# The Road Towards the Ultimate Direct Detection of **WIMP** Dark Matter

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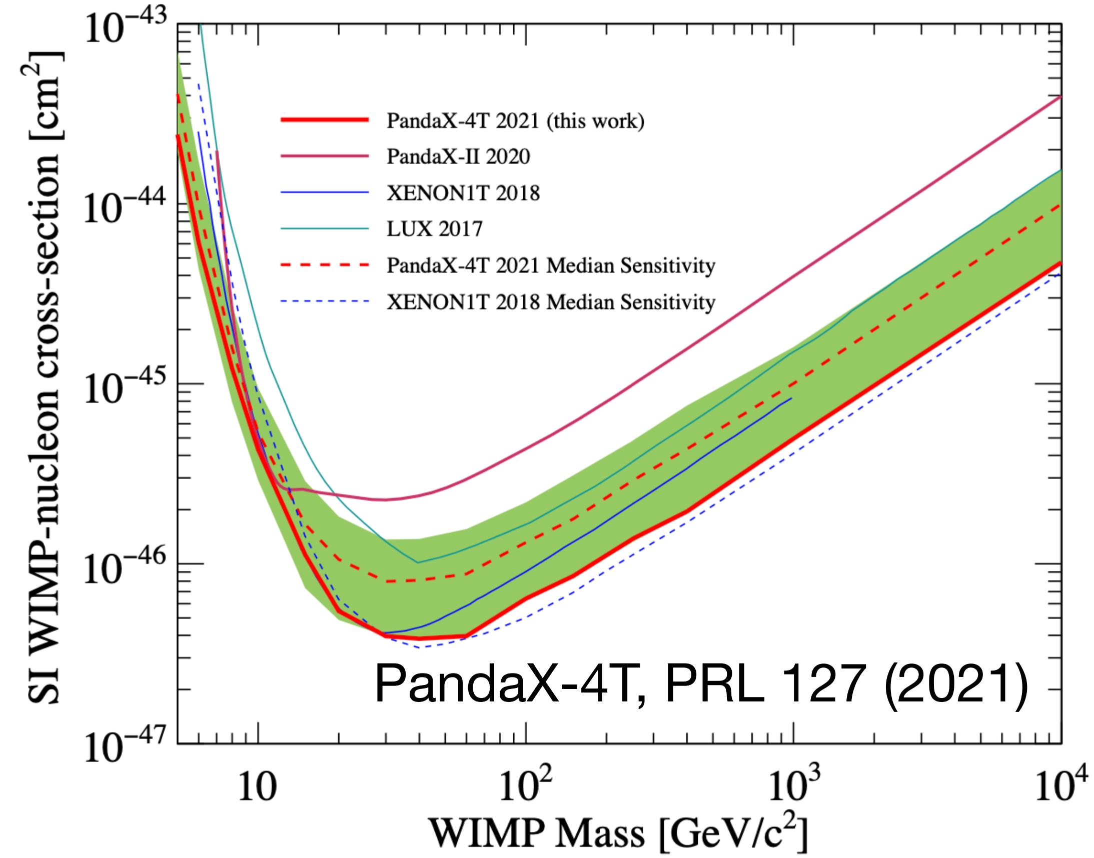
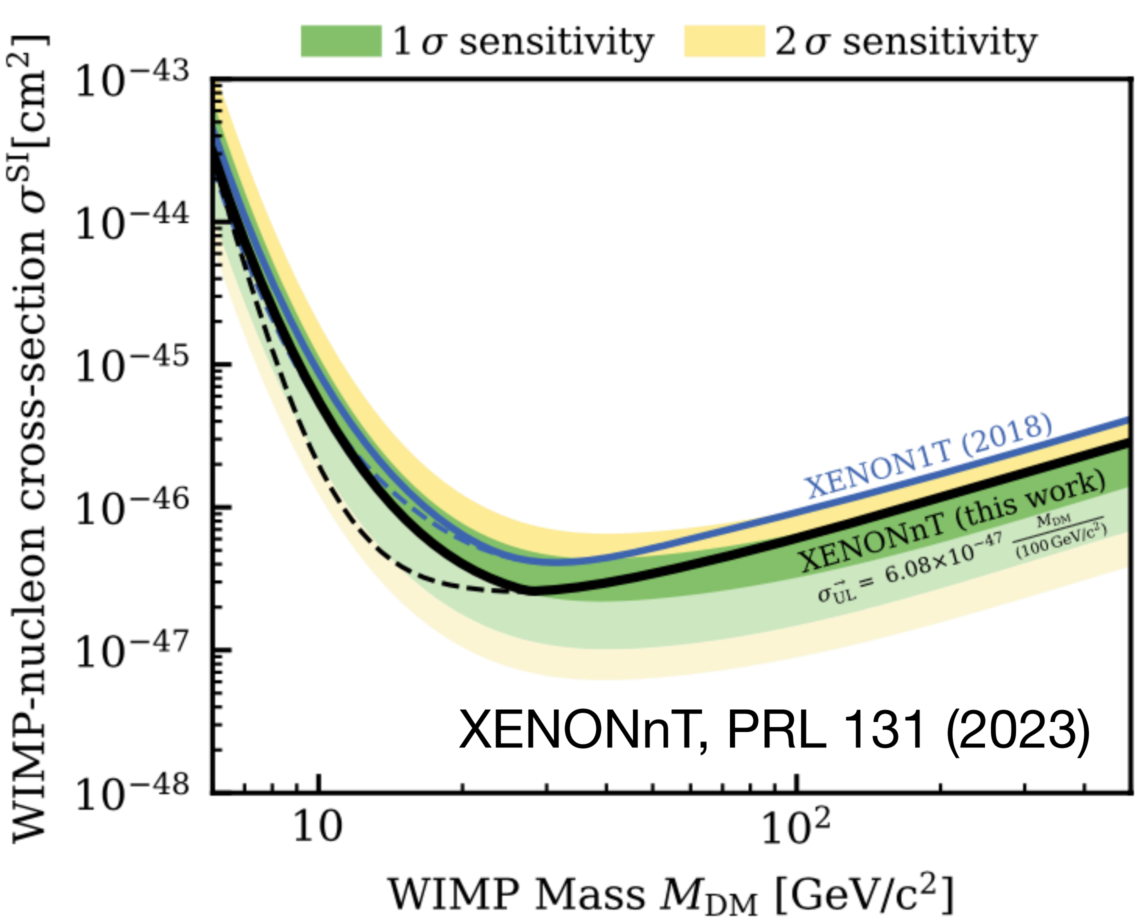
# Summary

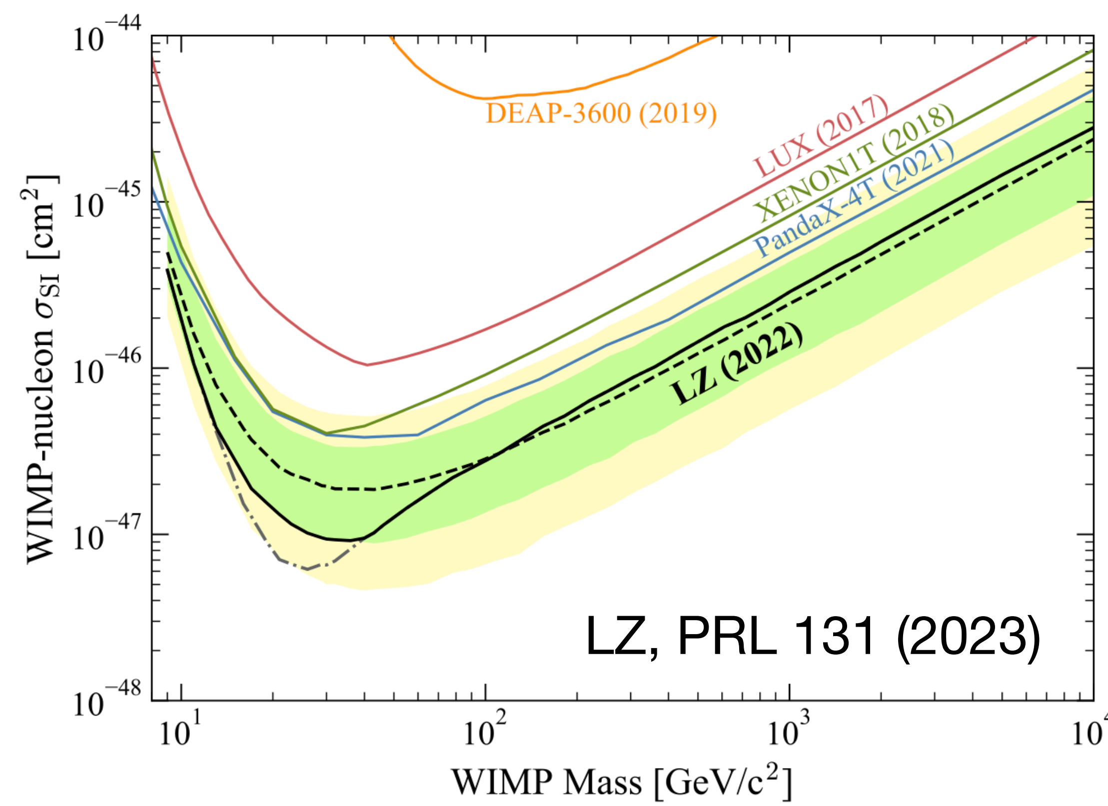
- **It has been a great year for dark matter direct detection!**
  - tighter constraints for both heavy and light dark matter models
  - improved limits for both SI and SD models
  - new theoretical development probing lighter dark matter
- **We are still in the dark!**
  - watch out new WIMP detectors coming online in 2019 and beyond: **XENONnT, PandaX-4T, LZ**, DarkSide-20t
  - dedicated low-mass and light dark matter experiments under development: SuperCDMS, CDEX, CRESST, DAMIC, SENSEI, LBECA, DarkSide-lowmass, etc.

# What happened to WIMPs in the last five years?

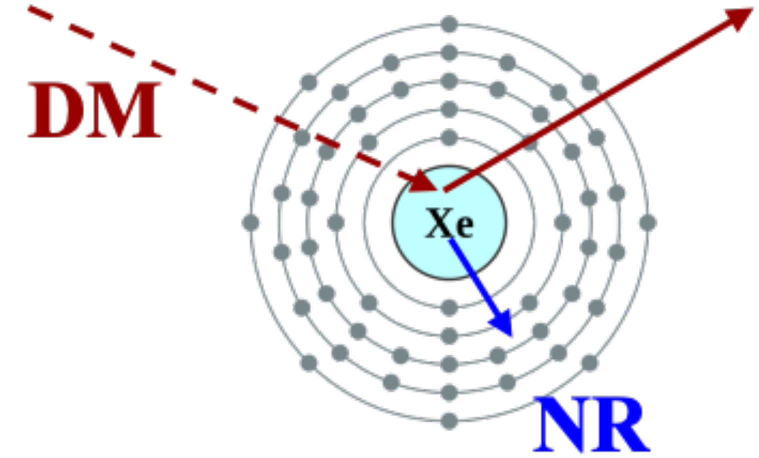
- **We are still in the dark! However…**
    - New WIMP search results obtained from first runs of PandaX-4T, XENONnT, LZ!
    - More data accumulated as today

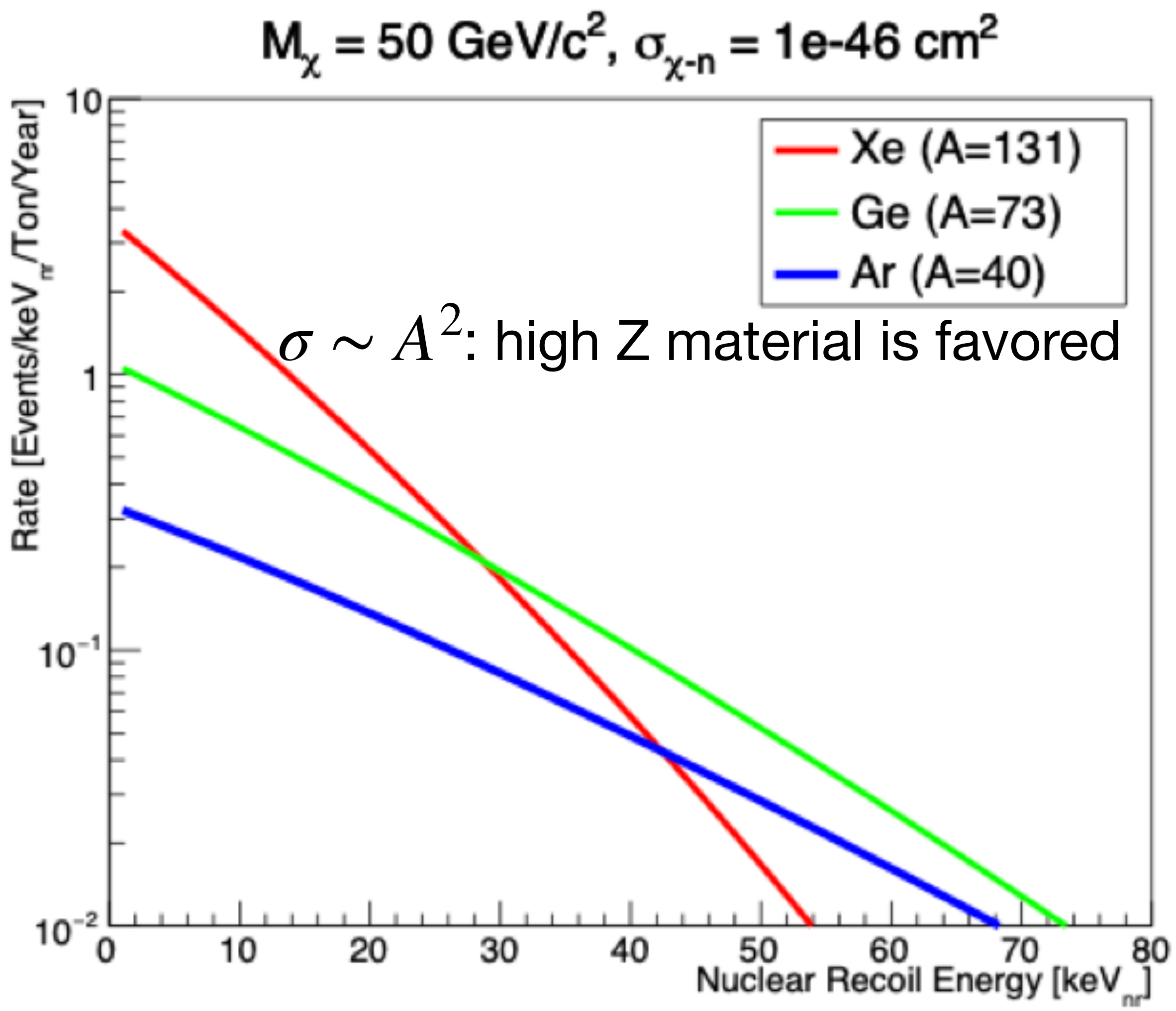


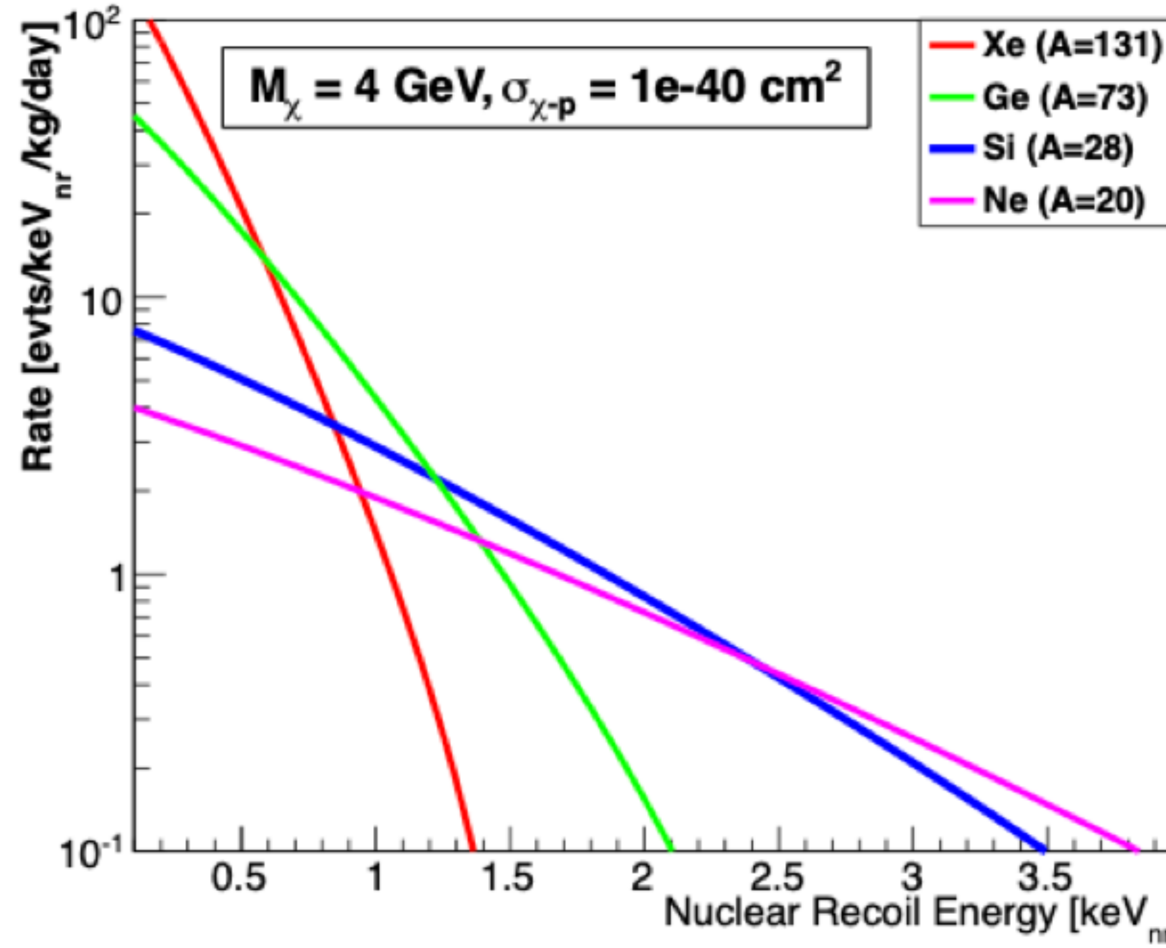



# Detect WIMPs via Nuclear Recoils



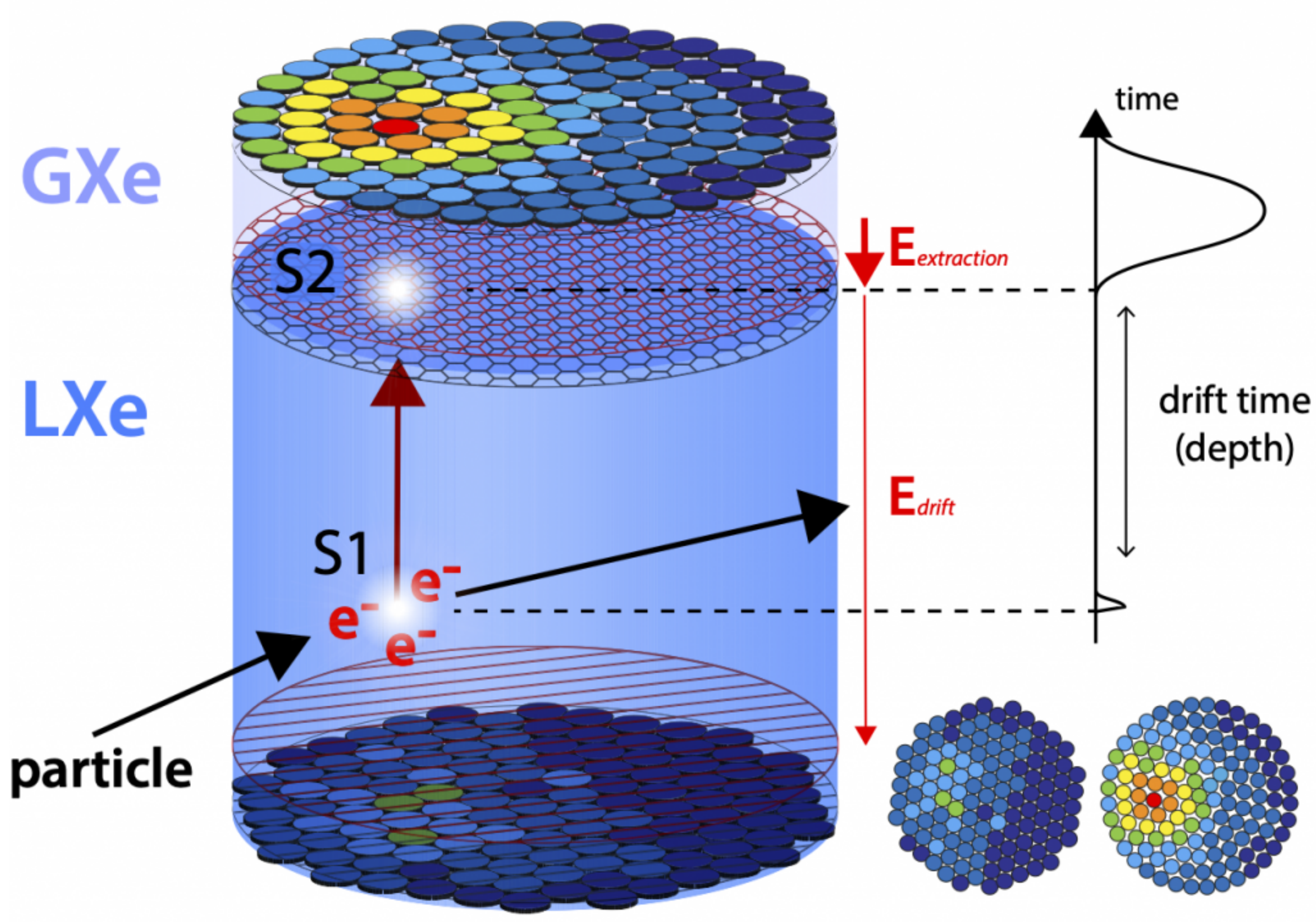




- The current limit for 50 GeV WIMPs is below 1e-46 cm$^2$ -> ~1 event/keV/ton/year. need **low threshold** + **extremely-low background** + **multi-ton scale** detectors

- Lower mass DM -> lower recoil energy -> ultra-low threshold detectors -> light DM searches (Henry Wong's talk yesterday)

# Why Liquid Xenon so powerful for WIMP searches?



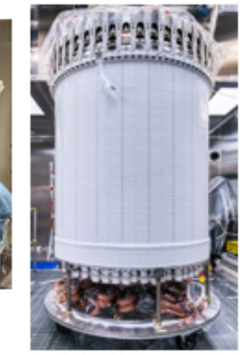

- WIMP cross section is low: need large target
  - **high Z** material is favored: $\sigma \sim A^2$
  - **dense** material is favored: solid/liquid better than gas
  - **liquid** target is more favorable than solid target: purification in situ to remove intrinsic radioactive elements
  - **monolithic** large target is more favorable than small crystals: self-shielding external background
- Low energy nuclear recoils: need low energy (~keV) threshold detector

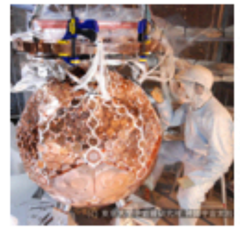
# The Liquid Xenon Detector Evolution

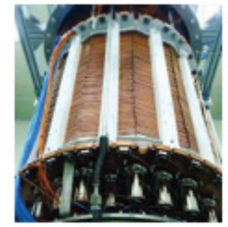
PandaX-4T

XENONnT (6T)

LZ (7T)







**Concept of using LXe for DM Detection**

DAMA/LXe, ZEPLIN-I, XMASS, XENON

**G1 Experiments (100-1000 kg)**

XENON100, LUX, PandaX-I/II, XMASS

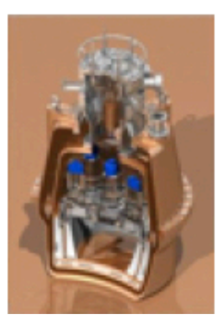
**G2 Experiments (1-10 Ton, two-phase)**

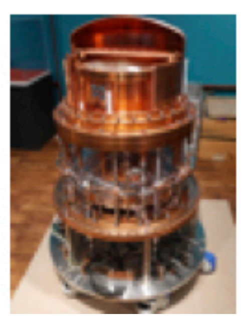
XENON1T/nT, PandaX-4T, LZ

**~2000** — **2007** — **2010** — **2017** — **2020** — **2025**

**First Results from Two-Phase Xe detectors (~10-kg)**

XENON10, ZEPLIN-II/III





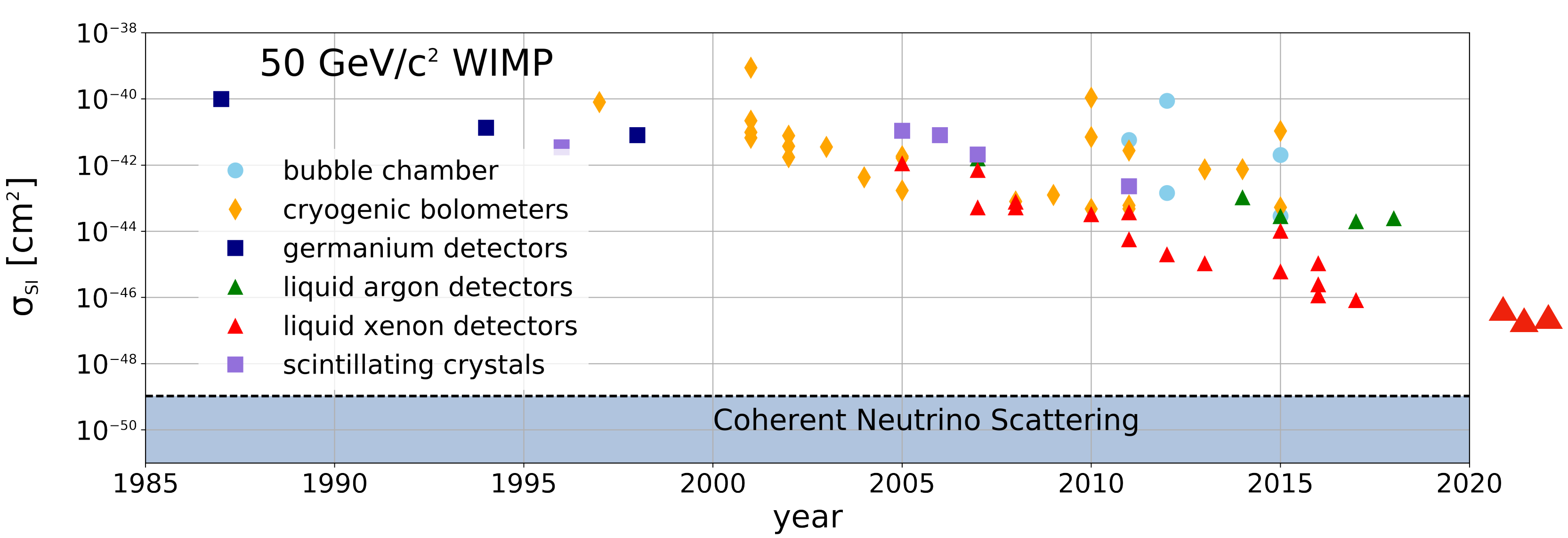
**Results from the first ton-scale LXe detector**

XENON1T

**G3 Experiments (40~80 T)**

**XLZD (XENON/LZ/DARWIN)**

**PandaX-xT**




PandaX-4T, LZ, XENONnT

# The most sensitive WIMP detectors (all with **liquid xenon** TPC - time projection chambers)

PandaX-4T

- TPC diameter: ~1.2 m
- TPC height: ~1.2 m
- Target LXe: 3.7-tonne
- Total LXe: **5.6-tonne**
- TPC PMTs: 368 R11410
- Veto PMTs: 105 R8520
- Location: CJPL, China

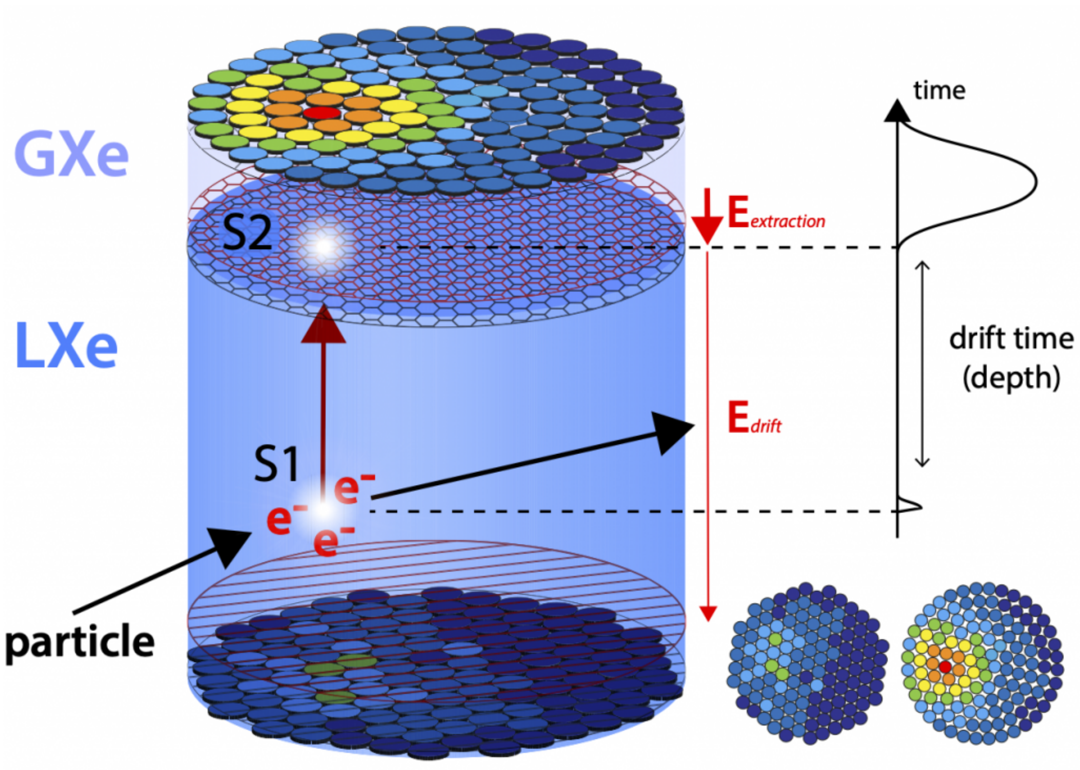
XENONnT

- TPC diameter: ~1.3 m
- TPC height: ~1.5 m
- Target LXe: 5.9-tonne
- Total LXe: **8.3-tonne**
- TPC PMTs: 494 R11410
- Location: LNGS, Italy

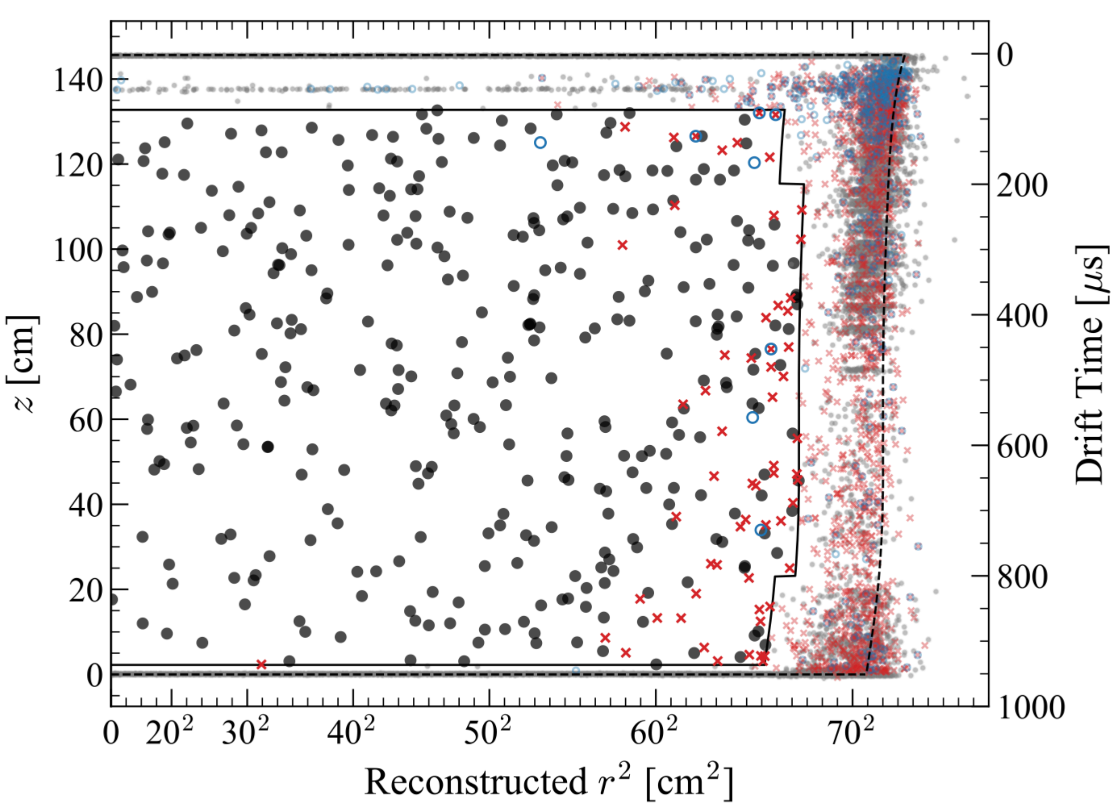
LZ

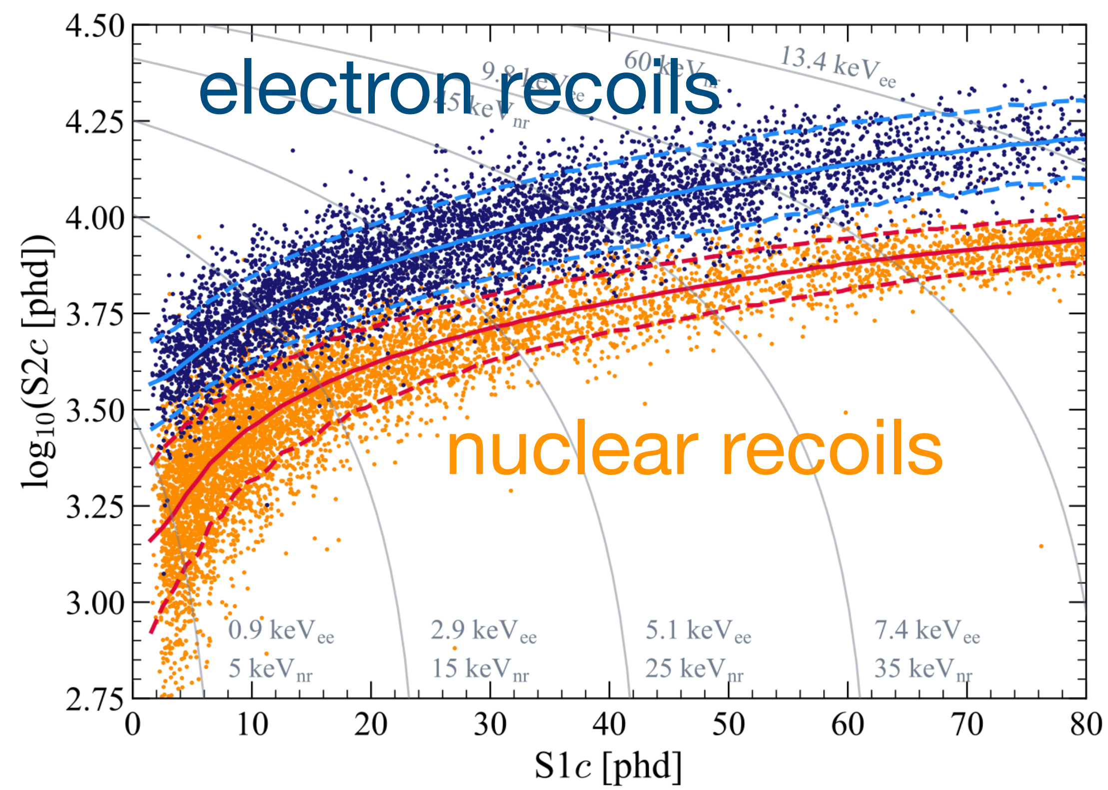
- TPC diameter: ~1.5 m
- TPC height: ~1.5 m
- Target LXe: 7-tonne
- Total LXe: **10-tonne**
- TPC PMTs: 494 R11410
- Veto PMTs: 93 R8520/38 R8778
- Location: SURF, USA

# Liquid Xenon Time Projection Chambers




- Two-phase Xe TPC:
  - 3D fiducialization: exclude background from external radiation
  - Electronic(ER)/nuclear(NR) recoils discrimination: ~3 orders electron recoil background suppression
  - low energy threshold: ~5 keV NR threshold determined by S1

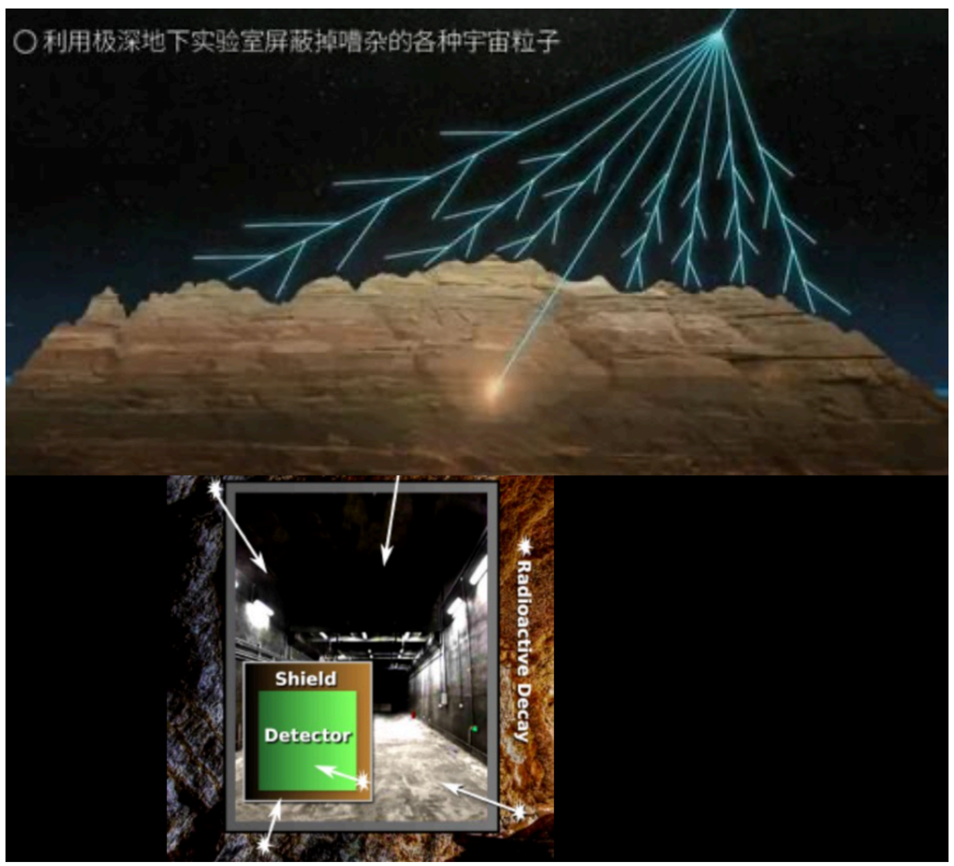



example figures from *LZ (PRL 2023)*

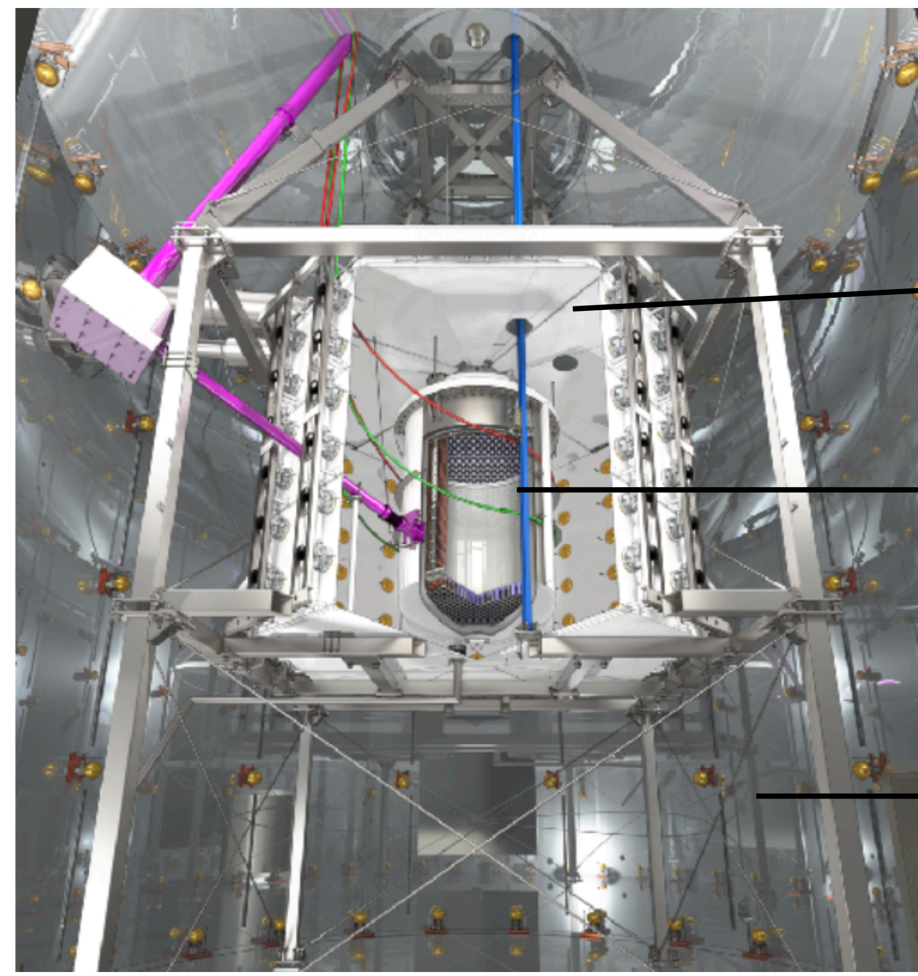
# Reducing the external backgrounds

reduce cosmic ray muon induced background by going deep underground




reduce gamma/neutron background from lab environment with shielding

XENONnT (Gd-doped water)



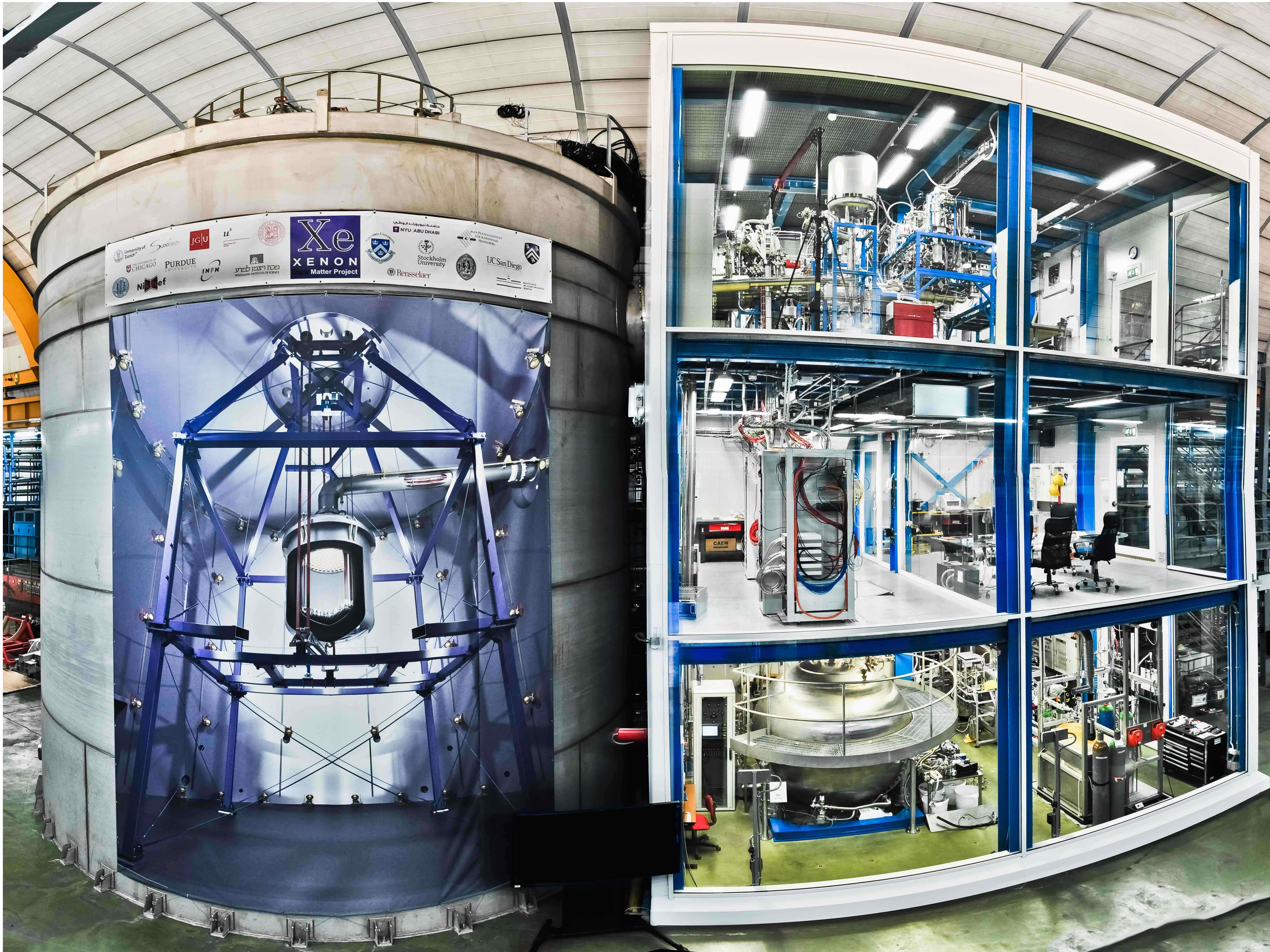
neutron veto

LXe detector

muon veto

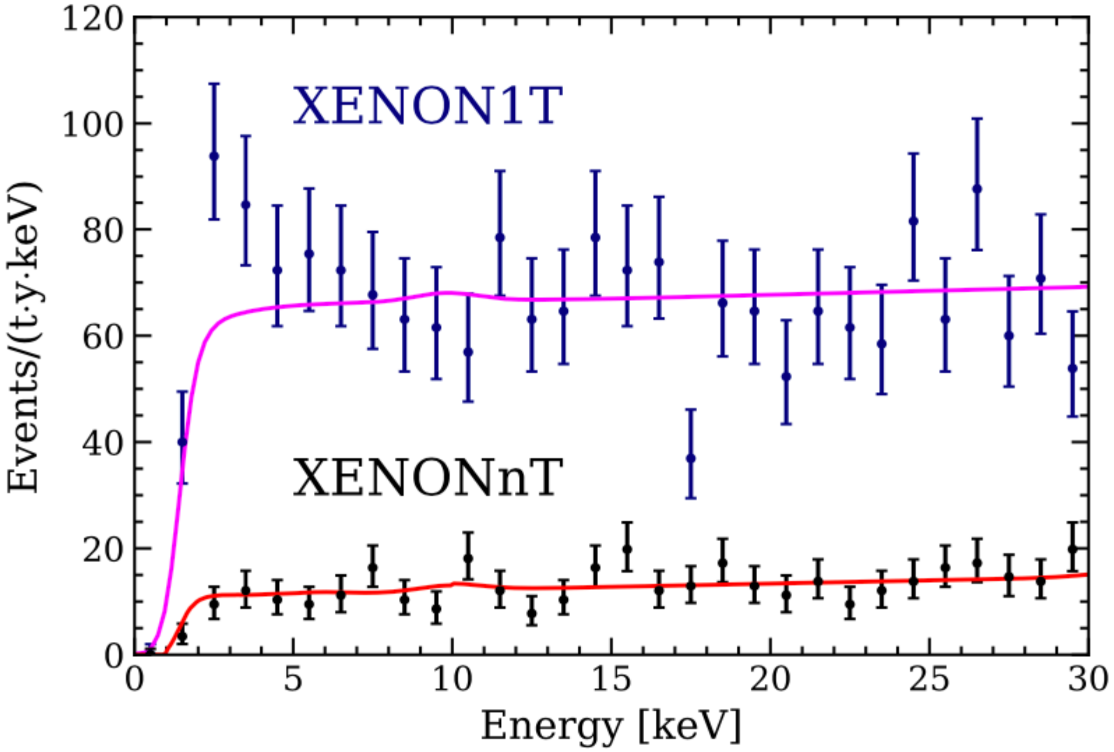
~10 meter

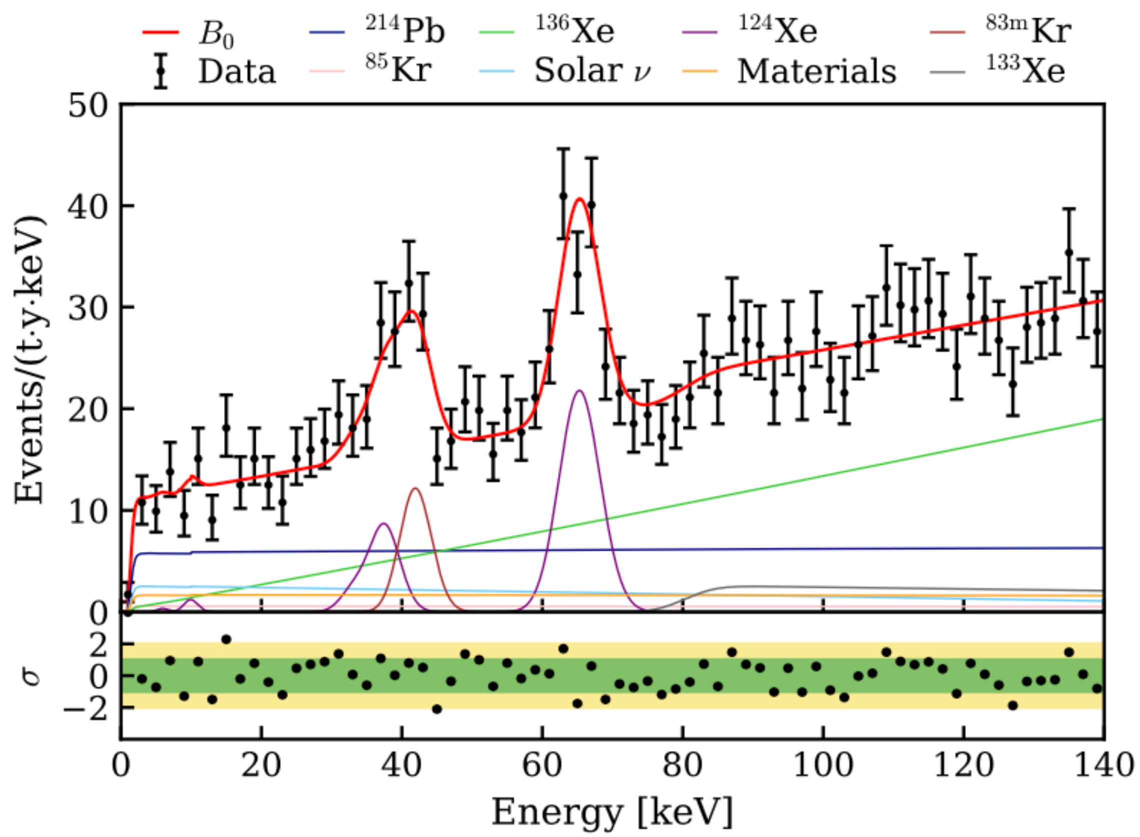
# XENON1T/nT Experiment at Gran Sasso, Italy



# Reducing the internal background: electron recoils (ER)

from XENONnT, PRL (2022)

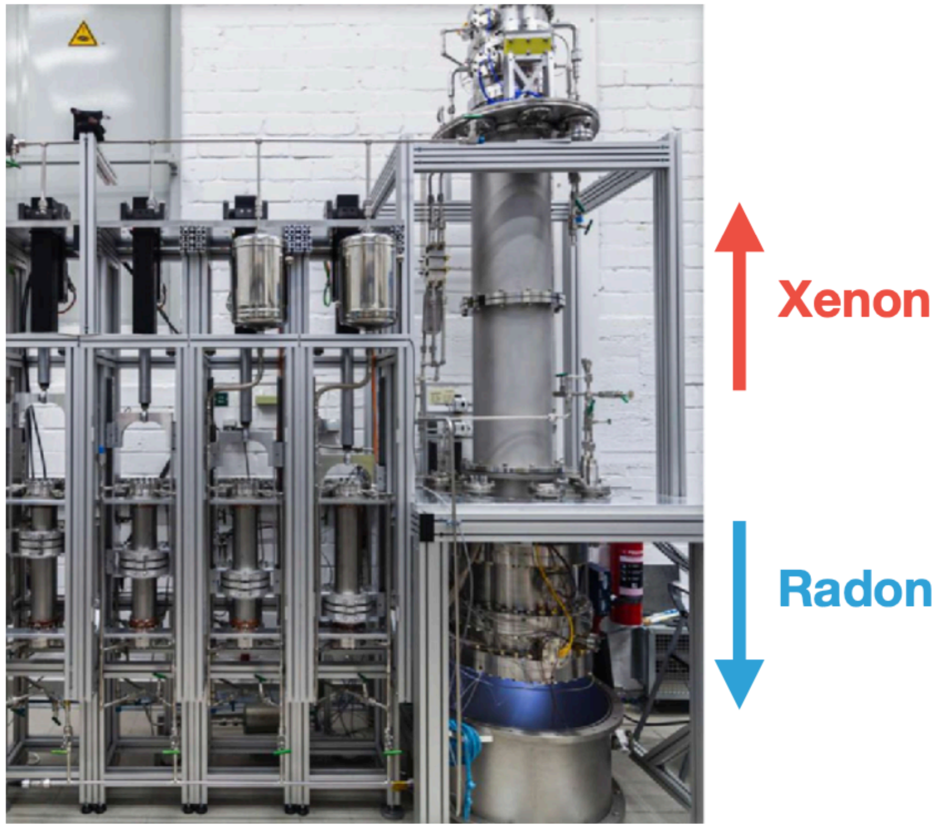


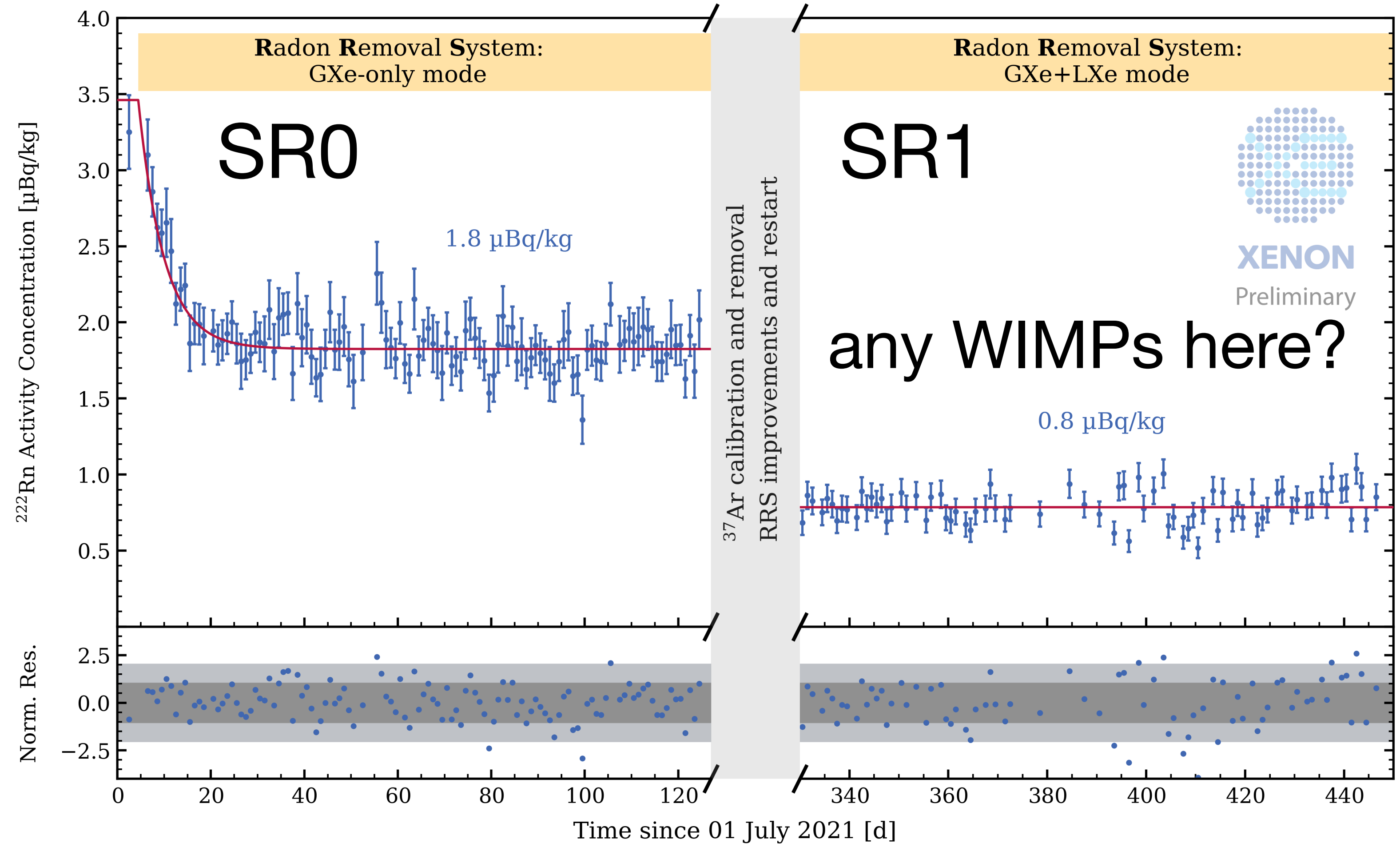



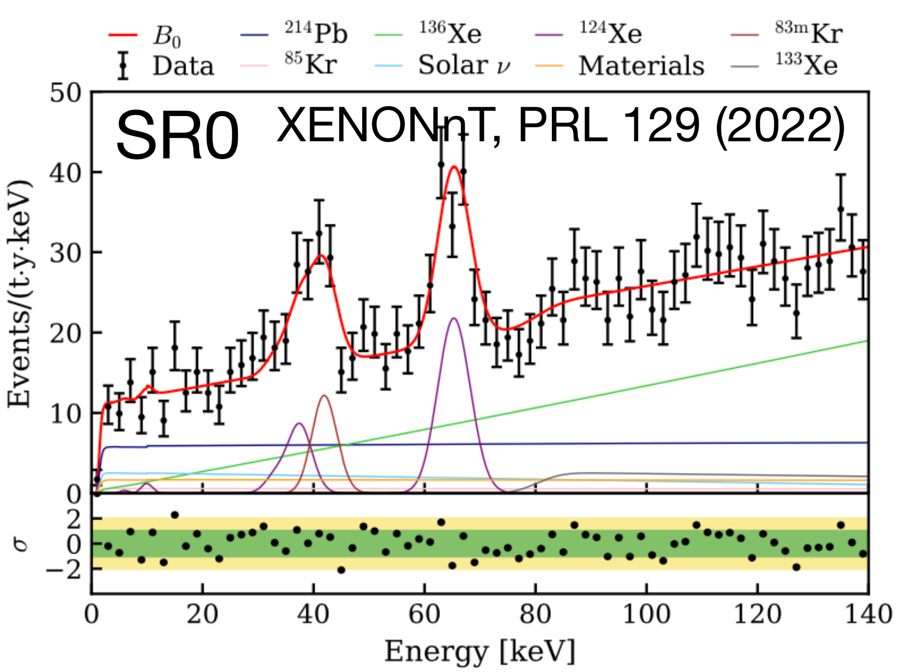

- The observed "low energy ER excess" in XENON1T (very likely due to trace level of tritium in xenon ~ 0.4 events/ton-day) is gone
- XENONnT achieved **the lowest ER background in any DM detector**: 15.8+/-1.3 evts/keV/ton/year below 30 keV
- Remaining ER BKG dominated by Pb-214 (daughter of Rn-222: 1.8 $\mu$Bq/kg of Xe)
- Solar neutrino (can't shield or reduce!) is the second highest background: ~1/2 of the bkg event rate from Pb-214 below 10 keV

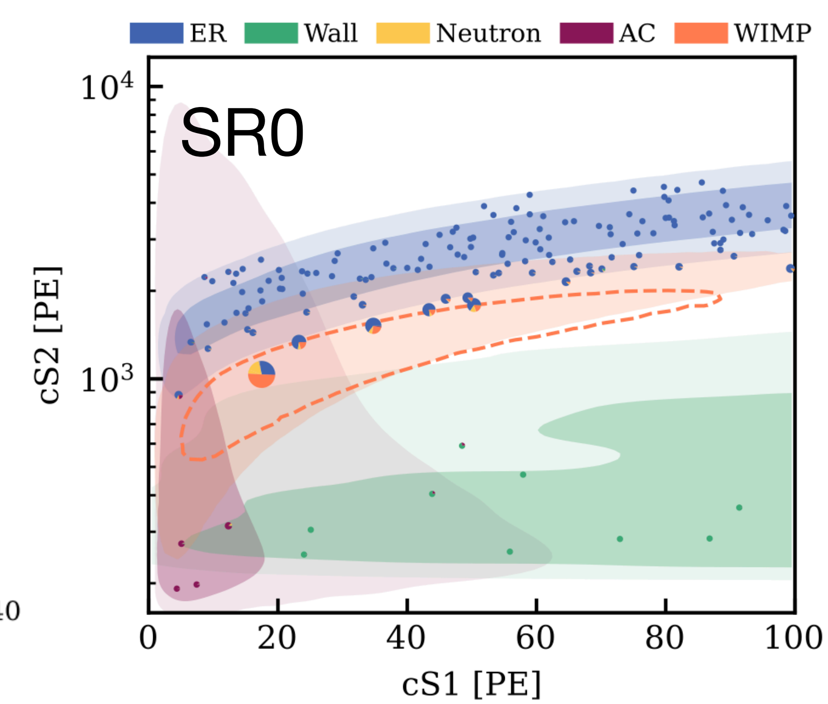
# Current Status of XENONnT

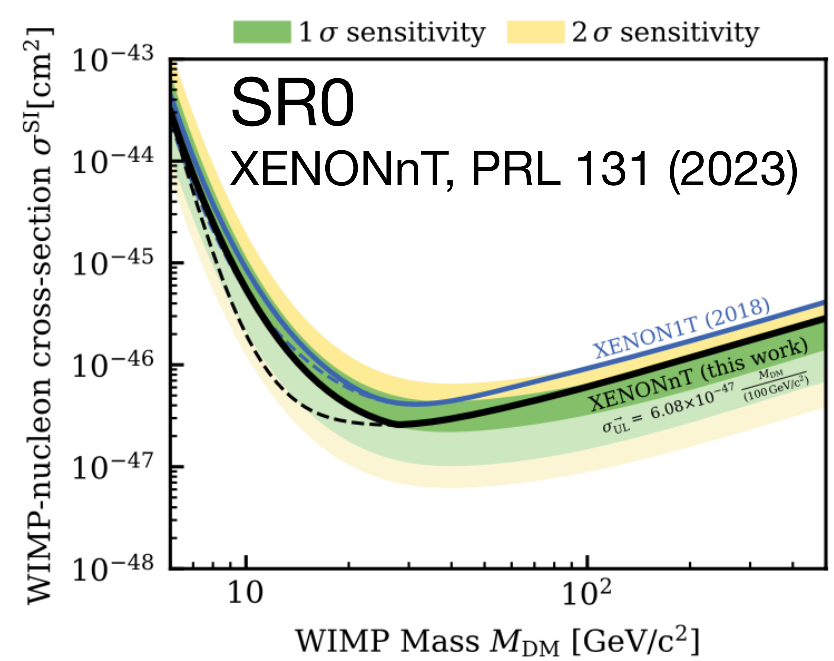
- Continuous data taking with reduced Radon from 1.8 $\mu$Bq/kg (SR0) to 0.8 $\mu$Bq/kg (SR1)



# Current Status of PandaX-4T

Commissioning Run, PandaX-4T, PRL 127 (2021)

## After commissioning

PANDA X

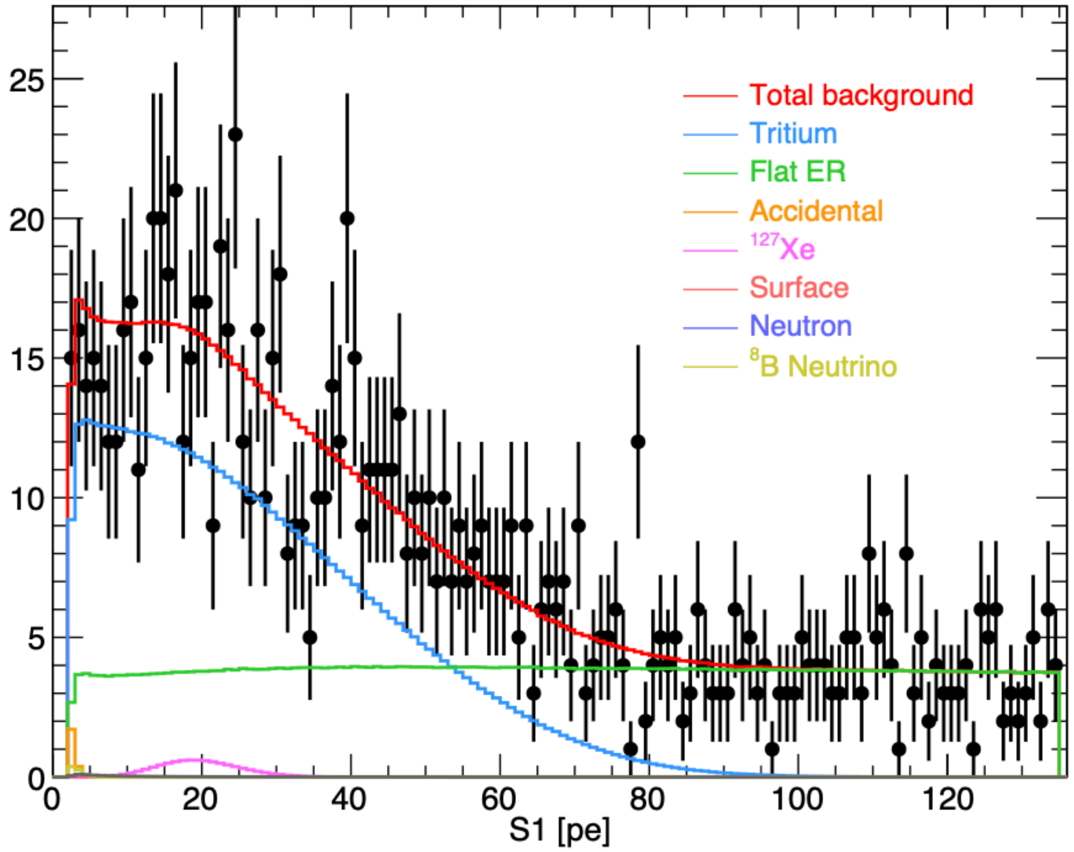
- **Tritium removal**
  - xenon distillation, gas flushing, etc
- **2021/11 – 2022/05: physics run (Run1)**
  - 164 days: ~ 1 tonne-year
- **2022/09** - 2023/10: hall construction
  - xenon recuperation
  - detector upgraded
- **Expect to resume** by the end of 2023



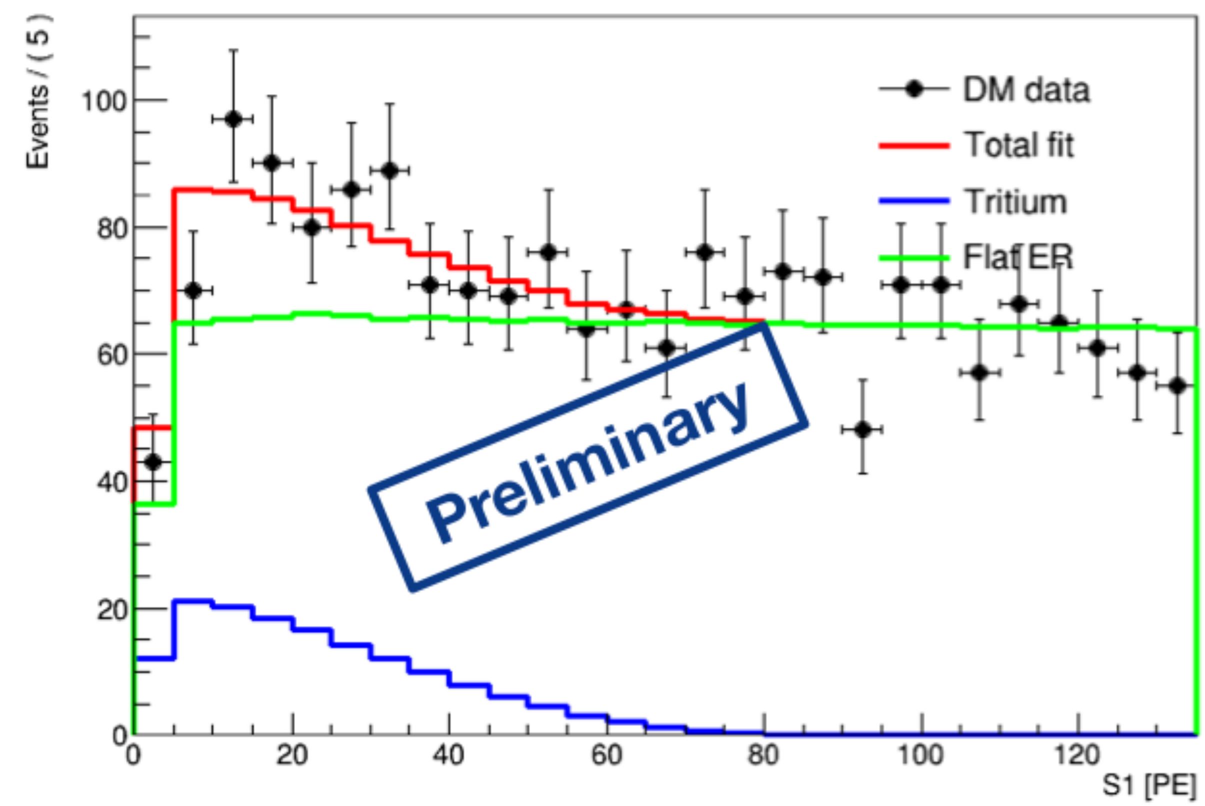

slide from Qing Lin, Symposium on Frontiers of Underground Physics, Oct.30-Nov.1, 2023, Chengdu

# Fighting the internal ER background

PandaX-4T Run0 (PRL 2021)




PandaX-4T Run1



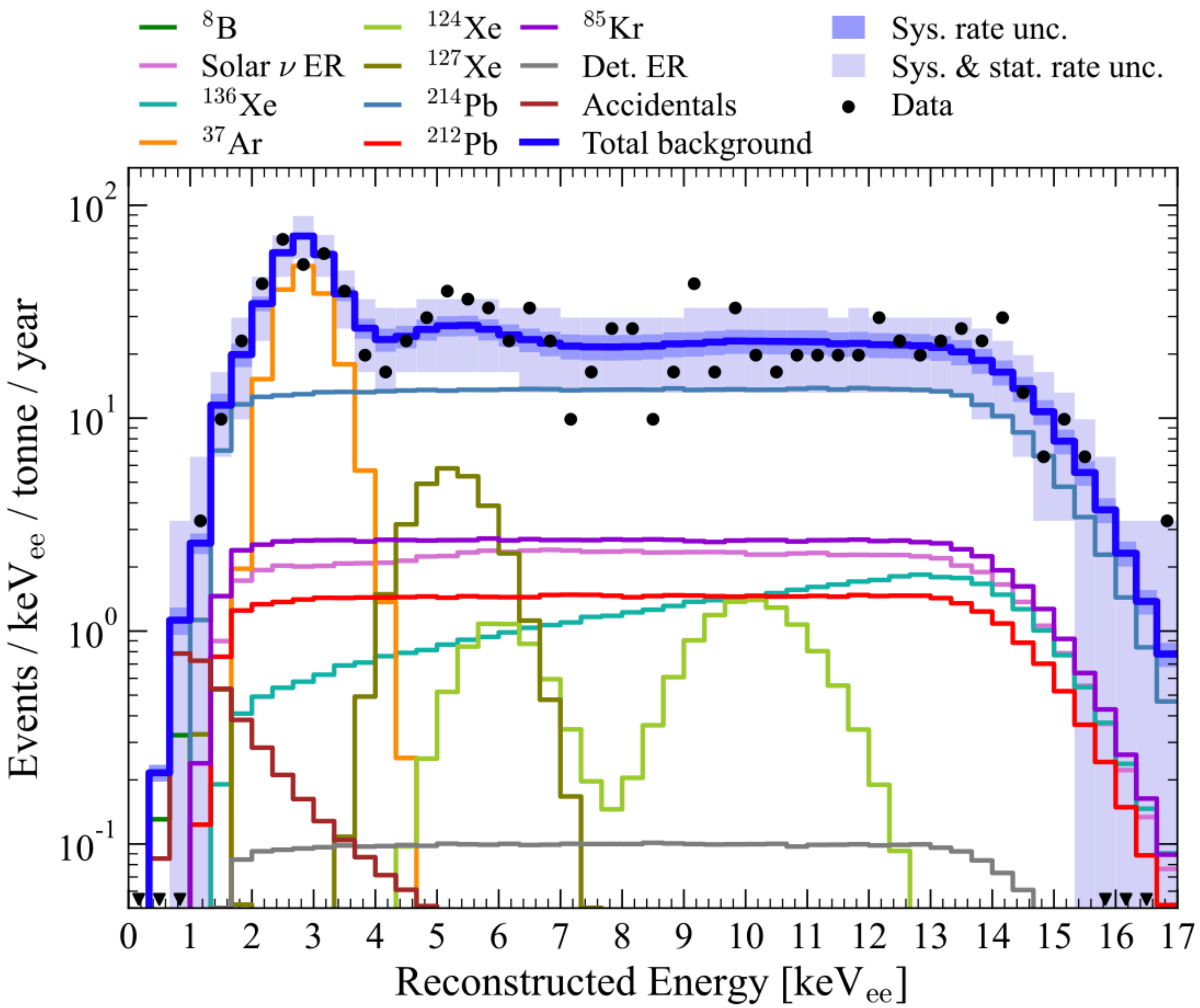

| Tritium level | Run0 Set 4 | Run0 Set 5 | Run1 |
|---|---|---|---|
| Counts/day/tonne | **3.0 ± 0.3** | **1.6 ± 0.2** | **0.4 ± 0.1** |

- Tritium is being removed from PandaX's xenon and further removal will improve the detector's sensitivity
- Radon background is 7.1 $\mu$Bq/kg (Run0) and 8.7 $\mu$Bq/kg (Run1)

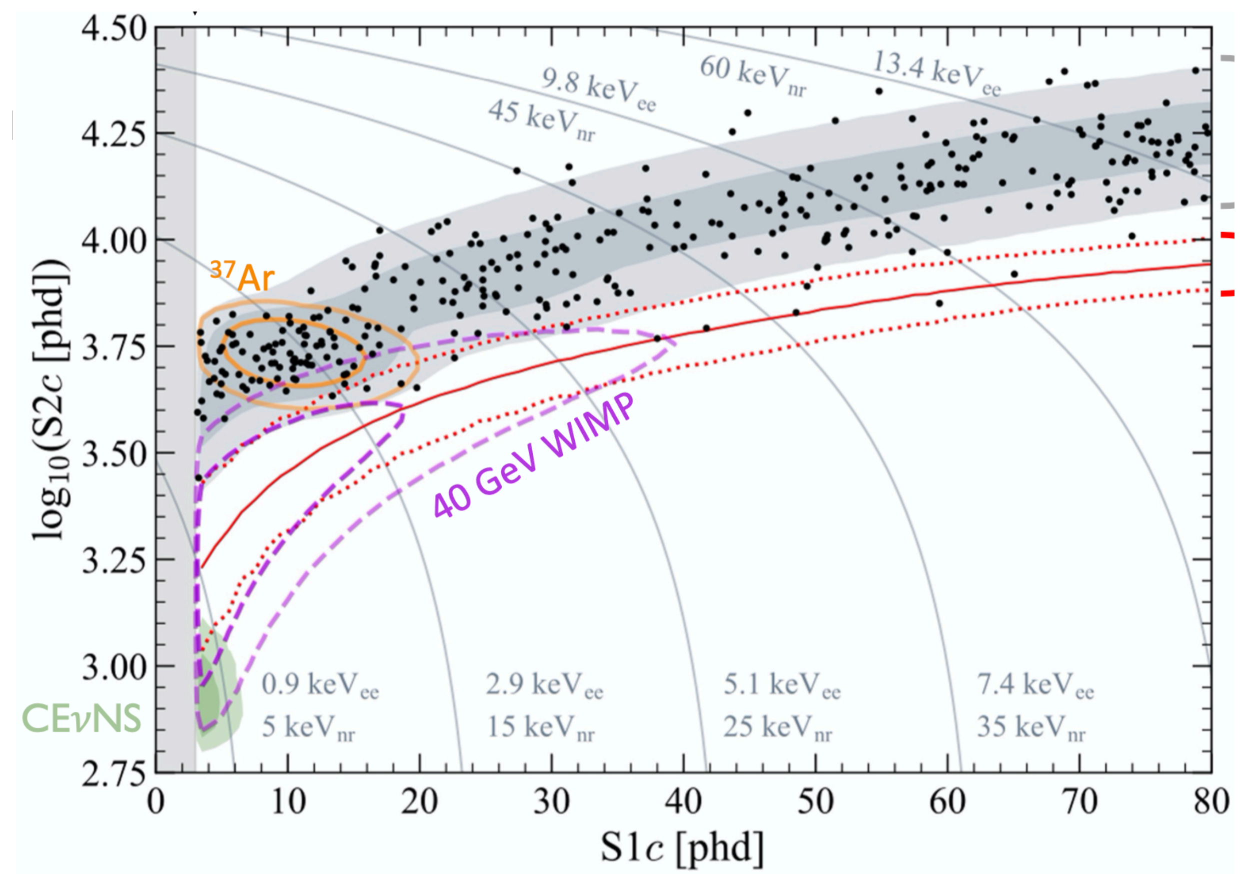
slide from Qing Lin, Symposium on Frontiers of Underground Physics, Oct.30-Nov.1, 2023, Chengdu

# Reducing the background towards WIMP search

from LZ, PRD (2023)




from LZ, PRL (2023)




- First run (SR1) ER BKG dominated by Ar-37 (expect to decay away with 35 day half-life)
- The second ER BKG is the Pb-214 (3.3 $\mu$Bq/kg)
- Fiducial Volume, ER/NR discrimination and Other selections achieve almost zero background for WIMP search

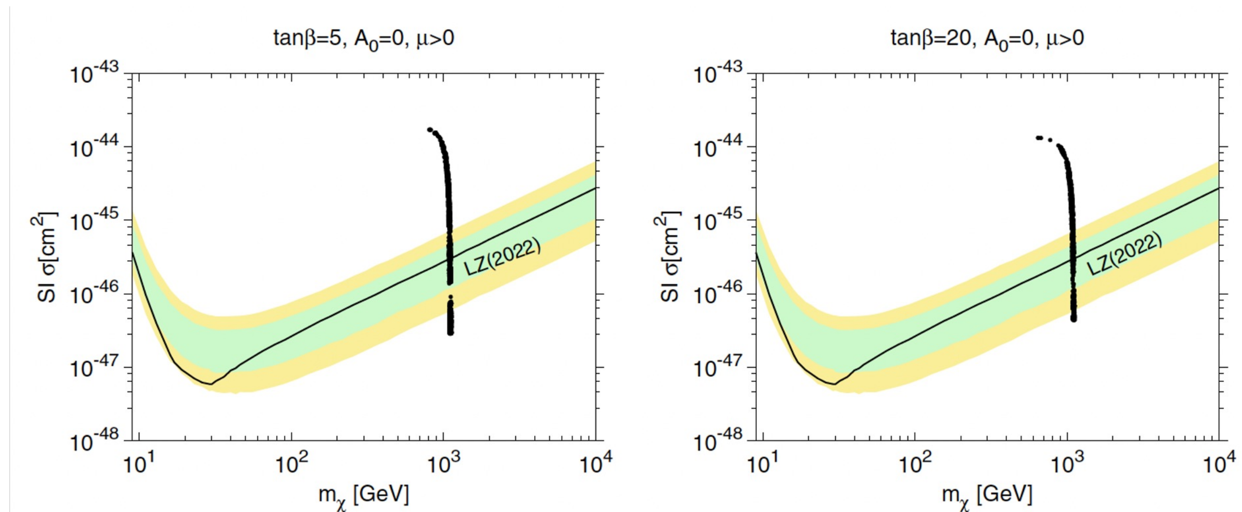
# Next for LZ

[1]LZ WIMP search sensitivity paper: Phys. Rev. D 101, 052002 (2020)
[2]LZ S2-only and Migdal sensitivity: https://arxiv.org/abs/2101.08753 (2021)
[3]LZ Xe136 $0\nu\beta\beta$ sensitivity: Phys. Rev. C 102, 014602 (2020)
[4]LZ Xe124 $0\nu\beta\beta$ sensitivity: Phys. Rev. C 104, 065501 (2021)

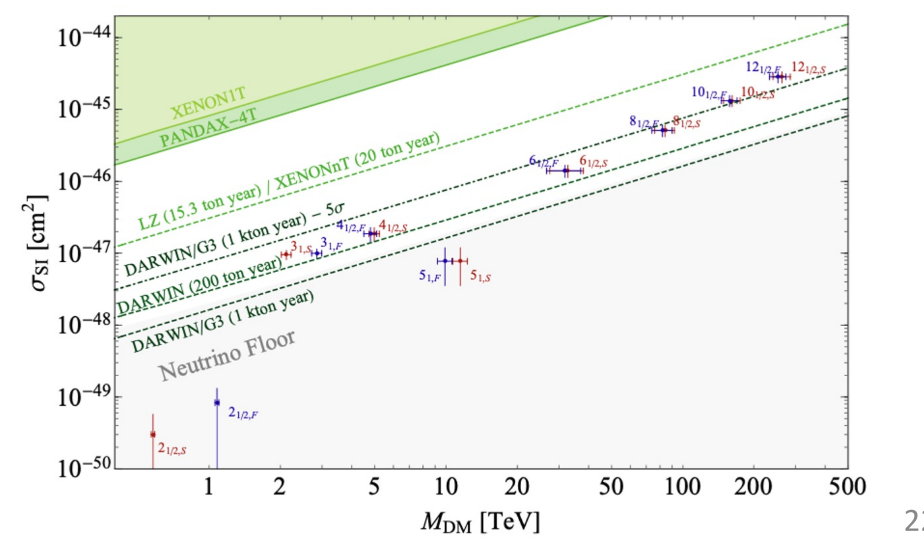
## |Outlook

## What's next?

- There's much more data to come! Planning for a total 1000 live days (x 17 more exposure than SR1)
- More physics searches to look forward to, among them:
    - $^{8}B$ solar neutrinos (S2-only)[2]
    - Neutrinoless double-beta decay searches with $^{136}Xe$ & $^{124}Xe$ [3,4]
    - High energy EFT searches
    - Ultraheavy/multiply interacting dark matter

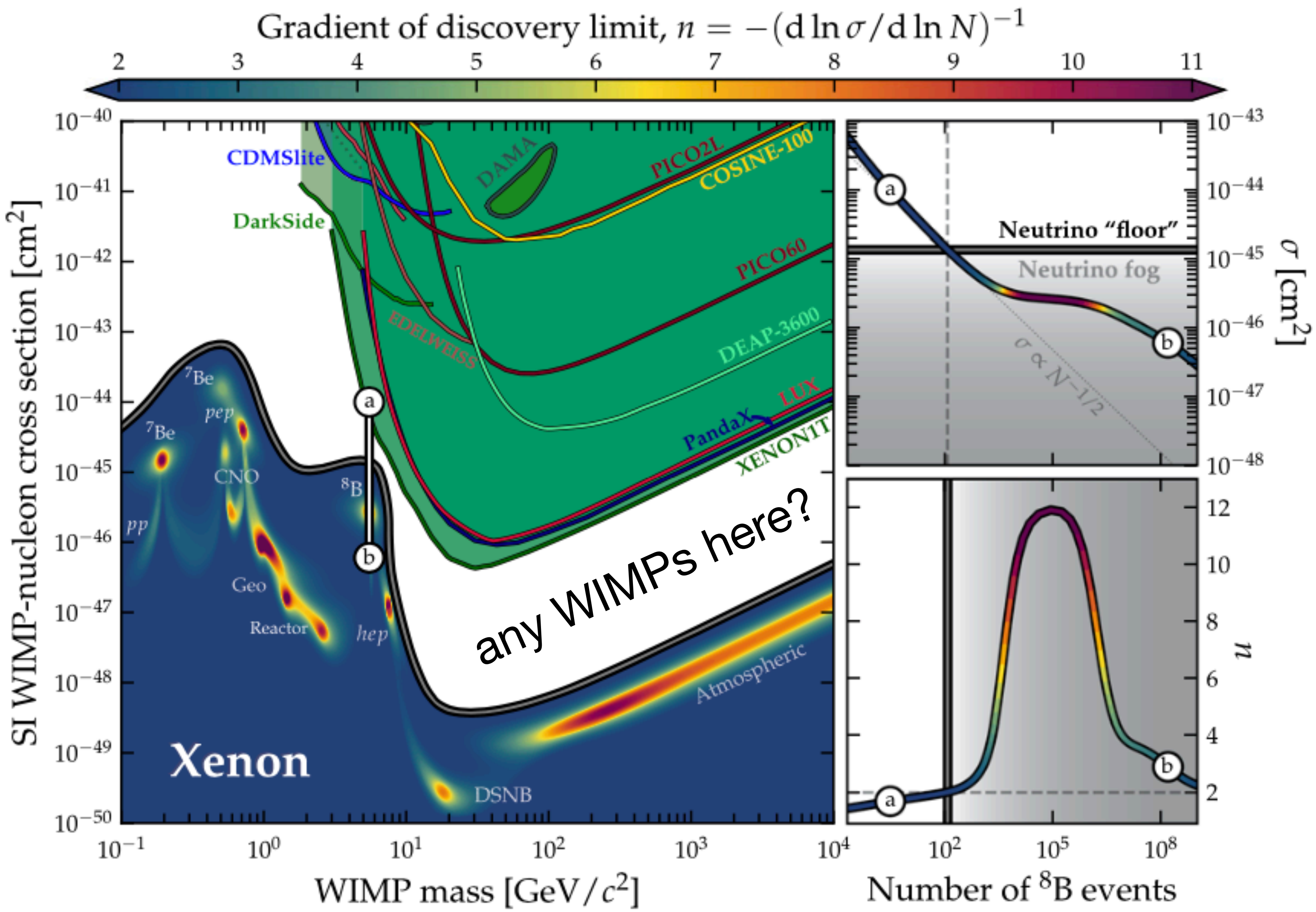


Ellis et al., EPJC Vol. 83: 246 (2023)



Bottaro et al., Eur. Phys. J. C**82**, 992 (2022)

# Liquid Xenon is pushing hard in searching for WIMPs




Ciaran A.J. O'Hare
PRL 2021

- The next generation WIMP search experiment will meet the irreducible neutrino background, thus entering into a "neutrino fog".

- n is the index with which the discovery limit scales with N bkg events: $\sigma \propto N^{-1/n}$

# The community starts to unite to build the ultimate WIMP detector: XLZD

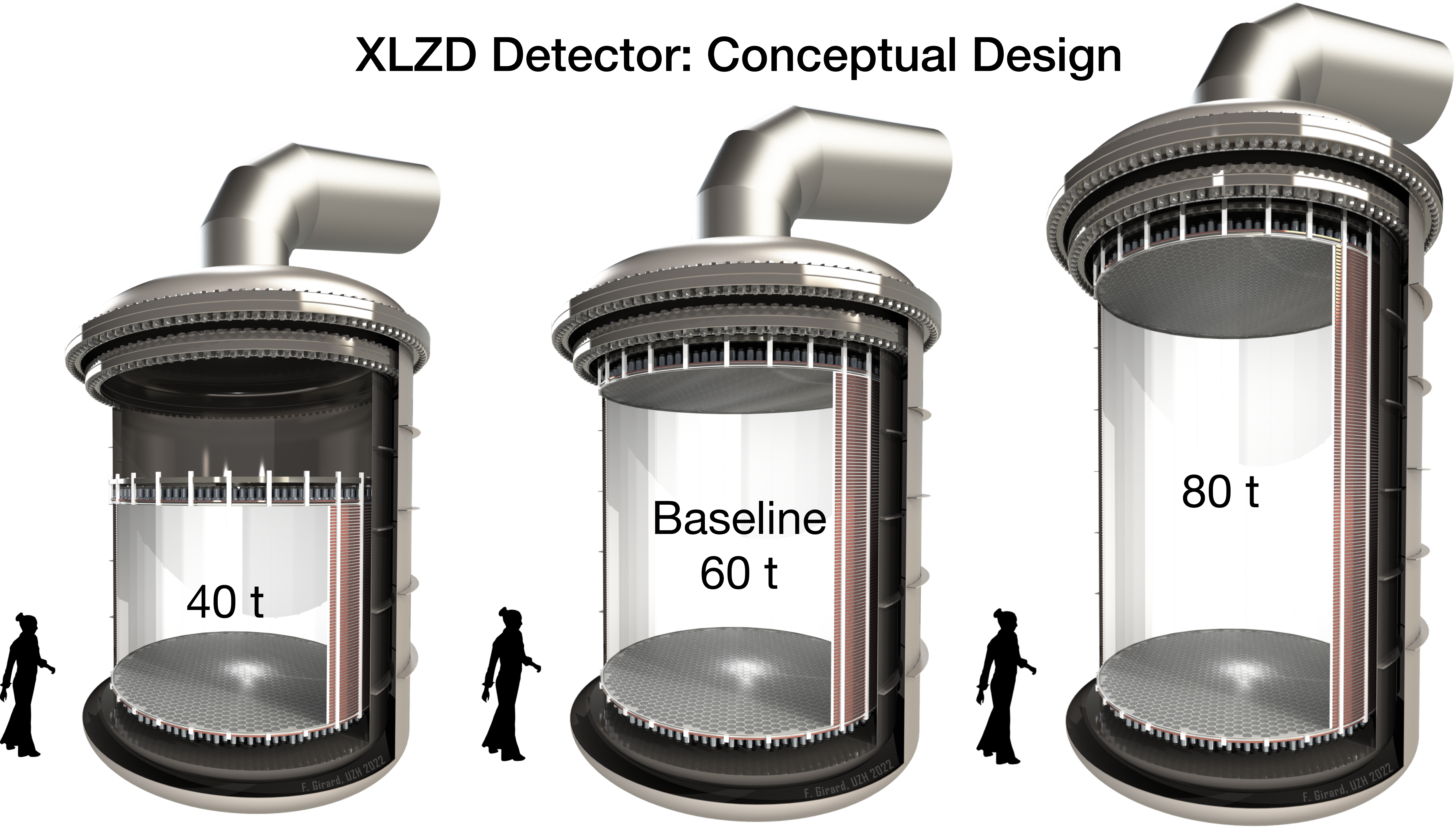
KIT, 2022


UCLA, 2023

XLZD

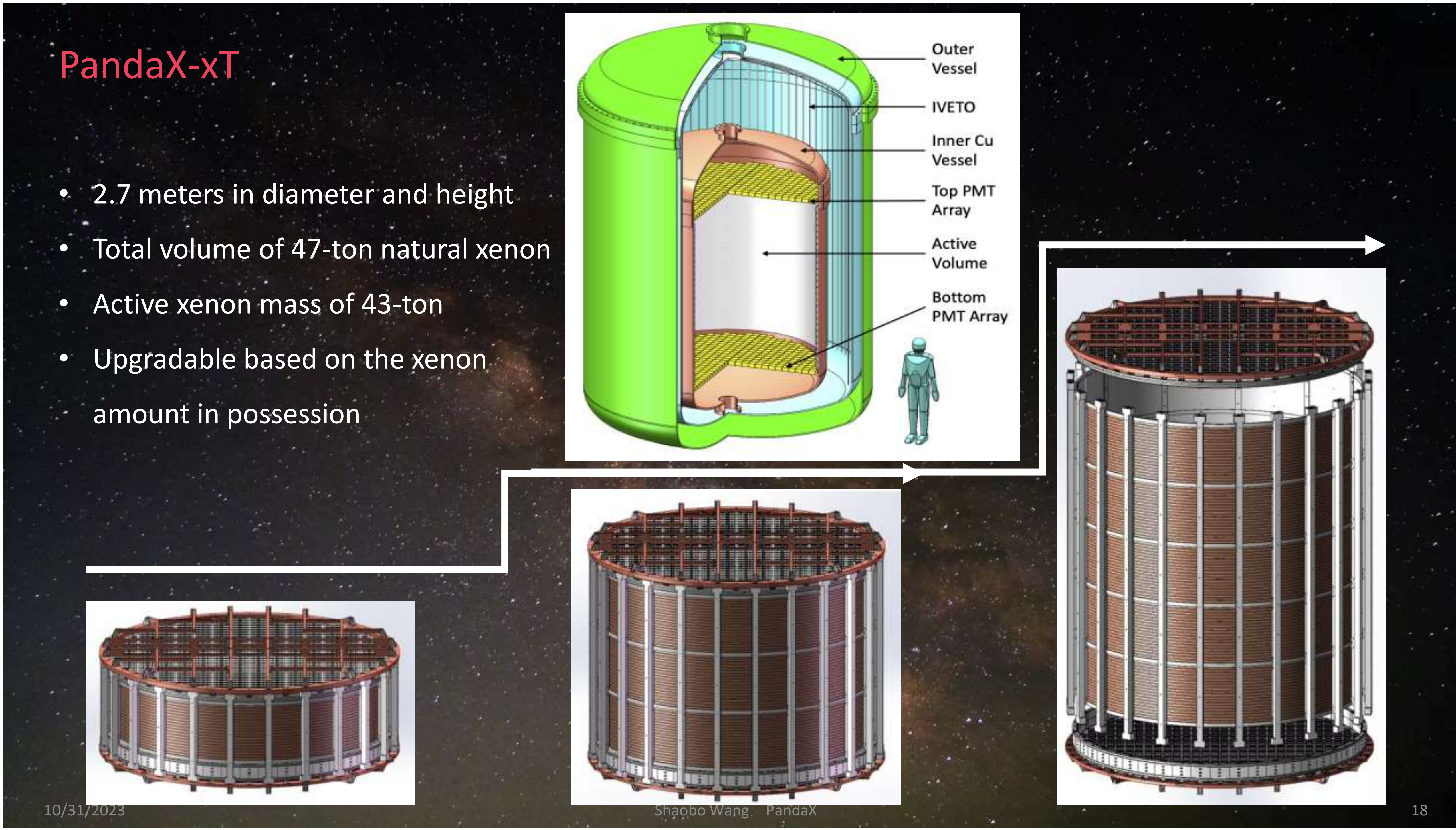
- July 2021: **X**ENON, **L**UX-**Z**EPLIN, **D**ARWIN (**XLZD**) Consortium MOU signed (60+ institutions).
- Community signed (also include PandaX) white paper (arXiv:2203.02309) for the next generation LXe observatory
- Two XLZD in-person meetings to discuss science strategy, working groups, siting
  - June 2022 (KIT)
  - April 2023 (UCLA)
- http://xlzd.org

# XLZD Detector: Conceptual Design




- Dual-phase Xenon-TPC technology (3 m in diameter) as used in LZ/XENONnT
- ~x10 the active target (60 t, ~3 m height) as the “baseline”
- 40 t “early science” (if Xe gas delivery is slow) and 80 t “opportunity” (if any sign of signal observed in early phase)

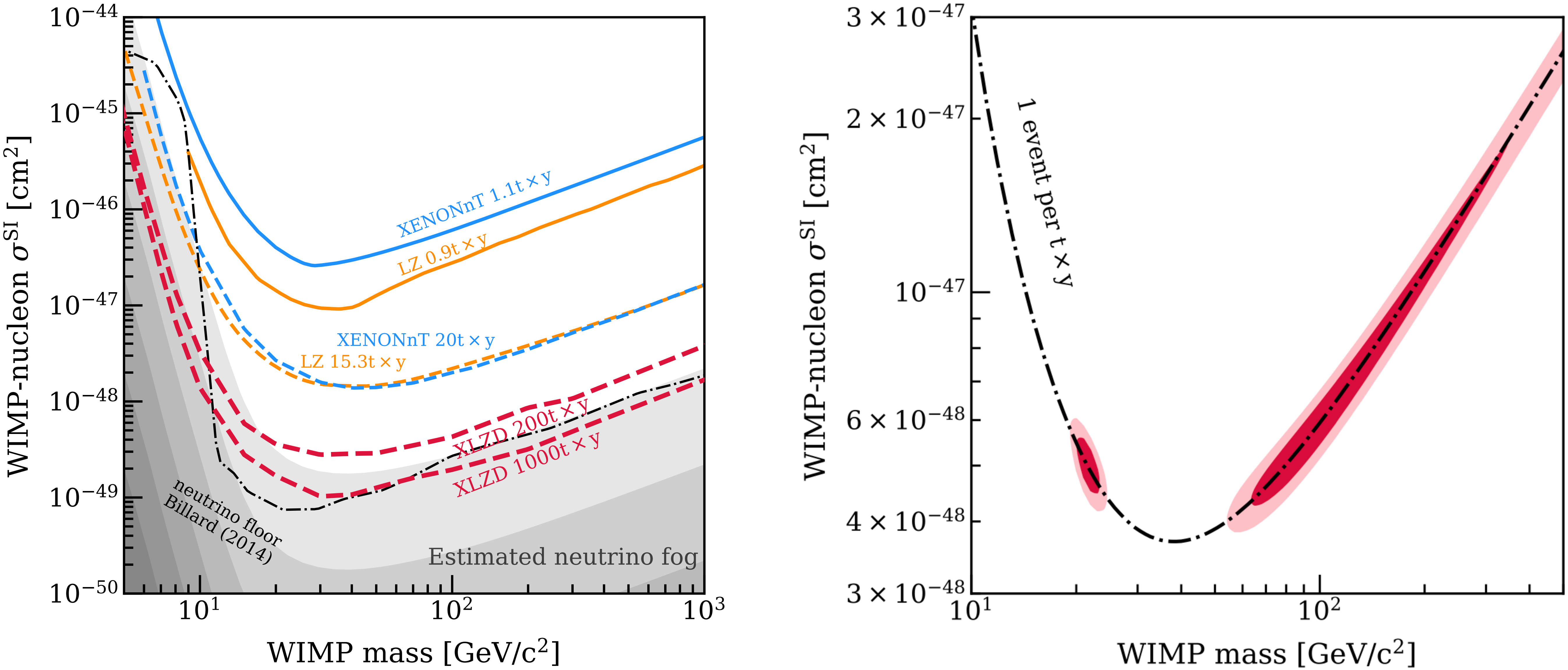
# PandaX-xT: a parallel LXe program to search for WIMPs at China's Jinping Underground Lab




slide from Shaobo Wang, Symposium on Frontiers of Underground Physics, Oct.30-Nov.1, 2023, Chengdu

# XLZD: Spin-independent WIMP Dark Matter Sensitivity

arXiv:2203.02309

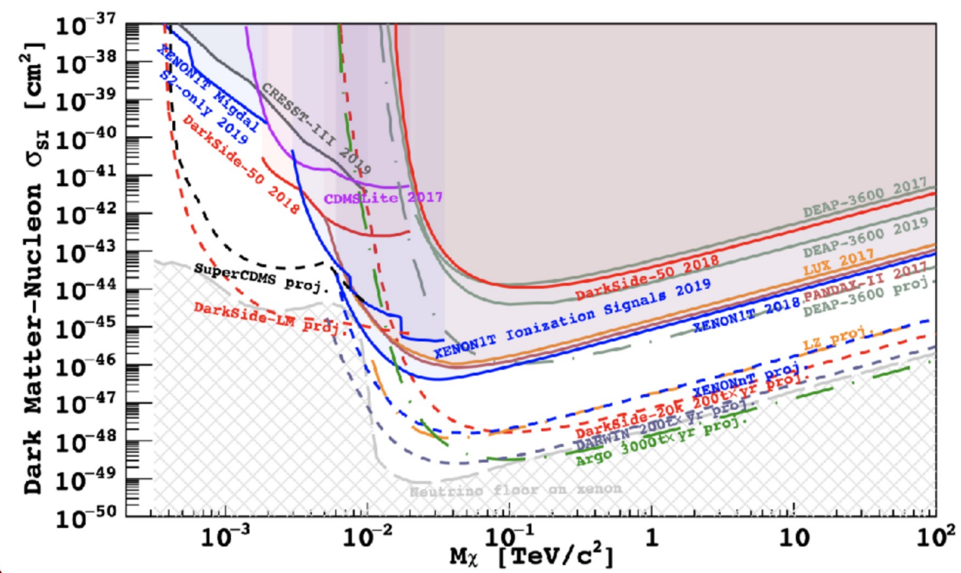


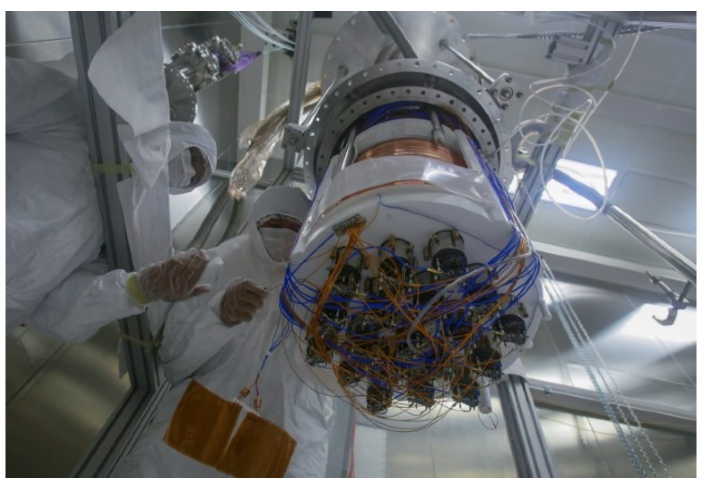

- (Left) Projected SI WIMP sensitivity with 200 t x y (1000 t x y) exposure
- (Right) 1-sigma/2-sigma CL contours of WIMP detection with 1000 t x y exposure

# Other promising WIMP detection target: Liquid Argon

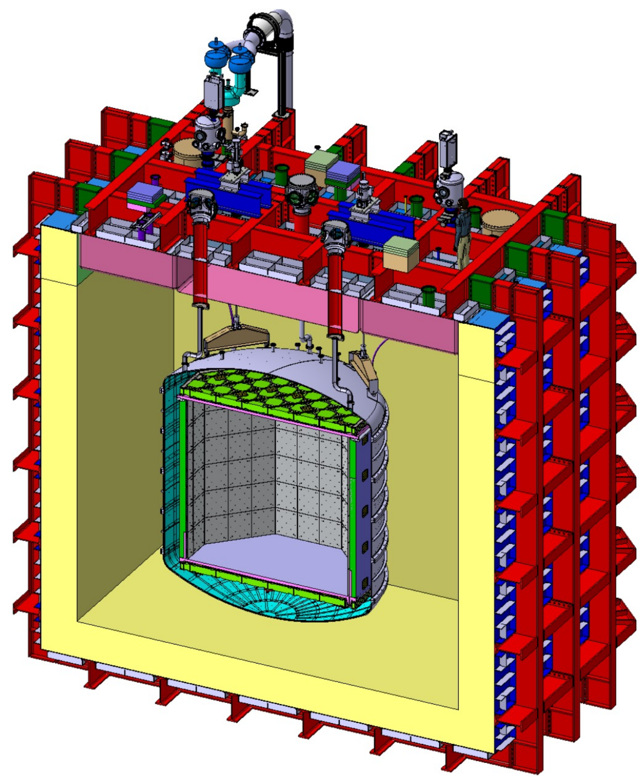
## The Roadmap of DarkSide

- Direct WIMP dark matter search with argon;
- Dual phase argon time projection chamber (TPC);
- Deep underground laboratory.



**DarkSide-50 @LNGS**
**46.4 kg (active)**
2013~2021



**DarkSide-20k @LNGS**
**49.7 tonnes (active)**
2026~

**ARGO (for high mass WIMPs)**
**3000 tonne-year exposure**
2030s

**DarkSide-LowMass**
**1 tonne-year exposure**

10/31/2013 Symposium on the Frontiers of Underground Physics, Chengdu 2

slide from Yi Wang, Symposium on Frontiers of Underground Physics, Oct.30-Nov.1, 2023, Chengdu

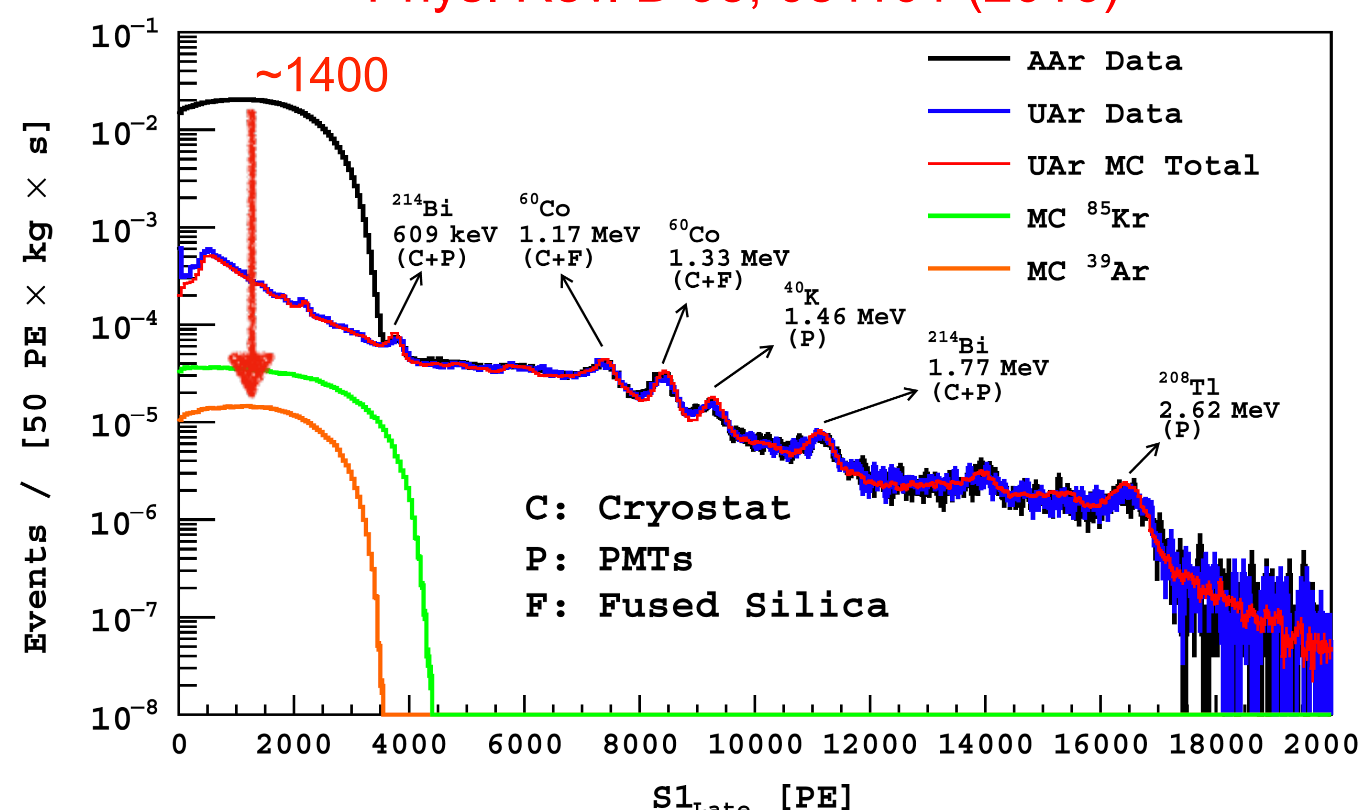
# Other promising WIMP detection target: Liquid Argon

## Underground Argon (UAr)

- Atmospheric argon (AAr) has intrinsic $^{39}$Ar radioactivity ~1 Bq/kg;
- β decay with 565 keV endpoint, 269 years half-life;
- $^{39}$Ar activities set the threshold at low energies.

- $^{39}$Ar is a cosmogenic isotope;
- Argon from underground sources has significantly lower $^{39}$Ar concentration than AAr;
- $CO_2$ well in Colorado, USA;
- 160 kg UAr extracted for DarkSide-50:
    - ➢ $^{39}$Ar reduction factor ~1400.

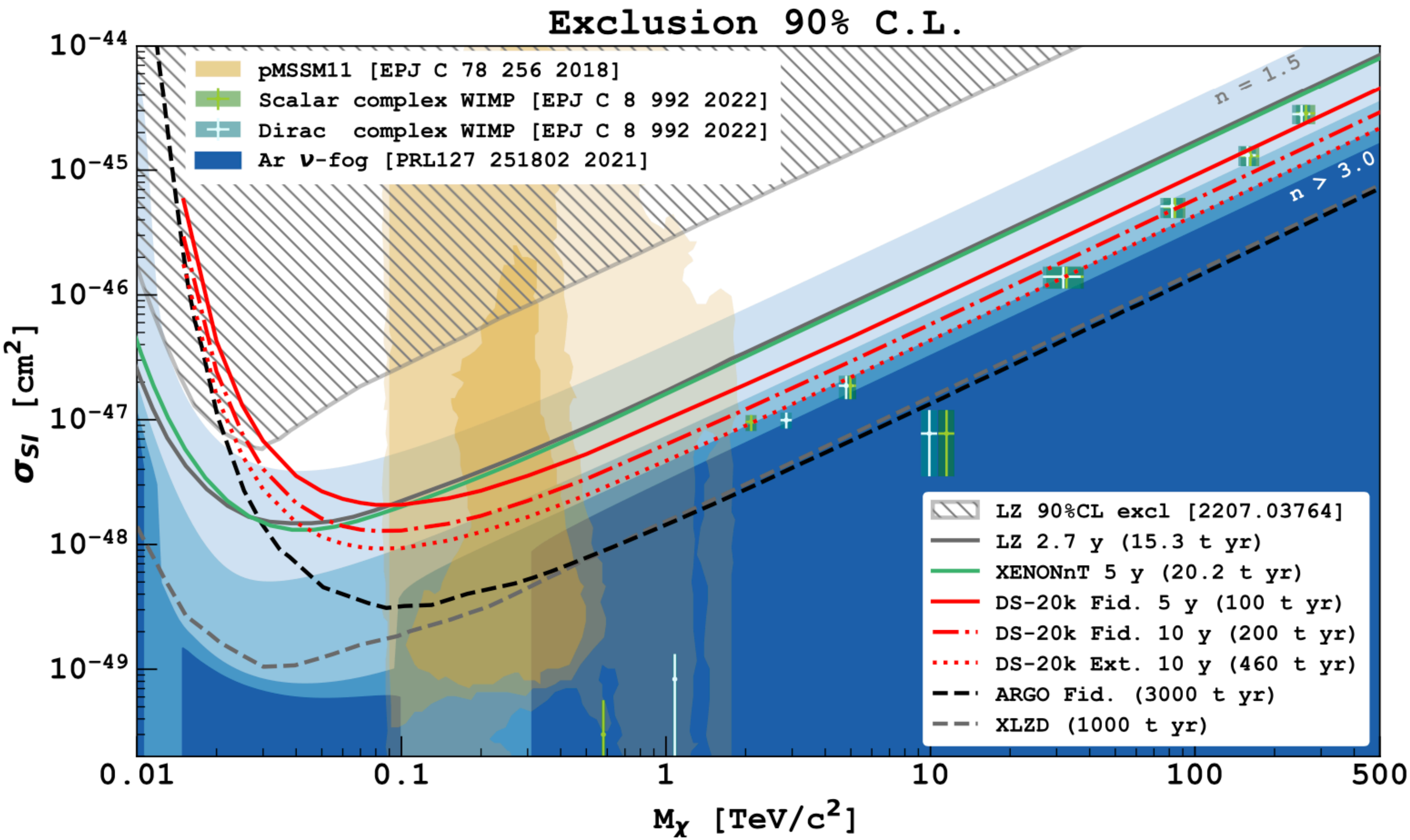
Phys. Rev. D 93, 081101 (2016)





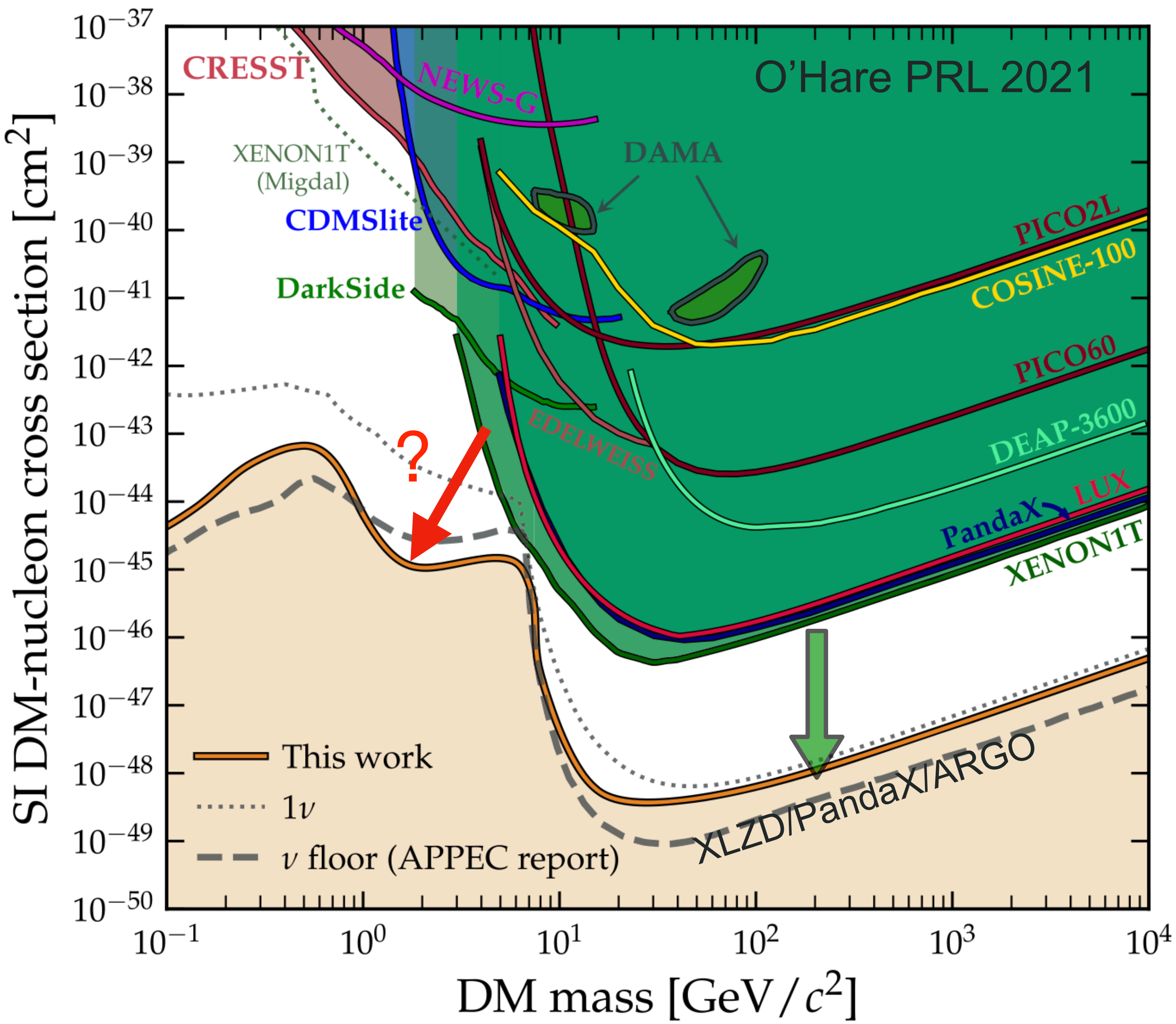

slide from Yi Wang, Symposium on Frontiers of Underground Physics, Oct.30-Nov.1, 2023, Chengdu

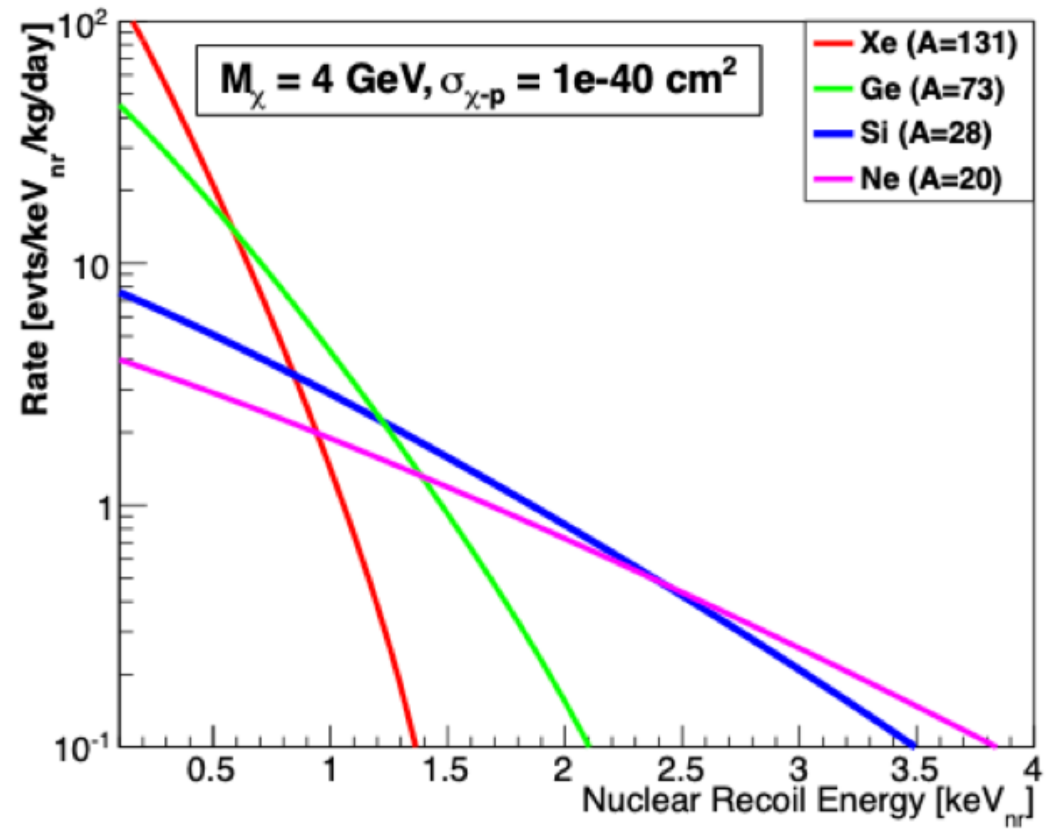
# DarkSide-20k/ARGO Sensitivity Reach, compared with XENONnT/LZ/XLZD




from Yi Wang, Symposium on Frontiers of Underground Physics, Oct.30-Nov.1, 2023, Chengdu

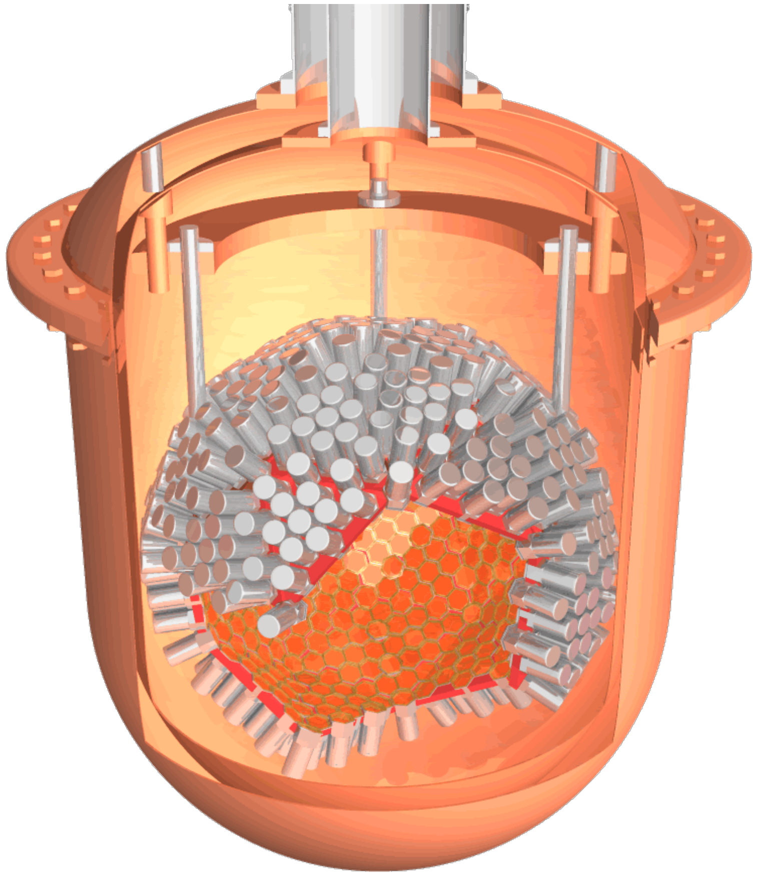
# Can Liquid Xe do more for Low Mass WIMPs?



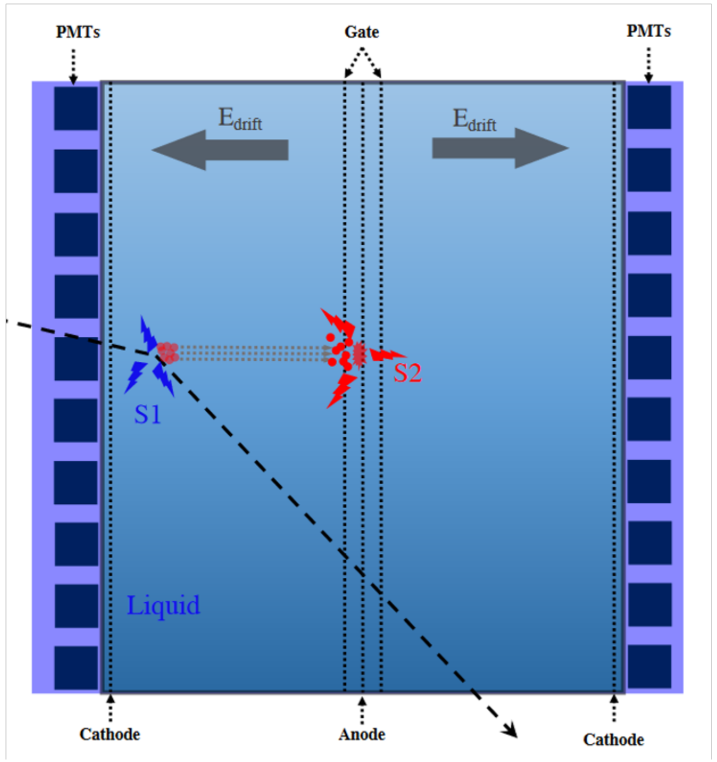

- LXe has already produced many tight limits for low-mass/light DM with ionization-only and model-dependent "boosted" approach.
- Can we improve the detector design to do "background free" light/low-mass DM searches? ->need to decrease the energy threshold (no need large target mass)

# A single-phase approach to lower the energy threshold

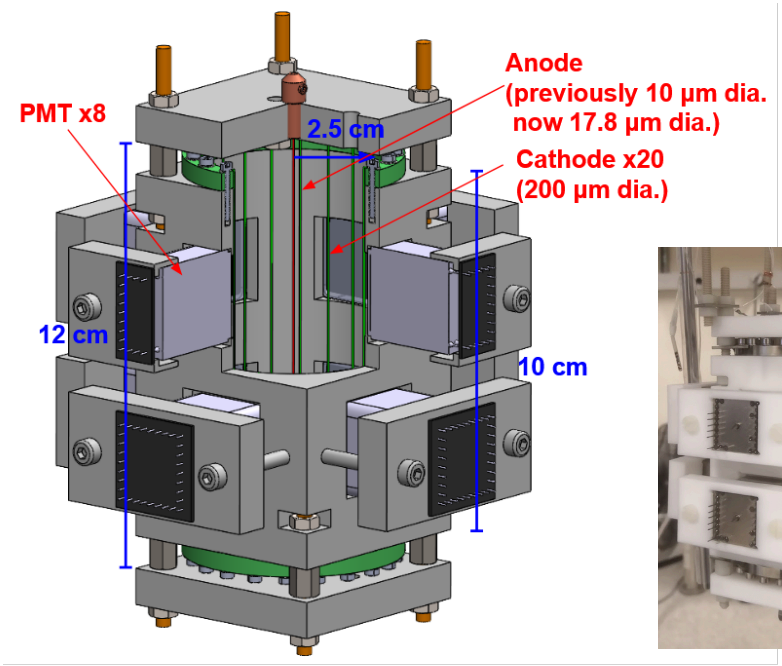


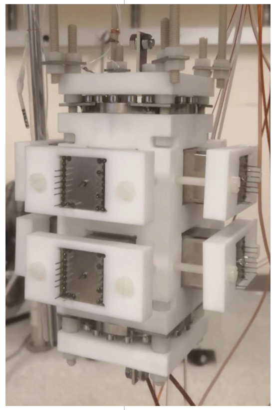
XMASS: high S1 yield, but no S2

Proposal of a Single-Phase LXe detector with S2/S1 discrimination (Qing Lin, JINST 16 P08011, 2021)

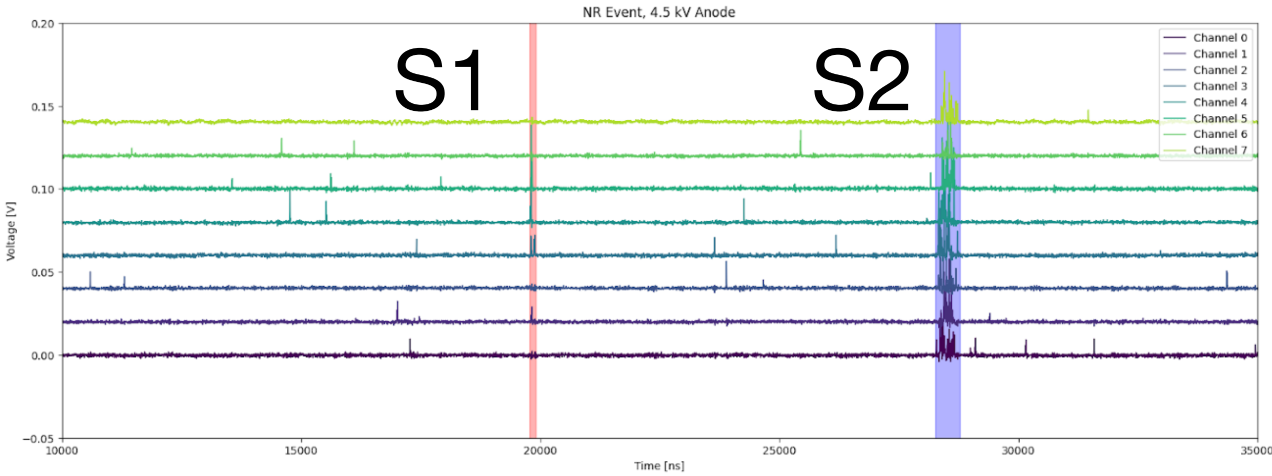


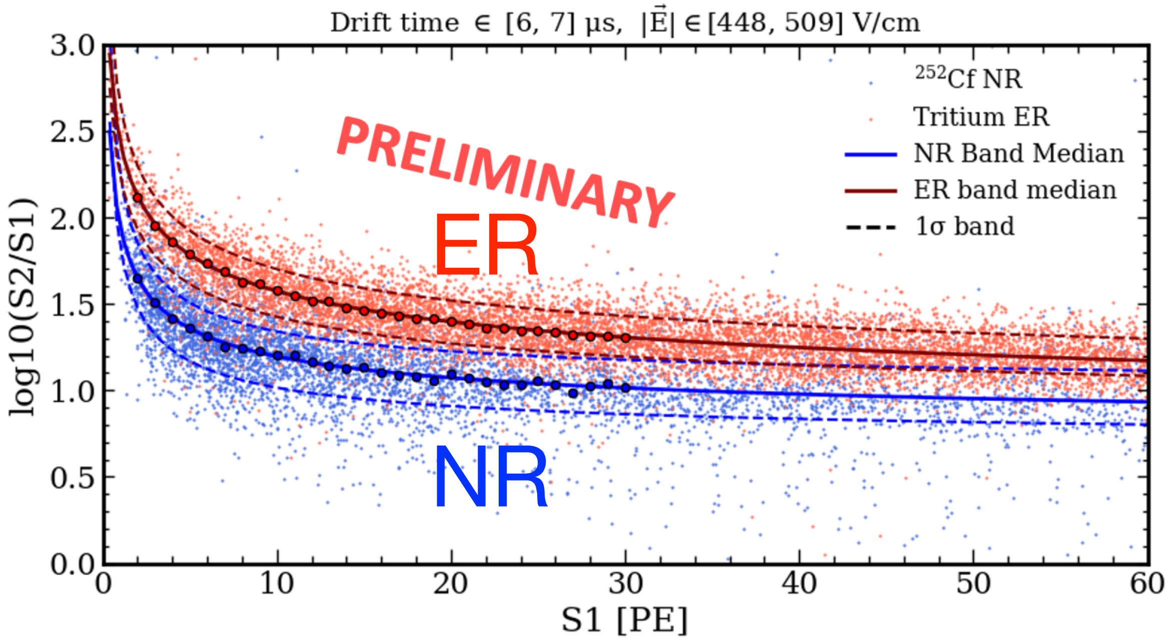

Principle demonstration at UCSD
arXiv: 2111.09112, JINST 2022
arXiv: 2301.12296, JINST 2023
more new results coming…



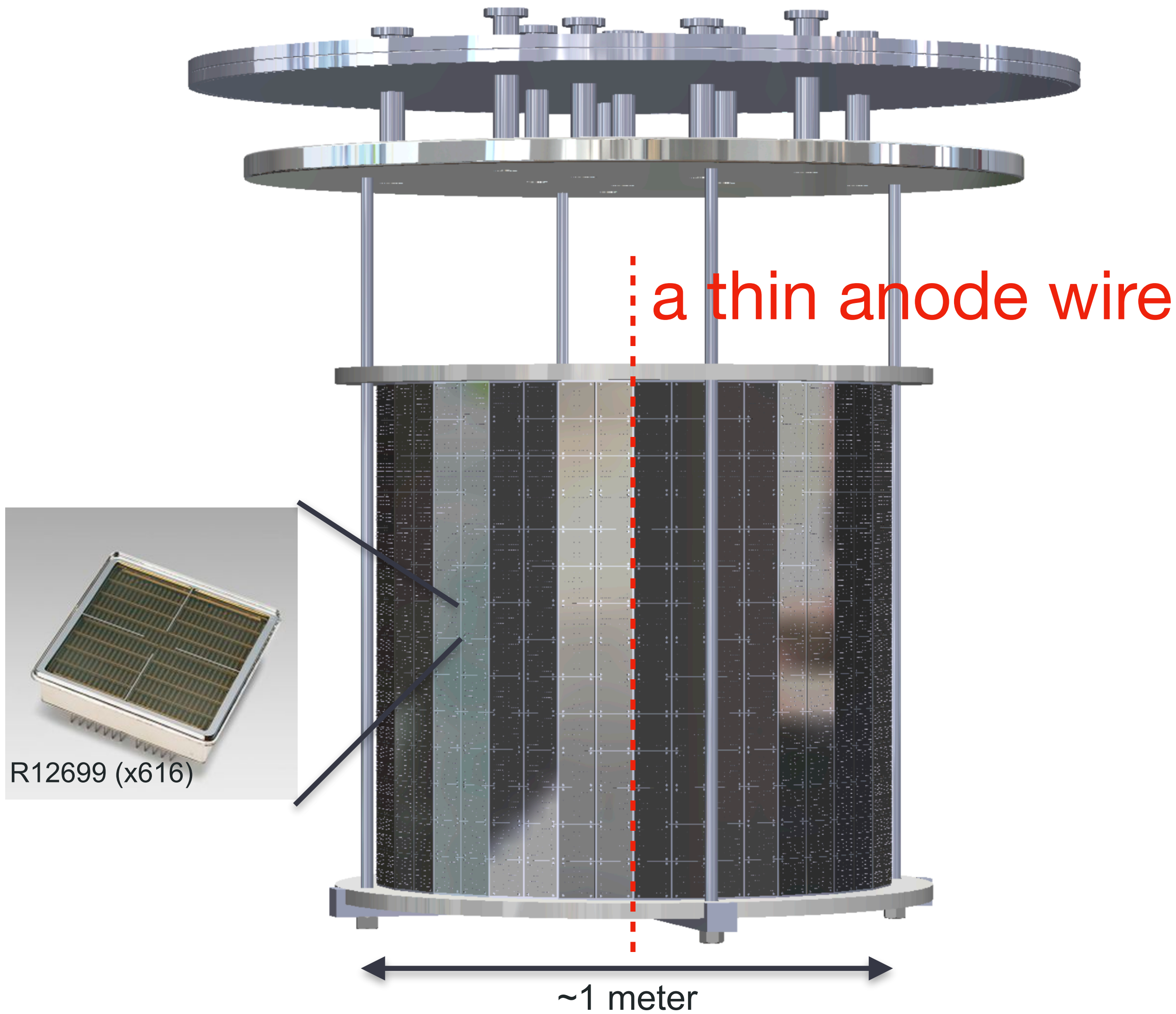



a low energy nuclear recoil event (Anode: 4.5 kV)



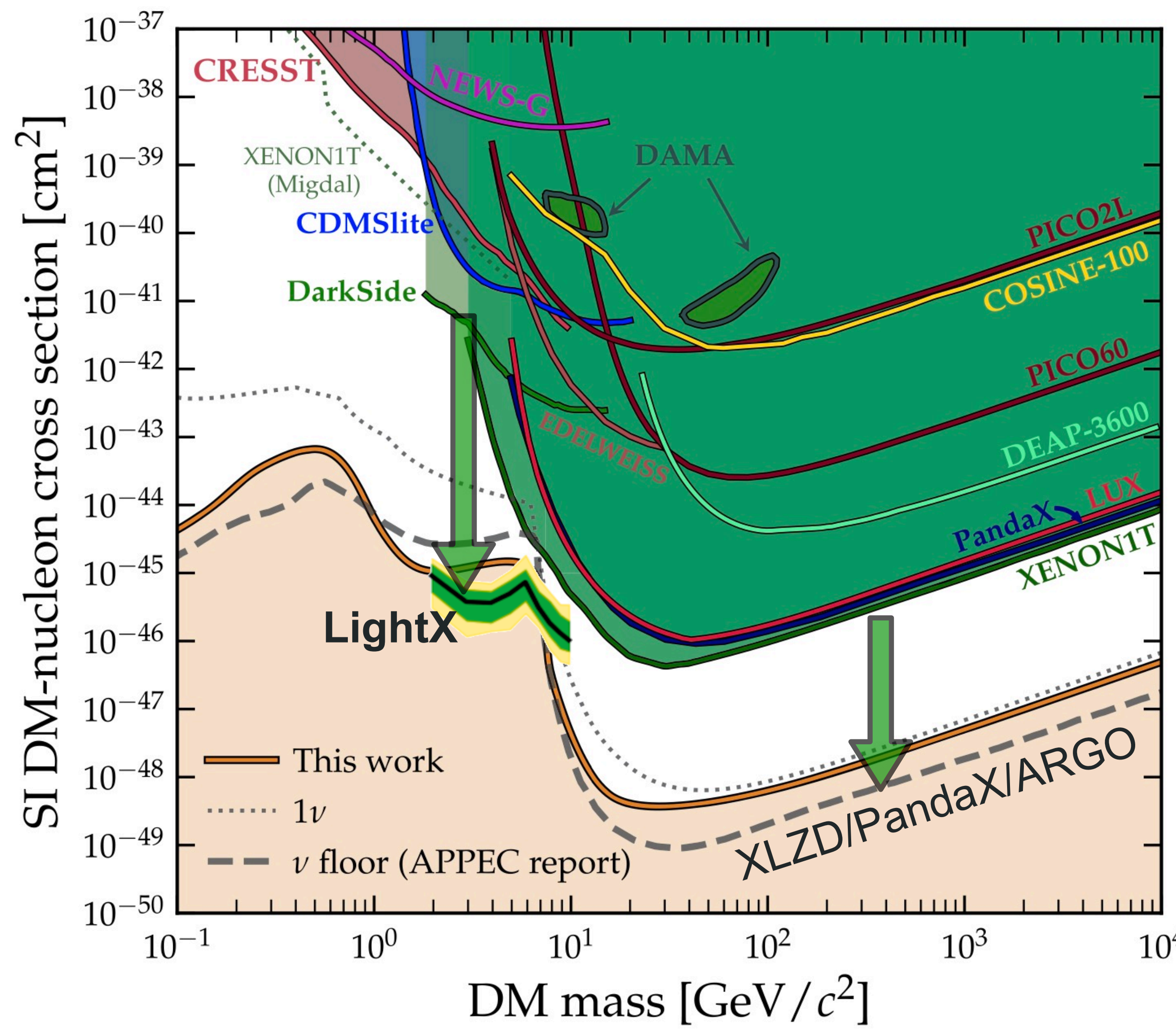



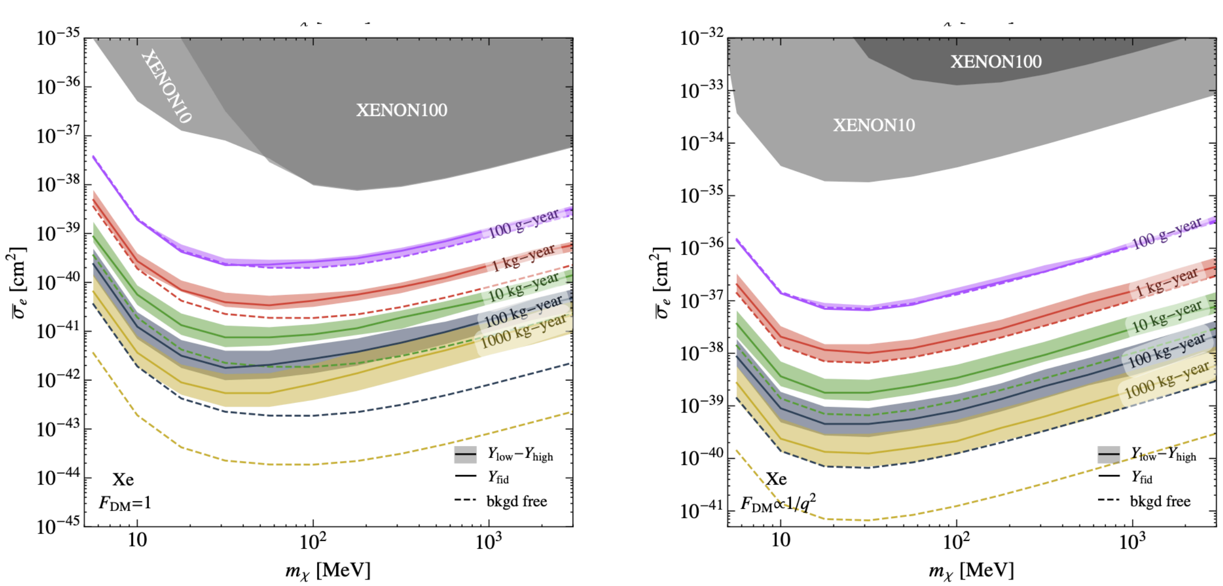
# LightX: a conceptual ton-scale single-phase LXe detector for Light/Low-Mass Dark Matter




**Sensitivity Projection Assumptions:**

- g1: 0.3 PE/photon (~x2 achieved in nT/LZ)
- g2: 7~10 PE/e-
- 2-fold coincidence
- 10 ton-year exposure



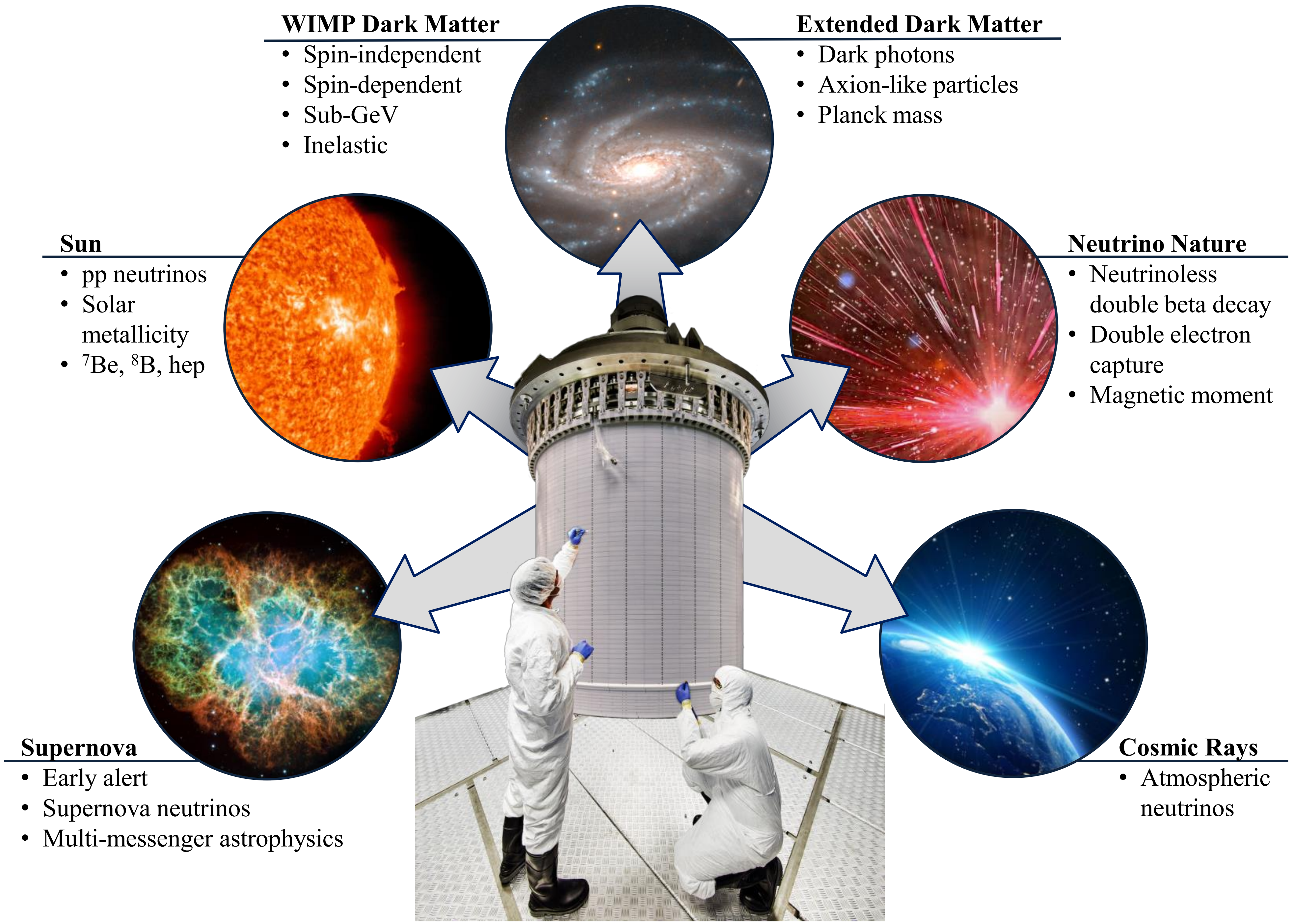

also improves significantly DM-e scattering for sub-GeV DM with "background free"

Essig, Sholapurkar, Yu, arXiv:1801.10159 (PRD 2018)

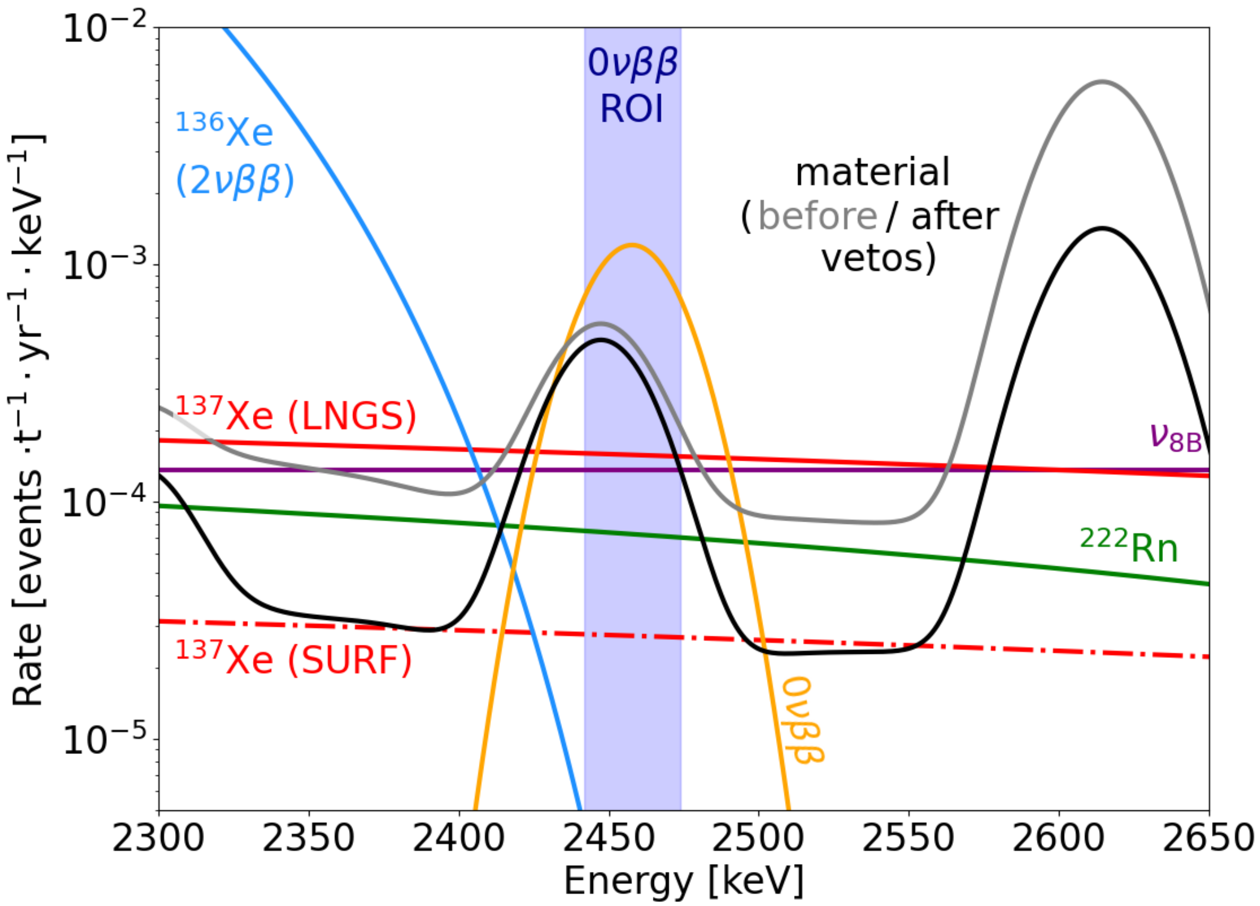
# XLZD Science Channels

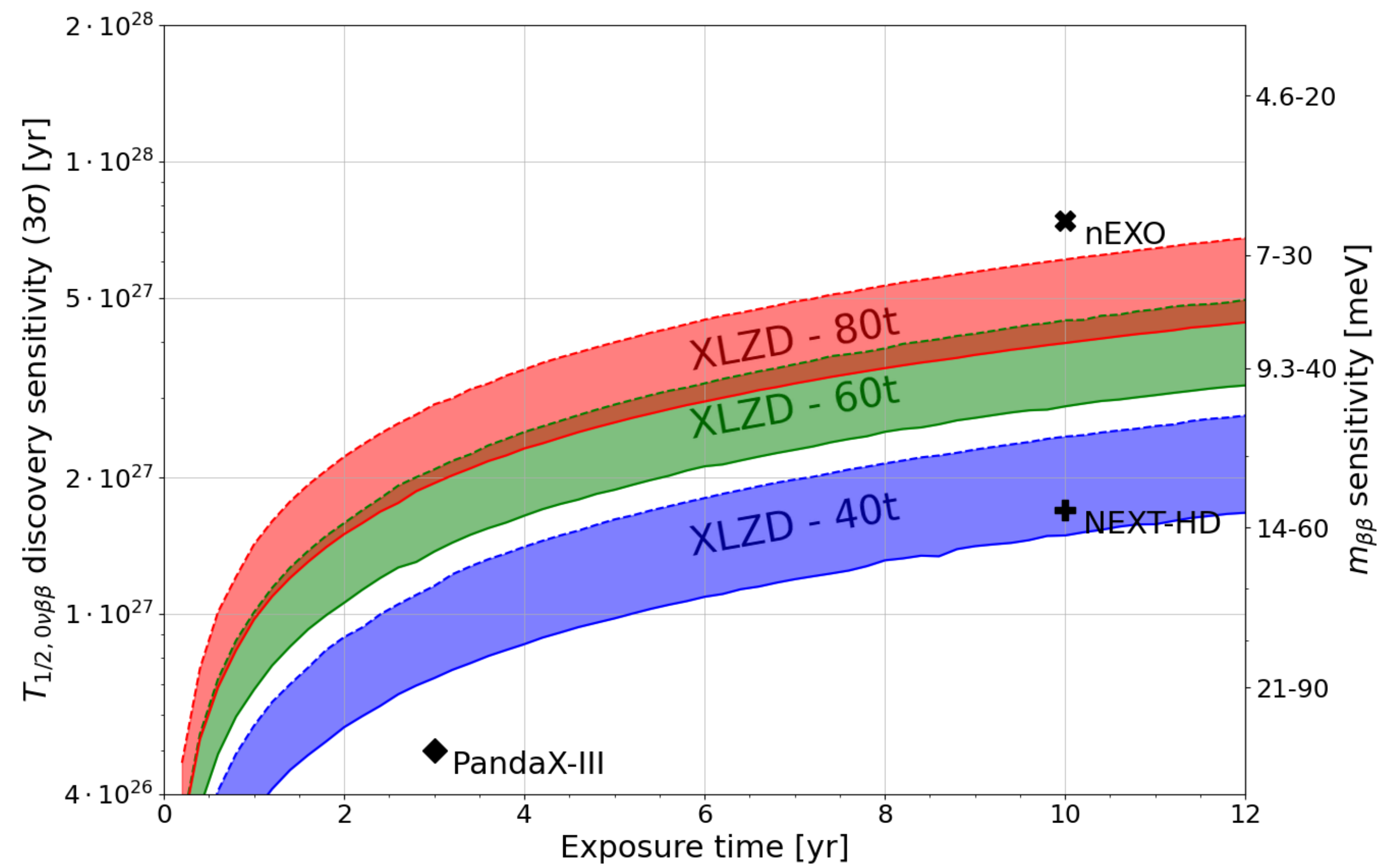
Primary goal is to search for Dark Matter, but is also a neutrino observatory.

arXiv:2203.02309



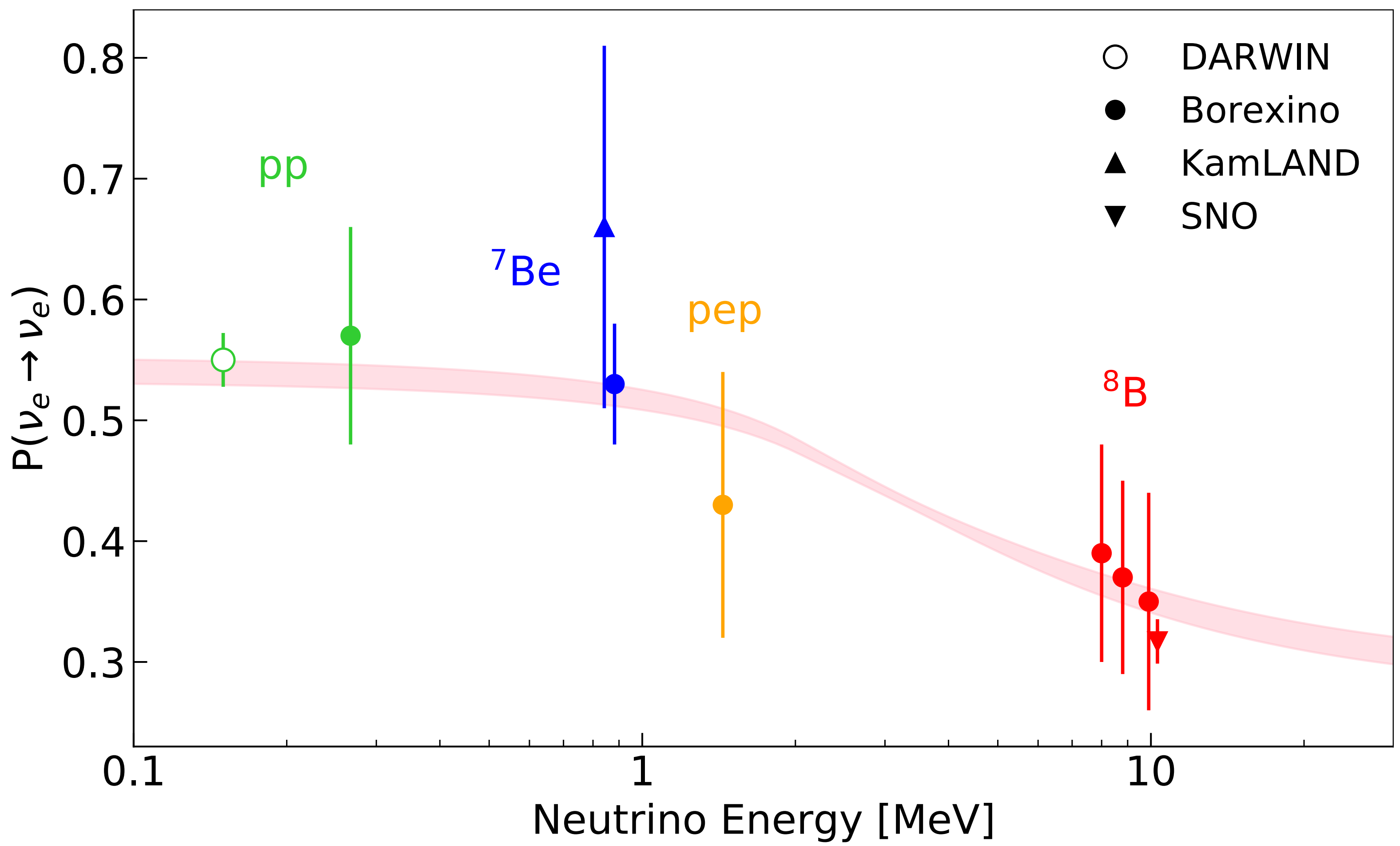
# Enabling the other science with the ultimate dark matter detector with Xenon




- 8.9% Xe-136 in natural xenon provides opportunities to search for neutrino-less double beta decay
- <1% energy resolution at the 0vbb energy was achieved in two-phase XeTPCs, improving the bkg suppression.
- more than $3\sigma$ discovery sensitivity for 0vbb half-life > 5e27 yr (probe Inverted Mass-Ordering, ~10 meV sensitivity $m_{\beta\beta}$)

# Ultimate dark matter detector becomes a neutrino observatory




- 300 t-y exposure of a Xe detector (DARWIN) to measure pp-solar neutrino survival probability to 3~4%, testing the main energy production mechanism in the Sun

- A galactic core-collapse supernova at 10 kpc would produce O(100) events in XLZD

# Summary

- We still haven't found WIMPs. But….
  - more data are being accumulated from PandaX-4T, XENONnT and LZ (stay tuned for new results before CosPA 2024!)
  - DarkSide-20k will come online ~2026 and offer a chance to detect WIMPs with a different target (LAr)
- **Next two decades**: the world is entering into the final stage of WIMP hunting and we are probing into the "neutrino fog"
  - PandaX-xT and XLZD: 40~80 tonnes of active target (up to 1000 ton-year exposure with LXe)
  - ARGO: 3000 ton-year exposure with LAr
  - More parameter space to explore for light/low-mass DM with less $$