Results from the first science run of the XENONnT experiment

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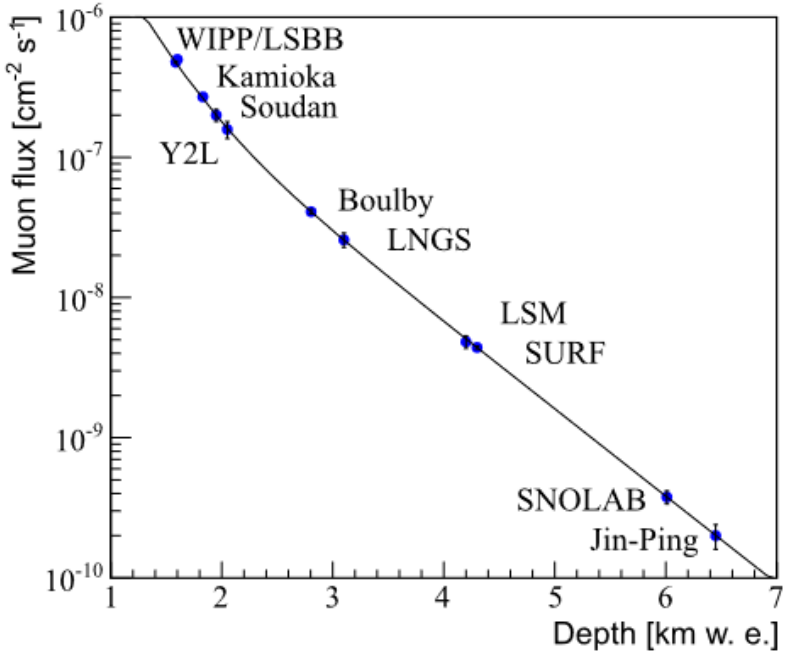
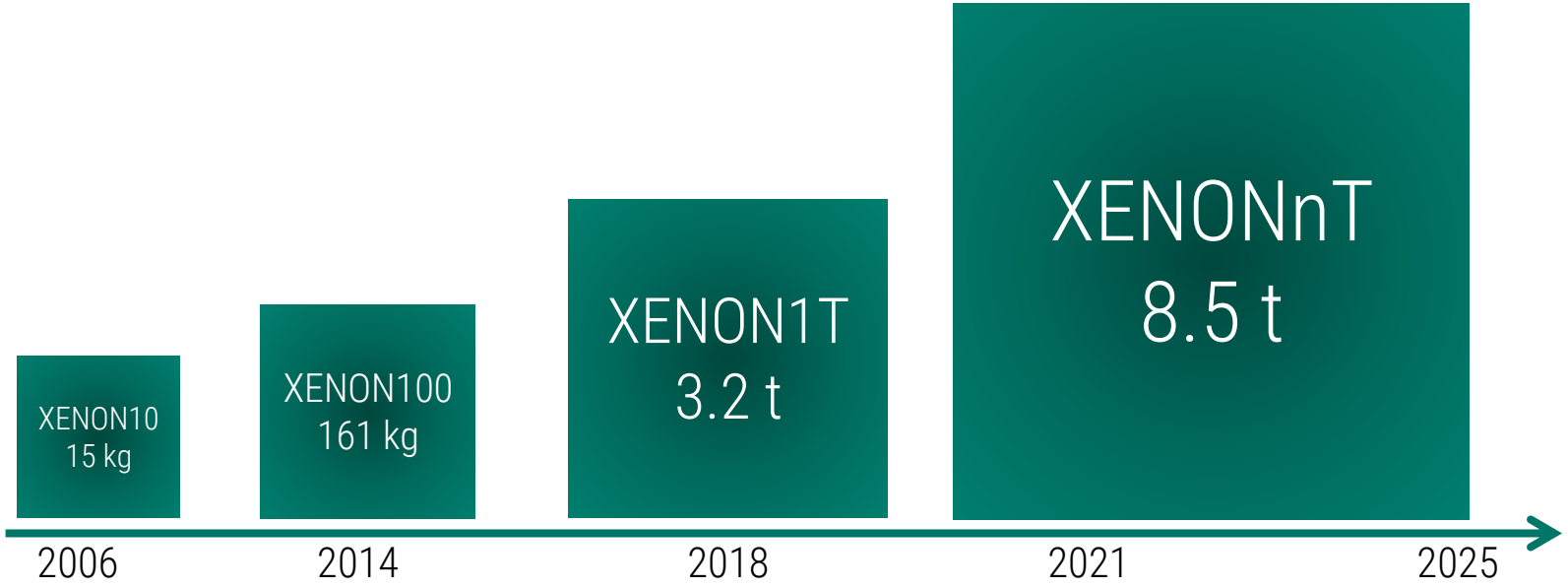
The XENON project

- ✓ Dark matter direct detection experiment
- ✓ 180 scientists, 27 institutions, 12 countries
- ✓ Laboratori Nazionali del Gran Sasso (LNGS)
- ✓ Dual phase xenon time projection chamber

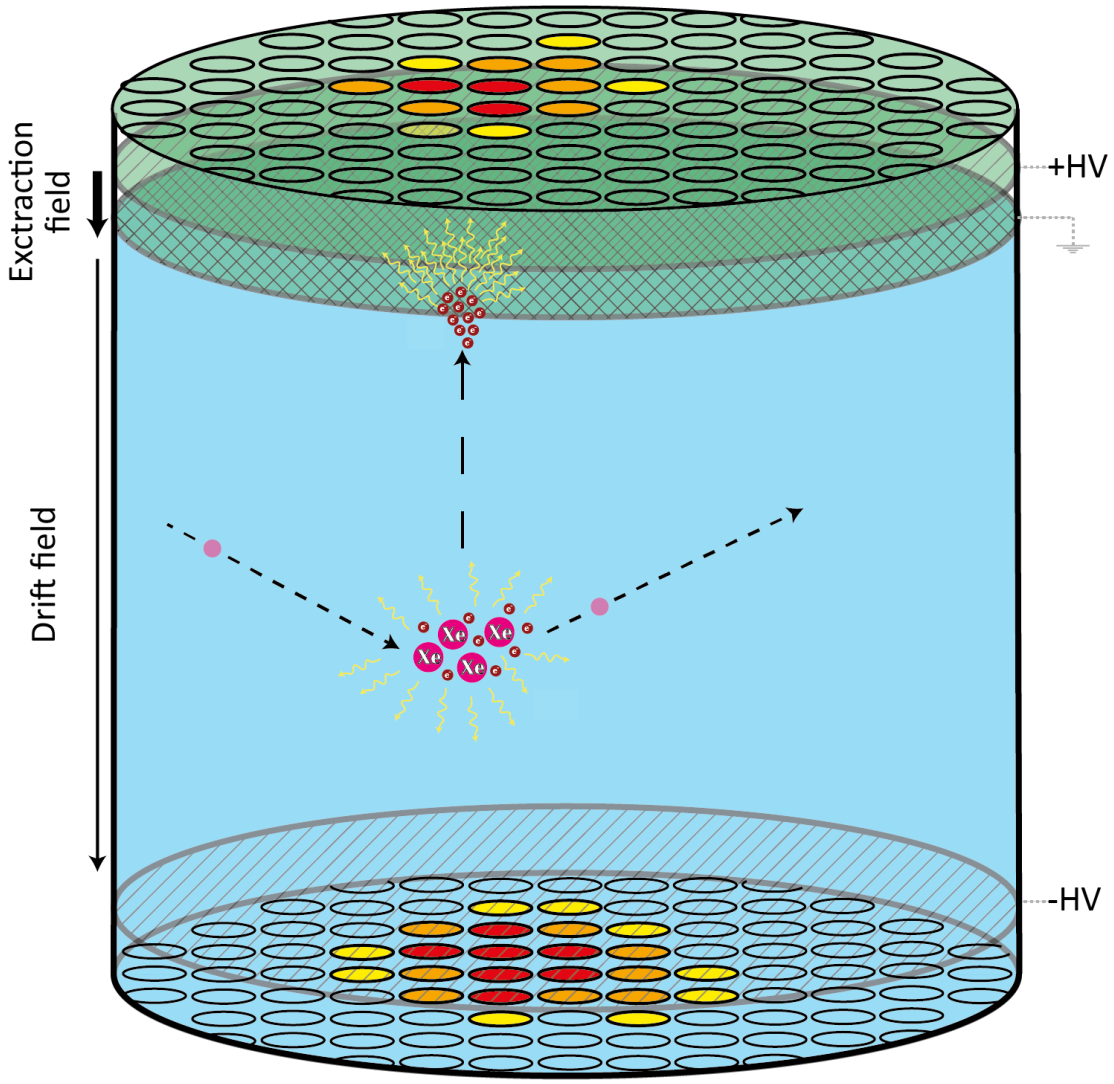




XENON

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

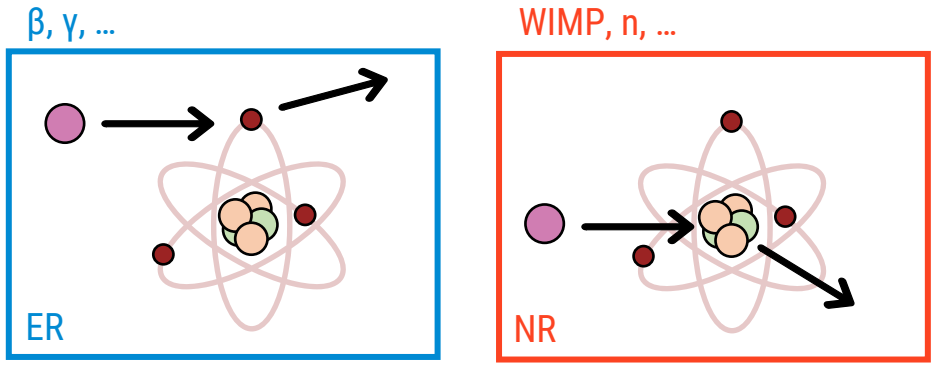
Detection principle



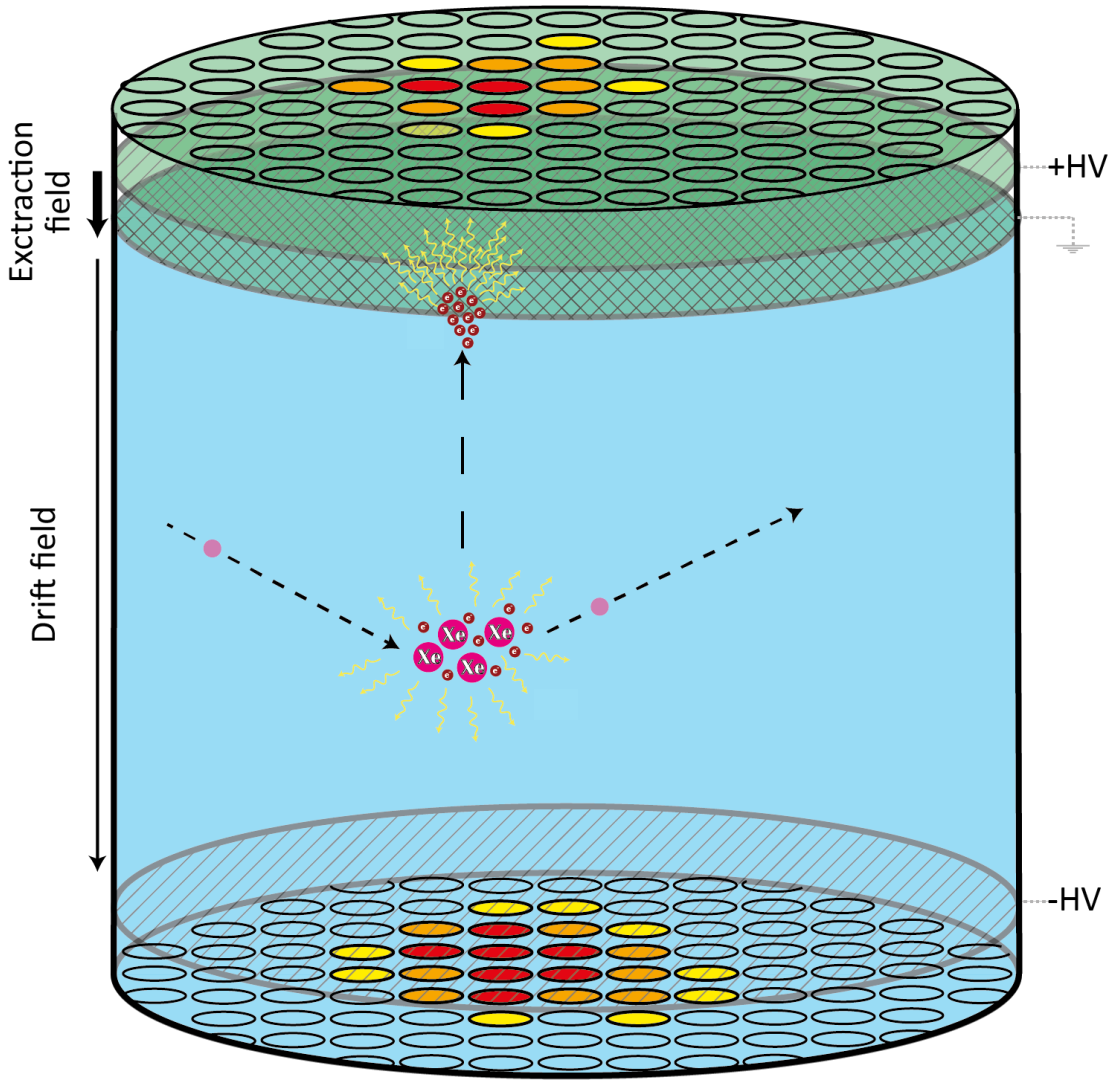
Scintillation photons (S1) and free electrons (∝ S2) are produced from an impinging particle.

Combination of S1 and S2 signals allows for:

- ✓ 3D position reconstruction
- ✓ Energy reconstruction: $E_{dep} \propto (n_\gamma + n_{e^-}) = ({}^{S1}/_{g_1} + {}^{S2}/_{g_2})$
- ✓ ER/NR discrimination via the charge-to-light ratio



Detection principle



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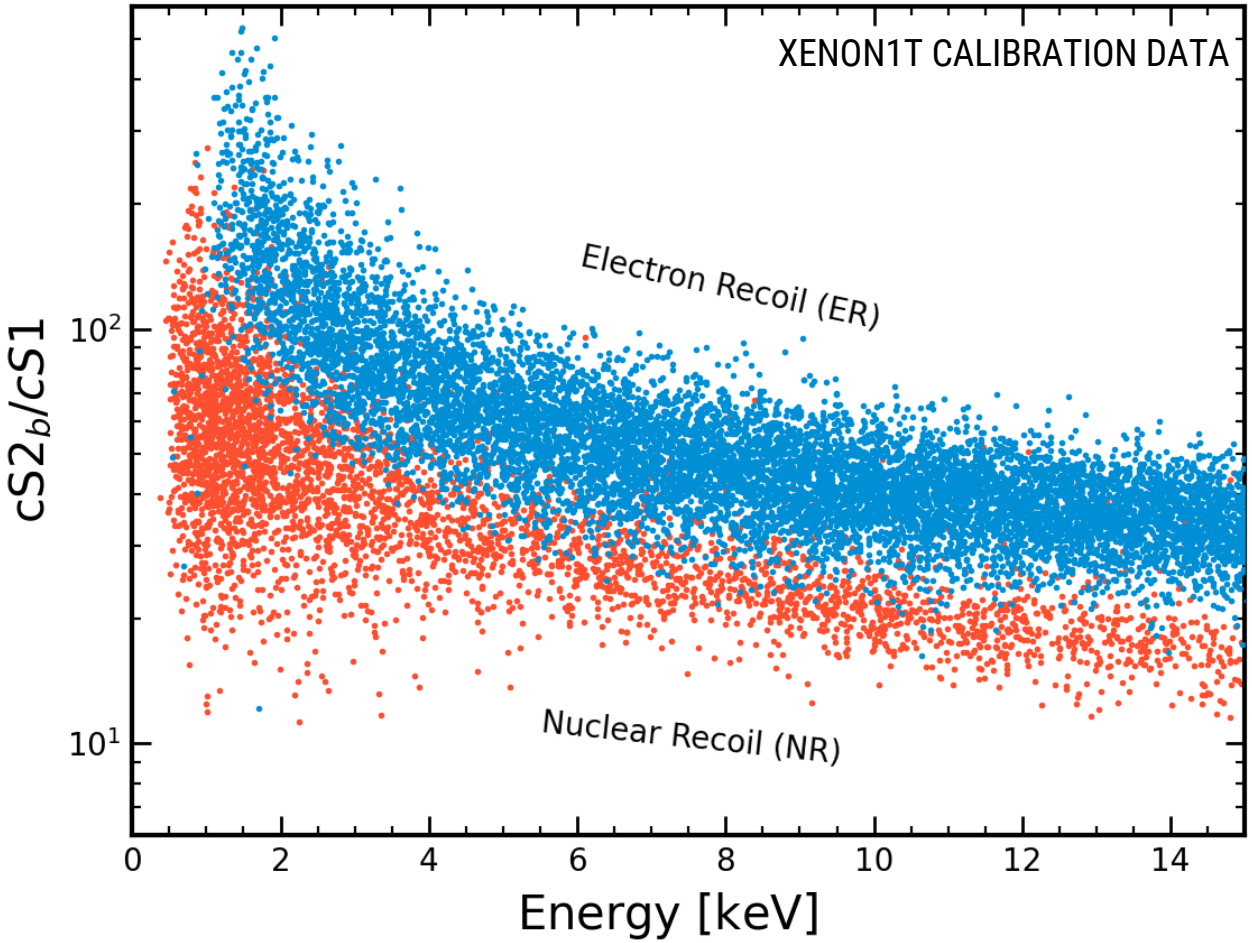
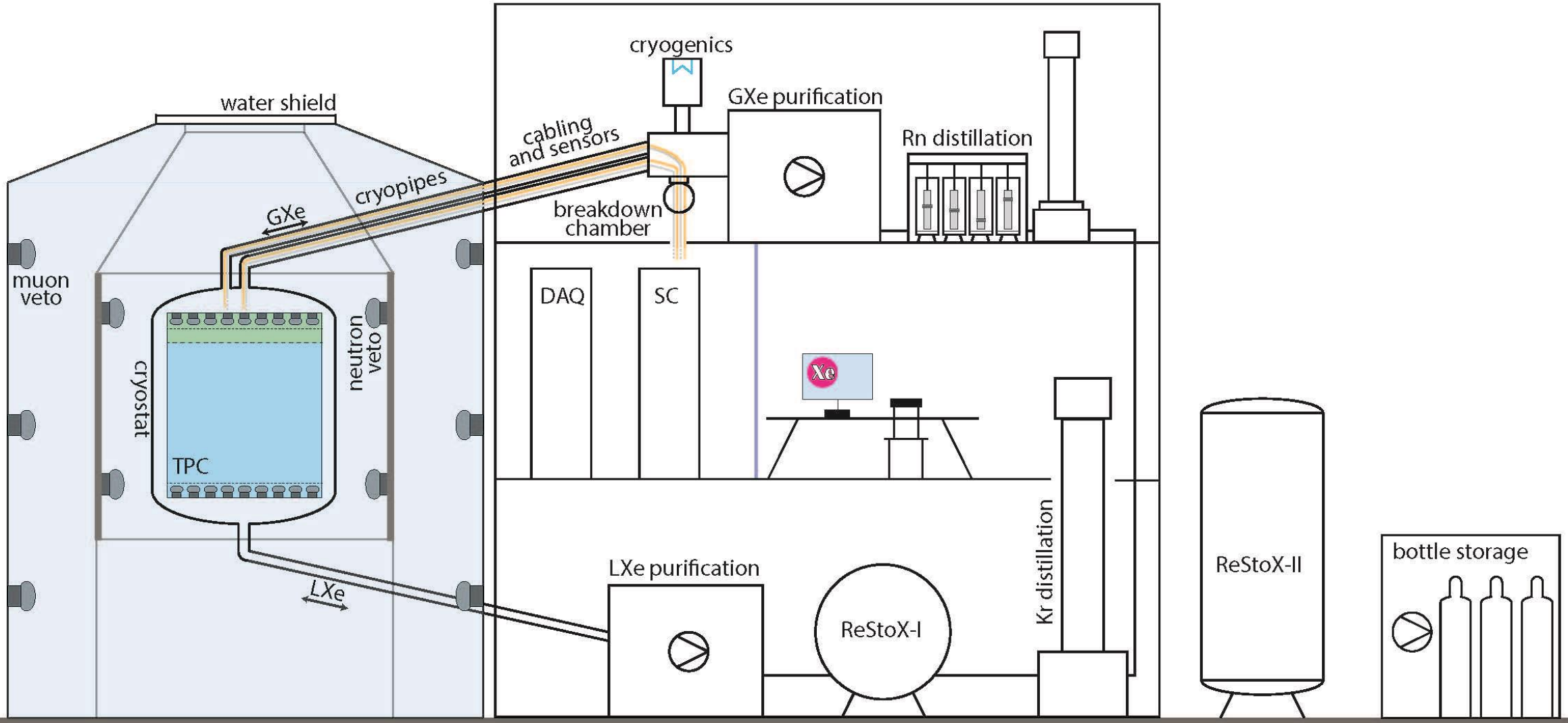


The XENONnT experiment

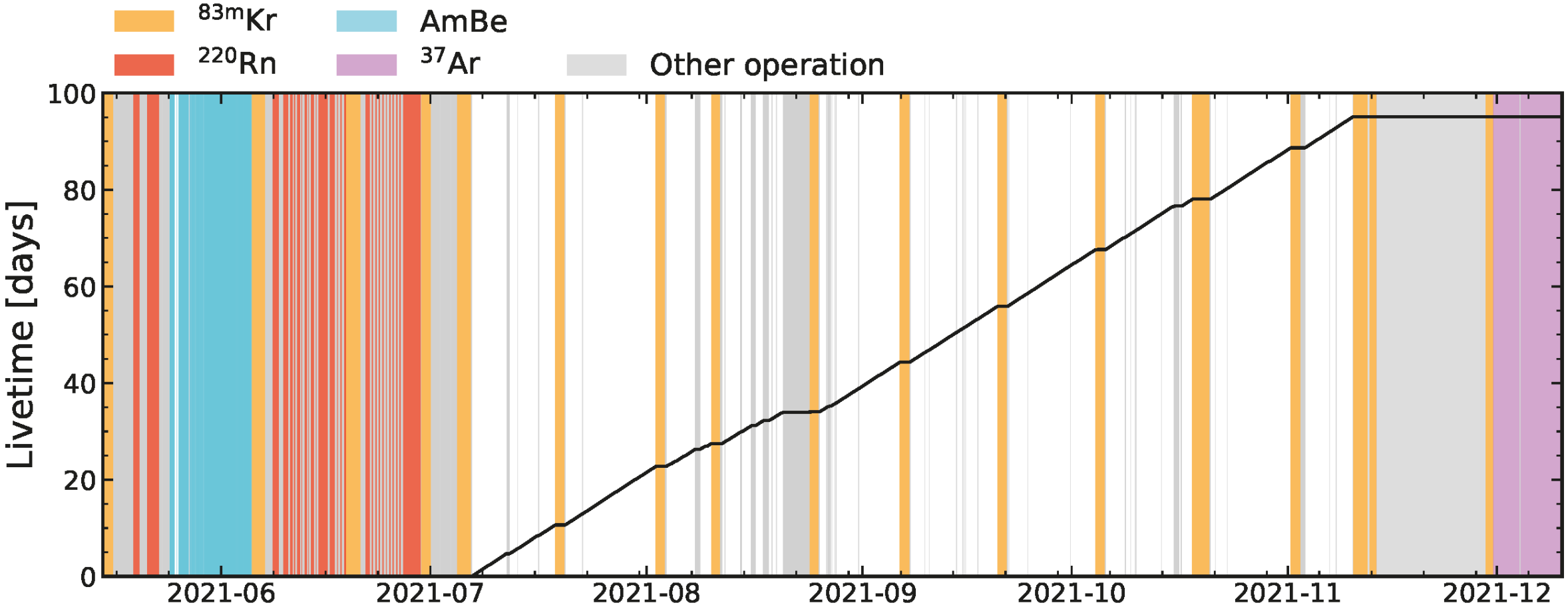
JINST 9 P11006
JCAP 11 (2020) 031

- ✓ Three nested detectors (muon veto, neutron veto, TPC) in a ~10 m ×10 m water tank
- ✓ Three-floor auxiliary building hosting experiment infrastructure



The first XENONnT science data (SR0)

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

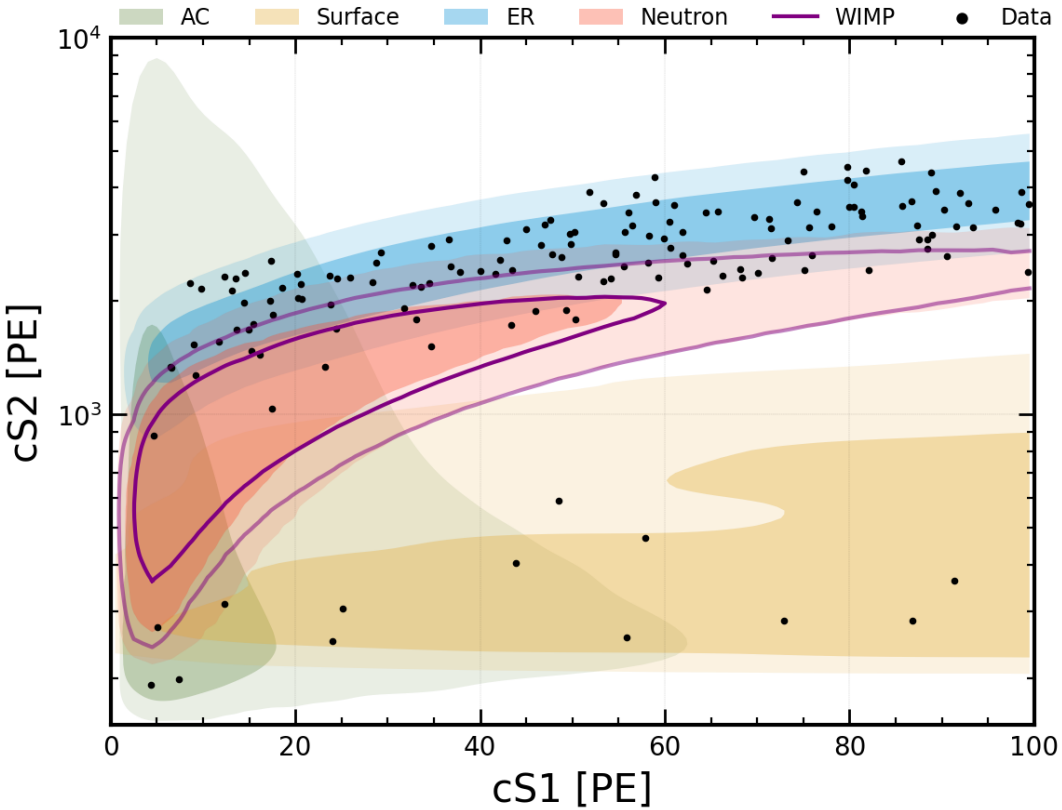


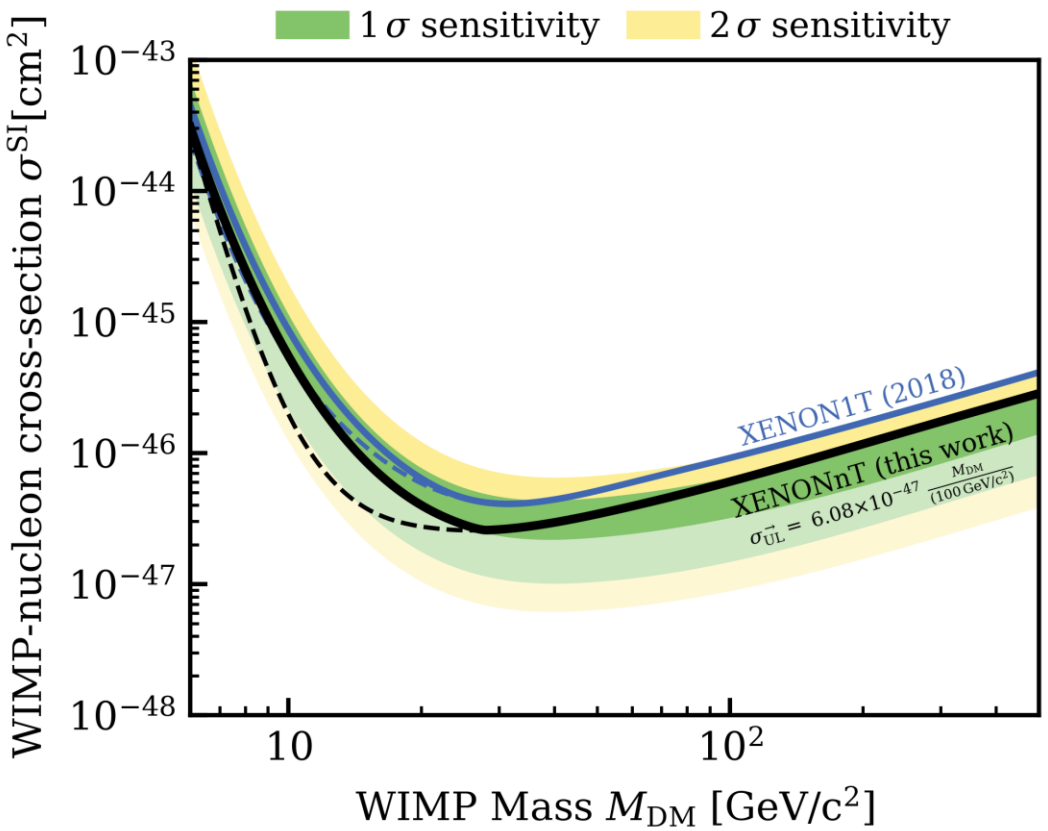
- ✓ Three ER internal calibration sources: ^{83m}Kr (TPC response monitoring and characterization), ^{220}Rn (ER response model and data quality cuts development), and ^{37}Ar (low-energy TPC response characterization)
- ✓ ^{241}AmBe external calibration for NR response model and neutron veto characterization

WIMP search

Phys. Rev. Lett. 131, 041003 (2023)

- ✓ WIMP search performed in a blinded fashion
- ✓ SR0 (1.1 t × yr) WIMP search data interpreted using unbinned likelihood in (cS1, cS2, r) parameter space
- ✓ Detailed background (4 components) and signal models



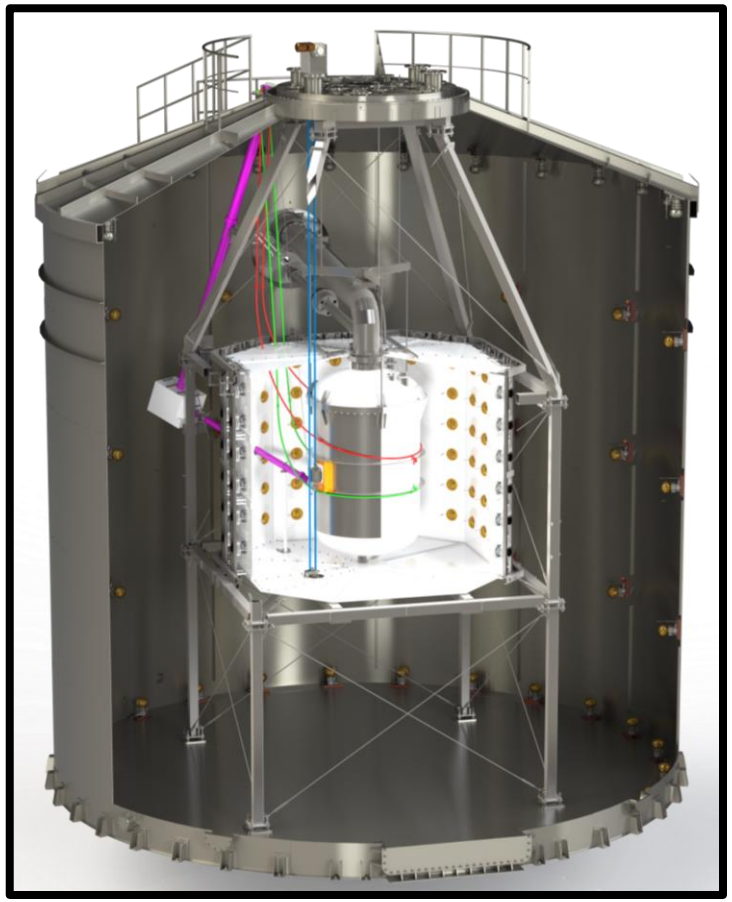


- ✓ Several signals from a wide range of WIMP masses were tested. None of them were statistically significant
- ✓ Lowest ER background rate measured in dark matter detectors: (15.8±1.3) events/(t × yr × keV), in 4.37 tonnes and within (1, 30) keV

How did we get there?!

The upgrades of XENONnT

Larger TPC

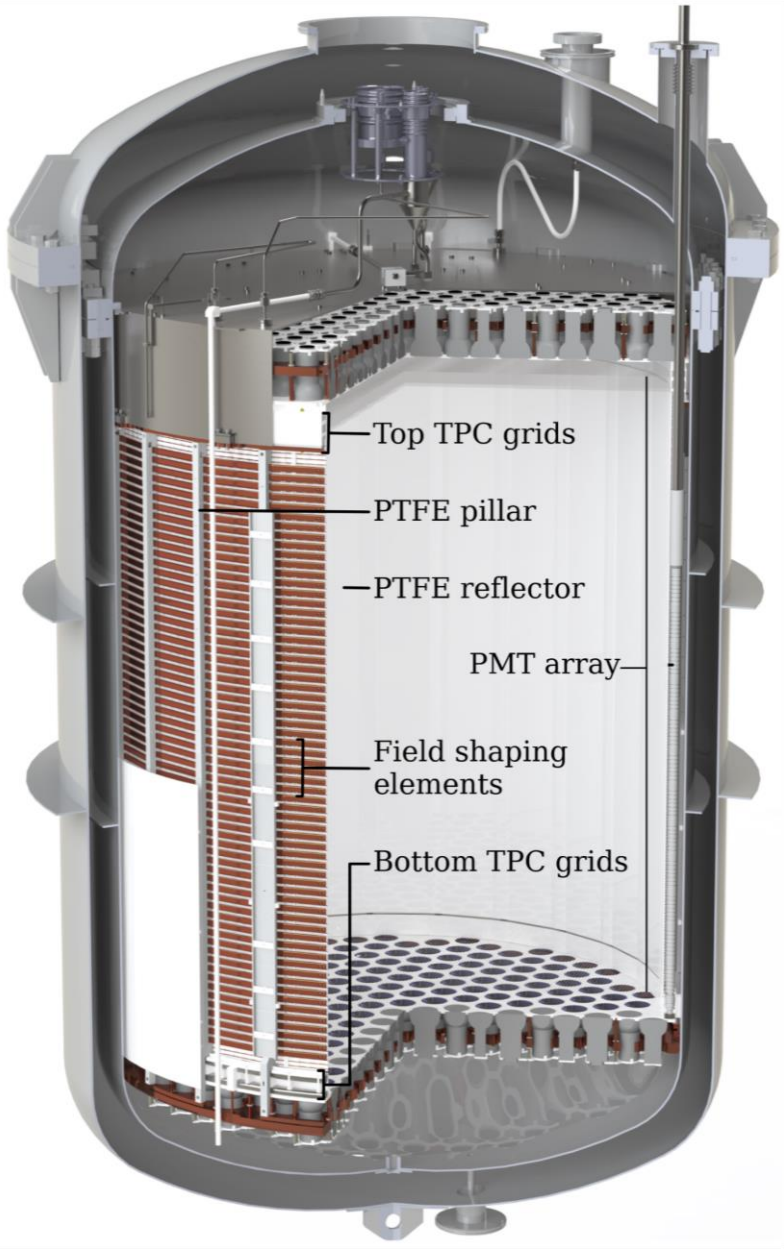


Neutron veto

^{222}Rn distillation

LXe purification

Dual-phase time projection chamber



- ✓ 1.5 m high and 1.3 m in diameter
- ✓ Total of 8.5 tonnes of LXe, 5.9 tonnes of which instrumented (×3 WRT XENON1T)
- ✓ 5 electrodes and 2 sets of field shaping elements
- ✓ 494 Hamamatsu R11410-21 3-inch PMTs (×2 WRT XENON1T)
- ✓ Materials selected prior to an extensive radioassay campaign

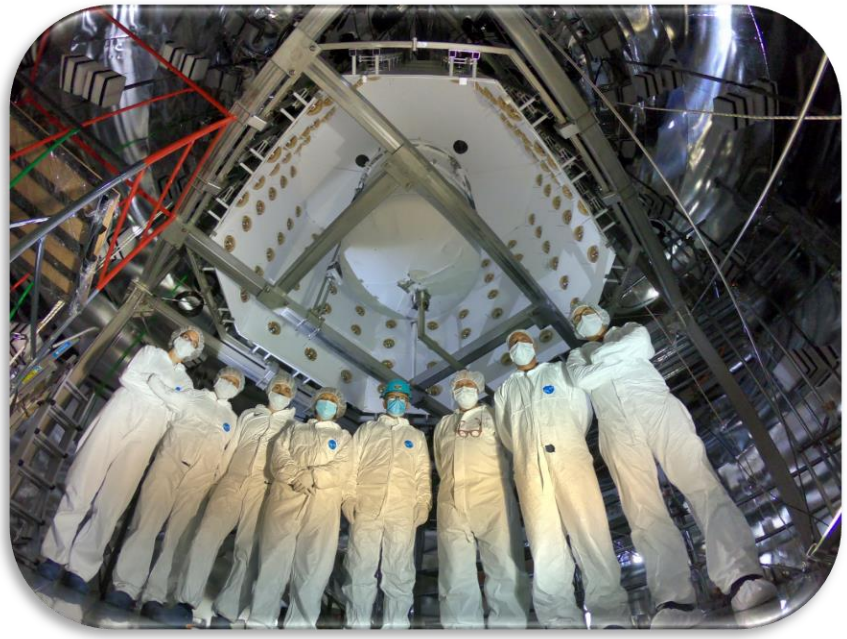
153 PMTs from XENON1T; the remaining 341 PMTs were selected after a meticulous testing campaign.

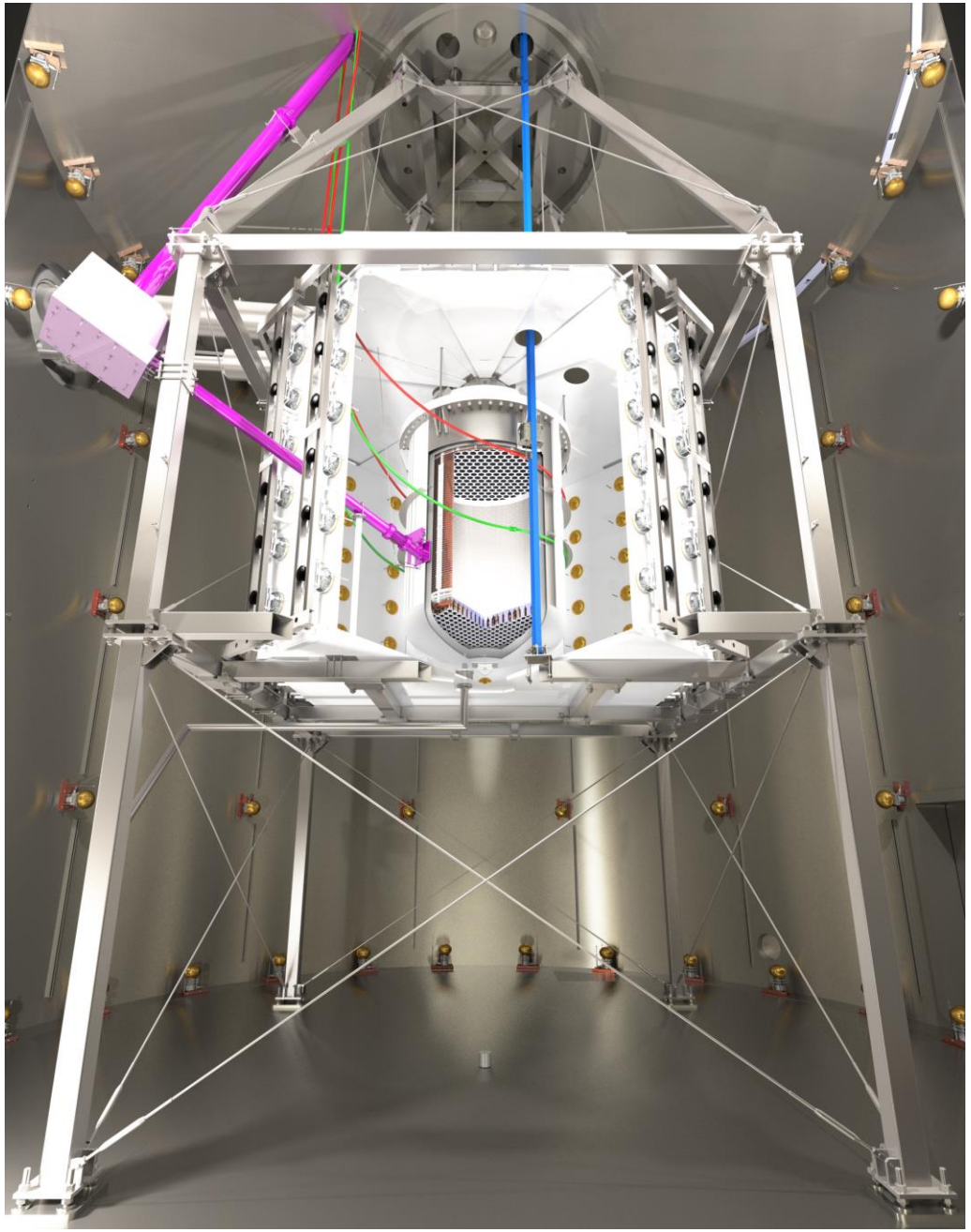
2021 *JINST* 16 P08033

Phys. Rev. Lett. 131, 041003 (2023)

Veto systems

- ✓ NV optically separated from MV by high reflectivity ePTFE panels cage
- ✓ Tag neutrons through the neutron-capture on hydrogen which releases a 2.22 MeV γ-ray
- ✓ Measured (68 ± 3) % tagging efficiency @ 600 μs window and a 5-fold PMT coincidence, and 5 PE threshold
- ✓ 53.3% tagging efficiency with SR0 configuration (250 μs veto window)

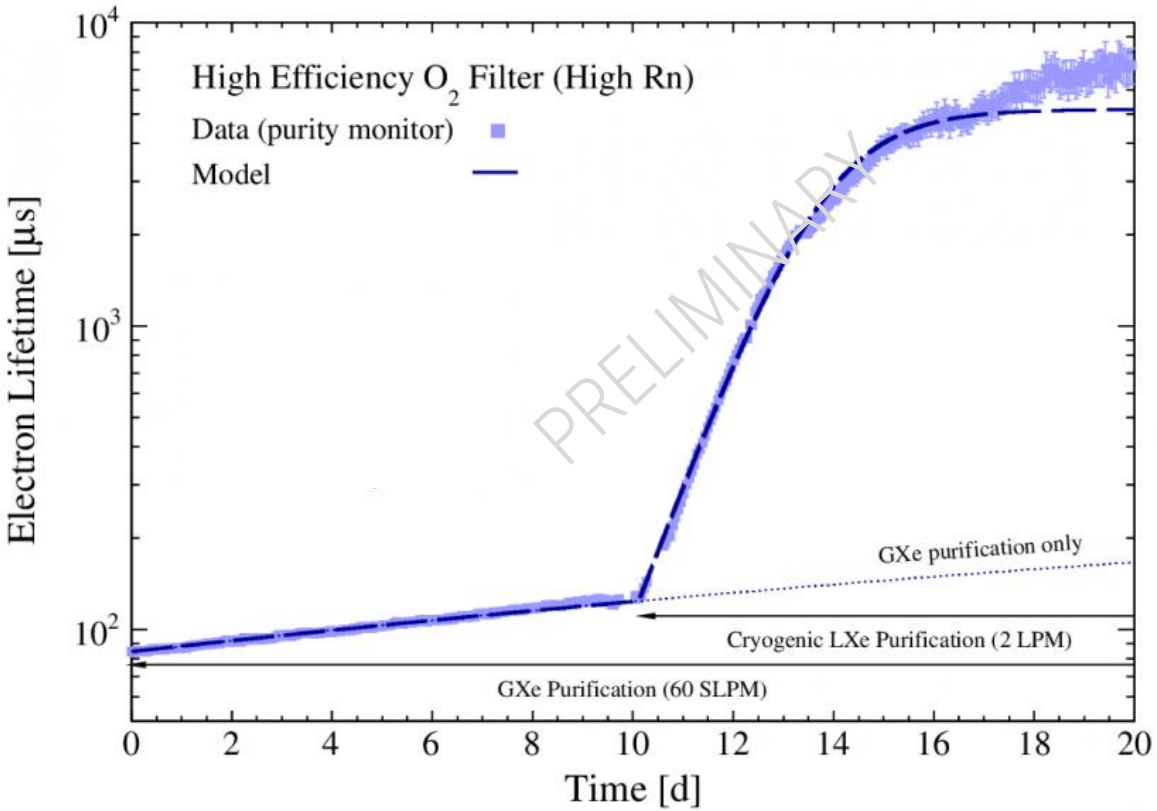




Purification of XENONnT

Eur. Phys. J. C 78, 604 (2018)
Eur. Phys. J. C 82, 860 (2022)
Phys. Rev. Lett. 129, 161805 (2022)

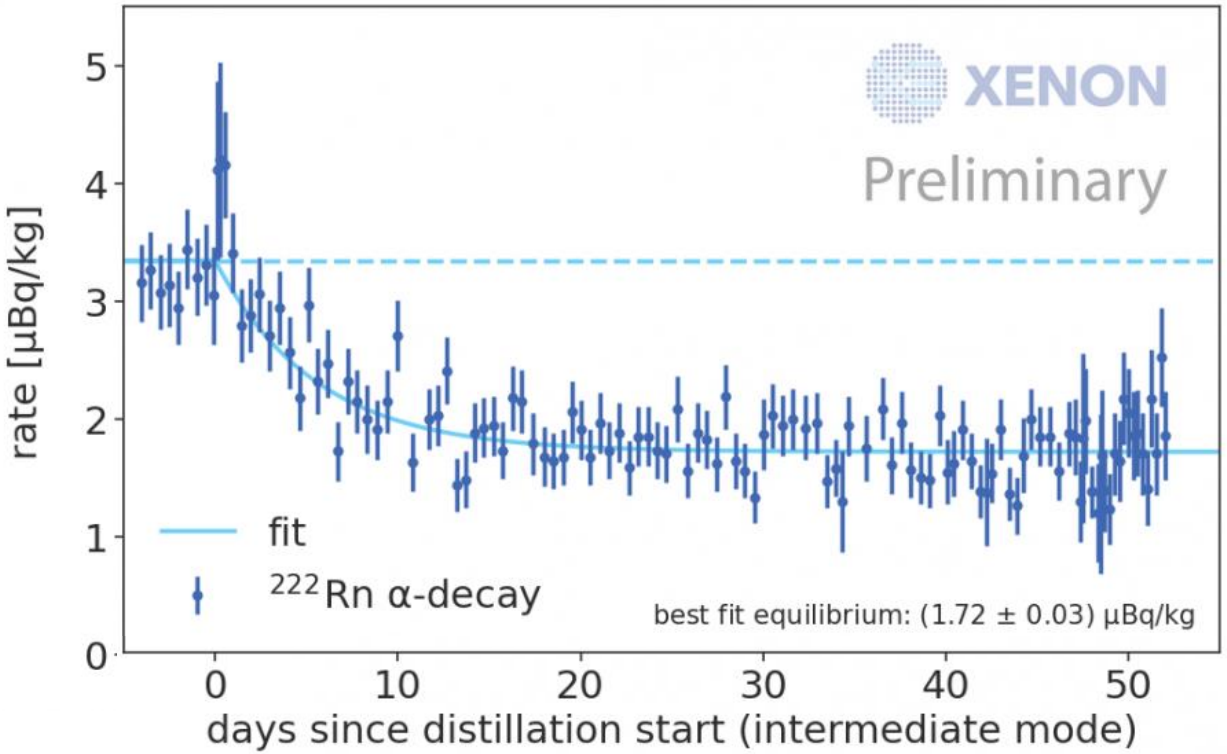
- ✓ Electronegative impurities (mainly O_2 and H_2O) induce a z dependence on the size of S2
- ✓ In addition, they can absorb the xenon scintillation photons leading to a worse S1 light collection efficiency
- ✓ Improved the inherited gas purification line (high-temperature rare-gas purifier) and installed new liquid purification line (two filters: SAES St707 getter pills and Engelhard Q-5 filter)
- ✓ Achieved electron lifetimes greater than 10 ms, greatly exceeding the TPC's maximum drift time of about 2 ms

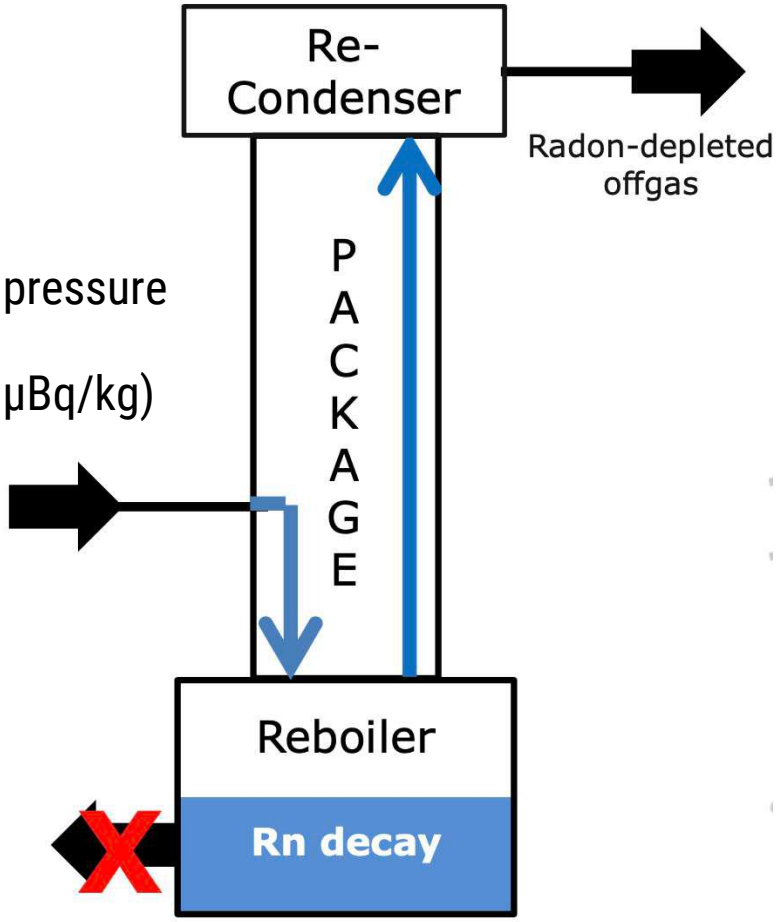


XENON distillation

Eur. Phys. J. C 77, 275 (2017)
PTEP Vol 2022, Issue 5, May 2022
Eur. Phys. J. C 77, 358(2017)
Eur. Phys. J.C 82, 110 (2022)

- ✓ Background mitigation through cryogenic distillation of the xenon
- ✓ Ar/Kr distillation performed before the science run data acquisition
- ✓ ^{nat}Kr concentration achieved: (56 ± 36) ppq, (660 ± 110) ppq in XENON1T
- ✓ Novel online distillation column to separate Rn from Xe thanks to its lower vapor pressure
- ✓ Online gas-mode Radon distillation, x10 reduction with respect to XENON1T(~12 μBq/kg)





DAQ and software

- ✓ Triggerless data acquisition
- ✓ Dual gain digitization for top PMT array
- ✓ Online processing and live monitoring

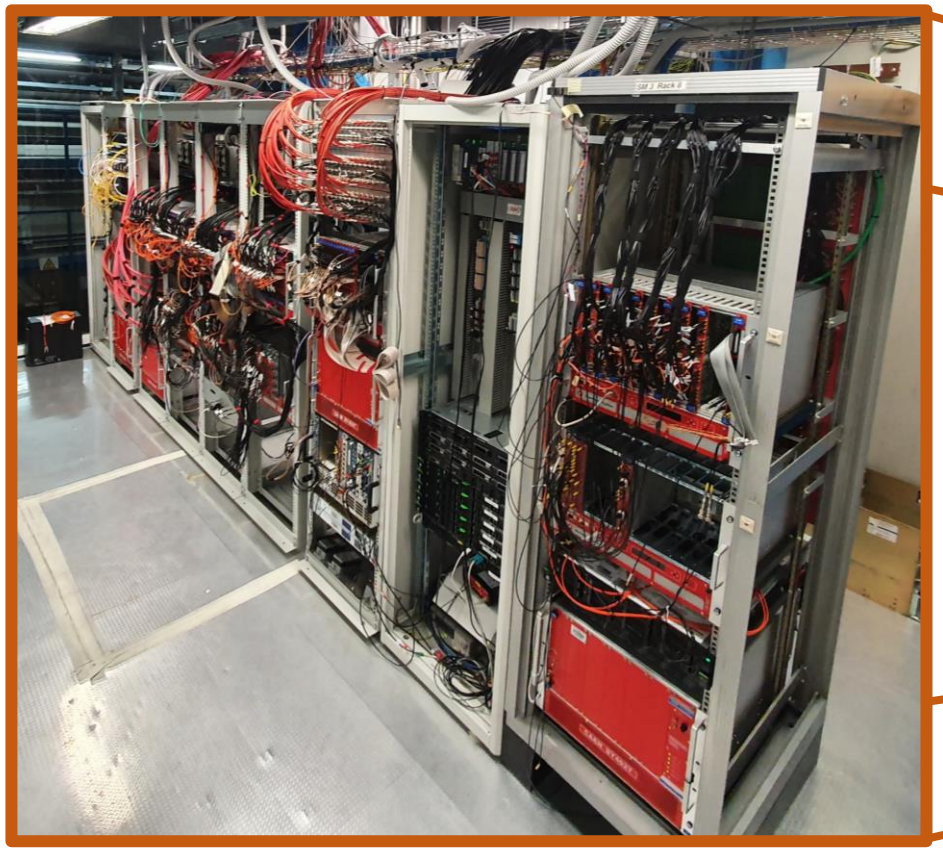
Open-source software

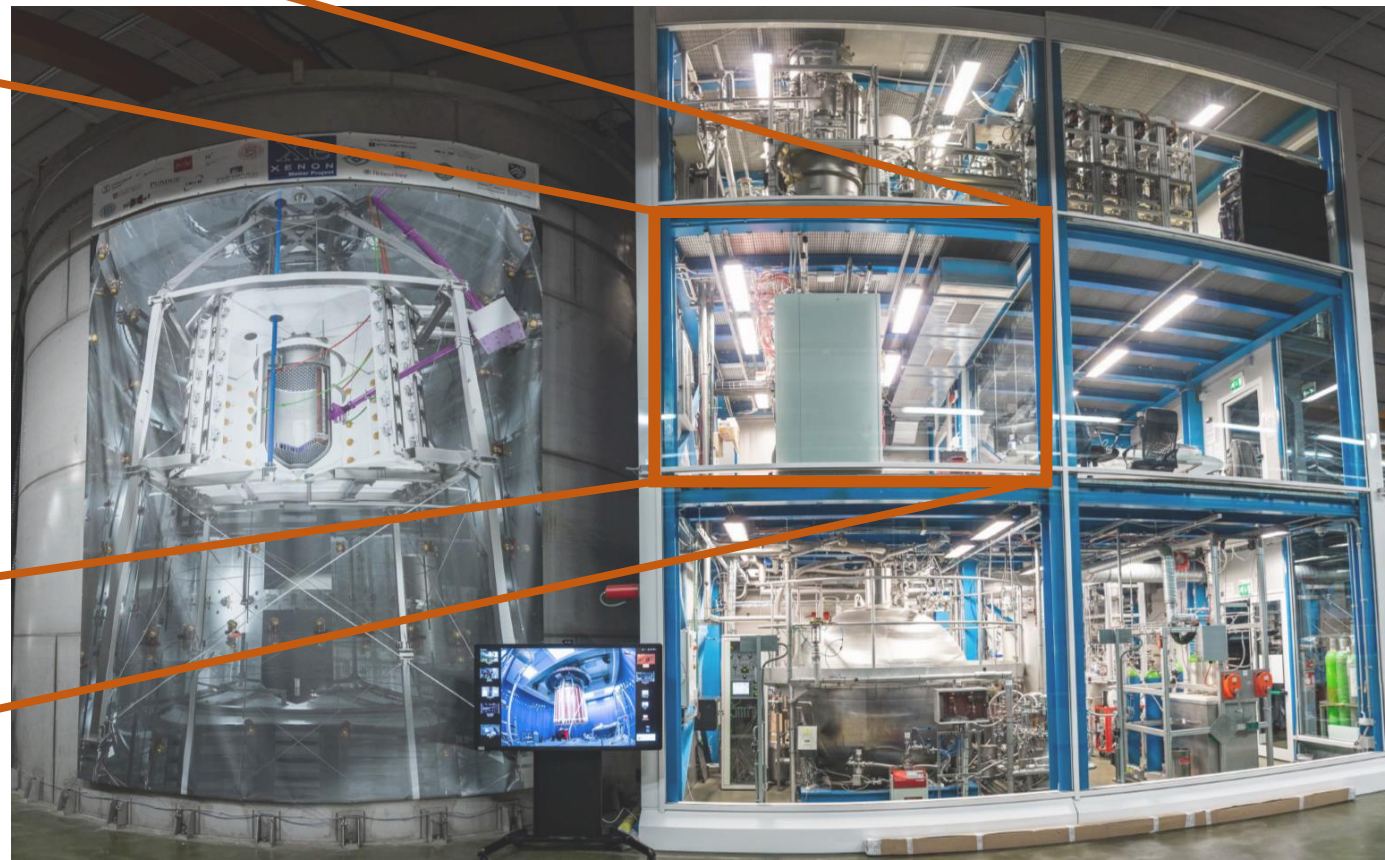
strax
Streaming analysis for xenon experiments
github.com/AxFoundation/strax

straxen
Streaming analysis for XENON(nT)
github.com/XENONnT/straxen

XeDocs
XENON metadata management tool
github.com/XENONnT/xedocs
zenodo.org/record/7945375

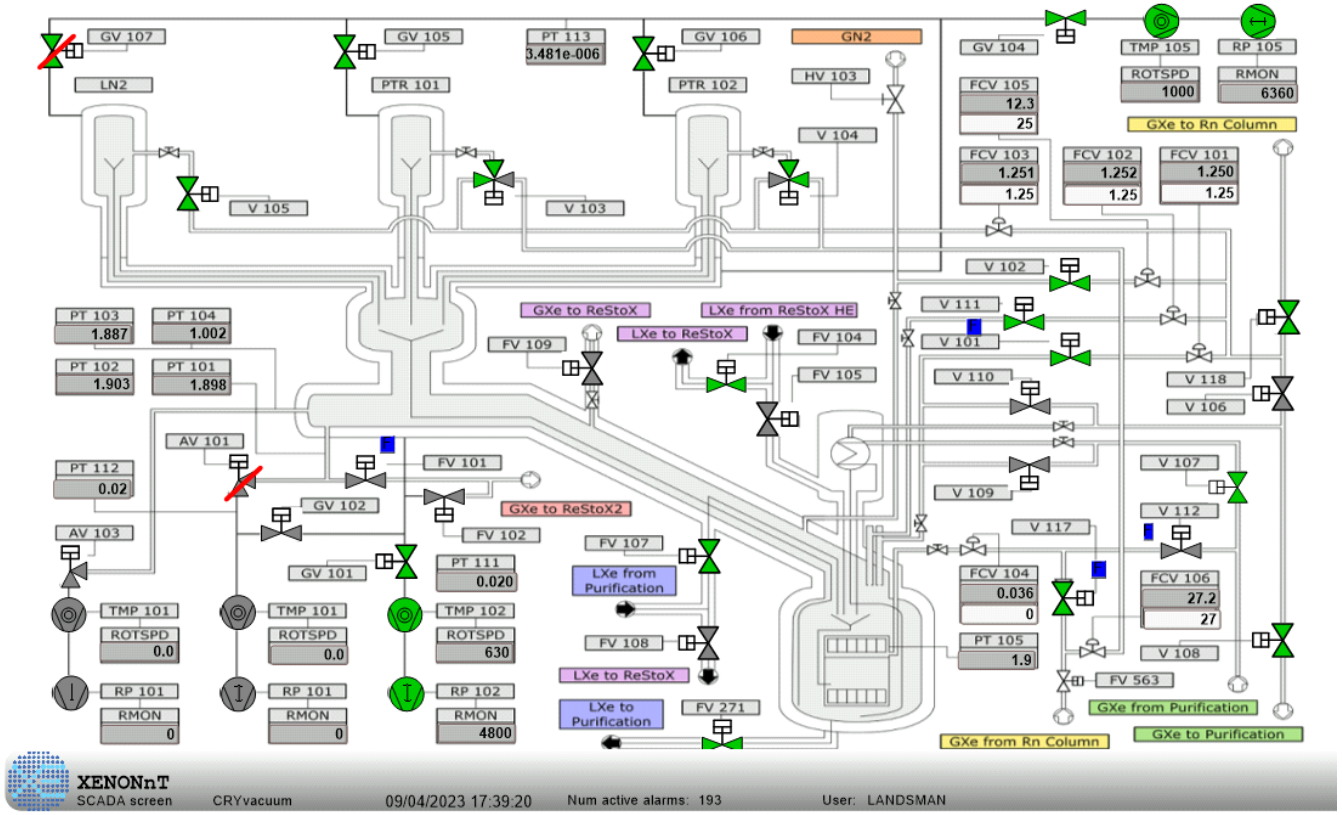
WFSim
The XENON waveform simulator
github.com/XENONnT/wfsim

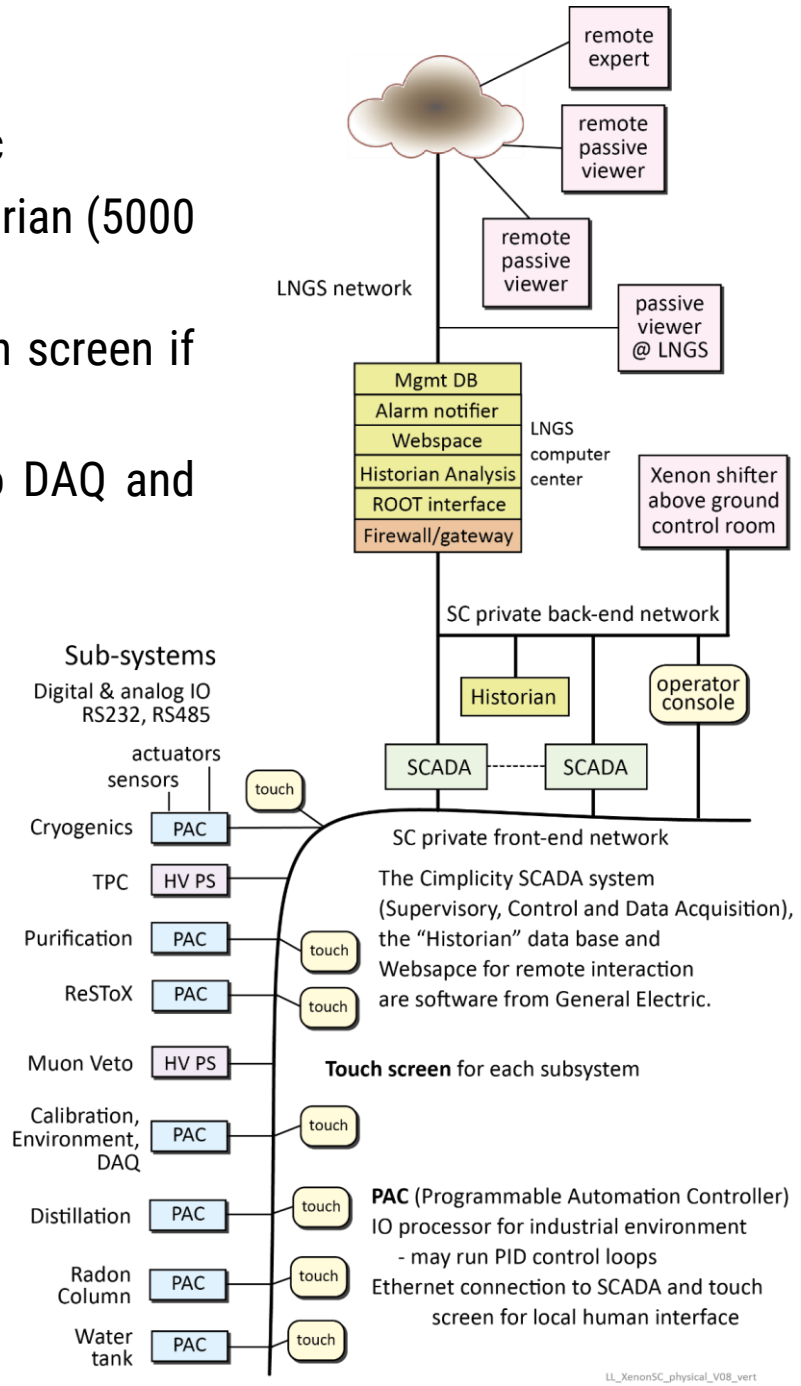




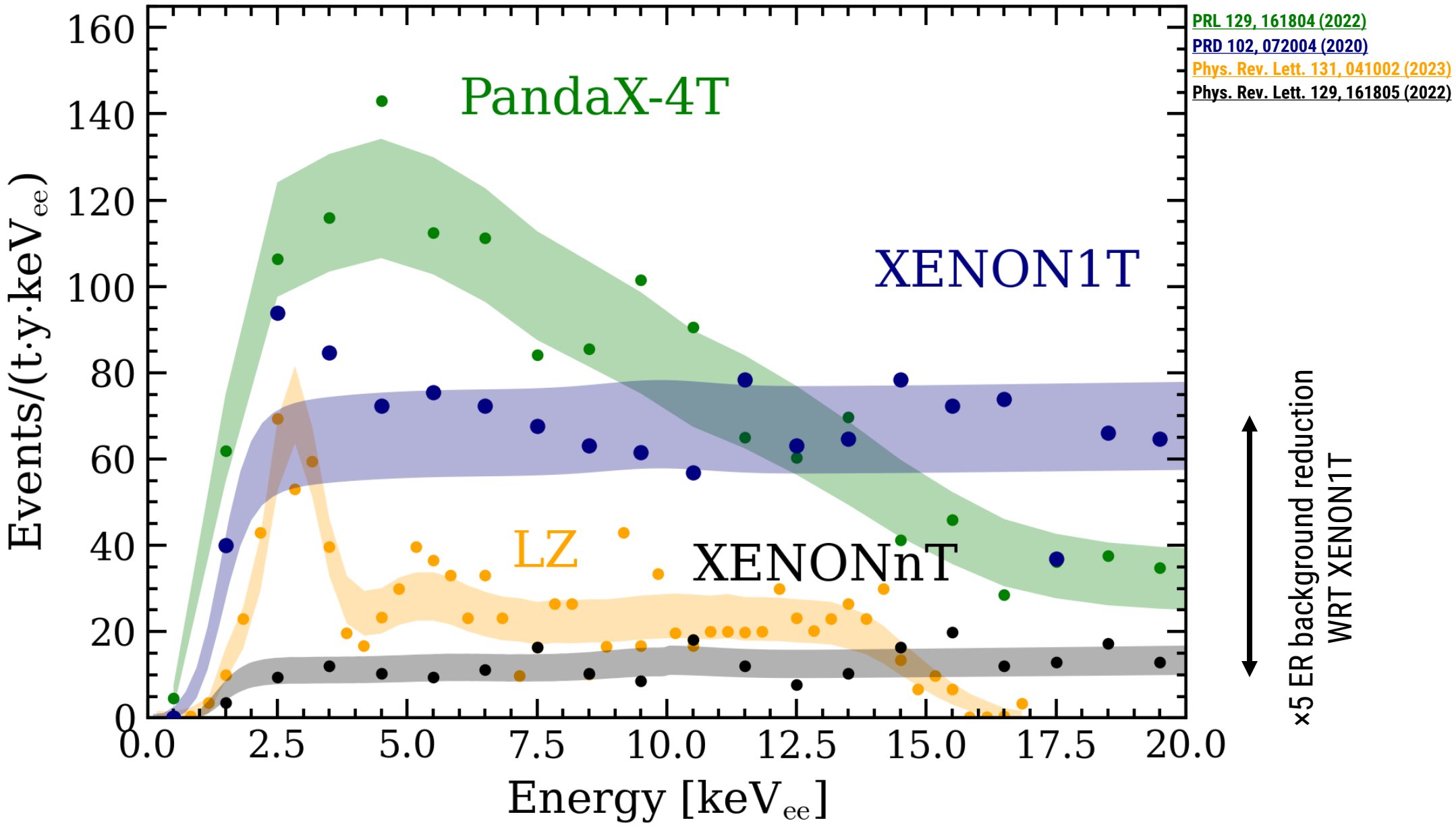
Slow Control system

- ✓ Based on industrial process control hardware and software from General Electric
  - Central failover SCADA, human interface, alarms, user authentication, Historian (5000 data points, ~1 Hz archiving)
- ✓ Controllers for each subsystem that can be operated autonomously via a touch screen if necessary
- ✓ Web-based platform display of all variables and alarms and API interfaces to DAQ and analysis systems



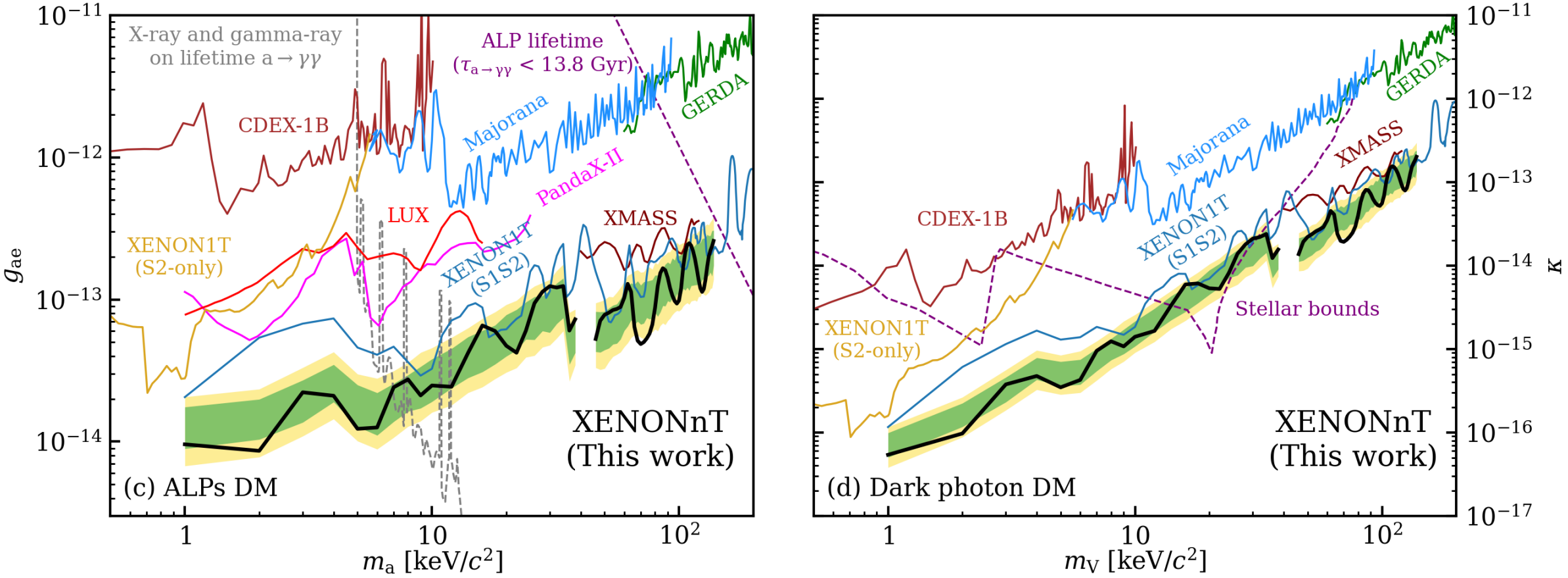


XENON1T vs XENONnT



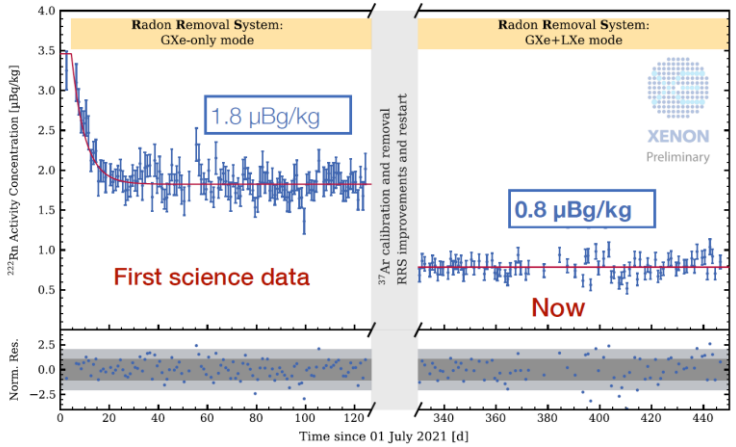
Low-energy electronic-recoil analysis results

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



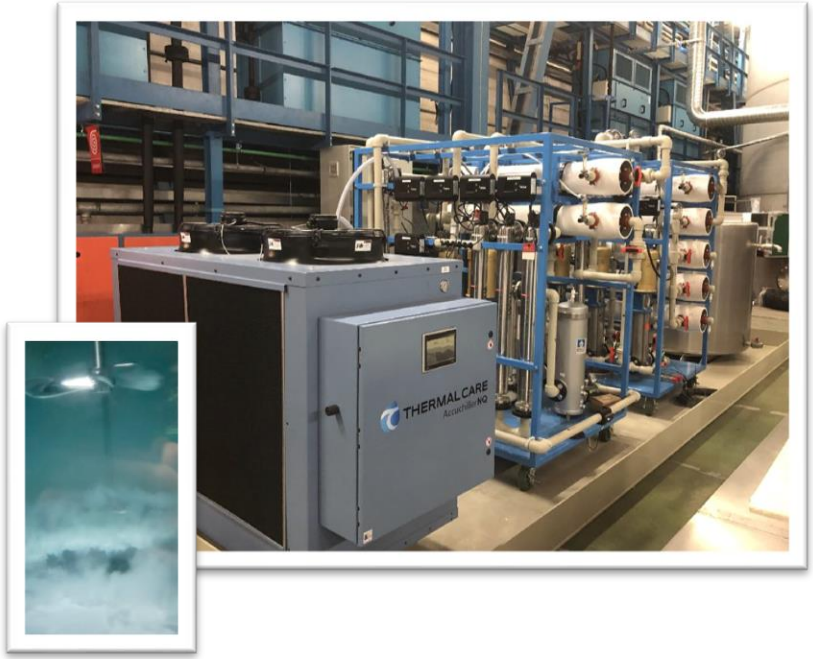
Conclusion and prospects

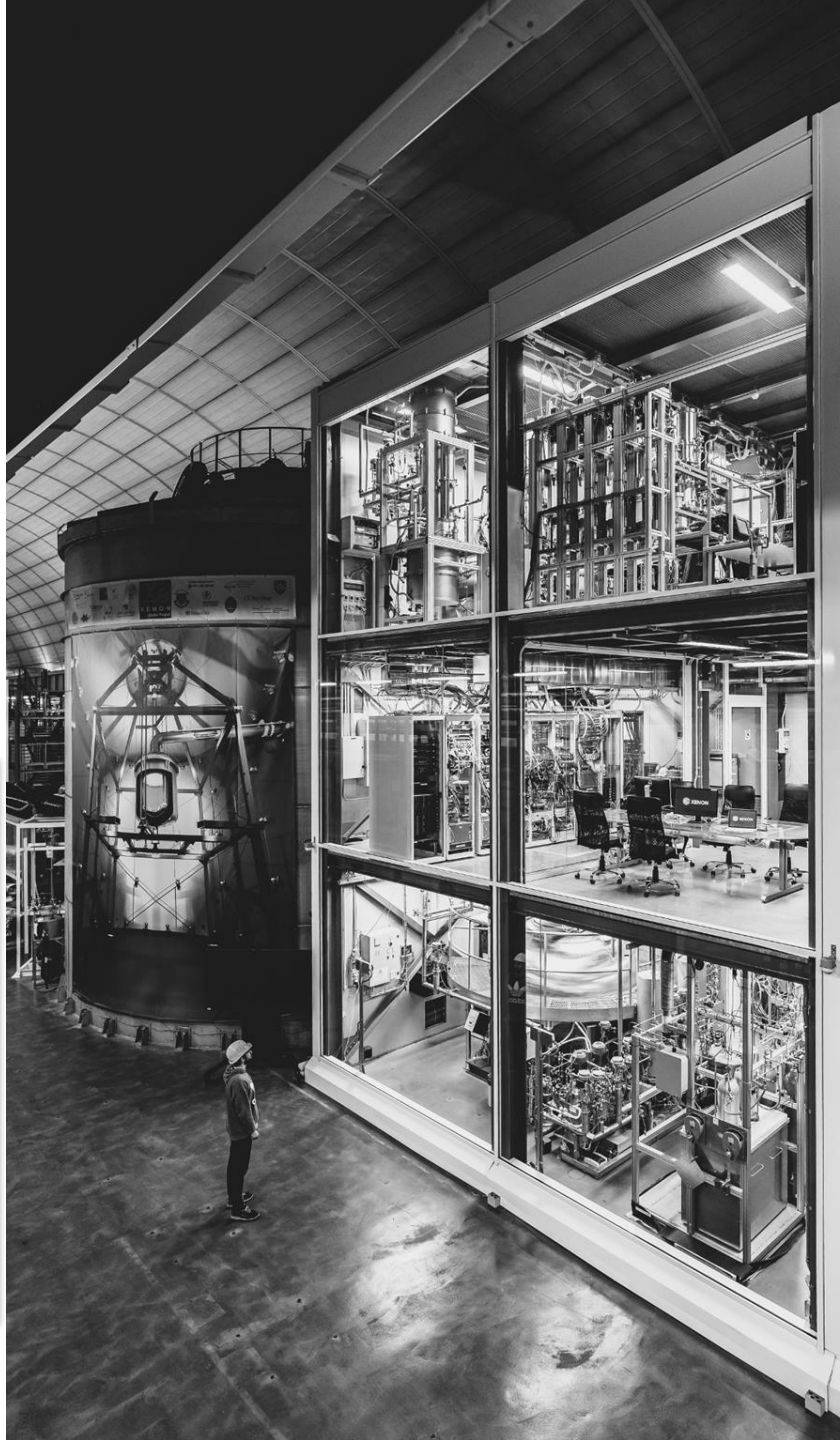
- ✓ XENONnT was fully assembled in 2020/2021, and successfully commissioned
- ✓ First blinded (SR0) WIMP dark matter search with **1.1 tonne-year exposure** performed in 2021. More data have been acquired and are currently being analyzed
- ✓ No evidence of new physics from SR0 data
- ✓ Unprecedented low ER background of 16 events/(t×yr×keV)



Further reduction of ER background by improved radon distillation flow path

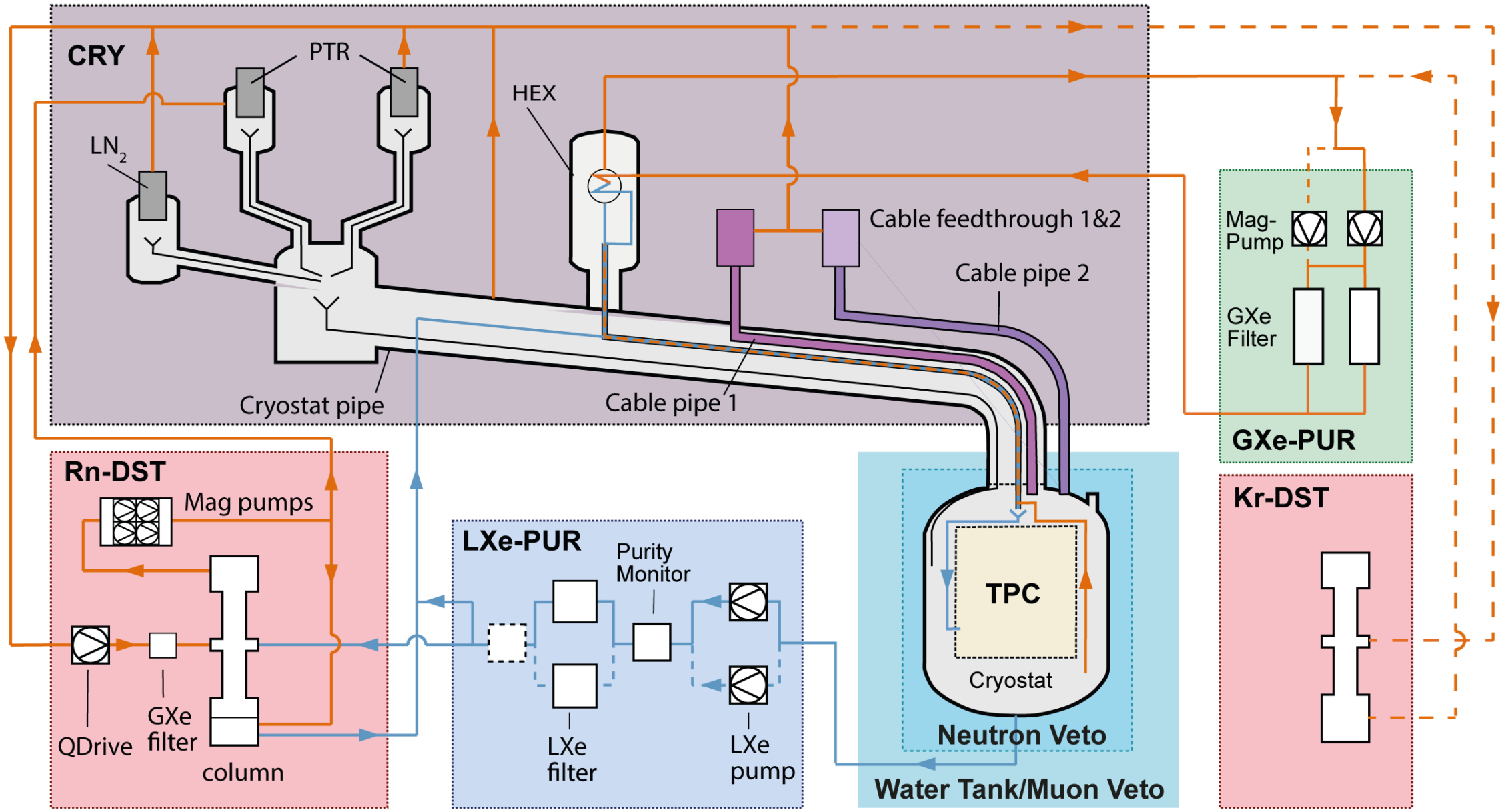
Better neutron tagging efficiency with Gadolinium in the NV



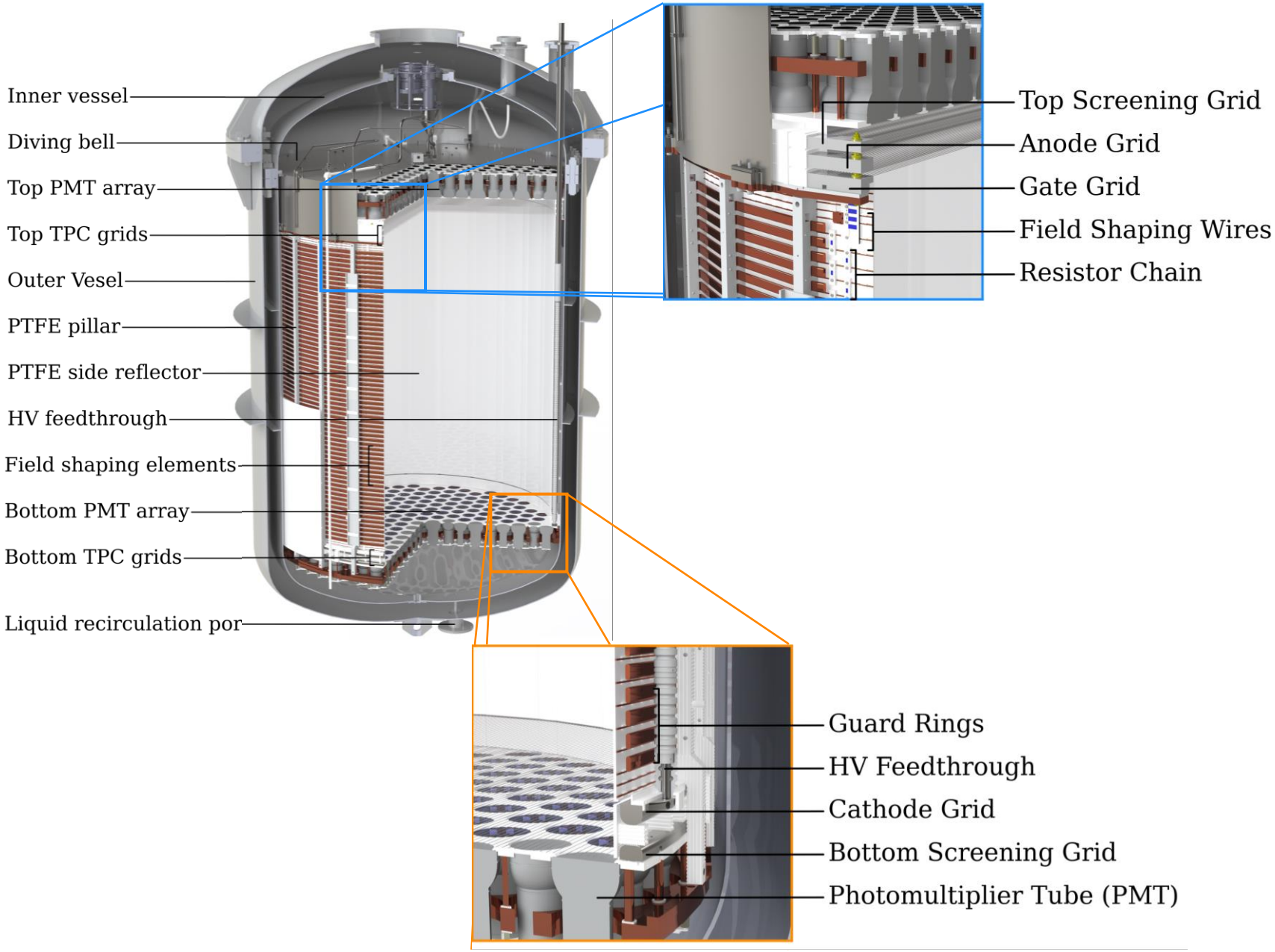


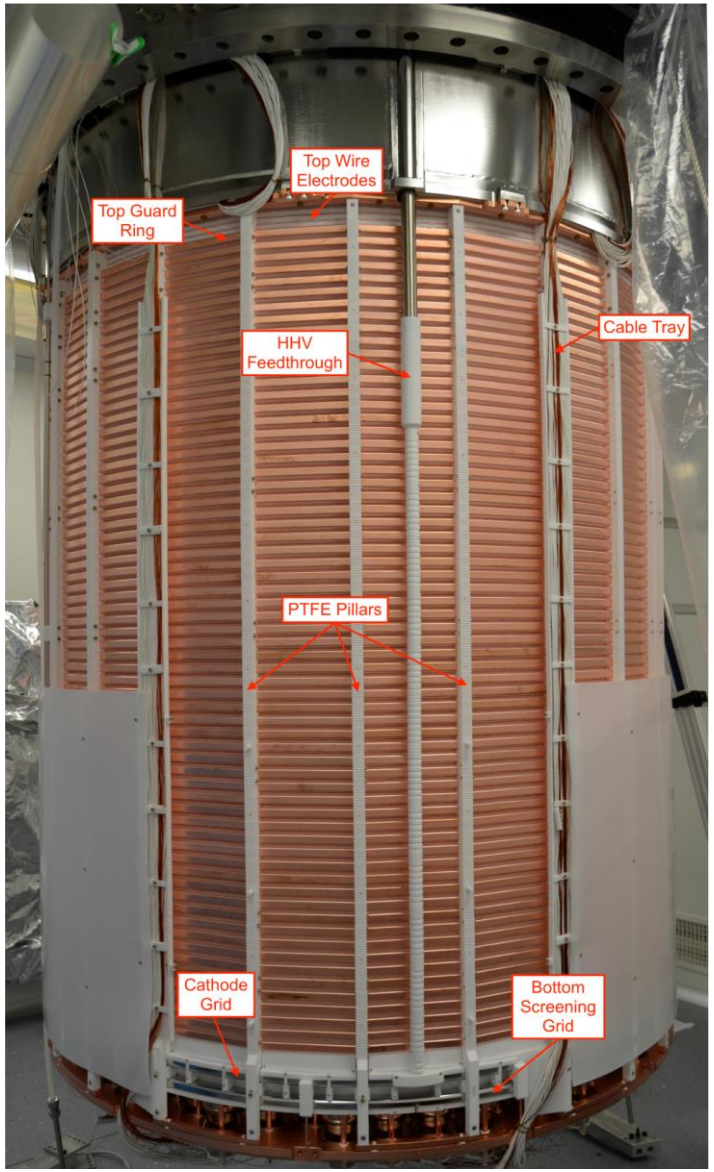
Backup slides

Schematic of the XENONnT experiment



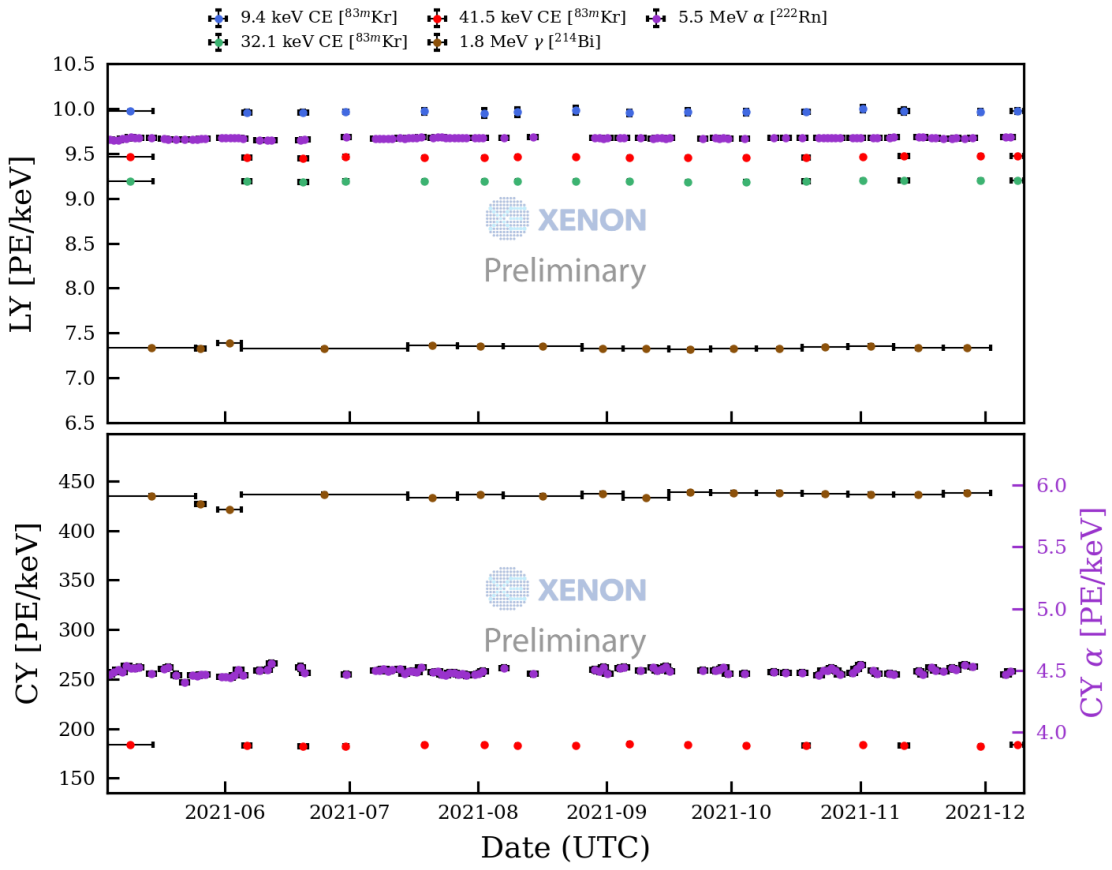
The dual-phase Time Projection Chamber

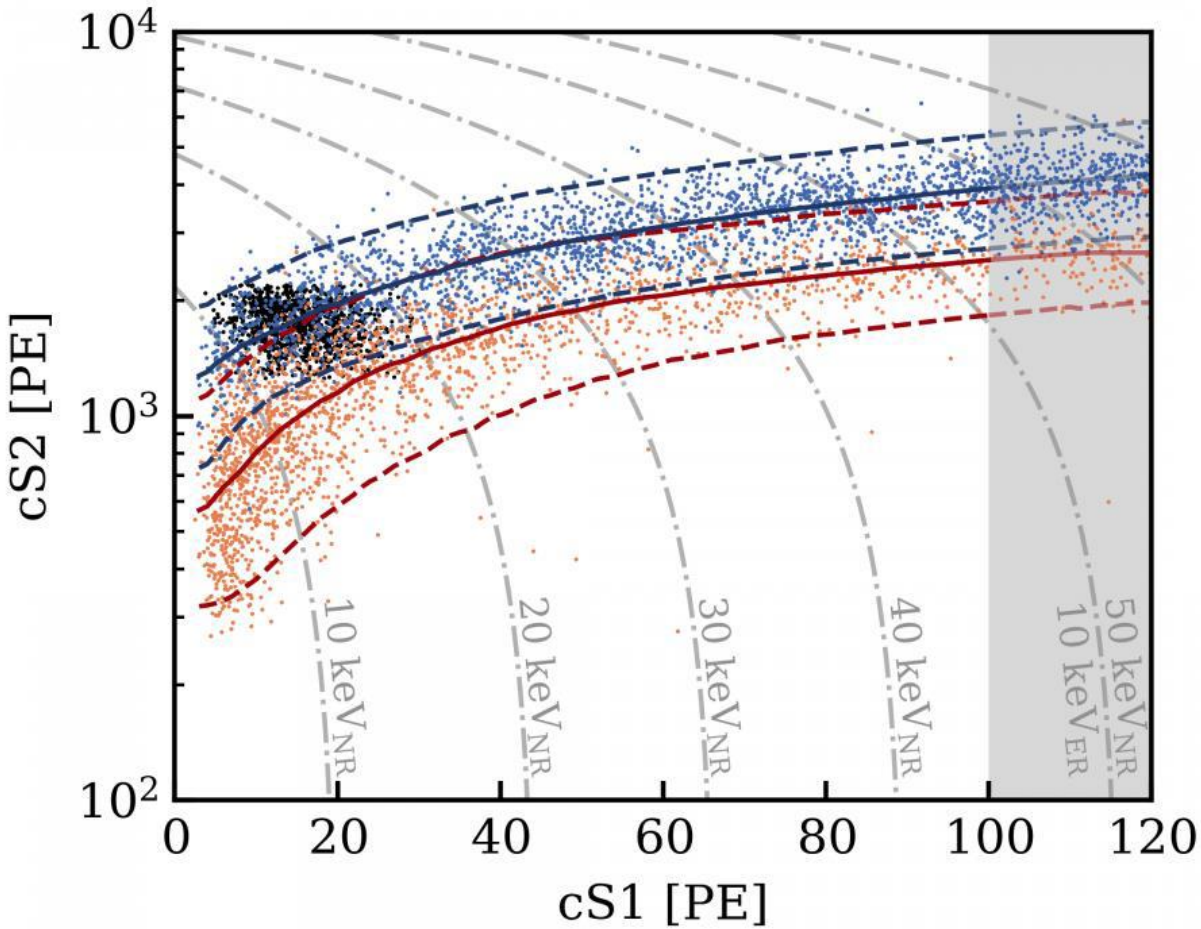




Detector response characterization

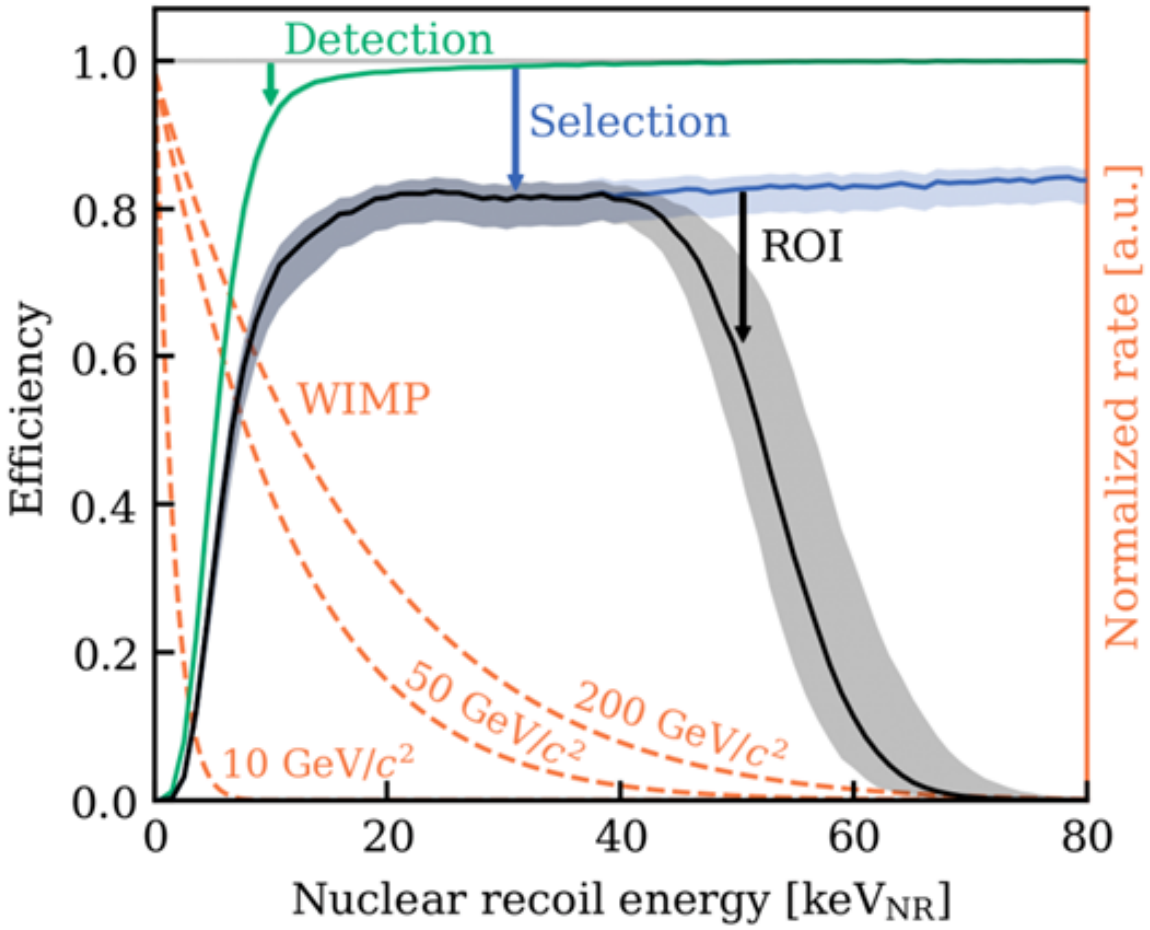
- ✓ Calibrate uniform S1 and S2 via data-driven correction based on ^{83m}Kr calibration source
- ✓ Light and charge yield monitoring using ^{83m}Kr and background sources
- ✓ LXe NR response derived via ^{241}AmBe calibration data fit
- ✓ Combined fir of ^{220}Rn and ^{37}Ar for LXe ER response model



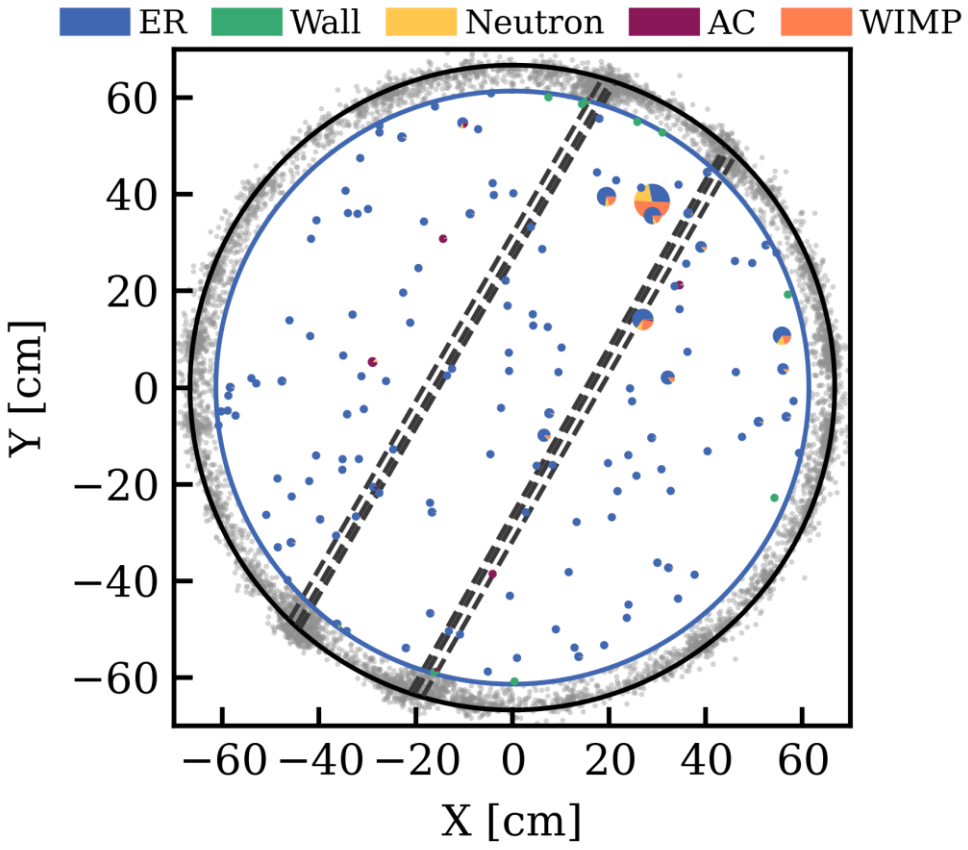


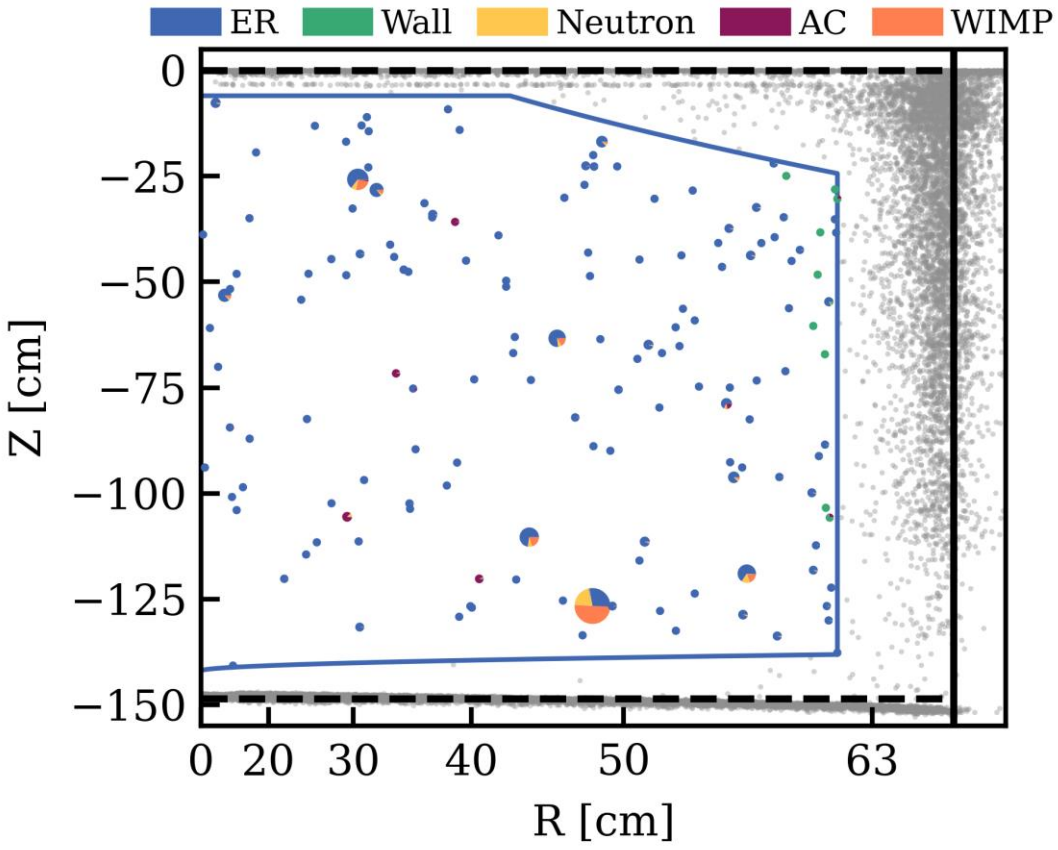
Detection and selection efficiency

- ✓ Detection efficiency:
  - Threshold driven by a 3-fold PMT coincidence for S1
  - Simulation-driven: Full waveforms
  - Data-driven: Bootstrapping from ^{83m}Kr and ^{37}Ar S1
  - Both processed with analysis framework
- ✓ Data quality selection evaluated using ER/NR calibration data
- ✓ ROI defined to fully contain WIMP spectra
  - cS1 [0 pe, 100 pe]
  - cS2 [$10^{2.1}$ pe, $10^{4.1}$ pe]
- ✓ Total acceptance > 10 % between [3 keV_{NR}, 60 keV_{NR}]

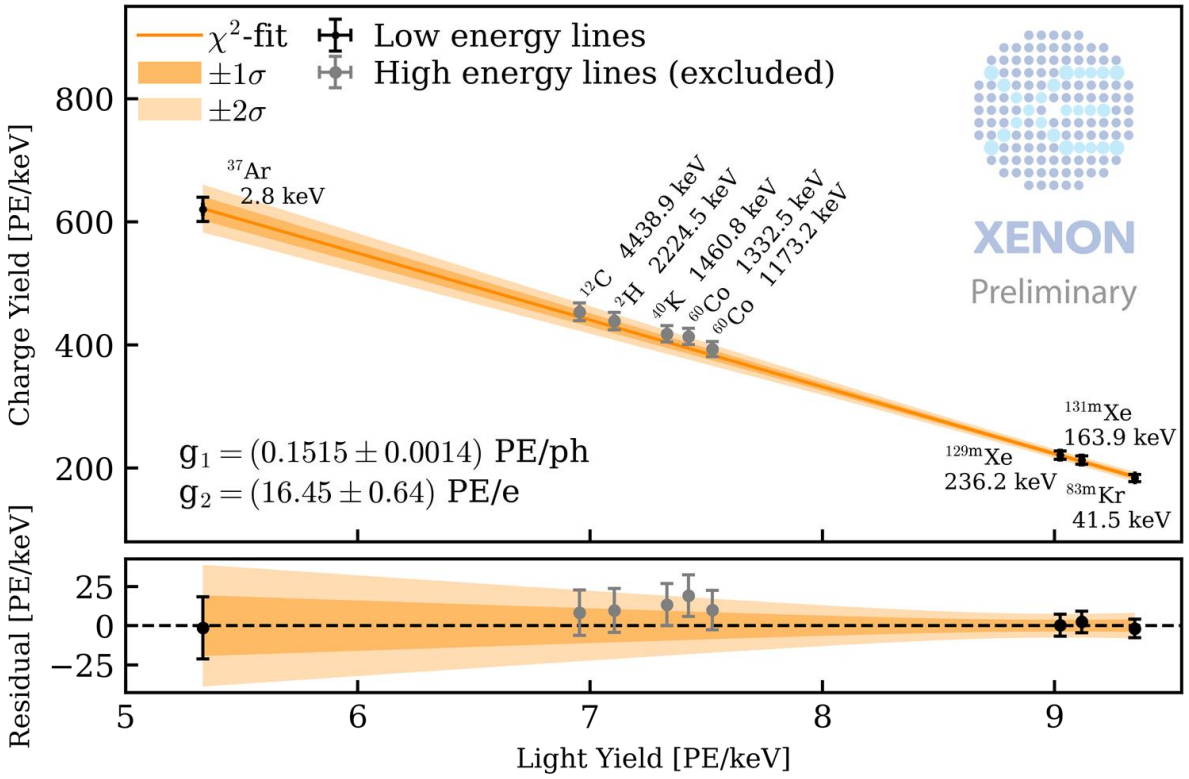


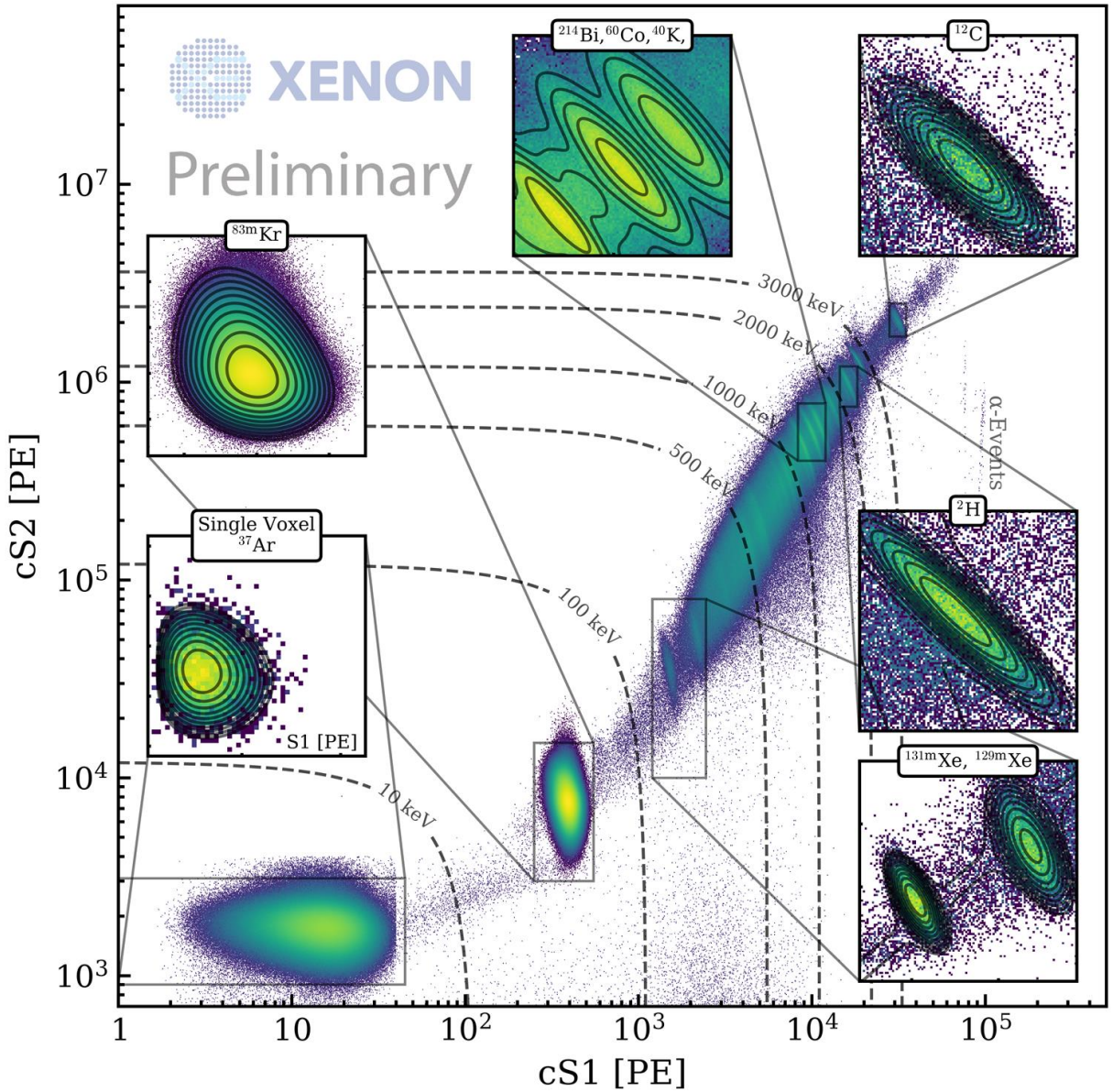
WIMP search fiducial volume





Energy calibration





- ✓ The g1 and g2 are detector parameters obtained by studying the anti-correlation between S1 and S2 using different mono-energetic calibration sources
- ✓ Energy scale important to forward fold WIMP spectrum into cS1 and cS2 (: $E_{nr} = E_{er} \times f_{quenching}$)

Low energy ER analysis