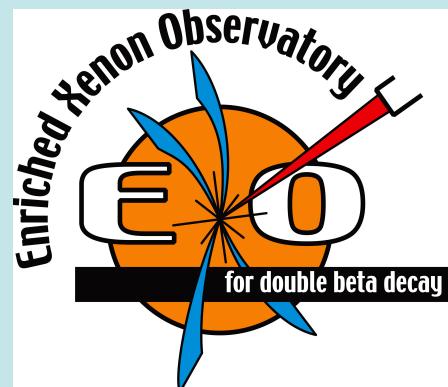


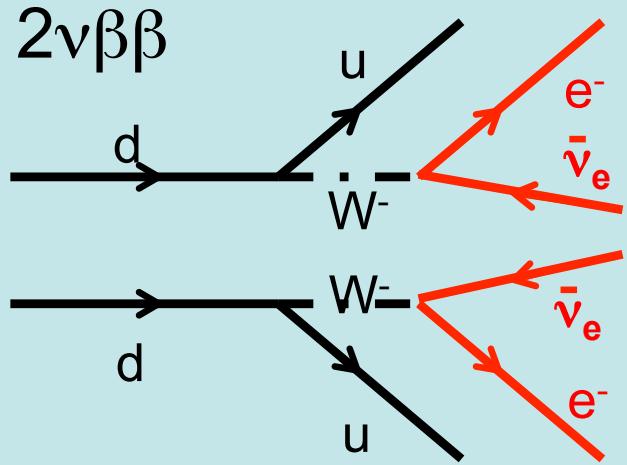
The EXO Search for Neutrinoless Double Beta Decay

Kevin Graham - Carleton University
for the EXO Collaborations

CAP Edmonton, June 17, 2015

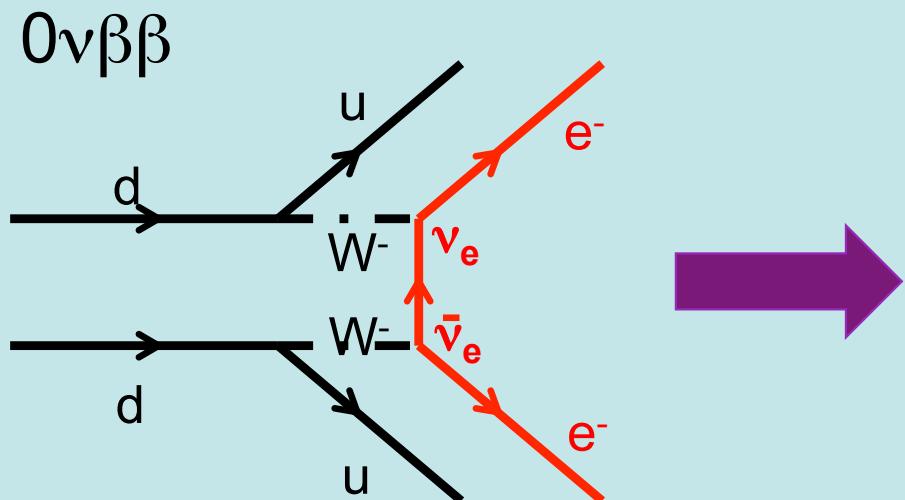


Neutrinoless Double Beta Decay



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

G = phase space factors (easy)
 $|M|$ = nuclear matrix elements (hard)
 $m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$

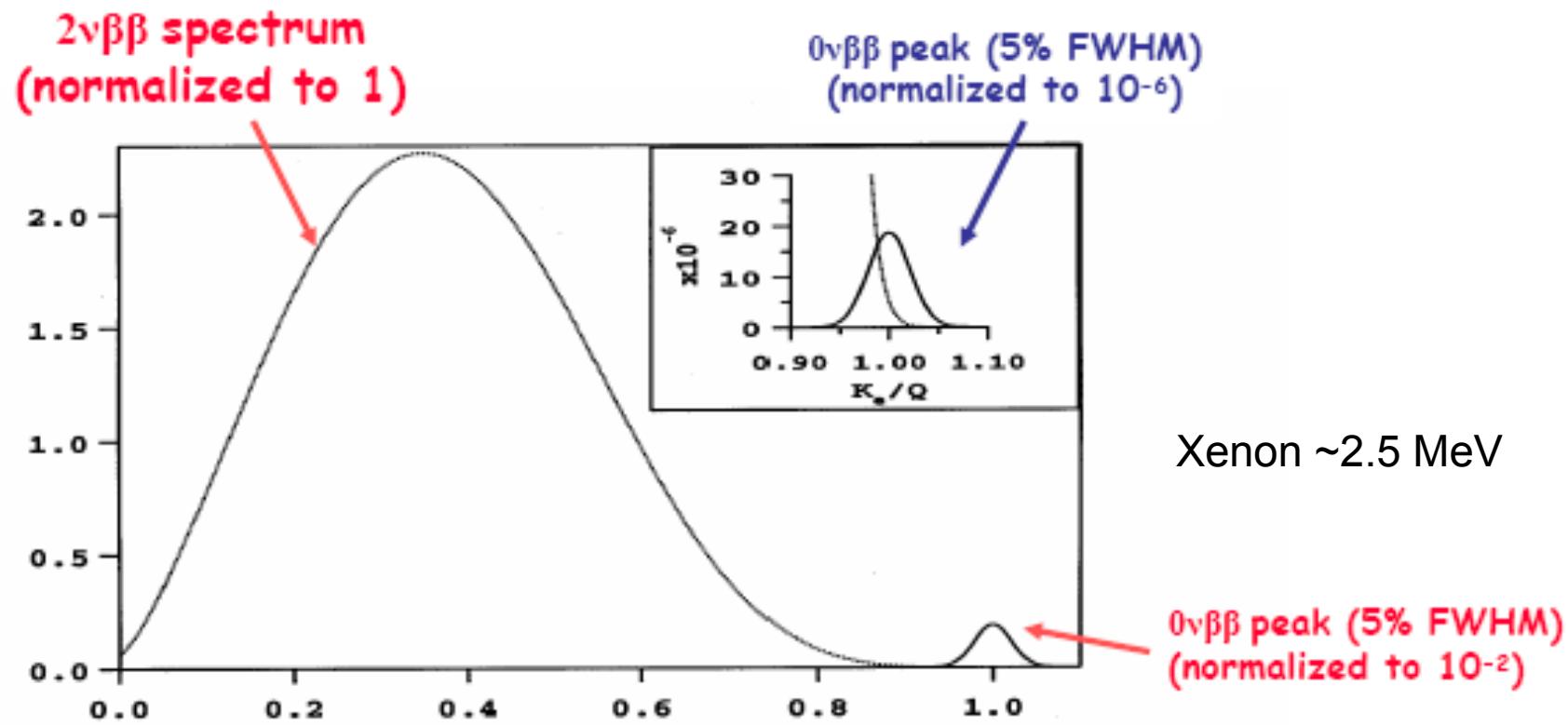


are neutrinos Majorana particles?
 $\Delta L=2$ lepton number violation?
 neutrino mass scale
 neutrino mass hierarchy

Double Beta Decay of ^{136}Xe



- search for excess of events at sum energy of the electrons ~ 2.5 MeV
- key is to have extremely low backgrounds in that energy range



EXO Program

- EXO-200
 - liquid phase time projection chamber at WIPP
 - a number of published and submitted results
 - status and plans at WIPP (renew running with upgrades)
- nEXO
 - developing next generation 5-tonne detector
 - liquid-phase with improved detector response
 - sensitivity to inverted hierarchy
- Barium tagging
 - continuing to pursue both gas and liquid phase options
 - laser spectroscopic tag suitable for either case

Canadian Contingent Growing!

- Carleton University
 - Razvan Gornea (joint TRIUMF...joining this summer), Kevin Graham, Thomas Koffas, David Sinclair
 - 2 RAs, 4 graduate students, undergrads, and technical staff
- Laurentian University
 - J. Farine, U. Wichoiski, B. Cleveland (SNOLAB Sen. RS),
 - 1 RA, 1 graduate student, undergrads, and technical staff
- McGill University
 - Thomas Brunner (joint TRIUMF...joining this summer)
- TRIUMF
 - Jens Dilling, Reiner Kreuken, Fabrice Retiere
 - students and technical staff

Canadians Playing Lead Roles

- EXO-200
 - analysis coordinator for first physics results (K Graham)
 - shift coordinator (B Mong)
 - energy calibration group coordinator (C Liccardi)
 - fitting group coordinator (C Liccardi)
 - chair of Scientific Board (J Farine)
 - shift experts (Carleton student contributed ‘most shifts’ in a recent year)
- nEXO
 - light detector systems coordinator (F Retiere)
 - simulation group coordinator (K Graham)
 - radon measurement and control (J Farine)
 - chair of Scientific Board (D Sinclair)
 - members of Executive Committee (F Retiere, D Sinclair)
- Ba Tagging
 - T Brunner, J Dilling, R Gornea, T Koffas, D Sinclair

The EXO-200 Collaboration



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

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Colorado State University, Fort Collins CO, USA - C. Chambers, A. Craycraft, W. Fairbank, Jr., T. Walton

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Duke University, Durham NC, USA - P.S. Barbeau

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

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Laurentian University, Sudbury ON, Canada - B. Cleveland, A. Der Mesrobian-Kabakian, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, C. Hall

University of Massachusetts, Amherst MA, USA - J. Abdollahi, S. Johnston, K. Kumar, A. Pocar, D. Shy

IBS Center for Underground Physics, Daejeon, South Korea - D.S. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, T. Daniels, J. Davis, A. Dragone, K. Fouts, R. Herbst, A. Johnson, K. Nishimura, A. Odian, C.Y. Prescott, A. Rivas, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen

University of South Dakota, Vermillion SD, USA, - R. MacLellan

Stanford University, Stanford CA, USA - T. Brunner, J. Chaves, R. DeVoe, D. Fudenberg, G. Gratta, M. Jewell, S. Kravitz, D. Moore, I. Ostrovskiy, A. Schubert, K. Twelker, M. Weber

Stony Brook University, SUNY, Stony Brook, NY, USA - K. Kumar, O. Njoya, M. Tarka

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

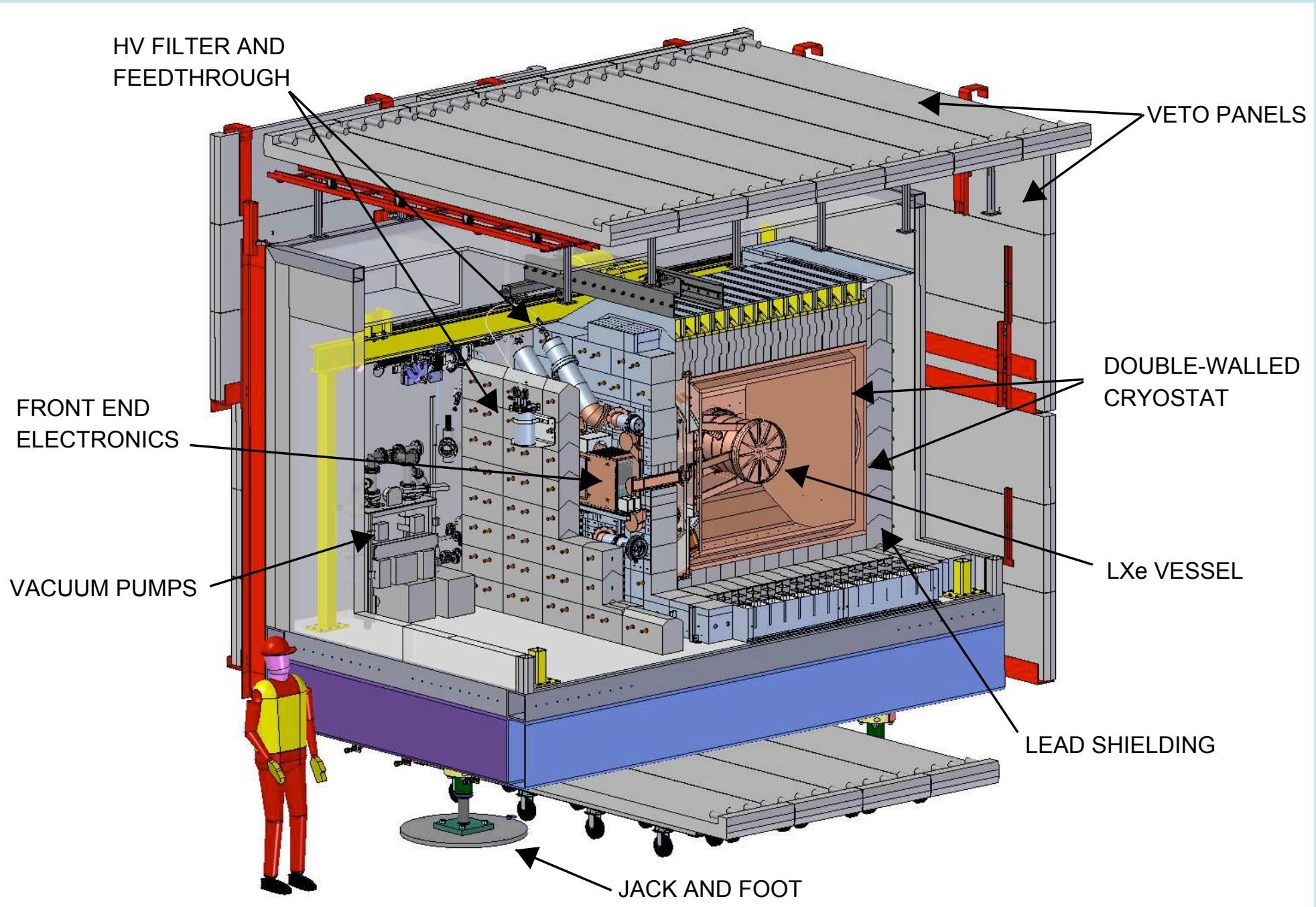
TRIUMF, Vancouver BC, Canada - J. Dilling, R. Krücken, F. Retière, V. Strickland

EXO-200 at WIPP



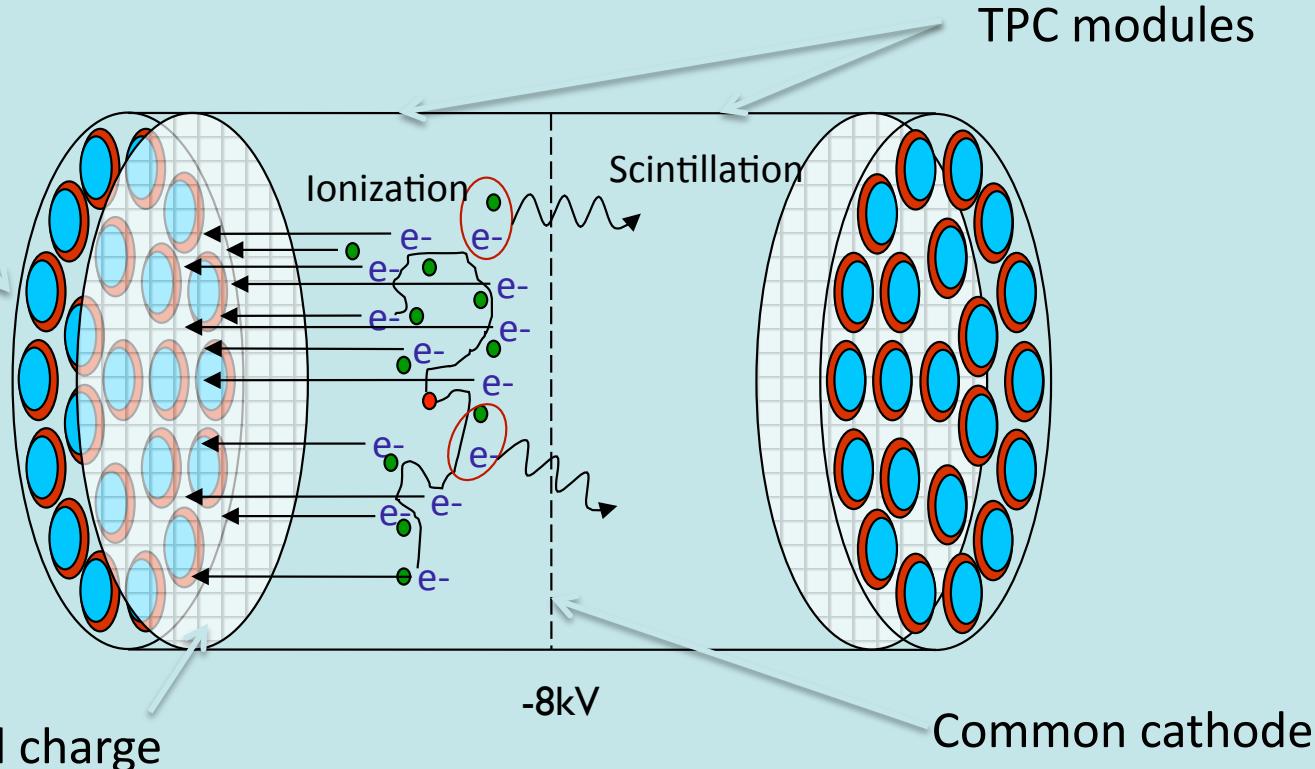
Depth of 655m (1650m.w.e.)

EXO-200 Detector



EXO200: Liquid Xenon (~ 200 kg) Time Projection Chamber

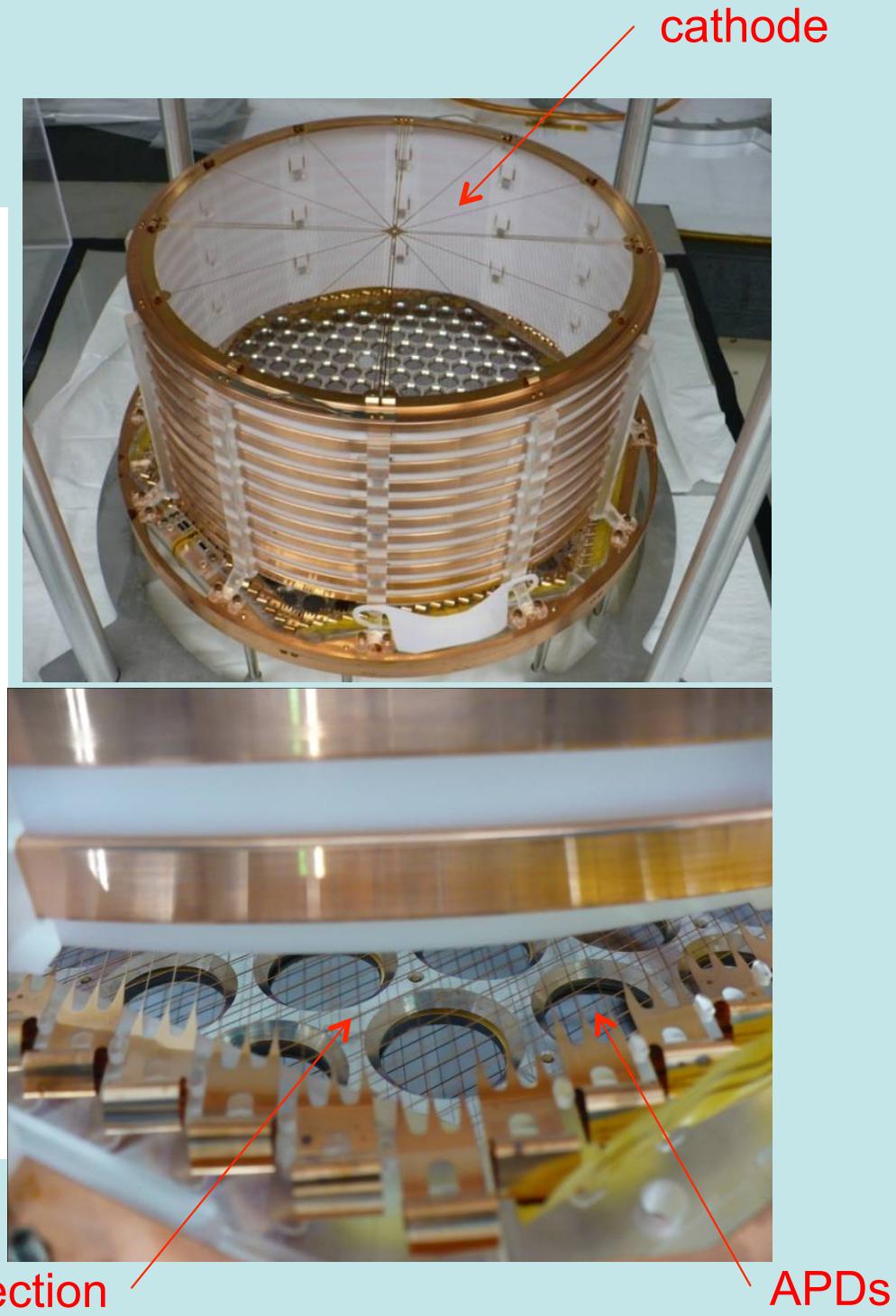
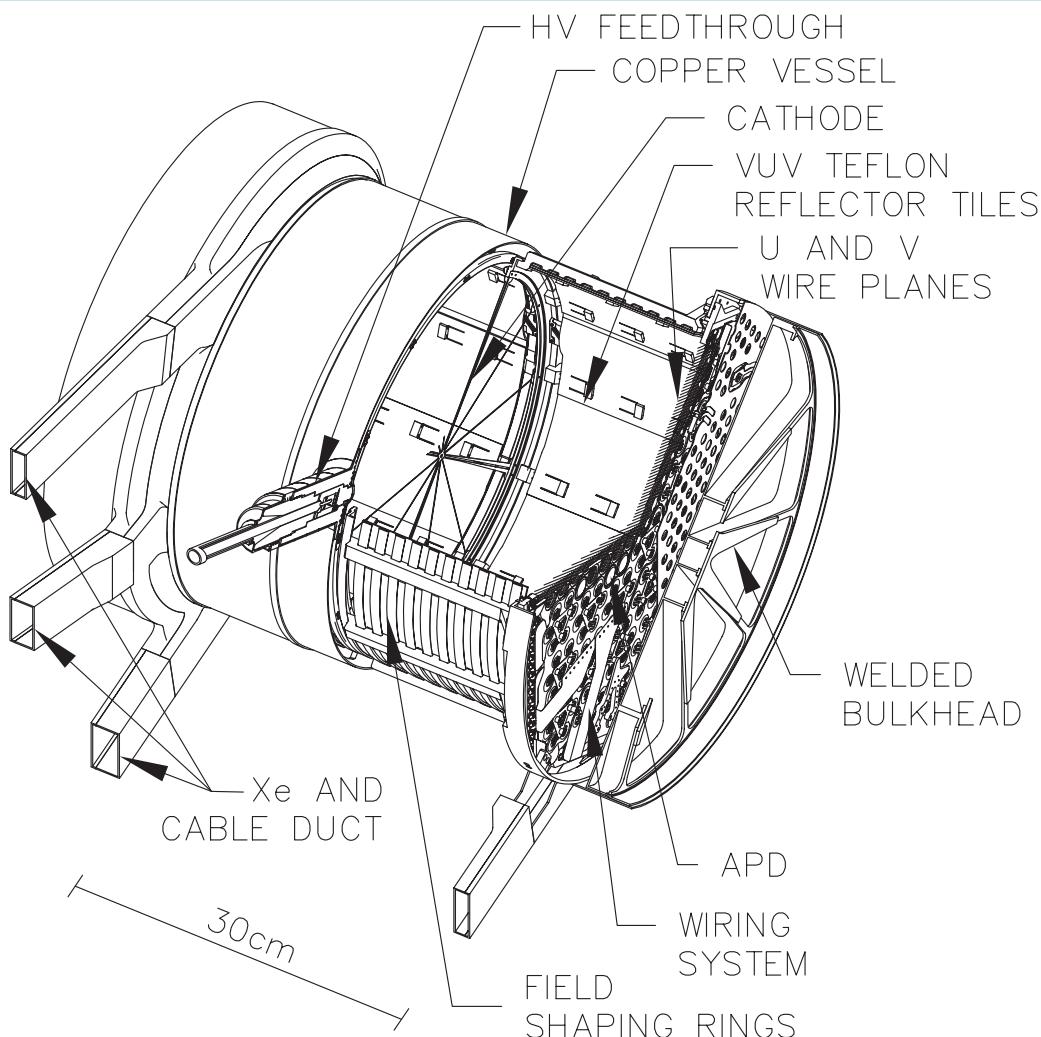
Avalanche photodiode (APD)
array observes
prompt scintillation



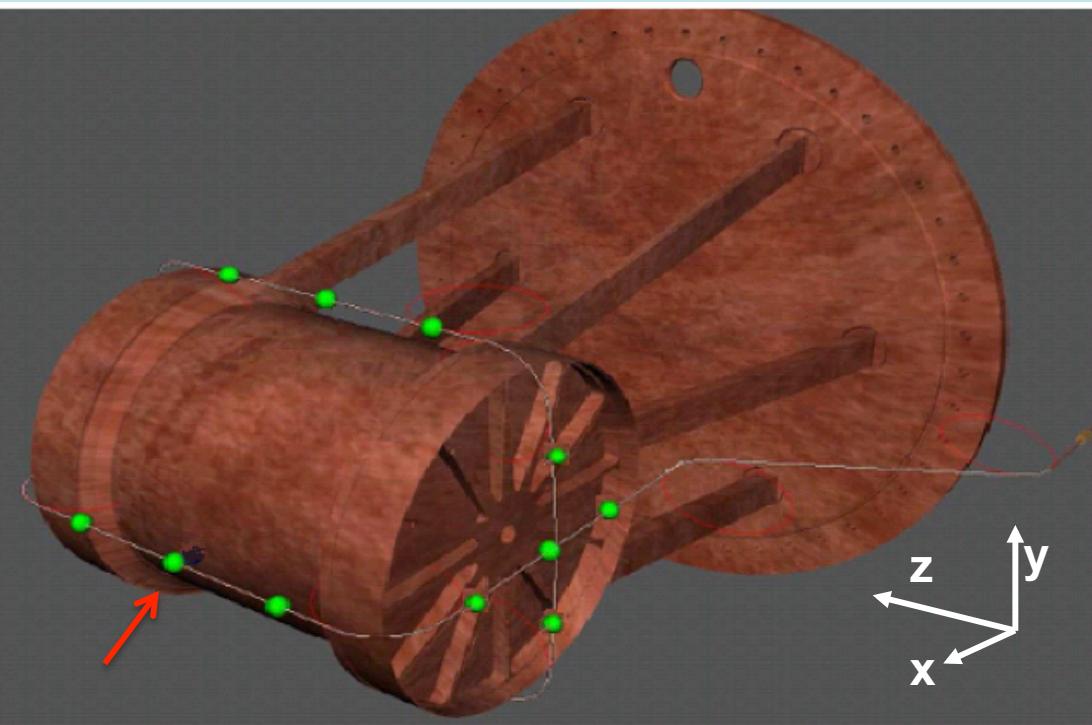
Crossed shielding and charge
collection grids give x,y position
z measured from timing

- Measure both **ionization (wires)** and **scintillation (APDs)**
- Event energy from the combination of ionization and scintillation
- reject some gamma backgrounds because Compton scattering results in multiple energy deposits

Detector Construction



Calibration System - Laurentian

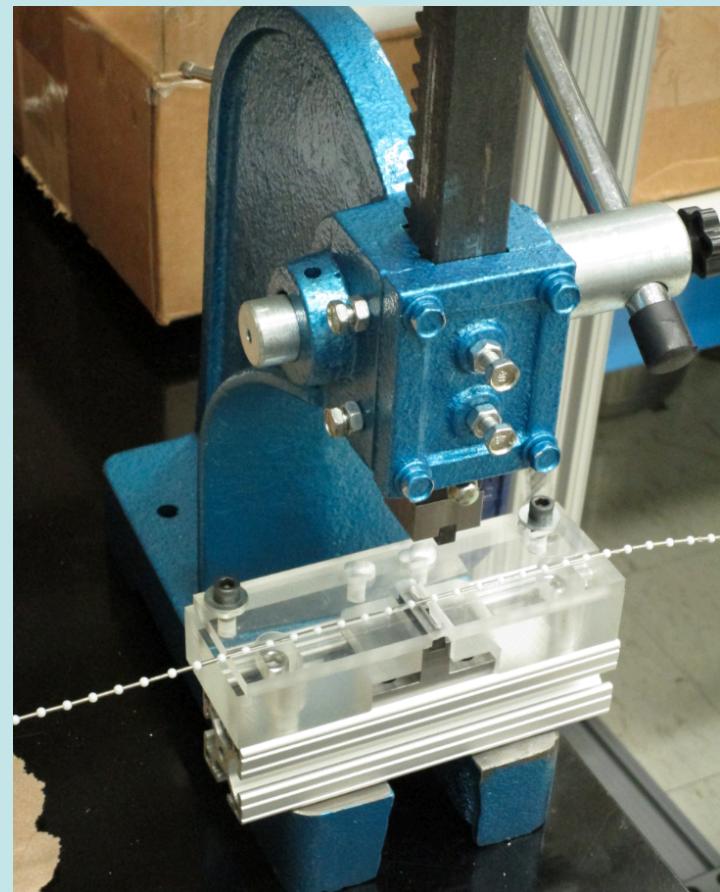
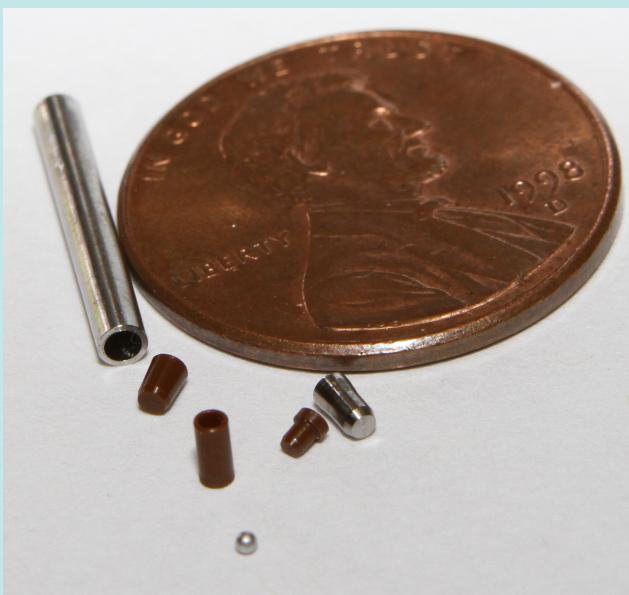


Calibration source locations

Sources:

^{137}Cs , ^{60}Co , ^{228}Th

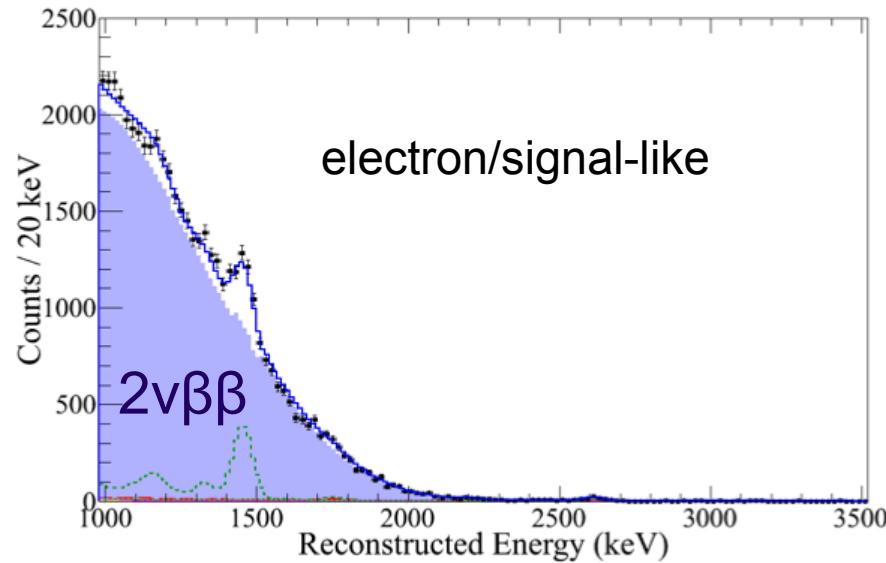
Custom designed,
miniature source



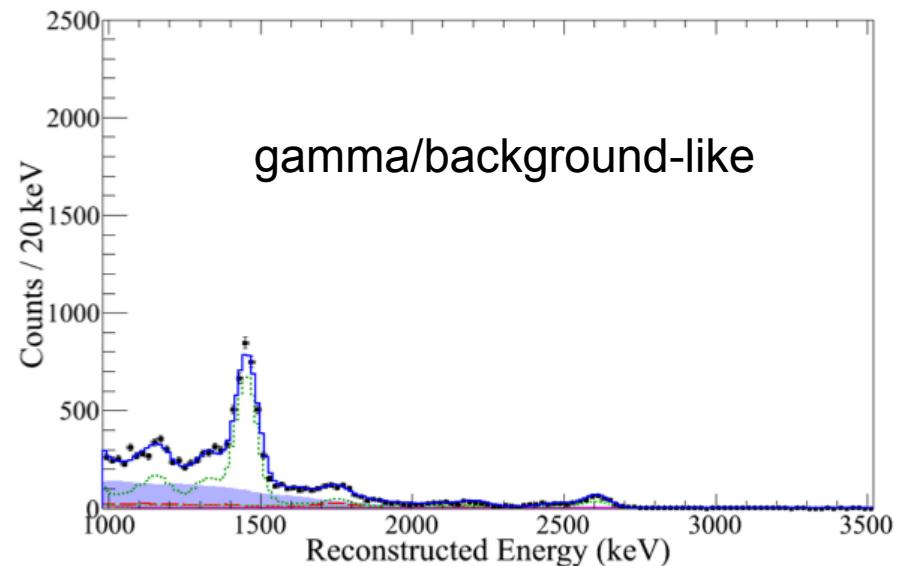
Background Rejection

Low Background Data

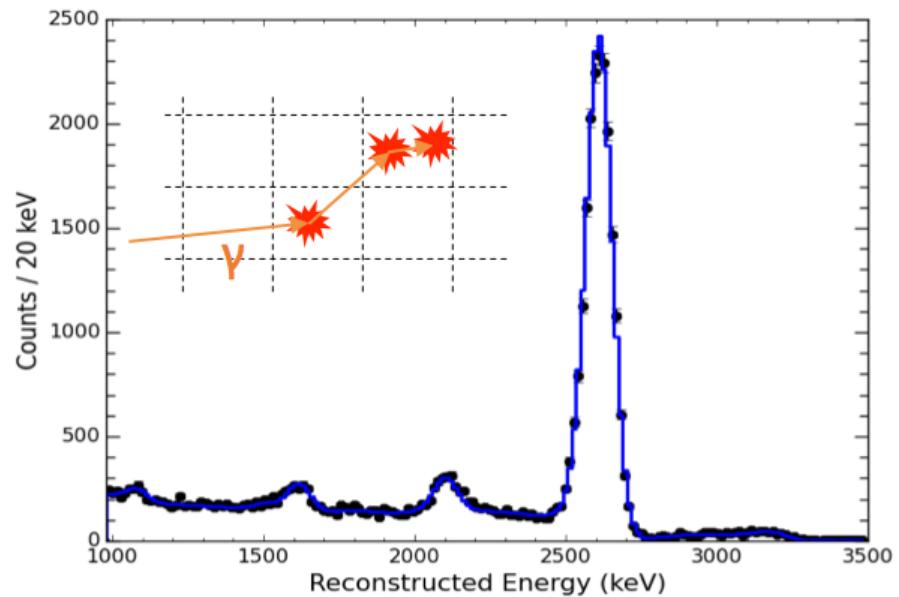
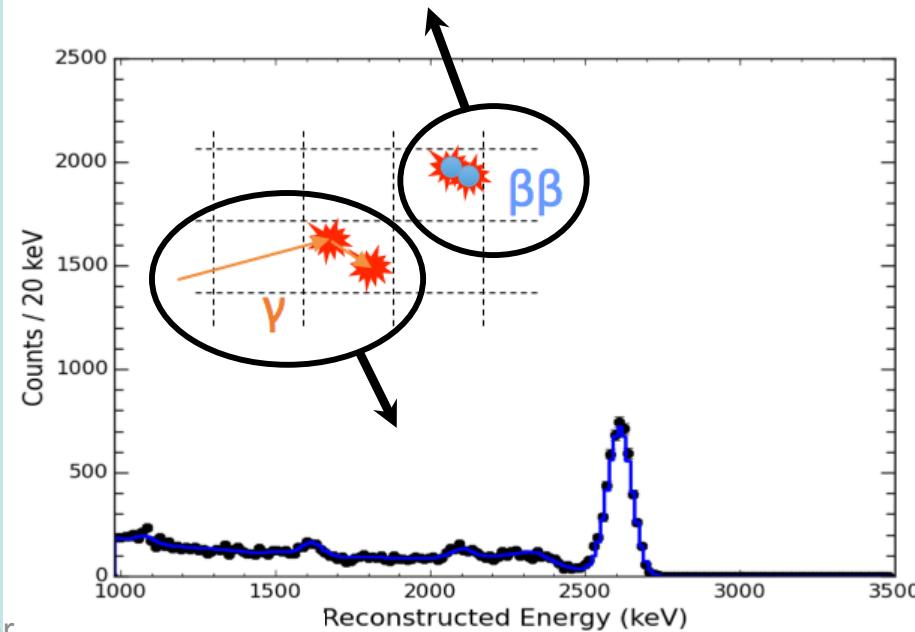
Single Site (SS)



Multiple Site (MS)

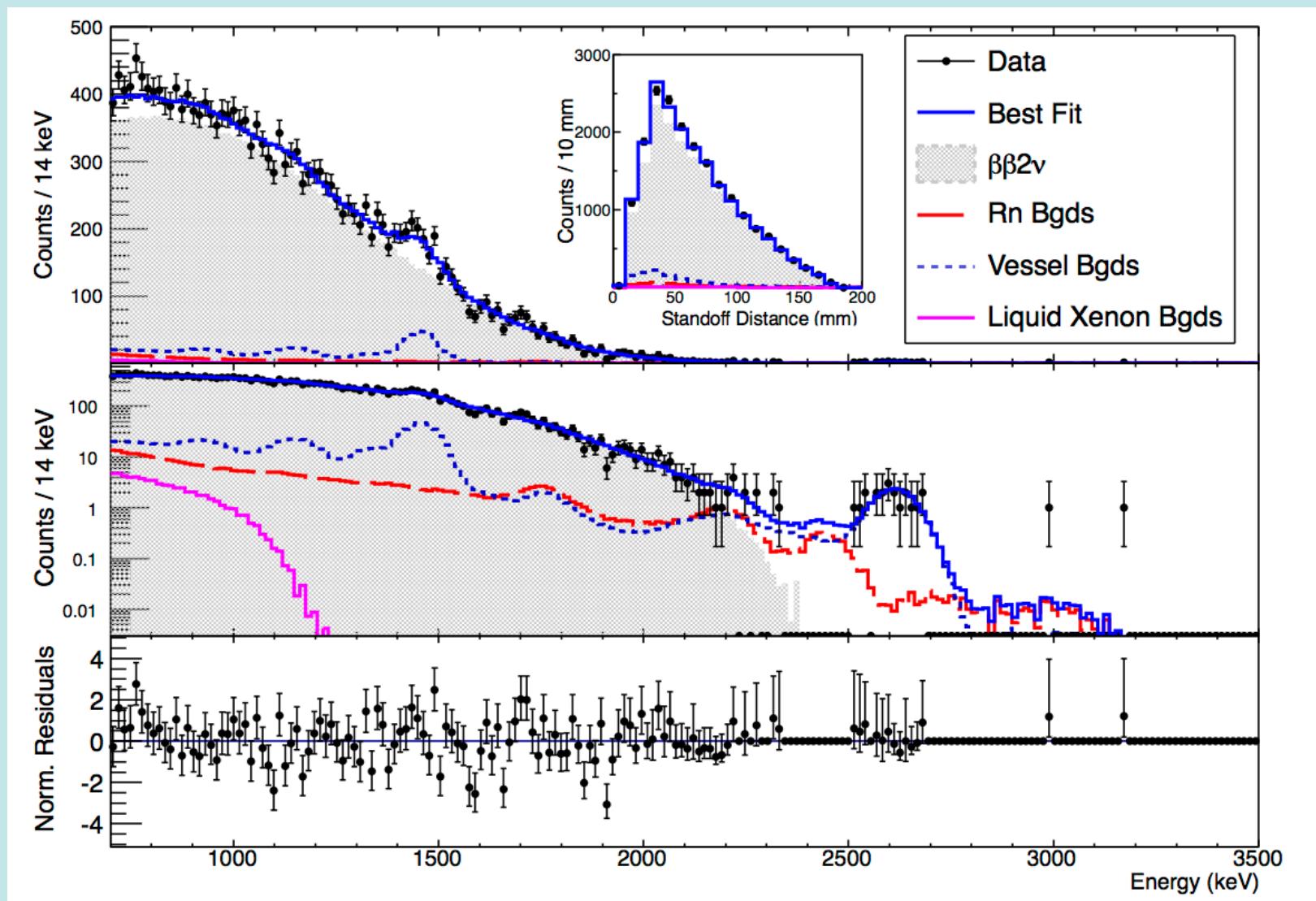


2²⁸Th Calibration Source



$2\nu\beta\beta$ Update Paper (2013)

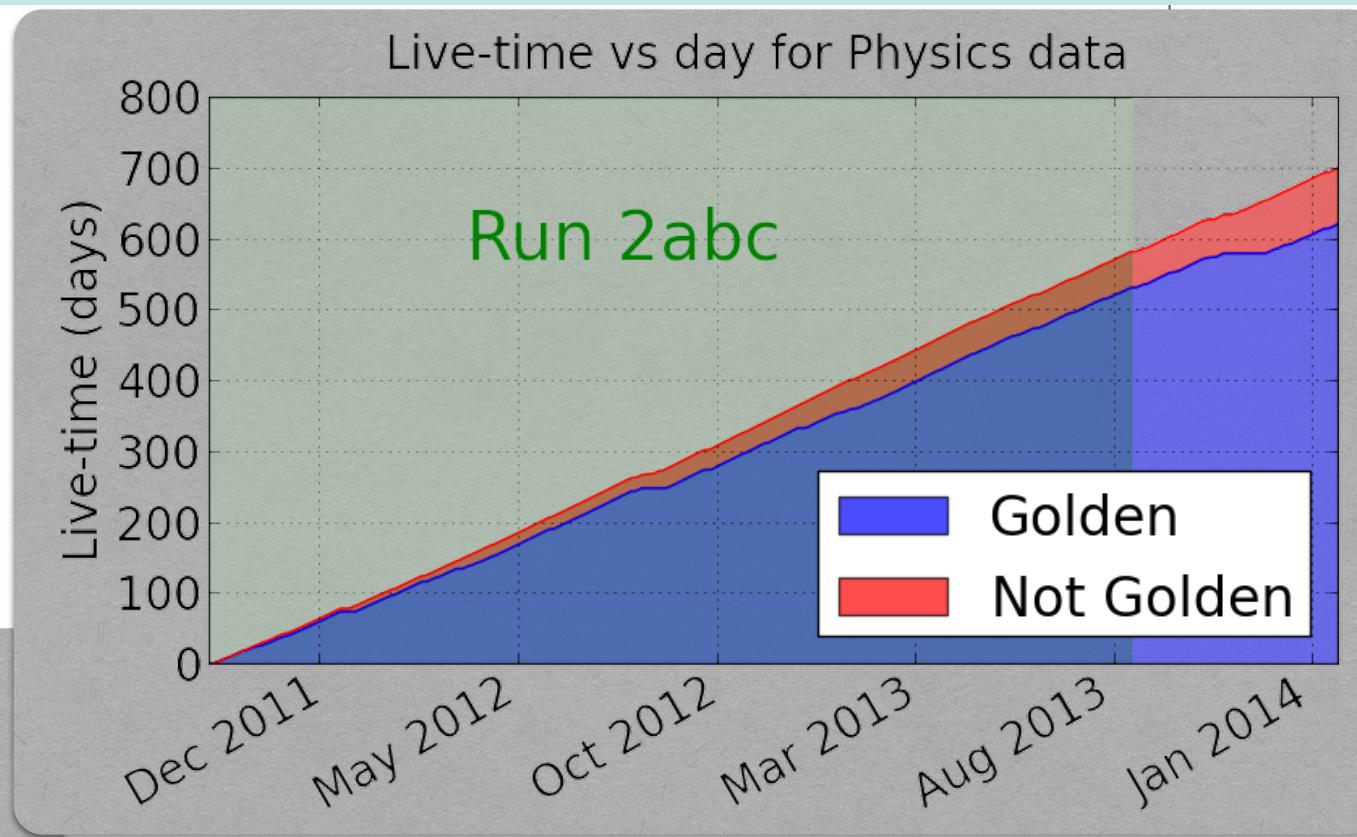
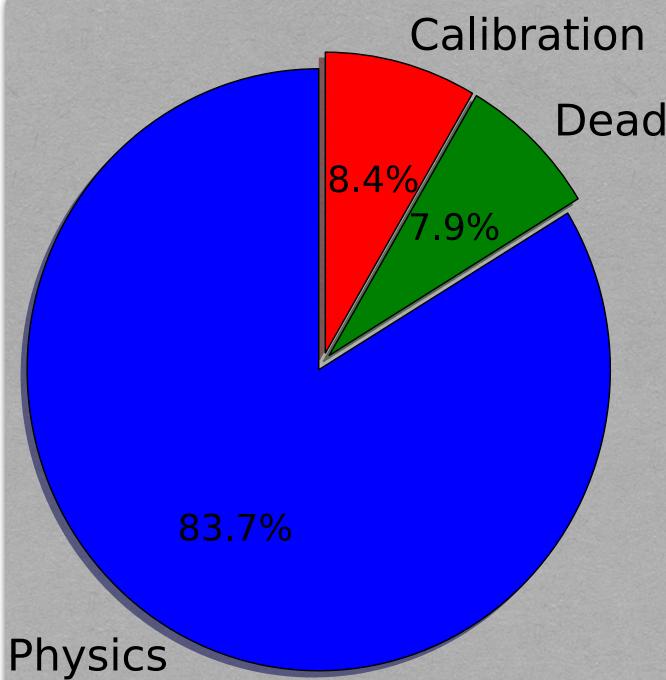
$$2\nu\beta\beta \quad T_{1/2} = (2.165 \pm 0.016 \text{ stat} \pm 0.059 \text{ sys}) \times 10^{21} \text{ yr}$$



Updated $0\nu\beta\beta$ Dataset

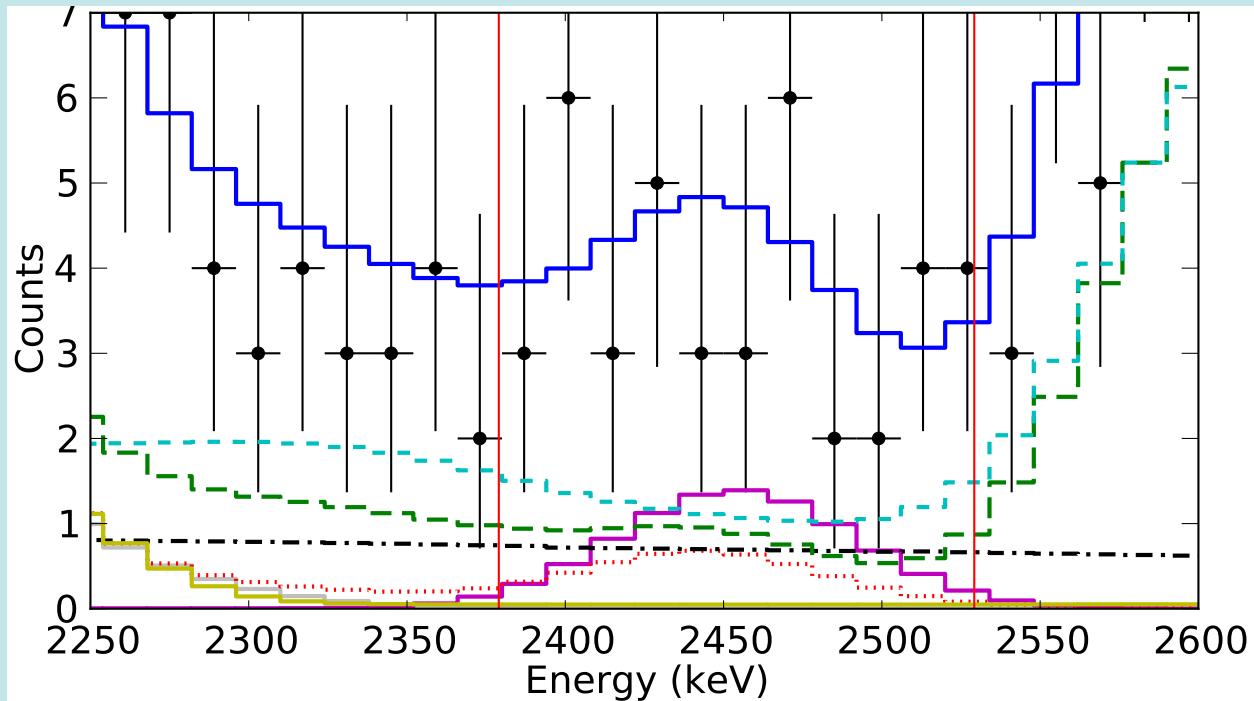
nature

(12 June 2014, online 4 June)
doi:10.1038/nature13432



Accumulation of “Golden” data
 447.60 ± 0.01 days livetime
($100 \text{ kg}\cdot\text{yr}$, $736 \text{ mol}\cdot\text{yr}$ ^{136}Xe
exposure)
(6 Oct 2011- 1 Sep 2013)

$0\nu\beta\beta$ Search Update (2014)



- Data
- Best Fit
- Rn
- LXe bgd
- n -capture
- ^{232}Th (far)
- Vessel
- $0\nu\beta\beta$
- $2\nu\beta\beta$

Backgrounds in $\pm 2\sigma$ ROI

Th-228 chain 16.0

U-232 chain 8.1

Xe-137 7.0

Total 31.1 ± 3.8

From profile likelihood:

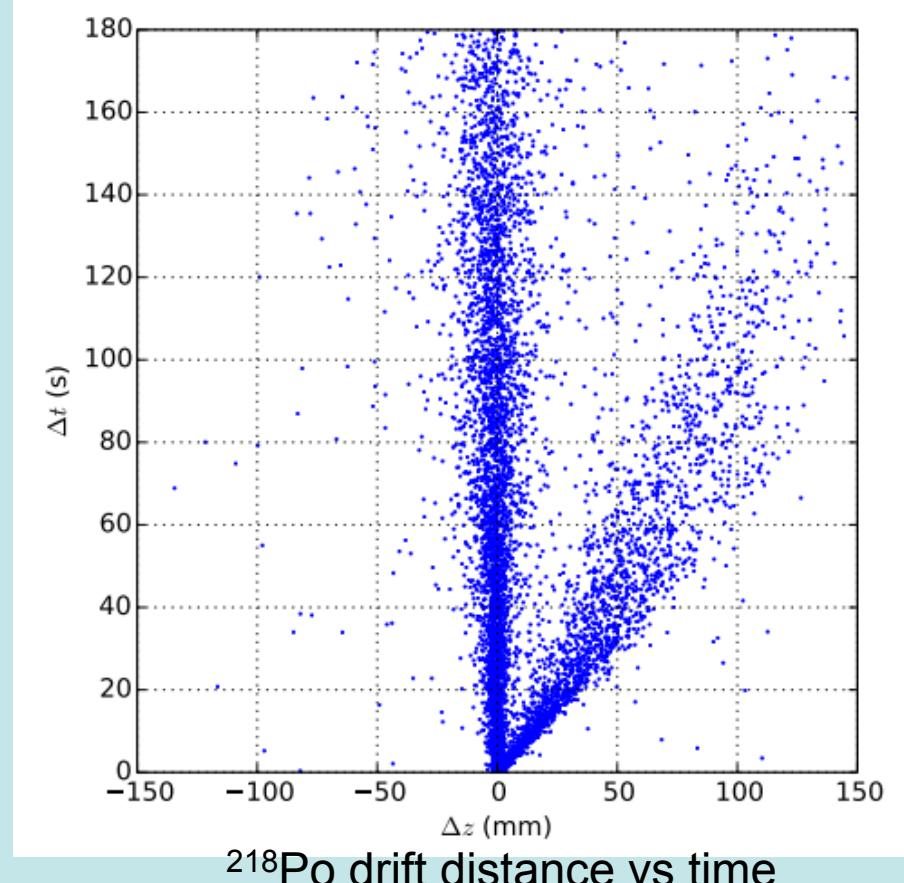
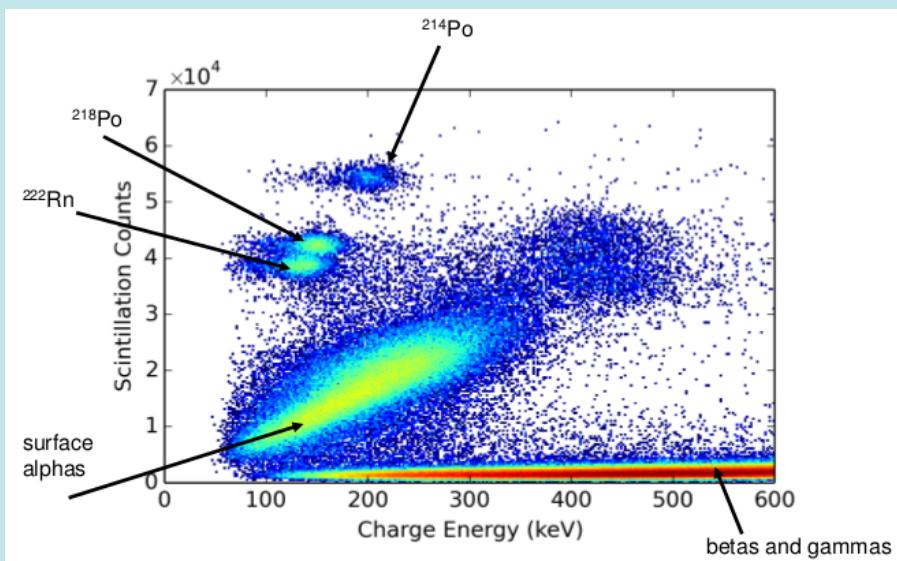
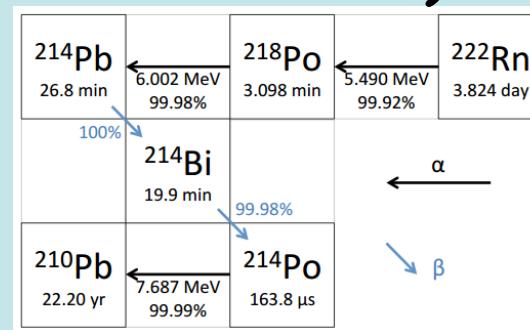
$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25} \text{ yr}$
 $\langle m_{\beta\beta} \rangle < 190 - 450 \text{ meV}$
(90% C.L.)

Nature (2014)
doi:10.1038/nature13432

Ion Studies Using Alpha Decays

(Brian Mong - Laurentian)

- ^{218}Po and ^{214}Bi created from ^{222}Rn decays can be neutral or charged.
- By measuring drift velocity, the fractions of charged ^{218}Po and ^{214}Bi were estimated.⁵
- $^{218}\text{Po}^+$: $50.3 \pm 3.0\%$
- $^{214}\text{Bi}^+$: $76.4 \pm 5.7\%$



⁵

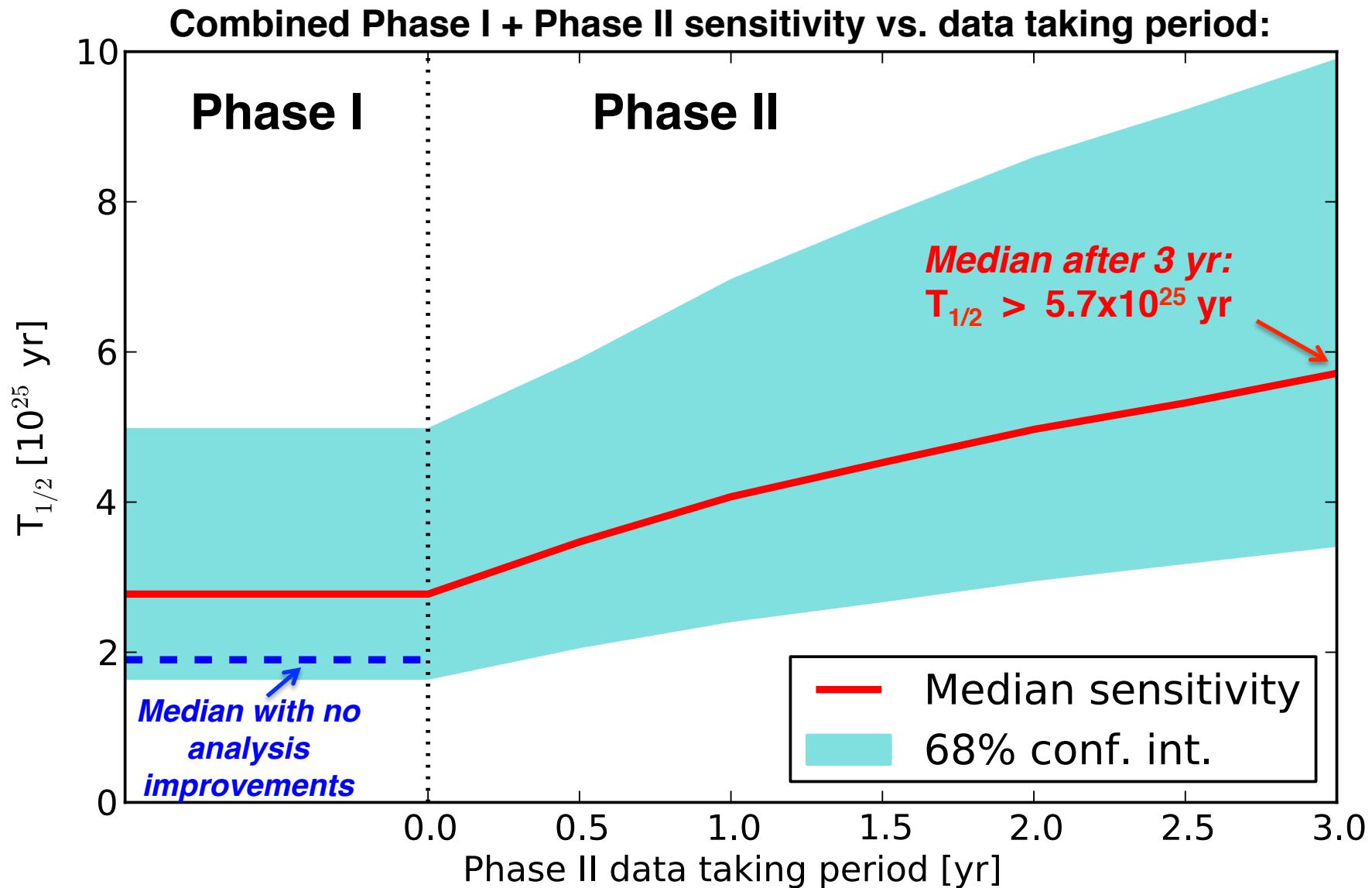
J.B. Albert, et al., "Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200", to be submitted to PRX, arxiv:1506.00317

EXO-200/WIPP Update

- Feb. 5 2014: - Fire in WIPP underground
- Feb. 14 2014: - Airborne radiological event
- Feb. 2014: - Xe was successfully recovered (with remote access as designed), followed by controlled warm up of TPC/Cryostat.
- Sept. 2014: lost underground power but regained access.
- Feb. 2015: power restored in
- Sample salt near the experiment shows virtually zero contamination from the radiological event
- Ongoing cleanup and equipment repair/replacement underway
- Aim to cool and fill TPC with LXe in the summer 2015
- Implement upgrades (electronics, air gap radon reduction, analysis)
- Data taking in the fall 2015
- 3-year run plan improved 0nbb sensitivity

Sensitivity vs. time

- For each of the toy MC distributions, also calculate the combined Phase I and Phase II sensitivity



The nEXO Collaboration



University of Alabama, Tuscaloosa AL, USA - T. Didberidze, M. Hughes, A. Piepke, R. Tsang

University of Bern, Switzerland - S. Delaquis, R. Gornea, T. Tolba, J-L. Vuilleumier

Brookhaven National Laboratory, Upton NY, USA - M. Chiu, G. De Geronimo, S. Li, V. Radeka, T. Rao, G. Smith, T. Tsang, B. Yu

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University of Illinois, Urbana-Champaign IL, USA - D. Beck, M. Coon, S. Homiller, J. Ling, J. Walton, L. Yang

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University of Massachusetts, Amherst MA, USA - J. Dalmasson, S. Johnston, A. Pocar

Oak Ridge National Laboratory, Oak Ridge TN, USA - L. Fabris, D. Hornback, R.J. Newby, K. Ziock

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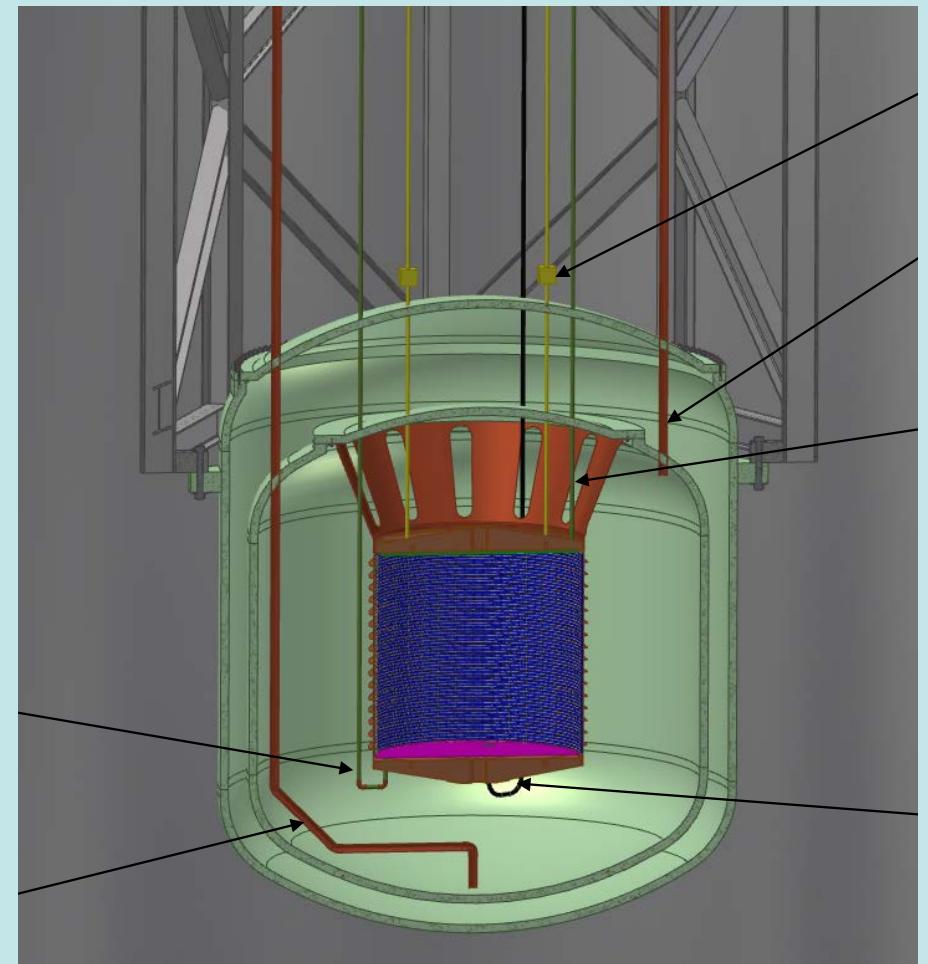
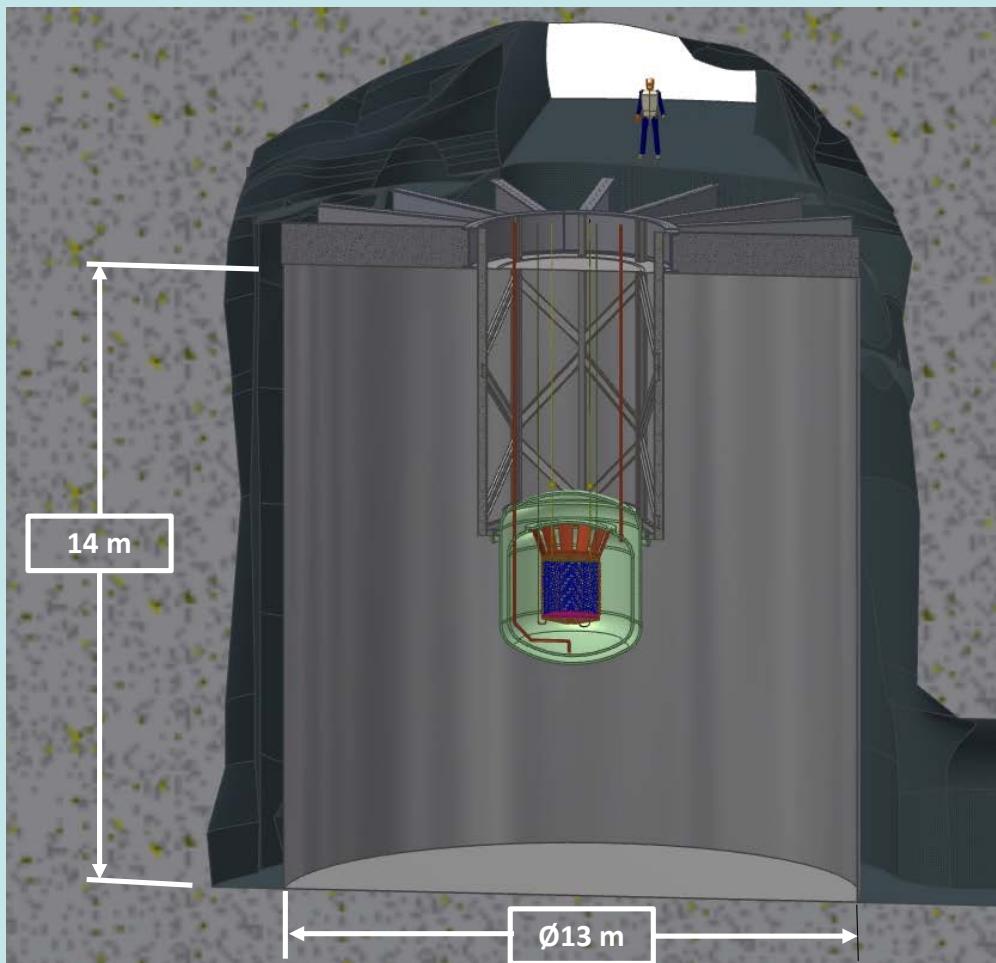
Stony Brook University, SUNY, Stony Brook, NY, USA - K. Kumar, O. Njoya, M. Tarka

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

TRIUMF, Vancouver BC, Canada - J. Dilling, P. Gumplinger, R. Krücken, F. Retière, V. Strickland

nEXO Detector Concept

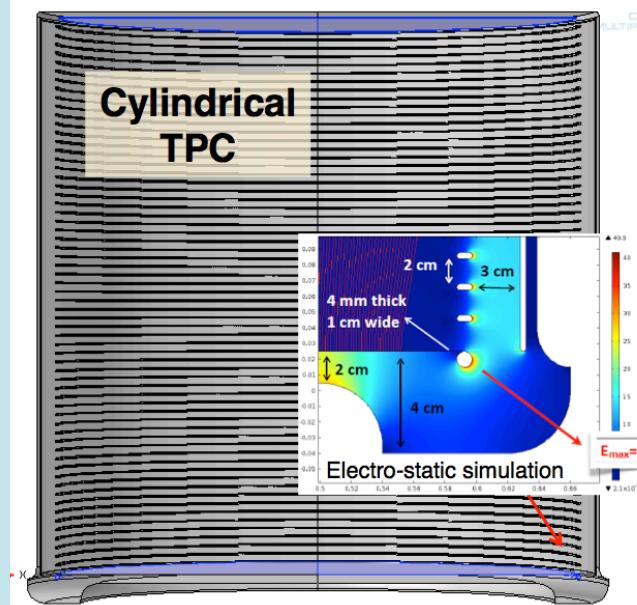
- follow success of EXO-200 with **key detector improvements**
 - reduced electronics noise
 - improved energy resolution ($\sim 1\%$) (improved light coverage)
 - finer charge readout granularity (better multi-site ID)
 - increased self-shielding (very low backgrounds in central region)



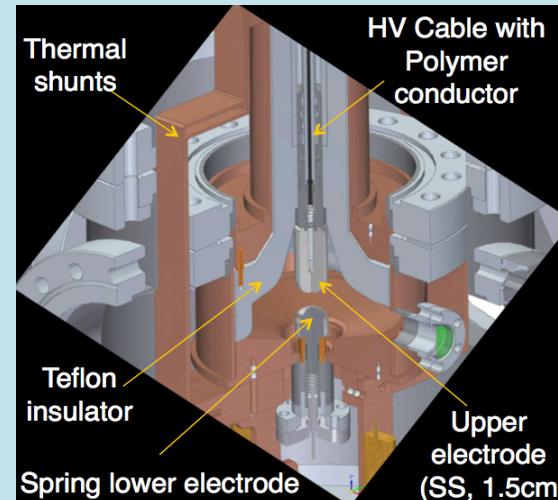
R&D towards nEXO

- examples of R&D in progress for several detector components:
 - Field cage design and electrostatic simulations
 - High voltage testing and prototyping
 - Characterization of light detectors (Silicon Photo Multipliers)
 - Design and testing of charge readout tiles

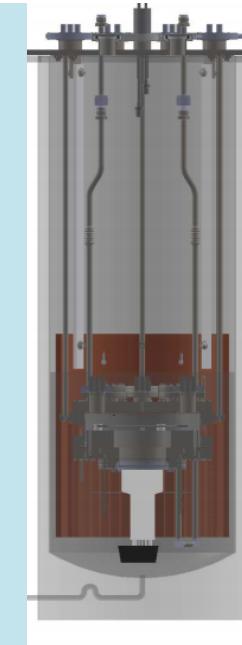
TPC E-field simulations:



HV testing setup:



Charge readout LXe test cell:



SiPMs:

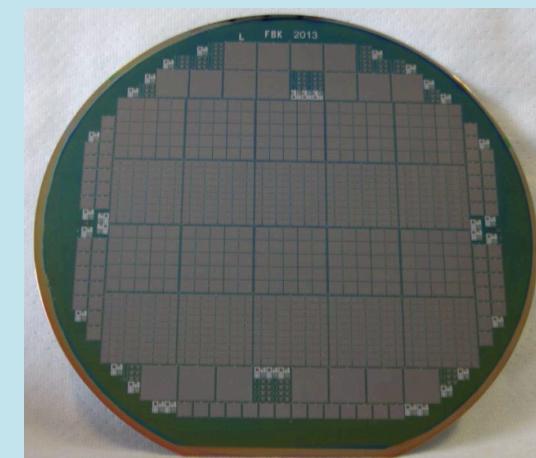
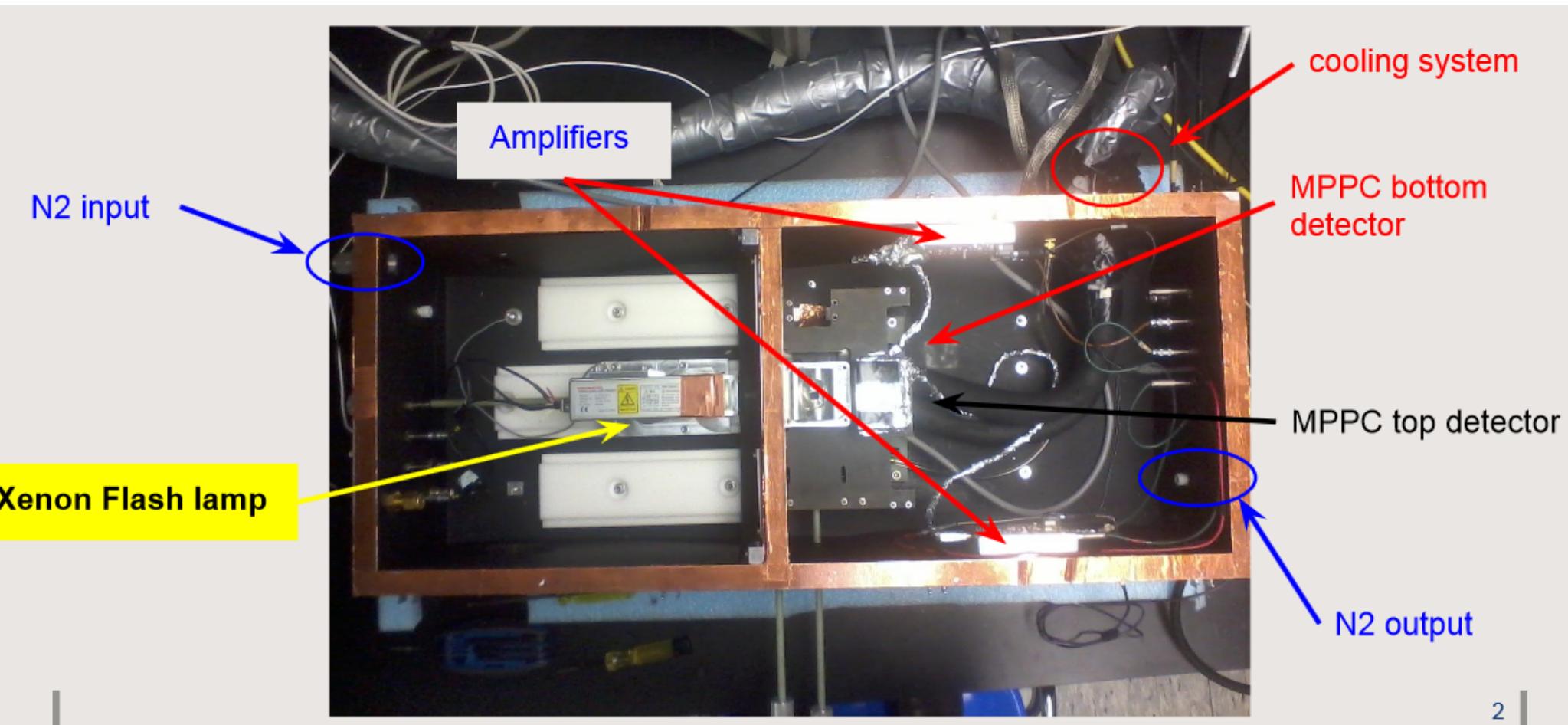


Photo-detector development for nEXO

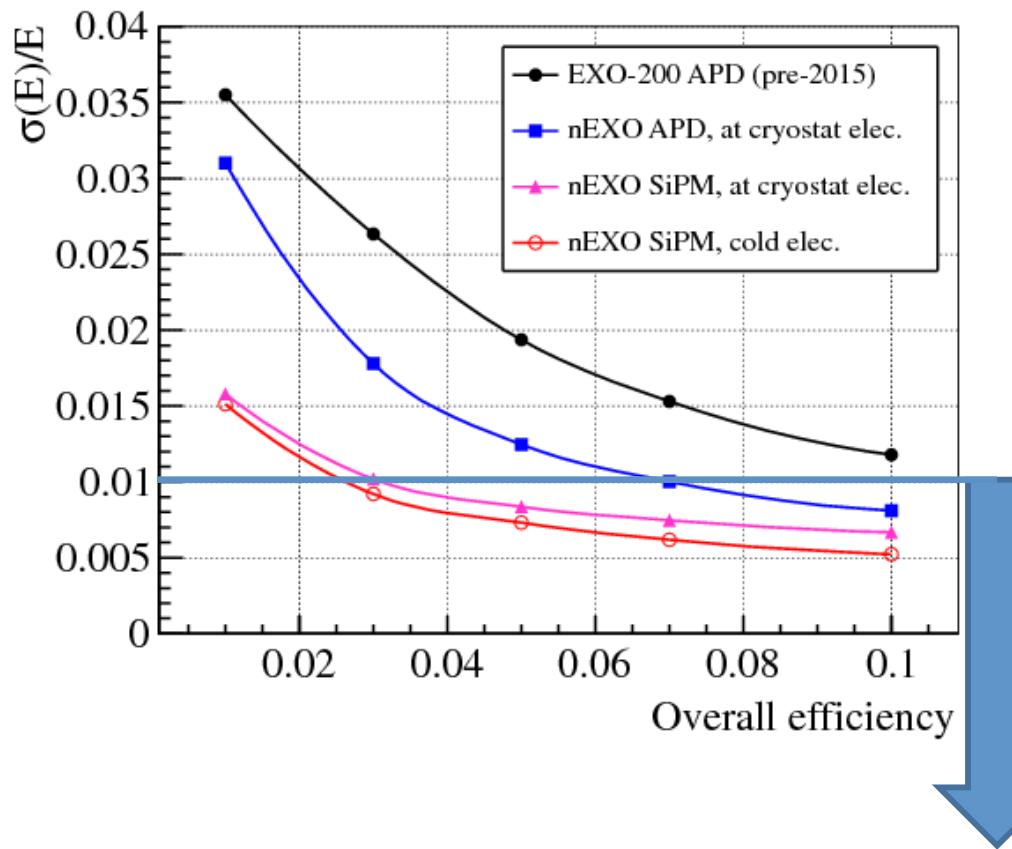
TRIUMF - Fabrice Retiere

- Goals: >3% overall photon detection efficiency
 - Guarantee less than 1% energy resolution at ${}^{36}\text{Xe}$ $0\nu\beta\beta$ energy
- Need photo-detector efficiency >15%
 - And very efficient mirrors
 - Dark noise and correlated noise should also be very small
- Need 4m² photo-detector area
 - Electronics challenge
- Canadian contribution
 - Leading photo-detector group
 - Investigating 3D integrated technology with U.Sherbrooke and Dalsa
 - Photo-detector test at TRIUMF
 - Focusing on rapid turn around characterization
 - Identify possible viable solutions
 - Then move to large area photo-detector investigation
 - First in gas/vacuum (next year)
 - Eventually in liquid Xenon

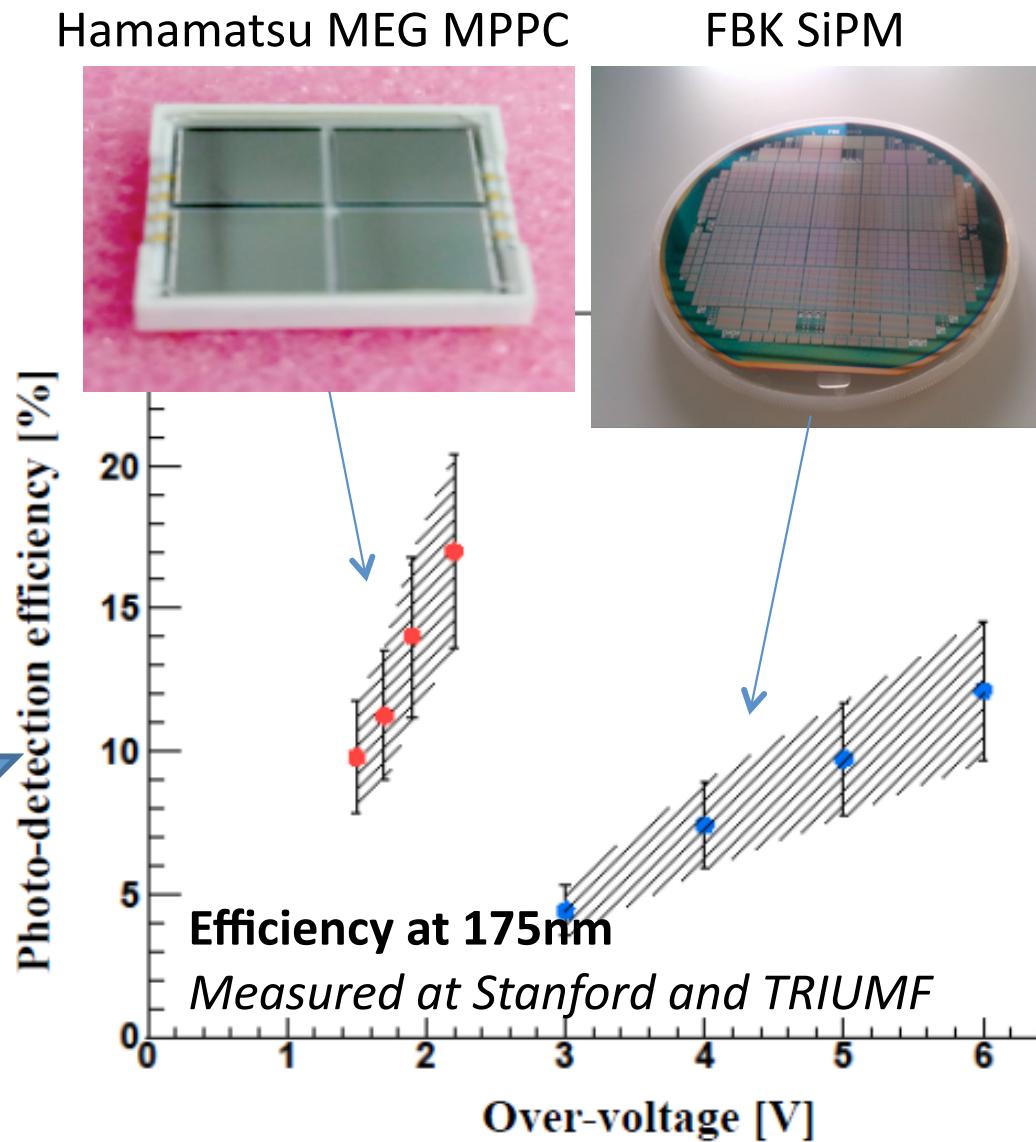
Photo-detector test setup at TRIUMF



nEXO photo-detector approaching the required efficiency



Better than 1% energy resolution required
Expected collection efficiency ~30%
Required photo-detector efficiency >15%



Calibration Tools and Radon Control for nEXO

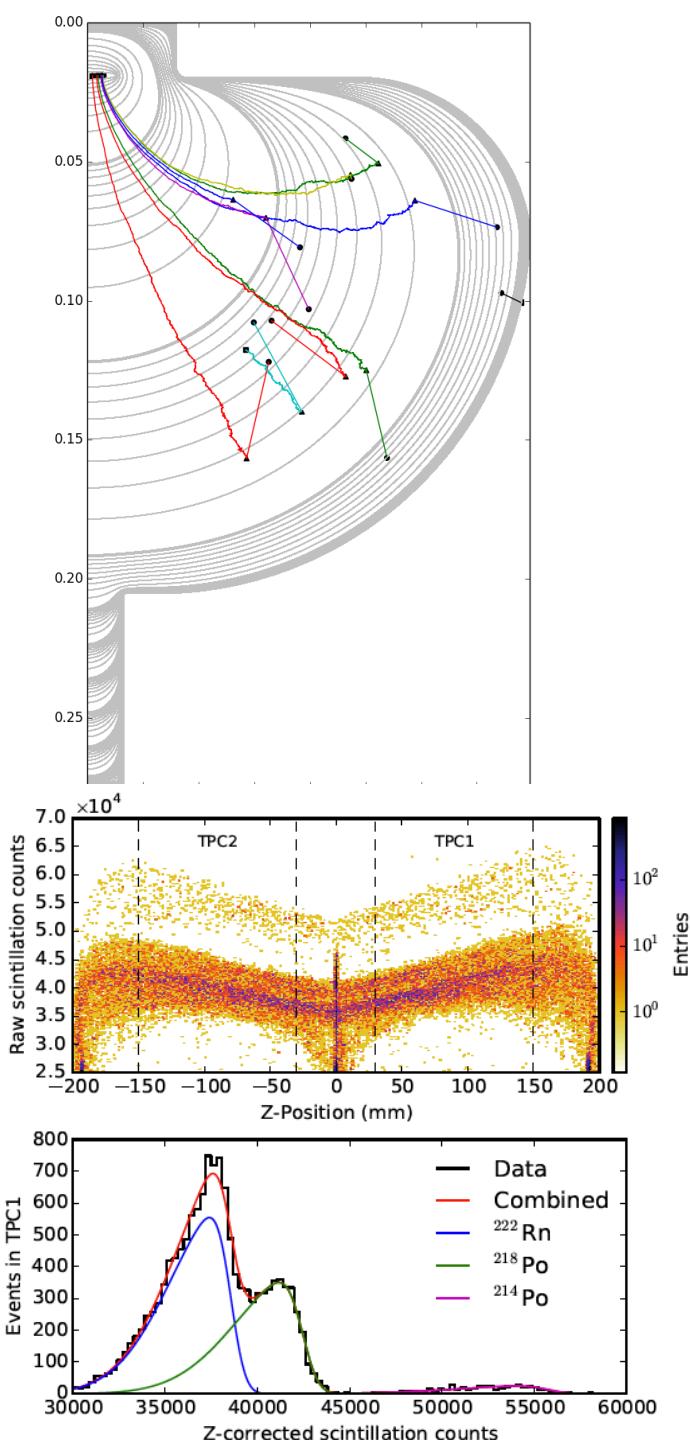
Laurentian - Jacques Farine

continued calibration hardware development

- R+D for external sources (g/n) + deployment system
- sources fab now 100% at LU, deployment system @ UdeM

radon mitigation

- material screening:
 - sensitivity at 5–10 ${}^A\text{Rn}/\text{day}$, A=222, 220, 219
 - array of 6 counters @ SNOLAB, 1 @ WIPP
- nEXO R+D:
 - in-line Rn trap for Xe (atm. p; high flow); built a copy of the EXO–200 recirc. pump for stability during tests
 - Rn counters with improved sensitivity:
 - larger detectors ($10 > 80 \text{ L}$) with lower BGND (0.1 cpd)
 - full physical model of Rn detector to support design
 - aggressive campaign to further reduce backgrounds



nEXO MC Simulation

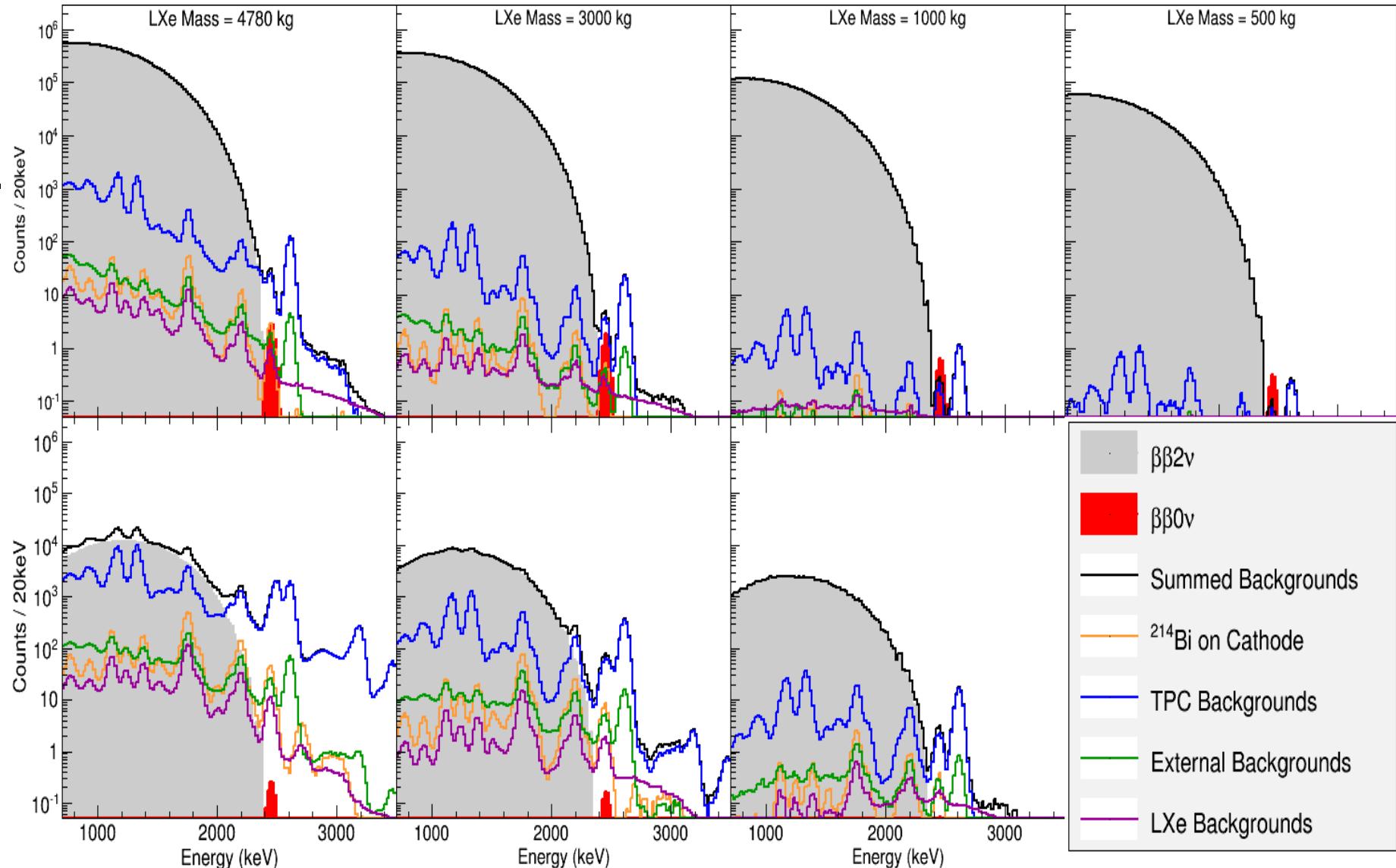
Carleton - Kevin Graham

- Assume measured activities for all detector materials (**JINST 7 (2012) P05010**)
- Have compared to EXO-200 data to confirm validity of these assumptions
- Measured background rate from EXO-200 is $B_{EXO-200} = 151 \pm 19 \text{ ROI}^{-1} \text{ ton}^{-1} \text{ yr}^{-1}$,
 $(\text{ROI} = Q_{\beta\beta} \pm 0.5 \cdot \text{FWHM})$ *Nature 510*, 229 (2014),
arXiv:1402.6956
- Agrees with predicted nEXO rate in outer 16.2 cm for same assumptions
- The following improvements over EXO-200 are assumed:
 - Improved energy resolution ($\sigma/Q_{\beta\beta} = 0.01$) (light collection + reduced noise)
 - Improved SS/MS discrimination (finer charge collection pitch)
 - Cu activity from improved sensitivity radio assay
 - Reduced ^{137}Xe rate at SNOLAB
 - Reduced ^{222}Rn density, longer time window in $^{214}\text{Bi}-^{214}\text{Po}$ coincidence cut
- Total nEXO background prediction in outer 16.2 cm: $B_{nEXO} = 3.7 \text{ ROI}^{-1} \text{ ton}^{-1} \text{ yr}^{-1}$
- Improvements give reduction of $\sim 40x$ in background in this background index relative to EXO-200

nEXO MC Simulations

- extensive GEANT4 simulations are being carried out to optimize nEXO
- reject backgrounds with: 1) multiplicity 2) self-shielding 3) energy spectrum
- use a multi-dimensional fit to optimize information use

single-site



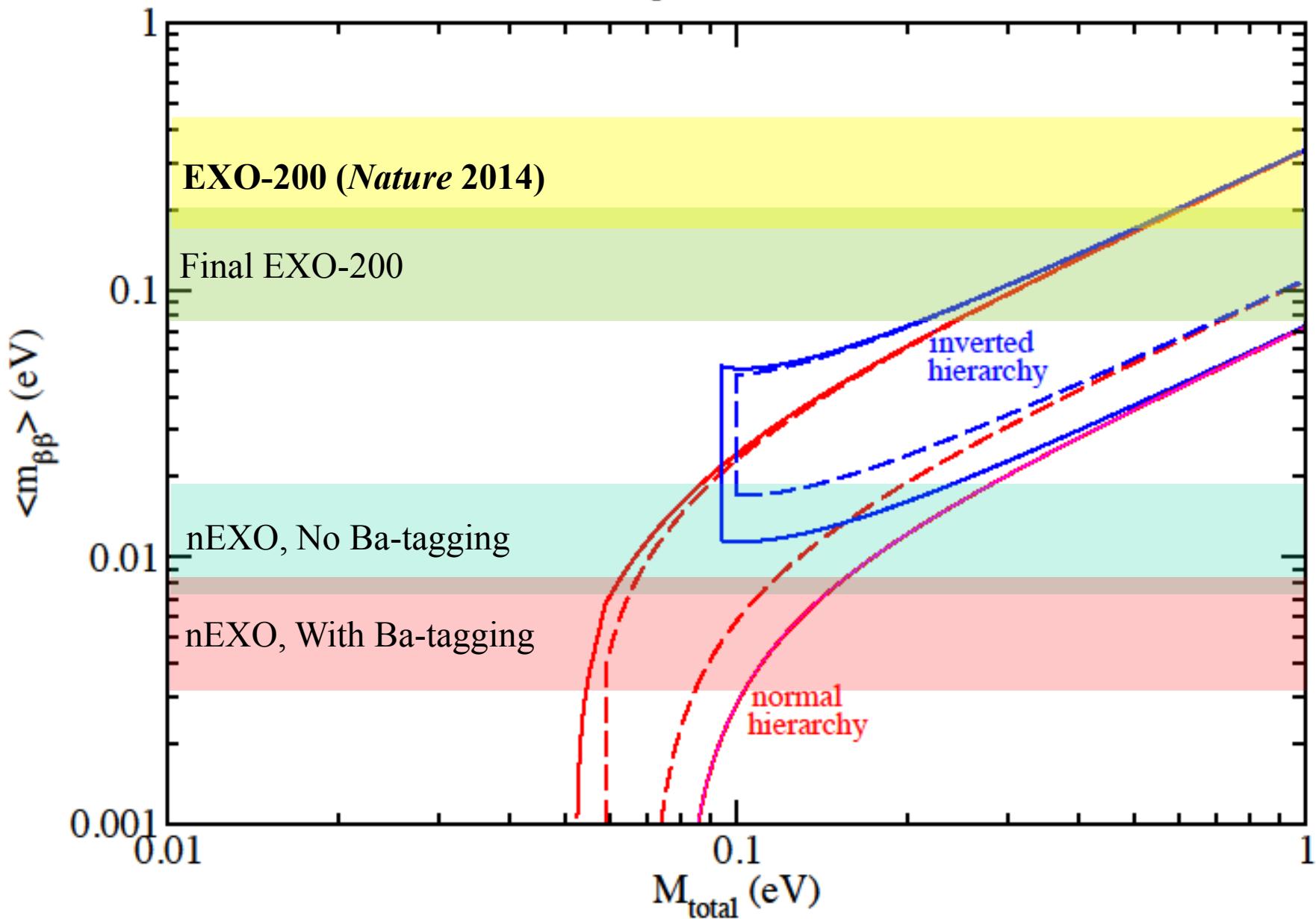
5 years exposure

$0\nu\beta\beta$ counts corresponding to $T_{1/2} = 6.6 \cdot 10^{27}$ yr

nEXO Sensitivity

Effective Majorana mass vs. M_{total}

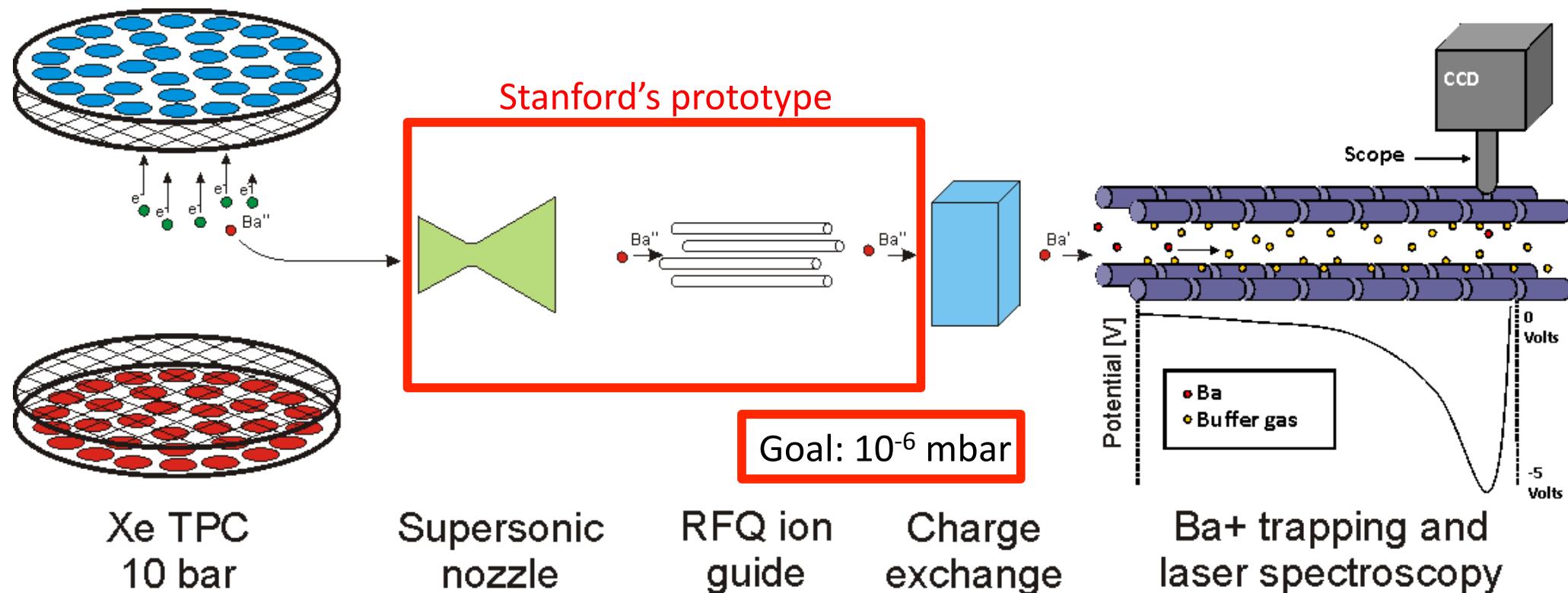
For the mean values of oscillation parameters (dashed) and for the 3σ errors (full)



Ba⁺⁺ Tagging in Xe gas

Carleton and McGill (Brunner, Koffas, Sinclair)

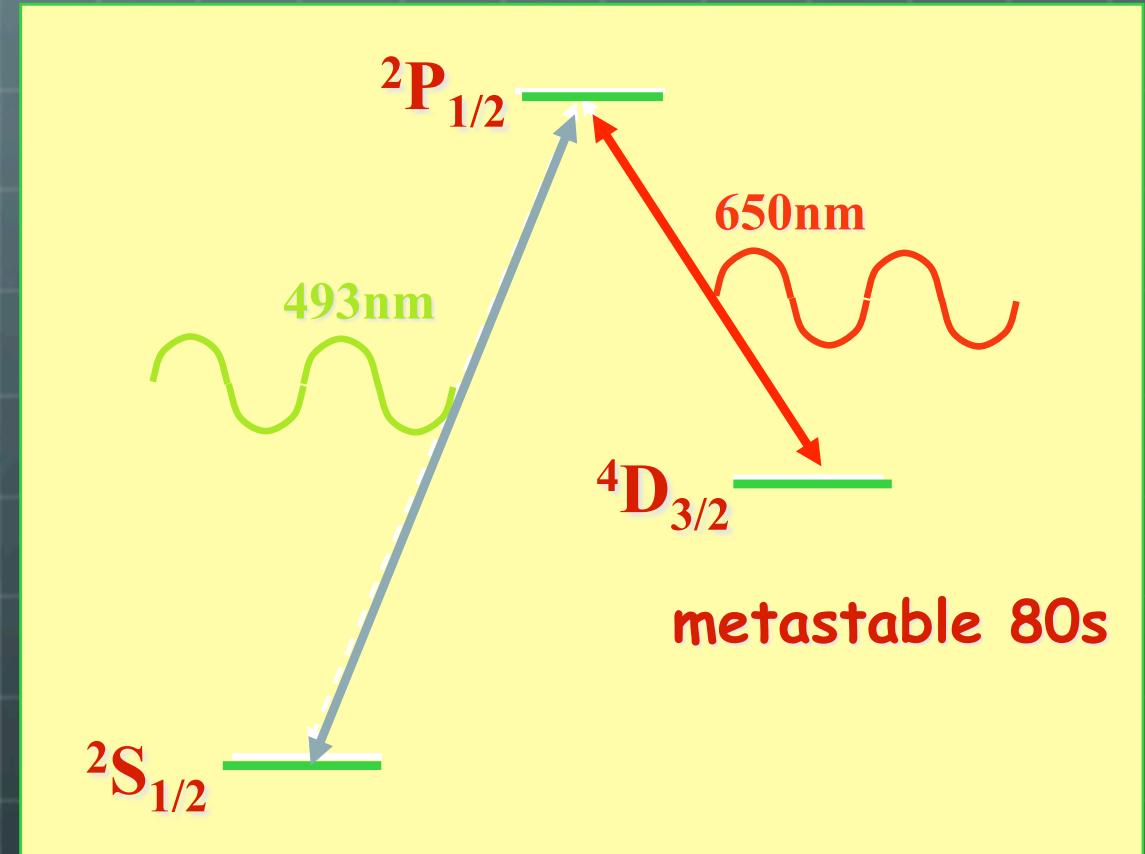
- Guide Ba⁺⁺ in high pressure Xe inside the TPC (10 bar) to a nozzle
- Extract Ba⁺⁺ with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide Ba⁺⁺ to identification

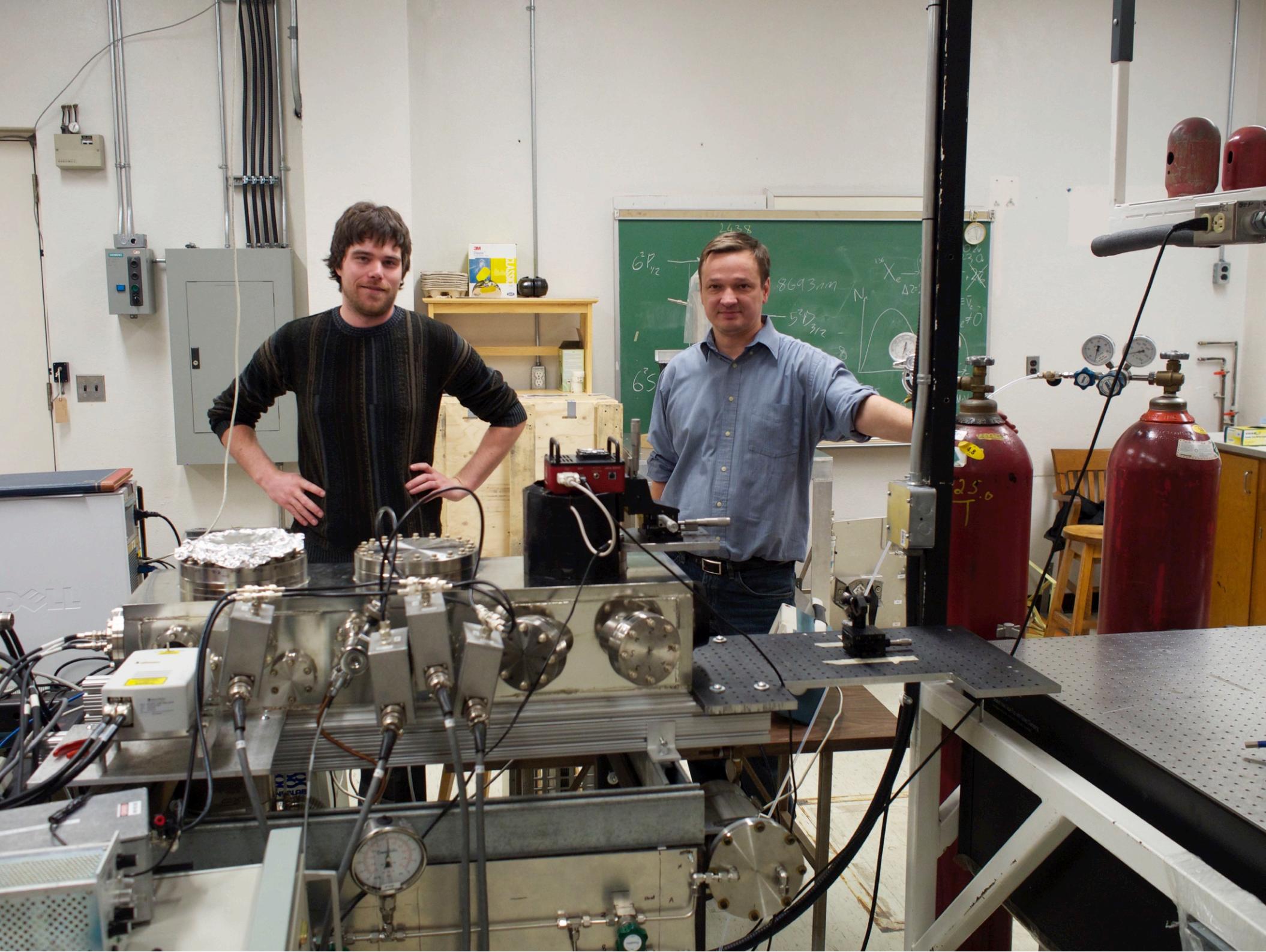


Barium tagging

Double beta decay
produces Ba⁺⁺

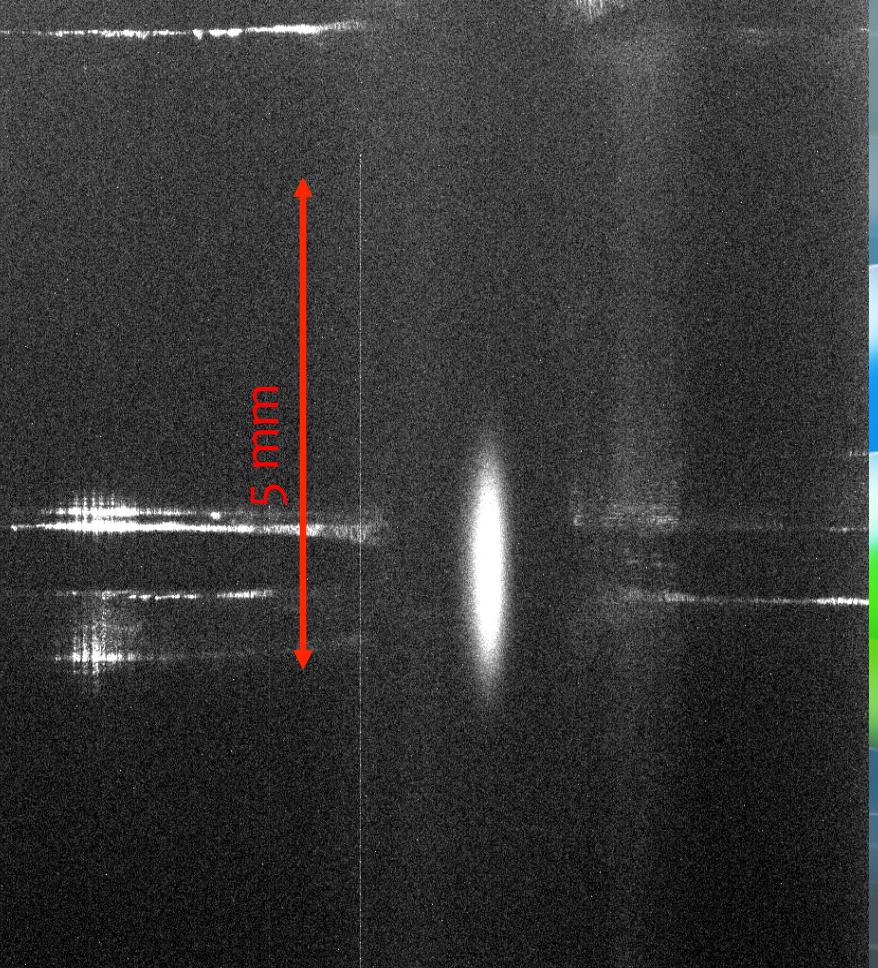
Requires Ba⁺ ion:
hydrogen-like levels
- laser spectroscopy



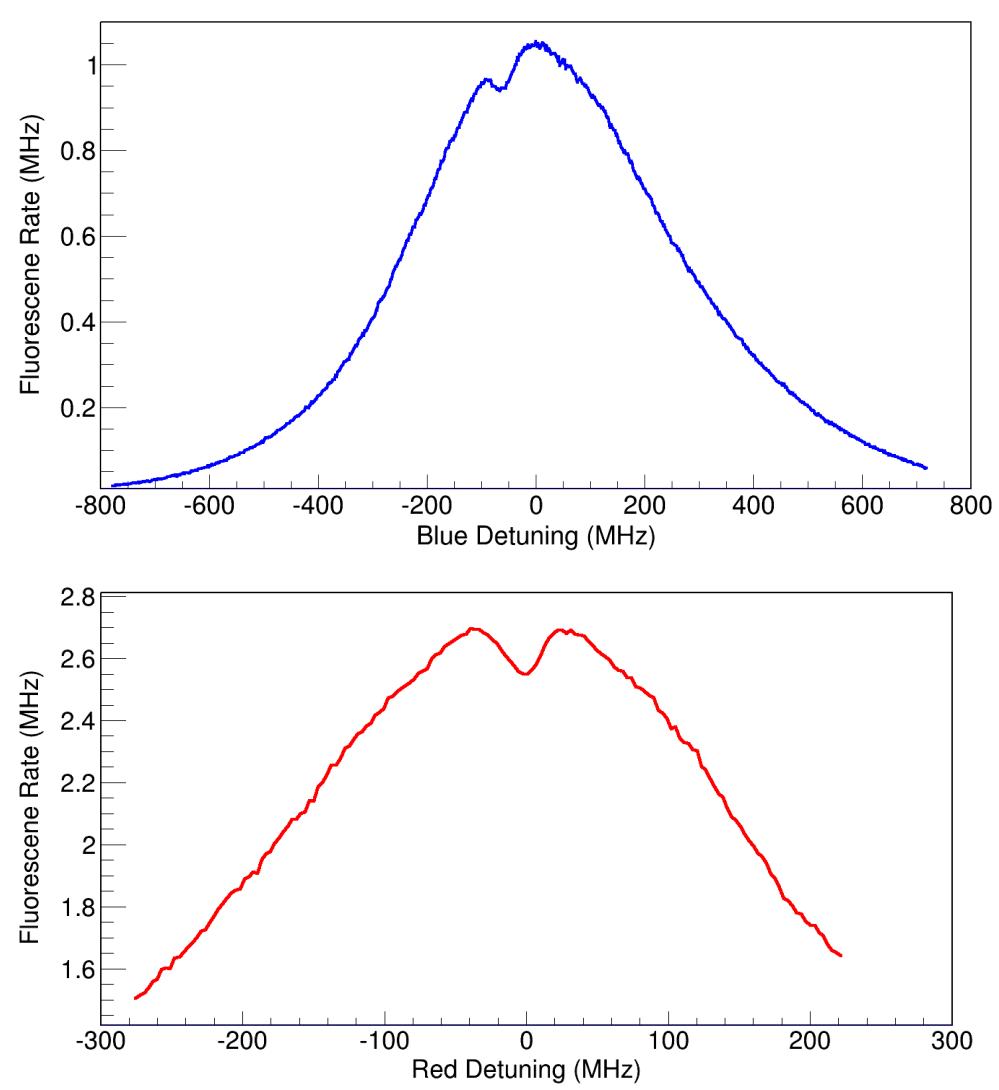


$$\begin{aligned} & 2438 \\ & 6^2P_{1/2} \rightarrow \\ & 869.3\text{ nm} \\ & 5^2D_{3/2} \\ & 6^2S_1 \\ & X_e \rightarrow \Delta E \\ & N \end{aligned}$$

25.0



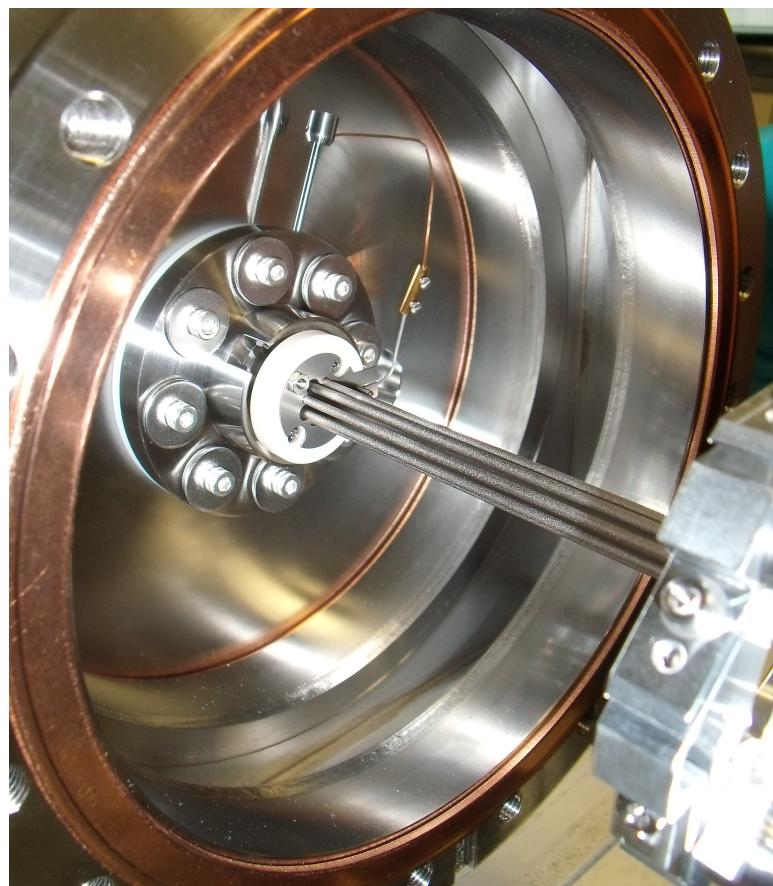
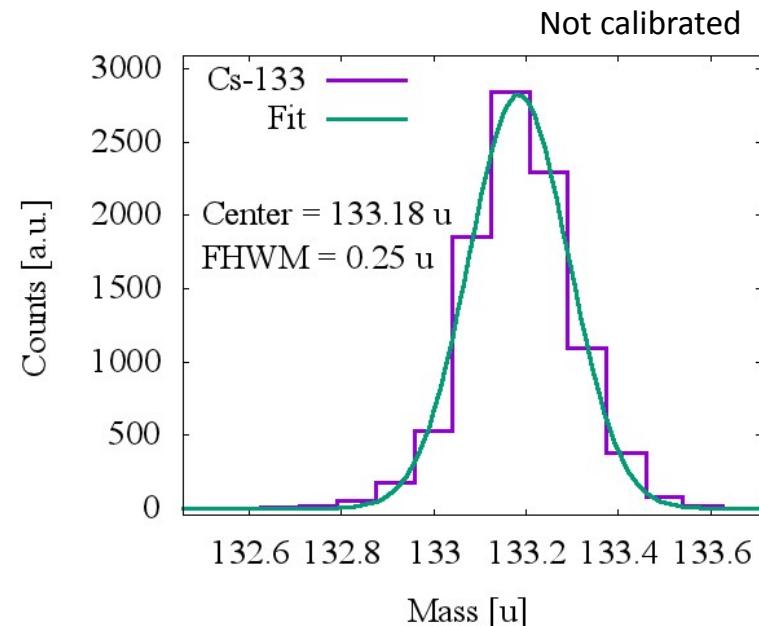
Trapping potential defined by the two 5mm segments at -10V



Laser wavelength scans
of blue and red light

Ion identification

- Commercial Thermo Finnigan LTQ mass spectrometer (Loan from TRIUMF)
- Modified spectrometer for reverse ion injection (verified with Cs-133)



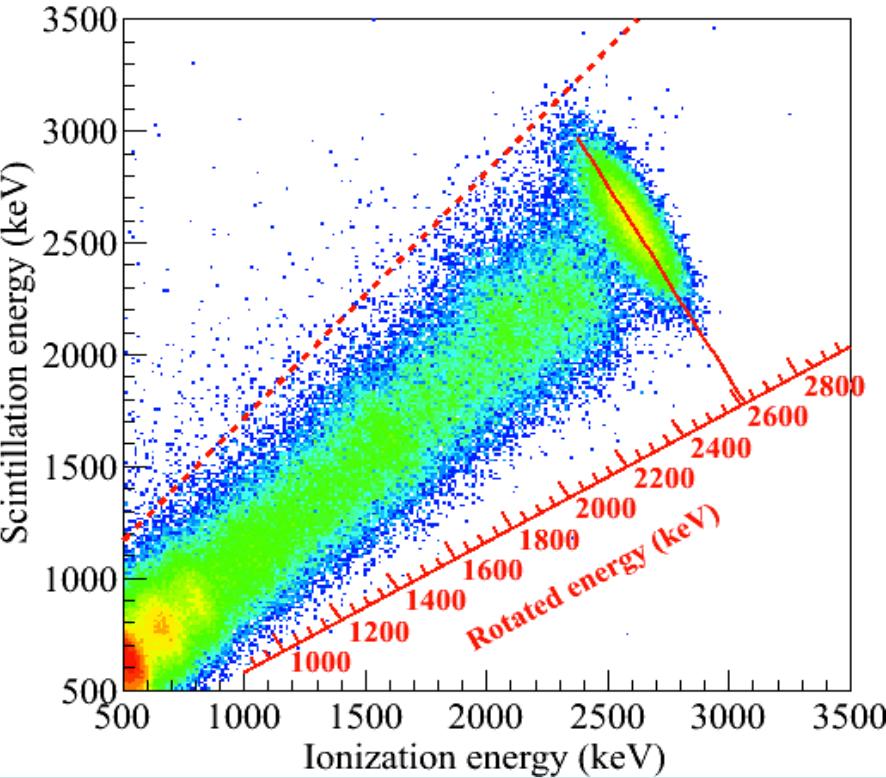
Summary

- Canadians playing lead roles on EXO-200 and nEXO
- have met original EXO-200 operational/sensitivity goals
- generated a number of physics and technical publications
- two accidents at WIPP...now have ‘normal’ access
- aim for 3 additional years of running with upgrades
- nEXO design development and R&D well underway
- follow EXO-200 success with key improvements
- aim to build a detector with discovery potential to bottom of inverted hierarchy region
- Ba tagging developments continue
- key is to measure single atom tagging efficiency

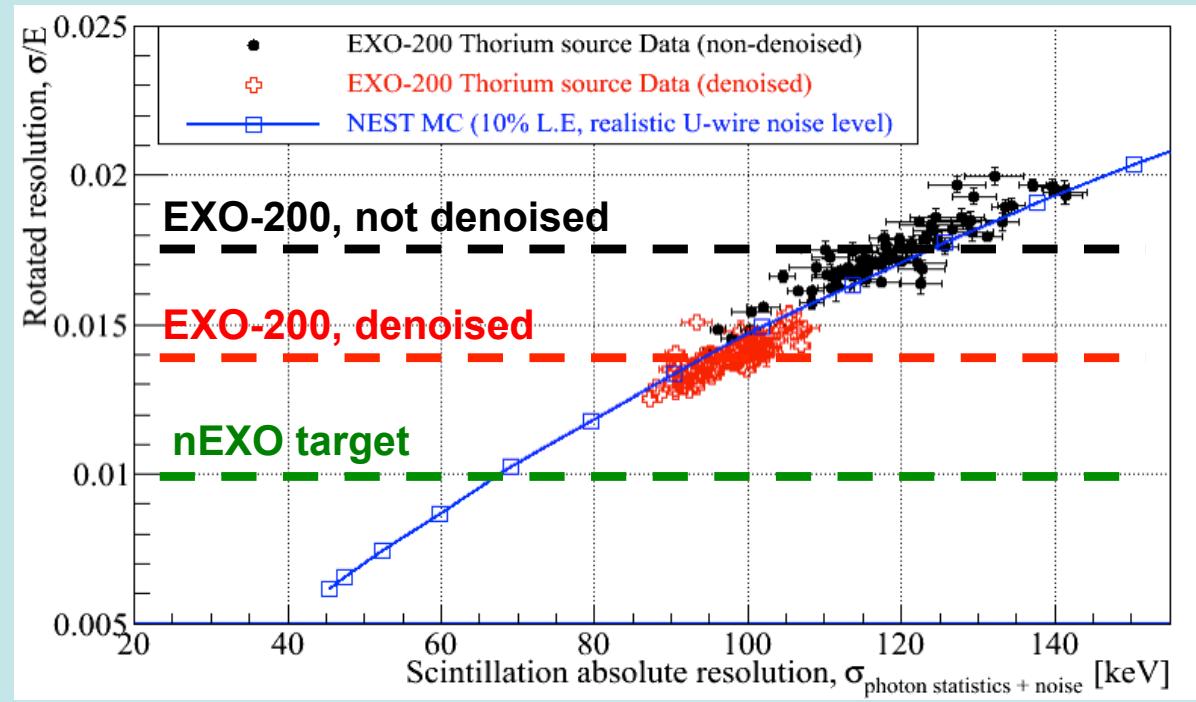
Energy resolution

- nEXO requires $\sigma_E/E < 1\%$ at $Q_{\beta\beta}$ (30 keV FWHM), which requires measuring both charge and light with minimal readout noise
- Have demonstrated 1.4% resolution in EXO-200, simulations indicate that 1% resolution is attainable with improved readout electronics for light sensors
- Planned upgrades to EXO-200 electronics aim to achieve 1% resolution

Scintillation vs. ionization, EXO-200 data:

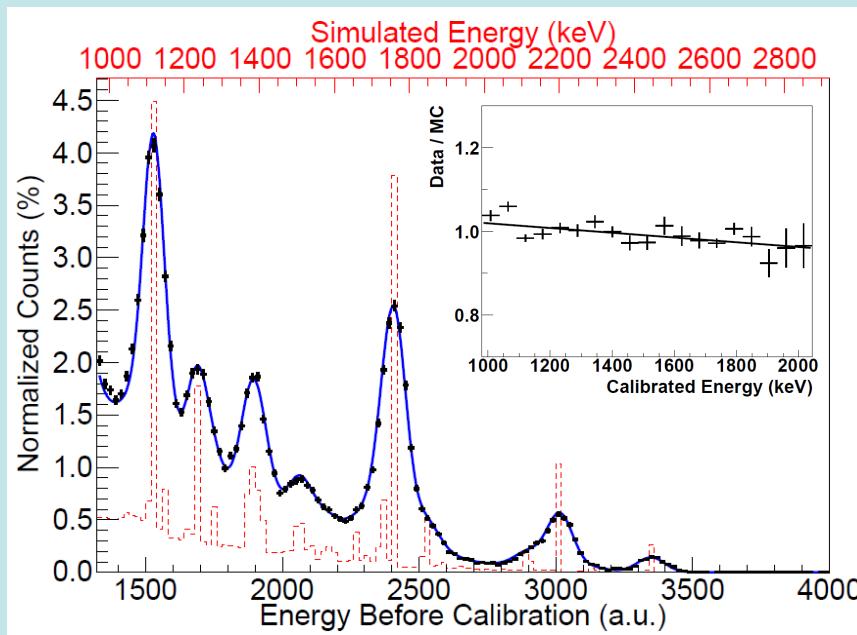


Simulated rotated resolution vs. readout noise:

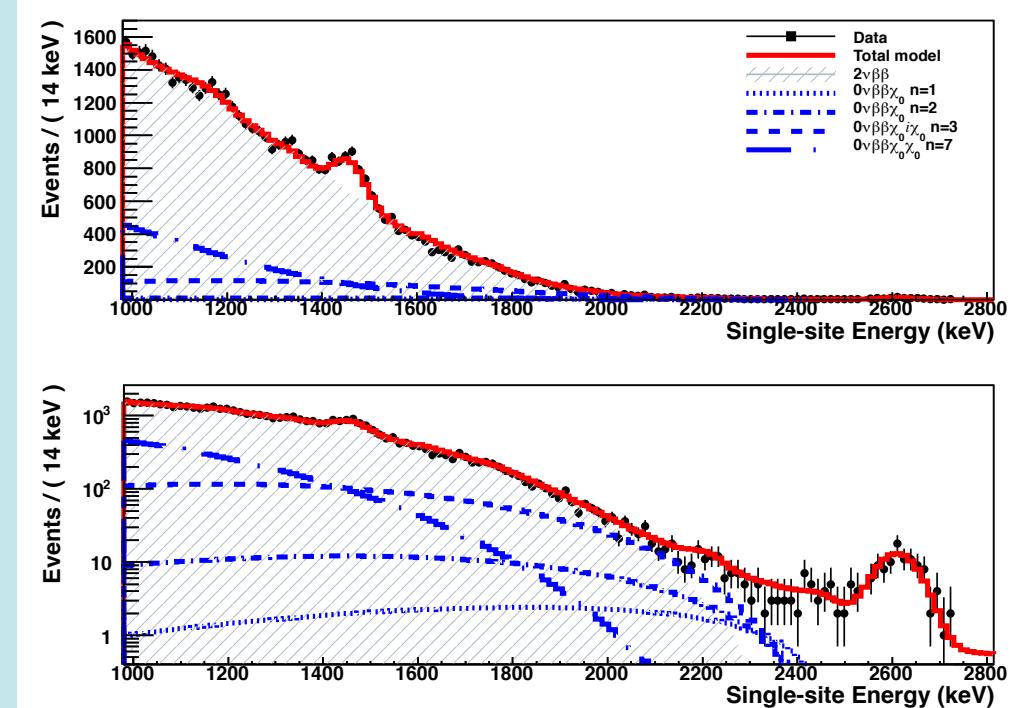


Search for Majoron-emitting Modes

^{222}Ra Calibration Data



Low Background Data



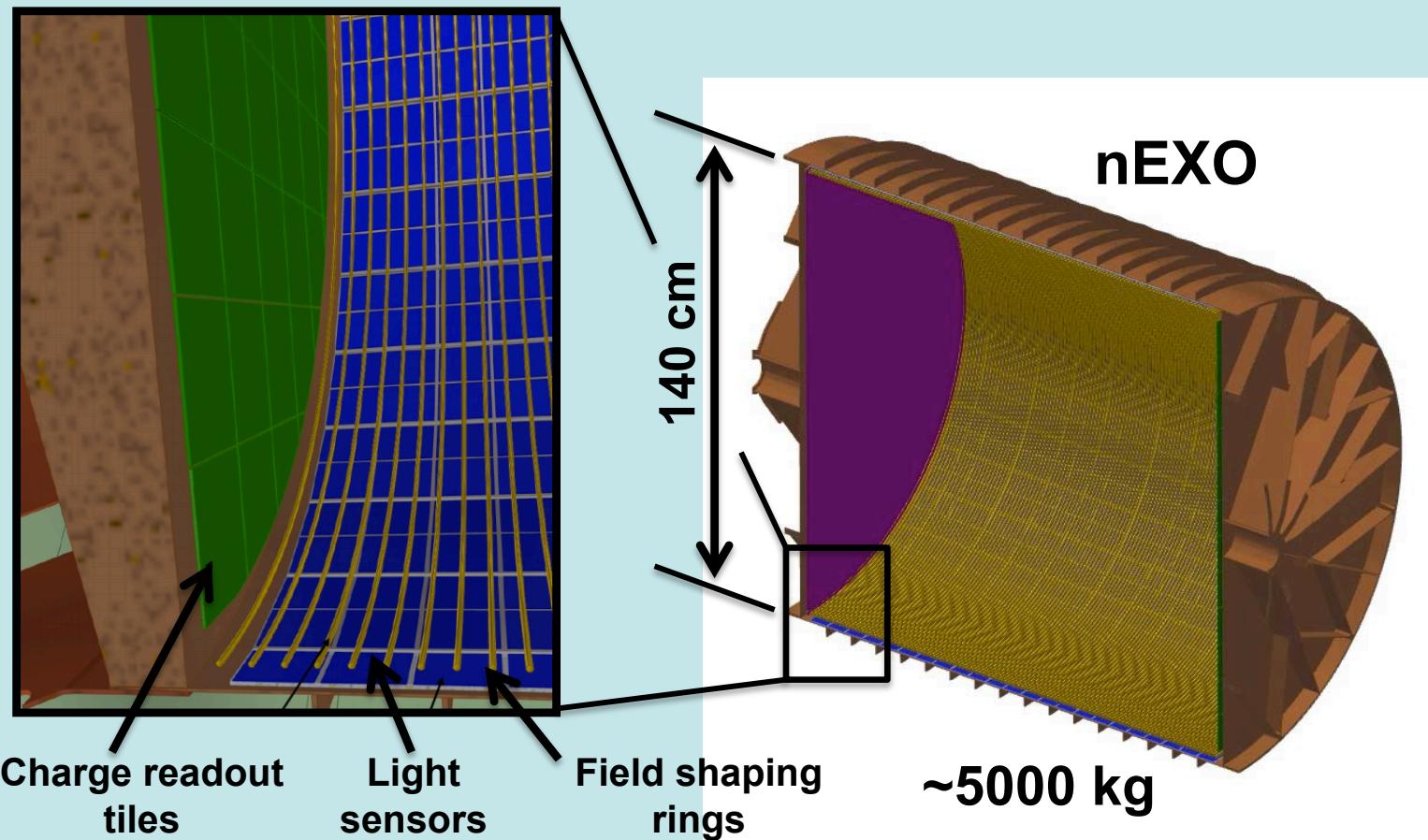
No Evidence for Majoron Modes

Phys.Rev. D90 (2014)

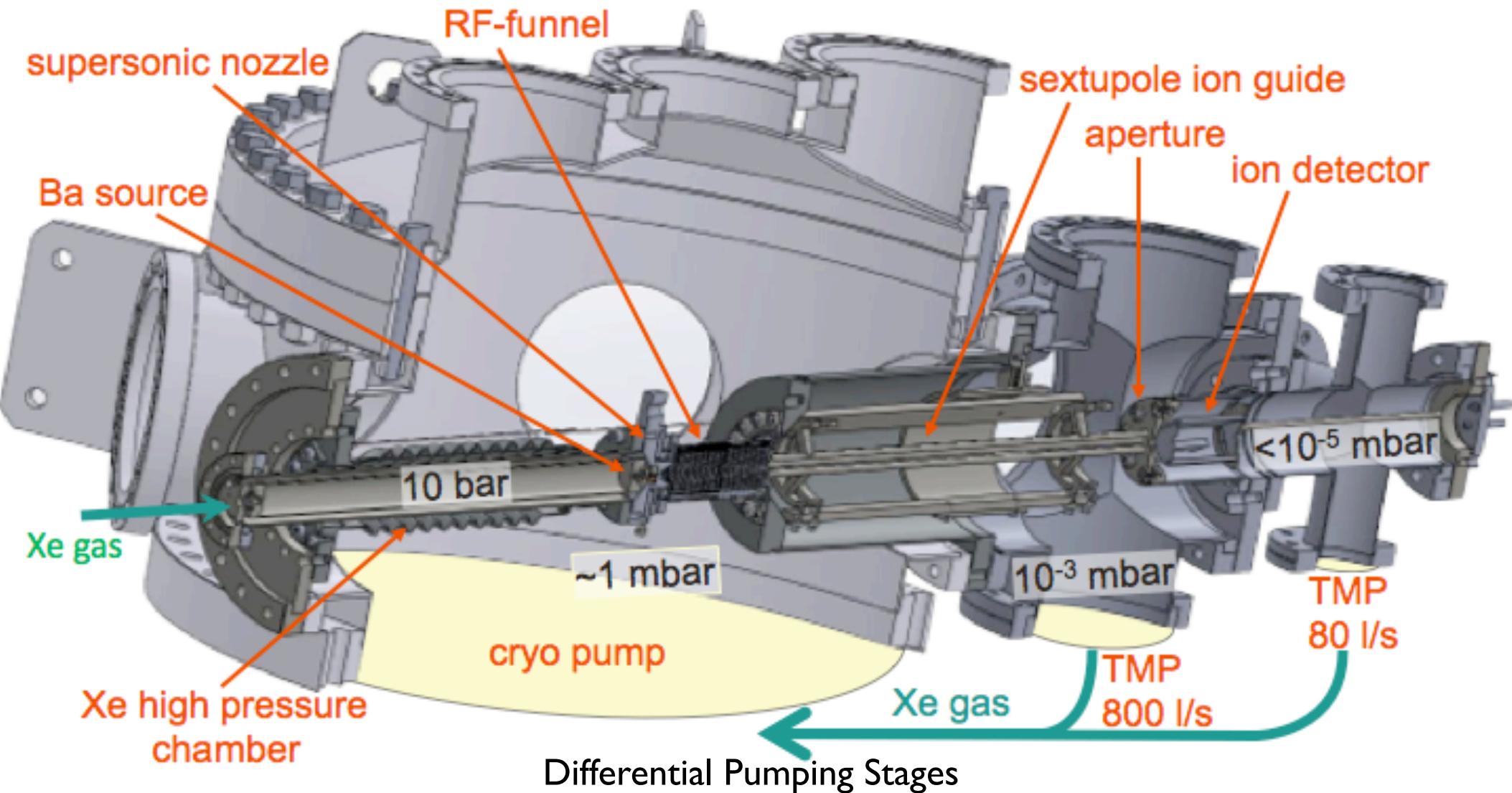
Decay mode	Spectral index, n	Model types	$T_{1/2}$, yr	$ \langle g_{ee}^M \rangle $
$0\nu\beta\beta\chi_0$	1	IB, IC, IIB	$>1.2 \cdot 10^{24}$	$<(0.8\text{-}1.7) \cdot 10^{-5}$
$0\nu\beta\beta\chi_0$	2	“Bulk”	$>2.5 \cdot 10^{23}$	—
$0\nu\beta\beta\chi_0\chi_0$	3	ID, IE, IID	$>2.7 \cdot 10^{22}$	$<(0.6\text{-}5.5)$
$0\nu\beta\beta\chi_0$	3	IIC, IIF	$>2.7 \cdot 10^{22}$	<0.06
$0\nu\beta\beta\chi_0\chi_0$	7	IIE	$>6.1 \cdot 10^{21}$	$<(0.5\text{-}4.7)$

nEXO TPC concept

- maximize ‘clean’ volume with all components at edges...self-shielding
- proof-of-principle demonstrated with EXO-200
- large reduction in backgrounds at centre for nEXO...detailed measurement of background from outer portions



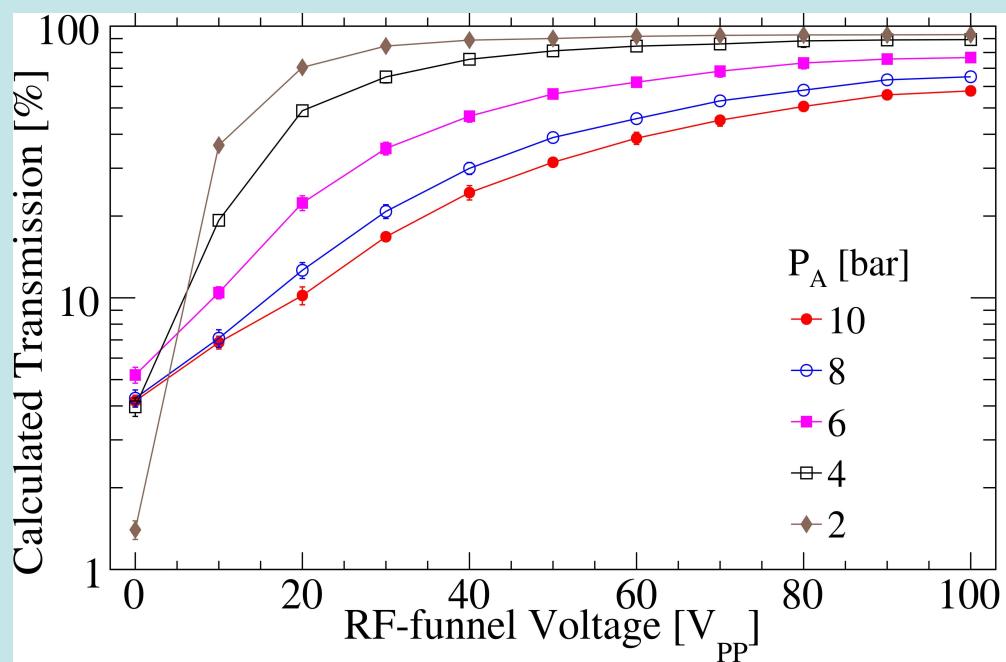
Stanford's Prototype (to McGill)



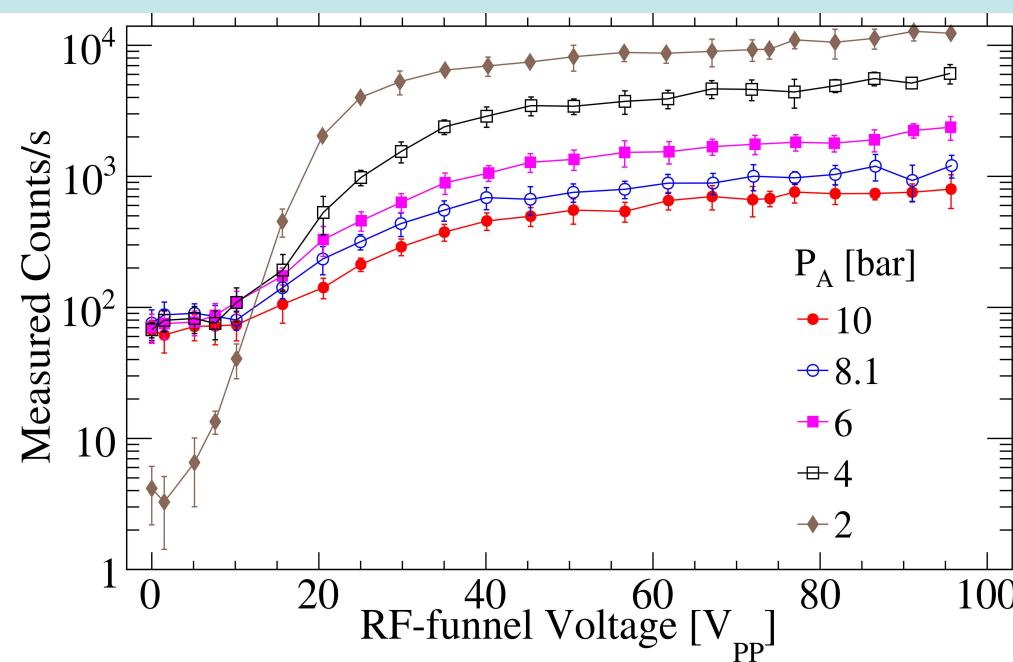
Chamber A	Chamber B	Chamber C	Chamber D
High pressure Xe gas	Funnel chamber	SPIG chamber	Detection chamber
10 bar	$\sim 1 \text{ mbar}$	$1.2 \times 10^{-3} \text{ mbar}$	$2.4 \times 10^{-6} \text{ mbar}$

Ion extraction in xenon gas

Calculation



Measurement



- General shape well reproduced
- Ion extraction up to 10 bar!
- Ions not identified!
- Ion extraction efficiency unknown!