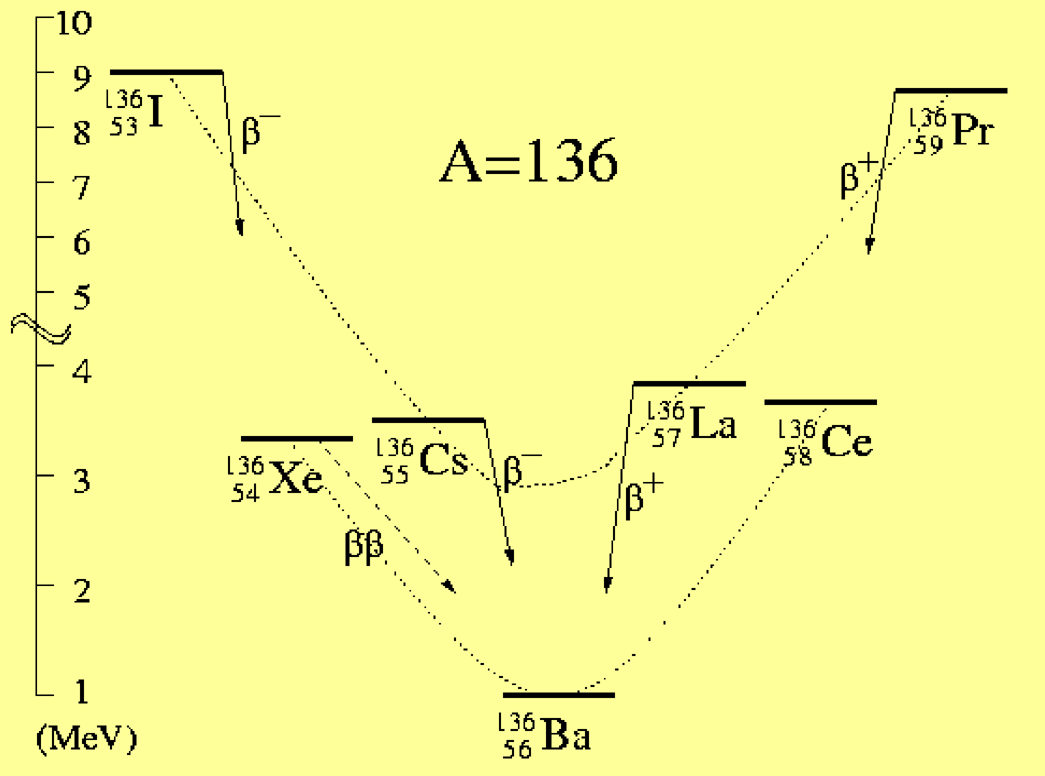
Double beta decay: Xenon Experiments

Andreas Piepke
University of Alabama

Brief introduction

Is a second order weak decay simultaneously converting two neutrons into two protons.

Because of the nucleon pairing energy for some nuclides ββ-decay is the only way to achieve the lowest mass state.



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Because of the nucleon pairing energy for some nuclides ββ-decay is the only way to achieve the lowest mass state.

There are many ways this can be achieved. The two most popular modes are:

$$\mathrm{A}(\mathrm{Z},\mathrm{N}) \rightarrow \mathrm{A}(\mathrm{Z}+2,\mathrm{N}-2) + 2\mathrm{e}^- + 2\overline{\mathrm{v}}_\mathrm{e} \qquad (2v\beta\beta)$$

$$\mathrm{A}(\mathrm{Z},\mathrm{N}) \rightarrow \mathrm{A}(\mathrm{Z}+2,\mathrm{N}-2) + 2\mathrm{e}^- \qquad (0v\beta\beta)$$

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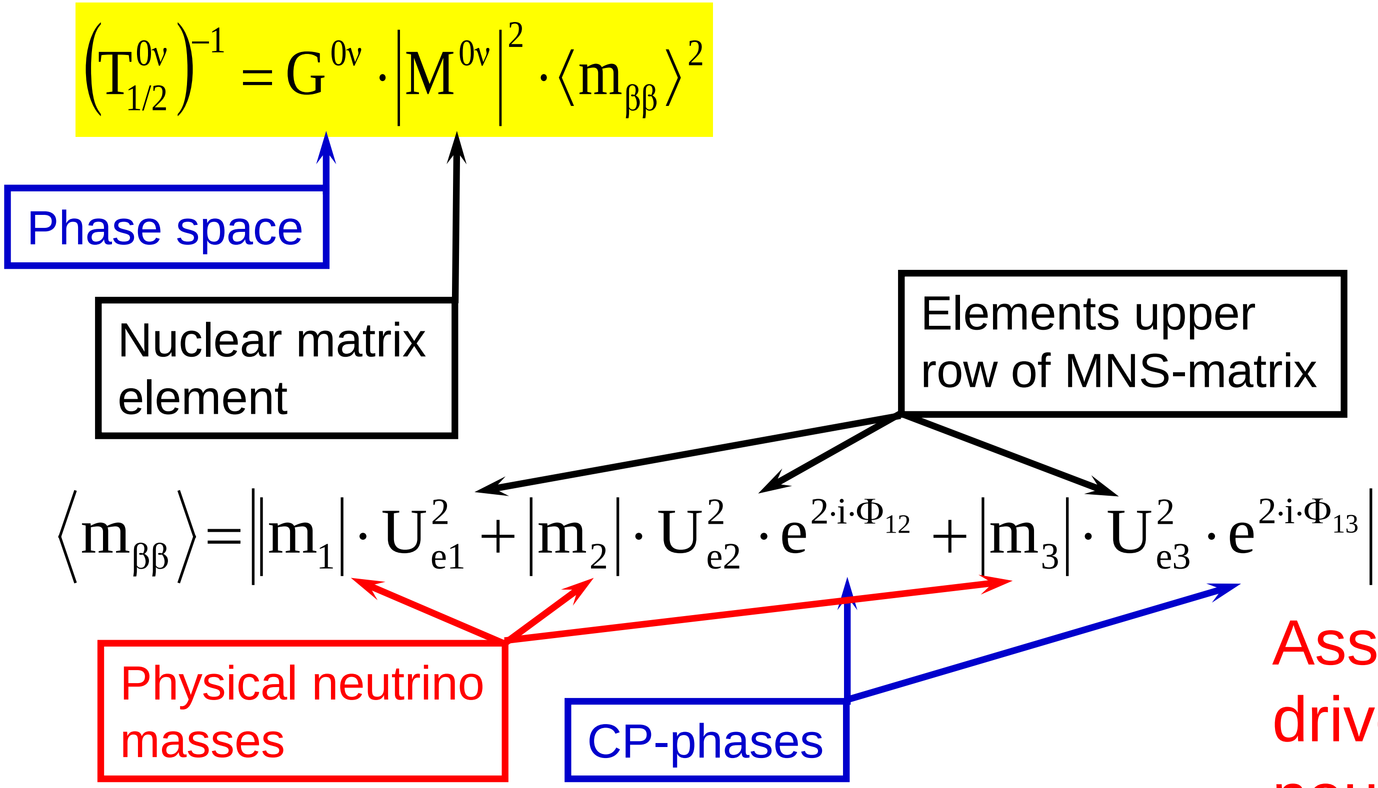
$$A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- + 2\overline{\nu}_e \qquad (2\nu\beta\beta)$$

$$\boxed{A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- \qquad (0\nu\beta\beta)}$$

- Violates Lepton number by two units
- Requires neutrino anti-neutrino identity (Majorana character)
- Driven by neutrino exchange: rate determines neutrino mass

Focus on light neutrino exchange mode

Decay rate depends on an effective Majorana mass. Its calculation requires knowledge of nuclear physics quantities.



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^{2} \cdot \langle m_{\beta\beta} \rangle^{2}$$

Phase space

Nuclear matrix element

Elements upper row of MNS-matrix

$$\langle m_{\beta\beta} \rangle = \left| |m_1| \cdot U_{e1}^{2} + |m_2| \cdot U_{e2}^{2} \cdot e^{2 \cdot i \cdot \Phi_{12}} + |m_3| \cdot U_{e3}^{2} \cdot e^{2 \cdot i \cdot \Phi_{13}} \right|$$

Physical neutrino masses

CP-phases

Assumes decay is driven by light neutrino exchange.

Focus on light neutrino exchange mode

Decay rate depends on an effective Majorana mass. Its calculation requires knowledge of nuclear physics quantities.

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^{2} \cdot \langle m_{\beta\beta} \rangle^{2}$$

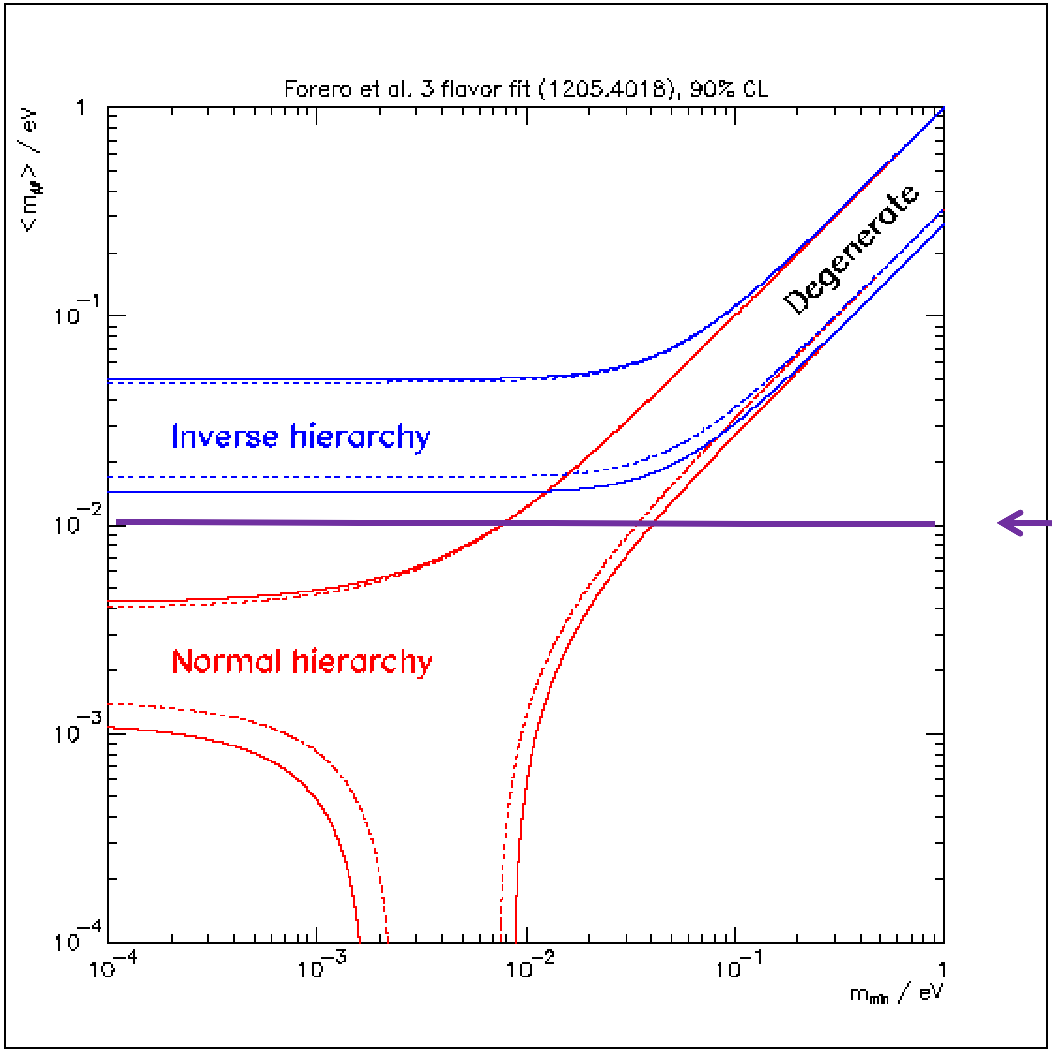
Phase space

Nuclear matrix element

Because of the imaginary phases cancellations may occur.

$$\langle m_{\beta\beta} \rangle = \left| |m_1| \cdot U_{e1}^{2} + |m_2| \cdot U_{e2}^{2} \cdot e^{2 \cdot i \cdot \Phi_{12}} + |m_3| \cdot U_{e3}^{2} \cdot e^{2 \cdot i \cdot \Phi_{13}} \right|$$

Assumes decay is driven by light neutrino exchange.



Measurement of $\beta\beta0\nu$ is the only practical way to test the possible particle anti-particle identity. $\langle m_{\beta\beta}\rangle$ determines the yet unknown mass scale.

←

^{76}Ge: $(1.4\text{-}7.7)\cdot10^{28}$ yr
^{130}Te: $(0.22\text{-}1.3)\cdot10^{28}$ yr
^{136}Xe: $(0.32\text{-}2.2)\cdot10^{28}$ yr

This neutrino mass goal defines the scale of new experimental searches.

90% CL 3-flavor fit errors provided by M. Tortola.

ν-oscillation experiments define a "range of opportunity" for Majorana-ν tests. World wide many projects are taking data, are under construction, or being contemplated. The main contenders (my subjective choice) currently are:

1) ^{76}Ge (GERDA, Majorana)
2) ^{82}Se (Super NEMO)
3) ^{130}Te (CUORE, SNO+)
4) ^{136}Xe (EXO, KamLAND-Zen, NEXT)

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KamLAND-Zen (Kamioka 2700 mw.e.)

Dissolve isotopically enriched Xe in KamLAND's ultra low background liquid scintillator.

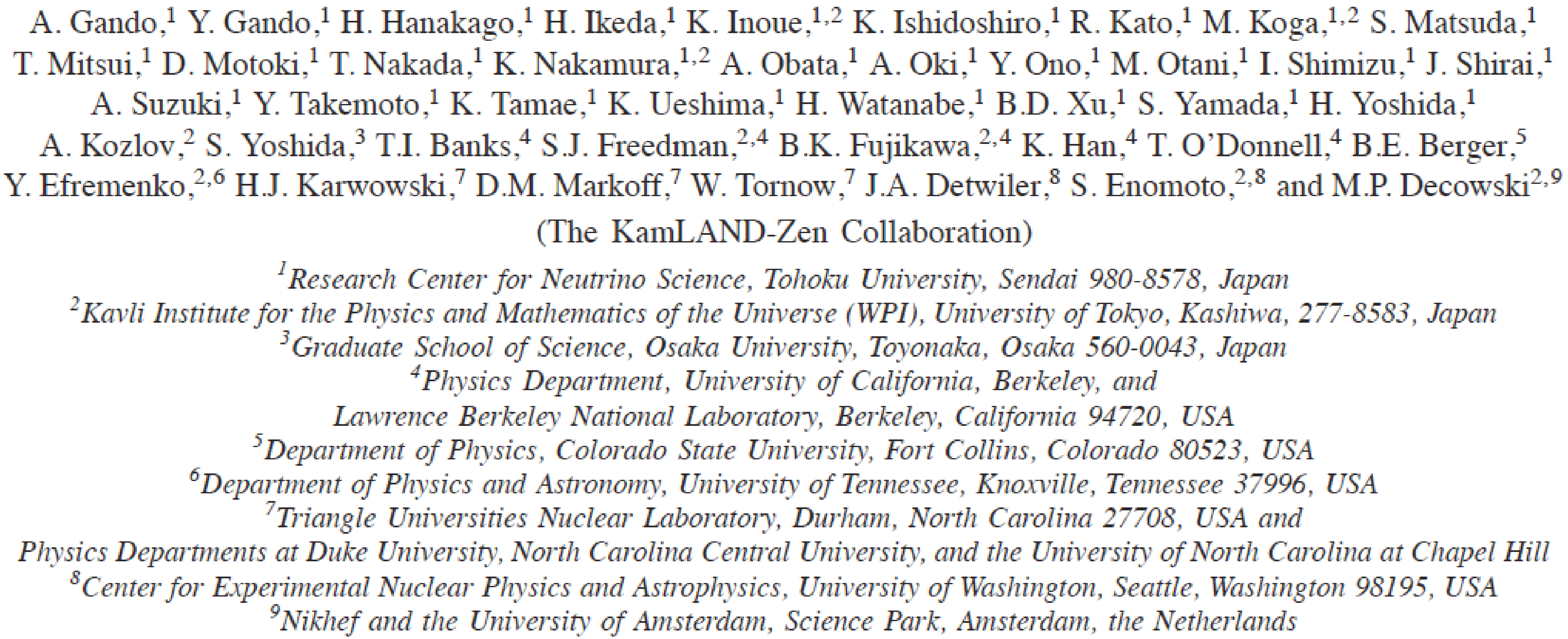
Calorimetrically measure the ββ–electron sum energy at limited energy resolution.

Contain the Xe-loaded scintillator in a small balloon to fiducialize. Very little funding needed for detector, concentrate all funding on enriched Xe purchase, maximize decaying mass. Highly scalable up to several tons of Xe at "moderate" cost. Limited resolution: discovery potential?

P. Decowski's talk 9/10

Thanks to P. Decowski and K. Inoue for the material

KamLAND-Zen Collaboration



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(The KamLAND-Zen Collaboration)

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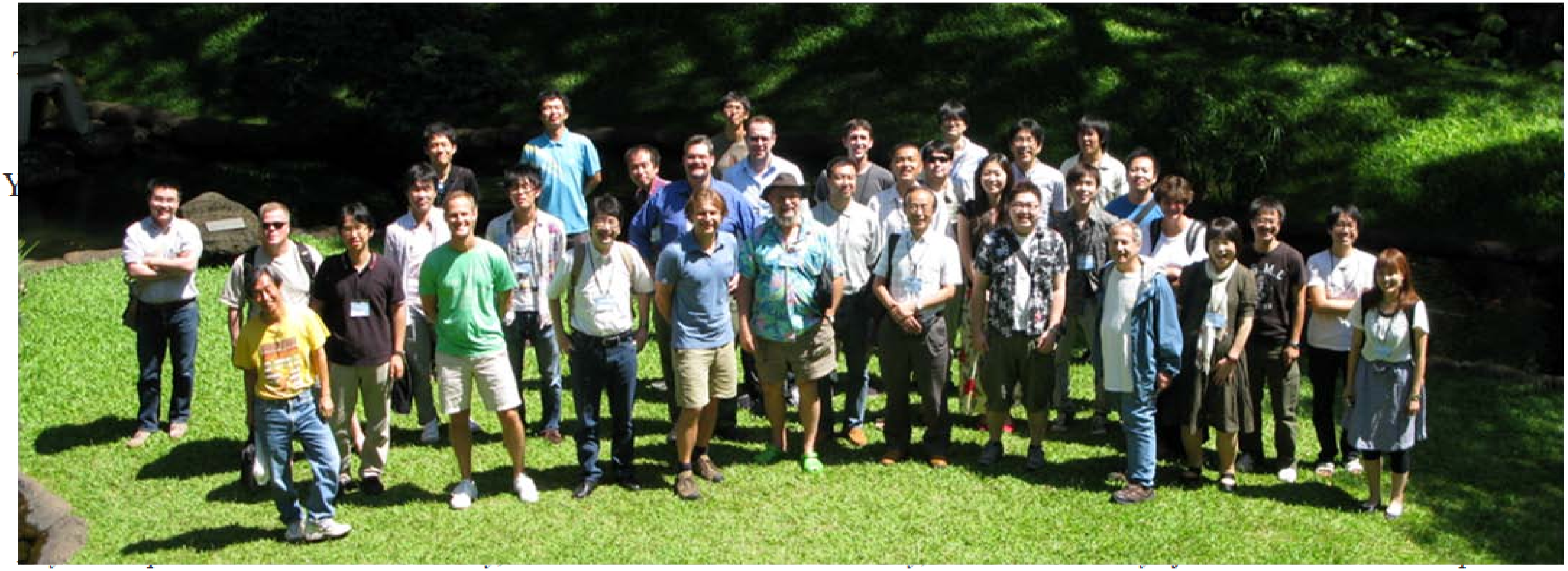
[9]Nikhef and the University of Amsterdam, Science Park, Amsterdam, the Netherlands

42 members (subset of KamLAND collaboration) and still growing

KamLAND-Zen Collaboration

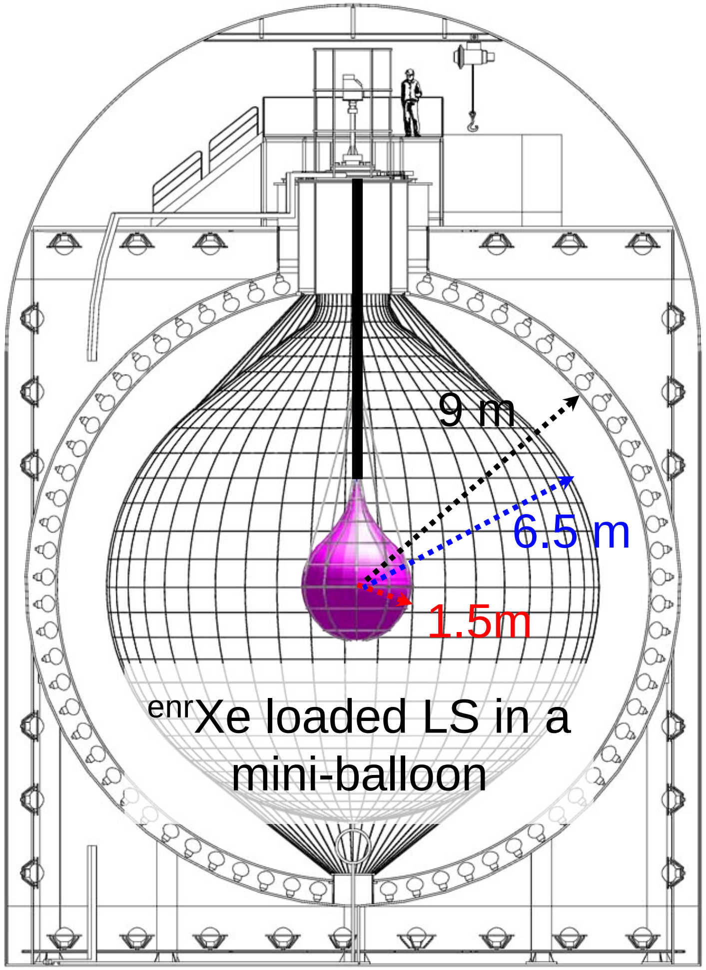


[8] *Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195, USA*
[9] *Nikhef and the University of Amsterdam, Science Park, Amsterdam, the Netherlands*

42 members (subset of KamLAND collaboration) and still growing

KamLAND-Zen

Zero Neutrino
double beta decay search



~320 kg 90% enriched ^{136}Xe installed

615 kg in hand

Because of large detector size no escape or invisible energy from β, γ
→ helps in BG identification

anti-neutrino observation continues
→ geo-neutrino, Japanese reactors

Production of real Mini-balloon

- fabrication in Class 1 super-clean-room
  (class 1 = less than one 0.5 micron particle in 1 cube feet

minimum material → 25 µm Nylon 6

transparency 99.4% @400nm

strength 19.4 N/cm

Xe permeability < 220 g/year

low radioactive impurity

→ specially made no filler film

U : 150 → 2x10^{-12}g/g

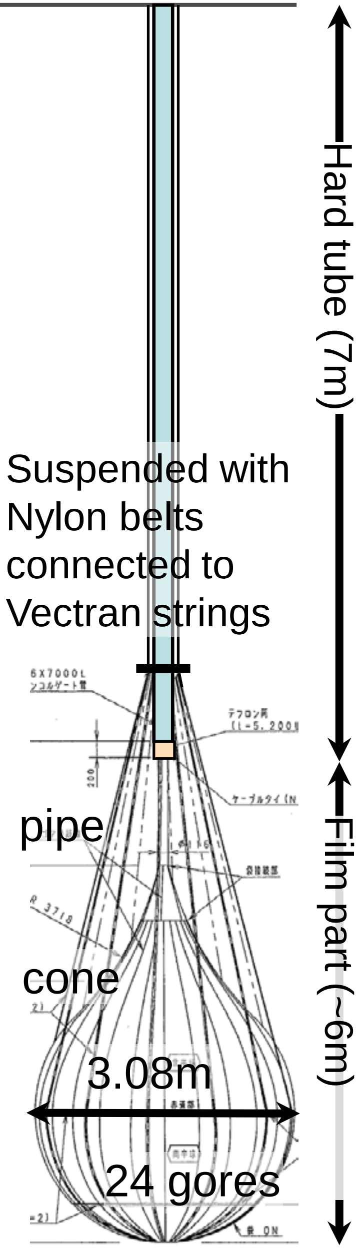
Th : 59 → 3x10^{-12}g/g

^{40}K : 140 → 2x10^{-12}g/g

Ultra-sonic washer

24 gores from the film

Newly developed welding



- All tools and parts washed here

DAQ started on September 24, 2011

(only 2 years from the project start)

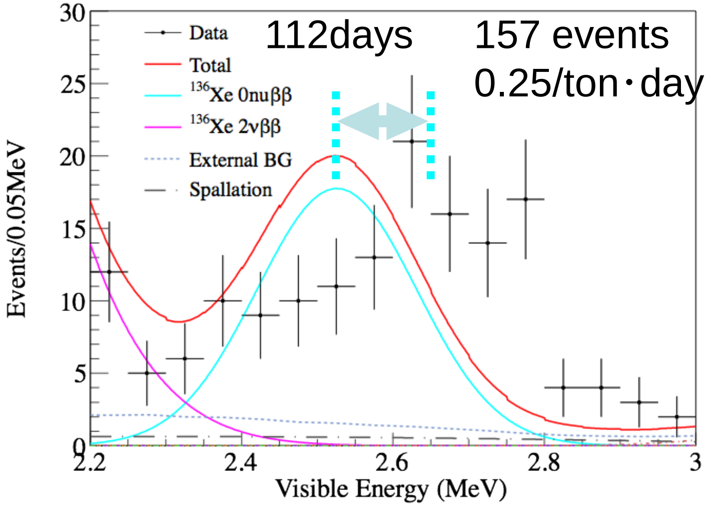
Observed 2νββ-decay January 2012:

$T_{1/2}=(2.30\ \ 0.02^{stat}\ \ 0.12^{syst})10^{21}$ yr

measured half life was found to be consistent with the EXO-200 value.

Background situation

Peak fit with 0v signal



112days

157 events

0.25/ton・day

Peak position is different from that of expected 0v.

0v only is rejected at more than 8σ level.

Background 2 possibilities :

- Long-lived <u>radio-impurity</u>
- <u>Muon spallation</u> which should have time/space correlation with muon

http://ie.lbl.gov/databases/ensdfserve.html

Thorough survey of all decay path of all nuclei in ENSDF

<100 sec timing correlation <0.007 /ton・day (90% CL). → small

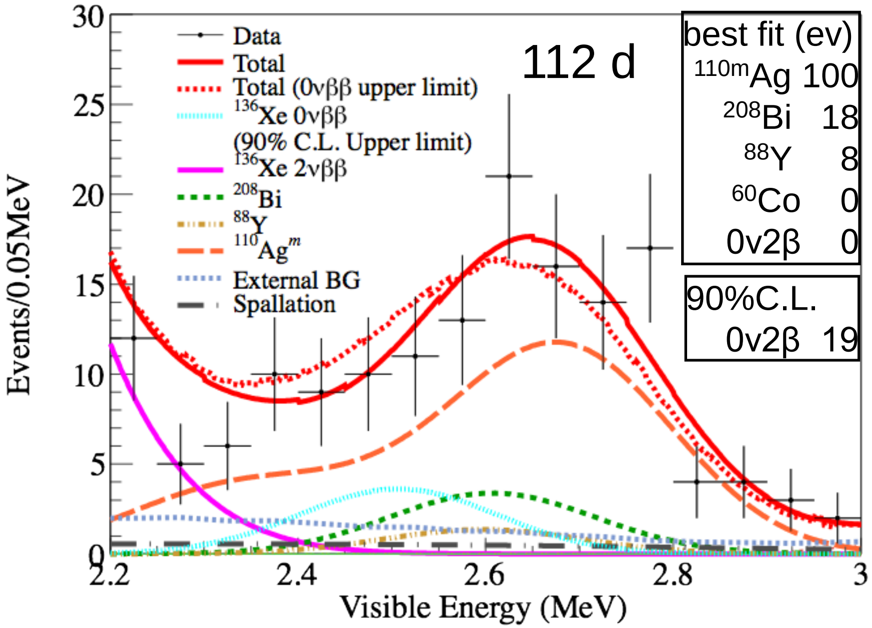
100 sec - 30 days timing correlation :
limit from energy spectra of close A,Z nuclei → negligible

Small cross section of all (α, γ), (α, αγ), (n, γ) → negligible

Only 4 candidates peak at 0v region with more than 30 days half-lives

^{110m}Ag ($T_{1/2}$=250 d), ^{208}Bi(3.68x10^5 y), ^{88}Y(107 d), ^{60}Co(5.27 y)

Limit on the 0v2β half life

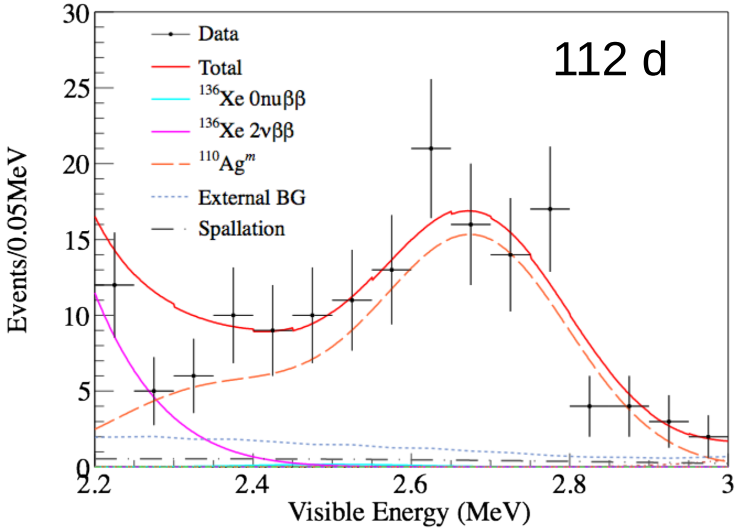


(χ² at 2.2~3.0MeV)

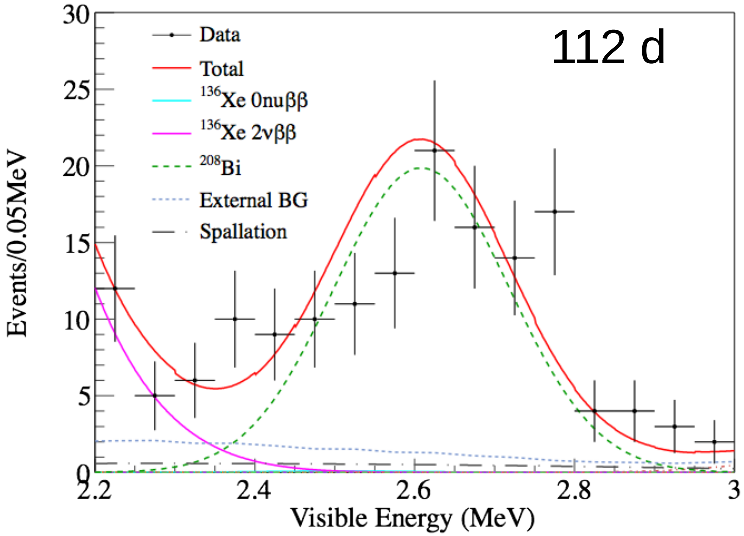
Candidates from ENSDF survey

	χ^2	
simul. fit	11.6	
0v+^{110m}Ag	13.1	
0v+^{208}Bi	22.7	△
0v+^{88}Y	22.2	△
0v+^{60}Co	82.9	✕
0v only	85.0	✕

BG is likely ^{110m}Ag.



^{110m}Ag fits well.



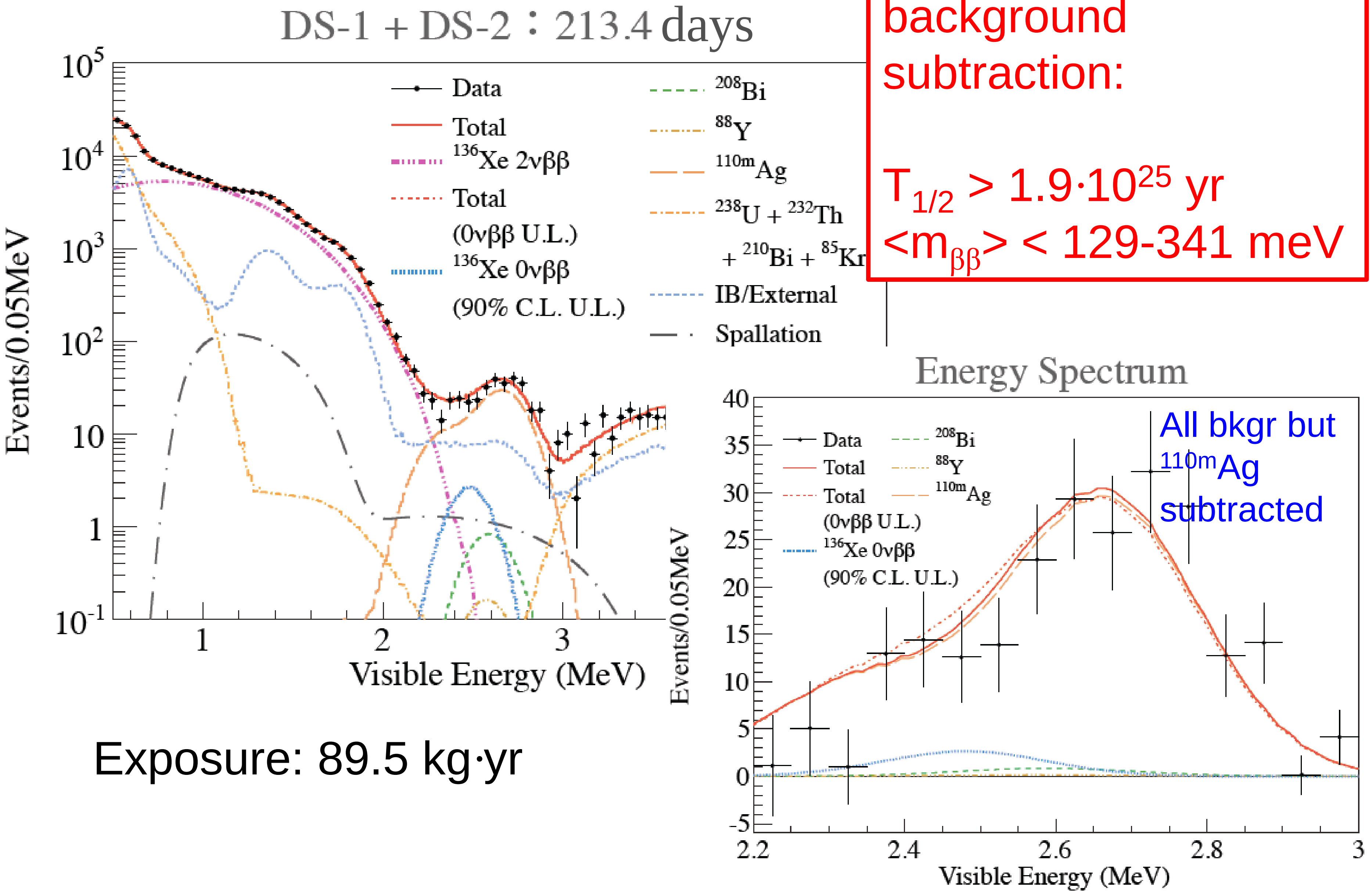
^{208}Bi doesn't fit well.

KamLAND-Zen phase I

Half life limit (90% CL) derived using this background subtraction:

$T_{1/2} > 1.9 \cdot 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 129\text{-}341$ meV



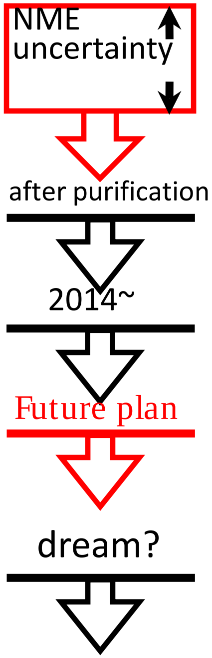
All bkgr but ^{110m}Ag subtracted

Exposure: 89.5 kg·yr

Prospects

KamLAND-Zen is a top runner and being improved.

Target sensitivity
1000 kg enriched
Xe: 20 meV in 5 yr.



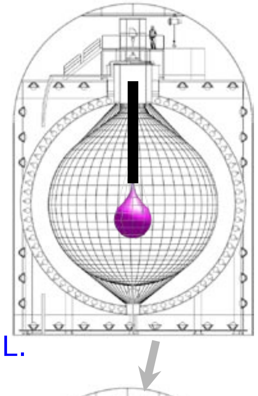
KamLAND-Zen 89.5 kg-yr
$\langle m_{\beta\beta} \rangle$ <160~330 meV @90% C.L.
the world best

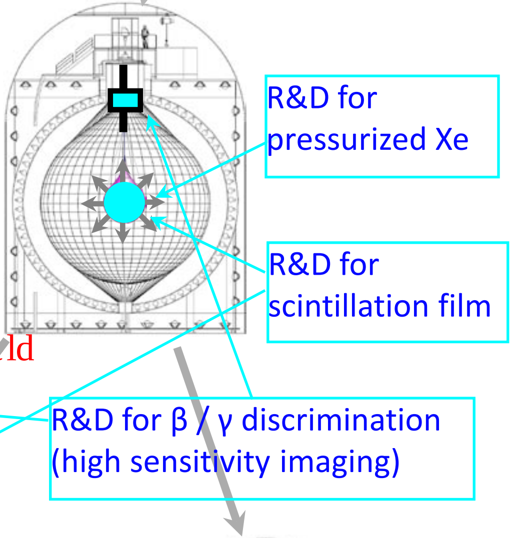
KamLAND-Zen 2nd phase (2013 fall -)
100 times ^{110m}Ag reduction expected

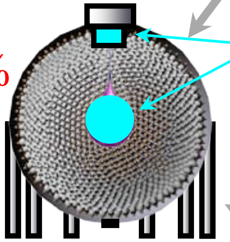
KamLAND-Zen 600 kg
with clean mini-balloon

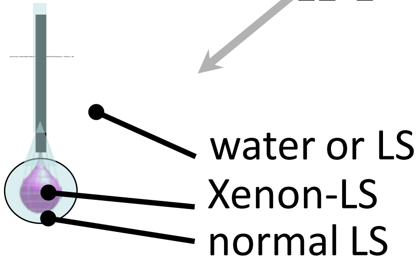
KamLAND2-Zen : high QE PMT, high yield LS, light concentrator
σ_E(2.6MeV)=4%→<2.5%

Super-KamLAND-Zen

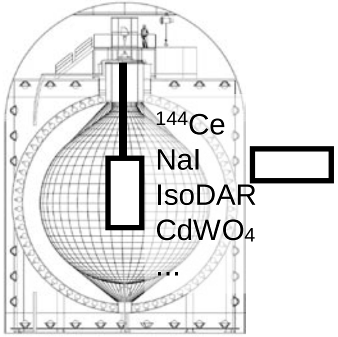








precision anti-neutrino physics
p→νK$^+$ is also possible.



Various low BG measurement can be accommodated.

NEXT (Canfranc 2450 mw.e.)

Use enriched Xe in a gas TPC, read out ionization and scintillation to obtain good energy resolution.

Use tracking for active background suppression by discriminating e from γ. Use low medium density to distinguish 1 from 2 electron events for further background suppression.

100 kg enriched Xe at hand, detector under construction.

J.A. Hernando’s talk 9/10
Thanks to J.J. Gomez-Cadenas for the material

NEXT Collaboration

UAM (Madrid) • U. Girona • IFIC (Valencia) • U. Santiago • U.P. Valencia • U. Zaragoza

LBNL • Texas A&M • Iowa State

U. Coimbra • U. Aveiro

http://next.ific.uv.es/

JINR (Dubna)

UAN (Bogotá)

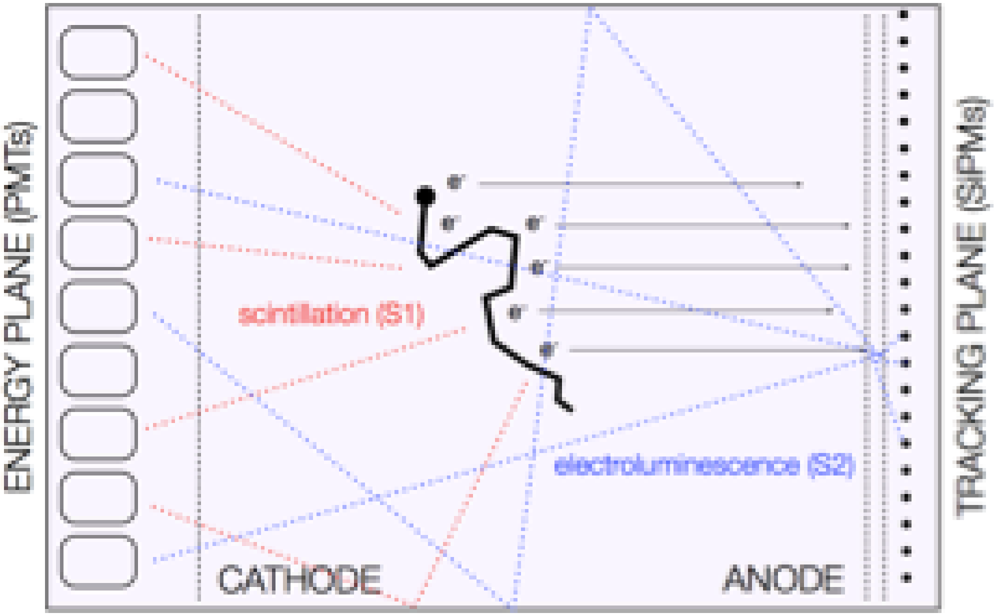
NEXT CONCEPTUAL IDEA, light production

LIGHT PRODUCTION PROCESS

- Electrons excite and ionize Xe
- Excited Xenon emits scintillation light (172nm) that is detected by the PMTs at Energy Plane (SIGNAL 1)
- Electrons from ionization are **drifted** by a weak electric field to the Electro-Luminescence (EL) region
- There, a larger E field accelerate electrons such to excite the Xe, but not enough to ionize it. This process produce a large amount of 172nm photons that will be detected in both photo-sensors planes (SIGNAL 2)

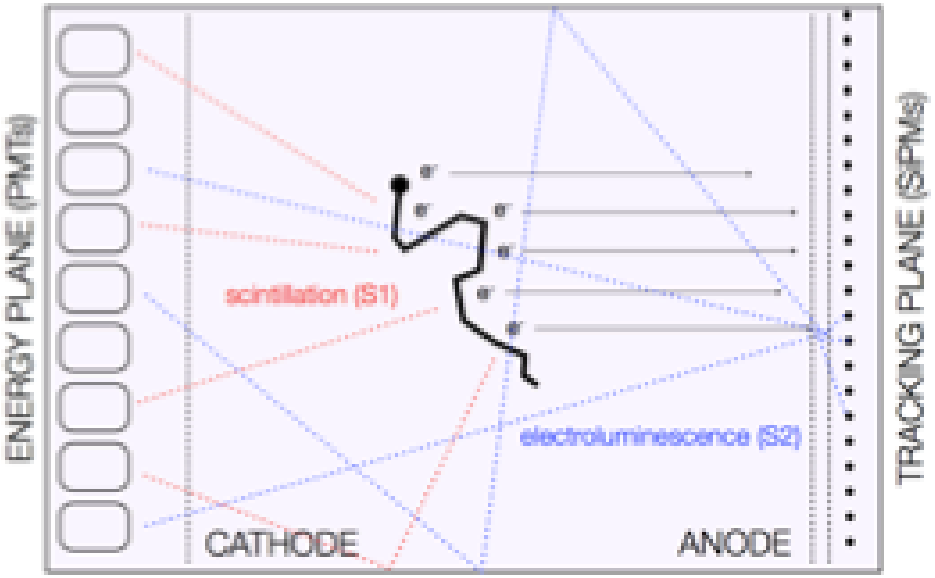
-The **PMTs** in the energy plane will accurately measure the energy

- The **SiPMs** in the tracking plane will allow to reconstruct the track followed by the original particle.

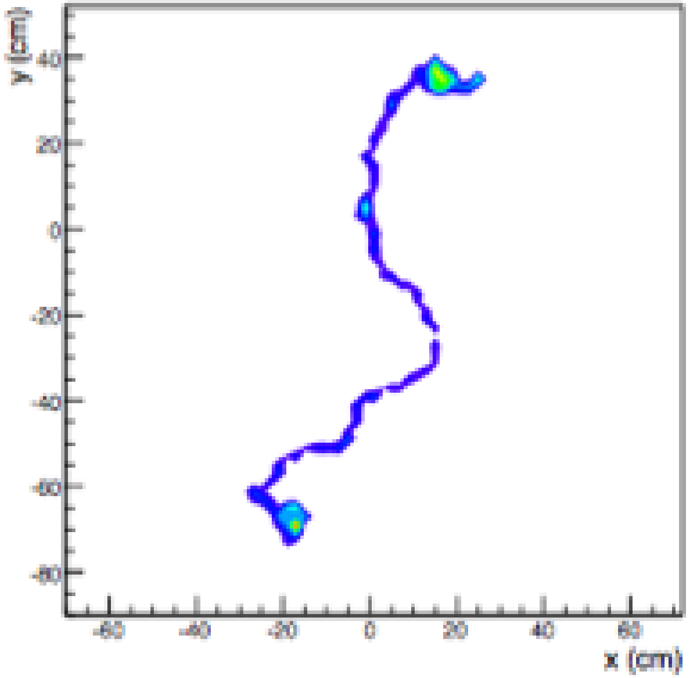


Tetra **P**henyl **B**utadiene (TPB) Wave-Length-Shifter is used to convert the light from UV to 430 nm to make it visible t the SiPMs & increase the number of photons for improving energy resolution

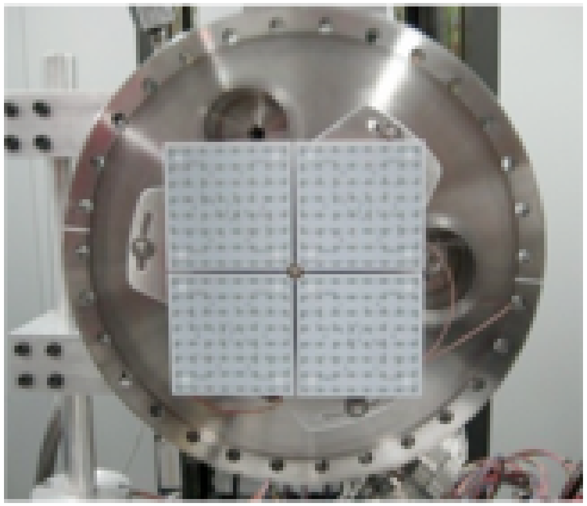
NEXT CONCEPTUAL IDEA, tracking



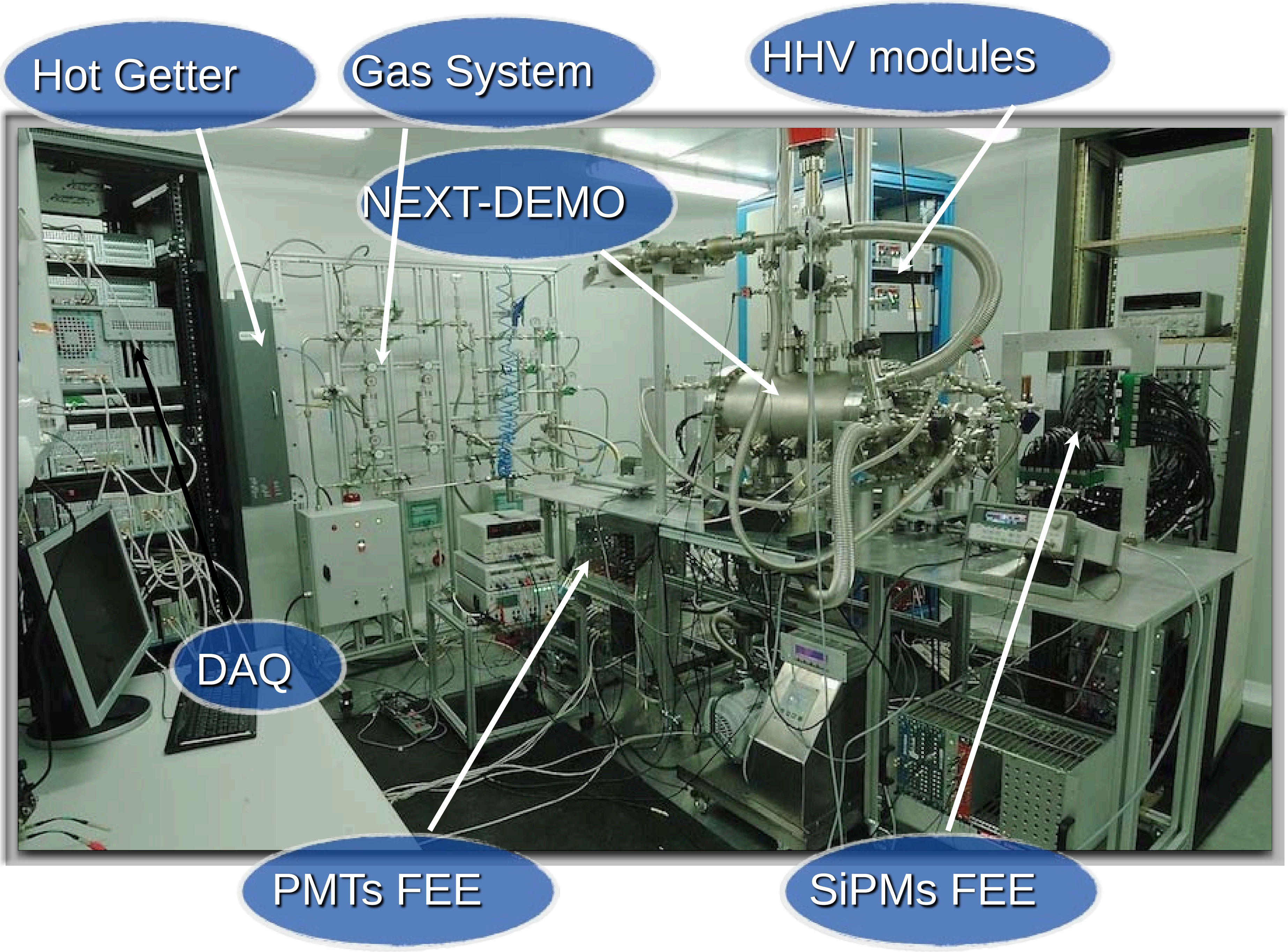
reconstructed tracks from a MC simulated ββ0ν event



Tracking Plane of NEXT-DEMO, with 256 SiPMs for tracking

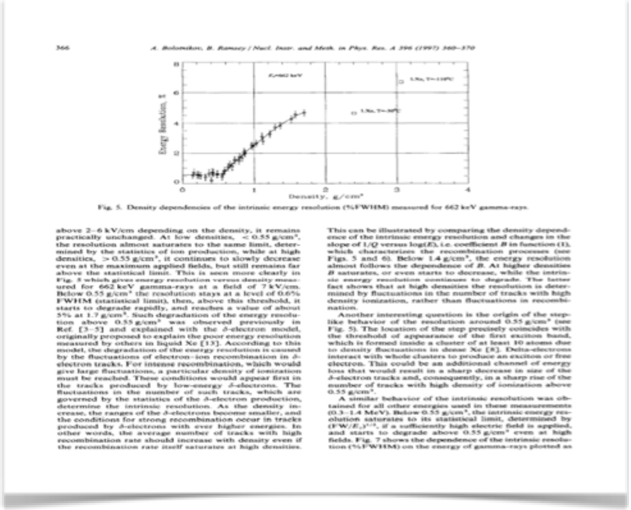


The signature of the electron is a twisted track with a strong energy deposition at its end


Hot Getter
Gas System
HHV modules
NEXT-DEMO
DAQ
PMTs FEE
SiPMs FEE

NEXT ENERGY RESOLUTION IS VERY GOOD

Bolotnikov and Ramsey, NIM A 396 (1997)



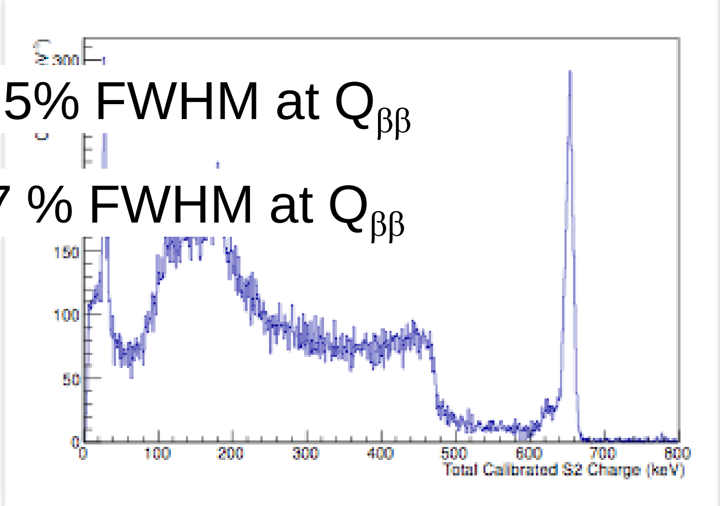
366 A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

above 2–6 kV/cm depending on the density, it remains practically unchanged. At low densities, < 0.55 g/cm³, the resolution almost saturates to the same limit, determined by the statistics of ion production, while at high densities, > 0.55 g/cm³, it continues to slowly decrease even at the maximum applied fields, but still remains far above the statistical limit. This is seen more clearly in Fig. 5 which gives energy resolution versus density measured for 662 keV gamma-rays at a field of 7 kV/cm. Below 0.55 g/cm³ the resolution stays at a level of 0.6% FWHM (statistical limit), then, above this threshold, it starts to degrade rapidly, and reaches a value of about 5% at 1.7 g/cm³. Such degradation of the energy resolution above 0.55 g/cm³ was observed previously in Ref. [3–5] and explained with the δ-electron model, originally proposed to explain the poor energy resolution measured by others in liquid Xe [13]. According to this model, the degradation of the energy resolution is caused by the fluctuations of electron–ion recombination in δ-electron tracks. For intense recombination, which would give large fluctuations, a particular density of ionization must be reached. These conditions would appear first in the tracks produced by low-energy δ-electrons. The fluctuations in the number of such tracks, which are governed by the statistics of the δ-electron production, determine the intrinsic resolution. As the density increase, the ranges of the δ-electrons become smaller, and the conditions for strong recombination occur in tracks produced by δ-electrons with ever higher energies. In other words, the average number of tracks with high recombination rate should increase with density even if the recombination rate itself saturates at high densities. This can be illustrated by comparing the density dependence of the intrinsic energy resolution and changes in the slope of 1/Q versus log(E), i.e. coefficient B in function (1), which characterizes the recombination processes (see Figs. 5 and 6). Below 1.4 g/cm³, the energy resolution almost follows the dependence of B. At higher densities B saturates, or even starts to decrease, while the intrinsic energy resolution continues to degrade. The latter fact shows that at high densities the resolution is determined by fluctuations in the number of tracks with high density ionization, rather than fluctuations in recombination.

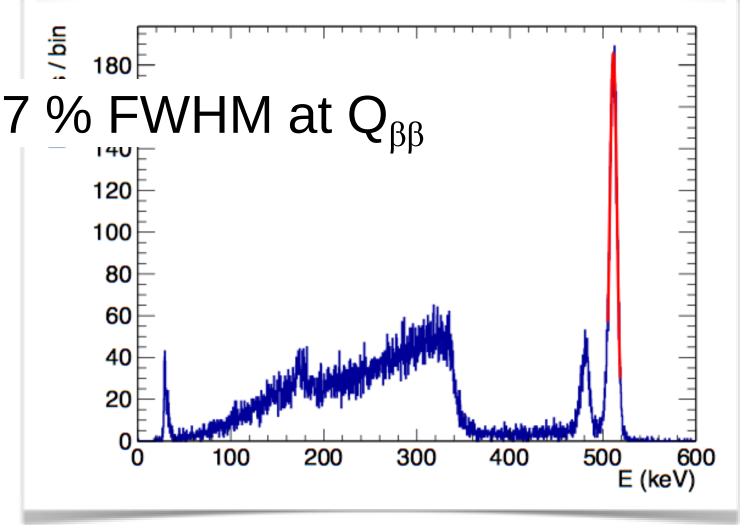
Another interesting question is the origin of the step-like behavior of the resolution around 0.55 g/cm³ (see Fig. 5). The location of the step precisely coincides with the threshold of appearance of the first exciton band, which is formed inside a cluster of at least 10 atoms due to density fluctuations in dense Xe [8]. Delta-electrons interact with whole clusters to produce an exciton or free electron. This could be an additional channel of energy loss that would result in a sharp decrease in size of the δ-electron tracks and, consequently, in a sharp rise of the number of tracks with high density of ionization above 0.55 g/cm³.

A similar behavior of the intrinsic resolution was obtained for all other energies used in these measurements (0.3–1.4 MeV). Below 0.55 g/cm³, the intrinsic energy resolution saturates to its statistical limit, determined by $(FW/E_\gamma)^{1/2}$, if a sufficiently high electric field is applied, and starts to degrade above 0.55 g/cm³ even at high fields. Fig. 7 shows the dependence of the intrinsic resolution (%FWHM) on the energy of gamma-rays plotted as



0.5% FWHM at $Q_{\beta\beta}$

0.5-0.7 % FWHM at $Q_{\beta\beta}$



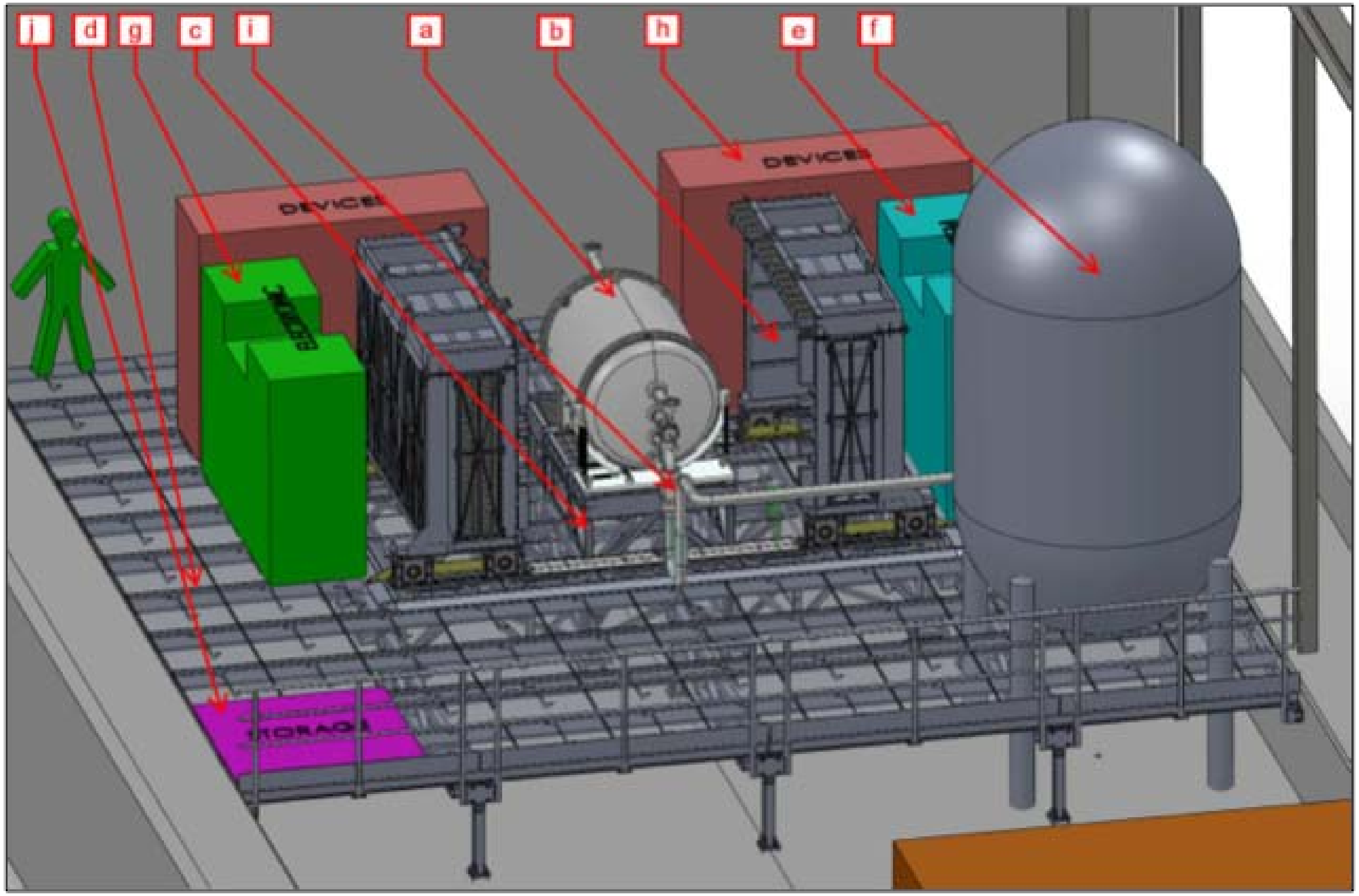
0.7 % FWHM at $Q_{\beta\beta}$

V.~Alvarez *et al*. [NEXT Collaboration], ``Initial results of NEXT-DEMO, a large-scale prototype of the NEXT-100 experiment,'' arXiv:1211.4838 [physics.ins-det].

V.~Alvarez, *et al.* [NEXT Collaboration], "Near-Intrinsic Energy Resolution for 30 to 662 keV Gamma Rays in a High Pressure Xenon Electroluminescent TPC," arXiv:1211.4474 [physics.ins-det].

DRAFT NEXT-100 AMADE University of Girona (2)

I-Infrastructures at Canfranc Laboratory.



NEXT-100 stage-I: operation in 2014 with 10 kg Xe.
100 kg enriched Xe at hand

Plans

- Start taking data in 2014 with 10 kg enriched Xe and 20% of instrumentation.
- Resolution and background goal: $\sigma/Q_{\beta\beta} = 0.21\%$, $b = 5 \cdot 10^{-4}$ cnts/(keV·yr·kg)
- Estimated sensitivity in 5 yr running: $T_{1/2} > 5 \cdot 10^{26}$ yr or $\langle m_{\beta\beta} \rangle < 25\text{-}67$ meV.

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These are certainly very ambitious goals!

EXO-200 (WIPP 1585 mw.e.)
nEXO

Large liquid (enriched) liquid Xe tracking calorimeter (TPC) with simultaneous read-out of ionization and scintillation.

Use tracking to discriminate electron *(single site)* from α *(light to charge ratio)* and γ *(multi site)* events → active background tagging. Achieve reasonable energy resolution (2νββ not an important bkgr).

Build a detector from low activity materials. Explore possibility to extract decay product Ba to eliminate virtually all random backgrounds.

T. Daniel's and K. Twelker's talks 9/10

Is taking data since May 2011.

Run 1 (5/2011-7/2011, 31.36 d, 63 kg (of 110 kg active) Xe, *charge read-out only*): first observation of 2νββ–decay of ^{136}Xe

Run 2a (9/2011-4/2012, 120.69 d, 82.1 and 98.5 kg Xe): most accurate measurement of any 2νββ–decay rate, one of most stringent limits on 0νββ–decay and Majorana neutrino mass, challenge of ^{76}Ge evidence.

Run 2 (9/2011-6/2013, 439.6 d, 97.7 kg Xe): 3.6 times exposure compared to 2012 data set. 0νββ–analysis not finalized yet.

Run 3 (6/2013...): taking data

The EXO Collaboration

Enriched Xenon Observatory

EXO

for double beta decay

University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke

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Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith

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

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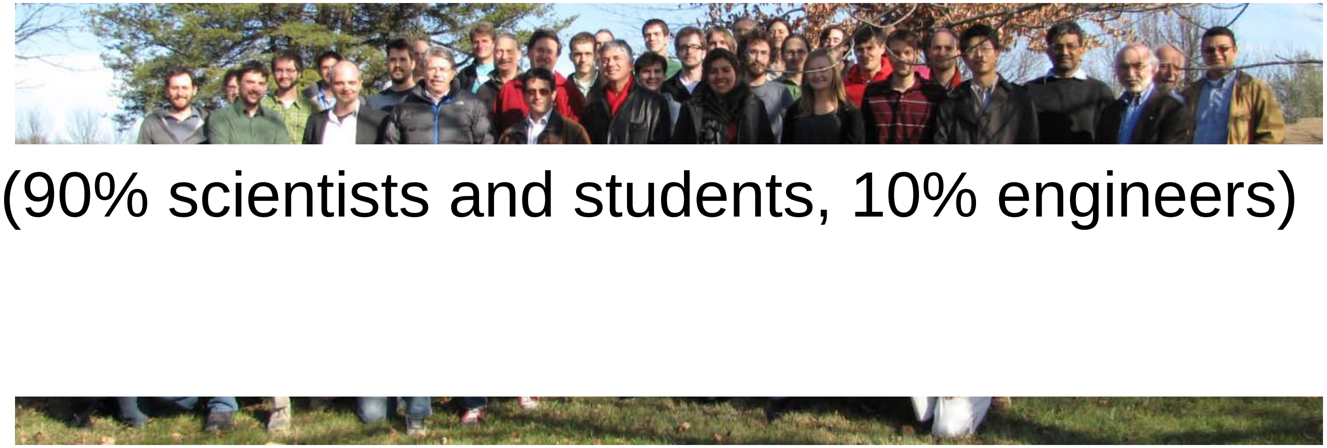
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

TRIUMF, Vancouver BC, Canada – P.A. Amandruz, D. Bishop, J. Dilling, P. Gumplinger, R. Kruecken, C. Lim, F. Retiere, V. Strickland

The EXO Collaboration



115 collaborators (90% scientists and students, 10% engineers)
20 institutions
7 countries

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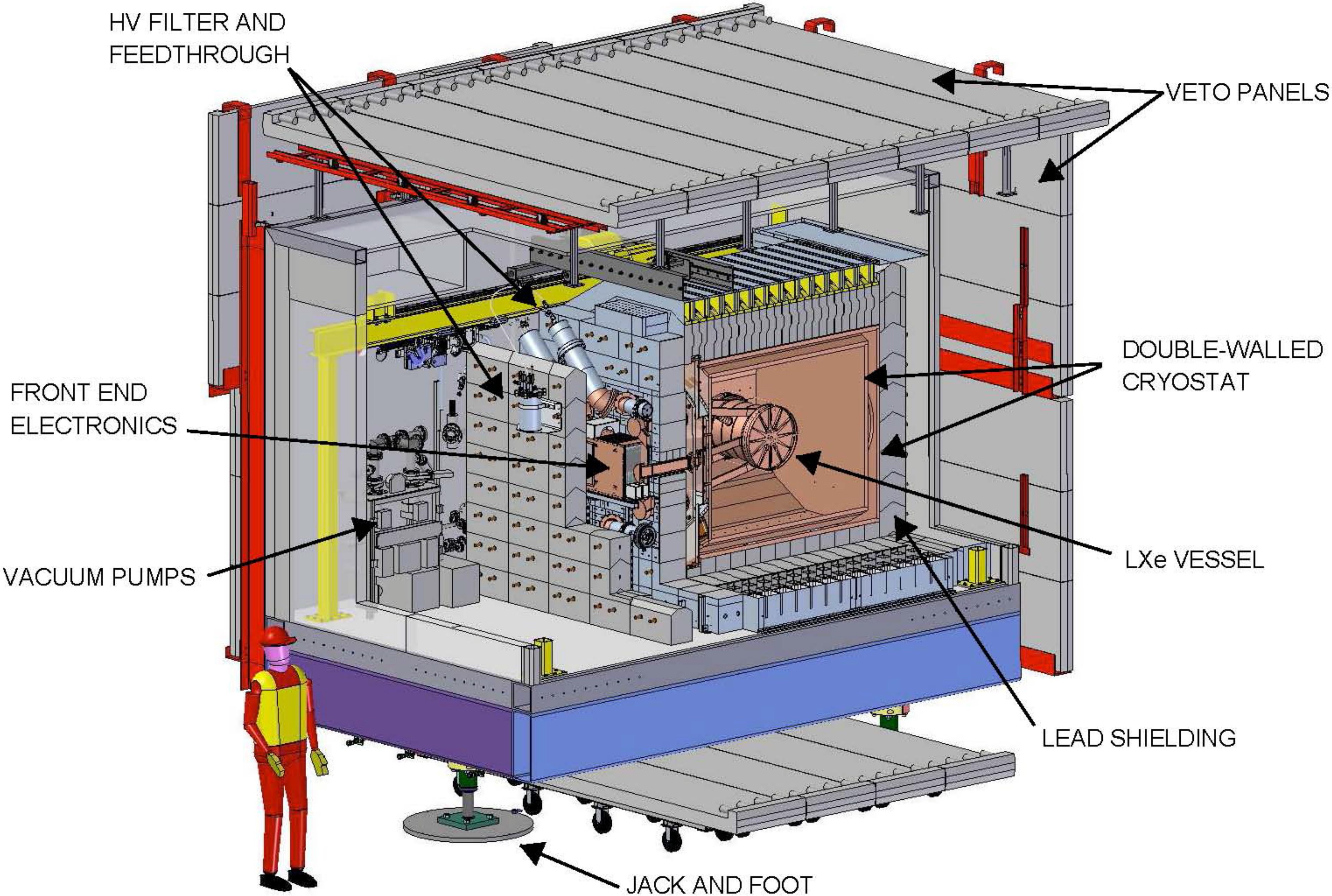
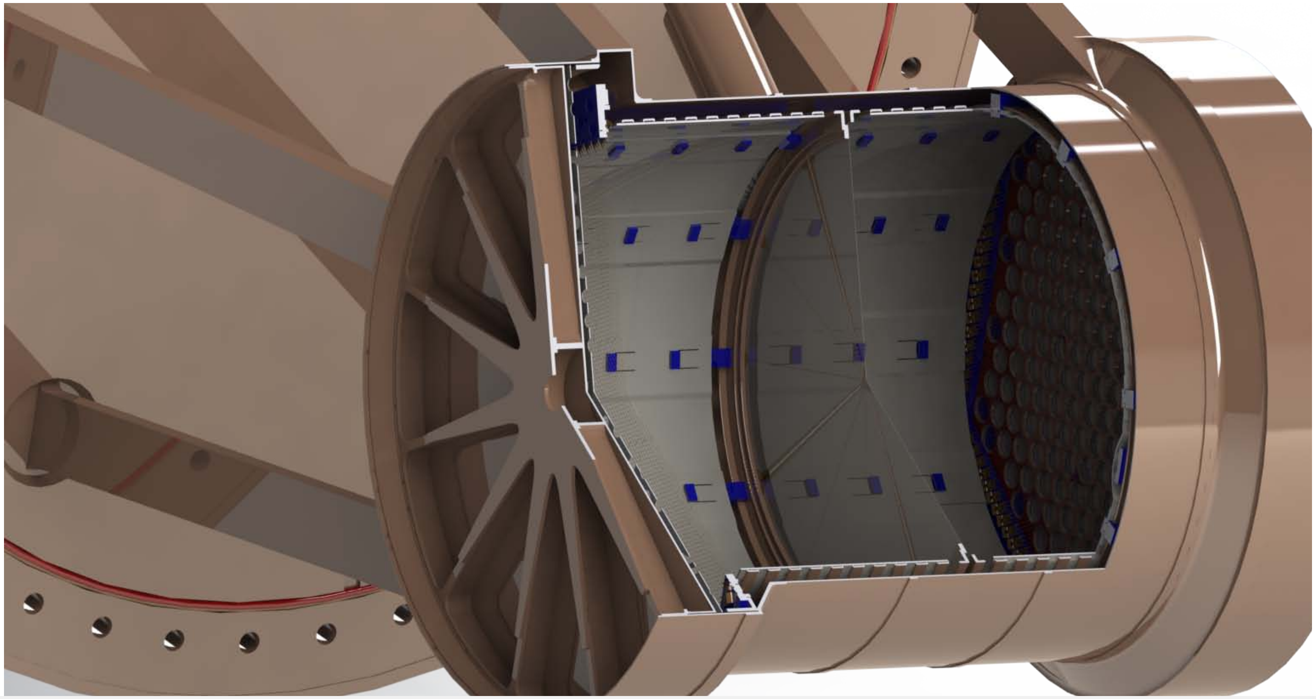

HV FILTER AND
FEEDTHROUGH
VETO PANELS
DOUBLE-WALLED
CRYOSTAT
FRONT END
ELECTRONICS
VACUUM PUMPS
LXe VESSEL
LEAD SHIELDING
JACK AND FOOT

Charge and light read-out on either end, HV cathode in the middle.



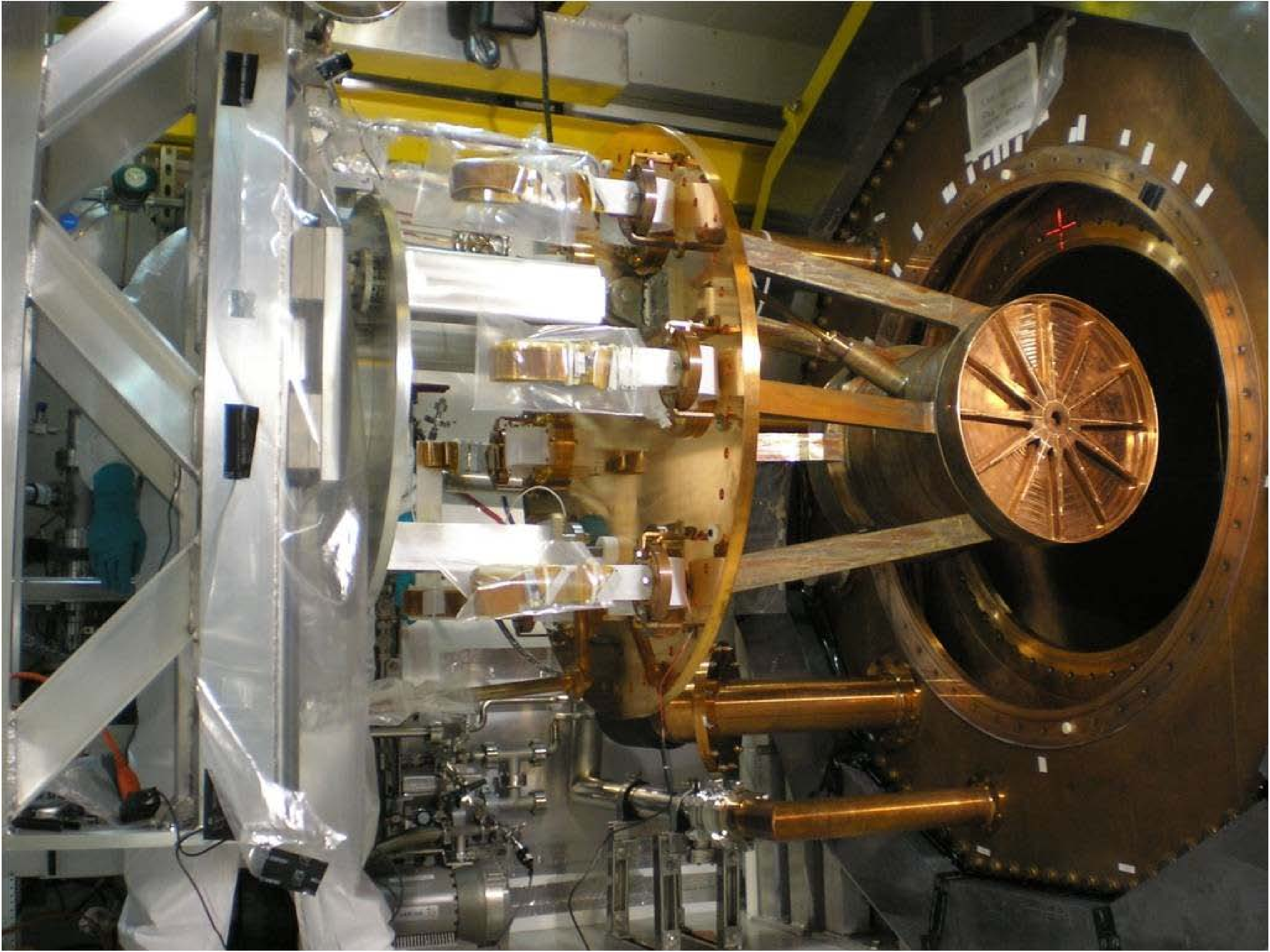
Charge collection and x-y position reconstruction by crossed wires.

Scintillation light readout via 468 Avalanche Photo Diodes.

Time difference of the two signal gives the 3rd spatial coordinate.

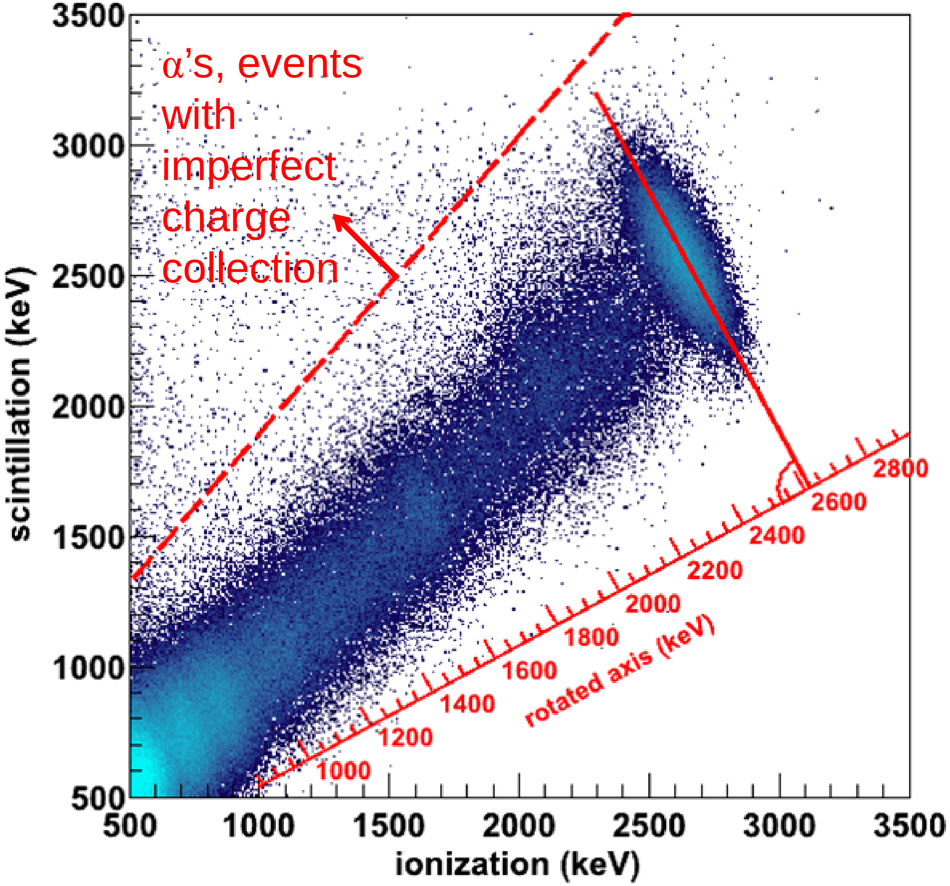
γs: multiple Compton scattering (MS) → background

βs: point-like interaction (SS) → signal

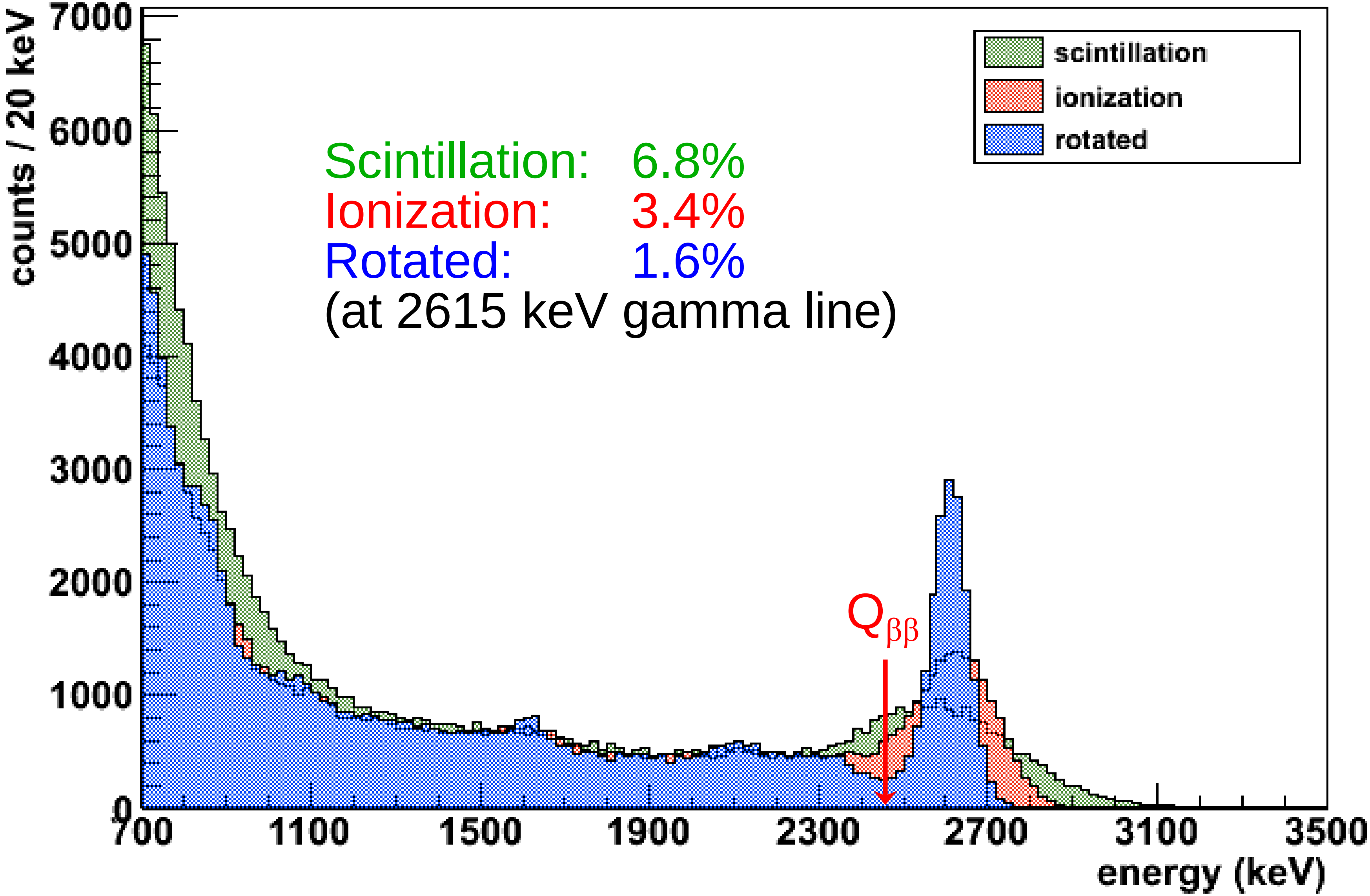


Combine ionization & scintillation

^{228}Th source



- Ionization and scintillation energies are anti-correlated.
- Energy measured along a rotated axis offers improved energy resolution.
- Rotation angle chosen to optimize resolution at 2615 keV.



Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(at 2615 keV gamma line)

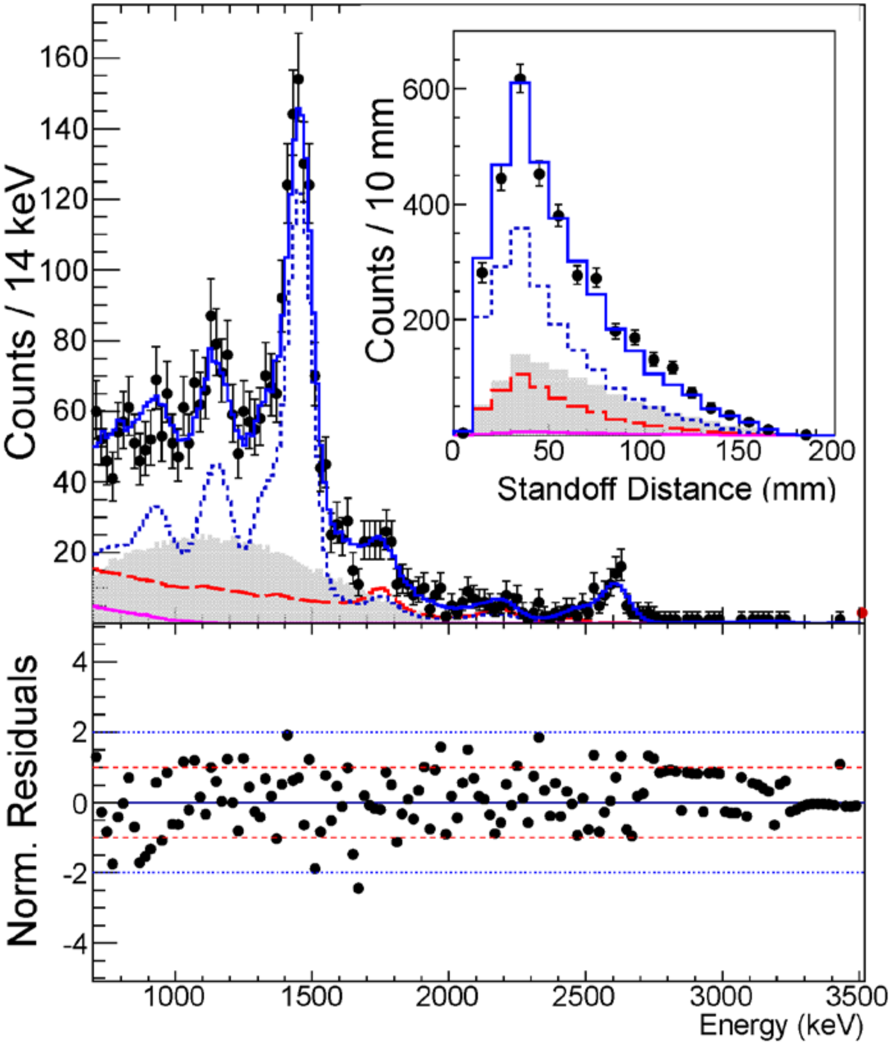
2νββ-decay

EXO-200 2νββ-data (82.1 kg Xe, 127.6 d, 28.69 kg·yr)

Utilize tracking capability: MS data contains mostly γ events, has good diagnostic power for identifying the background components.

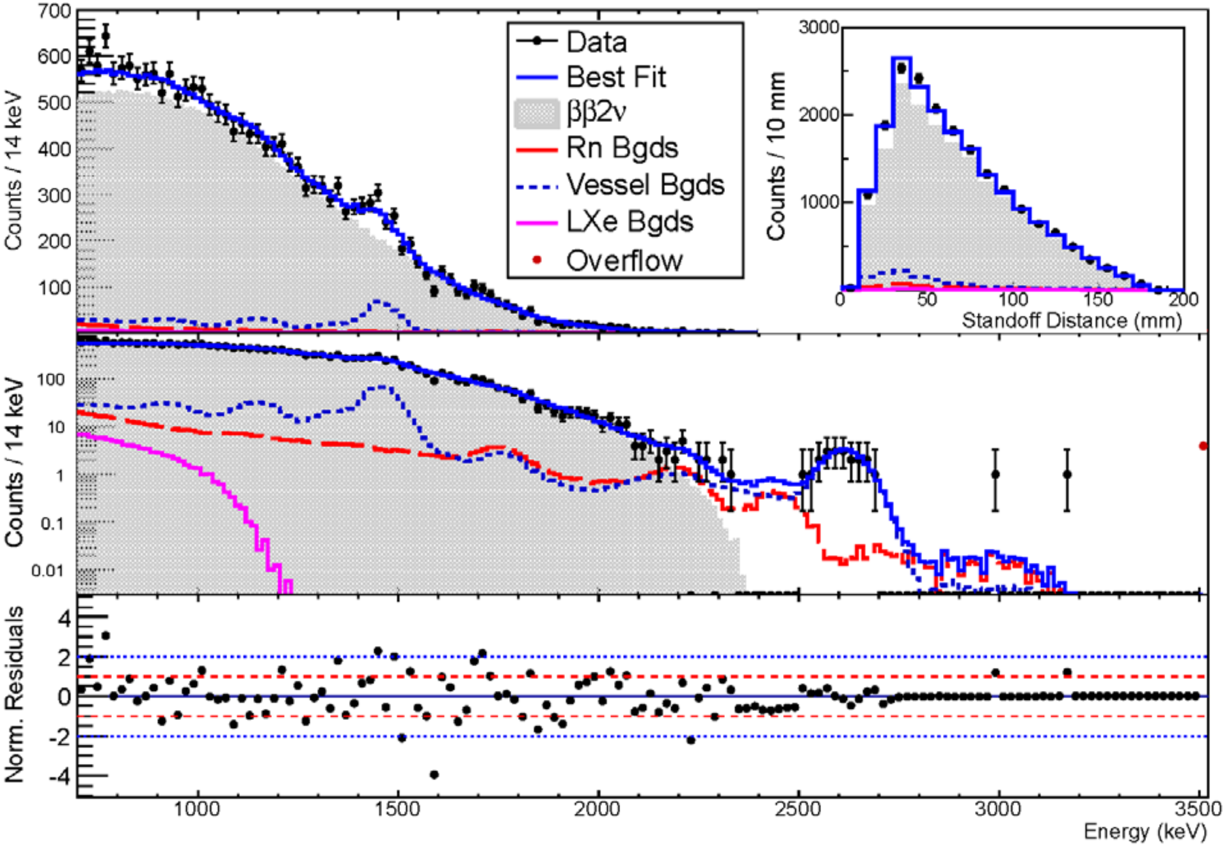
- Purple: ^{135}Xe and Rn in Xe
- Red: Rn in Pb shield
- Blue: ^{40}K, ^{54}Mn, ^{60}Co, ^{65}Zn, ^{232}Th, ^{238}U in TPC materials.

χ^2 / ndf = 104.5 / 77.0



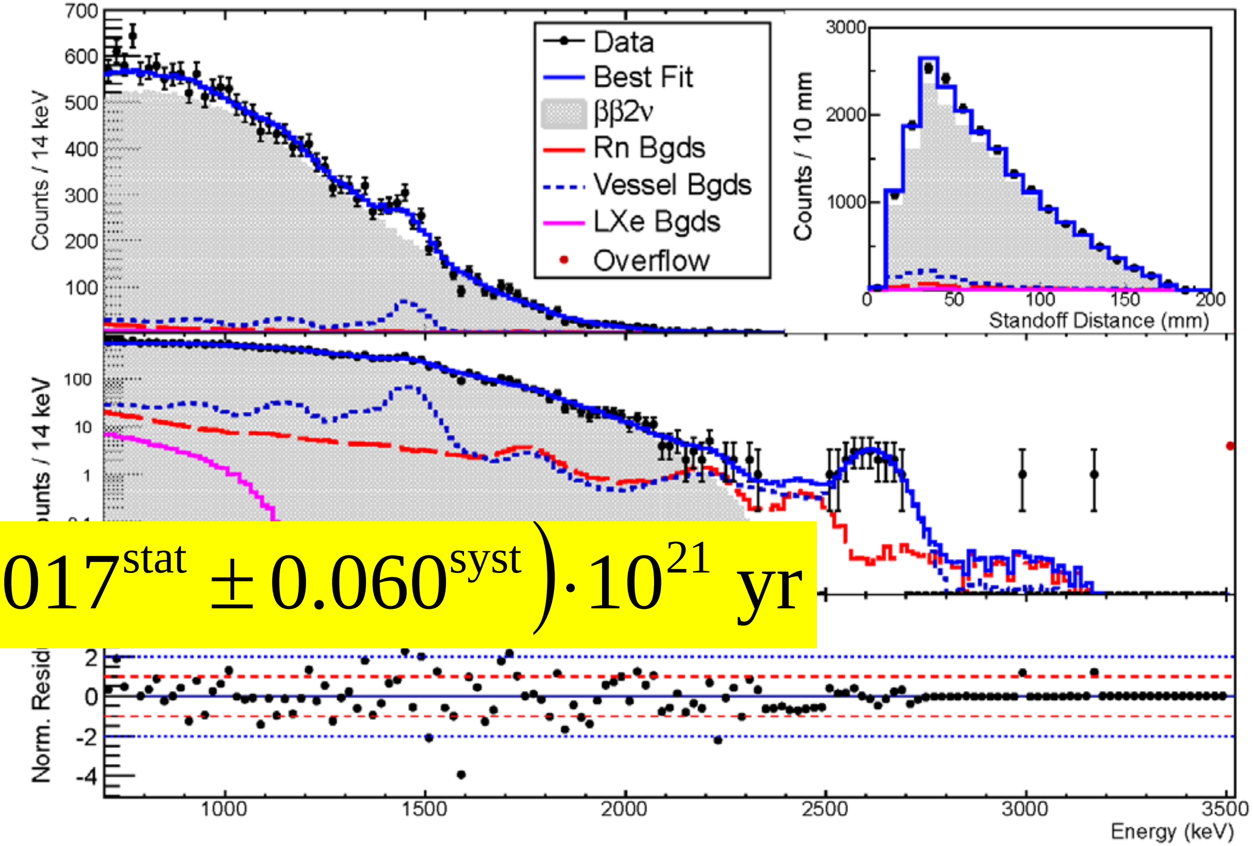
χ^2 / ndf = 82.5 / 74.5

SS event set dominated by point-like β–events. Perform coupled MS and SS data fit to obtain:



χ^2 / ndf = 82.5 / 74.5

SS event set dominated by point-like β–events. Perform coupled MS and SS data fit to obtain:



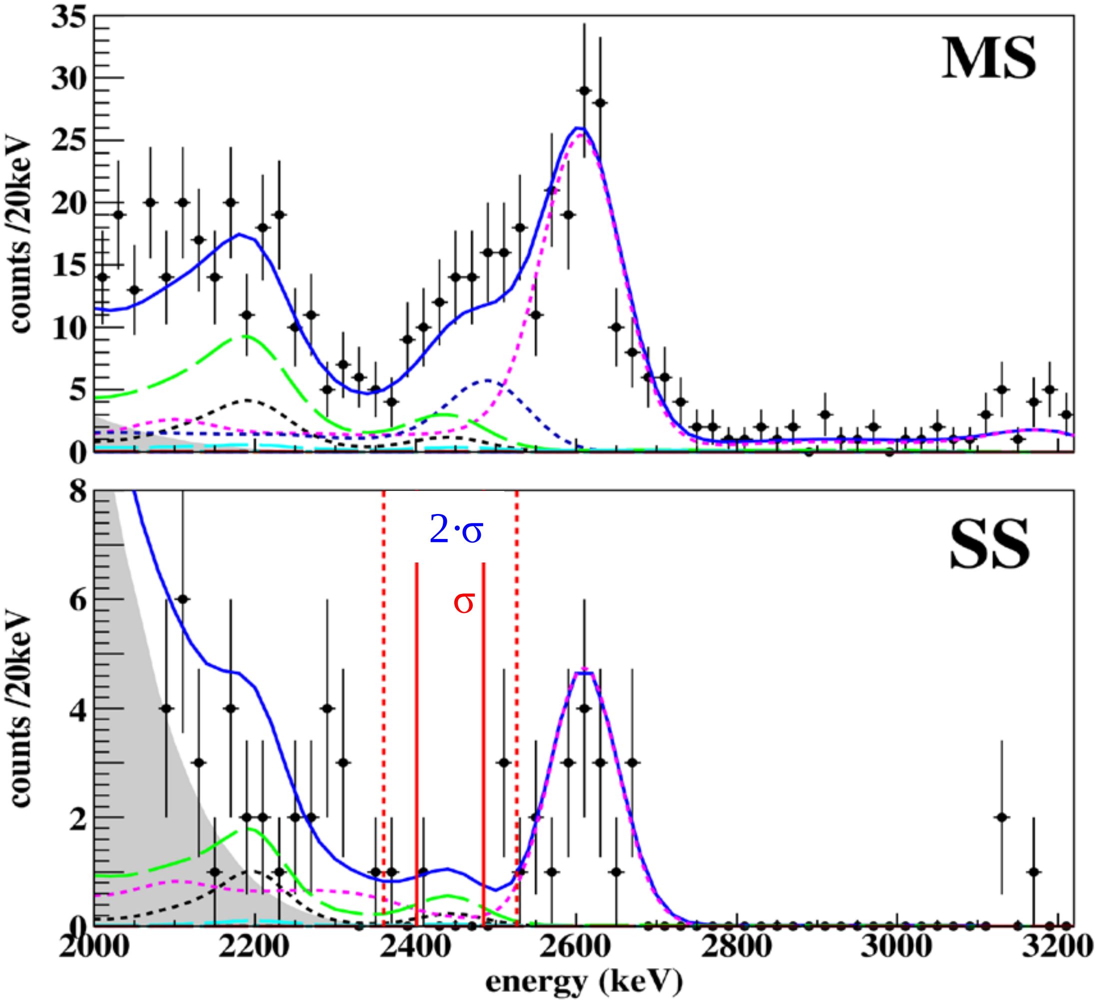
$$T_{1/2}^{2\nu\beta\beta} = \left(2.171 \pm 0.017^{\text{stat}} \pm 0.060^{\text{syst}}\right) \cdot 10^{21}\ \text{yr}$$

The longest and most precisely measured 2νββ–decay half life.

Smallest and best known 2νββ–matrix element: 0.0217 0.0003 MeV^{-1}.

0νββ-decay

EXO-200 0νββ-data (32.6 kg·yr). By now we have more than three times the data.



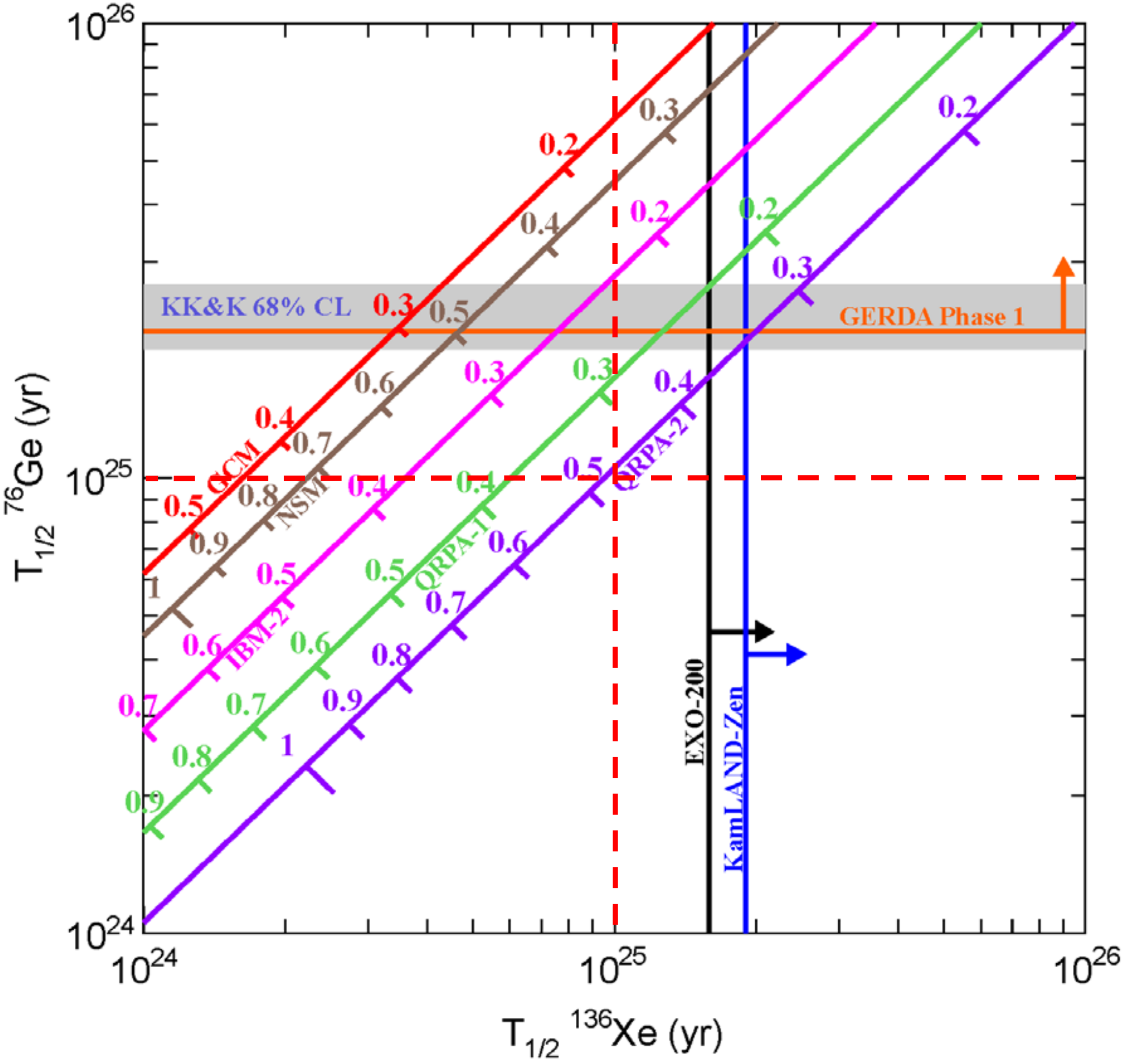
No peak observed at $Q_{\beta\beta}$.

MC background model:
$1.5\cdot10^{-3}$ cnts/(keV·yr·kg)

Measured background:
153 69 cnts/(2·σ·ton·yr)
31 31 cnts/(σ·ton·yr)

$T_{1/2}^{0\nu\beta\beta} > 1.6\cdot10^{25}\ yr$ (90% CL)

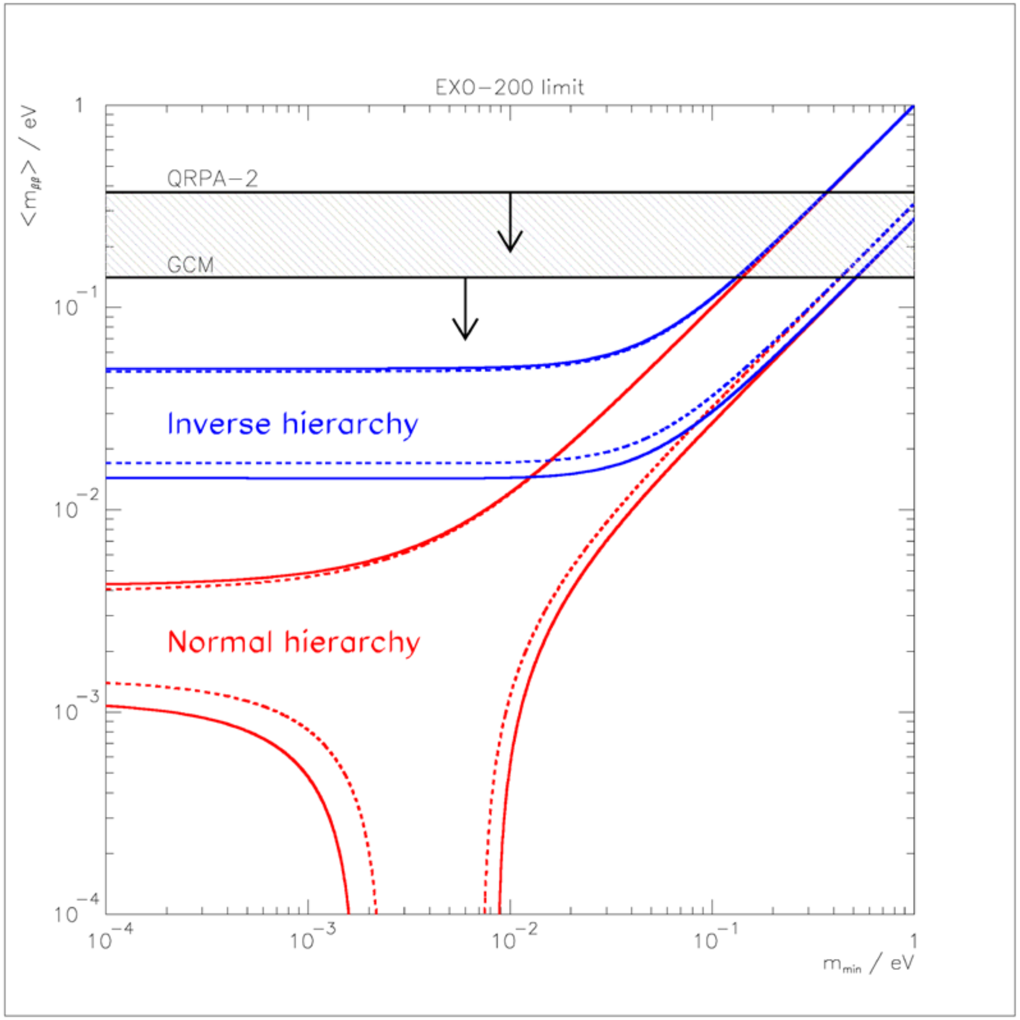
$\langle m\rangle_{\beta\beta} < 140 - 380$ meV



Using different nuclear matrix elements the absence of a 0νββ-peak in EXO-200 is compared to the evidence published for ^{76}Ge.

For most matrix element calculations there is tension between these new experiments and the 0νββ-evidence.

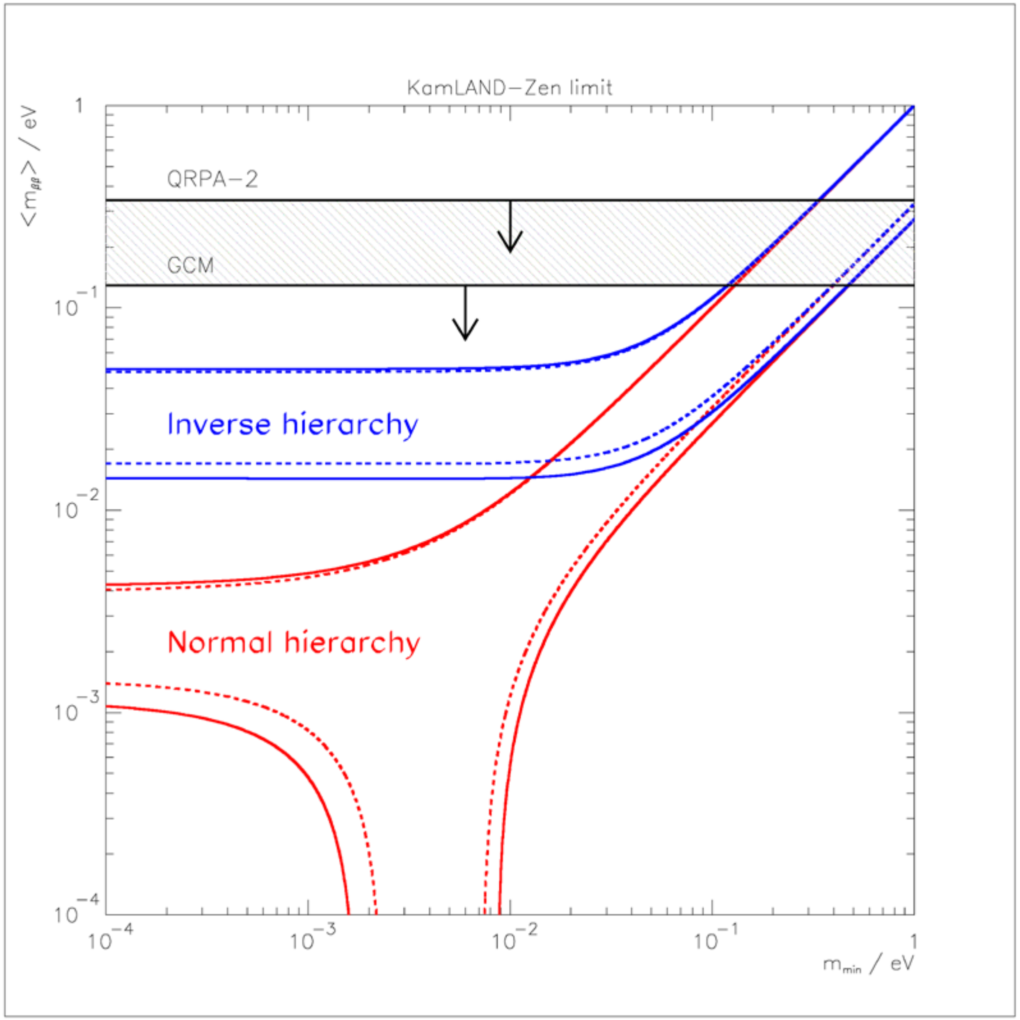
H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett., A21 (2006) 1547.



Current Majorana ν–mass limits published by EXO-200 and KamLAND-Zen.

The degenerate mass space is being covered.

3-flavor analysis D.V. Forero et al. arXiv:1205.4018v4



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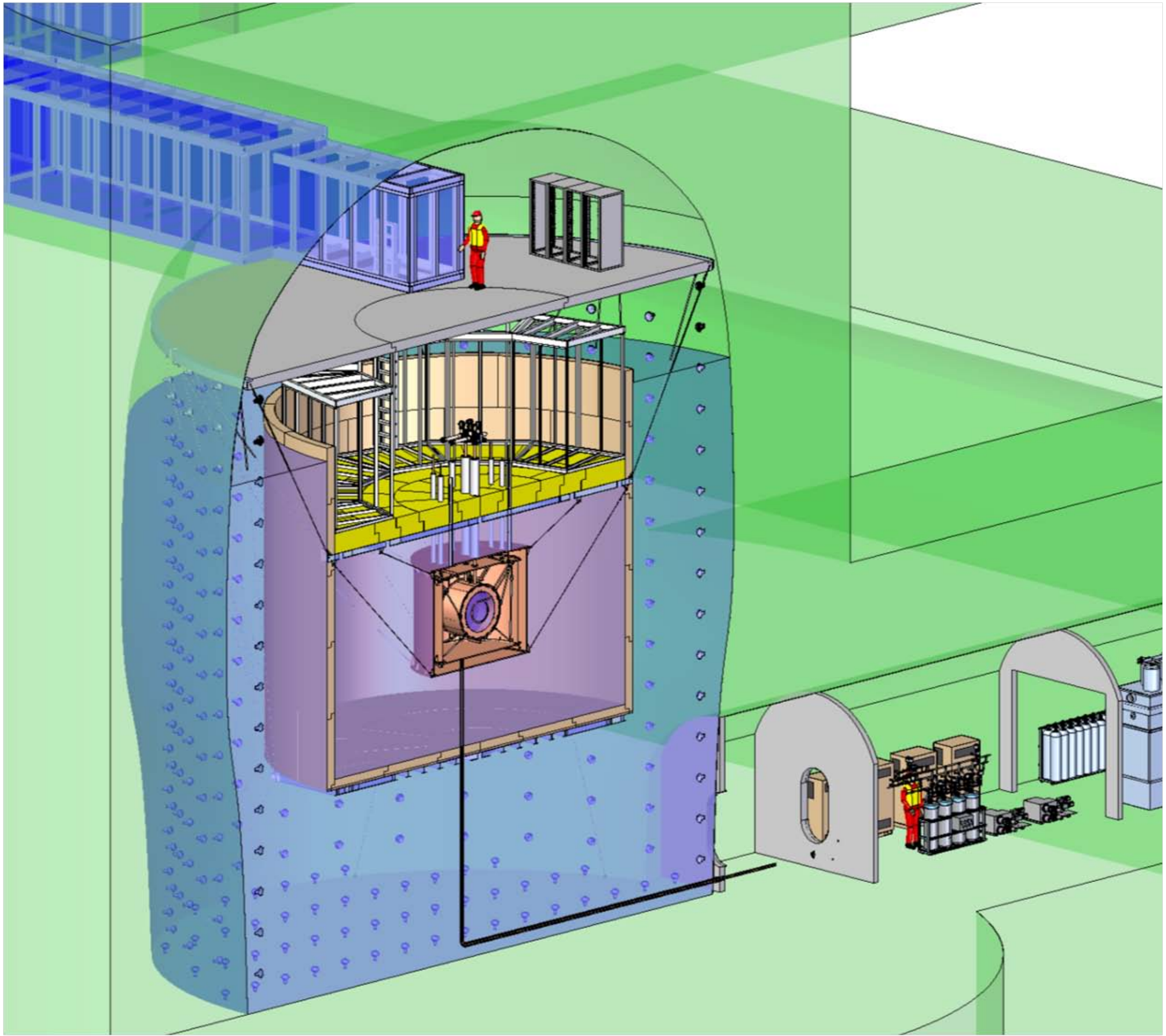
The future

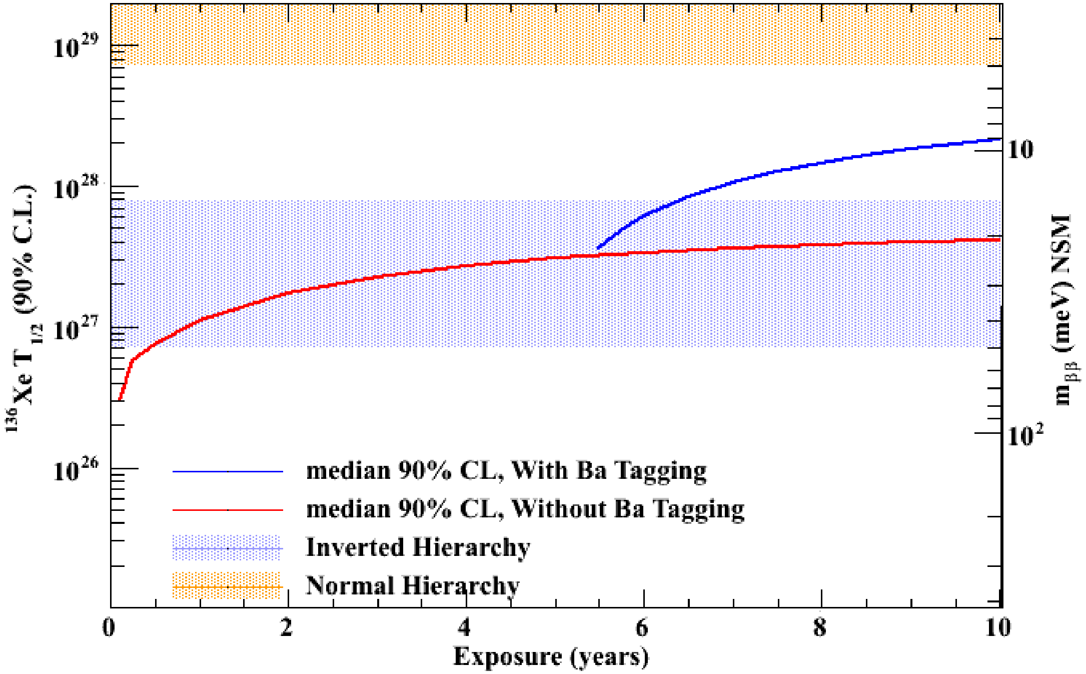
- Funded to run until the end of 2014.
- Considering an electronic upgrade to improve the energy resolution and to install a Rn removal device to reduce the background by perhaps a factor 2. Run till end of 2016.
- Improve (90% CL) $0\nu\beta\beta$-half life sensitivity to (3-5.5) 10^{25} yr. Discover the decay should it be there.
- Corresponding Majorana neutrino mass range: $\langle m_{\beta\beta}\rangle < 75$-270 meV, cover degenerate neutrino mass range.
- Demonstrate the technology for a next generation experiment. → nEXO

- EXO-200 the collaboration started to study the case for a 5 ton (~4.5 ton fiducial) Xe experiment, *initially* without Ba- tagging. Tagging should remain an option, you could consider it a (background) risk mitigation tool.
- Assume:
  - 4.5 tons of active ^{enr}Xe (80% or higher).
  - 1.5% (σ) energy resolution.
  - Background from Monte Carlo using normalizations derived from EXO-200 data and materials assay.
  - 3 times finer wire pitch than EXO-200, lower energy threshold → 2 times better e-γ discrimination than EXO-200.

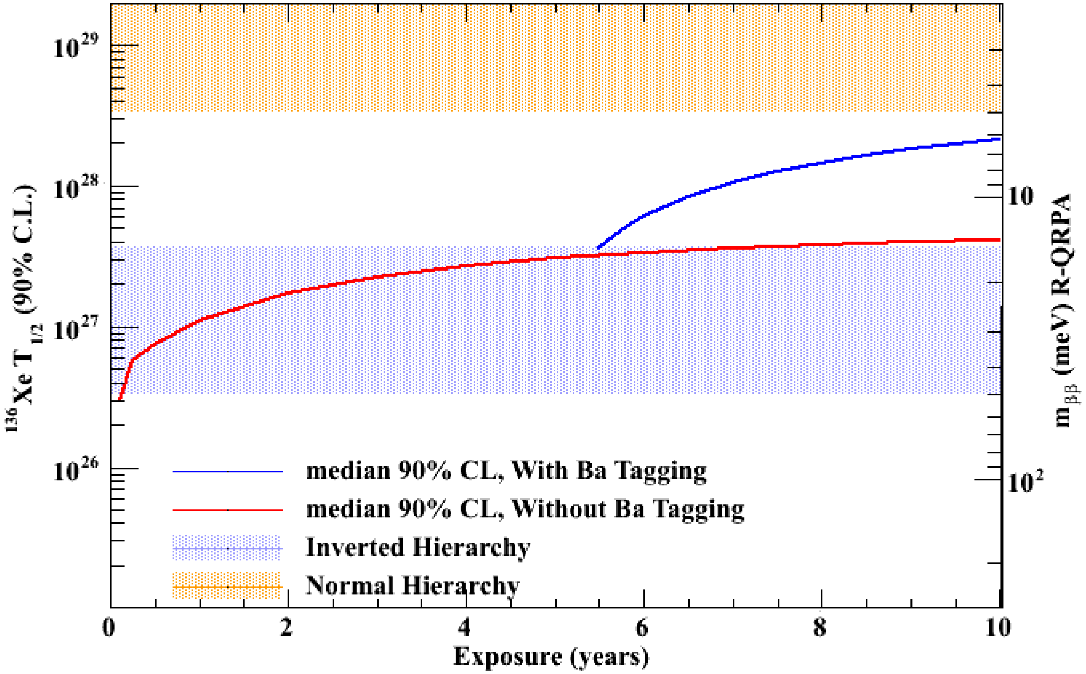
We call this nEXO.

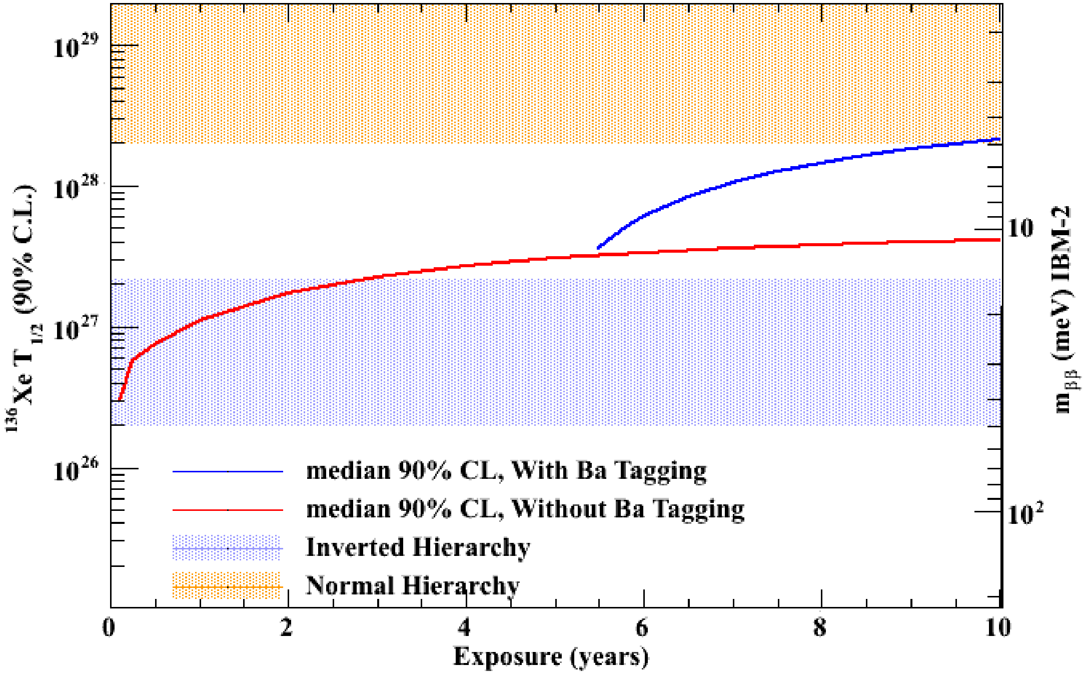
At the end: how such a detector, installed in SNOLab's cryopit may look like.





10^{29}
10^{28}
10^{27}
10^{26}
^{136}Xe $T_{1/2}$ (90% C.L.)
10
10^2
$m_{\beta\beta}$ (meV) NSM
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy
0
2
4
6
8
10
Exposure (years)


10^{29}
10^{28}
10^{27}
10^{26}
^{136}Xe $T_{1/2}$ (90% C.L.)
10
10^{2}
$m_{\beta\beta}$ (meV) R-QRPA
0
2
4
6
8
10
Exposure (years)
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy


10^{29}
10^{28}
10^{27}
10^{26}
^{136}Xe T$_{1/2}$ (90% C.L.)
10
10^2
$m_{\beta\beta}$ (meV) IBM-2
0
2
4
6
8
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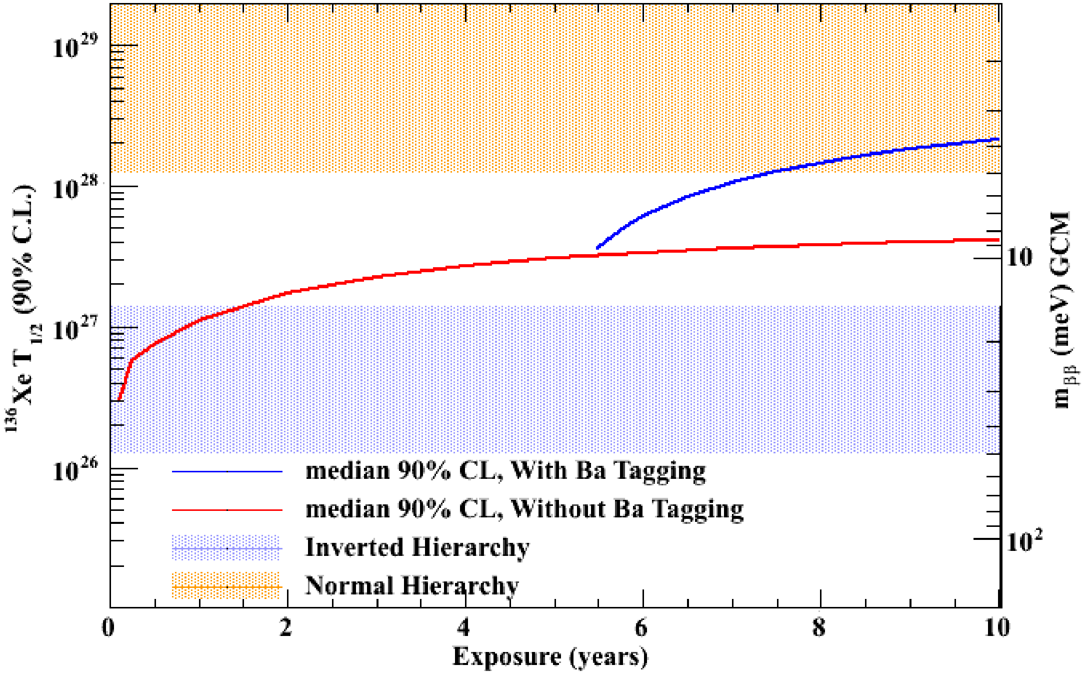
Exposure (years)
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy


10^{29}
10^{28}
10^{27}
10^{26}
^{136}Xe $T_{1/2}$ (90% C.L.)
10
10^2
$m_{\beta\beta}$ (meV) GCM
median 90% CL, With Ba Tagging
median 90% CL, Without Ba Tagging
Inverted Hierarchy
Normal Hierarchy
0
2
4
6
8
10
Exposure (years)

Conclusion

Many thanks to all colleagues who supplied the material for this talk! All mistakes or misrepresentations are entirely my fault.

Xe experiments are at the fore front of Majorana neutrino mass tests: *Ge no longer rules supreme*.

The techniques being explored are scalable and could form the basis for a next generation of experiments using enriched isotopes on the ton scale to test the inverted neutrino mass hierarchy. Current experiments validate this, far beyond the Monte Carlo only approach.

The End!