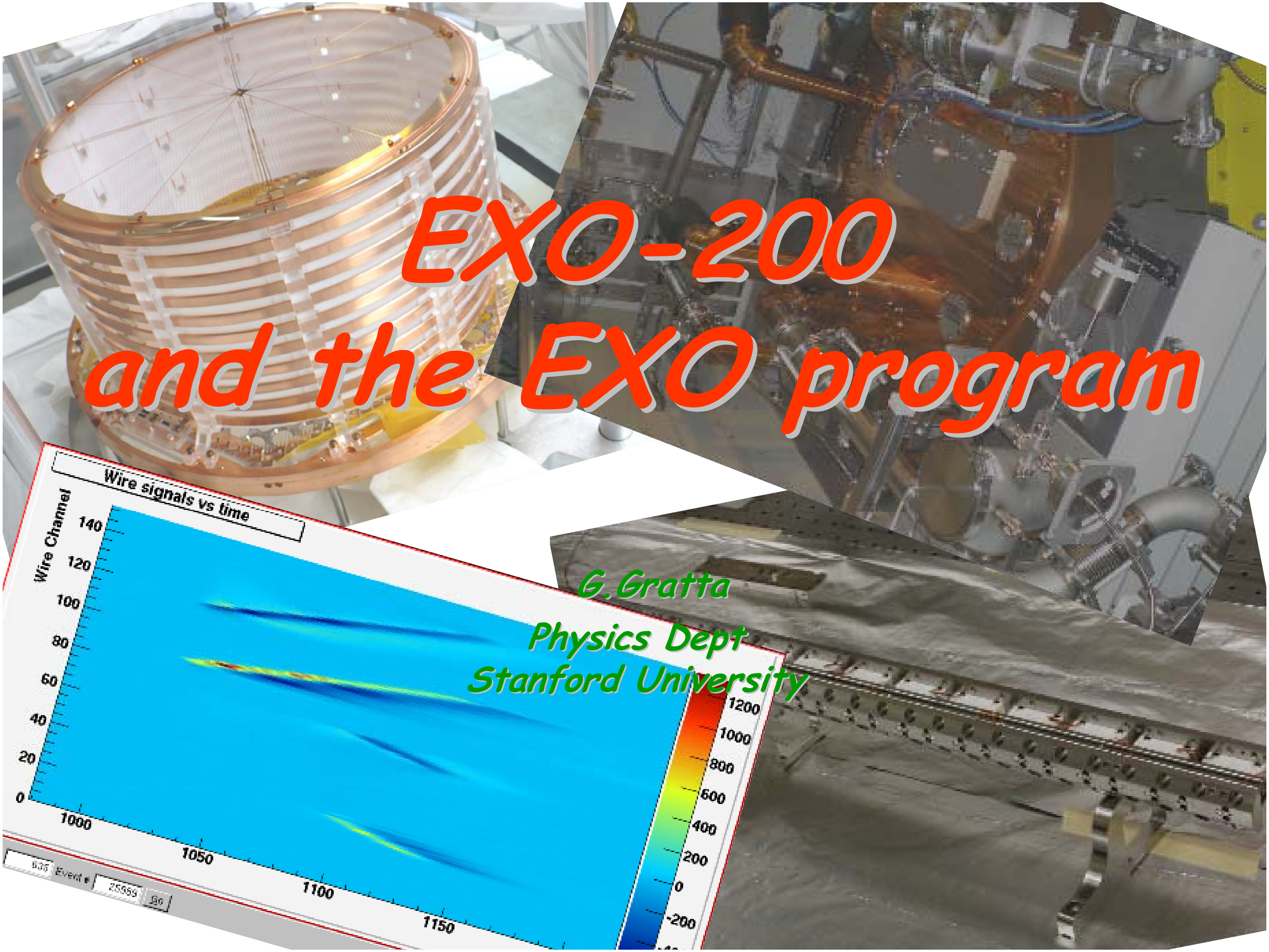
EXO-200
and the EXO program



G.Gratta
Physics Dept
Stanford University

Last 20 yrs: the age of ν physics

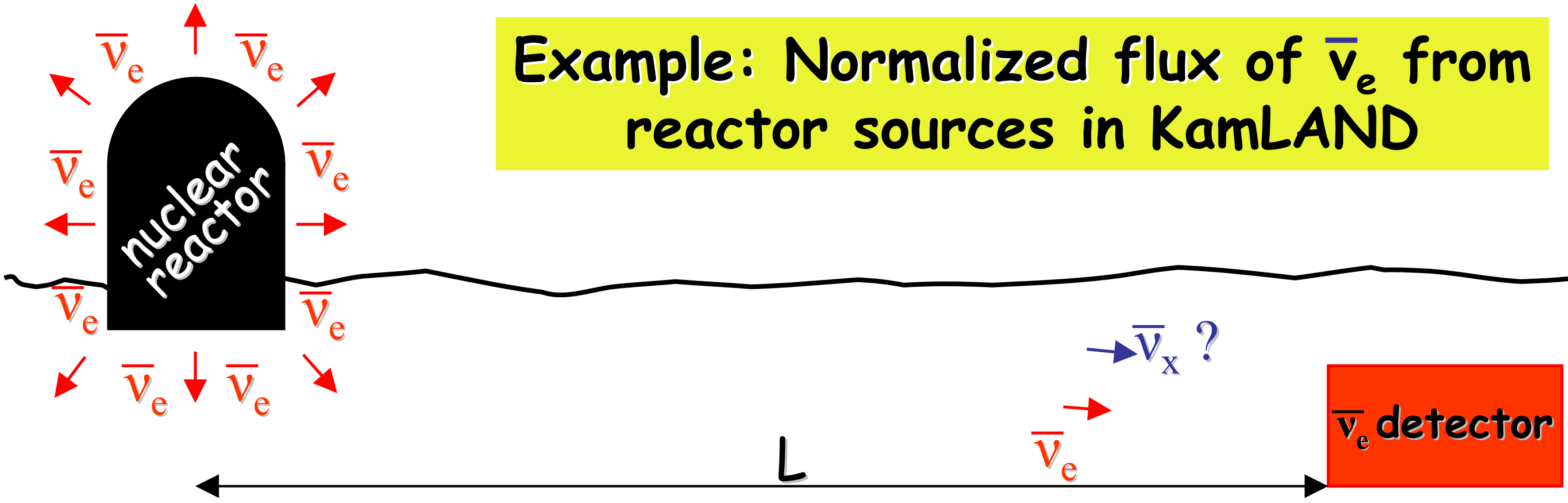
Discovery of ν flavor change

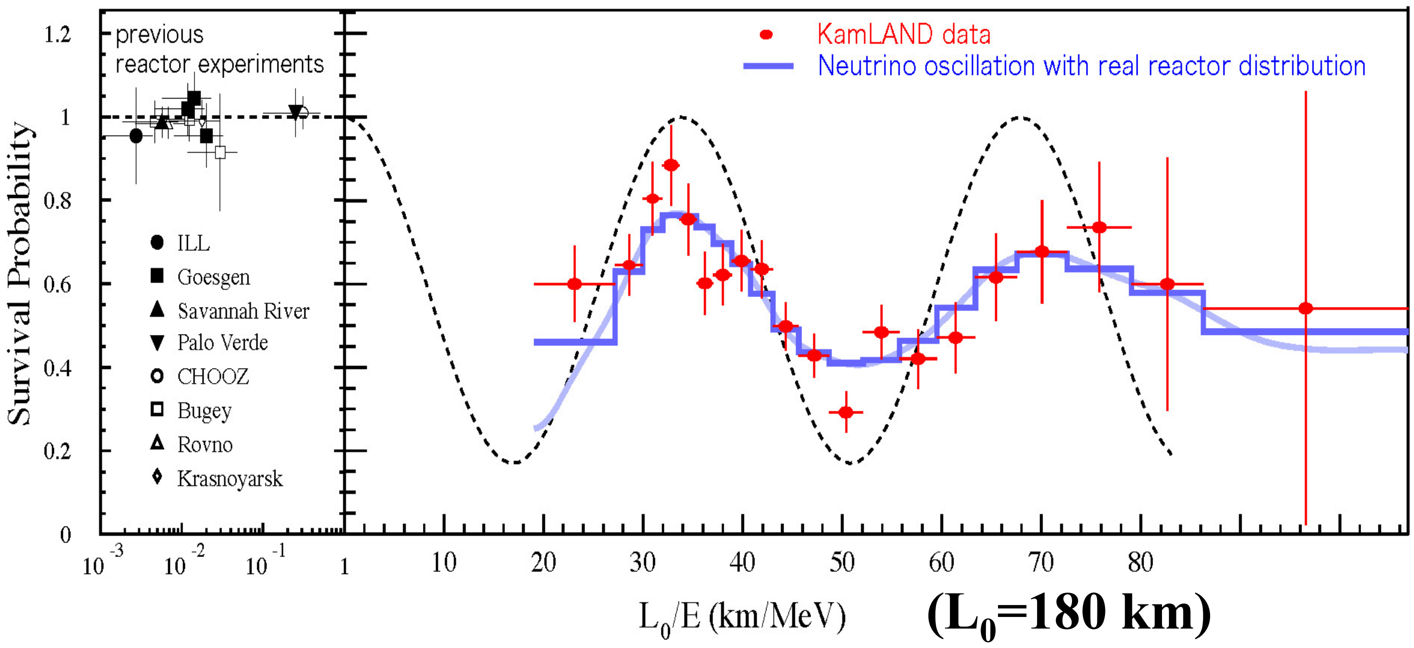
- *Solar neutrinos (MSW effect)*
- *Reactor neutrinos (vacuum oscillation)*
- *Atmospheric neutrinos (vacuum oscillation)*
- *Accelerator neutrinos (vacuum oscillation)*

We found that:

- ν masses are non-zero
- there are 2.981±0.008 ν (Z lineshape)
- 3 ν flavors were active in Big Bang Nucleosynthesis
- The Sun emits neutrinos as expected
- Supernovae emit neutrinos

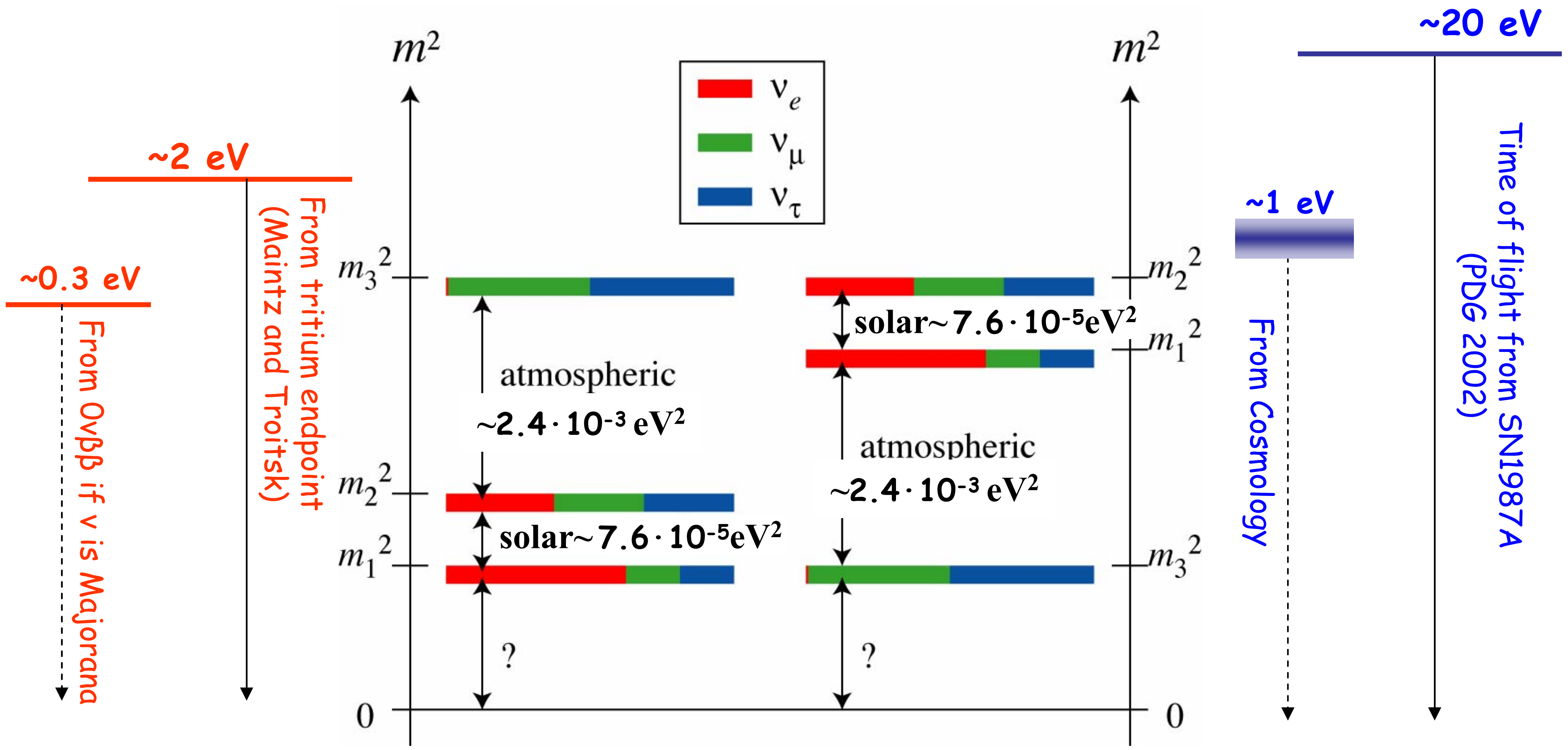
Example: Normalized flux of $\bar{\nu}_e$ from reactor sources in KamLAND





(L_0=180 km)

Our knowledge of the ν mass pattern



~0.3 eV

From 0νββ if ν is Majorana

~2 eV

From tritium endpoint (Maintz and Troitsk)

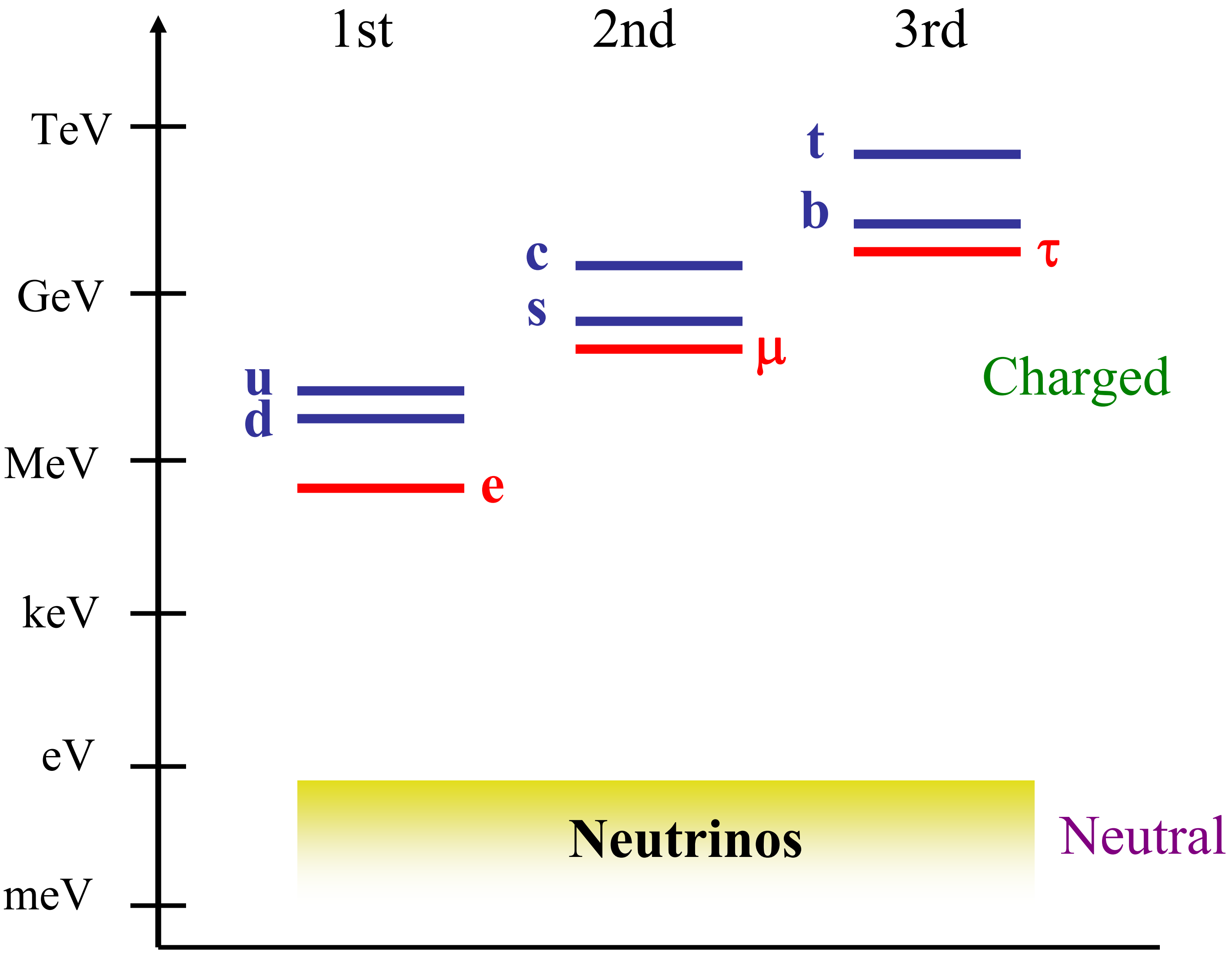
~1 eV

From Cosmology

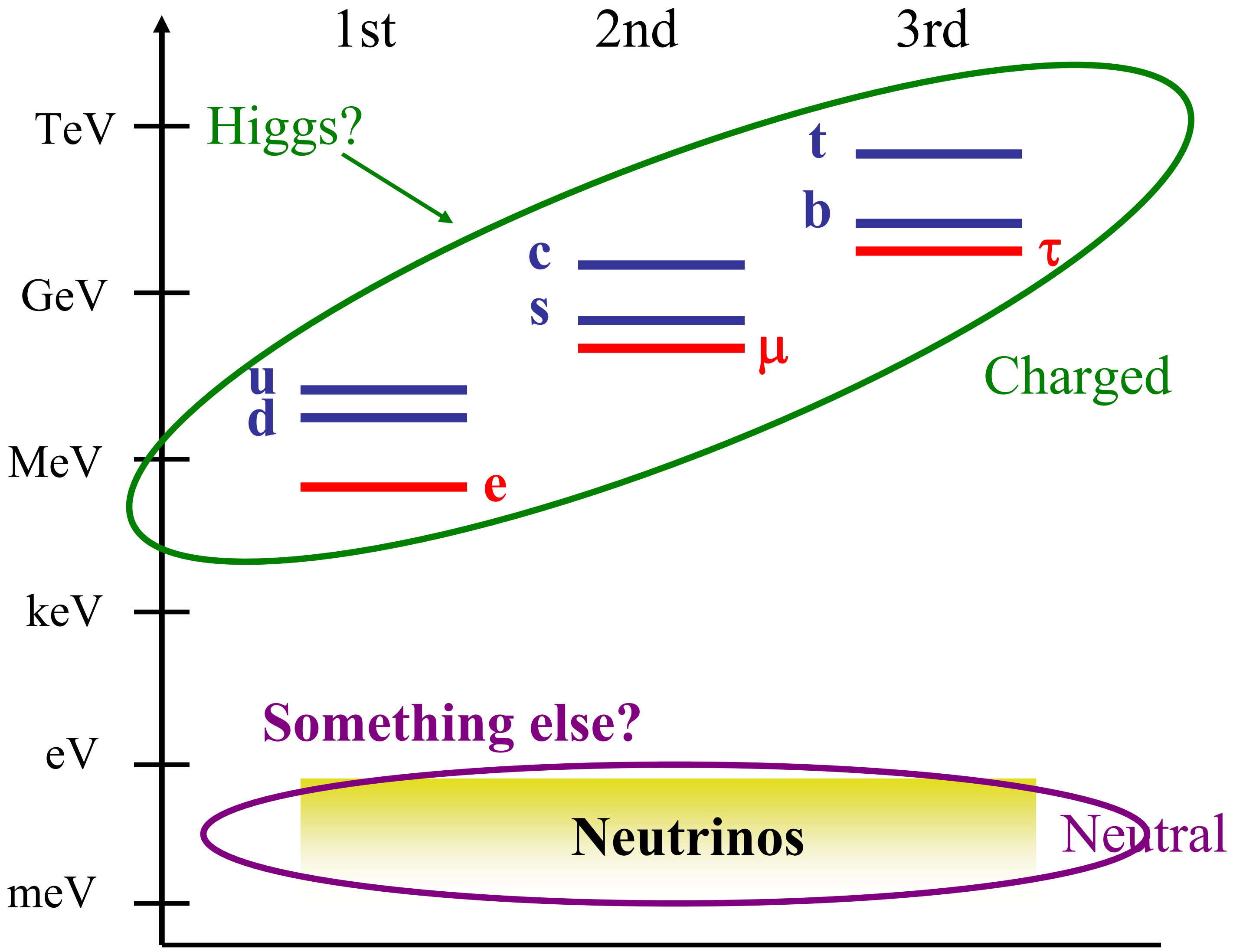
~20 eV

Time of flight from SN1987A (PDG 2002)

Fermion mass spectrum



Fermion mass spectrum



Neutrinos have other peculiarities: They are the only electrically neutral fermions

		Generation		
		1st	2nd	3rd
	1	e^+	μ^+	τ^+
	2/3	u	c	t
	1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
Charge	0	ν_e	ν_μ	ν_τ
	-1/3	d	s	b
	-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
	-1	e^-	μ^-	τ^-

Neutrinos do not carry charge
What about lepton number?

Could it be that the mass and charge peculiarities are somehow related?

Say that for neutrinos $\overline{\nu} = \nu$, since they have no charge…

But… isn't there a lepton number to conserve?

No worries: lepton number conservation is not as "serious" as energy conservation

Lepton number conservation is just an empirical notion.

Basically lepton number is conserved "because", experimentally, $\overline{\nu} \neq \nu$ Of course this is verified only to a certain accuracy

We have two possible ways to describe the neutrino:

“Dirac” neutrinos

(some “redundant” information but the “good feeling” of things we know…)

$$\nu^D = \begin{pmatrix} \nu_L \\ \overline{\nu}_L \\ \nu_R \\ \overline{\nu}_R \end{pmatrix}$$

“Majorana” neutrinos

(more efficient description, no lepton number conservation, new paradigm…)

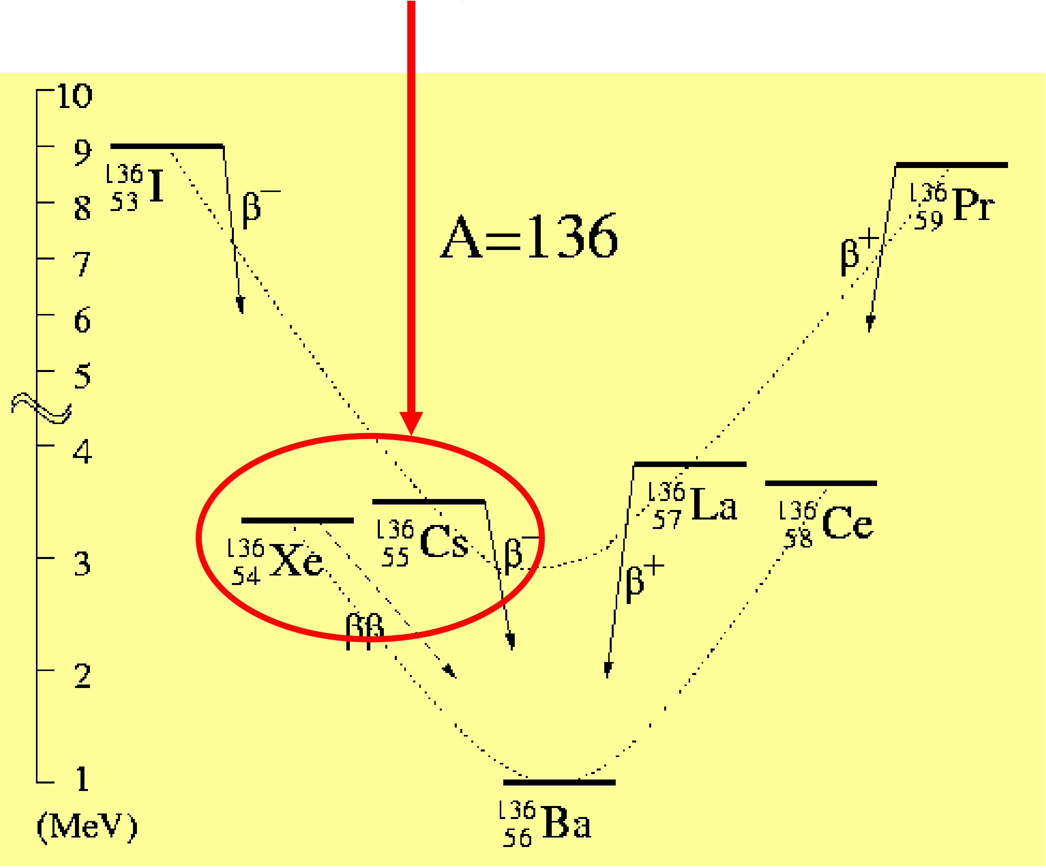
$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Which way Nature chose to proceed is an experimental question

But the two descriptions are distinct and distinguishable only if $m_\nu \neq 0$

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:

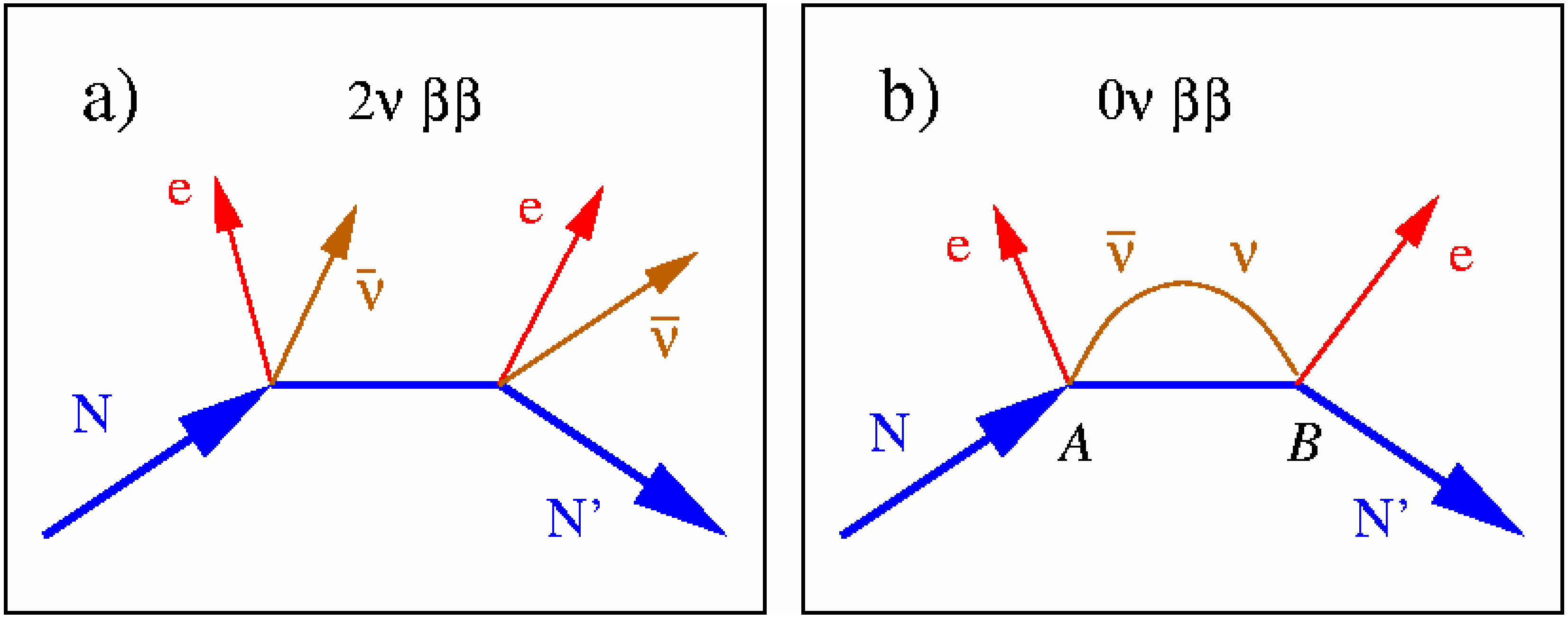
a conventional
2^{nd} order process
in nuclear physics

0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$

$\nu = \overline{\nu}$

$|\Delta L|=2$

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



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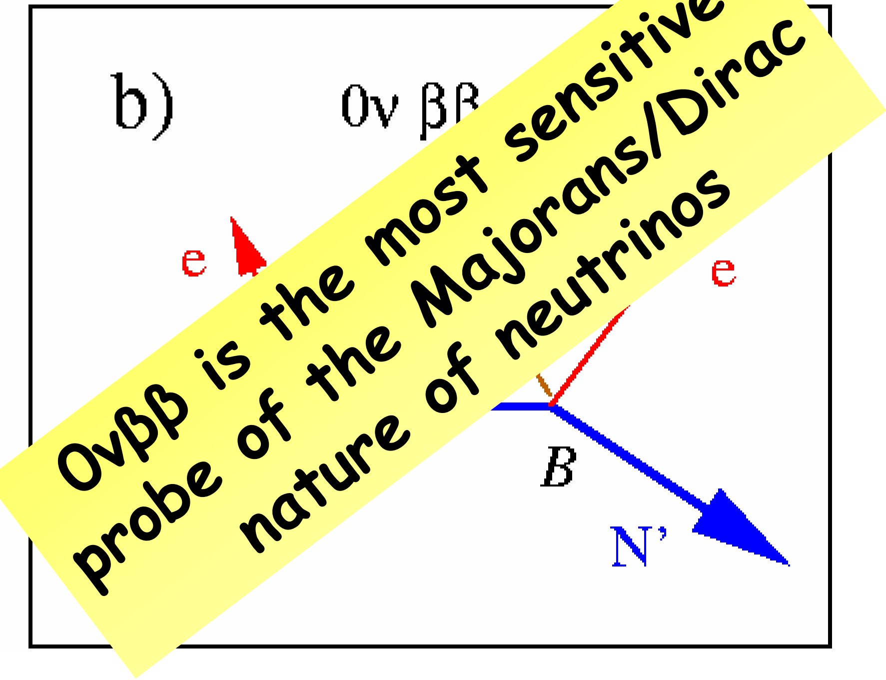


0νββ is the most sensitive probe of the Majorans/Dirac nature of neutrinos

If 0νββ 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

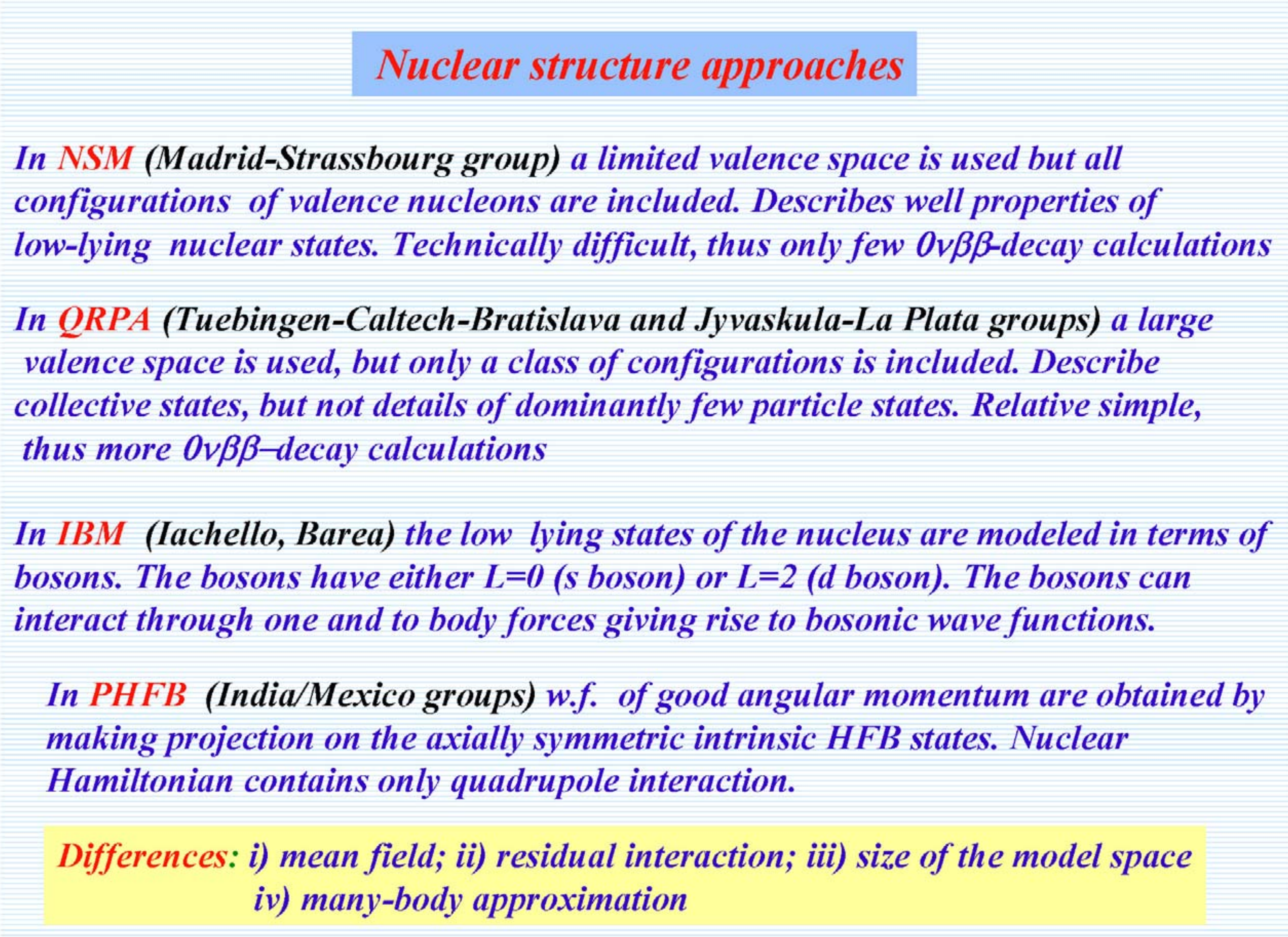
$G^{0\nu\beta\beta}$ a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ 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)



Nuclear structure approaches

In NSM **(Madrid-Strassbourg group)** *a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states. Technically difficult, thus only few 0νββ-decay calculations*

In QRPA **(Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata groups)** *a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more 0νββ–decay calculations*

In IBM **(Iachello, Barea)** *the low lying states of the nucleus are modeled in terms of bosons. The bosons have either L=0 (s boson) or L=2 (d boson). The bosons can interact through one and to body forces giving rise to bosonic wave functions.*

In PHFB **(India/Mexico groups)** *w.f. of good angular momentum are obtained by making projection on the axially symmetric intrinsic HFB states. Nuclear Hamiltonian contains only quadrupole interaction.*

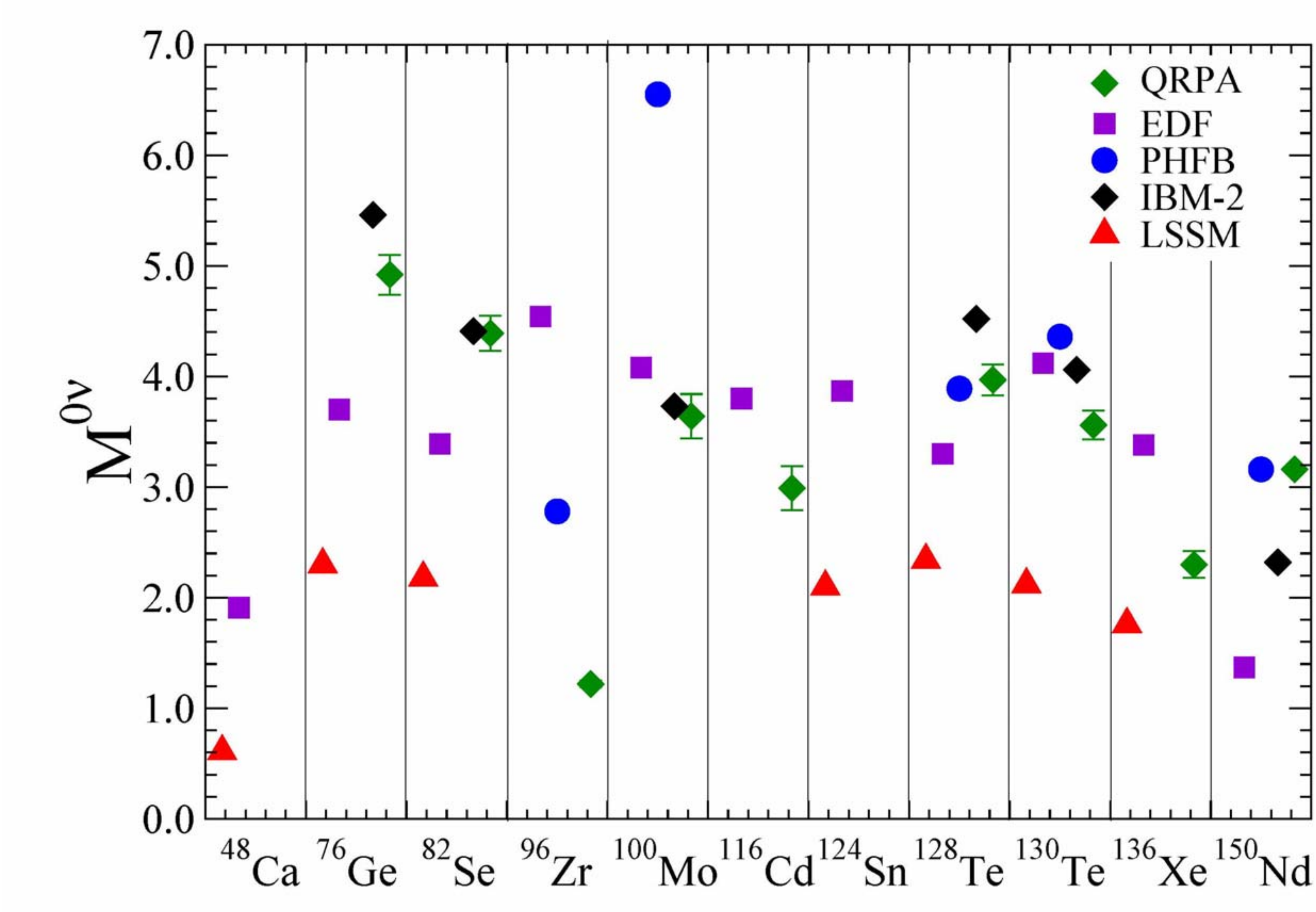
Differences: i) mean field; ii) residual interaction; iii) size of the model space iv) many-body approximation

F. Simkovic, Neutrino 2010

Good news: a number of new groups and ideas are entering the game!

Calculations differ by about a factor of two

(but care is necessary in treating some of them generally regarded as obsolete)



S.M. Bilenky and C.Giunti arXiv:1203.5250v2

Note, however, that to discover Majorana neutrinos and lepton number violation the value of the nuclear matrix element is inessential!

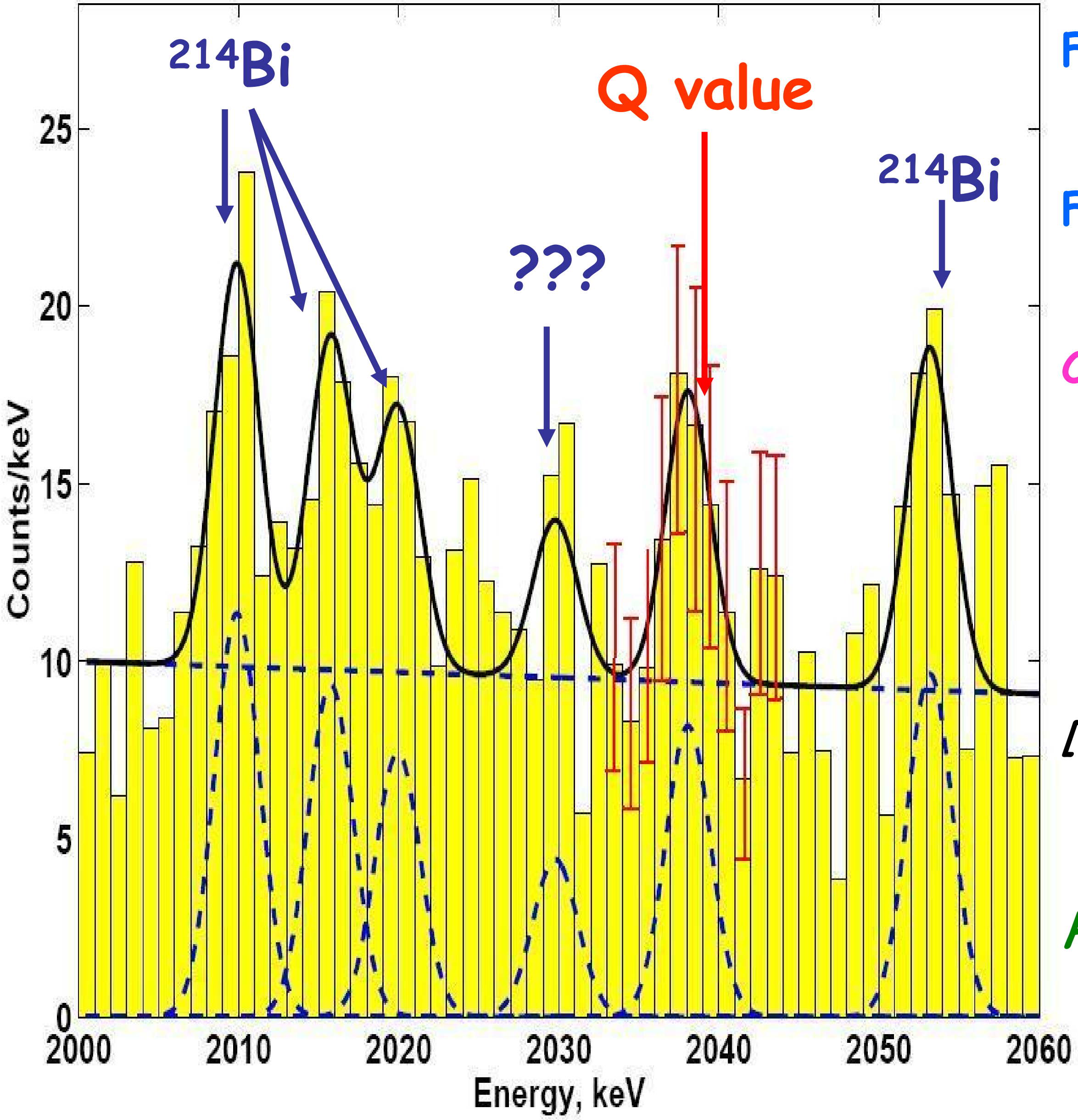
→ $0\nu\beta\beta$ decay always implies new physics

This is comforting for the ones of us spending their time building experiments!

Simplified List of Limits for ββ0ν decay (pre-2012)

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			>5.8*10^{22} (90%CL)	
^{76}Ge	Ge diode	47.7	>1.9*10^{25} (90%	<0.35
^{82}Se			>2.1*10 L)	
^{96}Zr			>9 (90%CL)	
^{100}Mo	Foil.Geiger tubes		10^{23} (90%CL)	
^{116}Cd			1.7*10^{23} (90%CL)	
^{128}Te			>1.1*10^{23} (90%CL)	
^{130}Te	TeO$_2$	12	>3*10^{24} (90%CL)	<0.19-0.68
^{136}Xe	X	~4.5	>1.2*10^{24} (90%CL)	<1.1-2.9
^{150}Nd			>1.8*10^{22} (90%CL)	
160			>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

$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}\, yr$$

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

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

*However, this is a
very controversial matter*

Before moving on, let's take a look at the $2\nu\beta\beta$ decay, a Standard Model process that has been observed in many isotopes

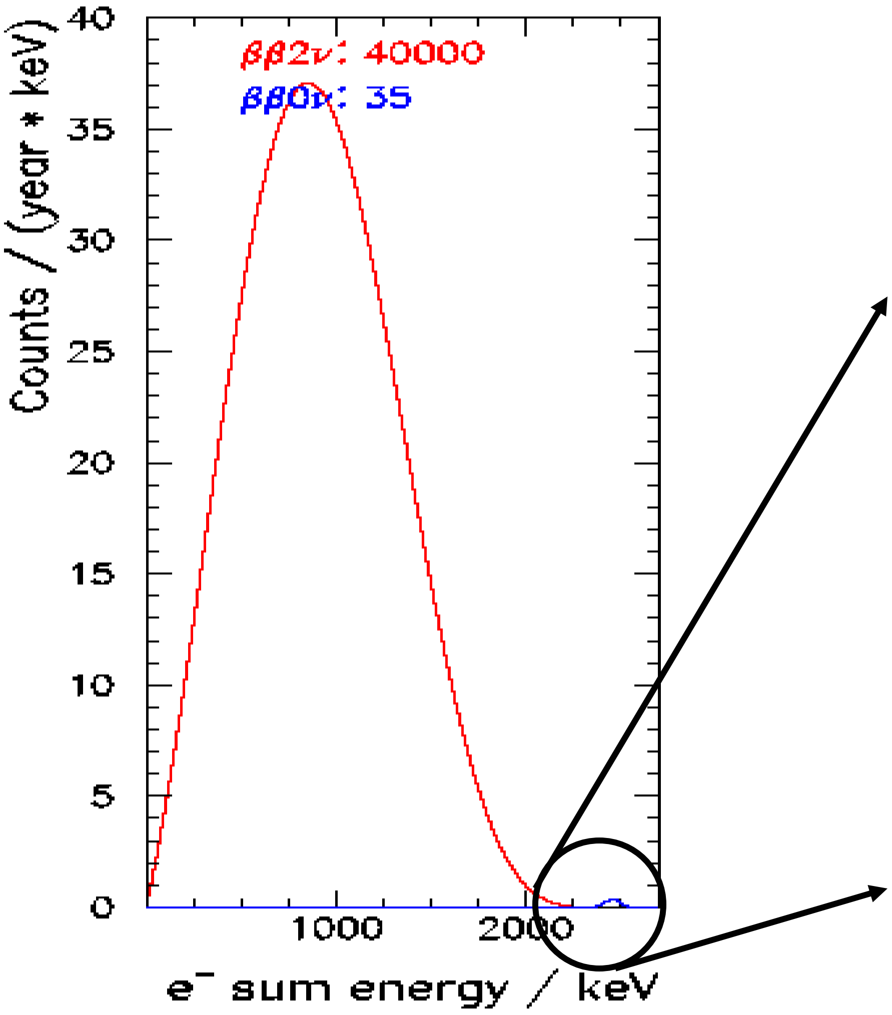
Isotope	Experimental $T_{1/2}^{2\nu}$ (yr)
^{48}Ca	$(4.3\pm2.2)\cdot10^{19}$
^{76}Ge	$(1.77\pm0.12)\cdot10^{21}$
^{82}Se	$(9.6\pm1)\cdot10^{19}$
^{96}Zr	$(9.4\pm3.2)\cdot10^{18}$ § $(2.1\pm0.6)\cdot10^{19}$
^{100}Mo	$(5.7\pm1.2)\cdot10^{20}$
^{116}Cd	$(2.9\pm0.4)\cdot10^{19}$
^{128}Te	$(7.2\pm0.4)\cdot10^{24}$ §
^{130}Te	$(7\pm0.9\pm1.1)\cdot10^{20}$
^{136}Xe	$>1.1\cdot10^{22}$ 90% CL
^{150}Nd	$(1.4\pm0.7)\cdot10^{20}$
^{238}U	$(2.0\pm0.6)\cdot10^{21}$ *

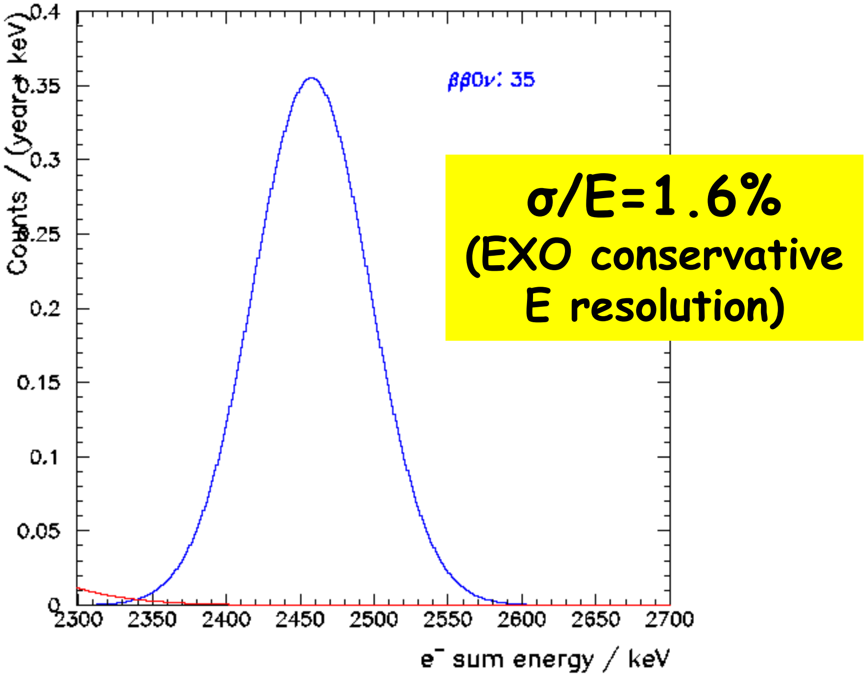
§Geochemical experiment
*Radiochemical experiment

← More on this later!

Pre-Aug 2011 table
arbitrarily simplified
from PDG

Background due to the Standard Model 2νββ decay





σ/E=1.6%
(EXO conservative E resolution)

The two can be separated in a detector with sufficiently good energy resolution

Topology and particle ID are also important to recognize backgrounds

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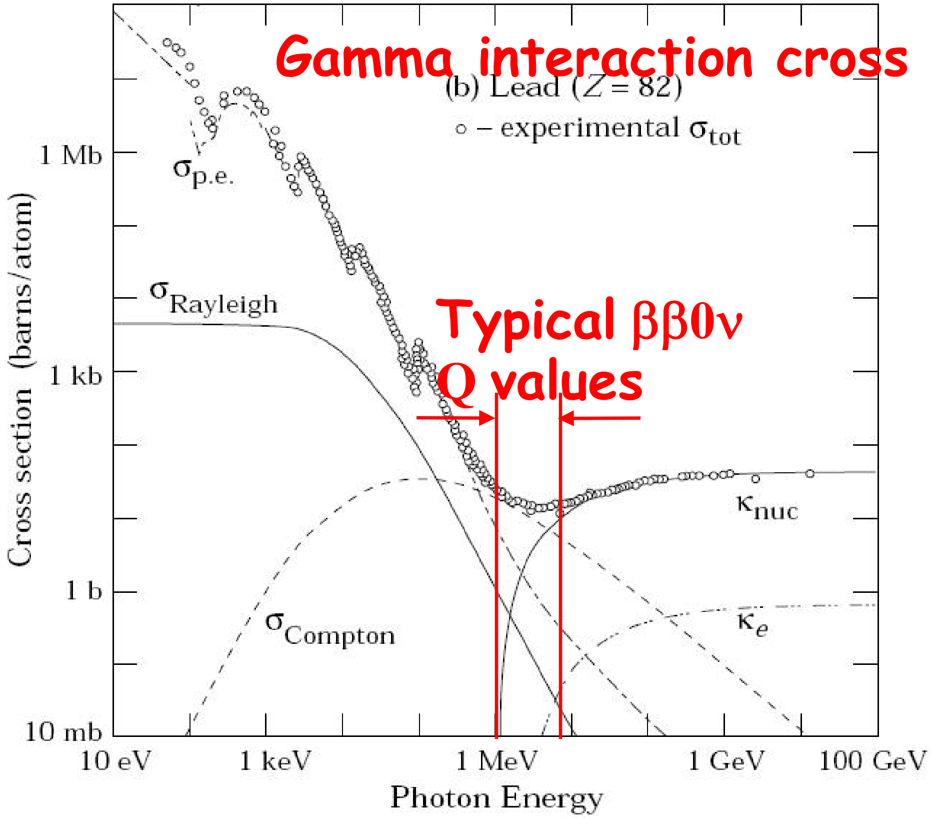
For no bkgnd $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

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

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



Gamma interaction cross section

Typical ββ0ν Q values

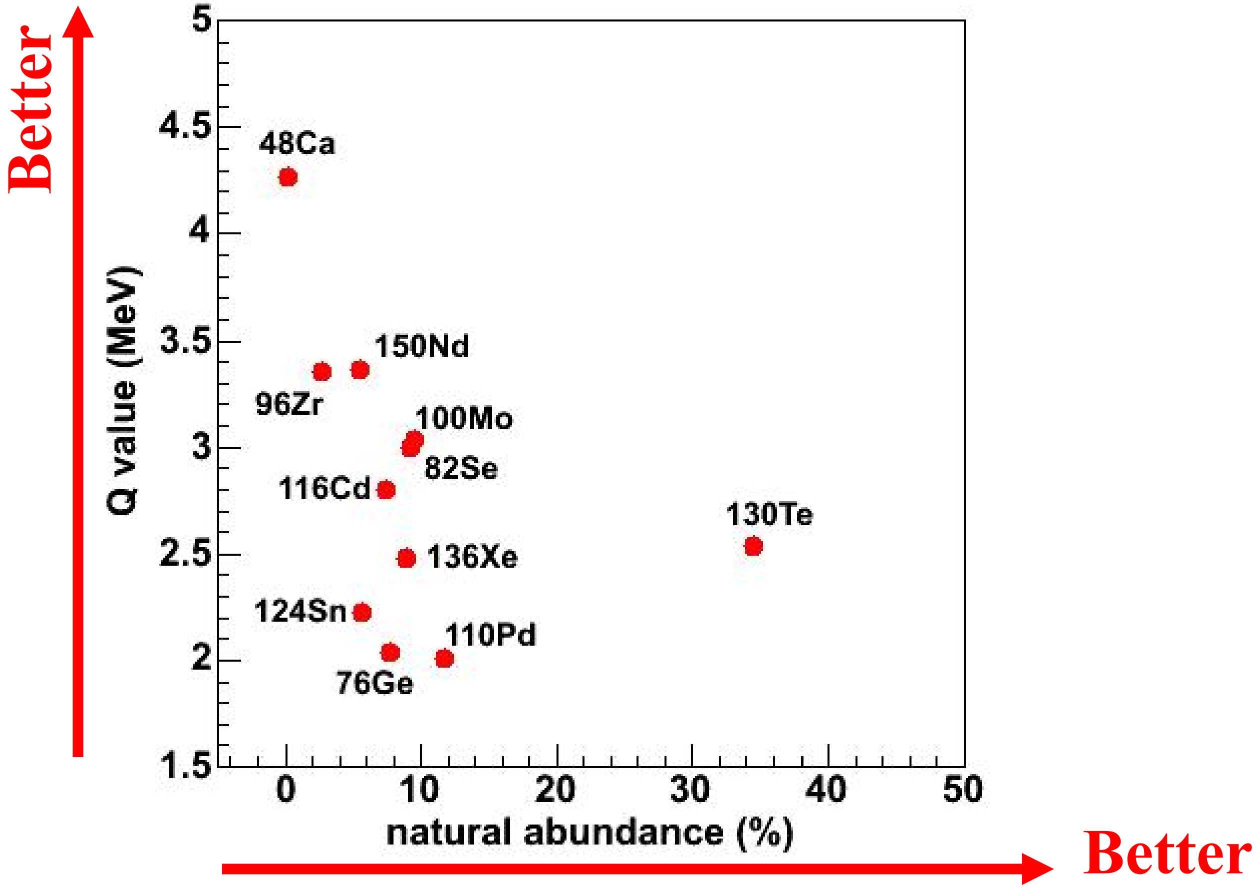
Example:

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

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

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 (apparently quite small for ^{136}Xe)*
- *The elucidation of the mechanism producing the decay requires the analysis of more than one isotope*

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

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  - \- No distinction between 0ν, 2ν or other modes

Need a real time detector to discover $\beta\beta0\nu$!!
(…also IDing the final state would be nice)

- "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

Xe is ideal for a large experiment

- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu
- Only known case where final state identification appears to be not impossible
  → elominate all non-ββ backgrounds
- ^{129}Xe is a hyperpolarizable nucleus, under study for NMR tomography… a joint enrichment program ?

Ba-tagging, added to a high resolution Xe imaging detector may provide the tools to develop a background-free experiment with the highest possible sensitivity

Assume an ultimate fiducial mass of 5 tons of ^{136}Xe at 80%

Mainly going in light bulbs, plasma displays and satellite propulsion

A somewhat natural scale:

- World production of Xe is ~40 ton/yr
- Detector size
- $2 \cdot 10^3$ size increase: good match to the 10^{-2} eV mass region

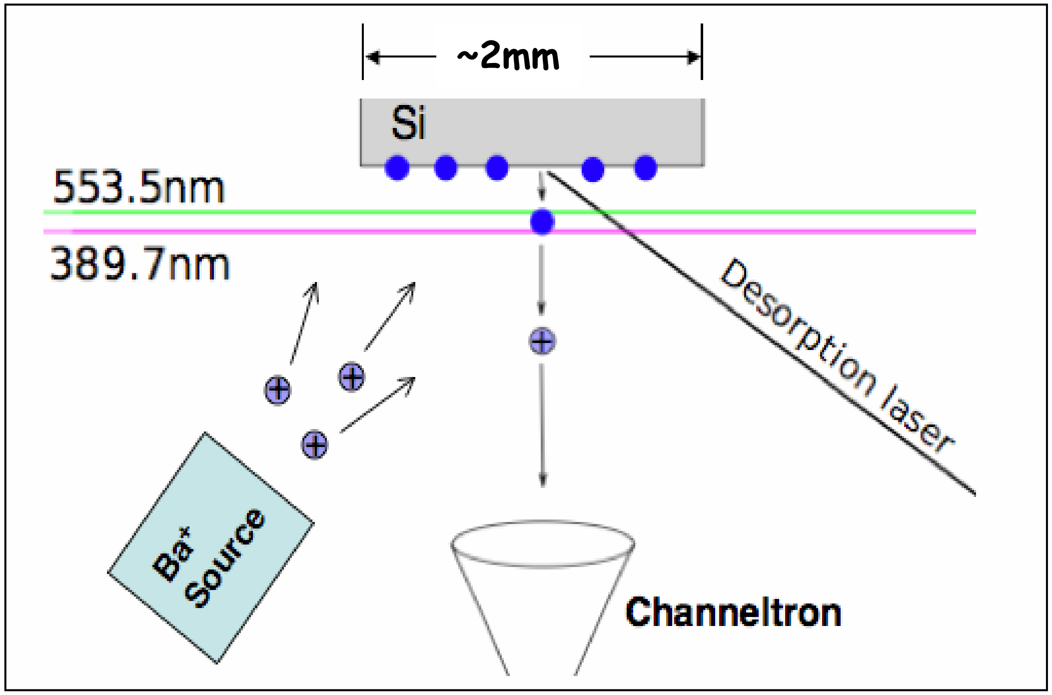
Substantial R&D program to tag in quasi-real-time the final state Ba atom

Test several techniques

- Retrieve Ba from LXe and feed it to an ion trap with spectroscopic identification
  - Hot probe mover
  - Icy probe
- RIS probe
- Tag from gas

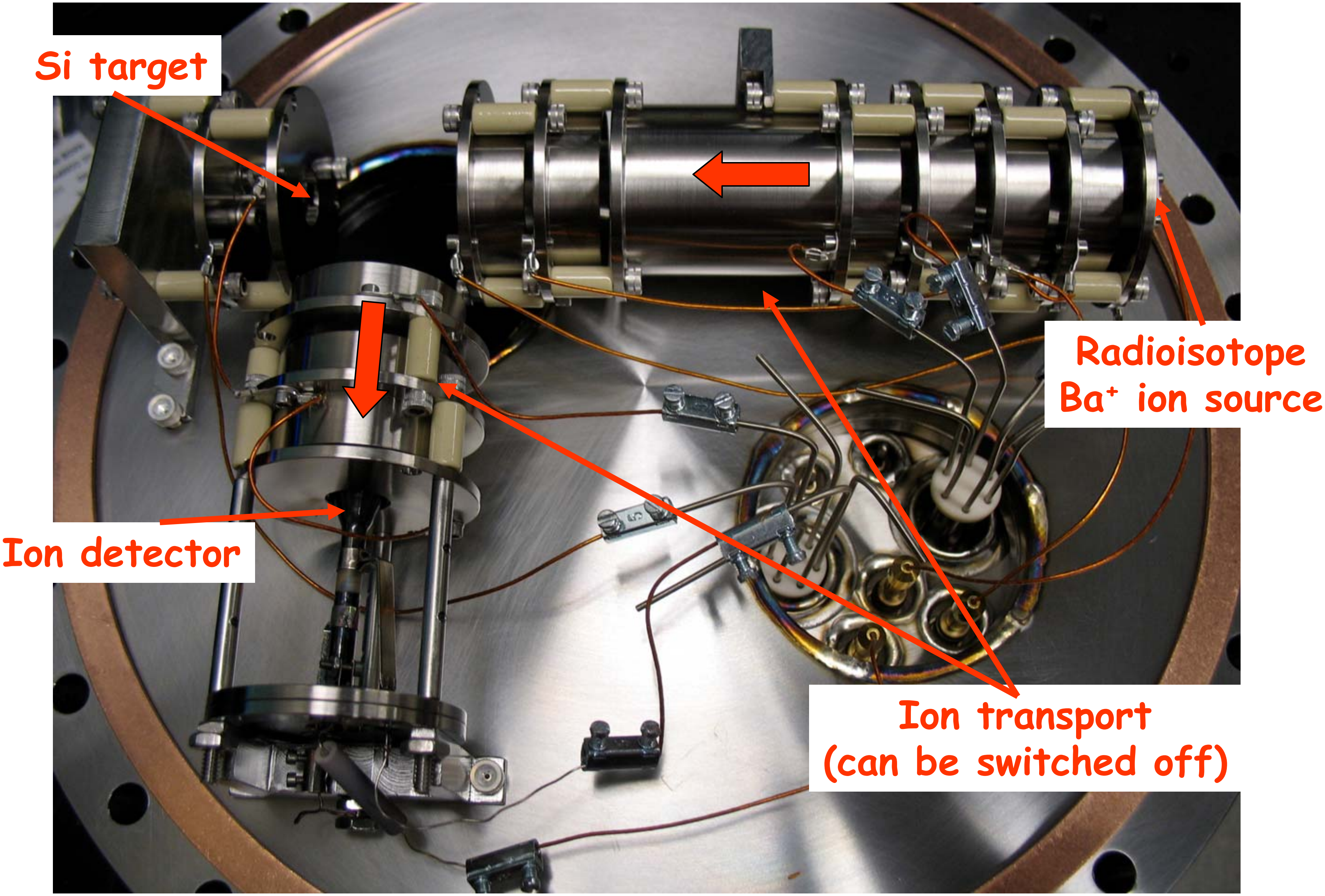
Ba transport/tagging by Resonant Ionization Spectroscopy

- Ba^+ or Ba^{++} is electrostatically attracted (from LXe) onto a clean substrate (Si works well)
- The substrate is transported to vacuum
- An 1064nm YAG laser pulse is used to desorb the Ba
- ~1μs later a pair of laser pulses of appropriate freq re-ionize to Ba^+

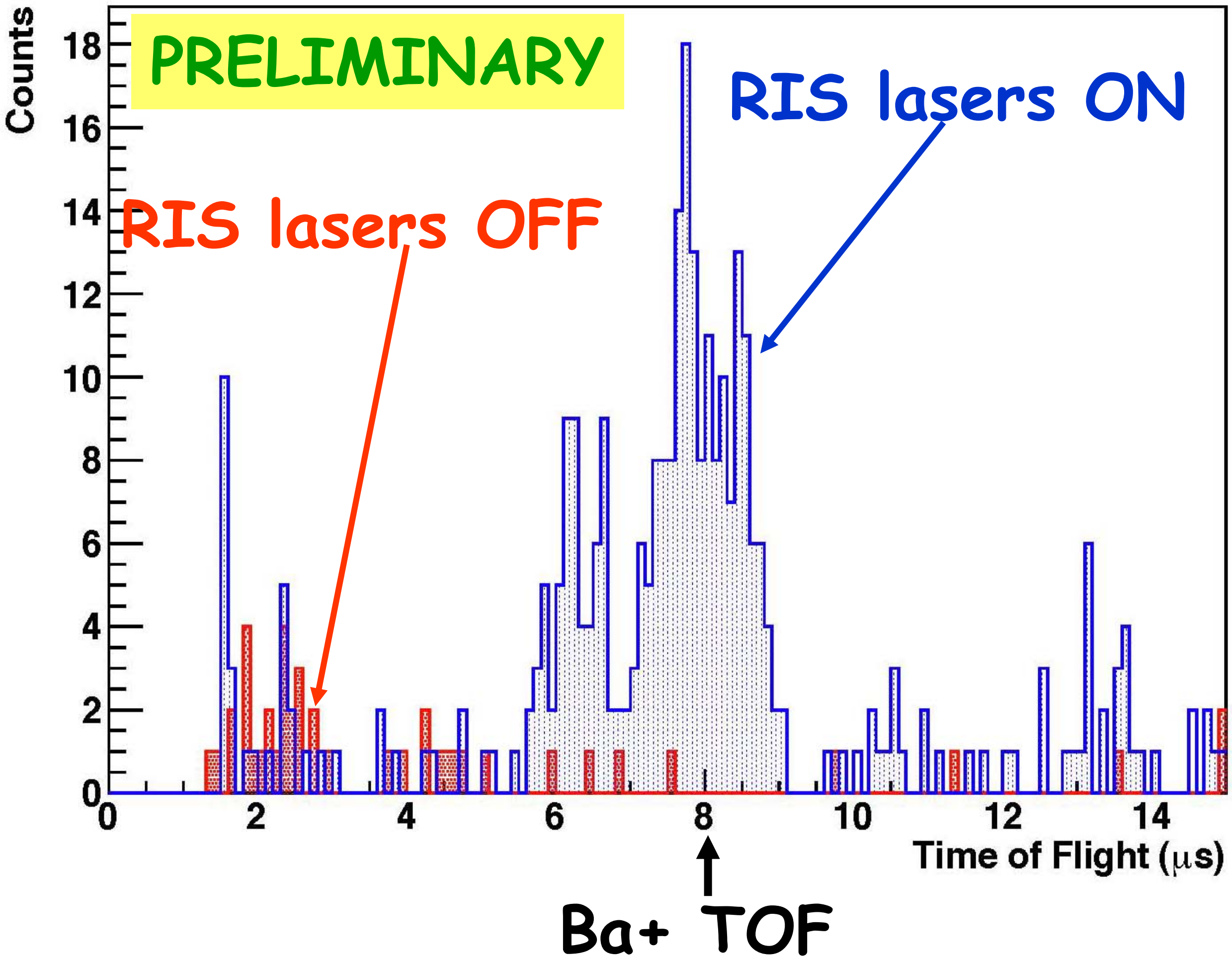


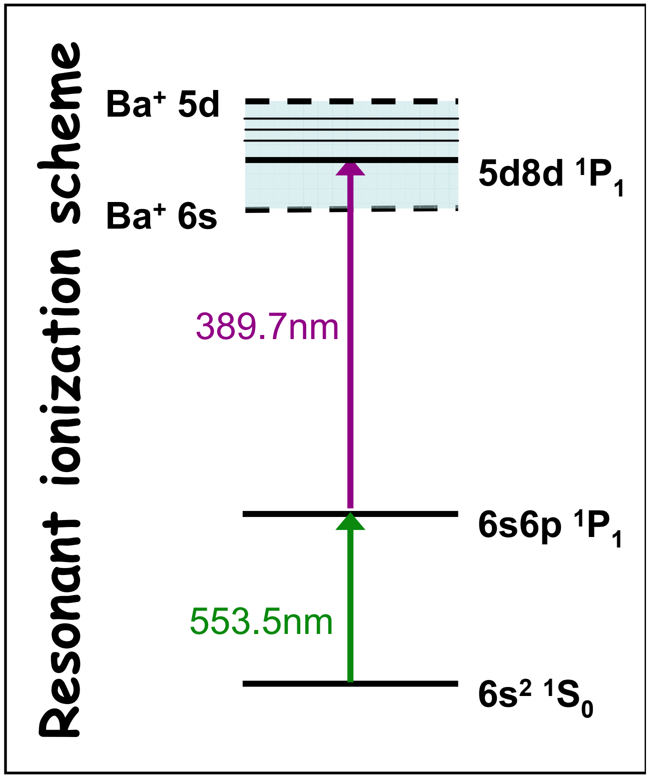
- For the moment test uses stationary substrate in vacuum

Clean apparatus, never exposed to Ba beam

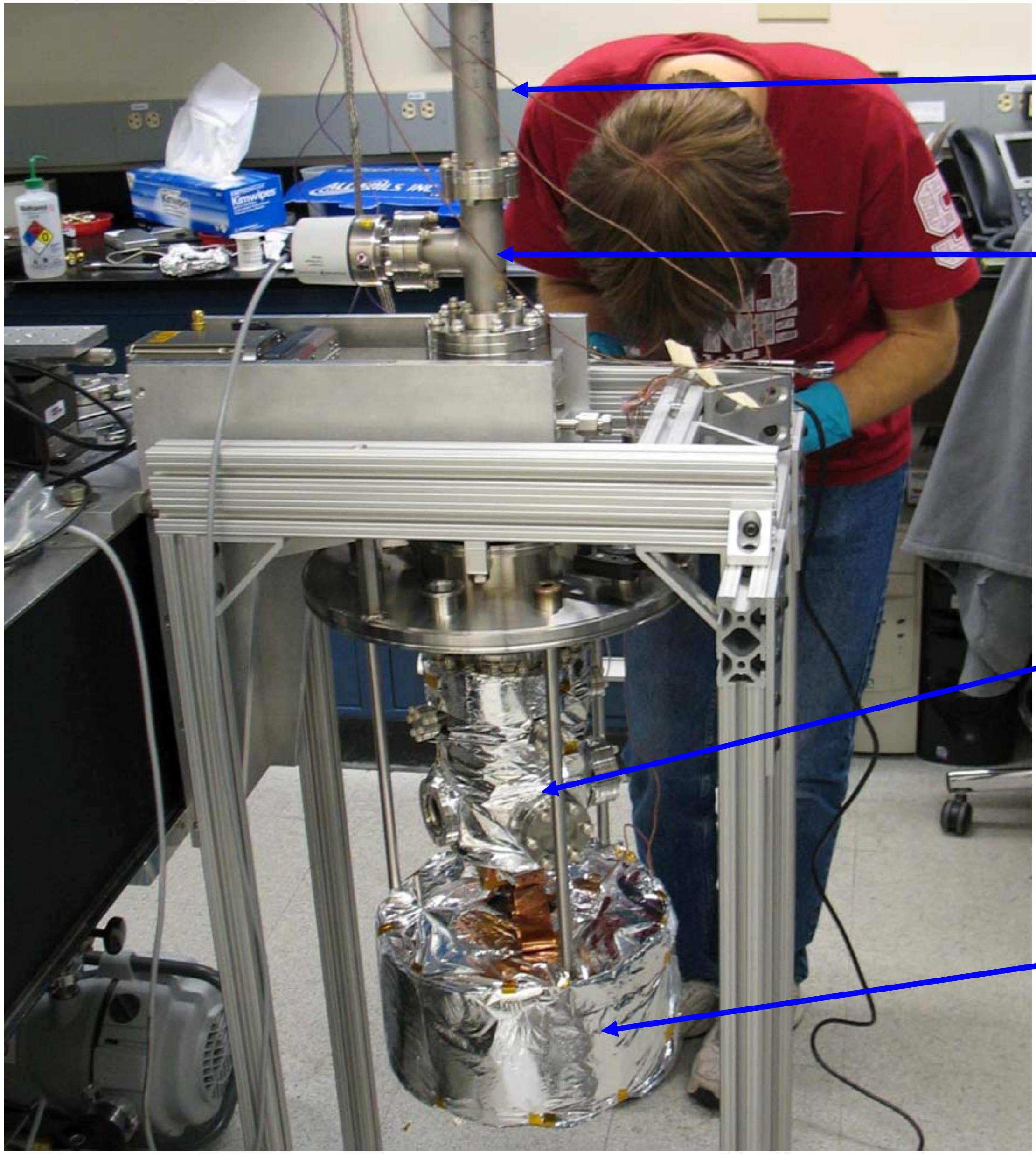


- Loading/retrieving efficiency is now ~2% (preliminary, involves some assumptions, not very reproducible yet)
- Background is negligible
- New setup to fish from LXe being commissioned





New system to go fishing for Ba in LXe



Probe access tube

RIS chamber and TOF spectrometer (not installed)

LXe cell

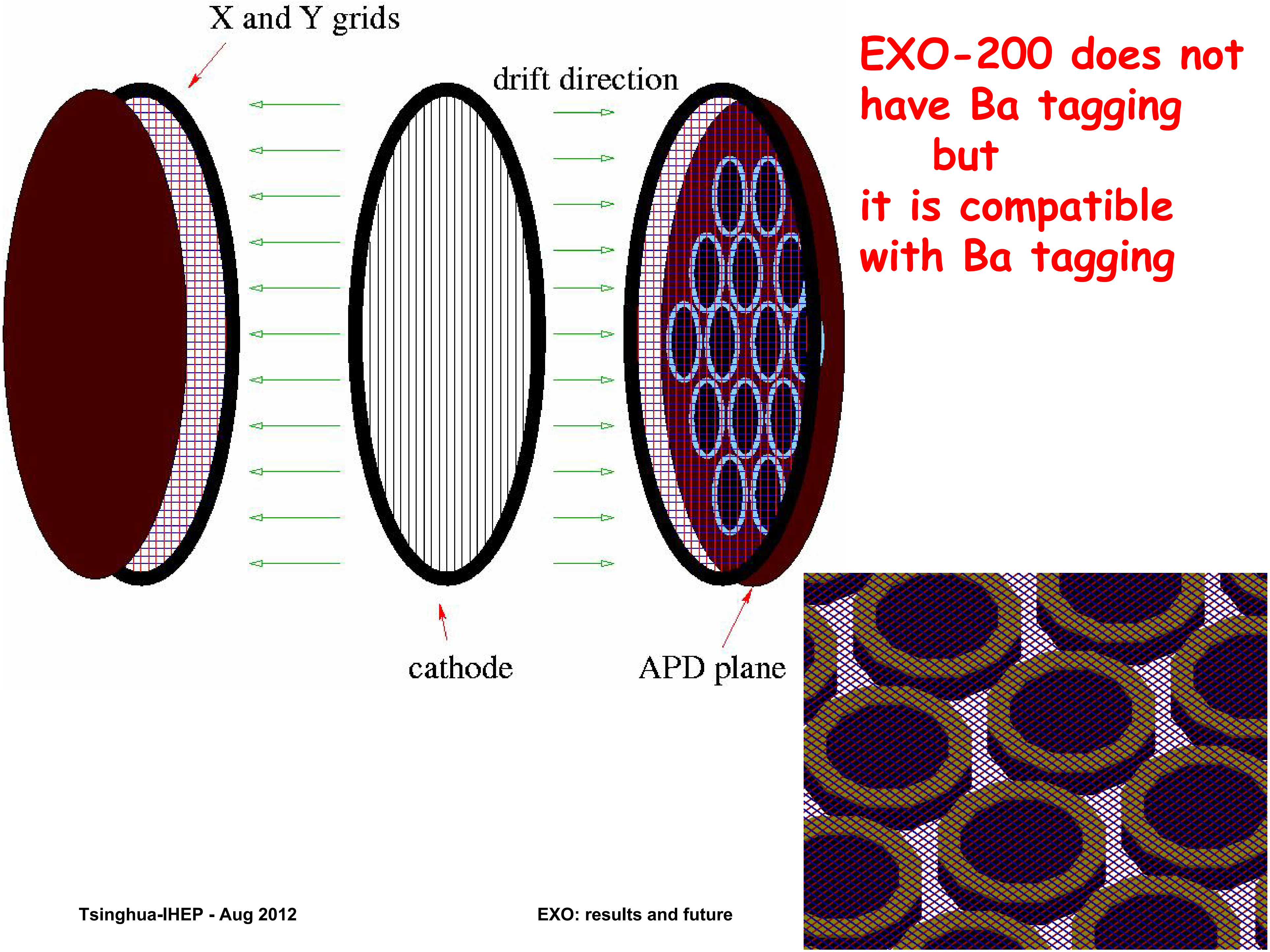
LN2 reservoir

EXO-200:

an intermediate detector <u>without</u> Ba tagging

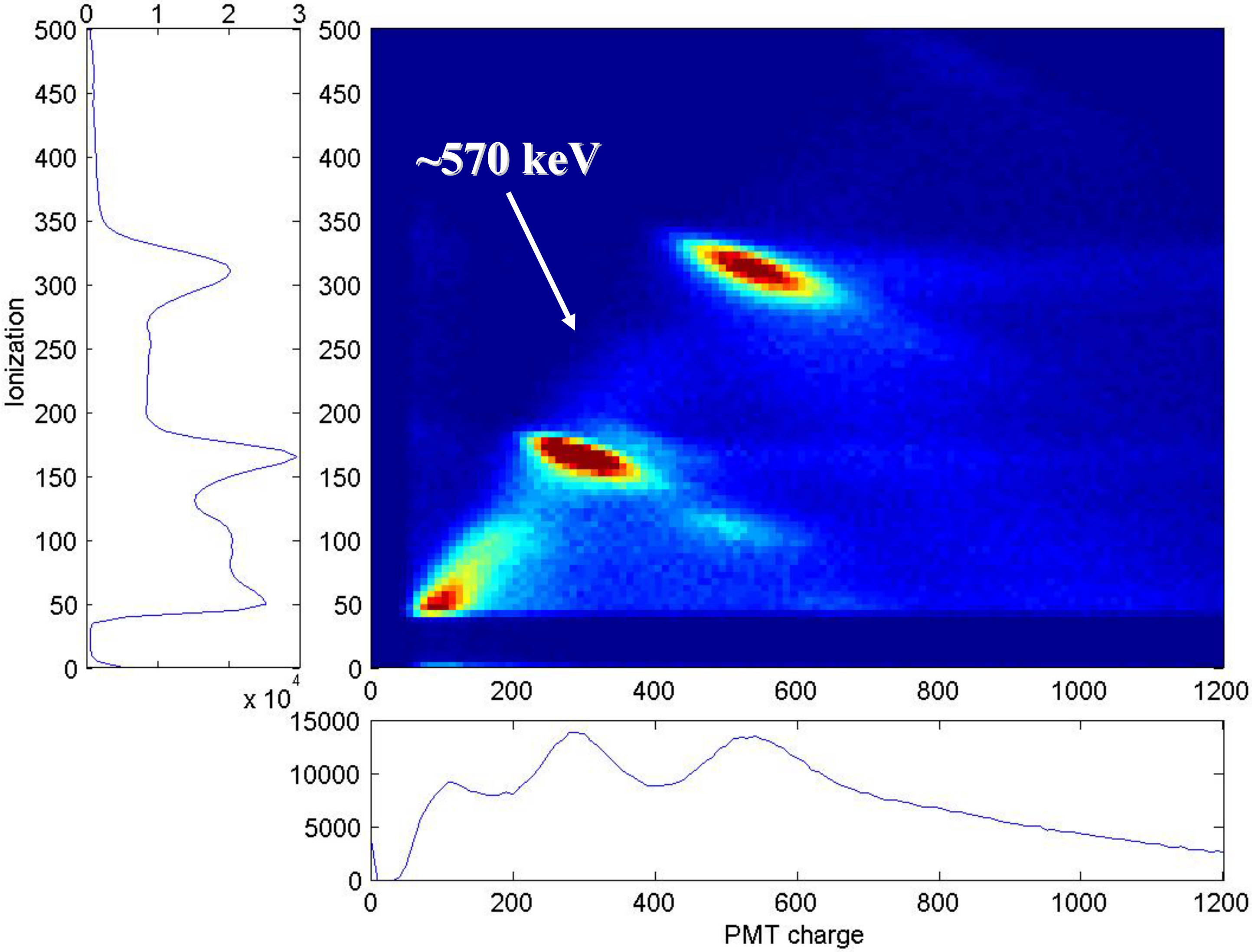
Underground location:
Waste Isolation Pilot Plant (WIPP) Carlsbad, NM

- ~1600 meter water equivalent flat overburden
- Relatively low levels of U and Th (<100 ppb in EXO-200 drift)
- Low levels of Rn (~20 Bq/m^3)
- Rather convenient access with large conveyance

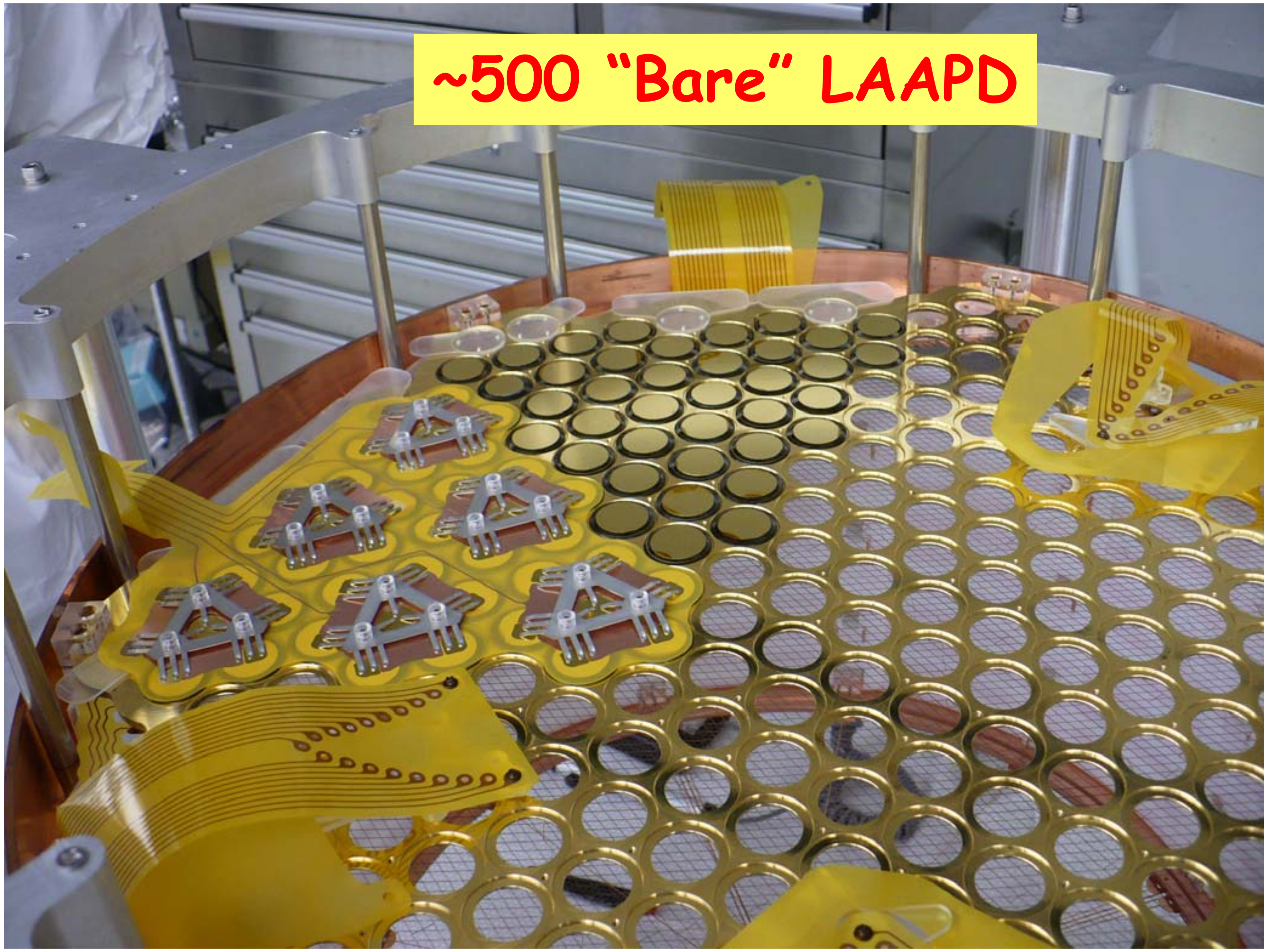


EXO-200 does not have Ba tagging
but
it is compatible with Ba tagging

EXO R&D showed the way to improved energy resolution in LXe: *Use (anti)correlations between ionization and scintillation signals*



R. Neilson, et al. NIM A 608 (2009) 6875



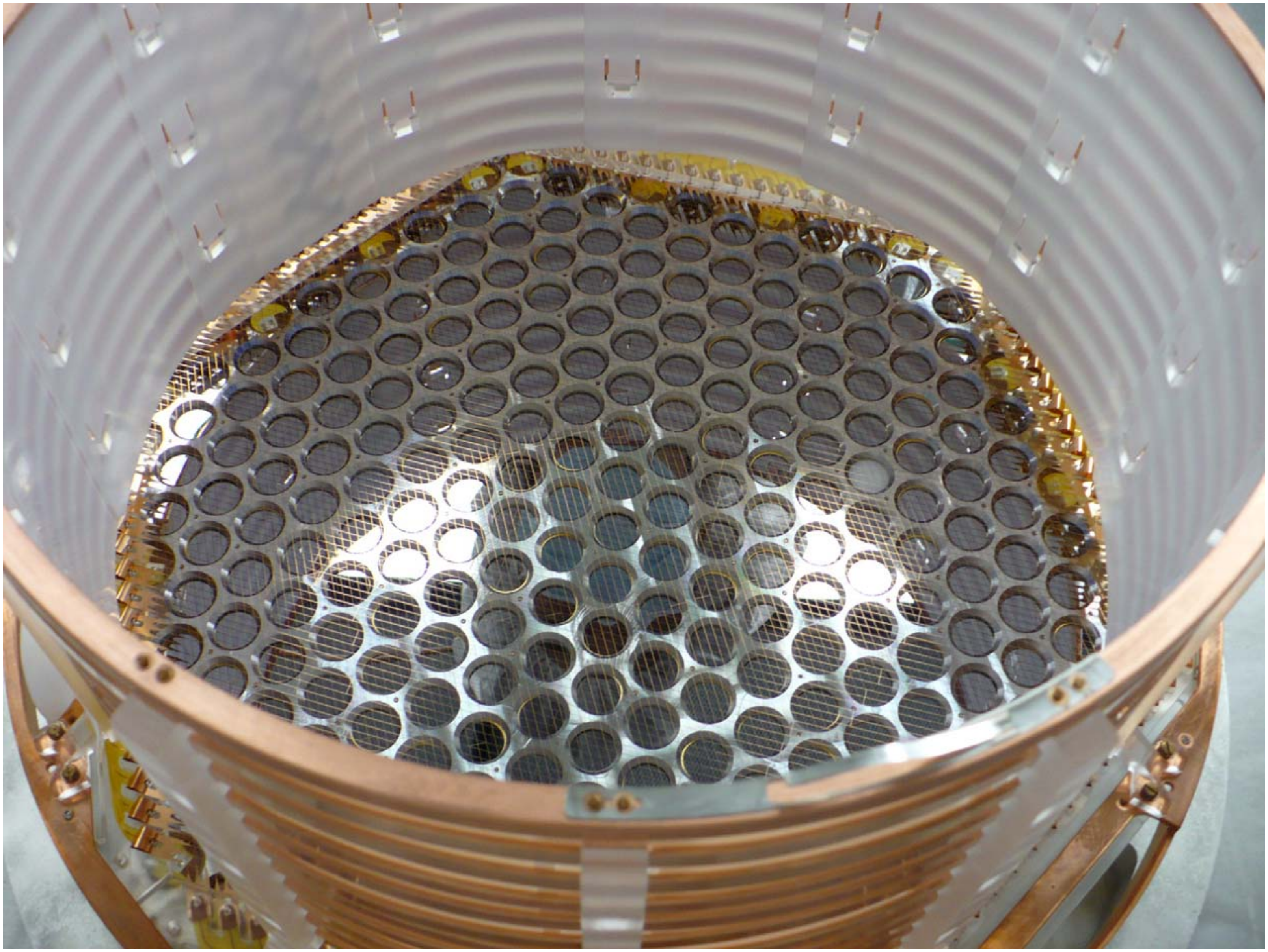
~500 “Bare” LAAPD

APDs are ideal for our application:

- very clean & light-weight,
- very sensitive to VUV

QE > 1 at 175nm

Gain set at 100-150
V~1500V
ΔV < ±0.5V
ΔT < ±1K APD is the driver for temperature stability
Leakage current OK cold

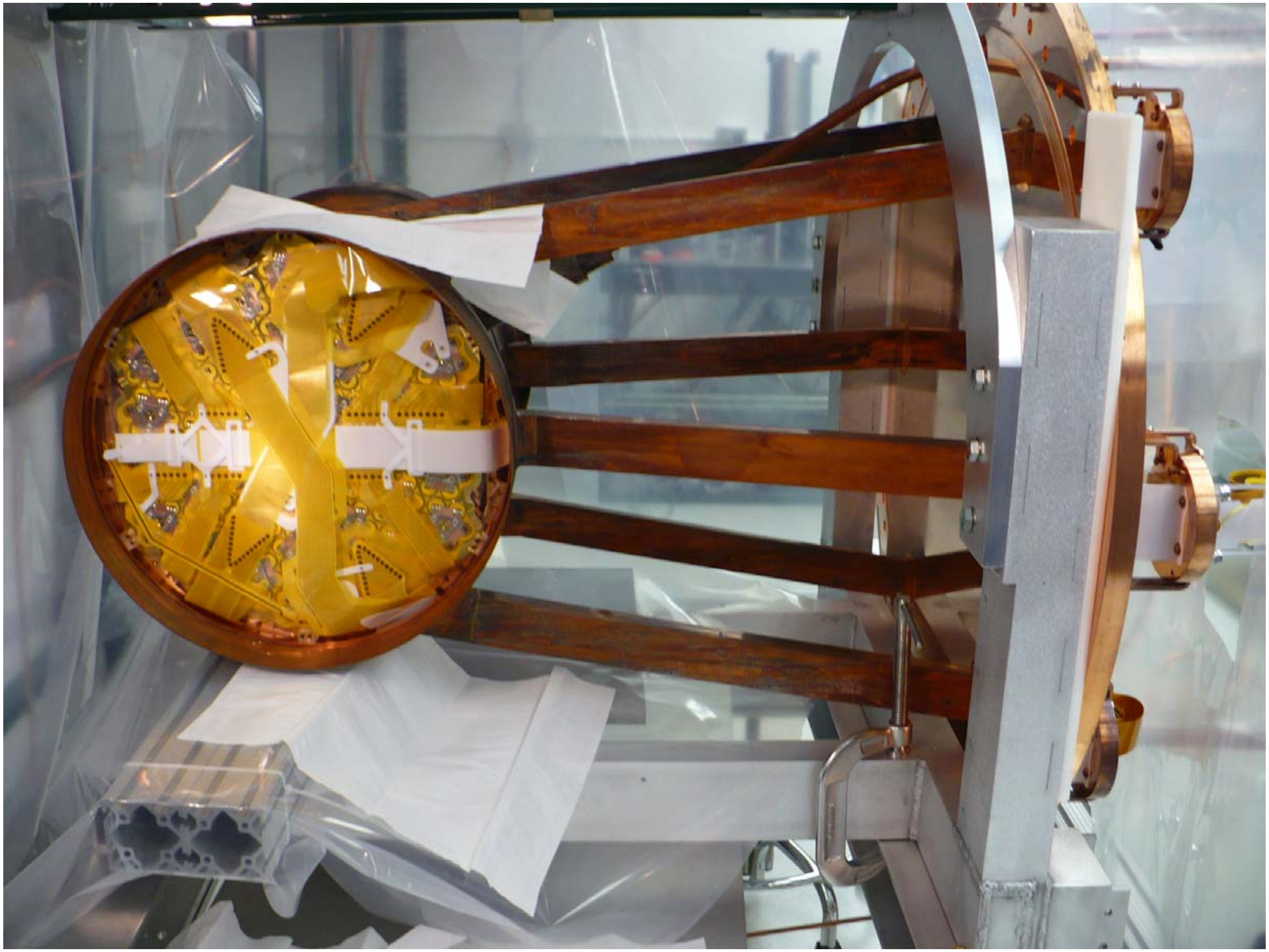


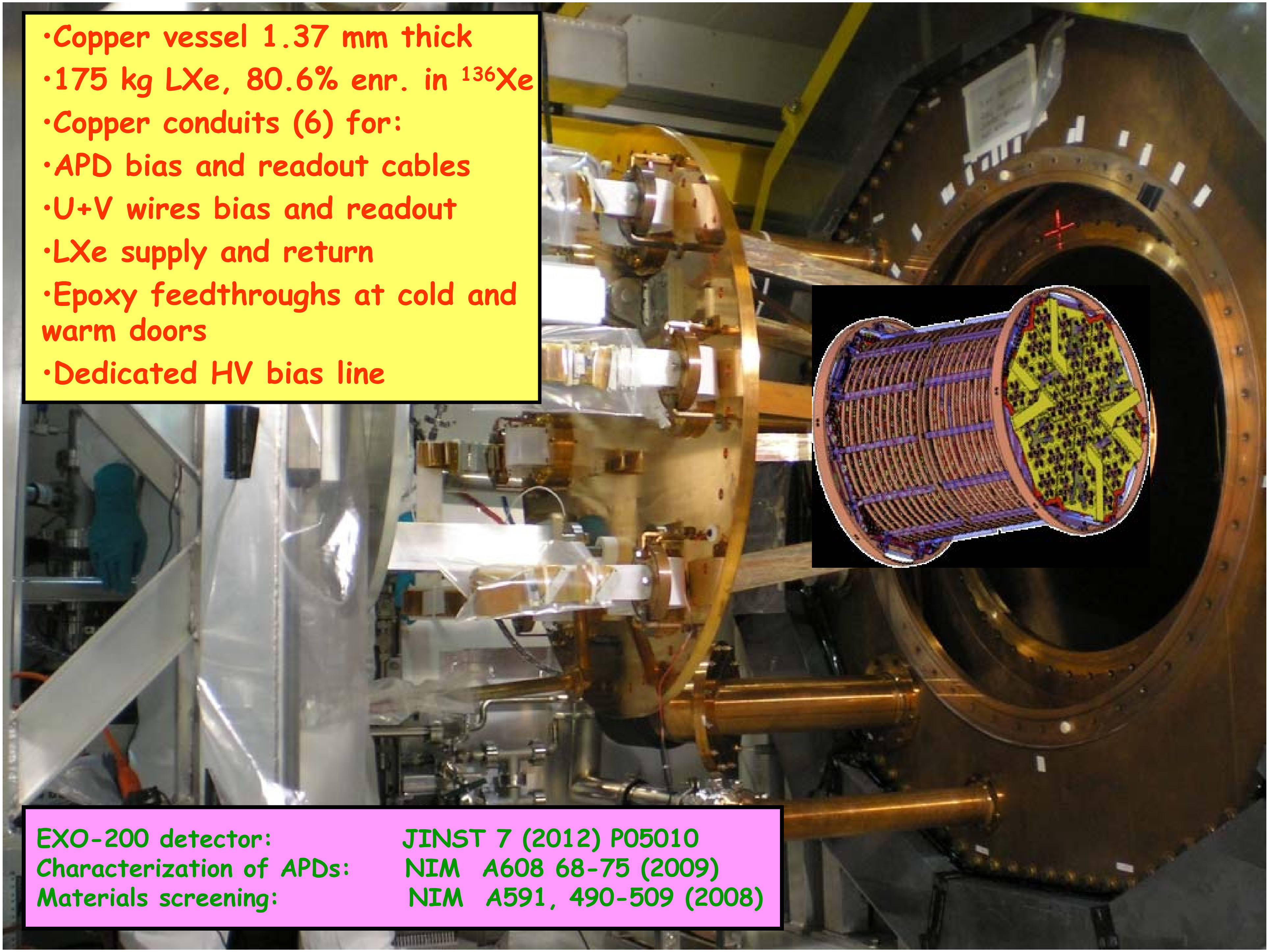
Ultra-low activity Cu vessel

- Very light (~1.5mm thin, ~15kg) to minimize materials

- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by in the CR-shielded HEPL building)

EXO-200 TPC Assembled

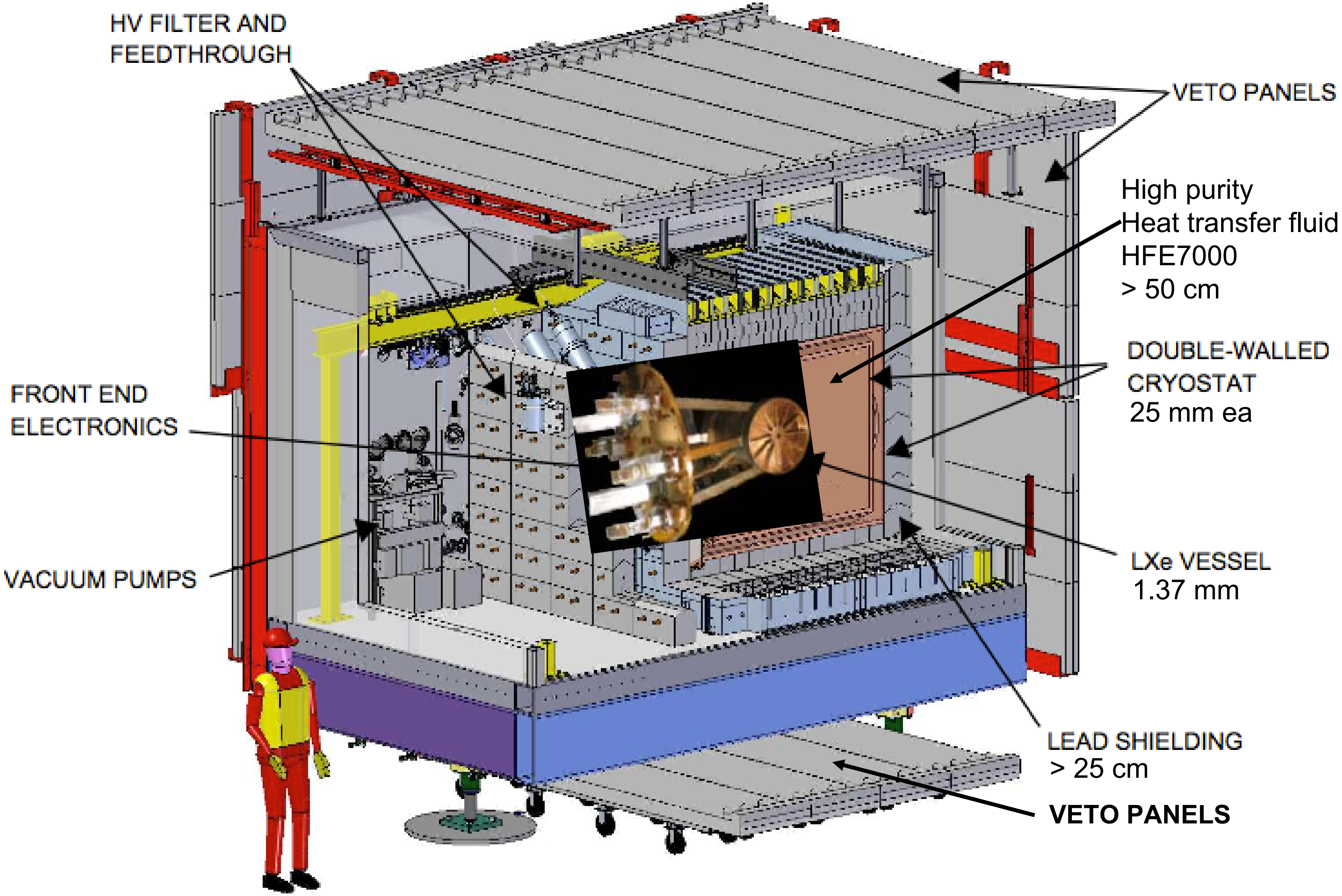




- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
- Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line

EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

The EXO-200 Detector



HV FILTER AND
FEEDTHROUGH

VETO PANELS

High purity
Heat transfer fluid
HFE7000
> 50 cm

FRONT END
ELECTRONICS

DOUBLE-WALLED
CRYOSTAT
25 mm ea

VACUUM PUMPS

LXe VESSEL
1.37 mm

LEAD SHIELDING
> 25 cm

VETO PANELS

Massive effort on material radioactive qualification using:

- NAA
- Low background γ-spectroscopy
- α-counting
- Radon counting
- High performance GD-MS and ICP-MS

At present the database of characterized materials includes >300 entries

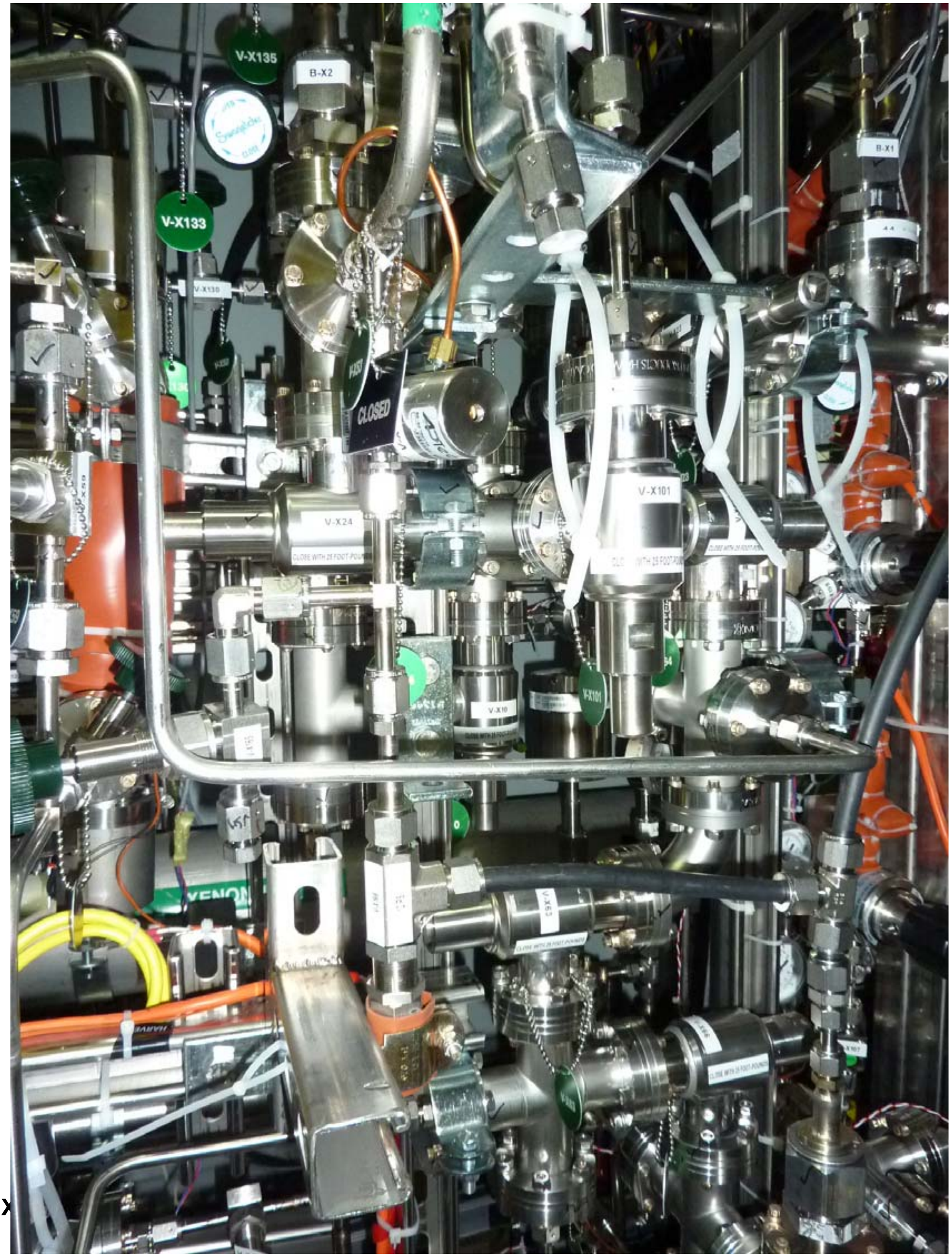
D.S. Leonard et al., Nucl. Ins. Meth. A 591, 490 (2008)

The impact of every screw within the Pb shielding is evaluated before acceptance

→ Goal: 40 cnts/2yr in the 0νββ ±2σ ROI in 140kg of LXe

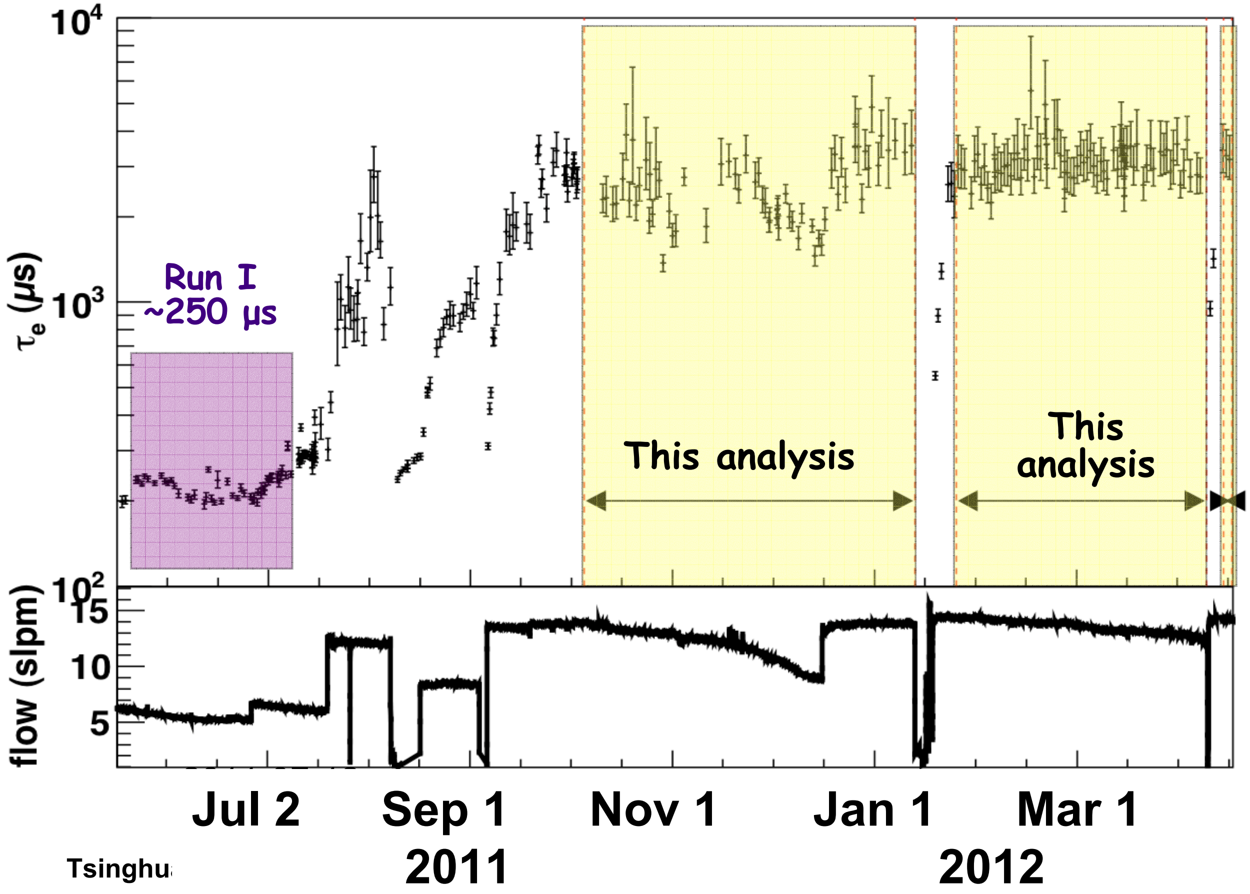
A substantial system is required to

- protect the 1.5mm thin LXe container from pressure
- recirculate Xe in gas phase to purify it
- fill/empty the detector
- manage emergencies



Data taking phases and Xenon Purity

	Run I	Run 2 (this analysis)
Period	May 21, 11 – Jul 9, 11	Sep 22, 11 – Apr 15,12
Live Time	752.7 hr	2,896.6 hr
Exposure	3.2 kg-yr	32.5 kg-yr
Publ.	PRL 107 (2011) 212501	arXiv:1205:5608 (May 2012)

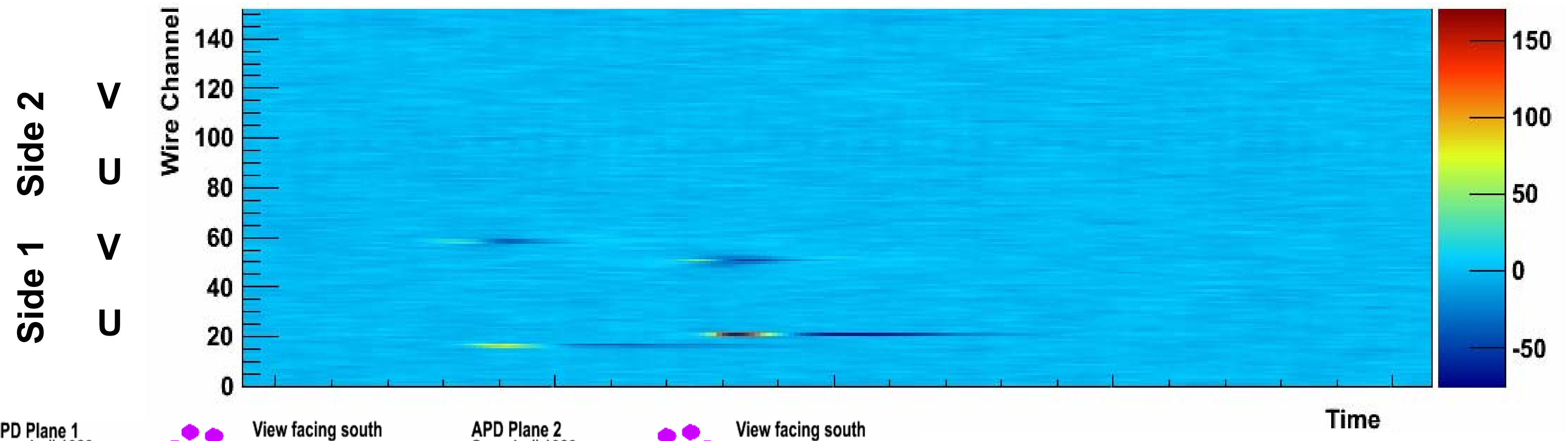


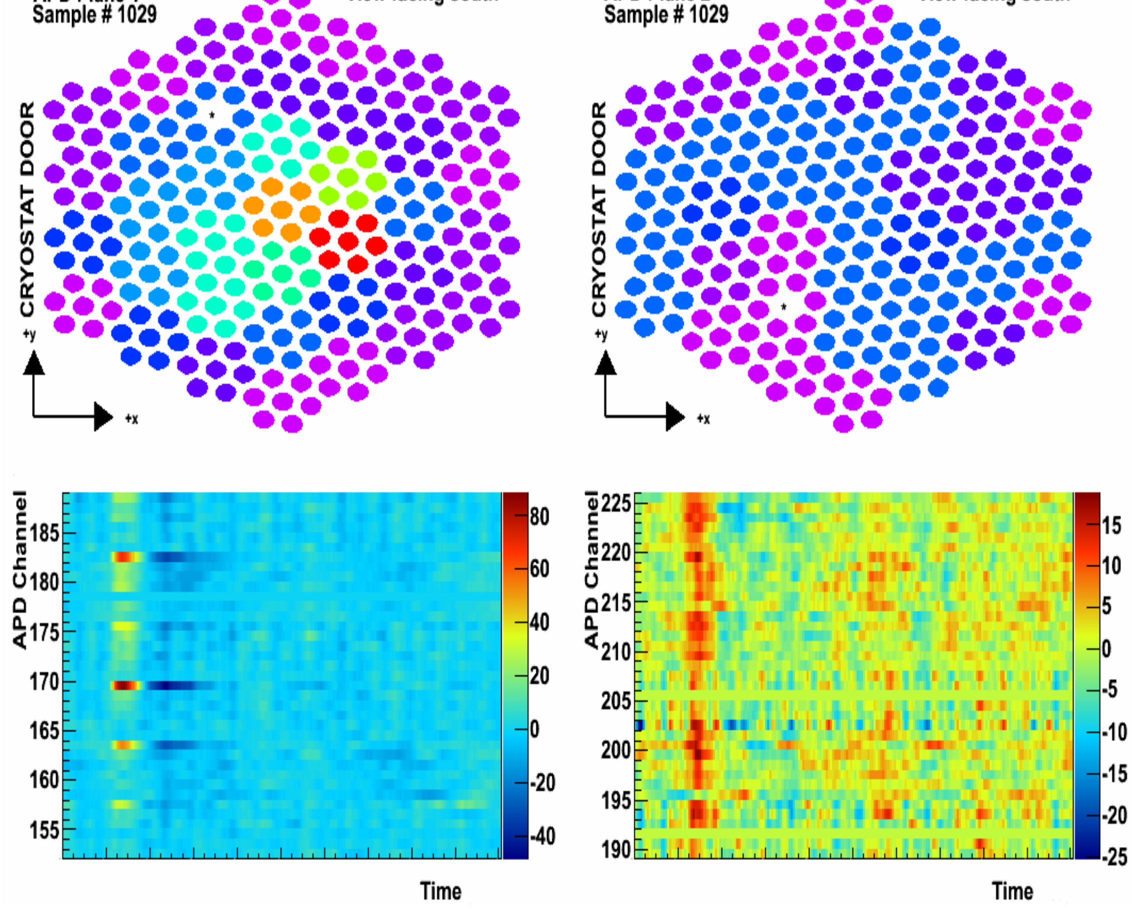
Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

Electron lifetime τ_e:
→ measure ionization signal attenuation as a function of drift time for the full-absorption peak of γ ray sources

At τ_e = 3 ms:
- drift time <110 *μs*
- loss of charge: 3.6% at full drift length

Ultraclean pump:
Rev Sci Instr. 82 (10) 105114
Xenon purity with mass spec:
NIM A675 (2012) 40
Gas purity monitors:
NIM A659 (2011) 215





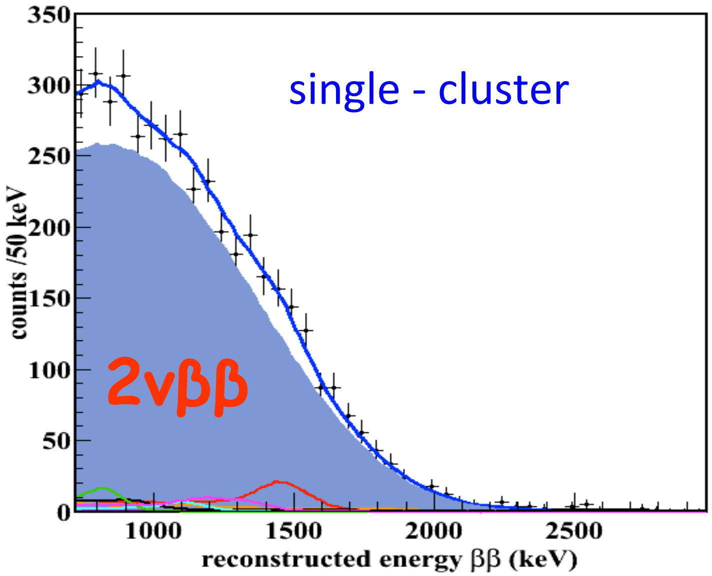
A two-site Compton scattering event.

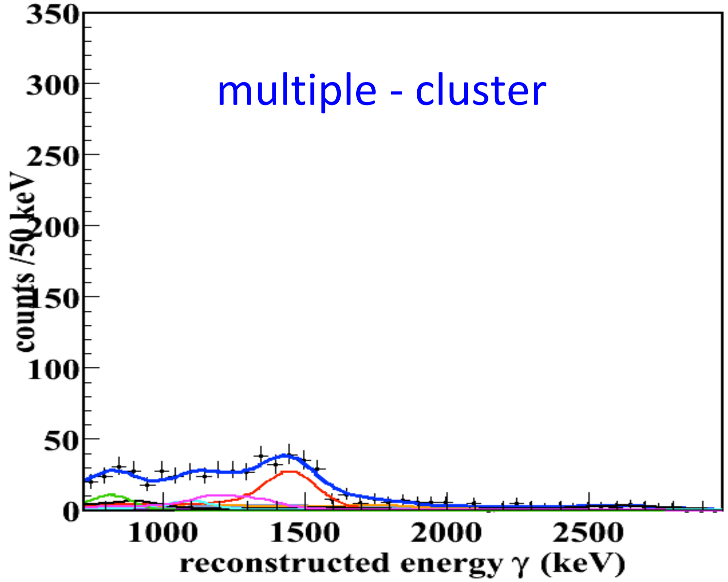
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

The scintillation light is Brighter and more localized on Side 1 where the scattering occurs

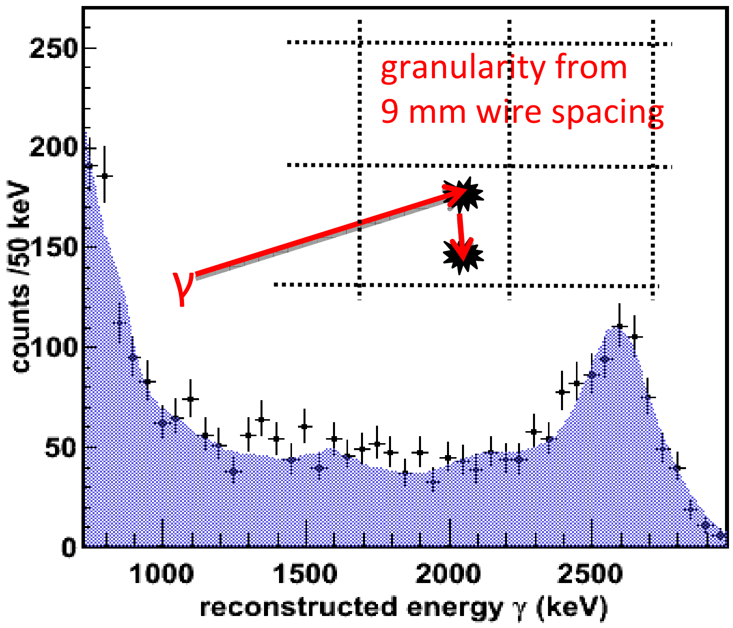
Pattern recognition can be a very powerful tool against background

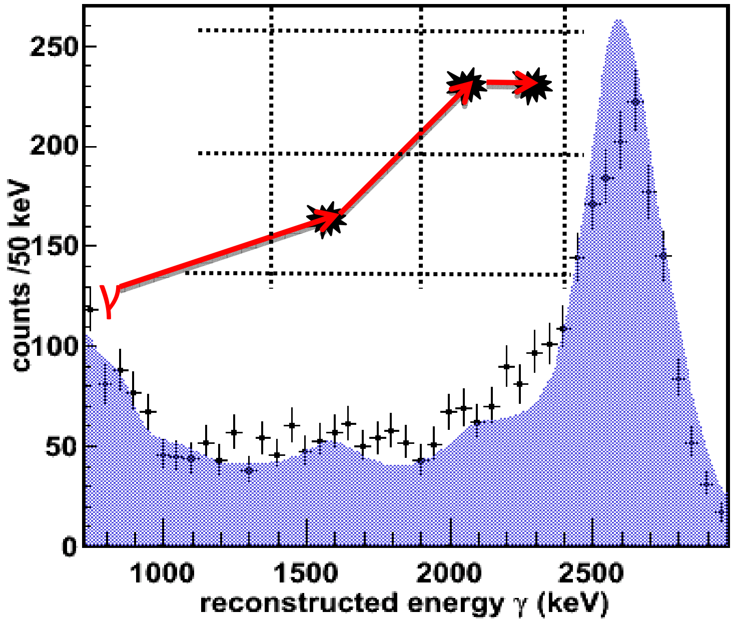
Low background data





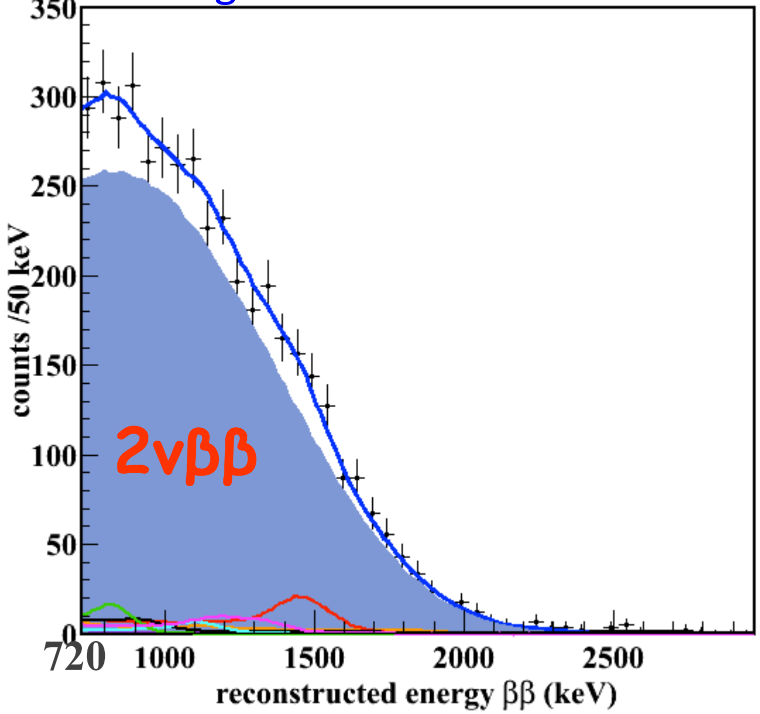
^{228}Th calibration source



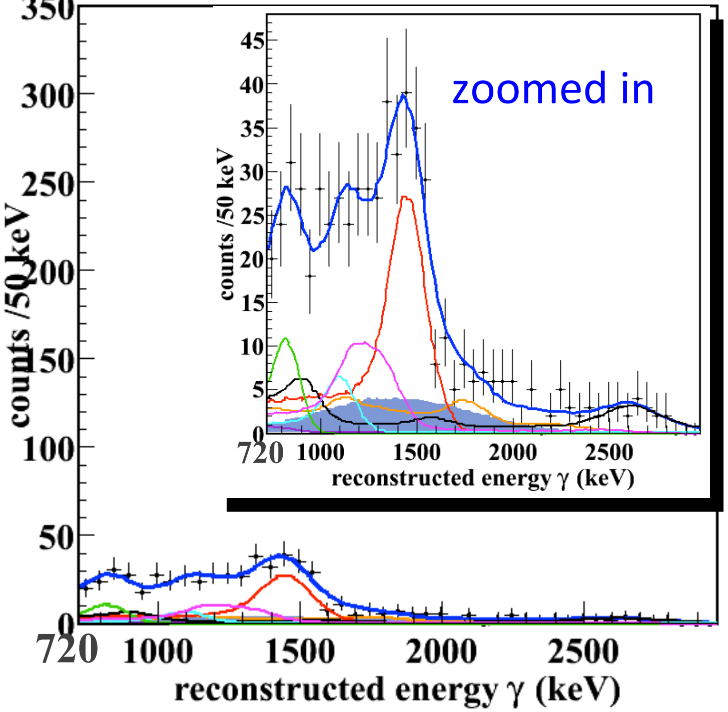


First observation of the 2νββ decay in ^{136}Xe

single - cluster



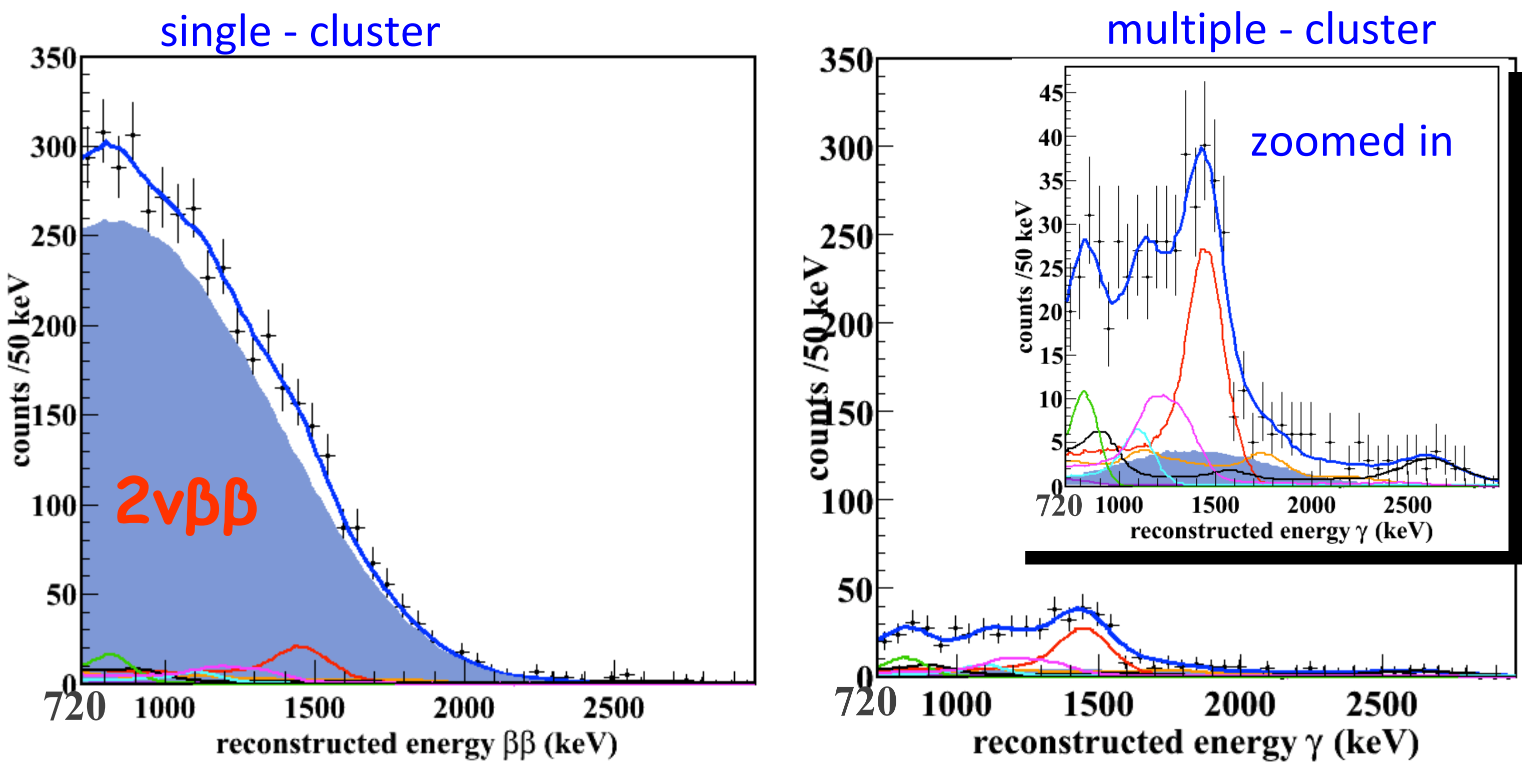
multiple - cluster



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

[Ackerman et al Phys Rev Lett 107 (2001) 212501]

First observation of the 2νββ decay in ^{136}Xe


single - cluster

multiple - cluster

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

[Ackerman et al Phys Rev Lett 107 (2001) 212501]

In significant disagreement with previous limits:

$T_{1/2}$ > $1.0 \cdot 10^{22}$ yr (90% C.L.) (R. Bernabei *et al.* Phys. Lett. B 546 (2002) 23)
$T_{1/2}$ > $8.5 \cdot 10^{21}$ yr (90% C.L.) (Yu. M. Gavriljuk *et al.*, Phys. Atom. Nucl. 69 (2006) 2129)

Later confirmed by KamLAND-ZEN

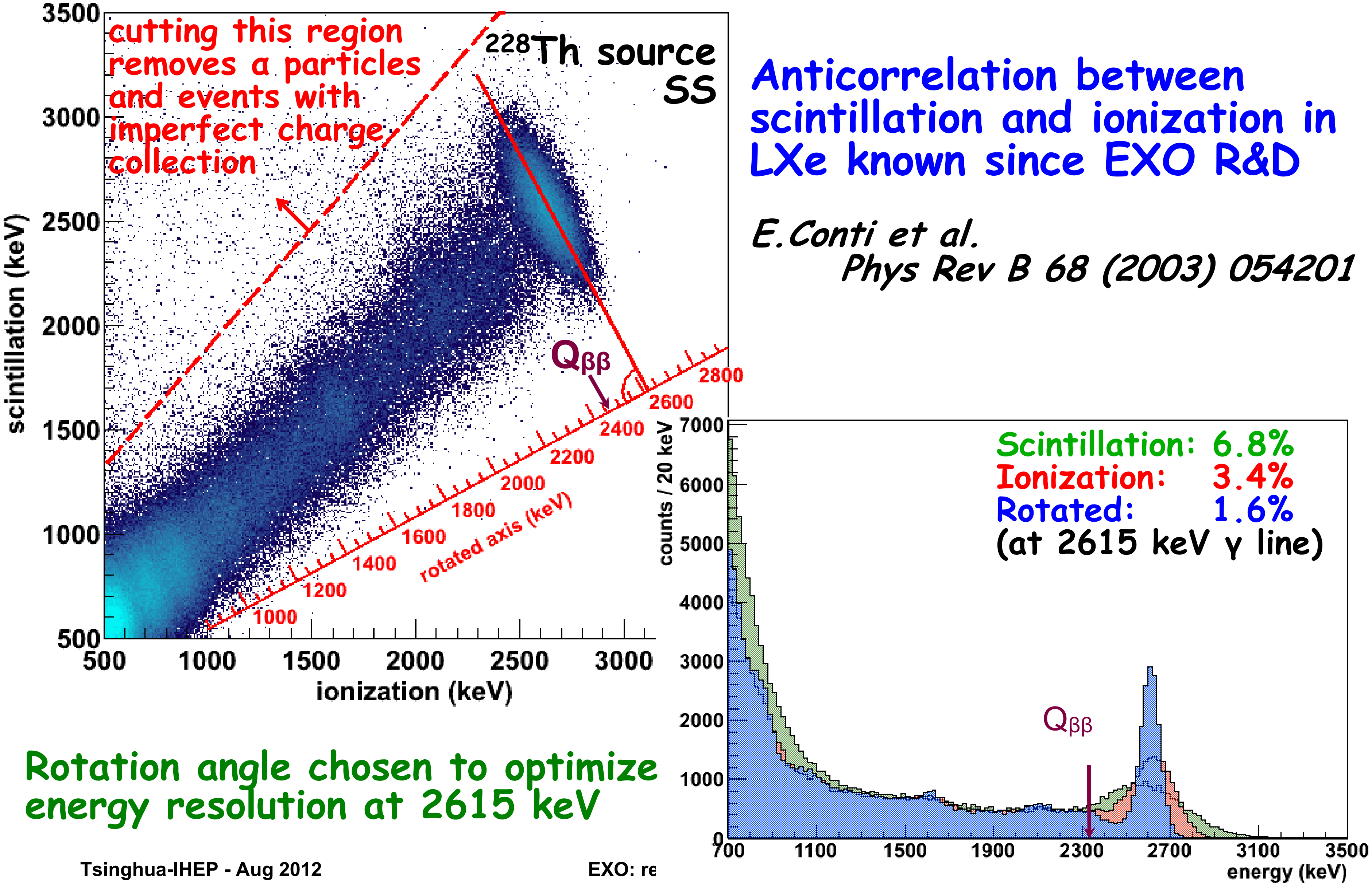
$T_{1/2}$=(2.38 ± 0.02stat ± 0.14sys)$\cdot 10^{21}$ yr

[A.Gando et al. Phys Rev C 85 (2012) 045504]

Combining Ionization and Scintillation

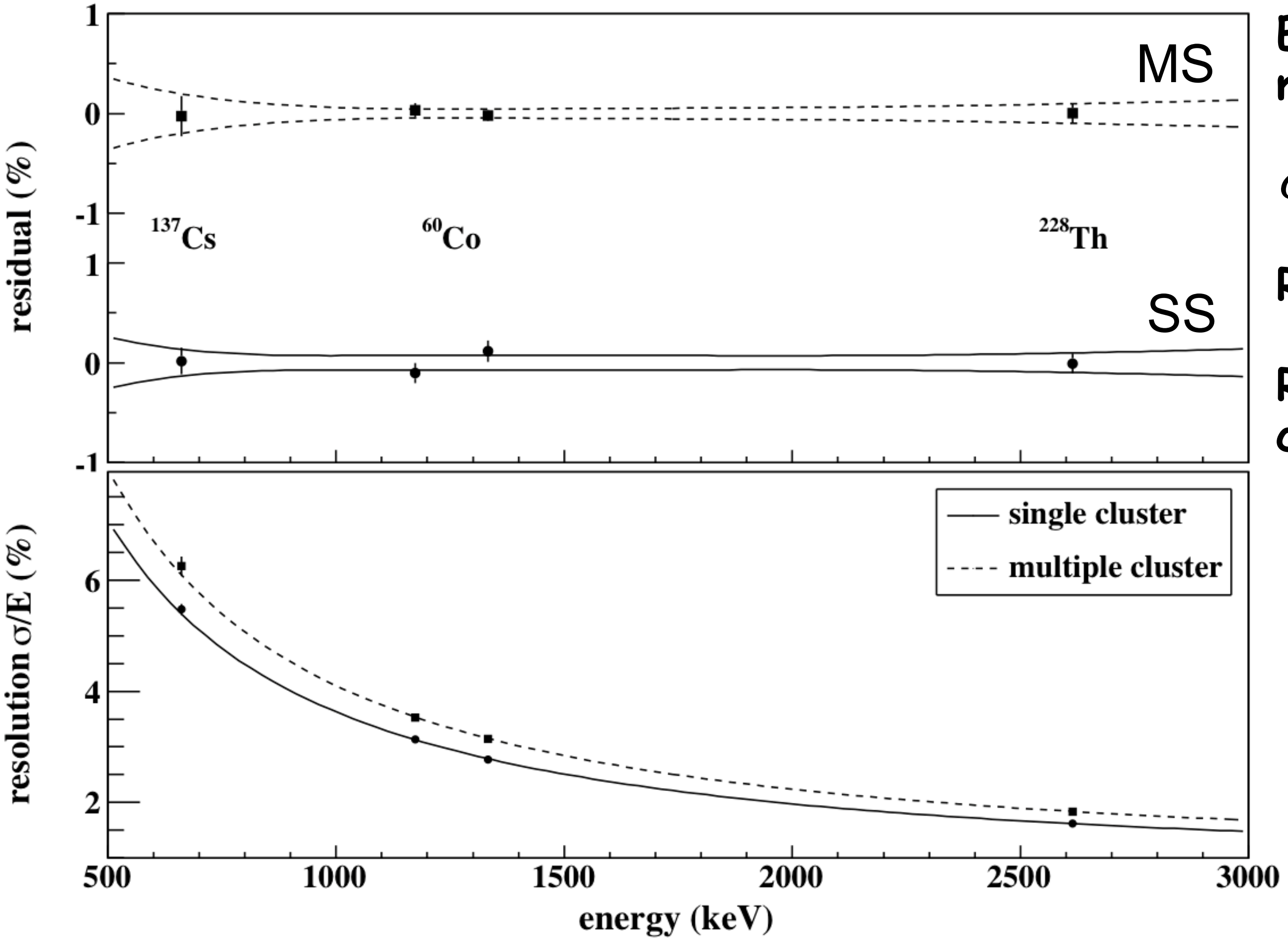
Anticorrelation between scintillation and ionization in LXe known since EXO R&D

E.Conti et al.
Phys Rev B 68 (2003) 054201



Rotation angle chosen to optimize energy resolution at 2615 keV

Energy Calibration



Energy resolution model:

$$\sigma_{tot}^2 = p_0^2 E + p_1^2 + p_2^2 E^2$$

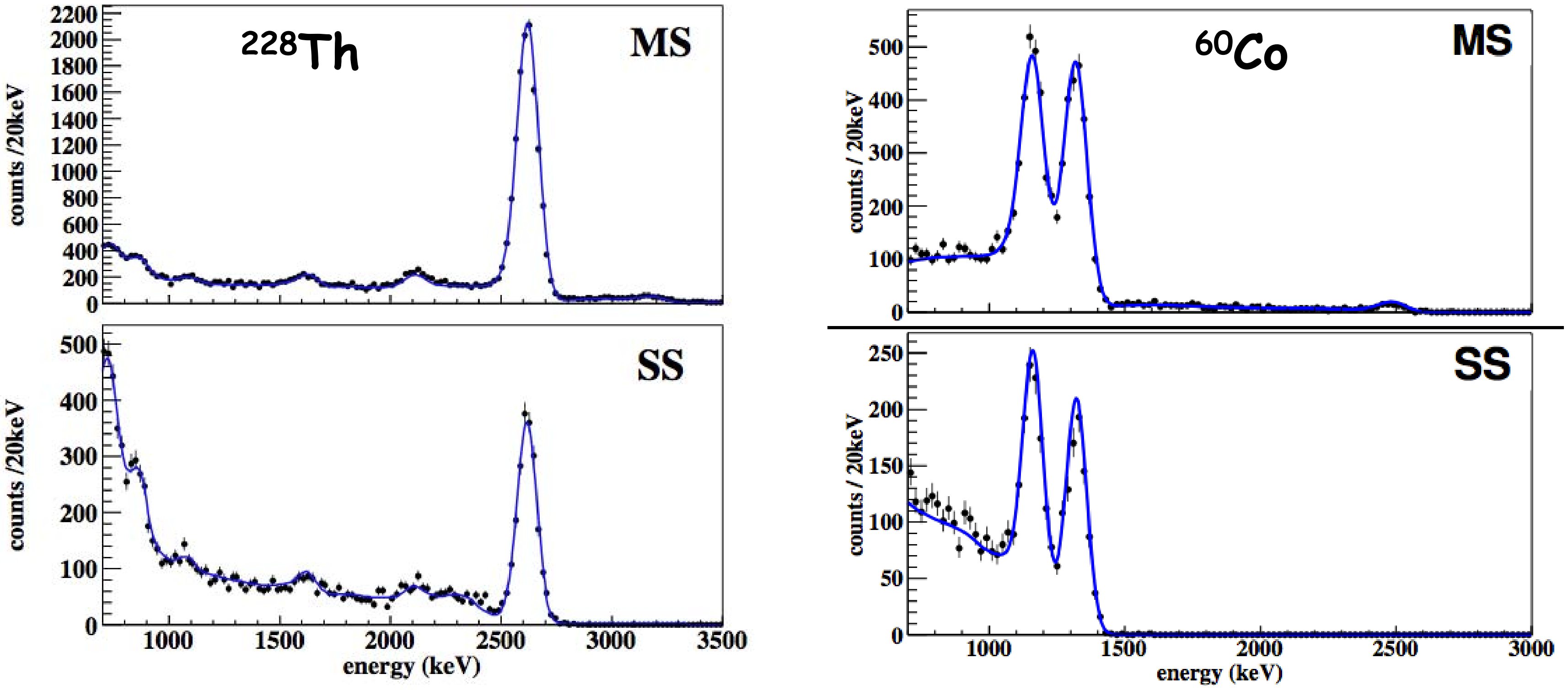
Residuals <0.1%

Resolution dominated by constant (noise) term p_1

At $Q_{\beta\beta}$ (2458 keV):

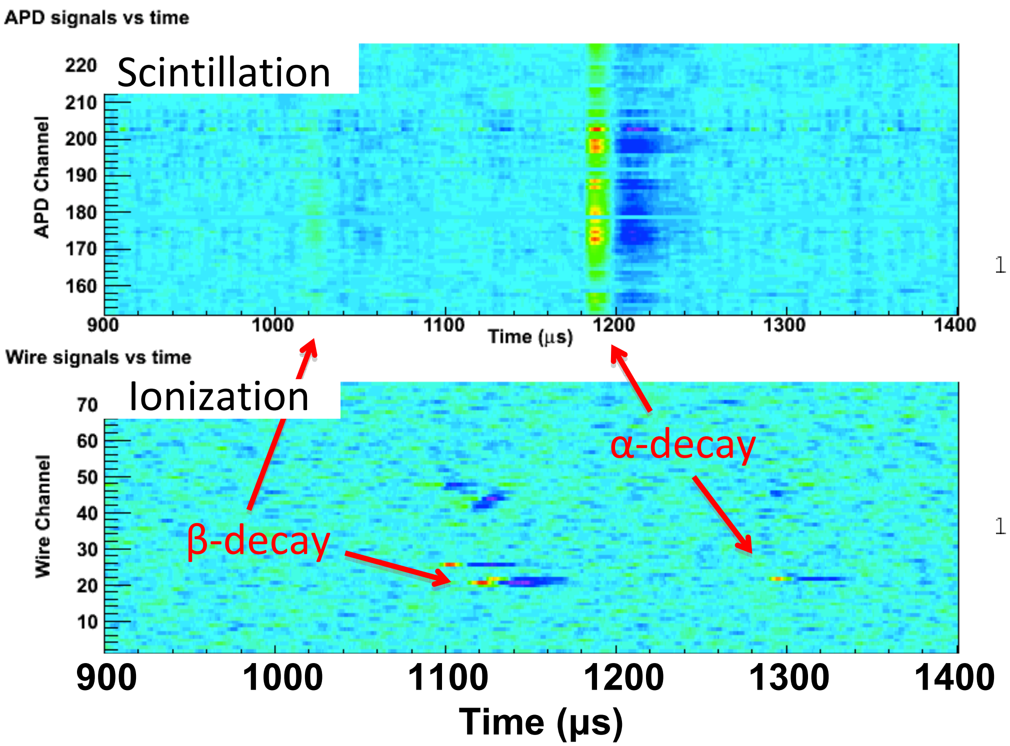
σ/E = 1.67 % (SS)
σ/E = 1.84 % (MS)

Source Data/MC Agreement

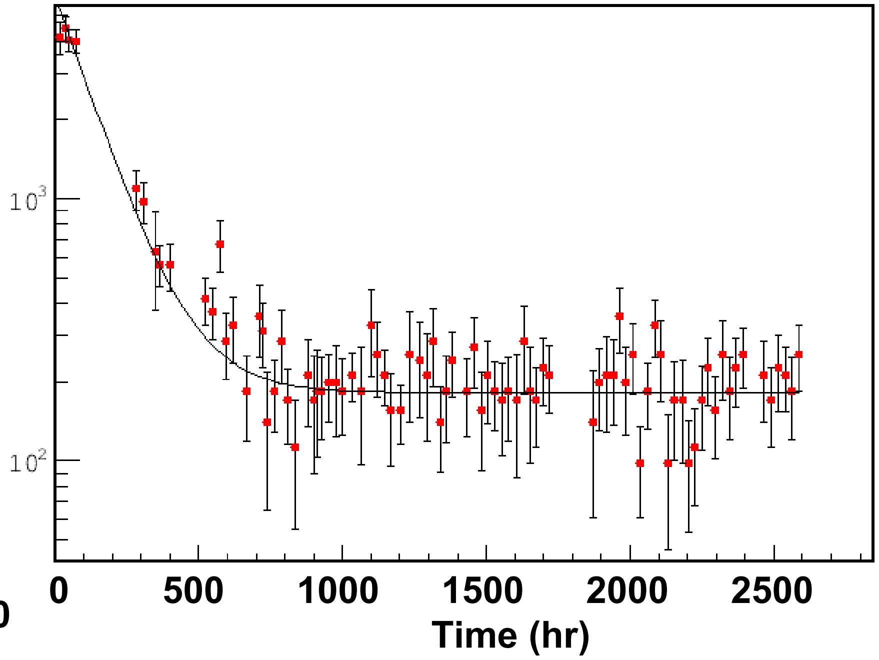


- Single site fraction agrees to within 8.5%
- Source activities measured to within 9.4%

Rn Content in Xenon



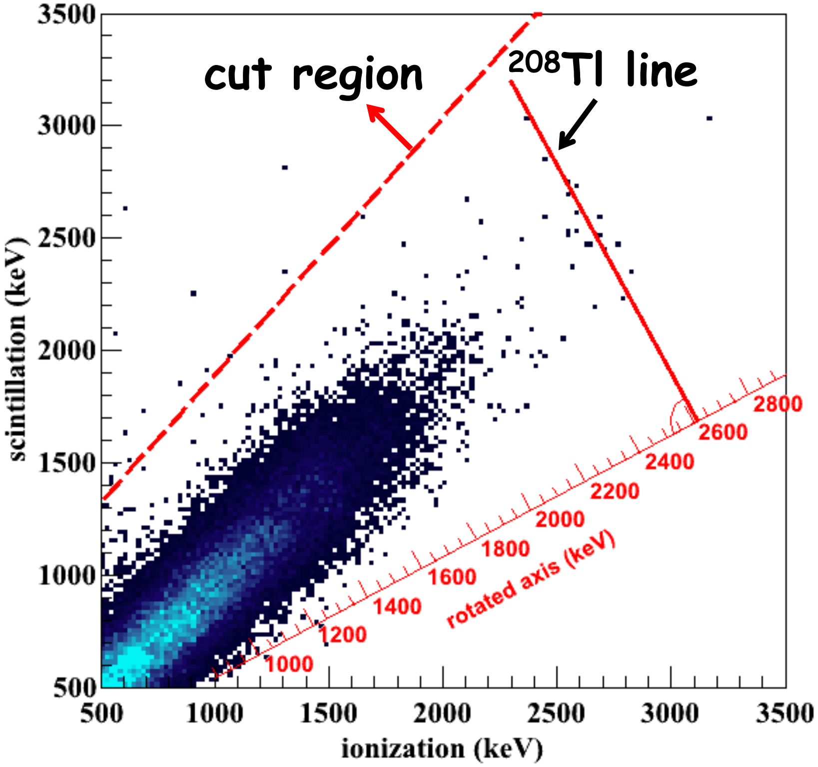
^{214}Bi – ^{214}Po correlations in the EXO-200 detector

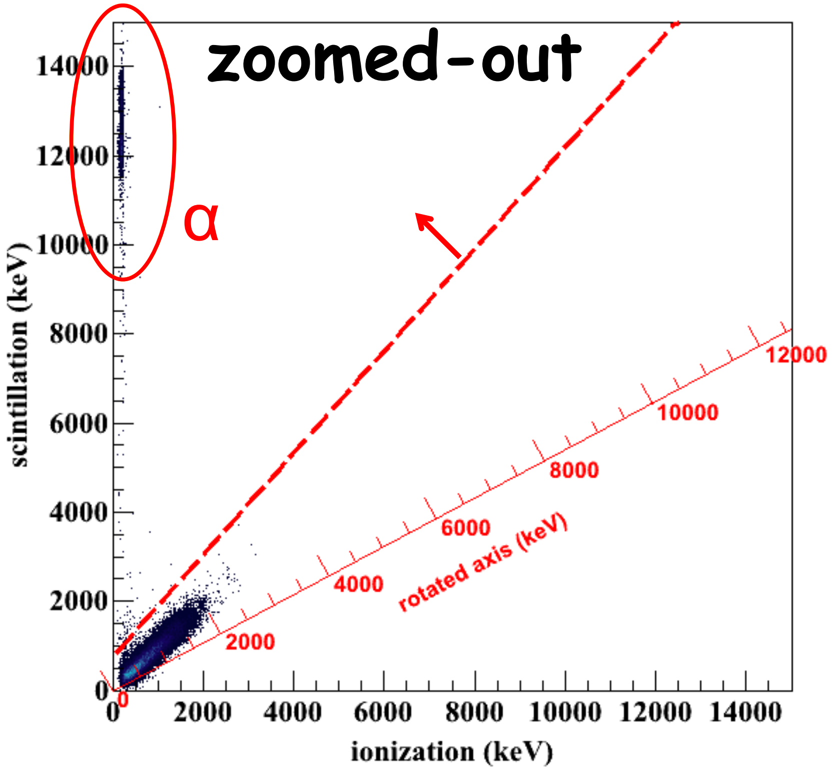


Total ^{222}Rn in LXe after initial fill

Long-term study shows a constant source of ^{222}Rn dissolving in ^{enr}LXe: 360 ± 65 μBq (Fid. vol.)

Low Background 2D SS Spectrum

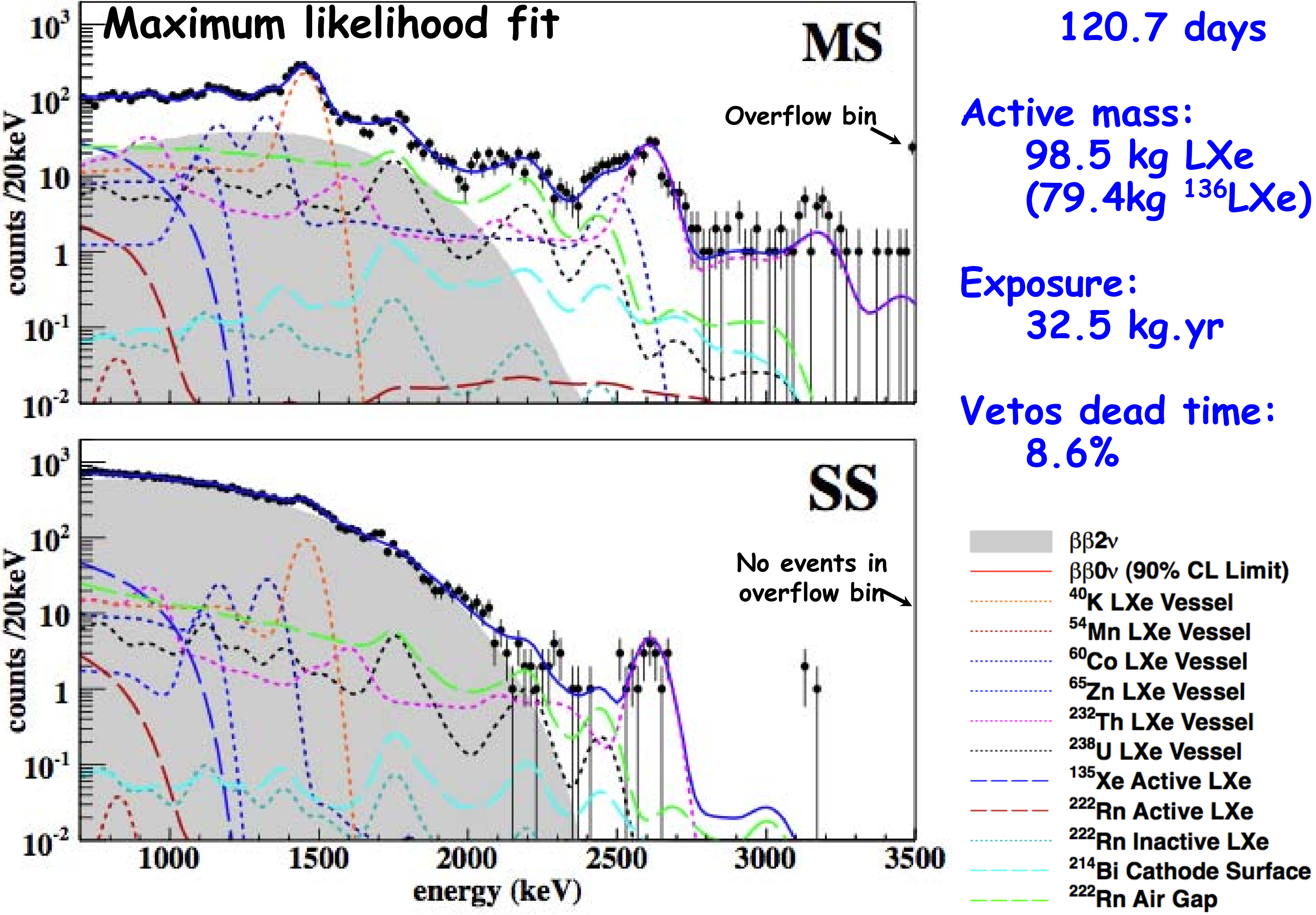




Events removed by diagonal cut:

- α (larger ionization density → more recombination → more scintillation light)
- events near detector edge → not all charge is collected

Low Background Spectrum


Maximum likelihood fit

Overflow bin

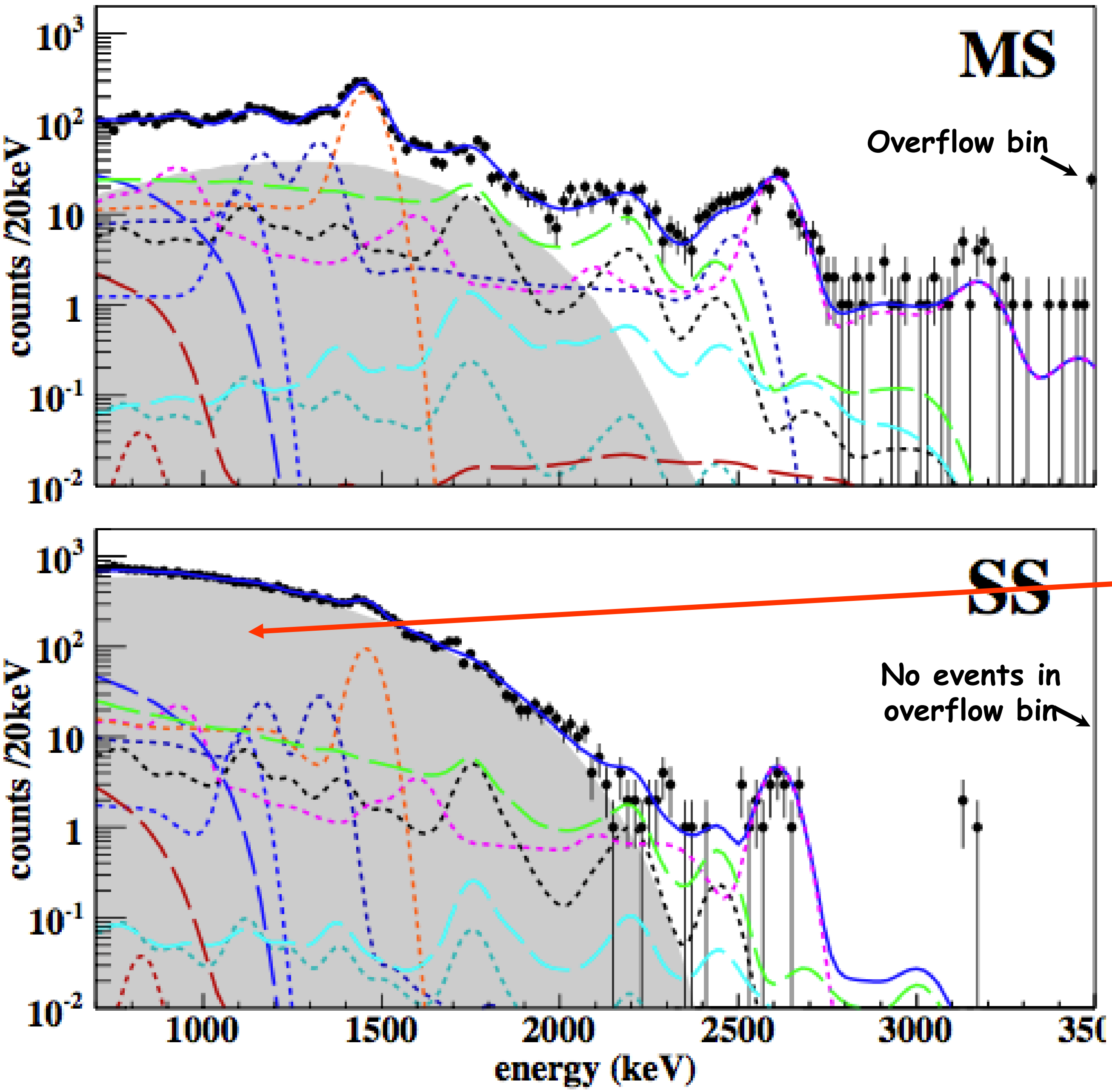
No events in overflow bin

Low background run livetime:
120.7 days

Active mass:
98.5 kg LXe
(79.4kg ^{136}LXe)

Exposure:
32.5 kg.yr

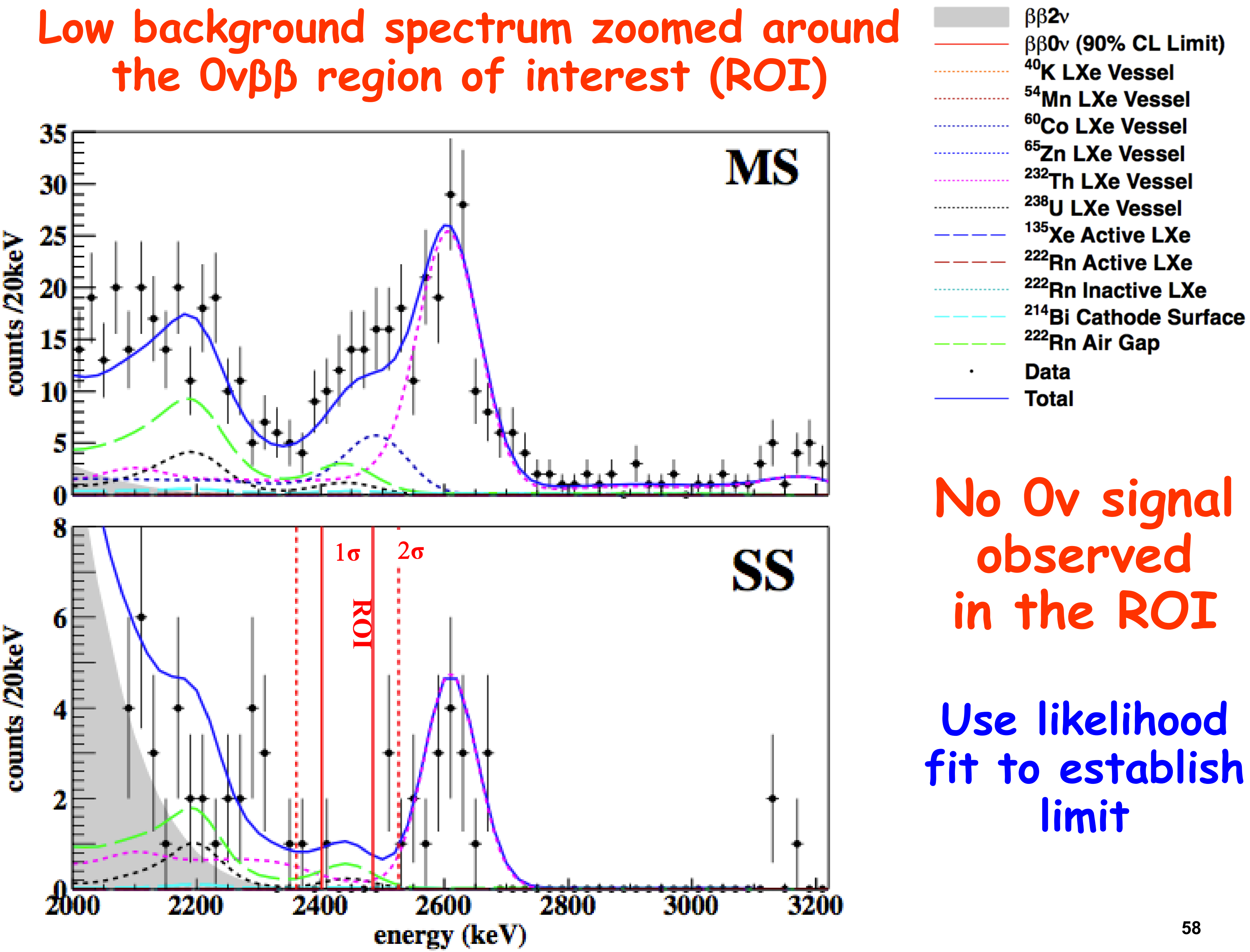
Vetos dead time:
8.6%



~22,000 2νββ events !

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

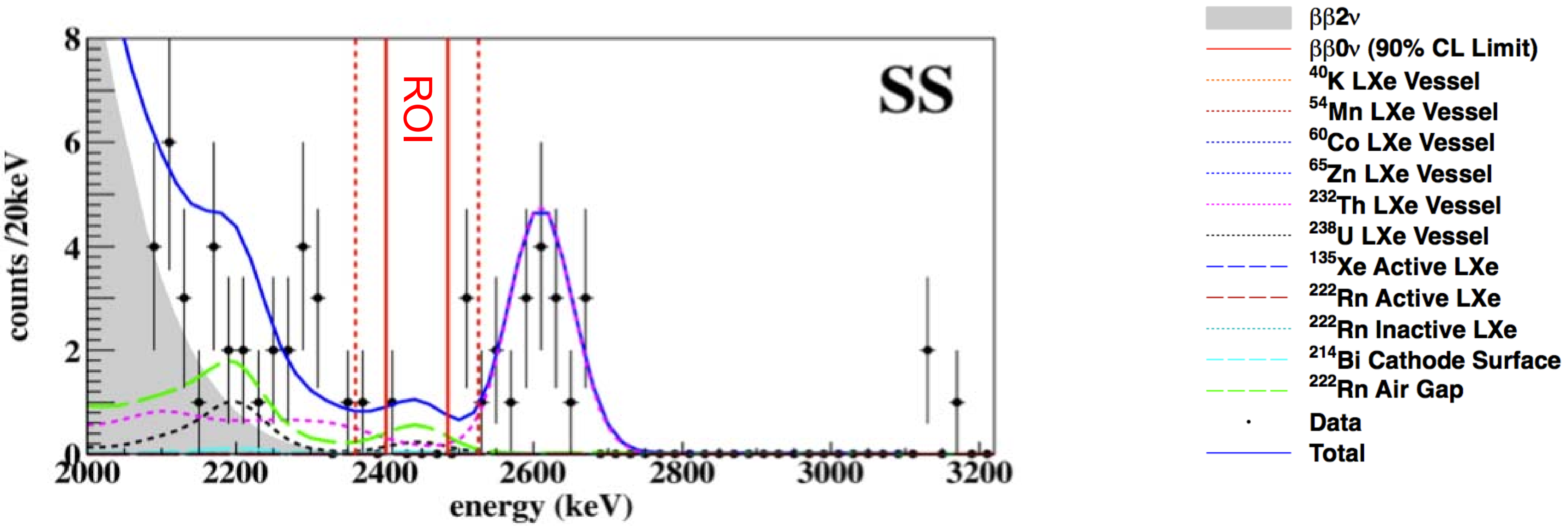
Low background spectrum zoomed around the 0νββ region of interest (ROI)



No 0ν signal observed in the ROI

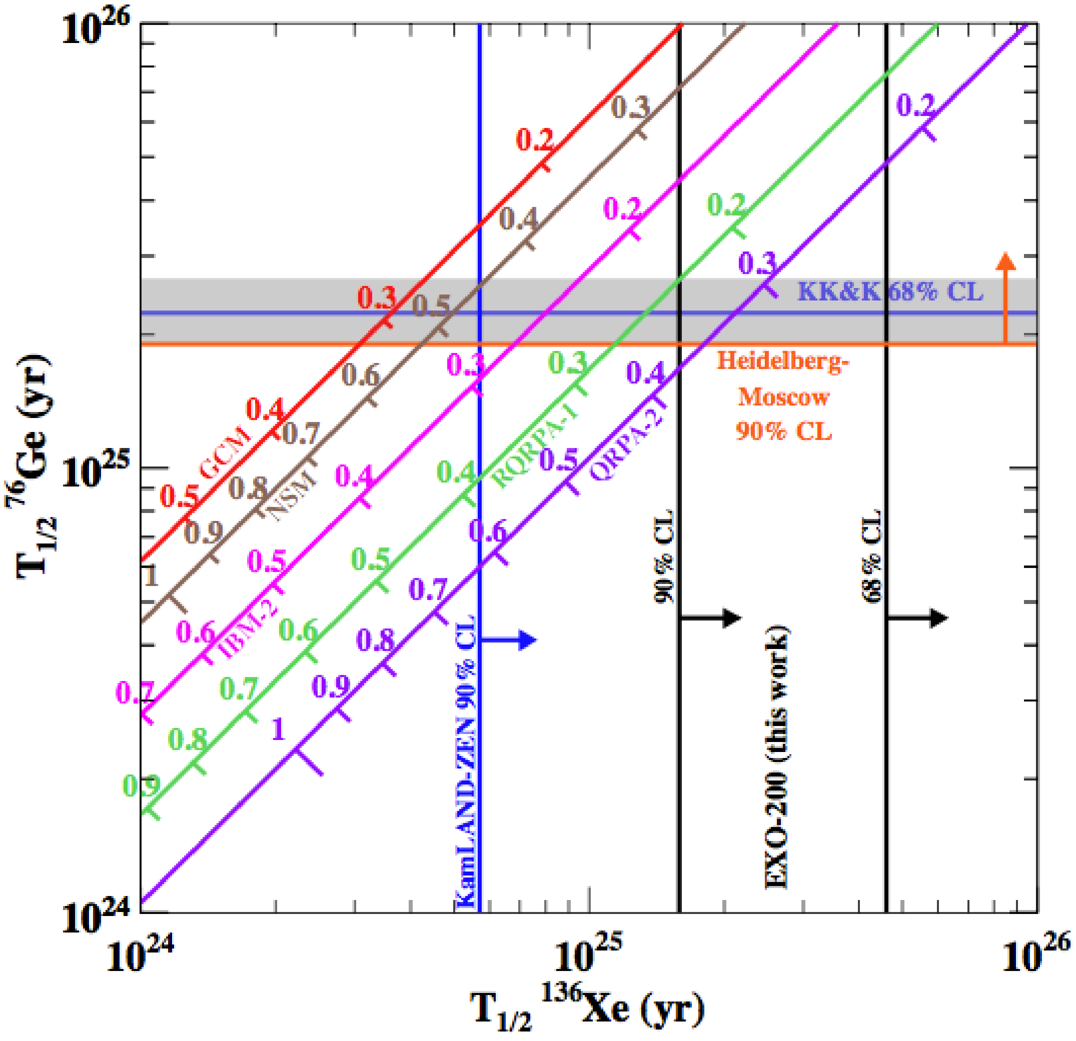
Use likelihood fit to establish limit

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})	1.5·10^{-3} ± 0.1		1.4·10^{-3} ± 0.1	

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



From profile likelihood:

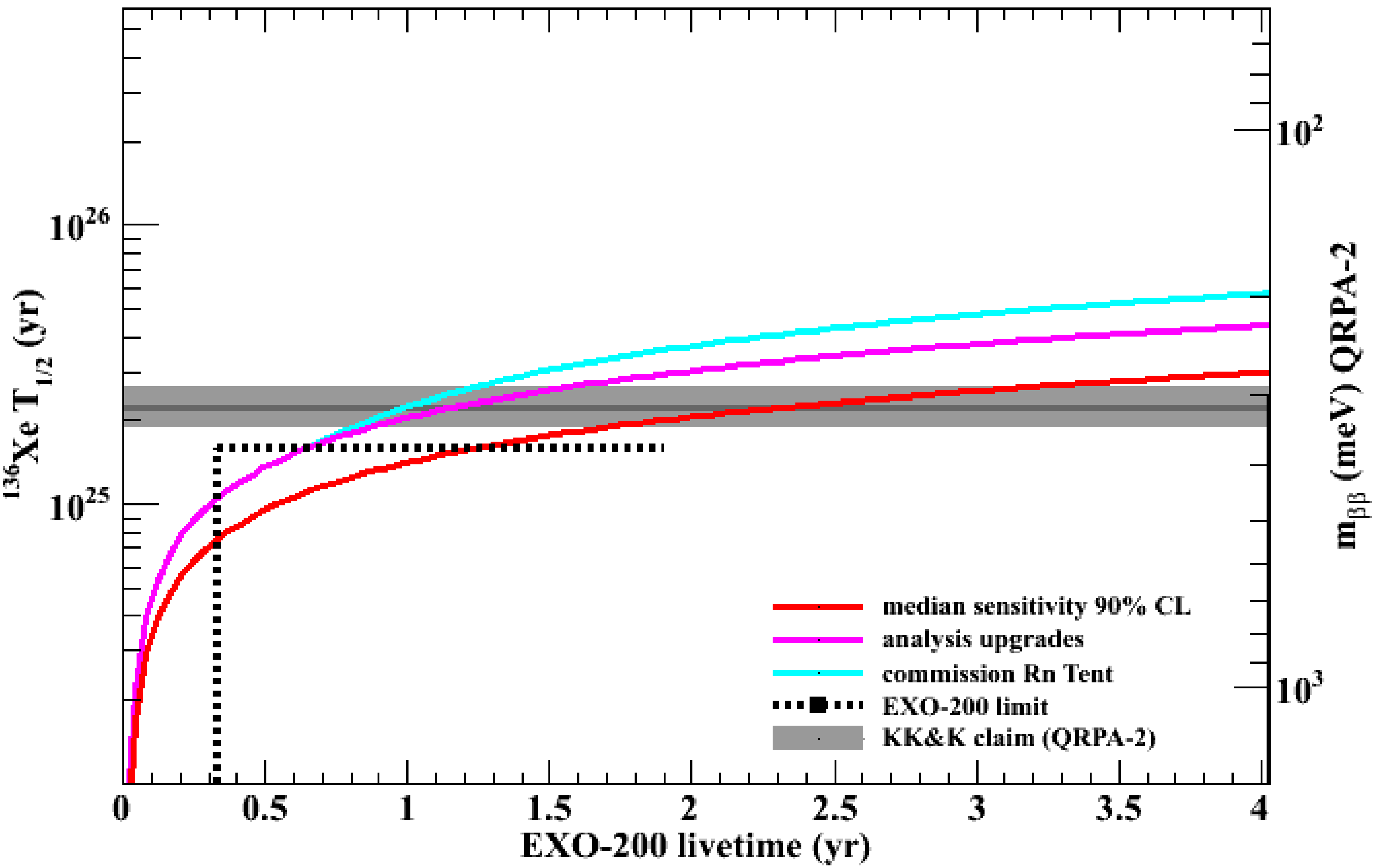
$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

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

(90% C.L.)

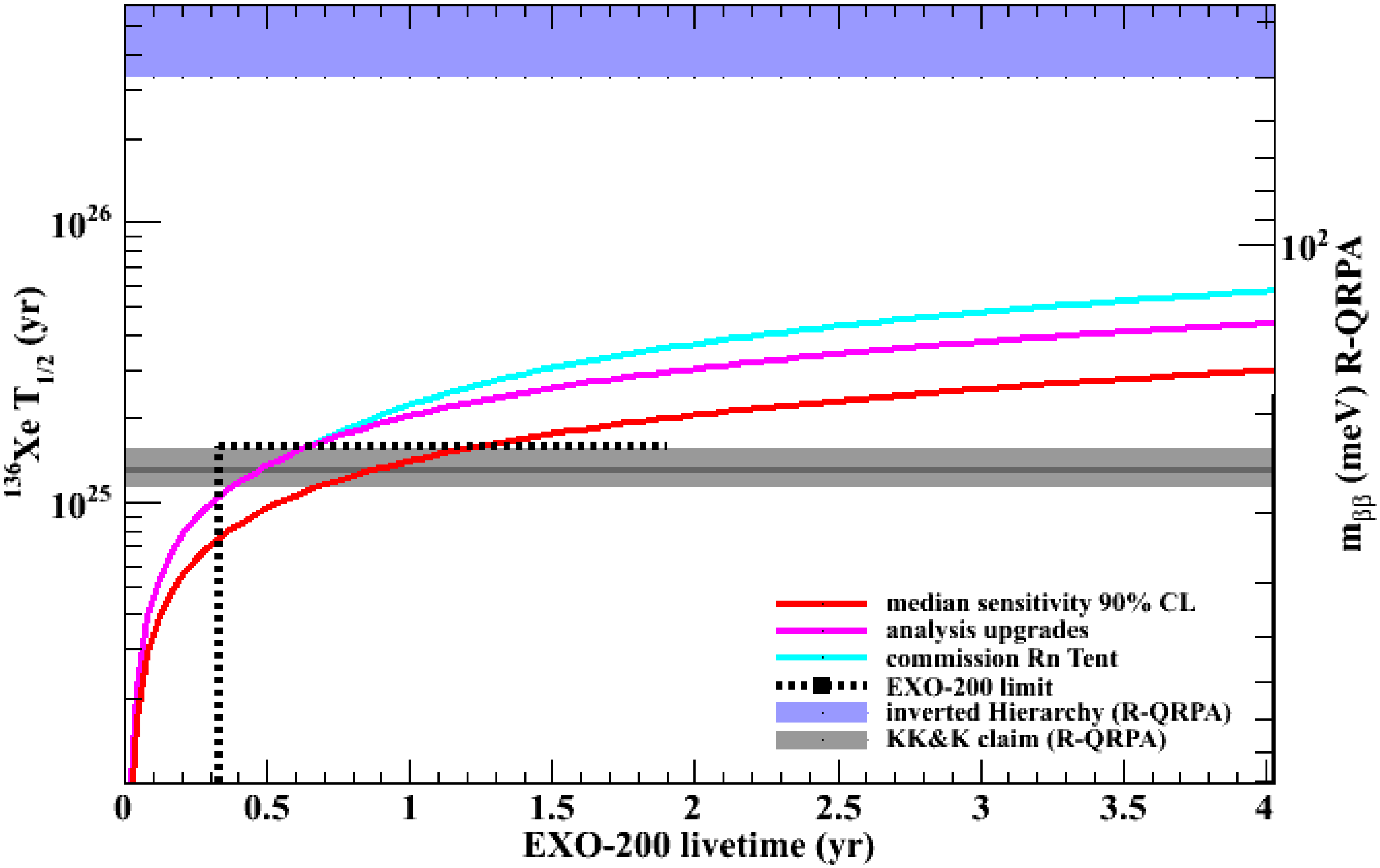
Phys Rev Lett 109 (2012) 032505

QRPA-2



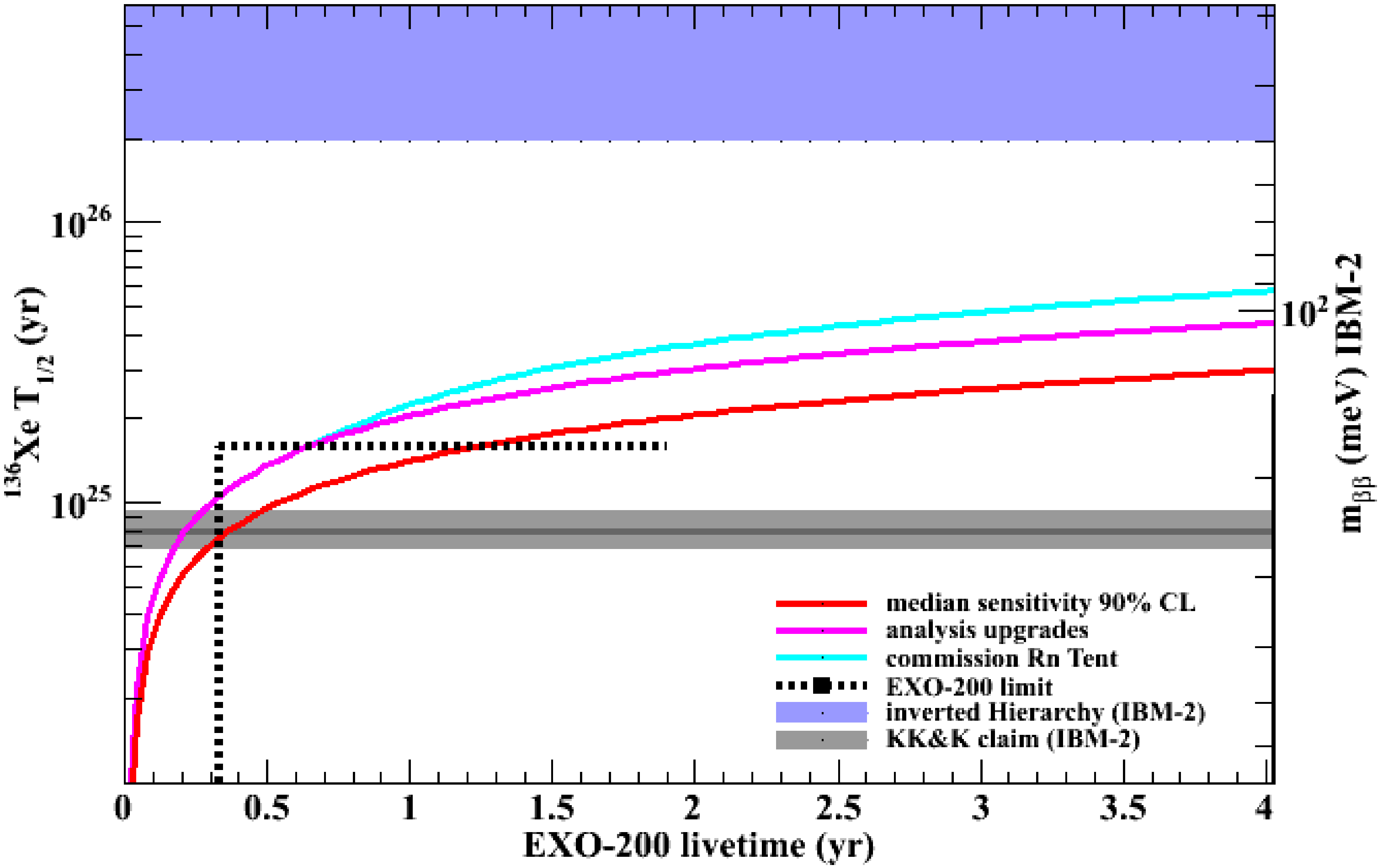
^{136}Xe $T_{1/2}$ (yr)
10^{26}
10^{25}
$m_{\beta\beta}$ (meV) QRPA-2
10^{2}
10^{3}
0
0.5
1
1.5
2
2.5
3
3.5
4
EXO-200 livetime (yr)
median sensitivity 90% CL
analysis upgrades
commission Rn Tent
EXO-200 limit
KK&K claim (QRPA-2)

R-QRPA

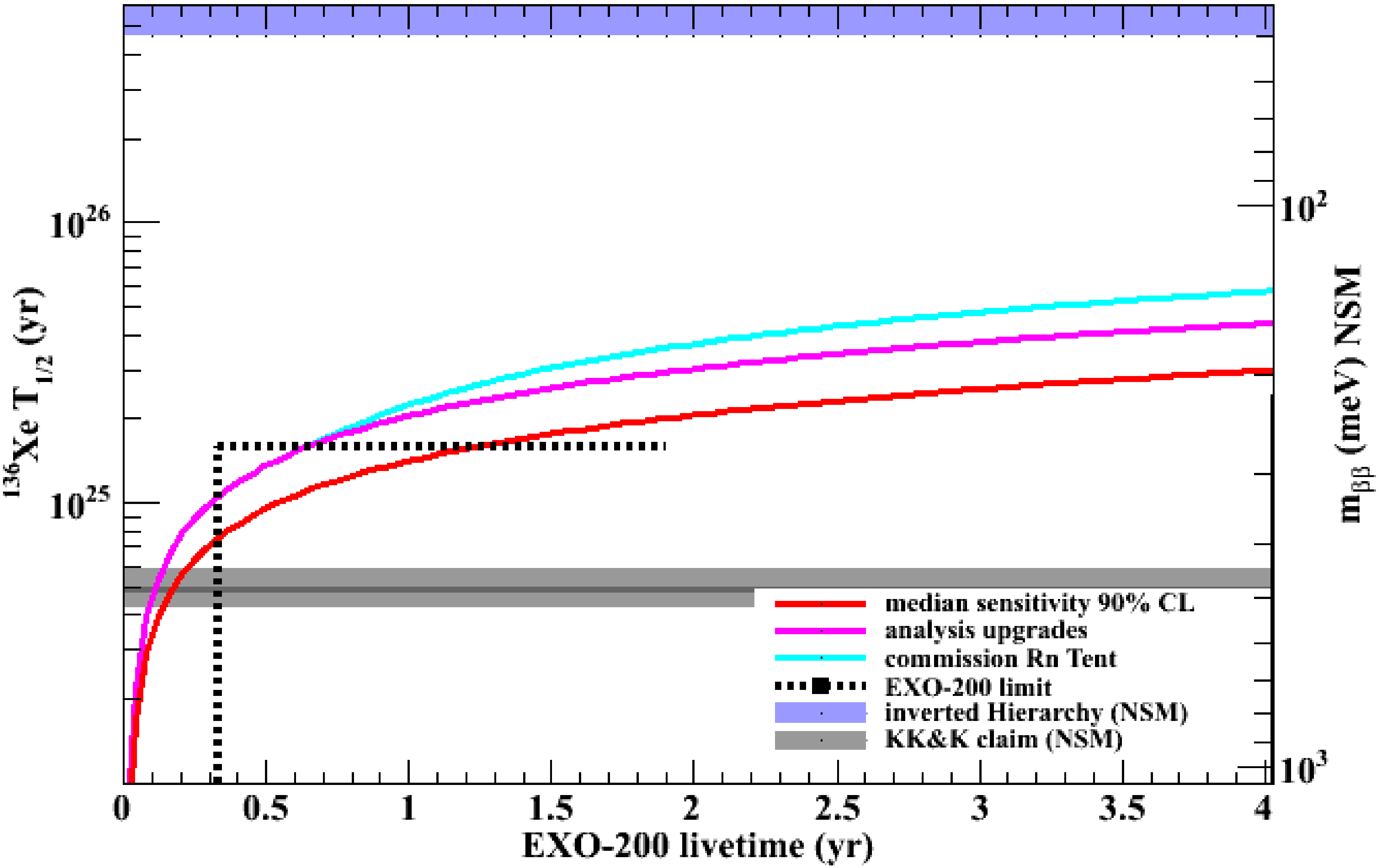


^{136}Xe $T_{1/2}$ (yr)
10^{26}
10^{25}
$m_{\beta\beta}$ (meV) R-QRPA
10^{2}
0
0.5
1
1.5
2
2.5
3
3.5
4
EXO-200 livetime (yr)
median sensitivity 90% CL
analysis upgrades
commission Rn Tent
EXO-200 limit
inverted Hierarchy (R-QRPA)
KK&K claim (R-QRPA)

IBM-2

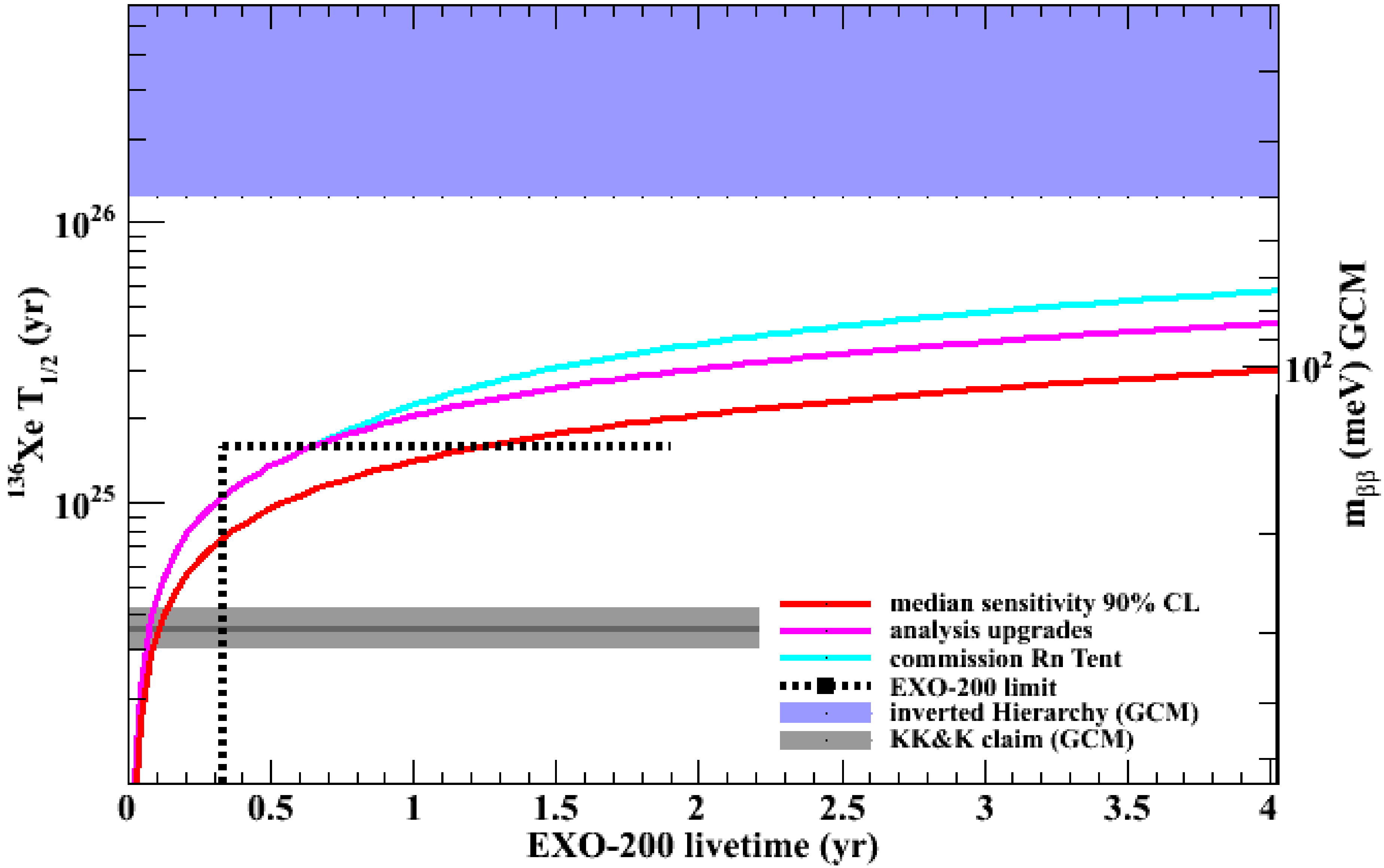

^{136}Xe $T_{1/2}$ (yr)
10^{26}
10^{25}
$m_{\beta\beta}$ (meV) IBM-2
10^2
0
0.5
1
1.5
2
2.5
3
3.5
4
EXO-200 livetime (yr)
median sensitivity 90% CL
analysis upgrades
commission Rn Tent
EXO-200 limit
inverted Hierarchy (IBM-2)
KK&K claim (IBM-2)

NSM



^{136}Xe $T_{1/2}$ (yr)
10^{26}
10^{25}
$m_{\beta\beta}$ (meV) NSM
10^{2}
10^{3}
0
0.5
1
1.5
2
2.5
3
3.5
4
EXO-200 livetime (yr)
median sensitivity 90% CL
analysis upgrades
commission Rn Tent
EXO-200 limit
inverted Hierarchy (NSM)
KK&K claim (NSM)

GCM

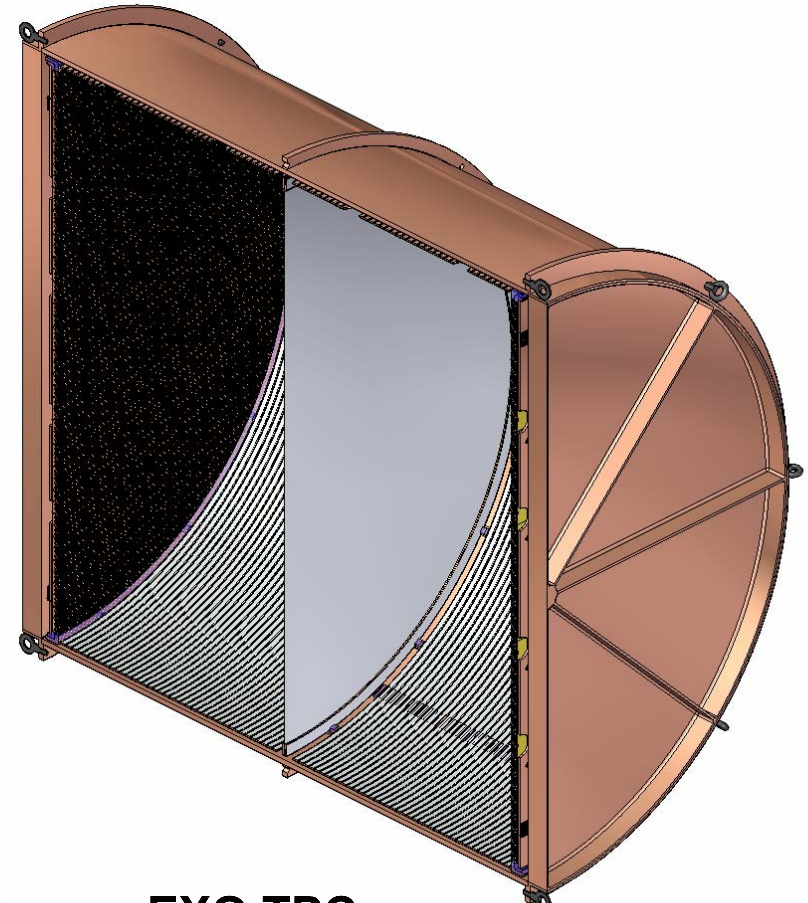


10^{26}
10^{25}
^{136}Xe $T_{1/2}$ (yr)
10^{2}
$m_{\beta\beta}$ (meV) GCM
0
0.5
1
1.5
2
2.5
3
3.5
4
EXO-200 livetime (yr)
median sensitivity 90% CL
analysis upgrades
commission Rn Tent
EXO-200 limit
inverted Hierarchy (GCM)
KK&K claim (GCM)

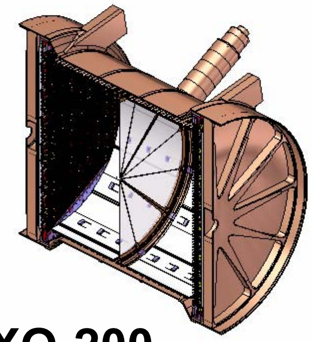
nEXO, a 5-tonne detector

EXO-200 success shows that a larger detector using the same technology can be built NOW.

This will do at least as well as other, un-demonstrated technologies



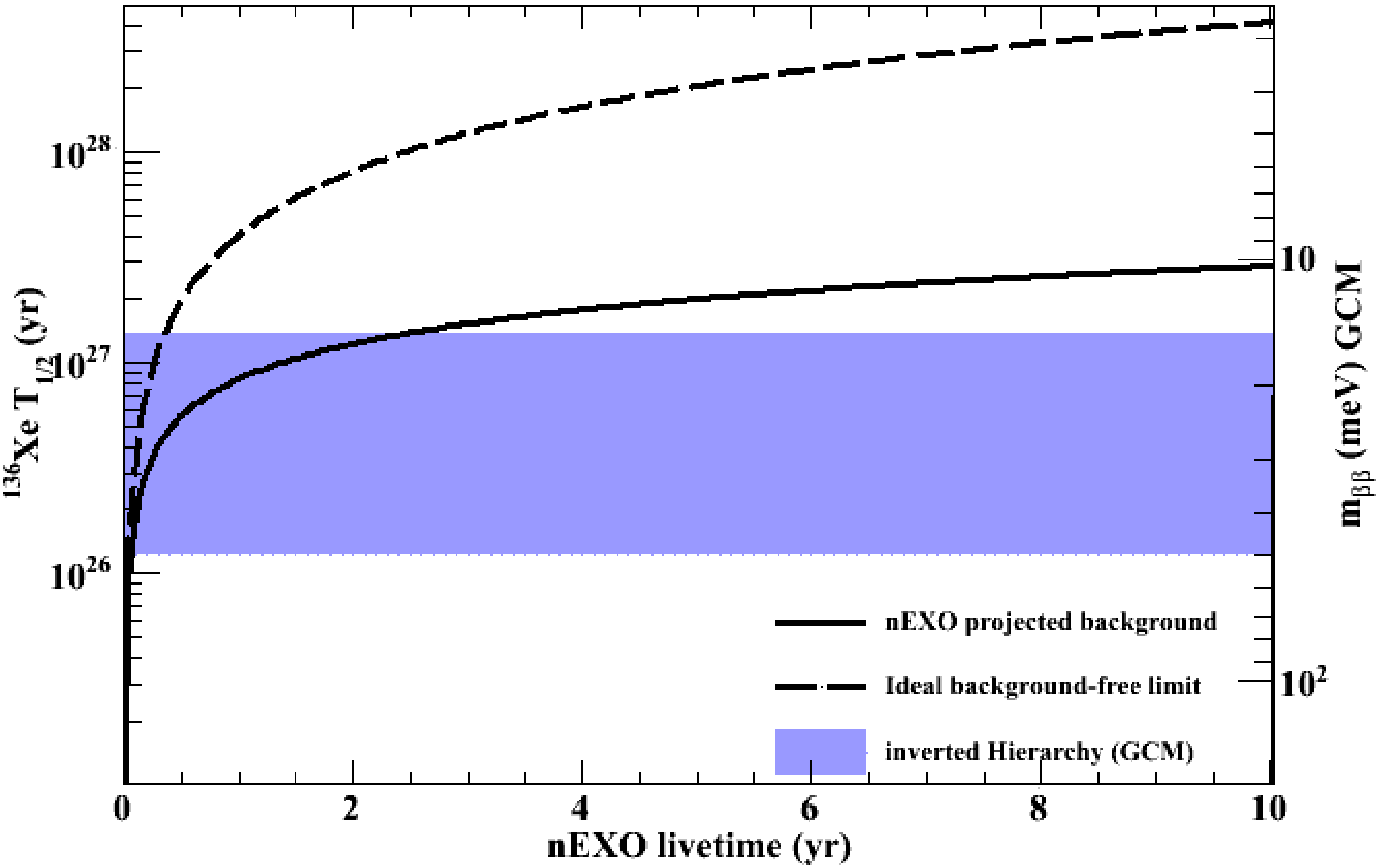
nEXO TPC concept



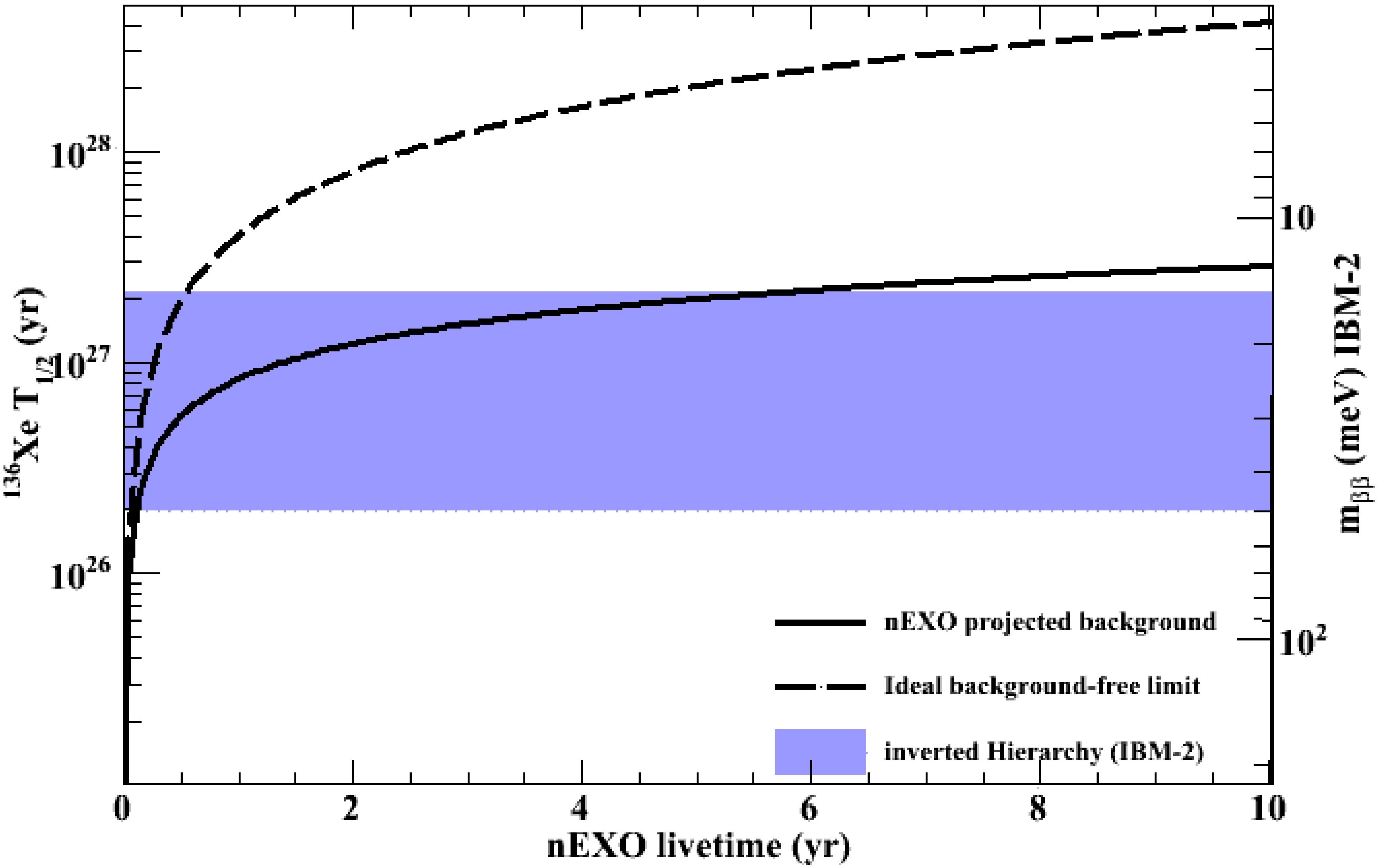
EXO-200 TPC

Ba-tagging can be retrofitted, if needed and when available

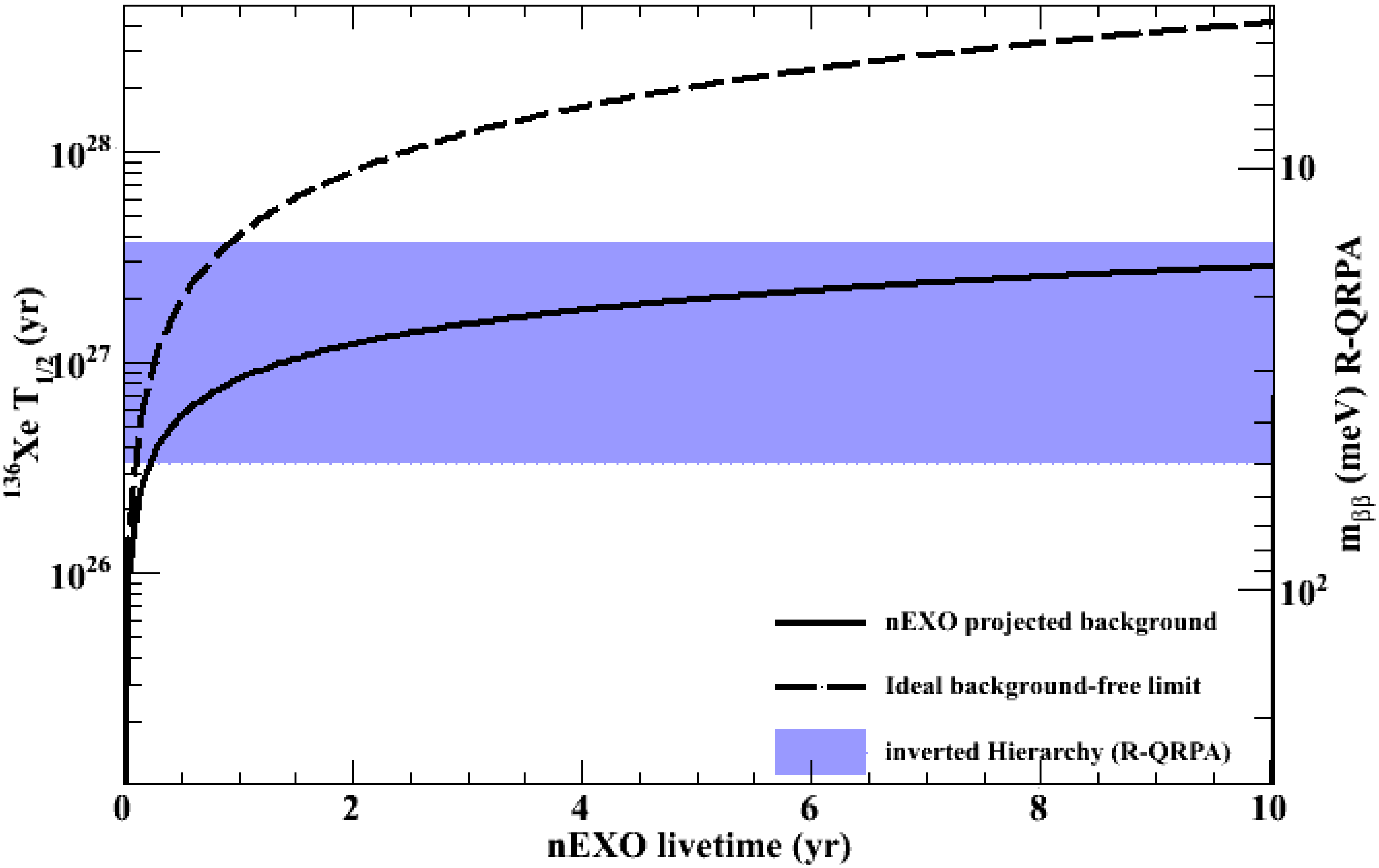
nEXO projected sensitivity



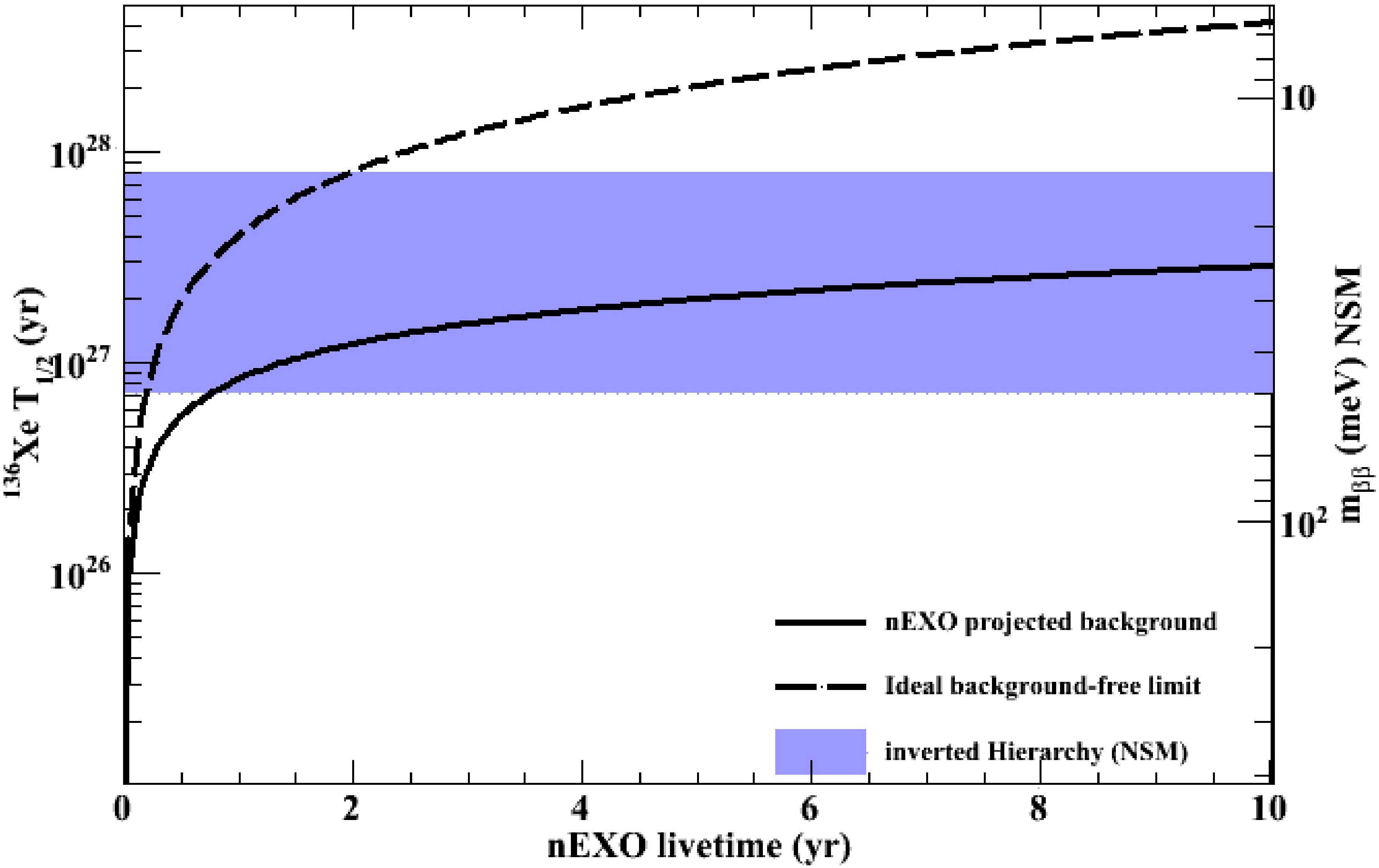
nEXO projected sensitivity



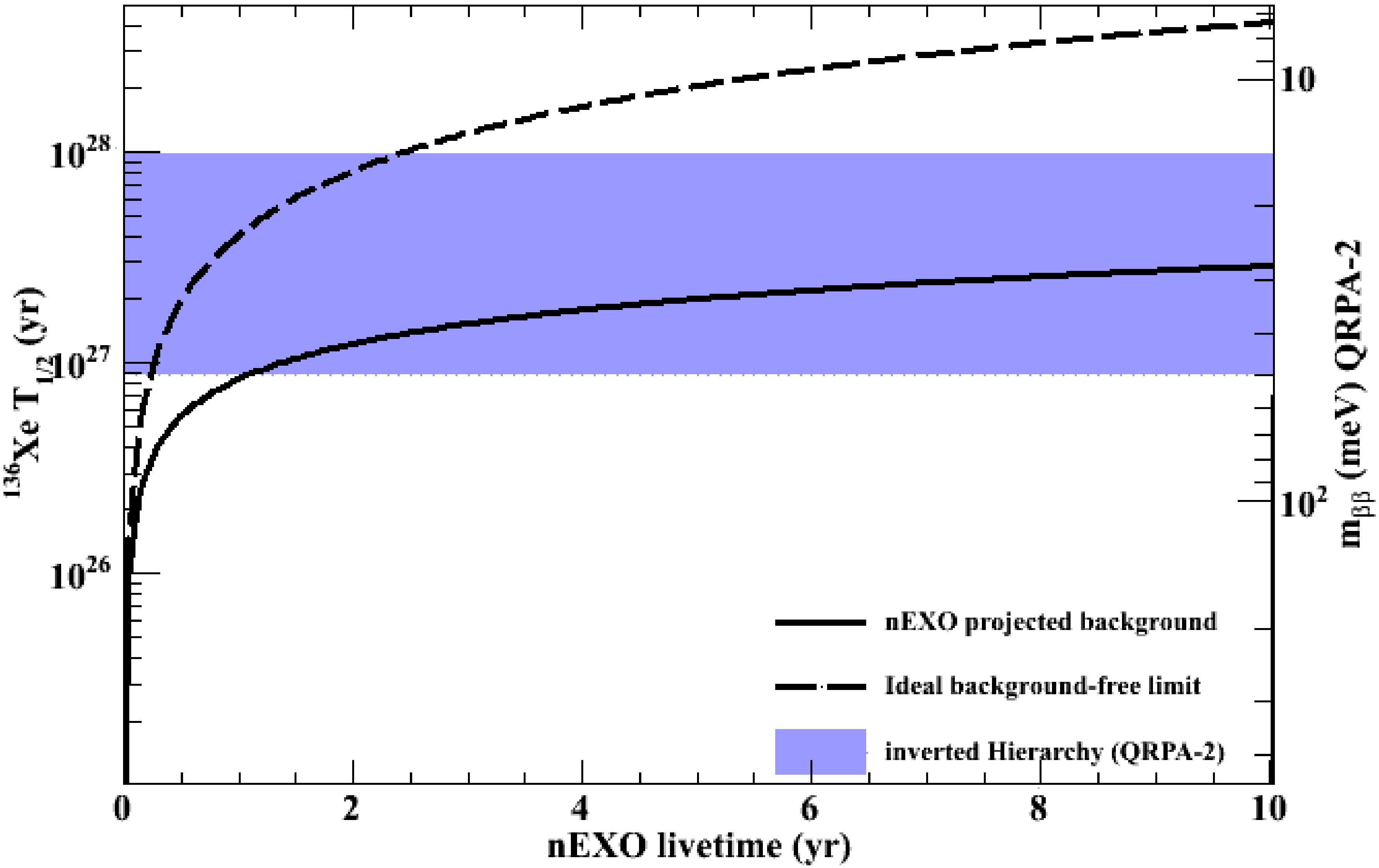
nEXO projected sensitivity



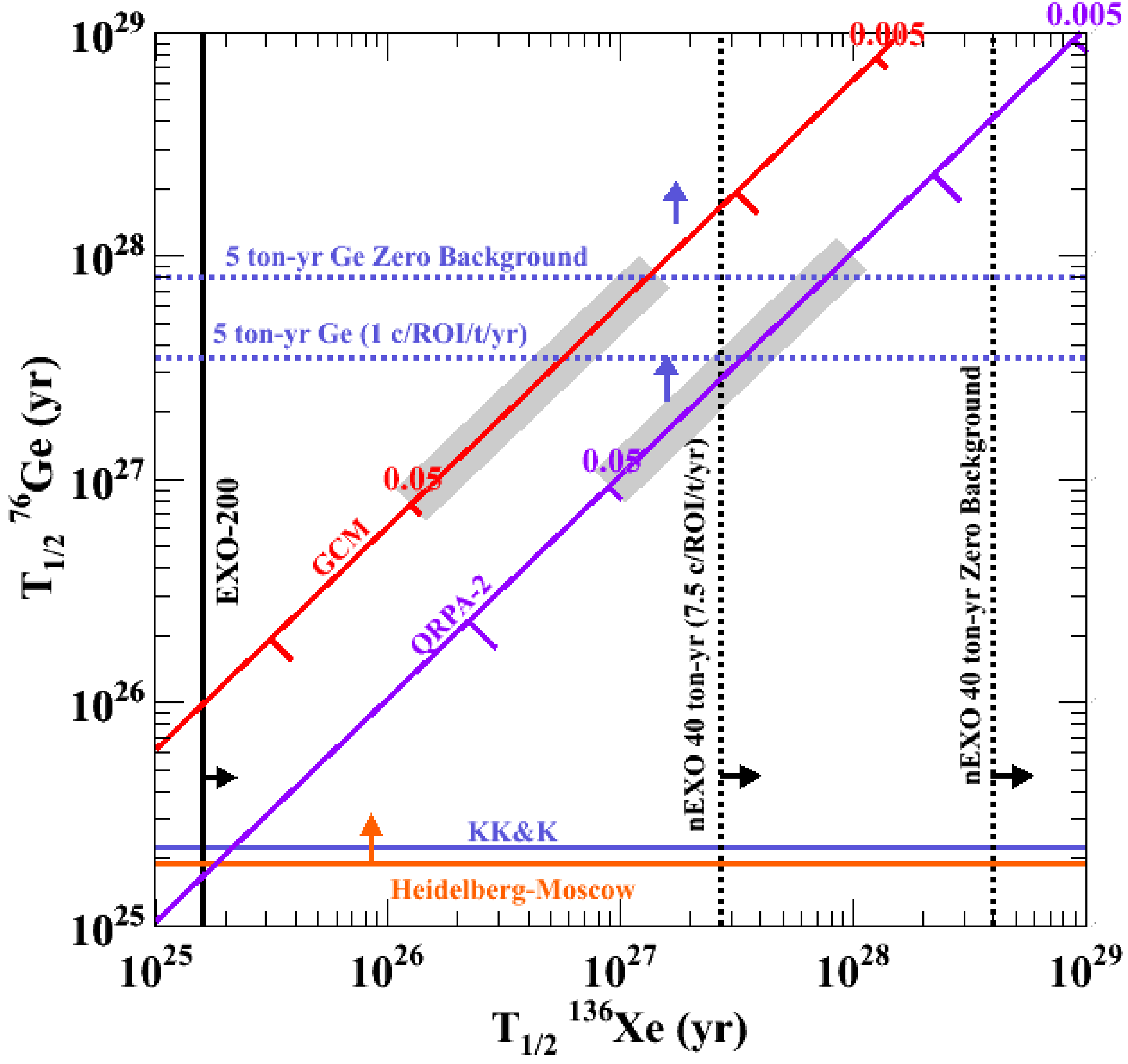
nEXO projected sensitivity



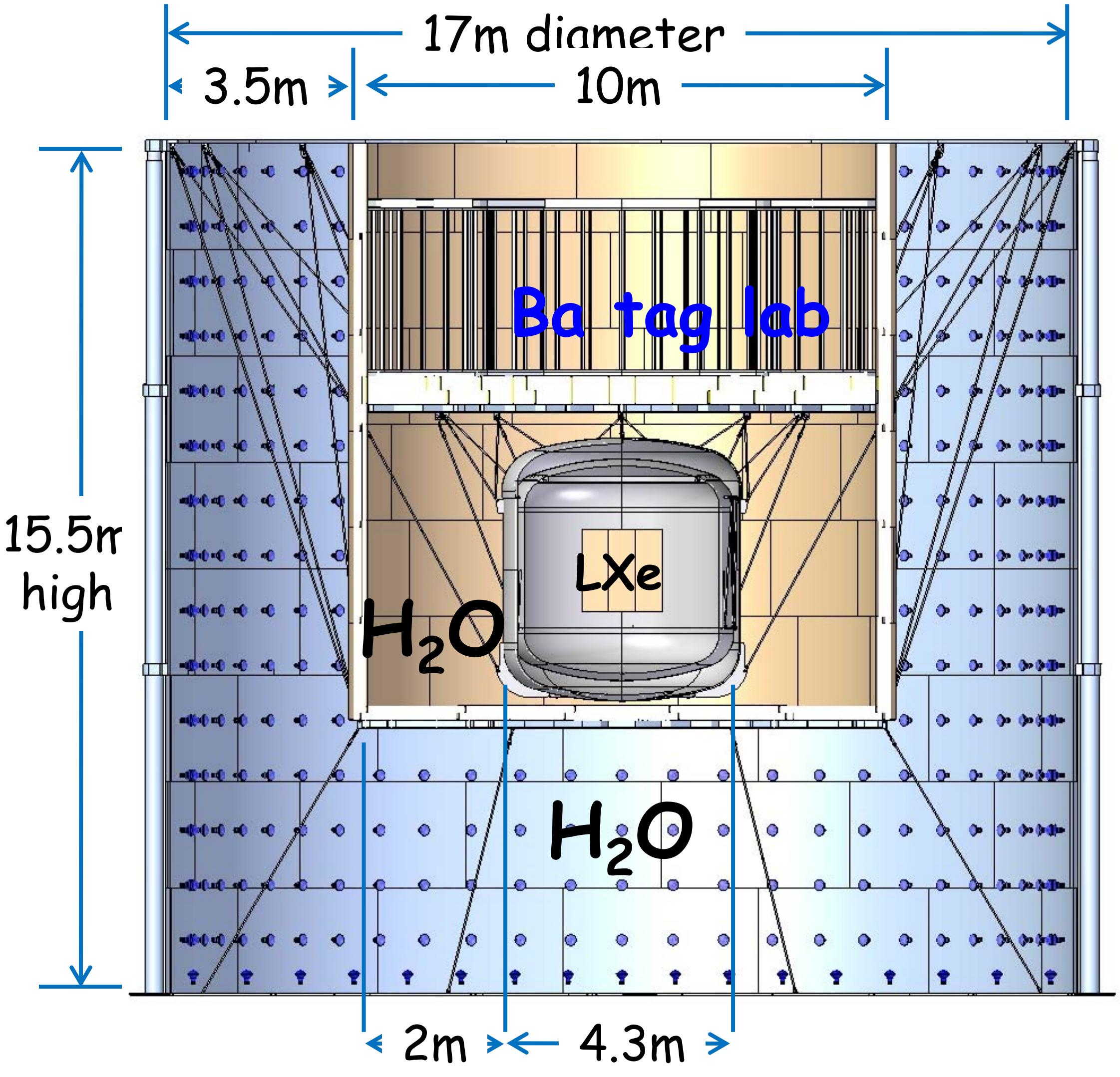
nEXO projected sensitivity



nEXO projected sensitivity



Concept of nEXO with shielding



Summary

- EXO-200 taking data since Jun 2011
- Detector already reached nominal performance for resolution and background
- Discovered the 2νββ decay in ^{136}Xe
- Very competitive limit on the 0νββ decay with the first 4 month of data: almost exclude the Klapdor claim
- Also KamLAND-ZEN and GERDA taking data and EXO-200 has by now ~3x data set
- Working on the design of nEXO
- Next few years will be very exciting!

The EXO collaboration

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TUM, Garching, Germany
W. Feldmeier, P. Fierlinger, M. Marino

The idea of double-beta decay is almost as old as neutrinos themselves:

The possibility of neutrinos-less decay was first discussed in 1937:

E. Majorana, Nuovo Cimento 14 (1937) 171

G. Racah, Nuovo Cimento 14 (1937) 322

Even earlier the study of nuclear structure led to the conclusion that the 2 neutrino mode would have half lives in excess of 10^{20} years

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

Note that along with the double β⁻ decay

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+2}N' + e^{-} + e^{-} $$

there is also a β⁺ mode that in practice would appear as a single or double electron capture

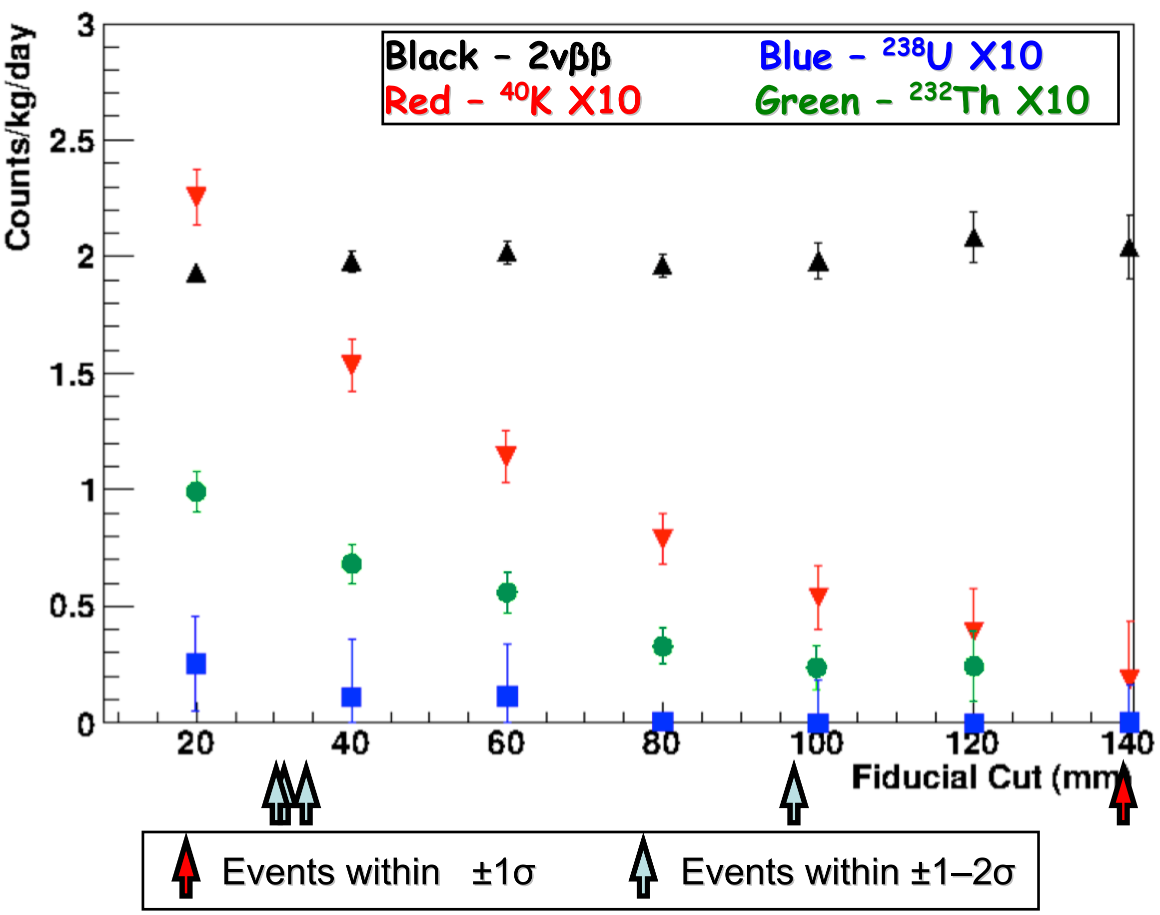
$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z-2}N' + e^{+} + e^{+} $$

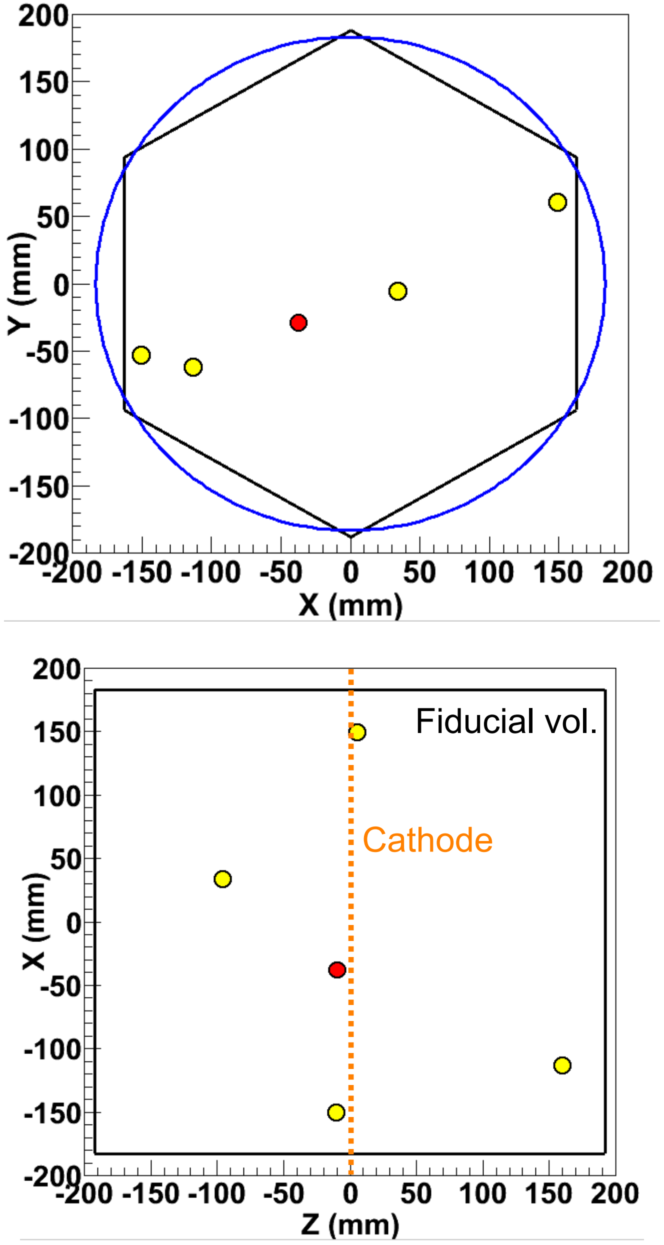
$$ {}^{A}_{Z}N + e^{-} \rightarrow {}^{A}_{Z-2}N' + e^{+} $$

$$ {}^{A}_{Z}N + e^{-} + e^{-} \rightarrow {}^{A}_{Z-2}N' $$

All these processes are phase-space suppressed respect to the β⁻ case and isotope fractions low in natural mix: usually not considered

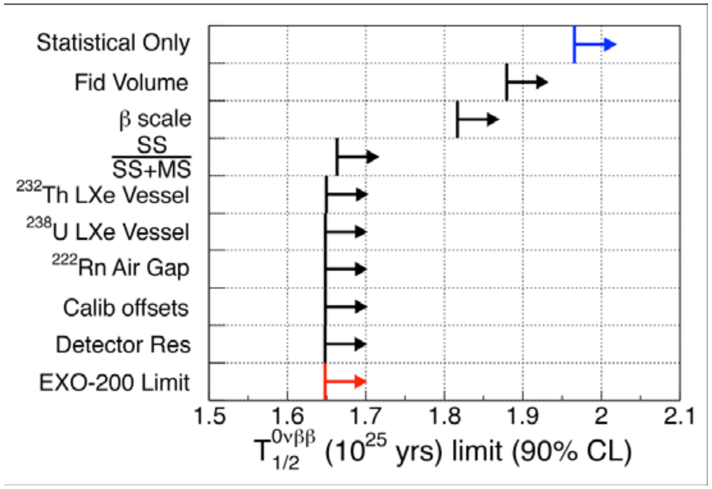
Spatial distributions





- 2νββ rate does not change with fiducial volume
- Background gammas rates drop towards the inside of the detector
- Events in the ±1,2σ ROIs: statistics is too low to conclude on their parent distribution

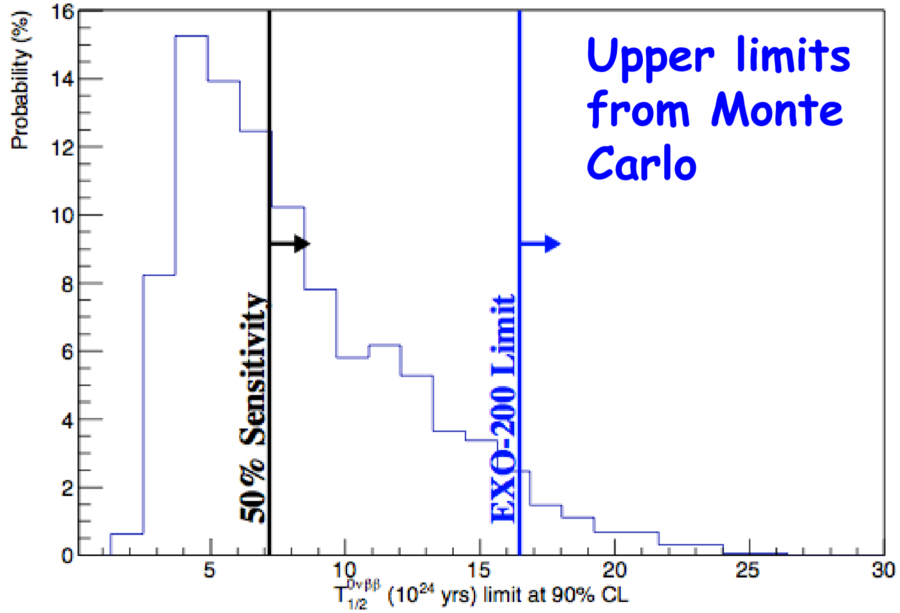
Systematics and sensitivity



Error breakout: expected 90% CL limit given absolute knowledge (0 error) of a given parameter or set of parameters

Term	%
Fiducial Volume	12.34
β scale	9.32
SS / (SS + MS)	0.93
^{232}Th LXe Vessel	0.11
^{238}U LXe Vessel	0.04
^{222}Rn Air Gap	0.04
Calibration offsets	0.04

Distribution of 0νββ $T_{1/2}$ 90% CL



Upper limits from Monte Carlo

From estimated background, expect to quote a 90% CL upper limit on $T_{1/2}$:

$\geq$ 1.6 × 10^{25} yr 6.5% of the time
$\geq$ 7 × 10^{24} yr 50% of the time