Universität Zürich^{UZH}

XENON Dark Matter Project

Photodetectors for the XENON1T Dark Matter Experiment

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for the XENON1T Collaboration

Invisibles Workshop
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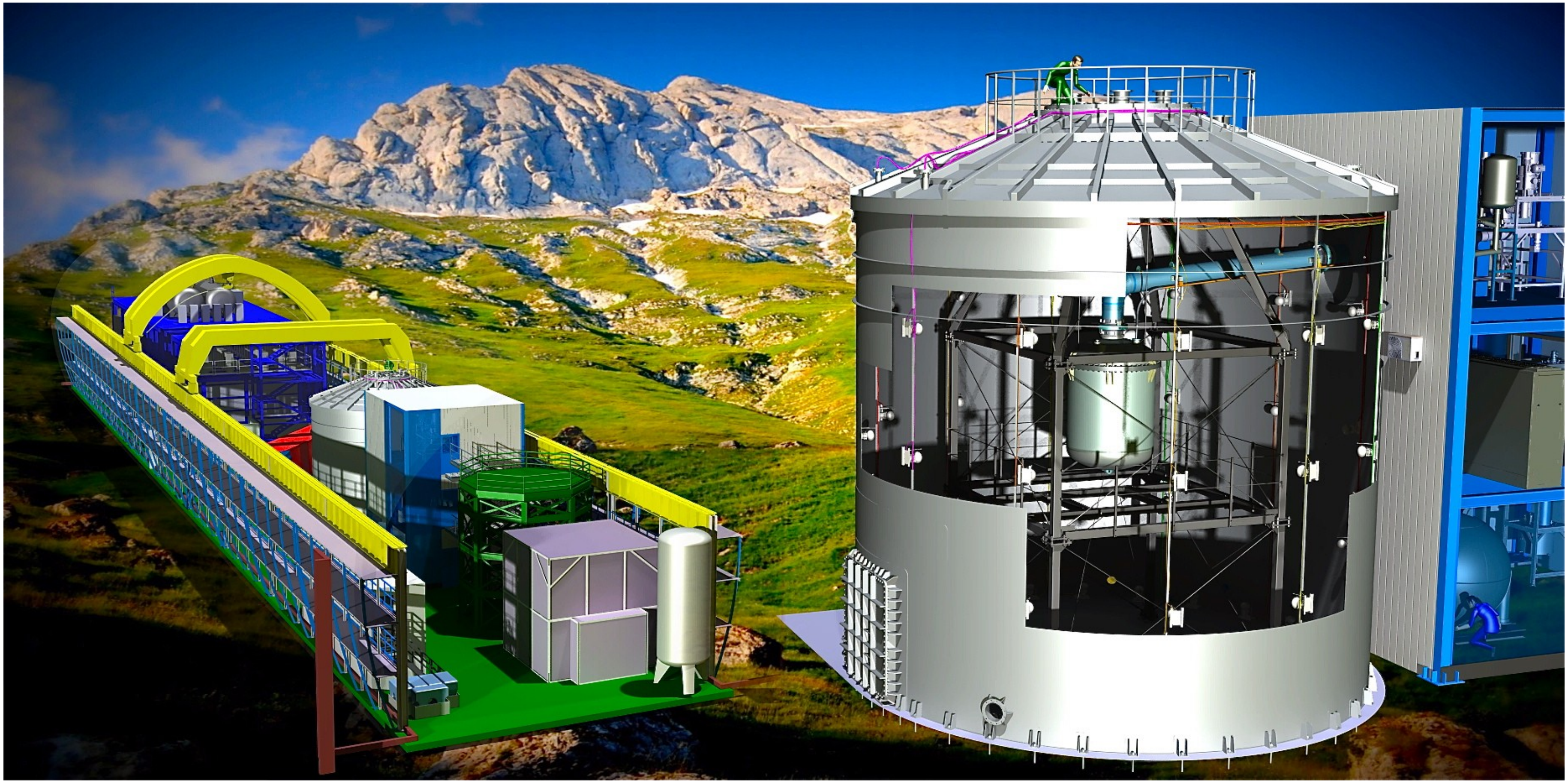
invisibles
neutrinos, dark matter & dark energy physics

PEOPLE

MARIE CURIE ACTIONS

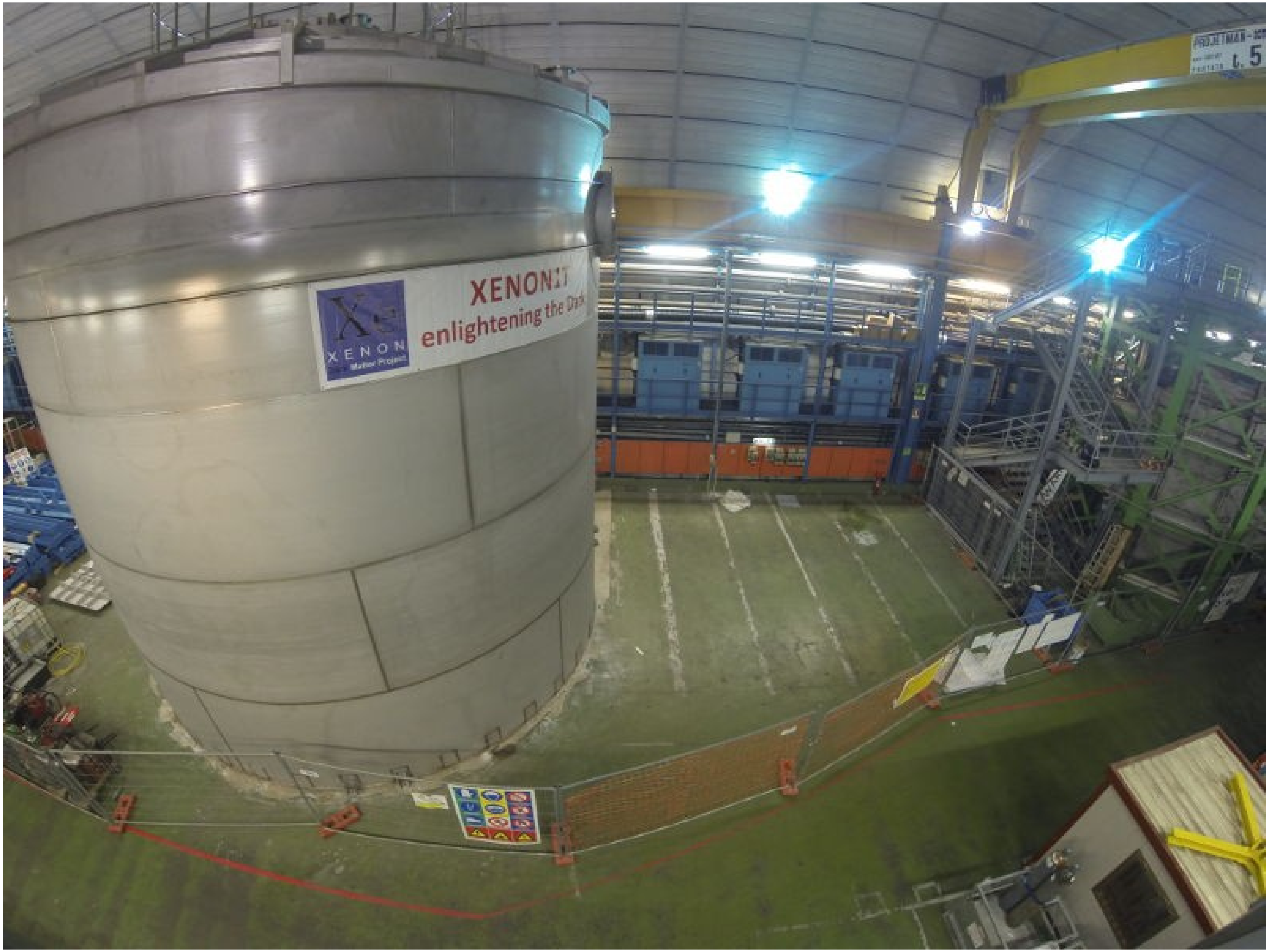
The XENON1T experiment

The XENON1T dark matter detector is currently under construction below the mountains of Gran Sasso at LNGS in Italy.

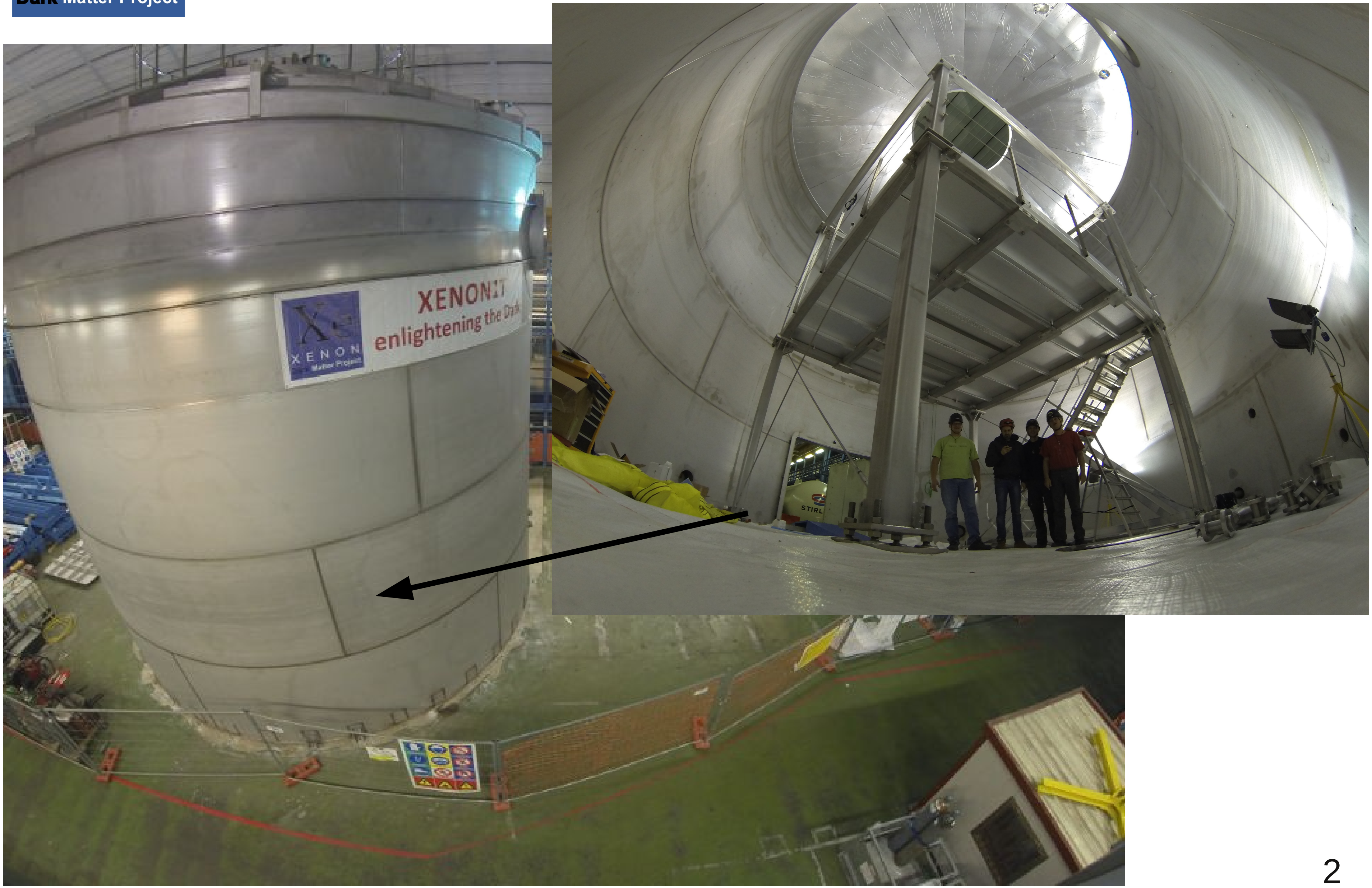


The XENON1T experiment

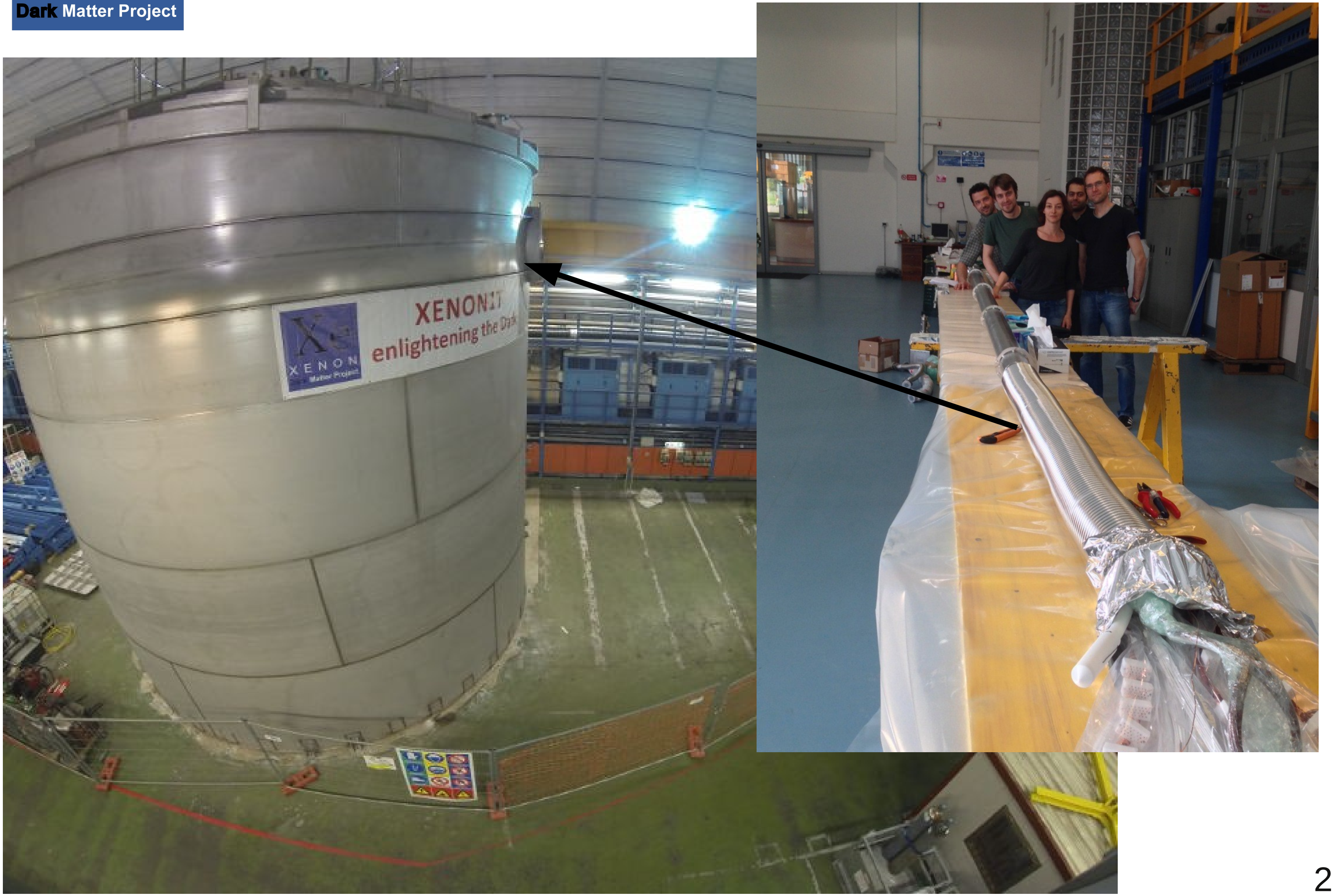
Some highlights of the construction:



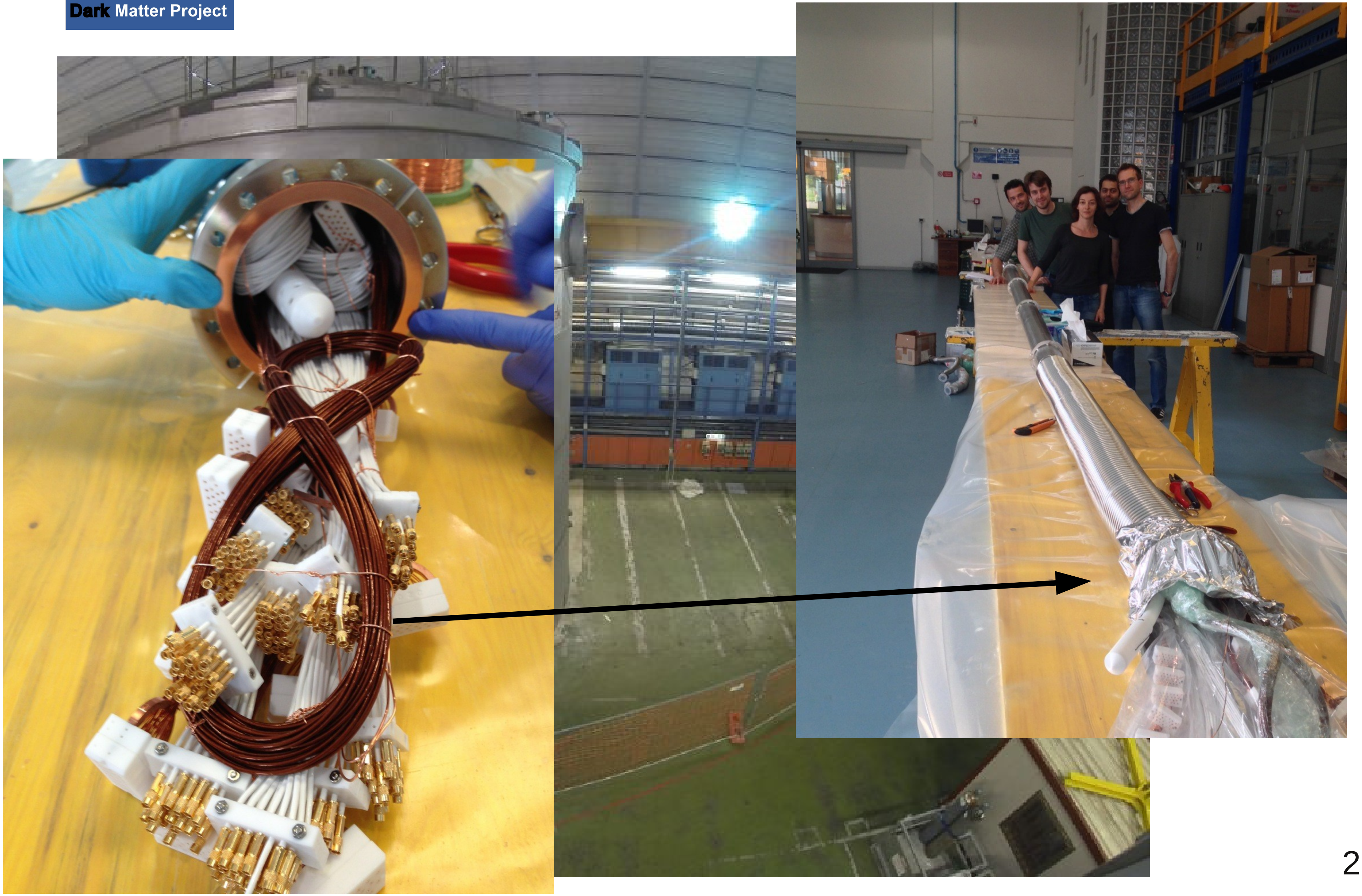
The XENON1T experiment



The XENON1T experiment

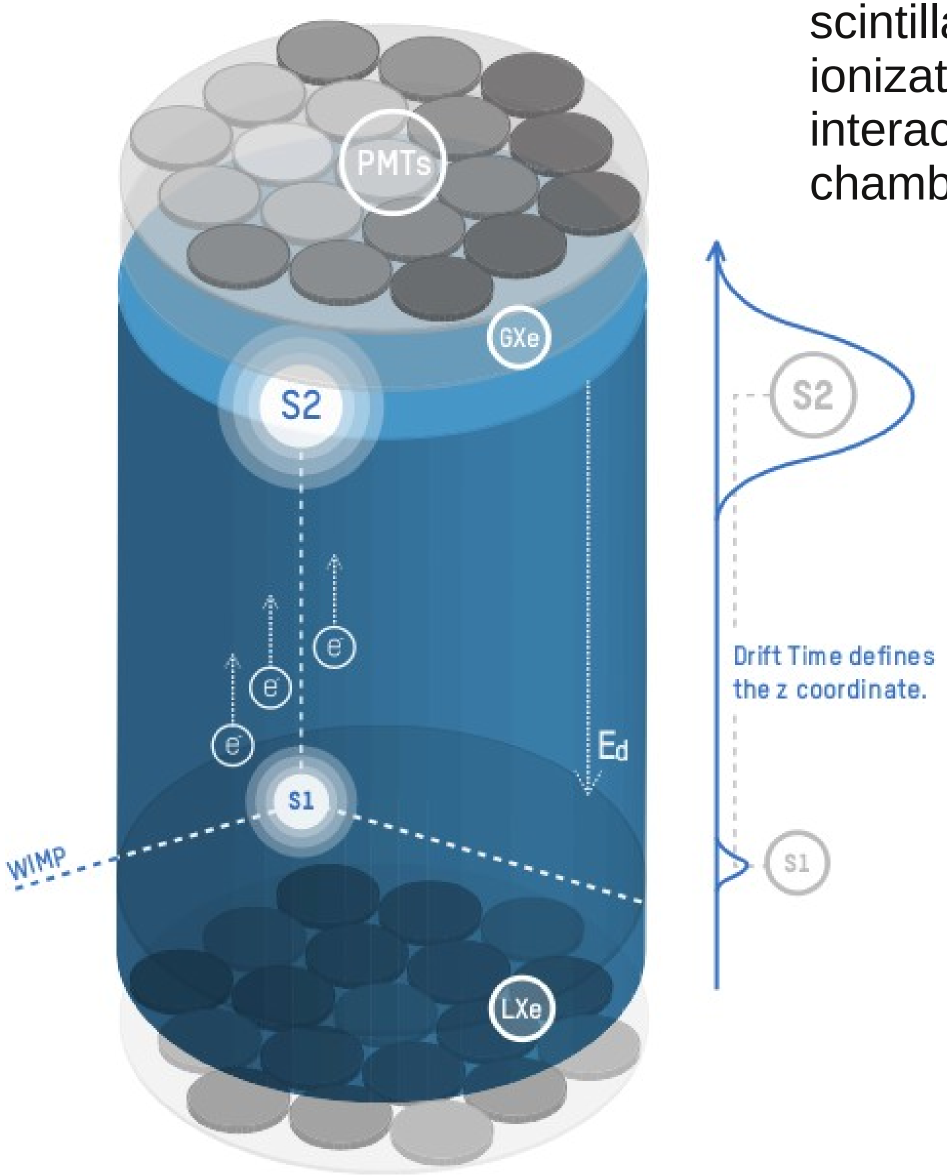


The XENON1T experiment



The XENON1T experiment

XENON1T is designed to search for dark matter WIMPs by measuring simultaneously the primary scintillation (**S1**) and proportional scintillation from ionization electrons (**S2**) produced by a WIMP interaction within a two phase time projection chamber (**TPC**) filled with liquid xenon (**LXe**).



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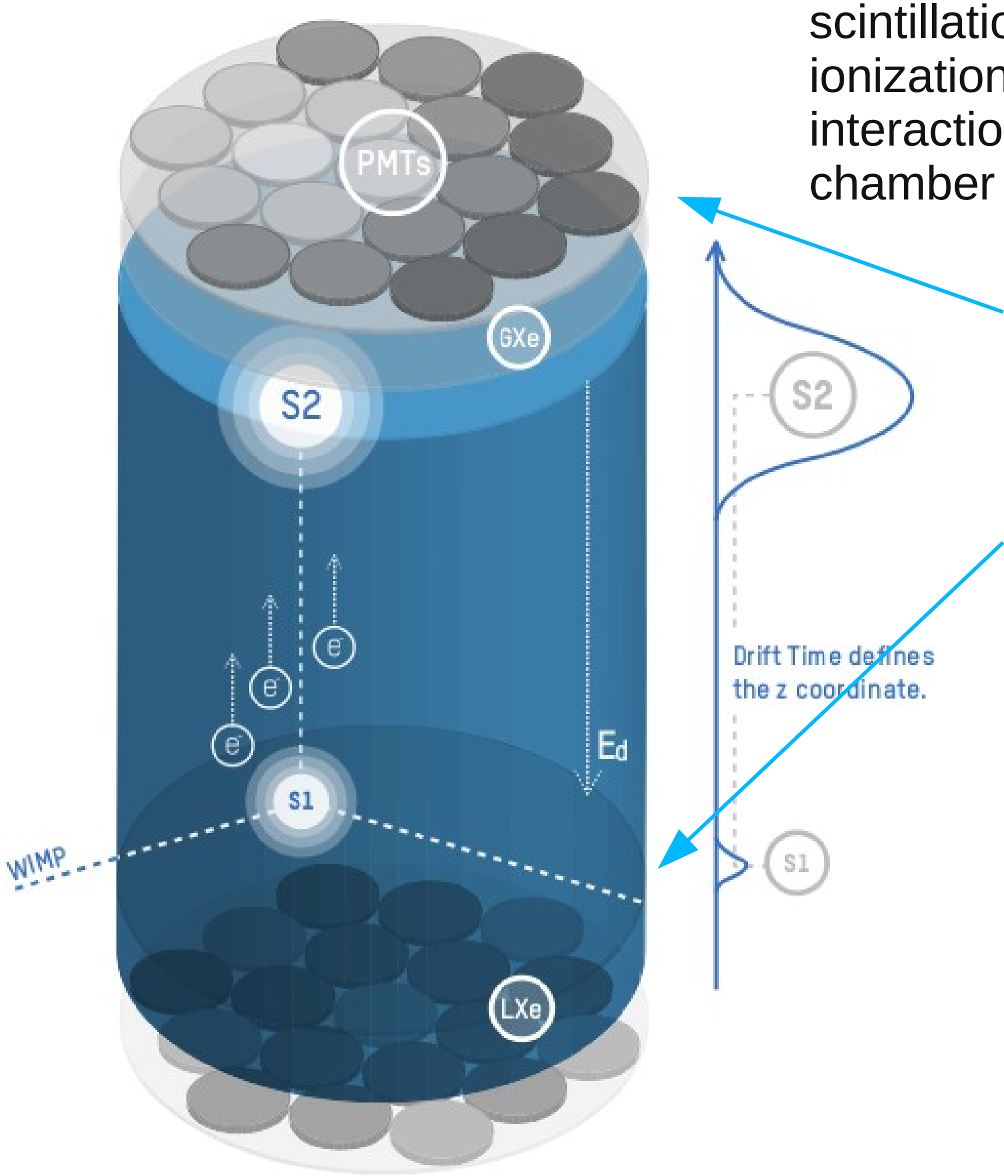

- The **top PMTs** in GXe detect S2 and give *xy* position with mm precision.
- The **bottom PMTs** are fully immersed in LXe to efficiently detect the S1 signal.

The XENON1T experiment

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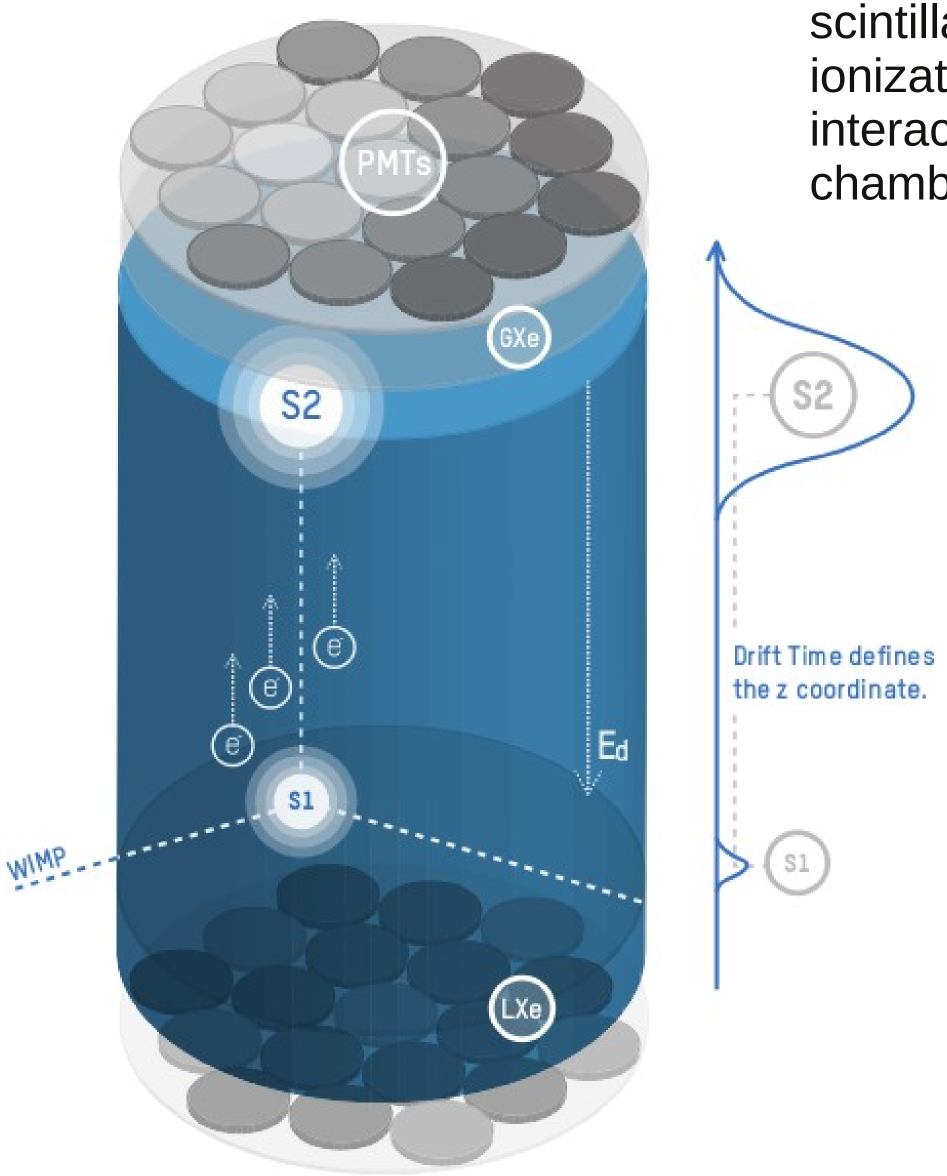
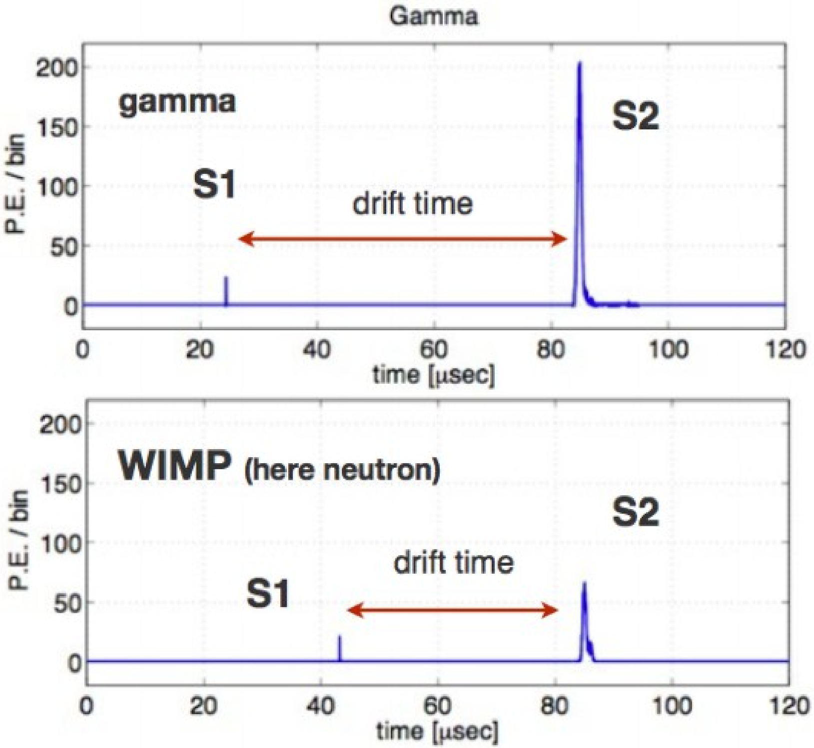




The Photomultiplier Tubes

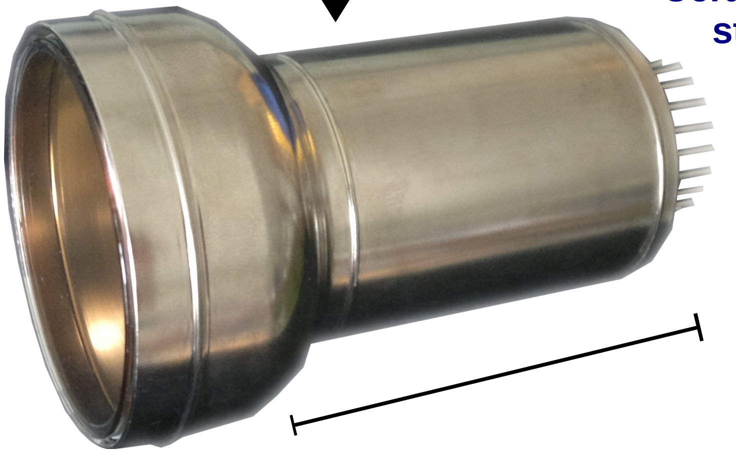
Hamamatsu R11410-21 low radioactivity **3 inch** PMTs.

Operating temperature range:
-110 to 50 deg. C

Metal casing:
Cobalt free, low radioactivity

Ceramic stem.

Quartz window:
Transparent to VUV photons



Bialkali photocathode:
Sensitive to 178 nm wavelength.
Typical QE of 32.5%

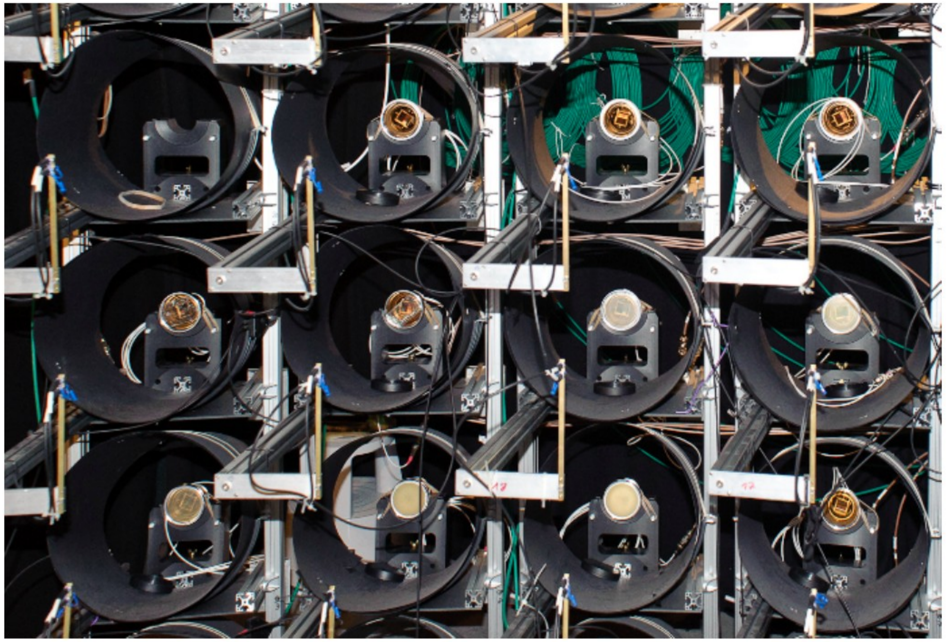
12 dynode stages:
Average gain 3.5×10^6

TPC:
Talk by
Peter Barrow

Top array: 127 PMTs.

Bottom array: 121 PMTs.

PMT characterization at MPIK Heidelberg

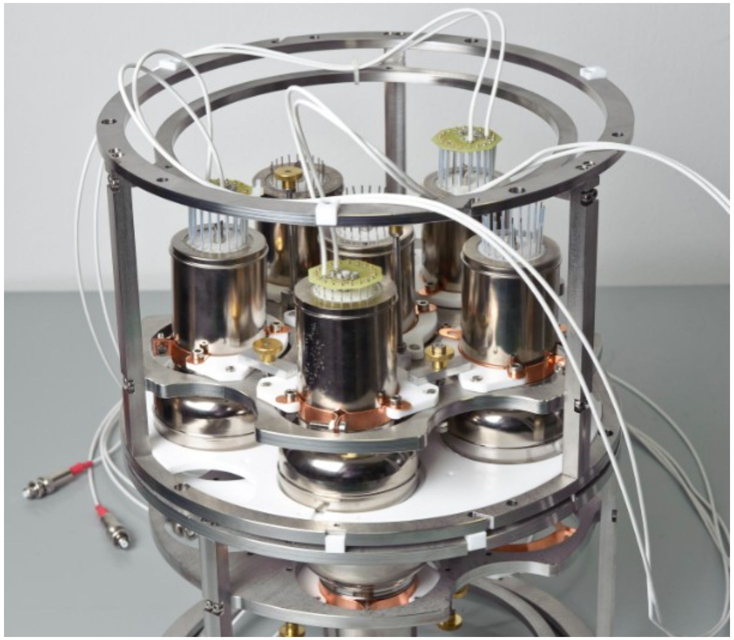


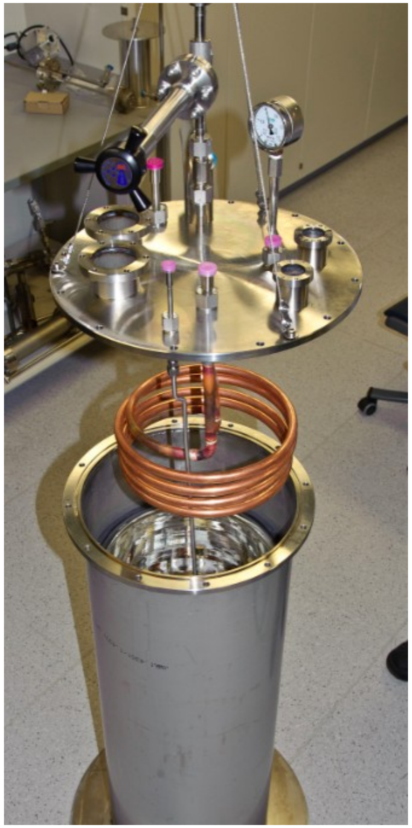
Upon arrival all PMTs are tested at room temperature:

- DC rate
- HV scan (1320 − 1680) V
- Afterpulses
- Transit time

If all parameters OK → cool down

MPIK setup to cool down and measure 12 PMTs simultaneously:
Nitrogen vapor cooled by LN through a copper coil.





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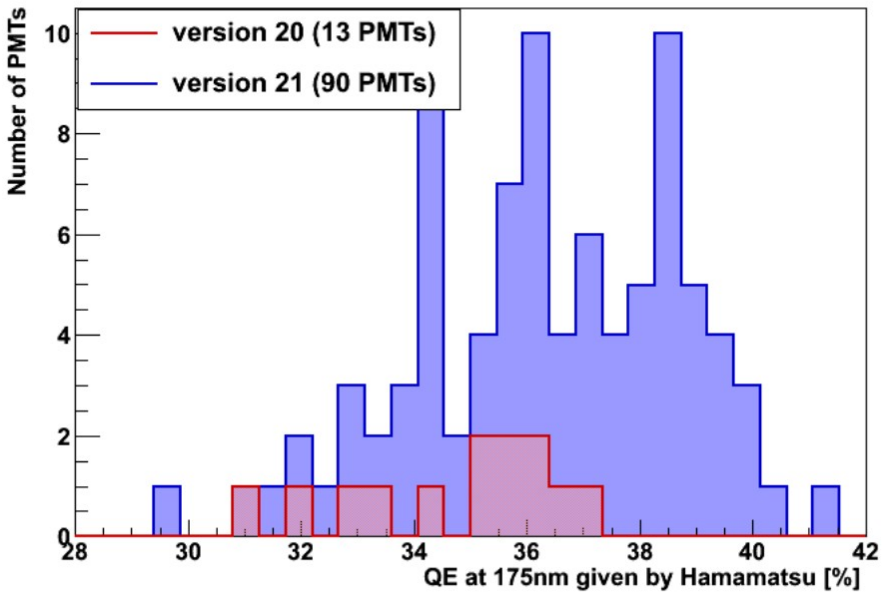
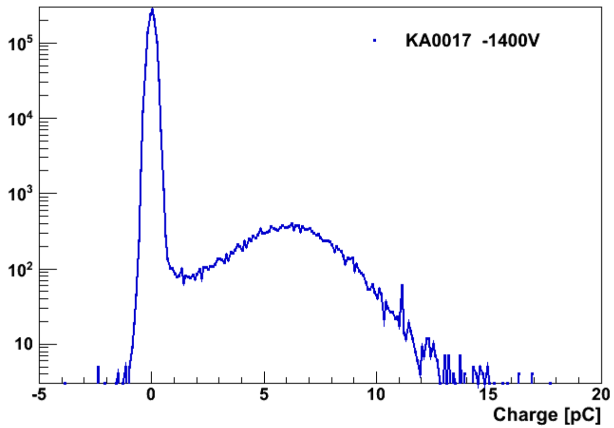
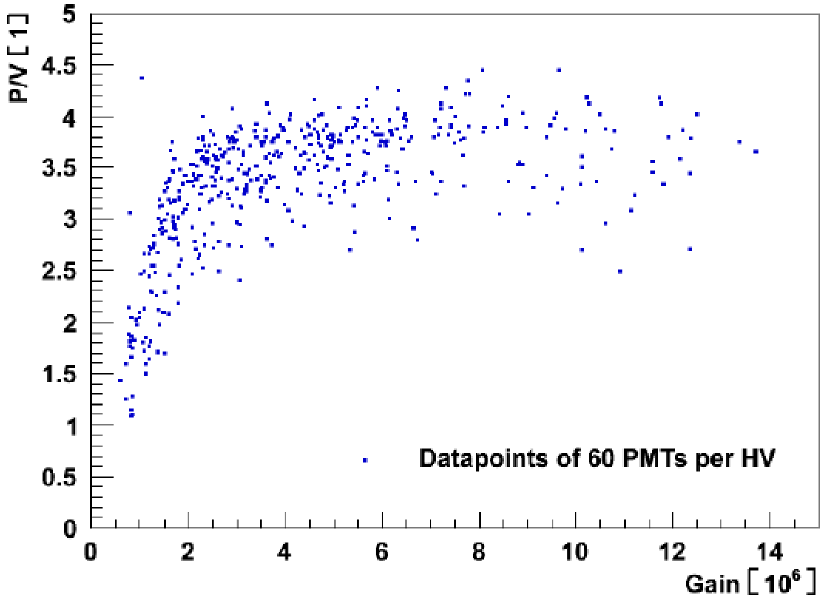


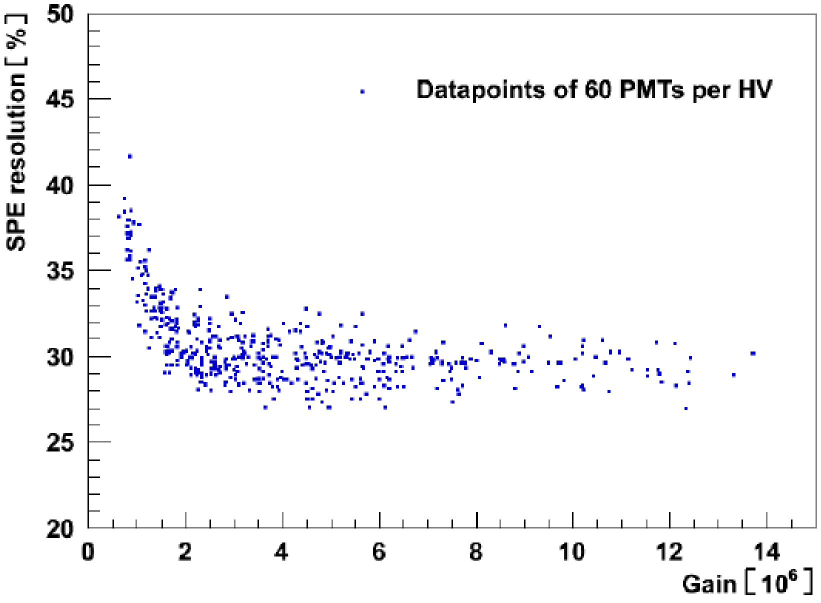
Average QE:
36%

Average gain
3.3 x 10^6
at -1500 V



P/V and resolution close to maximum at a gain of around:
2 x 10^6 (about -1400 V)

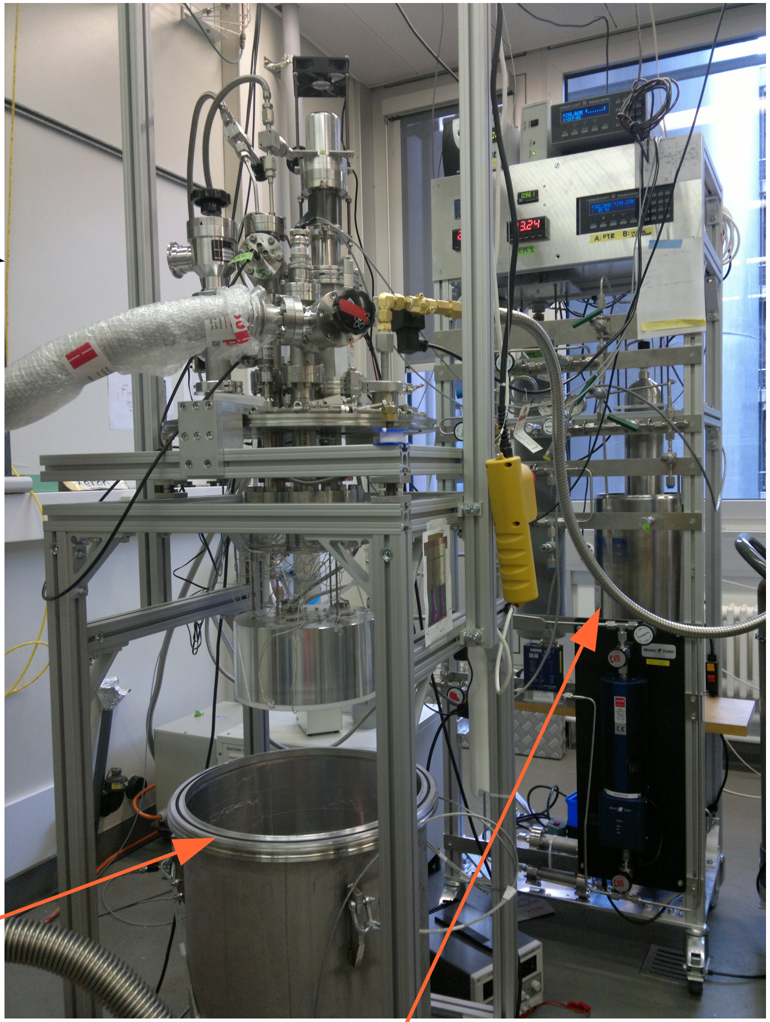




Figures by Meike Danisch

PMT characterization at UZH

The performance of the R11410 **PMTs in LXe** is tested at UZH with a dedicated experimental setup.



Double walled vacuum insulated cryostat to maintain the subzero temperatures.

Gas system to purify and circulate the Xe from its storage bottles into the detector chamber.

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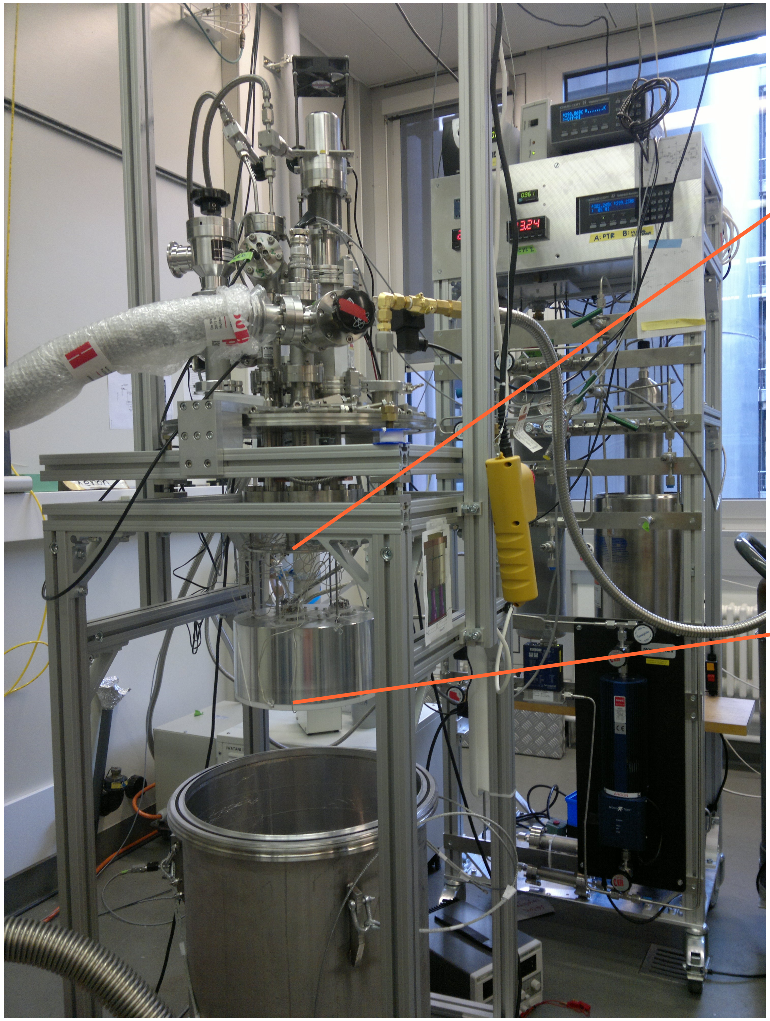

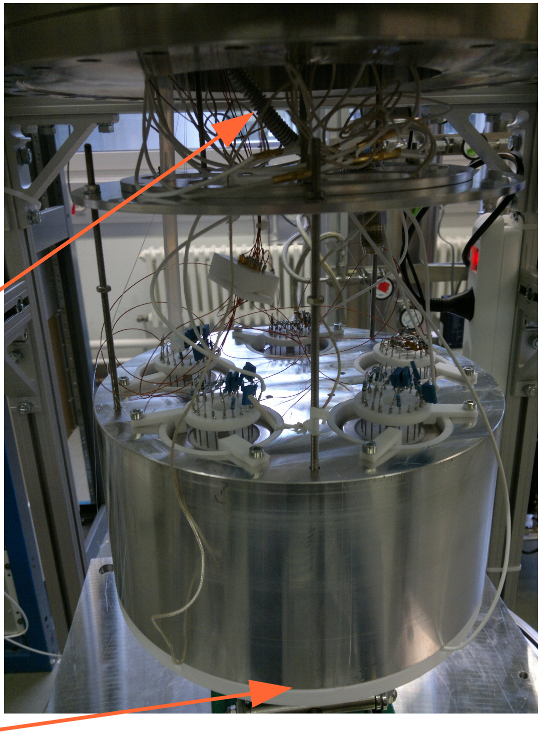

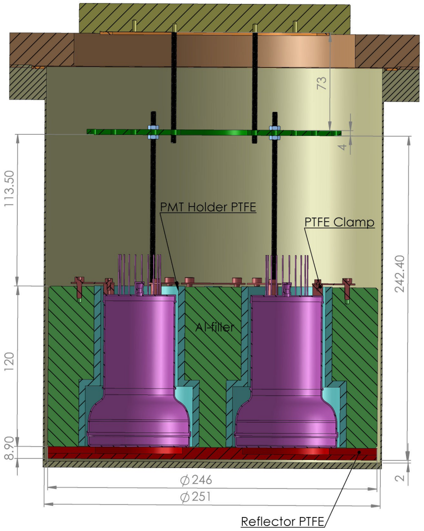

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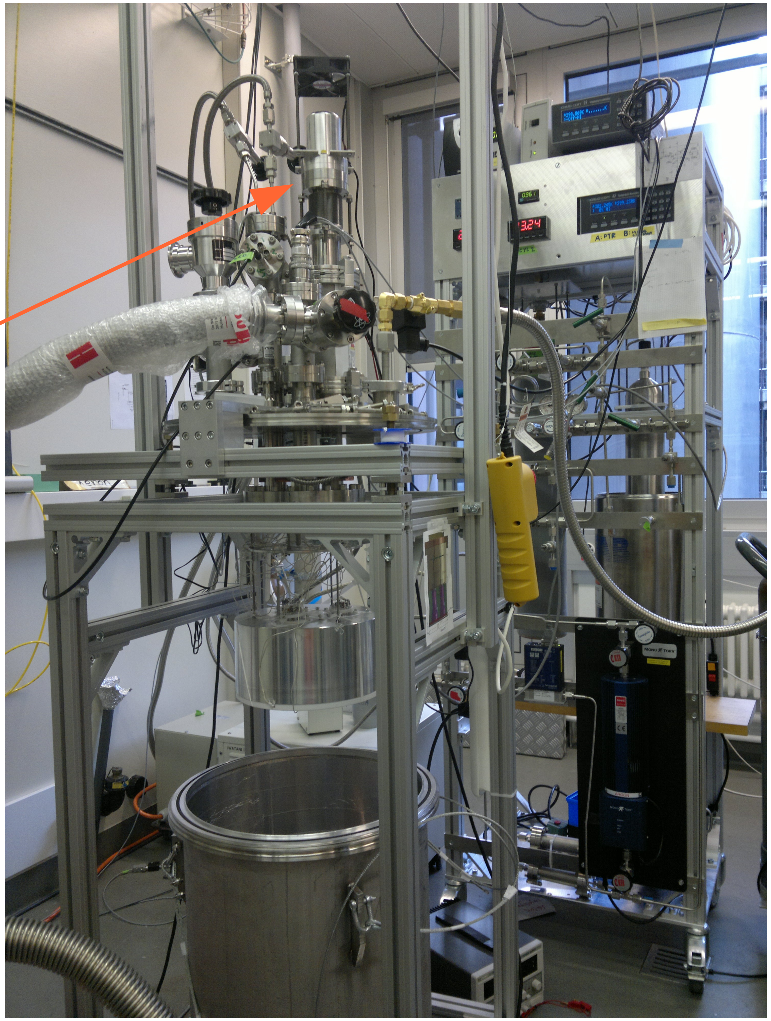
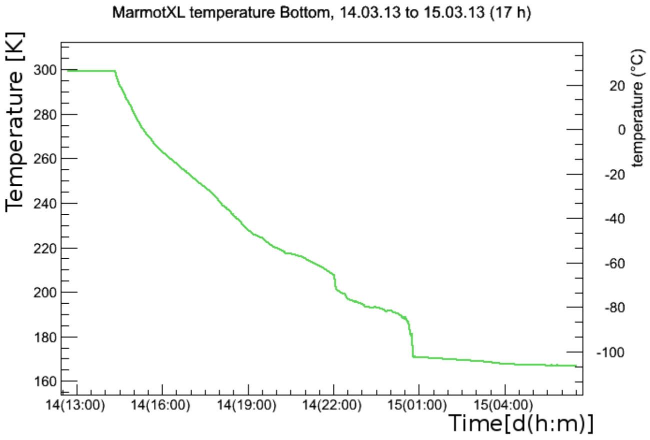


Xe liquefaction to ~170 K is achieved with a Pulse Tube Refrigerator



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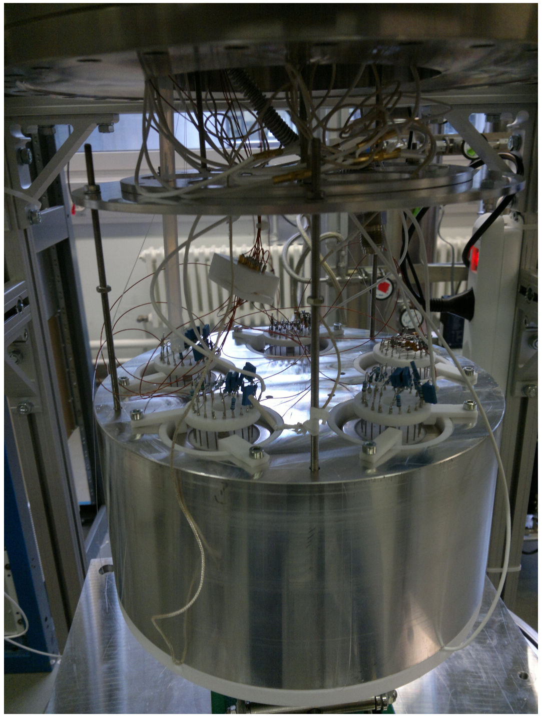
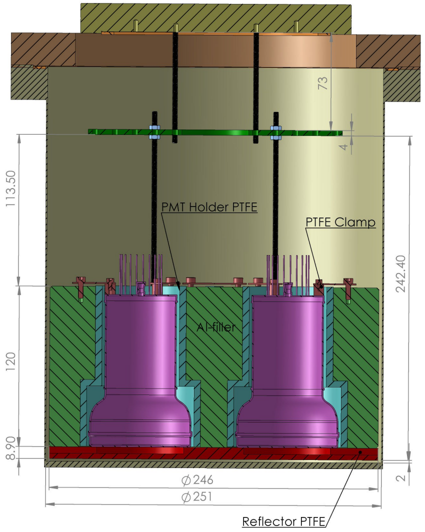
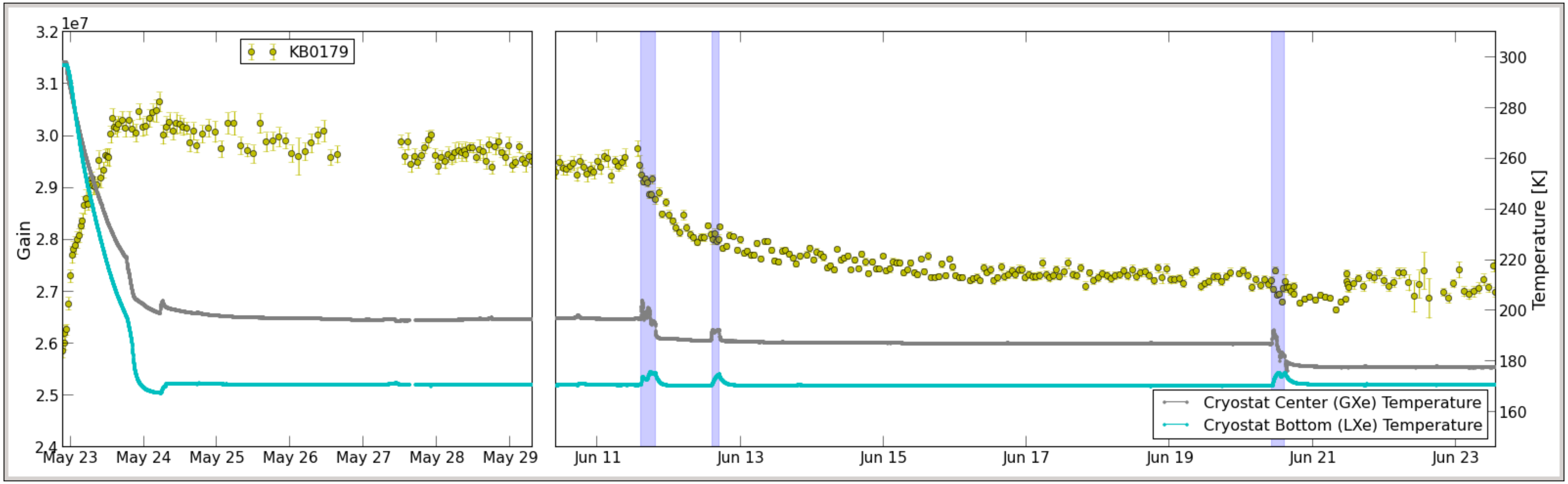




Gain evolution during cool down

Effect of the temperature on the PMT gain:

+15%

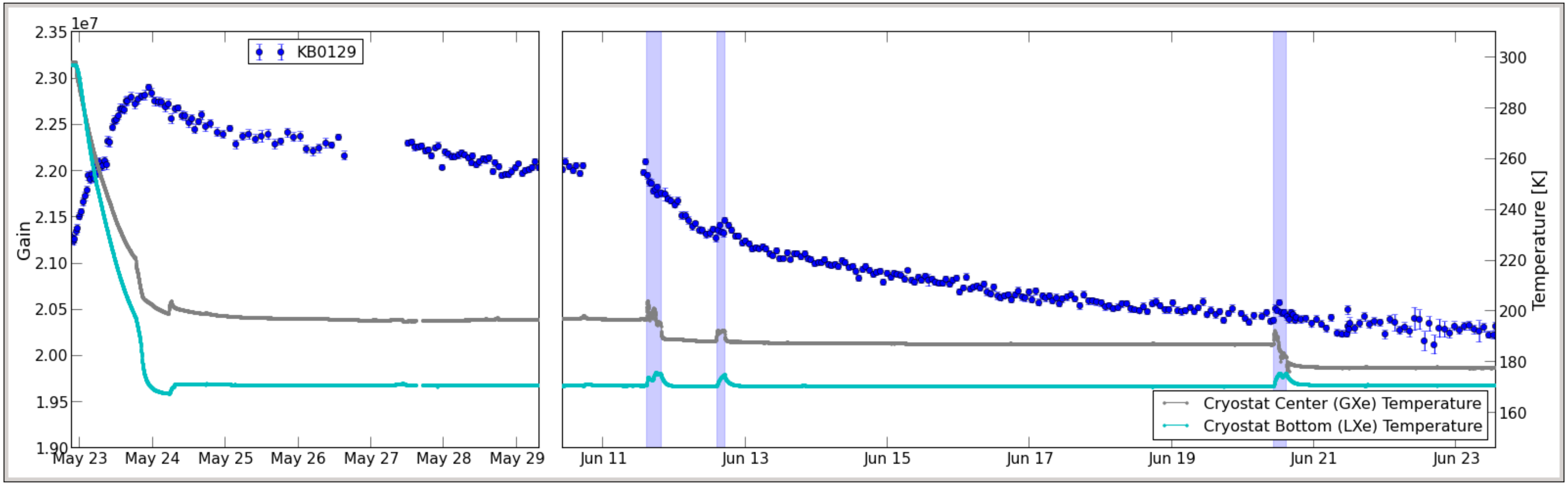


-10%

GXe only

PMTs covered in LXe

+5%



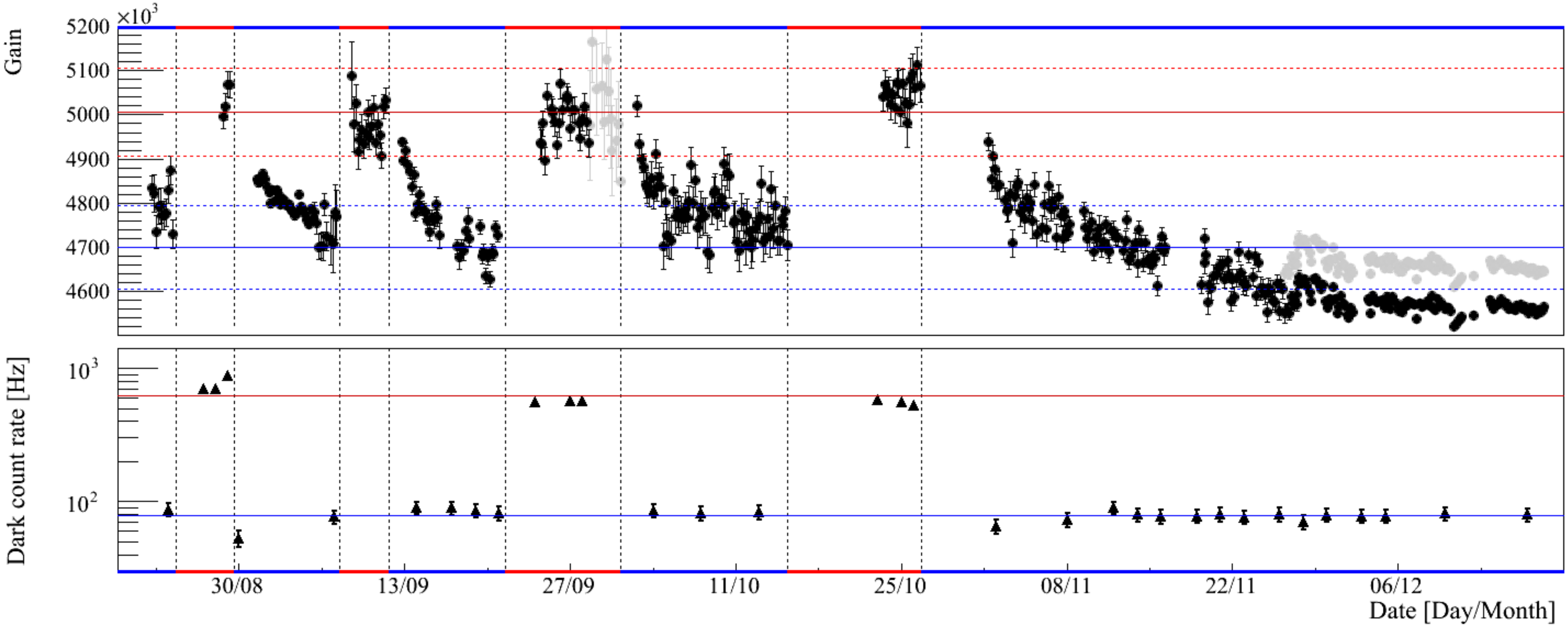
-10%

These values include a x10 amplification factor from an external amplifier.

Long term stability tests

Thermal cycling: In order to test the stability of the PMTs in LXe, the tubes are submitted to a series of cool downs (170 K) and warm ups (room temp.) where the gain and dark count rate are monitored constantly.

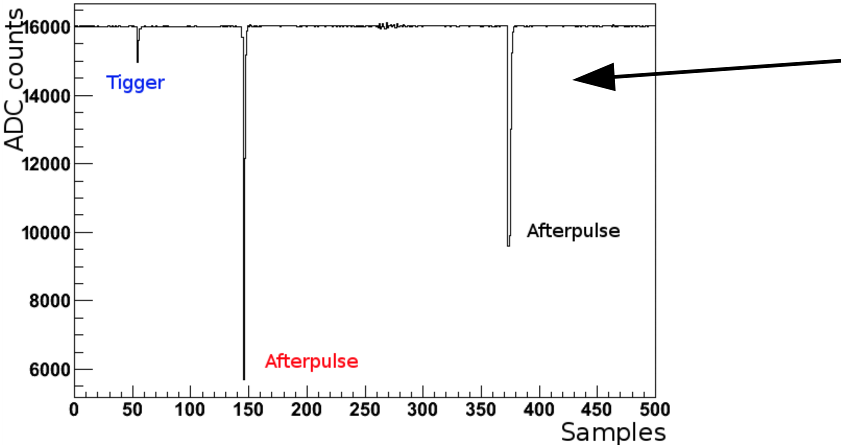
Dark Current:
Thermal emission from the photocathode produces signals in the PMT.



- At room temperature the gain remains constant within 2%.
- When at LXe temperature, the gain decreased around 5%.
- The DC rate decreased by a factor 10.

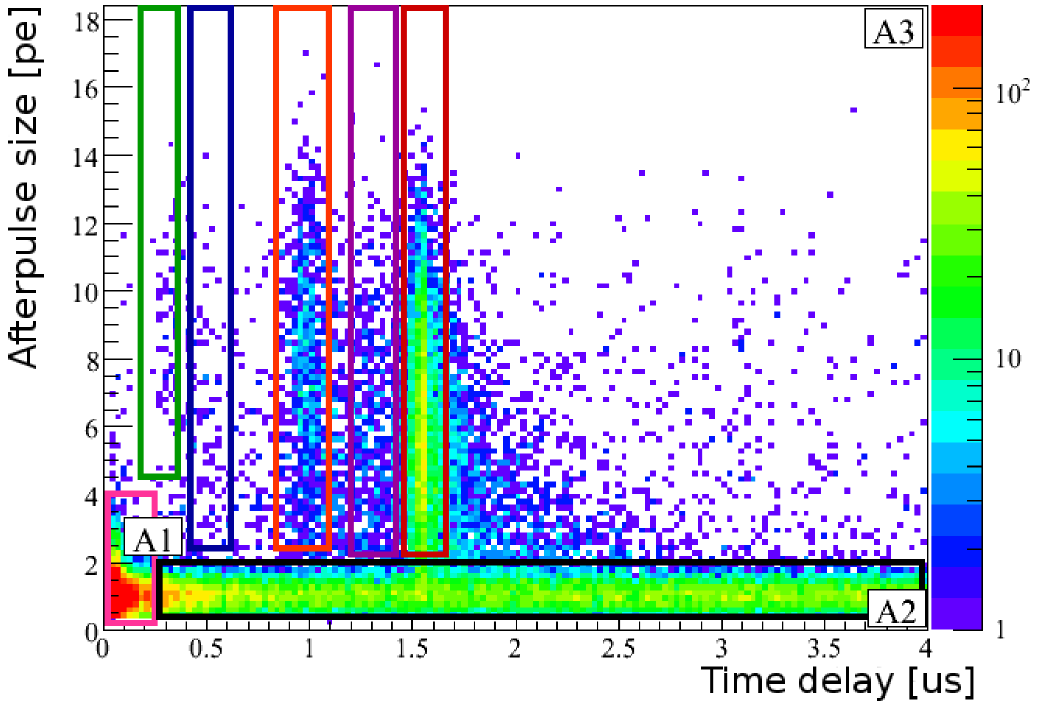
L. Baudis et al. JINST 8 P04026 (2013)

Study of Afterpulses



Afterpulses are signals that appear after the trigger signal.

It is important to have a low rate of afterpulses (**below 10%**, as specified by the producer) so that they do not interfere with the identification of S1 and S2 signals.

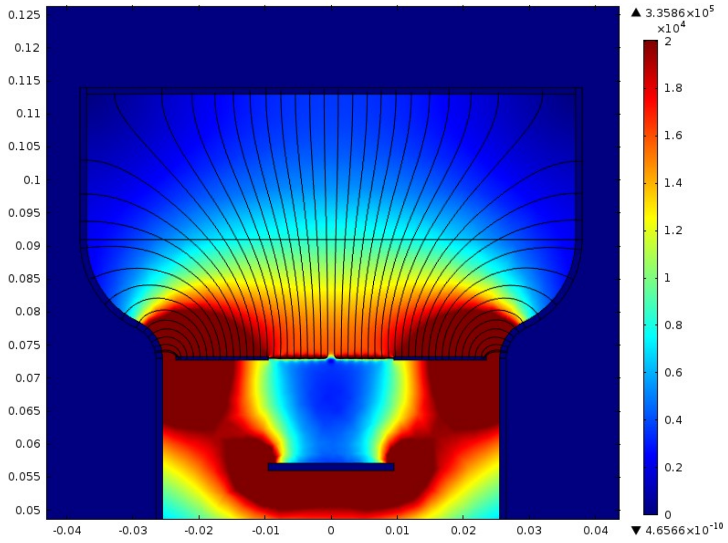


Three groups of afterpulses are observed:

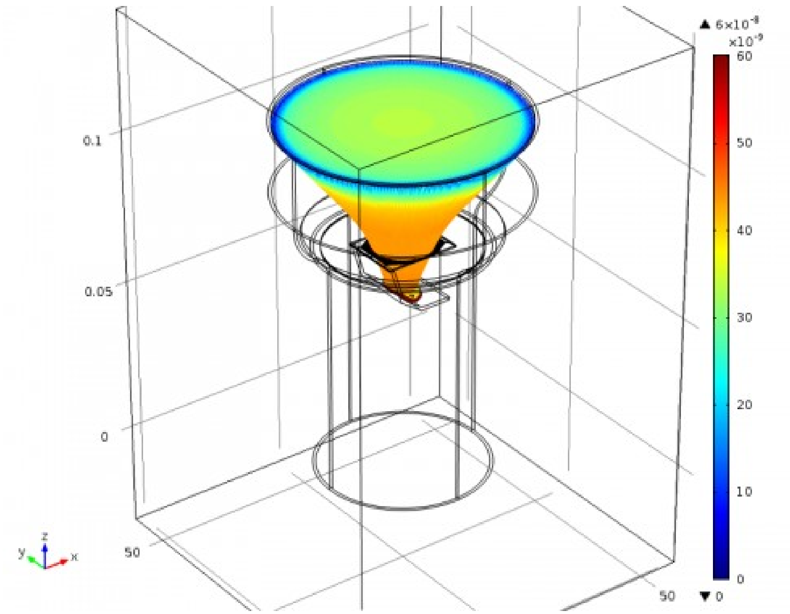
- **A1:** Pulses of short delay (tens of ns), caused by elastic scattering electrons on the first dynode.
- **A2:** Populated mostly by dark pulses and single photoelectrons.
- **A3:** Pulses produced by positive ions from gas molecules within the PMT.

  These afterpulses can be used as a diagnosis of the vacuum quality and identification of contaminants (CH$_4$,CO$_2$, etc.) inside the tube.

PMT field simulations

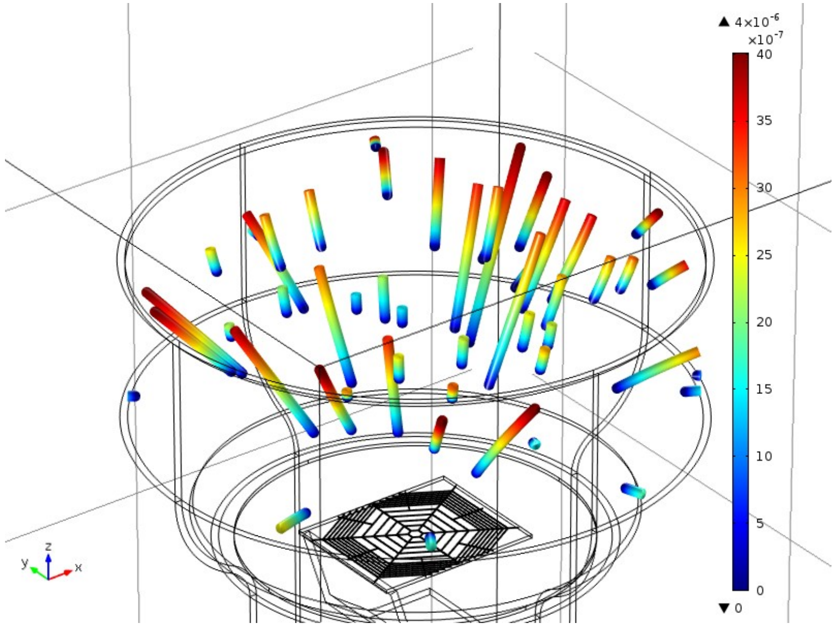


In order to understand the nature of afterpulses, the PMT field and the tracks of ions and electrons have been simulated with COMSOL.



Drift time

Simulated photo-electrons have a drift time of around 46 ns, with a collection efficiency of 95%.

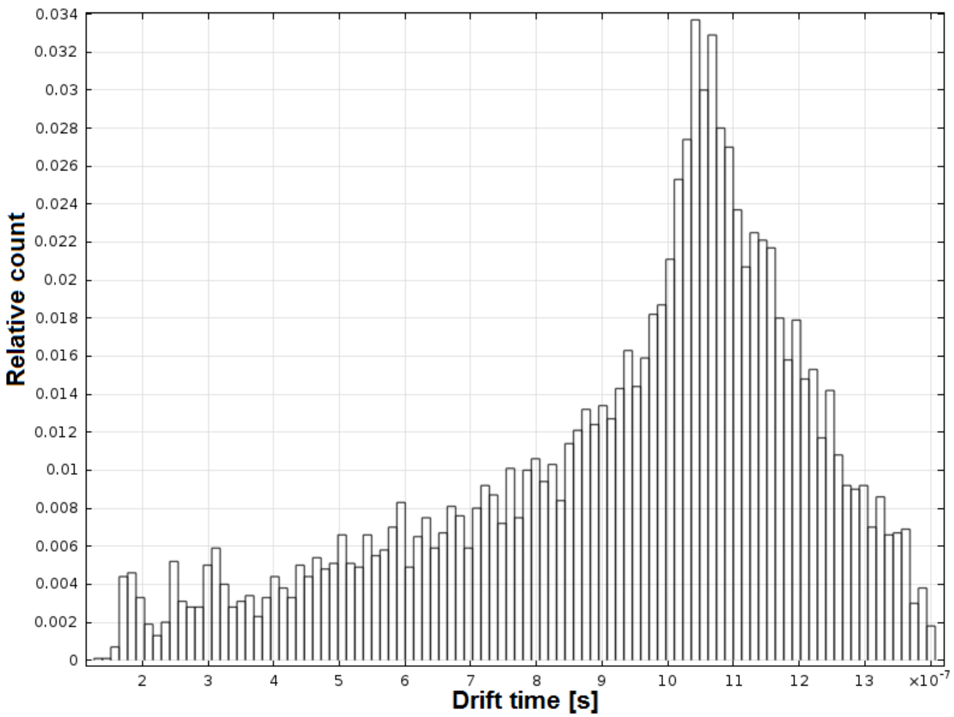


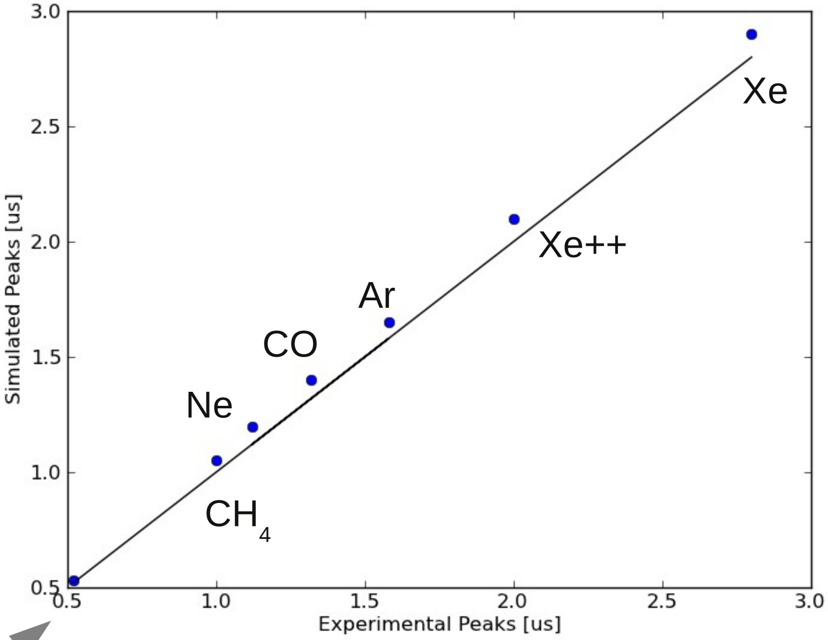
The paths of ions produced in the volume of the PMT are also simulated.

Simulations by Peter Barrow.

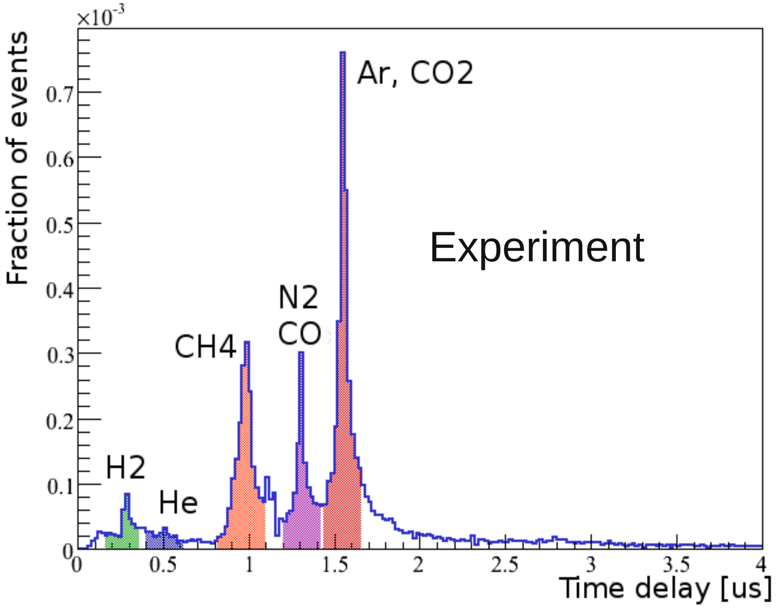
Simulation and experiment

CH_4 drift time from simulation:





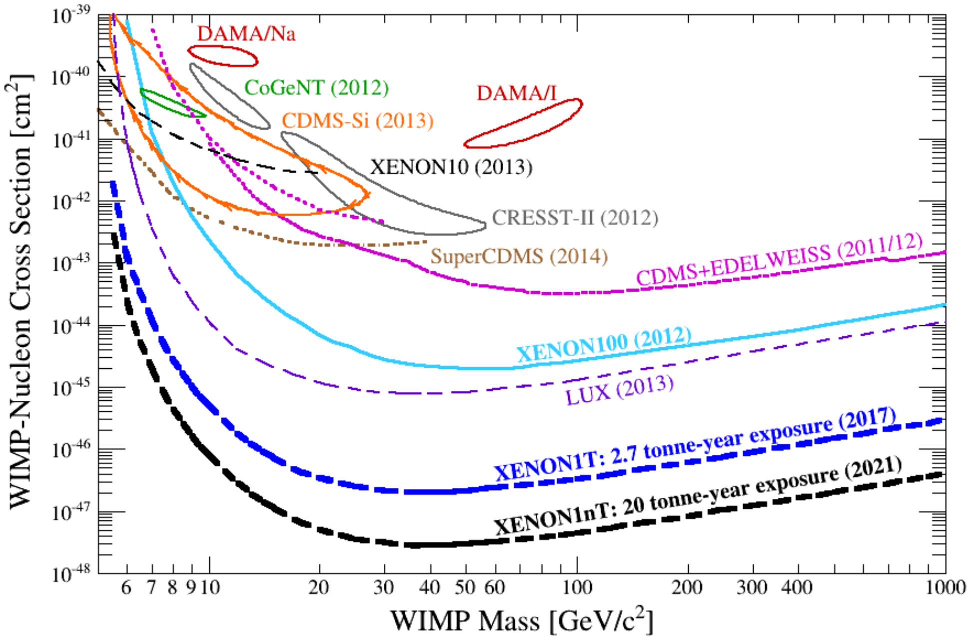
The simulated drift times are in agreement with the experimental results within 5%.



The afterpulse analysis allows to identify the gas remnants within the PMT and helps **identify leaks or impurities**.

Outlook

- The construction of XENON1T has started at LNGS.
- MPIK and UZH will continue testing the R11410 PMTs before their final installation in XENON1T.
- Data taking will start in 2015 and over the next few years a sensitivity of 2×10^{-47} cm^2 will be achieved.



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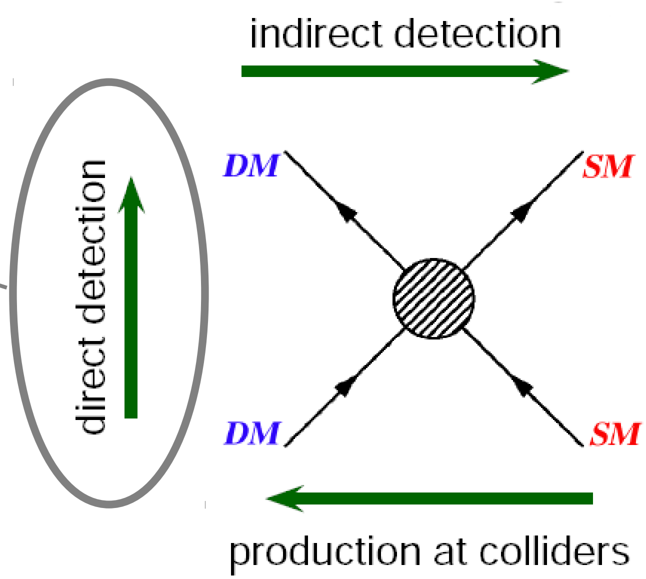
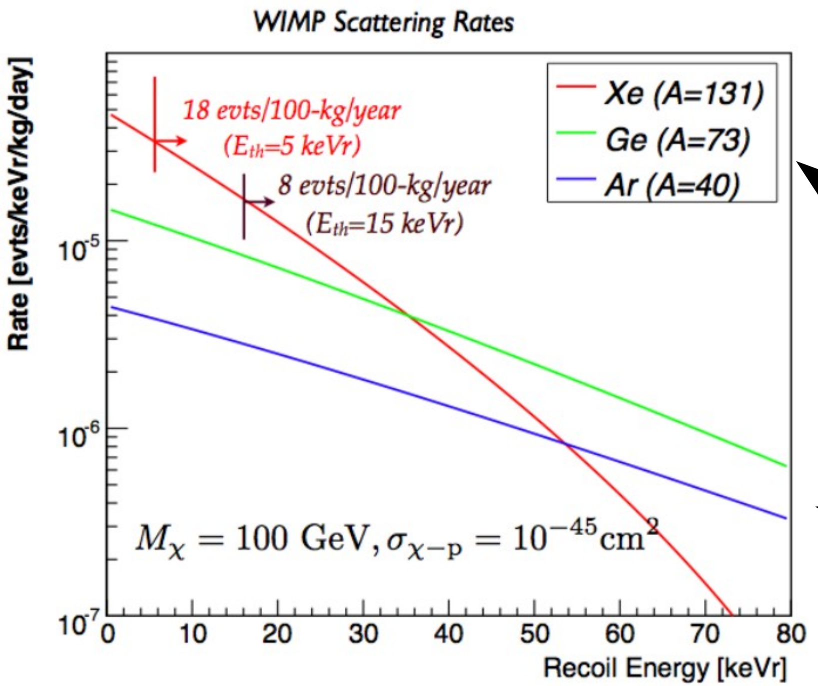
Direct detection with LXe

Why Xe?

- ✔ Large atomic mass, high stopping power.
- ✔ Self shielding.
- ✔ No long lived radioisotopes.
- ✔ Efficient scintillator.
- ✔ Scalable.

Search for **WIMP elastic scattering** off nuclei.



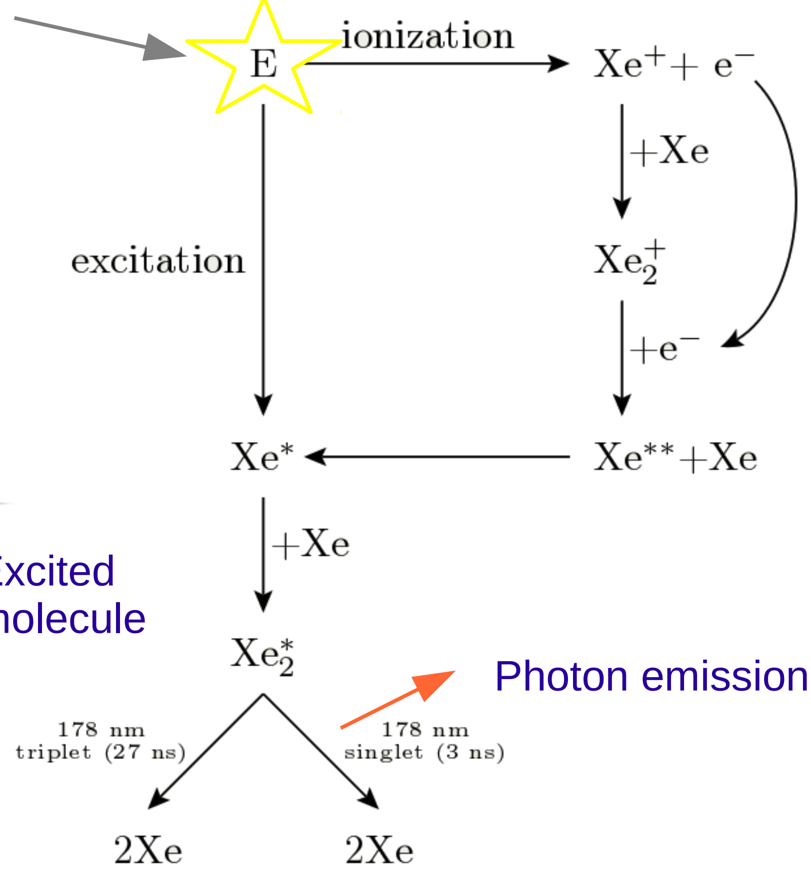


Using large mass detectors with a dense target material.

Nuclear recoil spectrum with exponential shape.

The photon emission principle

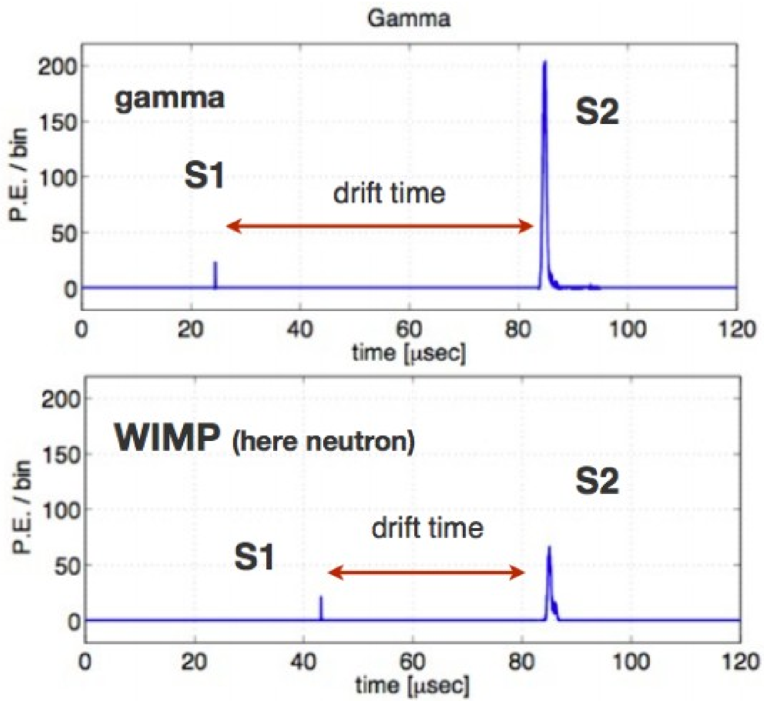
Wimp interaction



Excited molecule

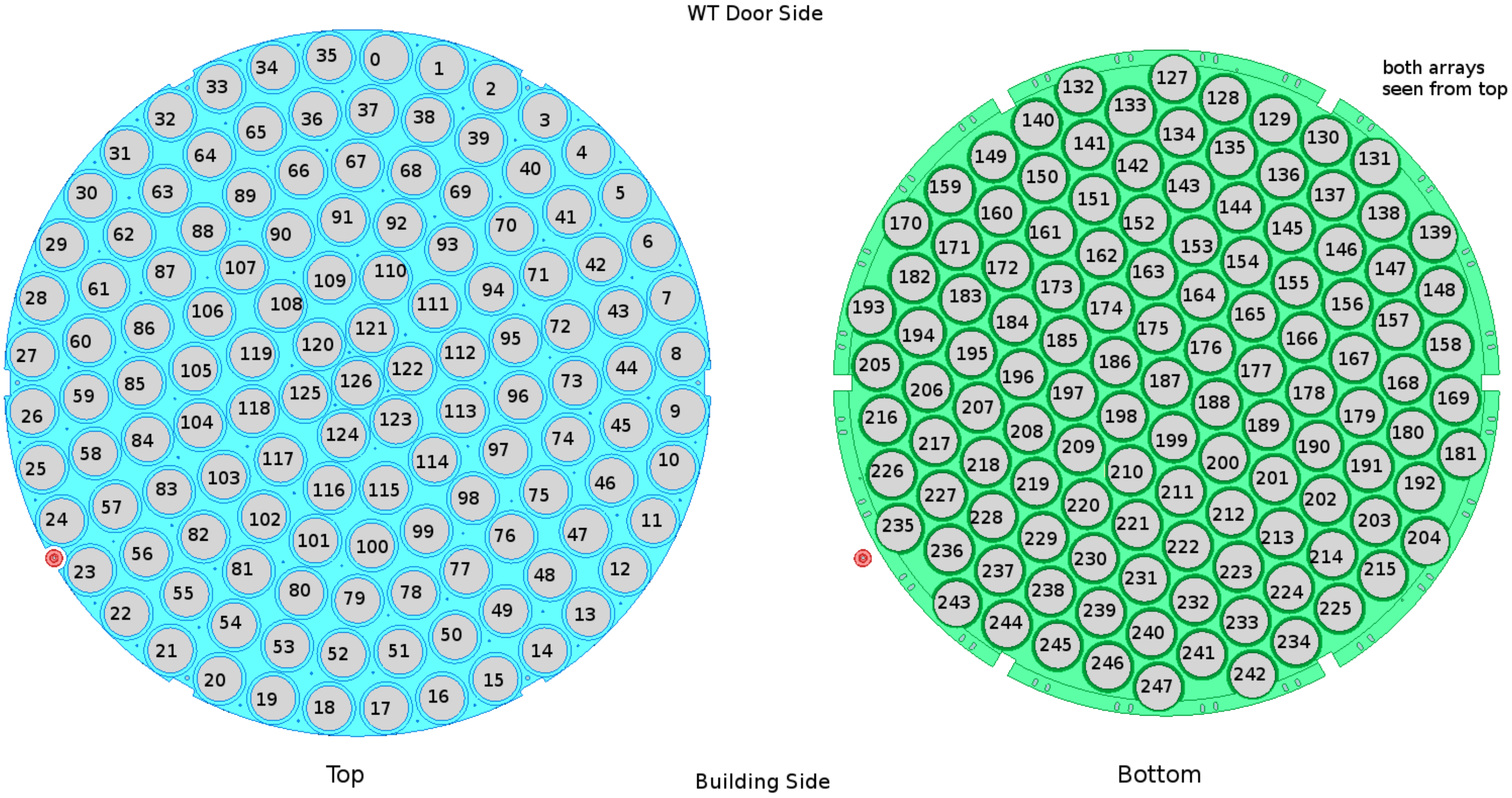
Photon emission **S1**

Some electrons drift to the anode and produce the **S2** signal, while others **recombine** with Xe ions.



The **S2/S1** ratio allows to distinguish WIMPs (nuclear recoils) from the main backgrounds (electronic recoils).

XENON1T PMT map



Top

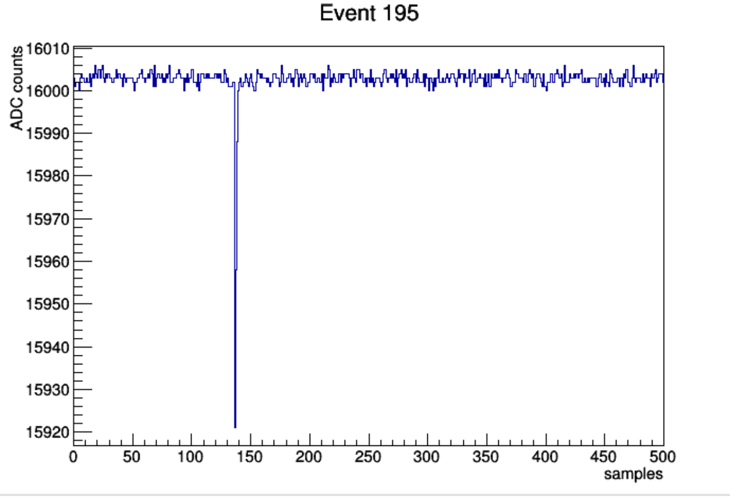
Bottom

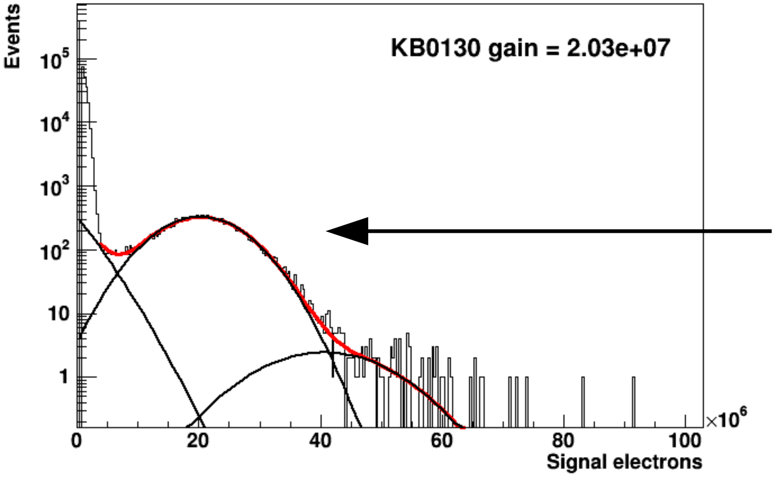
127 PMTs

121 PMTs

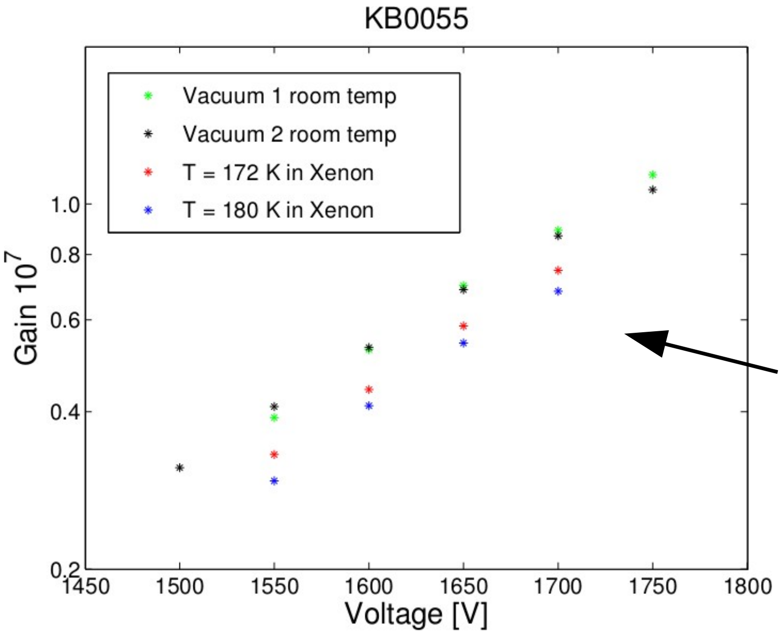
PMT Spectrum and Gain

Example event:
Photon signal from LED.



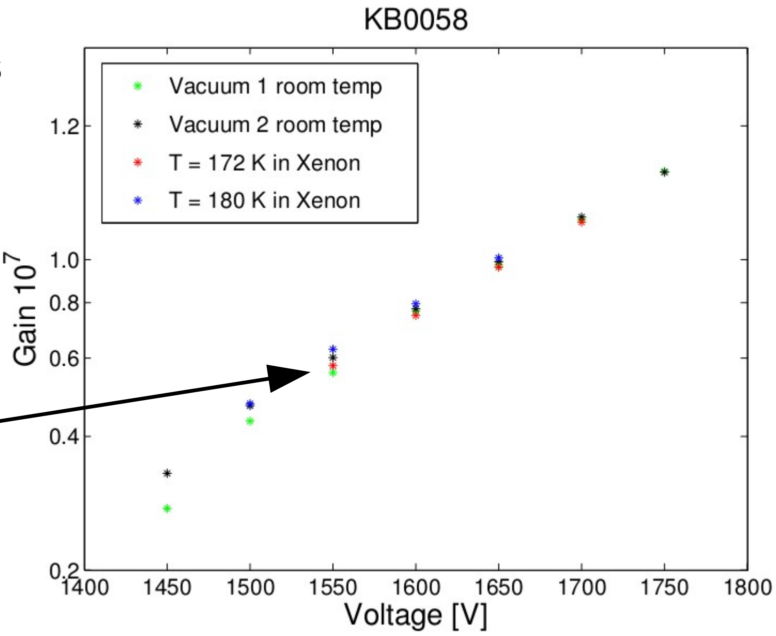


The PMT gain is estimated from the spectrum by identifying the single photo-electron peak, separated from the **noise** and double photo-electrons.

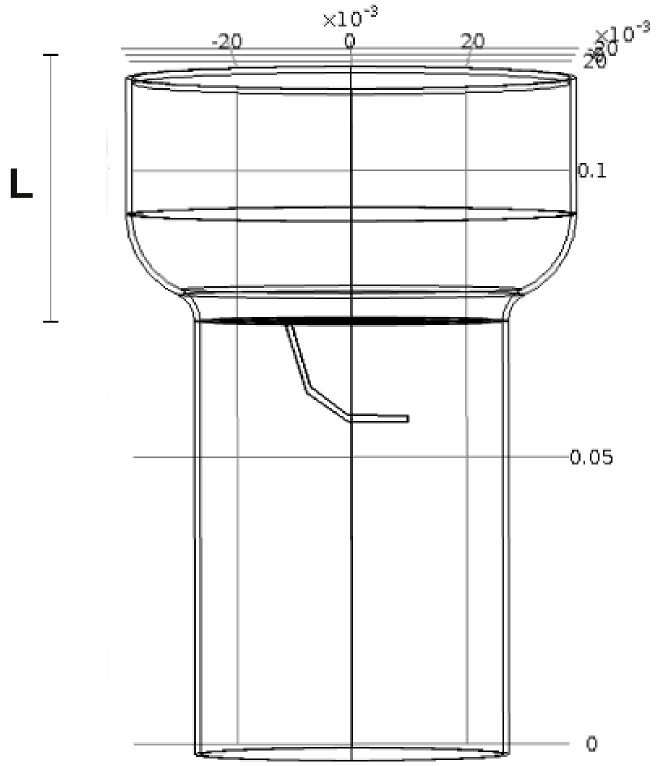


The gain of each PMT is measured at different voltages.

When operated in LXe, some PMTs show a decrease of around 10%, while in others the change is very small.



Afterpulse Peak ID



Consider the arrival time:

$$t = \int_{s_0}^{L} \frac{1}{v} ds = \sqrt{\frac{m}{2q}} \int_{s_0}^{L} [V(s_0) - V(s)]^{-1/2} ds,$$

where ***m*** and ***q*** are the mass and charge of the ion, $\boldsymbol{s_0}$ is the position of ionization and ***V(s)*** is the electric potential.

The field in a hemispherical PMT can be approximated as quadratic:

$$V(s) = V_0 \left(1 - \frac{s}{L}\right)^2$$

So the arrival time calculated from the integral gives:

$$t = \frac{4}{\pi} \sqrt{\frac{2m}{qV_0}} L,$$

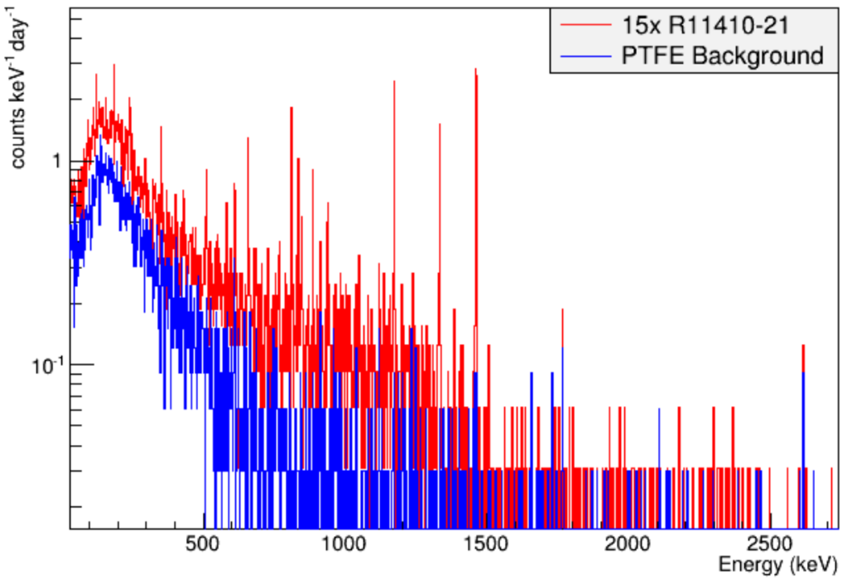
The mass/charge of the ion producing an afterpulse at time *t* is:

$$\frac{M}{Q} = \left(\frac{\pi t}{4L}\right)^2 \frac{V_0}{2} \frac{q_p}{m_p}$$

The mass/charge of the ion is then proportional to $\boldsymbol{t^2}$:

$$\frac{M}{Q} = A t^2$$

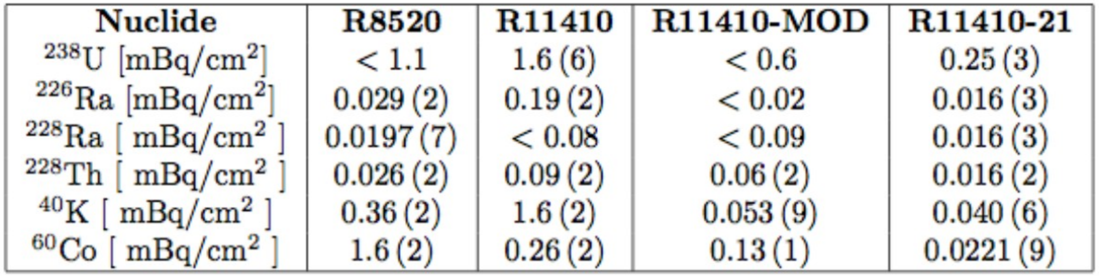
PMT radioactivity and XENON1T background



XENON100 and XENON1T PMTs

Radioactivity evolution

(values normalized per optical window area)



Nuclide	R8520	R11410	R11410-MOD	R11410-21
^{238}U [mBq/cm^2]	< 1.1	1.6 (6)	< 0.6	0.25 (3)
^{226}Ra [mBq/cm^2]	0.029 (2)	0.19 (2)	< 0.02	0.016 (3)
^{228}Ra [mBq/cm^2]	0.0197 (7)	< 0.08	< 0.09	0.016 (3)
^{228}Th [mBq/cm^2]	0.026 (2)	0.09 (2)	0.06 (2)	0.016 (2)
^{40}K [mBq/cm^2]	0.36 (2)	1.6 (2)	0.053 (9)	0.040 (6)
^{60}Co [mBq/cm^2]	1.6 (2)	0.26 (2)	0.13 (1)	0.0221 (9)

Expected XENON1T background from MC simulations with GEANT4:

Gamma background:
Single scatter, 1 ton fiducial volume, [2-12] keVee, 99.75% ER rejection.

0.05 ev/y

Mainly from the Cryostat (50%), PMTs (30%) and TPC components (< 10%)

Neutron background:
Single scatter, 1 ton fiducial volume, [5-50] keVr, 50% NR acceptance

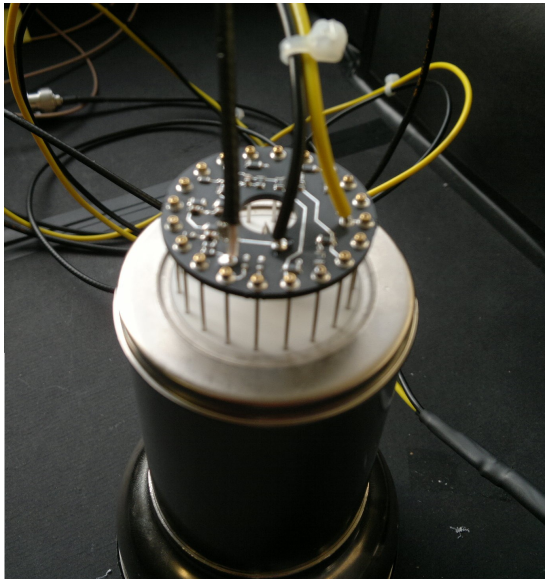
0.2 ev/y

Mainly from Cryostat (30%), PMT +Bases (30%) and PTFE (20%).

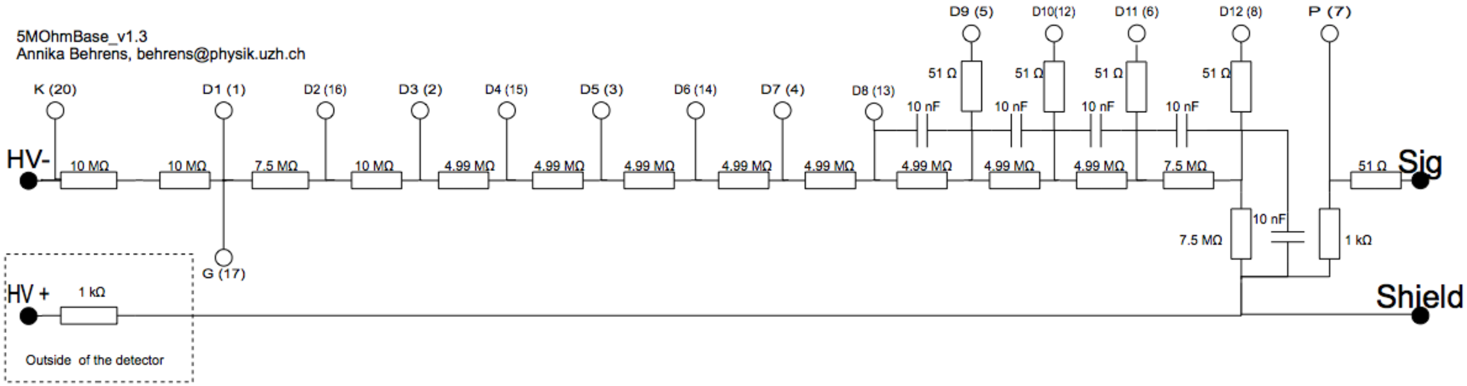
Information from F. Piastra and A. Kish

HV divider base

The base placed at the pins of the PMT provides the voltage difference over the PMT dynodes. **It has been developed and optimized at UZH for:**



- **Linearity**. Up to 50k PE (approx. 1 MeV particle energy).
- **Low heat dissipation** (total under 10W).
- **Sub-zero** temperature performance
- **Good P/V** ratio and **high gain**



Screening results with **Gator**:

Units: mBq	^{238}U	^{226}Ra	^{228}Ra	^{228}Th	^{235}U	^{40}K	^{60}Co	^{137}Cs
PMT only	< 13	0.50 +- 0.10	0.50 +- 0.10	0.50 +- 0.06	0.37 +- 0.05	13 +- 2	0.71 +- 0.03	< 0.19
PMT + base	< 16	0.95 +- 0.07	0.70 +- 0.10	0.60 +- 0.06	0.43 +- 0.05	13 +- 2	0.72 +- 0.03	< 0.21