Double-beta decay:

G.Gratta
Physics Dept
Stanford University

DURA meeting
SLAC, 5 Mar 2013

Double-beta decay:

a very IMPORTANT experiment

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Double-beta decay:

a very DIFFICULT experiment

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 0νββ decay:

- *→ Discovery of the neutrino mass scale*
- *→ Discovery of Majorana particles*
- *→ Doscovery of Majorana masses*
- *→ Discovery of lepton number violation*

Need very large fiducial mass (tons) of isotopically separated material (except for ^{130}Te)

[using natural material typically means that 90% of the source produced background but not signal]

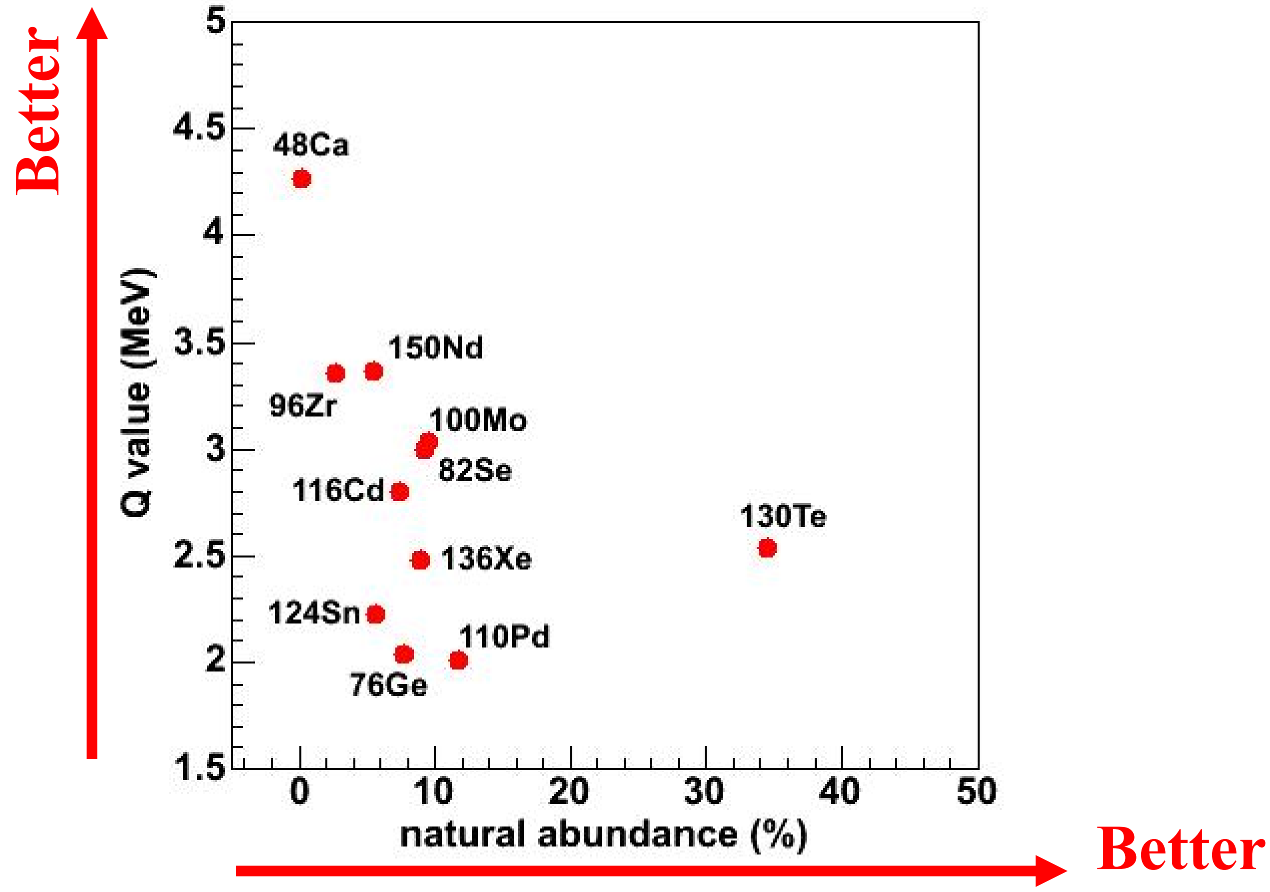
This is expensive and provides encouragement to use the material in the best possible way:

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
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

For no bkgnd $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

For statistical bkgnd subtraction $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

How to "organize" an experiment: the source



C.Hall SLAC Summer Institute 2010

- 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

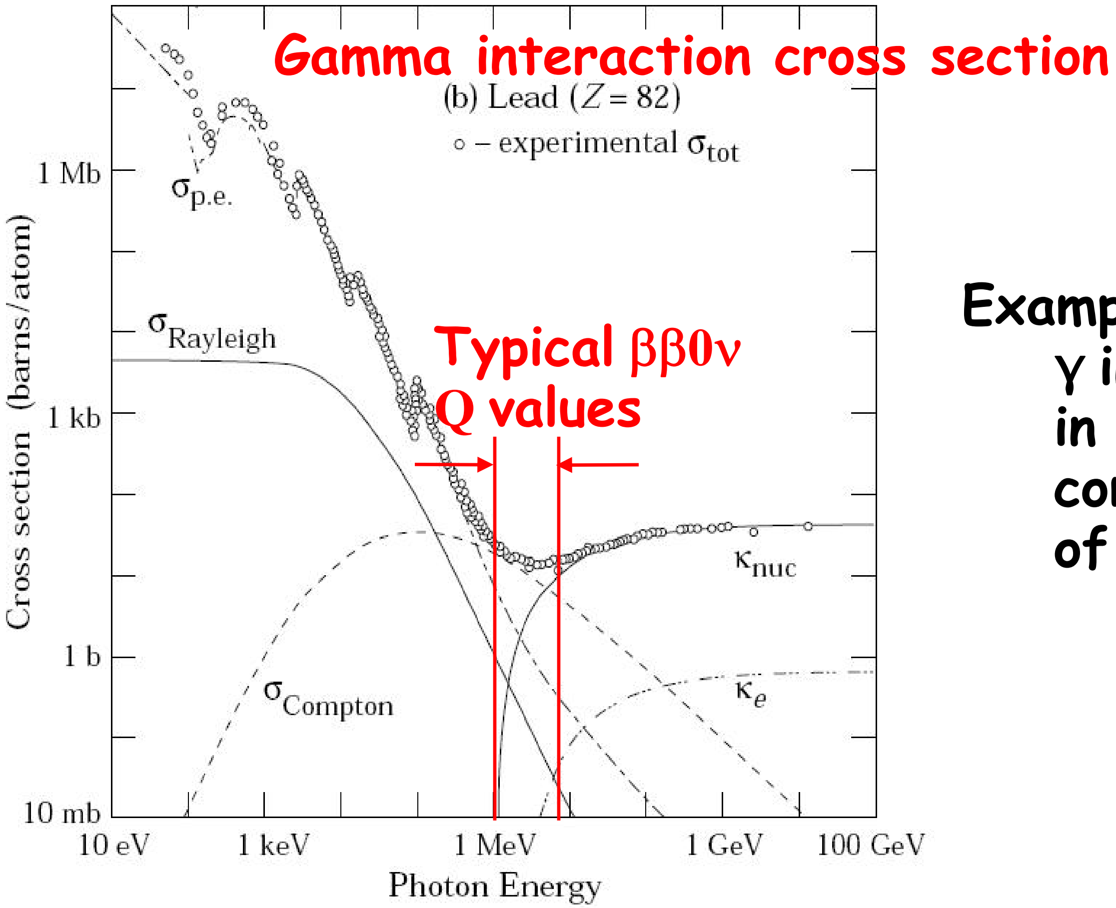
The importance of clean, multi-parameter measurements grows as the size of detectors grows, making cross-checks painfully slow and expensive

"Background" runs with un-enriched or depleted material do not seem to be a panacea as isotopic separation alters, sometimes drastically, the background in the source

How to "organize" an experiment: the technique

- 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≠detector
  - + Energy/some tracking available (can distinguish modes)
  - + In principle universal (b)
  - - Many γ backgrounds can fake signature
  - - Exposure is limited by human patience

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

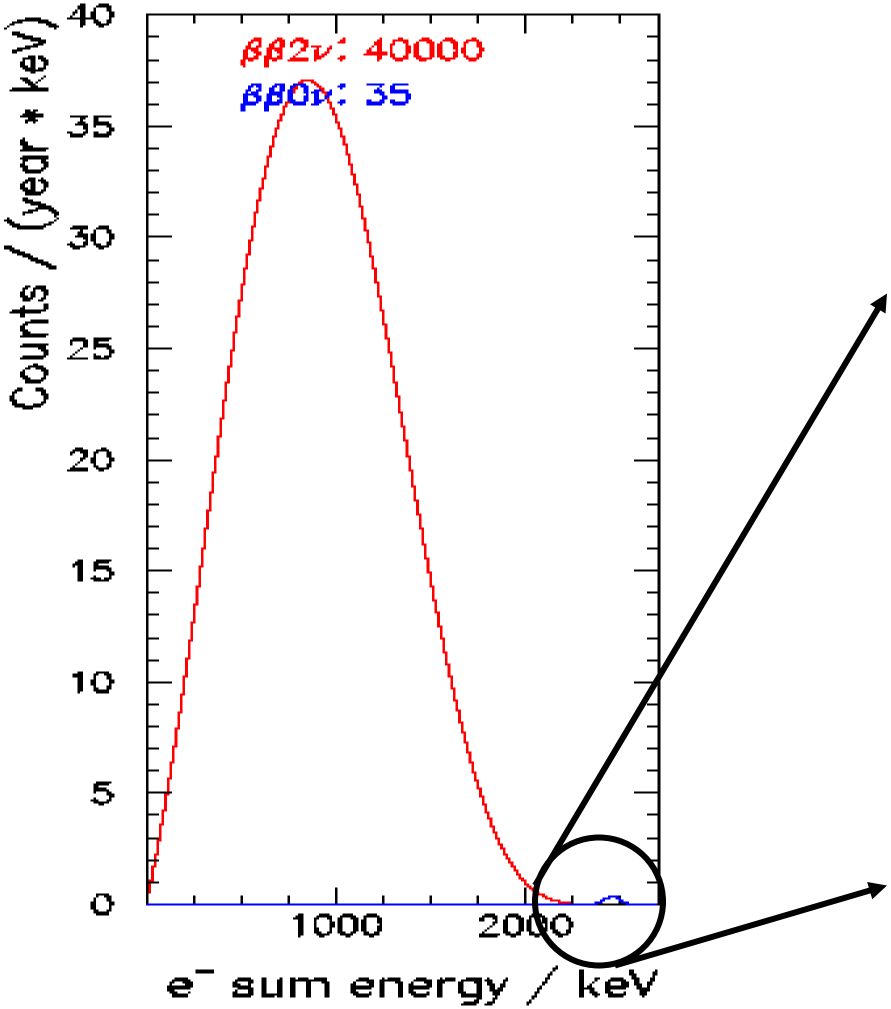


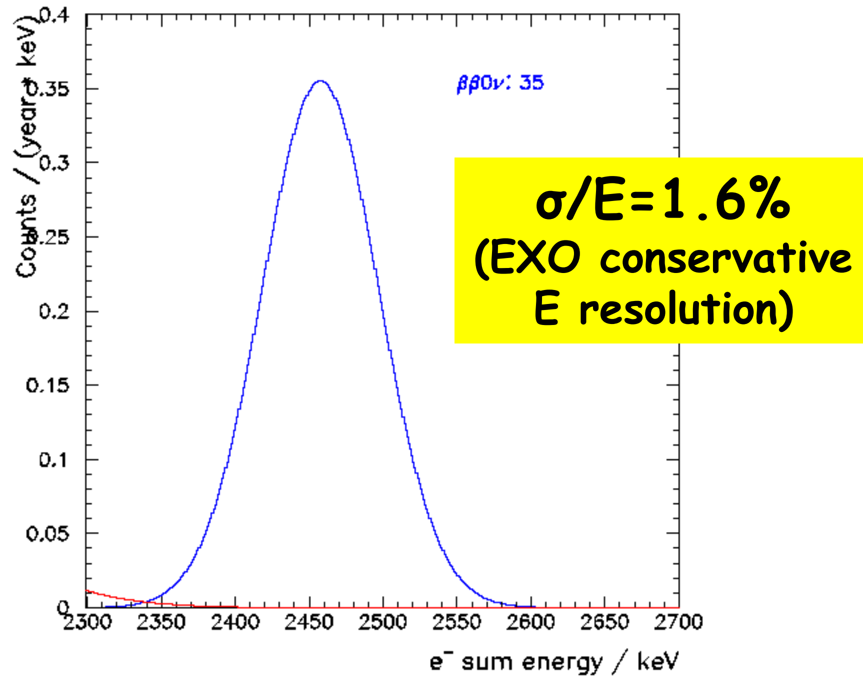
Example:

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

Background due to the Standard Model 2νββ decay

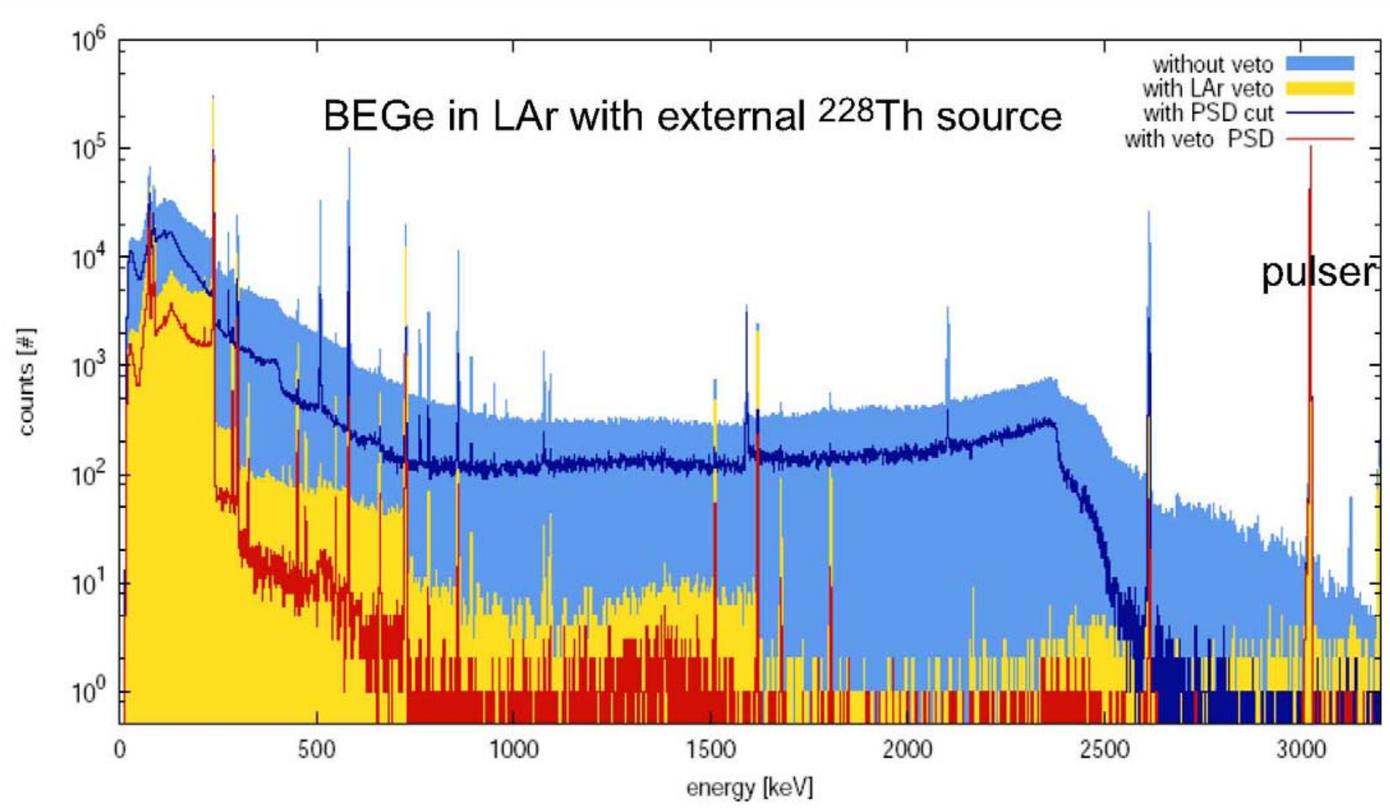




<u>**The two can be separated in a detector with sufficiently good energy resolution**</u>

<u>Topology and particle ID are also important to recognize backgrounds</u>

About energy resolution



Superior energy resolution:

^{76}Ge (diode): 0.2% FWHM

^{130}Te (bolometer): 0.4% FWHM

Intermediate energy resolution:

^{136}Xe (liquid TPC): 3.3% FWHM

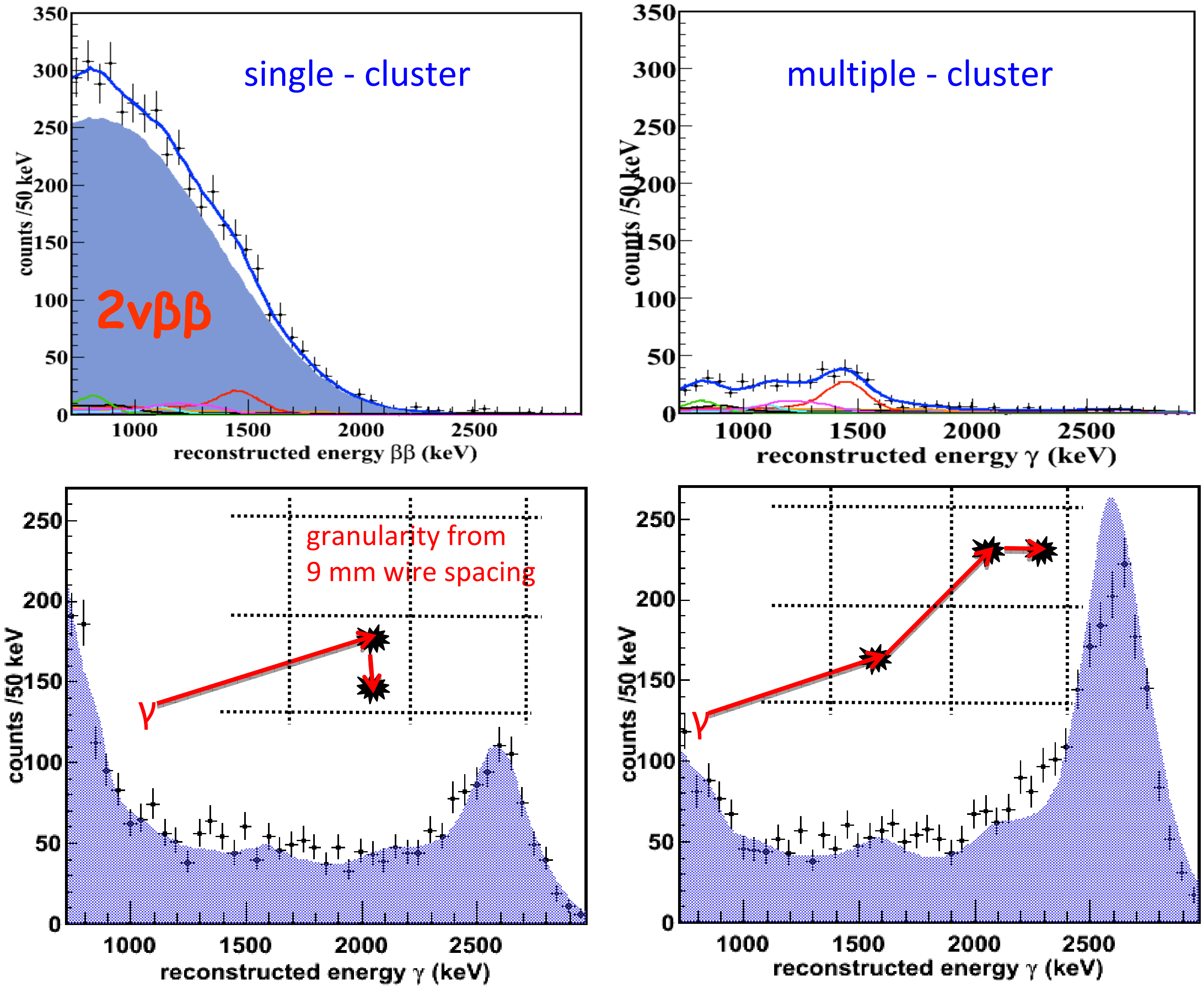
Modest energy resolution:

^{100}Mo, ^{136}Xe, ^{150}Nd (scintillators): 10%-15% FWHM

Pattern recognition can be a very powerful tool against background (example from 2νββ in EXO-200)

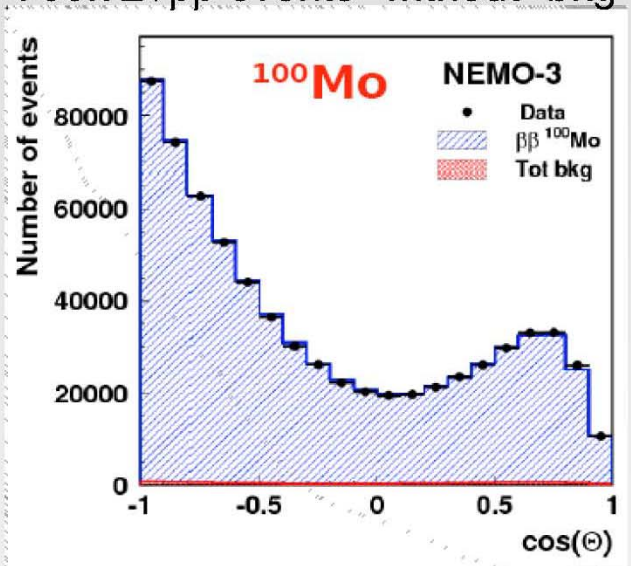
Low background data

^{228}Th calibration source



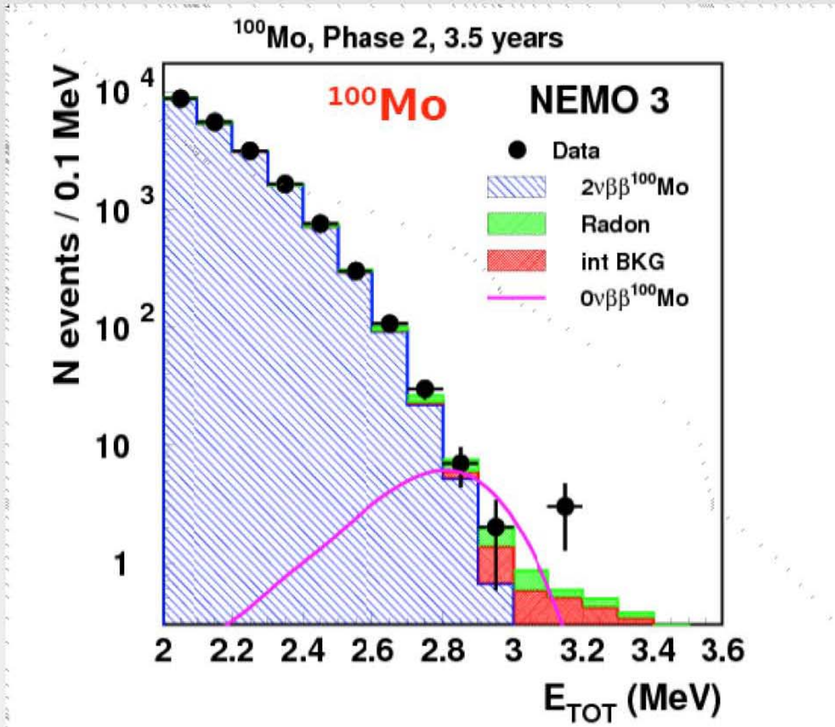
"Extreme" pattern recognition (at the expense of fiducial mass)

700k 2νββ events "without" bkg



$T^{0\nu}_{1/2} = (7.16 \pm 0.54) \cdot 10^{18}$ y (prelim.)

2νββ results also for other six isotopes, see Victor Tretyak's talk at MEDEX 2011



[2.8 , 3.2] MeV:

ε(0ν) = 0.055

Tot MC= 11.0±0.8 , Data: 12 events

MC 2vbb = 5.8±0.4

MC radon = 2.5±0.4

MC int bkg=2.7±0.4 (^{214}Bi=0.4,^{208}Tl=2.3)

for 4.5 years

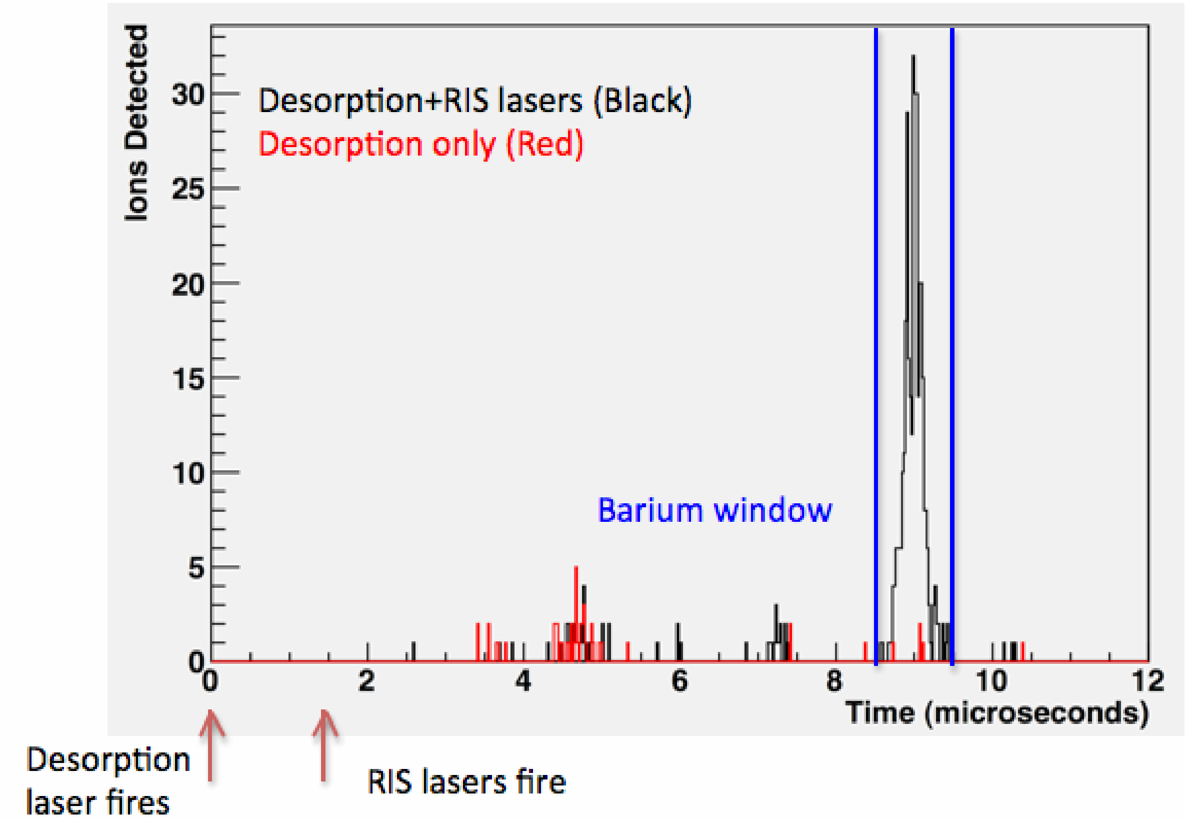
$T^{0\nu}_{1/2} > 1.0 \cdot 10^{24}$ y

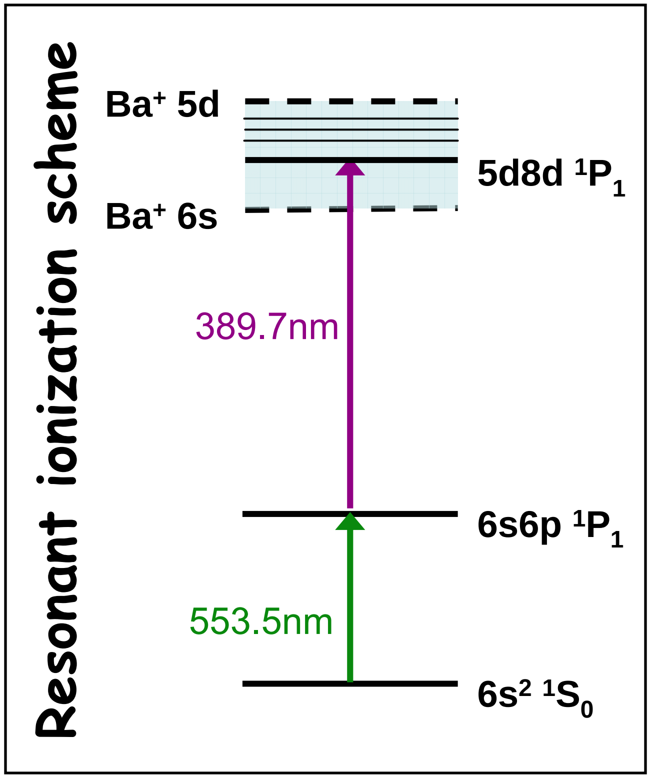
at 90% CL

$<m_{ee}>$ < 0.5-1 eV

TAUP 2011, Munich Schwingenheuer, Double Beta Decay 18

Xe possibly offers an extra tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++} e^- e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)





~2% Ba tagging efficiency obtained in the lab.

Plenty of R&D still left to do to demonstrated if the technique is viable

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 $0\nu\beta\beta$ decay was discovered*
- *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*

Experiments taking data or under construction

Isotope	Experiment	Main principle	Fid mass	Start low background data taking	Lab
^{76}Ge	Majorana Demo	Eres,2site tag, Cu shield	30 kg	End 2014	SUSEL
	Gerda	Eres,2site tag, LAr shield	15-35 kg	Nov 2011	G Sasso
^{150}Nd	SNO+	Size/shielding	44 kg	Apr 2014	SNOlab
$^{130}Te^{*}$	CUORE	E Res.	204 kg	End 2014	G Sasso
^{136}Xe	KamLAND-Zen	Size/shielding	400 kg	Fall 2011	Kamioka
	EXO-200	Tracking/Eres	150 kg	Jun 2011	WIPP

* No isotopic enrichment

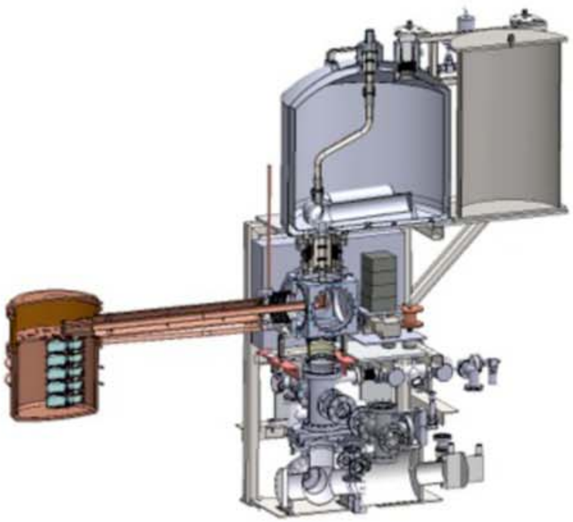
➔ Double beta is back!

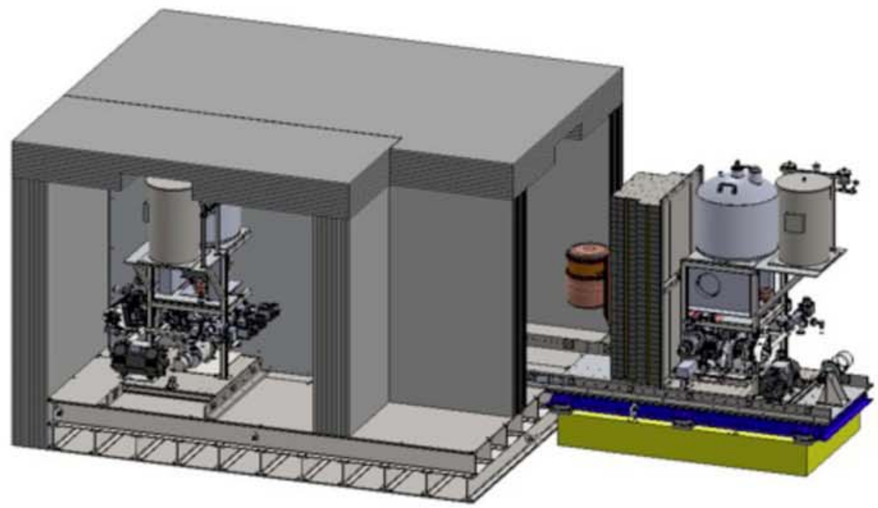
MJD Implementation

- Three Steps
  - Prototype Cryostat* (2 strings, ^{nat}Ge)
  - Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge)
  - Cryostat 2 (7 strings ^{enr}Ge)

Commissioning dates
(Estimated)

- **(Spring 2013)**
- **(Late 2013)**
- **(Fall 2014)**





*Same design as Cryos 1 & 2, but fabricated using OFHC Cu (non-electroformed) components.

J.Detwiler

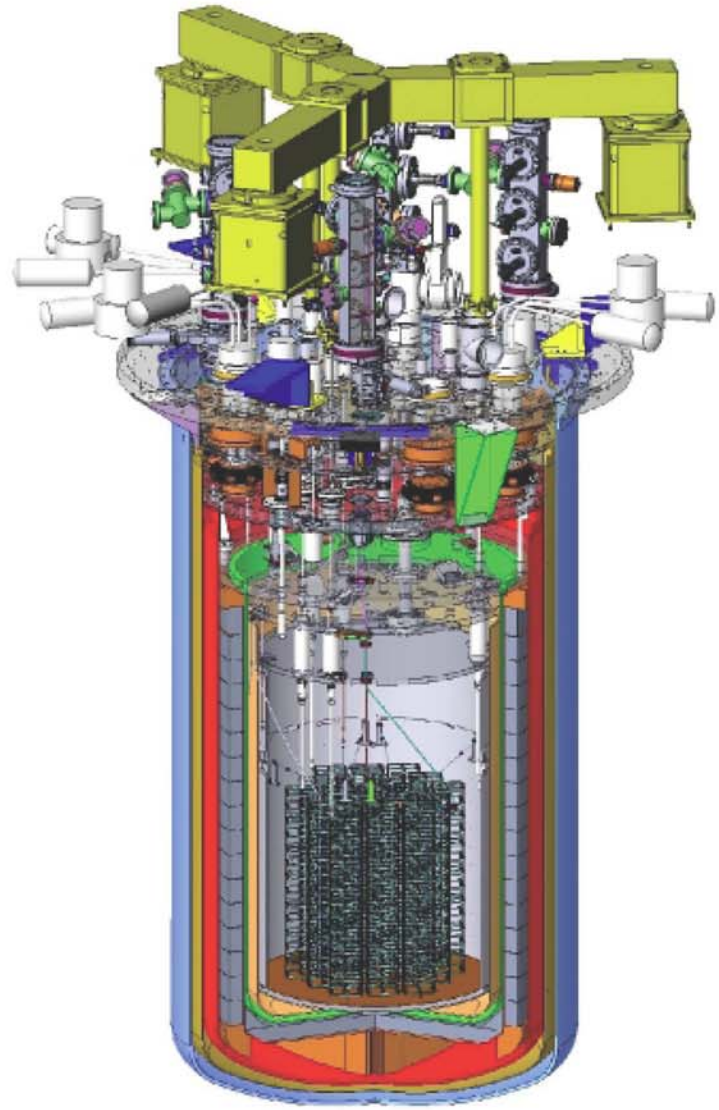
CUORE

Array of 988 TeO_2 crystals

- **19** towers suspended in a cylindrical structure
- **13** levels, **4** crystals each
- 5x5x5 cm^3 (750g each)
- ^{130}Te: 33.8% natural isotope abundance

750 kg TeO_2 => 200 kg ^{130}Te

- New pulse tube refrigerator and cryostat
- Radio-purity techniques and high resolution achieve low backgrounds
- Joint venture between Italy (INFN) and US (DOE, NSF)
- Under construction (expected start of operations by end of 2014)
- Expect energy resolution of 5 keV FWHM and background of ~0.01 counts/(kg*keV*year) in ROI



CUORE Status

Clean room & assembly line

Underground storage

Dilution Unit

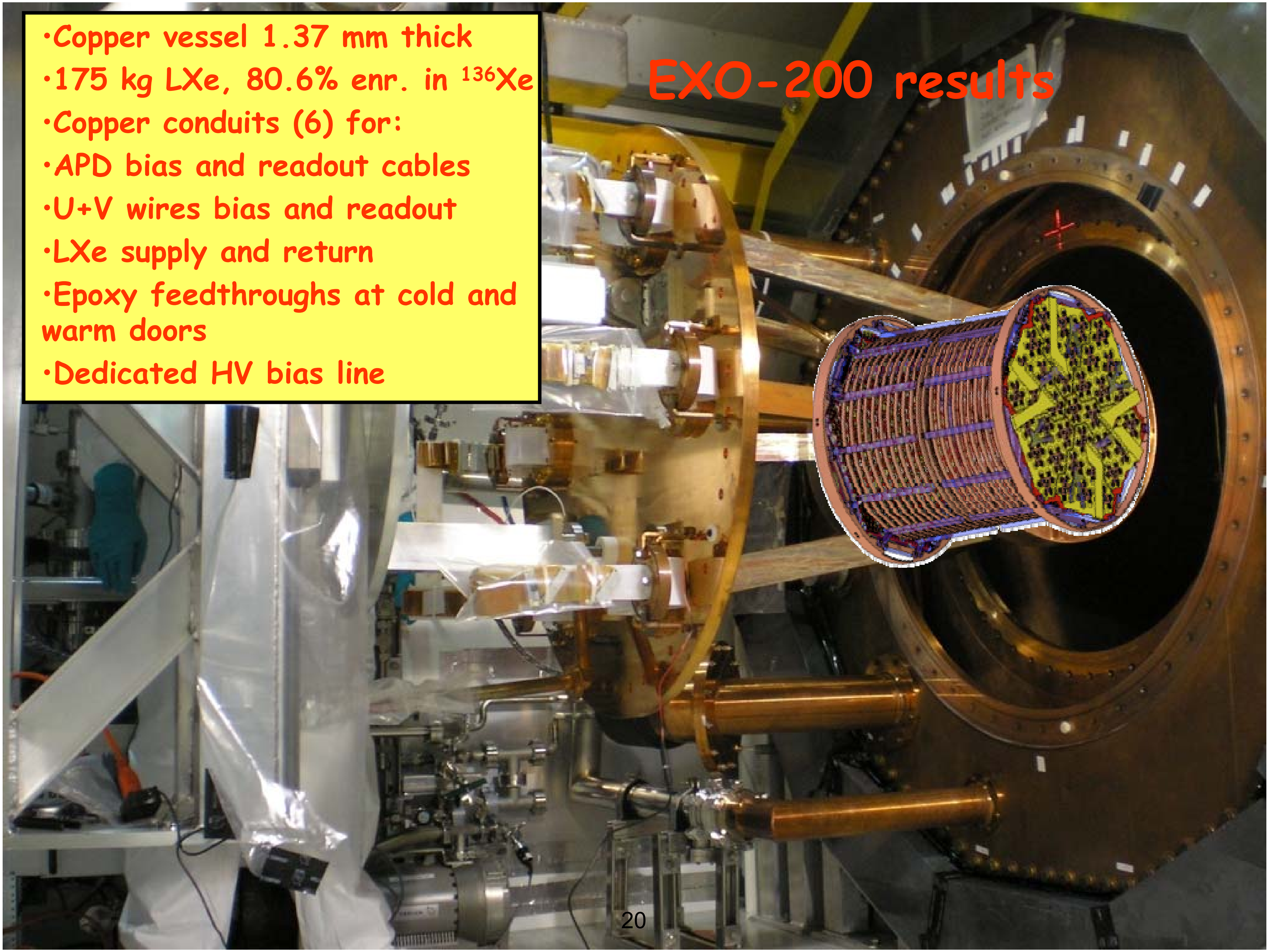
300K vessel

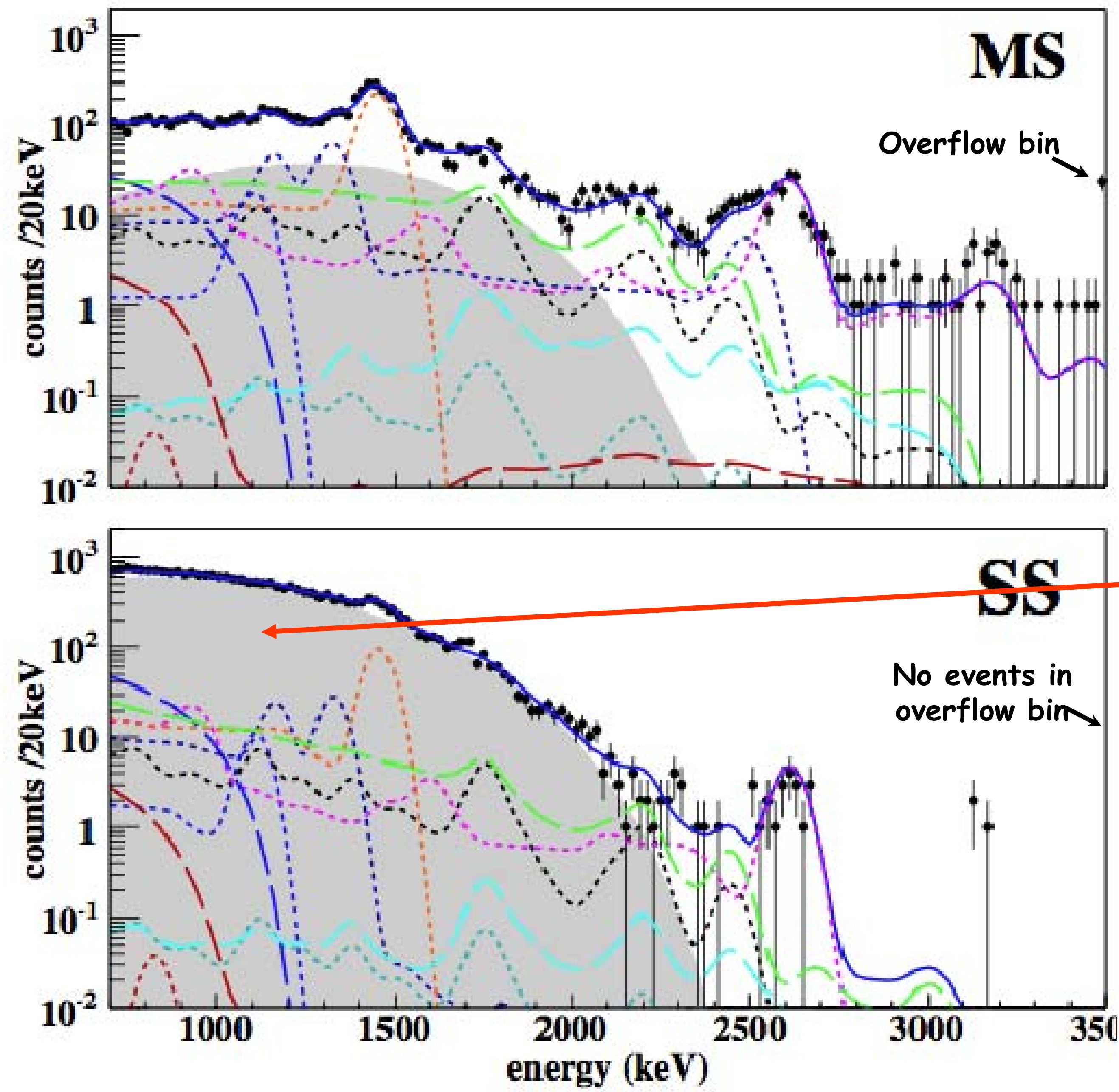
- Hut and clean room: fully equipped
- Radon abatement system: operating
- Cryostat: in commissioning
- Dilution unit: delivered, <8 mK reached
- Copper parts: cleaning proceeding, to be delivered by end of 2013
- Crystals: 95% in LNGS underground storage, last batch being produced
- Thermistors: 90% delivered, last batch being produced
- Detector assembly line: operational, first tower being assembled
- CUORE-0 (single tower in Cuoricino cryostat): operations restarted

Yu.Kolomensky

EXO-200 results

- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
- Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line





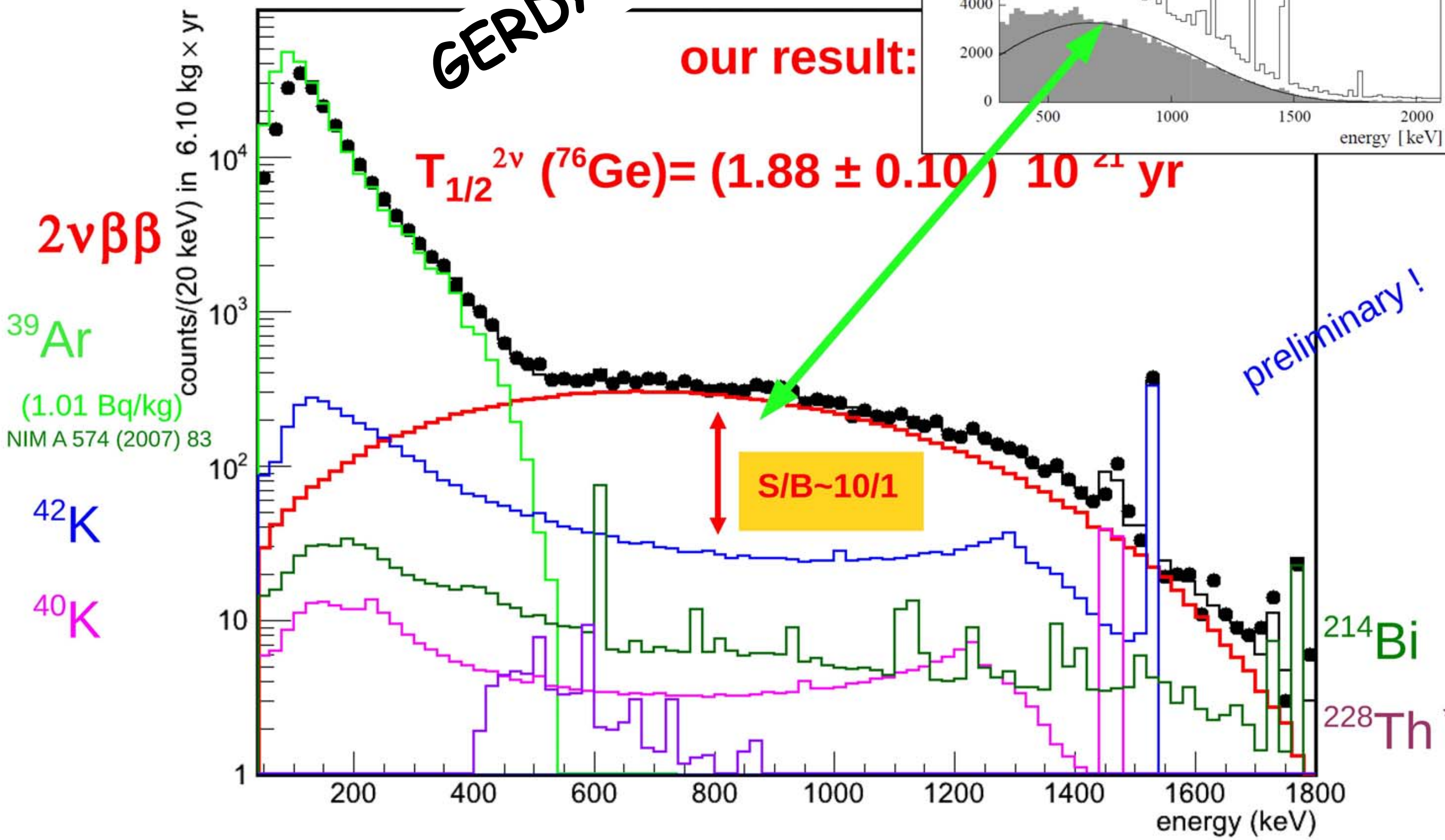
~22,000 2νββ events !

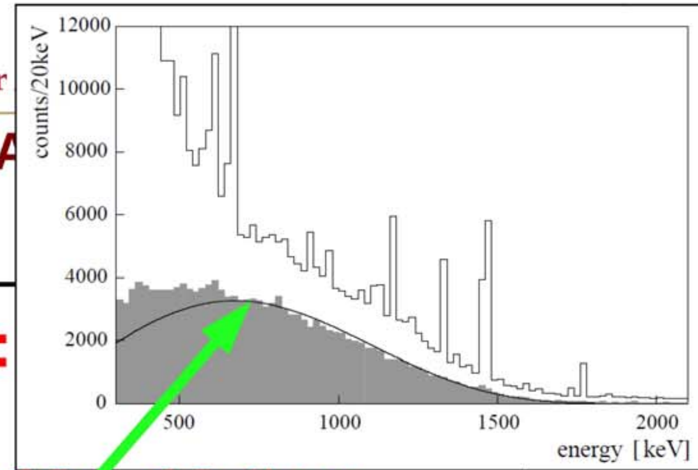
This is a mode that until Aug 2011 we did not know existed!

summed electron energy spect... GERDA

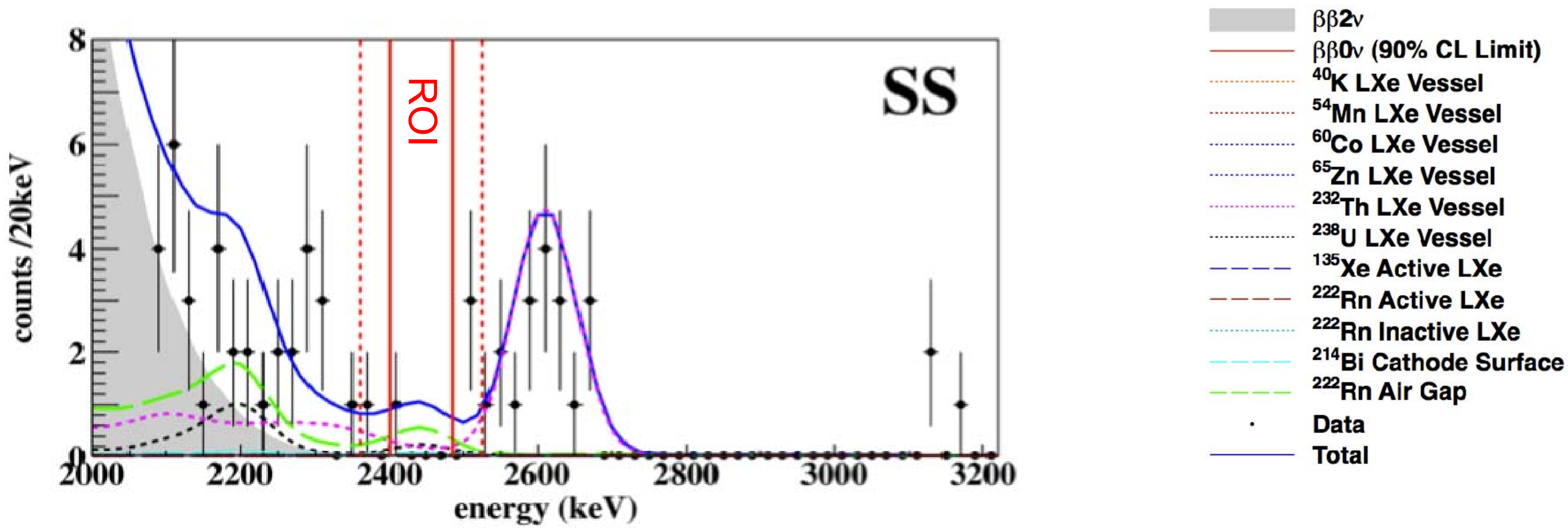
GERDA on 2μββ

exposure : 6.1 kg yr



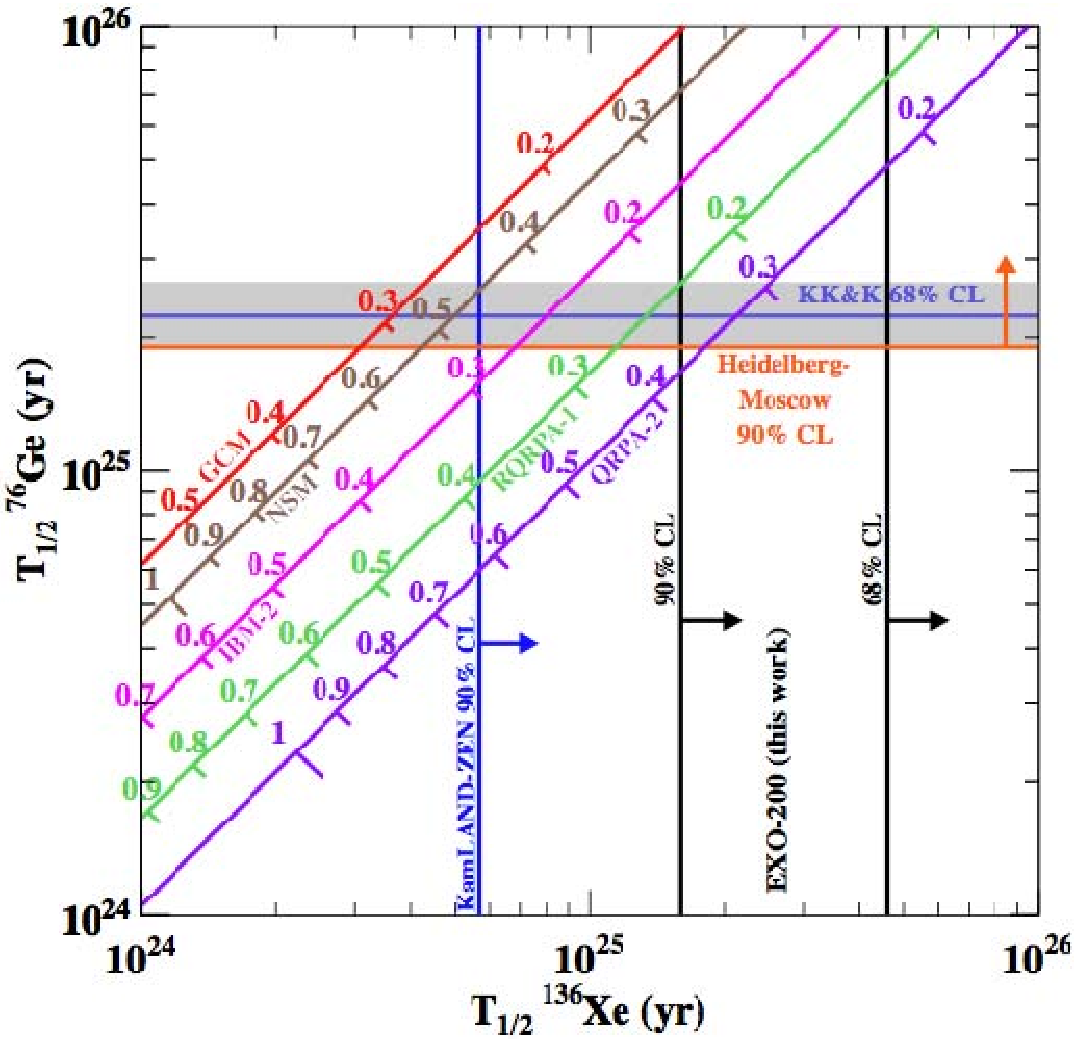


Background counts in ±1,2 σ ROI



	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5 \cdot 10^{-3}$ ± 0.1		$1.4 \cdot 10^{-3}$ ± 0.1	

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$



From profile likelihood:

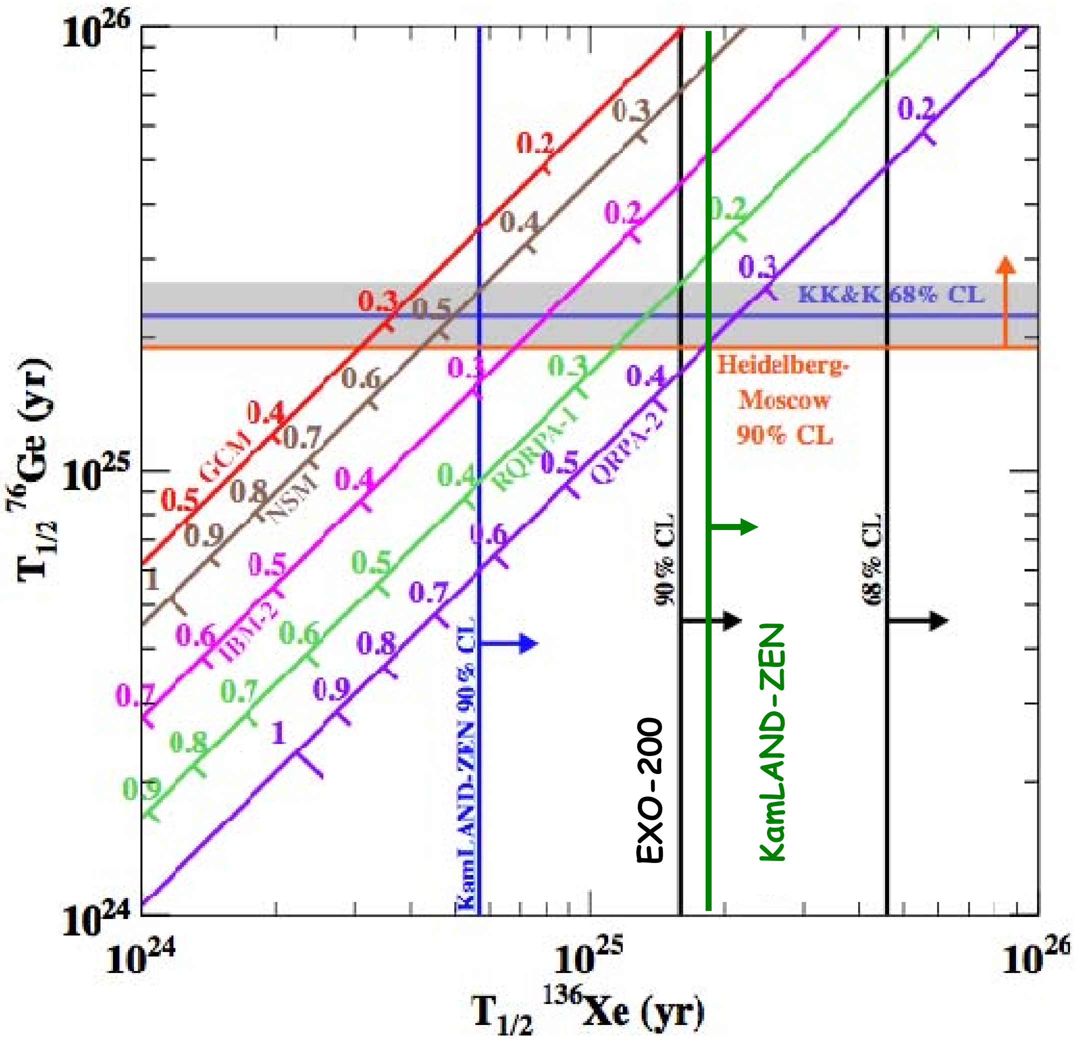
$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 140\text{–}380$ meV

(90% C.L.)

Phys Rev Lett 109 (2012) 032505

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta}\rangle$



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(90% C.L.)

Phys Rev Lett 109 (2012) 032505

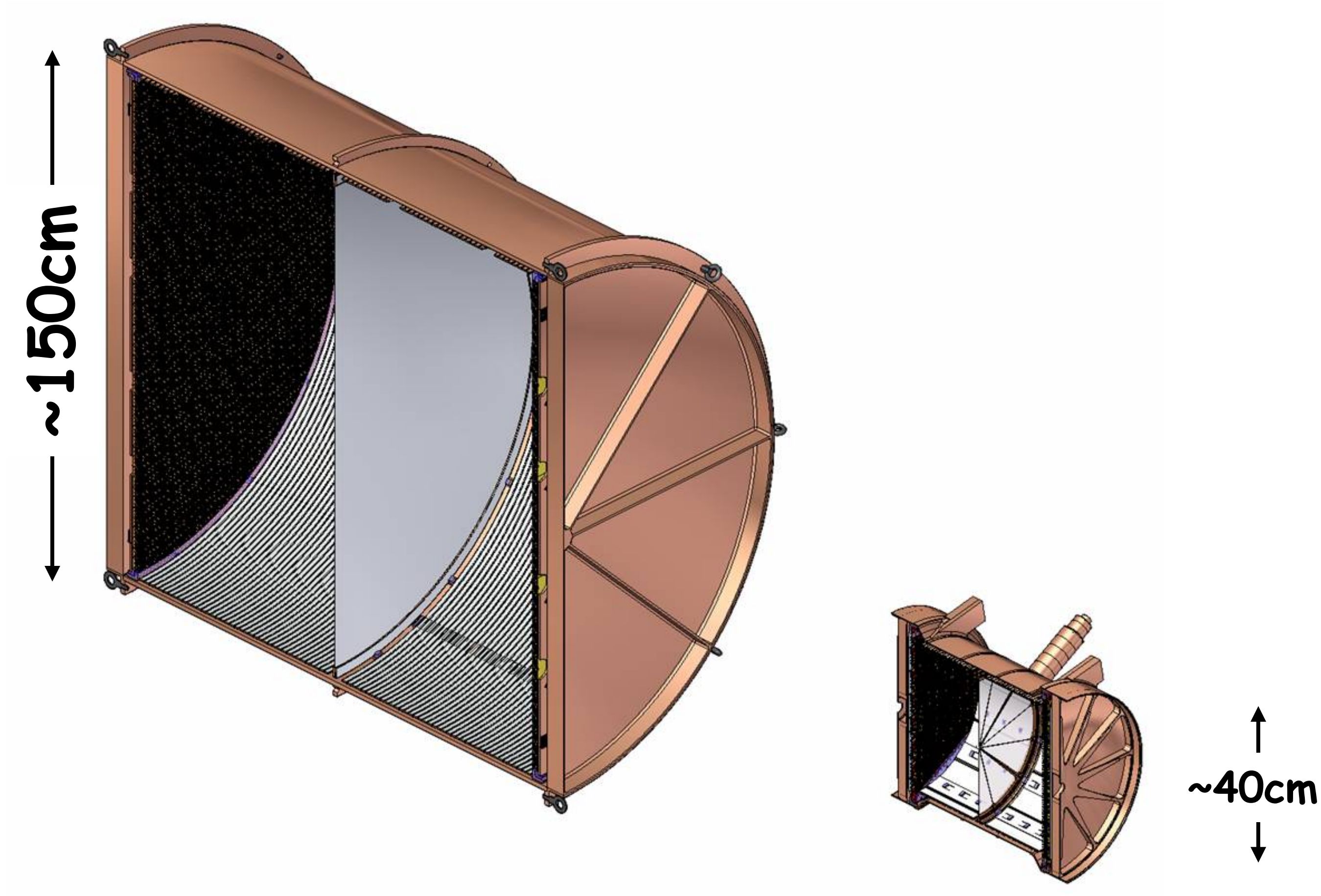
KamLAND-ZEN
Phys Rev Lett 110 (2013) 062502

Some of the detectors being planned *(not a complete list!)*

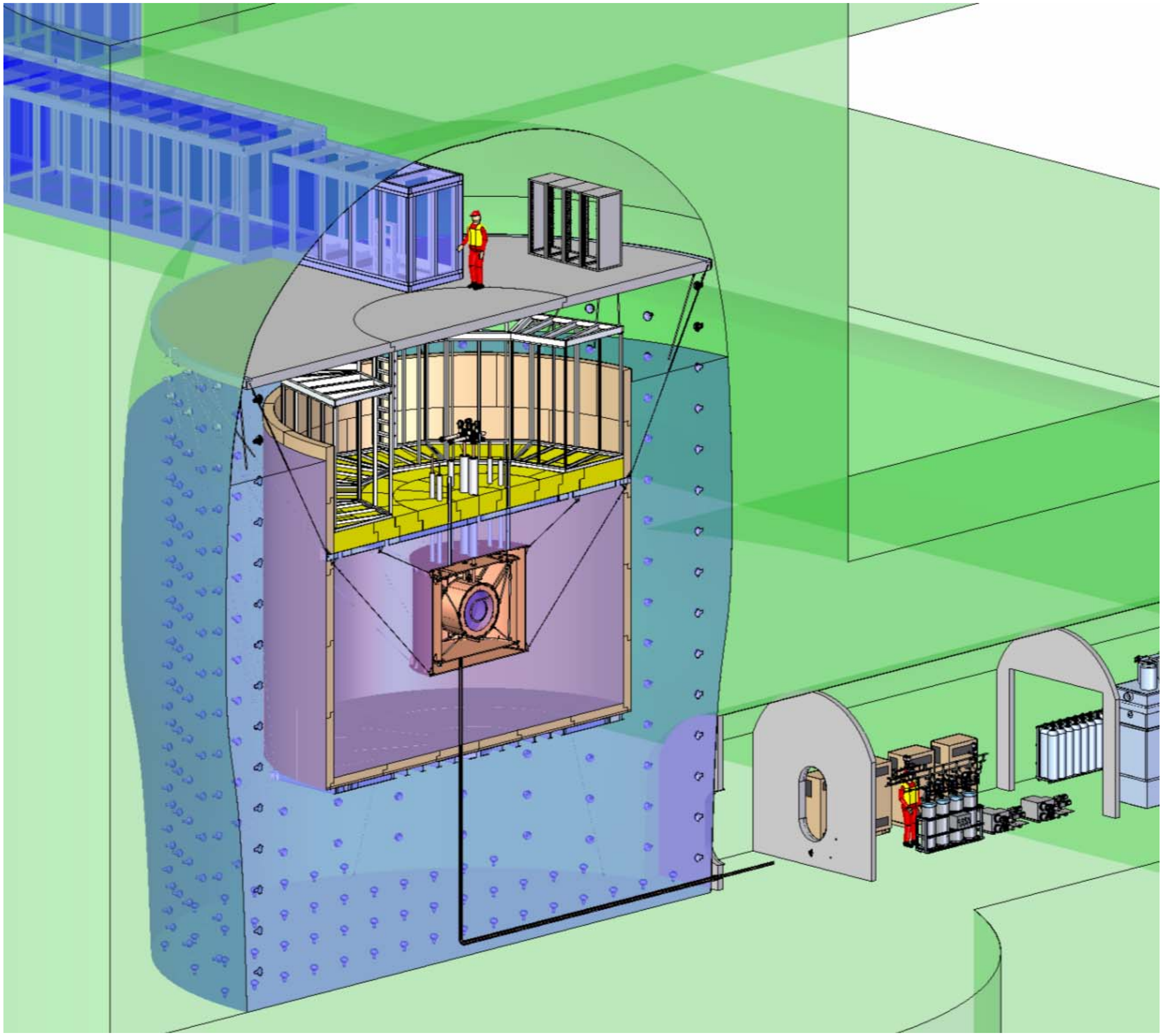
Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	MaGe/GeMa	Best from GERDA and Majorana	~1ton	
^{116}Cd	Cobra	Eres/tracking		Gran Sasso
^{48}Ca	CandlesIII	Size/shielding	0.35 kg	Oto-Cosmo
^{150}Nd	DCBA	Tracking	32 kg	
^{150}Nd ^{82}Se	MOON	Tracking		
^{82}Se	SuperNEMO	Tracking	~100 kg	Modane
	Lucifer	Eres + particle ID		
^{136}Xe	NEXT	Tracking/Eres	100 kg	Canfranc
	nEXO	Tracking/Eres, Phase2 Ba tag	5 ton	SNOlab(?)

nEXO @SNOlab

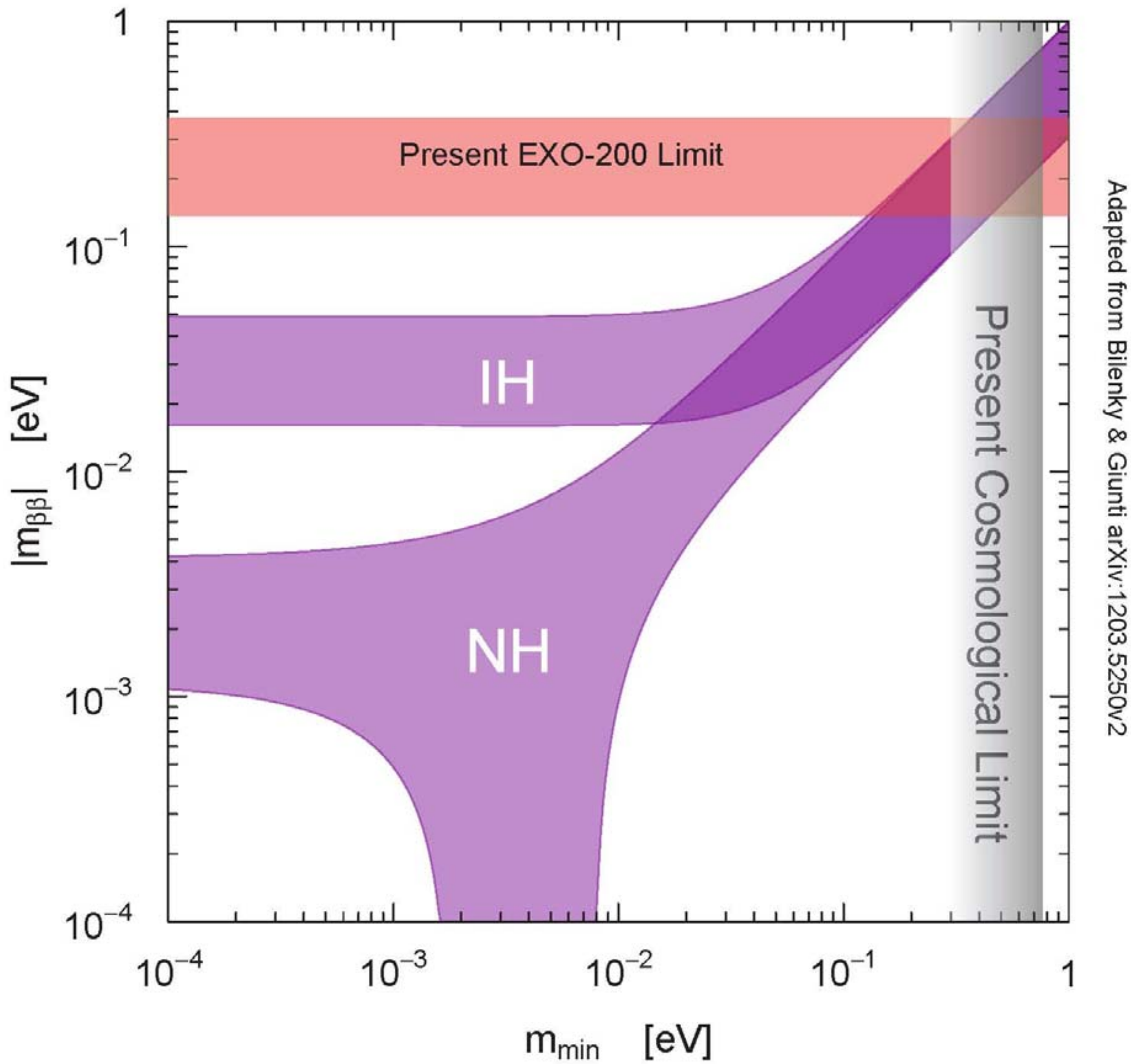
- 5 tonne LXe TPC "as similar to EXO-200 as possible"
- Provide access ports for a possible later upgrade to Ba tagging



nEXO in the SNOlab Cryopit with Xe and HFE Systems on Lower Level



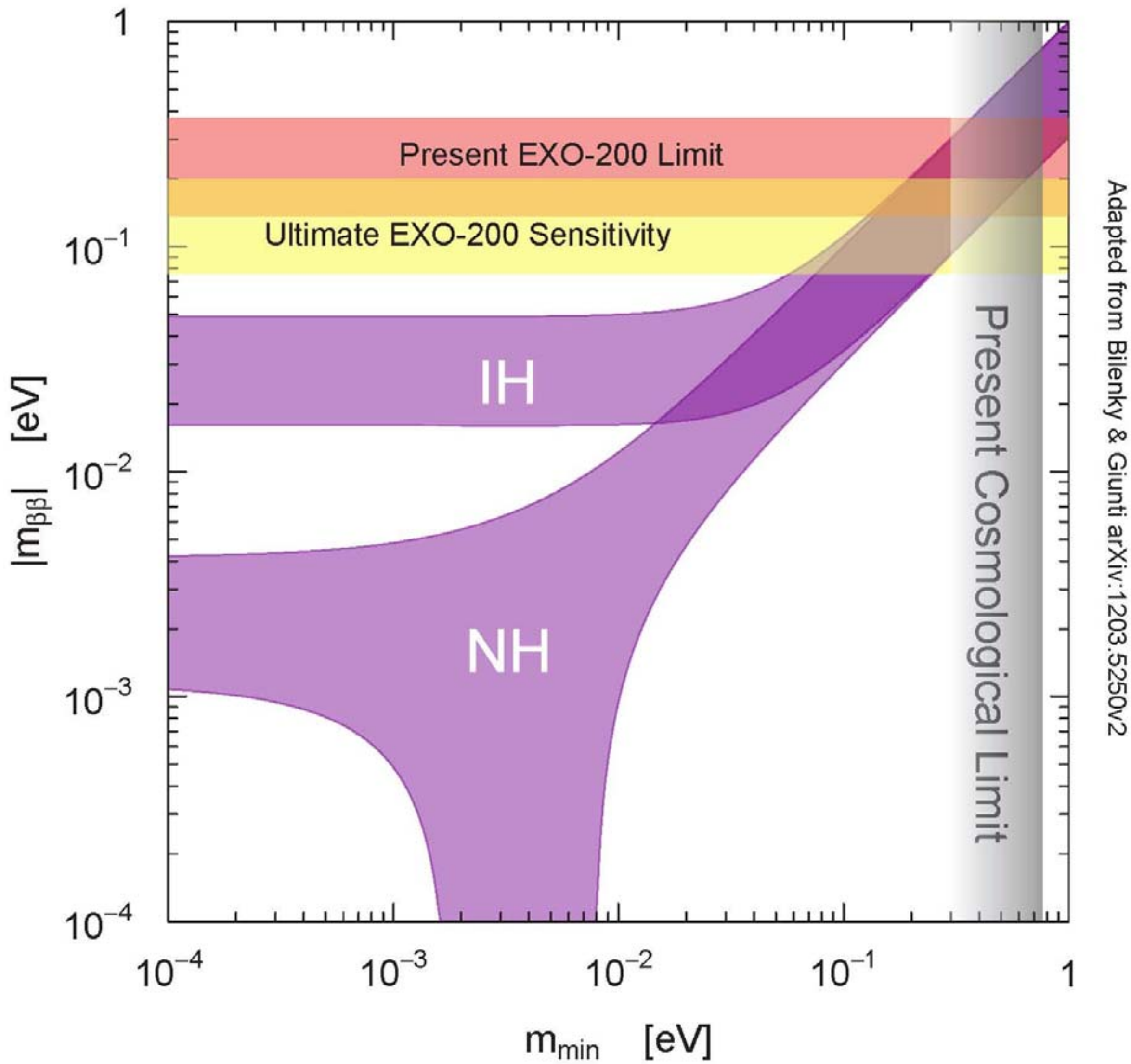
EXO-200 and nEXO projected sensitivities



Blue bands are 68%CL from oscillation experiments for "Inverted" and "Normal" Hierarchy

The EXO-200 "Present limit" is the 90%CL envelope of Limits (for different NMEs) from PRL 109 (2012) 032505

EXO-200 and nEXO projected sensitivities



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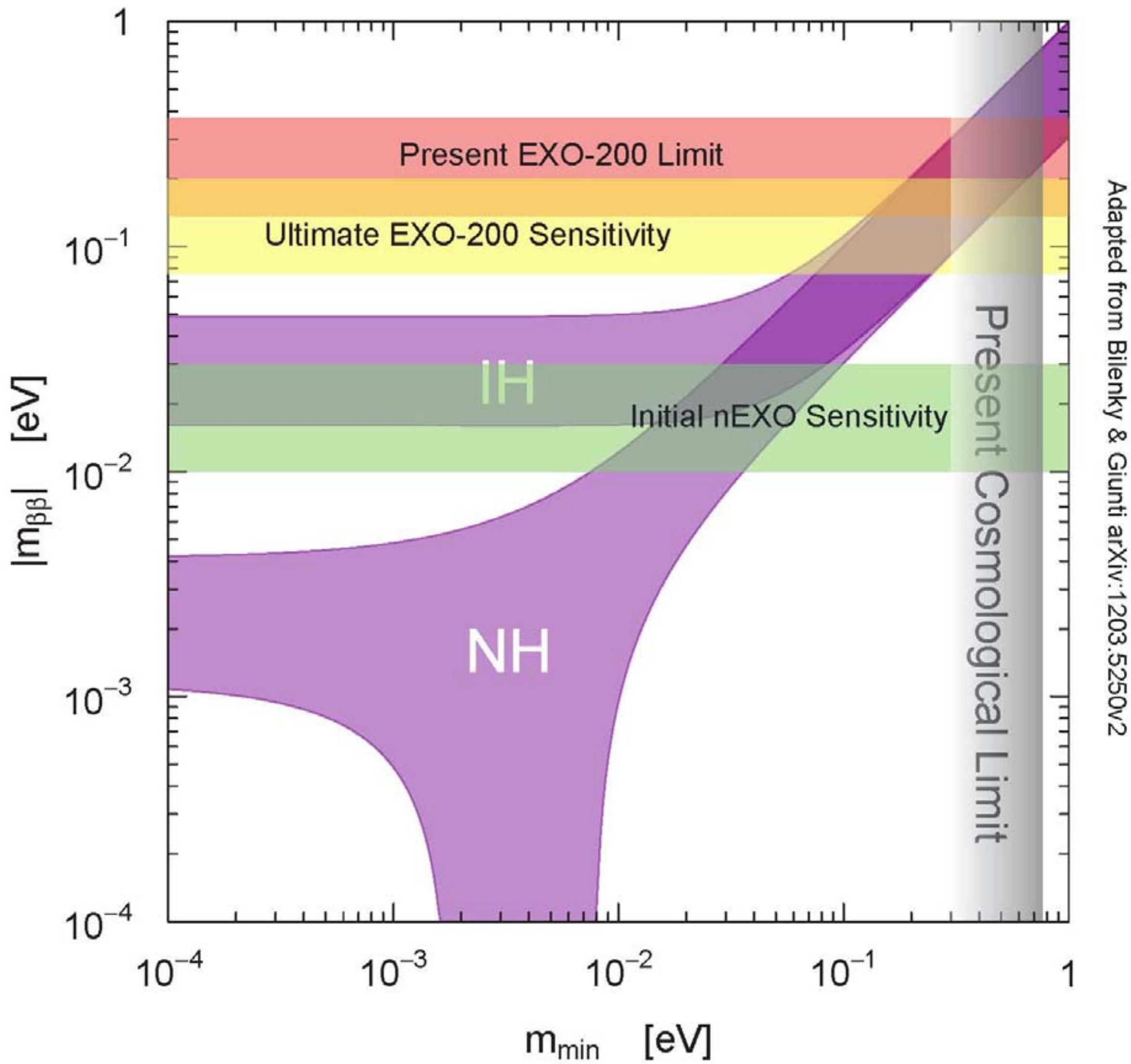
The EXO-200 "Ultimate" sensitivity: 90%CL for no signal in 4 yrs livetime with new analysis & Rn removal

EXO-200 and nEXO projected sensitivities



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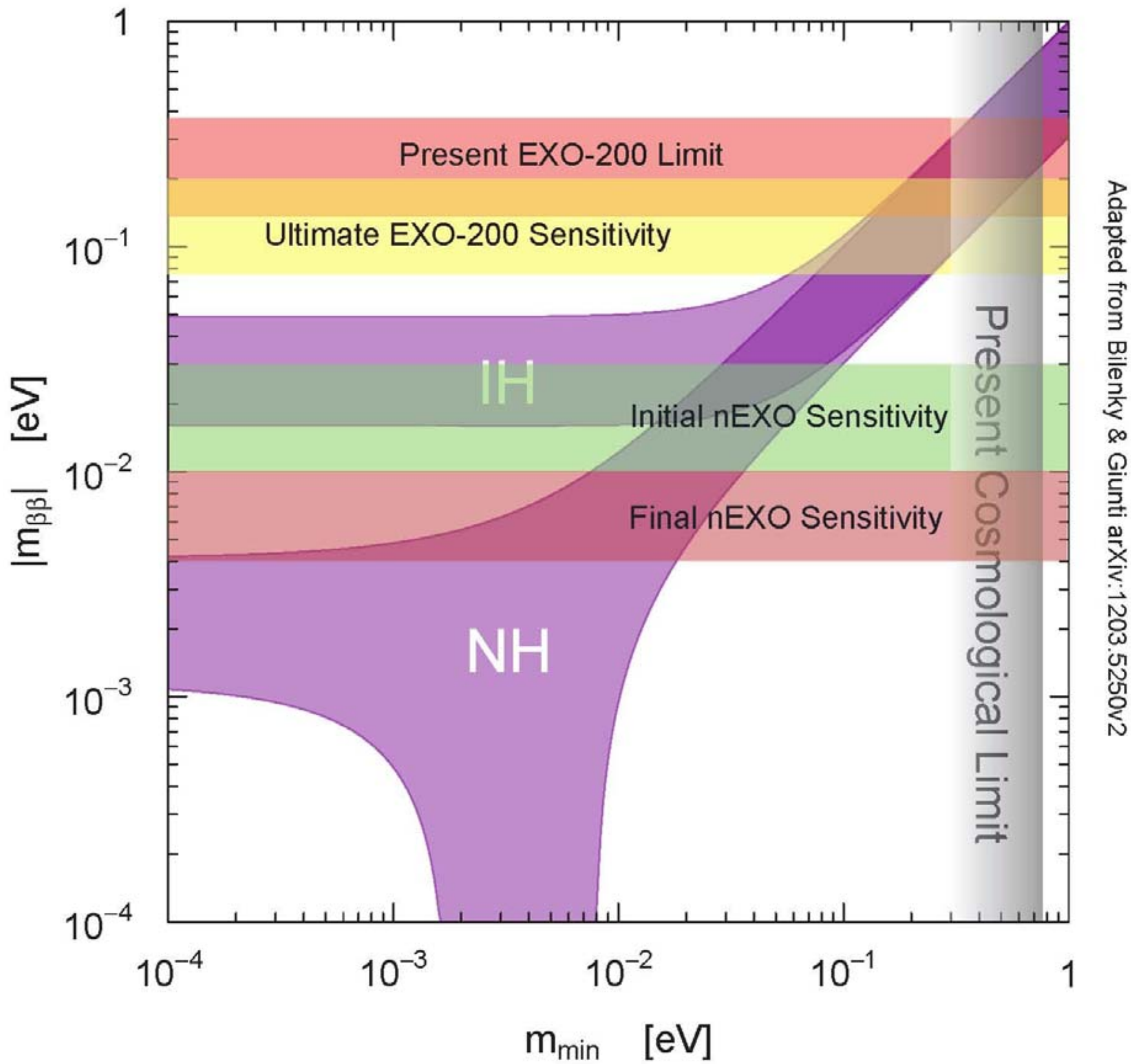
The "Initial nEXO" band refers to a detector directly scaled from EXO-200, including its measured background and 10yr livetime.

EXO-200 and nEXO projected sensitivities



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The "Initial nEXO" band refers to a detector directly scaled from EXO-200, including its measured background and 10yr livetime.

The "Final nEXO" band refers to the same detector and no background other than 2ν

Conclusions

Over the years neutrino physics has provided plenty of surprises and required forays in many different areas of science and technology

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

- **Isotope enrichment on a large scale is a reality**
- **100kg-class experiments have started data taking**
- **ton-class experiments are being planned for the near future using exquisite techniques**