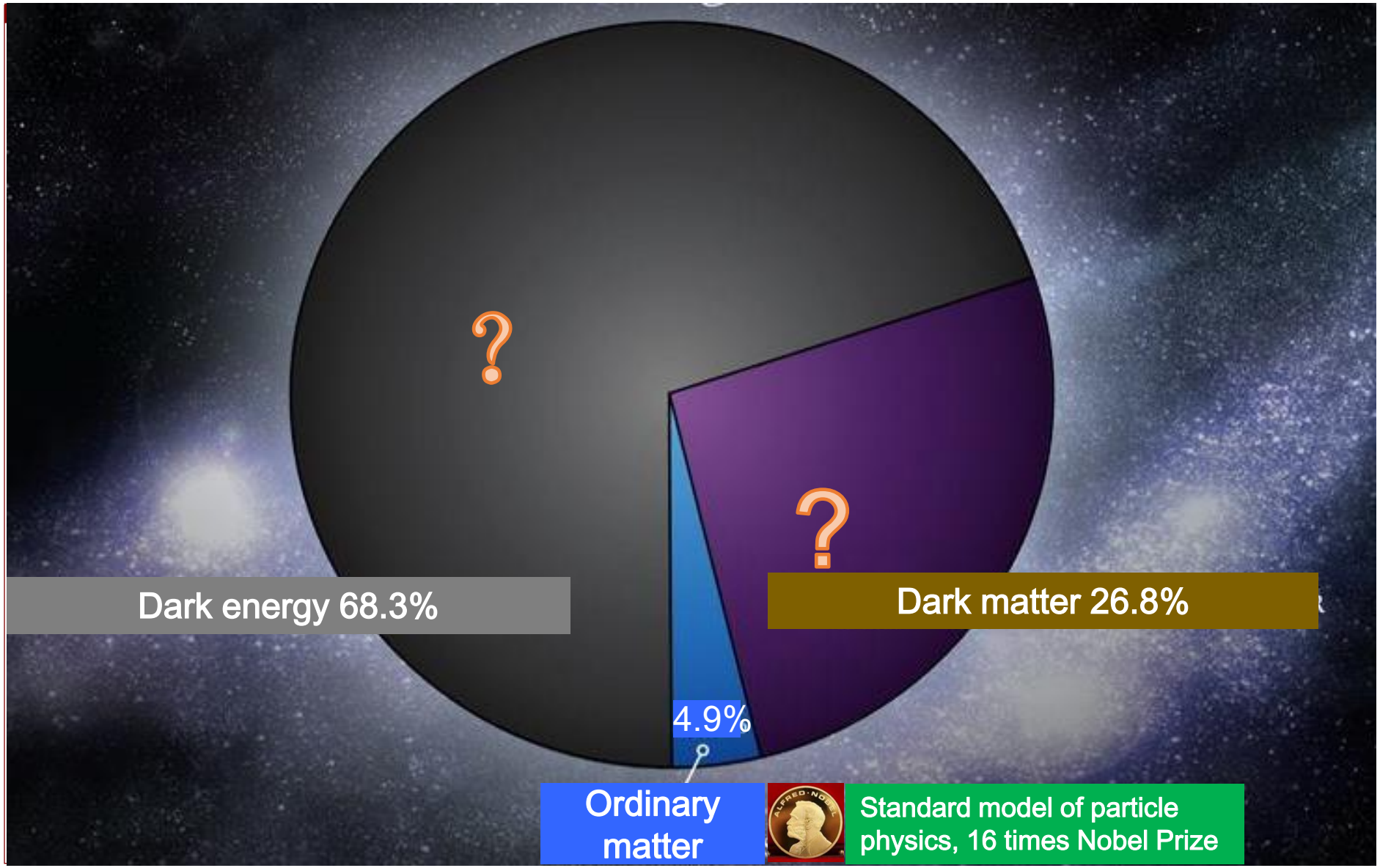
PandaX 暗物质实验最新结果

刘江来
上海交通大学
代表 PANDA X 国际合作组

Universe Today



WIMP Miracle

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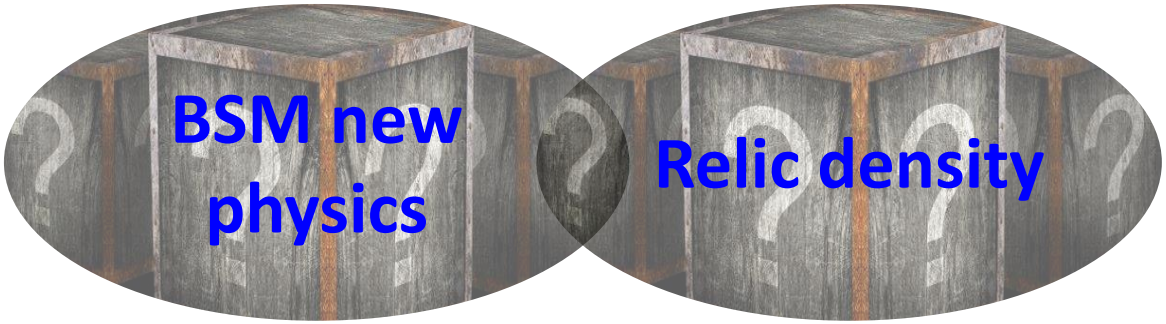

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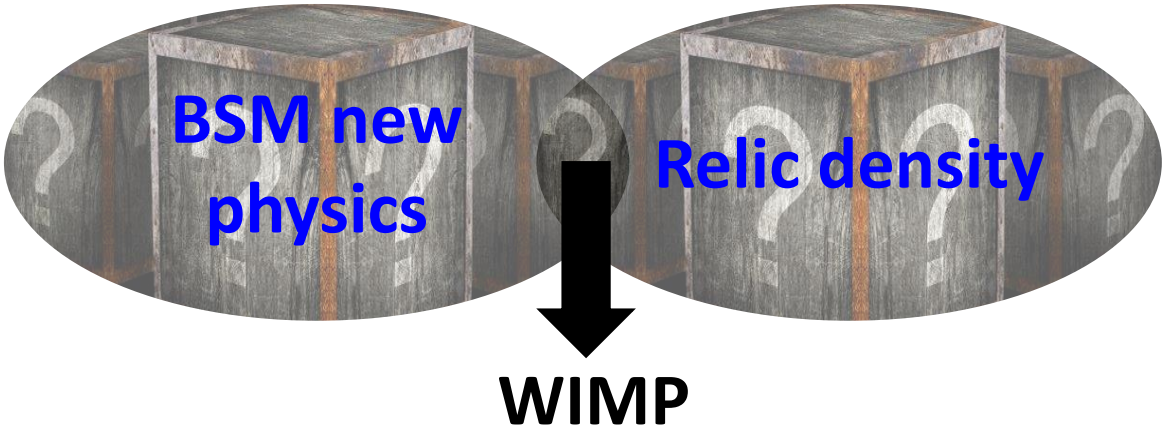

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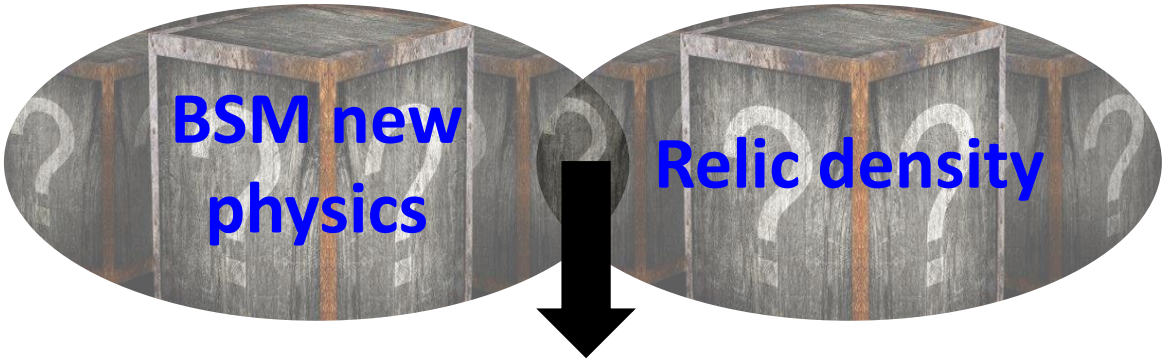

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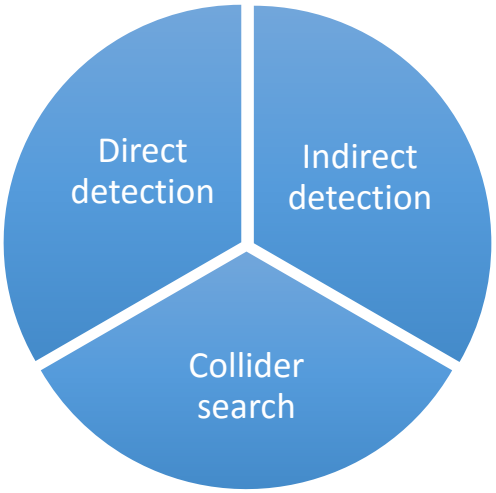
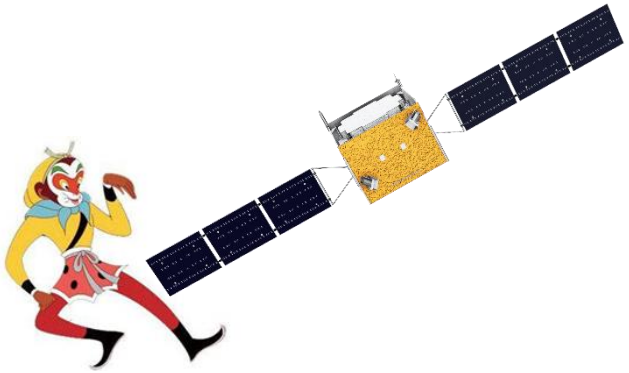
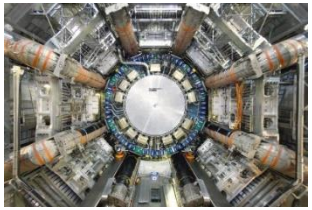
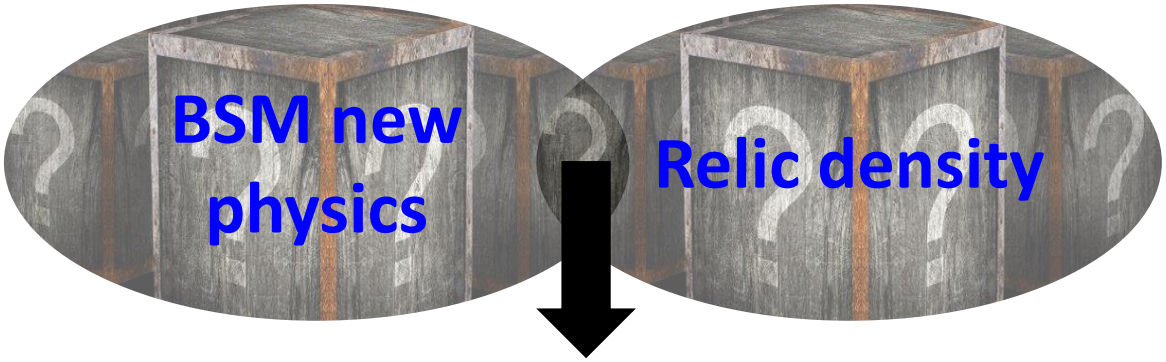


PANDA X

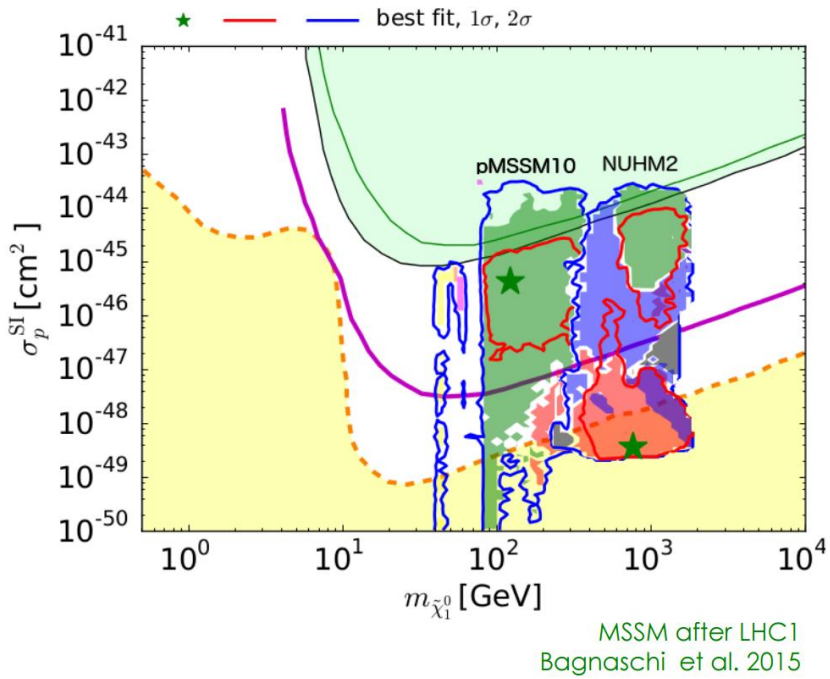




WIMP Miracle



WIMP



Excellent case for more sensitive DM detector and complementarity of collider and direct searches!

Xenon experiments

Large target

3D camera

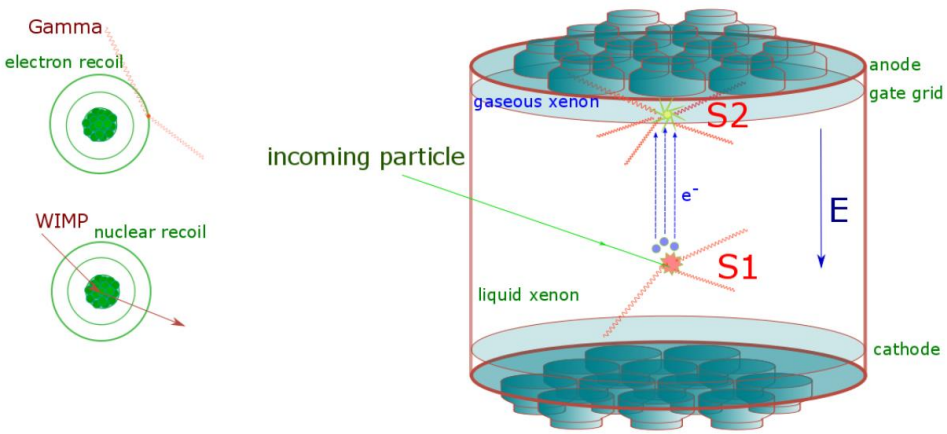
Signal/bkg discriminator

Self-shielding body

XENON100, 60 kg, completed 2012, Gran Sasso
XENON1T in preparation

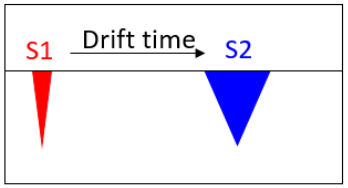
LUX, 250 kg, completed 2016, Sanford Lab
LZ(multi-ton) in preparation

Dual phase xenon TPC

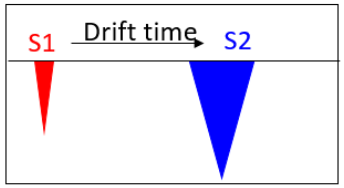


DM direct detection: recoil of atomic nucleus in the detector (Goodman & Witten, 1985), <10 keV_{ee} energy

Dark matter: nuclear recoil (NR)

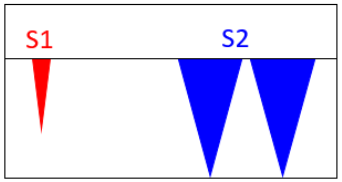


γ background: electron recoil (ER)



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

Multi-site scattering background (ER or NR)

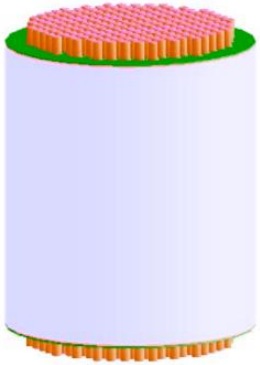


PandaX experiment

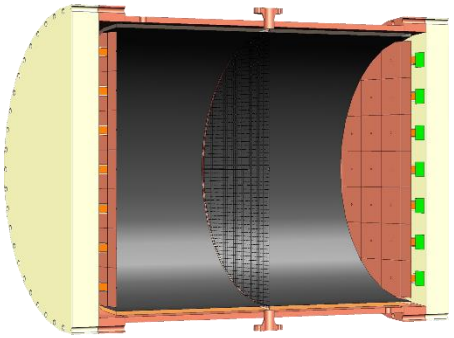
PandaX＝Particle and Astrophysical Xenon Experiments

PandaX-I: 120 kg DM experiment 2009-2014

PandaX-II: 500 kg DM experiment 2014-2017



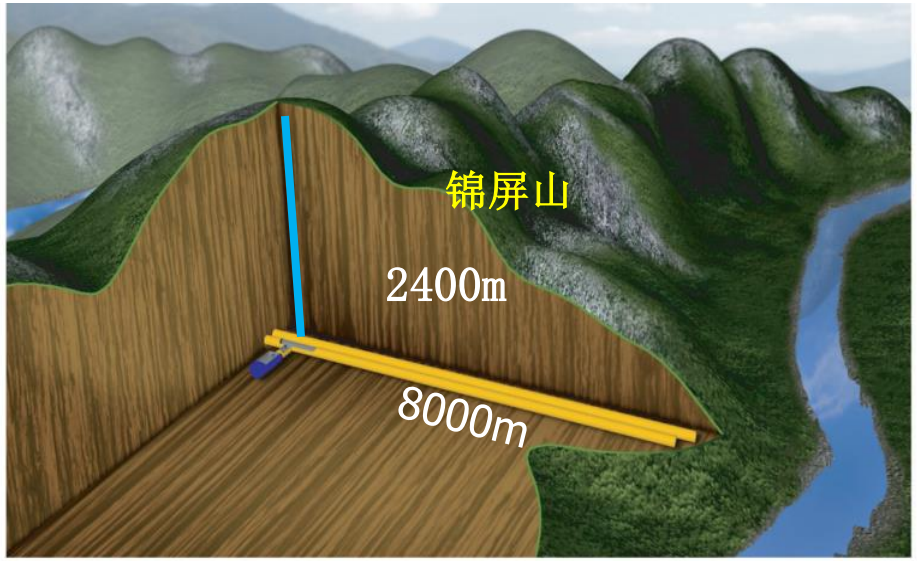
PandaX-xT: multi-ton DM experiment 2016-

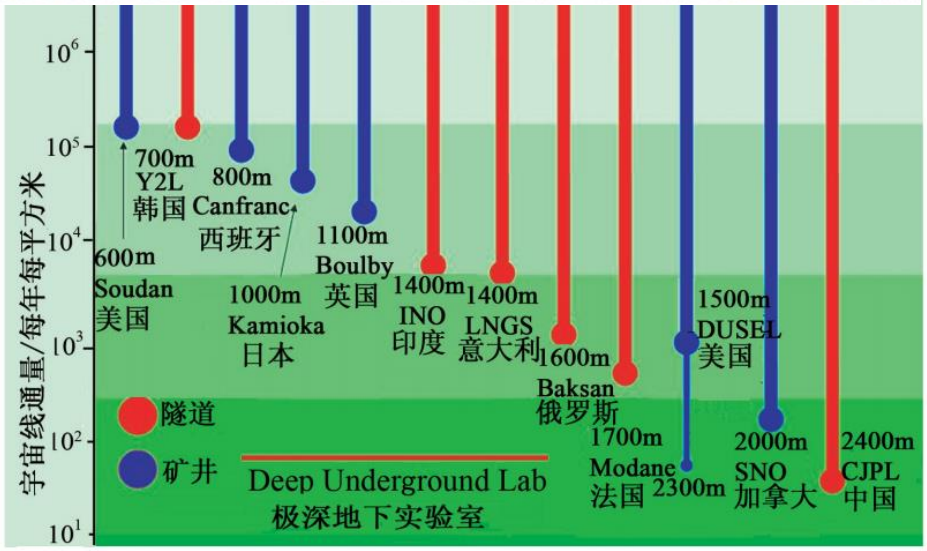


PandaX-III: 200 kg to 1 ton ^{136}Xe 0vDBD experiment 2016-

China Jinping Underground Lab

Deepest in the world (1μ/week/m²) and Horizontal access!





PandaX collaboration

~50 people

Started in 2009

- 上海交通大学 (2009-)
- 北京大学 (2009-)
- 山东大学(2009-)
- 中科院上海应用物理研究所 (2009-)
- 中国科技大学 (2015-)
- 中国原子能科学研究院 (2015-)
- 中山大学 (2015-)
- 雅砻水电 (2009-)
- University of Maryland (2009-)
- Alternative Energies & Atomic Energy Commission(2015-)
- University of Zaragoza(2015-)
- Suranaree University of Technology(2016-)

Talks at this conference

8/22:
分会四
15:20-15:40 PandaX-III:锦屏地下实验室的无中微子双贝塔衰变实验， 韩柯
15:40-16:00 PandaX-III无中微子双贝塔衰变实验的预期本底研究， 谌勋
晨光杯
15:50-16:05 First dark matter search results from the PandaX-I experiment; Low-mass dark matter search results from full exposure of the PandaX-I experiment， 肖梦姣

8/23
分会4:
14:00-14:20 PandaX第二期实验首批物理数据分析，杨勇
14:20-14:40 PandaX-II实验中的刻度及重建过程，周小朋
14:40-15:00 PandaX 4吨级暗物质直接探测实验，Zhou Ning，

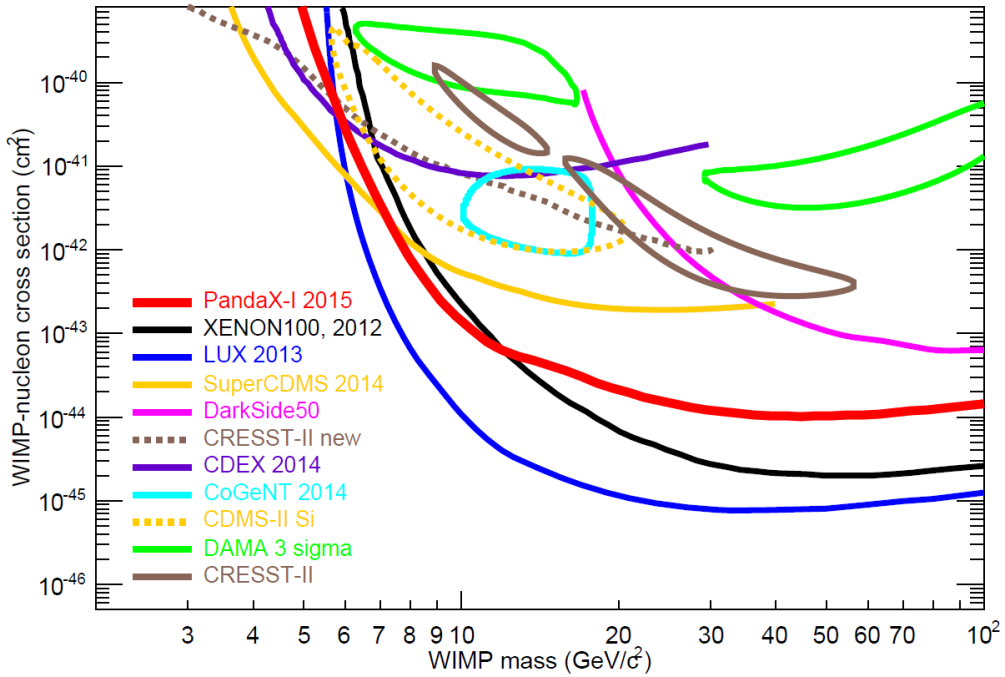
details of PandaX-II analysis

分会5:
14:00-14:20 PandaX III 实验的TPC原型进展，李兴隆
14:20 – 14:40 PandaX-III读出电子学设计， 董家宁
14:40 – 15:00 PandaX-I&II 电子学与数据获取系统，任祥祥
15:00 – 15:20 PandaX实验中放射性本底测量与控制， 符长波
15:50 – 16:10 PandaX PPT级精馏塔与氪测量系统， 崔祥仪

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

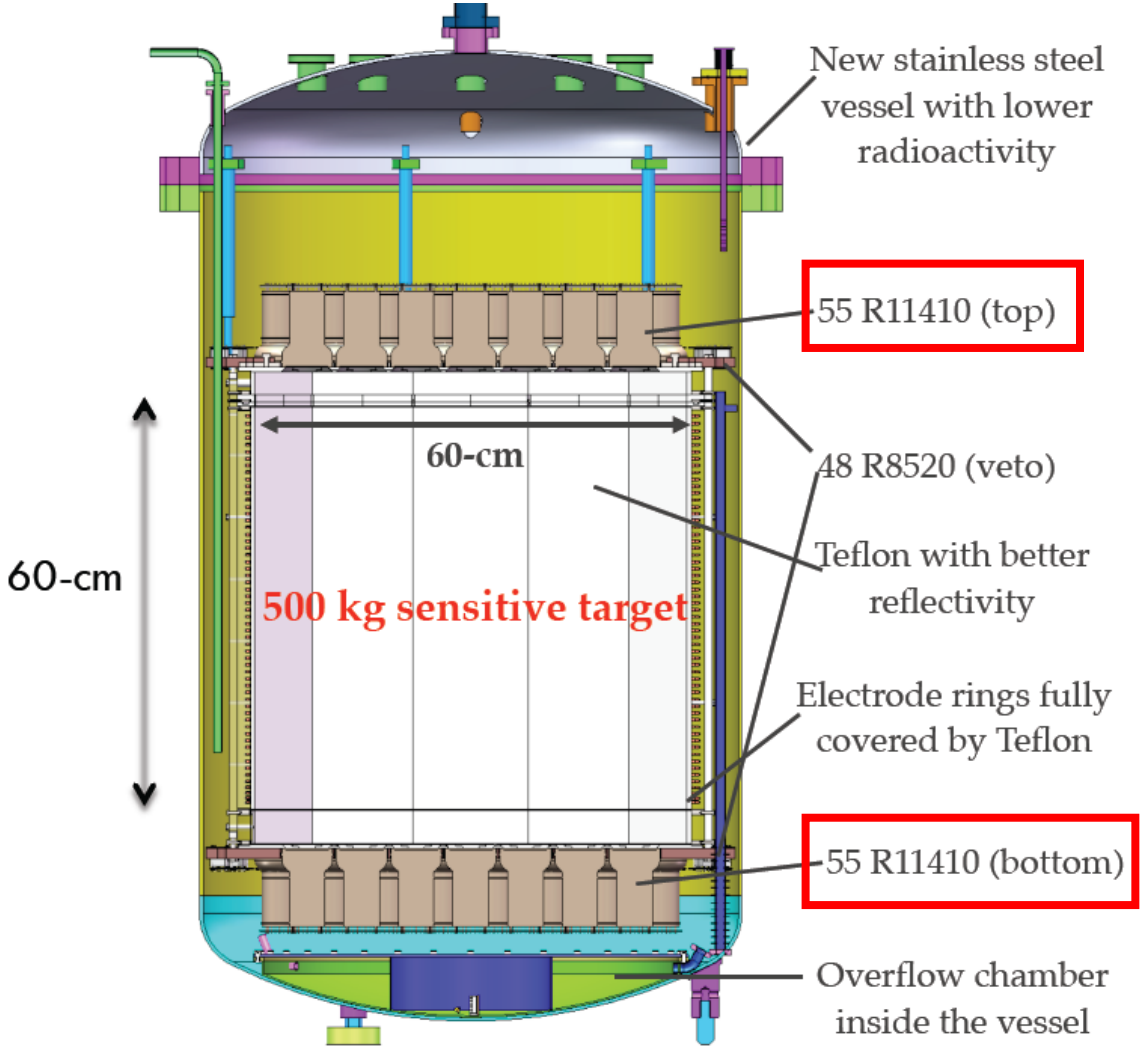
Final Results from PandaX-I

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



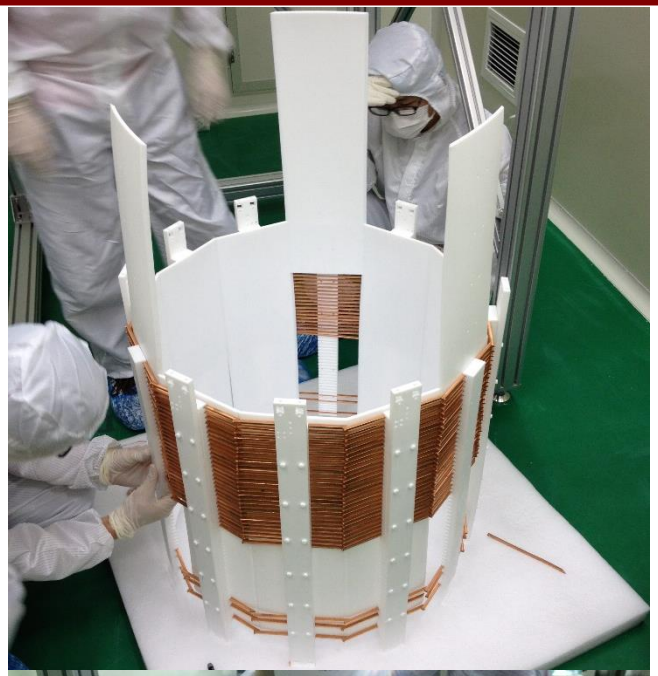
- Completed in Oct. 2014, with 54.0 x 80.1 kg-day exposure
- Data strongly disfavor all previously reported claims
- Competitive upper limits for low mass WIMP in xenon experiments

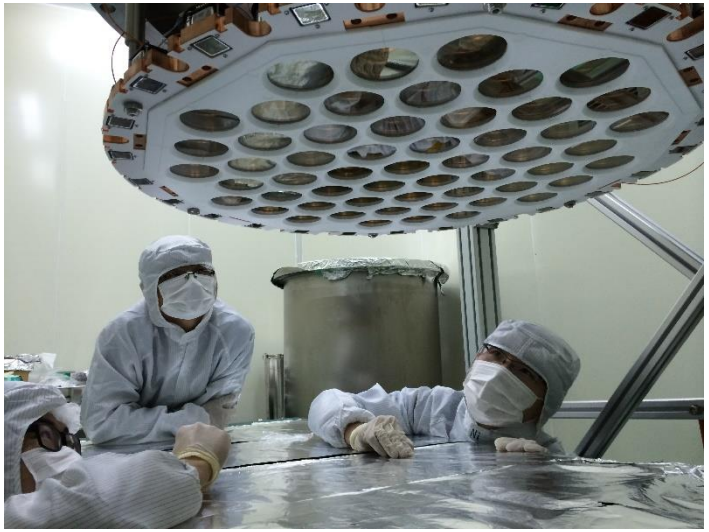
PandaX-II

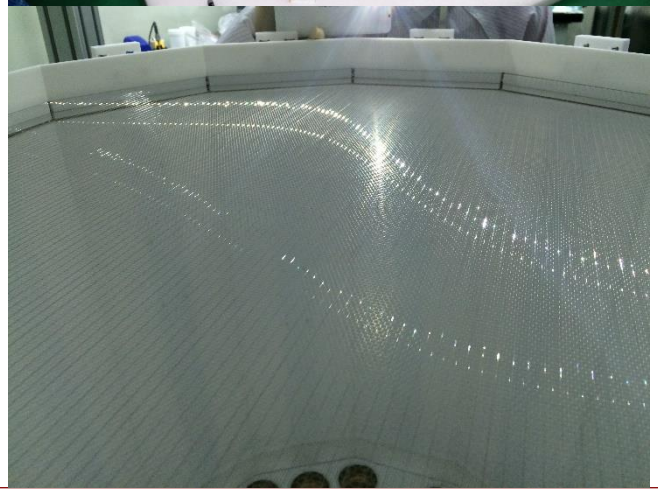


- New inner vessel with clean SS
- New and taller TPC with brand-new electrodes
- More 3” PMTs and improved base design
- New separate skin veto region

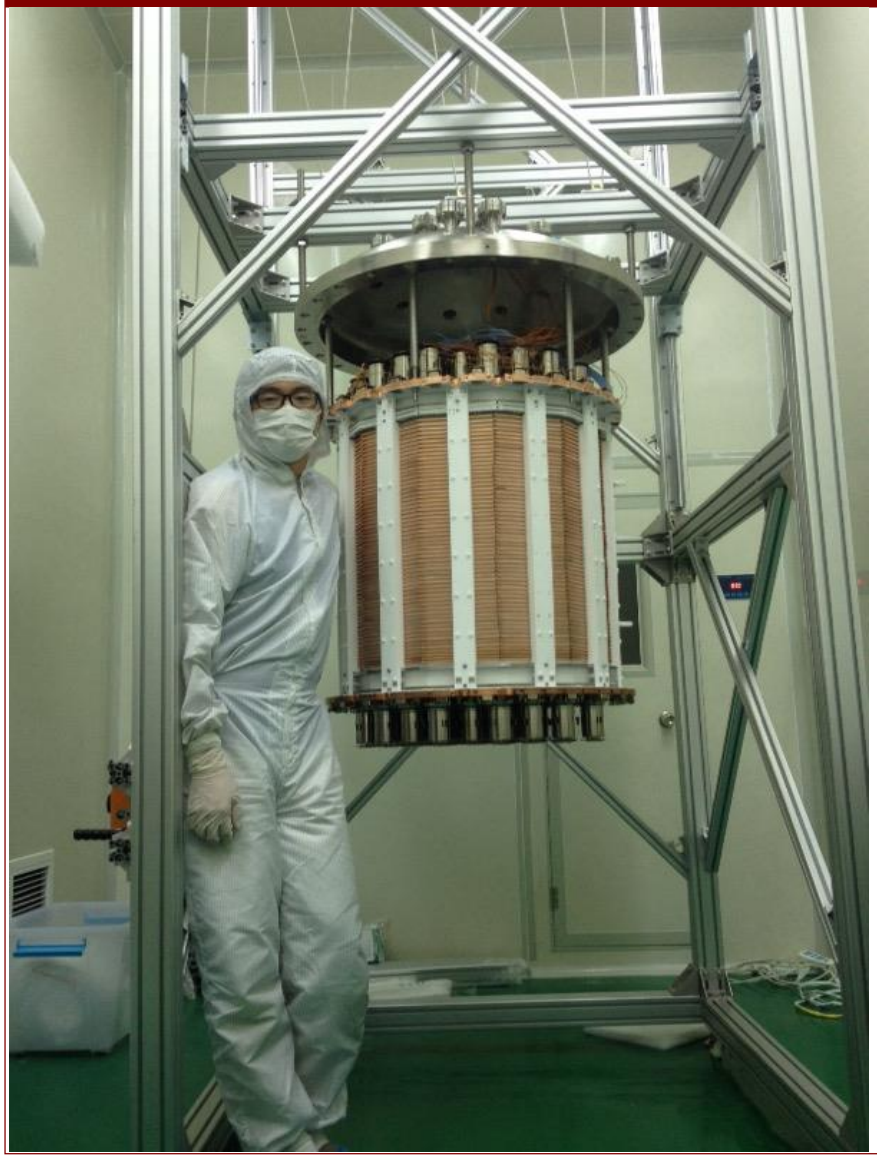
Assembling the detector

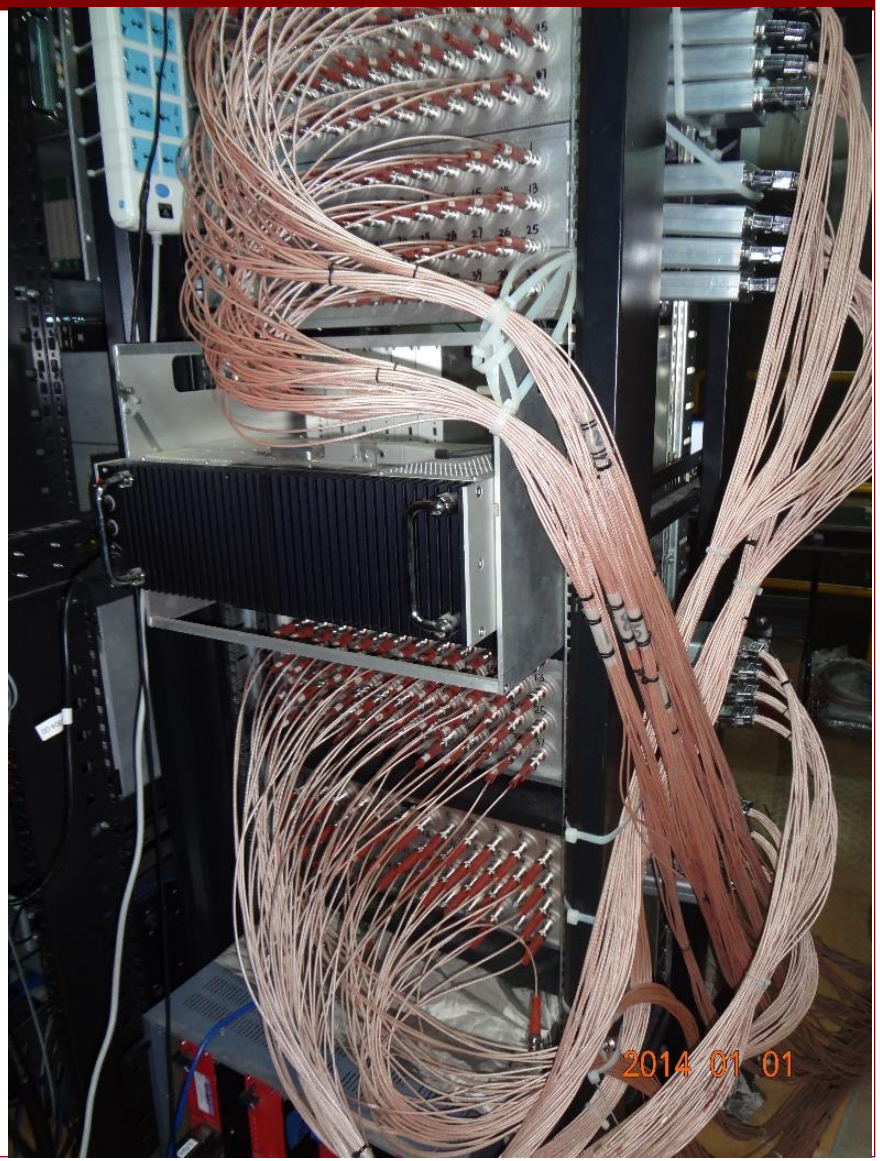






Assembling the detector



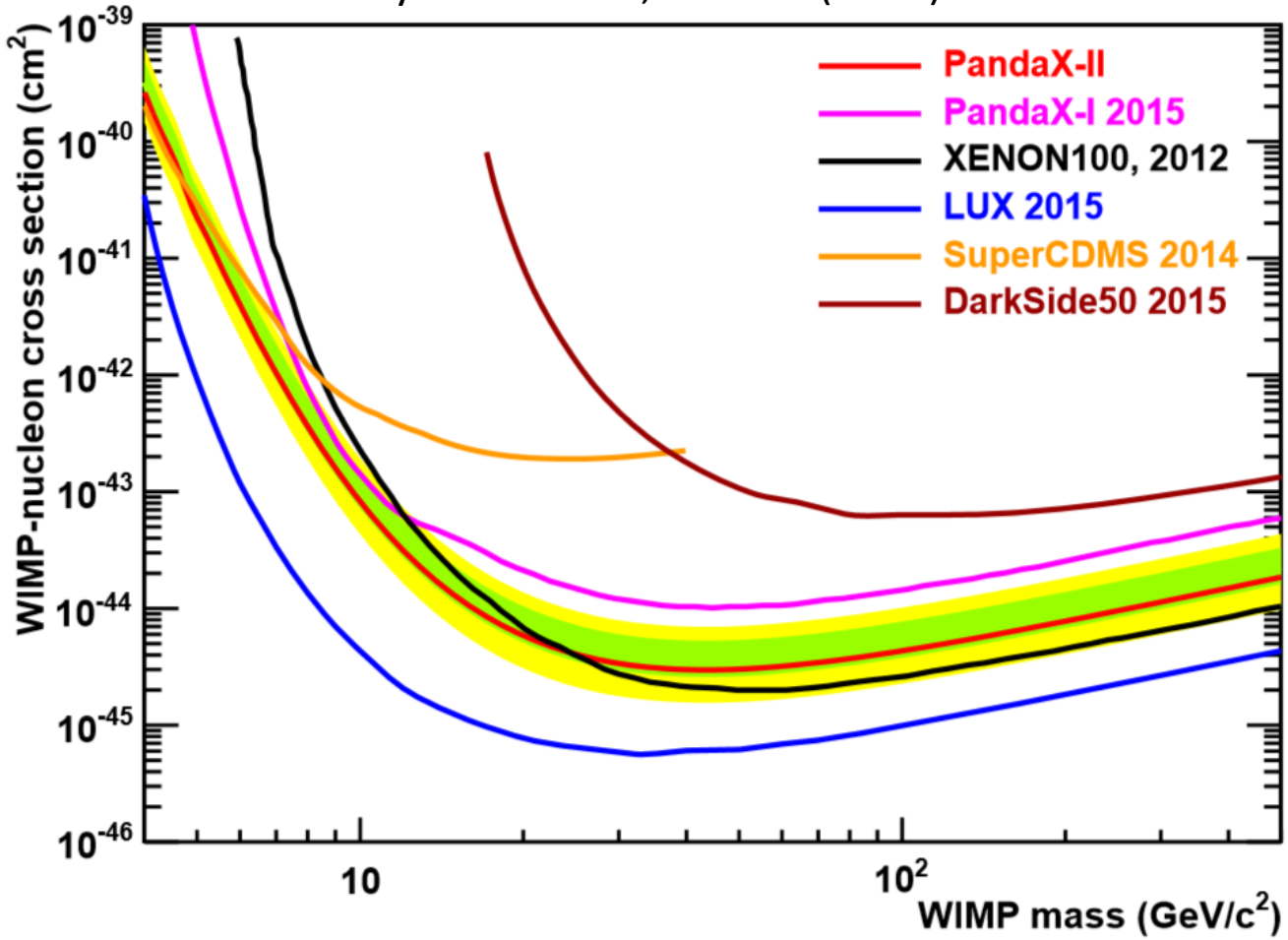


Run history

- 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 from Mar. 9 to Jun. 30, in total 79.6 live-day (Run 9)

Results from PandaX-II Run 8

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

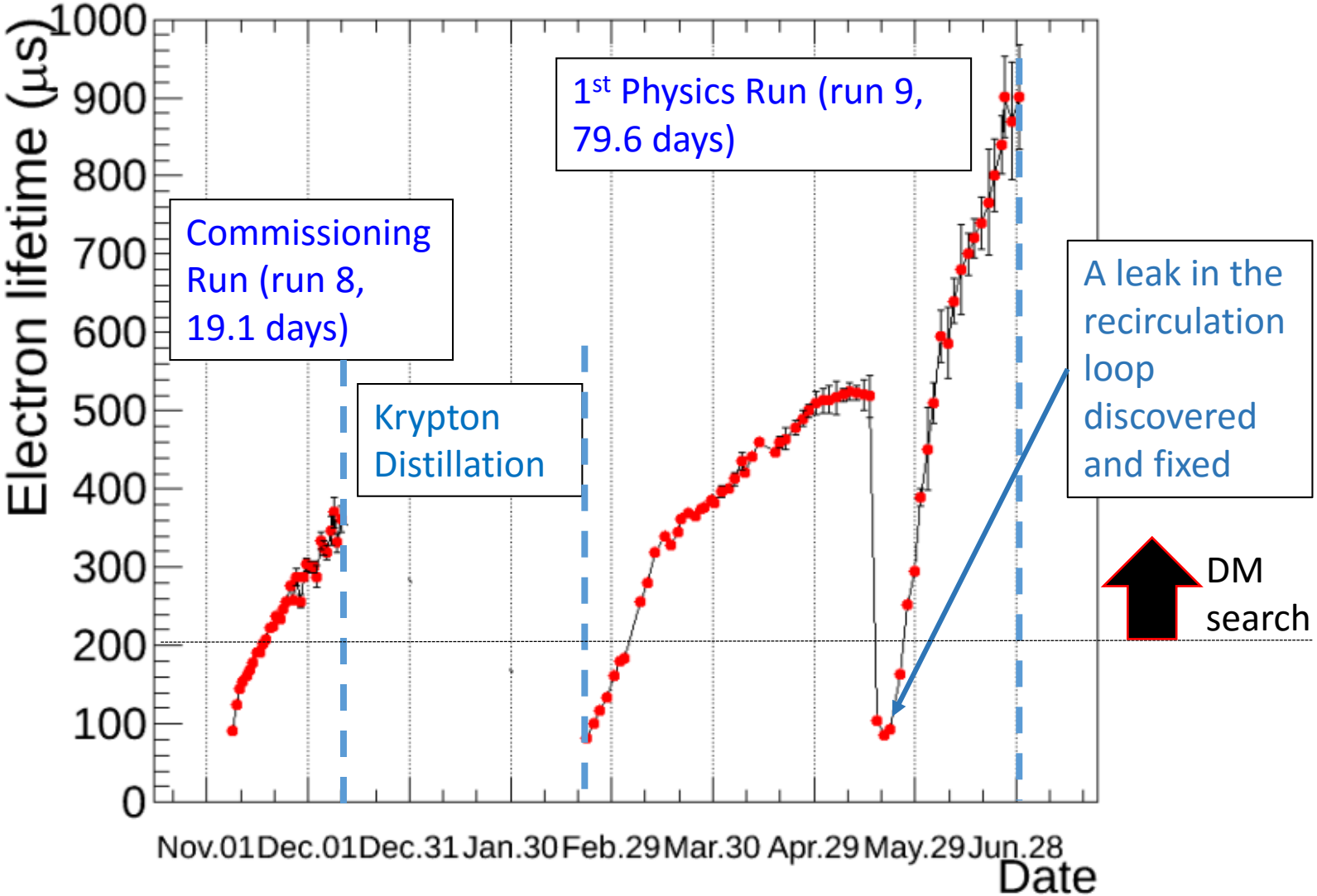


- Low mass: competitive with SuperCDMS;
- High mass: similar exclusion limit as XENON100 225-day

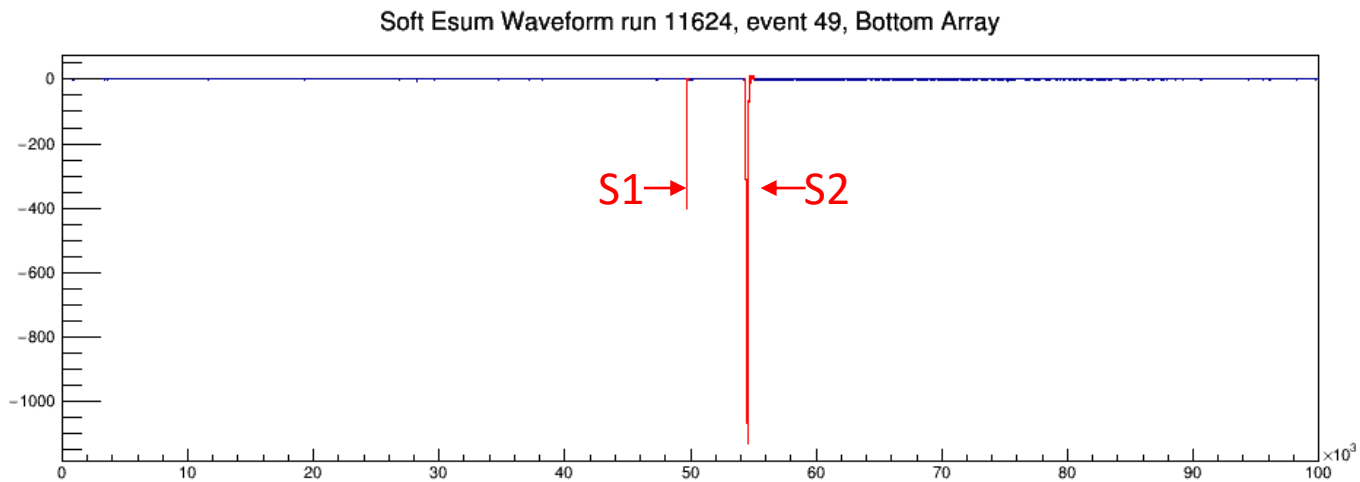
Major upgrades in Run 9

Items	Status in Run 9
Krypton level	Reduced by x10
Exposure	Increased x4 (79.6 vs 19.1 day)
ER calibration	Using tritium calibration
NR calibration	Statistics x6
Analysis	Improved position reconstruction
Background	Accidental background suppressed more than x3 using BDT

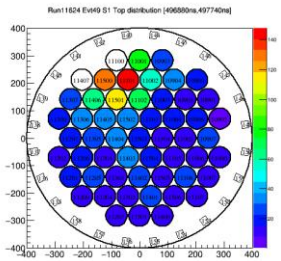
Electron lifetime evolution



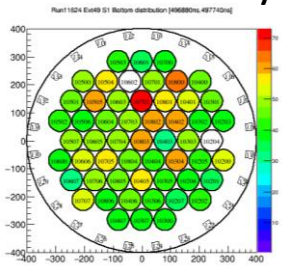
Typical single scatter waveform



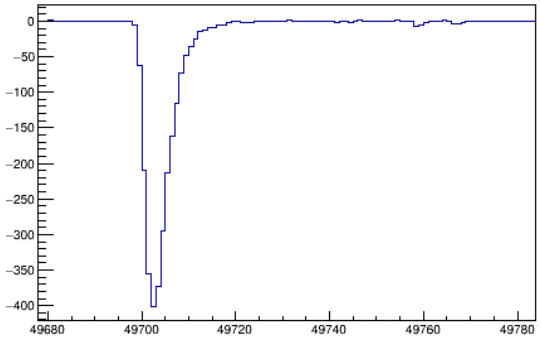
Top Array



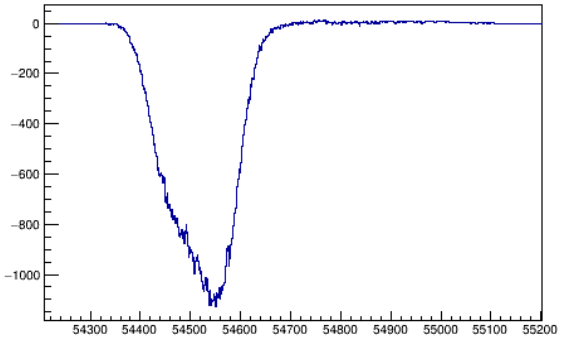
Bottom Array



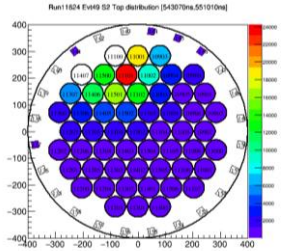
S1 waveform



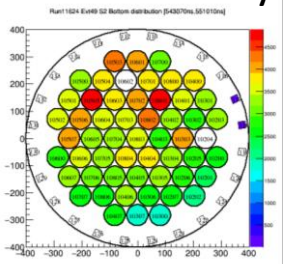
S2 waveform



Top Array

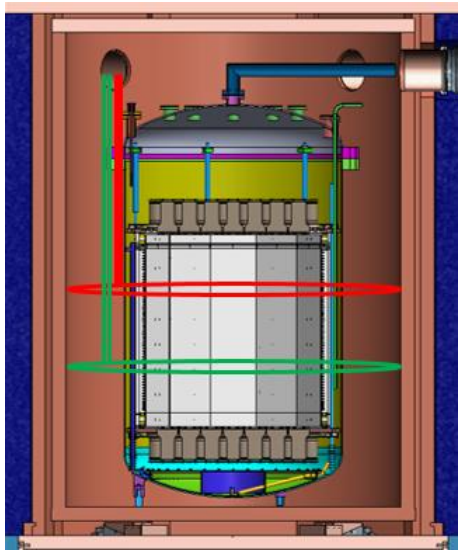


Bottom Array



Extensive calibration program

- Internal/external ER peaks:
  - Detector uniformity corrections
  - Light/charge collection parameters



- Low rate AmBe neutron source:

$\Rightarrow$ Simulate DM NR signal

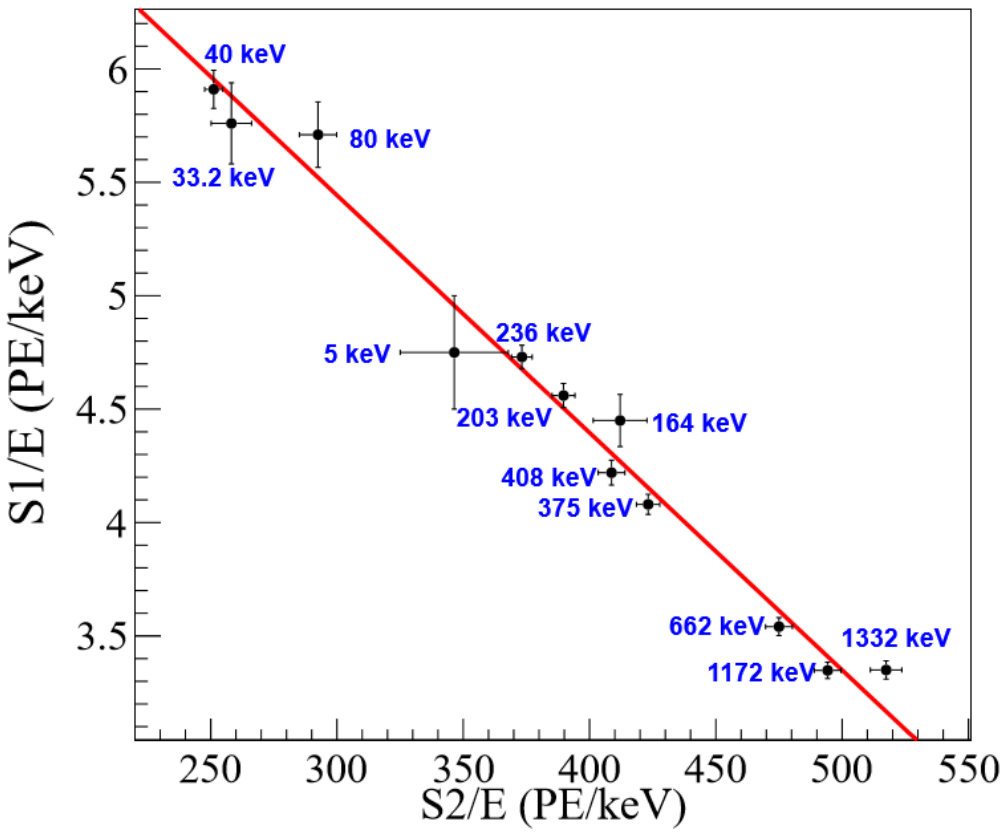
- CH_3T injection: tritium beta decays

$\Rightarrow$ Simulate ER background

Extracting detector parameters

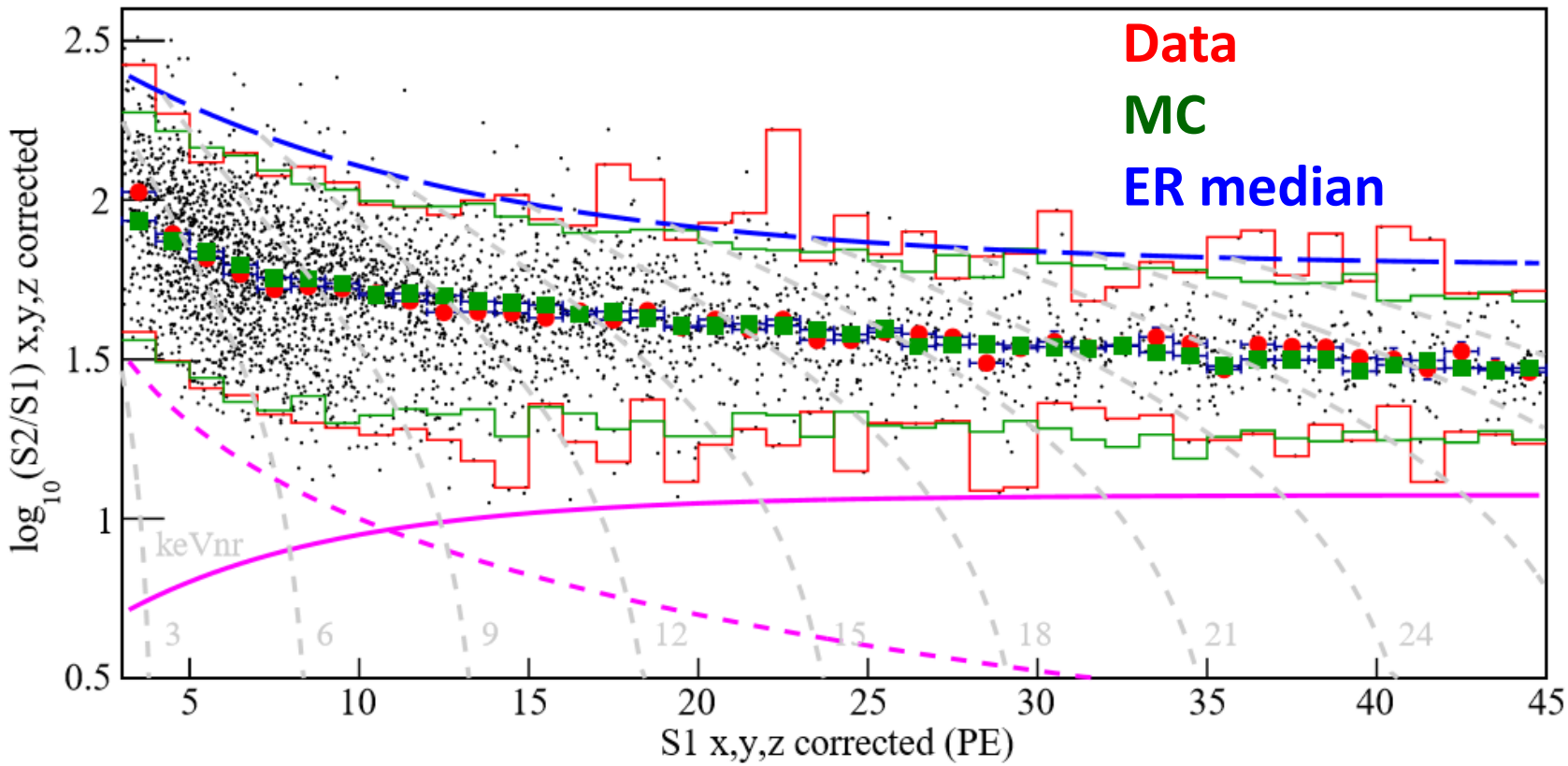
$$E_{ee} = W \times \left(\frac{\mathrm{S1}}{\boxed{\mathrm{PDE}}} + \frac{\mathrm{S2}}{\boxed{\mathrm{EEE}} \times \boxed{\mathrm{SEG}}}\right)$$

W = 13.7 eV



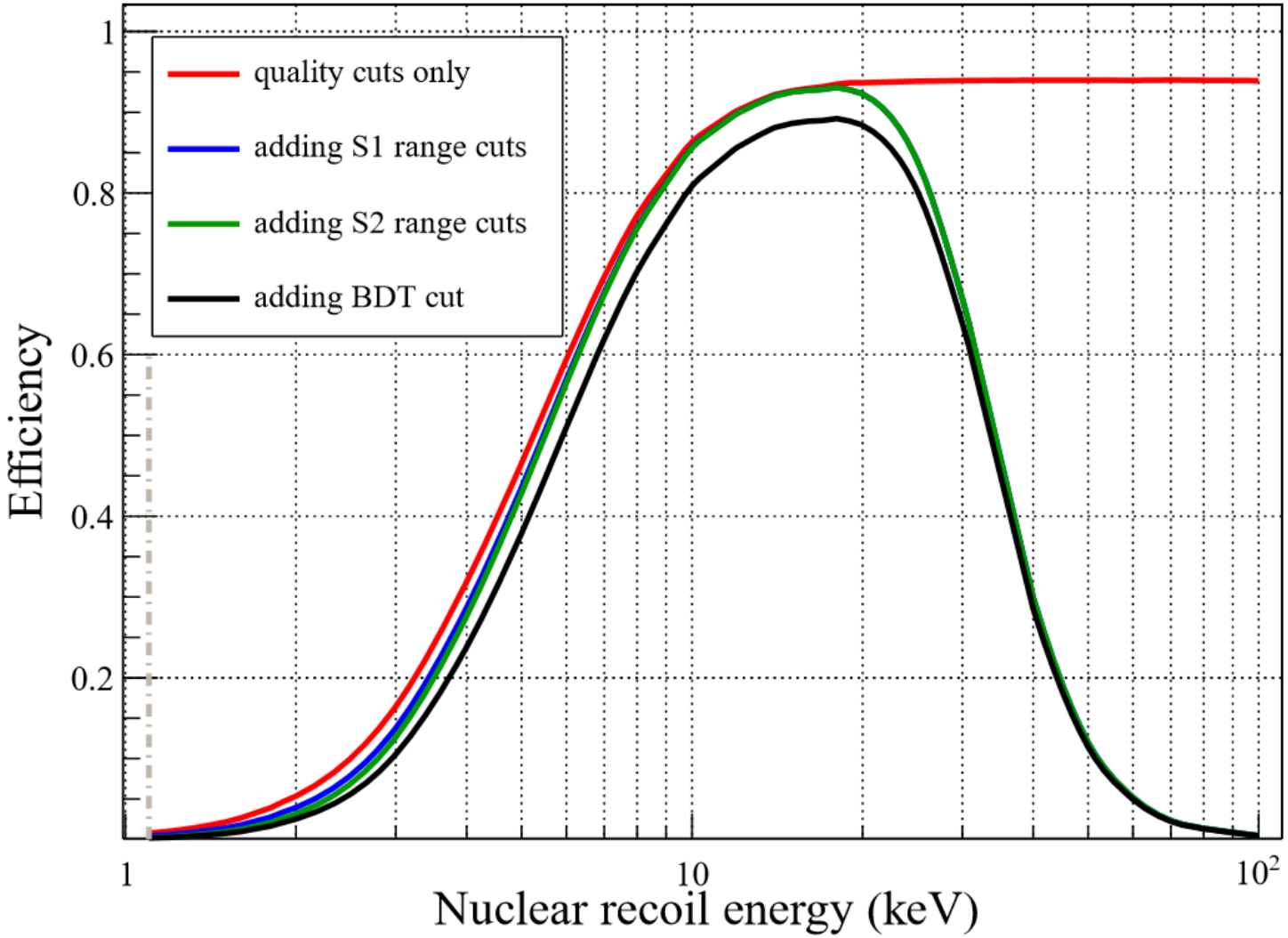
- Gaussian fits to all ER peaks in data
- Uncertainty on each data point estimated using energy nonlinearity
- Linear fit in S1/E vs S2/E to extract PDE and EEE

NR calibration

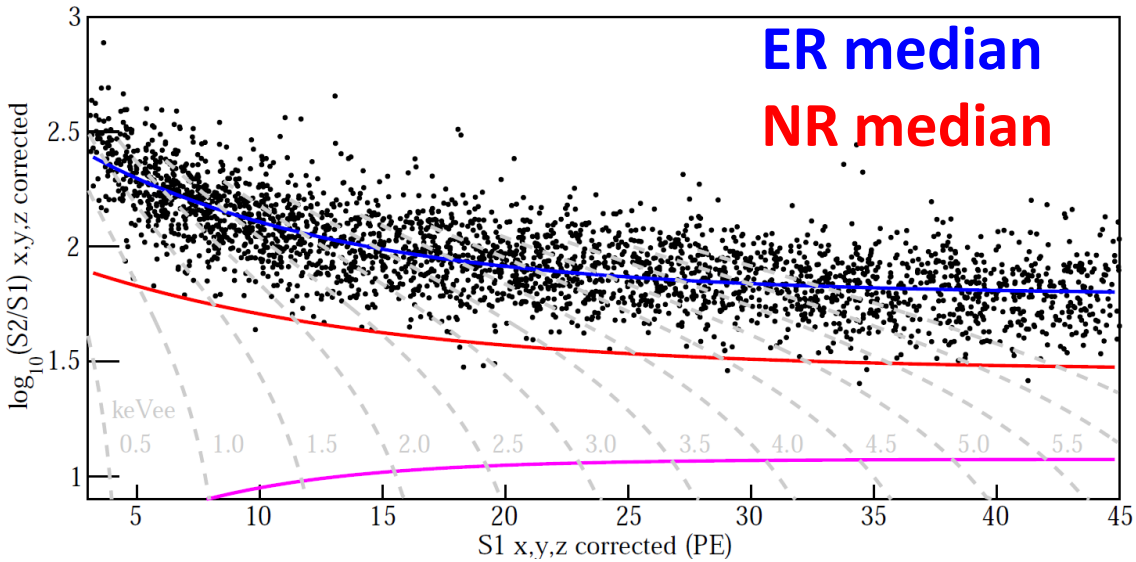


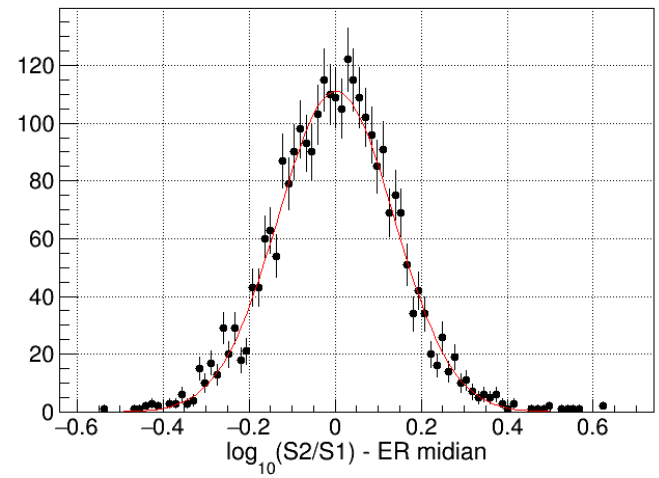
- 162.4 hours of AmBe data taken, with ~3400 low energy single scatter NR events collected
- NR median curve and NR detection efficiency determined

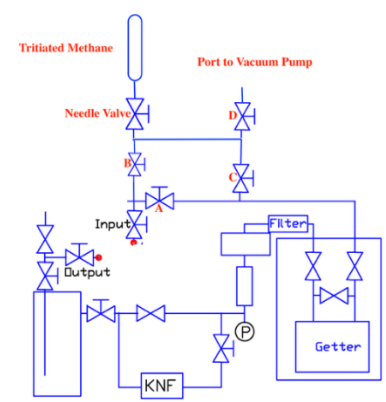
NR efficiency



ER calibration with CH_3T







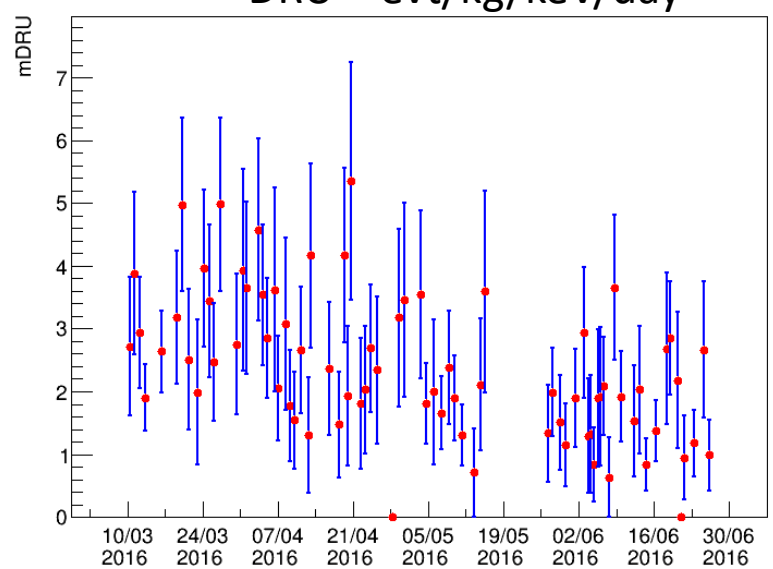
- 18.0 hours of tritium data taken, with ~2800 low energy ER events collected
- 9 events leaked below NR median, $(0.32 \pm 0.11)\%$
- Consistent with Gaussian expectation

Low energy background in Run 9

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

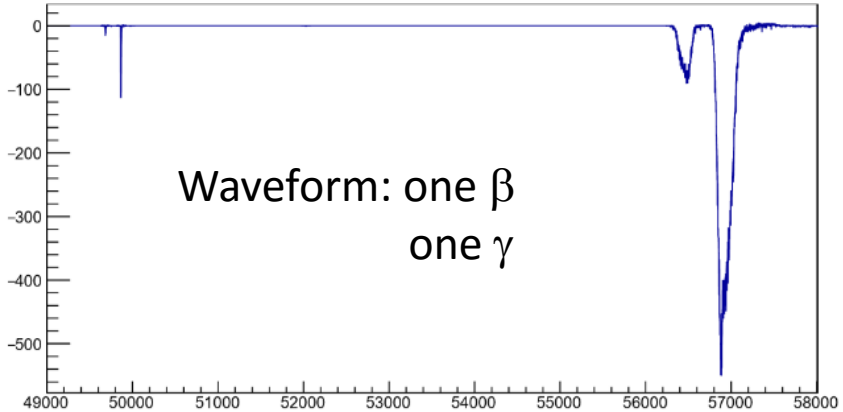
Item	Run 8 (mDRU)	Run 9 (mDRU)
^{85}Kr	11.7	1.19
^{127}Xe	0	0.42
^{222}Rn	0.06	0.13
^{220}Rn	0.02	0.01
Detector material ER	0.20	0.20
Total	12.0	1.95

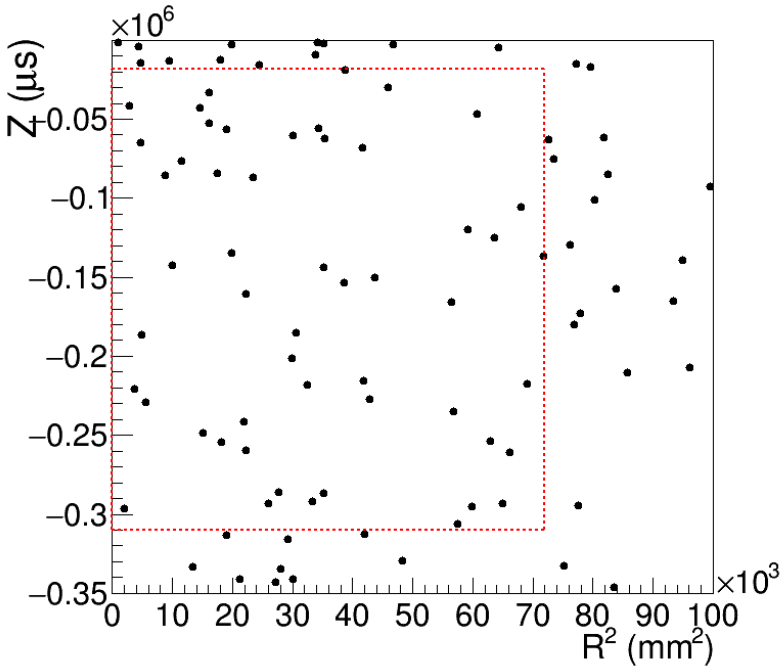
DRU = evt/kg/keV/day

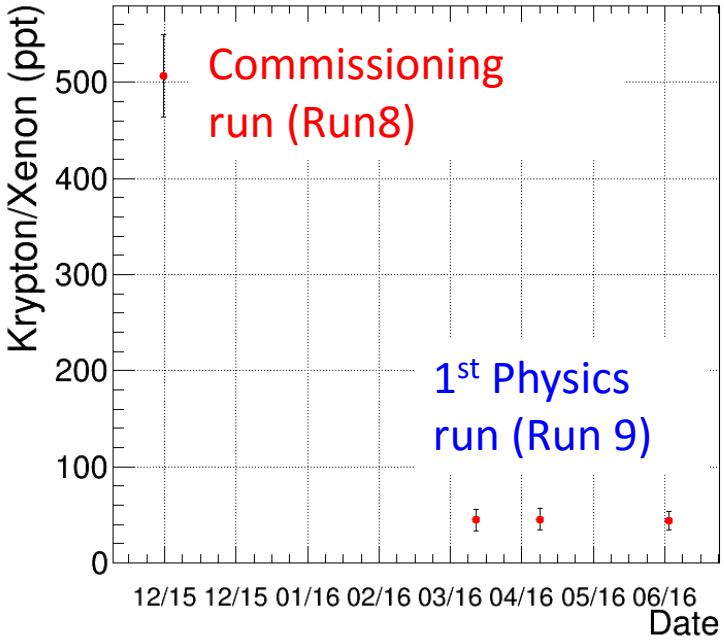


^{85}Kr

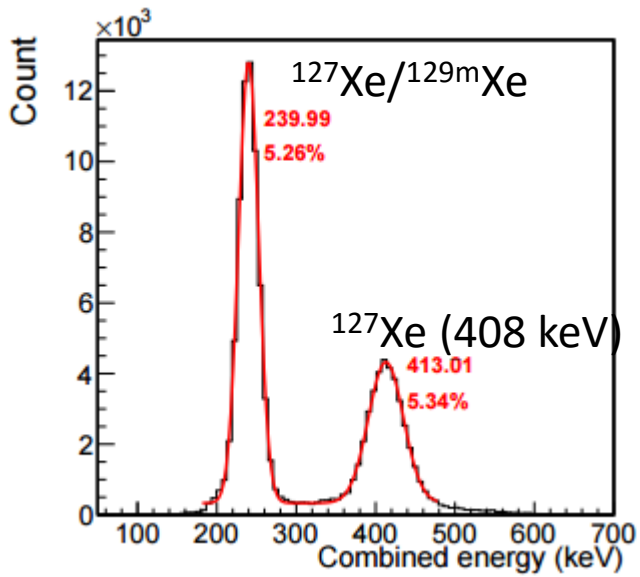
- Estimated from delayed β–γ coincidence analysis
- Uniformly distributed
- Significantly reduced after distillation

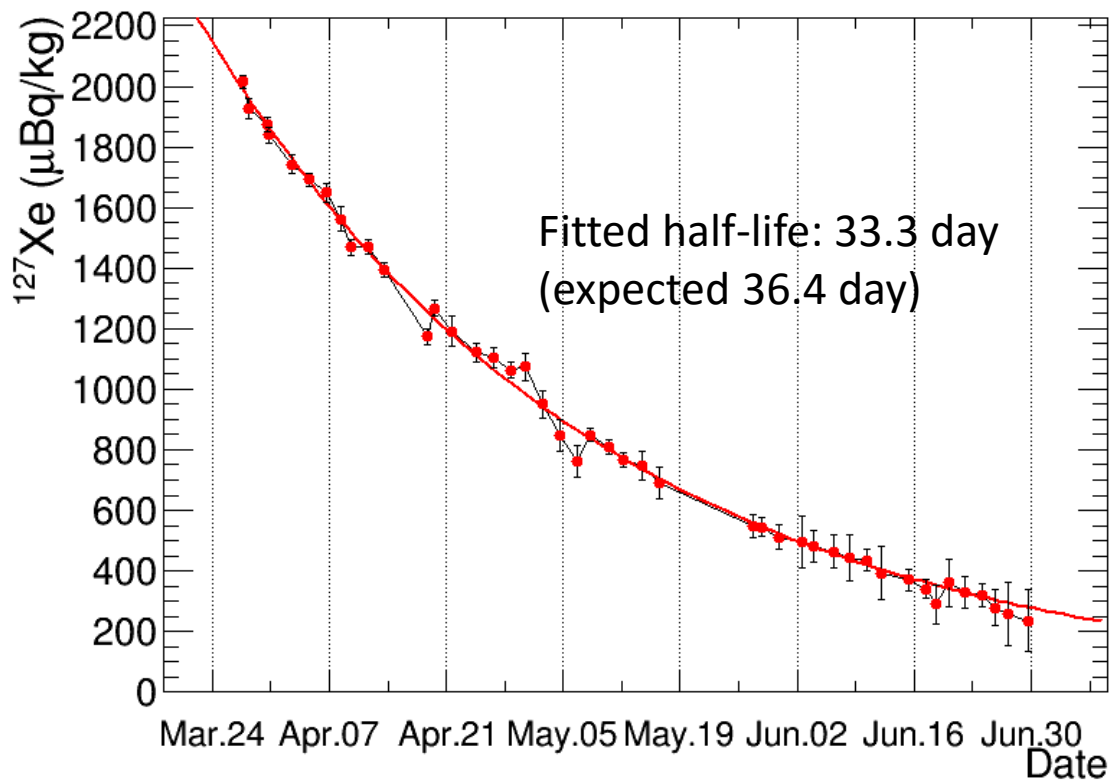






^{127}Xe

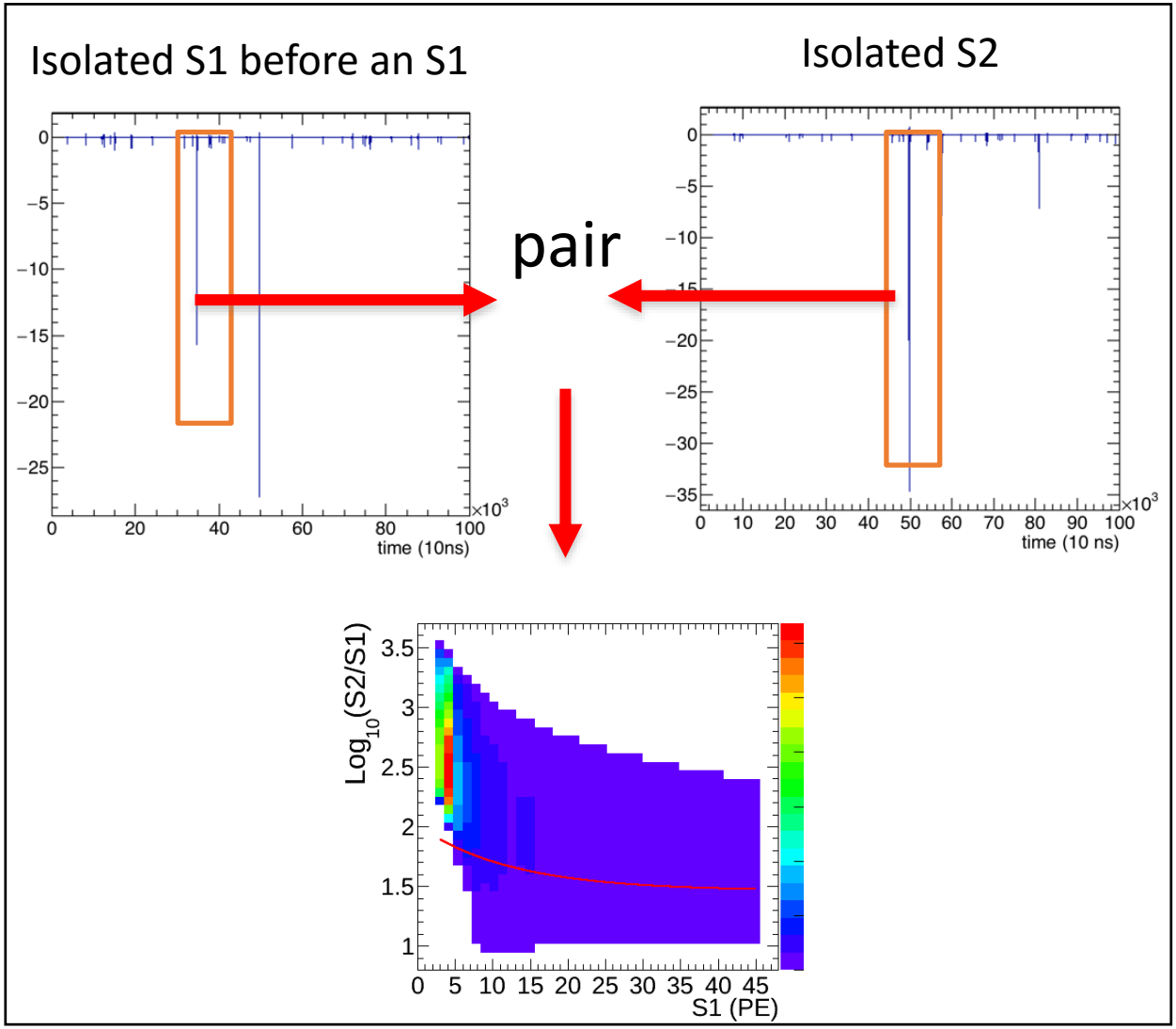




Average ^{127}Xe rate in the low energy DM search region (<10 keV) estimated to be 0.42±0.10 mDRU

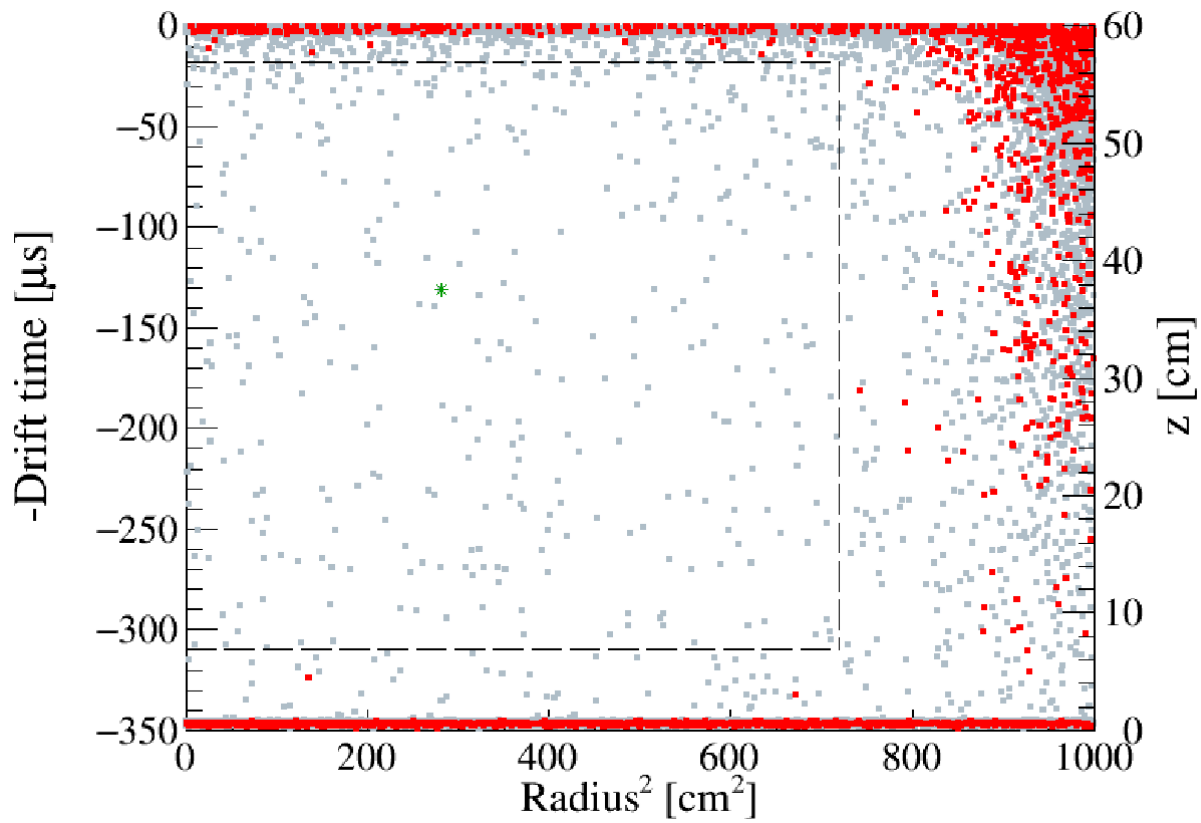
Accidental background

- Isolated S1 and S2 were selected and randomly paired to simulate accidental events
- Further suppressed this background by x3 using boosted decision tree (BDT) technique



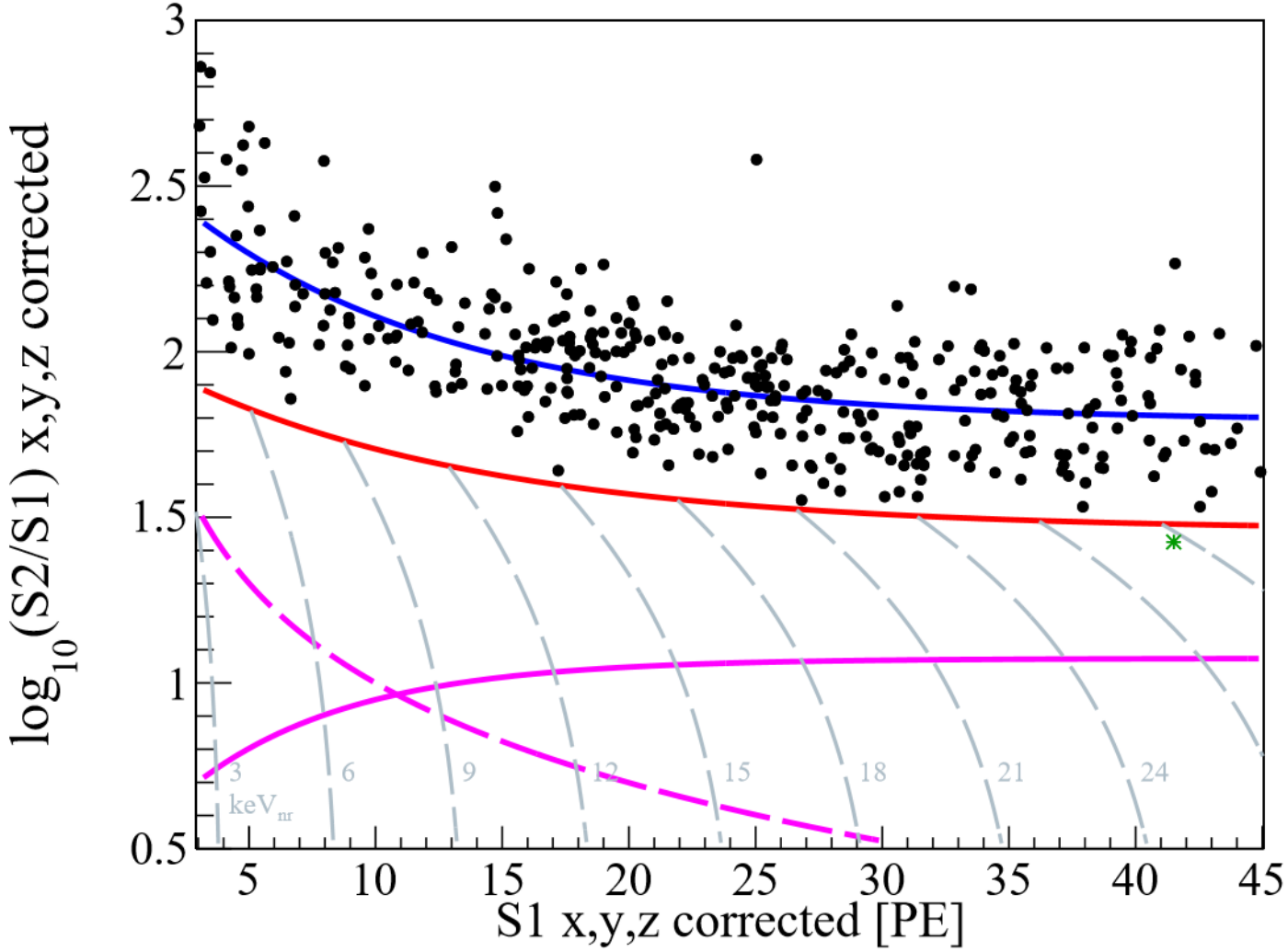
Final candidates

Gray: all
Red: below NR median
Green: below NR median and in FV

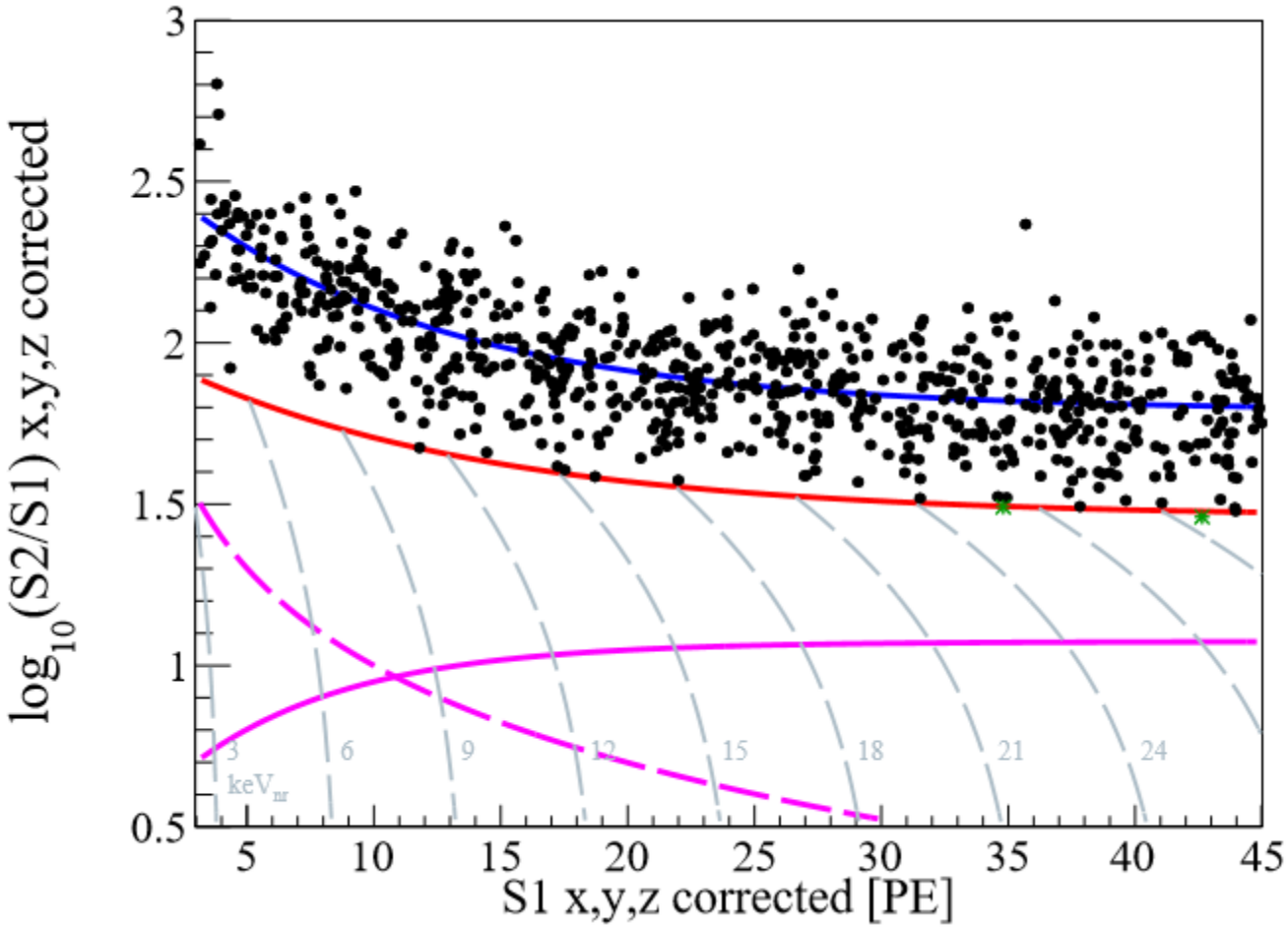


- 389 total candidates found in the FV (329 kg)
- 1 below NR median
- Outside FV, edge events more likely to lose electrons, leading to S2 suppression

Final candidates



Candidates in Run 8

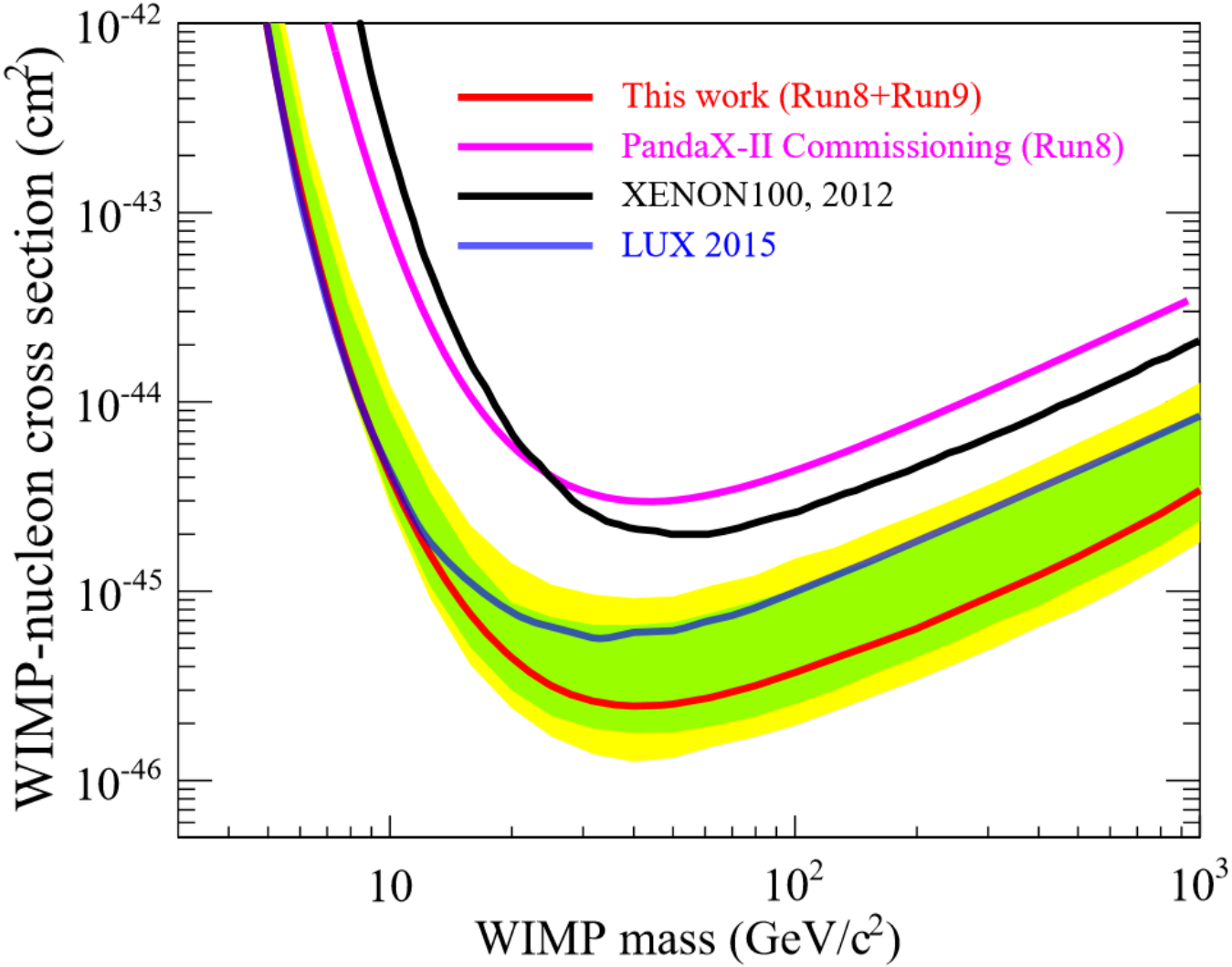


Final candidates summary

	ER	Accidental	Neutron	Total Expected	Total observed
Run 8	622.8	5.20	0.25	628±106	734
Below NR median	2.0	0.33	0.09	2.4±0.8	2
Run 9	377.9	14.0	0.91	393±46	389
Below NR median	1.2	0.84	0.35	2.4±0.7	1

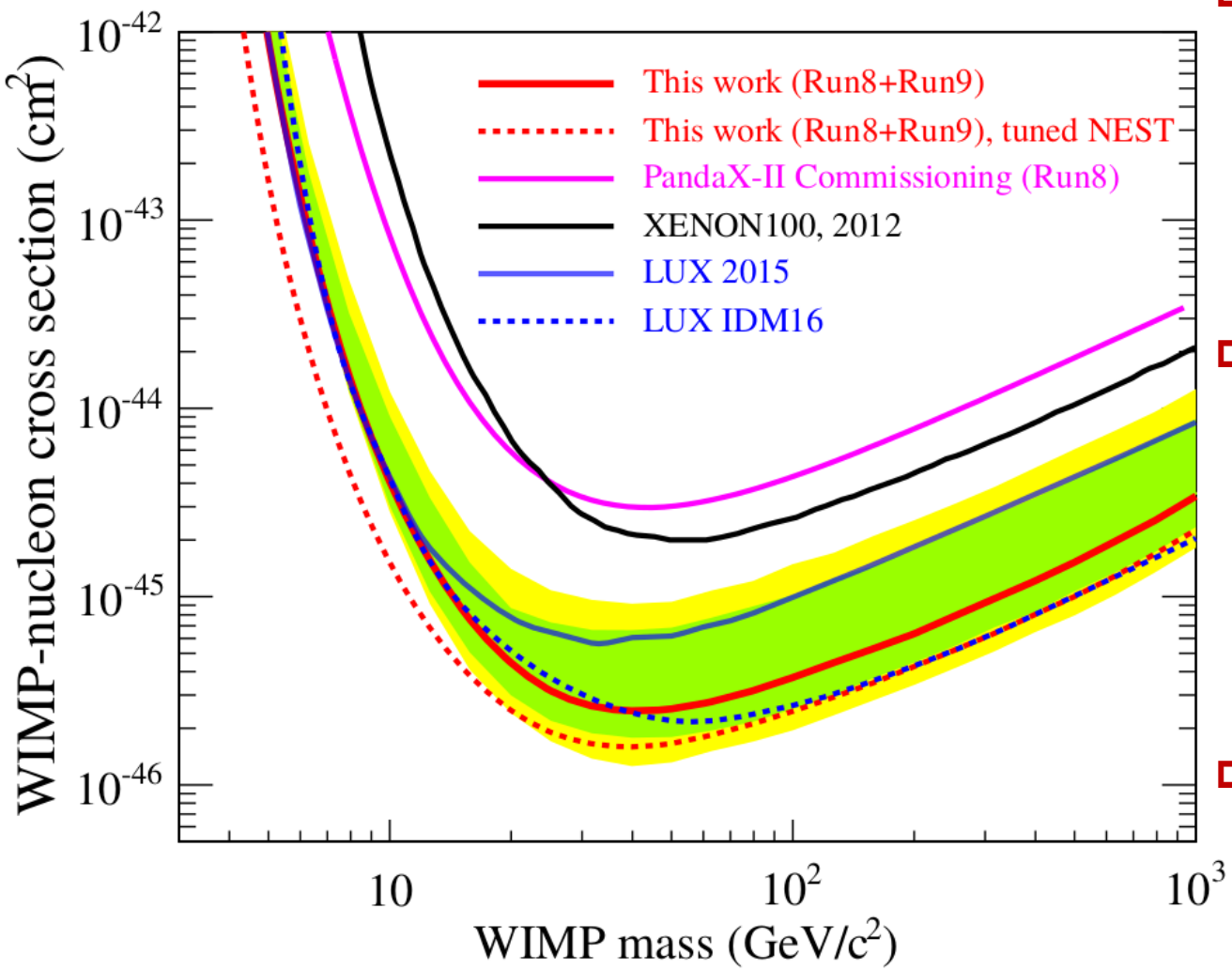
Total exposure: 33,000 kg-day

Combined results



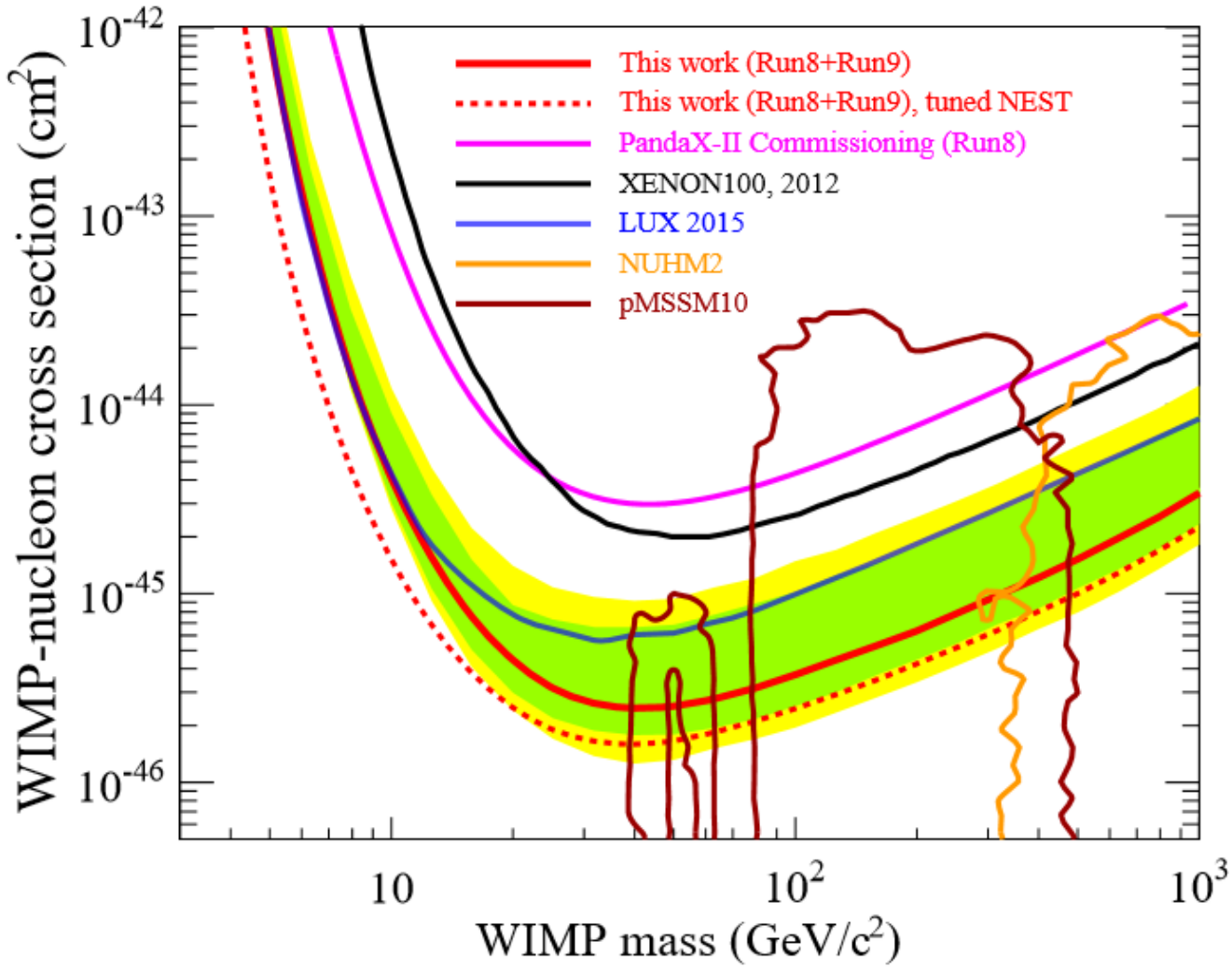
- Profile likelihood analysis with CL_s
- Minimum upper limit for isoscalar SI elastic cross section at 2.5×10^{-46} cm^2
- More than x10 improvements from Run 8
- More than a factor of 2 improvement compared to the LUX 2015 results

Comparison with LUX



- LUX presented results from their final data set similar exposure same day at IDM conference
- A more constraining result is obtained if a tuned NR model is used (agreeing better with our own calibration)
- We chose to use a conservative NR energy model to report official results

Comparison with global constraint



Release history

- Jul. 21, released results at the IDM conference. LUX collaboration released results with similar exposure (332-day) at IDM the same day with similar DM exclusion
- Jul. 22, press release in Shanghai
- Jul. 24, paper in arXiv,
- Jul. 26, submission to PRL
- Aug. 16, accepted by PRL ("Editor's suggestion"), LUX results not in arXiv yet

Dark Matter Results from First 98.7-day Data of PandaX-II Experiment

Andi Tan,[2] Mengjiao Xiao,[1] Xiangyi Cui,[1] Xun Chen,[1] Yunhua Chen,[3] Deqing Fang,[4] Changbo Fu,[1] Karl Giboni,[1] Franco Giuliani,[1] Haowei Gong,[1] Ke Han,[1] Shouyang Hu,[5] Xingtao Huang,[6] Xiangdong Ji,[1,7,2,*] Yonglin Ju,[8] Siao Lei,[1] Shaoli Li,[1] Xiaomei Li,[5] Xinglong Li,[5] Hao Liang,[5] Qing Lin,[1,†] Huaxuan Liu,[8] Jianglai Liu,[1,‡] Wolfgang Lorenzon,[9] Yugang Ma,[4] Yajun Mao,[10] Kaixuan Ni,[1,§] Xiangxiang Ren,[1] Michael Schubnell,[9] Manbin Shen,[3] Fang Shi,[1] Hongwei Wang,[4] Jiming Wang,[3] Meng Wang,[6] Qiuhong Wang,[4] Siguang Wang,[10] Xuming Wang,[1] Zhou Wang,[8] Shiyong Wu,[3] Xiang Xiao,[1] Pengwei Xie,[1,¶] Binbin Yan,[6] Yong Yang,[1] Jianfeng Yue,[3] Xionghui Zeng,[3] Hongguang Zhang,[1] Hua Zhang,[8] Huanqiao Zhang,[5] Tao Zhang,[1] Li Zhao,[1] Jing Zhou,[5] Ning Zhou,[1,11] and Xiaopeng Zhou[10]

(PandaX-II Collaboration)

[1] *INPAC and Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai Laboratory for Particle Physics and Cosmology, Shanghai 200240, China*
[2] *Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[3] *Yalong River Hydropower Development Company, Ltd., 288 Shuanglin Road, Chengdu 610051, China*
[4] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, 201800, Shanghai, China*
[5] *Key Laboratory of Nuclear Data, China Institute of Atomic Energy, Beijing 102413, China*
[6] *School of Physics and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Jinan 250100, China*
[7] *Center of High Energy Physics, Peking University, Beijing 100871, China*
[8] *School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[9] *Department of Physics, University of Michigan, Ann Arbor, MI, 48109, USA*
[10] *School of Physics, Peking University, Beijing 100871, China*
[11] *Department of Physics, Tsinghua University, Beijing 100084, China*

(Dated: August 17, 2016)

We report the WIMP dark matter search results using the first physics-run data of the PandaX-II 500 kg liquid xenon dual-phase time-projection chamber, operating at the China JinPing underground Laboratory. No dark matter candidate is identified above background. In combination with the data set during the commissioning run, with a total exposure of 3.3×10^4 kg-day, the most stringent limit to the spin-independent interaction between the ordinary and WIMP dark matter is set for a range of dark matter mass between 5 and 1000 GeV/c^2. The best upper limit on the scattering cross section is found 2.5×10^{-46} cm^2 for the WIMP mass 40 GeV/c^2 at 90% confidence level.

Summary and outlook

PandaX-II has reached the forefront of the DM search!

- 79.6 live-day of dark matter data with much suppressed background (15⇒2 mDRU)
- In combination with commissioning run (19.1 day), ~33,000 kg-day exposure in total. No DM particles found
- The WIMP-nucleon elastic SI scattering cross sections are constrained to $<2.5\times10^{-46}$ cm^2. Other physics results (e.g. SD) expected soon
- Continue PandaX-II data taking till end of 2017.
- In preparation for PandaX-xT and PandaX-III!

Talks at this conference

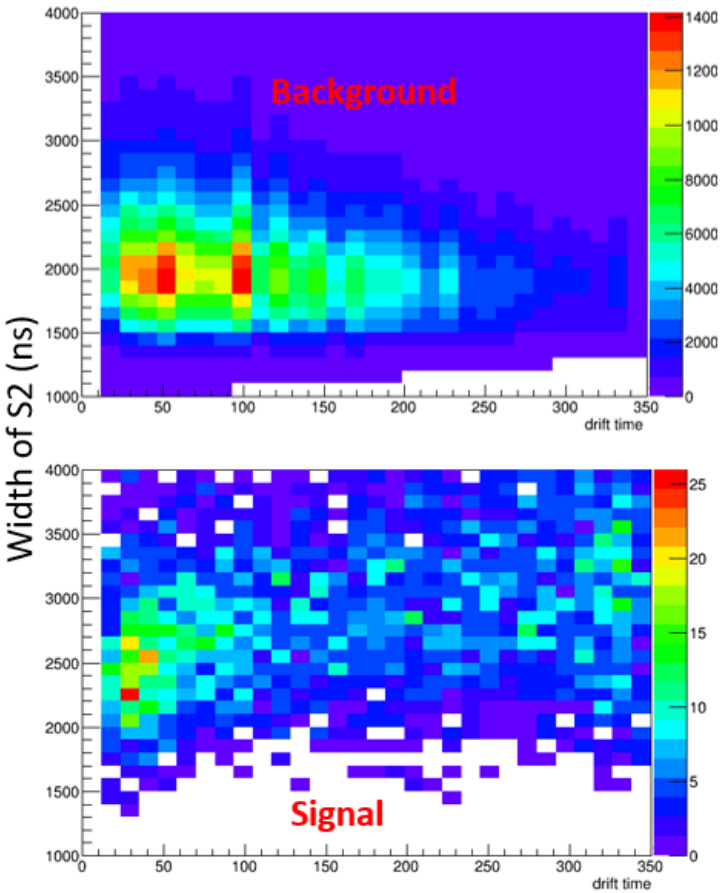
8/22:
分会四
15:20-15:40 PandaX-III:锦屏地下实验室的无中微子双贝塔衰变实验， 韩柯
15:40-16:00 PandaX-III无中微子双贝塔衰变实验的预期本底研究， 谌勋
晨光杯
15:50-16:05 First dark matter search results from the PandaX-I experiment; Low-mass dark matter search results from full exposure of the PandaX-I experiment， 肖梦姣

8/23
分会4:
14:00-14:20 PandaX第二期实验首批物理数据分析，杨勇
14:20-14:40 PandaX-II实验中的刻度及重建过程，周小朋
14:40-15:00 PandaX 4吨级暗物质直接探测实验，Zhou Ning，
分会5:
14:00-14:20 PandaX III 实验的TPC原型进展，李兴隆
14:20 – 14:40 PandaX-III读出电子学设计， 董家宁
14:40 – 15:00 PandaX-I&II 电子学与数据获取系统，任祥祥
15:00 – 15:20 PandaX实验中放射性本底测量与控制， 符长波
15:50 – 16:10 PandaX PPT级精馏塔与氪测量系统， 崔祥仪

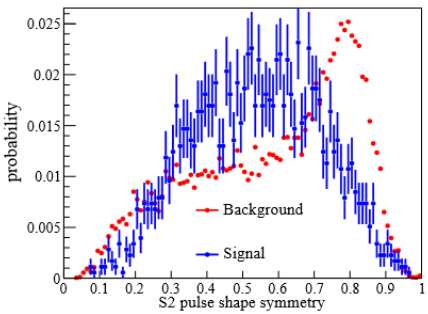
谢谢大家！感谢我们领域的同行这些年对我们的支持和帮助！

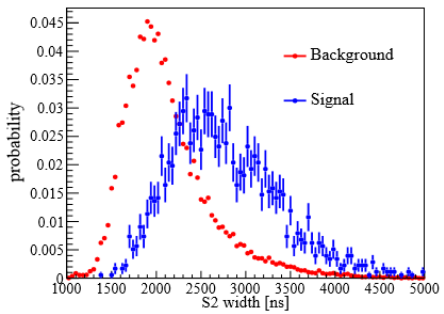
BDT discrimination power

- Accidental S1 and S2 lack intrinsic correlations



- Single S2 likely originated from the gate grid (small width, large asymmetry)





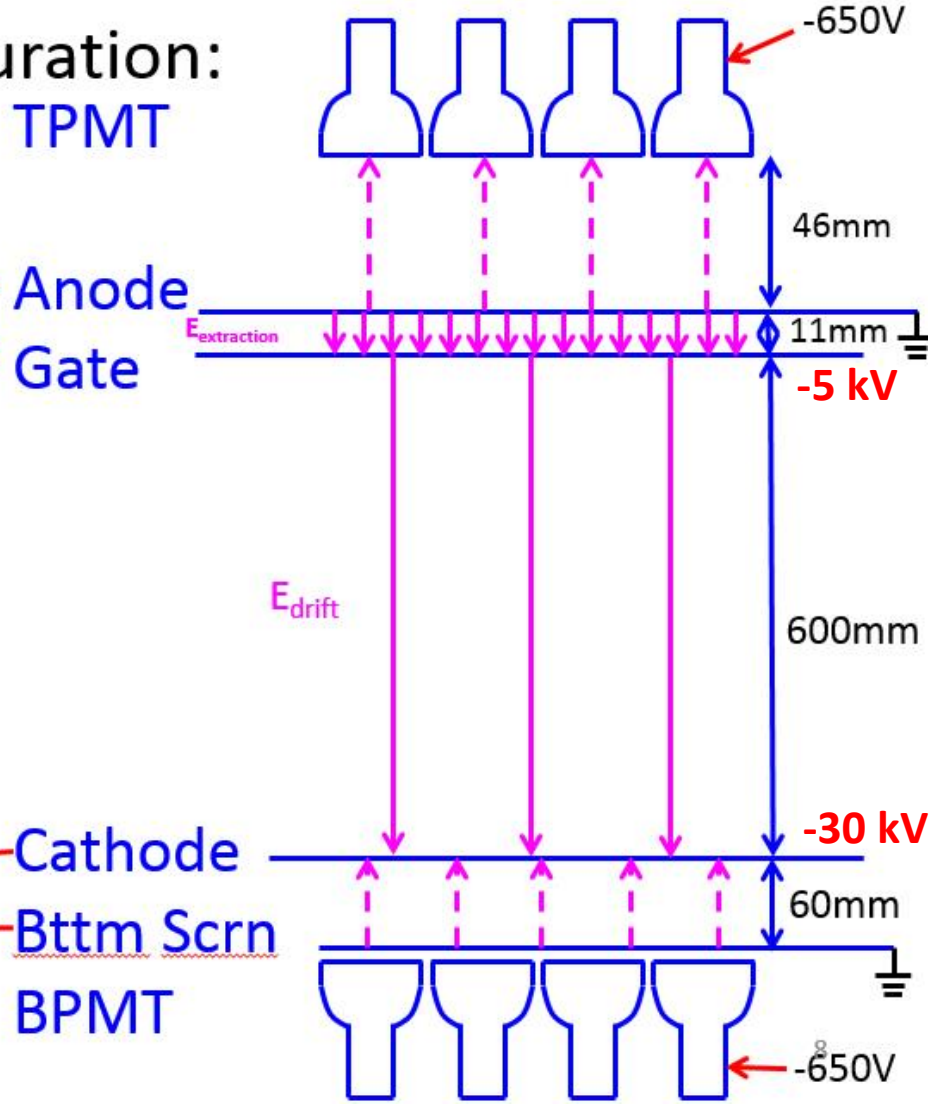
Referee comments

Report of Referee A -- LU16246/Tan ----------
I would first like to congratulate the PandaX collaboration on this significant result to our field. Once published, this result will be the strongest published exclusion of spin-independent WIMPs to date. Furthermore, the article signifies another "major player" entering into the race to directly-detect particle dark matter, which is extremely welcomed.

Report of Referee B -- LU16246/Tan ----------
….
The paper is of high scientific importance and should be published in PRL, after the following comments are addressed by the authors.

Report of Referee C -- LU16246/Tan ----------
This new result, coming from the first low-background run of the PandaX-II detector, represents the most sensitive high-mass WIMP search in the world (excepting the final results from the LUX detector, which are noted by the authors and are public but not yet published). This result is clearly appropriate for publication in PRL.

Configuration of fields



Data sets with different fields

Condition	live time (day)	E_{drift} (V/cm)	E_{extract} (kV/cm)
1	7.76	397.3	4.56
2	6.82	394.3	4.86
3	1.17	391.9	5.01
4	63.85	399.3	4.56

Mar. 9-Jun 30, in total 79.6 live-day of under slightly different conditions to maximize drift and extraction filed while avoiding spurious photon/electron emissions.

Improved position reconstruction

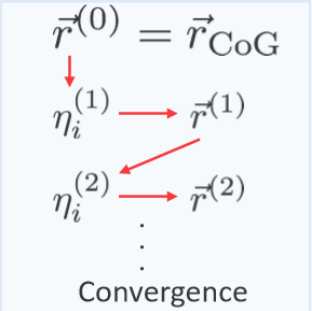
Major difficulties：

- 3” PMT: optimizing photon collection, but naively causing coarse quantization
- Complicated optics, particularly due to the photon reflections on the PTFE reflector

- Construct and fit photon acceptance function(PAF) of Each PMT

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

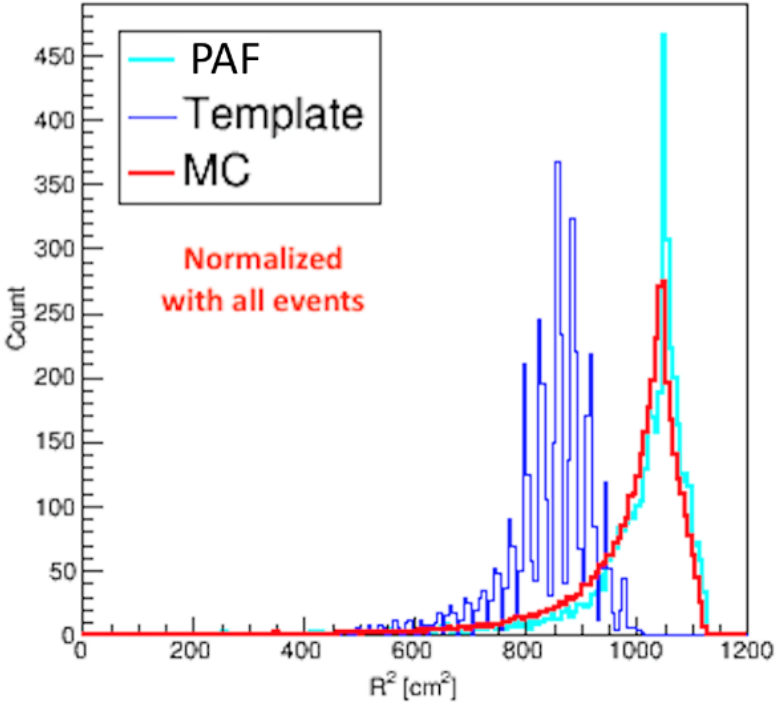
- Event-by-event max likelihood fit on charge pattern to reconstruct position
- Iterations to improve PAFs based on data



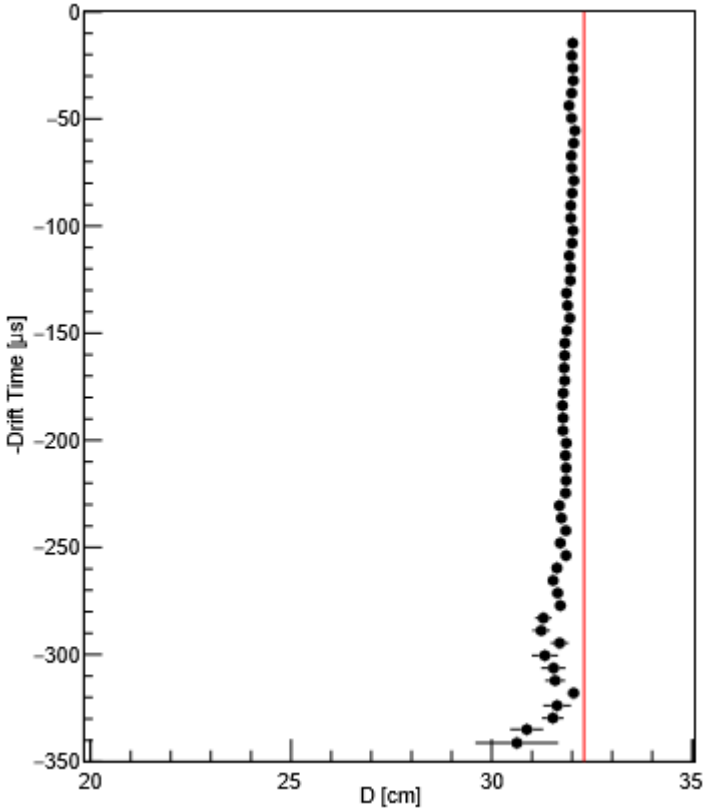
V. N. Solovov *et al*, *IEEE* doi: 10.1109/TNS.2012.2221742

Internal background distribution

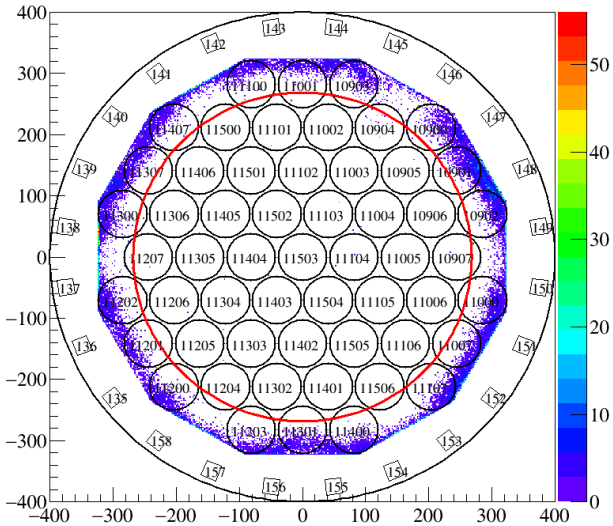
33.2keV from ^{127}Xe event R^2 distribution

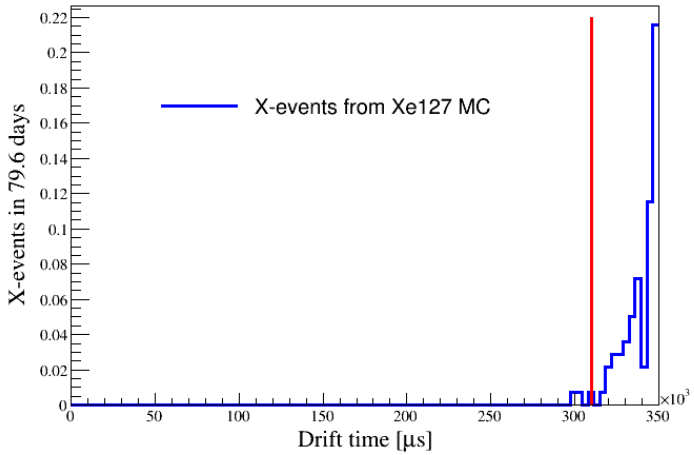


^{210}Po events from the PTFE wall



Final selection cuts





- 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

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 background budget

	ER	Accidental	Neutron	Total Expected
Run 8	622.8	5.20	0.25	628±106
Below NR median	2.0	0.33	0.09	2.4±0.8
Run 9	377.9	14.0	0.91	393±46
Below NR median	1.2	0.84	0.35	2.4±0.7