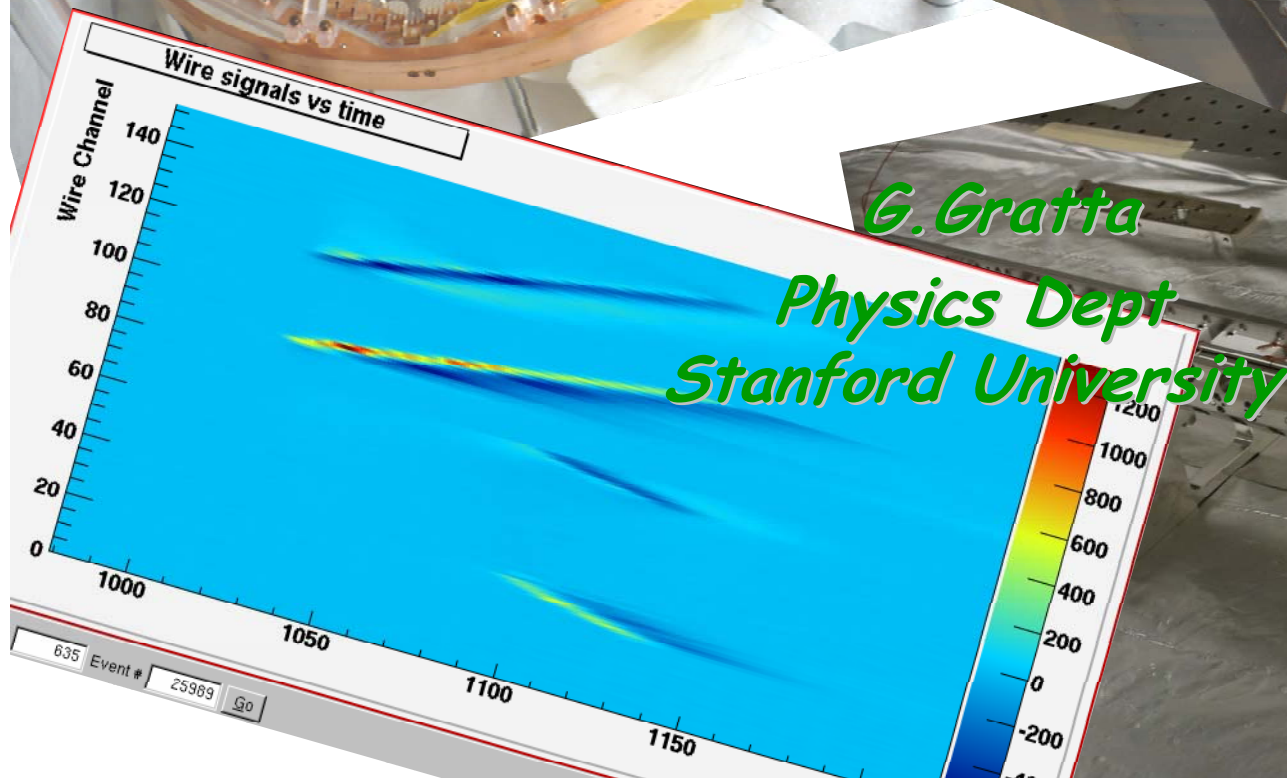


Double Beta Decay

the last year



G. Gratta

*Physics Dept
Stanford University*

Last 20 yrs: the age of ν physics

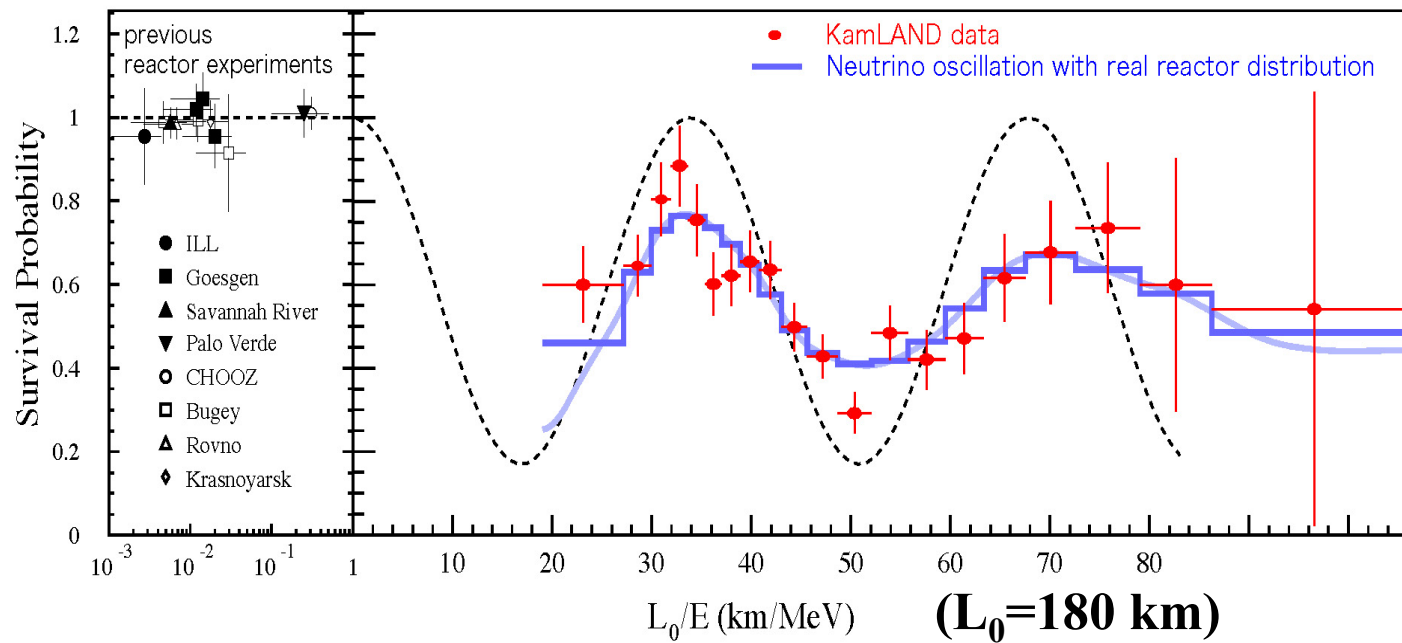
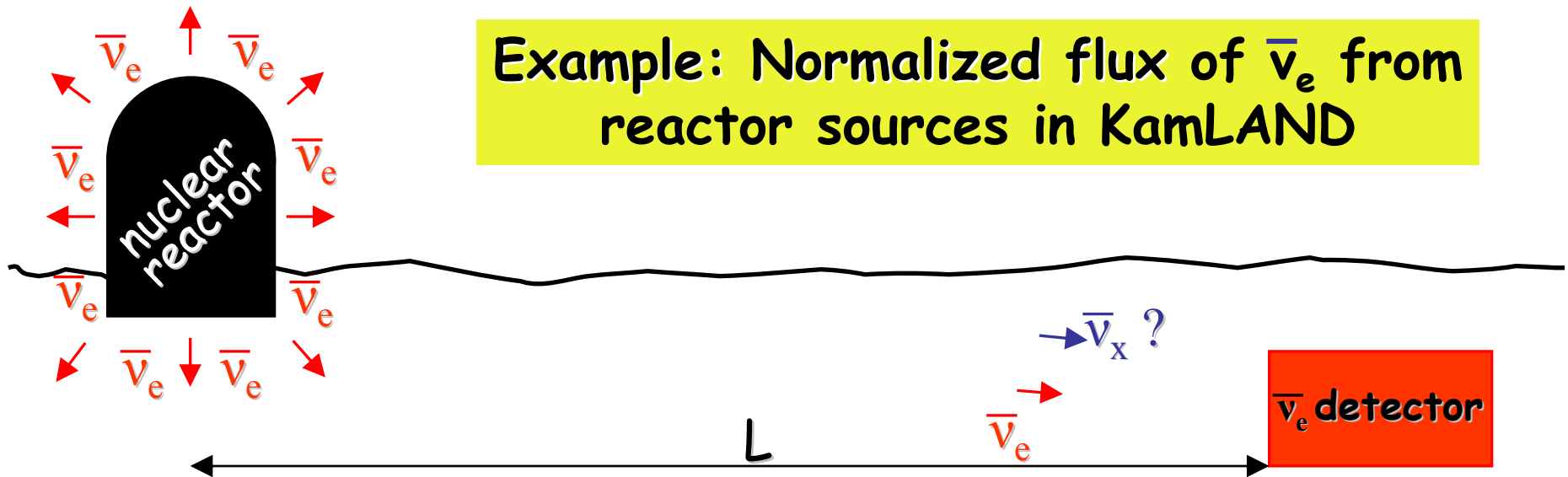
Discovery of ν flavor change

- *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



If $m_\nu \neq 0$ neutrinos show a different image depending on our vantage point:

- “Weak interaction eigenstate”

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

this is the state of definite flavor: interactions couple to this state

- “Mass eigenstate”

$$\begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

this is the state of definite energy: propagation happens in this state



It is easier to write things for 2 flavors only:

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

θ is the mixing parameter

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \sin^2 \frac{1.3 \Delta m^2 L}{E}$$

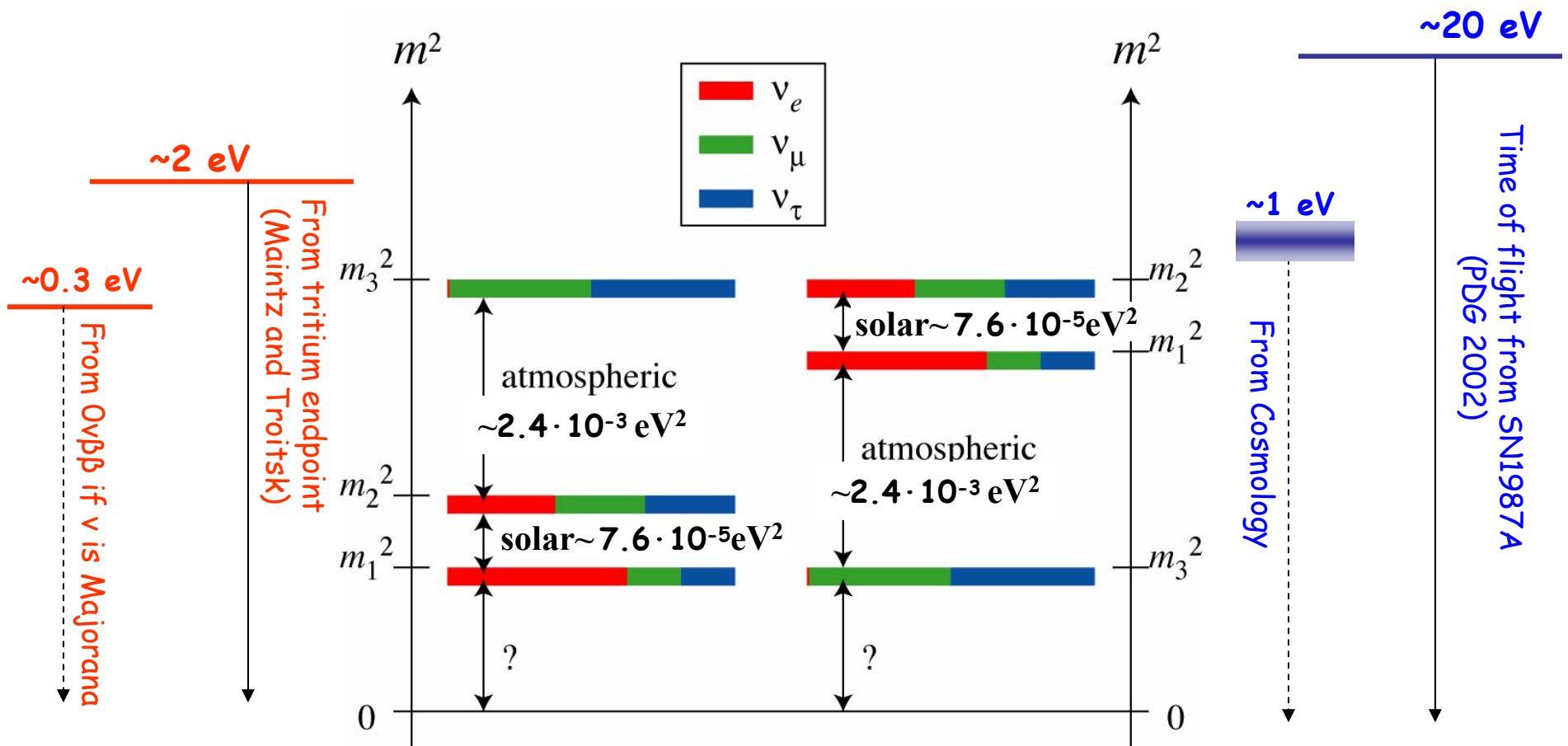
$m_1^2 - m_2^2$ [eV²]

[km]

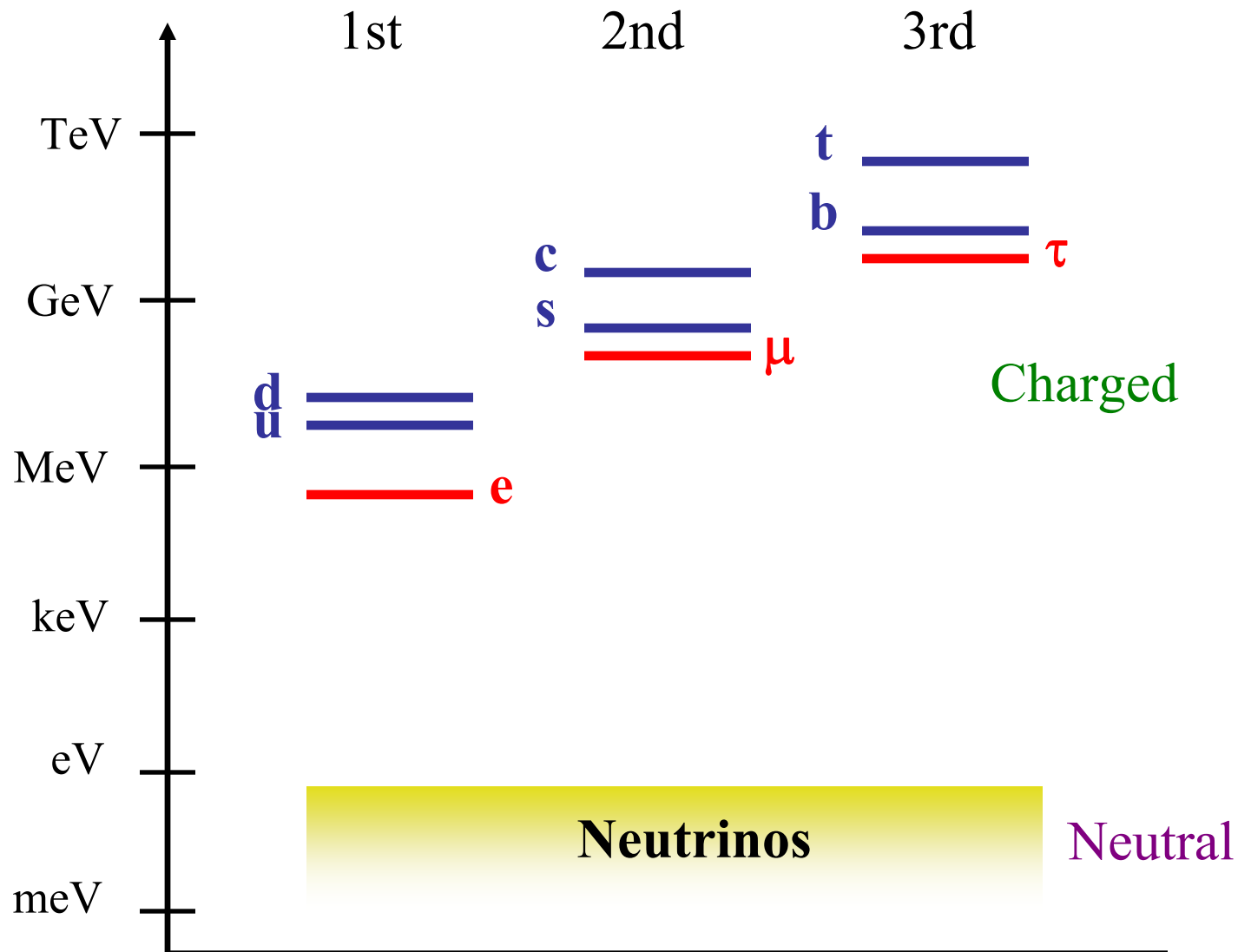
[MeV]

Neutrino oscillations $\Rightarrow m_\nu \neq 0$

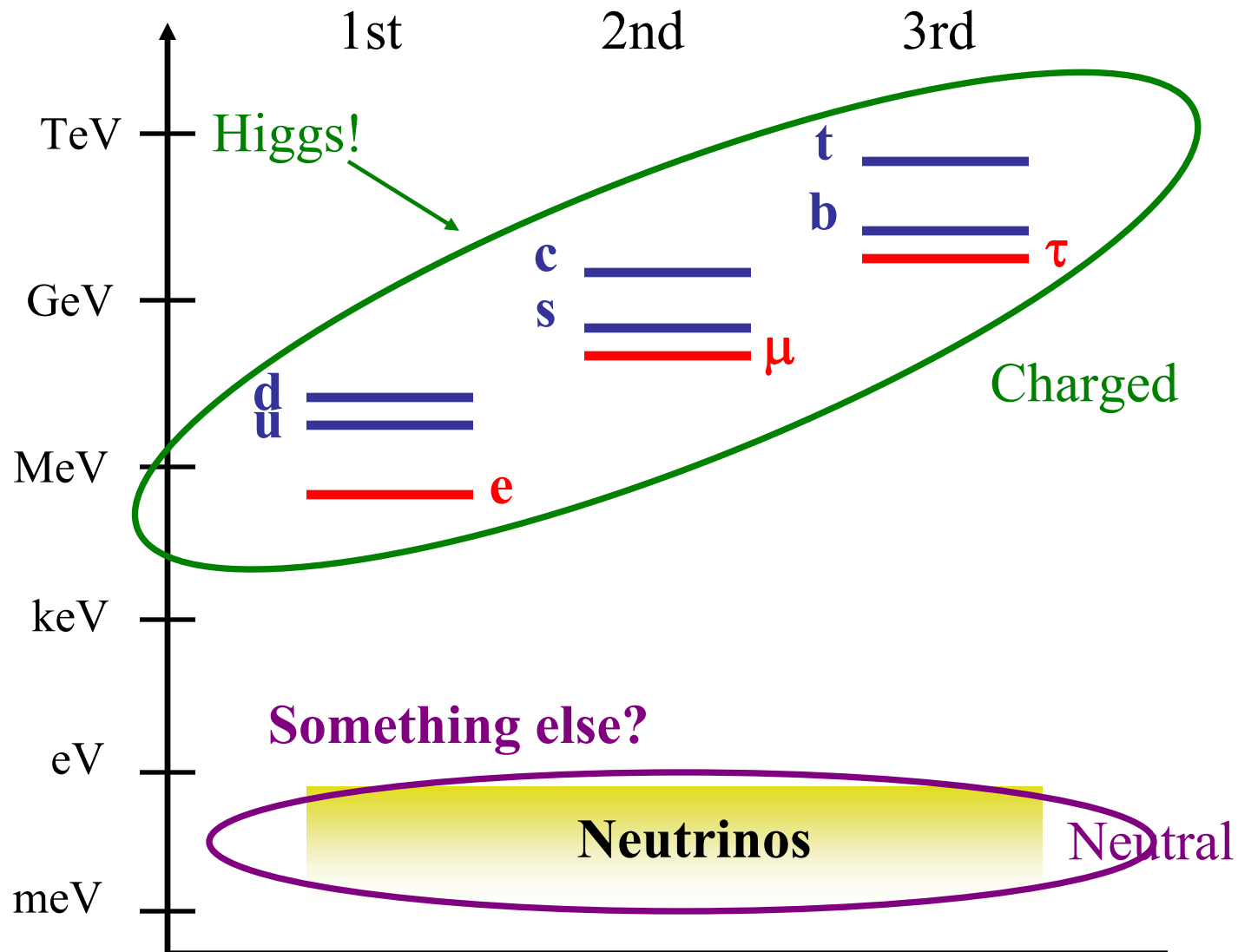
Our knowledge of the ν mass pattern



Fermion mass spectrum



Fermion mass spectrum



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

		Generation		
		1 st	2 nd	3 rd
Charge	1	e^+	μ^+	τ^+
	2/3	u	c	t
	1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
	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 $\bar{\nu} = \nu$, 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, $\bar{\nu} \neq \nu$ 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...)

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



“Majorana” neutrinos

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

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

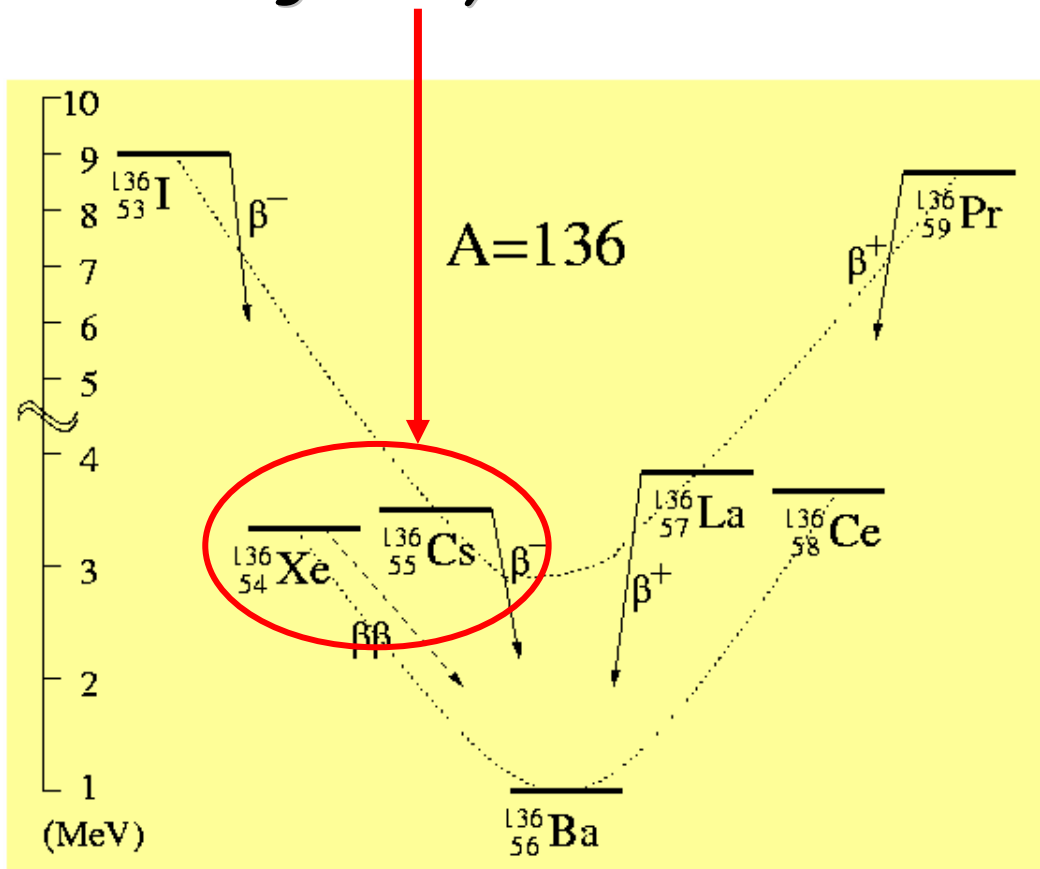


Which way Nature chose to proceed is an experimental question

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

There are two varieties of $\beta\beta$ decay

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

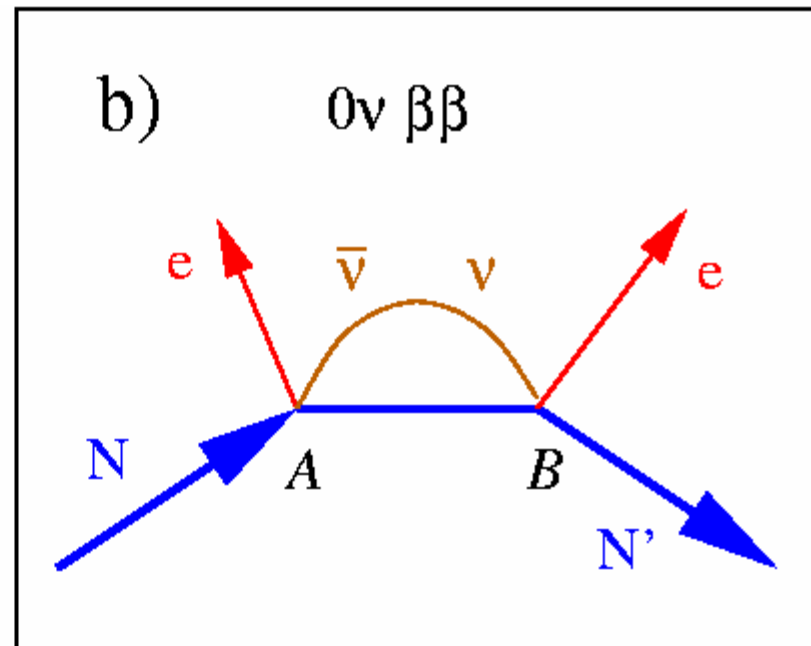
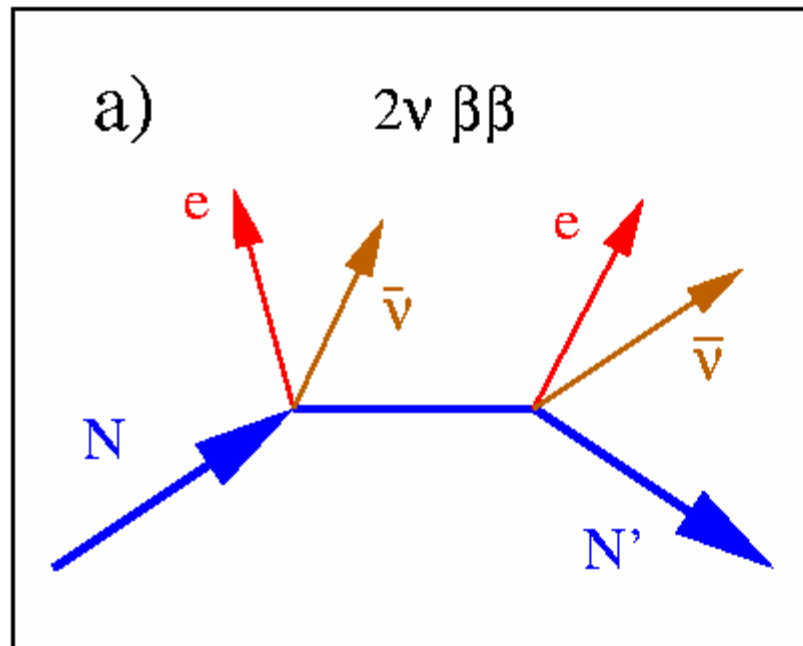
0ν mode: a hypothetical
process can happen

only if: $M_\nu \neq 0$

$$\nu = \bar{\nu}$$

$$|\Delta L|=2$$

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



There are two varieties of $\beta\beta$ decay

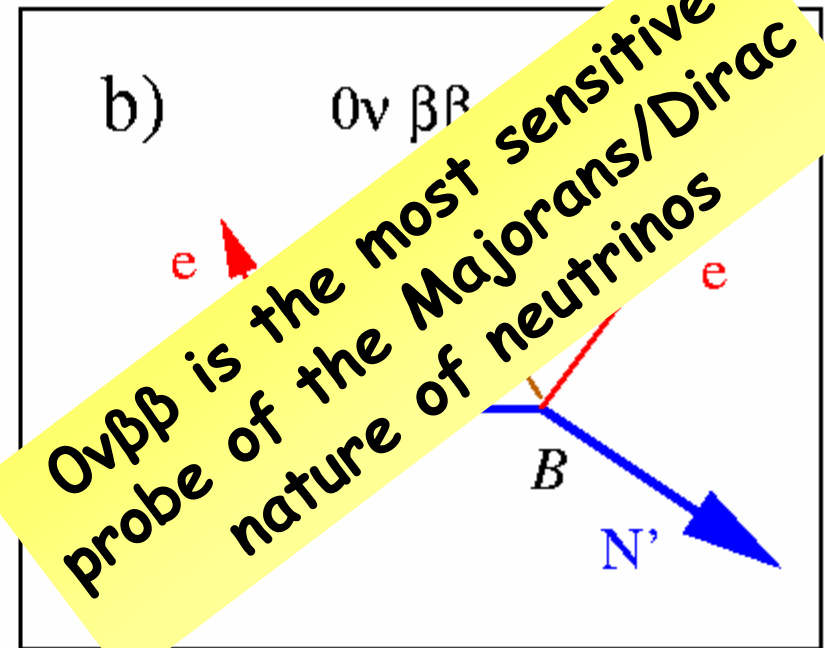
0ν mode: a hypothetical process can happen

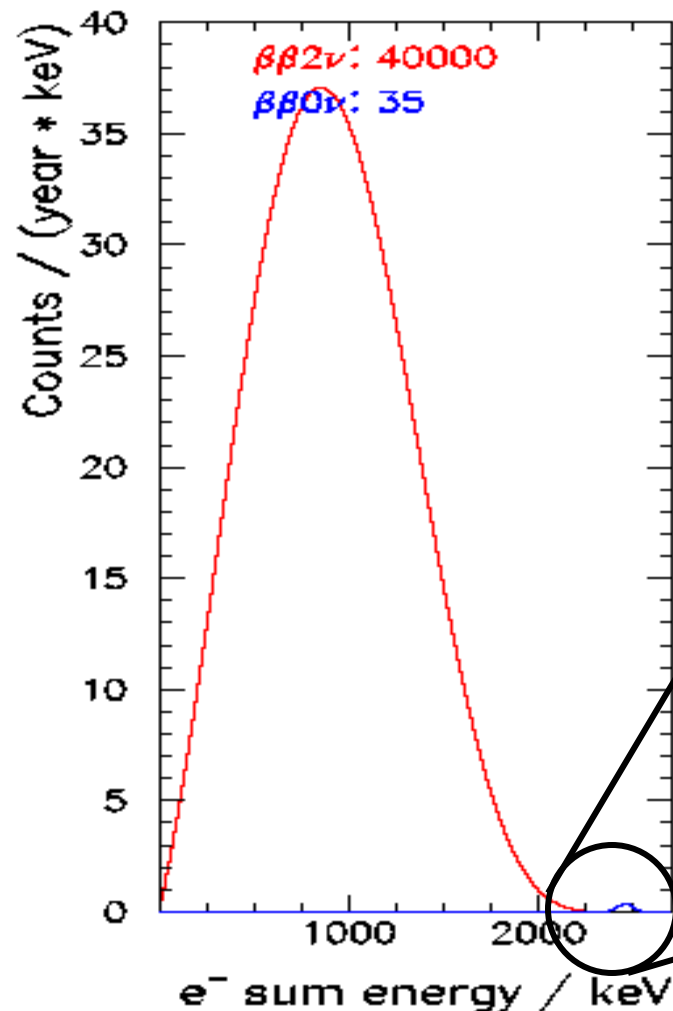
only if: $M_\nu \neq 0$

$$\nu = \bar{\nu}$$

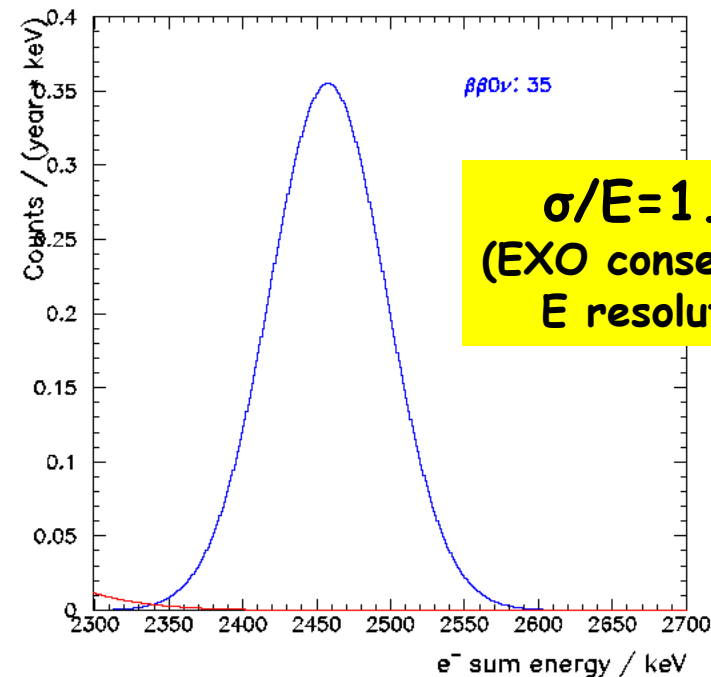
$$|\Delta L|=2$$

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





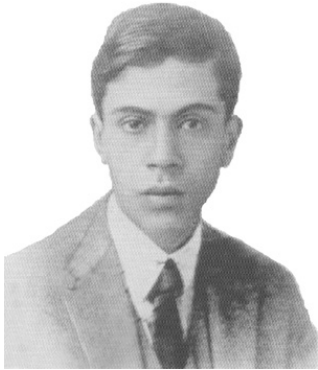
Background due to the
Standard Model $2\nu\beta\beta$ decay



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

Topology and particle ID are also important to recognize backgrounds

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



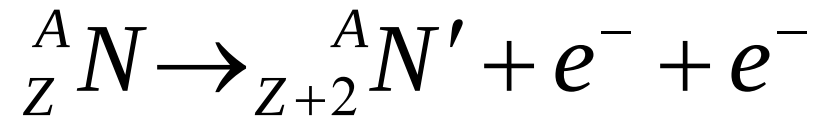
G. Racah, Nuovo Cimento 14 (1937) 322

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

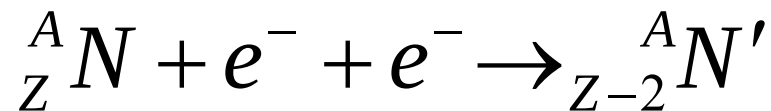
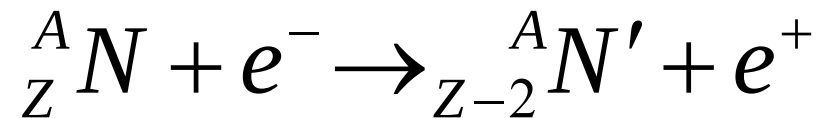


M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512

Note that along with the double β^- decay



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



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

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

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

$$M_F^{0\nu\beta\beta} \text{ and } M_{GT}^{0\nu\beta\beta}$$

can be calculated within
particular nuclear models

$$G^{0\nu\beta\beta}$$

a known phase space factor

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

is the quantity to
be measured

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

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

Nuclear structure approaches

*In **NSM** (Madrid-Strasbourg 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 $0\nu\beta\beta$ -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 $0\nu\beta\beta$ -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 two 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.*

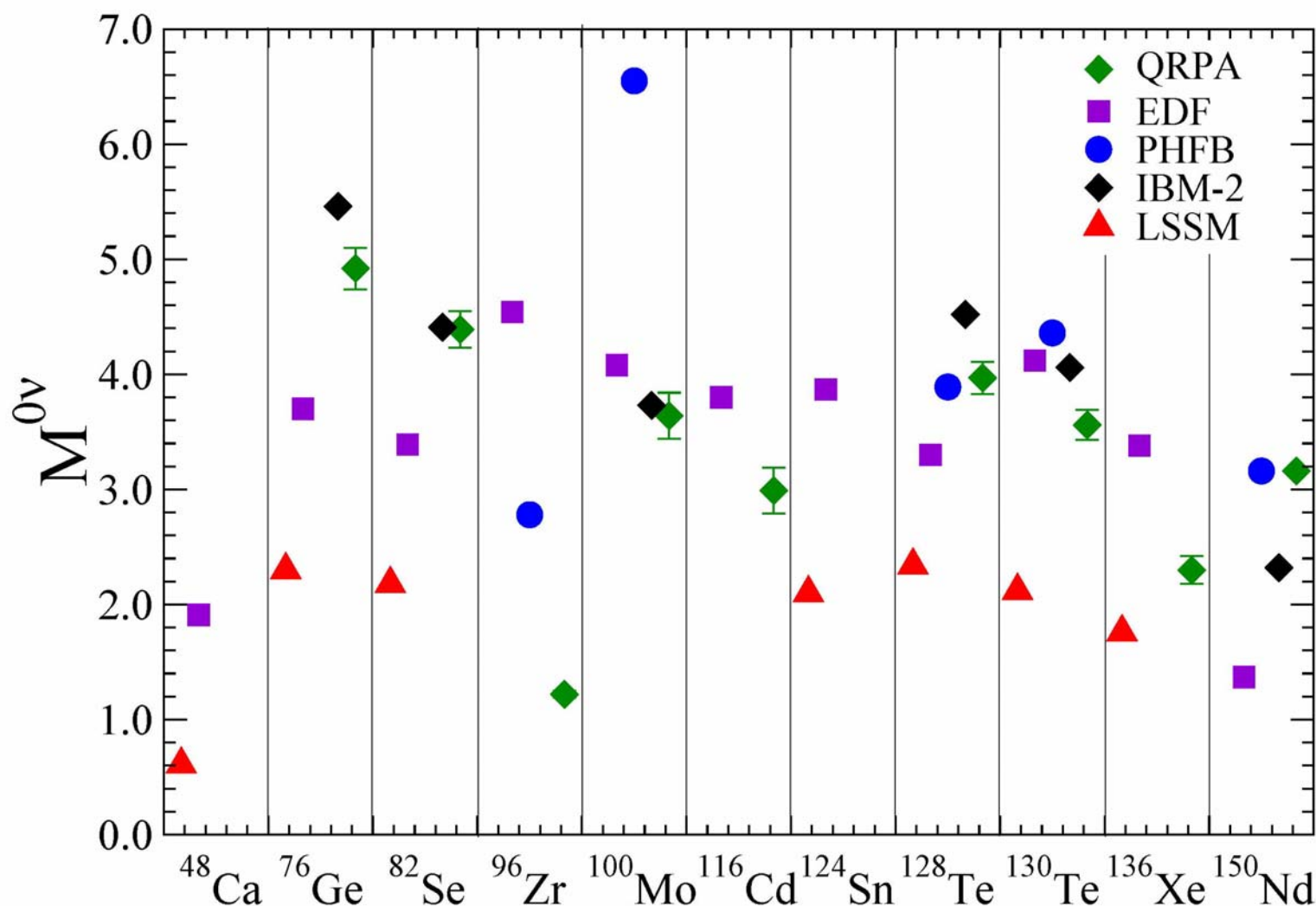
*Differences: i) mean field; ii) residual interaction; iii) size of the model space
iv) many-body approximation*

**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



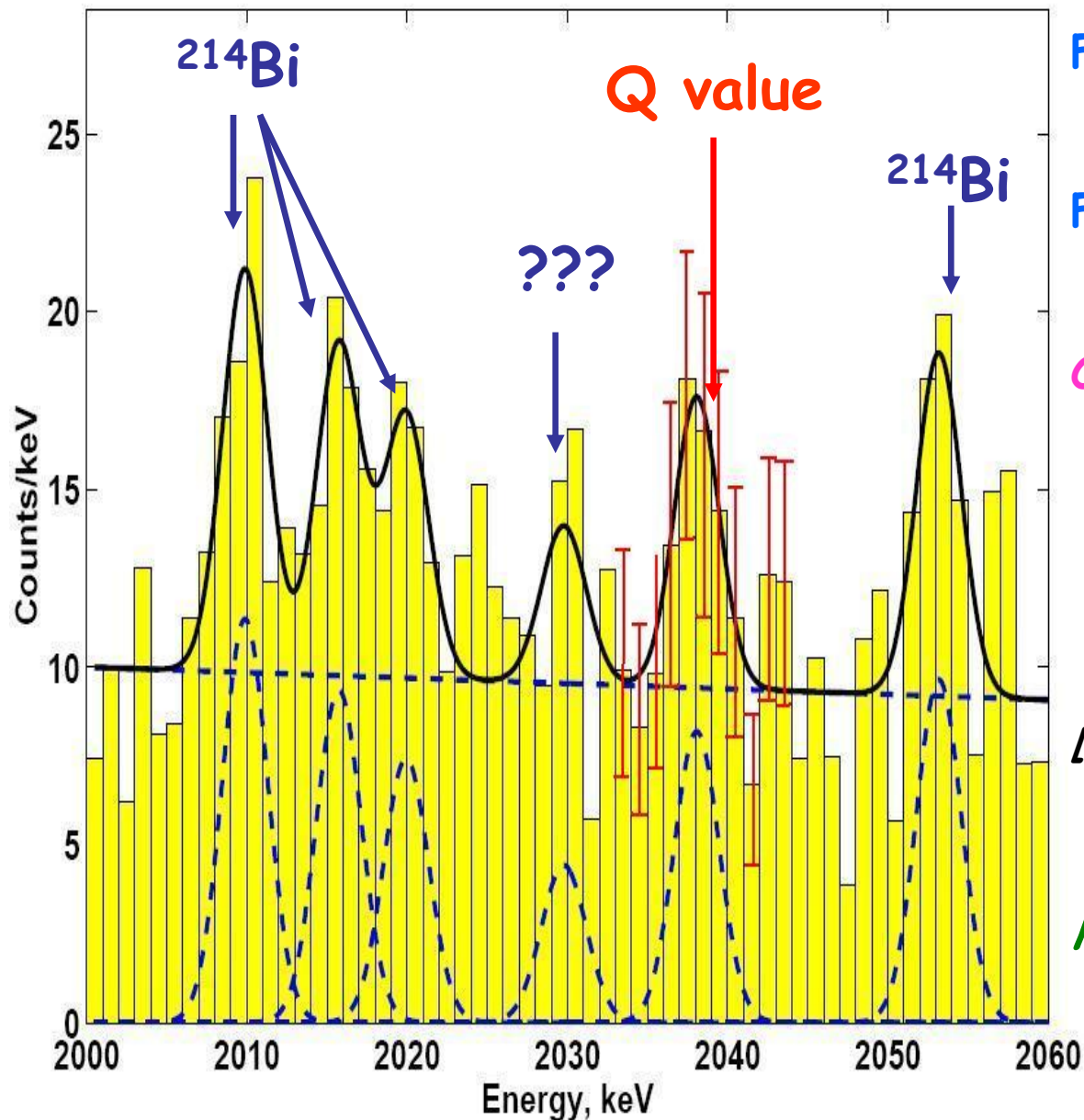
Note, however, that to discover Majorana neutrinos and lepton number violation the value of the nuclear matrix element is inessential!

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

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

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	$\langle m \rangle$ (eV)
^{48}Ca	Ge diode	47.7	$>5.8 \cdot 10^{22}$ (90%CL)	<0.35
^{76}Ge			$>1.9 \cdot 10^{25}$ (90%CL)	
^{82}Se			$>2.1 \cdot 10^{23}$ (90%CL)	
^{96}Zr			$>9 \cdot 10^{23}$ (90%CL)	
^{100}Mo			$>1.1 \cdot 10^{23}$ (90%CL)	
^{116}Cd	Foil.Geiger tubes		$>1.7 \cdot 10^{23}$ (90%CL)	
^{128}Te			$>1.1 \cdot 10^{23}$ (90%CL)	
^{130}Te			$>3 \cdot 10^{24}$ (90%CL)	$<0.19-0.68$
^{136}Xe	Foil.Geiger tubes	~ 4.5	$>1.2 \cdot 10^{24}$ (90%CL)	$<1.1-2.9$
^{150}Nd			$>1.8 \cdot 10^{22}$ (90%CL)	
^{160}Gd			$>1.3 \cdot 10^{21}$ (90%CL)	

$\beta\beta 0\nu$ discovery claim



Fit model:

6 gaussians + linear bknd.

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

Claimed significance: 4.2σ

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

$$\langle m_{\nu} \rangle = 0.32 \pm 0.03 \text{ eV}$$

[H. V. Klapdor-Kleingrothaus
and I. Krivosheina,
Mod. Phys. Lett. A 21 (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	$(4.3 \pm 2.2) \cdot 10^{19}$
^{76}Ge	$(1.77 \pm 0.12) \cdot 10^{21}$
^{82}Se	$(9.6 \pm 1) \cdot 10^{19}$
^{96}Zr	$(9.4 \pm 3.2) \cdot 10^{18} \text{ §}$ $(2.1 \pm 0.6) \cdot 10^{19}$
^{100}Mo	$(5.7 \pm 1.2) \cdot 10^{20}$
^{116}Cd	$(2.9 \pm 0.4) \cdot 10^{19}$
^{128}Te	$(7.2 \pm 0.4) \cdot 10^{24} \text{ §}$
^{130}Te	$(7 \pm 0.9 \pm 1.1) \cdot 10^{20}$
^{136}Xe	$> 1.1 \cdot 10^{22} \text{ 90\% CL}$
^{150}Nd	$(1.4 \pm 0.7) \cdot 10^{20}$
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21} \text{ *}$

§ Geochemical experiment

* Radiochemical experiment

← More on this later!

*Pre-Aug 2011 table
arbitrarily simplified
from PDG*

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]

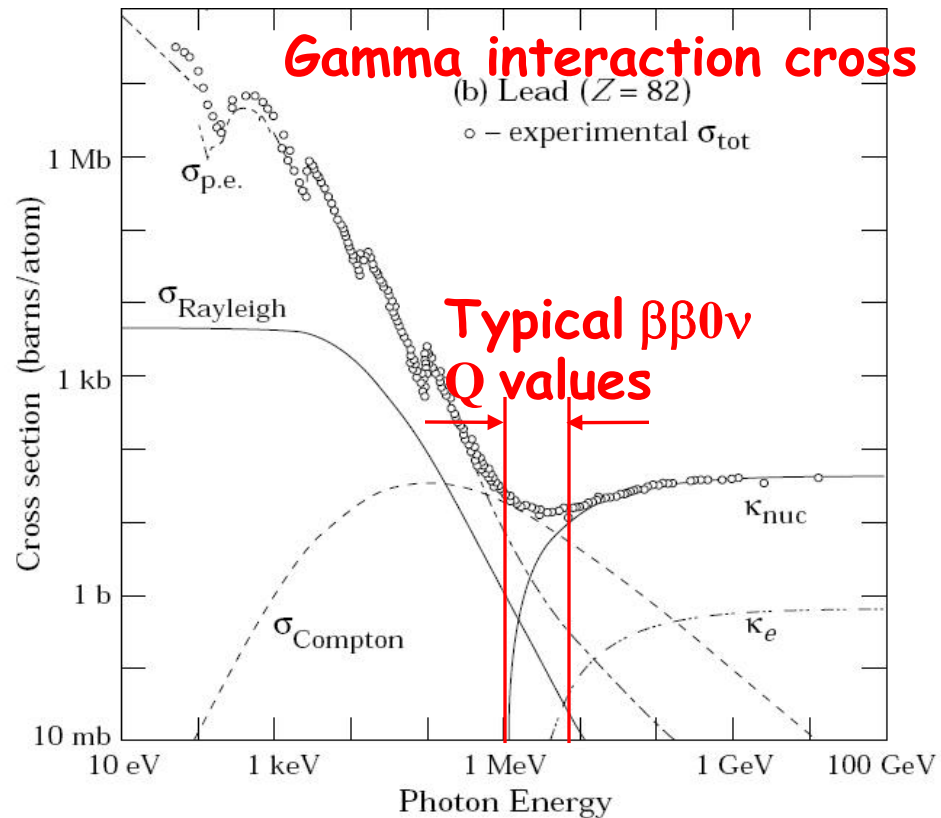
This is expensive and provides encouragement to use the material in the best possible way:

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

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

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



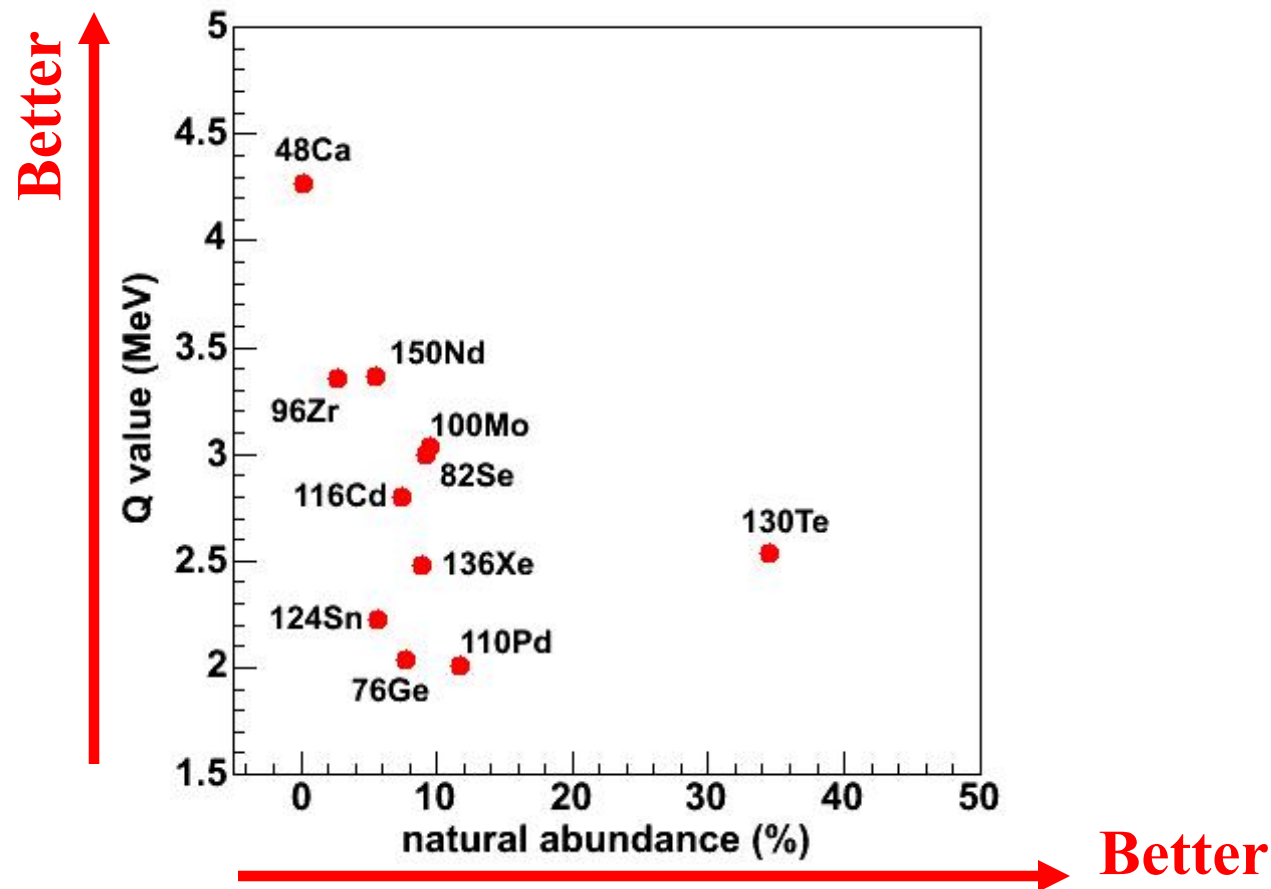
Example:

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

*Shielding $\beta\beta$ decay detectors is much harder
than shielding Dark Matter ones*

*We are entering the "golden era" of $\beta\beta$ 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 $\neq$ detector
 - + Energy/some tracking available (can distinguish modes)
 - + In principle universal (b)
 - Many γ backgrounds can fake signature
 - Exposure is limited by human patience

state ID: 1) "Geochemical": search for an abnormal ratio of (A,Z+2) in a material

2) "Radiochemical": separate the material and search for (A,Z) to find (A,Z+2)

+ 1000 tonnes of material are required (particularly for 1)

Large masses

- Possible only for a few isotopes (in the case of ^{235}U)
- No distinction between 0ν , 2ν or other modes

- state ID: 1) "Geochemical": search for an abnormal ratio of (A,Z+2) in a material
- 2) "Radiochemical": separate the material and search for (A,Z) to find (A,Z+2)
- + 1000 tonnes of material are required (particularly for 1)
- Large masses
- Possible only for a few isotopes (in the case of ^{235}U)
 - No distinction between 0ν , 2ν or other modes

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 $\sim \Delta m$. For Xe 4.7 amu
- Only known case where final state identification appears to be not impossible
 - eliminate all non- $\beta\beta$ backgrounds
- ^{129}Xe is a hyperpolarizable nucleus, under study for NMR tomography... a joint enrichment program ?

Discovery of the Ω^-

VOLUME 12, NUMBER 8

PHYSICAL REVIEW LETTERS

24 FEBRUARY 1964

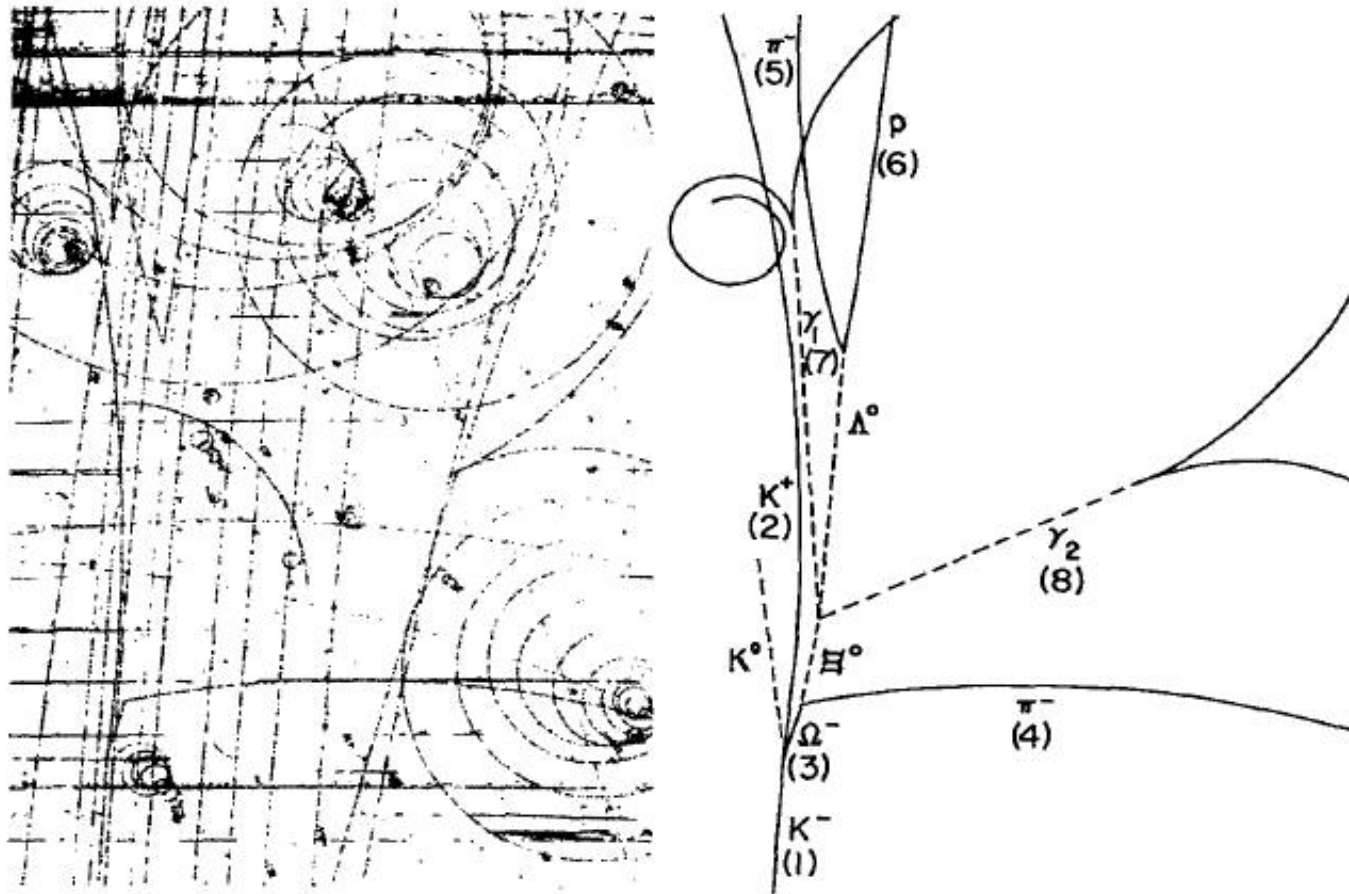


FIG. 2. Photograph and line diagram of event showing decay of Ω^- .

The statistical significance of a signal is determined by how strongly you reject the null hypothesis.

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% $\rightarrow$ nEXO

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

Mainly going in light bulbs, plasma displays and satellite propulsion

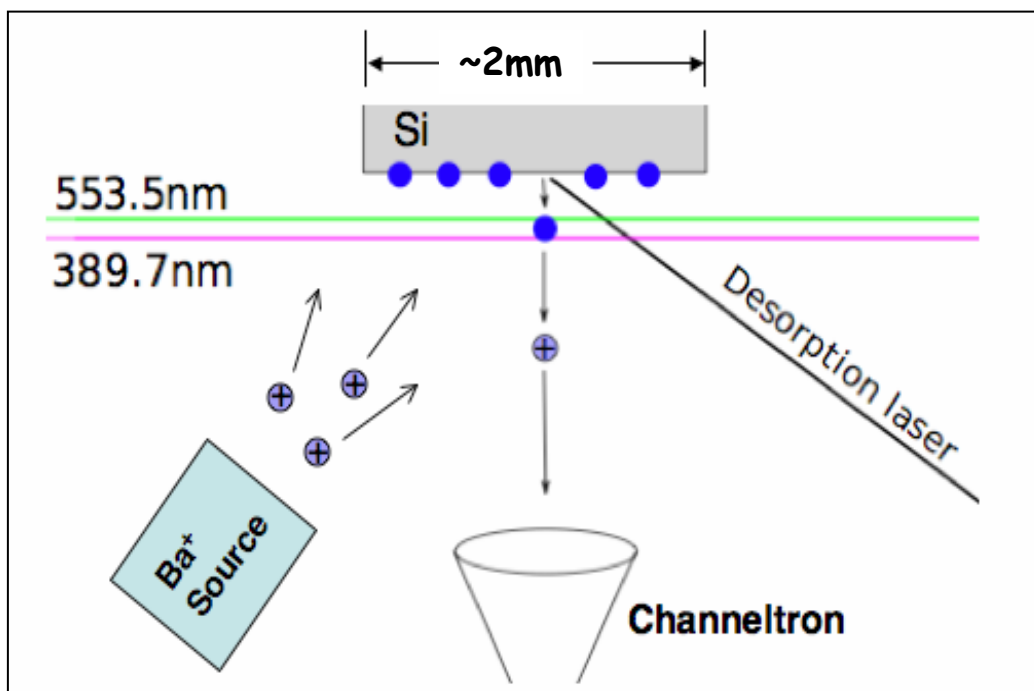
Substantial R&D program to tag
in quasi-real-time the final state Ba atom

Test several techniques

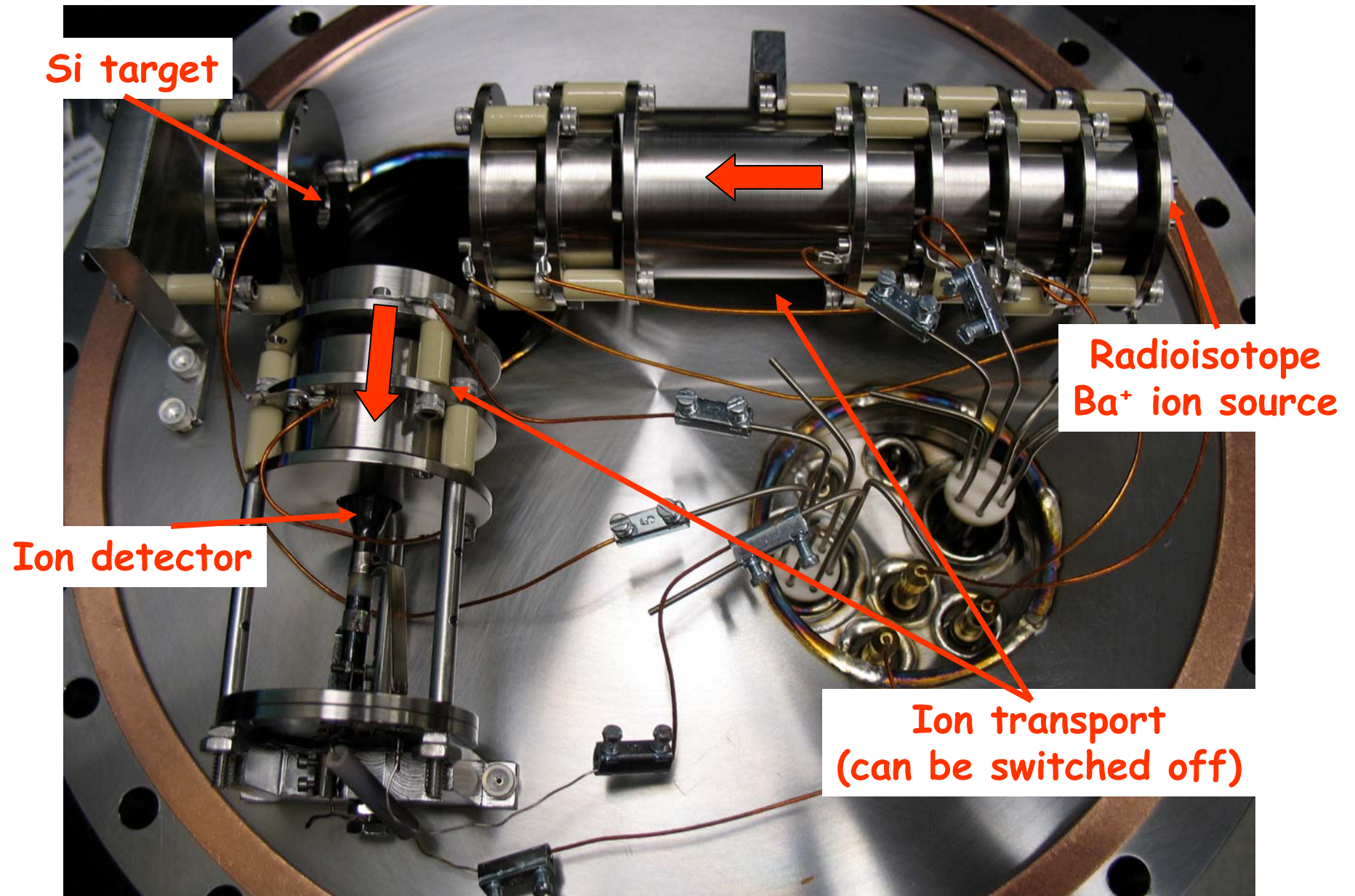
- Retrieve Ba from LXe and feed it to an ion trap with spectroscopic identification
 - Hot probe mover
 - Icy probe
- RIS probe
- Tag from gas

Ba transport/tagging by Resonant Ionization Spectroscopy

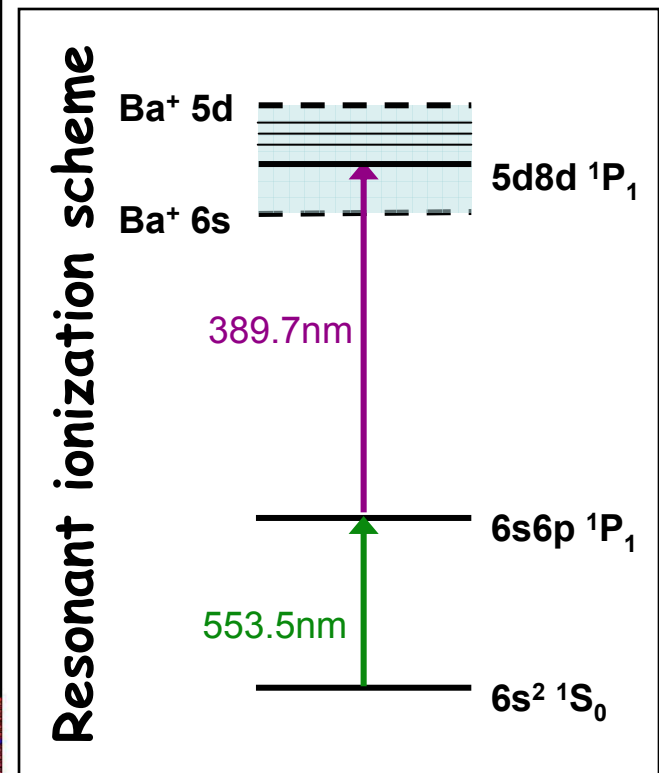
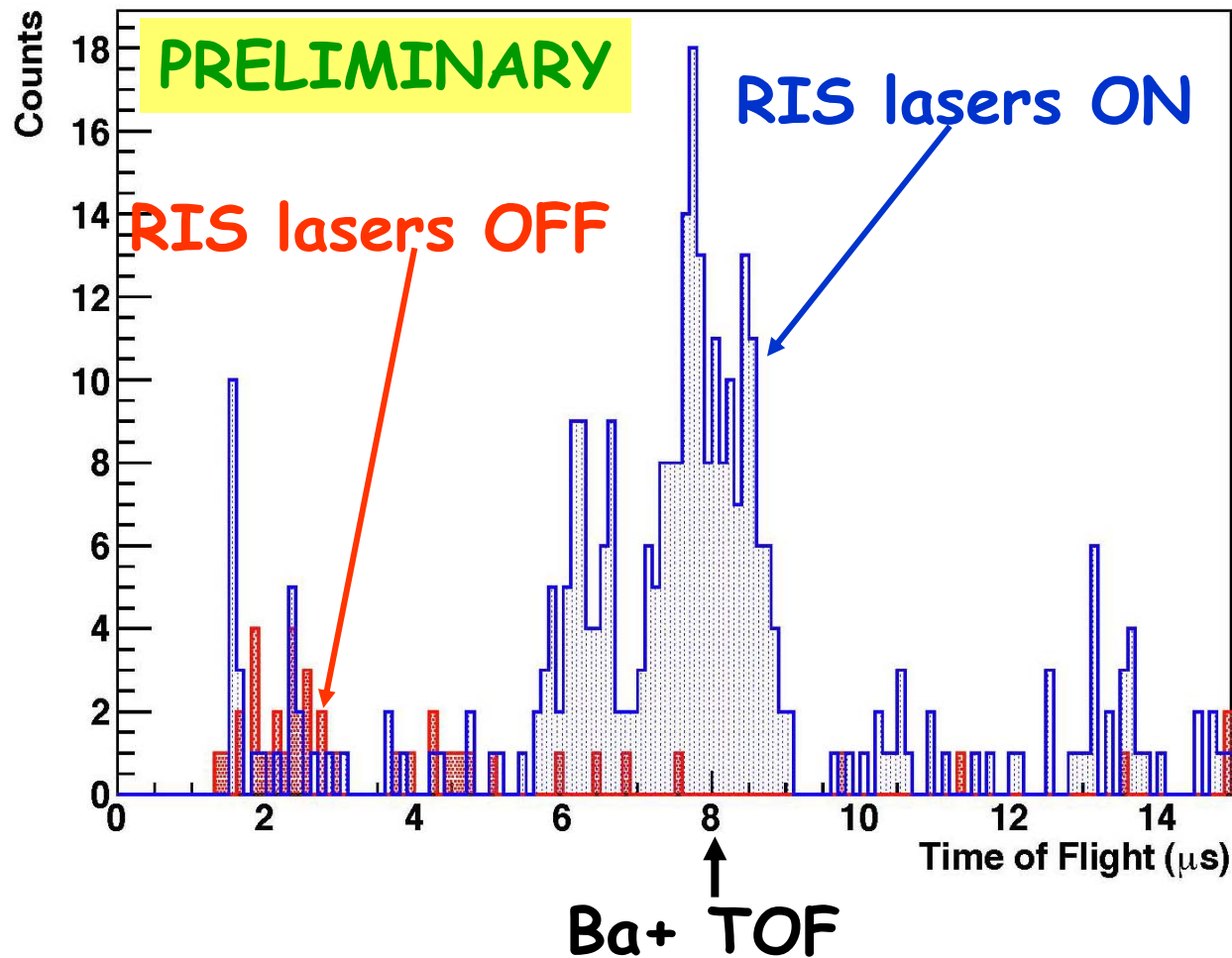
- Ba^+ or Ba^{++} is electrostatically attracted (from LXe) onto a clean substrate (Si works well)
- The substrate is transported to vacuum
- An 1064nm YAG laser pulse is used to desorb the Ba
- $\sim 1\mu\text{s}$ later a pair of laser pulses of appropriate freq re-ionize to Ba^+
- For the moment test uses stationary substrate in vacuum



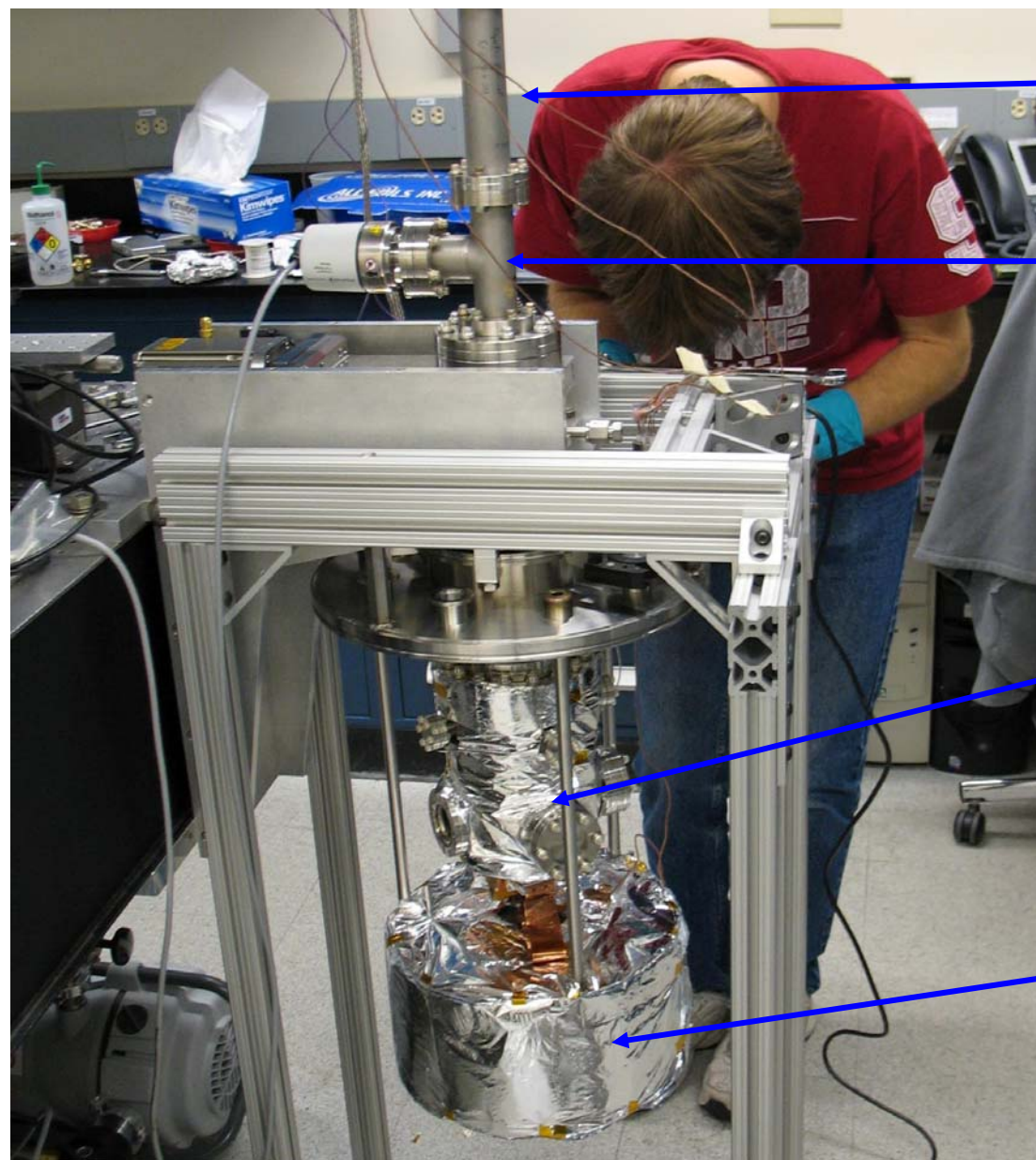
Clean apparatus, never exposed to Ba beam



- 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

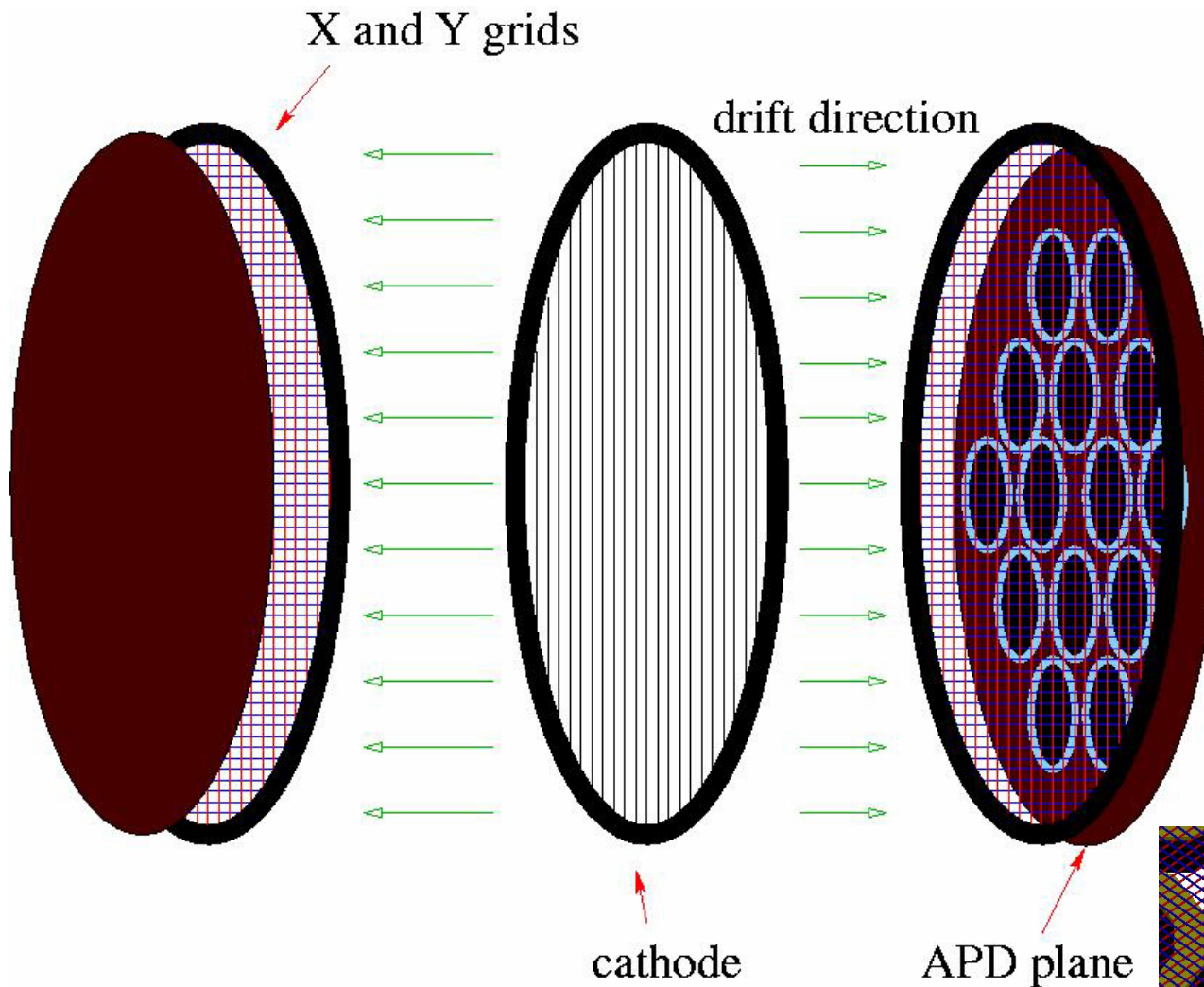
LN2 reservoir

EXO-200:
an intermediate detector without Ba tagging

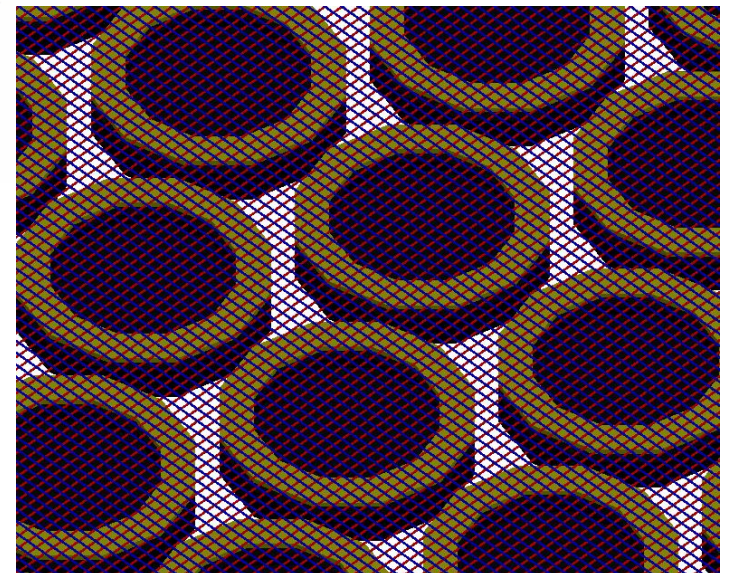
Underground location: Waste Isolation Pilot Plant (WIPP) Carlsbad, NM

- ~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/m³)
- Rather convenient access with large conveyance

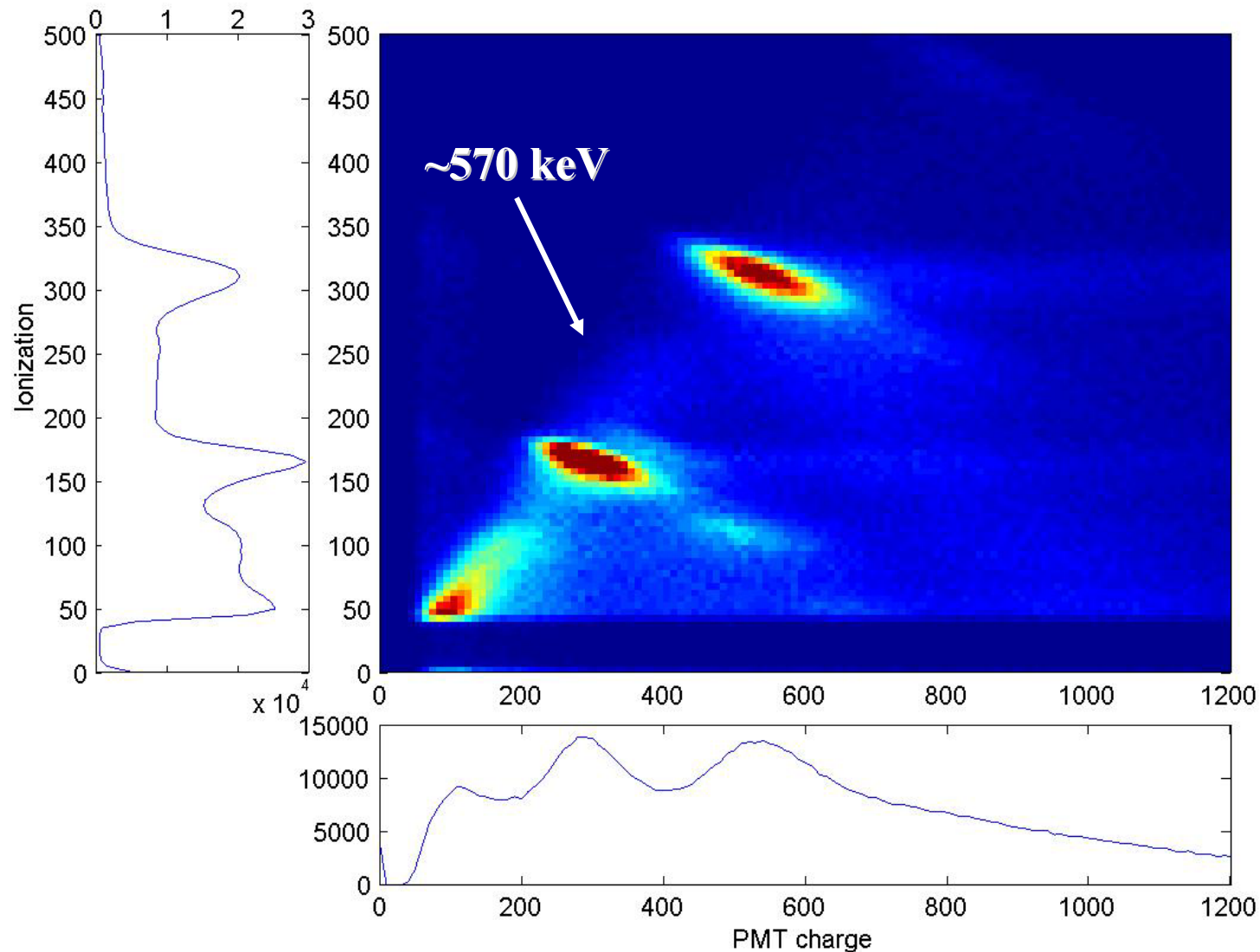




**EXO-200 does not
have Ba tagging
but
it is compatible
with Ba tagging**



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





APDs are ideal for our application:

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

QE > 1 at 175nm

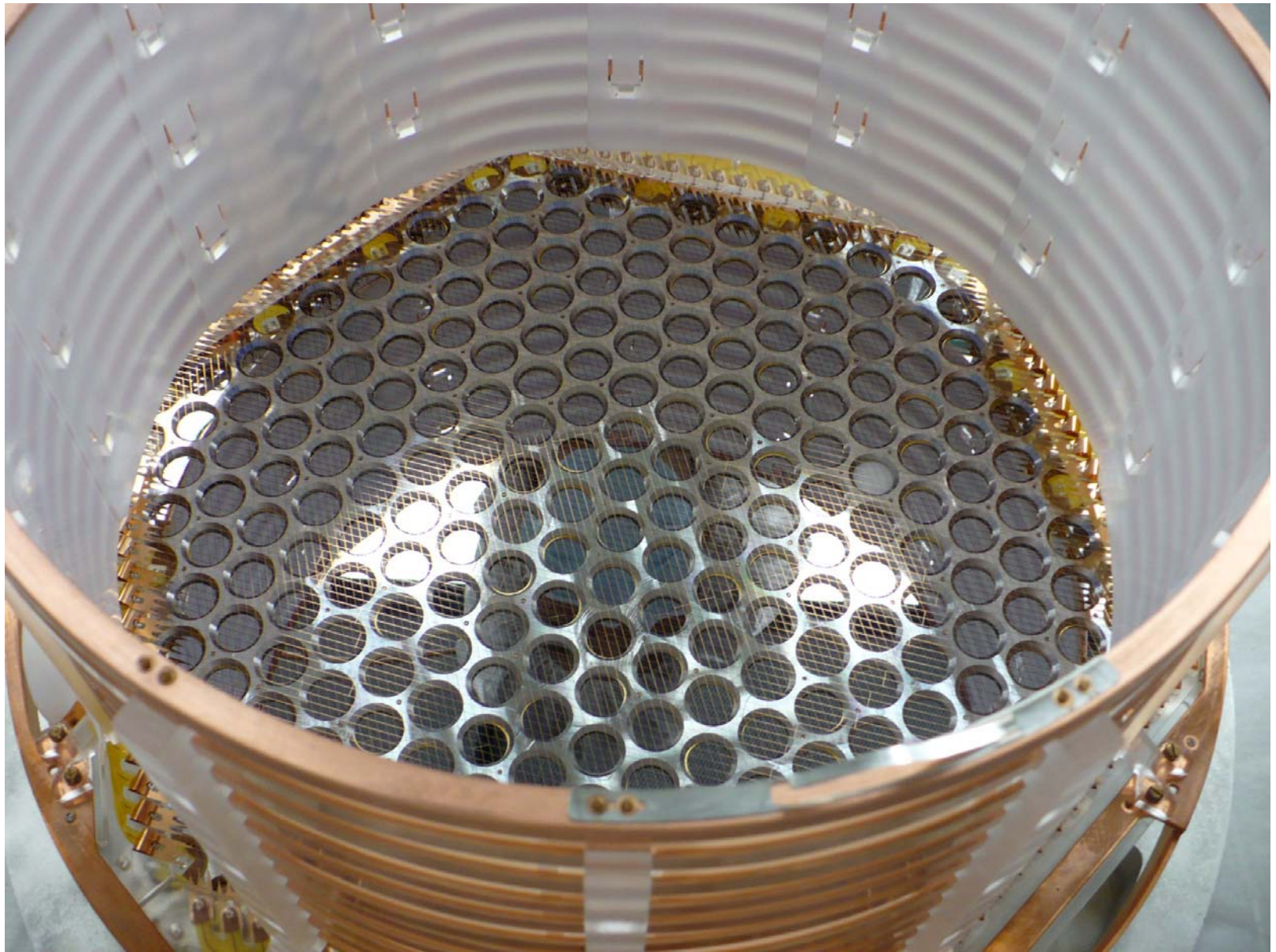
Gain set at 100-150

V~1500V

$\Delta V < \pm 0.5V$

$\Delta T < \pm 1K$ APD is the driver
for temperature stability

Leakage current OK cold



Ultra-low activity Cu vessel

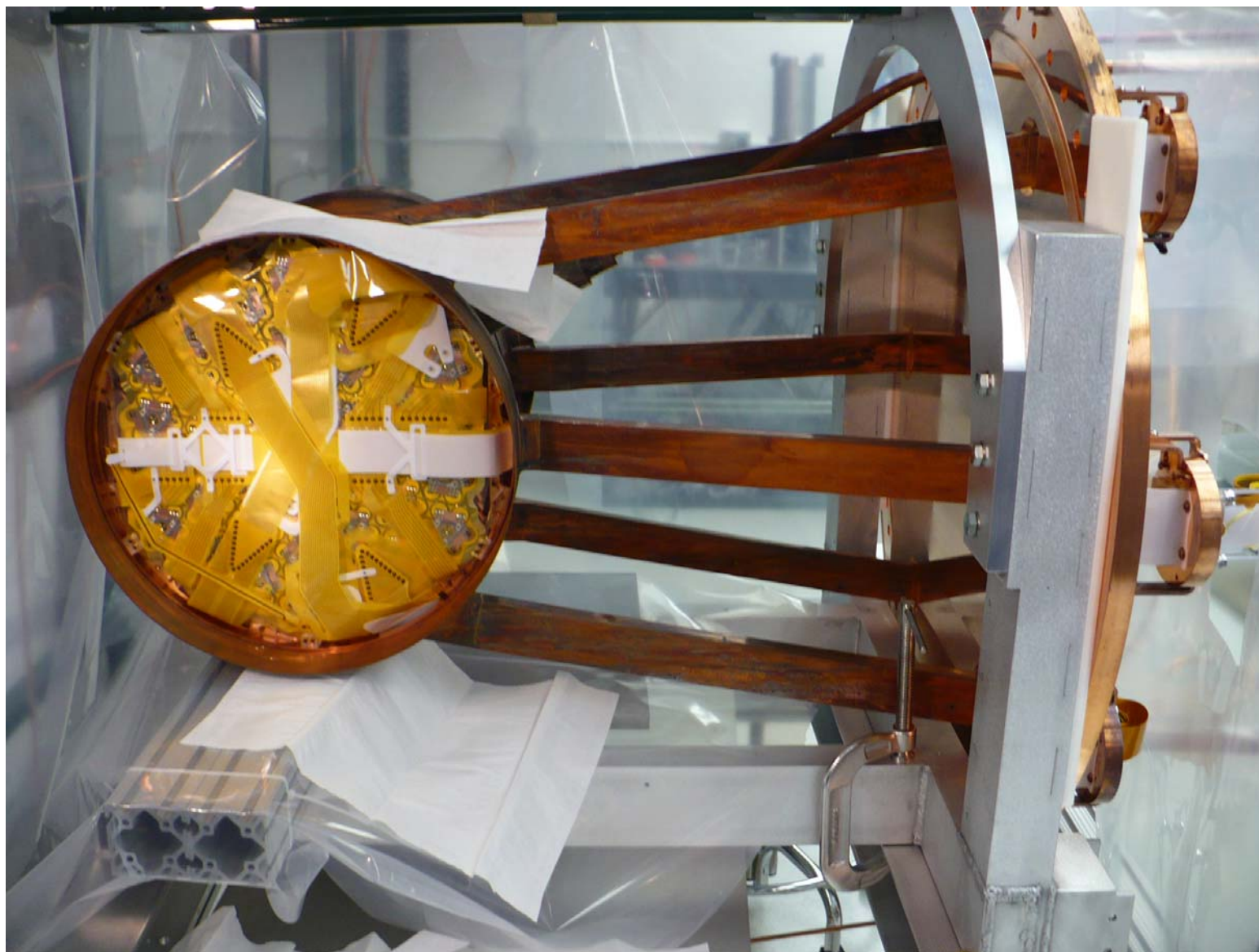


U Chicago, Feb 14, 2013

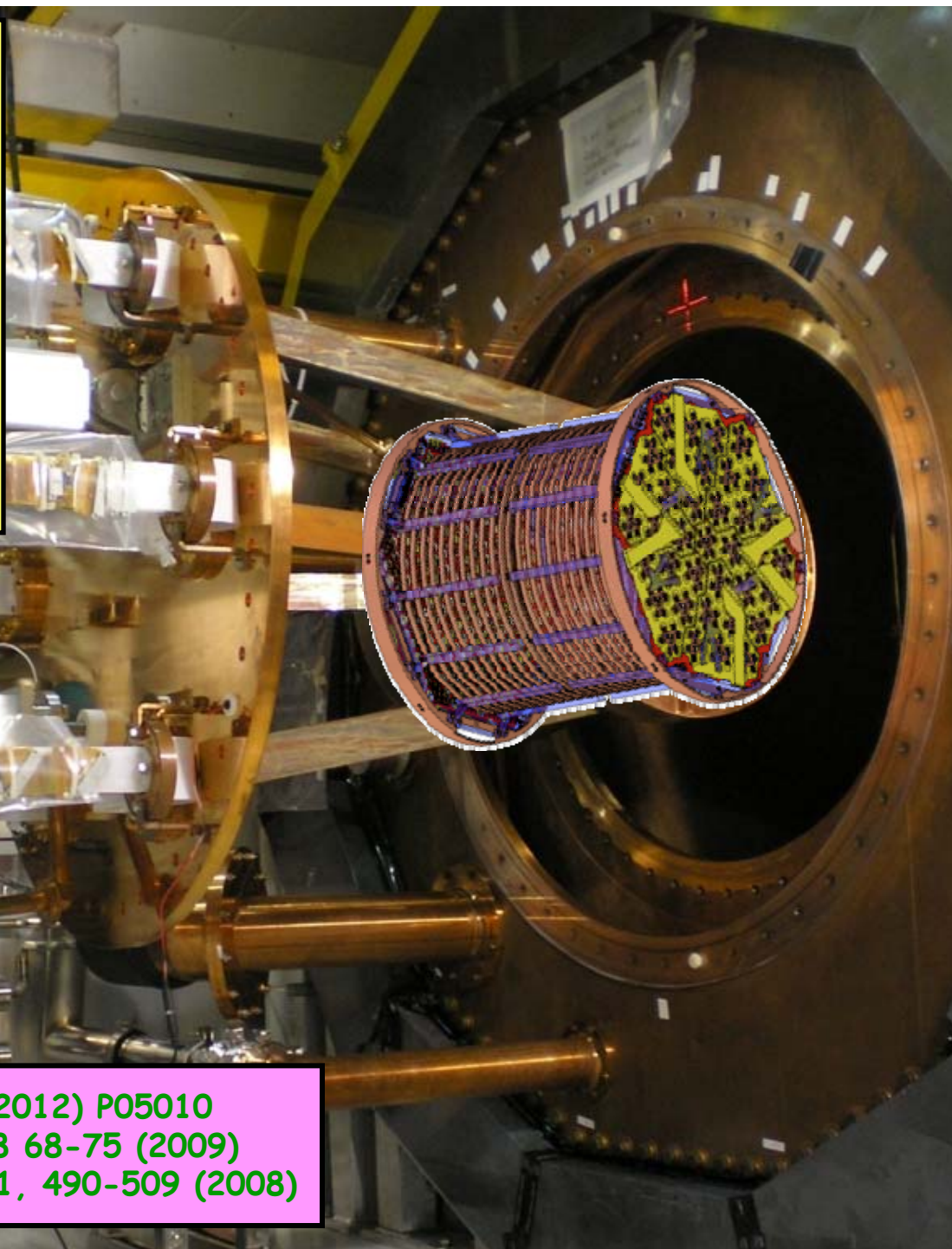
Giorgio Gratta

- 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



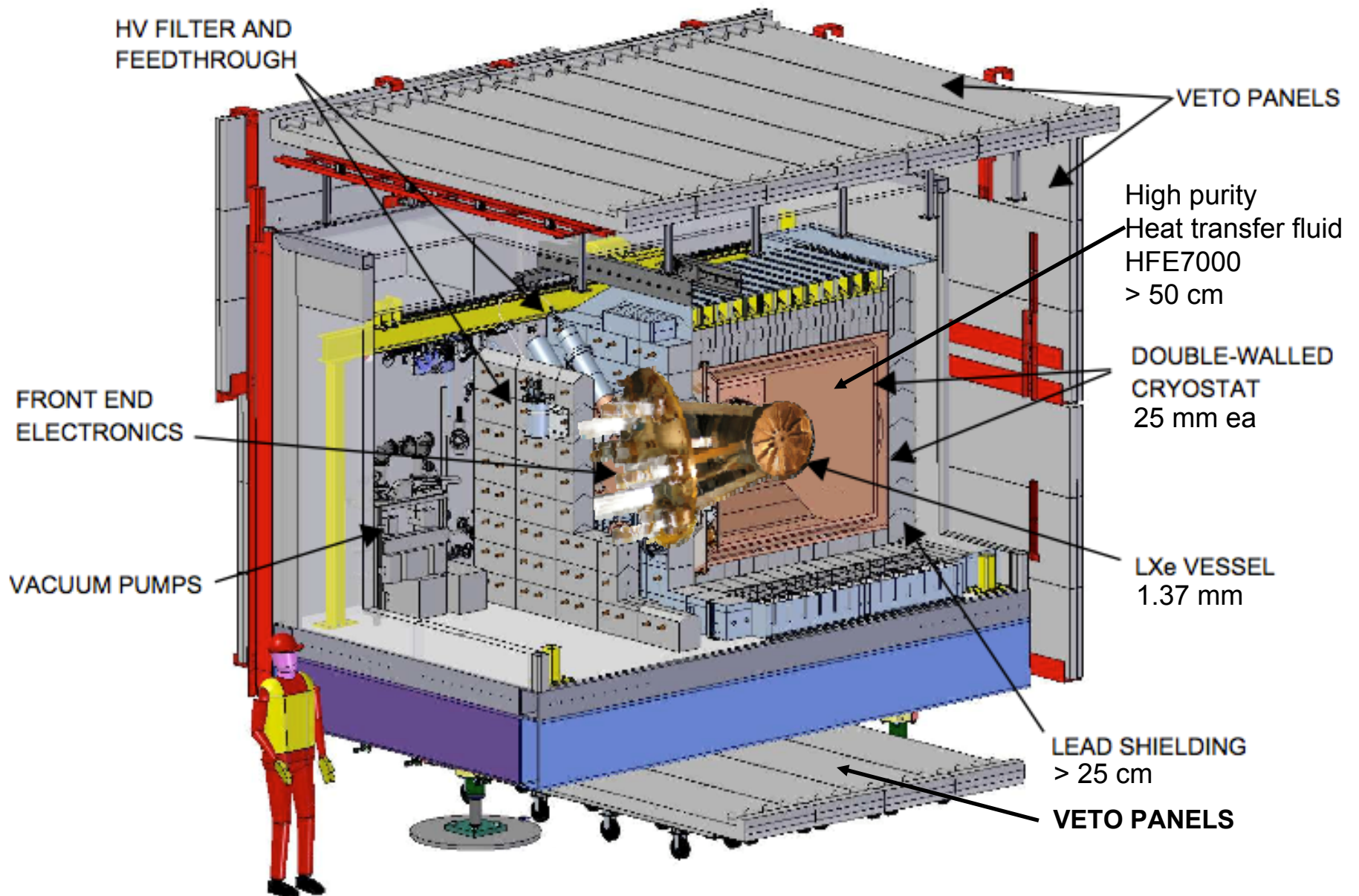
- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
 - APD bias and readout cables
 - U+V wires bias and readout
 - LXe supply and return
 - Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line



EXO-200 detector:
Characterization of APDs:
Materials screening:

JINST 7 (2012) P05010
NIM A608 68-75 (2009)
NIM A591, 490-509 (2008)

The EXO-200 Detector



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

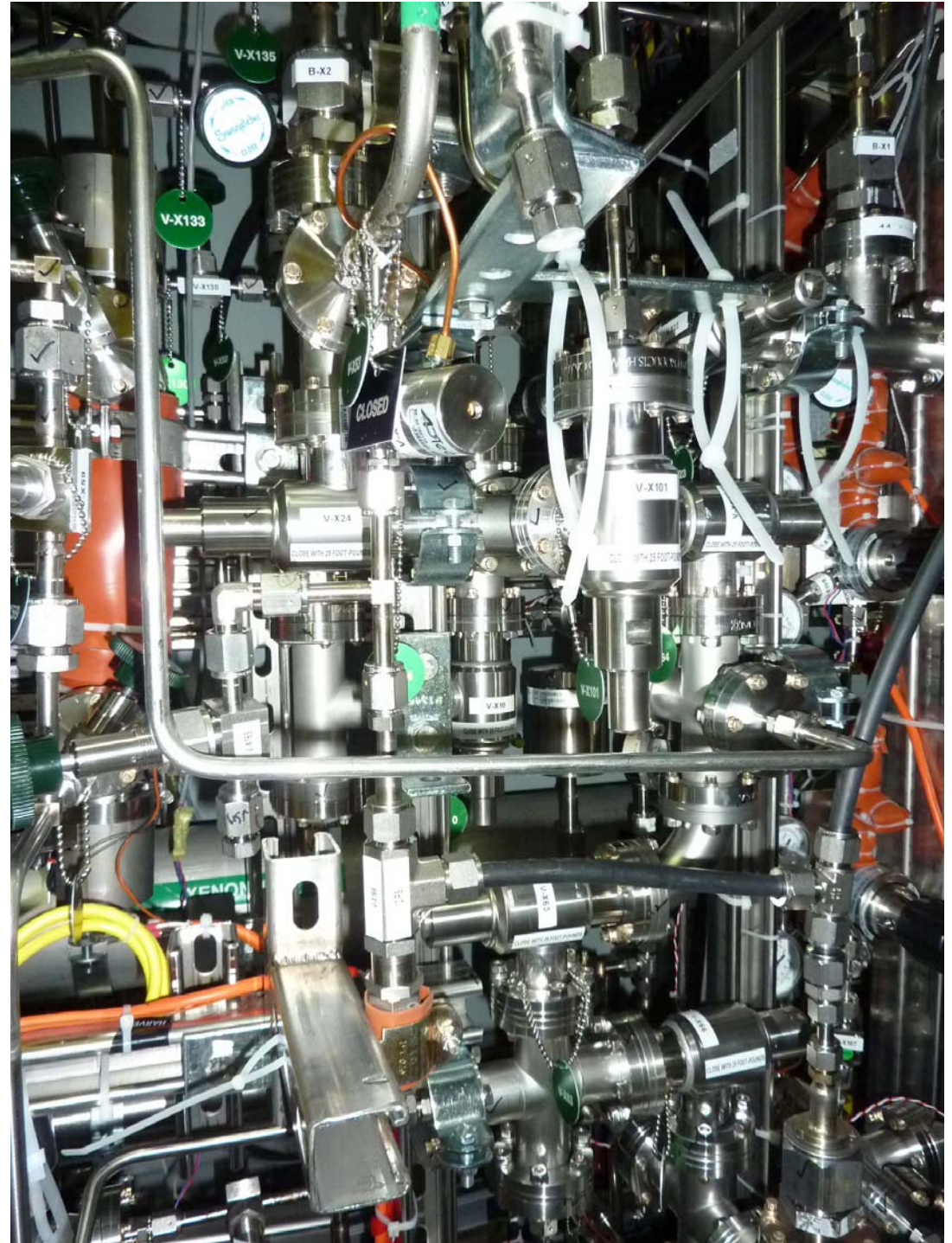
D.S. Leonard et al., Nucl. Ins. Meth. A 591, 490 (2008)

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

→ Goal: 40 cnts/2yr in the $0\nu\beta\beta \pm 2\sigma$ 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



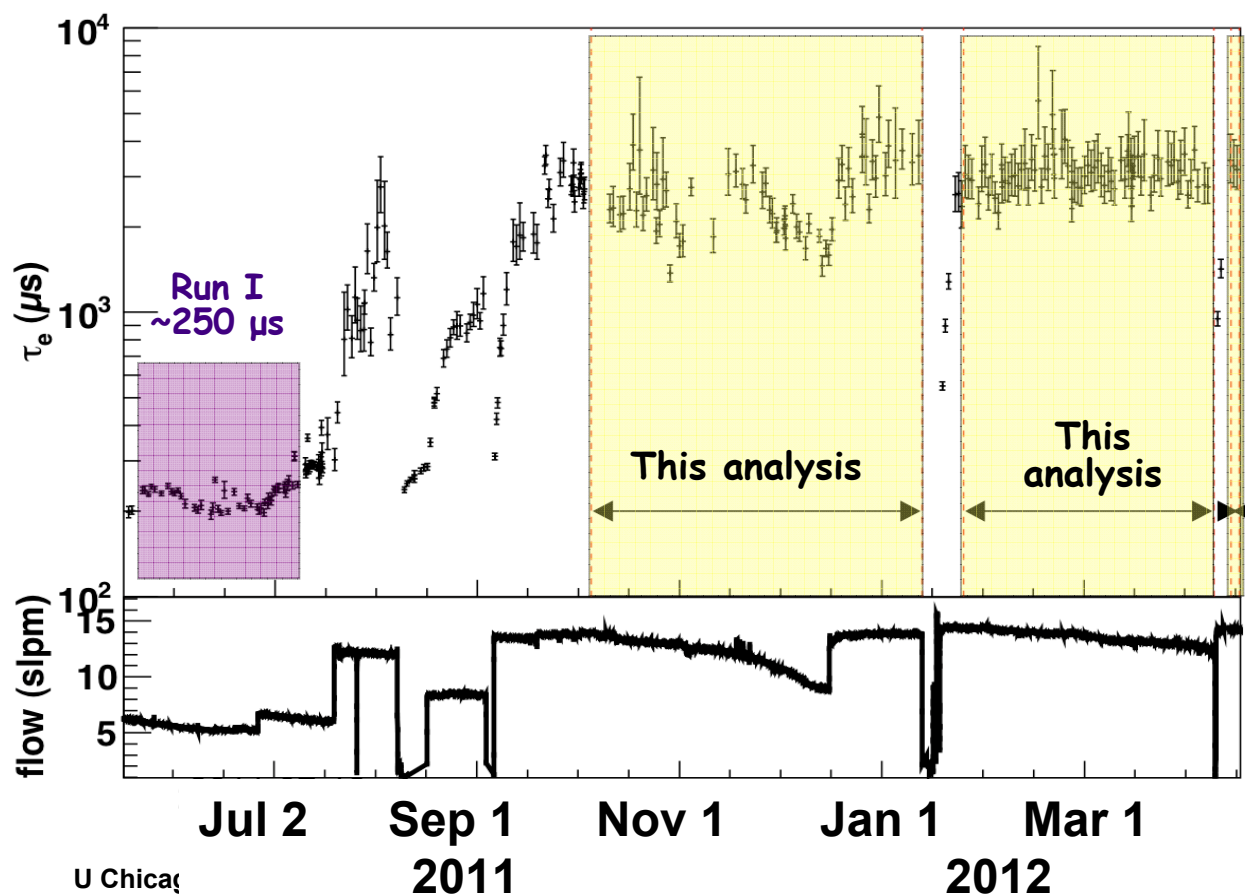
Data taking phases and Xenon Purity

	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)

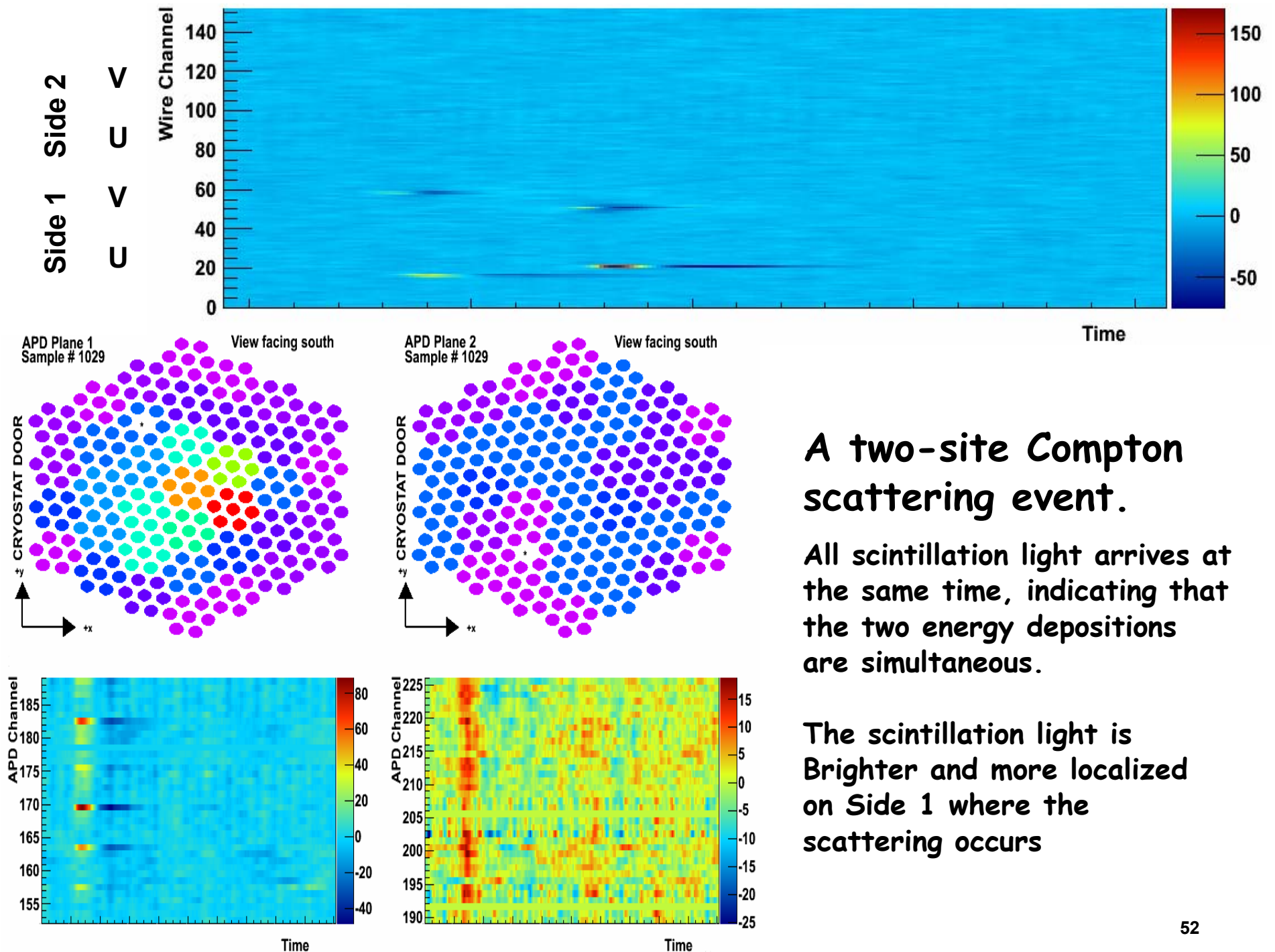
Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

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

At $\tau_e = 3$ ms:
- drift time $< 110 \mu\text{s}$
- loss of charge: 3.6% at full drift length

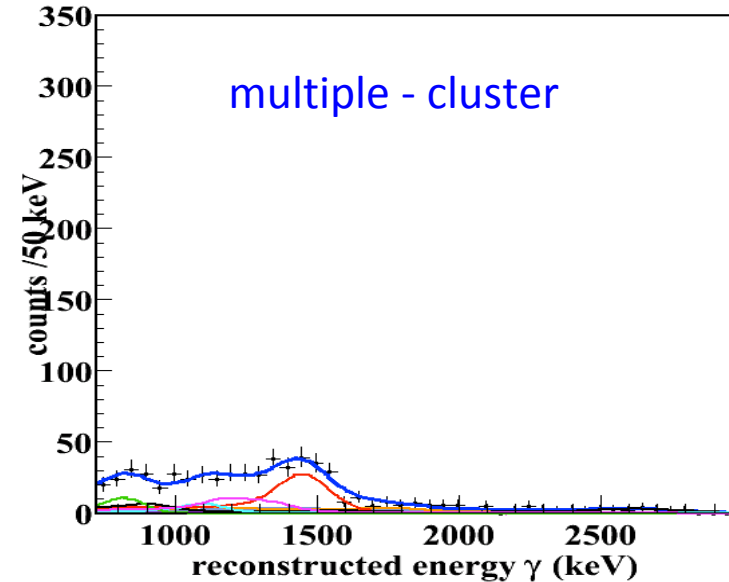
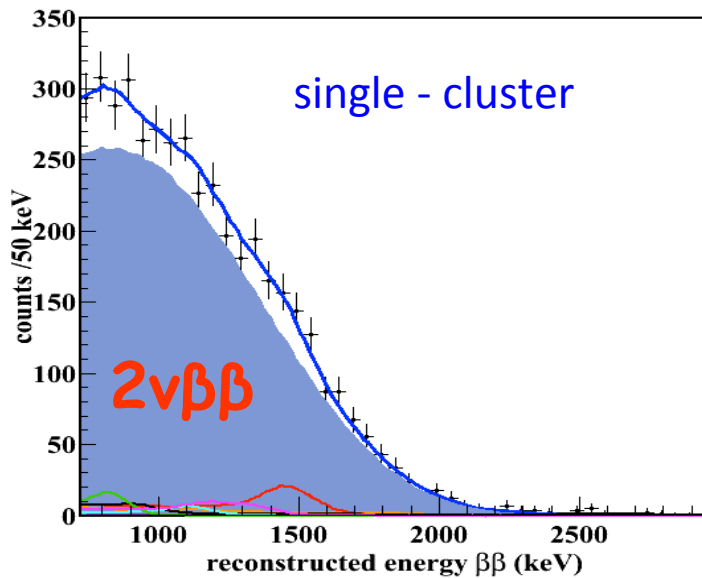


Ultraclean pump:
Rev Sci Instr. 82 (10) 105114
Xenon purity with mass spec:
NIM A 675 (2012) 40
Gas purity monitors:
NIM A 659 (2011) 215

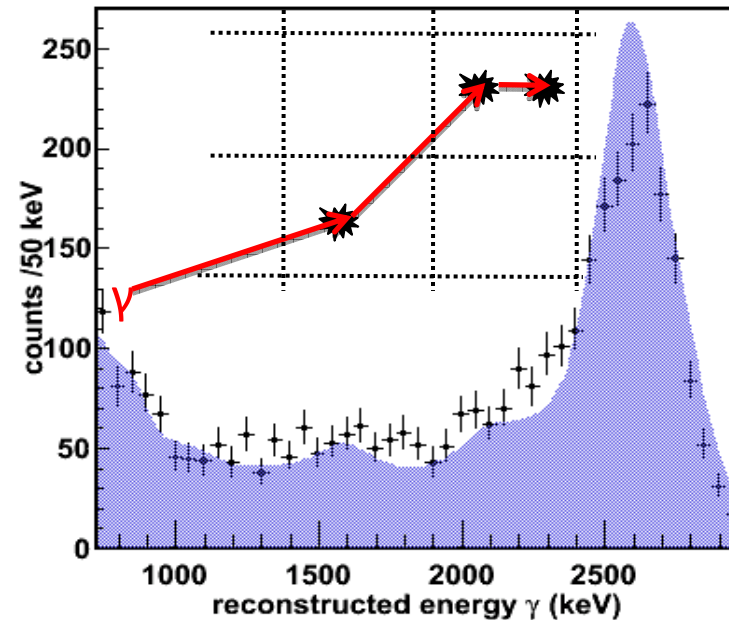
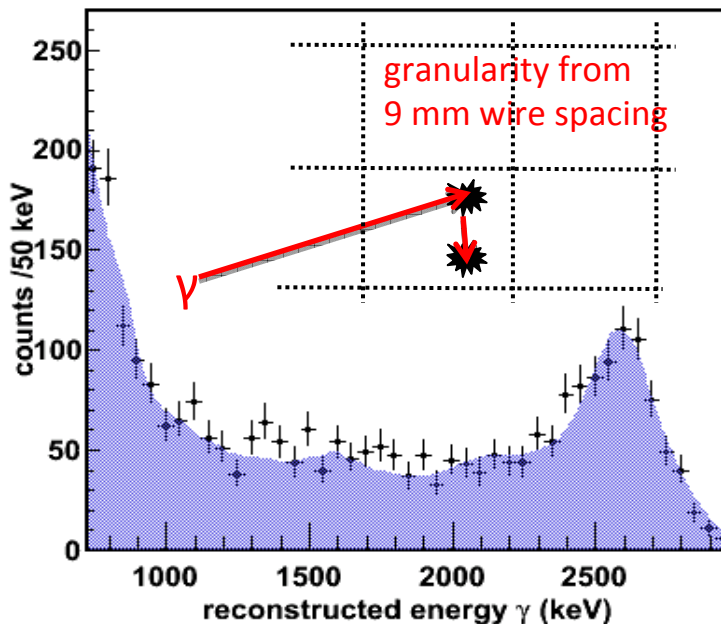


Pattern recognition can be a very powerful tool against background

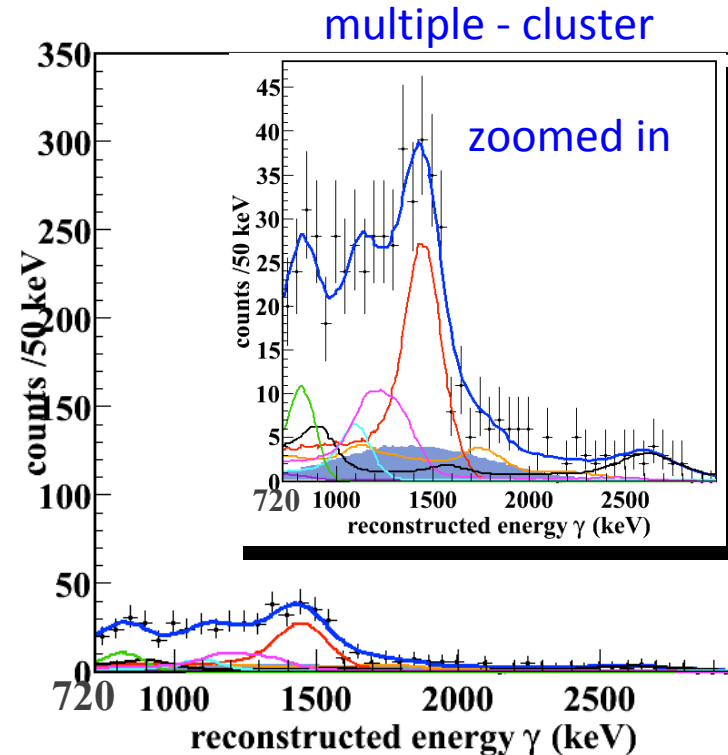
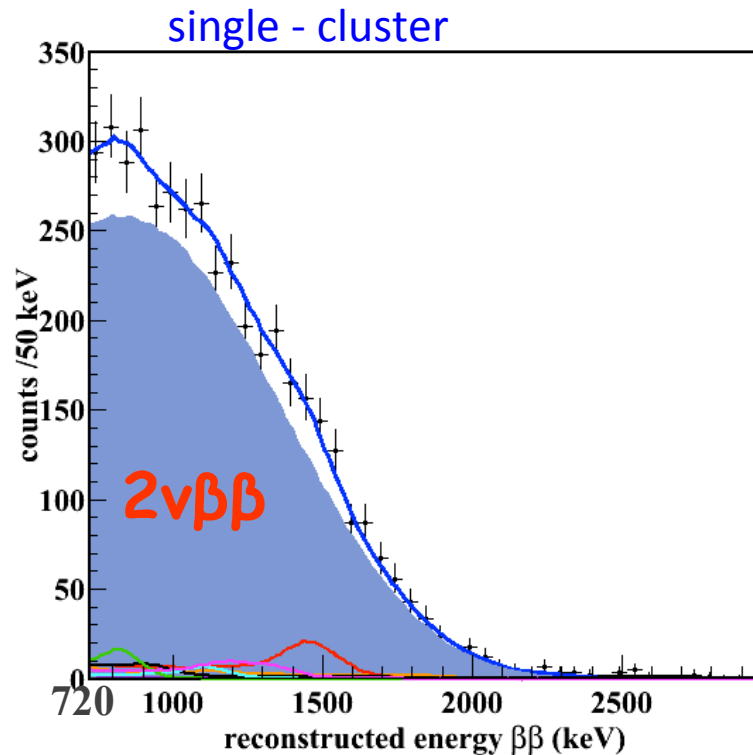
Low background data



^{228}Th calibration source

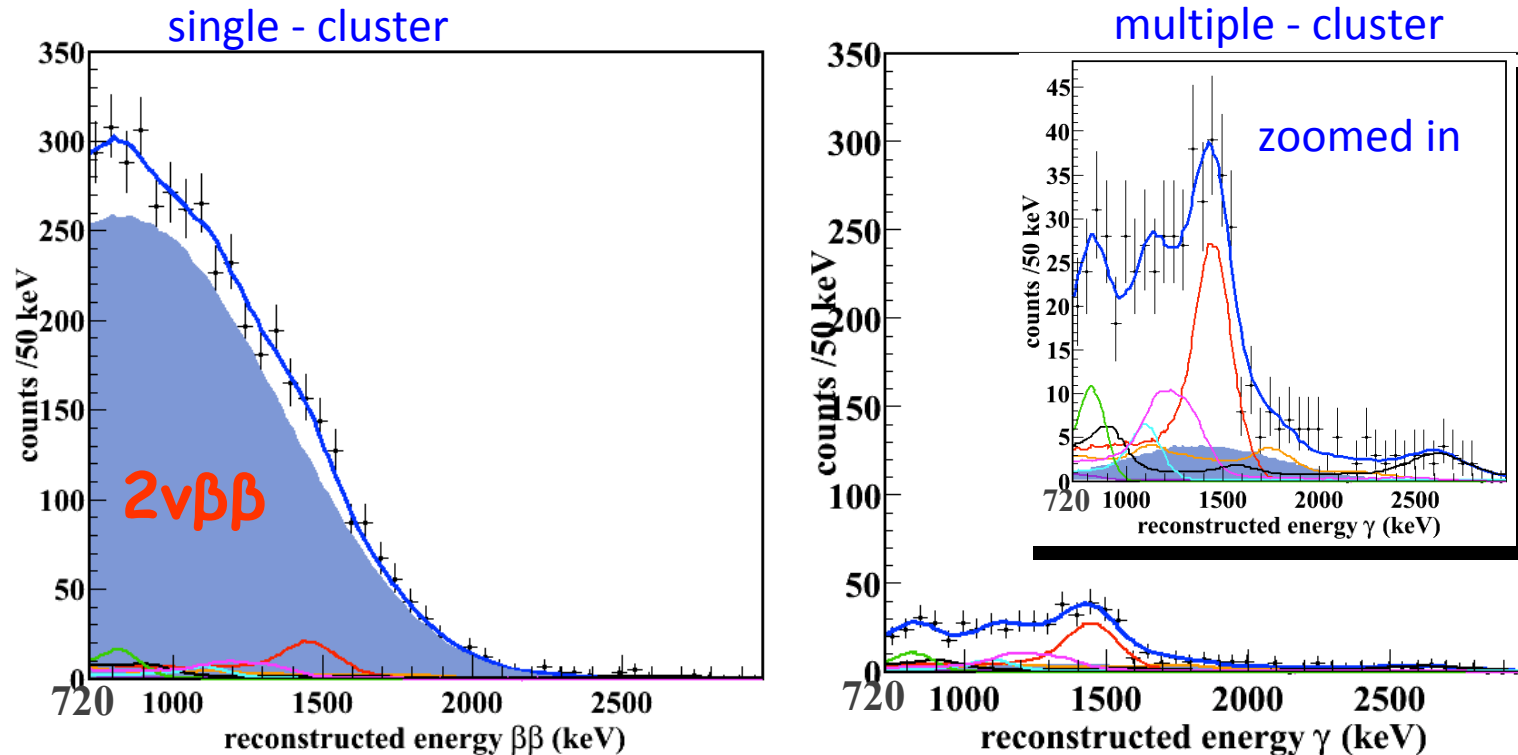


First observation of the $2\nu\beta\beta$ decay in ^{136}Xe



$T_{1/2} = (2.11 \pm 0.04 \text{ stat} \pm 0.21 \text{ sys}) \cdot 10^{21} \text{ yr}$
[Ackerman et al Phys Rev Lett 107 (2001) 212501]

First observation of the $2\nu\beta\beta$ decay in ^{136}Xe



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

[Ackerman et al Phys Rev Lett 107 (2011) 212501]

In significant disagreement with previous limits:

$$T_{1/2} > 1.0 \cdot 10^{22} \text{ yr (90\% C.L.) (R. Bernabei et al. Phys. Lett. B 546 (2002) 23)}$$

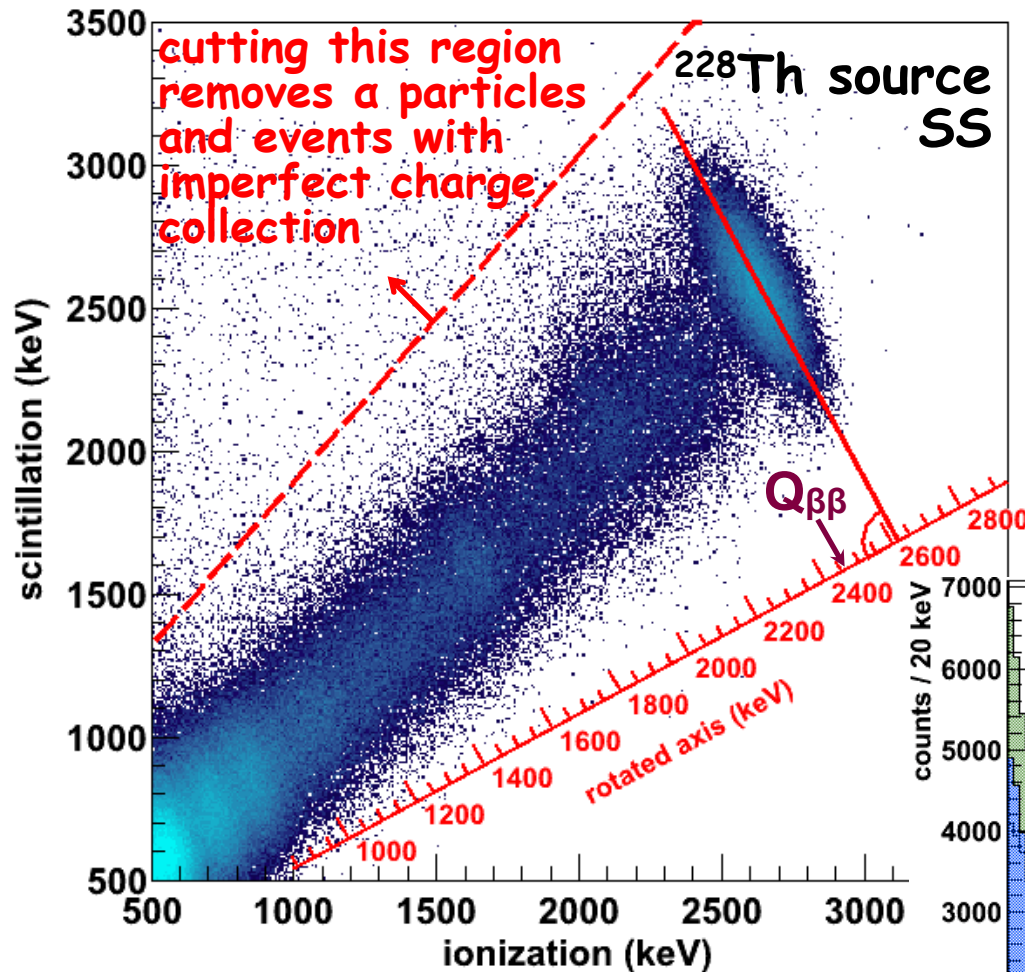
$$T_{1/2} > 8.5 \cdot 10^{21} \text{ yr (90\% C.L.) (Yu. M. Gavriljuk et al., Phys. Atom. Nucl. 69 (2006) 2129)}$$

Later confirmed by KamLAND-ZEN

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

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

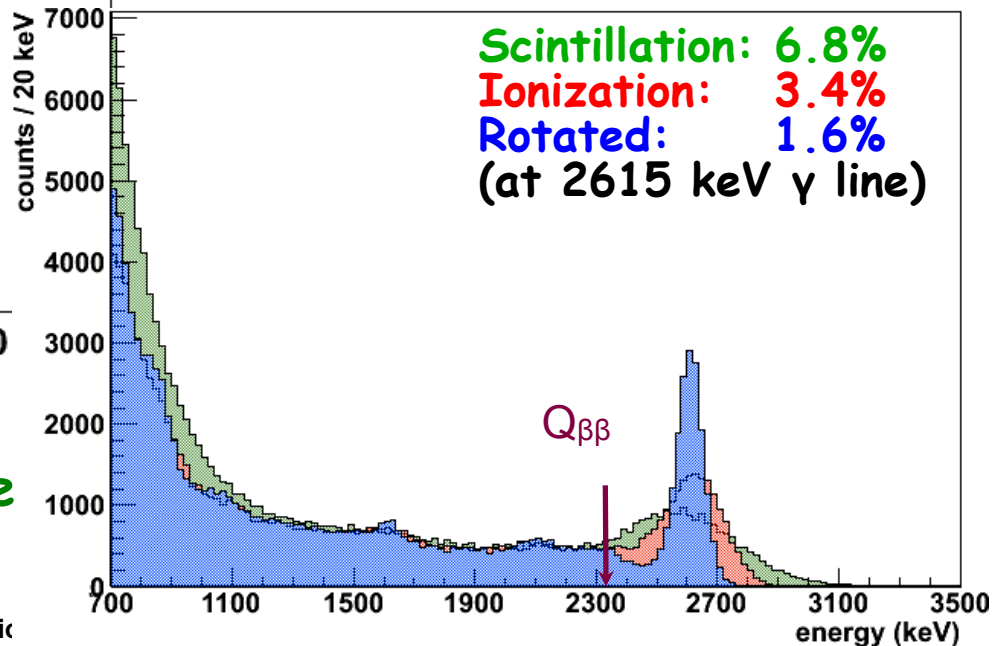
Combining Ionization and Scintillation



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

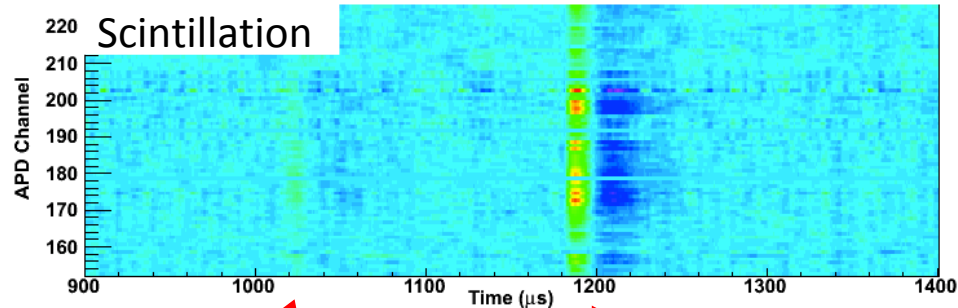
E. Conti et al.
Phys Rev B 68 (2003) 054201

Rotation angle chosen to optimize energy resolution at 2615 keV

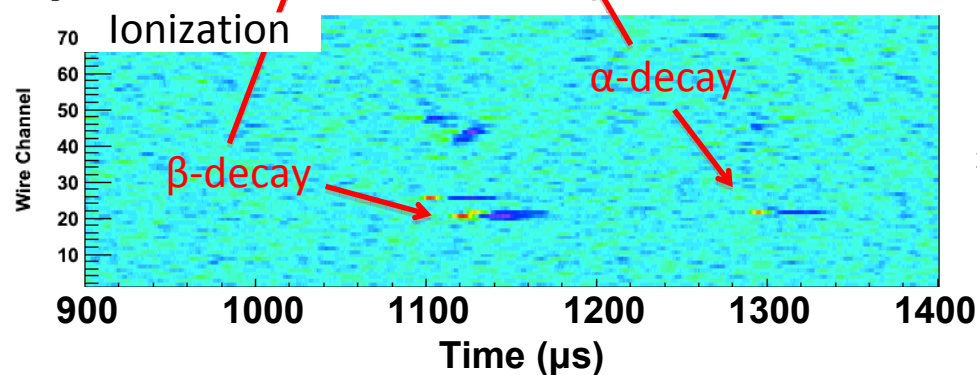


Rn Content in Xenon

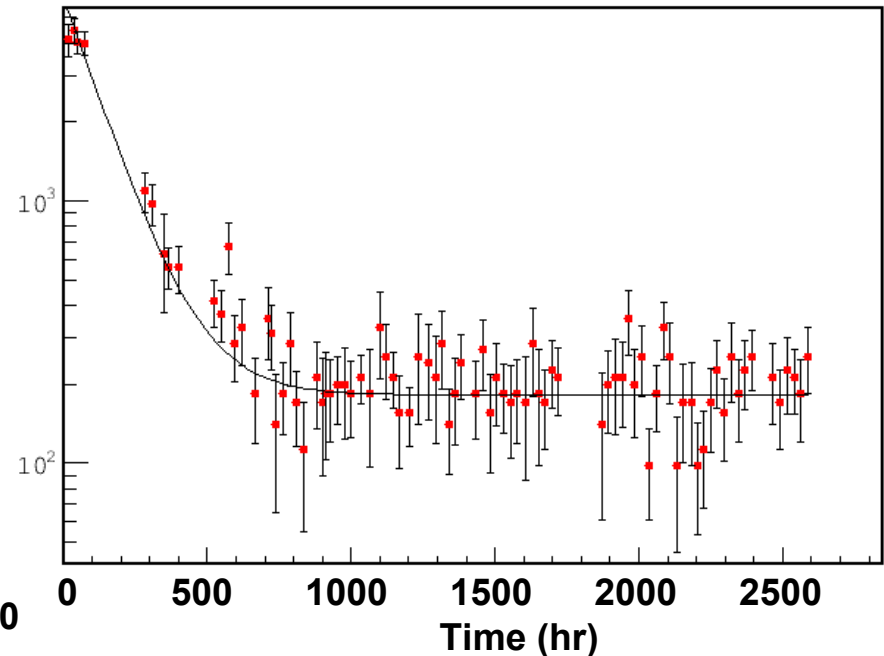
APD signals vs time



Wire signals vs time



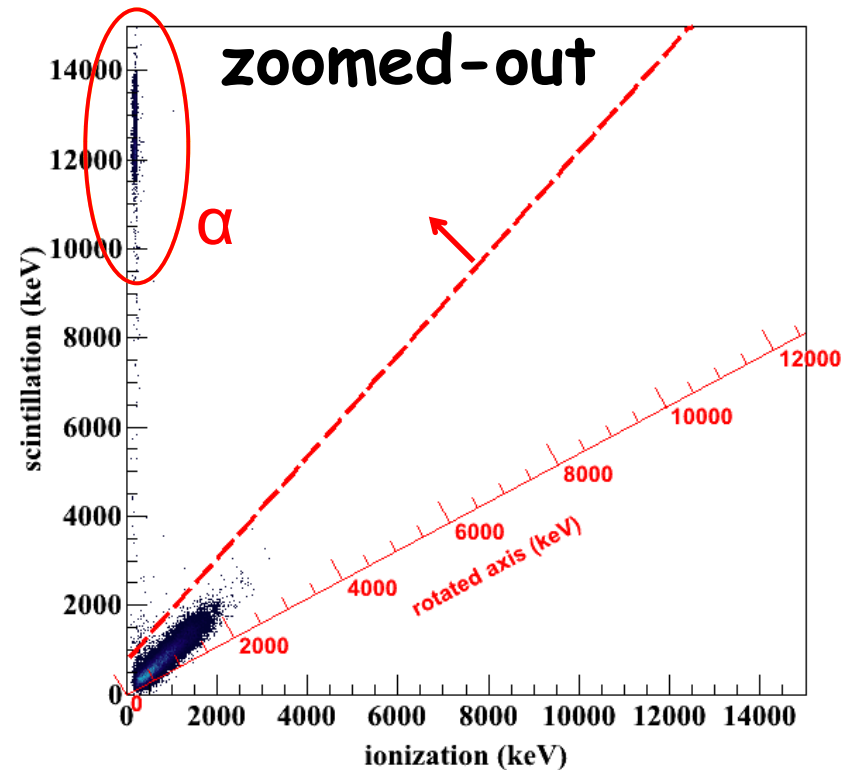
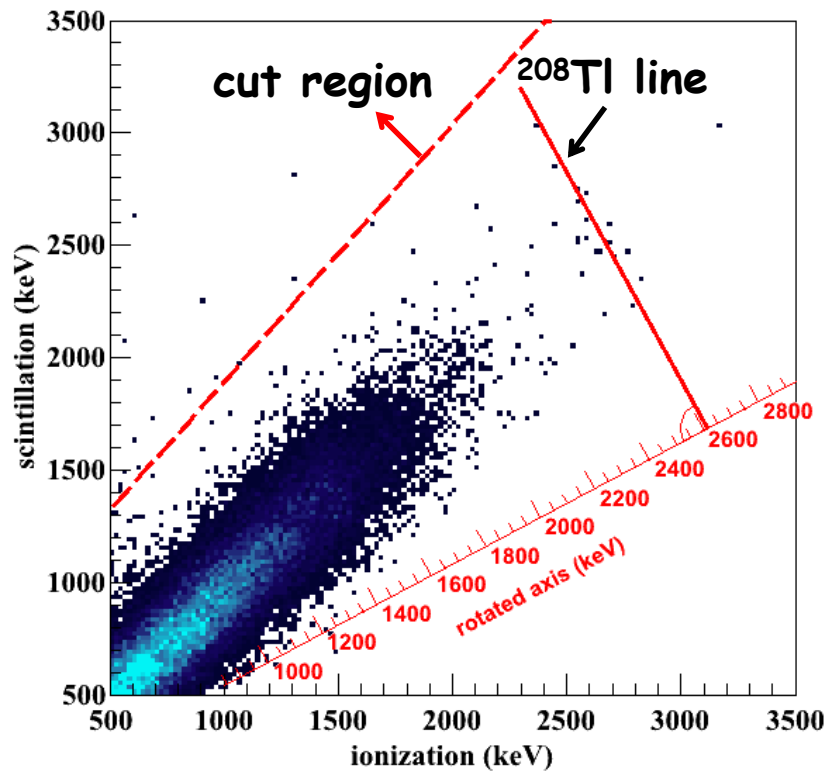
$^{214}\text{Bi} - ^{214}\text{Po}$ correlations
in the EXO-200 detector



Total ^{222}Rn in LXe after initial fill

Long-term study shows a constant source of
 ^{222}Rn dissolving in $^{\text{enr}}\text{LXe}$: $360 \pm 65 \mu\text{Bq}$ (Fid. vol.)

Low Background 2D SS Spectrum



Events removed by diagonal cut:

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

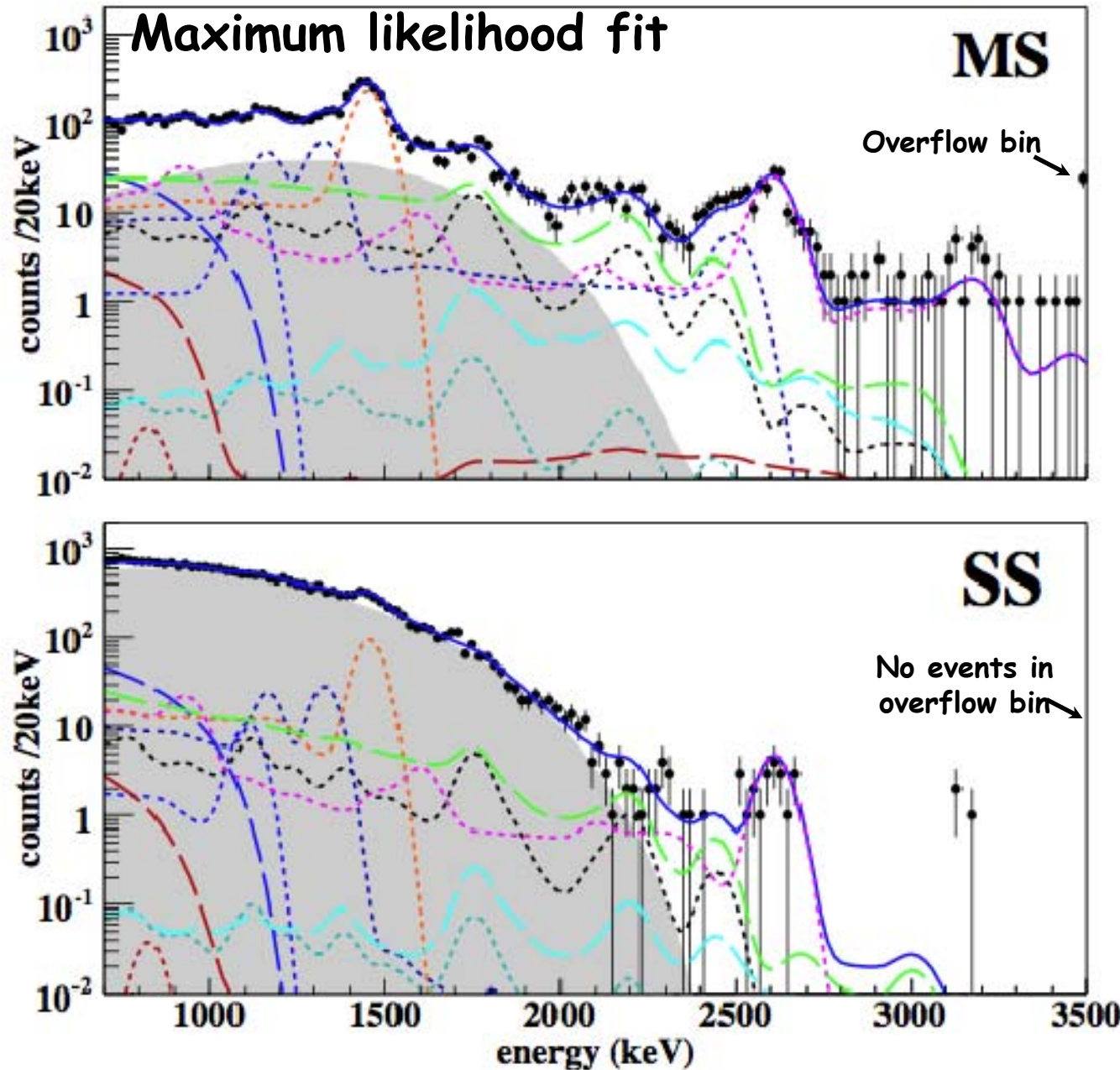
Low Background Spectrum

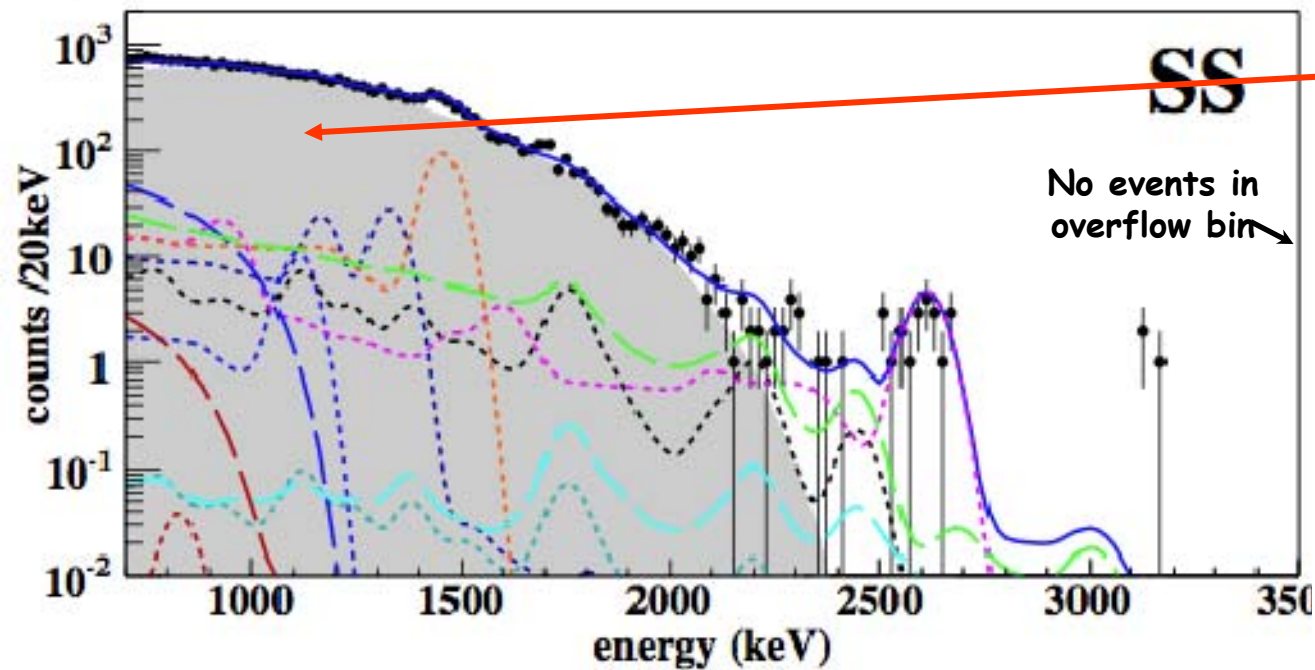
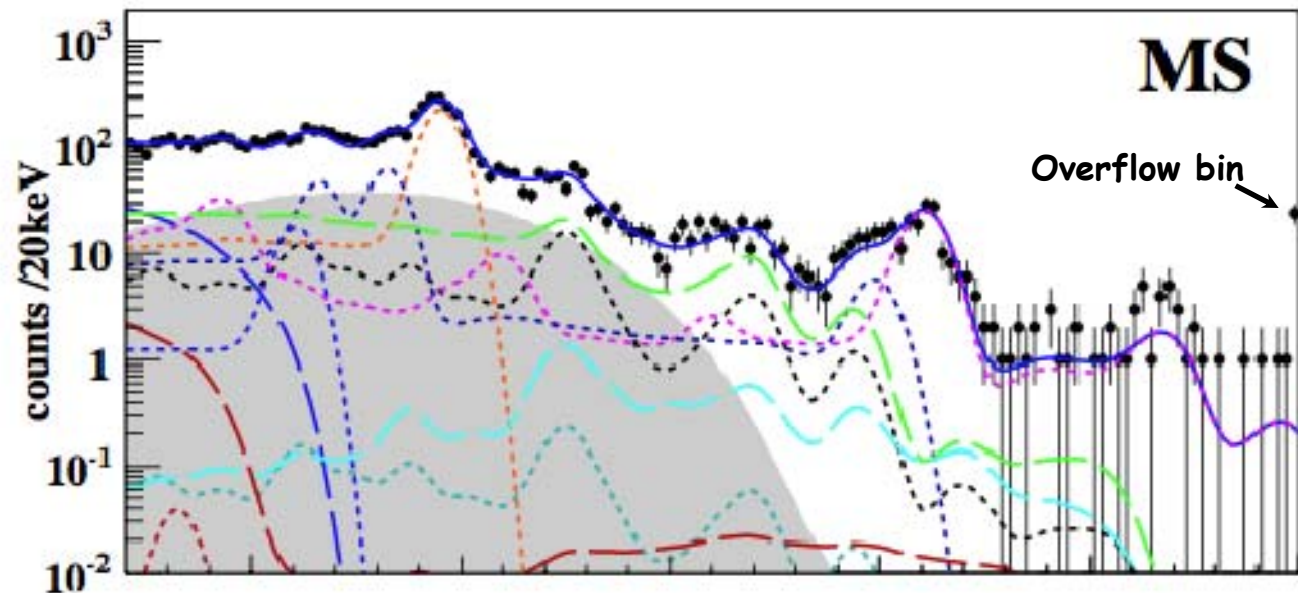
Low background
run livetime:
120.7 days

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

Exposure:
32.5 kg.yr

Vetos dead time:
8.6%

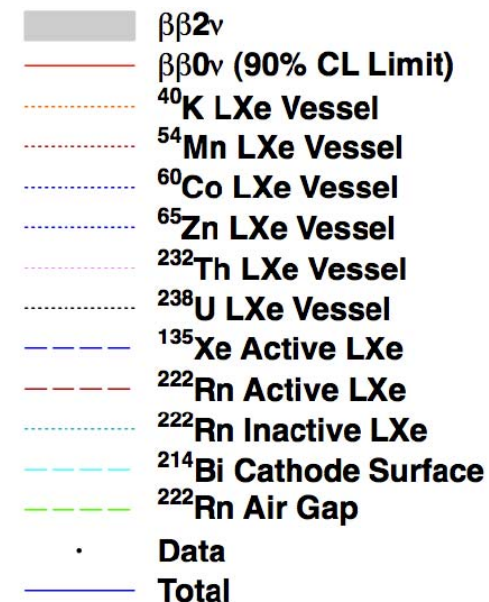
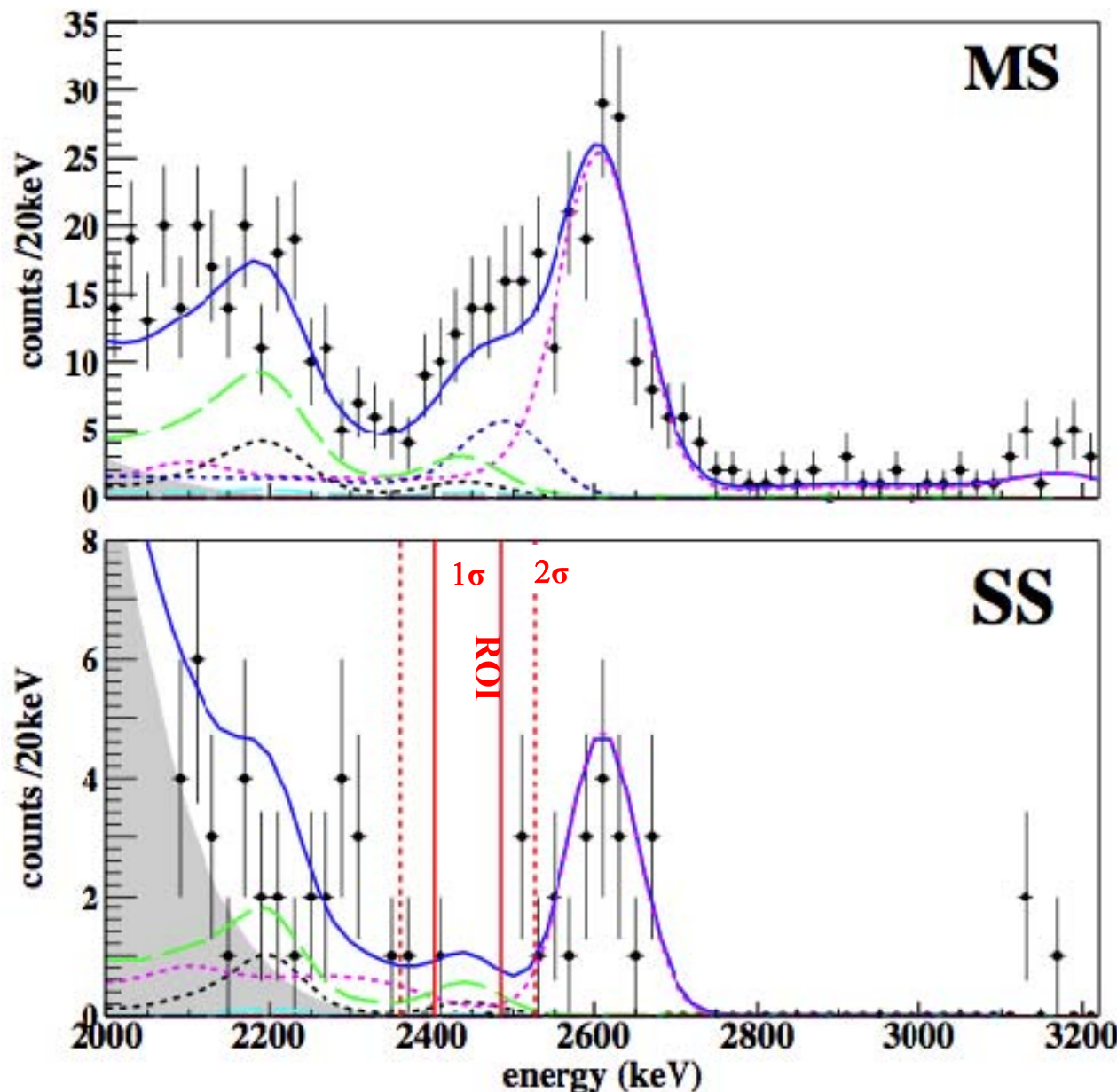




~22,000 $2\nu\beta\beta$ events !

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

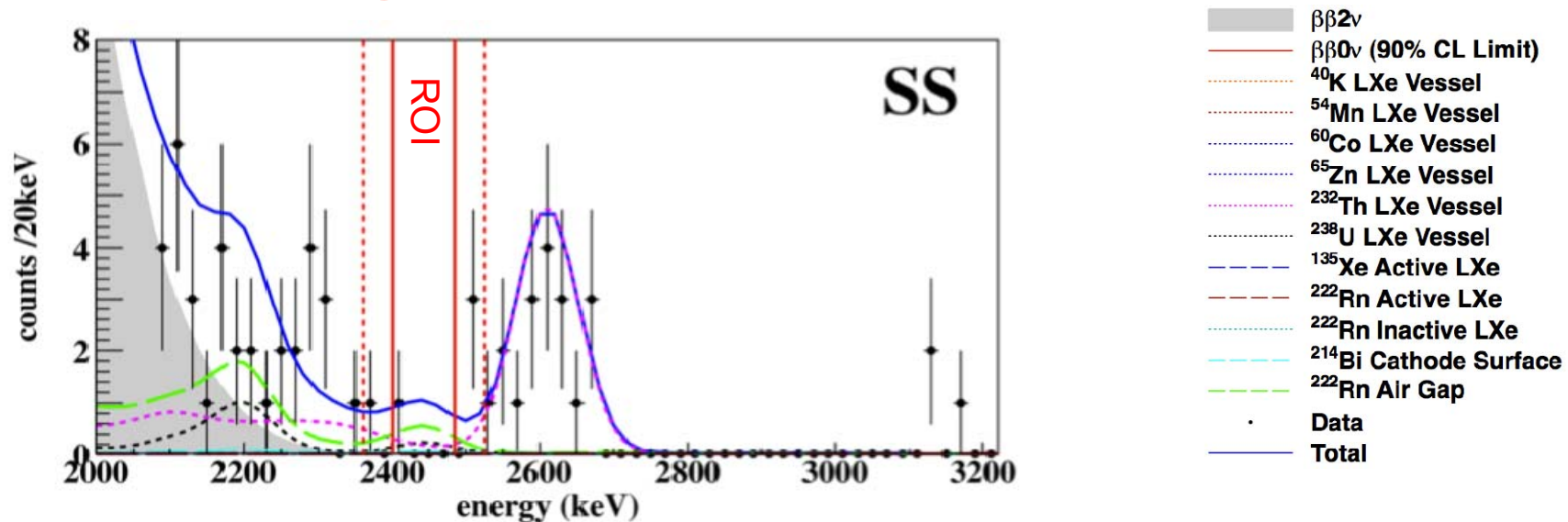
Low background spectrum zoomed around the $0\nu\beta\beta$ region of interest (ROI)



No 0ν signal observed in the ROI

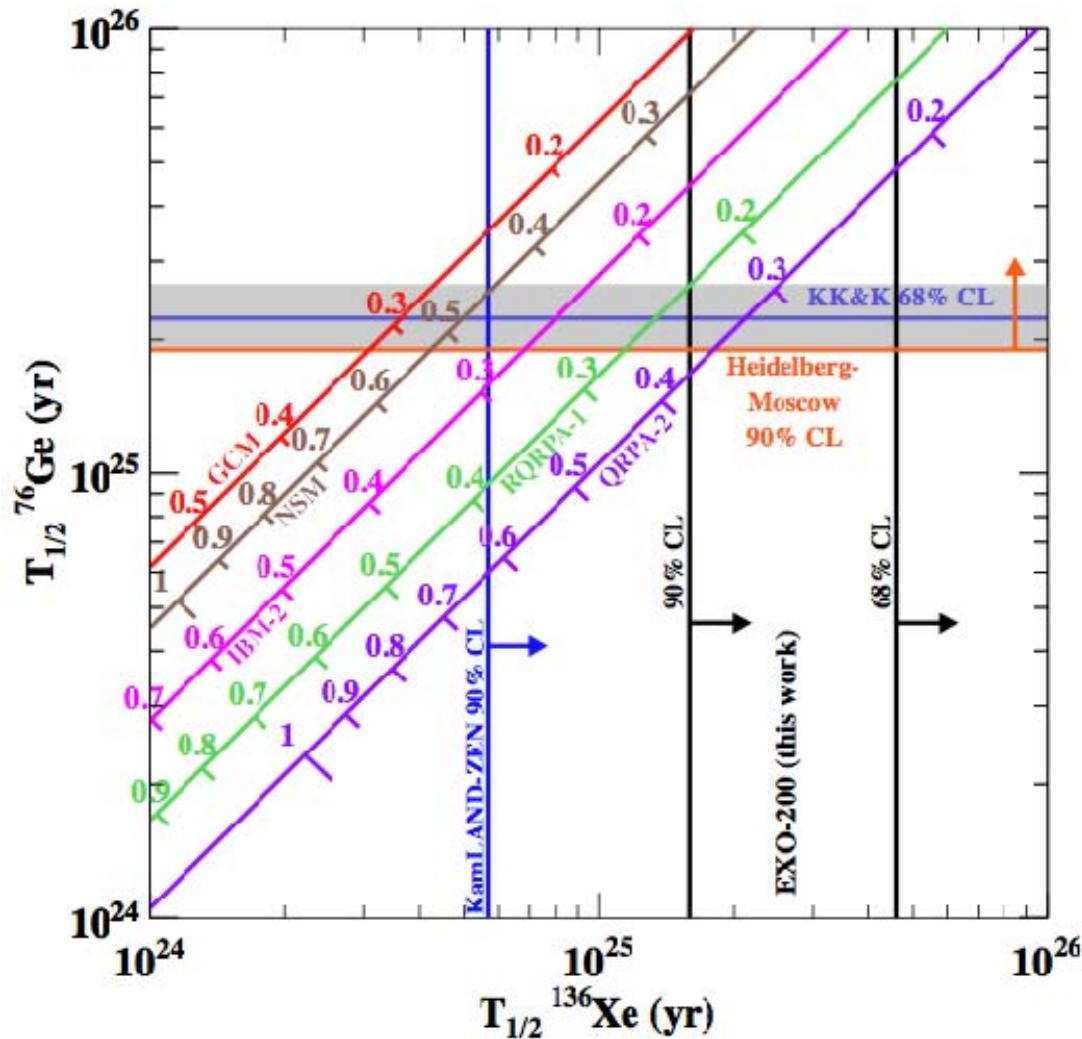
Use likelihood fit to establish limit

Background counts in $\pm 1, 2 \sigma$ ROI



	Expected events from fit			
	$\pm 1 \sigma$		$\pm 2 \sigma$	
^{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 ($\text{kg}^{-1}\text{yr}^{-1}\text{keV}^{-1}$)	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	

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



From profile
likelihood:

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

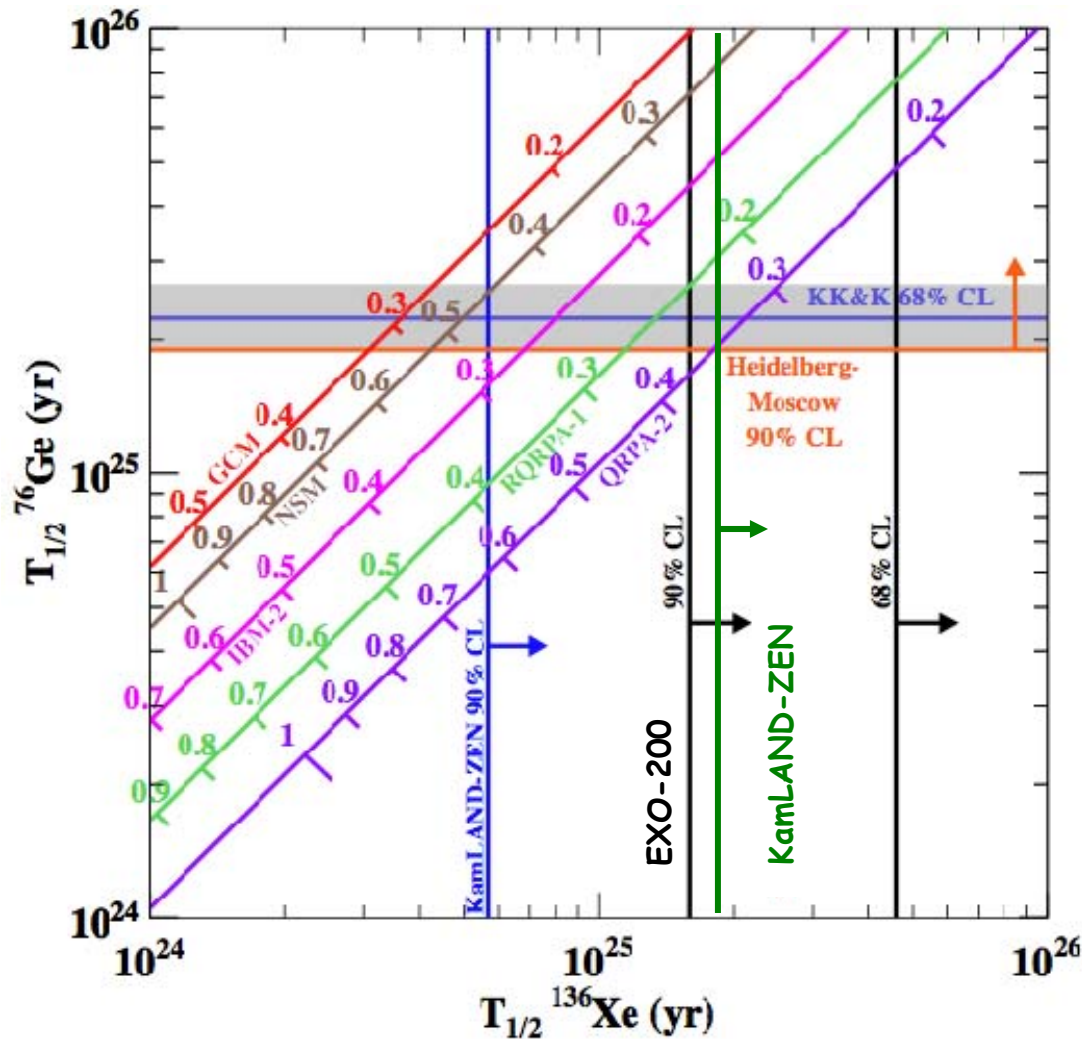
$$\langle m_{\beta\beta} \rangle < 140\text{--}380 \text{ meV}$$

(90% C.L.)

Phys Rev Lett

109 (2012) 032505

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



From profile
likelihood:

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

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

(90% C.L.)

Phys Rev Lett
109 (2012) 032505

KamLAND-ZEN
arXiv:1211.3863 (16Nov2012)

Some (arbitrarily selected) experiments taking data or in design/construction phase

Isotope	Experiment	Main principle	Fid mass	Status	Lab
^{76}Ge	Majorana [†]	Eres, 2site tag, Cu shield	30-60kg	Construction	SUSEL
	Gerda [†]	Eres, 2site tag, LAr shield	34.3 kg	Data taking	G Sasso
	MaGe/GeMa	See above	~1 ton	Planning	?
^{150}Nd	SNO+	Size/shielding	44 kg	Construction	SNOLab
^{82}Se	SuperNEMO [‡]	Tracking	100 kg	Planning	Canfranc Frejus
$^{130}\text{Te}^*$	CUORE	E Res.	204 kg	Construction	G Sasso
^{136}Xe	KamLAND-Zen	Size/shielding	400 kg	Data taking	Kamioka
^{136}Xe	EXO-200	Tracking/Eres	150 kg	Data taking	WIPP
	nEXO	Track/Eres, Ba tag	5 ton	Planning	SNOLab?

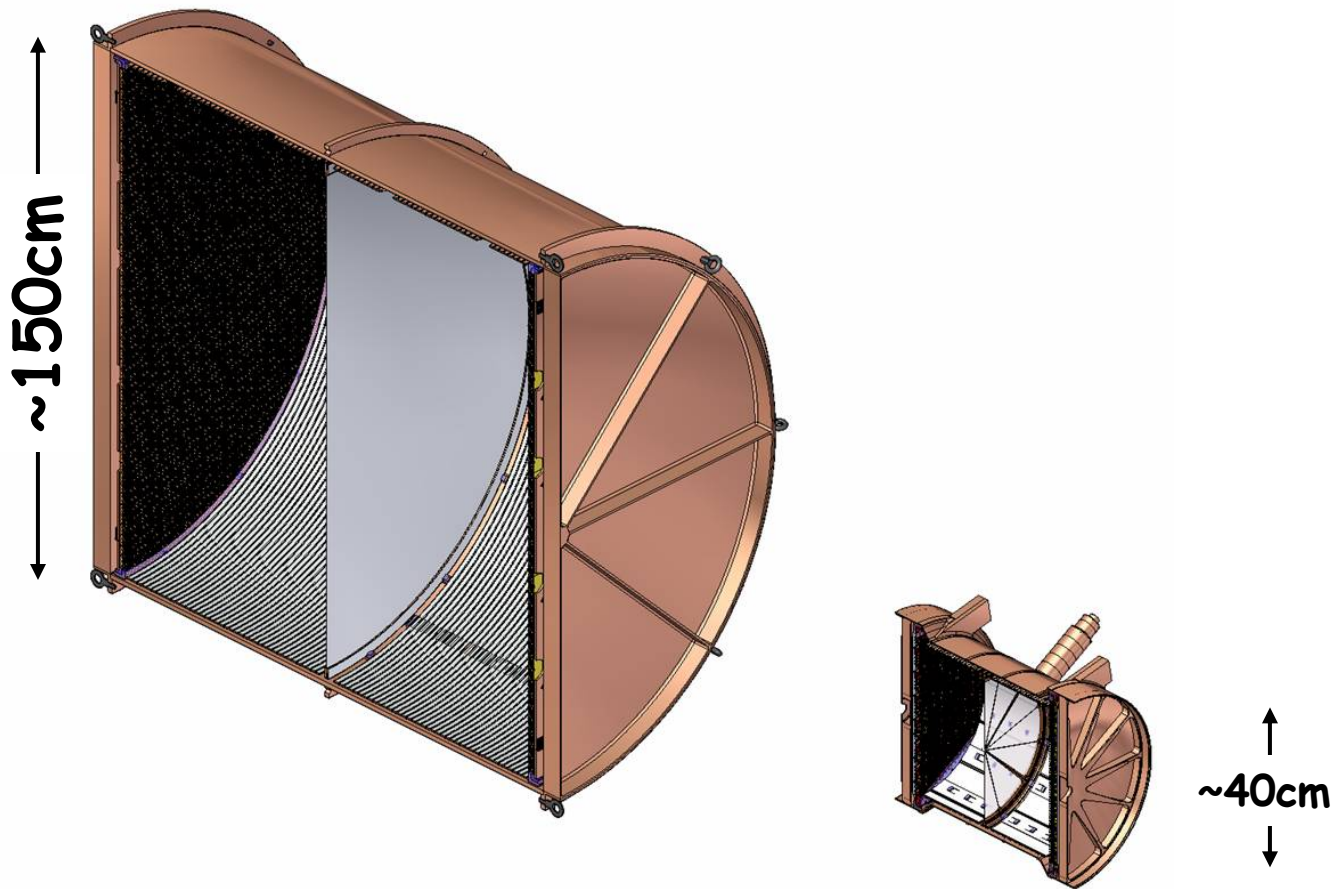
* No isotopic enrichment in baseline design

† Plan to merge efforts for ton-scale experiment

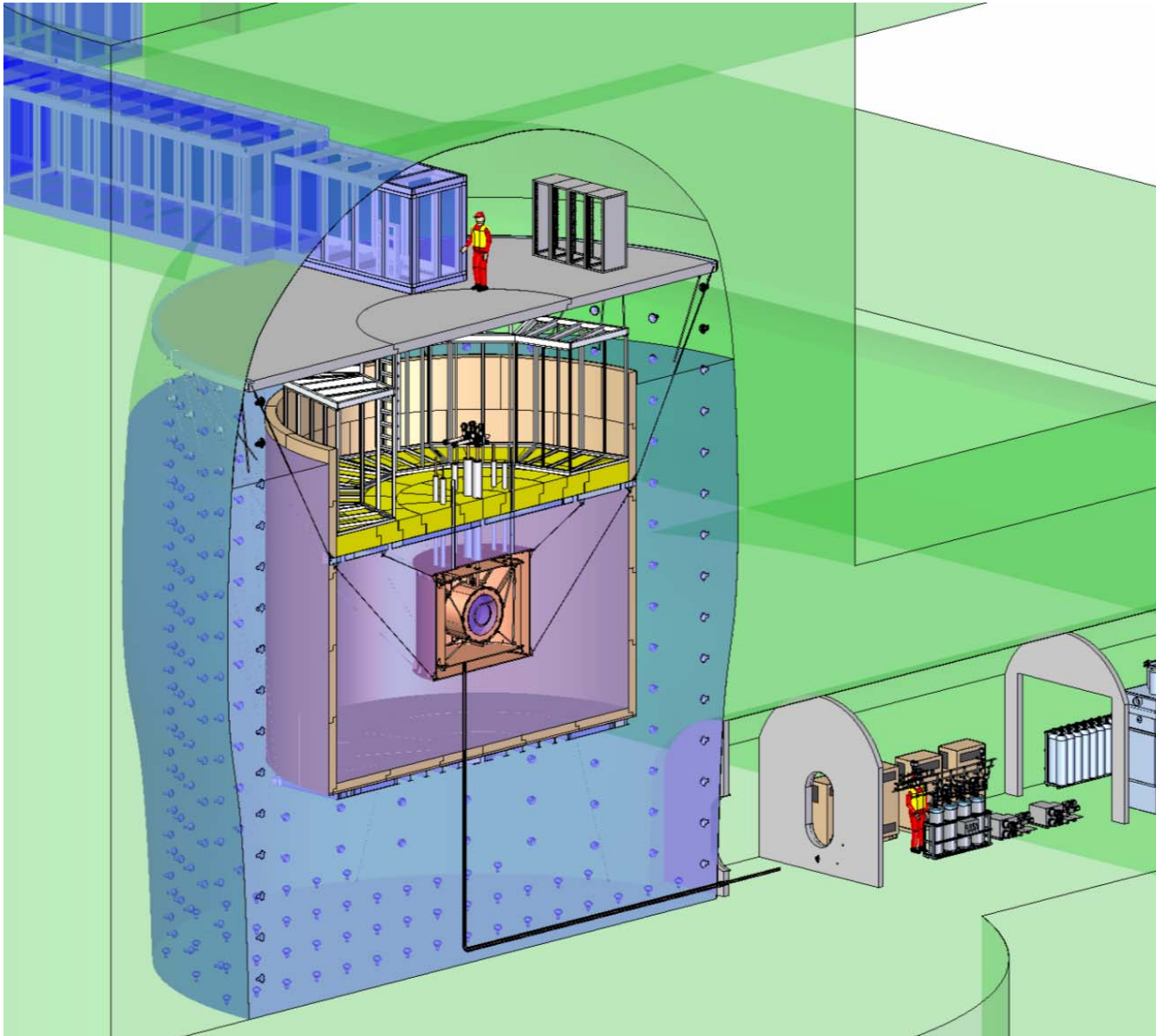
‡ Non-homogeneous detector

nEXO @SNOLab

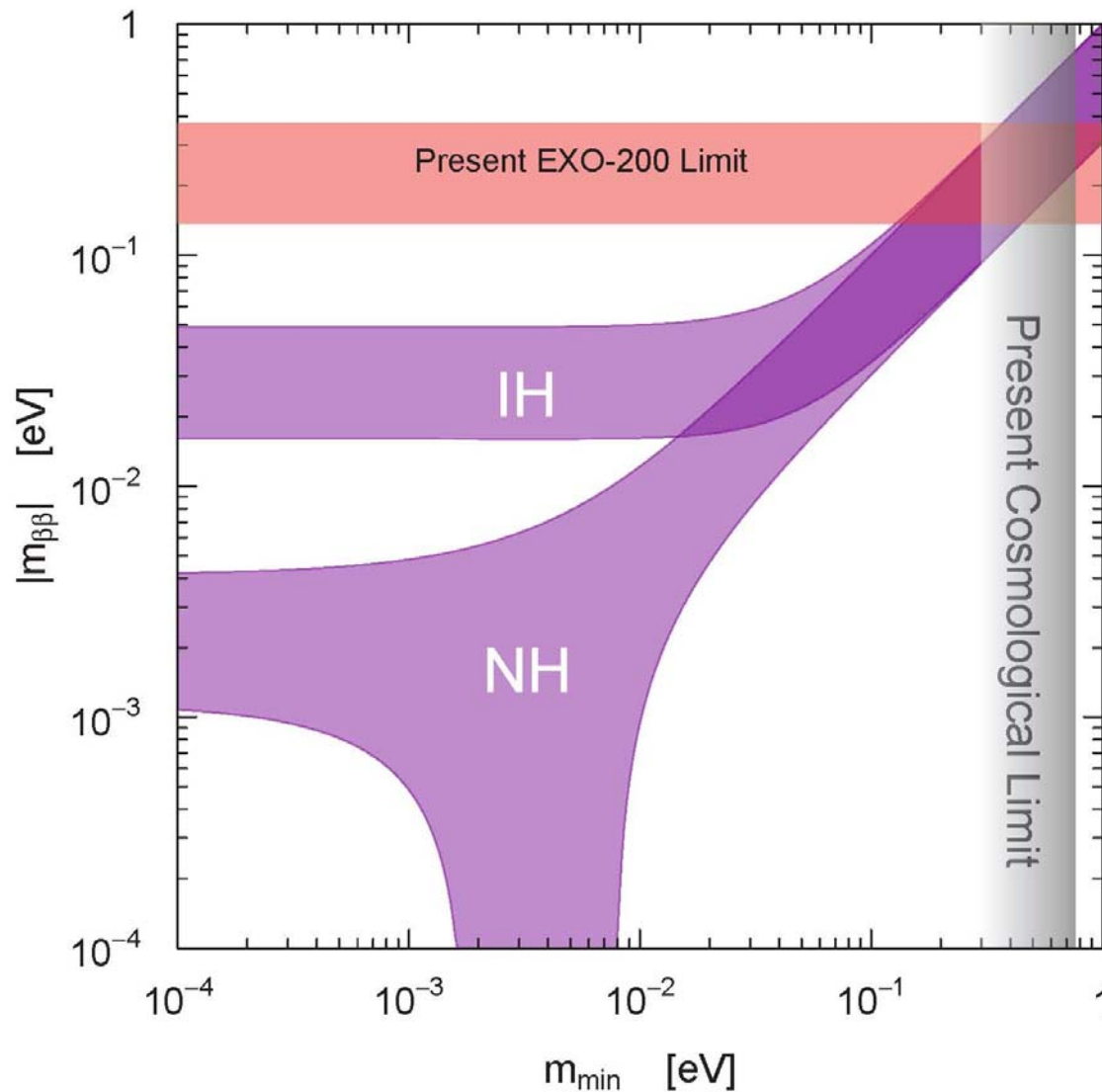
- 5 tonne LXe TPC “as similar to EXO-200 as possible”
- Provide access ports for a possible later upgrade to Ba tagging



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



EXO-200 and nEXO projected sensitivities

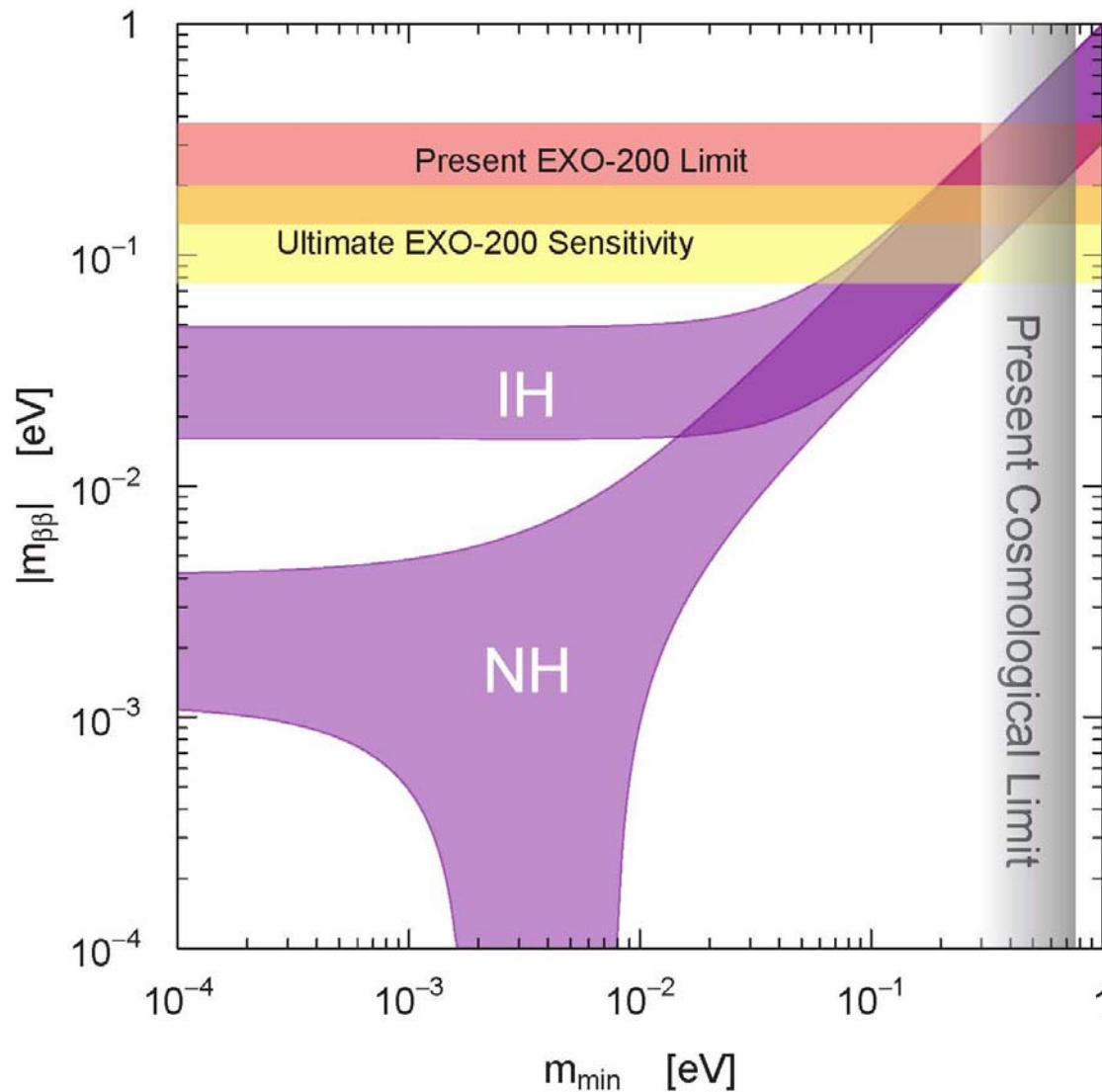


Blue bands are 68%CL from oscillation experiments for "Inverted" and "Normal" Hierarchy

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

Adapted from Bilenky & Giunti arXiv:1203.5250v2

EXO-200 and nEXO projected sensitivities



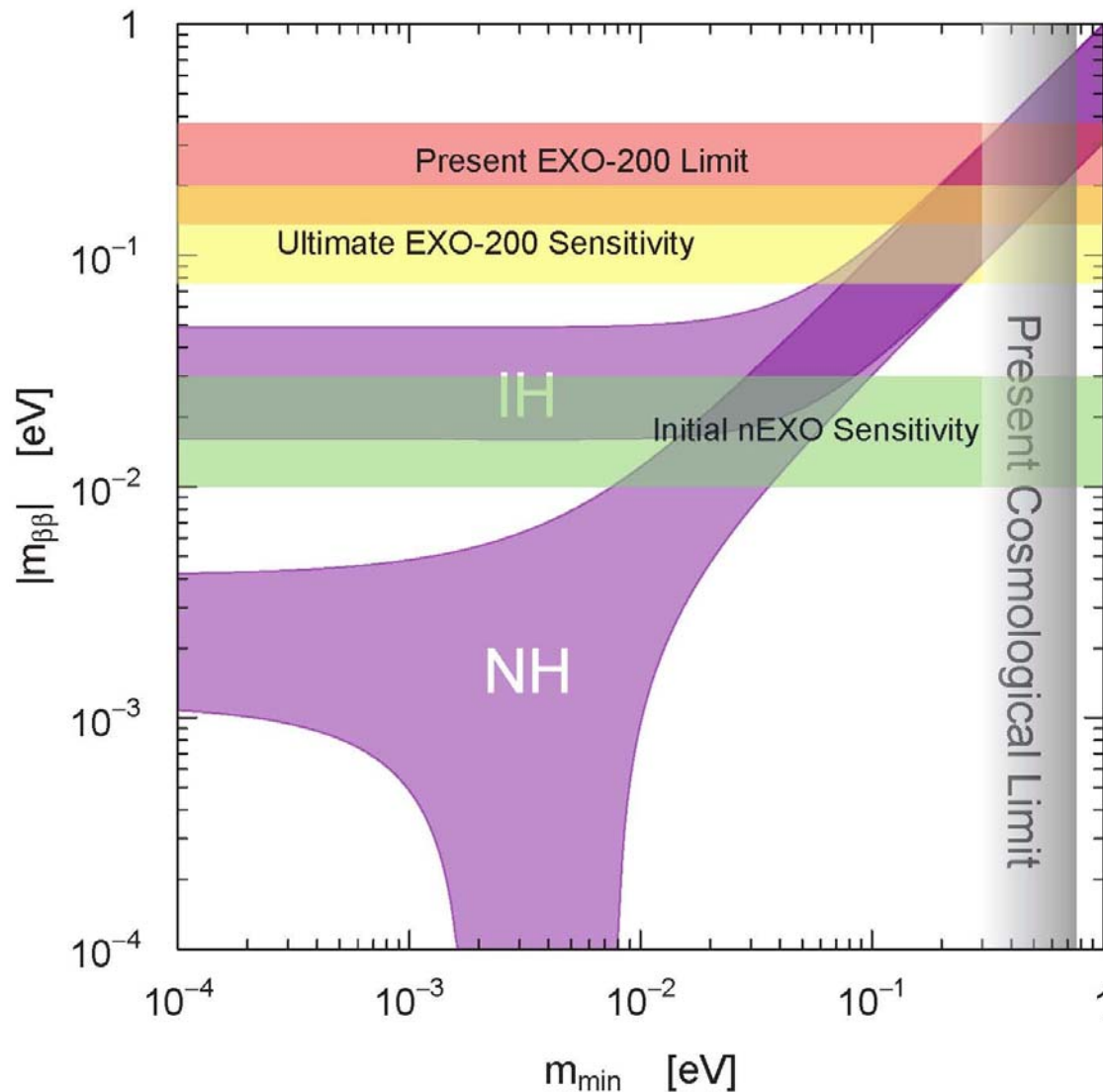
Blue bands are 68%CL from oscillation experiments for "Inverted" and "Normal" Hierarchy

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

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

Adapted from Bilenky & Giunti arXiv:1203.5250v2

EXO-200 and nEXO projected sensitivities



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

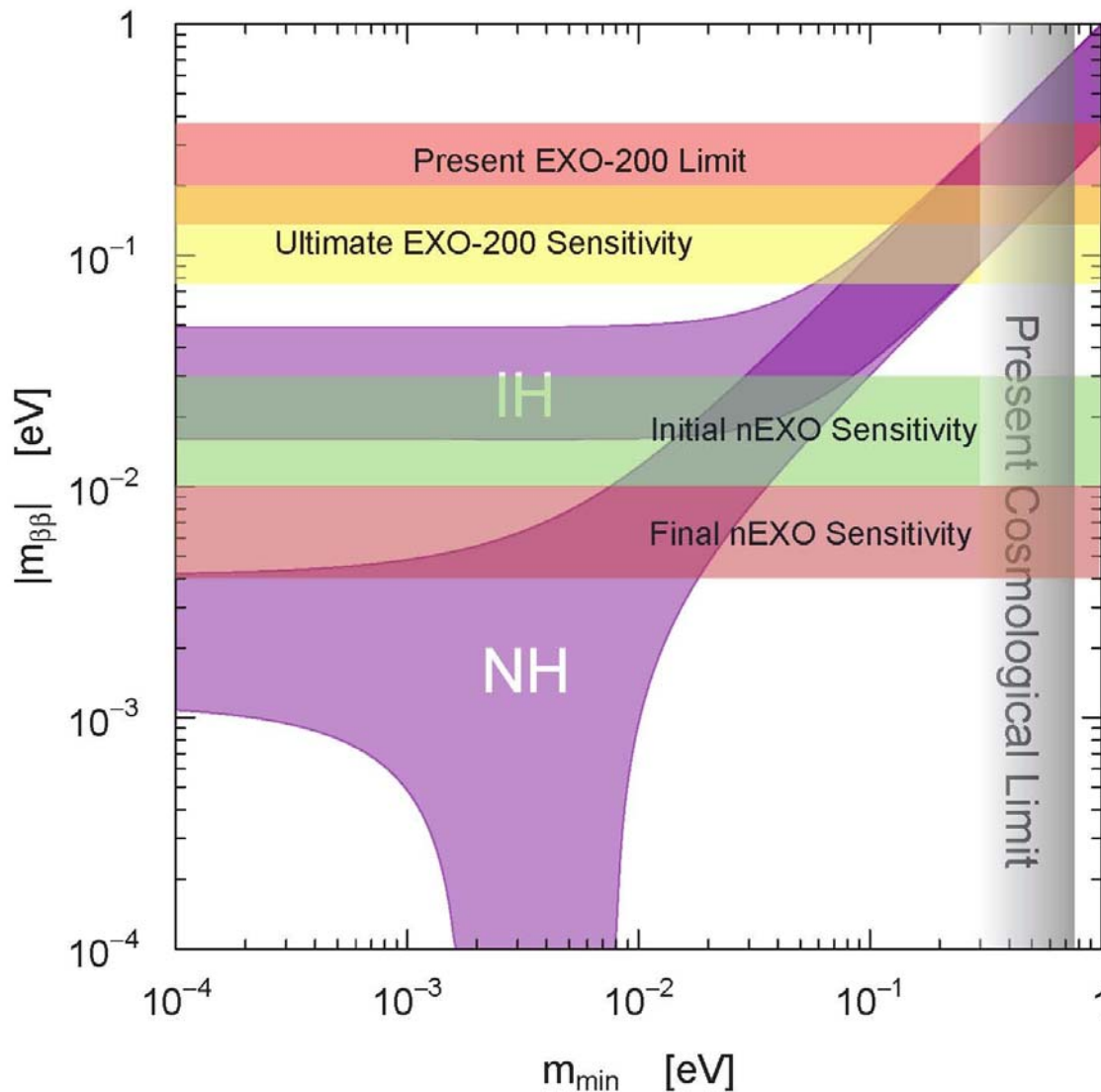
The EXO-200 "Present limit" is the 90%CL envelope of Limits (for different NMEs) from PRL 109 (2012) 032505

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

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

Adapted from Bilenky & Giunti arXiv:1203.5250v2

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

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

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 2v

Summary

- EXO-200 taking data since Jun 2011
- Detector already reached nominal performance for resolution and background
- Discovered the $2\nu\beta\beta$ decay in ^{136}Xe
- Very competitive limit on the $0\nu\beta\beta$ 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 $\sim 3\times$ data set
- Working on the design of nEXO
- Next few years will be very exciting!



The EXO Collaboration



University of Alabama, Tuscaloosa AL, USA - D. Auty, M. Hughes, A. Piepke, K. Pushkin, M. Volk

University of Bern, Switzerland - M. Auger, S. Delaquis, D. Franco, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier, M. Weber

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada - A. Coppens, M. Dunford, K. Graham, C. Hägemann, C. Hargrove, F. Leonard, C. Oullet, E. Rollin, D. Sinclair, V. Strickland

Colorado State University, Fort Collins CO, USA - S. Alton, C. Benitez-Medina, C. Chambers, A. Craycraft, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, T. Walton

Drexel University, Philadelphia PA, USA - M.J. Dolinski, E. Smith

University of Illinois, Urbana-Champaign IL, USA - D. Beck, J. Walton, M. Tarka, L. Yang

IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, L. Wen, Y. Zhao

Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, T. Johnson, L.J. Kaufman

University of California, Irvine, Irvine CA, USA - M. Moe

ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

Laurentian University, Sudbury ON, Canada - E. Beauchamp, D. Chauhan, B. Cleveland, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, M. Lodato, C. Mackeen, K. Malone, A. Pocar, J.D. Wright

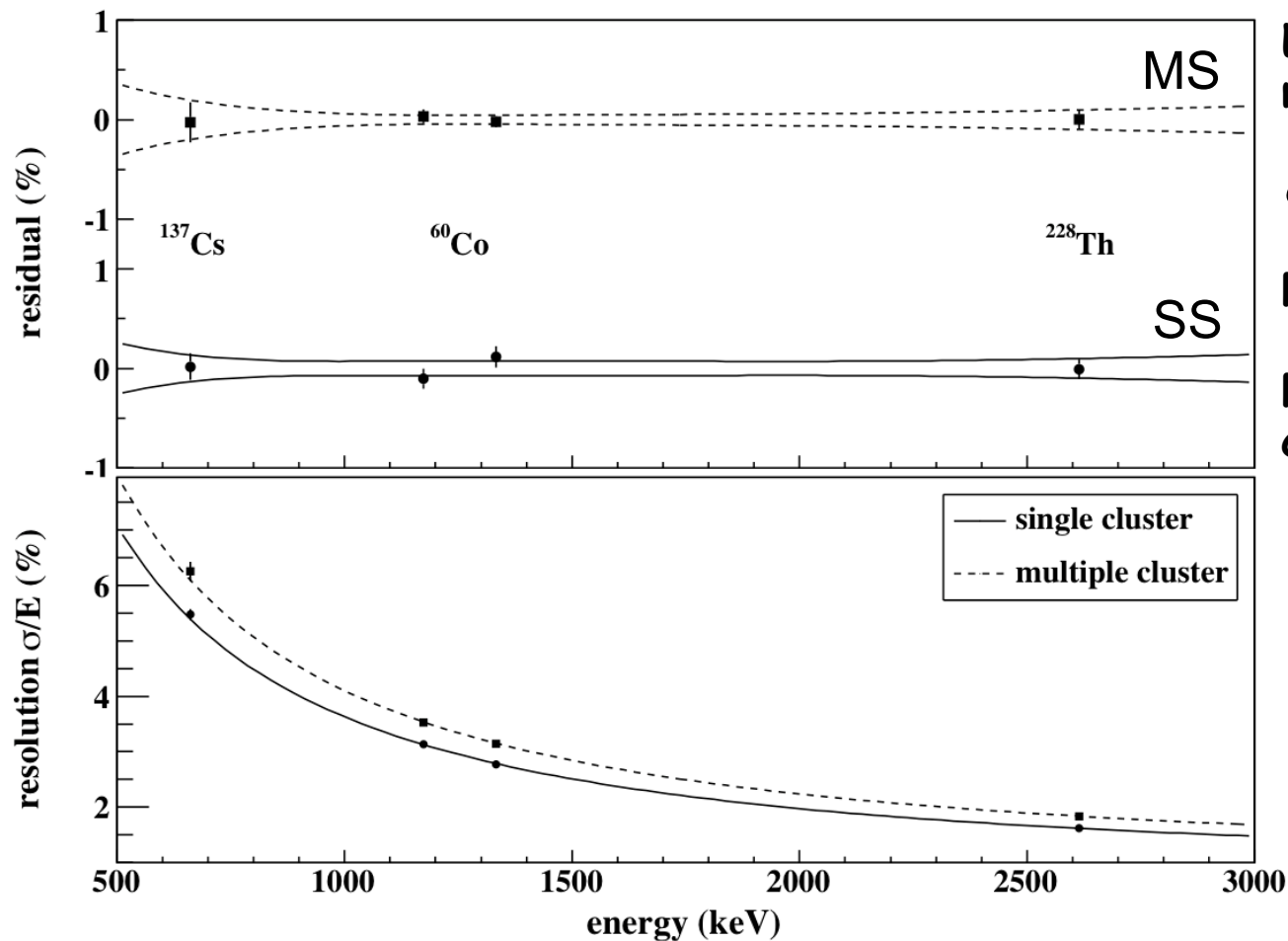
University of Seoul, South Korea - D. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, K. Fouts, R. Herbst, S. Herrin, J. Hodgson, A. Johnson, R. MacLellan, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen, J. Wodin

Stanford University, Stanford CA, USA - P.S. Barbeau, J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S. Kravitz, M. Montero-Díez, D. Moore, I. Ostrovskiy, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

Energy Calibration



Energy resolution model:

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

Residuals < 0.1%

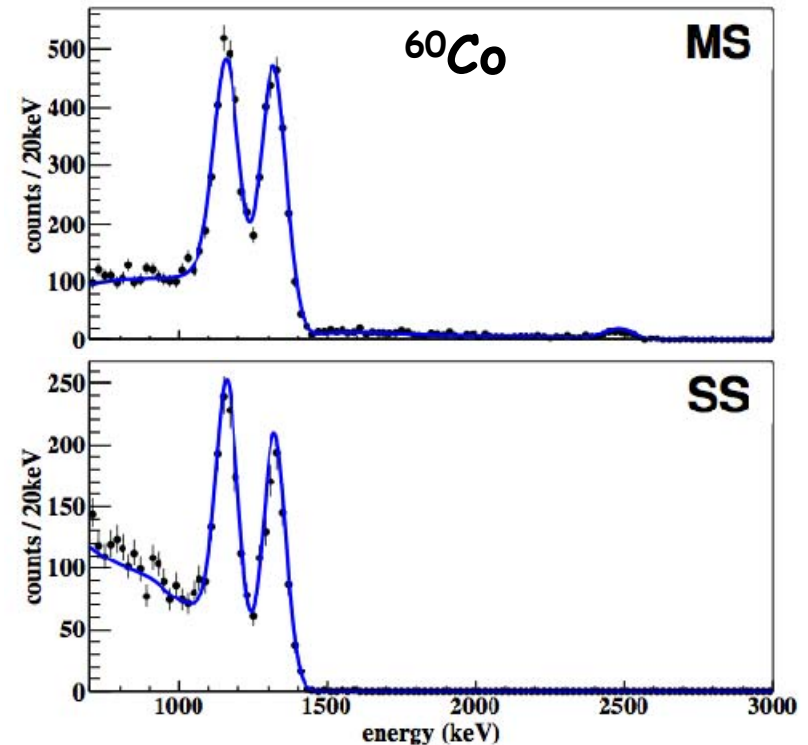
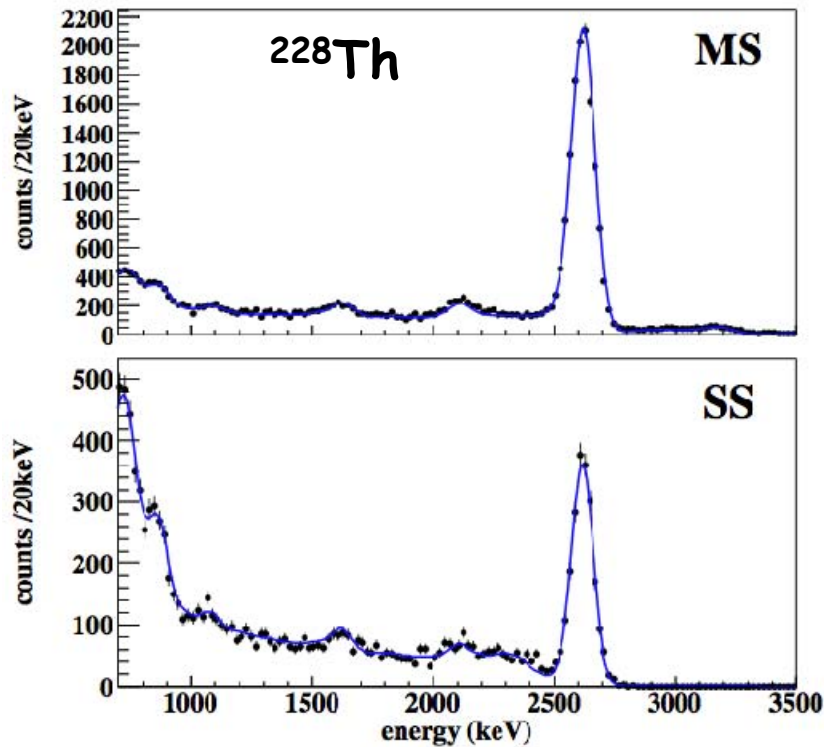
Resolution dominated by constant (noise) term p_1

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

$\sigma/E = 1.67\%$ (SS)

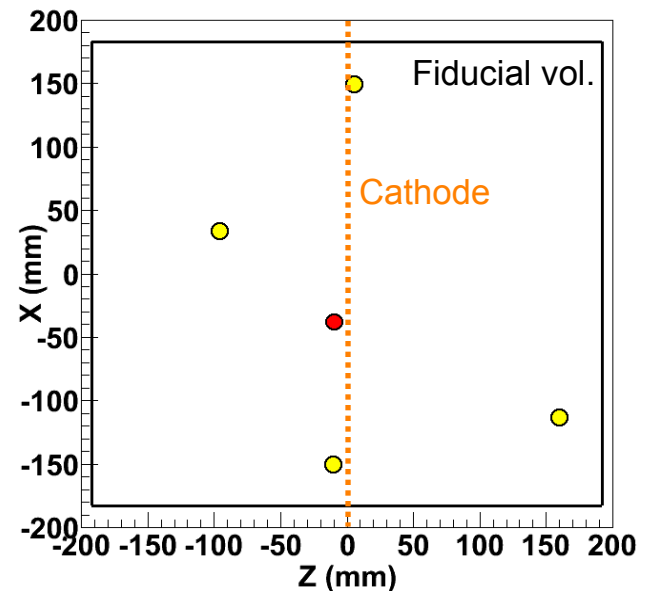
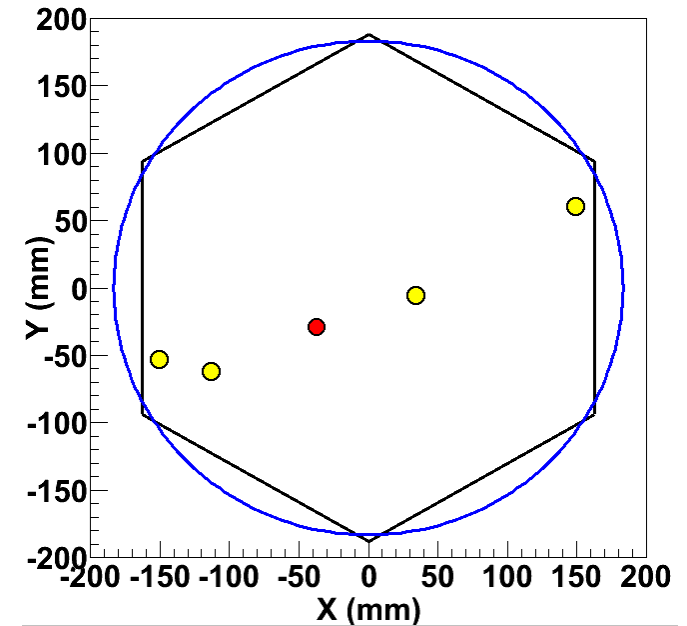
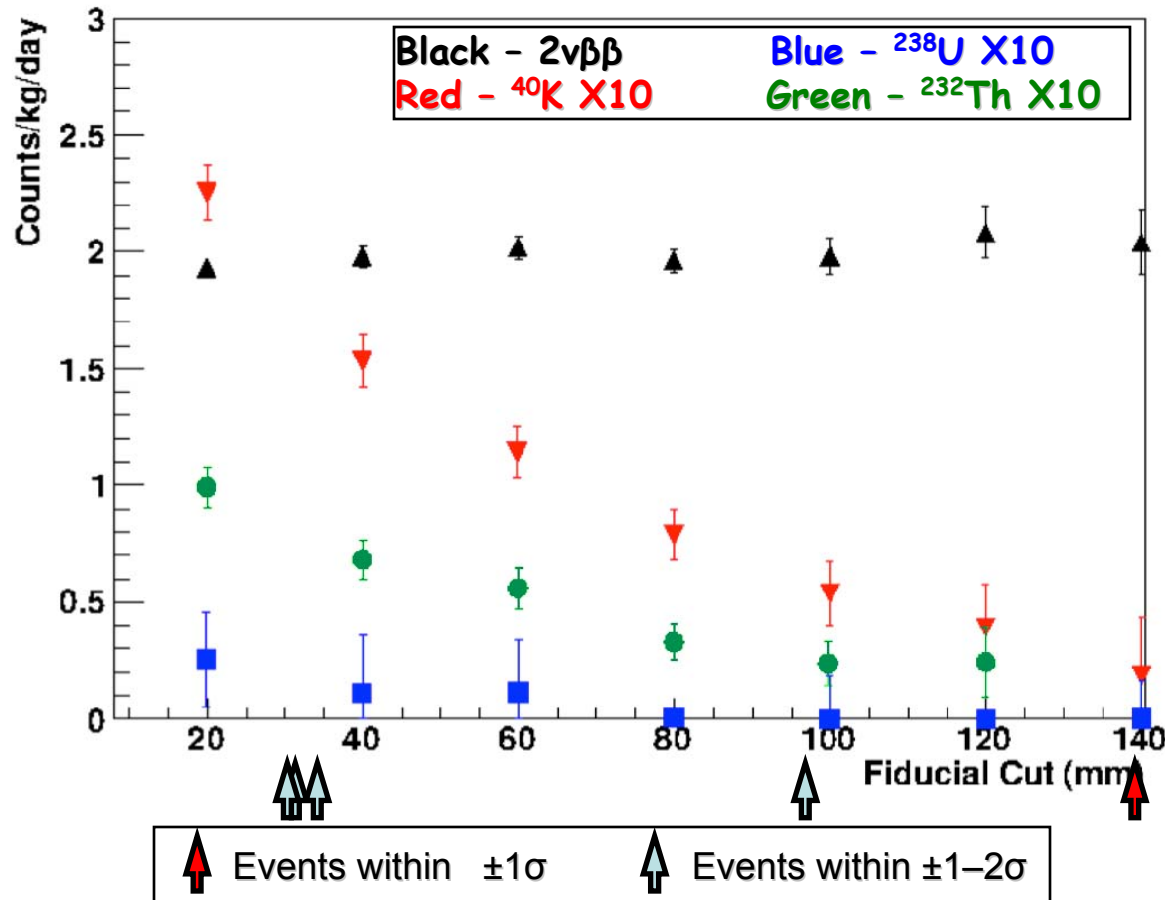
$\sigma/E = 1.84\%$ (MS)

Source Data/MC Agreement



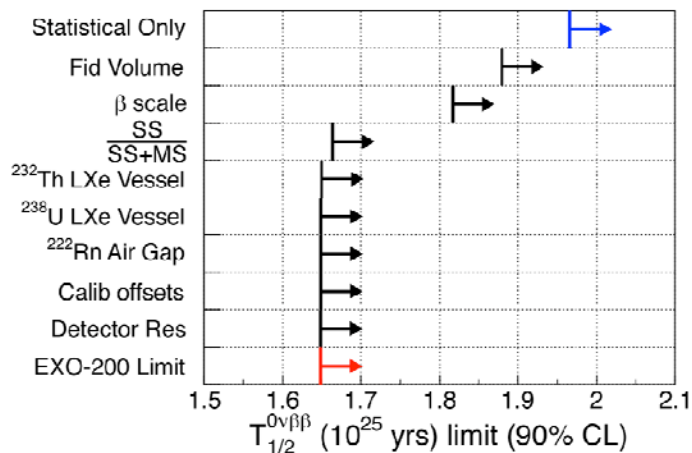
- Single site fraction agrees to within 8.5%
- Source activities measured to within 9.4%

Spatial distributions



- $2\nu\beta\beta$ rate does not change with fiducial volume
- Background gammas rates drop towards the inside of the detector
- Events in the $\pm 1, 2\sigma$ ROIs: statistics is too low to conclude on their parent distribution

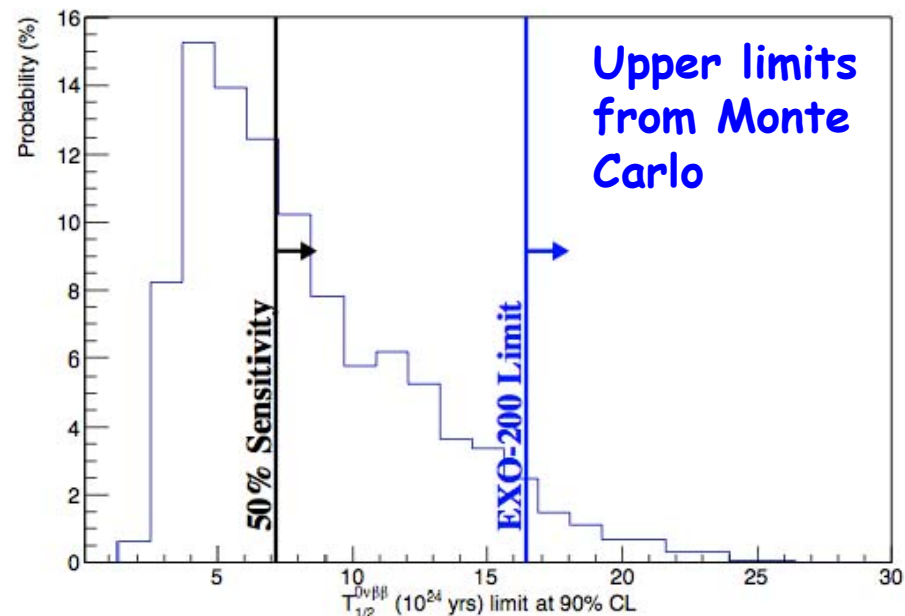
Systematics and sensitivity



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

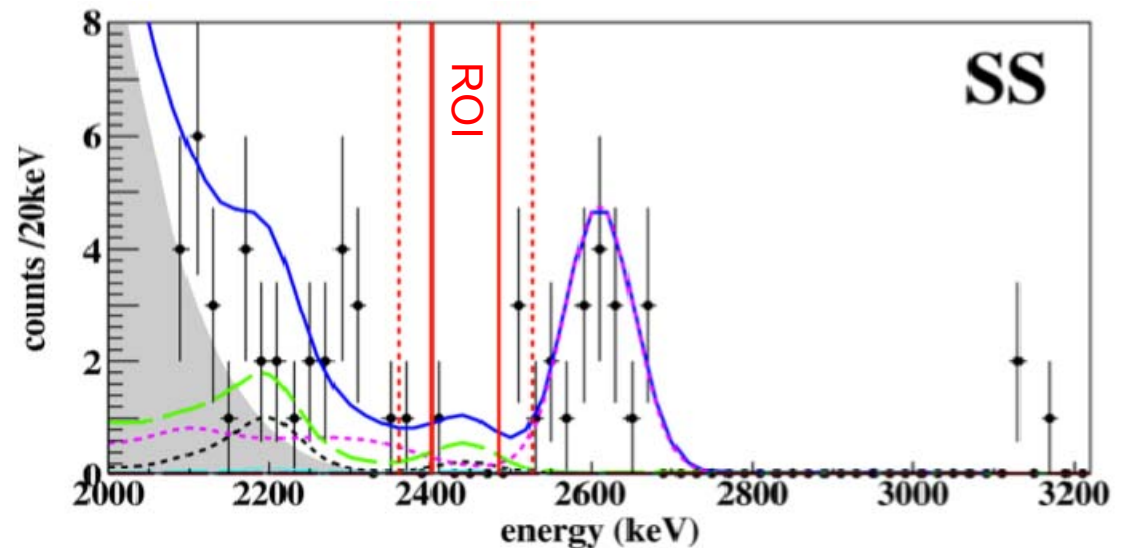
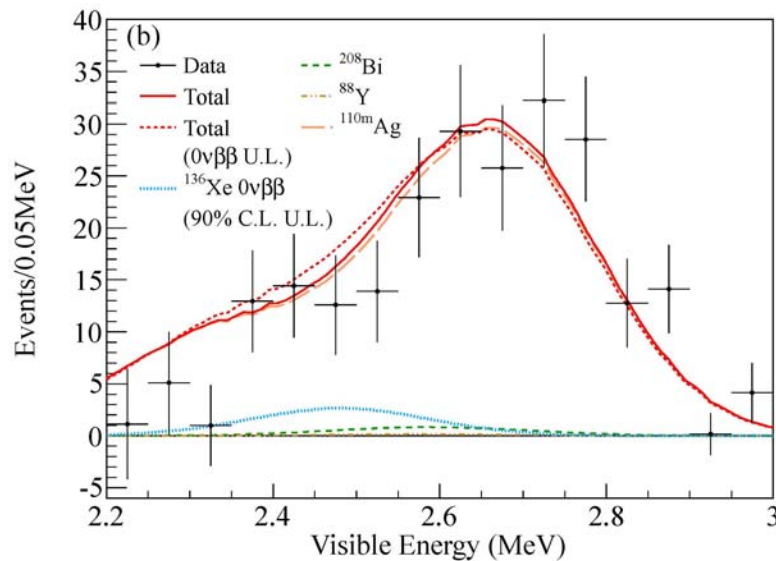
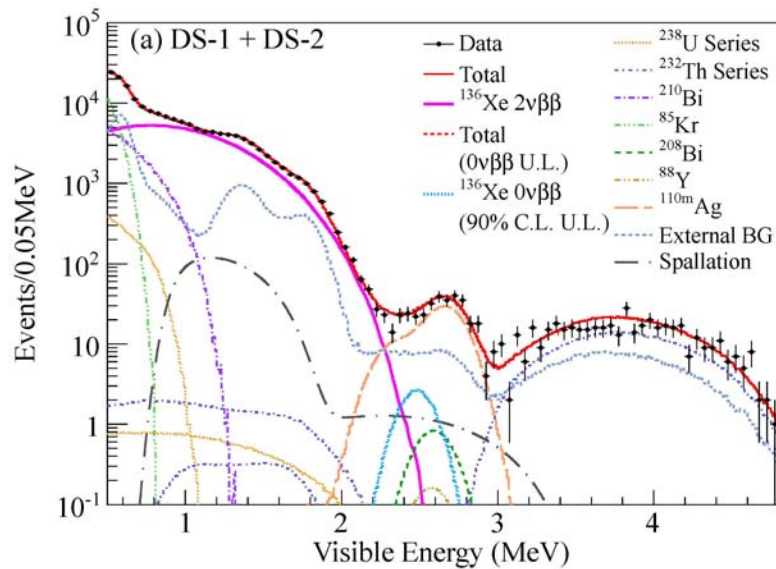
Distribution of $0\nu\beta\beta$ $T_{1/2}$ 90% CL



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

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

Comparison with KamLAND-ZEN
latest result (arXiv:1211.3863)



EXO-200 spectrum
(PRL 109 (2012) 032505)

FIG. 1: (a) DS-1 + DS-2 spectrum with the total spectrum and the upper limit (90% C.L. U.L.) for the $136\text{Xe } 0\nu\beta\beta$ transition; (b) zoomed-in view of the DS-1 + DS-2 spectrum for $2.2 < E < 3.0$ MeV. The total spectrum (red solid line) and the $136\text{Xe } 0\nu\beta\beta$ (90% C.L. U.L.) (cyan dotted) are shown together with the background components.

KamLAND-ZEN
spectrum

Some sensitivity numbers for EXO-200 and nEXO

The final sensitivity of EXO-200 may surpass “Ultimate” with a possible electronics upgrade currently under discussion.

Band	Fiducial Mass (tonne)	Livetime (yr)	$T_{1/2}$ sensitivity (yr)	Bracketing NMEs		Conditions
				QRPA-2 (meV)	GCM (meV)	
EXO-200 “Ultimate”	0.1	4	$5.5 \cdot 10^{25}$	200	75	EXO-200 with Rn removal and new analysis
Initial nEXO	4.5	10	$2.5 \cdot 10^{27}$	30	11	Extrapolation from EXO-200 using EXO-200 backgrounds
Final nEXO	4.5	5+5	$2.2 \cdot 10^{28}$	10	4	Second 5 yr background-free (e.g. Ba tagging)

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