XENON

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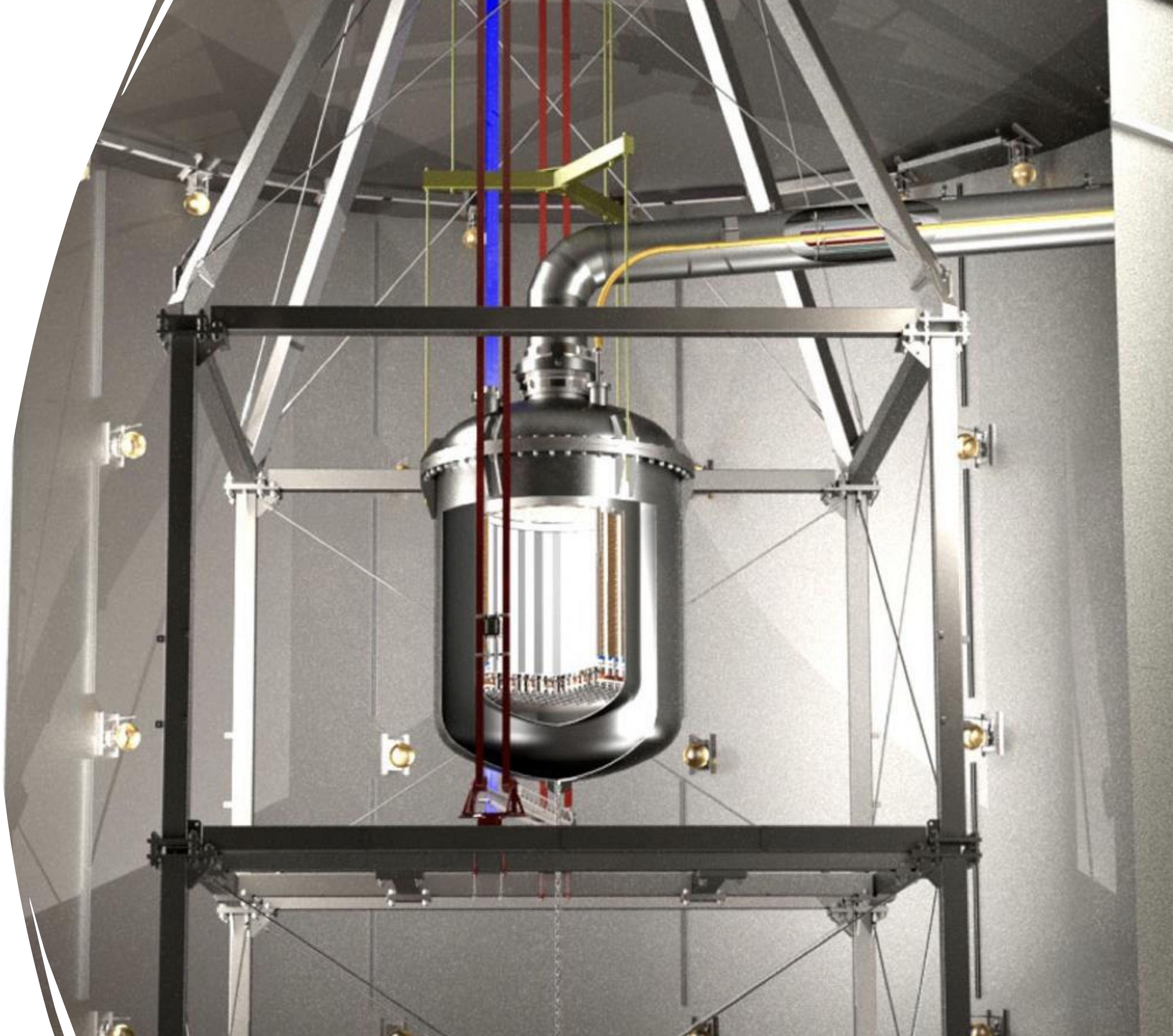
The XENON program

This program is a long-term, multi-stage effort to directly detect dark matter using dual-phase liquid xenon time projection chambers

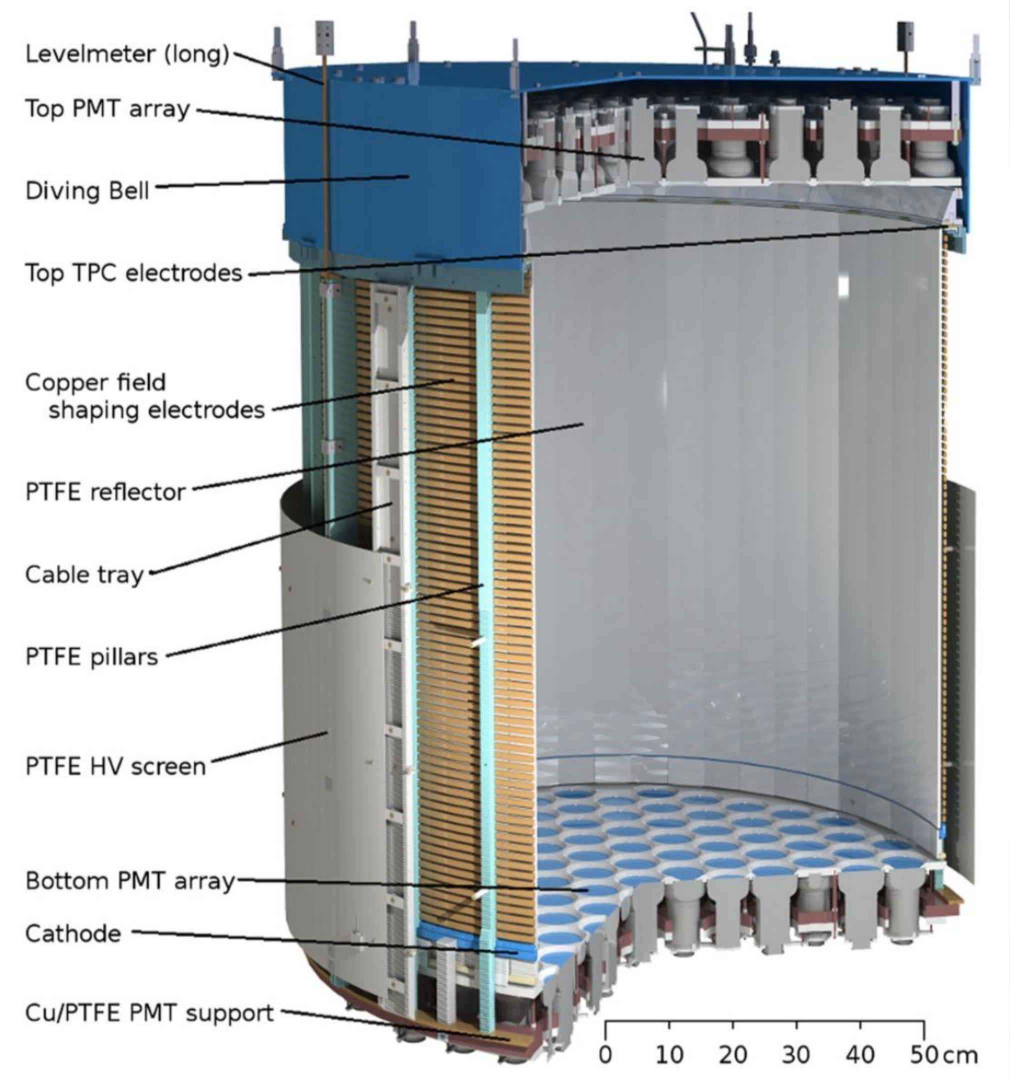
- XENON10:
  - demonstrated the capabilities that define all later detectors:
    - TPC
    - Production of two distinct signals: prompt scintillation (S1) and proportional scintillation (S2) from ionization electrons extracted into the gas phase
    - Xenon ultrapure
  - set the first competitive limit on WIMPs
- XENON100:
  - increased the xenon mass
  - lowered radioactive backgrounds:
    - selecting ultraclean materials
    - adding an active xenon veto around the TPC
  - improved sensitivity by nearly two orders of magnitude
- XENON1T:
  - the first tonne-scale liquid xenon detector
  - water tank that served as a powerful shield against muon-induced and environmental backgrounds
  - set the world’s best limits on WIMP interactions

- XENONnT:
  - the highest purity ever reached in such a detector
  - has achieved the lowest background levels ever measured in a dark matter



Time Projection Chamber (TPC)

- central sub-detector
- to detect and precisely characterize the extremely rare energy depositions that might be produced by dark matter interactions.
- converts every particle interaction occurring in liquid xenon into two measurable observables to reconstruct the deposited energy
- Purpose:
  - measurement
  - Discrimination
- All higher-level detectors (the water tank, the neutron veto, the distillation systems) support the TPC reducing backgrounds

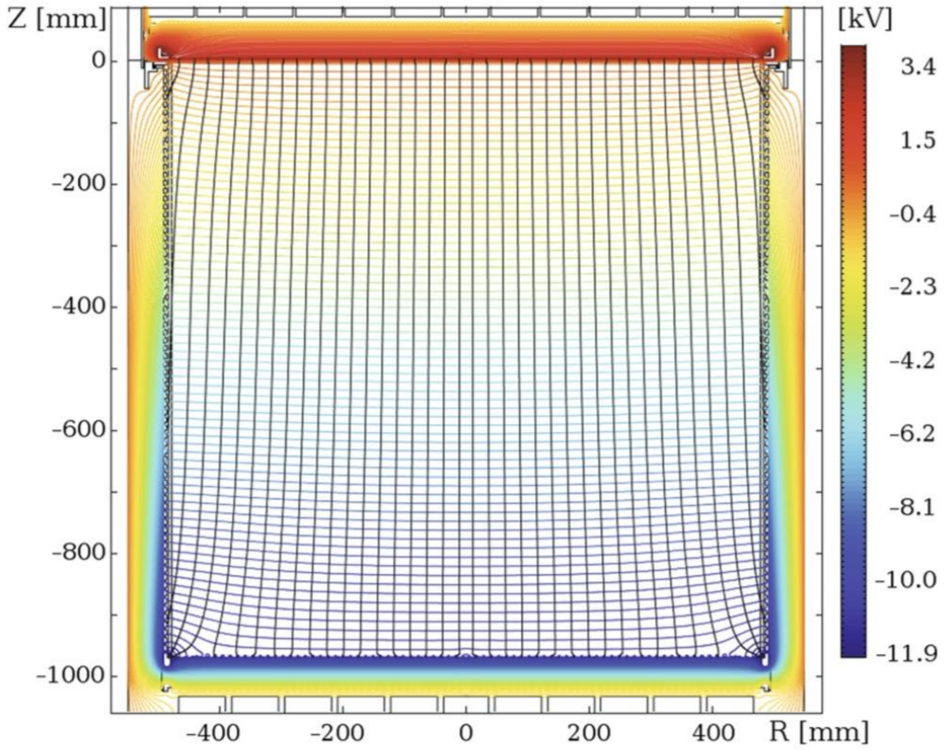


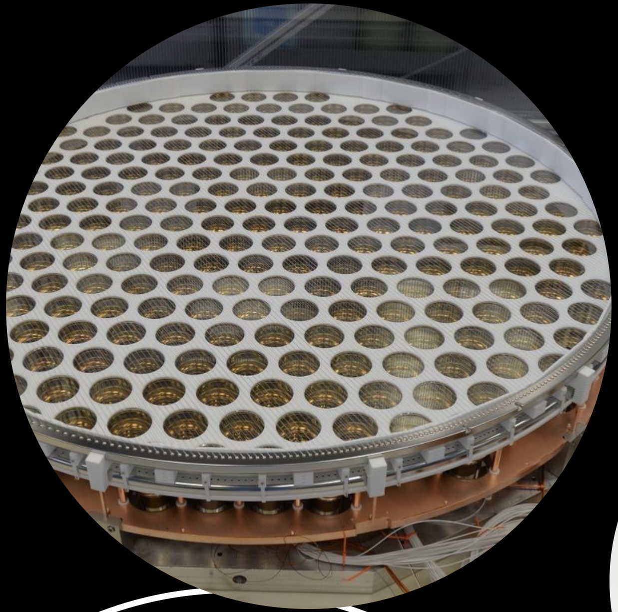
The main quantity to be measured:

The main quantity measured by this subdetector are:

1. energy of the interaction
   - derived from S1 and S2, not directly mesured
2. three-dimensional position
   - From temporal difference of S1 – S2 signal = drift time
   - x-y from S2 light on top PMT array
3. type of interacion
   - Electronic recoil —> background
   - Nuclear recoil —> possible WIMP (or neutrons)
   - By S2/S1 ratio (low)

- These quantities—energy, position, and recoil type—are the essential physical observables needed for dark-matter searches

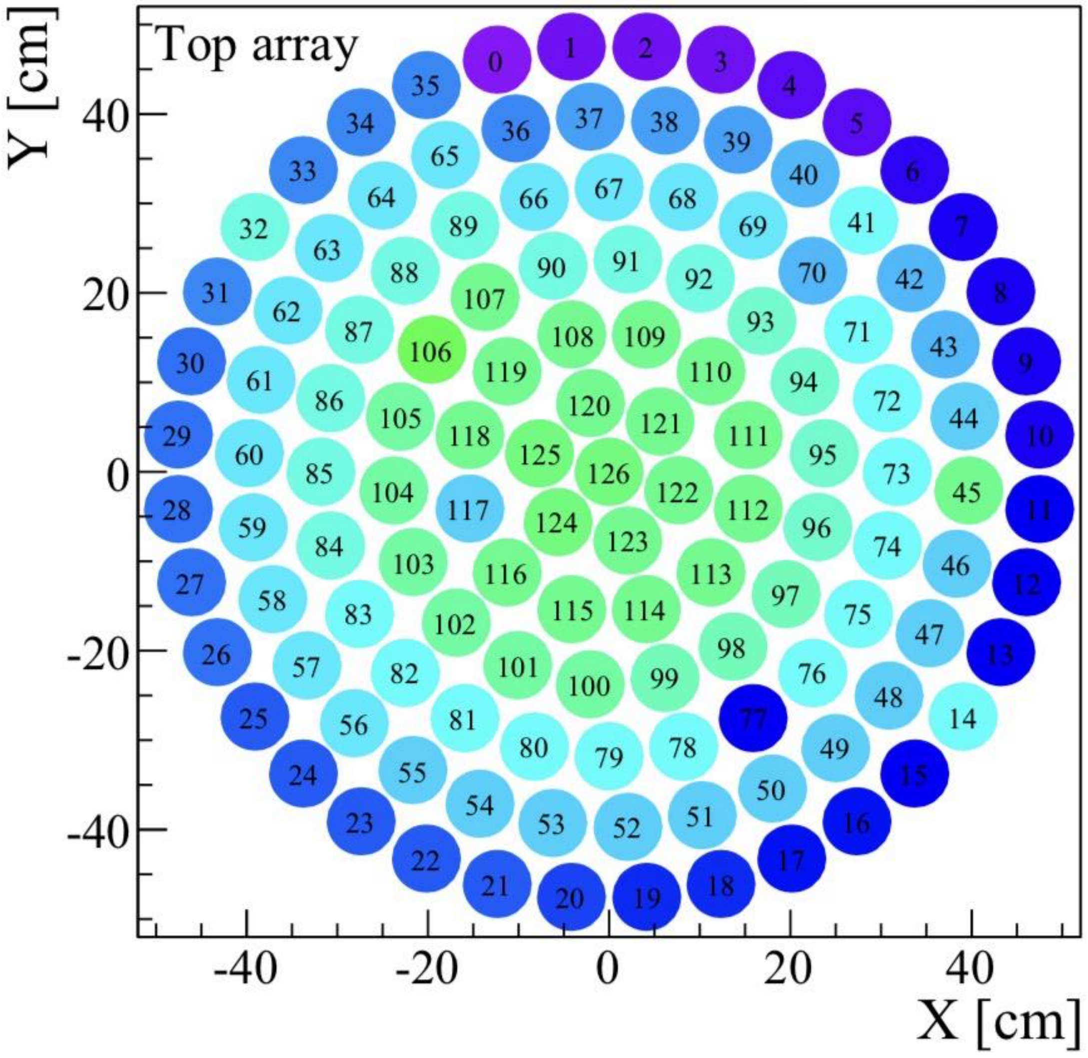




The smallest detection element:

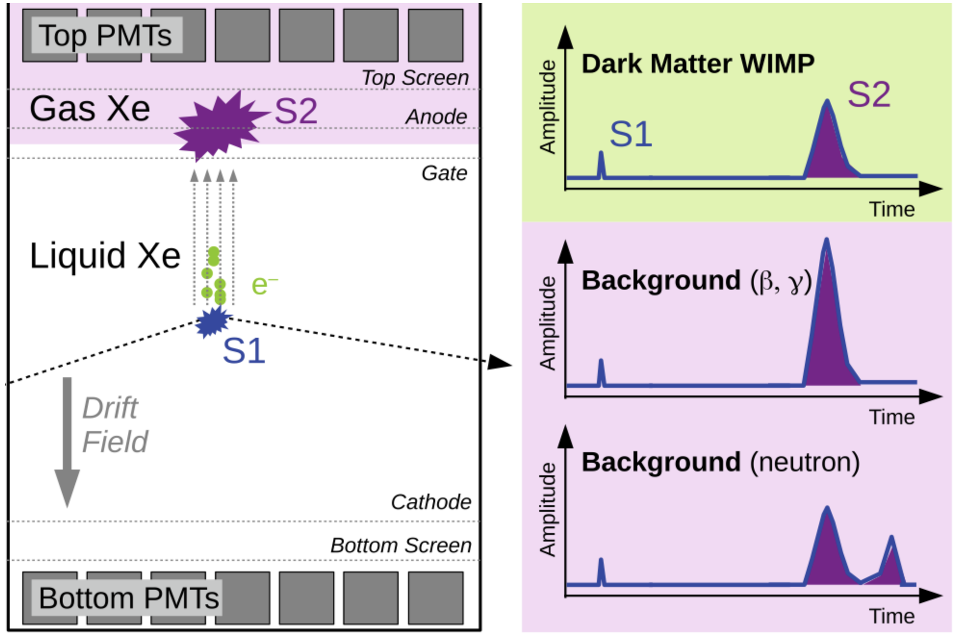
- the smallest detection elements is the individual photomultiplier tubes (PMTs): Hamamatsu R11210-21
- 248 PMTs for the top and 248 for the bottom(253 + 241PMTs for XENONnT)
- They detect ultraviolet photons
- distributed across a top and a bottom array,
  - Top: reconstruction of x-y
  - Bottom: S1, improve energetic resolution, define fiducia volume
- particle interacts —> produces an S1 scintillation flash —> S2 electroluminescence signal in the gas above the liquid

- The large number of PMTs allows the detector to measure:
    - the total light
    - the spatial distribution of photons, especially in the S2 signal
- the basic microscopic unit of measurement is the single-photon detection at each PMT
- the increased PMT count
    - improved optical coverage
    - reconstruction of energy and position more accurate and reliable



This figure shows the top PMT array in X–Y coordinates.
Each circle is a PMT, and the color/size represents the amount of S2 light recorded.

The physical phenomenon the detecting technology is based on



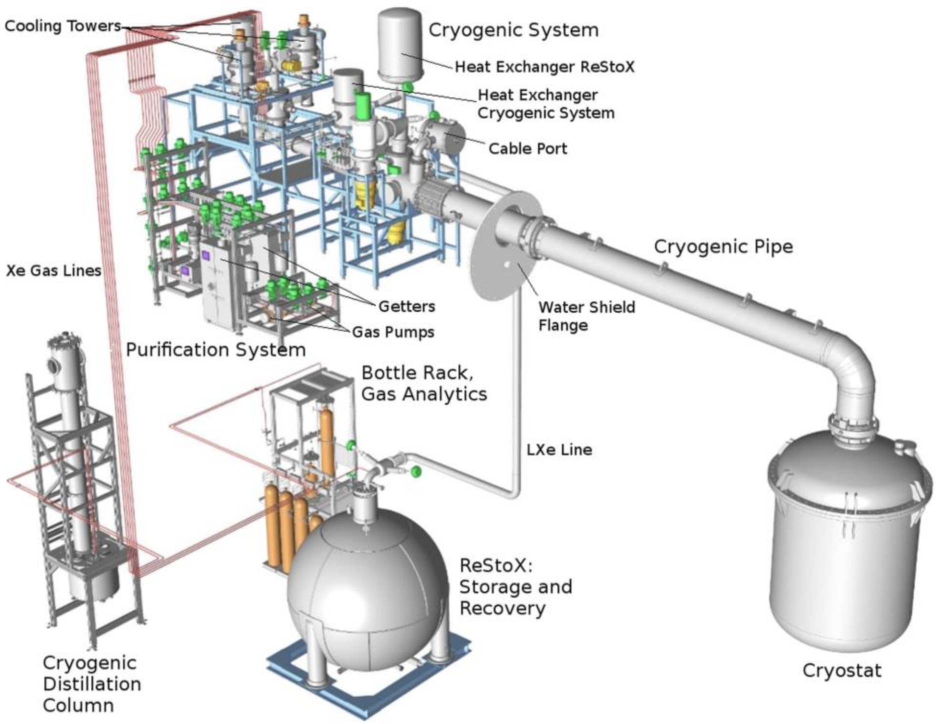
scintillation and ionization

particle deposits energy in liquid xenon —>excites xenon atoms —> form short-lived excimers (Xe*_2)

- $Xe^* + Xe \longrightarrow Xe^*_2 \rightarrow 2Xe + h\nu$
- that decay by emitting vacuum-ultraviolet scintillation photons (178 nm)—> S1 signal
- Simultaneously—> ionization of xenon atoms —> free electrons that drift upward under a uniform electric field.
- field pulls the electrons produced from xenon ionization into the gas phase
- they collide with xenon atoms and generate electroluminescence light—> S2 signal

efficiency enhanced by the excellent optical properties of xenon and the PTFE reflectors that line the TPC walls, maximizing the collection of scintillation light

The use of detector information



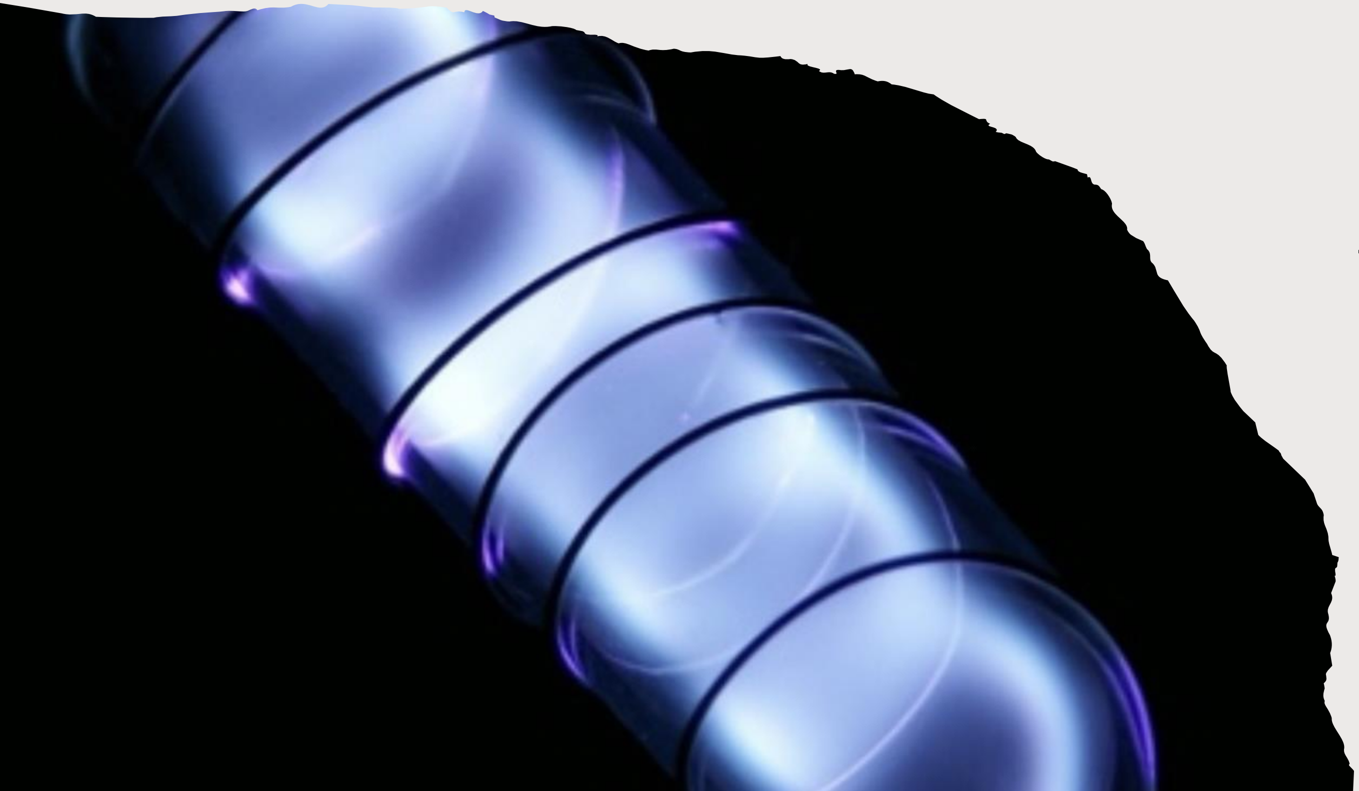
The readout begins with the PMTs

- digitize the waveform of every detected photon—> reconstruction software
    - identify individual pulses, measure their integrals, and apply position-dependent corrections
- corrected signals:
    - cS1–> scintillation signal corrected
    - cS2 —> ionization signal corrected
- converted into energies and 3D positions

After reconstruction:

- events are statistically as electronic or nuclear recoils based on their location in the S2/S1 plane
- data-quality cuts + fiducial volume cuts + veto coincidences to remove background-like events
- the remaining candidate events are analyzed using high-level statistical techniques
- repeated calibration cycles and comparisons with fast detector simulations to validate

Materials used in the program



Liquid xenon:

- it scintillates and ionizes efficiently
- high density (3 g/cm^3) and large atomic number (Z=54) provide powerful self-shielding against external radiation

Action on particles:

- Neutrons: elastic scattering
- Charged particles: stopped (alpha in um, electrons mm-cm)
- neutrinos and WIMPs: traverse the detector with minimal attenuation
- most γ and β backgrounds: absorbed or multiple scatterings in the outer layers of the xenon

The materials surrounding the TPC strengthen this effect:

- PTFE reflectors improve light collection and contributing to the moderation of low-energy particles
- copper cryostat —> gamma and slow neutrons absorption
- large water —>provides additional absorption, moderation of muons and neutrons, works as Cherenkov veto

Key performance numbers

Background rate:

- quantifies how many non–dark-matter events are expected per unit mass, time, and energy
- 16.1 ± 1.3 events/(ton·year·keV)
- the lowest ever measured in a dark-matter detector and one of the defining performance achievements

Background source	Type	Rate $[(t \times y)^{-1}]$	Mitigation approach
^{222}Rn (10 μBq/kg)	ER	620	Material selected for low Rn-emanation; ER rejection
Solar pp- and ^{7}Be-neutrinos	ER	36	ER rejection
^{85}Kr (0.36 ppt of ^{nat}Kr)	ER	56	Cryogenic distillation; ER rejection
$2\nu\beta\beta$ of ^{136}Xe	ER	9	ER rejection
Material radioactivity	ER	30	Material selection; ER and multiple scatter rejection; fiducialization
Radiogenic neutrons	NR	0.55	Material selection; multiple scatter rejection; fiducialization
CNNS (mainly solar ^{8}B-neutrinos)	NR	0.6	–
Muon-induced neutrons	NR	< 0.01	Active Cherenkov veto [44]; multiple scatter rejection; fiducialization

Electron lifetime:

- The electron lifetime is the average time an ionization electron can drift in liquid xenon before being captured by impurities
- exceeds 2 ms (10 ms for XENONnT) thanks to the new liquid purification technology
- ensures that ionization electrons can drift over the full height of the TPC without being captured by impurities (maintaining high energy and position resolution)

Impurity level

- 10^-9 (O2-equivalent)

Quantum efficiency of the PMT

- Probability that an incident photon produces a detectable photoelectron
- at 187 nm: 30% of the Xenon wavelength
- one third of the e- is a signal

The operational conditions

cryogenic conditions:

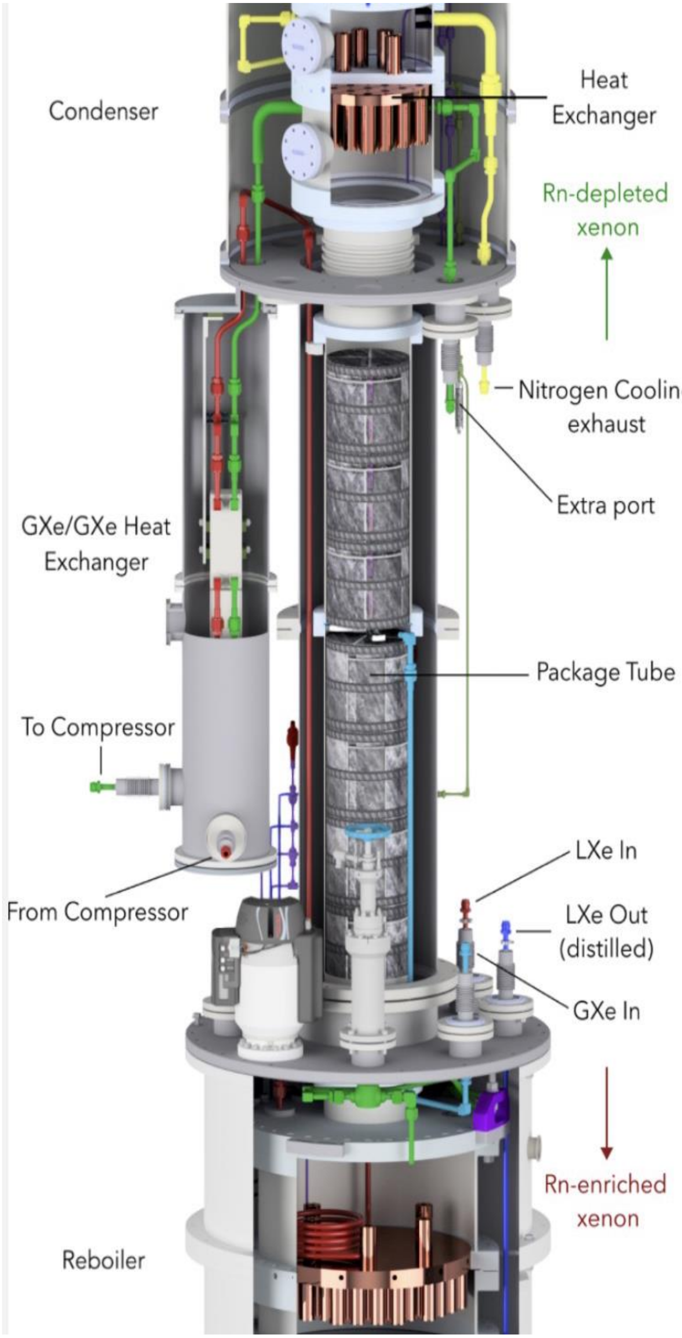
- keeping xenon in the liquid phase at −96 °C

controlled electric fields:

  - Cathode -12kV / -8 kV
  - Gate 0kV
  - Anode +4 kV / 5kV
  - Drift field 120V/cm/ 90 V/cm
- a uniform drift field across the liquid xenon volume
- a stronger extraction field at the interface

Pression stable:

- around 1.6-2.0 bar



supporting systems needed to maintain stable operation:

- continuous xenon circulation through rare-gas purifiers to remove electronegative impurities
- krypton removal via a cryogenic distillation column
- radon removal using a high-flow distillation system
- calibration campaigns with internal sources to track spatial response variations, electrode distortions, and light-collection effects

- The TPC is also operated inside a large water tank that acts as a passive shield and, in XENONnT

Sources:

- XENON Collaboration . “The XENON1T Dark Matter Experiment.” European Physical Journal C, vol. 77, 2017, article 881. DOI: 10.1140/epjc/s10052-017-5326-3.

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- XENON Collaboration. “Dark Matter Search Results from a One Ton-Year Exposure of XENON1T.” Physical Review Letters 121, 111302 (2018). DOI: 10.1103/PhysRevLett.121.111302