LIQUID XENON DETECTORS
LECTURE 2

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Lecture structure

- LECTURE 1:
  - General xenon characteristics
  - Scintillation & ionization processes
- LECTURE 2:
  - Xenon purity & radiopurity
  - Signal yields, resolution and calibration strategies
  - Photon detection
- LECTURE 3:
  - Low energy searches: dark matter & CEνNS
  - Search for neutrinoless double-beta decay
  - Xenon calorimeters and medical applications

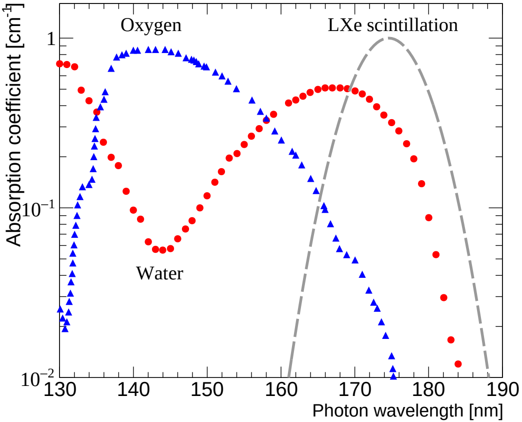
XENON PURITY

Xenon purity

- Xenon is obtained from the distillation of air
- Trace impurities in the gas at ppm level
- Outgassing from detector materials
- Radioactive impurities

figure from www.linde-gas.com

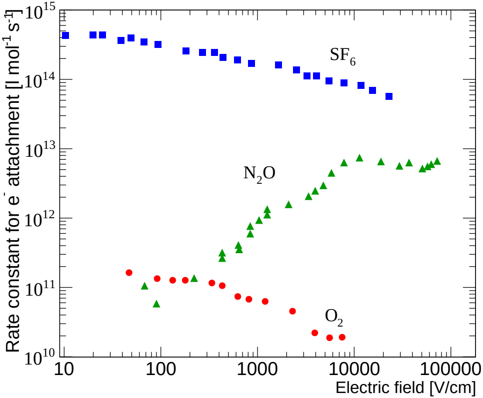
Absorption of light by impurities



Absorption data from K. Ozone (2005)

- Overlap with the xenon scintillation spectrum
- Water suppresses the overall detector light yield

Attachment of electrons to impurities



Data from G. Bakale er al. (1976)

- Electron attachment to impurities (e.g. oxygen) while drifting
- $\kappa_s \rightarrow$ the rate constant for e^- attachment
- Attachment is impurity- and field-dependent

The 'electron lifetime'

Reduction in the number of electrons due to attachment:

$$\frac{dN_e}{dt} \propto -\kappa_s \cdot N_e \cdot N_S, \quad (1)$$

N_e: concentration of electrons & N_S: concentration of impurities.

For an electron cloud drifting through liquid xenon:

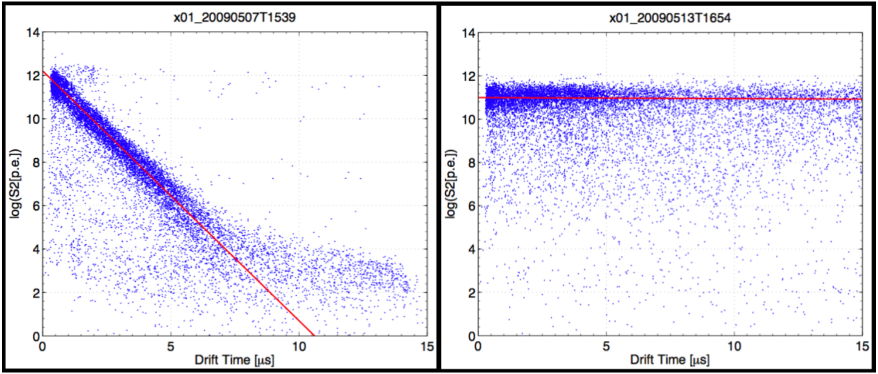
$$N_e(z) = N_e(0) \cdot \exp(-\kappa_s \cdot N_S \cdot z), \quad (2)$$

z is the spatial drift coordinate.

The electron lifetime τ_e represents the time that an electron can drift through the liquid before it is attached to an impurity:

$$\tau_e = (-\kappa_s \cdot N_S)^{-1}. \quad (3)$$

Purity and electron lifetime



S2 in the Xürich detector @ University of Zürich

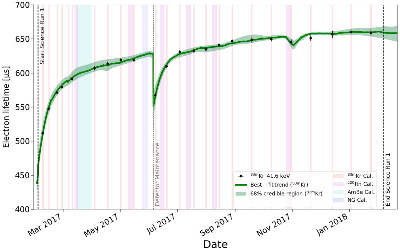
- Improvement of purity through constant purification
- No visible loss of S2s after 6 days of purification

Detector purity

Picture of the XENON1T purification system

- Removal of electronegative impurities below 1 ppb (O_2 equiv.)
- Continuous recirculation of xenon gas through hot getters (SAES)

- Evolution of the 'electron lifetime'
- Determined using calibration & background data



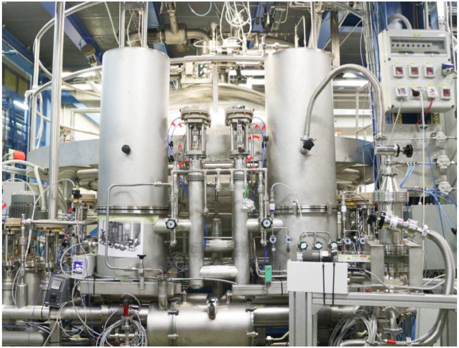
XENON1T electron lifetime evolution during SR1

Our local purification system

HeXe purification system @ MPIK

Purification techniques

- Liquid purification $\rightarrow$ faster circulation of the target possible
- Less power consumption, no need to recondense



XENONnT liquid purification system

- Other purification methods:
  - Adsorption by Oxysorb columns
  - Purification via spark discharge techniques

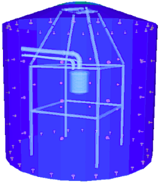
Radioactive impurities

Figure from DEVIANT ART

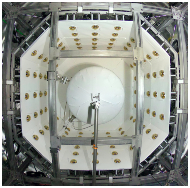
- ^{85}Kr from bomb tests and reactor fuel re-processing **Q**
- Xenon unstable isotopes: ^{124}Xe (double EC), ^{136}Xe ($\beta\beta$ decay)
- Radon emanation

$\rightarrow$ also external radioactivity
(from detector and cavity materials + cosmic rays)

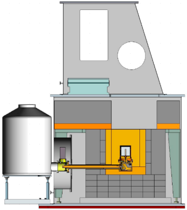
External background suppression in XENONnT



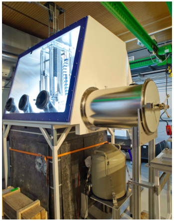
Scheme of XENON1T muon veto



XENONnT neutron veto installed



Scheme GeMPI detecor

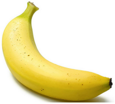


Giove @ MPIK

- Active water-Cherenkov muon shield, XENON1T, JINST 9 (2014) P11006
- Neutron veto will be added around the cryostat of XENONnT
- High sensitive HPGe spectrometers

$\rightarrow$ GeMPIs and Gator detectors at LGNS with $\sim$ 10 μBq/kg sensitivity in U & Th

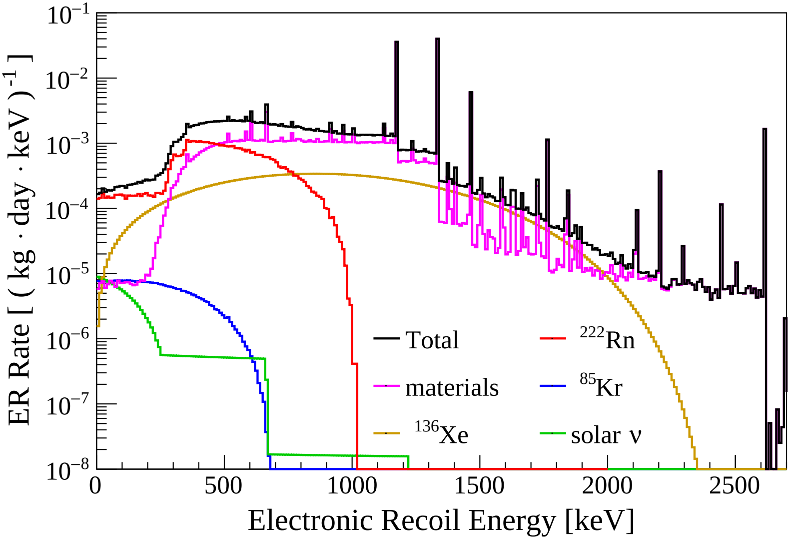
$+$ detectors at MPIK shallow depth lab



vs

While a banana contains 15 Bq ^{40}K,
a XENON1T PMT contains 15 mBq

Backgrounds for electronic recoils

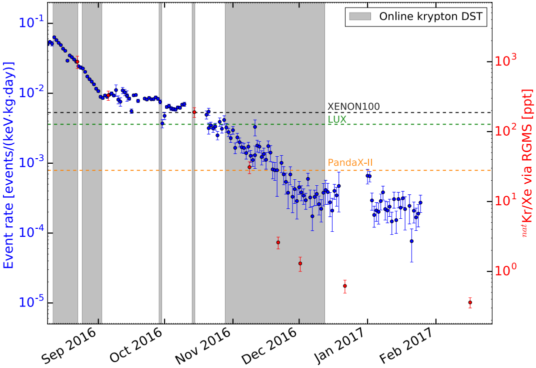


XENON1T, JCAP04 (2016) 027, arXiv:1512.07501

Krypton reduction in XENON1T

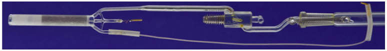
- Krypton background reduced by cryogenic distillation
  - XENON1T, Eur. Phys. J. C 77 (2017) 275
- Krypton level measured independently by RGMS
  Eur. Phys. J. C 74 (2014) 2746

  → Sensitivity of the measurement: 6 ppq ^{nat}Kr in Xe

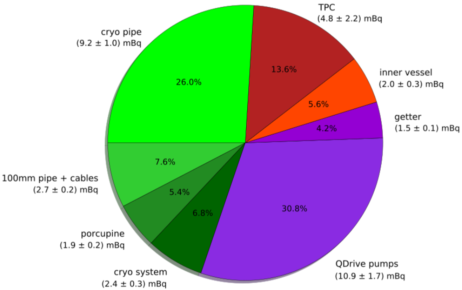


Radon budget and material selection

- Radon emanation measurements for material selection **Q**

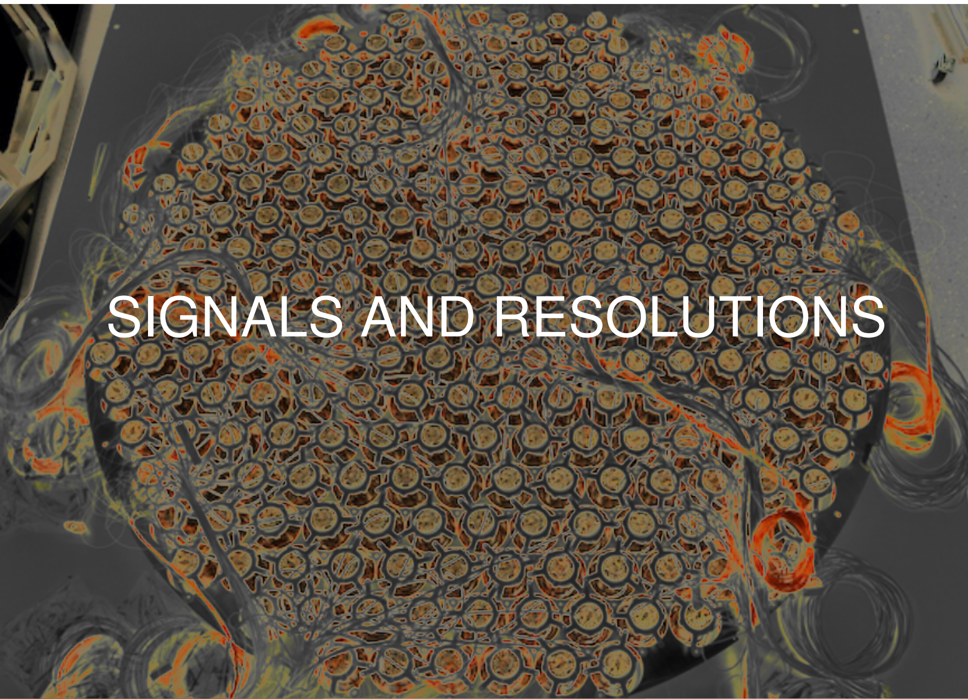


miniaturized proportional counter



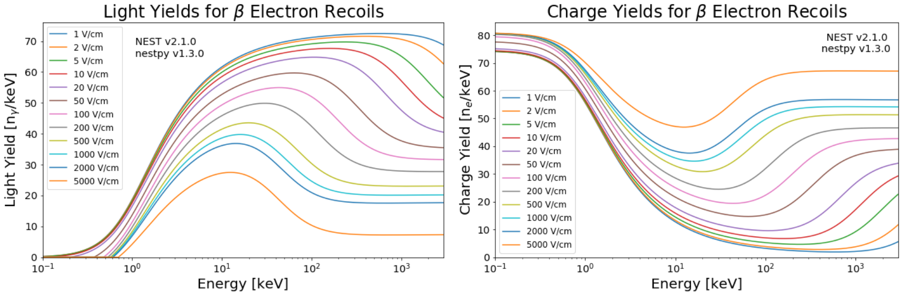
Radon budget in XENON1T (preliminary)

- $\sim$ 10 μBq/kg achieved in XENON1T
- Lowered to 4 μBq/kg ^{222}Rn with online cryogenic distillation + new full-metal pumps



SIGNALS AND RESOLUTIONS

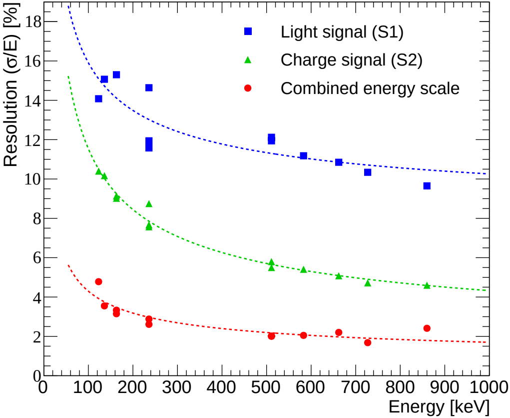
Signal yields



Figures from the NEST noble element simulation technique

- Energy-dependent yield for β-, α-particles and nuclear recoils
- Electric field dependence of the yields

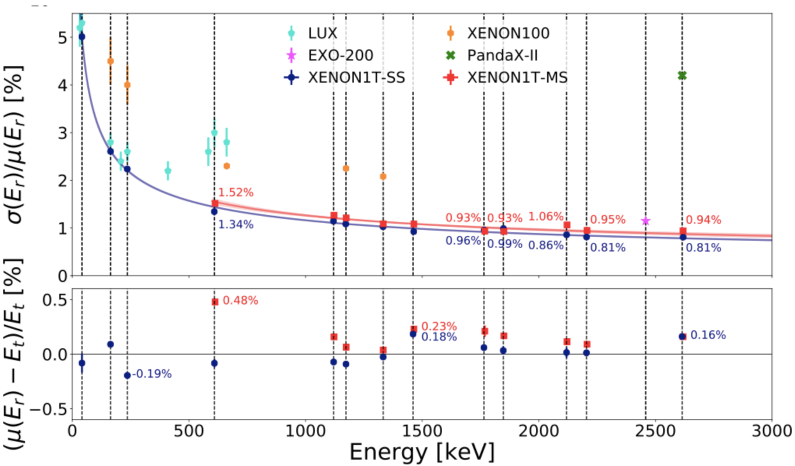
Energy resolution



Data from XENON10, Astropart. Phys. 34 (2011) 679 & arXiv:1001.2834.

- Combining light (S1) and charge (S2) signals results into an improved energy resolution

Energy resolution



XENON1T, Eur. Phys. J. C 80 (2020) 8, 785 & arXiv: 2003.03825

- Improvements in resolution $\rightarrow$ important for $0\nu\beta\beta$
- XENON1T reached recently $\sigma/\mu \sim$ 0.8% @ 2.45 MeV

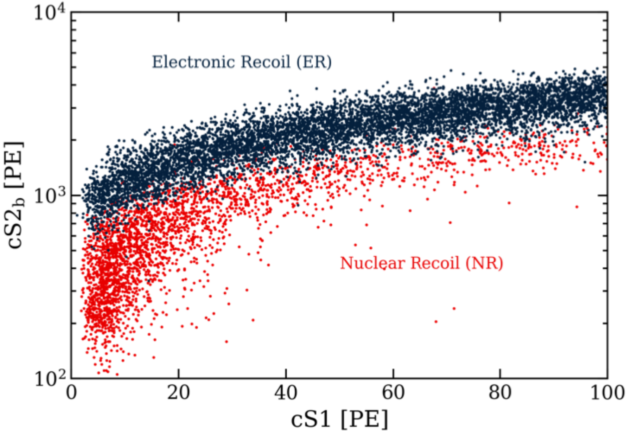
Calibration strategies

- Determination of the NR and ER signal regions

  (important for dark matter and CEνNS searches)

- Energy calibration for NR and ER

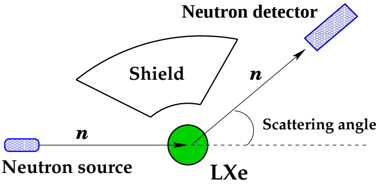
Calibration of signal and background regions



Calibration data from the XENON1T detector

- ER: calibrated using a ^{220}Rn source (β-decays of ^{212}Pb)
- NR: calibrated using a neutron generator / AmBe-neutron source
  $\rightarrow$ Lowest energies 3 PE ($\sim$ 1 keV_{er} or $\sim$ 5 keV_{nr})

Calibration of the nuclear recoil energy scale

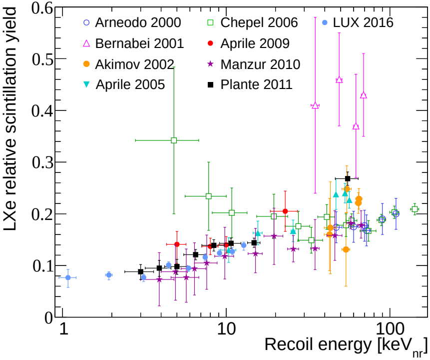


$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

$S1$: measured signal in p.e.

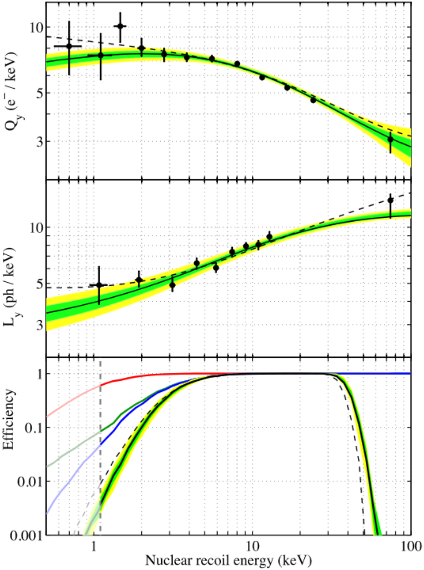
L_y: LY for 122 keV γ in PE/keV

S_e/S_r: quenching for 122 keV γ/NR due to drift field



J. Phys. G: 43 (2016) 1, arXiv:1509.08767

MC/Data comparison



LUX, Phys. Rev. Lett. 116, 161301 (2016)

- Response of the LUX detector to nuclear recoils
- Energy range (0.7 – 74) keV

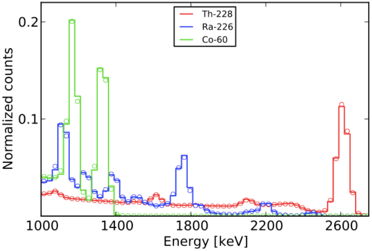
→ Experimental data

- DD-fusion neutron generator producing mono-energetic 2.45 MeV neutrons

→ Monte Carlo

- Detailed modelling of light and charge production
- Including detector effects: corrections and resolutions

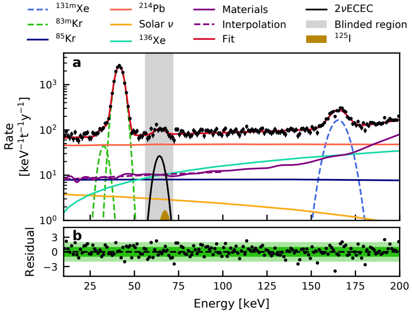
Energy calibration



EXO-200, Phys. Rev. C 101, 065501 (2020)

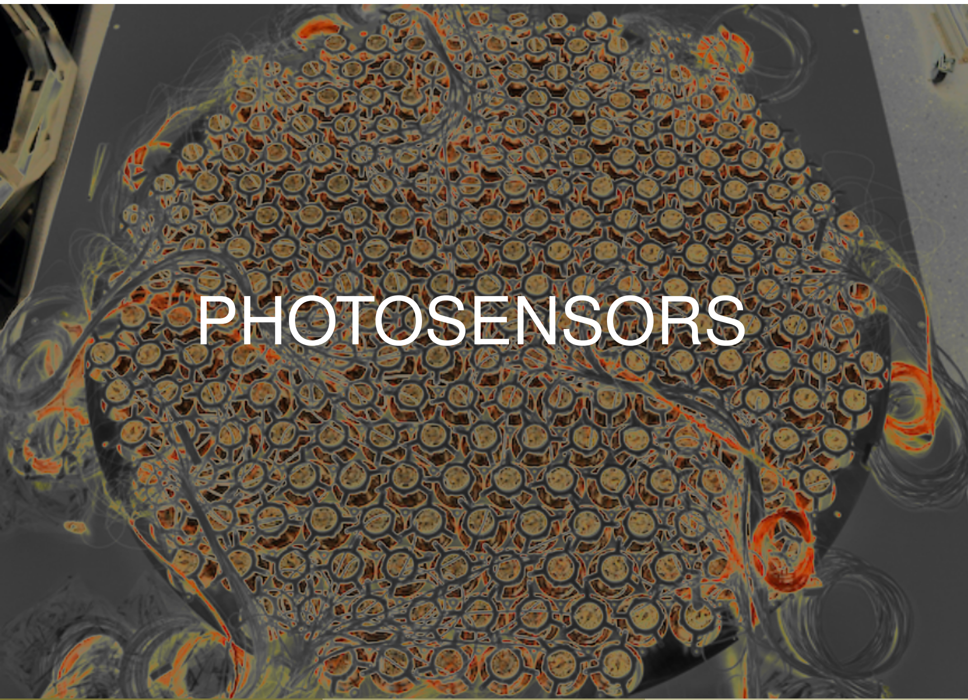
- **External** γ-sources:
  - ^{57}Co, ^{137}Cs, ^{60}Co, ^{228}Th ...
  - Reach a few cm inside the target
  - Adequate for 'small' detectors

- **Internal** sources necessary for large detectors:
  - ^{83m}Kr for detector characterization
  - ^{37}Ar at keV and sub-keV energies **Q**
  - Activated xenon isotopes: ^{127}Xe, ^{129m}Xe, ^{131m}Xe ...



XENON1T, Nature 568 (2019) 7753, 532

PHOTOSENSORS

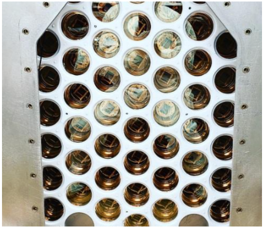


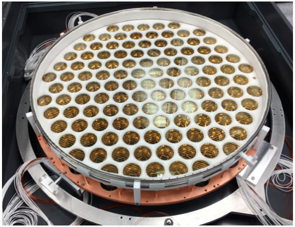
Photon detection

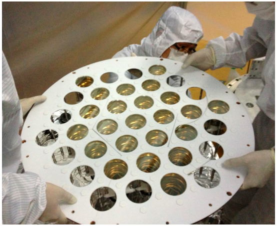
- Requirements for a dark matter experiment:
  - Low radioactivity & low dark-count rate
  - UV sensitivity & stable performance at cryogenic temperatures
  - High quantum and electron collection efficiency (QE/CE)
  - Time resolution in ns regime

Light sensors for nobel gas detectors

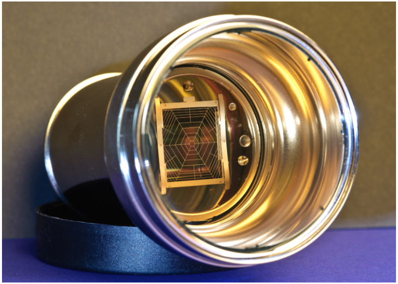
- State-of-the-art 3” photomultipliers from Hamamatsu:
  - R11410 (for LXe) for XENON1T/nT, PandaX and LZ
  - R11065 (for LAr) used by DarkSide (and Gerda)

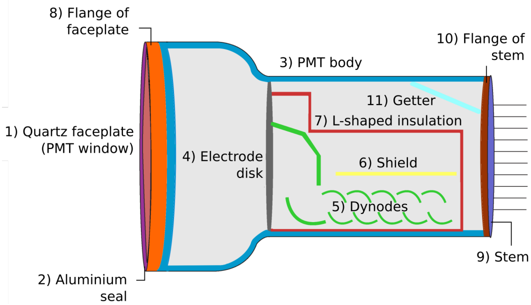

Section of LZ array


Bottom array of XENON1T

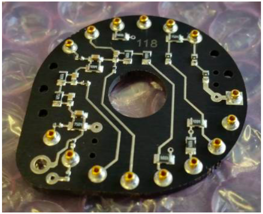

Bottom array of the PandaX detector

3" R11410 photomultipliers





- High QE: $\sim 35\,\%$ at 175 nm for a low energy threshold
- High gain: 5×10^6 @1500 V
- Read-out with a 'simple' voltage divider

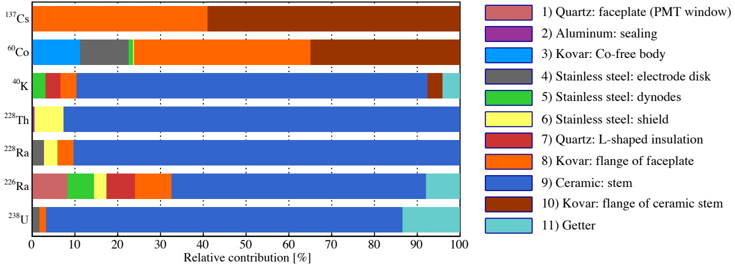


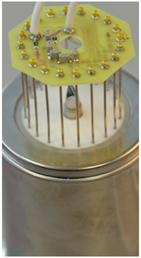
Low radioactivity PMT for XENON1T

- Main PMT parts screened separately
- PMT fulfils background requirements
- Major contributor to radioactivity identified: the ceramic stem

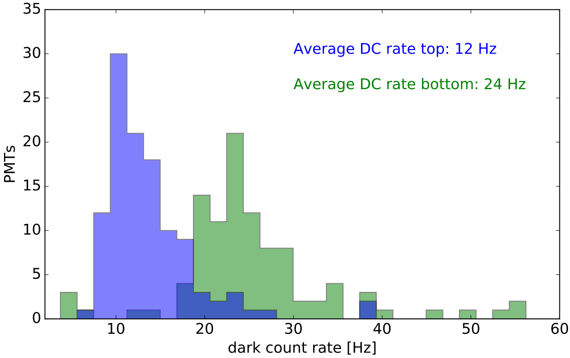
XENON collaboration,
EPJC75 (2015) no.11, 546 & arxiv:1503.07698

Component	Radioactivity
^{238}**U**	$<$ 10 mBq/PMT
^{228}**Th**	$\sim$ 0.5 mBq/PMT
^{226}**Ra**	$\sim$ 0.6 mBq/PMT
^{235}**U**	$\sim$ 0.3 mBq/PMT
^{60}**Co**	$\sim$ 0.8 mBq/PMT
^{40}**K**	$\sim$ 12 mBq/PMT





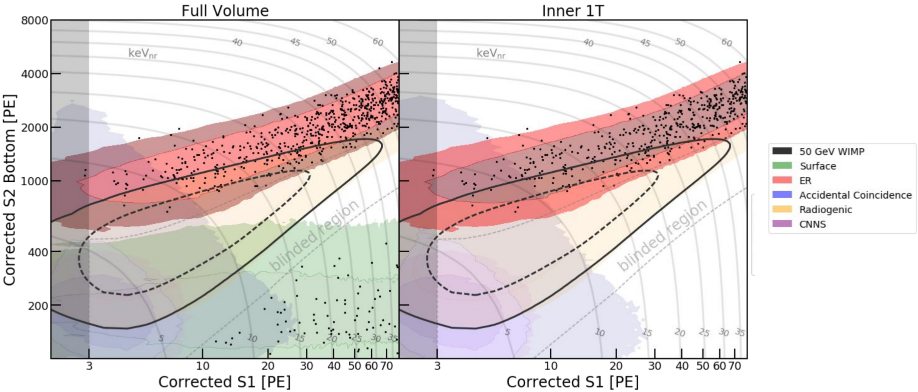
Low dark count rate



Dark count rates of all XENON1T PMTs. Measurement in XENON1T with cold xenon gas.
Figure adapted from L. Rauch PhD thesis

- Smallest signals considered in dark matter
  $\rightarrow$ Threshold of only 2-3 photoelectrons
- Accidental coincidences from dark pulses contribute to the detector background

Role of accidental coincidences

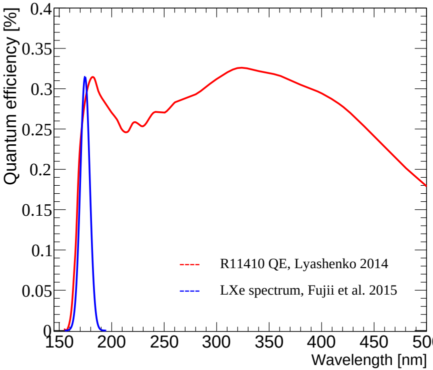


Data and background distributions from XENON1T

- Accidental coincidences dominate in the low energy region and below the nuclear recoil region
- Limiting the measurement of dark matter and the CEνNS

Sensitivity to UV light

- Bialkali photocathodes are used for liquid xenon applications
- Photocathode resistivity drops with decreasing temperature
- Strips or aluminum underlay in early PMTs
  $\rightarrow$ low temperature bialkali from Hamamatsu



Comparison: R11410 QE and LXe scintillation spectrum

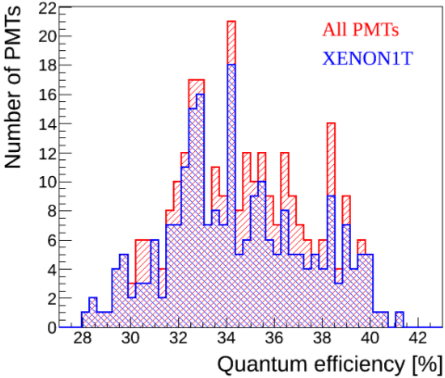


Figure from Barrow et al. JINST 12 (2017) P01024

High collection efficiency

PMTs arranged in a hexagonal pattern → high filling factor

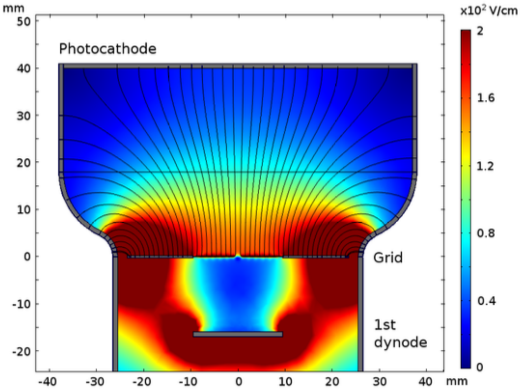
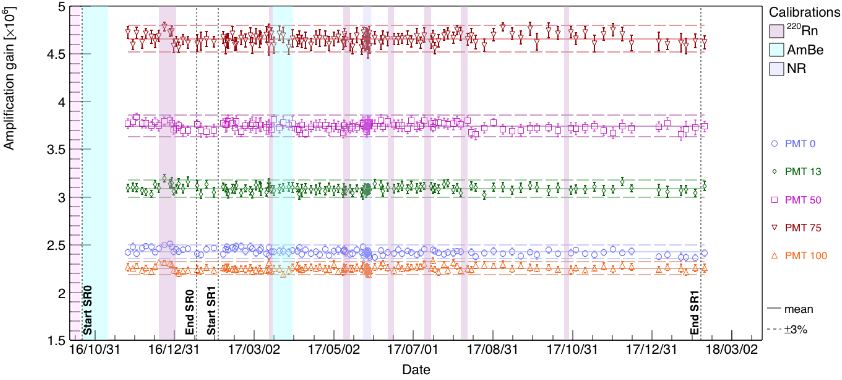


Figure from Barrow et al. JINST 12 (2017) P01024

- Collection efficiency of the R11410 of (90 – 95) %
- Flat entrance window → very different electron paths resulting in a long time jitter of ∼ 9 ns

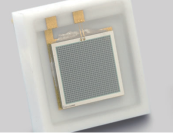
Stability in a cryogenic environment

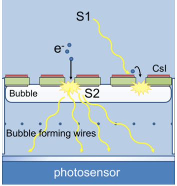


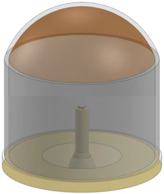
Gain stability of XENON1T PMTs during the science runs

- Stable gain for most well performing PMTs
- A fraction of the PMTs have tiny leaks which result into gain degradation & light emission

Alternative photosensors







Several SiPMs being considered:

- MPPCs from Hamamatsu
- SiPMs from FBK
- Digital SiPM
- ...

LHM: Liquid Hole Multiplier

- Gas bubble is produced by heating wires hold underneath a 'GEM-like' perforated electrode
- CsI photocathode coated into the electrode

Hybrid tubes, Photocathode + APD/SiPM

- QUPID, ABALONE
- SiGHT, VSiPMT

Lots of references for these works - not included in the slide for clarity

Summary

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  - Xenon calorimeters and medical applications