PANDA X

Dark Matter Direct Detection Results from PandaX-II Experiment

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On behalf of PandaX Collaboration

ISHBSM 2016, Weihai

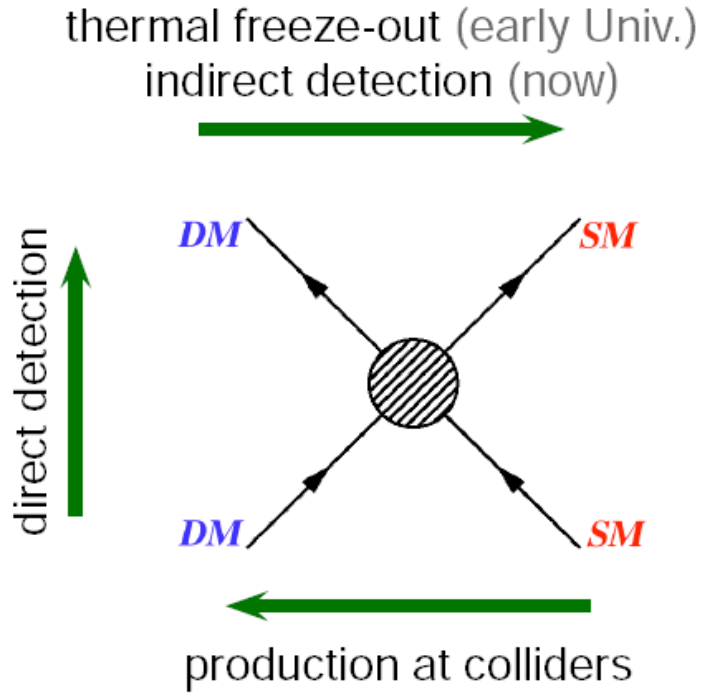
Dark Matter Search

- Dark matter candidate: WIMP

- Direct Detection
  - Detection of WIMP scattering with target atom

- Indirect Detection
  - WIMP annihilation or decay products

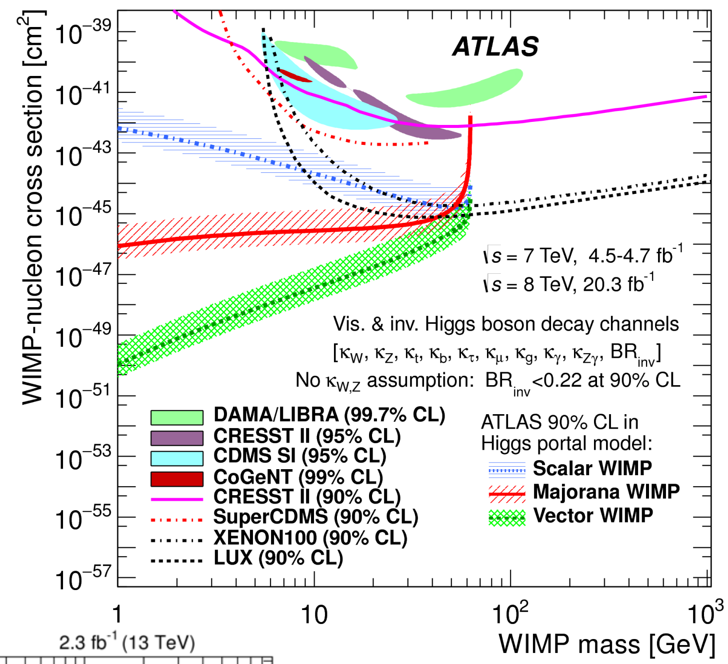
- Collider Search
  - WIMP produced from collision

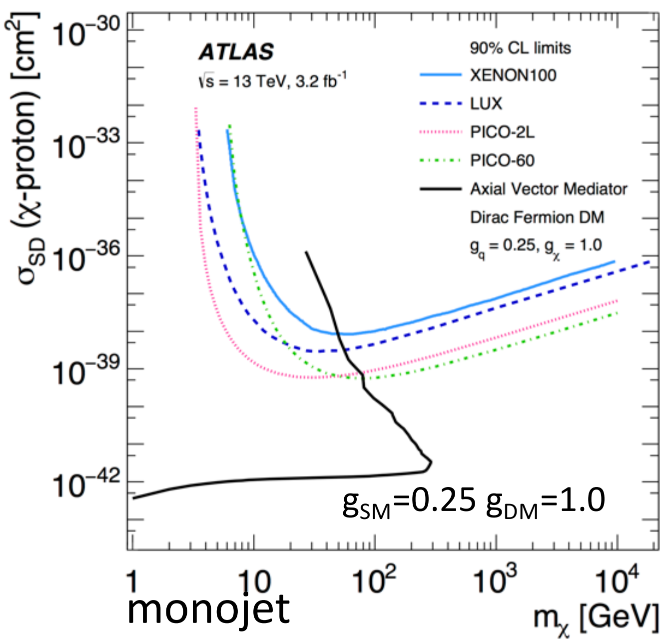


Collider Search

- Collider may produce WIMPs
- Sensitive to low mass WIMPs
- Strongly depending on the production models

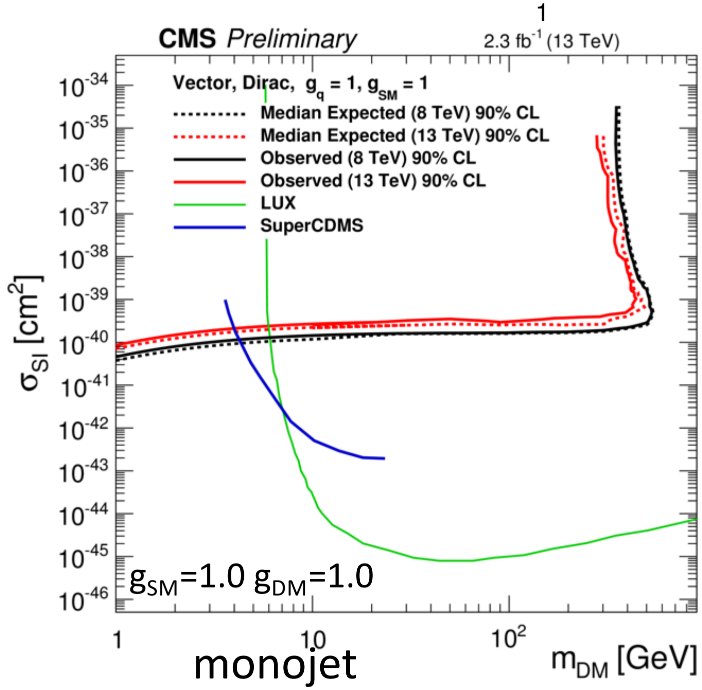
Higgs-portal





g_{SM}=0.25 g_{DM}=1.0

monojet

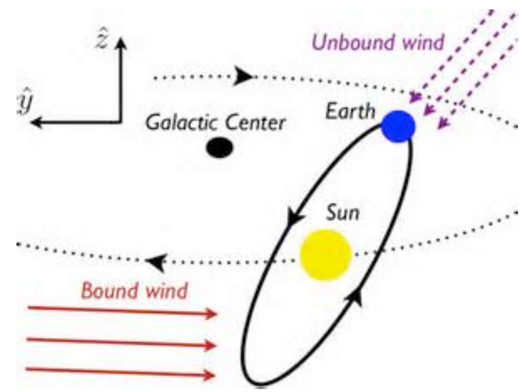


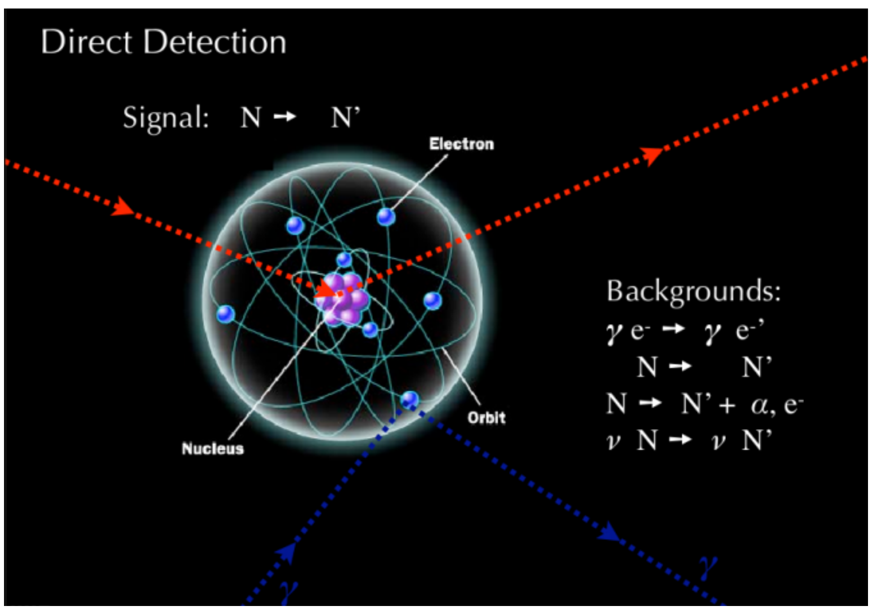
g_{SM}=1.0 g_{DM}=1.0

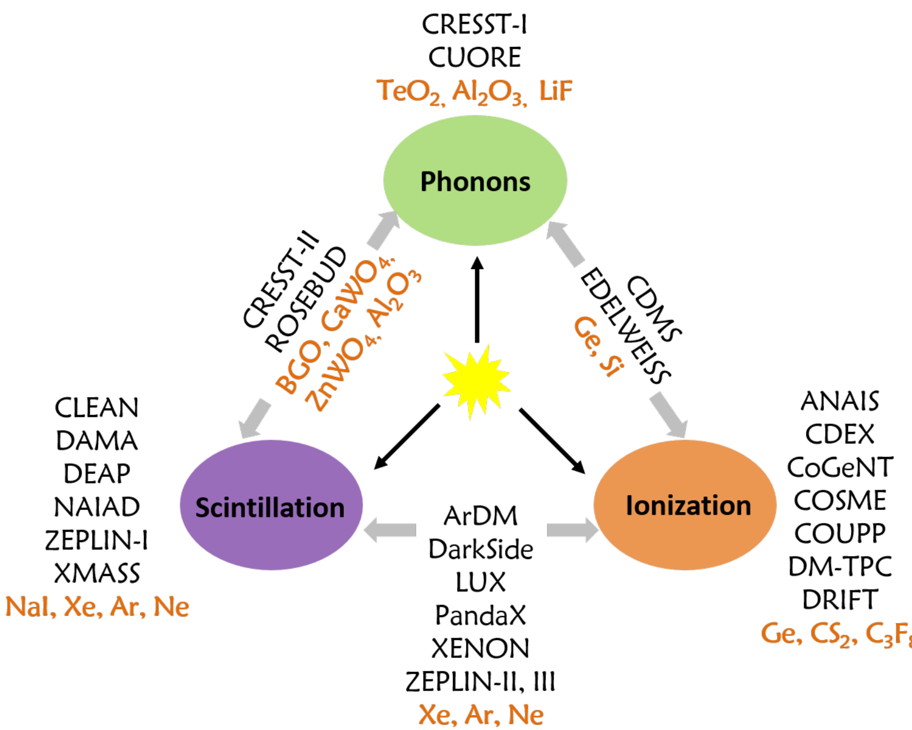
monojet

Direct Detection

- Incoming WIMP near the solar system
- Measurement of nucleus recoil signal
  - Scintillation, Ionization or Phonons

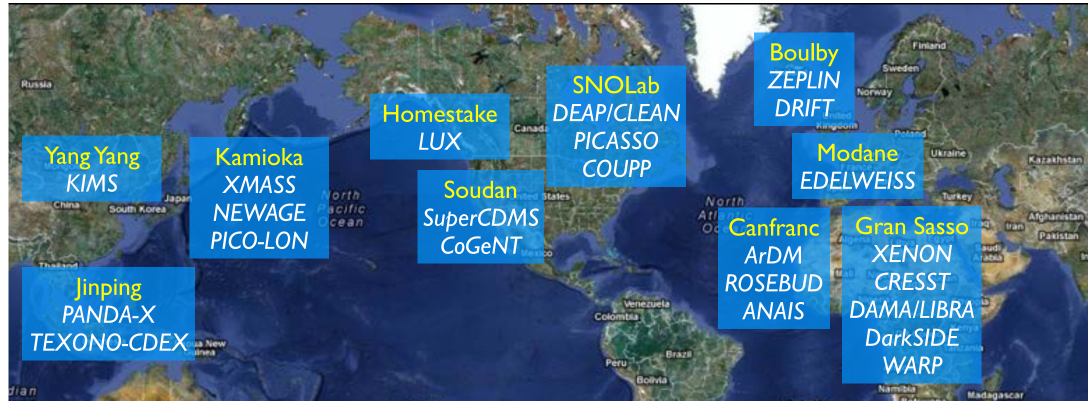




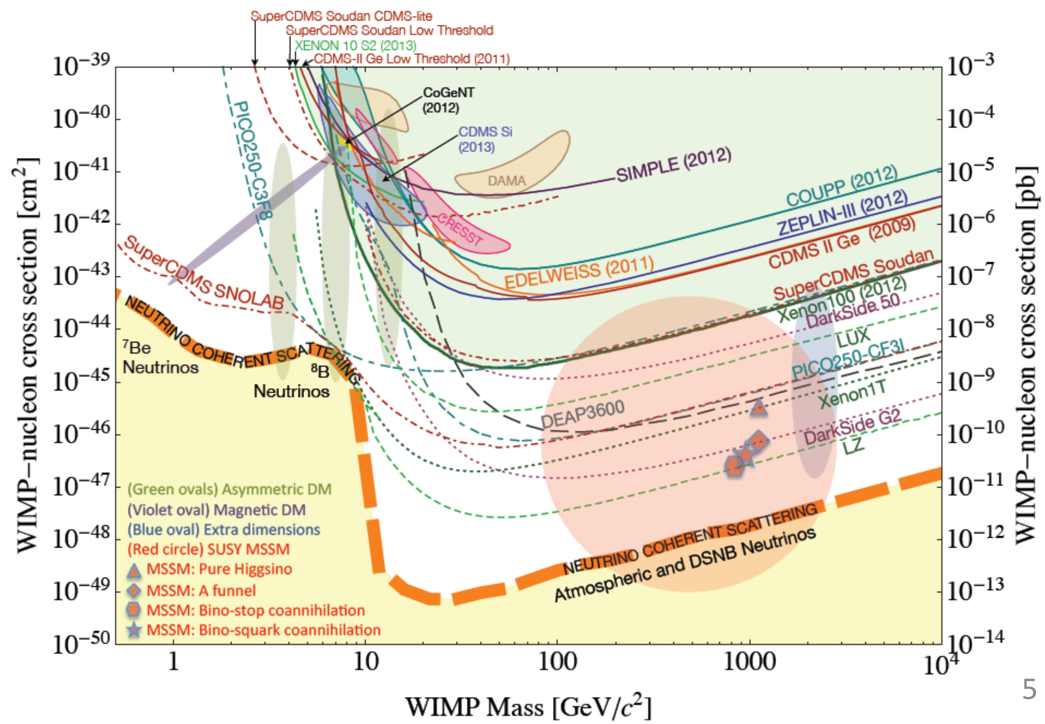


Current Status

- Sensitivity to WIMP continues to be pushed forward
  - LUX (250kg LXe) finishes data-taking (332 days)
  - PandaX-II (500kg LXe) continues data-taking (latest result with 98.7 days)
  - Xenon1T (2ton LXe) started early in 2016, now is in commissioning run
  - LZ (7ton LXe) is under construction, to start in 2020



- In IDM2016, LUX and PandaX-II reported their latest results
  - SI limit on the WIMP-nucleon scattering xsec reaches 2×10^{-46} cm^2



PandaX Collaboration

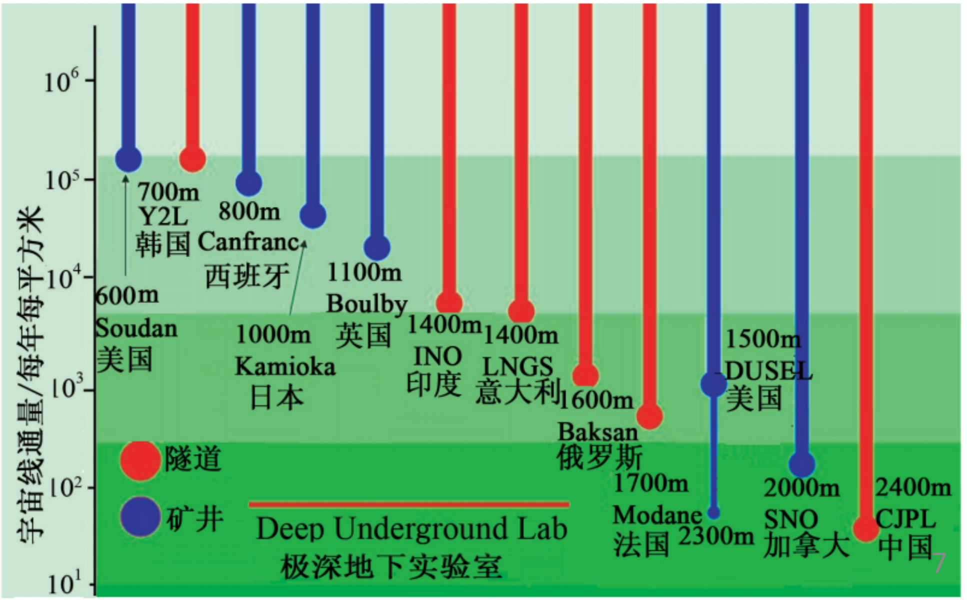
- ~50 people

Started in 2009

- Shanghai Jiao Tong University (2009-)
- Peking University (2009-)
- Shandong University (2009-)
- Shanghai Institute of Applied Physics, CAS (2009-)
- University of Science & Technology of China (2015-)
- China Institute of Atomic Energy (2015-)
- Sun Yat-Sen University (2015-)
- Yalong Hydropower Company (2009-)
- University of Maryland (2009-)
- Alternative Energies & Atomic Energy Commission(2015-)
- University of Zaragoza(2015-)
- Suranaree University of Technology(2015-)

China Jinping Underground Laboratory

- Deepest in the world (1μ/week/m^2)
- Horizontal access!

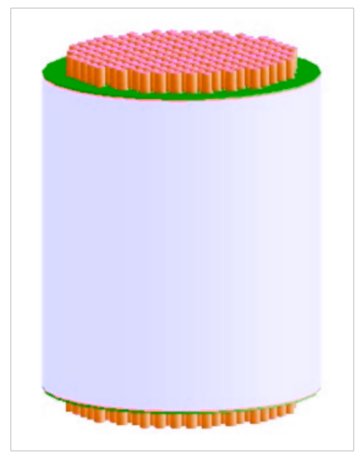


PandaX

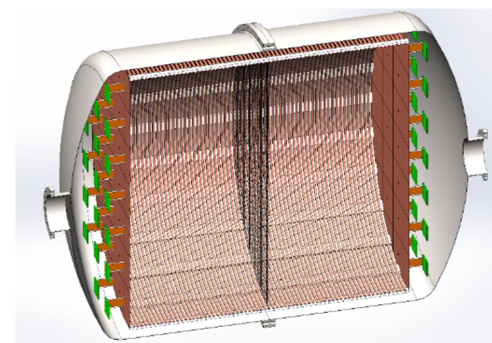
- PandaX = Particle and Astrophysical Xenon Experiments

Phase I:
120 kg DM
2009-2014

Phase II:
500 kg DM
2014-2017



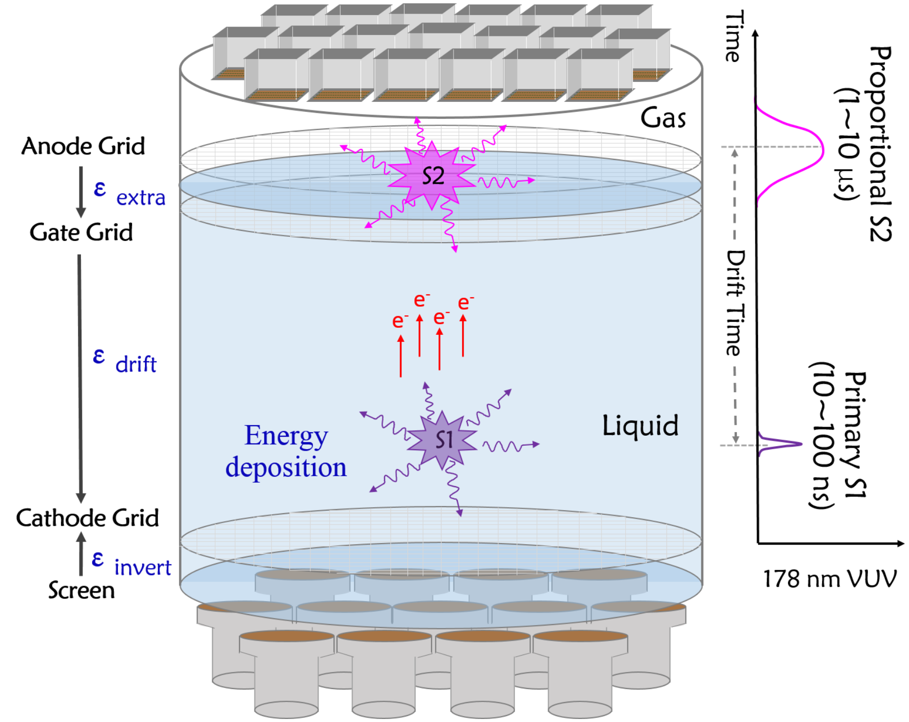
PandaX-xT:
multi-ton DM
future

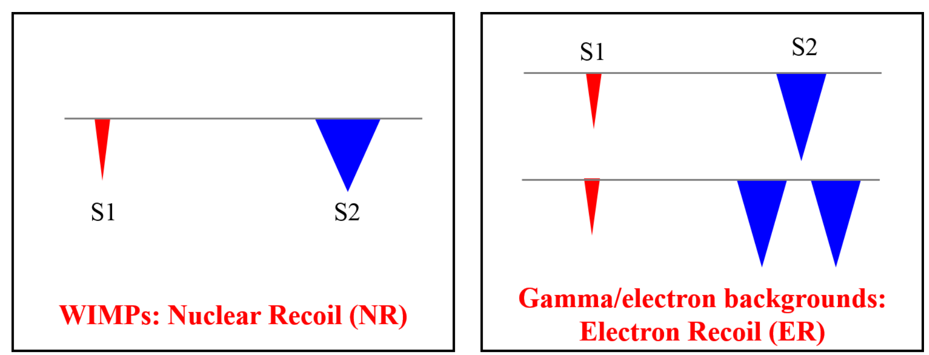


PandaX-III:
200 kg to 1 ton
^{136}Xe 0vDBD
future

Double-Phase Xenon Detector

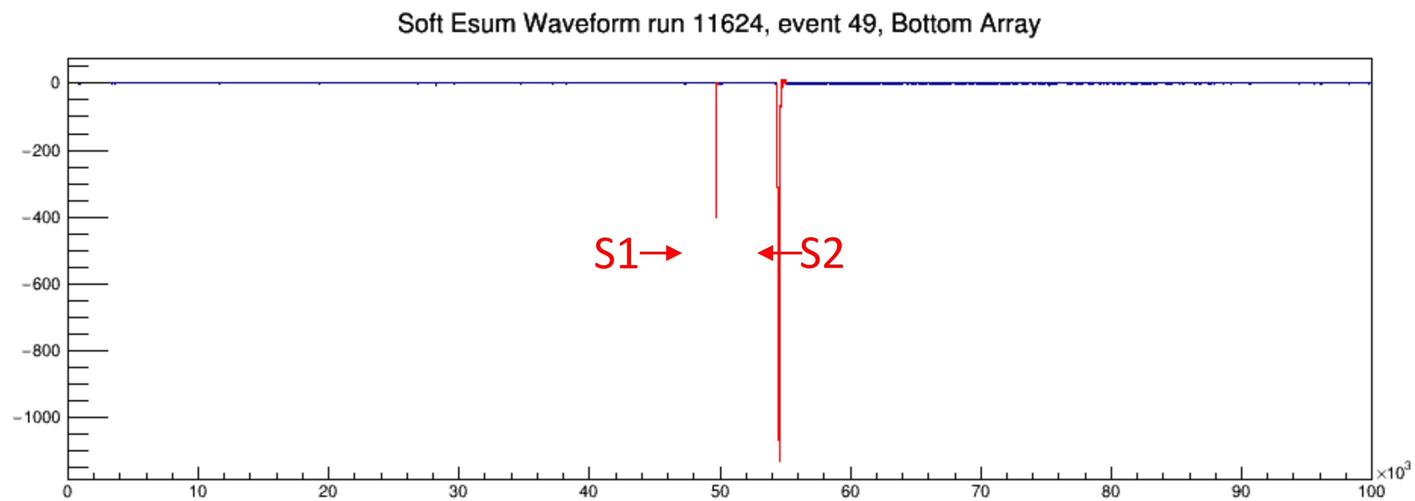
- S1: Scintillation in LXe
- S2: Ionization in LXe
  - Scintillation in GXe
- 3-D position reconstruction
  - X, Y from the PMT light collection array
  - Z from the ionized electron drift time
- Energy reconstruction from S1 and S2
- S2/S1 separate signal and background



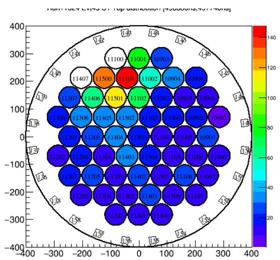


$(S2/S1)_{NR} << (S2/S1)_{ER}$

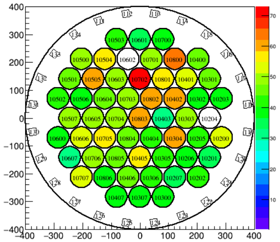
Typical Signal Waveform

- 

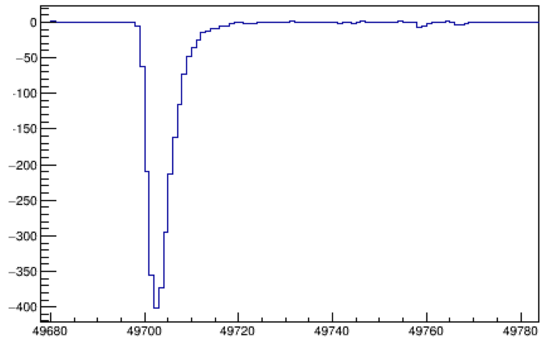
Top Array



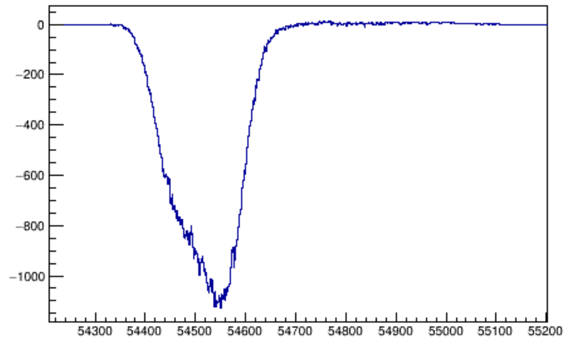
Bottom Array



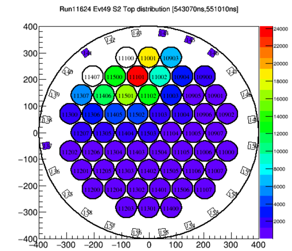
S1 waveform



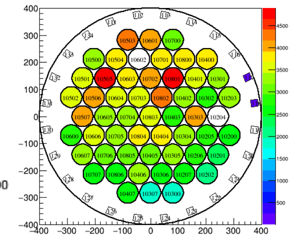
S2 waveform



Top Array



Bottom Array



First delivery of PandaX equipment to Jinping lab, Aug. 16, 2012

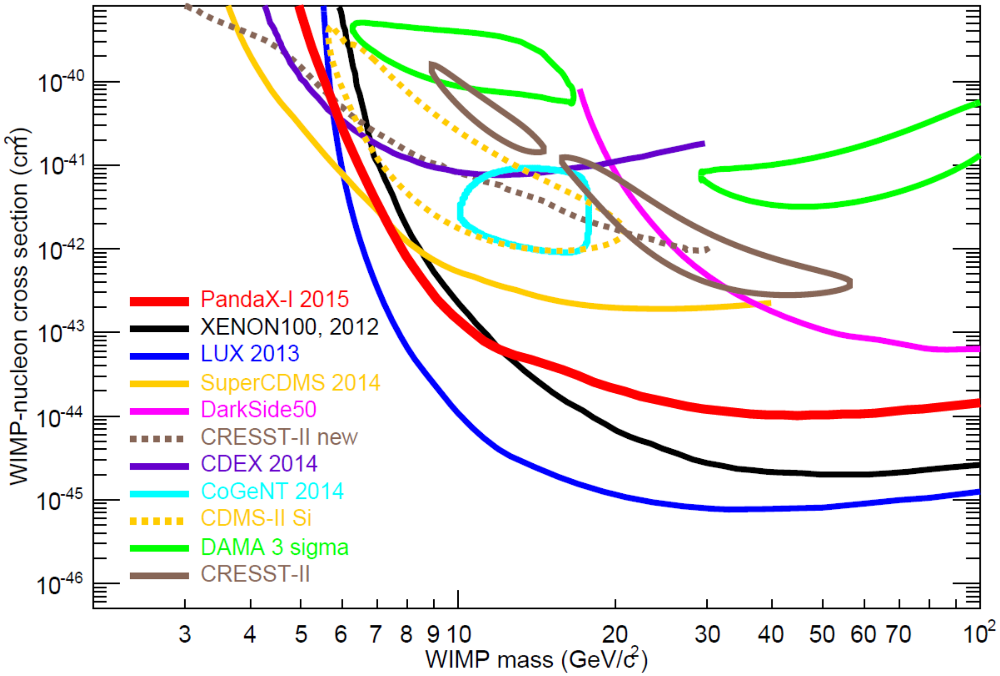
PandaX Detector

- PandaX at CJPL

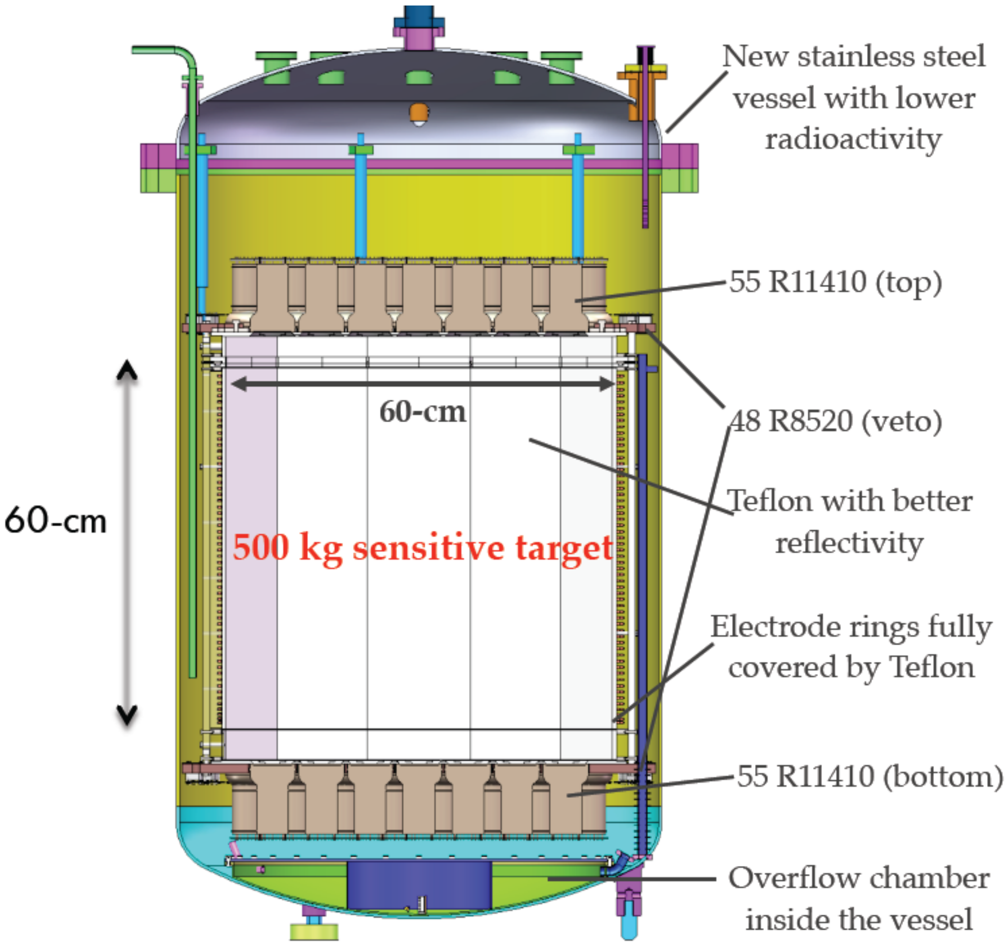
PandaX-I Result

- 120 kg LXe
- Completed in Oct. 2014, with 54.0 x 80.1 kg-day exposure
- Data strongly disfavor all previously reported claims
- Competitive upper limits for low mass WIMP in xenon experiments

Phys. Rev. D **92**, 052004(2015)



PandaX-II



- New Inner Vessel with clean SS
- New and taller TPC with brand-new electrodes
- More 3” PMTs and improved base design
- New separate skin veto region

Configuration of E-fields

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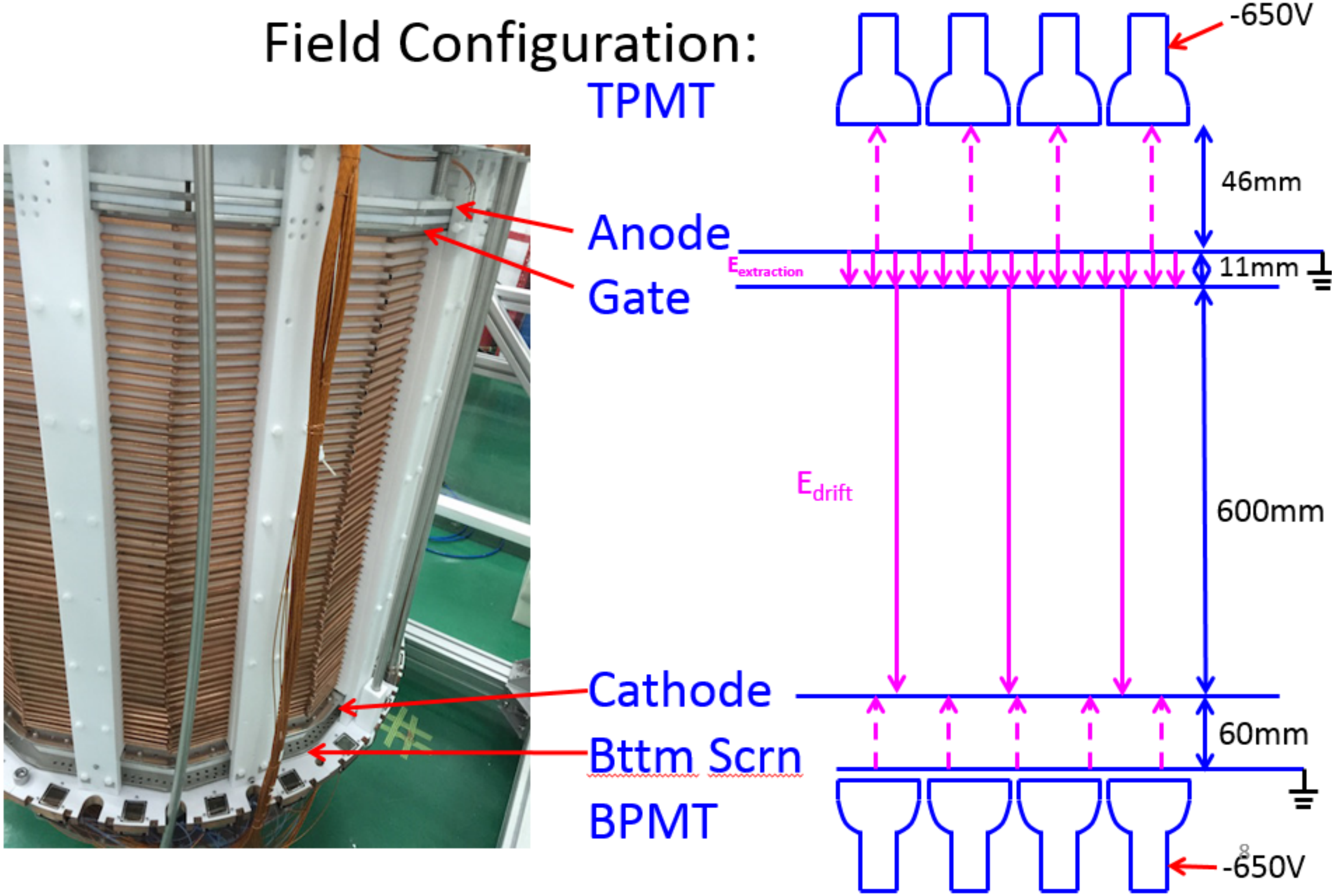

Assembling the detector

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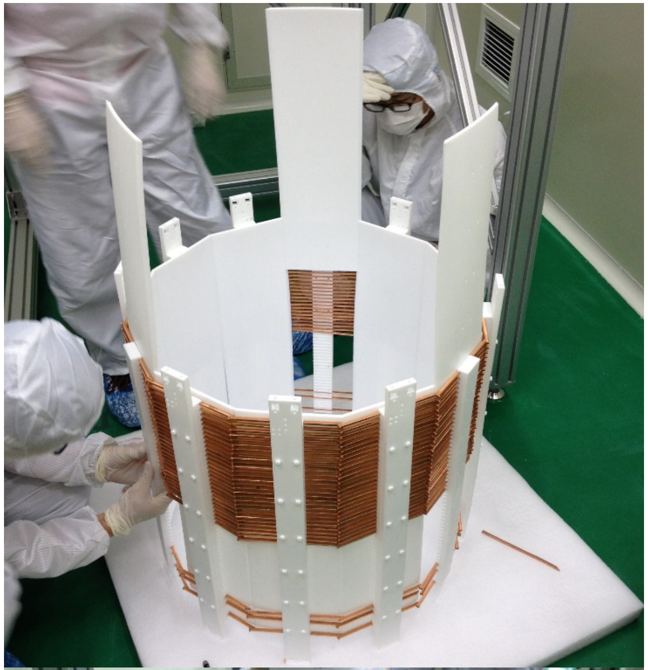

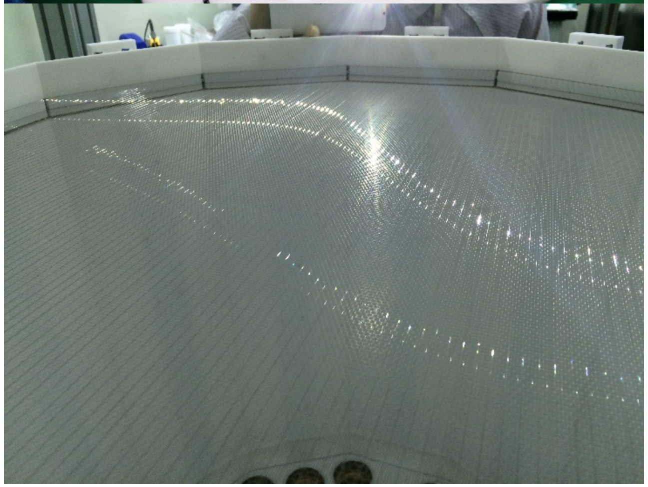

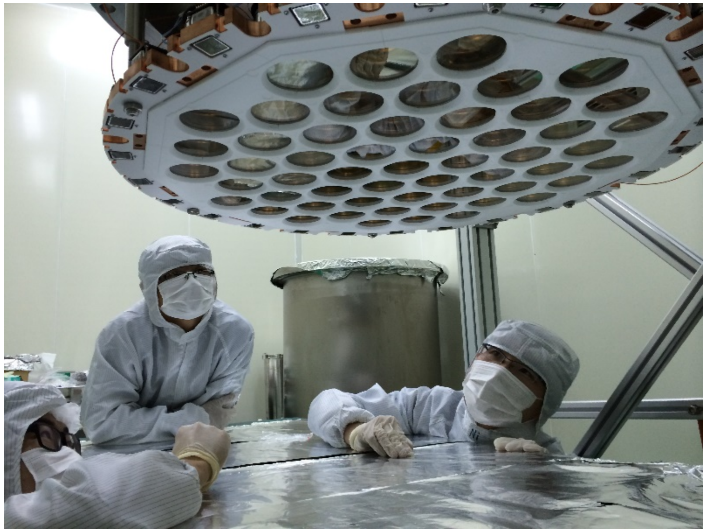

Assembling the Detector

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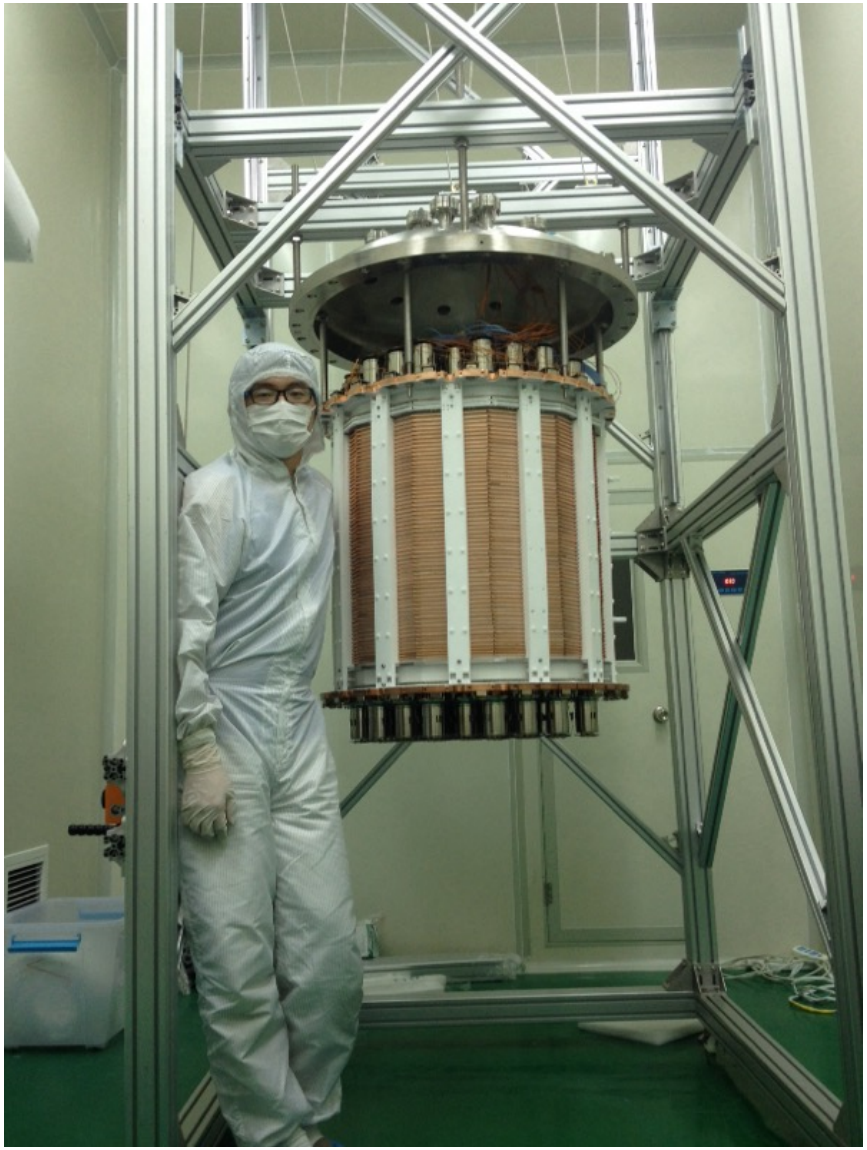
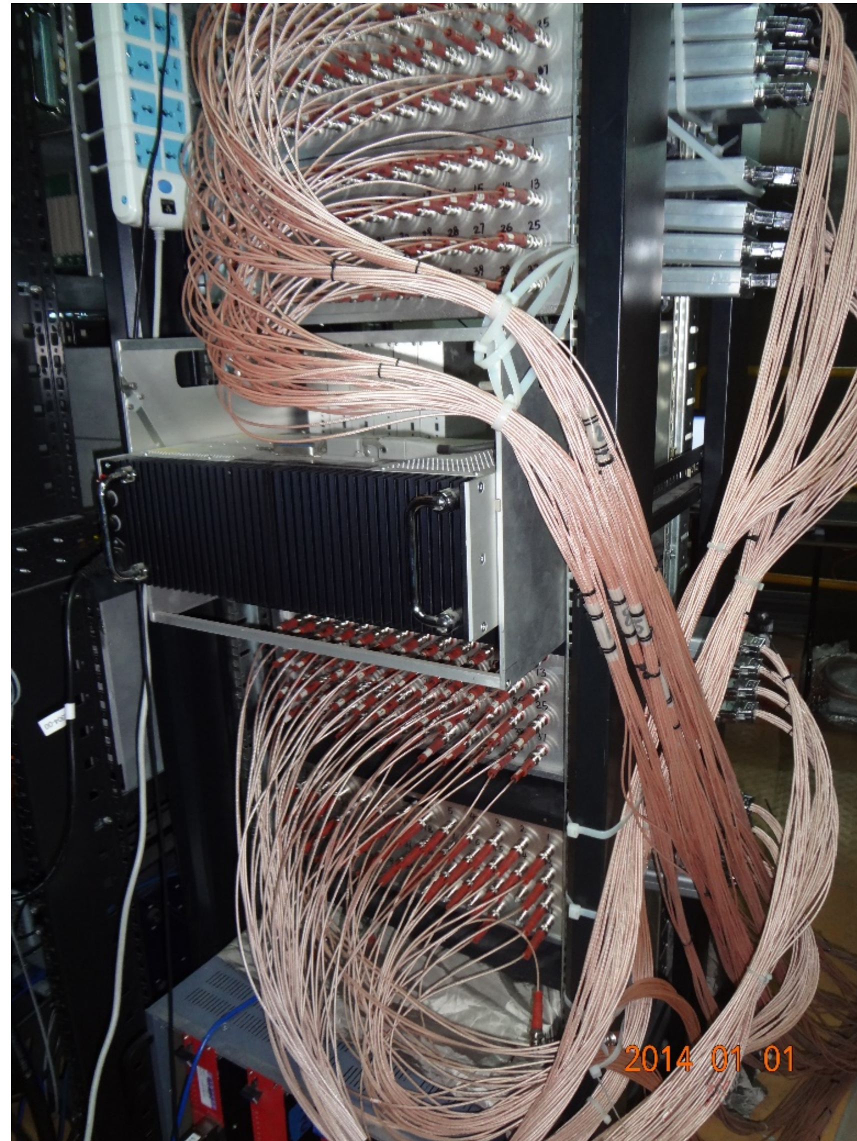




Run History

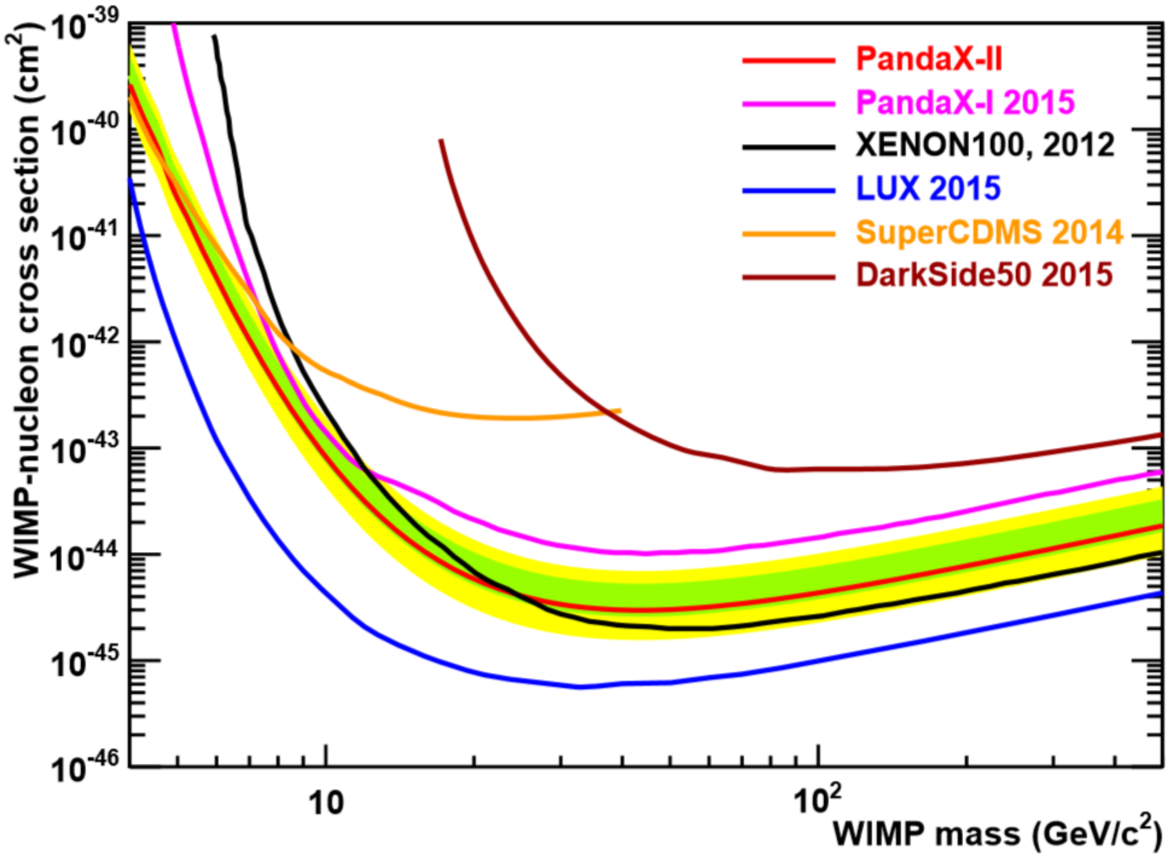
- We had a series of engineering runs in 2015, fixing various problems as we were testing all the components of the setup

- Commissioning run (Run 8): Nov. 22 – Dec. 14 (19.1 live-day x 306 kg FV) but with high Kr background (Phys. Rev. D. 39, 122009 (2016))

- After a Kr distillation campaign, the detector was refilled. Physics data taking started in Mar. 2016 (Run 9)

Results from PandaX-II Run 8

Phys. Rev. D. 39, 122009 (2016)



- Simple counting analysis based on an expected background of 3.2(0.7) evts and 2 observed evts
- Sizable (x2) difference of using original NEST or tuned NEST to predict DM distribution due to DM acceptance, but within 1σ band
- Low mass: competitive with SuperCDMS; high mass: similar exclusion limit as XENON100 225-day

Major Upgrades on Run 9

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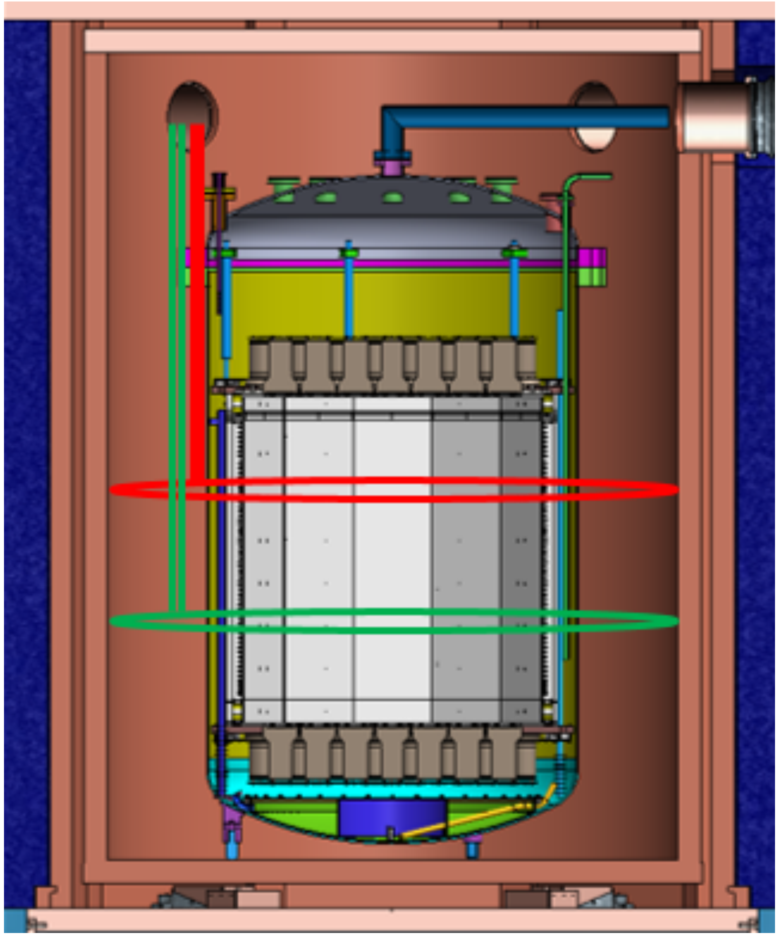
Items	Status in Run 9
Krypton level	Reduced by x10
Exposure	Increased x4 (79.6 vs 19.1 day)
ER calibration	Now have tritium calibration
NR calibration	Statistics x6
Analysis	Improved position reconstruction
Background	Accidental background suppressed more than x2 using BDT

Calibration Program

- Internal/external ER peaks:
  - Detector uniformity corrections
  - Light/charge collection parameters
- Low rate AmBe neutron source:
  - Simulate DM NR signal
- CH_3T injection: tritium beta decays
  - Simulate ER background



Improved Position Reconstruction

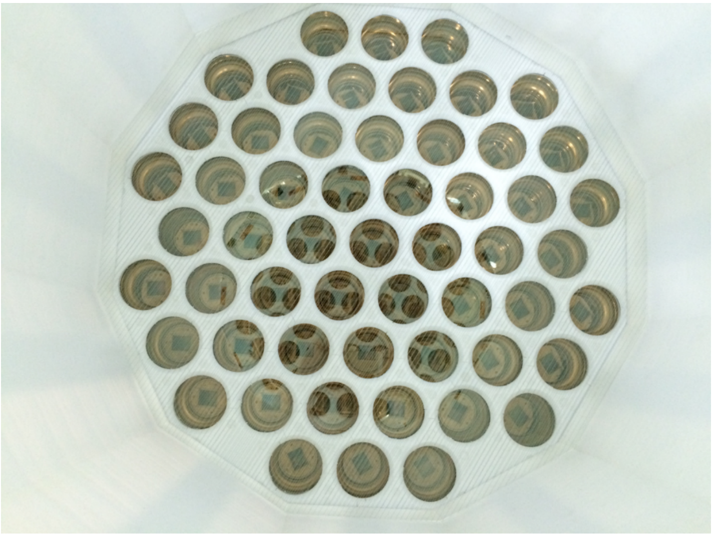
- Maximum Likelihood
  - Function of position only

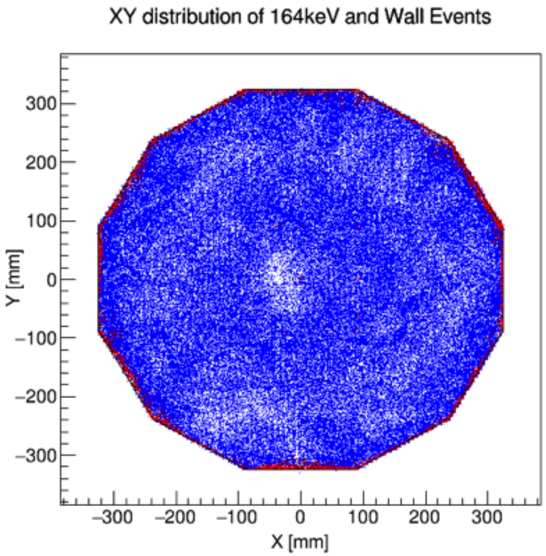
$$-\ln \tilde{L}(\vec{r}) = -\sum_i \frac{n_i}{\mathrm{qS2T}} \ln \frac{\eta_i(\vec{r})}{P(\vec{r})}$$

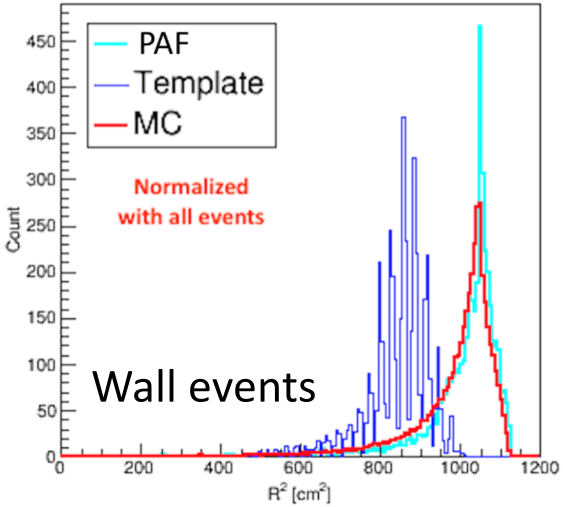
- Photon Acceptance Function(PAF) of Each PMT
- The iteration to determine the PAFs

$$\eta(r) = A \cdot \exp(-\frac{a \cdot \rho}{1+\rho^{1-\alpha}} - \frac{b}{1+\rho^{-\alpha}}), \quad \rho = \frac{r}{r_0}$$

- Training sample:
  - Kr^{85} in run 8 and CH_3T in run 9 (evenly distributed in the detector)
  - ^{210}Po (located on the wall)



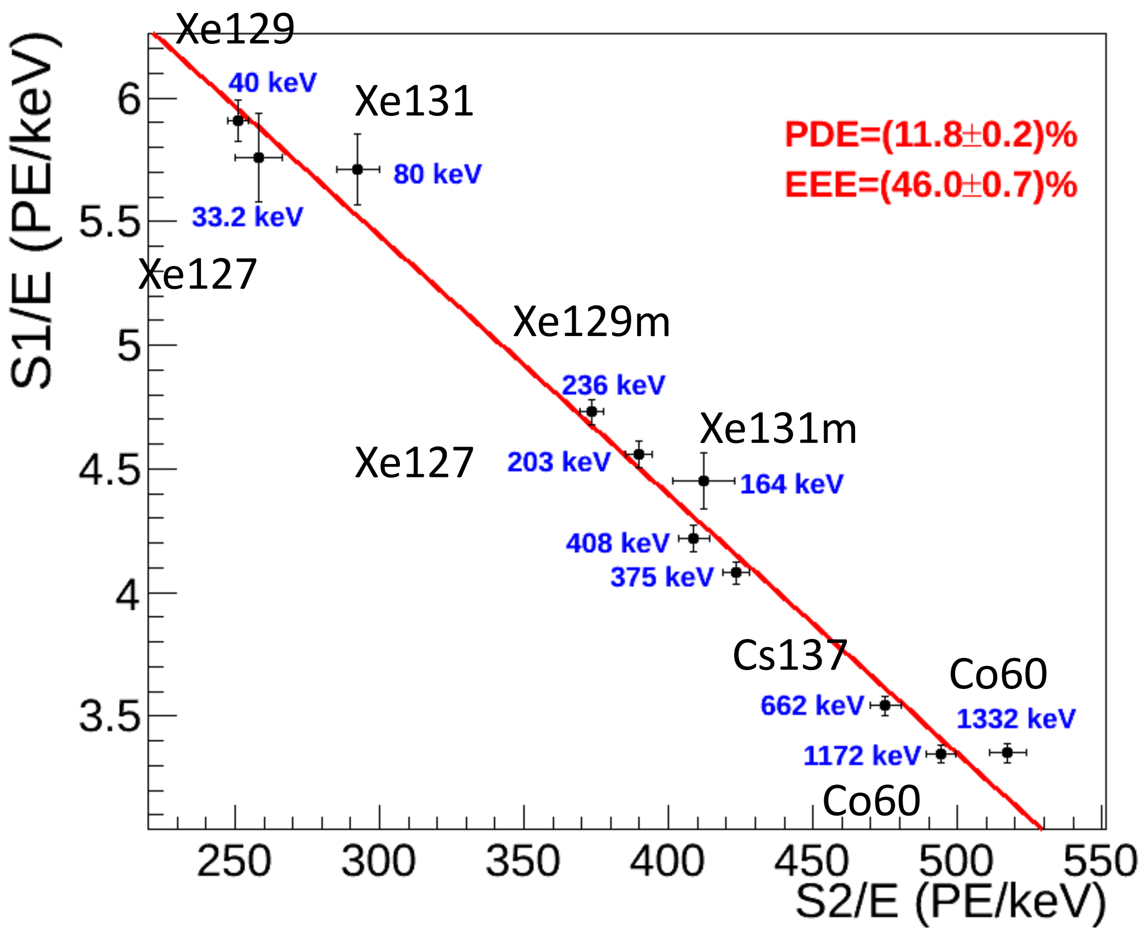




Extracting Detector Parameters

$$E_{ee} = W \times \left(\frac{\mathrm{S1}}{\boxed{\mathrm{PDE}}} + \frac{\mathrm{S2}}{\boxed{\mathrm{EEE}} \times \boxed{\mathrm{SEG}}}\right)$$

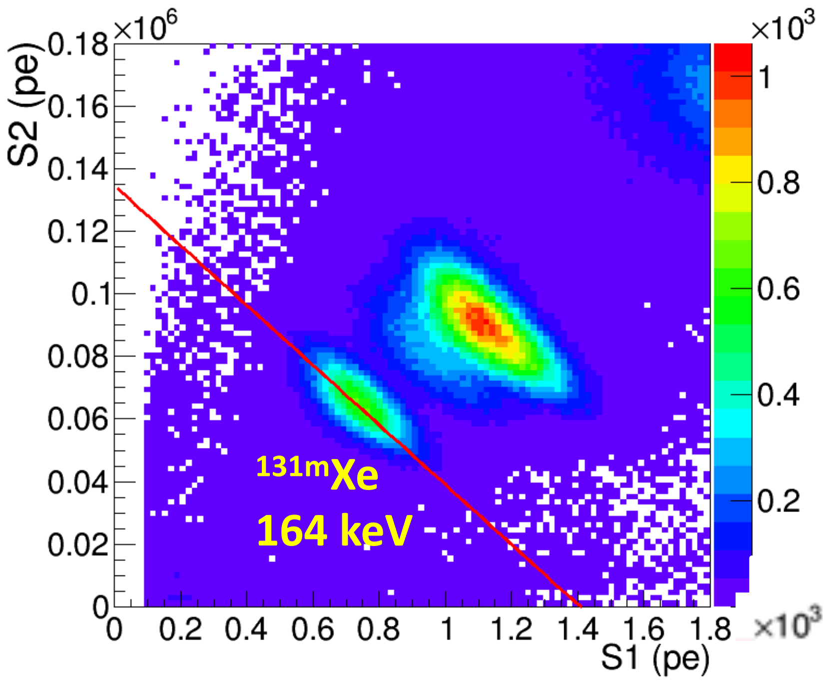
W = 13.7 eV

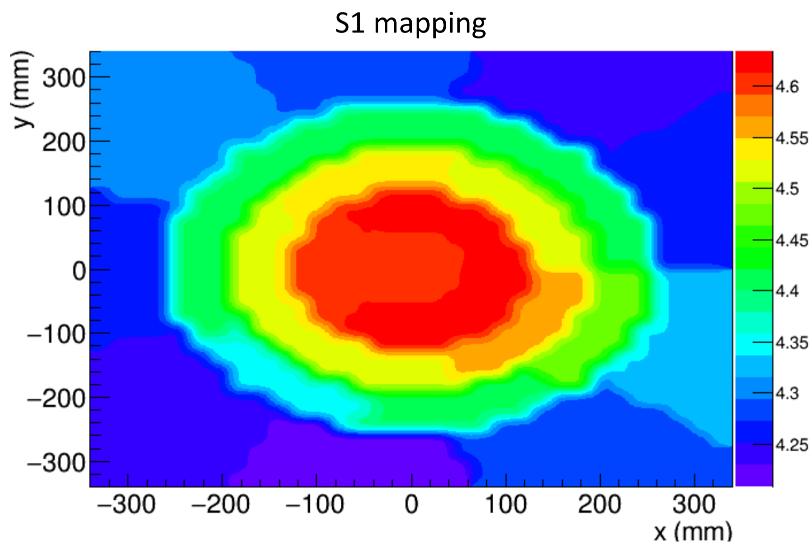


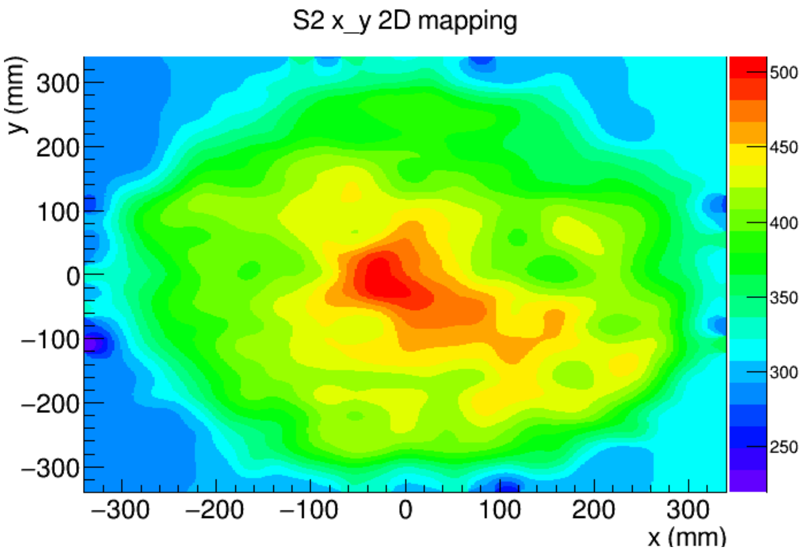
- Gaussian fits to all ER peaks in data
- Uncertainty on each data point estimated using energy nonlinearity
- Linear fit in S1/E vs S2/E to extract PDE and EEE

Uniformity Correction for S1 and S2

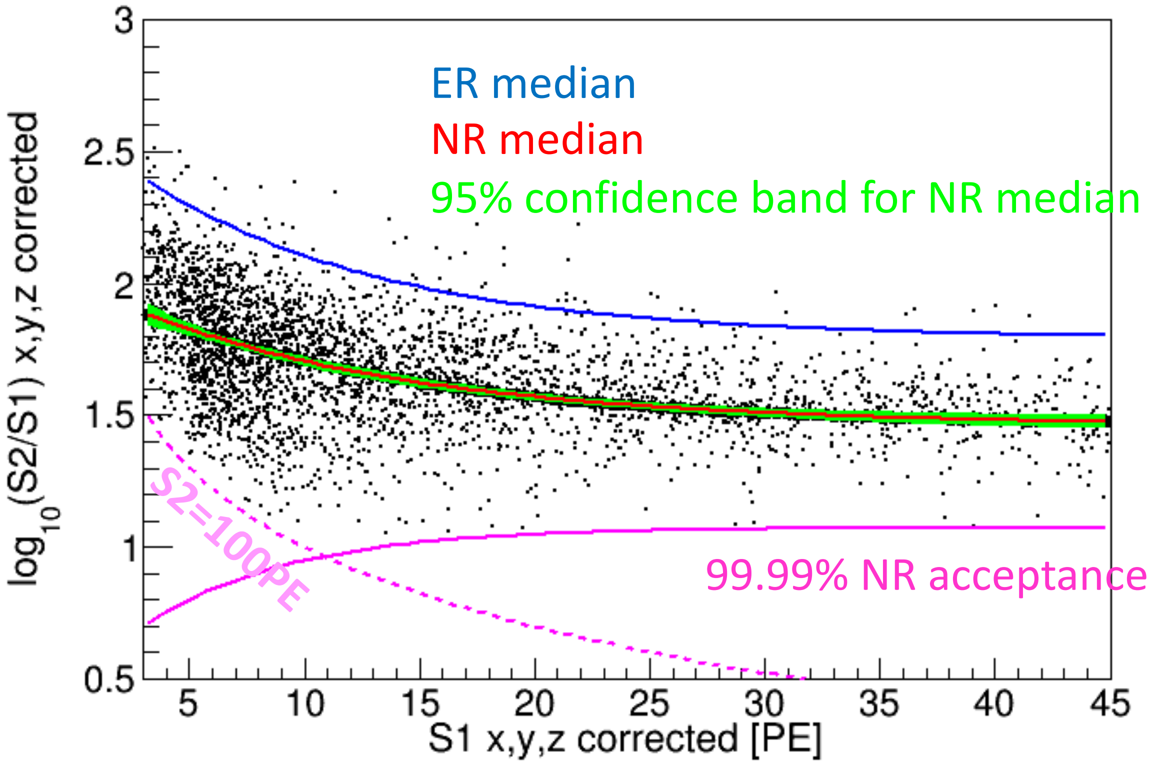
- PE/keV @ 164 keV vs. horizontal position
- Vertical non-uniformity corrected by electron lifetime



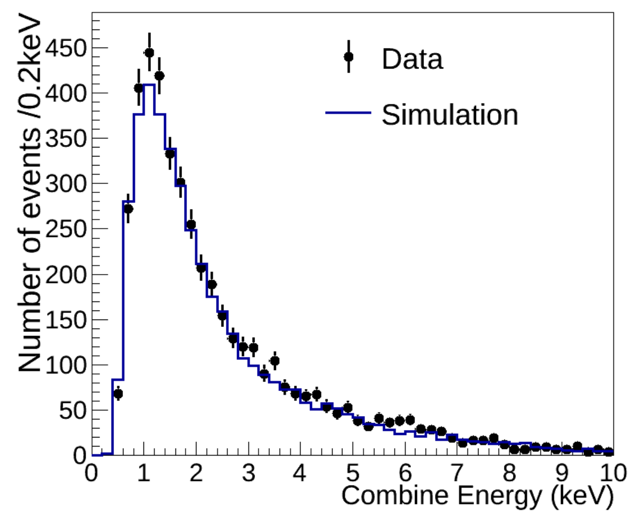




NR calibration

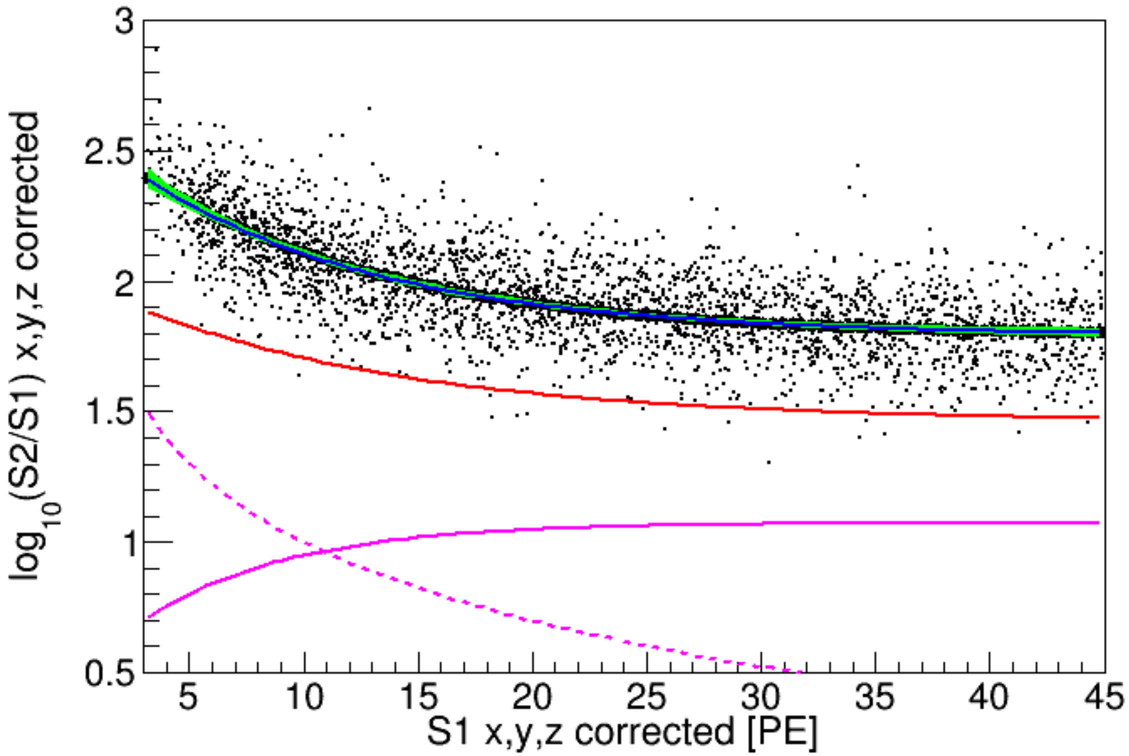


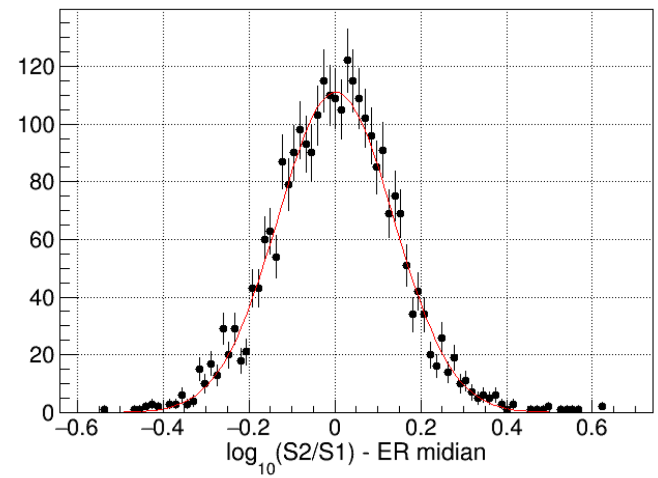
Data/MC comparison



- 162.4 hours of AmBe data taken, with ~3200 low energy single scatter NR events collected
- NR median curve and NR detection efficiency determined

ER calibration with CH_3T



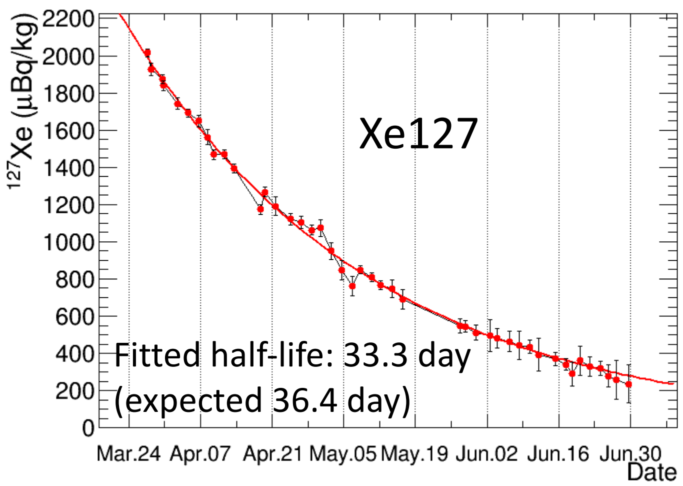


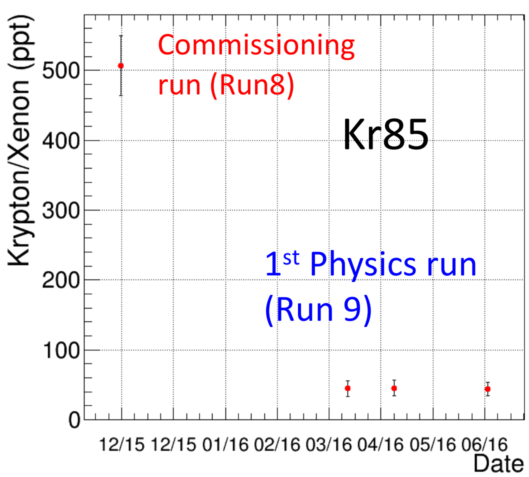
- 18.0 hours of tritium data taken, with ~2800 low energy ER events collected

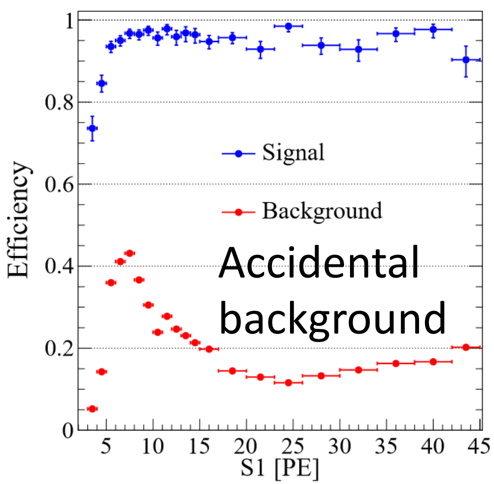
- 14 events leaked below NR median, $(0.5 \pm 0.1)\%$
- Consistent with Gaussian expectation, 0.55%

Background

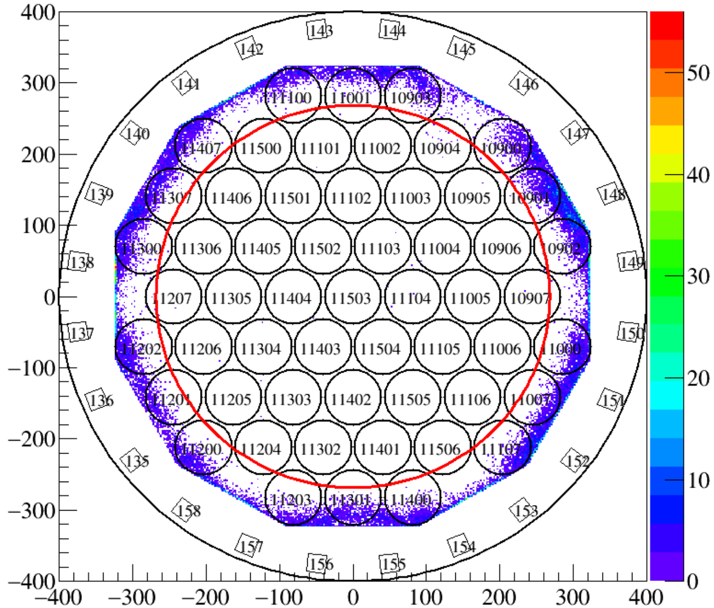
- Like before, ER and accidental background identified in the data
- ER background
  - ^{127}Xe (due to surface exposure of xenon during distillation)
  - ^{85}Kr (suppressed by a factor 10)
  - Others
- Accidental background (determined by data)

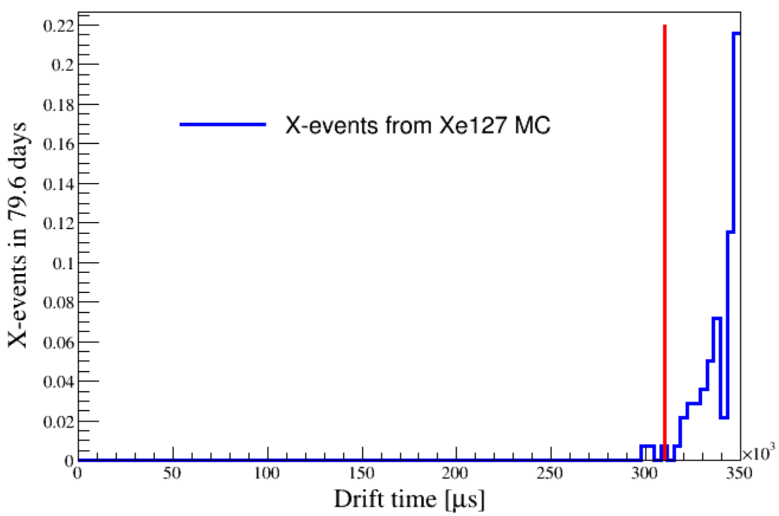






Final Candidates





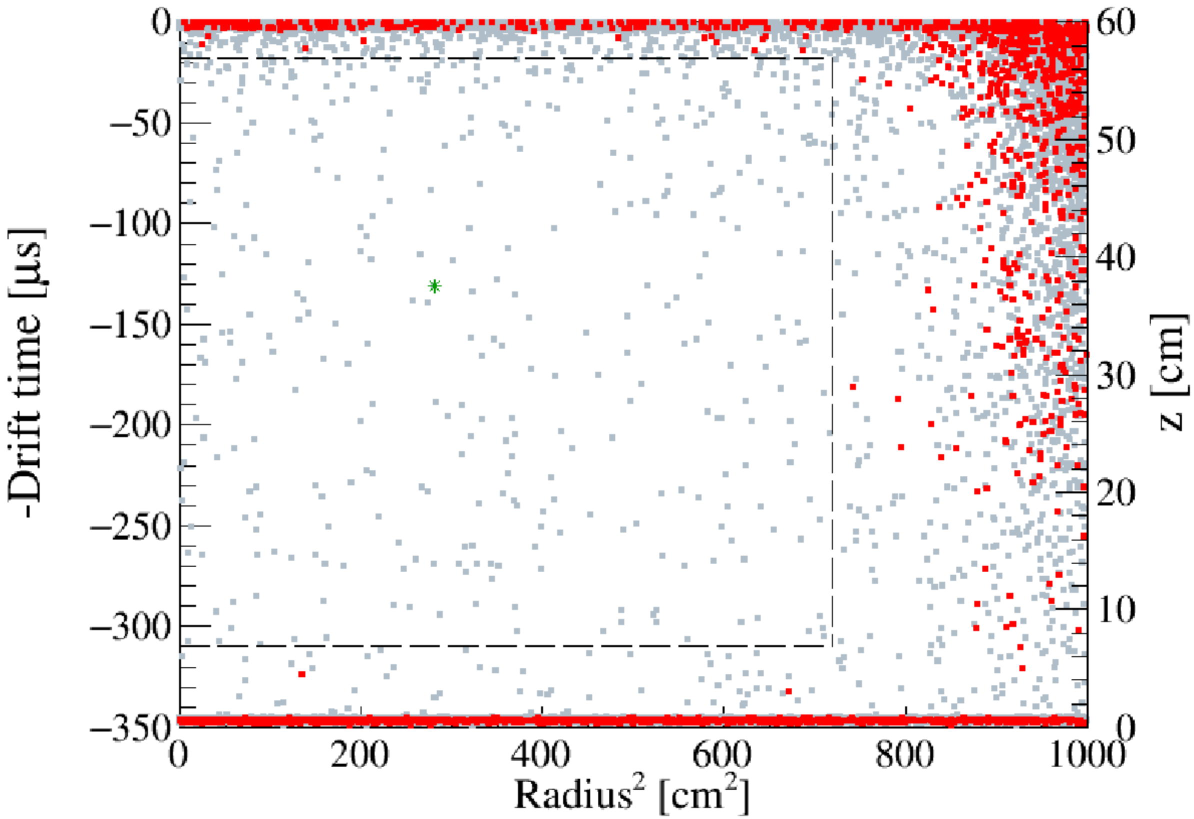
- Horizontal cut determined by distribution of events with S1 between [45,200] PE and suppressed S2
- Vertical cut: Upper boundary consistent with the previous analysis; Lower boundary determined by X-events from ^{127}Xe MC
- FV in Run 9 with 328.9 kg
- S1 cut:[3,45]PE & S2 cut[100raw, 10000] PE: consistent with previous analysis

Final Candidates

Gray: all

Red: below NR median

Green: below NR median and in FV



- 389 total candidates found in the FV
- 1 candidate below NR median
- Outside FV, edge events more likely to lose electrons, leading to S2 suppression

Final Candidates

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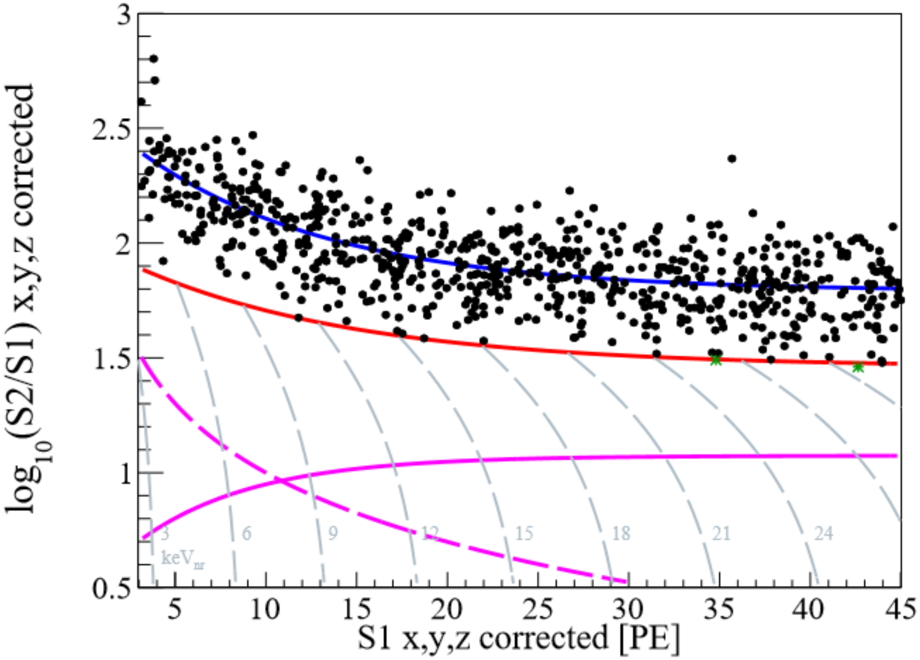
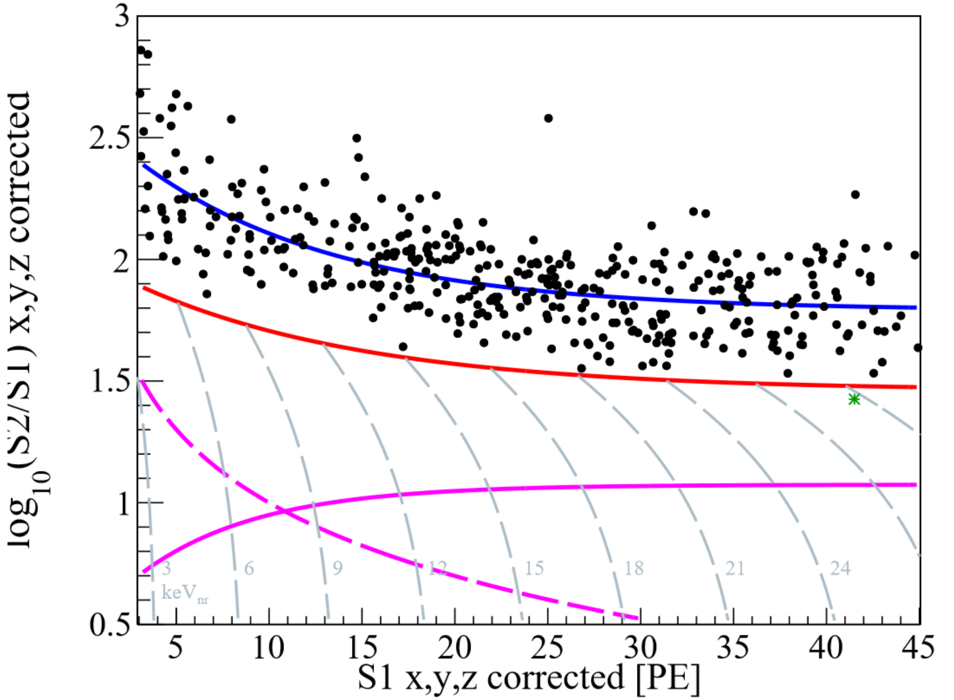
Run 8



Run 9



Combined results

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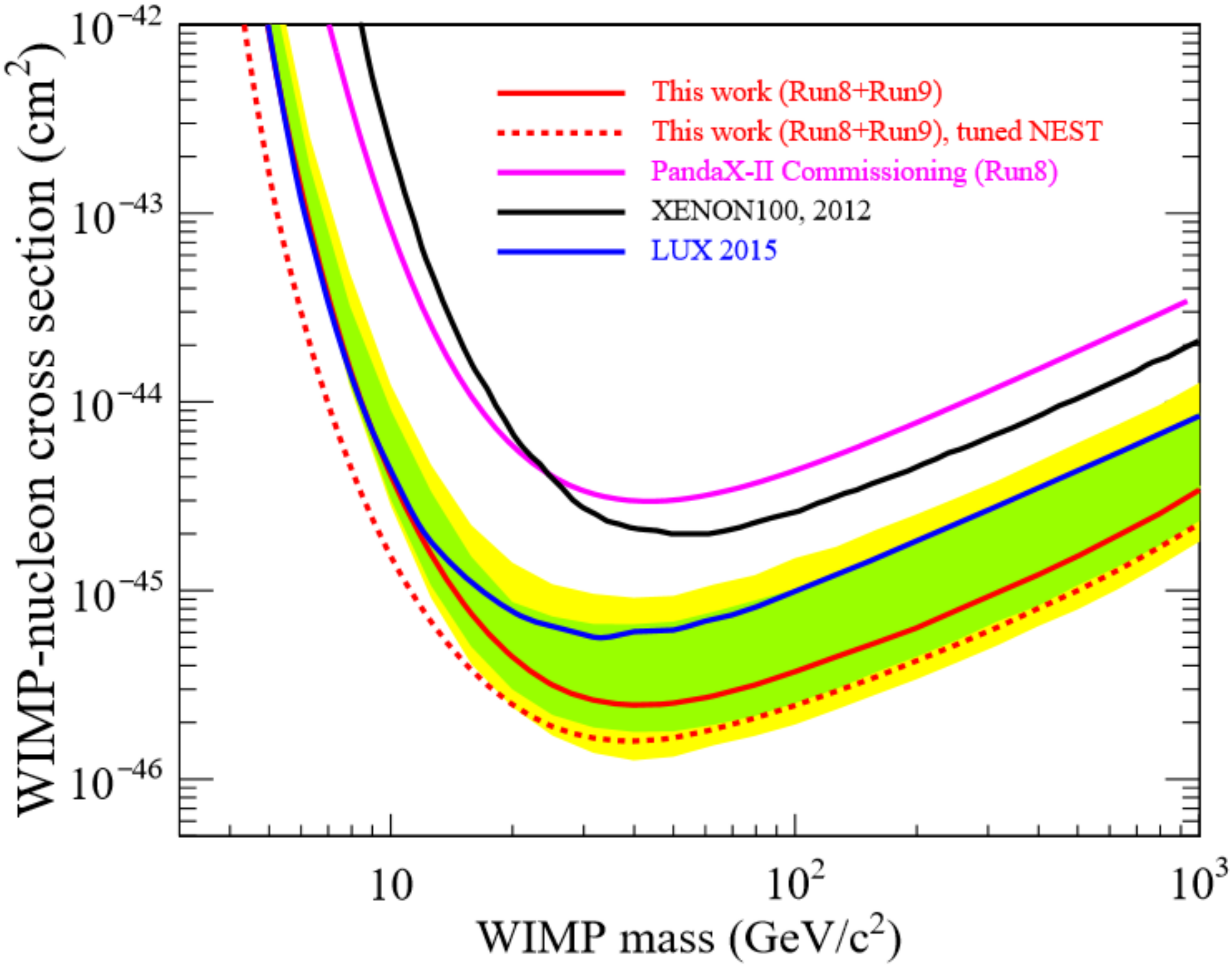
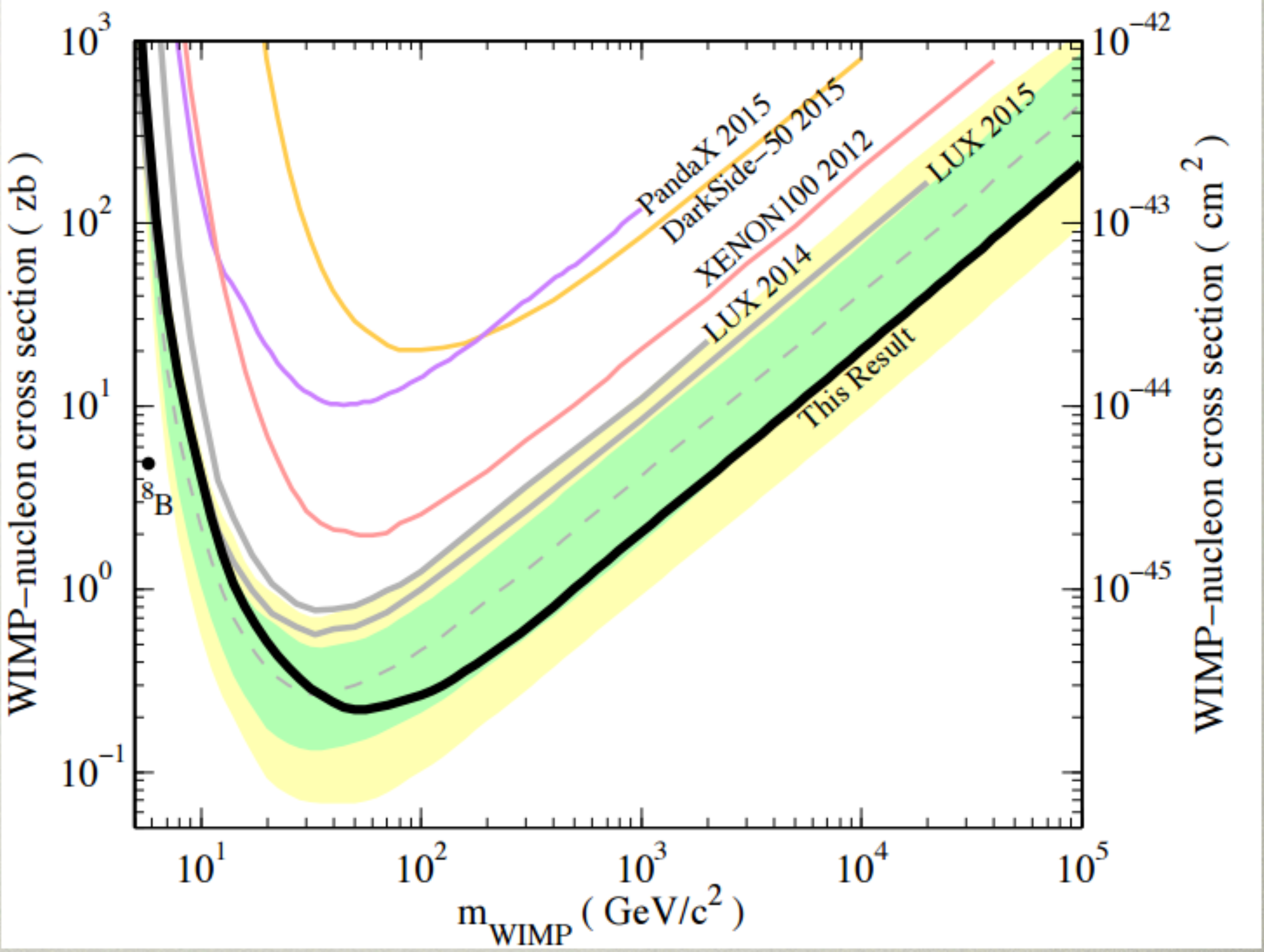


Minimum upper limit for SI elastic cross section at 2.5×10^{-46} cm^2, more than a factor of 2 improvement compared to the LUX 2015 results

Released on July 21st
Submitted on July 26th
Accepted by PRL on Aug 16th ! (US time, just three hours ago)

SI WIMP-nucleon exclusion

- Brazil bands show the 1- and 2-sigma range of expected sensitivities, based on random BG-only experiments.
- **Factor of 4 improvement** over the previous LUX result in the high WIMP masses
- Minimum exclusion of **2.2 x 10^{-46} cm^2** at 50 GeV



Summary and outlook

- 79.6 live-day of dark matter data were taken with much reduced background compared to the commissioning run (15 -> 2 mDRU)

- Extensive calibration studies with neutron and tritium

- In combination with commissioning run (19.1 day), ~33,000 kg-day exposure in total. No DM particles are found

- The WIMP-nucleon elastic scattering cross checking are constrained to $<2.5 \times 10^{-46}$ cm^2

BackUp

Improved position reconstruction

- Maximum Likelihood $$-\ln \tilde{L}(\vec{r}) = -\sum_i \frac{n_i}{\mathrm{qS2T}} \ln \frac{\eta_i(\vec{r})}{P(\vec{r})}$$
- Photon Acceptance Function(PAF) of Each PMT
- The iteration to determine the PAFs

$$\eta(r) = A \cdot \exp(-\frac{a \cdot \rho}{1+\rho^{1-\alpha}} - \frac{b}{1+\rho^{-\alpha}}), \quad \rho = \frac{r}{r_0}$$

$$\vec{r}^{(0)} = \vec{r}_{\mathrm{CoG}}$$

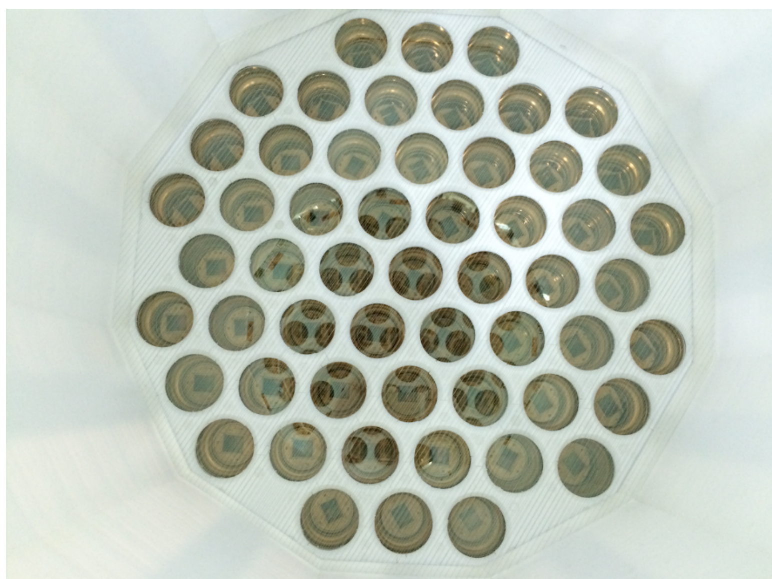
$$\eta_i^{(1)} \rightarrow \vec{r}^{(1)}$$

$$\eta_i^{(2)} \rightarrow \vec{r}^{(2)}$$

⋮

Converge

V. N. Solovov *et al*, *IEEE* doi: 10.1109/TNS.2012.2221742

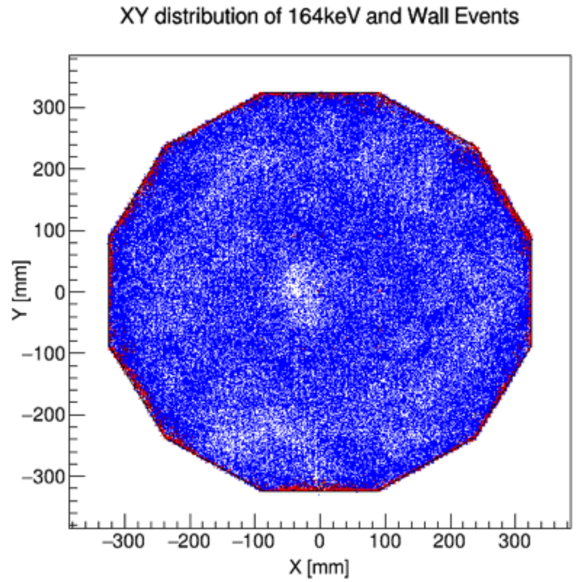


- Big 3” PMT
- Big separations between PMTs
- Big gap between outermost PMTs and the physical boundary of TPC wall

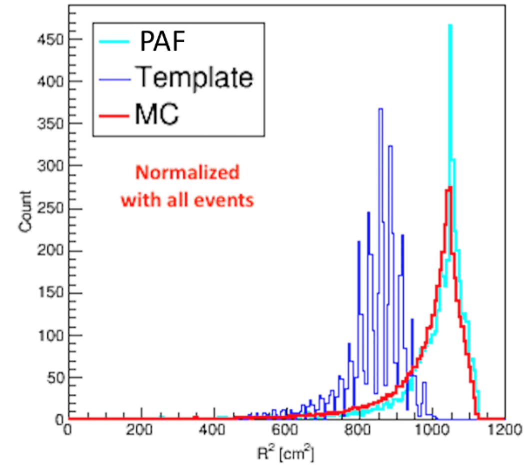
Have to abandon isotropic assumption of PAF of outside PMTs

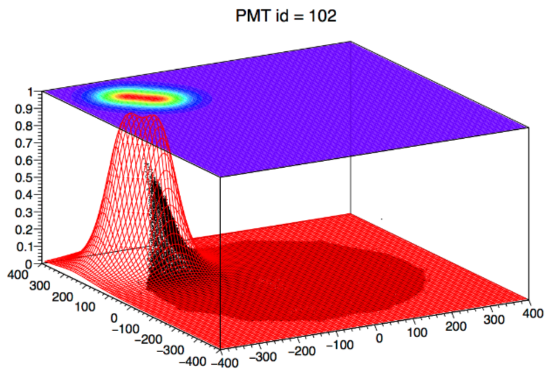
Reflection Component of the PAF

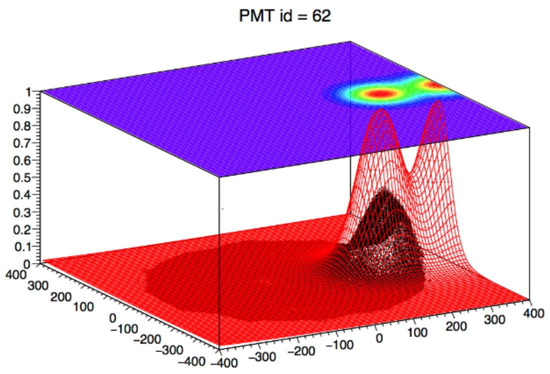
- For ^{210}Po events close to the top to be reconstructed onto the wall, reflection components were added into PAFs for peripheral PMTs



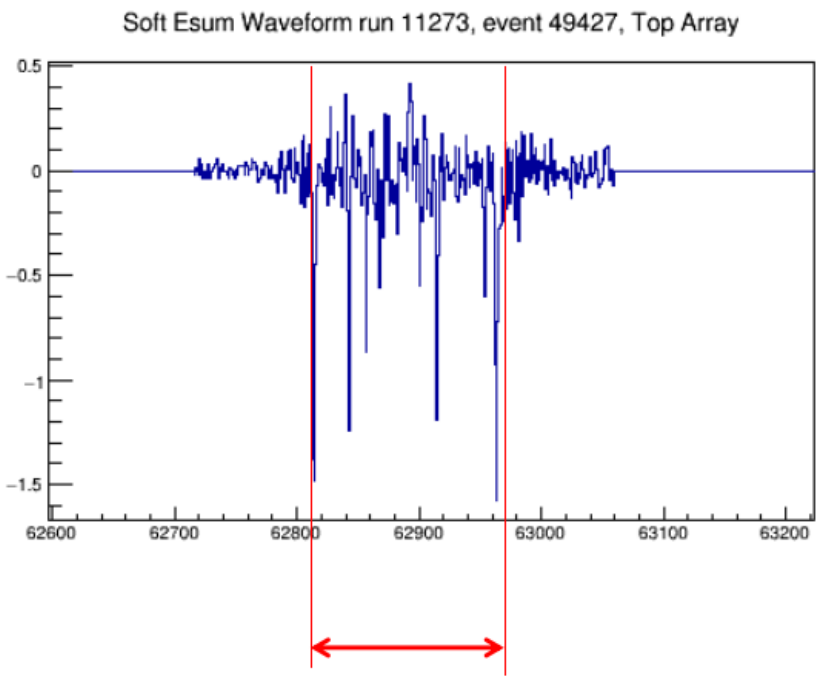
33.2keV event R^2 distribution

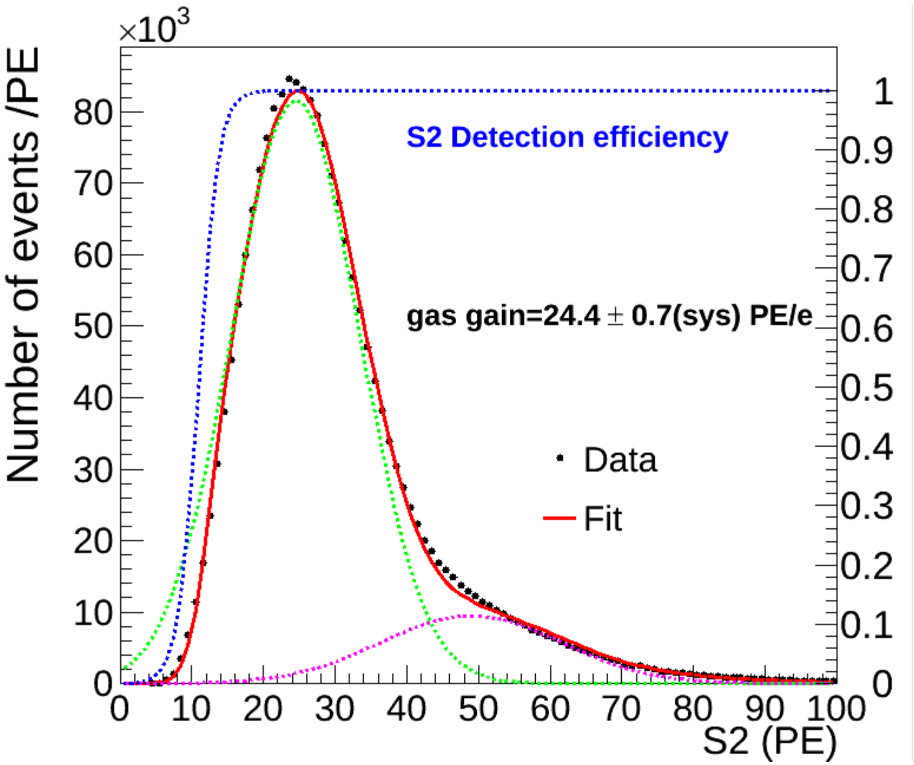






Single electron gain

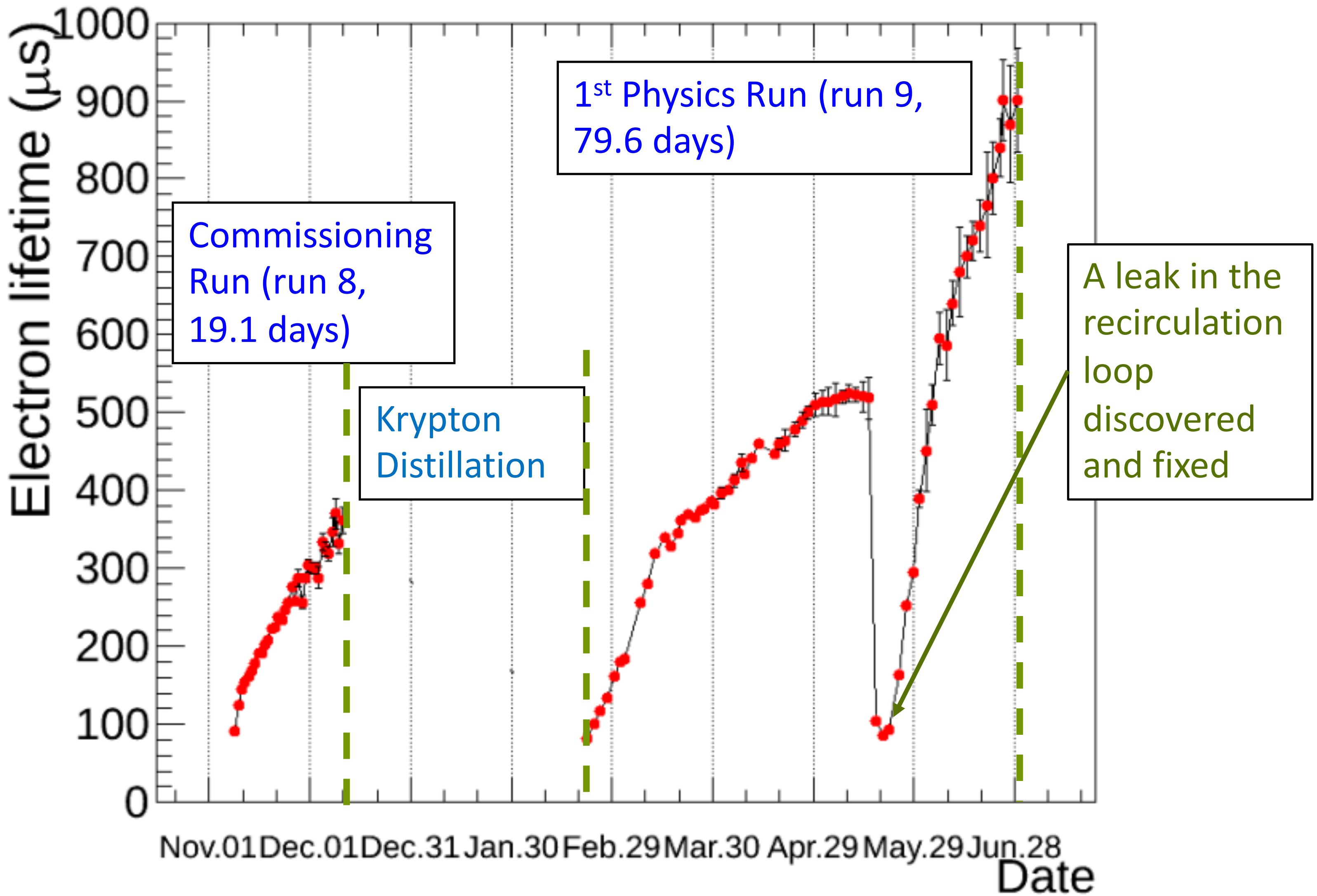




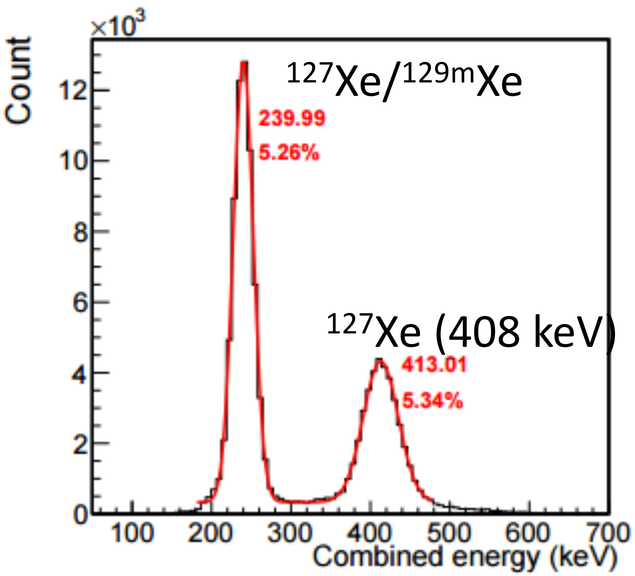
- Identify smallest S2 in the data
- Varying selection method and fits to study systematic uncertainty

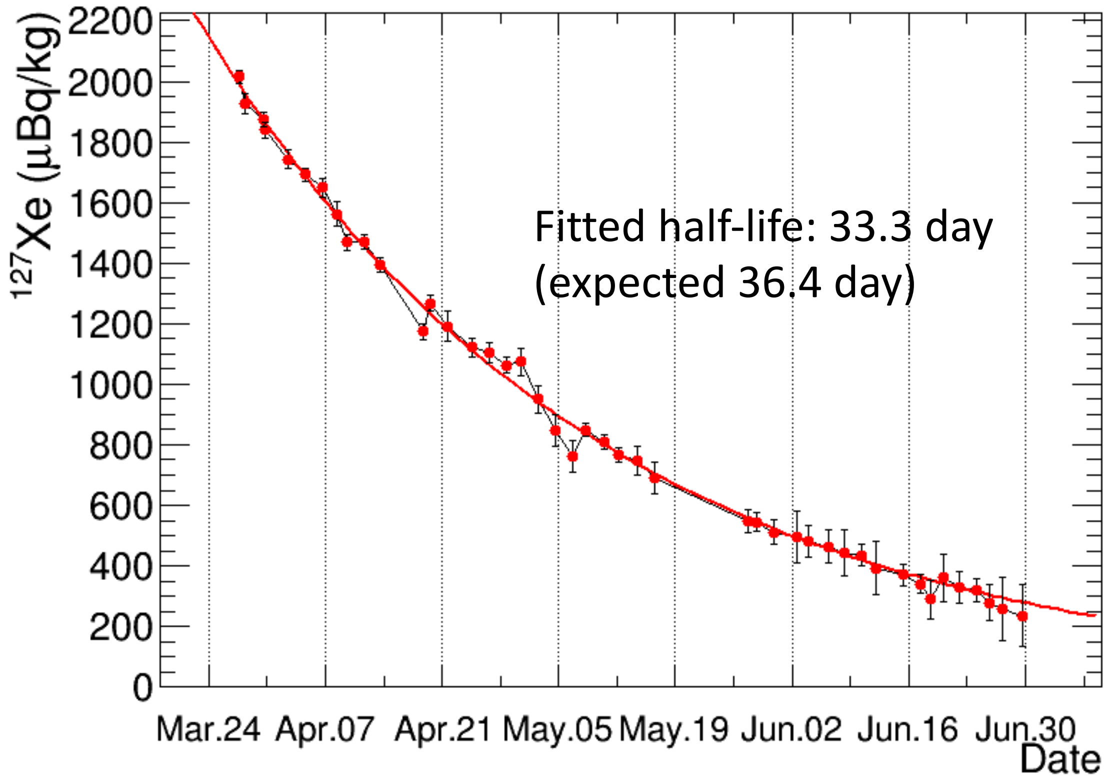
  $\Rightarrow$ 24.4± 0.7 PE/e

Electron lifetime evolution



^{127}Xe

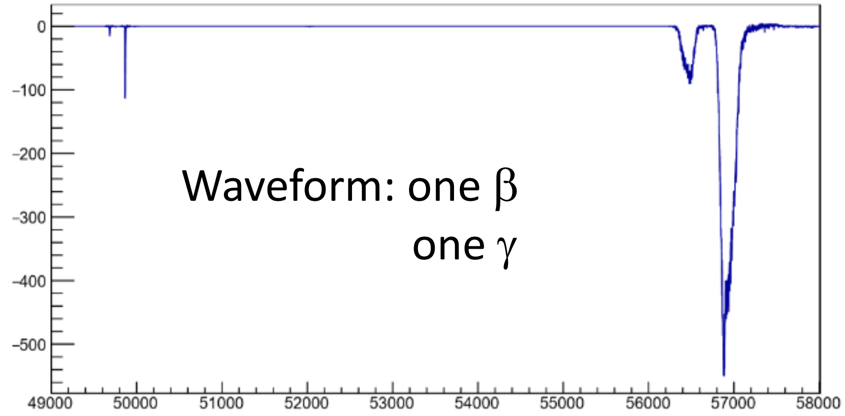


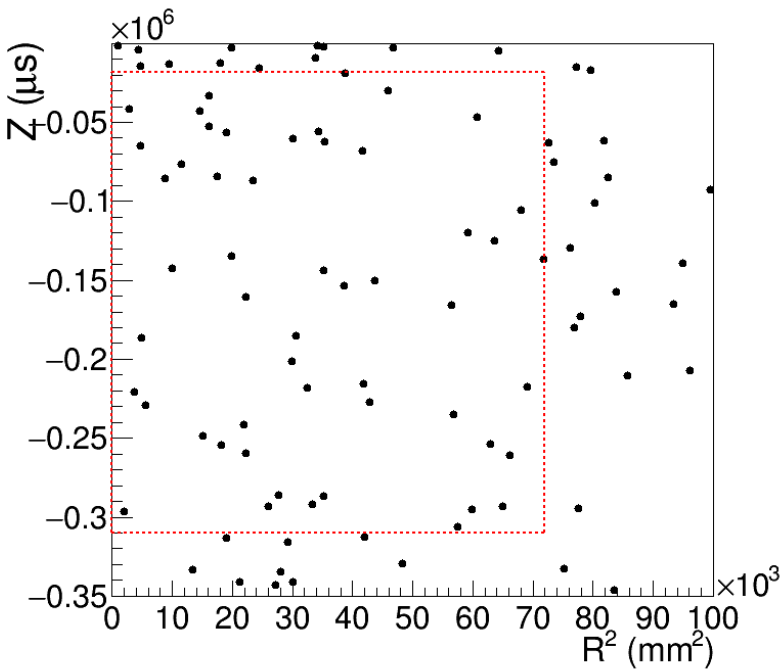


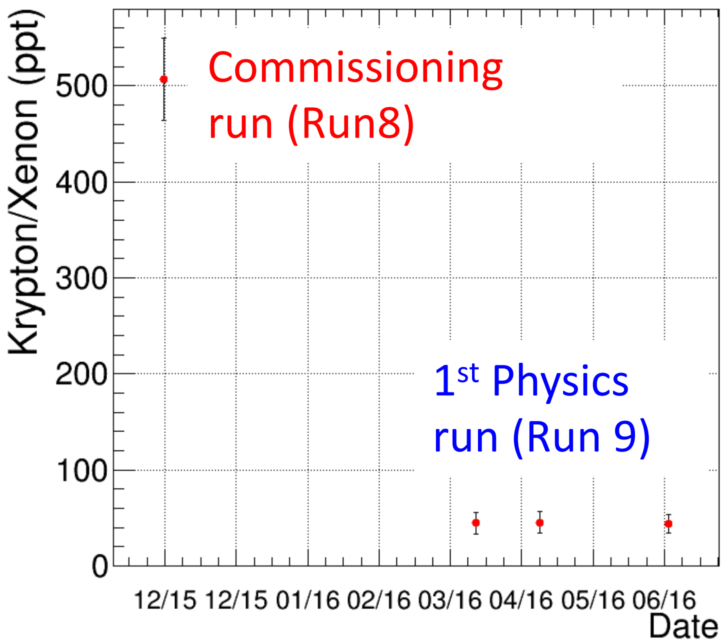
Rate of ^{127}Xe estimated by fitting the 408 keV (375 keV+33.2 keV) peak

^{85}Kr

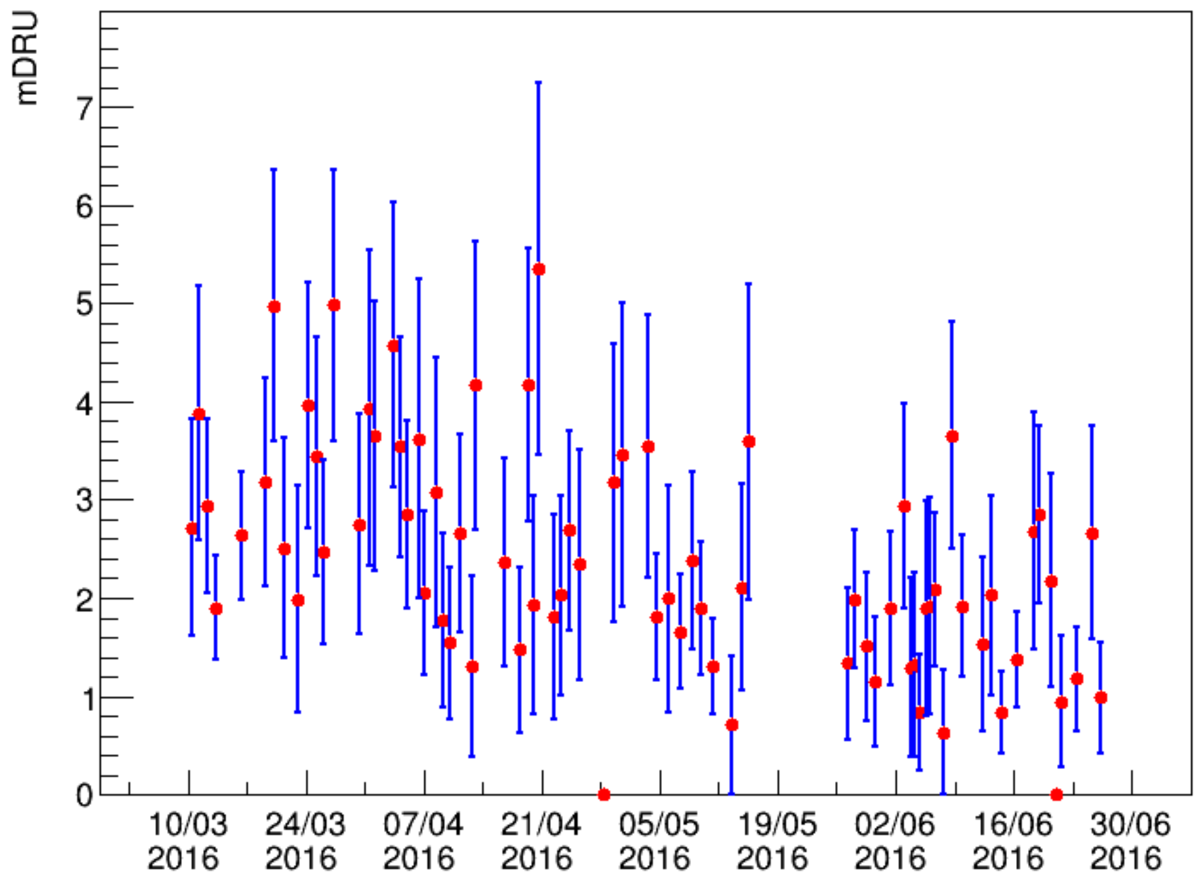
- Estimated from delayed β–γ coincidence analysis
- Uniformly distributed
- Significantly reduced after distillation







Low energy background in Run 9



- Events selected with energy <10 keV
- ~2 mDRU on average (15.3 mDRU in Run 8)
- Decrease over time due to ^{127}Xe decay

Xenon experiments comparison

Experiments	FV (kg)	Total exposure (kg-day)	Background level (mDRU)
XENON100 100 day	48	4843	22
XENON100 225 day	34	7650	5
LUX 2015	147	14000	3
PandaX-I	54	4325	23.6
PandaX-II (run8)	306	5845	15.3
PandaX-II (run9)	~300	~24000	~2
PandaX-II run8+9	~300	33200	2-15