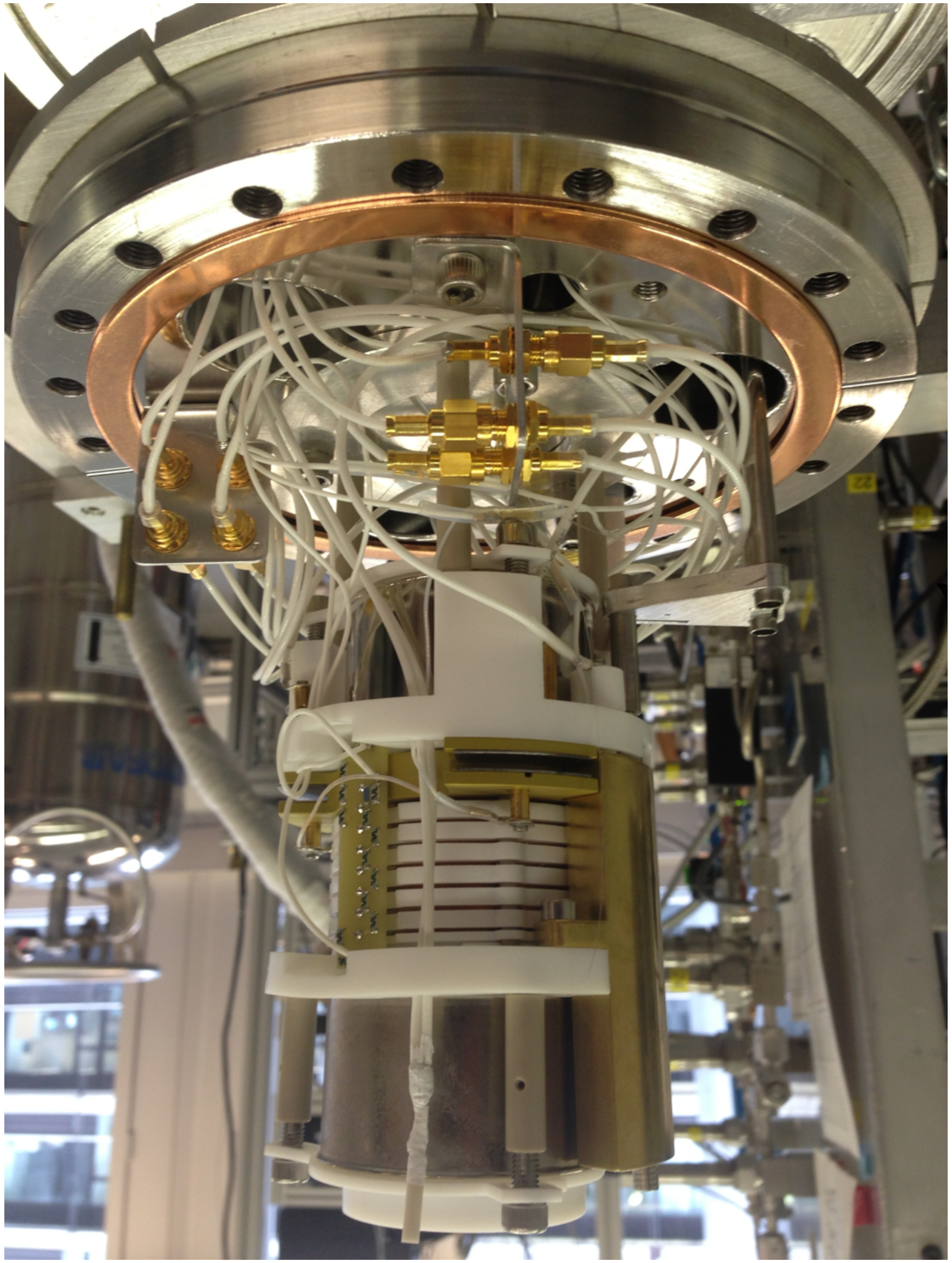
Swiss Physical Society Annual Meeting
Geneva, Switzerland
25 August 2017

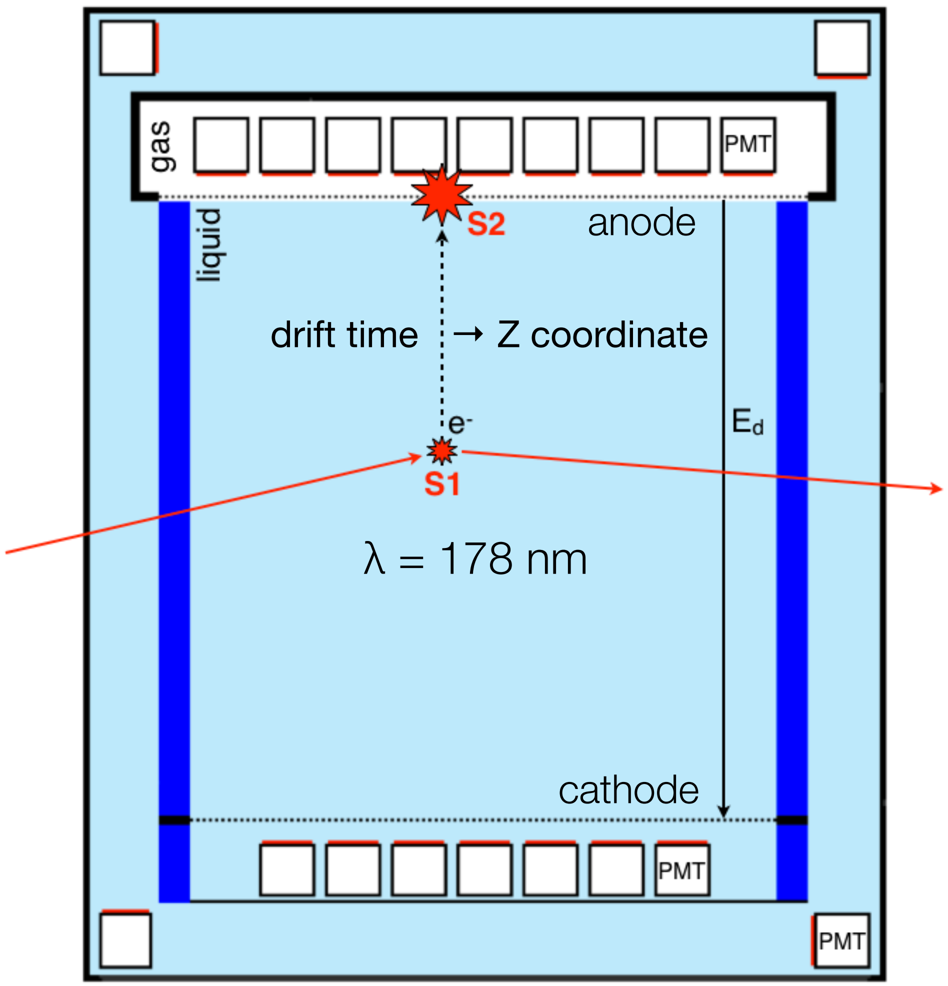
Xürich II:

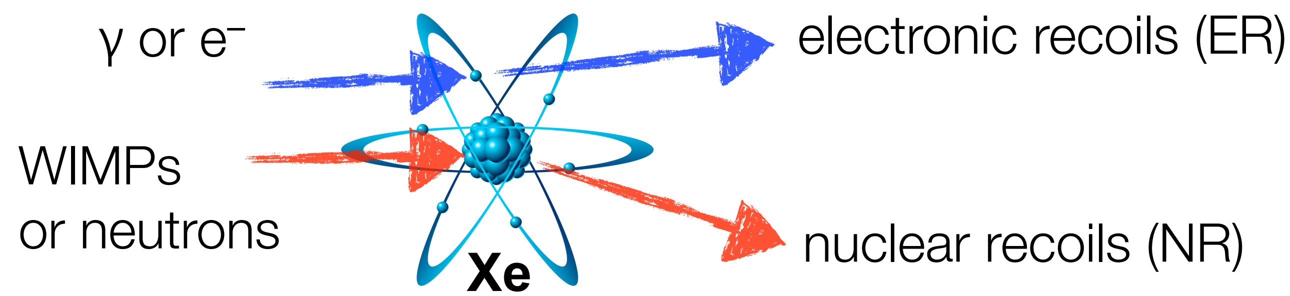
A Dual-phase TPC for Scintillation and Ionization Yield Measurements in Liquid Xenon



Dr. Alexander Kish
University of Zurich

Particle detection principle with a dual-phase TPC



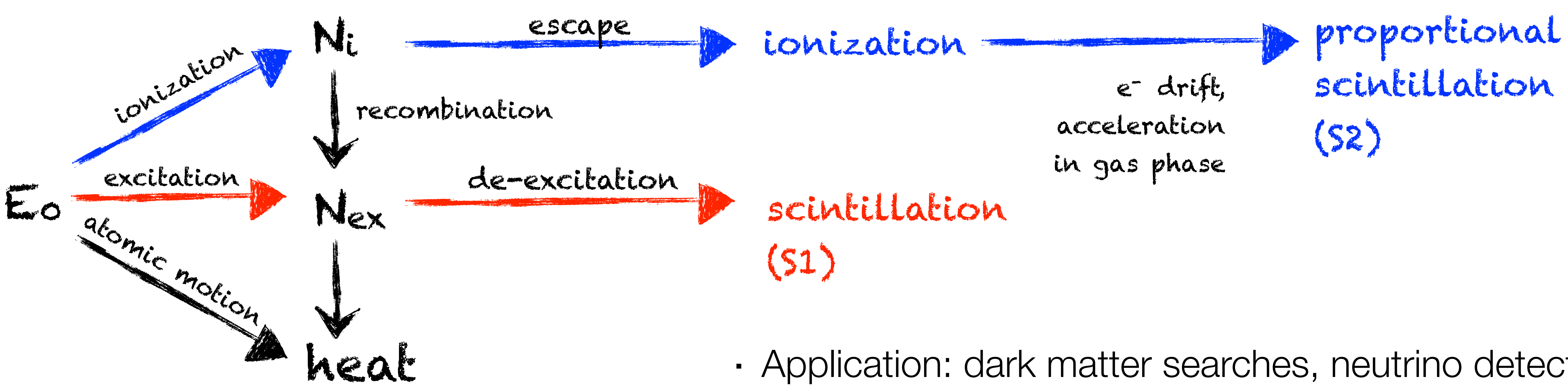


- Two signal channels (S1 and S2)

- Ratio depends on *dE/dx*, different probability for electron-ion pairs recombination

→ event vertex reconstruction in 3D
(interaction depth from delay between S1 and S2)

→ particle type discrimination: $(S2/S1)_{ER} > (S2/S1)_{NR}$
(factor ~ 200 and higher efficiency)

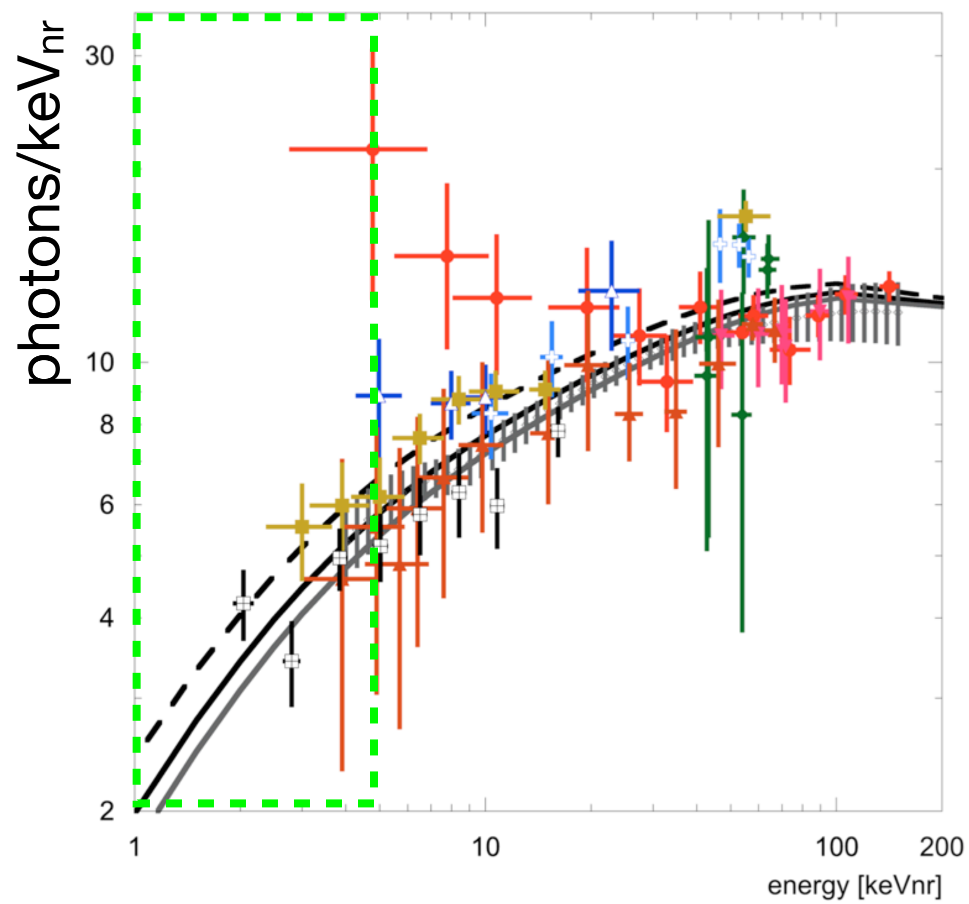


- Application: dark matter searches, neutrino detection

Light yield/L_{eff} measurements:

- below keV_{nr} only LUX (down to 1.1 keV_{nr} @ 181 V/cm)
- Plante down to 3 keV_{nr}

→ new data below 3keV_{nr} is valuable



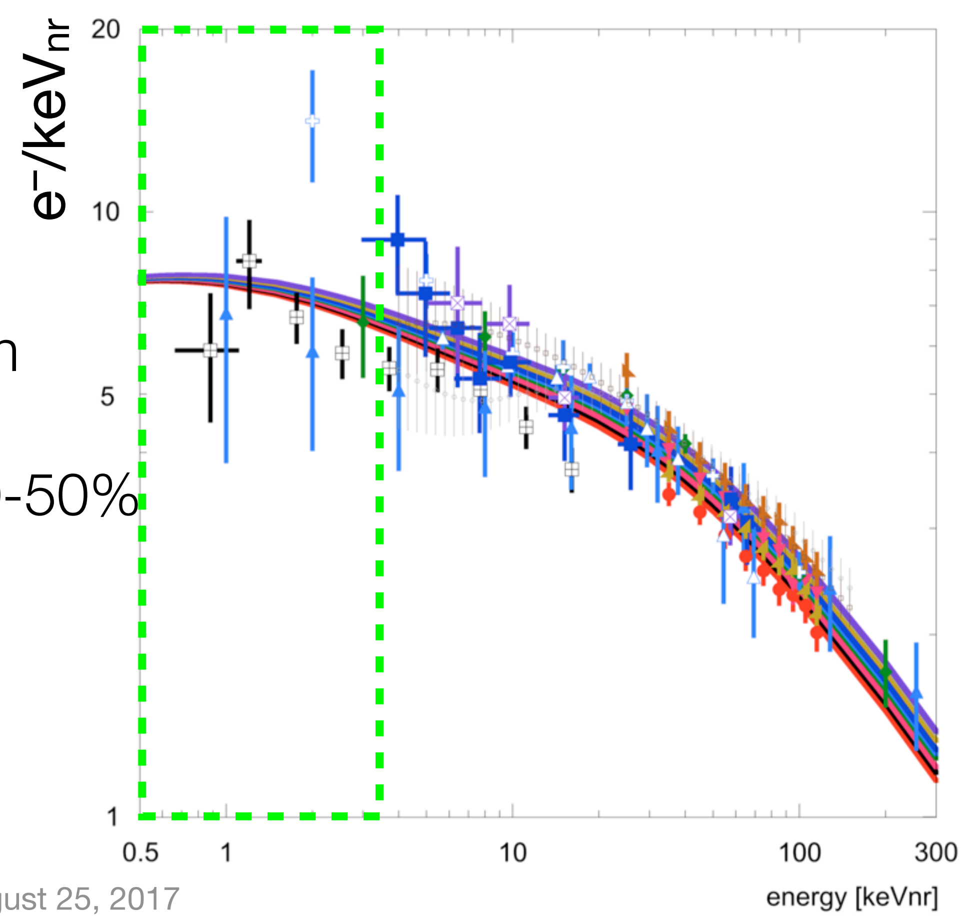
LUX DD 2014 *preliminary* same color and shape as for charge plot (black squares with crosses)

ZEPLIN-III (M. Horn) averaged over both runs (3,650 V/cm field): dark grey points (AmBe)

Charge yield measurements:

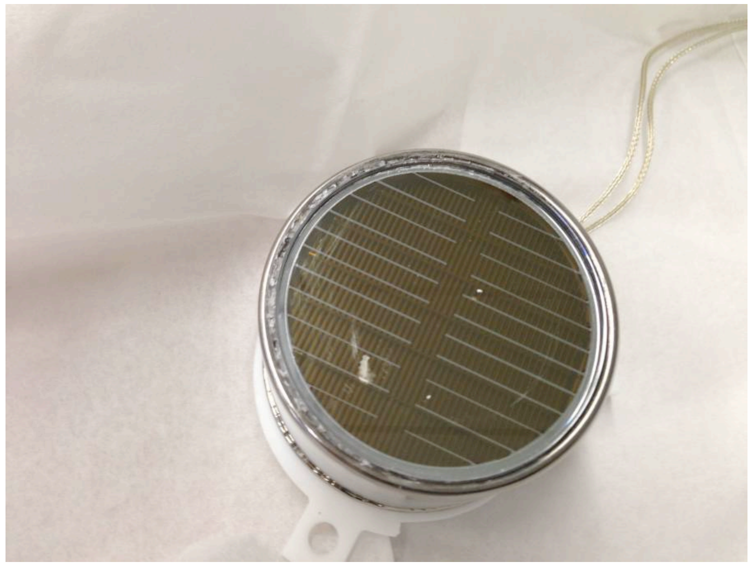
- mostly indirect measurements
- LUX down to 0.7 keV_{nr} @ 181 V/cm

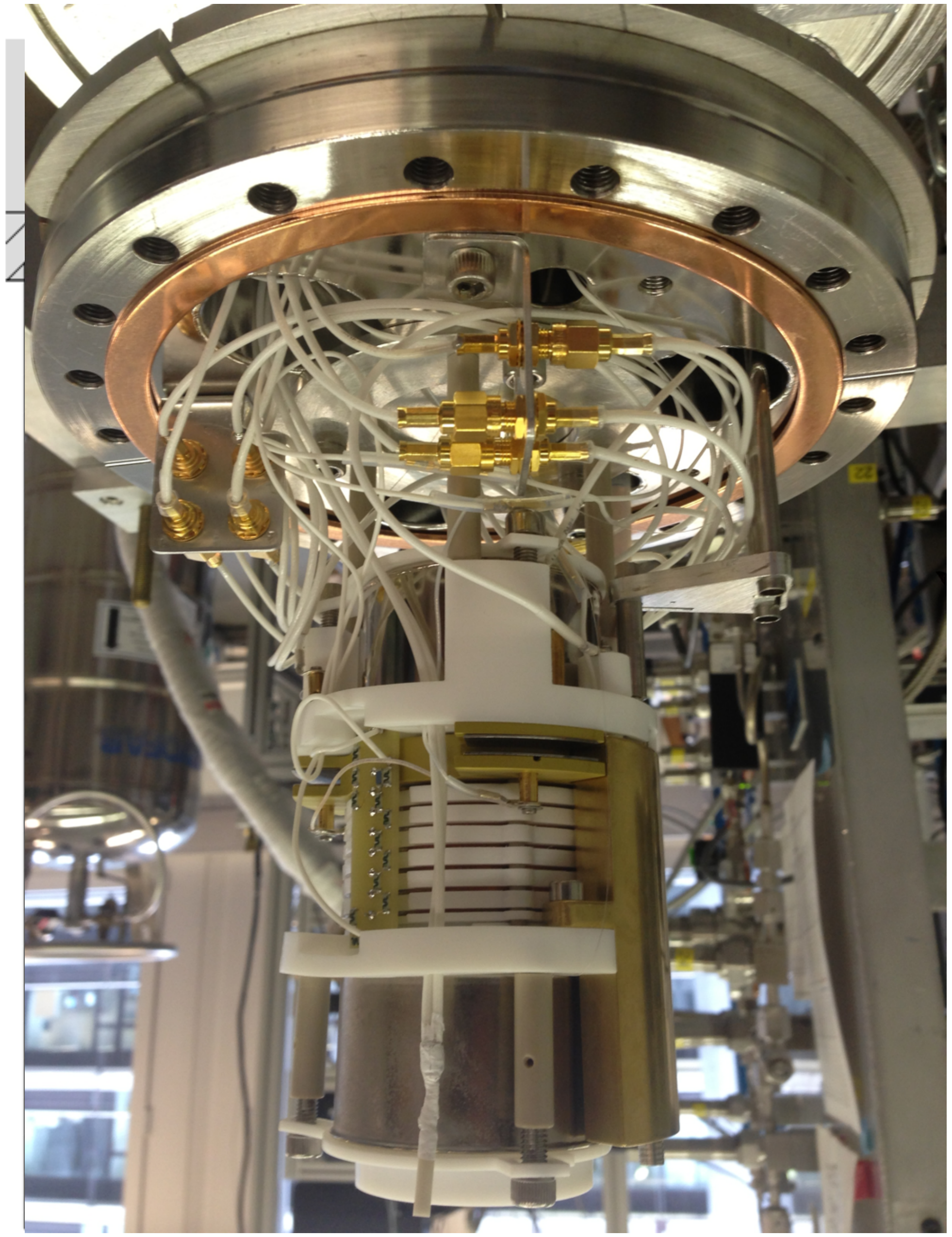
→ uncertainties are large, order of 30-50%

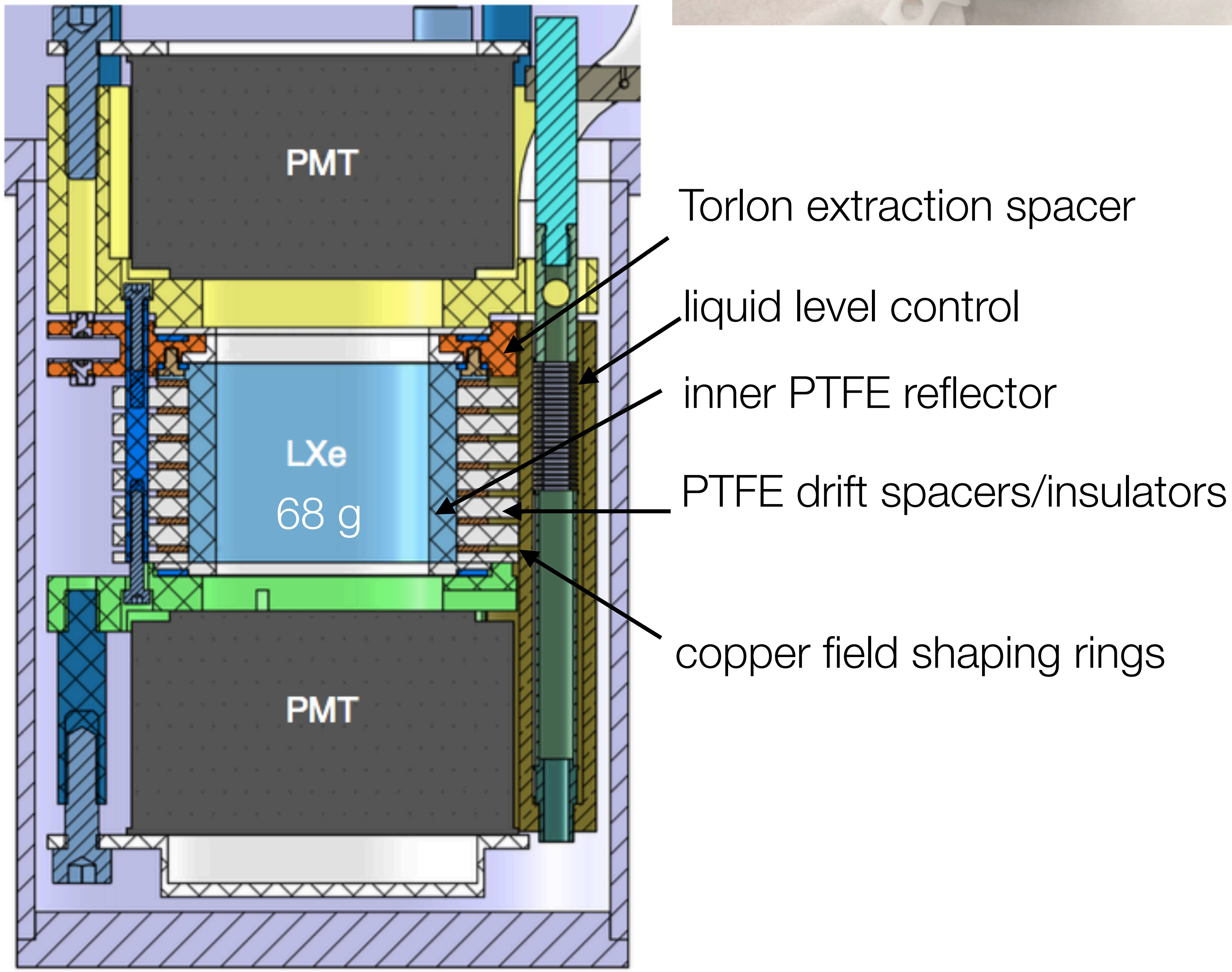


Xurich II detector design

- Active volume: 3.1 cm diameter and 3.1 cm height
- Two 2-inch PMTs, Hamamatsu Photonics R9869
  bialkali photocathode (16 cm^2) with QE ~35% @ 178 nm





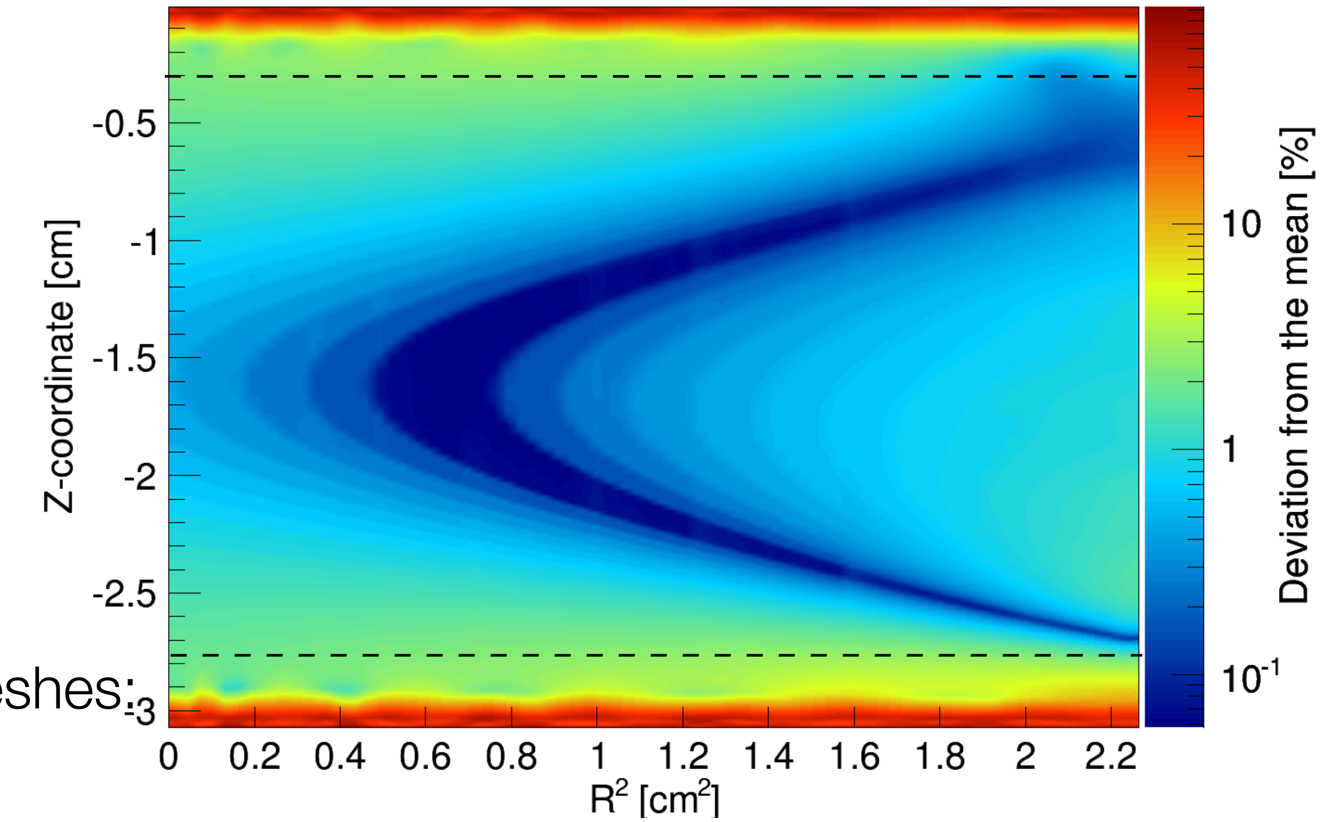


Electric field configuration

Electric field cage design optimised on simulations with COMSOL and KEMfield

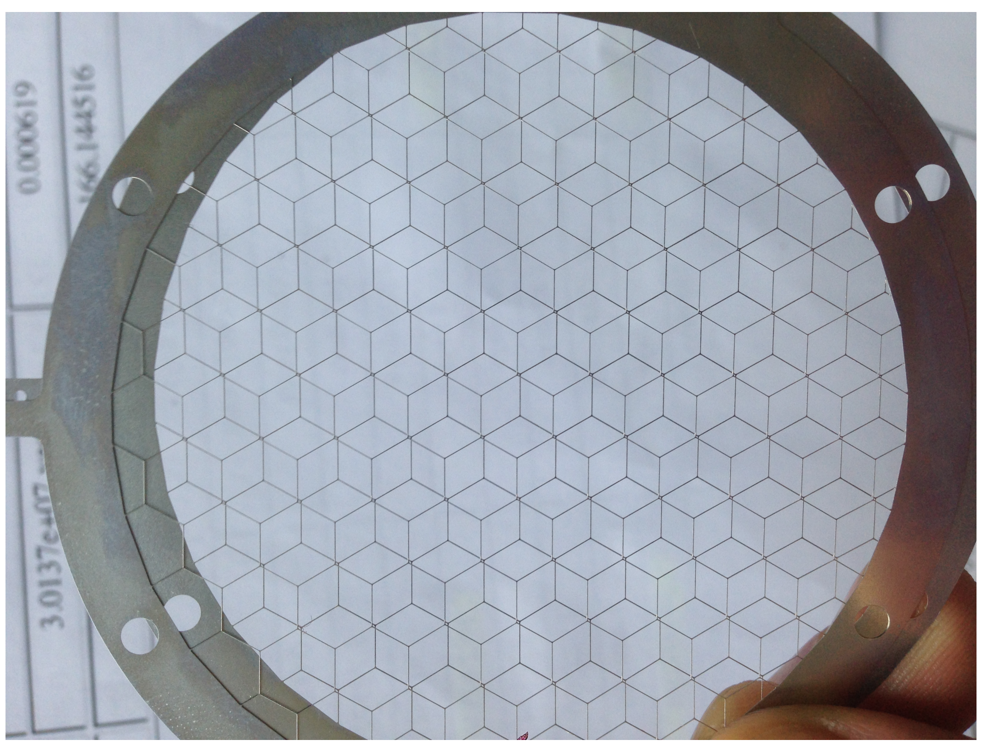
Deviation of electric field from uniformity:

- target volume 2.8%
- fiducial volume 0.9%



Electrodes from chemically etched stainless steel meshes:

- wire diameter 100 μm, pitch 2.7 mm
- 93% optical transparency

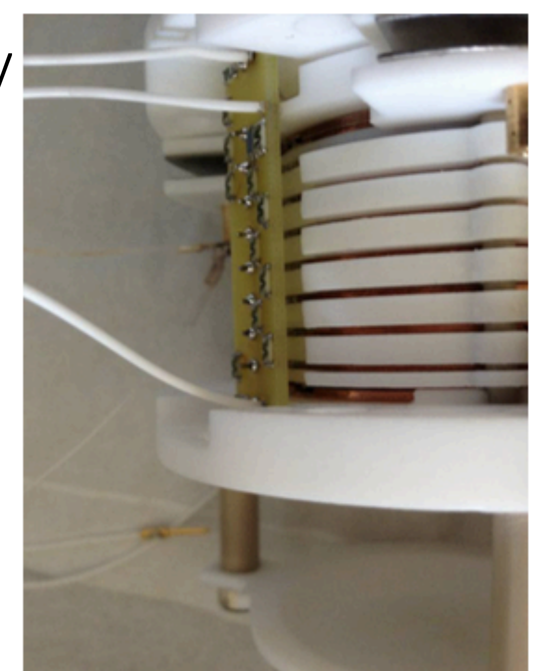


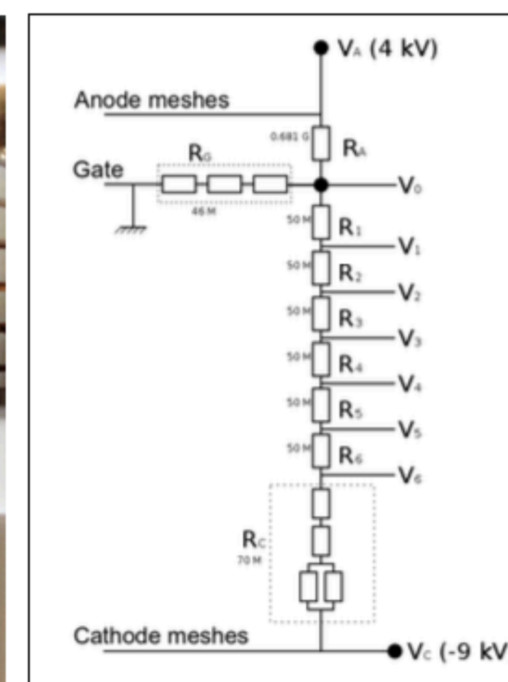
- voltage divider circuit with R = 1.5 GΩ
- cathode HV up to 6 kV

  → e– drift field 2 kV/cm

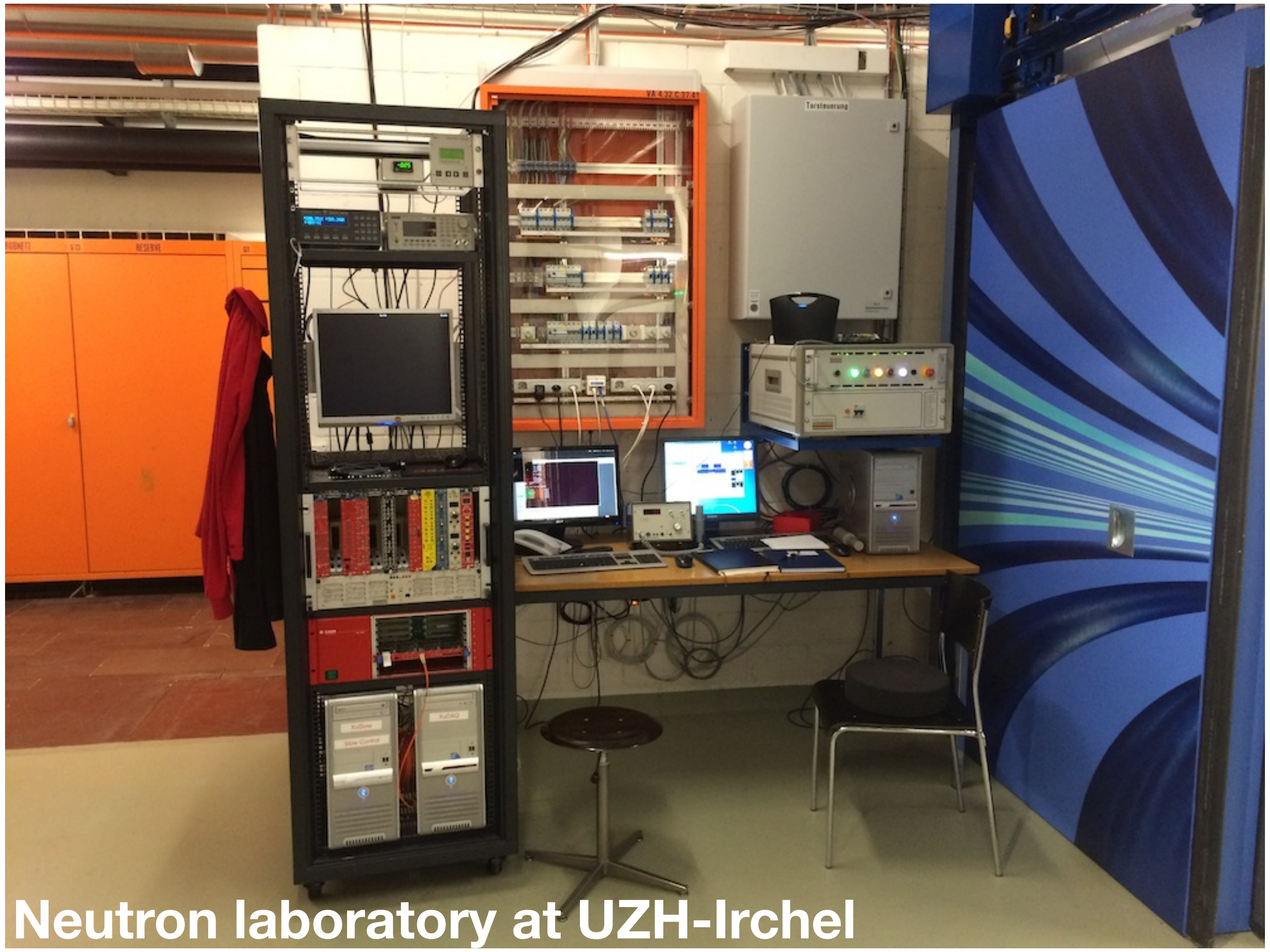
- anode at 4 kV

  → extraction field (10.32±0.14) kV/cm





Xenon Liquefaction, Purificatoin, DAQ



- Data digitised with CAEN V1724 Flash ADC:
  10 ns sampling period
  2.25V full scale
  14-bit resolution
  40 MHz bandwidth

- Cooling by a copper cold finger immersed in a liquid nitrogen bath (automatic refill system with a solenoid valve, 160L dewar lasts ~5 days)

- Temperature control with 5W heater at the top flange of the inner cryostat vessel

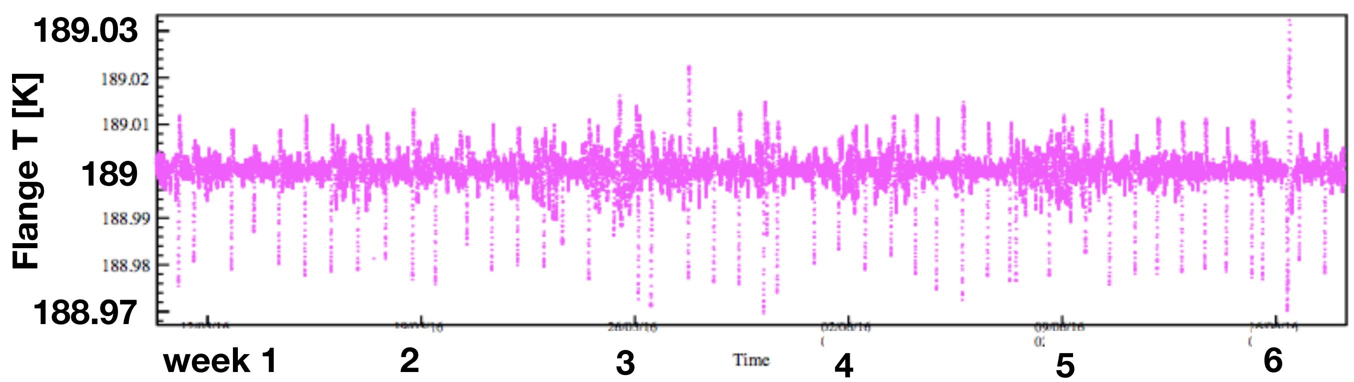
- Xenon gas is constantly purified by circulation through a hot metal getter with flow rate ~0.7 slpm

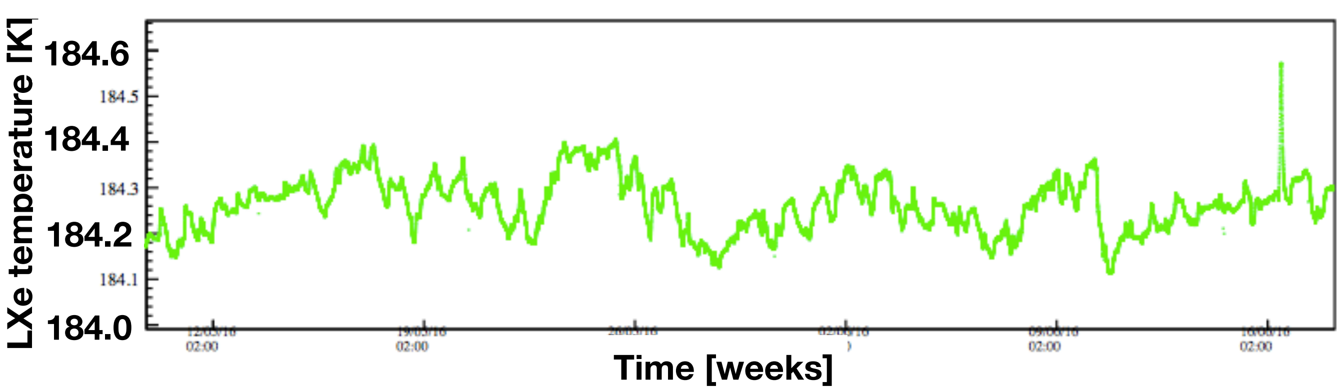
Operational parameters and their stability

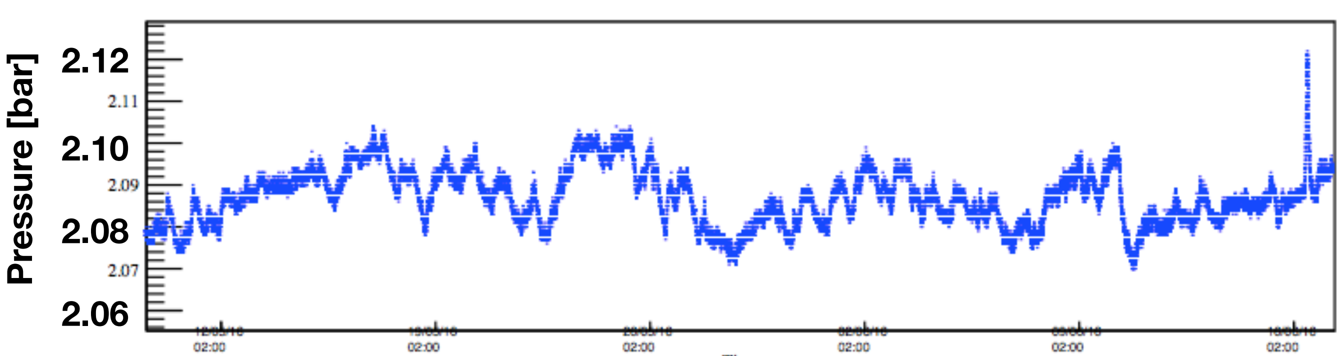
- PID-based feedback system for temperature control

- Two Pt100 resistive thermometers:
  – at the top flange (next to the heaters) – control T
  – at the bottom of the LXe volume

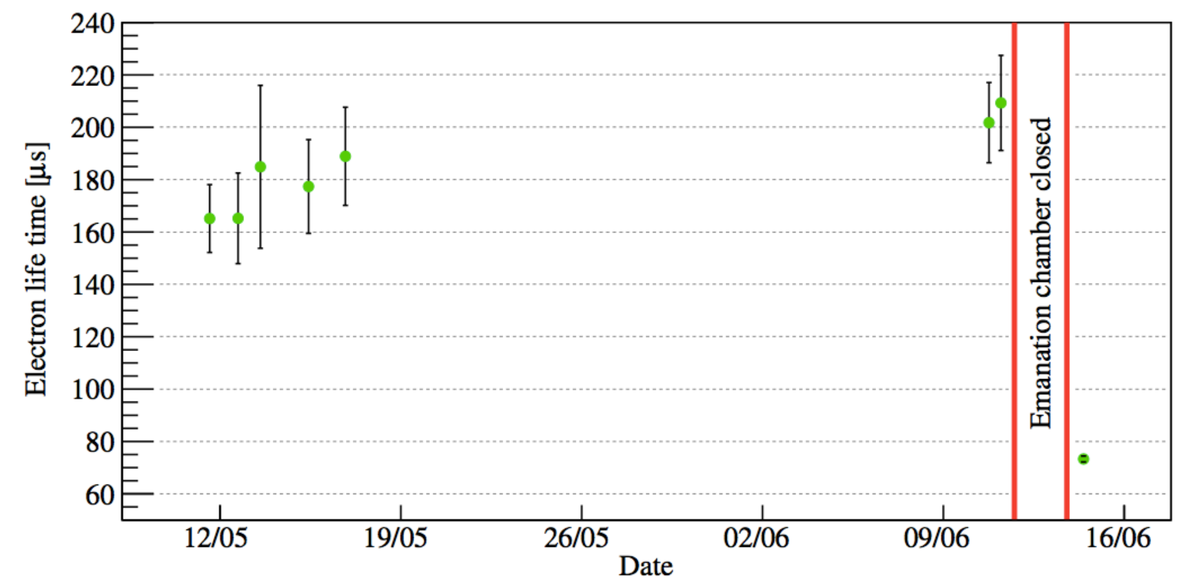
→ T and P stable within 0.2%



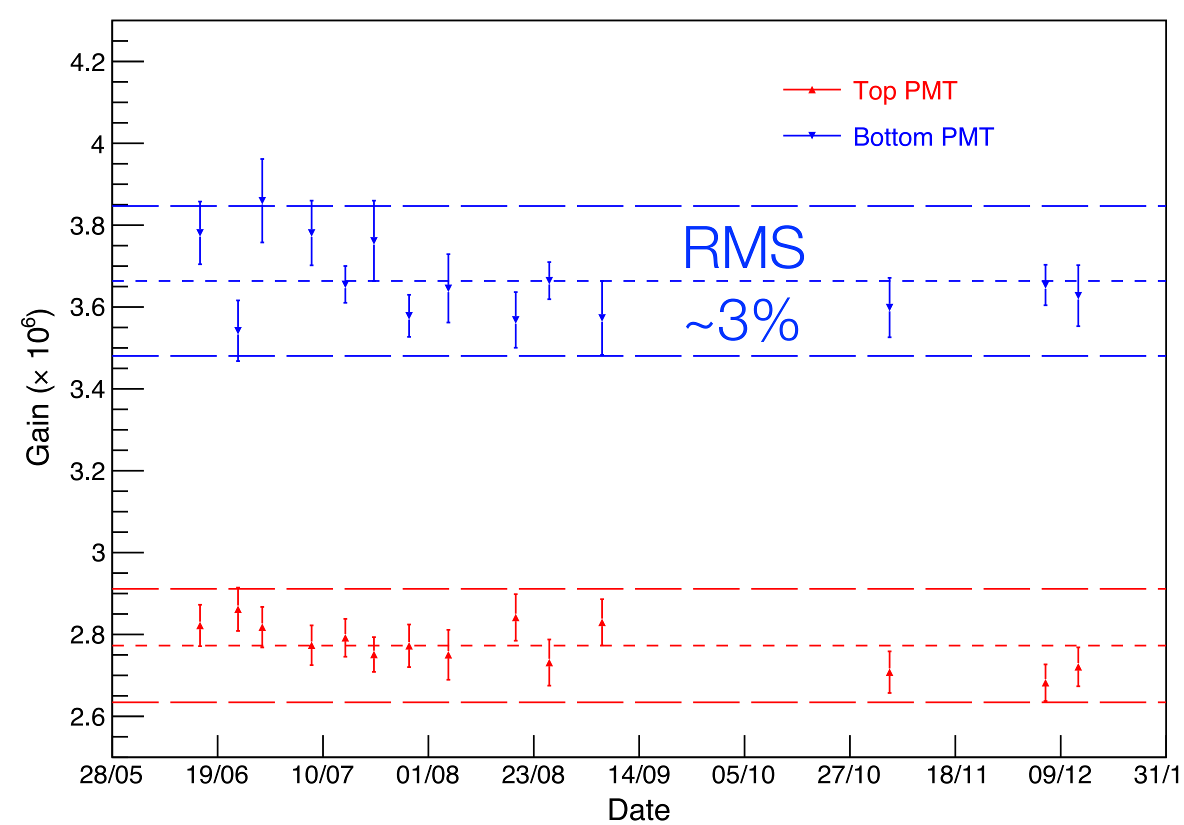




- Electron lifetime ~200 μs
  (TPC drift lentgh ~20 μs)

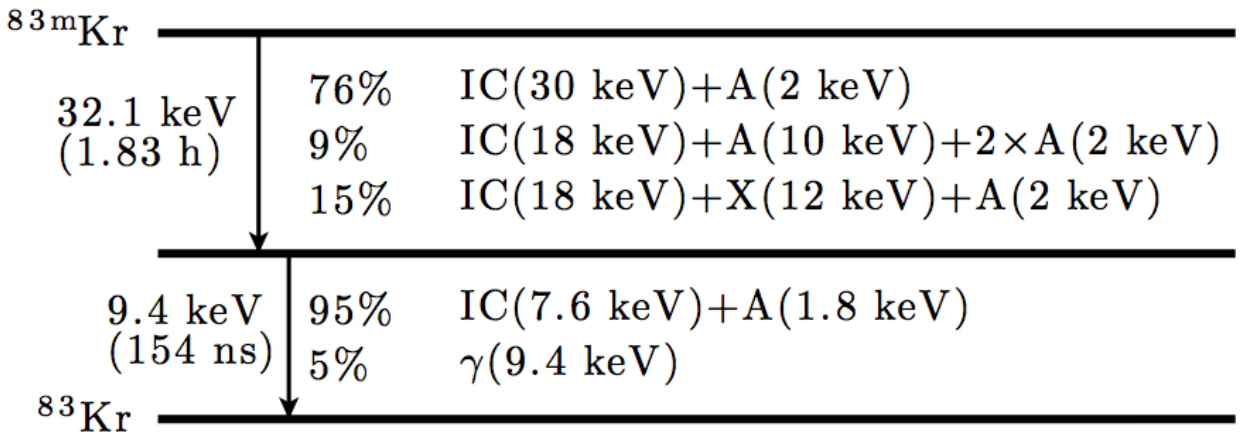


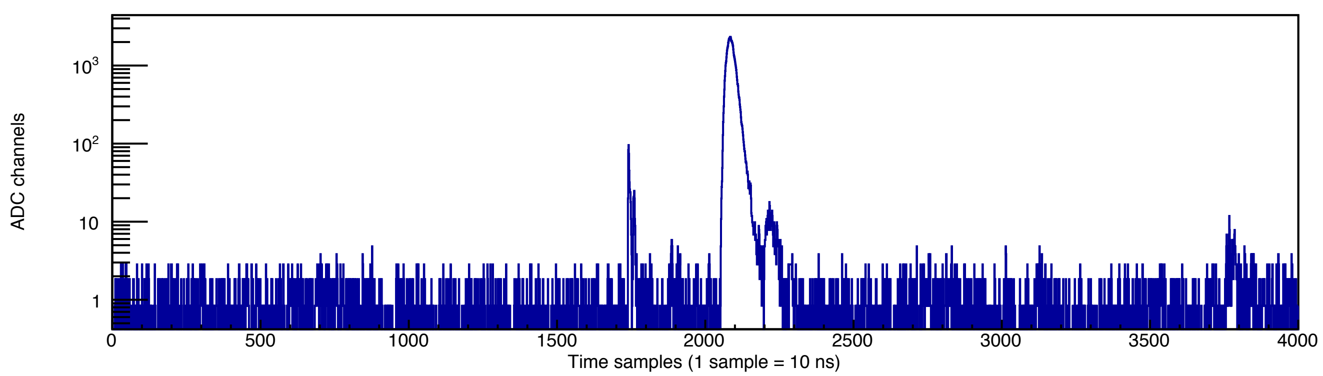
- PMT gains regularly calibrated:
  Top PMT (2.90±0.04)×10^6 @ 870 V
  Bottom PMT (3.73±0.09)×10^6 @ 940 V

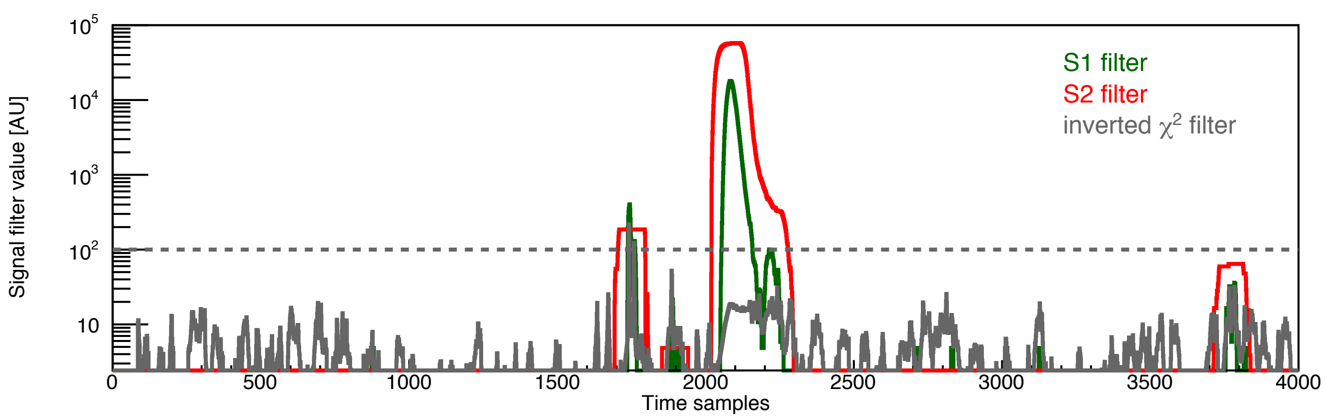


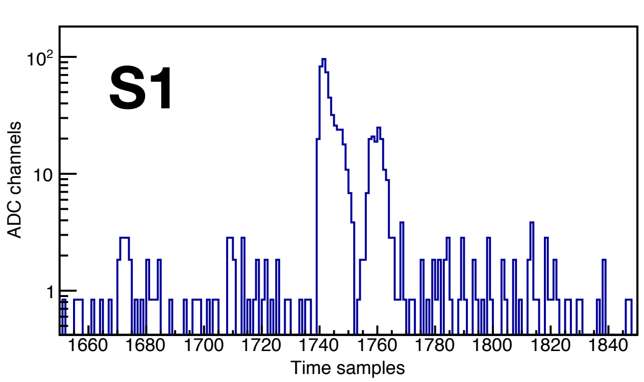
Signal search and identification algorithm

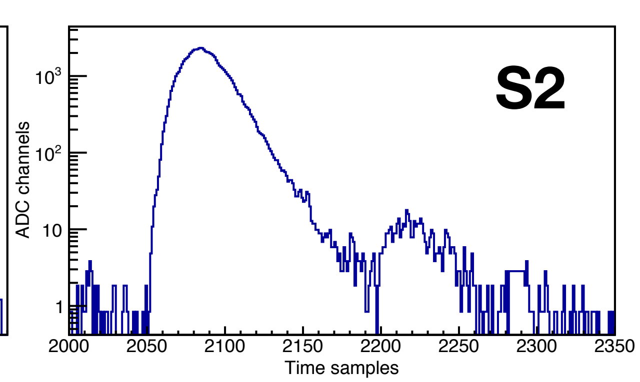
- Calibration by injection of meta-stable ^{83m}Kr gas









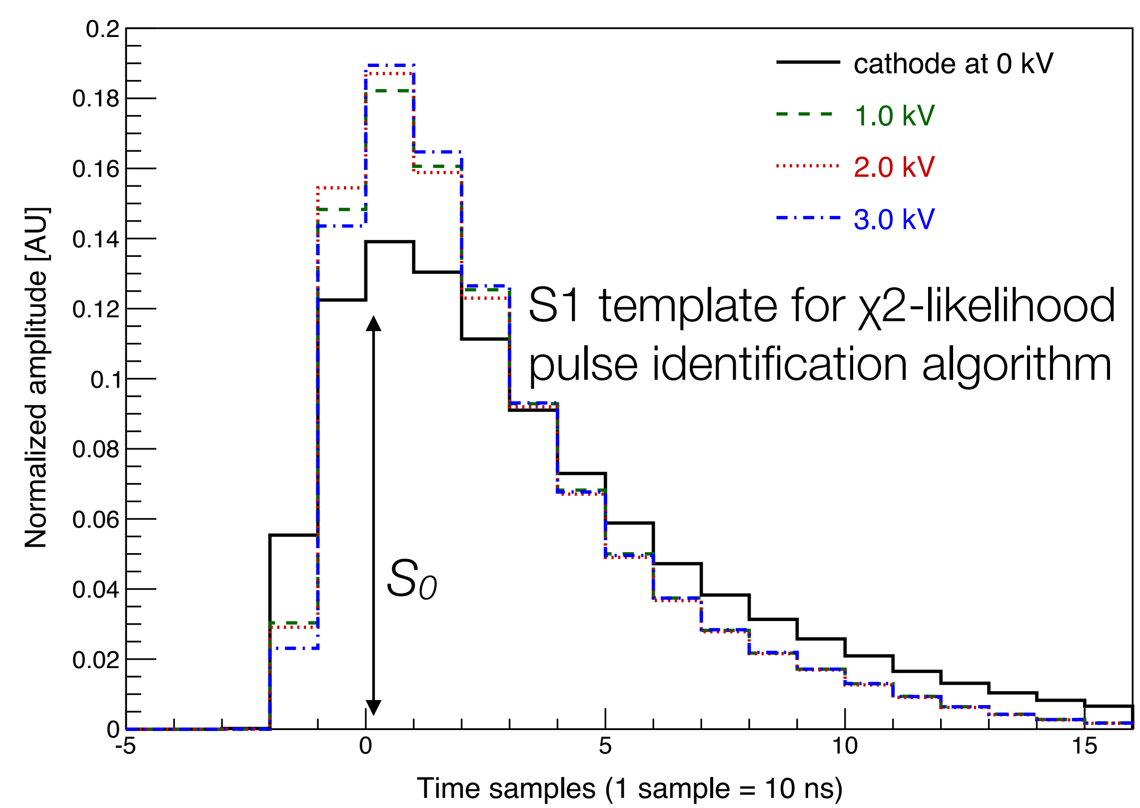


- Identification of S1- and S2-like pulses with two width-based filters and a χ2-likelihood filter

$$A_i[1] = \sum_{j=i-\frac{w_1}{2}}^{i+\frac{w_1}{2}} S_j$$

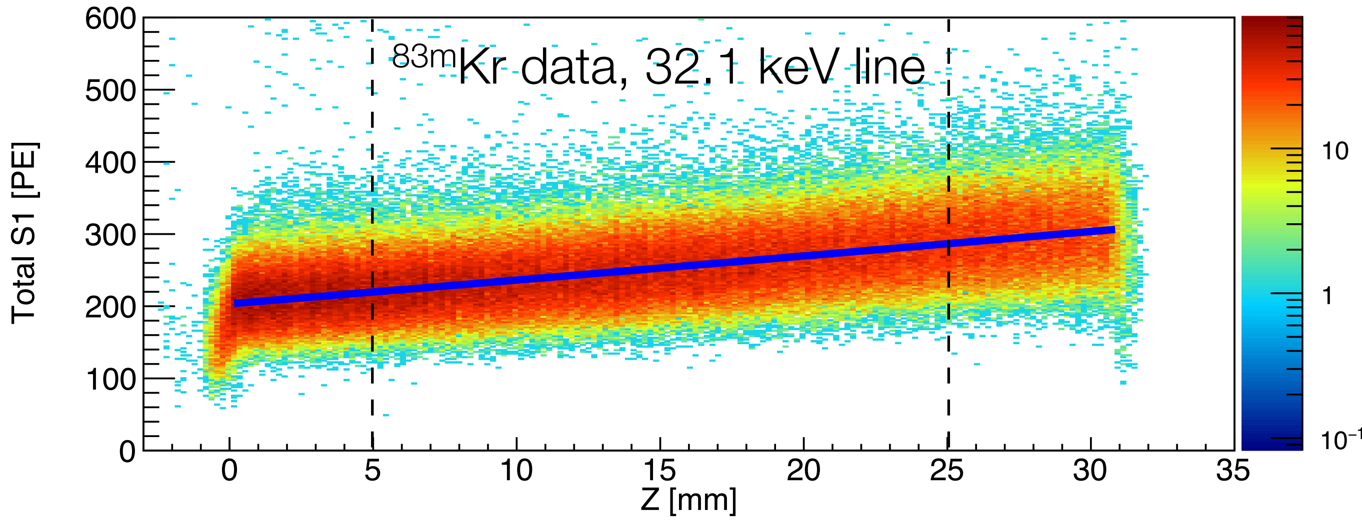
$$A_i[2] = \sum_{j=i-\frac{w_2}{2}}^{i+\frac{w_2}{2}} S_j - \max_{[j=i-\frac{w_2}{2},\, i+\frac{w_2}{2}]} A_j[1]$$

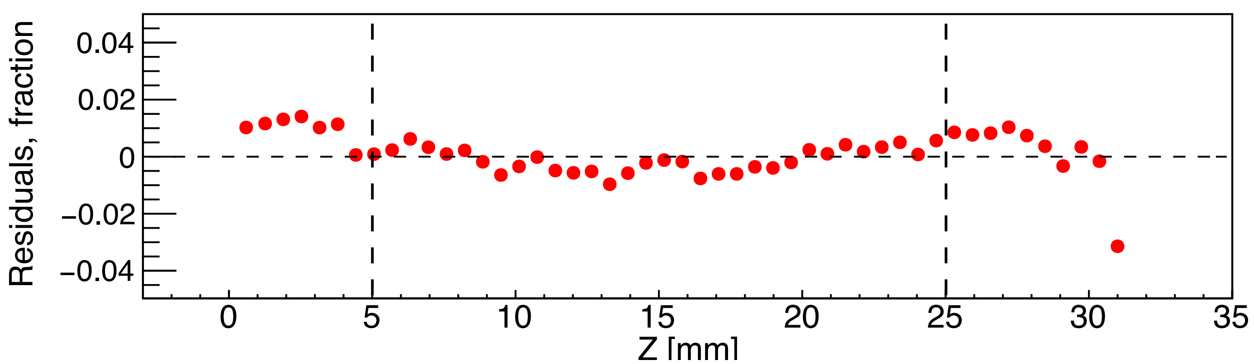
$$\chi_i^2 = \sum_{k=-l}^{r} \left(T_k - \tilde{S}_{i+k} \right)^2$$



Scintillation light collection efficiency

- 30% variation of response due to reflections of S1 scintillation light from the PTFE surfaces and at the liquid/gas interface





→ 2% variation after applying the correction

- Radial variation:

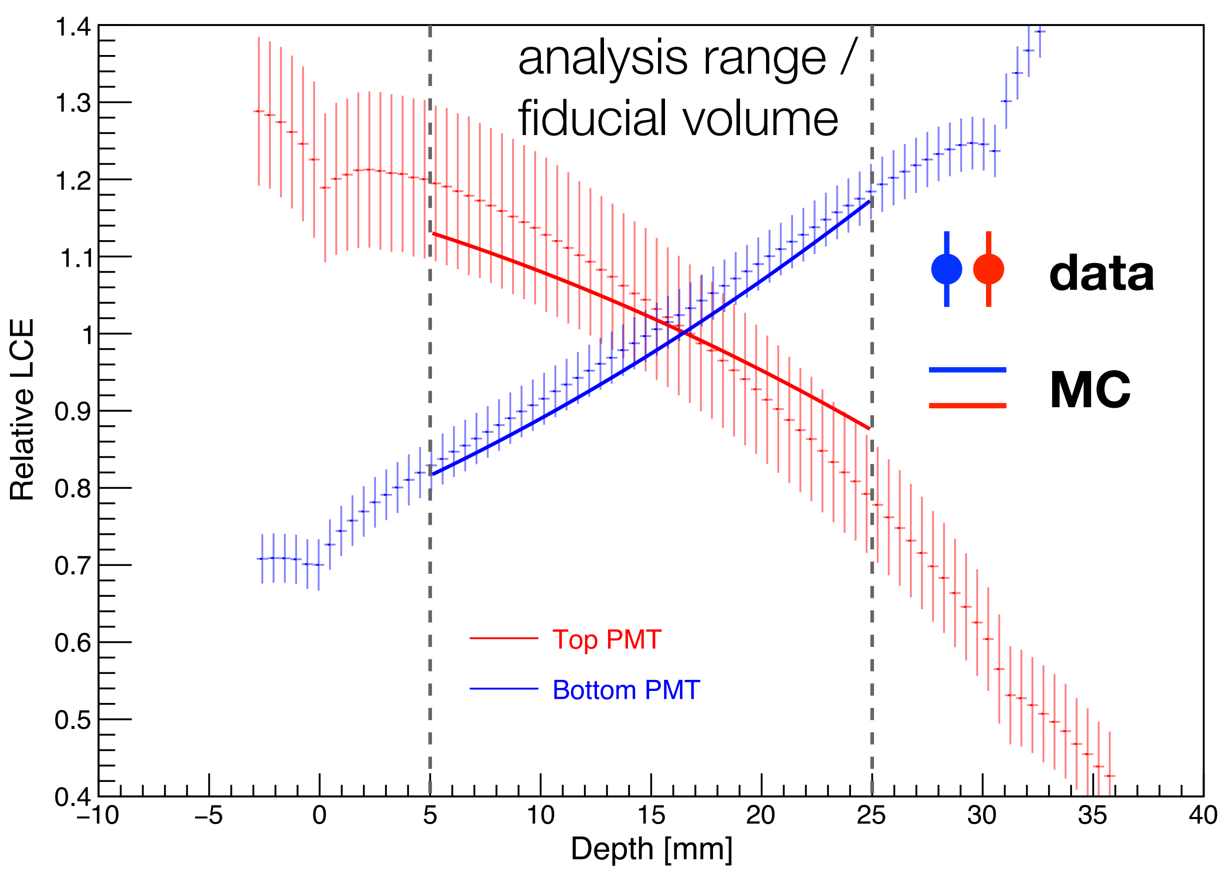
top PMT ±5%, bottom ±0.5%, both ±1.5%

- Volume-averaged LCE:

top PMT	(12.5±0.1)%
bottom PMT	(47.0±0.1)%
top+bottom	(59.8±0.1)%

- Optical response studies with Monte Carlo simulations (GEANT4):
  - 10^6 interaction vertices
  - 10^3 photons at each point, generated isotropically and with random polarisation

Parameter	Value
LXe refractive index	1.63
LXe Rayleigh scattering length	30 cm
LXe absorption length	50 m
Gas Xe refractive index	1.0
Gas Xe Rayleigh scattering length	100 m
Gas Xe absorption length	100 m
PTFE refractive index	1.58
PTFE reflectivity	0.95



Energy calibration

- The energy shared between scintillation and ionisation fluctuates on an event basis with a strong anti-correlation
→ measure by fitting a 2D elliptical Gaussian function

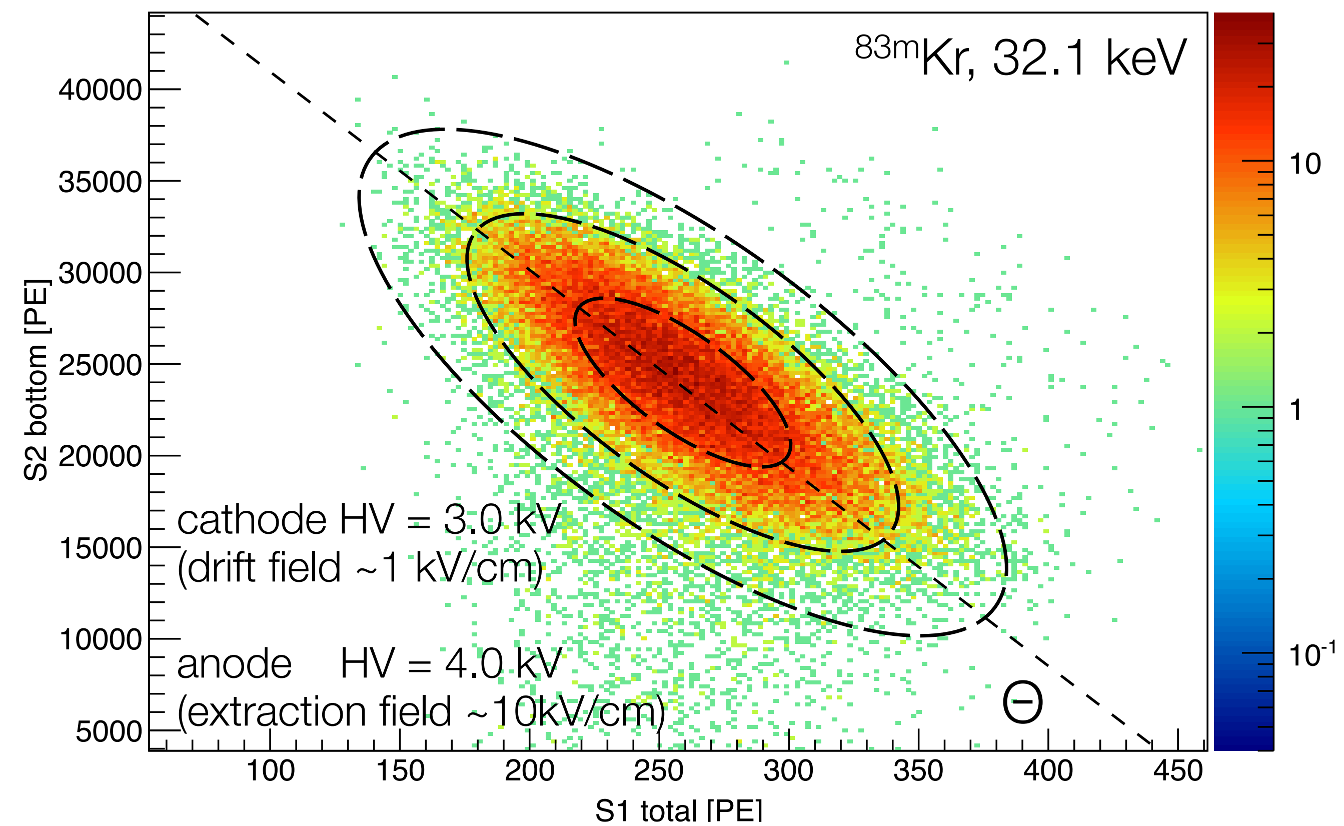
- The proportion of light (S1) and charge (S2) is different at various drift fields, but their sum remains constant

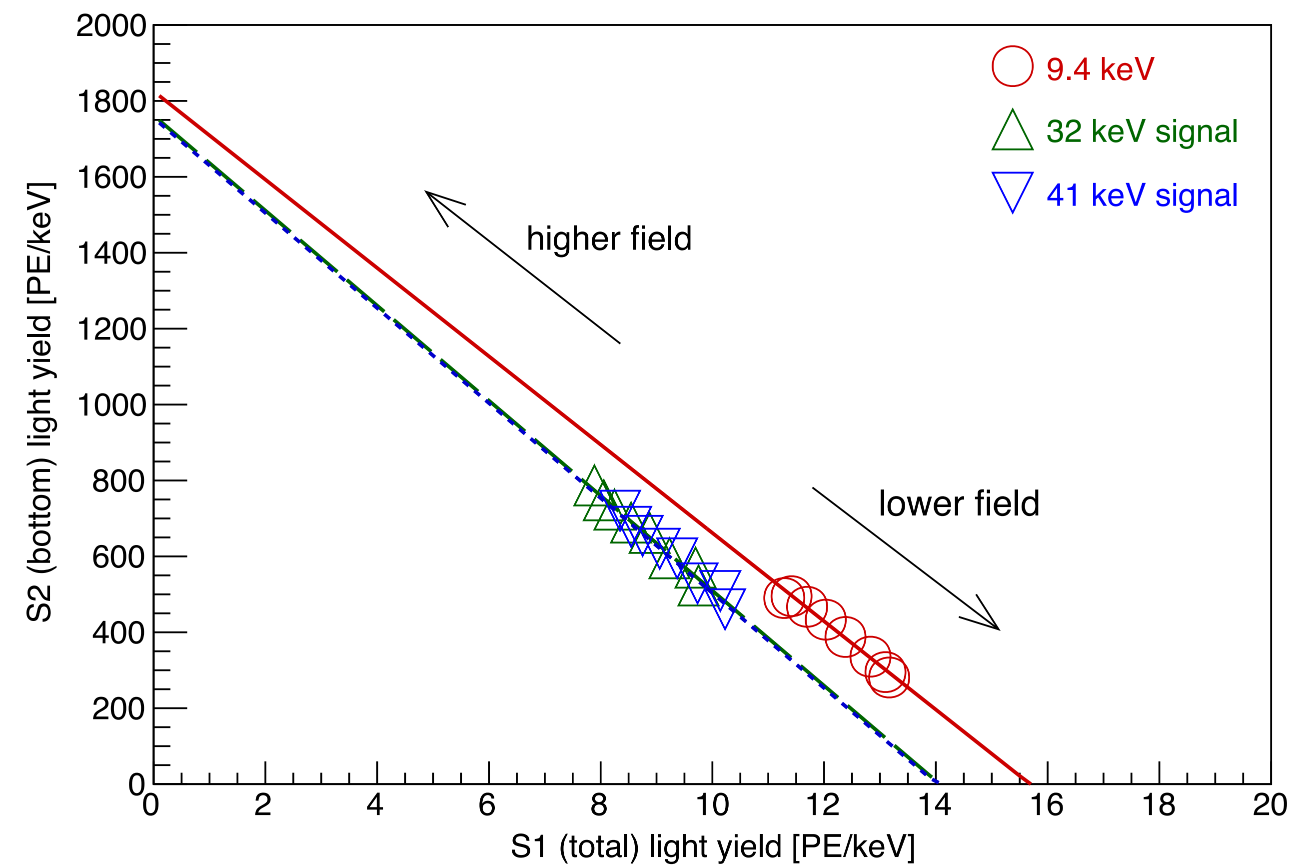
$$E_{CES} = W(n_\gamma + n_e) = W\left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right)$$

W = (13.7±0.2) eV – energy required to produce an excited or ionised atom

- Photon detection efficiency for prompt scintillation
  g_1 = (0.191±0.006) PE/photon

- Charge amplification gain
  g_2 = (24.4±0.4) PE/e⁻





Energy resolution

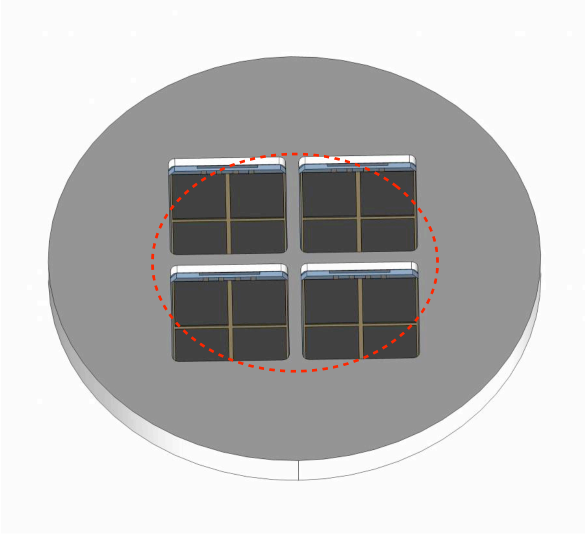
- Fluctuation of the sum (S1+S2) is smaller than that of individual signals

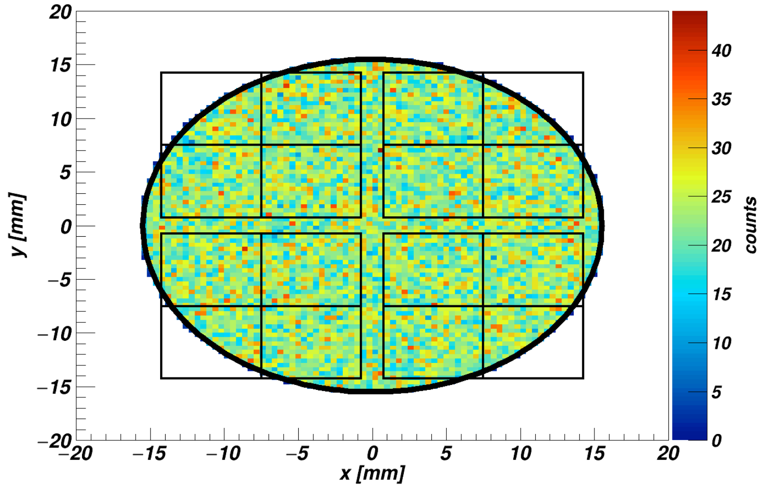
→ energy resolution can be significantly improved by combining S1 and S2

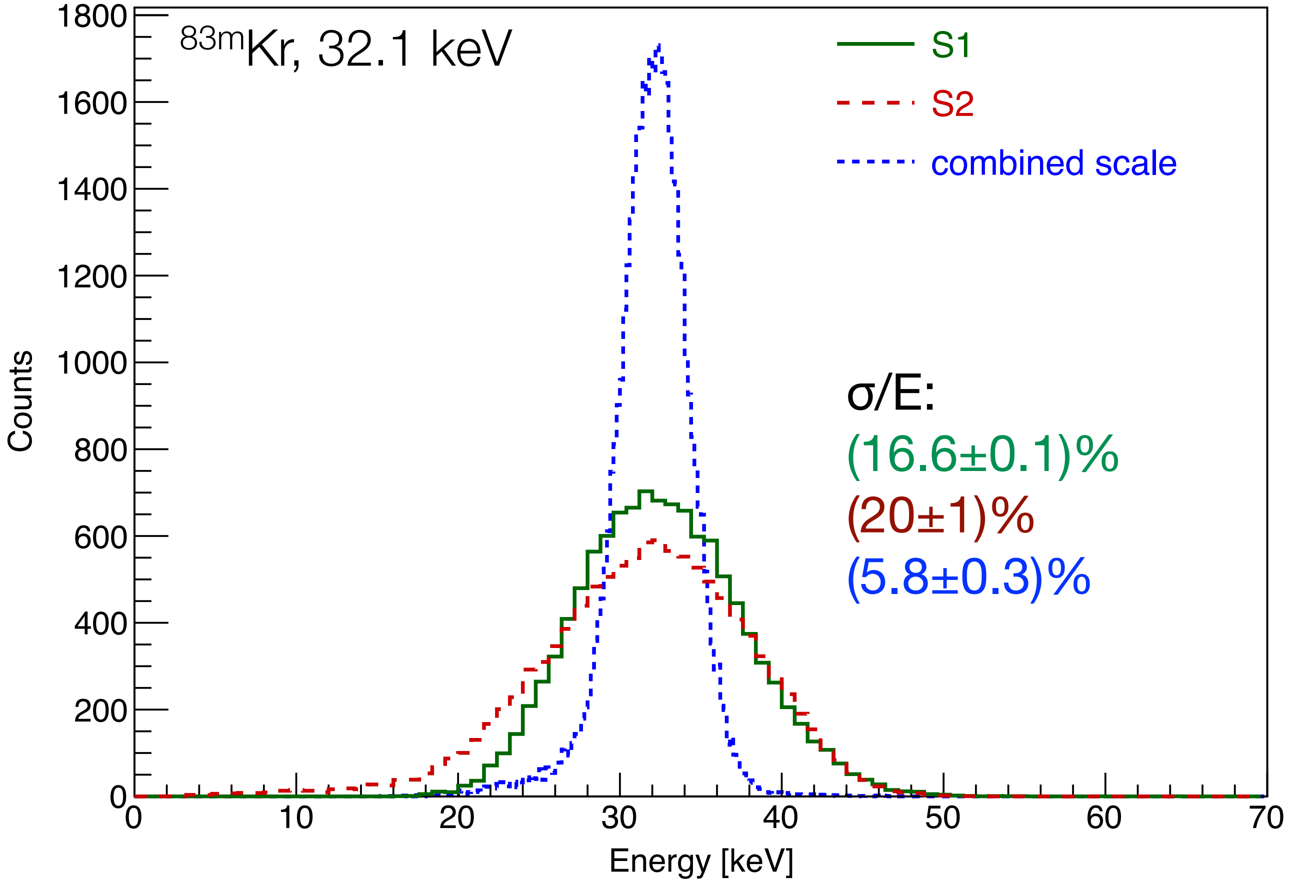
- S2 resolution is expected to be better than using S1 due to higher number of photons in the proportional scintillation channel

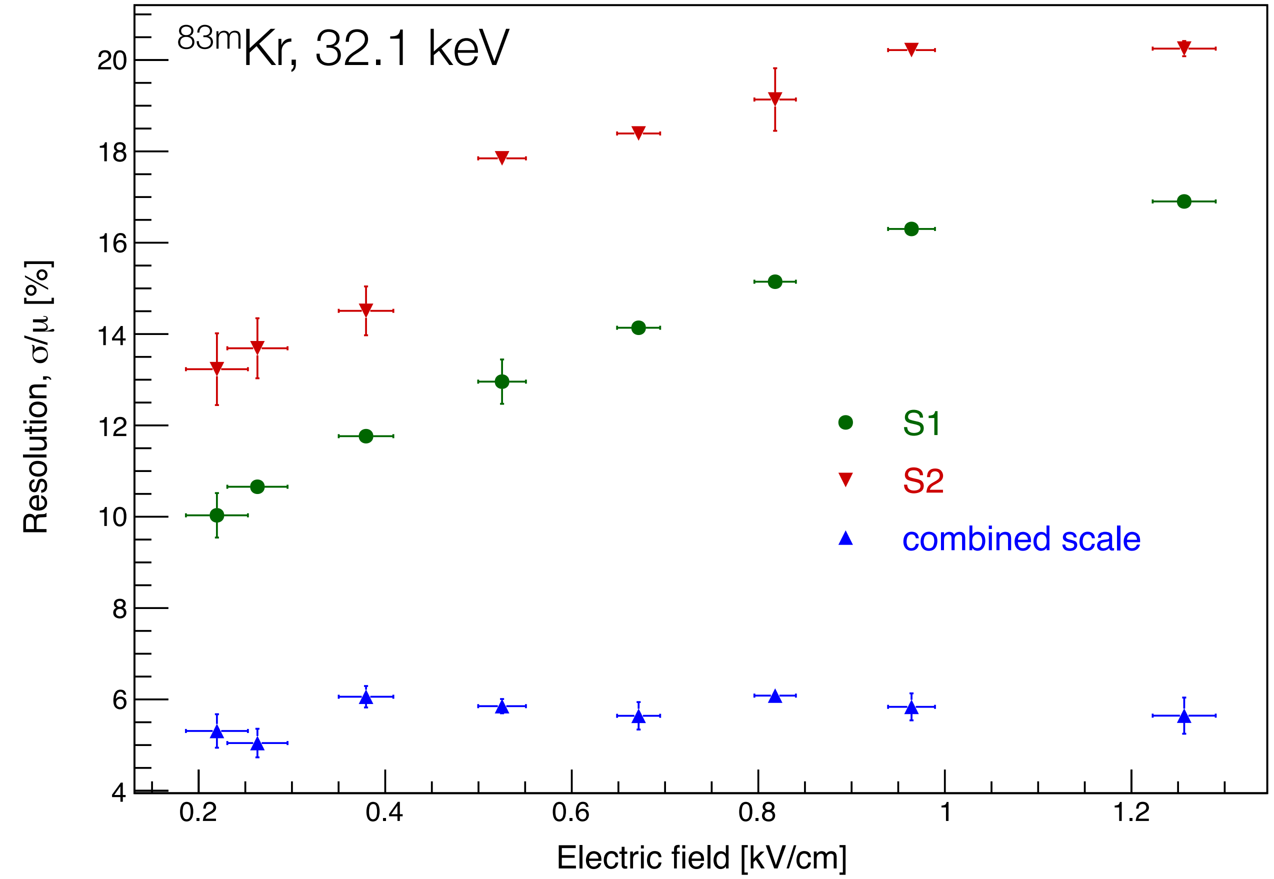
→ not the case, most likely due to edge-effects (charge trapping on PTFE surface and reduced electron collection efficiency)

→ will improve by replacing the top PMT with segmented photosensors (e.g. SiPM array) for *(x,y)* event localisation

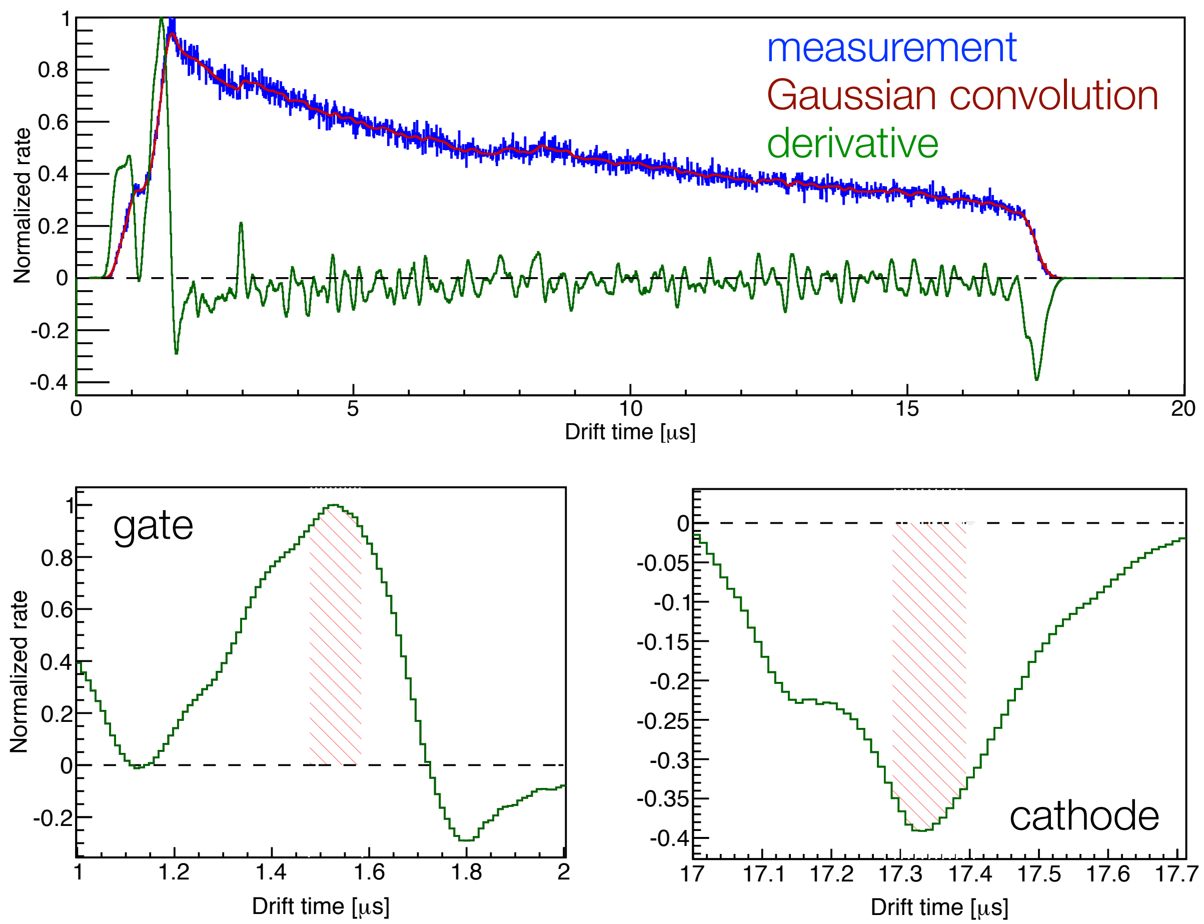


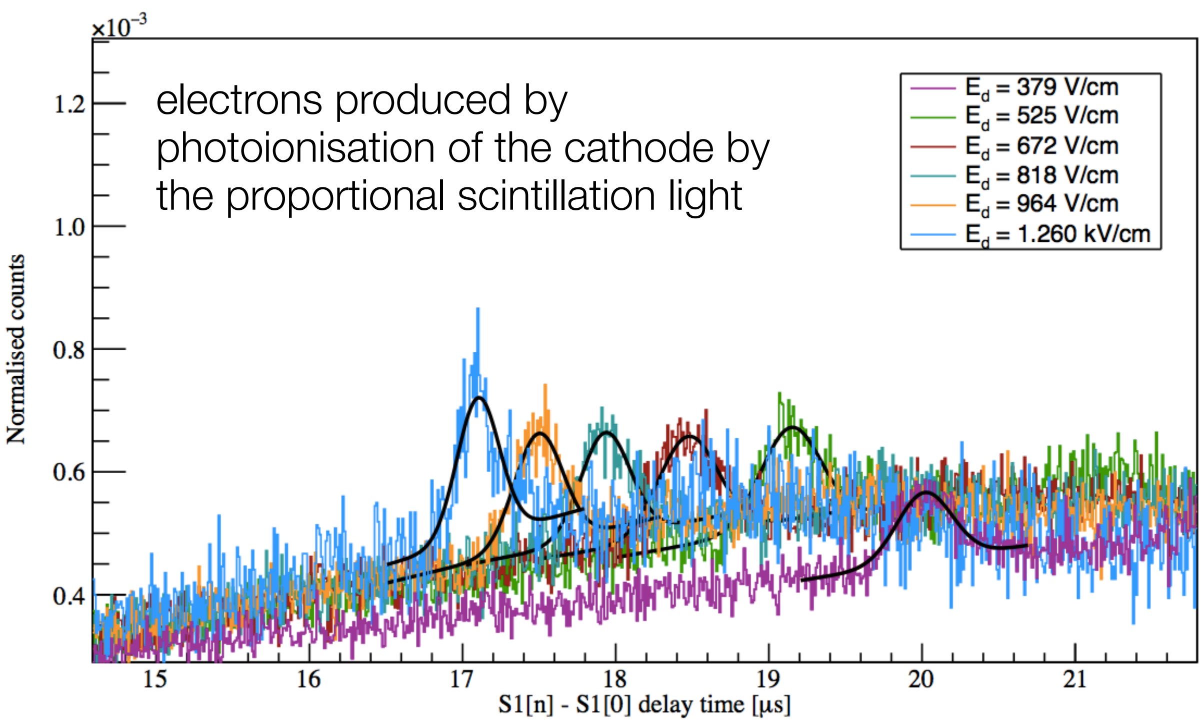




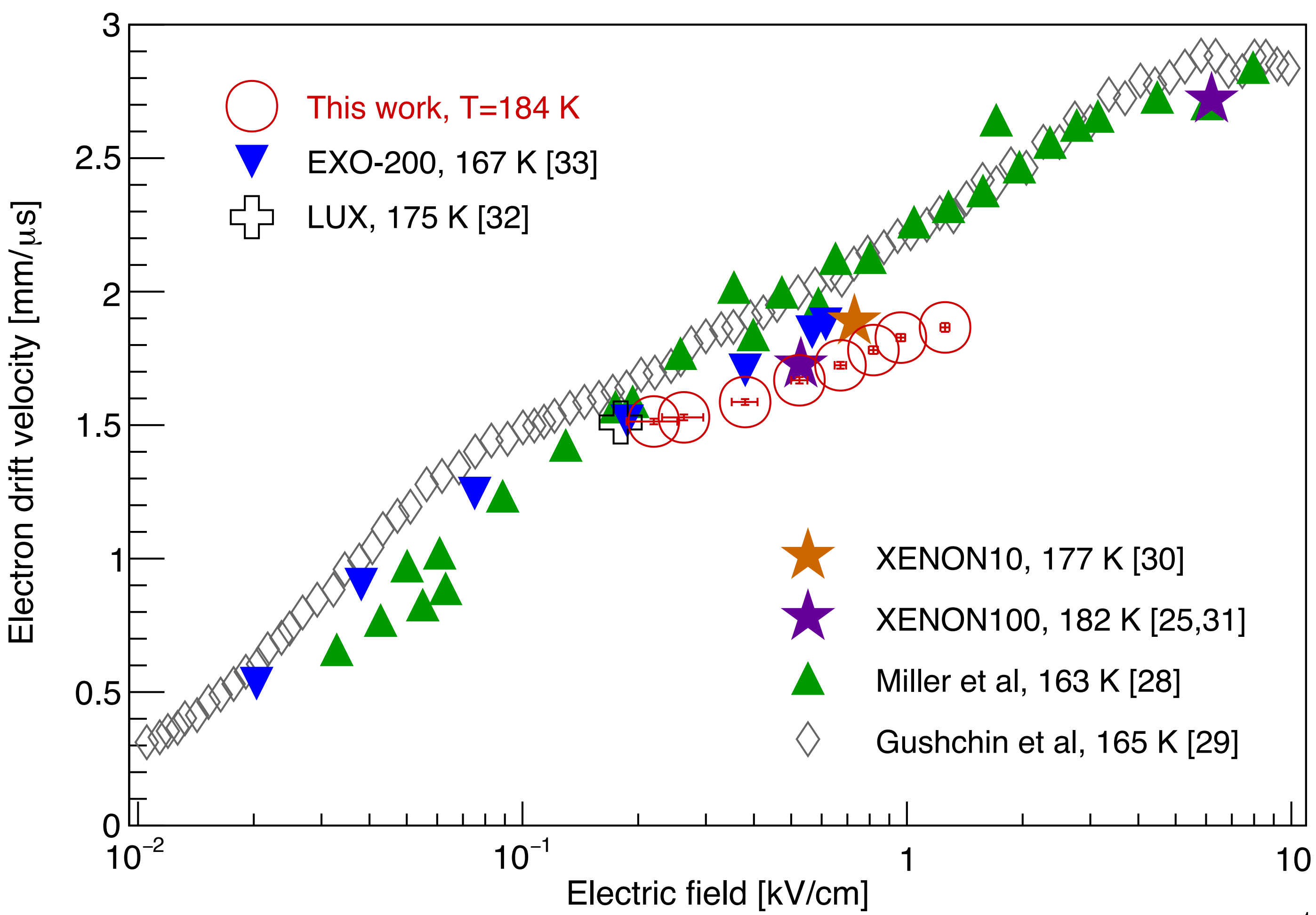


Electron drift velocity measurement





- Systematic measurement of the electron drift velocity as a function of drift field (0.2 kV/cm – 1.3 kV/cm)
- Dominant uncertainty is due to 200 μm tolerance in the machining of structural components
- Error bars on the electric field represent variation from average in the volume used for analysis (from MC)
- Transverse diffusion will be studied with an upgraded (*xy*-position sensitive) detector



Summary

- A new, small-scale dual-phase xenon TPC has been developed at the University of Zurich, optimised for low-energy charge and light yield measurements

- High signal yields:

  light yield: 15.0 PE/keV @ 9.4 keV and 14.0 PE/keV @ 32.1 keV (at zero drift field)
  10.8 PE/keV @ 9.4 keV and 7.9 PE/keV @ 32.1 keV (at drift field ~1kV/cm)

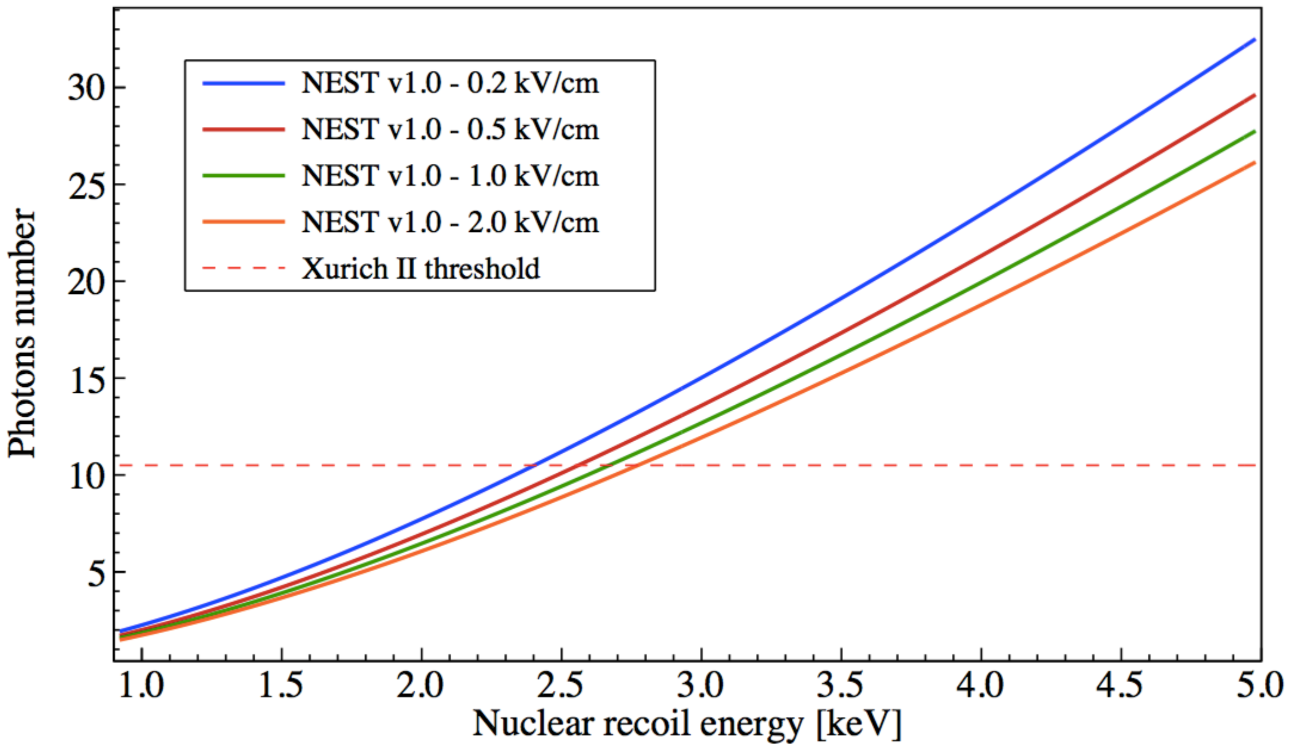
  charge yield: 28 e^-/keV @ 9.4 keV and 31 e^-/keV @ 32.1 keV, with S2 yield of 24 PE/e^-

- Energy resolution using a linear combination of scintillation and ionisation signals is $\sigma/E = (5.8\pm0.3)\%$, comparable to other state-of-the-art small-scale (*x*,*y*)-position sensitive xenon detectors

- Energy (analysis) threshold is ~2.5 keV_{NR}

- Electron drift velocity systematically measured for the fields from 0.2 to 1.3 kV/cm

- Instrument paper is at the final review stage



Contributions

- Theses with contributions to the Xürich II project:

Hrvoje Dujmovic (B.Sc. 2012)
"Simulation and Optimisation of the Electric Field in a Liquid Xenon Time-projection Chamber"

Dario Biasini (B.Sc. 2014)
"Monte Carlo Simulations of a Liquid Xenon Detector Response To Low-energy Neutrons"

Hrvoje Dujmovic (M.Sc. 2014)
"Characterization and Calibration of a Liquid Xenon Time-projection Chamber"

Payam Pakarha (Ph.D. 2017)
"Calibration System of the Photosensors for the XENON1T Dark Matter Search Experiment, and Response of Liquid Xenon to Low-energy Interactions"

Francesco Piastra (Ph.D. 2017)
"Materials Radioassay for the XENON1T Dark Matter Experiment,and Development of a Time-projection Chamber for the Study of Low-energy Nuclear Recoils in Liquid Xenon"

Yanina Biondi (M.Sc. – defence by the end of 2017)
"Measurement and Modelling of Scintillation and Charge Signals in a Dual-phase Xenon TPC"

Chiara Capelli (Ph.D. – ongoing)

Julien Wulf (Ph.D. – ongoing)