Acknowledgements:
(incomplete!)

J. Chaves, C. Davis, J. Farine, G. Gratta, C. Hall, A. Pocar, P. Vogel, L. Yang,
and the entire EXO Collaboration

EXO-200 and nEXO: Recent Results and Future Prospects

Krishna S. Kumar
University of Massachusetts, Amherst

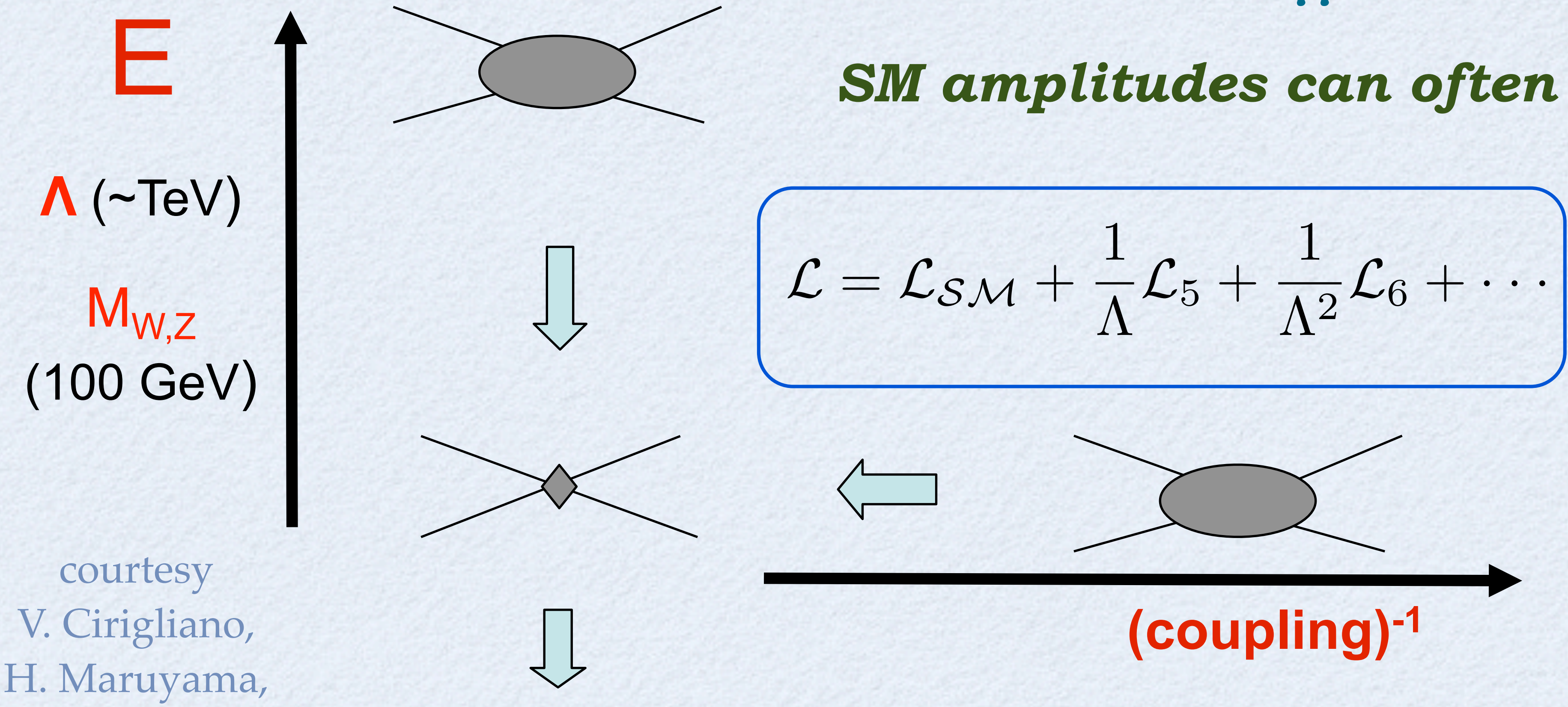
Nuclei and Fundamental Symmetries:
Theory Needs for the Next-Decade Experiments,
INT, Seattle
23 August 2013

Intensity Frontier (HEP)
Fundamental Symmetries and Neutrinos (NP)

Observables at scales much lower than the scale of EW Symmetry Breaking

High Energy Dynamics

Many theories predict new forces/dynamics that disappeared when the universe cooled



SM amplitudes can often be precisely predicted

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators can be systematically classified

Dark Sector

courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov

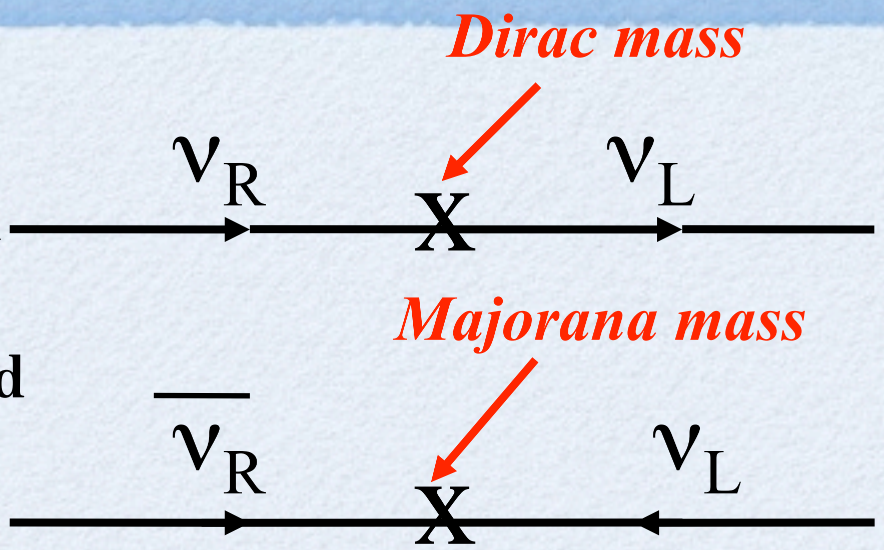
Heavy Z's & neutrinos, Light Z's (dark forces), technicolor, compositeness, extra dimensions, SUSY…

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy….

In most cases, observables exploit a symmetry principle

Lepton Number Violation

Mass terms behave like an interaction between left-handed and right-handed fields



Conserves lepton number

Changes lepton number by two units

Neutrinos may have Dirac masses, Majorana masses, or both

But the Standard Model Higgs only generates Dirac masses

The see-saw

generated by the Higgs

Suppose m_{Dirac} ~ 100 GeV, e.g. top quark

and $m_{Majorana}$ ~ 10^{15} GeV

generated by new physics at the Grand Unification Energy Scale

$$\frac{1}{\Lambda}\mathcal{L}_5$$

Then we would observe two Majorana neutrinos, with

like atmospheric ν oscillations

$$m_1 \approx \frac{m_D^2}{M_{GUT}} \approx 10^{-2}\ \text{eV}$$

too large to be seen directly

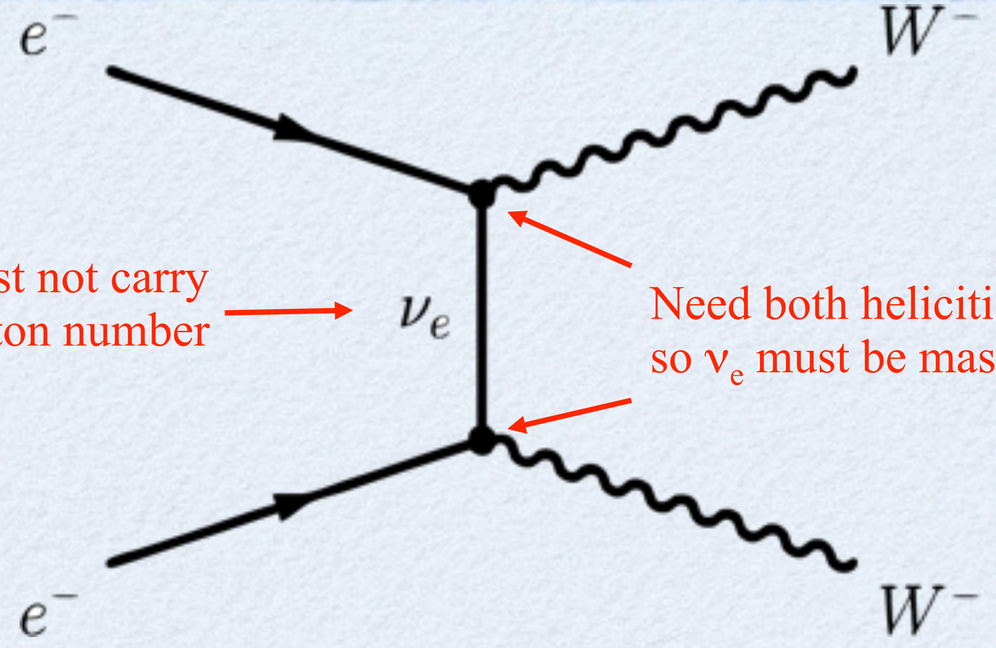
$$m_2 \approx M_{GUT}$$

Dream Scenario: Leptogenesis

CP-violation in the decays of heavy neutrinos into SM particles generates the matter-antimatter asymmetry in the universe

Experimental Strategy

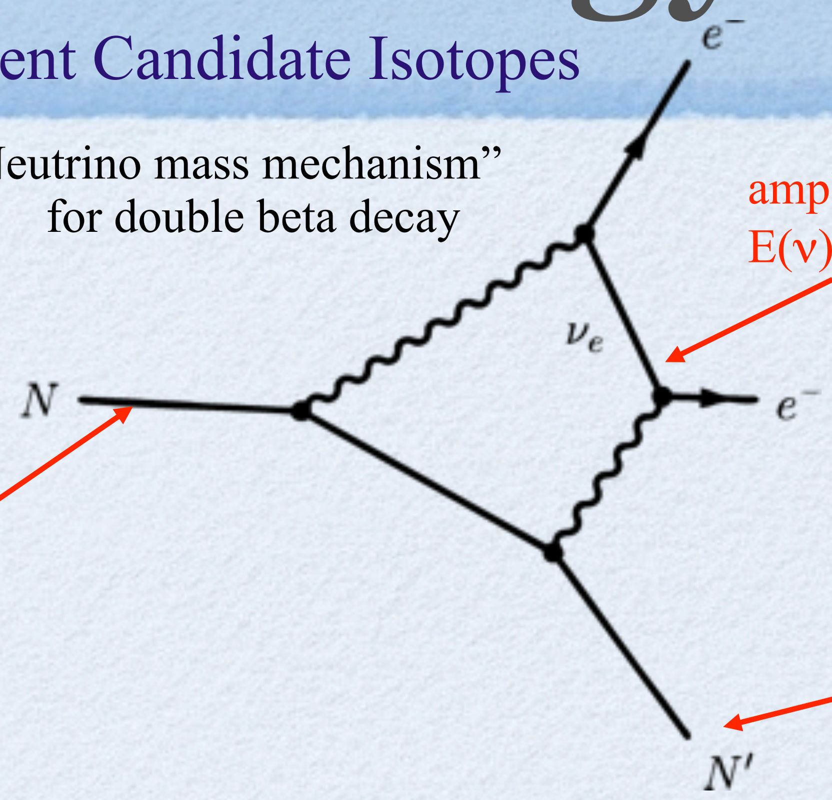
A worldwide Program in Several Different Candidate Isotopes



must not carry lepton number

Need both helicities, so ν_e must be massive

“Neutrino mass mechanism” for double beta decay

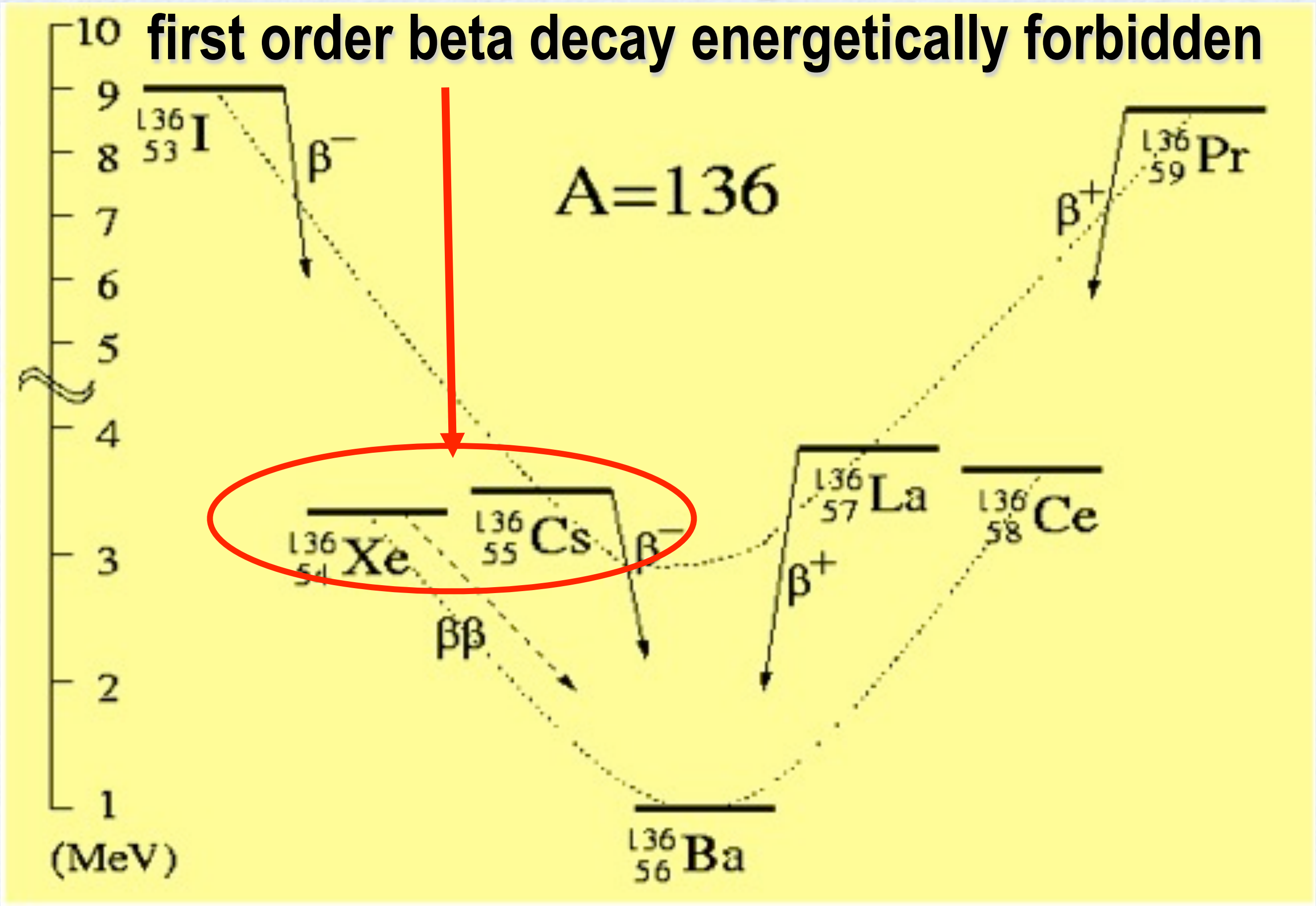


amplitude ~ m(ν)/E(ν), E(ν) ~ 100 MeV

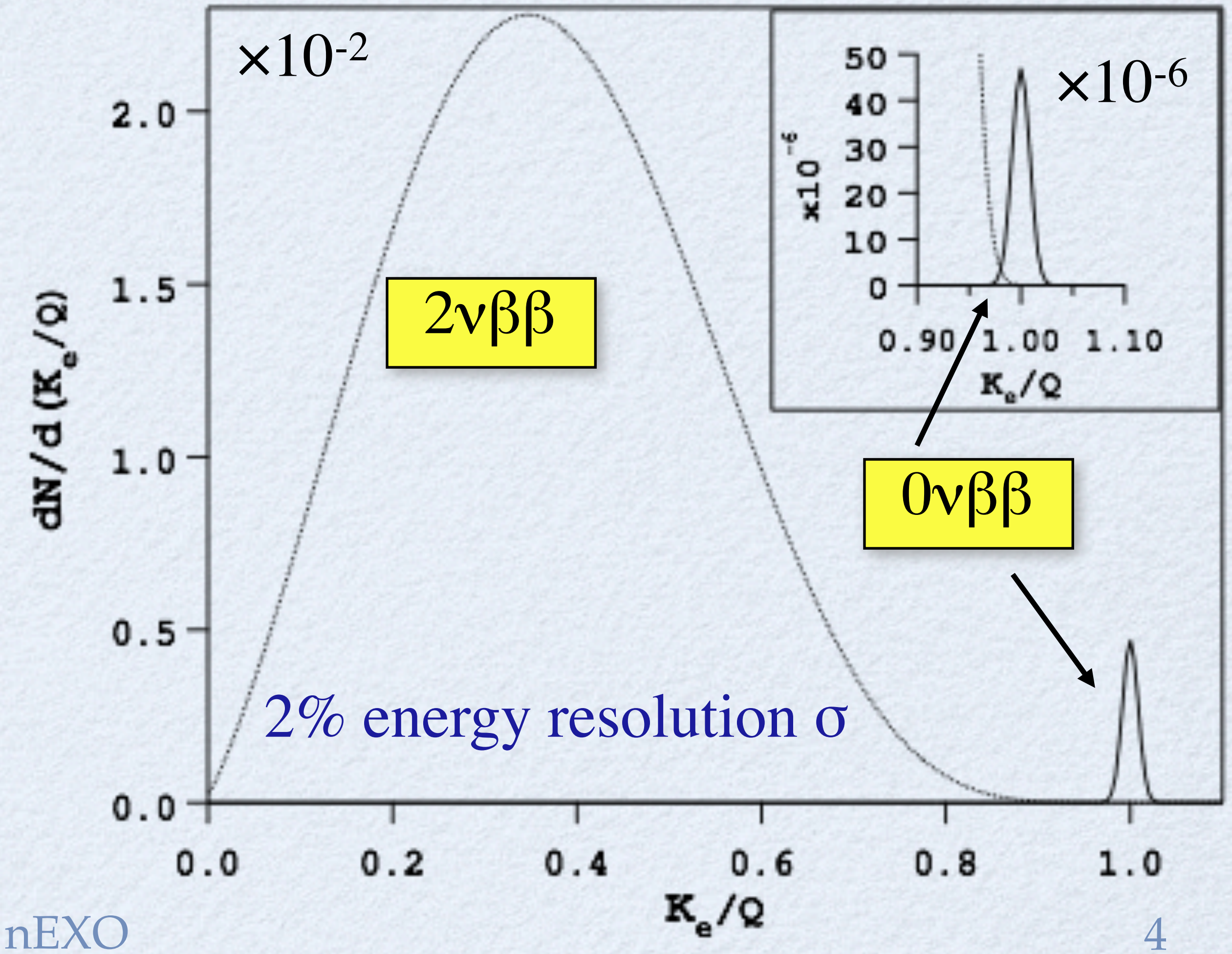
N(Z,A)

N(Z+2,A)

Double-beta decay:



first order beta decay energetically forbidden



2% energy resolution σ

Weighing Neutrinos? Maybe...

Majorana neutrino mass: ONE kind of BSM physics leading to ββ0ν

Two caveats to ββ0ν as a mass measurement:

1) we must have a reliable calculation of the nuclear matrix element
2) the neutrino mass mechanism must dominate the decay

Right handed weak currents, leptoquarks, supersymmetry, doubly charges scalars etc.,
but
A simple theorem guarantees that in gauge theories
these models always require Majorana neutrinos.

$$\frac{1}{\Lambda^5}\mathcal{L}_9$$

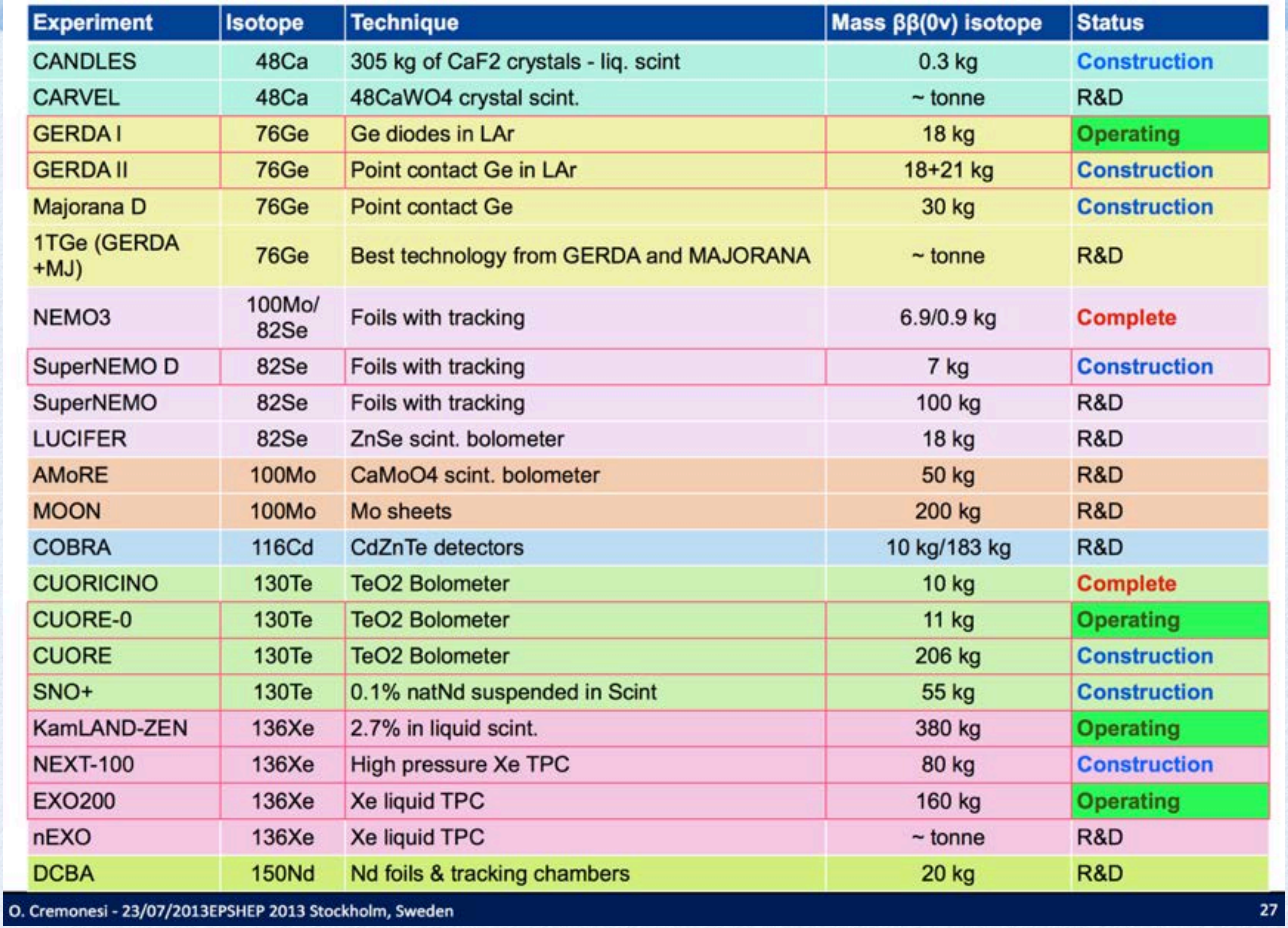
1 TeV

$$\frac{1}{\Lambda}\mathcal{L}_5$$

10^{15} GeV

without caveats: ββ0ν ➠ Majorana neutrinos

Experiments Summary



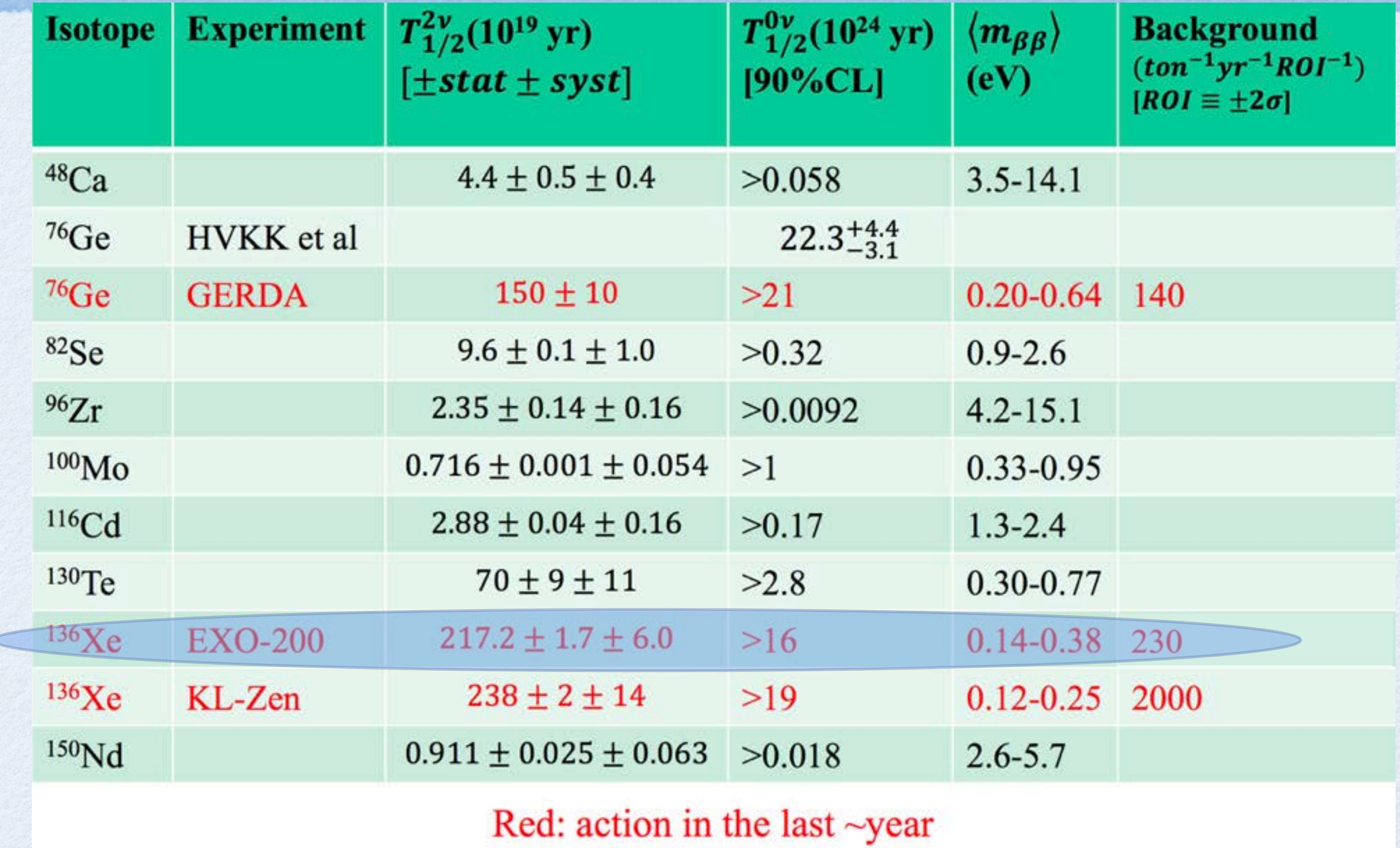
Experiment	Isotope	Technique	Mass ββ(0ν) isotope	Status
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
GERDA I	76Ge	Ge diodes in LAr	18 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	18+21 kg	Construction
Majorana D	76Ge	Point contact Ge	30 kg	Construction
1TGe (GERDA +MJ)	76Ge	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	100Mo/ 82Se	Foils with tracking	6.9/0.9 kg	Complete
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.1% natNd suspended in Scint	55 kg	Construction
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

O. Cremonesi - 23/07/2013EPSHEP 2013 Stockholm, Sweden 27

Global Strategy

- A healthy program requires more than 1 isotope (3?)
  - Unknown gamma transitions always a possibility
    - "End point" observation in one isotope may not be replicated in another
  - Nuclear matrix elements not accurately known: which isotope is better?
  - Different isotopes require vastly different experimental techniques
  - 2-ν background is different in each case (small for ^{136}Xe!)
  - Proof of "neutrino-mass mechanism"?

Results by Isotope



Isotope	Experiment	$T^{2\nu}_{1/2}(10^{19}\ \text{yr})$ $[\pm stat \pm syst]$	$T^{0\nu}_{1/2}(10^{24}\ \text{yr})$ [90%CL]	$\langle m_{\beta\beta} \rangle$ (eV)	Background $(ton^{-1}yr^{-1}ROI^{-1})$ $[ROI \equiv \pm 2\sigma]$
^{48}Ca		$4.4 \pm 0.5 \pm 0.4$	>0.058	3.5-14.1	
^{76}Ge	HVKK et al		$22.3^{+4.4}_{-3.1}$		
^{76}Ge	GERDA	150 ± 10	>21	0.20-0.64	140
^{82}Se		$9.6 \pm 0.1 \pm 1.0$	>0.32	0.9-2.6	
^{96}Zr		$2.35 \pm 0.14 \pm 0.16$	>0.0092	4.2-15.1	
^{100}Mo		$0.716 \pm 0.001 \pm 0.054$	>1	0.33-0.95	
^{116}Cd		$2.88 \pm 0.04 \pm 0.16$	>0.17	1.3-2.4	
^{130}Te		$70 \pm 9 \pm 11$	>2.8	0.30-0.77	
^{136}Xe	EXO-200	$217.2 \pm 1.7 \pm 6.0$	>16	0.14-0.38	230
^{136}Xe	KL-Zen	$238 \pm 2 \pm 14$	>19	0.12-0.25	2000
^{150}Nd		$0.911 \pm 0.025 \pm 0.063$	>0.018	2.6-5.7	

Red: action in the last ~year

Xenon as the Candidate Isotope

Many Significant Advantageous Factors

Isotopic enrichment easier & known: ***Xe is a gas and ^{136}Xe is the heaviest isotope.***

Xenon is "reusable": ***can be re-purified (noble gas: relatively easy) during measurement and easily recycled into a different detector (no crystal growth)***

.... replace ^{136}Xe with $^{nat'l}$Xe if signal observed

Monolithic detector: ***LXe is self shielding, surface contamination minimized.***

Minimal cosmogenic activation: ***no long lived radioactive isotopes of Xe.***

Energy resolution in LXe improved: ***scintillation light + ionization anti-correlation.***

Standard $2\nu\beta\beta$ is slow! (see later): ***get away with modest energy resolution***

… admits a novel coincidence technique: ***background reduction by Ba tagging***

.... potentially access normal hierarchy

The EXO Strategy

Goal:

^{136}Xe experiment sensitive enough to probe the inverted mass heirarchy (get comfortably over $T^{0\nu}_{1/2} > 10^{27}$ years)

How:

multi-ton scale enriched Xe (80% ^{136}Xe) time projection chamber (TPC) with scintillation light collection and ^{136}Ba^{+} identification (possibility unique to ^{136}Xe), for an experiment virtually free of external background

Phased approach:

- **EXO-200 "prototype" detector (200 kg of enriched xenon, 80% ^{136}Xe, liquid, no Ba tagging, producing important results)**
- **^{136}Ba^{+} identification R&D as a parallel effort**
- **nEXO 5 ton detector as similar to EXO-200 as possible**
- **Add Ba tagging to comprehensively access inverted mass hierarchy and begin to probe the normal hierarchy**

The EXO Collaboration

The EXO Collaboration

Enriched Xenon Observatory for double beta decay

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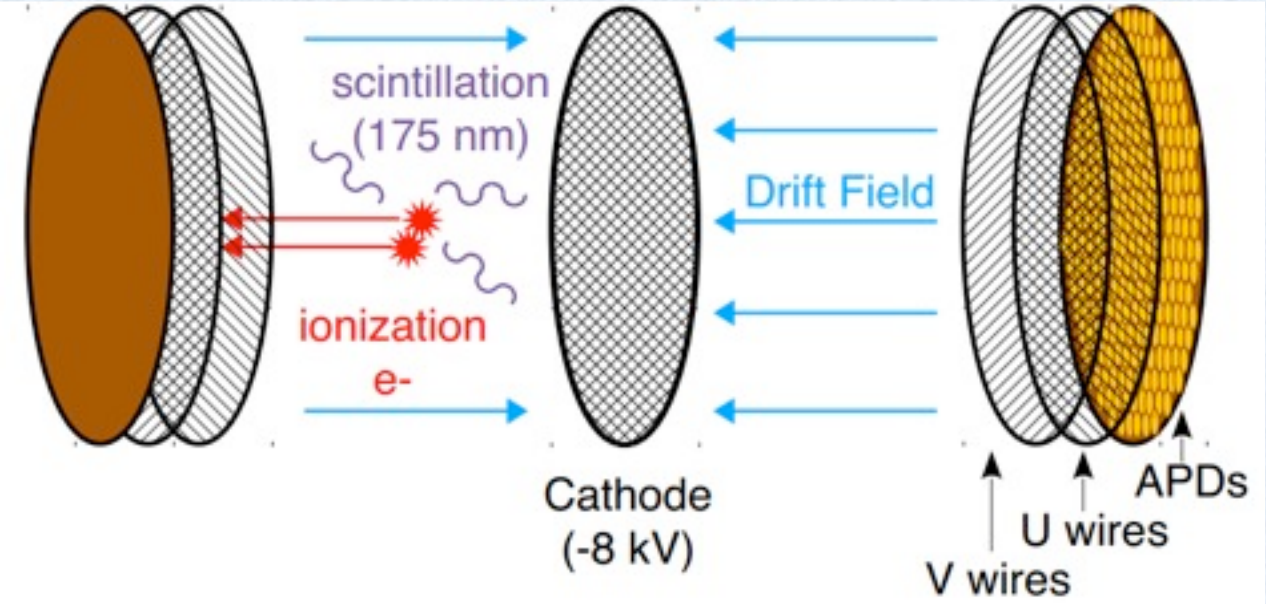
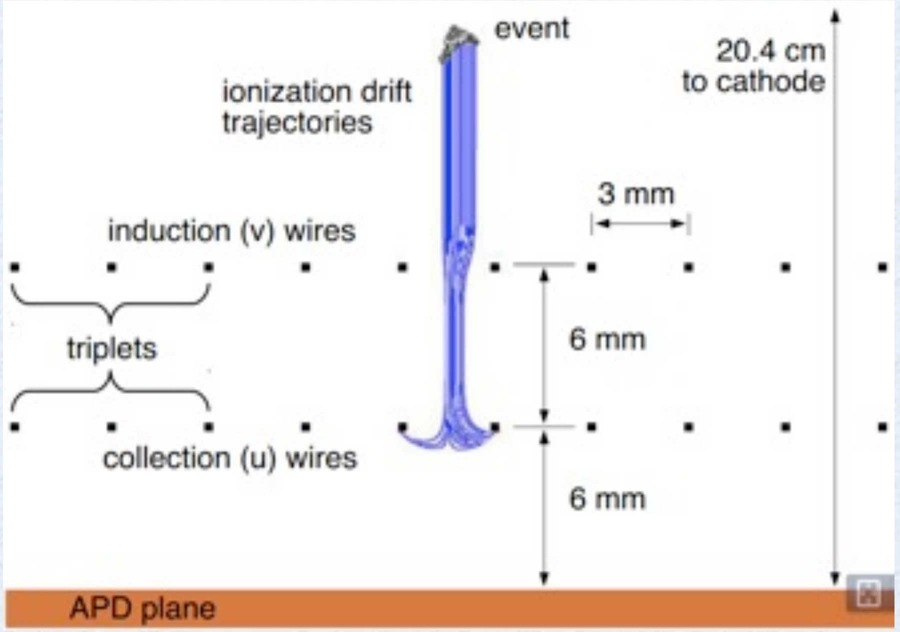
Stanford University, Stanford CA, USA - P.S. Barbeau, J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S.Kravitz, D. Moore, I. Ostrovskiy, A. Rivas, A. Schubert, D. Tosi, K. Twelker, L. Wen
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

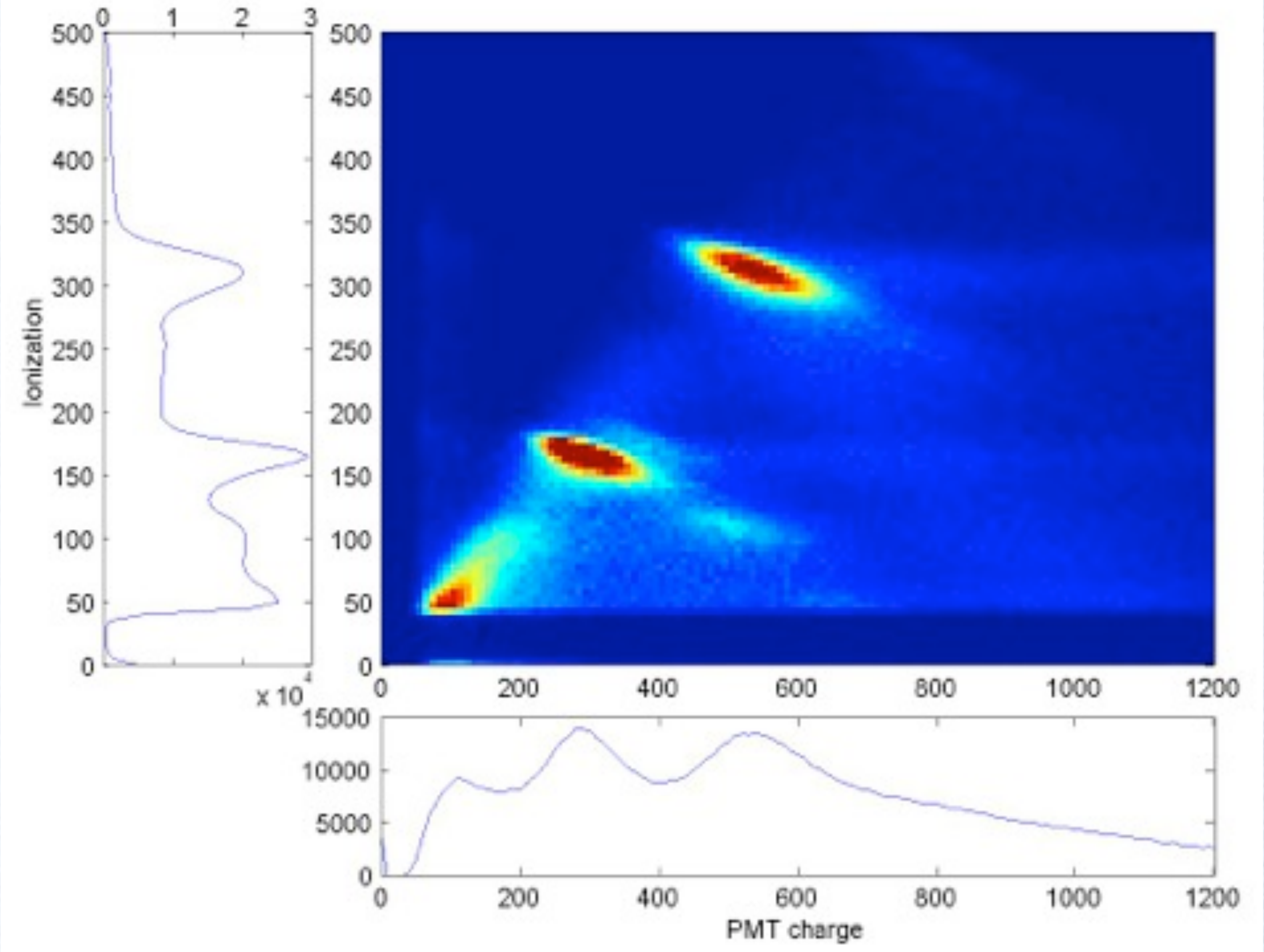
EXO-200 Concept



EXO R&D showed the way to improved energy resolution in LXe:

Use (anti)correlations between ionization and scintillation signals

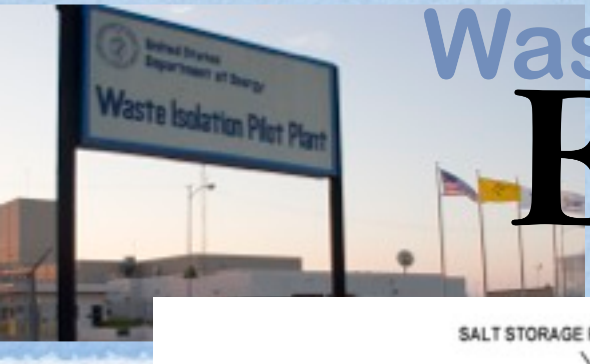




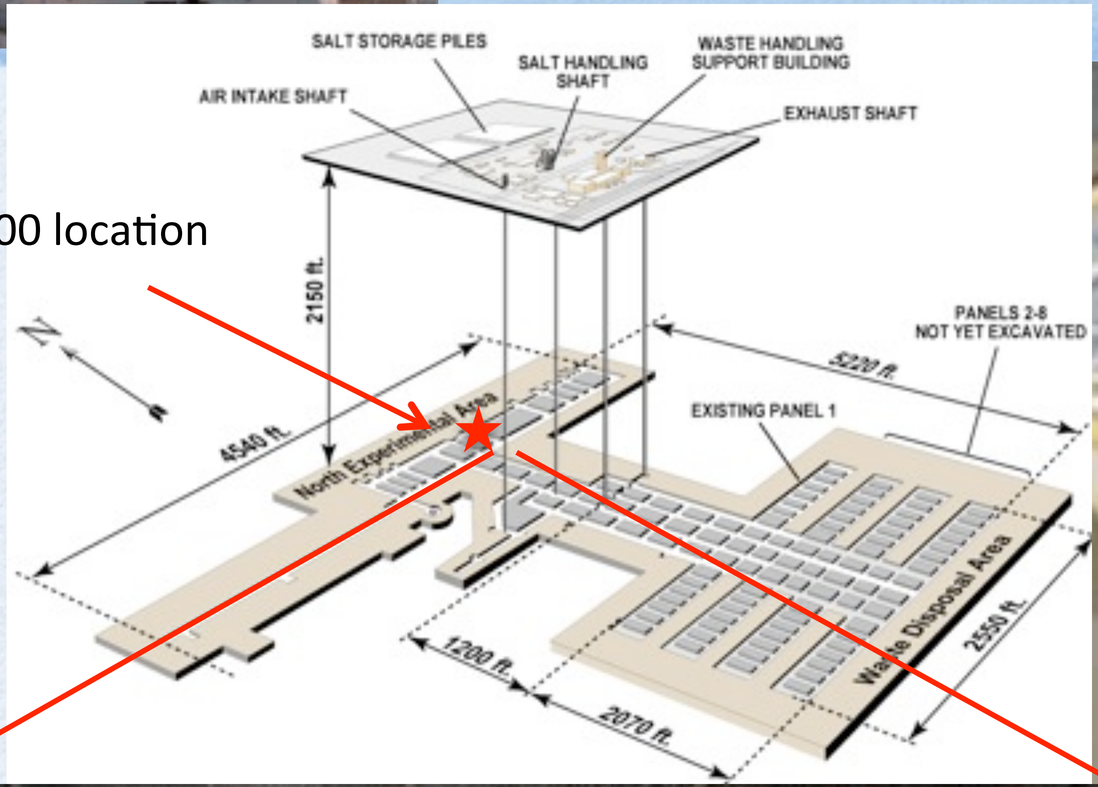
- **Two TPCs with common cathode in middle**
- **APD planes observe prompt scintillation for drift time measurement.**
- **V-position given by induction signal on shielding grid.**
- **U-position and energy given by charge collection grid.**

Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP



EXO-200 location



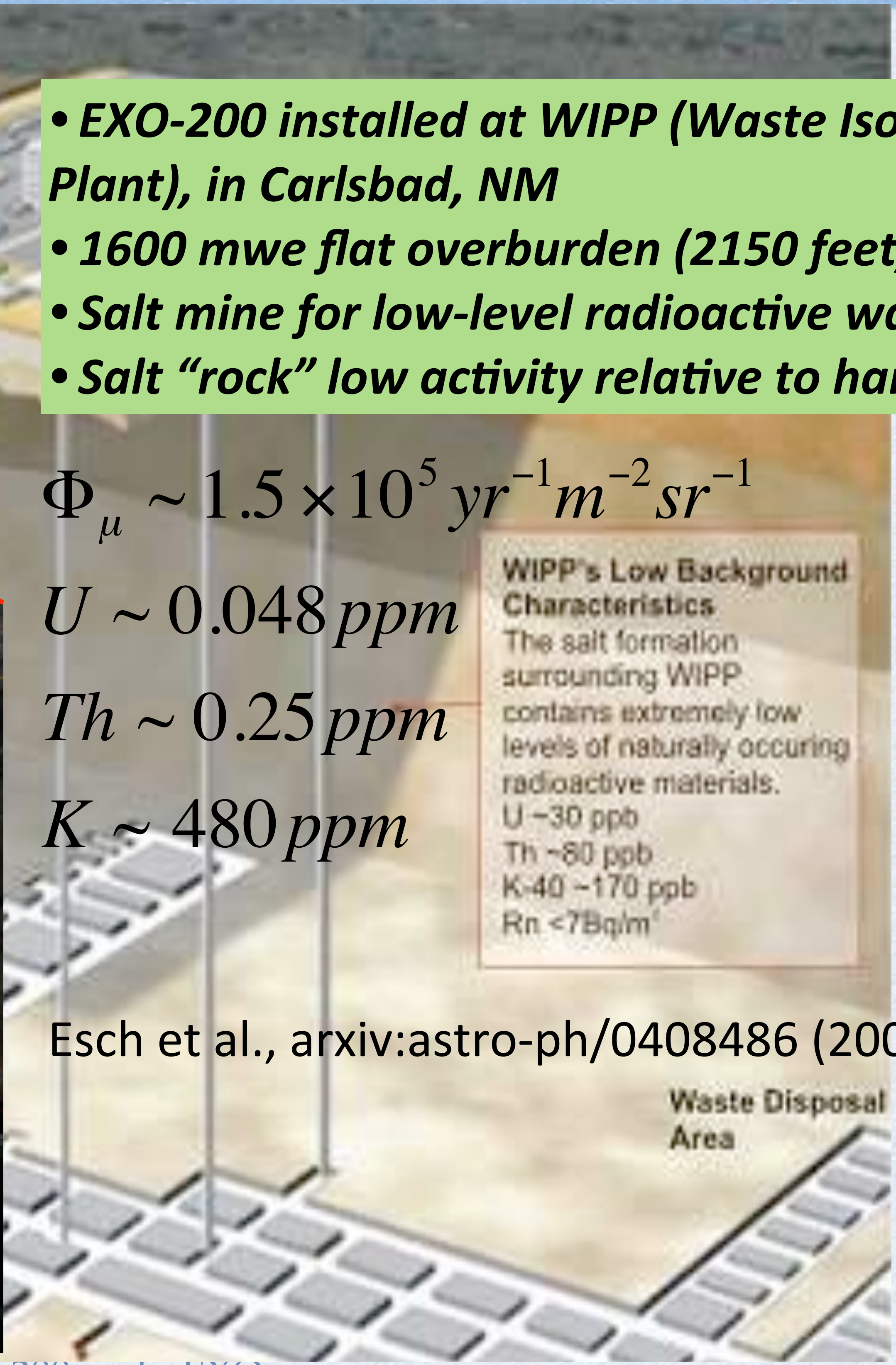
- ***EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM***
- ***1600 mwe flat overburden (2150 feet, 650 m)***
- ***Salt mine for low-level radioactive waste storage***
- ***Salt "rock" low activity relative to hard-rock mine***

$$\Phi_\mu \sim 1.5\times10^5\, yr^{-1}m^{-2}sr^{-1}$$

$$U \sim 0.048\, ppm$$

$$Th \sim 0.25\, ppm$$

$$K \sim 480\, ppm$$



WIPP's Low Background Characteristics

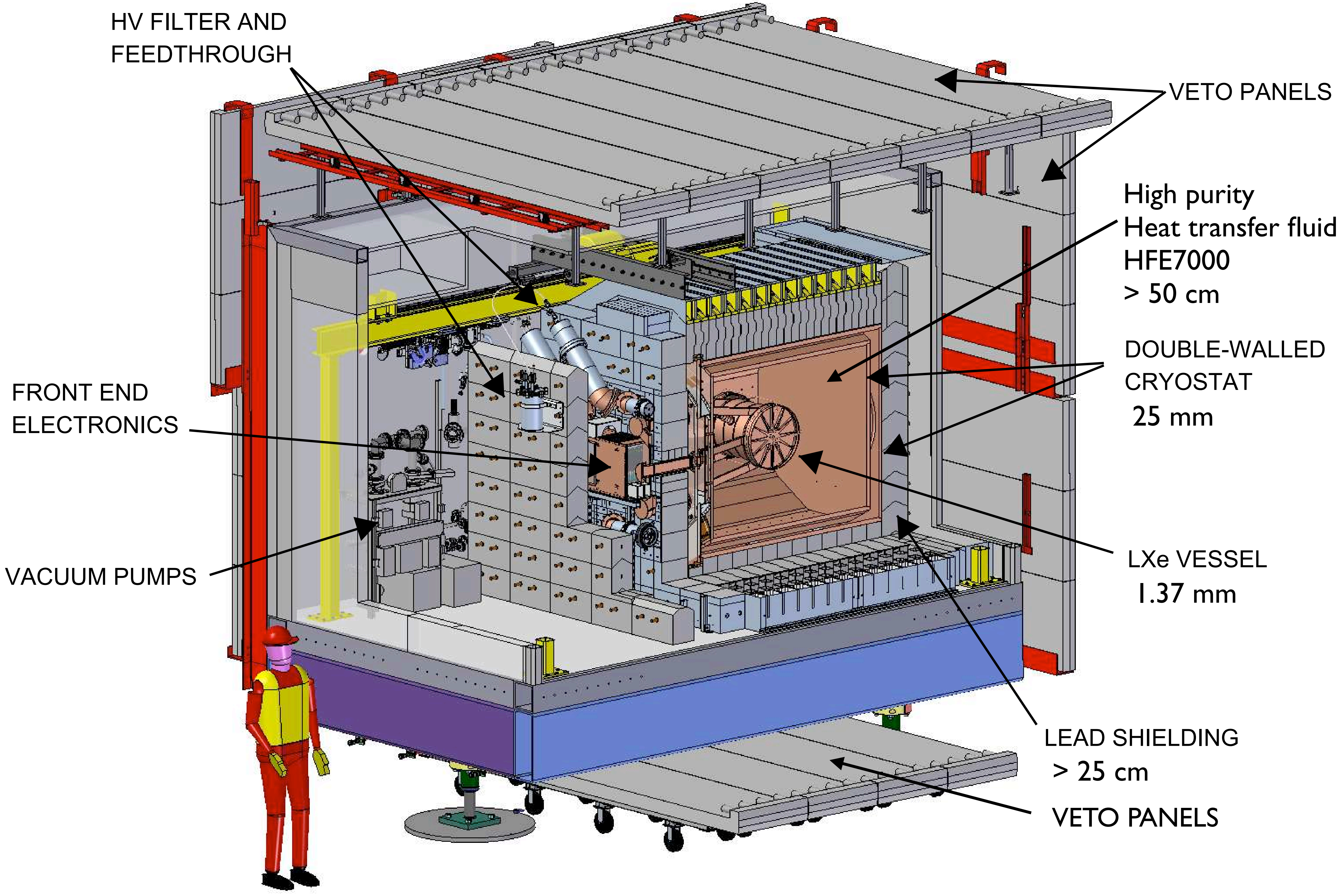
The salt formation surrounding WIPP contains extremely low levels of naturally occuring radioactive materials.

U ~30 ppb
Th ~80 ppb
K-40 ~170 ppb
Rn <7Bq/m³

Esch et al., arxiv:astro-ph/0408486 (2004)

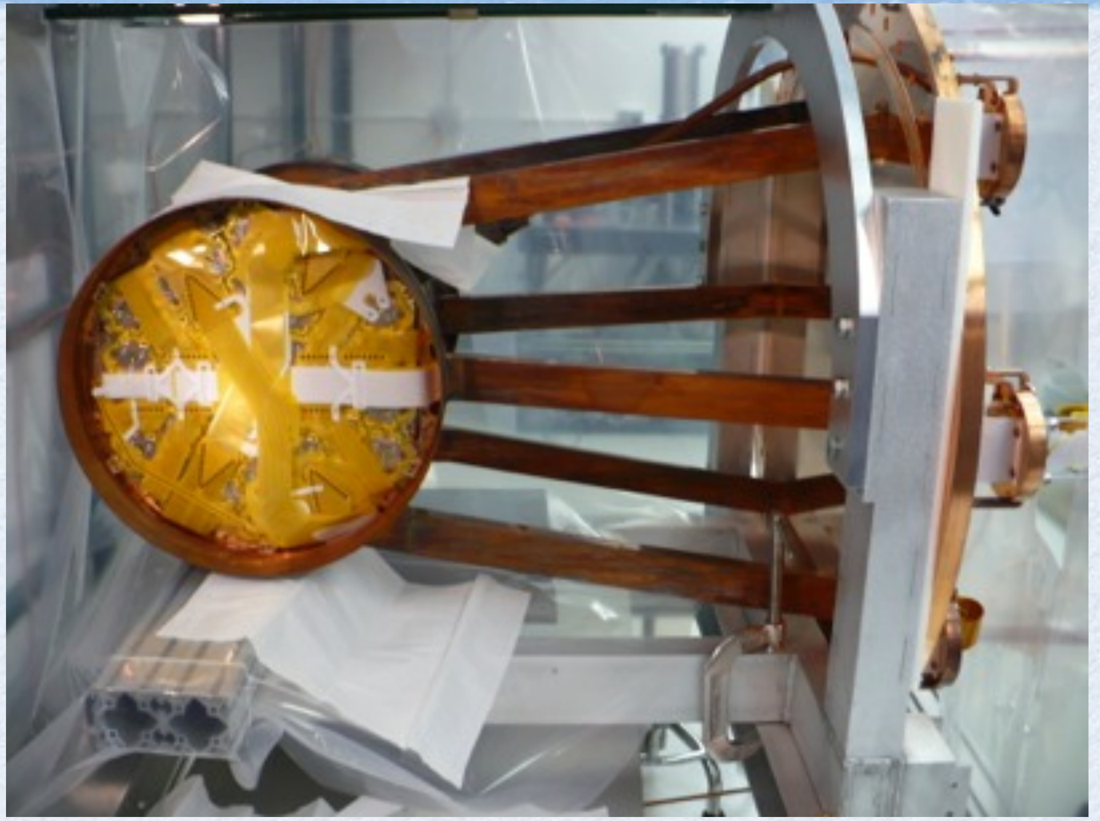
EXO-200 @ WIPP

Module 1


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

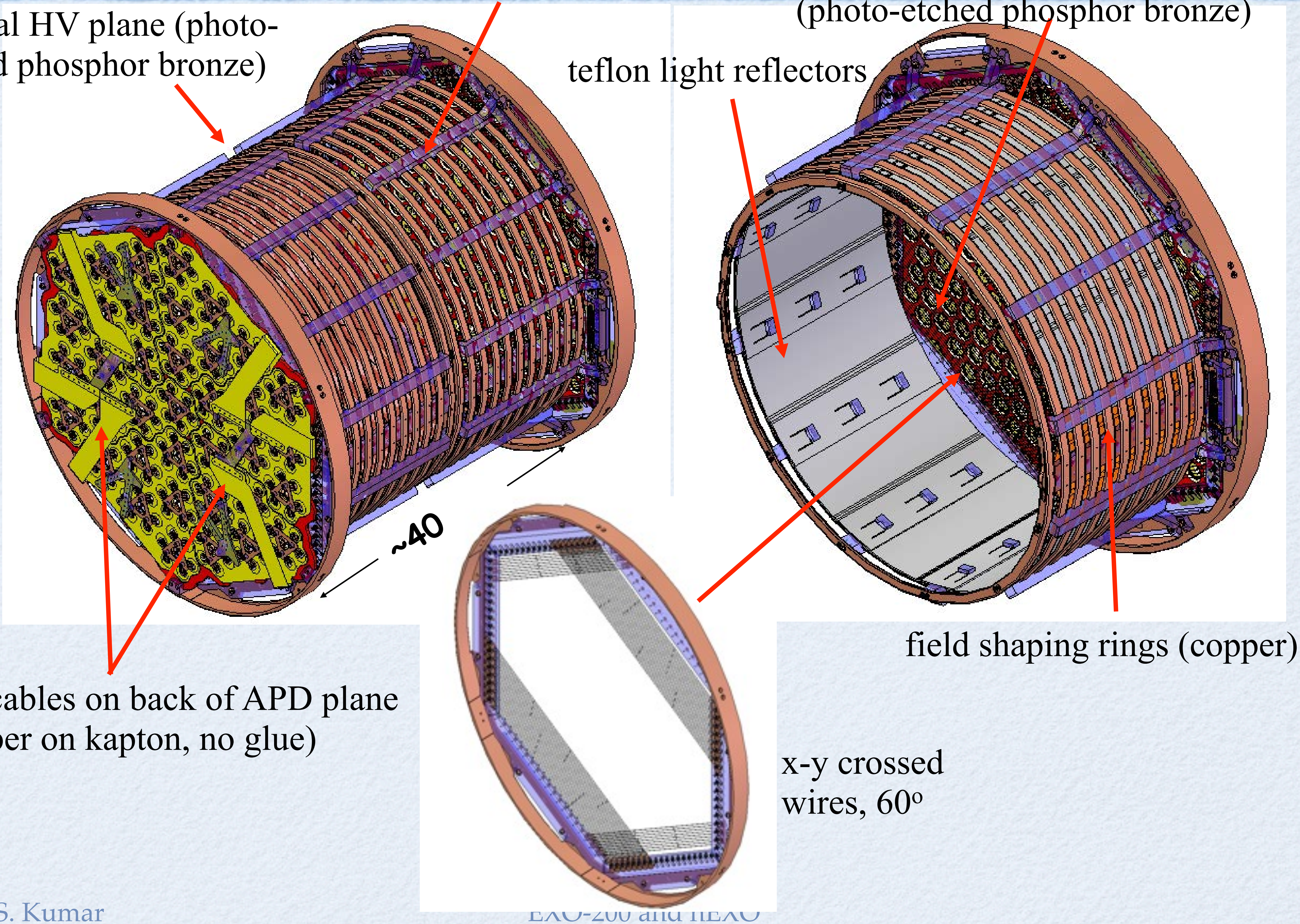
Ultra-low Activity Cu Vessel

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



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

TPC Design



acrylic supports

LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)

Central HV plane (photo-etched phosphor bronze)

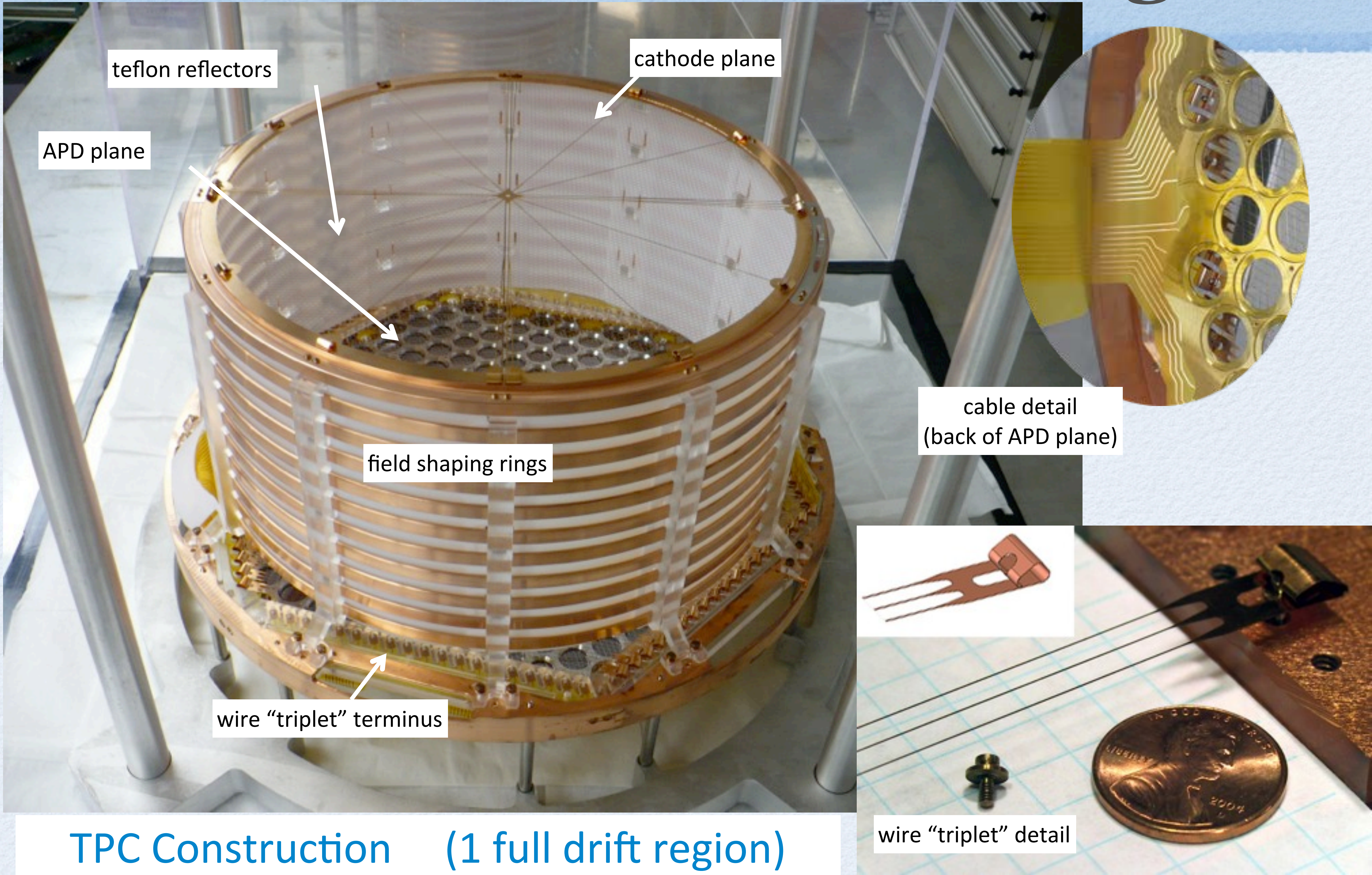
teflon light reflectors

field shaping rings (copper)

flex cables on back of APD plane (copper on kapton, no glue)

x-y crossed wires, 60°

TPC: The Real Thing



TPC Construction (1 full drift region)

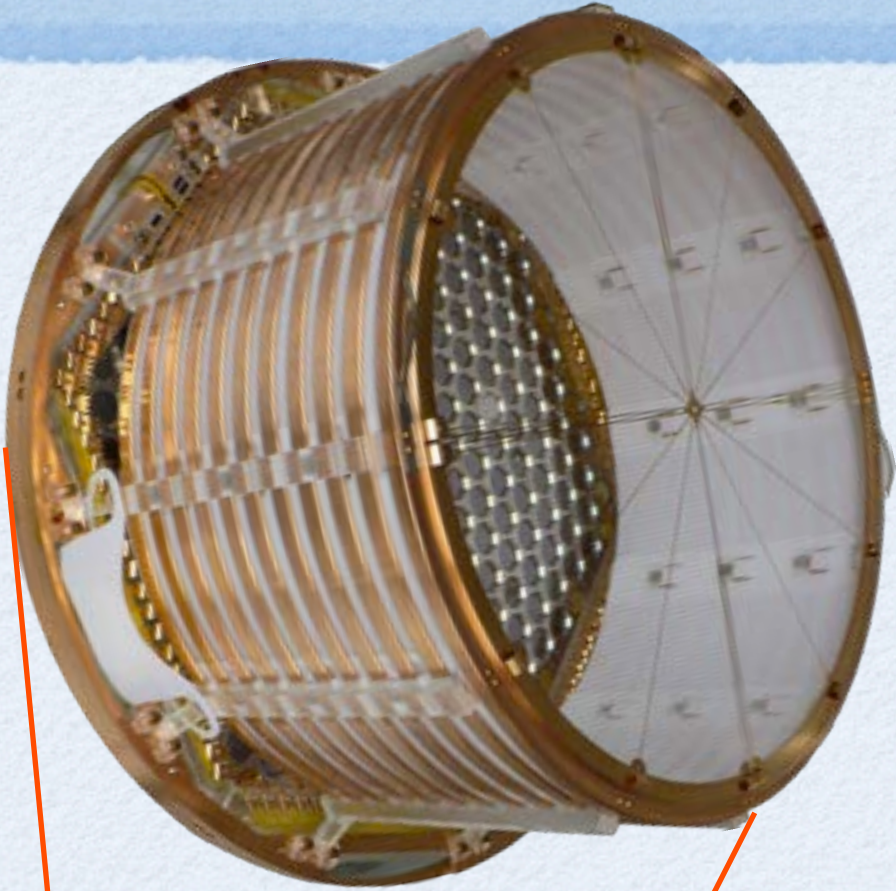
cable detail
(back of APD plane)

wire “triplet” detail

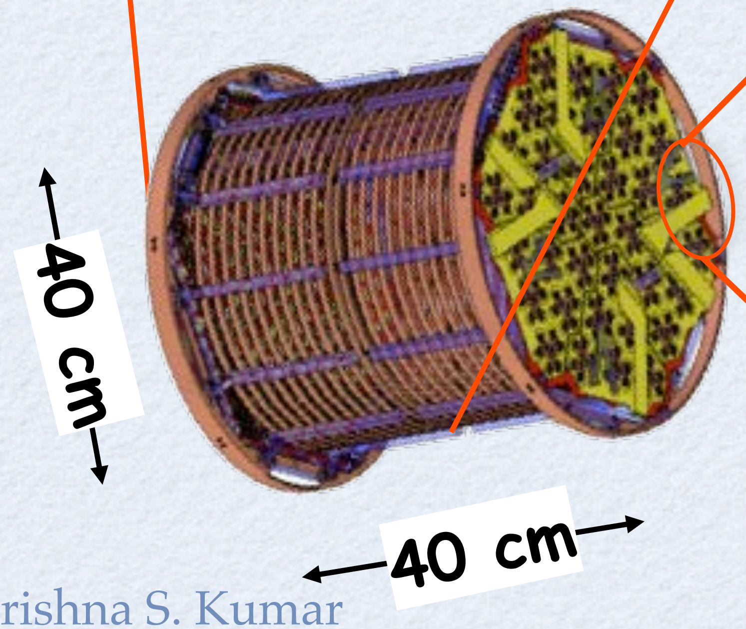
APD Installation

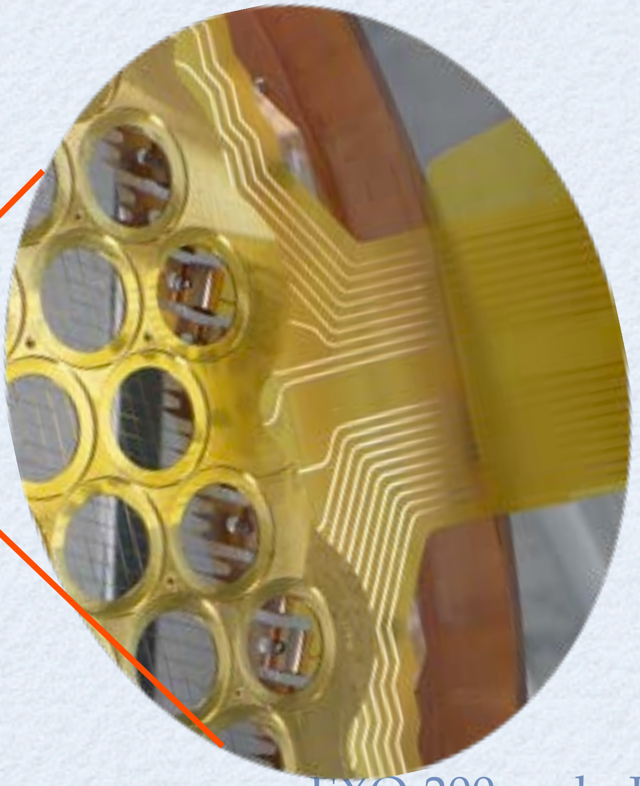
TPC Summary

Two almost identical halves reading ionization and 178 nm scintillation, each with:



- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, at 60° (induction)
- 234 large Avalanche PhotoDiodes (in gangs of 7)
- Triplet pitch 9 mm
- Wire planes 6 mm apart and 6 mm from APDs
- Signals digitized at 1 MS/s, ±1024s around trigger
- Drift field 376 V/cm





- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue; no soldered contact nor connector
- Vast material screening program

Principal Backgrounds

- γ (2449 keV) from ^{214}Bi decay (from ^{238}U and ^{222}Rn decay chains)
- γ (2615 keV) from ^{208}Tl decay (from ^{232}Th decay chain)
- γ (1.4 MeV) from ^{40}K (was a concern for the 2νββ)
- ^{60}Co: 1173 + 1333 keV simultaneous γ's (from ^{63}Cu(α,n)^{60}Co)
- other γ's in ^{238}U and ^{232}Th chains
- other cosmogenic products of Cu (was a concern for the 2νββ)
- in situ cosmogenic products in Xe, neutron capture de-excitations, ...
- ^{222}Rn anywhere (Xe, HFE, air gaps inside lead shield)

Materials Screening

- **Massive effort on material radioactive qualification:**
  - Neutron Activation Analysis
  - Alpha-counting
  - Radon counting
  - High performance GD-MS and ICP-MS

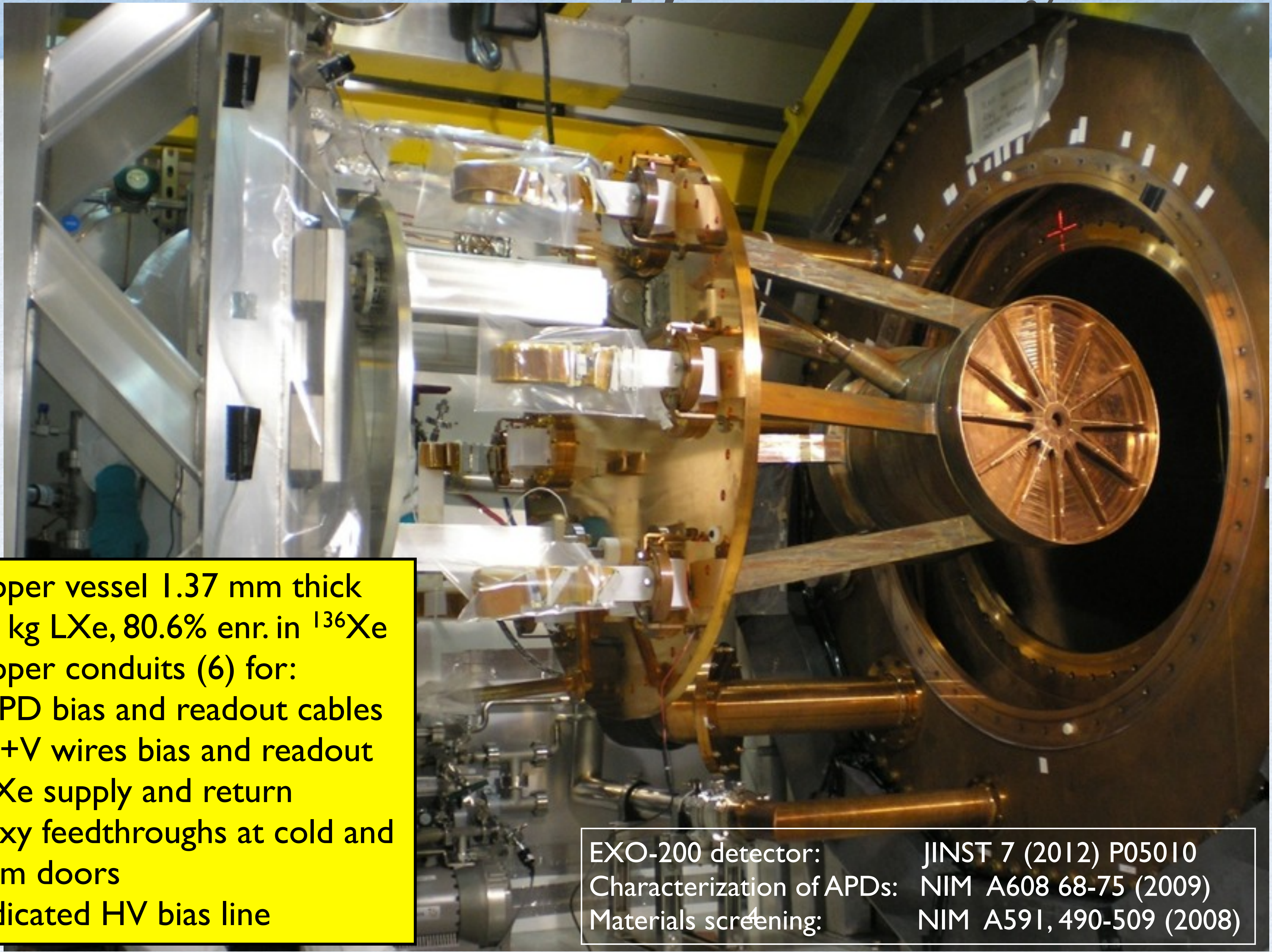
[EXO collaboration; D. Leonard et al., Nucl. Instr. Meth. A 591 (2008) 490]

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

Component	K 10^{-9} g/g	Th 10^{-12} g/g	U 10^{-12} g/g	^{210}Po Bq/kg
3M Novec HFE-7000, 1-methoxyheptafluoropropane	<1.08	<7.3	<6.2	
Lead shielding	<7	<1	<1	17-20
Copper	<55	<2.4	<2.9	
Acrylic	<2.3	<14	<24	
TPC grid wires	<90	47 +/- 2	320 +/- 2	

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

TPC entering the Cryostat



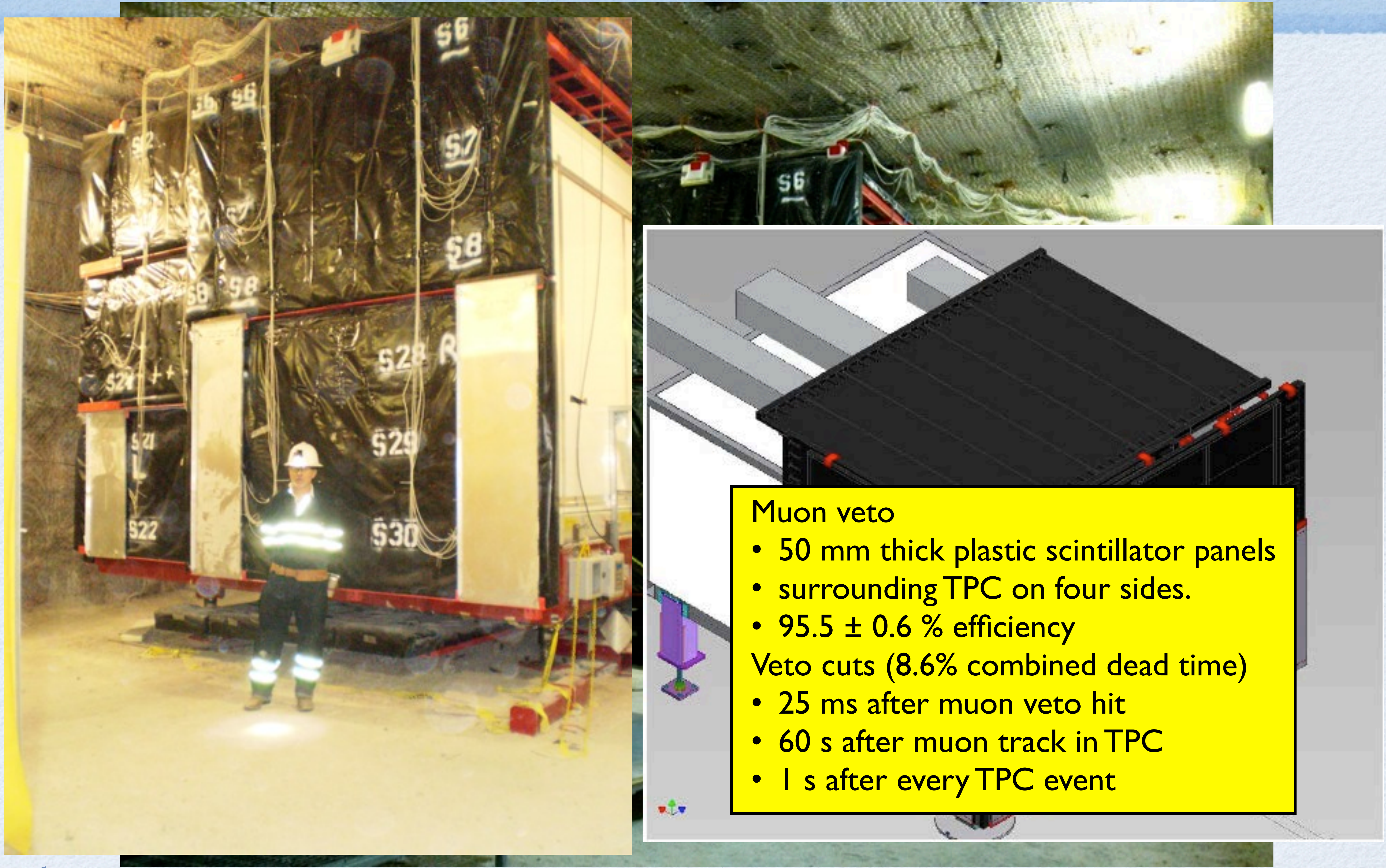
Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in ^{136}Xe
Copper conduits (6) for:

- 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)

Cosmic Ray Veto



Muon veto
- 50 mm thick plastic scintillator panels
- surrounding TPC on four sides.
- 95.5 ± 0.6 % efficiency

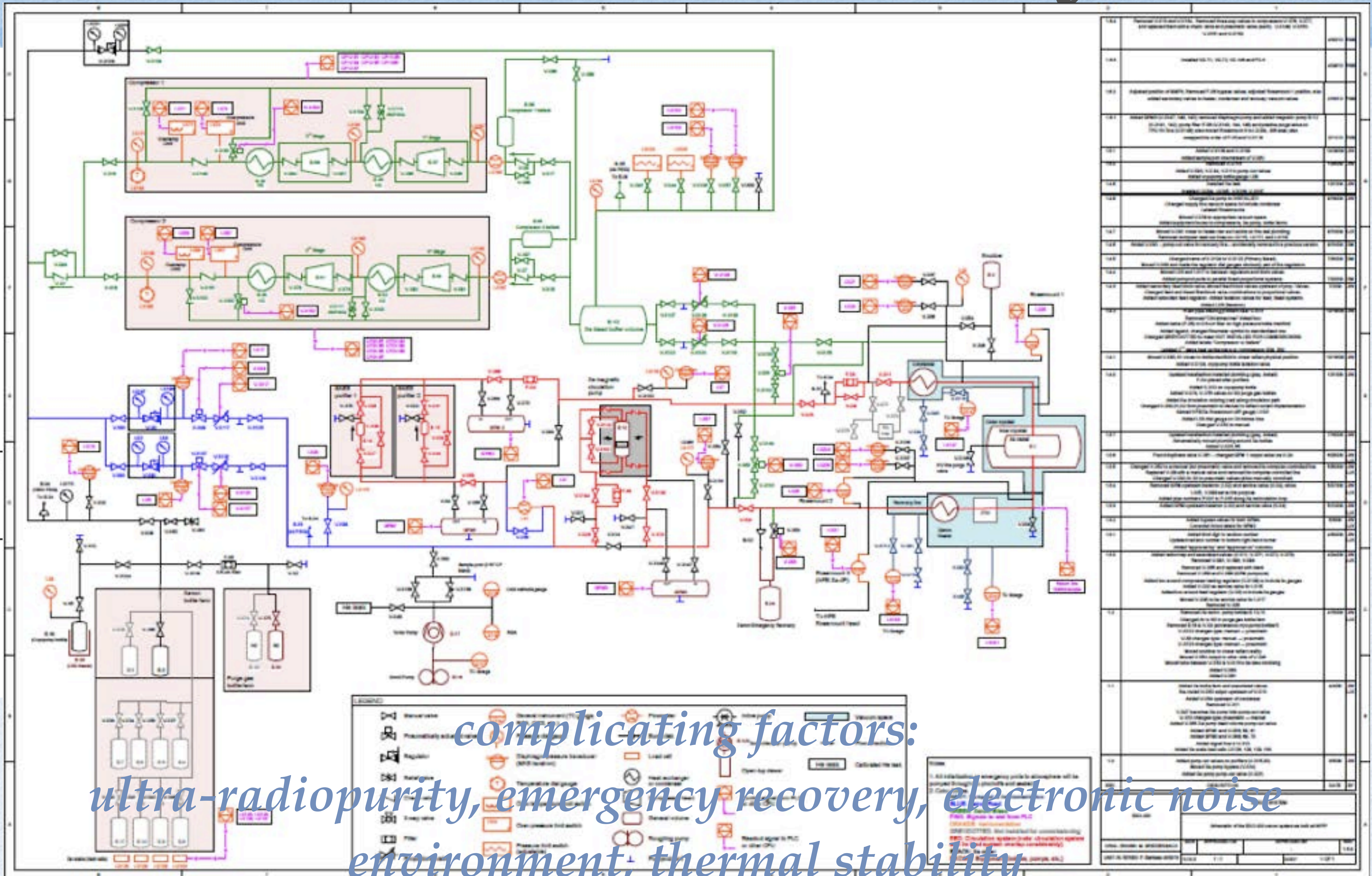
Veto cuts (8.6% combined dead time)
- 25 ms after muon veto hit
- 60 s after muon track in TPC
- 1 s after every TPC event

EXO-200 “Plumbing”

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

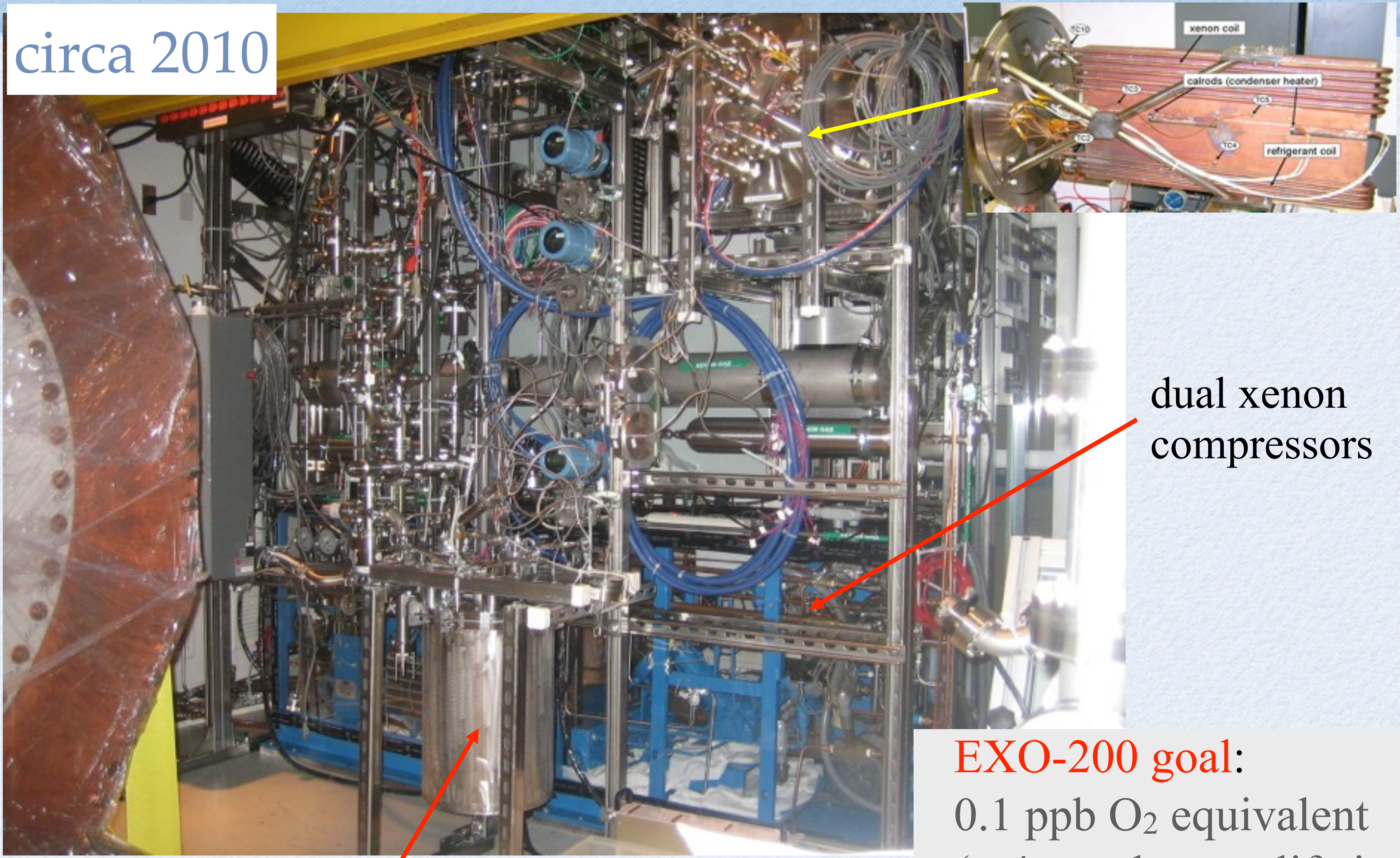
Xenon Recirculation System



complicating factors:

ultra-radiopurity, emergency recovery, electronic noise environment, thermal stability

EXO-200 Module 2



circa 2010

xenon condenser

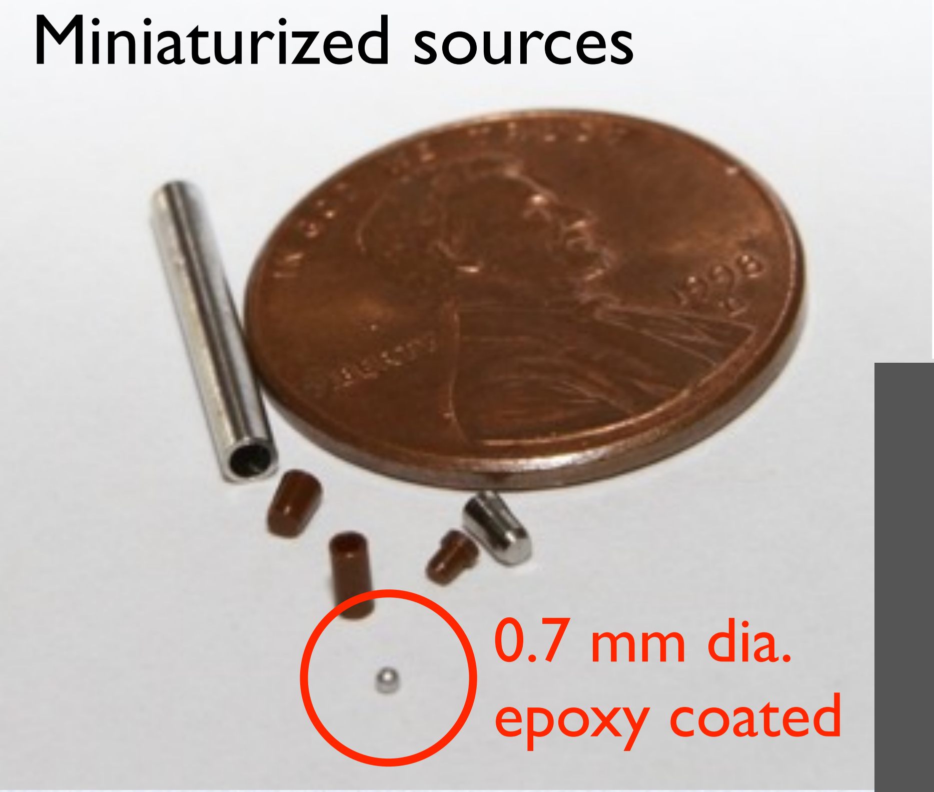
dual xenon compressors

LXe boil-off heater

EXO-200 goal:
0.1 ppb O_2 equivalent
(~ 4 ms electron lifetime)

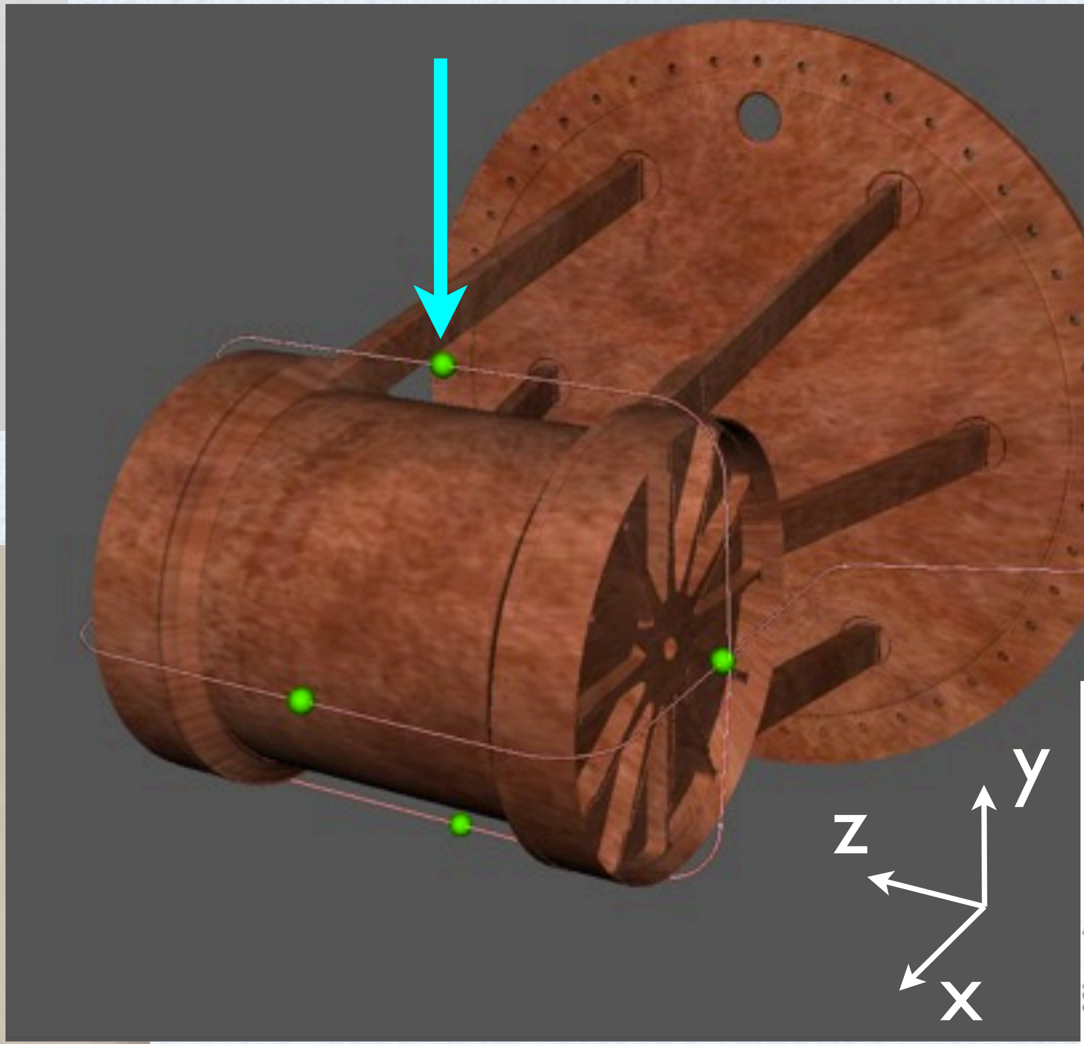
Calibration System

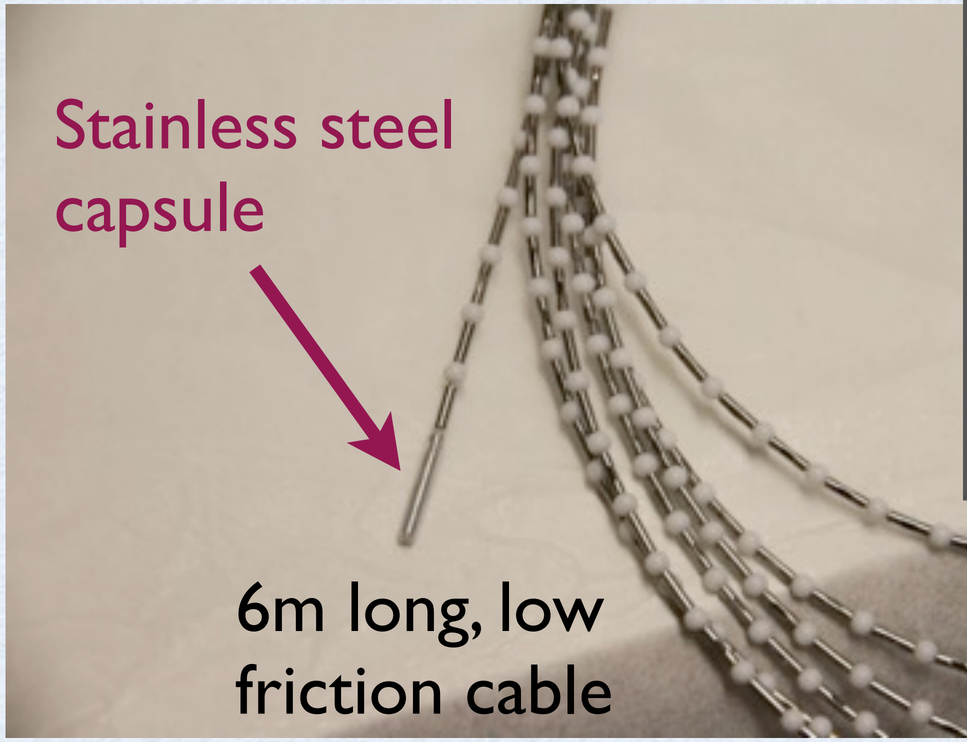
Miniaturized sources



Source	Weak (kBq)	Strong (kBq)
60-Co	3.0	15.0
137-Cs	0.5	7.2
228-Th	1.5	38.0

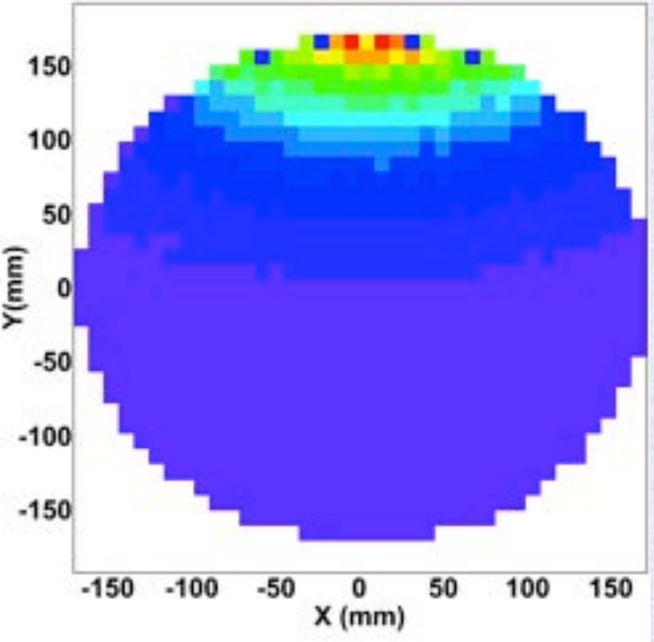
new ^{226}Ra source recently added





Provide 4 full energy deposition peaks in the energy range 662 keV – 2615 keV

weak ^{228}Th

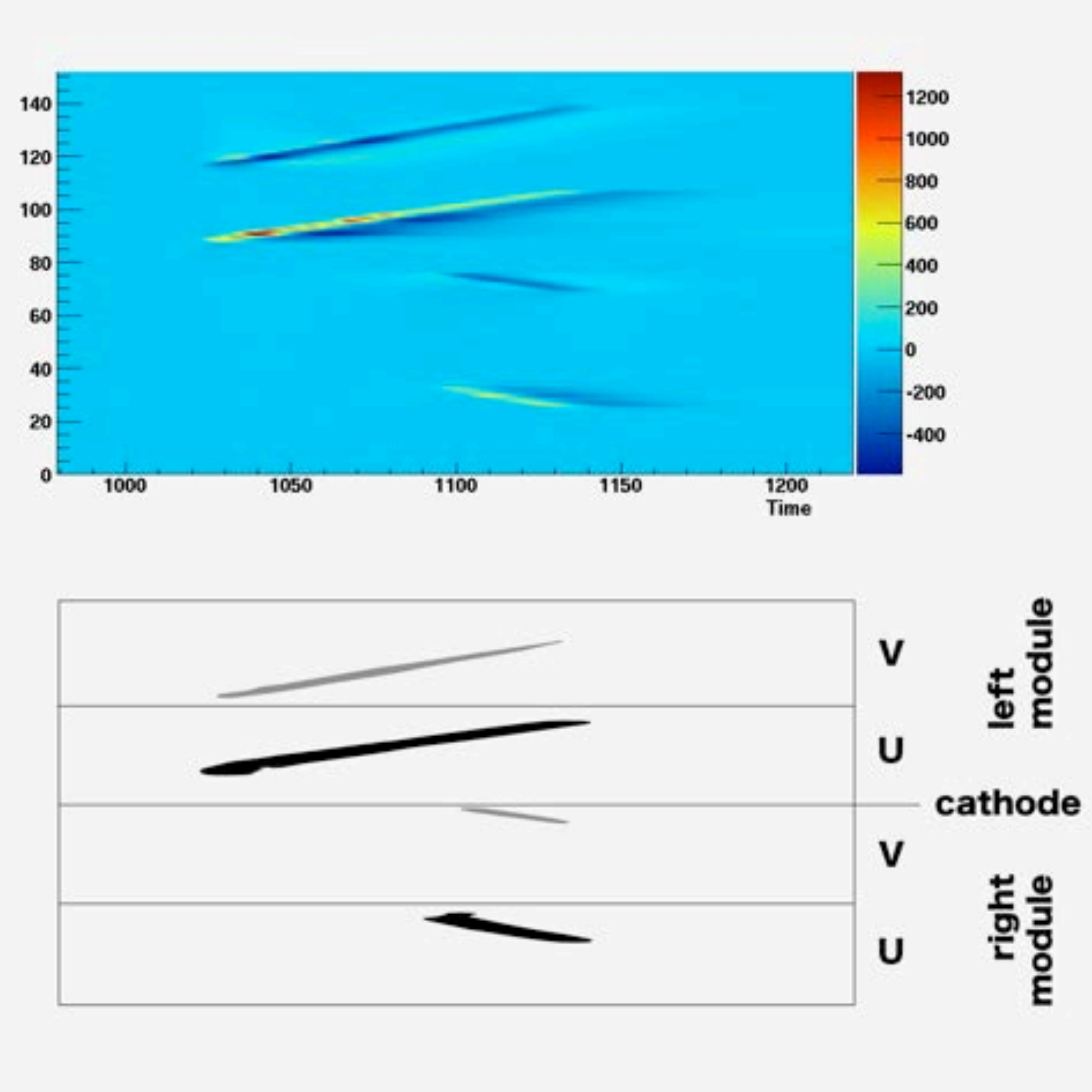


Data Taking Status

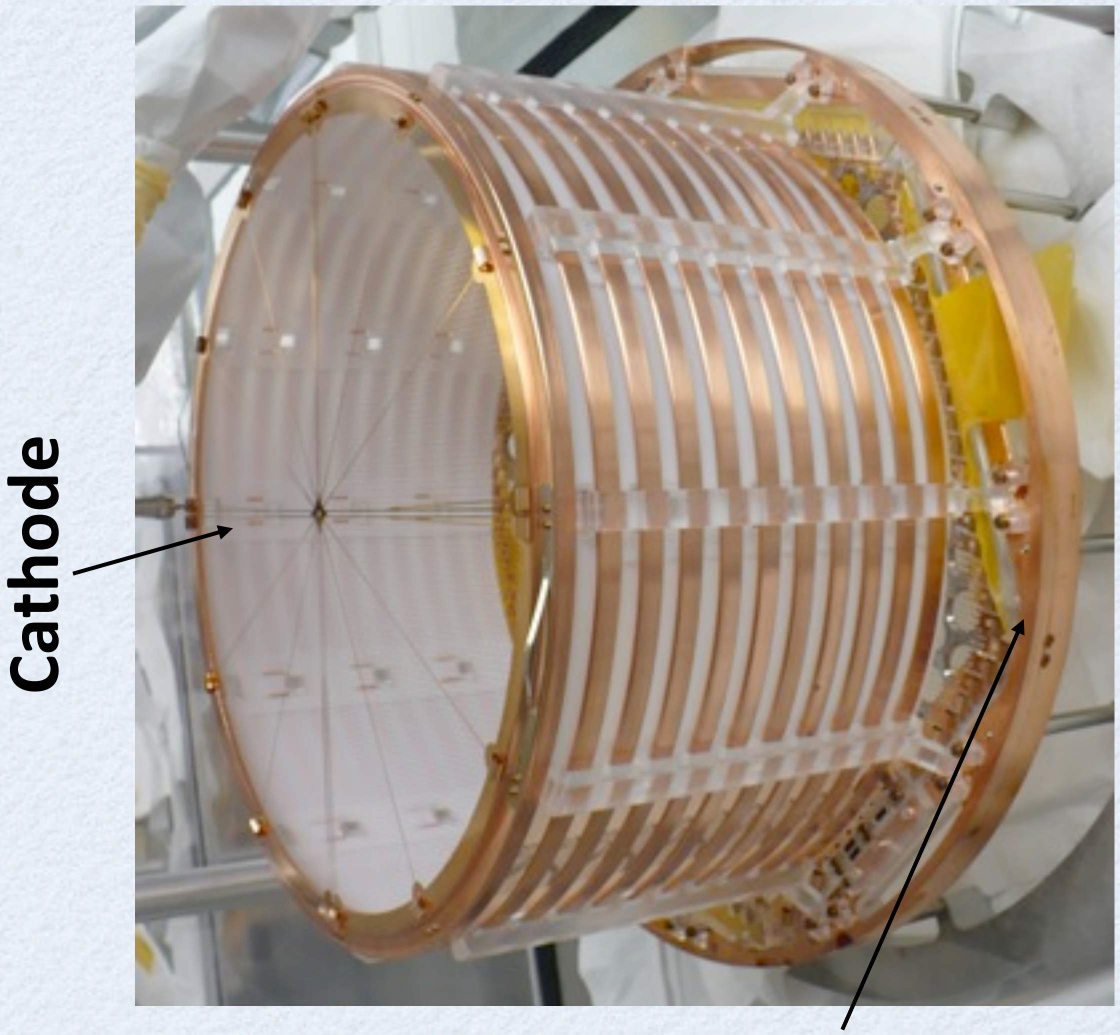
	Run 1 (2νββ Discovery)	Run 2a (0νββ limit)	Run 2a (Precision 2νββ)
Period	May 21, ‘11 – Jul 9, ’11	Sep 22, ‘11 – Apr 15, ’12	Sep 22, ‘11 – Apr 15, ‘12
Live Time	752.7 hr	2896.6 hr	3062.4 hr
Exposure	3.2 kg-yr	32.5 kg-yr	23.14 kg-yr
Publ.	PRL 107 (2011) 212501	PRL 109 (2012) 032505	arXiv:1306.6106 (Jun 2013)

- Review previous two results
- Subsequent improvements
- Report details of new precise 2νββ measurement
- Note: Smooth running is ongoing and we expect to unmask and release a new 0νββ update with ~ x3 more data soon

Cosmic Ray Muon!



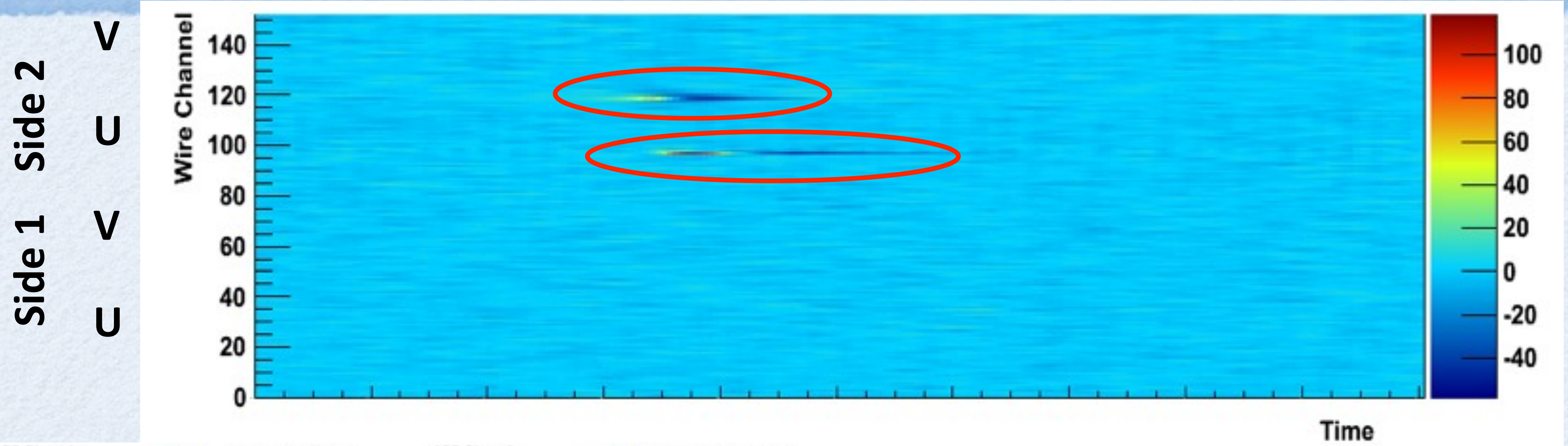
One of the two TPC modules

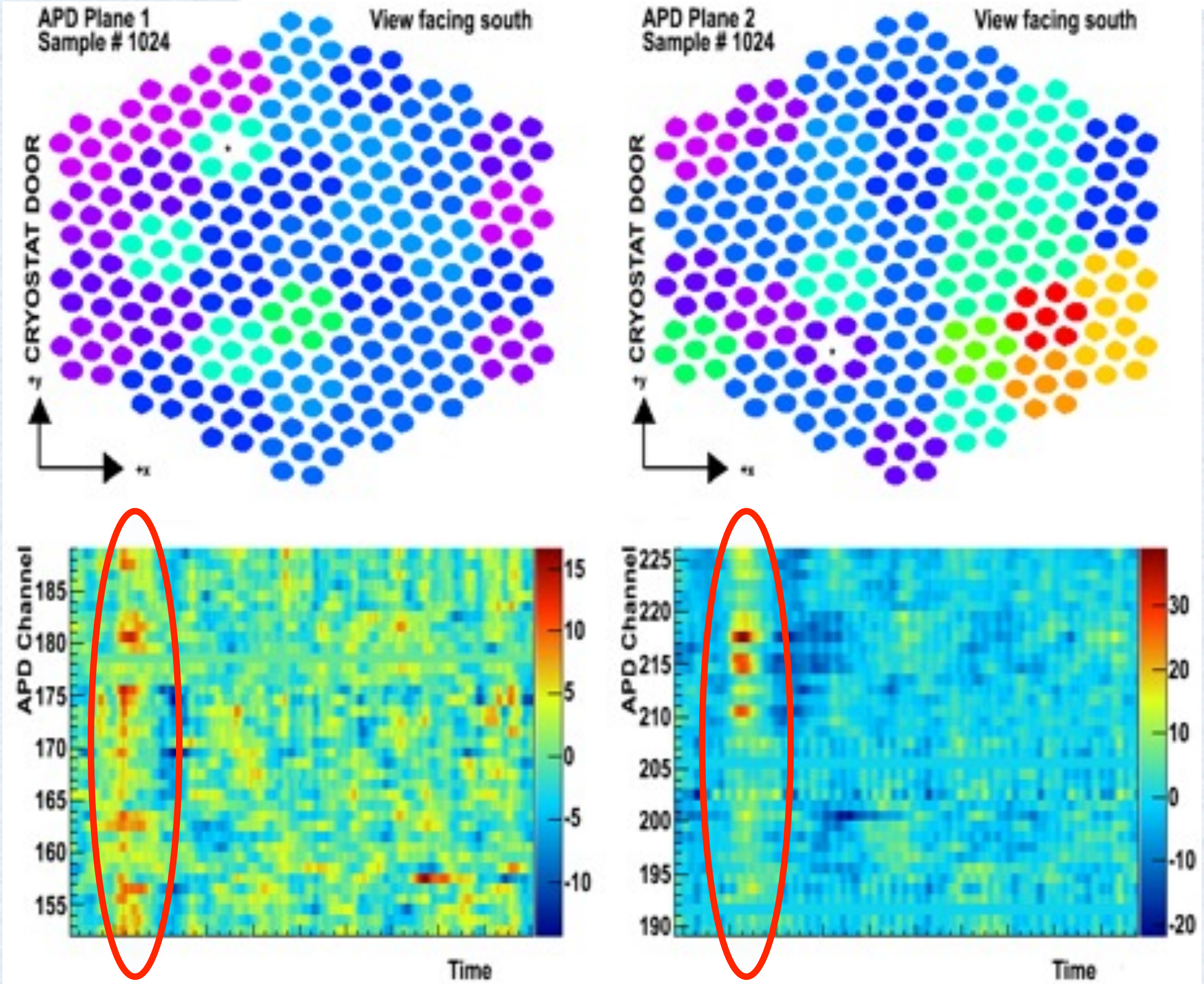

Cathode

U and V wires

The horizontal axis represents time while the vertical is the wire position (see sketch).
V wires see inductive signals while U wires collects the charge.
The muon in the present event traverses the cathode grid, leaving a long track in one TPC module and a shorter one in the other.

Single Site Event





Top display is charge readout (V are induction wires and U are collection wires).

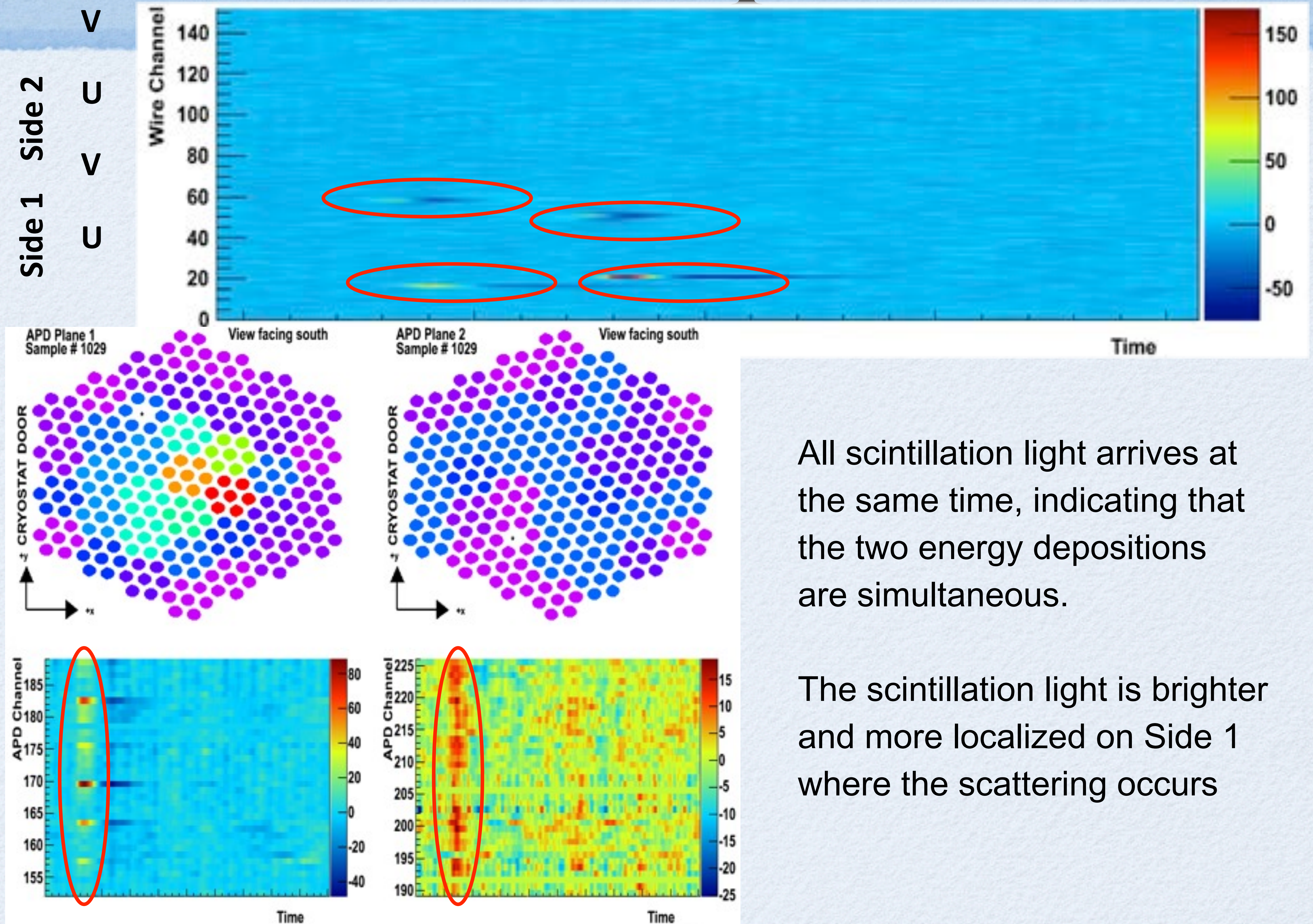
Left display is light readout. APD map refers to the sample with max signal.

Scintillation light is seen from both sides, although more intense and localized on side 2, where the event occurred.

Small depositions produce induction signals on more than one V wires but are collected by a single U wire. V signal always comes before U.

Light signals precede in time the charge ones

Two-Site Compton Event



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

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

Run 1: May 21 to July 9, 2011

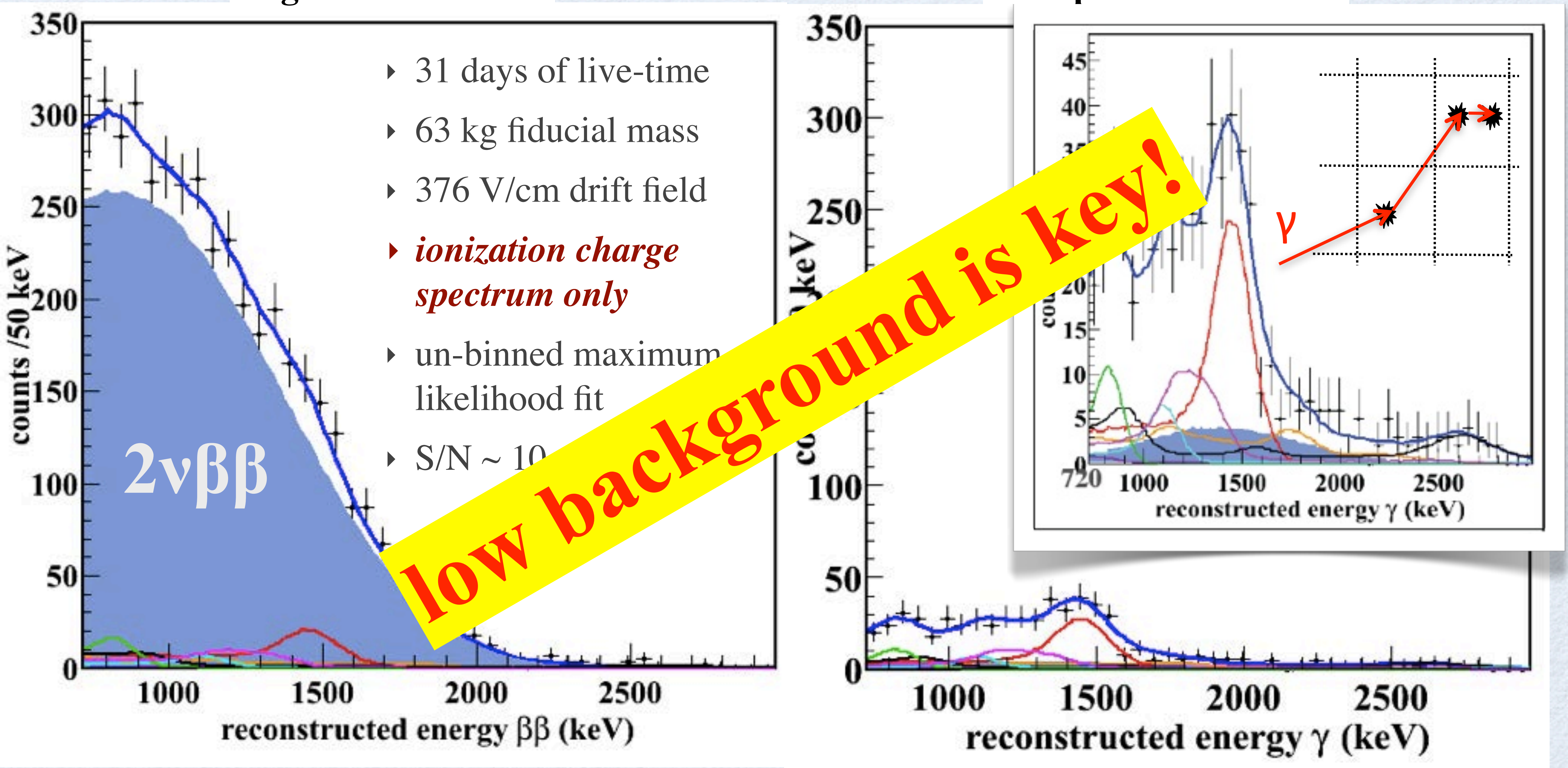
First Low Background Data

Immediately saw "plenty" of single site events!

Ionization signals from ^{60}Co and ^{228}Th sources understood

single cluster events

multiple cluster events

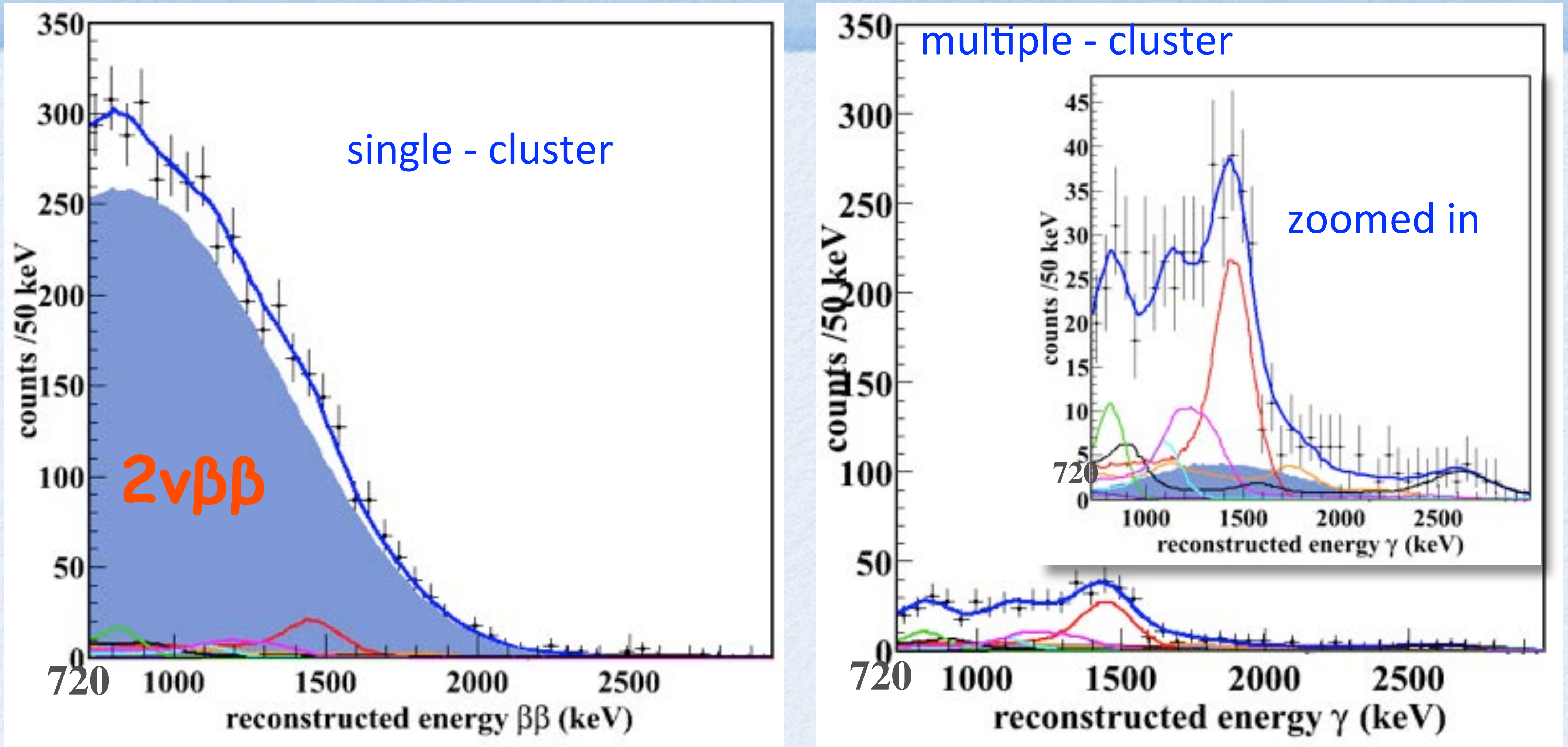


- 31 days of live-time
- 63 kg fiducial mass
- 376 V/cm drift field
- ***ionization charge spectrum only***
- un-binned maximum likelihood fit
- S/N ~ 10

low background is key!

May-July 2011: 3.2 kg-yr

First Observation of ^{136}Xe 2νββ



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

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

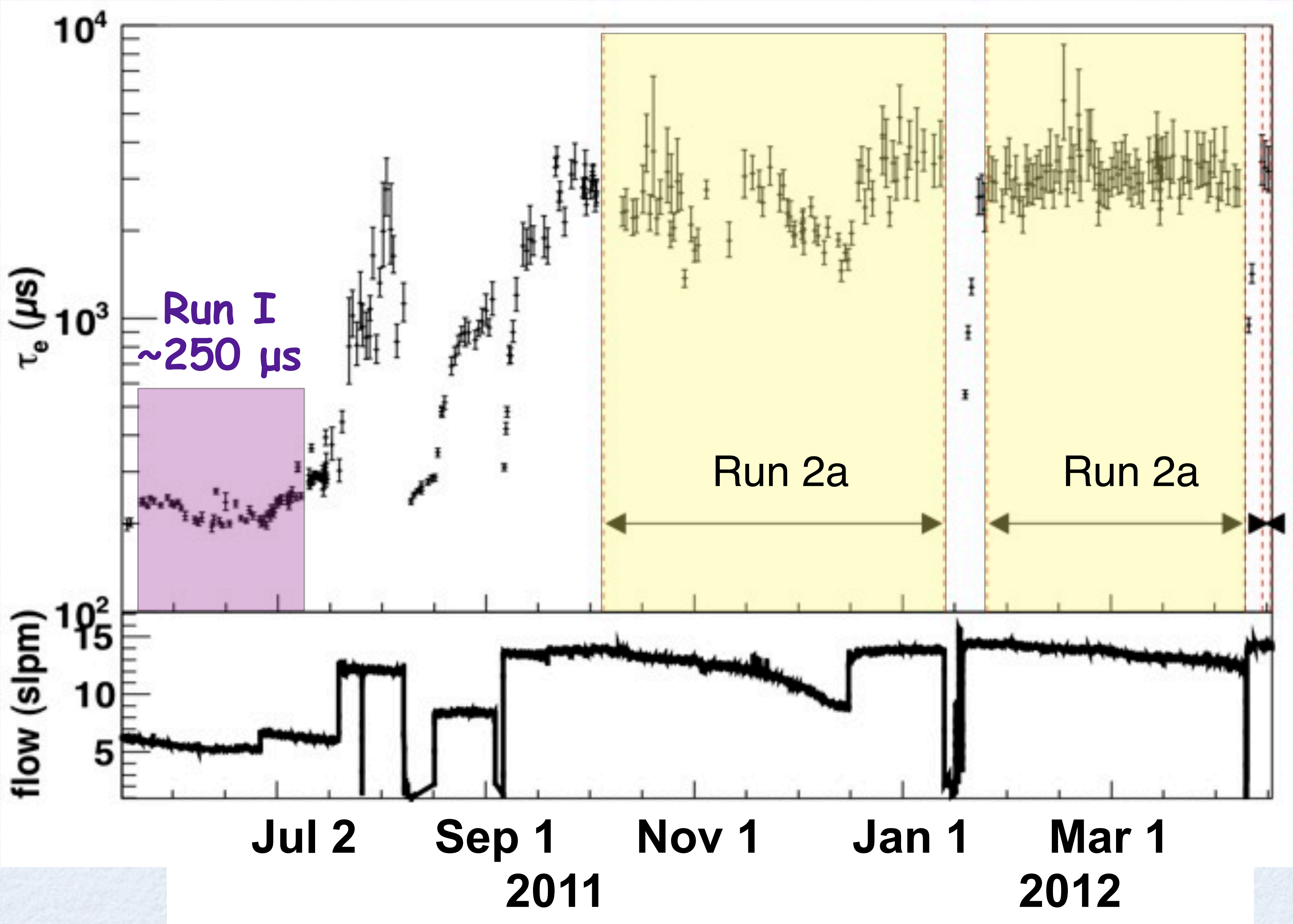
In significant disagreement with previous limits:

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

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

Later confirmed by KamLAND-ZEN

Xenon Purity Progress



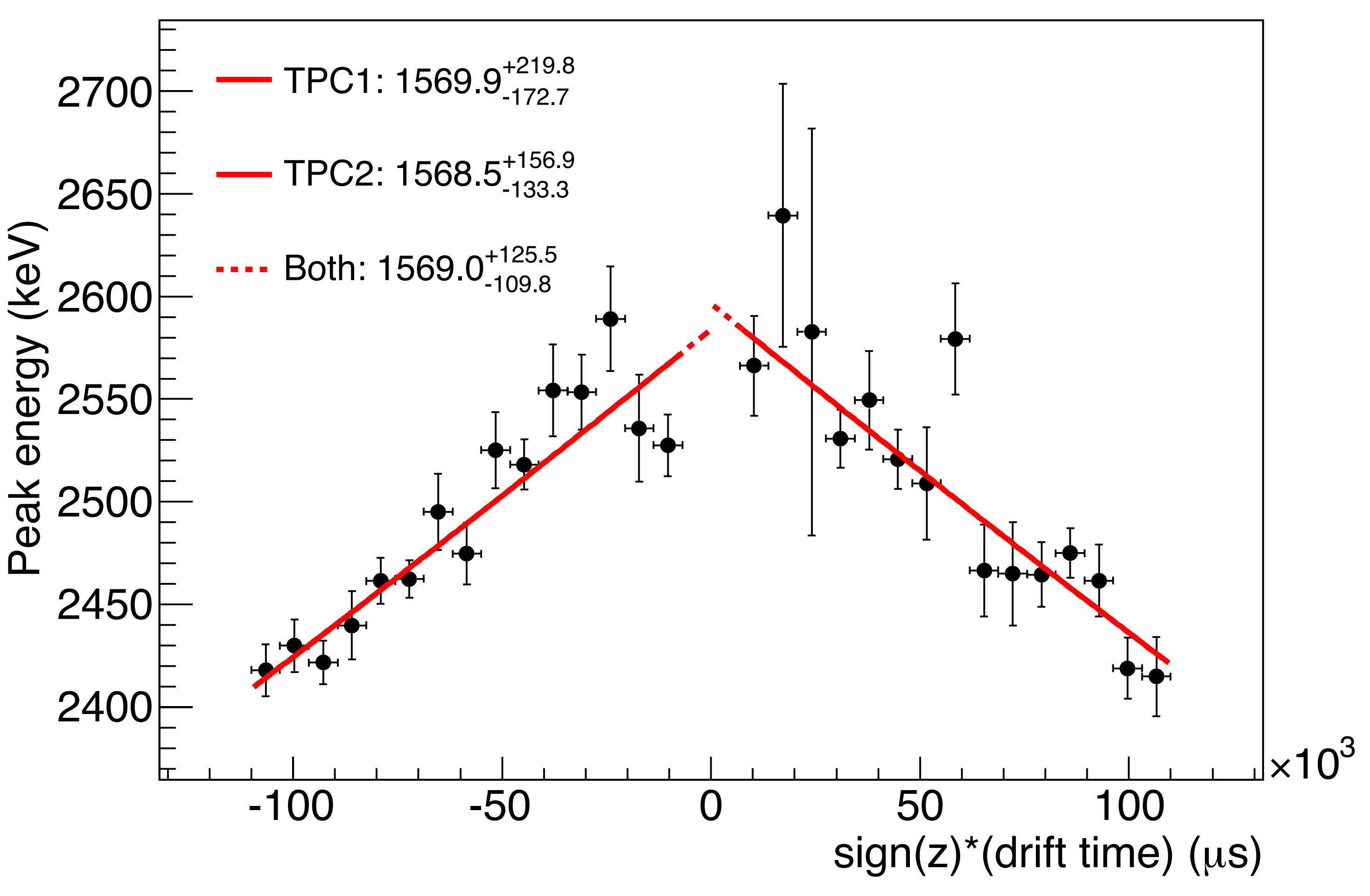
Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

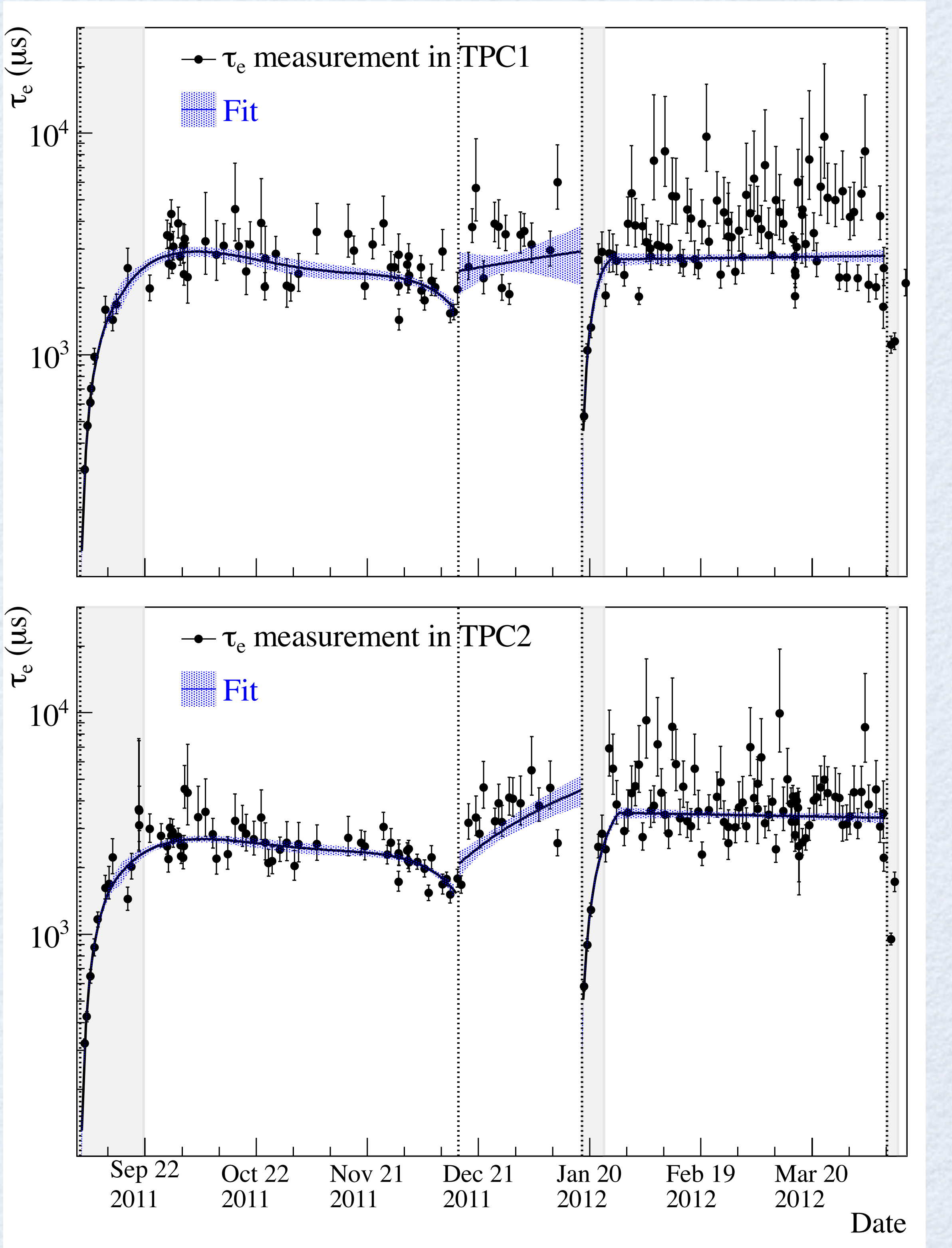
Electron lifetime τ_e: measure ionization signal attenuation as a function of drift time for the full-absorption peak of γ ray sources

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

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

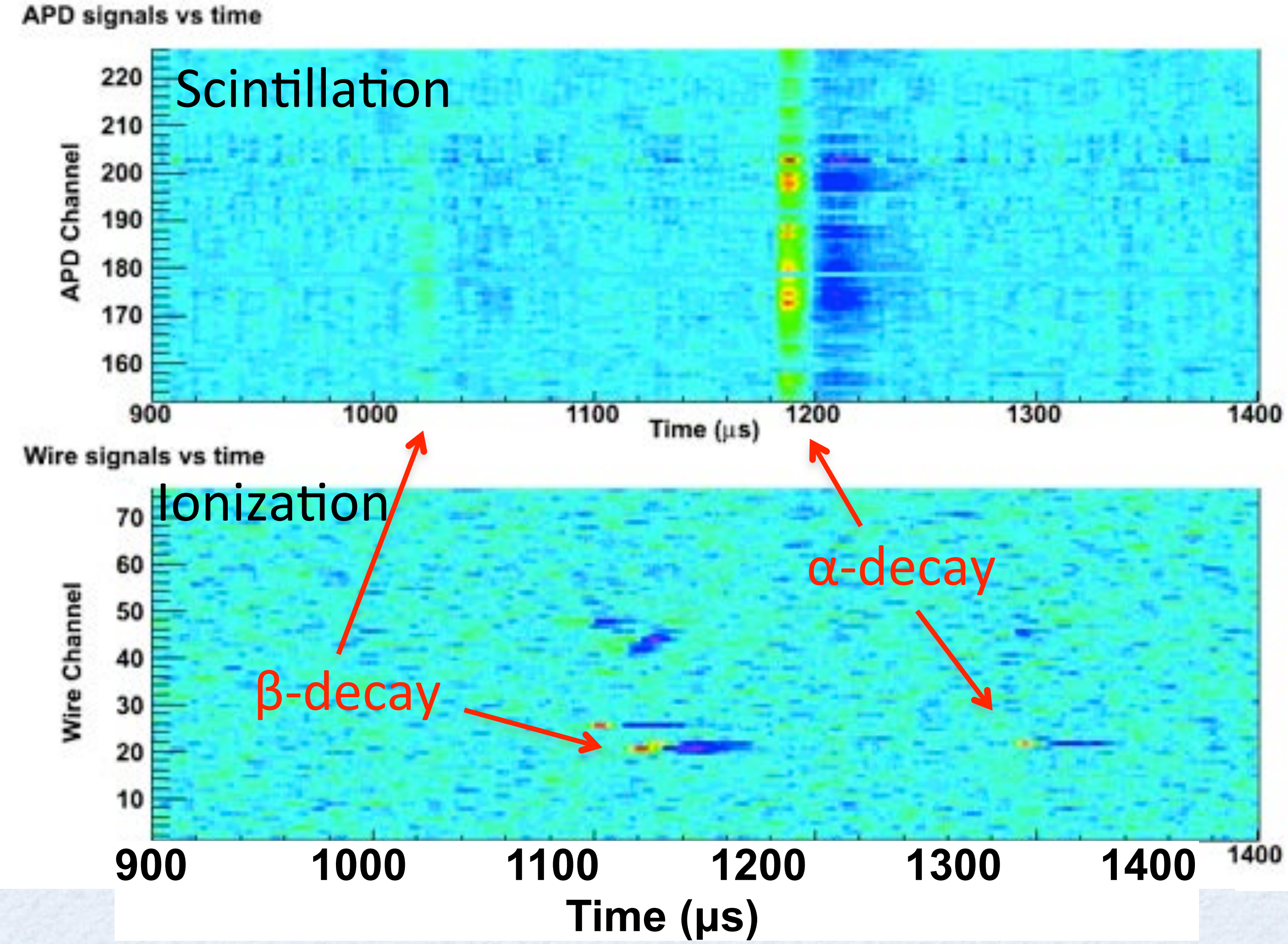
Electron Lifetime in Run 2a

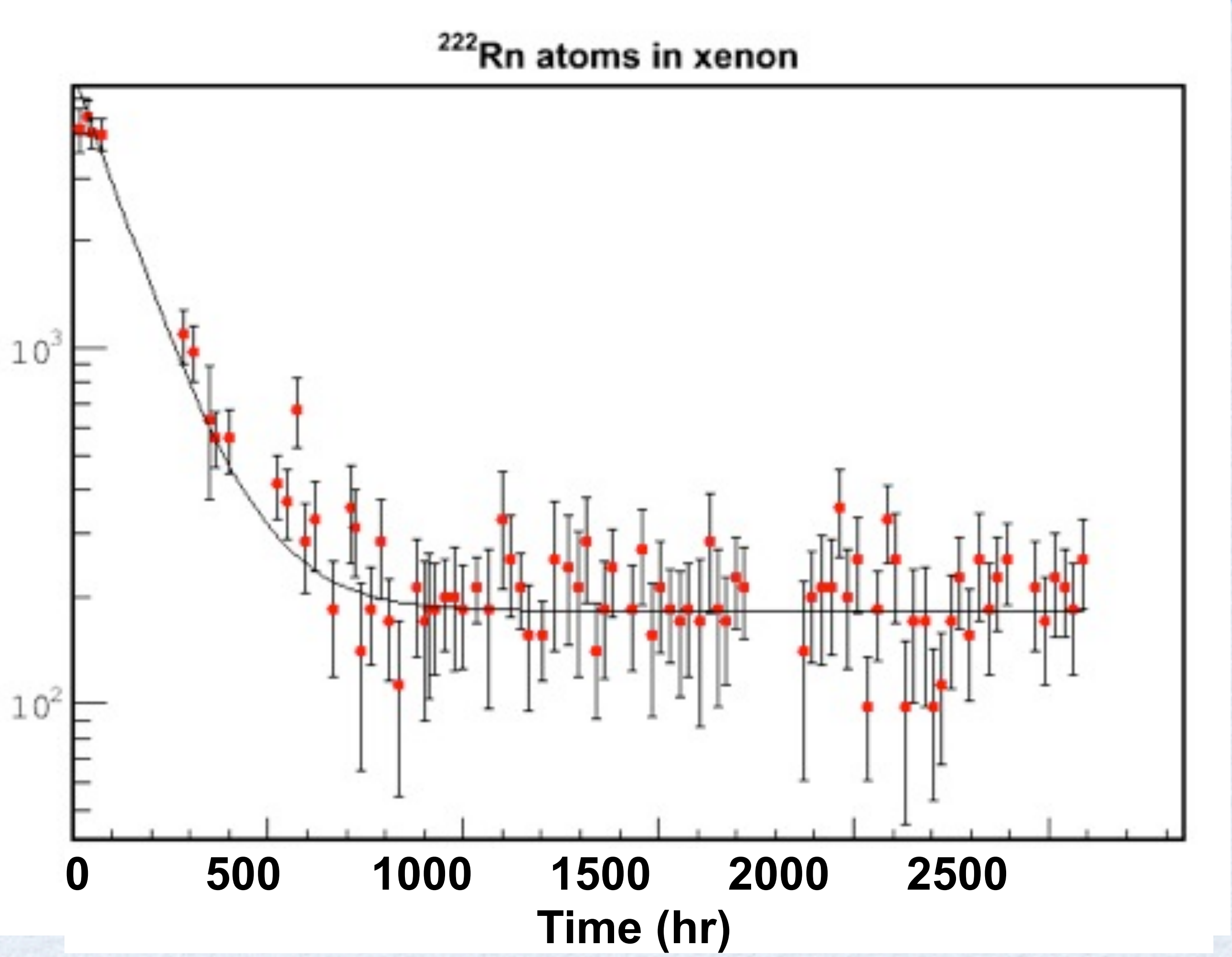




- Regular fits to full energy peaks ^{228}Th source runs
- Vertical lines: xenon gas feed “events” or other interruptions to xenon recirulation
- Shaded regions excluded from final dataset

Rn Content in Liquid Xe



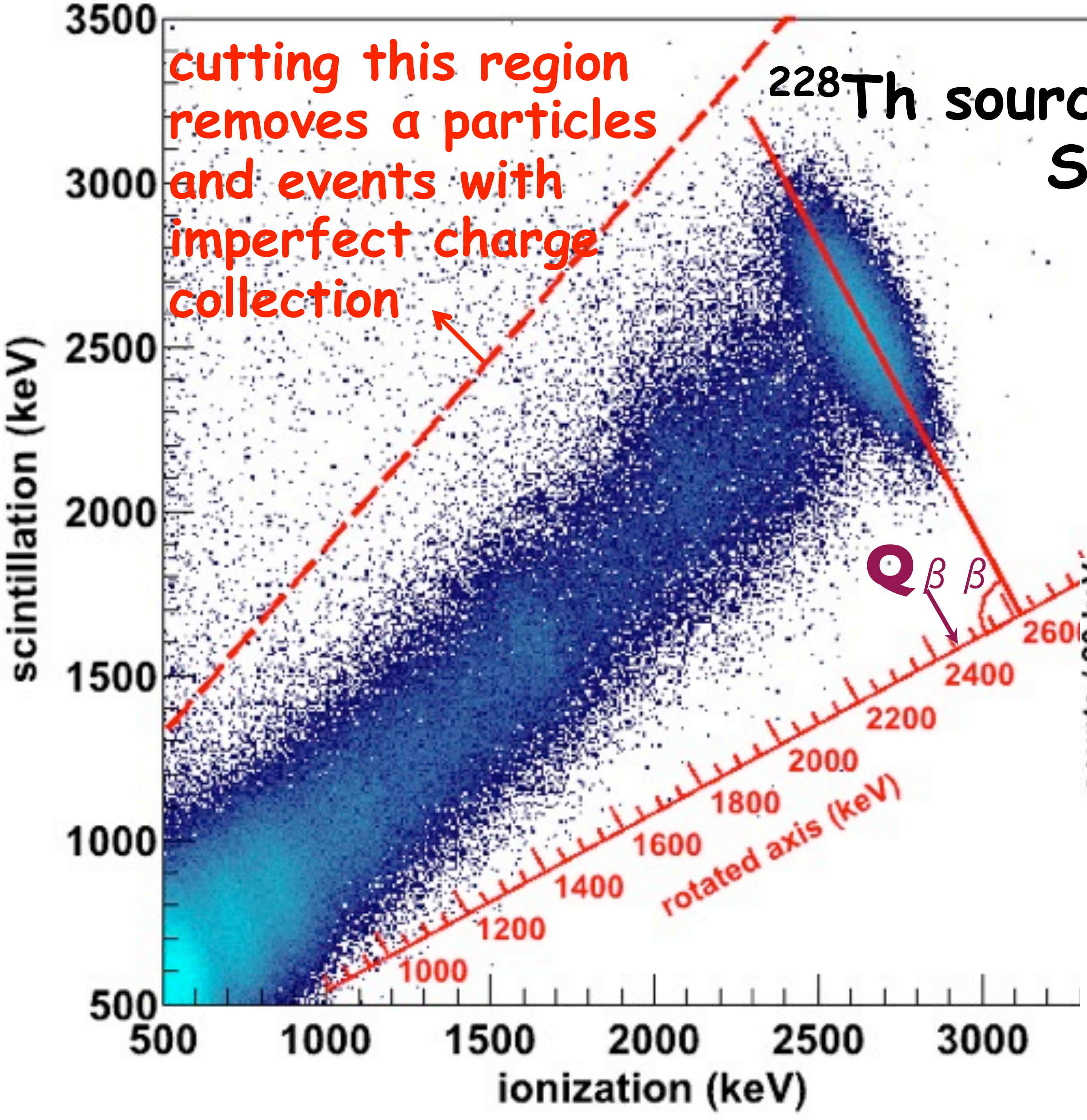


^{214}Bi – ^{214}Po correlation
in the EXO-200 detector

Total ^{222}Rn in LXe after initial fill

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

Energy Resolution: Run 2a



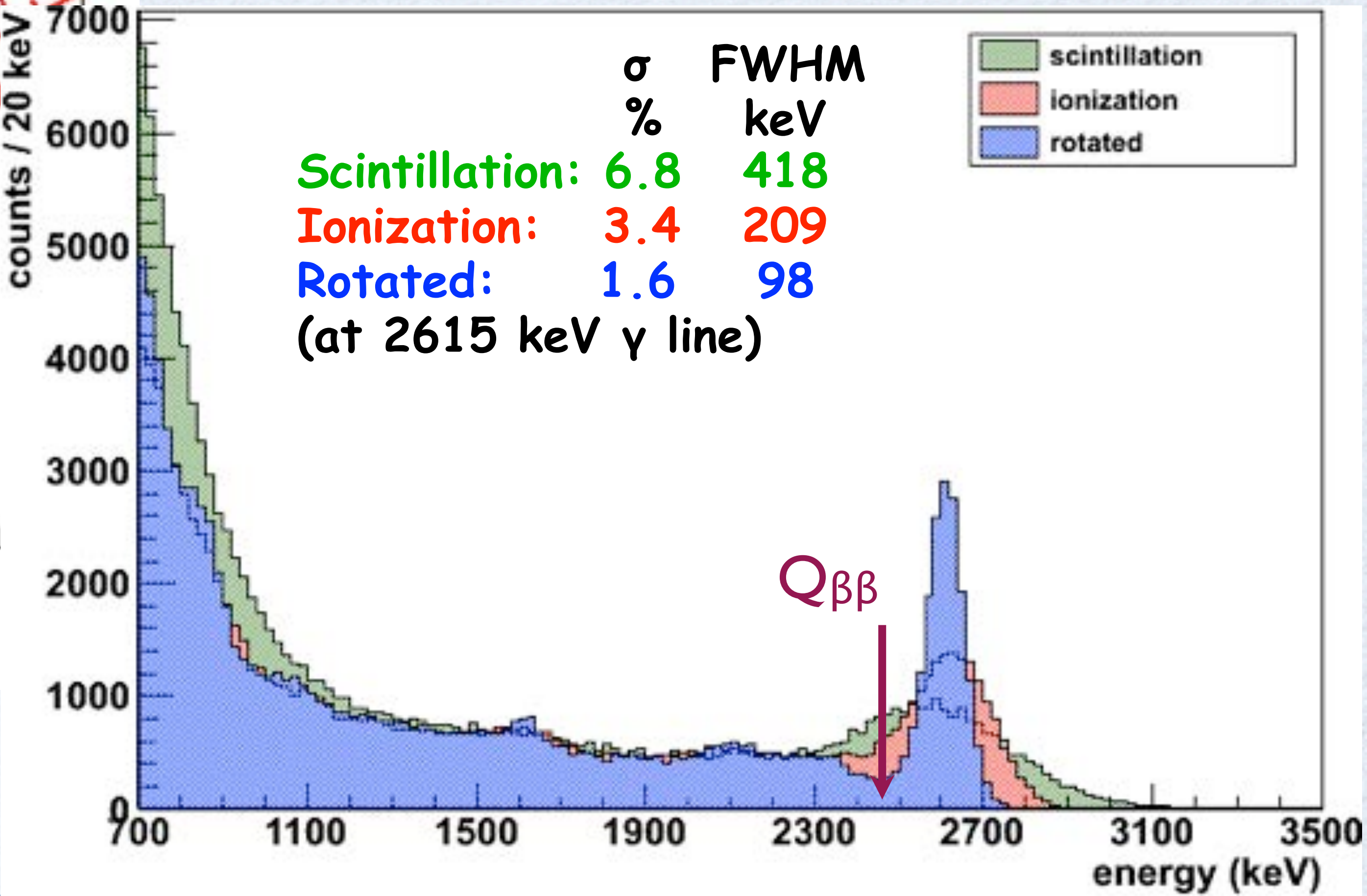
cutting this region removes α particles and events with imperfect charge collection

^{228}Th source SS

Rotation angle chosen to optimize energy resolution at 2615 keV

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

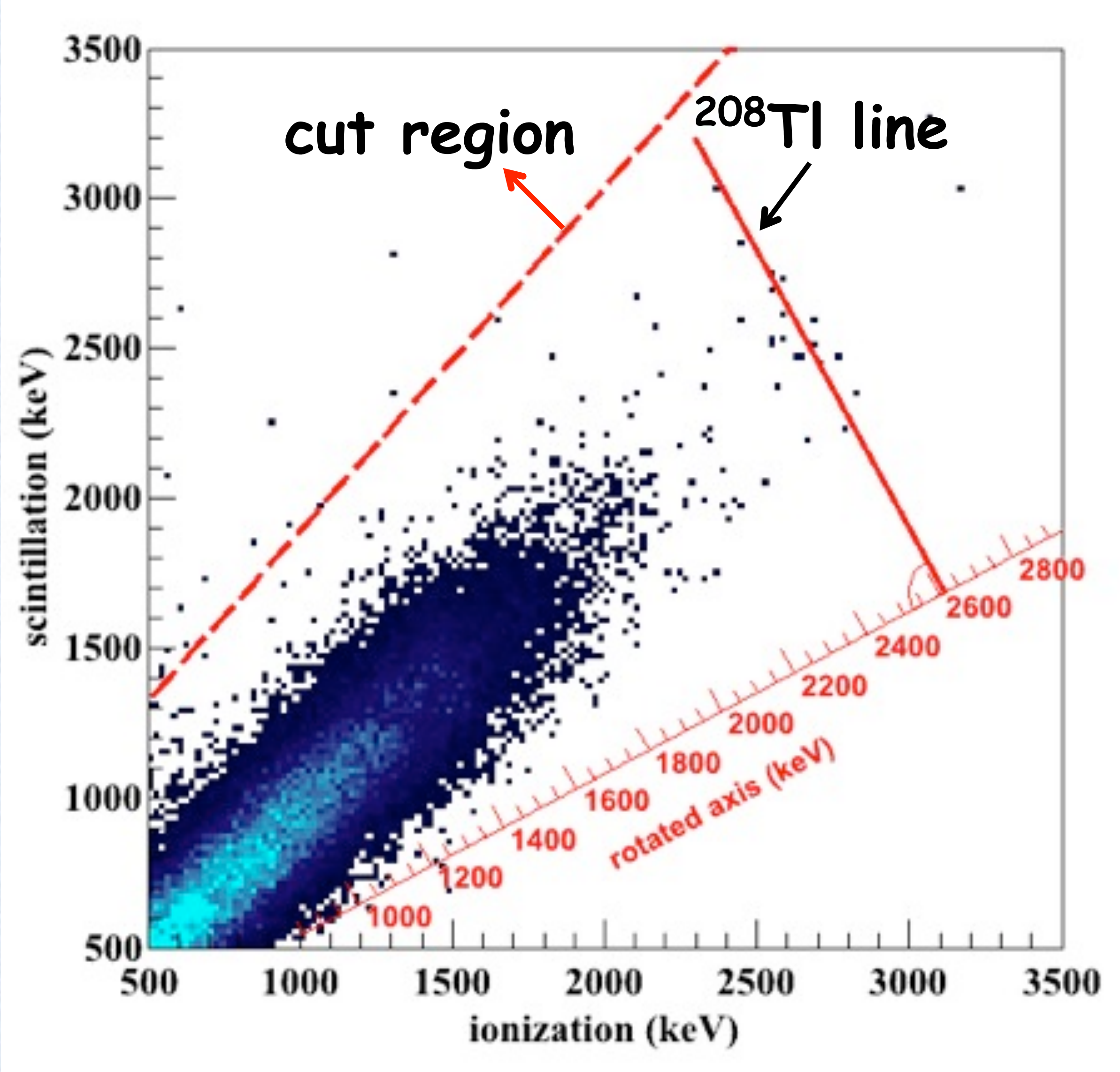
E.Conti et al.
Phys Rev B 68 (2003) 054201



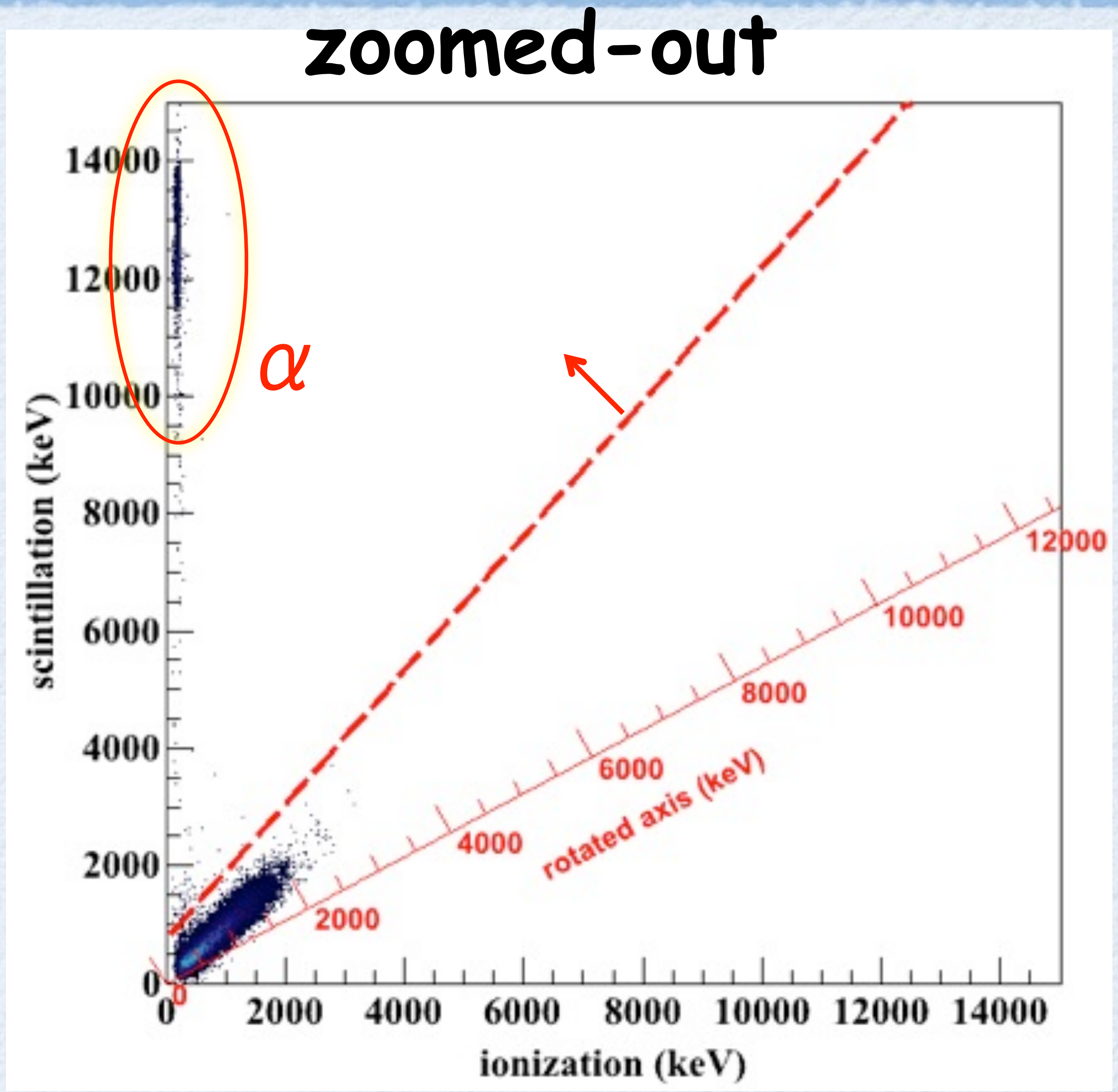
	σ %	FWHM keV
Scintillation:	6.8	418
Ionization:	3.4	209
Rotated:	1.6	98

(at 2615 keV γ line)

Run 2a Data



zoomed-out



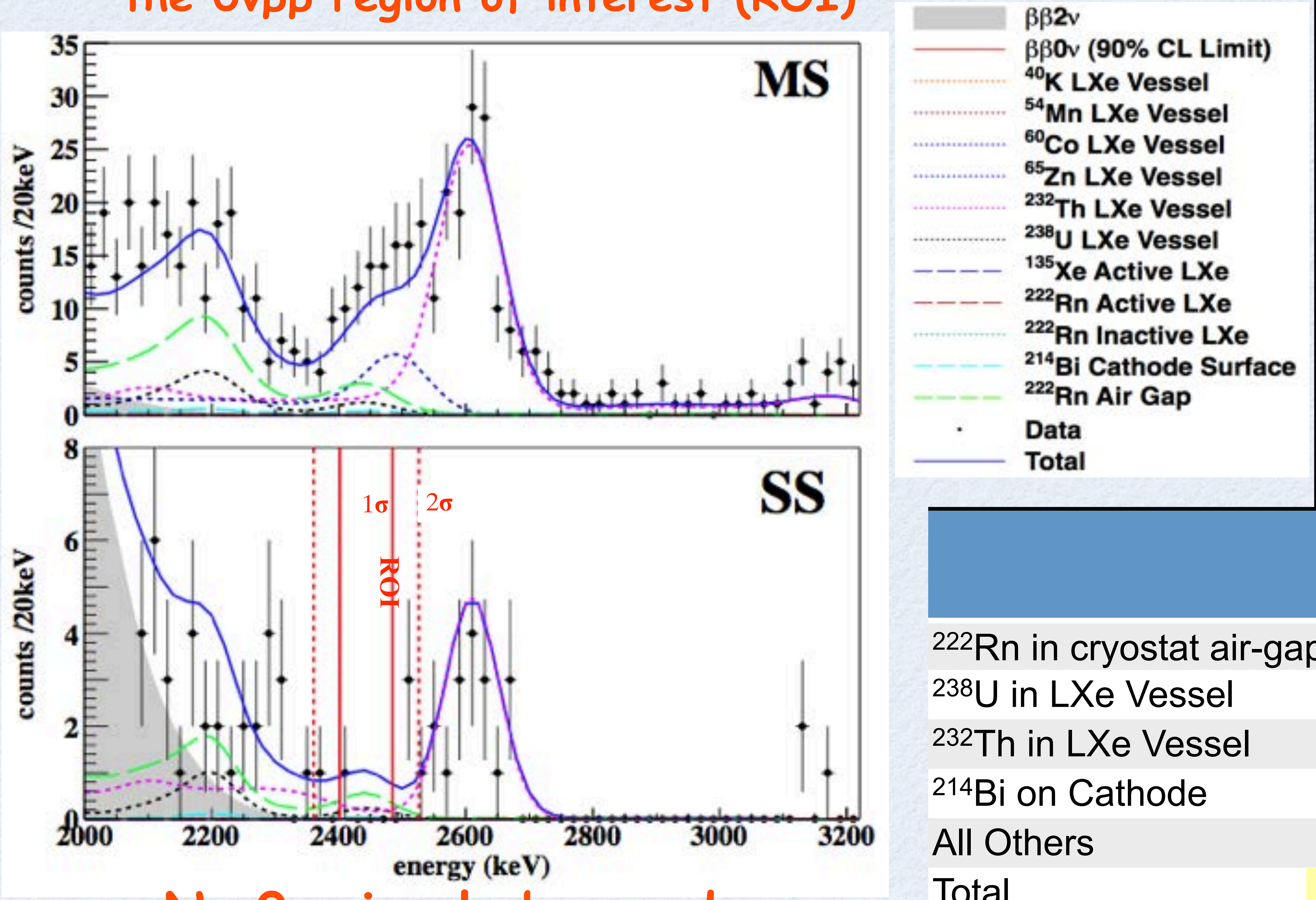
Events removed by diagonal cut:

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

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)



From profile likelihood:

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

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

(90% C.L.)

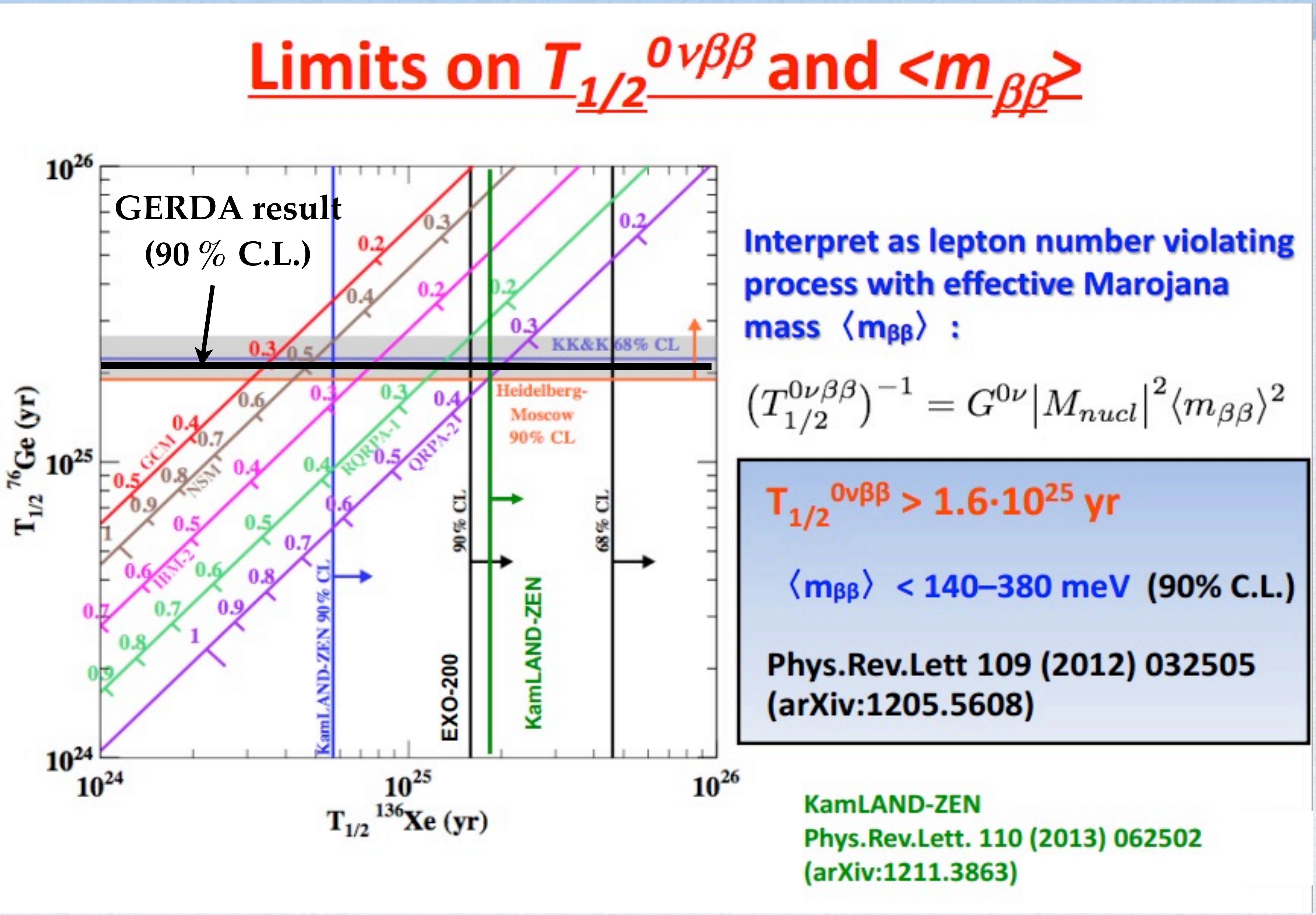
Phys Rev Lett 109 (2012) 032505

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

No 0ν signal observed in the ROI

Use likelihood fit to establish limit

EXO-200 Result Summar



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

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

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

$T_{1/2}^{0\nu\beta\beta} > 1.6\cdot10^{25}$ yr

⟨$m_{\beta\beta}$⟩ < 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)

New Precision Measurement

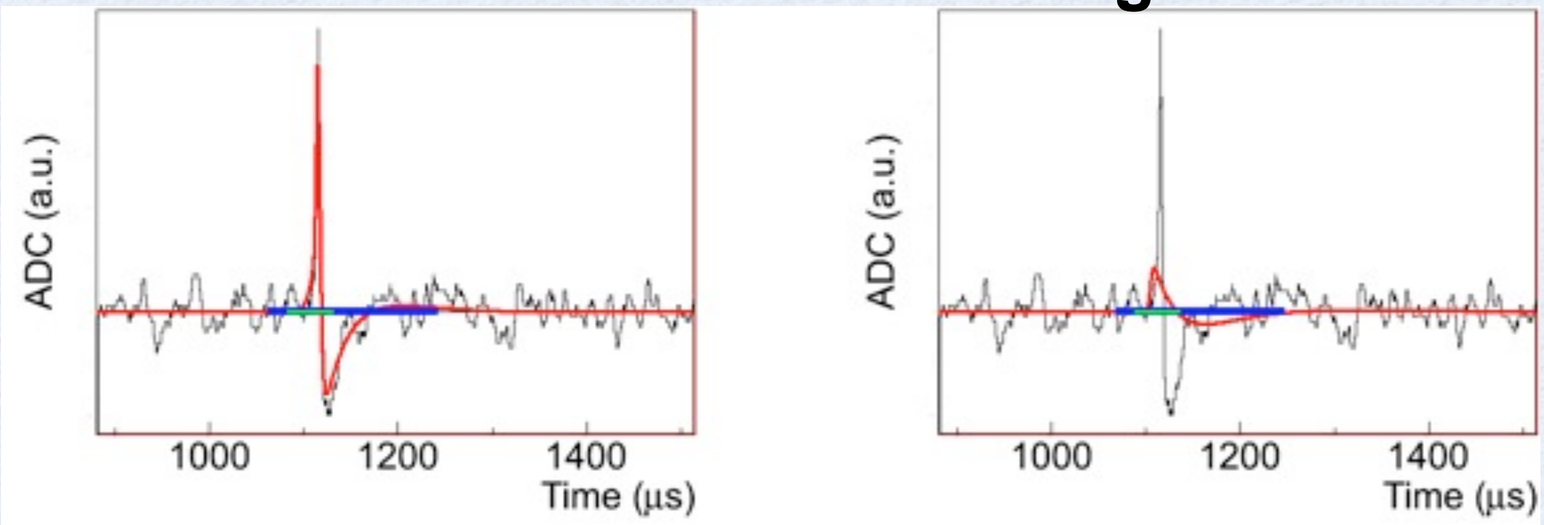
Improved $2\nu\beta\beta$ analysis with same dataset

- Improved event reconstruction
- Improved and more detailed (geometry) simulations
- More precise detector response calibration
- numerous other small improvements....

Improve Induction Signal Identification

- Identify induction signal on U-wires
- Mistakenly reconstructing as collection leads to single-site/multi-site misclassification
- 77% induction rejection, 99.5% collection efficiency

Fit to Induction and Collection Signal Models



Standoff Fits

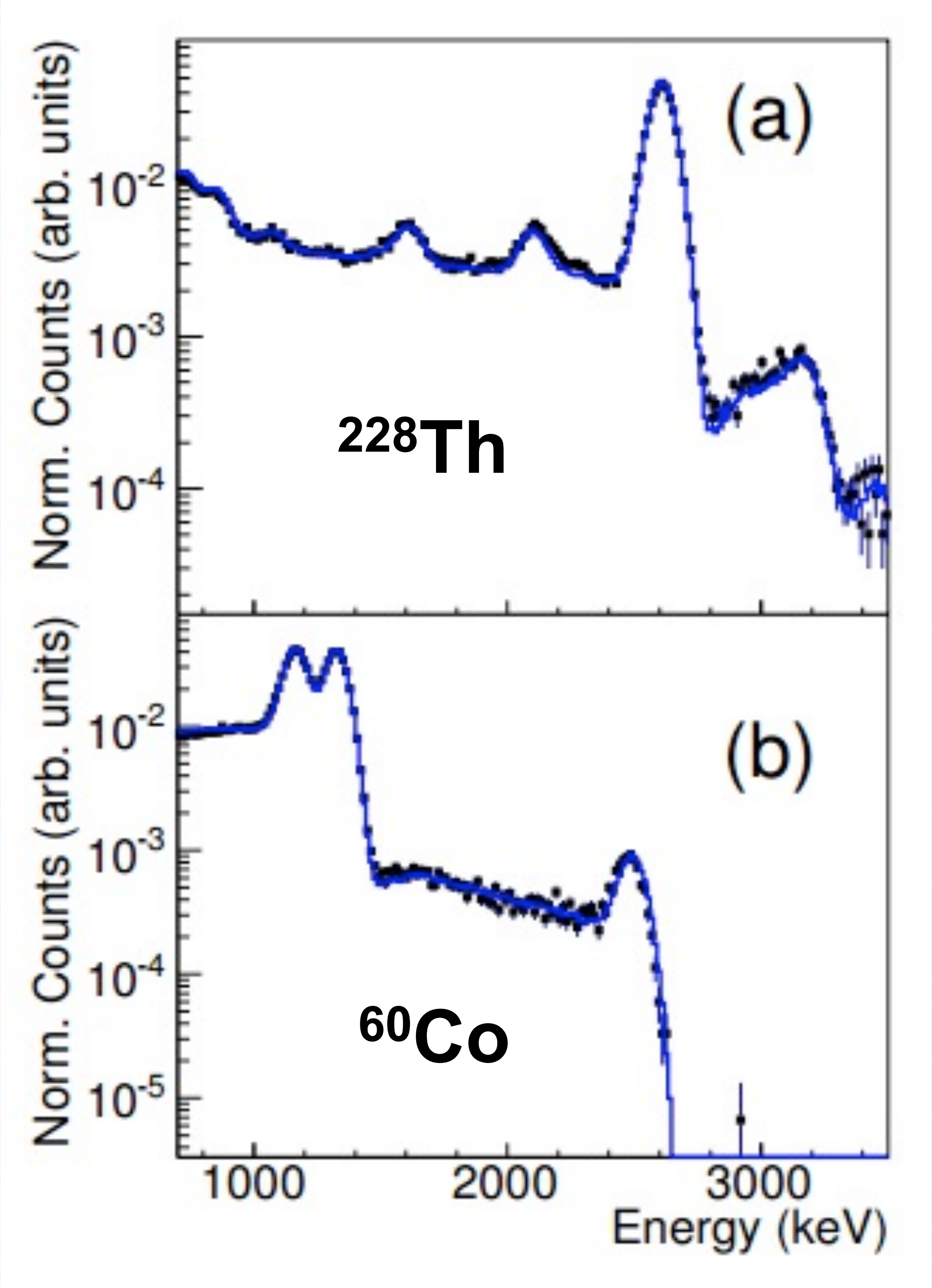
Previously: simultaneously fit SS and MS event datasets using energy PDFs

Now: added Standoff Distance as an additional fit dimension (PDFs are 2D, energy and standoff)

Standoff Distance improves background estimates

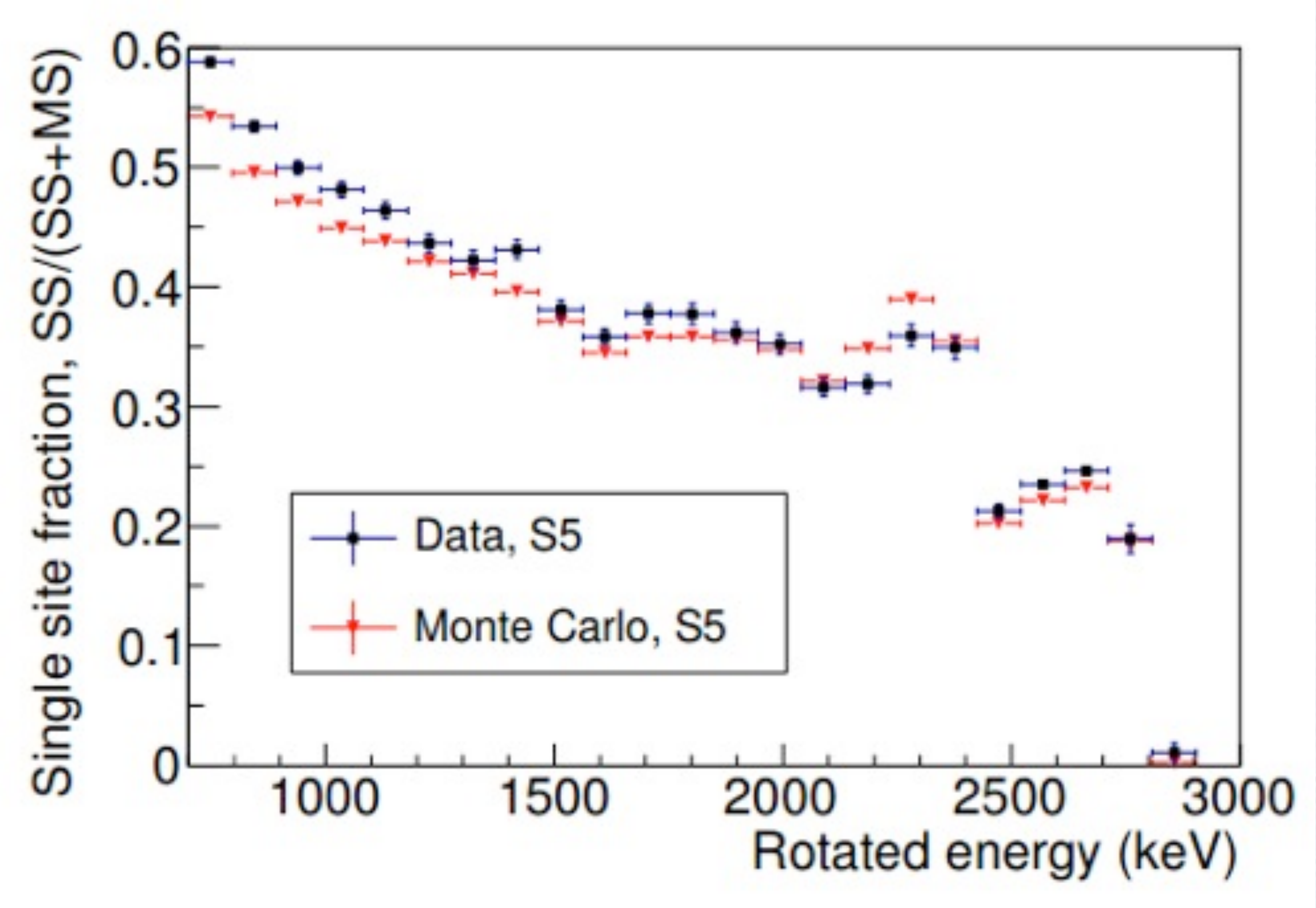
background contribution on total error: 1.2% -> 0.83%

Source Data/MC Agreement



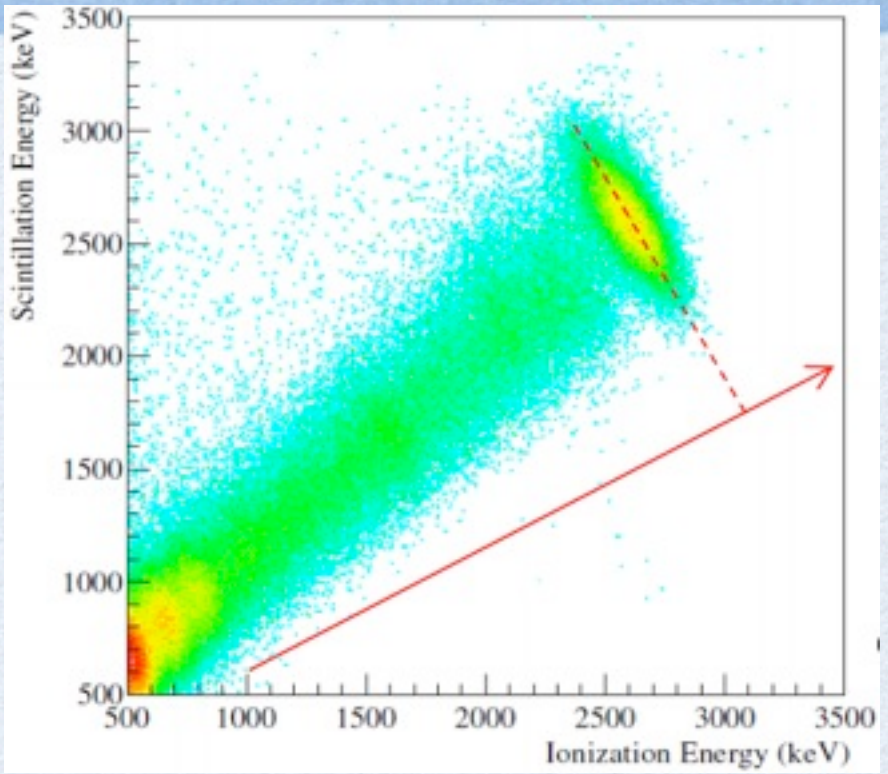
Improved MC and event reconstruction

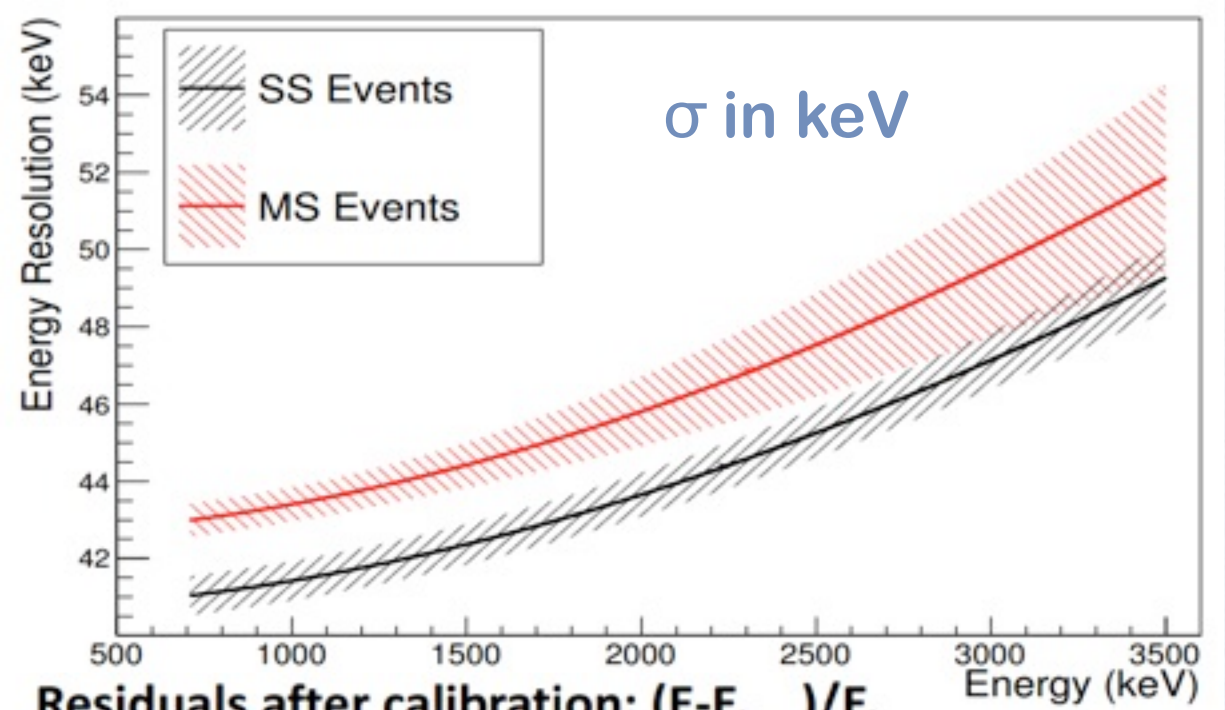
- **Source rate agreement to within 4% (9.4% in 0νββ analysis)**
- **Excellent spectral shape agreement**
- **Sufficient SS/MS agreement**



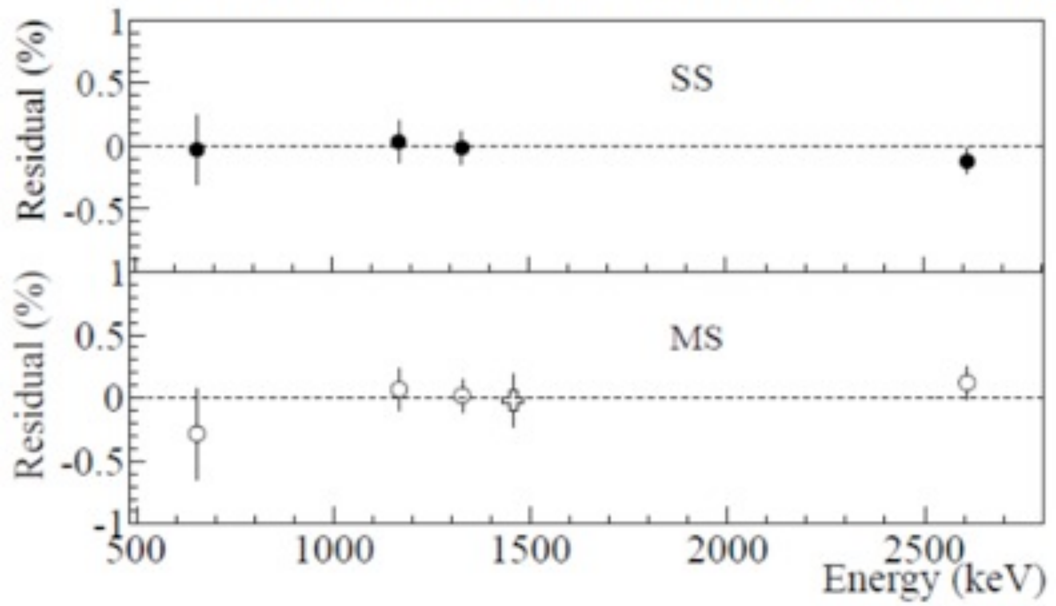
Energy Calibration Results

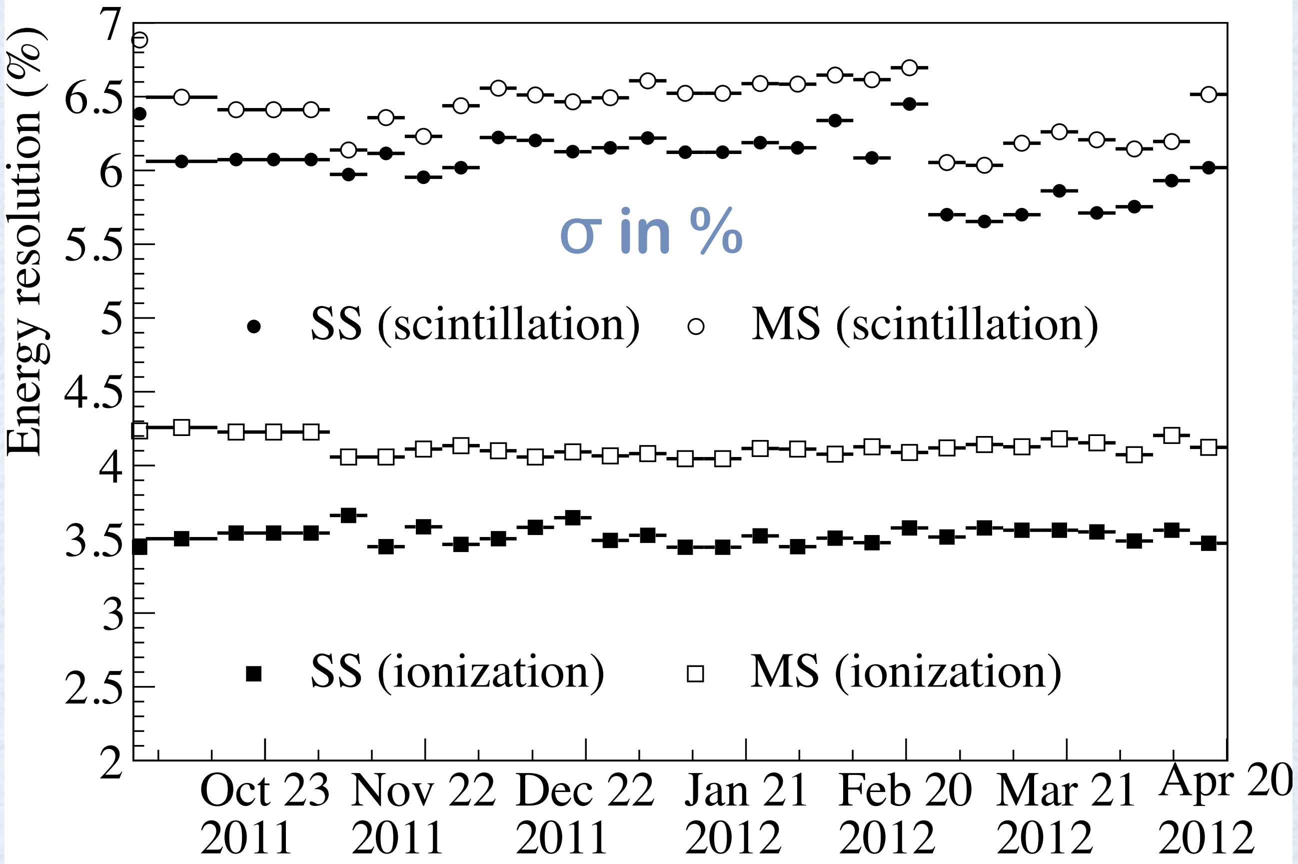
- Optimal rotation angle measured weekly
- New iterative approach developed to extract energy resolution curve
- Time-averaged energy resolution used for final LB fit





Residuals after calibration: $(E-E_{true})/E_{true}$





Fiducial Volume

Previous analysis: 79.4 kg of ^{136}Xe

This analysis: 66.2 kg of ^{136}Xe

2vββ analysis is systematics-dominated

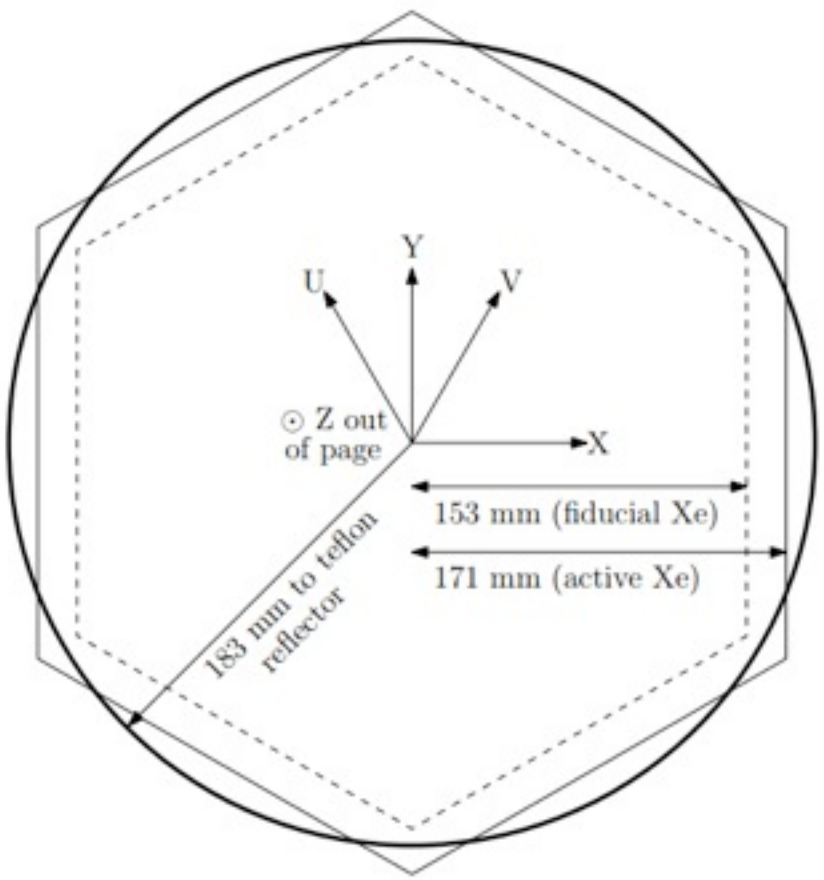
Chose smaller fiducial volume where detector response is better understood

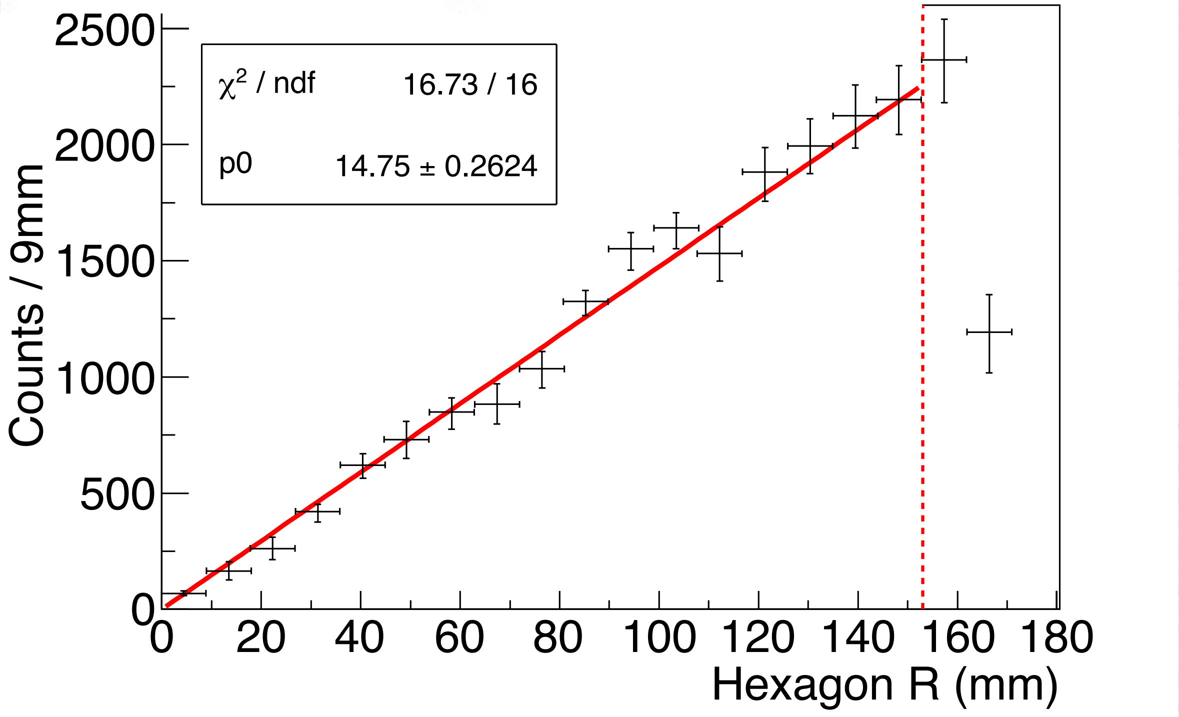
Decrease related systematic uncertainties

Hexagonal cut in U,V based on: 2vββ rate vs apothem

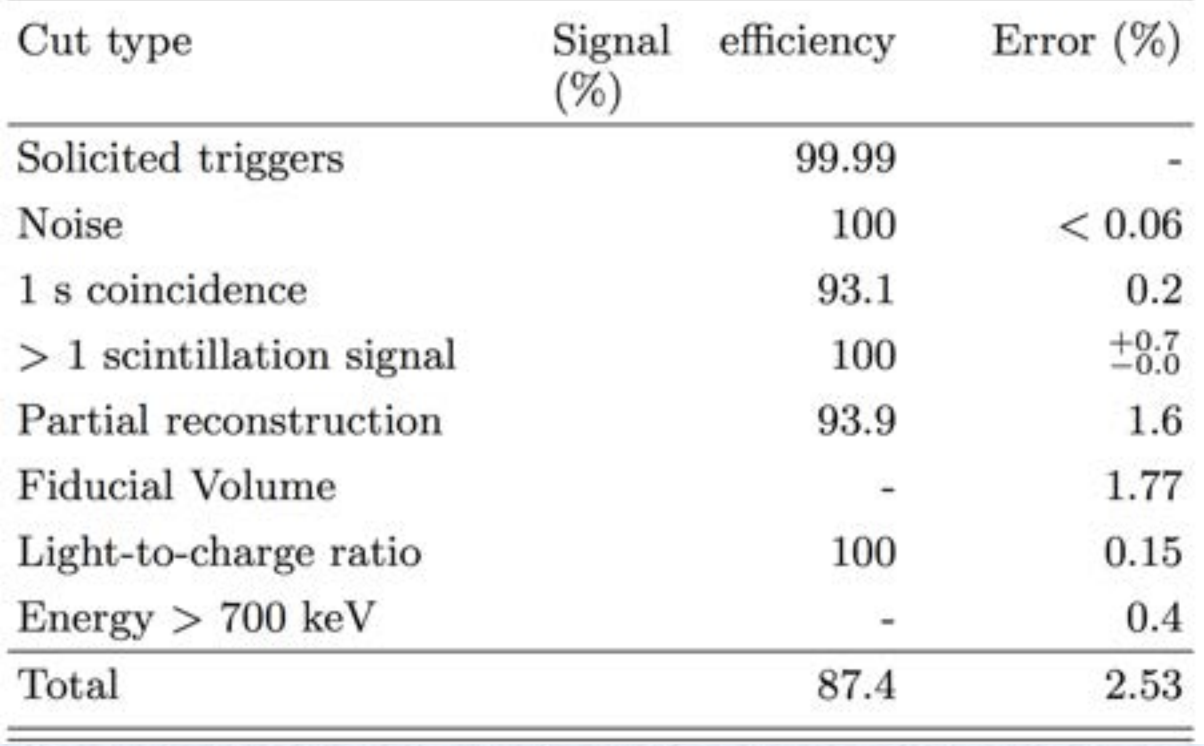
Z cut based on:

- **Field non-uniformity near cathode**
- **Grid-efficiency correction due to V-Wire plane**

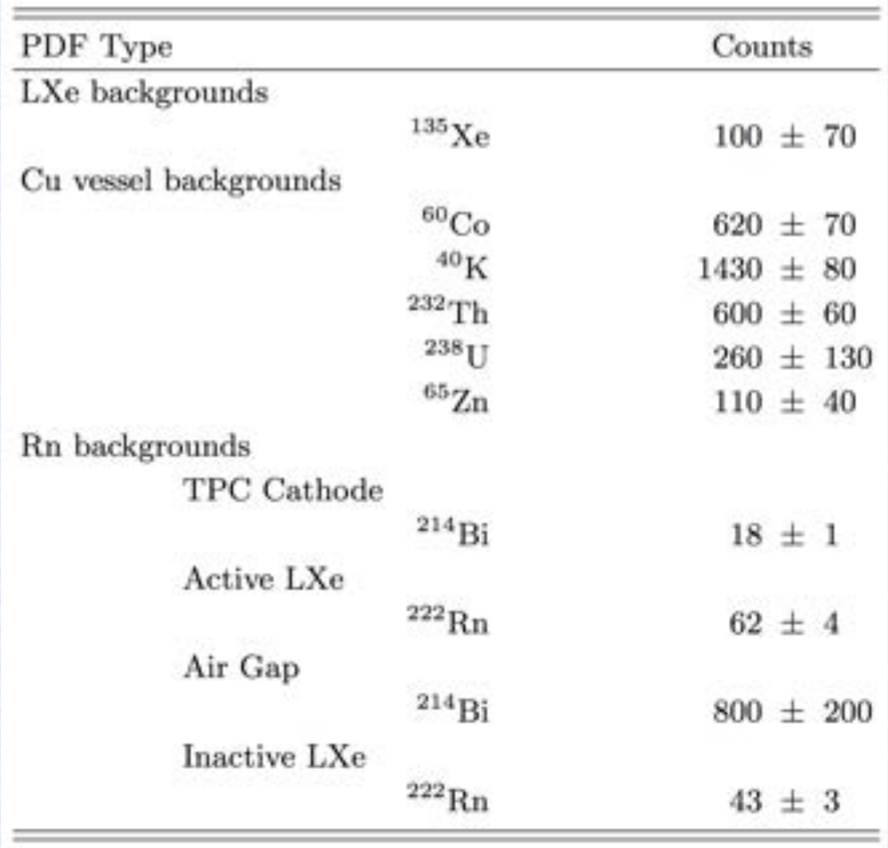




Systematics Summary

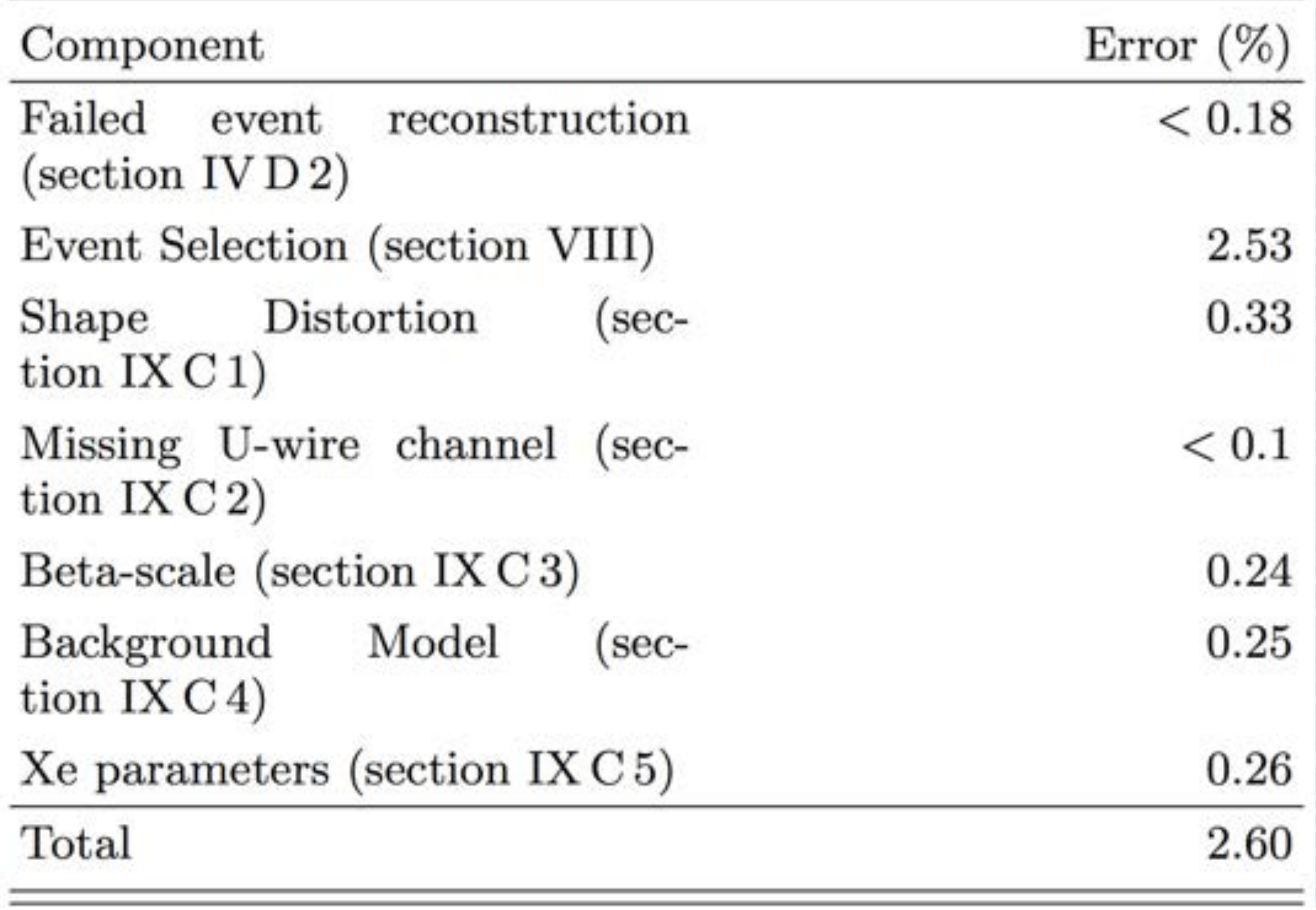


Cut type	Signal efficiency (%)	Error (%)
Solicited triggers	99.99	-
Noise	100	< 0.06
1 s coincidence	93.1	0.2
> 1 scintillation signal	100	$^{+0.7}_{-0.0}$
Partial reconstruction	93.9	1.6
Fiducial Volume	-	1.77
Light-to-charge ratio	100	0.15
Energy > 700 keV	-	0.4
Total	87.4	2.53

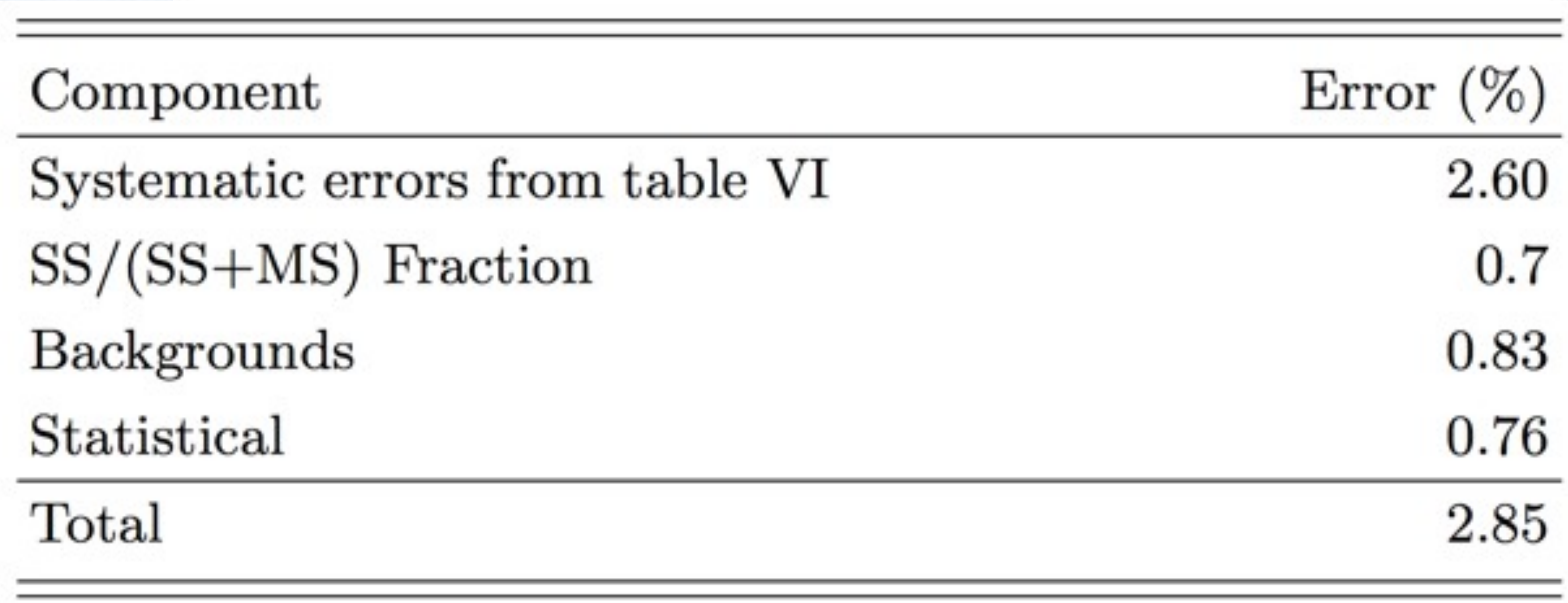


PDF Type		Counts
LXe backgrounds		
	^{135}Xe	100 ± 70
Cu vessel backgrounds		
	^{60}Co	620 ± 70
	^{40}K	1430 ± 80
	^{232}Th	600 ± 60
	^{238}U	260 ± 130
	^{65}Zn	110 ± 40
Rn backgrounds		
TPC Cathode		
	^{214}Bi	18 ± 1
Active LXe		
	^{222}Rn	62 ± 4
Air Gap		
	^{214}Bi	800 ± 200
Inactive LXe		
	^{222}Rn	43 ± 3

18,900 2νββ events

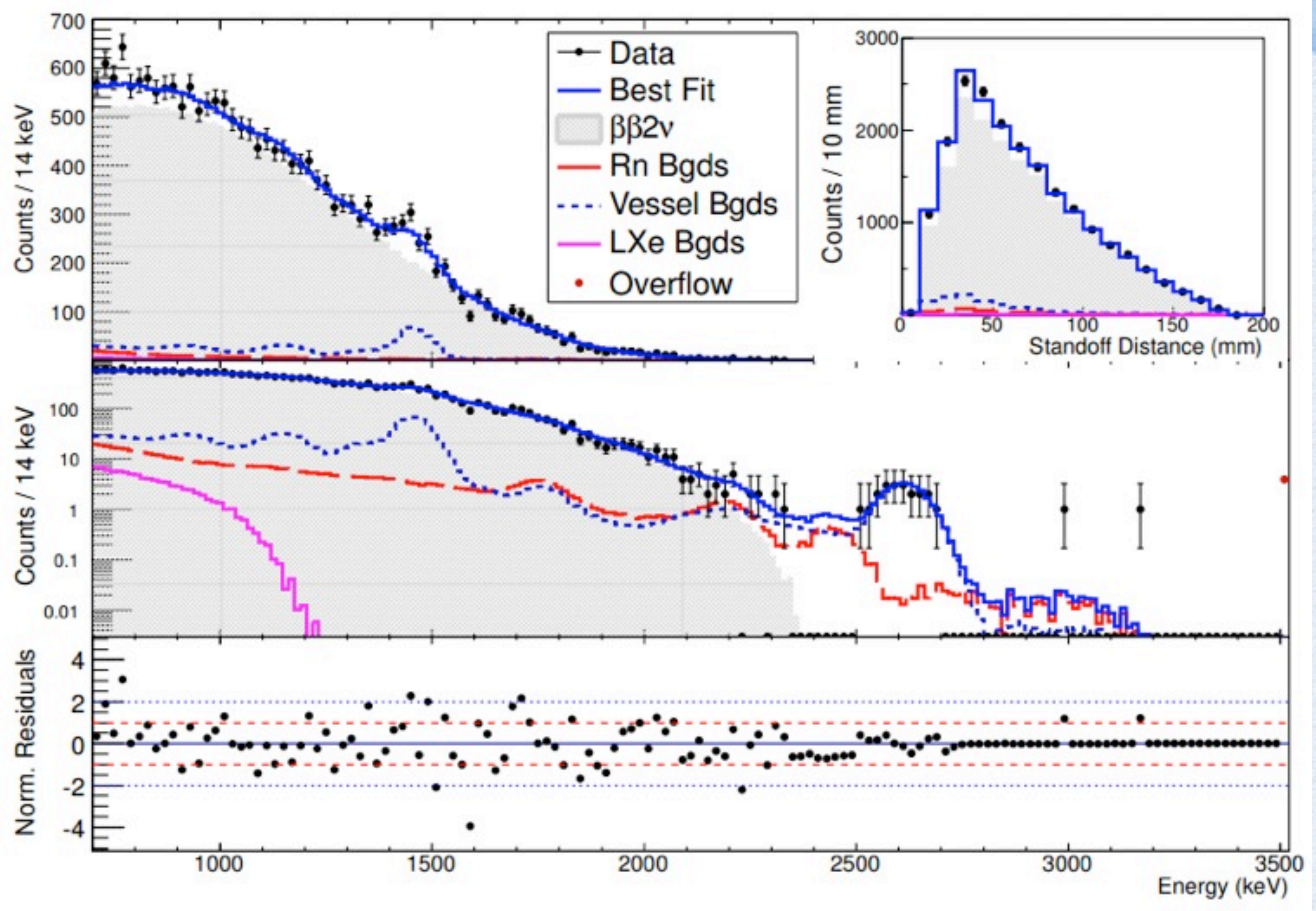


Component	Error (%)
Failed event reconstruction (section IV D 2)	< 0.18
Event Selection (section VIII)	2.53
Shape Distortion (section IX C 1)	0.33
Missing U-wire channel (section IX C 2)	< 0.1
Beta-scale (section IX C 3)	0.24
Background Model (section IX C 4)	0.25
Xe parameters (section IX C 5)	0.26
Total	2.60



Component	Error (%)
Systematic errors from table VI	2.60
SS/(SS+MS) Fraction	0.7
Backgrounds	0.83
Statistical	0.76
Total	2.85

New Precision 2νββ Result

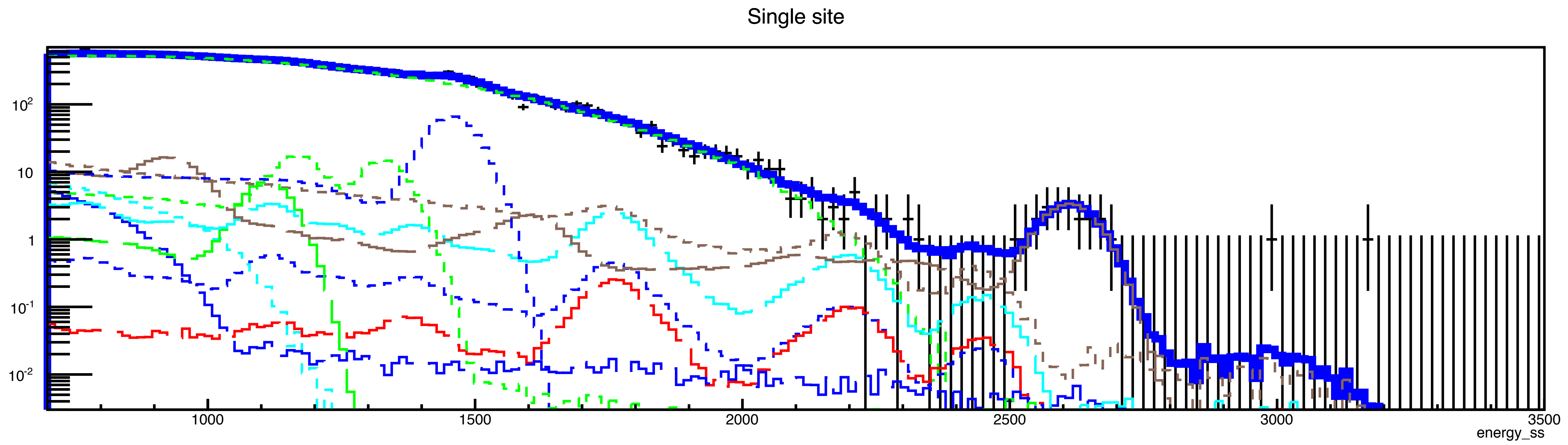


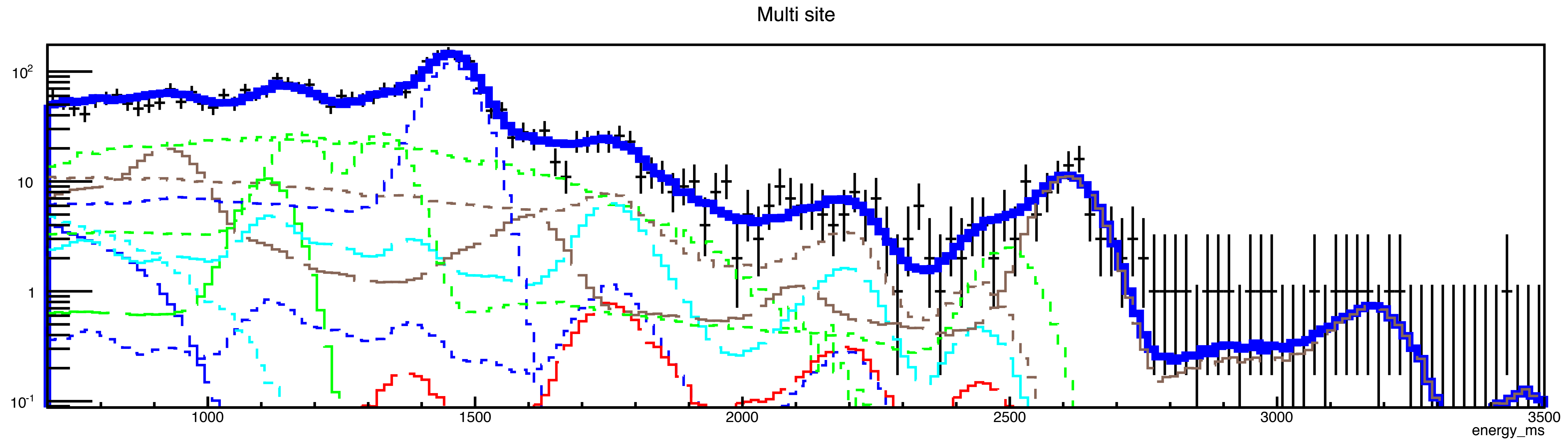
$T_{1/2}^{2\nu\beta\beta}$ = (2.172 ± 0.017(stat) ± 0.060(sys)) • 10^{21} years

Total relative uncertainty: 2.85%

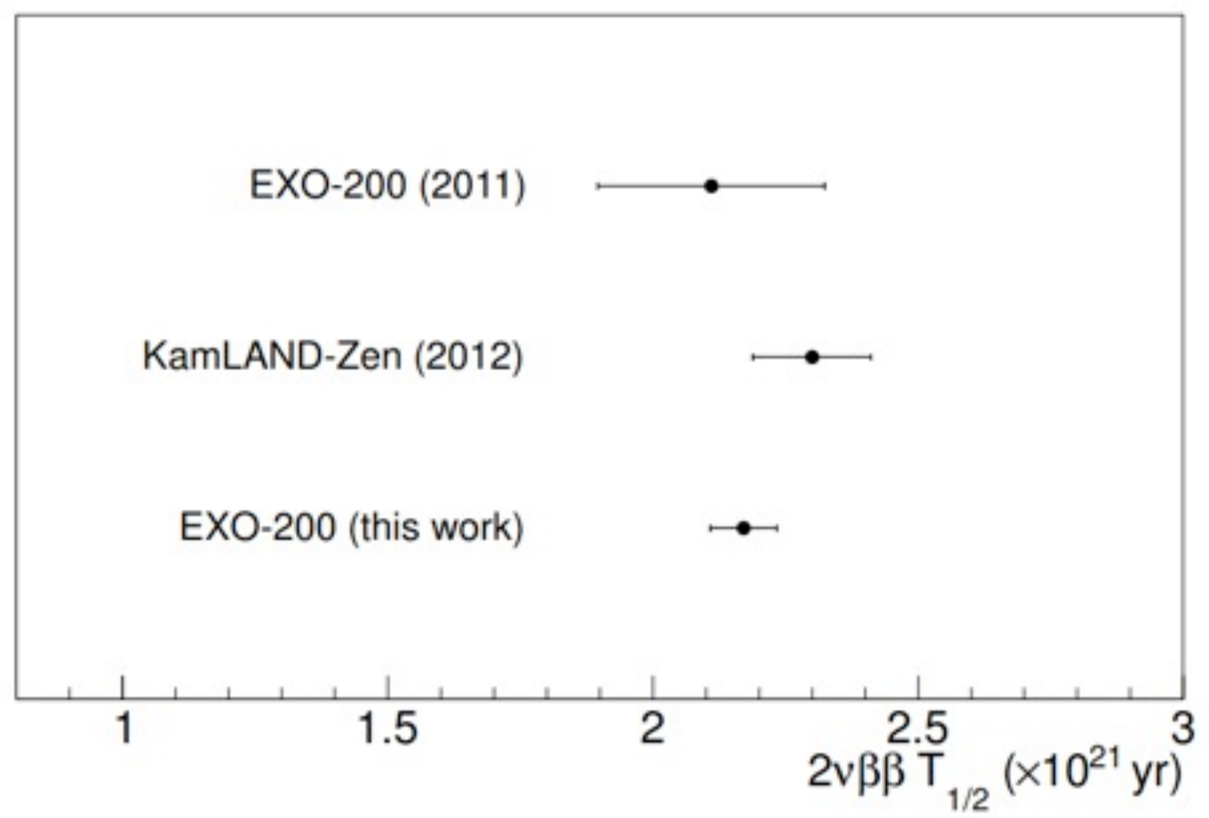
Improved analysis of $T_{1/2}^{2\nu\beta\beta}$ submitted to PRC (arxiv:1306.6106)

Simultaneous Fit

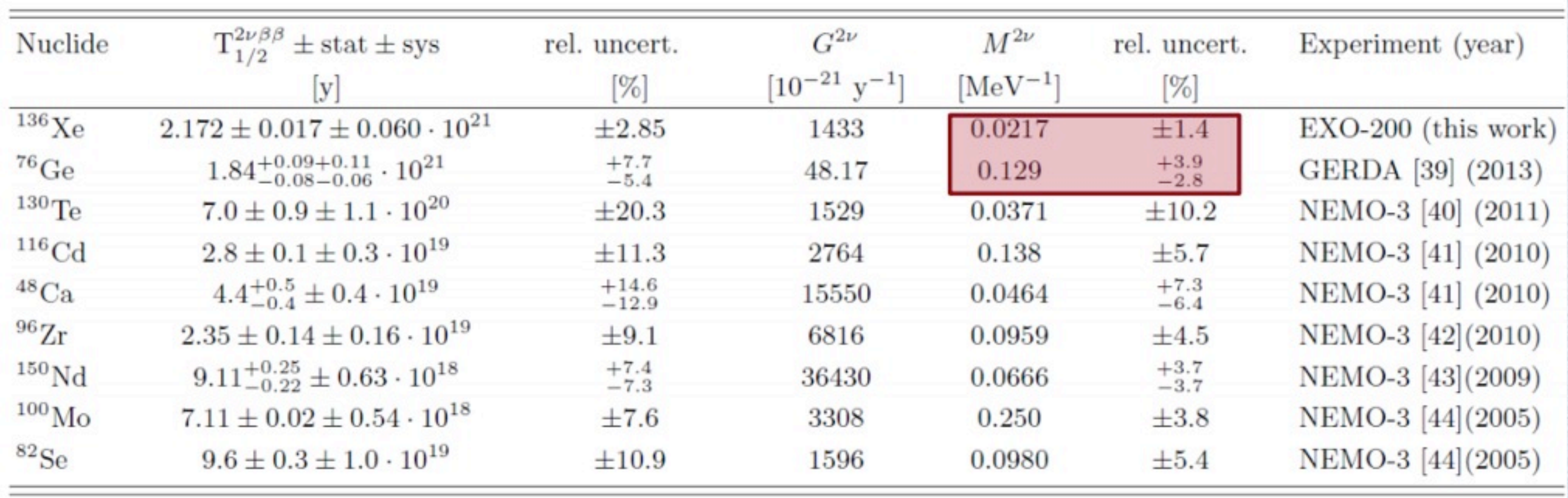




Comparisons



This result is the most precisely measured half-life of any 2νββ decay process to date



Nuclide	$T^{2\nu\beta\beta}_{1/2} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.172 \pm 0.017 \pm 0.060 \cdot 10^{21}$	± 2.85	1433	0.0217	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	48.17	0.129	$^{+3.9}_{-2.8}$	GERDA [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0464	$^{+7.3}_{-6.4}$	NEMO-3 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42](2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	$^{+7.4}_{-7.3}$	36430	0.0666	$^{+3.7}_{-3.7}$	NEMO-3 [43](2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44](2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44](2005)

Future Prospects

- For the next 0vββ result, will have ~4x data sample
- Further electronics upgrades
- Deradonator to remove ^{222}Rn from air around cryostat

R&D for nEXO, proposed ton-scale successor of EXO-200

A. Pocar,
T. Daniels et al

Deradonator

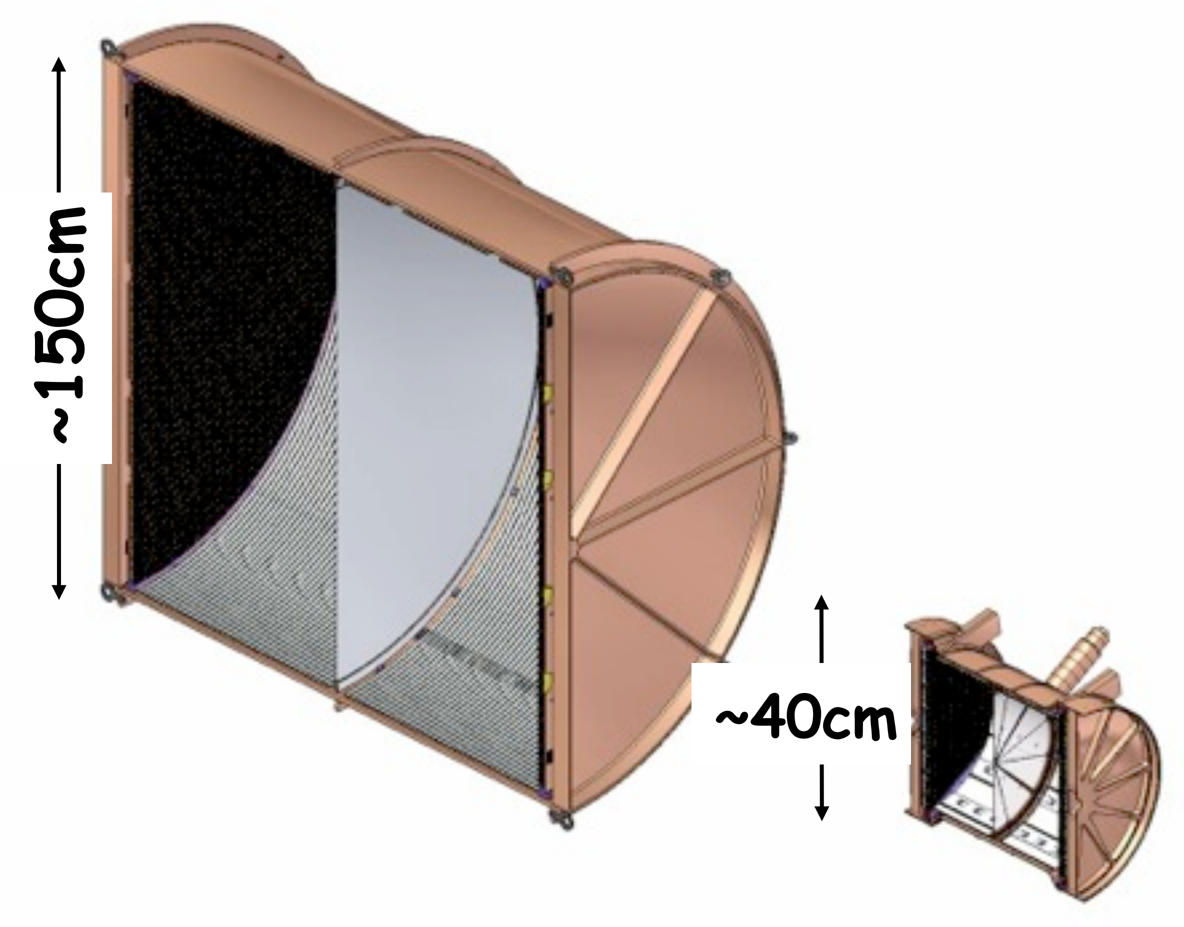
being assembled and
tested at UMass

- Charcoal-based
- Room temperature
- self-regenerating
- 10-30 cfm delivered
- ship to WIPP very soon!

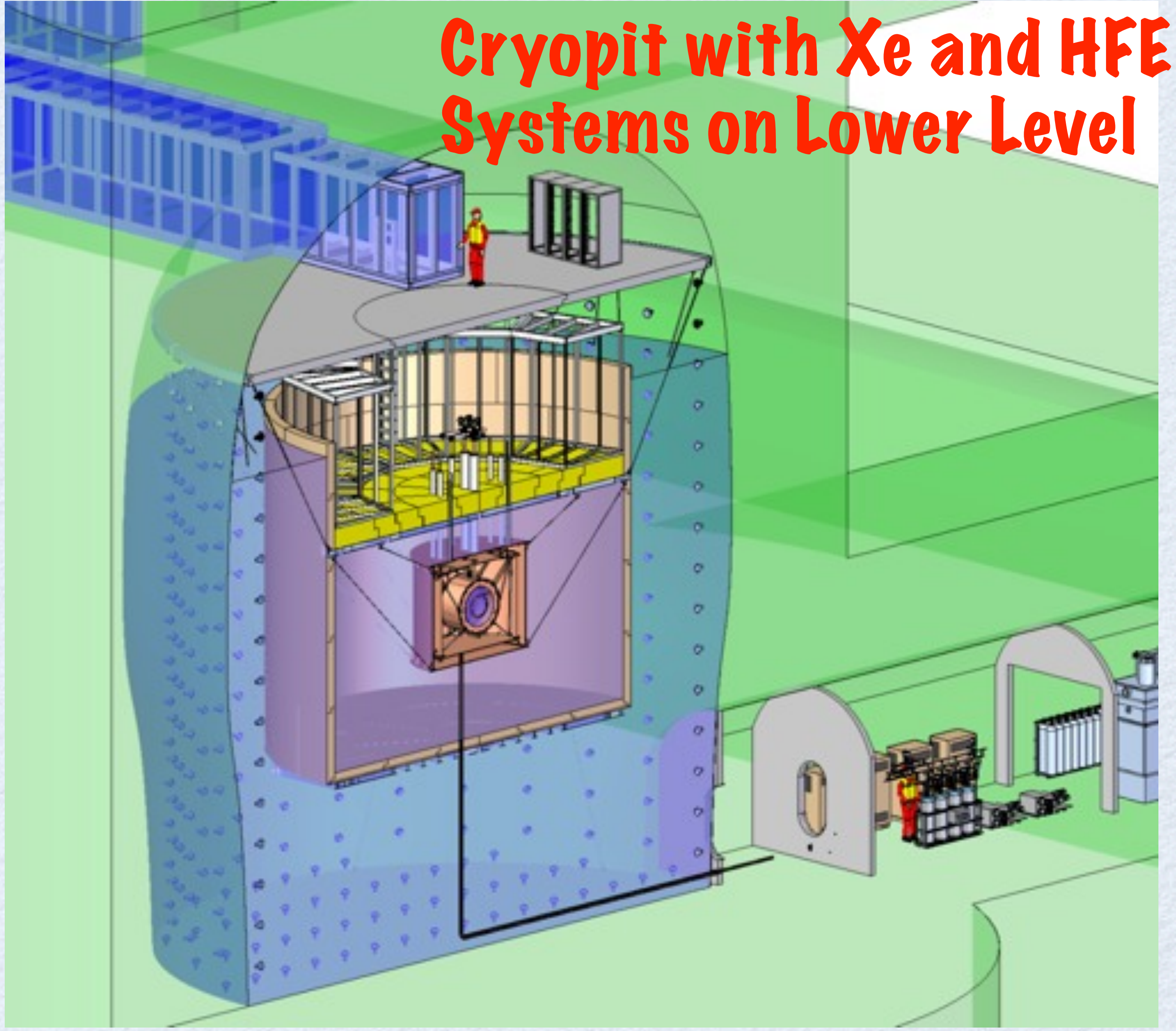
nEXO: Multi-Ton Next Phase

- **5 tonne LXe TPC "as similar to EXO-200 as possible"**
- **Entirely cover the inverted heirarchy**
- **Provide access ports for a possible later upgrade to Ba tagging**

ongoing R&D towards conceptual design



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



5 tonnes of LXe, enriched to 90%* in isotope 136

- ^{136}Xe enrichment easier and safer:

➔ 90% enriched ^{136}Xe: ~10$/g

90% enriched ^{76}Ge: ~90$/g (+xtal growth)

➔ Very top-down nEXO cost estimate: ~150M$

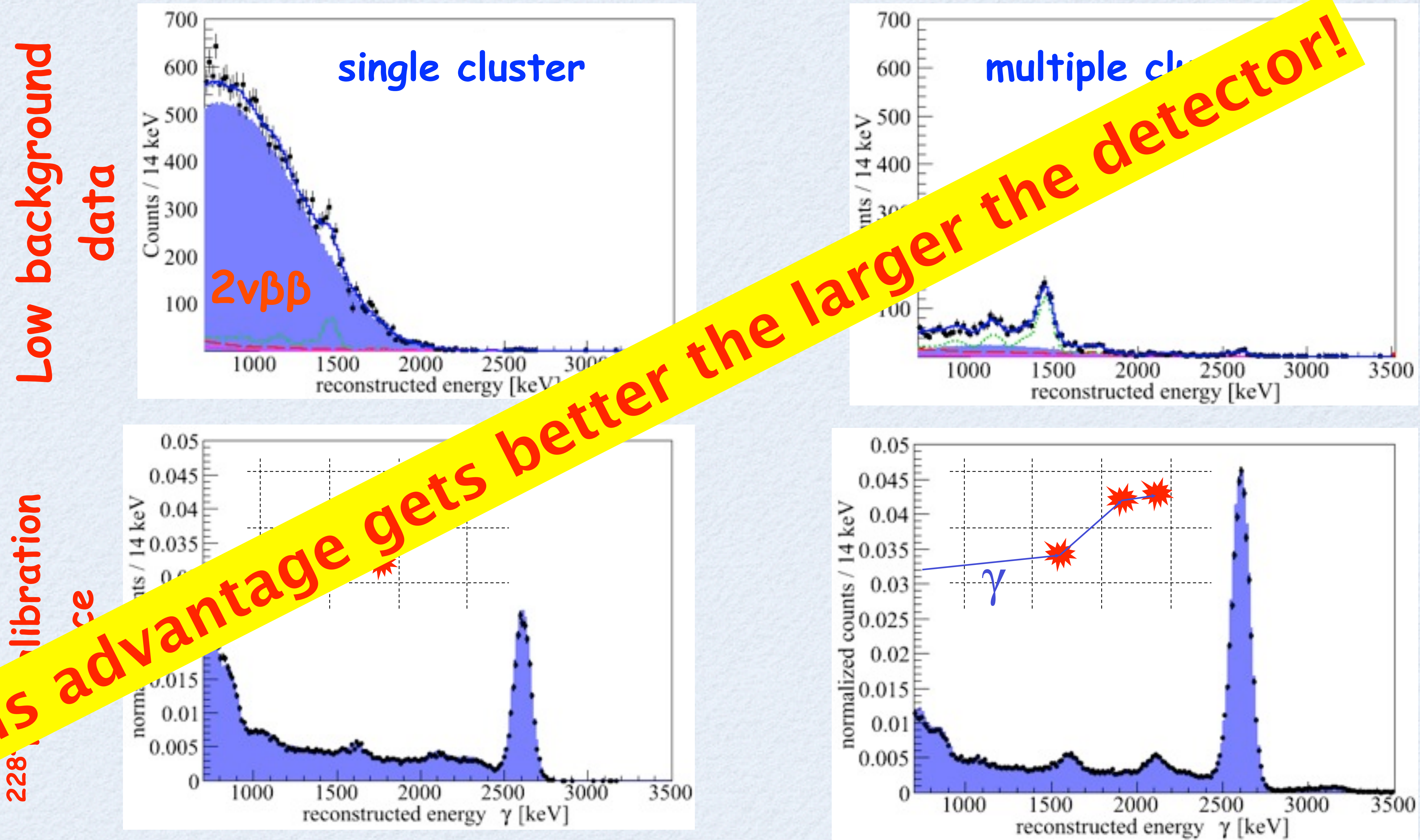
---

* EXO-200 uses 80% enriched Xe. It now seems customary to do 90% and it appears that there is no major cost difference

Scaling to Multi-Ton

But the devil is in the details (and backgrounds)

- EXO-200 has proven that an homogeneous TPC is ideal to suppress main backgrounds that for ßß decay is due to ~MeV γ-rays



This advantage gets better the larger the detector!

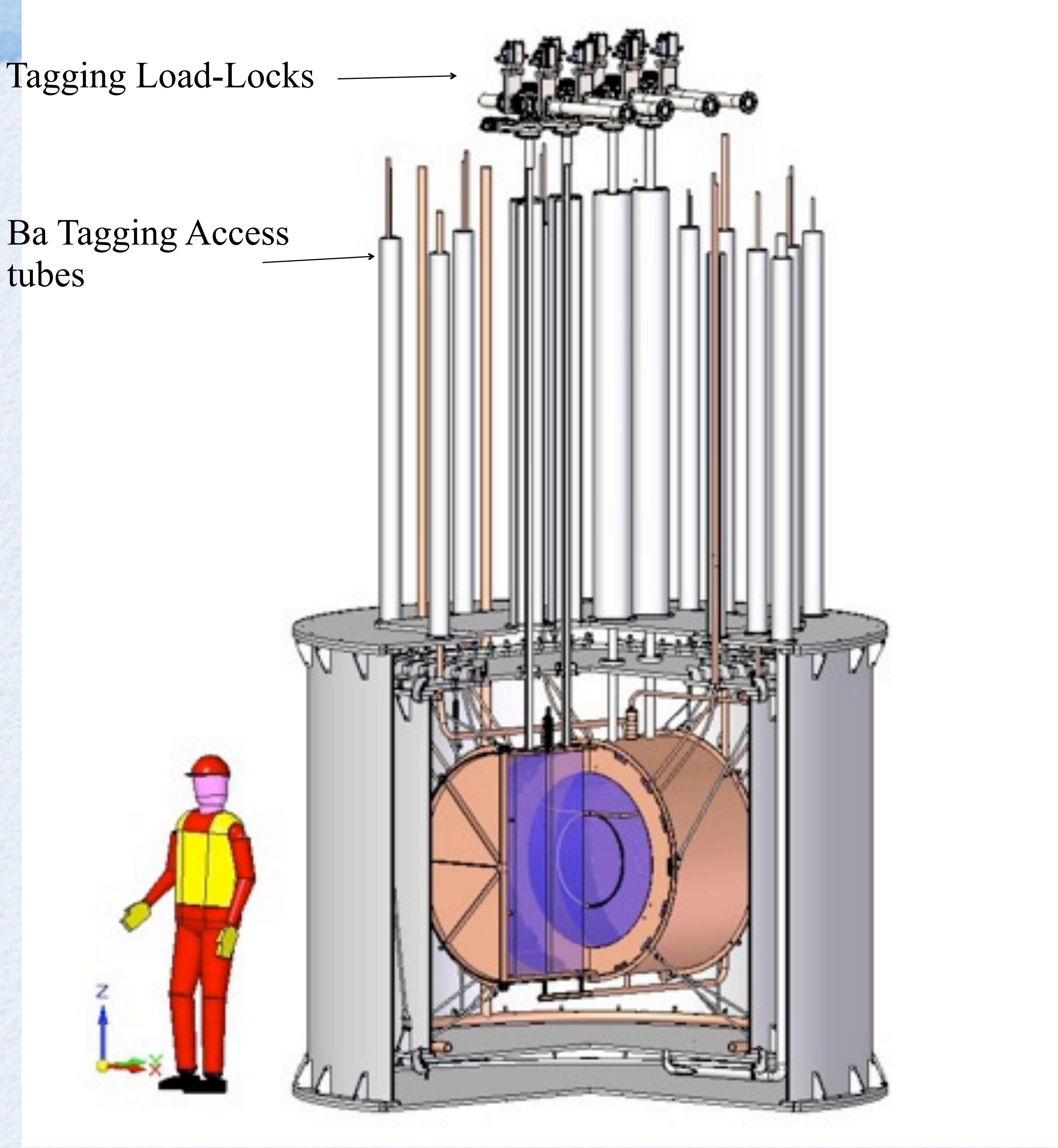
nEXO Strategy Overview

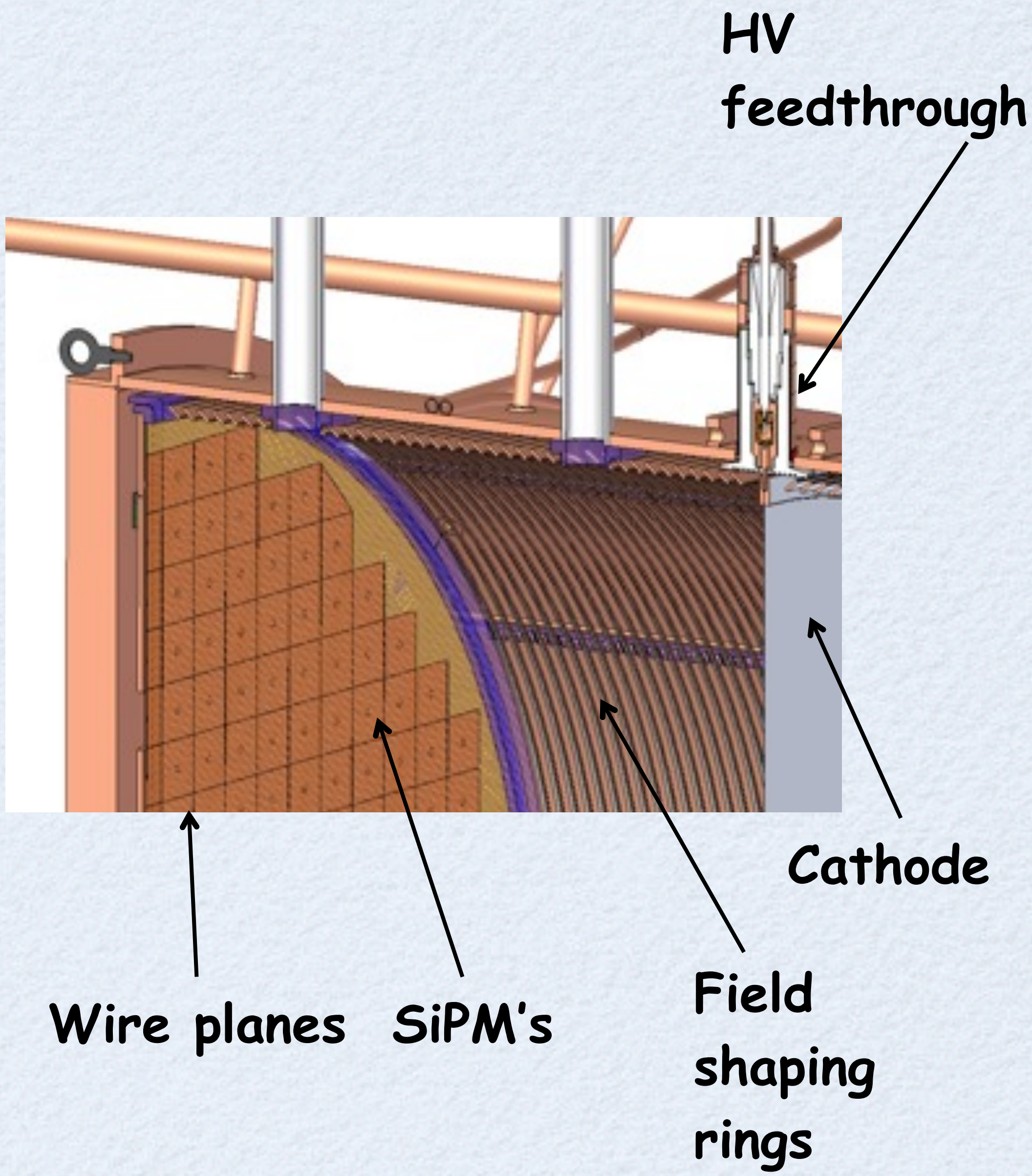
- **Closely follow the EXO-200 layout**
  - EXO-200 is an outstanding and successful "prototype" detector
  - Functioning collaboration (115 physicists/engineers, 20 institutions)
    - Experienced (young) manpower excited about detailed simulations, projections and R&D
  - R&D to improve some items that do not scale well
    - Many EXO institutions assigned R&D tasks
    - Plan for a "CD-1 quality" design by end of calendar 2015
- **Propose to locate nEXO in SNOLab Cryopit**
  - Letter of Intent submitted
  - If funded: 10-15 year program with outstanding physics potential
- **Combination of conservative and aggressive choices**
  - open to upgrade paths as desirable for a large experiment

(Incomplete) R&D Task List

- **SNOLab specific engineering**
- **Conceptual Engineering**
- **Engineering Simulations & Design**
  - Electrostatics and Charge Readout
  - Fluid Mechanics and Cryogenics
  - Control System and Thermodynamics
  - Counterflow heat exchanger and Xenon recirculation
- **High Voltage Stability Tests**
- **Hardware R&D**
  - Cold Electronics (get rid of cables)
  - Photodetectors
- **Background Simulations**
- **Barium Tagging R&D**

Cryostat with Tagging Ports





There is lots of experience (not all positive!) on LXe cryogenics that is already being used to conceptually design nEXO's subsystems

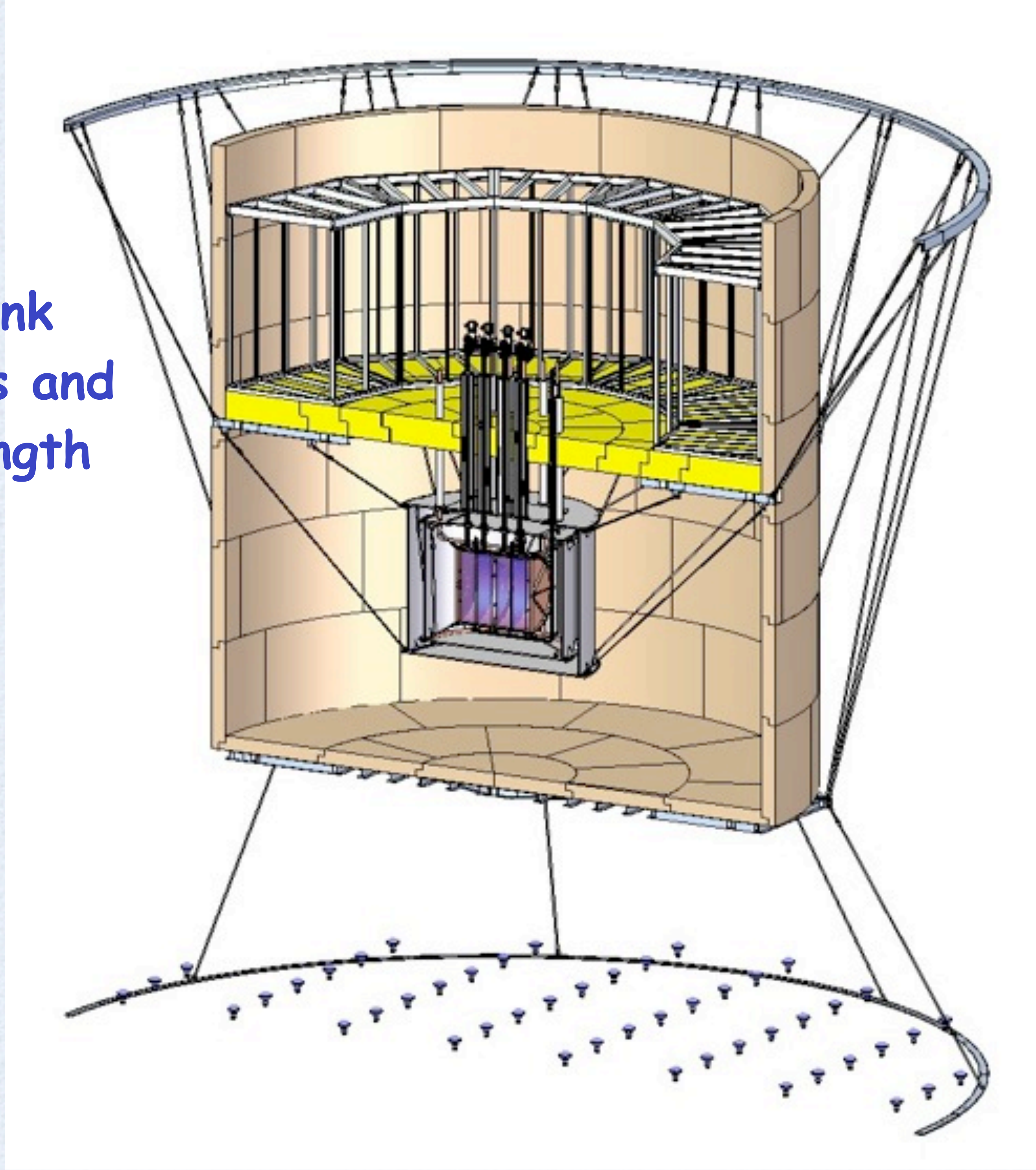
This has to happen together with the simulation effort

Cable Support Scheme

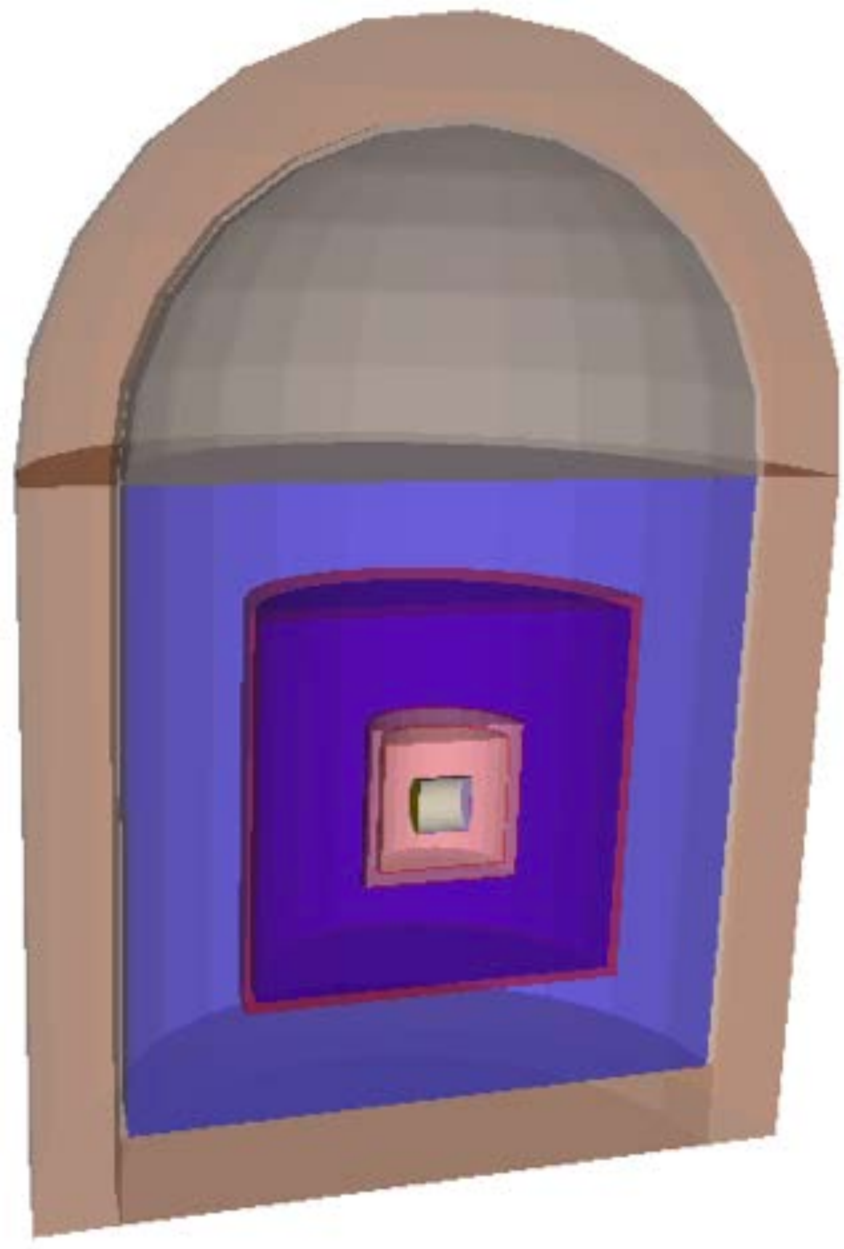
Present ideas include a secondary water tank that can be pumped dry for ease of access and a thin Pb shielding on top to reduce the length of penetrations for the Ba tagging system.

This assembly hangs from cables.

Other schemes are under consideration



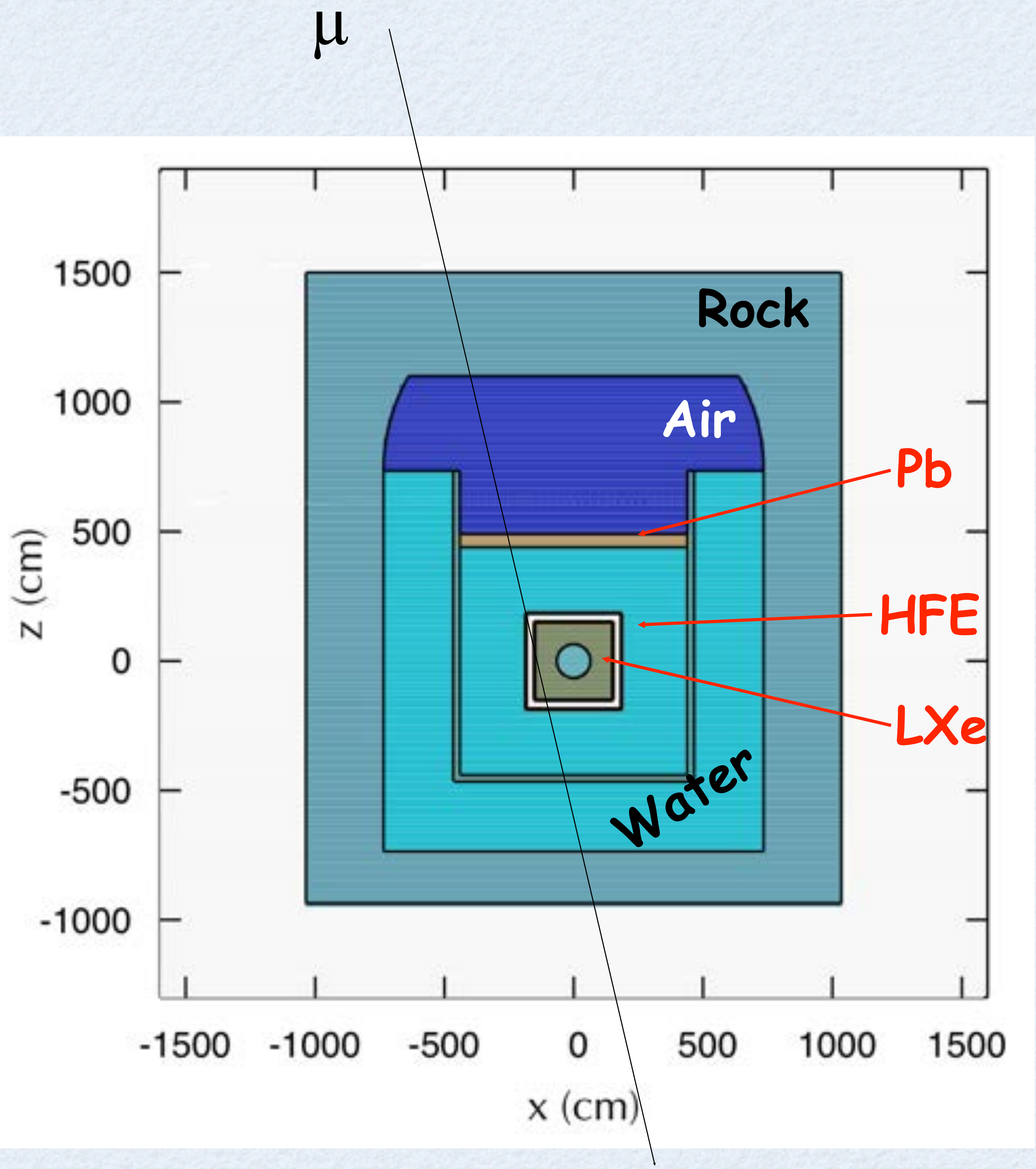
nEXO Projections



- Geant4 simulation for γ bkgnd
- Includes all major components of nEXO, as known now
- Cryopit full of water, detector centered
- σ_E = 1.5% (this is conservative)
- e-γ discrim. 2x that of EXO-200 (3x finer pitch & lower threshold)
- Scale material amounts and use EXO-200 material contaminations except where new numbers are available (e.g. copper)
- Short term work to be done:
  - Iterate for shielding thickness
  - Add LXe/readout physics (confirm or modify discrimination power)
  - Insert new figures for material radioactivity as they become available

Neutron Simulations

FLUKA with a slightly simplified geometry



Main background from n capture on ^{136}Xe

$$^{136}Xe + n \rightarrow {}^{137}Xe$$
$$\hookrightarrow {}^{137}Cs + \overline{\nu_e} + e^-$$

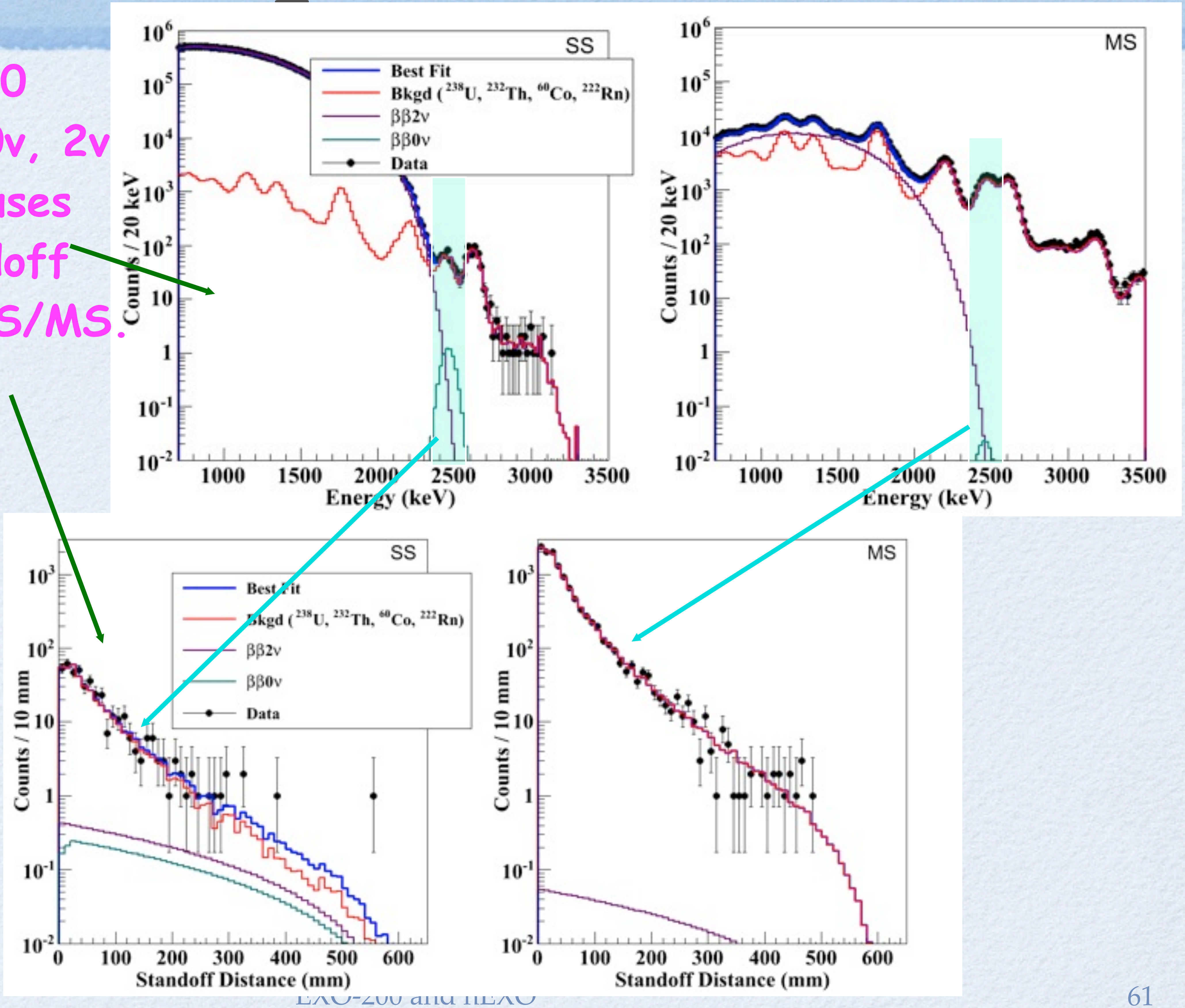
$T_{1/2}$=3.8min, Q=4.2MeV

$$\Rightarrow 1.5\,\frac{cts}{5yr\;5ton\;\pm 2\sigma ROI}$$

Backgrounds from prompt n and n from rock activity are greatly attenuated by the large water shield and negligible

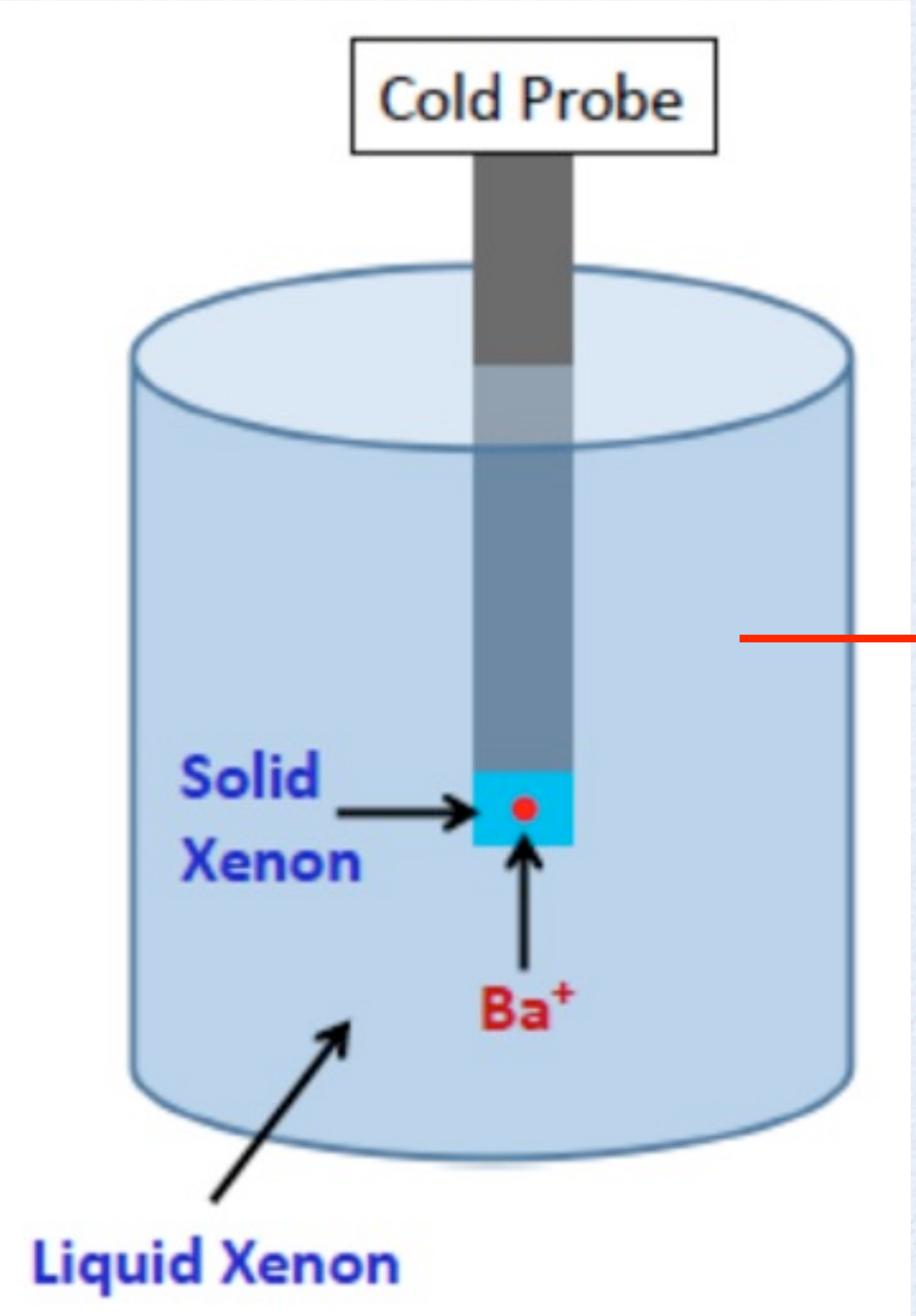
Example Results

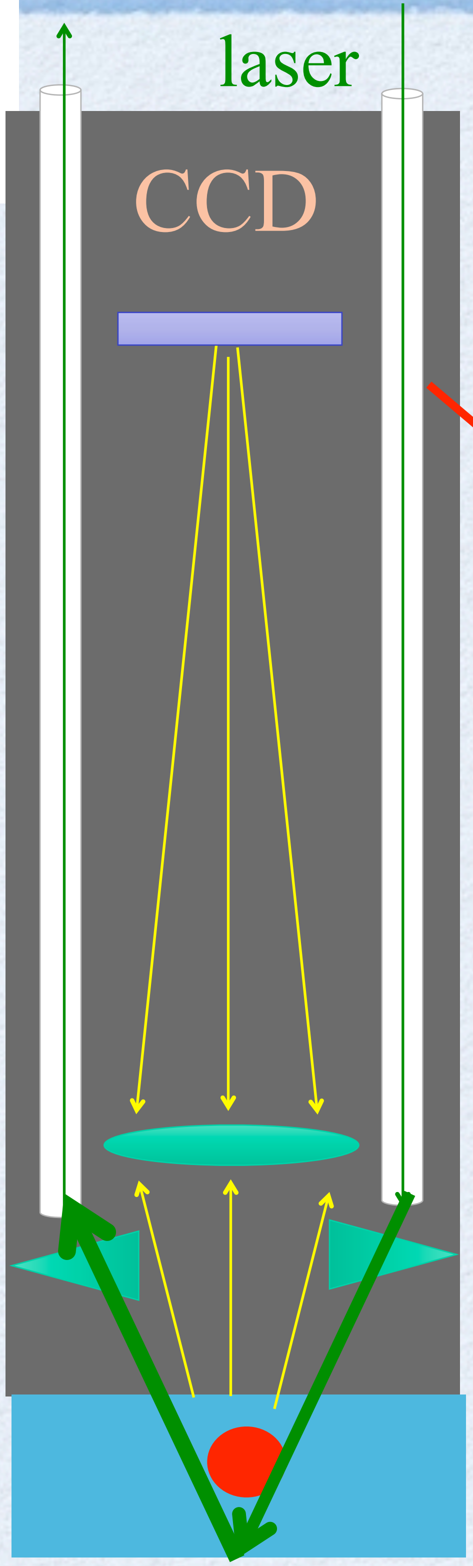
Like for EXO-200 data the fit to 0ν, 2ν and background uses energy and standoff separately for SS/MS.



Direct Ba Tagging in LXe

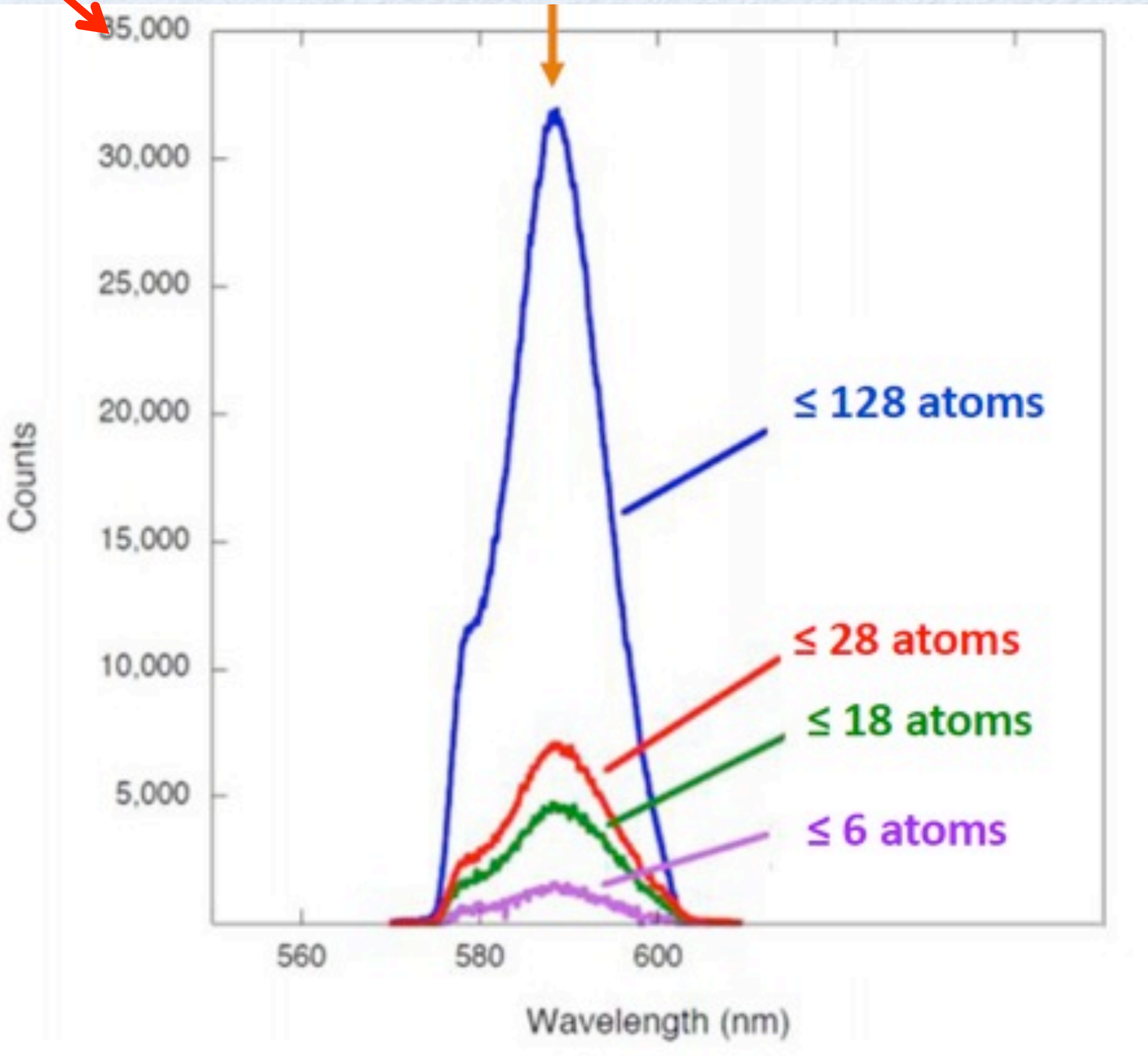
Trap barium daughter ion in SXe on a cooled probe



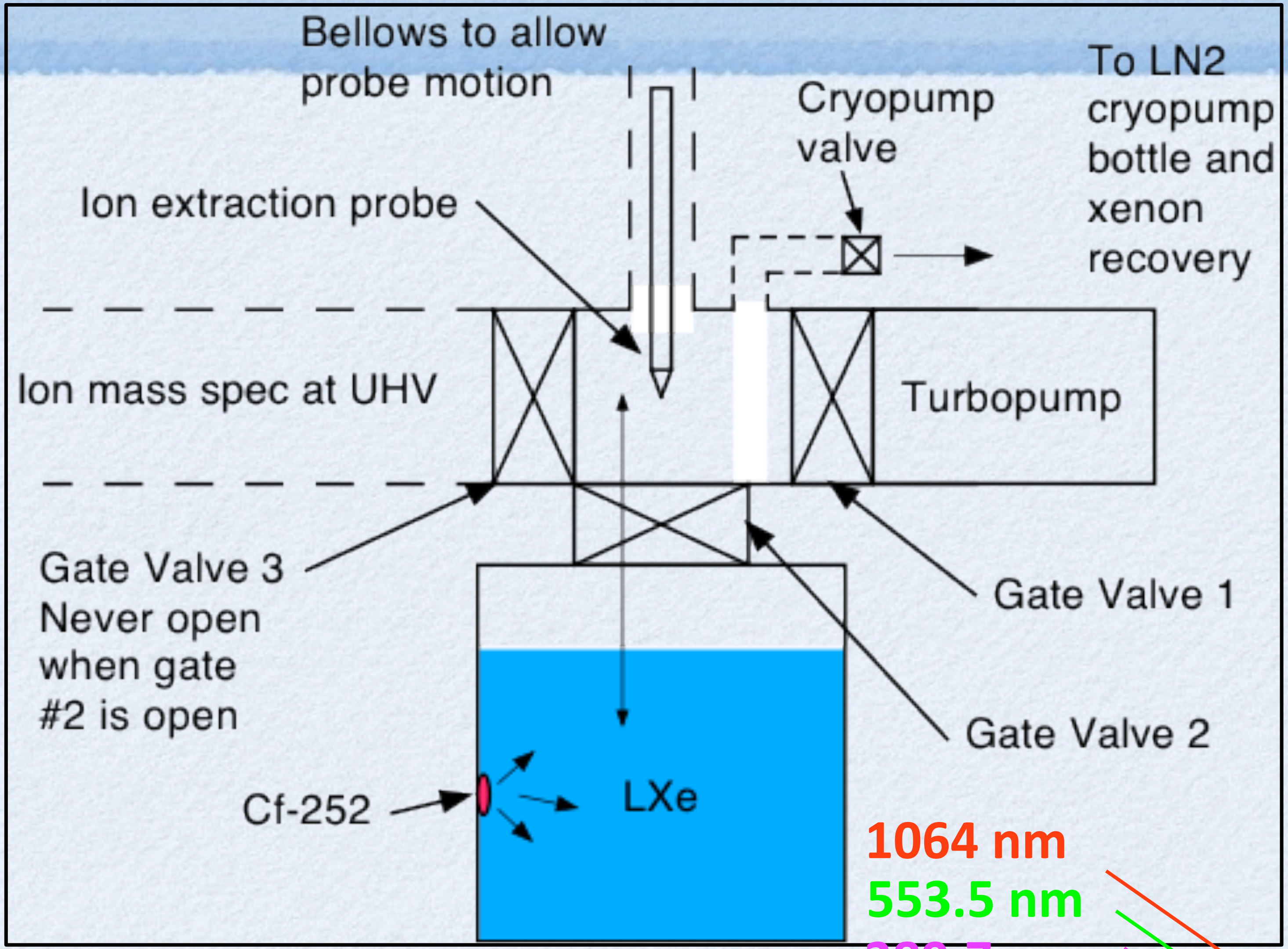


Detect single ion or atom on the probe with laser-induced fluorescence

Fluorescence peak of Ba in SXe after excitation w/ 558 nm laser



Removal and Tagging in Vacuum



Bellows to allow probe motion

Ion extraction probe

Cryopump valve

To LN2 cryopump bottle and xenon recovery

Ion mass spec at UHV

Turbopump

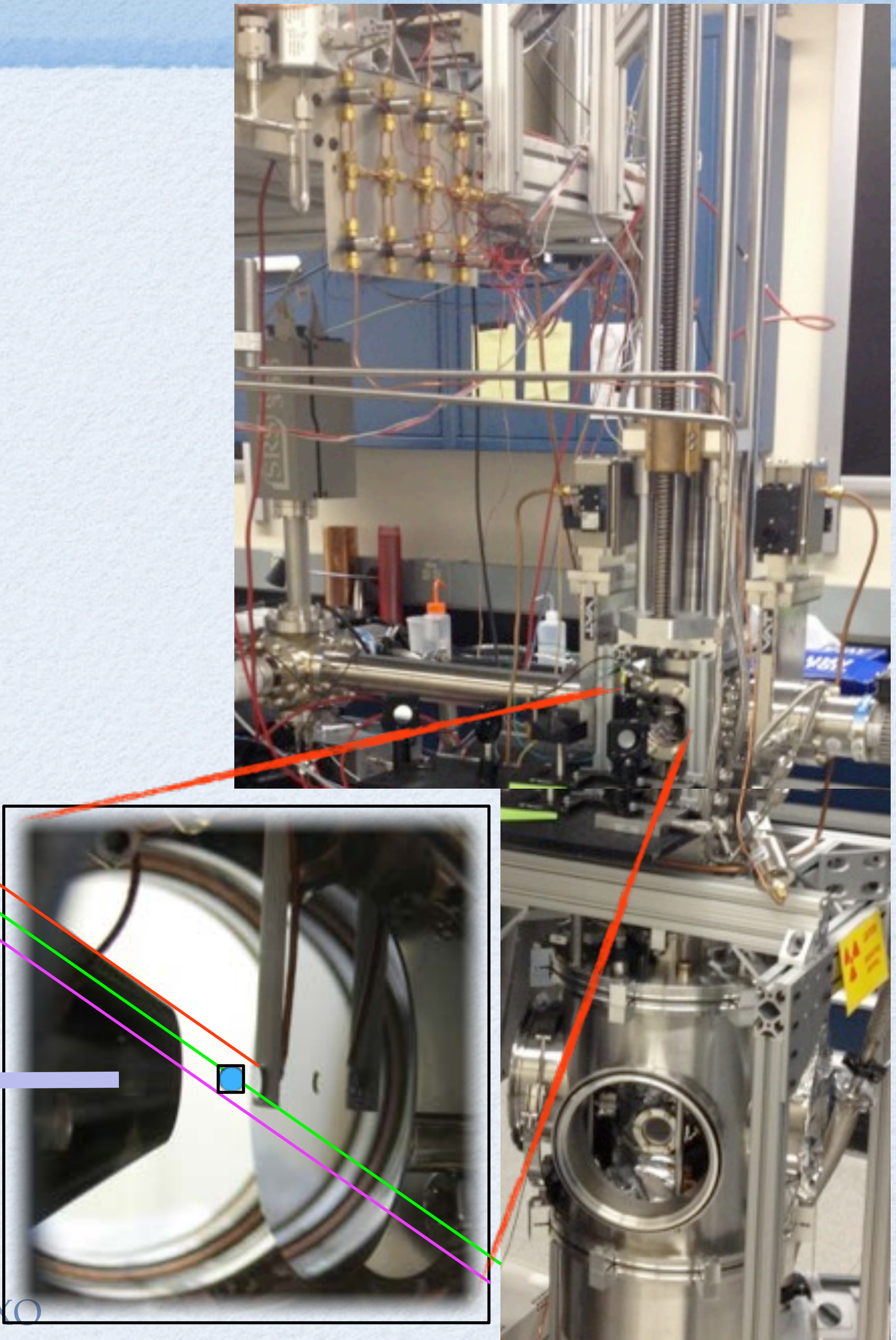
Gate Valve 3 Never open when gate #2 is open

Gate Valve 1

Gate Valve 2

Cf-252

LXe



1064 nm

553.5 nm

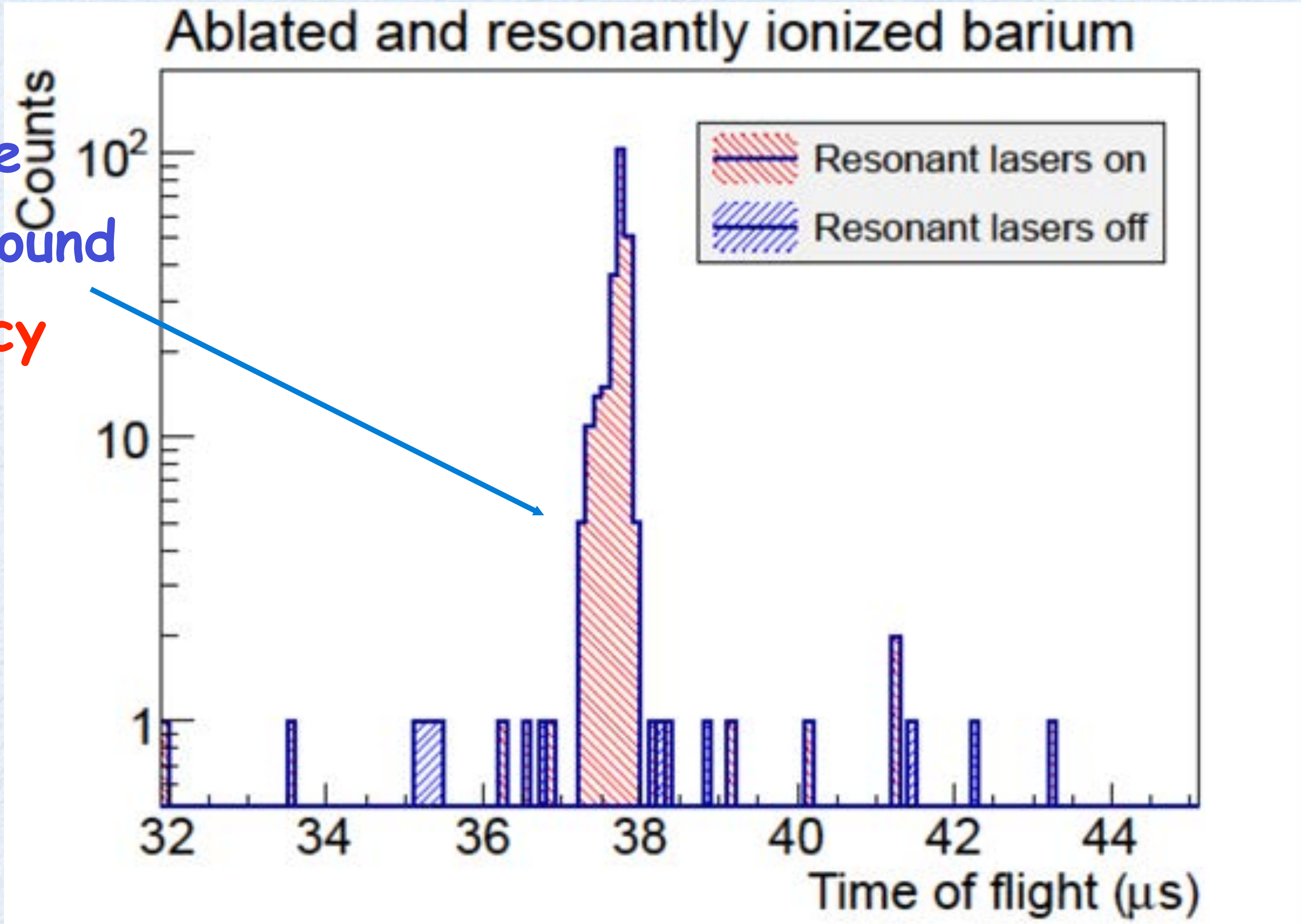
389.7 nm

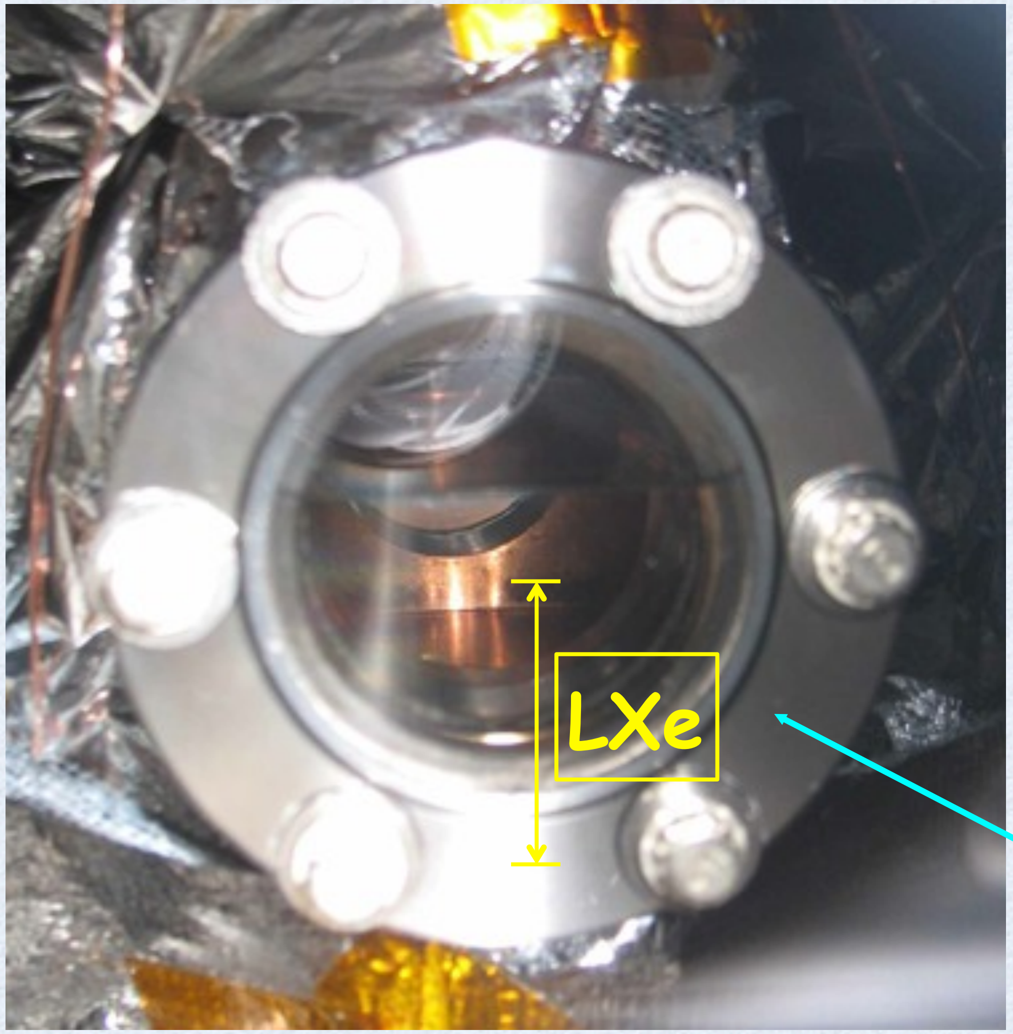
Ba^+

To Time of Flight Spectrometer

RIS Current Status

- Proper choice of material and surface prep ➔ signal with almost no background
- Ideal conditions + luck: >5% efficiency from deposition to detection



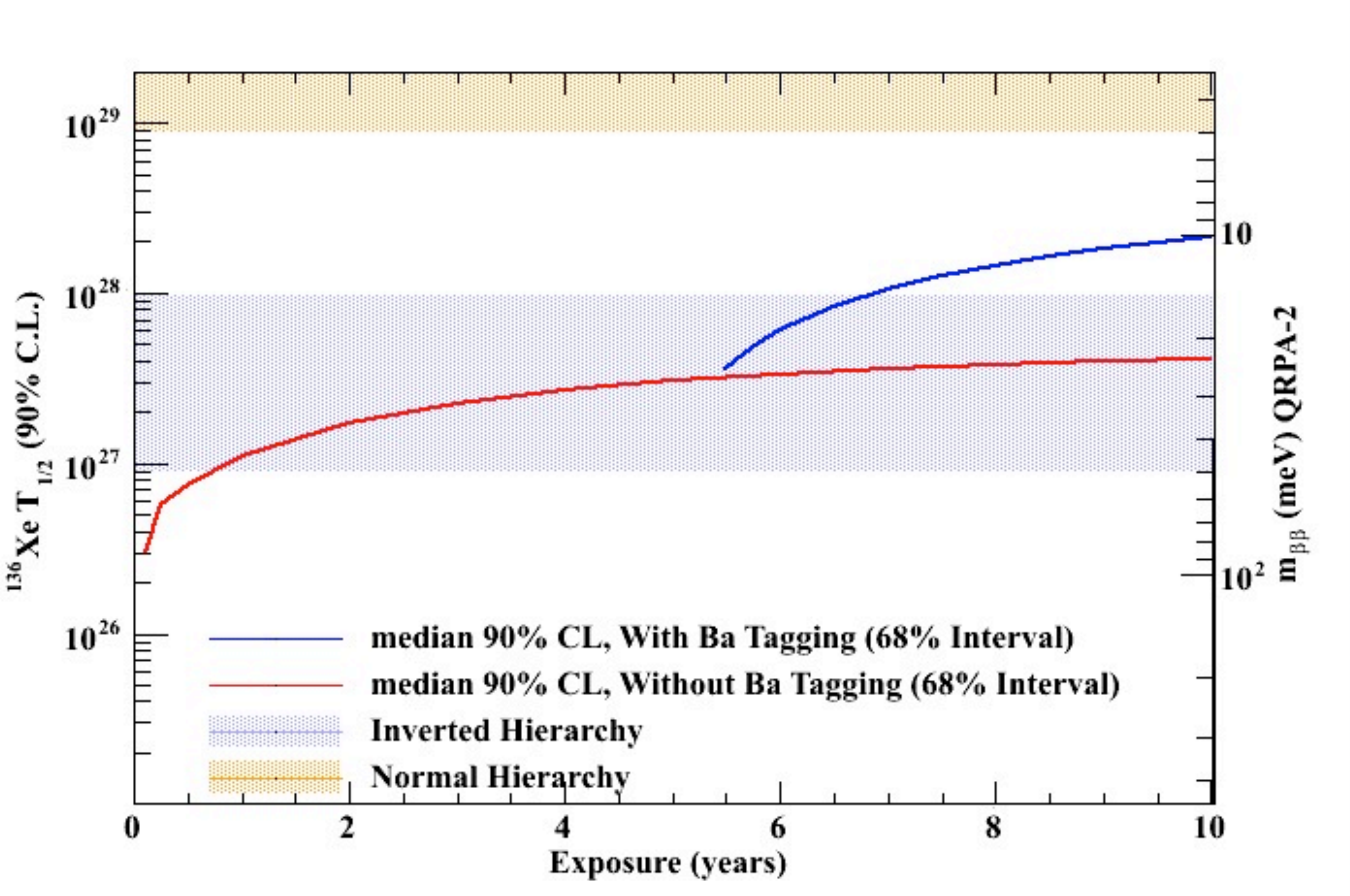


Next:

- Continued work on improving repeatability, efficiency
- Start operating in LXe

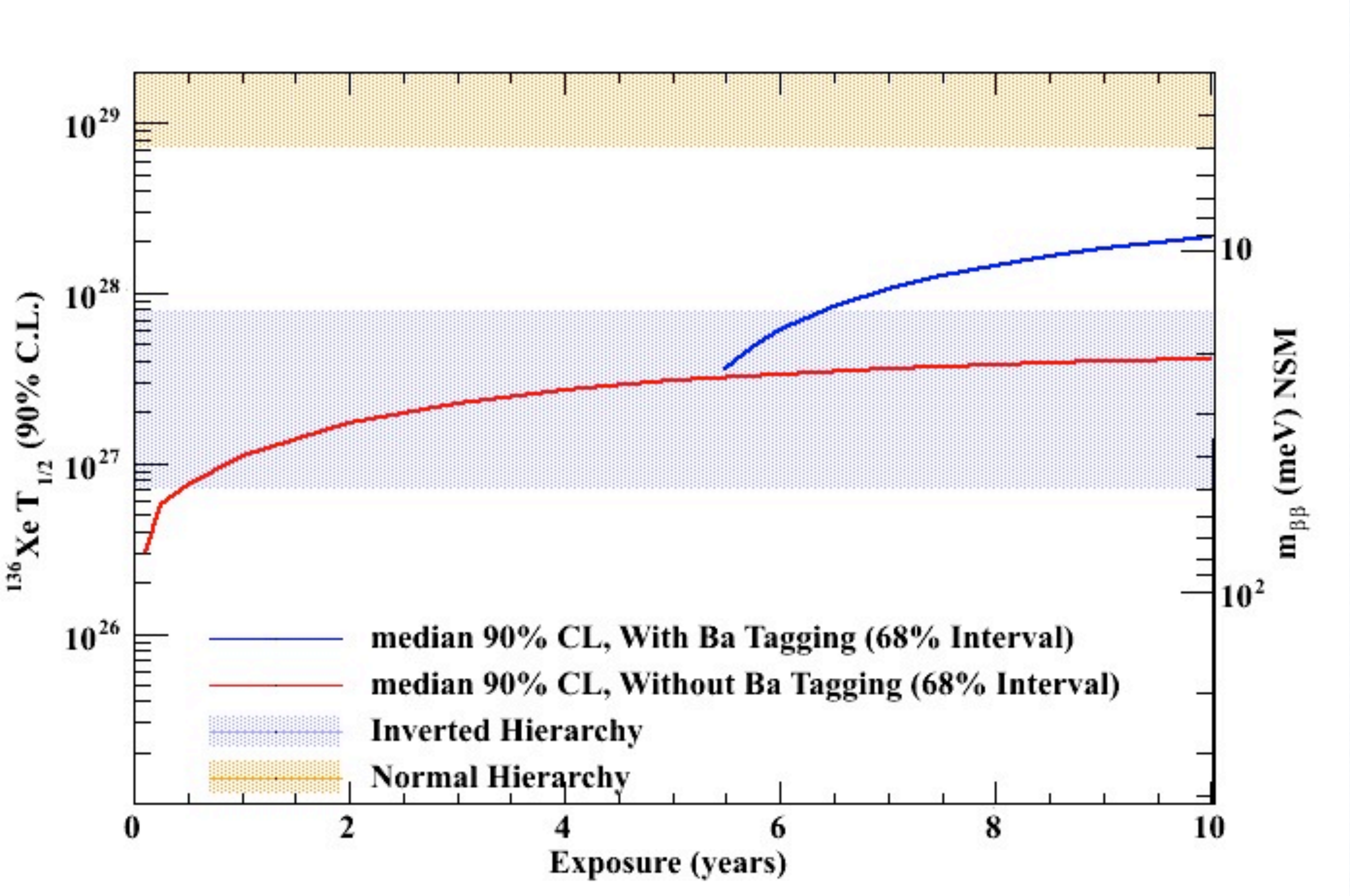
Sensitivity

5 years initial phase, then 5 years with Ba tagging



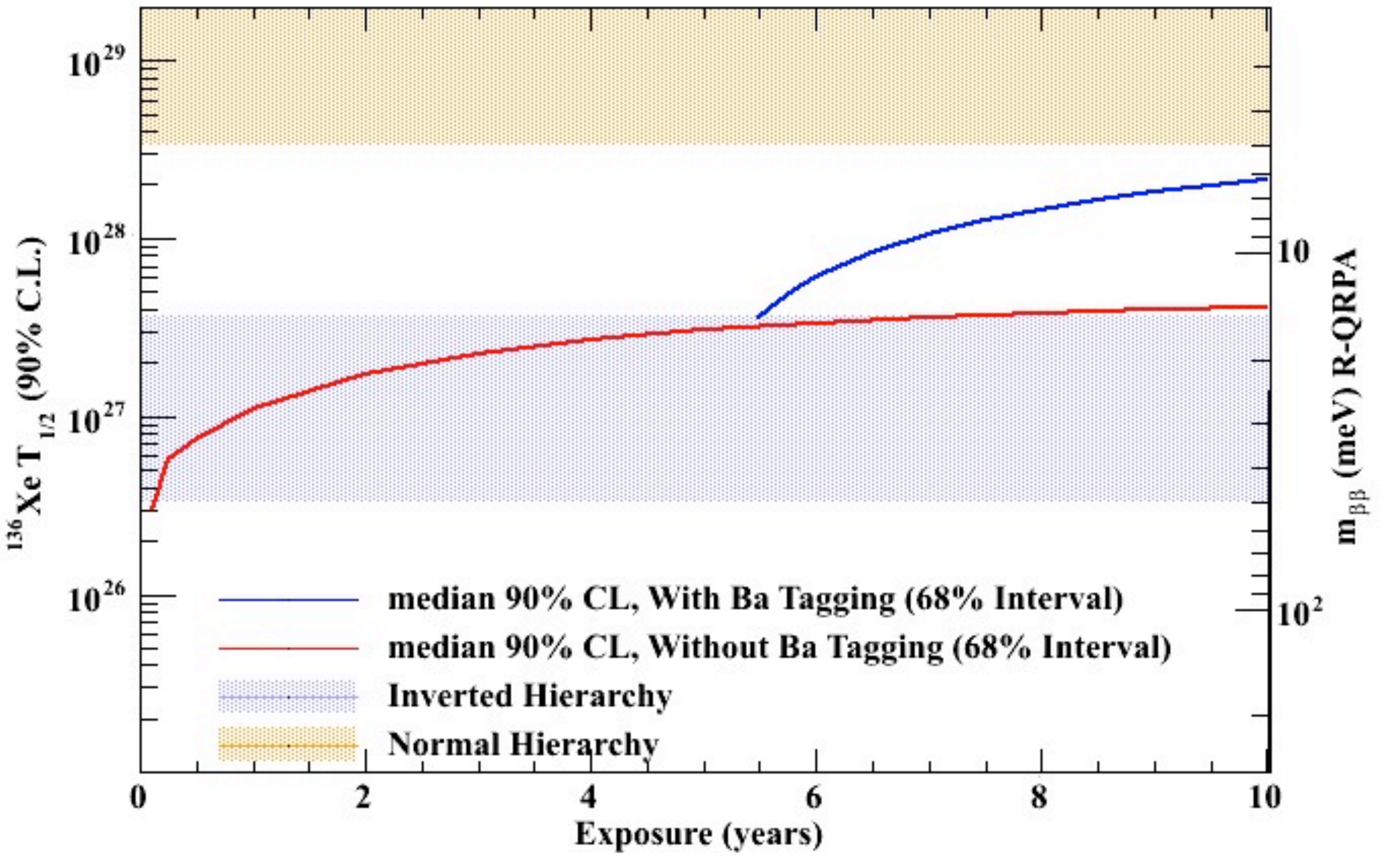
Sensitivity

5 years initial phase, then 5 years with Ba tagging



Sensitivity

5 years initial phase, then 5 years with Ba tagging



Sensitivity

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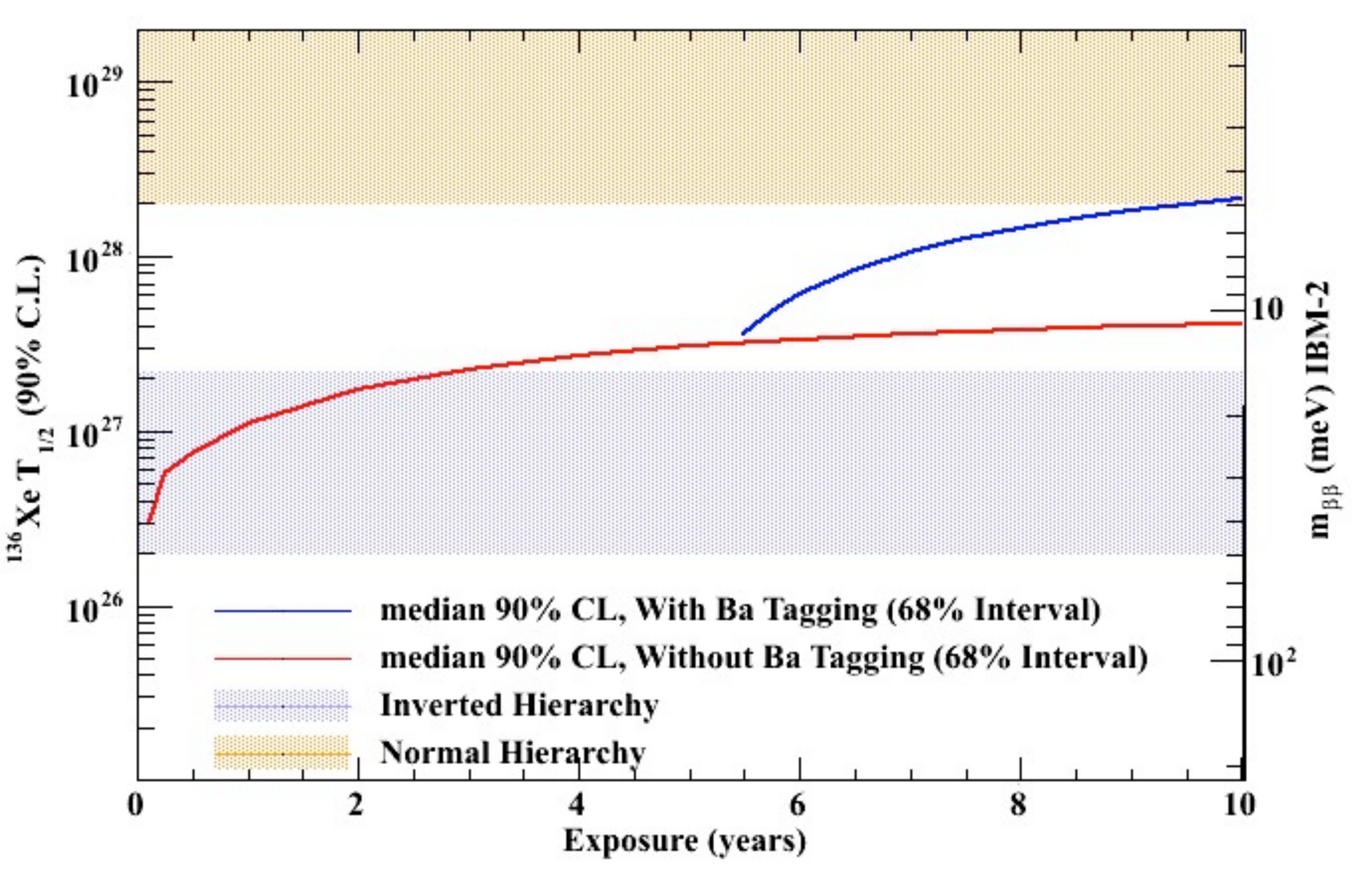

Sensitivity

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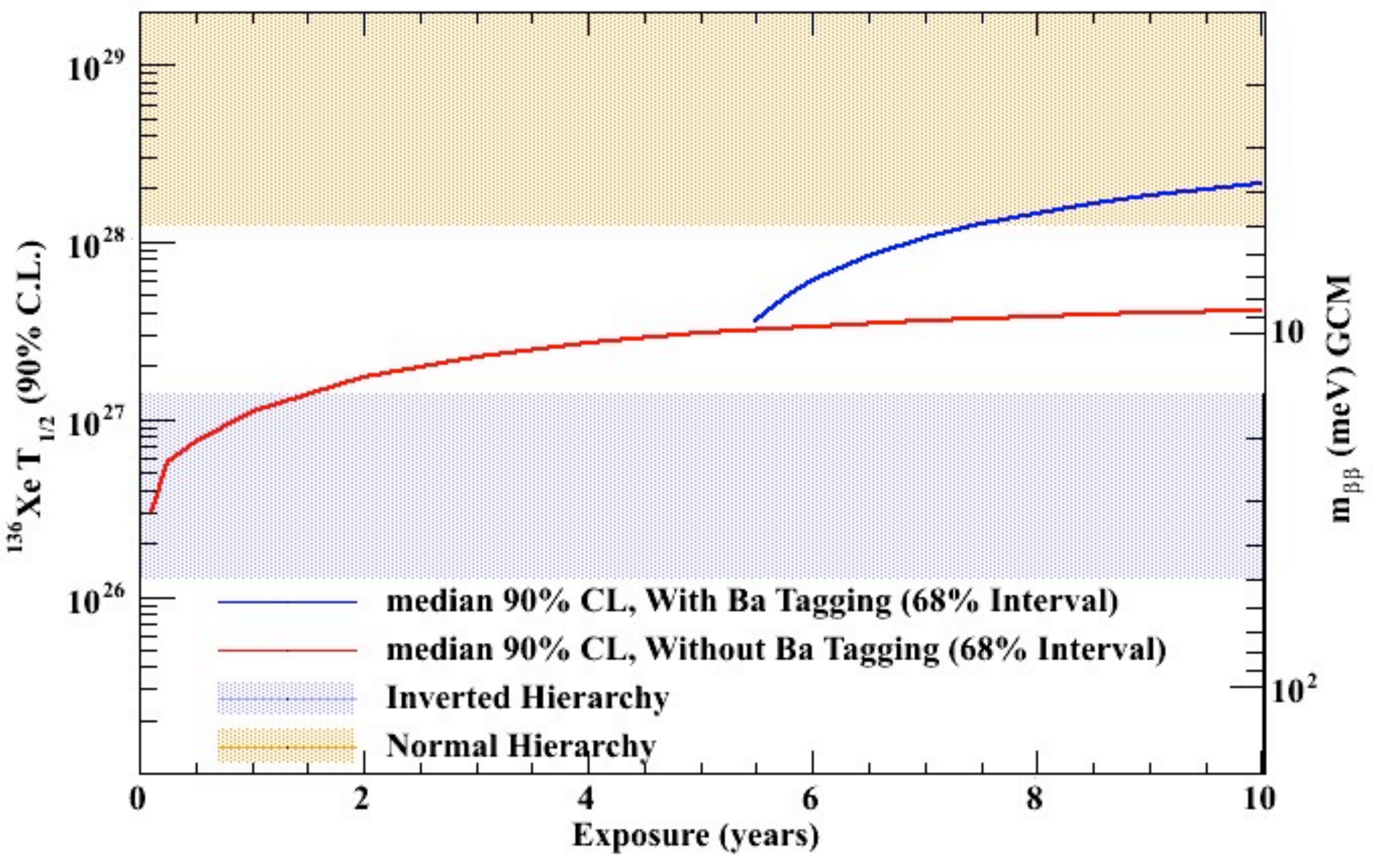
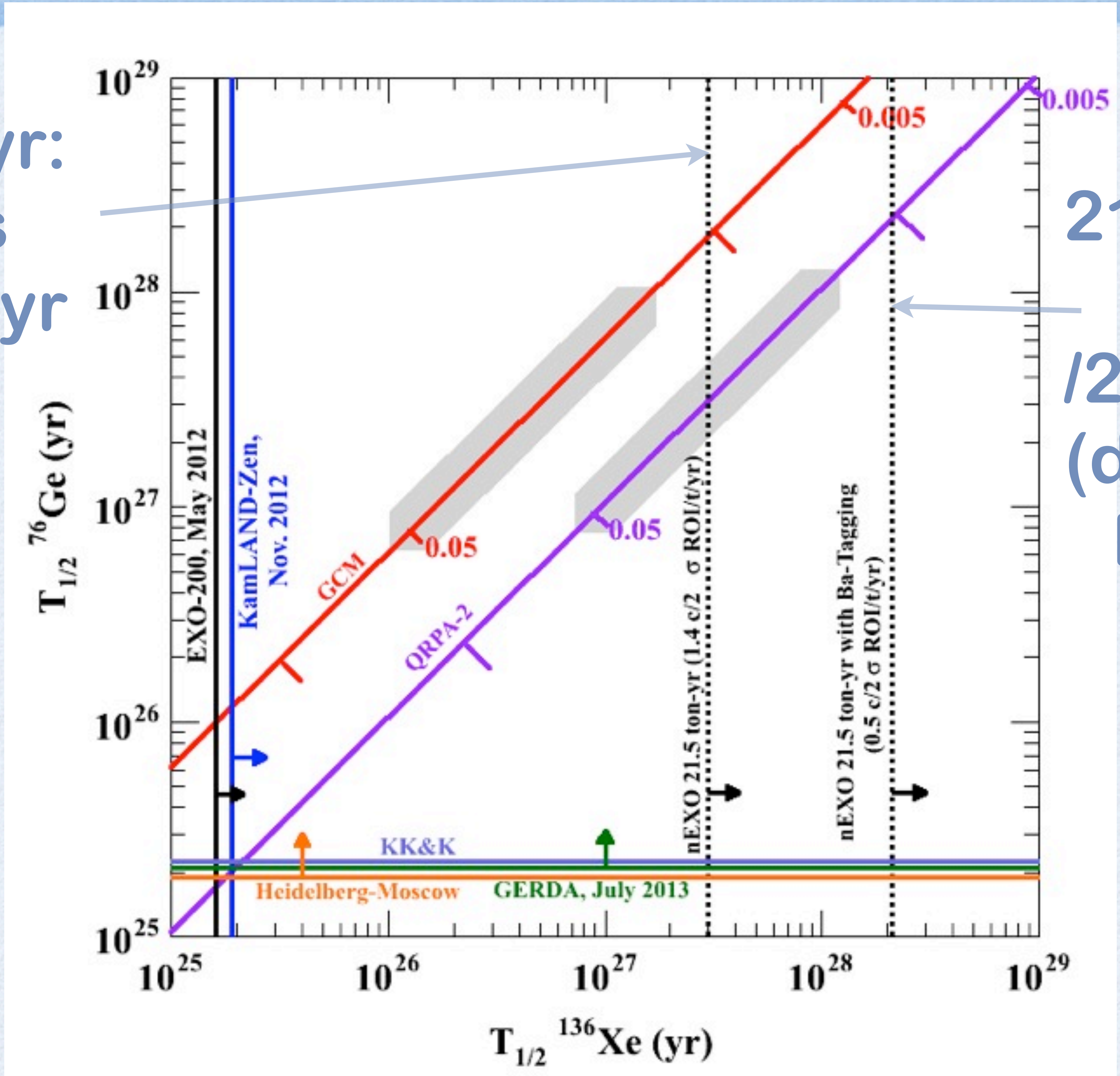


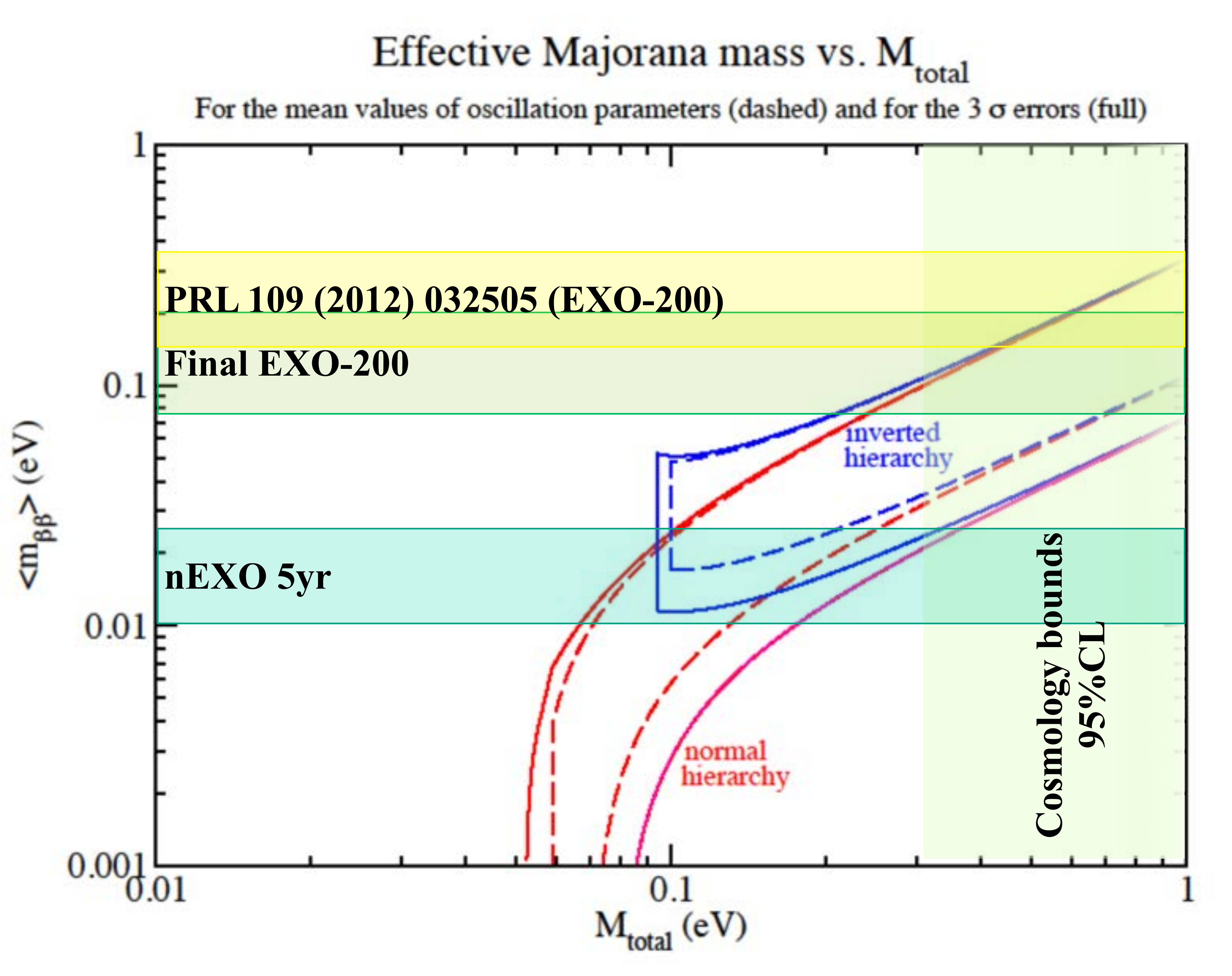
Summary Projection

21.5 ton-yr:
1.4 cnts
/2σ ROI/t/yr

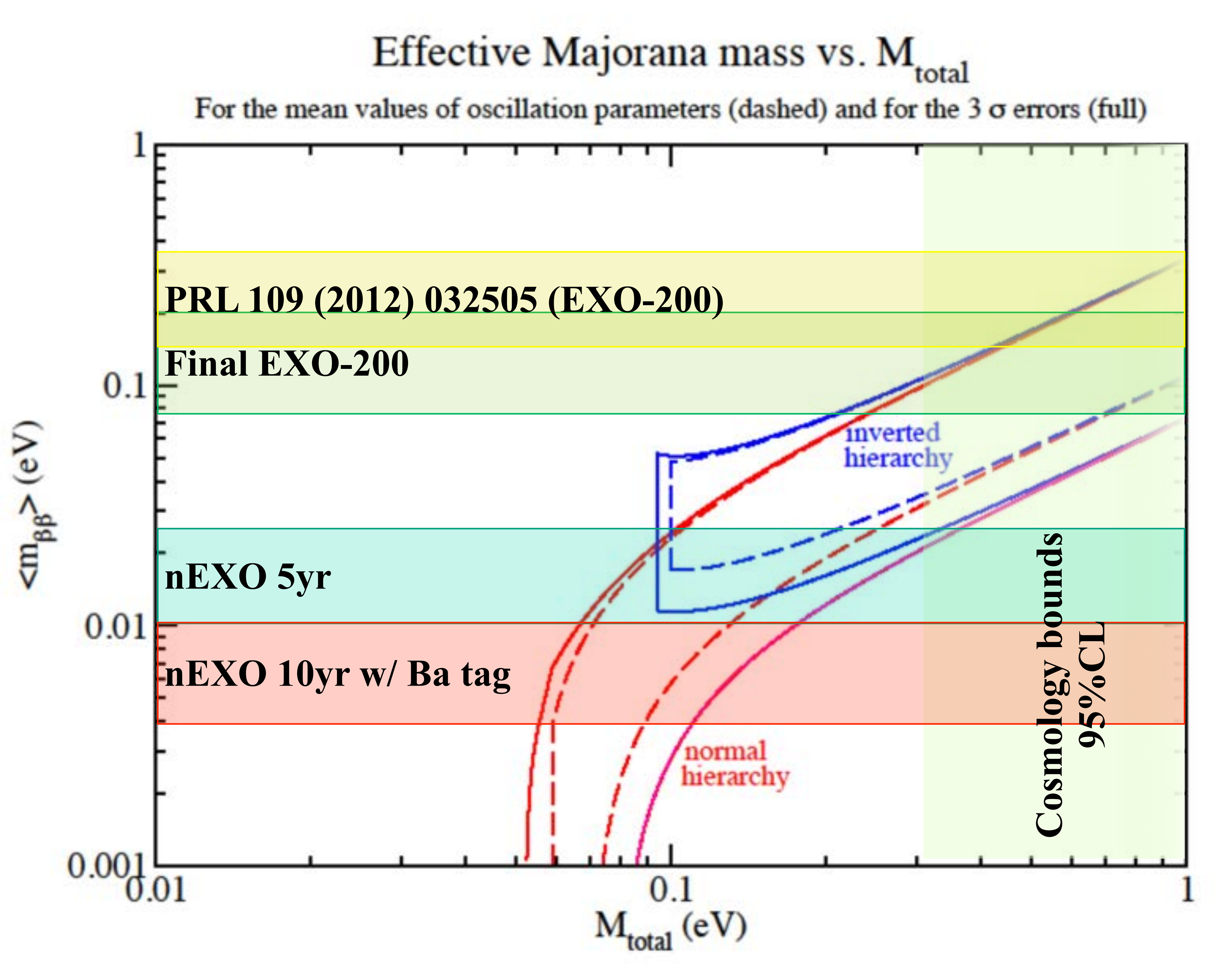


21.5 ton-yr:
0.5 cnts
/2σ ROI/t/yr
(dominated
by 2νββ)

Neutrino Mass Projections

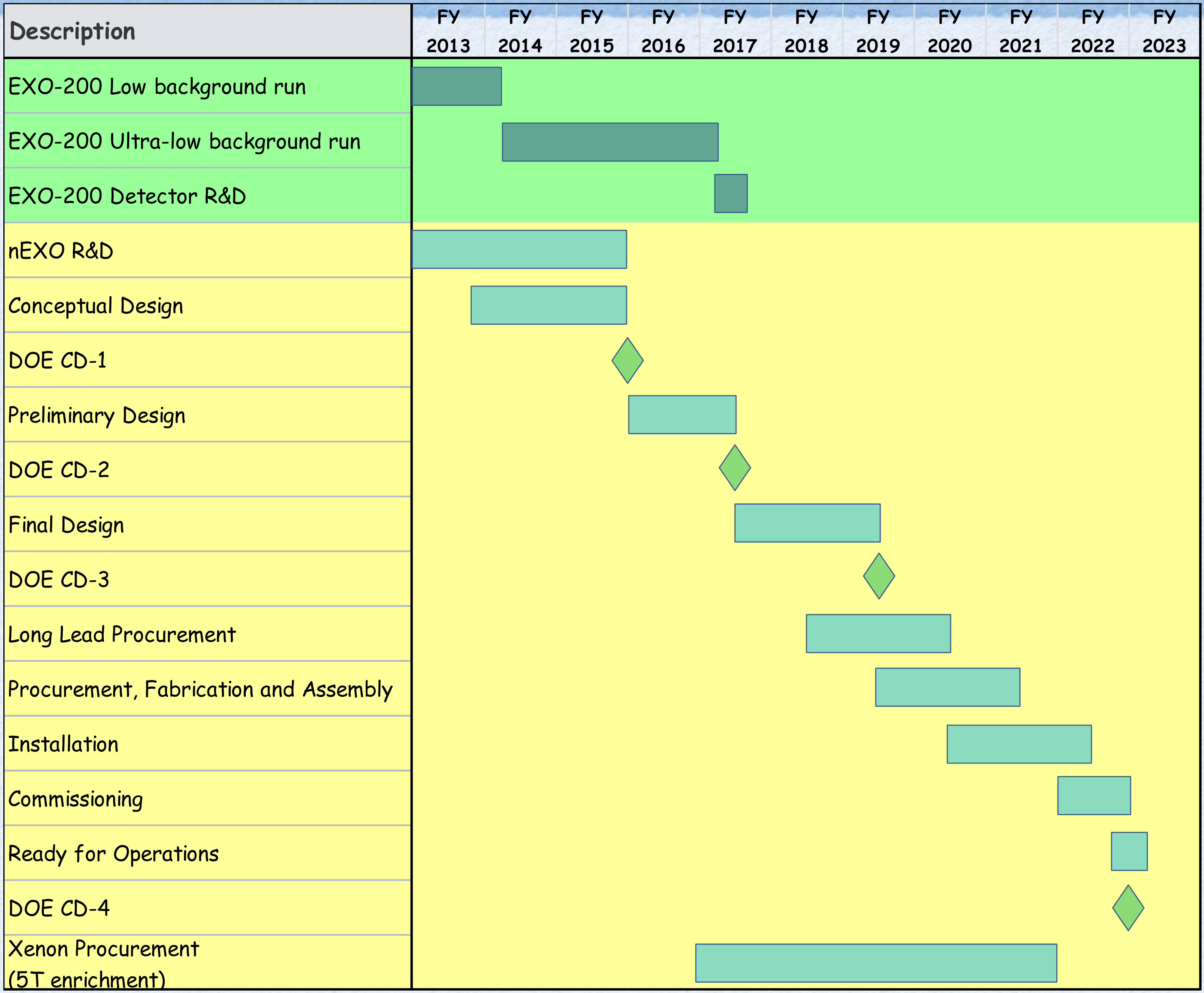


Neutrino Mass Projections



Notional Time Schedule

EXO view!



Conclusion and Outlook

- **EXO's Search for Lepton Number Violation:**
  - One of the highest priority topics in Nuclear and Particle Physics
  - EXO-200 made the first measurement of the ^{136}Xe 2νββ half-life
  - EXO-200 has made significant inroads in the 0νββ search
  - EXO-200 has recently made the most accurate ever measurement of any 2νββ half-life
  - nEXO plans to build on this success and aggressively reach for the inverted hierarchy scale of neutrino masses
- **Personal Remark**
  - depending on the success of Ba tagging R&D, the performance of the TPC and related hardware in an initial nEXO phase and the size of nuclear matrix elements, it is plausible to contemplate a long term strategy to attack the normal hierarchy with the EXO concept