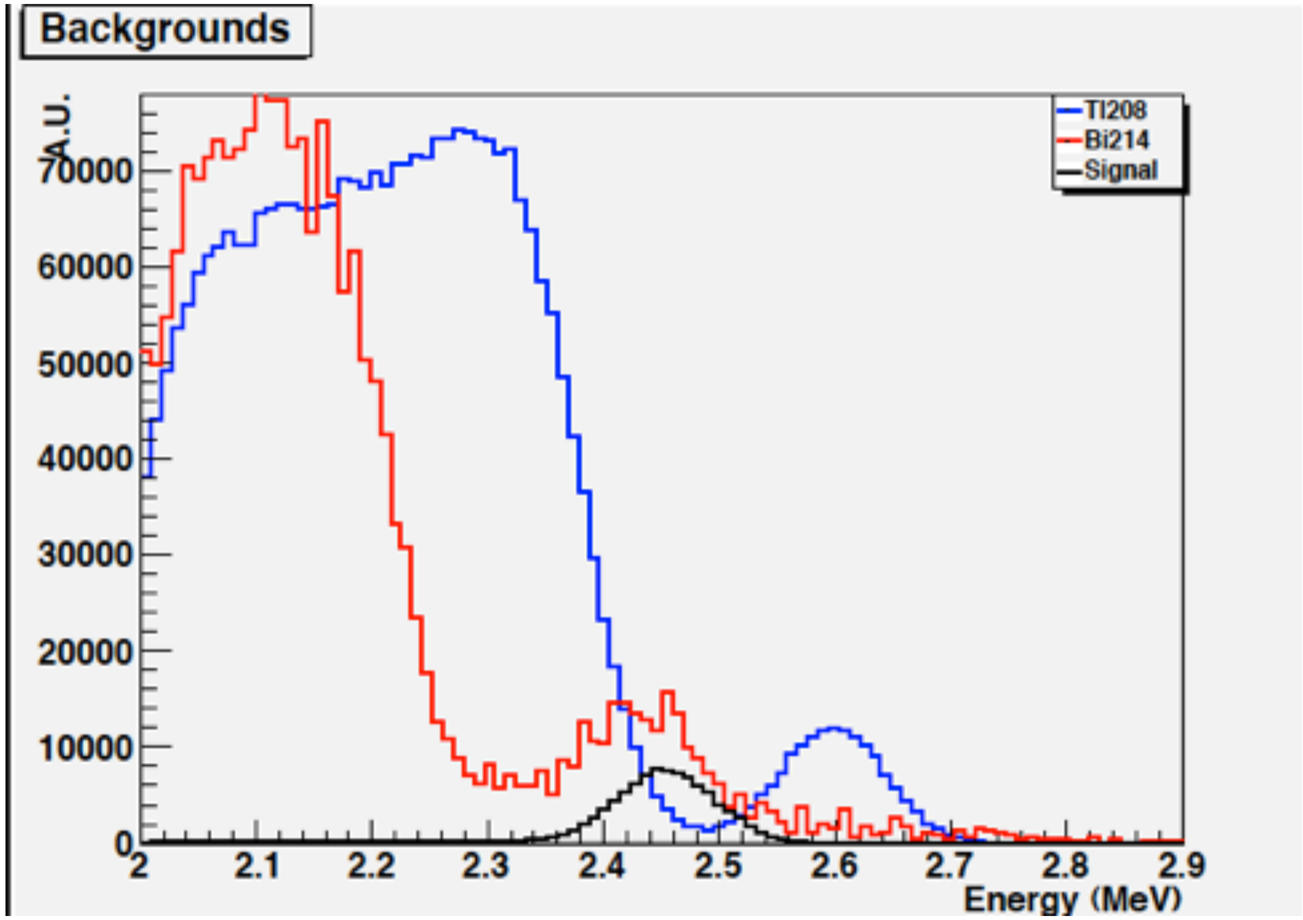
Xe TPCs are mostly affected by external backgrounds. Surface backgrounds are greatly reduced by defining a strict fiducial volume.

- EXO: (background model not very detailed in literature)

Xenon Landscape

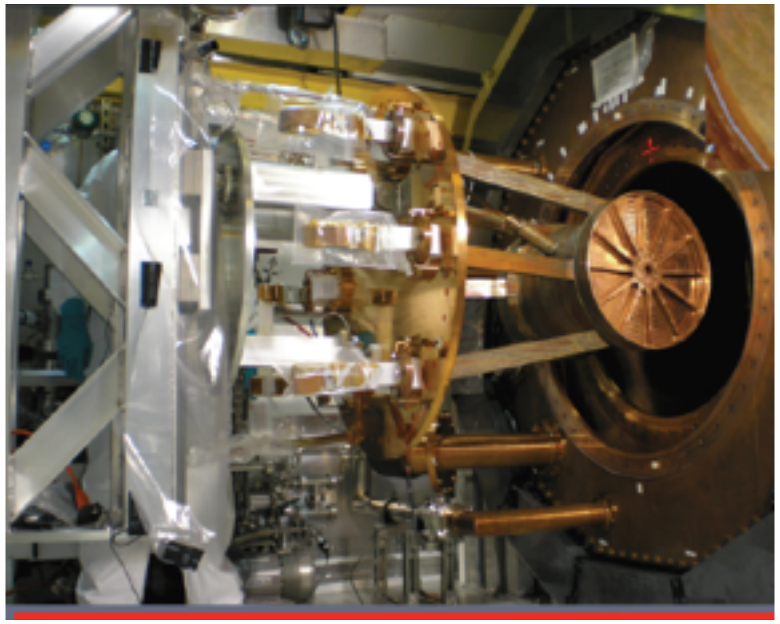


Intrinsic Xe resolution



LXe resolution

EXO cube



5×10^{-3} -- 10^{-3}

ckky

(efficiency?)

background

scalability (mass, cost)

feasibility & t0

160-1000 kg

Built and running

NEXT Collaboration

CIEMAT (Madrid) • U. Girona • IFAE (Barcelona) • IFIC (Valencia) • U. Santiago • U.P. Valencia • U. Zaragoza

LBNL • Texas A&M

CEA (Saclay)

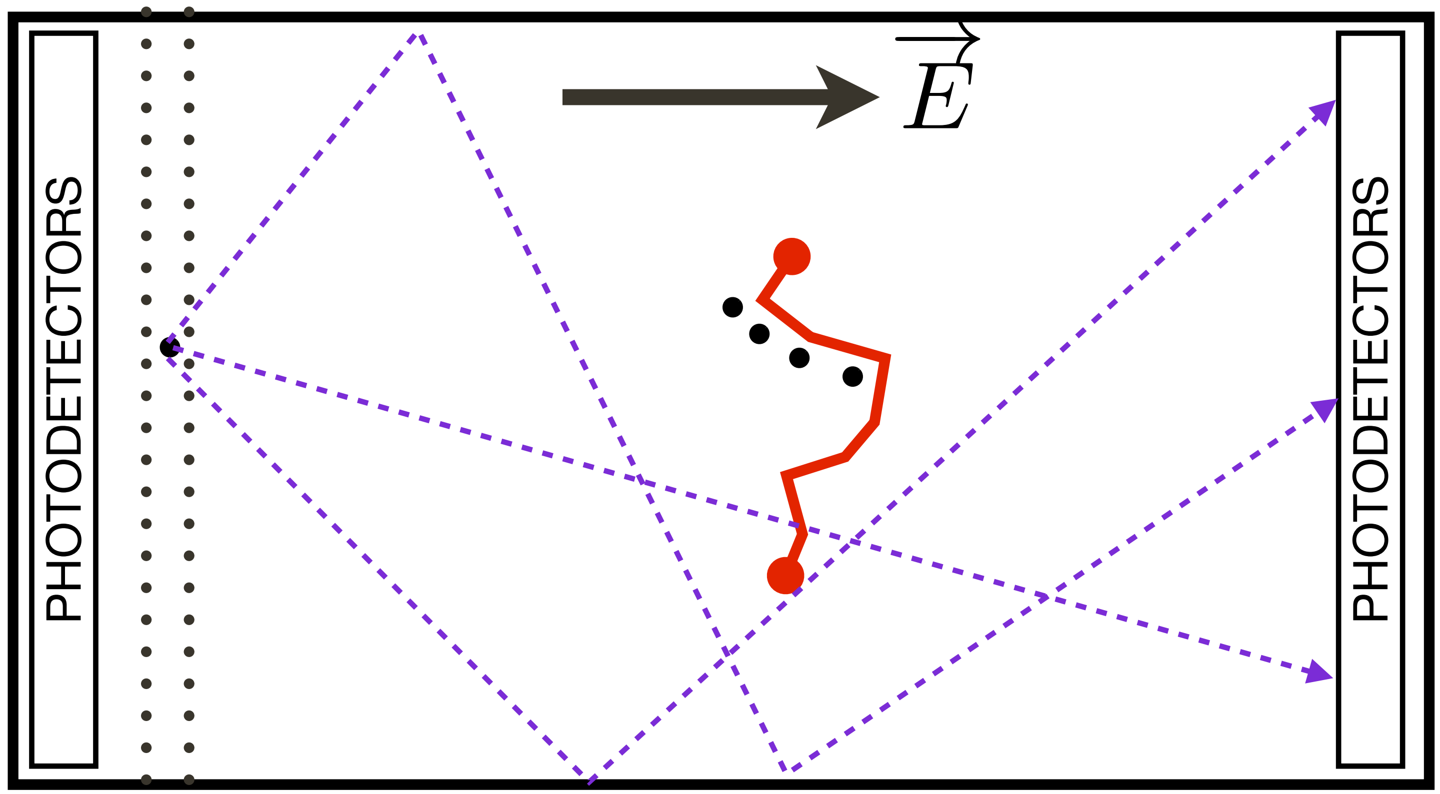
U. Coimbra • U. Aveiro

JINR (Dubna)

UAN (Bogotá)

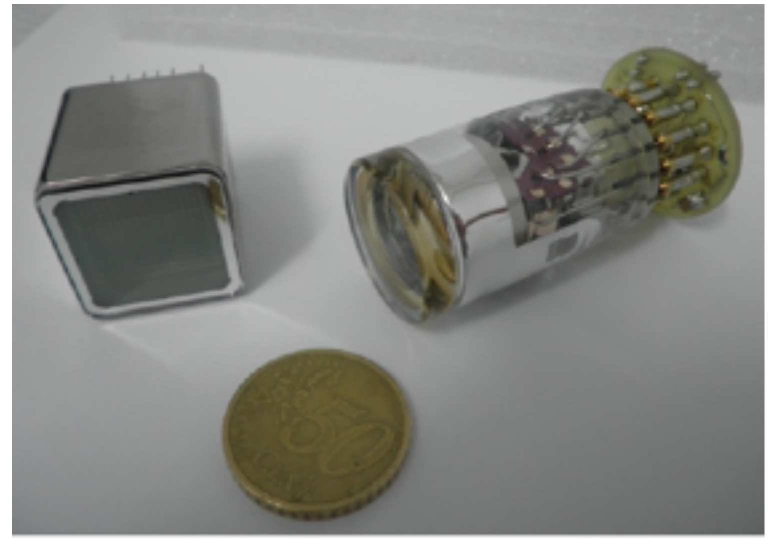
- 100 kg of (90%) enriched Xe (available)
- HPGXe detector at 15 bar
- Will operate at LSC (Canfranc)
- Advanced R&D phase
- NEXT-1 prototypes/demonstrator on the way

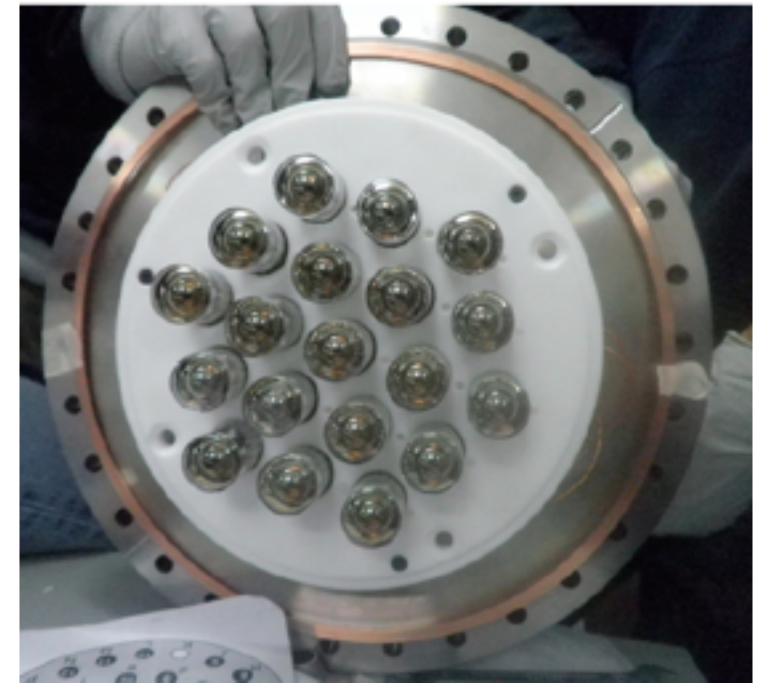
SOFT principle

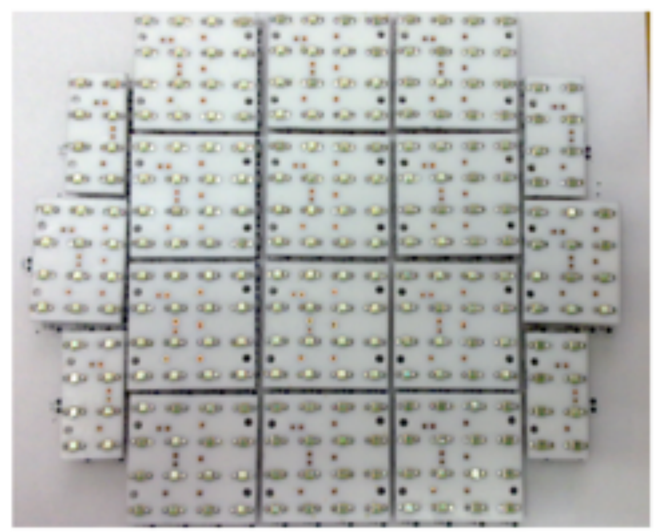


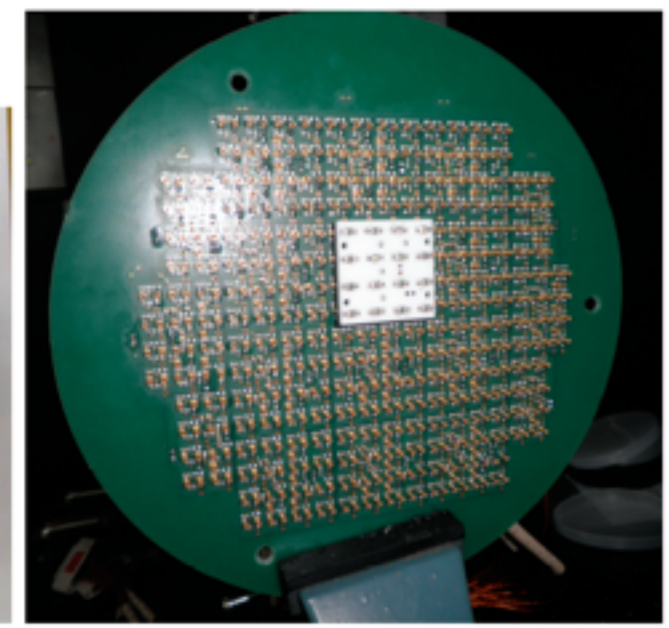
- Electroluminescence, emitted isotropically, also reaches cathode.
- Same array of photo-detectors used for t_0 measurement is also used for accurate calorimetry.
- Separated-Optimized functions.

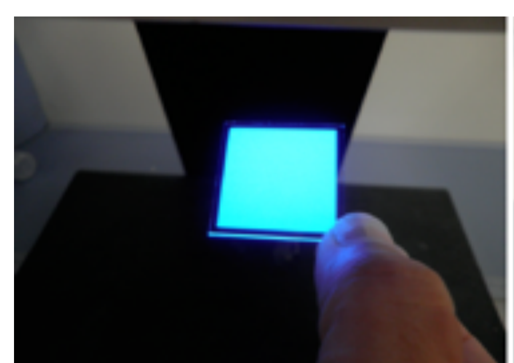
NEXT-1-EL

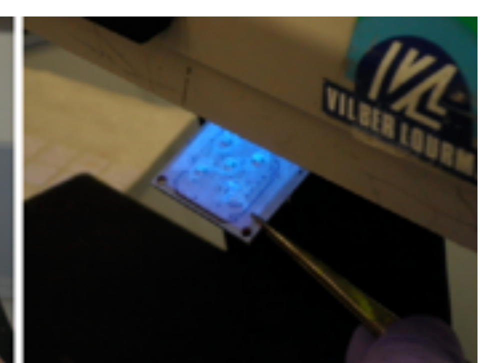




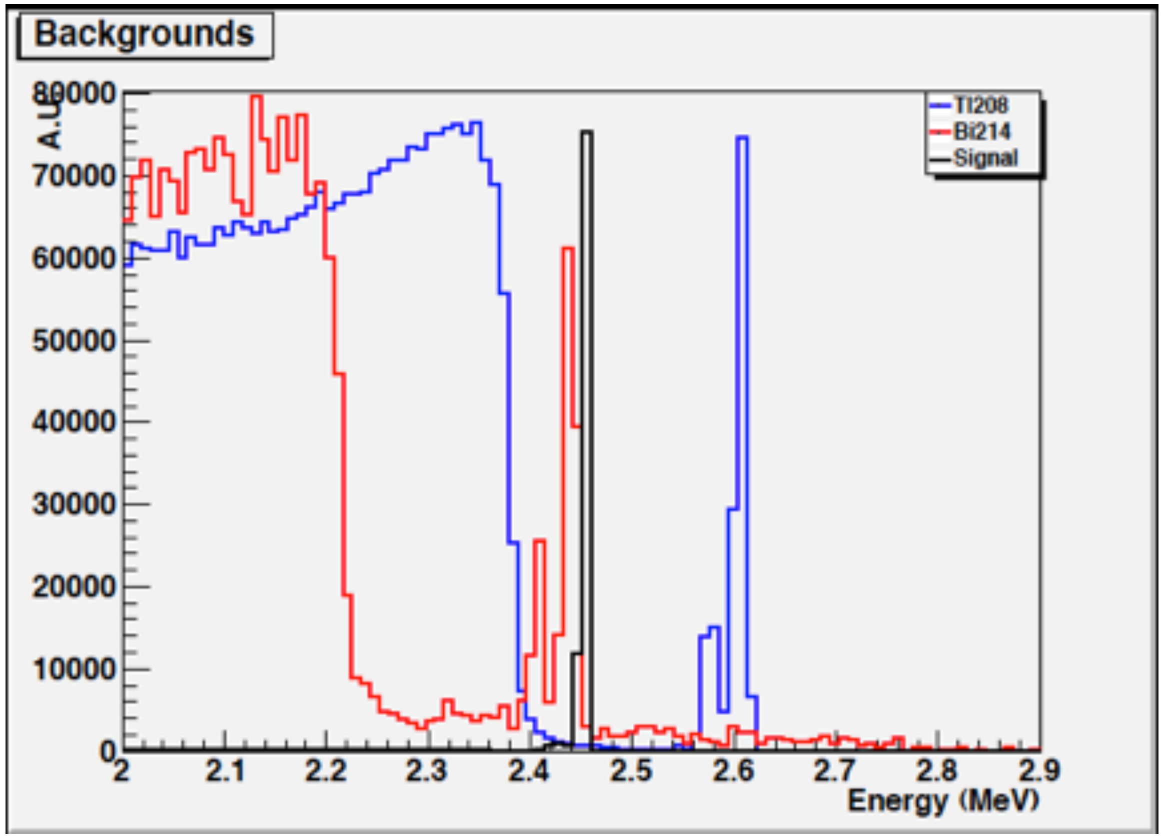


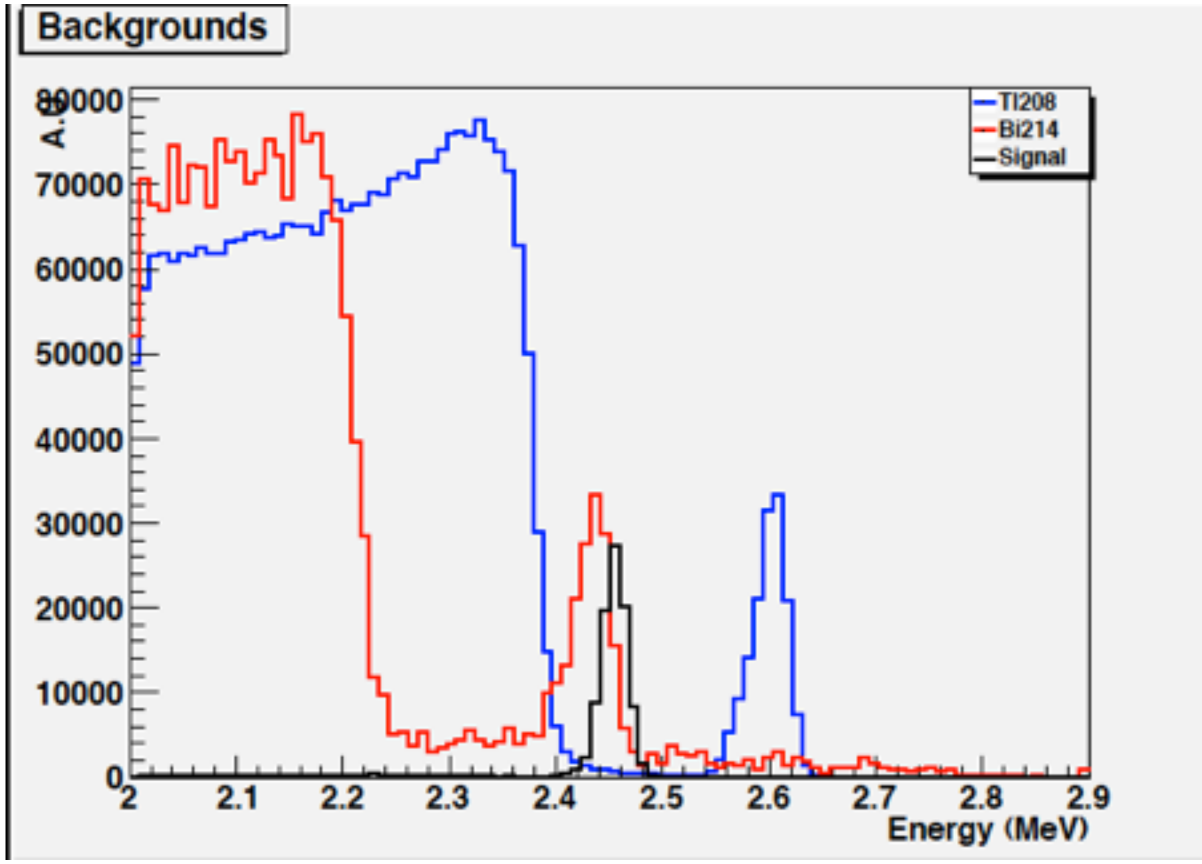


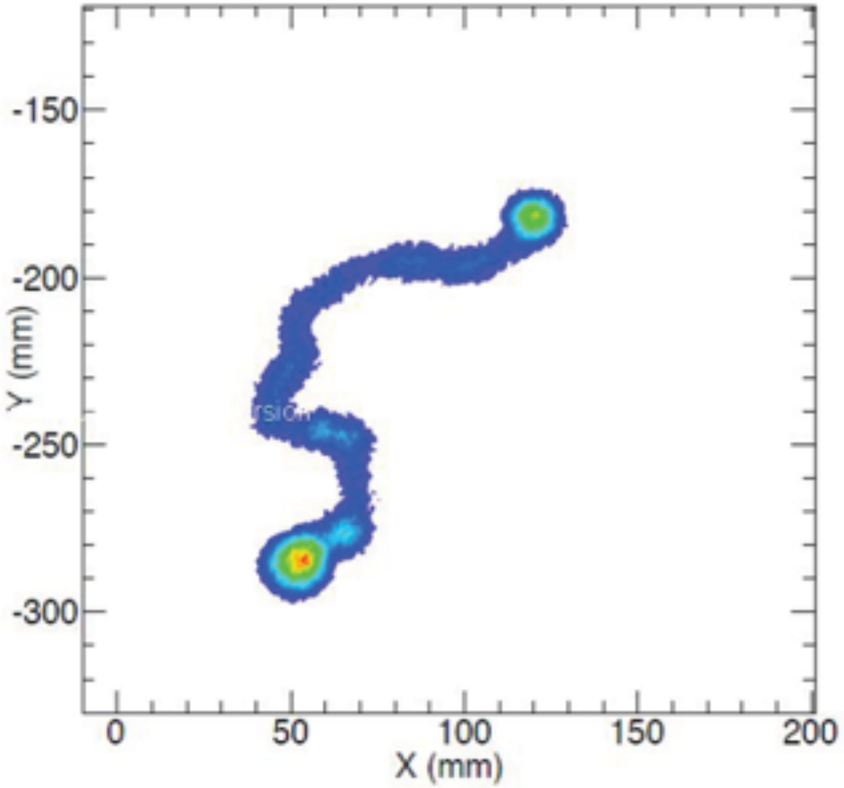




Background model







- Purely MC studies.
- Combines good energy resolution, fiducial definition (no surface backgrounds), detector transparency and topological signature
- Depends on assumptions about inner detector components and pressure vessel
- Tradeoff between background rejection and efficiency (on the topological signature).

NEXT cube

background

~5x10^{-4} --10^{-4}
ckky
(MC model)

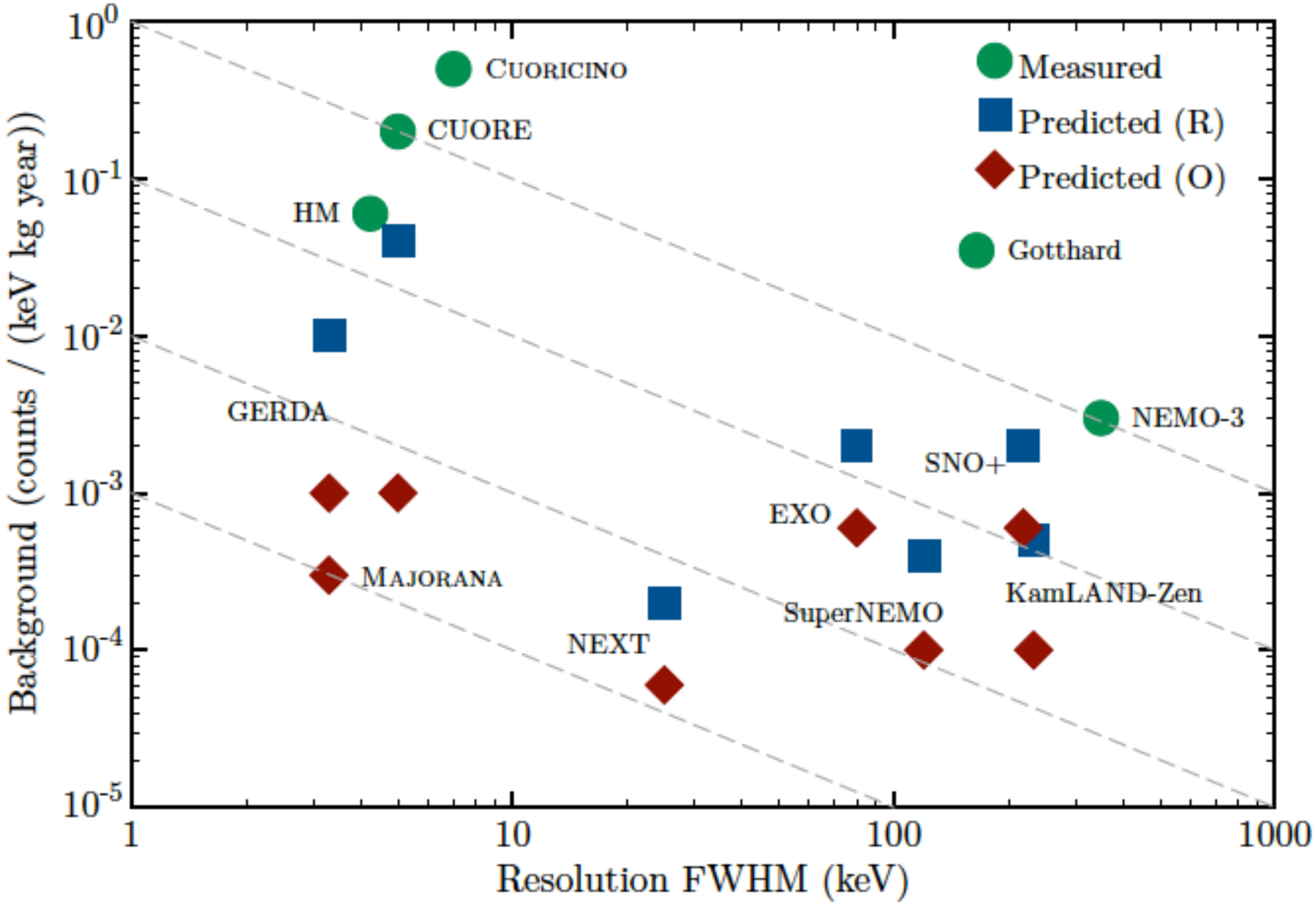
scalability (mass, cost)

90-1000 kg

feasibility & t0

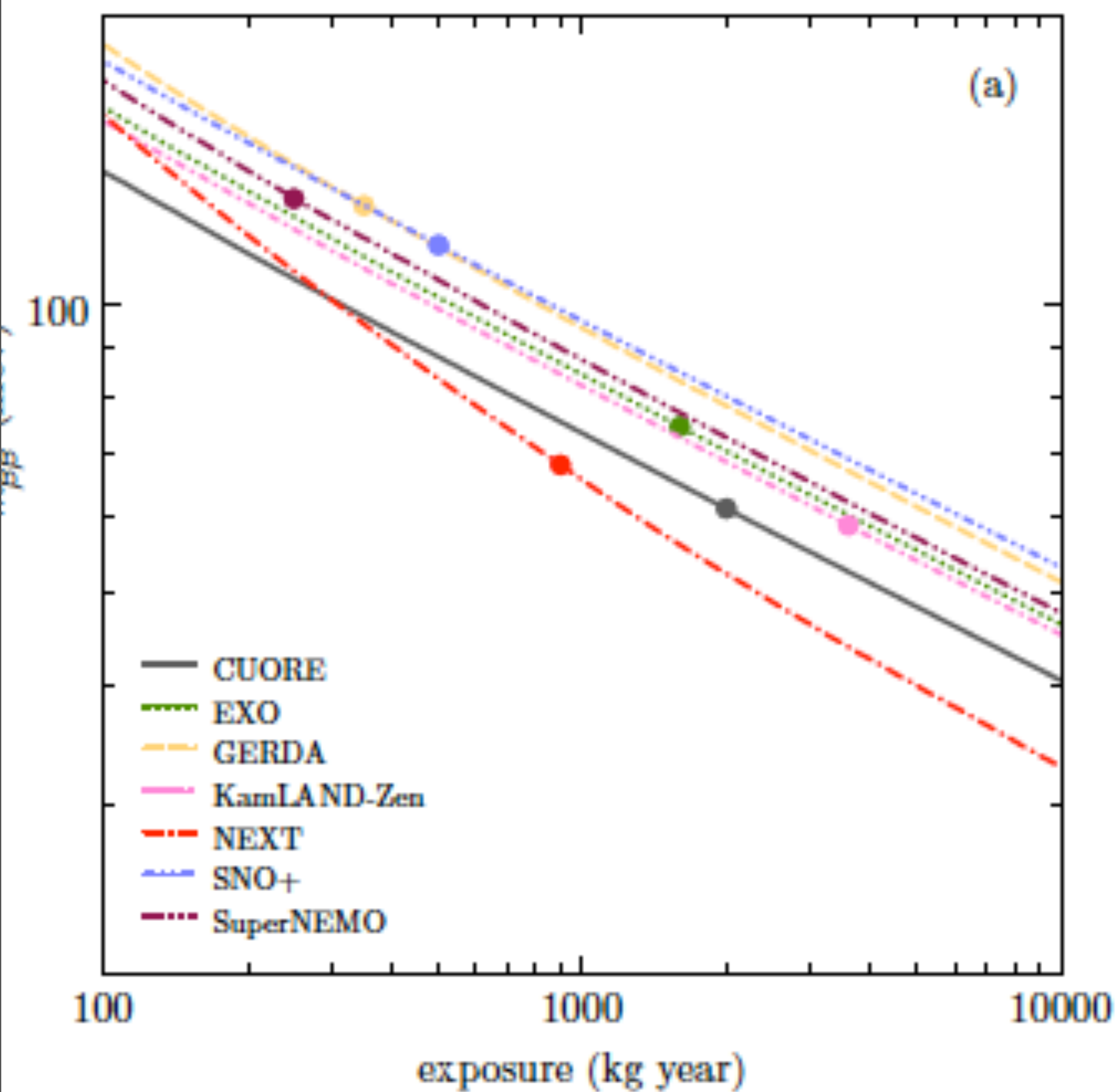
NEXT1 running
NEXT 100 schedule
in 2014
Can we make it?

Traum und Wirklichkeit?



Adapted from A. Giuliani

Sensitivity of proposals

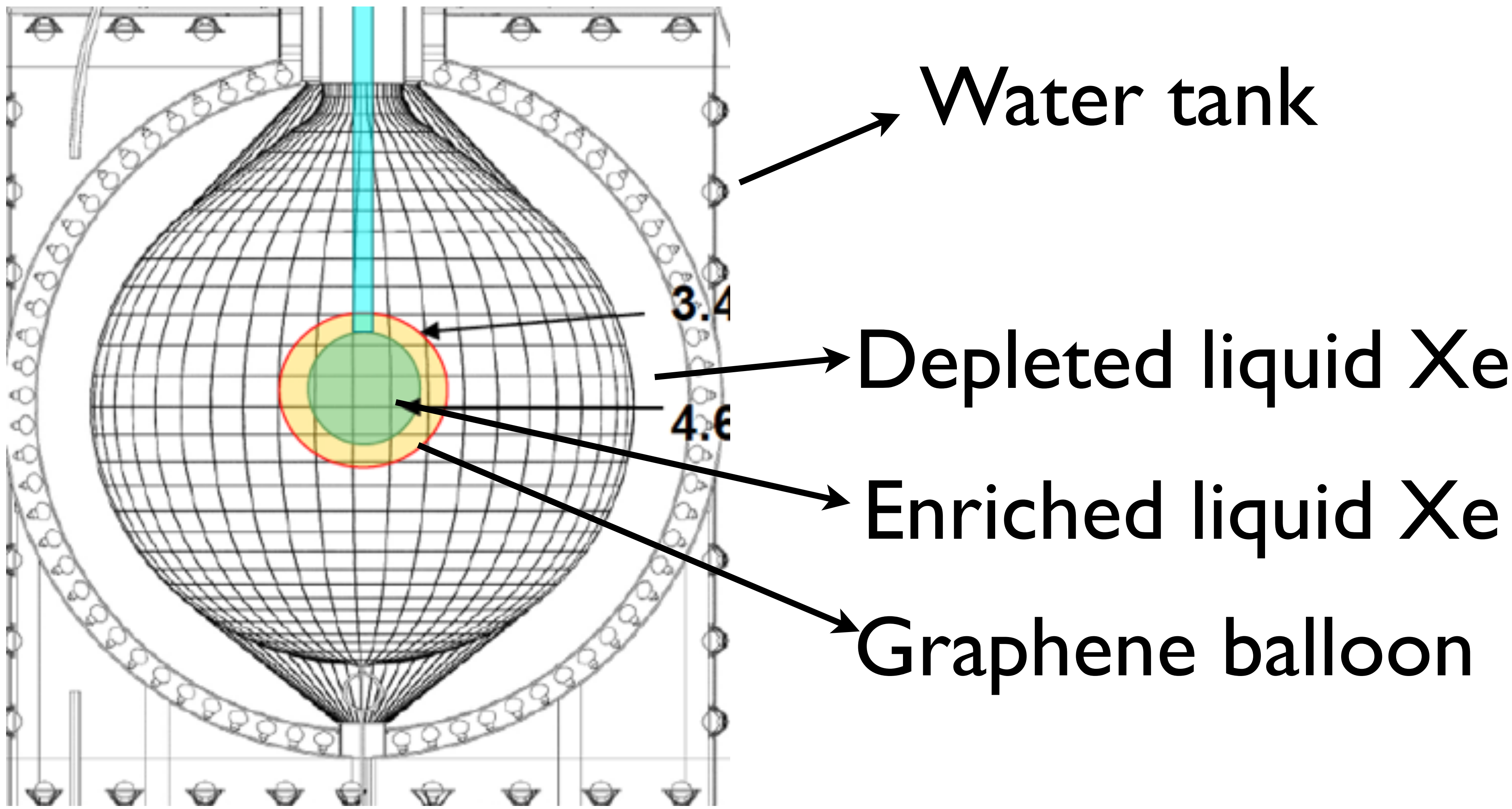


- Does not take into account "t0"
- Uses "conservative" background model (that can be more conservative for some experiments than for others)
- Uses central values for PMRs
- (should we use rather lower and upper limits of PMR?).
- Dots mean (10 years x mass)

Sense for DBD

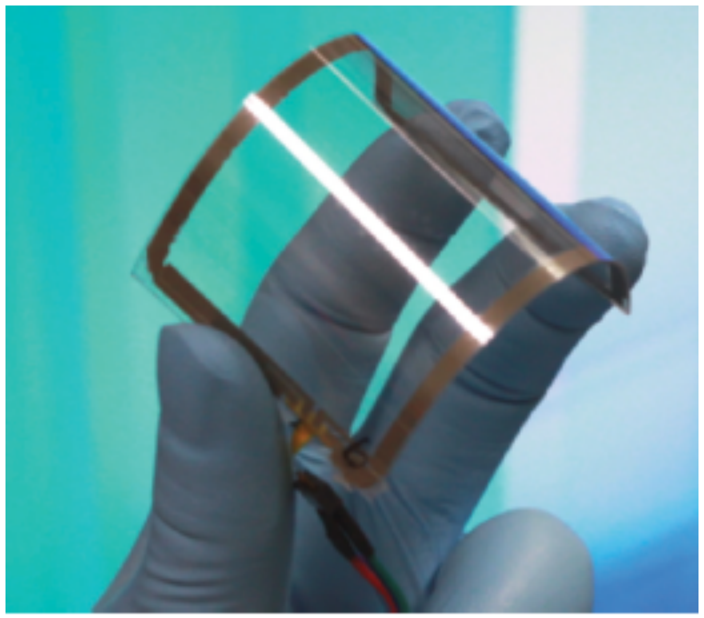
- Experiments need to be compared in 3D.
- It is not easy to dig up data from the literature. We suggest that experiments publish papers explaining their background model and providing a realistic range for the background rate. We have tried to do so in this work at our risk & peril.
- In the sort range (Klapdor, early discovery), already-running, or about to run experiments (GERDA, EXO, K-ZEN) may stand the best chances.
- On the other hand, Xenon based experiments appear to be the best to scale (Super-Nemo the most difficult to scale).
- If NEXT-1 proves energy resolution and topological signature, NEXT has a chance of becoming a major player.
- We haven't found yet the perfect DBD experiment...
- Or have we?

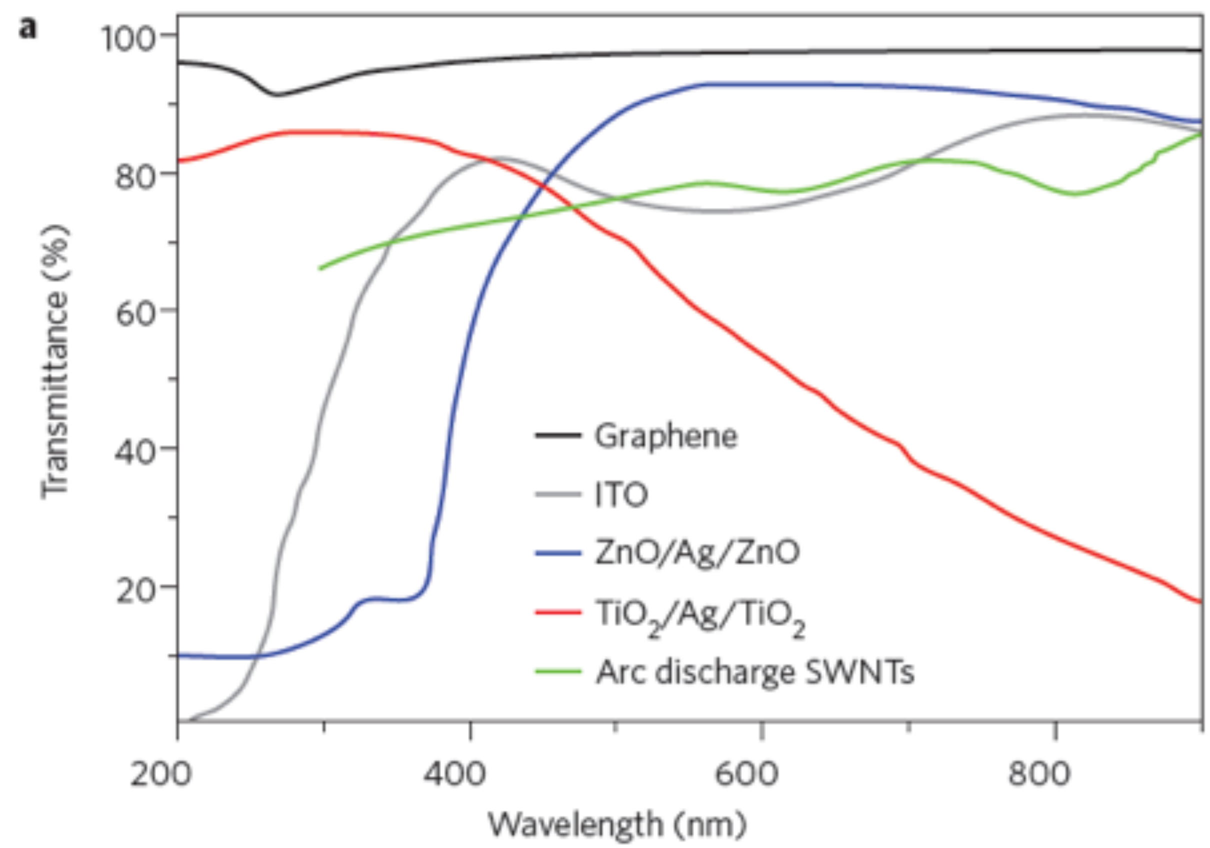
GraXe for DBD

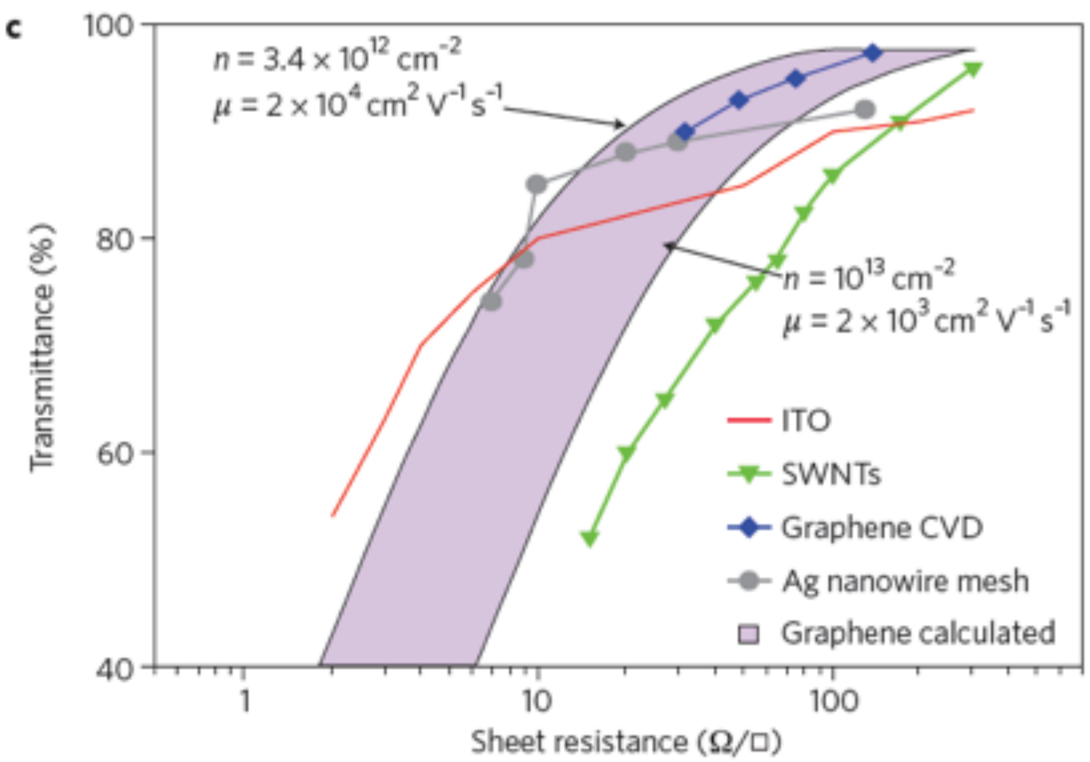


- F. Guinea, JJGC
- Ultimate DBD experiment?

GraXe for DBD







- Graphene is transparent to VUV light
- Strong, large area, "industrial" graphene sheets appear to be at reality.
- If one can manufacture a bag of Graphene to contain (liquid) Xenon and read the VUV primary scintillation light using external phototubes (shielded by natural Xenon) the experiment is virtually background free.

Good luck to us all!