Paving the way for the ultimate rare-events observatory with a liquid xenon detector

XENON

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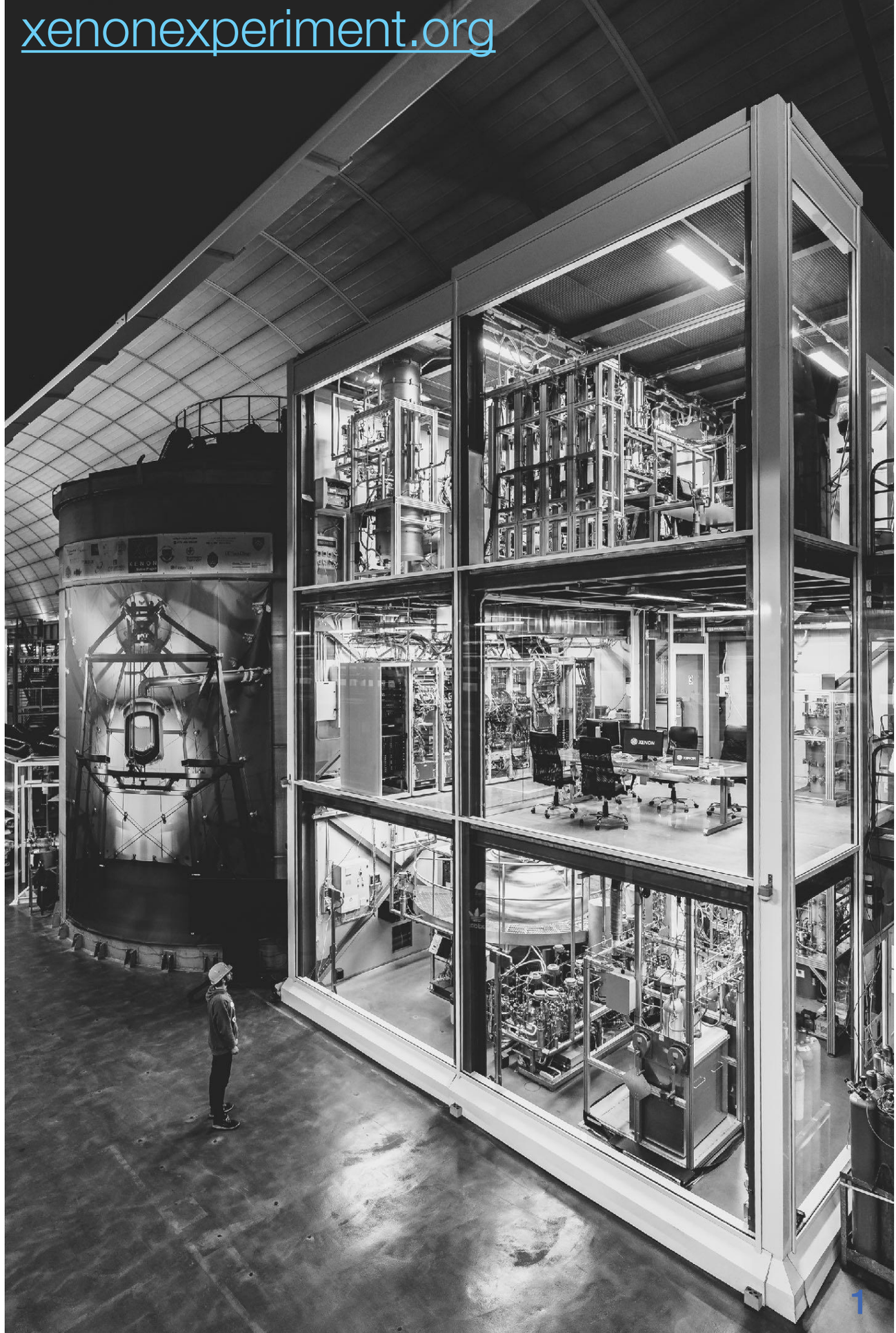
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

EDSU 2024
Noirmoutier, June 6,2024

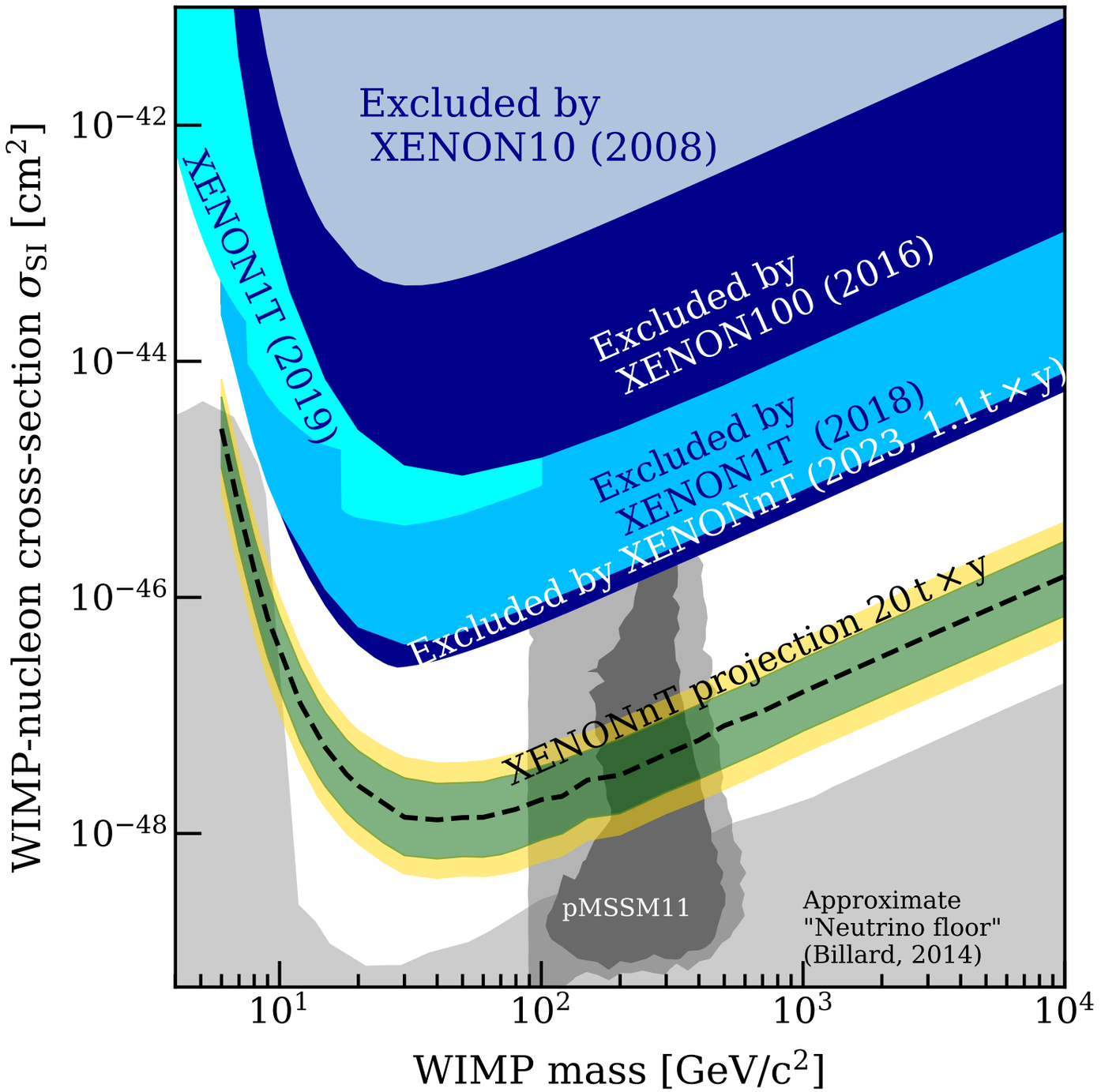
xenonexperiment.org



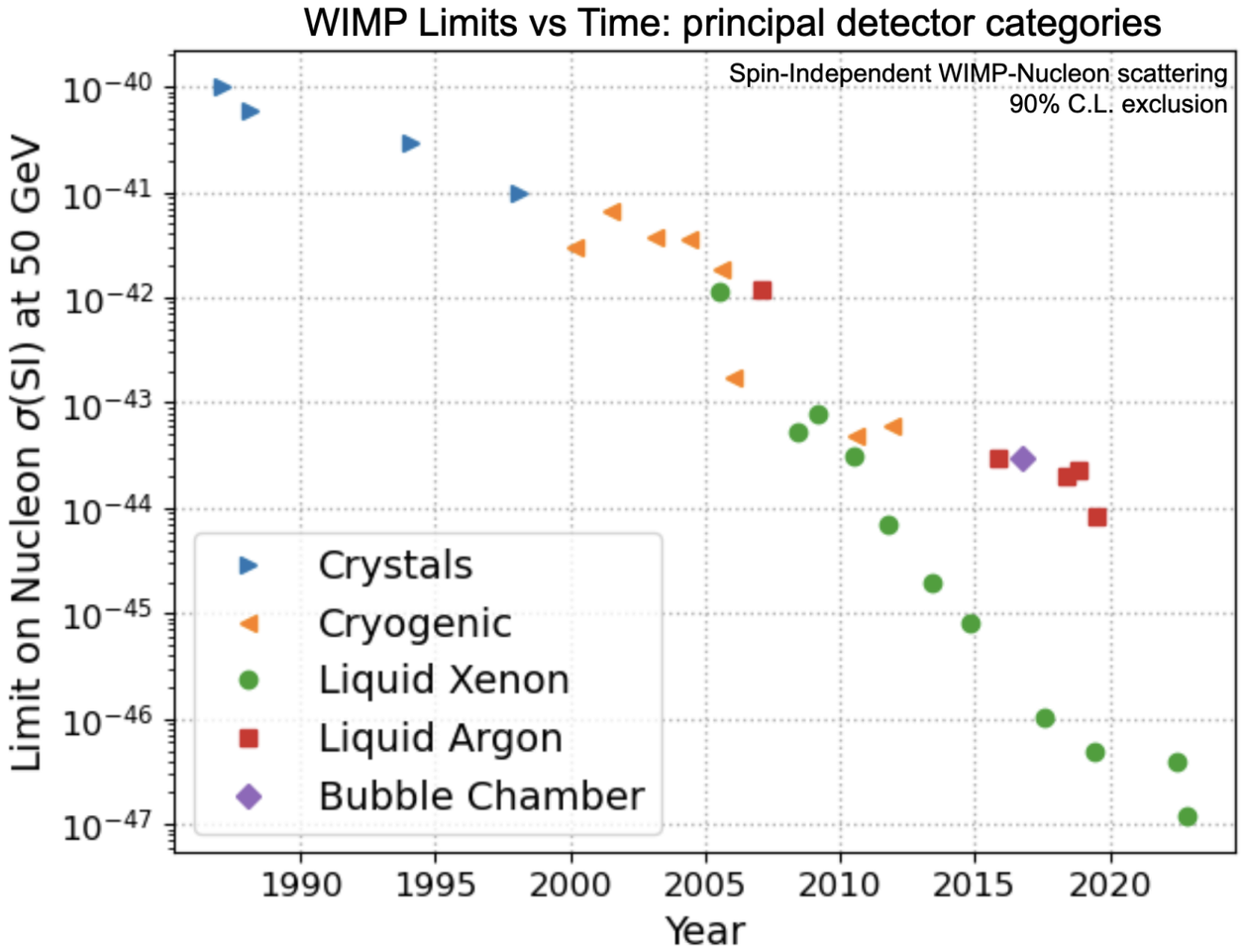
The XENON Dark Matter Project

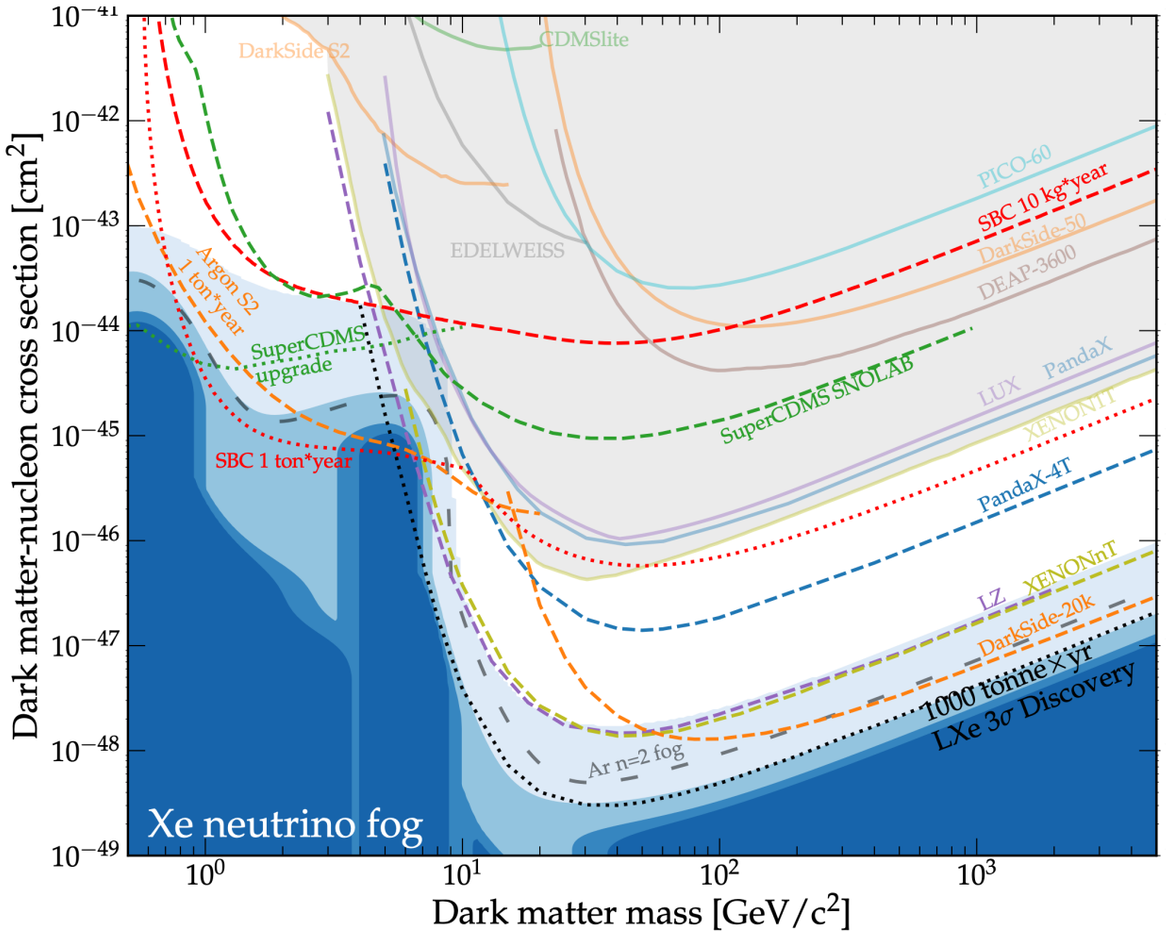
XENON10	XENON100	XENON1T	XENONnT
2005-2007	2008-2016	2012-2019	2020-2026 (taking science data)
15 kg Xe target	62 kg Xe target	2 t Xe target, 3.3t total	~6 t Xe target, 8.6t total
~10^{-43} cm^2	~10^{-45} cm^2	4 ×10^{-47} cm^2	Projection: 1.4×10^{-48} cm^2 for 20 tonne-year
~2000000 background ER events/(keV t y)	1800 background ER events/(keV t y)	82 background ER events/(keV t y)	16.1 background ER events/(keV t y)

XENON limits on WIMPs



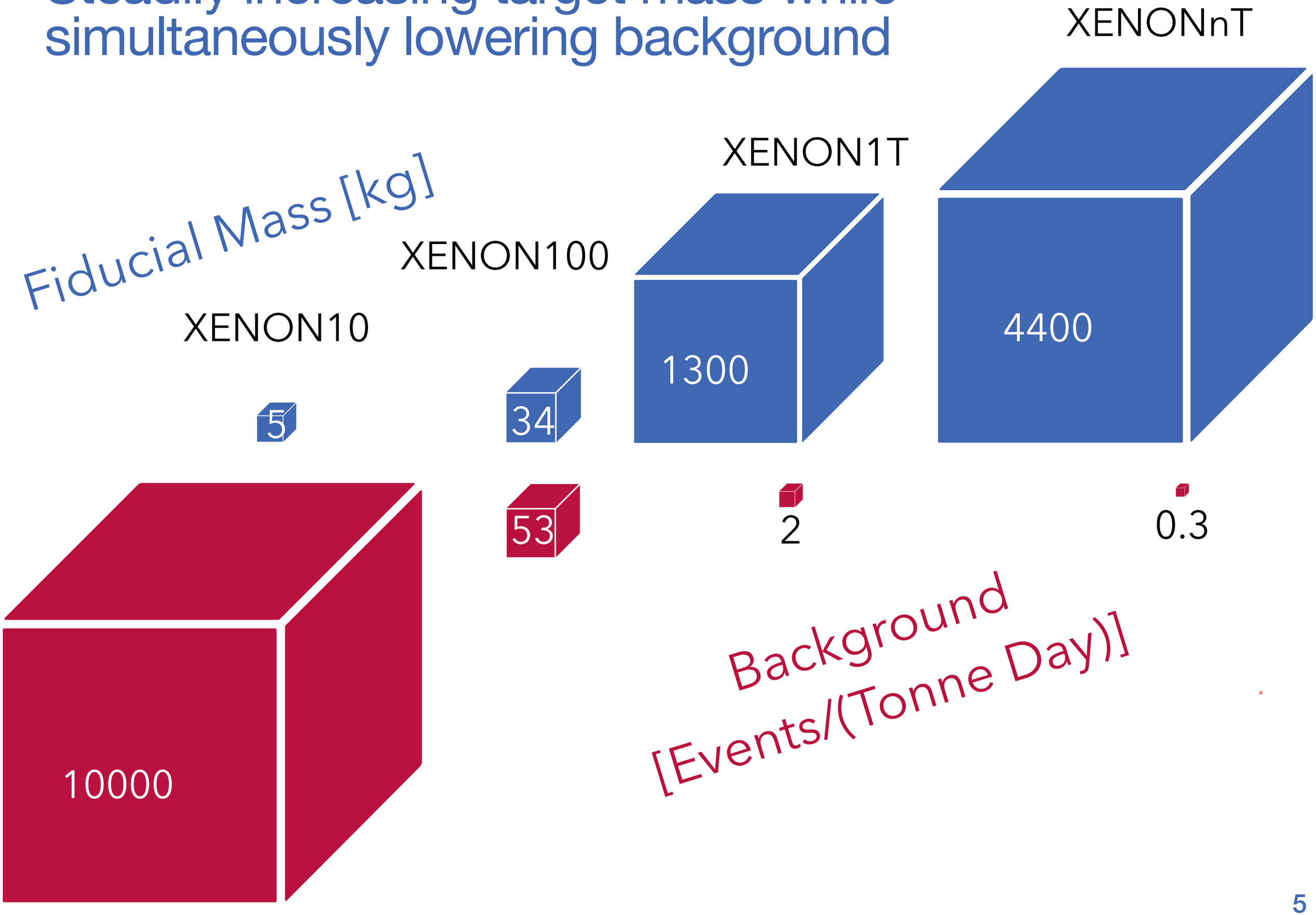
Liquid Xenon Detectors: Rapid Progress and Best WIMP Limits $> 10\ \mathrm{GeV/c^2}$





Snowmass 2021 Whitepaper on particle dark matter
arXiv:2203.08084

Steadily increasing target mass while simultaneously lowering background

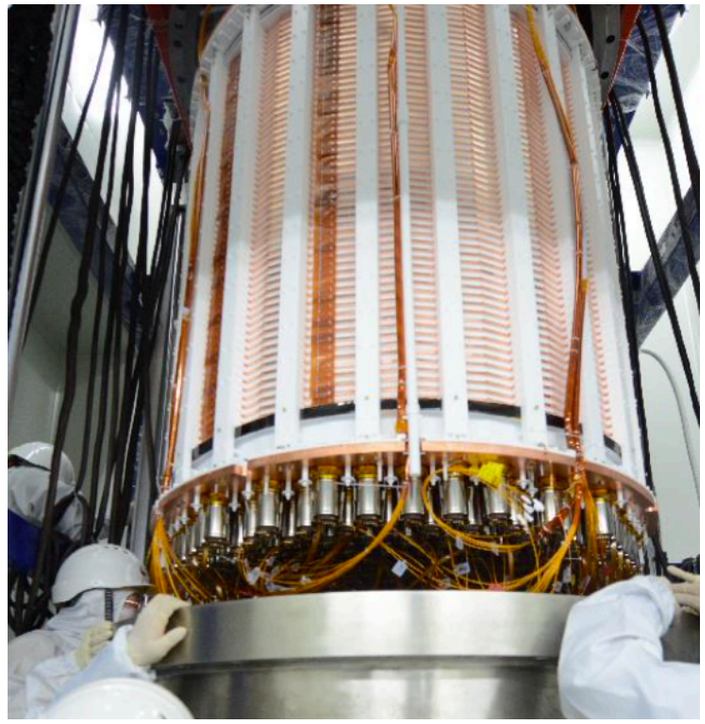


Current LXeTPCs

- LZ at SURF, PandaX-4T at CJPL
  XENONnT at LNGS
- Detector scale: 10 t (LZ), 6 t (PandaX-4T) and 8.6 t LXe (XENONnT) in total xenon mass
  - TPCs with 2 arrays of 3-inch PMTs
  - Different Kr and Rn removal techniques
  - Ultra-pure water shields, n & μ vetos
  - GXe and LXe Purification
- Status: PandaX-4T first result in 2021 (not blind analysis), LZ first results from 2022 run (not blind analysis), XENONnT first results (blind analysis) in 2021/22. All in data-taking mode.

LUX-ZEPLIN

XENONnT

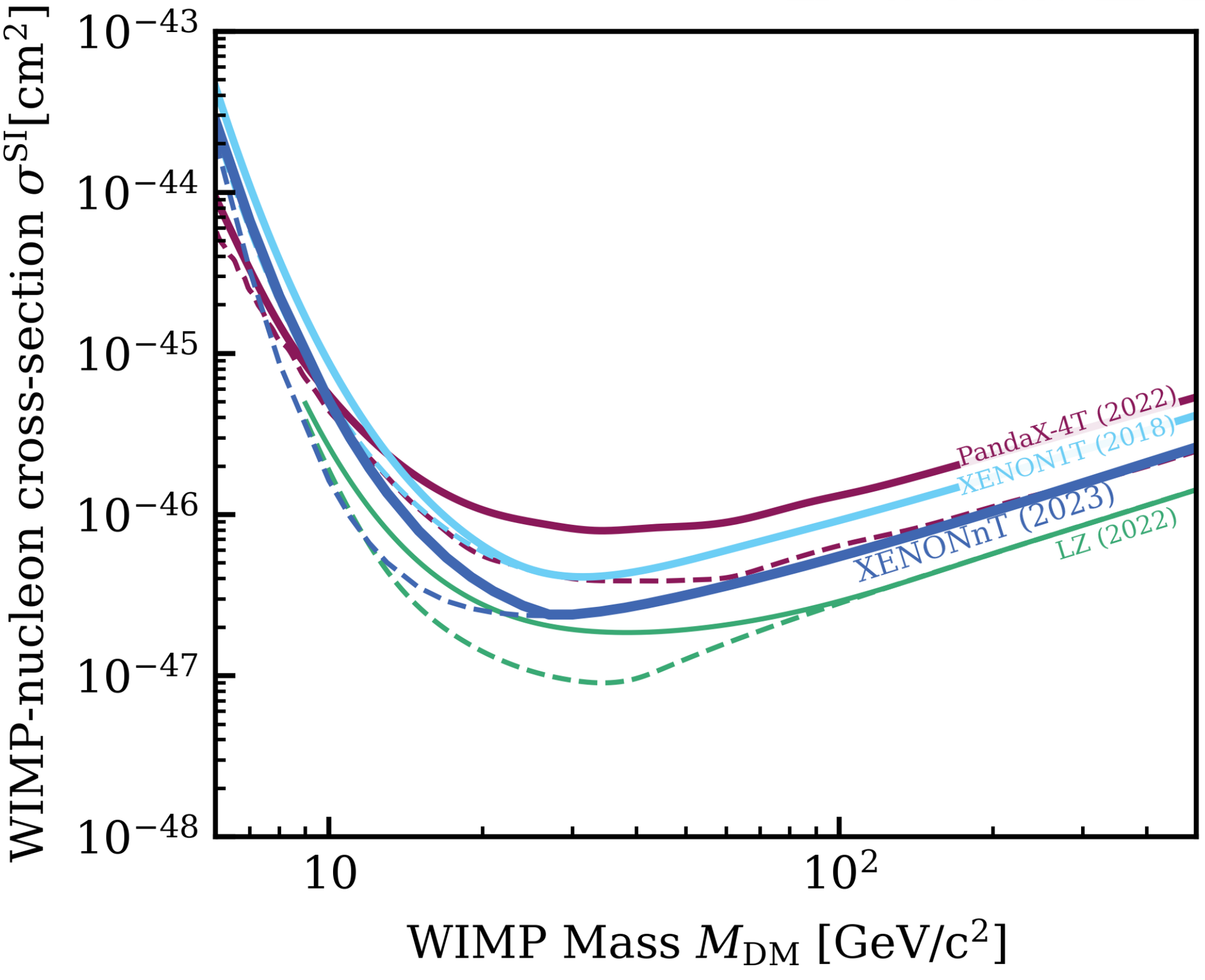


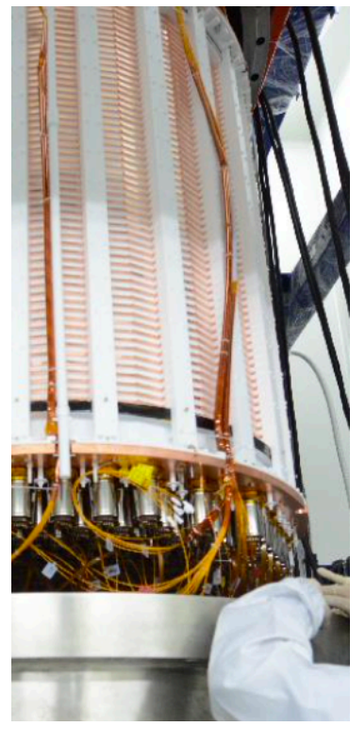
PandaX-4T

Current LXeTPCs

LUX-ZEPLIN

XENONnT

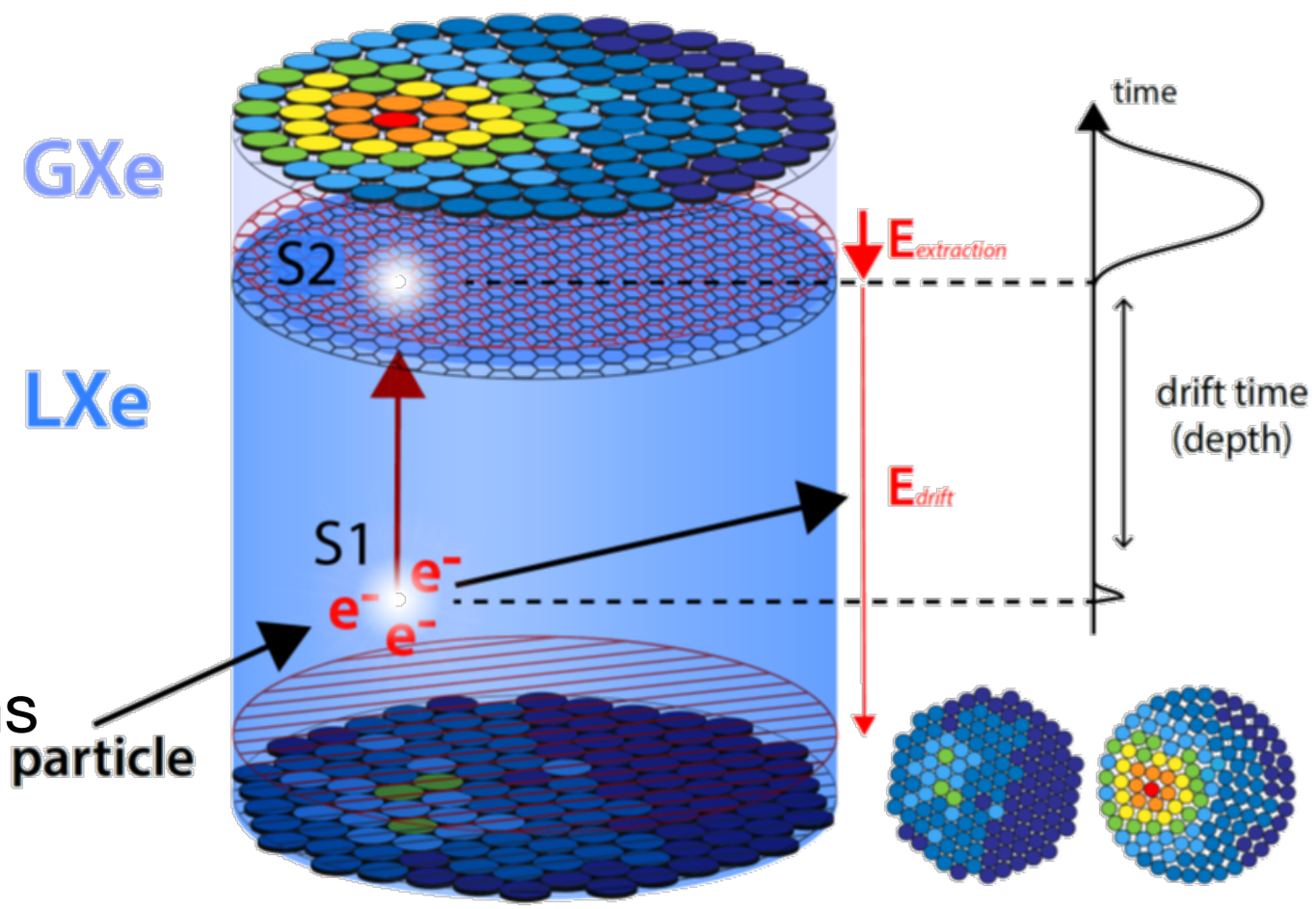




X-4T

Two-Phase Liquid Xenon Time Projection Chamber

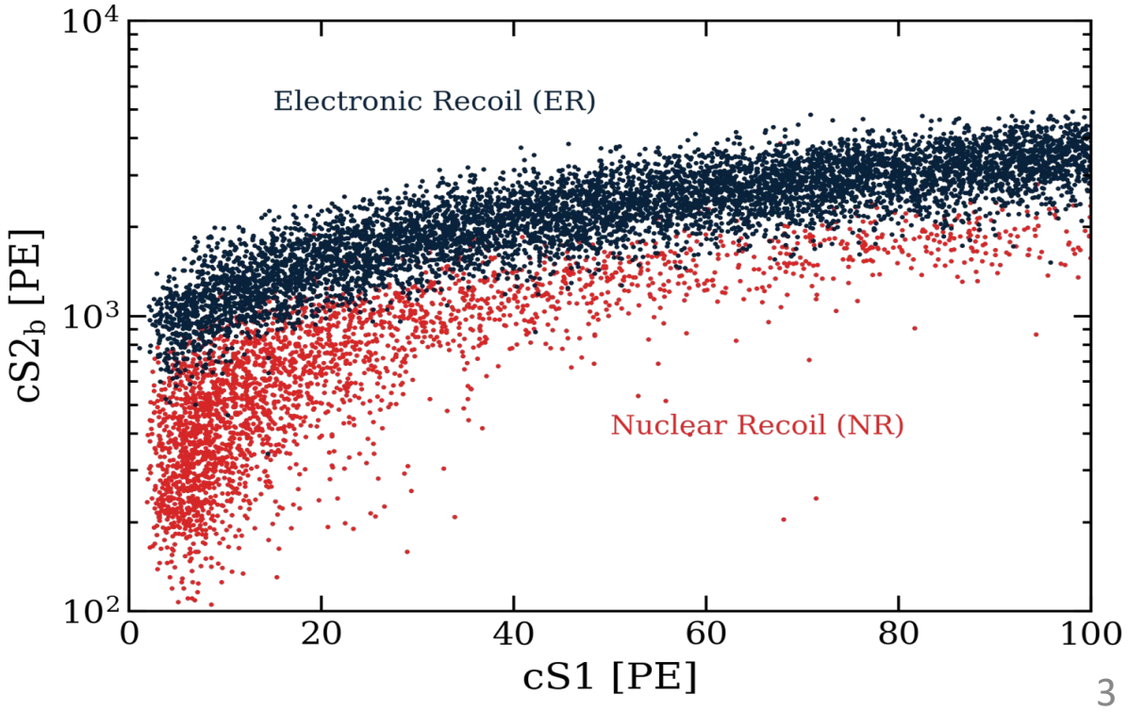
- S1: “Light signal”
  - prompt scintillation photons
- S2: “Charge signal”
  - Secondary scintillation photons from electroluminescence in GXe due to drifted electrons
- 3D-spatial reconstruction:
  - X,Y: S2 hit pattern
  - Z: S1-S2 drift time



NR (Nuclear Recoils)
WIMP signal, neutrons, CEvNs

ER (Electronic Recoils)
γ, β backgrounds

Discrimination from S2/S1
Larger for ER than NR

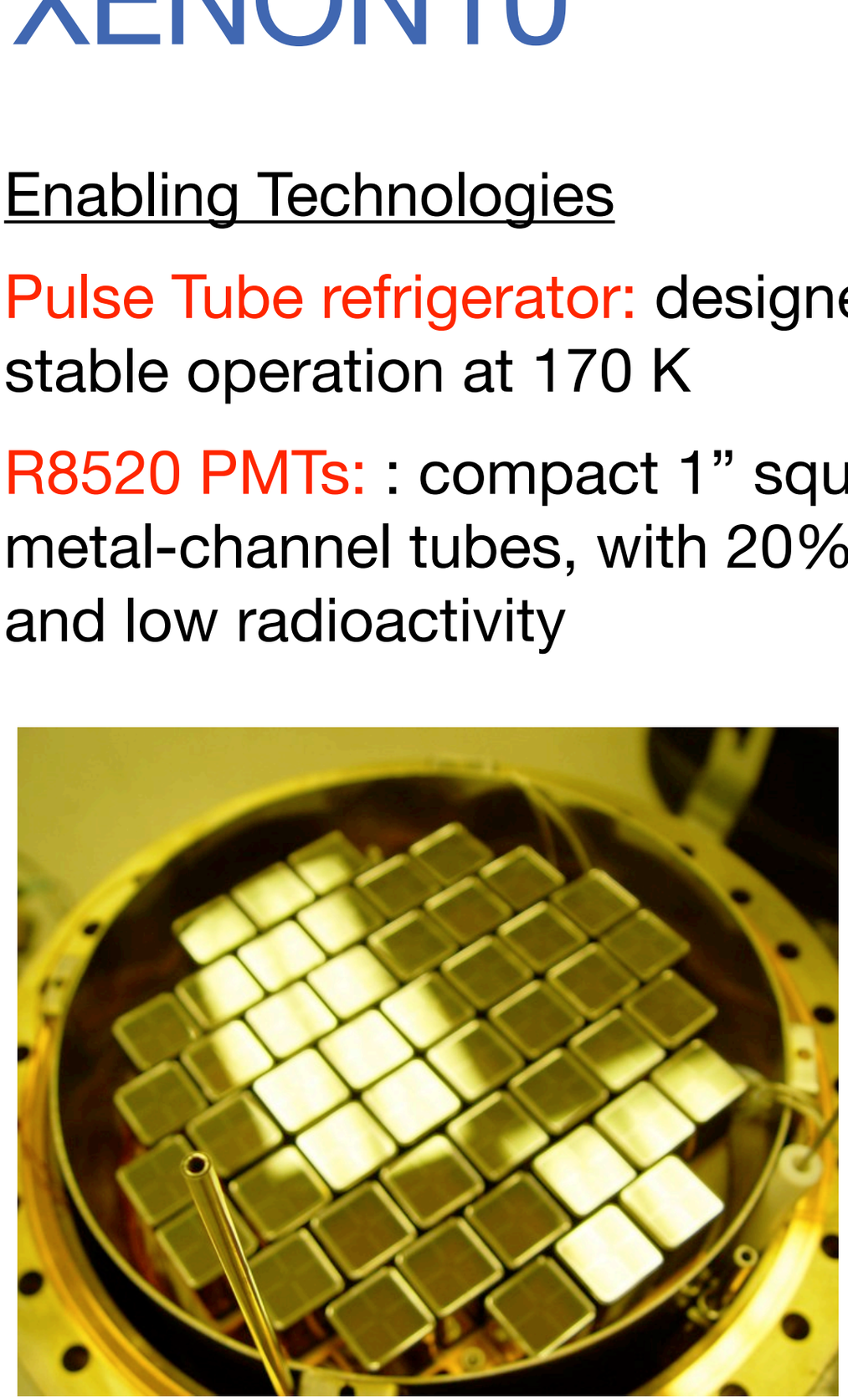


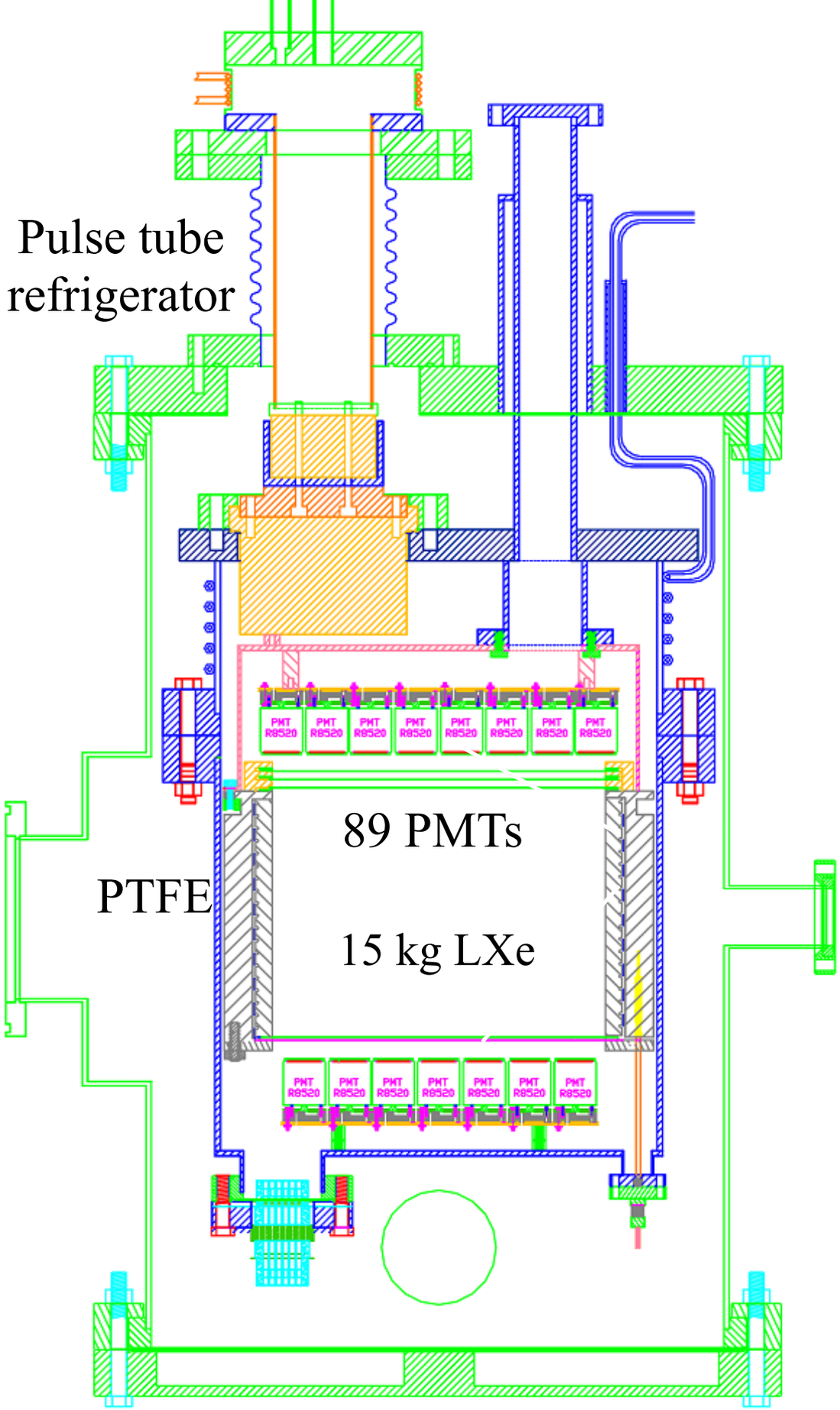
XENON10

Enabling Technologies

Pulse Tube refrigerator: designed for stable operation at 170 K

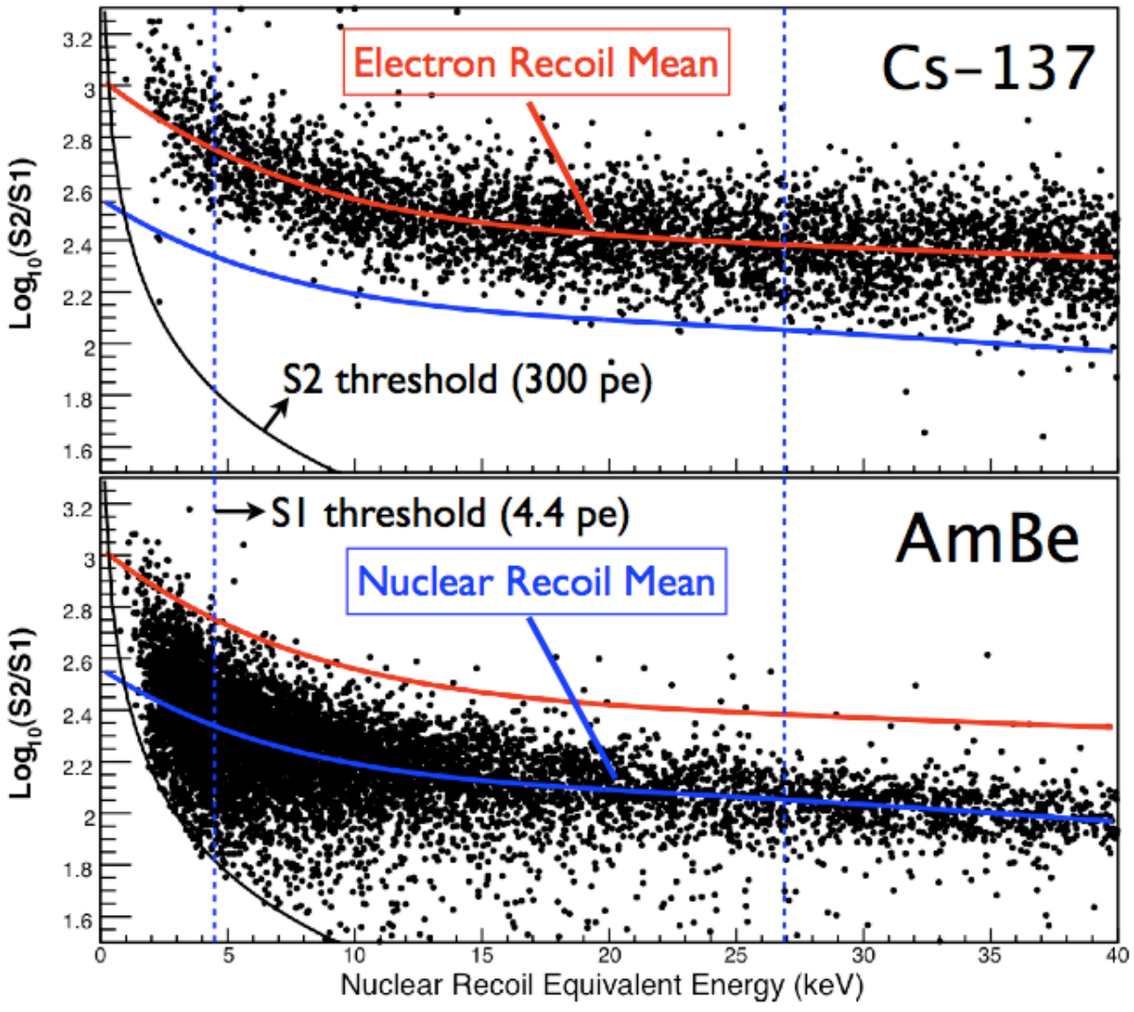
R8520 PMTs: : compact 1” square, metal-channel tubes, with 20% QE and low radioactivity



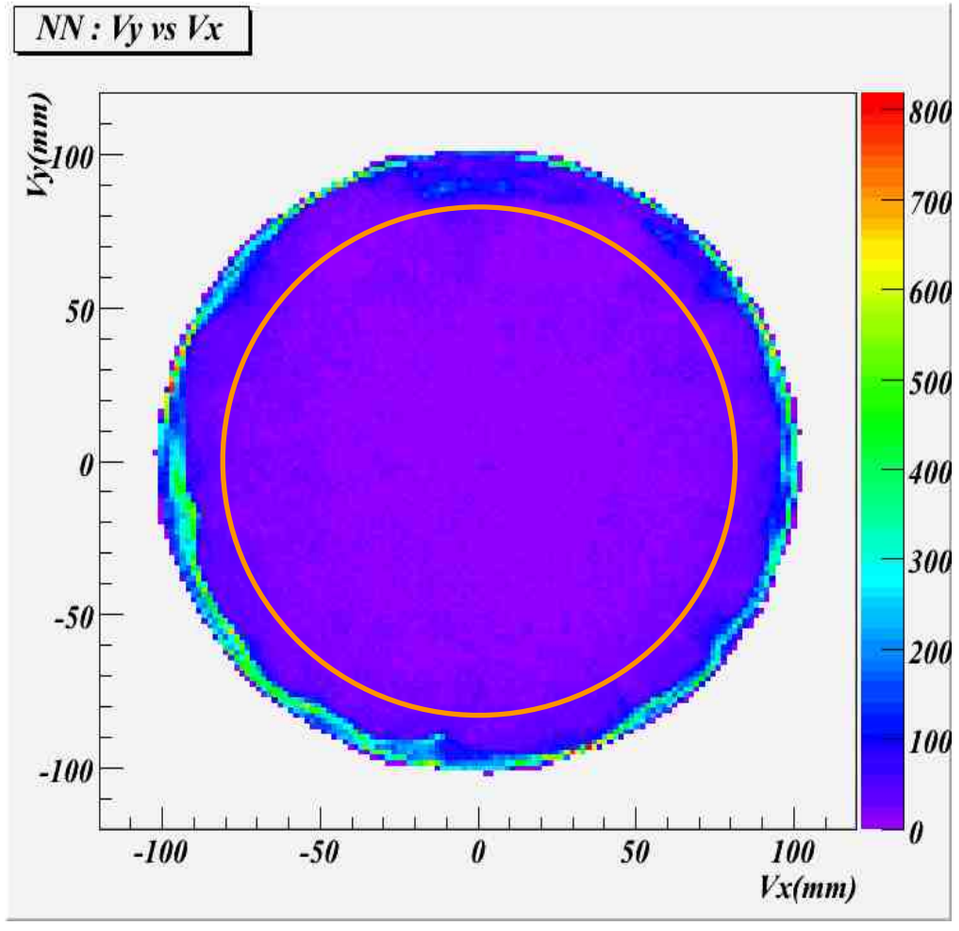


XENON10

Excellent signal-background discrimination demonstrated



- Reject electronic recoils with S2/S1: 99.5% of gamma events are above the mean nuclear recoil

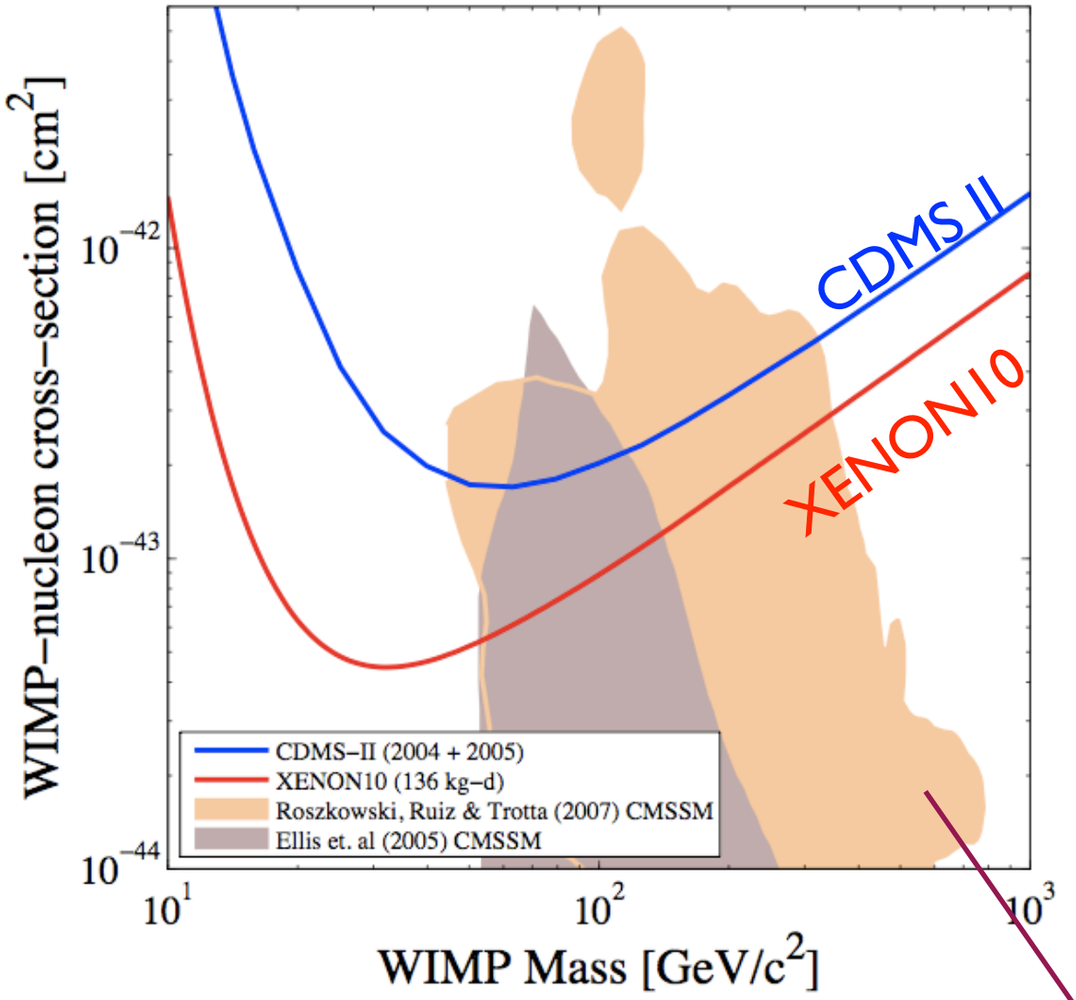


- Reject outside radioactivity with 3D-spatial reconstruction.
  $0.6\ \mathrm{events/(kg \cdot day \cdot keV_{ee})}$
  in the 5.4 kg fiducial mass

XENON10 WIMP Results

Spin-independent

Phys. Rev. Lett. ***100****, 021303 (2008)*



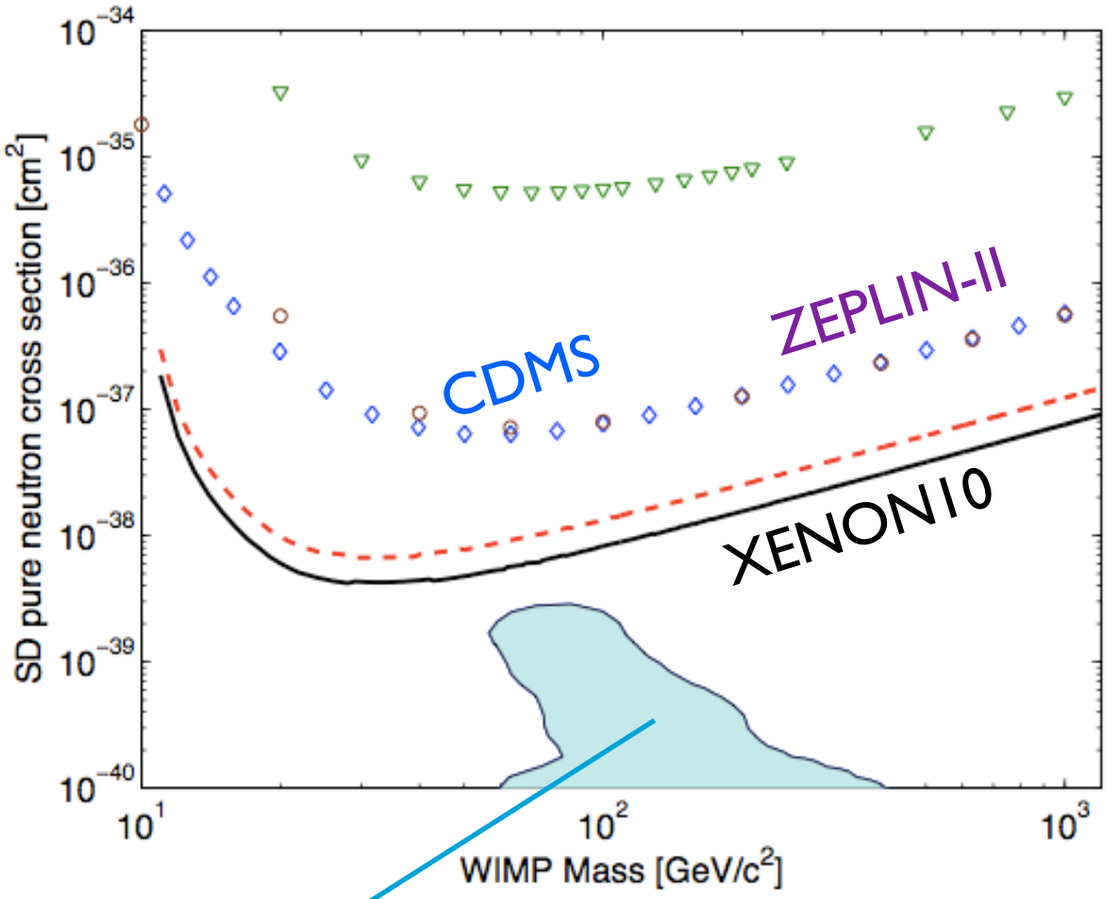
(NO BKG SUBTRACTION)

8.8 x 10^{-44} cm^2 at 100 GeV

4.5 x 10^{-44} cm^2 at 30 GeV

Spin-dependent

Phys. Rev. Lett. ***101****, 091301 (2008)*



(NO BKG SUBTRACTION)

6 x 10^{-39} cm^2 at 30 GeV

Constrained Minimal Supersymmetric Model

XENON10 WIMP Results

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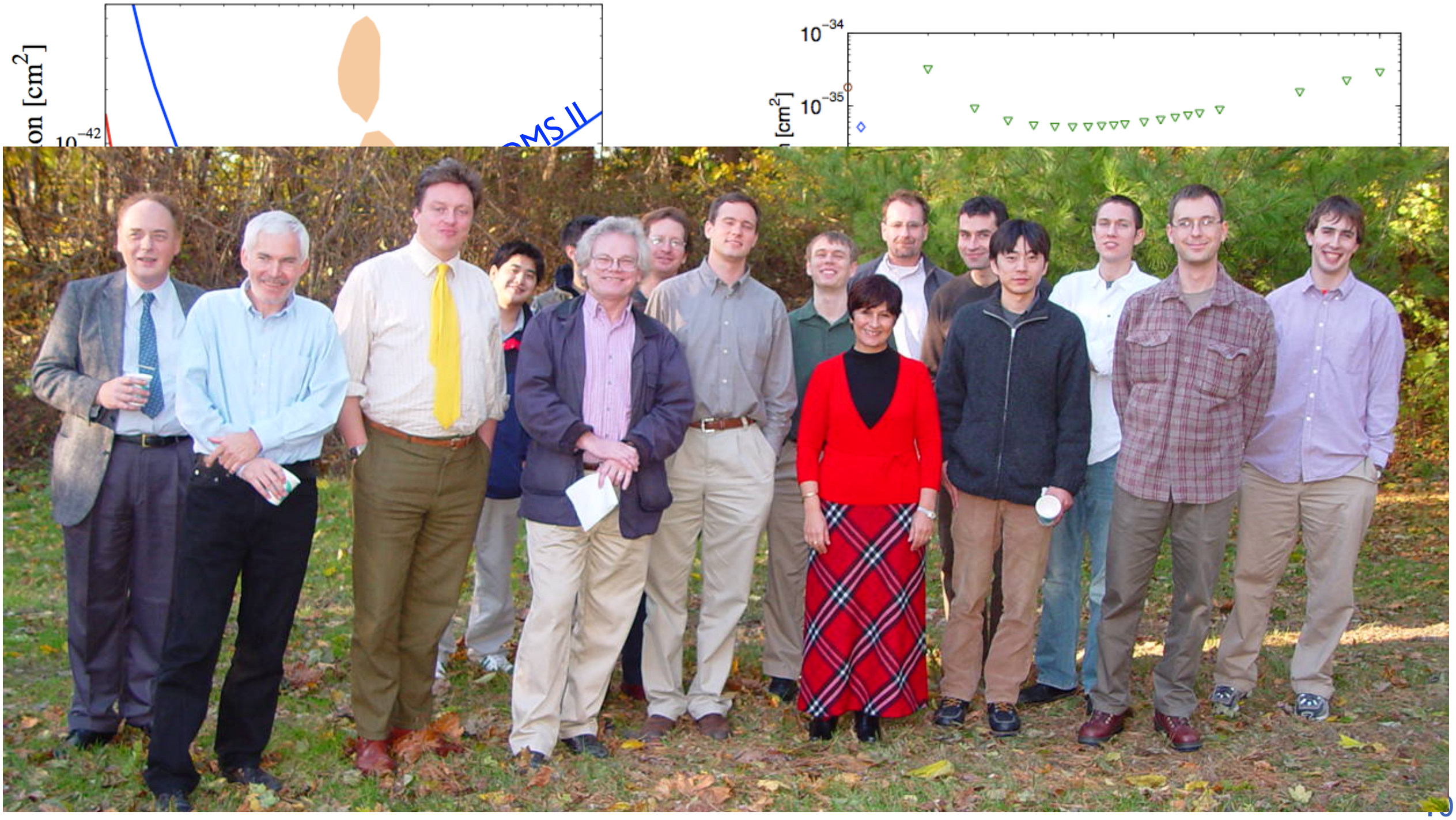
Phys. Rev. Lett. ***100****, 021303 (2008)*

Spin-dependent

Phys. Rev. Lett. ***101****, 091301 (2008)*



XENON100

Enabling Technologies

Cooling-at-a-distance: 200W PTR (PC150) mounted meters away from TPC

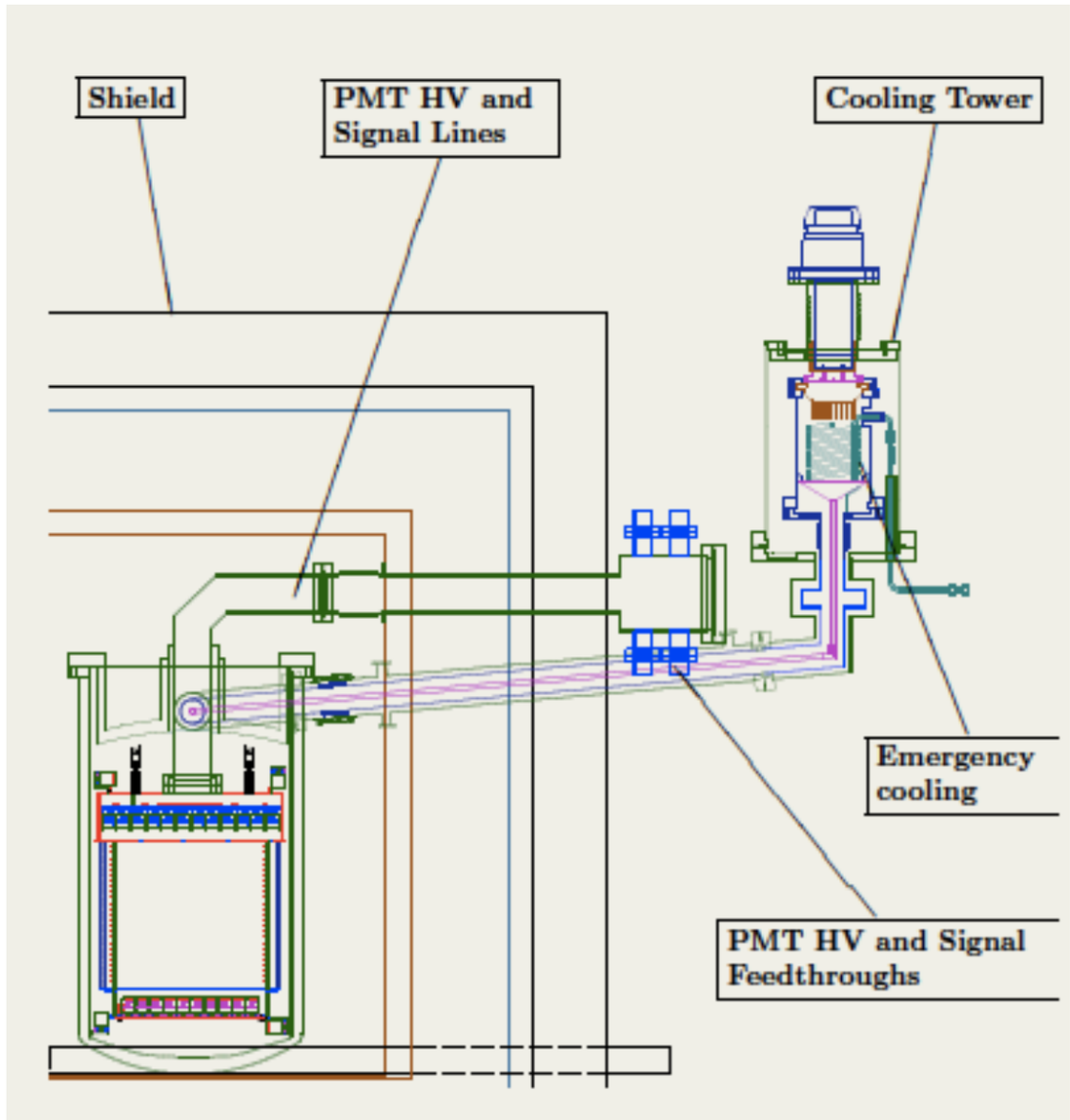
Low-radioactivity PMTs: $< 1\mu\mathrm{Bq}$ U/Th and 33% QE

Active LXe Veto: 100 kg of LXe outside TPC 50 kg active target

Kr/Xe reduction: to 50 ppb by cryogenic distillation measured with new diagnostic tools (ATTA and RGMS)

Novel Calibration Sources: $^{83m}\mathrm{Kr}$, $220\mathrm{Rn}$

Improved Analysis Tools: Profile Likelihood



XENON100

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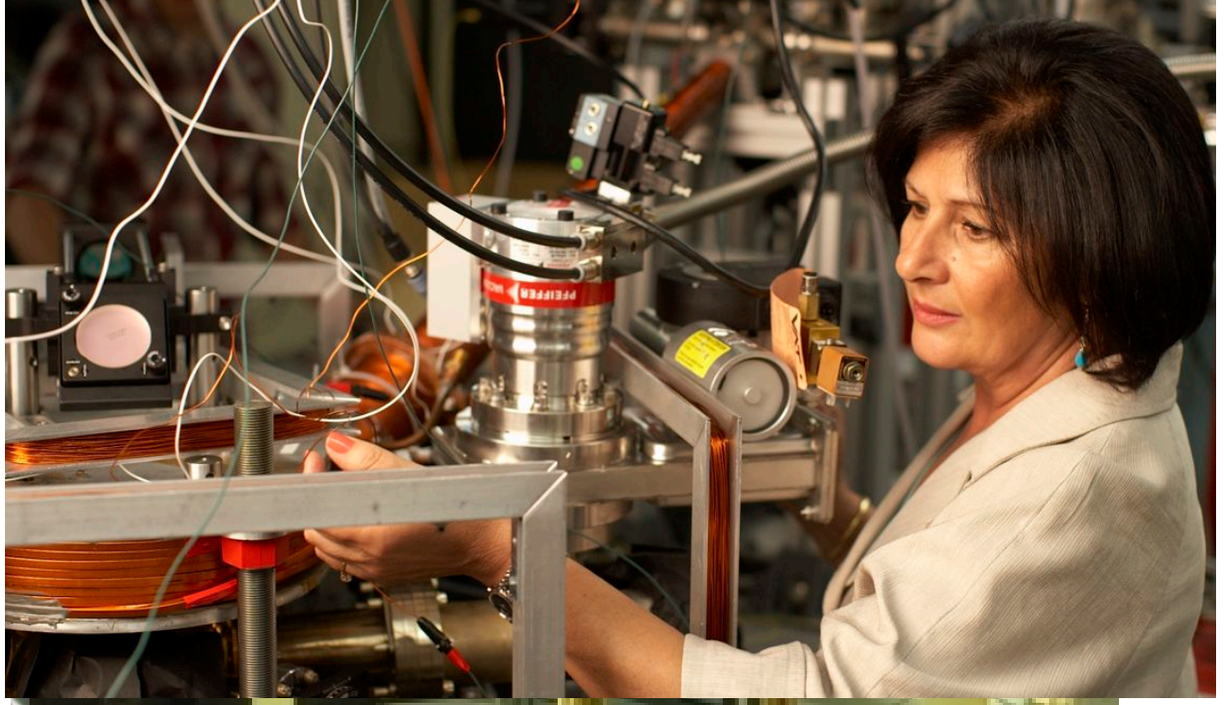
Improved Analysis Tools: Profile Likelihood

XENON100



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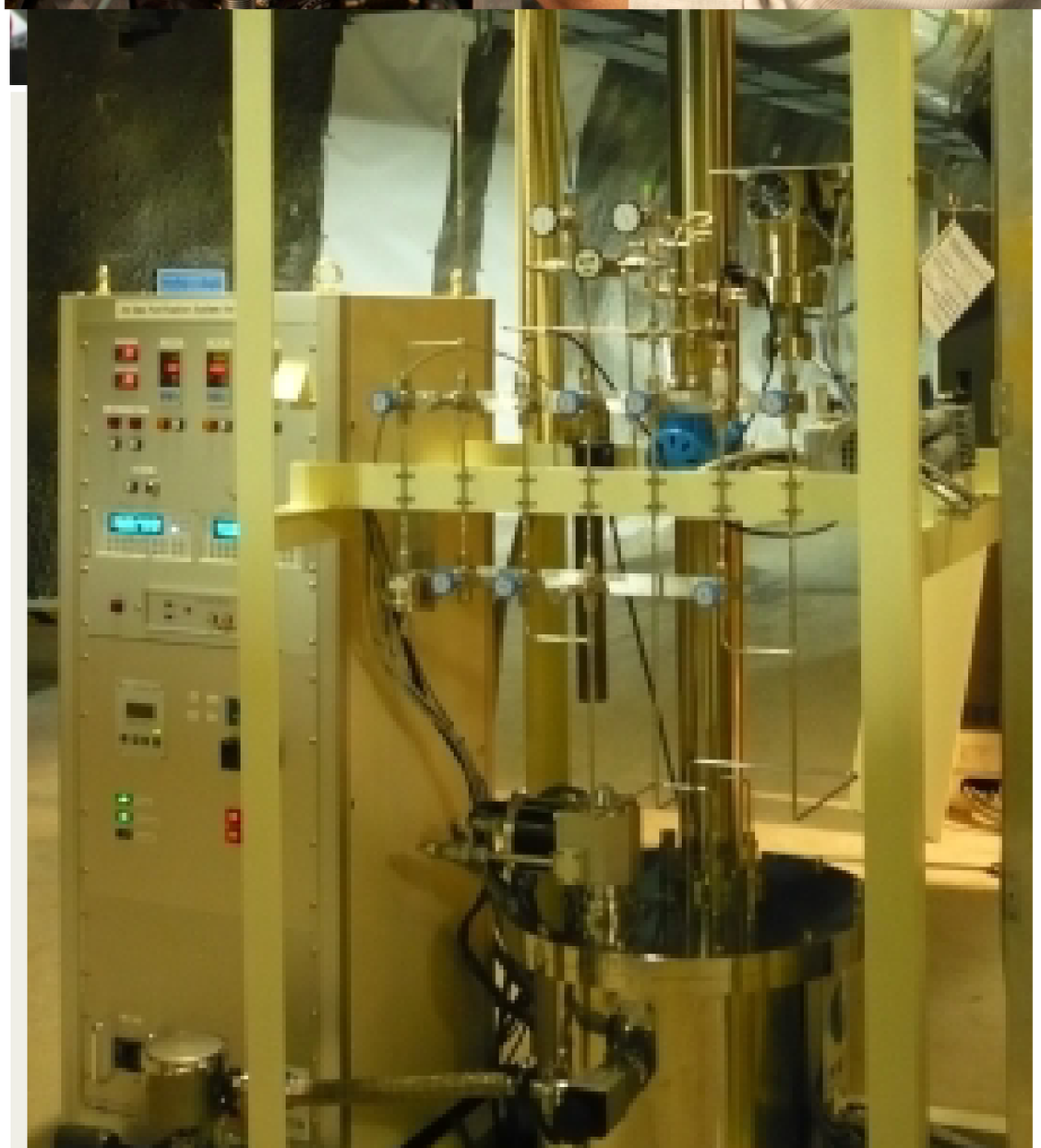
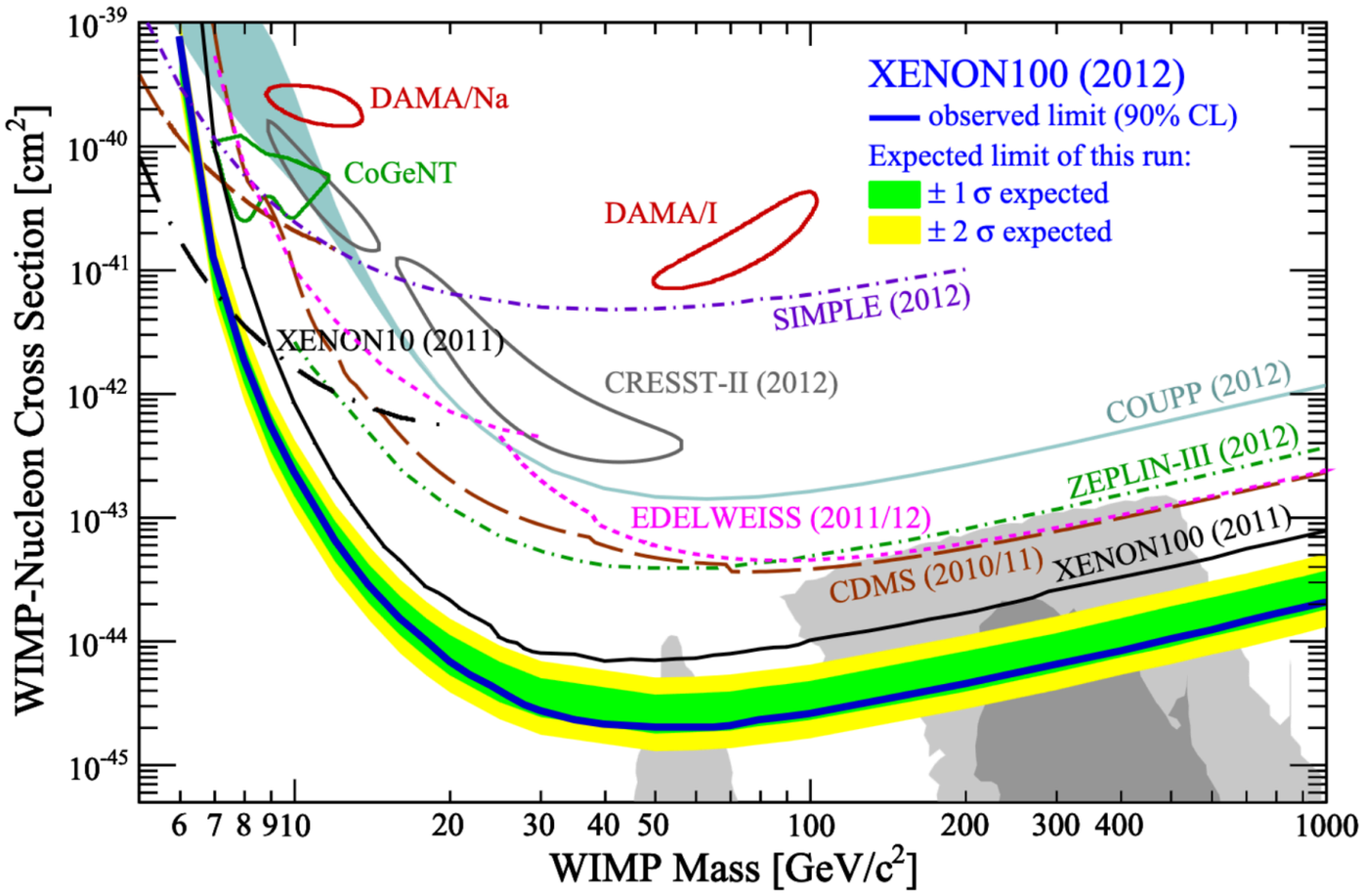
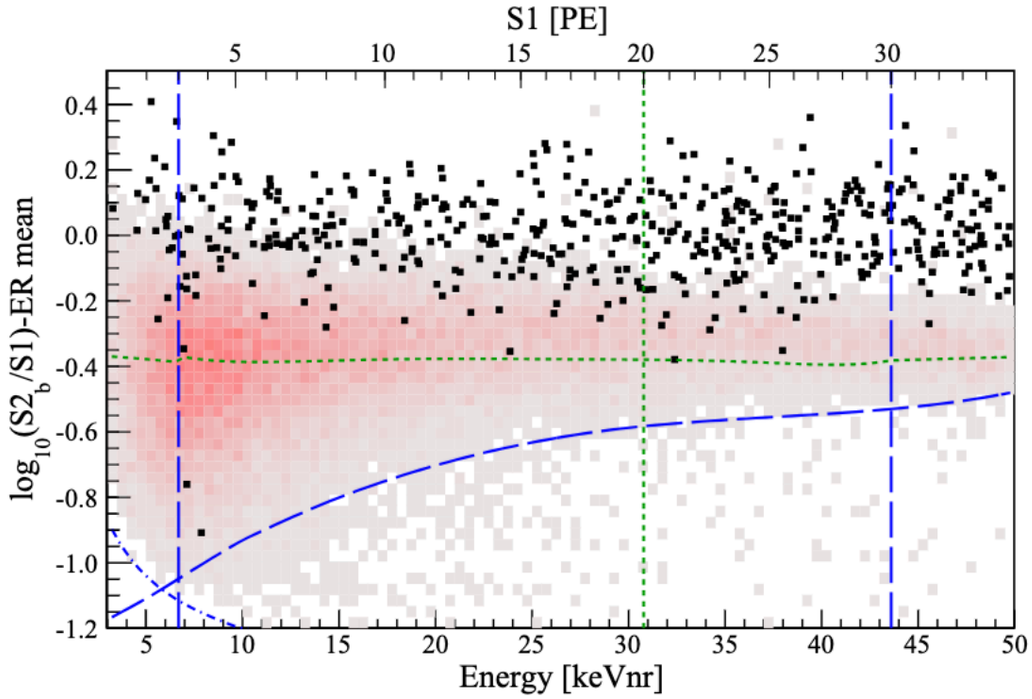
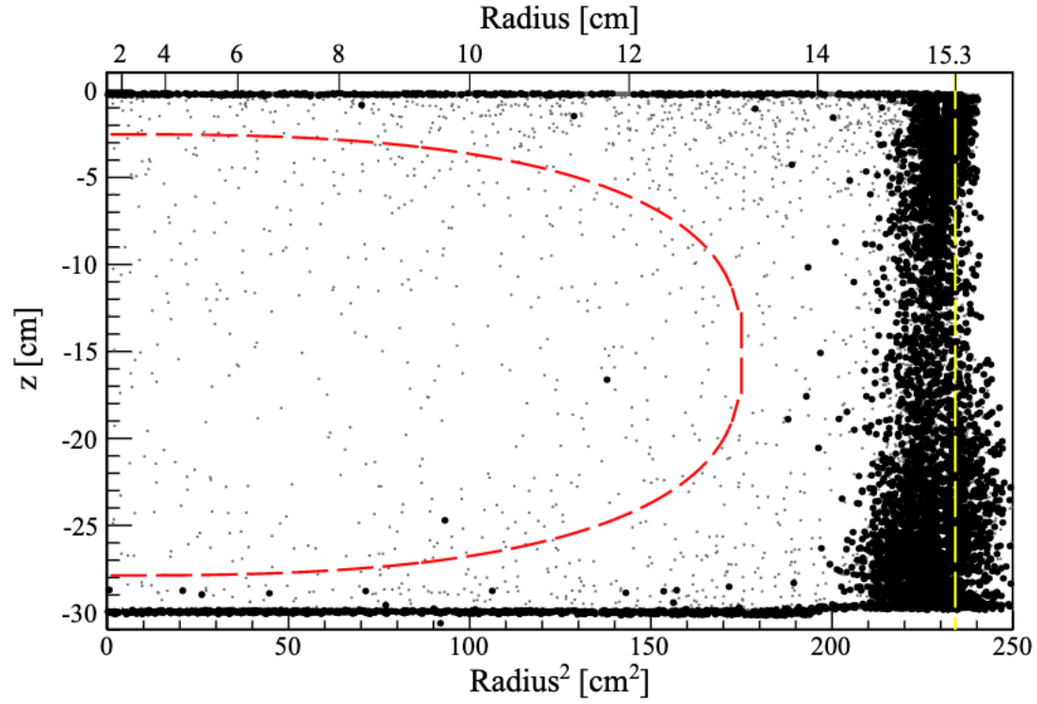


XENON100 WIMP Results

- blind analysis with 225 Live Days of data yielded strong limits and one of the most cited XENON papers







XENON Collaboration, Dark Matter Results from 225 Live Days of XENON100 Data
Phys. Rev. Lett. 109, 181301 (2012)

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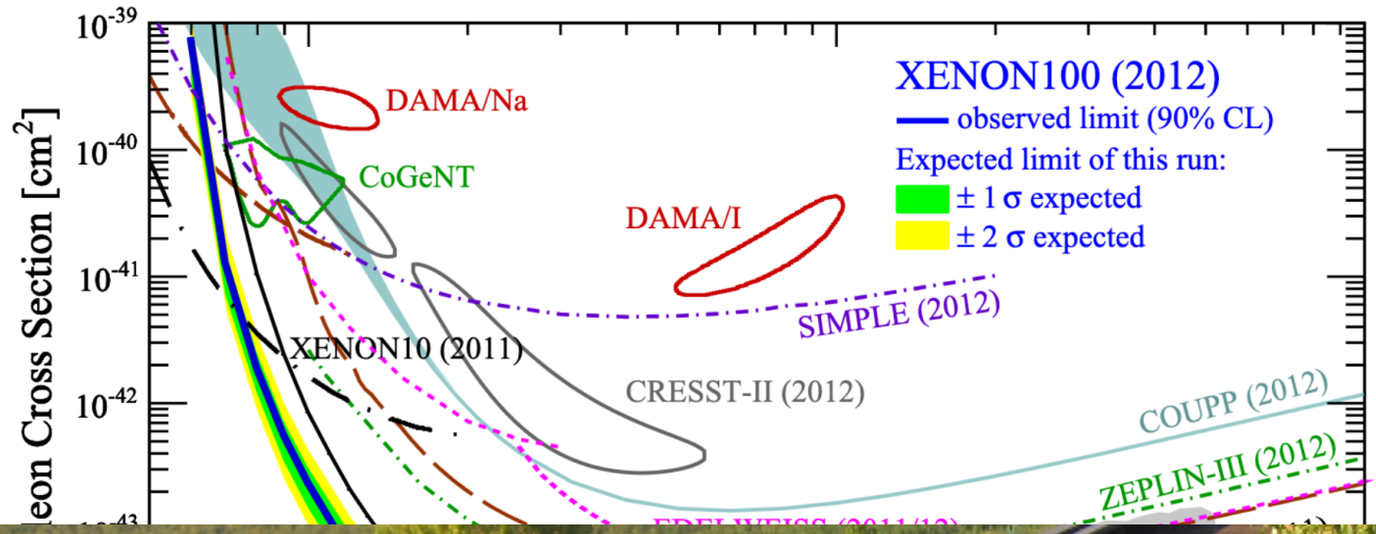
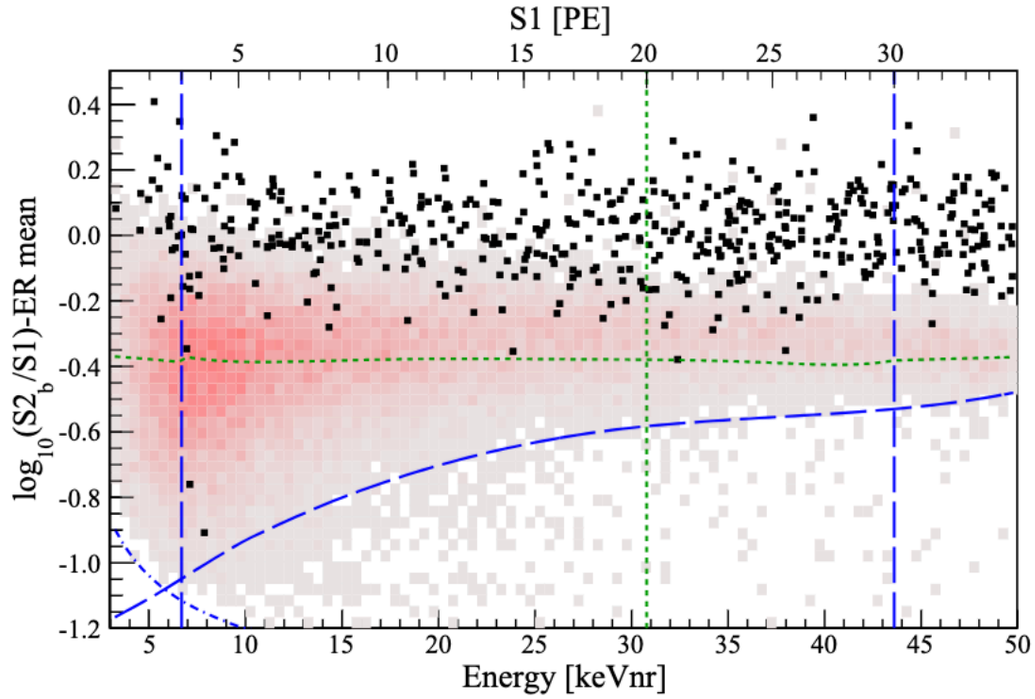
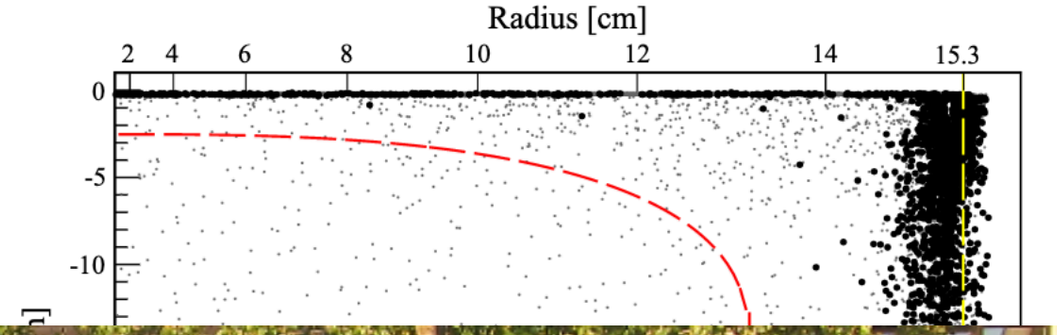
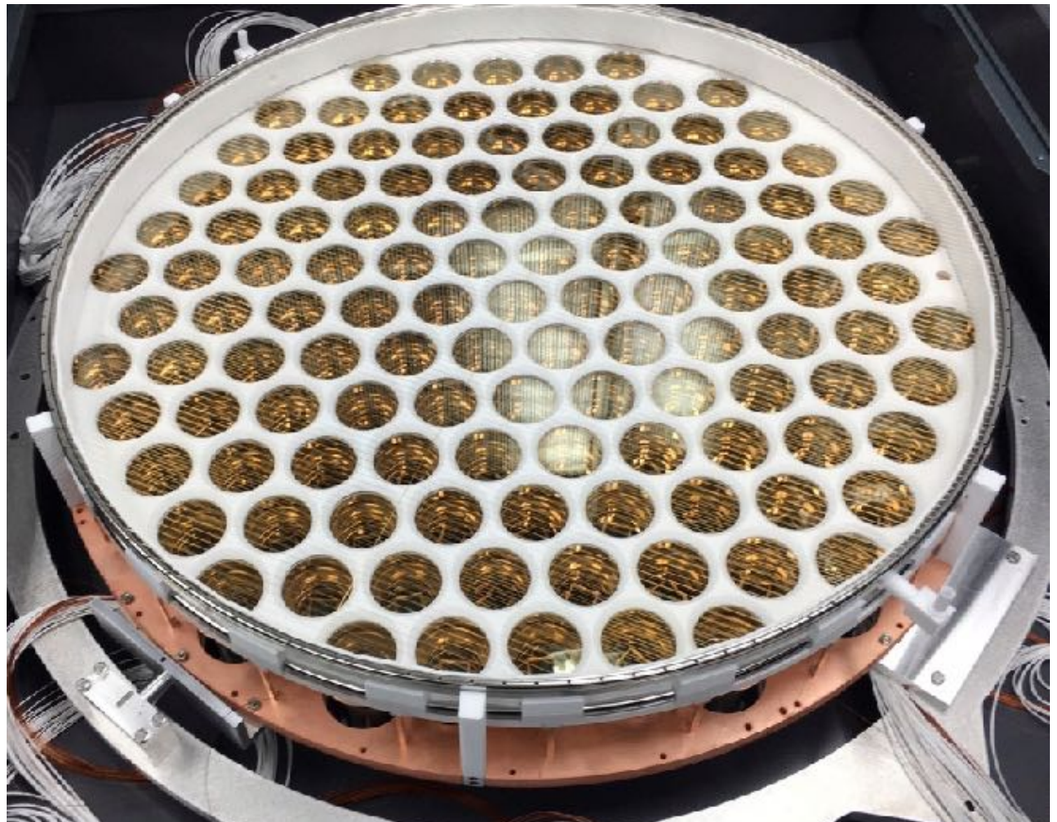






XENON1T

- The first tonne-scale LXeTPC, with a 2-tonne active mass.
- 1m diameter and height with 248 3” low-radioactivity PMTs
- TPC mounted in a cryostat suspended in center of a water Cerenkov muon veto detector



XENON1T

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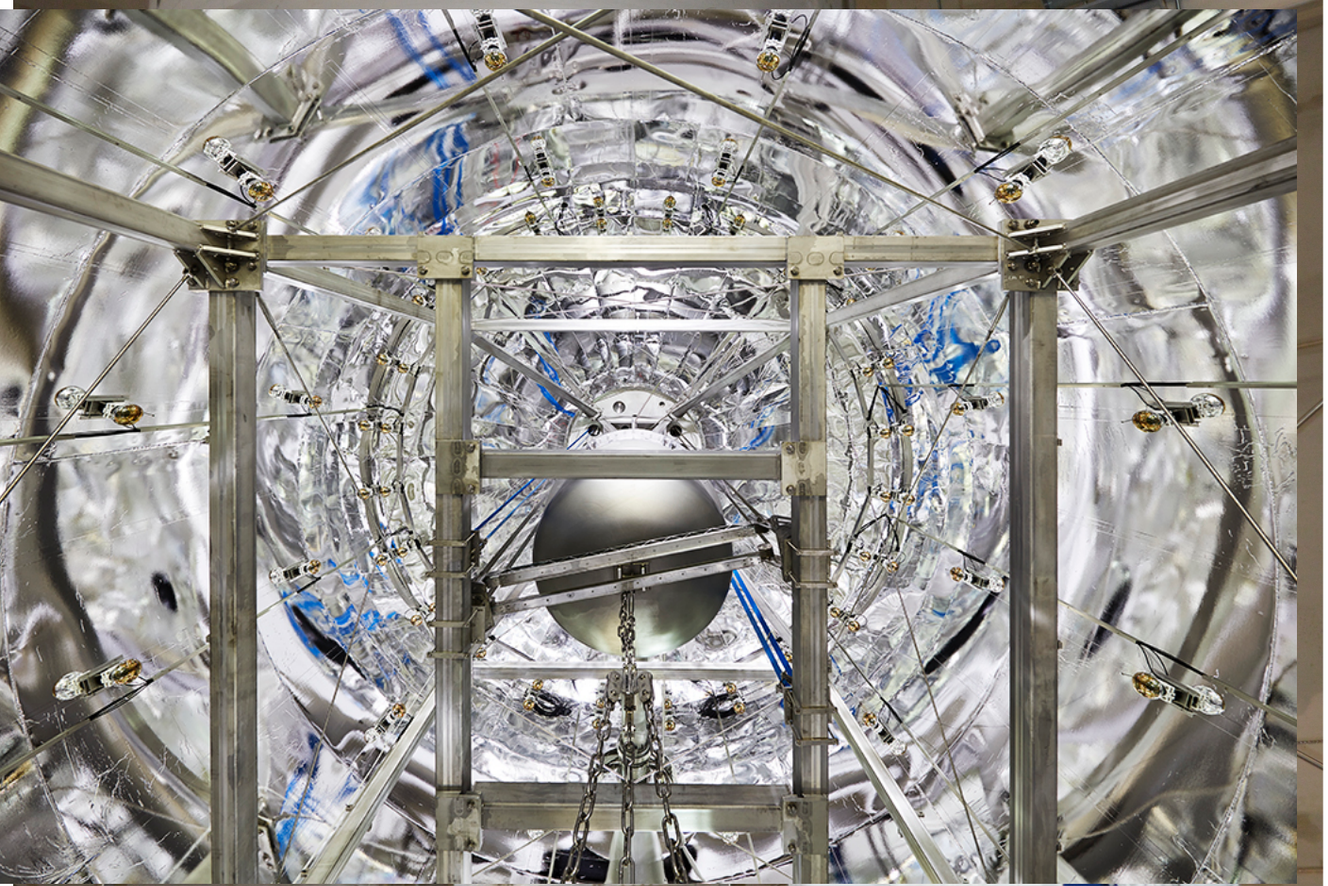
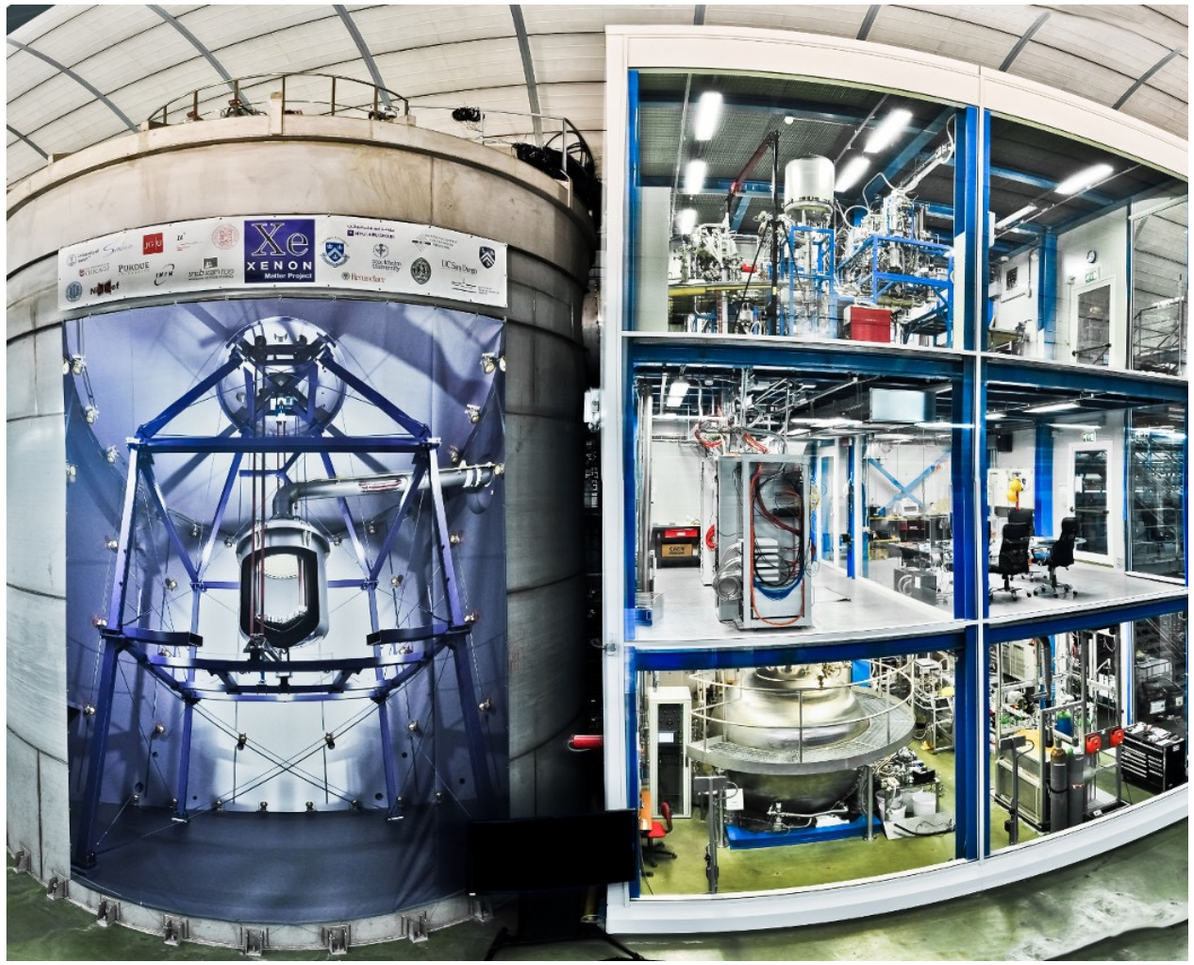
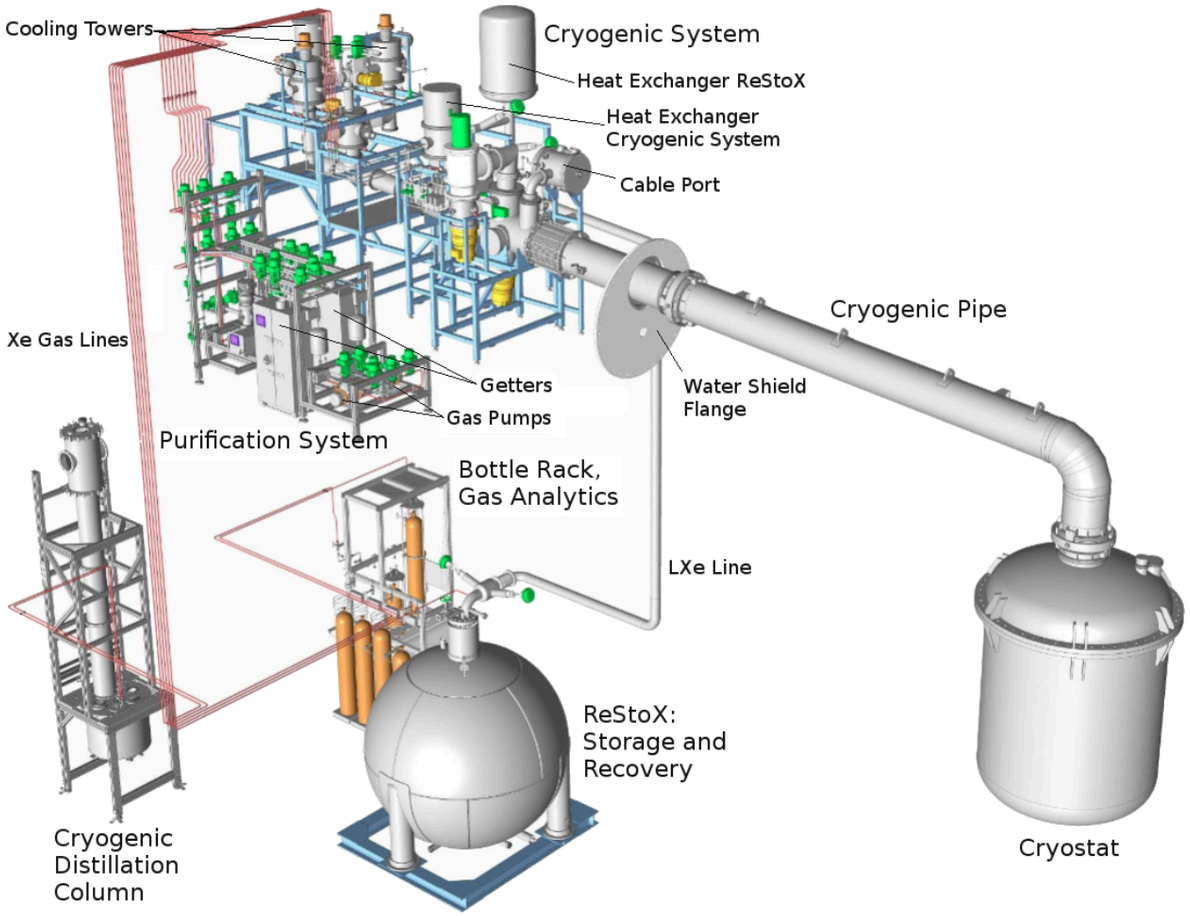


XENON1T

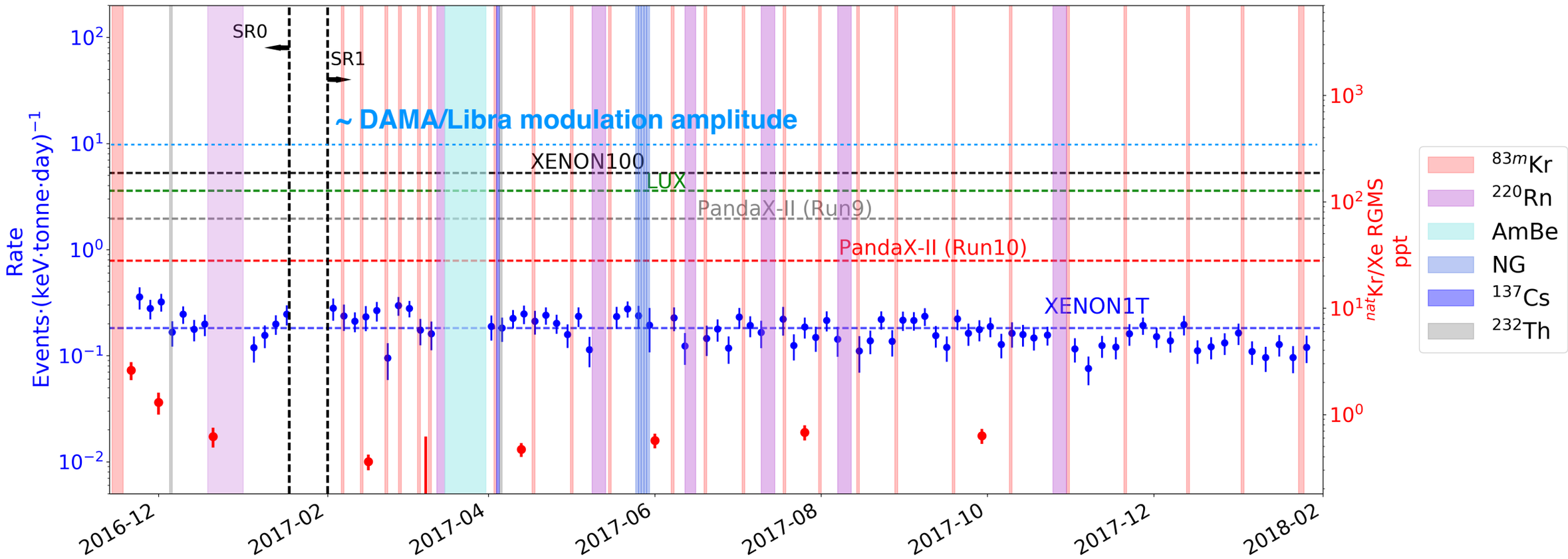
Extended infrastructure

- REMOTE COOLING TOWERS
  - 2 redundant towers with 240W pulse tube refrigerators
  - 1 backup liquid nitrogen cooling tower (300W)
- CONTINUOUS GAS PURIFICATION
  - through heated getter @ ~ 50 slpm
- STORAGE & RECOVERY GXe or LXe
  - LN cooled 2 m diameter sphere (70 bar)
  - for clean Xe storage & fast LXe recovery from TPC
- DISTILLATION COLUMN for Kr REDUCTION
  - 5.5m-tall with high throughput: 3kg/h at 105 separation
  - achieved in situ natKr/Xe concentration of 0.36 ppt





XENON1T Background



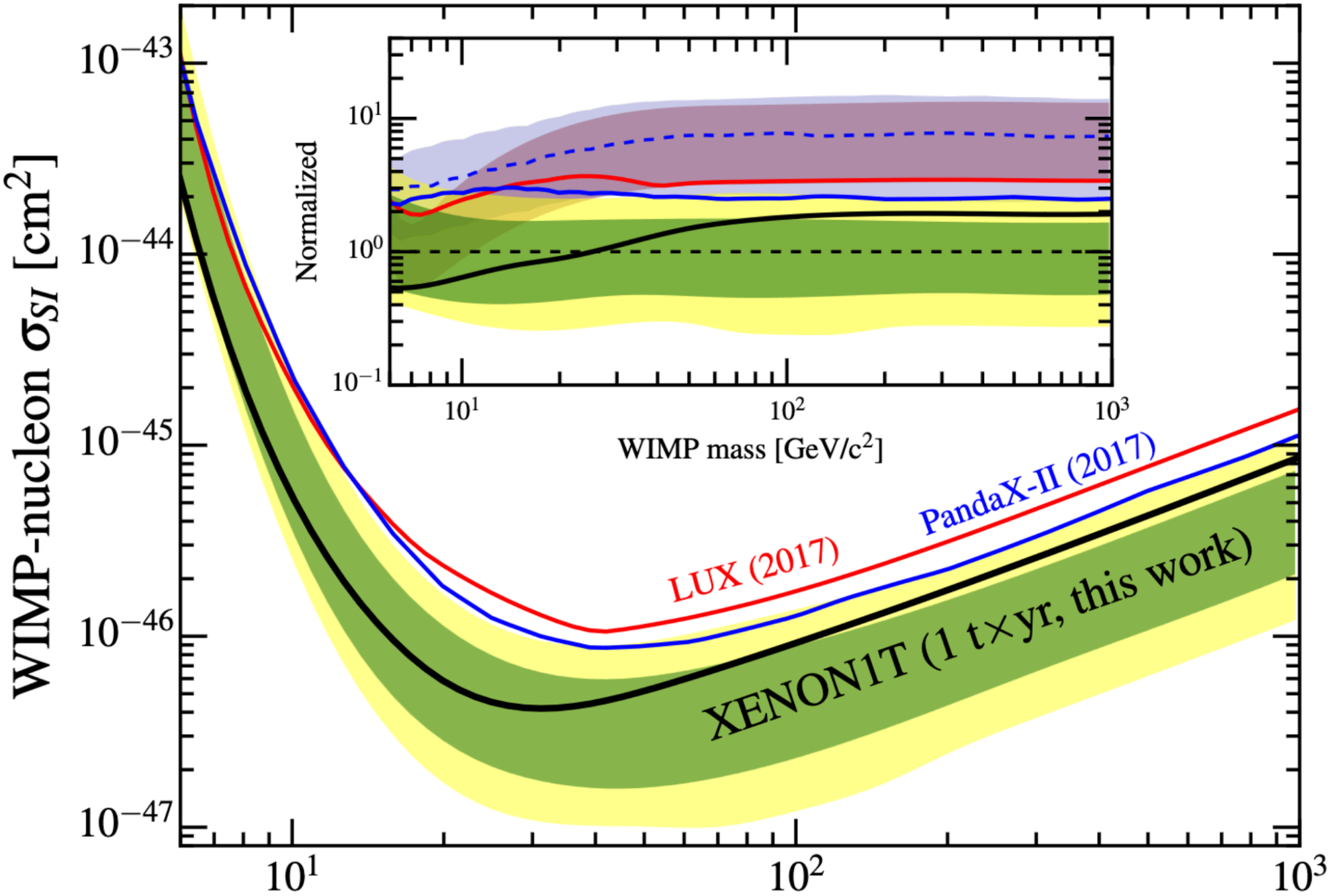
(82 ± 5) events / (t × yr × keV_{ee}) below 25 keVee

Lowest ER background achieved in a DM detector

Dominated by Pb214 from Rn222 (~ 10 uBq/kg)

XENON1T WIMP Results

- Final WIMP result used one tonne-year of data over two science runs, with world-leading sensitivity and limits



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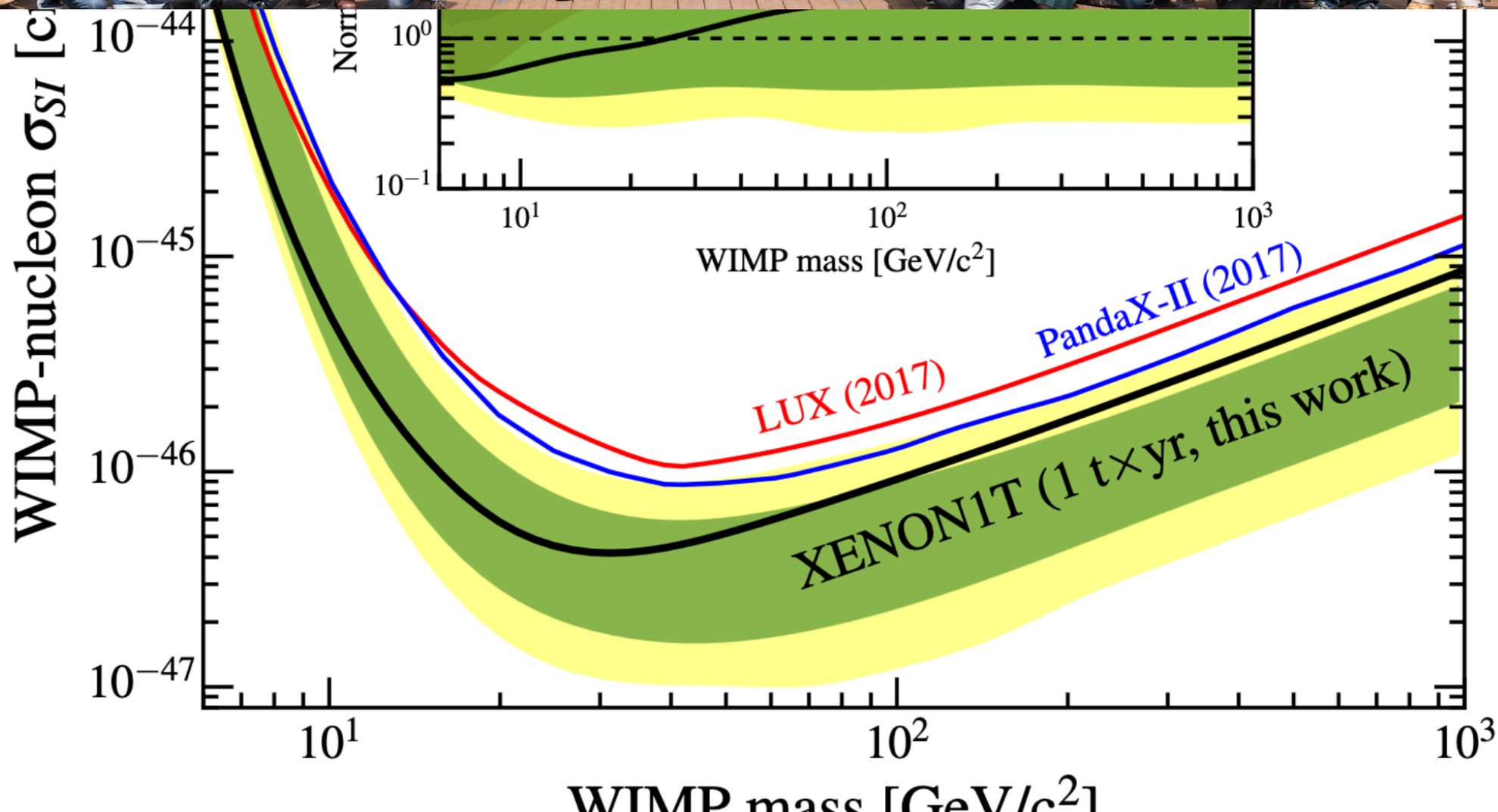
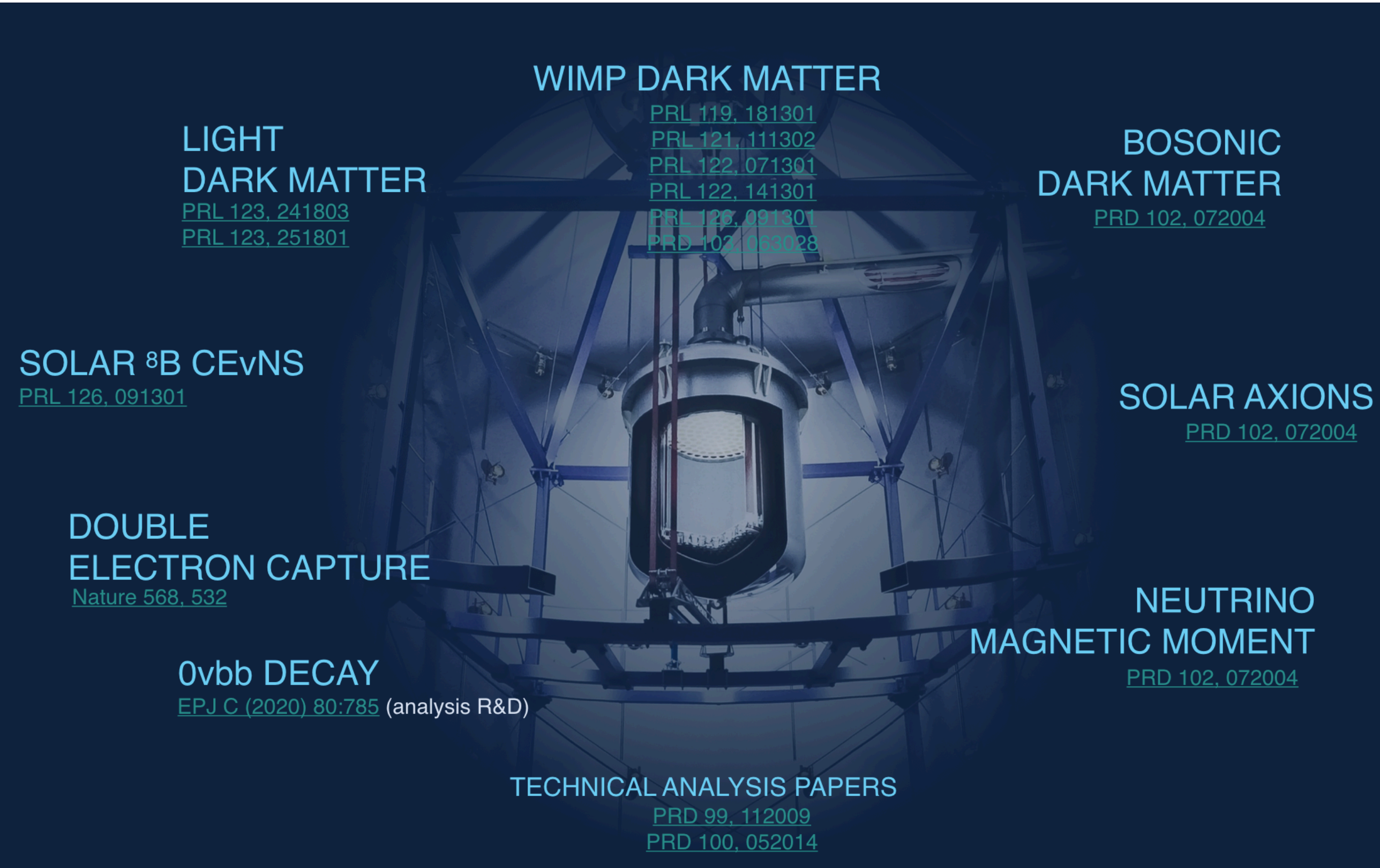


XENON1T WIMP Results



WIMP DARK MATTER
PRL 119, 181301
PRL 121, 111302
PRL 122, 071301
PRL 122, 141301
PRL 126, 091301
PRD 103, 063028

LIGHT DARK MATTER
PRL 123, 241803
PRL 123, 251801

BOSONIC DARK MATTER
PRD 102, 072004

SOLAR ^{8}B CEvNS
PRL 126, 091301

SOLAR AXIONS
PRD 102, 072004

DOUBLE ELECTRON CAPTURE
Nature 568, 532

NEUTRINO MAGNETIC MOMENT
PRD 102, 072004

0vbb DECAY
EPJ C (2020) 80:785 (analysis R&D)

TECHNICAL ANALYSIS PAPERS
PRD 99, 112009
PRD 100, 052014

XENONnT

XENON1T infrastructure and subsystems designed for a rapid and efficient upgrade for 10 x sensitivity gain.

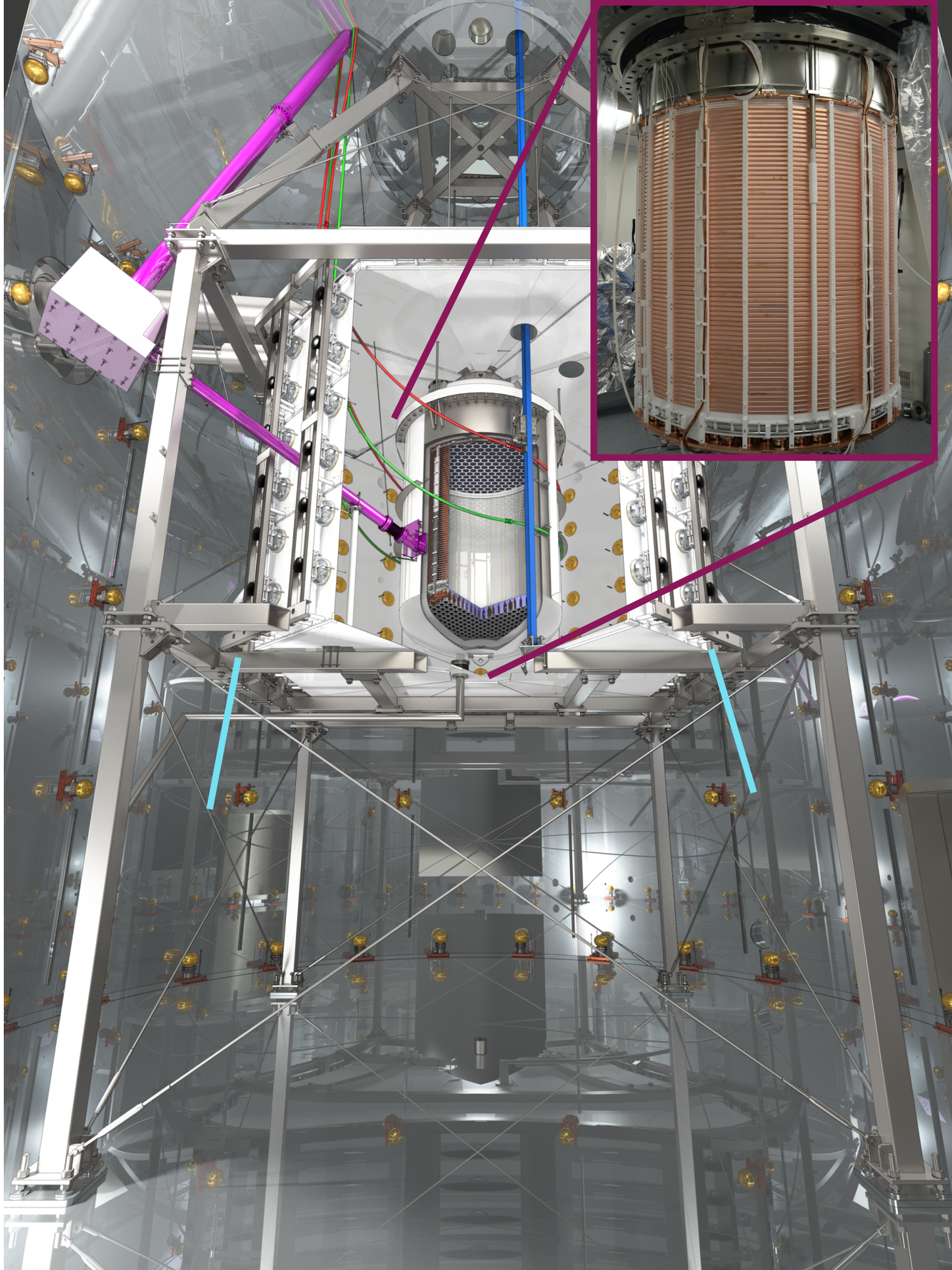
New TPC with:

- 1.5 m drift and 1.3 m diameter
- 8.6 t of LXe with 5.9 t as active mass
- 494 3” low-radioactivity PMTs

New Neutron Veto detector with:

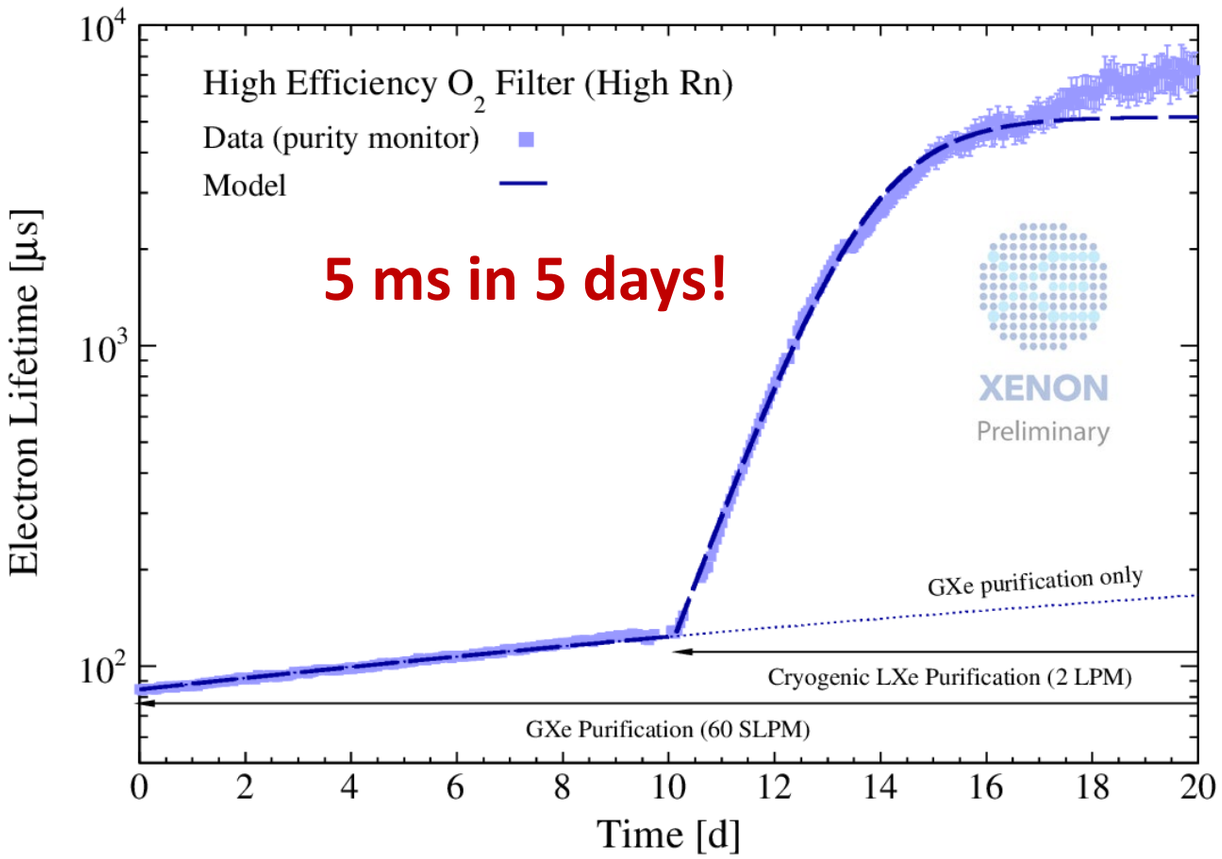
- 120 PMTs in 4m x 3m enclosure of reflective panels around TPC
- neutron tagging efficiency of 87% with Gd-doped water

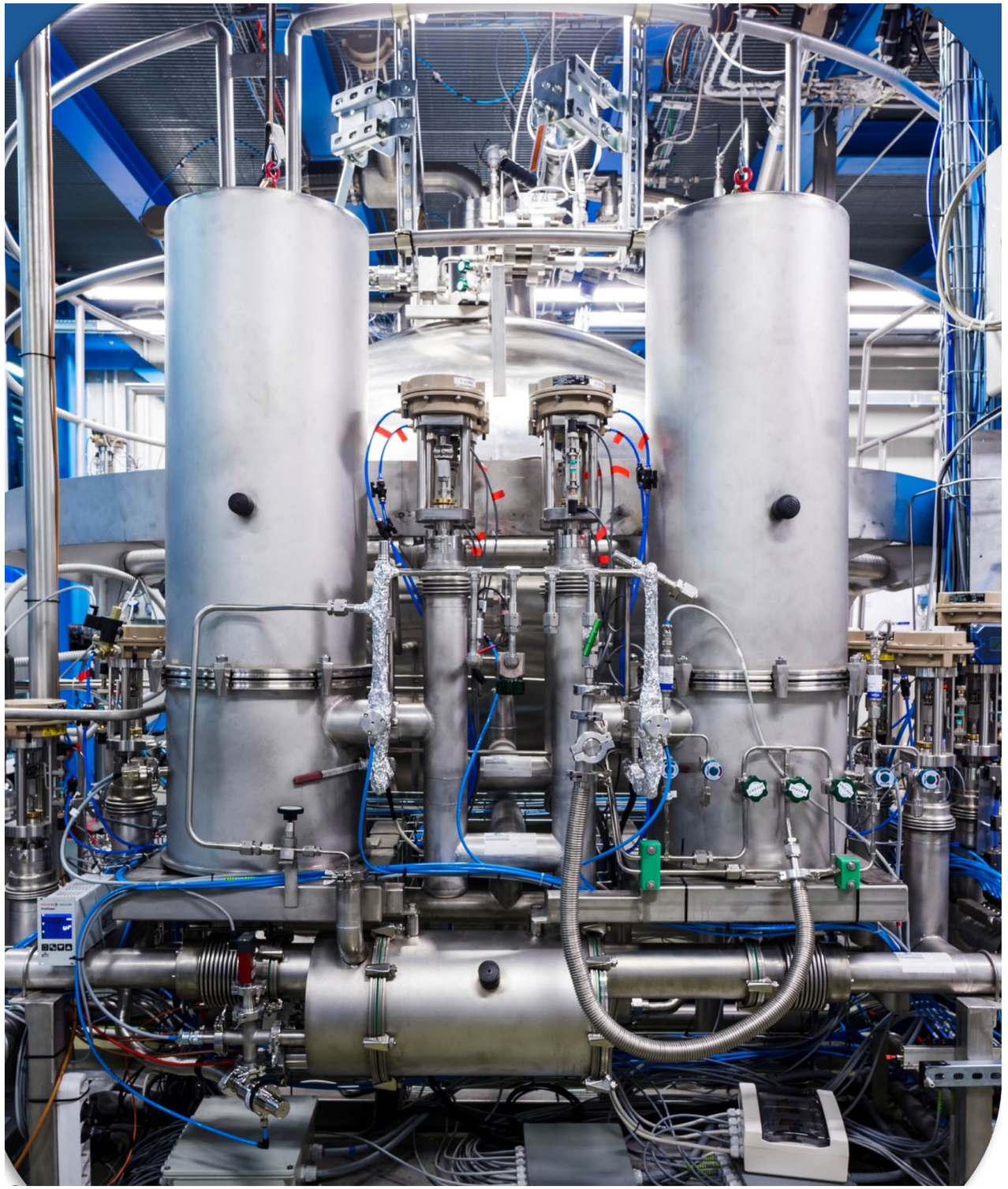
See Emanuele Angelino Talk later



New Liquid Phase Purification System

- continuously remove e-negative impurities from the LXe at a rate of 2L/min through special filters via a cryogenic liquid pump
- 18hr for entire 8.6 tonnes of LXe
- E-lifetime >15 ms in science runs



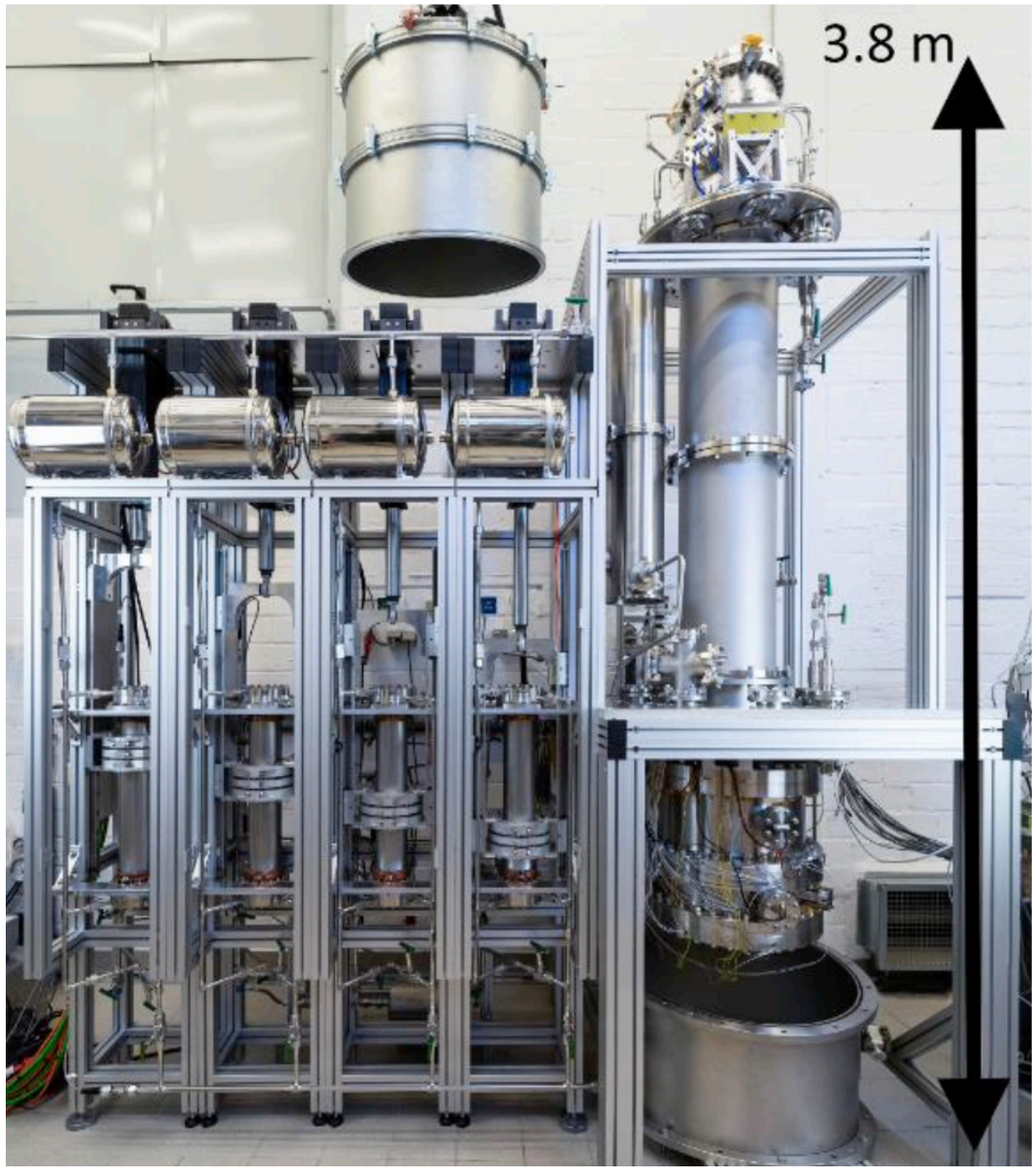


New Radon Distillation Column

- Intrinsic $^{85}\mathbf{Kr}$ and $^{222}\mathbf{Rn}(->^{214}\mathbf{Pb}$ serious ER background.

- Rn emanates from materials. Avoid and remove continuously from both the both gas and liquid xenon at high flows via cryogenic distillation.

- Dedicated column used to reduce Rn level in XENONnT to 0.8 μBq/kg.



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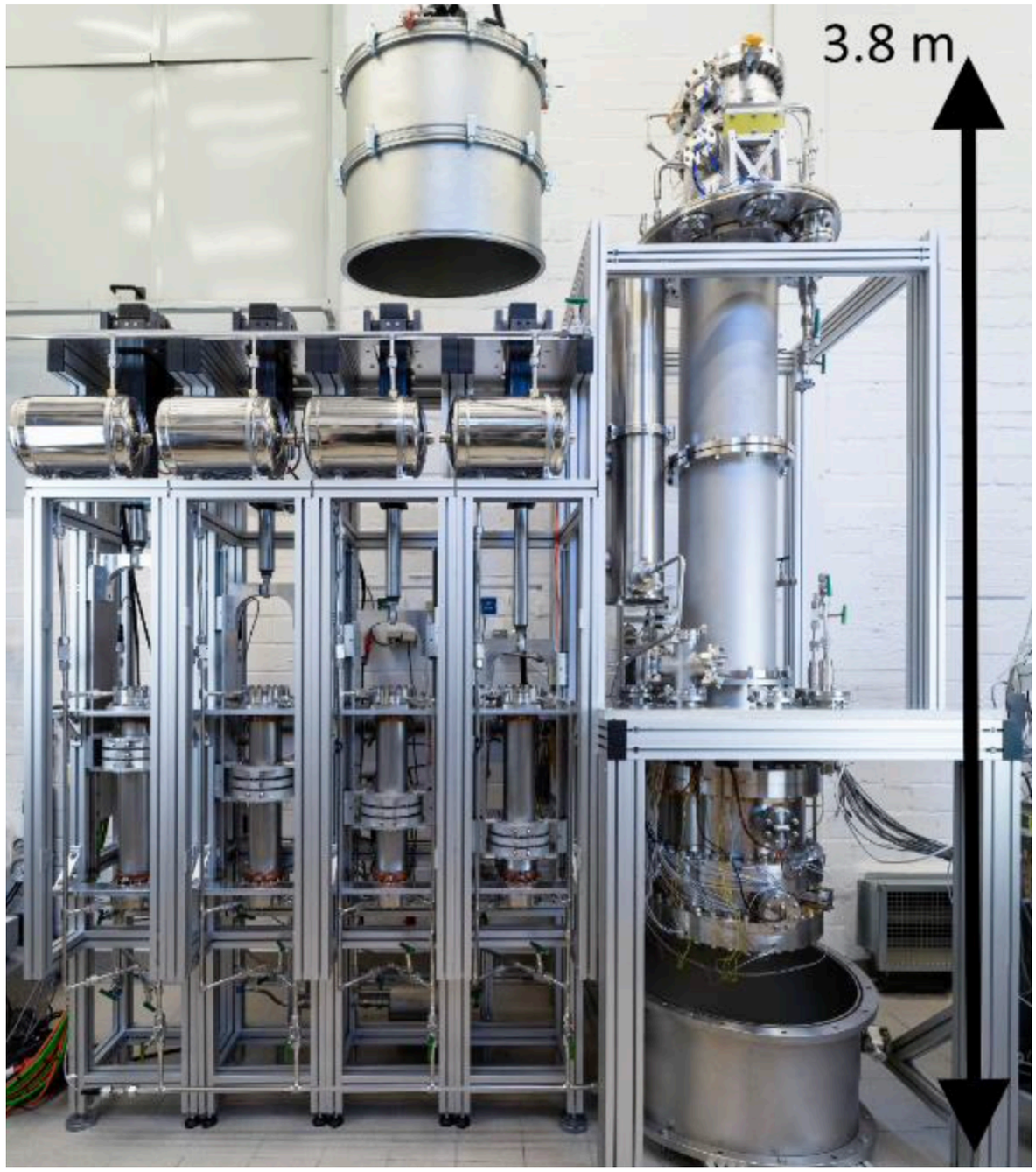
Eur. Phys. J. C 82, 1104 (2022) [2205.11492]
JINST 17 (2022) 05, P05037 [2203.01026]



XENON

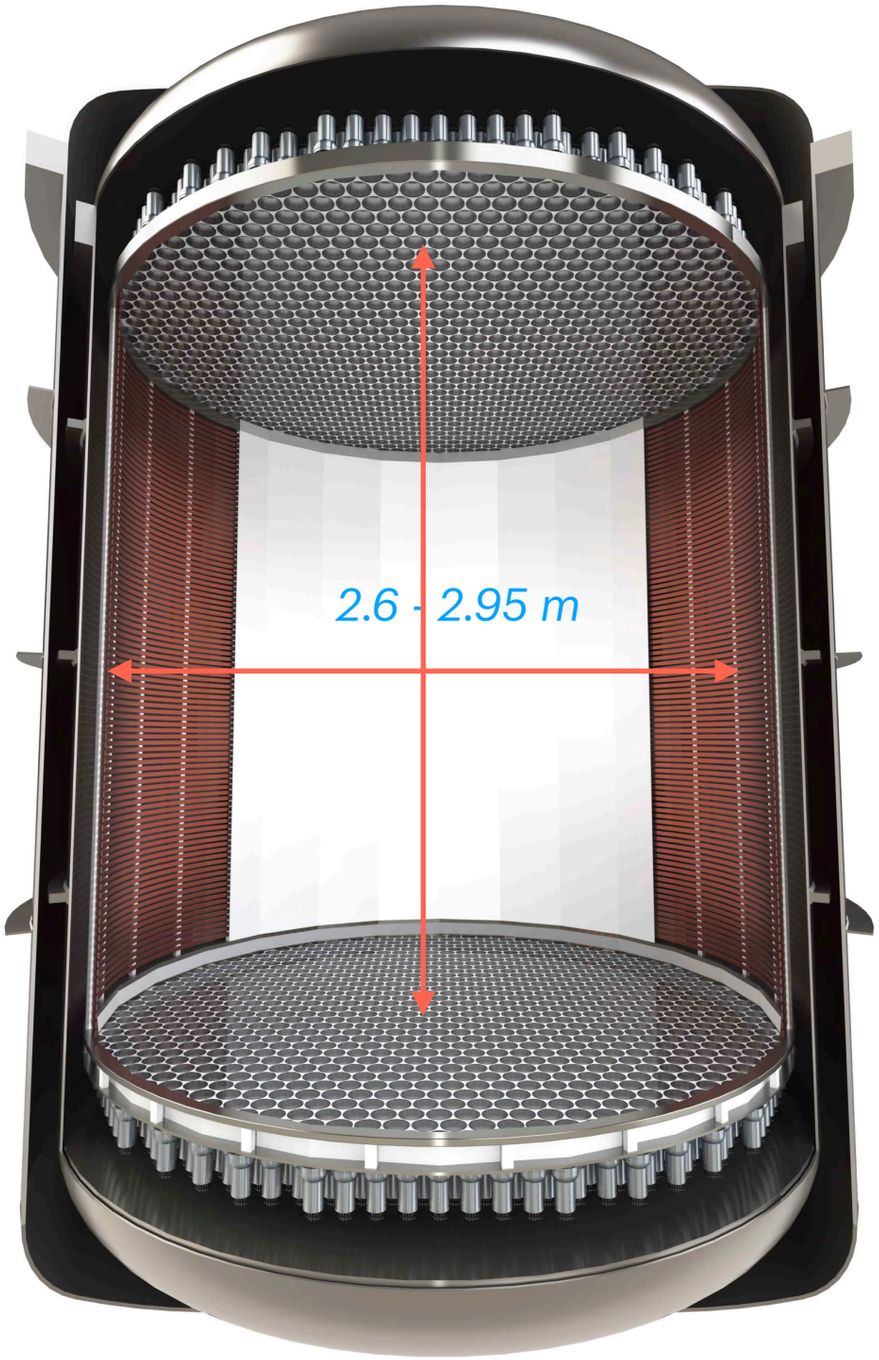
29 institutions

200 scientists

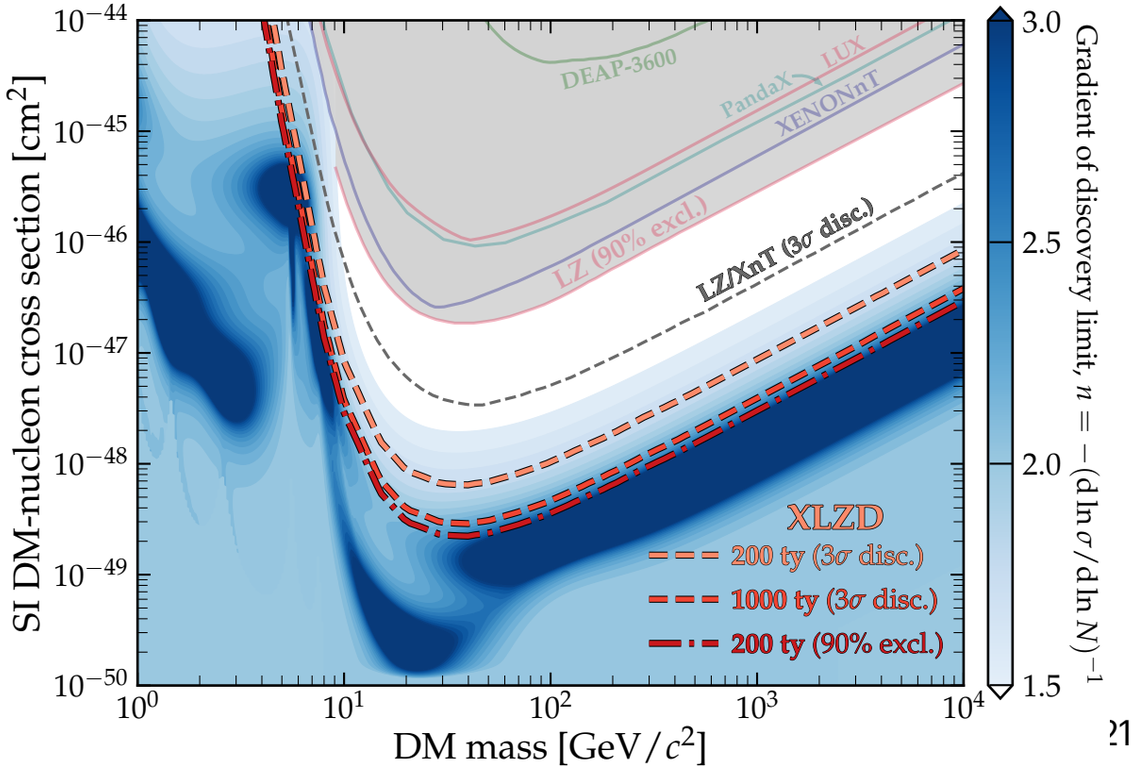
Collaboration meeting @ Paris, September 2023

BEYOND XENON: DARWIN/XLZD

- DARWIN: 50 t LXe (40 t active target in the TPC) at LNGS
- 1900 3-inch PMTs (baseline)
- Gd-doped water n and μ vetoes
- Funds for R&D and prototyping (with 3 ERCs)
- XLZD: 75 t LXe (60 t active target), several labs are considered
- Larger mass to reach sooner the neutrino fog limit (~1000 t x y)



DARWIN collaboration
JCAP 1611 (2016) 017



Increased size brings new challenges

- DARWIN/XLZD: 2.6 - 3.0 m (LZ and XENONnT: 1.5 m drift length and ~ 1.5 m diameter electrodes)
  - Electrodes design
  - HV handling and drift field
  - Xe cooling for operation over multiple years
  - Liquid level control
  - Cryogenic distillation of intrinsic radioactivities (below solar pp neutrino level)

Requirements for ^{222}Rn/Xe

- XENON1T: ~ 10 µBq/kg ~ 10^{-24}
- XENONnT: ~ 1 µBq/kg ~ 10^{-25}
- DARWIN: ~ 0.1 µBq/kg ~ 10^{-26}

Summary

- The XENON experiments with LXeTPCs of increasing target mass and decreasing background have been at the forefront of dark matter direct detection since 2007.
- The XENON1T phase saw the realization in 2017 of the first LXeTPC with multiple tons of Xe and with the lowest background of any dark matter experiment at the time.
- XENON1T demonstrated the scalability of the technology for dark matter searches paving the way for the current PandaX-4T, XENONnT and LZ scale experiments.
- The development of new enabling systems, the liquid purification and the radon removal column, was critical to achieve the further scale-up of target mass and background reduction of the XENONnT phase.
- XENONnT continues to accumulate data to explore the WIMP paradigm and beyond, and it will continue to pave the way towards DARWIN/XLZD.