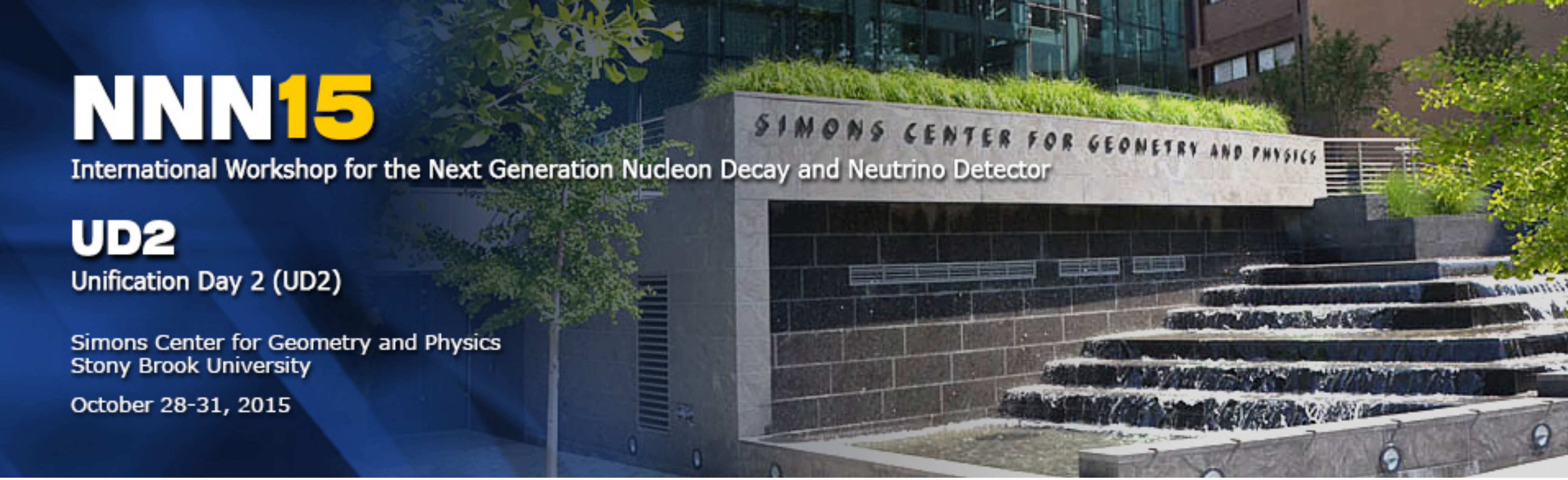


NNN15

International Workshop for the Next Generation Nucleon Decay and Neutrino Detector

UD2

Unification Day 2 (UD2)

Simons Center for Geometry and Physics
Stony Brook University

October 28-31, 2015

Liquid Xe detectors for double beta decay and connection with large LAr detectors

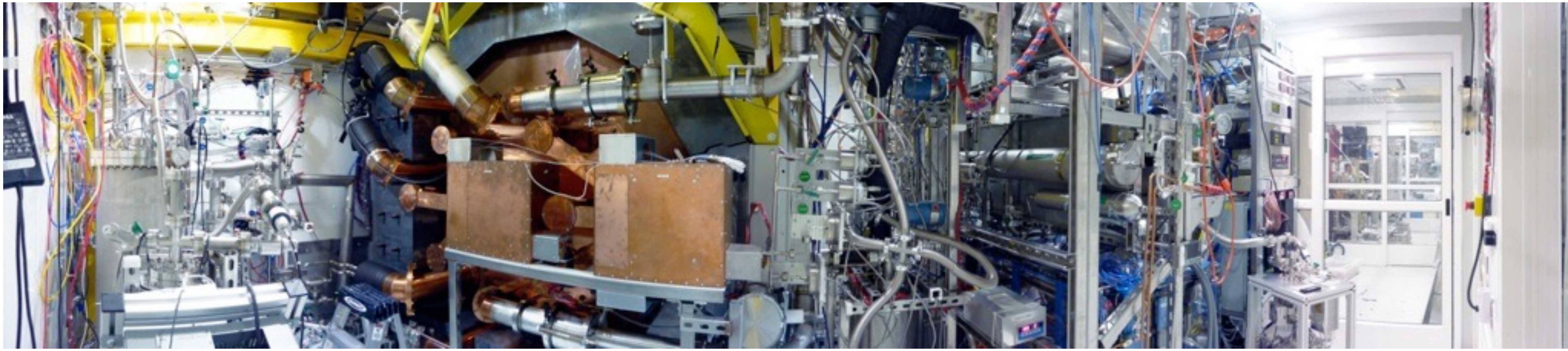
Andrea Pocar
University of Massachusetts, Amherst
Princeton University
(with the EXO-200/nEXO and DarkSide Collaborations)

Outline

Large LXe + LAr detectors for ultra-low background physics

- Physics goals
- General arena
- Focus on Time Projection Chambers (TPCs)
    - The EXO experience (0νββ decay)
    - The DarkSide experience (WIMP dark matter)
- Common threads, characteristic distinctions
- Outlook

Disclaimer: this is not a comprehensive review of the field



Liquid xenon (LXe) and liquid argon (LAr)

for low-background neutrino physics

Noble liquid detectors have risen to be a leading technology in low-energy rare event searches over the past ~decade (WIMP dark matter, $0\nu\beta\beta$ decay)

Scintillating calorimeters

- XMASS (LXe)
- DEAP-3600 (LAr)
- miniCLEAN (LAr)

TPCs

single phase

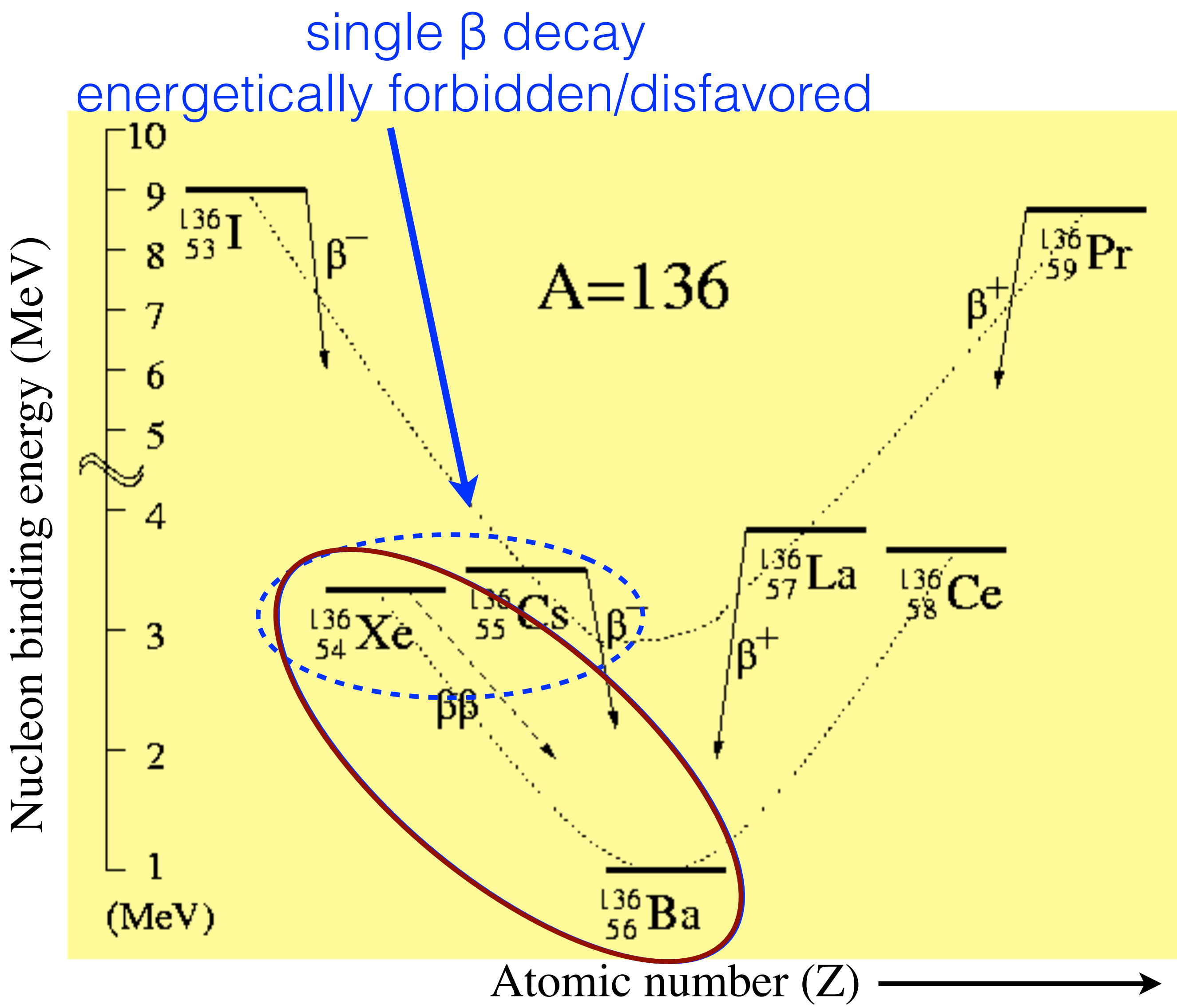
- EXO-200 / nEXO (LXe)

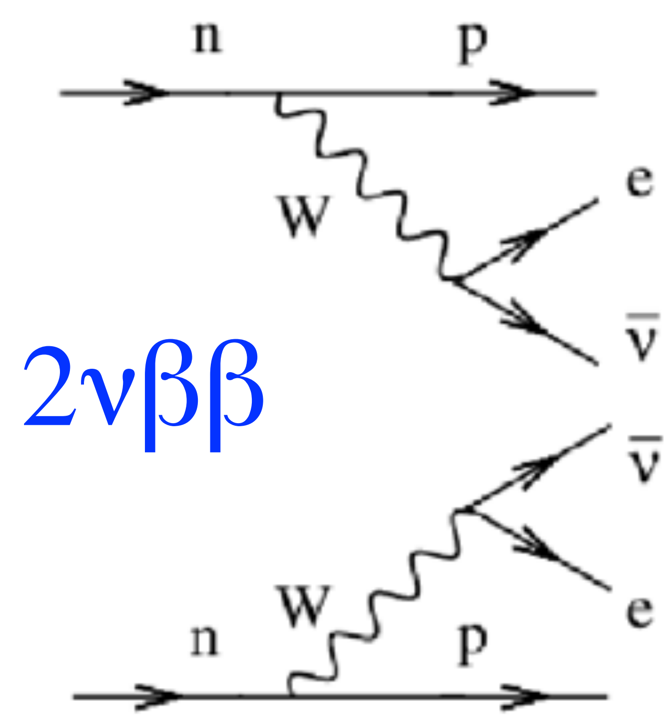
dual phase

- ZEPLIN (LXe)
- XENON 10/100/1T/nT (LXe)
- LUX / LZ (LXe)
- PandaX I-II (LXe)
- WaRP (LAr)
- ArDM (LAr)
- DarkSide-50 / DS-20k / ARGO (LAr)

all growing larger

Physics: Neutrino-less double beta (0νββ) decay



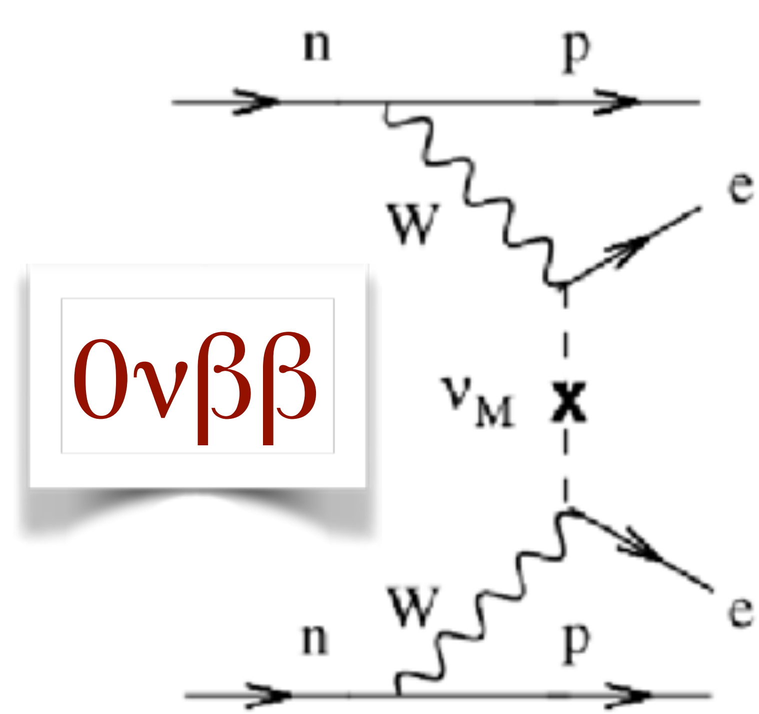


observation of 0νββ decay:

- massive, Majorana neutrinos
- lepton number violation

0νββ rate

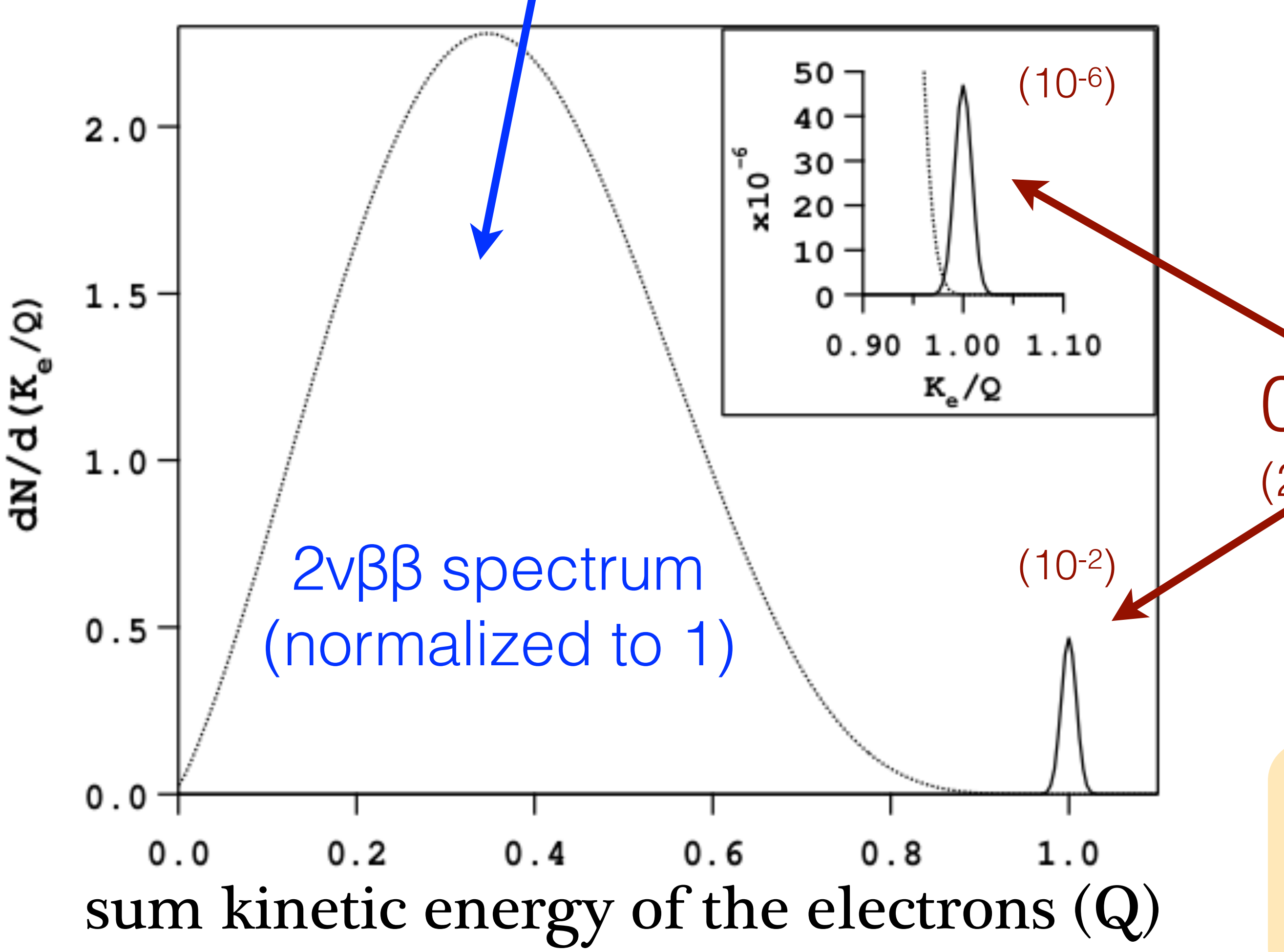
- absolute neutrino mass (model dependent)



[Schechter and Valle, PRD 25 (1982) 2951]

0νββ decay: what we measure

$$[T^{2\nu}_{1/2}]^{-1} = G_{2\nu}(Q_{\beta\beta}, Z) \left| M^{GT}_{2\nu} - \frac{g_V^2}{g_A^2} M^F_{2\nu} \right|^2$$



if 0νββ due to light Majorana ν's:

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q, Z) |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

nuclear physics ($M_{0\nu}$) links different isotopes

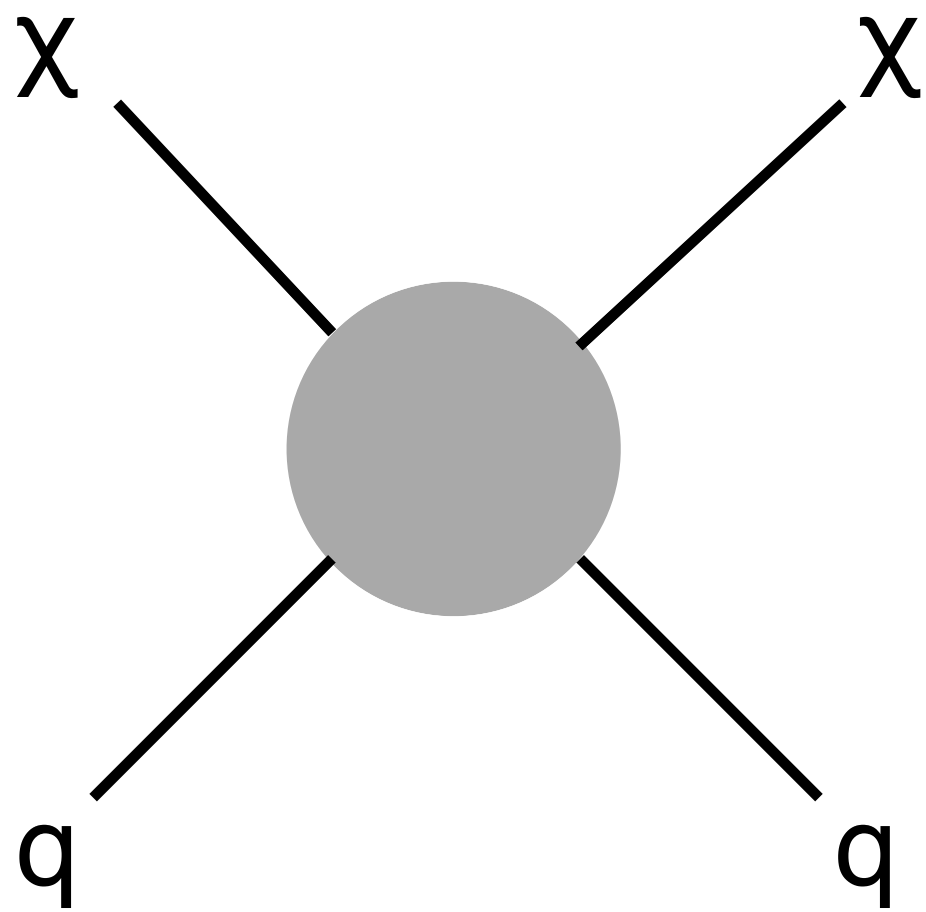
$$\langle m_{\beta\beta} \rangle^2 = \left| \sum_i^N |U_{ei}|^2 e^{i\alpha_i} m_i \right|^2 \quad (\text{all } m_i \geqslant 0)$$

➛ *look for event excess at the 2νββ endpoint, Q*

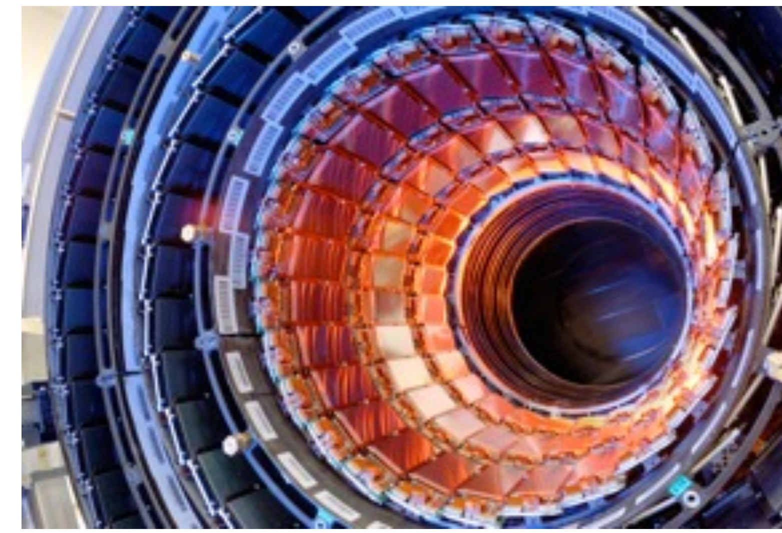
Physics: search for WIMP dark matter

Annihilation

Indirect Detection



Production



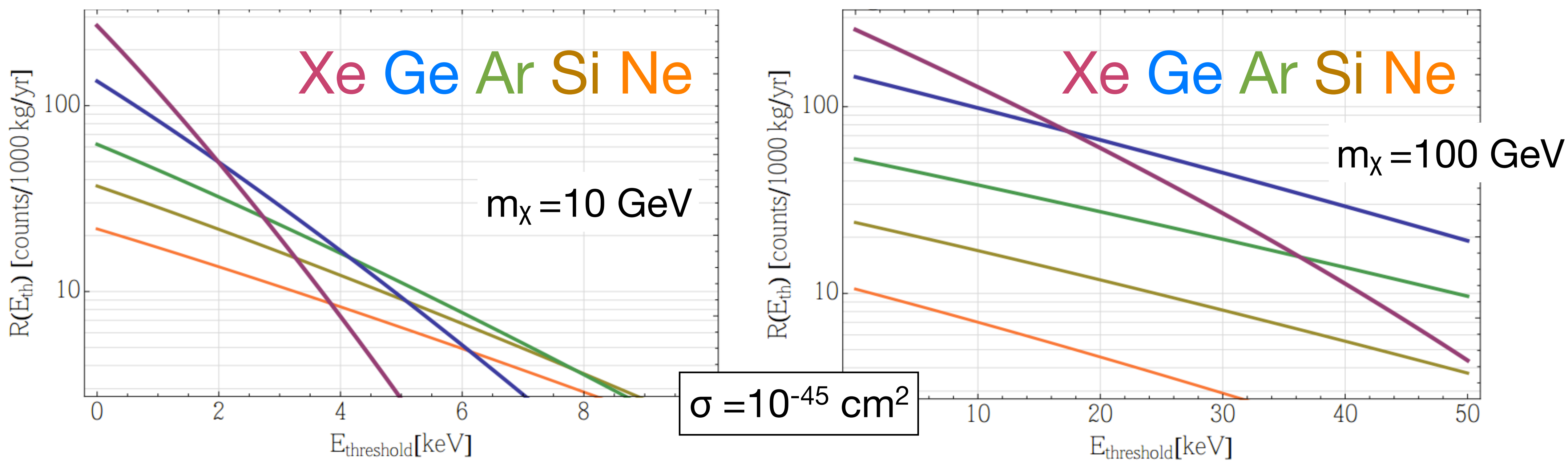
Colliders

Scattering

Direct Detection of nuclear recoils

Direct dark matter search: what we measure

➛ *look for excess of nuclear-like recoil events (low energy)*



arXiv:1310.8327v2 [hep-ex]

General features, requirements

Underlying concept:

- **Apply detector design concepts developed for low energy neutrinos to searches for WIMPs and 0νββ decay**

Strenghts:

- Powerful combination of low energy threshold, energy resolution, event ID
- LXe/LAr are excellent scintillators
- Background discrimination (technique-specific)
- Scalability
- Inline purification

- Large ‘empty’ volume filled with clean LXe/LAr
- ‘Dirty’ components pushed away from fiducial volume (self-shielding)
- Lightweight structure, selected materials

Background discrimination in a nutshell

$0\nu\beta\beta$ decay:

- β/γ discrimination

WIMP direct detection:

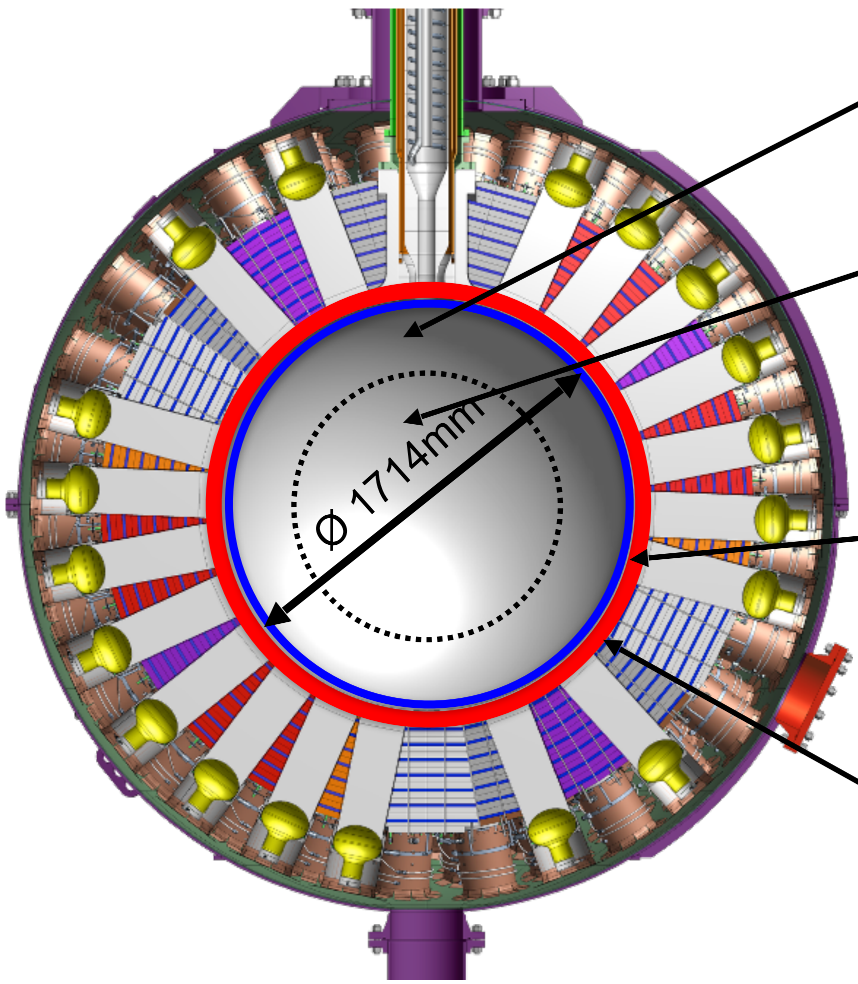
- nuclear / electron recoil discrimination

Single phase LXe: XMASS

- WIMPs, 0νββ decay, solar neutrinos
- 835 kg of LXe
- 630 PMTs
- Feature: relative simplicity
- Limitation: limited discrimination
- Key requirements:
  - low external background
  - low radon
  - fiducialization

Single phase LAr: DEAP-3600

slide courtesy of Fabrice Retière (adapted)

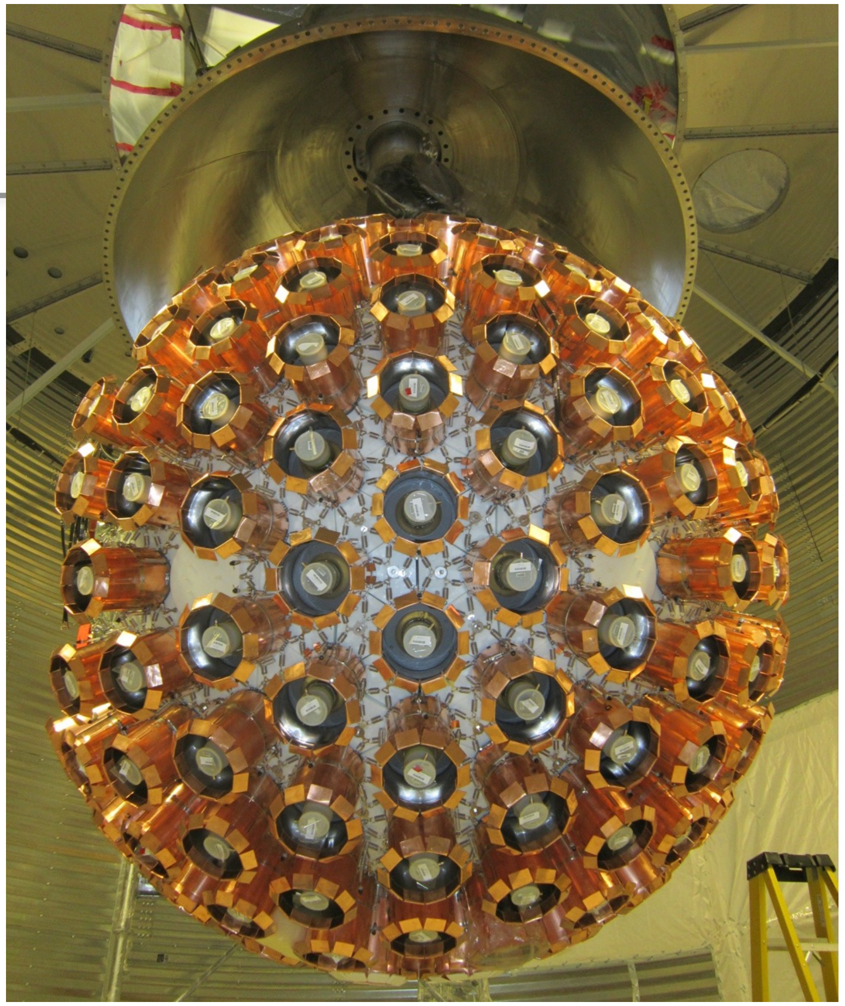


3600 kg of Liquid Argon

1000 kg Fiducial mass

Wavelength shifter
(distilled TPB)

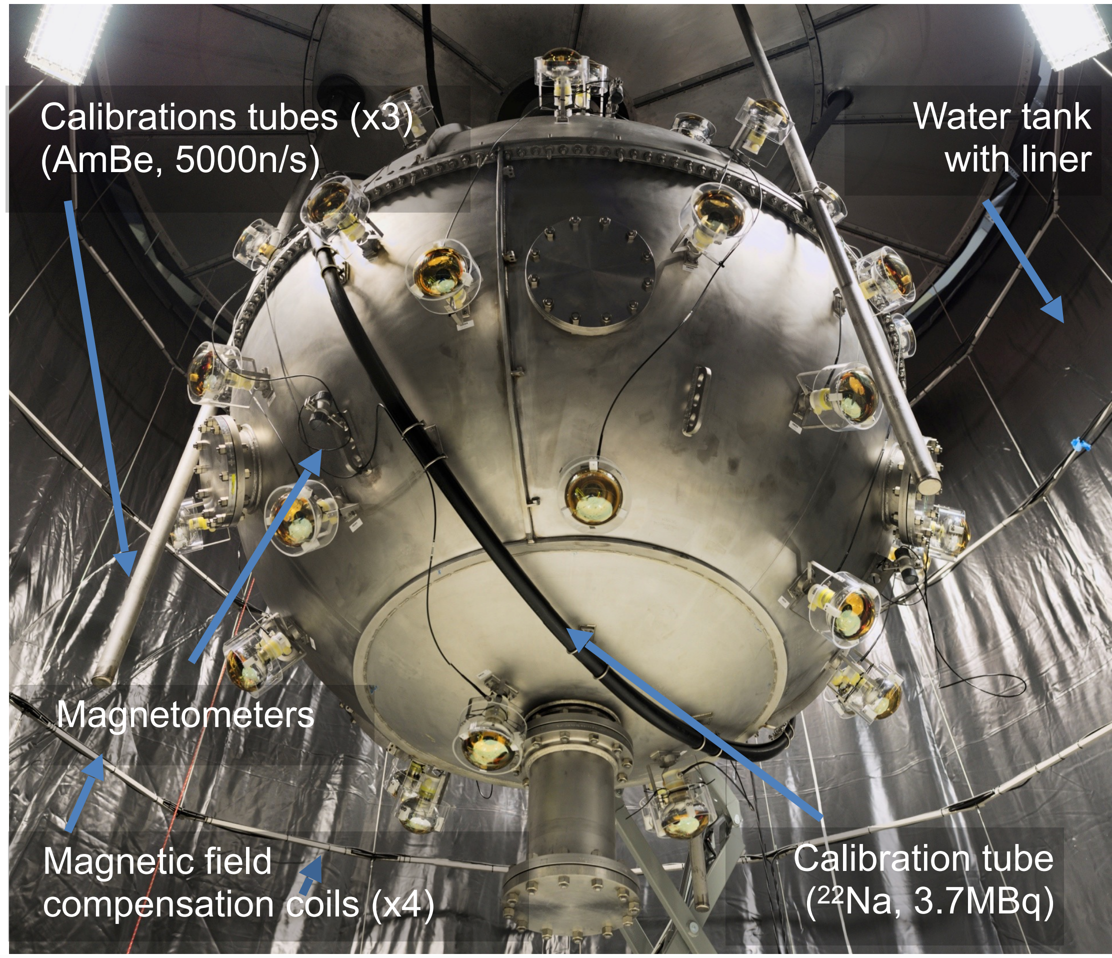
Vessel



WIMP search

Distinguish nuclear from electron recoils by Pulse Shape Discrimination (PSD) of the scintillation signal

(very powerful in Argon)



The Enriched Xenon Observatory (EXO)

Search for 0νββ decay of ^{136}Xe (Q=2458 keV) with enriched xenon TPC's (with scintillation readout) of increasing sensitivity and size

Enrichment is relatively simpler and less expensive

- 10% --> 80-90% proven on the 100's kg scale

Continuous re-purification possible

- from electronegative, radioactive contaminants

Xenon is reusable

- could be transferred between experiments

Monolithic detector, remarkable self-shielding

Good (enough) energy resolution

- with combined scintillation + ionization

ββ/γ discrimination

- event topology

Limited cosmogenic activation

- longest-lived 4 minutes

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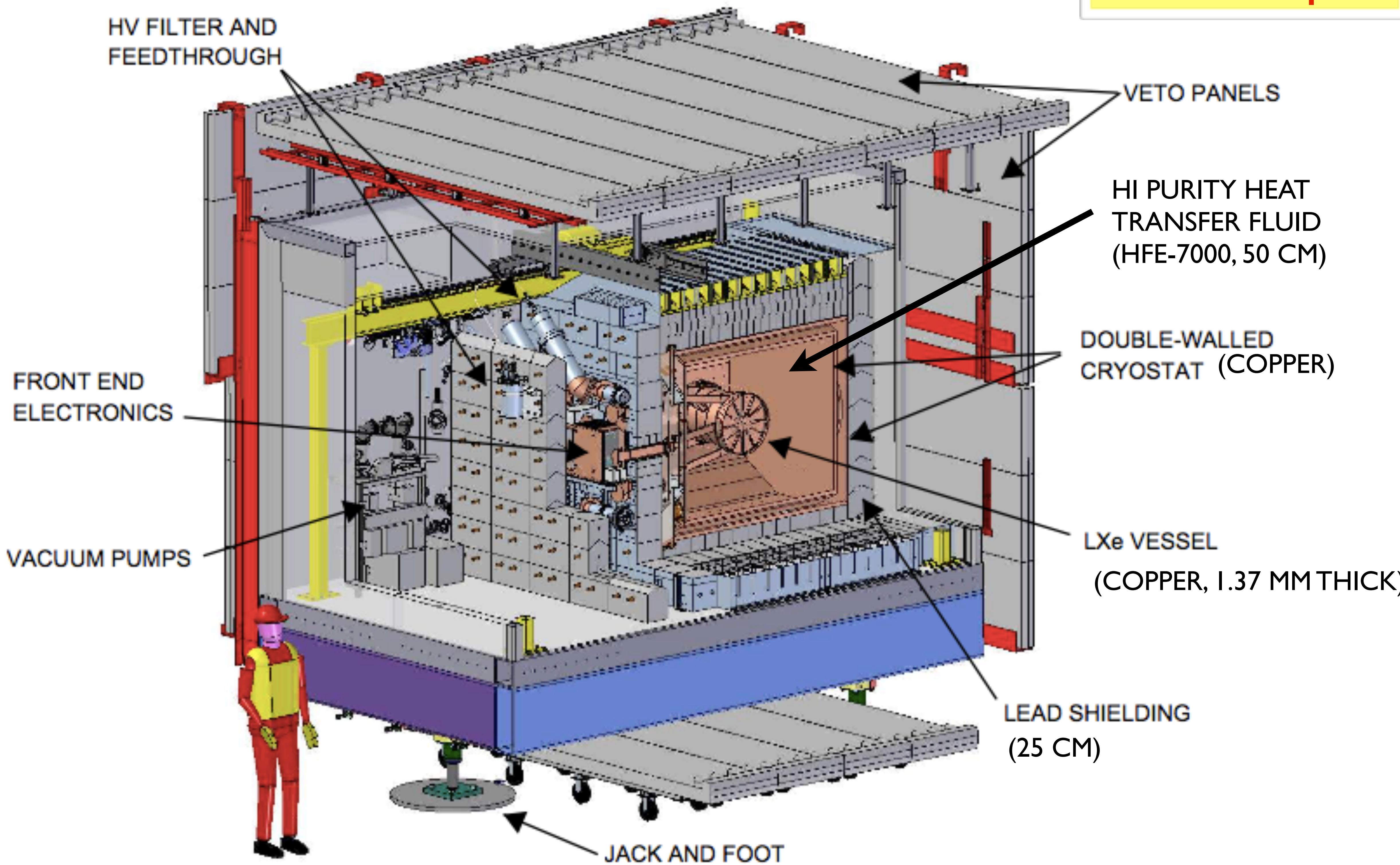
Xenon admits a novel coincidence technique
- Ba daughter tagging

M. Moe, PRC 44, R931 (1991)

The EXO-200 detector at WIPP (~1,500 m.w.e.)

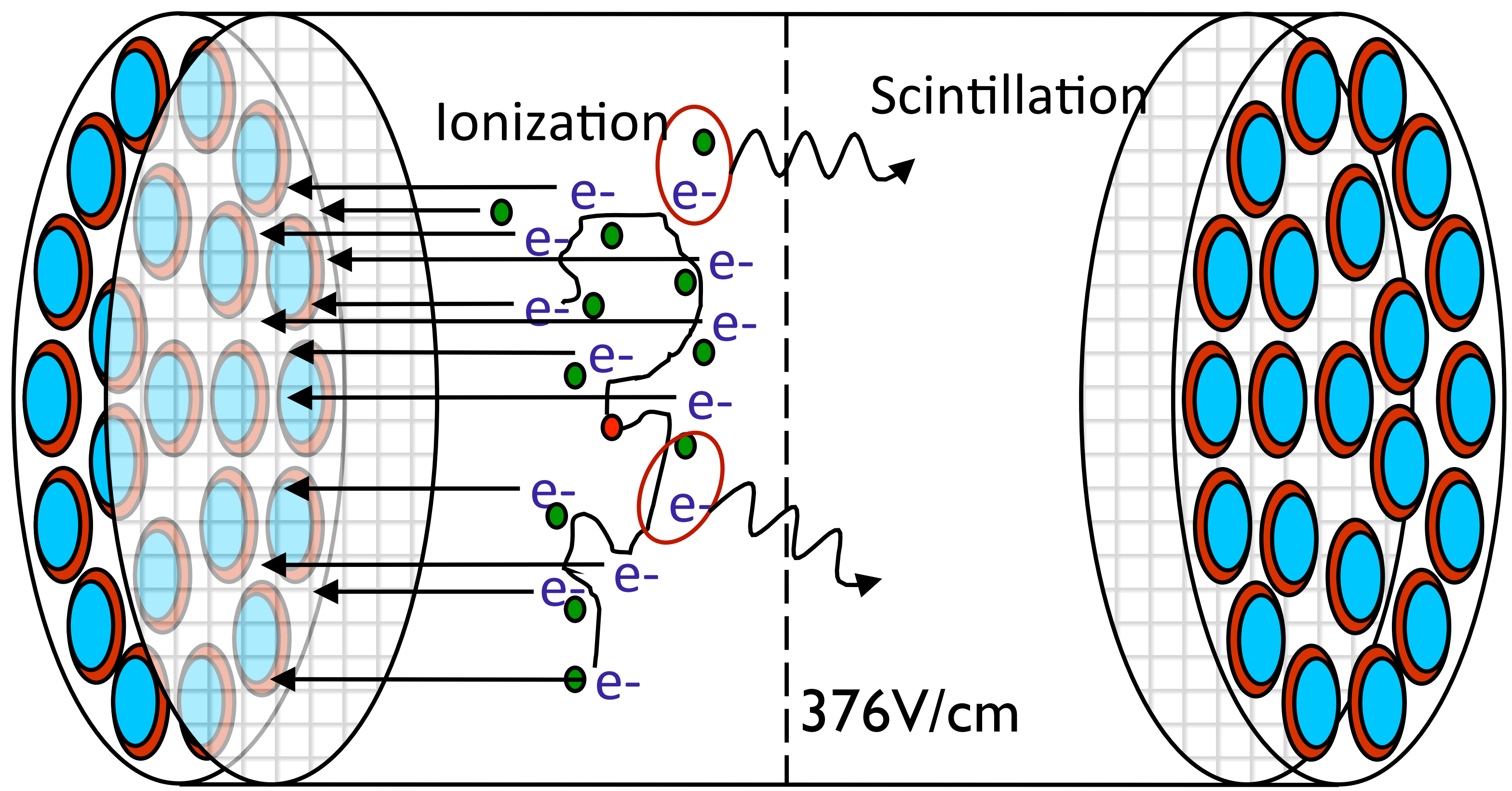
Rn: ~6 Bq/m^3

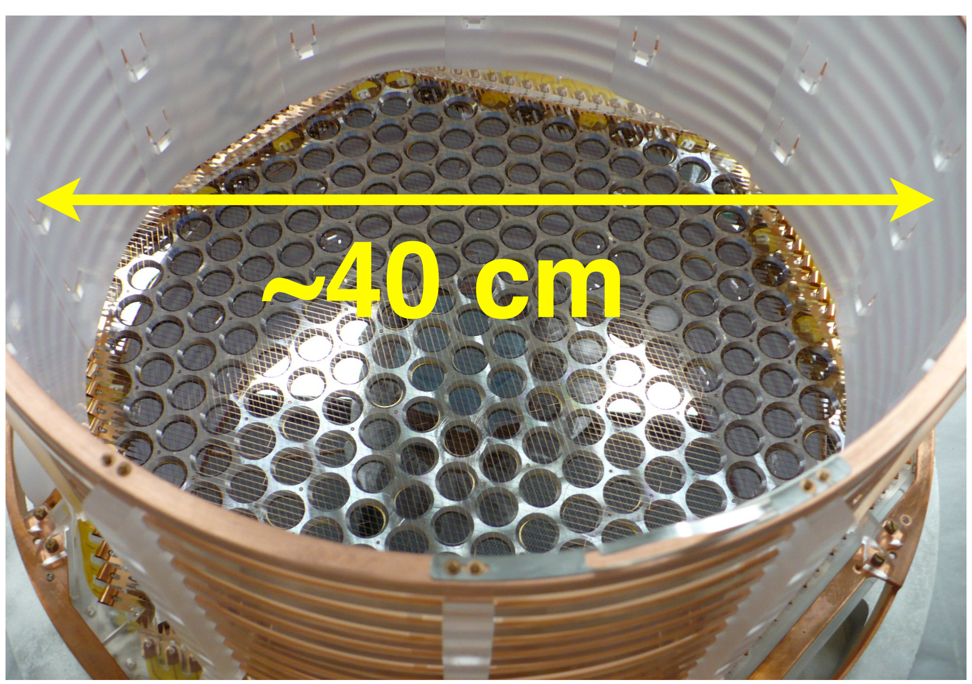


JINST 7 (2012) P05010

The EXO-200 Time Projection Chamber (TPC)

- ~150 kg ^{enr}LXe
- Cathode in center
- Light detected by APDs on end caps
- Charge detected by crossed u- and v-wire planes

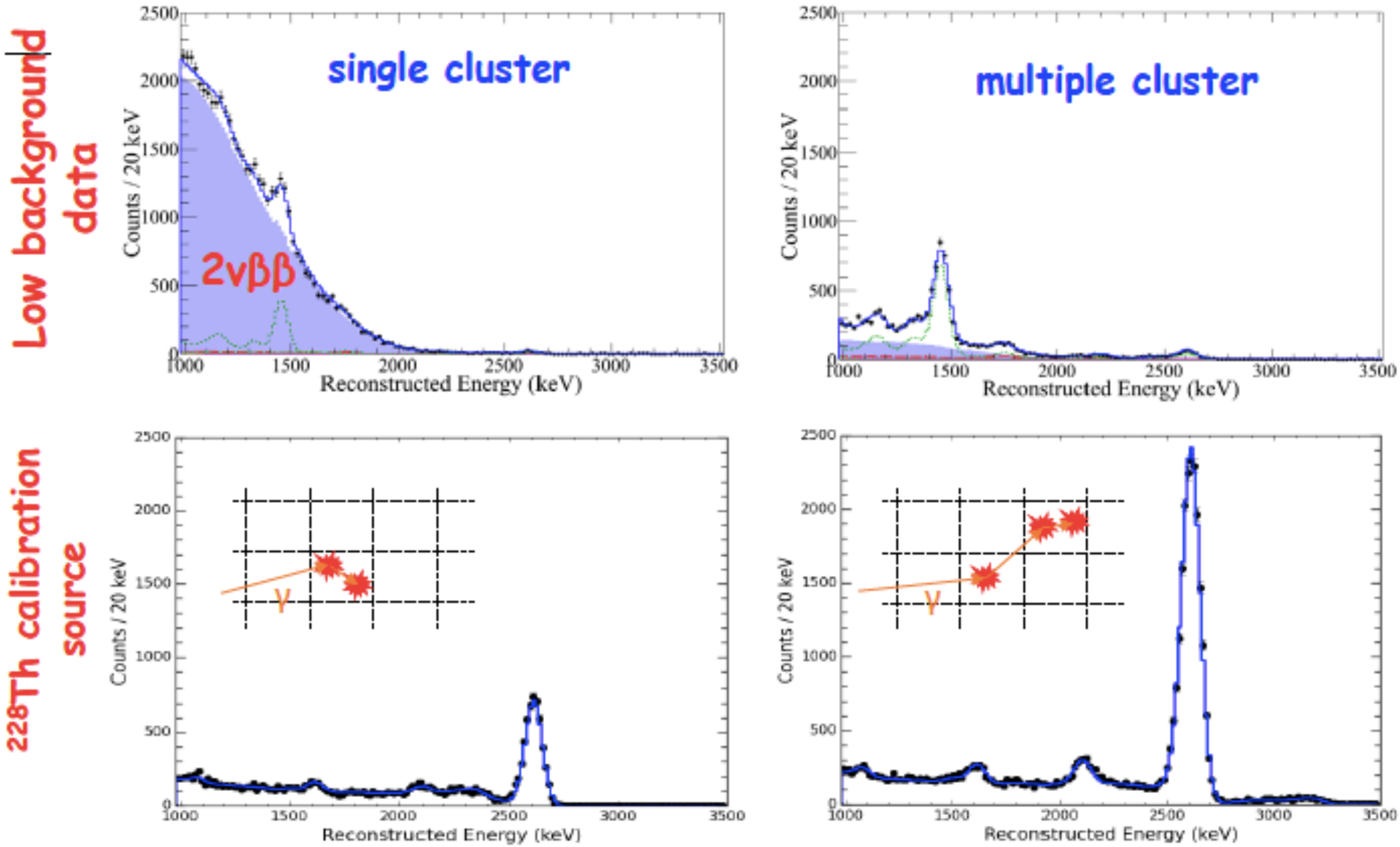




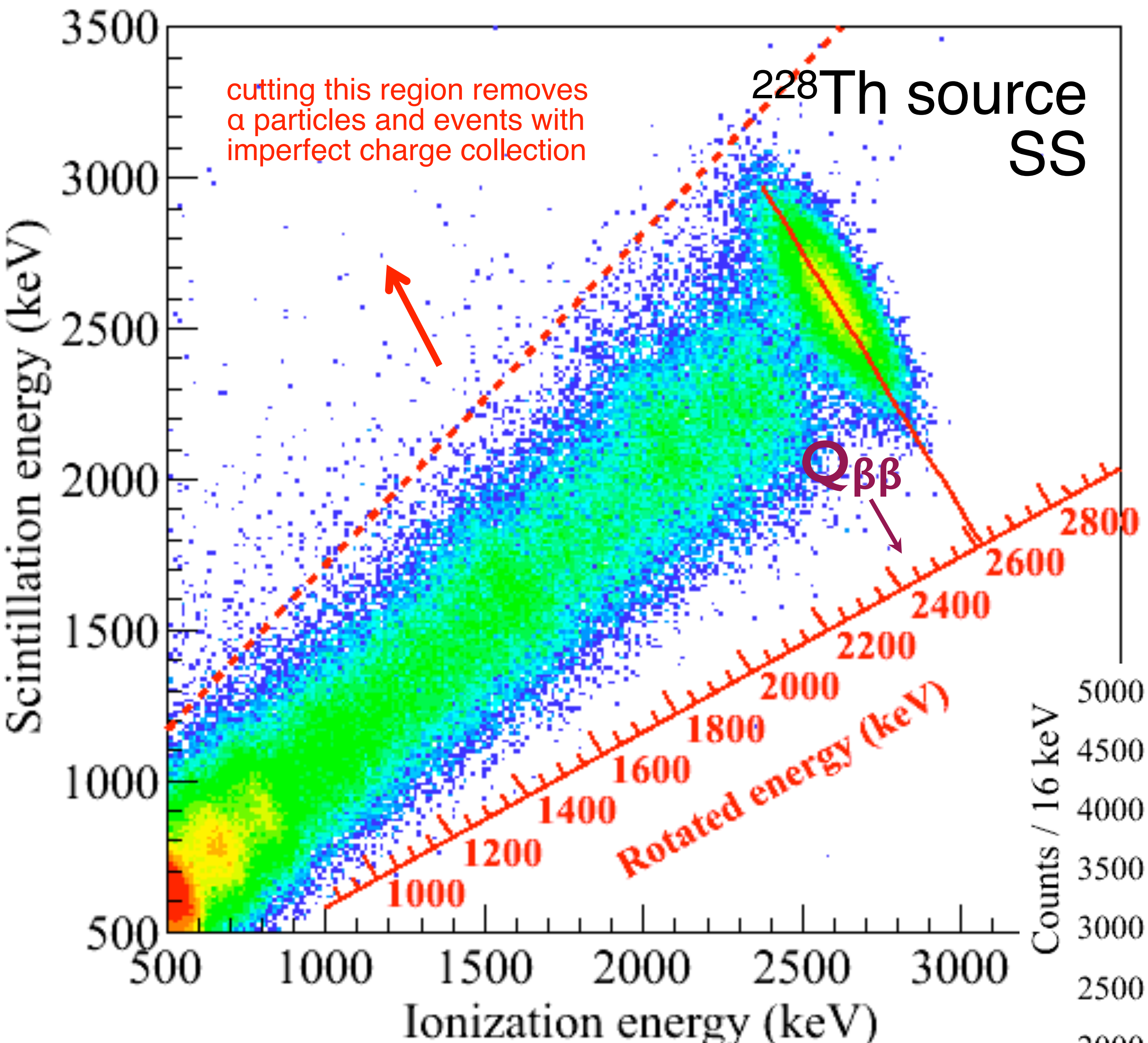
- v-wire plane measures induction
- u-wire plane collects charge
- Energy from u-wire and APD signals

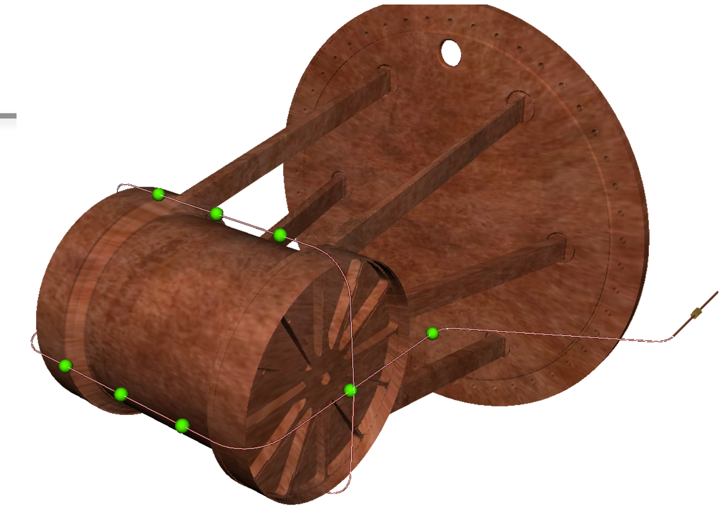
JINST 7 (2012) P05010

Tracking and event topology



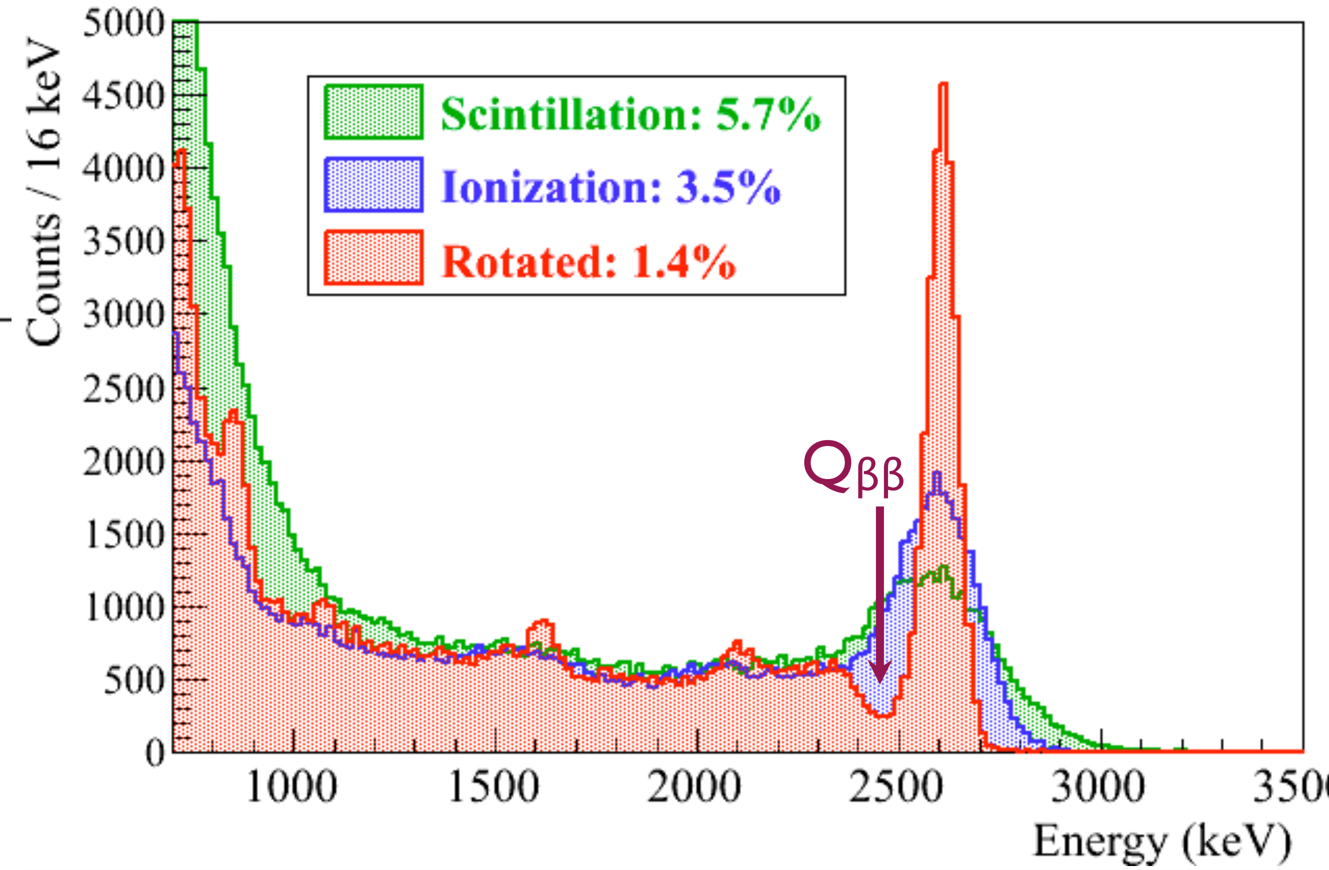
Energy resolution





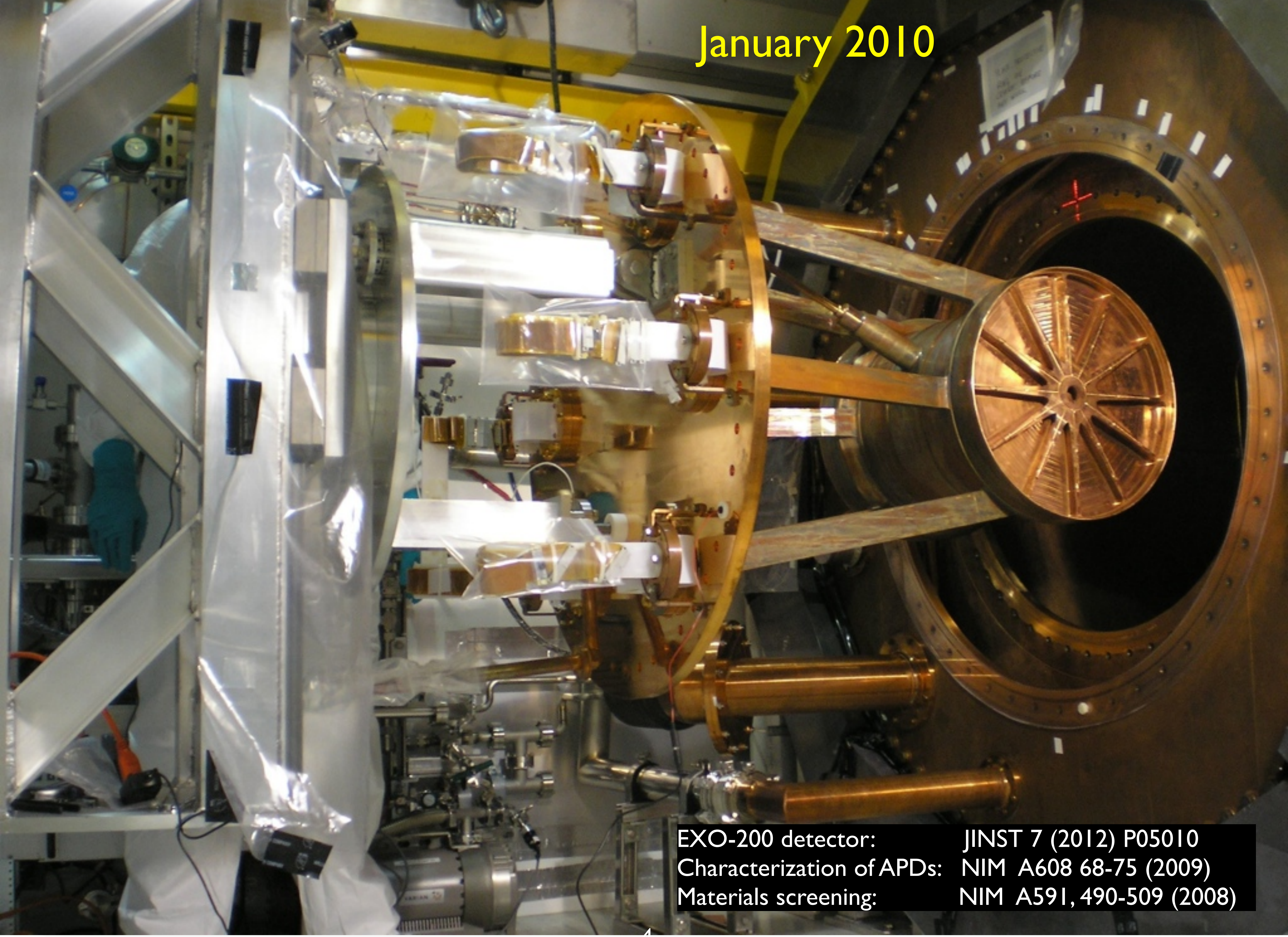
Takes into account anti-correlation of charge and scintillation response to improve energy resolution

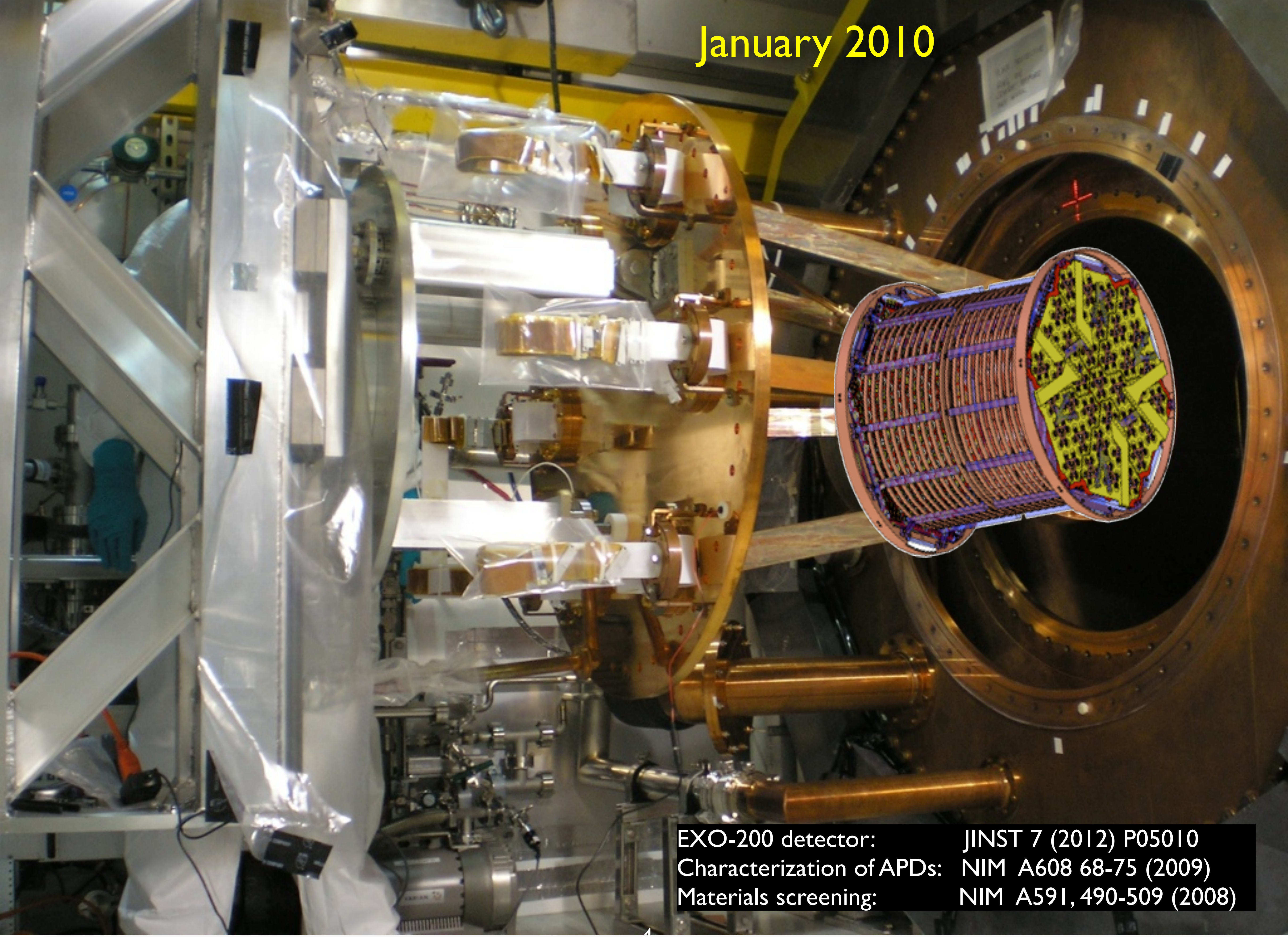
Calibration performed with ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{228}Th



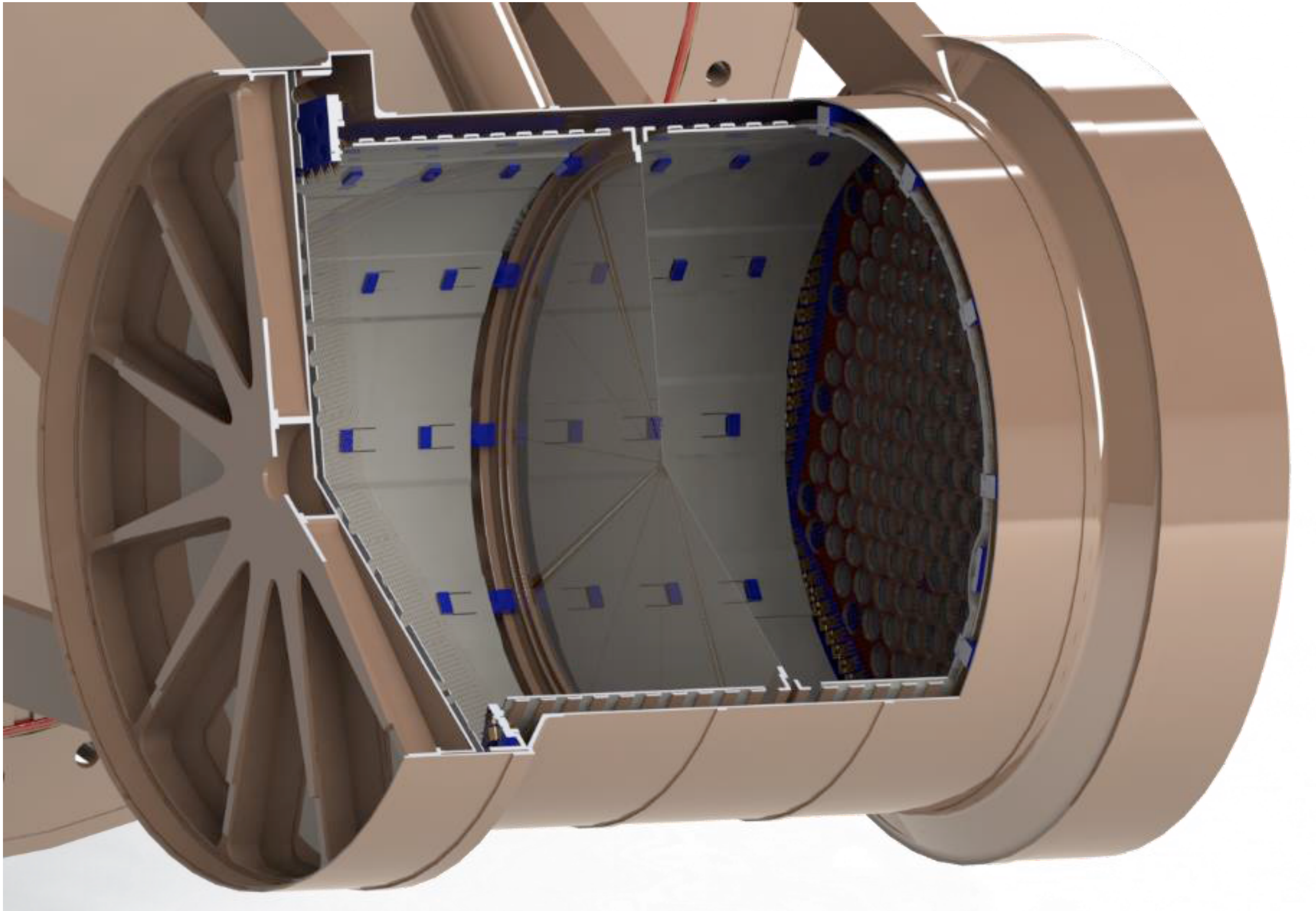
Molecular properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

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

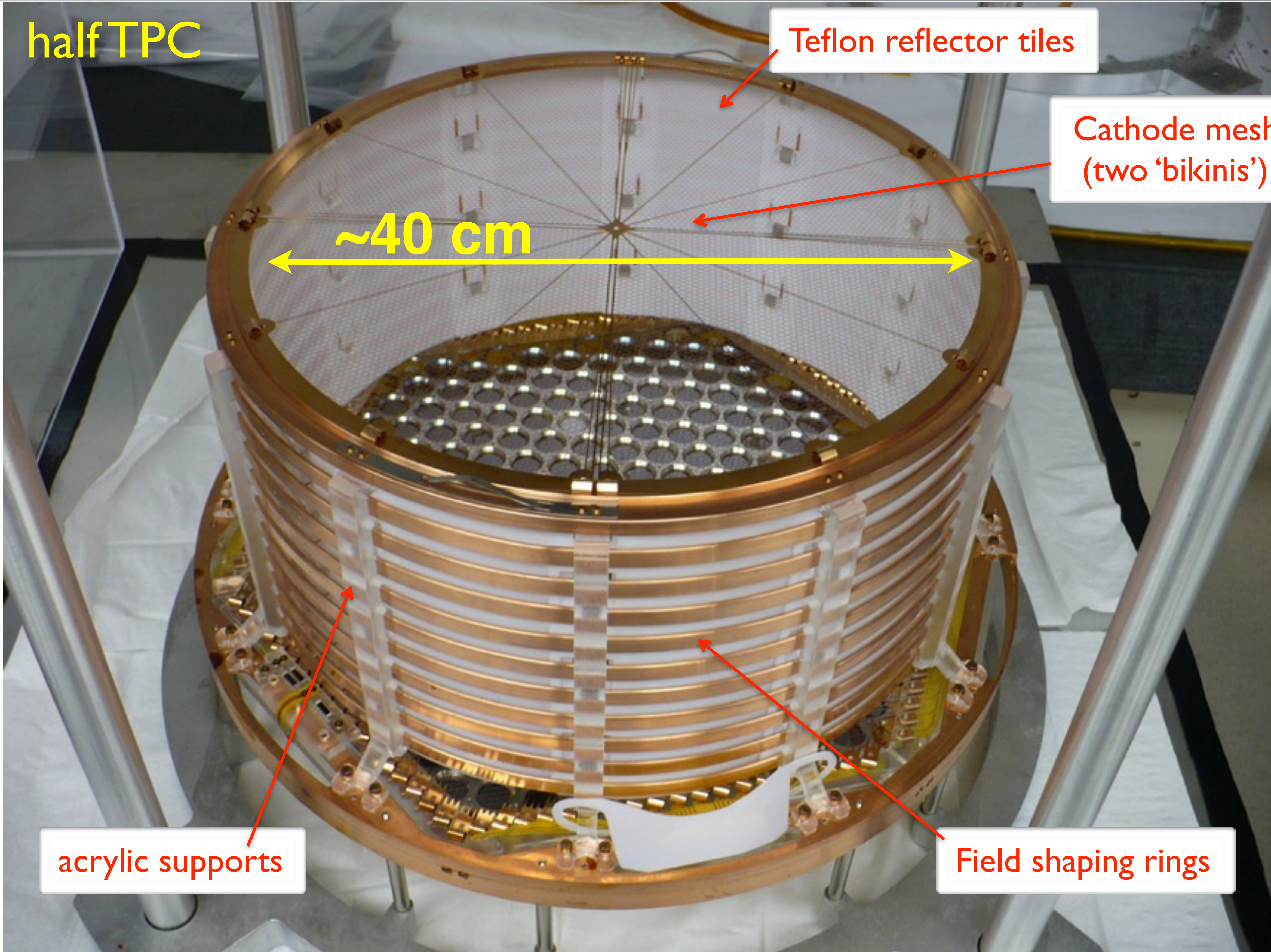

January 2010
EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)

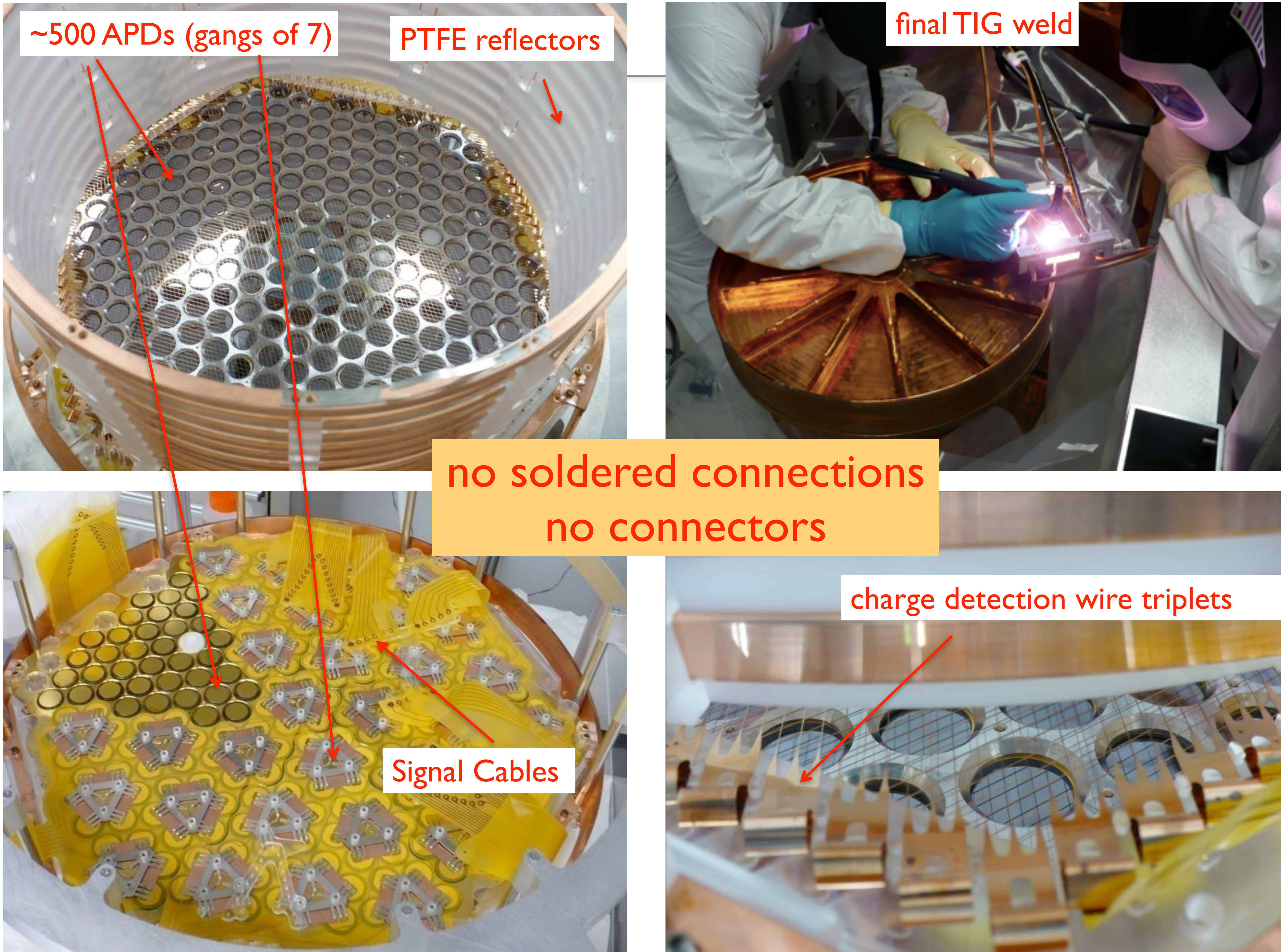

January 2010
EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)

EXO-200 Inner Detector

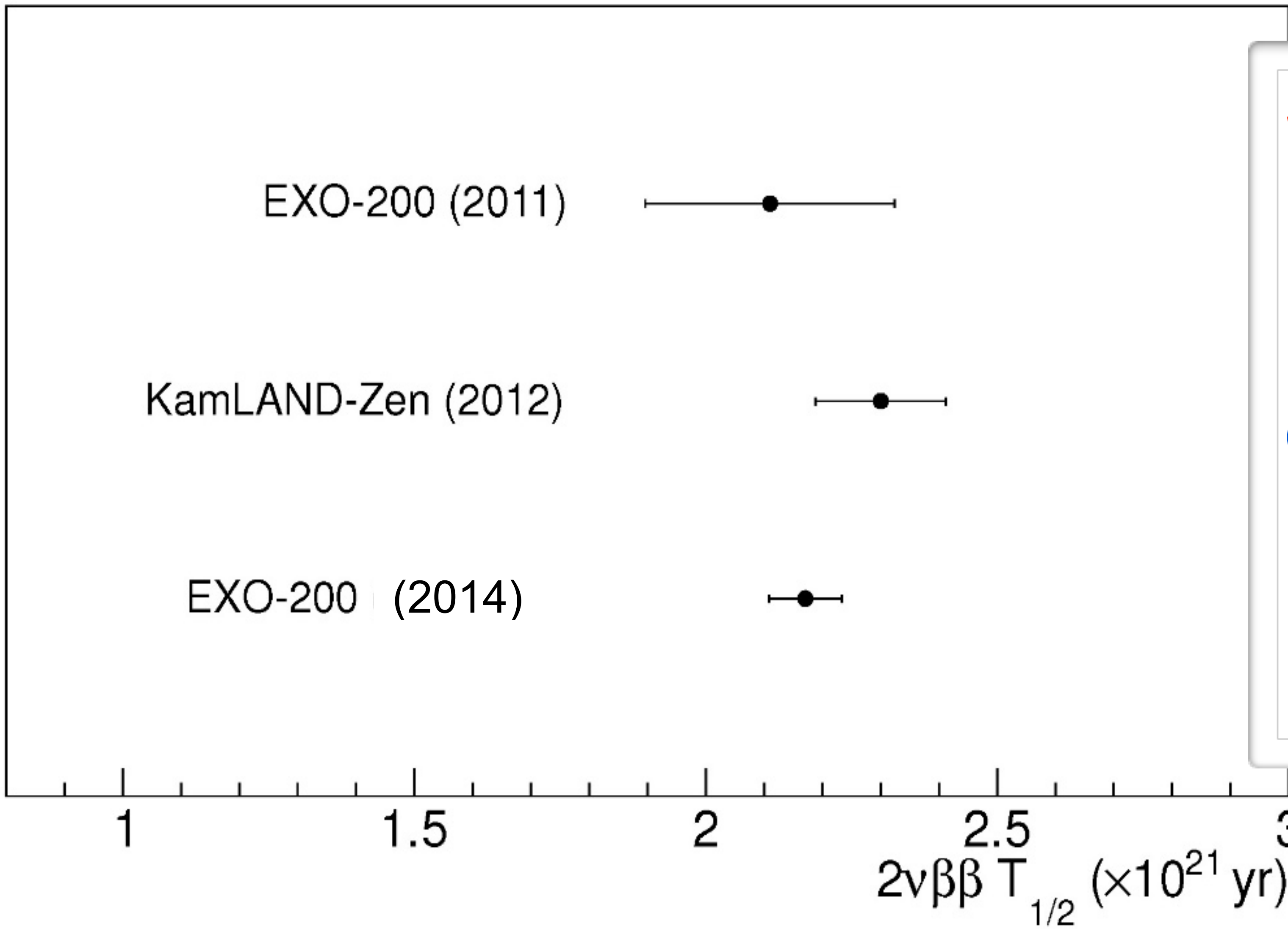


the EXO-200 TPC




~500 APDs (gangs of 7)
PTFE reflectors
final TIG weld
no soldered connections
no connectors
Signal Cables
charge detection wire triplets

Phase I, Run 2: precision measurement of 2νββ



Start data taking in June 2011

Discovery of 2νββ decay of 136Xe
[PRL 107, 212501 (2011)]

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

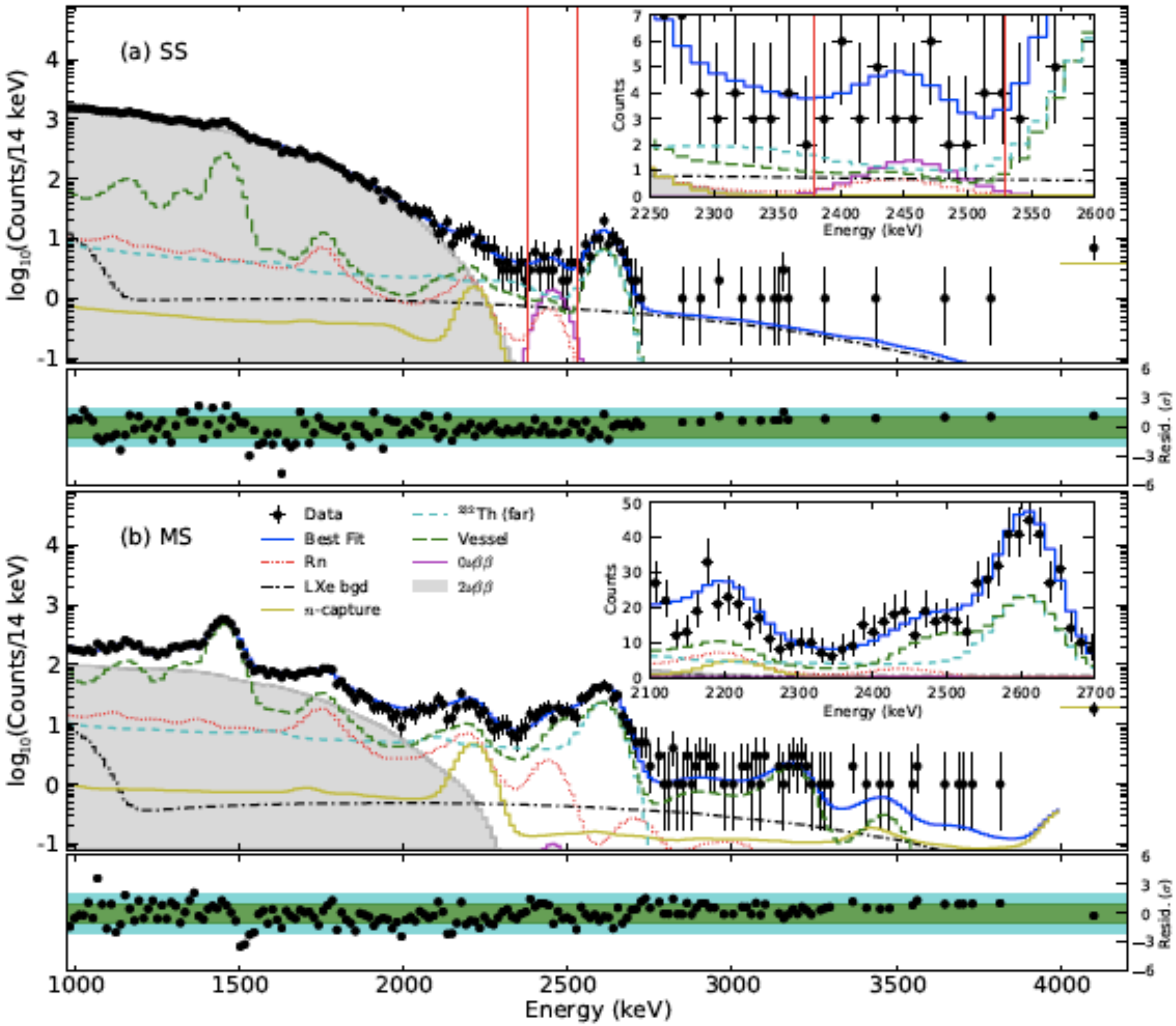
Precision measurement (~3%)
[PRC 89, 015502 (2014)]

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

(longest, yet most precisely (directly) measured 2νββ decay of all 'practical' isotopes)

Search for 0νββ decay (^{136}Xe exposure: 100 kg yr)

[Nature, 510, 229-234 (2014)]



$$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}\ \mathrm{yr}$$

$$(90\%\ C.L.)$$

energy resolution

$$\frac{\sigma}{E}(Q) = 1.53$$

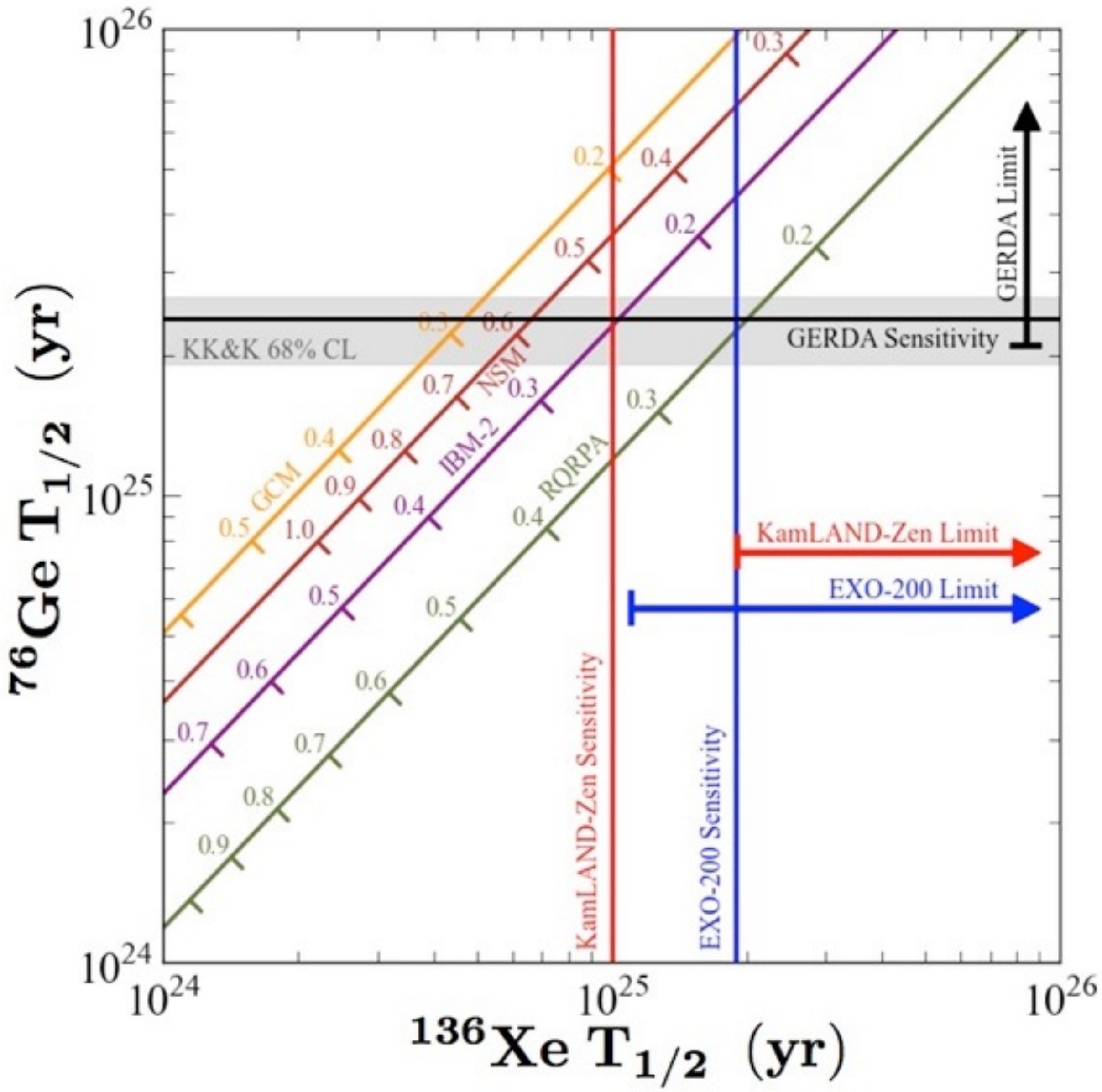
background index

$$(1.7 \pm 0.2) \times 10^{-3}$$

$$\mathrm{cts/(keV \cdot kg \cdot y)}$$

Phase I, Run2: search for 0νββ decay of ^{136}Xe

[Nature, 510, 229-234 (2014)]



EXO-200 limit:

$$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}\ \mathrm{yr}\ \ (90\%\ \mathrm{C.L.})$$

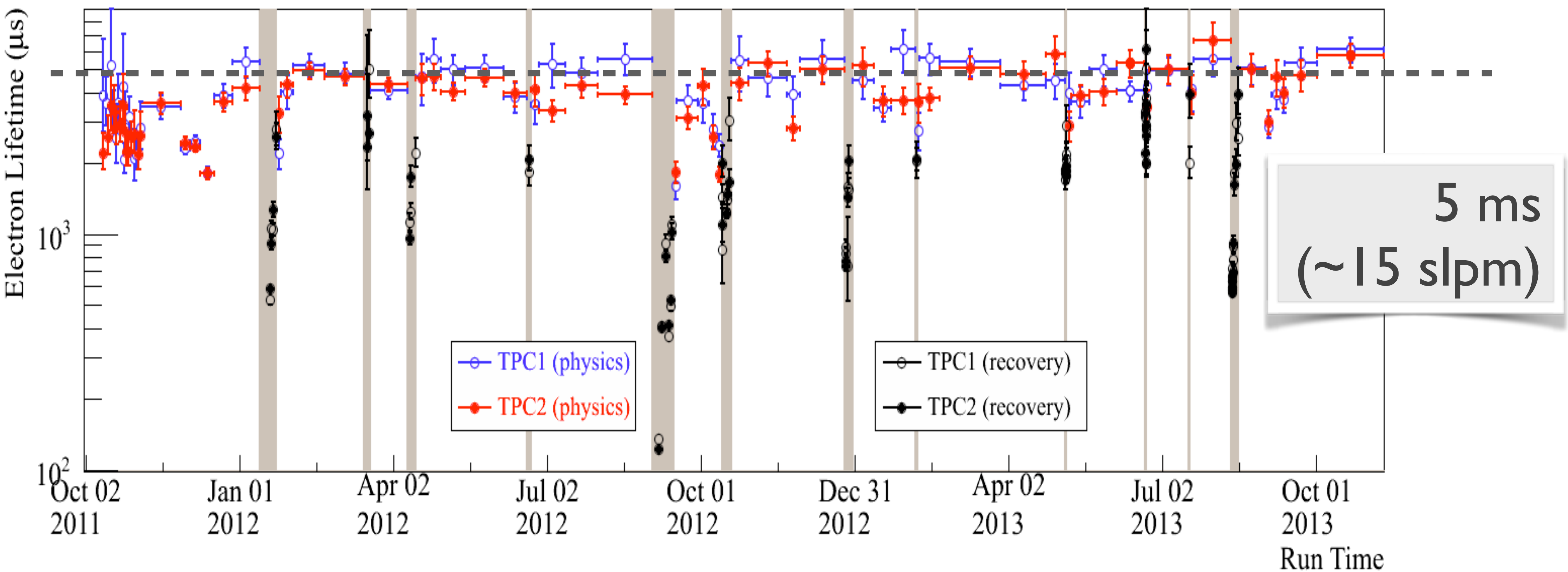
$$< m_{\beta\beta} >= 190 - 450\ \mathrm{meV}$$

EXO-200 sensitivity:

$$T_{1/2}^{0\nu\beta\beta} = 1.9 \times 10^{25}\ \mathrm{yr}$$

[GERDA: PRL 111, 122503 (2013)]
[KL-Zen: PRL 110, 062502 (2013)]

Xenon purity from electronegative species - Run 2



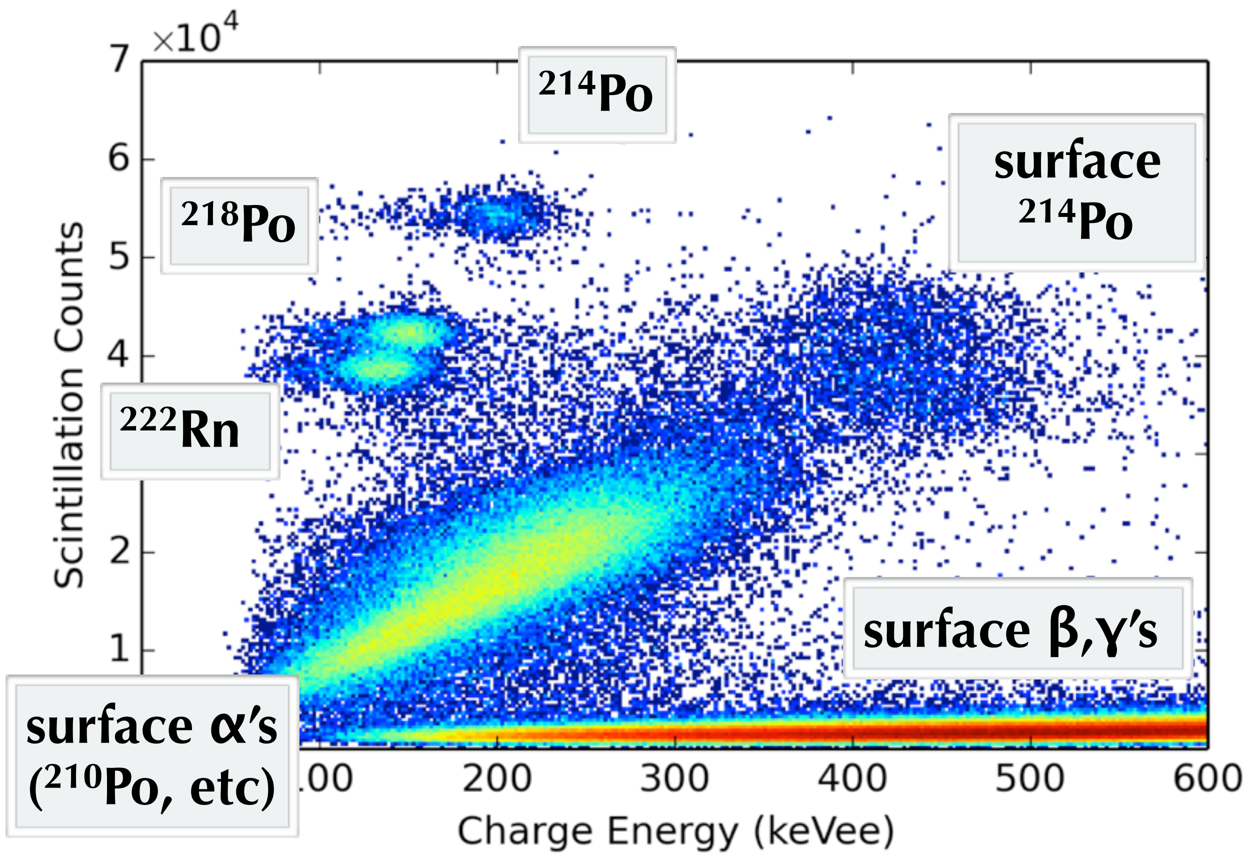
Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

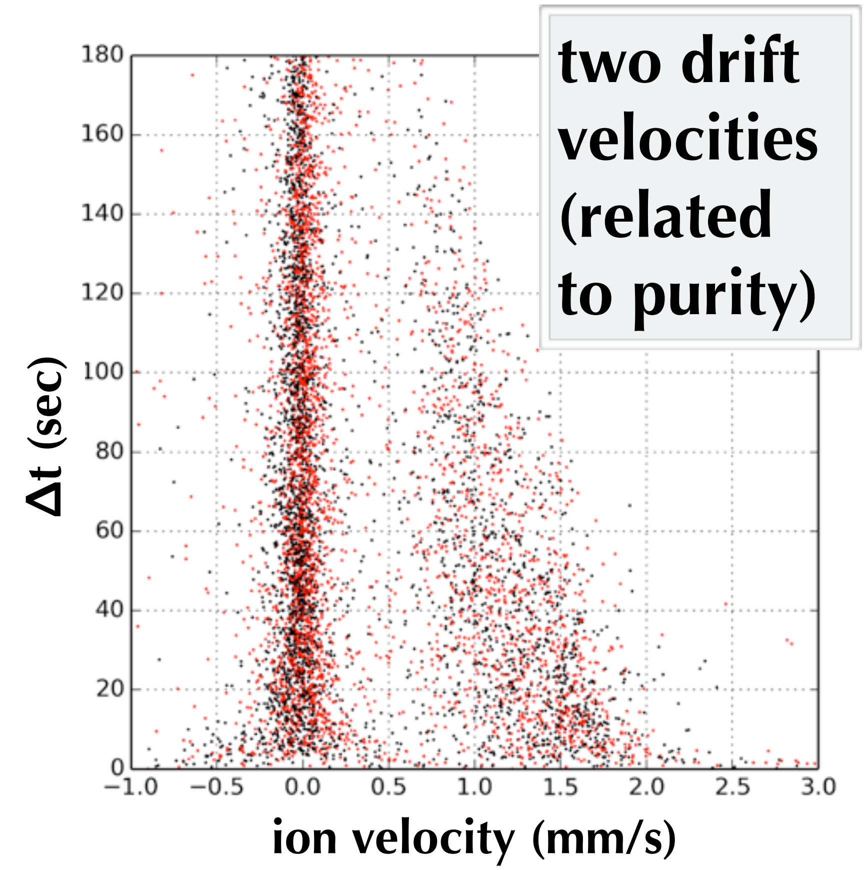
At τ_e = 3 ms:
- drift time <110 μs
- loss of charge:
  3.6% at full drift length

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

Radon products and alphas

Phys. Rev. C, 89, 015502 (2014).

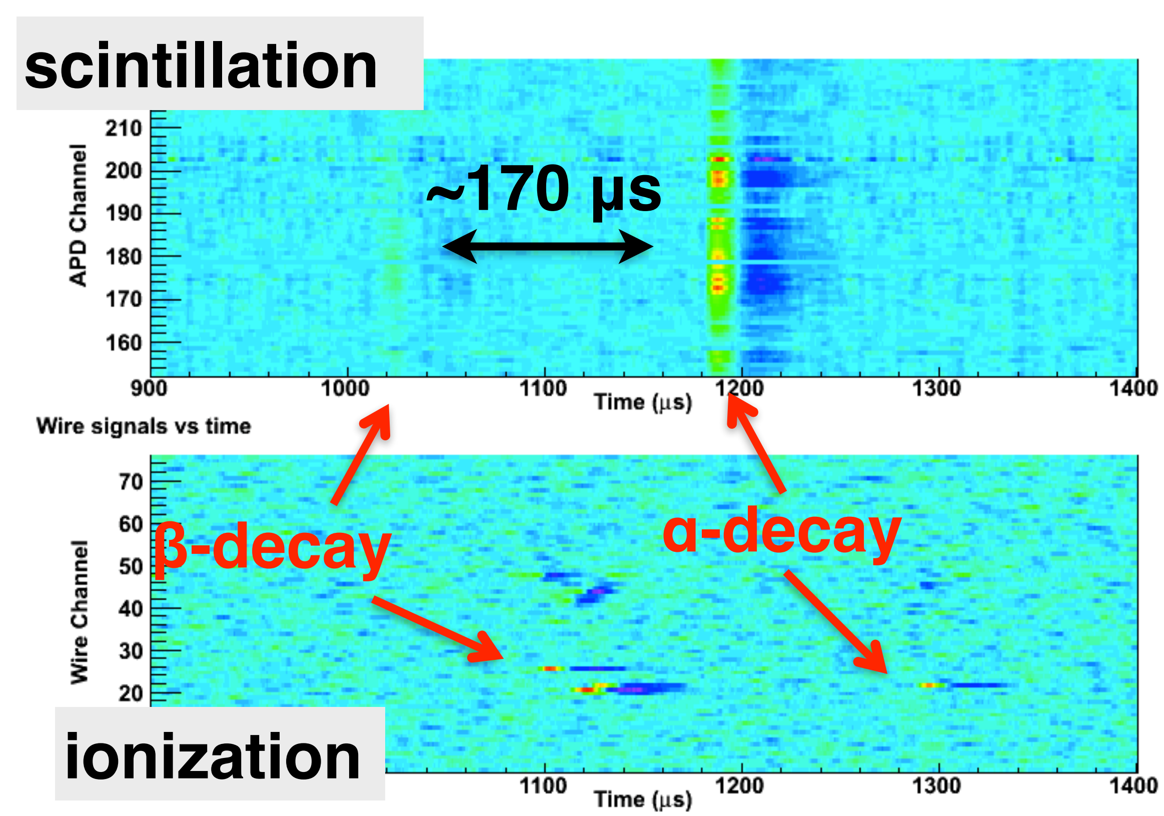




^{222}Rn-^{218}Po coincidences (3 minutes)

Steady state radon activity:
360 ± 65 μBq (fiducial volume)

~200 atoms of ^{222}Rn



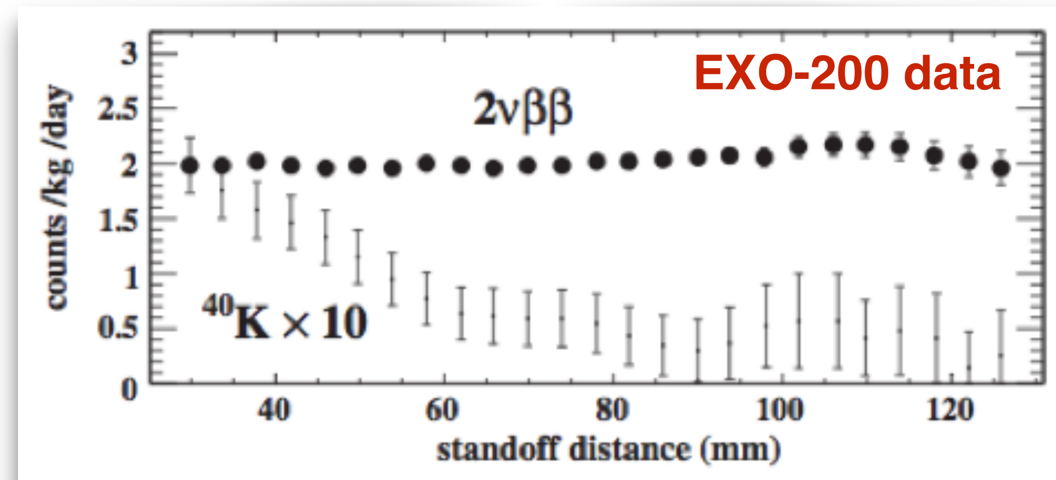
From EXO-200 to nEXO

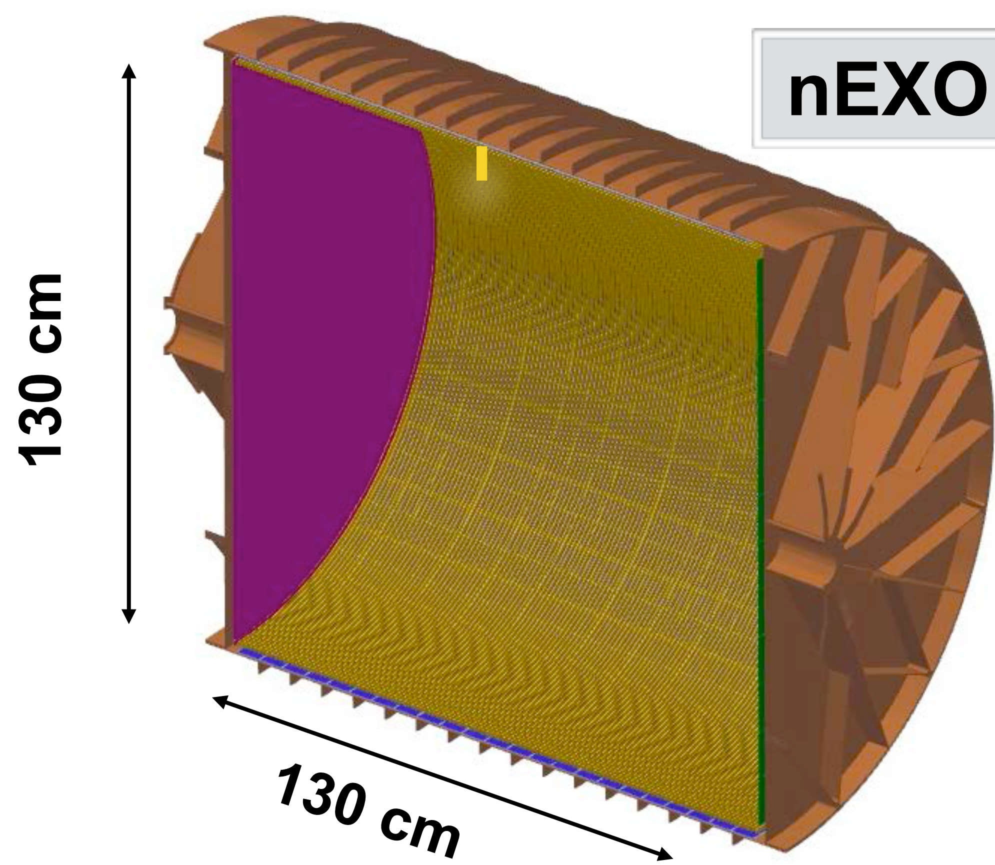
EXO-200 performance and backgrounds guided the decision to design a large LXe “discovery” detector: **nEXO**

- 5 tonnes of enriched LXe
- enhanced self-shielding
- x100 better $T_{1/2}$ sensitivity

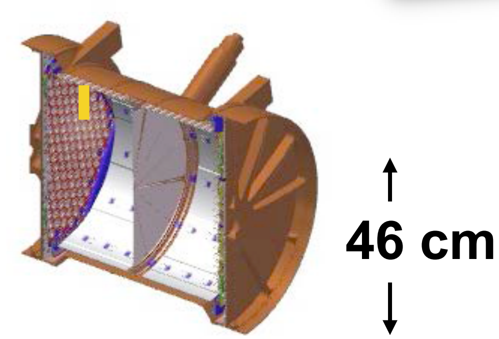
- < 1% energy resolution
- no central cathode
- ≳ 10 ms electron lifetime

the range of a 2.5 MeV γ-ay in LXe is 8.5 cm



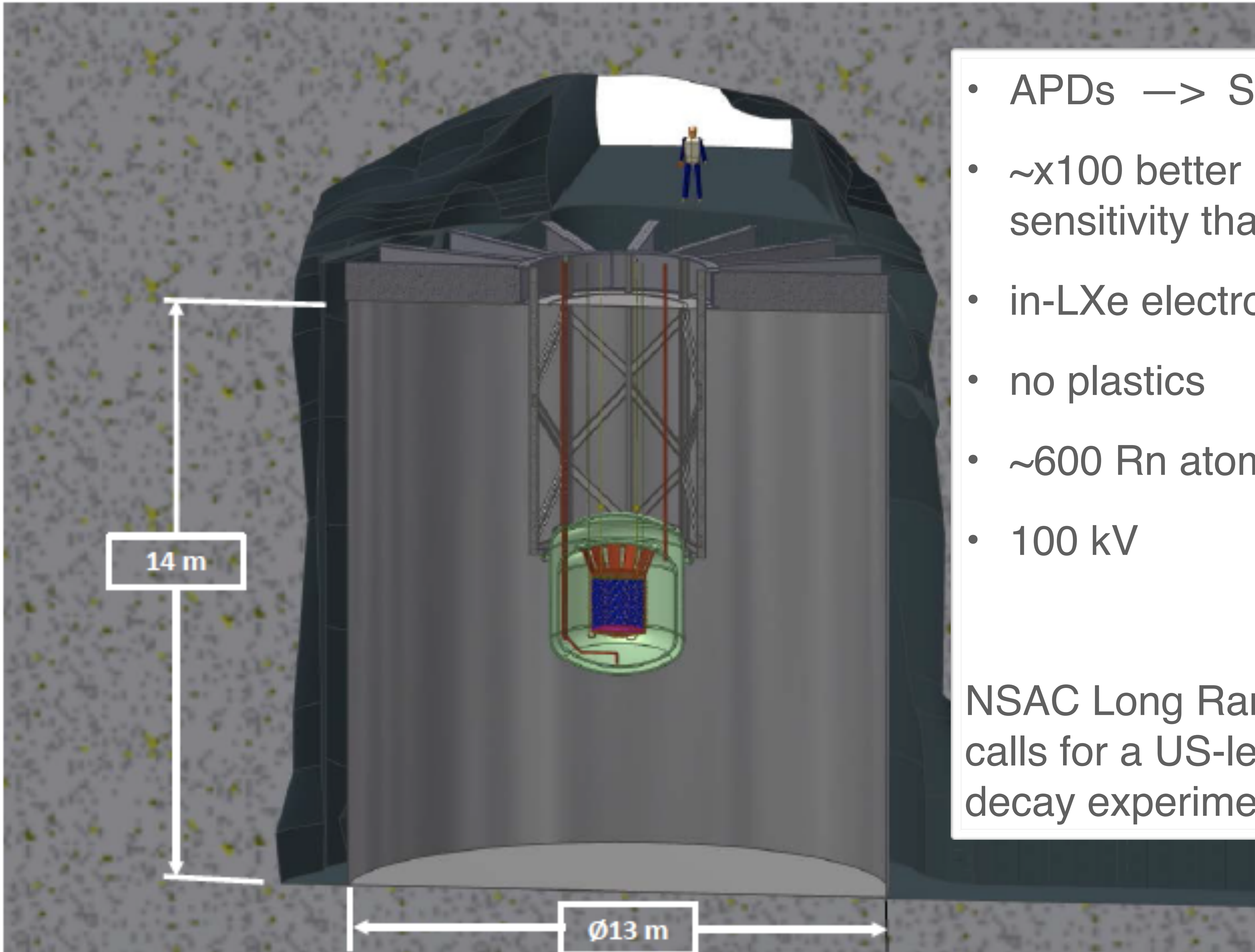


nEXO



EXO-200

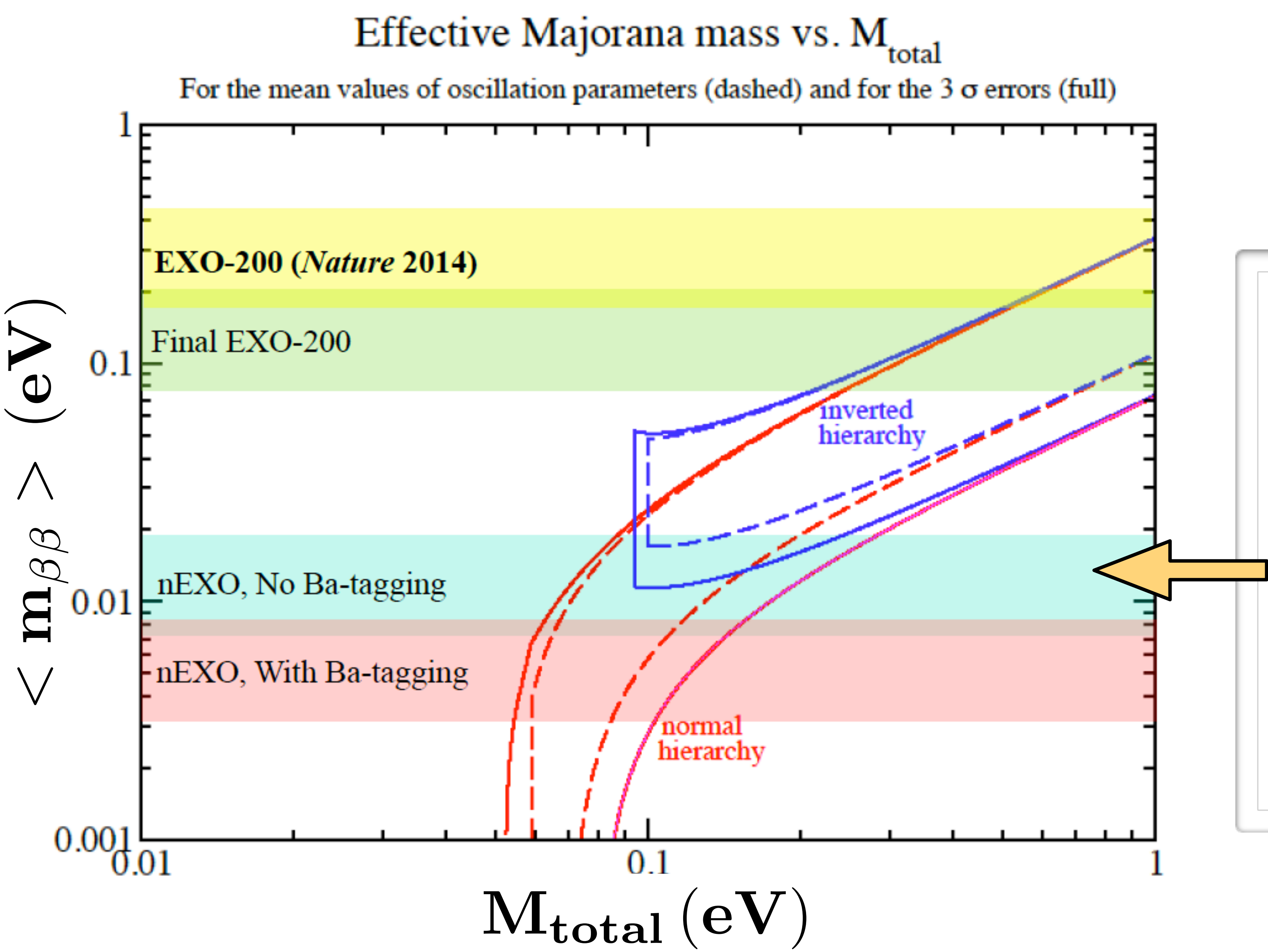
nEXO conceptual design (SNOLab)



- APDs —> SiPMs
- ~x100 better half-life sensitivity than EXO-200
- in-LXe electronics
- no plastics
- ~600 Rn atoms
- 100 kV

NSAC Long Range Plan calls for a US-led 0νββ decay experiment

EXO-200 and nEXO Physics Sensitivity



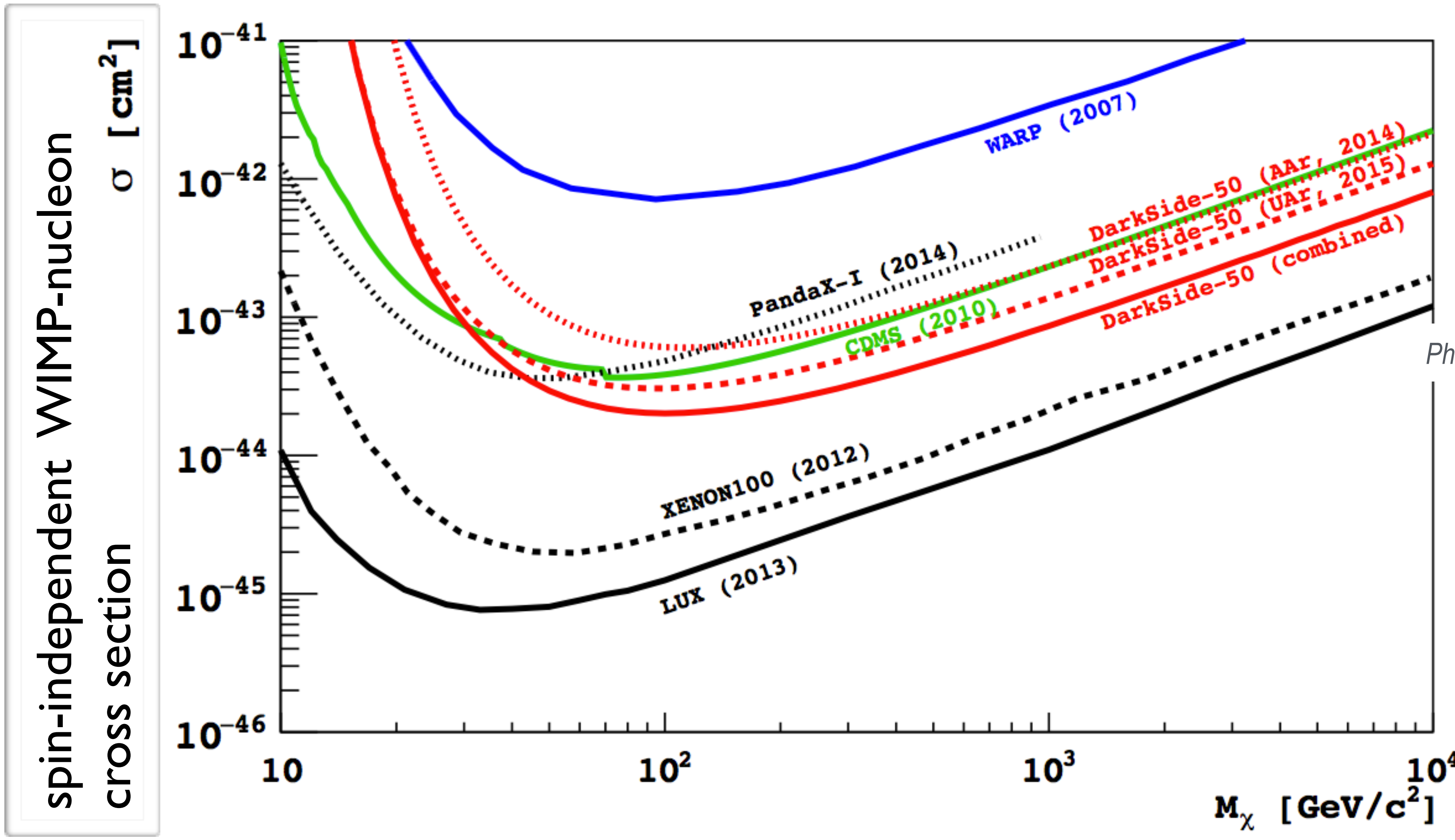
$T_{1/2} = 6 \times 10^{27}$ yr in 5 years of counting

Majorana neutrino mass $<m_{\beta\beta}>$ sensitivity of 7-18 meV

From 0νββ decay to WIMPS

Heavy WIMP searches: were do we stand?

Dual phase LXe: leaders for WIMP searches



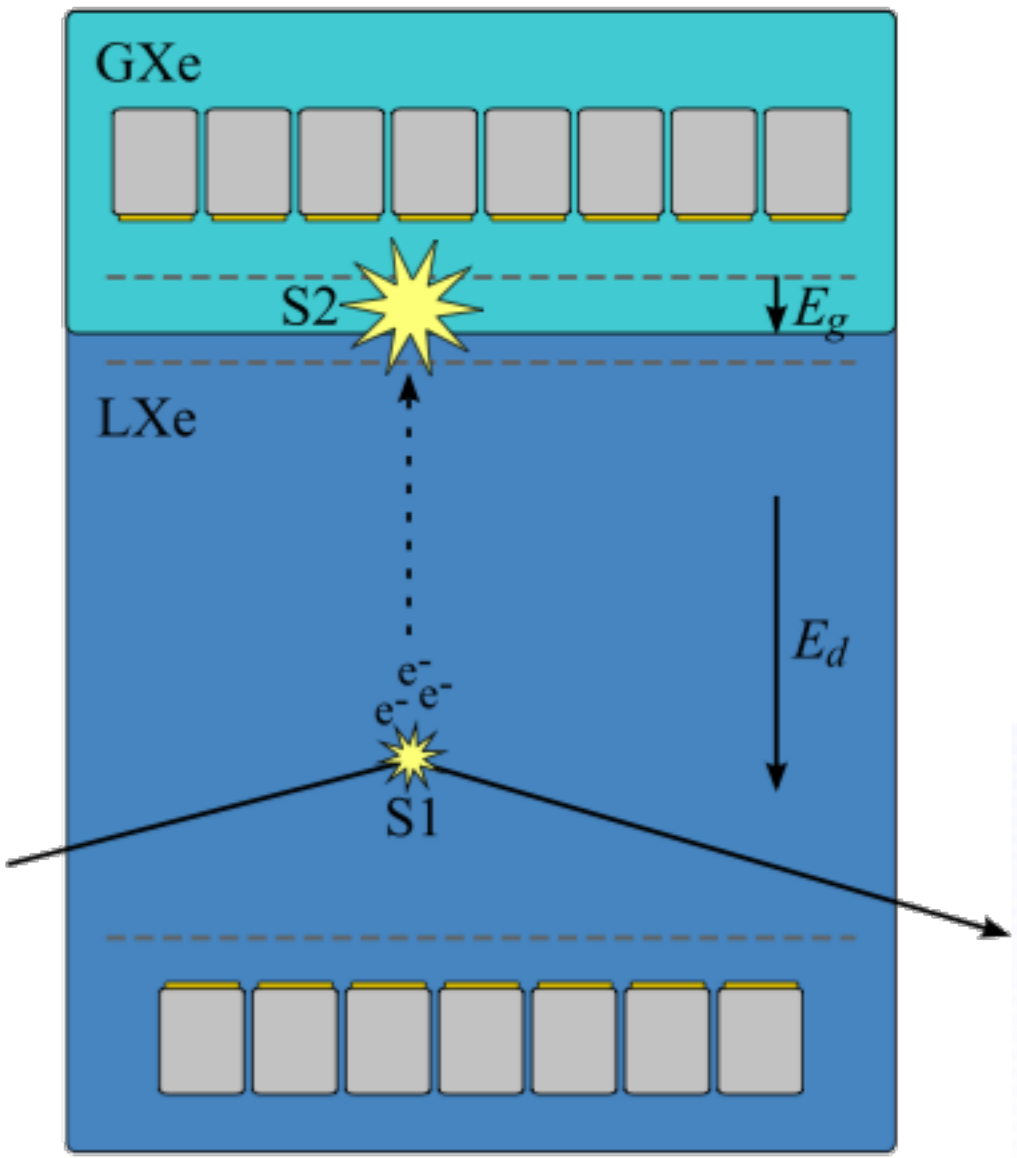
Phys. Rev. Lett. 109, 181301 (2012)

Phys. Rev. Lett. 112, 091303 (2014)

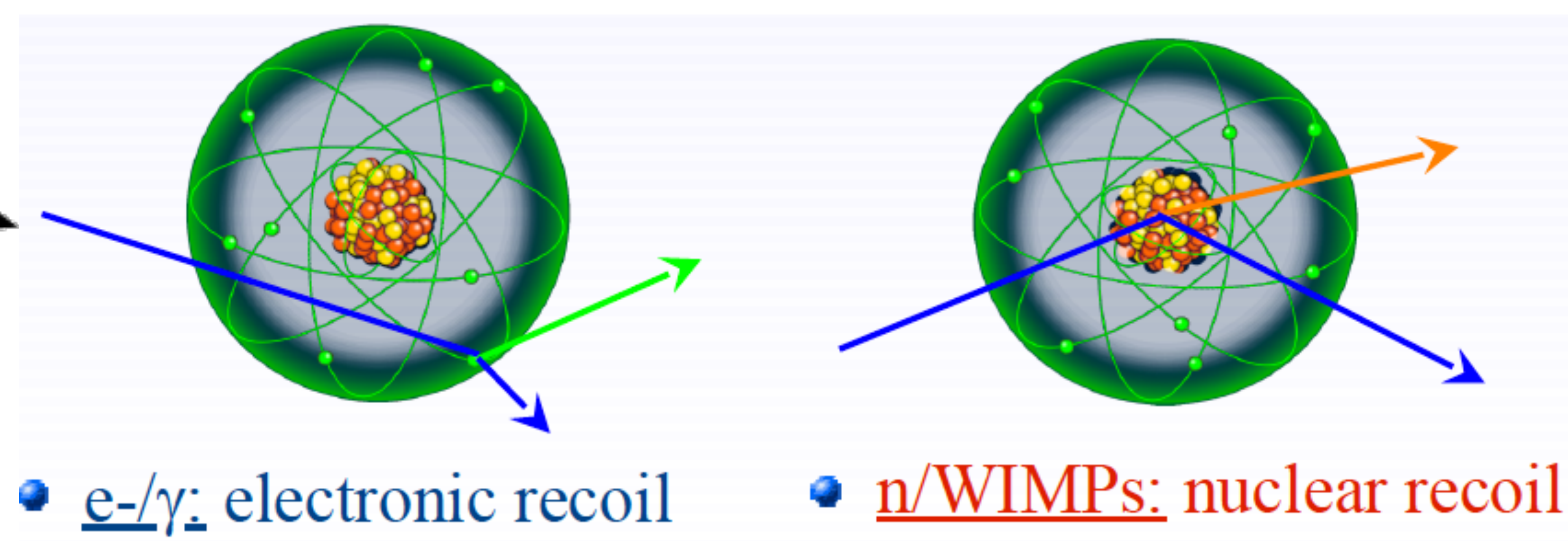
The three best results for heavy (m > few tens GeV/c^2) WIMP-nucleon spin-independent cross section are obtained with dual-phase LXe/LAr TPCs

Dual-phase LAr/LXe TPC

slide courtesy of Ethan Brown (adapted)



- Nuclear/electron recoil **excite** and **ionize** the LXe/LAr, producing **scintillation** light (S1)
- The electrons are extracted into the gas region, where they induce **electroluminescence** (S2)
- 3D position reconstruction
- Recoil discrimination (S2/S1, PSD on S1)



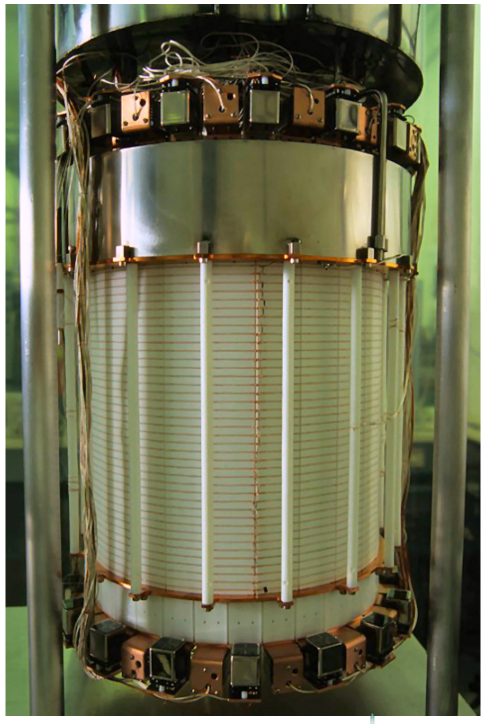
$(S2/S1)_{NR} < (S2/S1)_{ER}$

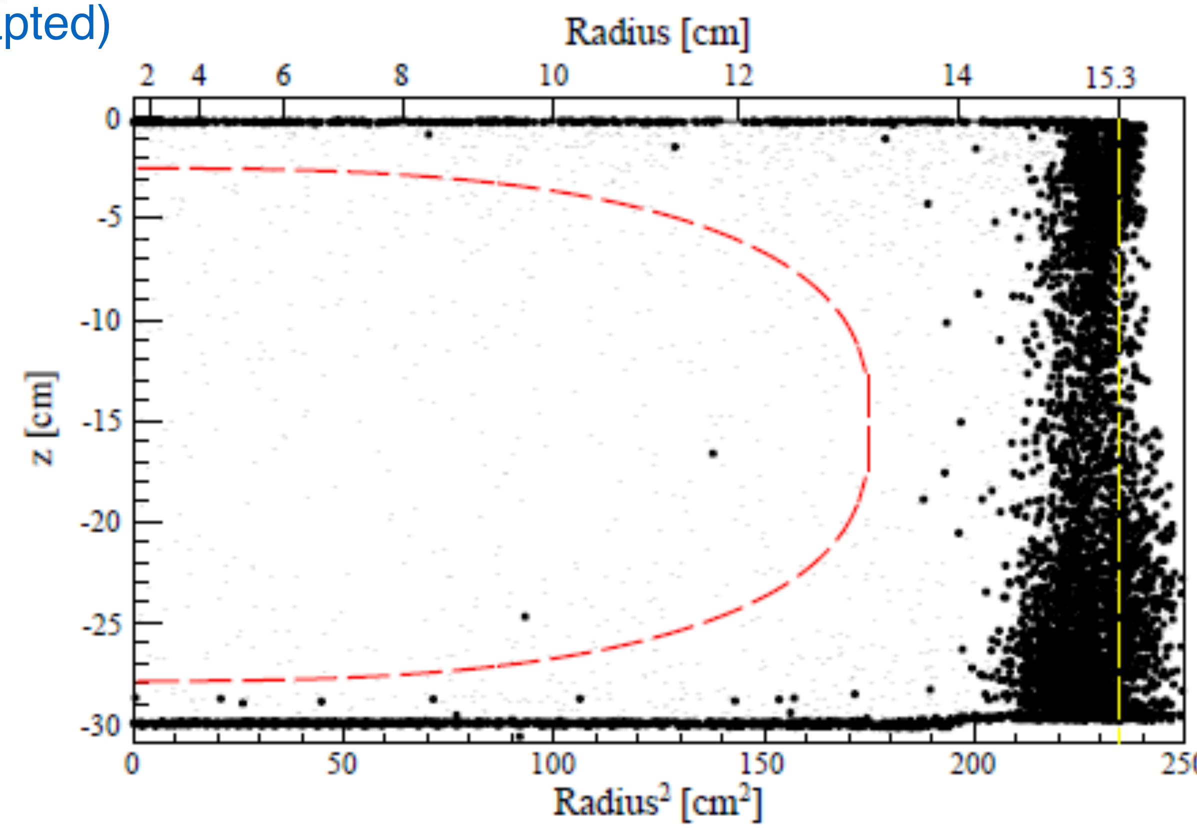
The XENON program at LNGS

slide courtesy of Ethan Brown (adapted)

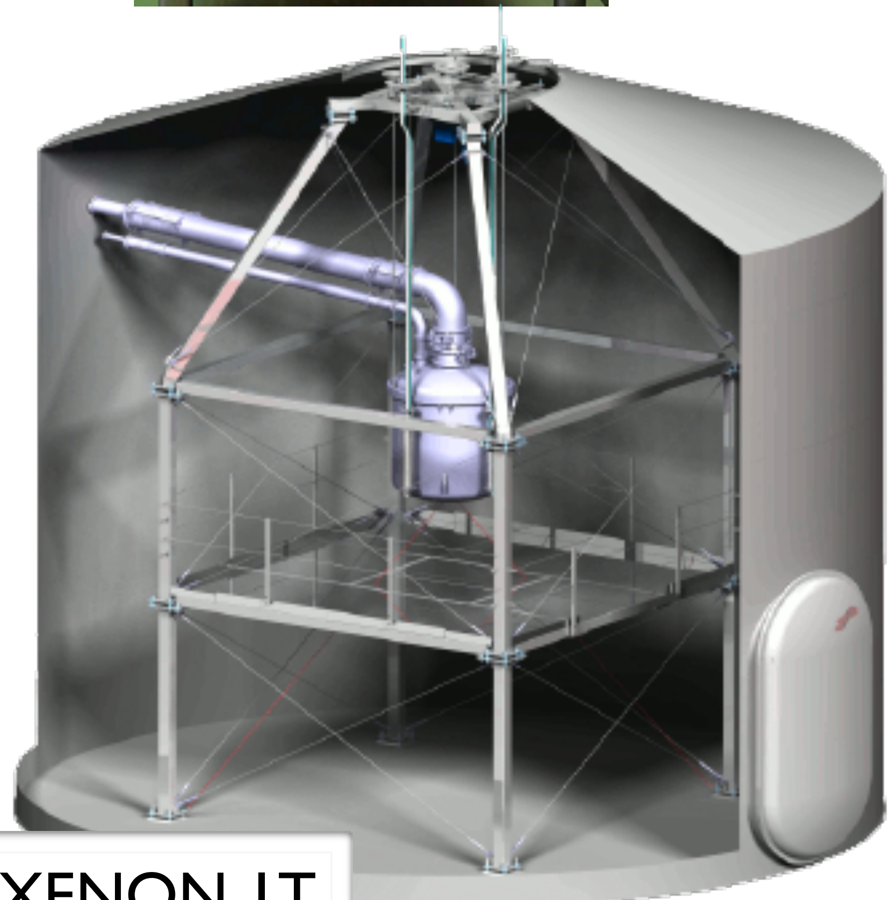
Phys.Rev.D83:08200(2011)
Astroparticle Physics 35, 573 (2012)
Phys. Rev. D 88, 012006 (2013)
Phys. Rev. D 90, 062009
Phys. Rev. Lett. 115, 091302 (2015)
Science 349, 851 (2015)

XENON 100

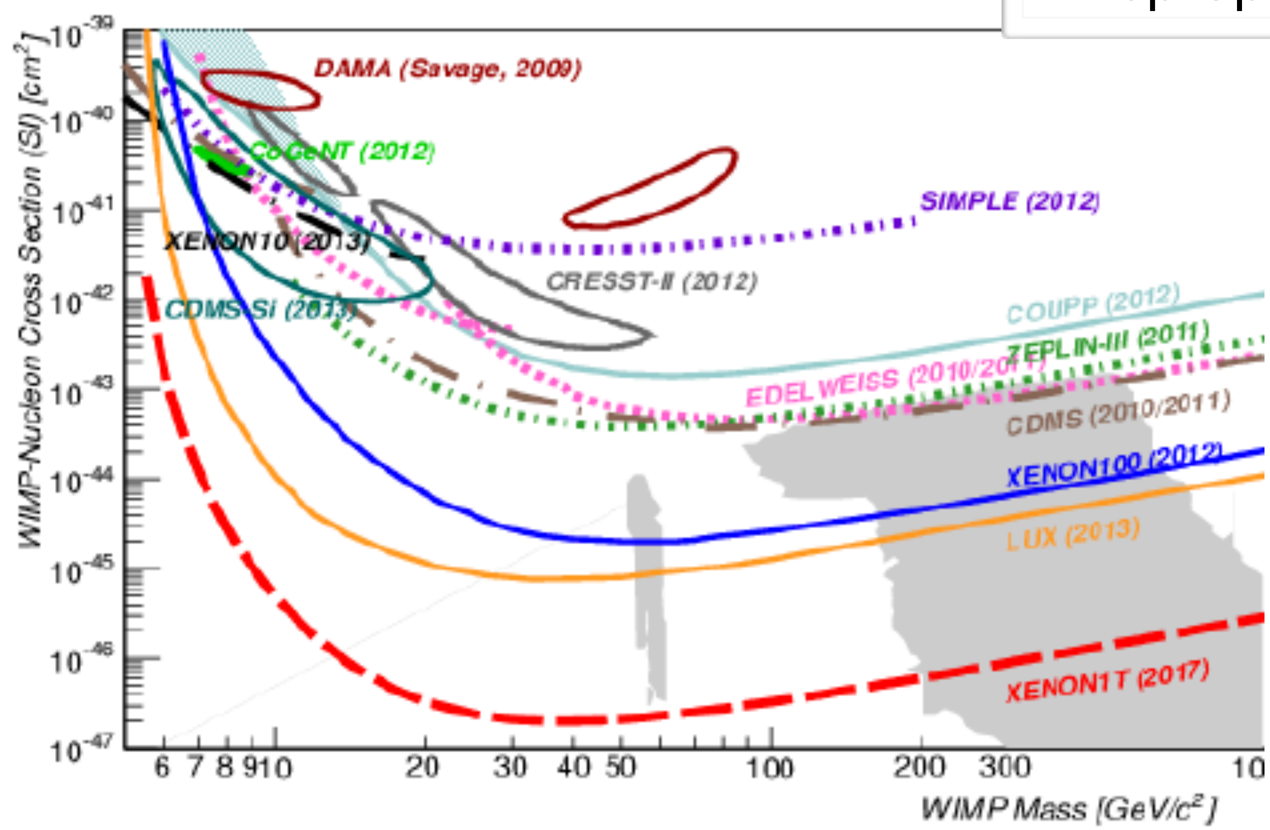




- 161 kg Xe (62 kg active)
- $\sigma_{SI} < 2.0 \times 10^{-45}$ cm^2 for 50 GeV/c2 WIMP
- Total bg = 1.0 ± 0.2 (0.17 NR, 0.79 ER)
- also SD, axions, leptophylic DM



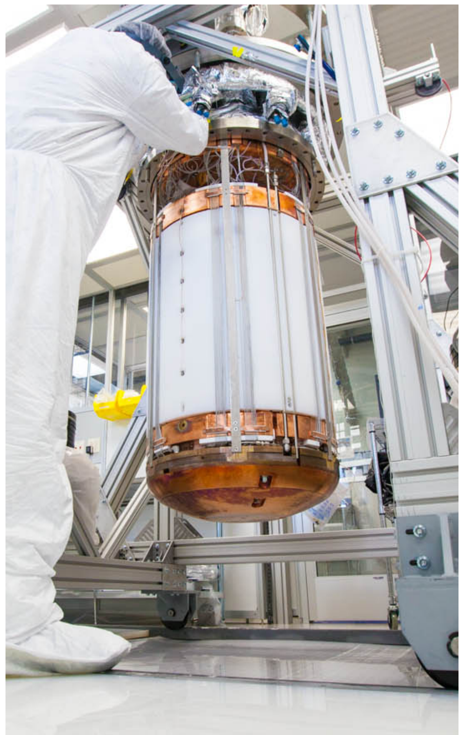
XENON 1T

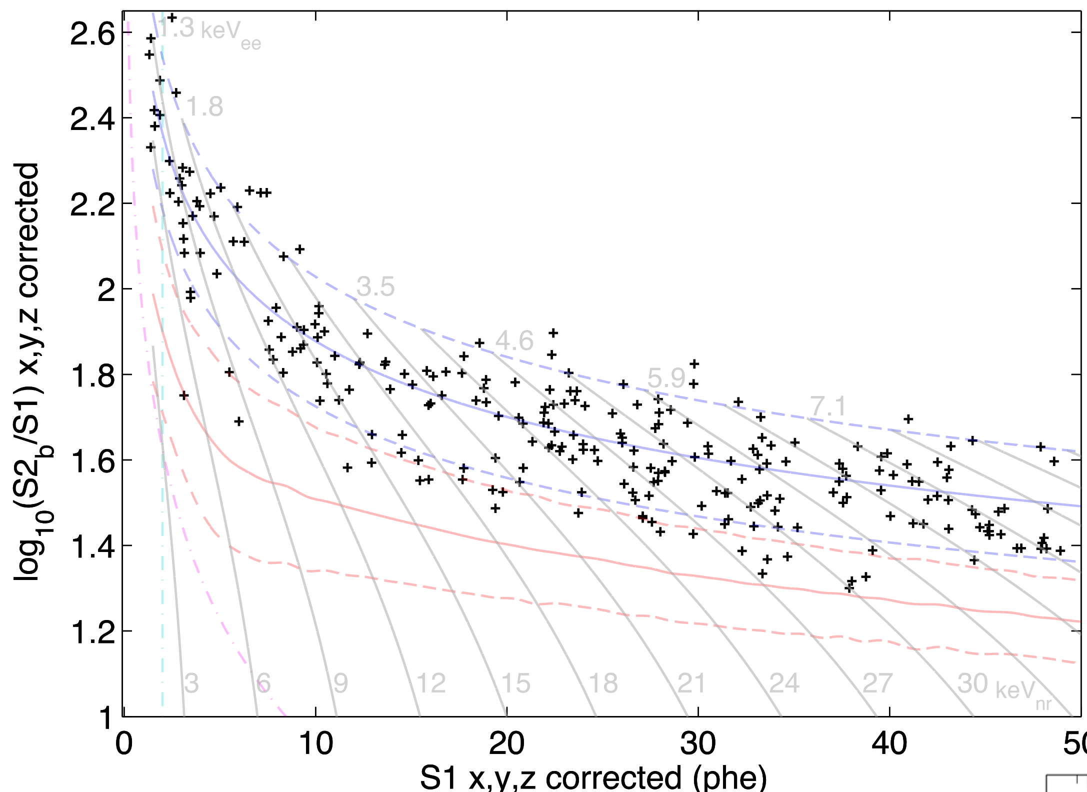


XENON nT

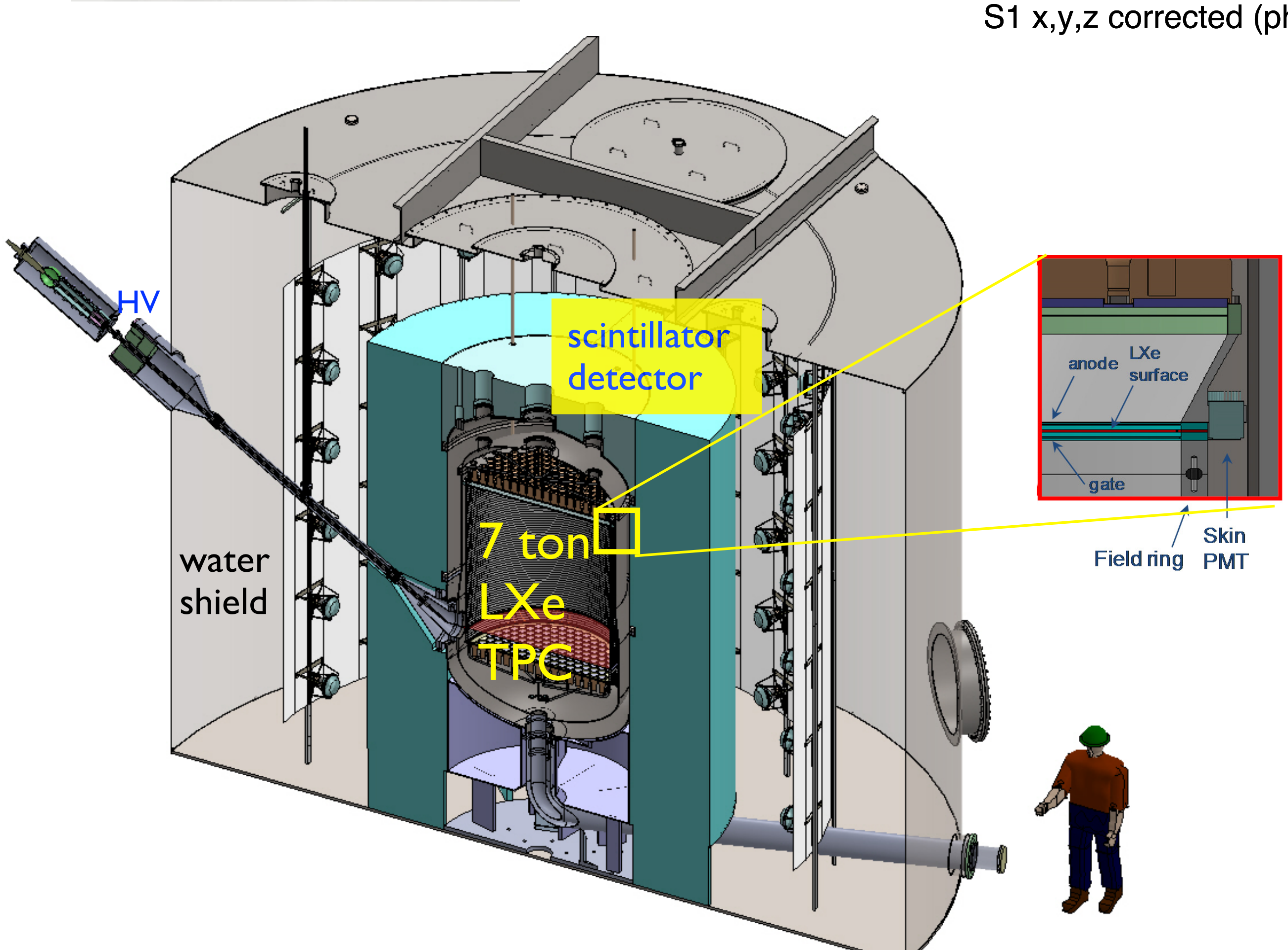
LUX —> LZ (LUX + Zeplin) program at Sanford Lab

slide courtesy of Dan Akerib (adapted)



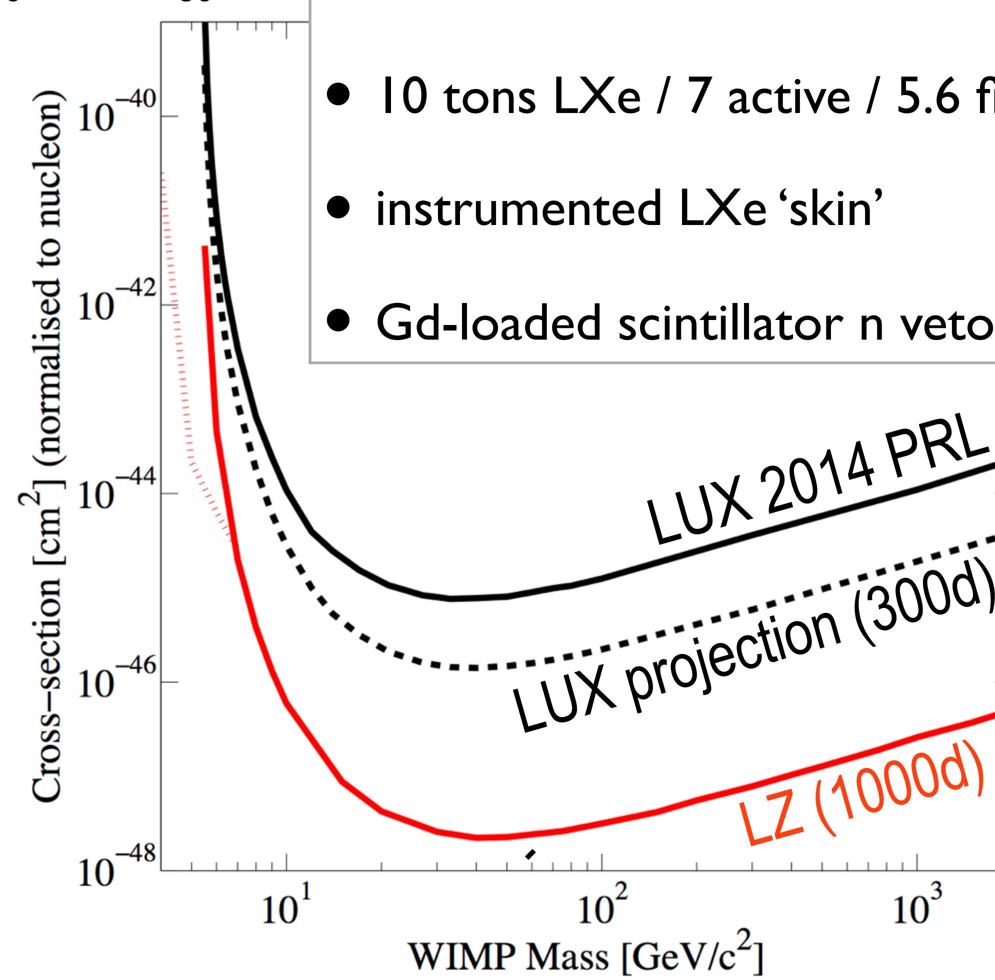


160 events in ER band
118 kg Xe fiducial



LZ

- 10 tons LXe / 7 active / 5.6 fiducial
- instrumented LXe 'skin'
- Gd-loaded scintillator n veto

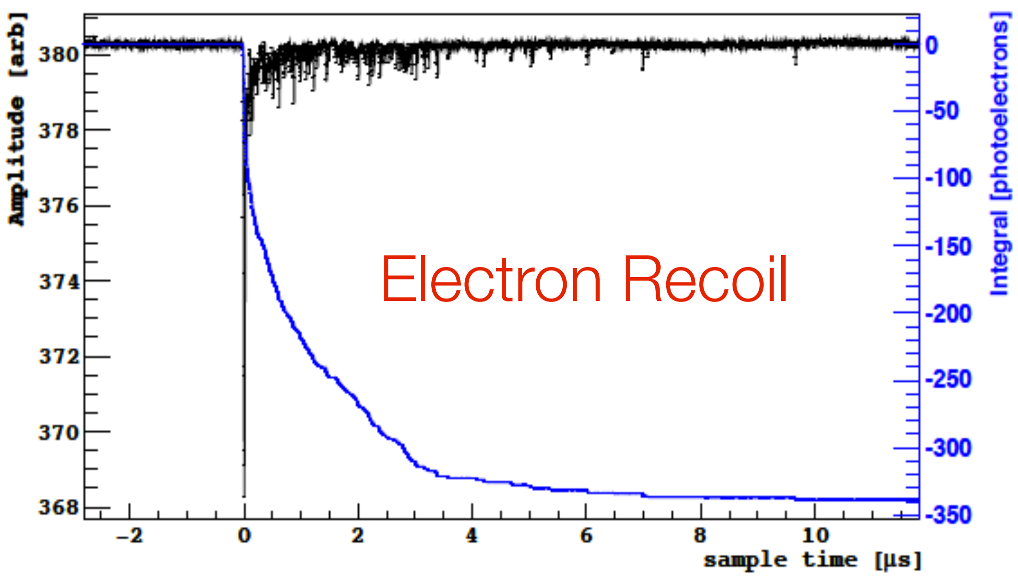


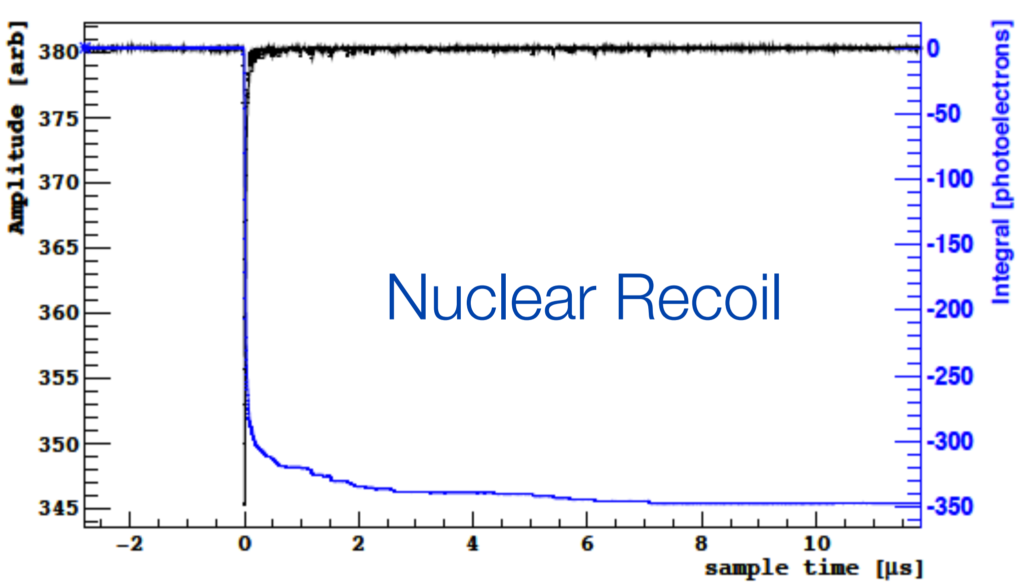
Pulse Shape Discrimination (S1) in LAr

Electron and nuclear recoils produce different excitation densities in the argon, leading to different **ratios of singlet and triplet excitation states**

$\tau_{\text{singlet}} \sim$ 7 ns

$\tau_{\text{triplet}} \sim$ 1500 ns

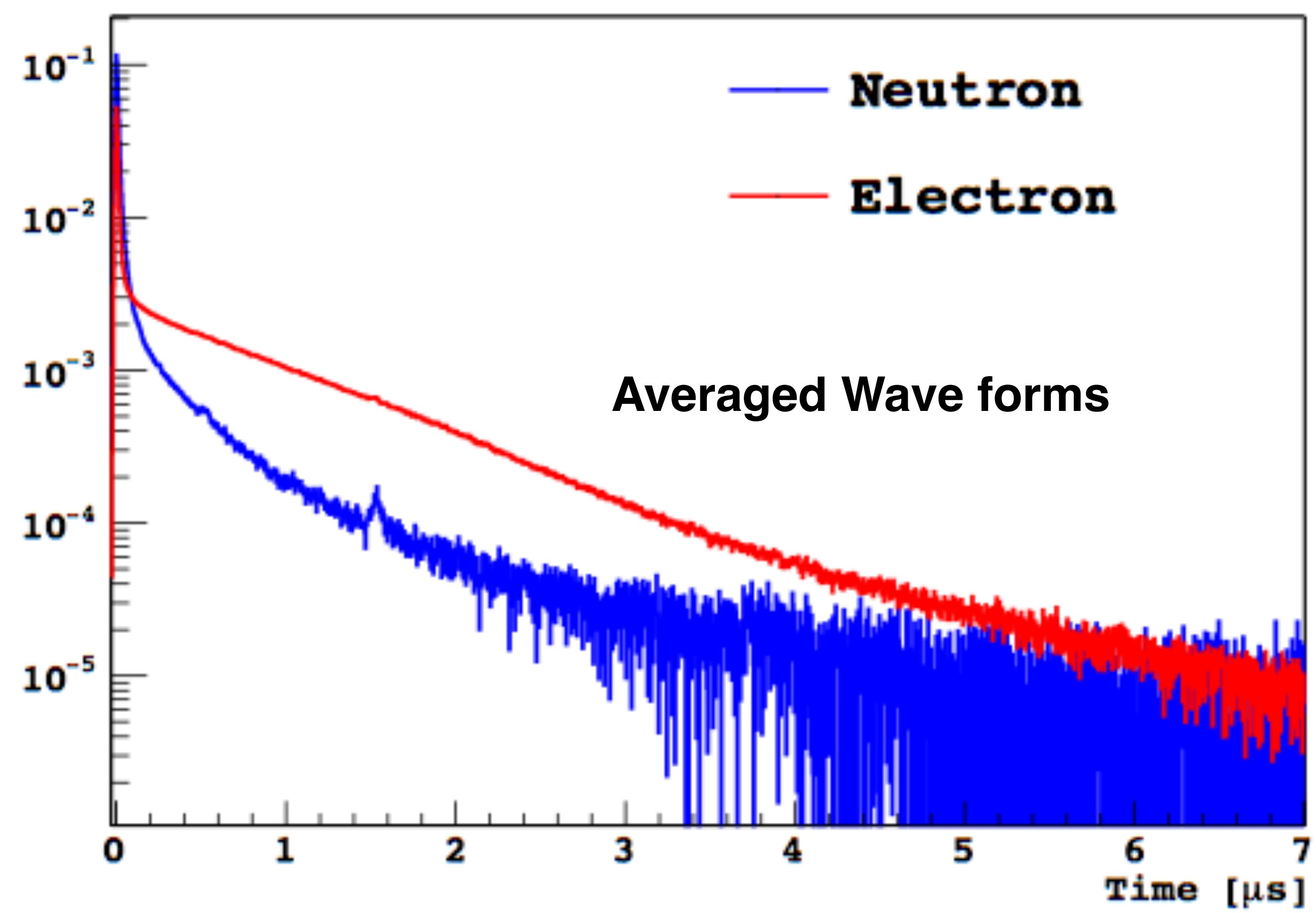




PSD parameter

F90: Ratio of detected light in the first 90 ns, compared to the total signal

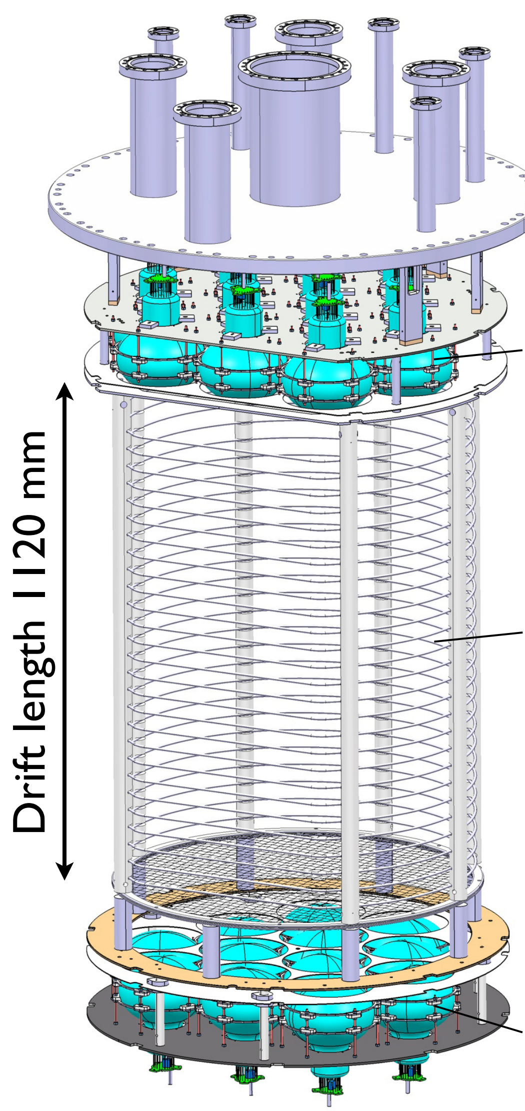
~ Fraction of singlet states

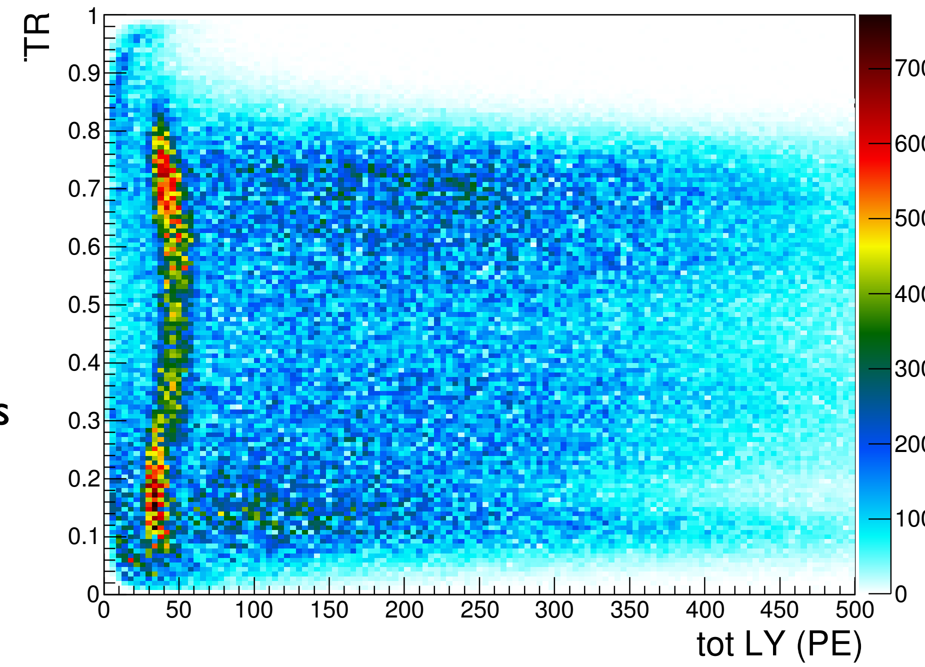


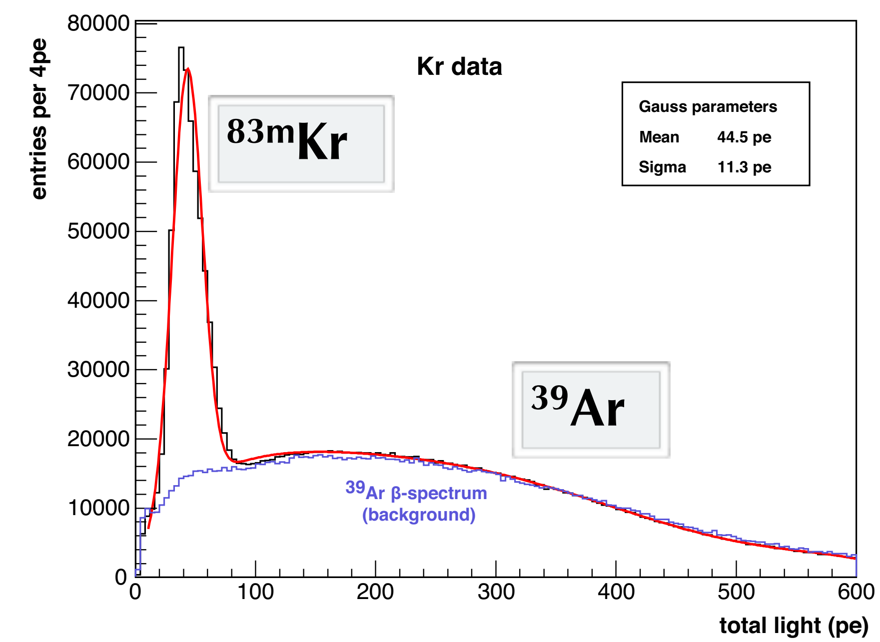
ArDM at Canfranc

slide courtesy of André Rubbia (adapted)

- **Direct search for Dark Matter particles with liquid argon**
- **First ton-scale LAr detector (proof for much larger detectors)**
- **ArDM Run I in single phase mode recently completed**



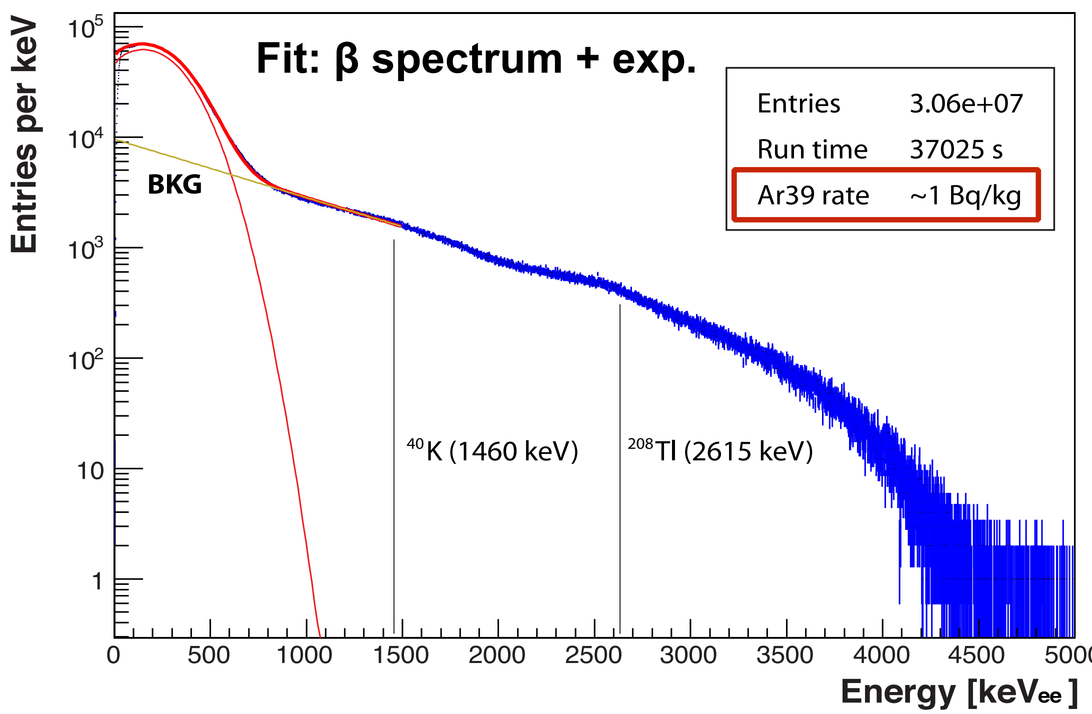




Looking at electron-like events to optimize the light propagation model and Monte Carlo
(~1 p.e./keV)

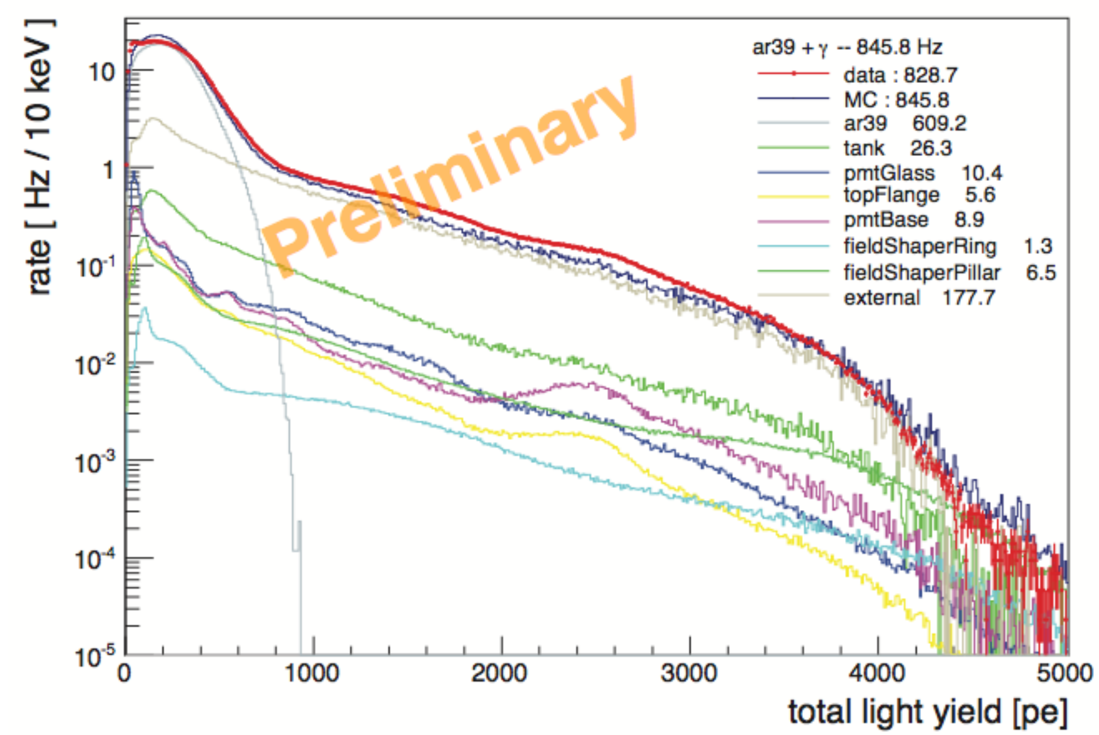
ArDM: Background studies - MC model with a full optical photon ray tracing

Measured e-like spectrum (dominated by ^{39}Ar)



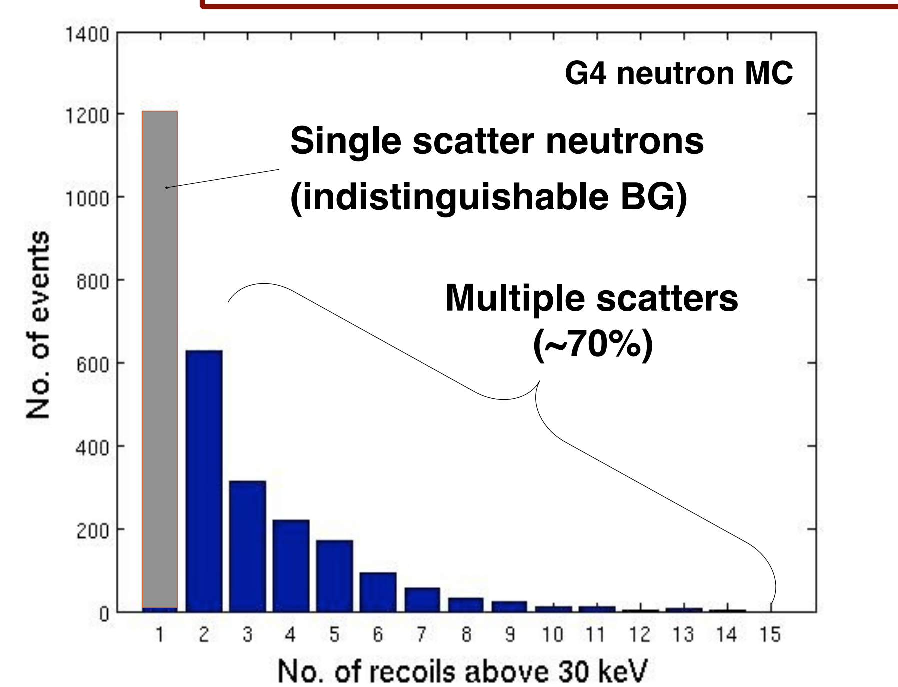
e-like data compared to MC

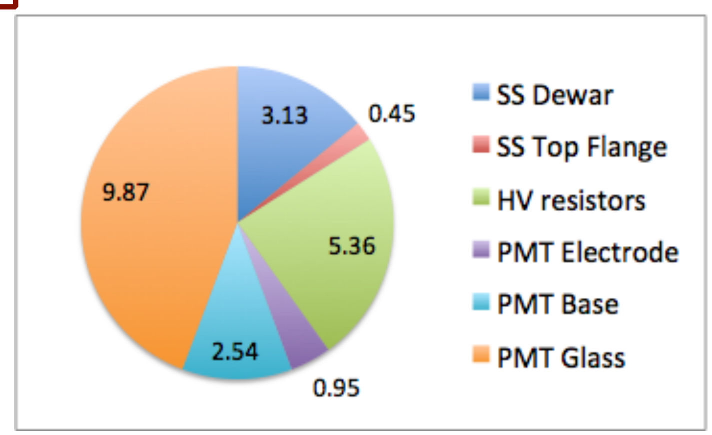
^{39}Ar (72%), external γ (21%), internal γ (7%)



Extension to nuclear recoils from neutrons

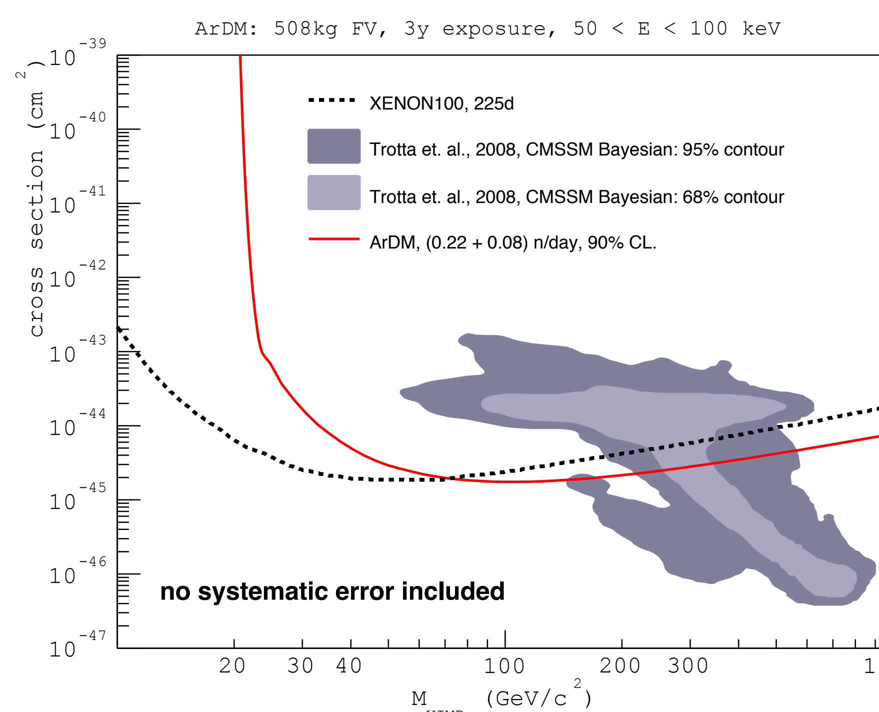
The power of large target size





84% of neutron BG originates from replaceable parts (mainly from the PMTs)

Expected sensitivity from present hardware configuration



Future plans: - proceed with analyses of the full data set - prepare dual phase run for 2016

The DarkSide program

Search for heavy WIMPs (>100 GeV/c^2) with (low ^{39}Ar) TPCs of increasing sensitivity and size

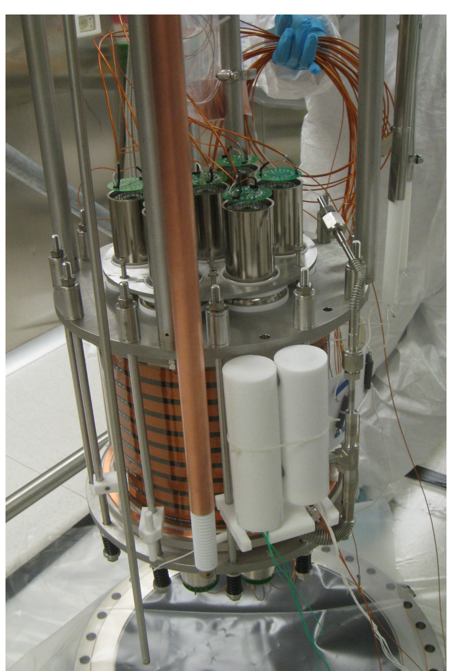
Continuous re-purification possible
- from electronegative, radioactive contaminants

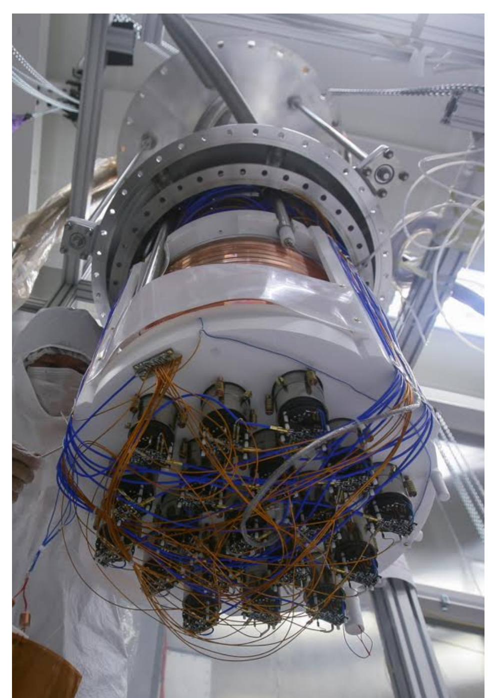
Argon is reusable
- can be transferred between experiments

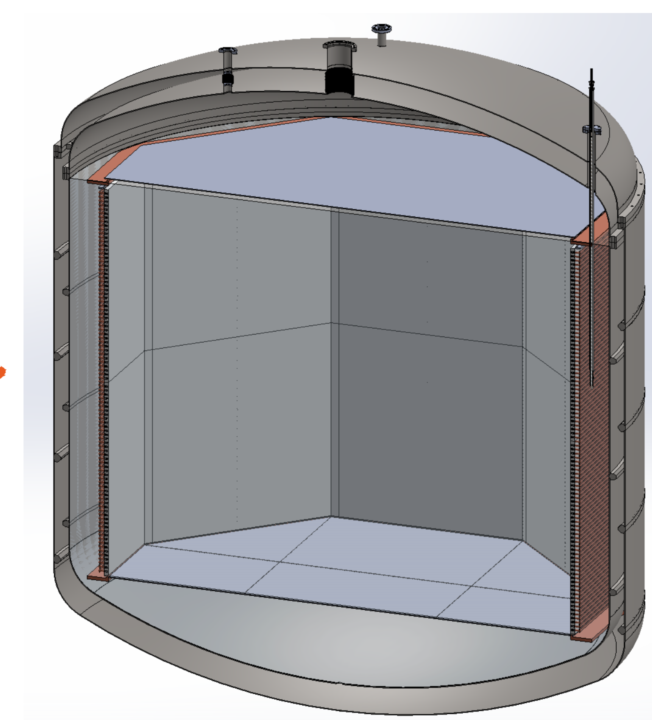
Monolithic detector, remarkable self-shielding

Nuclear/electron discrimination
- pulse shape discrimination
- charge-to-light ration
- event topology

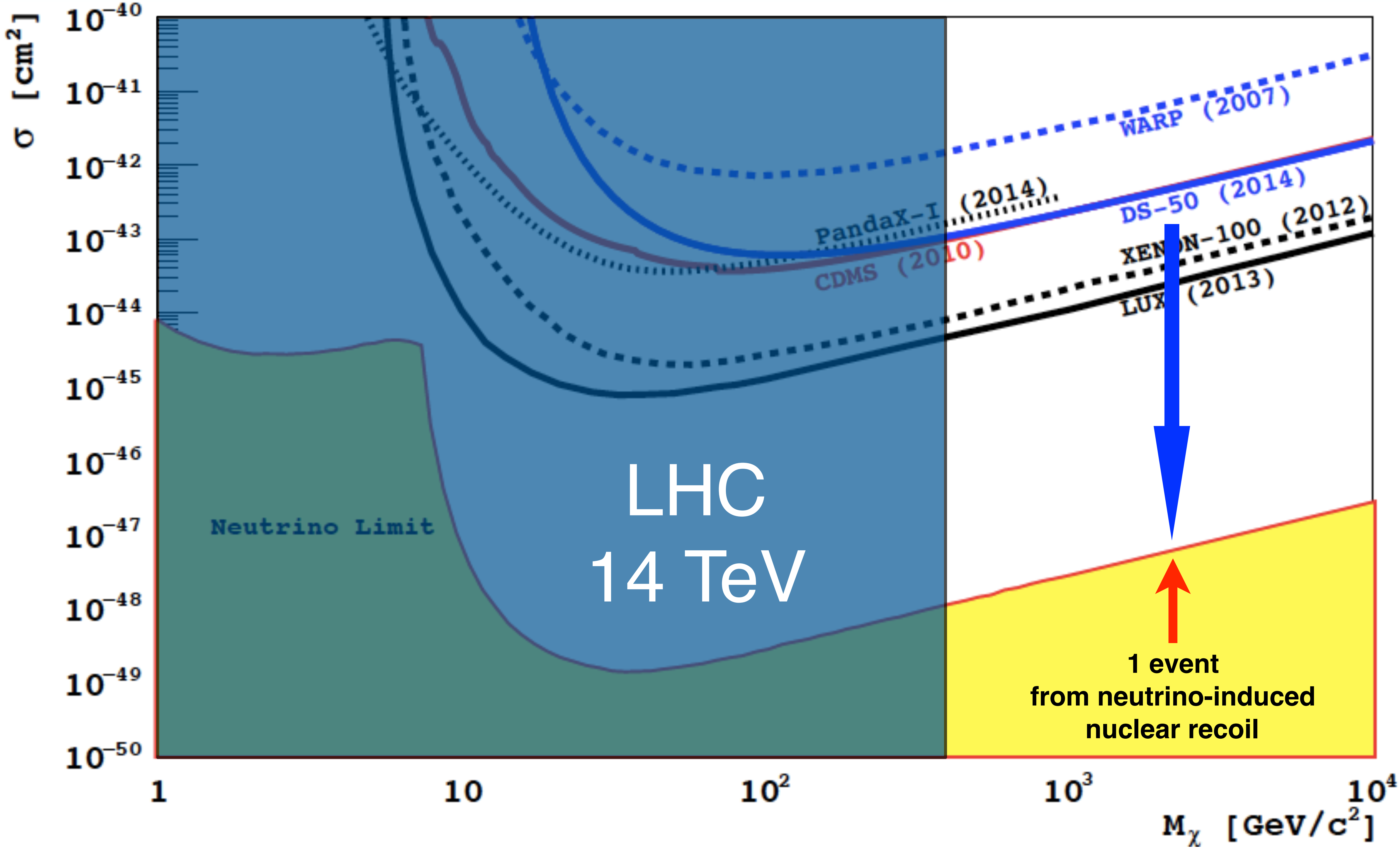
Identified source of low ^{39}Ar argon







DarkSide: path towards the “neutrino floor”



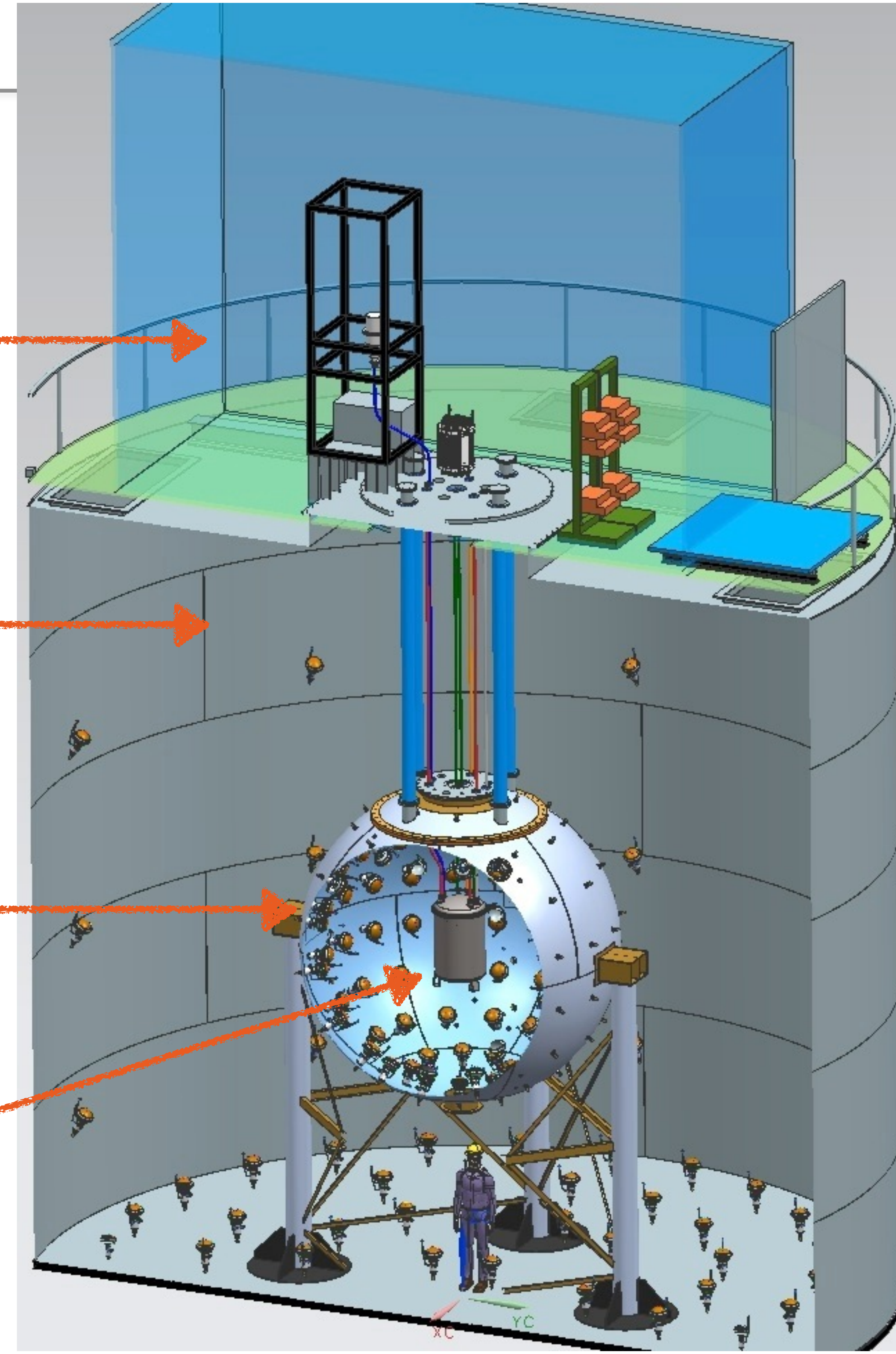
DarkSide 50

Radon-free **Clean Room**
(Rn levels < 10 mBq/m^3)

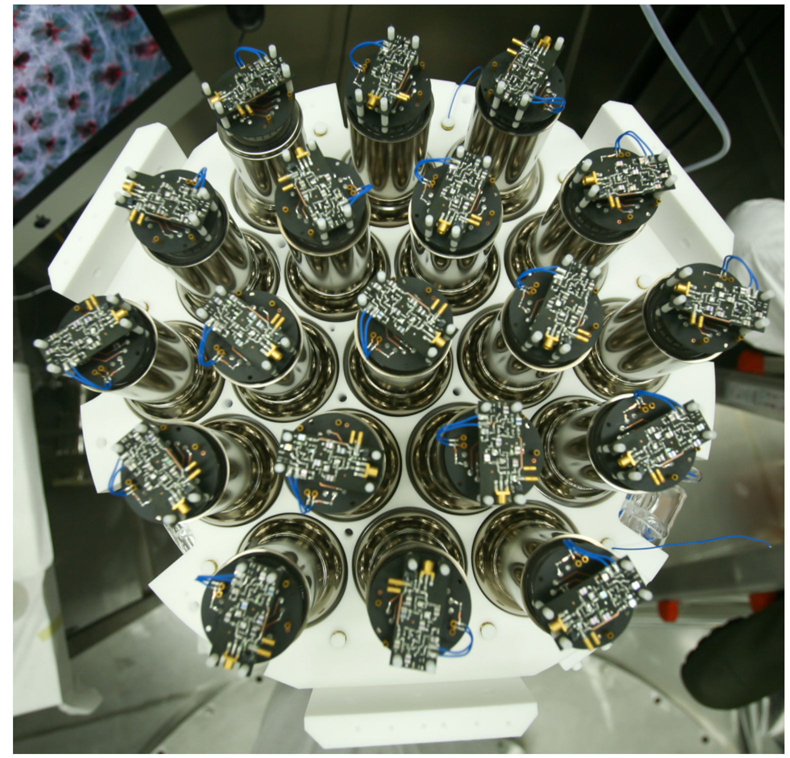
1,000-tonne Water-based Cherenkov
Cosmic Ray Veto

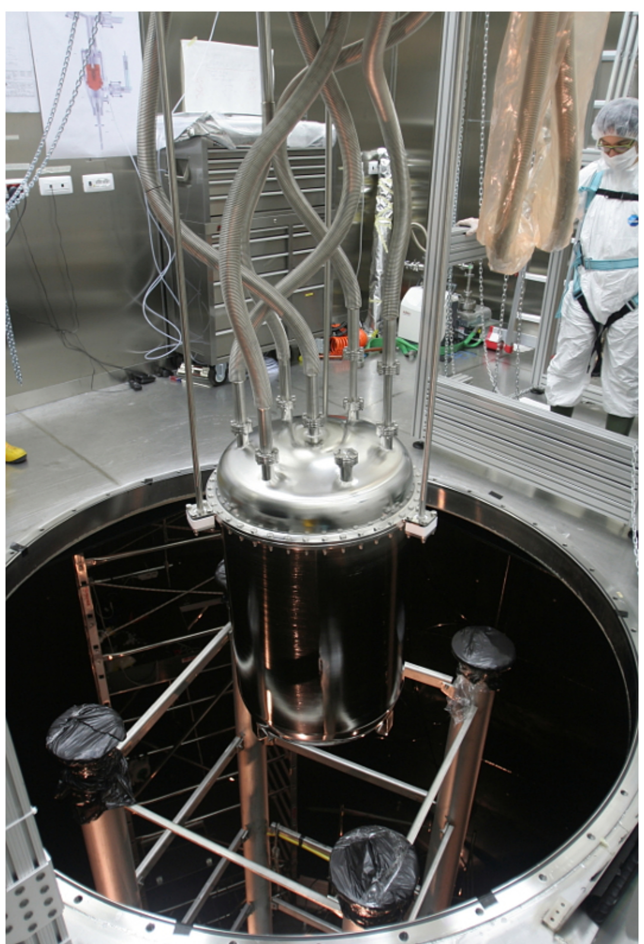
30-tonne Liquid Scintillator
Neutron and γ's Veto

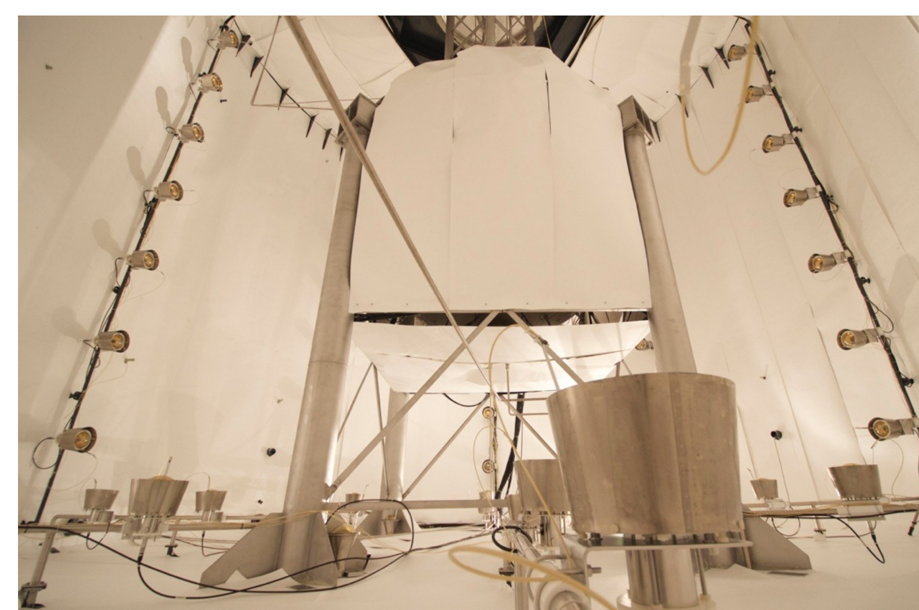
Inner detector **TPC**



DS50 Commissioning (Oct. 2013)

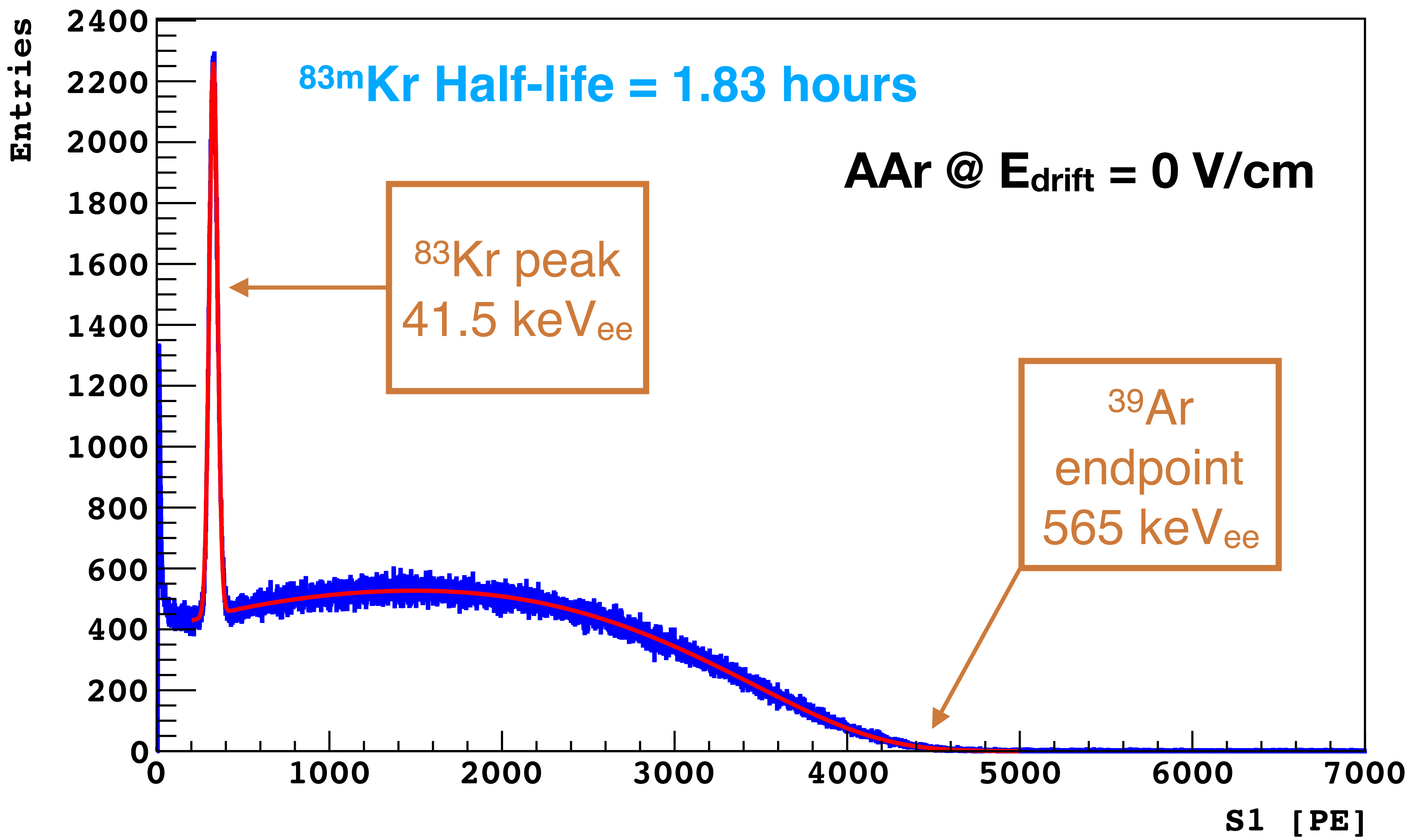






DarkSide-50: LY (electron recoils)

- ^{39}Ar (565 keV$_{ee}$ endpoint) present in AAr
- ^{83m}Kr gas deployed into detector (41.5 keV$_{ee}$)



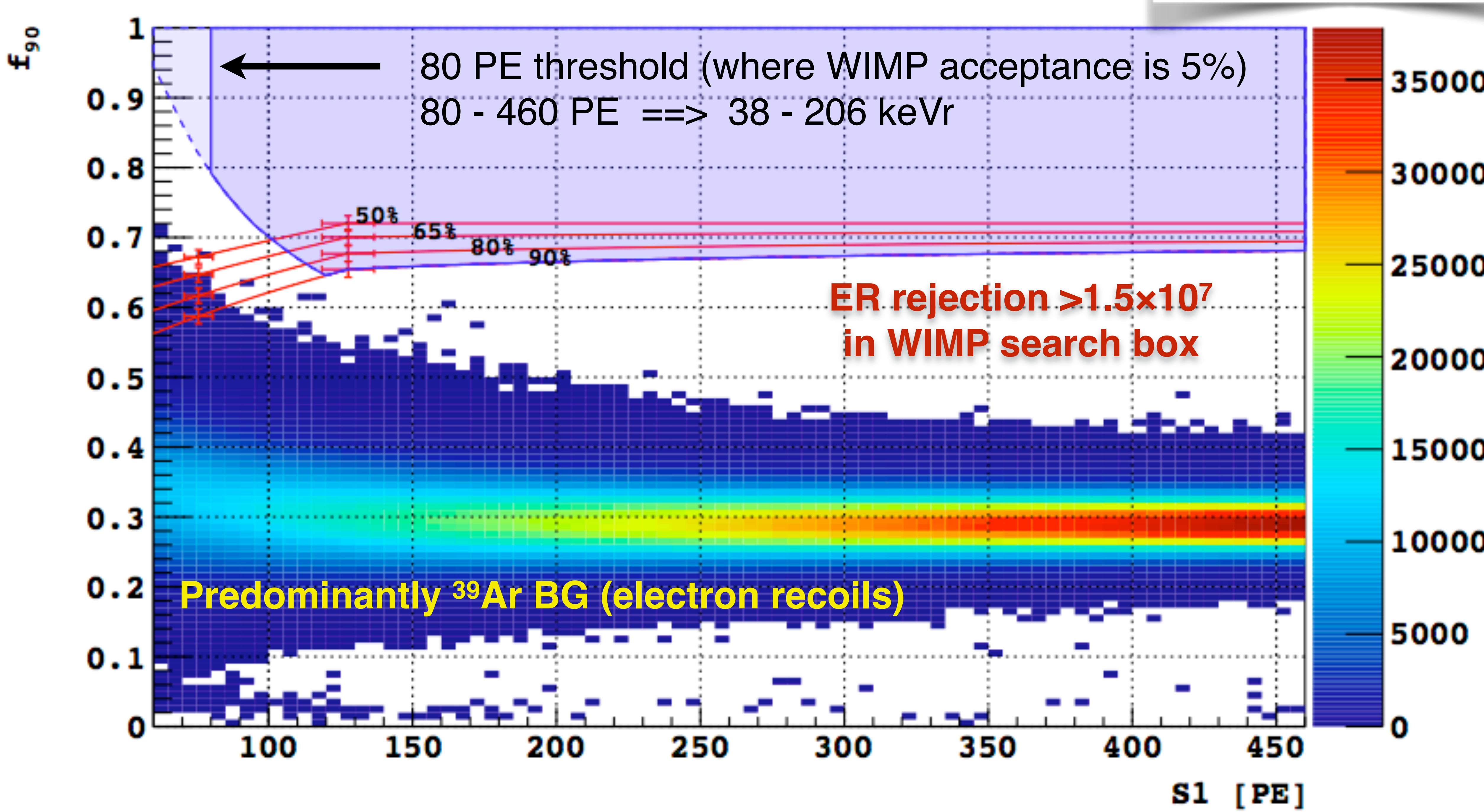
Fits to ^{39}Ar and ^{83m}Kr spectrum indicate
LIGHT YIELD: **7.9 ± 0.4** PE/keV$_{ee}$ at zero field and **7.0 ± 0.3** PE/keV$_{ee}$ at 200 V/cm

DS-50: first results

AAr: 1422 ± 67 kg·days

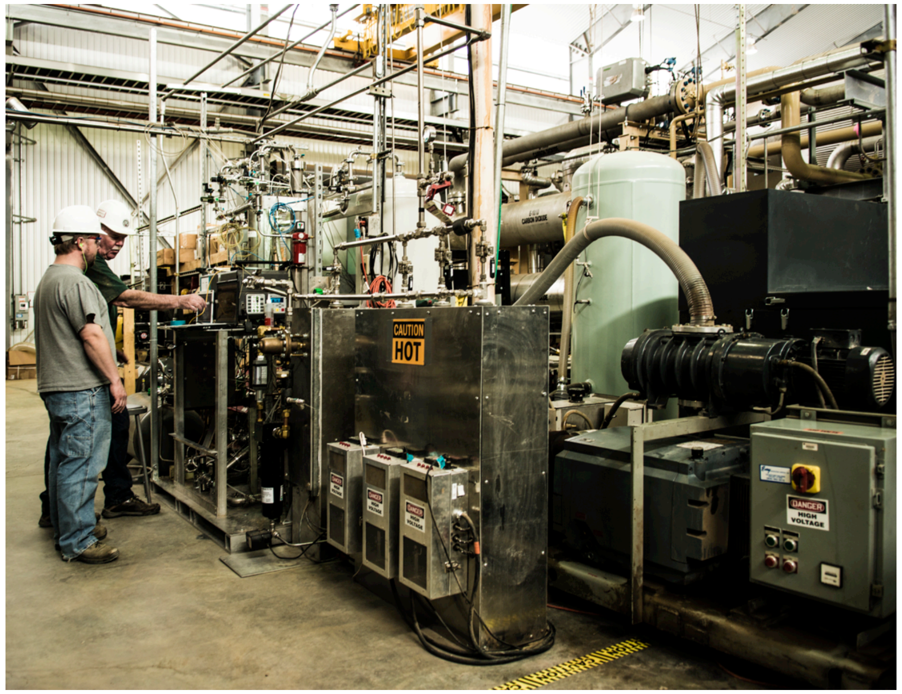
(36.9 ± 0.6 kg fiducial
vs 46.4 ± 0.7 kg active)

No WIMP candidates after all analysis cuts applied



Phys. Lett. B 743, 456 (2015)

Underground Ar



1. **Extraction at Colorado** (CO_2 Well)
   Extract a crude argon gas mixture (Ar, N_2, and He)

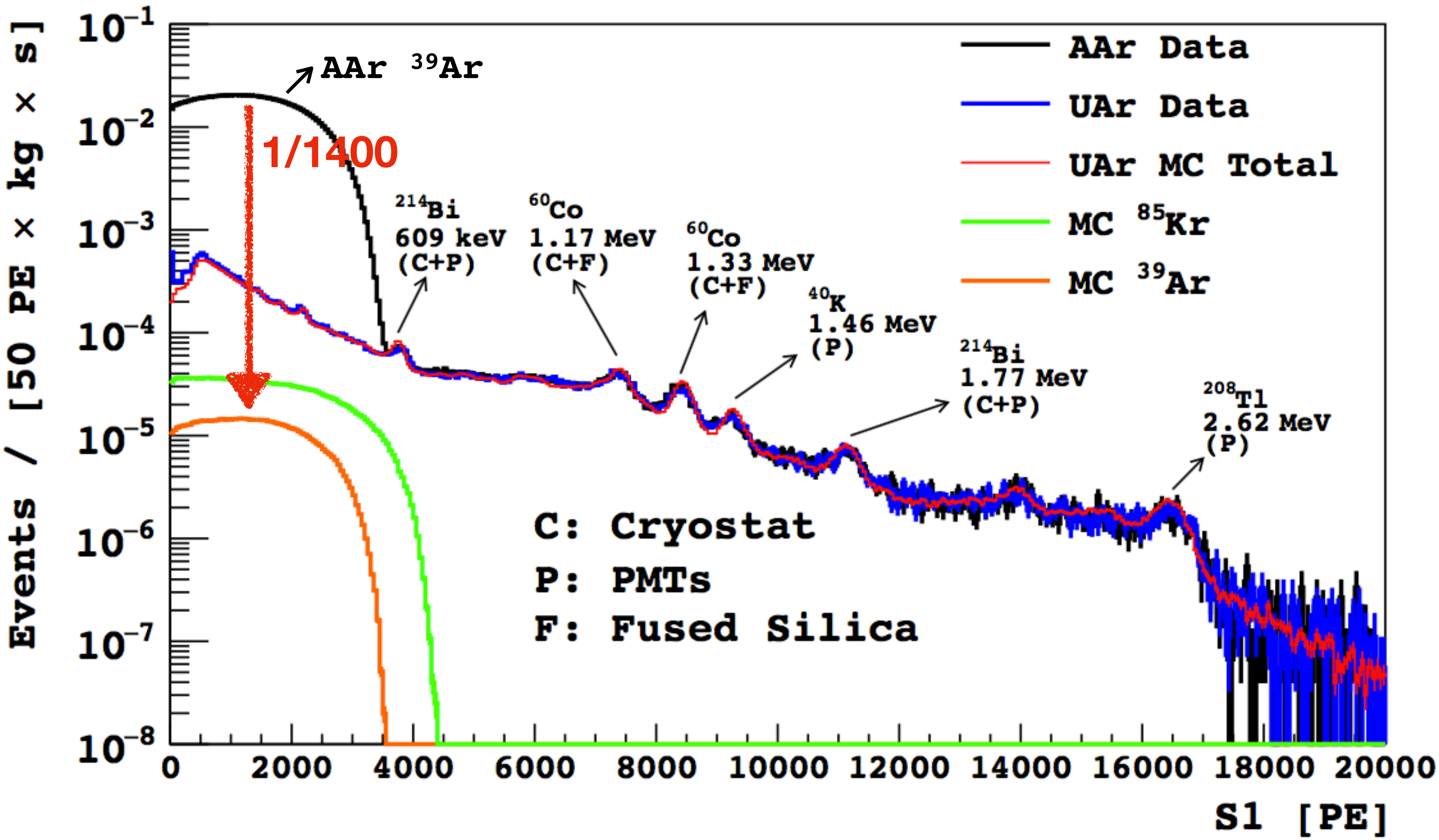
2. **Purification at Fermilab**
   Separate Ar from He and N_2

3. **Arrived at LNGS**
   Ready to fill into DS-50

UAr First Results

AAr vs UAr. Live-time-normalized S1 pulse integral spectra at **Zero** field.

^{39}Ar reduction factor of ~1400

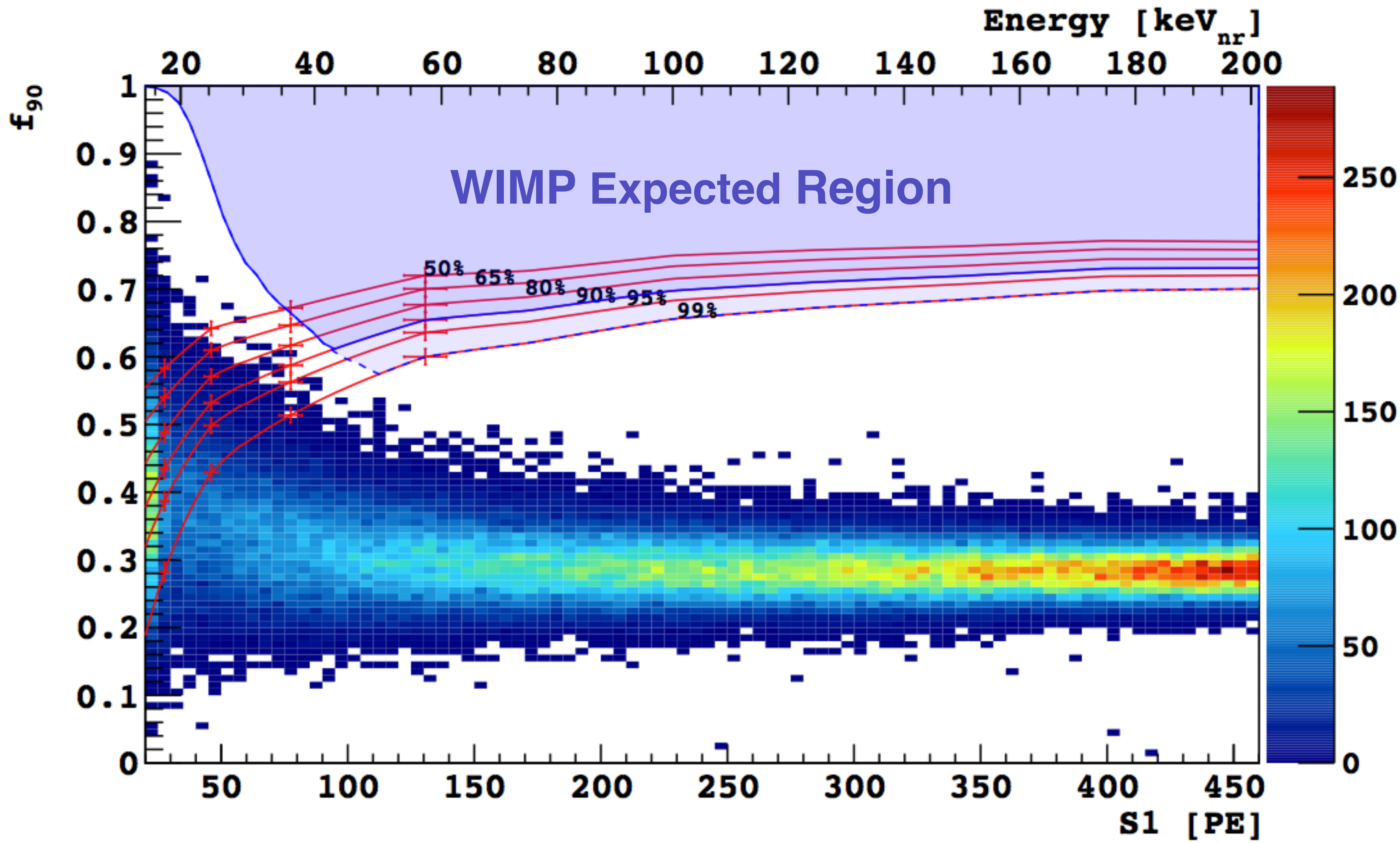


Low level of ^{39}Ar allows extension of DarkSide program to ton-scale detector.

UAr First Results

arXiv:1510.00702

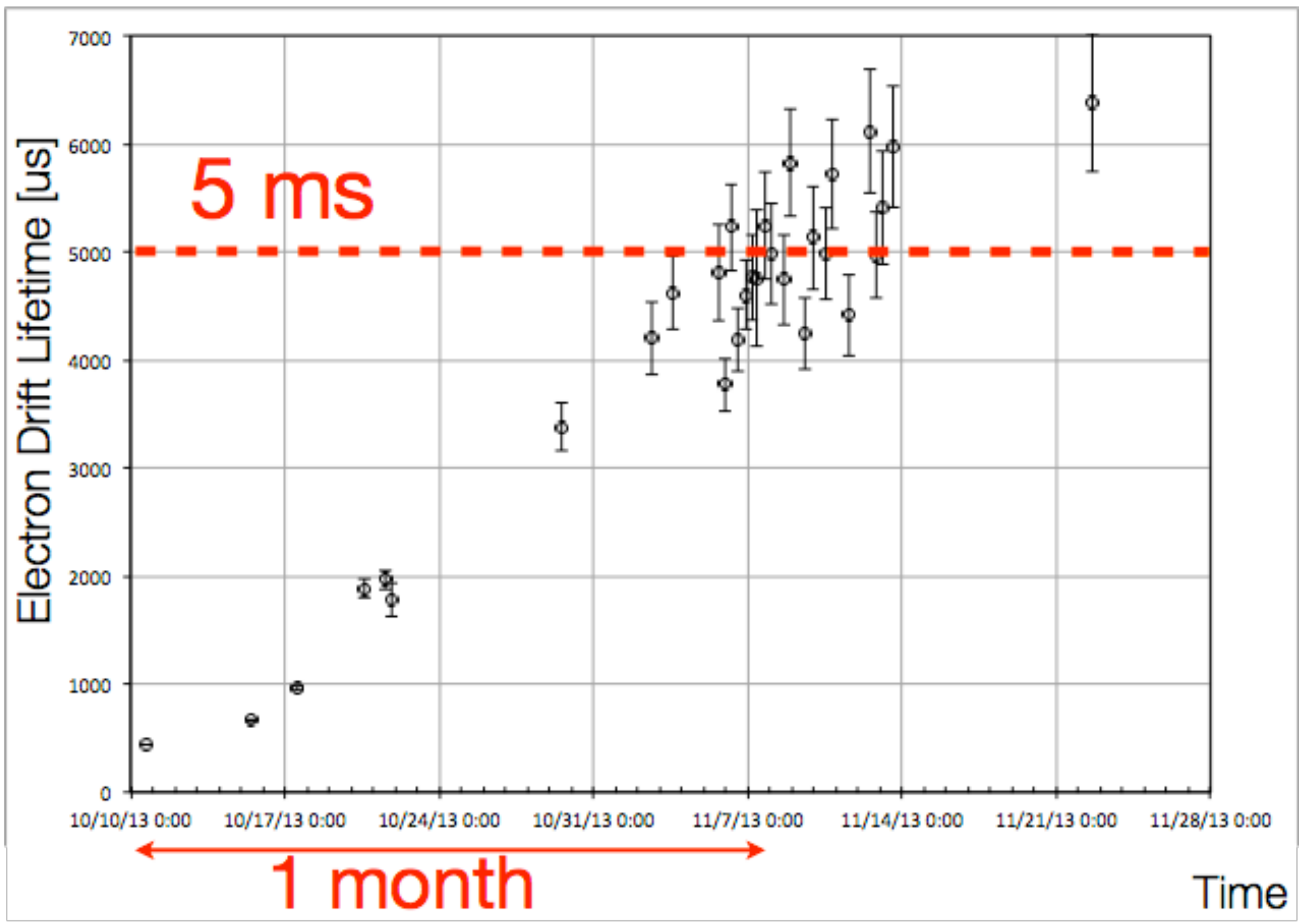
No background events in nuclear recoil (WIMP) region!



71 live-days after all cuts. (2616±43) kg day exposure.
Single-hit interactions in the TPC, no energy deposition in the veto.

Argon purity - very promising results from DS-50

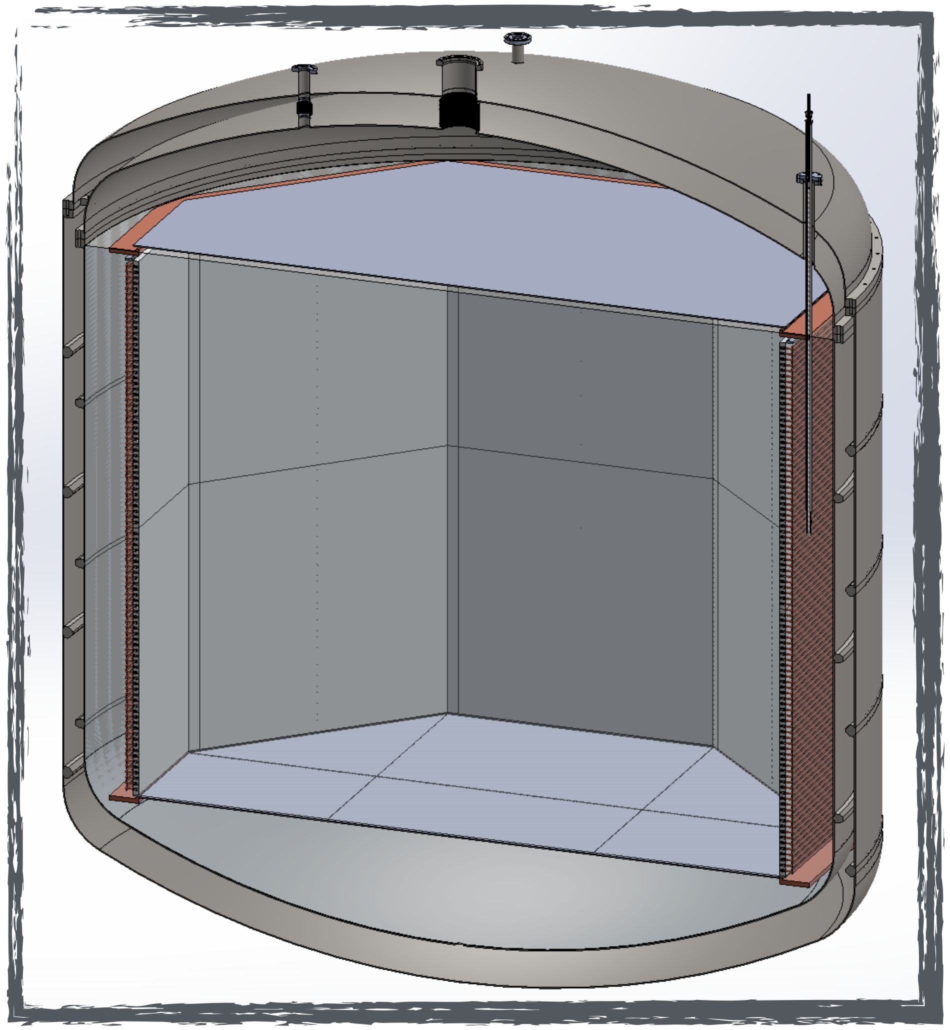
- Closed loop argon recirculation (~30 slpm)
- Gaseous phase purification using commercial getter
- Cryogenic charcoal trap to remove Rn contamination



Measured electron drift lifetime > 5 ms

to be compared to max. drift time of ~ 375 µs

DS-20k



DS-20k
30 tonne (20 tonne fiducial) detector

- no PMTs —> SiPMs (15 m^2)
- 50 kV
- 2.4 m drift length
- 100 tonne yr exposure
- ArDM facility to test tonne-scale UAr batches

More UAr, less ^{39}Ar

Urania (Underground Argon):

- Expansion of the argon extraction plant in Cortez, CO, to reach capacity of **100 kg/day** of Underground Argon

Aria (UAr Purification):

- Very tall column in the Seruci mine in Sardinia, Italy, for high-volume chemical and isotopic purification of Underground Argon

ARGO - a flight of fancy to the neutrino floor

- no PMTs —> SiPMs (15 m^2)

- 300 t UAr (200 t fiducial)
- 1,000 tonne yr exposure
- Cryogenically depleted UAr
- Further x10 discrimination with ~15% LY increase

- Background-free heavy WIMP search to the neutrino floor
- Sensitivity 9×10^{-49} cm^2 @1 TeV/cm^2
- Solar neutrino program

Heavy WIMP sensitivity

Experiment	σ [cm^2] @1 TeV/c^2	σ [cm^2] @10 TeV/c^2
LUX [10k kg×day Xe]	1.1×10^{-44}	1.2×10^{-43}
XENON [7.6k kg×day Xe]	1.9×10^{-44}	1.9×10^{-43}
DS-50 [1.4k kg×day Ar]	2.3×10^{-43}	2.1×10^{-42}
ArDM [1.5 tonne×yr Ar]	7×10^{-45}	7×10^{-44}
DEAP-3600 [3.0 tonne×yr Ar]	5×10^{-46}	5×10^{-45}
XENON-1ton [2] [2.7 tonne×yr Xe]	3×10^{-46}	3×10^{-45}
LZ [1] [15 tonne×yr Xe]	5×10^{-47}	5×10^{-46}
DS-20k [100 tonne×yr]	9×10^{-48}	9×10^{-47}
1 Neutrino Event [400 tonne×yr Ar or 300 tonne×yr Xe]	2×10^{-48}	2×10^{-47}
ARGO [1,000 tonne×yr]	9×10^{-49}	9×10^{-48}

nEXO and DS-20k

Similarities:

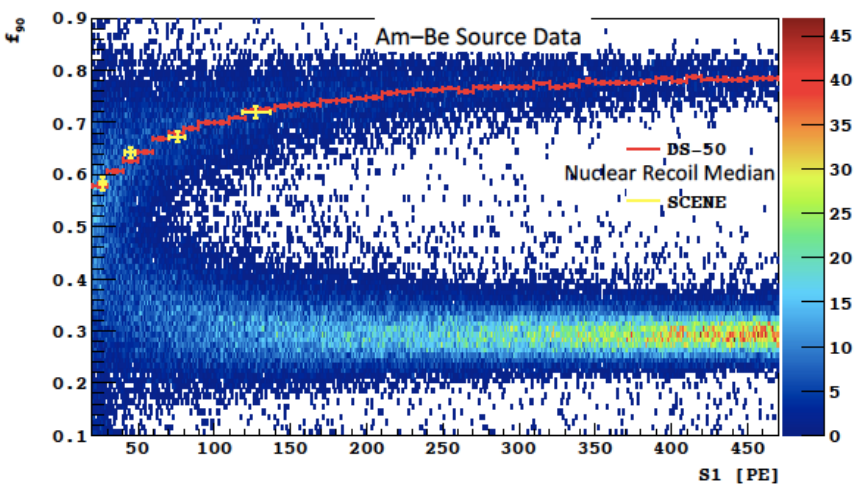
- Long drift length (~1.5 m)
- Need for very high light collection efficiency, use SiPMs (4 - 15 m^2)
- Need for very low radon
- >10 ms life time of drifting electrons
- Cold front-end electronics
- Data-driven background model (informed by radio-assay results)
- Isotopic enrichment/depletion
- Low ^{85}Kr, ^{39}Ar: centrifugation, cryogenic distillation
- Common challenges: HV, internal low-E calibrations, ….

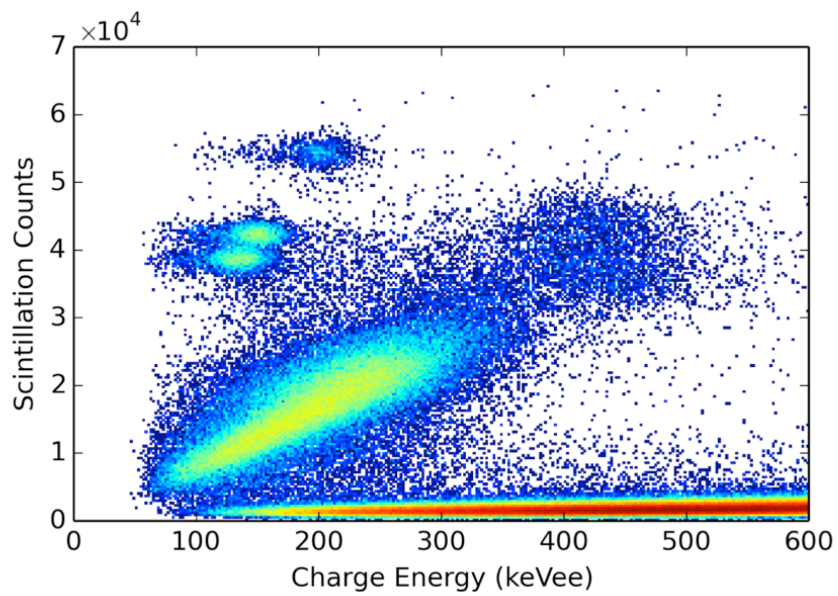
Differences (nEXO vs DS-20k):

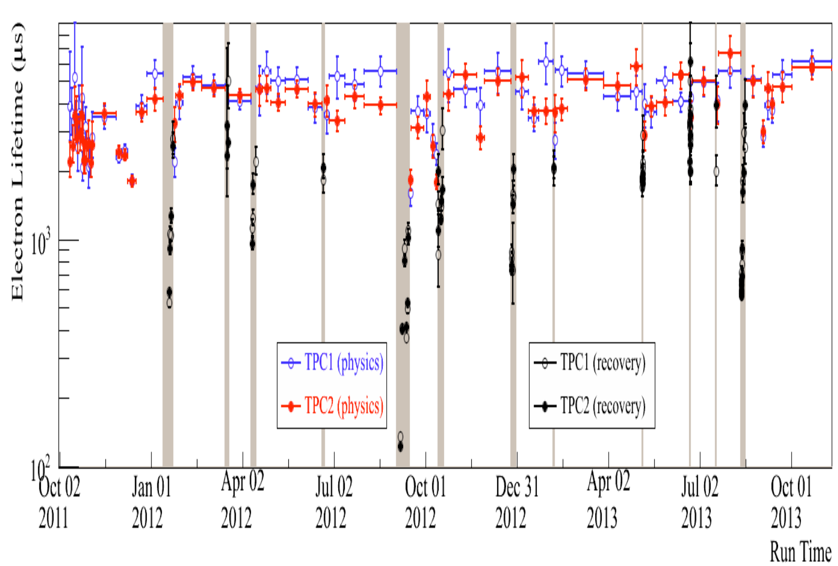
- nEXO: 'no' plastics
- Single- vs dual-phase
- Energy resolution vs energy threshold
- Integral vs time resolution (PSD) of S1 (affects SiPM readout)

The DarkSide program

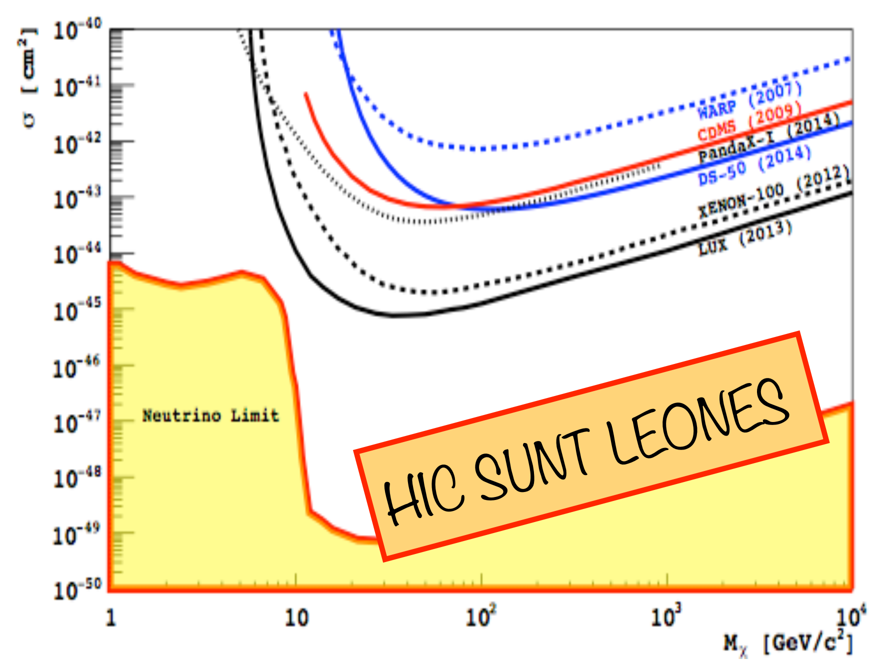
stay hungry, my friend

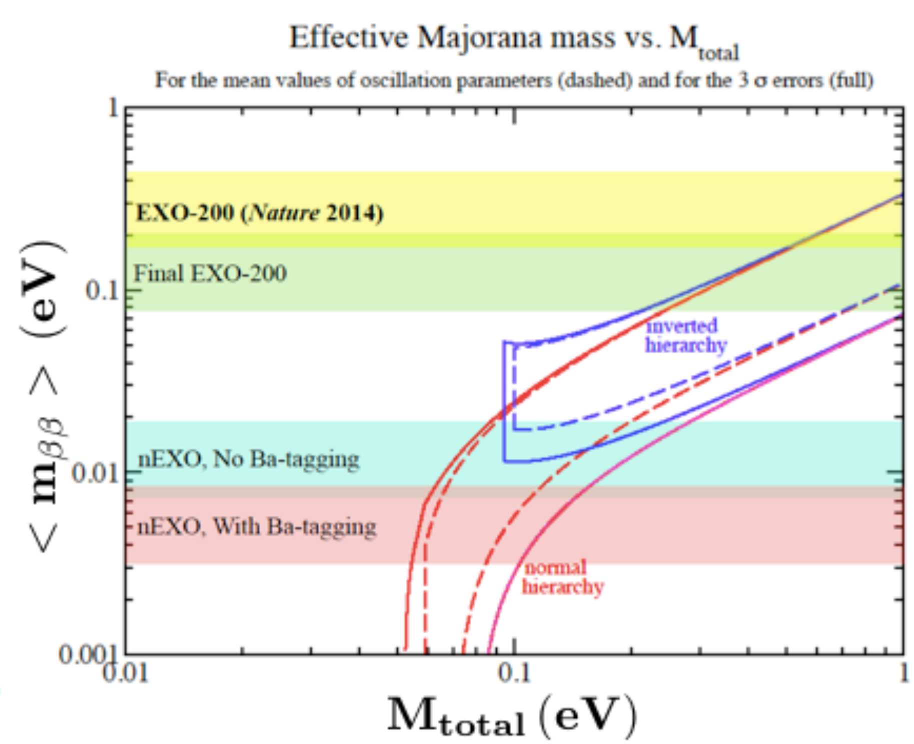


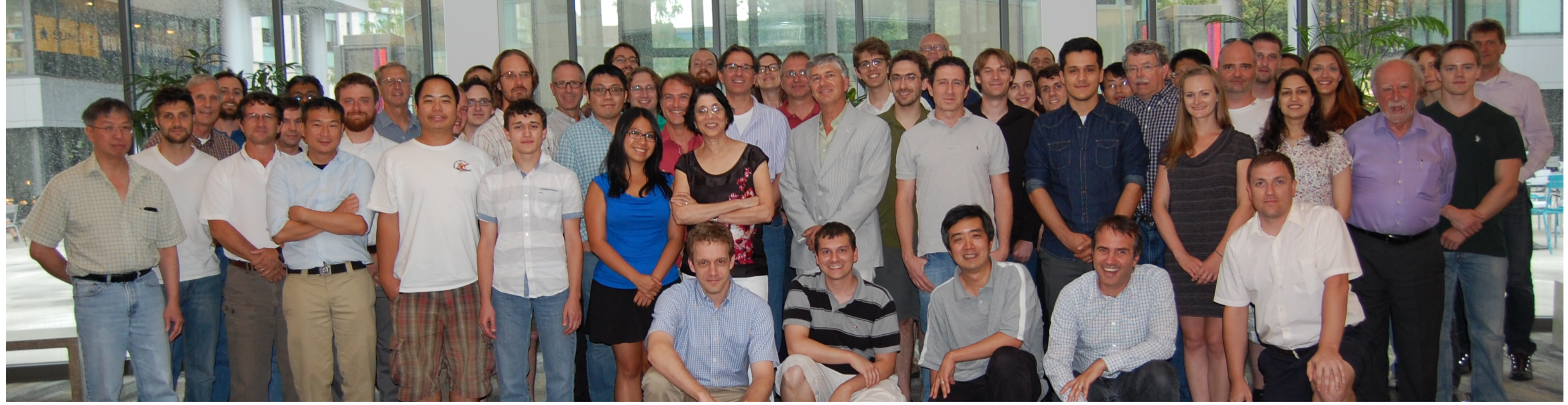




- LXe and LAr detectors, TPCs in particular, have become leading players in the search for 0νββ decay and WIMP dark matter
- Currently running TPCs are at the few hundred kg scale; tonne scale experiments are coming soon
- There is substantial synergy between LXe and LAr TPCs for rare event searches, both in terms of detector technology and low background requirements
- nEXO (5 tonnes) will search for 0νββ decay with mass sensitivity to cover the inverted neutrino hierarchy
- Detectors of tens and even hundreds of tonnes are being planned to search for WIMPs down to the neutrino floor







The nEXO Collaboration

University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang
University of Bern, Switzerland — S Delaquis, 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
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada — Y Baribeau, V Basque, M Bowcock, M Dunford, M Facina, R Gornea, K Graham, P Gravelle, R Killick, T Koffas, C Licciardi, K McFarlane, R Schnarr, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank Jr., T Walton
Drexel University, Philadelphia PA, USA — MJ Dolinski, YH Lin, E Smith, T Winick, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau, G Swift
University of Erlangen-Nuremberg, Erlangen, Germany — G Anton, R Bayerlein, J Hoessl, P Hufschmidt, A Jamil, T Michel, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
IHEP Beijing, People's Republic of China — G Cao, W Cen, X Jiang, H Li, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, J Zhao
University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, J Walton, L Yang
Indiana University, Bloomington IN, USA — JB Albert, S Daugherty, TN Johnson, LJ Kaufman, G Visser, J Zettlemoyer
University of California, Irvine, Irvine CA, USA — M Moe
ITEP Moscow, Russia — V Belov, A Burenkov, M Danilov, A Dolgolenko, A Karelin, A Kobyakin, A Kuchenkov, V Stekhanov, O Zeldovich
Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, B Mong, U Wichoski
Lawrence Livermore National Laboratory, Livermore CA, USA — O Alford, J Brodsky, M Heffner, G Holtmeier, A House, M Johnson,S Sangiorgio
University of Massachusetts, Amherst MA, USA — J Dalmasson, S Feyzbakhsh, S Johnston, J King, A Pocar
McGill University, Montreal PQ, Canada — T Brunner
Oak Ridge National Laboratory, Oak Ridge TN, USA — L Fabris, D Hornback, RJ Newby, K Ziock
Rensselaer Polytechnic Institute, Troy NY, USA — E Brown
SLAC National Accelerator Laboratory, Menlo Park CA, USA — T Daniels, K Fouts, G Haller, R Herbst, M Kwiatkowski, K Nishimura, A Odian, M Oriunno, PC Rowson, K Skarpaas
University of South Dakota, Vermillion SD, USA — R MacLellan
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, D Moore, I Ostrovskiy, A Schubert,K Twelker, M Weber
Stony Brook University, SUNY, StonyBrook, 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

DarkSide-20k and Argo LoI Signatories

D. Franco, A Tonazzo - APC Paris
D. Alton - Augustana College
A. Kubankin - Belgorod National Research University
K. Keeter, B. Mount - Black Hills State University
L. Romero, R. Santorelli - CIEMAT
S. Horikawa, K. Nikolics, C. Regenfus,
A. Rubbia - ETH Zürich
S. Pordes - Fermilab
A. Gola, C. Piemonte - FBK & TIFPA
S. Davini - GSSI
E. Hungerford, A. Renshaw - University of Houston
M. Guan, J. Liu, Y. Ma, C. Yang, W. Zhong - IHEP Beijing
N. Canci, F. Gabriele, G. Bonfini, A. Razeto, N. Rossi,
F. Villante - LNGS
C. Jollet, A. Meregaglia - IPHC Strasbourg
M. Misziazek, M. Woicik, G. Zuzel - Jagiellonian University
K. Fomenko, A. Sotnikov, O. Smirnov - JINR
M. Skorokhvatov - Kurchatov Institute Moscow
A. Derbin, V. Muratova, D. Semenov,
E. Unzhakov - PNPI Saint Peterburg
S. De Cecco, C. Giganti - LPNHE Paris
H. O. Back - PNNL
M. Ghioni, A. Gulinatti, L. Pellegrini, I. Rech, A. Tosi,
F. Zappa - Politecnico di Milano
C. Galbiati, A. Goretti, A. Ianni, P. Meyers,
M. Wada - Princeton University
A. Chepurnov, G. Girenok, I. Gribov, M. Gromov,
I. Zilcov - SINP MSU Moscow
C.J. Martoff, J. Napolitano, J. Wilhelmi - Temple University
E. Pantic - UCDavis
Y. Suvorov, H. Wang - UCLA
A. Pocar - UMass Amherst
A. Machado, E. Segreto - Campinas
A. Devoto, M. Lissia, M. Mascia,
S. Palmas - Università & INFN Cagliari
M. Pallavicini, G. Testera, S. Zavatarelli - Università & INFN Genova
D. D'Angelo, G. Ranucci - Università & INFN Milano
F. Ortica, A. Romani - Università & INFN Perugia
S. Catalanotti, A. Cocco, G. Covone, G. Fiorillo,
B. Rossi - Università Federico II & INFN Napoli
C. Dionisi, S. Giagu, M. Rescigno - Università La Sapienza & INFN Roma
S. Bussino, S. Mari - Università & INFN Roma 3
J. Maricic, R. Milincic, B. Reinhold - University of Hawaii
P. Cavalcante - Virginia Tech