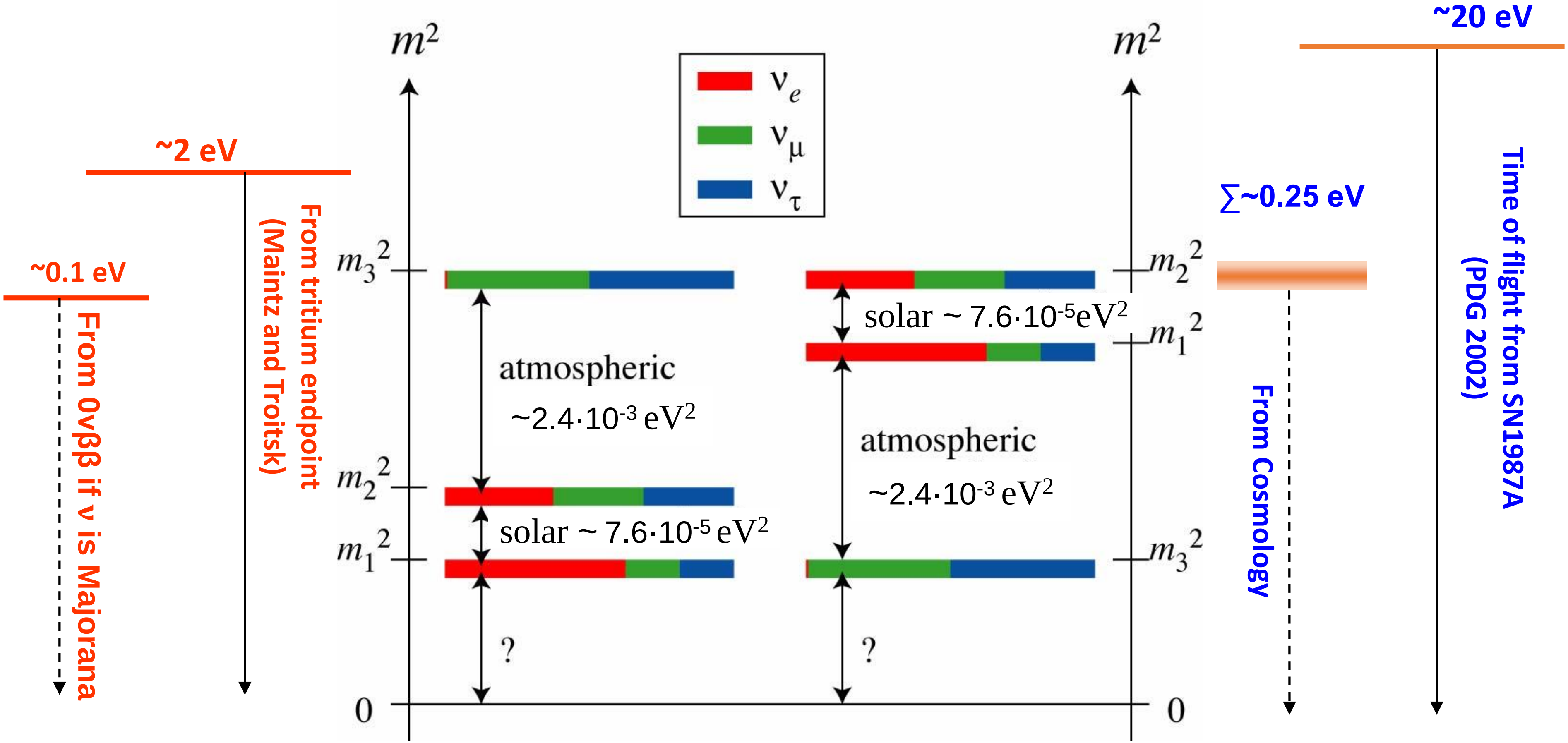
Searching for 0νββ with EXO-200 and nEXO

- Motivation for ββ search
- The EXO-200 experiment
- The nEXO project

Thomas Brunner for the nEXO collaboration
December 5, 2017

What we know about neutrinos



Neutrino oscillations

In Quantum Mechanics there are 2 representations for our neutrinos if $m_\nu \neq 0$:

- **“Weak interaction eigenstate”**

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

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

A source produces –say- ν_e <u>always</u> via weak interactions

- **“Mass eigenstate”**

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

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

$$\nu_{m1}(t) = e^{-i(\boxed{E_1 t -} p_1 L)}\nu_{m1}$$
$$\nu_{m2}(t) = e^{-i(\boxed{E_2 t -} p_2 L)}\nu_{m2}$$
$$\nu_{m3}(t) = e^{-i(\boxed{E_3 t -} p_3 L)}\nu_{m3}$$

$E_i = m_i c^2$

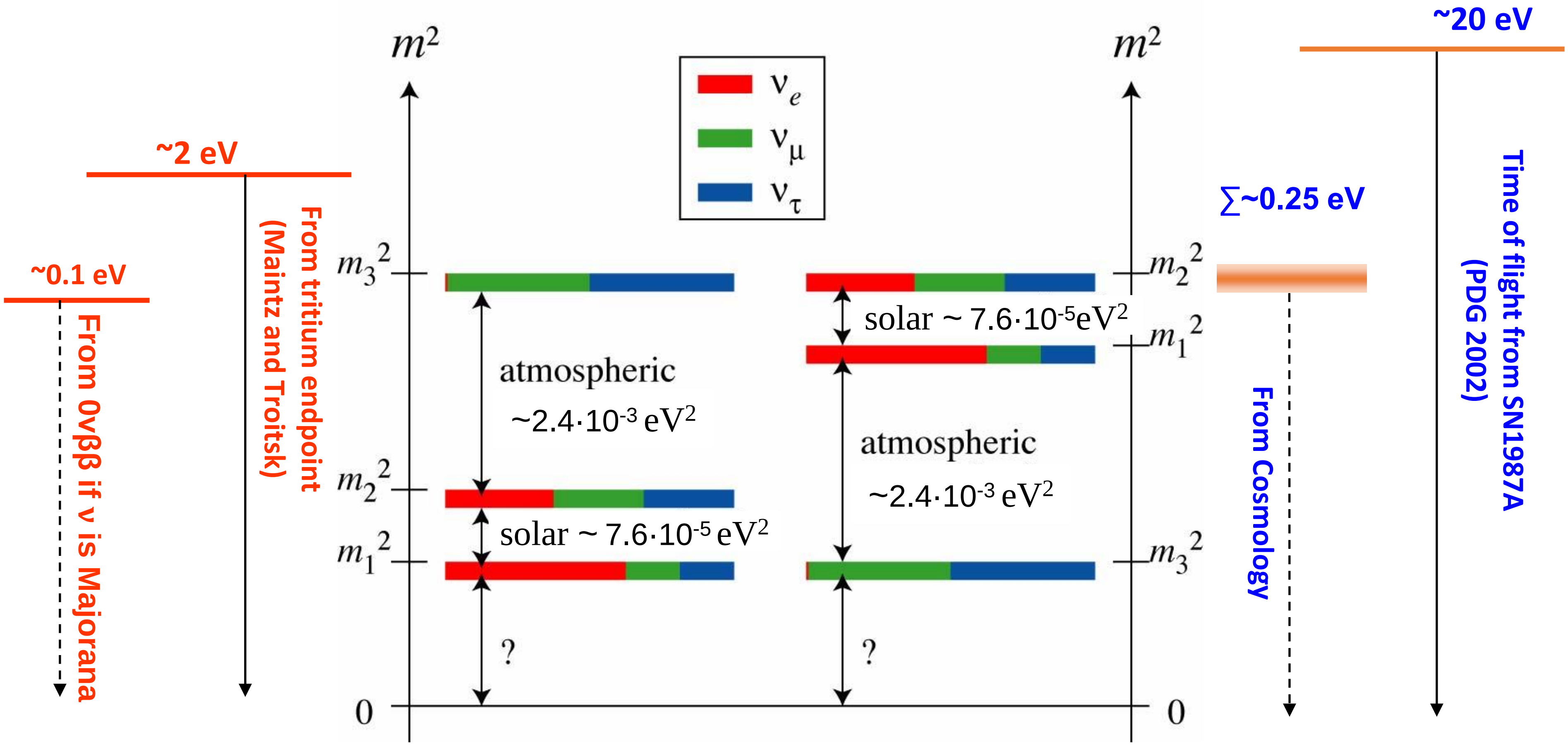
Neutrino oscillations – mixing matrix

The 2 eigenstates are connected by a 3·3 matrix (“mixing matrix”)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata matrix

What we know about neutrinos



Open questions in ν physics

- What is the absolute mass scale?
- Why is the neutrino mass so small?
- What is the nature of the ν: Dirac or Majorana?

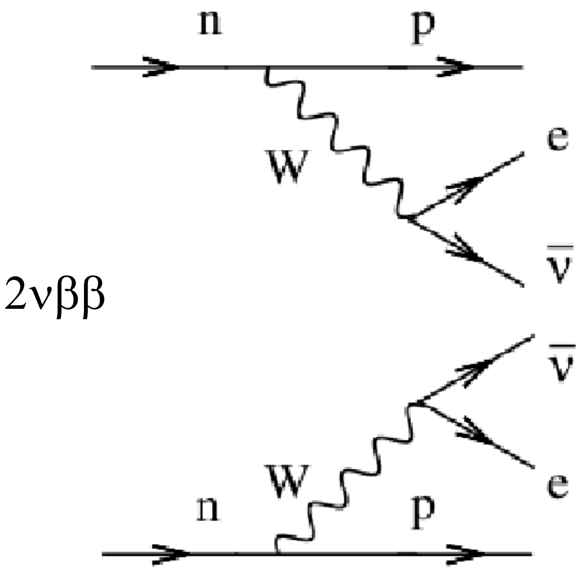
→ Search for 0νββ decay

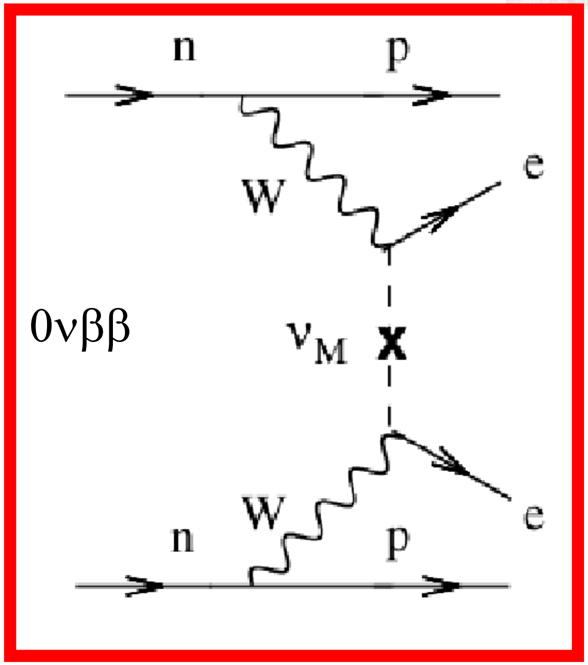
Double beta decay

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

The most promising approach to determine the nature of the neutrino!
Lepton number is violated in this decay!

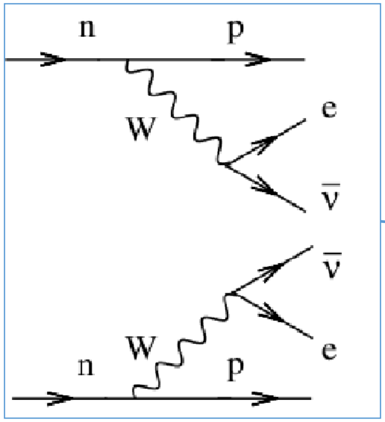
Ettore Majorana



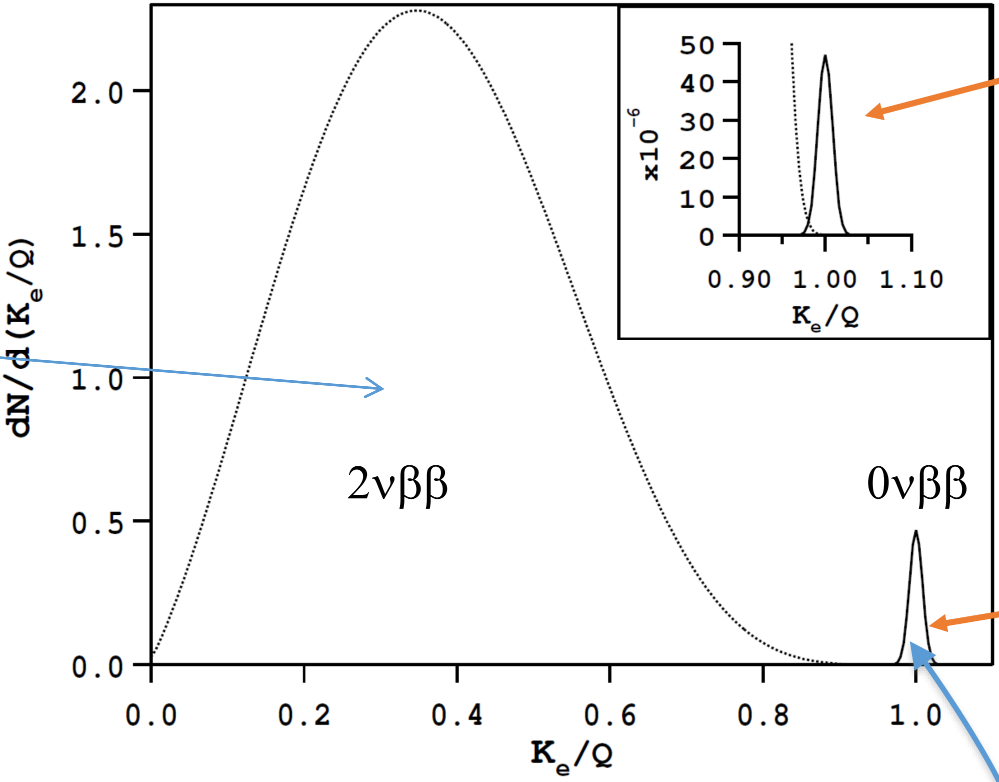


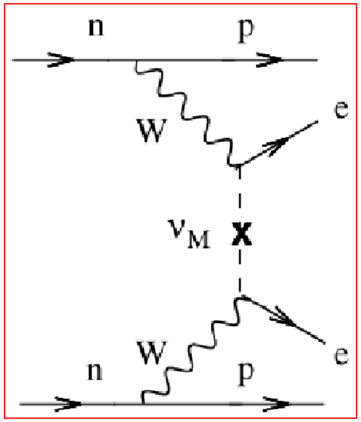
This process can only occur for a Majorana neutrino!

Neutrinoless double beta decay



[arXiv:hep-ph/0611243]





$0\nu\beta\beta$ peak (normalized to 10^{-6})

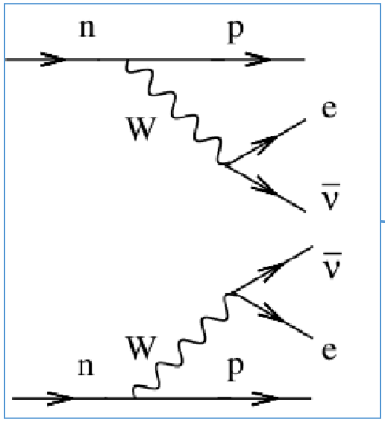
$0\nu\beta\beta$ peak (normalized to 10^{-2})

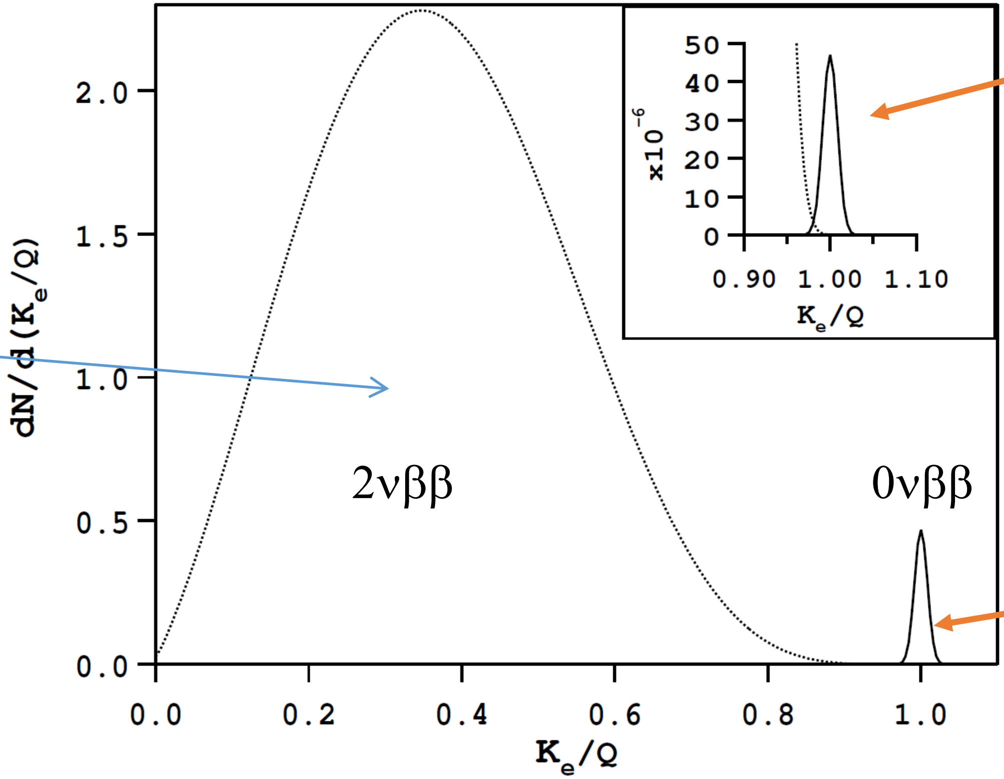
kinetic energy K_e of the two electrons in units of kinematic endpoint (Q)

Smeared by the energy resolution of the hypothetical detector

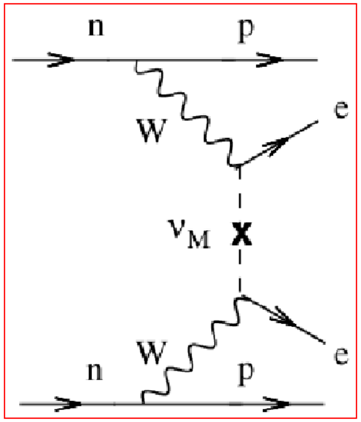
Neutrinoless double beta decay

[arXiv:hep-ph/0611243]





0νββ peak (normalized to 10^{-6})



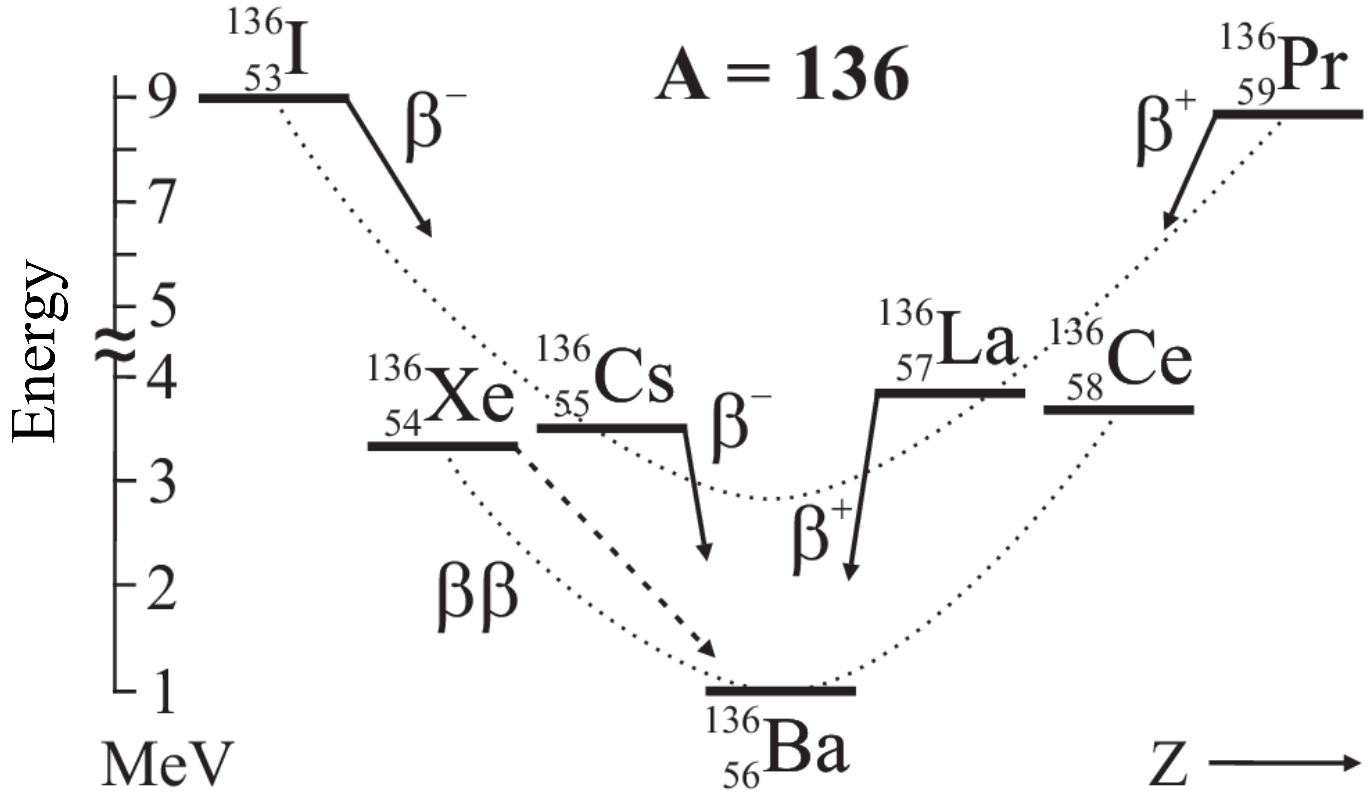
0νββ peak (normalized to 10^{-2})

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^{2}\langle m_\nu\rangle^{2}$$

$G^{0\nu}$ is a phase space factor
$M^{0\nu}$ is the nuclear matrix element

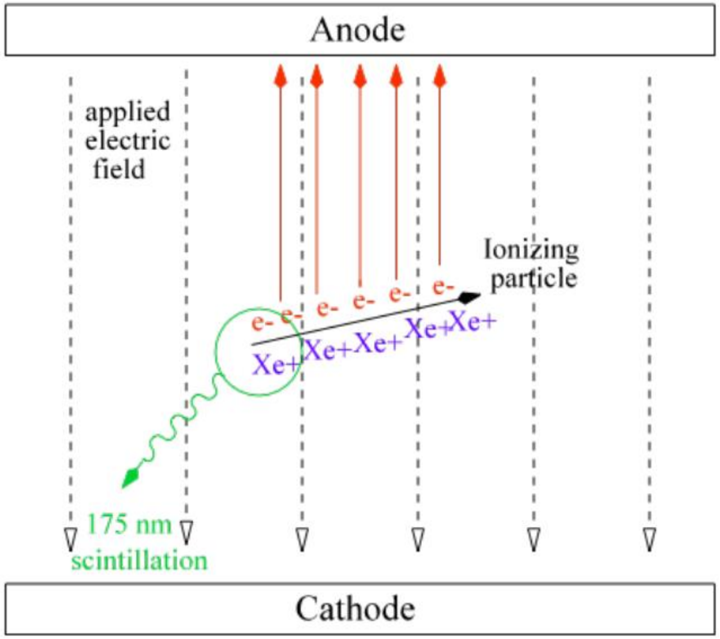
Effective Majorana mass: $\langle m_\nu\rangle = \left|\sum_i U_{ei}^2 m_i\, \varepsilon_i\right|$ (light neutrino exchange mechanism only)

Double Beta Decay



- If first-order beta decay is forbidden energetically or by spin, second-order double beta decay (a weak nuclear process) can be observed
- True for several isotopes such as: ^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe

Searching for $0\nu\beta\beta$ in ^{136}Xe with EXO



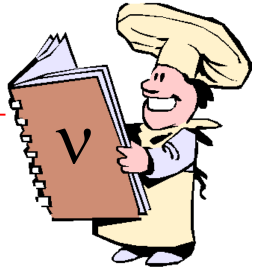
Liquid-Xe Time Projection Chamber

- Liquid Xe at 168K
- Cryogenic electronics in LXe
- Detection of scintillation light and secondary charges
- 2D read out of secondary charges at segmented anode
- Full 3D event reconstruction:
  1. Energy reconstruction
  2. Position reconstruction
  3. Event Multiplicity

<u>Natural radiation decay rates</u>

A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of ^{136}Xe (2ν)	~1 decay/10 min

$0\nu\beta\beta$ decay	>10000 x rarer than $2\nu\beta\beta$
Age of universe	1.4 x 10^{10} years



$T_{1/2}^{0\nu} > 10^{25}$ years !!

→Need:

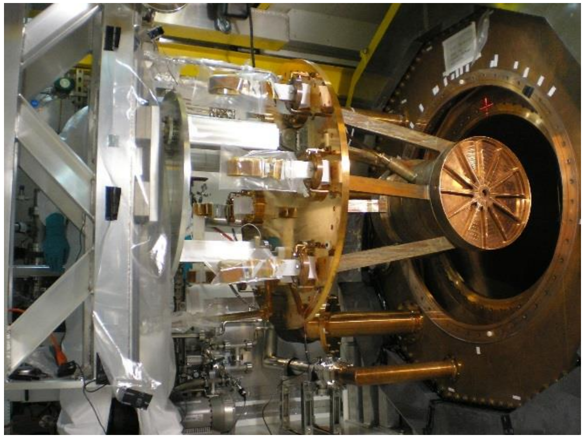
- high target mass
- high exposure
- low background rate
- good energy resolution

Searching for $0\nu\beta\beta$ in ^{136}Xe

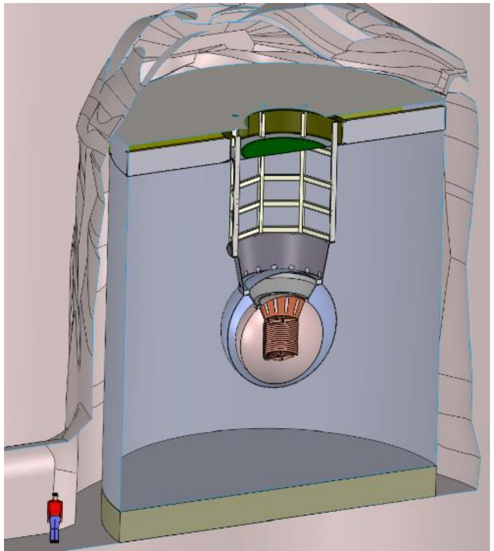
- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- Energy resolution: improves using scintillation and charge anti-correlation
- LXe self shielding
- Background can be potentially reduced by Ba^{++} tagging

Phased approach:

1. EXO-200: 200kg liquid-Xe TPC, taking data

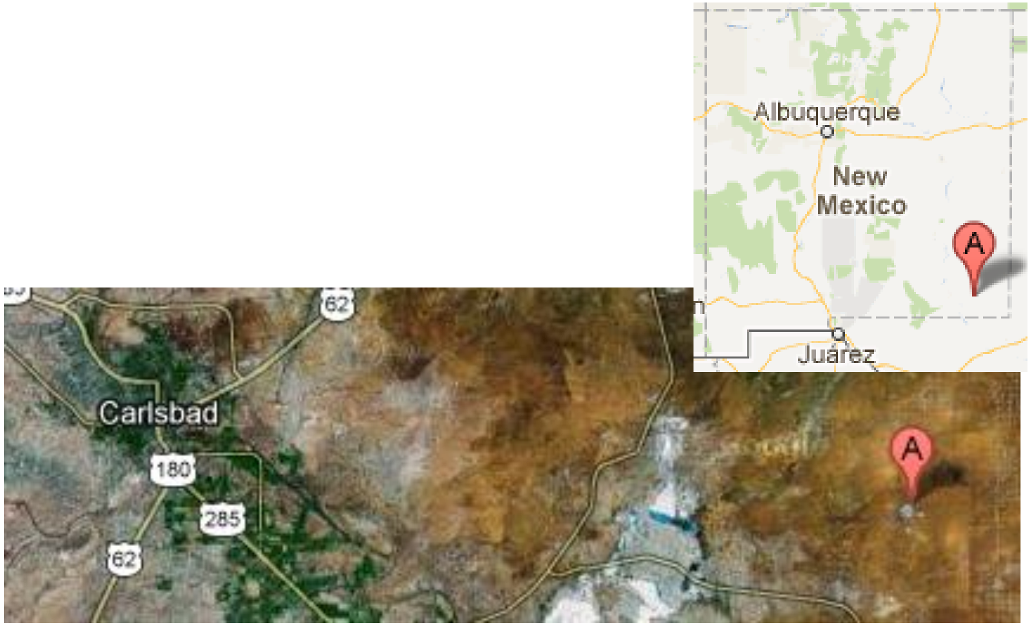


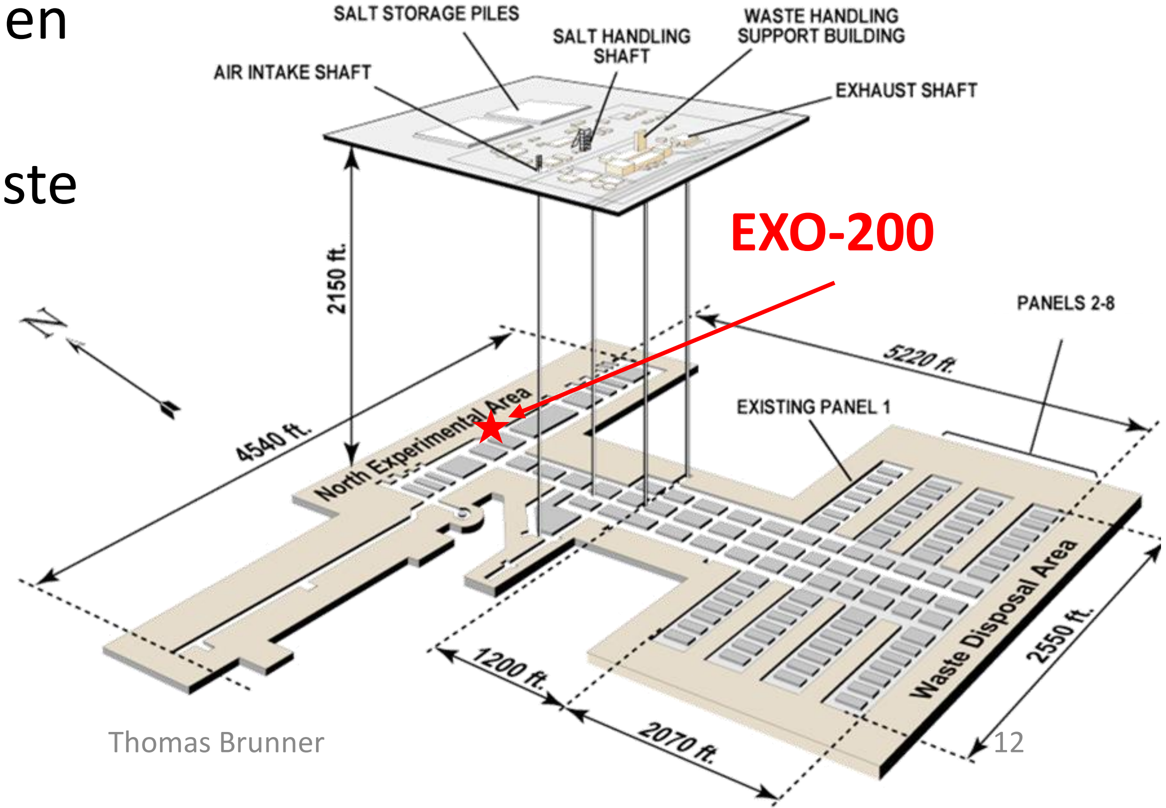
2. nEXO: future 5-ton liquid Xe TPC with Ba tagging option (SNO lab cryopit)



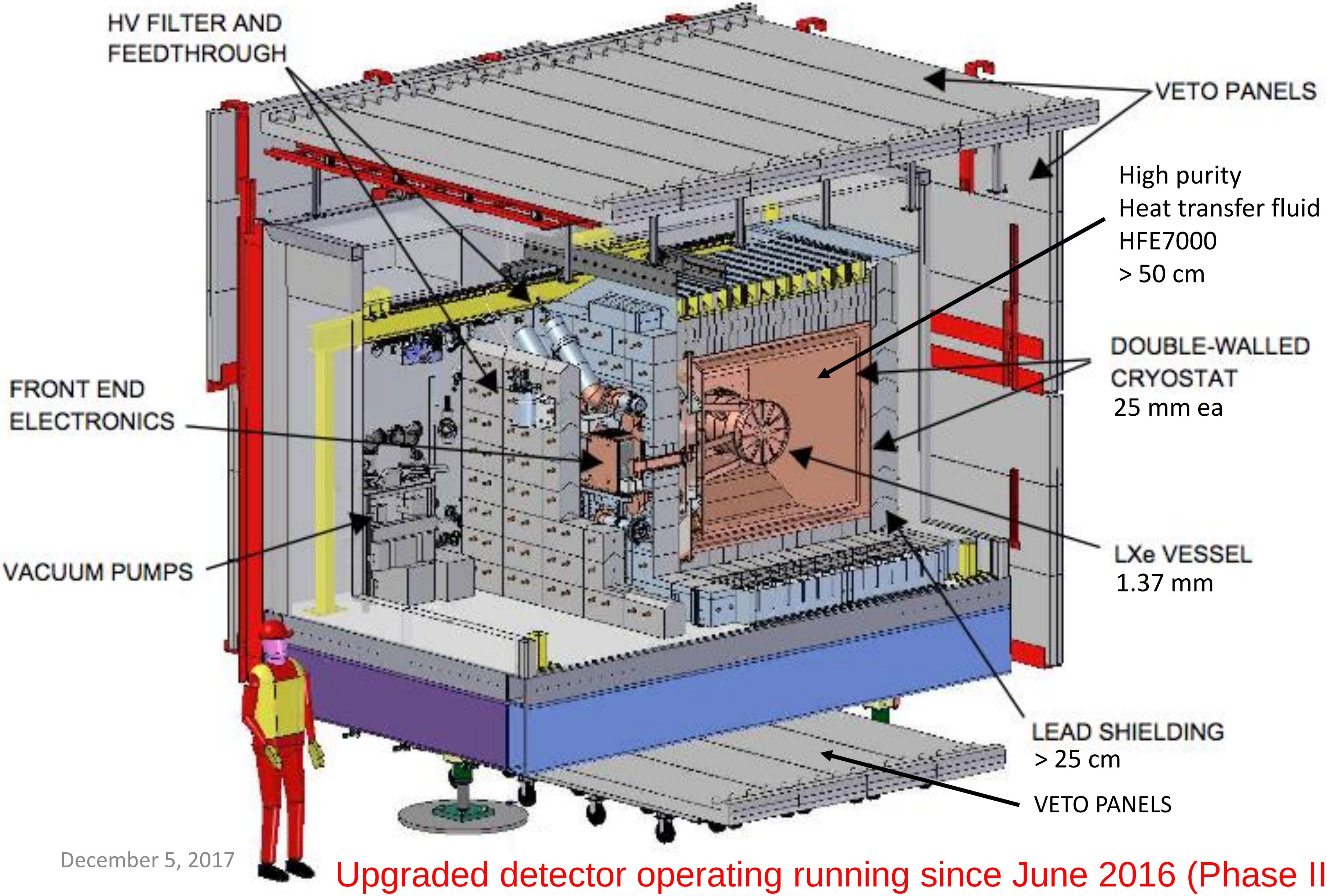
EXO-200

- Located at the Waste Isolation Pilot Plant at 32°22’30”N 103°47’34”W (Carlsbad, NM).
- 2150 feet depth (~655m), ≈1585 mwe flat overburden
- U.S. DOE permanent repository for nuclear waste
- Low radioactivity levels:
  - U, Th <100ppb
  - Radon background < 10 Bq/m^3

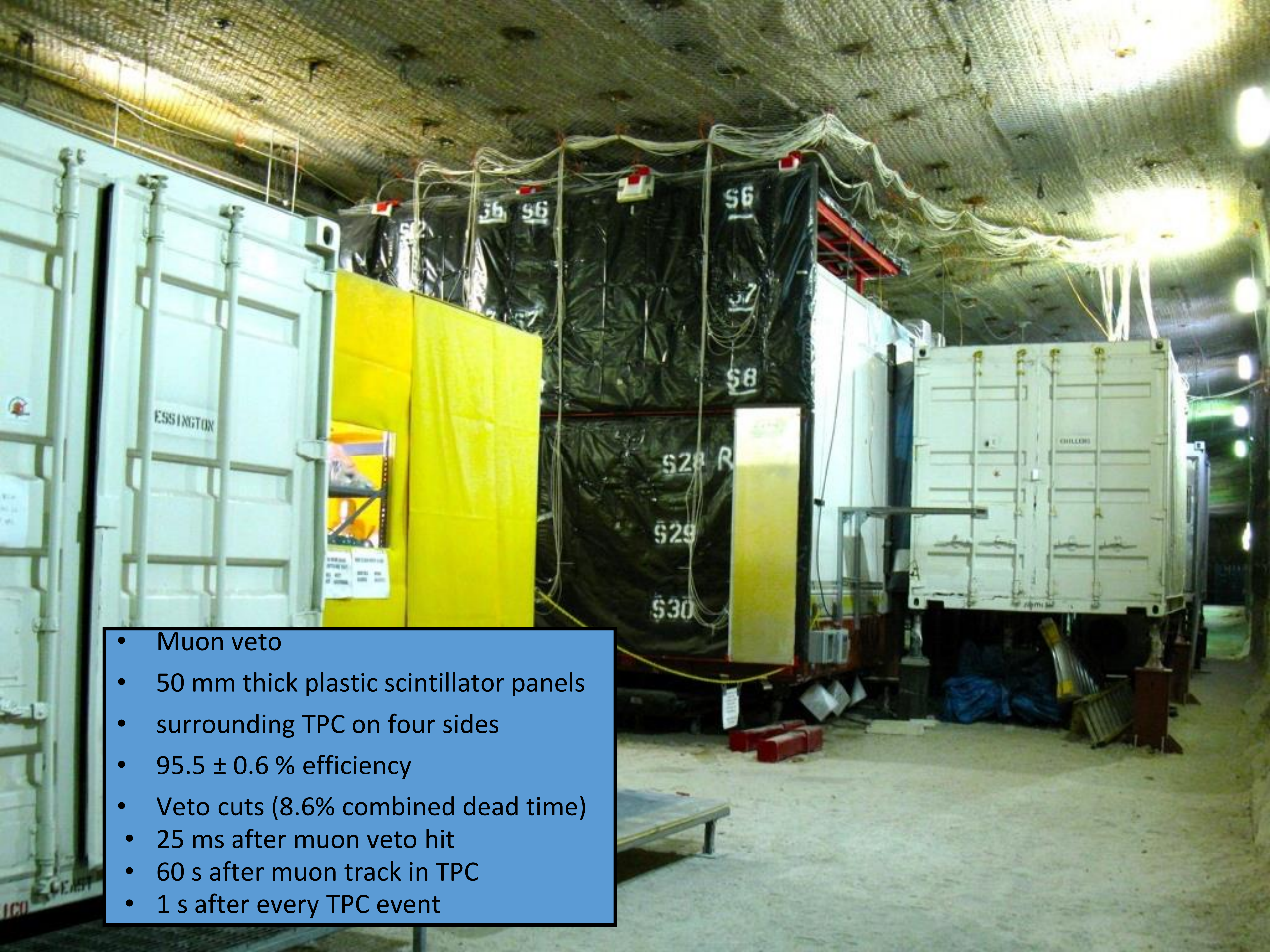




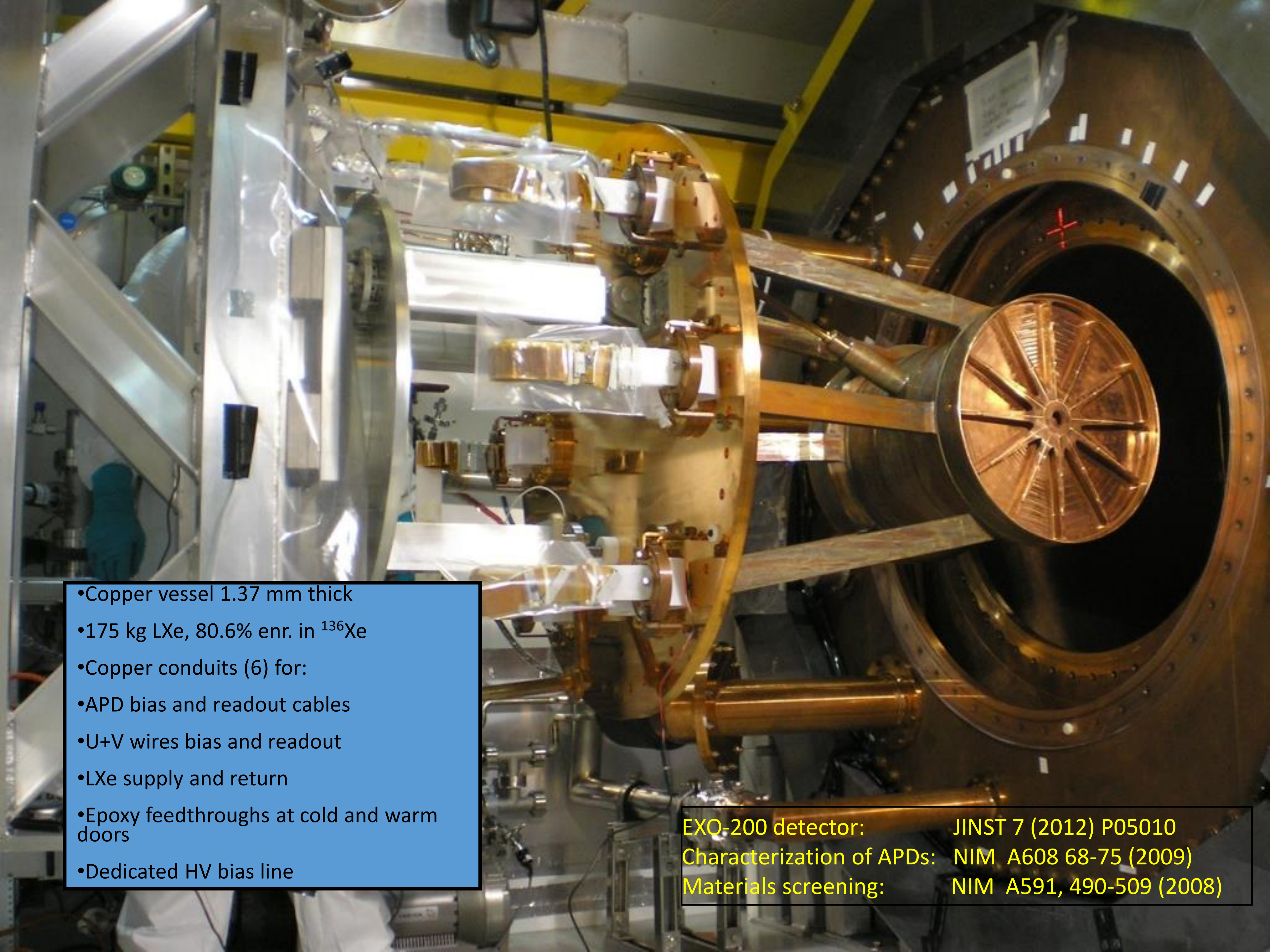
The EXO-200 Detector



Upgraded detector operating running since June 2016 (Phase II)

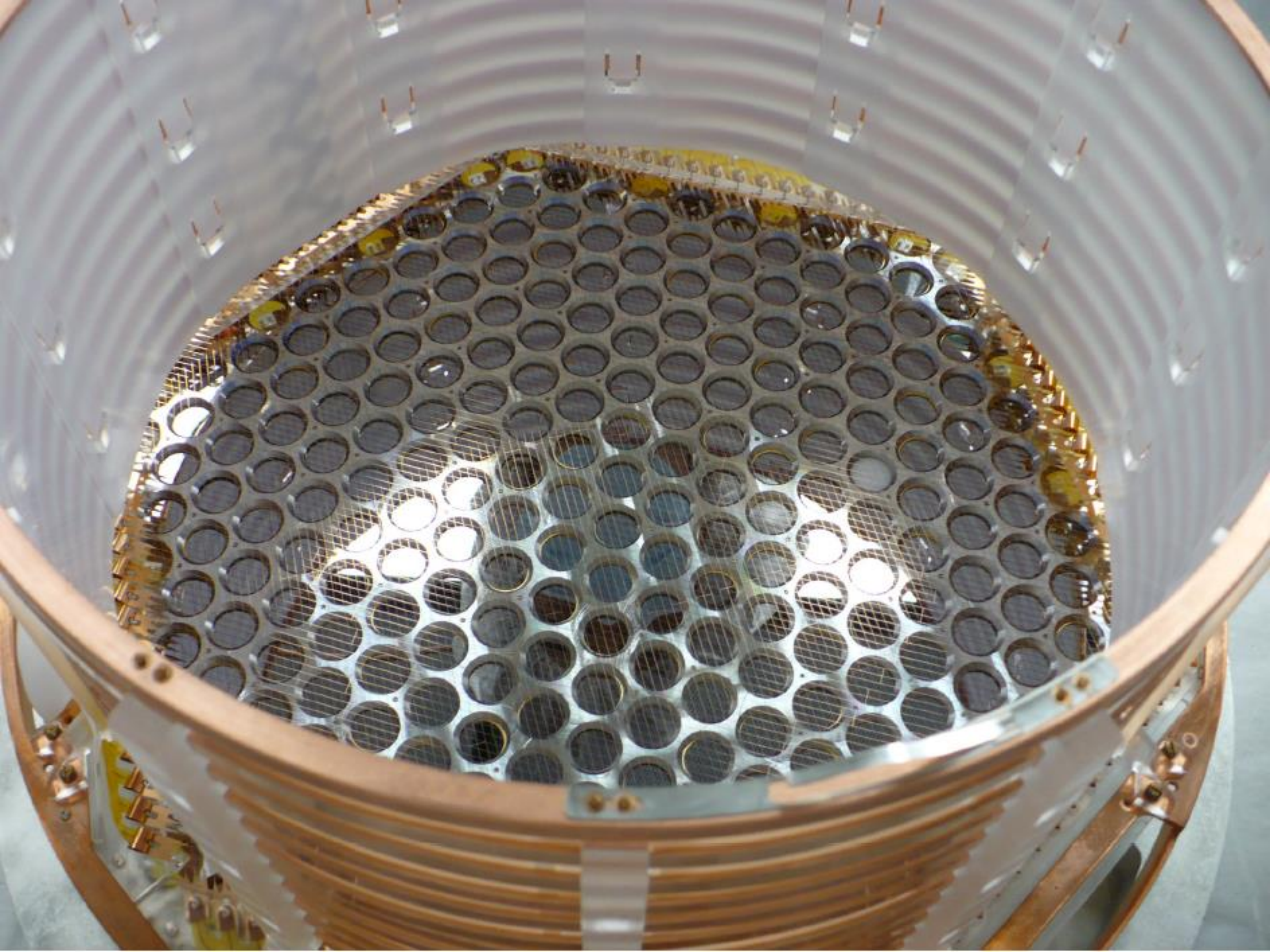


- Muon veto
- 50 mm thick plastic scintillator panels
- surrounding TPC on four sides
- 95.5 ± 0.6 % efficiency
- Veto cuts (8.6% combined dead time)
  - 25 ms after muon veto hit
  - 60 s after muon track in TPC
  - 1 s after every TPC event



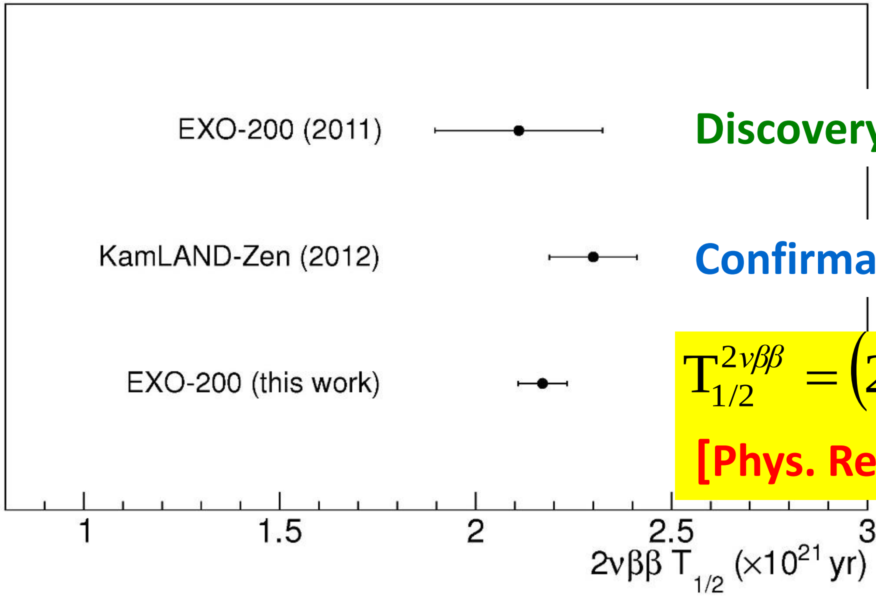
- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
- Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line

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



EXO-200 Phase-I Results

Precision ^{136}Xe 2νββ Measurement



EXO-200 start data taking in June 2011

Discovery of 2ν mode [PRL 107, 212501 (2011)]

Confirmation by KamLAND-Zen [PRC 85, 045504 (2012)]

$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\mathrm{stat}} \pm 0.059^{\mathrm{syst}}\right) \cdot 10^{21}\ \mathrm{yr}$$

[Phys. Rev. C 89 (2014) 015502]

Longest and most precisely measured 2νββ half-life

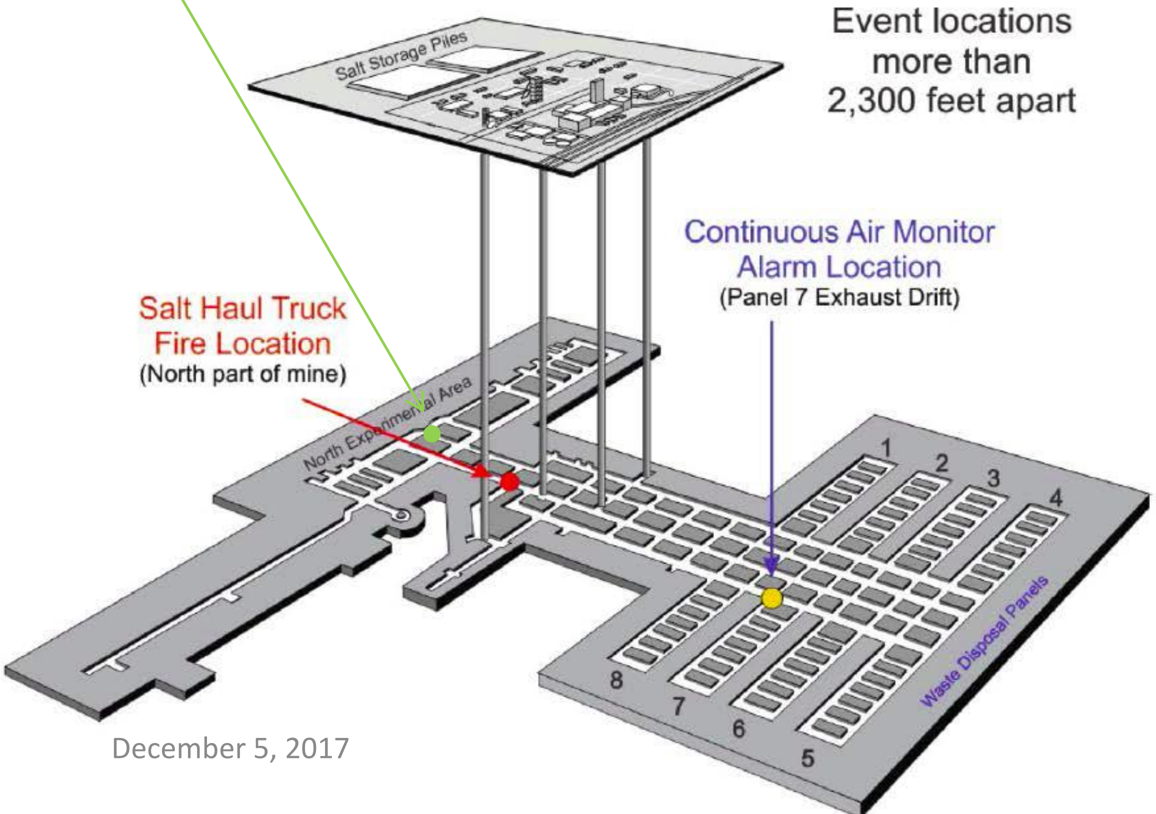
$$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}\ yr; \quad \langle m_{\beta\beta} \rangle < 190 - 450\ meV \quad (90\%\ C.L.)$$

Nature 510, 229 (2014)

Phys. Rev. Lett. 109, 032505 (2012)

The 2014 incidents

EXO-200 is about 1.2 km from the radiation event

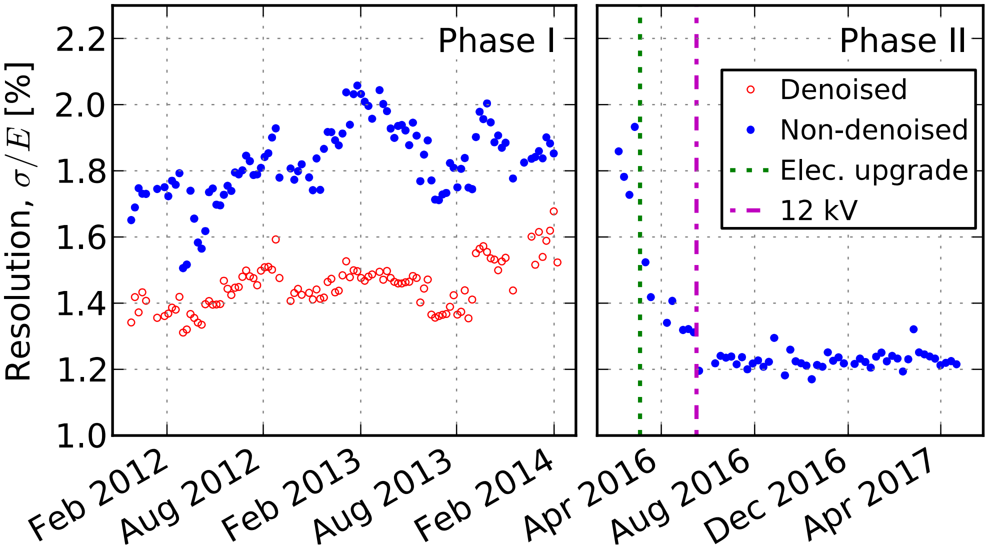


- **Feb. 5 2014:** Fire in WIPP underground
- **Feb. 14, 2014:** Radiation release event
- So far no radioactivity has been measured at EXO-200
- EXO clean up finished
- **Low background data taking resumed in April 2016**

Detector Upgrades in Phase II

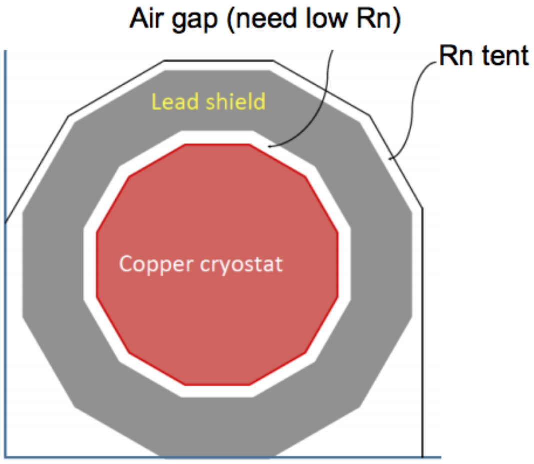
Front end electronics:

- Reduced APD read-out noise
- Increased high voltage
  - -8kV → -12 kV
- Effect in energy resolution:
  - Phase-I: $\sigma/E(Q)$ = 1.38%
  - Phase-II: $\sigma/E(Q)$ = 1.23%, steady



Deradonator:

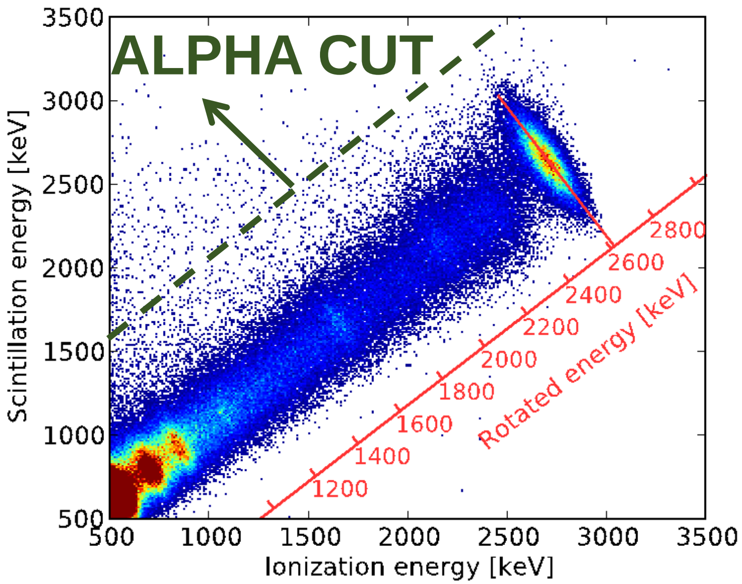
- System to suppress radon in air gap
- Direct air sampling shows radon levels reduced in the gap by >10x



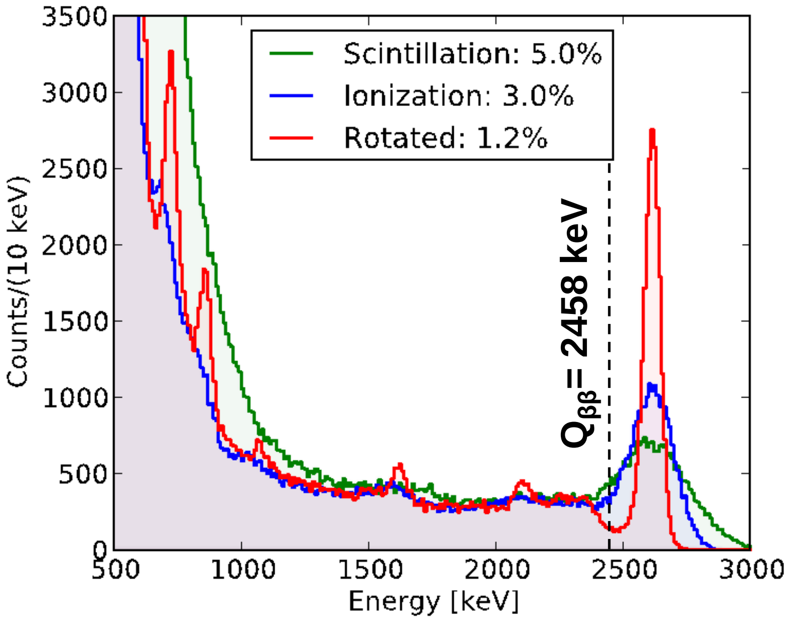
EXO-200 Clean Room Module 1

Energy measurement

Scintillation vs. ionization, ^{228}Th calibration:



Reconstructed energy, ^{228}Th calibration:

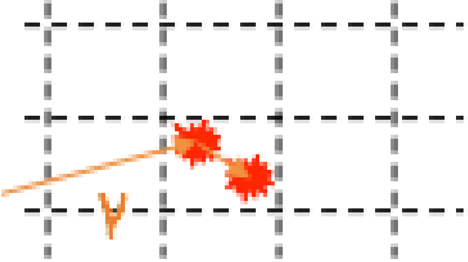


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved ~ 1.23% energy resolution at the double-beta decay Q value in Phase II.

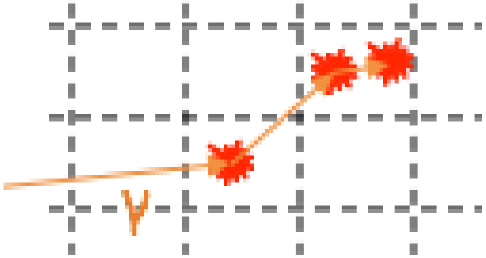
Position and multiplicity

Allows for background measurement and reduction

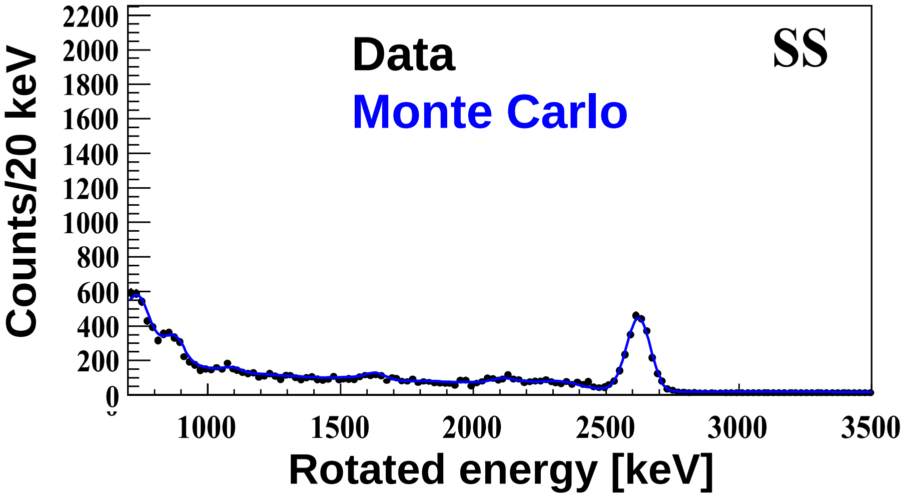
Events with **> 1** charge cluster: multi-site events
Events with **1** charge cluster: single-site events.



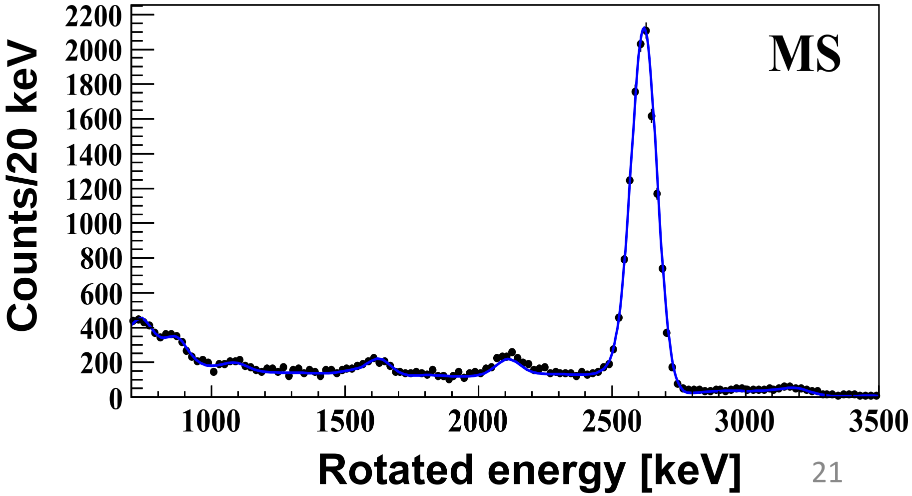
$0\nu\beta\beta$: ~90% SS
γ-rays: ~20% SS at $0\nu\beta\beta$ Q-value



^{228}Th calibration data, SS:



^{228}Th calibration data, MS:



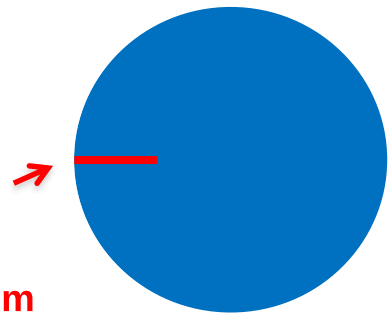
Improved γ-background Rejection

Additional discrimination in SS using *spatial distribution* and *cluster size*

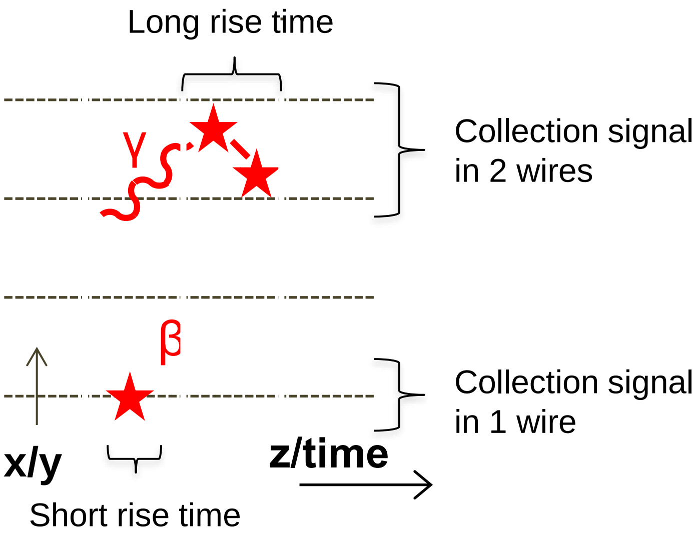
Entering γ-rays are exponentially attenuated by LXe self-shielding, providing an independent measurement of γ-backgrounds. We call this standoff distance.

The cluster size of individual events is estimated from pulse rise time (longitudinal direction) and the number of wires with a charge collection signal (transverse).

LXe self-shielding:



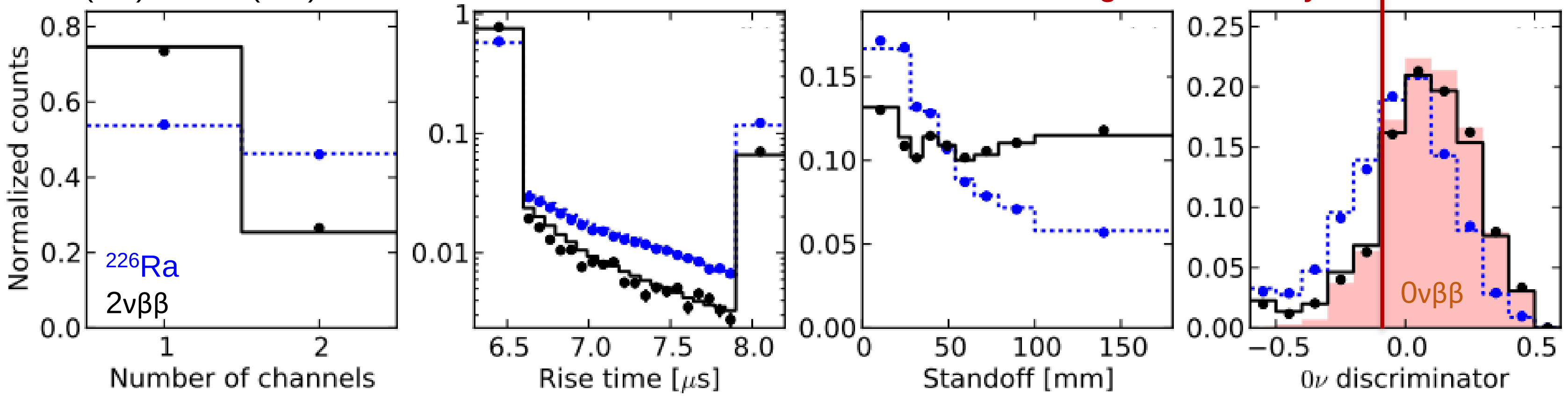
2.5 MeV γ attenuation length = 8.5 cm



Optimal $0\nu\beta\beta$ Discrimination

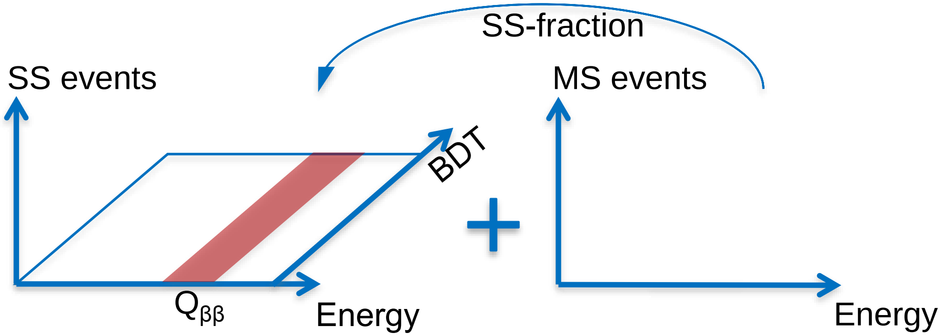
- Optimize SS discriminators into a more powerful one
  - Using a boosted decision tree (BDT)

Data (dot) vs MC (line)



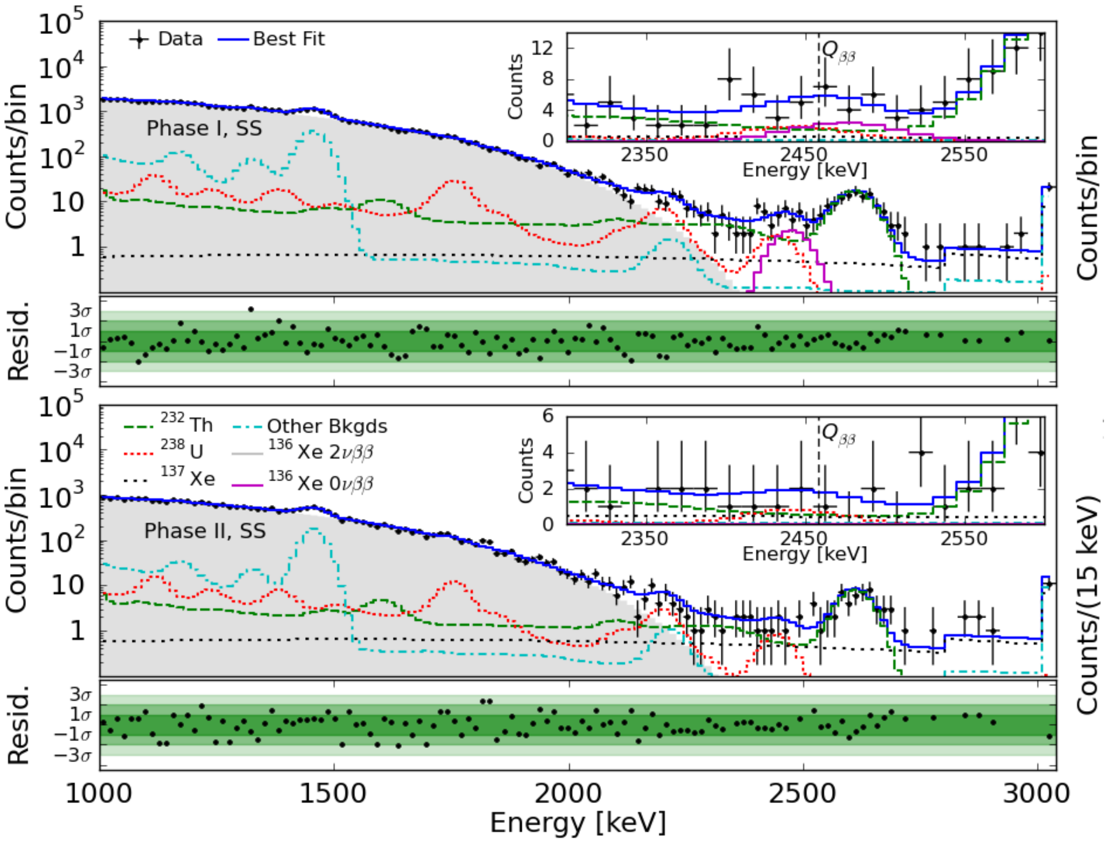
~35% γ-rejection
~90% signal efficiency

- Fitting $0\nu\beta\beta$ discriminators
  - Energy
  - SS/MS
  - *BDT → ~15% sensitivity improvement*

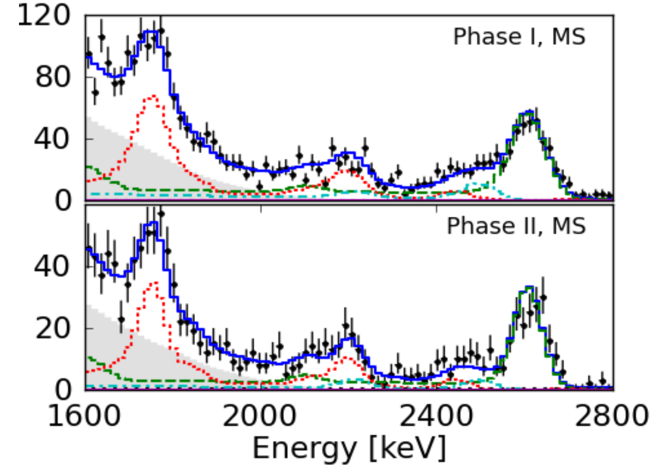


0νββ Search Results

- Background model + data → maximum likelihood fit
- Combine Phase I + Phase II profiles



Systematics	Phase I (%)	Phase II (%)
Detection efficiency	82.4 ± 3.0	80.8 ± 2.9
Shape differences	±6.2	±6.2
SS fraction	±5.0	±8.8



- Background index ~ 1.5±0.2 x10^{-3} counts/(kg yr keV)
- No statistically significant excess: combined p-value ~1.5σ

Sensitivity & Limits

Combined analysis of Phase I and Phase II:

- Total exposure = 177.6 kg yr

Sensitivity of 3.7 x 10^{25} yr (90% CL)

$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 147 - 398$ meV

(90% C.L.)

- Individual phase limits

	Livetime	Exposure	Limit (90% CL)
Phase I	596.7 d	122.0 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 1.0\text{x}10^{25}$ yr
Phase II	271.8 d	55.6 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 4.4\text{x}10^{25}$ yr

Caio Licciardi, TAUP 2017 and **arXiv:1707.08707**

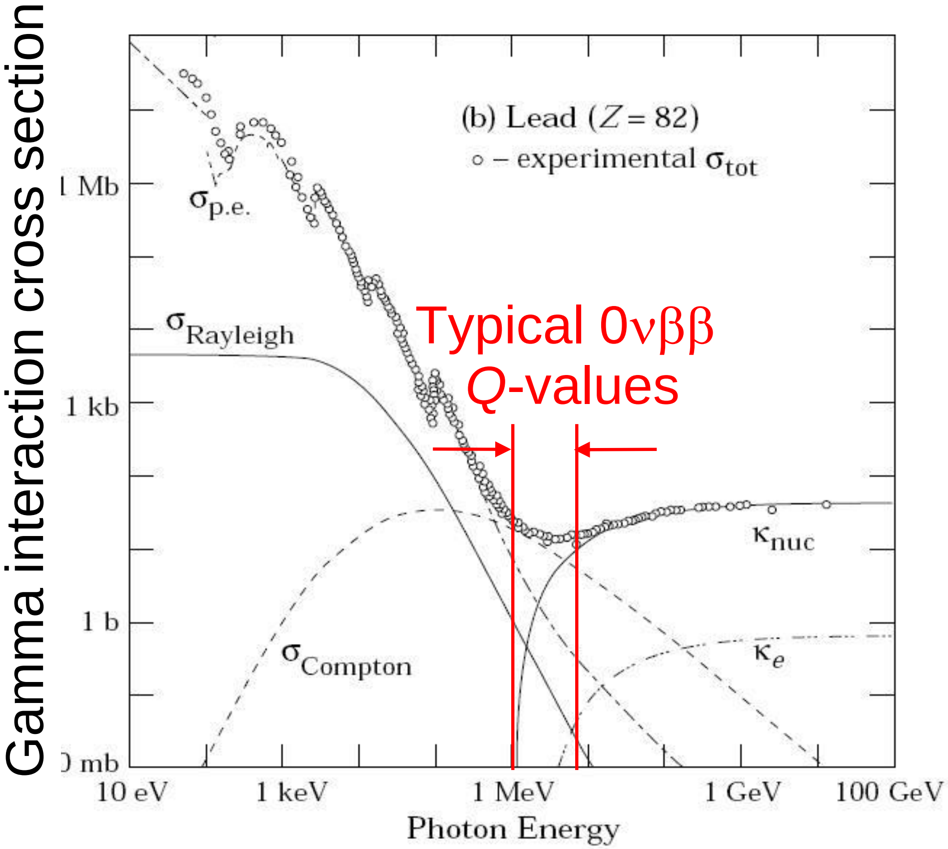
Current best $0\nu\beta\beta$ sensitivities

Isotope	Experiment	Exposure (kg yr)	$T_{1/2}^{0\nu\beta\beta}$ average sensitivity (10^{25}yr)	$T_{1/2}^{0\nu\beta\beta}$ (10^{25}yr) 90%CL	$< m_\nu >$ (meV) Range from NME*	Reference
^{76}Ge	GERDA	46.7	5.8	>8.0	<120-270	L. Pandola for GERDA Collab, TAUP 2017
	Majorana Demonstrator	10	>2.1	>1.9	<240-520	C.E. Aalseth, arXiv:1710.11608v1
^{130}Te	CUORE	86.3	0.7	>1.5	<140-400	C. Alduino, et al., arXiv:1710.07988v1
^{136}Xe	EXO-200	177.6	3.7	>1.8	<147-398	Albert et al. arXiv: 1707.08707 (2017)
	KamLAND-ZEN	504**	4.9	>11 (run 2)	<60-161	Gando et al., PRL 117 (2016) 082503

Note that the range of “viable” NME is chosen by the experiments and uncertainties related to g_A are not included. ** All Xe. Fiducial Xe is more like ~150 kg yr

To achieve higher sensitivity, the next generation of experiments will be at the ton-scale.

γ backgrounds – a challenge in $0\nu\beta\beta$ search



Shielding a detector from MeV gammas is difficult!

Example:

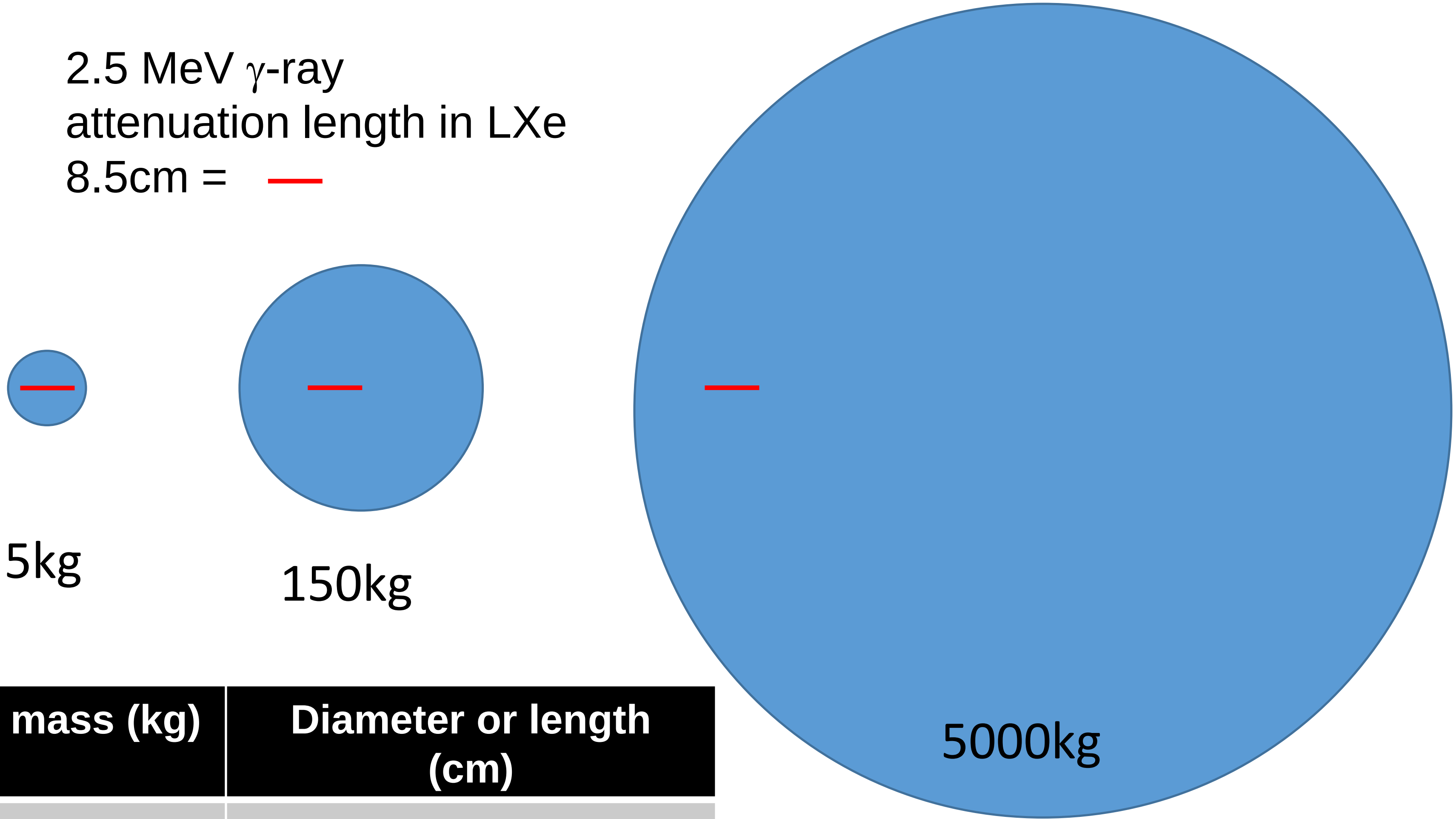
γ–ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding $0\nu\beta\beta$ decay detectors is much harder than shielding dark matter detectors

We are entering the "golden era" of $0\nu\beta\beta$ decay experiments as detector sizes exceed interaction length

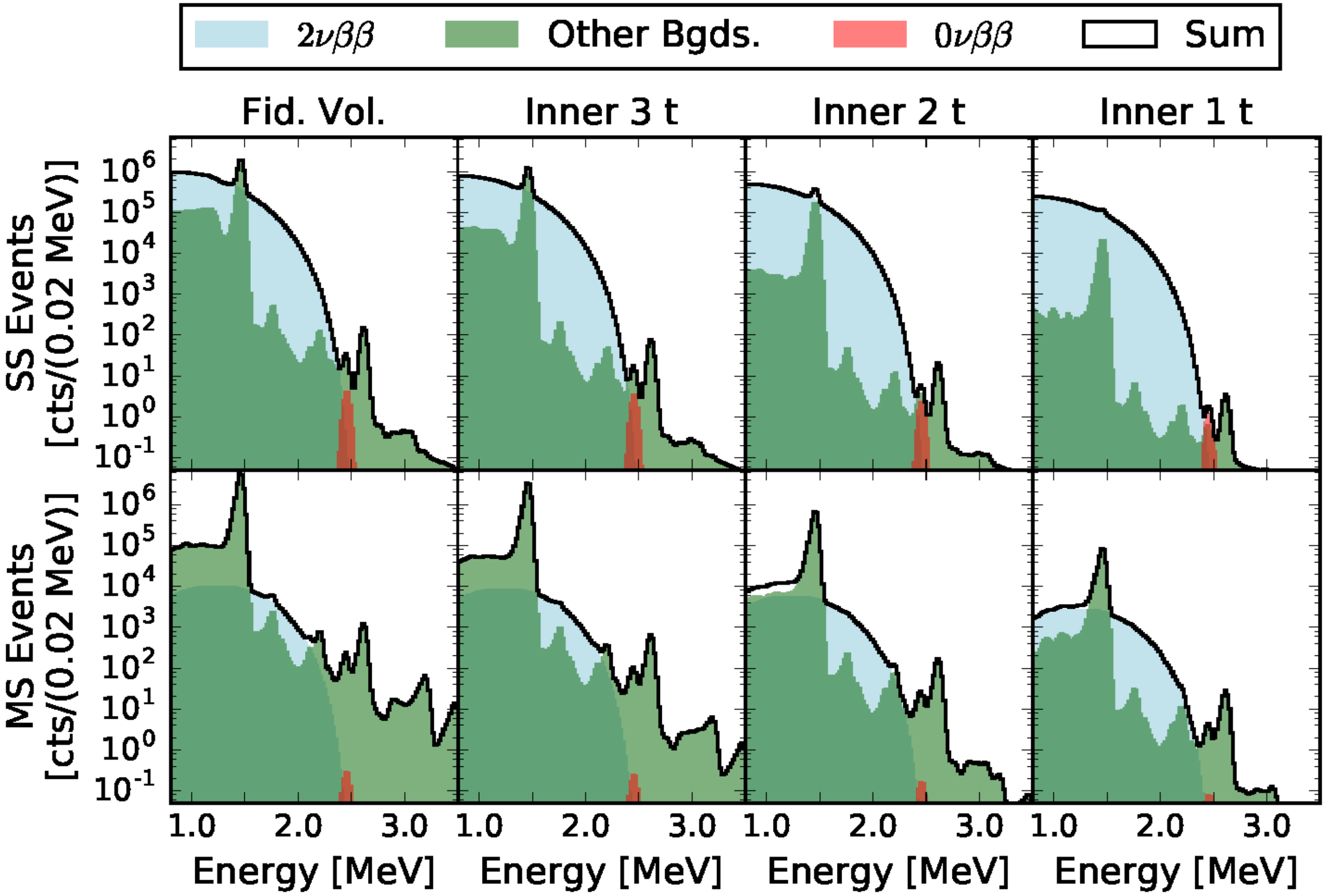
Monolithic detectors

2.5 MeV γ-ray
attenuation length in LXe
8.5cm = —



LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

nEXO discovery potential

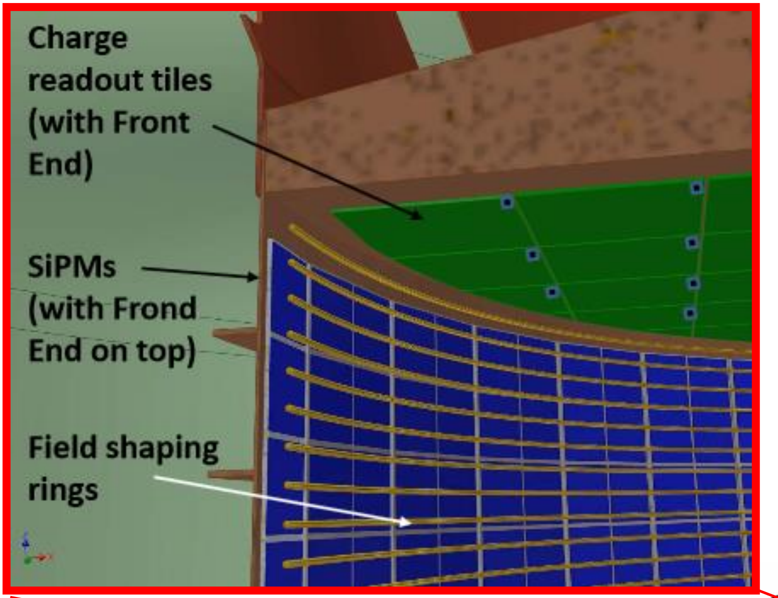


nEXO 10 year discovery potential at $T_{1/2}$=5.7x10^{27} yr

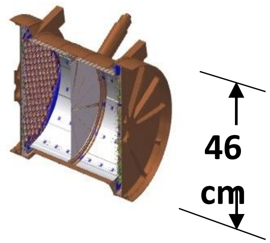
J.B. Albert et al., “Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay”, arXiv:1710.05075, 16 Oct 2017.

Searching for 0νββ with nEXO

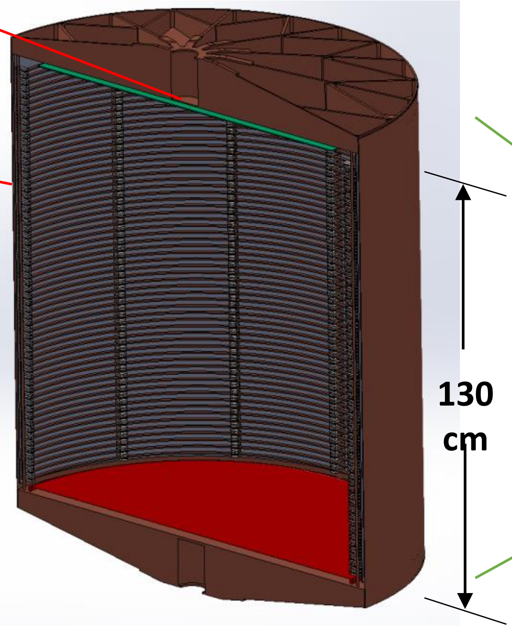
- 5 t liquid xenon TPC similar to EXO-200
- SiPM for light detection
- Tiles for charge read out
- 3D event reconstruction
- Required σ/E of 1% at Q-value
- Possible addition of Ba-tagging after 5 yrs



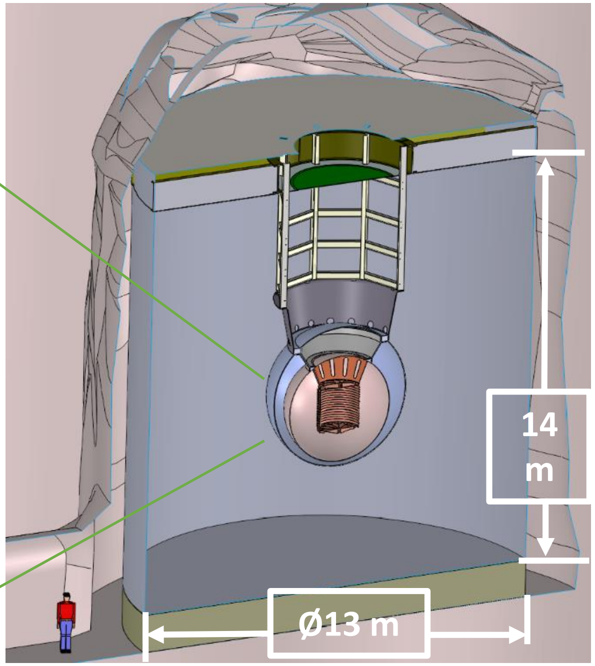
EXO-200 for size comparison



50x the size



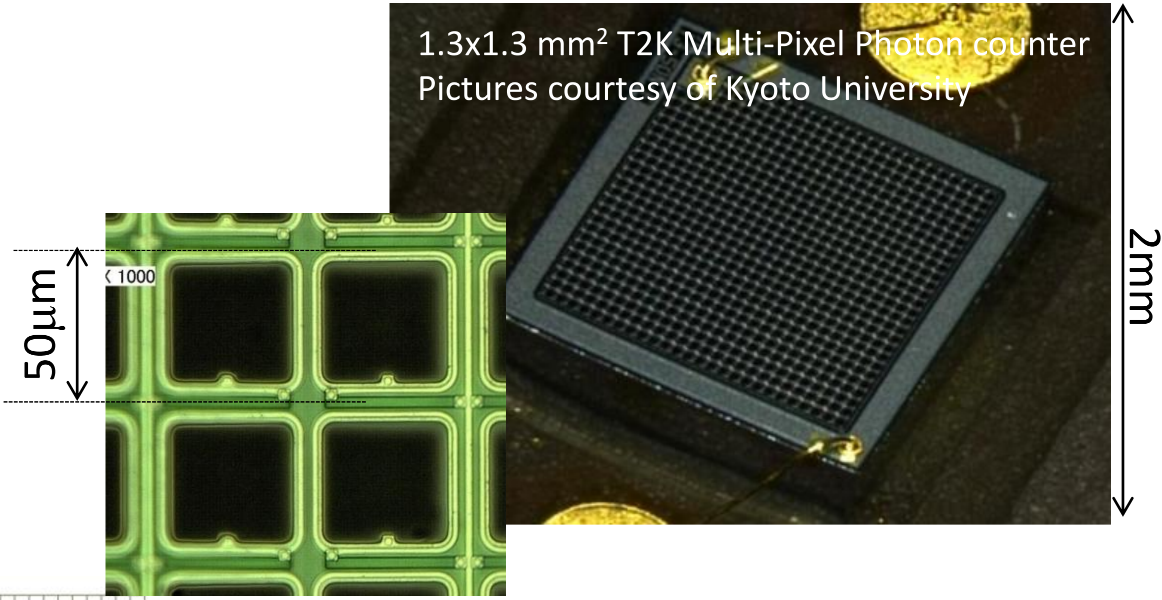
nEXO TPC

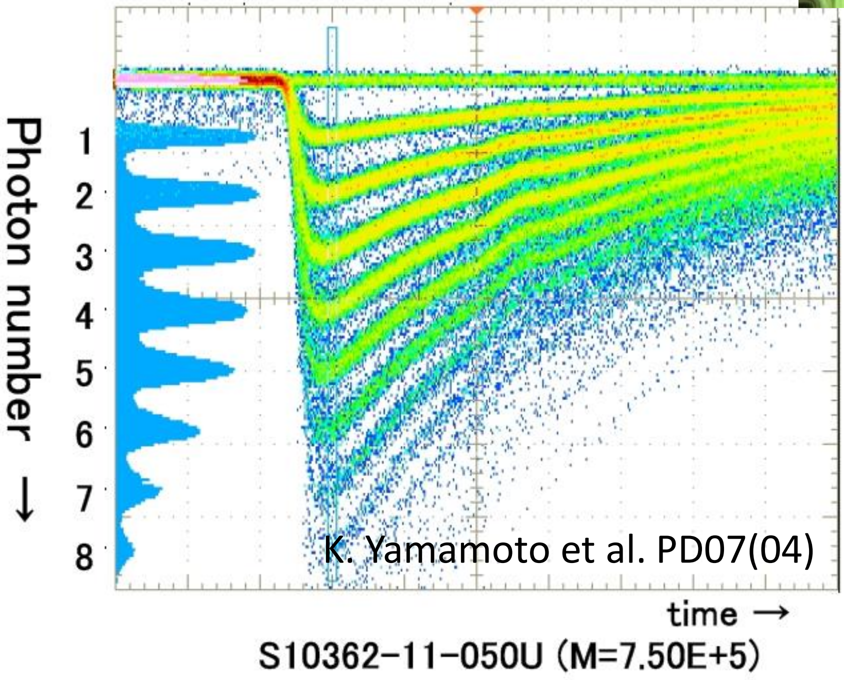


nEXO at the SNOlab Cryopit

Analog SiPMs - baseline solution for nEXO

- High gain (low noise)
- Large manufacturing capabilities (> 4 m^2)
- But efficiency and radioactivity need work


1.3x1.3 mm^2 T2K Multi-Pixel Photon counter
Pictures courtesy of Kyoto University

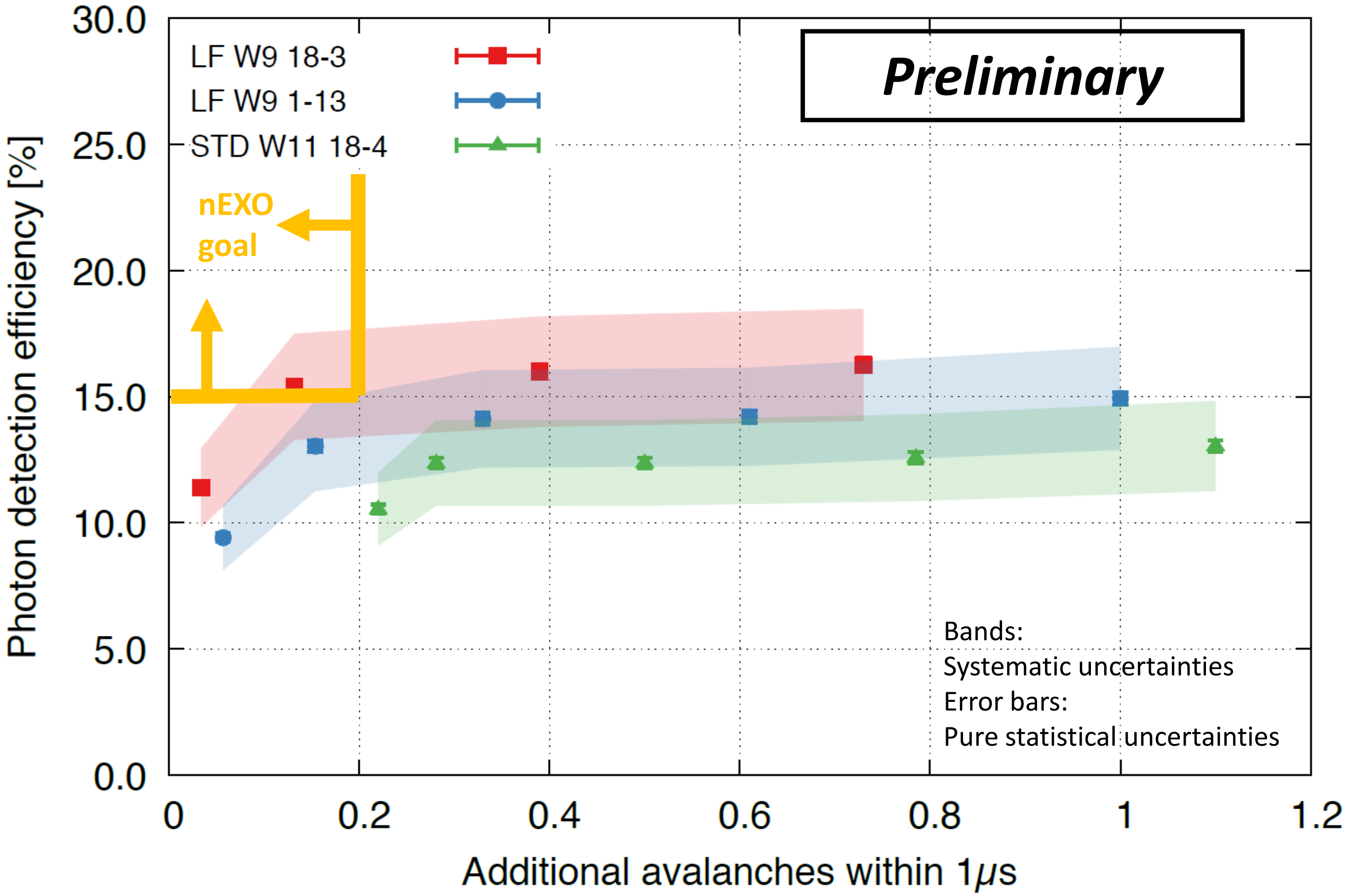

K. Yamamoto et al. PD07(04)

Requirements:

- Efficiency at 175nm > 15%
- Correlated avalanche rate < 20%
- Dark noise rate < 50Hz/mm^2
- Low radioactivity

SiPM Photodetector

At least one type of 6 x 6 mm^2 VUV devices now match our desired properties, with a bias requirement ~30V (as opposed to the 1500V of EXO-200 APDs)



FBK low field SiPM: Th = 0.45+/-0.12 ppt, U = 0.86+/-0.05 ppt

FBK standard field SiPM: Th = 0.44+/-0.05 ppt, U = 0.99+/-0.02 ppt

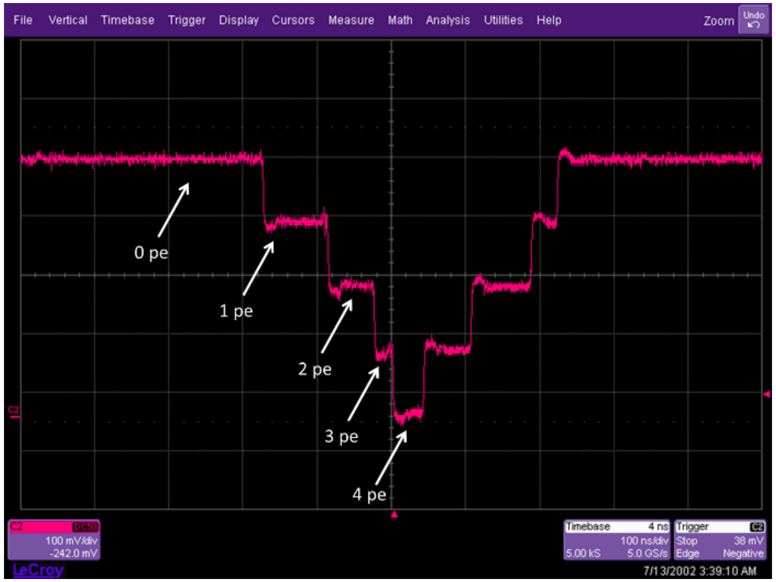
3D-integrated dSiPM for nEXO

Advantages over analog SiPM + analog electronics

- All in one chip assembly: **photon come in, bits come out**
- **Low power**: Power scales with avalanche count not with capacitance
- Allow lower power or better timing resolution and granularity
- After-pulsing can be completely eliminated for a given time scale

Challenges

- Need custom SPAD array
- Large scale scaling
- Significant R&D required

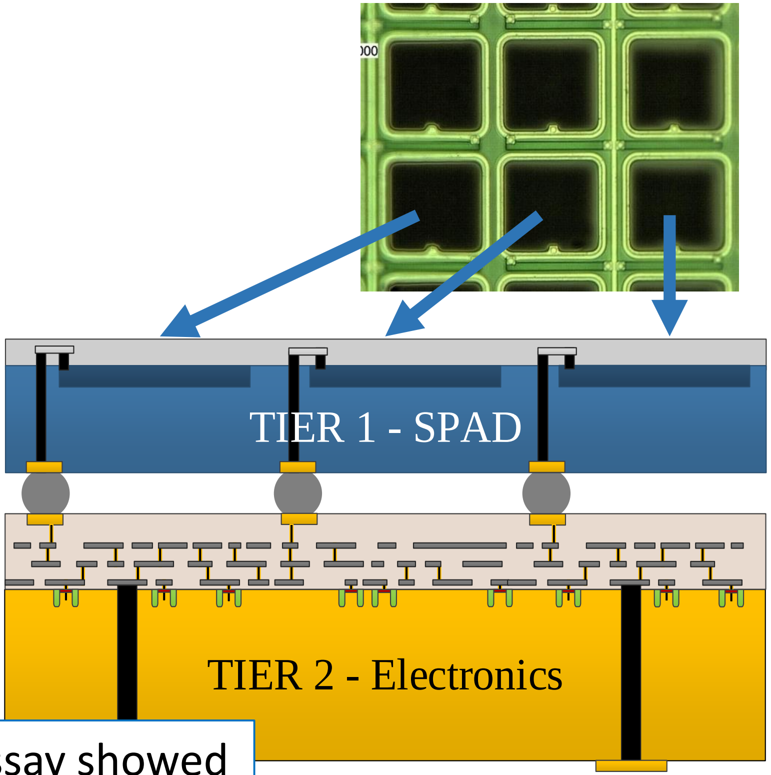


C2 DC50 100 mV/div -242.0 mV

Timebase 4 ns 100 ns/div 5.00 kS 5.0 GS/s

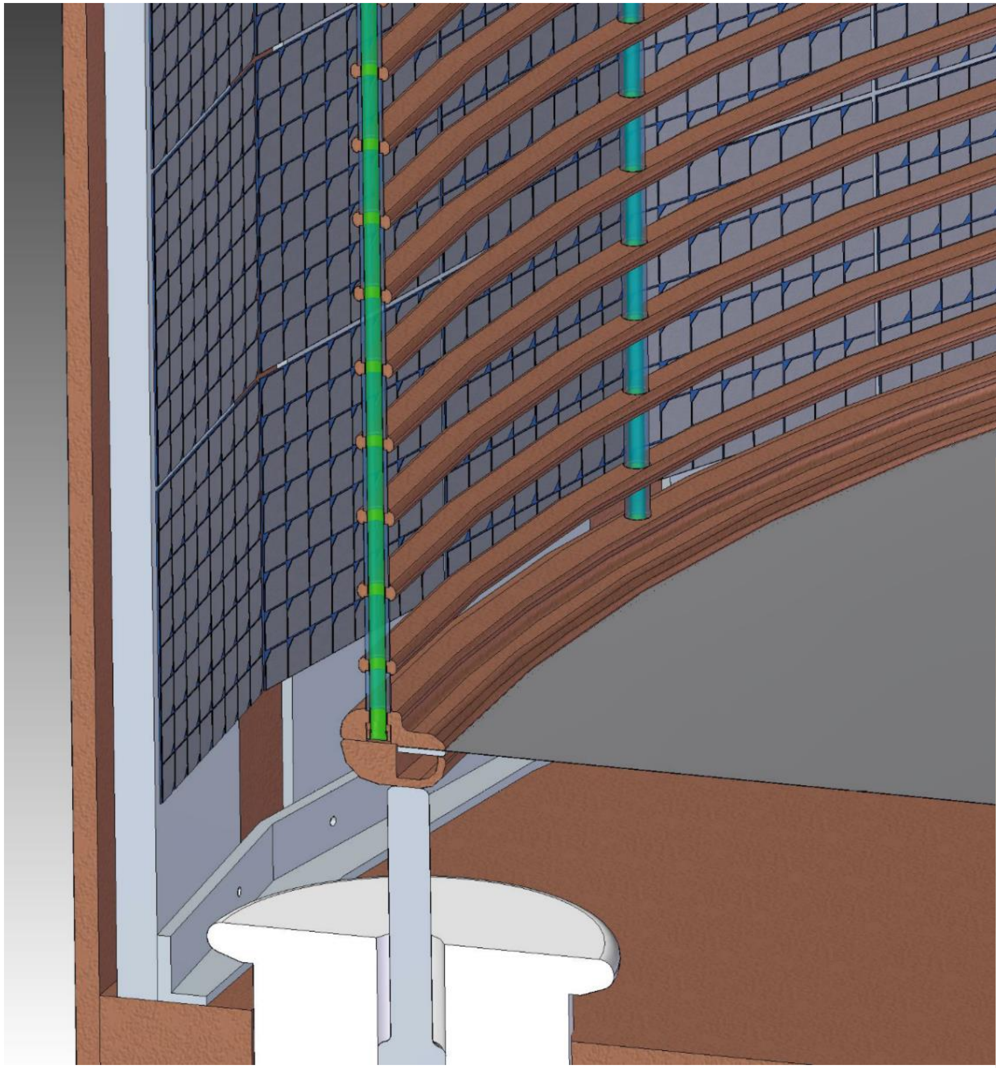
Trigger C2 Stop 38 mV Edge Negative

7/13/2002 3:39:10 AM

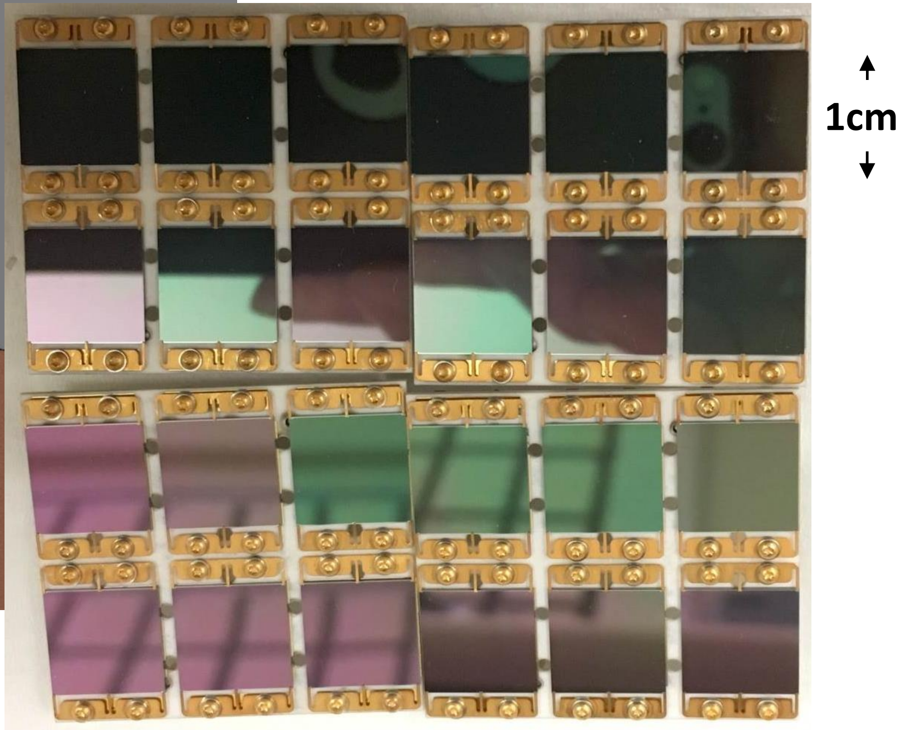


nEXO radio assay showed sub-ppt Th/U purity

Photon sensors



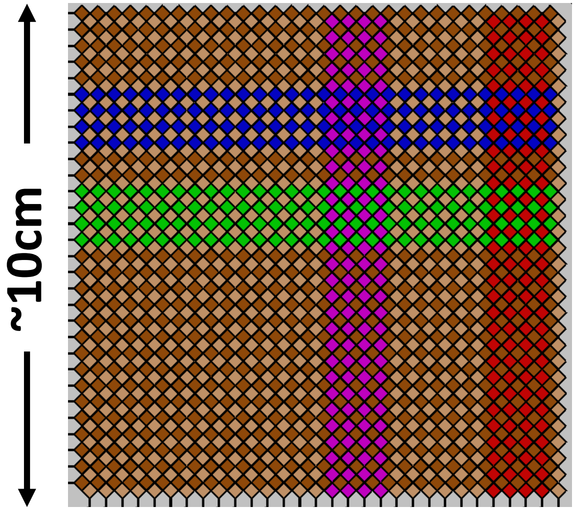
- **Need ~4m^2 of VUV-sensitive SiPMs**
- **SiPMs and electronics mounted in LXe**
- **Increase photon detection efficiency through reflective surfaces**

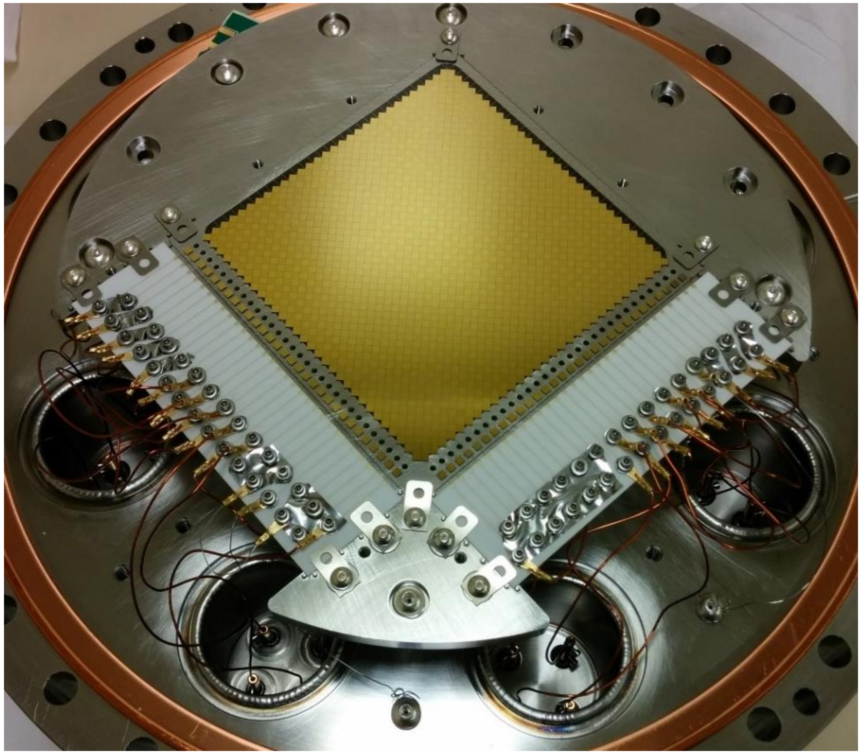


Charge Readout

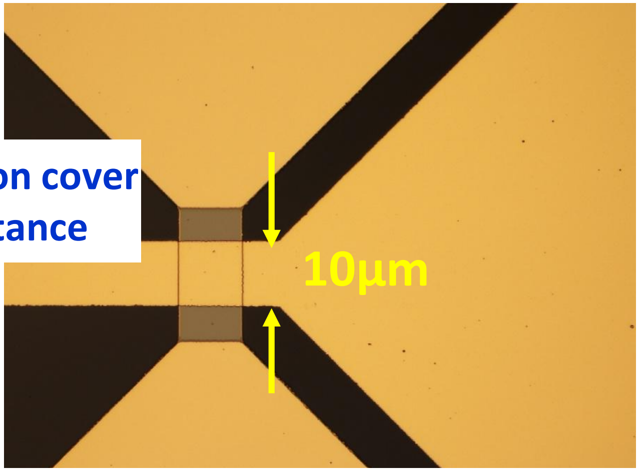
Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (low radioactivity quartz has been identified)

- Self-supporting/no tension
- Built-on electronics (on back)
- Far fewer cables
- Ultimately more reliable, lower noise, lower activity





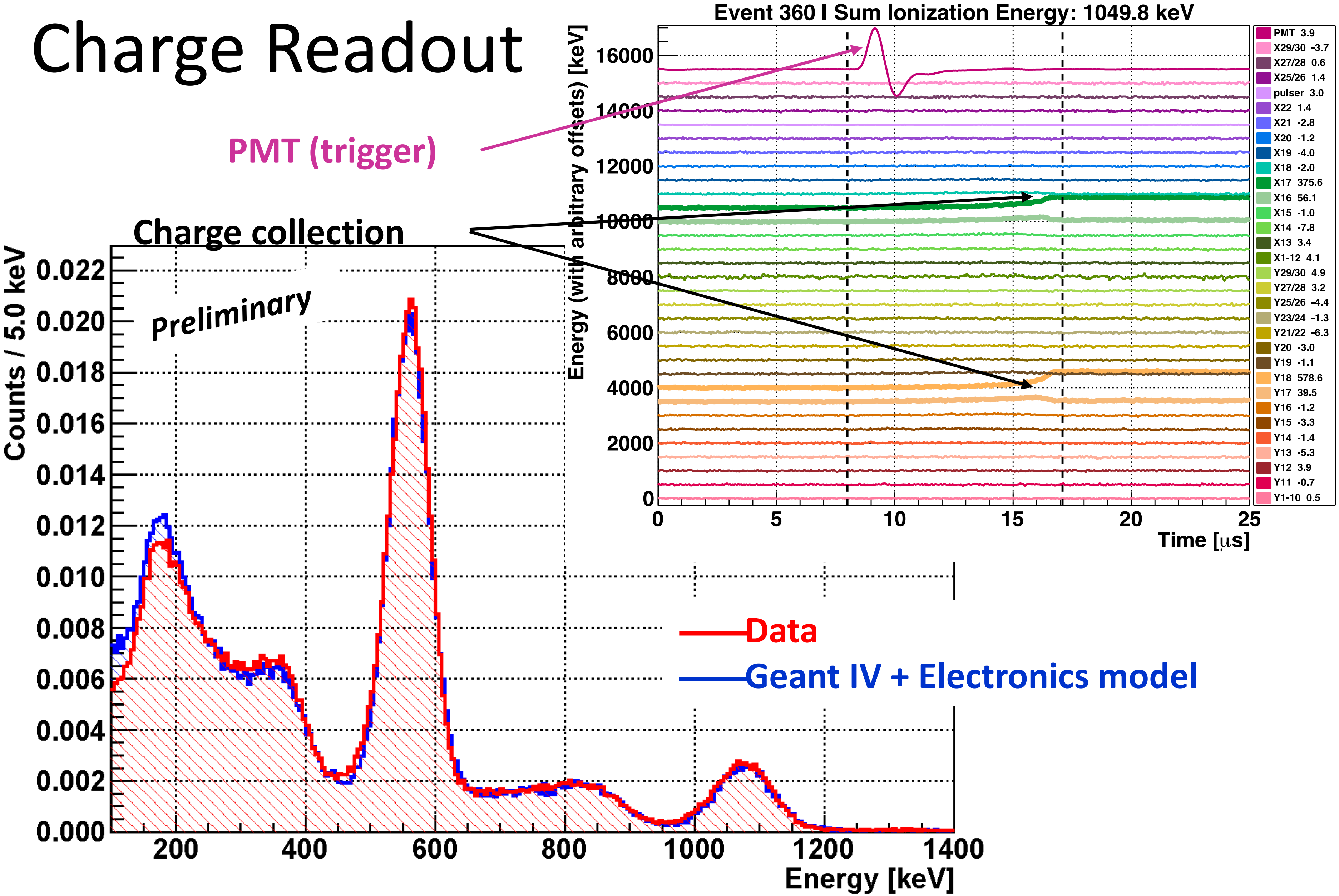
Max metallization cover with min capacitance



- 10 x 10cm^2 Prototype Tile
- Metallized strips on fused silica substrate
- 60 orthogonal channels (30 x 30), 3mm strip pitch
- Strip intersections isolated with SiO_2 layer

Characterization of an Ionization Readout Tile for nEXO, M. Jewell arXiv:1710.05109

Charge Readout



PMT (trigger)

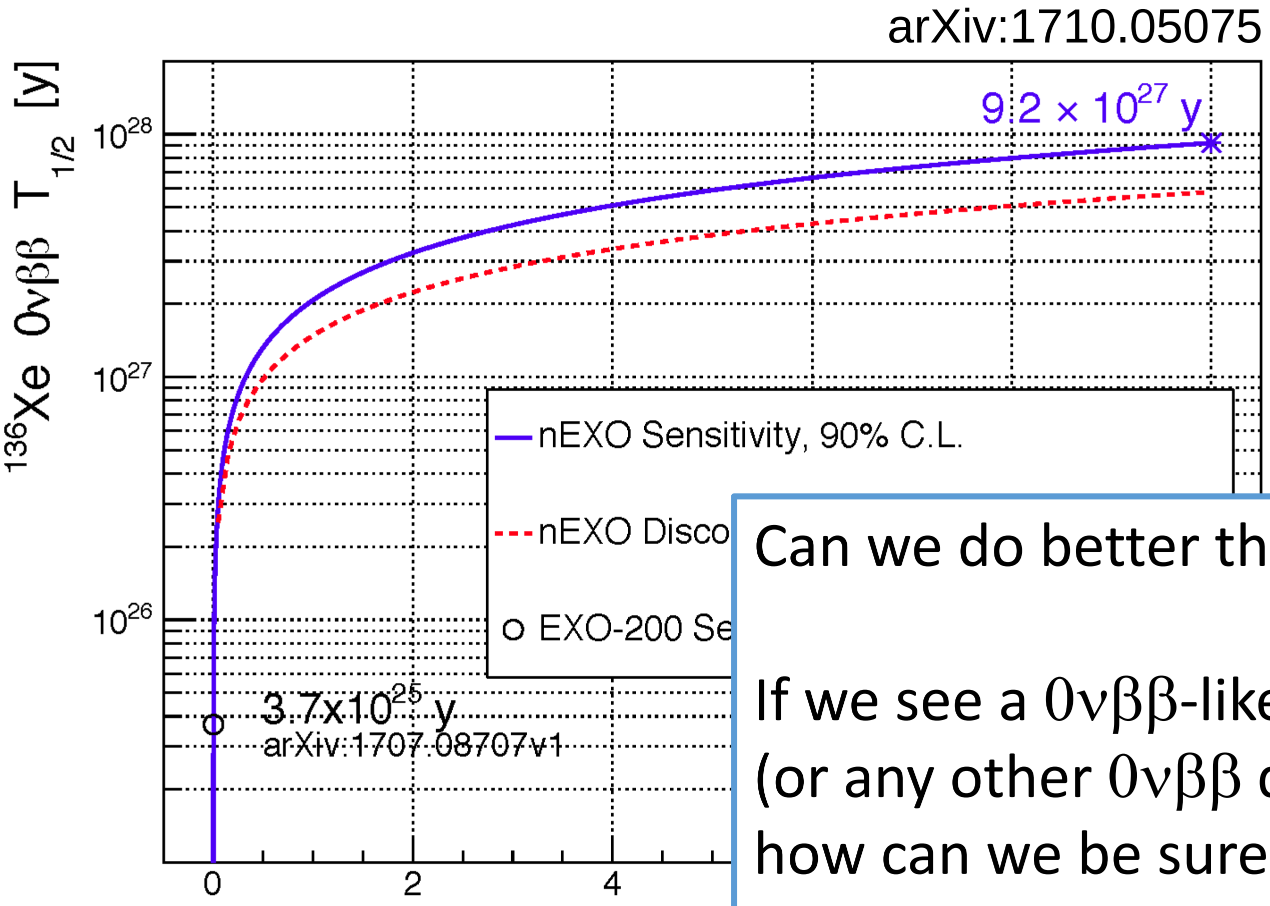
Charge collection

Data

Geant IV + Electronics model

Characterization of an Ionization Readout Tile for nEXO, M. Jewell arXiv:1710.05109

nEXO Sensitivity & Discovery Potential



Can we do better than this?

If we see a 0νββ-like signal with nEXO (or any other 0νββ detector), how can we be sure it really is 0νββ?

The answer might be Ba-tagging.

Methodology:

- 3860 kg fiducial Xe
- 90% enrichment
- 1% σE/E resolution

round
ed on

alysis

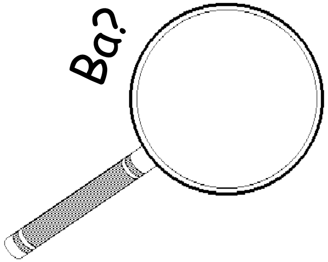
Ba-tagging concept

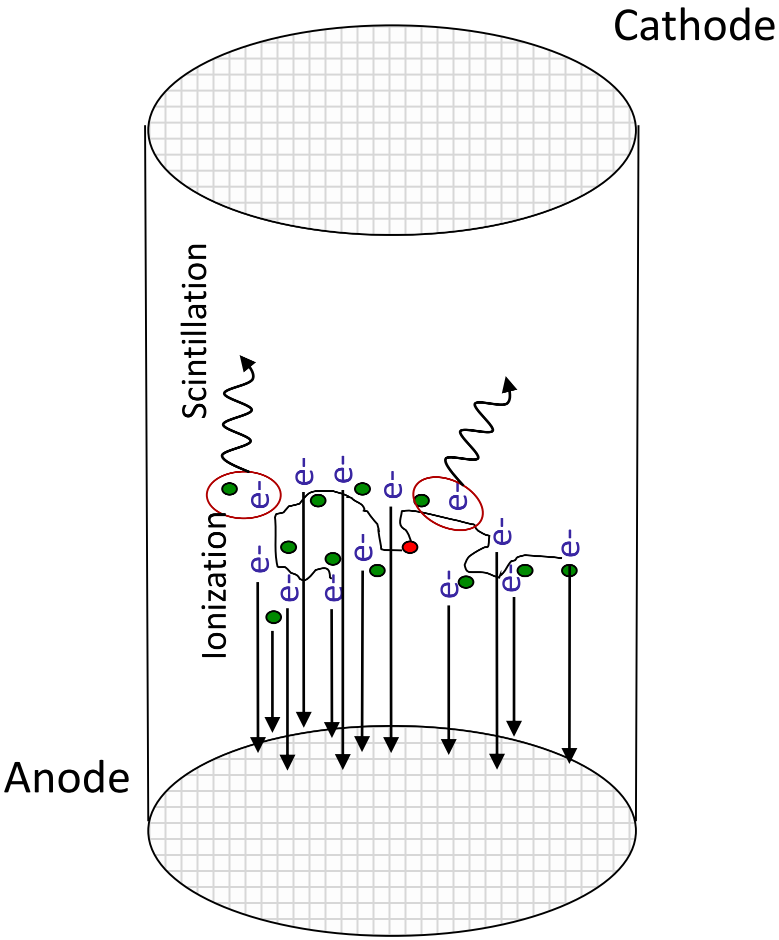
1. Localize event √
2. Is the event of interest? √
   - Close to Q-value?
   - Beta-like event?
3. Extract ion from detector volume ?
4. Identify ion: is it barium? √

Ion Fraction Measurement with EXO-200

$^{214}\mathrm{Bi}^{+}$ from $^{214}\mathrm{Pb}$ β decay: 76.4 ± 5.7%

Phys. Rev. C 92(2015)045504





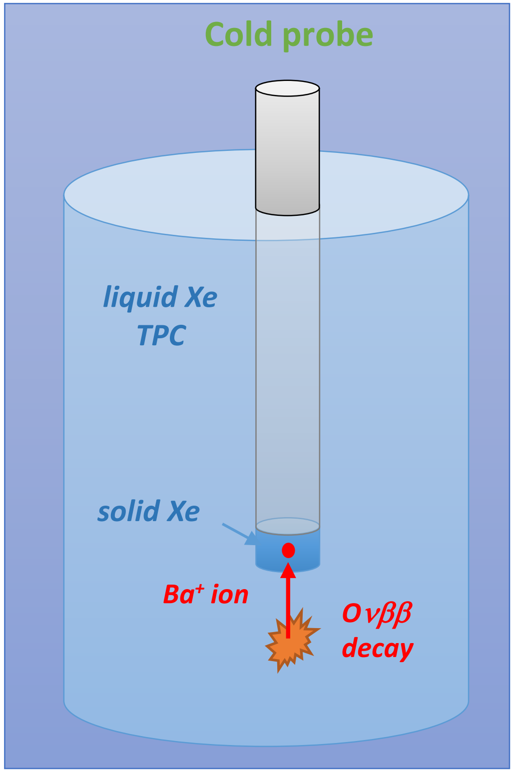
Ba tagging R&D ongoing for liquid- and gas-phase detector

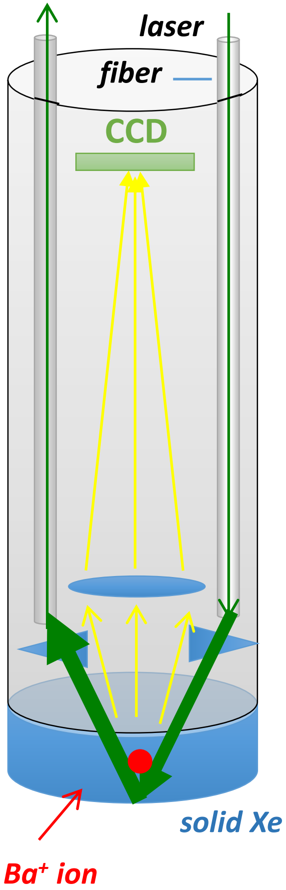
Barium tagging in solid xenon @ CSU

Tagging concept

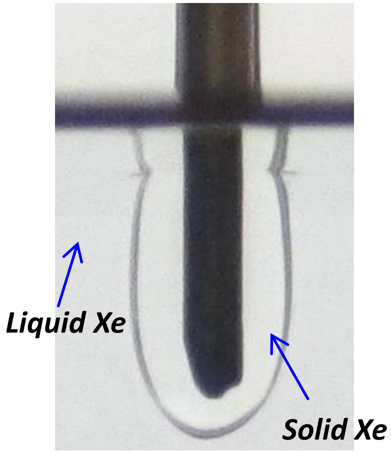
1, Capture Ba$^+$ daughter in solid xenon on a probe:

2, Detect single Ba$^+$ or Ba on probe by fluorescence:

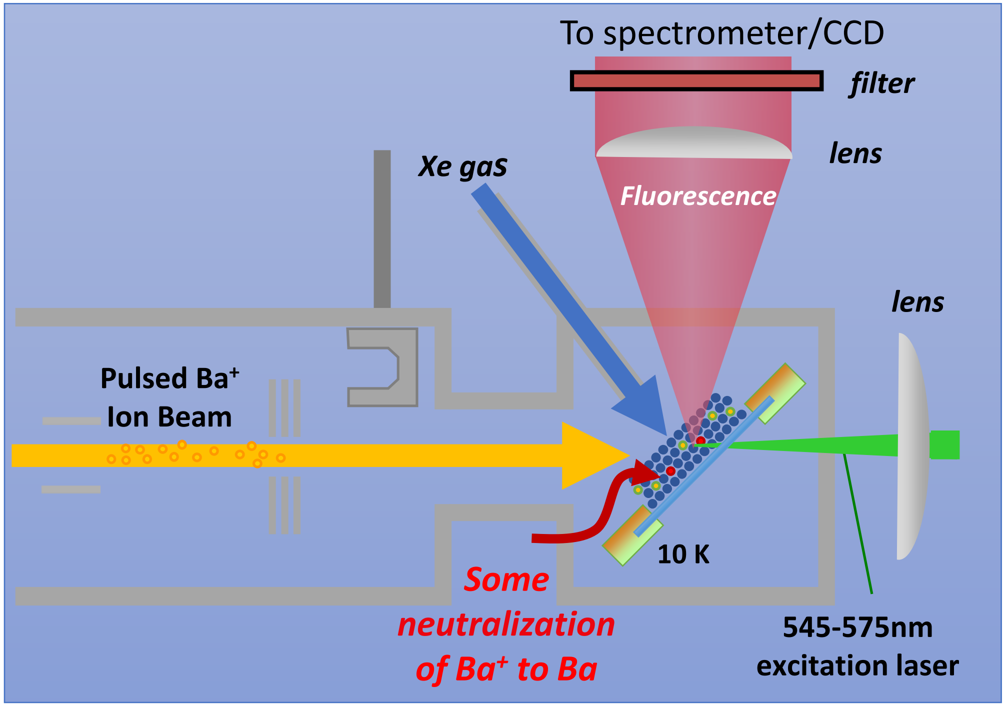




Solid Xe formed on a cryoprobe in liquid xenon



Barium tagging test apparatus



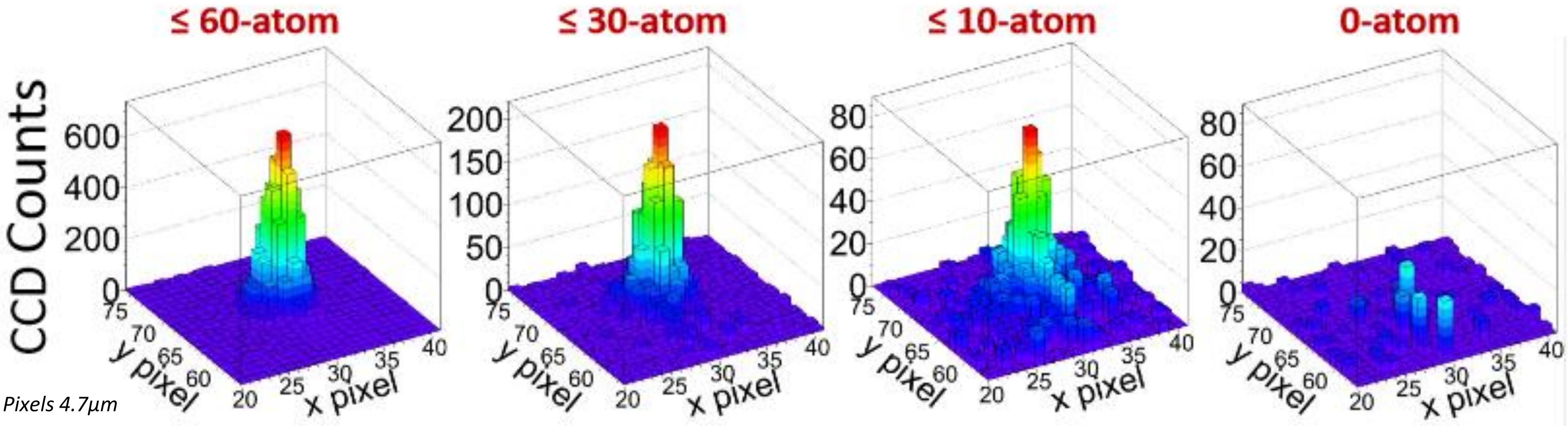
Details:
Mong et al. (nEXO collaboration), PRA 91, 022505 (2015)

Successful spectroscopy of Ba-ions in SXe (CSU)

Technique to reach small-number sensitivity:

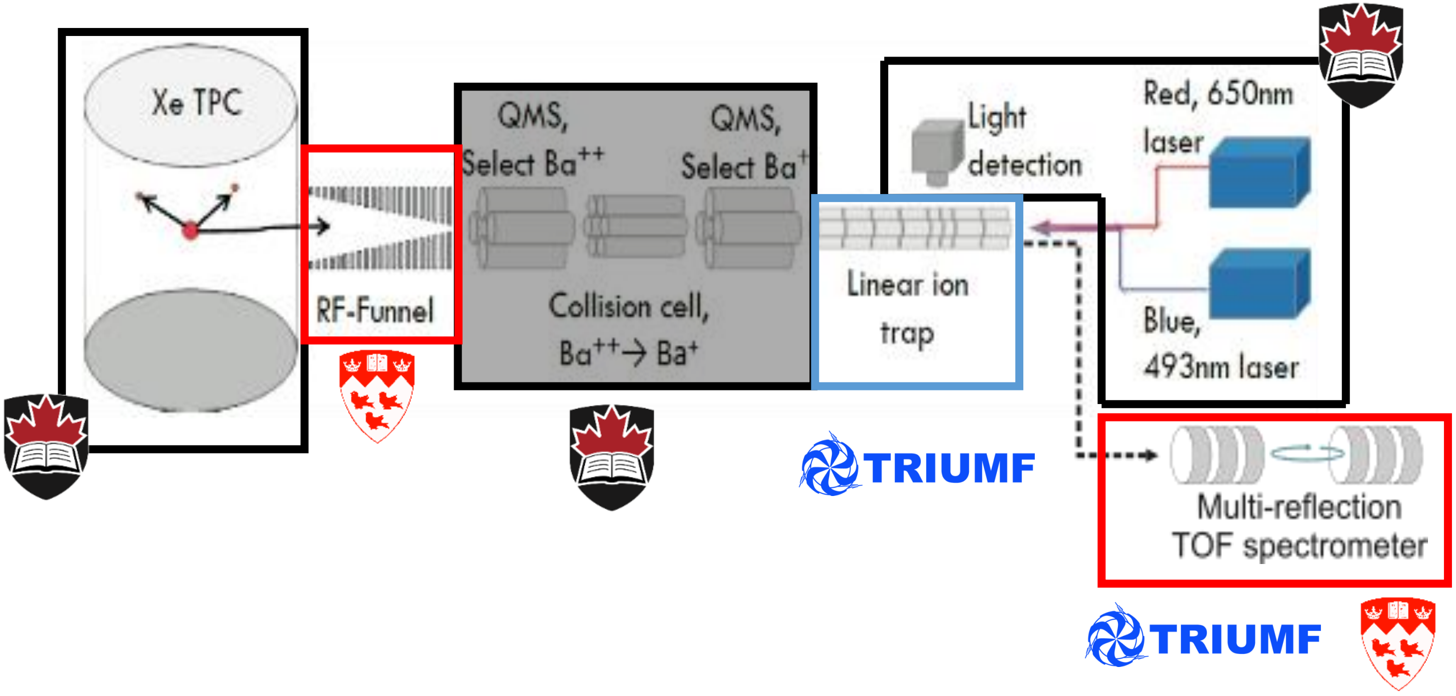
1. Focus laser down to w = 2.3μm for small viewing area
2. Pulse ion beam with varying numbers of pulses

Imaging 619nm Fluorescence
~220 cts/(atom *mW)



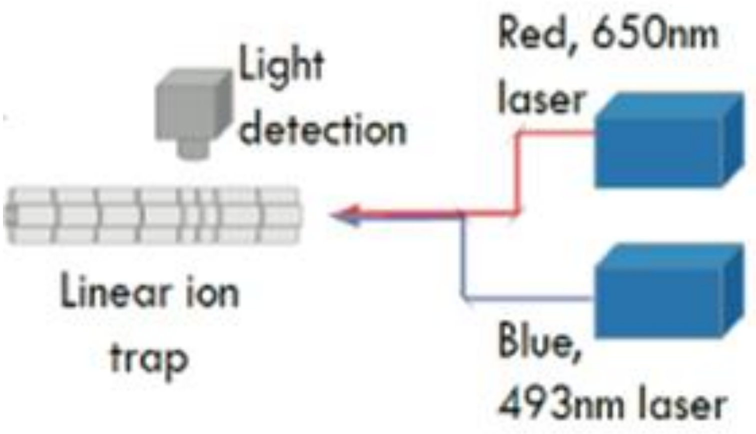
Pixels 4.7μm

Ba-ion extraction and identification – the Canadian approach

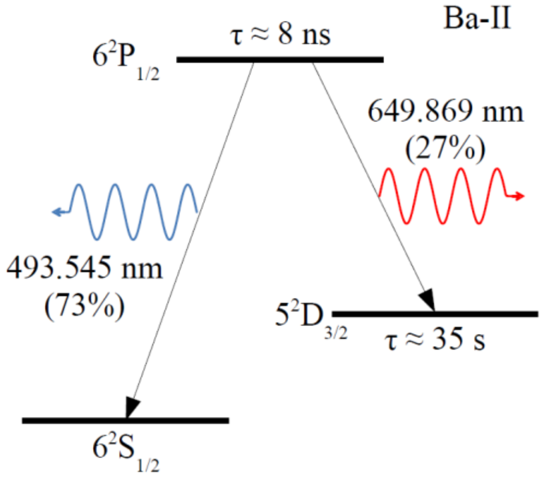


- Extract $Ba^{+(+)}$ from liquid Xe TPC into a Xe gas environment
- Extract $Ba^{+(+)}$ with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide $Ba^{+(+)}$ to identification

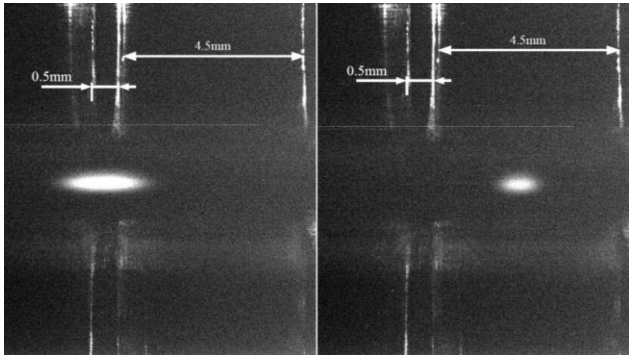
Ba ion detection & identification (Carleton)



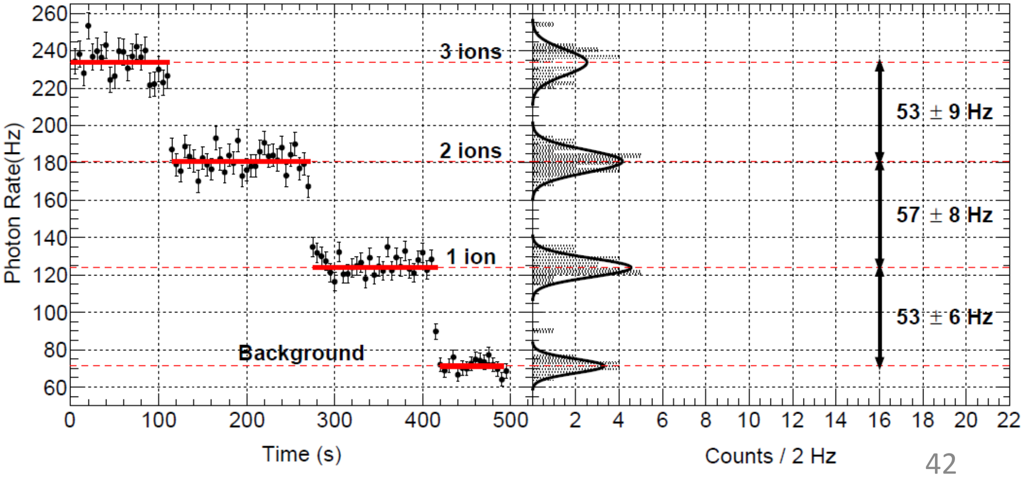
Using a relatively simple and well understood fluorescing system



Demonstrated ion cloud imaging and accurate position control

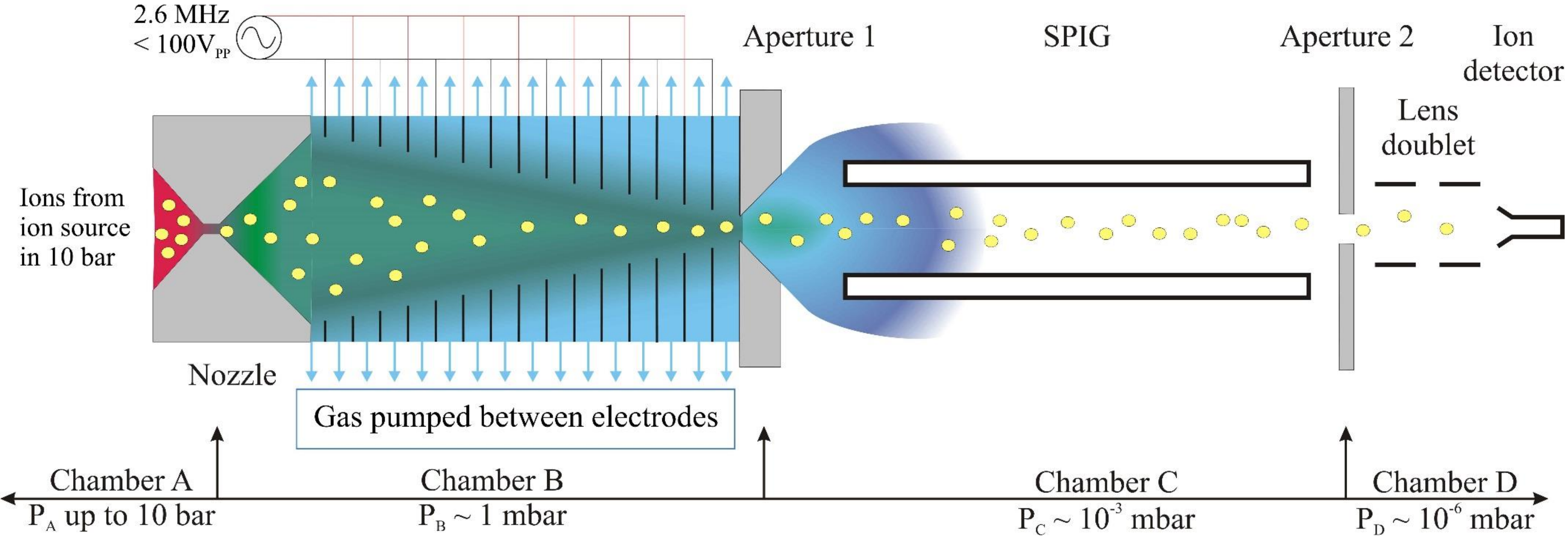


Demonstrated single ion sensitivity using intermodulation technique (background control)



Demonstrated by M. Green et al., Phys. Rev. A **76** 023404 (2007)

Stanford RF funnel (now at McGill)



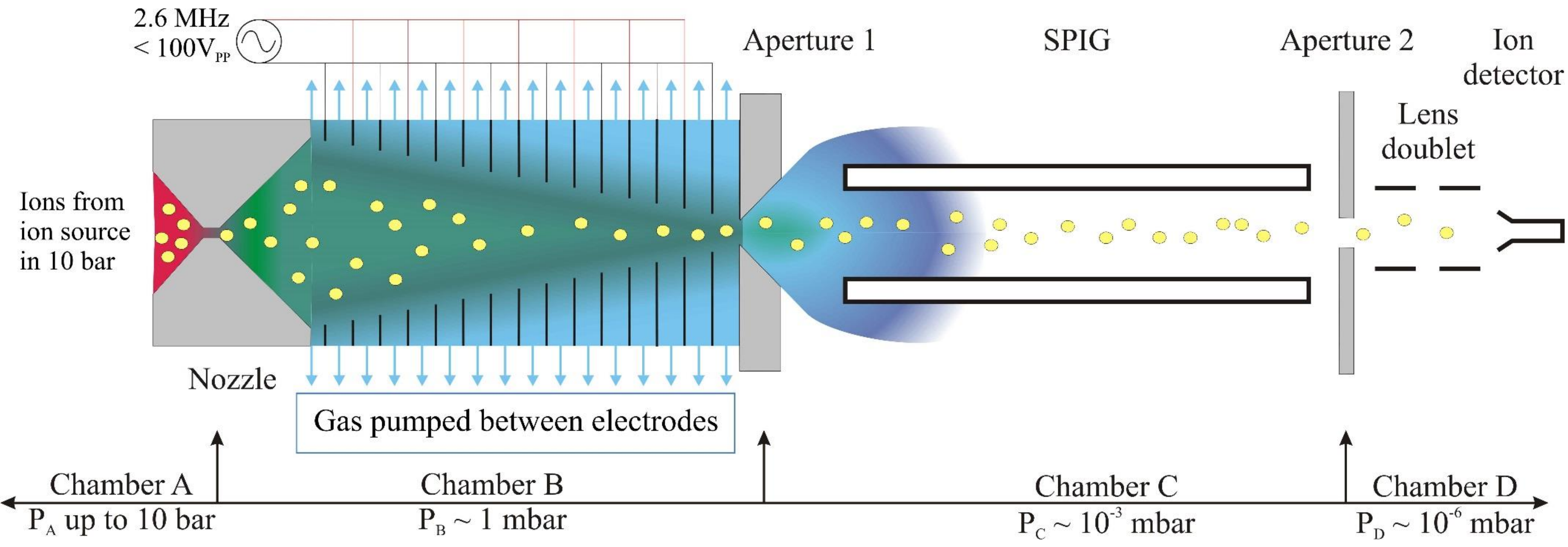
RF-funnel concept:

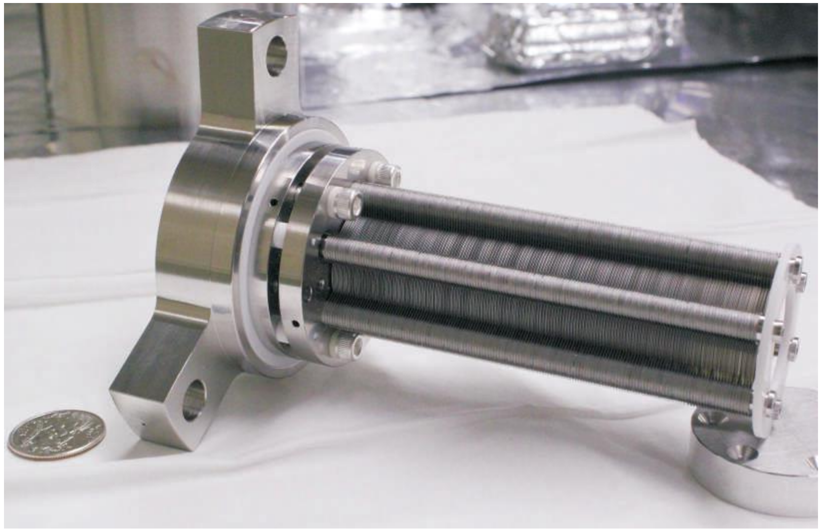
- Converging-diverging nozzle
- 2 Stacks total 301 electrodes
- RF-field applied to electrodes
- P_A = 10 bar, P_B = 1 mbar

V_{RF} = 120 V, f = 10 MHz
Simulated Ba$^+$ transmission
~95%

V_{RF} = 25V, f = 2.6 MHz
Simulated Ba$^+$ transmission
~72%

Stanford RF funnel (now at McGill)





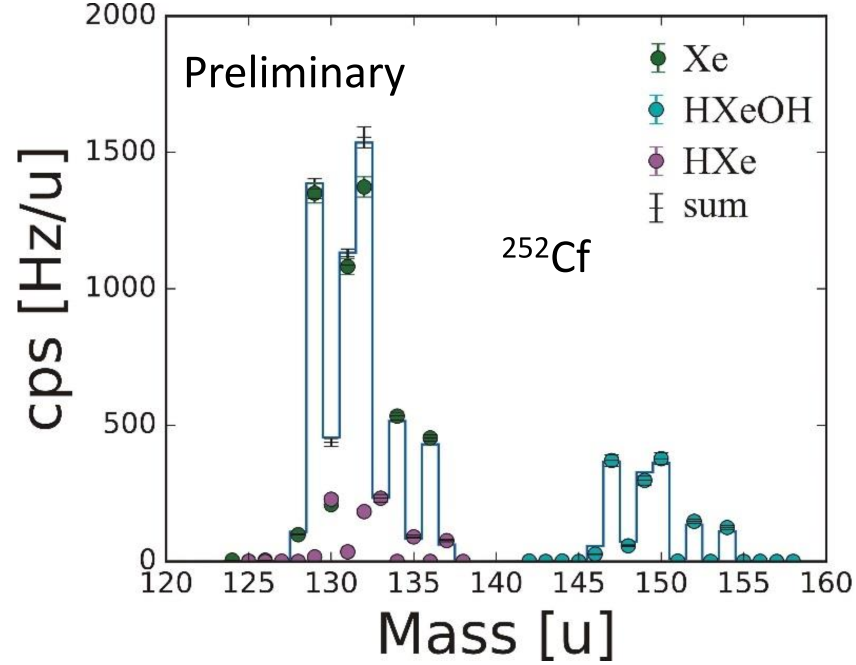
V_{RF} = 120 V, f = 10 MHz

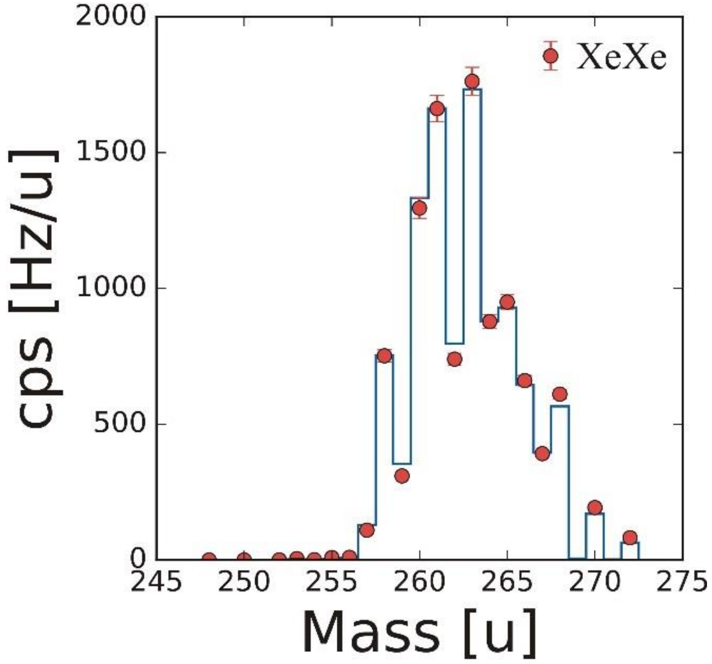
Simulated Ba$^+$ transmission ~95%

V_{RF} = 25V, f = 2.6 MHz

Simulated Ba$^+$ transmission ~72%

Ion extraction from xenon gas





- Ba-ions not identified!
- Ion extraction efficiency unknown!

- Ion extraction up to 10 bar

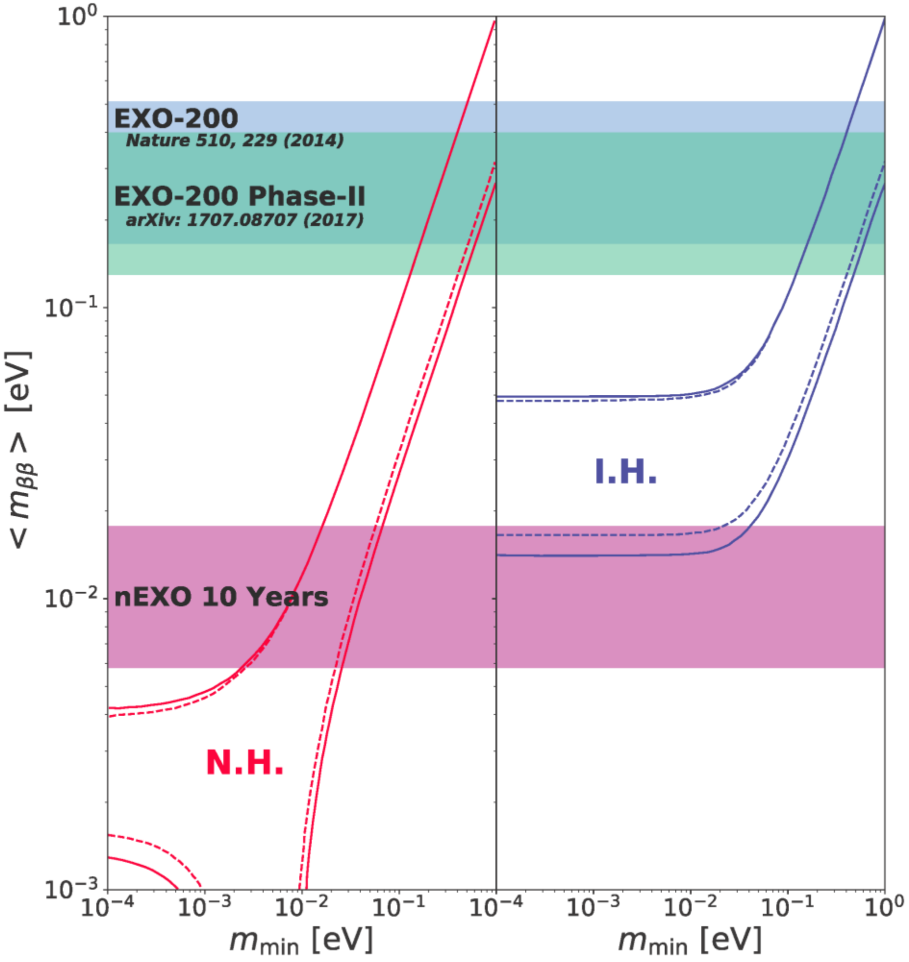
Int. J. Mass. Spectrom. (2015)
doi:10.1016/j.ijms.2015.01.003

$0\nu\beta\beta$ search with EXO

Multi-phase program :

- **EXO-200** – operational at WIPP mine:
  - ~175kg xenon enriched at ~80%
  - Current limit on $0\nu\beta\beta$: 1.8 x 10^{25} years (EXO-200)
  - Continue data taking for 1.5 more years
  - Sensitivity: 100-200 meV

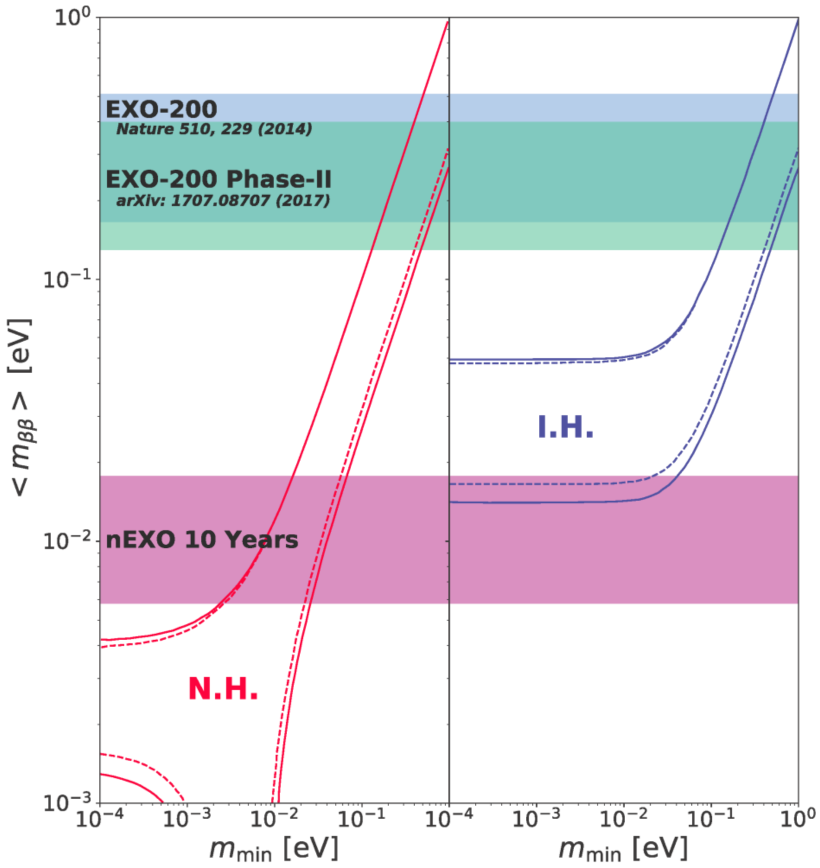
- **nEXO** - R&D underway:
  - 5T xenon enriched at ~90%
  - Sensitivity: 5-30 meV
  - Improved techniques for background suppression and possibly Ba tagging



→ **Development of nEXO is well advanced**

Summary

- 0νββ is the most practical way to test the Majorana nature of neutrinos.
- An observation of 0νββ always implies 'new' physics!



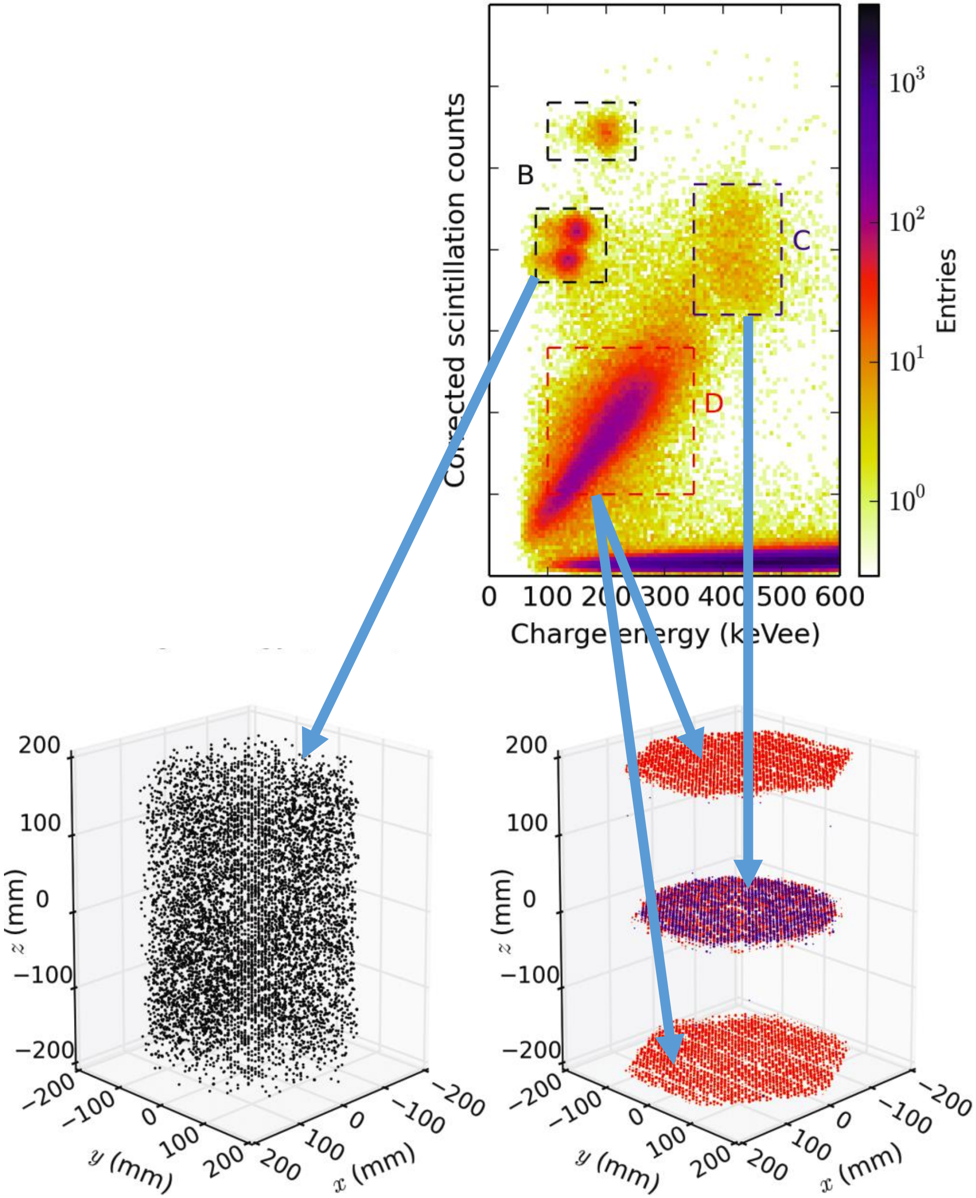
University of Alabama, Tuscaloosa AL, USA
M Hughes, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
University of Bern, Switzerland — J-L Vuilleumier
Brookhaven National Laboratory, Upton NY, USA
M Chiu, G Giacomini, V Radeka, E Raguzin, T Rao, S Rescia, T Tsang
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada — I Badhrees,
M Bowcock, W Cree, R Gornea, K Graham, T Koffas, C Licciardi, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers,
A Craycraft, W Fairbank Jr, D Harris, A Iverson, J Todd, T Walton
Drexel University, Philadelphia PA, USA
MJ Dolinski, E Hansen, YH Lin, E Smith, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
University of Erlangen-Nuremberg, Erlangen, Germany
G Anton, R Bayerlein, J Hoessl,
P Hufschmidt, A Jamil, T Michel, M Wagenpfeil, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea
DS Leonard
IHEP Beijing, People's Republic of China — G Cao, W Cen, Y Ding,
X Jiang, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, X Zhang, J Zhao
IME Beijing, People's Republic of China — L Cao, X Jing, Q Wang
ITEP Moscow, Russia — V Belov, A Burenkov, A Karelin,
A Kobyakin, A Kuchenkov, V Stekhanov, O Zeldovich
University of Illinois, Urbana-Champaign IL, USA
D Beck, M Coon, S Li, L Yang
Indiana University, Bloomington IN, USA
JB Albert, S Daugherty, G Visser
University of California, Irvine, Irvine CA, USA — M Moe

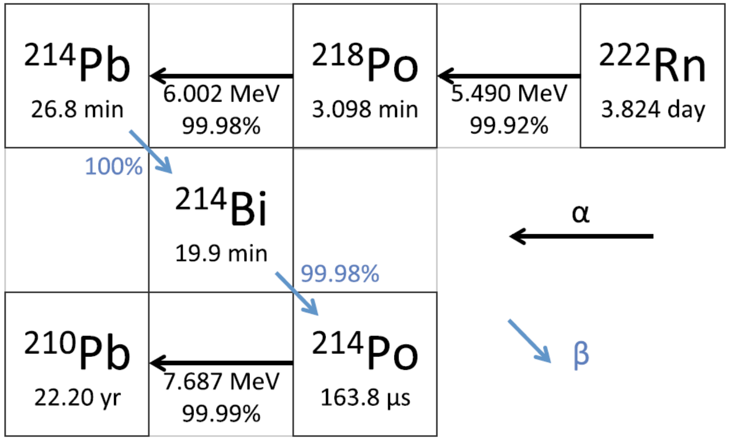
Laurentian University,Sudbury ON,Canada
B Cleveland, A Der Mesrobian-Kabakian, J Farine, A Robinson, U Wichoski
Lawrence Livermore National Laboratory, Livermore CA, USA
O Alford, J Brodsky, M Heffner, A House, S Sangiorgio
University of Massachusetts, **Amherst** MA, USA
S Feyzbakhsh, S Johnston, CM Lewis, A Pocar
McGill University, Montreal QC, Canada — T Brunner, Y Ito, K Murray
Oak Ridge National Laboratory, Oak Ridge TN, USA
L Fabris, RJ Newby, K Ziock
Pacific Northwest National Laboratory, Richland, WA, USA
I Arnquist, EW Hoppe, JL Orrell,
G Ortega, C Overman, R Saldanha, R Tsang
Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, K Odgers
Université de Sherbrooke
F Bourque, S Charlebois , M Côté, D Danovitch, H Dautet,
R Fontaine, F Nolet, S Parent, JF Pratte, T Rossignol, J Sylvestre, F Vachon
SLAC National Accelerator Laboratory, Menlo Park CA, USA
J Dalmasson, T Daniels, S Delaquis, A Dragone, G Haller,
LJ Kaufman, A Odian, M Oriunno, B Mong, PC Rowson, K Skarpaas
University of South Dakota, Vermillion SD, USA
J Daughhetee, R MacLellan
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg,
G Gratta, M Jewell, S Kravitz, G Li, A Schubert, M Weber, S Wu
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, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — Z Li, D Moore, Q Xia

The nEXO Collaboration

Backup

Ion Fraction in LXe after α and β Decay





^{214}Pb 26.8 min ← 6.002 MeV 99.98% ← ^{218}Po 3.098 min ← 5.490 MeV 99.92% ← ^{222}Rn 3.824 day

100%

^{214}Bi 19.9 min

99.98%

^{210}Pb 22.20 yr ← 7.687 MeV 99.99% ← ^{214}Po 163.8 μs

← α

↘ β

EXO-200 with drift field 380 ± 5 V/cm

Ion Fraction

^{214}Bi^{+} from ^{214}Pb β decay: 76.4 ± 5.7%

^{218}Po^{+} from ^{222}Rn α decay: 50.3 ± 3.0%

Phys. Rev. C 92(2015)045504