UHM Physics department colloquium

3:30pm, 2023 Sep 21, Room 112, Watanabe Hall, University of Hawai'i at Manoa

Search for solar neutrino and light dark matter with PandaX–4T

W. Ma et al. PhysRevLett.130.021802
S. Li et al. PhysRevLett. 130.261001

马文博
MA Wenbo
wenboma@sjtu.edu.cn
Shanghai Jiao Tong University

Personal profile

- **Wenbo Ma**
- 2018-2024, phd, physics, Shanghai Jiao Tong University
- PandaX-4T cryogenics onsite responsible person, 630 days @ CJPL, 2019-2022
- Looking for potential postdoc positions

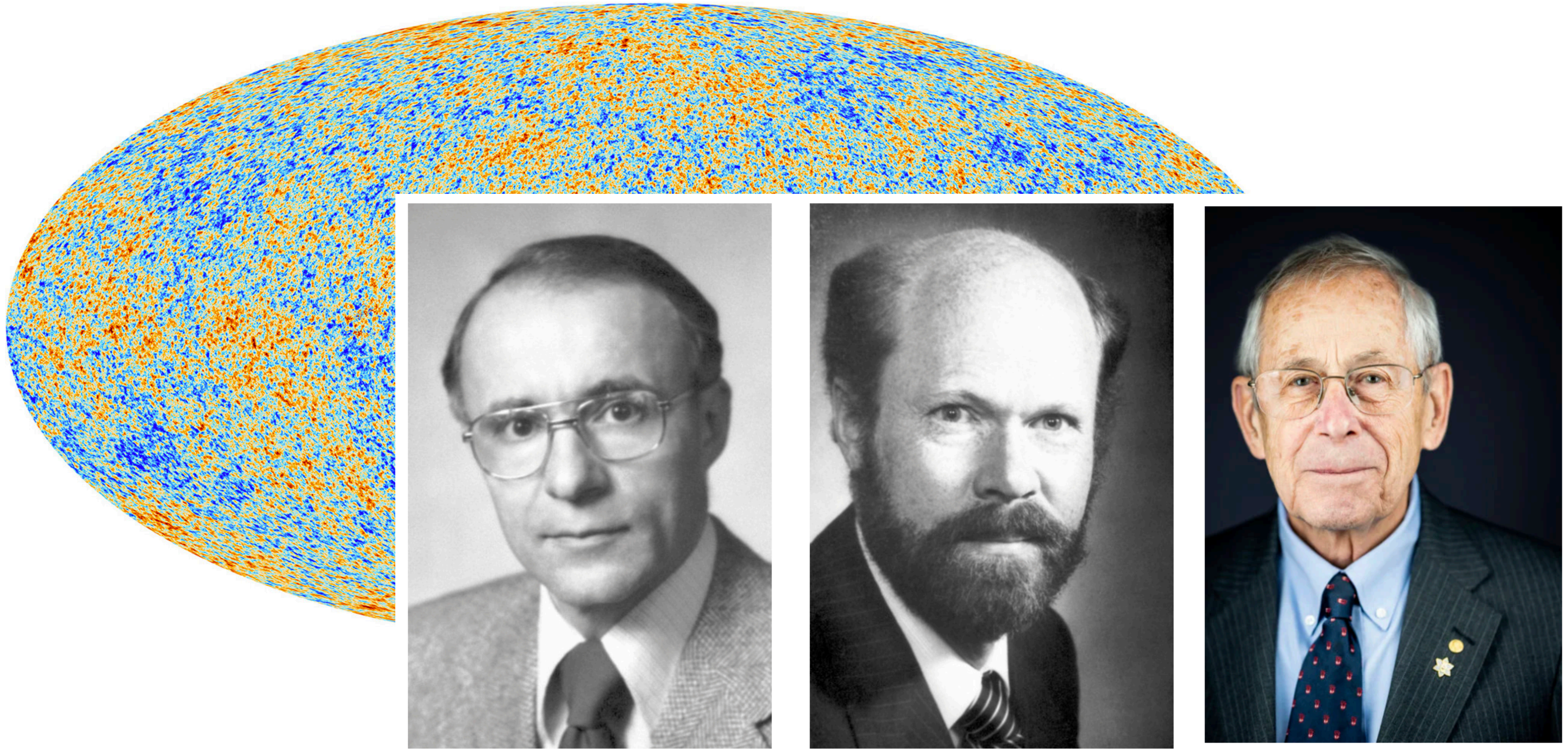
- **WIMP search of run0**, PhysRevLett.127.261802, major author
- **Solar ν search of run0**, PhysRevLett.130.021802, 1st author
- **Cryogenics and circulation system**, 2021 JINST 16 T06007, 3rd author
- **Fast recuperation system**, 2022 JINST 17 T10008, 2nd author
- **Rn220 calibration (PandaX-II)**, 2020 JINST 15 P12038, 1st author

- 2021 PandaX outstanding student first prize "WIMP search"
- 2022 PandaX outstanding student first prize "solar ν search"
- 2022 SJTU national scholarship
- 2022 SJTU annual student nominated award

Dark matter

Dark matter: bed rock of modern astronomy

- **Galactic rotation curve, gravitational lensing, bullet cluster, ...**
- **Cosmic microwave background radiation, lambda cold dark matter model, ...**



Arno Allan Penzias
1978

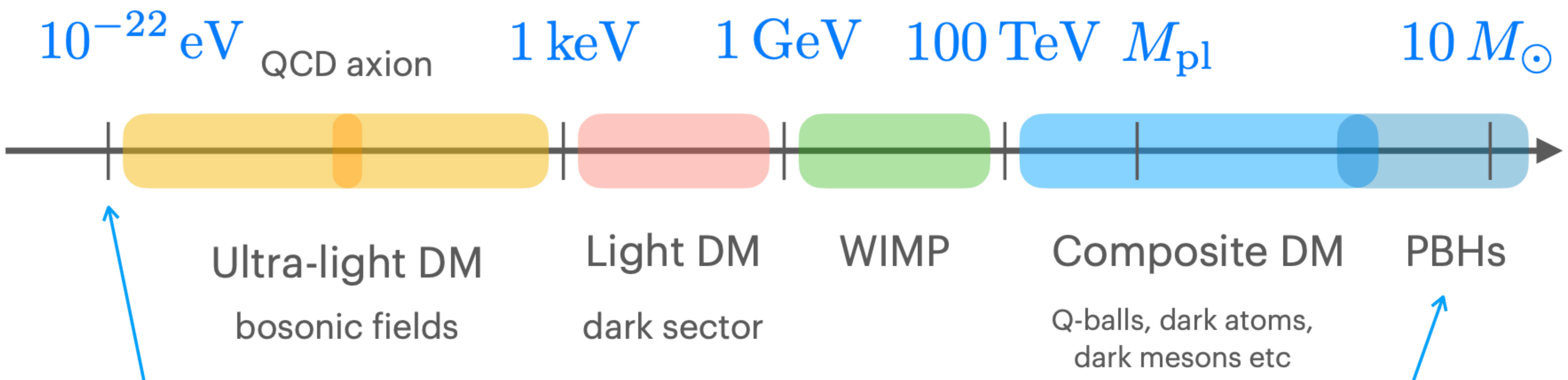
Robert Woodrow Wilson
1978

James Peebles
2019

"The results showed us a universe in which just five per cent of its content is known matter. The rest, 95 per cent, is unknown dark matter and dark energy."

Does it takes 100(?) years to find dark matter?

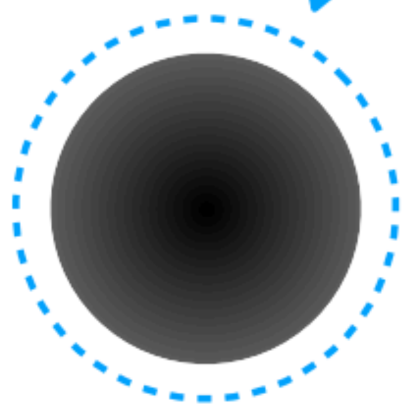
- Toward a detectable dark matter
- Many models, many experiments, many fake discoveries
- WIMP search with Xe: ruled-out a large parameter space in the recent decade

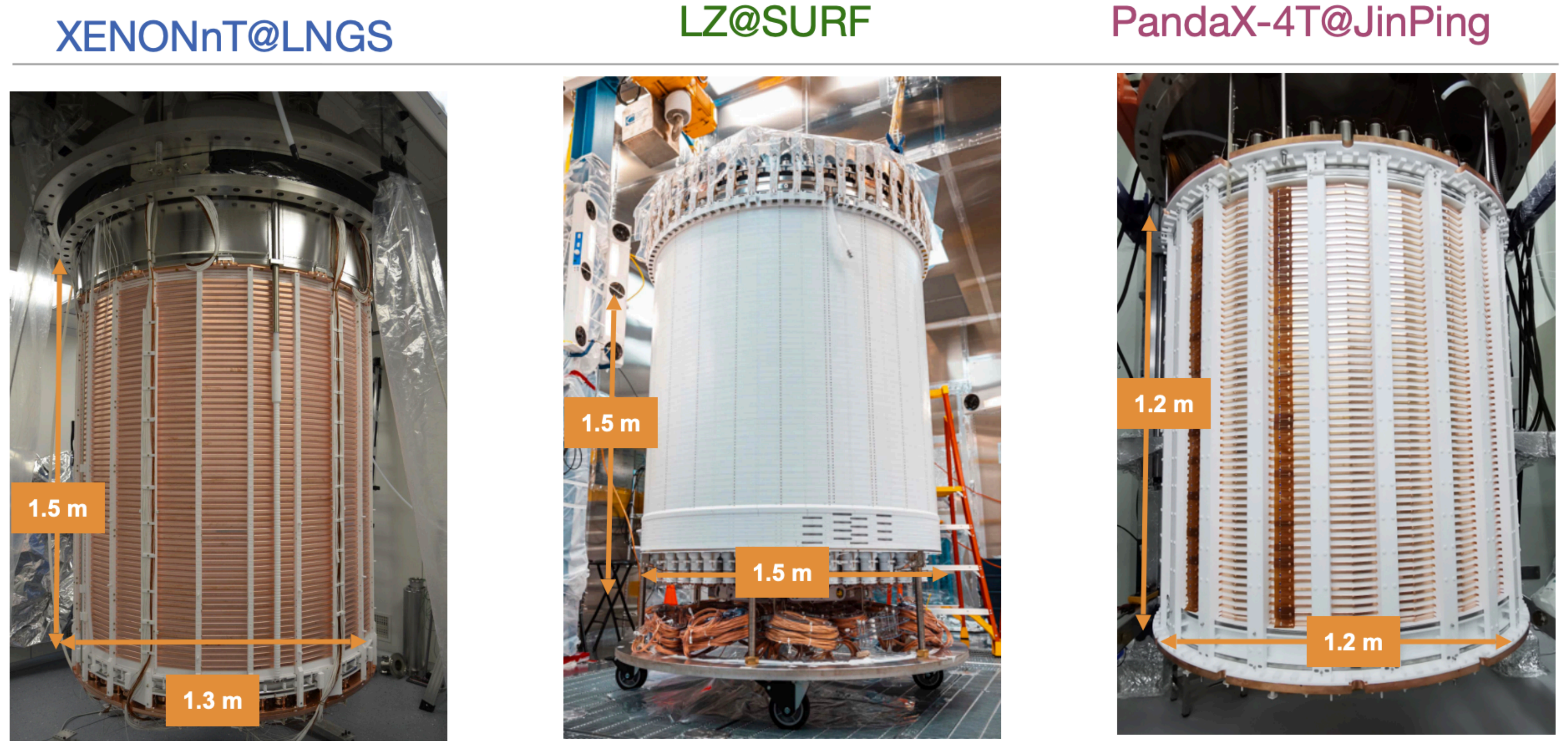


Structures on the scale of dwarf galaxies (kpc-scale) can form

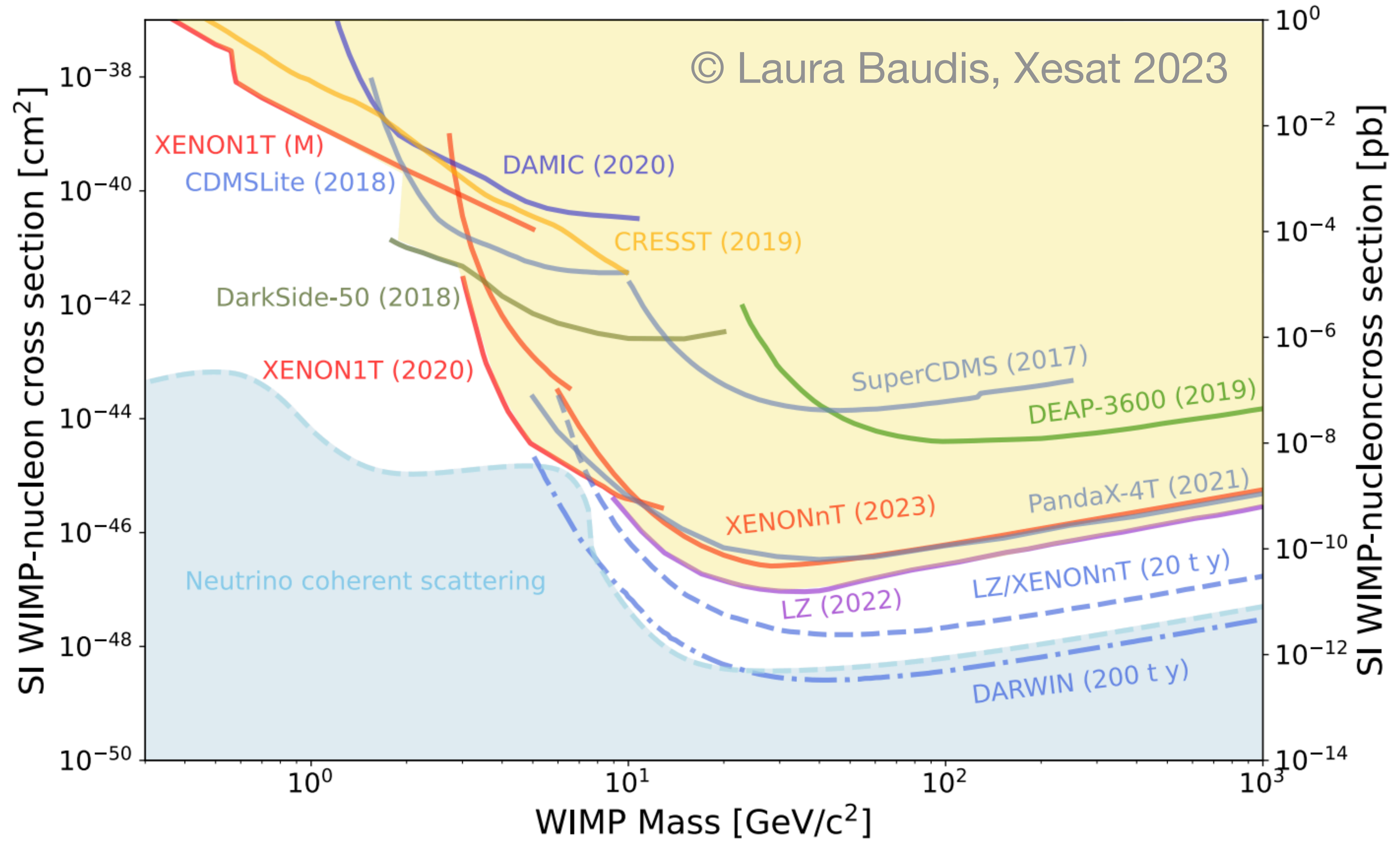
Credit: ESA/Hubble & NASA

$$\Delta p \Delta x \sim 1$$
$$\Delta p \sim m_\chi v$$
$$\Delta x \sim 2 r_{\rm halo}$$





© Elena Aprile, UCLA dark matter 2023



PandaX collaboration

PANDA X Particle and Astrophysical Xenon Experiments

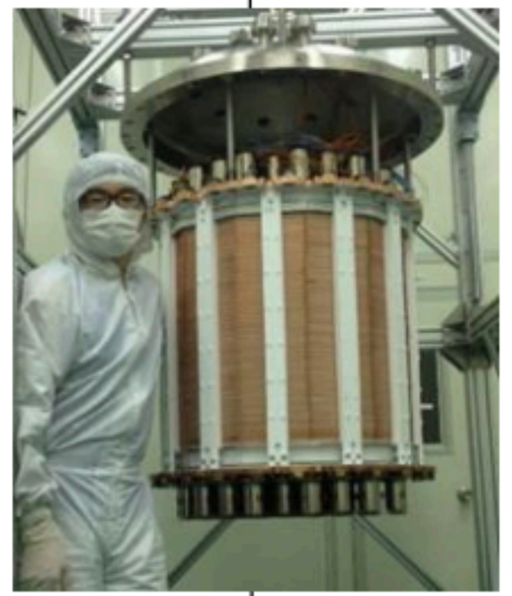
Collaboration formed

2009.3

2014.5-10

PandaX-I, 120 kg operation

PandaX-II, 580 kg operation

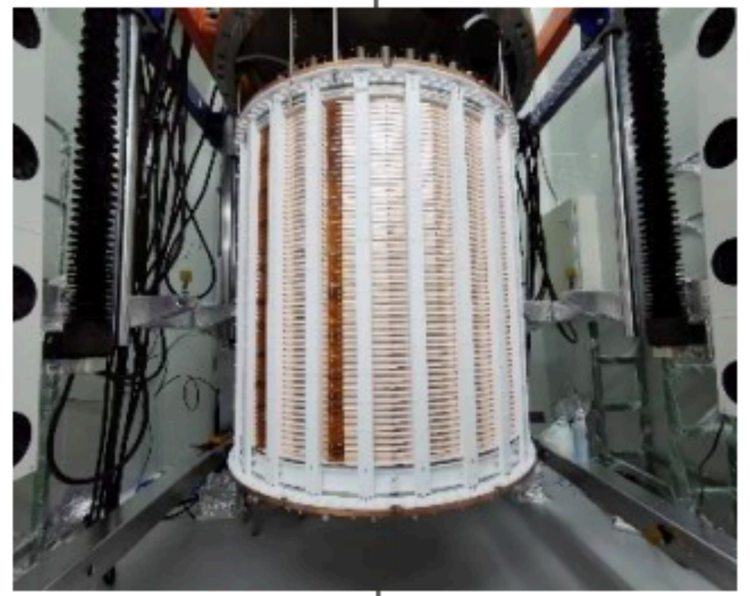


2016.7-2019.7

2019.8

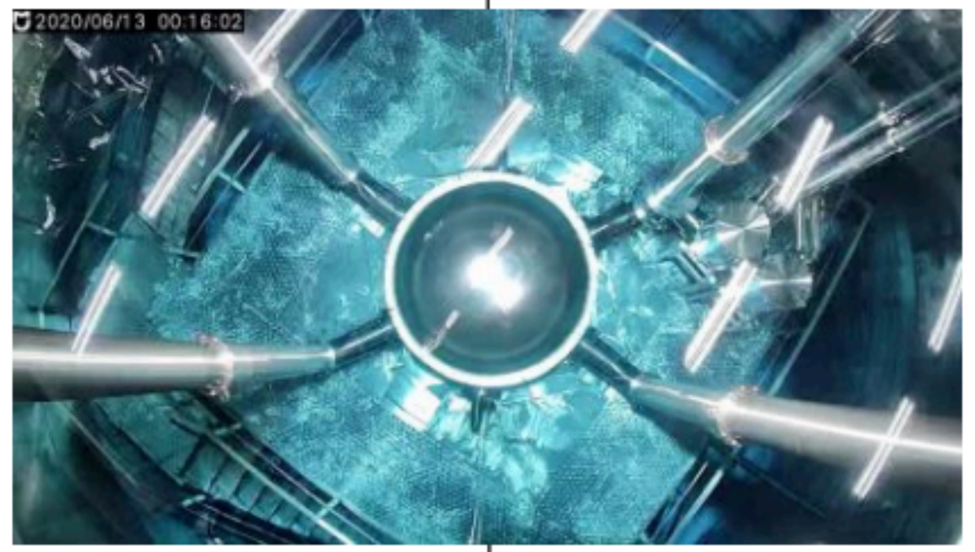
PandaX-4T moved to CJPL-II

PandaX-4T Commissioning



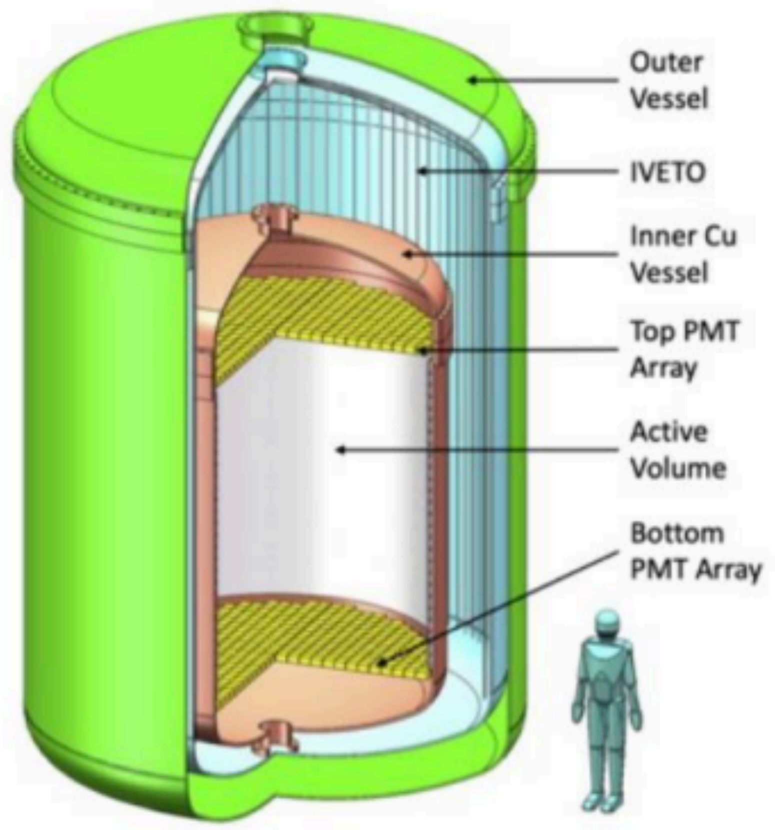
2020.11-2021.5

2021.11



PandaX-4T Run1

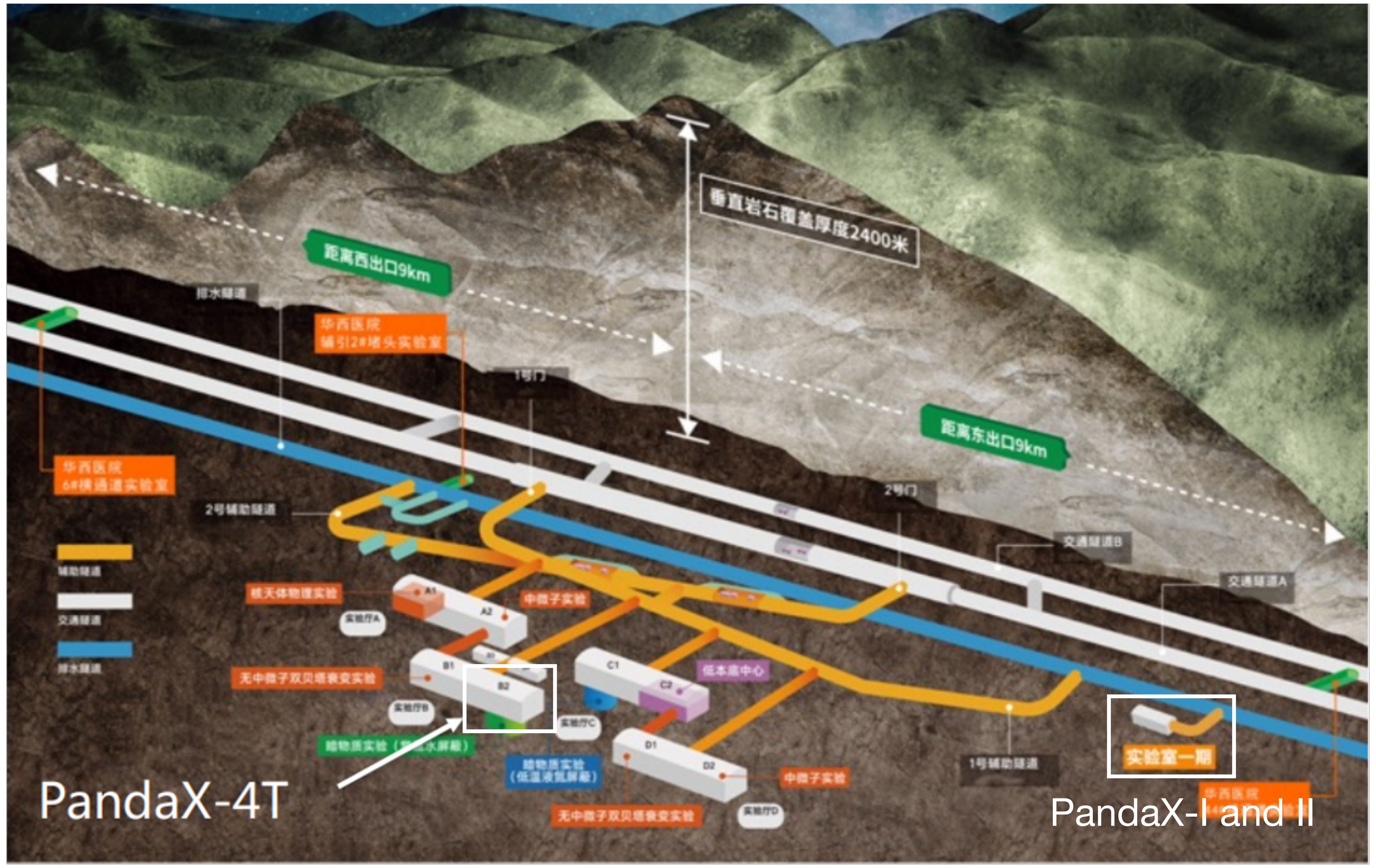
Ongoing

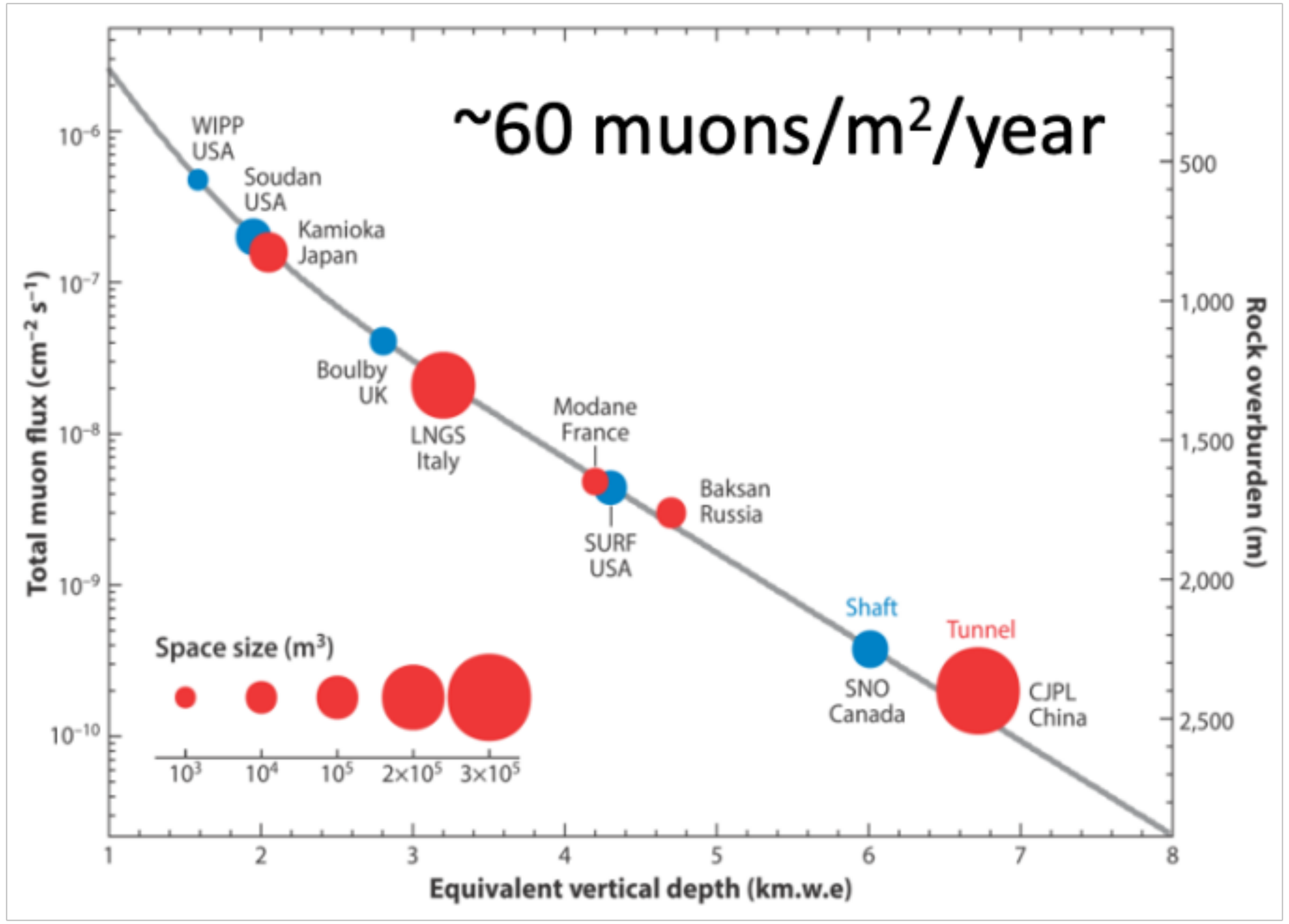


PandaX-xT

China Jin Ping underground Laboratory (CJPL)

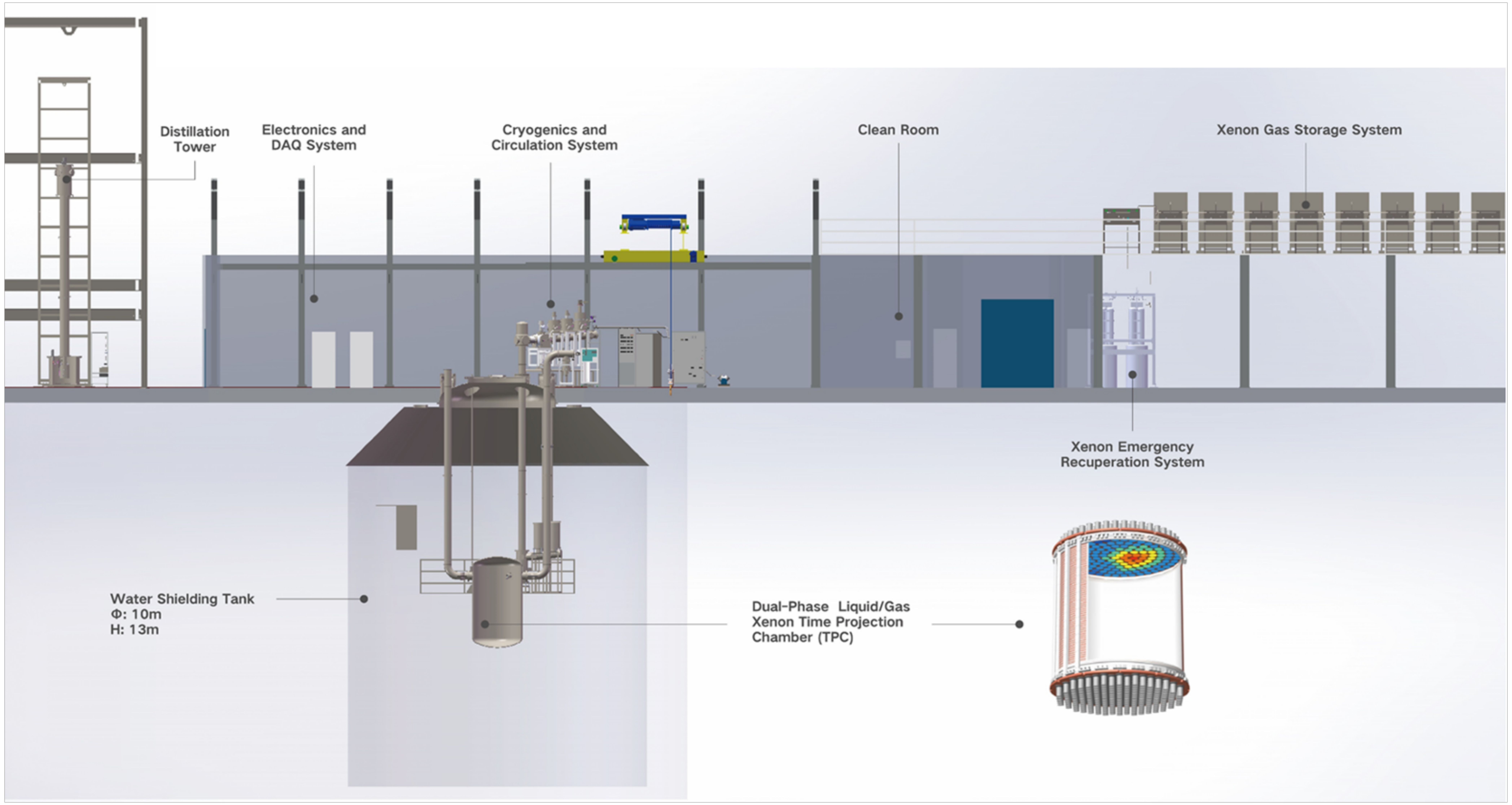
- Located at Sichuan province of China
- PandaX, CDEX, JUNA, ...
- Blast and decorate more halls to accommodate future experiments





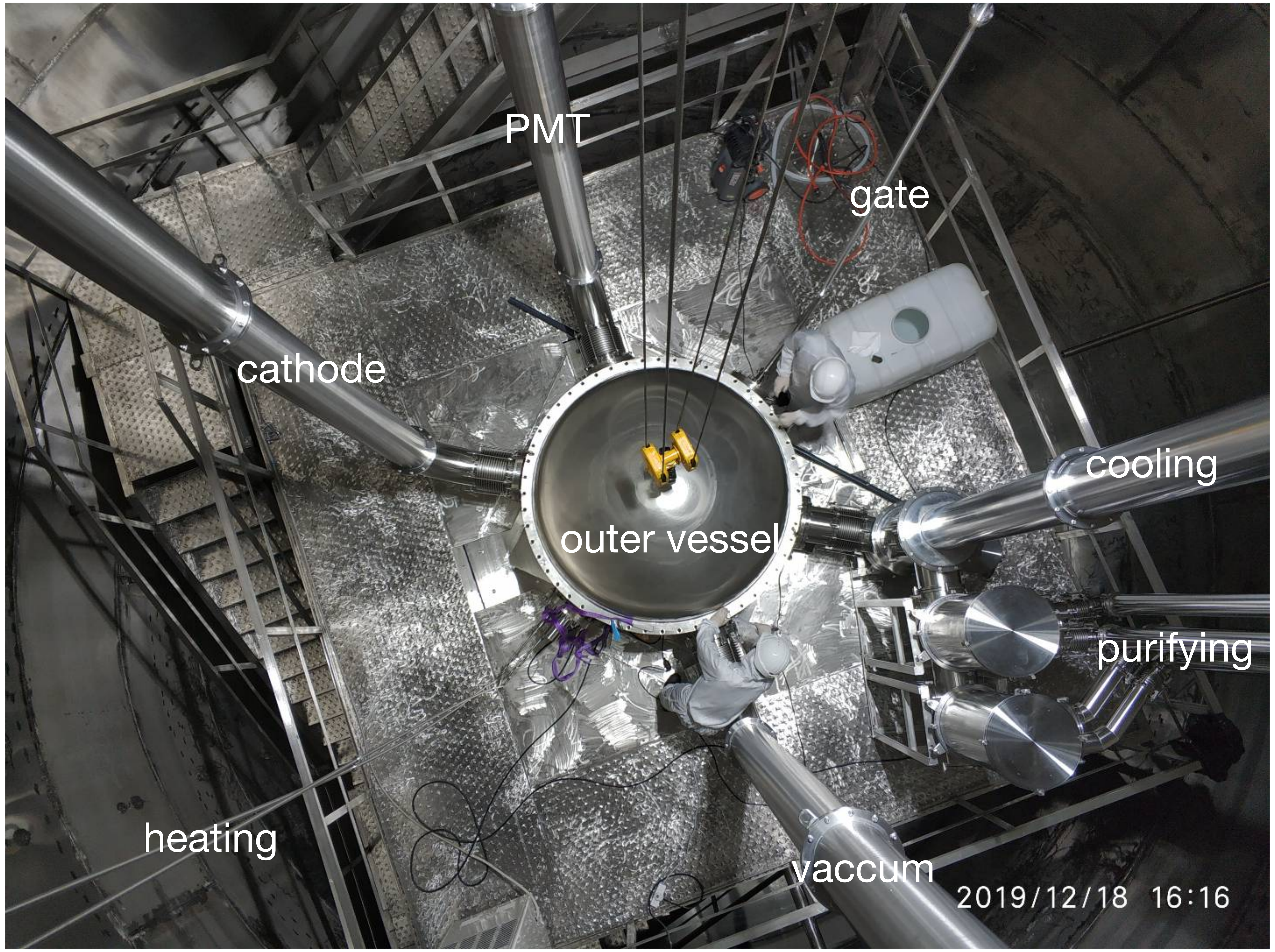
PandaX–4T experiment

- Giant detector maintanance system (cooling/purifying/shielding/data taking)
- 1.2m × 1.2m time projection chamber



Hardware design

cathode/pmt/gate/cryogenics/vaccum/recuperation pillars



My phone album

Album from my phone: Jinping camp

mountain view from the camp

drive into tunnel

Album from my phone: cryogenics "gang of four"

fix electric infrustructure by ourselves

cryogenics group @ 2019

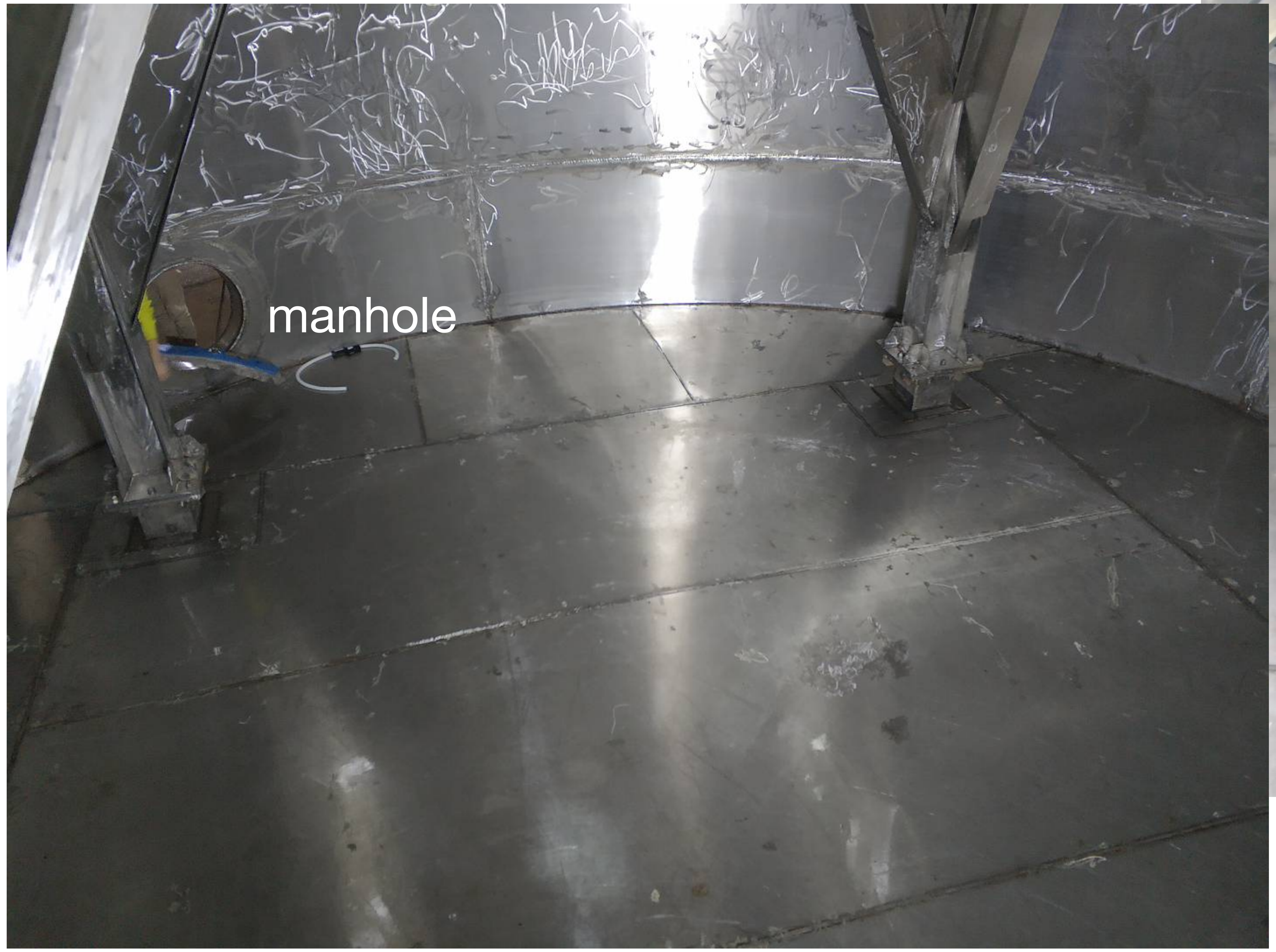
Album from my phone: 1st pillar

bare stainless steel platform

first pillar: cryogenics

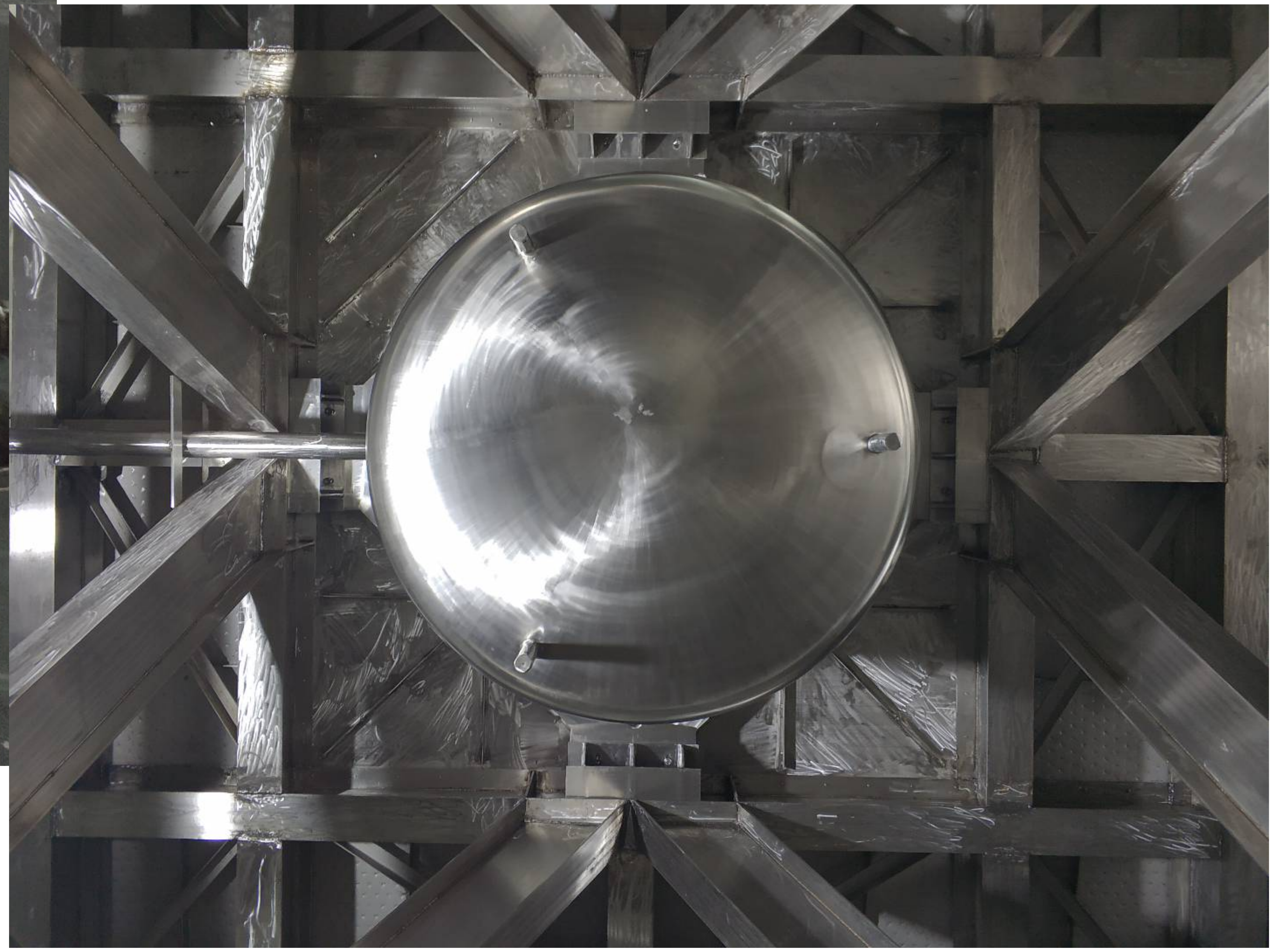
Album from my phone: water tank cleaning

bottom of water tank



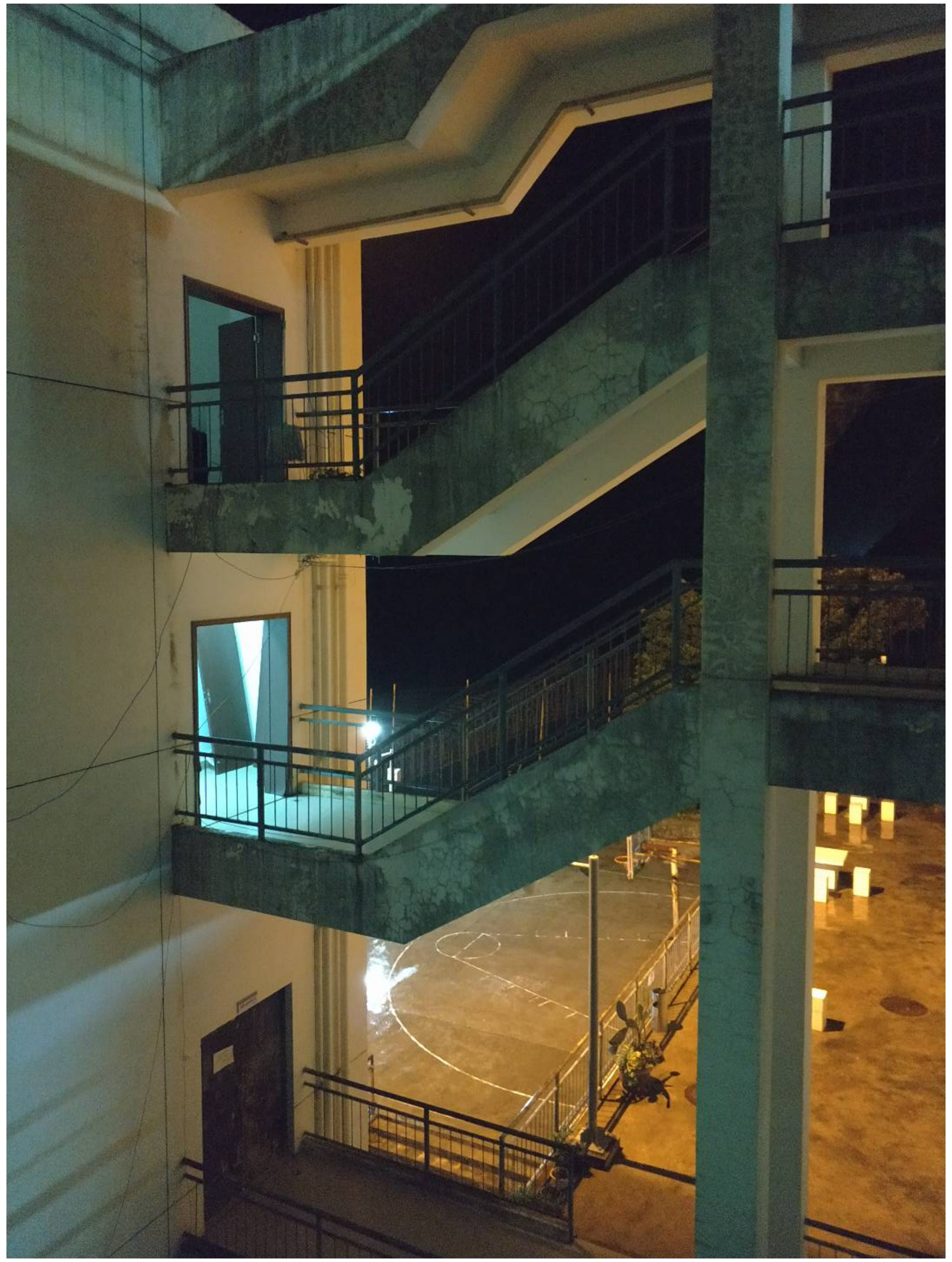
basic cleaning

look from bottom of outer vessel



Album from my phone: sometimes when it rains

corridor between dorm and office



half basketball field

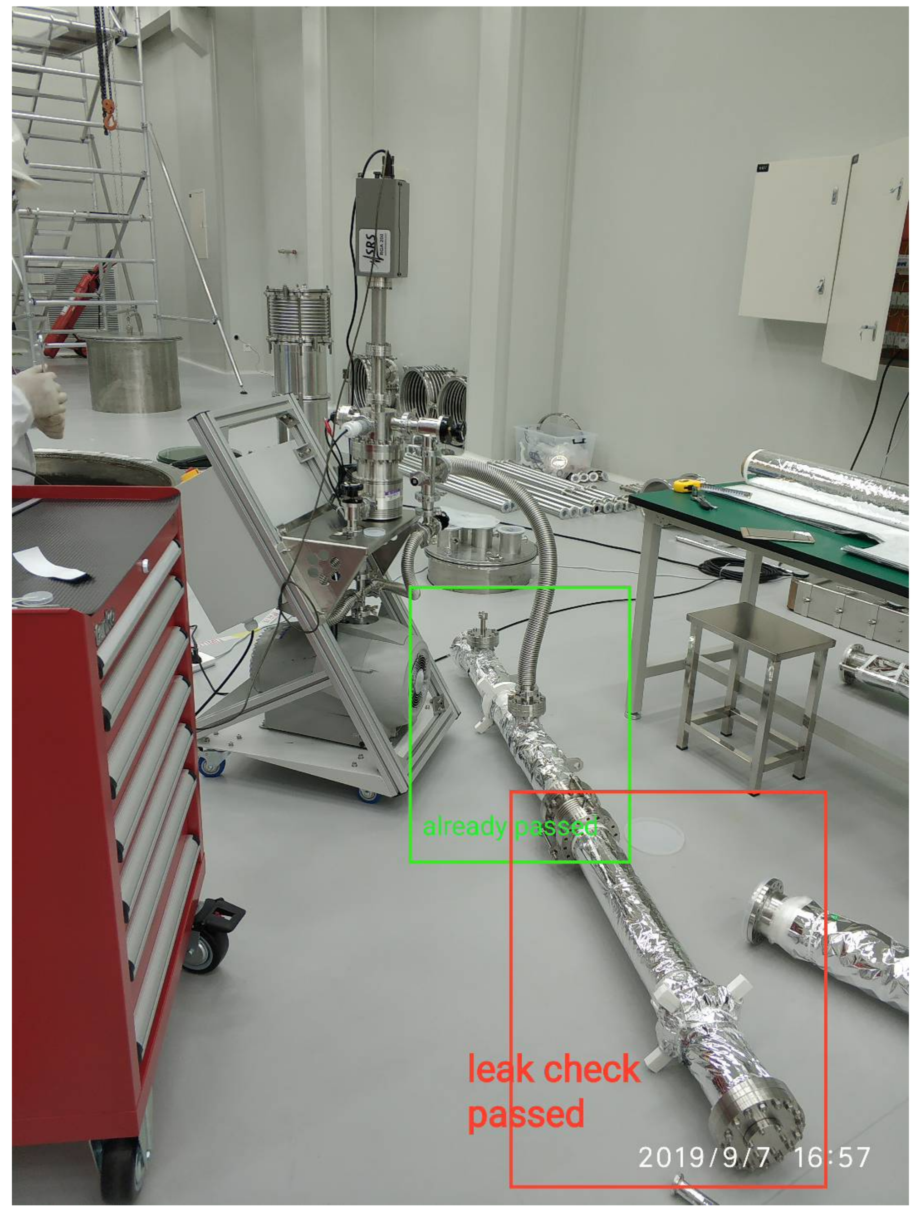
black cat outside the dorm

Album from my phone: the circulation

crane

cooling bus and circulation

leak checks



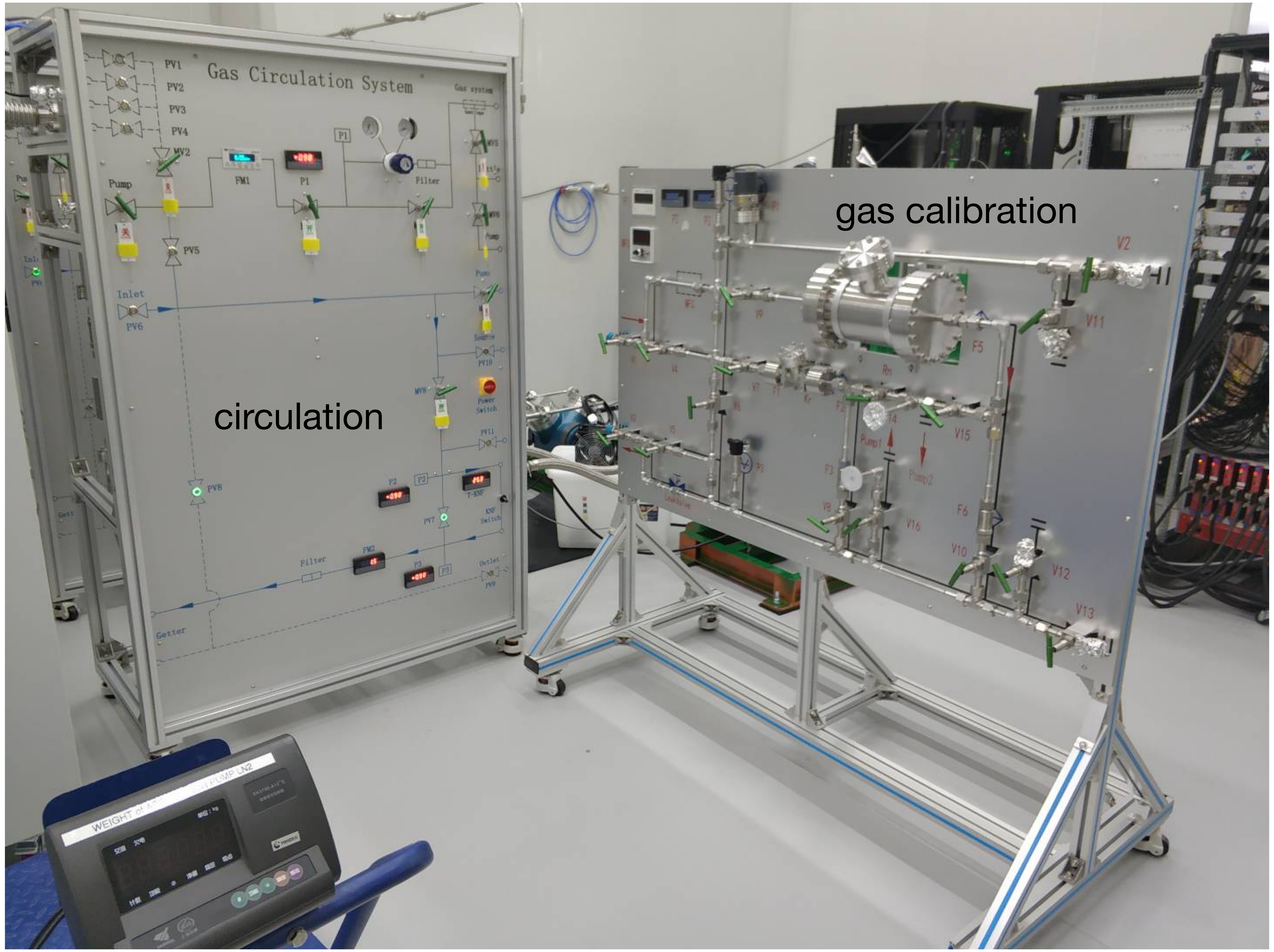
Album from my phone: "the six day" of cryogenics

from empty

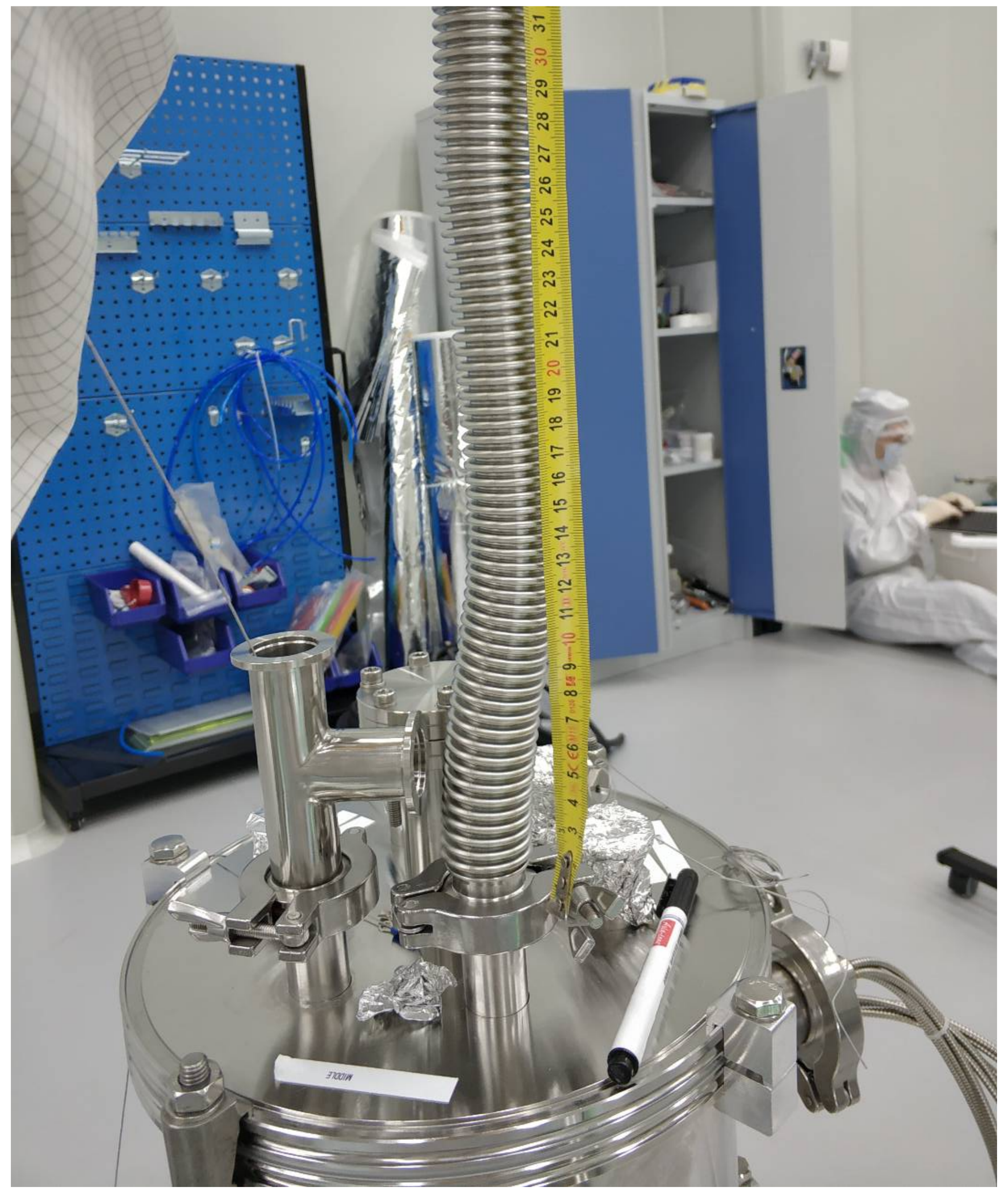
to everything

Album from my phone: christmas 2019

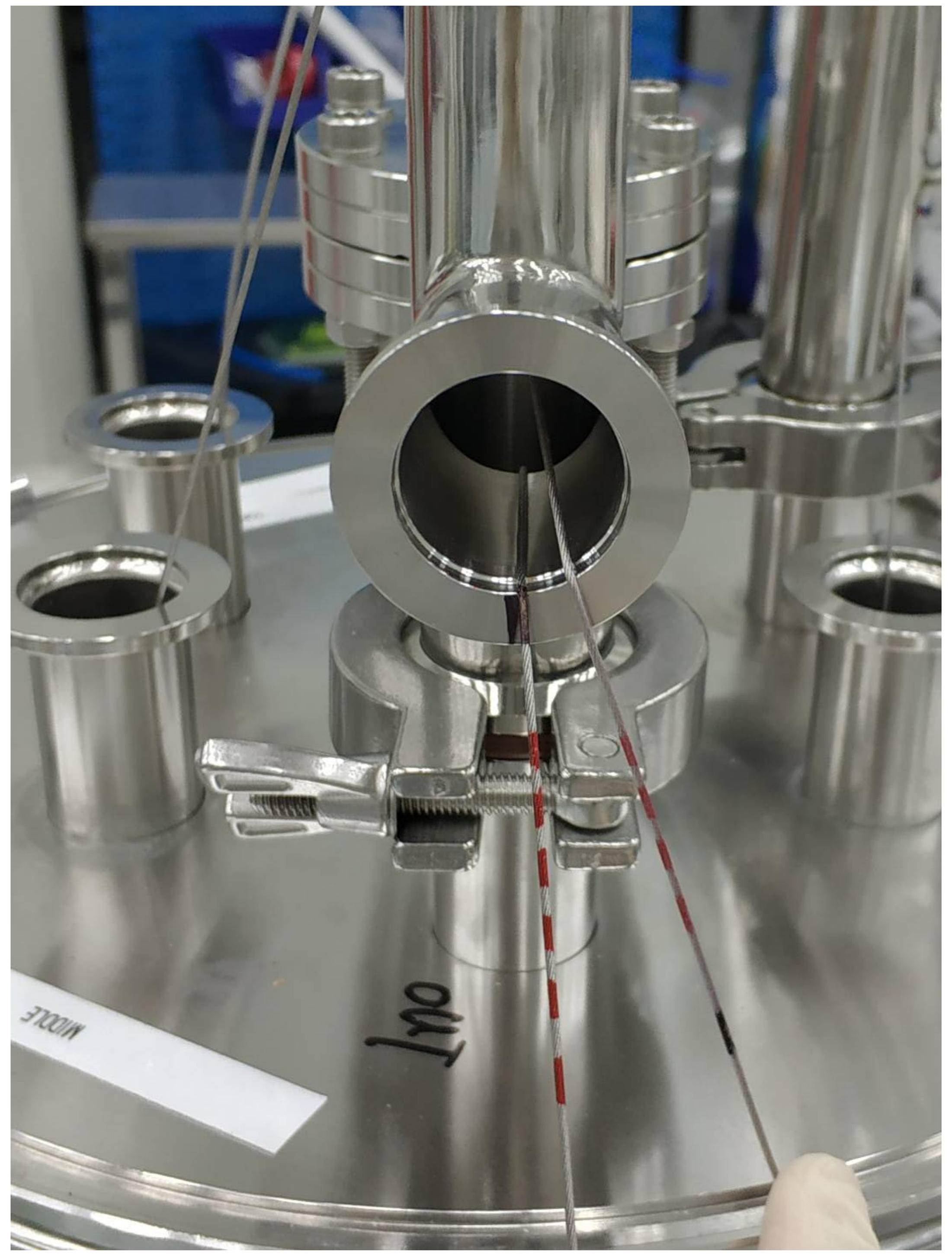
Album from my phone: calibration devices

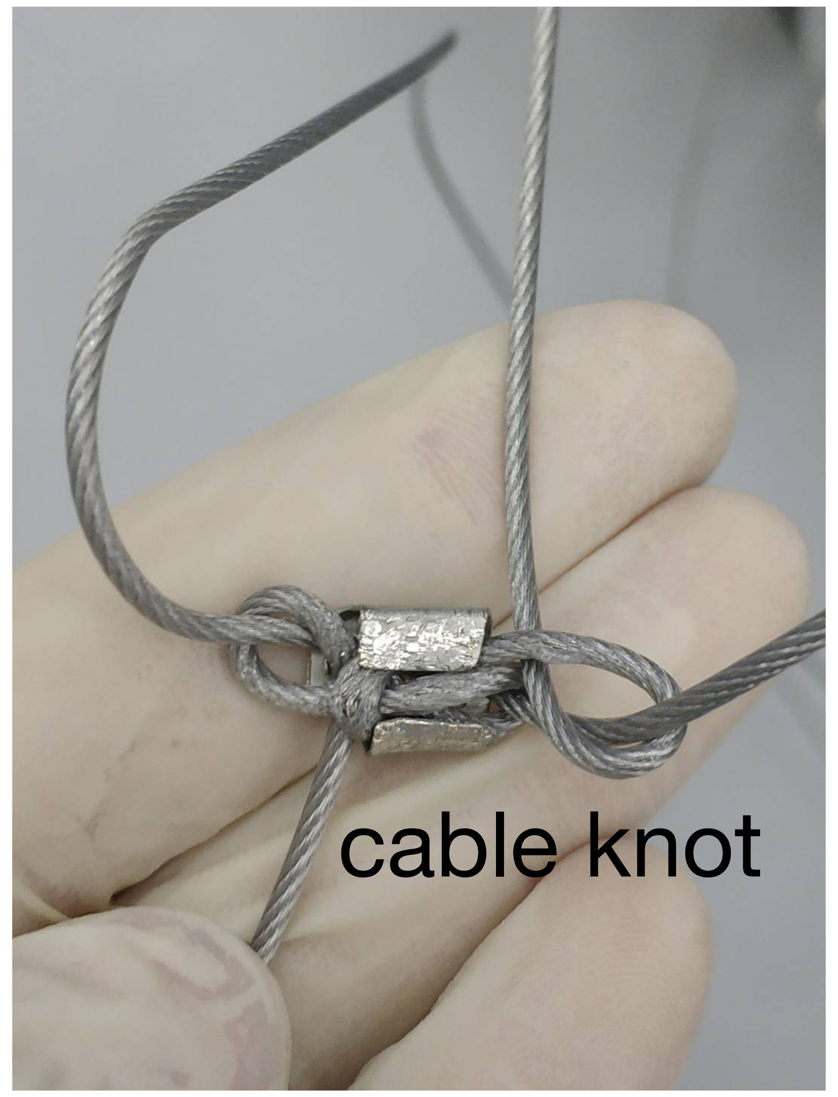


AmBe calibration tube



calibration mark: TPC P6





Album from my phone: corona virus, 2020/01 – 2020/04

nothing

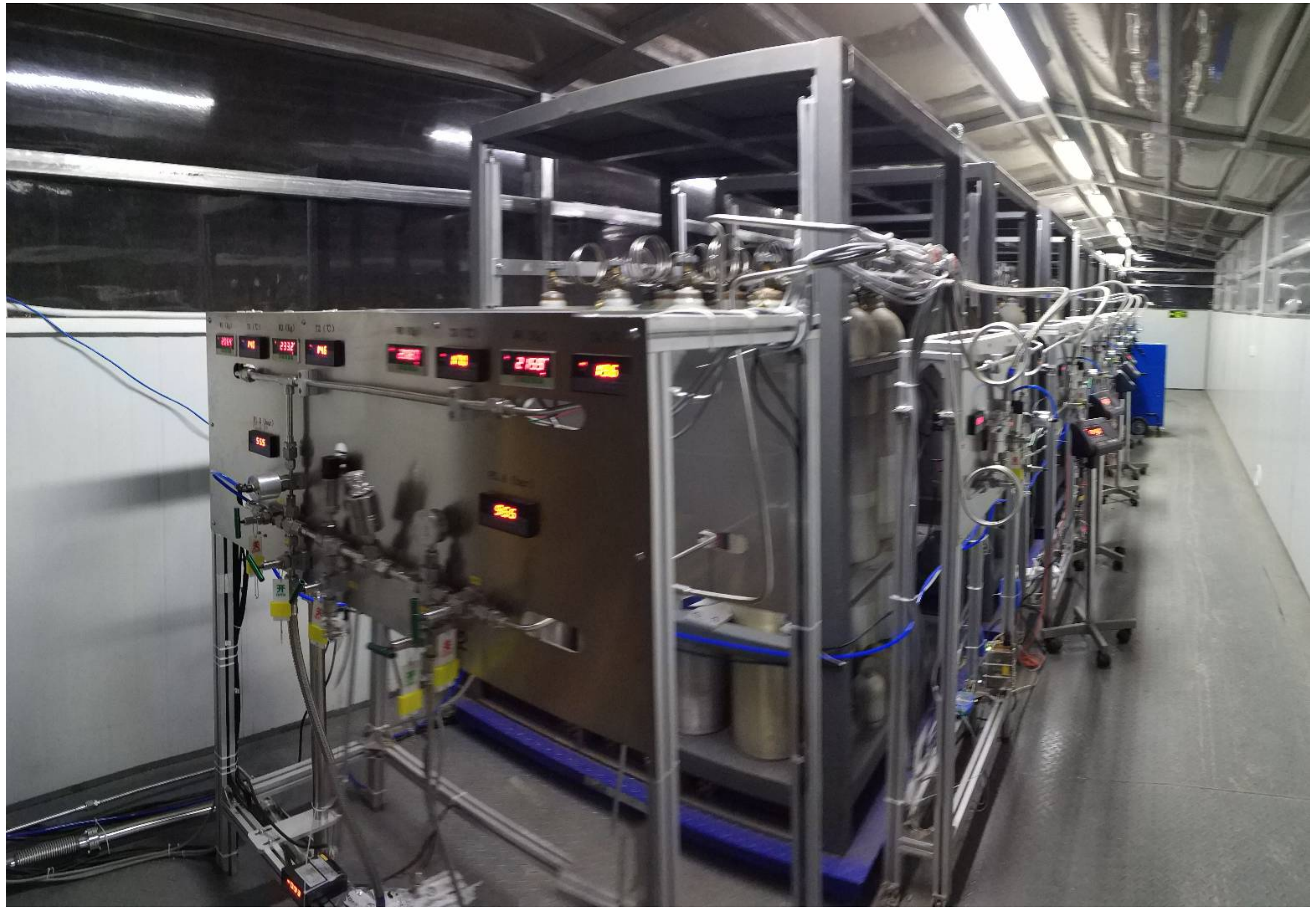
Album from my phone: inner vessel, 2020/04

closure of the inner vessel

leak check

Album from my phone: check 6 tonne of xenon

Xe control system

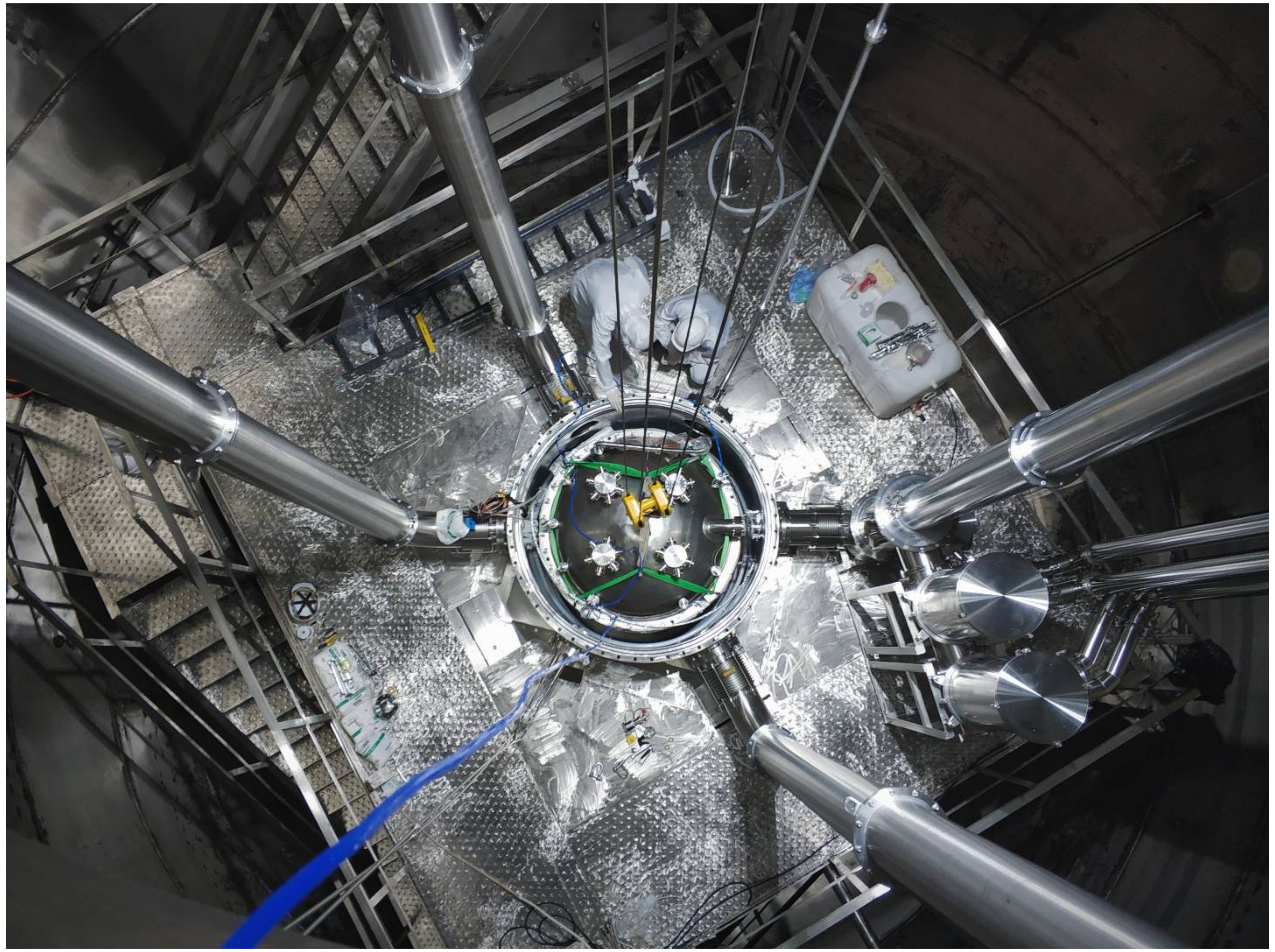


8 modules × 16 cylinders, 50 kg / cylinder

Album from my phone: inner vessel

tighten screws

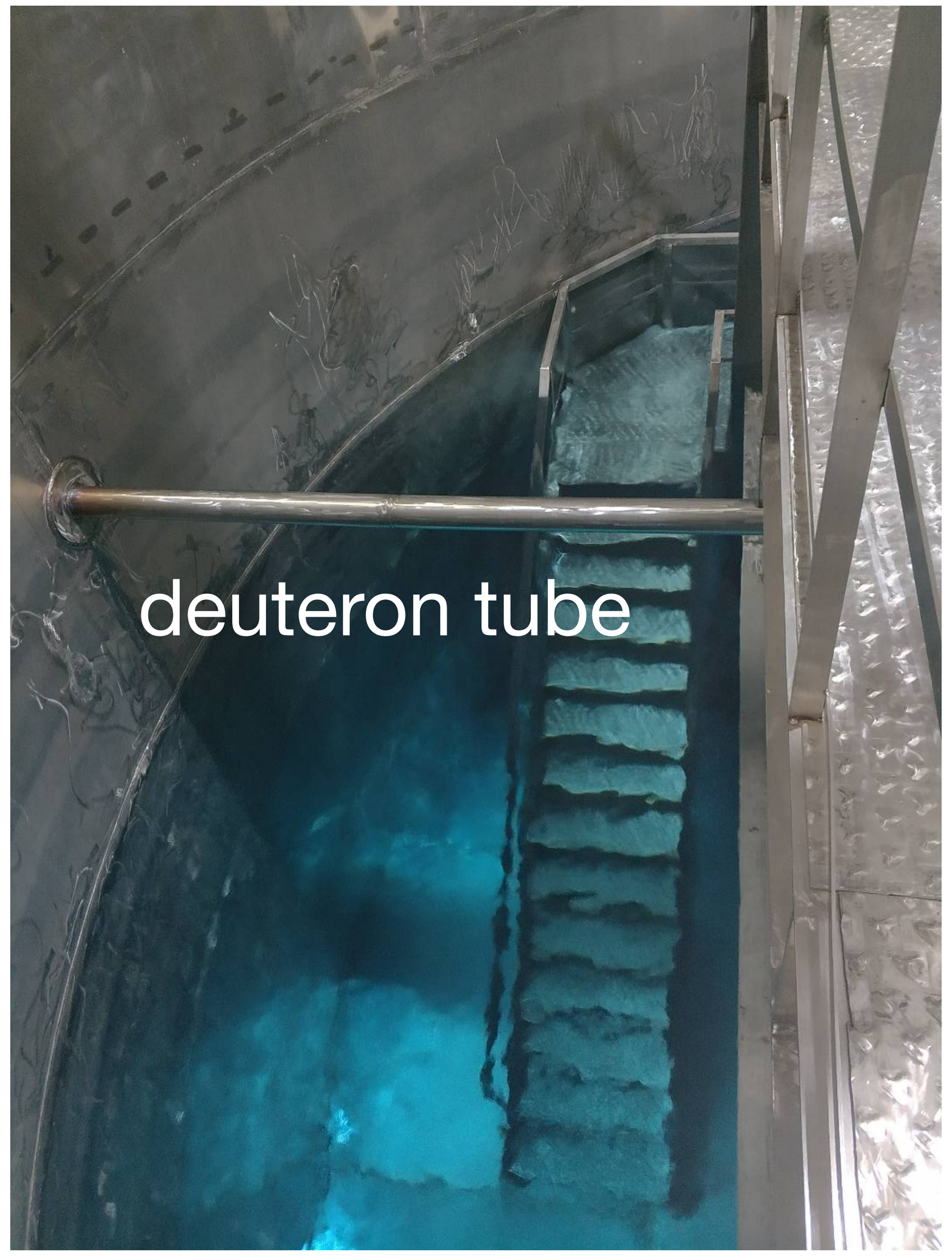
drove the crane to lift it down

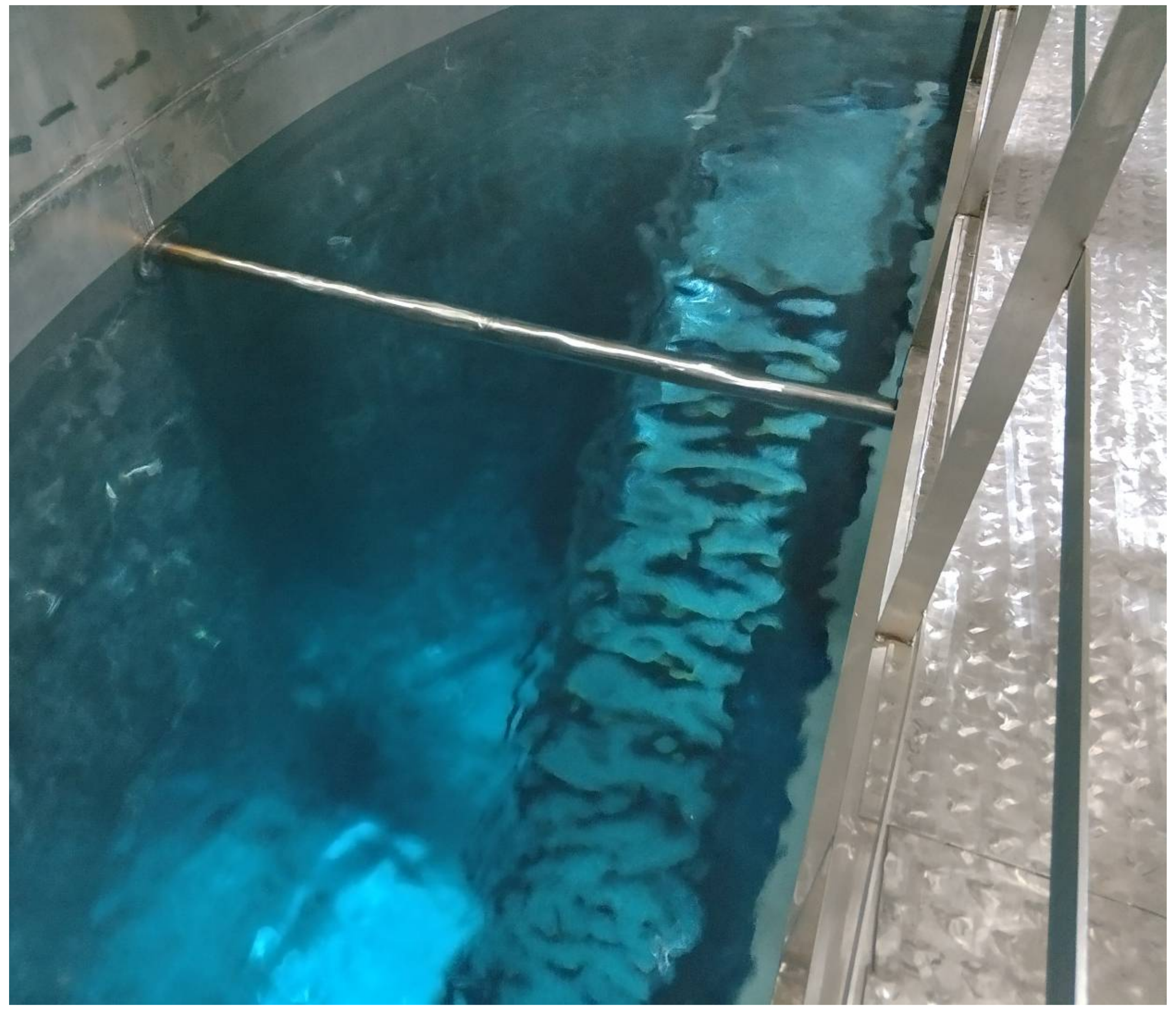


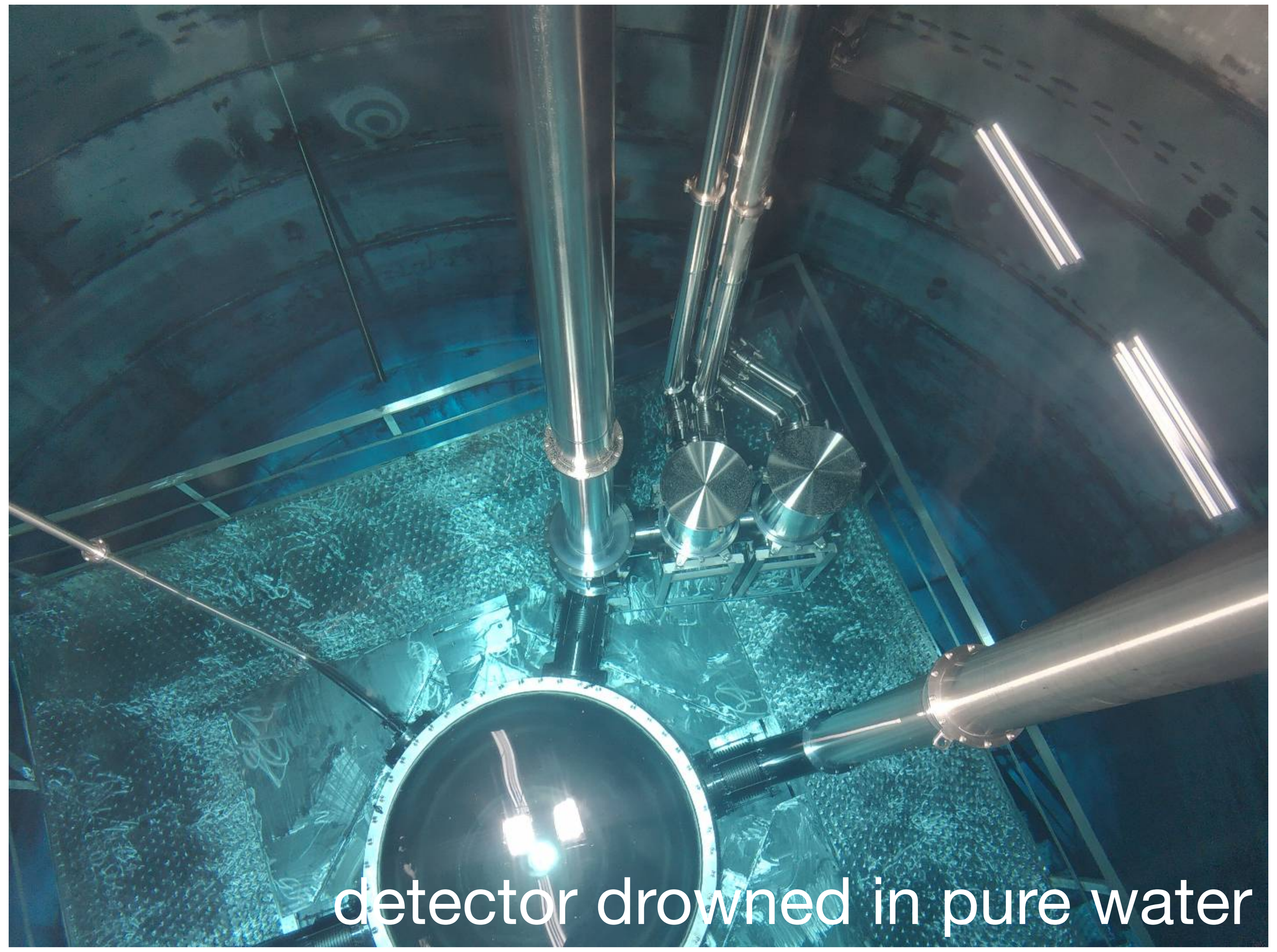
Album from my phone: check electronics system

should be our first S2?

Album from my phone: fill water







Album from my phone: celebration

Werewolf is our
favoraite party game

Album from my phone: fast recuperation

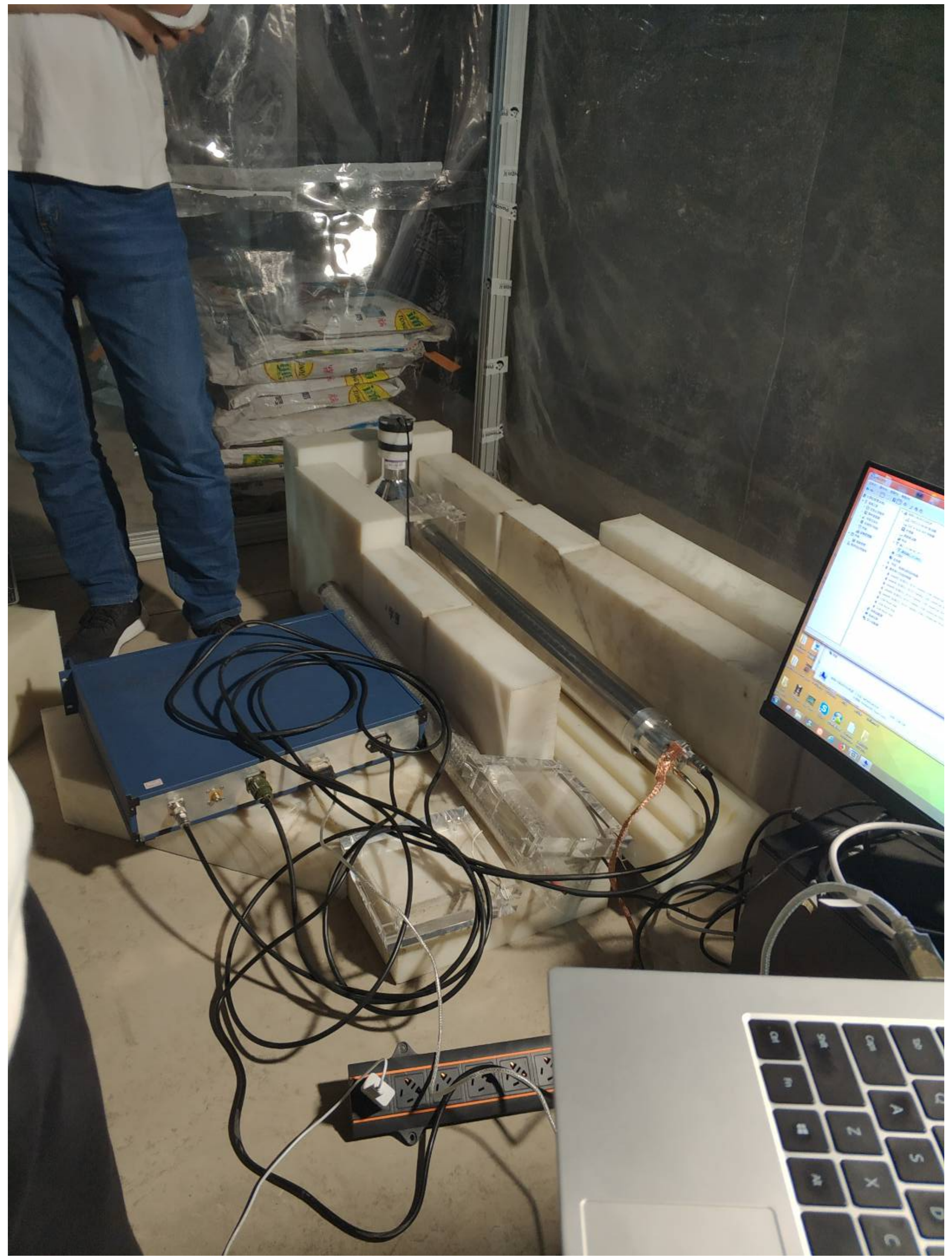
high pressure pump

heat compensation

Album from my phone: DD tunnel

PTFE lens

DD generator

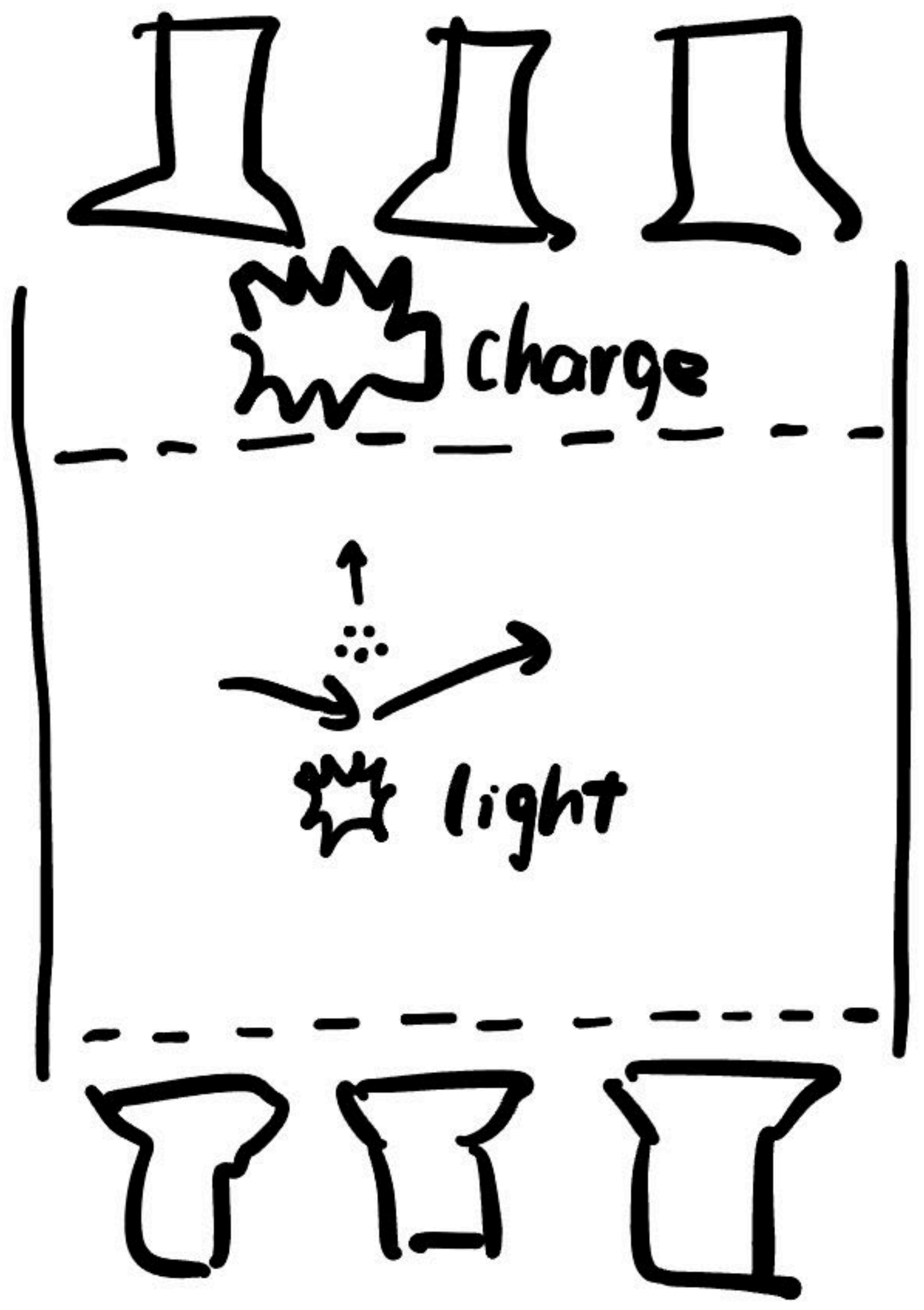


PTFE into DD tunnel

WIMP search with PandaX-4T

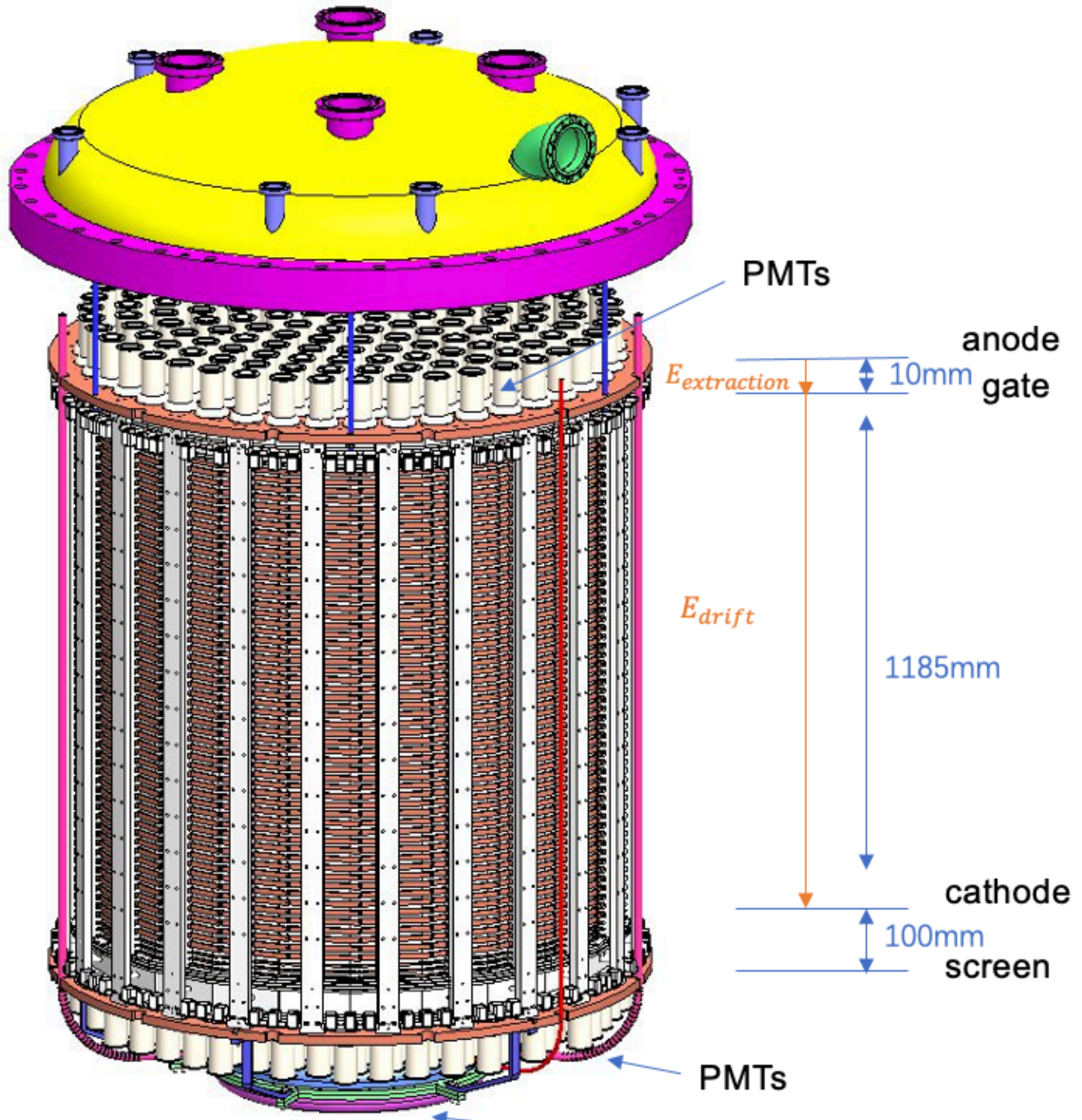
Liquid xenon time projection chamber (TPC)

- Incoming particles scatter with Xe (electrons or nucleus, **ER** or **NR**)
- See **light and delayed charge** together under electric field
- Light is called signal-1(**S1**), charge is called signal-2(**S2**)



PandaX–4T TPC

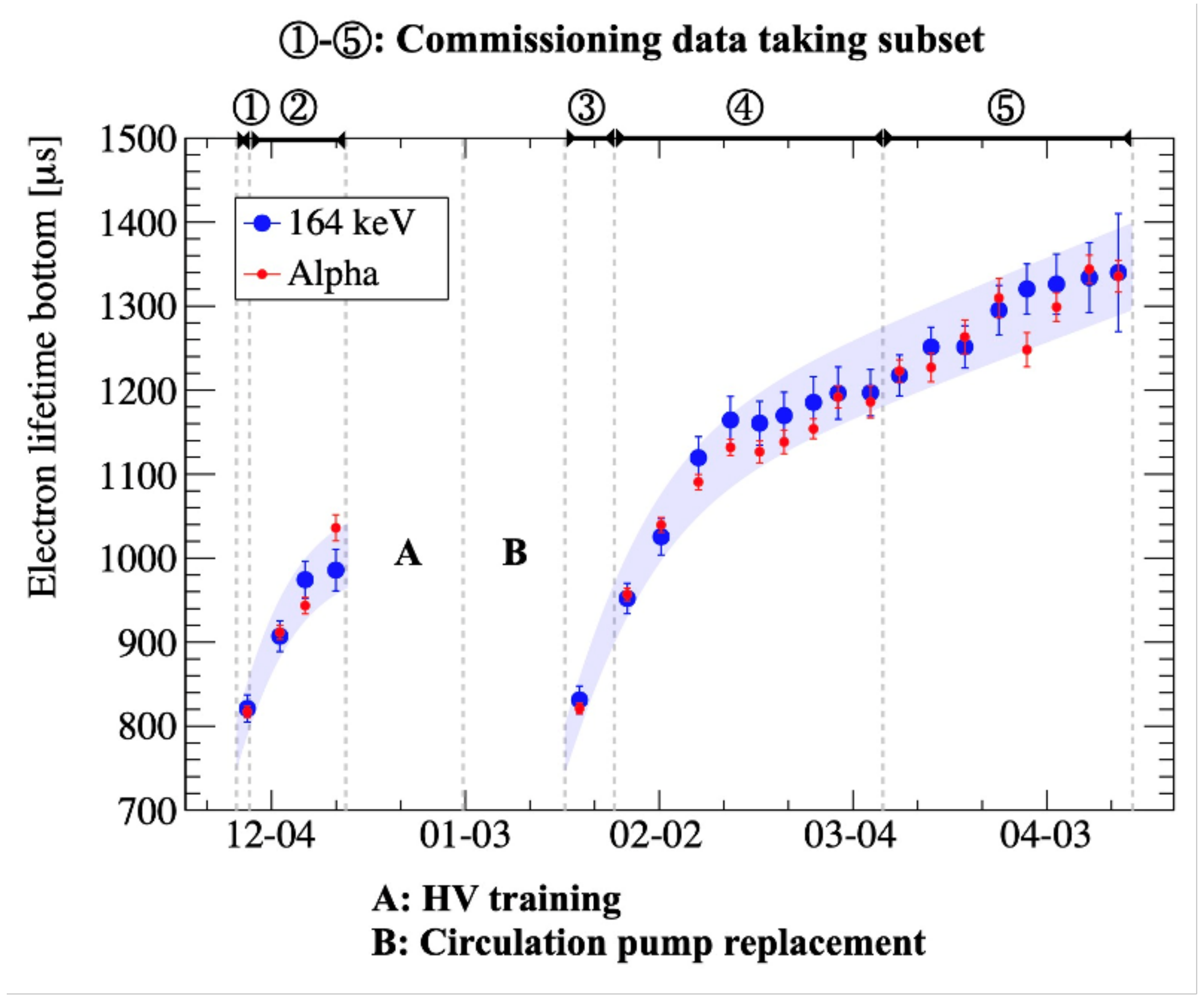
- 169 PMTs on top, 199 PMTs on bottom
- 3.7 tonne liquid xenon in sensitive volume
- Technical components: electrodes, shaping rings, PTFE wall, overflow chamber, Xe pipelines...



Xuyang Ning @ PPC2023

PandaX-4T commissioning run

- Stable data taking: 95 calendar days (86 days after selection)
- Excellent electron lifetime and voltage
- Data taking periods are seperated by hardware issues (voltage/circulation/sparking...)

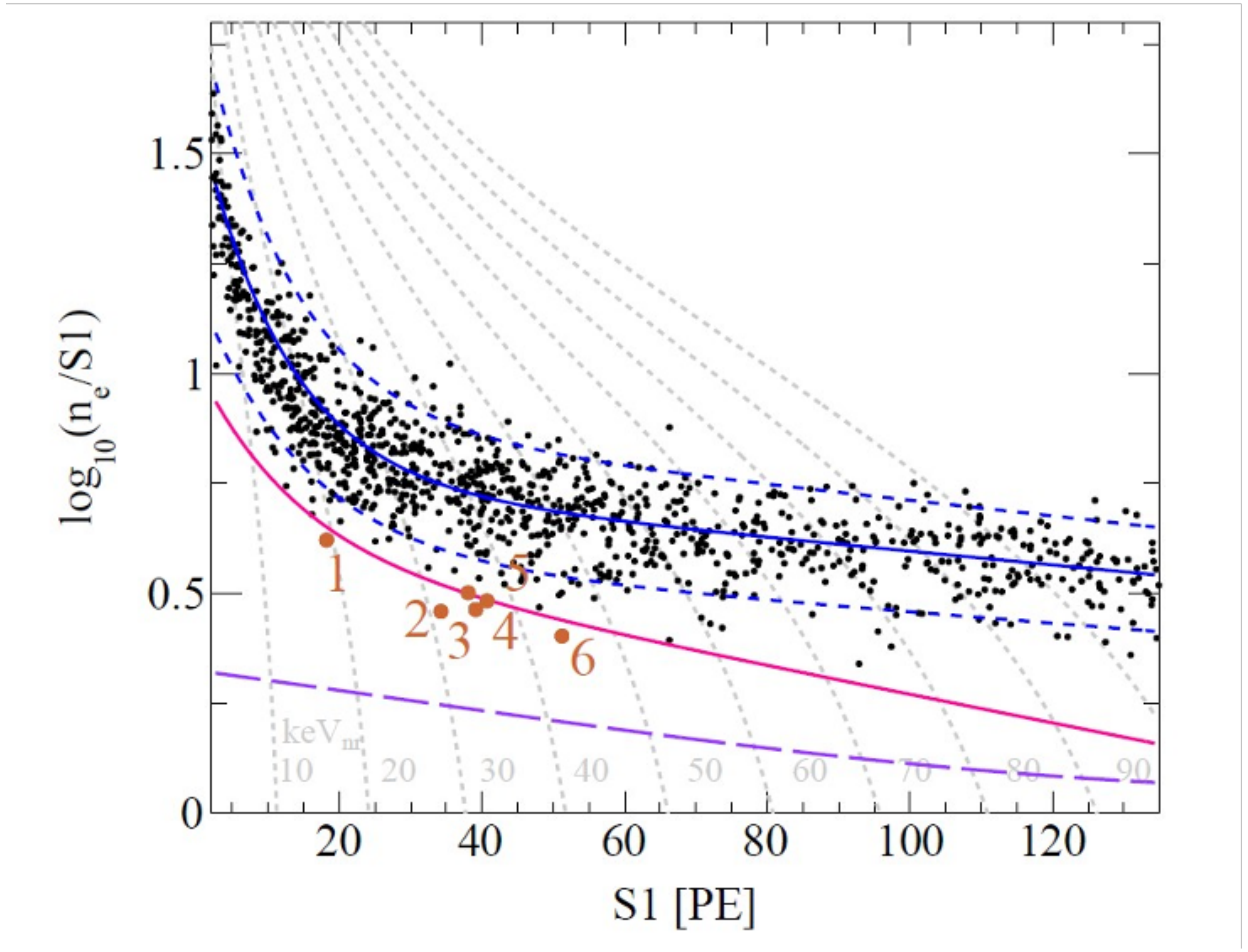


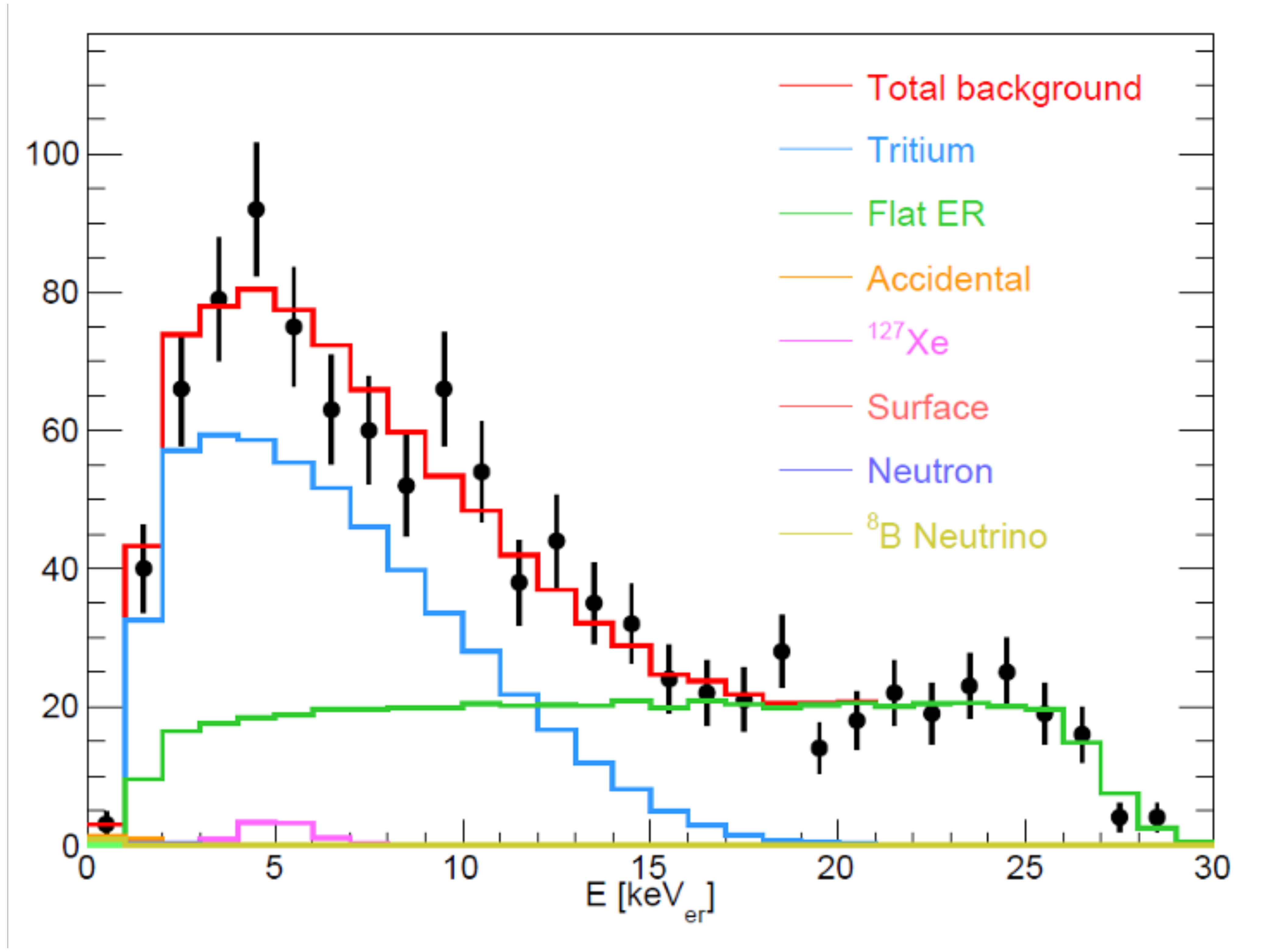
Set	1	2	3	4	5
Duration (days)	1.95	13.25	5.53	35.58	36.51
$\langle \tau_e \rangle$ (μs)	800.4	939.2	833.6	1121.5	1288.2
dt_{max} (μs)	800	810	817	841	841
V_{cathode} ($-$kV)	20	18.6	18	16	16
V_{gate} ($-$kV)	4.9	4.9	5	5	5
PDE (%)	9.0 ± 0.2		9.0 ± 0.2		
EEE (%)	90.2 ± 5.4		92.6 ± 5.4		
SEG$_b$ (PE/e)	3.8 ± 0.1		4.6 ± 0.1		

Data selection and background

- 0.63 tonne-year exposure
- WIMP ROI: S1 2-135 PE
- 1058 candidates, 6 below NR mediam

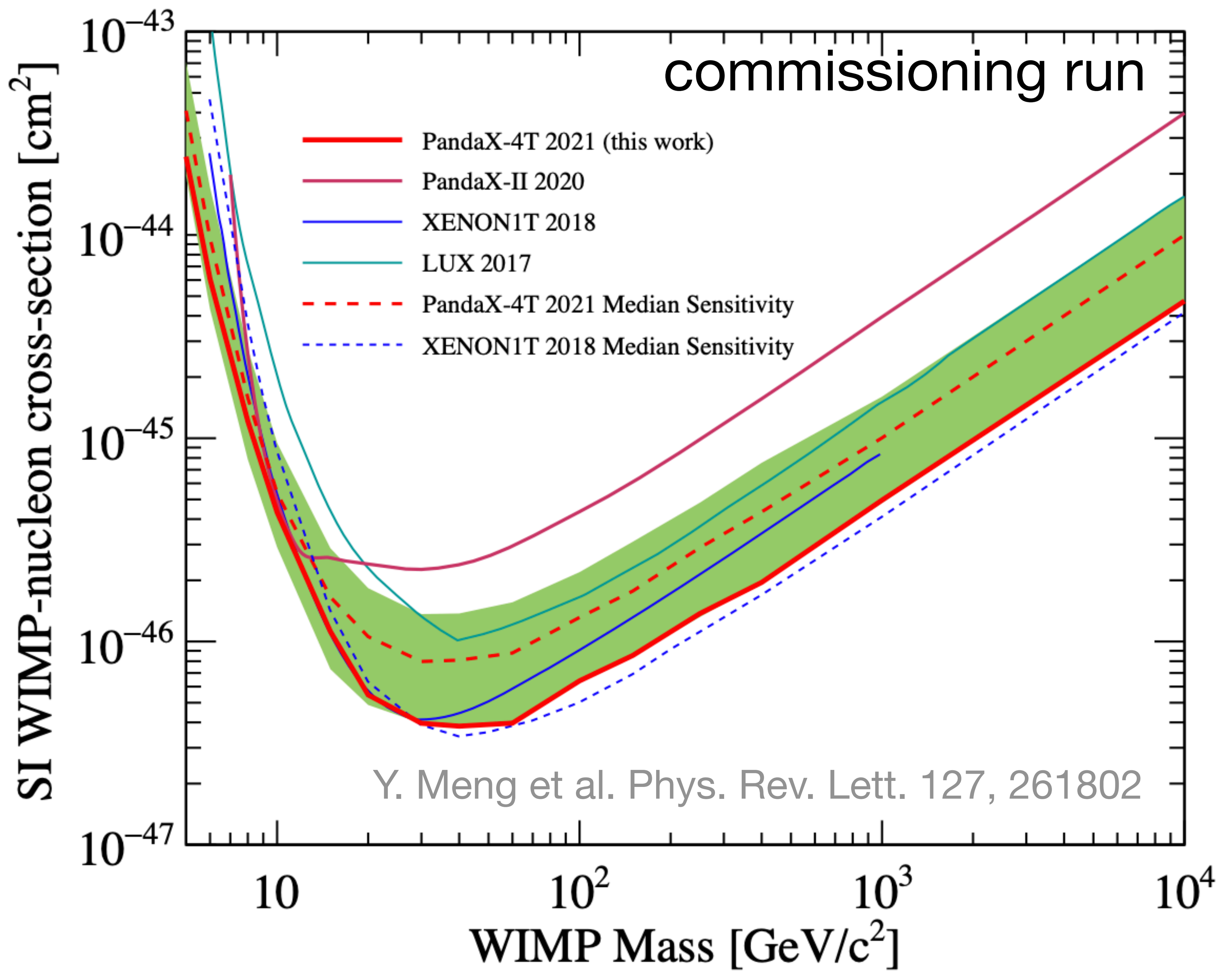
- Flat ER for Kr85, Rn222, 136Xe, solar v ER, and material ER
- Data agrees well with total background

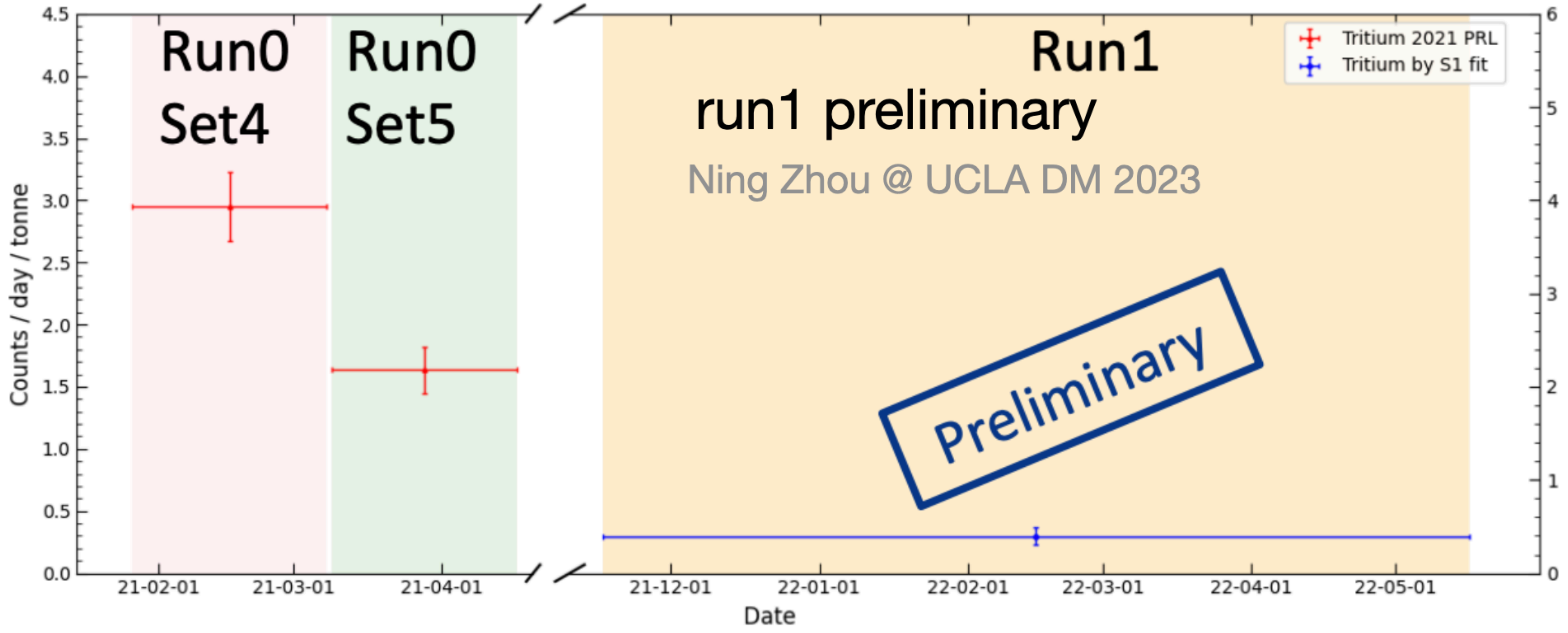




WIMP searches

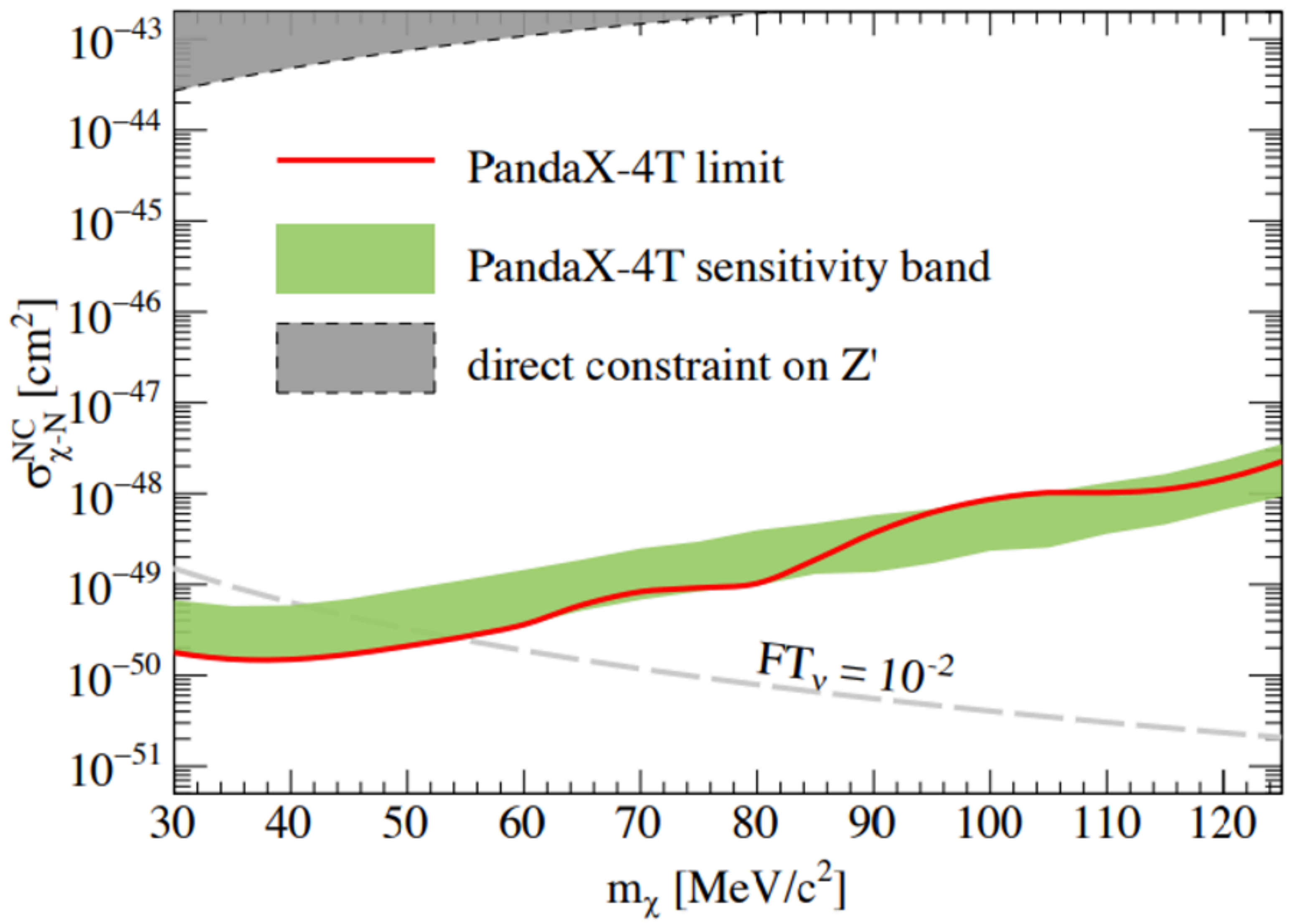
- 2020-2021: commissioning run, 95 days, 0.6 tonne-year
- 2021-2022: science run 1 after tritium removal, ~160 days



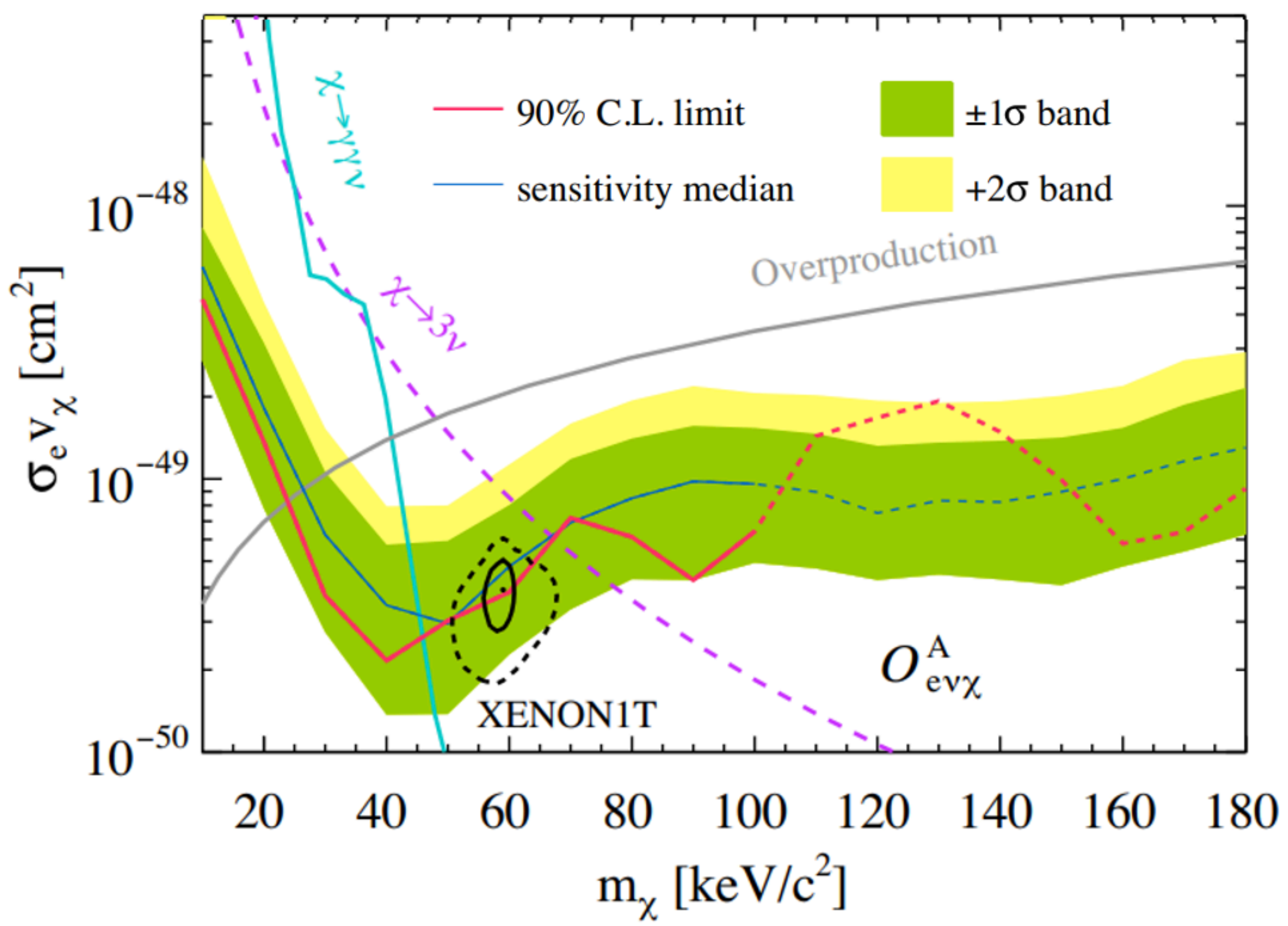


Phenomenological searches

Mono NR, L. Gu et al. PRL 129, 161803(2022)



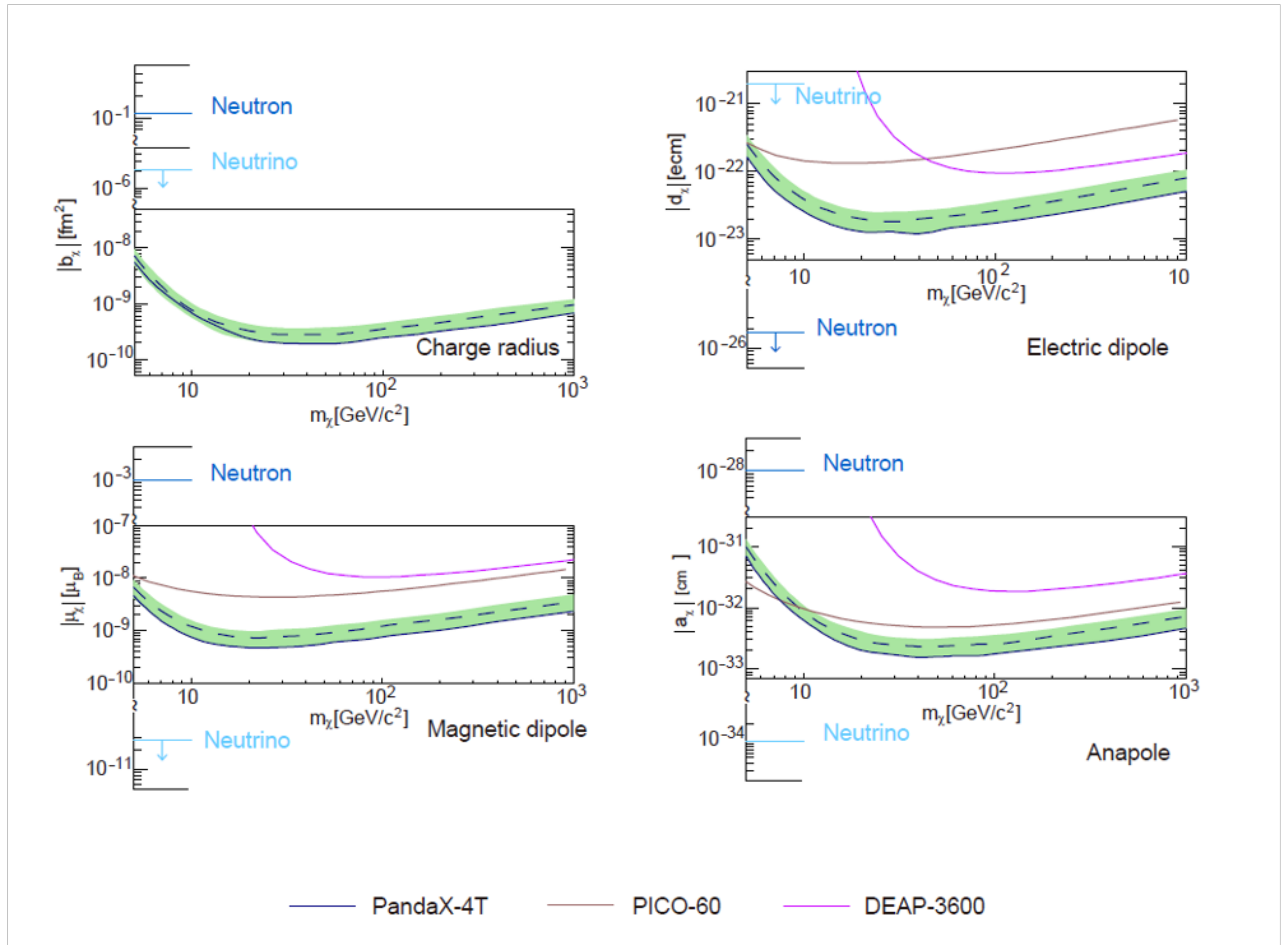
Mono ER, D. Zhang et al. PRL 129, 161804(2022)



EFT operators, X. Ning et al Nature 618, 47-50(2023)

Table 1 | Comparison of electromagnetic properties

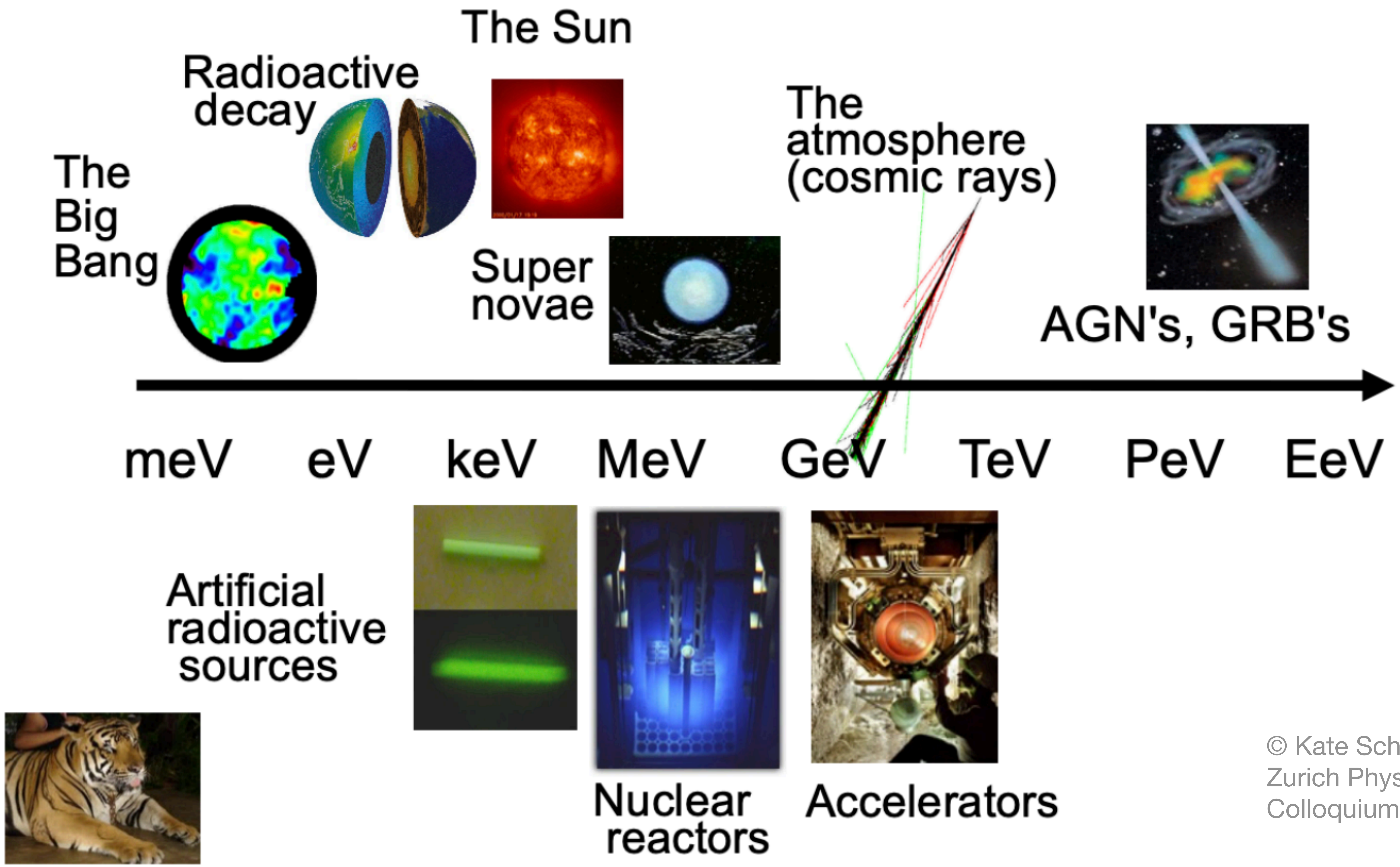
	dark matter	neutrino	neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$[-2.1,3.3]\times10^{-6}$ *	-0.1155 *
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ *	$(-2\pm8)\times10^{-22}$ *
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ *	-1×10^{-3} *
Electric dipole (ecm)	$<1.2\times10^{-23}$	$<2\times10^{-21}$ †	$<1.8\times10^{-26}$ *
Anapole (cm^2)	$<1.6\times10^{-33}$	$\sim10^{-34}$ ‡	$\sim10^{-28}$ §



Solar B8 neutrino CEvNS search

Xe TPCs as a neutrino detector

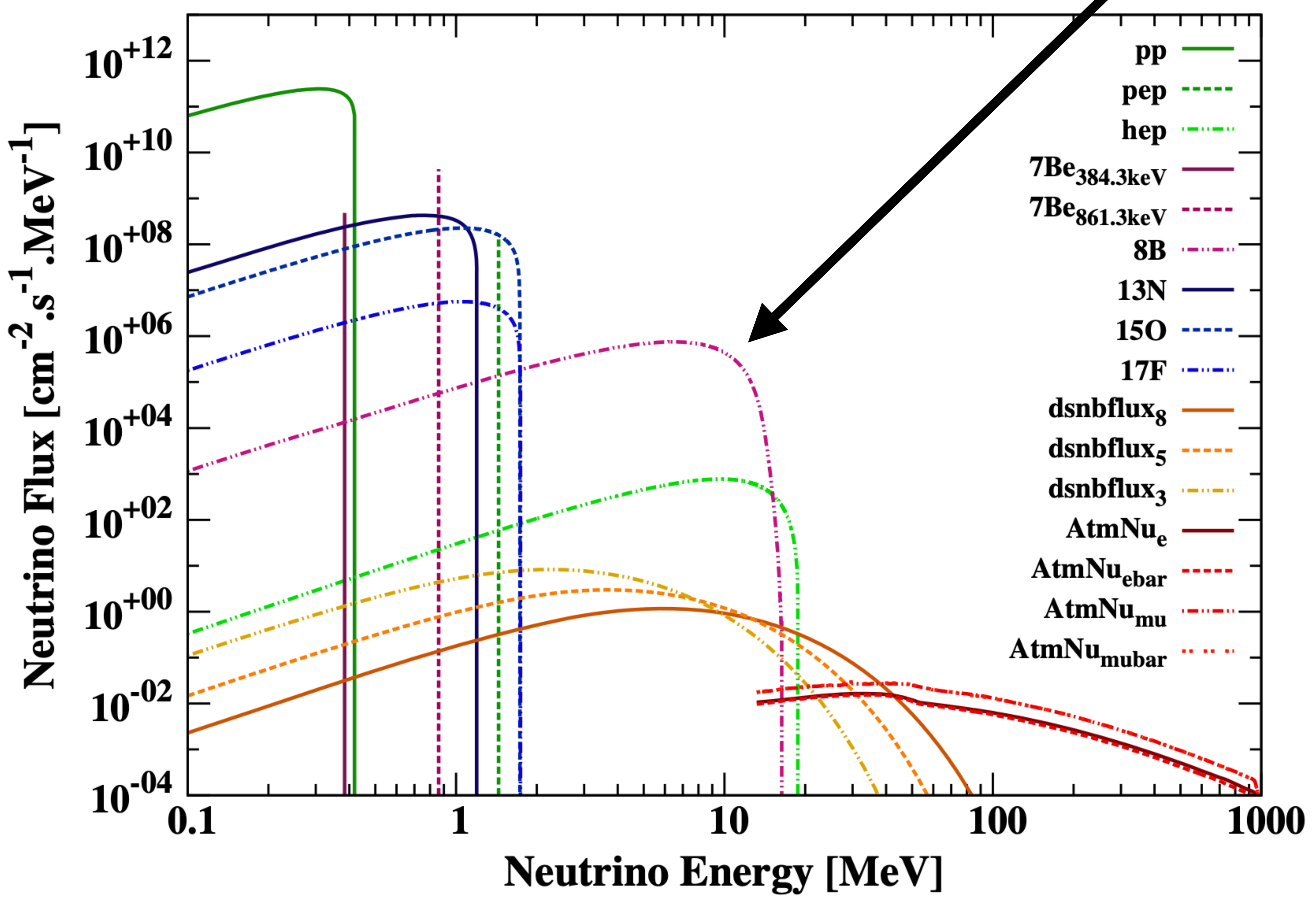
- Xe TPCs have senstivity at MeV with various channels

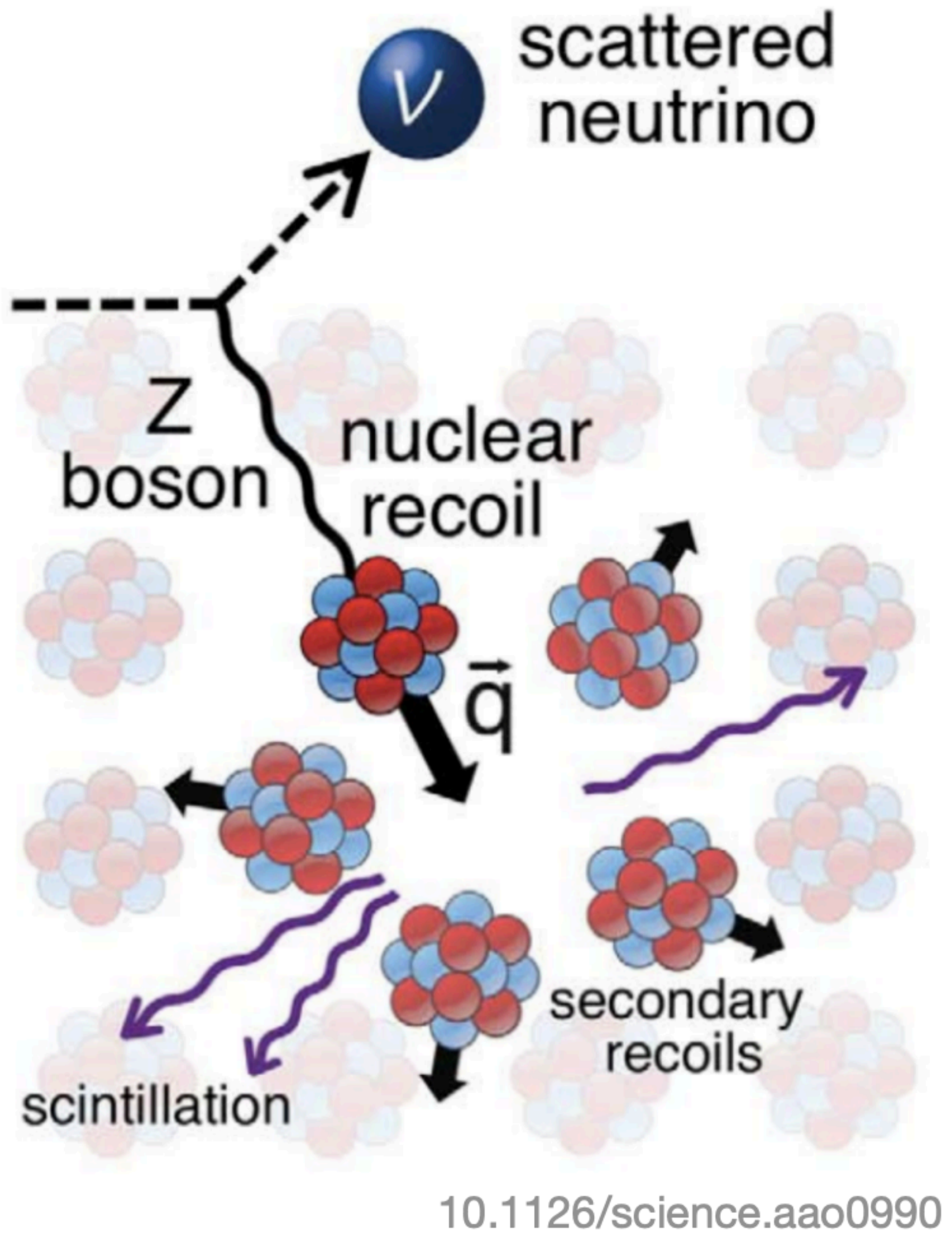


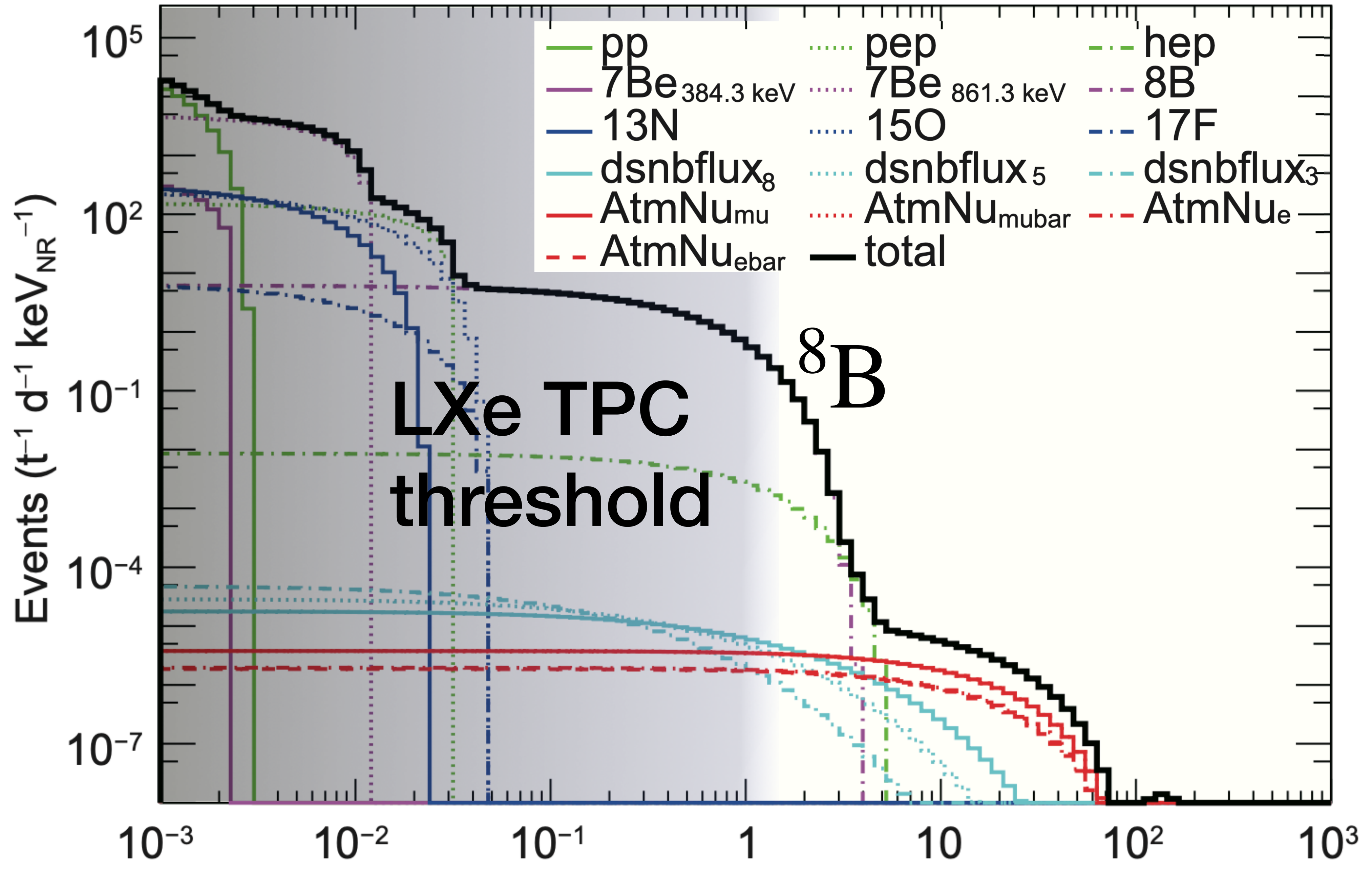
Solar neutrino

- solar fussion neutrino
- interact through CEvNS (coherent elastic neutrino-nucleus scattering)
- deposits several keVnr in LXe

solar $^{8}B\ \nu$ $\boxed{^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_{e}}$



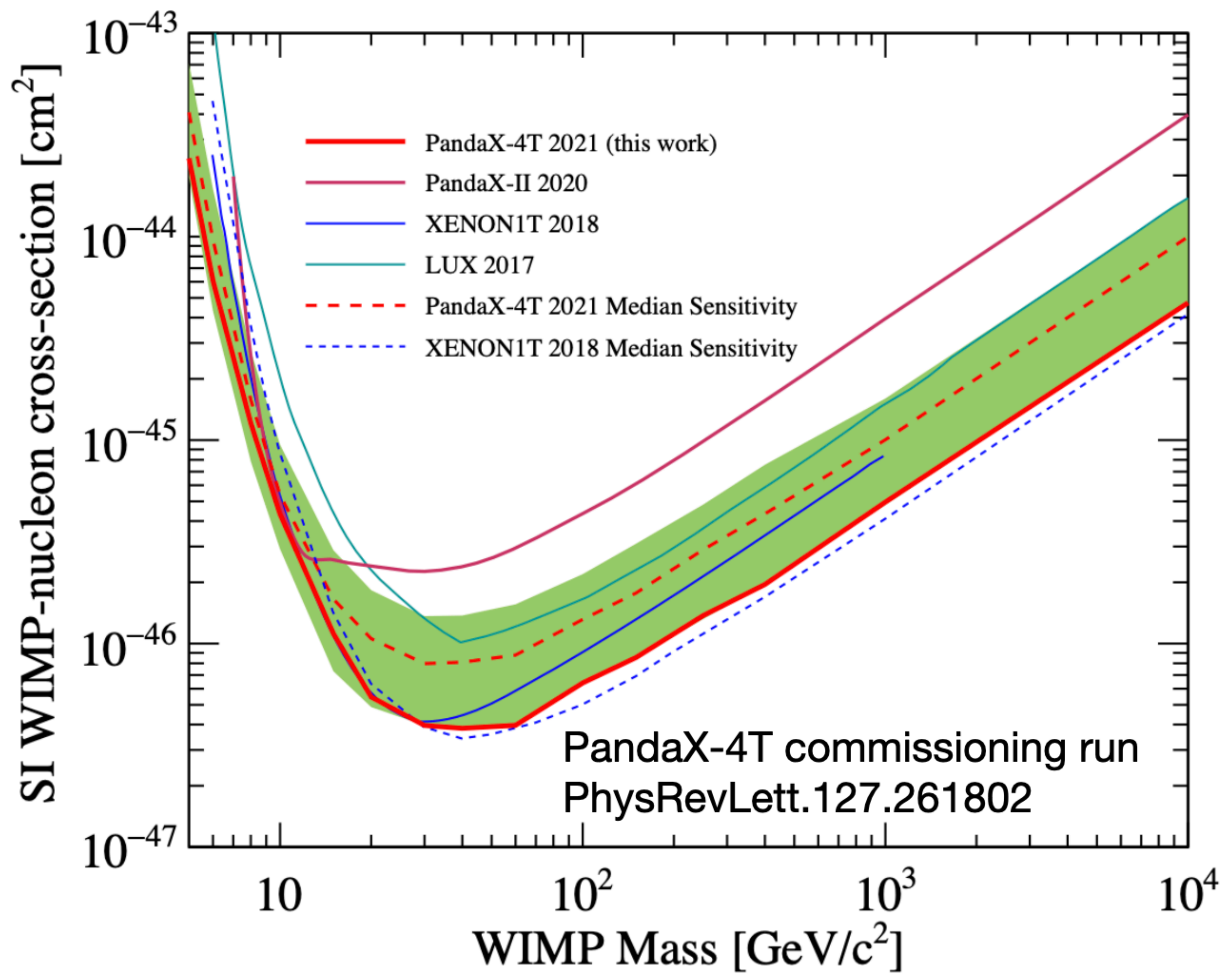


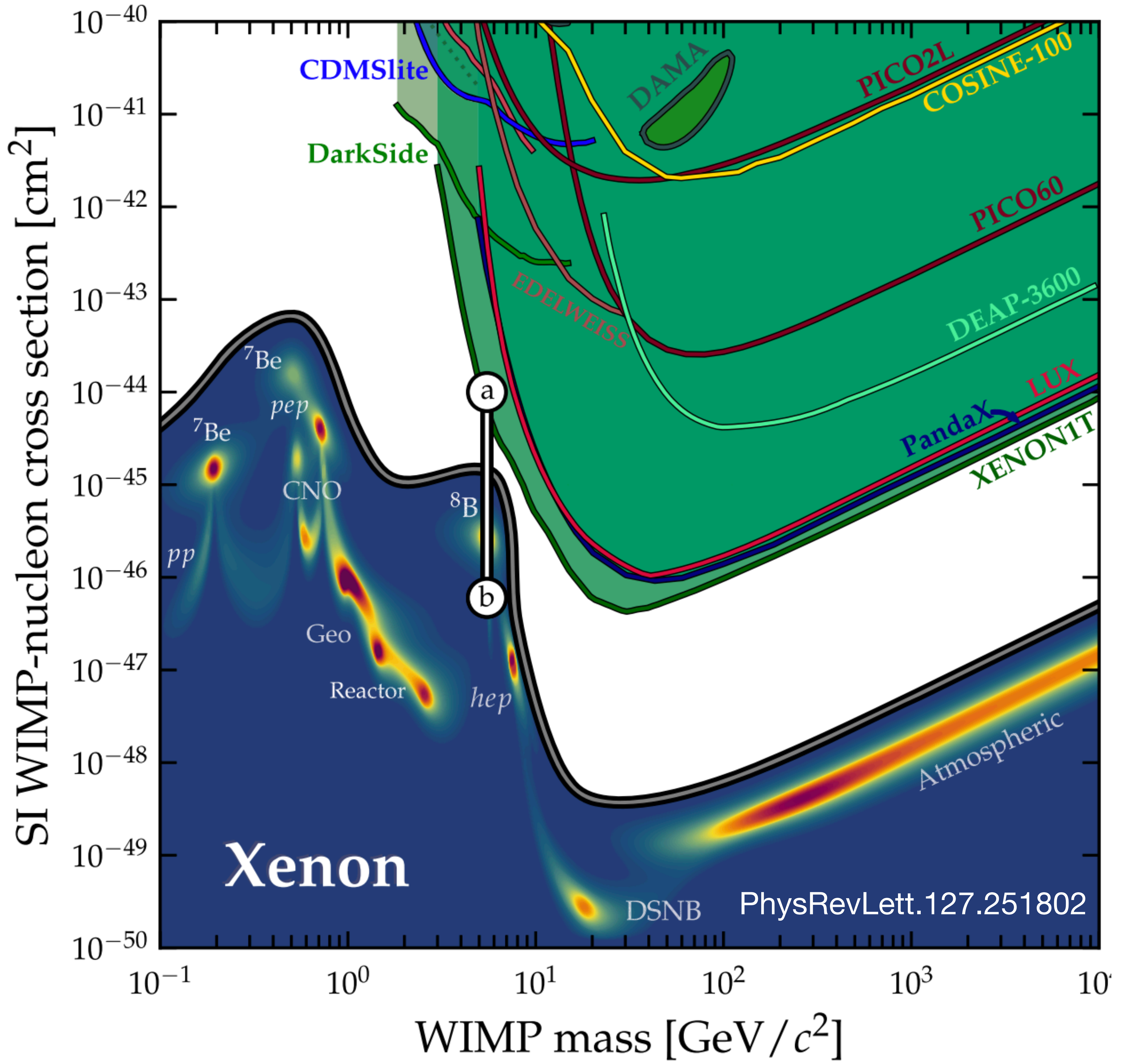


Recoil energy in liquid xenon

Neutrino floor/fog

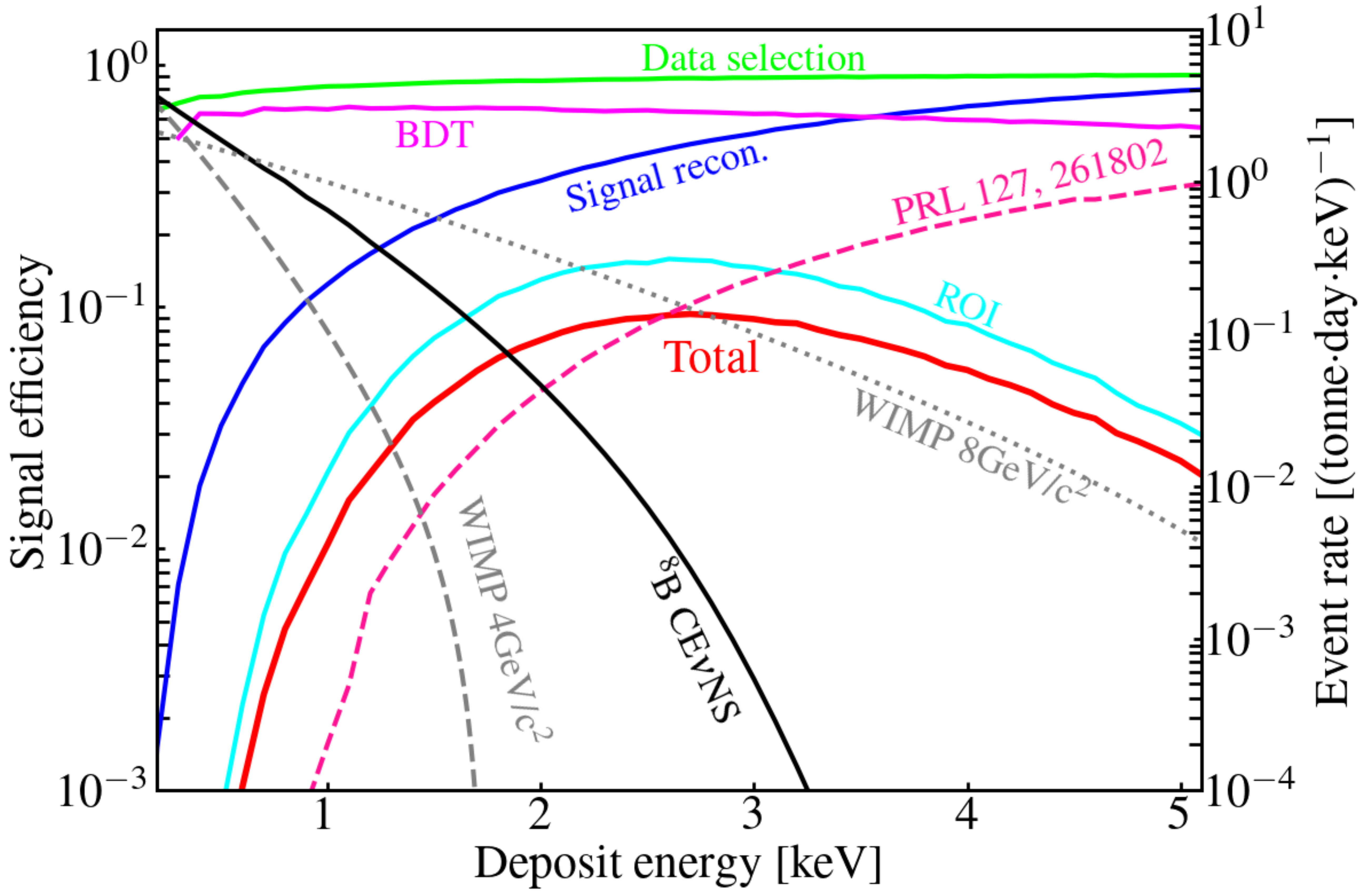
- Neutrino floor/fog: neutrino ultimately constrain the parameter space of deep-underground detectors
- Will be firstly encountered by tonne-scale Xe detectors: LZ, XENONnT, PandaX-4T
- Discovery of solar ν CEνNS in a few years?

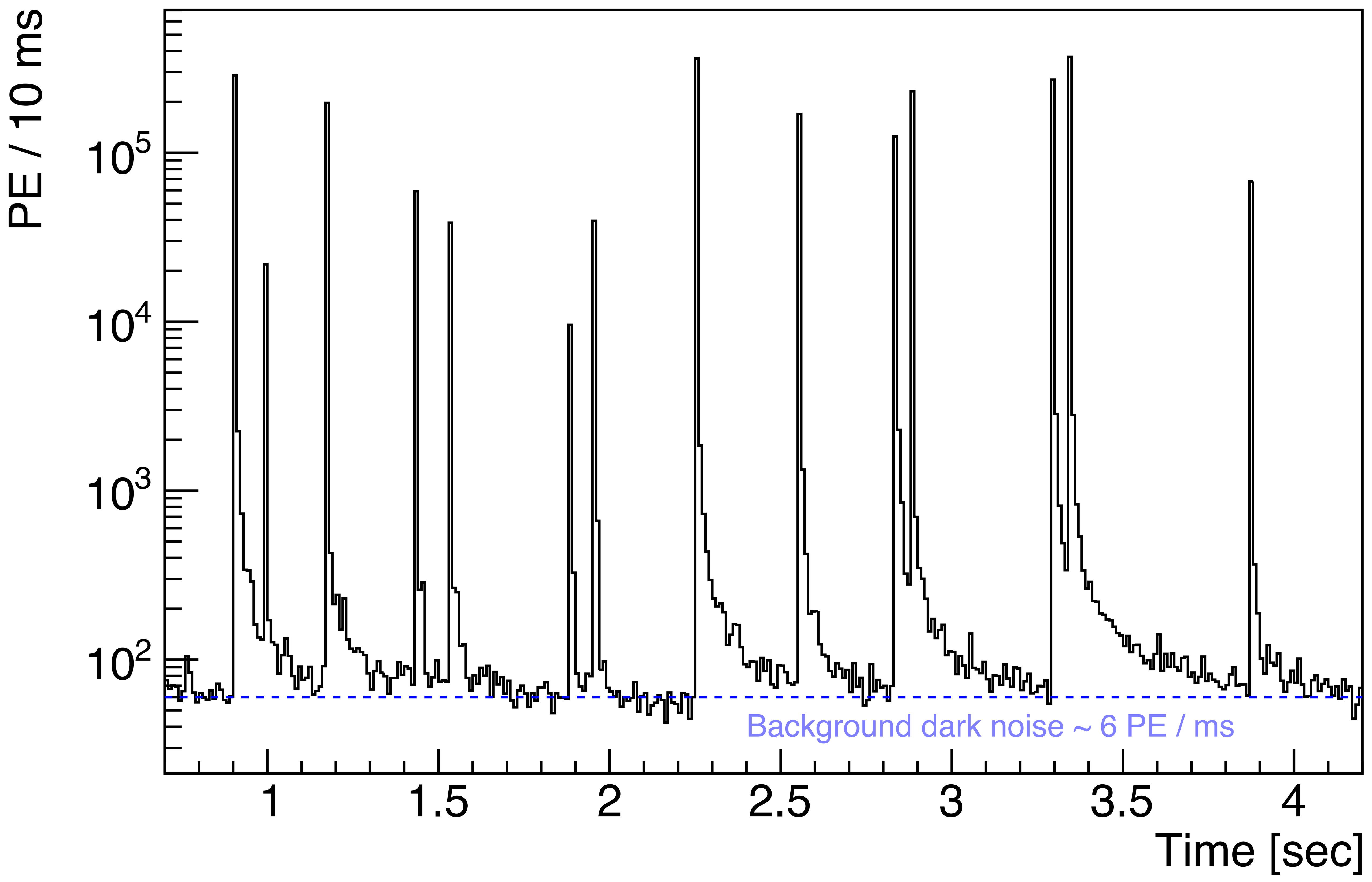




Pushing threshold

- 2 or 3 hits among the entrie PMT array(169+199 PMTs)
- 65 PE of S2 (~3 electron)
- Improvement on deadtime monitoring, signal reconstruction, and quality cuts

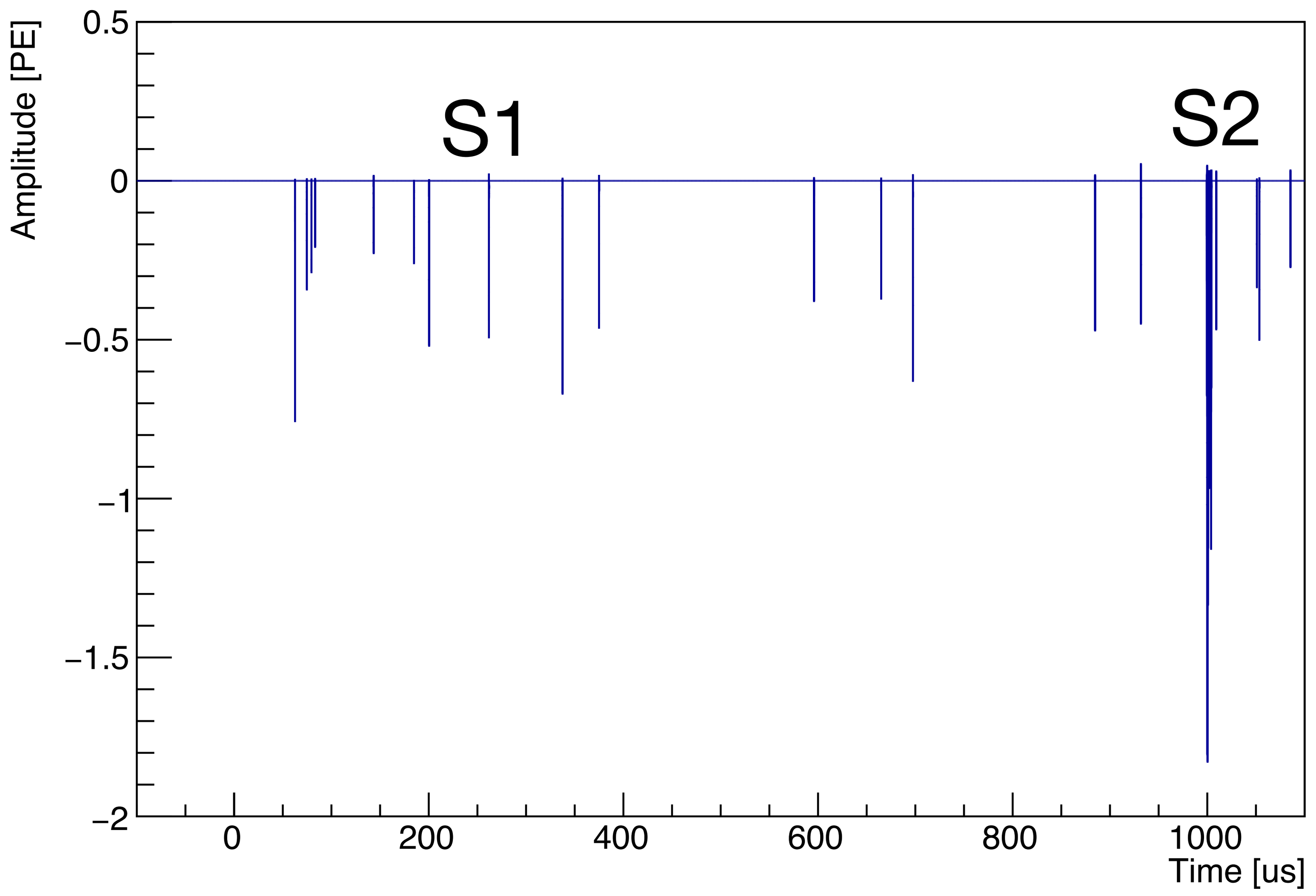




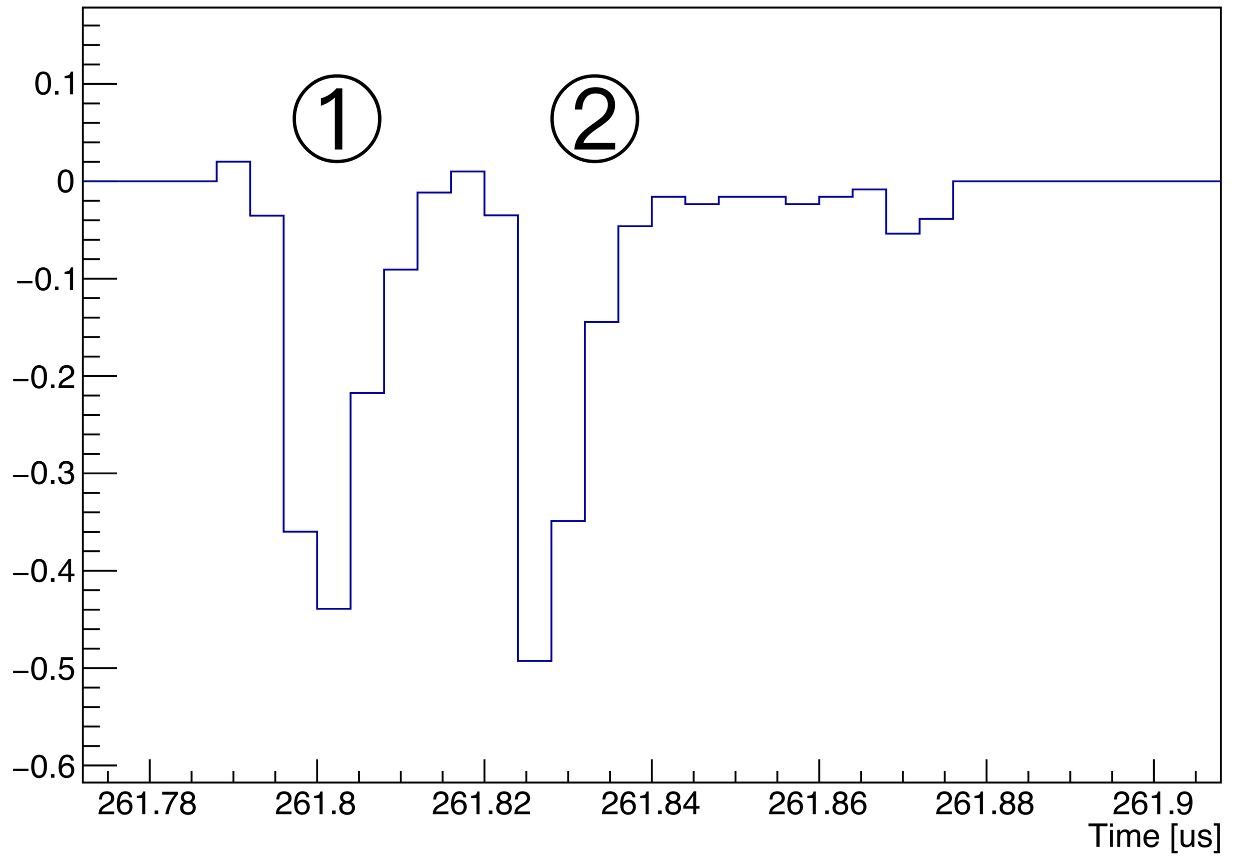
Waveform simulation

- Precise calculation for detection efficiency at each energy bin
- Detector-specified simulation for S1, S2, delay ionization, dark noise, etc with data-driven method
- Integrated with the real

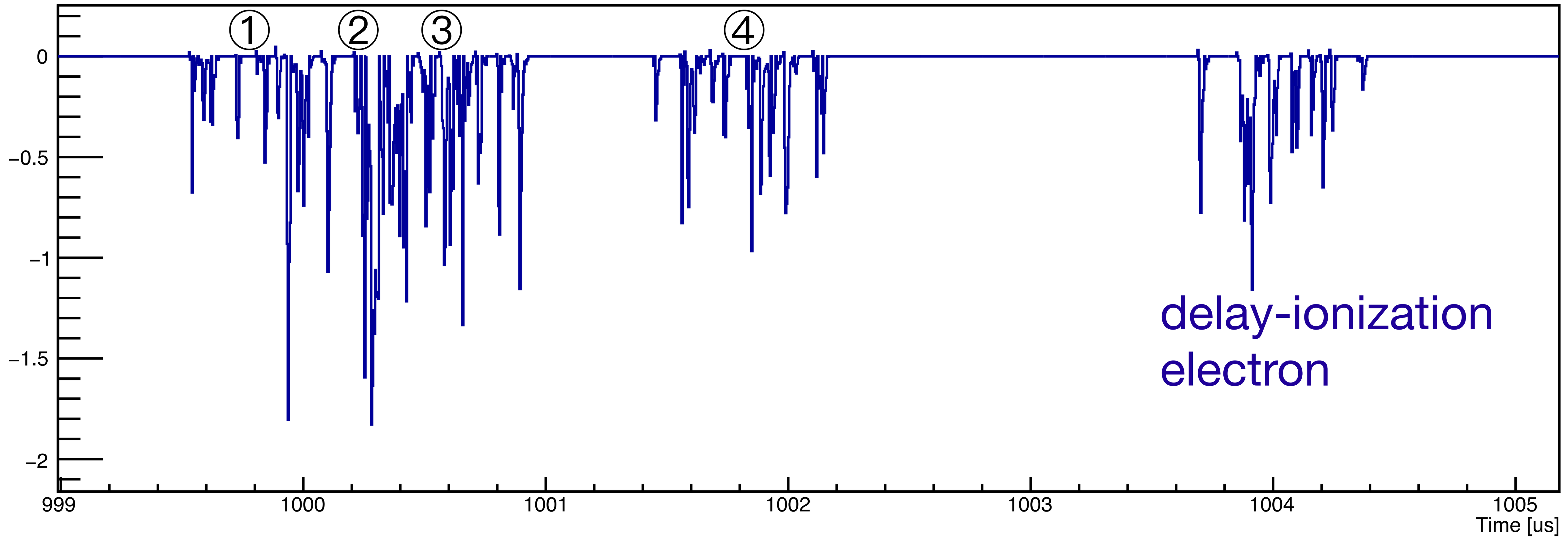
A complete simulation waveform



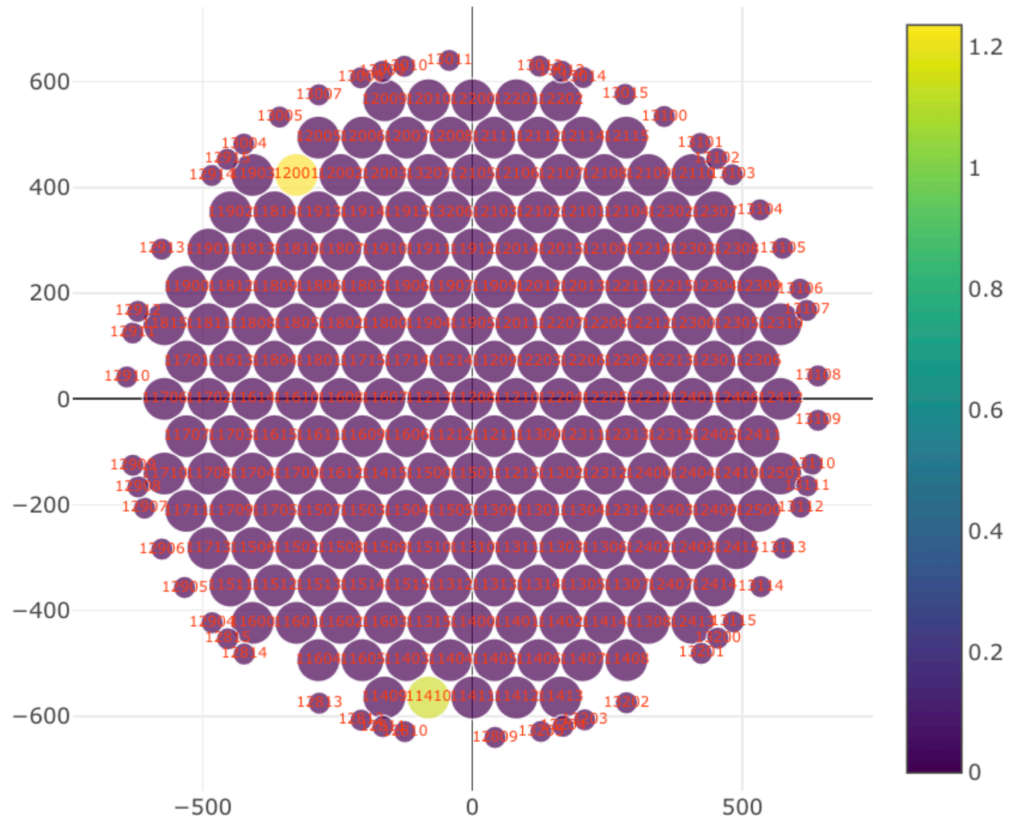
double-photon S1



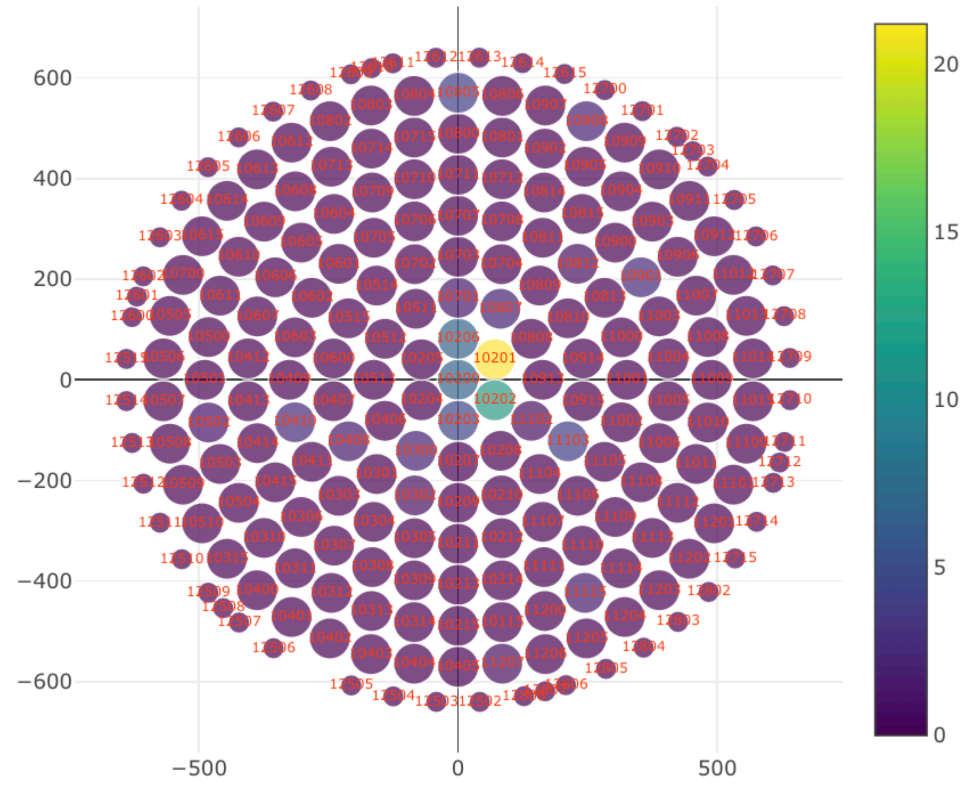
4-electron S2



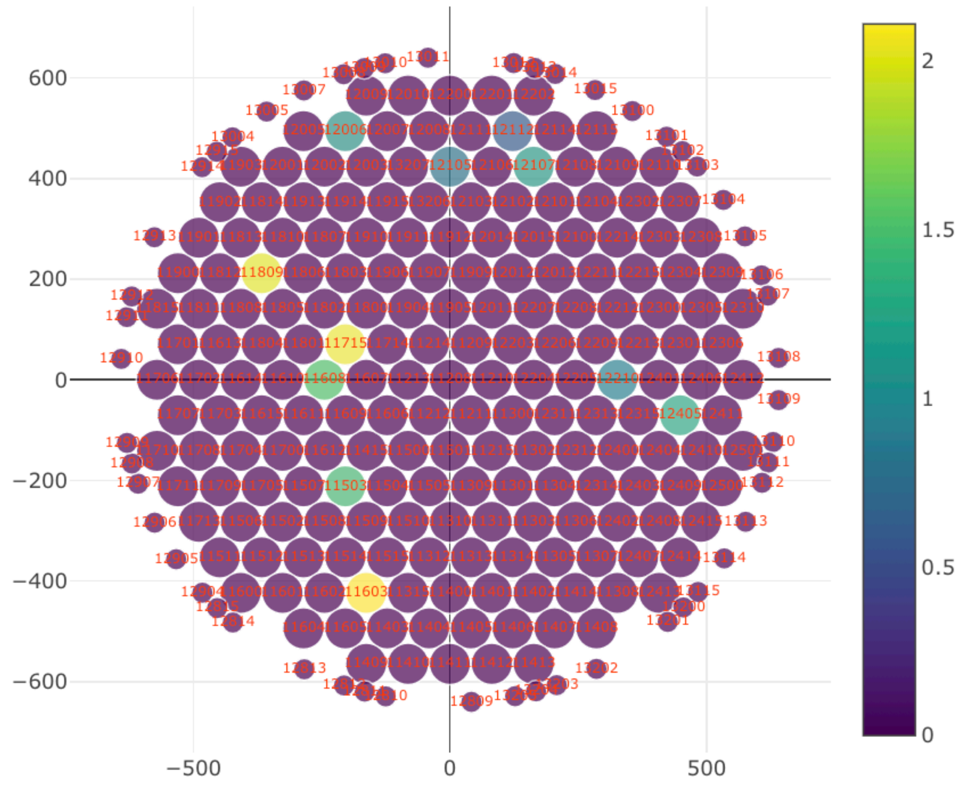
S1 pattern on the bottom array



S2 hit pattern on top

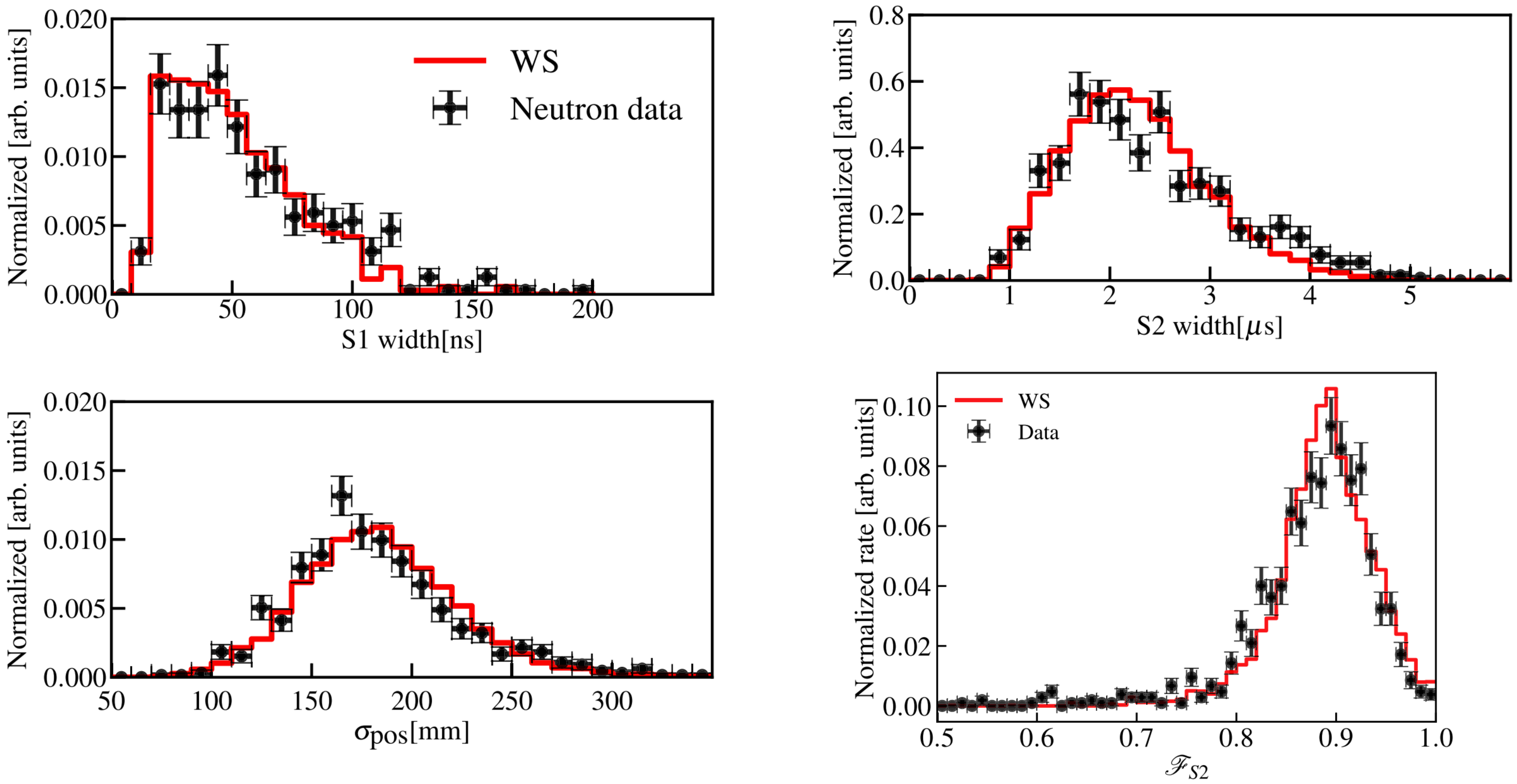


S2 hit pattern on bottom array



Waveform simulation

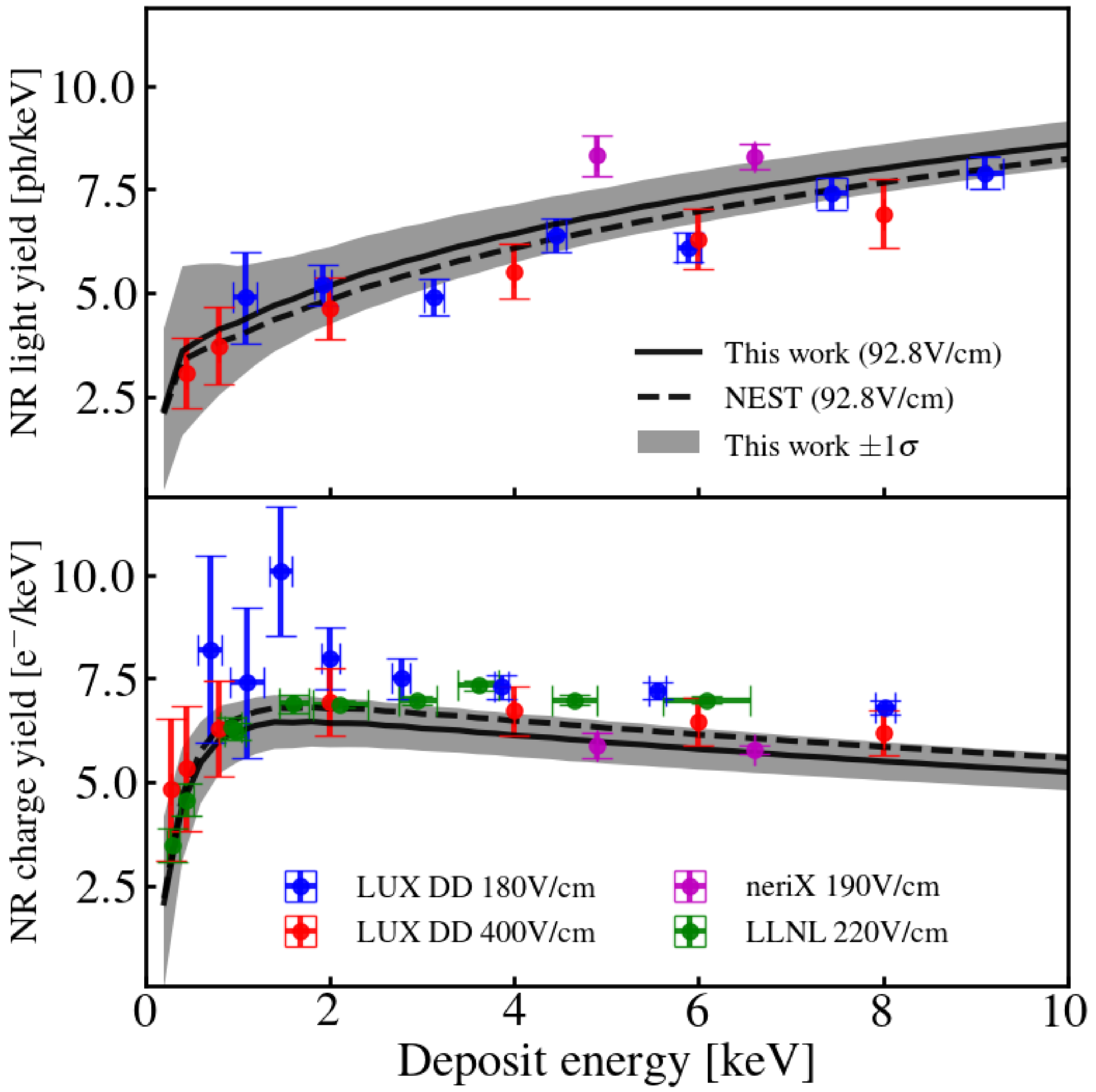
- Consistent with data on S1/S2 width, pattern, RMS, and other complicated variables
- Reweighted, and consistent with low-energy neutron calibration
- Prediction for B8 is taken as nominal



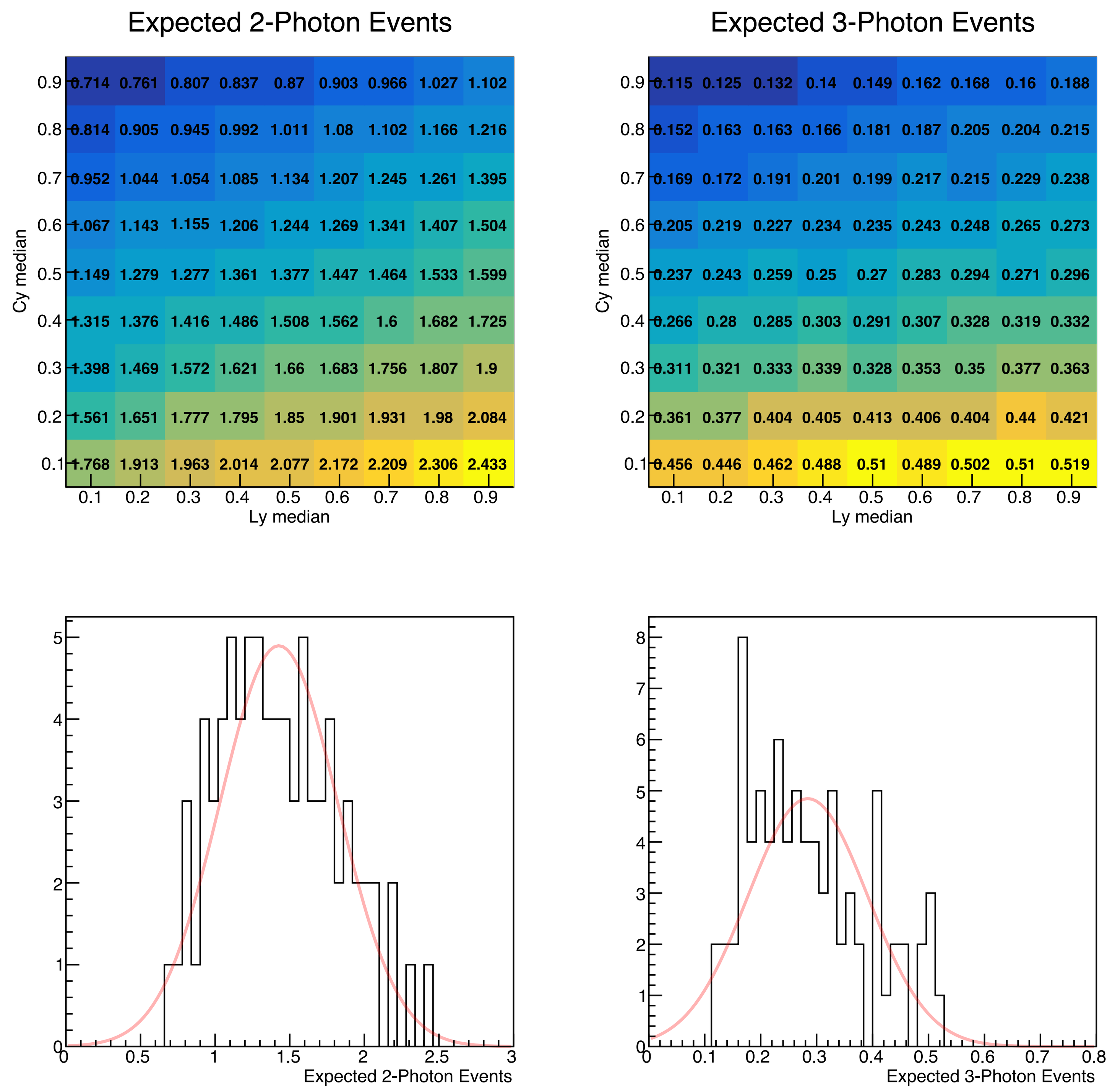
LXe light and charge yield uncertainty

- Nominal value fitted from WIMP 2021
- Uncertainty band from other experiments (NEST v2.3.6)
- Convert to counting uncertainty

Light and charge yield band



Uncorrelated analysis



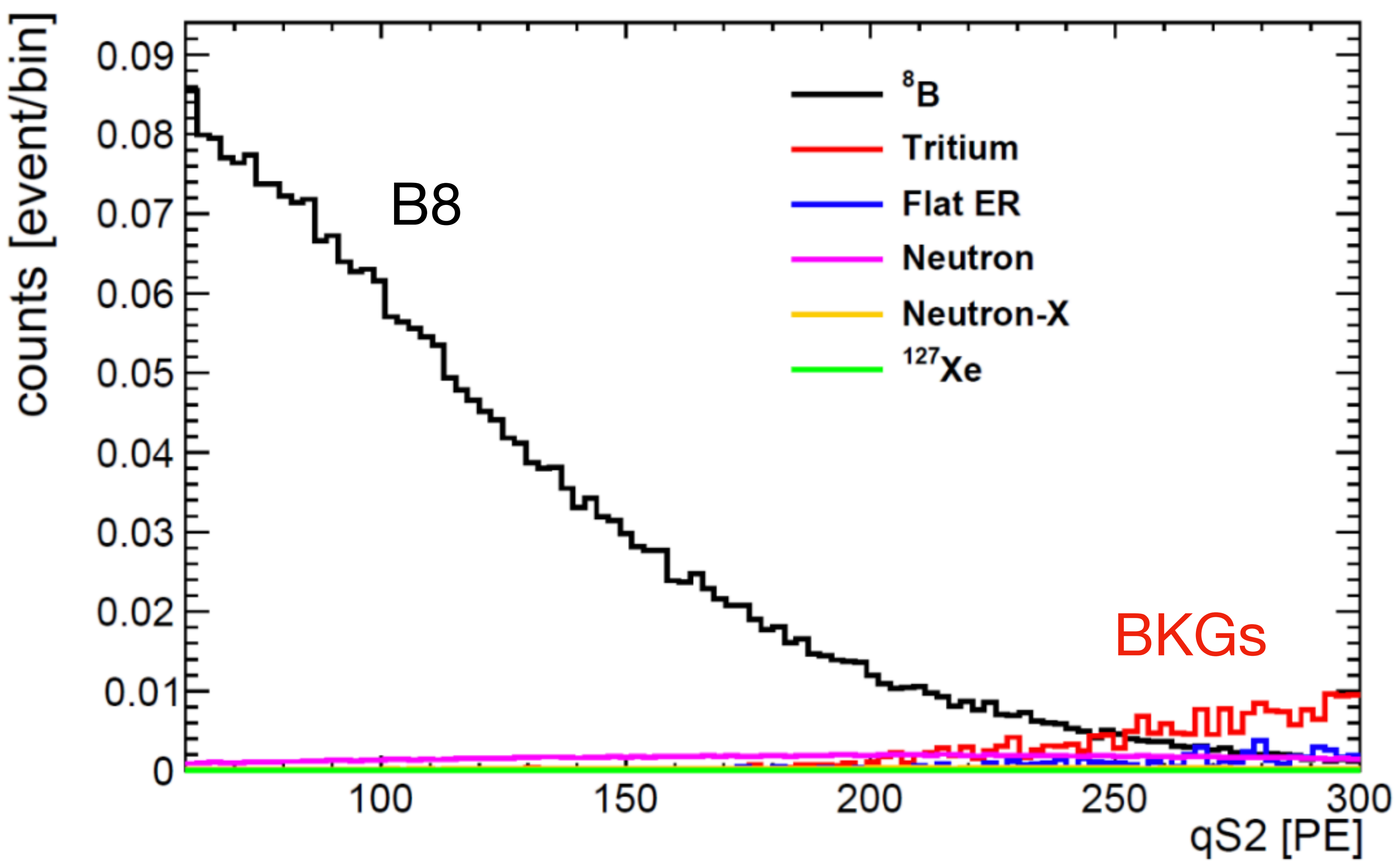
Counting uncertainty

Particle	2-hit uncertainty	3-hit uncertainty
4 GeV WIMP	0.45	0.60
B8	0.29	0.39
8 GeV WIMP	0.16	0.24

Background budget

- ER: LXe ER/NR discrimination
- NR: Different recoil energy spectrum
- Surface radioactivity: under control with the fiducial volume
- Accidental coincidence background is the real challenge

Two-hit channel S2 charge spectrum



Background budget

N-hit	S2 ROI [PE]	ER	NR	Surface	Accidental coincidence	B8
2	65-230	0.04	0.10	0.14	62.43	2.32
3	65-190	0.01	0.05	0.08	0.79	0.42

Accidental background

- Lower threshold → increase background
- Rate estimation + sample from data → prediction
- Check sideband prediction vs data, determine uncertainty

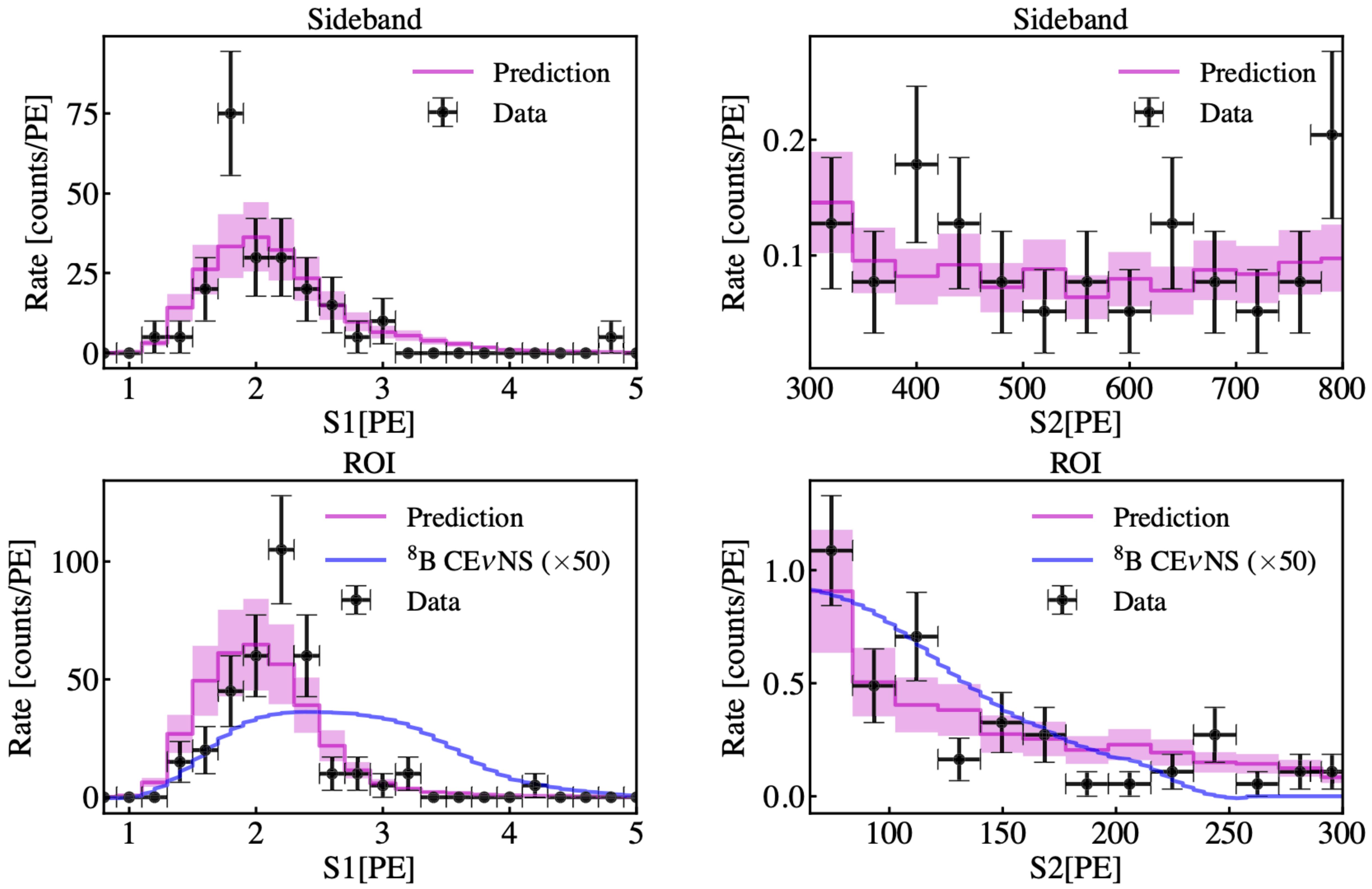
$$N_{\mathrm{AC}} = \epsilon_{\mathrm{cut}} R_{S1} R_{S2} T_{\mathrm{drift}} T_{\mathrm{livetime}}$$

Abdusalam Abdukerim et al 2022 Chinese Phys. C 46 103001

- R(S1): 6 kHz, picked from 1-ms-randomly-selected waveforms
- R(S2): ~ 1000 per day, are selected from 0.9-1.5ms offwindow
- Drift window: 760us
- Livetime: 64 days after more stringent deadtime cut

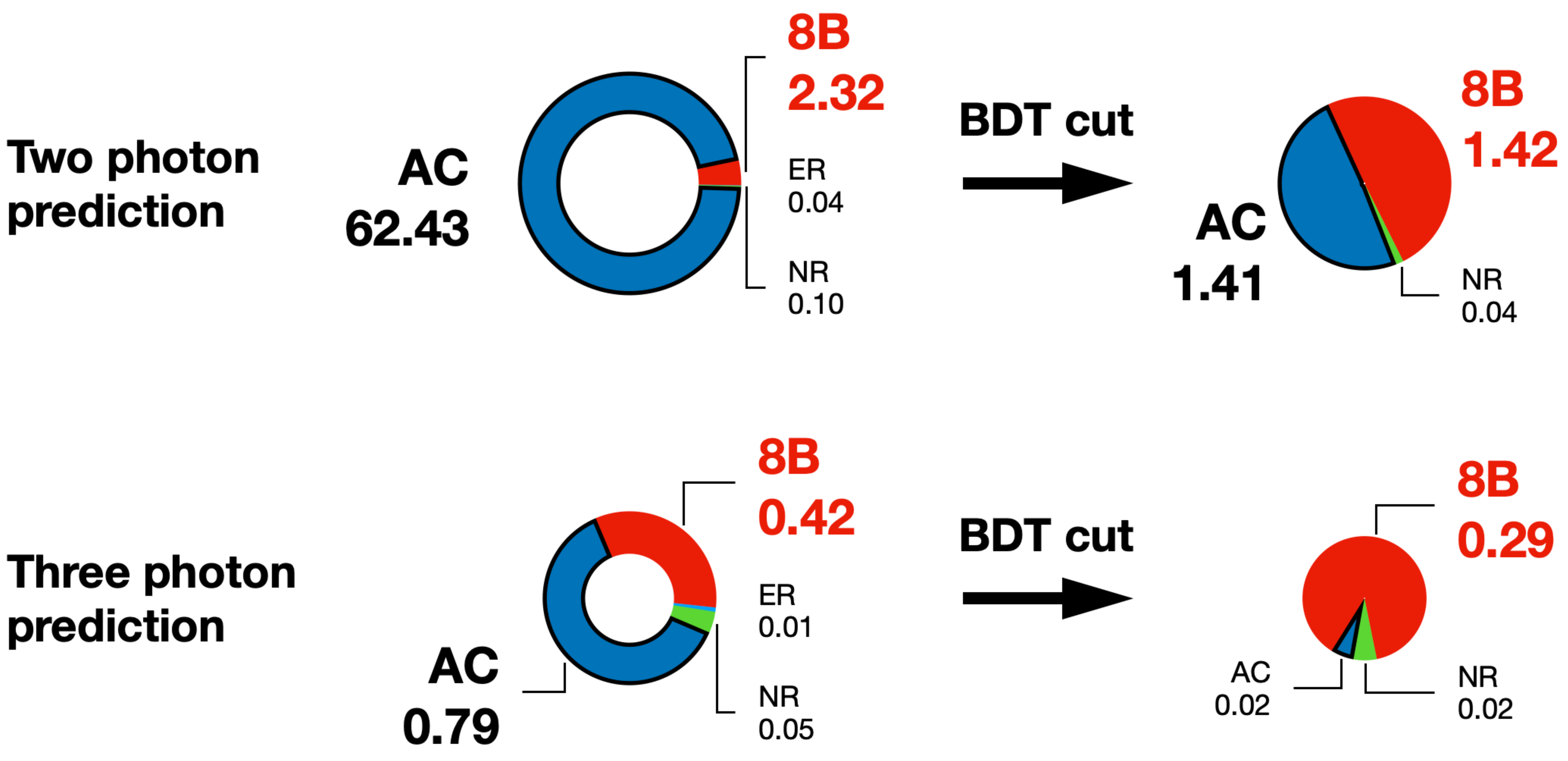
Sideband result

Number of Photons	Physical Events	Accidental Events	Total Prediction	Data
1	9.4	2060.5	2069.9	2043
2	10.1	33.8	43.9	47
3	6.9	2.2	9.1	7



Boosted decision tree

- Boosted decision tree (BDT): put tens of variables into a single value within 0 to 1
- 0: close to background; 1: close to signal
- Input variables: related to charge, width, top-bottom asymmetry and PMT top pattern of S1 and S2s (potential high-dimension correlations observed)



Unblinding procedure

- Optimize the BDT value together with S2 range (PE)
- Cross check with sideband at first
- Apply BDT on real data

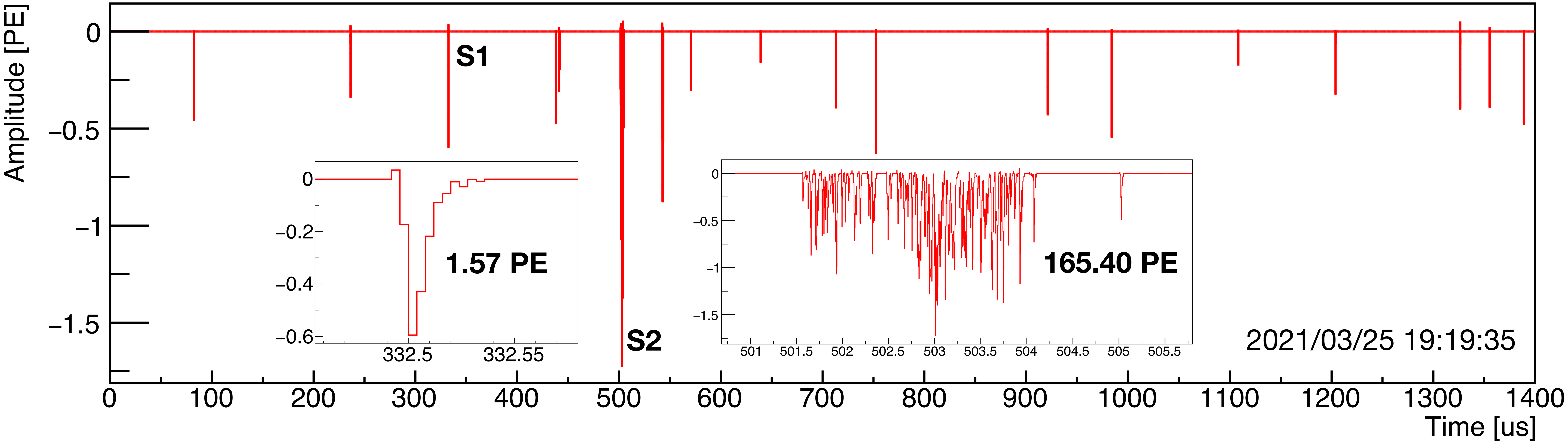
N_{hit}	$S2$ range (PE)	BDT	ER	NR	Surface	AC	Total prediction	^{8}B	Observation
2	65–230	pre	0.04	0.10	0.14	62.43	62.71	2.32	**59**
		post	0.02	0.04	0.03	1.41	1.50	1.42	**1**
3	65–190	pre	0.01	0.05	0.08	0.79	0.93	0.42	**2**
		post	0.00	0.02	0.03	0.02	0.07	0.29	**0**

Unblinding data: a well–prepared null result 😭

- Just one event was found
- 1-sigma downward fluctuation

Apply-BDT result

N-hit	Total bkg	B8	Data
2	1.50	1.42	1
3	0.07	0.29	0



Statistical interpretation

- Profile likelihood with two bins: 2-hit, 3-hit
- The data is translate to solar neutrino or WIMP seperately

Likelihood function with constrain terms

$$\mathcal{L} = G(\delta_\epsilon)G(\delta_s)G(\delta_b)G(\delta_\Phi) \times \left[\prod_i G(\delta^i_{\mathrm{BDT},s})G(\delta^i_{\mathrm{BDT},b}) \frac{\lambda_i^{N_i}}{N_i!} e^{-\lambda_i}\right]$$

neutrino

$$\lambda_i^\nu = N_\nu(1+\delta_s f_i^\nu)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},s}) + N_{\mathrm{AC}}(1+\delta_b)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},b}) + N_{\mathrm{other}},$$

DM

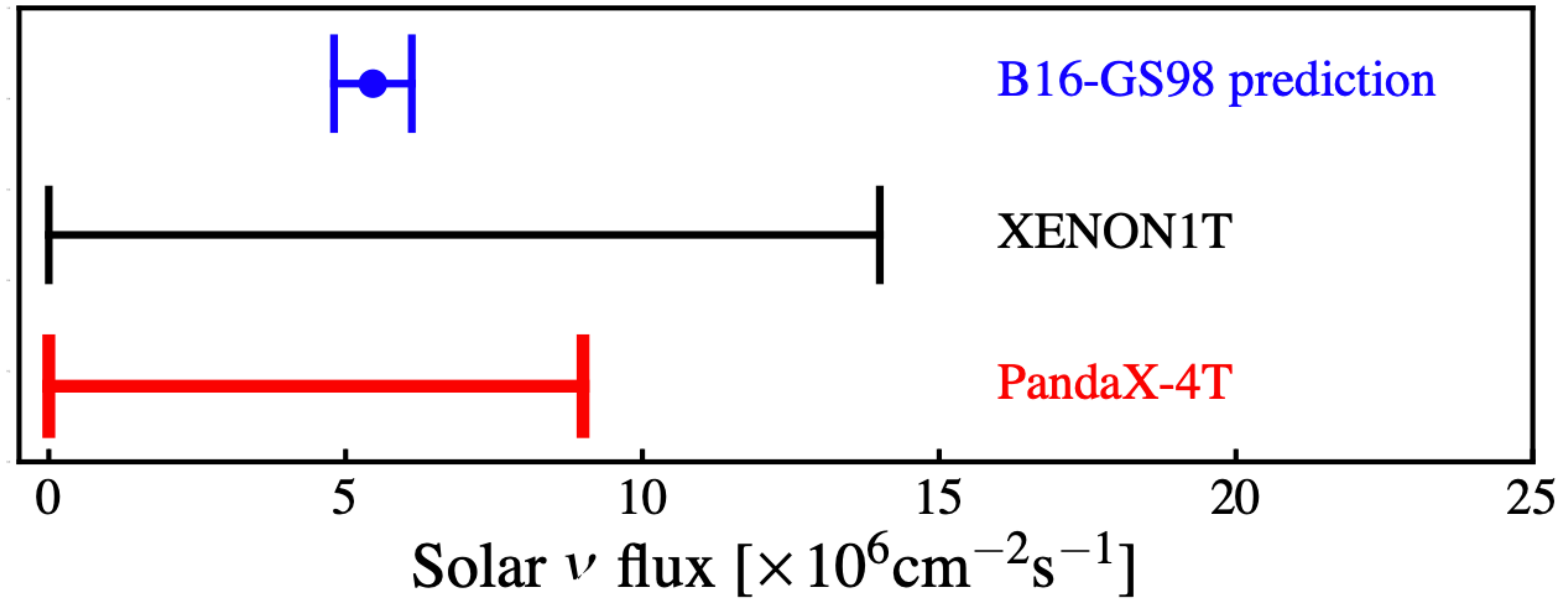
$$\lambda_i^\chi = N_\chi(1+\delta_s f_i^\chi)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},s}) + N_\nu(1+\delta_s f_i^\nu)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},s})(1+\delta_\Phi) + N_{\mathrm{AC}}(1+\delta_b)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},b}) + N_{\mathrm{other}},$$

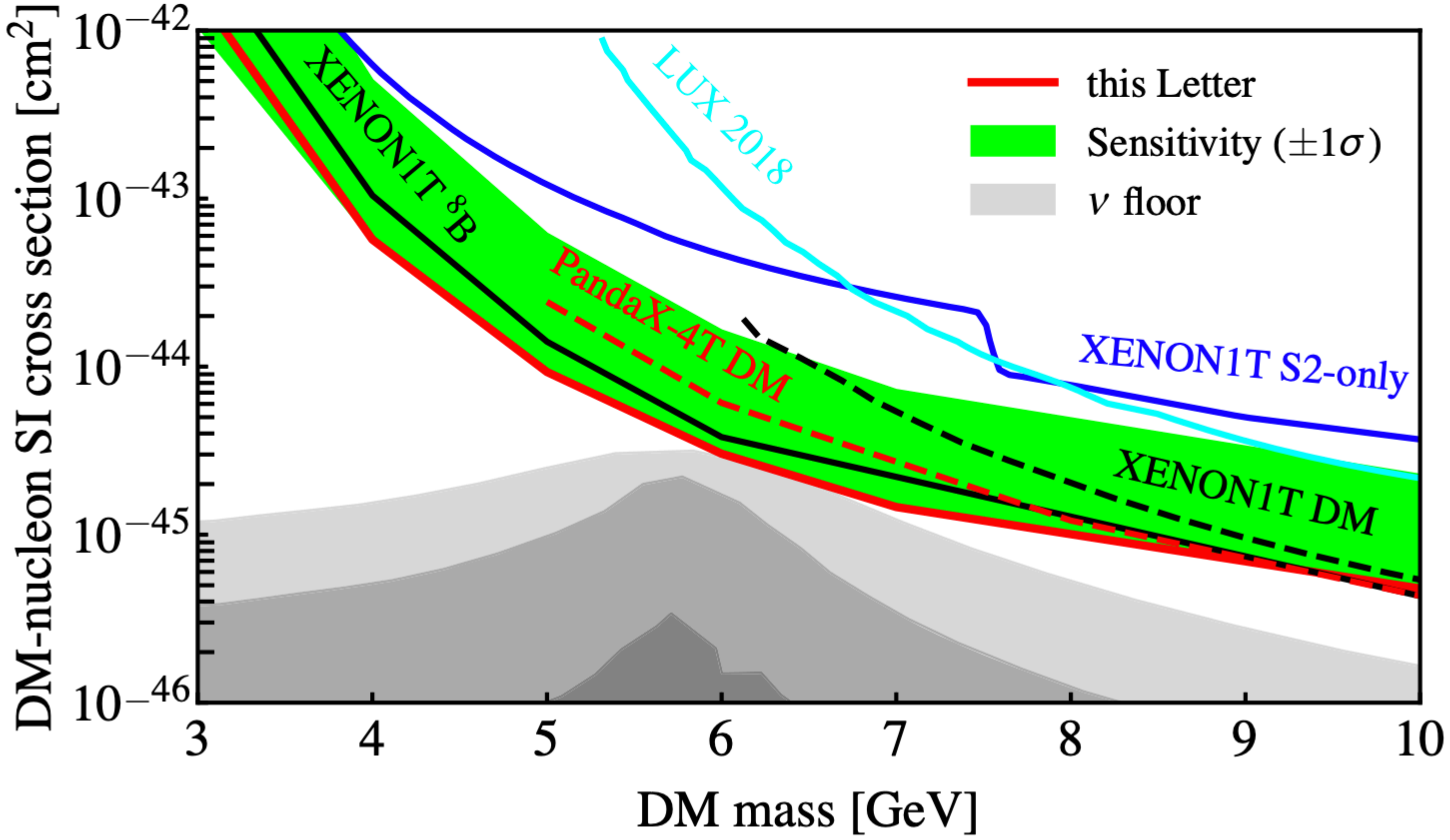
constrain terms

Uncertainties	2-hit bin	3-hit bin
quality cuts	0.14	0.14
light and charge yield	**0.29**	**0.39**
accidental bkg	**0.30**	**0.30**
BDT cut for signal	**0.14**	**0.13**
BDT cut for bkg	**0.19**	**0.18**
solar B8-v flux (SNO)	0.04	0.04

Final Constraints

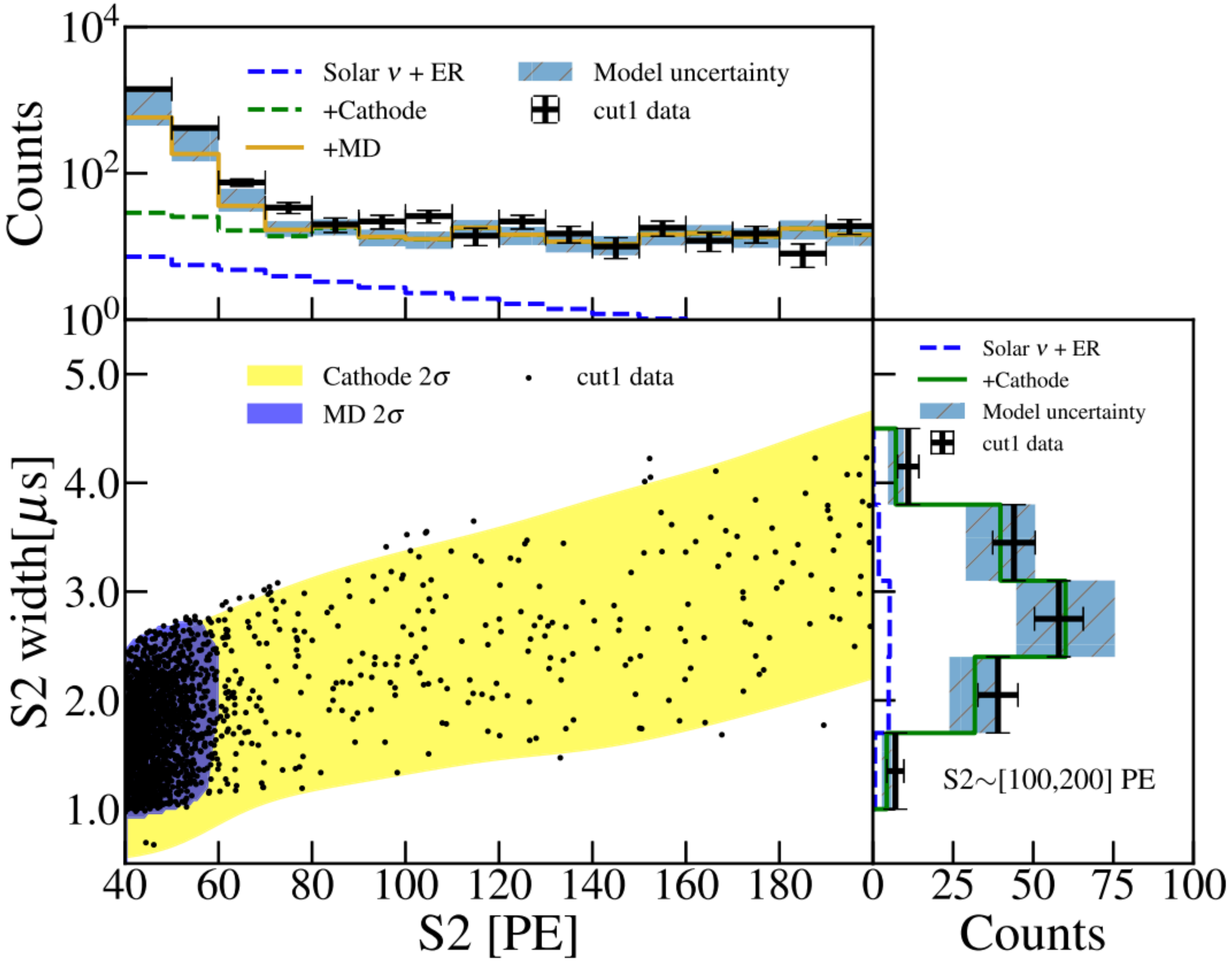
- Leading constraints on solar B8 CEvNS and 3-9 GeV WIMP

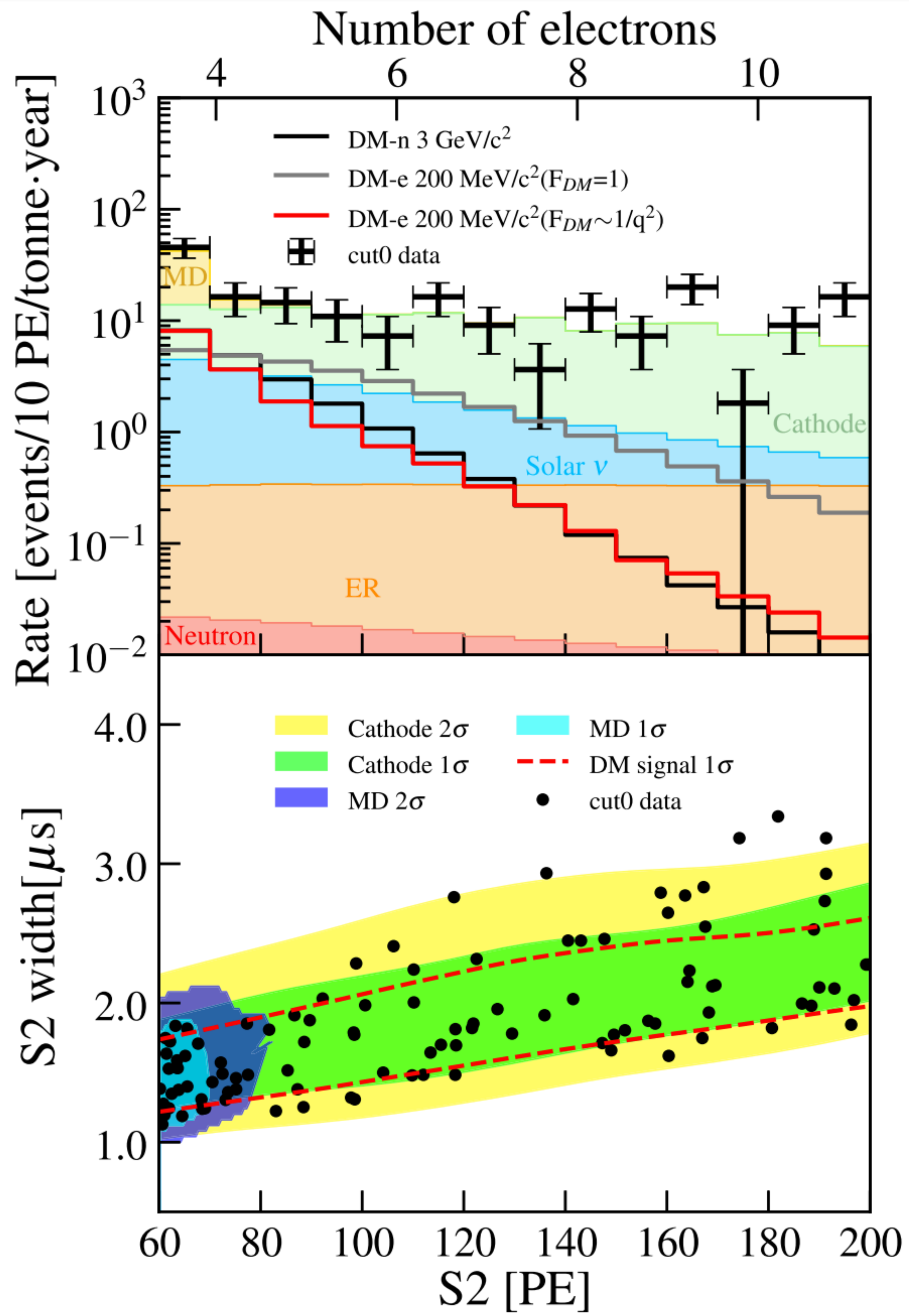




S2–only analysis and constraints

- Use consistent dataset and techniques, perform analysis on S2-only channel



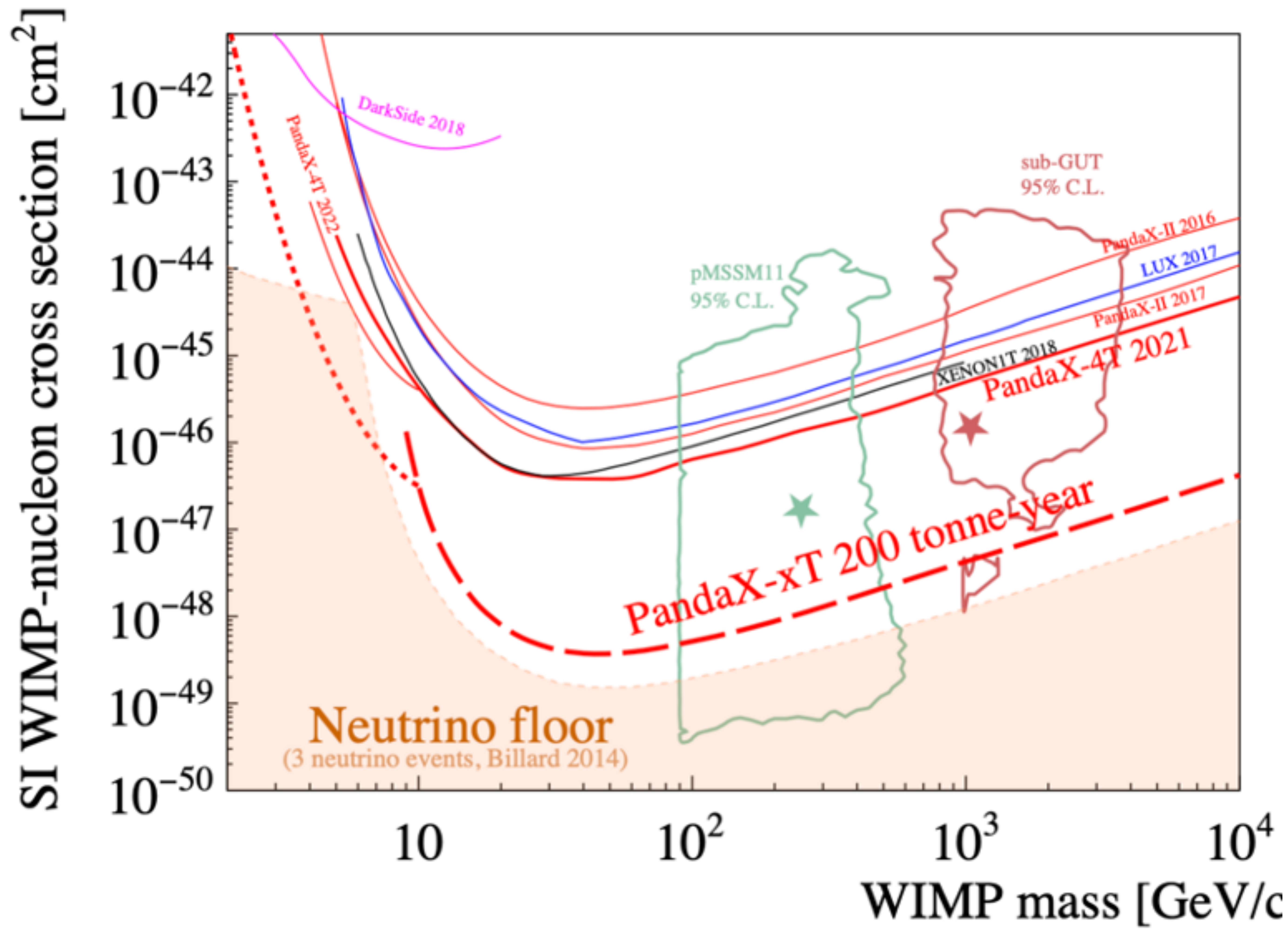


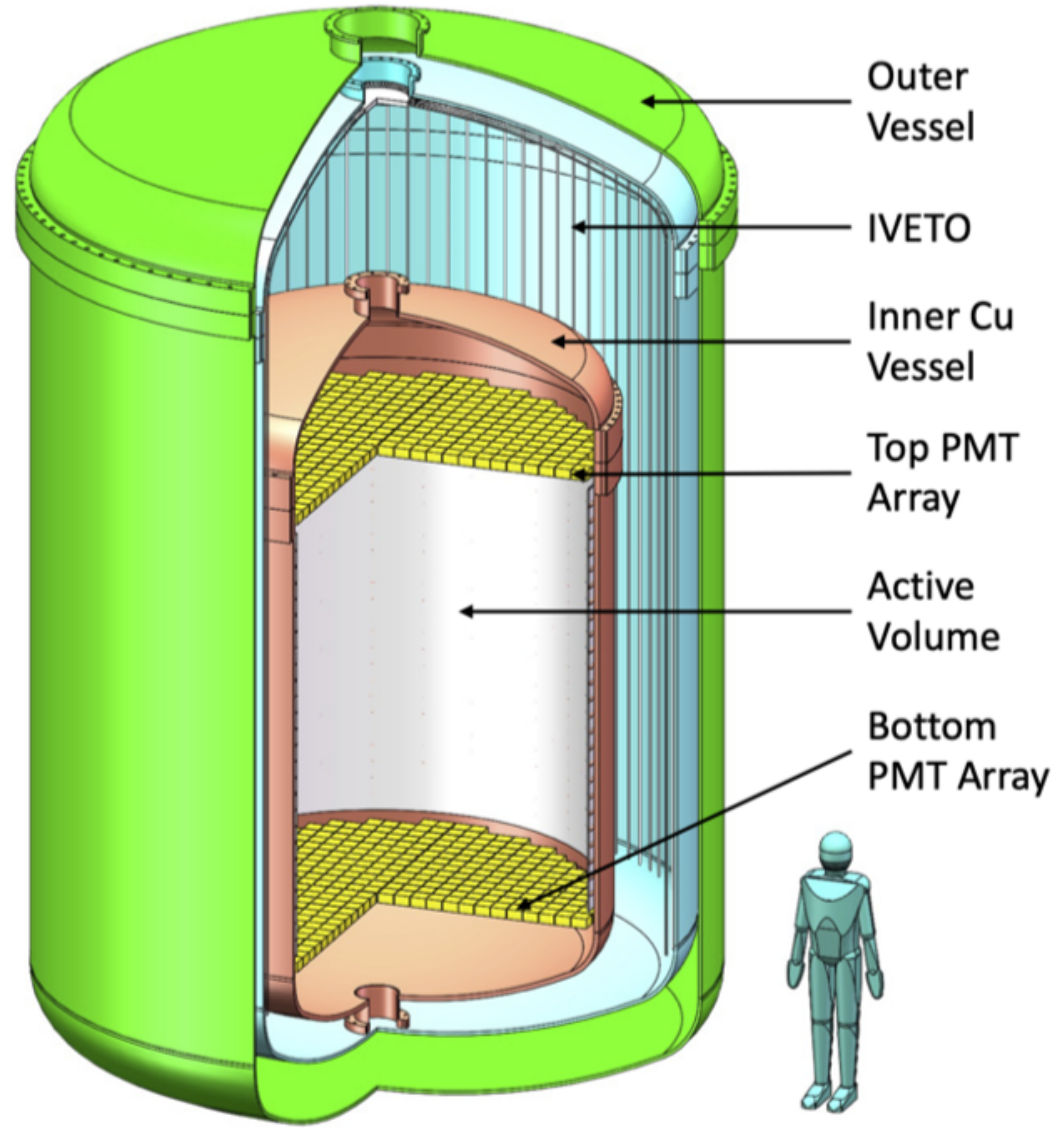
S2–only analysis and constraints

- Use consistent dataset and techniques, perform analysis on S2-only channel
- Better DM-n and DM-e constraints at low-mass region

PandaX-xT in the future

- Next generation liquid xenon experiment
- >30 tonne sensitive volume
- Decisive test on WIMP with 200 tonne-year





Summary

- PandaX-4T is pushing limits on WIMP and solar B8 v CEvNS.
- Robust hardware design enables stable data taking.
- A comprehensive waveform simulation guarantees the reliability of the s/b discrimination.

Backup

Complete analysis chain

- Low-level detector response is crucial for searching 8B
- Discriminate physical events out of noise
- Cuts suppress background
- Validated the complete process using data-driven waveform simulation

Photon detection (J. Yang et al 2022 JINST 17 T02004) → **waveform** → **Baseline correction** → **hit** → **Hit clustering** → **signal** → **Signal tagging**

- Low level efficiency

S1,S2,others → **Physical S1/S2 identification** → **event** → **Event build**

- Correctly identify S1-S2 pair out of dark noise, random electrons, sparking...

→ **Deadtime** → **Quality cut** → **BDT cut** → **Final candidates**

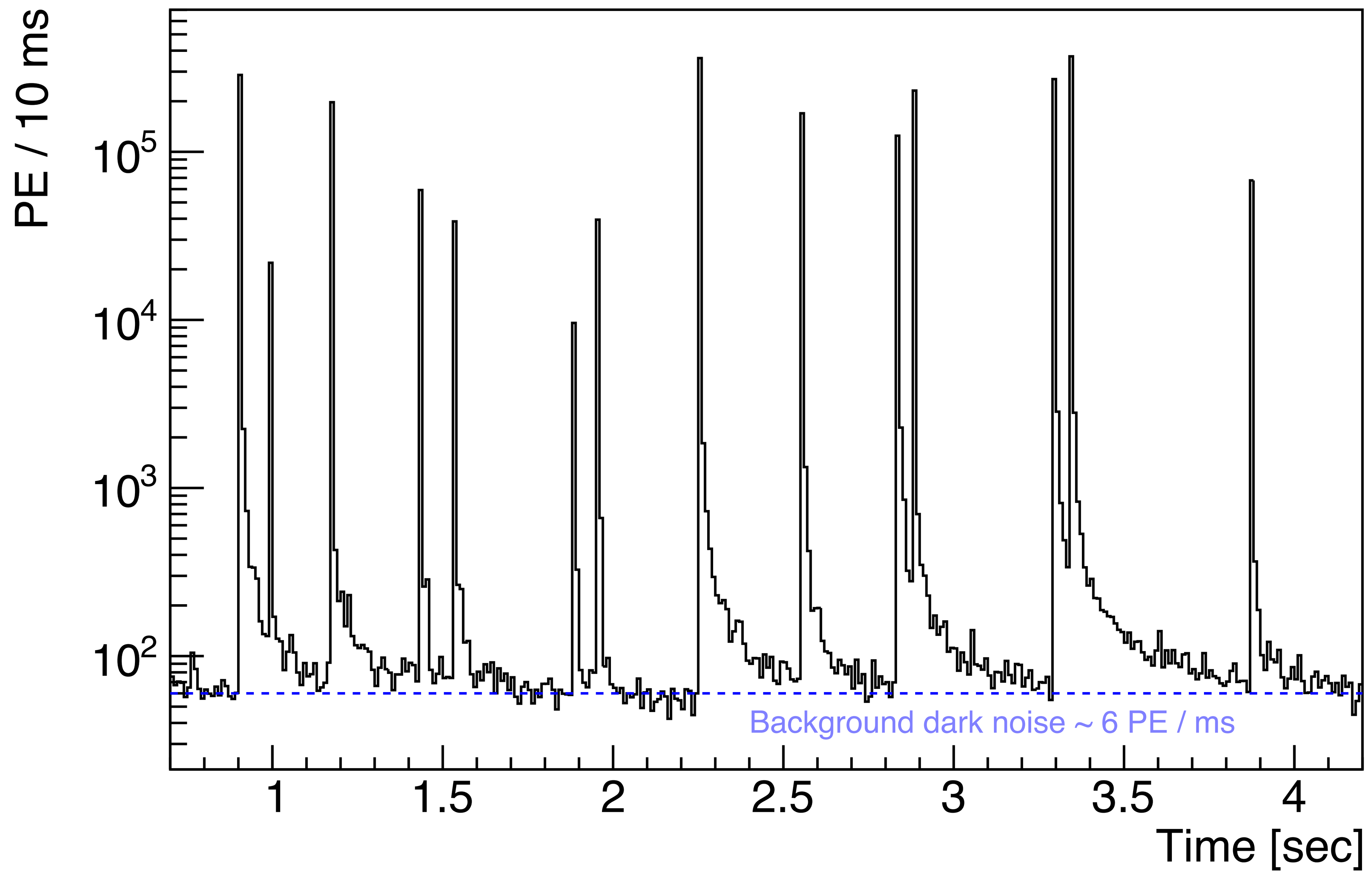
Deadtime:
- Reduce exposure

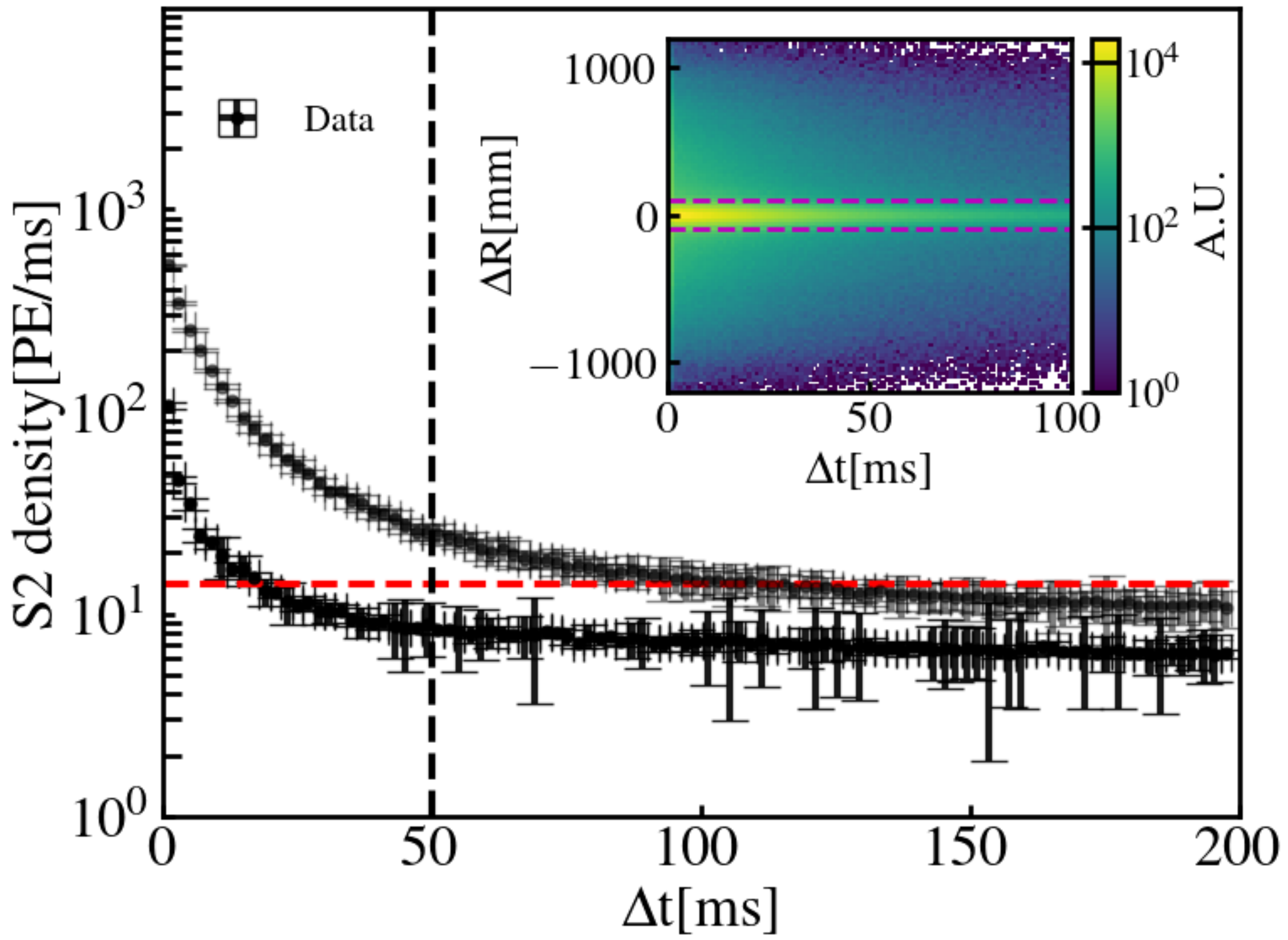
Quality cut:
- Fiducial volume
- multi-scattering veto
- S2 diffusion
- waveform cleanliness cuts

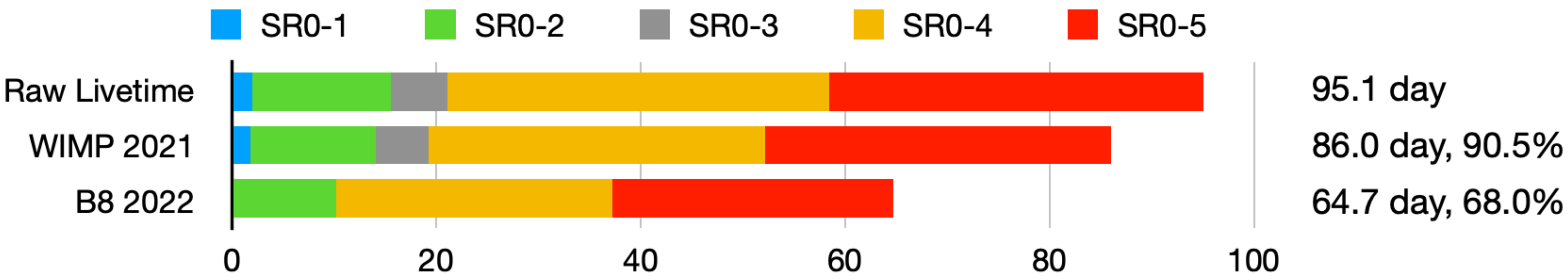
BDT cut:
- Optimize s/b

Deadtime Effect

- ~ 3% Bad data files with excessive noise
- 7 live days with excessive micro-discharge
- High-charge period induced by tail of large signals







Unblinded event

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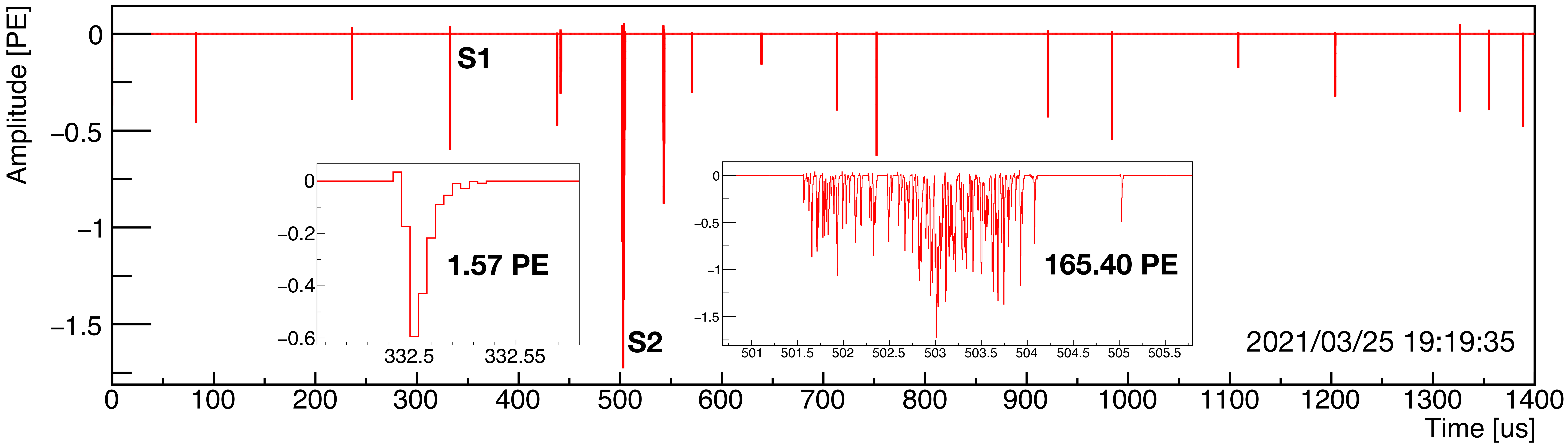
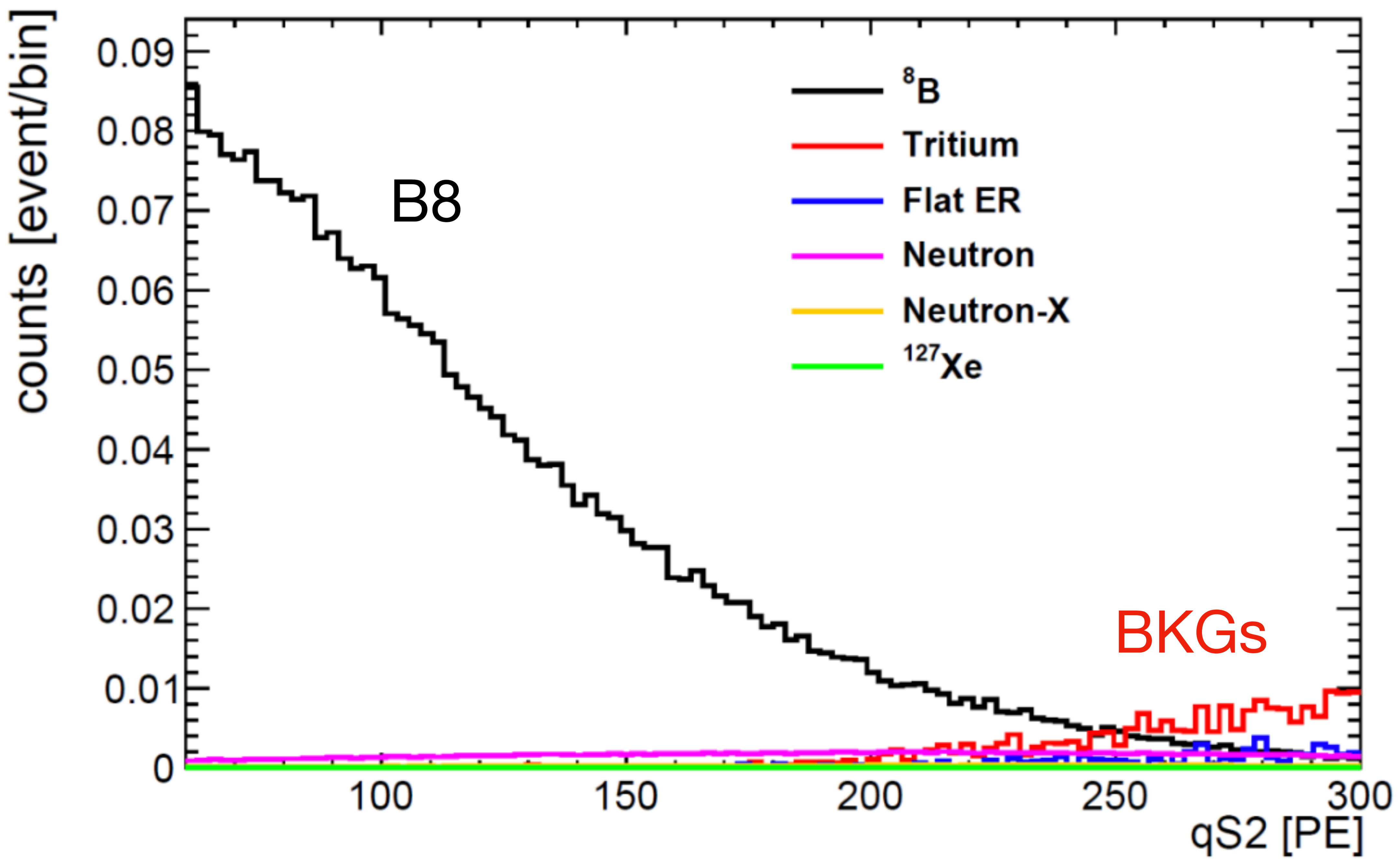
		post	0.02	0.04	0.03	1.41	1.50	1.42	**1**
3	65–190	pre	0.01	0.05	0.08	0.79	0.93	0.42	**2**
		post	0.00	0.02	0.03	0.02	0.07	0.29	**0**



Physical background

Two-photon channel



Three-photon channel