Double Beta Decay: *a brief summary*

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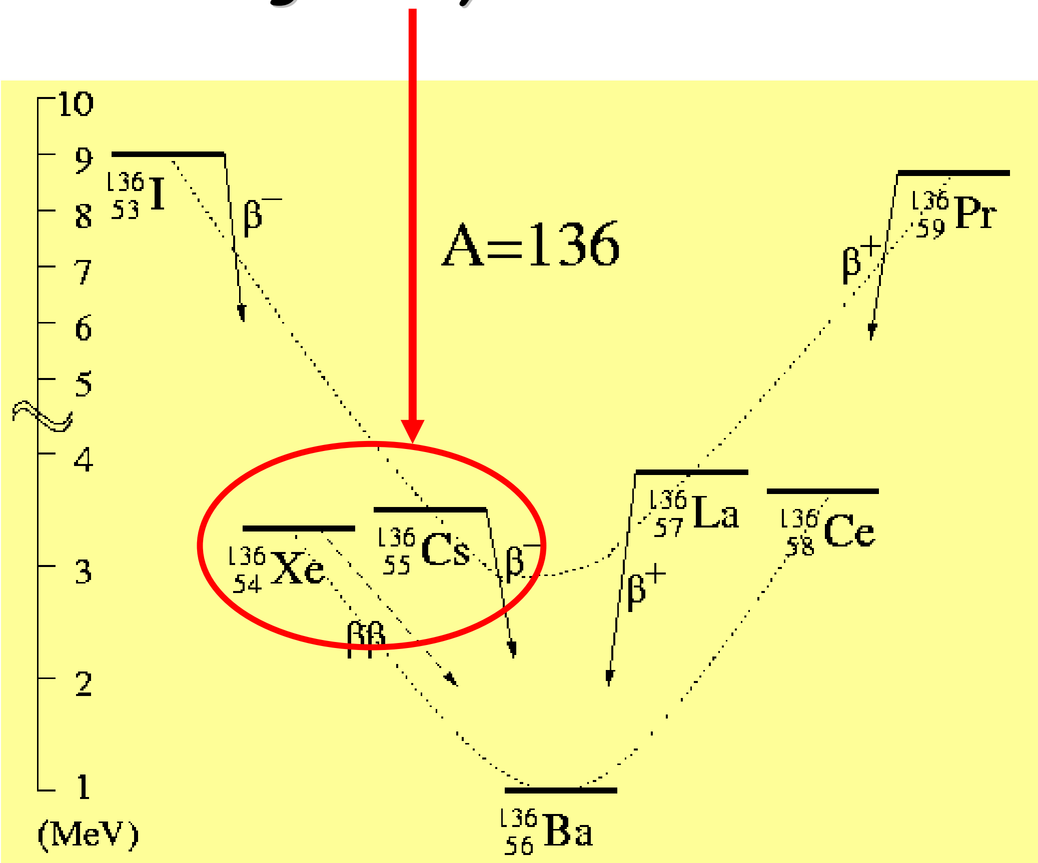
Double-beta decay:

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



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	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

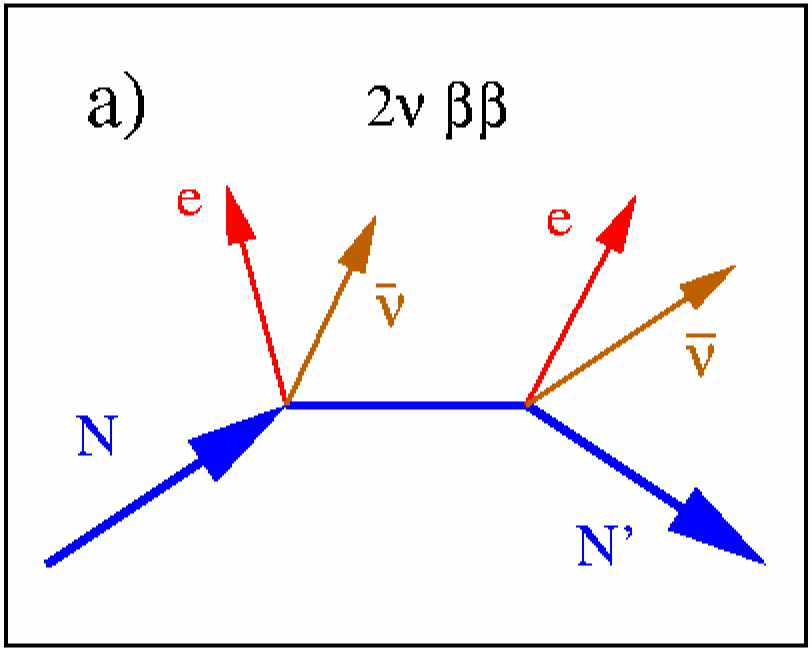
There are two varieties of ββ decay

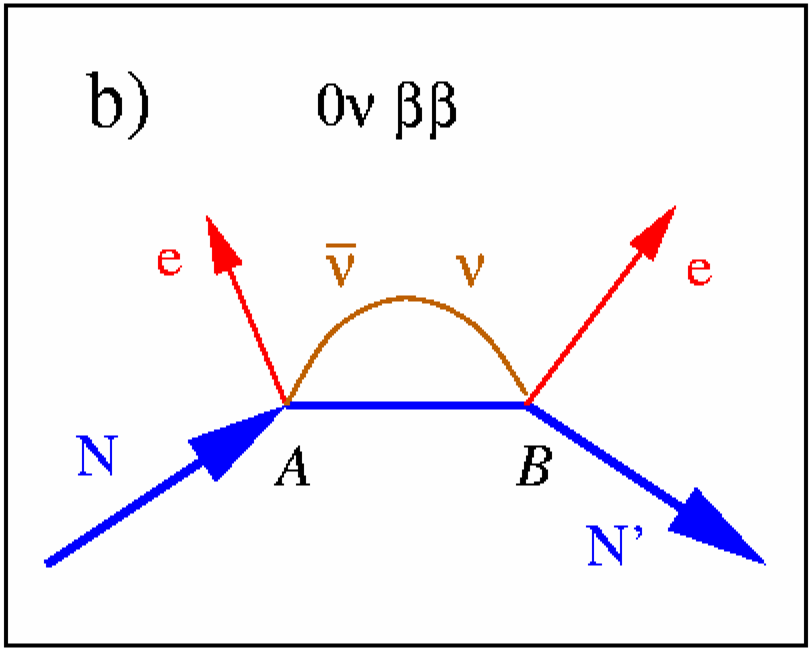
2ν mode:
a conventional
2nd order process
in nuclear physics

0ν mode: a hypothetical process can happen only if: $M_\nu \neq 0$, $\nu = \bar{\nu}$ (Since helicity has to "flip")

$|\Delta L| = 2$

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





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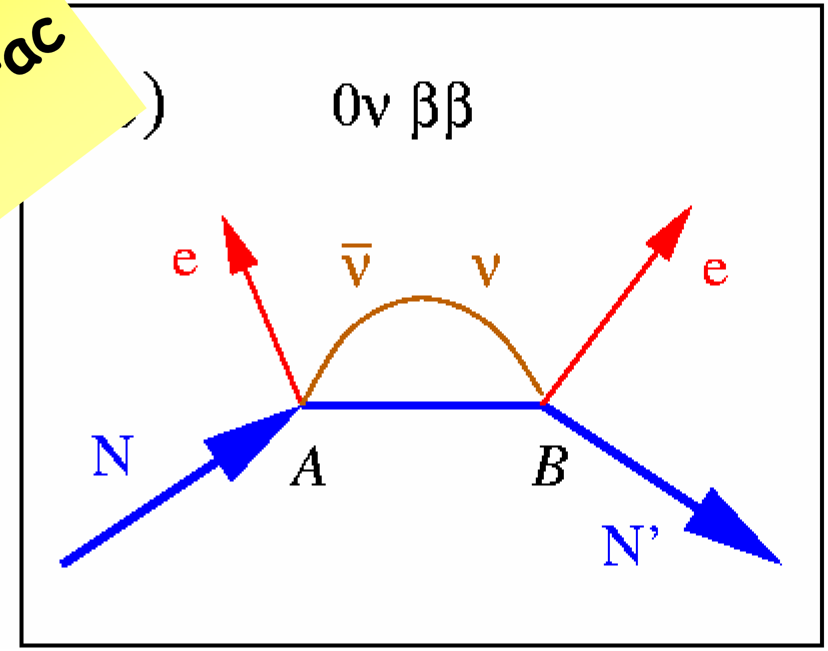
0νββ is the most sensitive probe of the Majorana/Dirac nature of neutrinos



In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
→ Think big: qualitative transition from cottage industry to large experiments

2) From "random shooting" to the knowledge that at least the inverted hierarchy will be tested

Discovering $0\nu\beta\beta$ decay:

→ Discovery of the neutrino mass scale
→ Discovery of Majorana particles
→ Discovery of lepton number violation

The ultimate frontier in Neutrino Physics

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \, G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

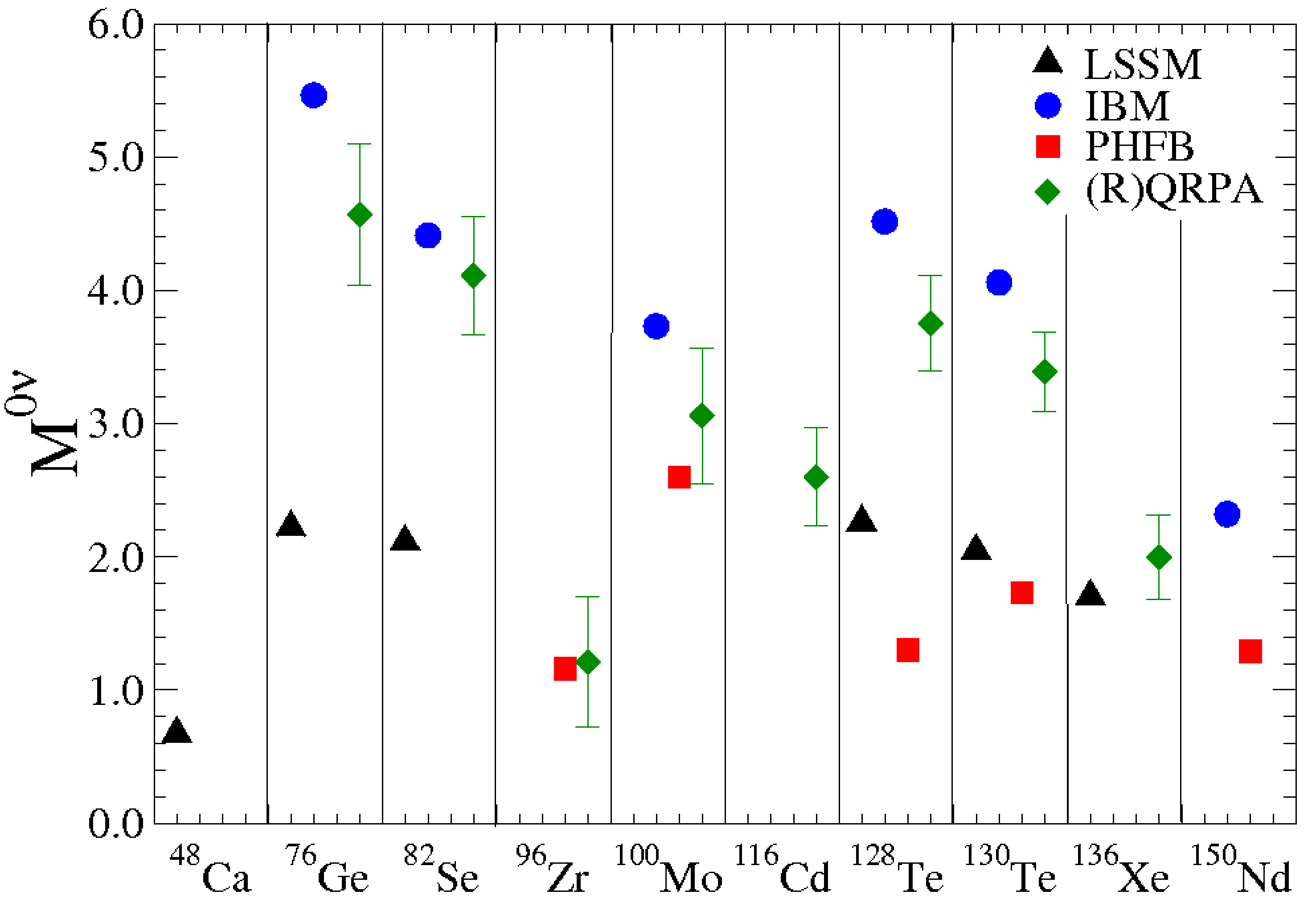
$G^{0\nu\beta\beta}$ a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \, \varepsilon_i$$

effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Lots of activity in the field of nuclear theory spurred by the experimental work



F. Simkovic, Neutrino 2010

But note that the knowledge of the nuclear matrix elements

is *not* required

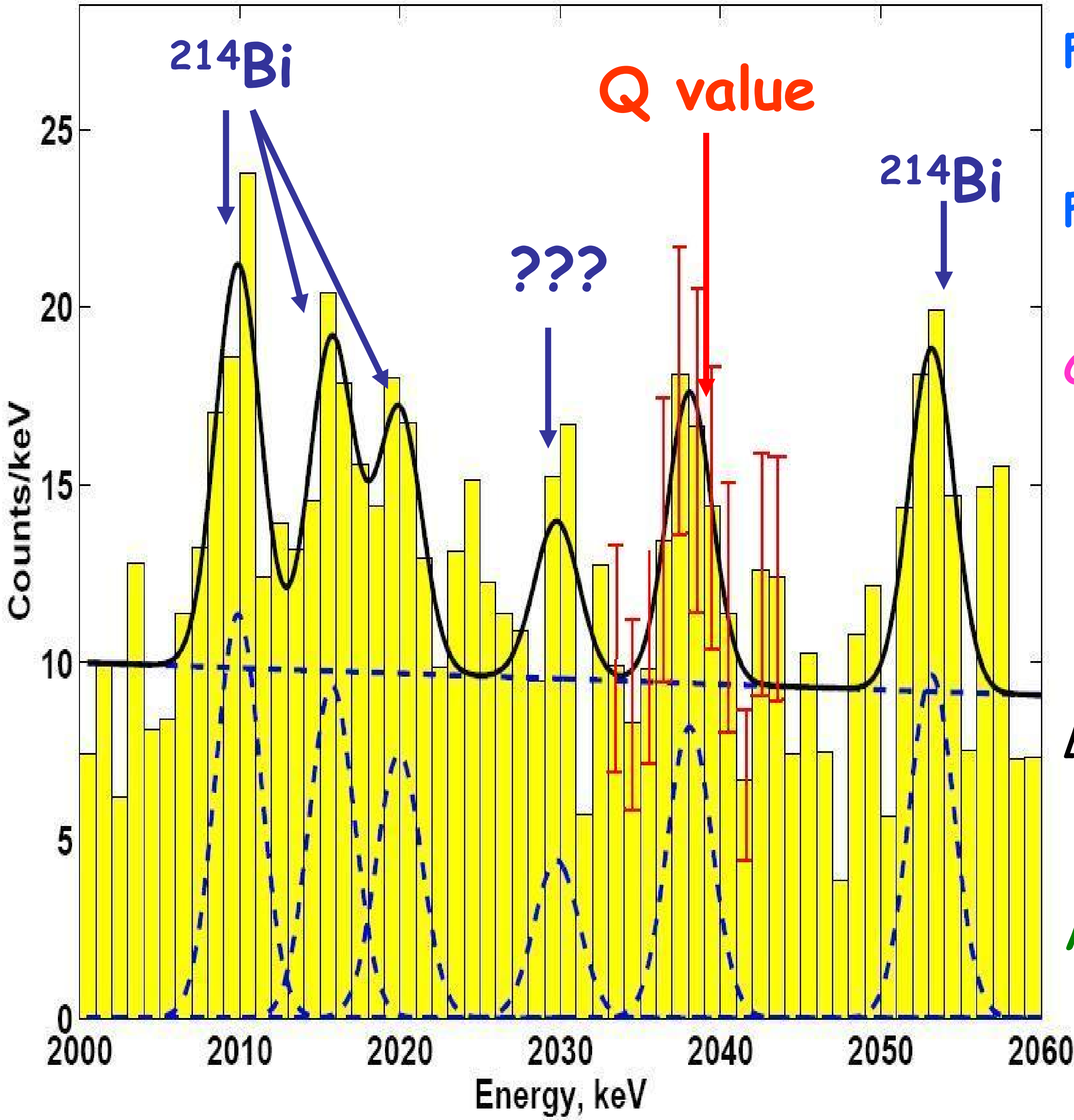
to discover

- Majorana particles and
- lepton number violation!

Simplified List of Limits for $\beta\beta0\nu$ decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>1.4*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	~47.7	$>1.9*10^{25}$ (90%CL)	<0.35
^{82}Se			$>2.1*10^{23}$ (90%CL)	
^{100}Mo			$>5.8*10^{23}$ (90%CL)	
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te	TeO_2 cryo		$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	$>3*10^{24}$ (90%CL)	<0.19 – 0.68
^{136}Xe	Xe scint	~4.5	$>1.2*10^{24}$ (90%CL)	<1.1 - 2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

$\beta\beta0\nu$ discovery claim



Fit model:
6 gaussians + linear bknd.

Fitted excess @ $Q_{\beta\beta}$
28.75 ± 6.86.

Claimed significance: 4.2 σ

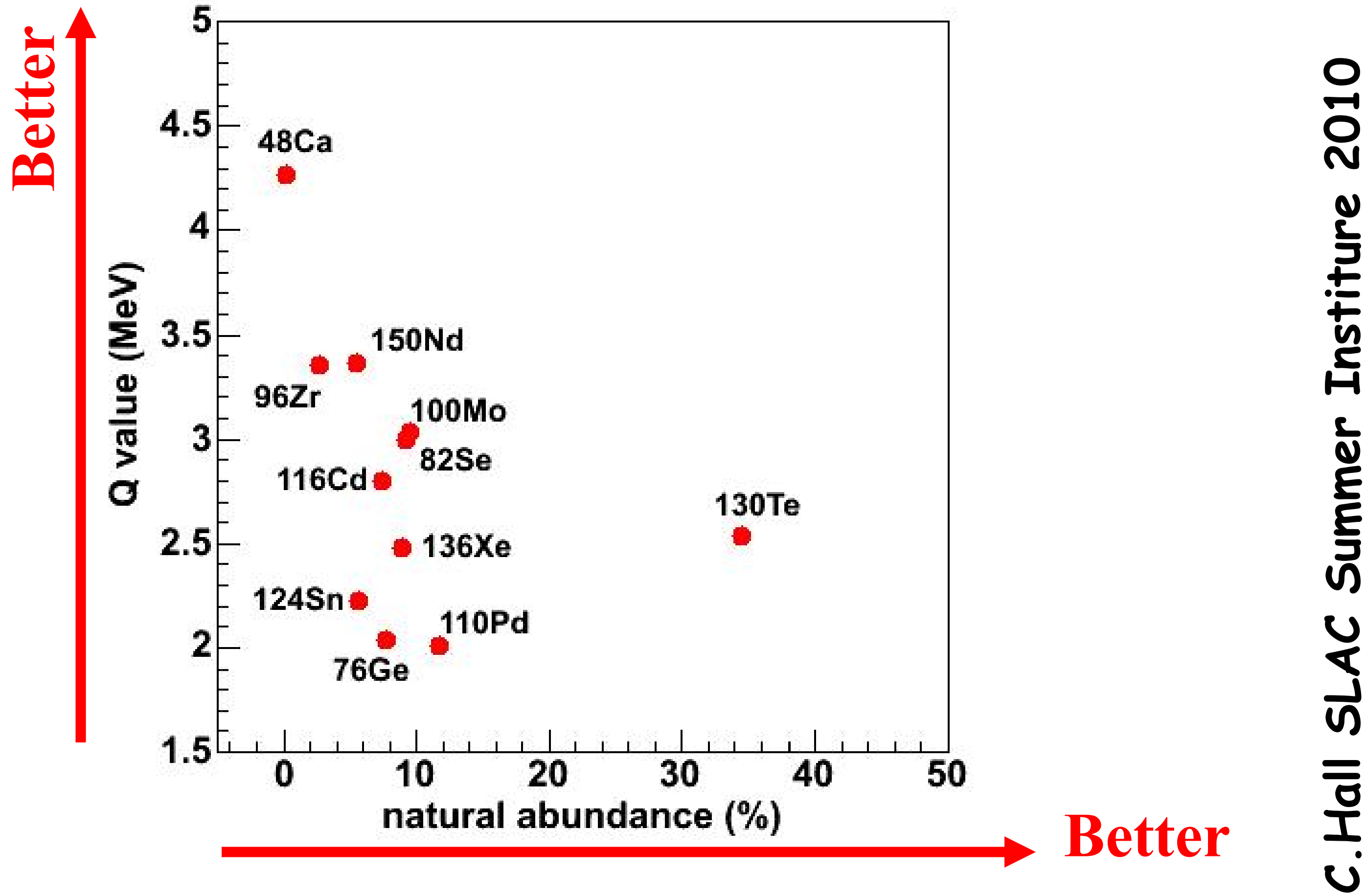
$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24}\, yr$$

$$\langle m_\nu \rangle = 0.32 \pm 0.03\, eV$$

[H.V.Klapdor-Kleingrothaus and I.Krivosheina, Mod.Phys.Lett. A21 (2006) 1547]

However, this is a very controversial matter

Is there an ideal source?



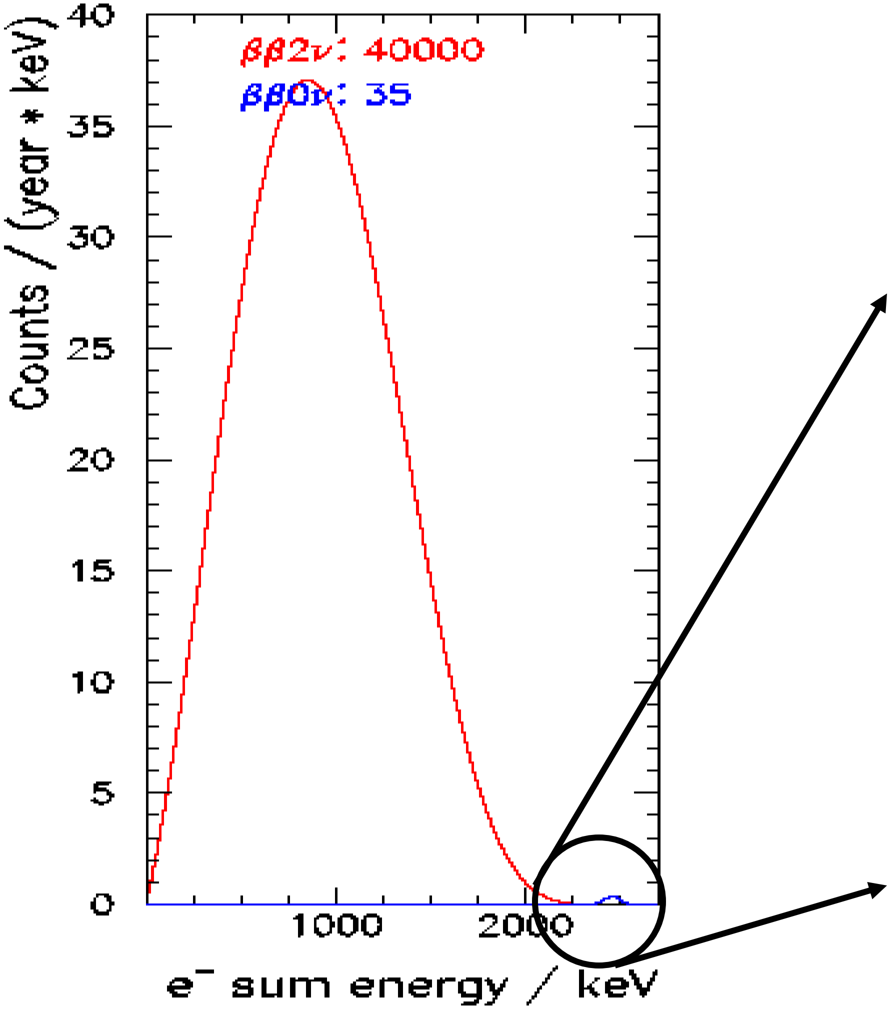
- High Q value reduces backgrounds and increases the phase space & decay rate,
- Large abundance makes the experiment cheaper
- A number of isotopes have similar matrix element performance

It is very important to understand that a healthy neutrinoless double-beta decay program requires more than one isotope. This is because:

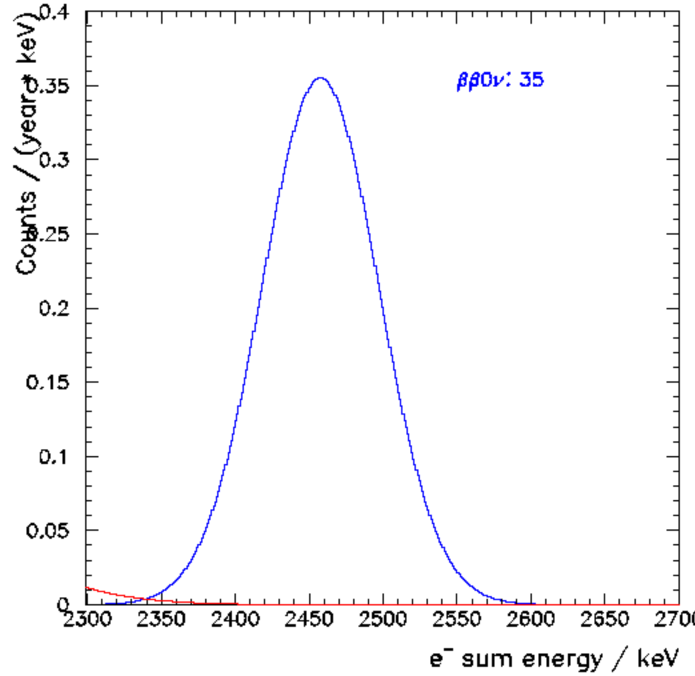
- ***There could be unknown gamma transitions and a line observed at the "end point" in one isotope does not necessarily imply that 0νββ decay was discovered (this issue may disappear for EXO with Ba tagging)***
- ***Nuclear matrix elements are not very well known and any given isotope could come with 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***

Different techniques

- Final state ID: 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
  + Very specific signature
  + Large live times (particularly for 1)
  + Large masses
  - Possible only for a few isotopes (in the case of 1)
  - No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source$\neq$detector
  + Energy/some tracking available (can distinguish modes)
  + In principle universal (b)
  - Many γ backgrounds can fake signature
  - Exposure is limited by human patience



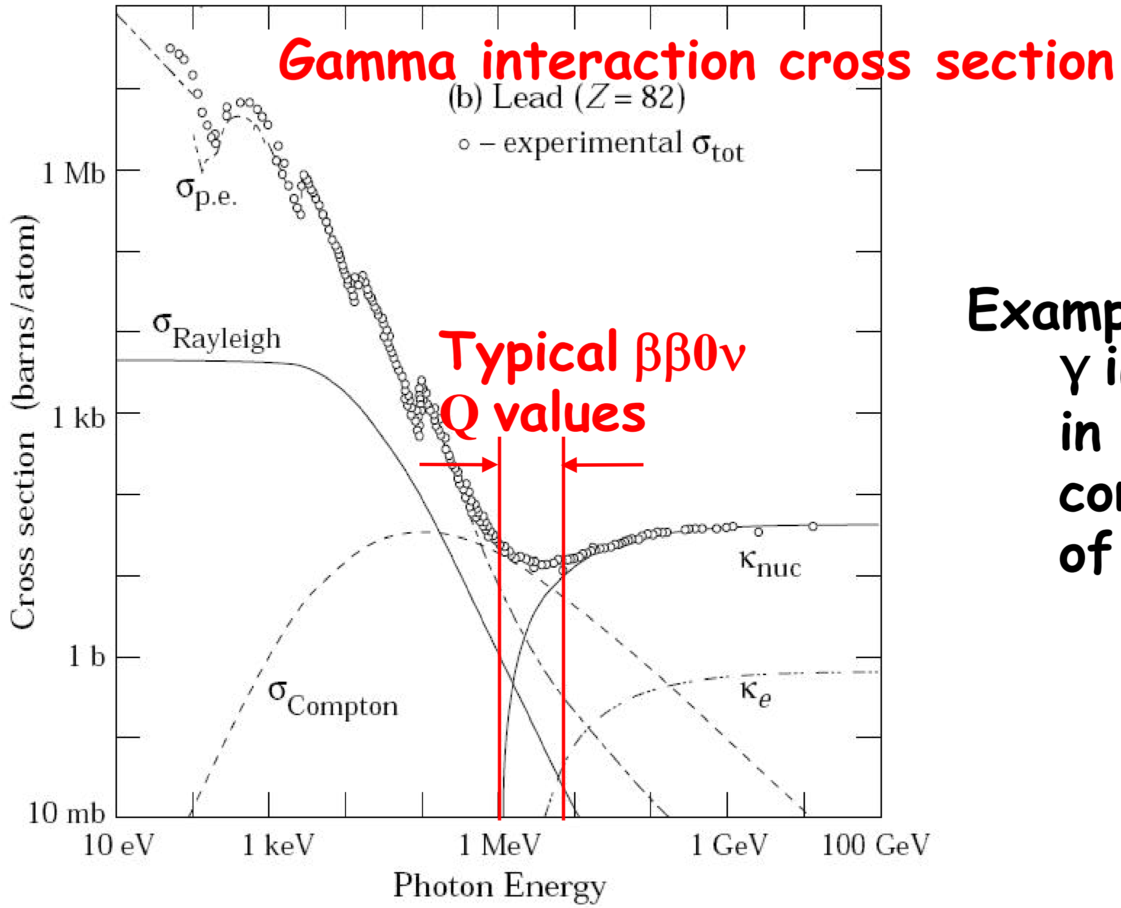
Background due to the 2νββ decay



0ν and 2ν decays can be separated in a detector with sufficiently good energy resolution

→ **Good energy resolution is key!**

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



Example:

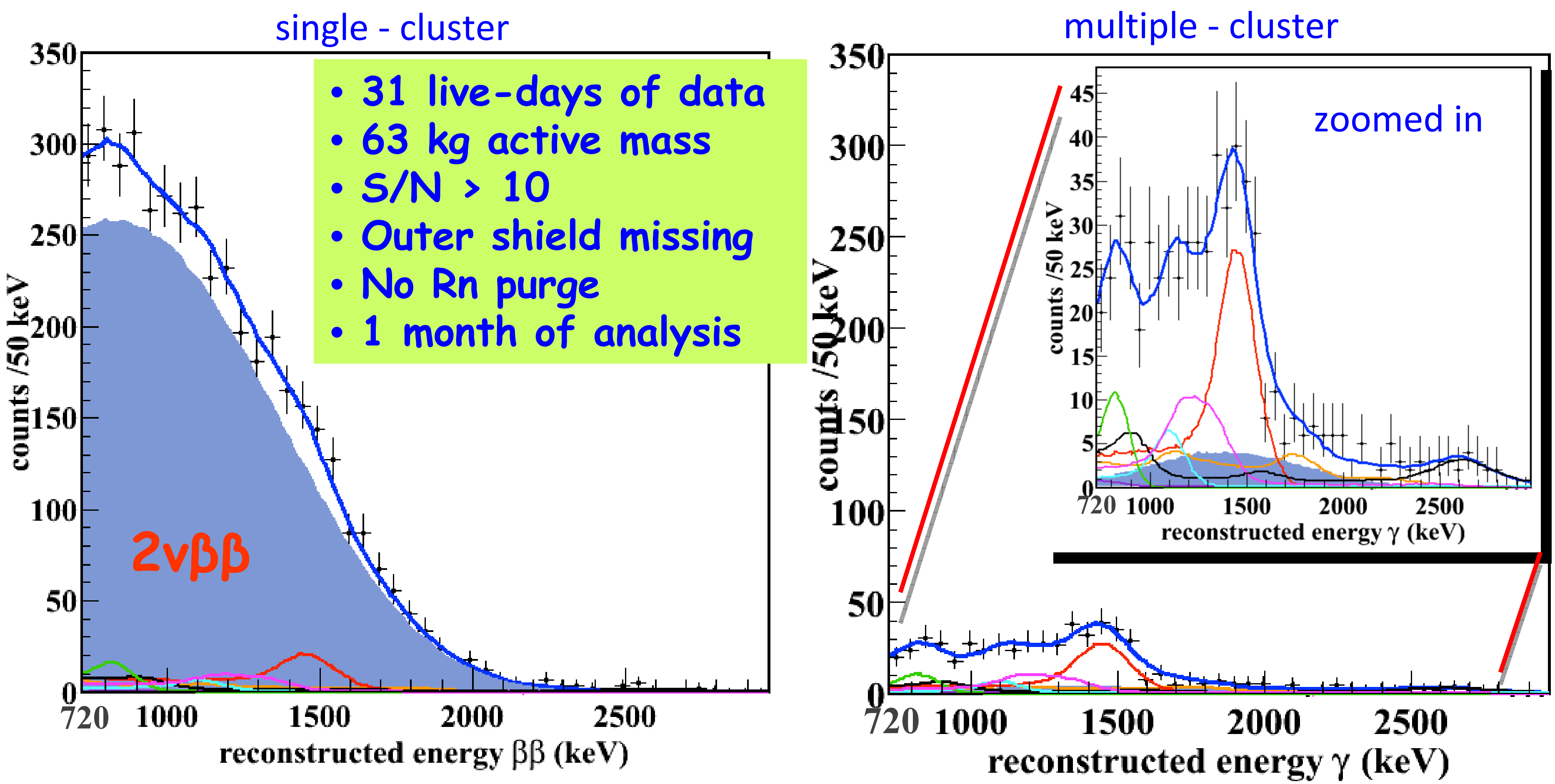
γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding double-beta decay detectors is much harder than shielding Dark Matter ones

Topology and particle ID very important to identify and reject backgrounds:

Two examples from the first EXO-200 physics run

Discovery of the 2ν mode in ^{136}Xe

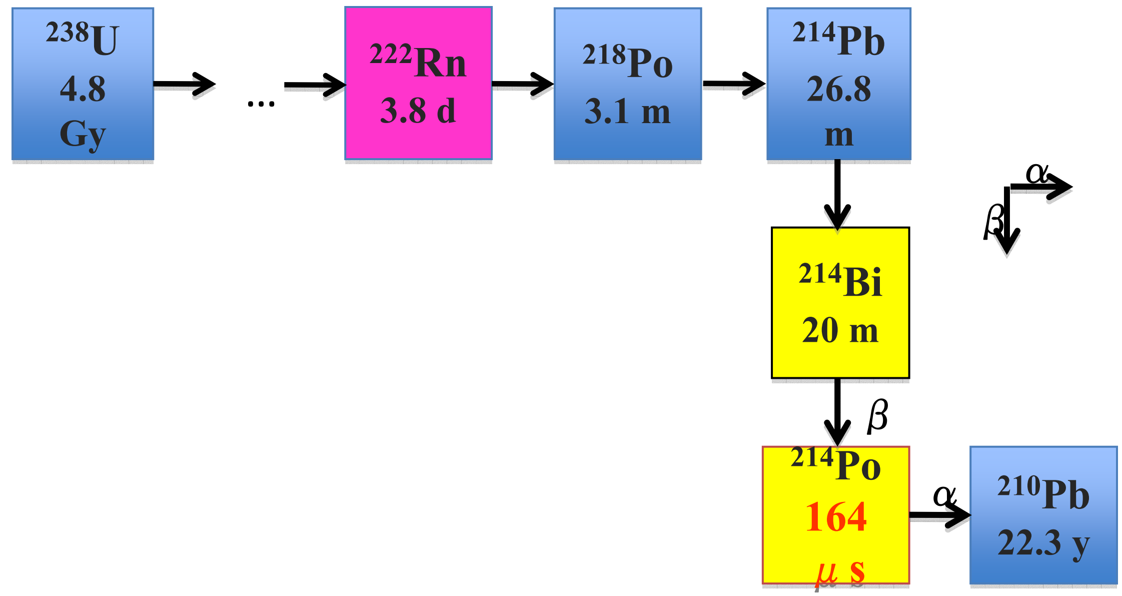


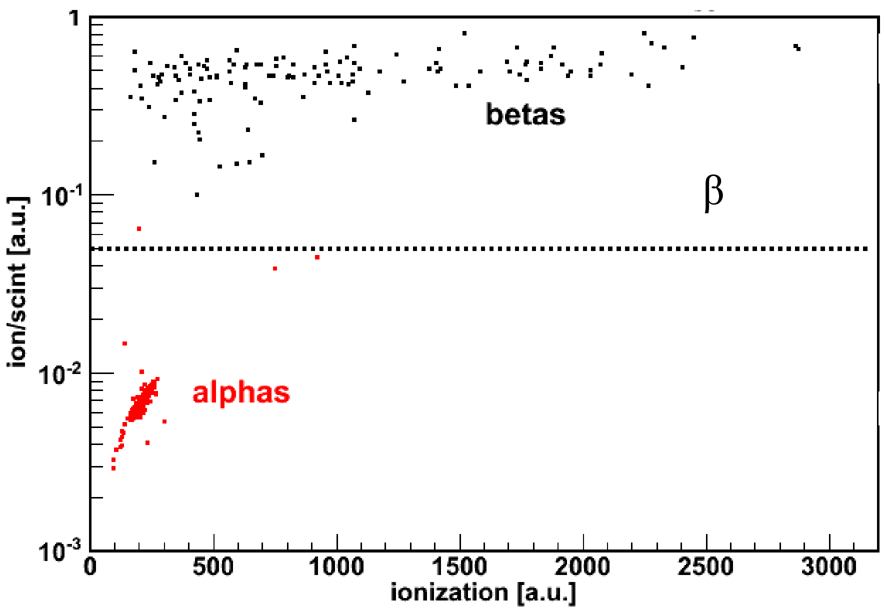
- 31 live-days of data
- 63 kg active mass
- S/N > 10
- Outer shield missing
- No Rn purge
- 1 month of analysis

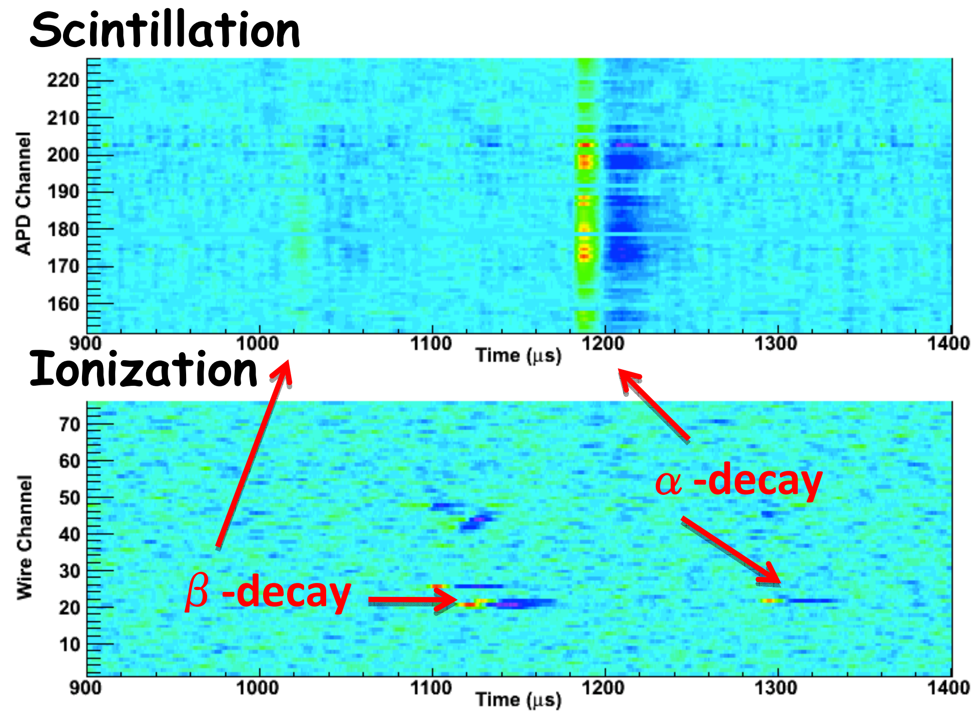
$T_{1/2} = 2.11 \cdot 10^{21}$ yr (±0.04 stat ±0.21 sys)

[Ackerman et al arXiv:1108.4193, to appear on Phys Rev Lett]

Can also measure independently the Rn content in the Xenon



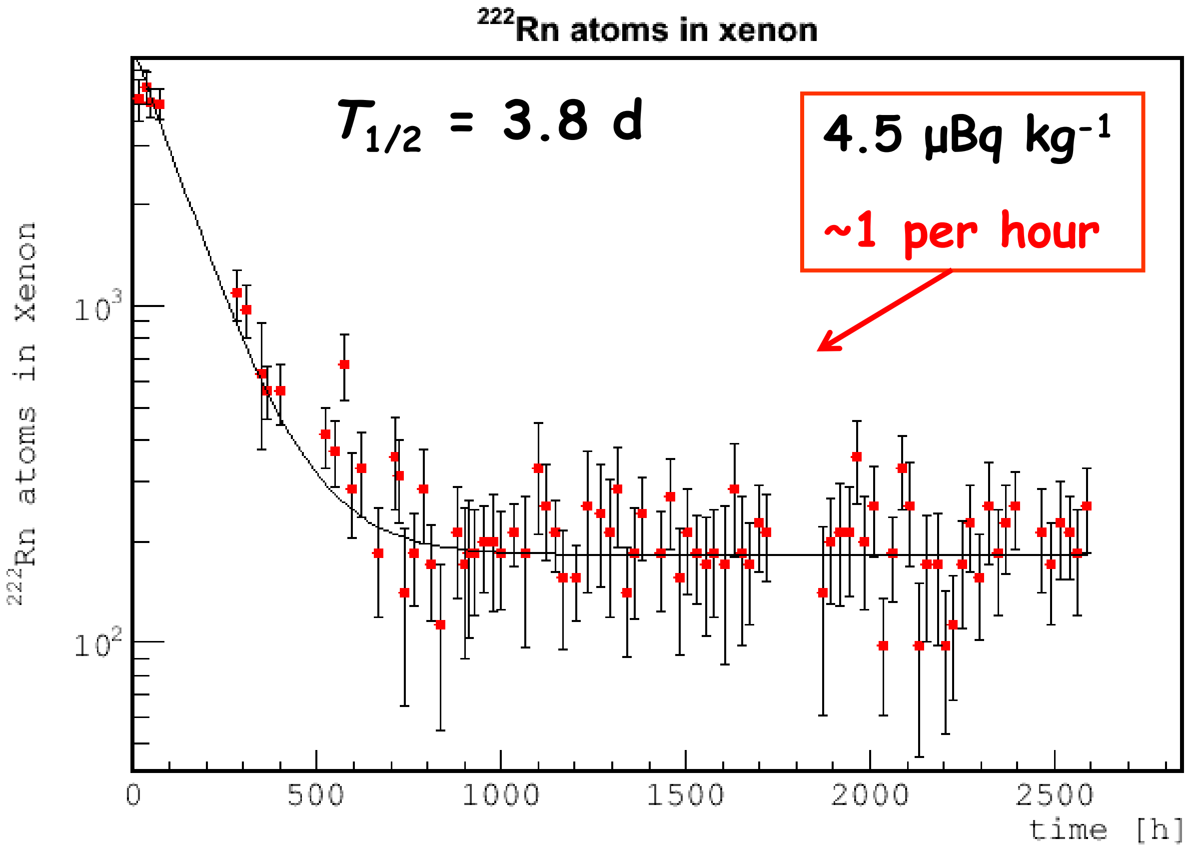




α : strong light signal, weak charge signal

β : weak light signal, strong charge signal

Rn Content in the Xenon



Some experiments running or in preparation

(*not a complete list*)

Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	Majorana†	Eres,2site tag, Cu shield	30-60 kg	SUSEL
	Gerda†	Eres,2site tag, LAr shield	15-35 kg	G Sasso
	MaGe/GeMa	See above	~1ton	DUSEL? GS?
^{150}Nd	SNO+	Size/shielding	44 kg	SNOlab
^{82}Se	SuperNEMO‡	Tracking	~100 kg	Modane
^{130}Te*	CUORE	E Res.	204 kg	G Sasso
^{136}Xe	KamLAND-Zen	Size/shielding	400 kg	Kamioka
^{136}Xe	EXO	Tracking/Eres	150 kg	WIPP
		Ba tag, Track/Eres	1-10ton	DUSEL?

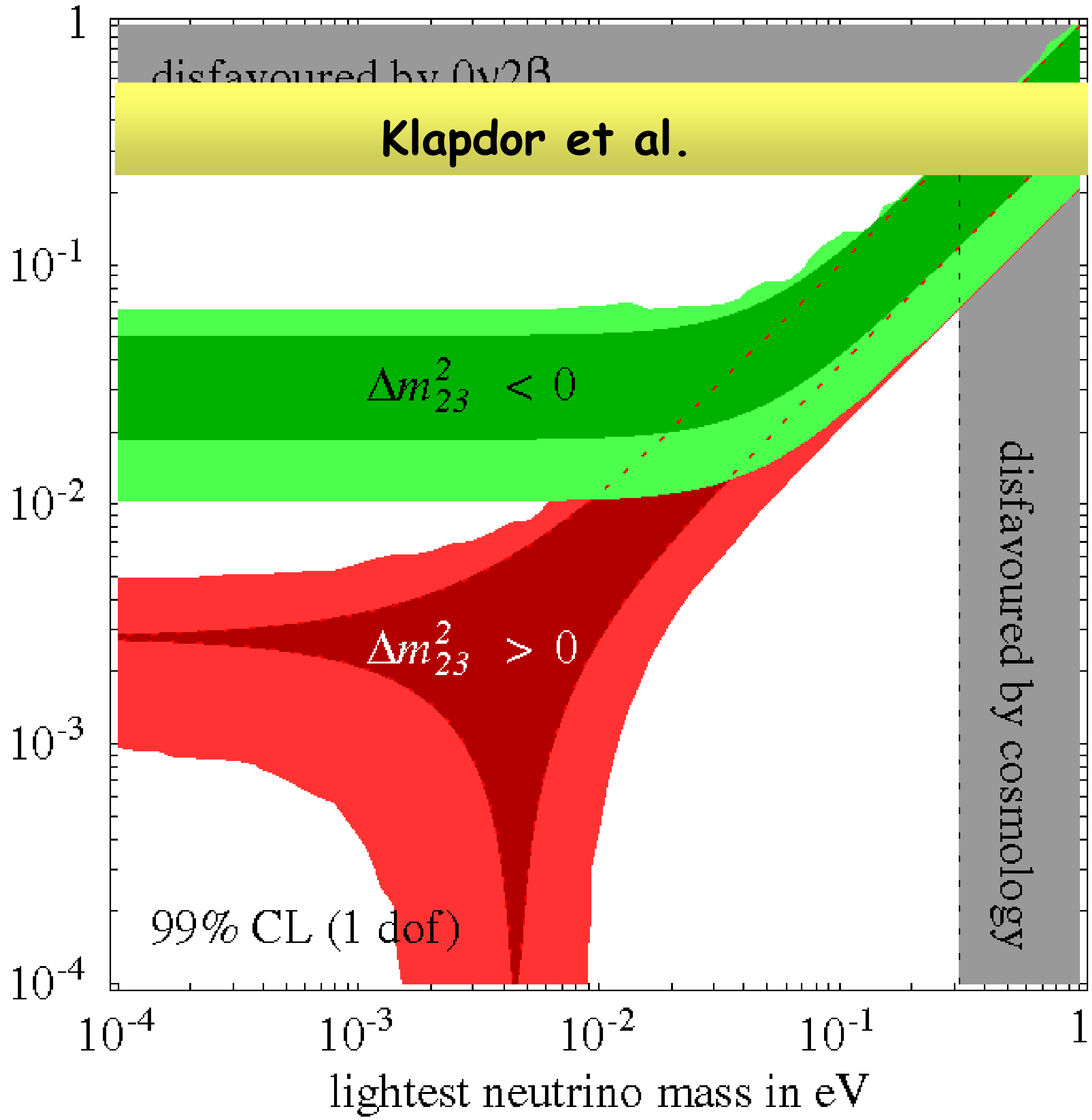
* No isotopic enrichment in baseline design

† Plan to merge efforts for ton-scale experiment

‡ Non-homogeneous detector

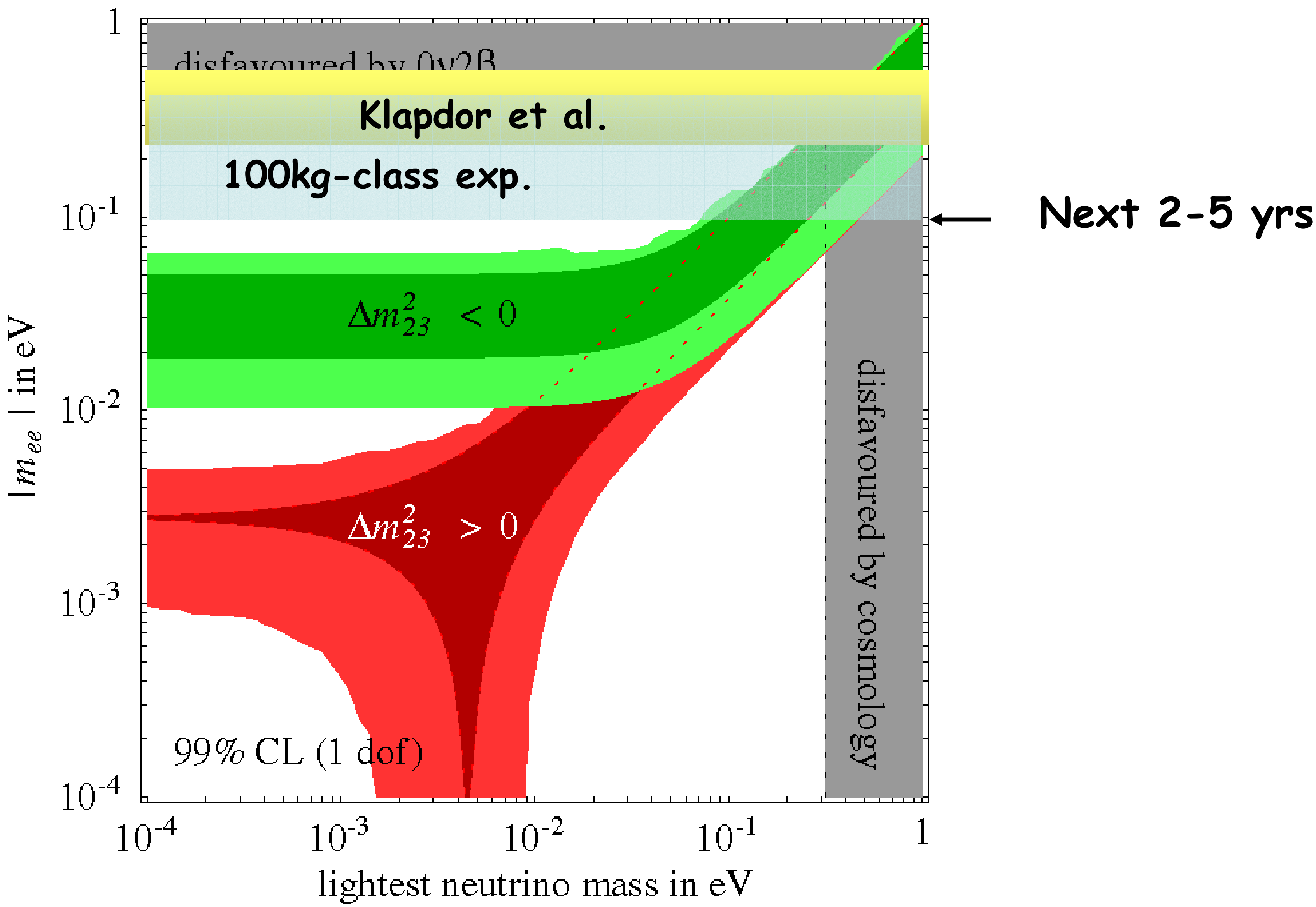
What to expect in the next 10-15 yrs

Figure from Strumia & Vissani, Nucl. Phys. B 726 294 (2005)



What to expect in the next ~decade

Figure from Strumia & Vissani, Nucl. Phys. B 726 294 (2005)



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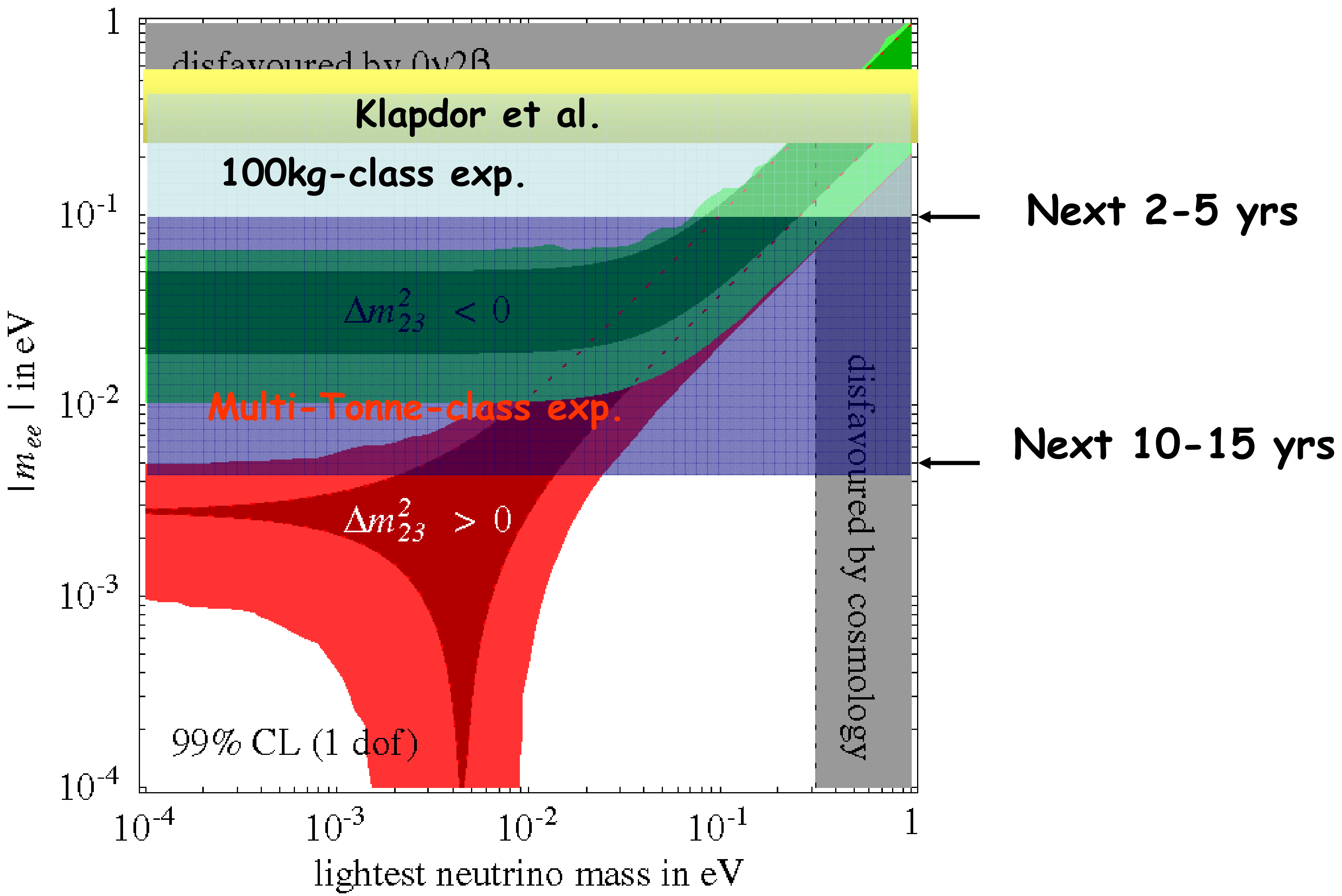
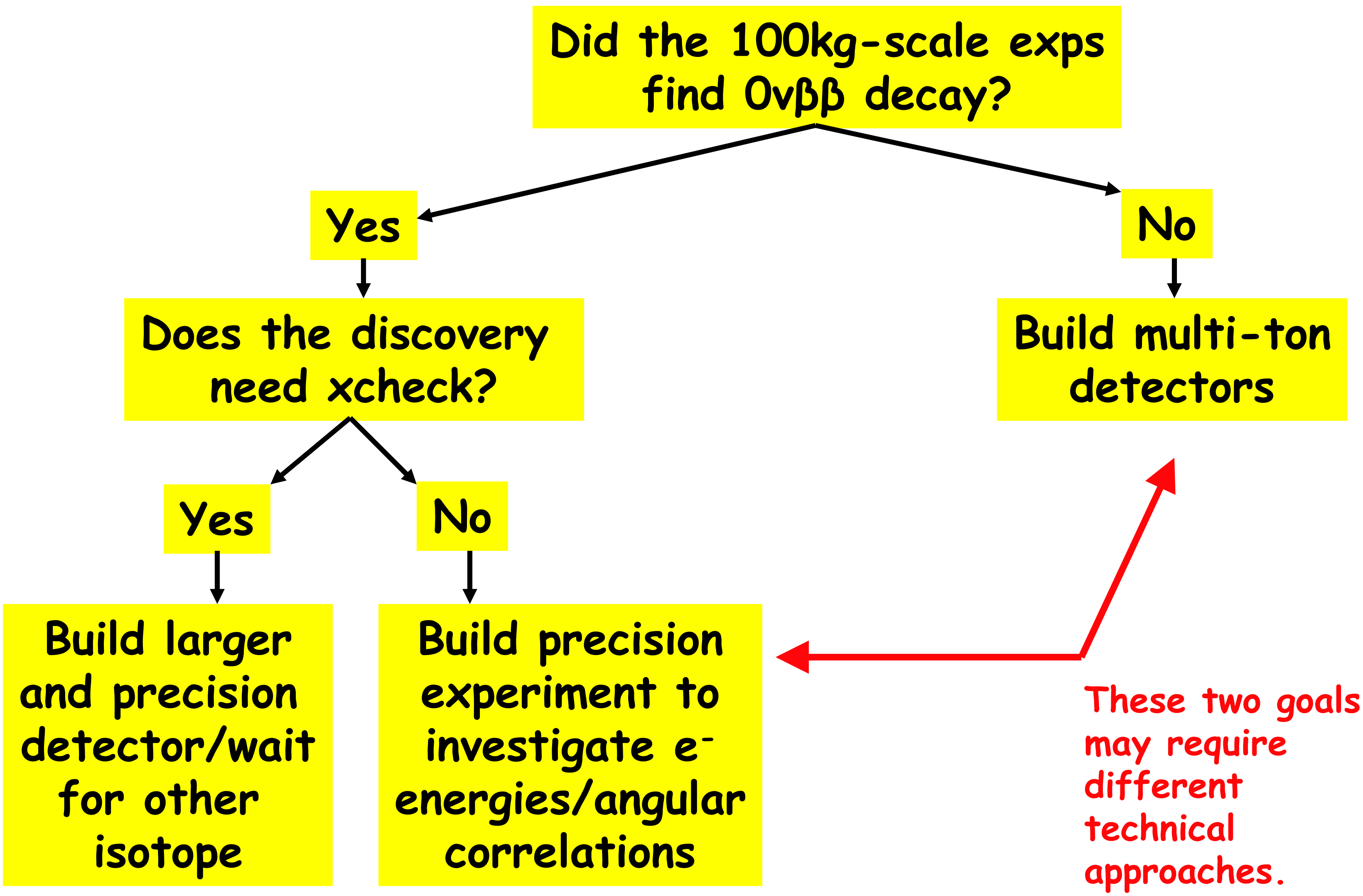
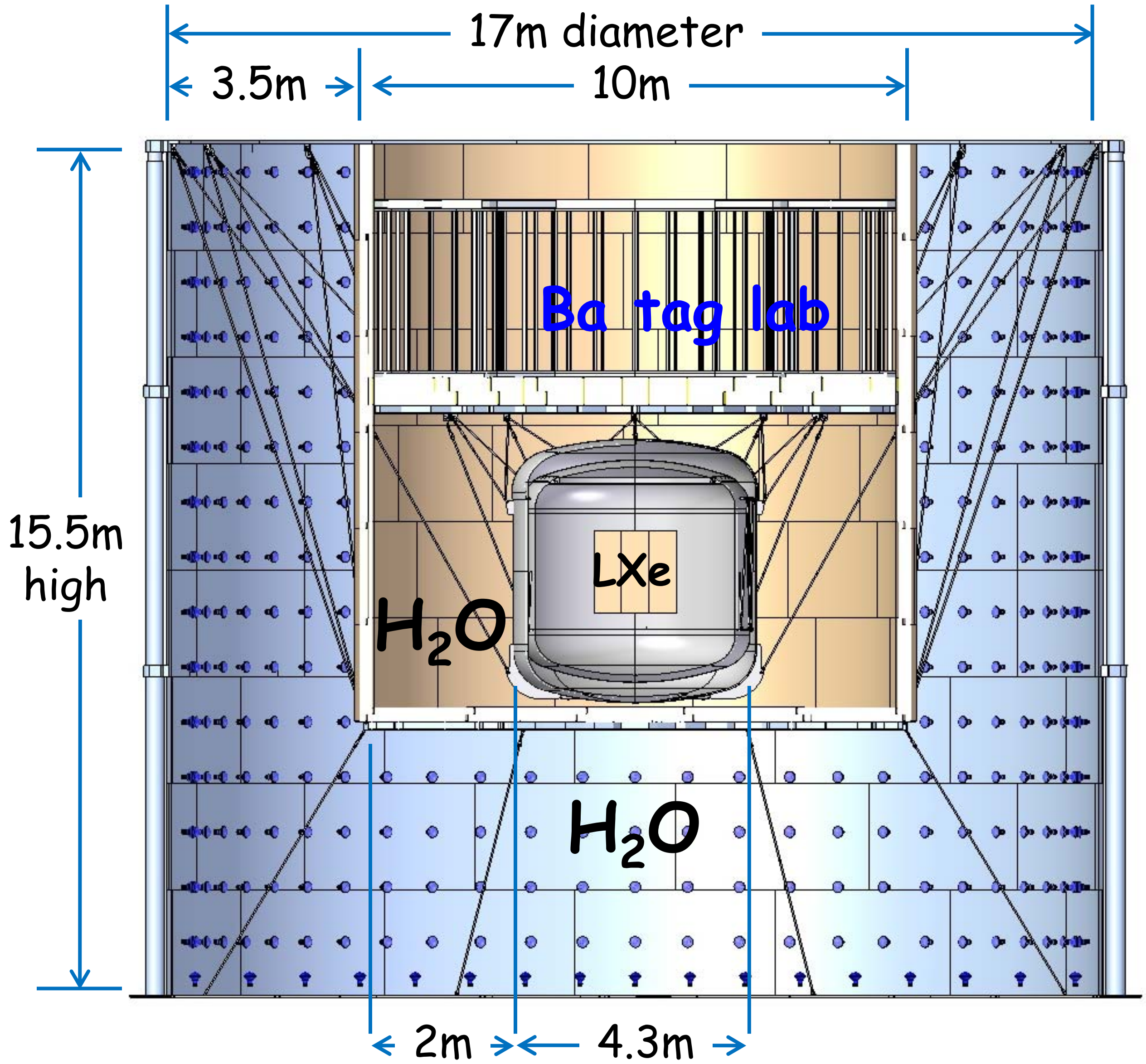


Discovery vs. Measurement
the program needs flexibility



We are talking or rather large detectors!



Conclusions

Over its glorious history neutrino physics has provided plenty of surprises and has required forays in many different areas of science and technology

The search for neutrinoless double beta decay really belongs to this tradition!

- **Several 100kg class experiments are coming online**
- **Many different/clever experimental ideas**
- **Many new theoretical ideas**
- **Ton-class experiments are being planned for the near future**

The US has played/is playing a leading role and we want to keep it this way!