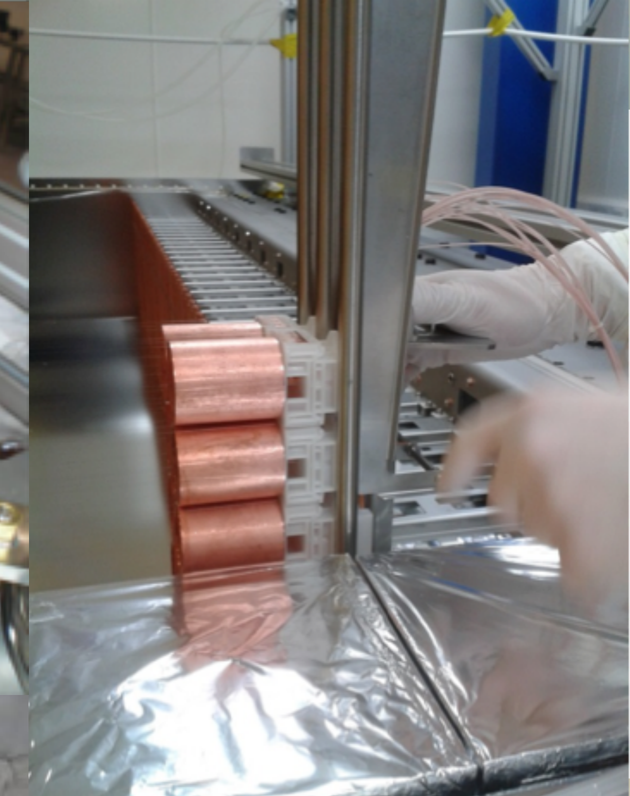
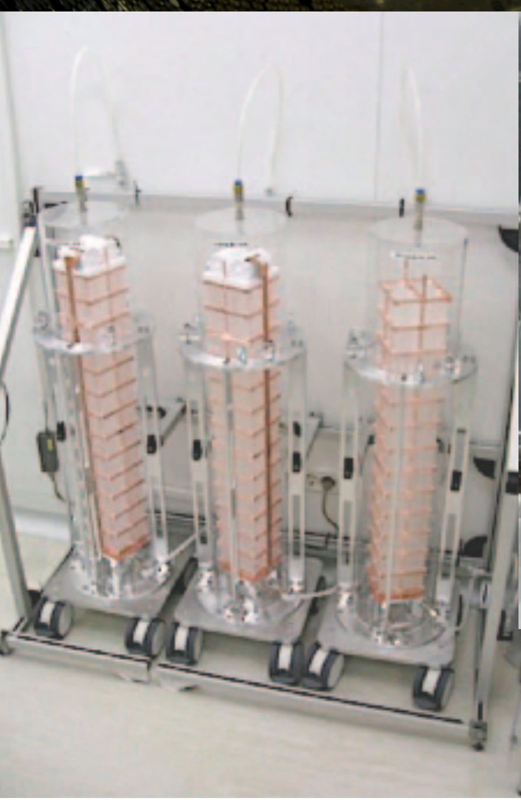
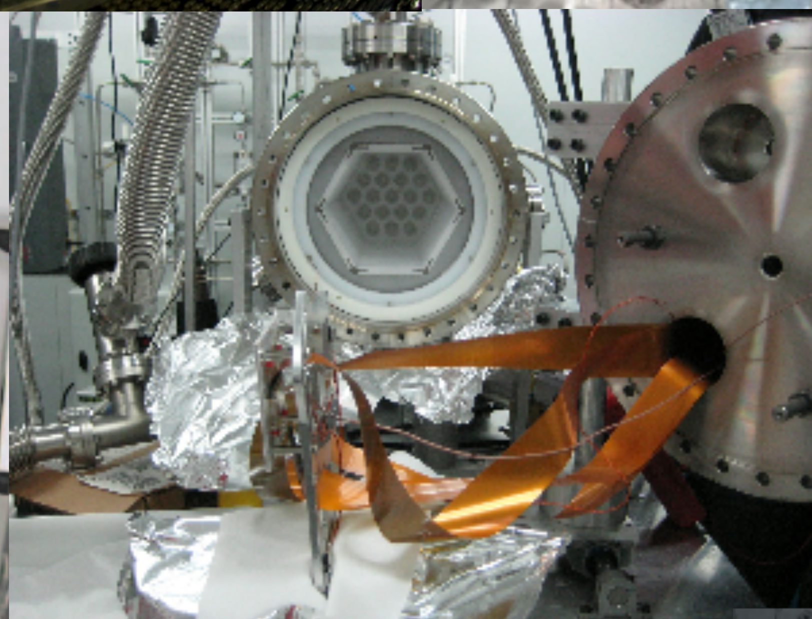
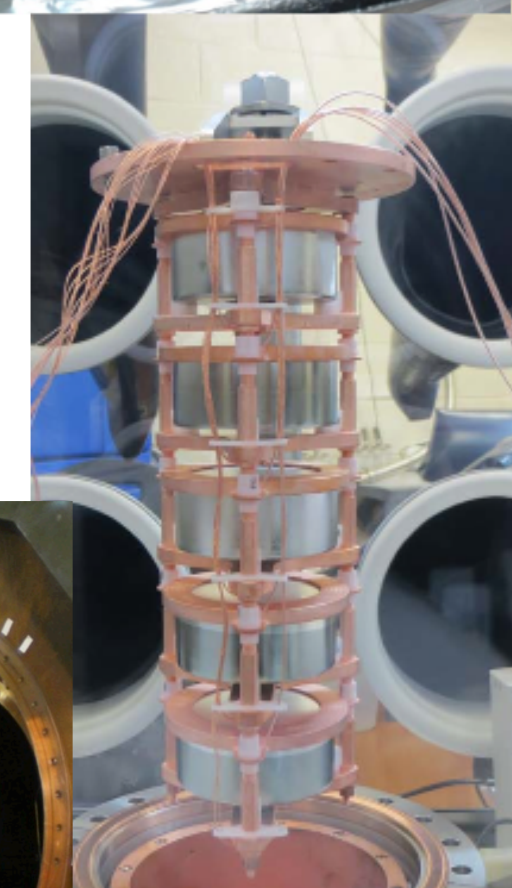
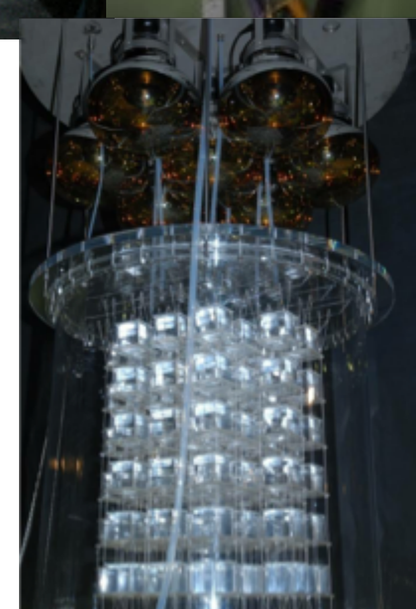
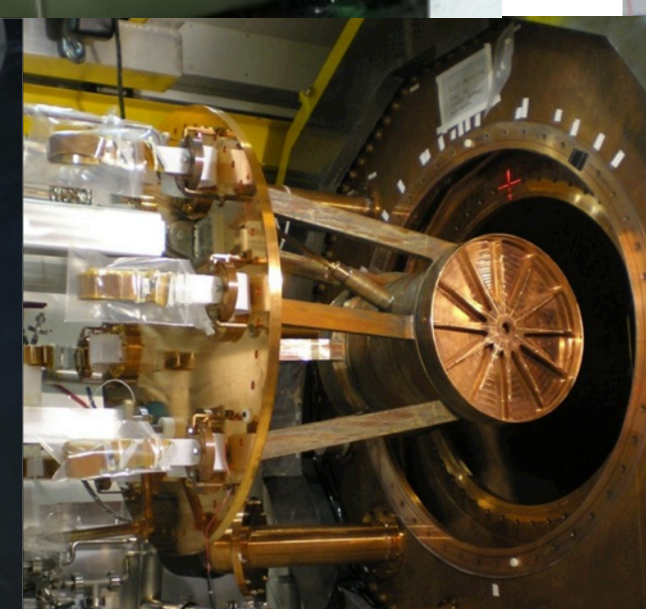


Neutrinoless Double Beta Decay Experiments

Mark Chen, Queen's University

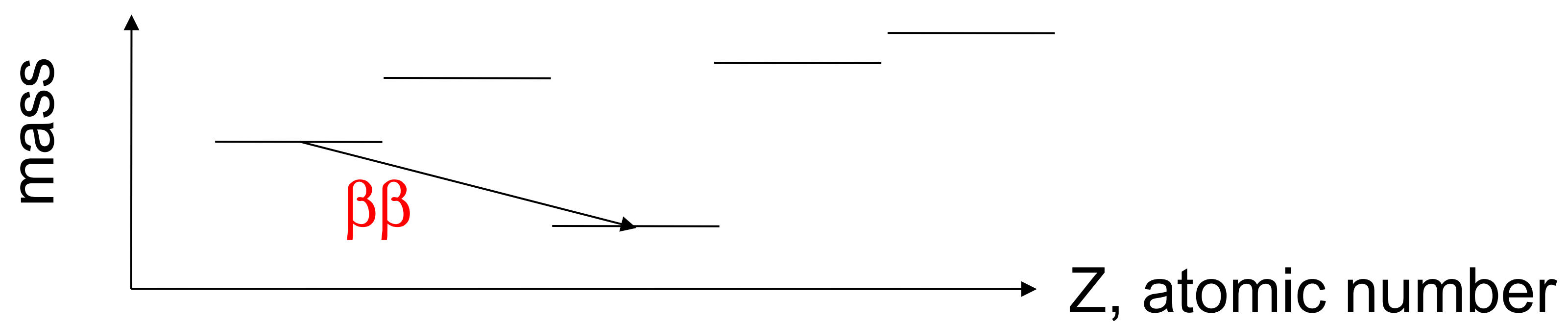
NuPhys 2013, December 20, 2013

Talk Outline

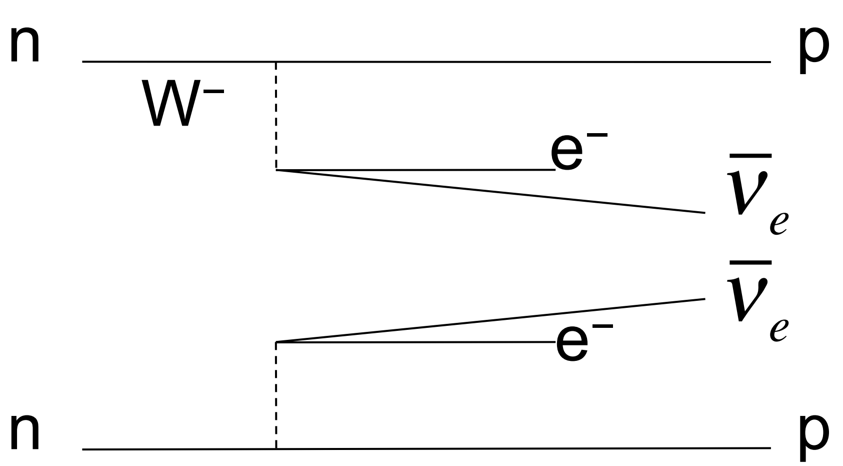
- Introduction to Neutrinoless Double Beta Decay
- Experiments that are Taking Data
- Experiments that are Under Construction
- Outlook and Summary

Double Beta Decay

- some even-even nuclei cannot β decay but can undergo double beta decay, a very rare second-order weak process
  - e.g. ^{76}Ge has half-life 1.8×10^{21} years



- BSM process: neutrinoless double beta decay (has never been observed…well, sort of never!)



2νββ

Double Beta Decay

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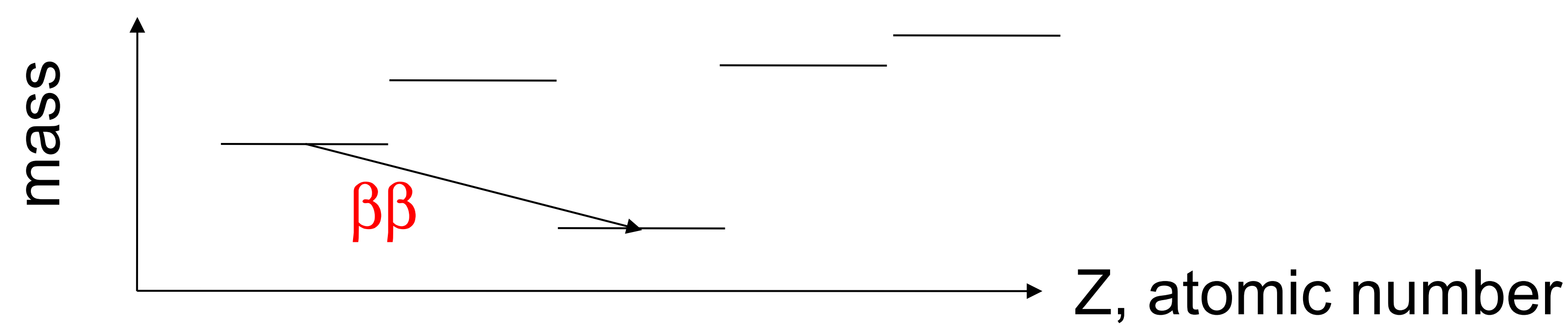

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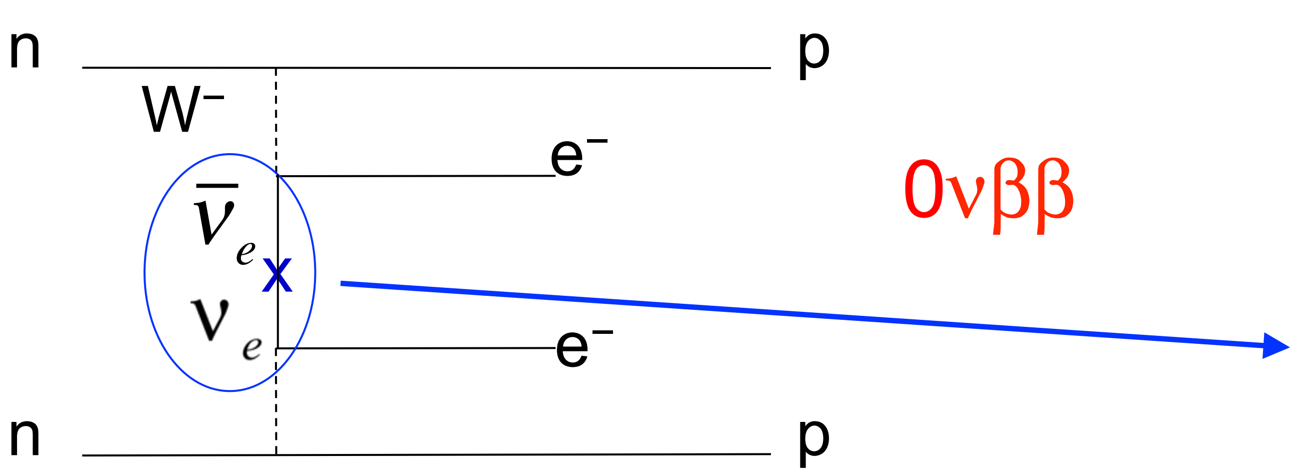


requires neutrinos to be their own antiparticle − i.e. Majorana fermions as opposed to Dirac fermions

Which Isotopes?

- 35 naturally-occurring isotopes can double beta decay
  - double beta isotopes with Q > 2 MeV

isotope	Q-value [MeV]	natural abundance	
^{48}Ca	4.27	0.19%	CANDLES, AMORE
^{150}Nd	3.37	5.6%	~~SNO+~~, DCBA
^{96}Zr	3.35	2.8%	
^{100}Mo	3.03	9.6%	MOON, AMORE
^{82}Se	3.00	9.2%	SuperNEMO, LUCIFER
^{116}Cd	2.80	7.5%	C0BRA
^{130}Te	2.53	34.5%	CUORE, SNO+
^{136}Xe	2.48	8.9%	KamLAND-Zen, EXO, NEXT
^{124}Sn	2.29	5.6%	Sn-loaded scintillator
^{76}Ge	2.04	7.8%	GERDA, MAJORANA
^{110}Pd	2.01	11.8%	

- 34 naturally-occurring isotopes can EC/EC, EC/β^+, β^+/β^+
  - only six of them have high enough Q to emit double positron

Why is 0νββ Interesting?

- if neutrinos are Majorana particles
  - lepton number is not conserved (L conservation is “ad hoc” in the Standard Model, so this is fine to throw out)
  - offers “simpler” theory for massive neutrinos
- light neutrino exchange can mediate the 0νββ process
  - rate (i.e. half-life) depends on effective Majorana neutrino mass
  - upcoming double beta decay experiments probe neutrino mass scales suggested by the inverted neutrino mass...the target is in site!
- possible connection to cosmology via CP-violating Majorana phases, $\Delta L \neq 0$ and leptogenesis giving rise to the matter-antimatter asymmetry in Universe
- *definite* connection to physics at higher energy scales (e.g. as in the simple see-saw mechanism)
- in EFT, the lowest-order extension to the Standard Model is a unique dimension-5 operator…and it’s Majorana neutrino mass

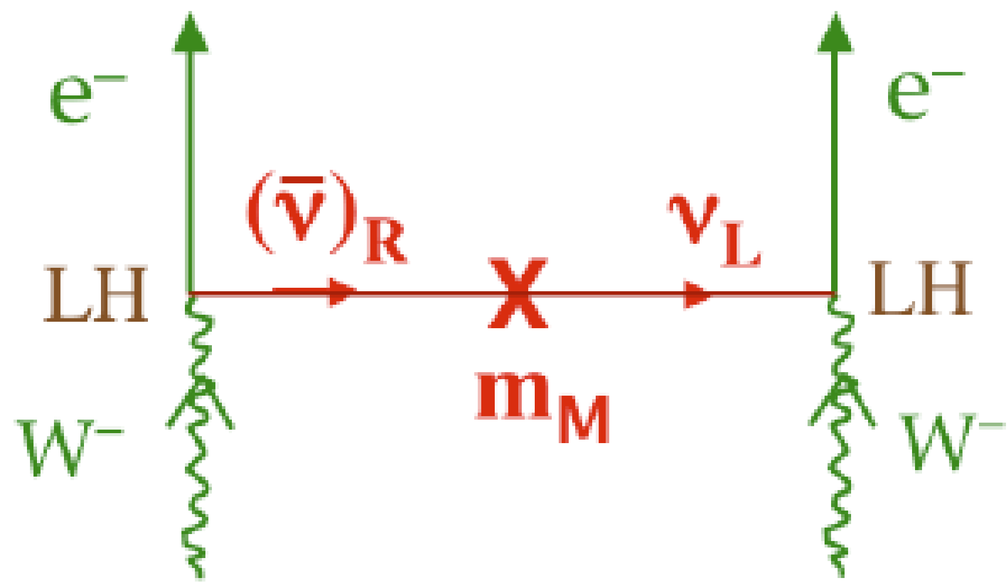
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \cdots$$

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right) + \text{h.c.}$$

d=5 operator coefficient $\langle\Phi\rangle^2/\Lambda$

$(246\ \text{GeV})^2/10^{15}\ \text{GeV} \approx 60\ \text{meV}$

Majorana Mass

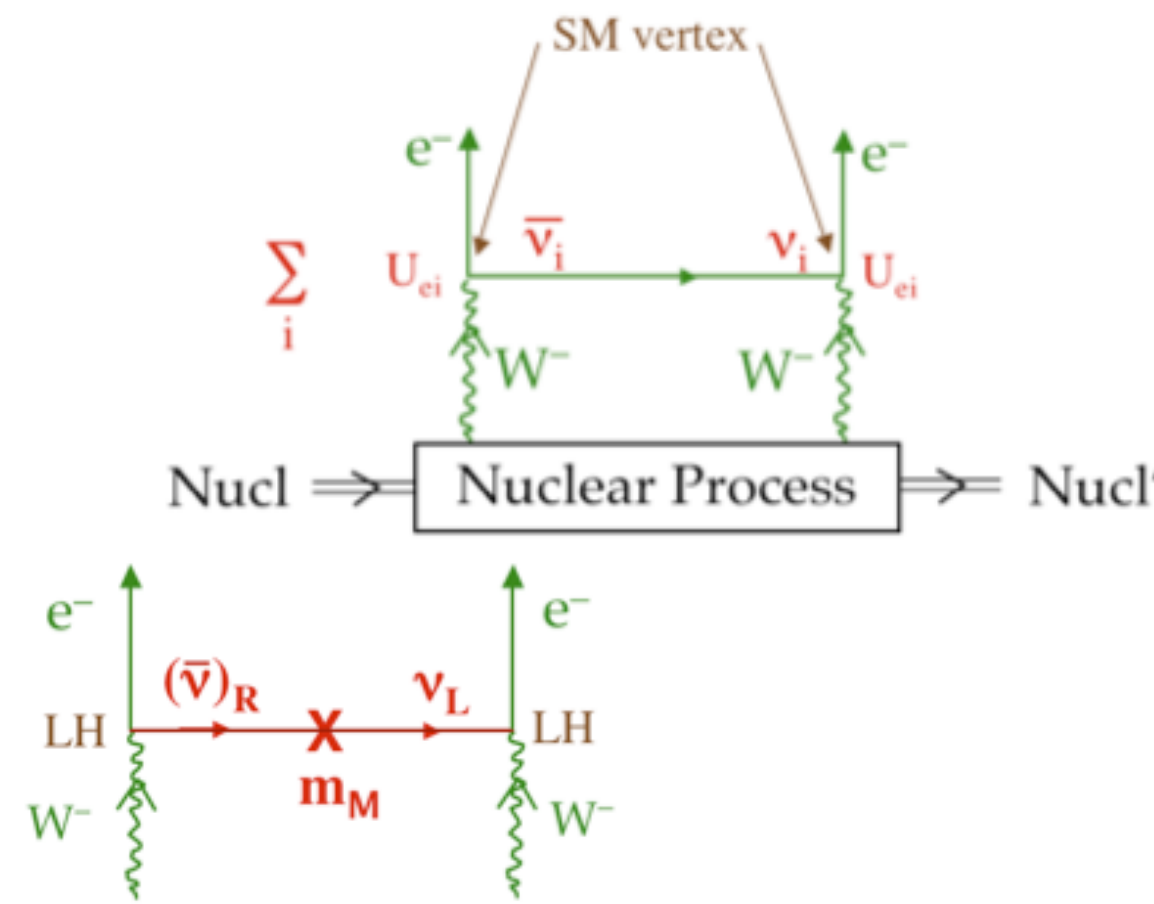


$$m\,\overline{\psi}_L^{\,C}\psi_L$$

is precisely the term in the Lagrangian that's responsible for this process

Neutrinoless Double Beta Decay Amplitude

- if and only if Majorana
  - antineutrino = neutrino
- helicity mismatch
  - antineutrino is dominantly right-handed helicity with component m/E that is left-handed helicity
- amplitude



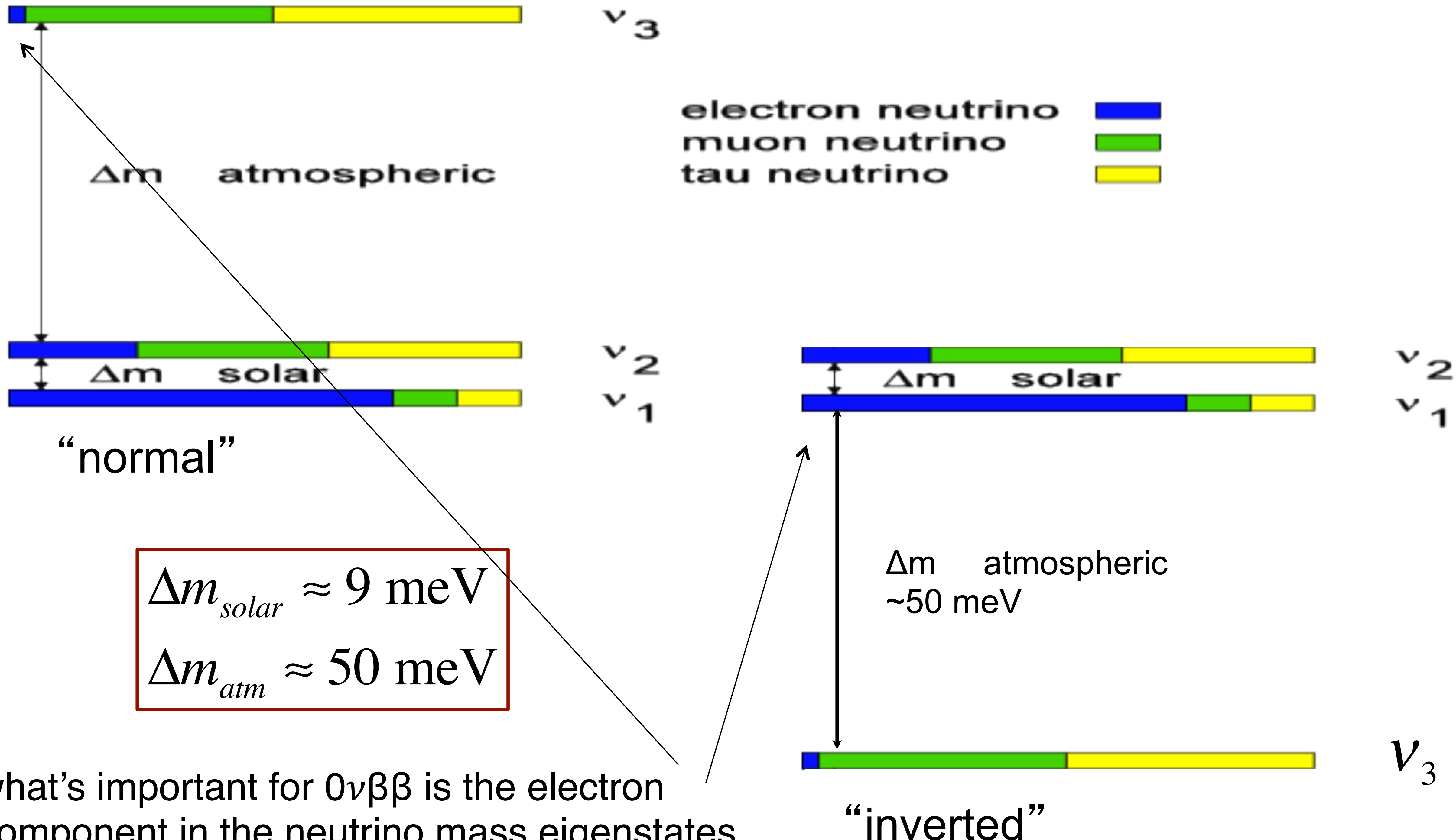
$$\left|\sum_i m_i U_{ei}^2\right| \equiv \langle m_{\beta\beta} \rangle$$

decay rate is amplitude squared, hence $\propto \langle m_{\beta\beta} \rangle^2$

take note: it's the sum of complex-valued U_{ei} with the "Majorana phases"

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}(1, \mathrm{e}^{\mathrm{i}\alpha_1}, \mathrm{e}^{\mathrm{i}\alpha_2})$$

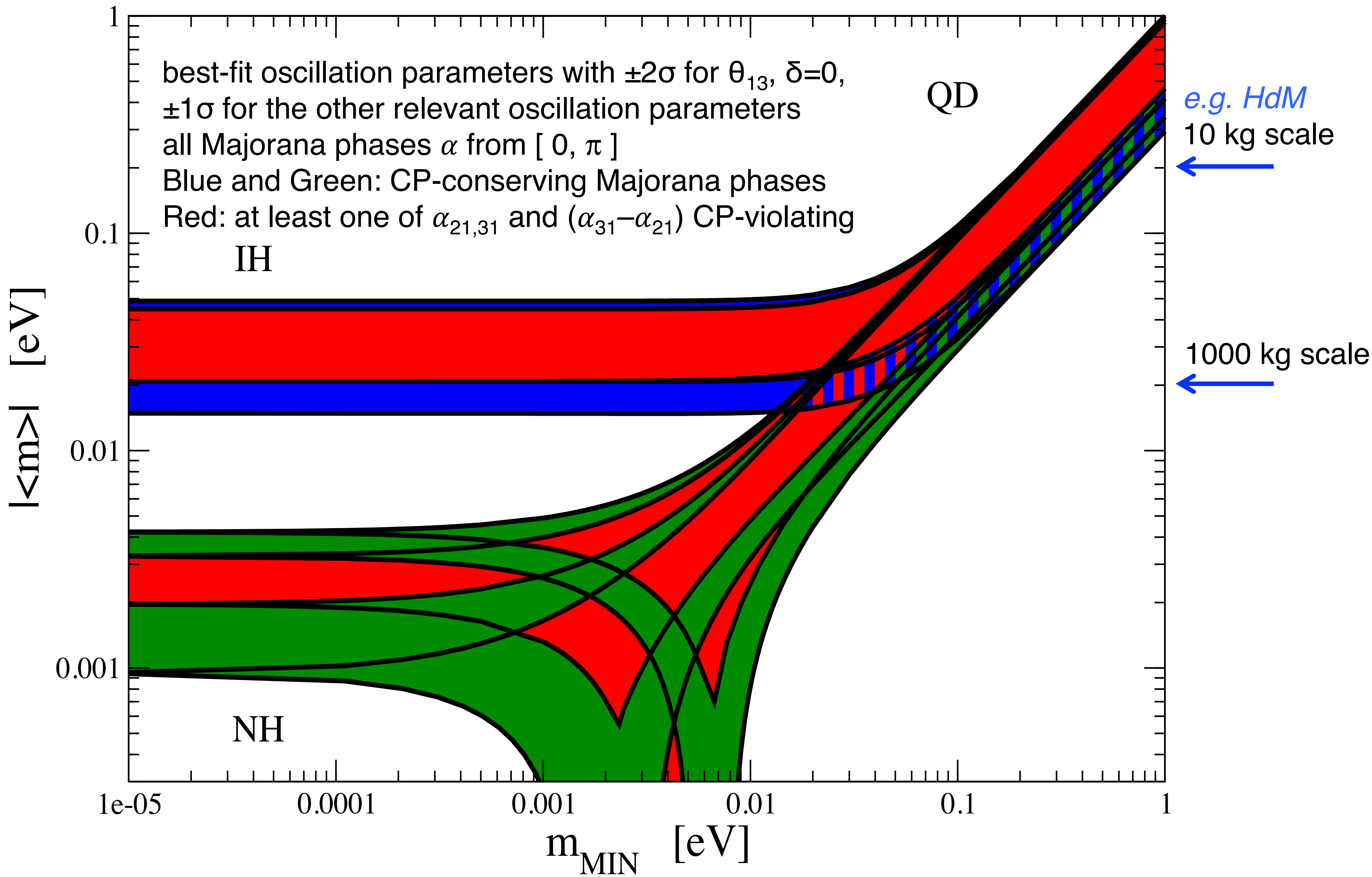
Neutrino Mass Hierarchy



$$\Delta m_{solar} \approx 9 \text{ meV}$$
$$\Delta m_{atm} \approx 50 \text{ meV}$$

what's important for $0\nu\beta\beta$ is the electron component in the neutrino mass eigenstates

$\langle m_{\beta\beta} \rangle$ and the Neutrino Mass Hierarchy



updated figure by S. Pascoli in RPP 2013 “Neutrino Mass, Mixing and Oscillations”,
originally in S. Pascoli and S. Petcov, PRD 77, 113003 (2008)

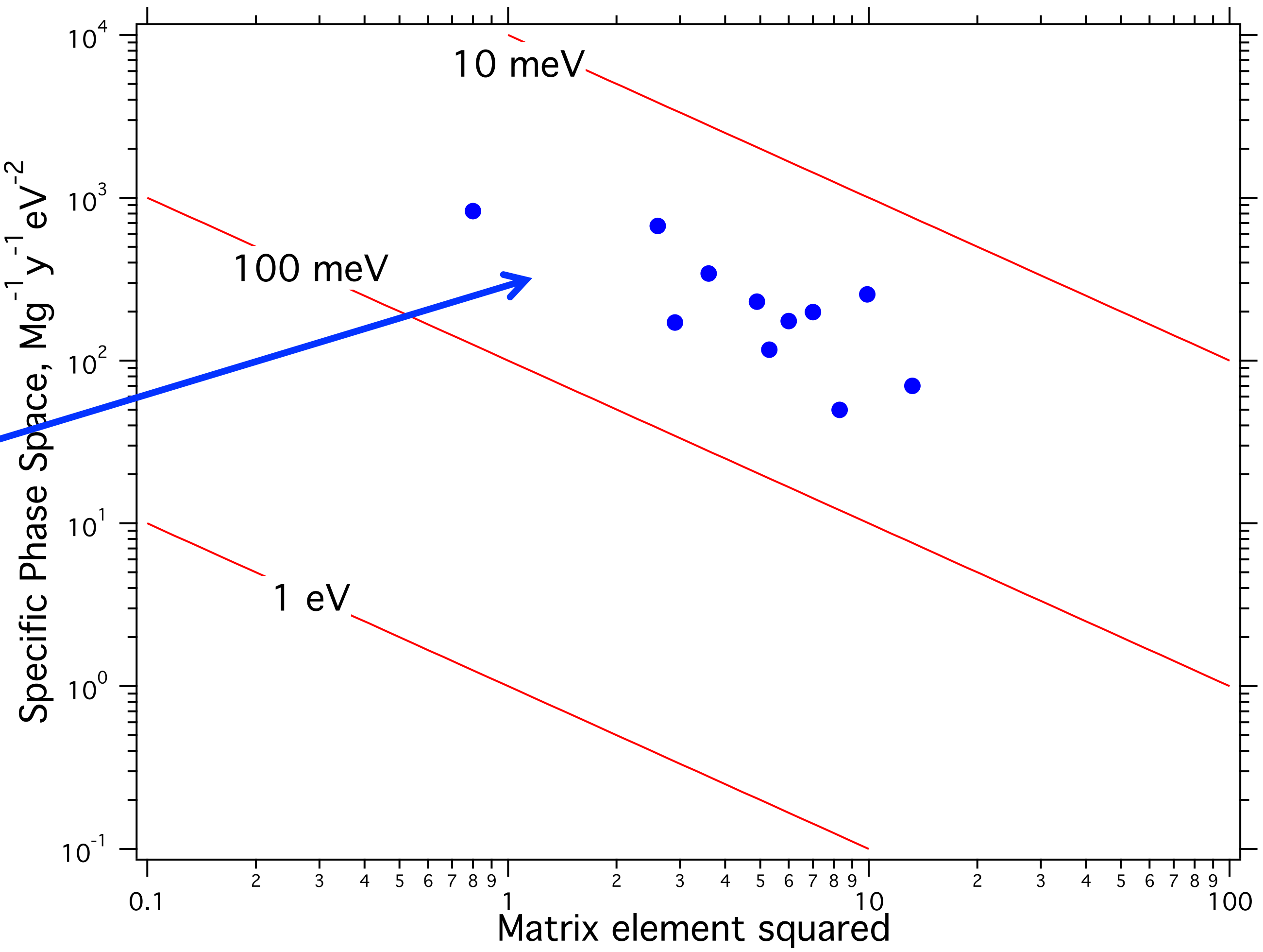
Decay Rate (or Half-Life)

- rate of $0\nu\beta\beta$ decay: $$\left[T_{1/2}\right]^{-1} = G_{0\nu}\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}\left|M_{0\nu}\right|^2$$

- $G_{0\nu}$ is the phase space integral (precisely calculable)
- $M_{0\nu}$ is the nuclear matrix element [next talk by F. Šimkovic]

- is there a favoured isotope?

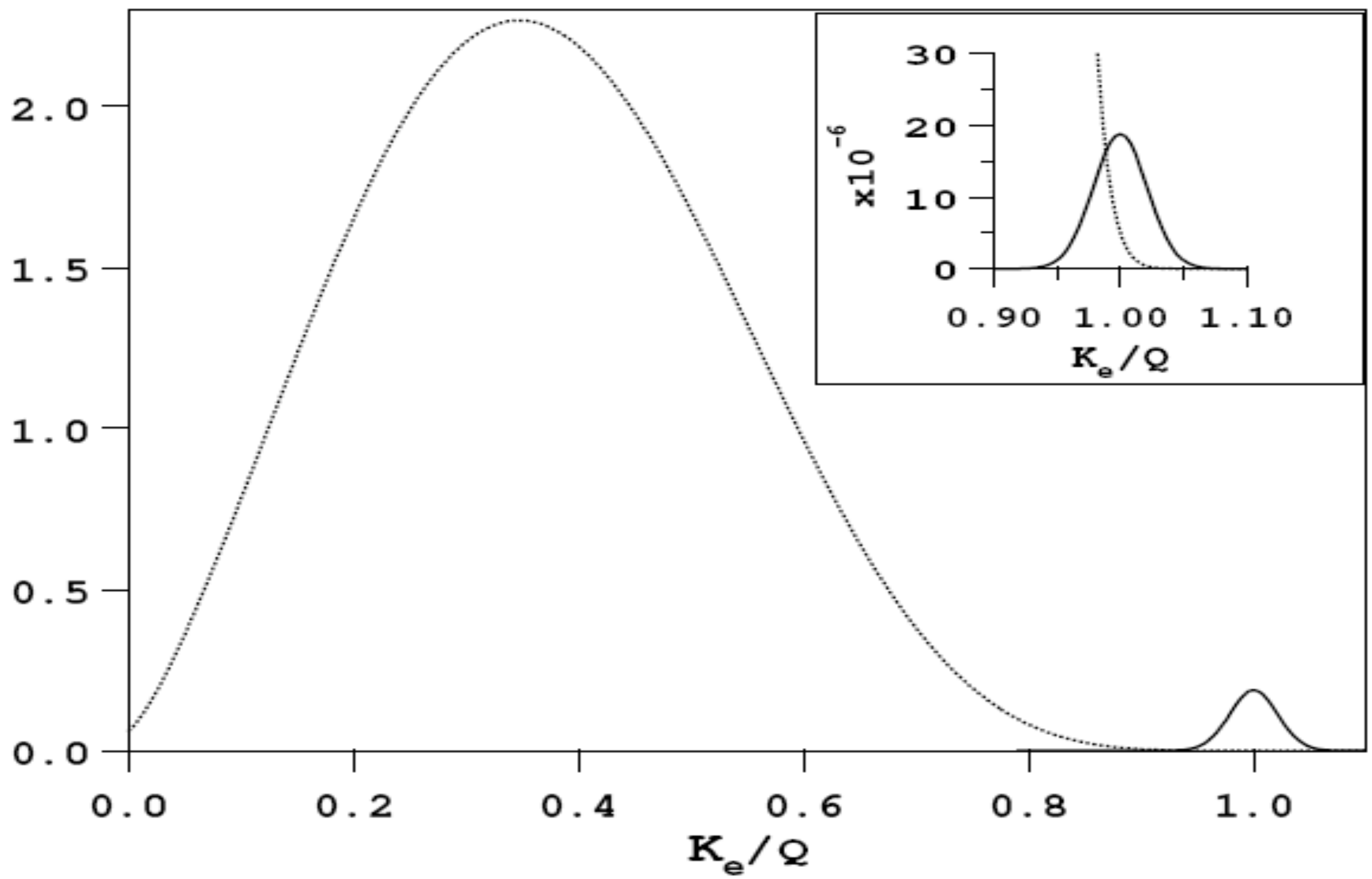
plot of phase space v. geometric mean of NME calculation…anti-correlated?
^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo, ^{110}Pd (from left to right)



from R.G.H. Robertson, arXiv:1301.1323

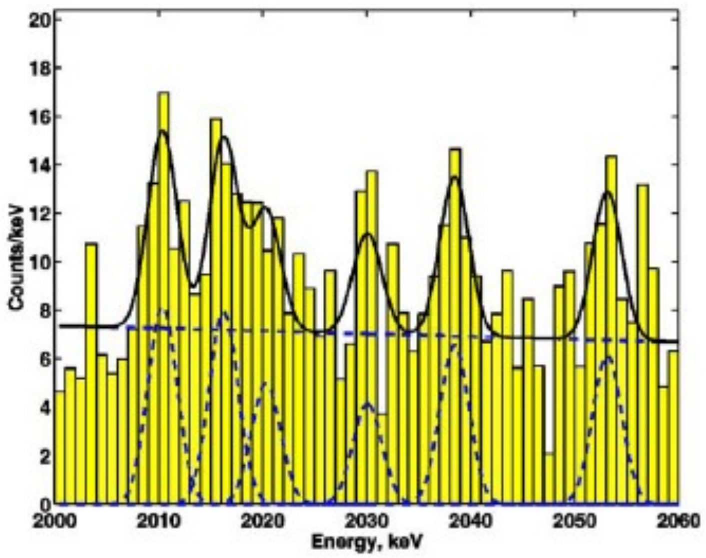
How to Search for $0\nu\beta\beta$?

- look at sum of energy of both electrons (calorimetry)
- search for a peak at the double beta endpoint



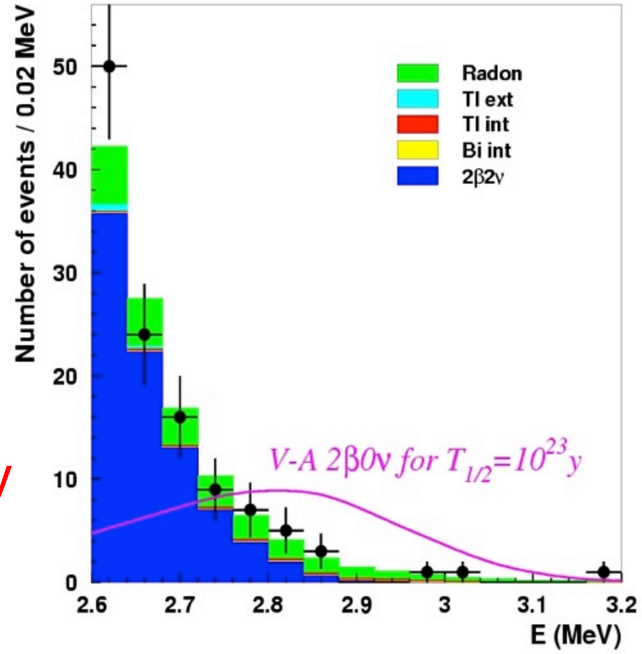
Backgrounds

- separation of 0νββ from 2νββ (hence energy resolution) is not the only important experimental requirement
- background reduction and rejection are necessary too
  - natural radioactivity (U, Th, K, Rn…all the usual suspects)
  - cosmogenic radioactivity – *will be more and more important as we increase the sensitivity of next-generation experiments*
  - selection of materials for detector components
  - radiopurity of the detection medium and the double beta isotope (often one and the same)
  - event "topology" – spatial and/or temporal – for background rejection



e.g. Ge detector with excellent energy resolution still has background counts under the peak

e.g. NEMO-3 with not-as-good energy resolution has excellent background rejection from track identification



In General:
Next-Gen Double Beta Experiments

NEED TO BE BIG

HAVE GOOD ENERGY RESOLUTION

AND HAVE ULTRA-LOW BACKGROUND

the more of these you have, the better your experimental sensitivity to the neutrinoless double beta decay process

Neutrinoless Double Beta Decay Experiments – Survey and Review

- limited time, so I will only speak about currently running experiments with >O(10)'s kg of detector material

  – and –

- such large experiments currently funded and under construction

- thanks to the experimental collaborations for slides which I am showing essentially unedited – I'm conveying the material from each experiment (their words) directly to you!

[my commentary will appear in purple italics]

- specific thanks: T. Kishimoto, S. Umehara, D. Waters, R. Saakyan, F. Avignone, E. Fiorini, O. Cremonesi, C. Brofferio, J.J. Gómez-Cadenas, G. Gratta, K. Kumar, J. Farine, K. Inoue, S. Schönert, R. Martin, S. Elliott, M. Green

Double Beta Decay Experiments

Currently Running Experiments (and their future plans)

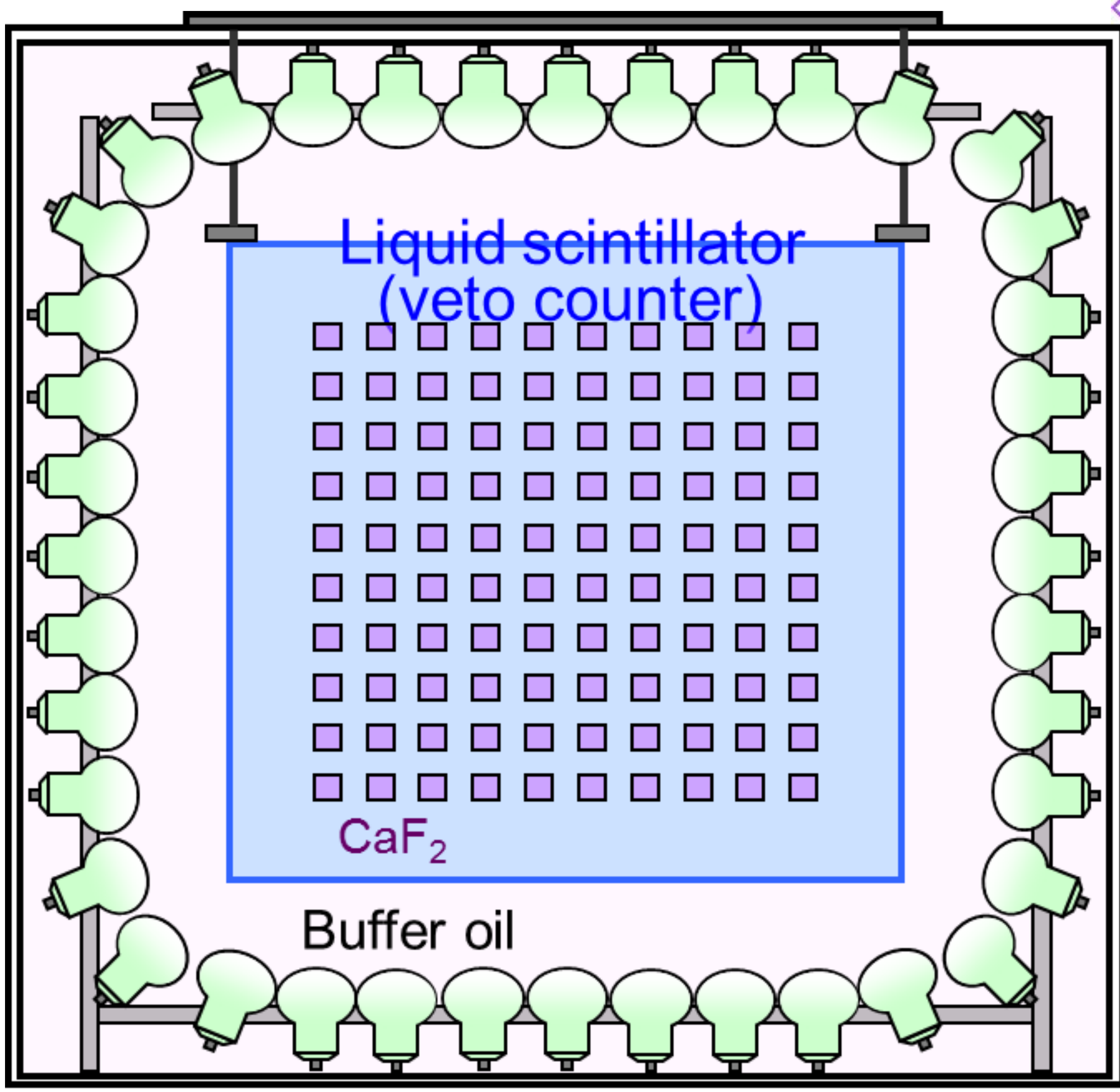
- CANDLES
- KamLAND-Zen
- EXO-200 at WIPP (and nEXO at SNOLAB)
- GERDA

Experiments Under Construction

- CUORE (currently running CUORE-0)
- MAJORANA “Demonstrator”
- NEXT
- SuperNEMO (and the recently dismantled NEMO-3)
- SNO+

CANDLES project

Schematic drawing of scintillator system



CANDLES System

- for ^{48}Ca ($Q_{\beta\beta}$=4.3MeV, 0.187%)
- CaF_2 detector
- 4π active shield
- enriched ^{48}Ca

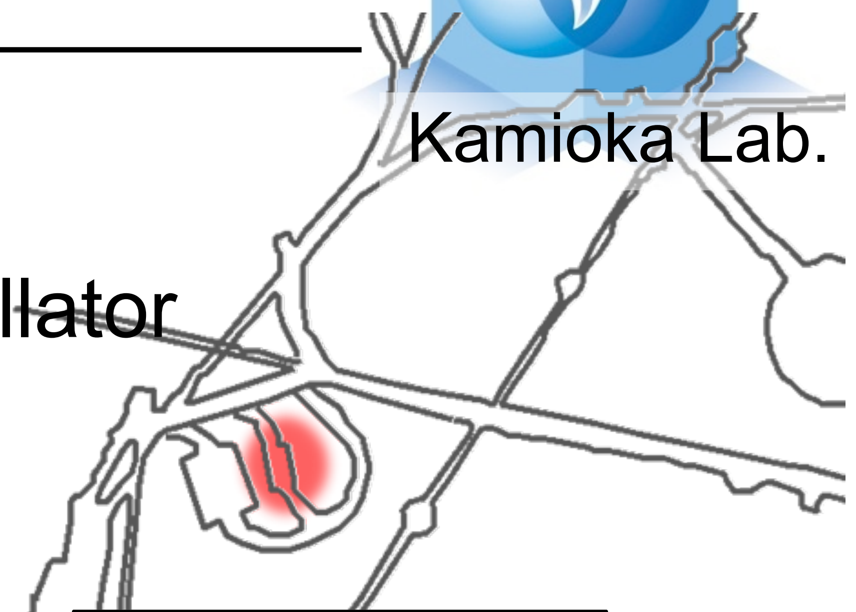
Sensitivity of CANDLES

- <m_ν> 80meV *[at tonnes scale]*
  with CaF_2 scintillator system
  beyond this value
  … bolometer

[^{48}Ca has the highest Q value and thus less prone to natural radioactivity backgrounds]

Current Status

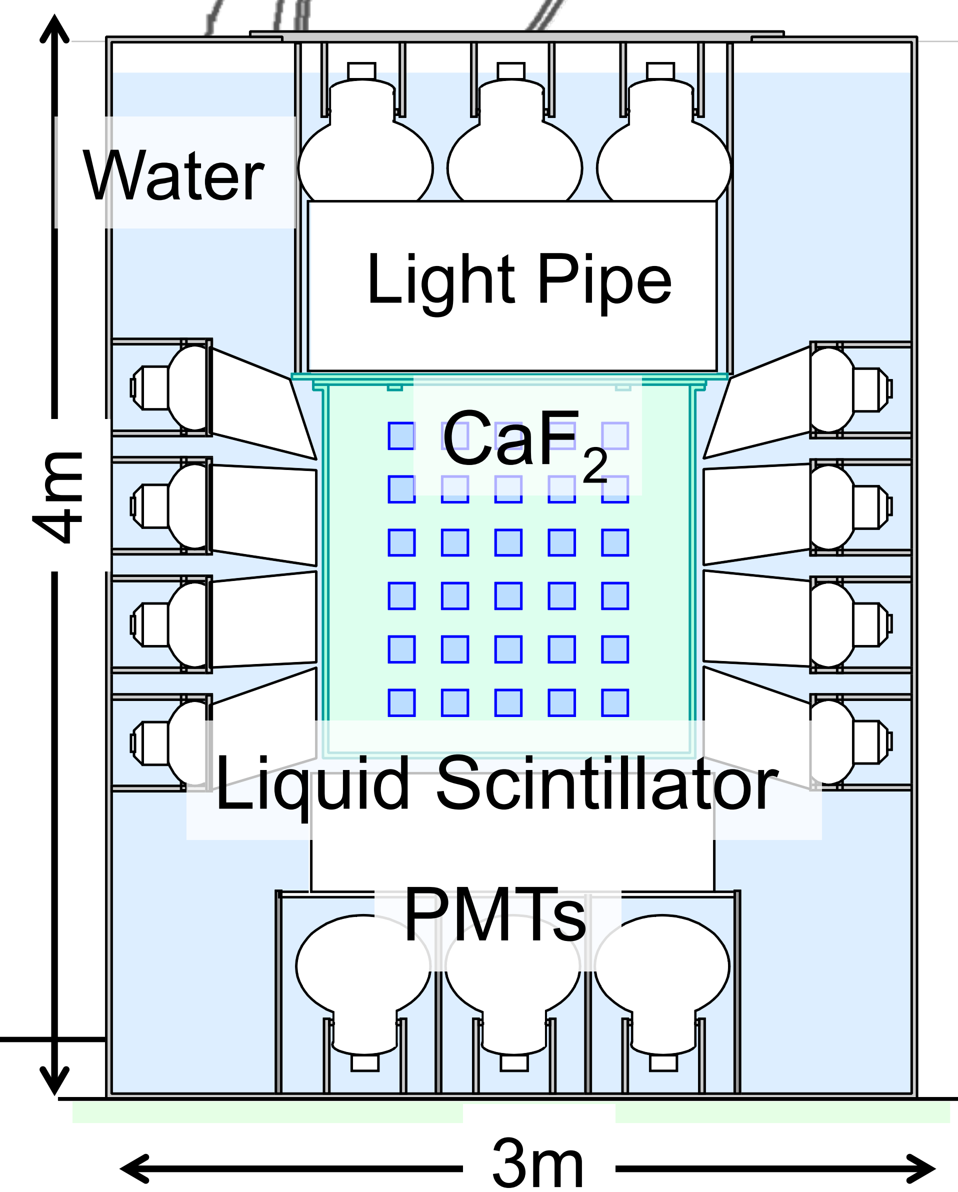
- CANDLES III at Kamioka Lab taking data
  - 96 CaF_2 (305kg, 0.187% ^{48}Ca) + liquid scintillator
  - Installation of light-pipe system in 2012.



CANDLES III

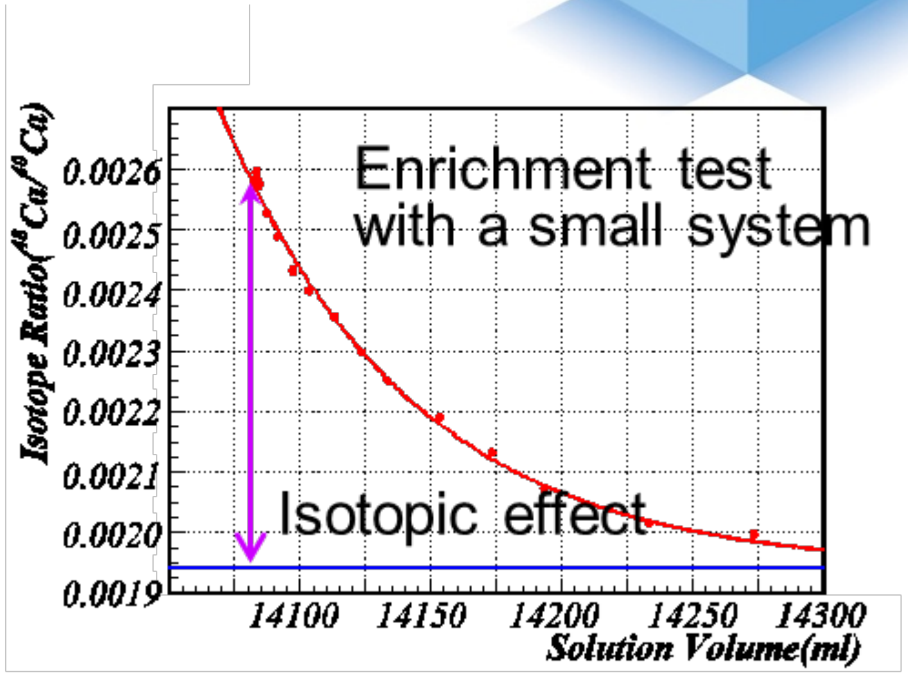
Inside Modules (CaF_2 Scintillators)

Inside View of Water Tank

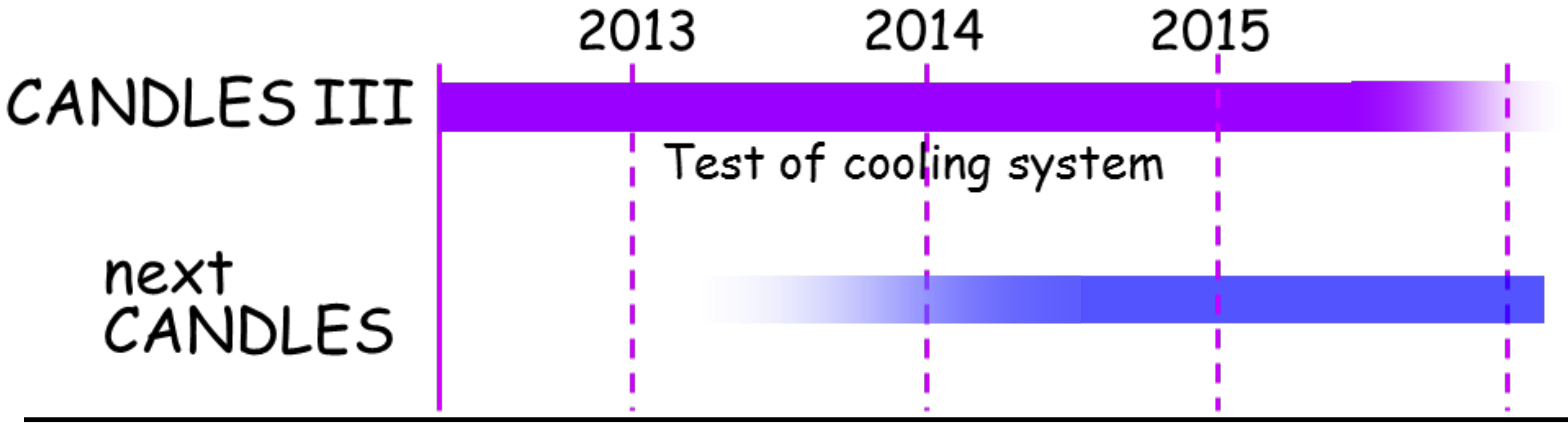


Future Experiment

- ^{48}Ca enrichment
  - R&D for next CANDLES system
  - Under development for a large amount of ^{48}Ca



- CANDLES IV & V
  - ^{48}Ca enrichment
  - Cooling system (~0℃) for good energy resolution
- Schedule



Measurement
at Kamioka Lab
sensitivity 0.5 eV

^{48}Ca enrichment
Construction of detector
. . . not funded yet

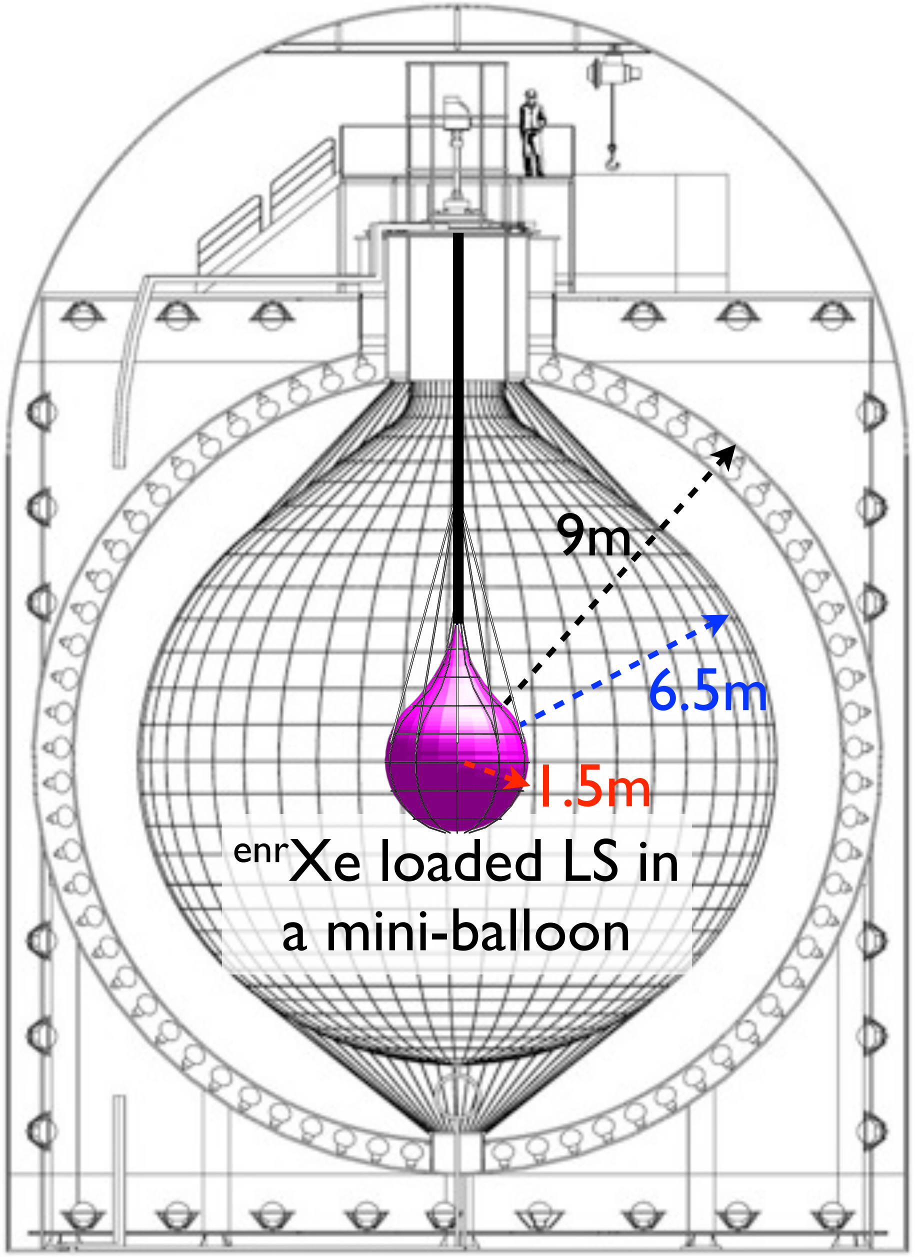
[massive quantity of isotope deployed in low-background scintillator]

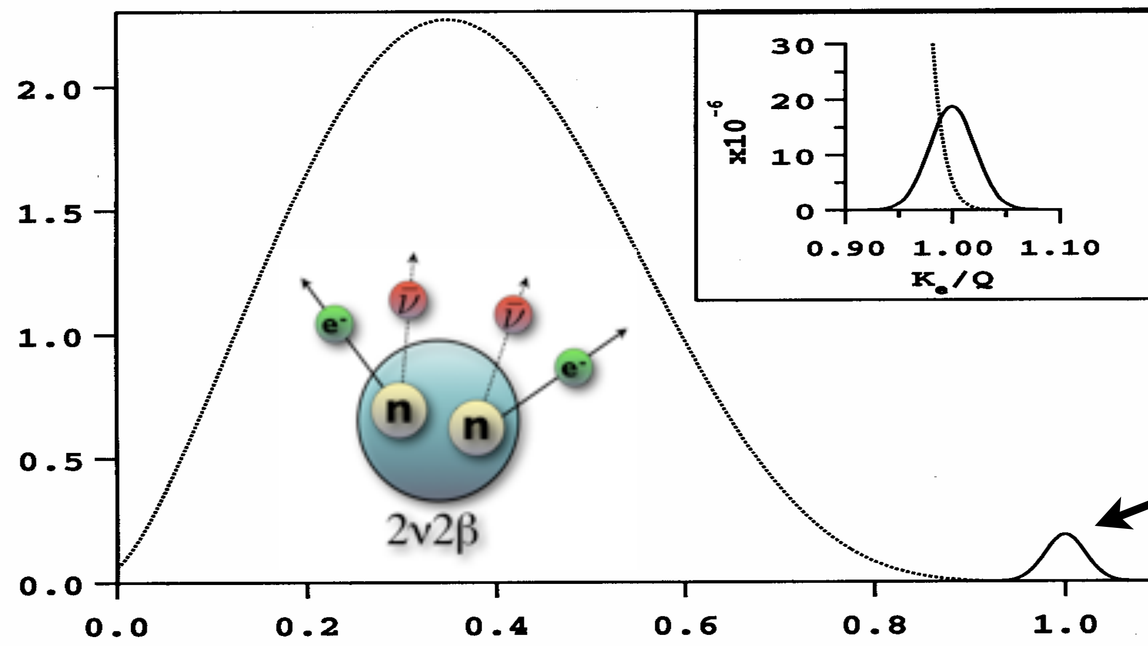
KamLAND-Zen

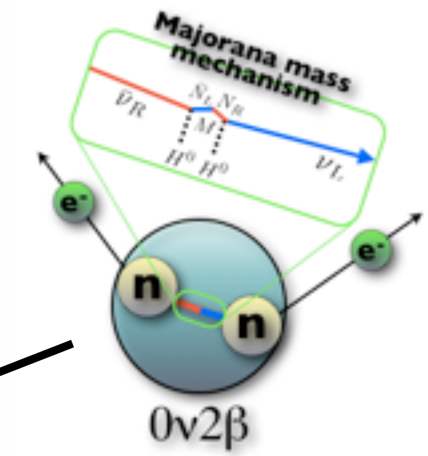
$$\langle m_{\beta\beta}\rangle = |\Sigma m_i |U_{ei}|^2 \epsilon_i|$$

$$\frac{1}{T_{1/2}} = G_{0\nu}|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

Zero Neutrino
double beta decay search







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

615 kg in hand

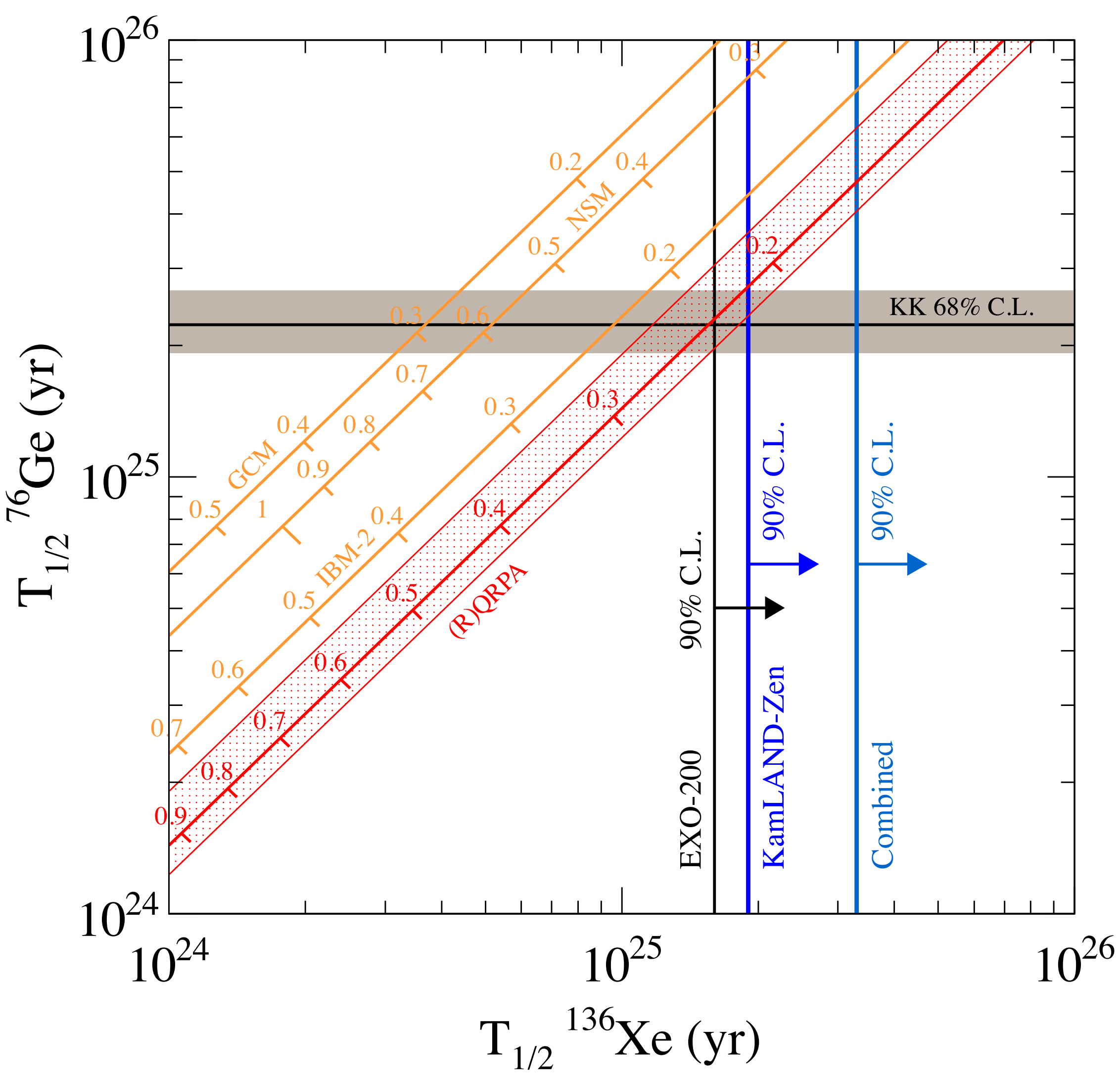
Good features of using KamLAND

- running detector
  → relatively low cost and quick start
- huge and clean (1200m^3, U: 3.5x10^{-18} g/g, Th: 5.2x10^{-17})
  → negligible external gamma

  (Xe and mini-balloon need to be clean)
- Xe-LS can be purified, mini-balloon replaceable if necessary, with relatively low cost
  → highly scalable (up to several tons of Xe)
- No escape or invisible energy from β, γ
  → BG identification relatively easy
- **anti-neutrino observation continues**
  → geo-neutrino w/o japanese reactors

Results from KamLAND-Zen phase I

comparison with KK claim



$T_{1/2}(^{136}Xe)$ → <m_{ee}> → $T_{1/2}(^{76}Ge)$

NME uncertainty NME uncertainty

Use the same model (the same parameter set)

g_A, short range correlations

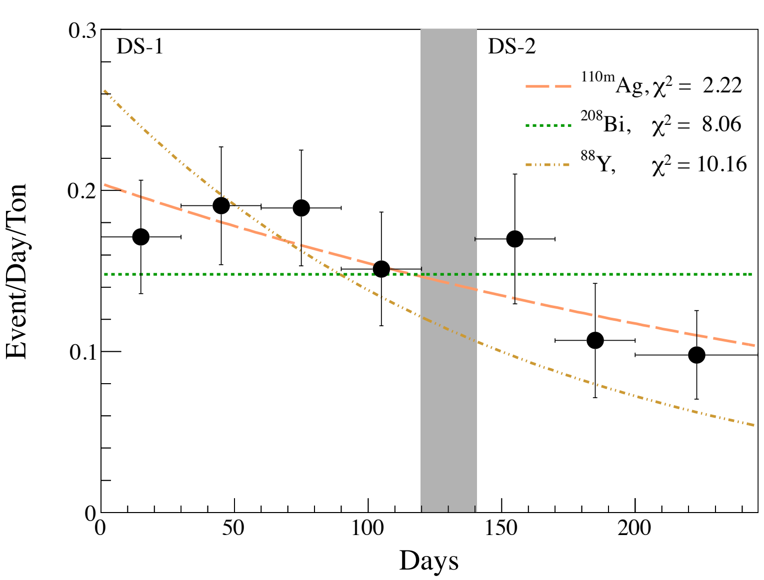
1. **The world best sensitivity**

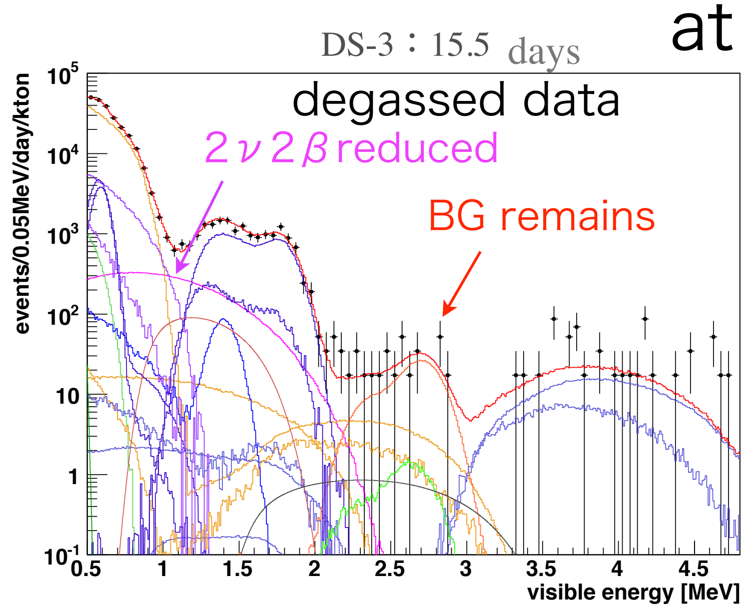
$T_{1/2}$ >1.9×10^{25} yr (KL-Zen)

> 3.4×10^{25} yr (combined)

$$\langle m_{\beta\beta}\rangle < 120 \sim 250\,\mathrm{meV}$$

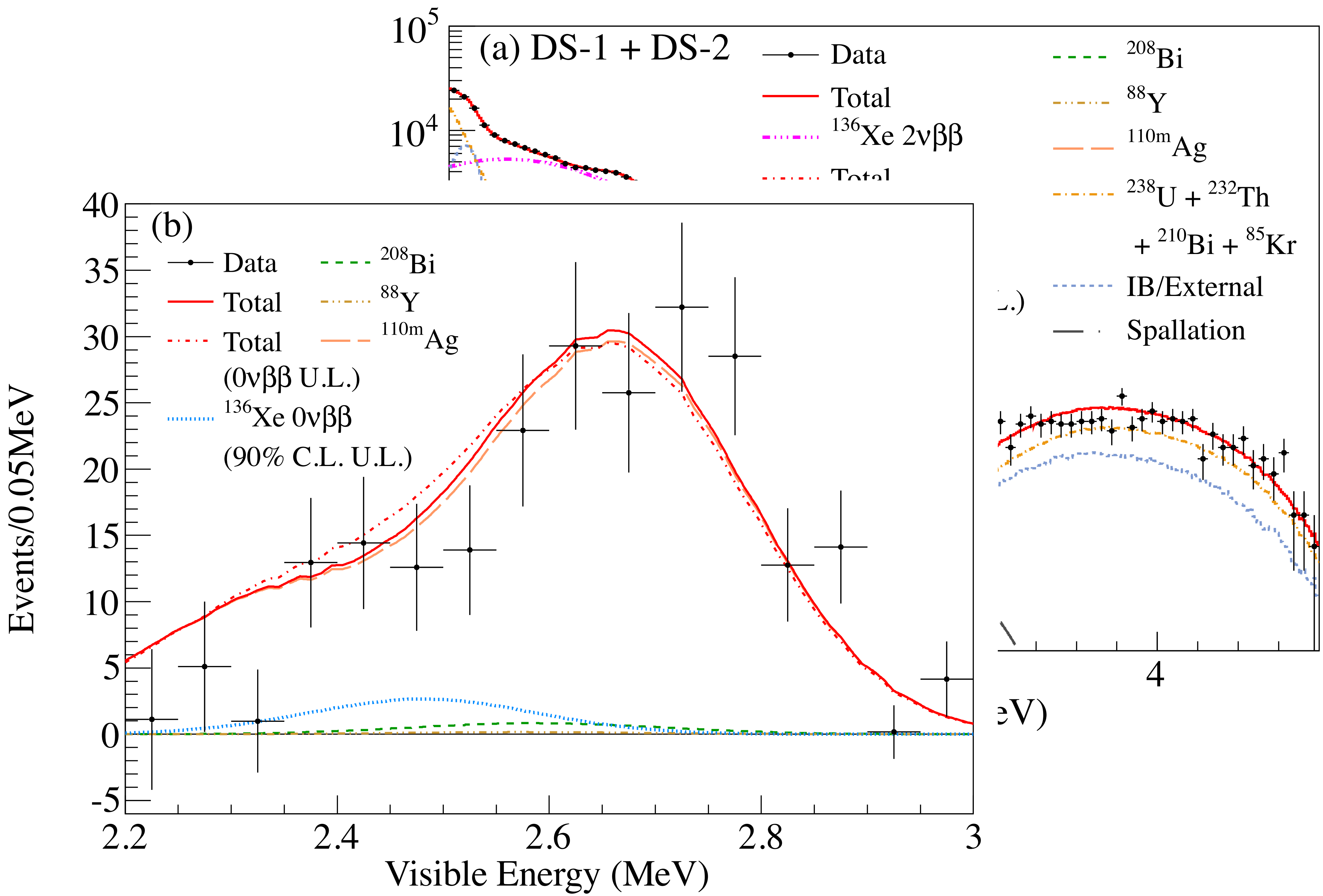
2. Assuming light-Majorana-neutrino exchange and using available NME calculations, **KK claim is rejected** at 97.5%CL (combined).





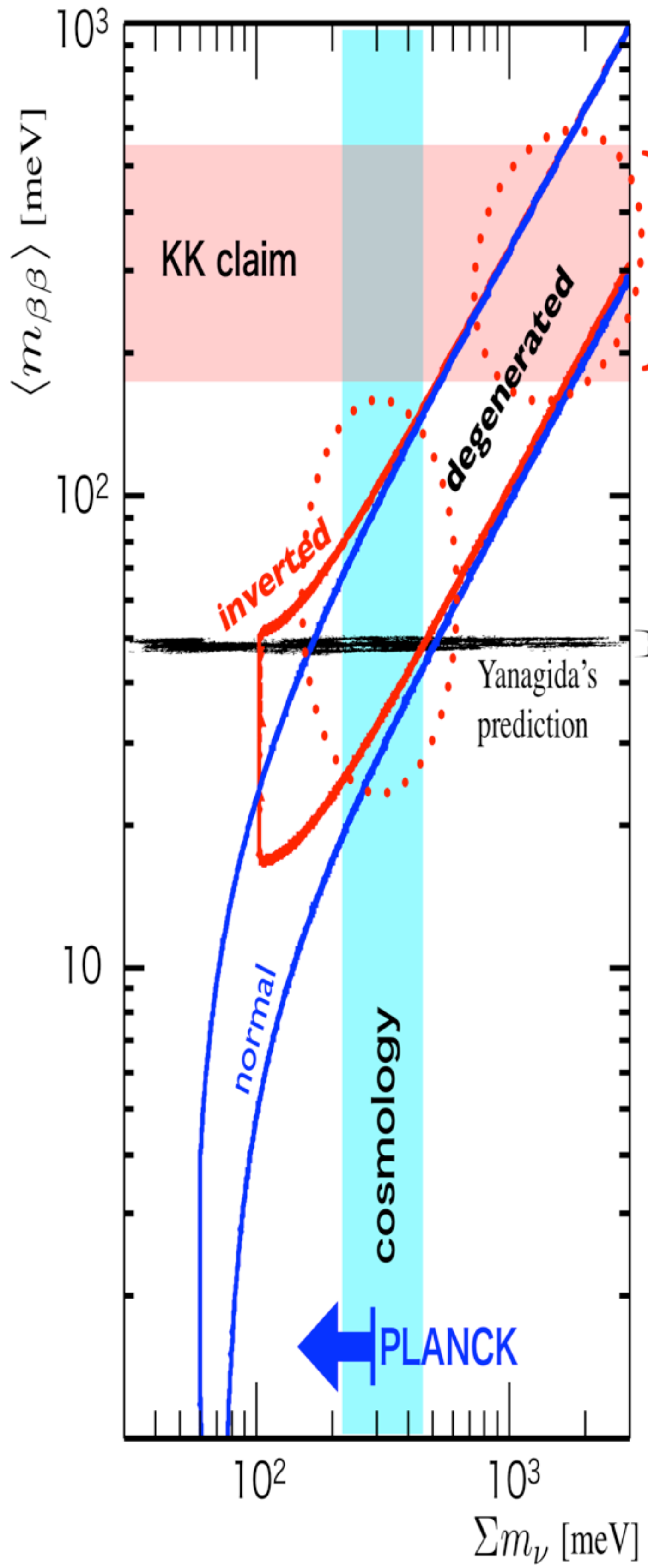
3.
- Main BG is identified as ^{110m}Ag.
- cosmogenic (during delivery) or fall-out not known yet but anyway reducible
- On-off measurement (w/ and w/o Xenon) has been done.

[Let's look closer at the data…]



[…cosmogenics are important and could be the source of ^{110m}Ag]

Prospects



KamLAND-Zen is a top runner and being improved.

[purification is possible]

NME uncertainty

after purification

2014~

Future plan

dream?

KamLAND-Zen 89.5 kg-yr

$\langle m_{\beta\beta} \rangle$ <160~330 meV @90% C.L.

the world best

Next target

KamLAND-Zen (w/ lower ^{110m}Ag)

just resumed with 380kg

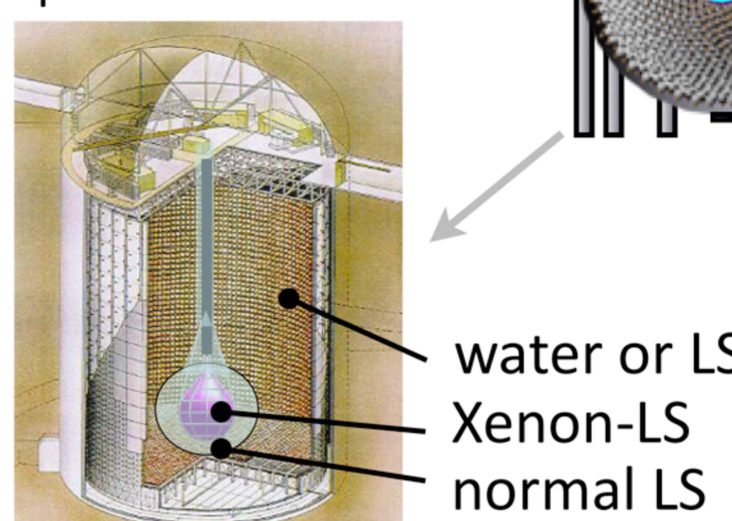
KamLAND-Zen 600kg

with clean mini-balloon

KamLAND2-Zen : high QE PMT, high yield LS, light concentrator

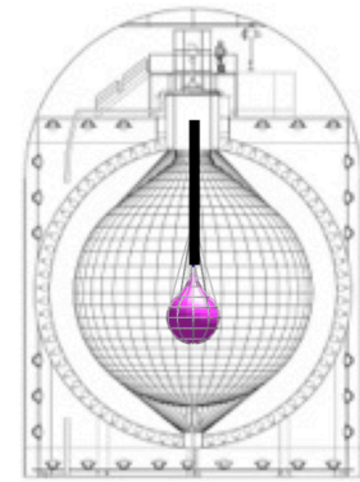
σ_E(2.6MeV)=4%→ <2.5%

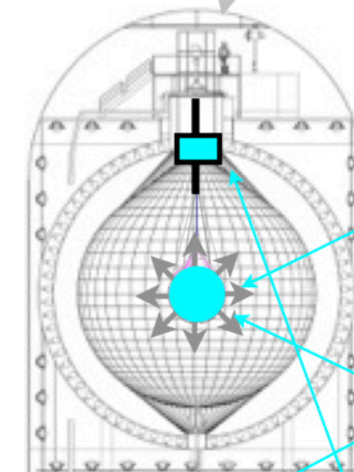
Super-KamLAND-Zen



precision anti-neutrino physics

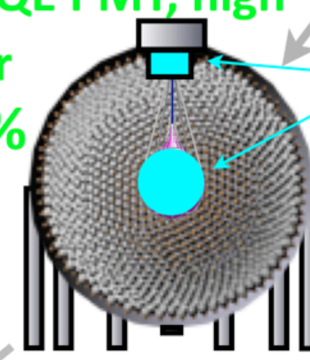
$p \rightarrow \nu K^+$ is also possible.



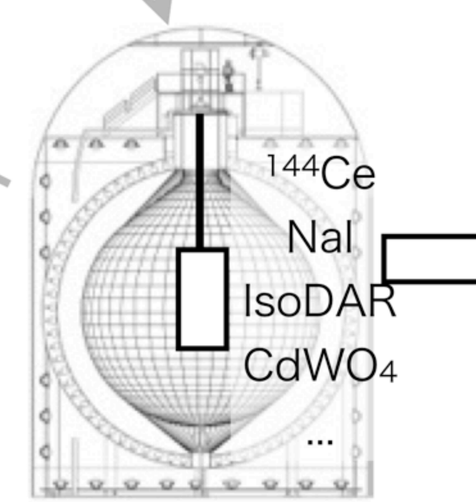


R&D for pressurized Xe

R&D for scintillation film

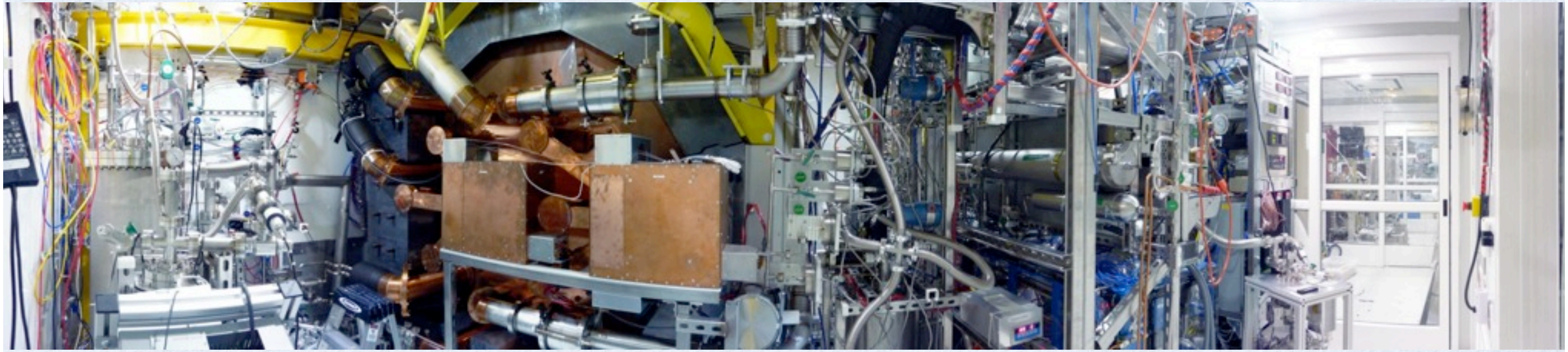


R&D for β / γ discrimination (high sensitivity imaging)



Various low BG measurements can be accommodated.

EXO-200 @ WIPP



[EXO Concept and Advantages]

^{136}Xe is probably the easiest (and cheapest) enriched double beta isotope that can be obtained

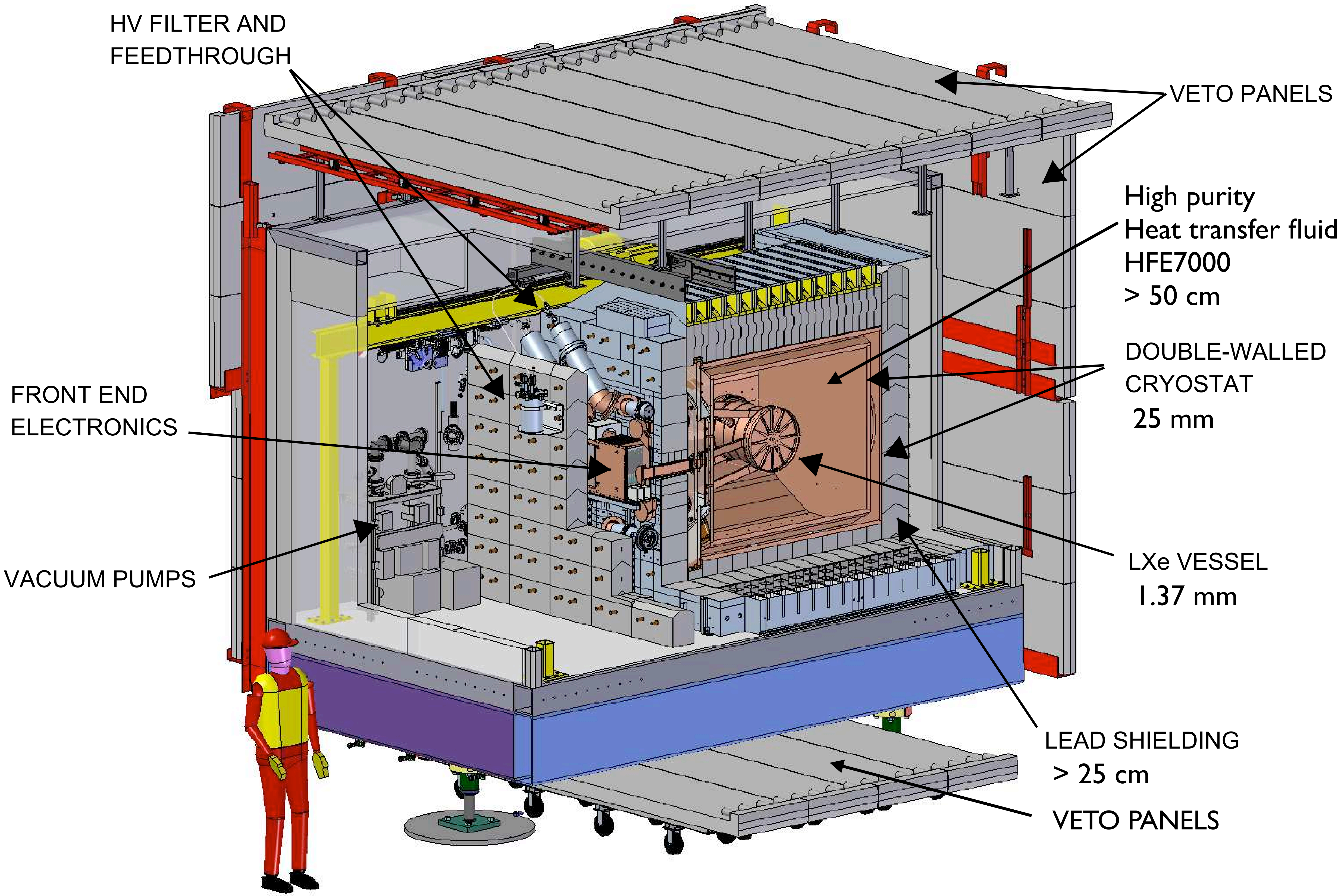
LXe TPC exploits event topology to reject multi-site backgrounds (from gammas)

good energy resolution

effective self-shielding for reducing external backgrounds

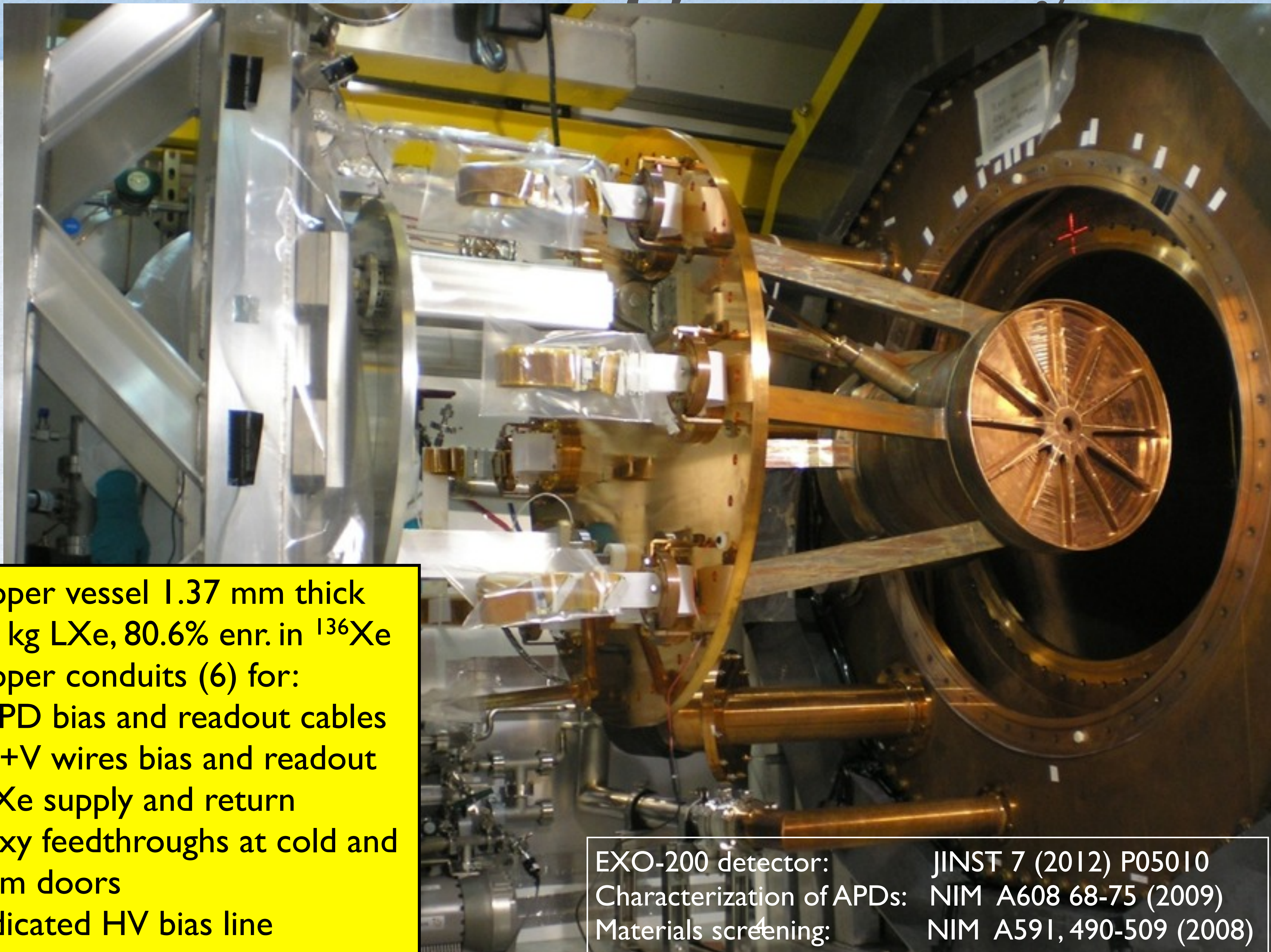
possibility to tag Ba (double beta daughter isotope)

Module 1



HV FILTER AND
FEEDTHROUGH
VETO PANELS
High purity
Heat transfer fluid
HFE7000
> 50 cm
FRONT END
ELECTRONICS
DOUBLE-WALLED
CRYOSTAT
25 mm
VACUUM PUMPS
LXe VESSEL
1.37 mm
LEAD SHIELDING
> 25 cm
VETO PANELS

TPC entering the Cryostat



Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in ^{136}Xe
Copper conduits (6) for:

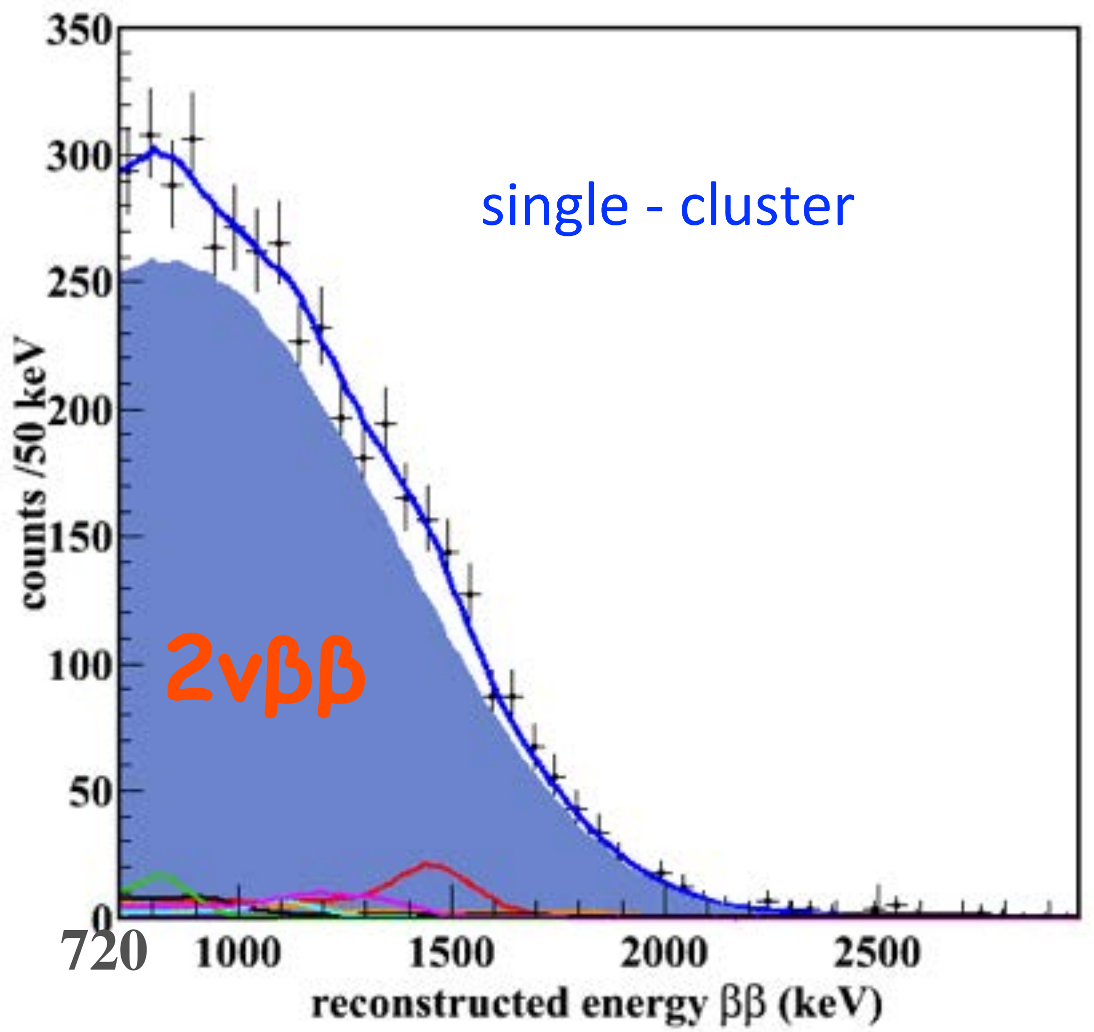
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return

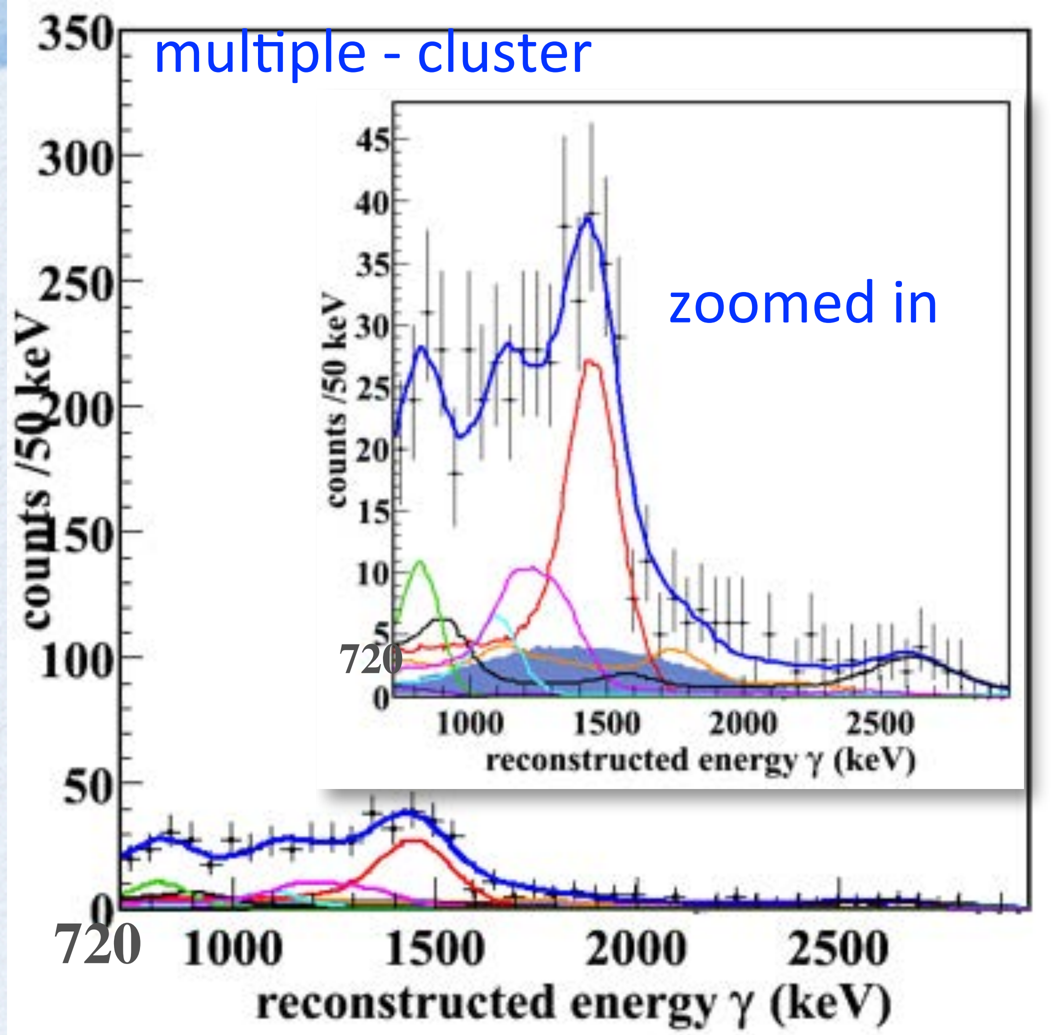
Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

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

May-July 2011: 3.2 kg-yr

First Observation of ^{136}Xe $2\nu\beta\beta$





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

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

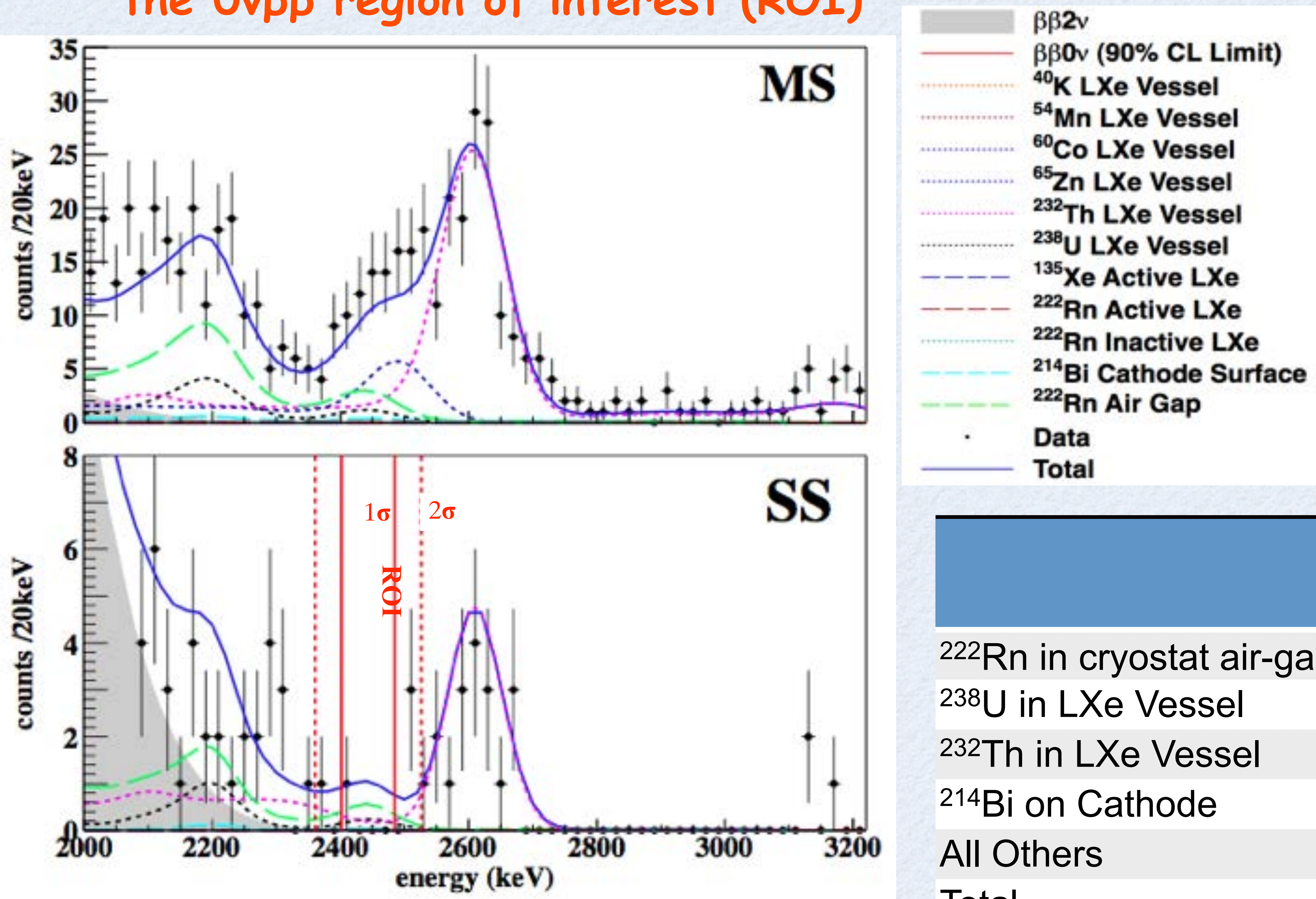
$T_{1/2}$ > $8.5 \cdot 10^{21}$ yr (90% C.L.) (Yu. M. Gavriljuk et al., Phys. Atom. Nucl. 69 (2006) 2129)

Later confirmed by KamLAND-ZEN

Sep 11 - Apr 12: 26.3 kg-yr

EXO-200 ^{136}Xe 0νββ Limit

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



No 0ν signal observed in the ROI

Use likelihood fit to establish limit

From profile likelihood:

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

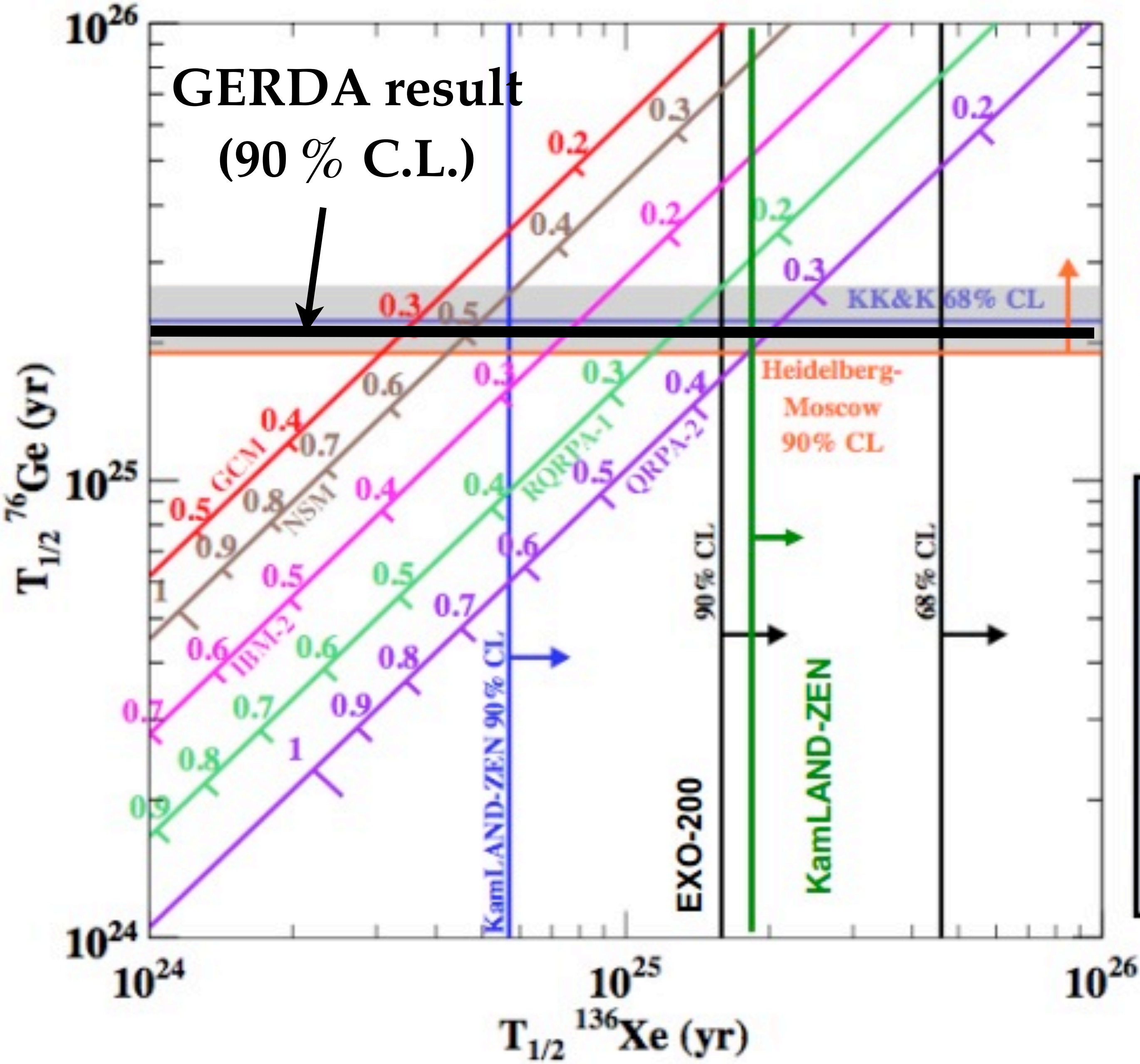
$\langle m_{\beta\beta}\rangle$ < 140–380 meV

(90% C.L.)

Phys Rev Lett 109 (2012) 032505

	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 ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5\cdot10^{-3}$ ± 0.1		$1.4\cdot10^{-3}$ ± 0.1	

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



Interpret as lepton number violating process with effective Marojana mass $\langle m_{\beta\beta}\rangle$:

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

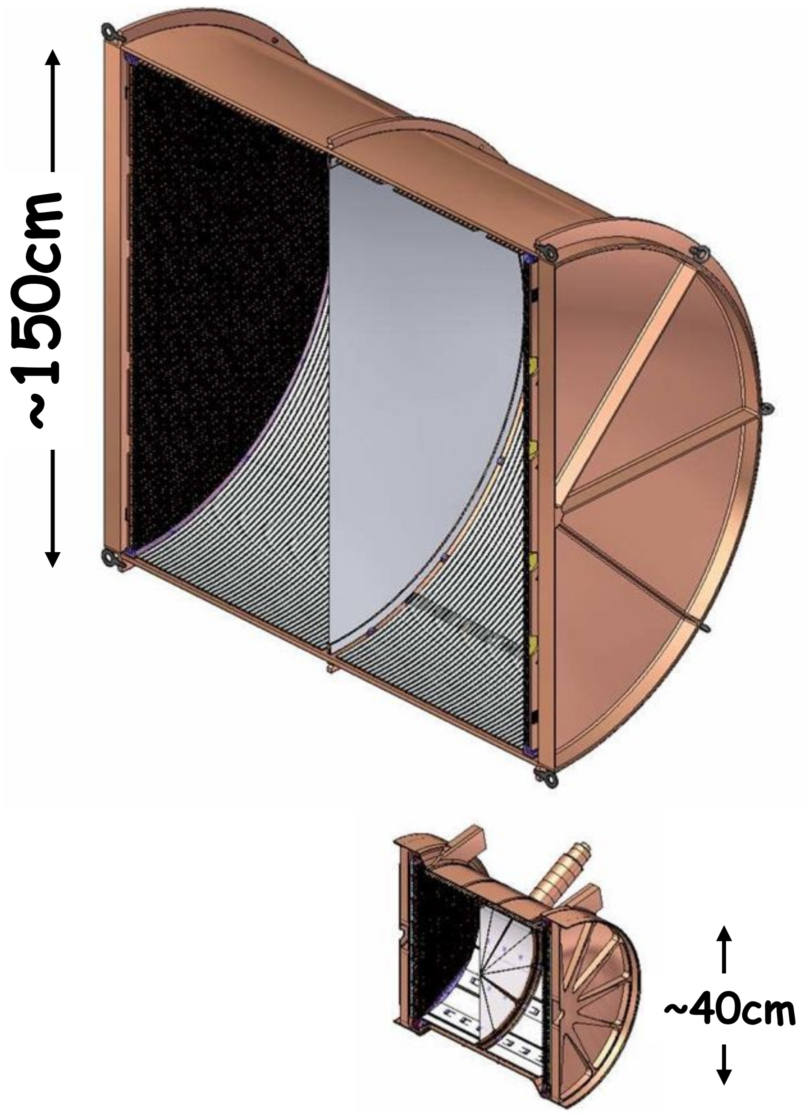
$T_{1/2}^{0\nu\beta\beta} > 1.6\cdot 10^{25}$ yr

$\langle m_{\beta\beta}\rangle$ < 140–380 meV (90% C.L.)

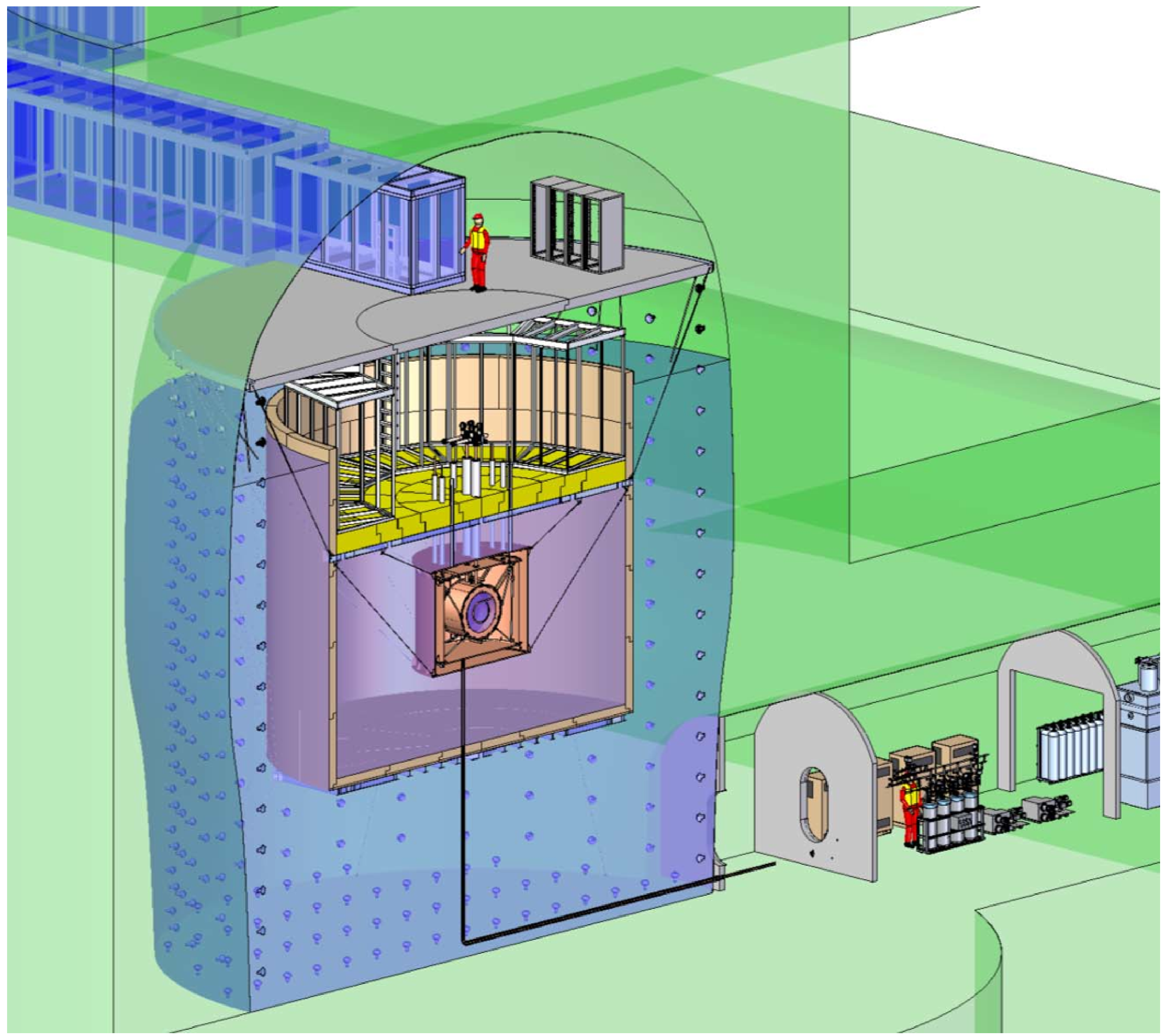
Phys.Rev.Lett 109 (2012) 032505 (arXiv:1205.5608)

KamLAND-ZEN
Phys.Rev.Lett. 110 (2013) 062502
(arXiv:1211.3863)

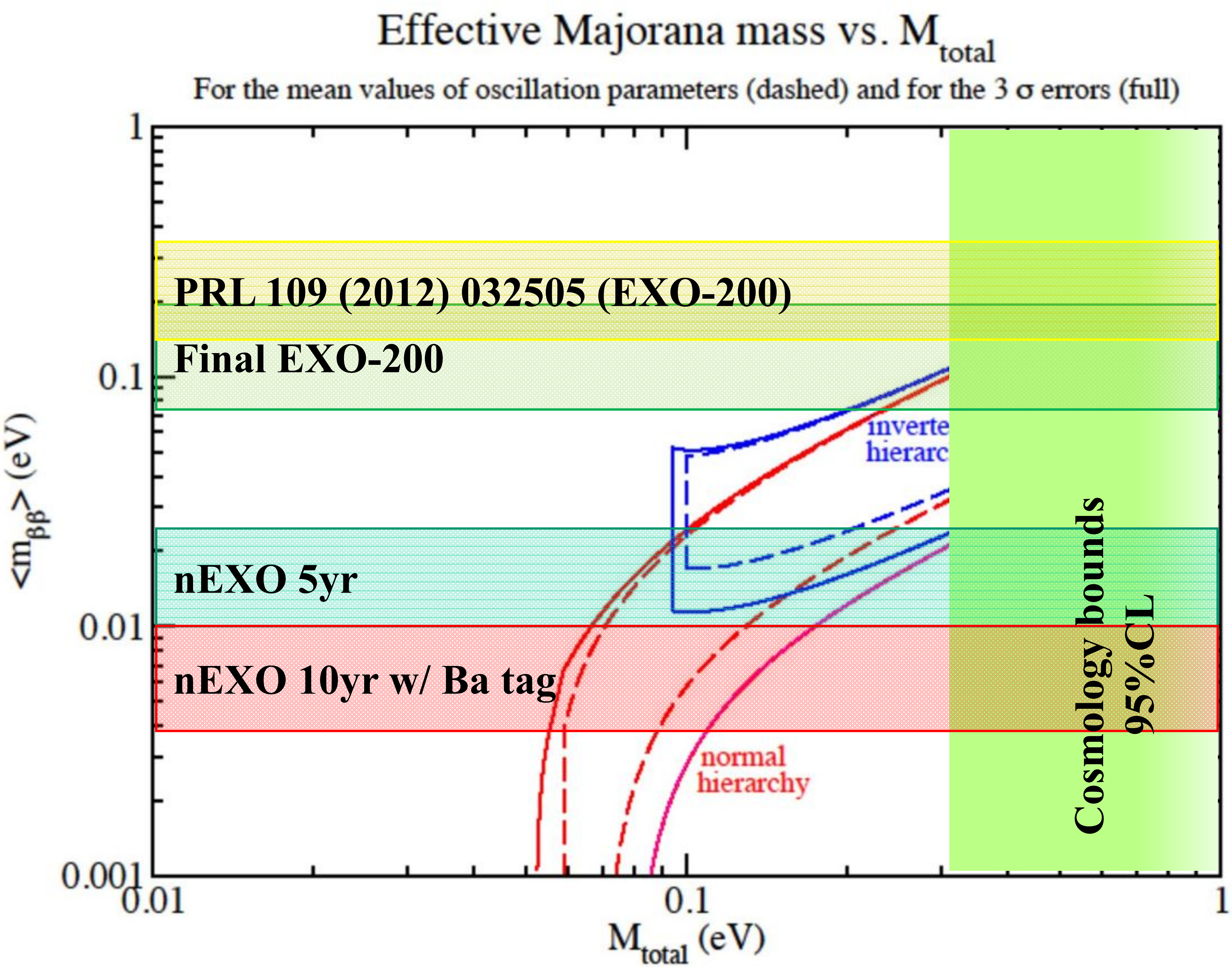
nEXO: 5 tonne LXe TPC
“as similar to EXO-200 as possible”



Sketch of nEXO in the SNOlab Cryopit



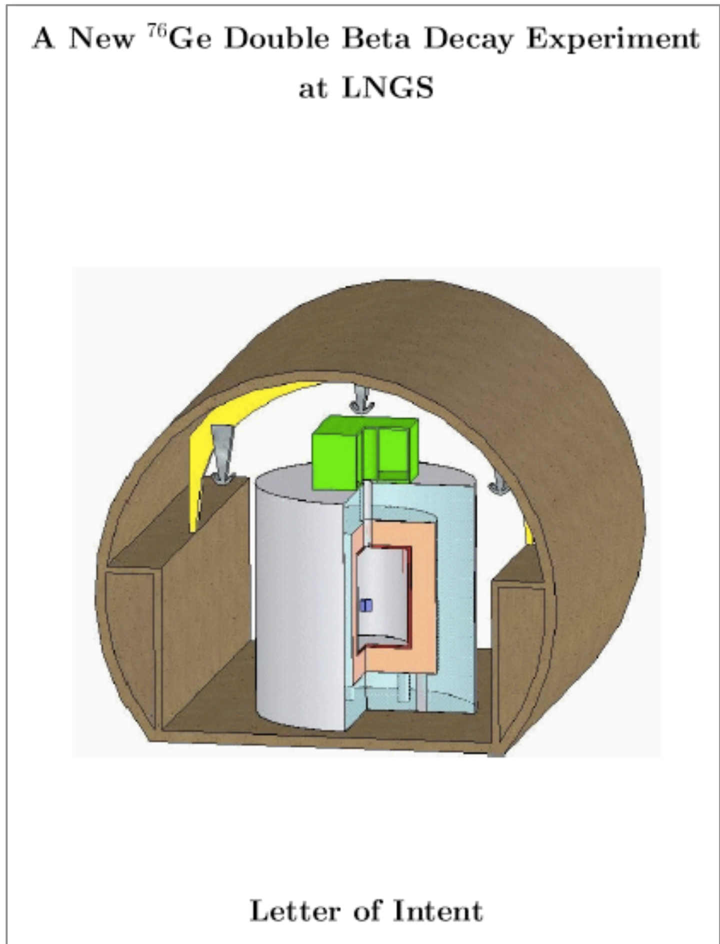
Constraints on neutrino masses



[32.5 kg-yr]

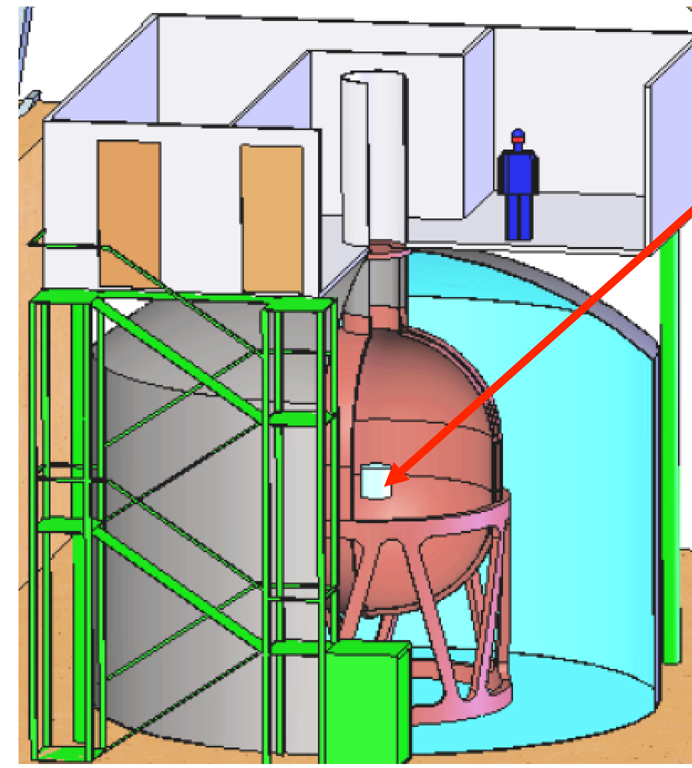
[5 tonne enriched Xe cost: ~$80 M (USD) for the isotope alone]

GERDA @ LNGS



A New ^{76}Ge Double Beta Decay Experiment at LNGS

Letter of Intent

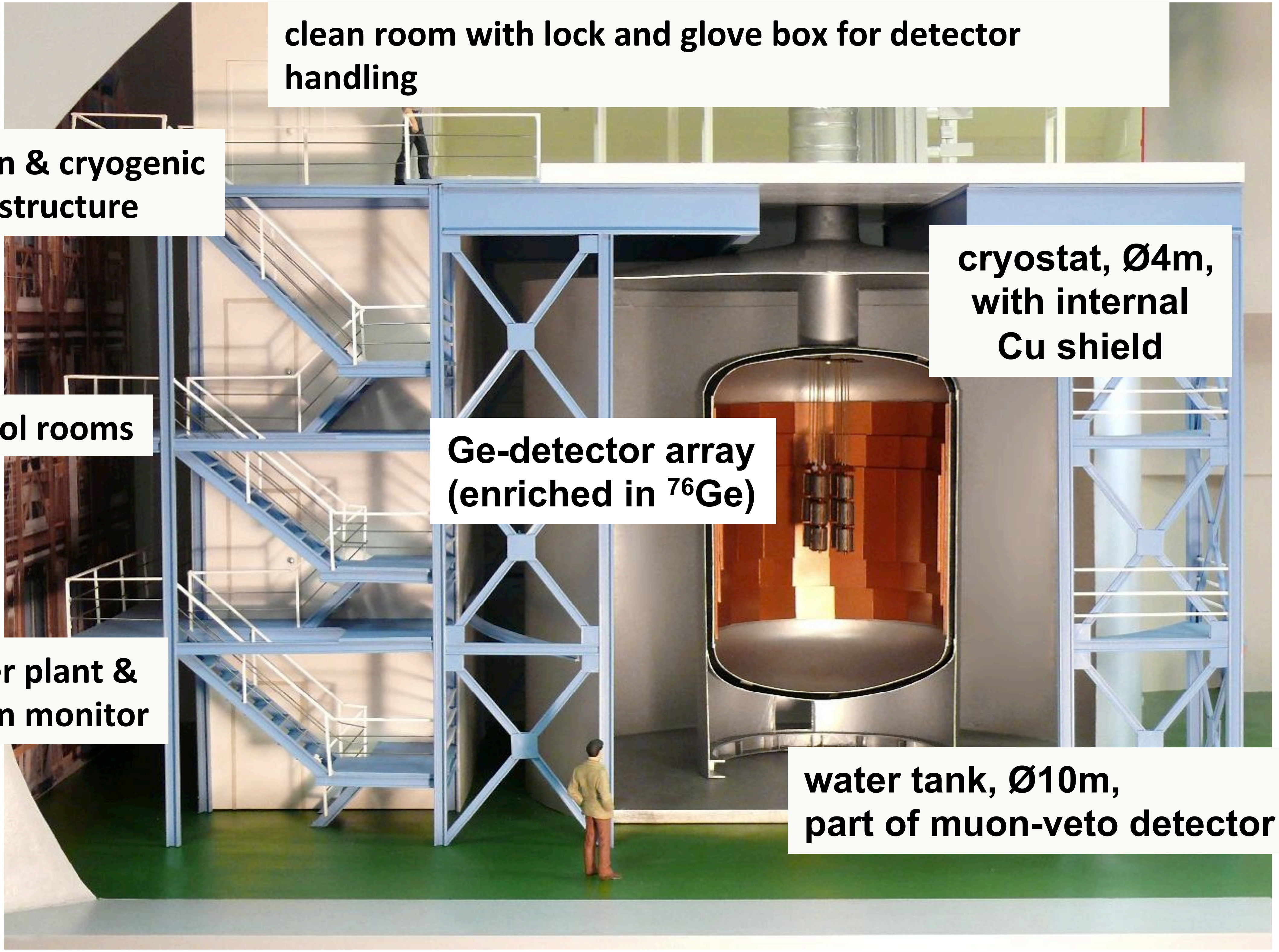


- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX)
- Phase II: add ~20 kg new enriched detectors

[excellent energy resolution of Ge detectors, careful control of backgrounds]

The GERDA experiment

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



Nov 2011: deployment of 3-string & start of phase I physics runs

8 refurbished enriched diodes from HdM & IGEX
- 86% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

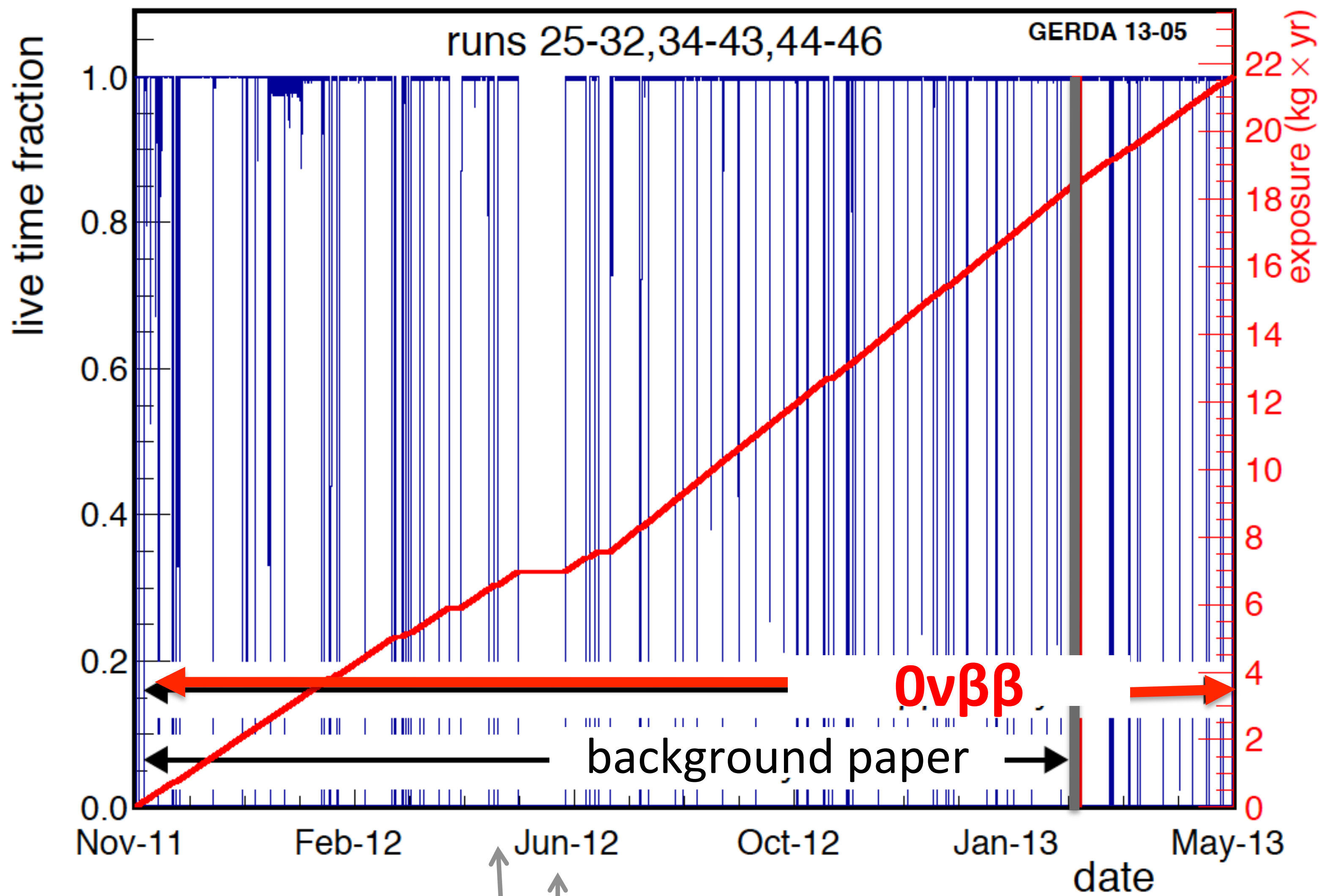
2 diodes shut off because leakage current high:
- total enriched enriched detector mass 14.6 kg

Overview of data taking

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

Total exposure for $0\nu\beta\beta$ analysis: 21.6 kg yr

(bi-)weekly calibration runs ('spikes')



Insertion of 5 Phase II ^{enr}BEGe

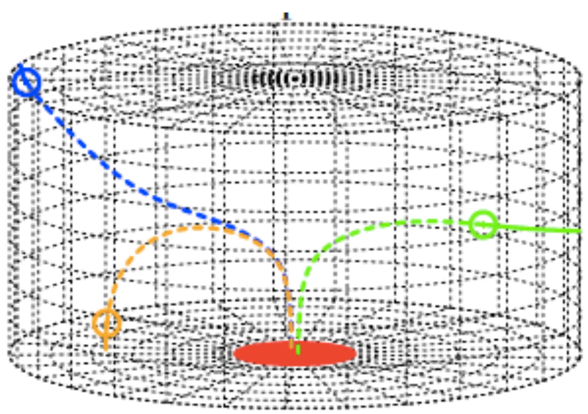
1^{st} physics: $2\nu\beta\beta$ analysis (5.04 kg yr)

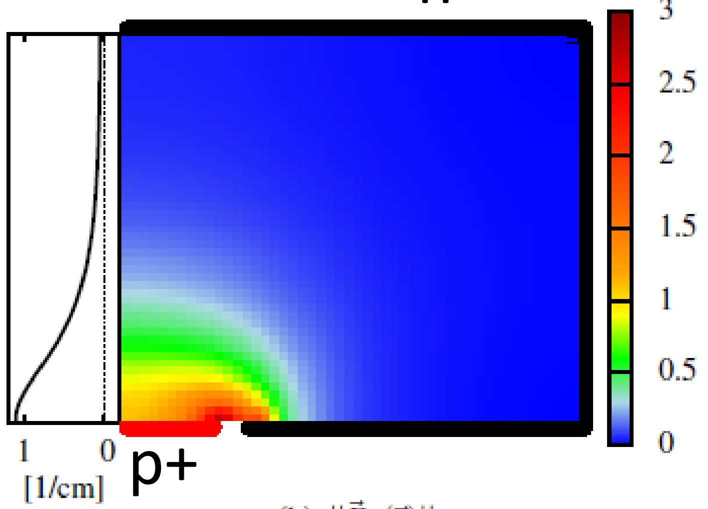
Data blinding:

- All events in $Q_{\beta\beta}\pm20$ keV removed in Tier 1
- 2 copies of raw data kept for processing after unblinding

Pulse shape discrimination: BEGe

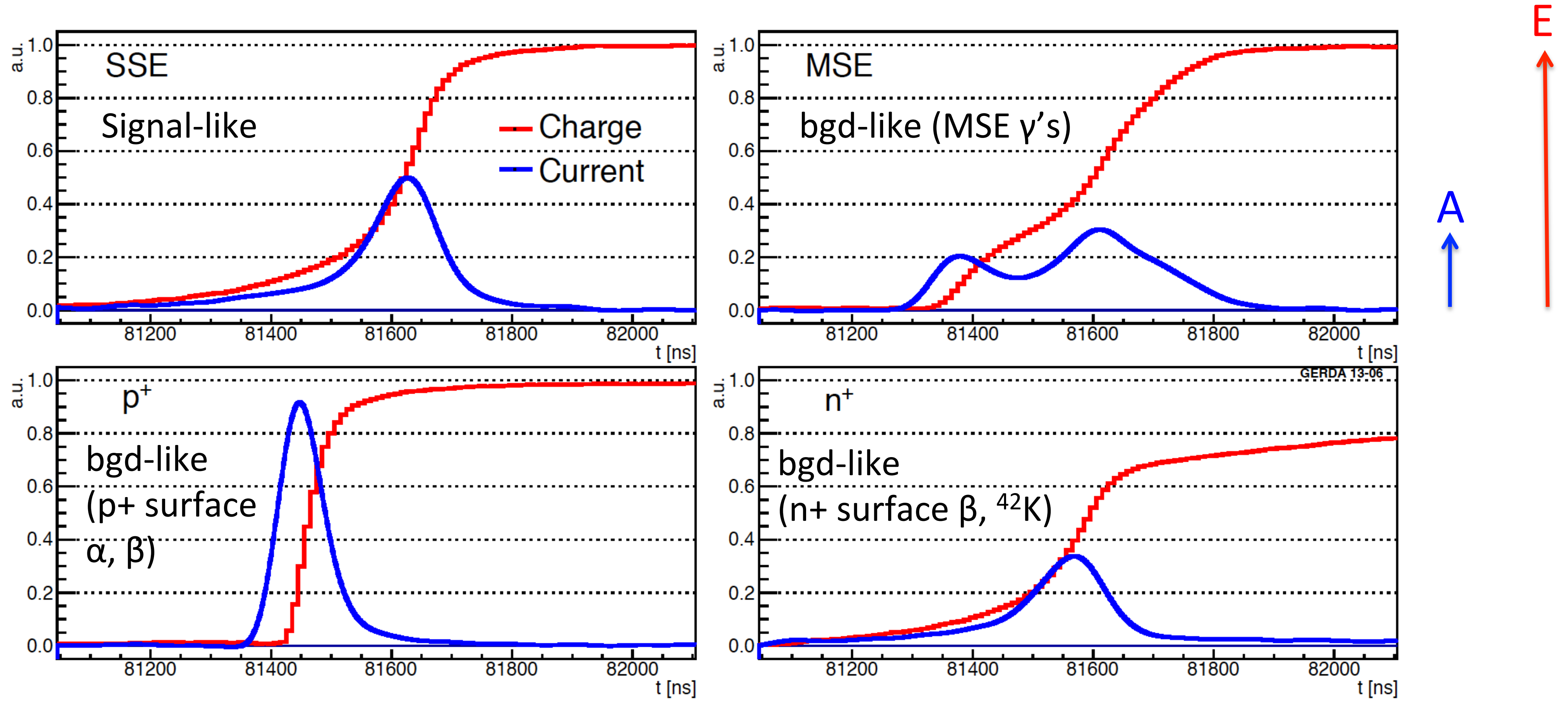
arXiv:1307.2610



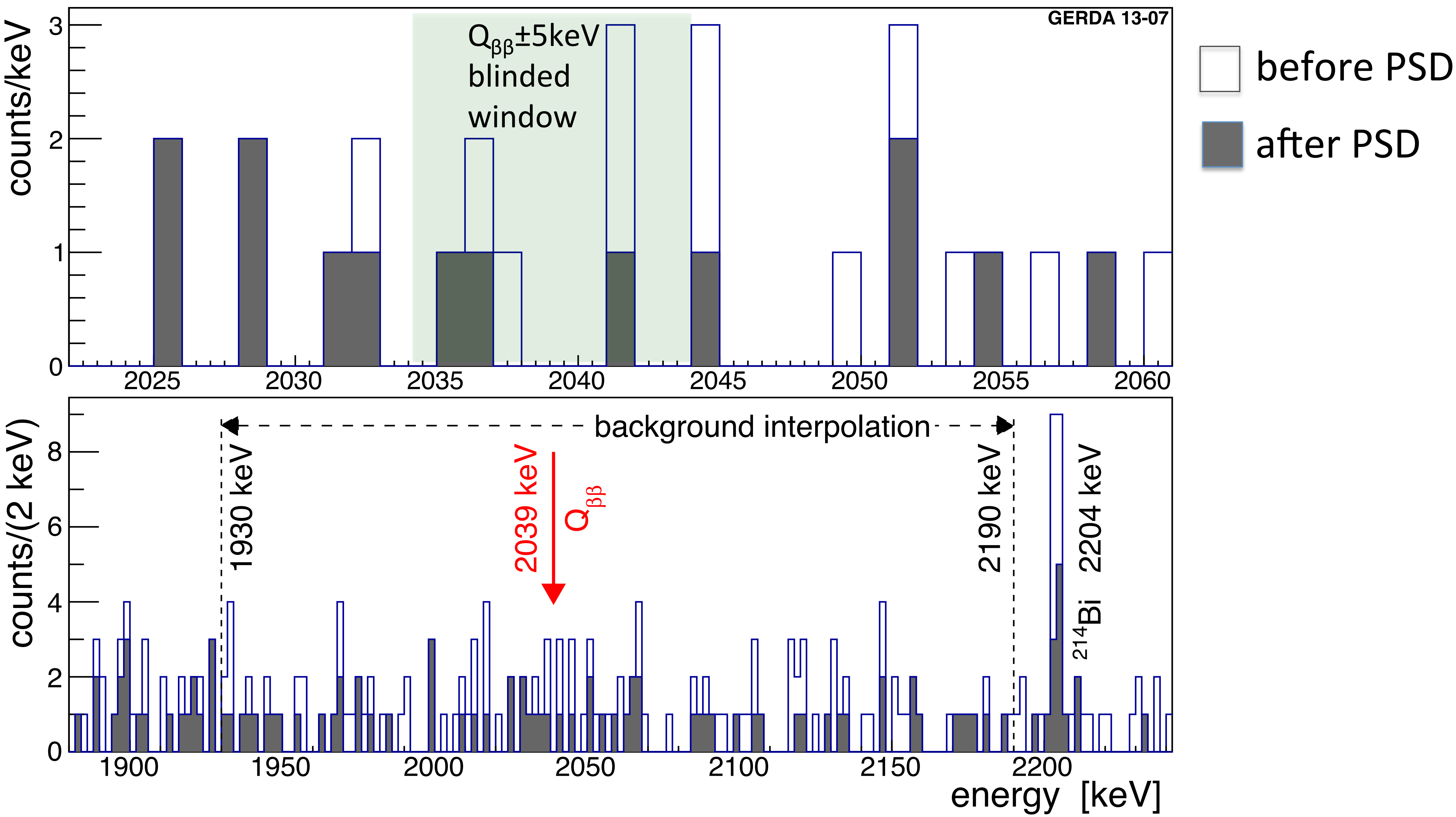


(b) $||\vec{E}_w(\vec{r})||$

PSD discrimination parameter: A/E



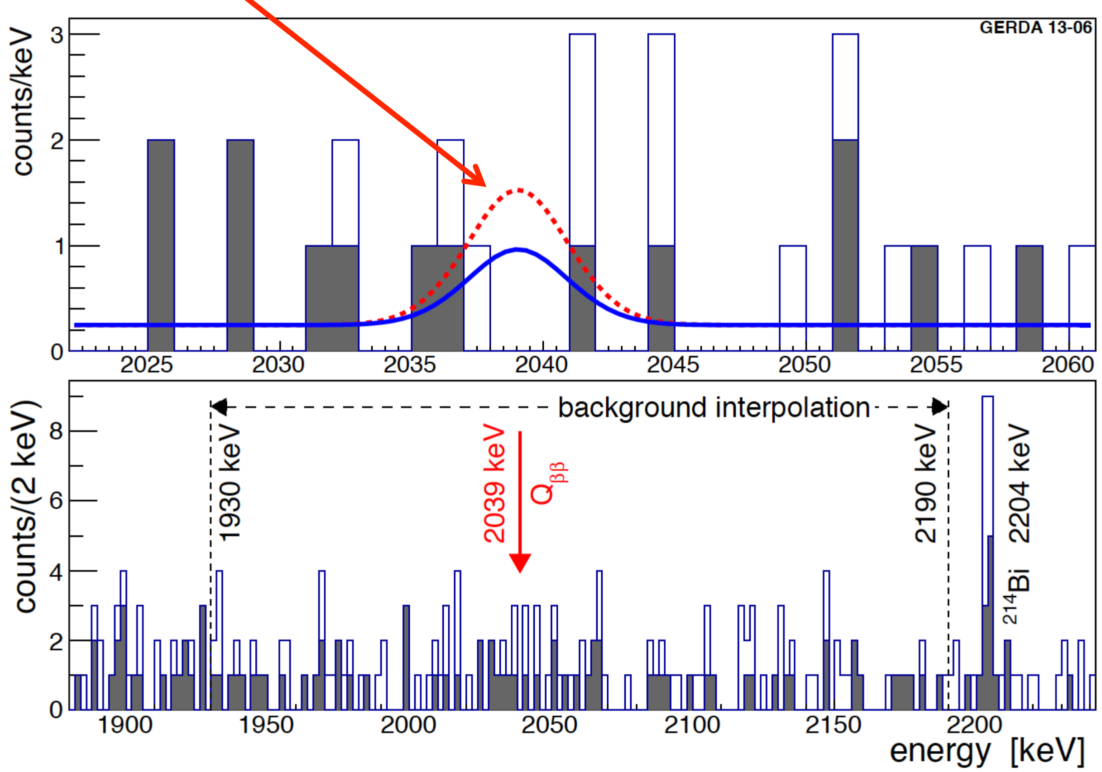
Unblinding: full data set (21.6 kg yr)

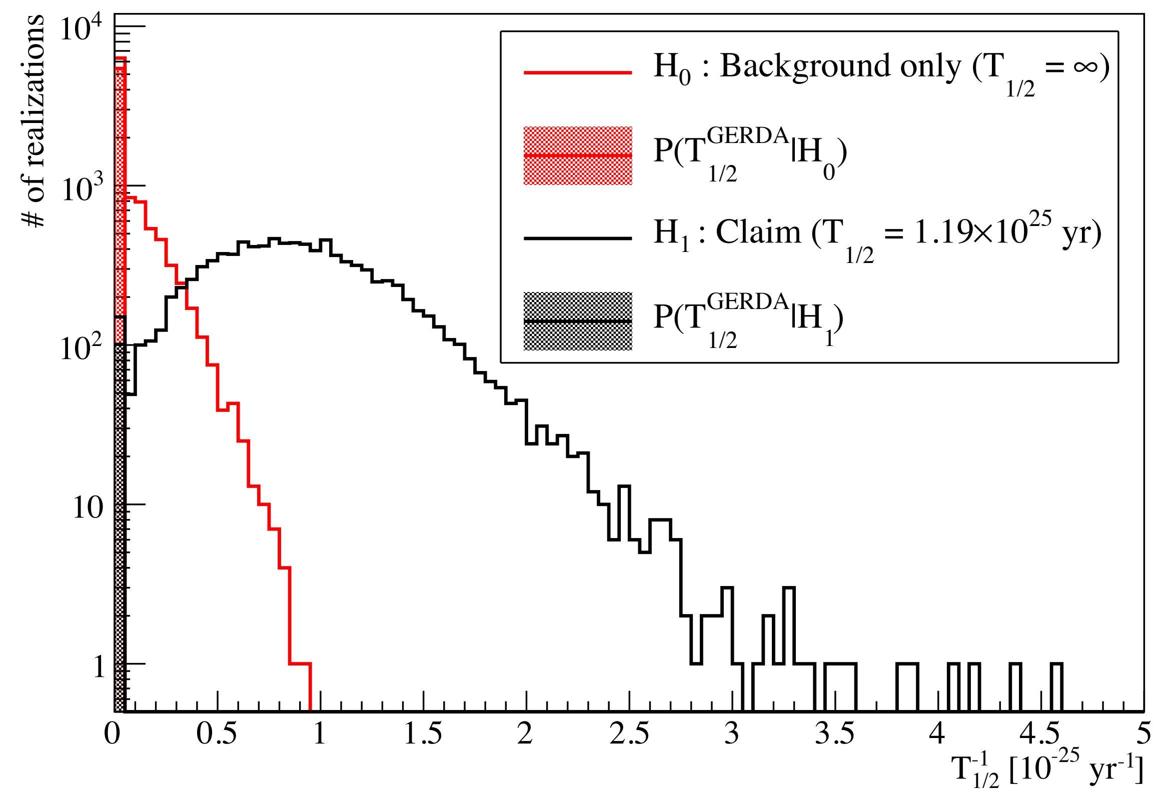


Full data set: 7 event in blinded window
3 event survive PSD cut

Expectation for claimed $T_{1/2}^{0\nu}$ =1.19×10^{25} yr (Phys. Lett. B 586 198 (2004)):

5.9±1.4 signal over 2.0±0.3 bgd in ±2σ energy window to be compared with 3 cts (0 in ±1σ)





H1: claimed signal plus background

H0: background only

Bayes factor: P(H1)/P(H0)=0. 024

p-value from profile likelihood

P(N=0|H1) = 0. 01 (0.006 if 1/T unconstrained)

→ Claim refuted with high probability

Summary & Outlook

- **GERDA Phase I design goals reached:**
  - Background index after PSD: 0.01 cts / (keV kg yr)
  - Exposure 21.6 kg yr *[HdM exposure: 35.5 kg-yr]*

- **No $0\nu\beta\beta$-signal observed at $Q_{\beta\beta}$ = 2039 keV; best fit: $N^{0\nu}$=0**
  - Background-only hypothesis H_0 strongly favored
  - Claim strongly disfavored (independent of NME and of leading term)

- **Bayes Factor / p-value:**
  GERDA: 2.4×10^{-2} / 1.0×10^{-2}
  GERDA+IGEX+HdM: 2×10^{-4} / -

- **Limit on half-life:**
  GERDA: $T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)
  GERDA+IGEX+HdM: $T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.) ($\langle m_{ee}\rangle < 0.2$-$0.4$ eV)

- Results reached after only 21.6 kg yr exposure because of **unprecedented low background:** bgd expectations in ±2σ after analysis cuts and correcting for efficiencies: 0.01 cts /(mol yr) (cf. EXO: 0.07, KL: 0.2)

- **Getting ready for Phase II.....**

Transition to GERDA Phase II

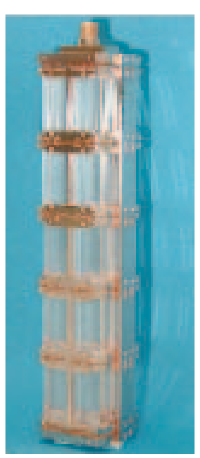
- Phase I ended September 30, 2013 – all Phase I detectors dismounted
- Phase II: additional 30 enriched BEGe detectors (adding 20 kg)
  - already produced by Canberra Olen and completely tested at Hades (Belgium)
- Suppress background by factor > 10
  - new front-end readout in close proximity (2 cm) to detectors and new front-end cabling
  - new HV and signnal cabling with improved radiopurity and lower Rn emanation
  - PSA discrimination with BEGe's
  - liquid argon scintillation veto being instrumented

- Ready for deployment of Phase II hardware in Spring 2014

0νββ research with TeO_2

- ^{130}Te is a good DBD candidate ($^{130}Te \rightarrow {}^{130}Xe + 2e^-$) with high natural i.a. (34.2 %) and reasonably high Q-value (Q~2528 keV) leading to high G(Q,Z) and low background
- TeO_2 is a compound with good mechanical and thermal properties containing ^{130}Te
- 5x5x5 cm^3 TeO_2 crystals have a high detection efficiency for 0νββ events: ~87.4%

MiDBD
1.8 kg ^{130}Te

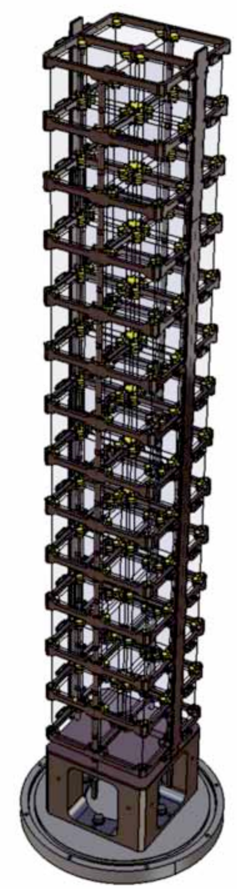


1997-2001

Cuoricino
11.3 kg ^{130}Te

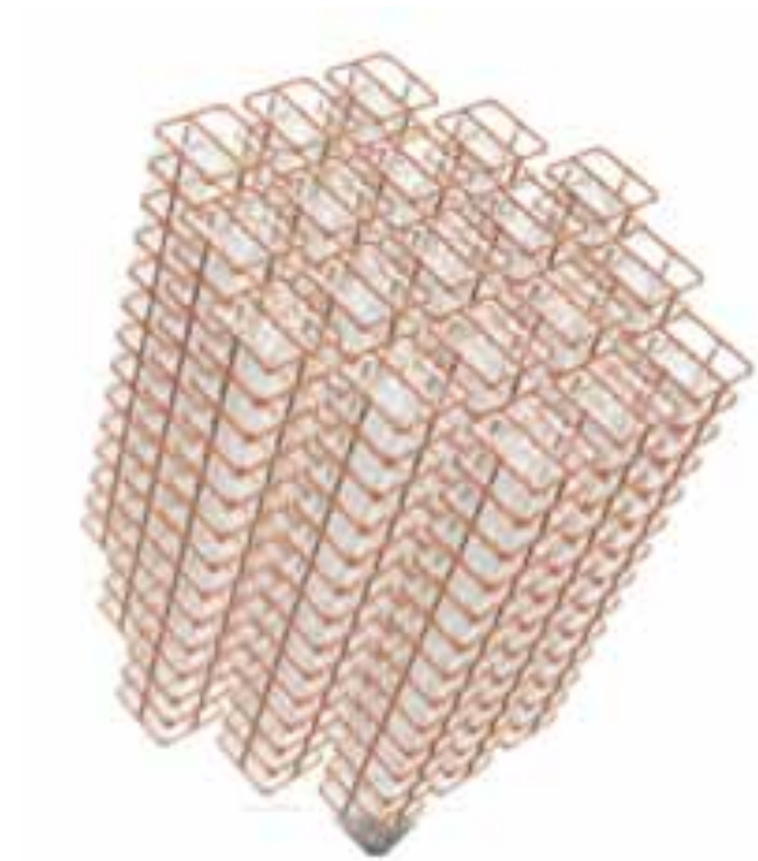
2003-2009

CUORE-0
11 kg ^{130}Te



2012...2014

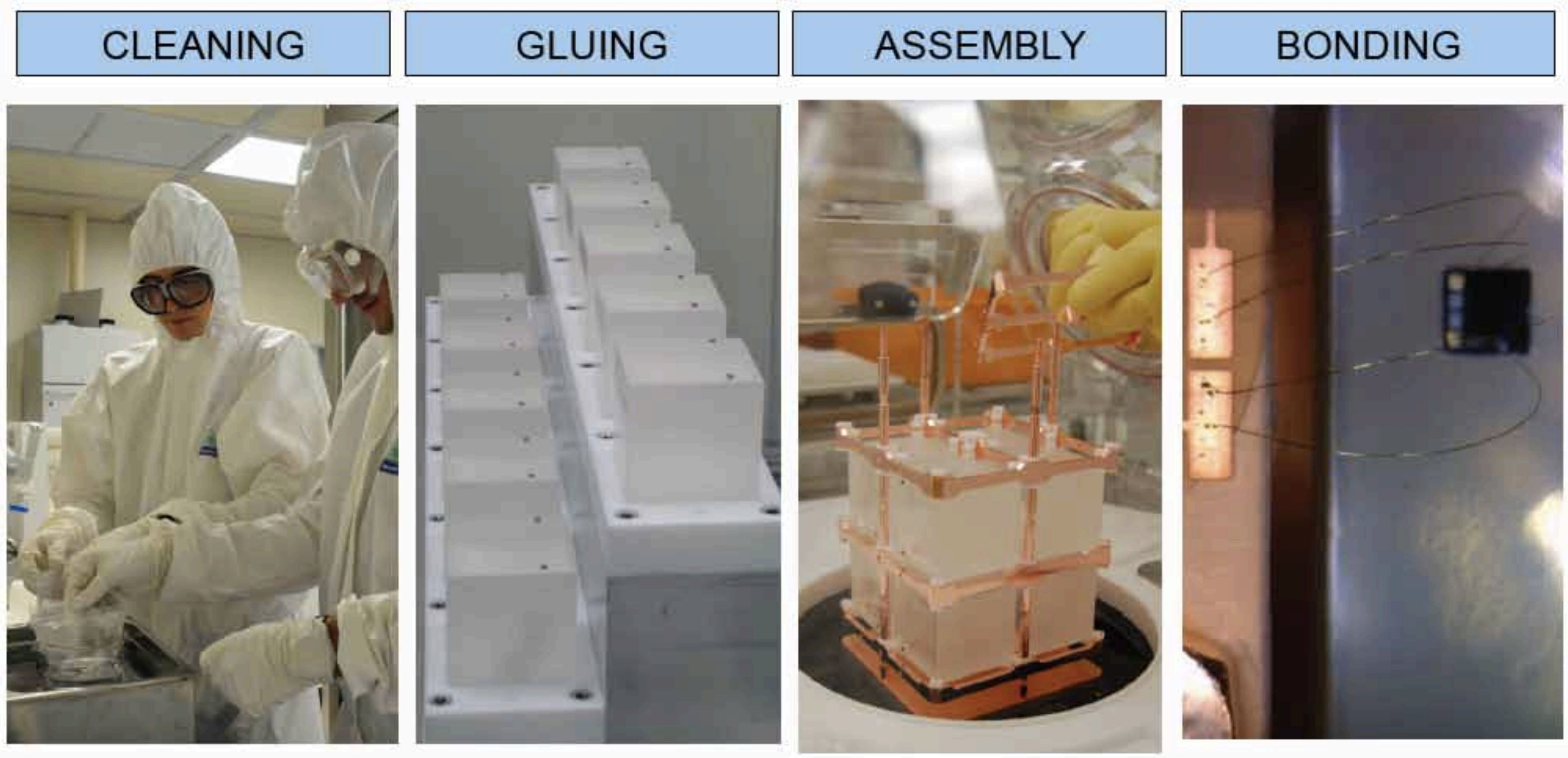
CUORE
206 kg ^{130}Te



2014...

[exquisite energy resolution of a bolometer, careful control of backgrounds, 34% natural abundance of ^{130}Te (no need to enrich)]

Detector assembly approach



CLEANING

- Gluing consumables
- Periodic cleaning of glove boxes (every ~ 3 towers)

GLUING

- Attach NTDs & heaters to crystals

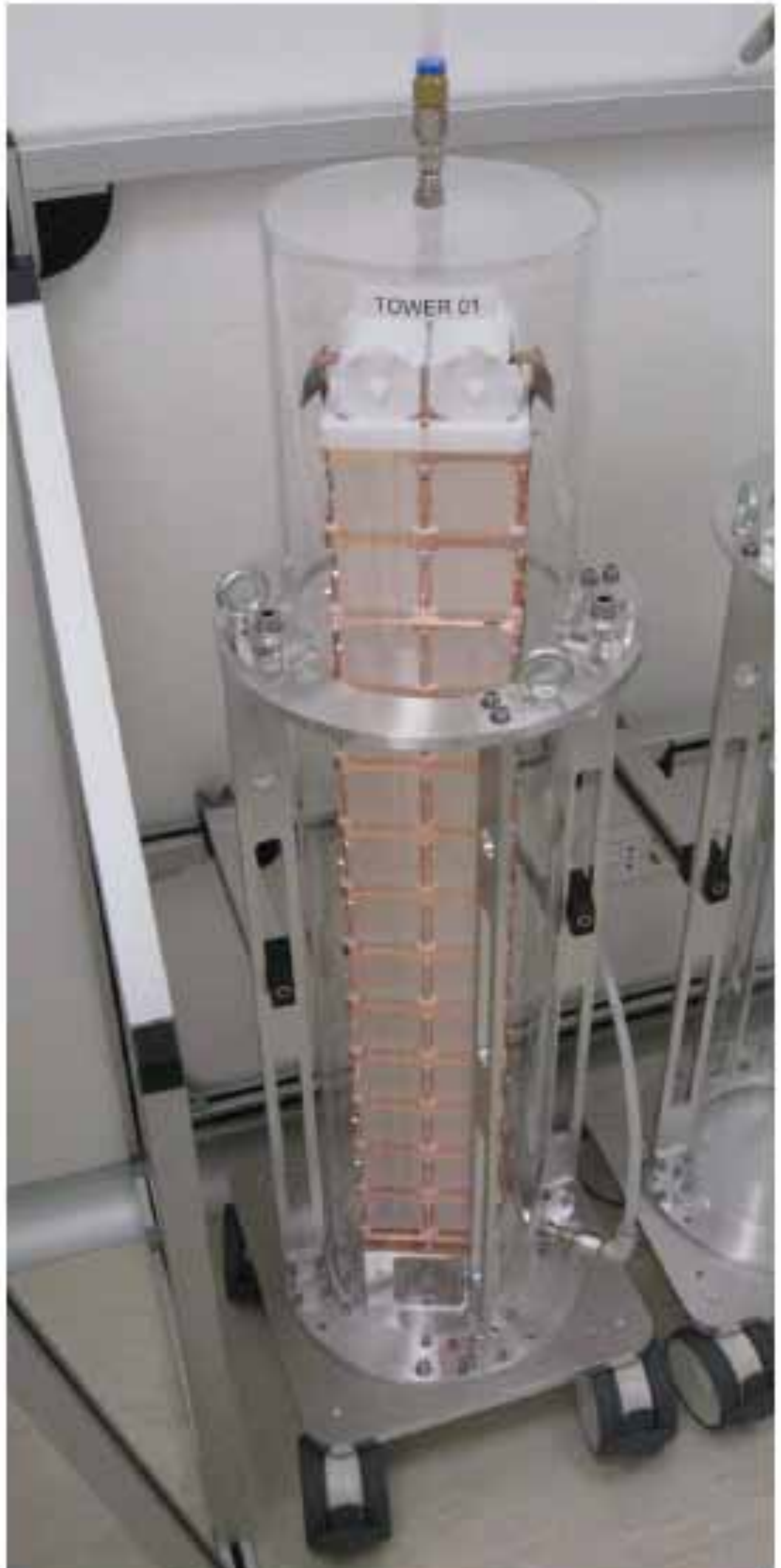
ASSEMBLY

- Mechanical assembly of crystals and copper into towers

BONDING

- Bond Au wires connecting NTDs & heaters to external traces

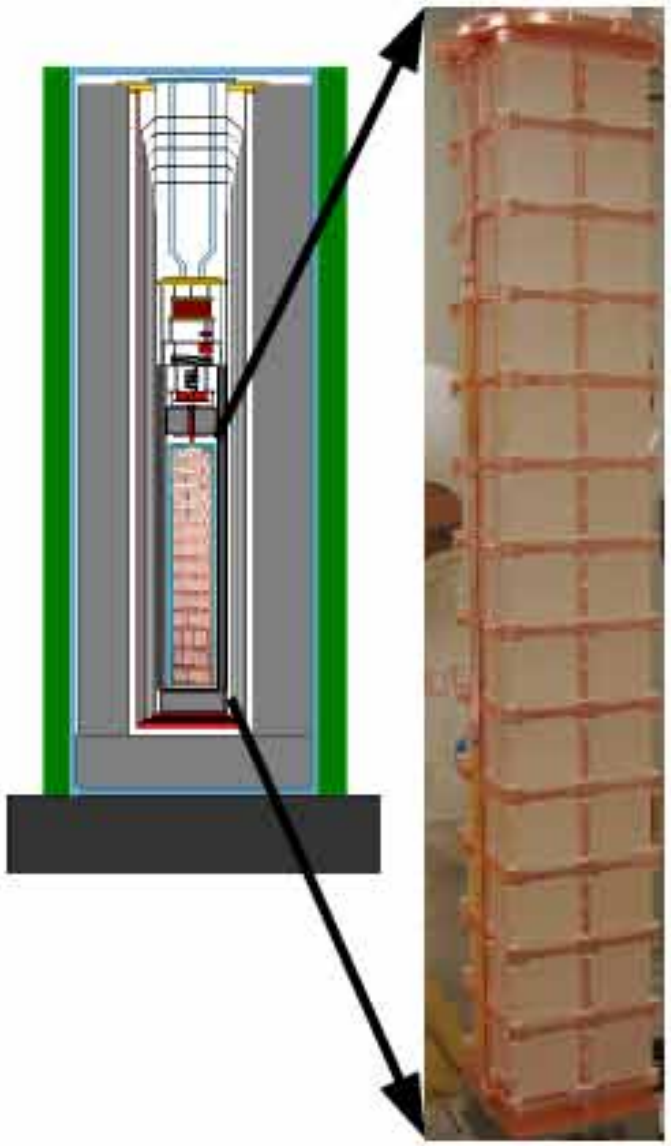
CUORE Status and schedule



- Detector assembly started in February 2013 and will finish in June 2014
  - Crystals for 10 towers already glued with heaters and thermistors
  - 7 towers assembled
  - 4 towers already bonded and put to storage (+3 by the end of october)
- Cryostat commissioning and tests are ongoing and will be completed in June 2014
- Detector installation and commissioning will take place in the second half of 2014
- Data taking will start at the beginning of 2015

Meanwhile….

CUORE-0: the Demonstrator



- A single CUORE-like tower:
  - 52 5x5x5 cm^3 TeO_2 bolometers

- Test of the CUORE cleaning procedures
- Test of the CUORE assembly procedures
- A sensitive 0vDBD experiment

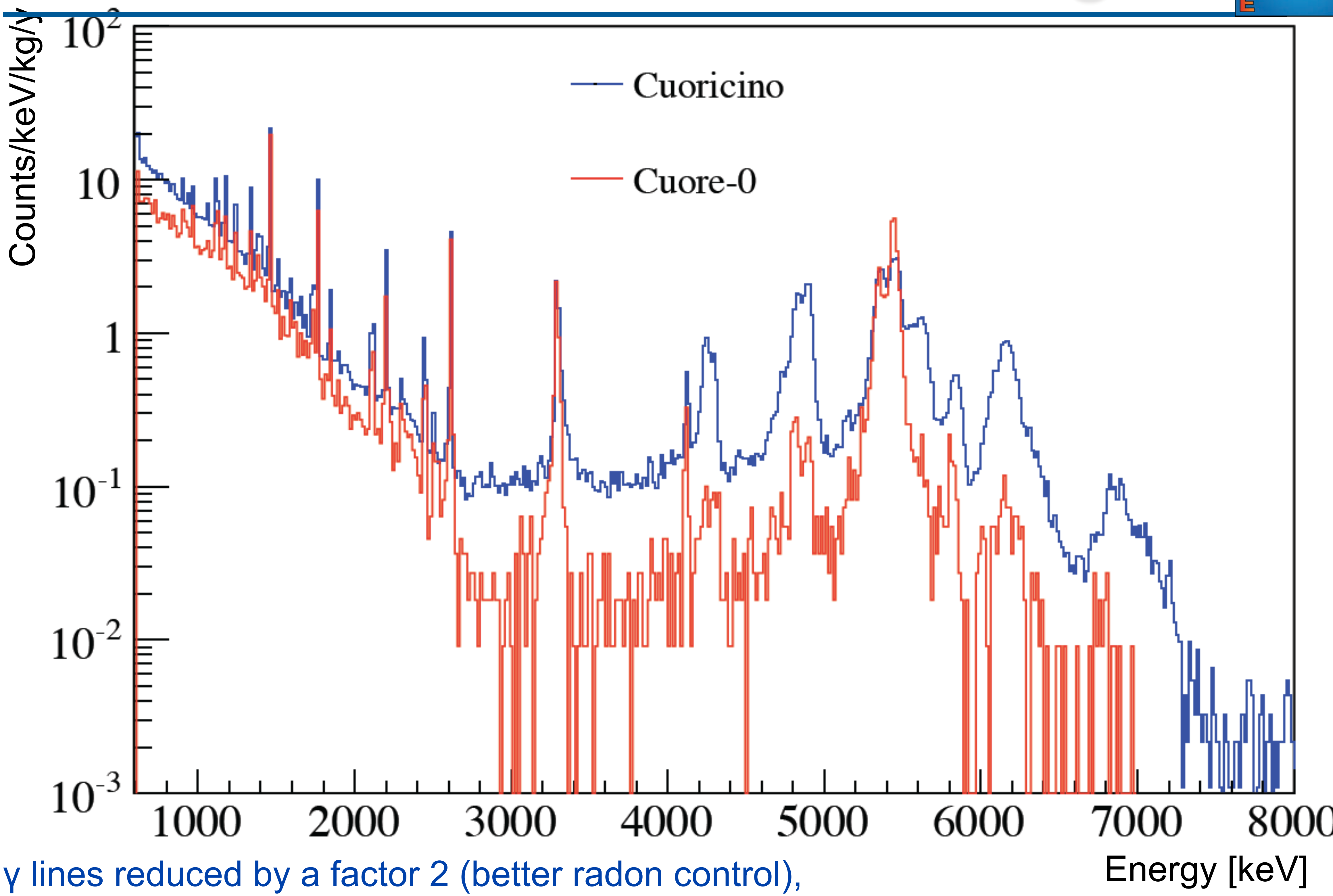
- Same detector mass as CUORICINO:
  - TeO2 mass: 39 kg
  - 130Te mass: 11 kg

- Shielding:
  - Internal and external lead shield
  - Borated pohlyethylene shield
  - Anti radon box

Started data taking in March 2013

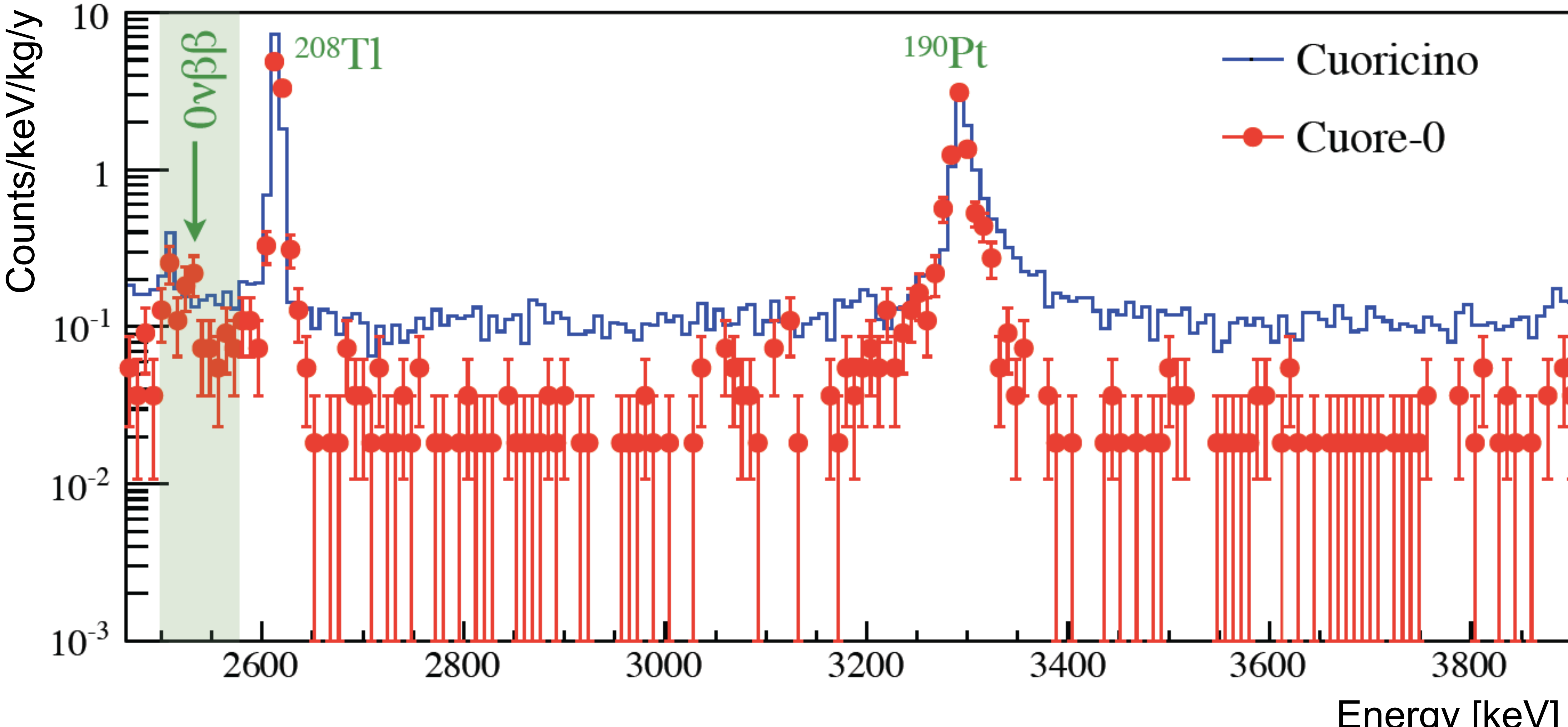
Operated in the CUORICINO cryostat:
γ background not expected to change ➡ study α background

Cuore-0 vs Cuoricino bkg



^{238}U γ lines reduced by a factor 2 (better radon control),
^{232}Th γ lines not reduced (originate from the cryostat).
^{238}U and ^{232}Th α lines reduced thanks to the new detector surface treatment.

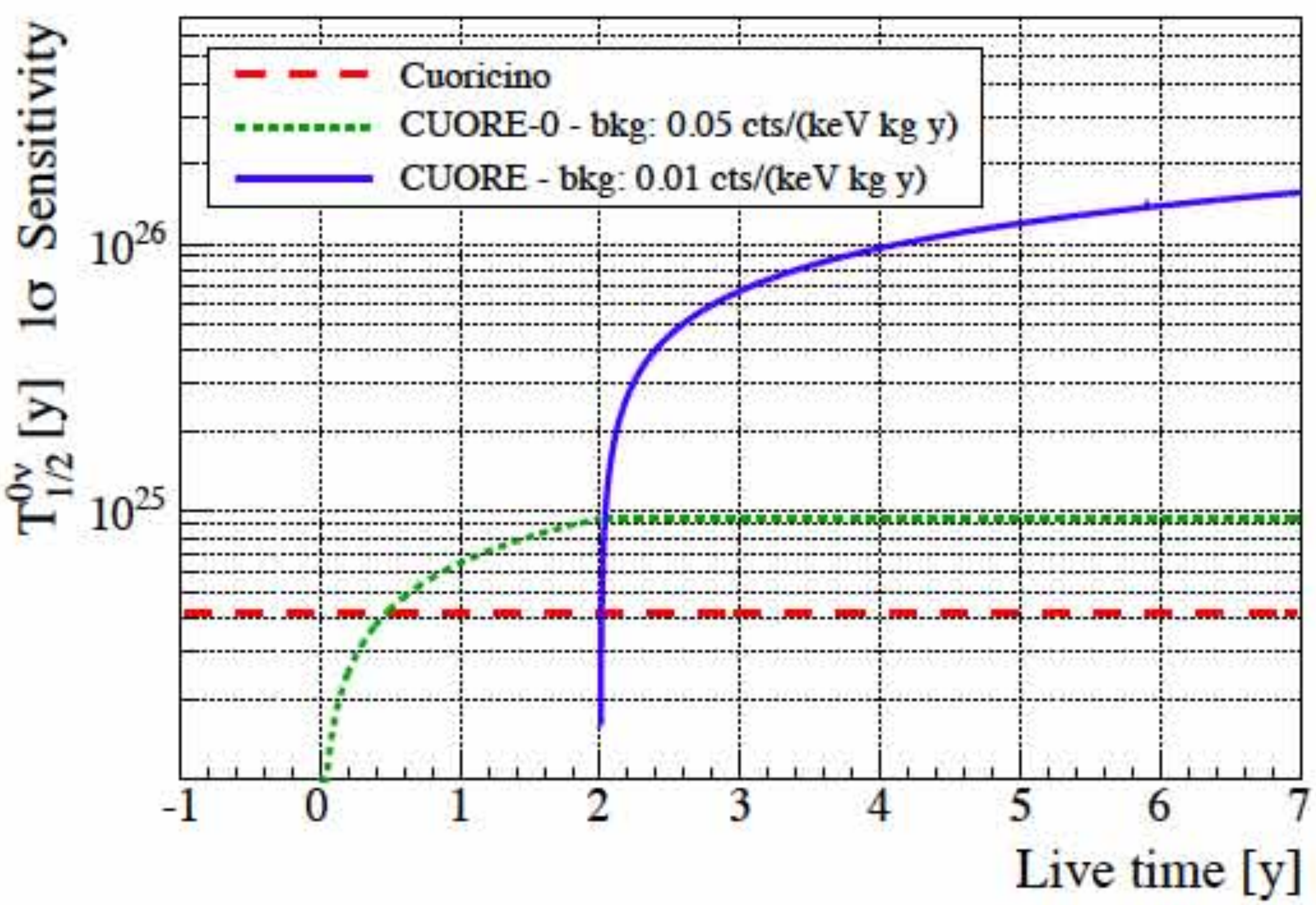
Flat alpha background

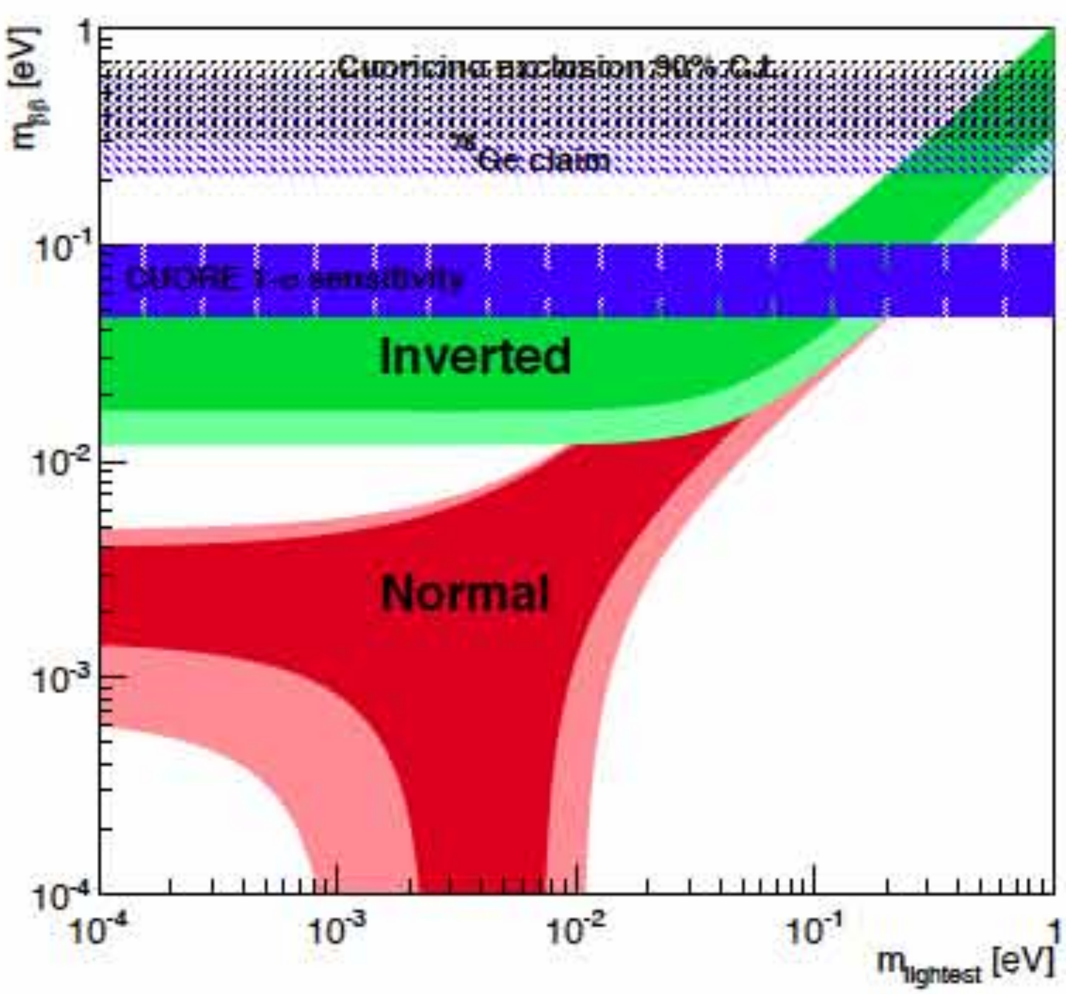


	Avg. flat bkg. [counts/keV/kg/y]		Signal eff. [%]
	$0\nu\beta\beta$ region	2700-3900 keV	(detector+cuts)
CUORICINO	0.153 ± 0.006	0.110 ± 0.001	83 ± 1
CUORE0	0.074 ± 0.012	0.019 ± 0.002	78 ± 1

Cuore-0 and Cuore Sensitivities

- 1σ sensitivity $T_{1/2}^{0\nu\beta\beta} = 1.6 \times 10^{26}$ y; effective Majorana mass down to 47-100 meV.
  - Assuming a background rate of 10^{-2} counts/(keV kg y), and 5 keV FWHM
  - 5 years of live time
- Detector assembly will be finished by June 2014, followed by installation in July and commissioning by the end of 2014.
- Data taking will start in 2015.



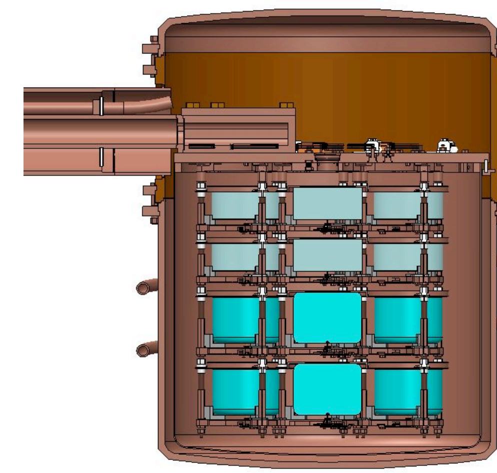


[excellent energy resolution of Ge detector, careful control of backgrounds]

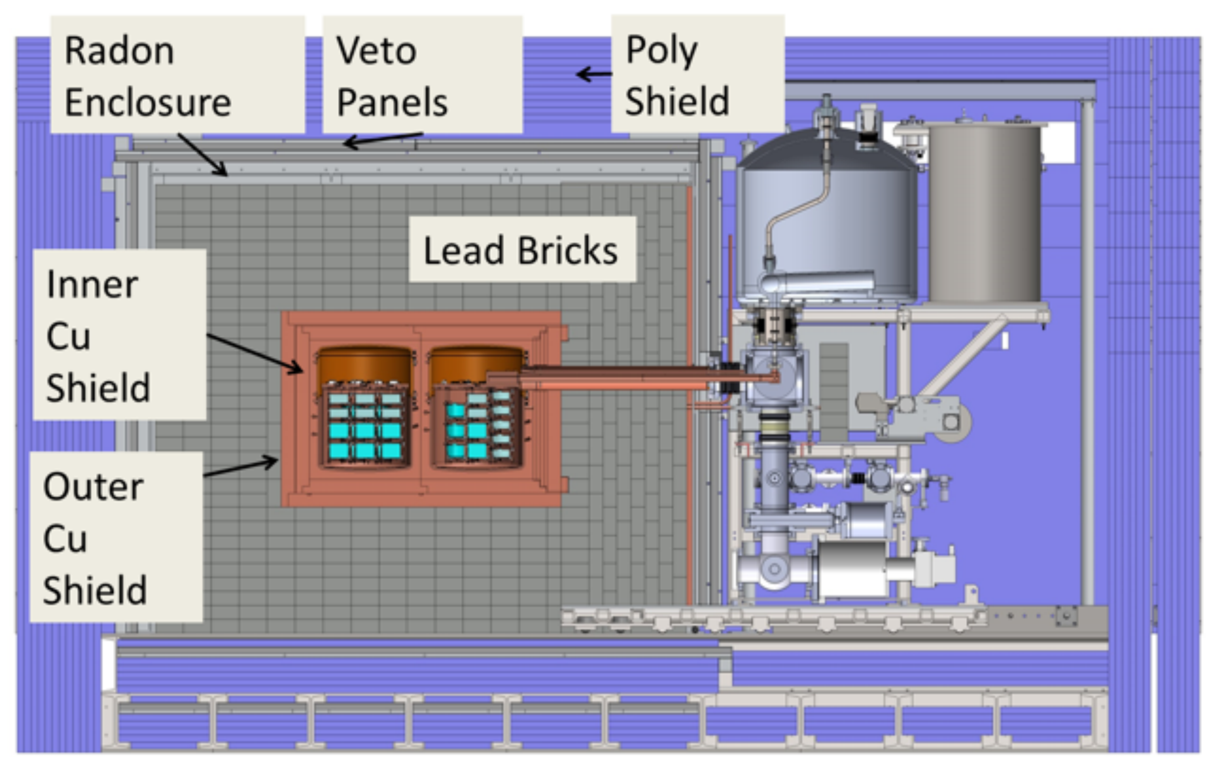
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics, with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Test Klapdor-Kleingrothaus claim.
- Searches for additional physics beyond the standard model.



- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  3 counts/ROI/t/y (after analysis cuts)
  scales to 1 count/ROI/t/y for a tonne experiment
- **40-kg of Ge detectors**
  – 30 kg of 86% enriched ^{76}Ge crystals
  – 10 kg of ^{nat}Ge
  – Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  – ultra-clean, electroformed Cu
  – 20 kg of detectors per cryostat
  – naturally scalable
- **Compact Shield**
  – low-background passive Cu and Pb shield with active muon veto

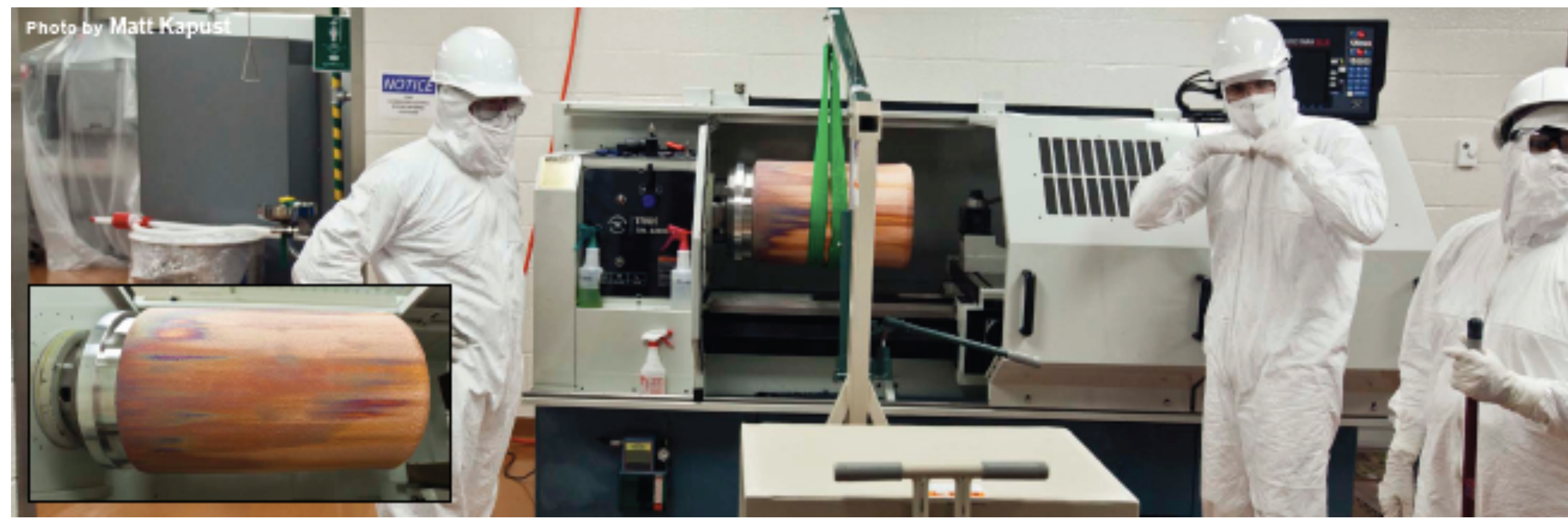


MJD Electroforming Cu

- Produced over 85% of the ultra-clean, low-activity electroformed copper that is used for cryostats, string components, and inner shielding. Most of this material has been electroformed at the Temporary Clean Room (TCR) facility that is being operated at the Ross 4850’ area. All has been machined at the MJD Davis campus.

Insertion of mandel into EF bath

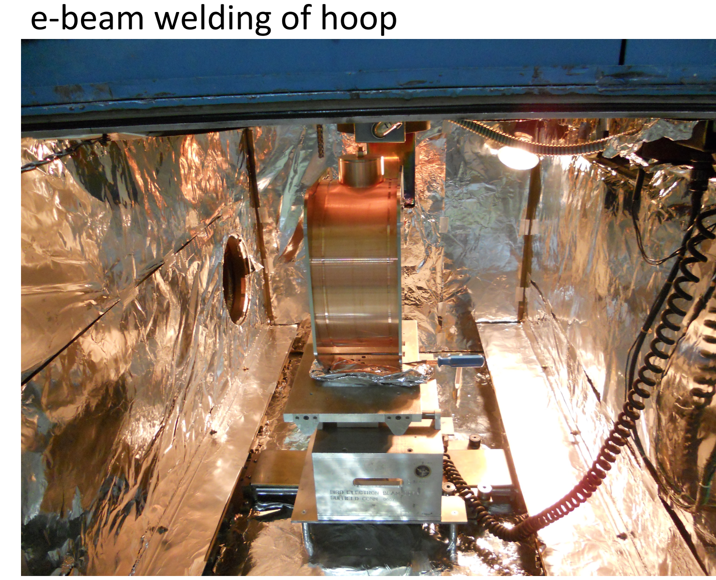
Preparing to machine electroformed copper mandrel in the clean machine shop, MJD Davis Campus, 4850’



Electroforming Baths in TCR

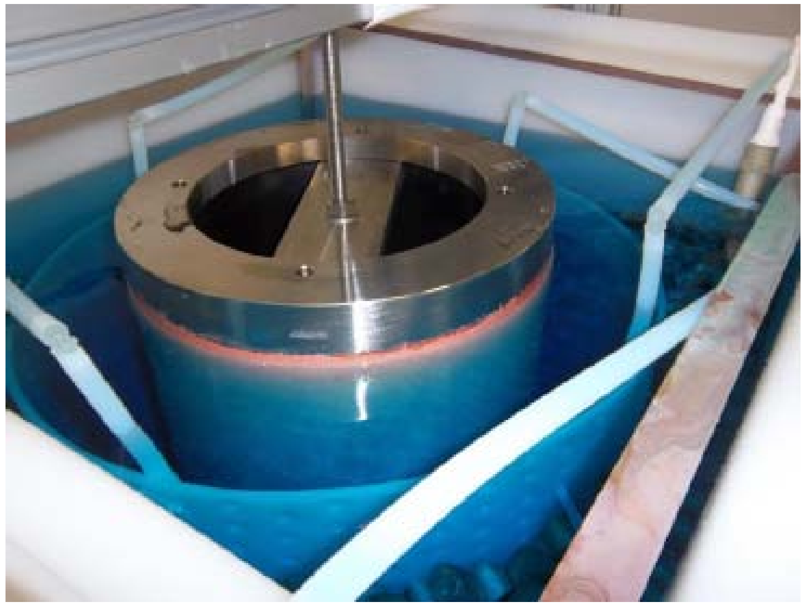
Inspection of EF copper on mandrels

e-beam welding of hoop



The cleanest copper in the world

The temporary clean room at SURF (4850)



Copper being electroformed on a stainless steel mandrel

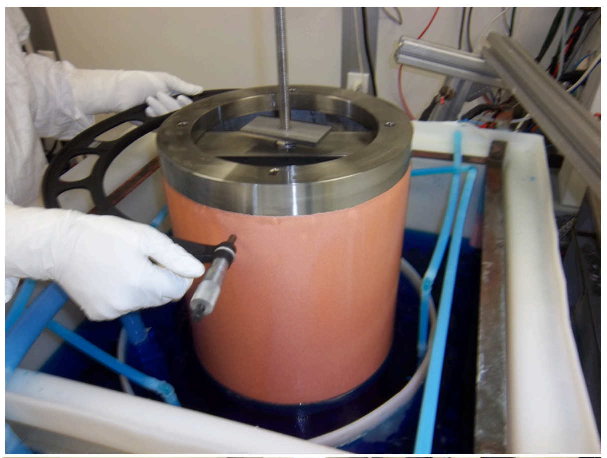
A clean machine shop underground

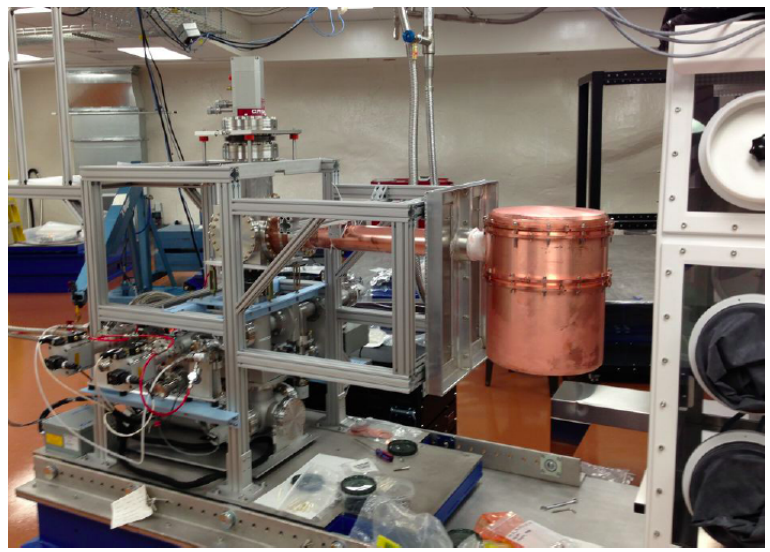
MAJORANA DEMONSTRATOR Summary

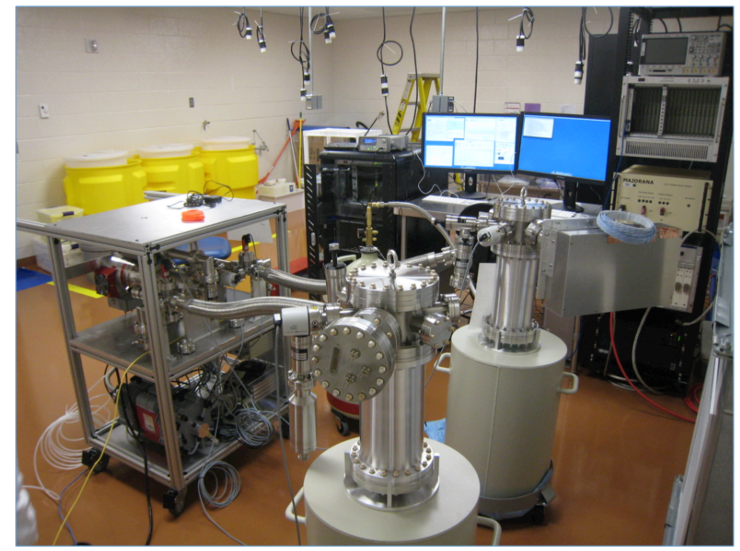
- Construction of MJD underway and proceeding on schedule.
  - Prototype Cryostat : in use
  - Cryostat 1 : Spring 2014
  - Cryostat 2 : FY2015
- Focus is on Cryo 1 activities
  - Cu and enriched detectors in hand
  - Cryo 1 vacuum system and cryostat
  - String building
  - Shield
  - We aim to should start collecting Cryo 1 data in 2014

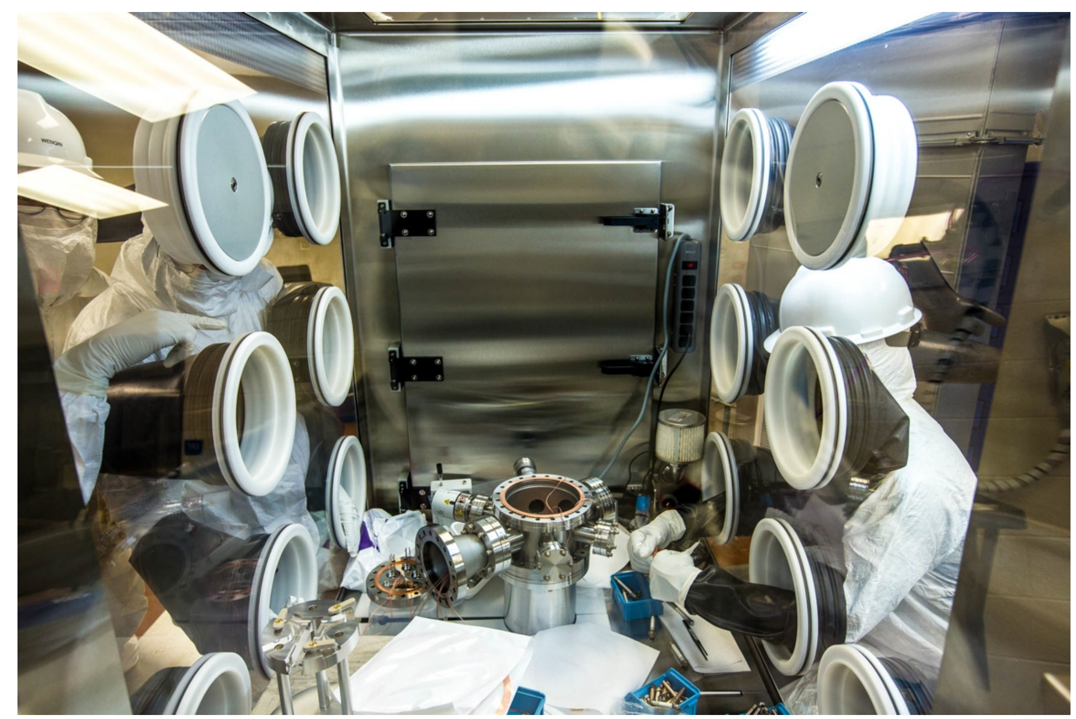
"The MAJORANA DEMONSTRATOR Neutrinoless Double-Beta Decay Experiment"
accepted to Advances in High Energy Physics, arXiv:1308.1633

MJD Progress towards Cryo 1

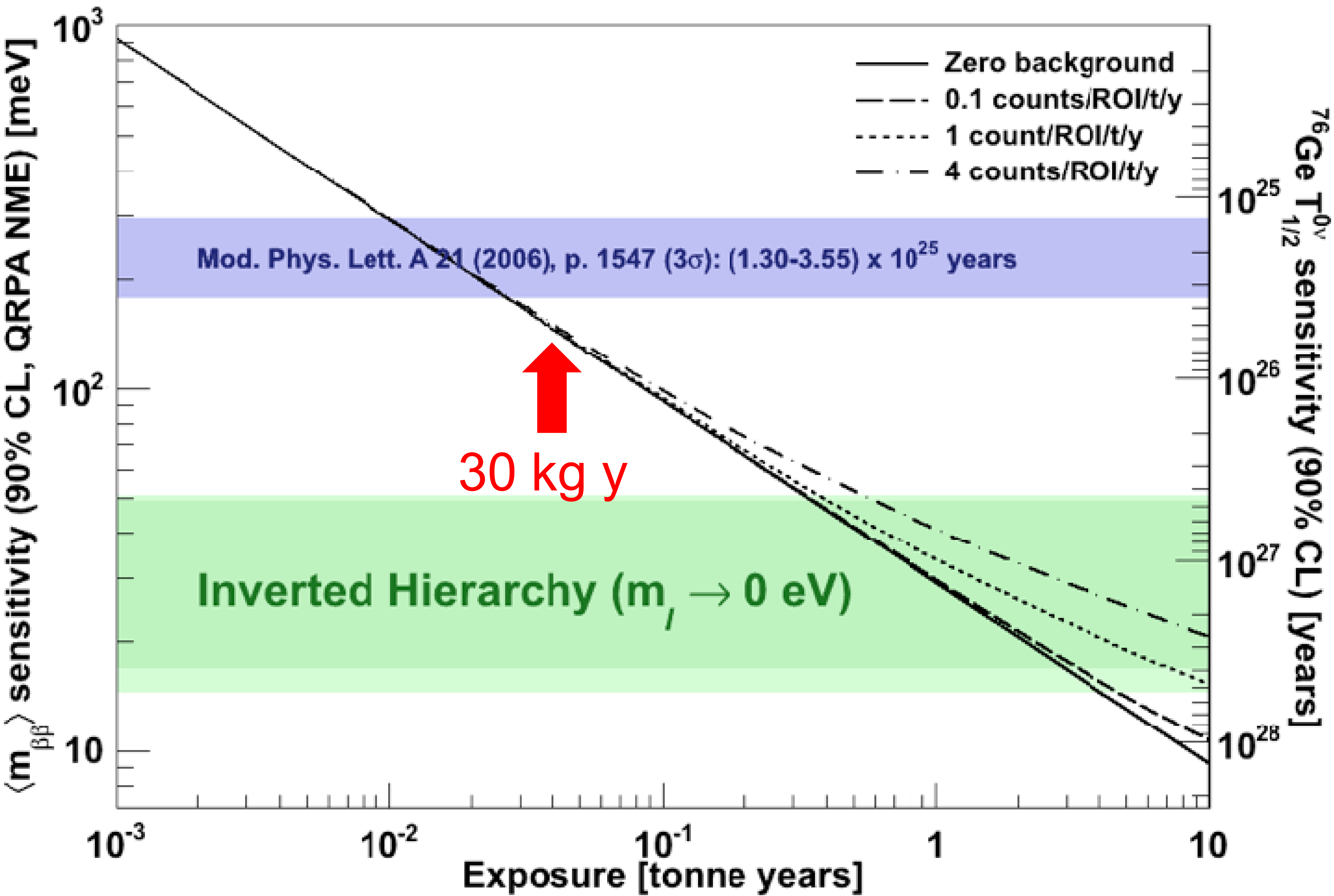




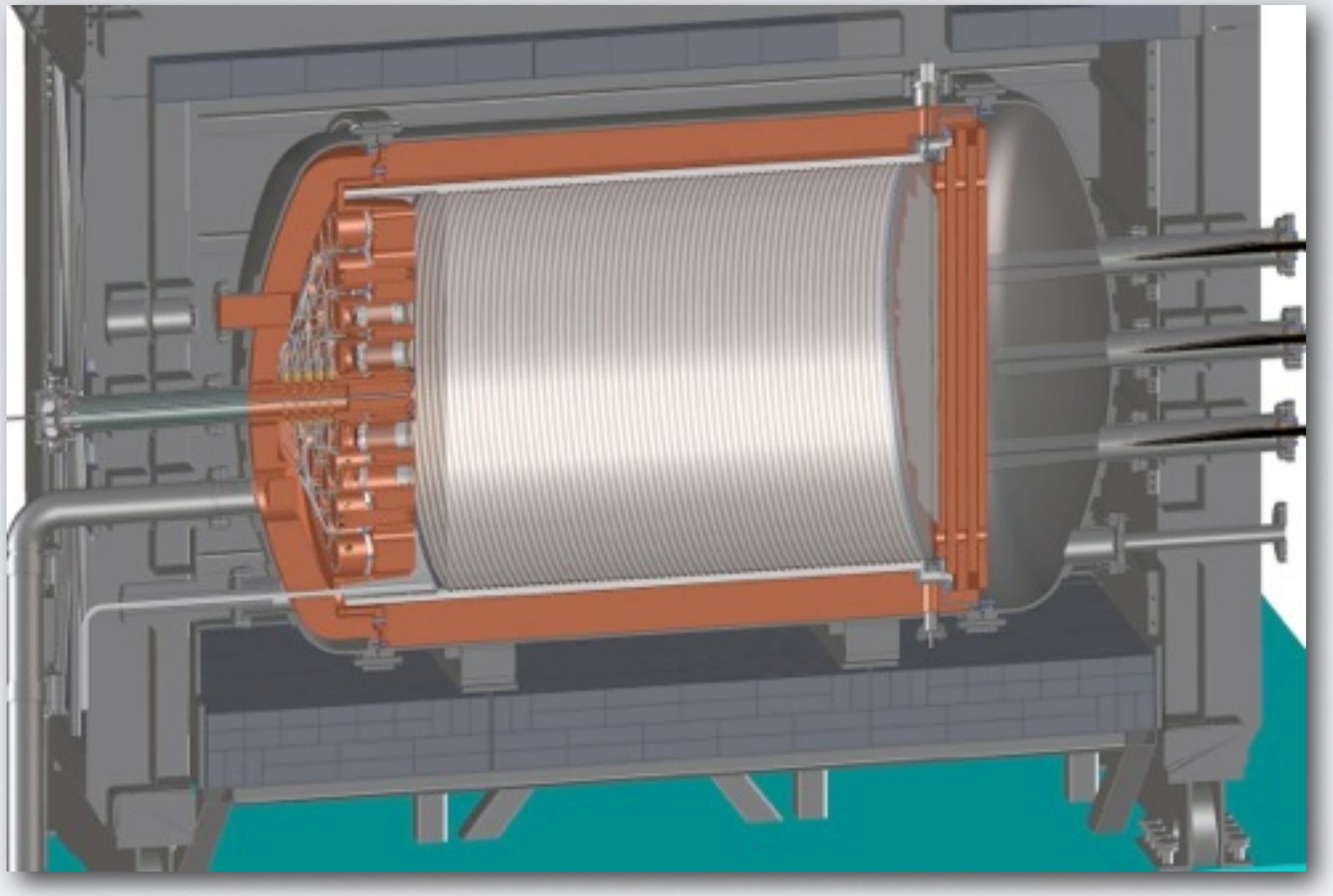




MJD Sensitivity



NEXT-100 detector



- A 100-150 kg HPXe TPC.
- Xenon gas enriched at > 90% in Xe-136 at 10-20 bar
- Uses electroluminescence to amplify signals.

[energy resolution and tracking using high pressure (gas) ^{136}Xe TPC w/EL readout]

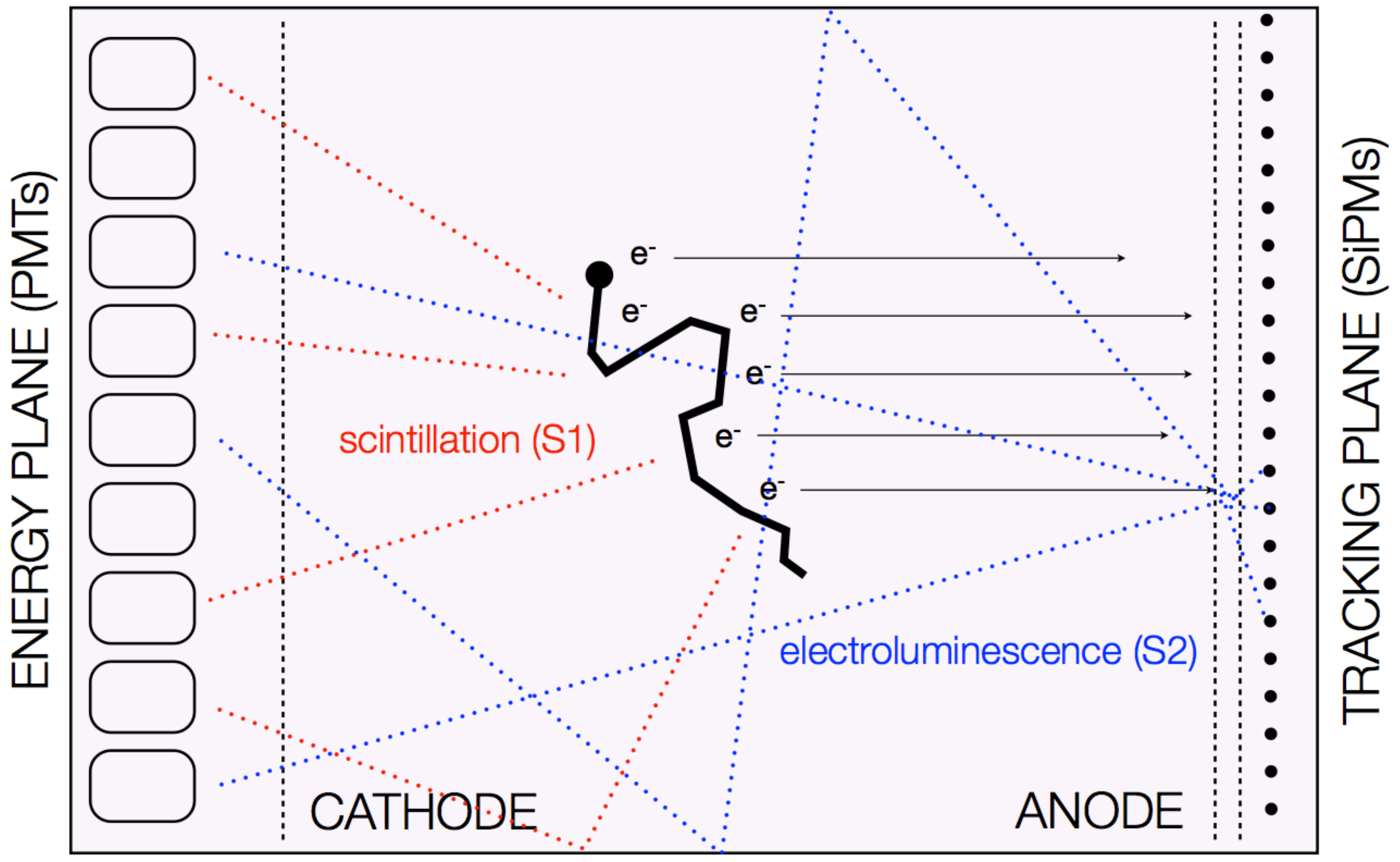
NEXT CONCEPTUAL IDEA, light production

LIGHT PRODUCTION PROCESS

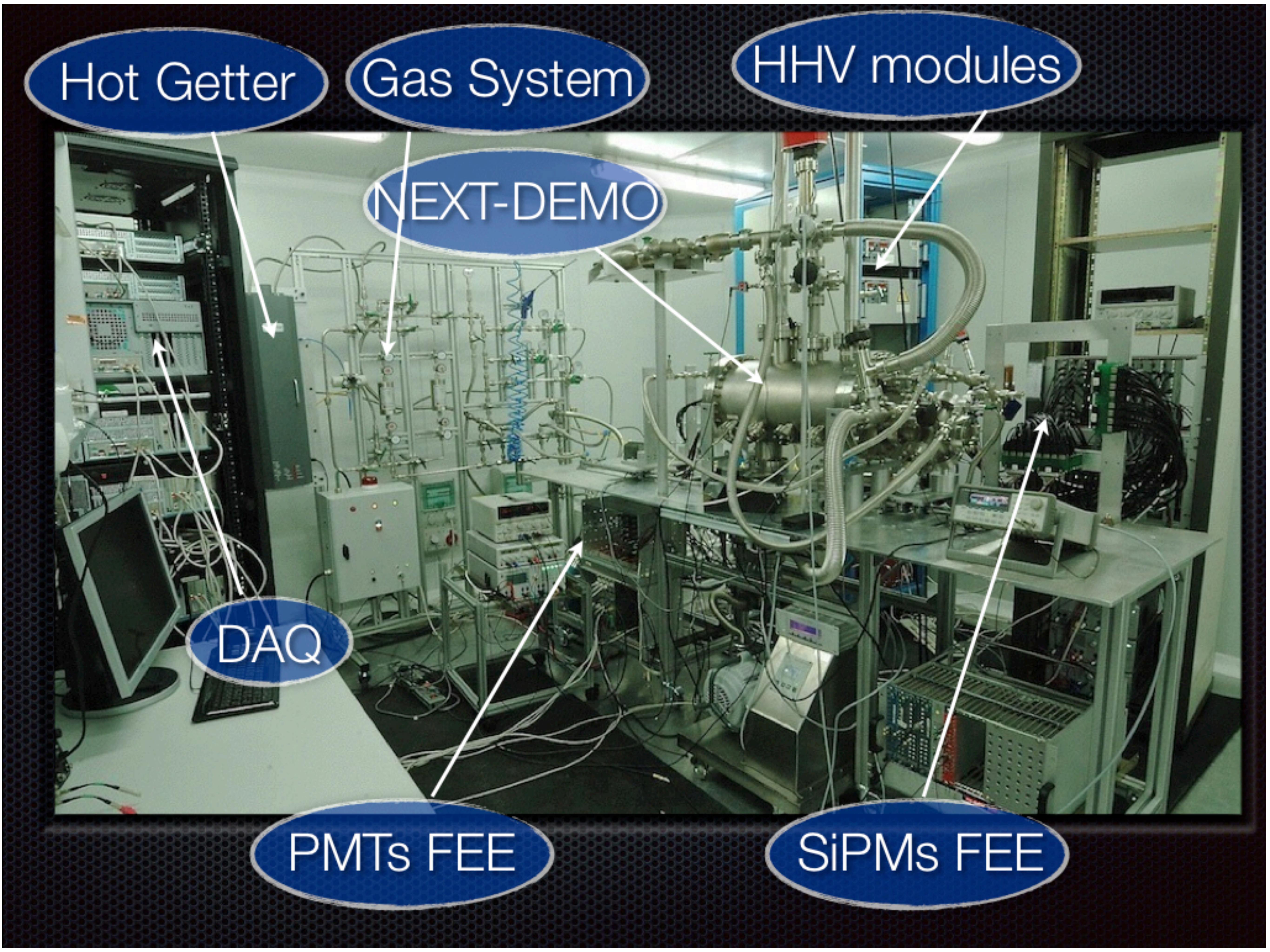
- Electrons excite and ionize Xe
- Excited Xenon emits scintillation light (172nm) that is detected by the PMTs at Energy Plane (SIGNAL 1)
- Electrons from ionization are **drifted** by a weak electric field to the Electro-Luminescence (EL) region
- There, a larger E field accelerate electrons such to 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

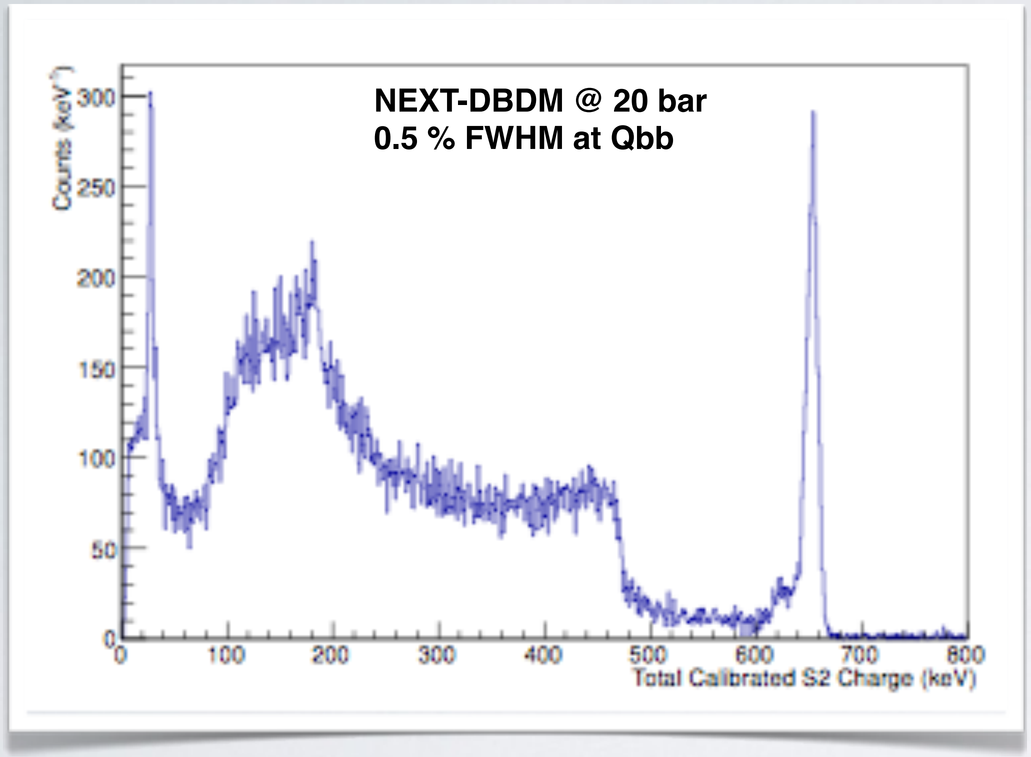
- The **SiPMs** in the tracking plane will allow to reconstruct the track followed by the original particle.

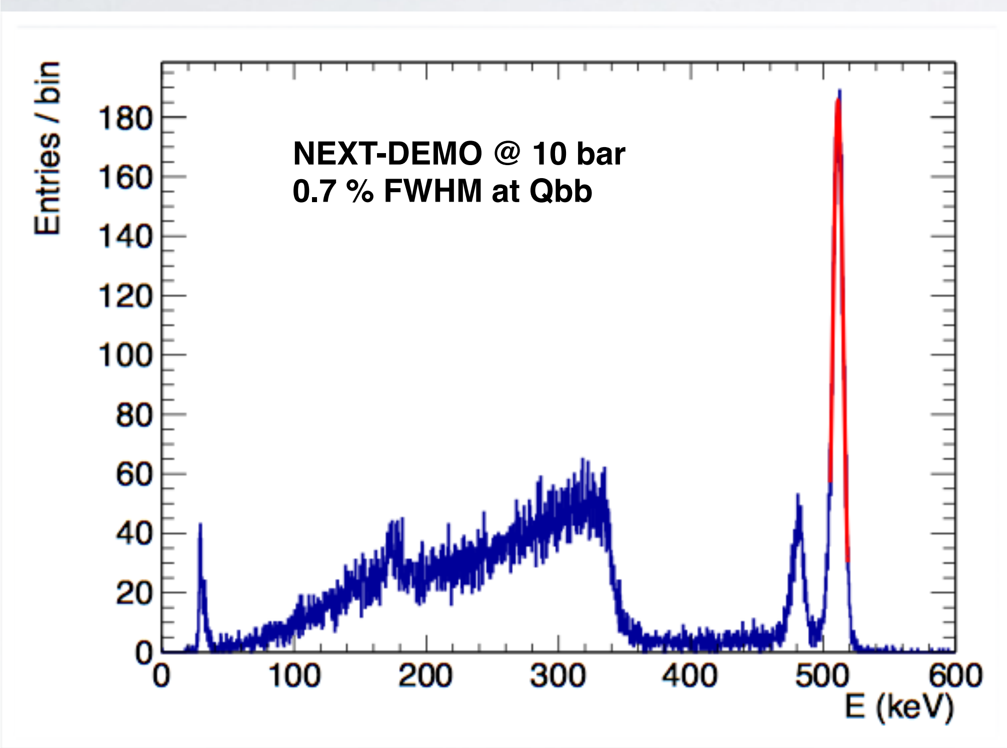


Tetra **P**henyl **B**utadiene (TPB) Wave-Length-Shifter is used to convert the light from UV to 430 nm to make it visible t the SiPMs & increase the number of photons for improving energy resolution


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

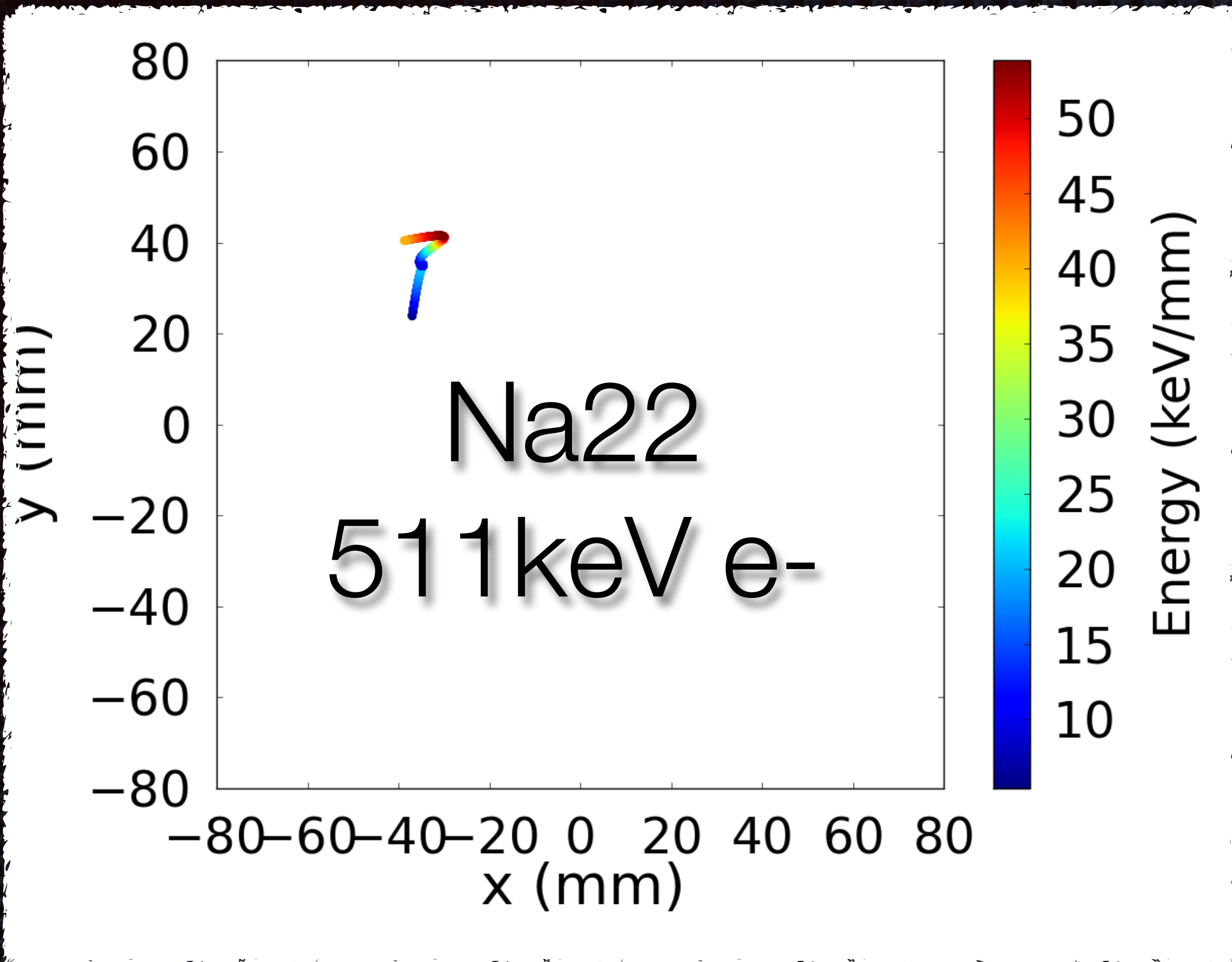
Energy resolution

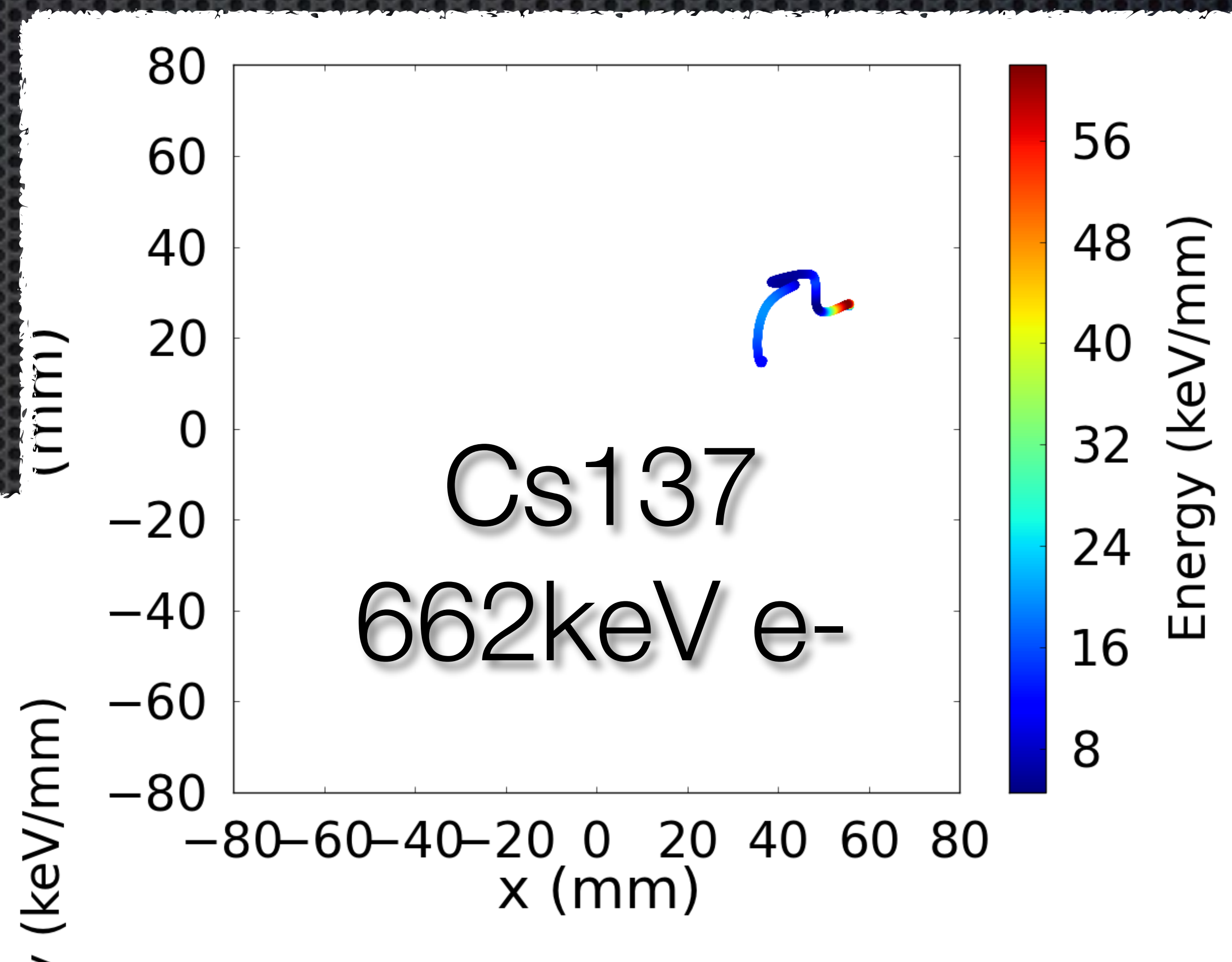


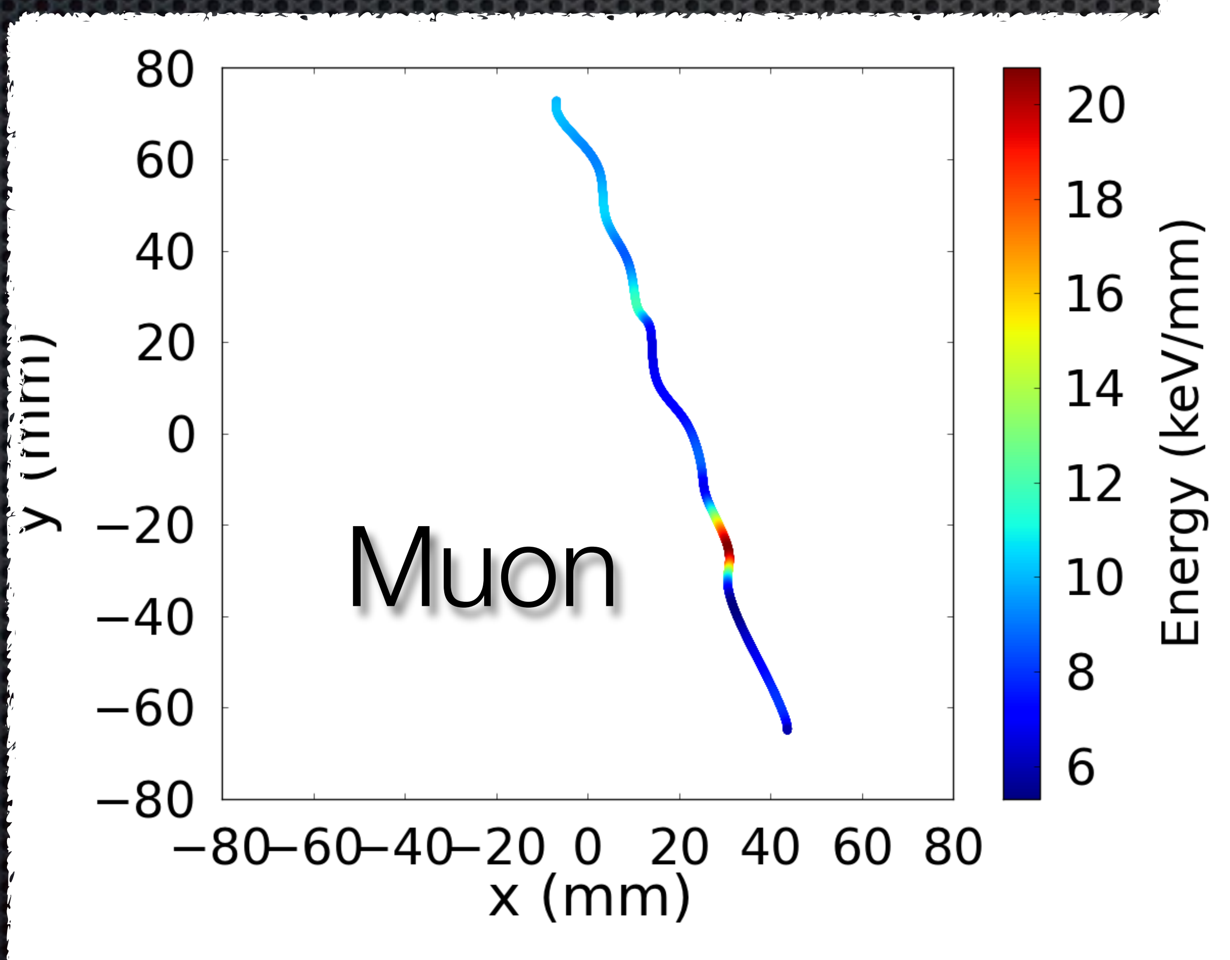


- Demonstrated with large-scale prototypes NEXT-DBBM (LBNL) and NEXT-DEMO (IFIC)
- Better than 0.5 % FWHM @ Qbb (using 660 keV cs-137 photo peak in NEXT-DBDM, central detector region, 20 bar.
- Better than 0.7 % FWHM @ Qbb (using 550 keV Na-22 photo peak in NEXT-DEMO, full fiducial region, 10 bar.

Tracks reconstructed for different energies

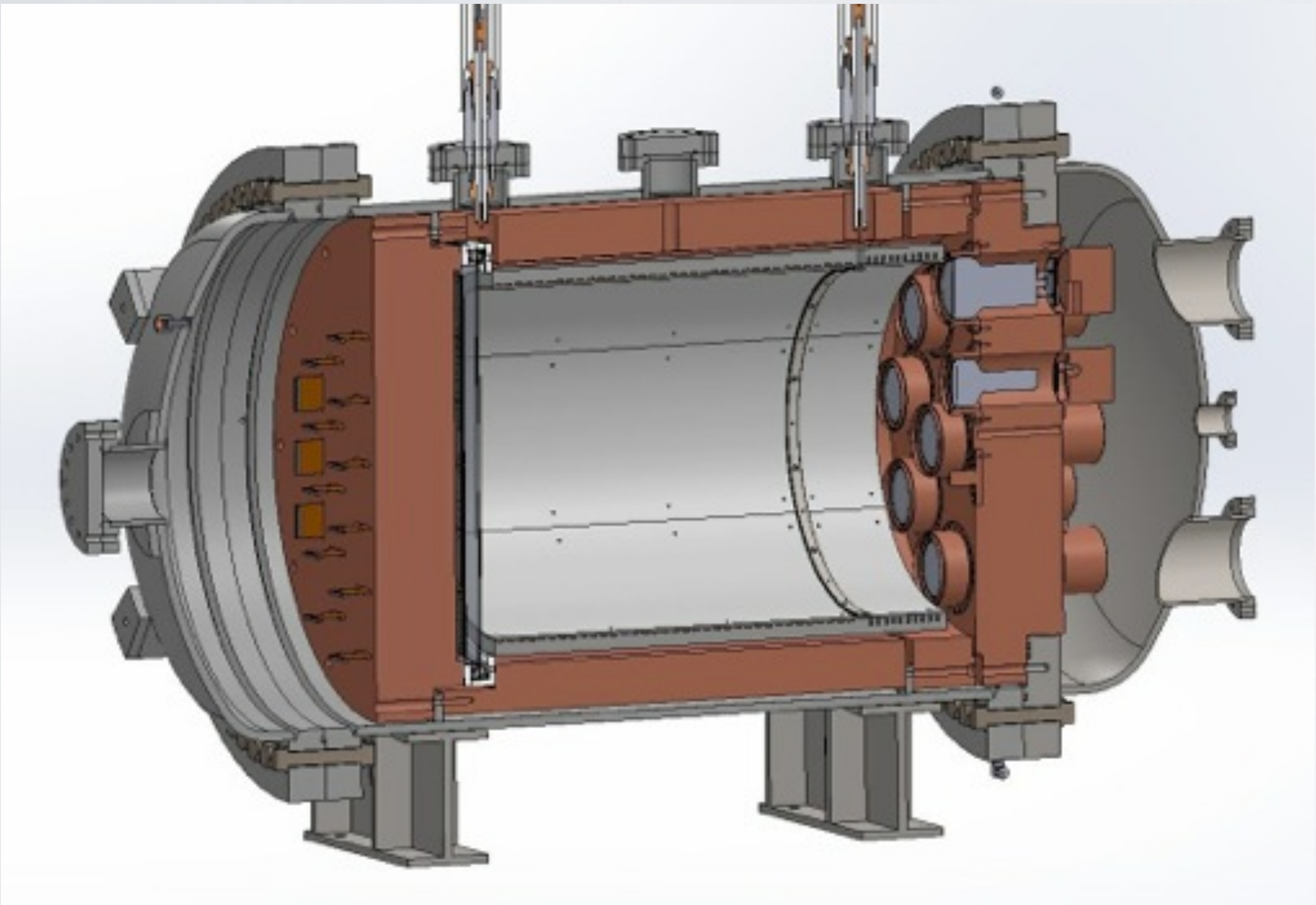






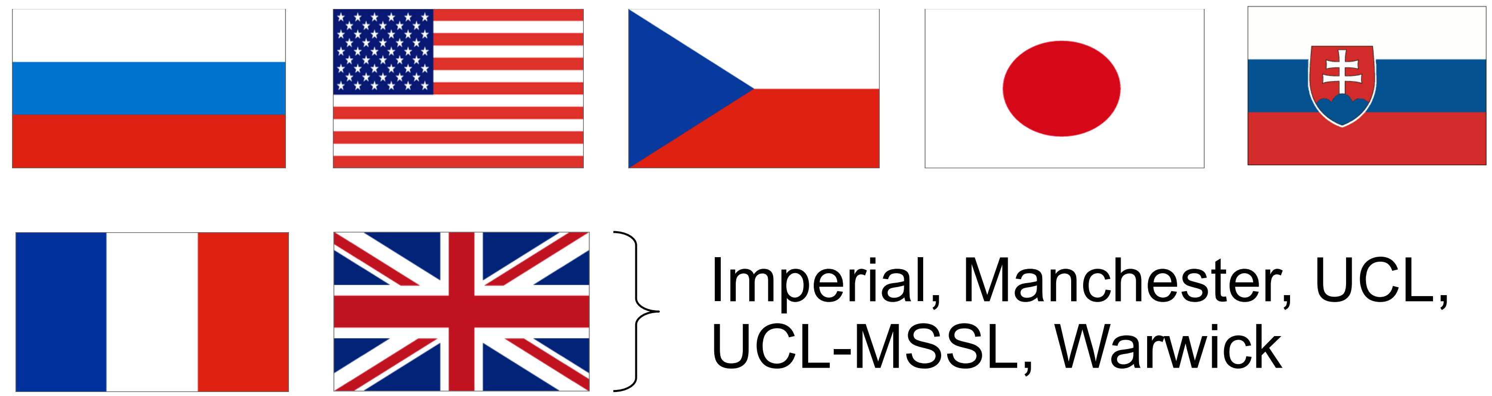
Different behavior between μ and e

NEXT-WHITE (NEW) detector



(Super)-NEMO

supernemo collaboration



Imperial, Manchester, UCL, UCL-MSSL, Warwick

The goals of SuperNEMO :

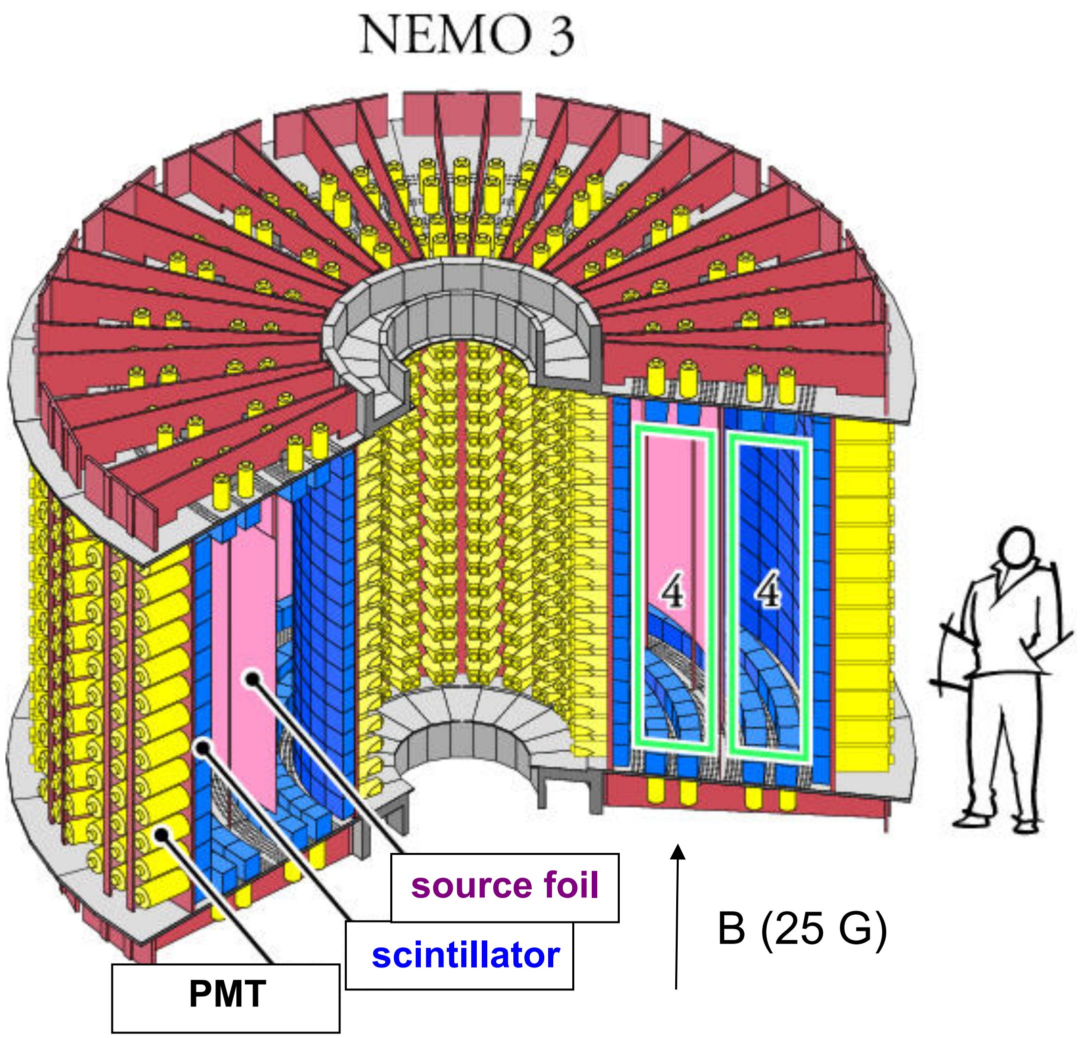
1. Build on the experience of the extremely successful NEMO-3 experiment.
2. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first phase.
3. Aim to reach the inverted mass hierarchy (~50 meV) region by the end of the decade.
4. In the event of a discovery by any of the next-generation experiments, the tracking-calorimeter approach is by far the best one for characterising the mechanism of $0\nu\beta\beta$ decay.

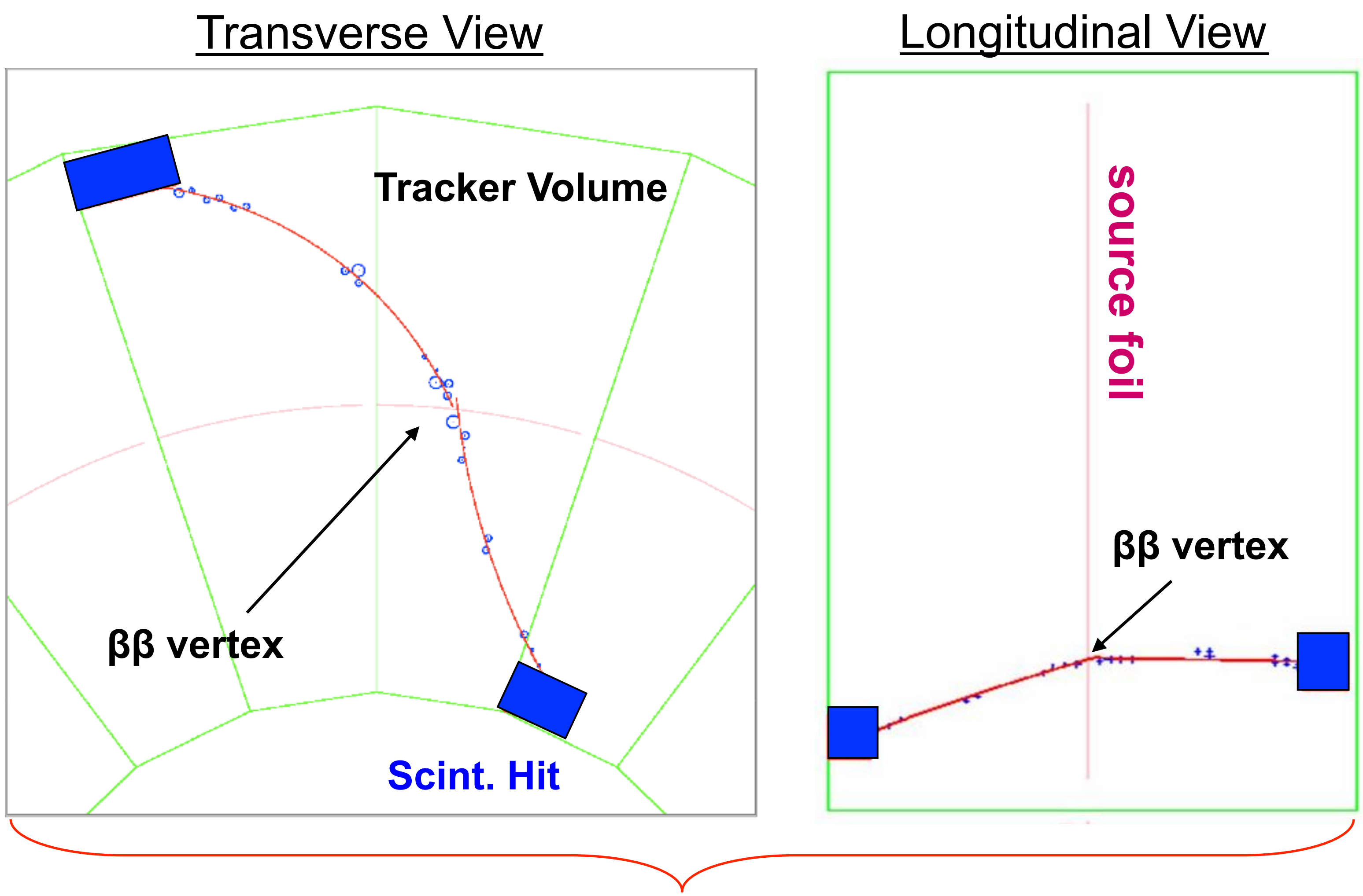
- *powerful tracking detector for superb background rejection (using event spatial topology)*

- *ability to study*
  - *single electron energy spectrum*
  - *angular correlation between the two emitted electrons*

…especially important for studying the decay mechanism in the event of a positive signal for neutrinoless double beta decay

NEMO-3





- The particle physicist's nuclear physics experiment.
- "Smoking gun" : complete event reconstruction for :
  - background rejection
  - signal characterisation (discovery!)

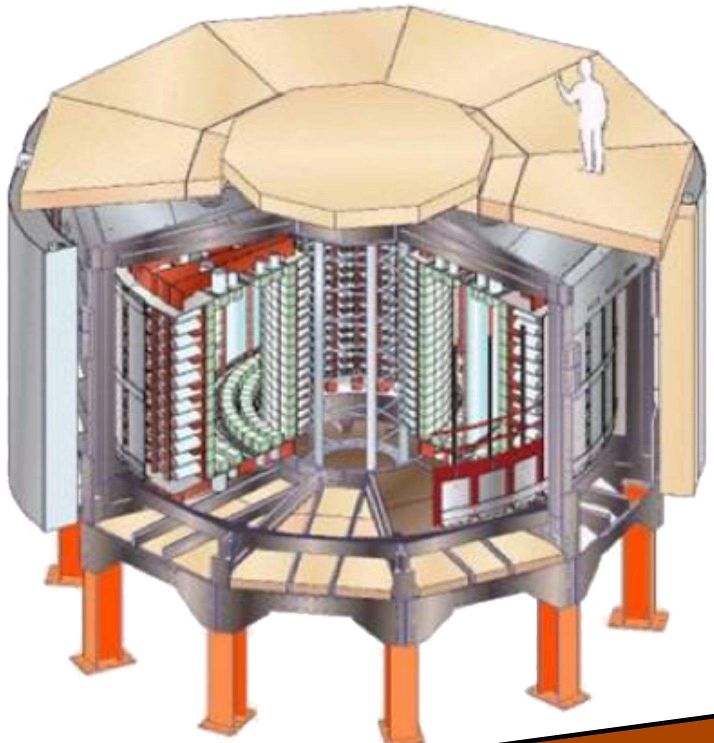
Isotopes

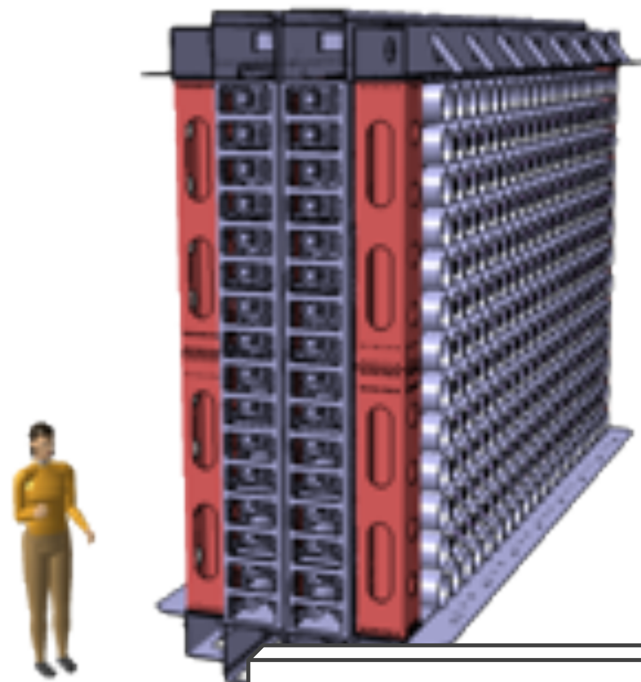
Large quantities: ^{100}Mo (7kg) ^{82}Se (1 kg)

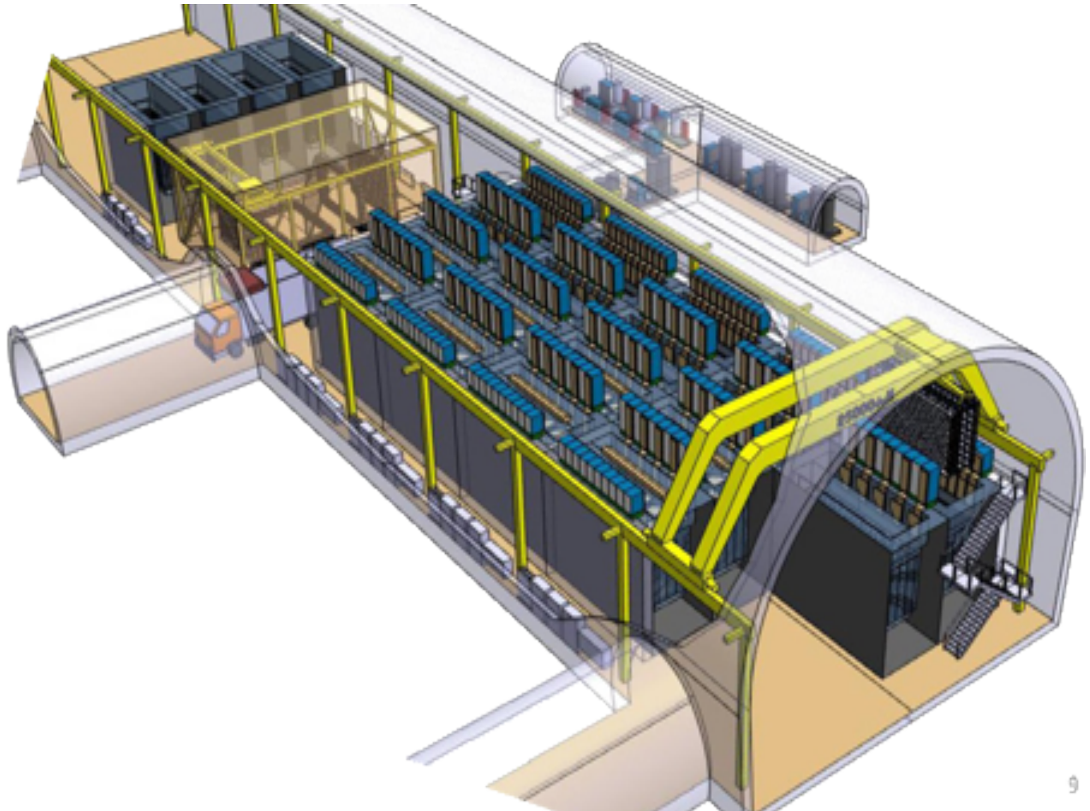
Small quantities: ^{116}Cd ^{150}Nd ^{48}Ca ^{96}Zr ^{130}Te

All major isotopes except ^{76}Ge and ^{136}Xe

SuperNEMO : Road Map





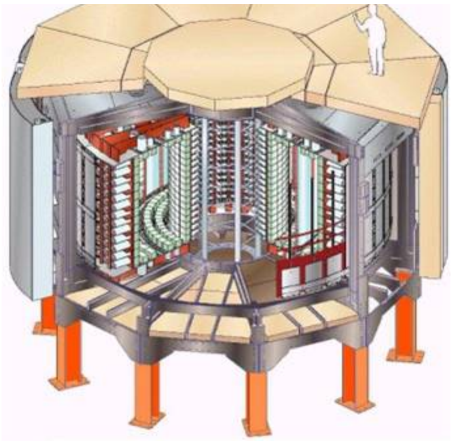


Demonstrator Module
Prove technology; reach
~200 meV sensitivity

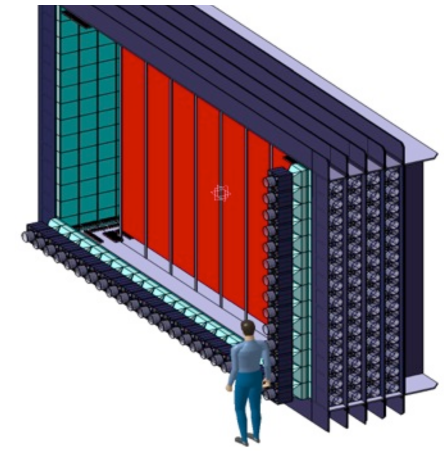
Full SuperNEMO
20 modules : 100 kg
Start to probe I.H.

SuperNEMO : How to Get There ?

NEMO-3

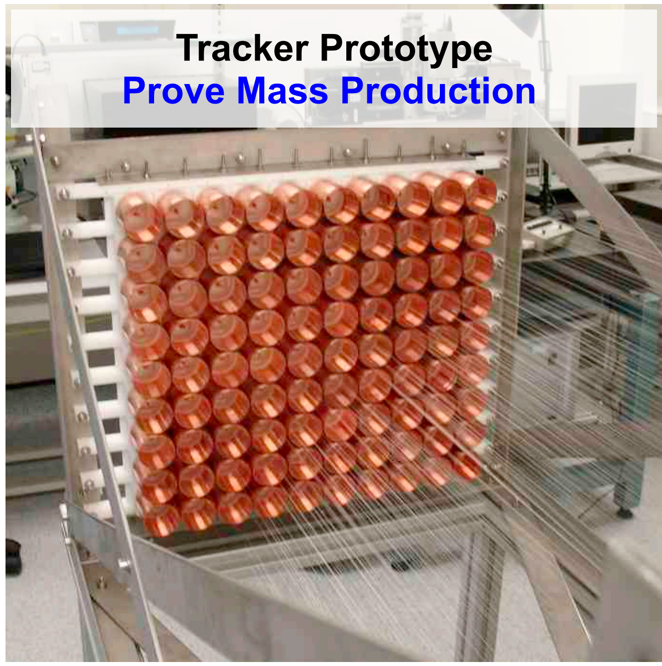


SuperNEMO

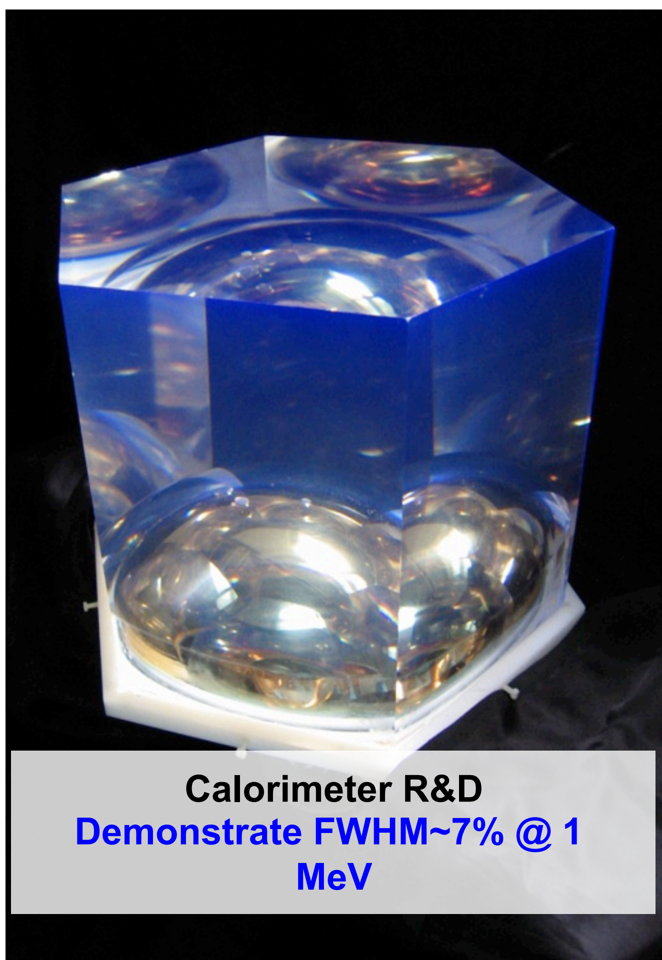


^{100}Mo	isotope	^{82}Se or other	
7 kg	isotope mass	100+ kg	
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: ~ 300 μBq/kg Rn: ~ 5 mBq/m^3	internal contamination ^{208}Tl ,^{214}Bi in the ββ foil Rn in the tracker	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg Rn ≤ 0.15 mBq/m^3	**a *background-free* Demonstrator Module Phase 1**
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV	**proven in UK R&D**
$T_{1/2}(0\nu\beta\beta)$ > 1-2 x 10^{24} y $\langle m_\nu \rangle$ < 0.3 – 0.9 eV		$T_{1/2}(0\nu\beta\beta)$ > 1 x 10^{26} y $\langle m_\nu \rangle$ < 0.04 - 0.11 eV	**factor ~100 in $T_{1/2}$** **factor ~10 in $\langle m_\nu \rangle$**

SuperNEMO Demonstrator Module : Overview



Tracker Prototype
Prove Mass Production

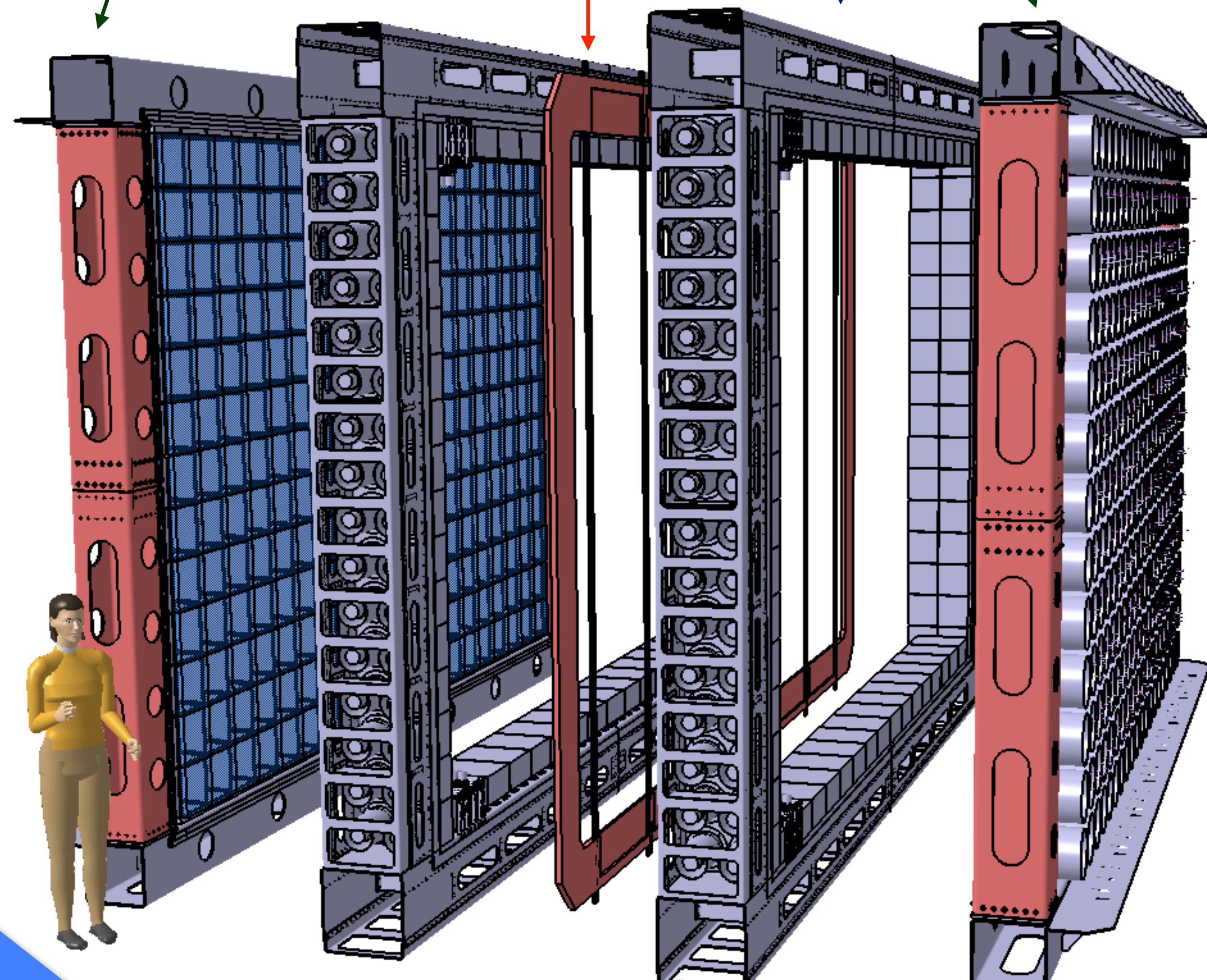


Calorimeter R&D
Demonstrate FWHM~7% @ 1 MeV

~700 calorimeter channels

2000 tracker cells

6-7 kg source foil



Demonstrator Module

Also :

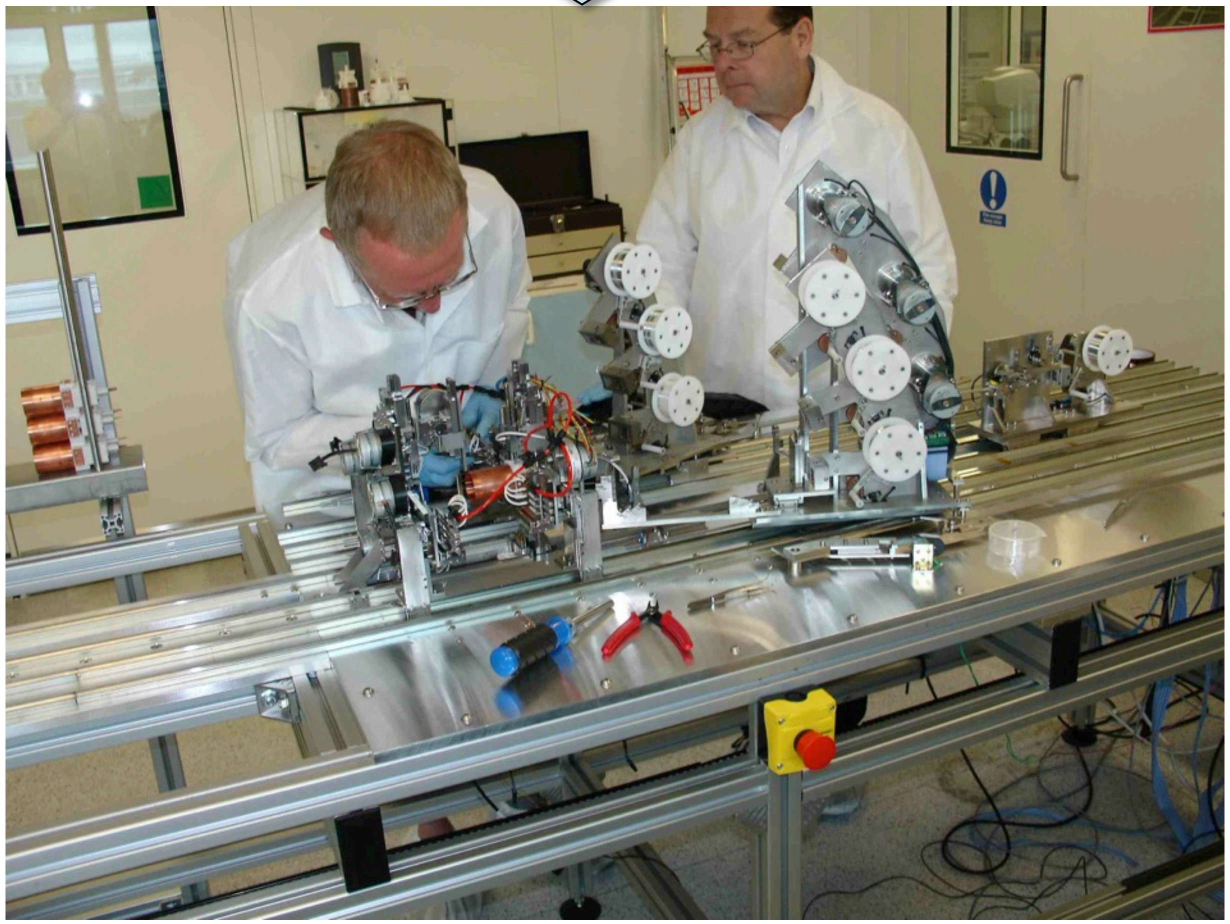
- Change isotope
  ^{100}Mo $\longrightarrow$ ^{82}Se
- Reduce radon in gas by factor 30
- Improved efficiency, calibration etc.

"BiPo" Detector
Measure source foil contamination to ^{208}Tl ≤ 2 μBq/kg
^{214}Bi ≤ 10 μBq/kg

Build a 2000 channel Geiger-mode tracking detector :

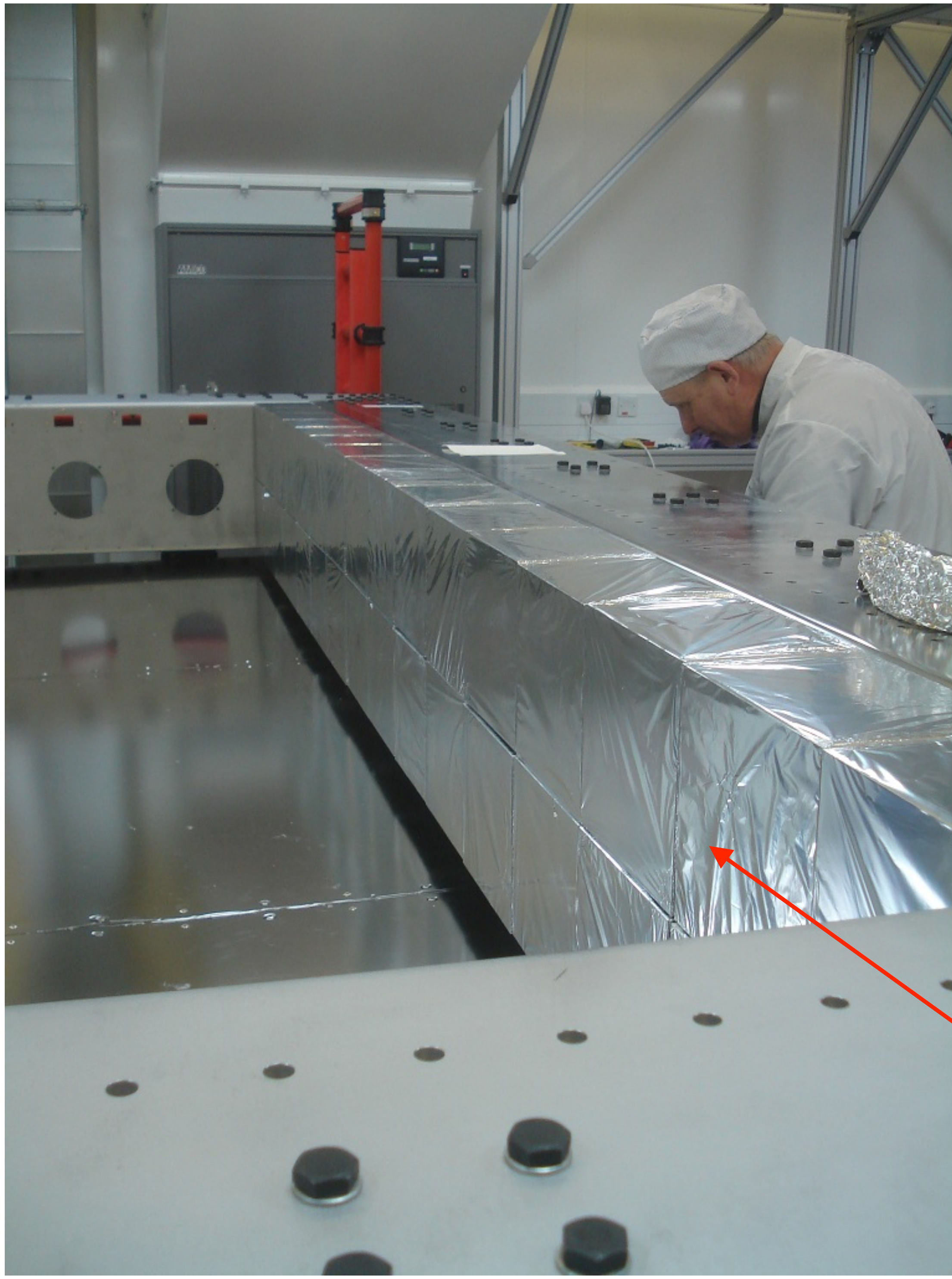
- Must reconstruct β−electron tracks with high efficiency and resolution.
- Must contribute zero background in the $0\nu\beta\beta$ analysis ➔ ultra-pure materials only.
- Must be impermeable to the diffusion of radon into the gas volume ➔ gas-sealing
- Robotic construction for accuracy, cleanliness and mass-production capability.
- Electronics, cabling, gas-system & software.

tracker robot being commissioned (Manchester)

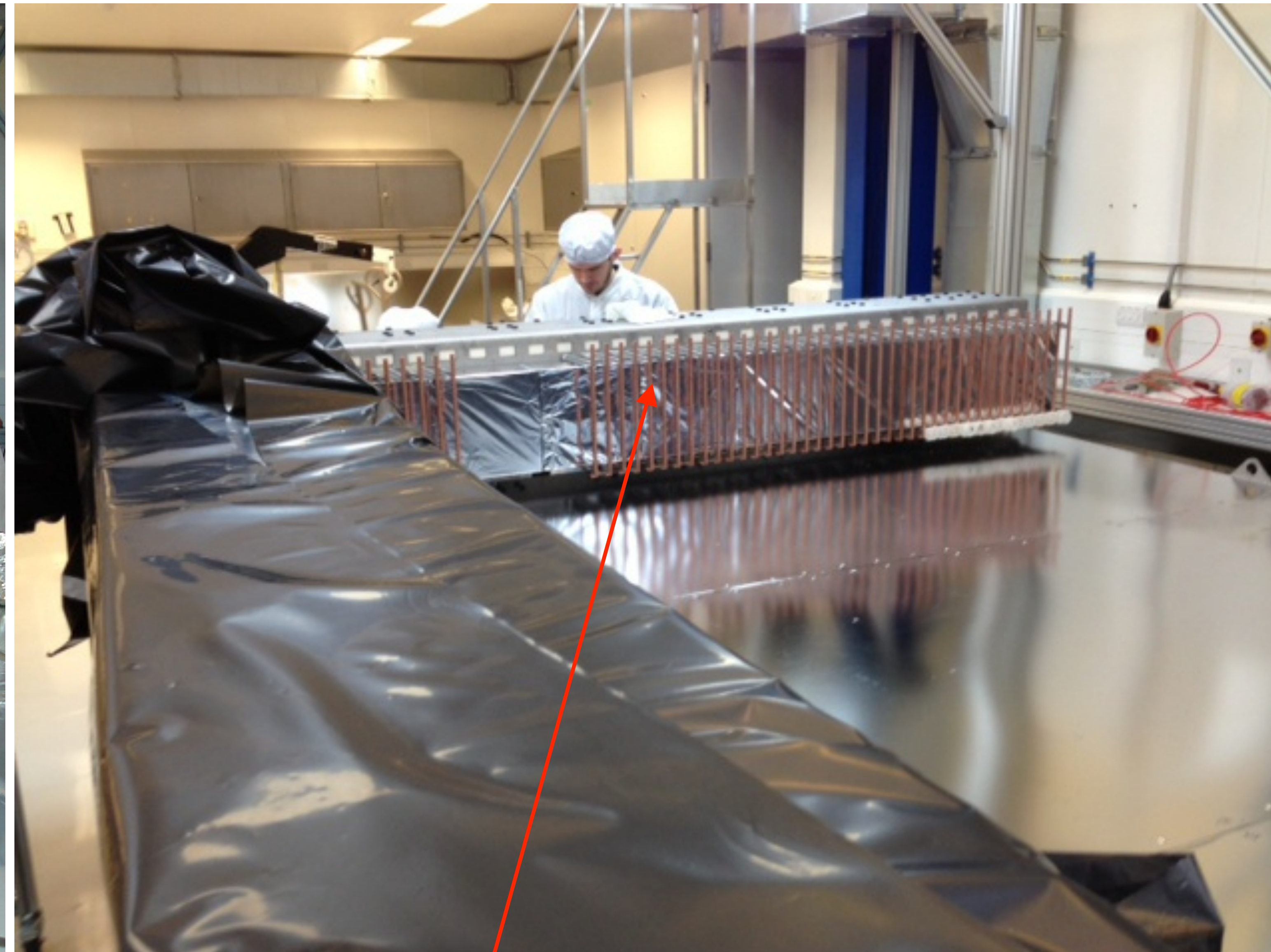


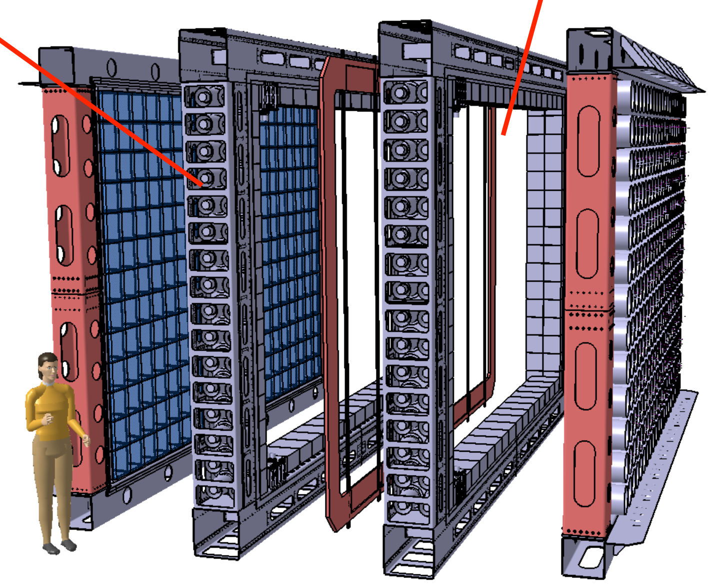
optical module production line (UCL)

Tracker Frame



Insertion of Optical Modules into tracker frame

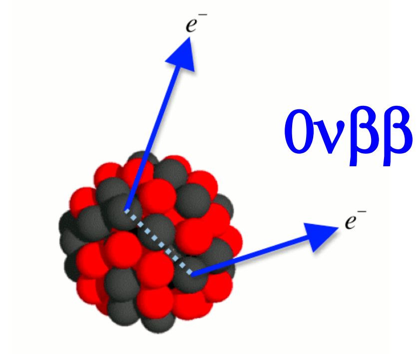




- Preparation of cell support structure.
- Test insertion of first tracker cells this week !

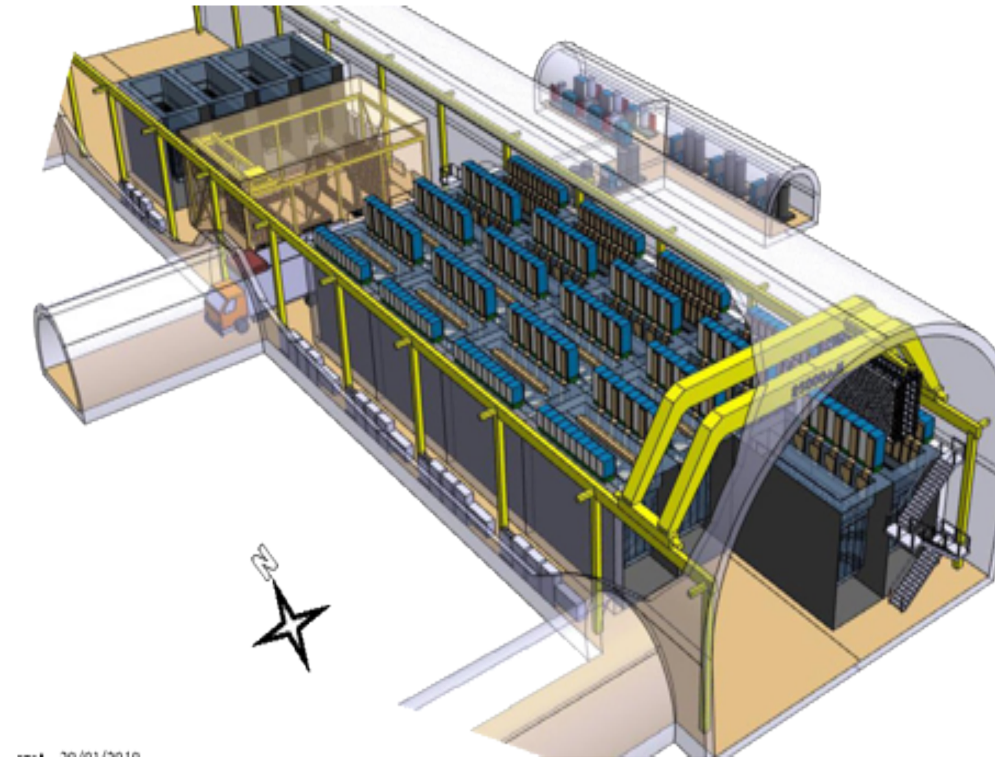
SuperNEMO : Timeline

Demonstrator Module
construction and commissioning



Demonstrator Module Running :

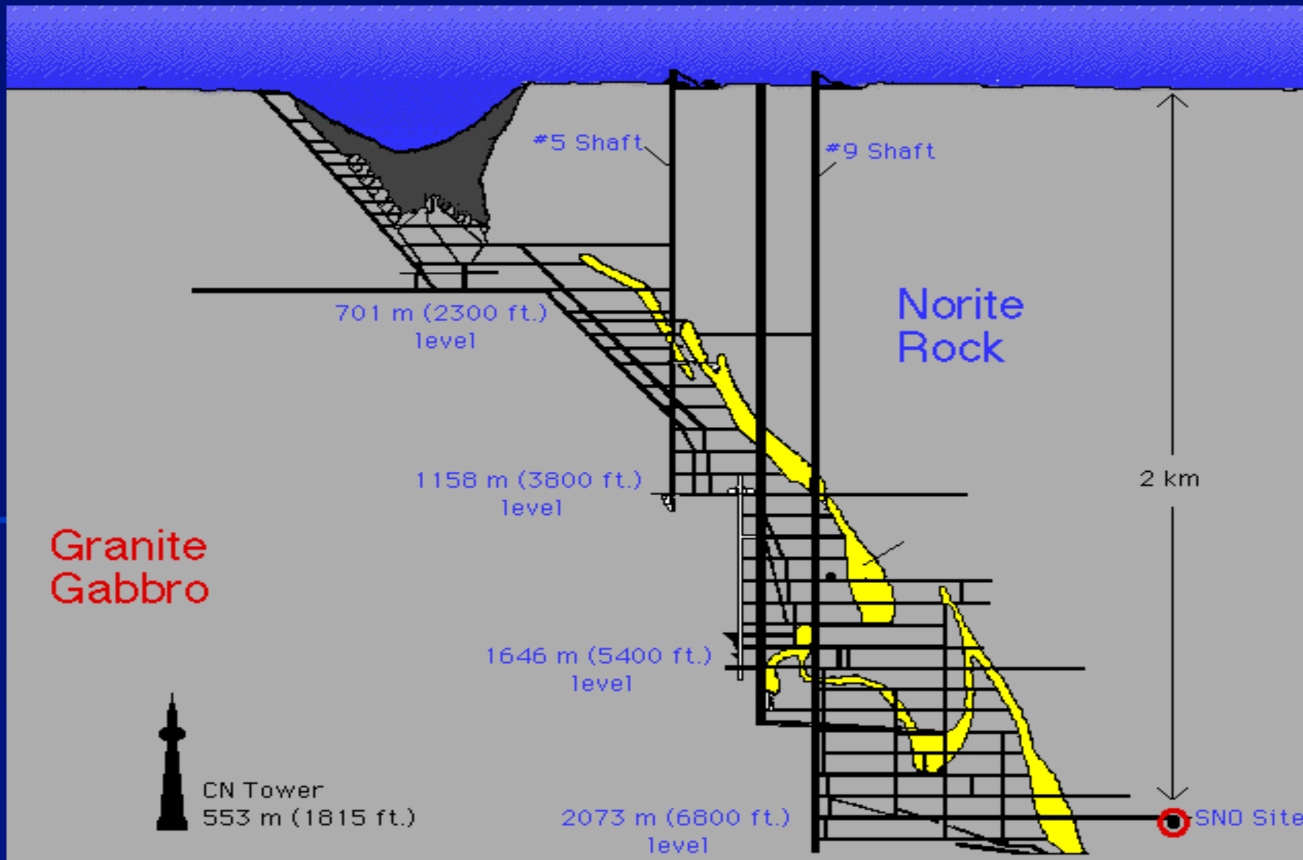
- Prove B~10^{-4} cts/keV/kg/yr : amongst best of *any* experiment.
- Limit on $T_{1/2}$ ~6.5×10^{24} yr.
- Unique ββ measurements.



2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	

Construction and deployment of successive SuperNEMO modules
Sensitivity with 100 kg :
$T_{1/2}$ (0νββ)~10^{26} yr $\langle m_\nu \rangle$ ~ 40-110 meV

Continuous operation of ≥1 SuperNEMO module



~~1000 tonnes D_2O~~ → 780 tonnes liquid scintillator

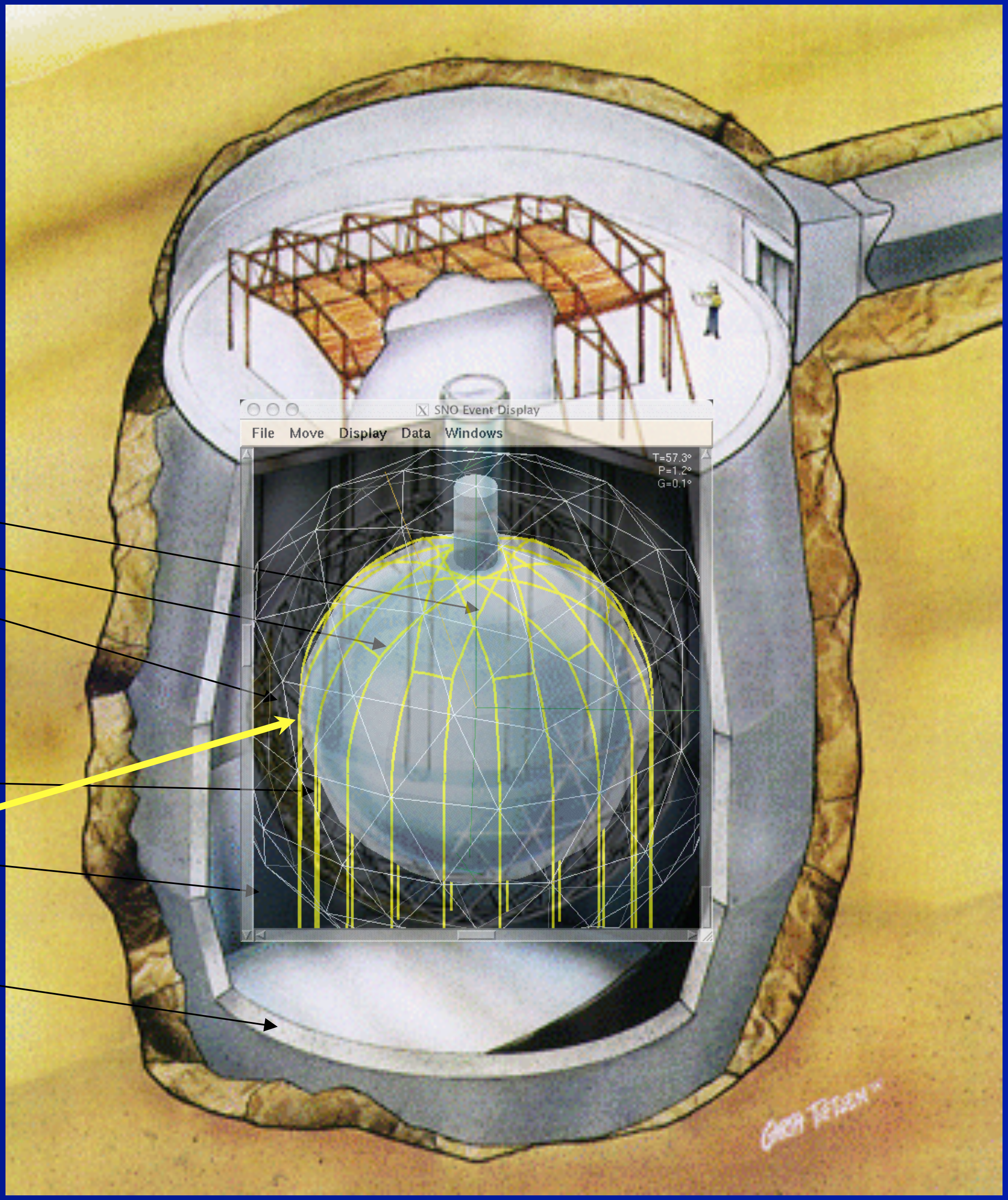
12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~54% photocathode coverage)

1700 tonnes inner shielding H_2O
5300 tonnes outer shielding H_2O
Urylon liner radon seal

hold-down rope net

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

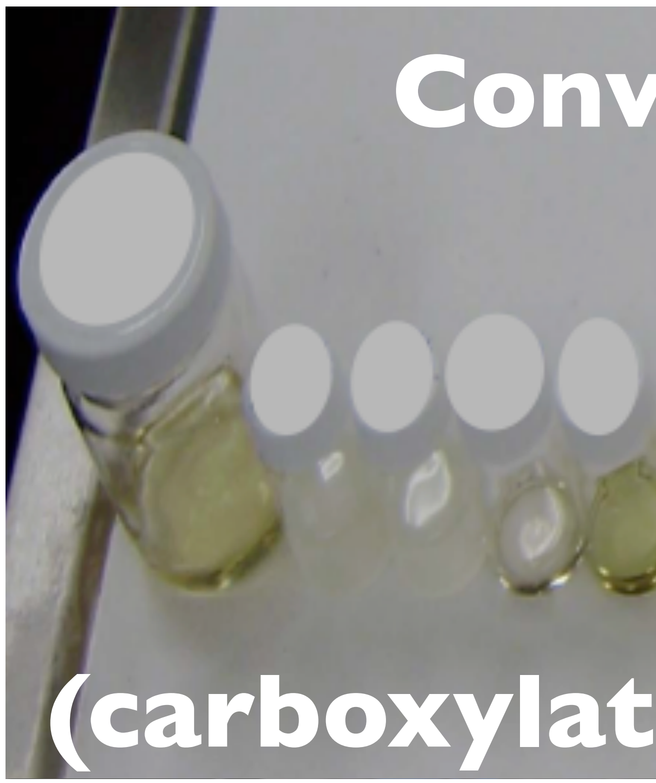


SNO+ with Te-Loaded Liquid Scintillator

- large natural isotopic abundance 34% for ^{130}Te
  - tonne scale for ^{130}Te isotope, cost is $1.5 million (b/c use natural Te)
  - 0.3% Te (by weight) in SNO+ is 2.34 tonnes of Te or **800 kg** of ^{130}Te ***isotope***…0.3% loading isn't a fundamental loading limit either!
- in the energy range where the Te endpoint is, the known U chain background (^{214}Bi-^{214}Po) can be rejected by factor >5,000!
  - *"temporal event topology" for background rejection*
- the $2\nu\beta\beta$ background is a factor 100 times smaller than in Nd (previous isotope developed for SNO+ double beta)
- if the TeLS is otherwise radiopure, the dominant background will be ^{8}B solar neutrinos

[huge quantity of isotope deployed, ultra-low background liquid scintillator; requires careful background control for the tellurium]

First Attempts at Te-Loaded Scintillator (at BNL)



- …then, a breal developed at BNL, and it wo cintillator!

SNO+ Tellurium Purification Studies

Outline of Te Purification Strategy

(paper in preparation)

(Stage 1)

2 Surface passes:

- Dissolve $Te(OH)_6$ in water
- Recrystalise using nitric acid
- Rinse with ethanol

>10^4 reduction

Allow up to 5 hr re-exposure to finish & transport UG

(Stage 2)

2 Underground passes:

- Dissolve in warm water (80°C)
- Cool to Recrystalise thermally

>10^2 reduction

(~50% Te "loss" recovered by recycling to surface system)

Cosmogenics

Isotope (Q > 2 MeV, $T_{1/2}$ > 20 days)	$T_{1/2}$ [5] [d]	Q-value [5] [MeV]	R (ϕ from [6][7]) [μBq/kg]	Events/yr in ROI after 1 yr surface exposure
^{44}Sc (daughter of ^{44}Ti)	0.17 (2.16E+4)	3.65	1.19 (0.052)	5.41
^{46}Sc	83.79	2.37	1.97	20.3
^{60}Co (direct and daughter of ^{60}Fe)	1925.27 (5.48E+8)	2.82	0.81 (0.367)	834
^{68}Ga (daughter of ^{68}Ge)	4.70E-2(271)	2.92	3.14 (1.28)	344
^{26}Al	2.62E+8	4.00	0.67	2.20E-4
^{82}Rb (daughter of ^{82}Sr)	8.75E-4(25.35)	4.40	(2.44)	440
^{88}Y (direct and daughter of ^{88}Zr)	106.63 (83.4)	3.62	3.14 (8.11)	3.61E4
^{42}K (daughter of ^{42}Ar)	0.51 (12016.73)	3.53	1.33 (0.24)	10.0
^{56}Co	77.2	4.57	0.13	0.350
^{58}Co	70.9	2.31	1.29	0.252
^{110m}Ag [a]	249.83	3.01	2.34	3.61E3
^{110}Ag (daughter of ^{110m}Ag) [b]	2.85E-4	2.89	(0.03)	48.6
^{106}Rh (daughter of ^{106}Ru)	3.47E-4 (371.8)	3.54	(0.06)	21.8
^{126m}Sb (direct and daughter of ^{126}Sn) [c]	0.01 (8.40E7)	3.69	71.42 (7.87)	8.63
^{126}Sb (direct and daughter of ^{126m}Sb) [d]	12.35 (0.01)	3.67	89.65 (^{126m}Sb)	1.29E4
^{22}Na	950.6	2.84	1.01	1.01E3
^{84}Rb [e]	32.8	2.69	1.29	24.2
^{90}Y (daughter of ^{90}Sr)	2.67 (10519.2)	2.28	2.69 (0.165)	7.90E-3
^{102}Rh (direct and daughter of ^{102m}Rh) [f]	207.3	2.32	11.77 (0.03)	35.9
^{102m}Rh [g]	1366.77	2.46	11.77	69.9
^{124}Sb	60.2	2.90	182.0	1.62E5

ACTIVIA code, cross sections from Silberberg et al. and TENDL-2009 database, flux parameterisations from Armstrong and Gehrels. Variations from using YIELDX code, TENDL-2012 database, and fluxes from Ziegler change estimated rates by up to a factor of two. Consistency also checked against CUORE beam activation study (Wang *et al.*) and KamLAND induced backgrounds.

(V. Lozza, paper in preparation)

Requires a reduction factor of >10^4 for these isotopes, which is also comparable to the reduction required for U/Th in "raw" Te material (ICP-MS: 2-3x10^{-11} g/g)

Purification Spike Tests

Spike Tests

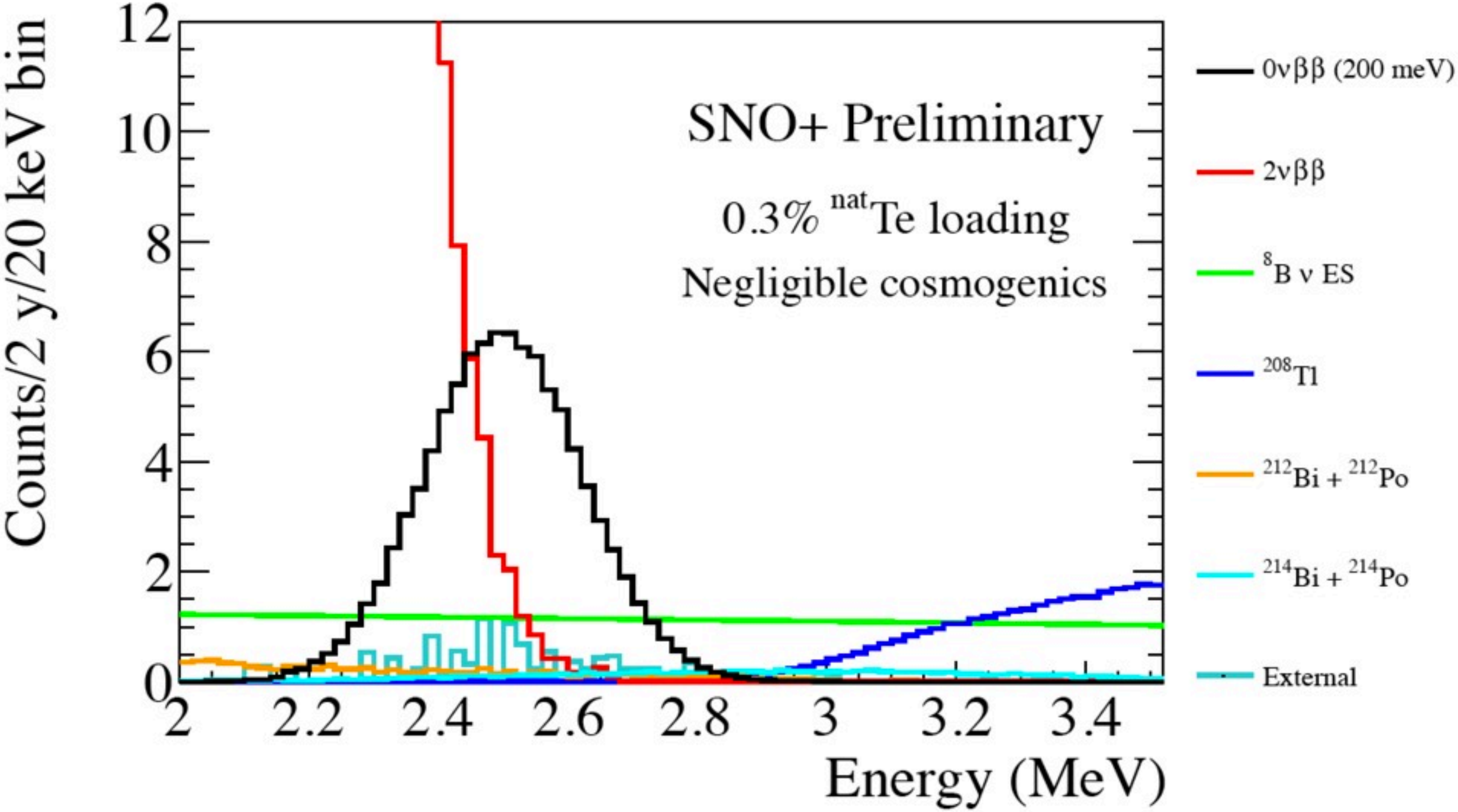
(Ongoing)

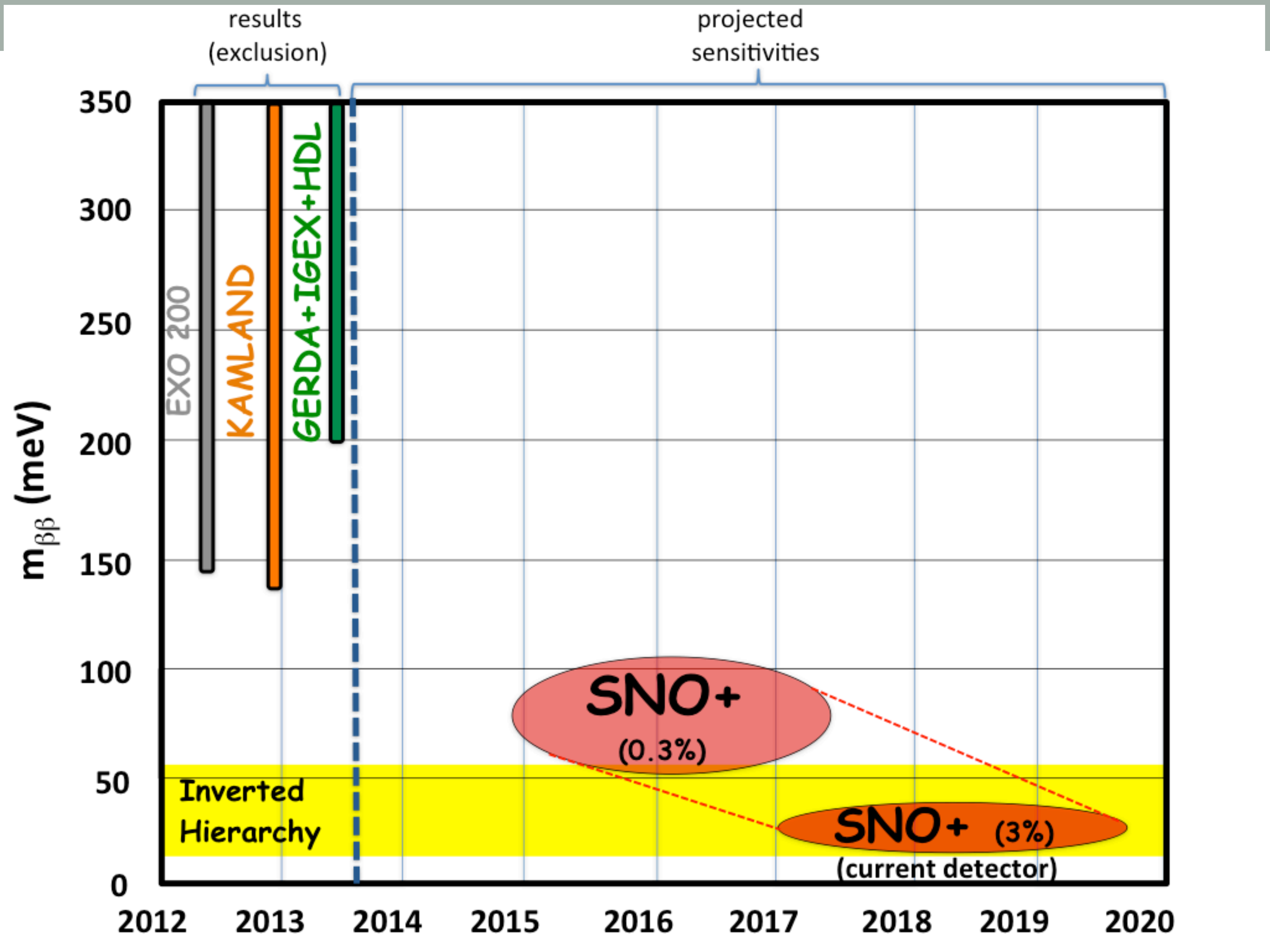
Element	Reduction Factor	Assay Technique
Stage 1 Te purification, single-pass spike test		
Co	1555± 326	XRF
Sb	>243	XRF
Sn	> 167	XRF
Fe	> 100	XRF
Na	> 346	XRF
Sc	> 165	XRF
Ge	> 333	XRF
Y	> 278	XRF
Zr	> 278	XRF
Ag	> 278	XRF
Pb-212	299± 22	$\beta - \alpha$ counting
Bi-212	348± 81	$\beta - \alpha$ counting
Ra-224	397± 20	$\beta - \alpha$ counting
Th-228	390±19	$\beta - \alpha$ counting
Stage 1 Te purification, double-pass spike test		
Co	3.7×10^5	XRF
Pb-212	$> 10^4$	$\beta - \alpha$ counting
Bi-212	$> 10^4$	$\beta - \alpha$ counting
Ra-224	$> 10^4$	$\beta - \alpha$ counting
Th-228	$> 10^4$	$\beta - \alpha$ counting
Stage 2 (UG) Te purification, single-pass spike test		
Co	12	XRF
Ag	> 20	XRF
Zr	17	XRF

acid-induced recrystalisation + ethanol wash

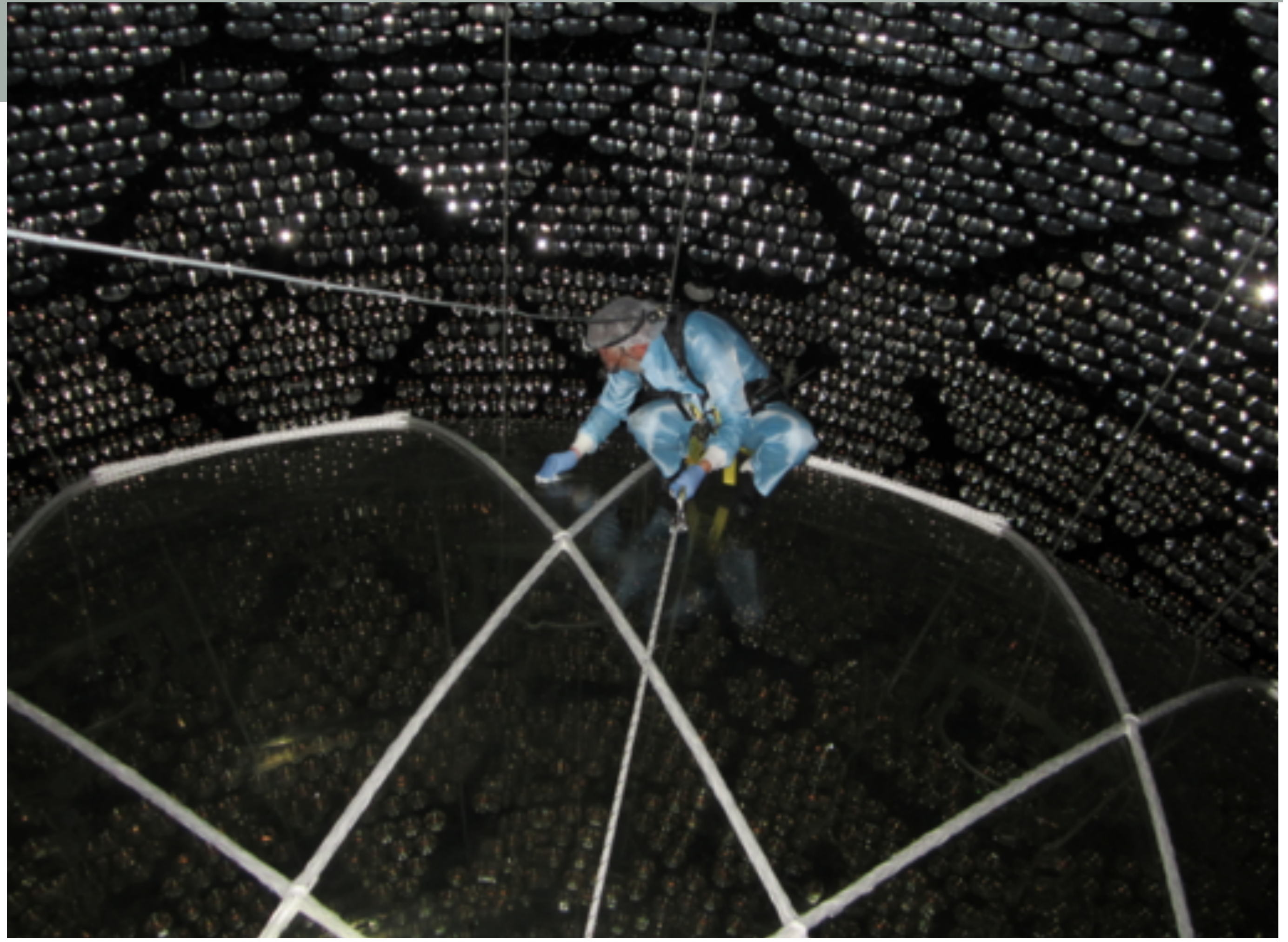
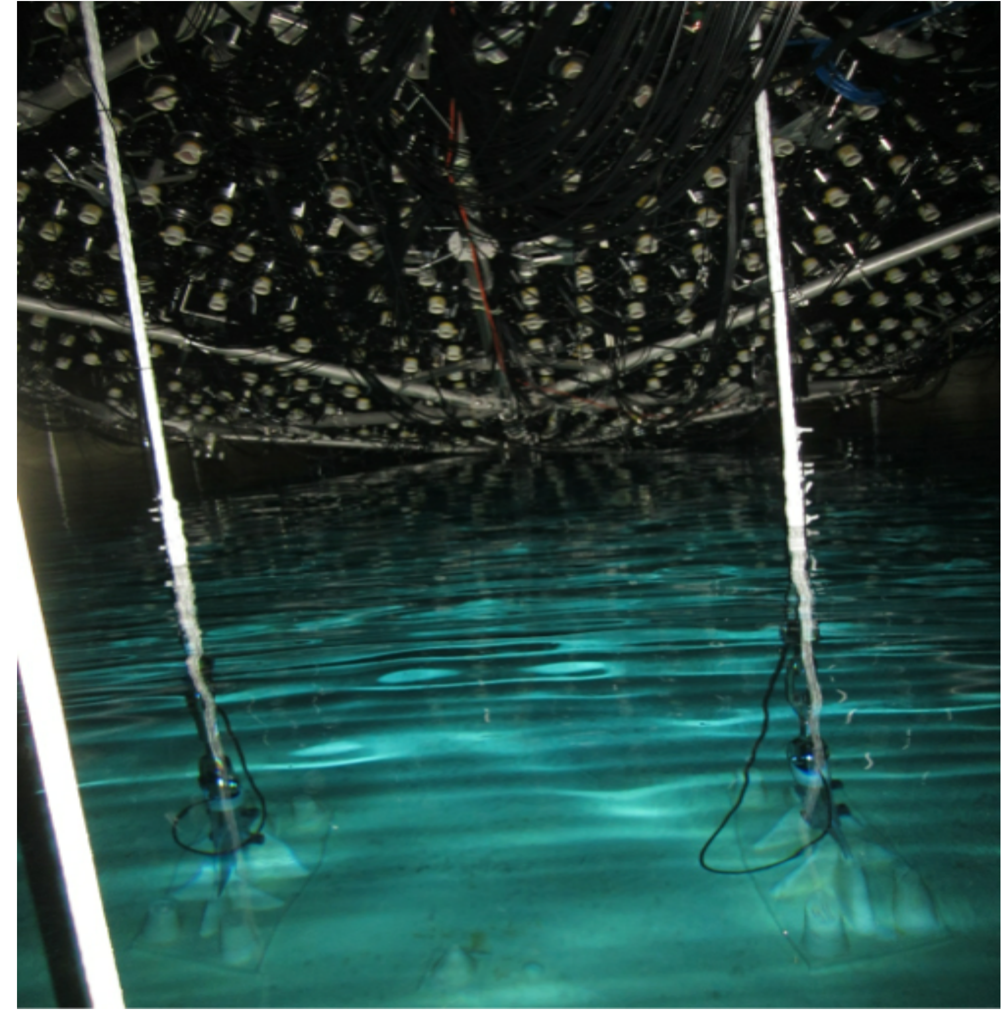
thermal recrystalisation

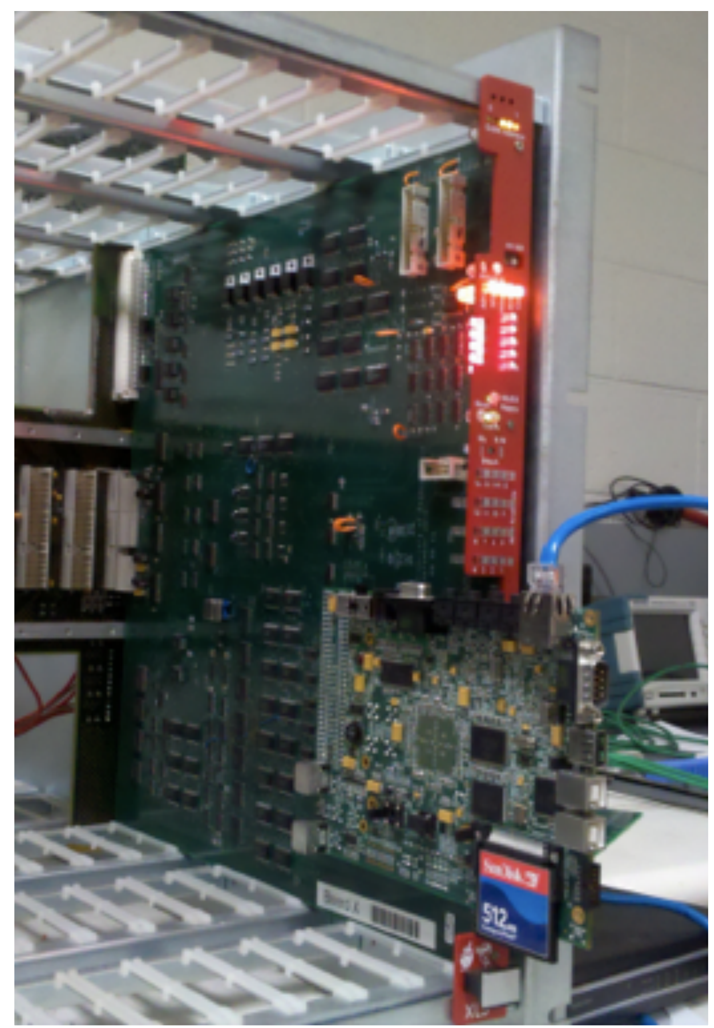
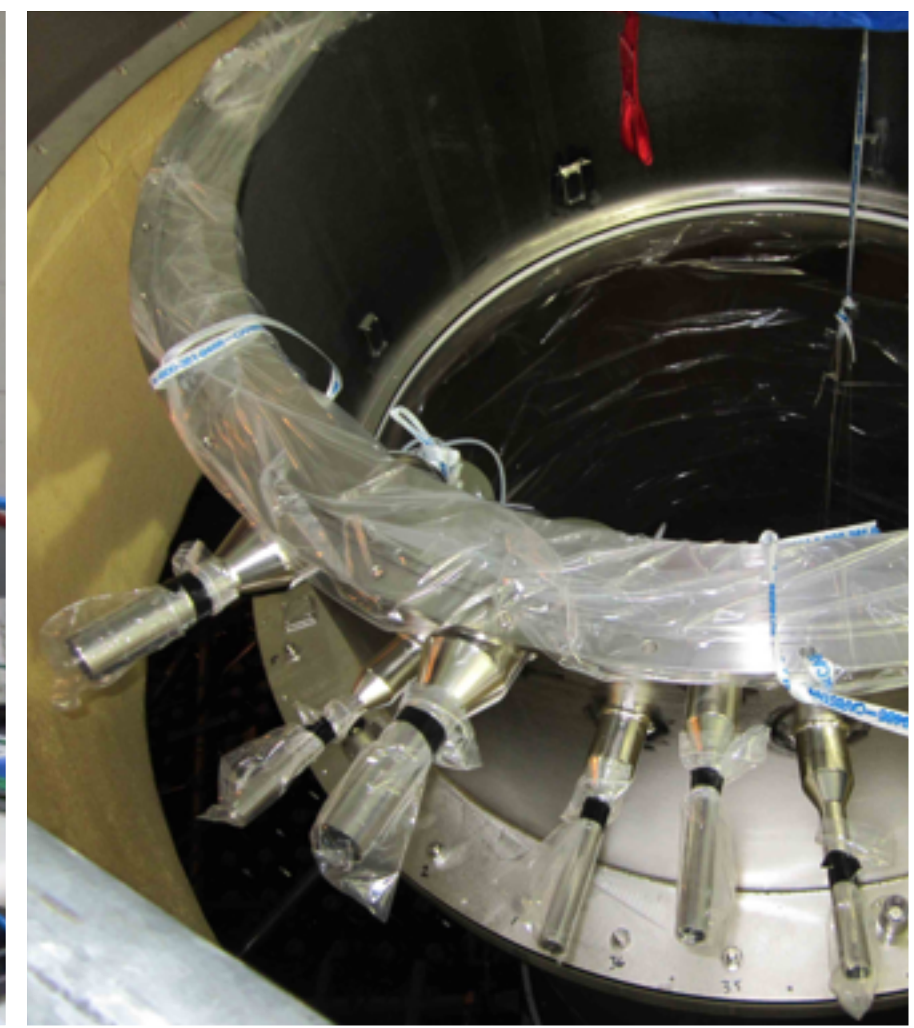
Expected Average Spectra of Contributing Backgrounds for Two Live Years of Data





results
(exclusion)
projected
sensitivities
350
300
250
200
150
100
50
0
$m_{\beta\beta}$ (meV)
EXO 200
KAMLAND
GERDA+IGEX+HDL
SNO+
(0.3%)
SNO+ (3%)
(current detector)
Inverted
Hierarchy
2012
2013
2014
2015
2016
2017
2018
2019
2020

Summary and Outlook

Exciting time as we close in on the IH! Possibilities to go beyond!

Different isotopes and varied experimental techniques…
if Majorana neutrinos are within reach, we will observe!