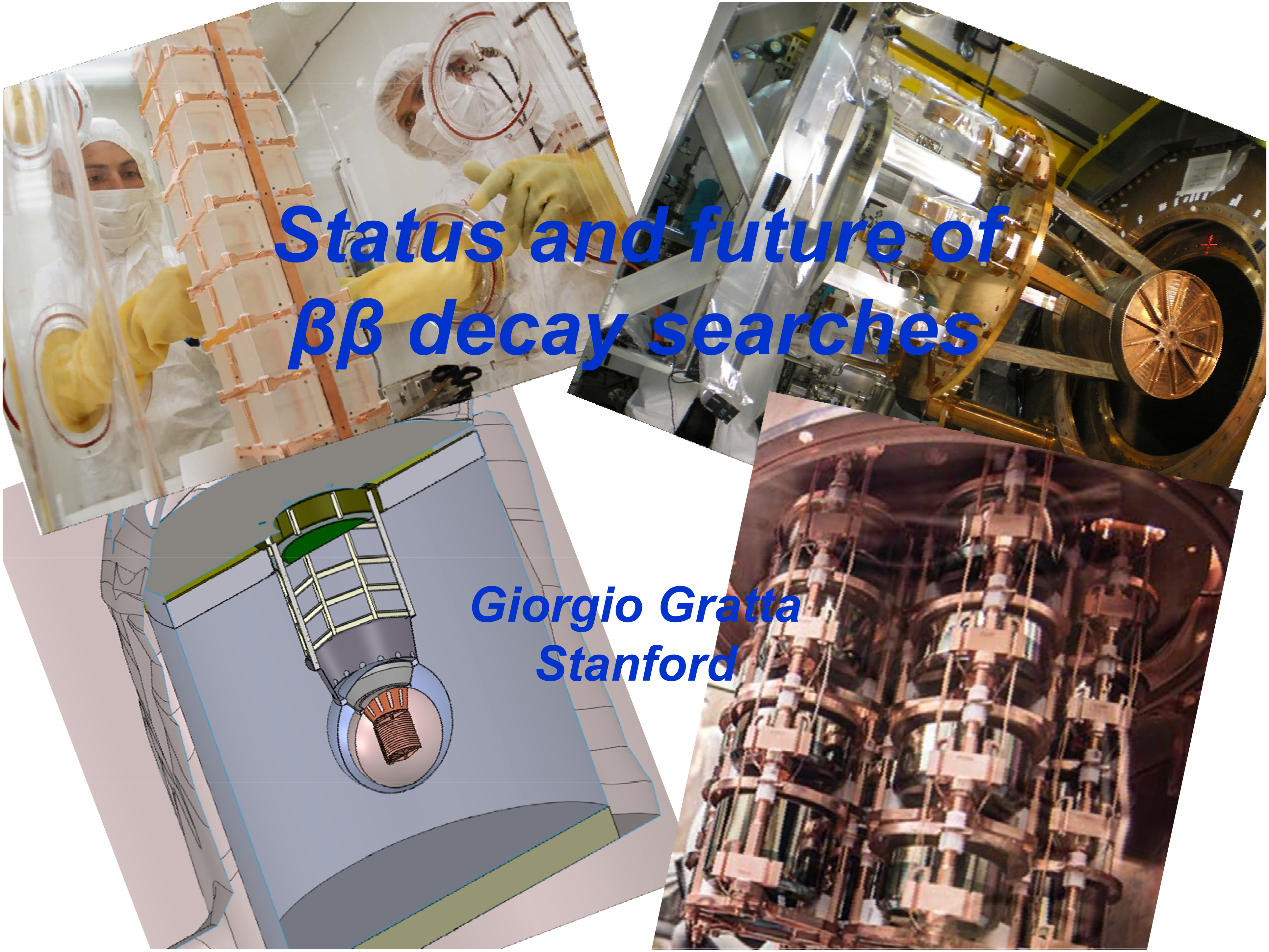
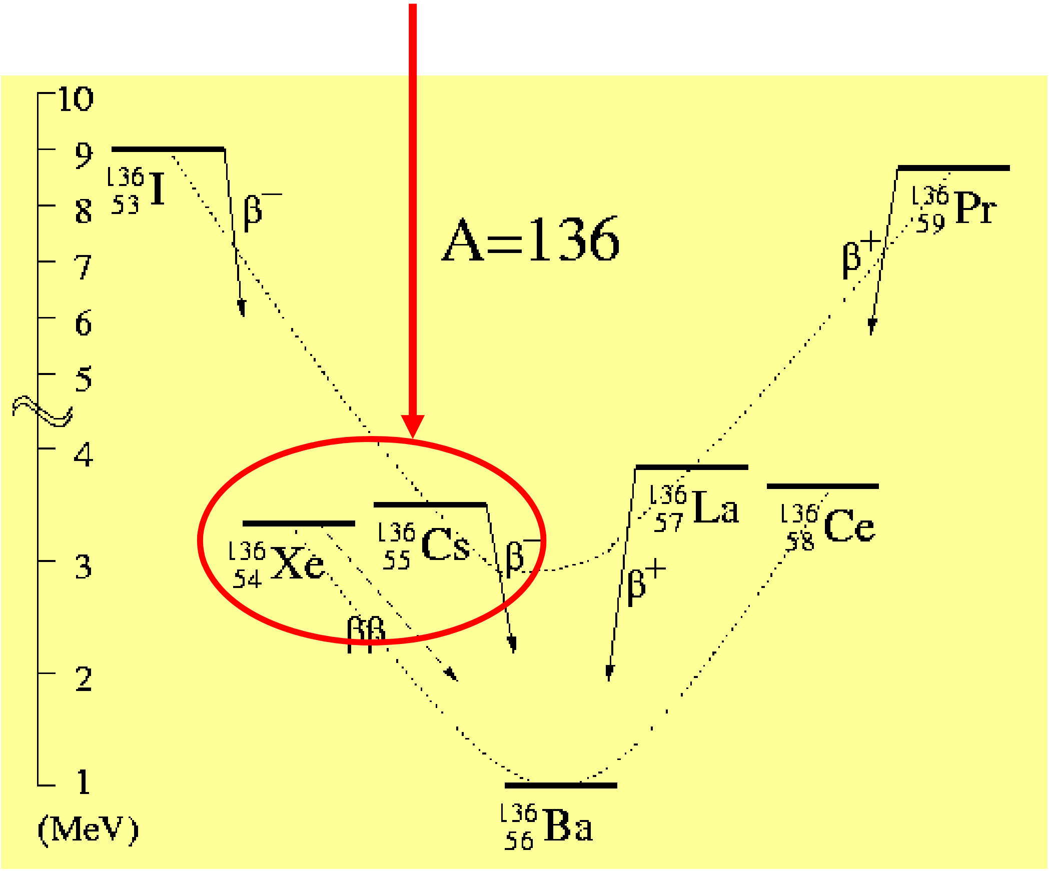


Status and future of ββ decay searches

Giorgio Gratta
Stanford

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

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

There are two varieties of ββ decay

2ν mode:
a conventional
2nd order process
in nuclear physics

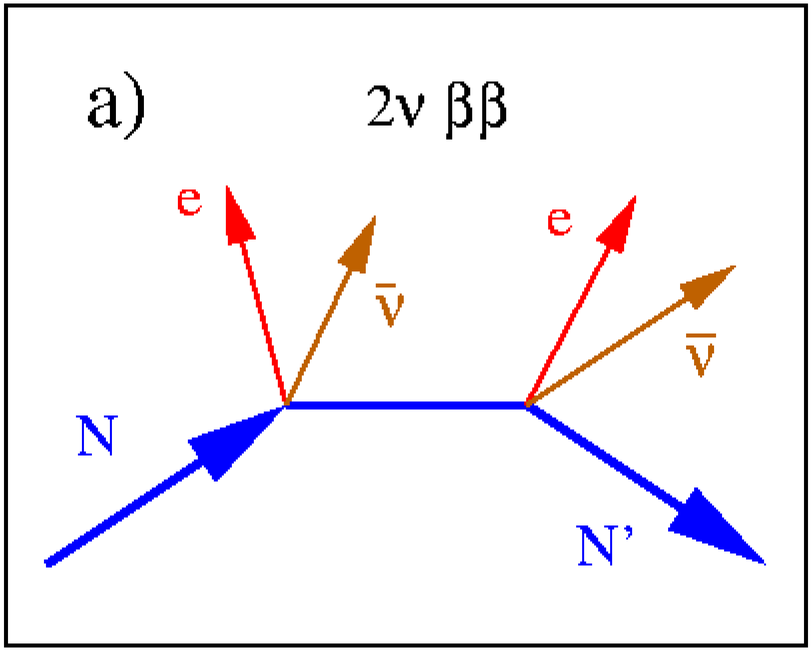
0ν mode: a hypothetical process can happen only if:

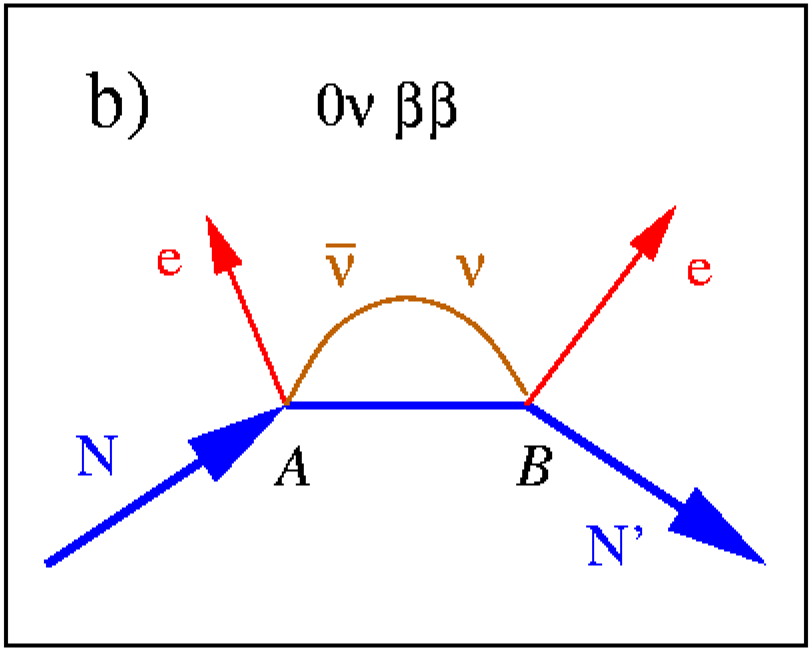
$M_\nu \neq 0$

$\bar{\nu} = \nu$

$|\Delta L|=2$

$|\Delta(B-L)|=2$





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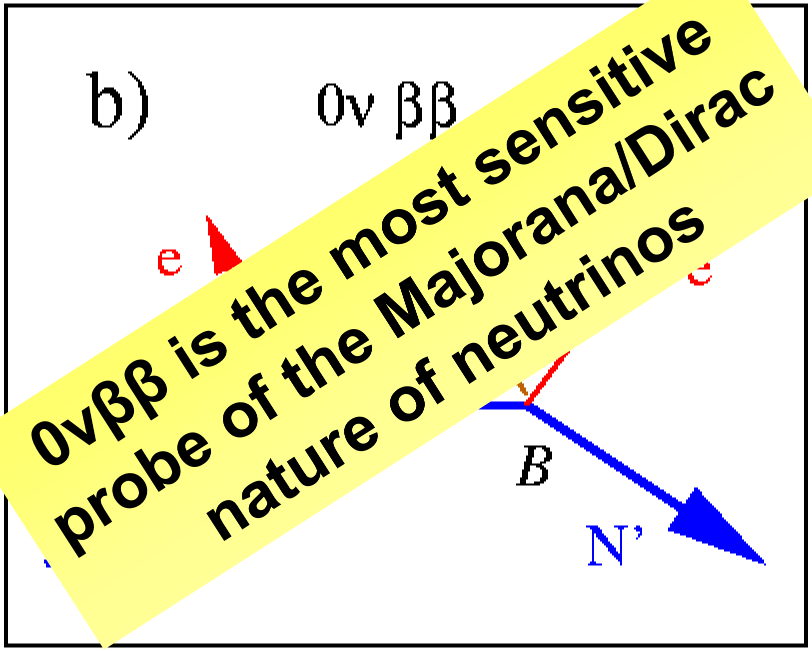
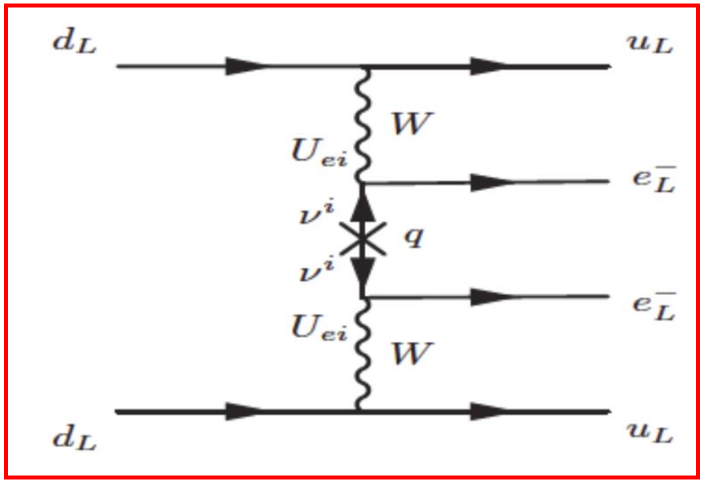
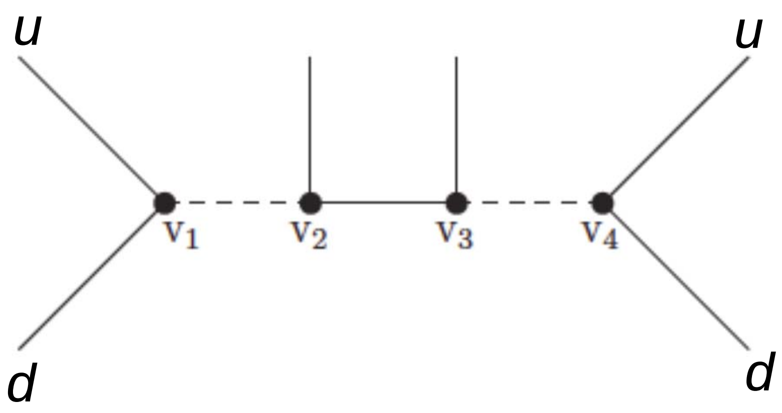


0νββ is the most sensitive probe of the Majorana/Dirac nature of neutrinos

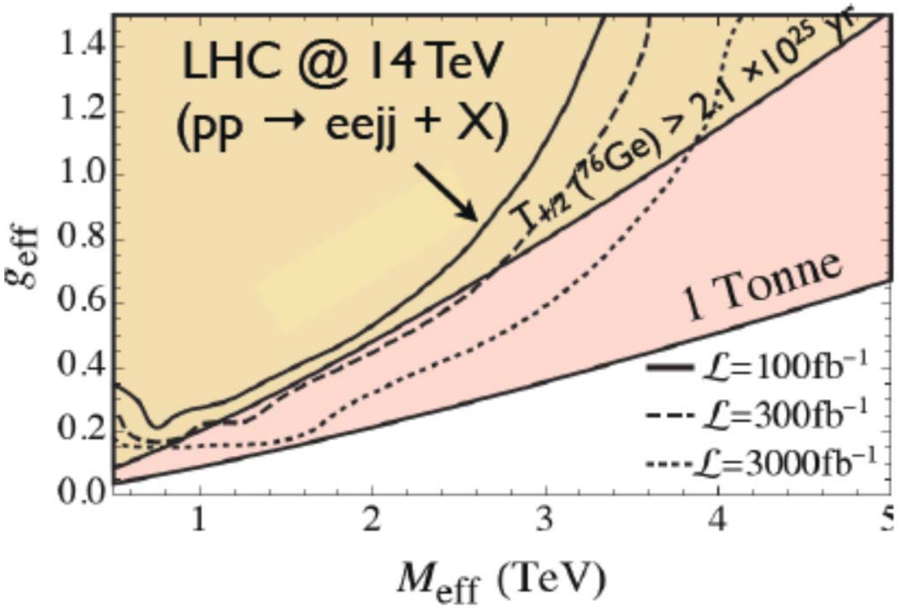
While it is often convenient to think in terms of the standard mechanism other mechanisms not directly related to neutrino masses can produce the lepton number violation



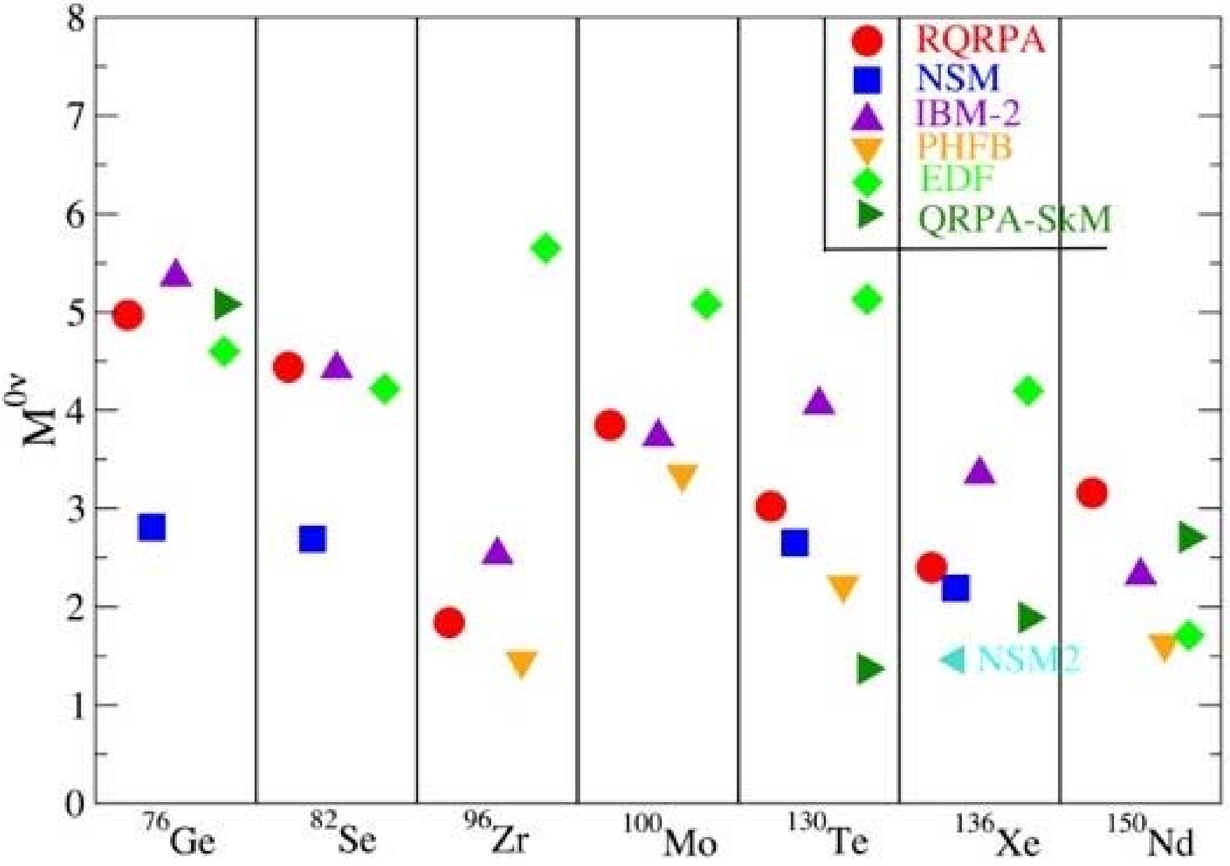
SUSY-inspired example:



Peng, Ramsey-Musolf, Winslow, 2015



Connecting the observable ($T^{0\nu\beta\beta}_{1/2}$) to parameters of Lepton Number Violating interactions ($\langle m_\nu \rangle$, …) requires a mechanism-dependent nuclear matrix element (here below and the "standard mechanism")



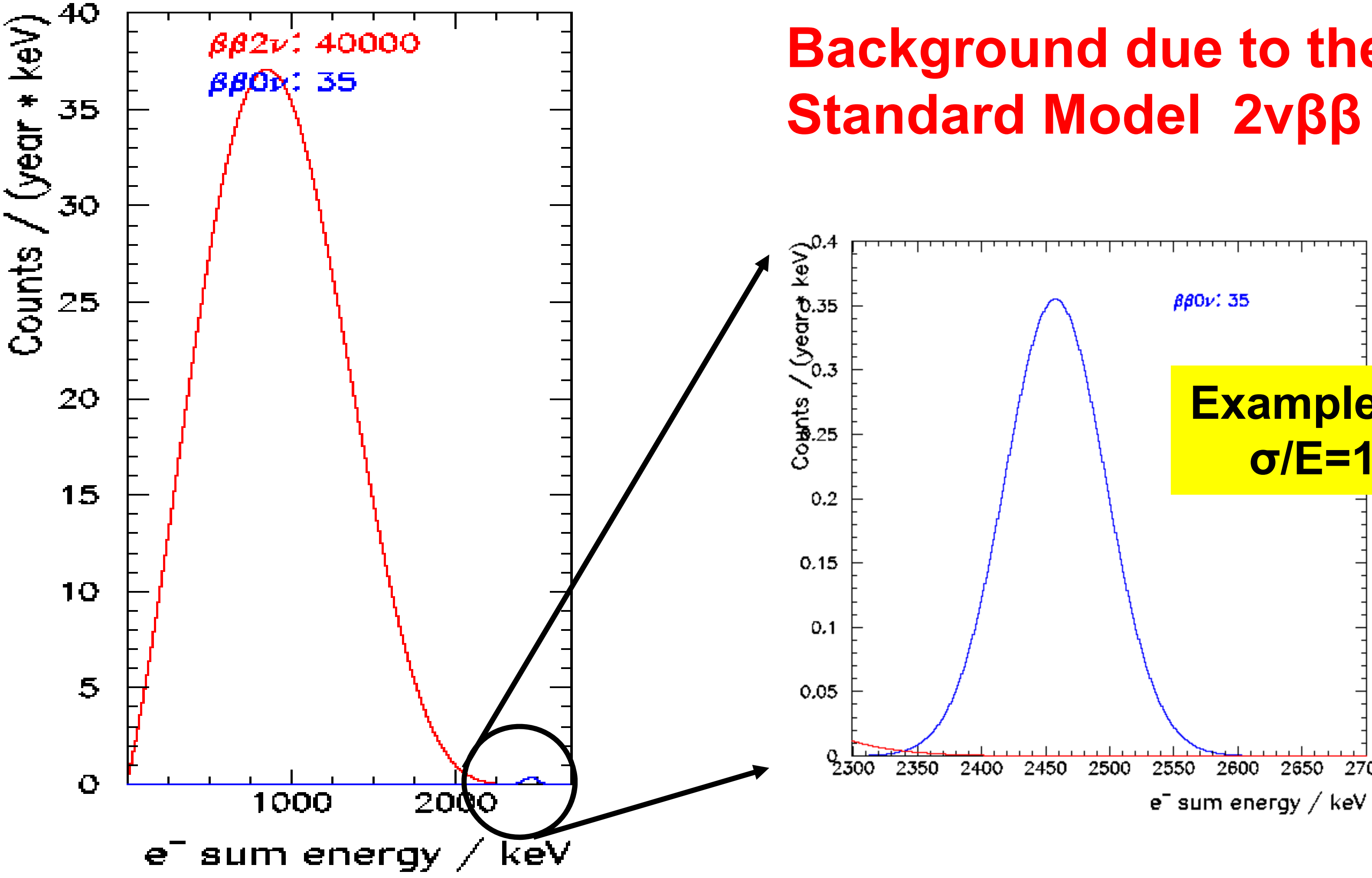
Petr Vogel, 2014

0νββ decay always implies new physics

There is no scenario in which observing 0νββ decay would not be a great discovery

- ➔ Majorana neutrinos
- ➔ Lepton number violation
- ➔ Probe new mass mechanism up to the GUT scale
- ➔ Probe key ingredient in generating cosmic baryon asymmetry

Background due to the Standard Model 2νββ decay



Example using σ/E=1.6%

- ➔ The two can be separated with sufficiently good energy resolution
- ➔ A large $T_{1/2}^{\beta\beta}$ helps

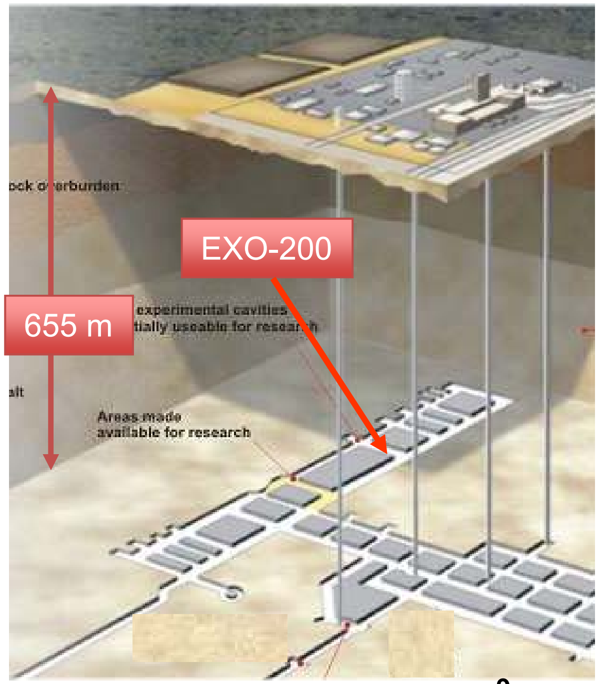
Four fundamental requirements for modern experiments:

1) Isotopic enrichment of the source material (that is generally also the detector)

100kg – class experiment running or completed.
Ton – class experiments under planning.

2) Underground location to shield cosmic-ray induced background

Several underground labs around the world, next round of experiments 1-2 km deep.



Four fundamental requirements for modern experiments:

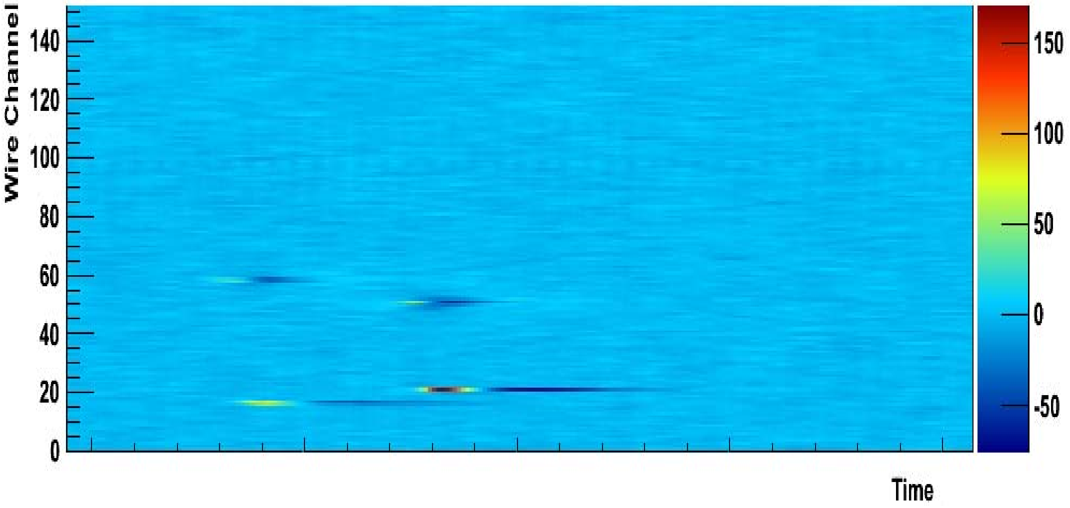
3) Ultra-low radioactive contamination for detector construction components

Materials used ≈<10^{-15} in U, Th
(U, Th in the earth crust ~ppm)

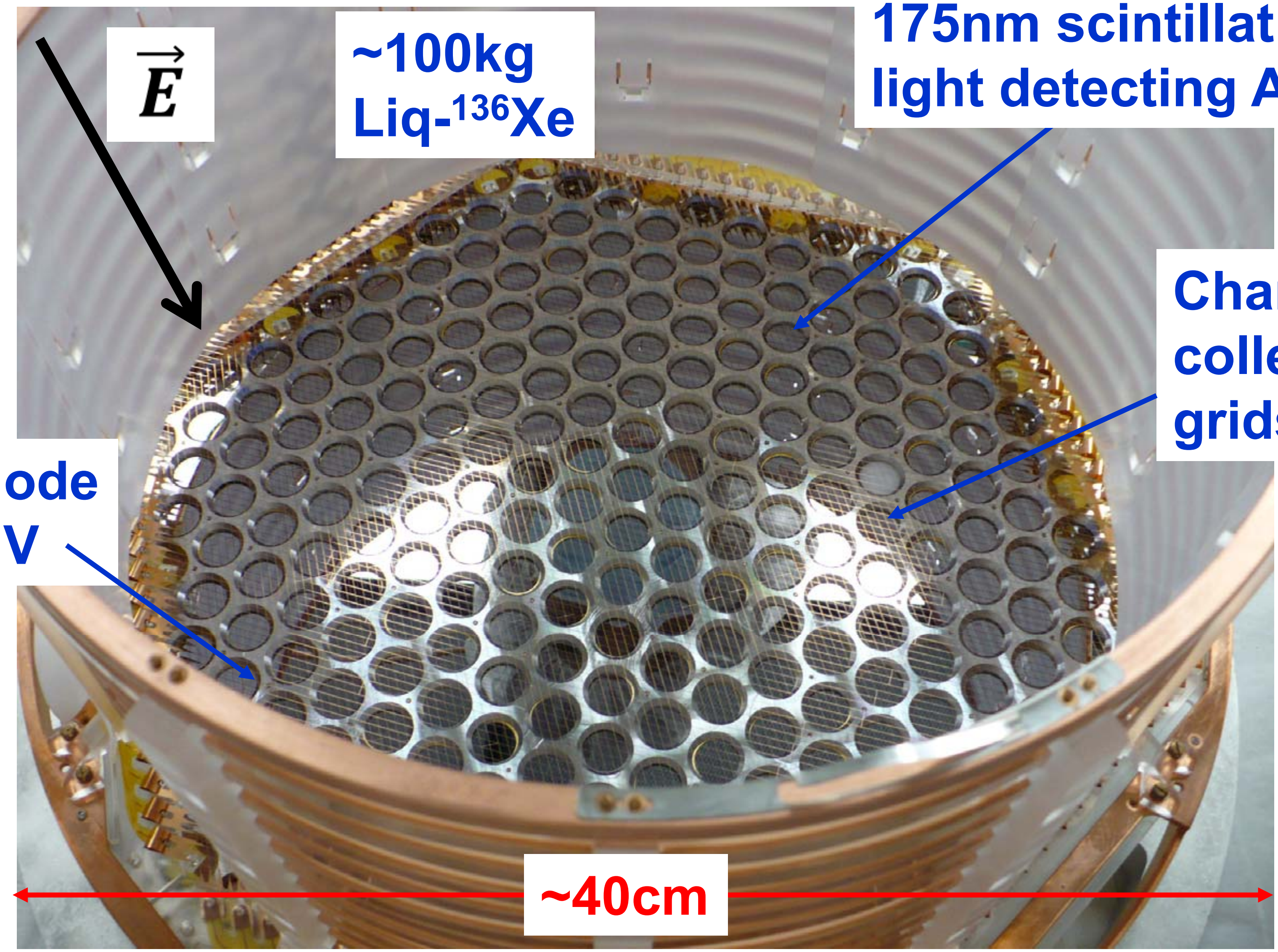
4) New techniques to discriminate signal from background

Non trivial for E~1MeV.

- *Signal ($2e^-$) more localized than most background.*
- *Good E resolution helps.*
- *Low density shows the two e^- tracks but hard for large fiducial masses.*
- *In some cases final state ID may be possible.*



Example: EXO-200, the first 100kg – class experiment Homogeneous liquid ^{136}Xe Time Projection Chamber (EXO)



$\vec{E}$

~100kg Liq-^{136}Xe

175nm scintillation light detecting APDs

Charge collection grids

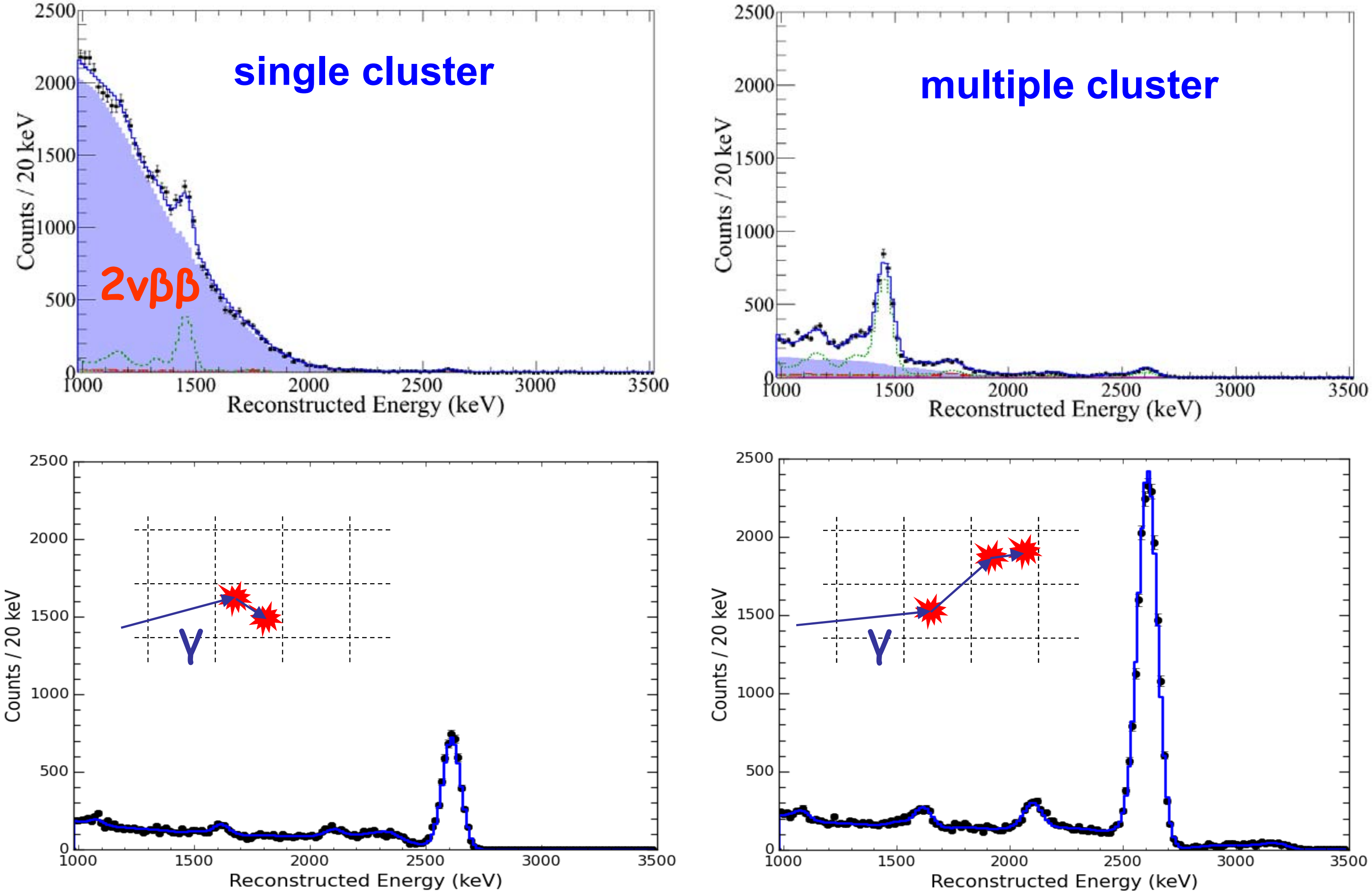
Cathode -HV

~40cm

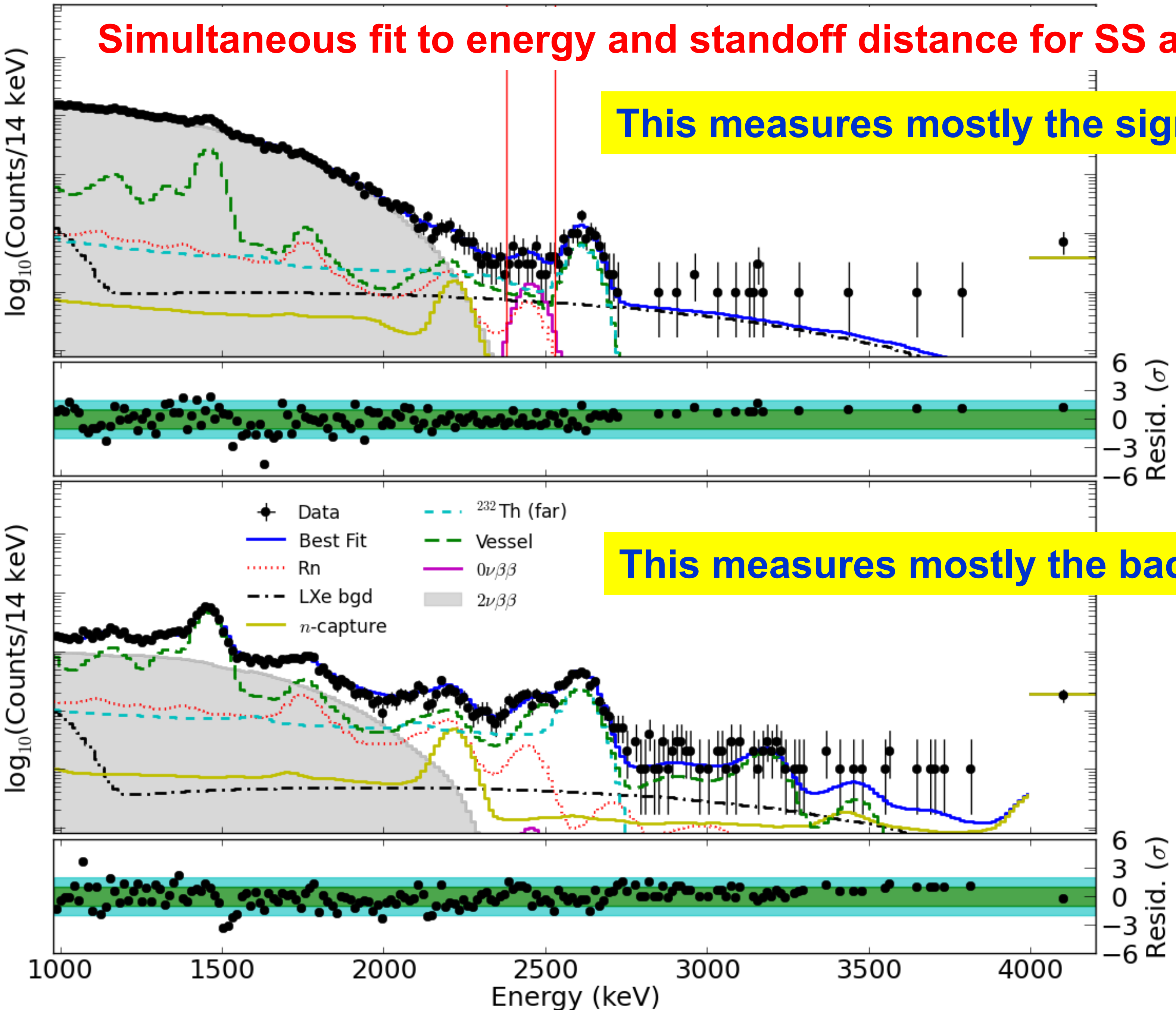
Using event multiplicity to recognize backgrounds

Low background data

^{228}Th calibration source



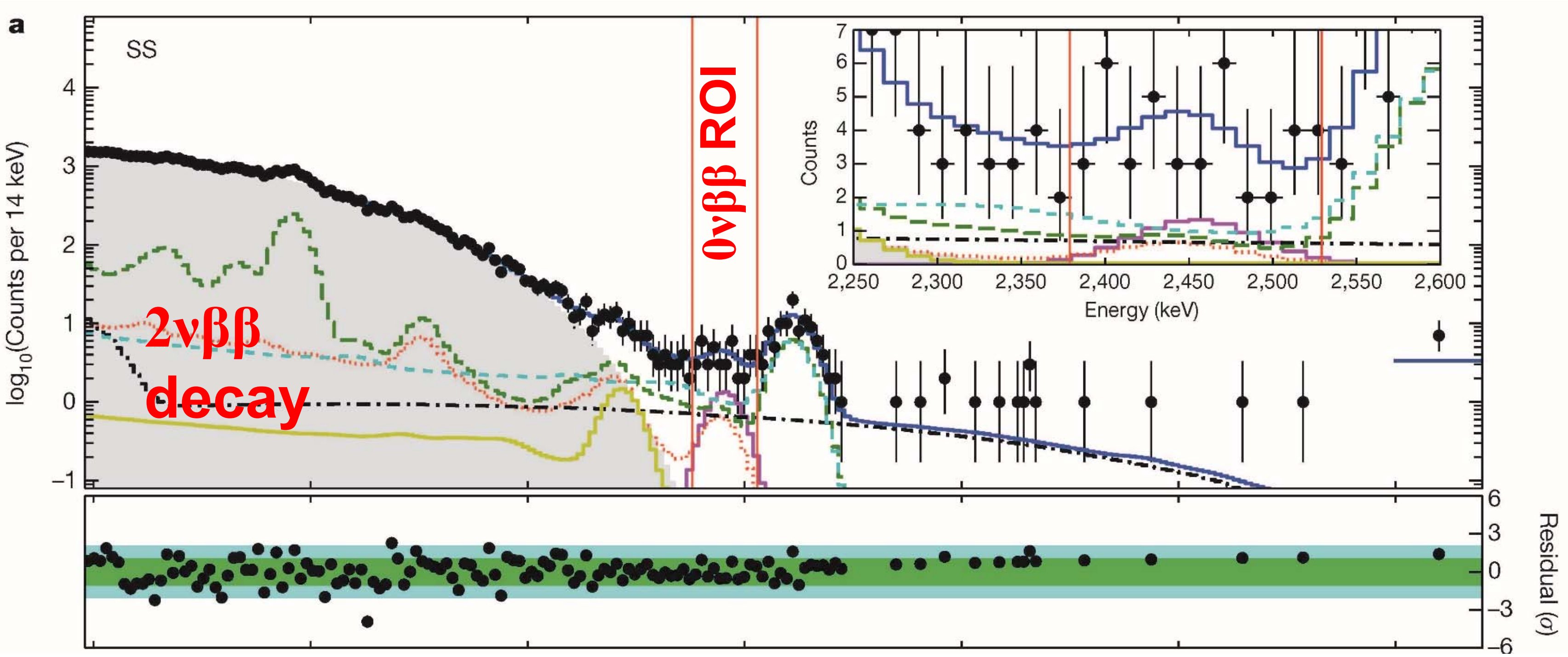
Simultaneous fit to energy and standoff distance for SS and MS



This measures mostly the signal

This measures mostly the background

Data from 76kg and 477 days (100kg·yr)

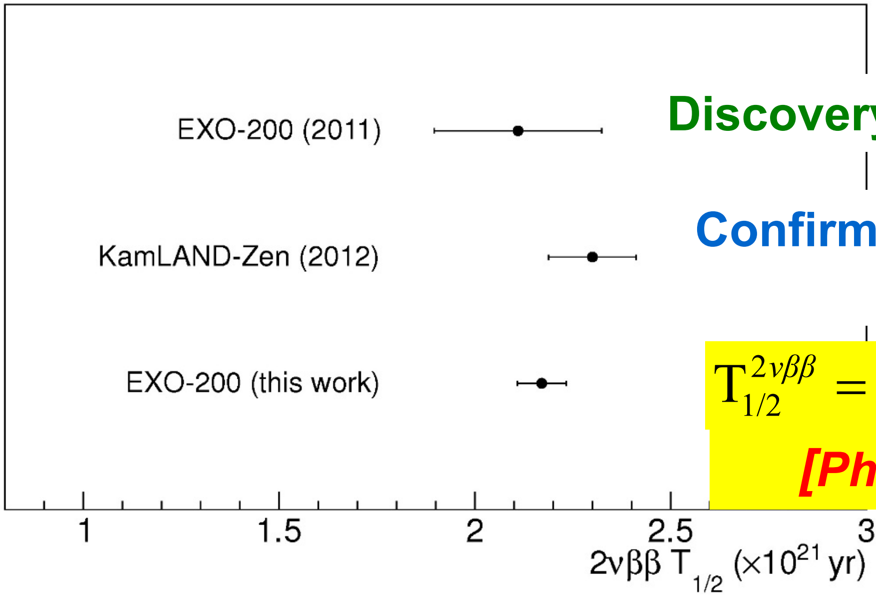


Background in the 0ν ROI: (1.7±0.2)·keV^{-1} ton^{-1} yr^{-1}

Much smaller than in Dark Matter experiments

(optimized for much lower energies)

2-neutrino half lives

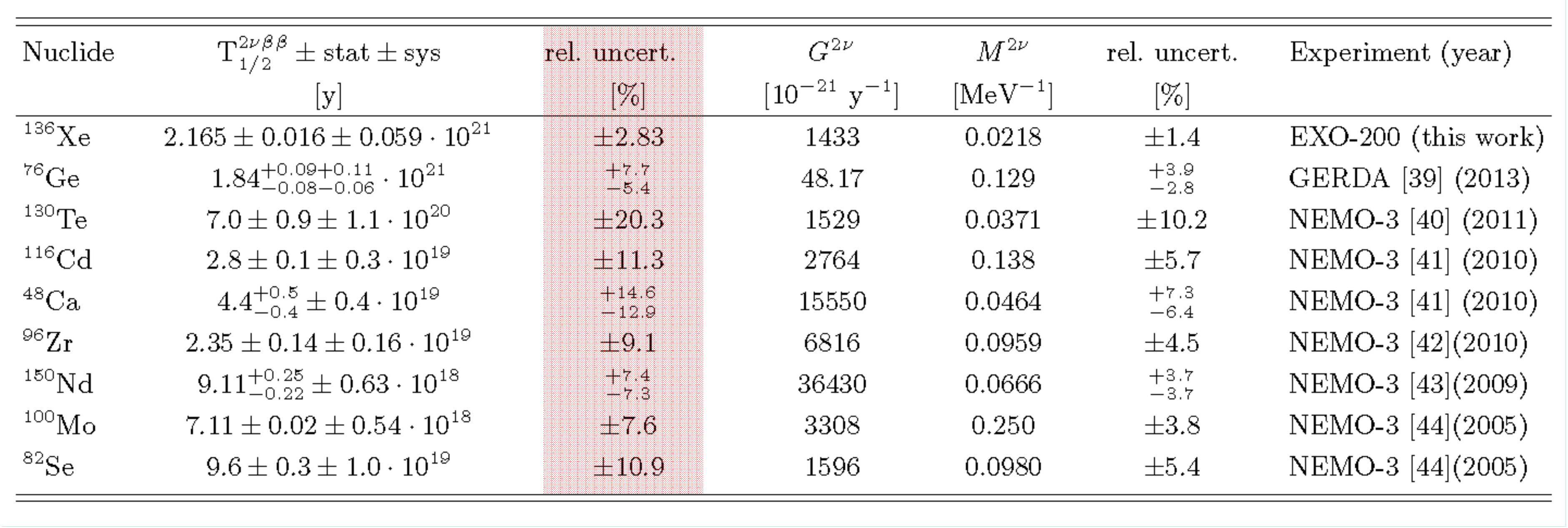


Discovery of 2v mode *[PRL 107, 212501 (2011)]*

Confirmation by KamLAND-Zen
[PRC 85, 045504 (2012)]

$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\mathrm{stat}} \pm 0.059^{\mathrm{syst}}\right) \cdot 10^{21}\ \mathrm{yr}$$

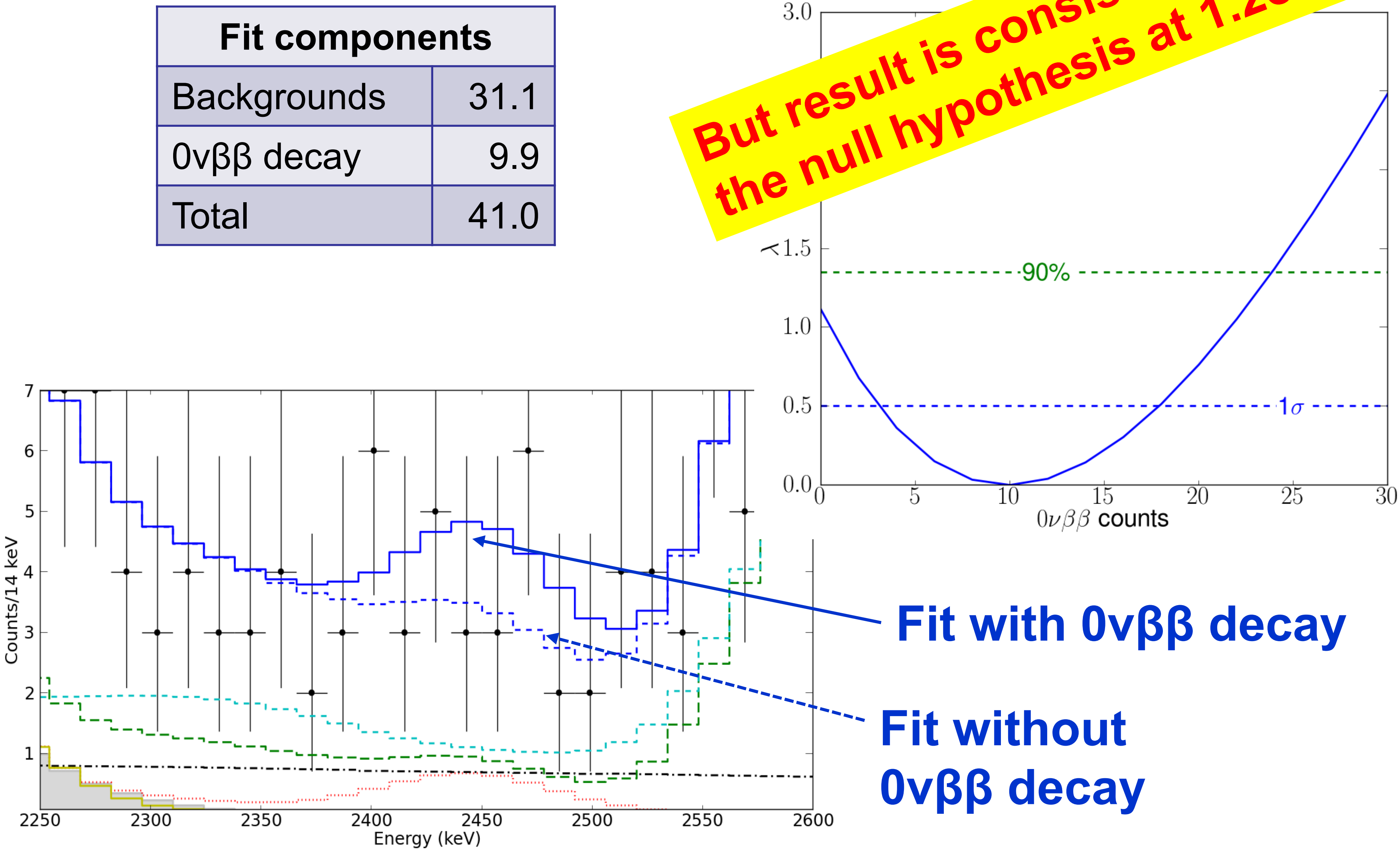
[Phys. Rev. C 89 (2014) 015502]



Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	48.17	0.129	$^{+3.9}_{-2.8}$	GERDA [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0464	$^{+7.3}_{-6.4}$	NEMO-3 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42](2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	$^{+7.4}_{-7.3}$	36430	0.0666	$^{+3.7}_{-3.7}$	NEMO-3 [43](2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44](2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44](2005)

0νββ decay and background fit:

Fit components	
Backgrounds	31.1
0νββ decay	9.9
Total	41.0



But result is consistent with the null hypothesis at 1.2σ level

Fit with 0νββ decay

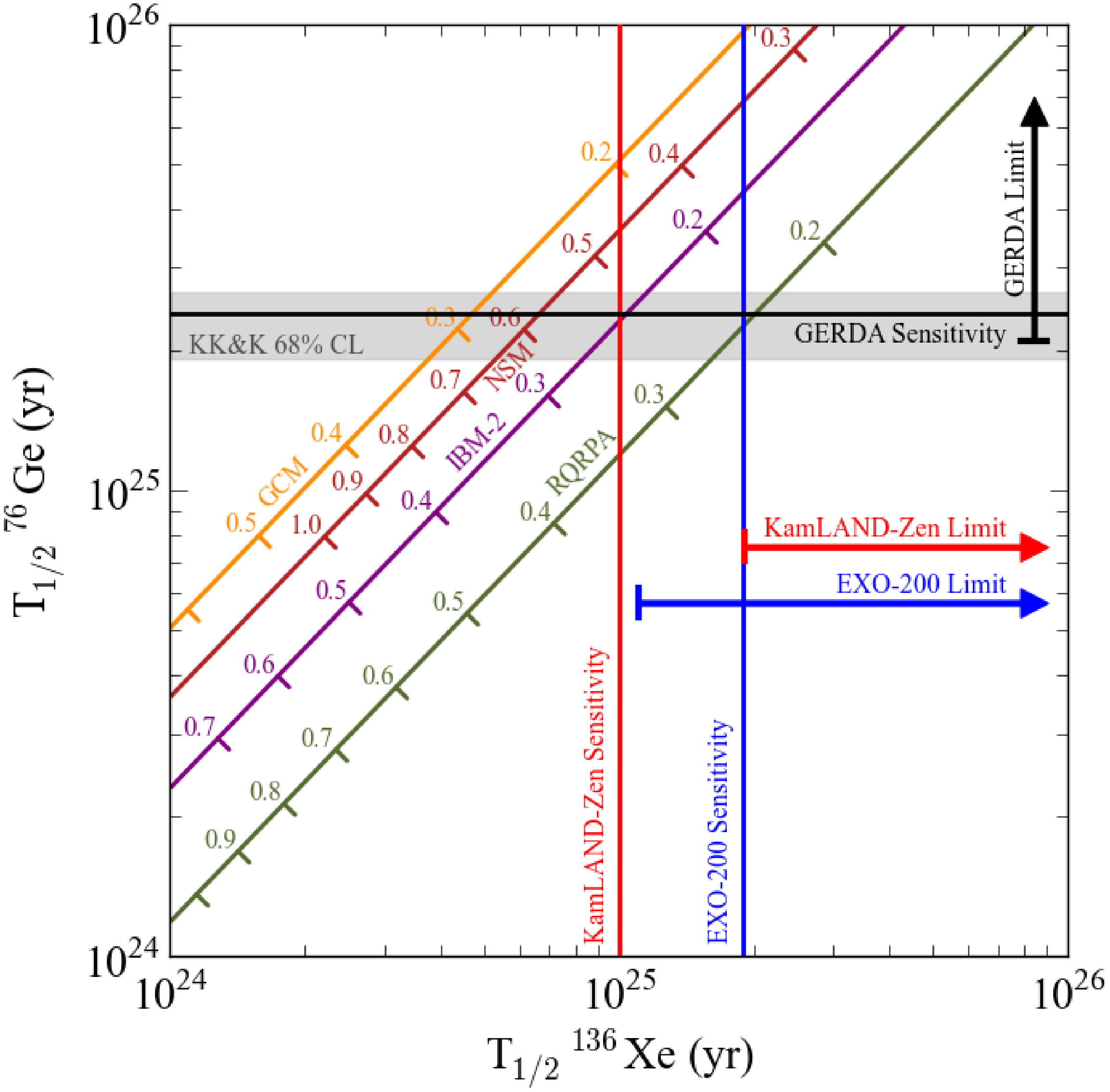
Fit without 0νββ decay

Recent results (>10^{25} yr half life)

Isotope	Experiment	Exposure (kg yr)	$T_{1/2}^{0\nu\beta\beta}$ average sensitivity (10^{25}yr)	$T_{1/2}^{0\nu\beta\beta}$ (10^{25}yr) 90%CL	$T_{1/2}^{0\nu\beta\beta}$ (13.8Gyr) 90%CL	$< m_\nu >$ (meV) Range from NME*	Reference
^{76}Ge	Gerda	21.6	2.4	>2.1	>1.5×10^{15}	200-400	Agostini et al., PRL 111 (2013) 122503
^{136}Xe	EXO-200	100	1.9	>1.1	>8.0×10^{14}	190-450	Albert et al. Nature 510 (2014) 229
	KamLAND-ZEN	89.5	1.0	>1.9	>1.4×10^{15}	120-250	Gando et al., PRL 110 (2013) 062502

* Note that the range of “viable” NME is chosen by the experiments

A useful way to compare results (assuming the standard mechanism)



The next step: ***ton-scale detectors entirely covering the inverted hierarchy***

Testing lepton number violation with 100x the current sensitivity

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

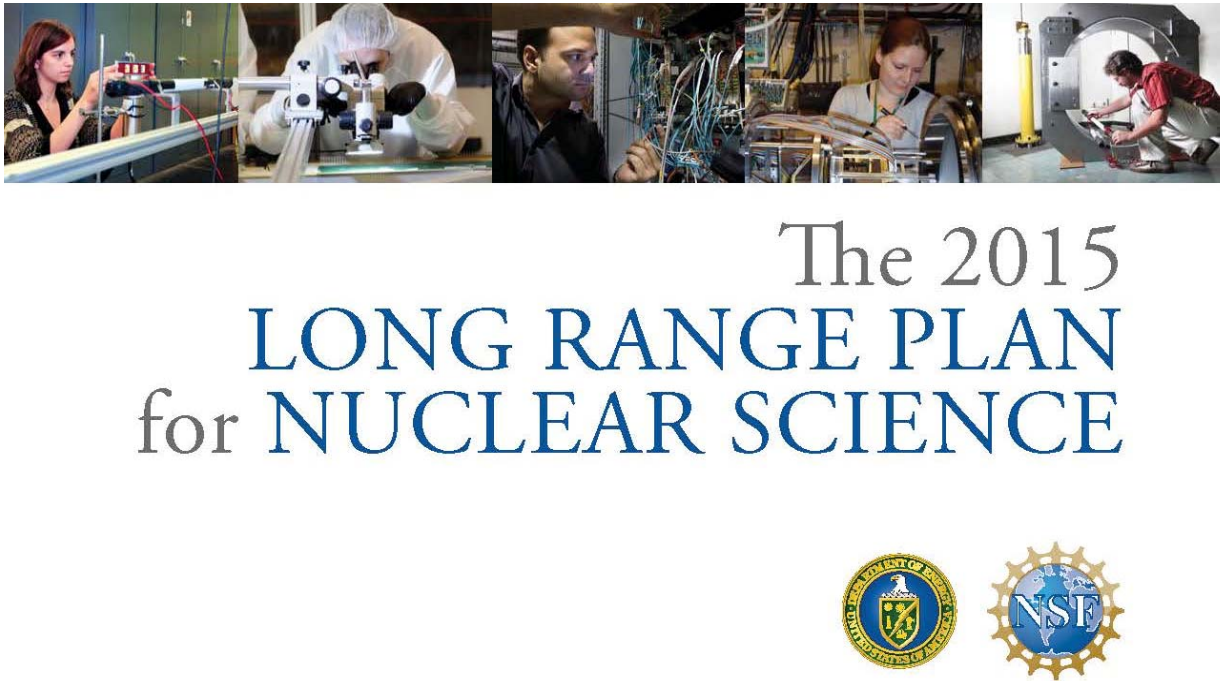
"RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

Initiative B

"We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC."



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

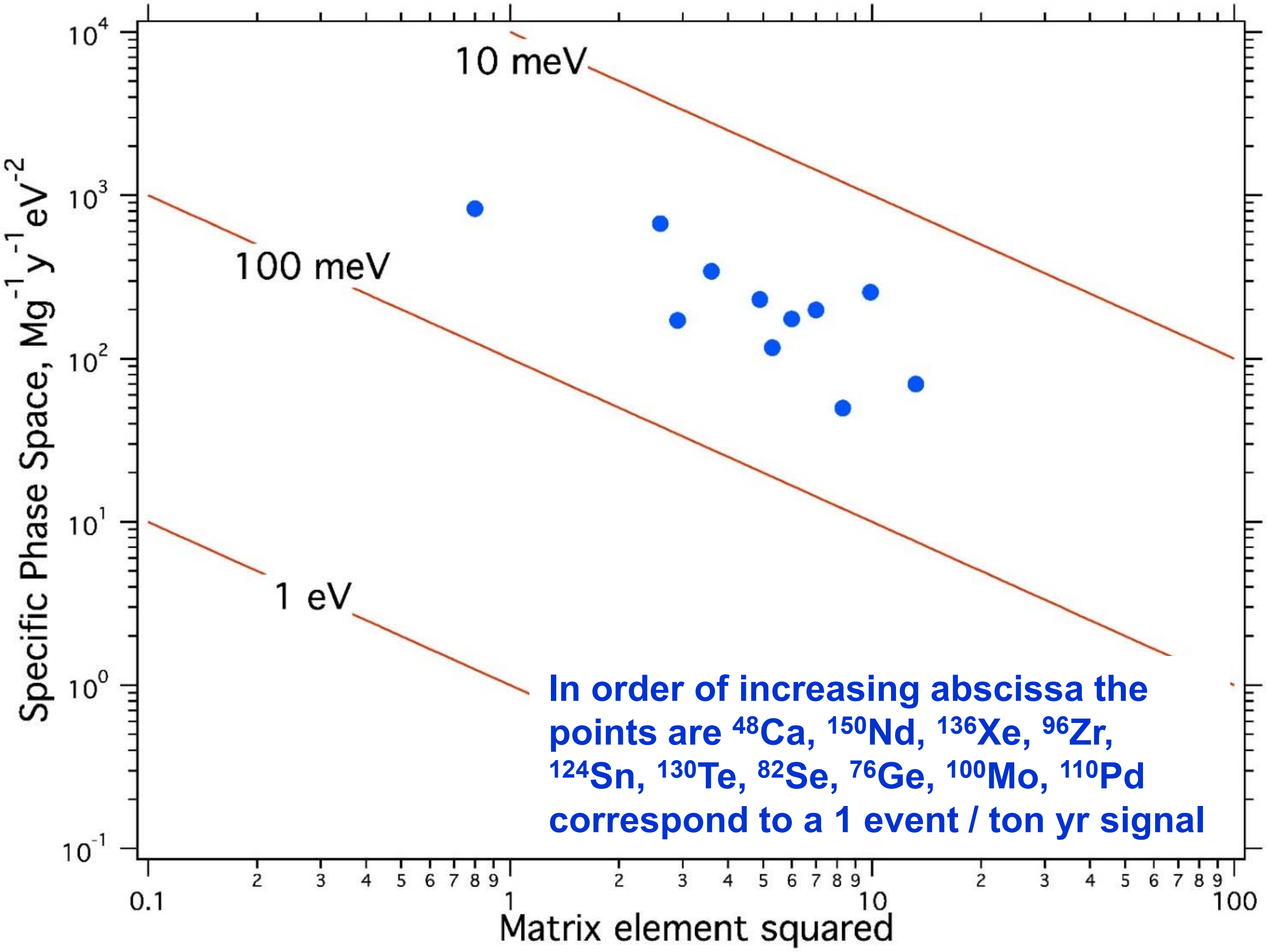
…further down:

“…It is foreseen that the U.S. would mount and lead at least one ton-scale experiment…”

…and…

“…A large community of U.S. nuclear physicists will coalesce around the challenge of reaching that goal with whichever experimental approaches emerge from the down-selection process within the next 2–3 years….”

Many isotopes have comparable sensitivities (at least in terms of rate per unit neutrino mass)



In order of increasing abscissa the points are ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo, ^{110}Pd correspond to a 1 event / ton yr signal

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

There is an “empirical” anticorrelation between phasespace and NME.

A healthy neutrinoless double-beta decay program requires more than one isotope.

This is because:

- ***There could be unknown gamma transitions and a line observed at the "end point" in one isotope does not necessarily imply the 0vββ decay discovery***
- ***Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities***
- ***Different isotopes correspond to vastly different experimental techniques***
- ***2 neutrino background is different for various isotopes***
- ***The elucidation of the mechanism producing the decay requires the analysis of more than one isotope***

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One (my own) possible classification of technologies

Low density trackers

- NEXT (^{136}Xe gas TPC)
- SuperNEMO (foils and gas tracking, ^{82}Se)

Pros: Superb topological information
Cons: Very large size

Liquid (organic) scintillators

- KamLAND-ZEN (^{136}Xe)
- SNO+ (^{130}Te)

Pros: “simple”, large detectors exist
Cons: Not very specific, hard to claim discovery

Crystals

- GERDA, Majorana (^{76}Ge)
- CUORE, CUPID (^{130}Te)

Pros: Superb energy resolution, possibly 2-parameter measurement
Cons: Intrinsically fragmented

Liquid TPC

- nEXO (^{136}Xe)

Pros: Homogeneous with good E resolution and topology
Cons: Does not excel in any single parameter

Interesting count rates are very small

$T_{1/2}$ (yr)	Signal (cnts ton^{-1} yr^{-1})
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1

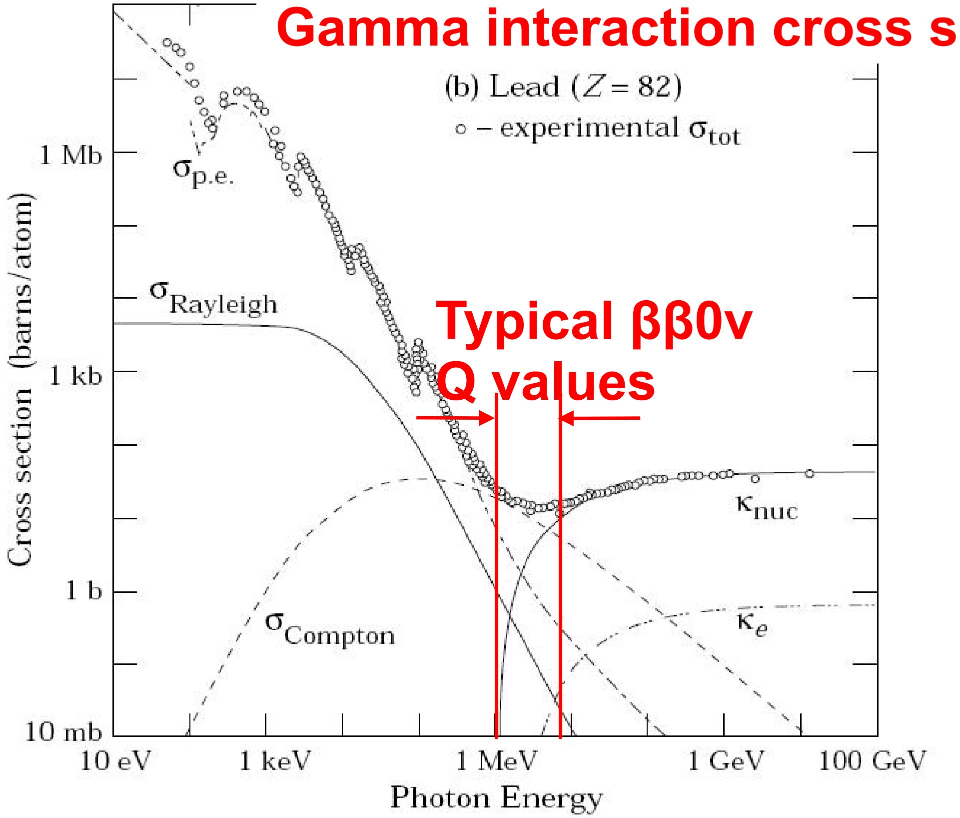
$$T_{1/2}^{0\nu} \propto effic. \times isotope\ abundance \times source\ mass \times time$$

Background-free case

$$T_{1/2}^{0\nu} \propto effic. \times isotope\ abundance \times \sqrt{\frac{source\ mass \times time}{bkgd}}$$

Background-limited case

Shielding a detector from gammas is difficult because the absorption cross section is small.



Gamma interaction cross section

Typical ββ0v Q values

Example:

γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding ββ decay detectors is much harder than shielding Dark Matter ones

We are entering the "golden era" of ββ decay experiments as detector sizes exceed int lengths

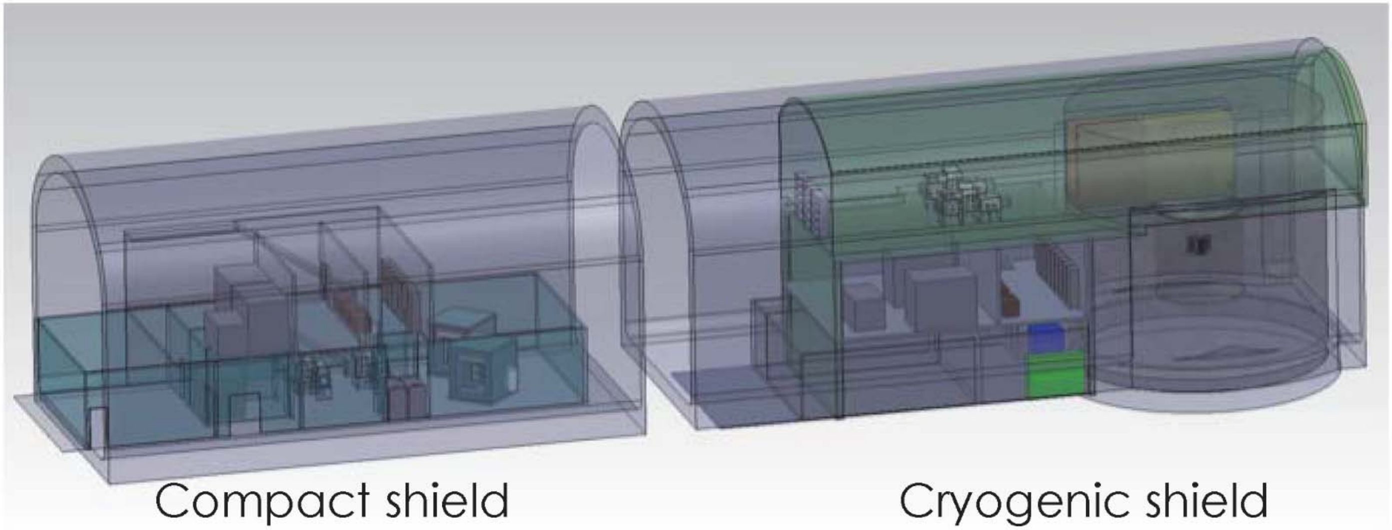
^{76}Ge

- MAJORANA and GERDA are working towards the establishment of a single international ^{76}Ge $0\nu\beta\beta$ collaboration. (Name not set: Ge1T, LSGe, …)
- Envision a phased, stepwise implementation;

  e.g. 250 → 500 → 1000 kg

  5 yr 90% CL sensitivity: $T_{1/2} > 3.2 \cdot 10^{27}$ yr

  10 yr 3σ discovery: $T_{1/2} \sim 3 \cdot 10^{27}$ yr
- 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



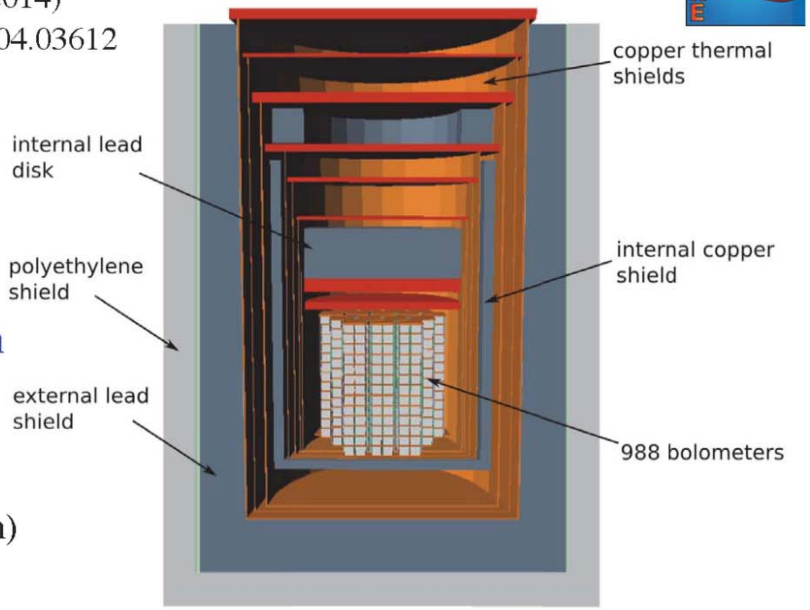
J.Wilkerson, NSAC long range planning presentation, Apr 2015

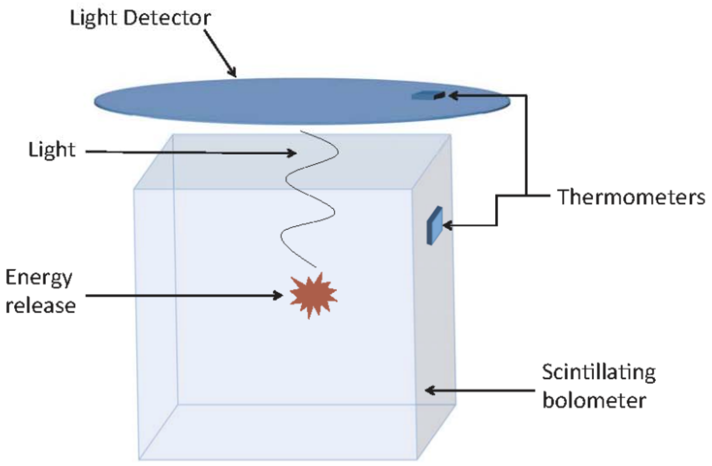
CUPID ^{130}Te (or ^{82}Se, ^{100}Mo)

Scintillator - Phonons

R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
White papers: arXiv:1504.03599 & arXiv:1504.03612

- Next-generation bolometric tonne-scale experiment with particle ID.
- Based on the CUORE design, CUORE cryogenics
  - ☞ Largest cryostat and DU built; mature technology
- 988 enriched (90%) crystals, PID with light detection
  - ❑ 4 crystals considered:
    - ☞ TeO_2 : phonons + Cherenkov detector
    - ☞ Options: ZnSe, $ZnMoO_4$, $CdWO_4$ (phonons+scintillation)
- Aim for zero-background measurement
- Sensitivity to entire IH region
  - ☞ CUORE geometry and background model
  - ☞ 99.9% α rejection @ >90% signal efficiency (5σ separation of α and β)
  - ☞ 5 keV FWHM resolution
  - ☞ Challenge: nearly zero background measurement: background goal <0.02 events / (ton-year)
  - ☞ Half-life sensitivity (2-5)×10^{27} years in 10 years (3σ)
  - ☞ $m_{\beta\beta}$ sensitivity 6-20 meV (3σ)

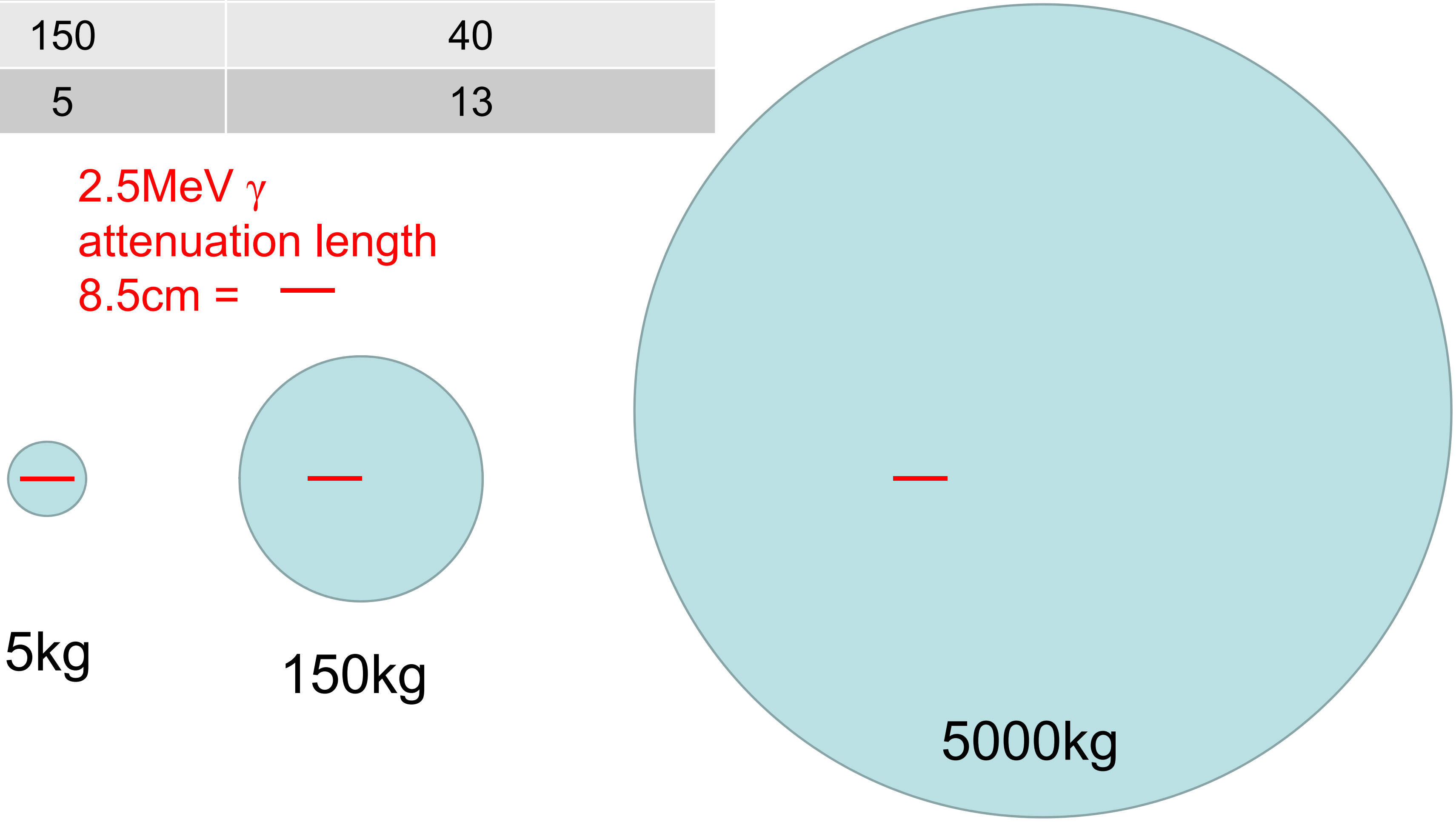




J.Wilkerson, NSAC long range planning presentation, Apr 2015

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

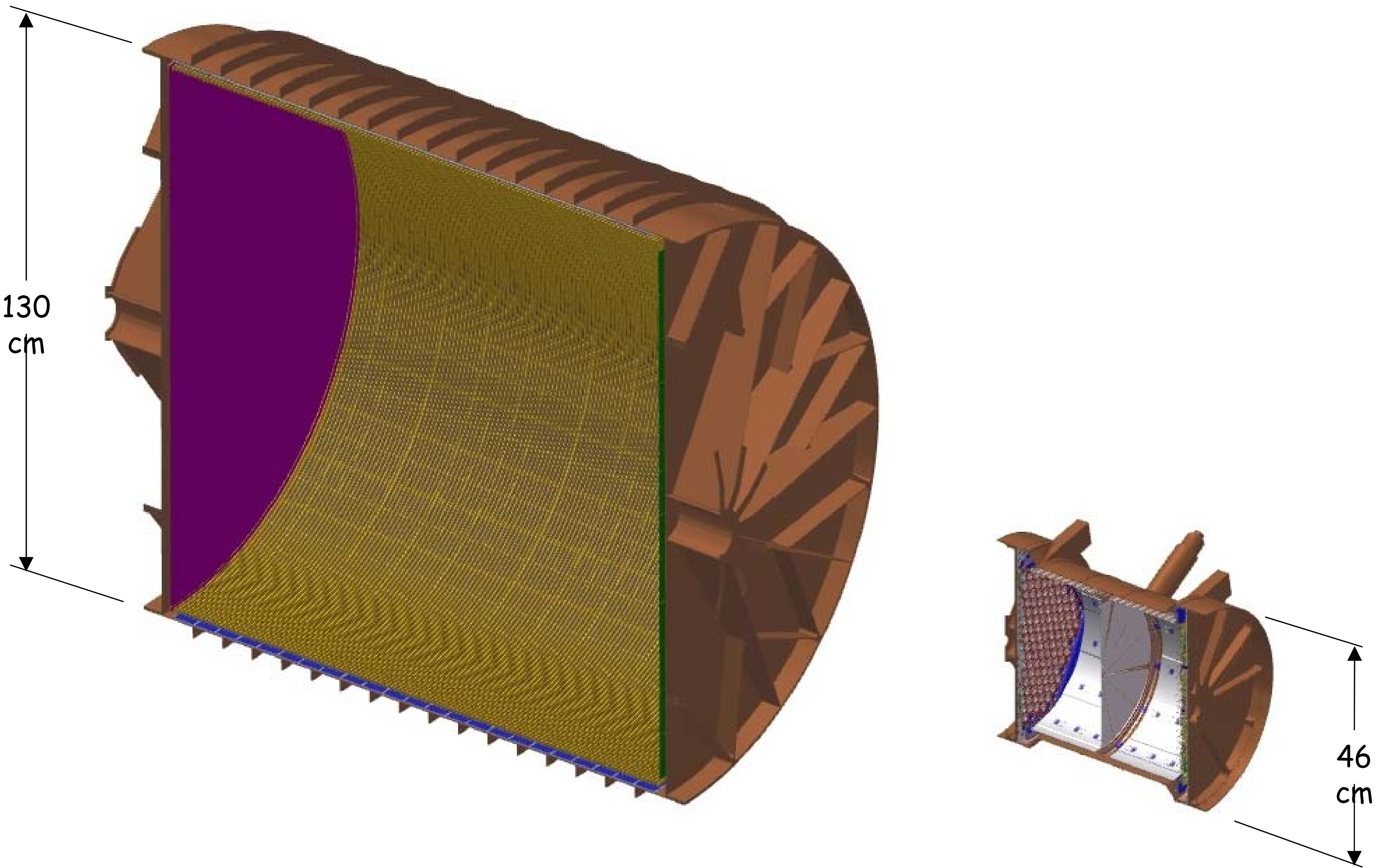
2.5MeV γ
attenuation length
8.5cm = —



This works best for a monolithic detector

From EXO-200 to nEXO

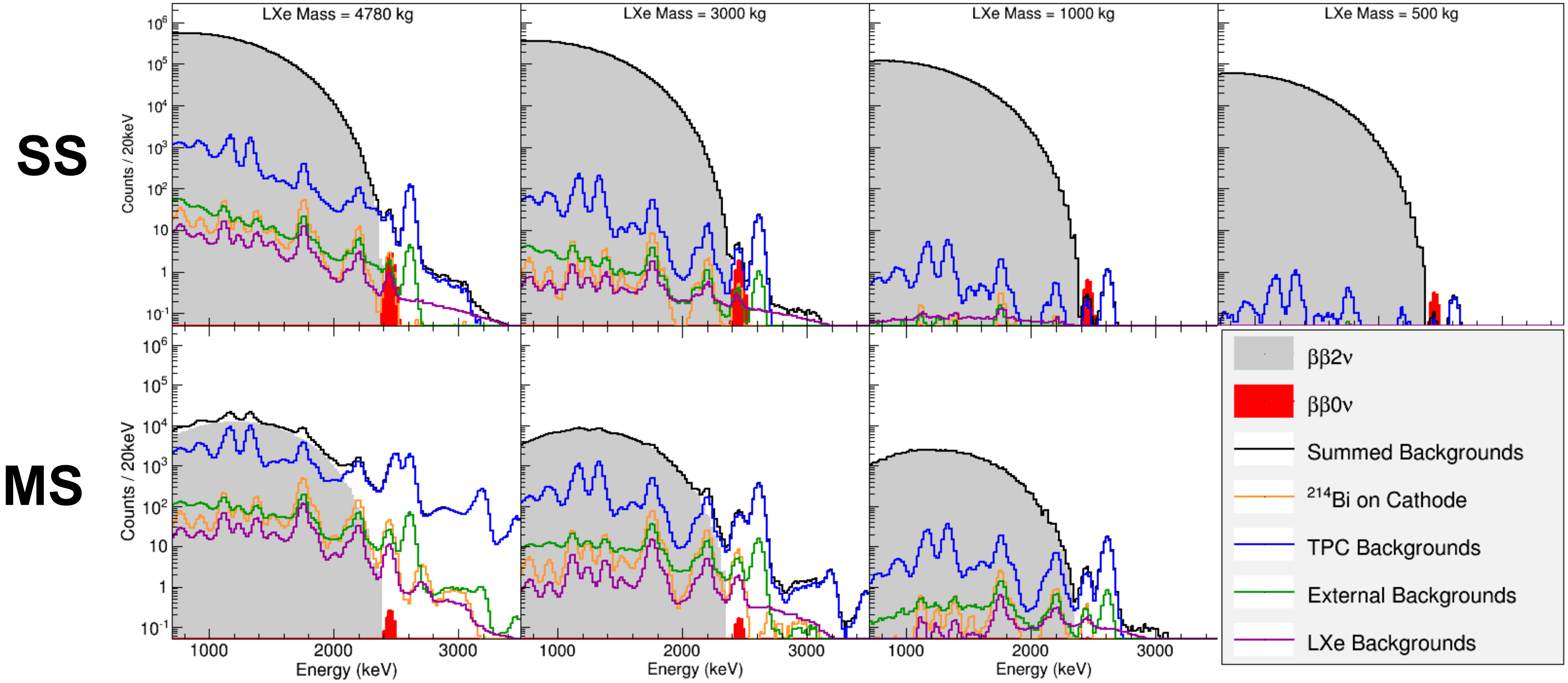
A 5000 kg enriched Lxe TPC,
directly extrapolated from the **EXO-200**



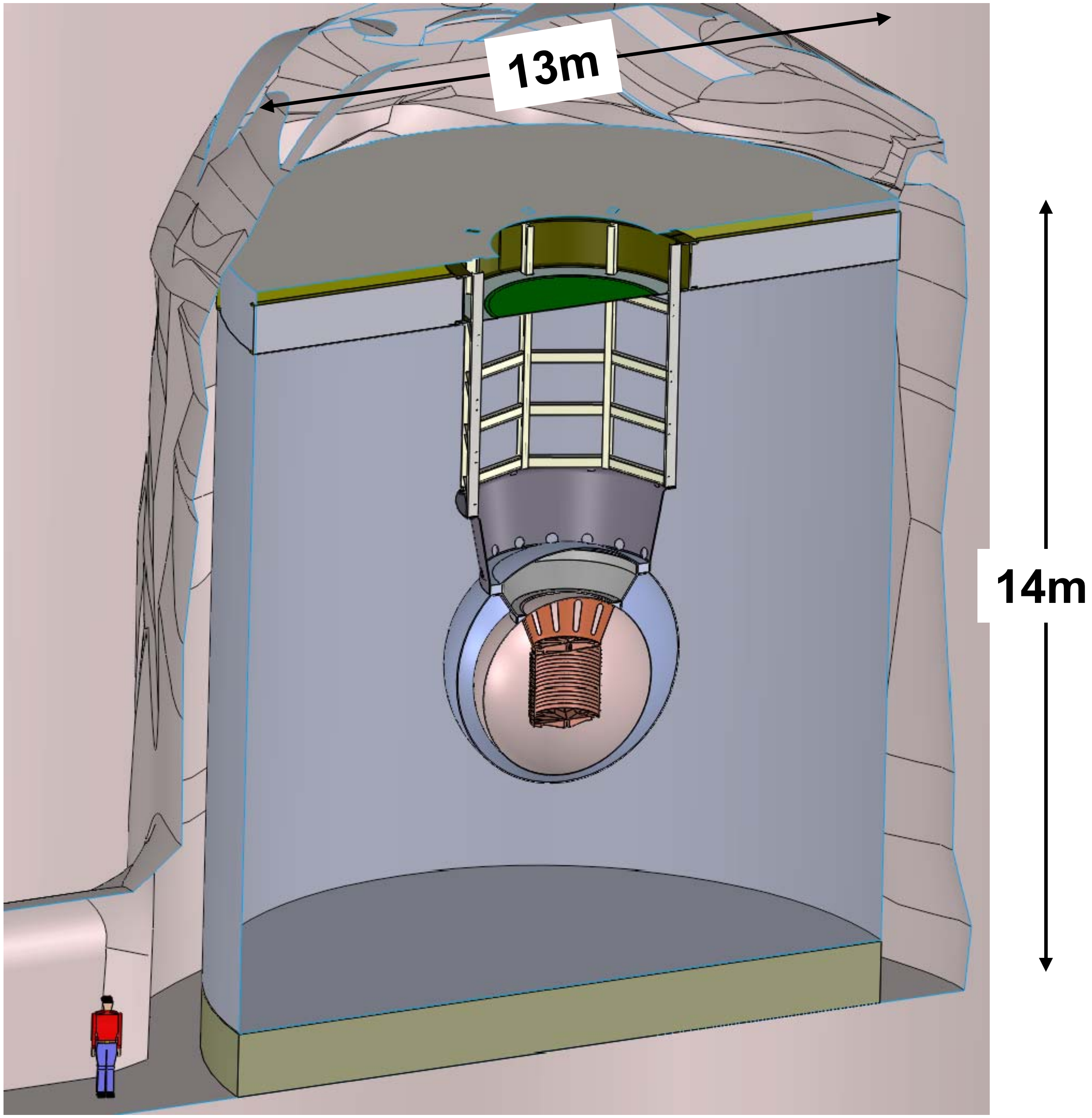
Particularly in the larger nEXO background identification and rejection fully use a fit that considers simultaneously energy, multiplicity and event position.

➔ *The power of the homogeneous detector,*
this is not just a calorimetric measureent!

5 yr data, 0νββ corresponding to $T^{1/2}=6.6\times10^{27}$ yr

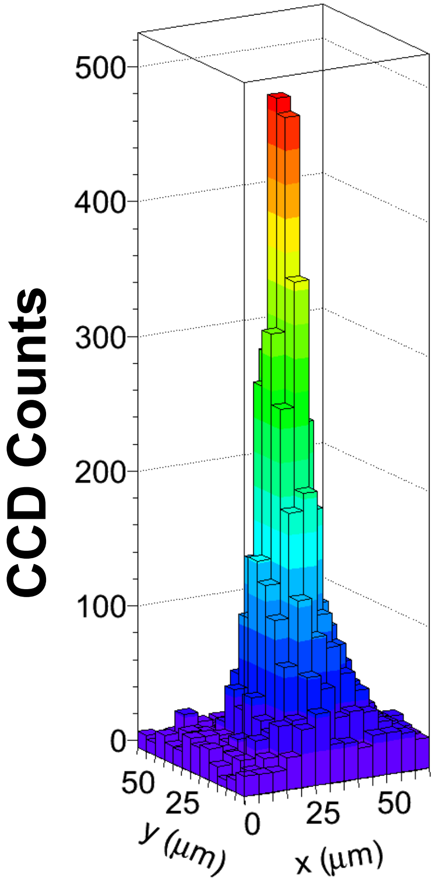


Preliminary artist view of nEXO in the SNOlab Cryopit

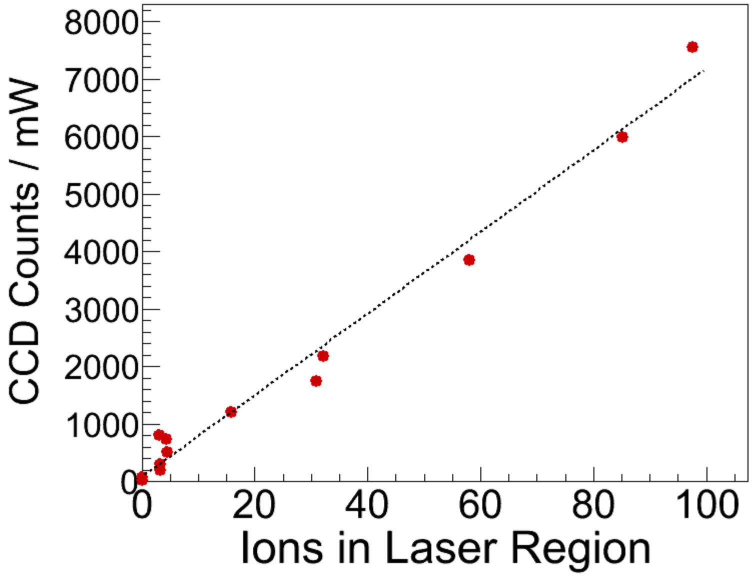


In a second phase nEXO may also be able to detect the Ba atom produced in the ββ decay of ^{136}Xe (this is not the baseline design but object of a long term R&D program). ➔ Unique among double-beta decay experiments'

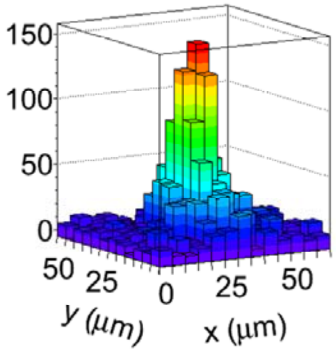
≤ 58 Ba atoms



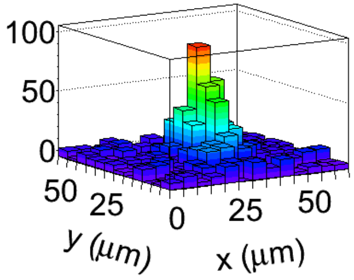
Spectroscopic detection of a few Ba atoms in a solid Xe matrix on a sapphire plate (like the end of an optical fiber)



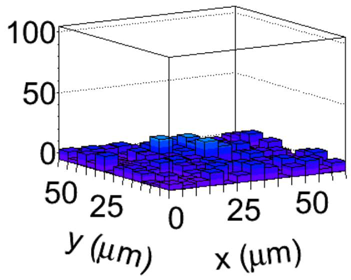
≤ 15 Ba atoms



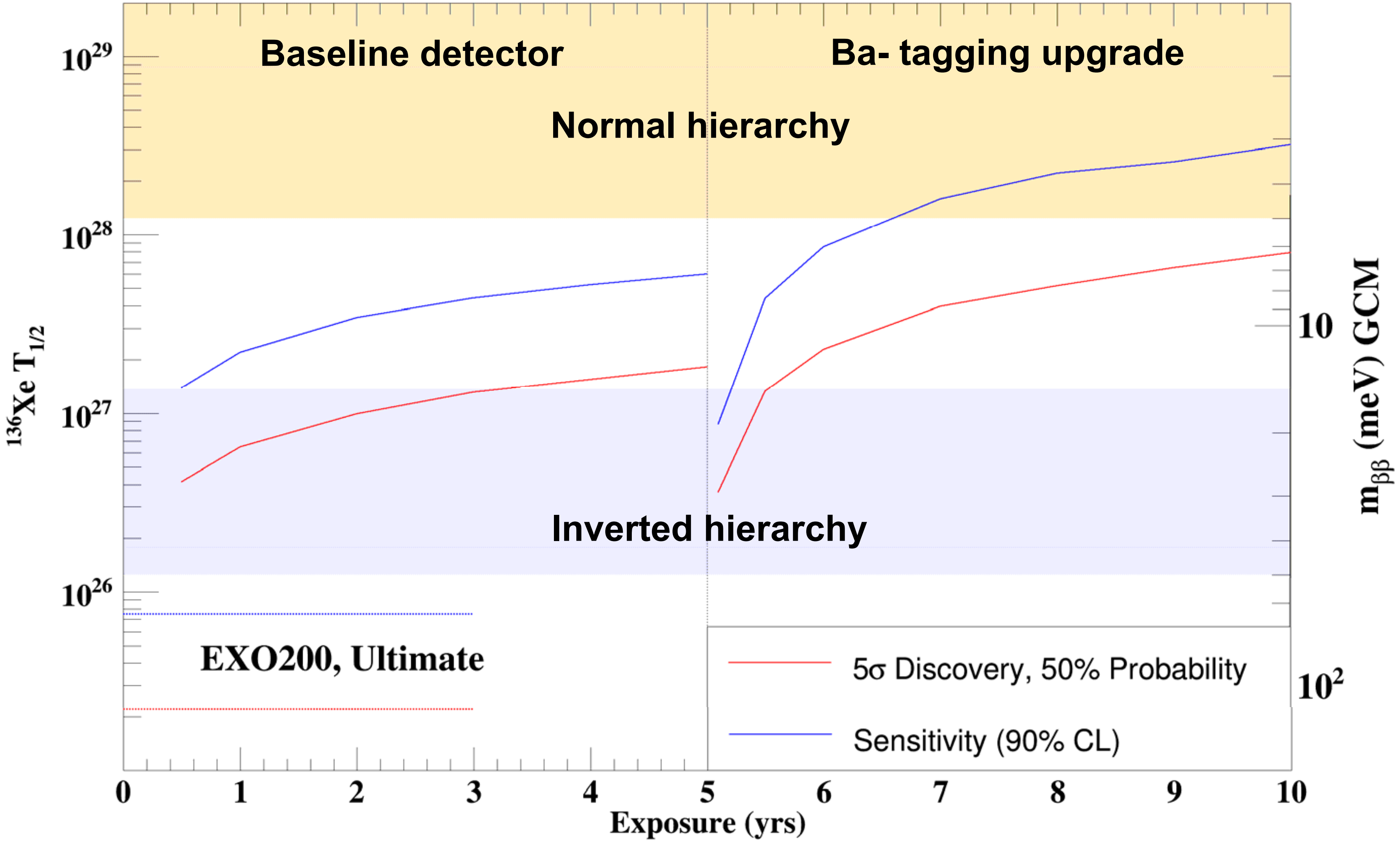
≤ 4 Ba atoms



0 Ba atoms



Sensitivity and discovery potential as a function of time



Conclusions

- 0νββ searches are discovery physics,
  with connections to many areas of modern physics
- Results from 100 kg yr searches are here!
- No discovery yet, with sensitivities ~10^{25} yr
- Looking at more than one isotope is important
- At least for some techniques we are ready to build
  ton-scale experiments with negligible background
- (in the US) the (NP) community has selected this
  effort as the top priority for the next large project
- The 10meV region is within reach!