Direct Detection with Xenon

Elena Aprile

Columbia University
in the City of New York

UCLA Dark Matter 2023

Los Angeles, March 29, 2023

Direct Detection with Xenon

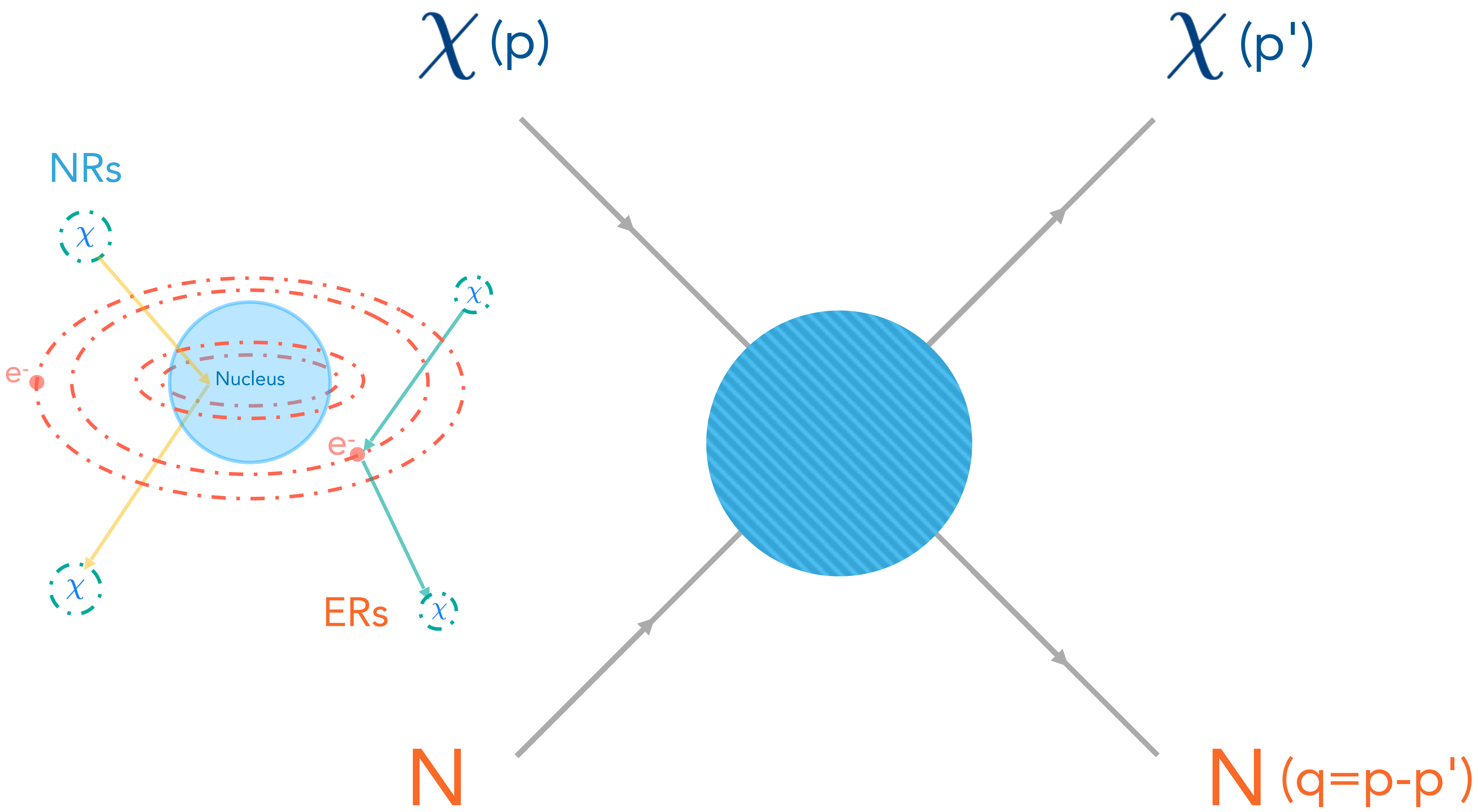
Maria Elena Monzani
Dark Matter search results from the LUX-ZEPLIN (LZ) Experiment
Friday, 03/31 7:30 am

Luca Grandi
XENONnT: a window to the Dark Universe
Friday, 03/31 7:45 am

Ning Zhou
Recent progress and plan of PandaX experiment
Friday, 03/31 9:30 am

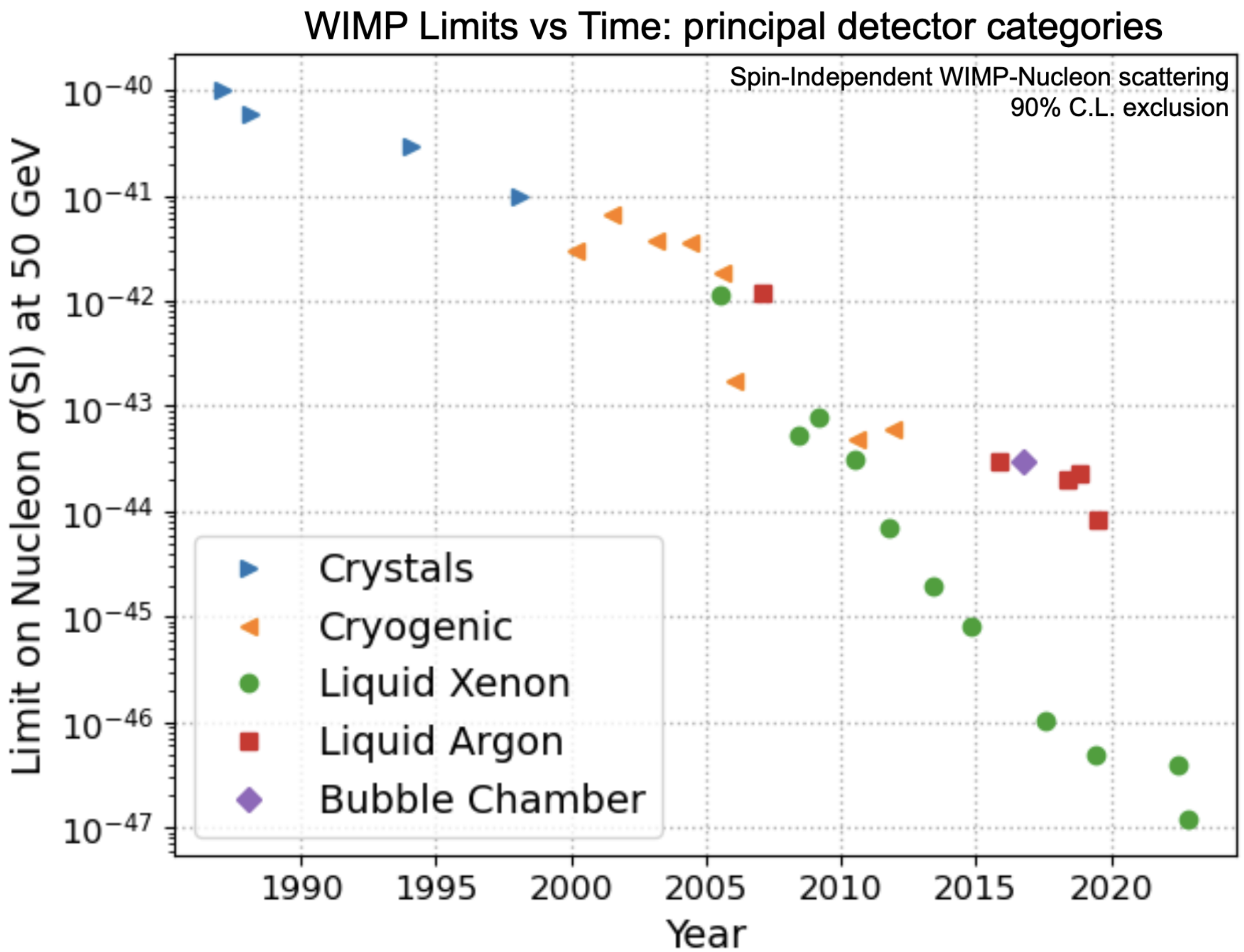
Abigail Kopec
DARWIN and the Future of Liquid Xenon Dark Matter Detectors
Friday, 03/31 9:15 am

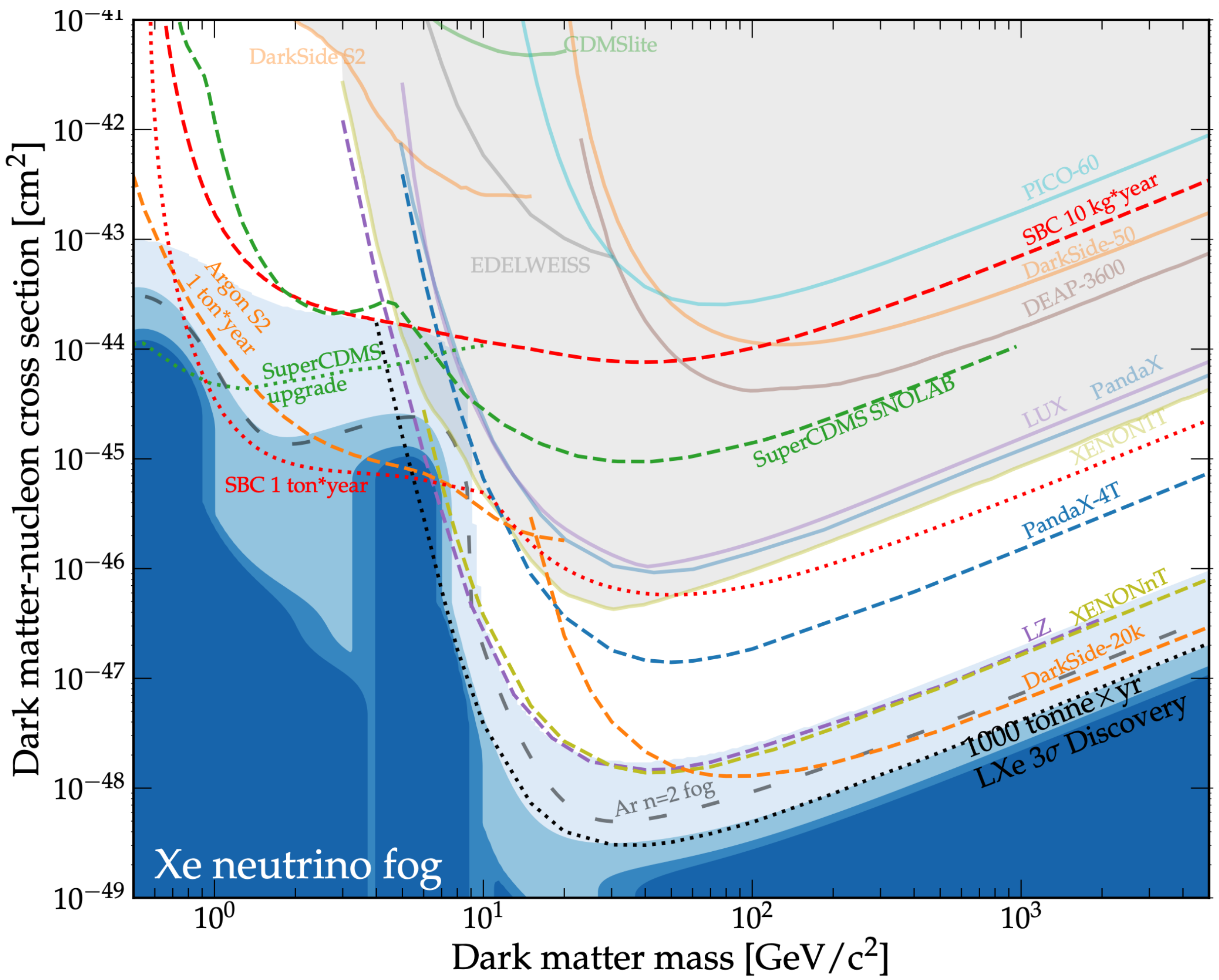
Dark Matter Direct Detection



Measure energy released in DM collisions with nuclei (NRs) or with atomic electrons (ERs)

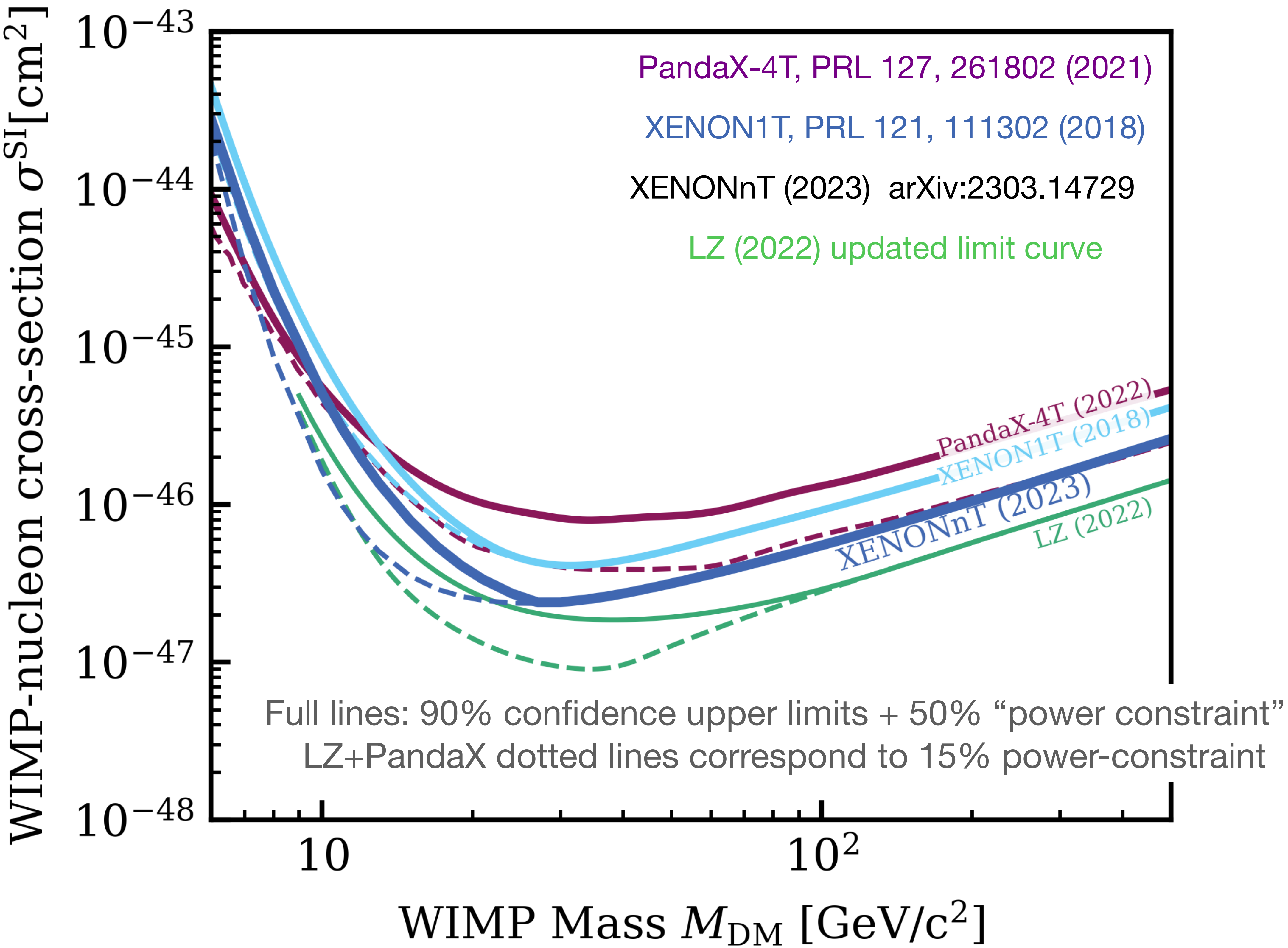
XeTPC Technology: World leading since 2007





Snowmass 2021 Whitepaper on particle dark matter
arXiv:2203.08084

State-of-the-Art



Why LXe for a Dark Matter Detector

Selected Properties of Xe

Property	Value
Atomic Number (Z)	54
Atomic Weight (A)	131.30
Number of Electrons per Energy Level	2,8,18,18,8
Density (STP)	5.894 g/L
BoilingPoint	−108.1 °C
Melting Point	−111.8 °C
Volume Ratio	519
Concentration in Air	0.0000087 % by volume

- *Z=54 and density of 3 g/cc at -100 C good for massive yet compact WIMP detector*
- *Large nucleus good for spin-independent WIMP-n interactions*
- *Presence of isotopes with spin good for spin-dependent WIMP-n interactions*
- *Highest ionization and scintillation yields among noble liquids good for radiation detection*

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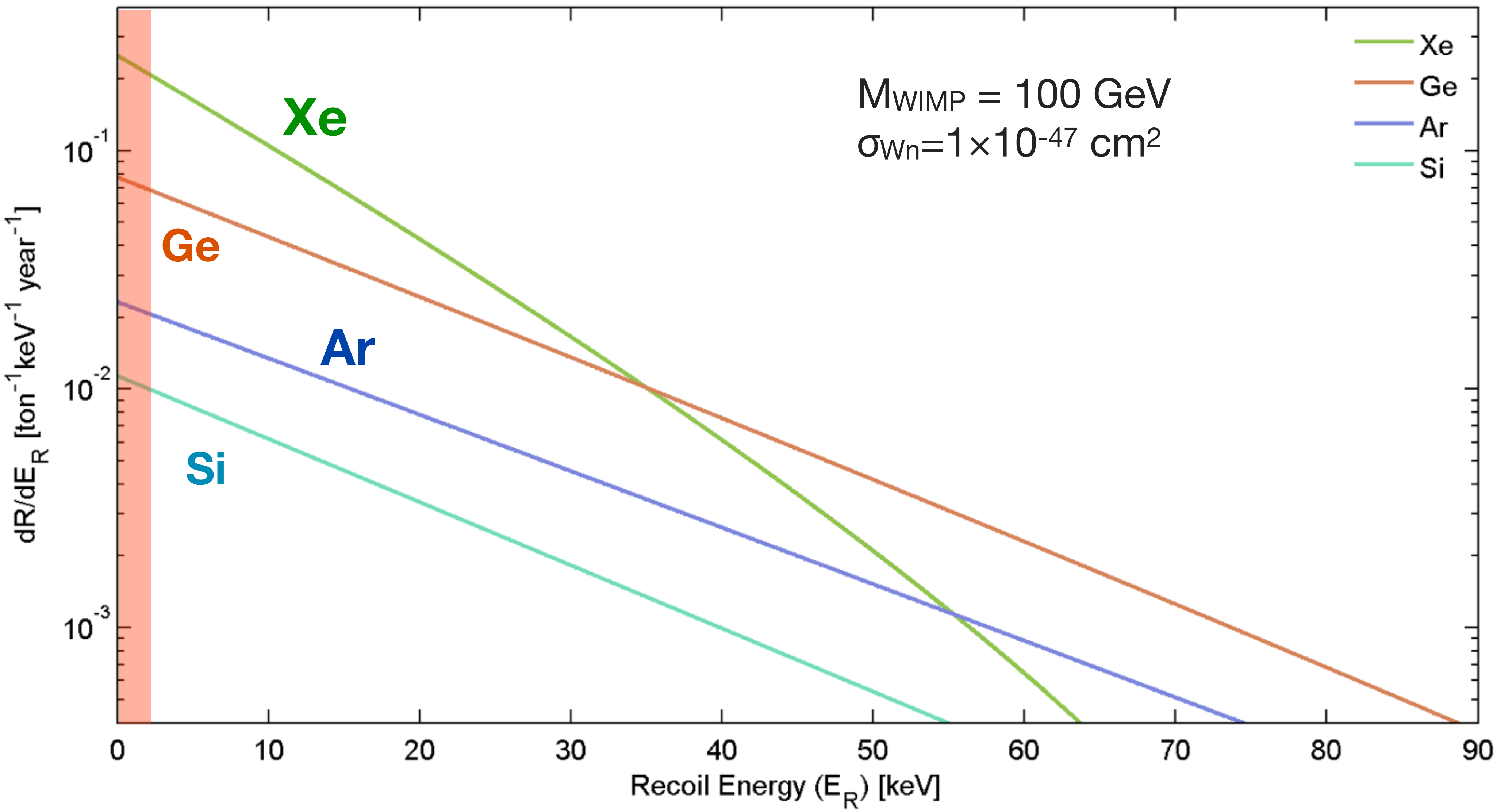

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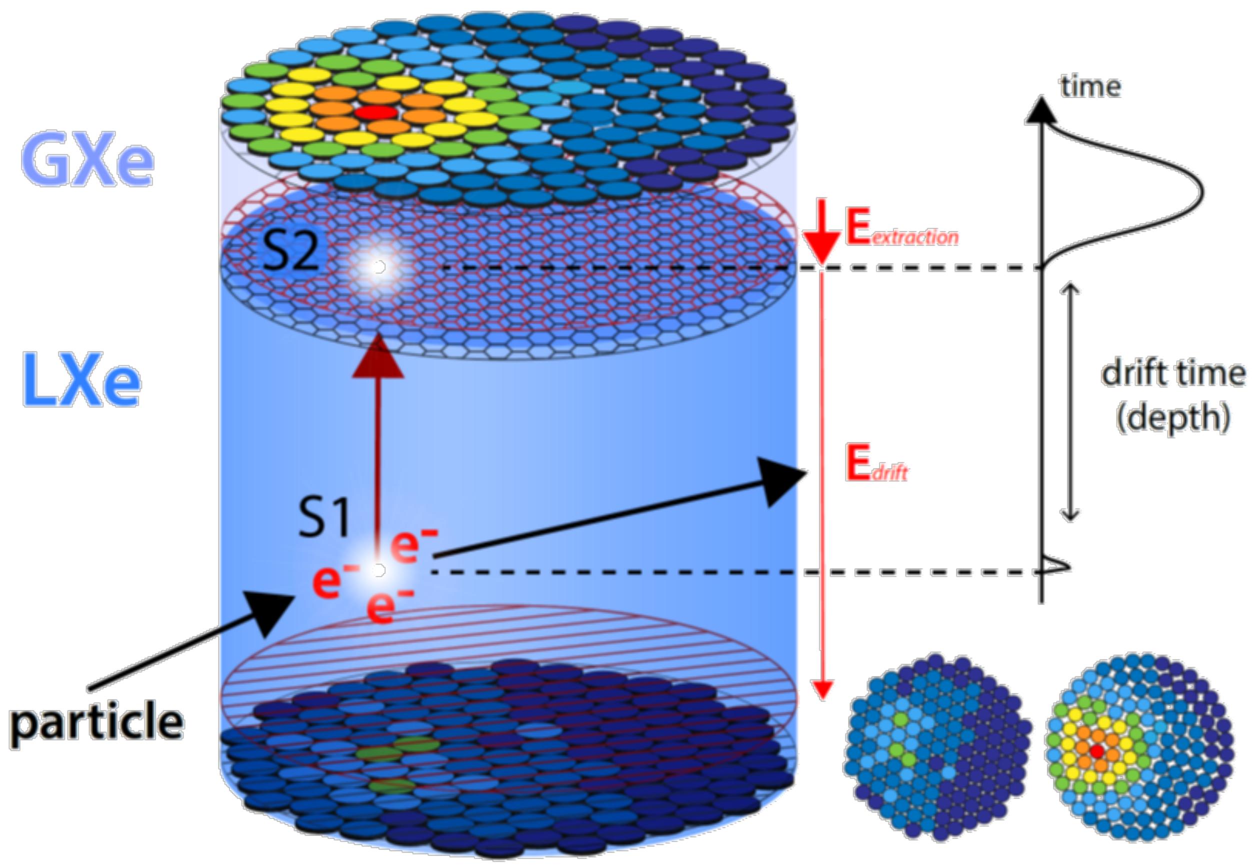
Two-Phase Xenon Time Projection Chamber



S1 light signal:

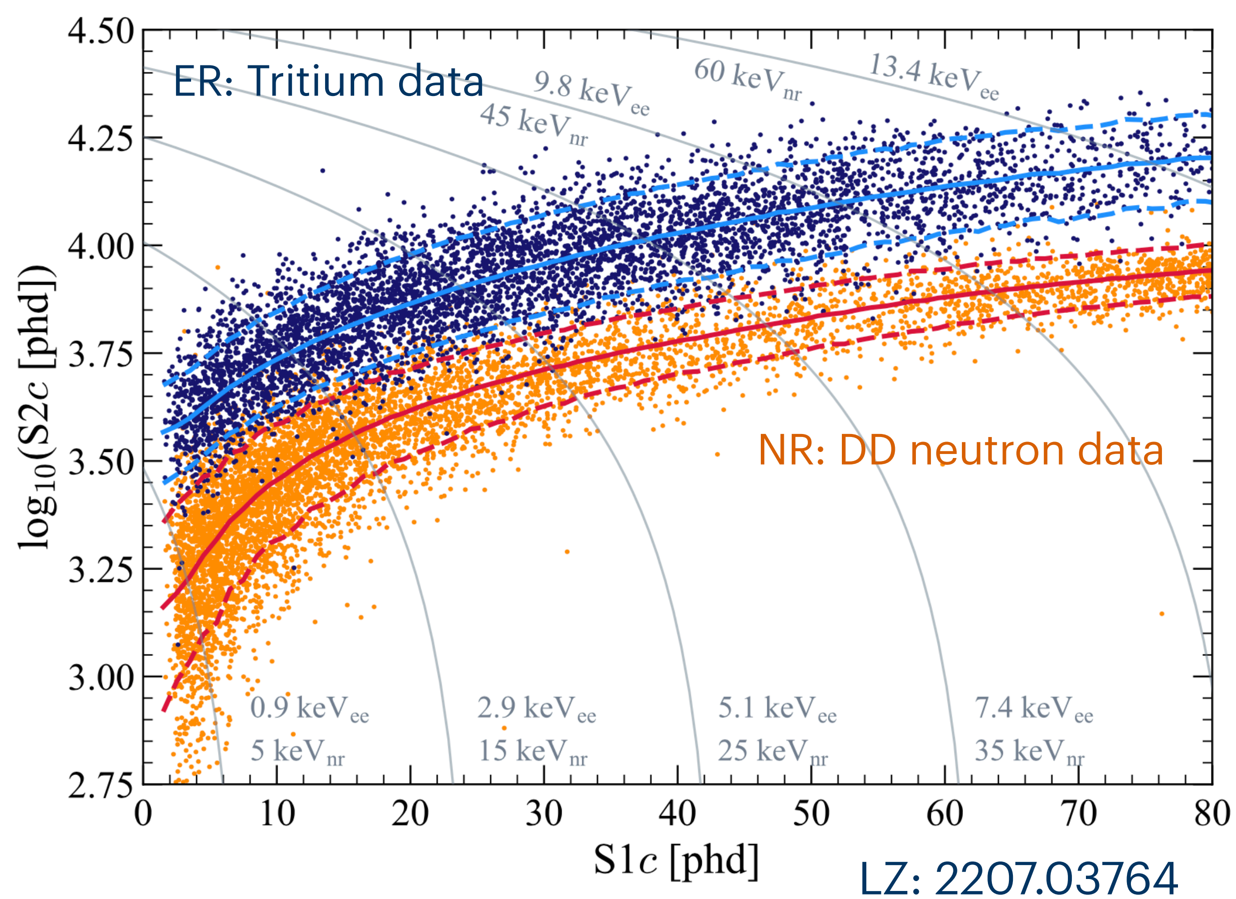
- prompt scintillation photons

S2 charge signal:

- secondary scintillation photons from electroluminescence in GXe due to drifted electrons

3D event position reconstruction:

- X,Y: S2 hit pattern
- Z: drift time S2-S1



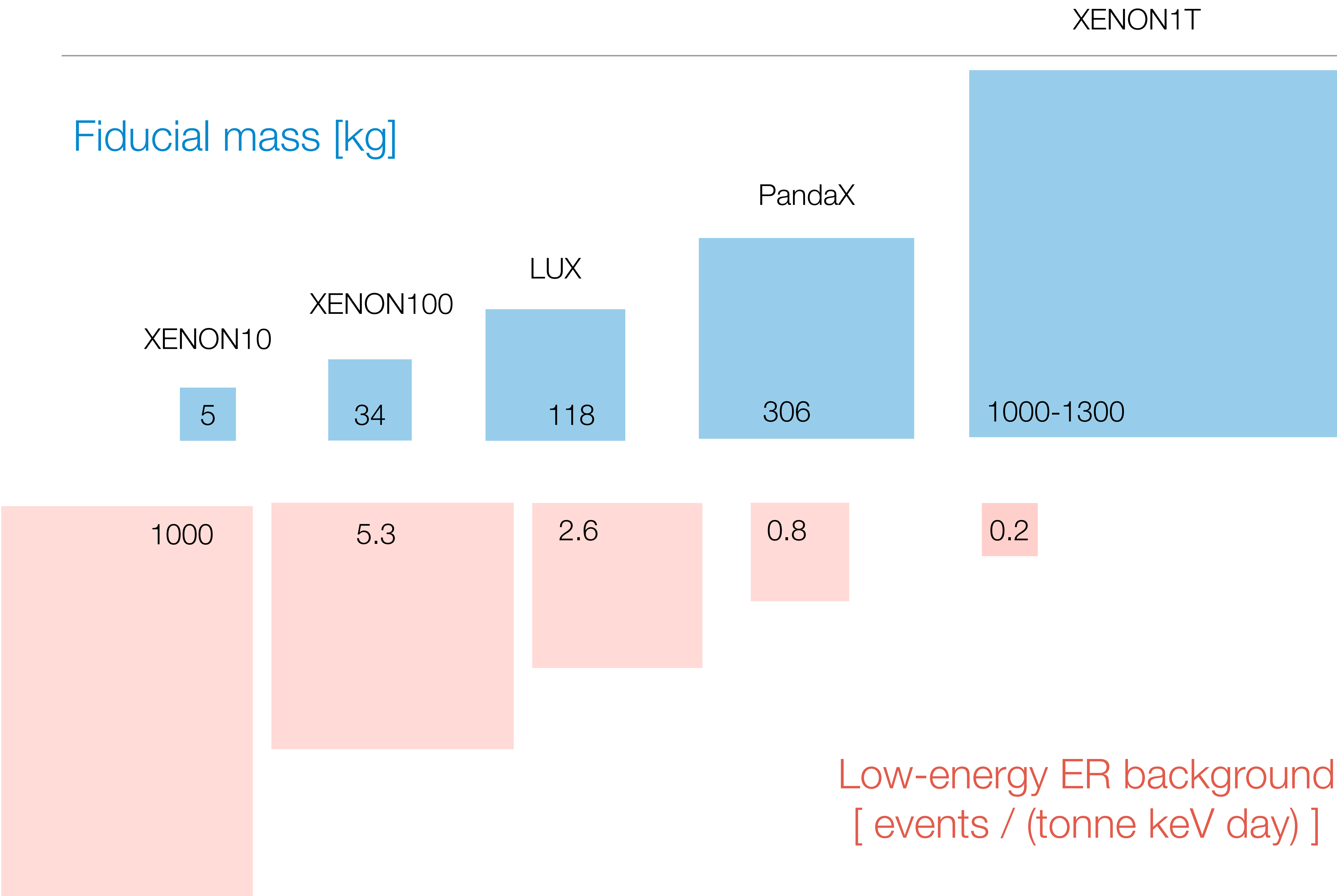
LZ: 2207.03764

NR (Nuclear Recoils)
WIMP signal, neutrons, CEvNS

ER (Electronic Recoils)
γ, β, ν backgrounds

Discrimination from S2/S1
Larger for ER than NR

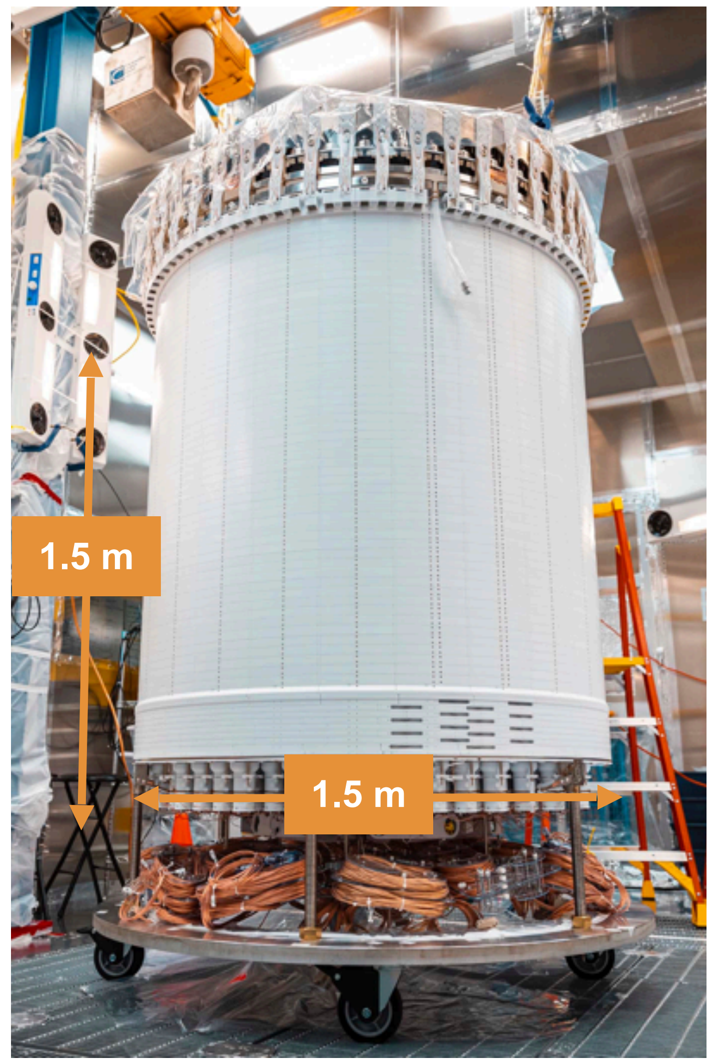
LXeTPCs as WIMP detectors from 2006 to 2018



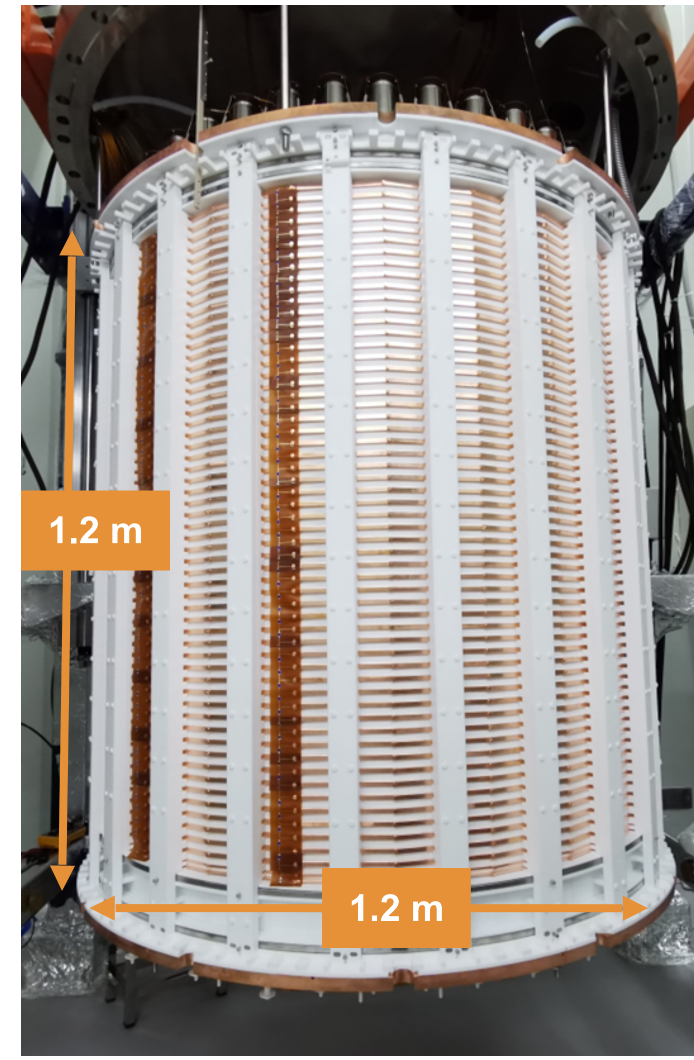
Current Two-Phase XeTPCs for WIMP Search

XENONnT@LNGS

LZ@SURF



PandaX-4T@JinPing



	XENONnT	LZ	PandaX-4T
Total (sensitive) mass	8.5 (5.9) tonnes	10 (7) tonnes	5.6 (3.7) tonnes
3-inch PMTs	494	494	368
Drift Field	23 V/cm	193 V/cm	93 V/cm

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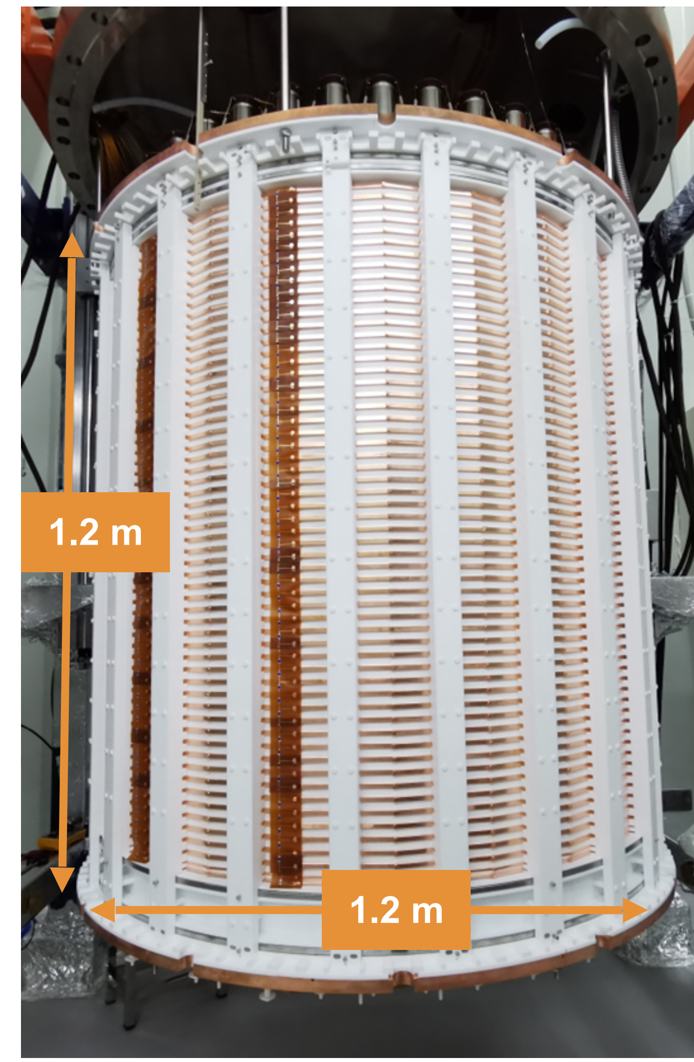

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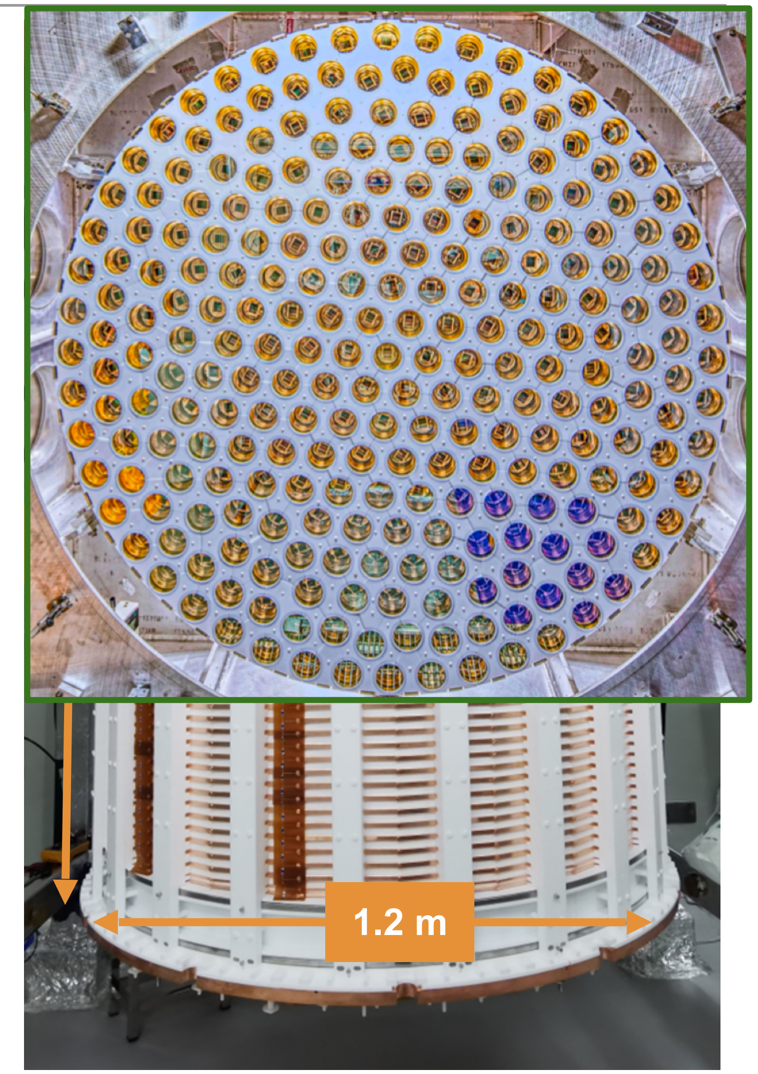

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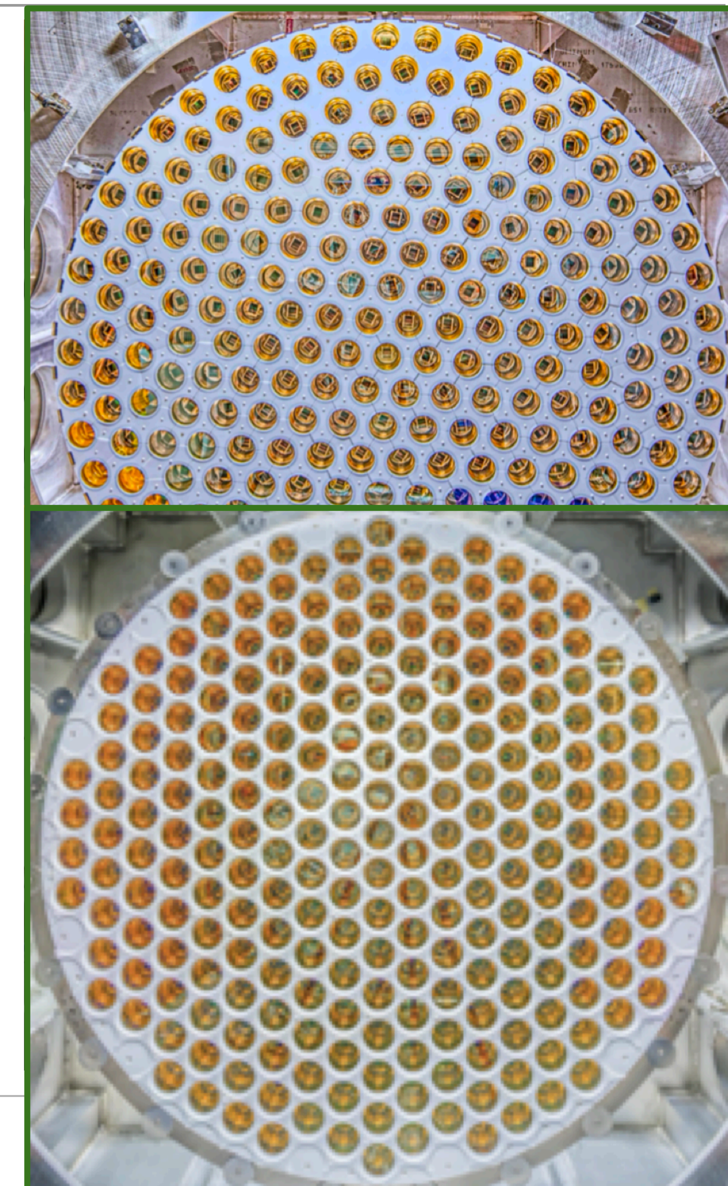

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Cryogenic System: Staying cool under pressure!

Detectors operate at about T = 178 K and p = 2 bar

➔ Keep temperature and pressure stable to sub-percent level over many years of operation.

➔ Redundancy required in case of equipment failure, maintenance periods.

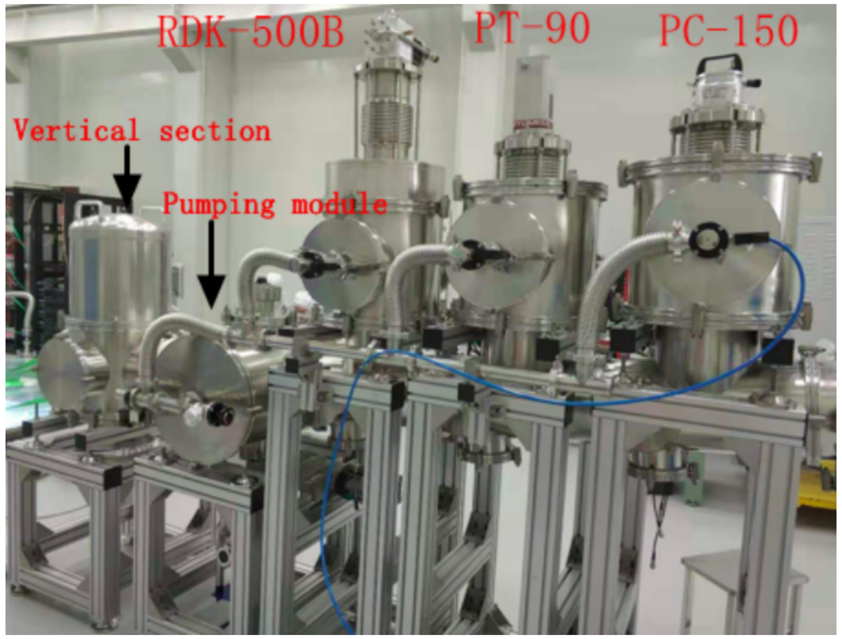
XENONnT

- System connected to cryostat by 6 m vacuum-insulated pipe.
- 2x redundant PTRs, each with 250 W
- Backup LN2 cooling power **> 600 W**

LZ

- Closed-loop N2 thermosyphons from a LN2 thermal bath to copper cold heads coupled to cryostat
- Thermal bath LN2 re-liquified by cryocooler or supplied from above ground
- Designed for **>700 W cooling**

PandaX-4T



L. Zhao *et al* 2021 *JINST* 16 T06007

- System connected to cryostat inside water tank via vacuum-insulated pipe
- 1x GM-type cooler + 2x PTRs
- Additional LN2 cooling tower
- Total cooling power **~580 W**

Cryogenic System: Staying cool under pressure!

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➔ Redundancy required in case of equipment failure, mai

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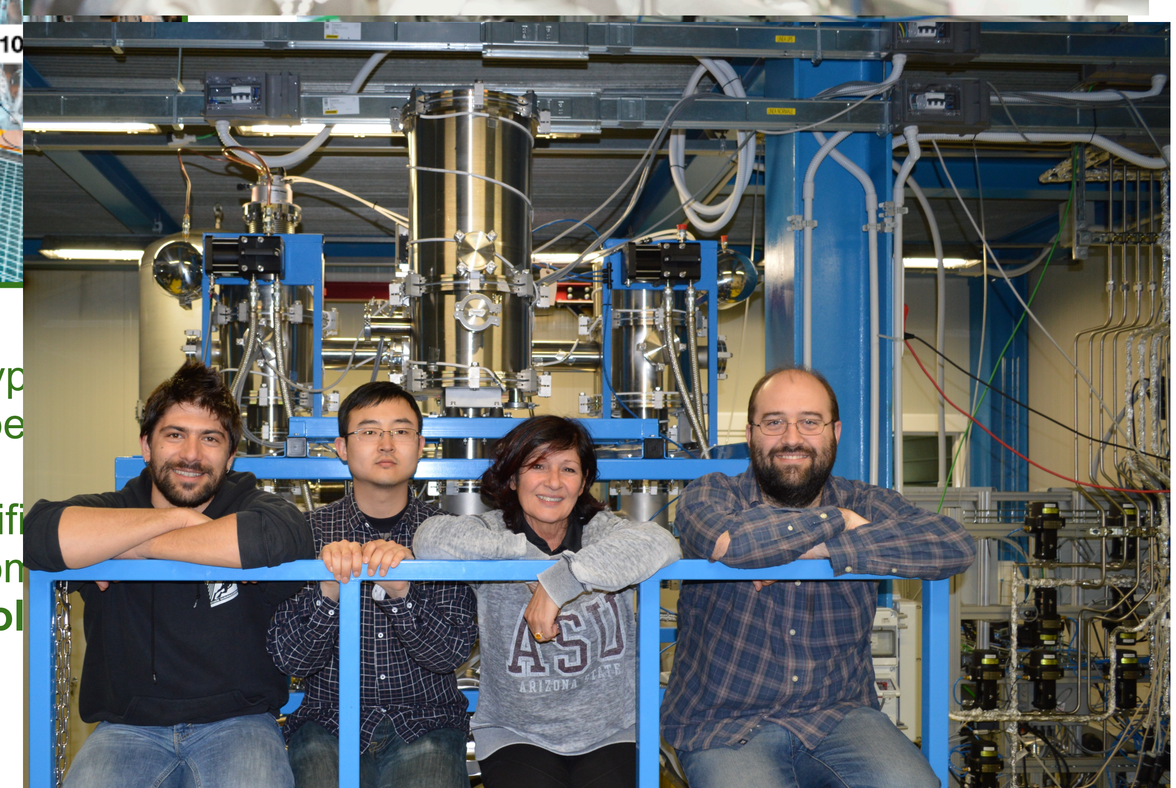

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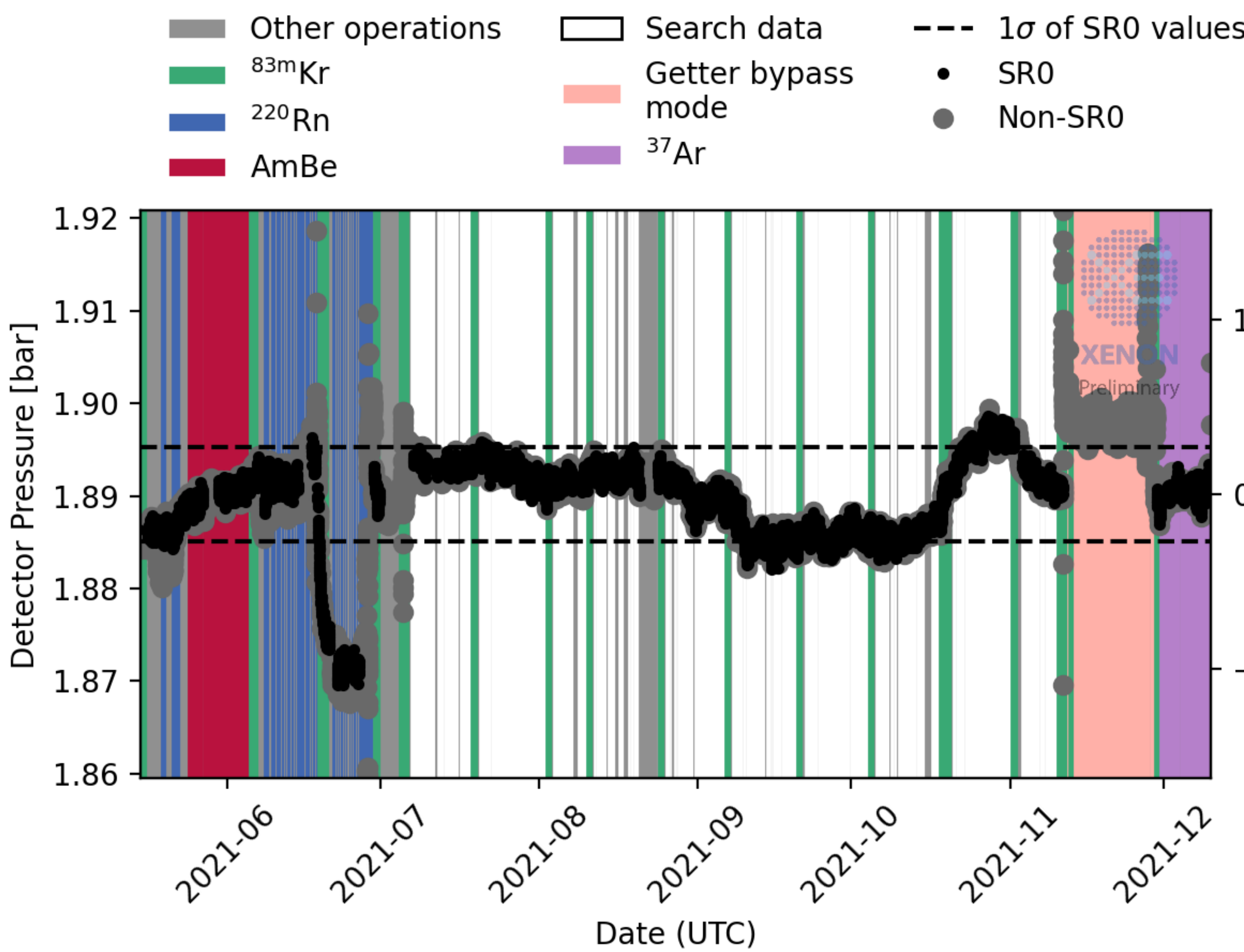
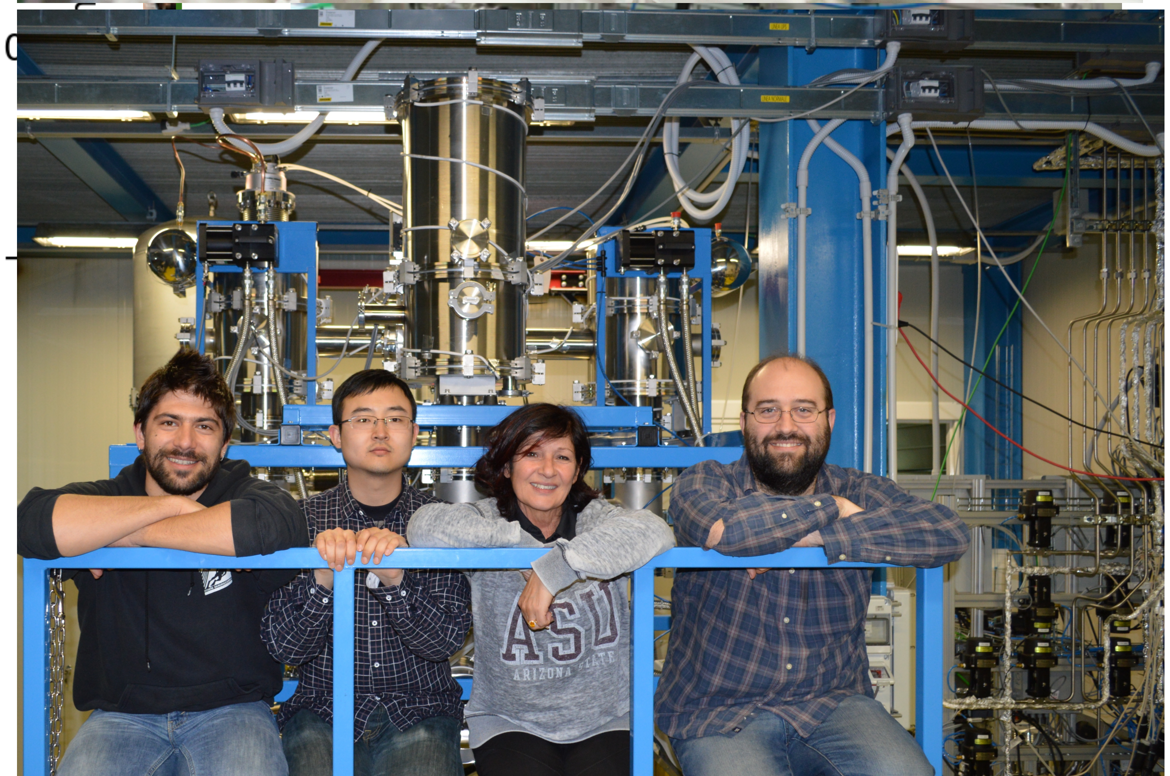


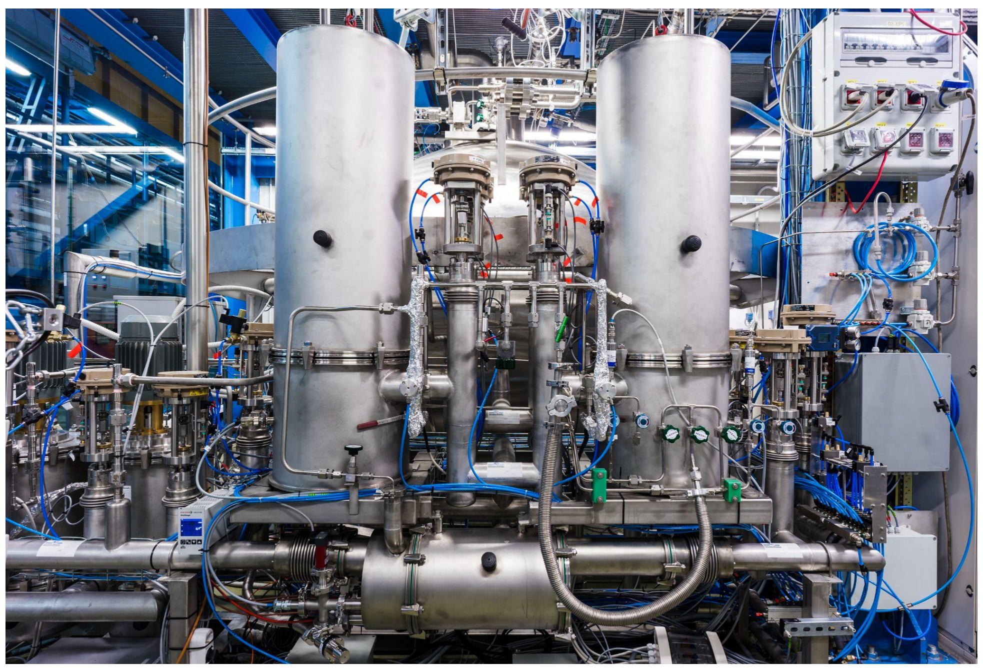


Removal of Electronegative Impurities

Electronegative impurities released in the LXe from detector components attenuate light and charge signals

➔ Continuous purification in gas and/or liquid phase is required
➔ LXe purity is expressed in terms of the attenuation of the ionization signal with drift - “Electron Lifetime”

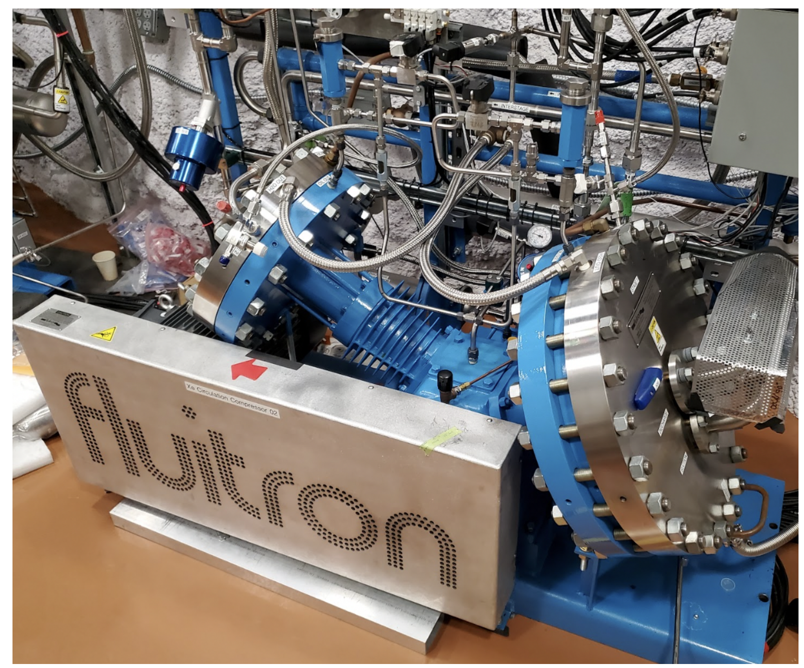
XENONnT



Liquid-phase purification

- Extraction and return directly in liquid-phase
- 2x redundant cryogenic liquid pumps
- Inline purity monitor for real time monitoring (and independently of TPC data)
- Custom LXe purifiers
  - getter pills composed of Zr, V and Fe
  - Q5 Copper-impregnated spheres
- 1000 slpm (8.4 t/d) with one pump
- **> 10 ms electron lifetime**

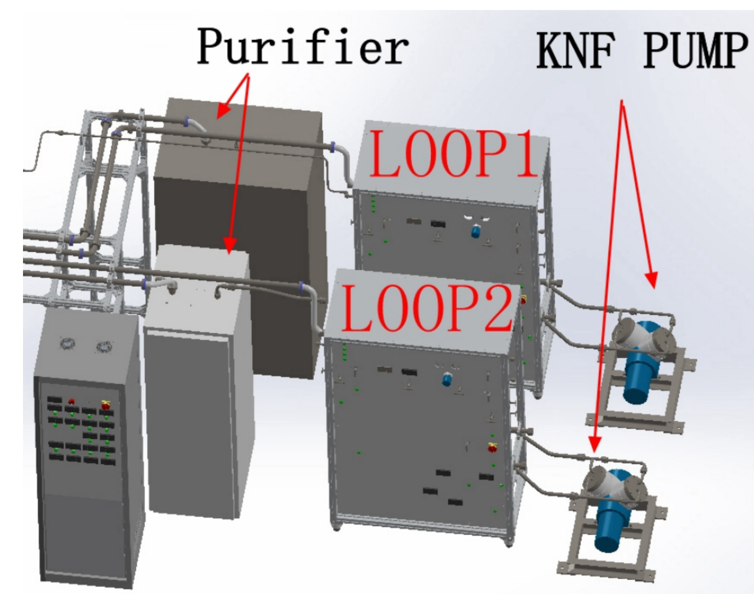
LZ



Gas-phase purification

- Evaporation and condensation via heat exchangers
- 2x Fluitron gas circulation compressors
- Hot SAES getter
- 330 slpm (2.9 t/d) with one pump
- **~5-8 ms electron lifetimes**

PandaX-4T



L. Zhao *et al* 2021 JINST 16 T06007

Gas-phase purification

- Evaporation and condensation via heat exchangers
- 2x double-headed diaphragm pump by KNF
- 1x hot SAES getter, 1x hot Simpure getter
- 155 slpm (1.4 t/d)
- **0.8-1.3 ms electron lifetimes**

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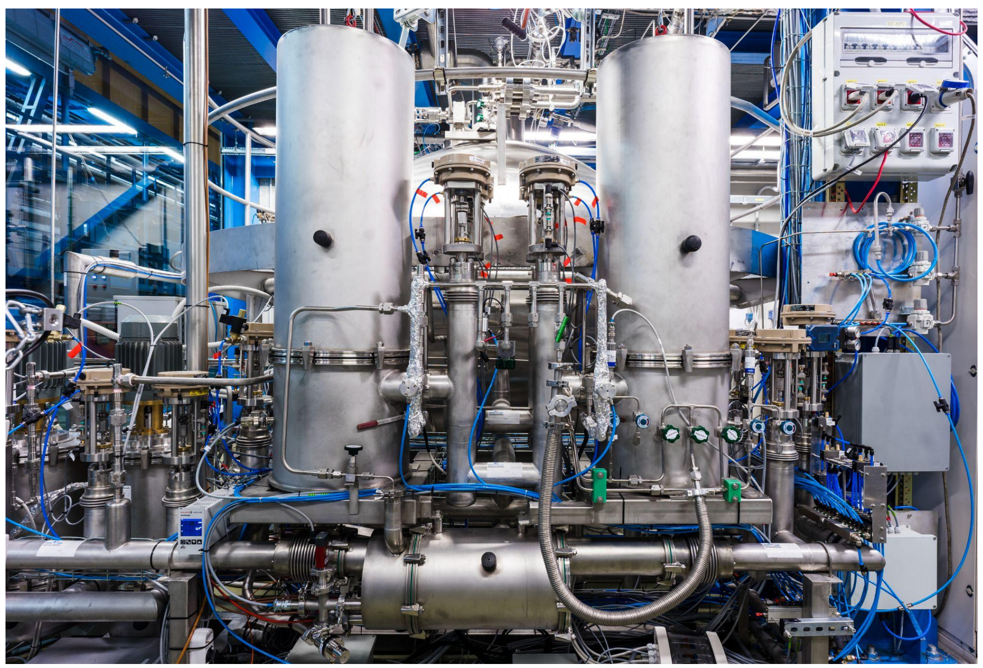

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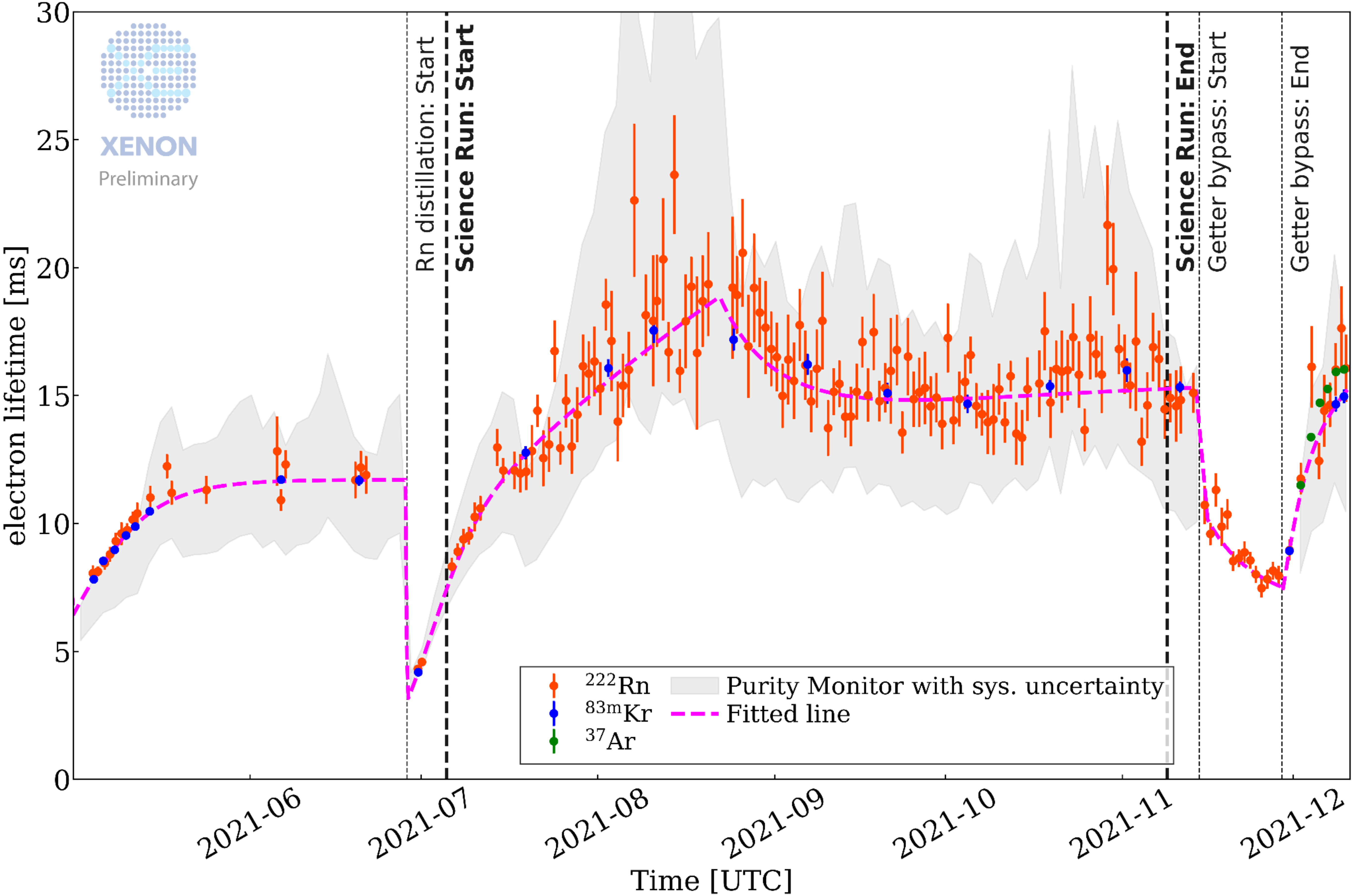
- **0.8-1.3 ms electron lifetimes**



XENON
Preliminary
Rn distillation: Start
Science Run: Start
Science Run: End
Getter bypass: Start
Getter bypass: End
^{222}Rn
^{83m}Kr
^{37}Ar
Purity Monitor with sys. uncertainty
Fitted line
electron lifetime [ms]
Time [UTC]
0
5
10
15
20
25
30
2021-06
2021-07
2021-08
2021-09
2021-10
2021-11
2021-12

Removal of Intrinsic Radioactive Contaminants: Kr-85

Intrinsic noble gas contaminants Kr-85 and Rn-222 (Pb-214) inside the xenon

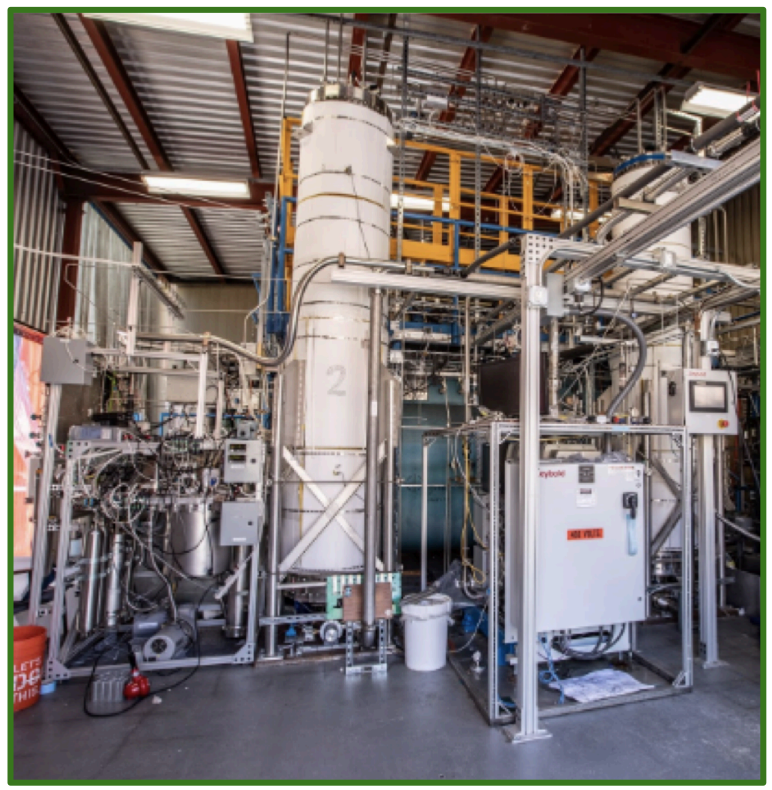
- ➔ electronic recoil events from the low energy β-spectrum of these radioactivities contaminate ROI for dark matter WIMP search
- ➔ searches for new physics using electronic recoil signals becomes possible when these radioactivities are drastically reduced
- ➔ Kr-85 originates from xenon extraction from air and needs to be **removed once** before the dark matter search to Kr-nat/Xe < 0.2 ppt
- ➔ commercial xenon comes with Kr-nat/Xe > 1 ppb with Kr-85 / Kr-nat ~ 2 x 10^{-11}

XENONnT

Cryogenic Distillation "online" at LNGS

- Initial Kr removal during filling
- Online removal by distilling the GXe inside the cryostat
- Online mode also removes radioactive Ar-37
- **Kr/Xe < 0.05 ppt**

LZ



Gas charcoal chromatography "offline" at SLAC

- Xe then shipped to SURF
- Handle Xe of varying initial Kr contamination - multiple passes if necessary
- Kr/Xe = 0.14 ppt

PandaX-4T

X. Cui *et al* 2021 *JINST* 16 P07046

Cryogenic Distillation "online" at CJPL

- Initial Kr removal during filling
- Online removal by distilling the GXe inside the cryostat
- Online mode also removes radioactive Ar-37
- **Kr/Xe = 0.33 ppt**

Removal of Intrinsic Radioactive Contaminants: Rn-222

Intrinsic noble gas contaminants Kr-85 and Rn-222 (Pb-214) inside the xenon

➔ electronic recoil events from the low energy β-spectrum of these radioactivities contaminate ROI for dark matter WIMP search
➔ searches for new physics using electronic recoil signals becomes possible when these radioactivities are drastically reduced
➔ Rn-222 emanates from detector materials and needs to be **avoided or removed continuously**
➔ Material screening and selection to avoid Rn-222 in the first place
➔ Main background in XENON1T, LUX and PandaX at Rn-222/Xe ~ 10μBq/kg - challenge for current experiments to reach 1μBq/kg
➔ Challenge met with continuous Rn removal by cryogenic distillation (XENONnT and PandaX) or by gas chromatography (LZ)

XENONnT

Cryogenic Distillation done “online” at XENONnT

- High-flow distillation column with LXe and GXe in- and outlets
- 200 slpm (1.8 t/d) LXe-phase mode and 25 slpm (0.2 t/d) GXe-phase mode
- **Rn-222/Xe = 1.8 μBq/kg (GXe-only mode)**
- **Rn-222/Xe = 0.8 μBq/kg (GXe+LXe mode)**

LZ

J. Aalbers et al, arXiv:2211.17120, 2022

Gas chromatography done “online” at LZ

- 0.5 slpm from gas conduits run to 10 kg cold synthetic charcoal
- keep Rn in charcoal for >3 half-lives
- Ongoing R&D to further suppress Rn
- **Rn-222/Xe = 4.6 μBq/kg**

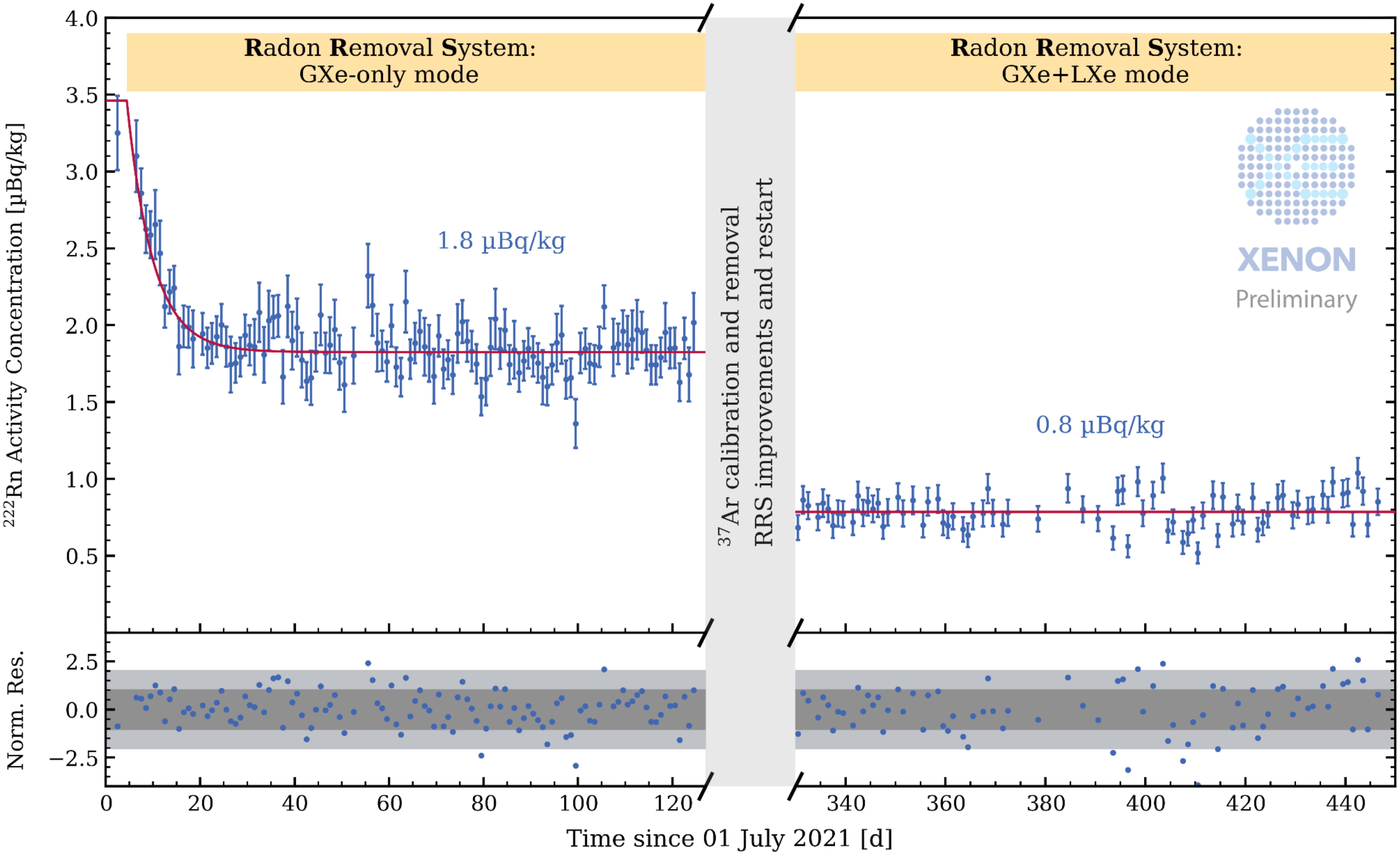
PandaX-4T

X. Cui *et al* 2021 JINST 16 P07046

Cryogenic Distillation done “online” at PandaX-4T

- Same as Kr removal system, but in reverse mode
- GXe in- and outlets
- 160 slpm (1.4 t/d)
- **Rn-222/Xe = 4.2 μBq/kg**

Removal of Intrinsic Radioactive Contaminants: Rn-222



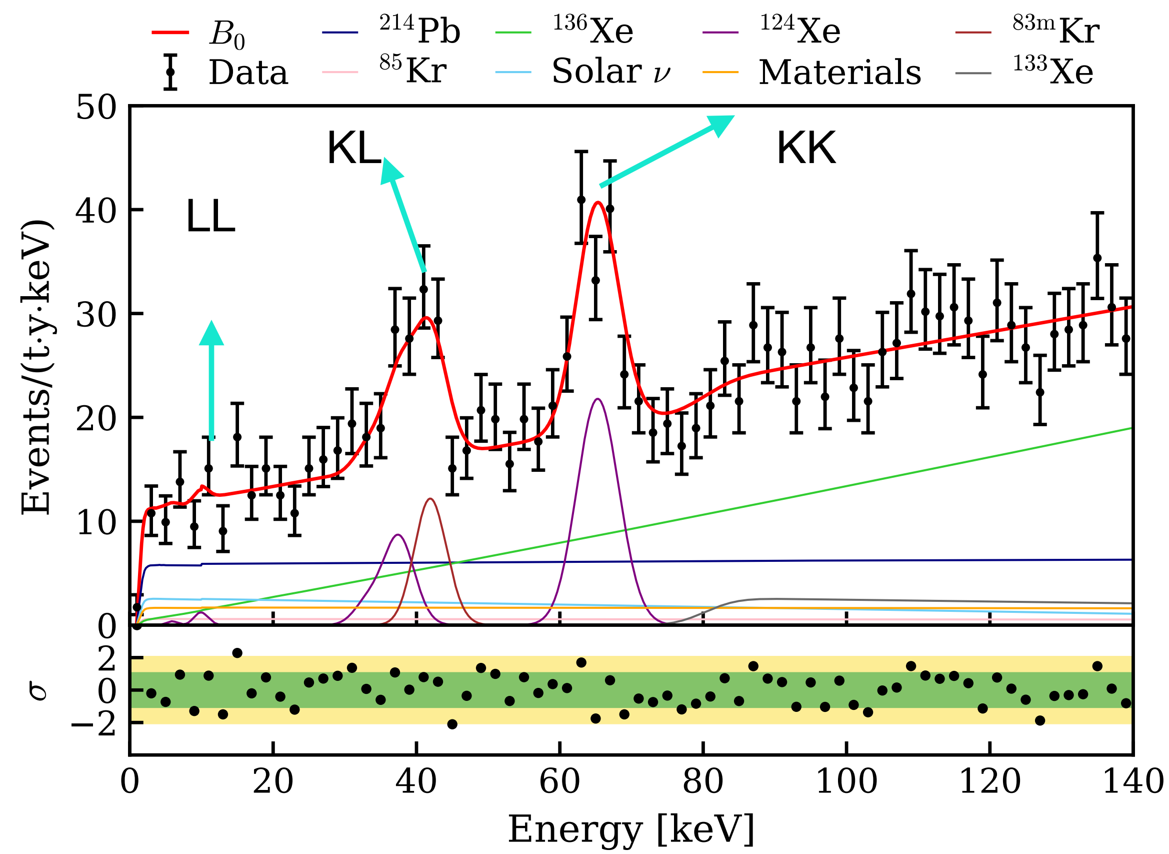
Electronic Recoil Background in XENONnT

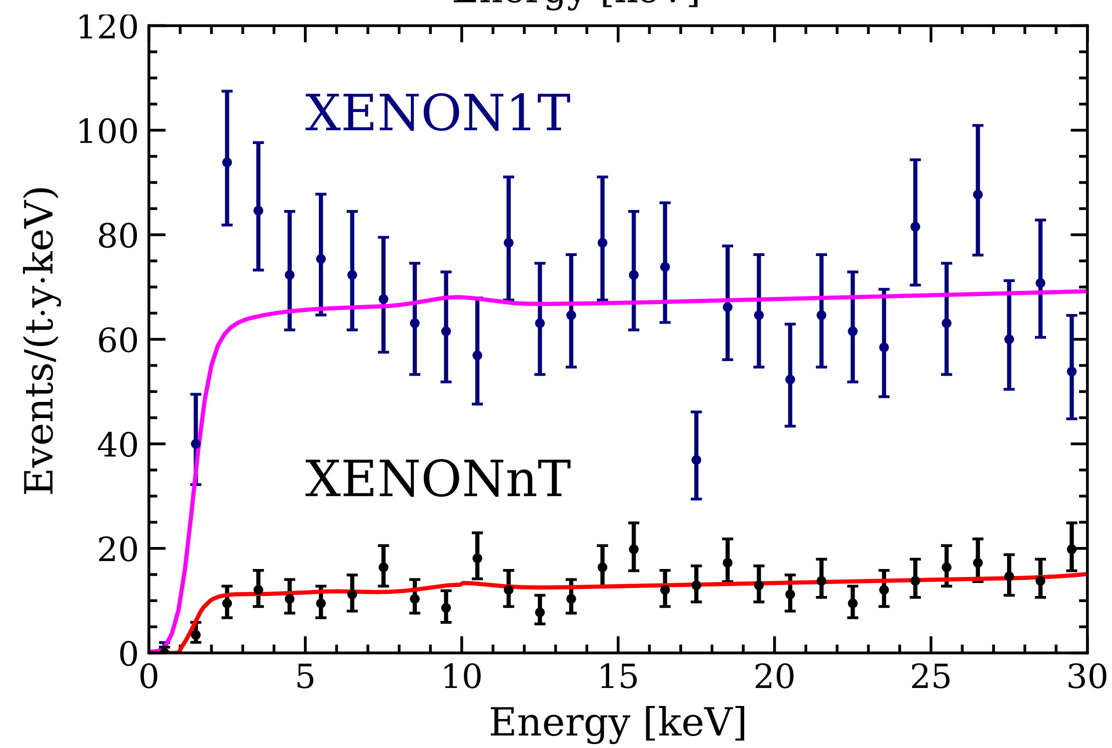
Lowest background achieved in a DM detector

- Spectral shape dominated by two double-weak decays: ^{136}Xe $2\nu\beta\beta$, ^{124}Xe 2νECEC
- Total ER background below 30 keV: 16 events/(t y keV) dominated by Pb214
- Solar neutrinos: second largest background below 10 keV
- No excess observed in XENONnT

	(1, 10) keV	(1, 140) keV
^{214}Pb	56 ± 7	980 ± 120
^{85}Kr	6 ± 4	90 ± 60
Materials	16 ± 3	270 ± 50
^{136}Xe	8.7 ± 0.3	1520 ± 50
Solar ν	25 ± 2	300 ± 30
^{124}Xe	2.6 ± 0.3	260 ± 30
AC	0.70 ± 0.03	0.71 ± 0.03
^{133}Xe	-	160 ± 60
^{83m}Kr	-	80 ± 16

XENON collaboration, PRL 129, 2022





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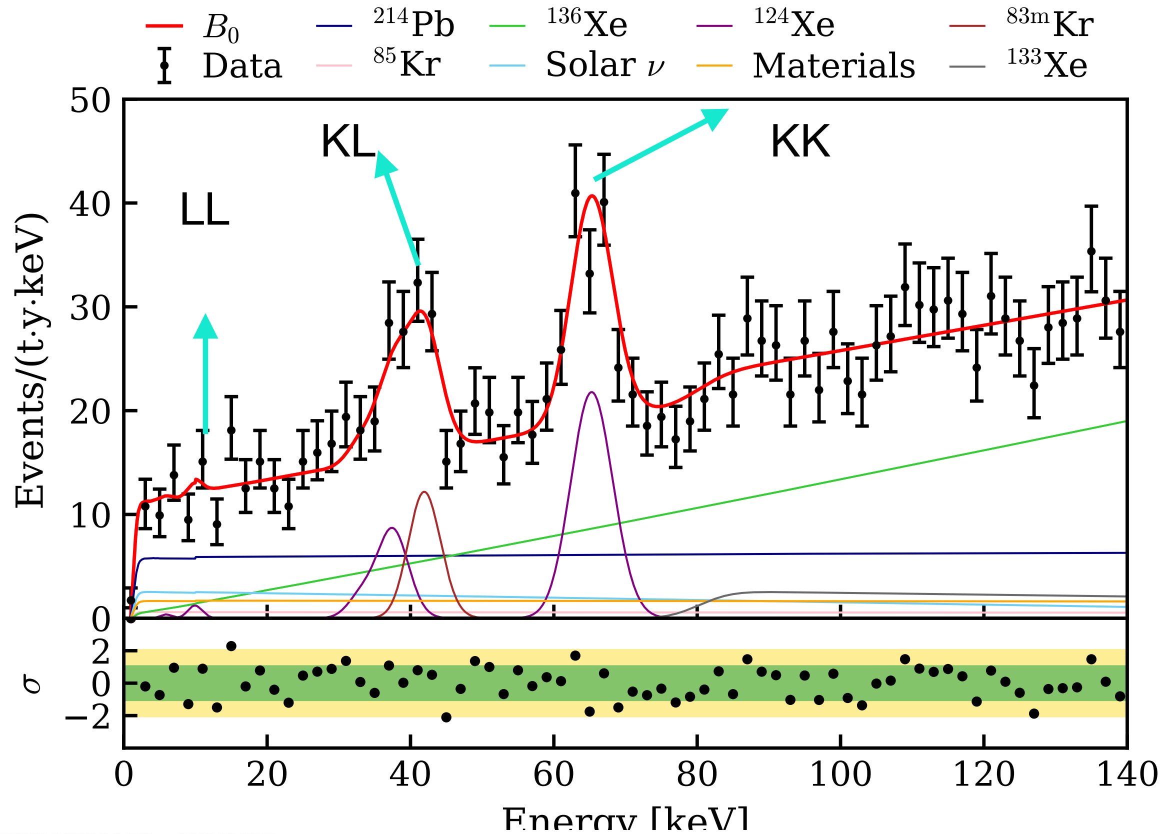
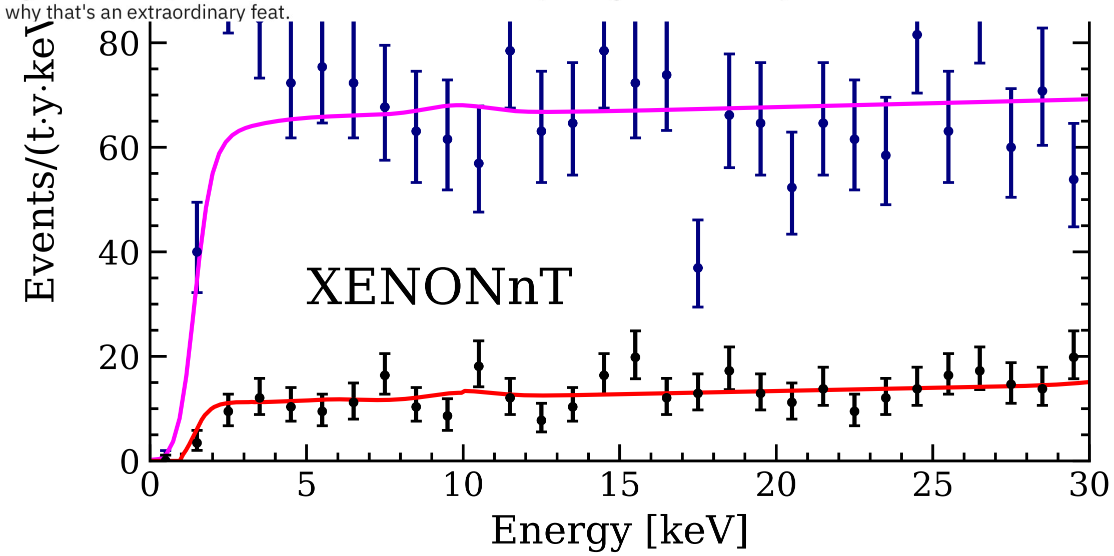


STARTS WITH A BANG — JULY 27, 2022

XENON's experimental triumph: No dark matter, but the best "null result" in history

Searching for dark matter, the XENON collaboration found absolutely nothing out of the ordinary. Here's why that's an extraordinary feat.



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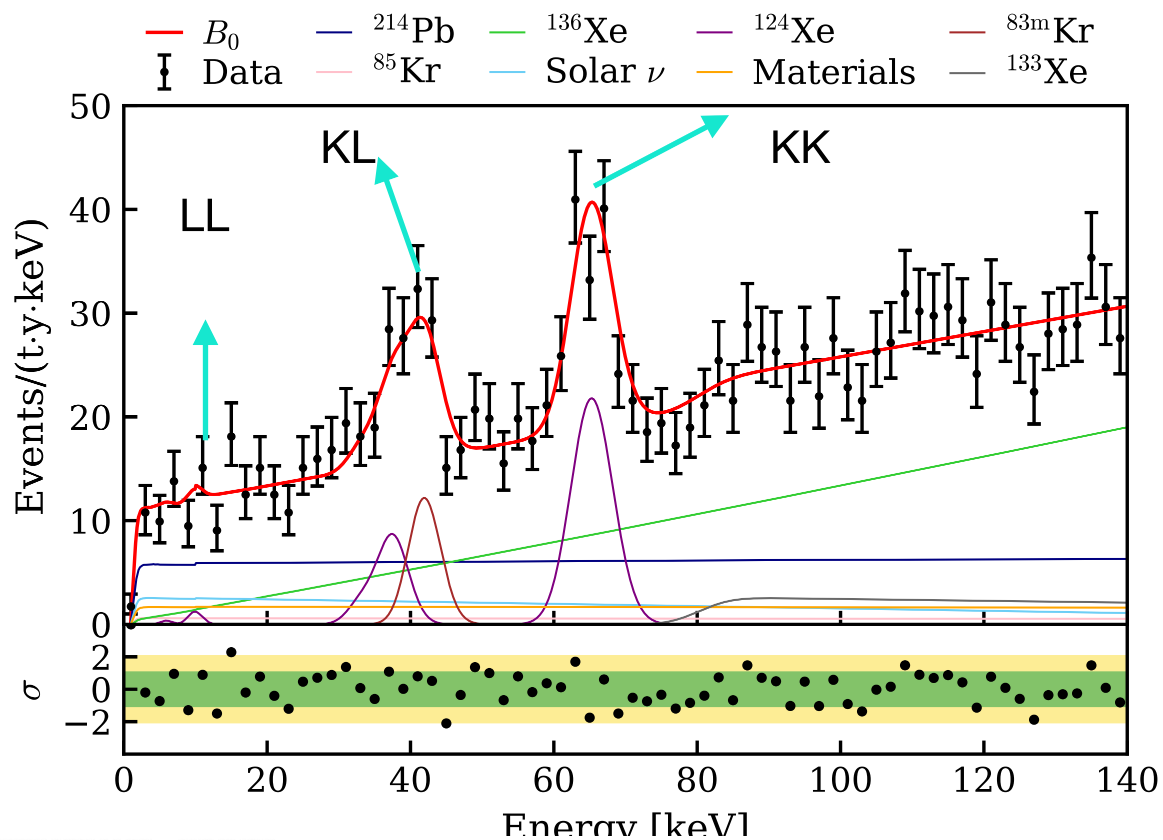
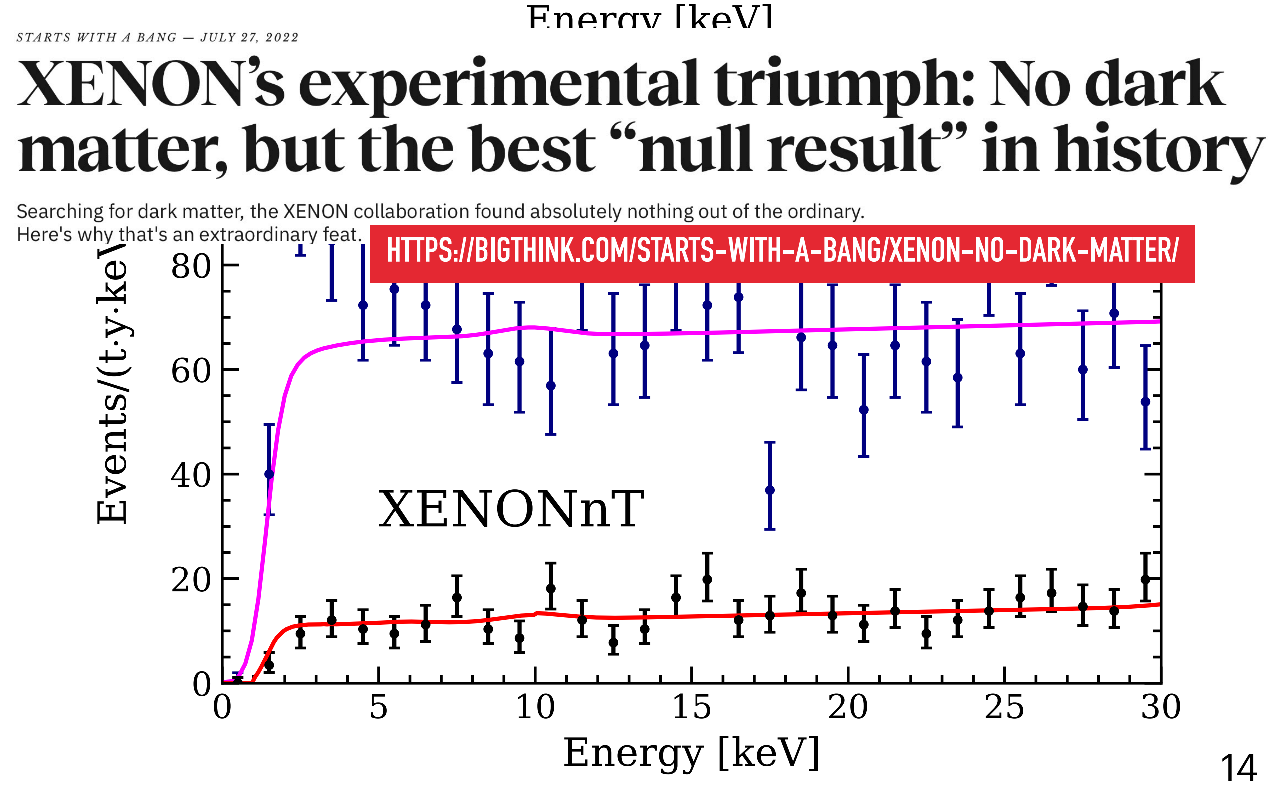
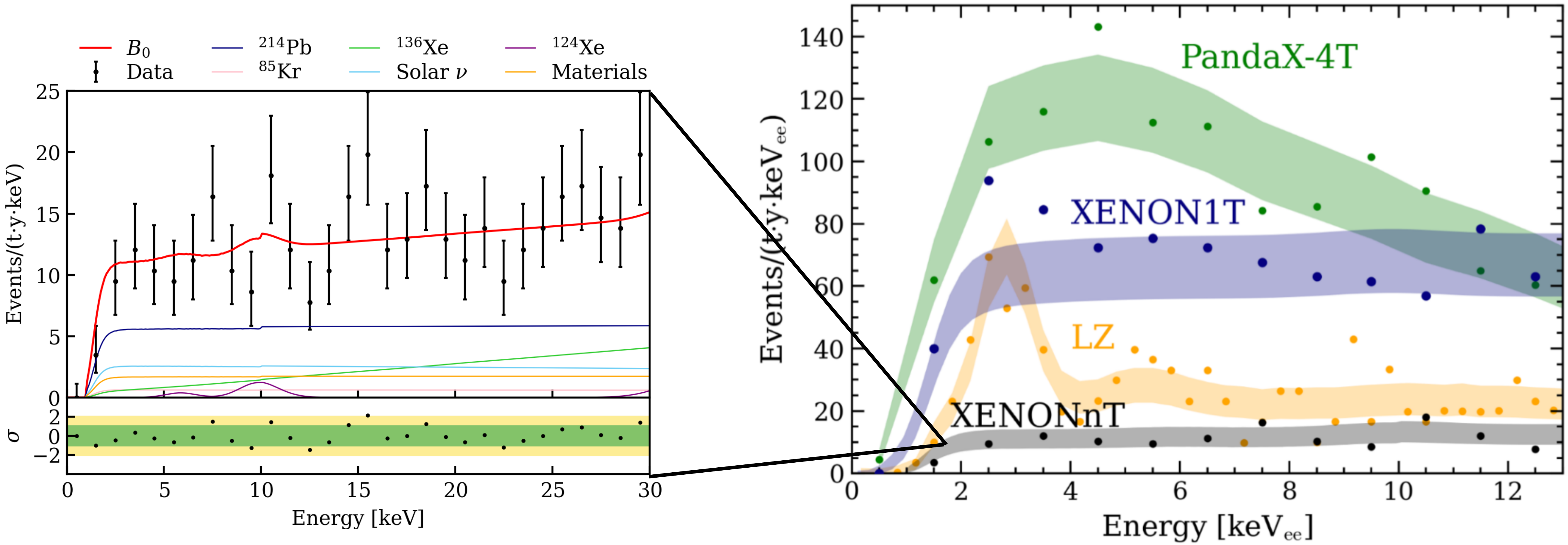




Electronic Recoil Background Comparison



PandaX-4T [PRL 129, 161804 (2022)]

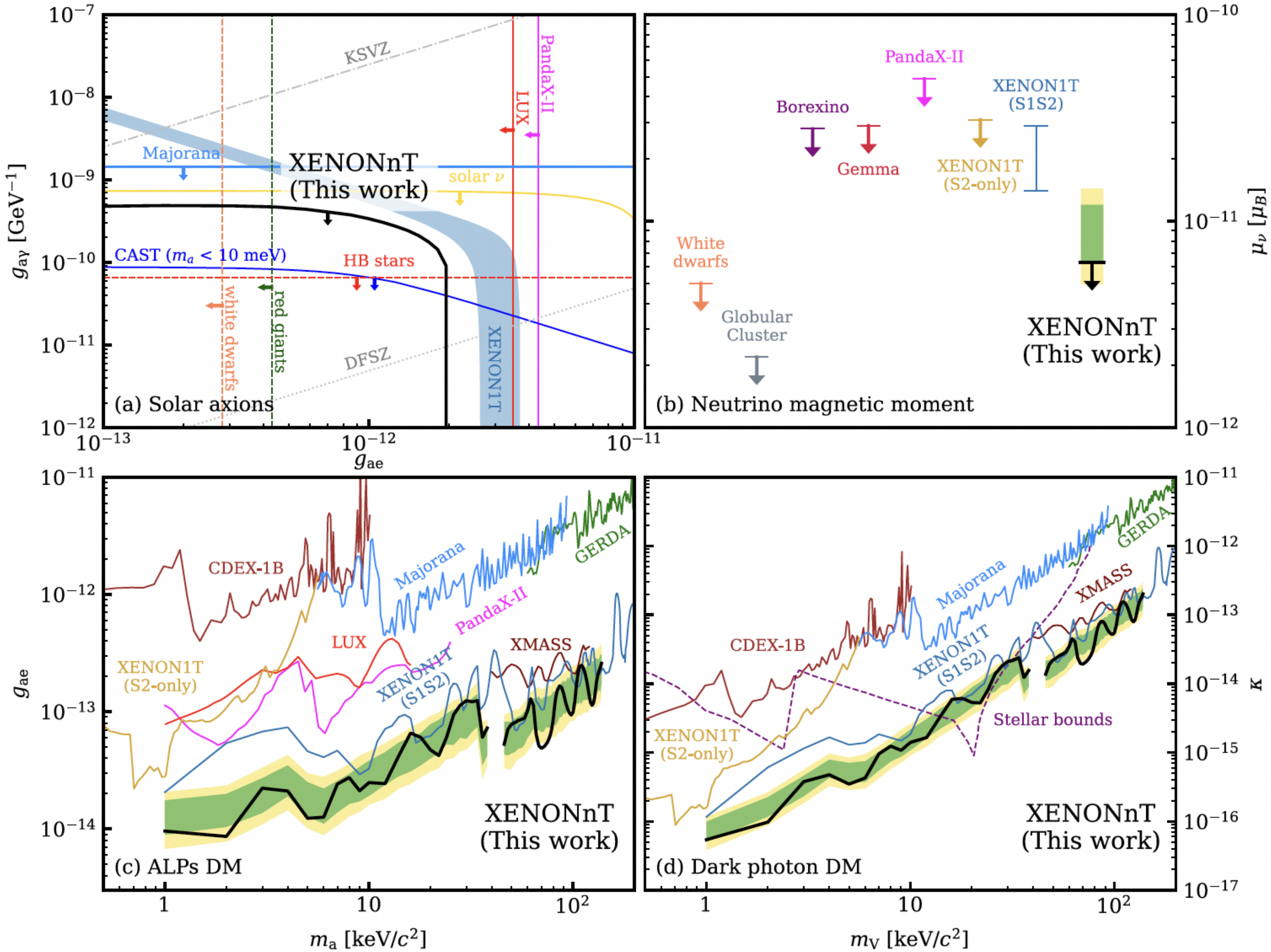
XENON1T [PRD 102, 072004 (2020)]

LZ [arXiv:2207.03764]

XENONnT [PRL 129, 161805 (2022)]

XENONnT Constraints on Solar Axions-ALPs-Neutrino Magnetic Moment-Dark Photon DM

XENON collaboration, PRL 129, 2022



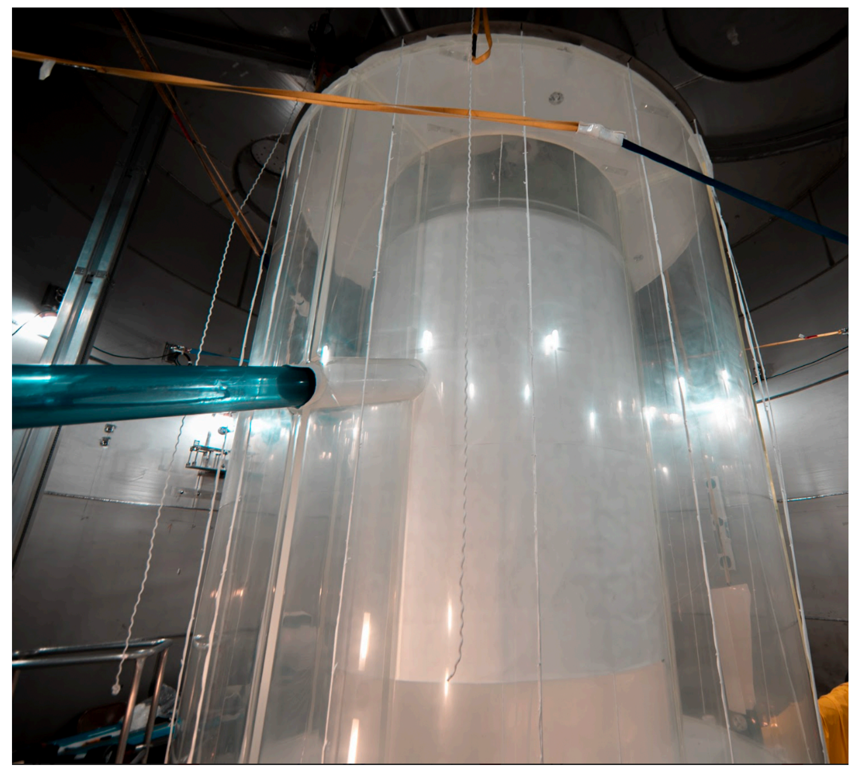
Neutron Background

Cosmogenic and radiogenic neutrons can mimic dark matter induced nuclear recoil signal —> neutron veto detectors developed to enclose the XENONnT and LZ XeTPC cryostats suspended inside water Cherenkov muon vetos

XENONnT

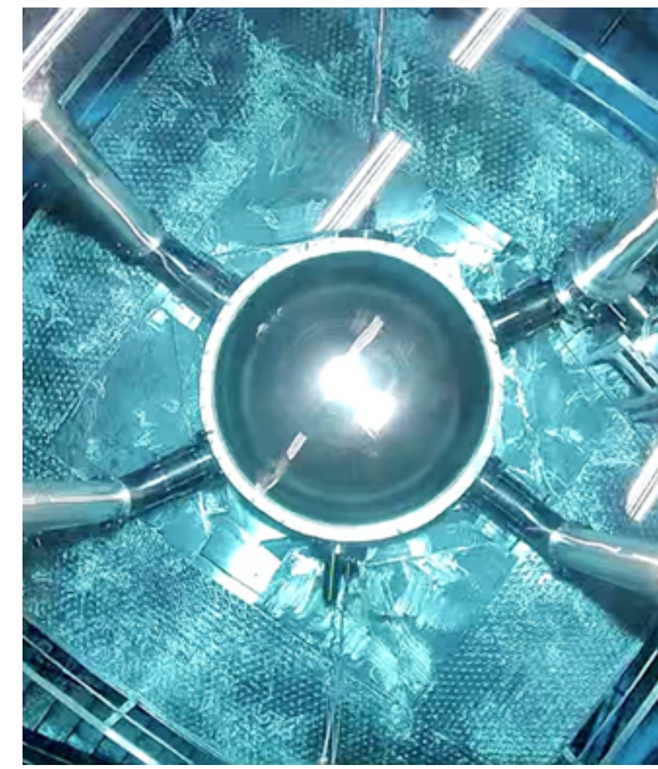
- 3.4 t Gd-loaded water (0.2% Gd)
- PTFE lined octagonal structure with 120 8" PMTs, surrounds the XeTPC cryostat
- Optically separated from Cherenkov Muon Veto, but not sealed
- Designed for 87% neutron tagging efficiency
- Used so far w/o Gd: up to 65% neutron tagging

LZ



- 17.3 t Gd-loaded LAB (0.1% Gd)
- 10 segmented acrylic vessels surrounding the XeTPC cryostat
- 120 8" PMTs enclosed by Tyvek reflector
- Designed for >95% neutron tagging efficiency
- Performance close to design

PandaX-4T



- Passive water shielding

Neutron Background

Cosmogenic and radiogenic neutrons can mimic dark matter induced nuclear recoil signal —> neutron veto detectors developed to enclose the XENONnT and LZ XeTPC cryostats suspended inside water Cherenkov muon vetos

XENONnT

- 3.4 t Gd-loaded water (0.2% Gd)
- PTFE lined octagonal structure with 120 8” PMTs, surrounds the XeTPC cryostat
- Optically separated from Cherenkov Muon Veto, but not sealed
- Designed for 87% neutron tagging efficiency
- Used so far w/o Gd: up to 65% neutron tagging

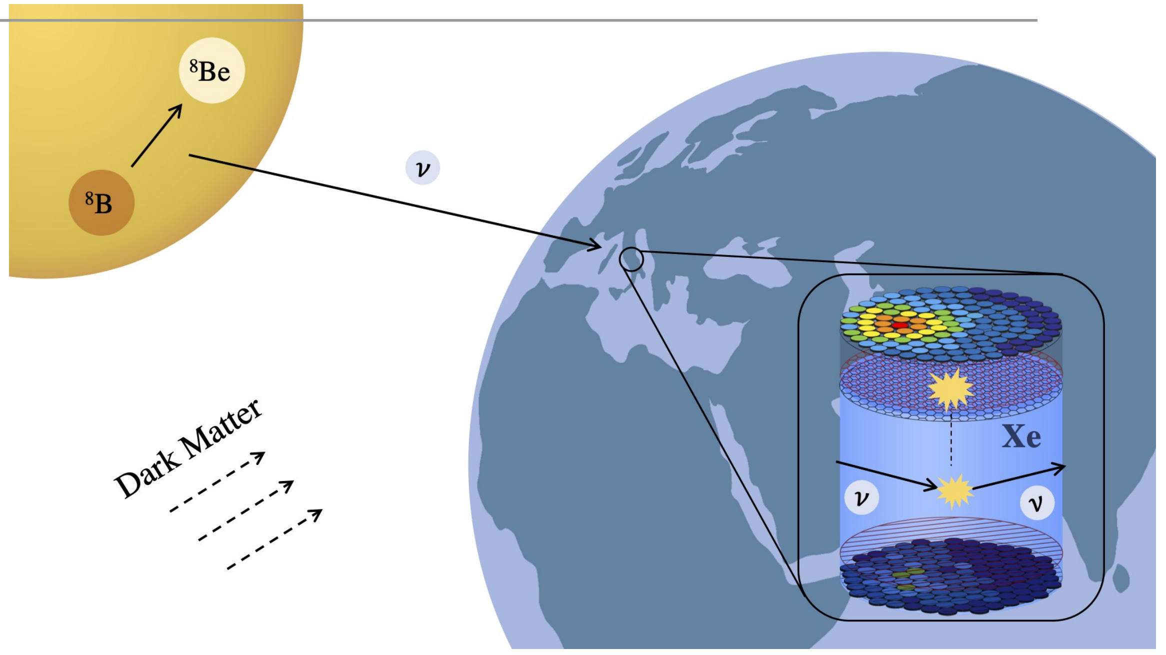
daX-4T

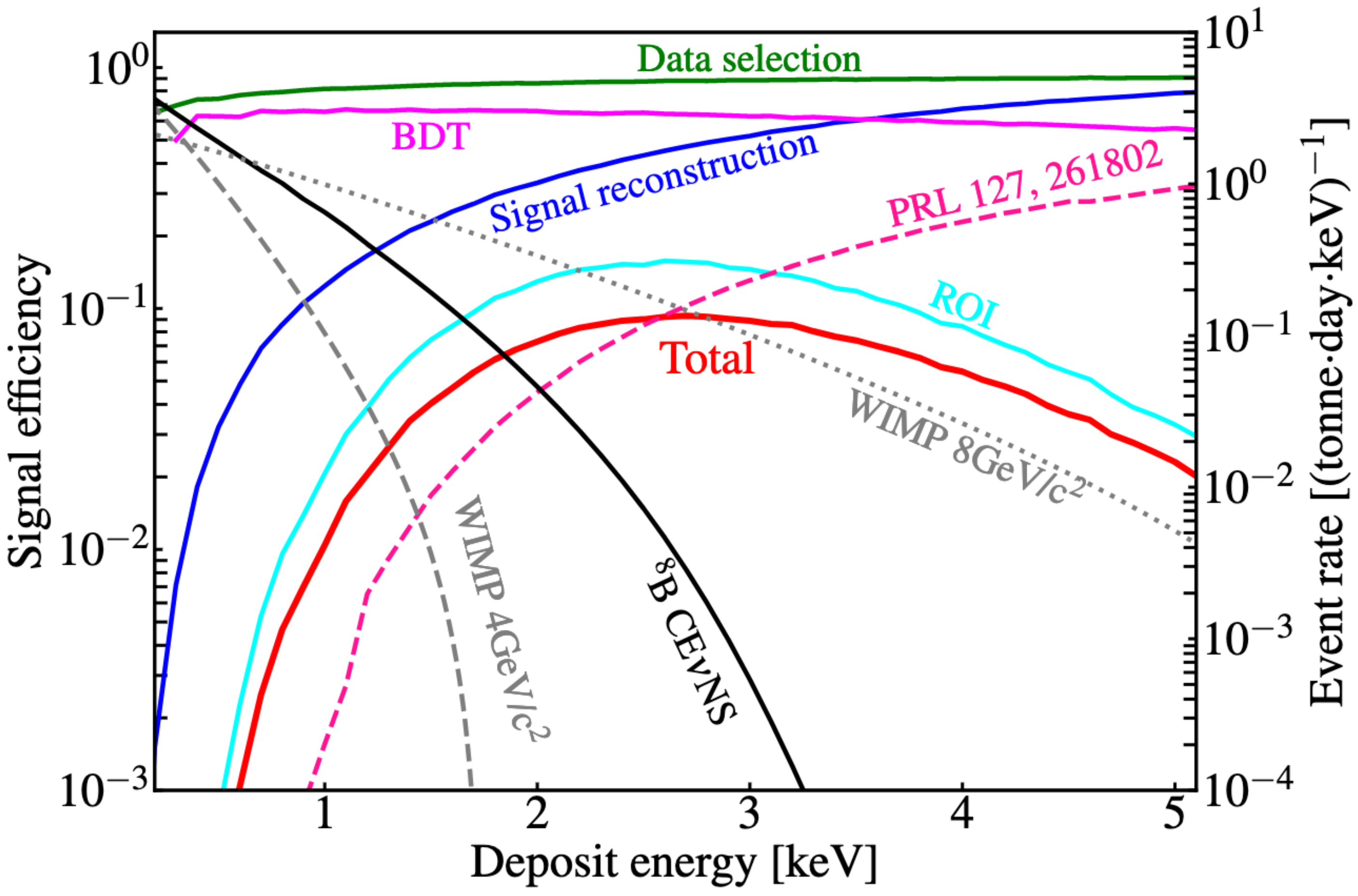
e water shielding

CEvNS: Background or a Signal Opportunity?

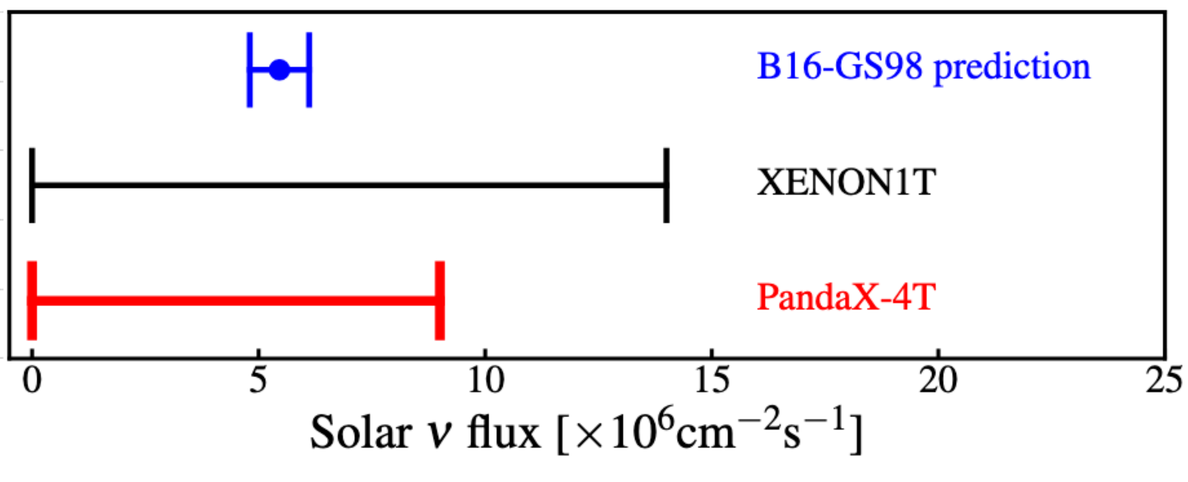
<u>talk by Fei Gao</u> on 3/31

- $^{8}\mathrm{B}$ solar neutrinos produce a low-energy NR recoil spectrum similar to that of a 6 GeV/c^2 WIMP
- Essential to lower energy threshold and to improve background discrimination with selective cuts
- Current generation of detectors with increased exposure should be able to observe this signal!

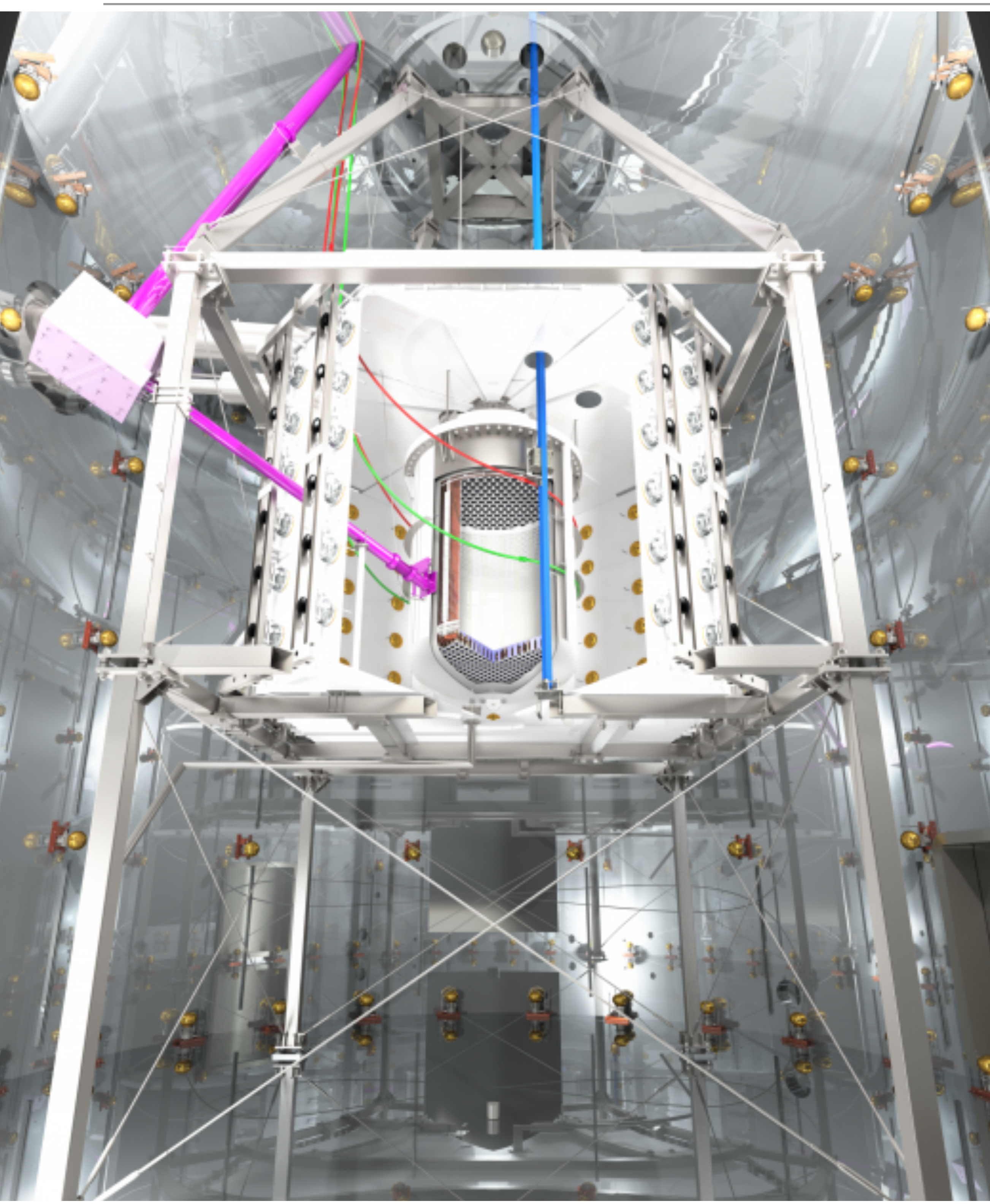


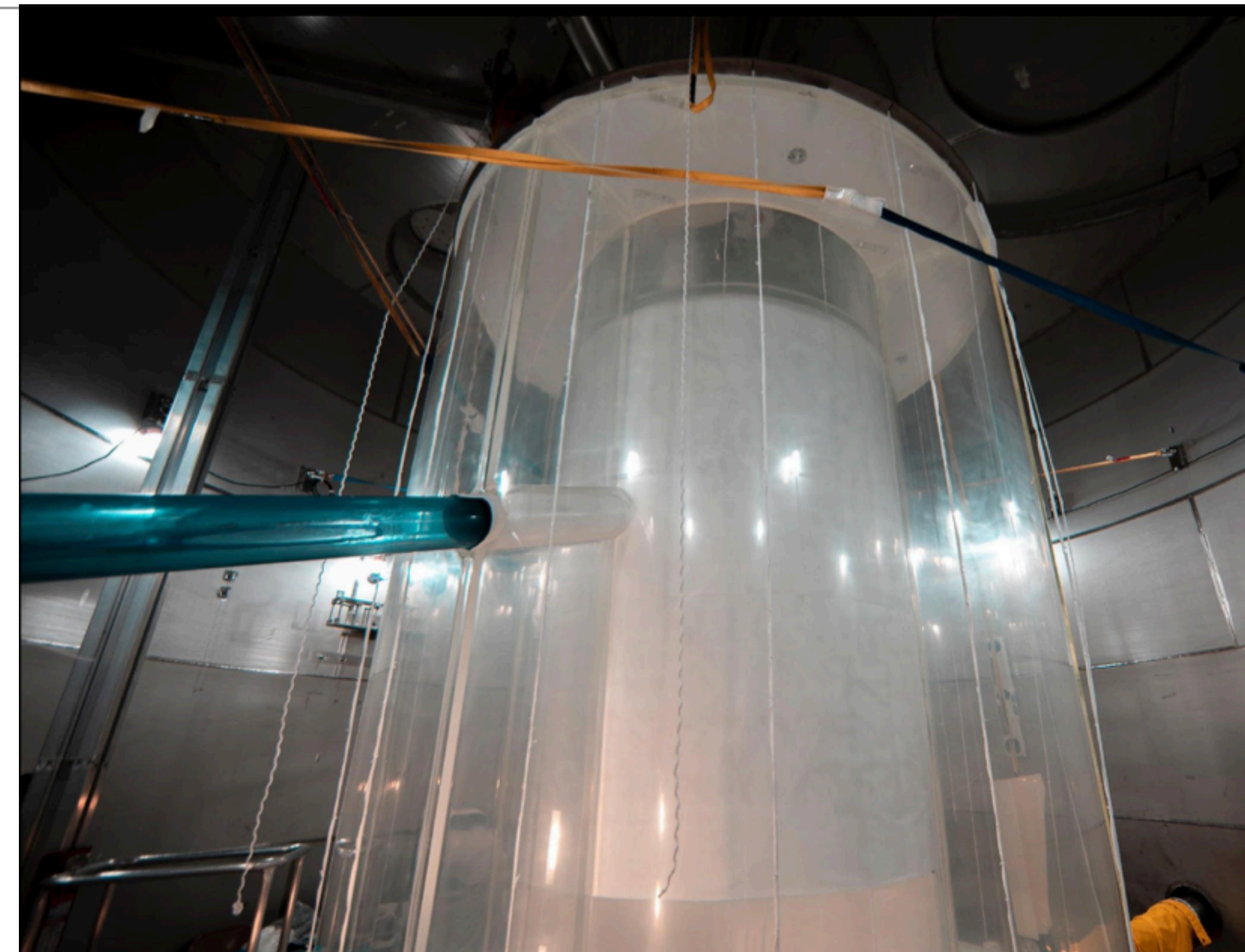


PandaX, Phys. Rev. Lett 127 (2021)



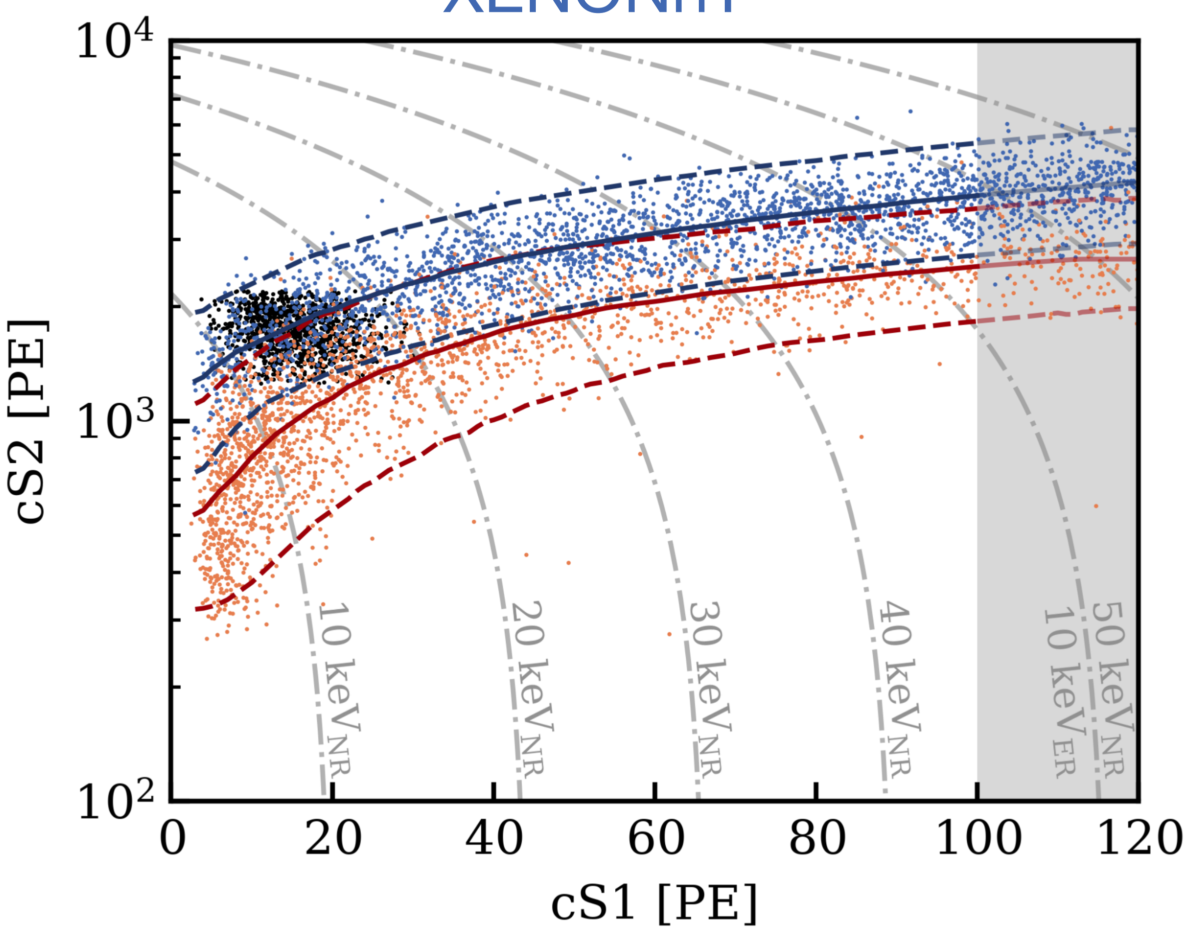
Calibrating these big XeTPCs: a challenge





Response to Electronic and Nuclear Recoils

XENONnT

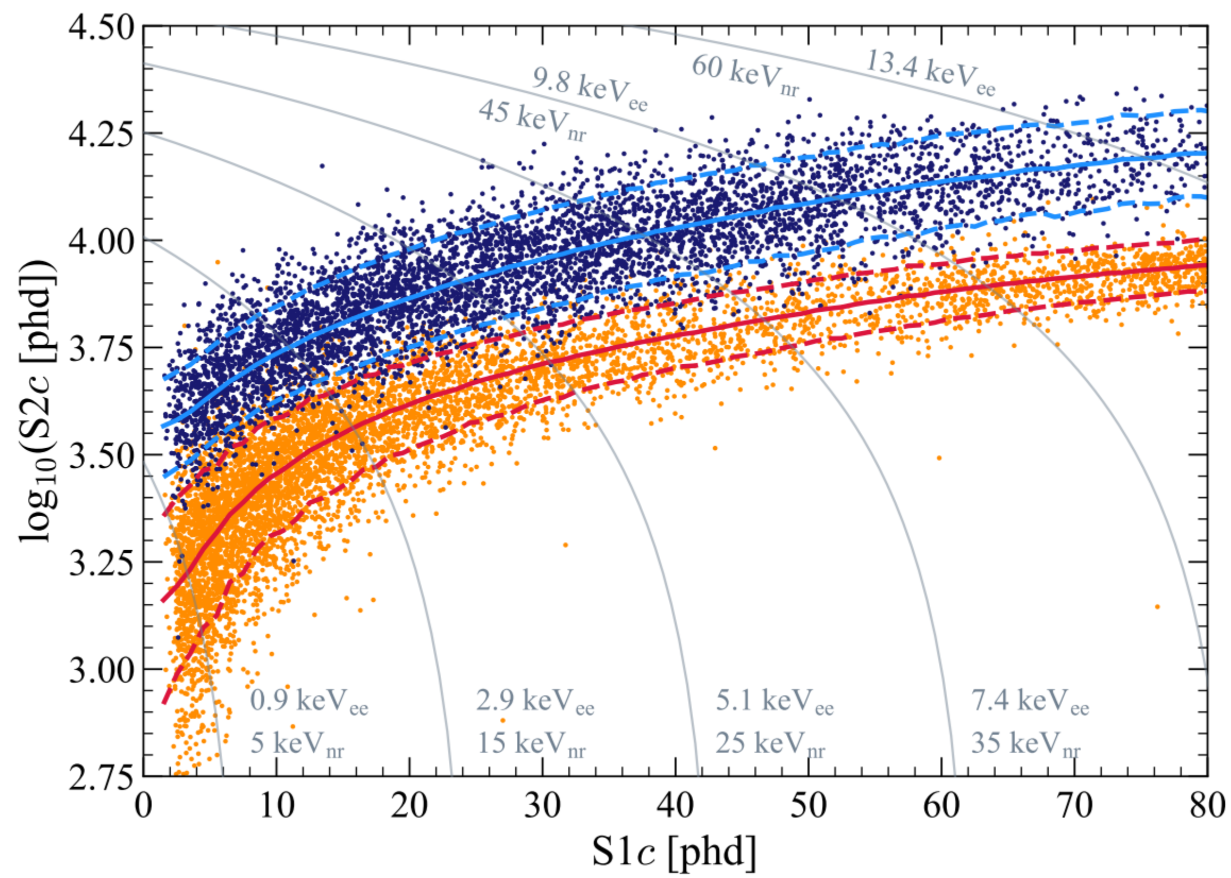


Electronic Recoil band calibration with β-decay of Pb-212 from an internal **Rn-220** source mixed into GXe

Nuclear Recoil band calibration with external **AmBe** source lowered into water tank

Additional **ER** calibration with an internal **Ar-37** source at low energies included in ER model

LZ



Electronic Recoil band calibration with β-decay of an internal **Tritium** source mixed into GXe

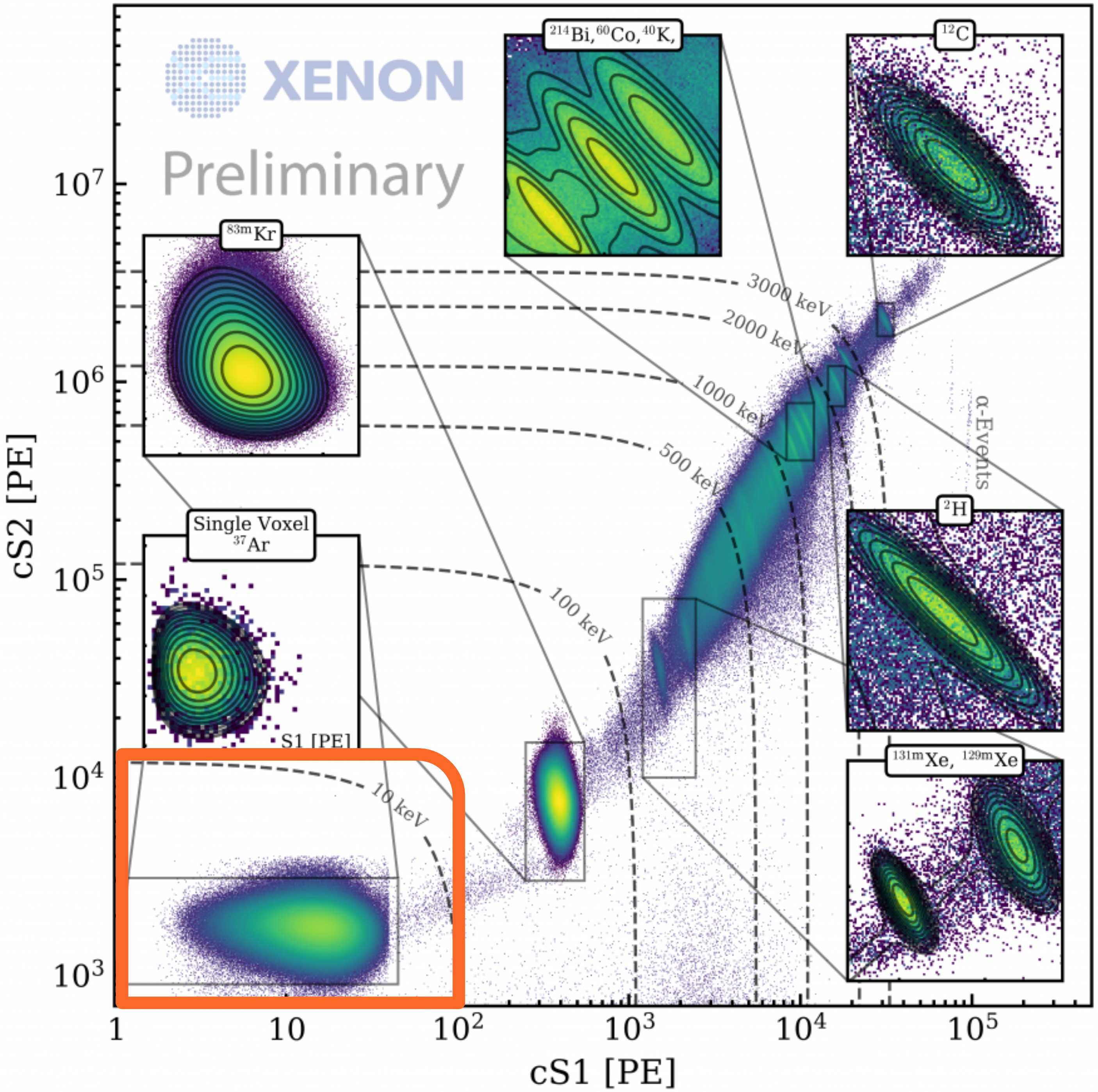
Nuclear Recoil band calibration with external **DD Neutron Generator**

***PandaX-4T** uses a different visualization of the bands making direct comparison difficult:

- ER calibration with internal Rn-220
- NR calibration with external DD Neutron Generator

XENONnT Energy Response and Resolution

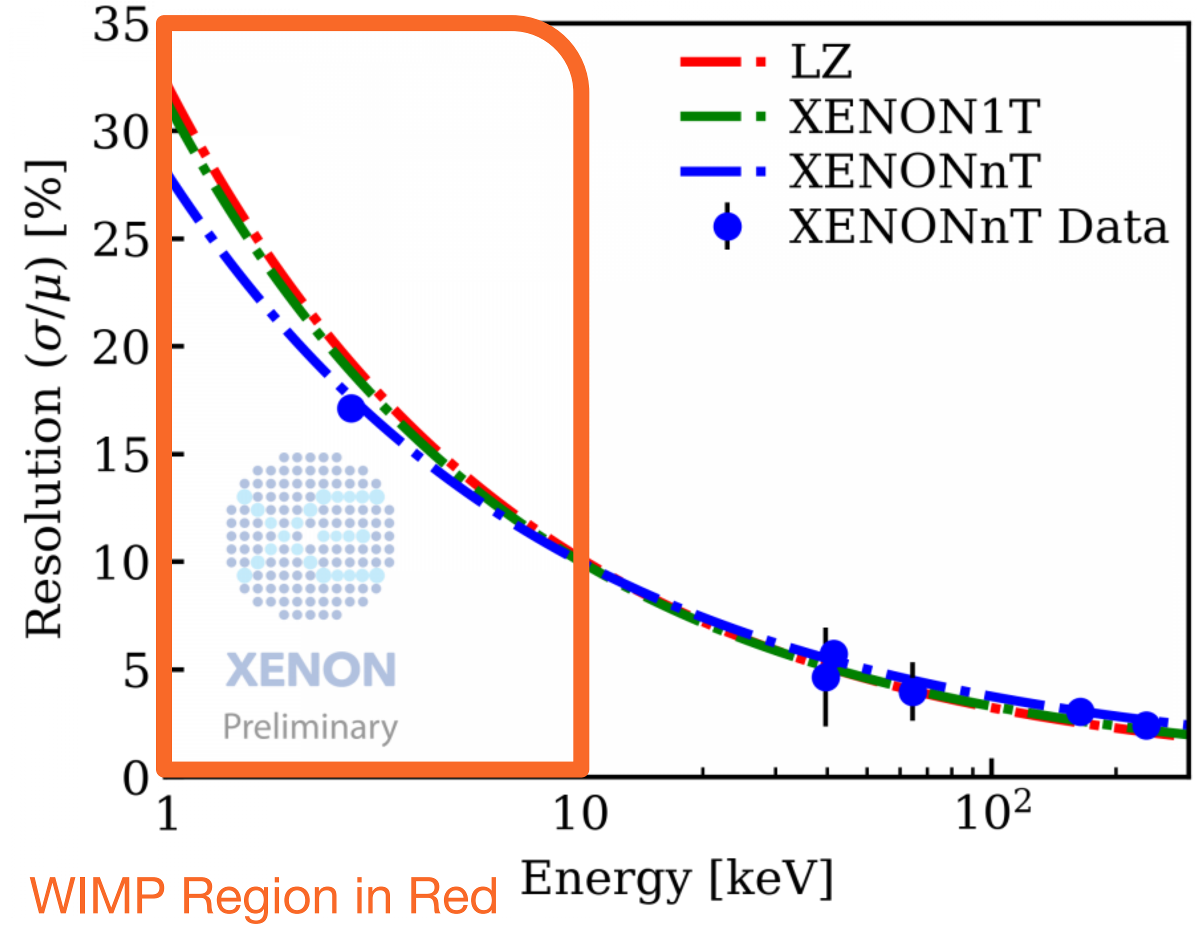
LXe TPCs response validated with several calibration and activation lines from keV to MeV energies



WIMP Region in Red

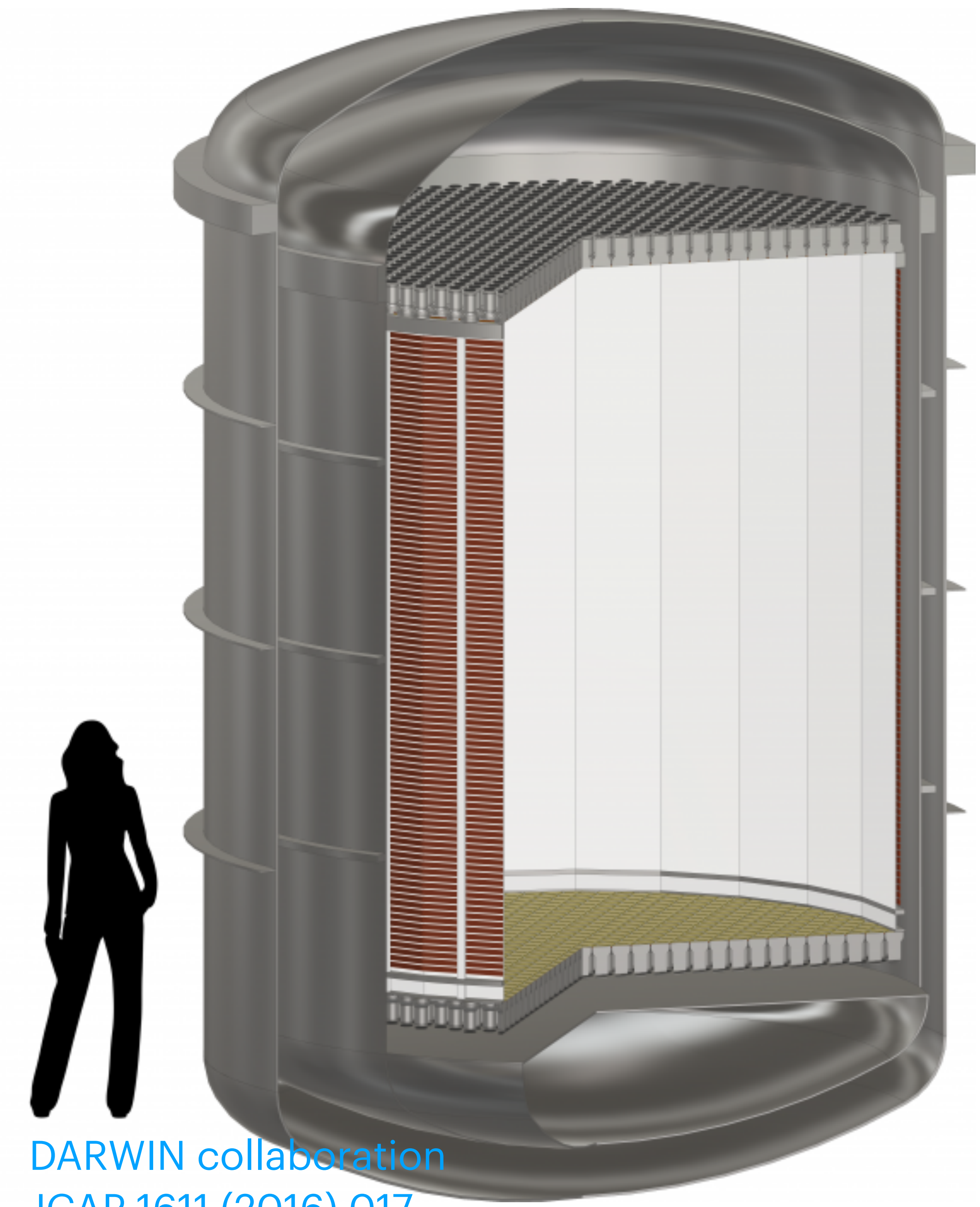
- Ar-37 and Kr-83m give high-statistics lines at low energies
- Material-lines (Bi-214, Co-60 and K-40) from the cryostat
- AmBe neutron calibration gives gammas from either C-12 alpha-capture or neutron capture (H-2)
- The AmBe calibration also gives activated Xe-129m and Xe-131m lines

At high energy, the resolution approaches %-level when all corrections have been included

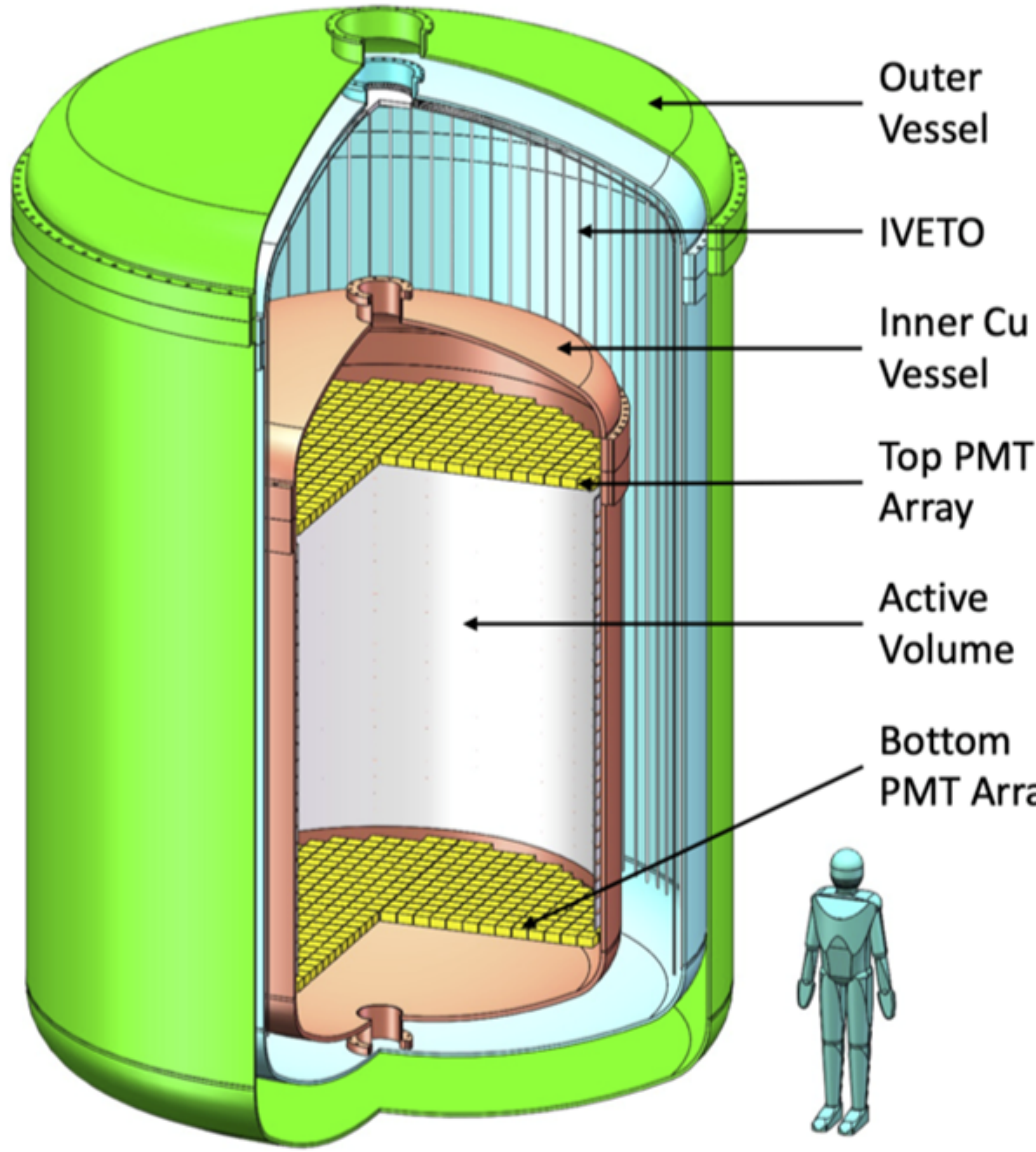


WIMP Region in Red

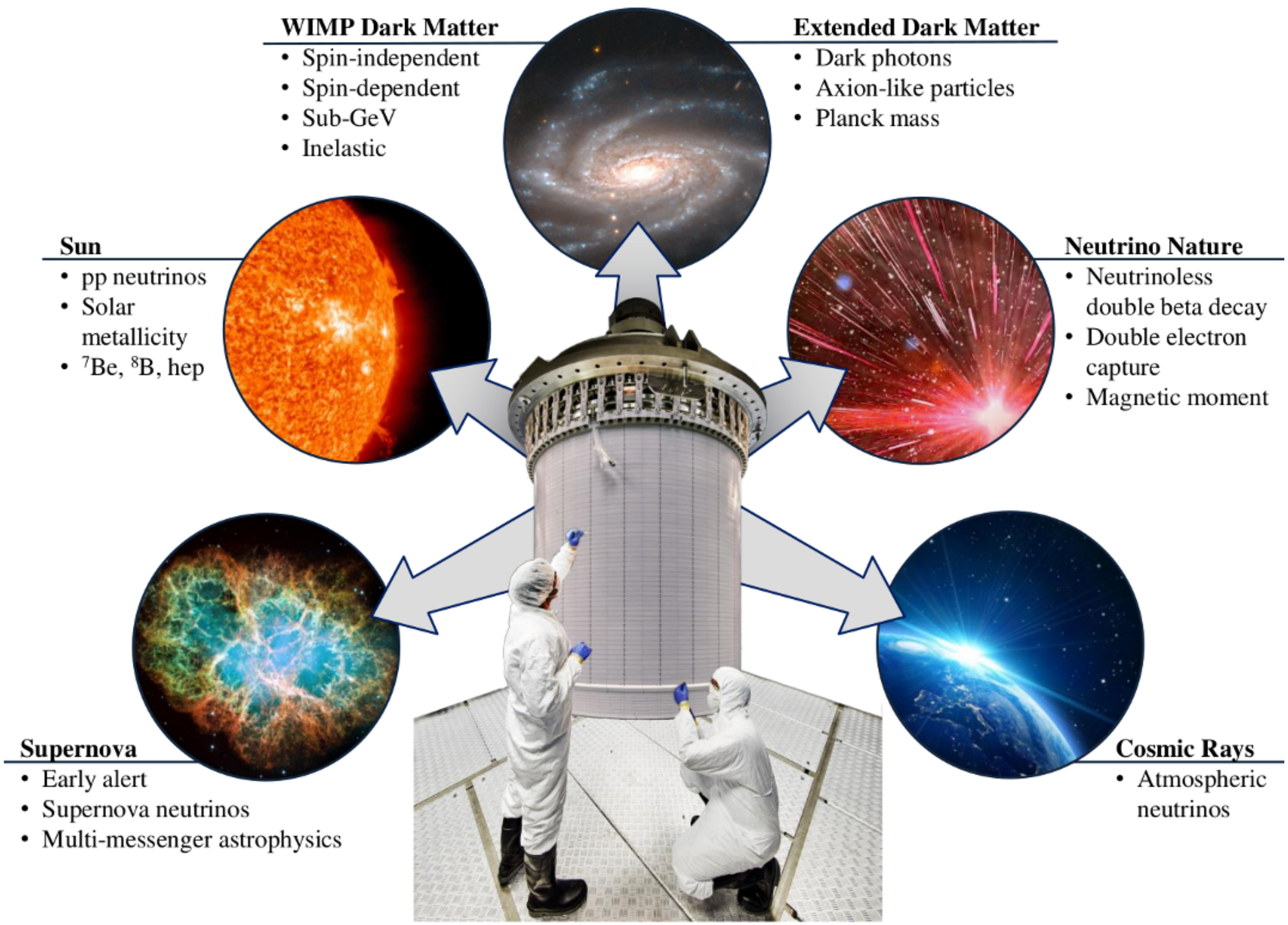
Future XeTPCs at the 50 tonne scale: DARWIN and PandaX-xT



DARWIN collaboration
JCAP 1611 (2016) 017



Broad Science Program



J.Phys.G 50 (2023) 013001

Future: XLZD Consortium (xlzd.org)

Merger of XENON, LUX-ZEPLIN and DARWIN collaborations to build and operate next-generation liquid xenon detector

- a unified community with demonstrated experience in xenon time projection chambers
- Consortium MoU signed in July, 2021 by 104 research group leaders XENONnT,LZ, DARWIN
- XENONnT and LZ continue to operate their independent programs, while informing technology choices for future, many tested within DARWIN
- first in-person meeting at KIT June, 2022; working groups to study science, detector, Xe procurement, R&D etc
- second in-person meeting at UCLA, following this DM conference

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Summary and Outlook

- The two-phase XeTPC technology has been at the forefront of dark matter direct detection since 2007 with XENON10 using a total of 25 kg of Xe.
- With XENON1T key technologies were developed to enable the scalability to several 1000 kg of Xe while achieving ultra-low background paving the way to today's experiments at the 10,000 kg scale.
- The current generation of XeTPCs (XENONnT, LZ and PandaX-4T) continue to take data and are likely to continue to lead DM direct detection for the rest of this decade.
- The only reasonable alternative to LXe in an experiment of similar sensitivity is LAr and this decade will see this realized with the the DS20K experiment.
- To fully explore WIMPs down to the irreducible neutrino background noble liquid detectors with even larger target mass and lower background are needed.
- To realize the ultimate Xe-based WIMP detector R&D and design studies are ongoing within the DARWIN/XLZD and PandaX-xT collaborations.