Overview of direct DM detections

26 Sep 2023

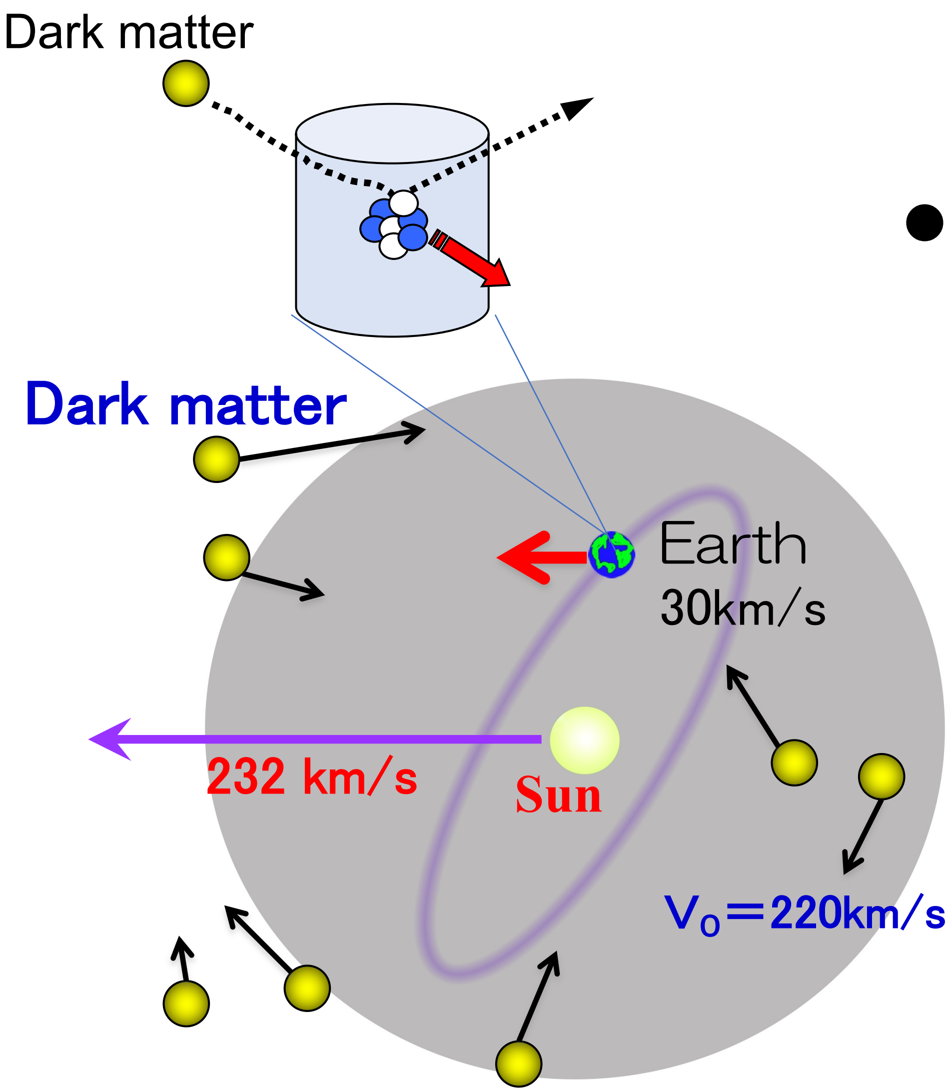
The 3rd DMnet symposium

"Dark Matter Studies in Accelerator Physics"

Yoshitaka Itow

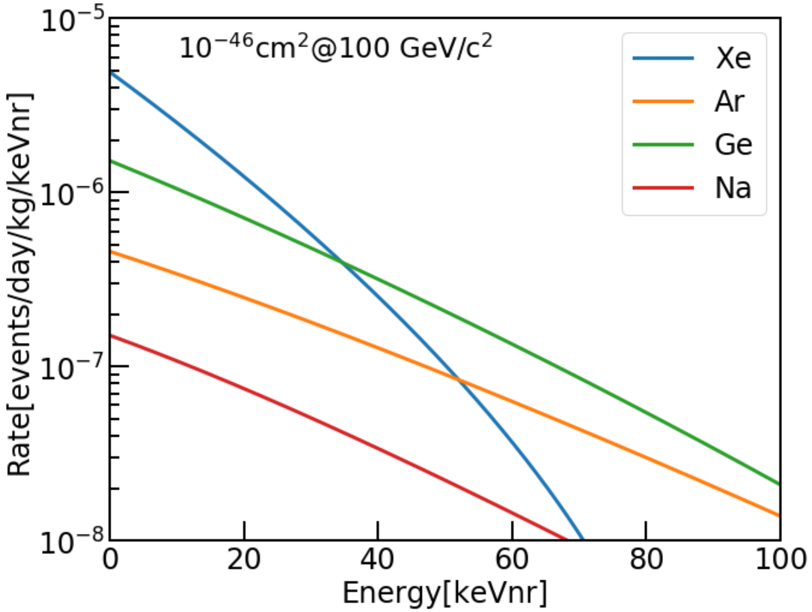
ISEE/KMI Nagoya University

Direct detection of particle dark matter



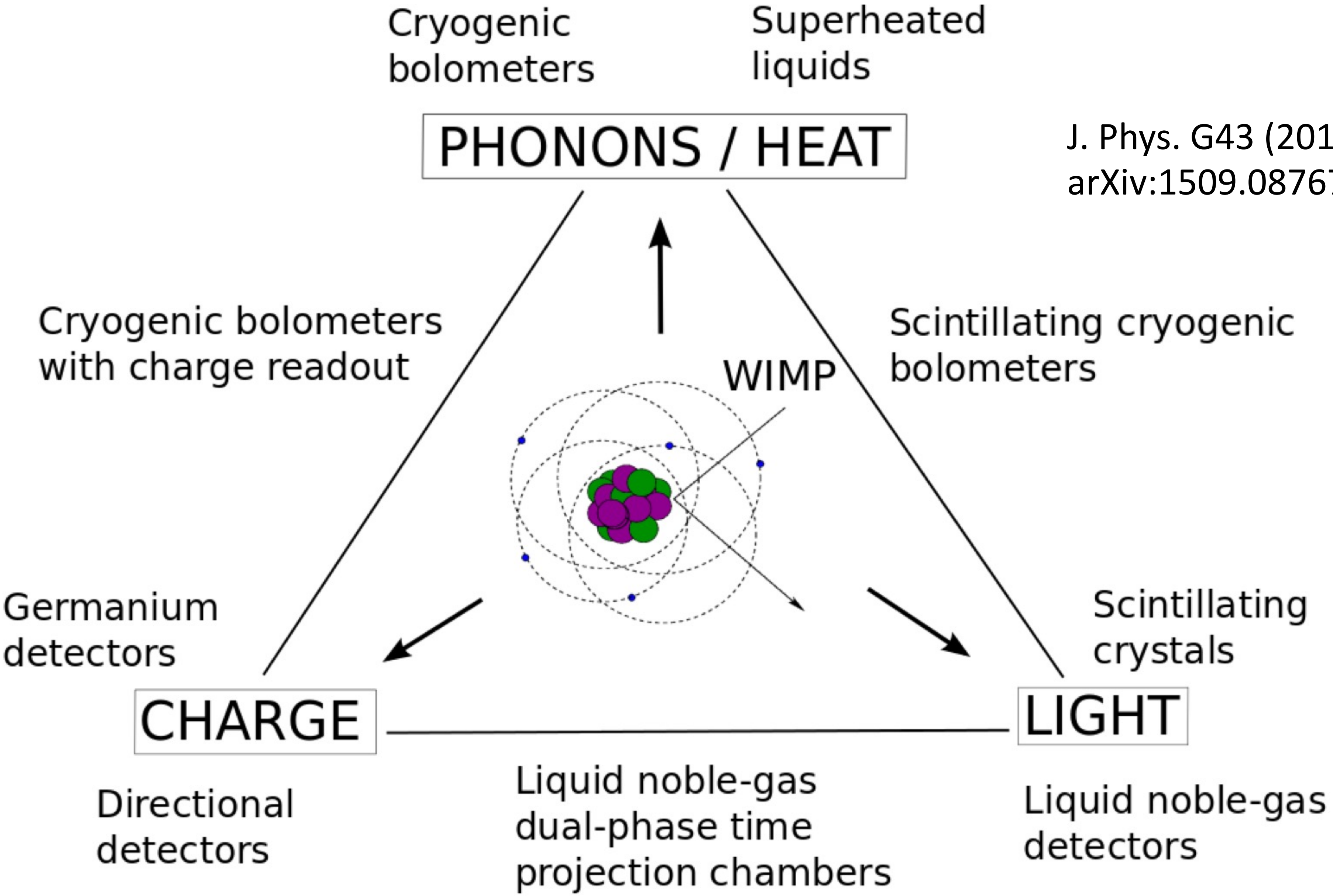
- Dark matter must be an unknown new particle
  - *Weakly Interacting Massive Particle (WIMP)*
  - *Or maybe some other new particles ?*
- Dark matter scattering off an atom can be detected by an ultra low-BG, low-threshold, massive detector

→ "Direct detection" gives a most clear evidence



Direct detection : Technology

J. Phys. G43 (2016) 1, 013001 &
arXiv:1509.08767



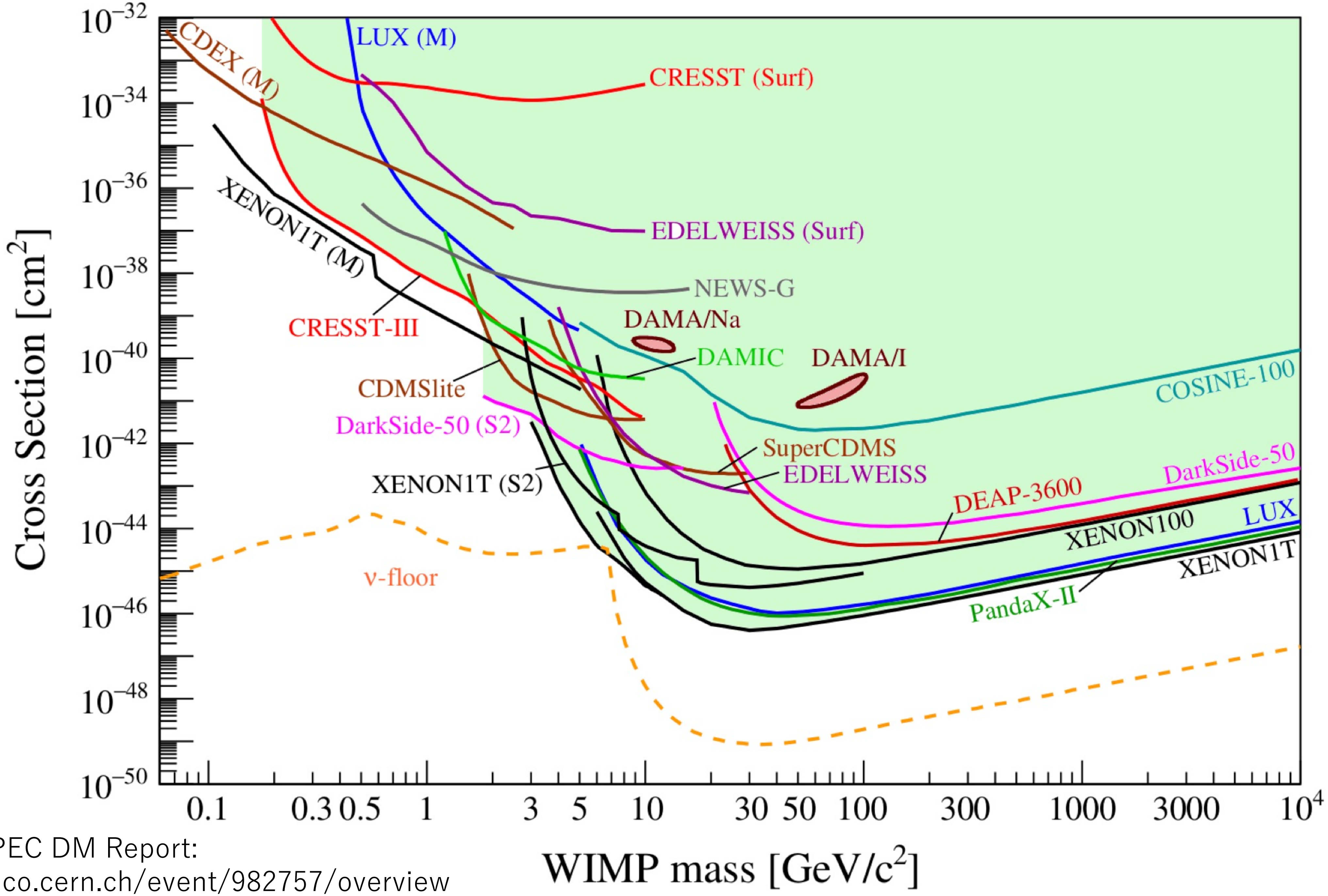
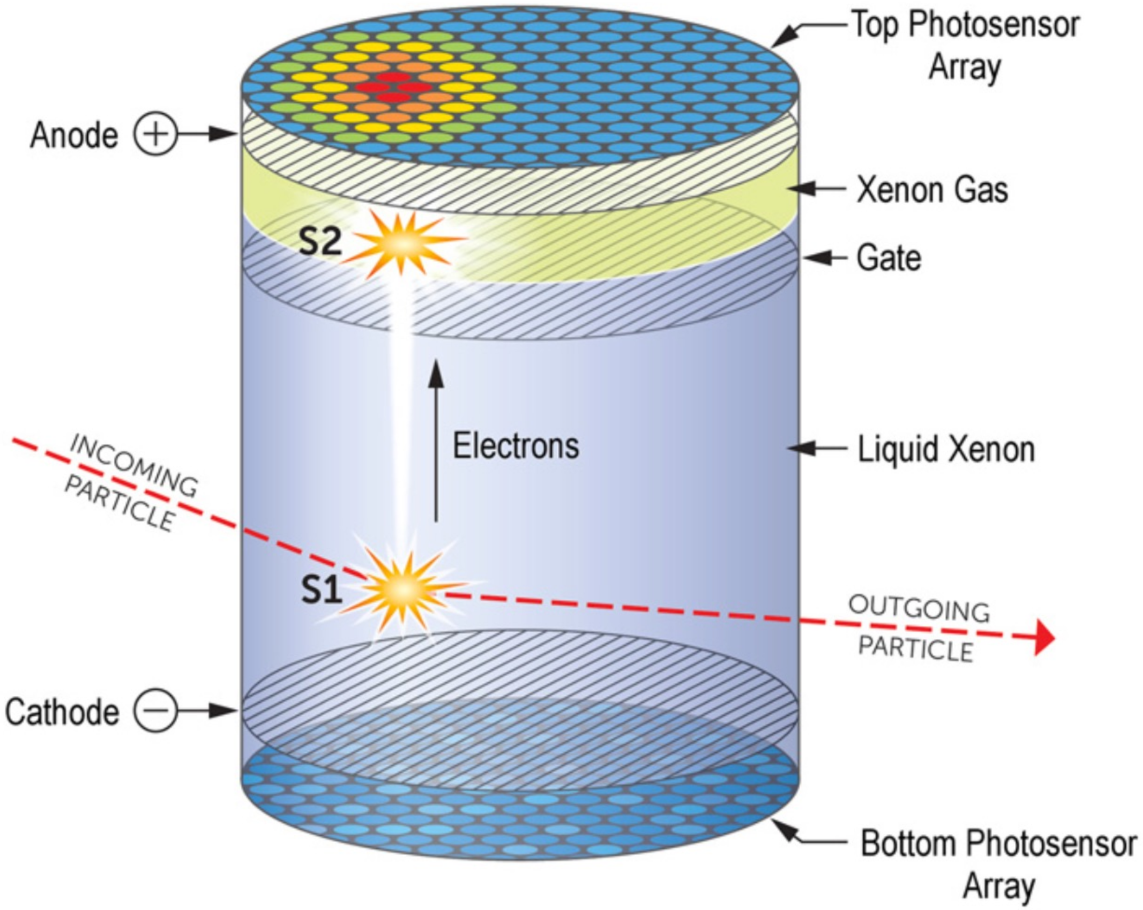


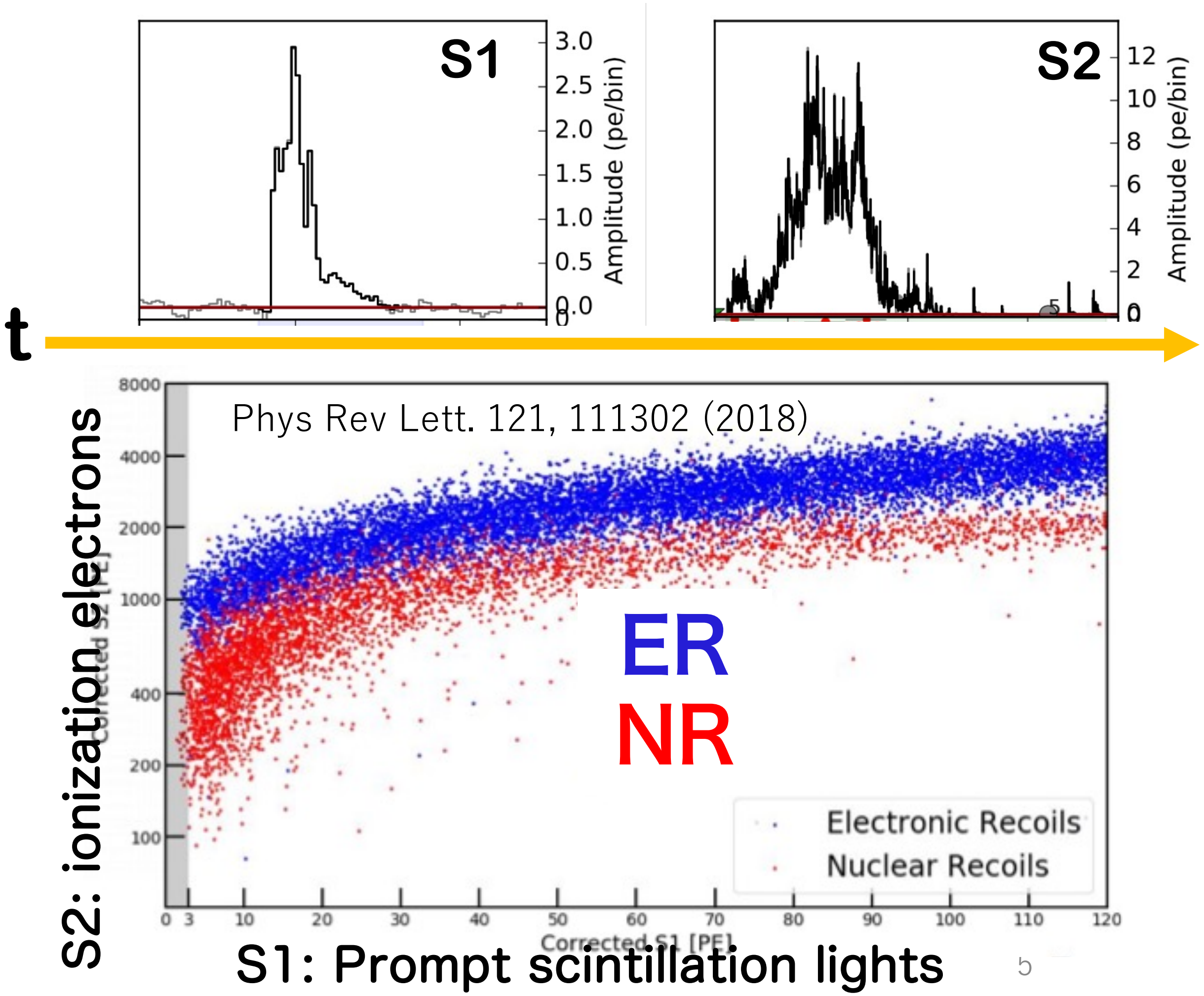
Figure: APPEC DM Report:
https://indico.cern.ch/event/982757/overview

Liquid/Gas 2-phase Time Projection Chamber

- Prompt scintillation lights (S1) and delayed proportional scintillation lights (S2)
- S1-S2 time difference → Z position, S2 spatial profile → X-Y position
- S1/S2 ratio → Discrimination of nuclear recoil (NR) from electron recoil (ER)



J. Phys. G. Nucl. Part. Phys 50 (2023) 013001



Generation-1 Direct DM detectors O(1t) (~2019)

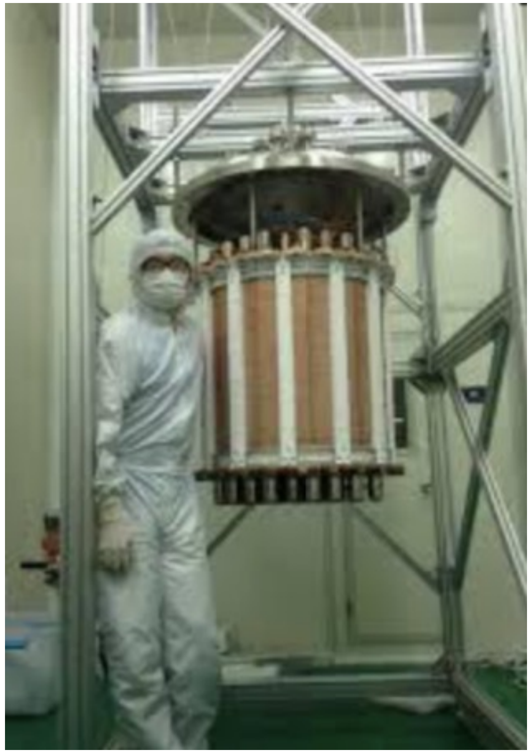
XENON1T(1t LXe)

Italy・GranSasso

LUX (370kg LXe)

USA・Sanford

Panda-X (580kg LXe)



China・Jinping

Generation-2 Direct DM detectors O(10t) (2020-)

XENONnT (5.9t LXe)

©XENON Collaboration

Italy・Gran Sasso

LZ (7t LXe)

©Nick Hubbard, Sanford Underground Research Facility

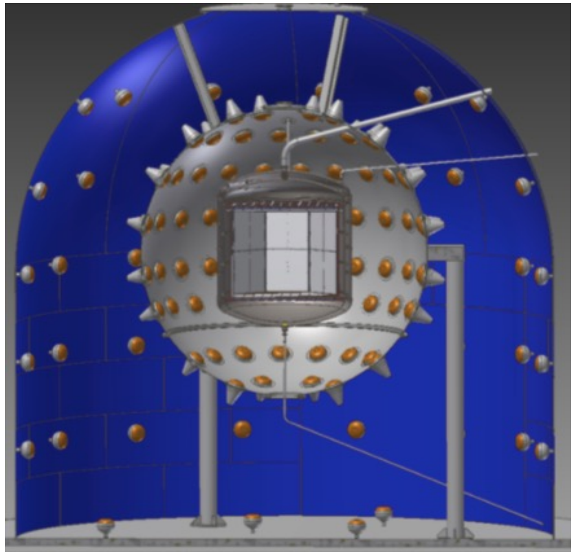
USA・Sanford Lab

PandaX-4T (3.7t LXe)

©PandaX Collaboration

China・Jinping

DarkSide-20k(23t LAr)



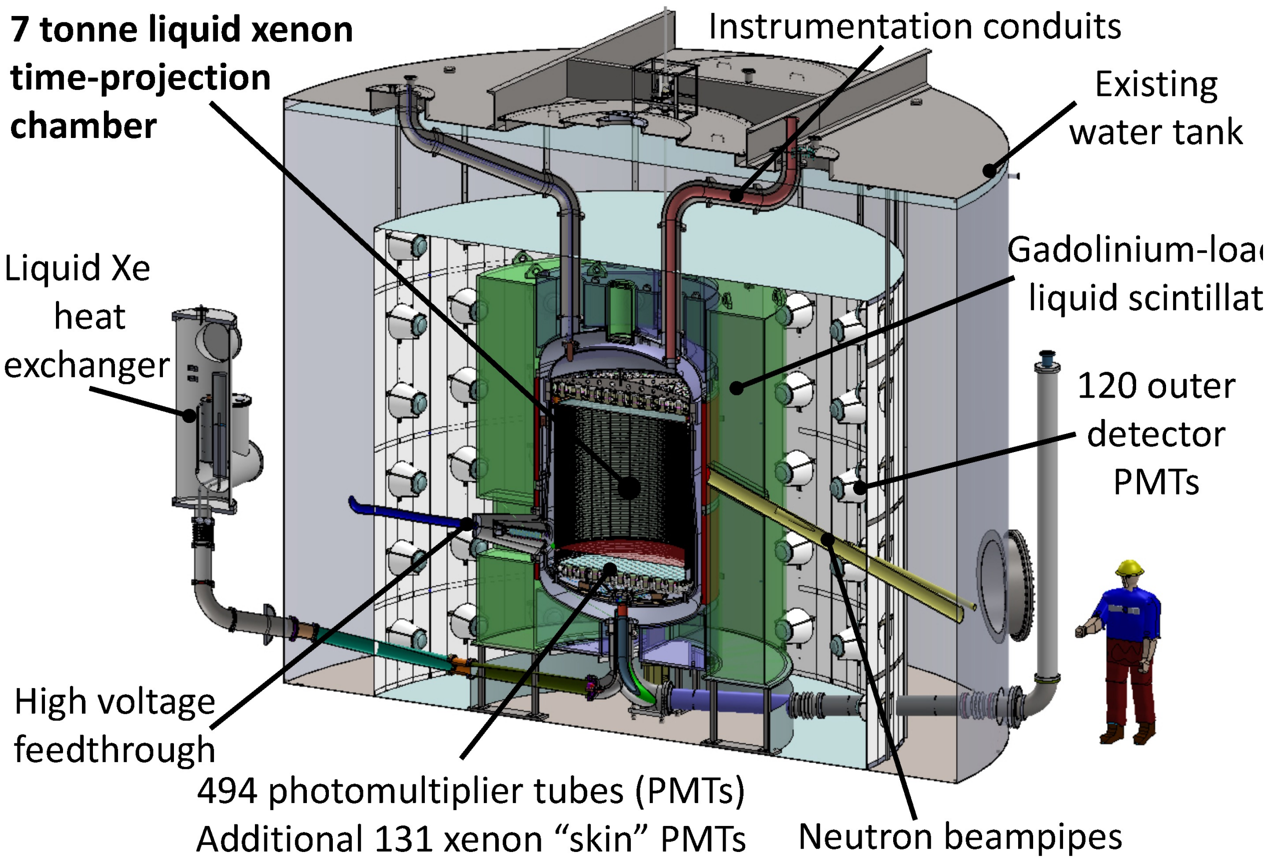
Eur. Phys. J. Plus (2018) 133: 131

Italy・Gran Sasso

LZ experiment

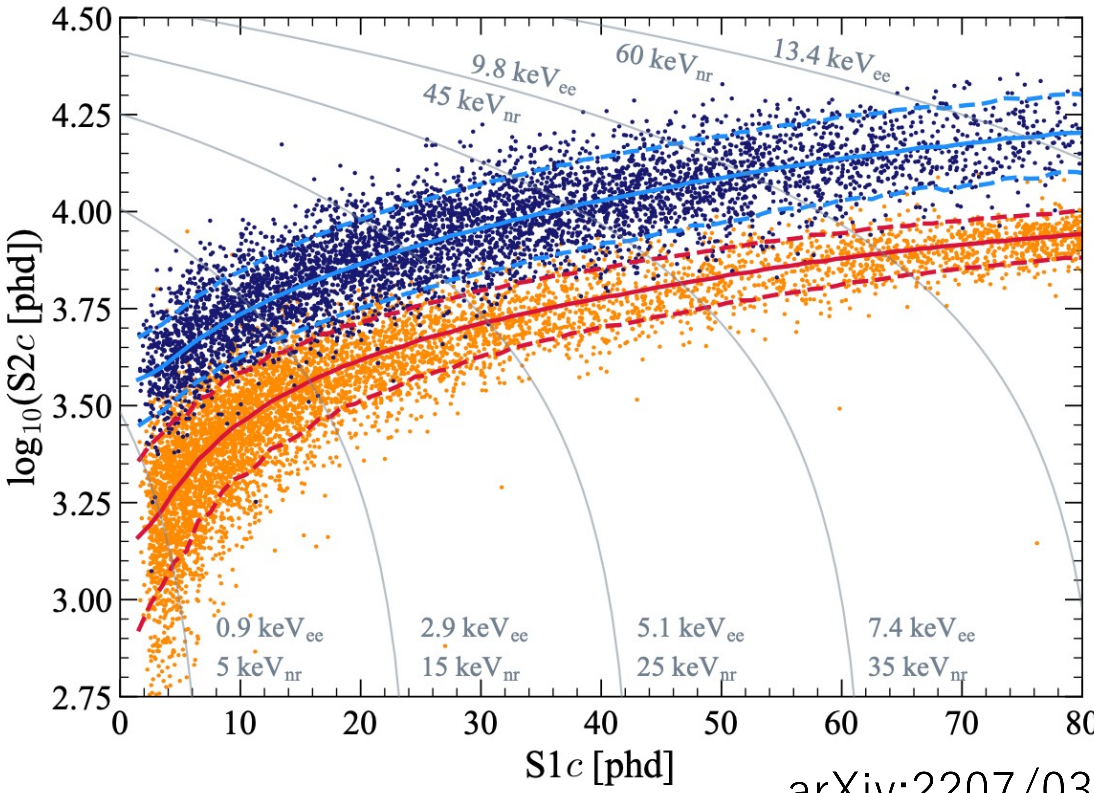
- 7-ton LXe TPC w/ a 193 V/cm drift field
- Gd-loaded lq. scintillator for neutron veto
- 238t pure water active muon veto

The LZ Detector



https://lz.lbl.gov/detector/

- ER calibrated by ^{83m}Kr, ^{131m}Xe, and CH_3T (post-search)
- NR calibrated by D-D neutrons

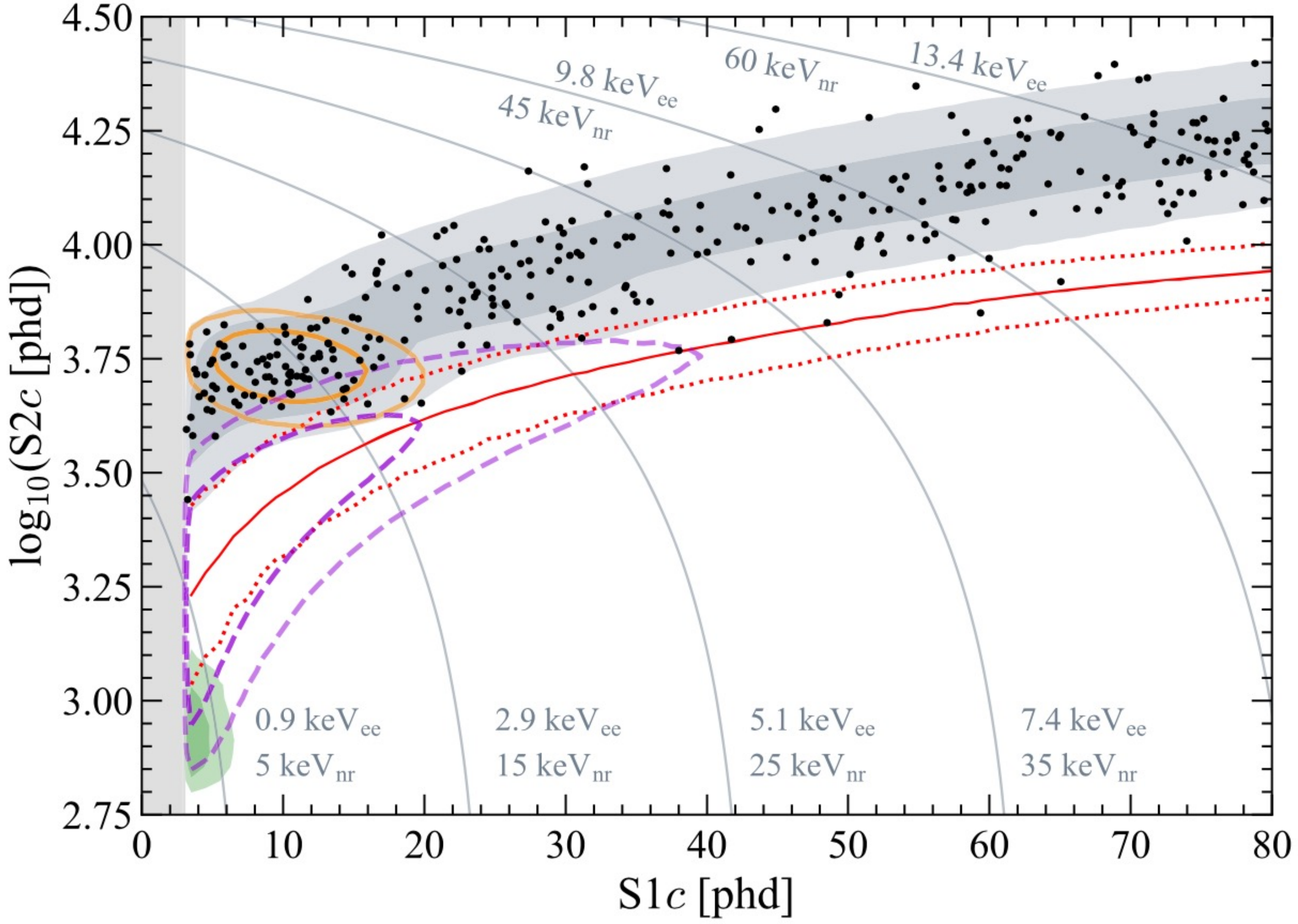


arXiv:2207/03764

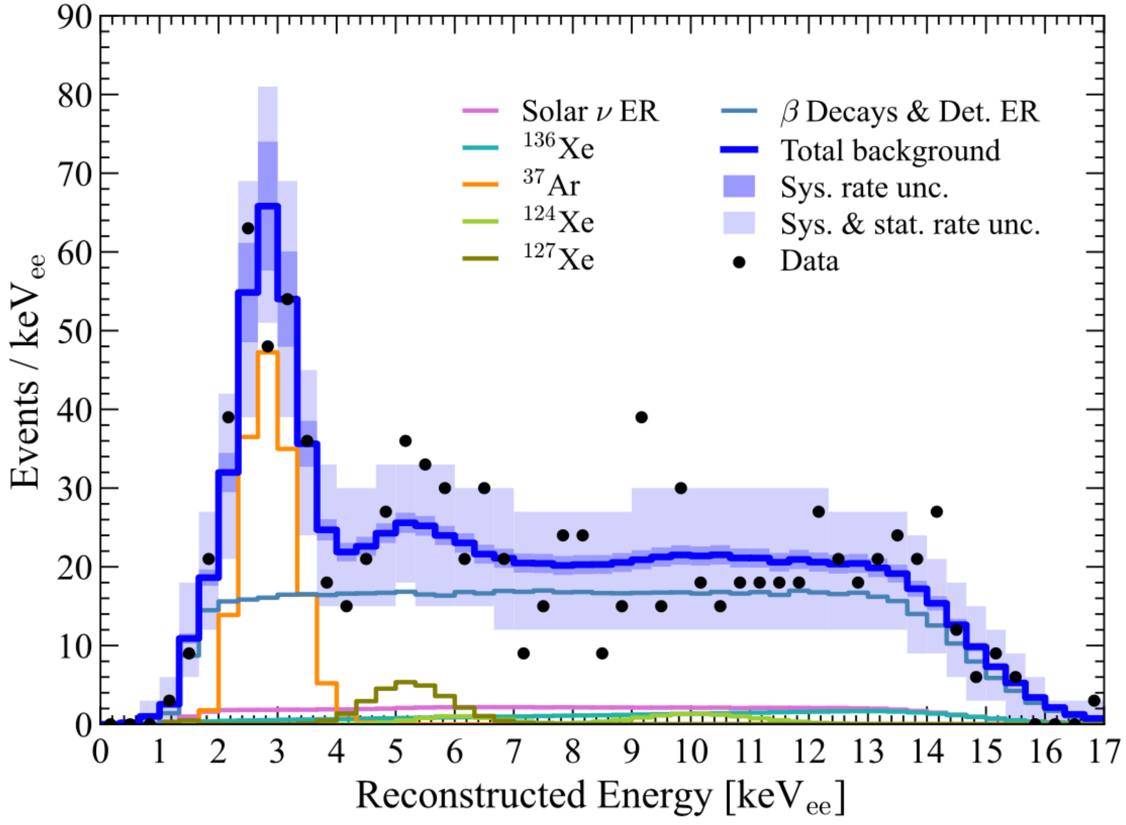
ER / NR calibration

LZ first WIMP search result *PRL 131, 041002 (2023)*

- **Data: 23Dec 2021-11May 2022**
- **60d x 5.5t exposure**
- **Flat ER BG due to Rn in LXe**
- **A large ^{37}Ar peak in ER so far produced at surface**
- **Data agreed with BG only model**



S1 vs S2

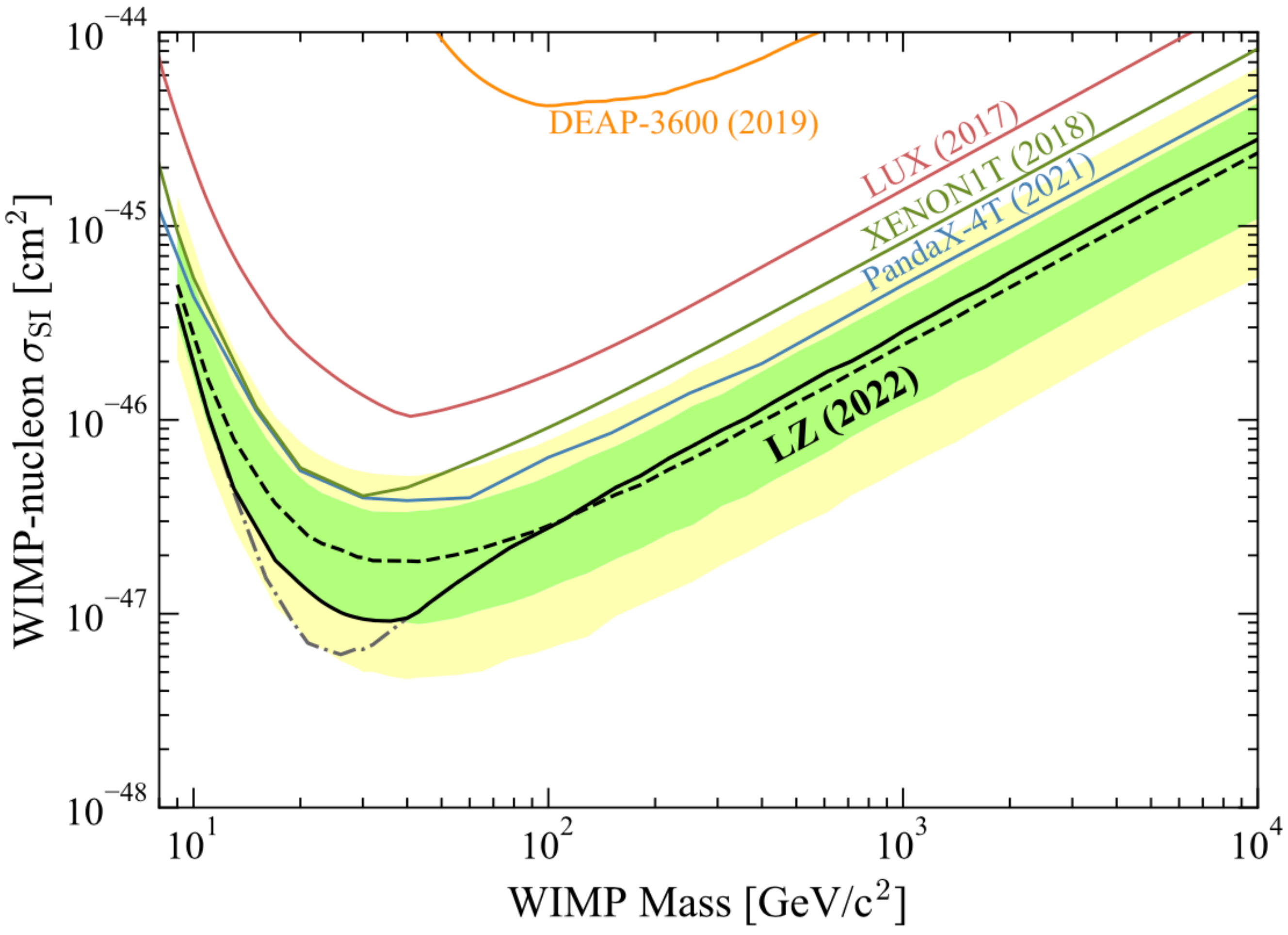


Energy spectrum with best fit model

LZ first WIMP SI upper limit

PRL 131, 041002 (2023)

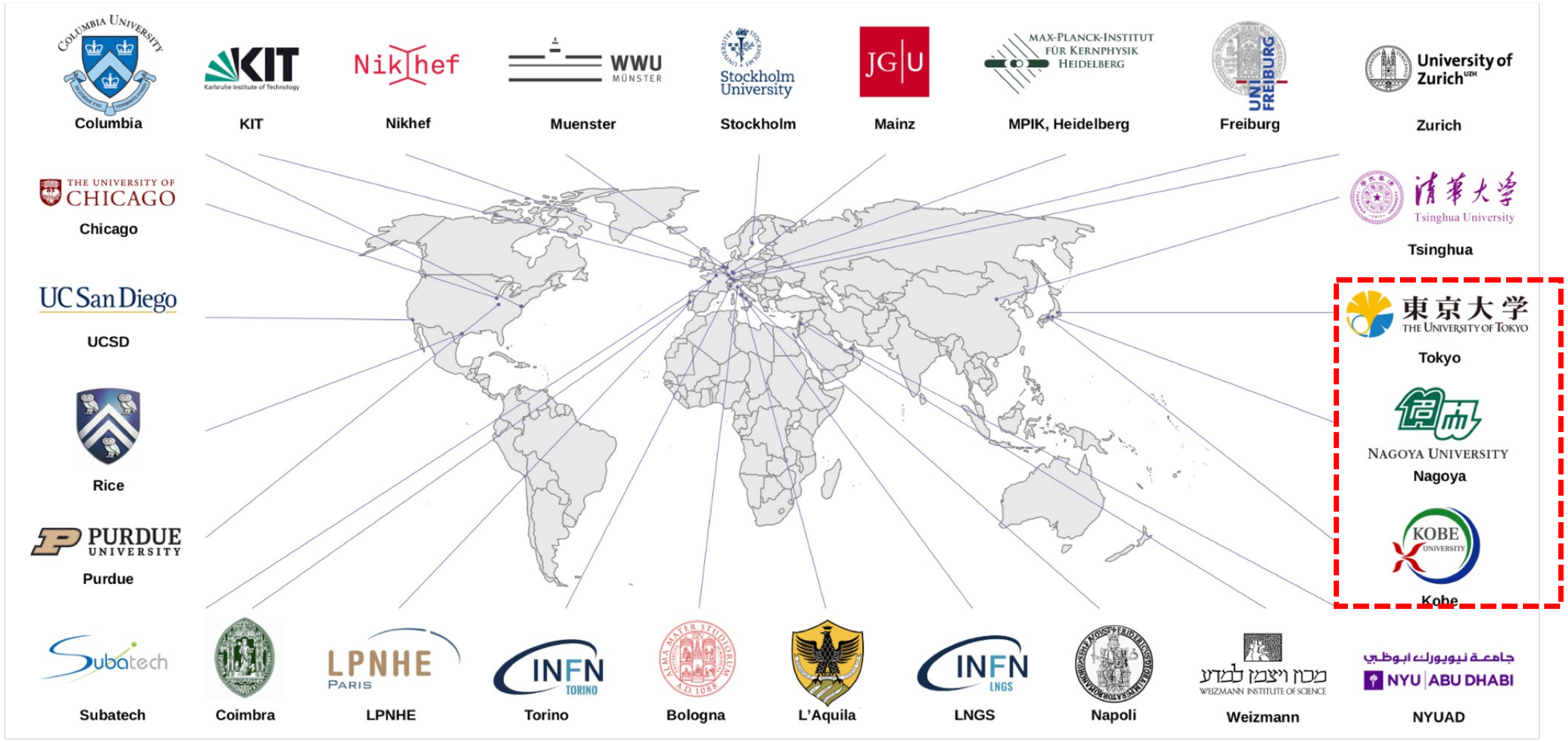
- **Note : Limits derived from non-blinded analysis**



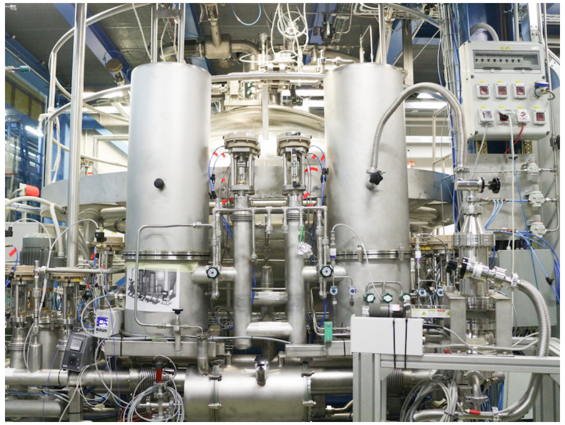
Source	Expected Events	Fit Result
β decays + Det ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	…	$0.0^{+0.6}$
Total	…	333 ± 17

XENON Collaboration

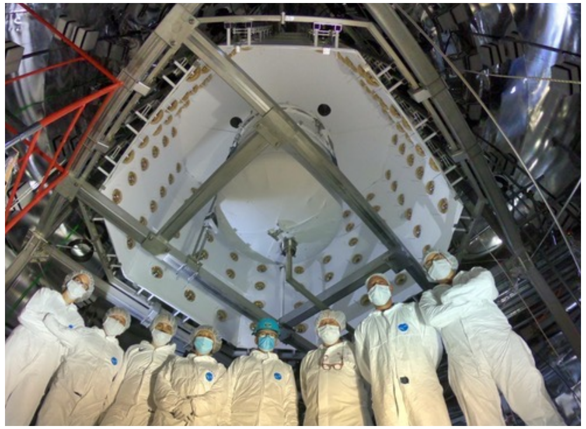
- 167 members from 27 institutions
- Nagoya , U.tokyo and Kobe from Japan has joined since 2018
- Japan bringing expertise developed in XMASS (low BG, Xe purification) and that in SK-Gd (Gd-loaded water Cherenkov neutron Veto)



LXe purification system



Neutron Veto by Gd-loaded Water Cherenkov



XENONnT experiment

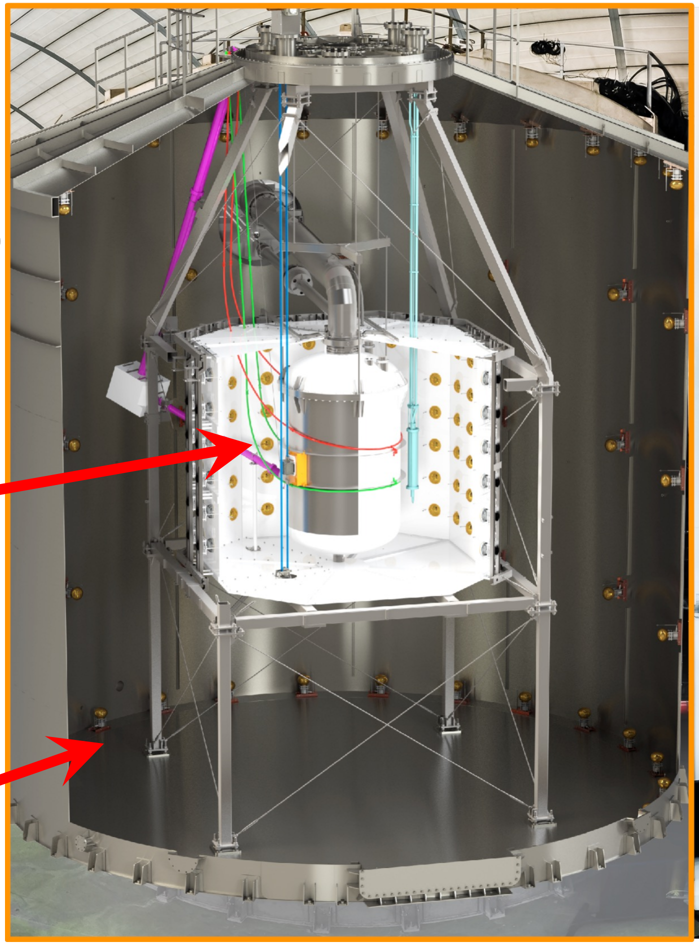
- Reuse XENON1T setup replaced by upgraded larger TPC
- Active 5.9t LXe (8.5 t total)

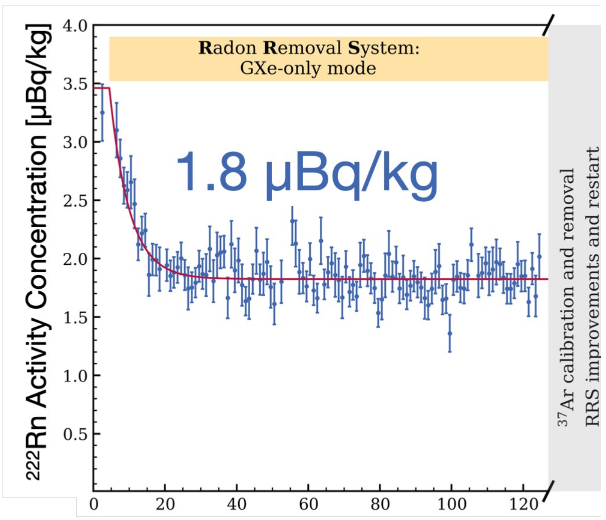
- Rn distillation column
  Online removal of Rn,
  strong reduction of ER BG

Gd-loaded water
water Cherenkov
(so far pure water)

Inner neutron
veto region

700t water tank
for muon veto

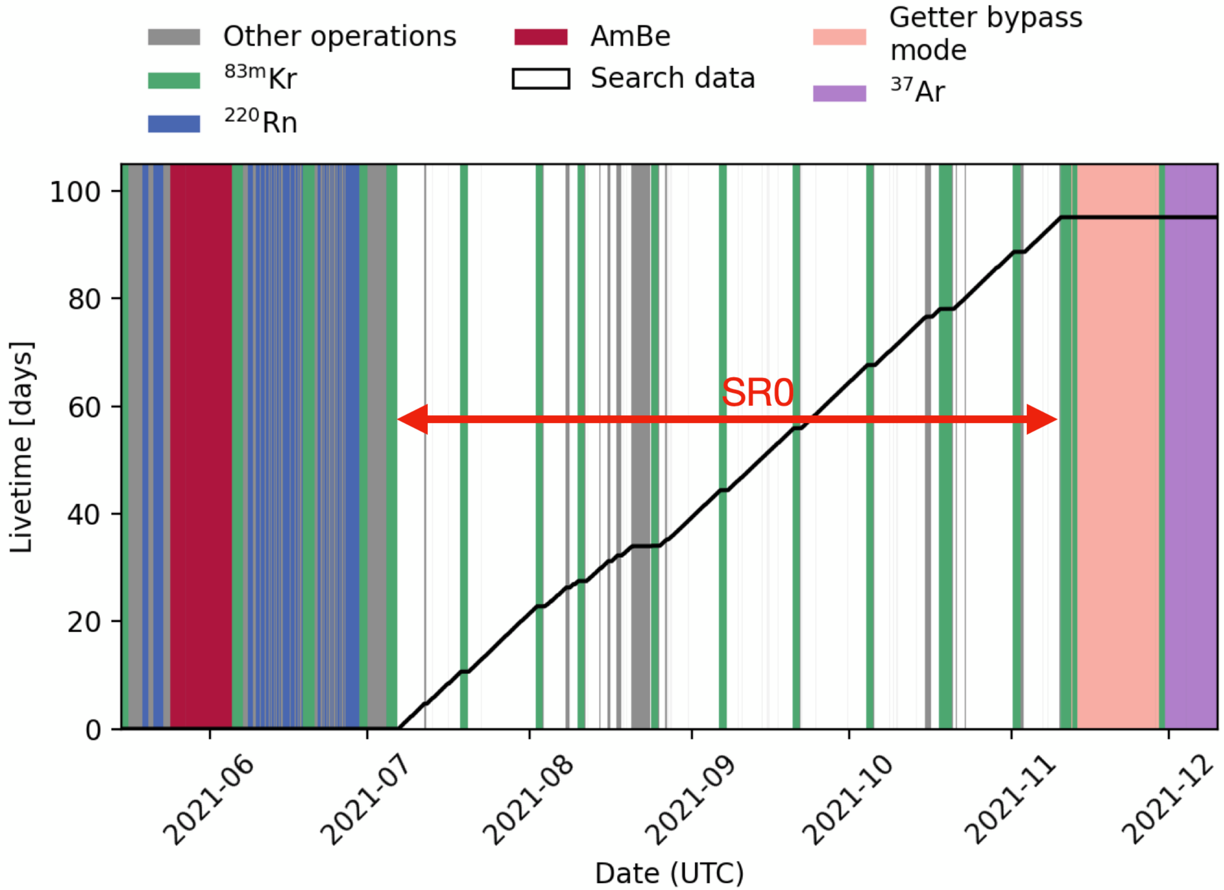




ER BG reduced by x5
from XENON1T

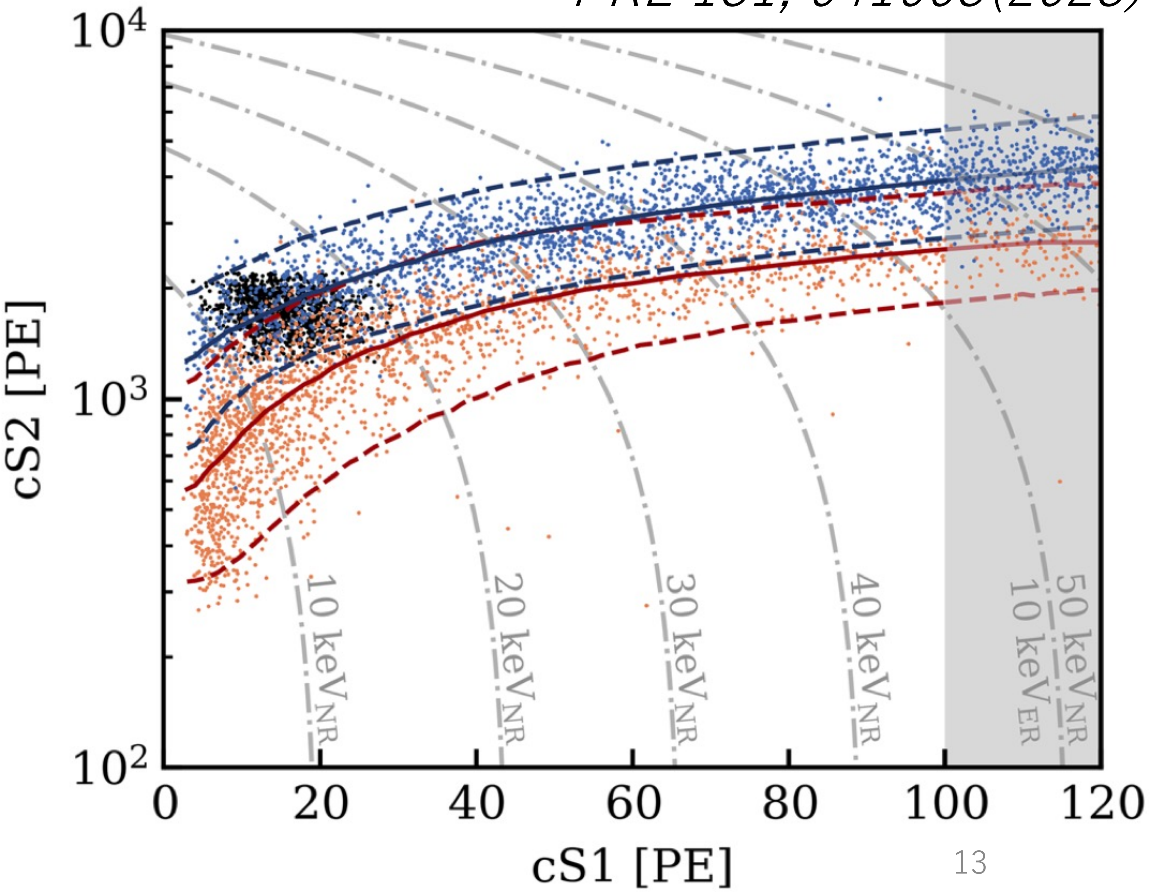
XENONnT first science run data “SR0”

- **SR0: Jul 6 2021 – Nov 10 2021, 95.1 live days**
- **Low drift field (23V/cm) due to electrode problem**
  Still comparable resolution & threshold to XENON1T
- **Blind analysis applied**

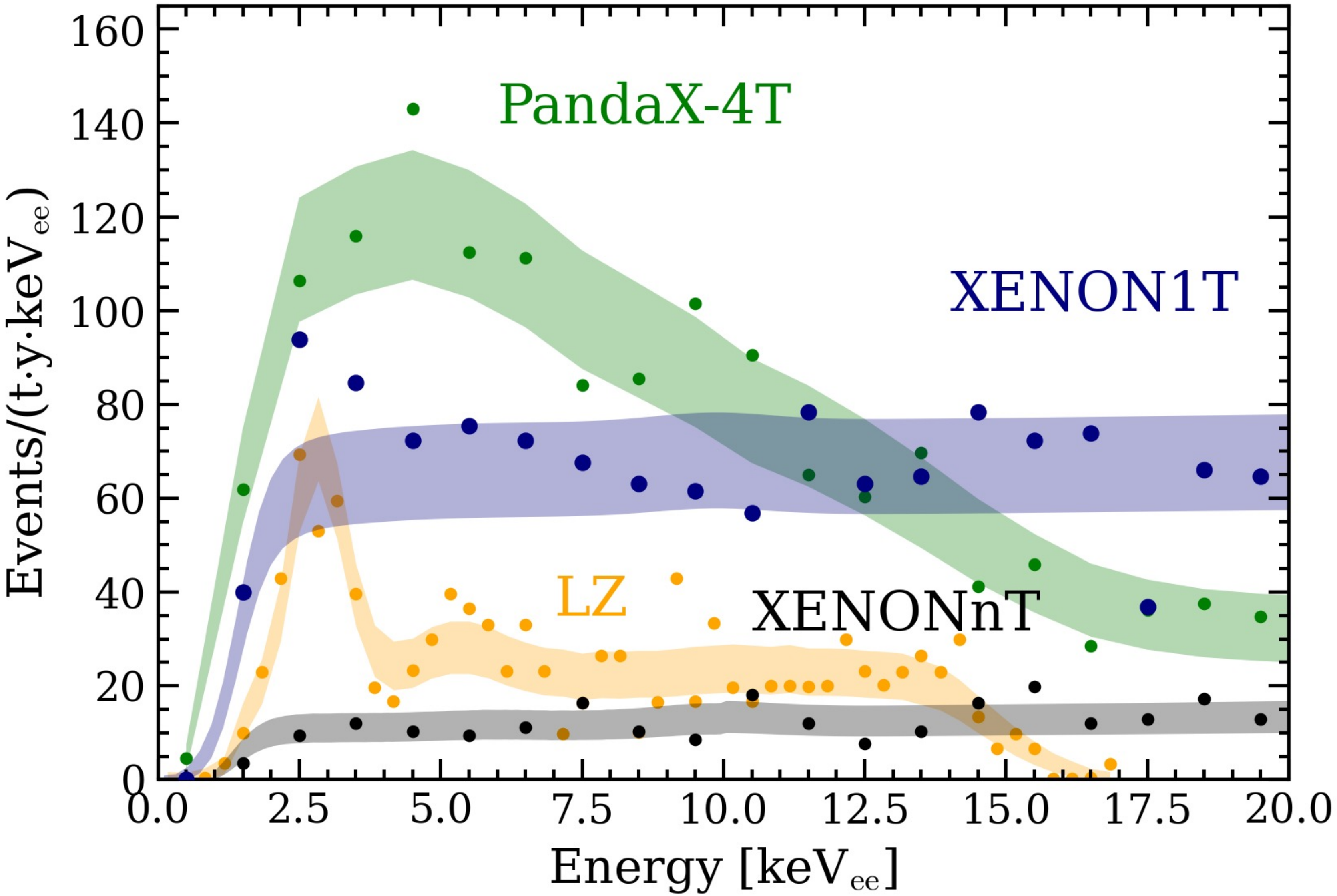


- **ER calibration: ^{220}Rn, ^{37}Ar, ^{83m}Kr (not contamination, intentionally put for calibration and removed)**
- **NR calibration: ^{241}AmBe**

PRL 131, 041003(2023)



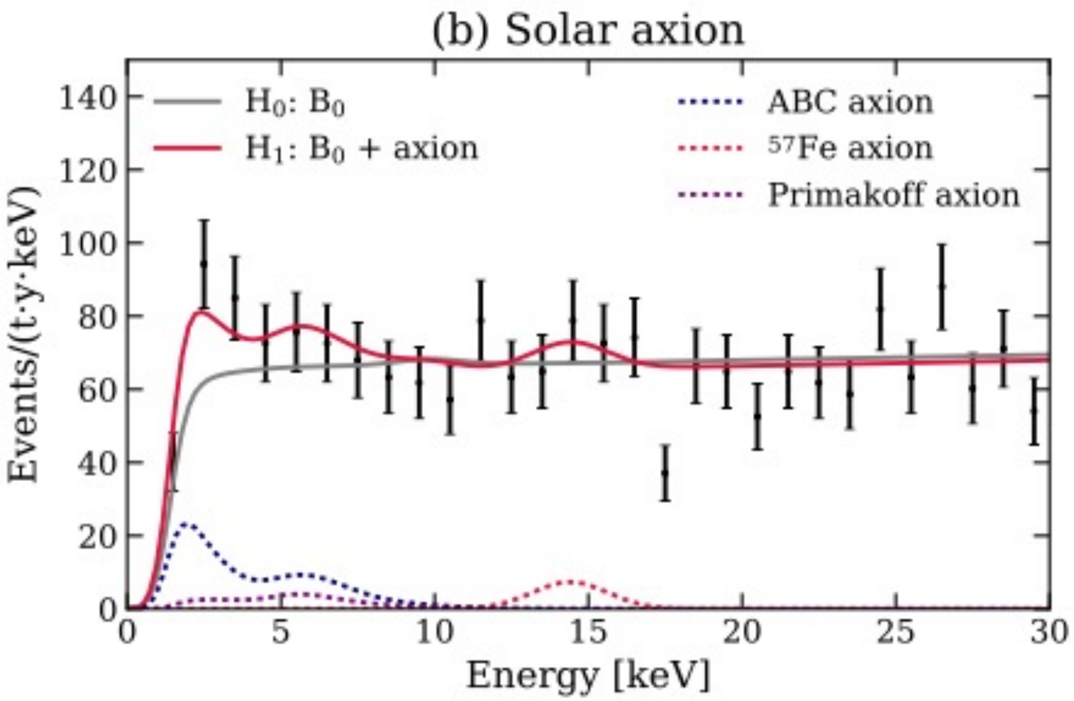
ER BG comparison



Low-E ER excess checked by XENONnT SR0

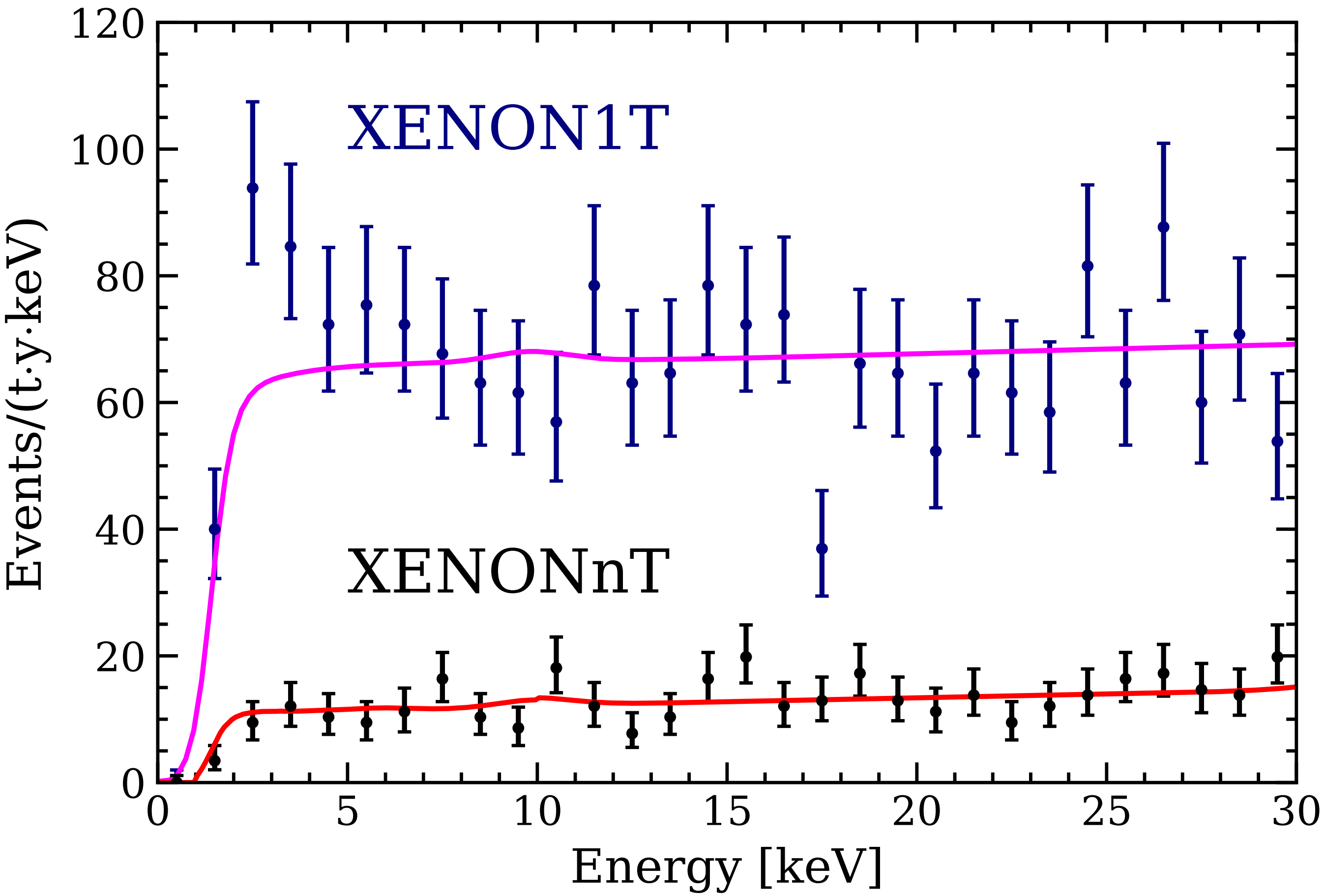
- **XENON1T low energy excess of ER**
- **Possible hint for solar axion or ^{3}H BG ?**

Phys.Rev.D 102 (2020) 7, 072004, arXiv:2006.09721



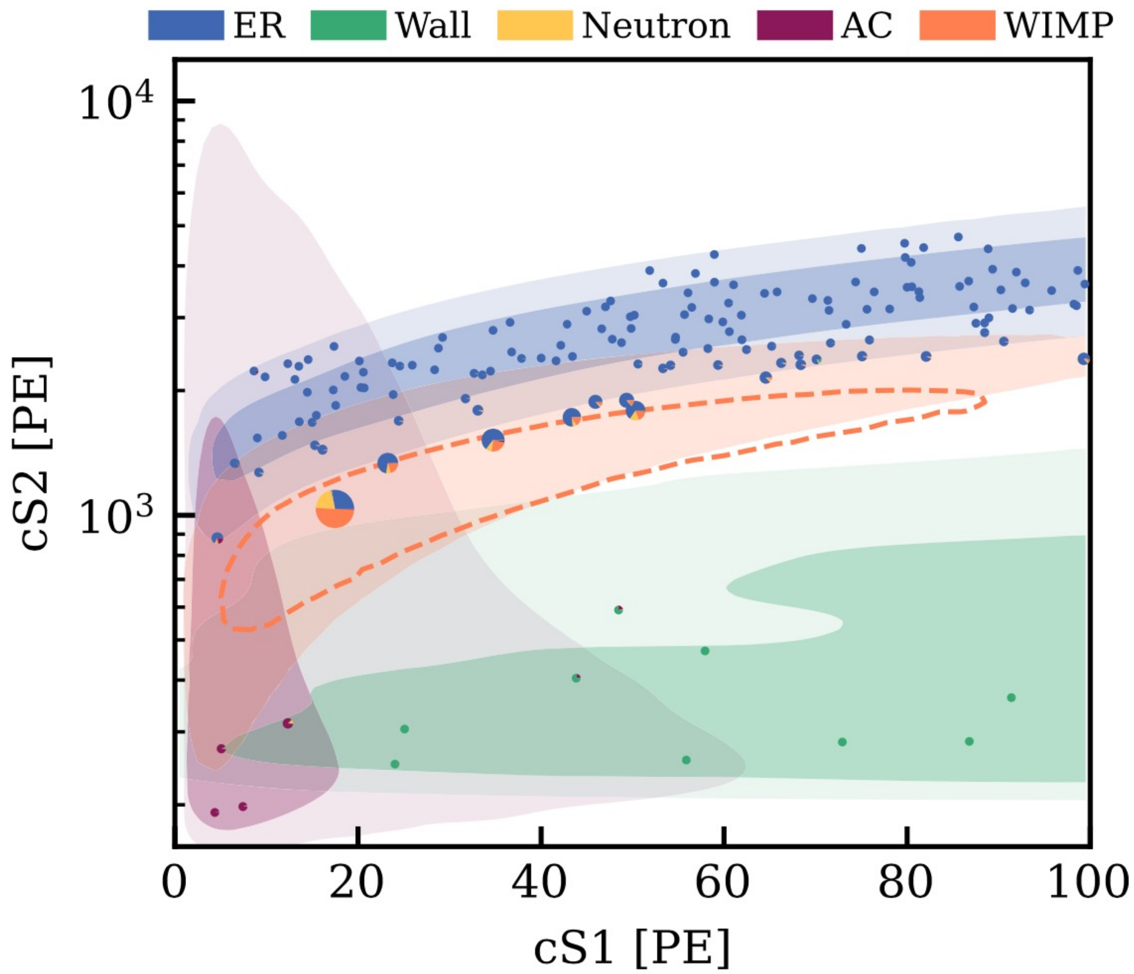
- **Thanks to x5 lower ER BG than XENON1T**
- **Excess was not confirmed in SR0 data**

Phys.Rev.Lett. 129 (2022) 16, 161805



XENONnT first WIMP search

- **After unblinding, 152 in ROI, 16 in WIMP region**
- **Best fit to the data is compatible with BG-only hypothesis**
  （3 observed, w/ BG 2.0 ± 0.2, 1.3 WIMP for 200GeV/c^2 case) *PRL 131, 041003(2023)*

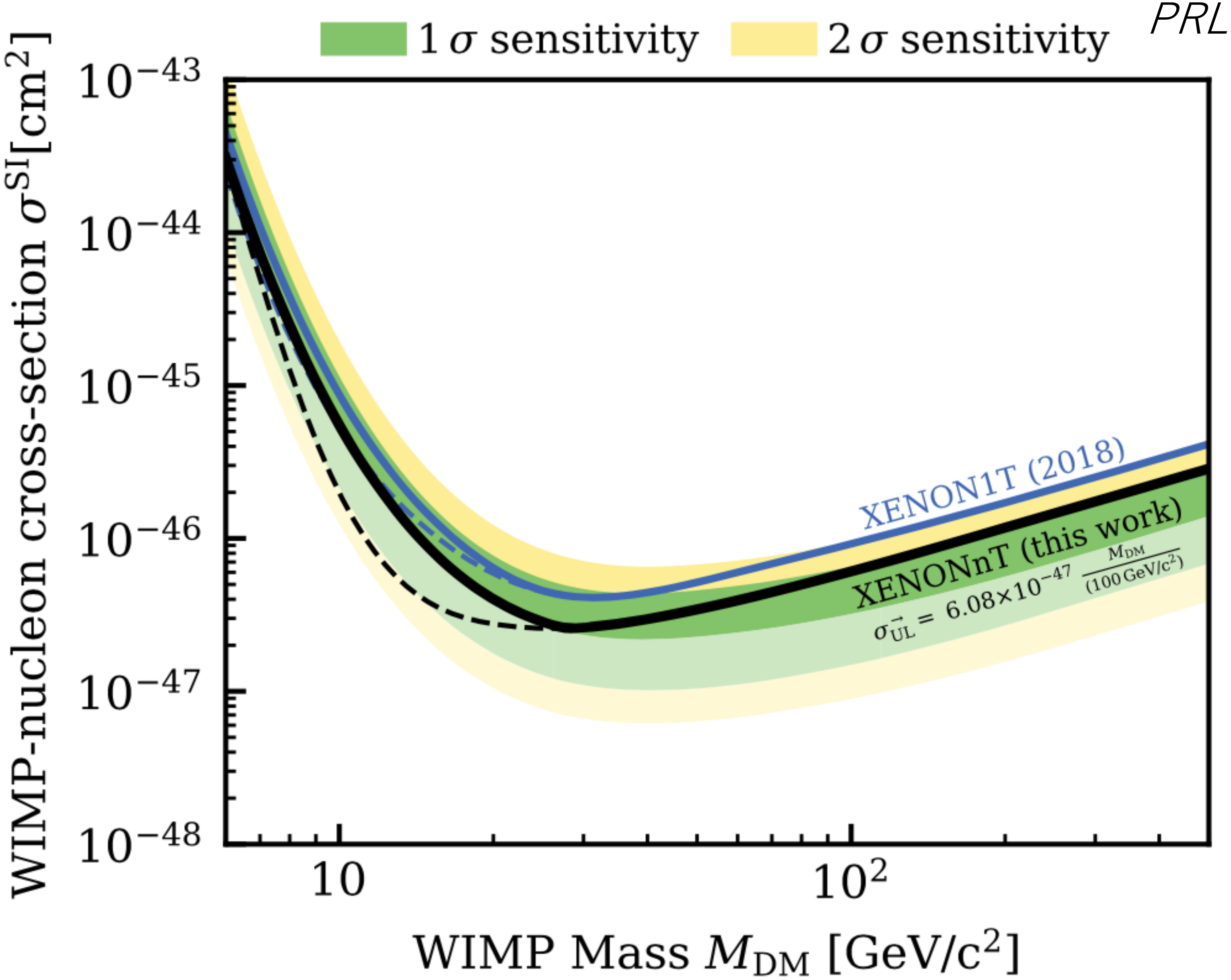


	Nominal	Best fit	
	ROI		Signal-like
ER	134	135^{+12}_{-11}	0.92 ± 0.08
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4	0.42 ± 0.16
CEνNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.006
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	0.32 ± 0.06
Surface	14 ± 3	12 ± 2	0.35 ± 0.07
Total background	154	152 ± 12	$2.03^{+0.17}_{-0.15}$
WIMP	…	2.6	1.3
Observed	…	152	3

Signal region for 200 GeV/c^2 WIMP case
Best-fit σ = 3.22 x 10^{-47} cm^2

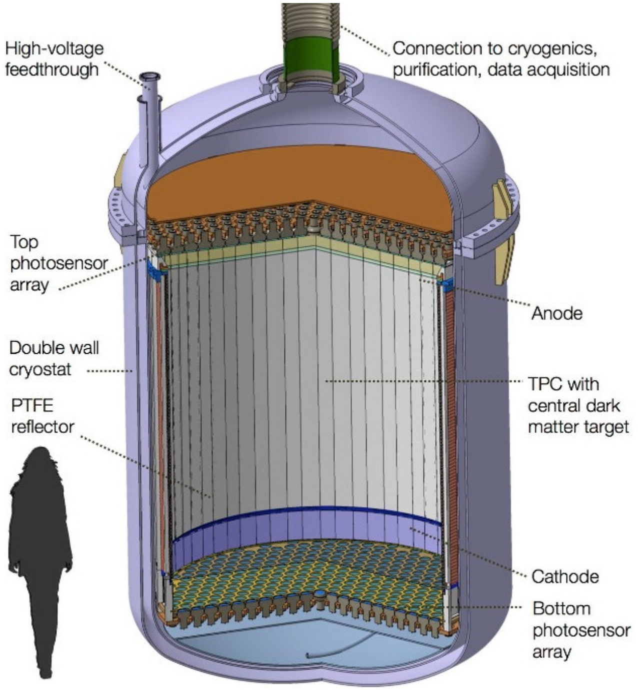
XENONnT SR0 WIMP limit S(σSI)

PRL 131, 041003(2023)



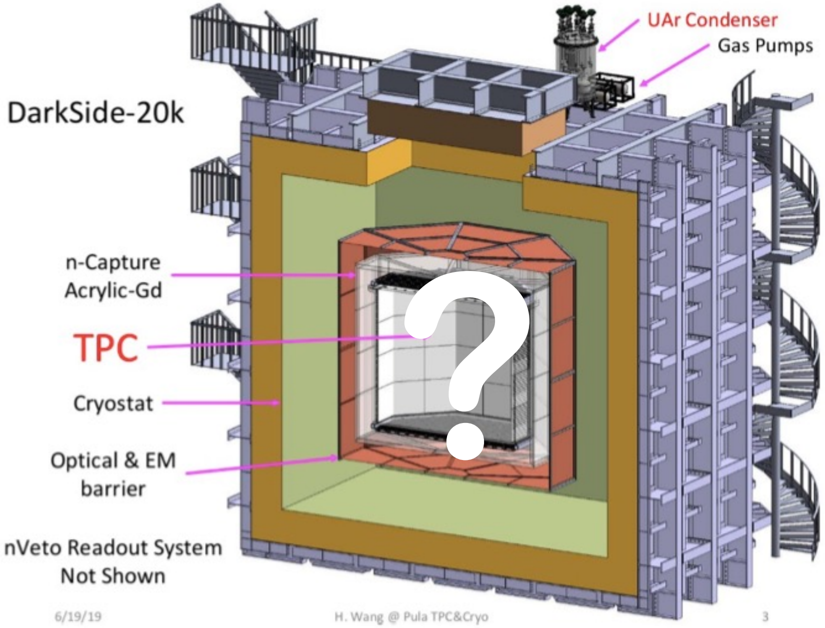
Generation-3 O(100t) future direct DM detectors (2027?-)

DARWIN(50t LXe) → XLZD



Site: TBD…

ARGO(300t LAr)



Canada・SNOLab ?

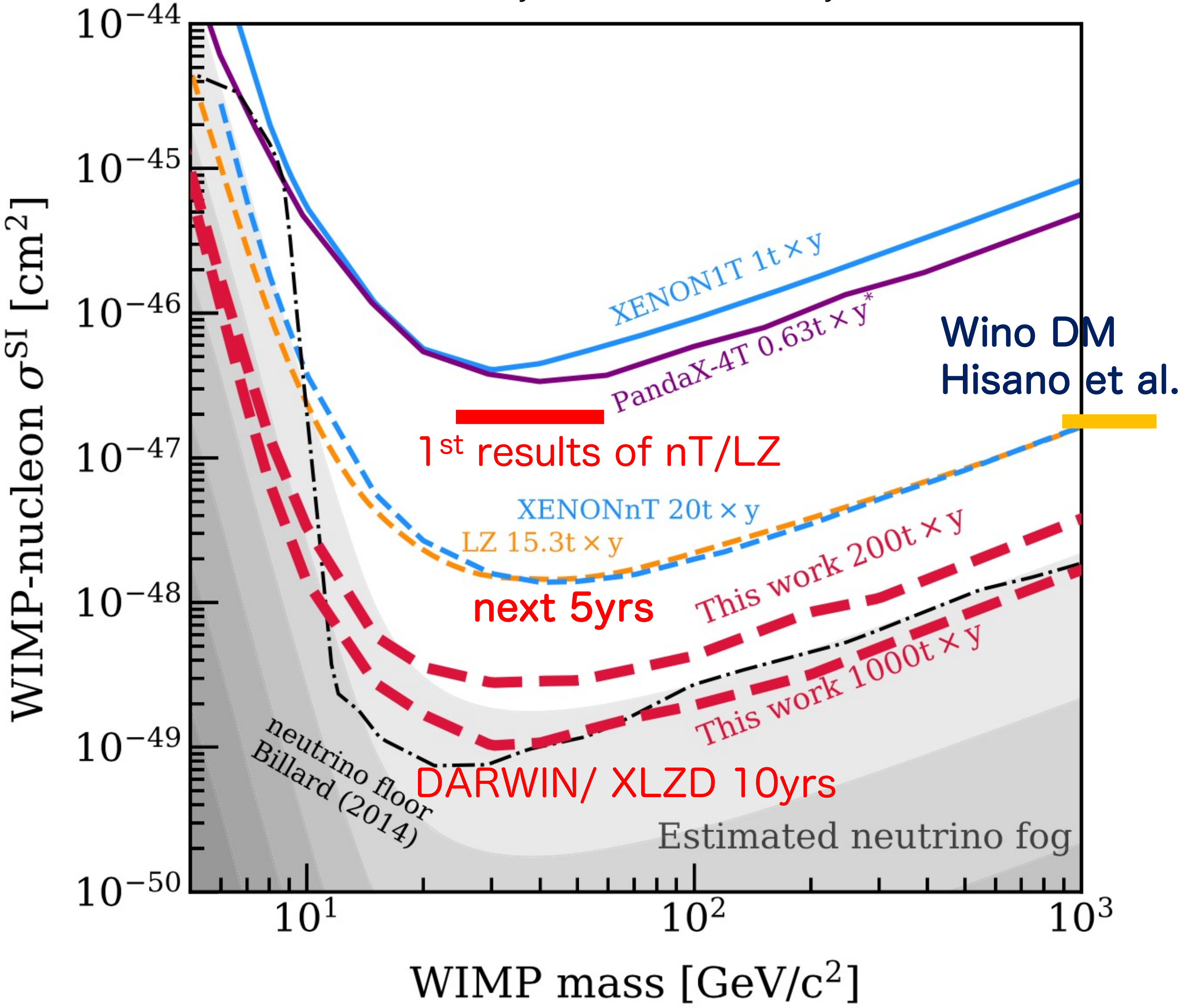
2021 Jul : MOU : XENON/DARWIN, LZ (XLZD)
2022 Jun : 1st Summer meeting at KIT

XLZD white paper :arXiv:2203.02309
“A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics”

Toward next generation LXe direct detection

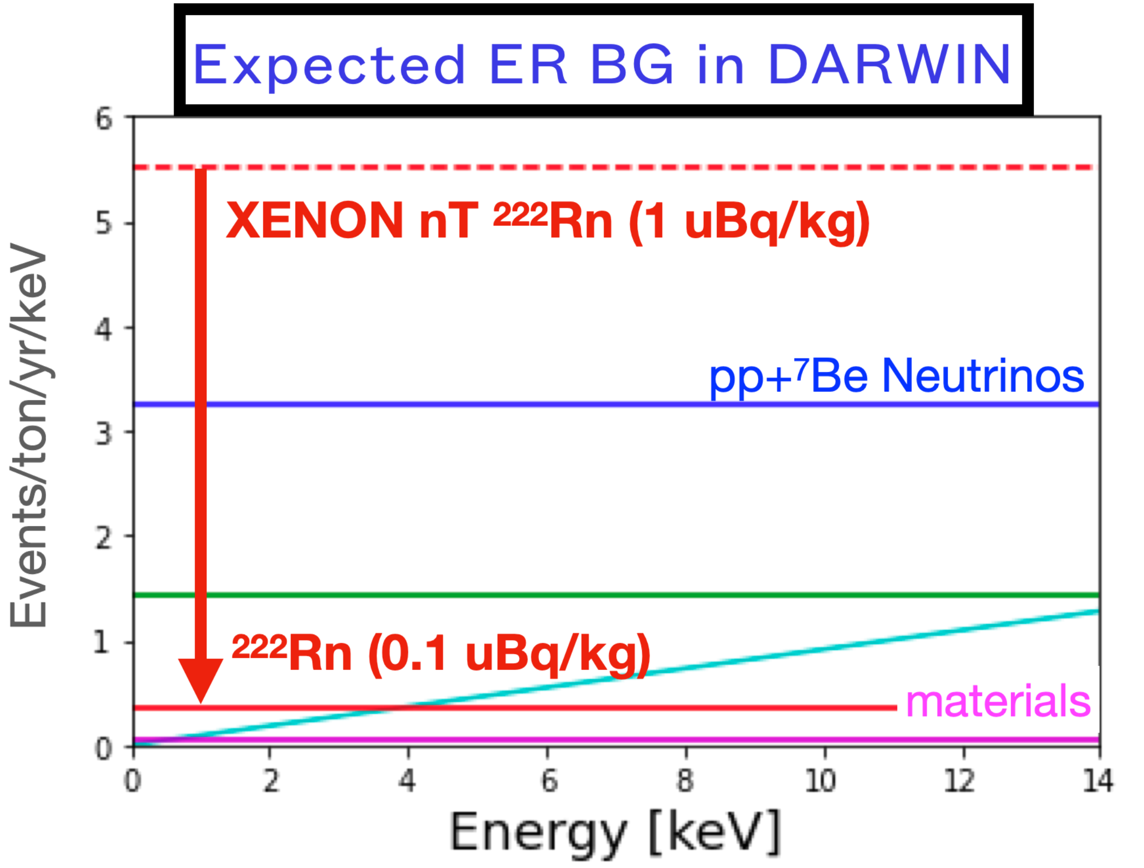
	XENON1T	XENONnT	DARWIN
Start	2016	2020	~2030
Total Xe	3.2 t	8.5 t	~50 t
TPC size	~1.0 m	~1.3 m	2.6 m
Rn in LXe	13 μBq/kg	1.8 μBq/kg	0.1 μBq/kg
σSI	10^{-46} cm²	10^{-48} cm²	10^{-49} cm²

J. Phys. G. Nucl. Part. Phys 50 (2023) 013001

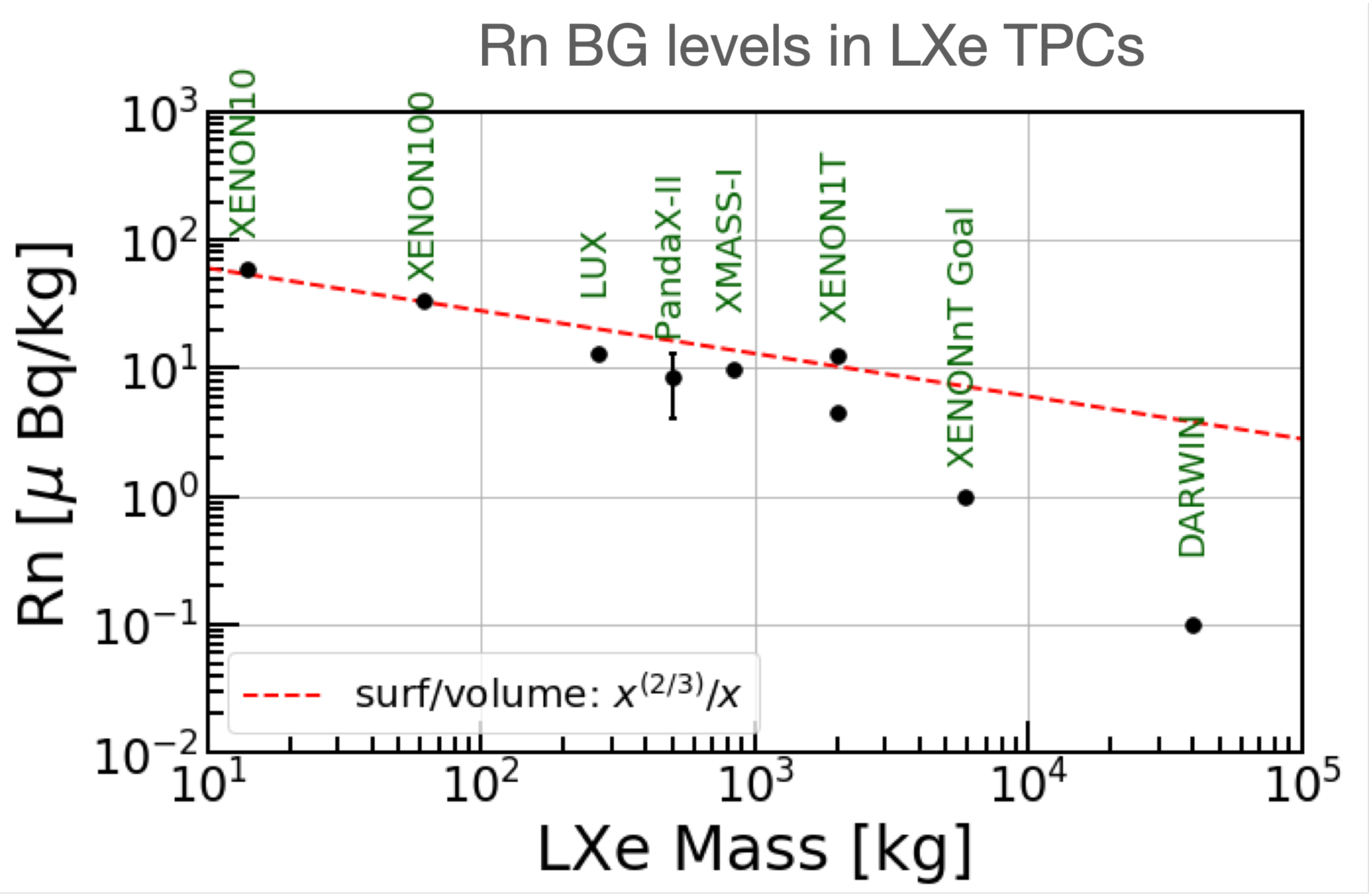


Target ER BG level in future LXe

Goal: Negligible to intrinsic Solar ν BG



Masaki Yamashita, TAUP2019

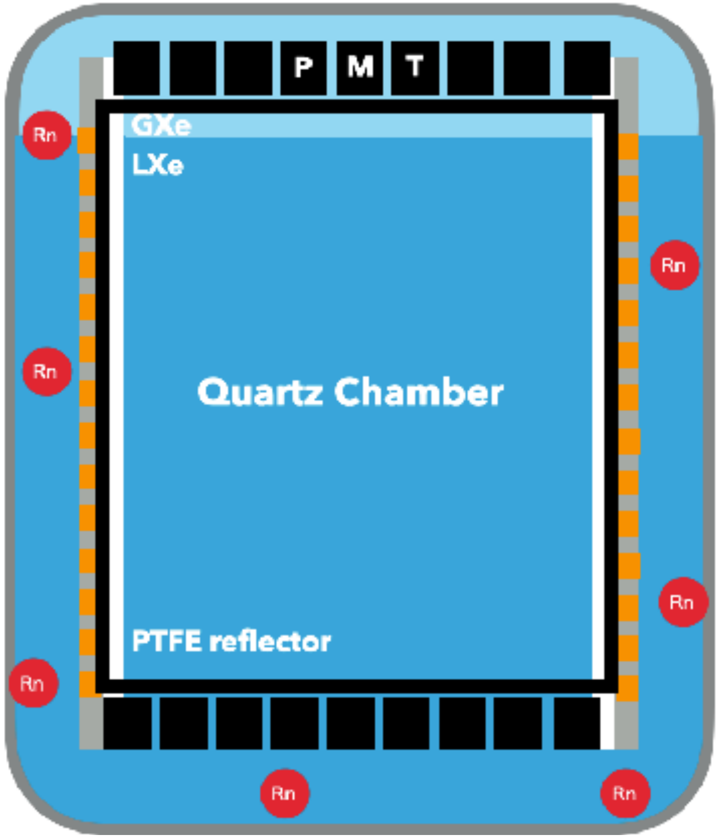


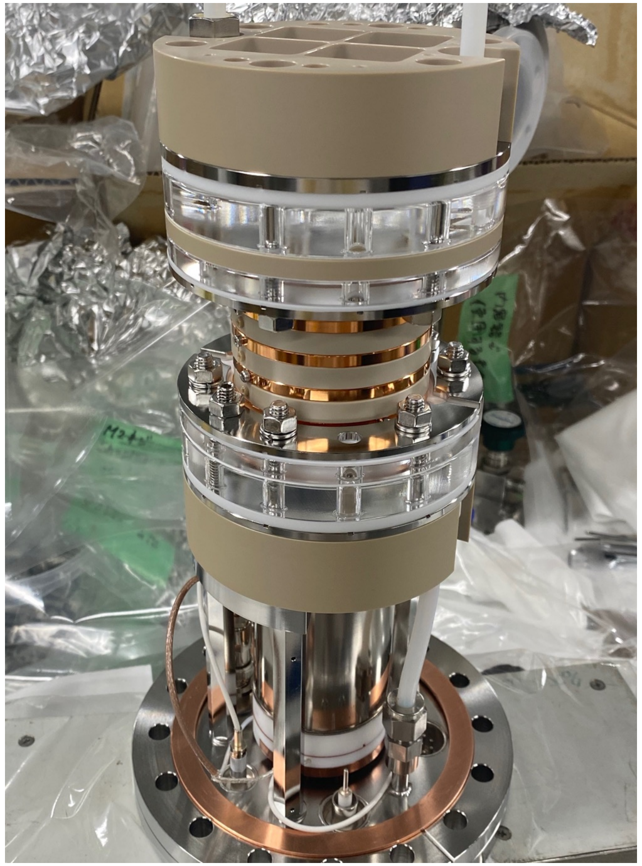
Masaki Yamashita, TAUP2019

R&D for the next generation LXe TPC

- How to achieve 1/10 Rn BG ?
- How to build x2 larger TPC ?
- How to procure x5 Xe ?

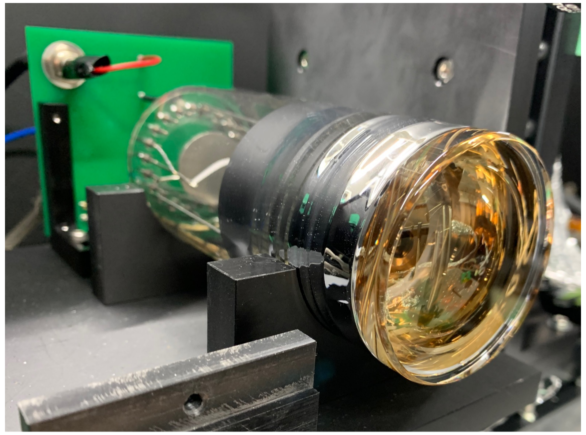
Hermetic TPC w/ quartz vessel



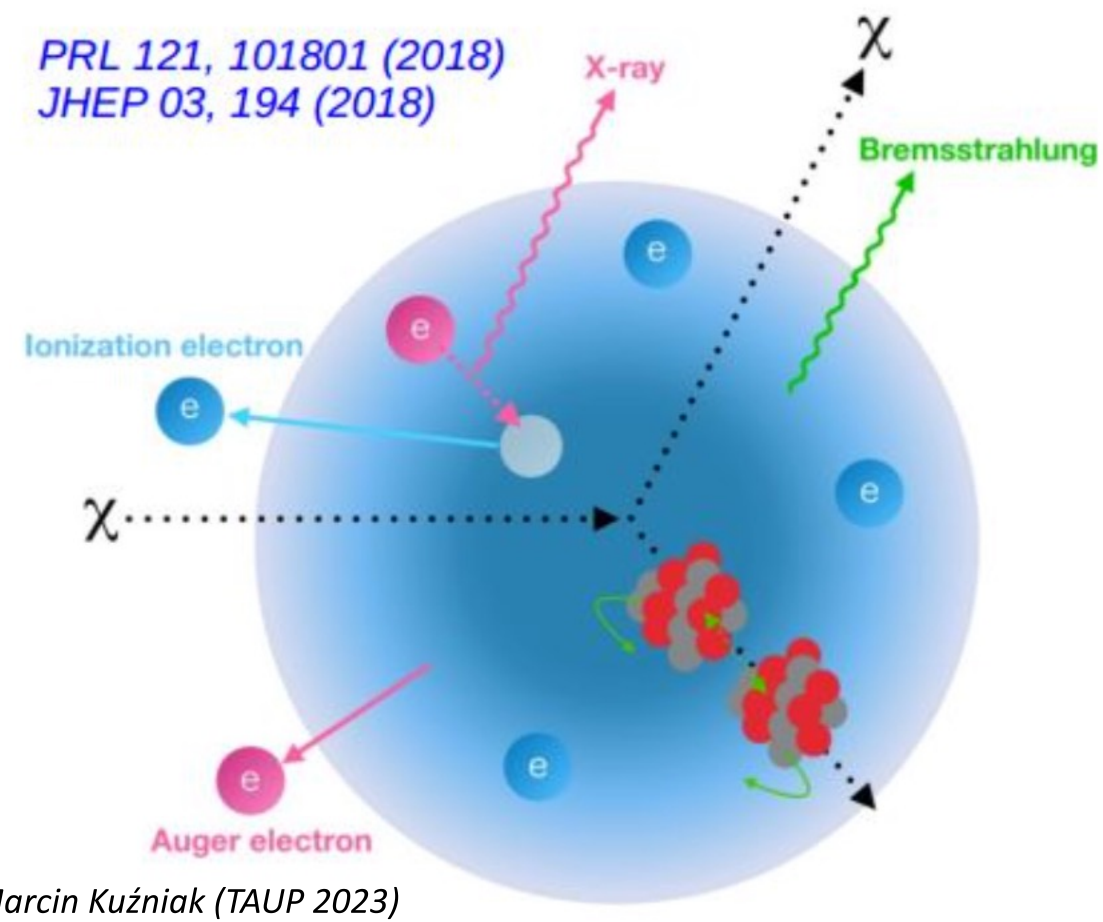


Lowest RI PMT (U.Tokyo)
R13111 (by XMASS)

MPPC hybrid PMT (Nagoya)



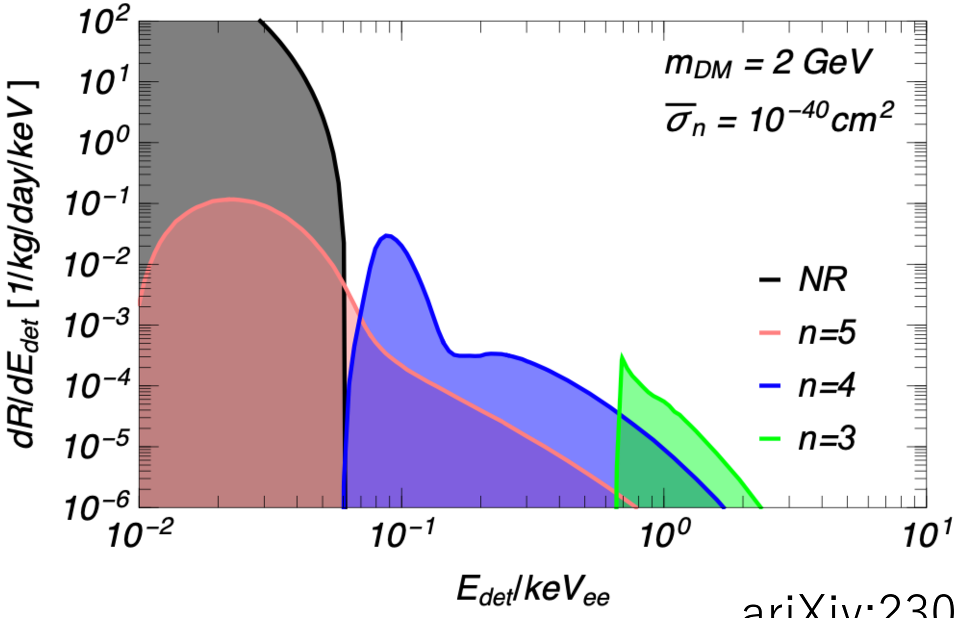
MIGDAL effect



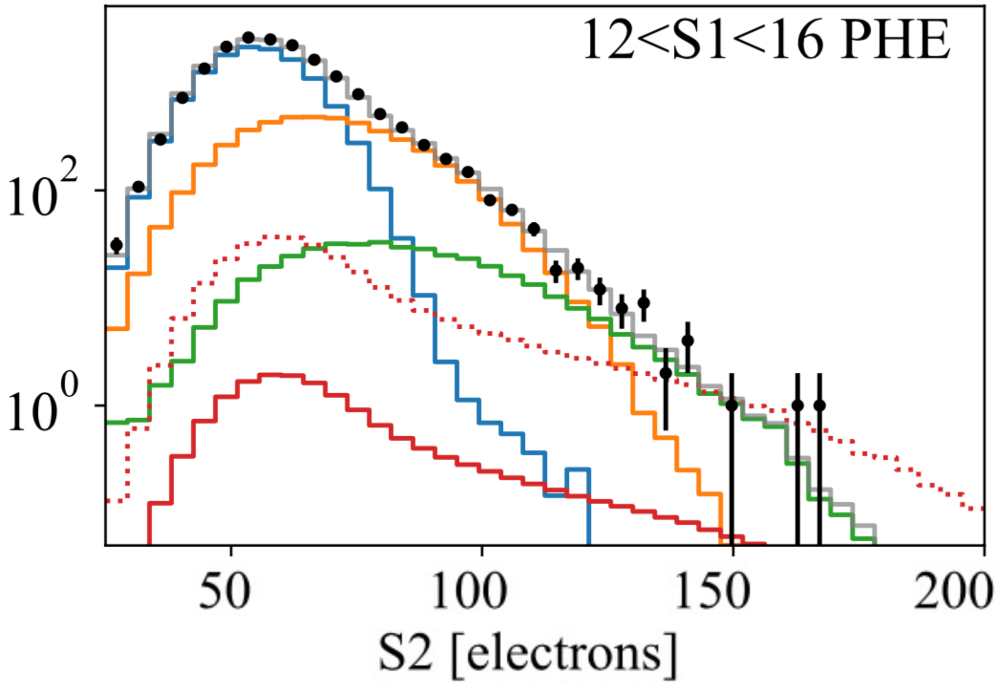
Marcin Kuźniak (TAUP 2023)

ER spectra at LXe target

JHEP 03, 194 (2018)



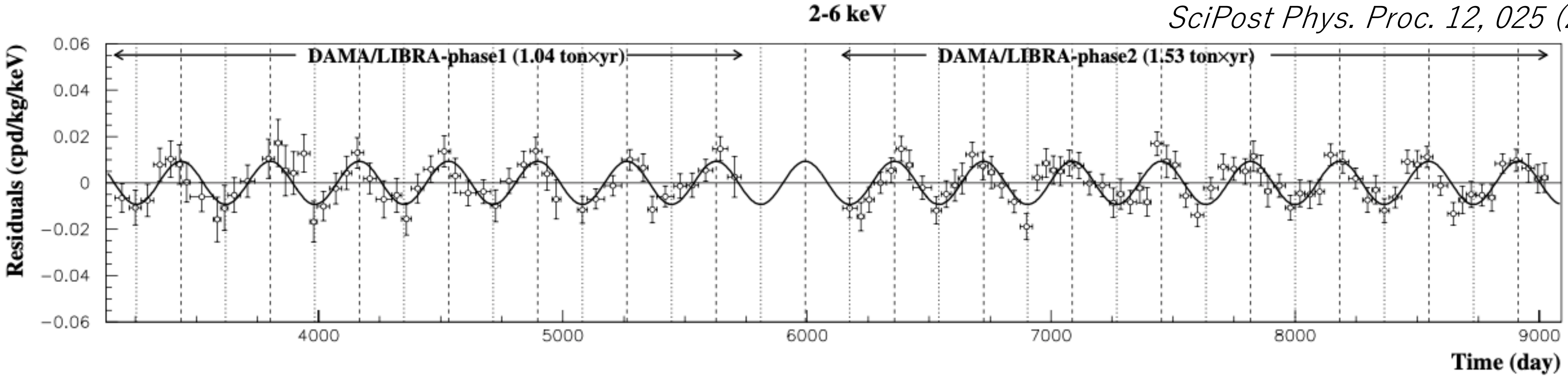
ariXiv:2307.12952

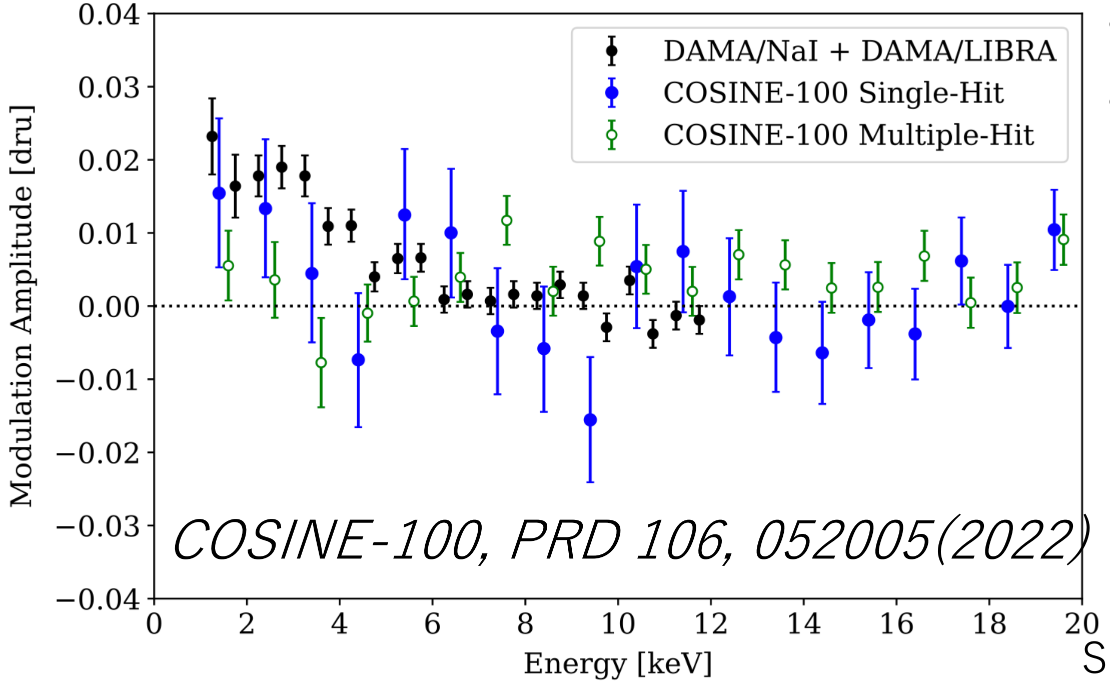


- **Migdal ER search by a LXe TPC w/ a tagged n-beam**
- **No signal found yet. Upper limit was set**

DAMA/LIBRA seasonable modulation

SciPost Phys. Proc. 12, 025 (2023)





COSINE-100, PRD 106, 052005(2022)

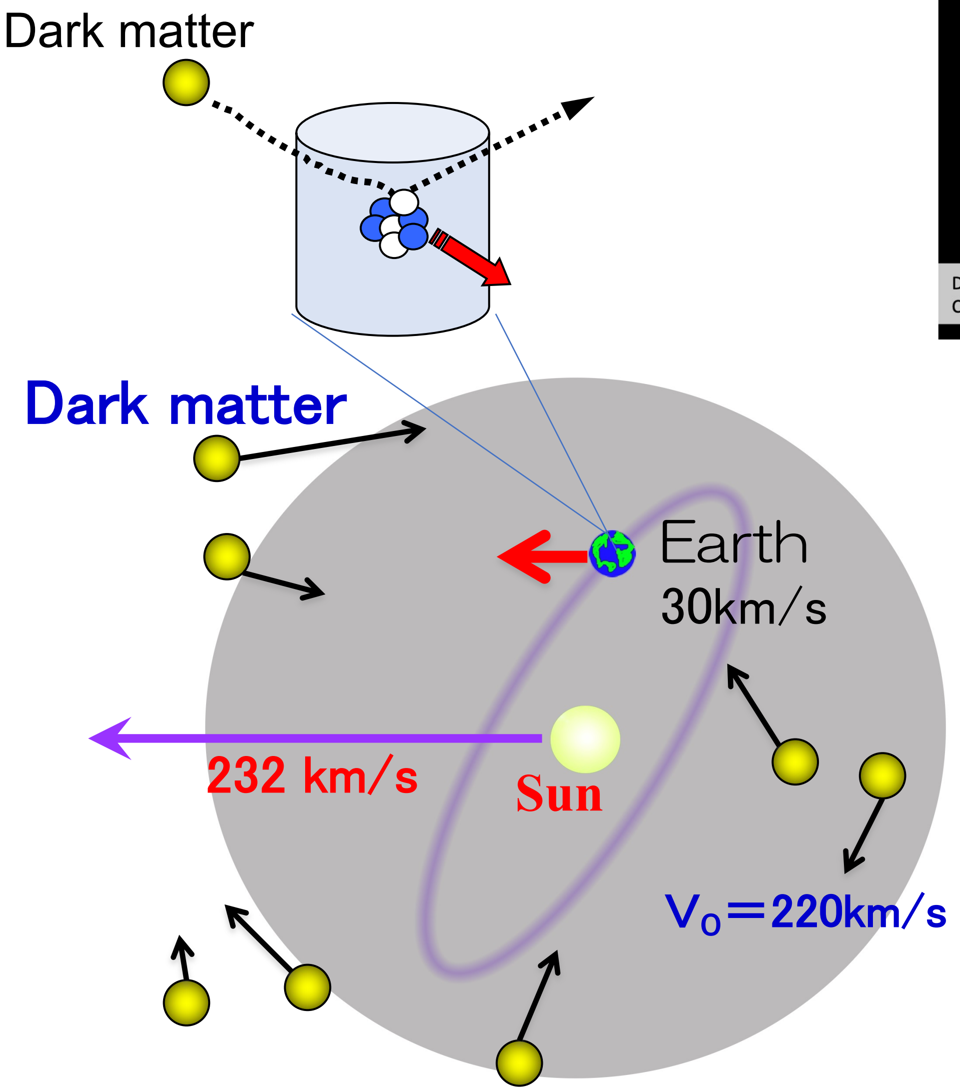
- DAMA+LIBRA (NaI 2.86t x 22 years) sees modulation ?
- Independent checking by NaI on-going
  - COSINE-100 (61.3kg NaI x 2.82 years)
  - ANAIS-112 (112.5kg NaI x 3 years)

1-6 keV modulation amplitude

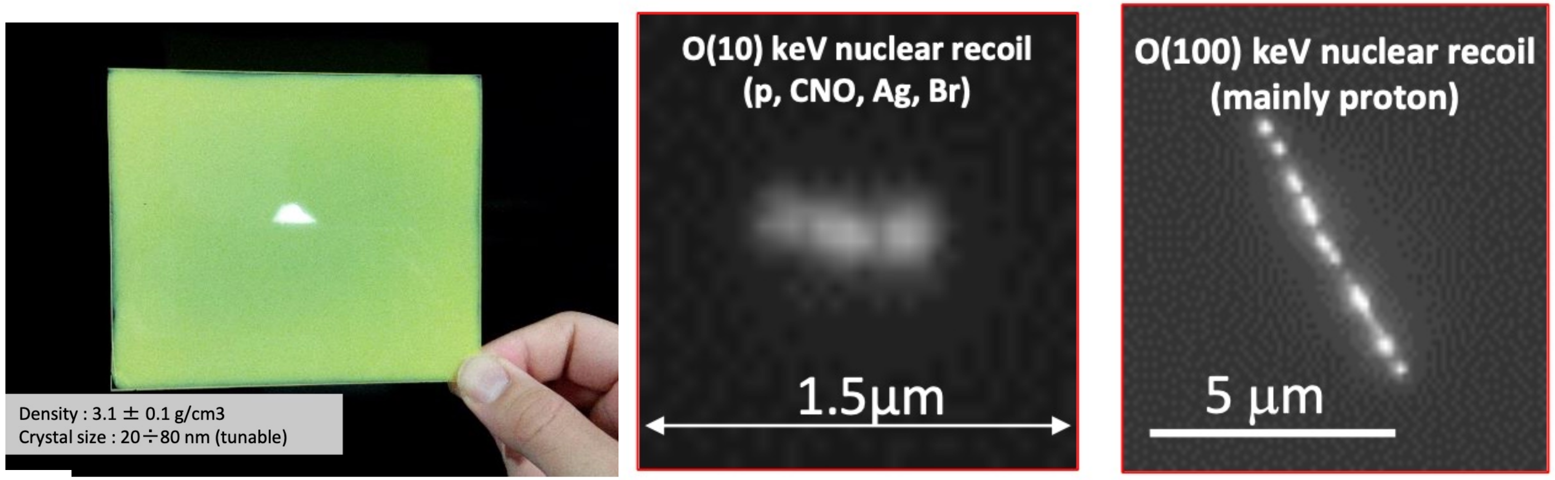
COSINE-100	0.0067 ± 0.0042
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

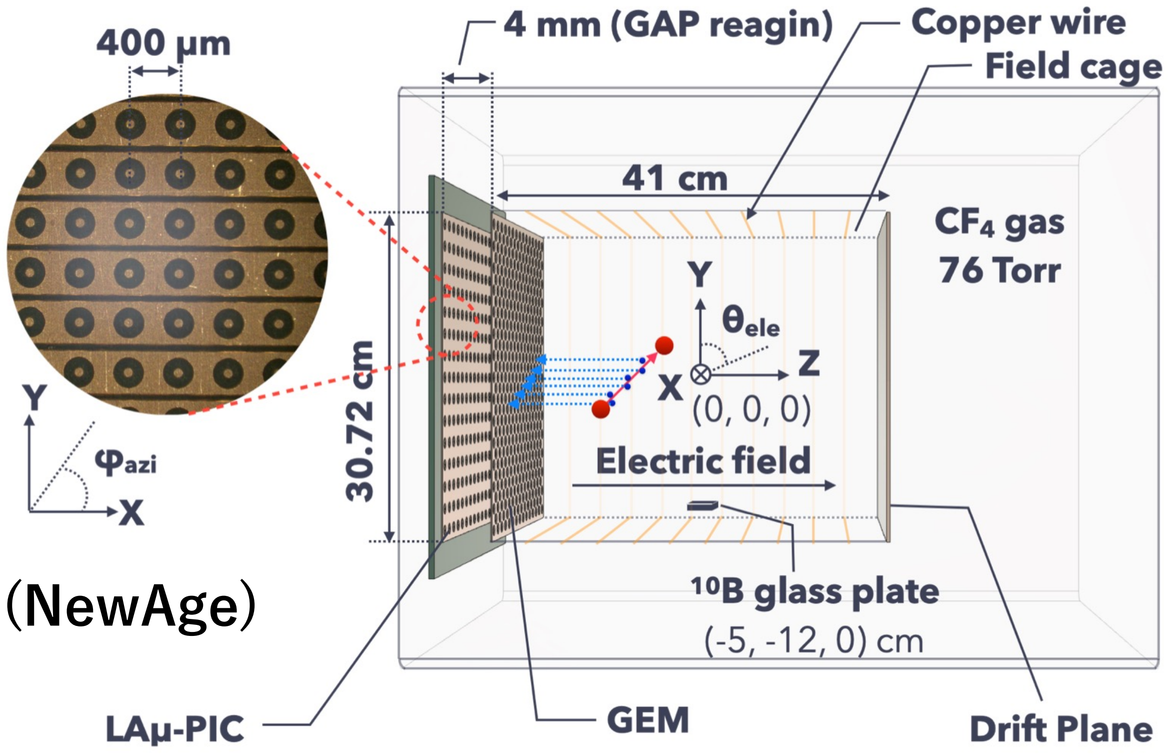
See Hyunsu Lee (IBS) talk in 2nd DMnet Symposium
https://indico.cern.ch/event/1181341/contributions/4964894/

Directional search



Nuclear Emulsion (NEWSdm)

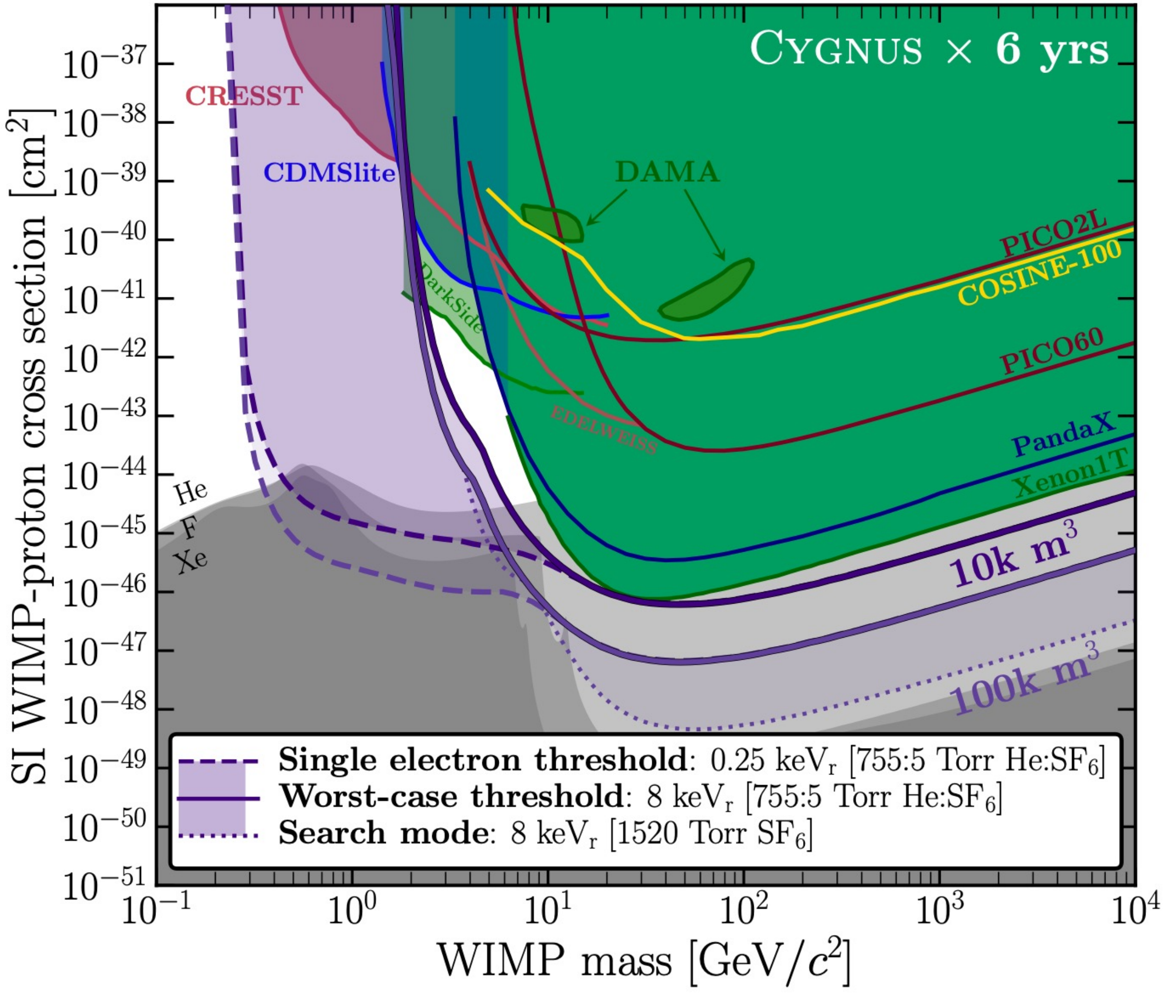




Gas TPC (NewAge)

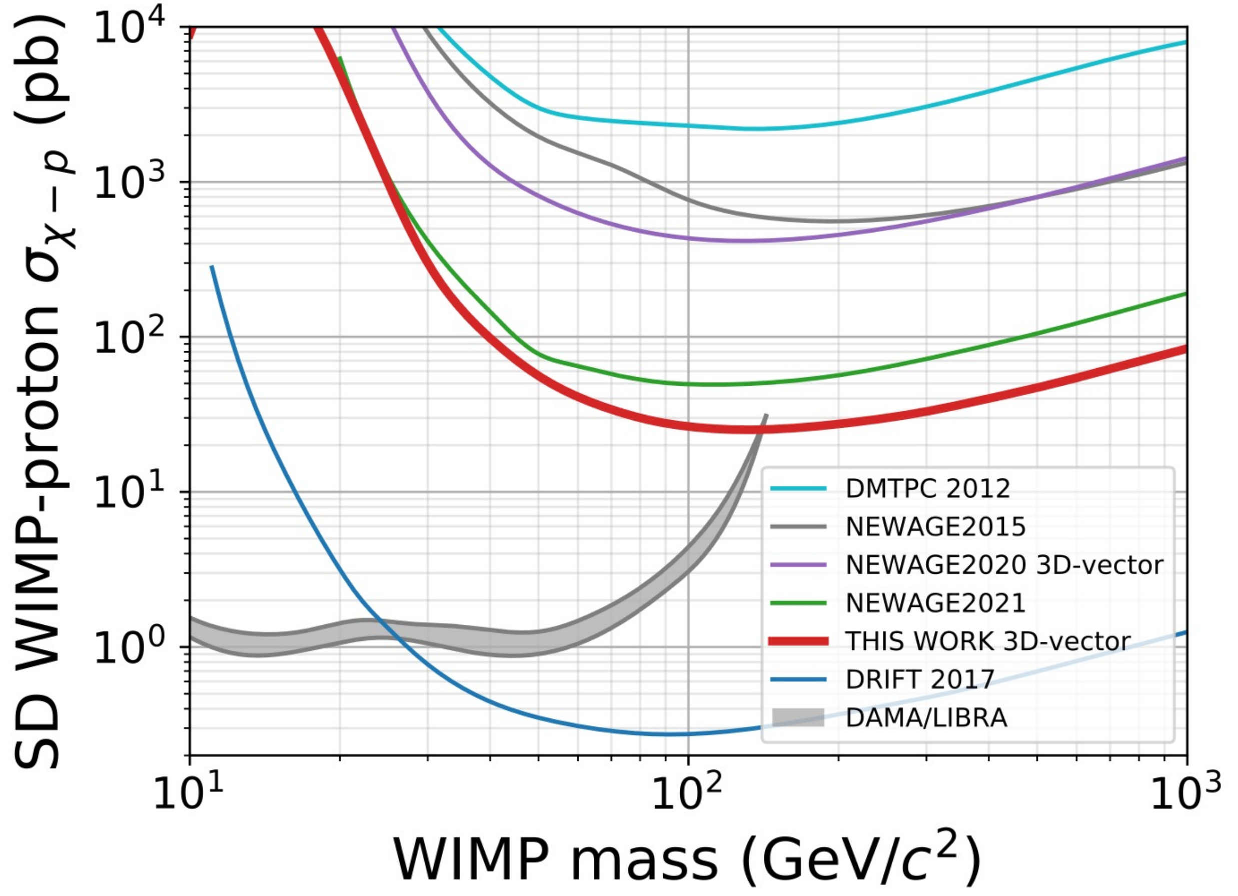
Directional search sensitivity (gas TPC)

arXiv 2008.12587



10-10K m2 TPC w/ He:SF6 gas at 755:5 Torr in 6 years

arXiv:2301.04779



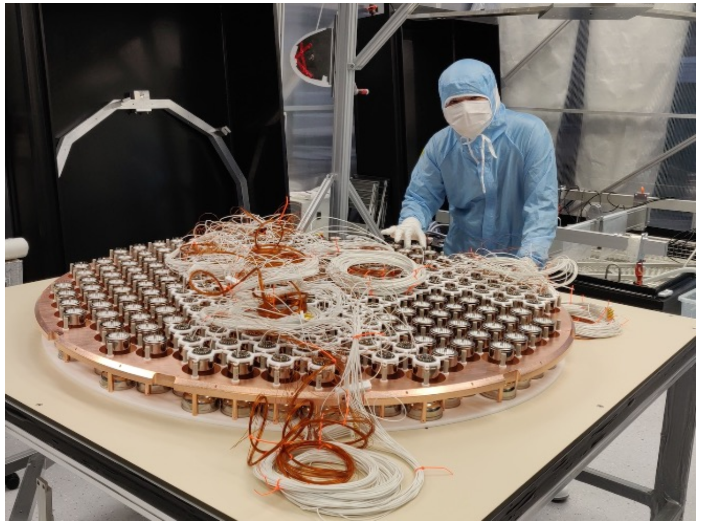
NEWAGE (28cmx24cmx41cm) latest result
(CF4, 10g, 318 days @ Kamioka)

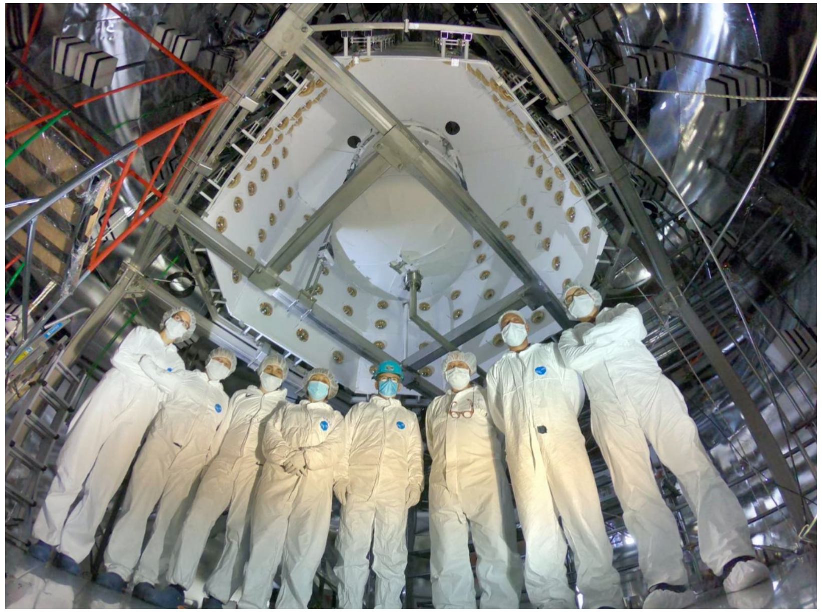
Summary

- Direct dark matter searches have been developed quite successfully by liquid xenon technology in this 20 years.
- O(10t) Gen-2 expts. XENONnT and LZ now successfully started and approaching $\sigma(SI) < 10^{-47}$ cm^2.
- XENON1T Low-E ER excess is excluded by XENONnT with x5 lower ER BG achieved.
- In next 5 years we may see first hint (i.e. WINO DM) with 20 t・yrs
- To get an evidence, O(100t) Gen-3 expts w/ >200t・yr desired. On-going R&D on DARWIN 50t, now being expanded by the new XLZD consortium.
- Directional searches will play a key role for ultimate future goal.

Backup

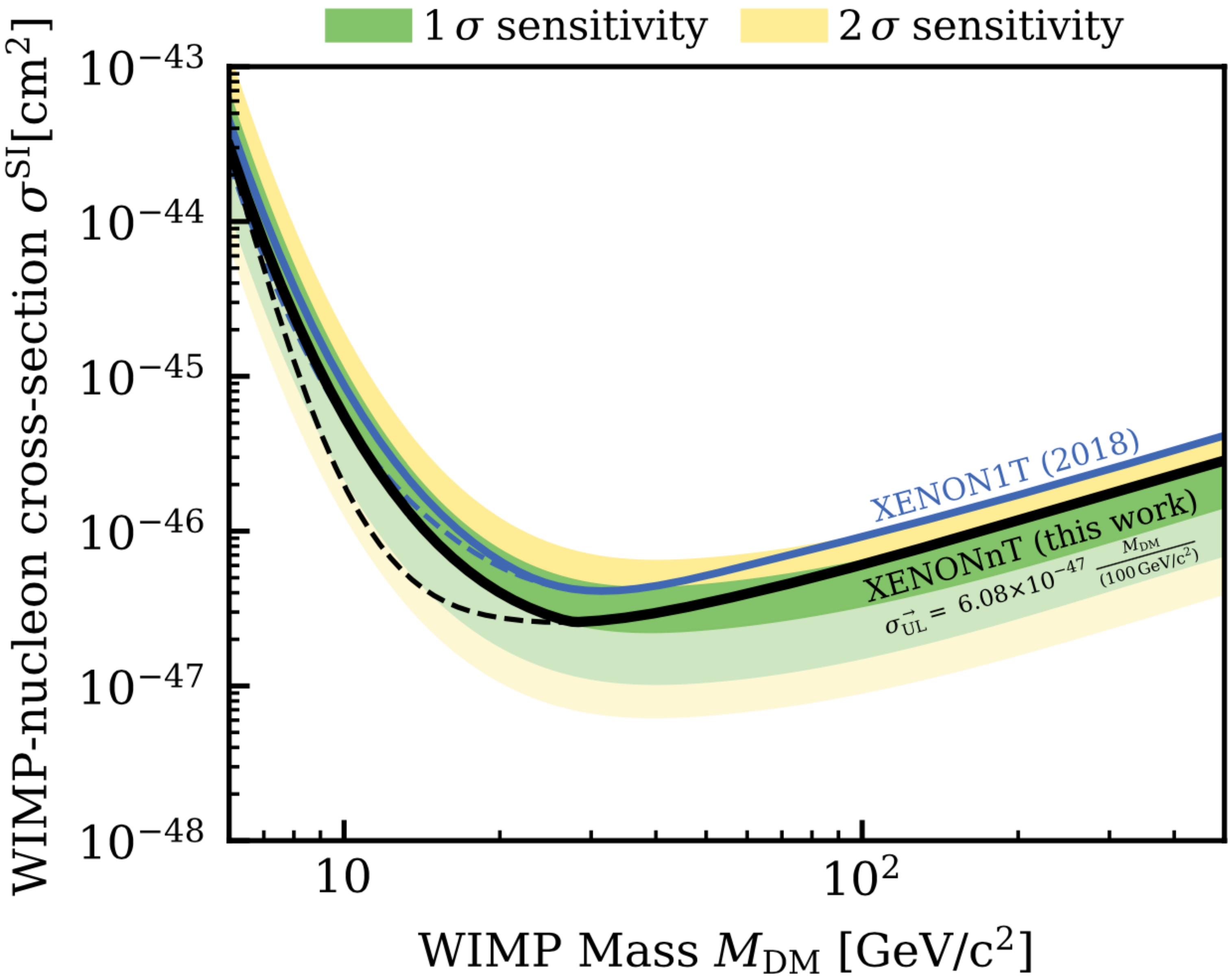
2019-2020 Construction under COVID-19





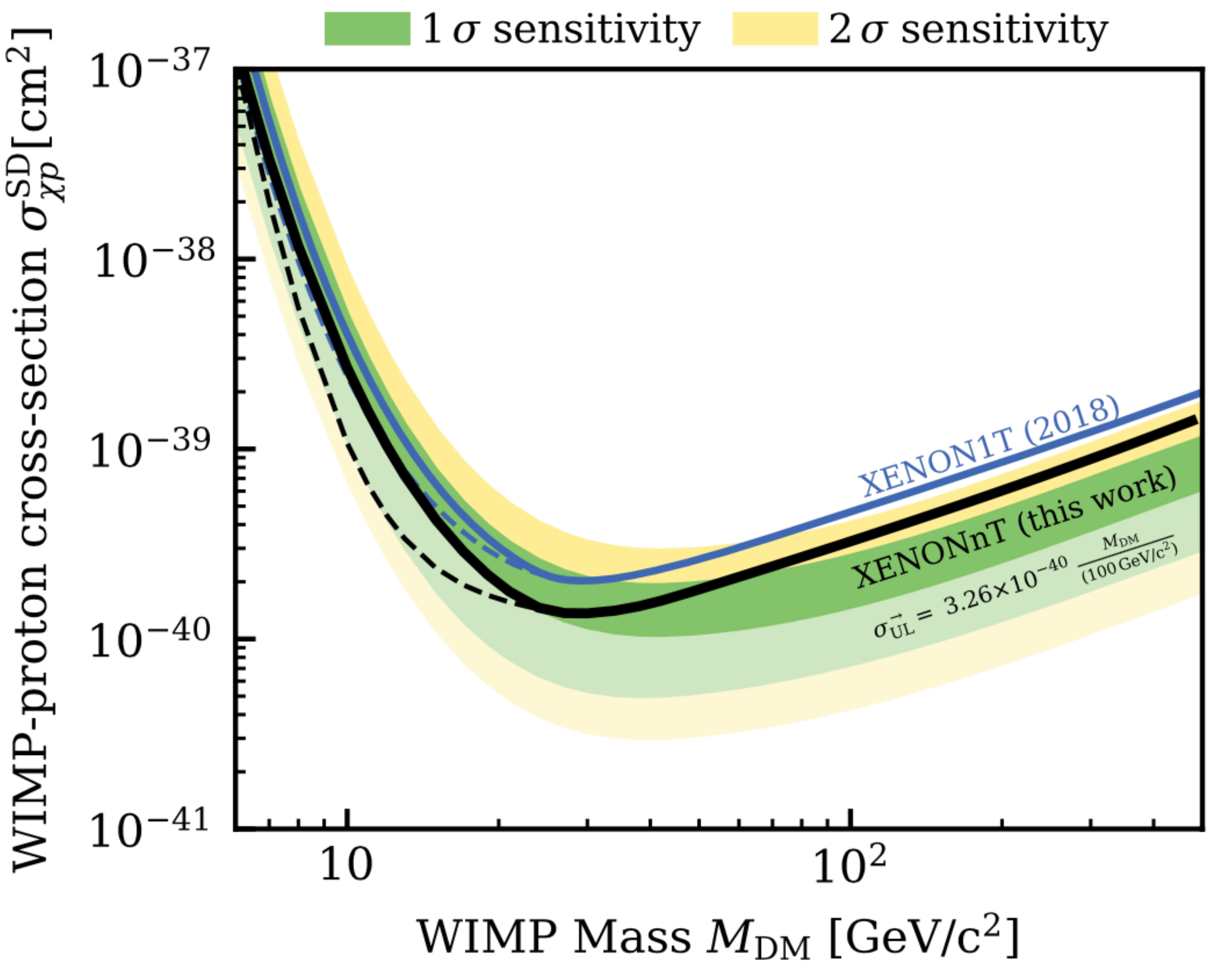
XENONnT SR0 WIMP limit S(σSI)

arXiv:2303.14729

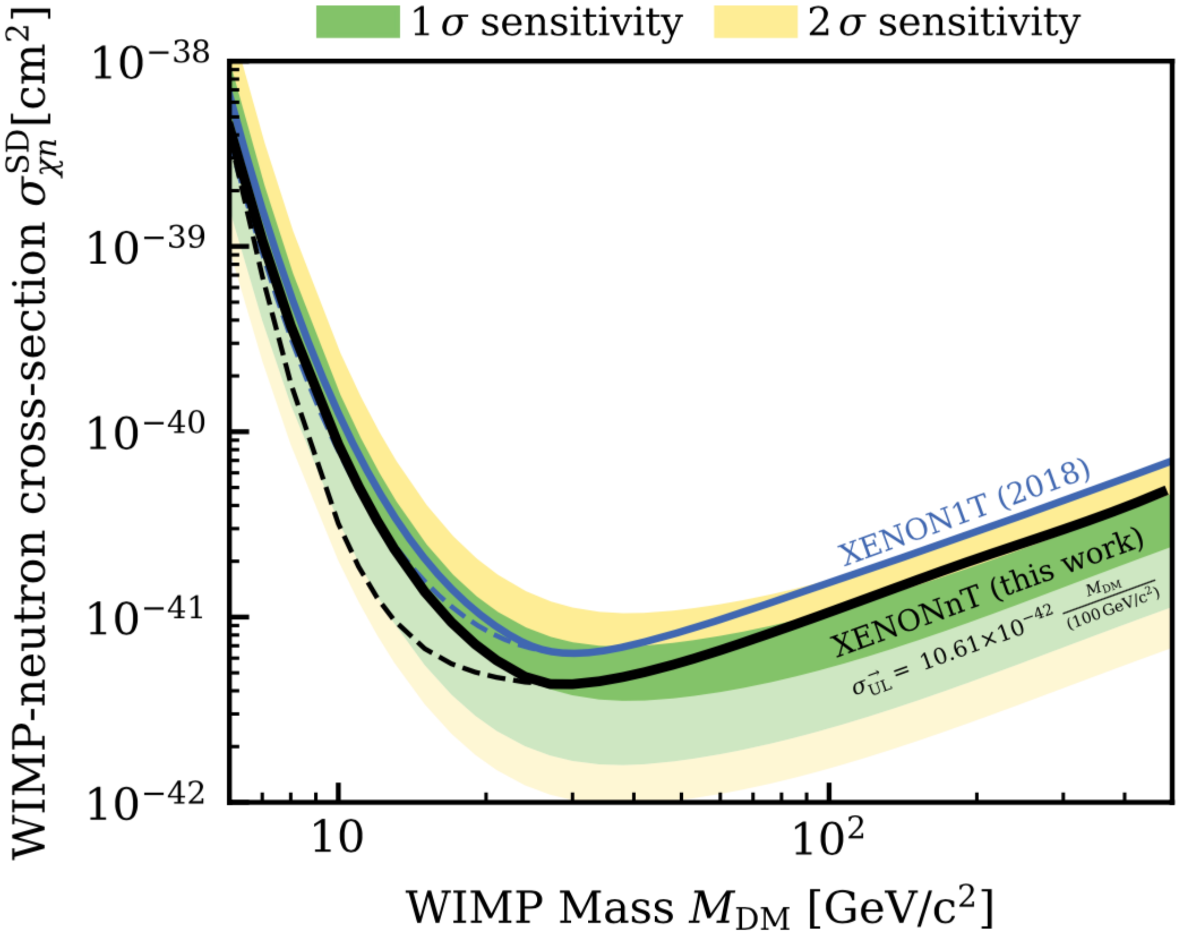


XENONnT SR0 WIMP limit S(σSD)

arXiv:2303.14729



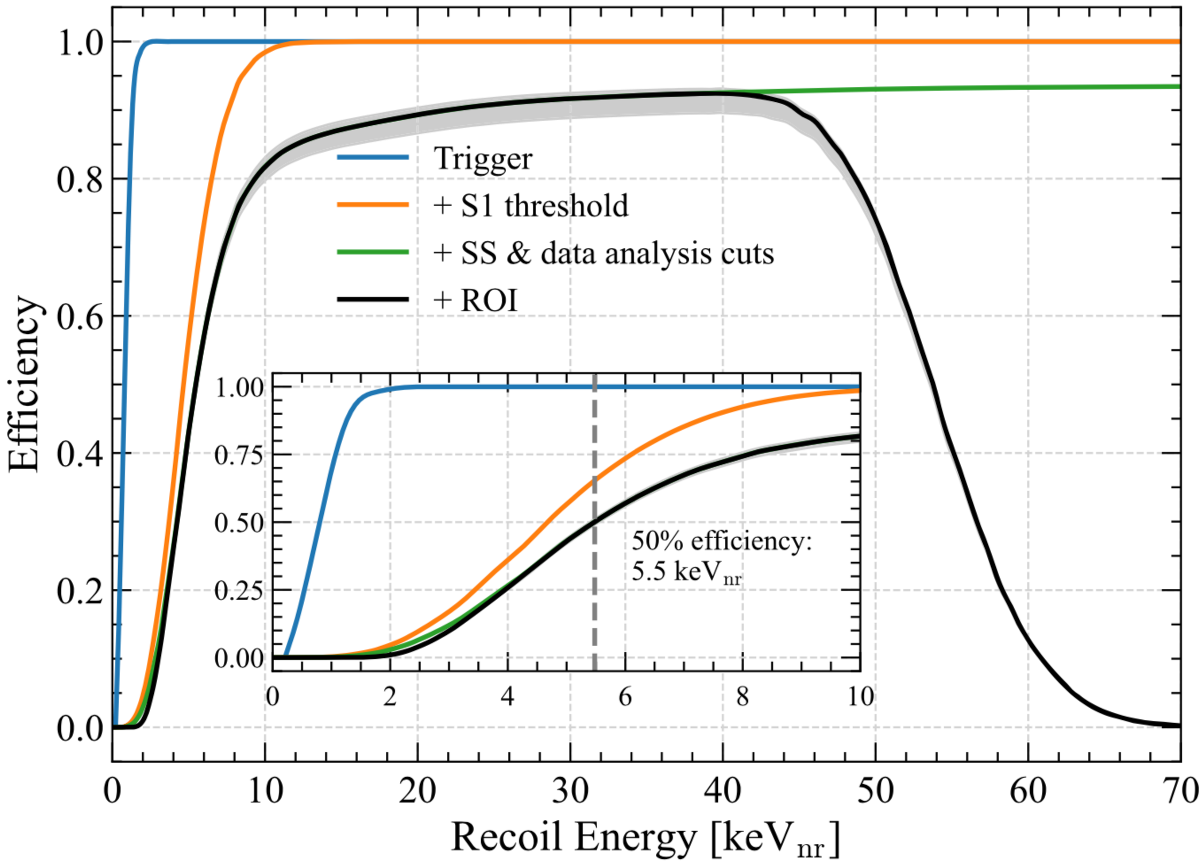
(a)



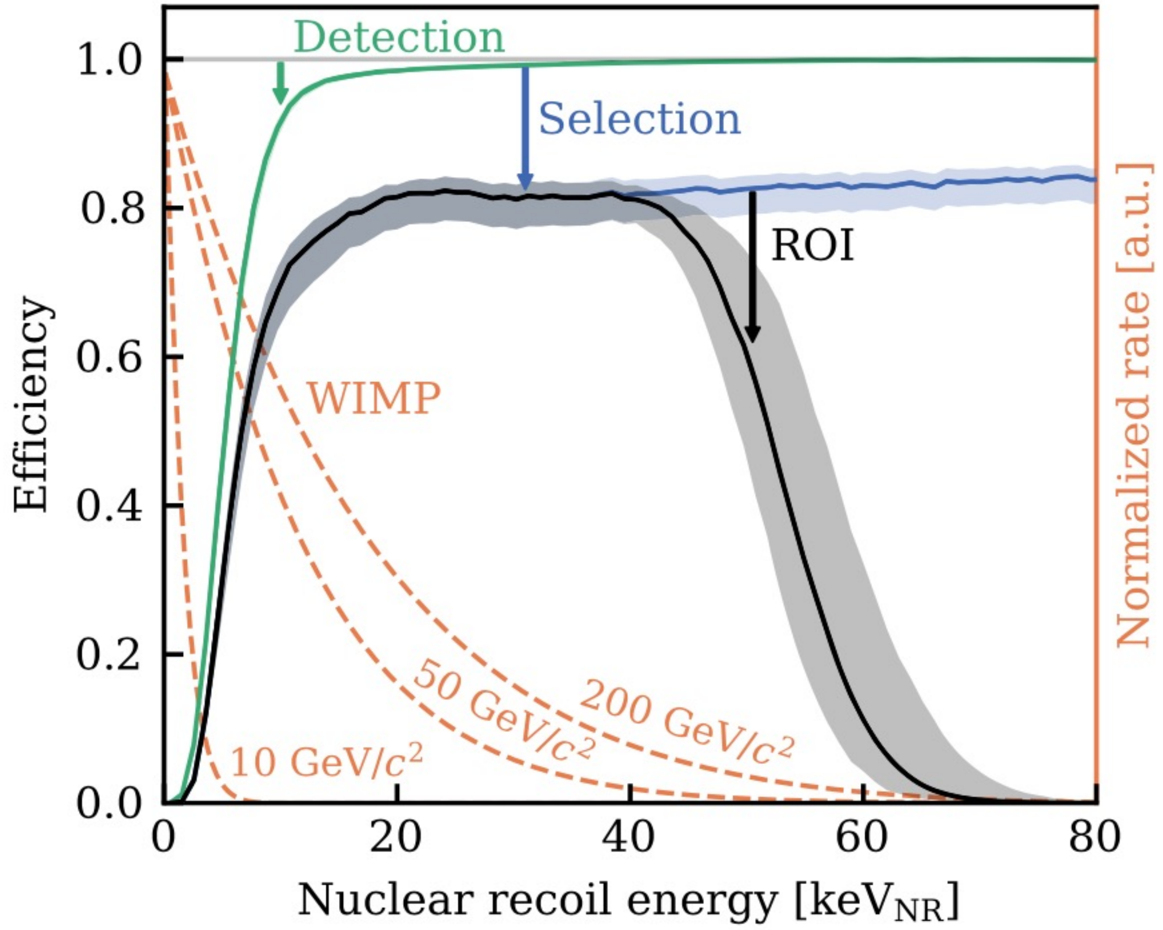
(b)

WIMP signal acceptance

LZ 1st data *PRL 131, 041002 (2023)*

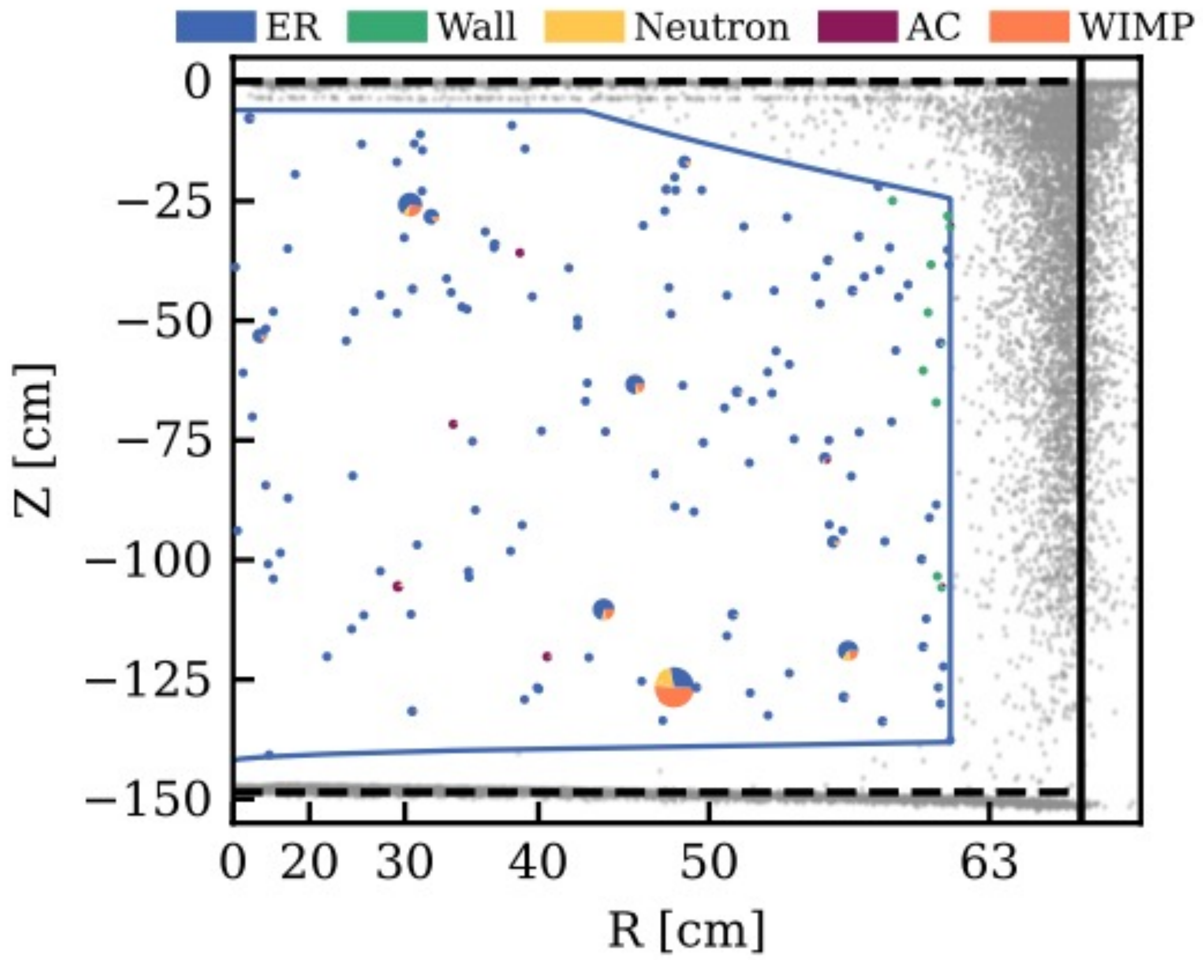


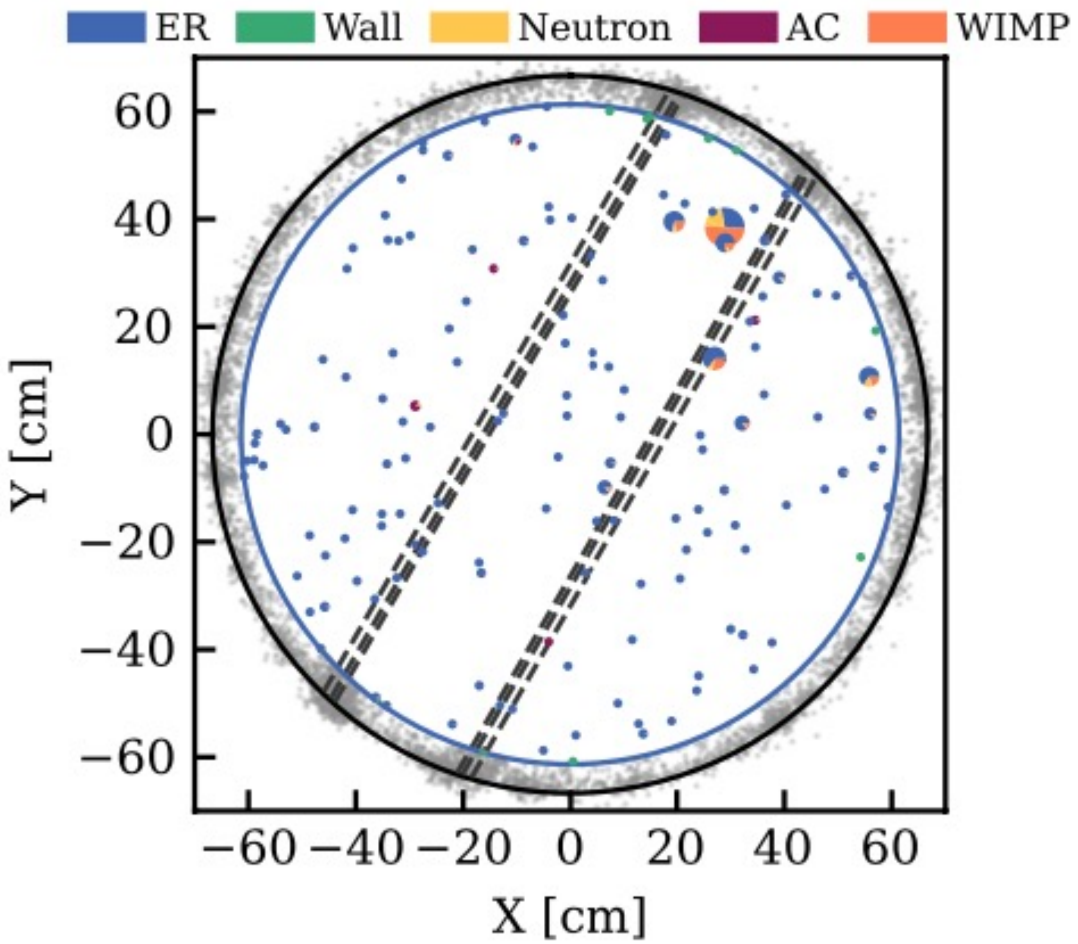
XENONnT SR0 *PRL 131, 041003(2023)*



XENONnT SR0 event locations

arXiv:2303.14729



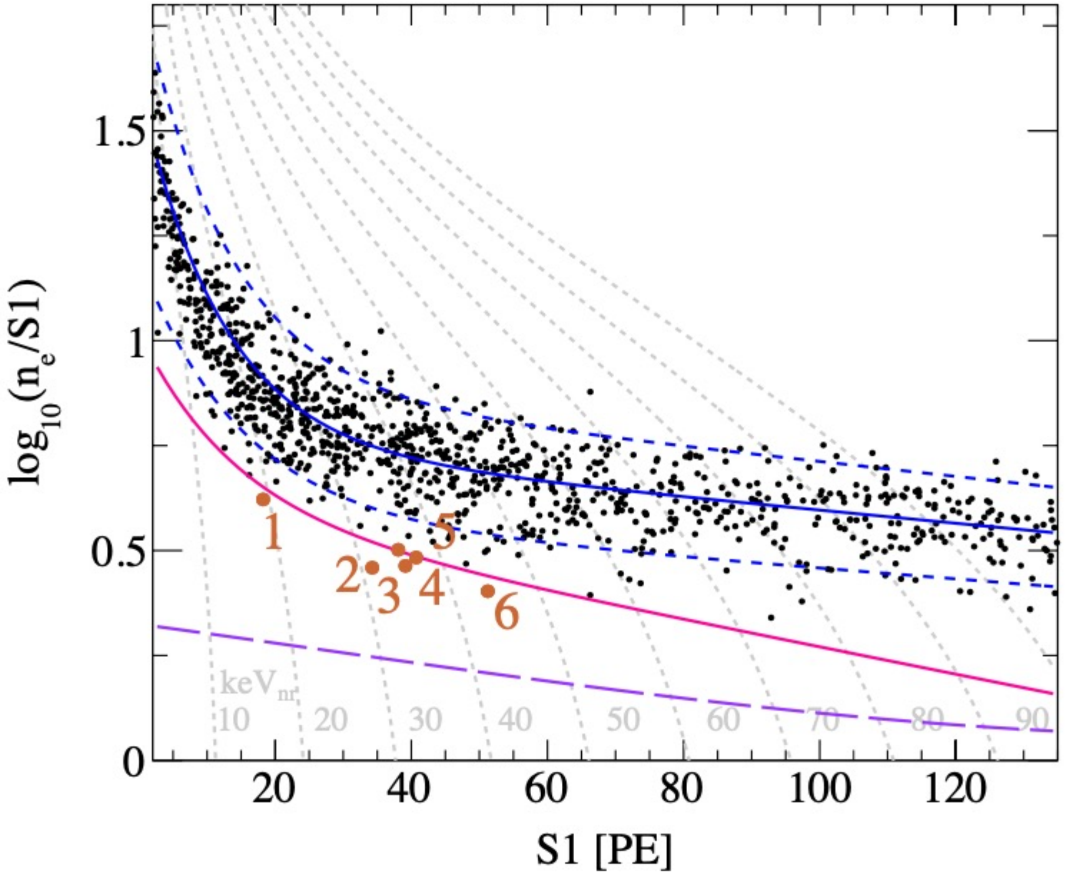


Unblinded events relatively concentrate upper-right
But no evidence of detector nonuniformity found

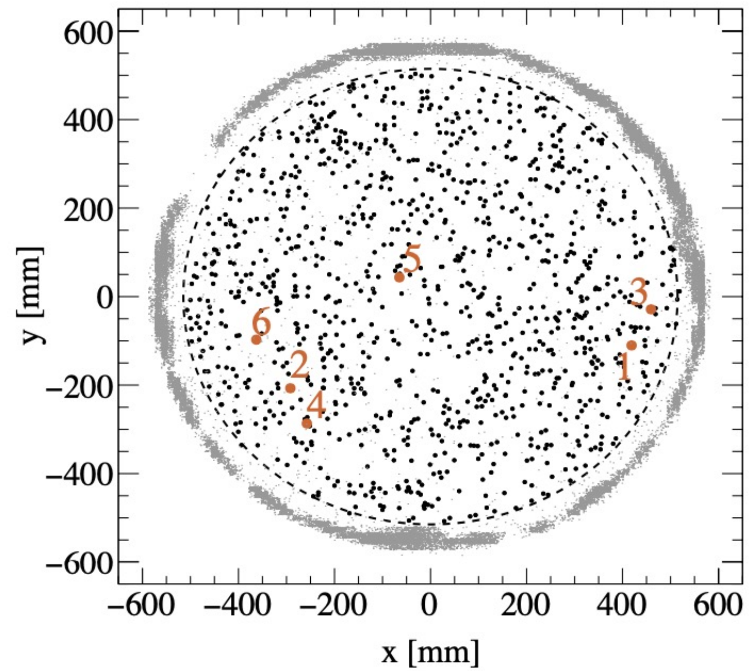
PandaX-4T

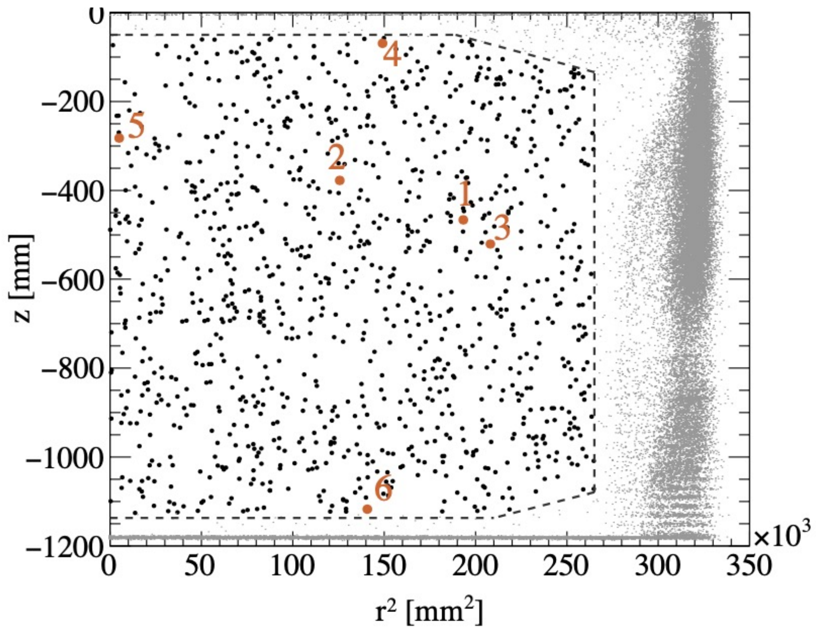
Phys.Rev.Lett. 127 (2021) 26, 261802

(a) $\log_{10}(n_e/S1)$ vs. $S1$

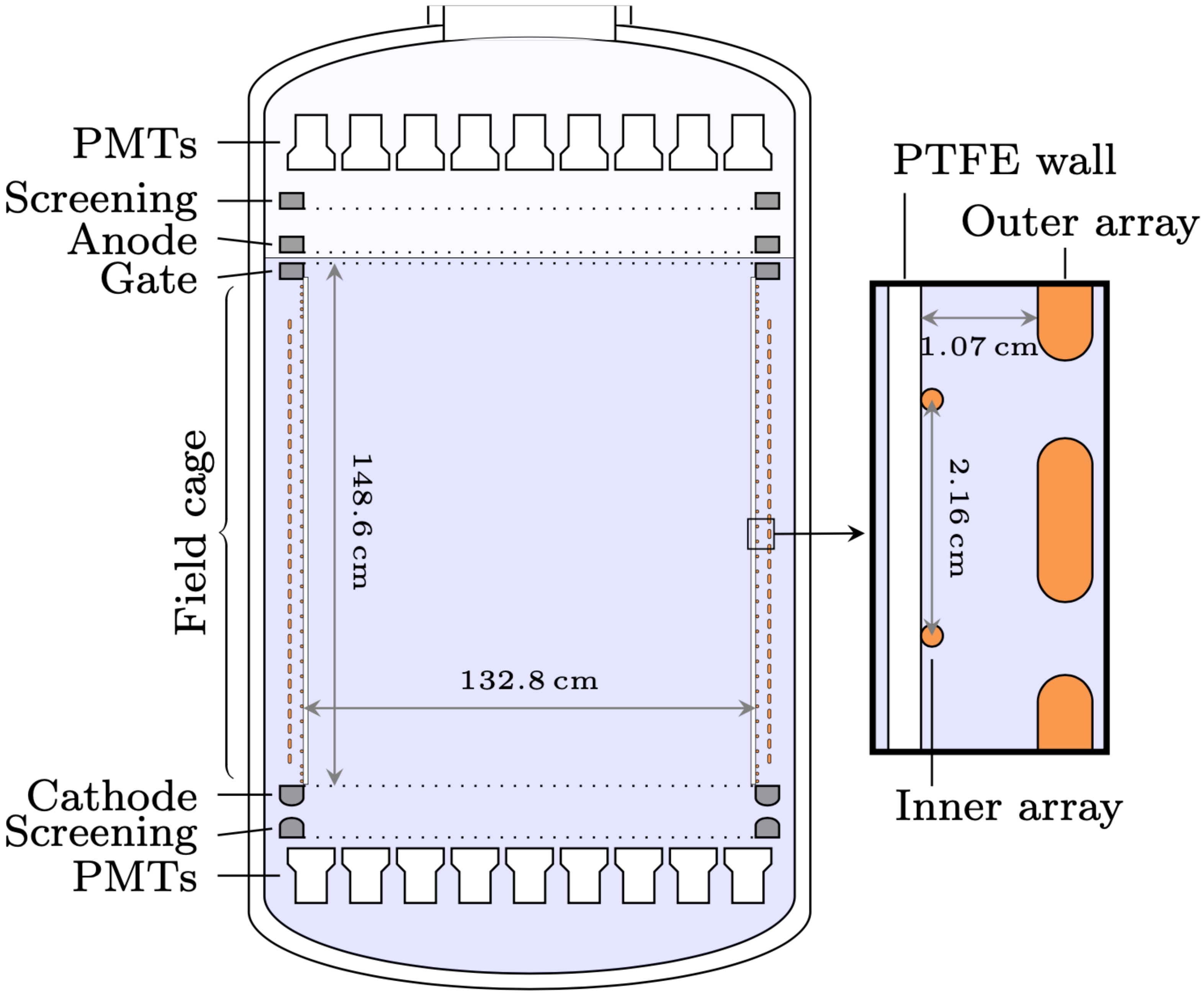


(c) y vs. x



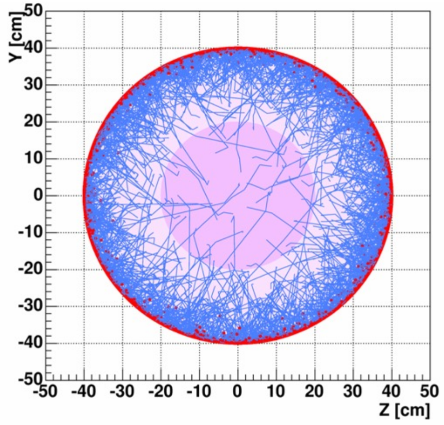


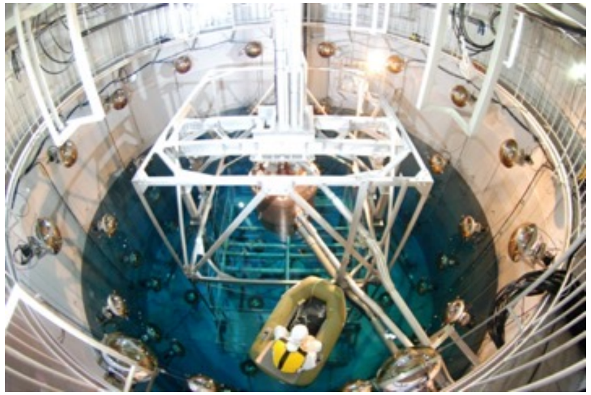
XENONnT field cage

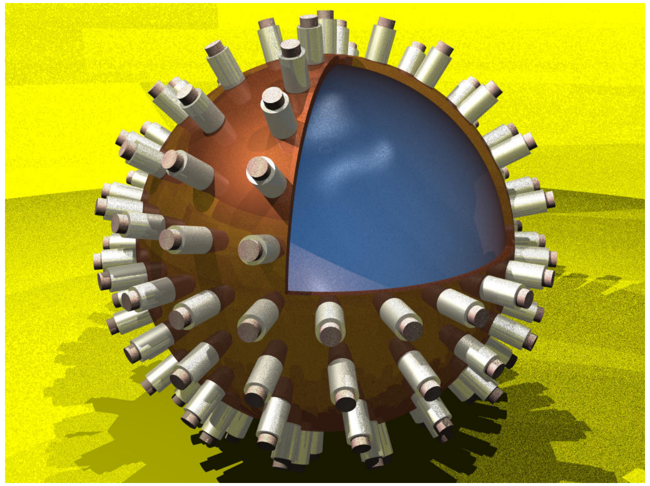


XMASS: 1st idea of 10-ton liquid Xe for DM and Sol-$\nu/\beta\beta$

- Many ground-breaking ideas since 2000
  - Pointing out LXe can be ideal multipurpose experiments
  - ^{85}Kr removal by distillation (essential break-through)
  - Self-shielding by high-Z LXe surface
  - 1kt Water Cherenkov neutron/muon veto
  - World best low-BG PMT







- Long term Japan-Korea collaboration in XMASS

Yeong Duk Kim, Nam Young Kim, Yong Hamb Kim (CUP,IBS)
Byeongsu Yang (CAPPR, IBS) (now SNU)
Min Kyu Lee, Kyoung Beom Lee (KRISS) **<u>as of 2019</u>**

RI-loaded rod for in-situ calibration contributed by Korea