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DARWIN

Xenoscope: a full-scale demonstrator for the DARWIN observatory

XeSAT22, Coimbra University

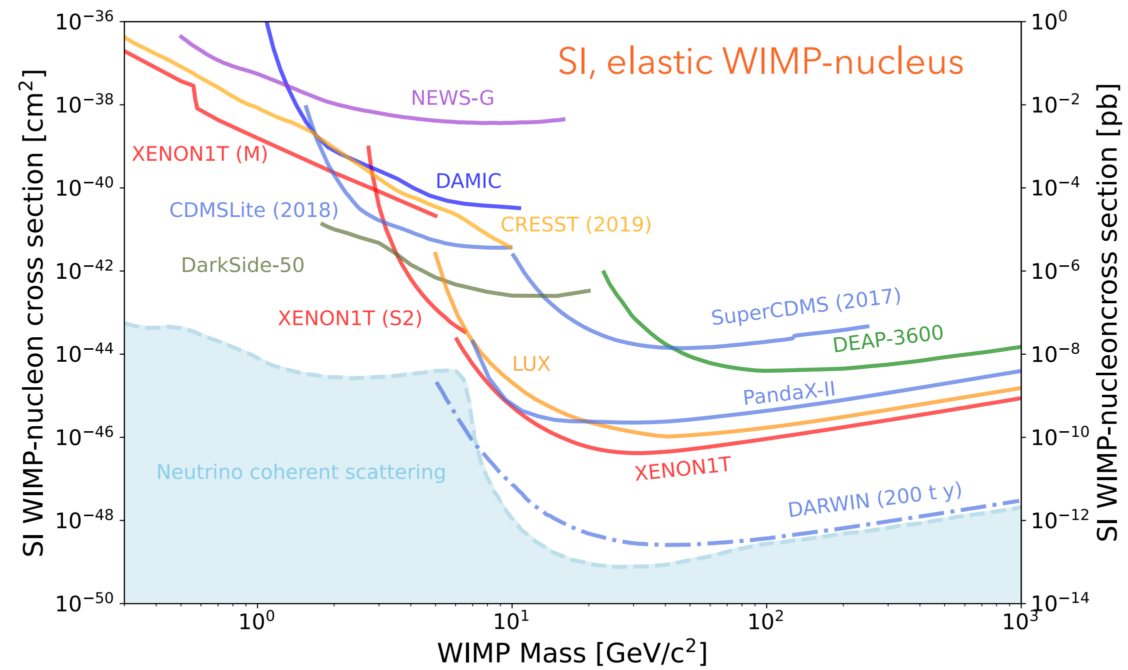
Laura Baudis, University of Zurich, May 24, 2022

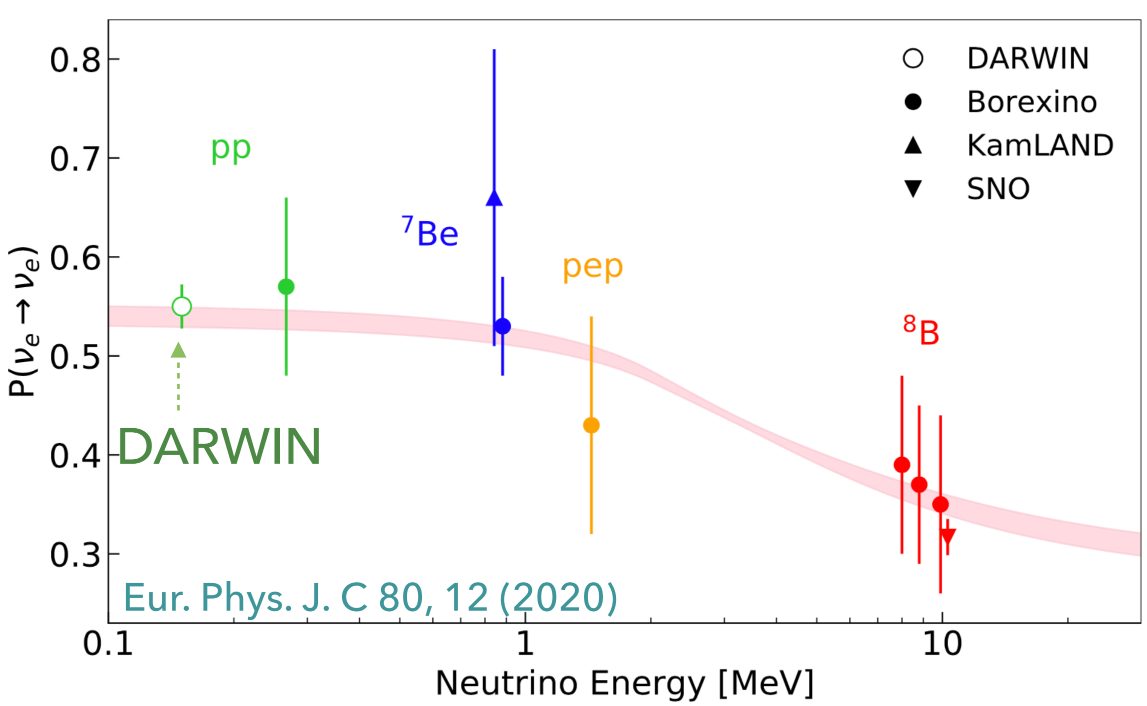
DARWIN: a multipurpose observatory for rare events

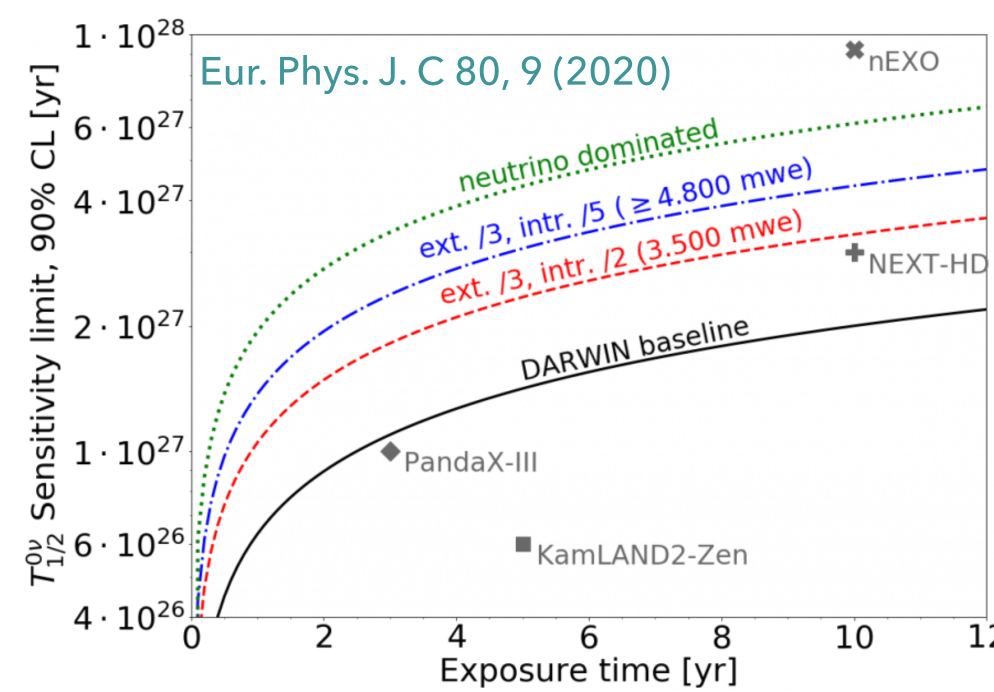
- Dark matter (WIMPs and light-DM)
- 0νββ-decay of ^{136}Xe
- Low-energy solar neutrinos
- ^{8}B solar ν's via CEνNS
- Supernova neutrinos
- Solar axions; galactic ALPs, dark photons

see also arXiv:2203.02309

DARWIN study: JCAP 10, 016 (2015)

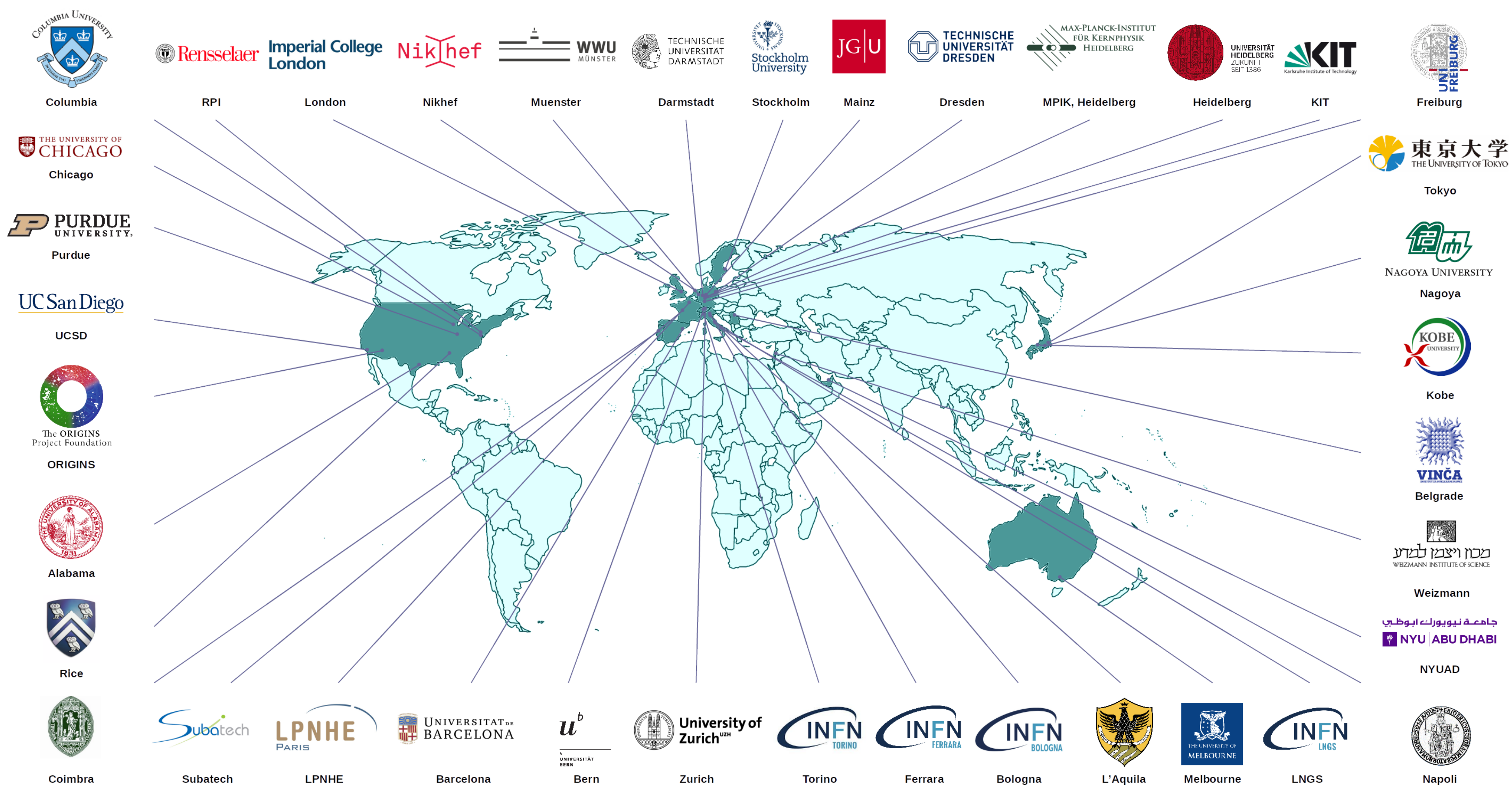






DARWIN Collaboration

- 190 members from 37 institutions in Europe, USA, Asia and Australia



Future: DARWIN-LZ Collaboration

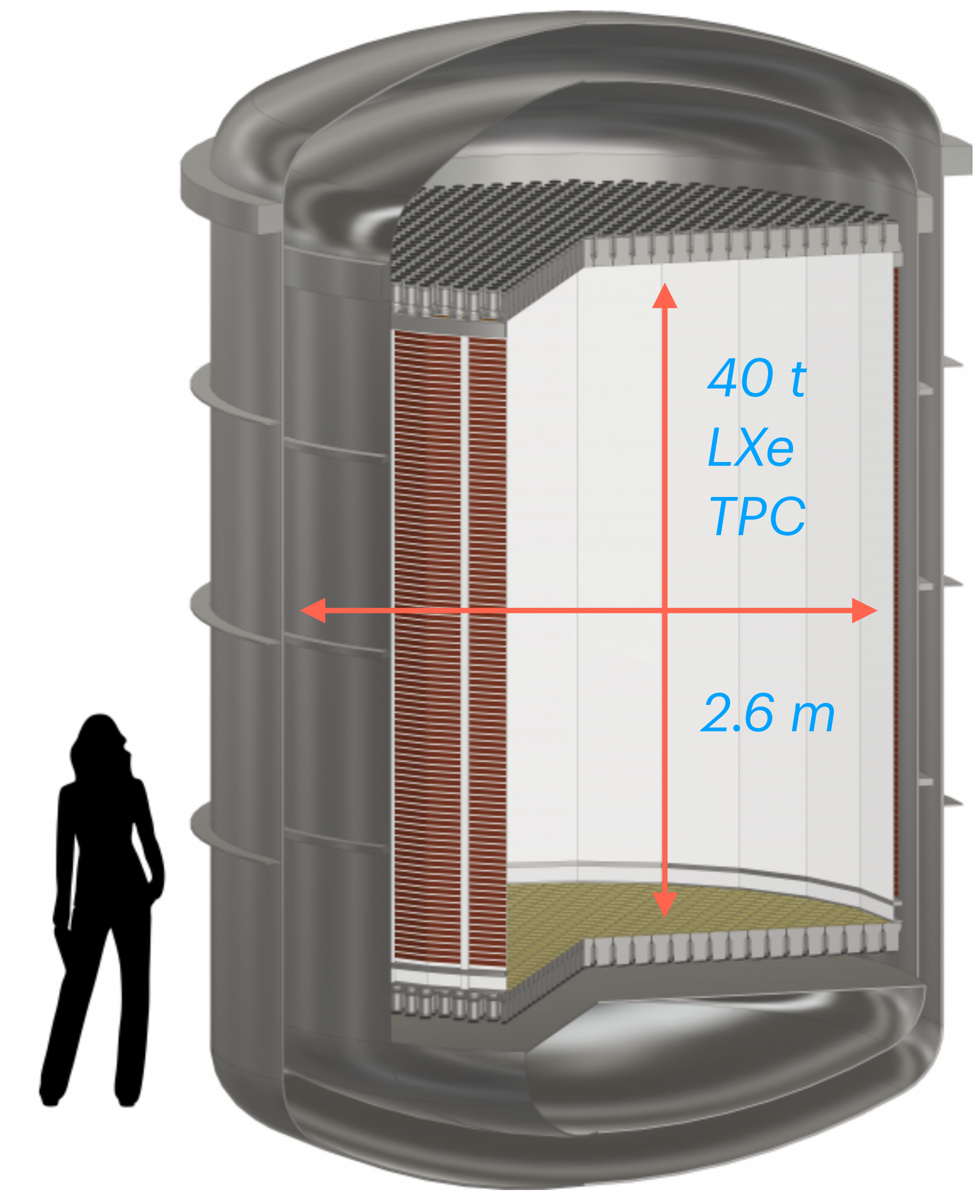
- Future merger of DARWIN/XENON and LUX-ZEPLIN collaboration to build and operate next-generation liquid xenon detector
  - new, stronger international collaboration
  - comes after LZ and XENONnT are done
- Paving the way now
  - first joint, successful DARWIN/XENON & LZ workshop, April 26-27 https://indico.cern.ch/event/1028794/
  - MoU signed July 6, 2021 by 104 research group leaders from 16 countries
  - Common summer meeting at KIT June 27-29, 2022; seven working groups in place to study science, detector, common R&D etc

XENON DARWIN LZ

DARWIN baseline scenario

- Two-phase xenon TPC with 2.6 m ø and 2.6 m height in a double-walled cryostat
- 50 t (40 t active) liquid xenon target
- Top & bottom arrays of photosensors (e.g., 1800 3-inch PMTs)
- PTFE reflectors and Cu field shaping rings
- Target drift field: ~ 200 V/cm
- Min 12 m x 12 m water Cherenkov shield (Gd-doped, as n- and μ-vetos)

Alternative TPC designs and photosensors under consideration

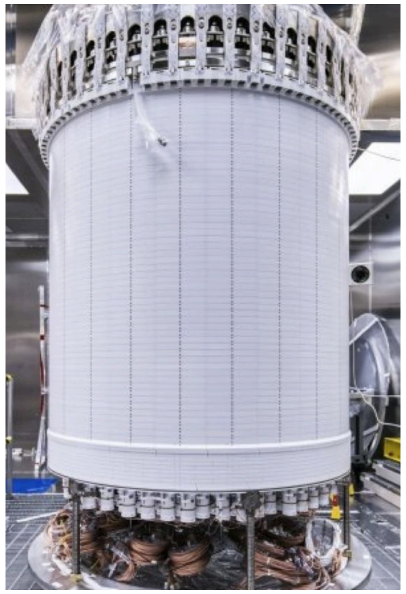


DARWIN collaboration
JCAP 1611 (2016) 017

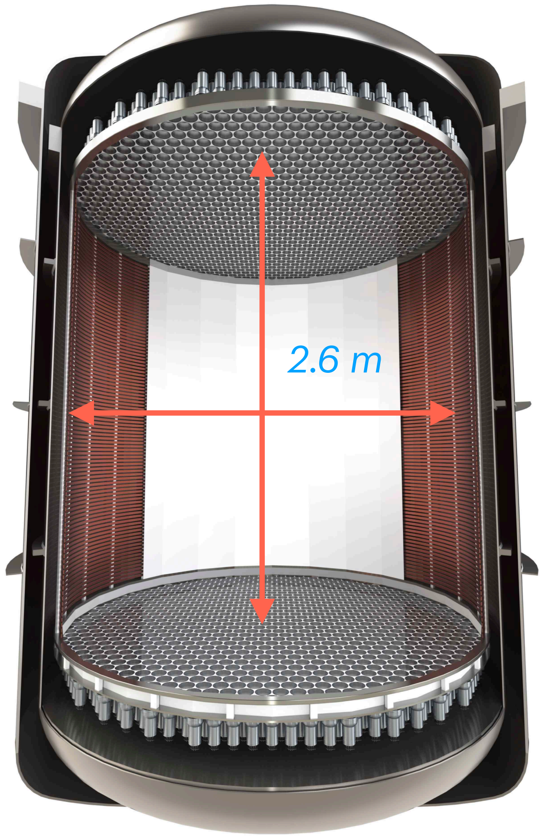
DARWIN: size matters

- LUX-ZEPLIN and XENONnT: 1.5 m e⁻ drift and ~1.5 m diameter electrodes
- DARWIN: 2.6 m ⇒ new challenges
    - Design of electrodes: robustness (minimal sagging/deflection), maximal transparency, reduced e⁻ emission
    - Electric field: ensure spatial and temporal homogeneity, avoid charge-up of PTFE reflectors
    - High-voltage supply to cathode design, avoid high-field region
    - Liquid level control
- Electron survival in LXe: > 10 ms lifetime*
- Diffusion of the e⁻-cloud: size of S2-signals

LUX-ZEPLIN



XENONnT



DARWIN

*G. Plante, E. Aprile, J. Howlett, Y. Zhang, 2205.07336

DARWIN R&D topics: overview

Detector design and time projection chamber

- demonstrate e^- drift over large distances, electrodes with 2.6 m diameter; high-voltage feedthroughs
- study alternative designs: sealed/hermetic TPC (to prevent radon diffusion into inner volume), single-phase TPC (simplify detector design, mitigate single e^- background)
- cryostat design: stability, reduce amount of material (hence gamma and neutron emitters) close to TPC

Photosensors

- baseline: VUV-sensitive, low-radioactivity PMTs (established technology, low dark count rate of ~ 0.02 Hz/mm^2)
- study low-field SiPMs, digital SiPMs & hybrid photosensors; also, low-noise, low heat dissipation, low-radioactivity readouts

Target and background control

- fast purification for large e^- lifetime, large distillation columns for low ^{222}Rn and ^{85}Kr levels
- "radon-free" circulation pumps; coating techniques to avoid radon emanation ((electrochemical, sputtering, epoxy based); storage and recuperation of large amounts of xenon
- identification of low-radioactivity material components

*see talks by Ricardo Peres, Masatoshi Kobayashi, Vera Hiu-Sze Wu, Igor Ostrovsky, Florian Tönnies, Julia Mueller

DARWIN Demonstrators

European Research Council
Established by the European Commission

- Two large-scale demonstrators, in *z* and in *x-y*, supported by ERC grants
  - *Xenoscope*, 2.6 m tall TPC and *Pancake*, 2.6 m ø TPC in double-walled cryostats
  - Both facilities available to the collaboration for R&D purposes

Vertical demonstrator: *Xenoscope*

L. Baudis et al, JINST 16, P08052, 2021

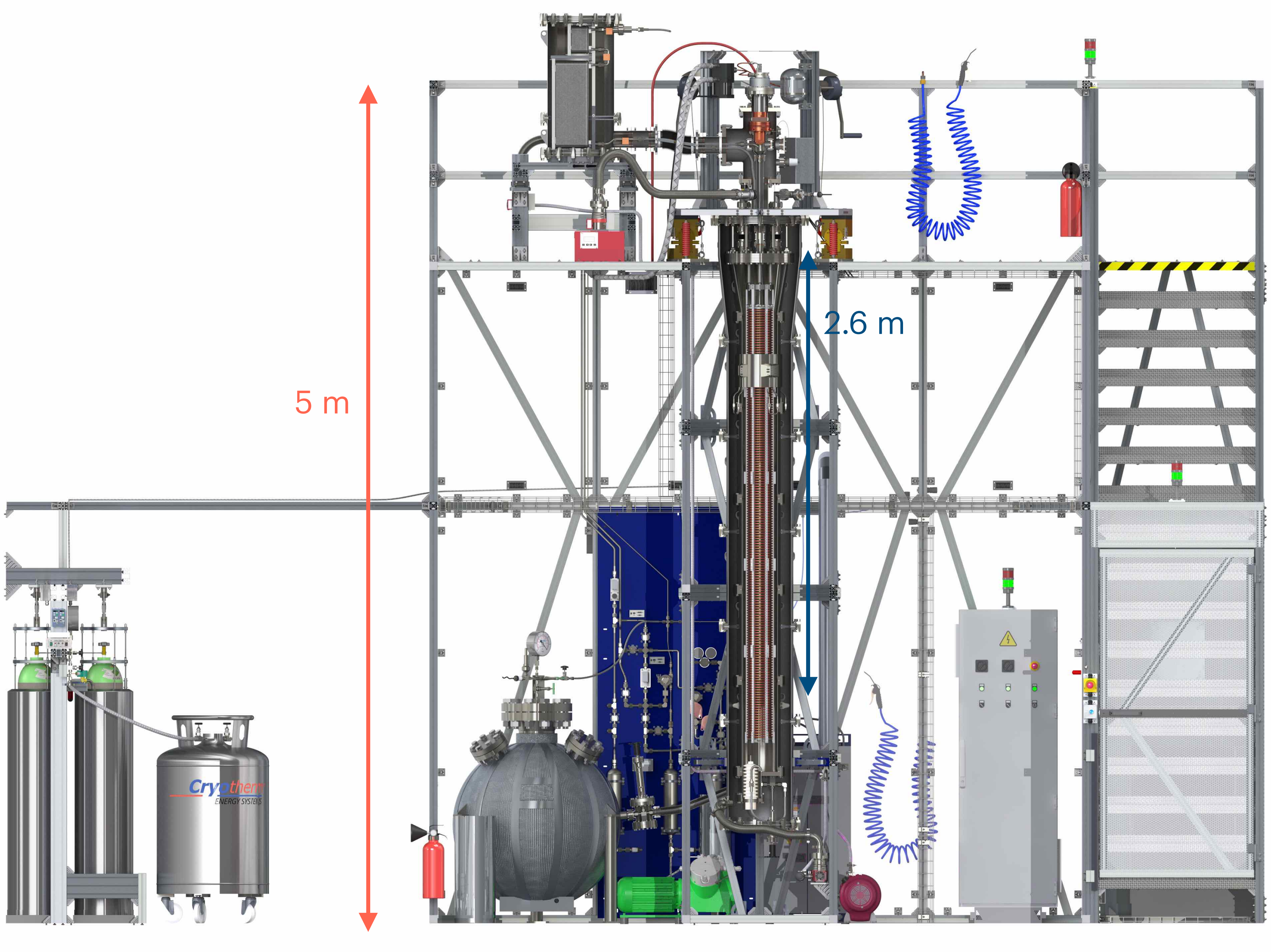
Horizontal demonstrator: *Pancake*

Test electrodes with 2.6 m Ø

see talk by Julia Mueller

Xenoscope: overview

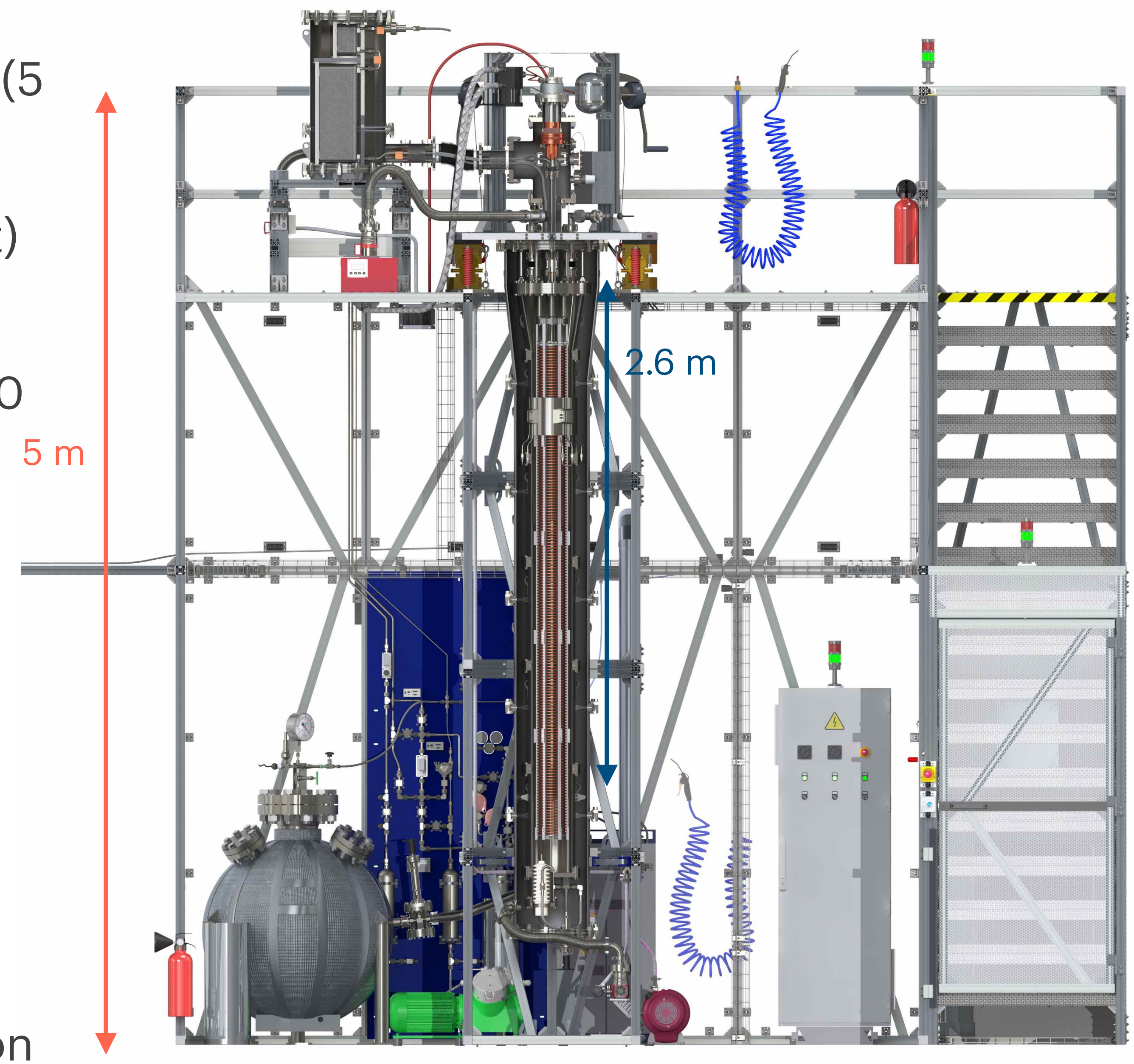
- **Full-height demonstrator goals:**
    - Electron drift > 2.6 m
    - Custom-made HV distribution
    - Electron cloud diffusion
    - Light attenuation measurements
    - Test of various light sensors (SiPMs, 2-inch PMTs, ...)
- **Total amount of xenon:**
    - ~ 400 kg



L. Baudis et al, JINST 16, P08052, 2021

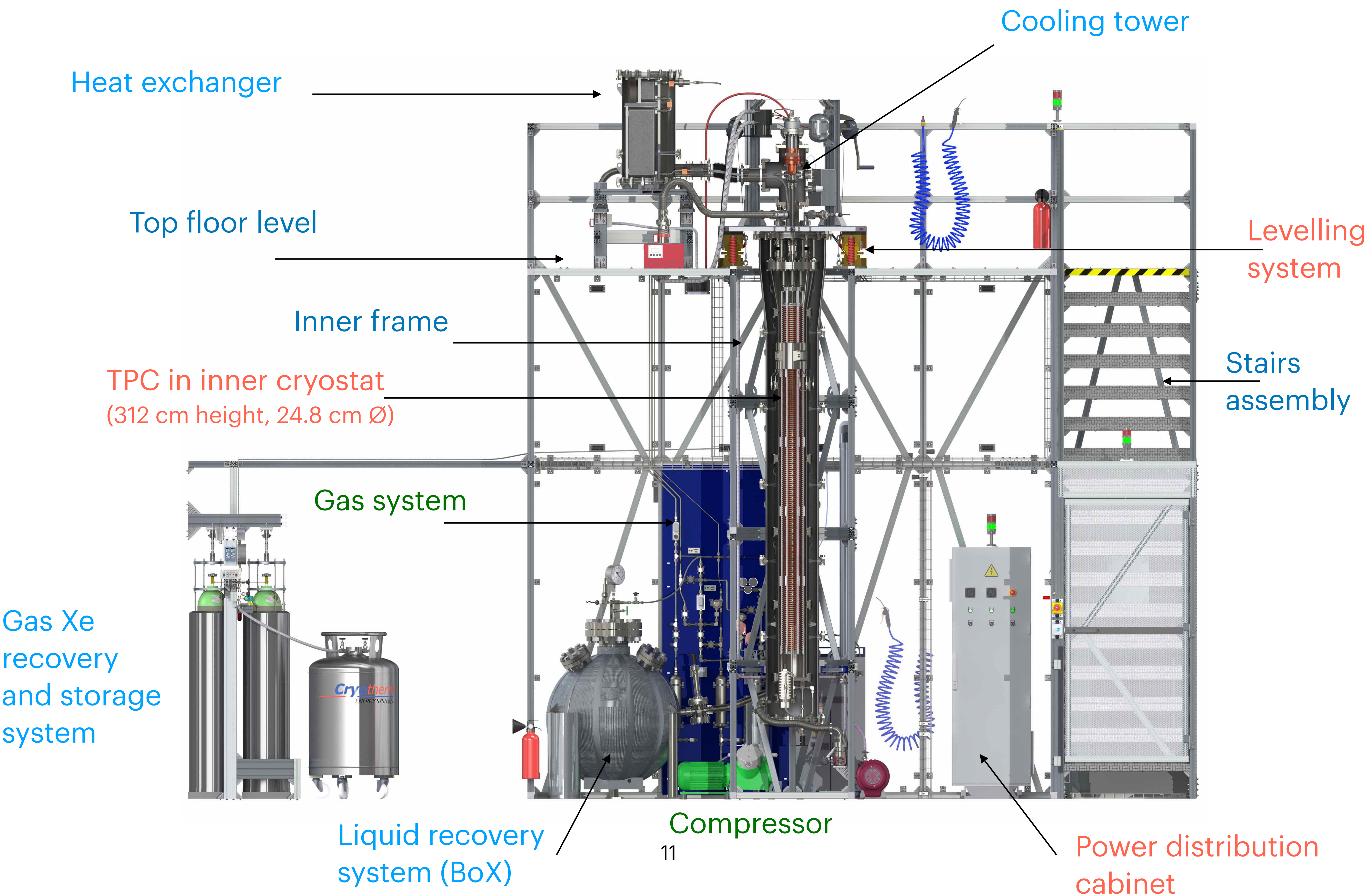
Xenoscope: overview

- Infrastructure
  - Support structure: 2 frames + stair assembly (5 cm x 5 cm extruded Al profiles)
  - Inner frame: weight of Xe-filled cryostat (1.2 t)
  - Outer frame (4x4x4 m^3): lateral support for inner frame + floor of top level (load up to 200 kg/m^2)
  - Acrylic panels minimise dust accumulation
- Power distribution
  - Designed for up to 100 kV test voltages
  - Emergency power from UZH generators
  - In addition: 20 kW, 3-phase UPS
  - Interlock system for safe operation with HV on (electrical safety system accredited by *Electrosuisse*)



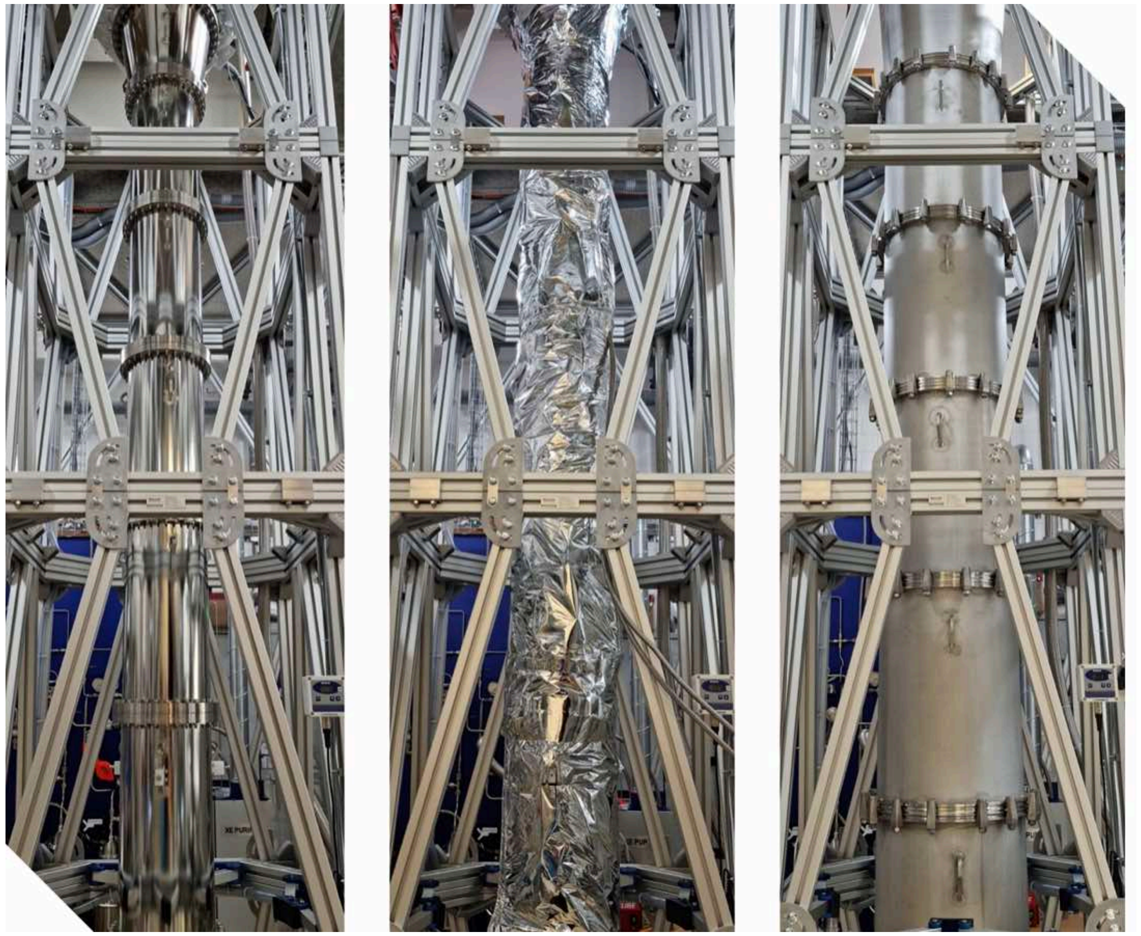
L. Baudis et al, JINST 16, P08052, 2021

Xenoscope: overview



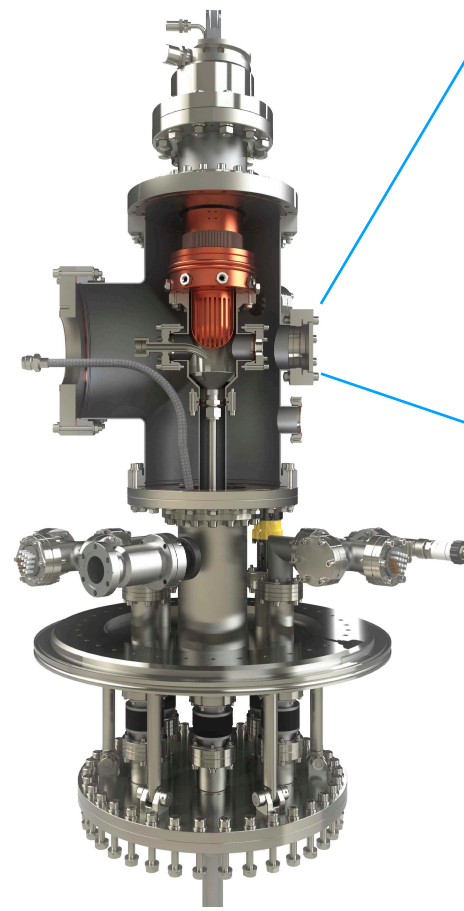
Cryostat and top flange

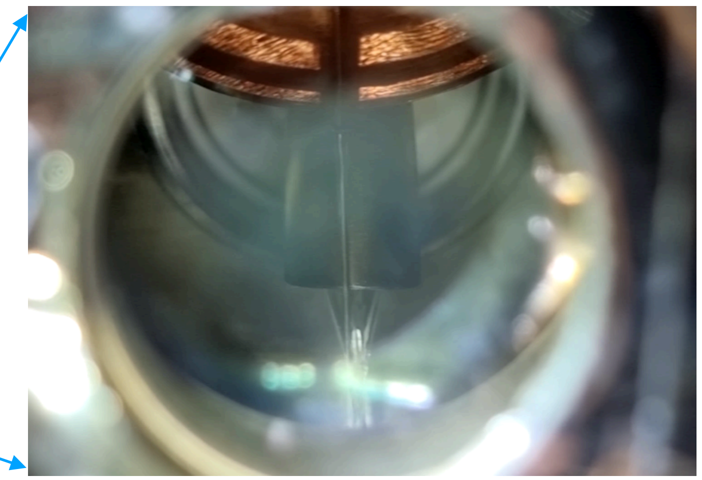
- **Cryostat**
  - Modular design to ease assembly
  - Outer vessel: 6 ISO-K-400 sections
  - Inner vessel: pressure vessel with 6 DN250CF sections, electropolished (operation conditions 2 bar & ~175 K, rated up to 8 bar)
  - Conical sections at top, for cables & instruments
- **Top flange**
  - Outer ISO-K-500, inner DN350CF
  - Joined by 6 swivel arms to relieve stress from contraction (~1 mm)
  - Six feedthroughs for cooling tower, cabling etc: joined by 6 bellows, with axial displacement

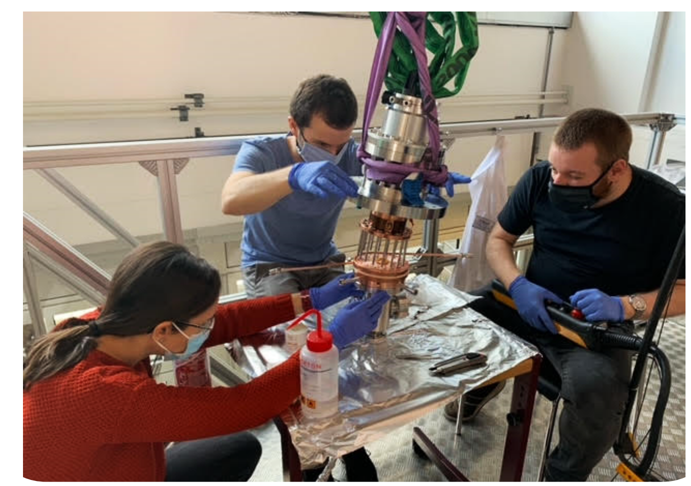


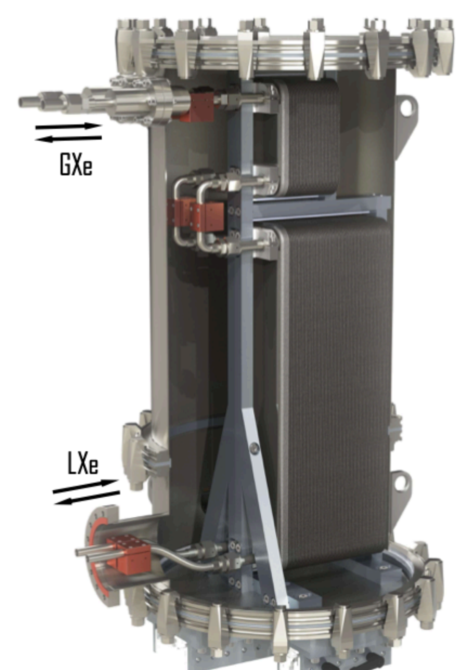
Cryogenics

- **Cooling tower**
  - Itawani PTR (~200 W cooling) and 180 W heater
  - LN_2 auxiliary cooling coil and LN_2 pre-cooler
  - Xe extracted from top of inner vessel; carried b funnel to bottom of inner vessel
- **Heat exchanger**
  - Two brazed stainless steel plates with A=5.3 m^2
  - Heat exchanged power: 1.5 kW
  - Six PT100 RTDs for monitoring
- **Superinsulation**
  - Double-walled cryostat, vacuum insulated
  - Multi-layer insulation (3 x 10 layers, double-sized aluminised polyethylene film) from RUAG Space
  - Max power transmission: 0.6 W/m^2



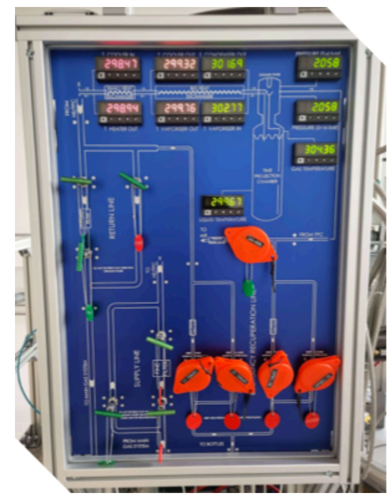


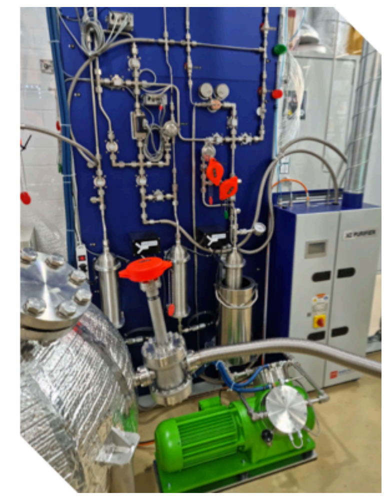




Gas handling & storage systems

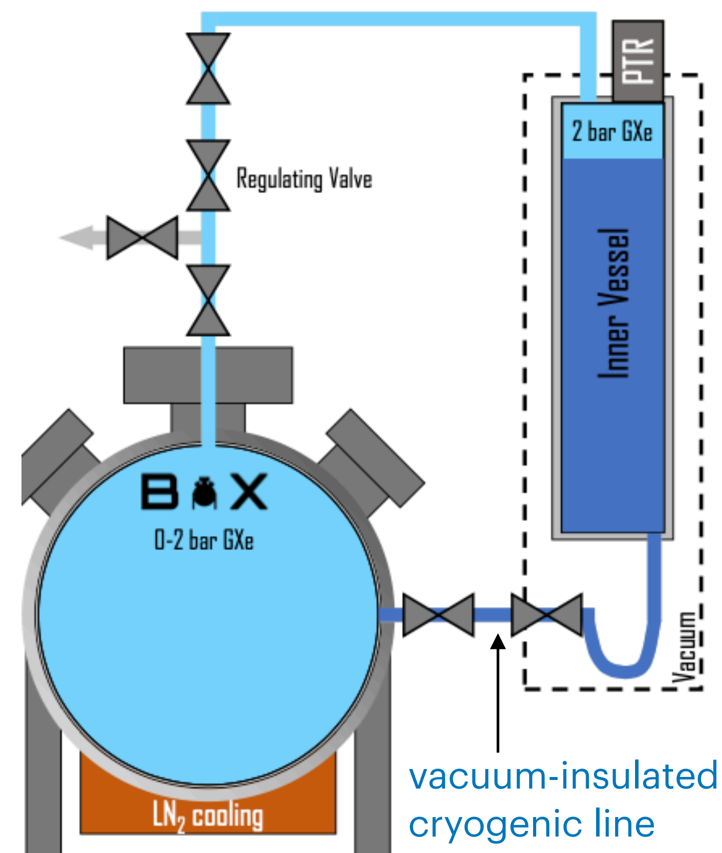
- **Gas handling system**
  - Hot zirconium getter for xenon purification
  - Double-diaphragm KNF pump (~ 80 slpm recirculation flow) with flow controller
  - Passive safety system (check-valves) recuperates gaseous xenon to storage array in case of pressure increase





- **Xenon storage**
  - Ten 40 l aluminum cylinders on mass scales (up to 470 kg of Xe)
  - Gas recuperation via cryo-pumping: ~ 3kg/h
  - BoX (Ball of Xenon): stainless steel pressure vessel rated at 90 bar, with passive insulation & LN_2 pre-cooler
  - Gravity-assisted* recuperation (can contain 450 kg of LXe) at ~ 20 kg/h (average)

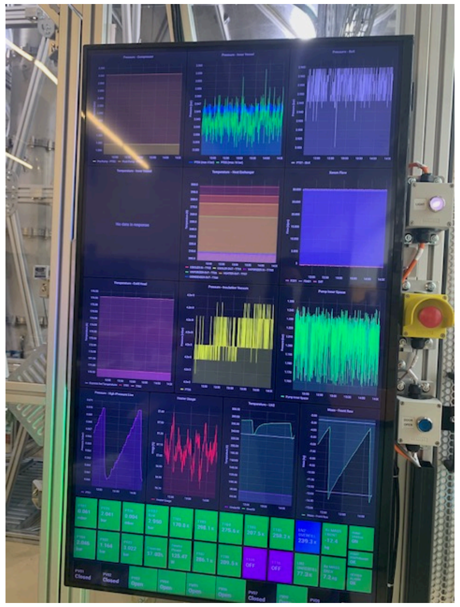
93 cm Ø



*L. Virone et al., NIM A 893, 2018

Slow control system

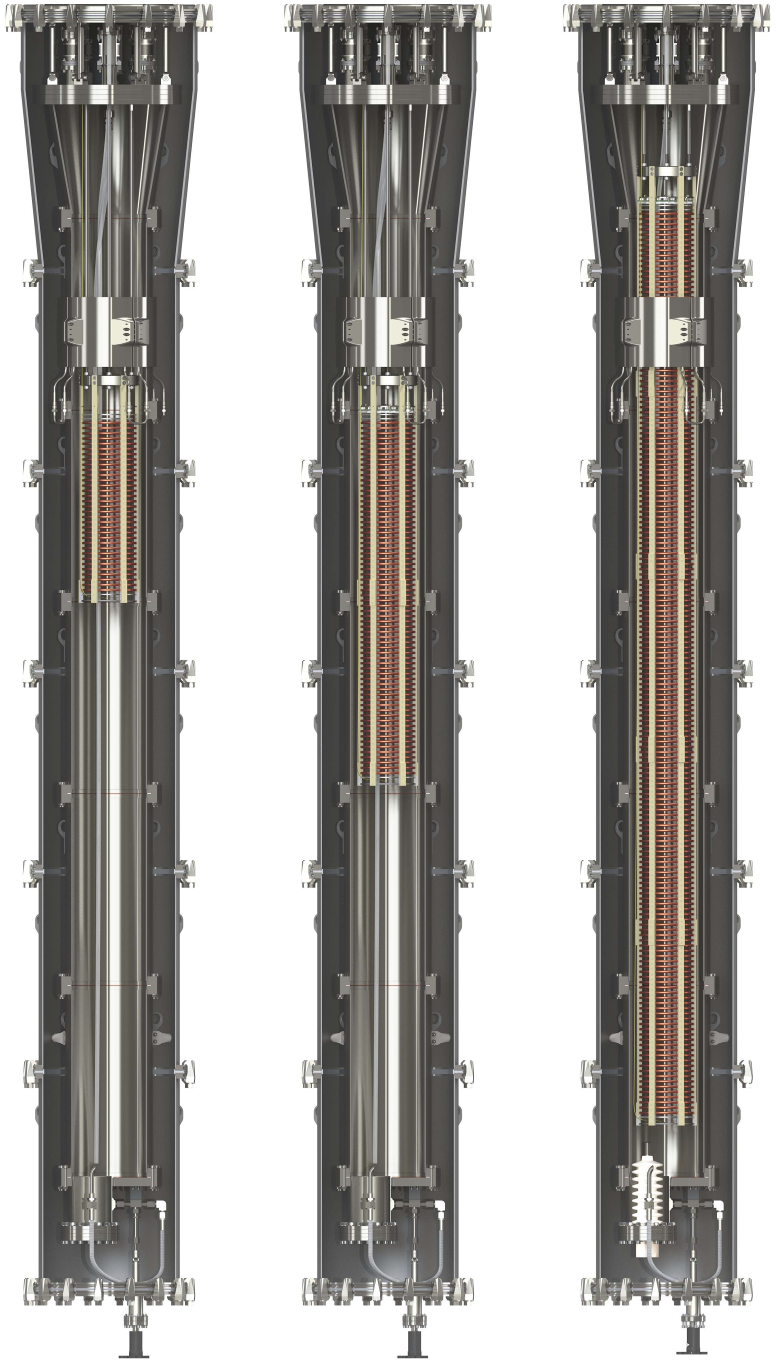
- **Monitor and control of the experiment; provides user with notifications in case of anomalies**
- Custom solution with open-source software & several independent systems
  - Micro-controllers: collect sensors data and control hard-wired actuators (valves, pumps, flow controllers); hardware: PLCs. Collected data is exposed through open network protocols
  - Prometheus: data ingestion, time-series database dedicated to monitoring & alarming
  - Grafana: visualisation platform, also allows to set alarm thresholds
  - Alarm and notification system: based on Prometheus tools (email and SMS)
  - Micro-service orchestration: Kubernets, makes sure all services are always running
- **Target service availability: 99.99%** (≡ 50 min downtime/year, including maintenance)



Slow control screen in the operations room

Inner detectors

- **Modular design with 3 phases**
  - Phase 1, currently ongoing: 525 mm purity monitor
  - Phase 2, to start in late summer 2022: 1.0 m TPC with signal amplification region and top SiPM array
  - Phase 3, early 2023: 2.6 m TPC (possibly with 2-inch or 3-inch PMTs at the bottom), with -50 kV applied to the cathode
- Structure: Cu field shaping rings (173 for the 2.6 m TPC), 6 Torlon pillars
- Electrode meshes: 0.1 mm thick, chemically etched stainless steel, 93% transparency

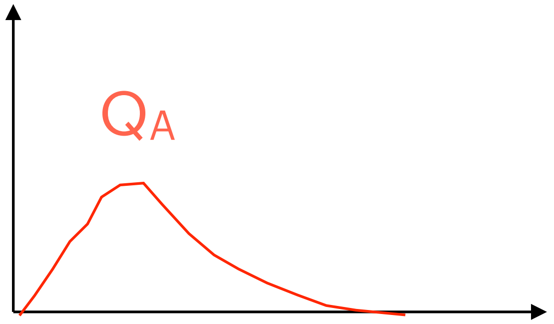


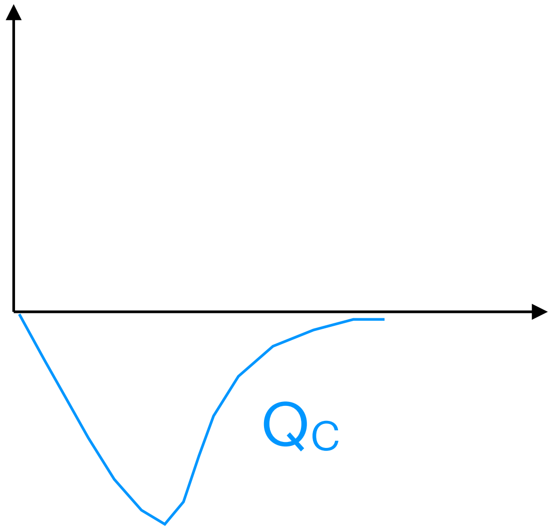
Purity monitor 1.0 m TPC 2.6 m TPC

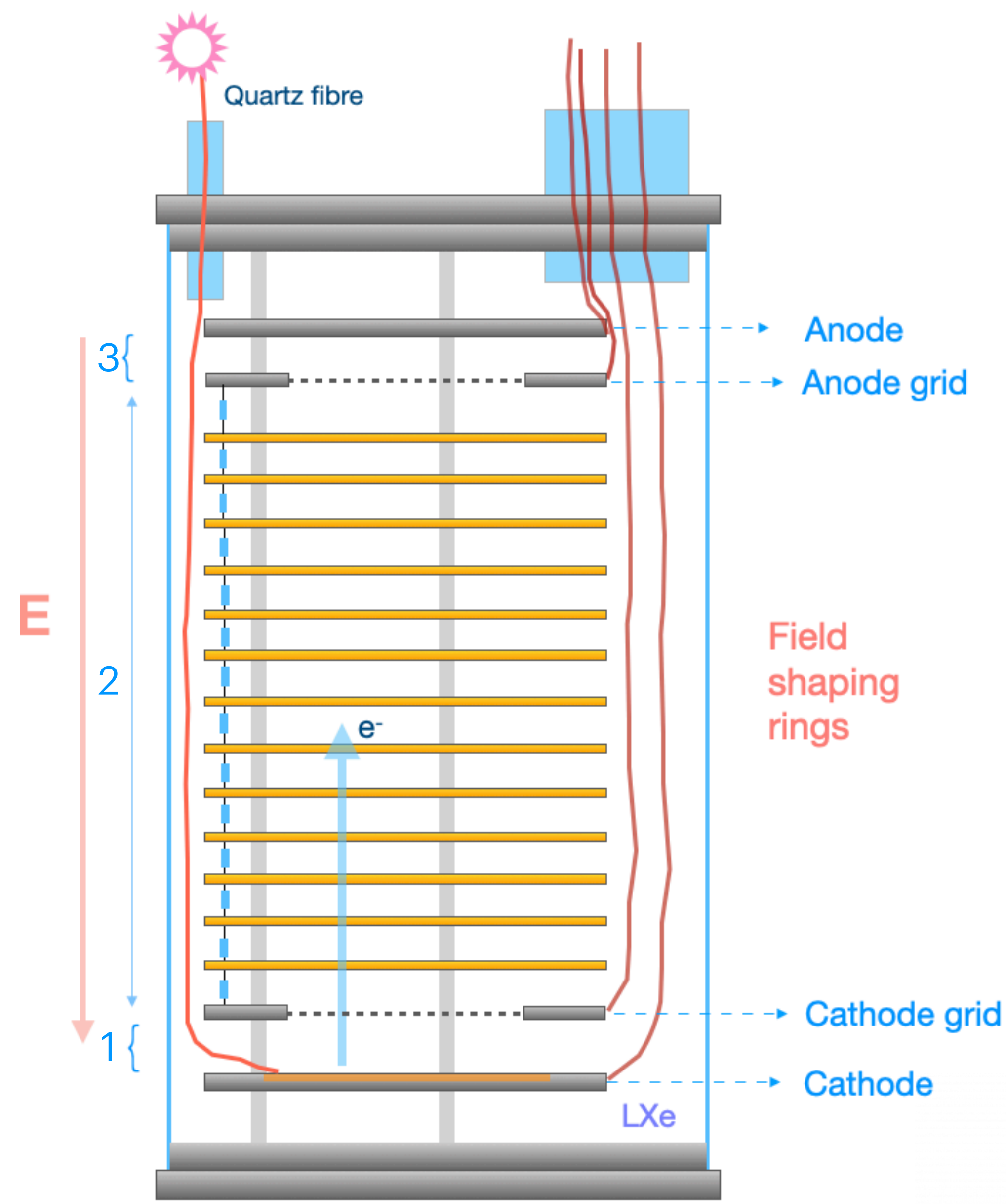
The purity monitor

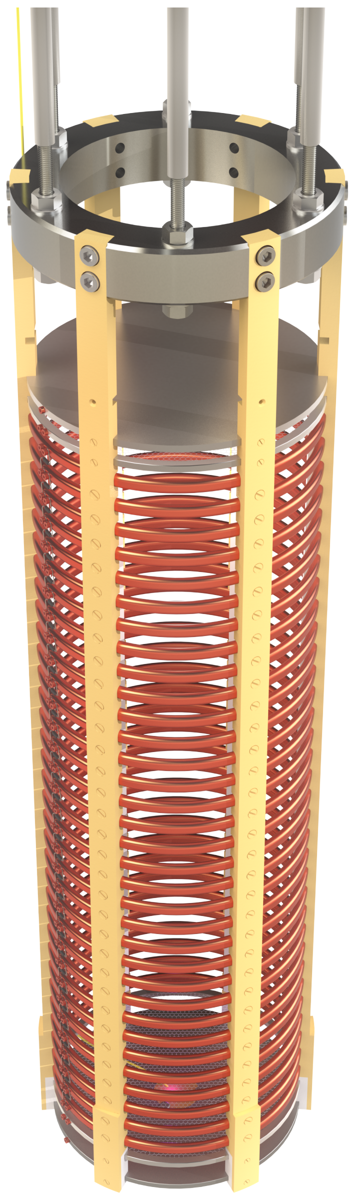
- Drift length: 525 mm
- Electron cloud: produced from in-house made, thin film Ag photocathode (on quartz substrate) via pulsed xenon flash lamp (Hamamatsu L7685)
- Charge readout on top (Q_A) and bottom (Q_C)
- Electrons are absorbed as they drift upwards (in region 2) towards the anode
- Ratio of signals: ∝ electron lifetime τ_e

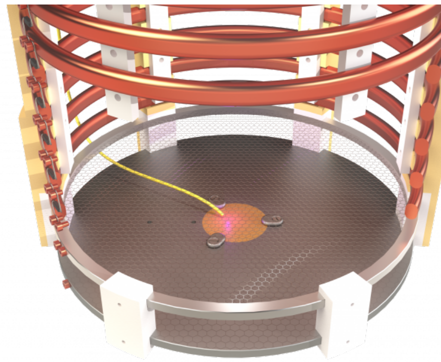
$$\frac{Q_A}{Q_C} = e^{-t_d/\tau_e}$$



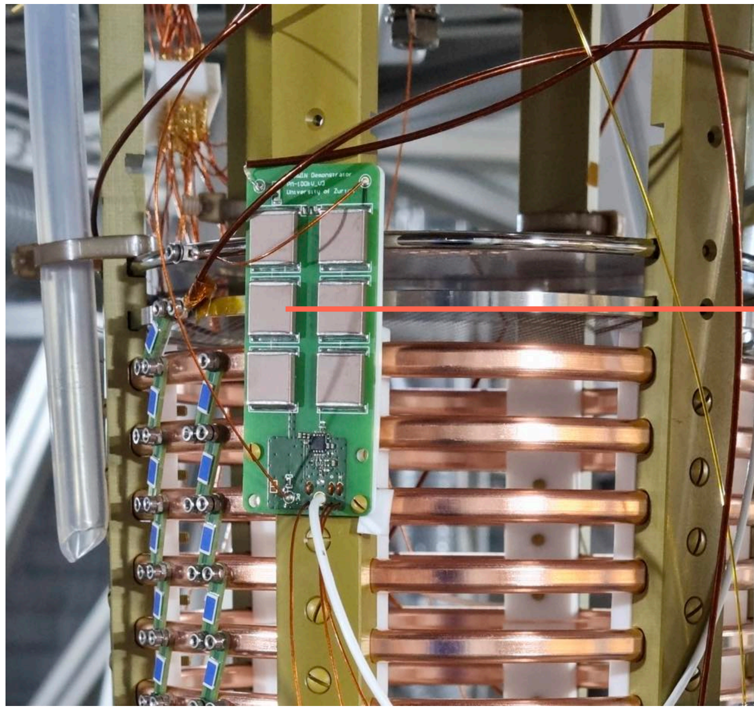




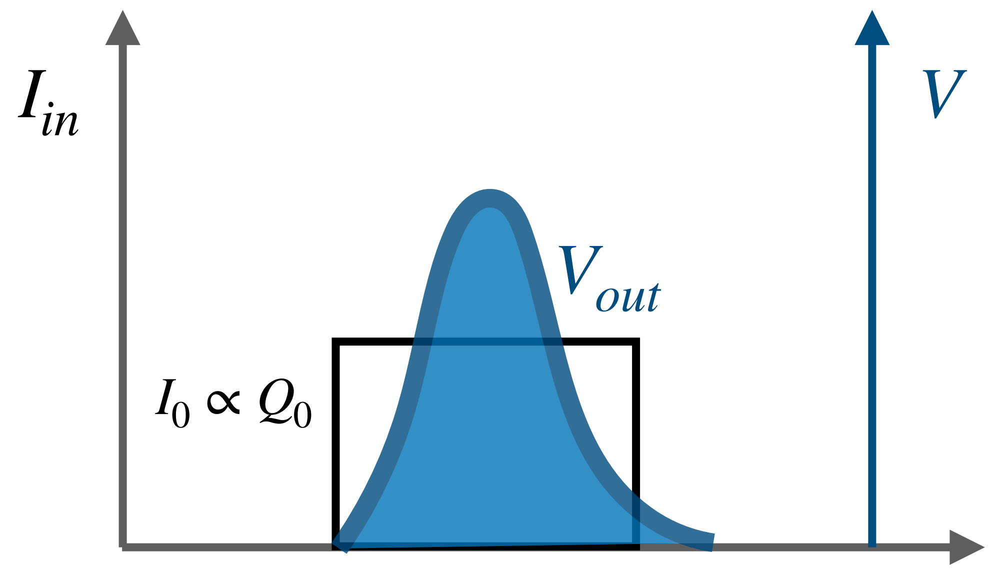


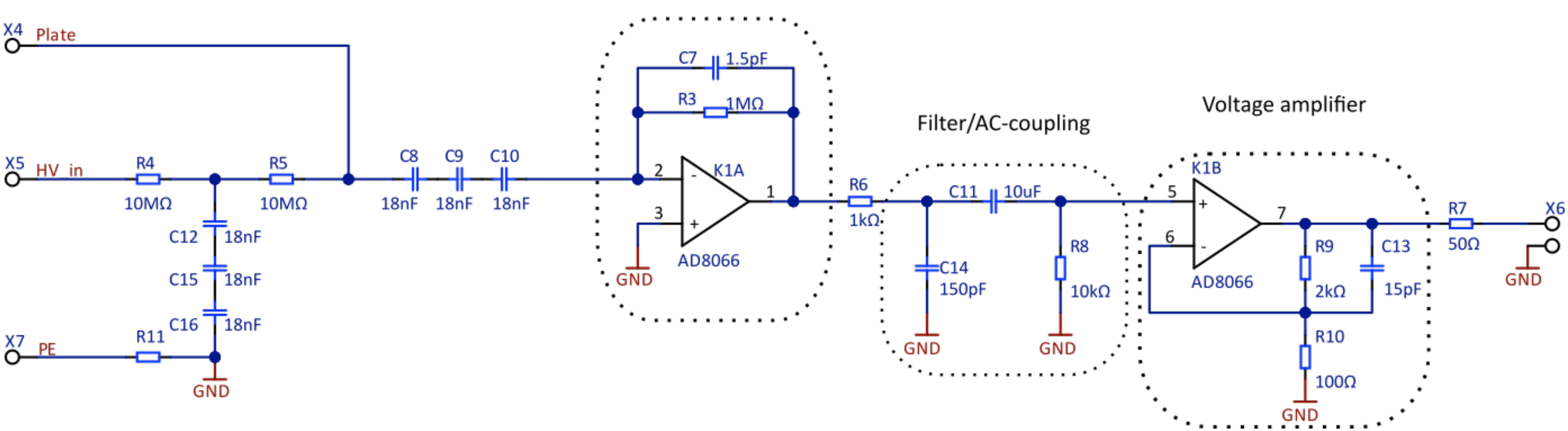


The purity monitor: signal readout



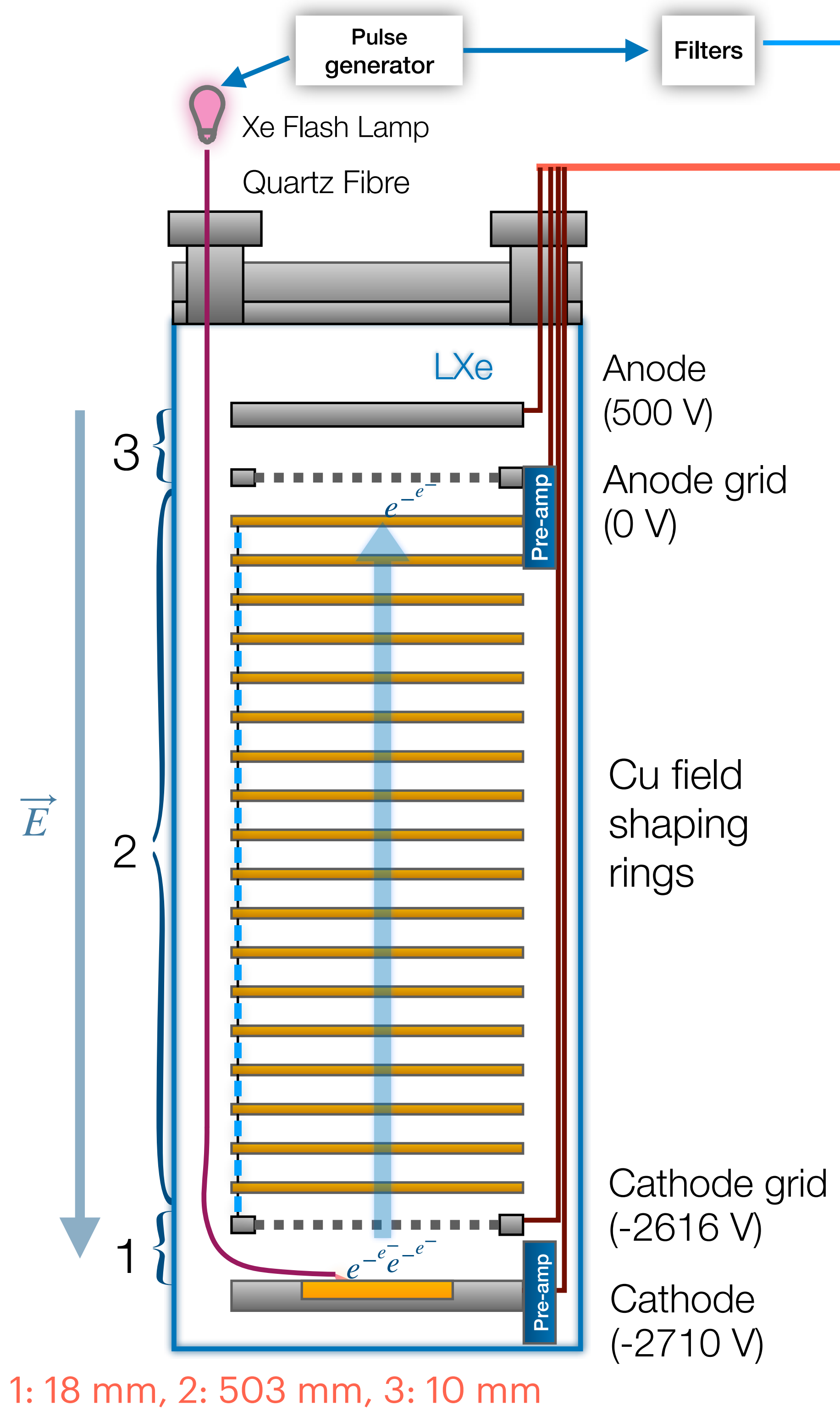
Cryogenic read-out: AC coupling followed by a transimpedance preamplifier + voltage amplifier operating at <180K

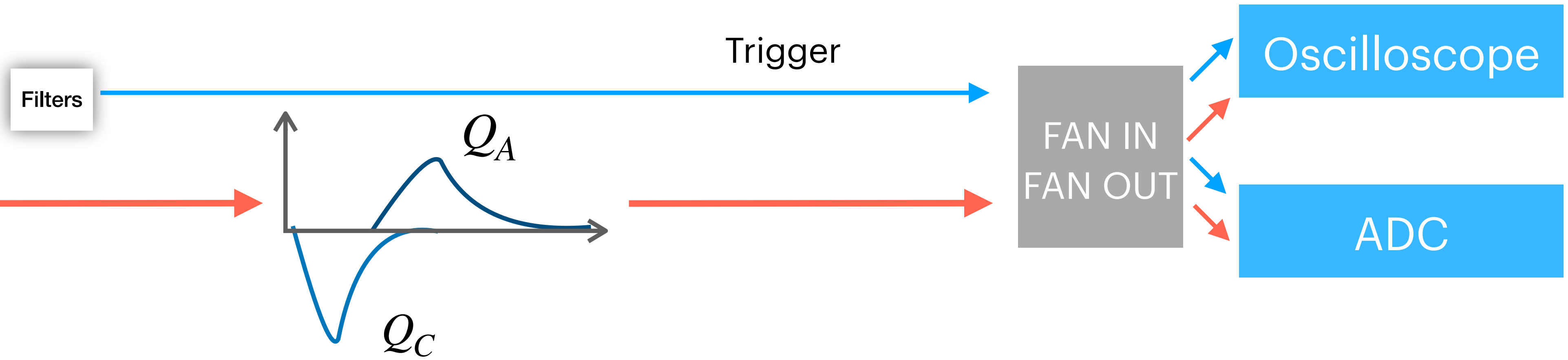




Amplification: ~ 1.4 V/pC

The purity monitor: signal readout

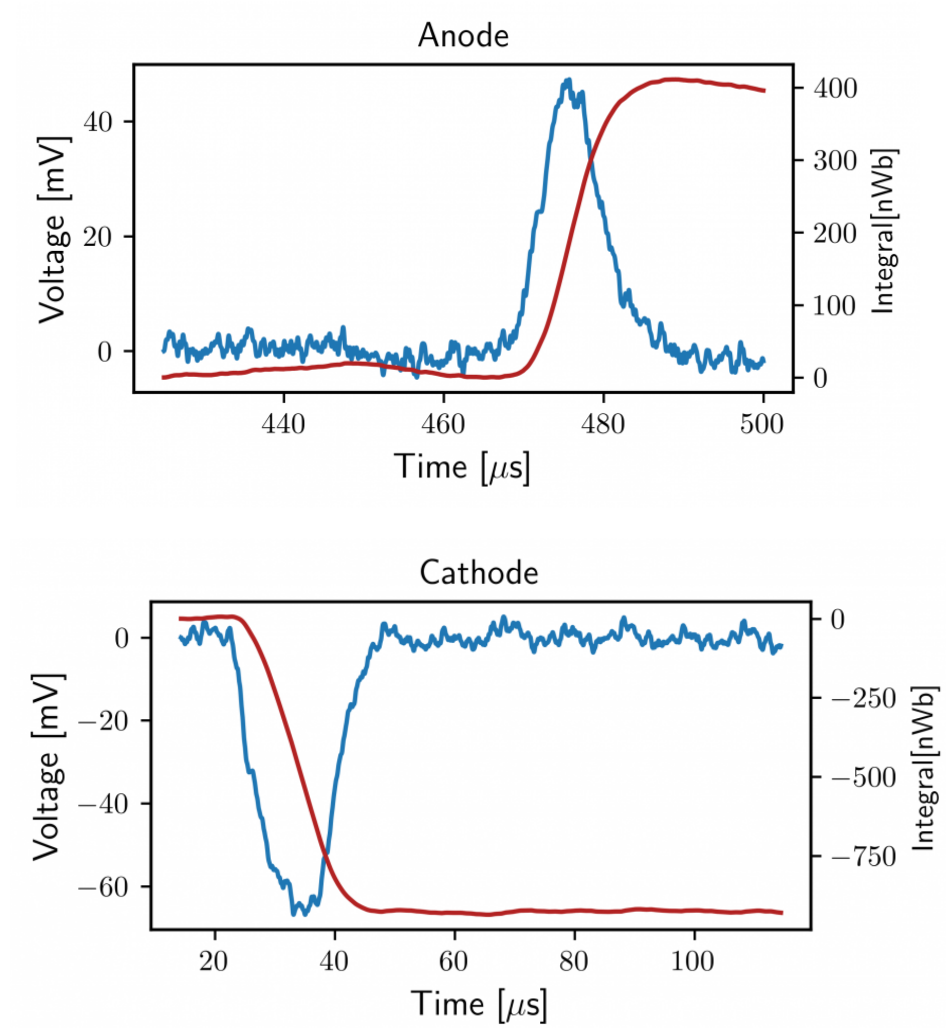


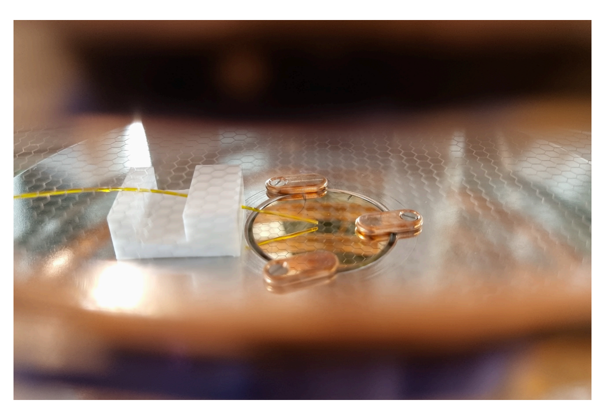


Lamp on at 1 Hz, for 7 μs: 1000 waveforms acquired ⇒ average waveform

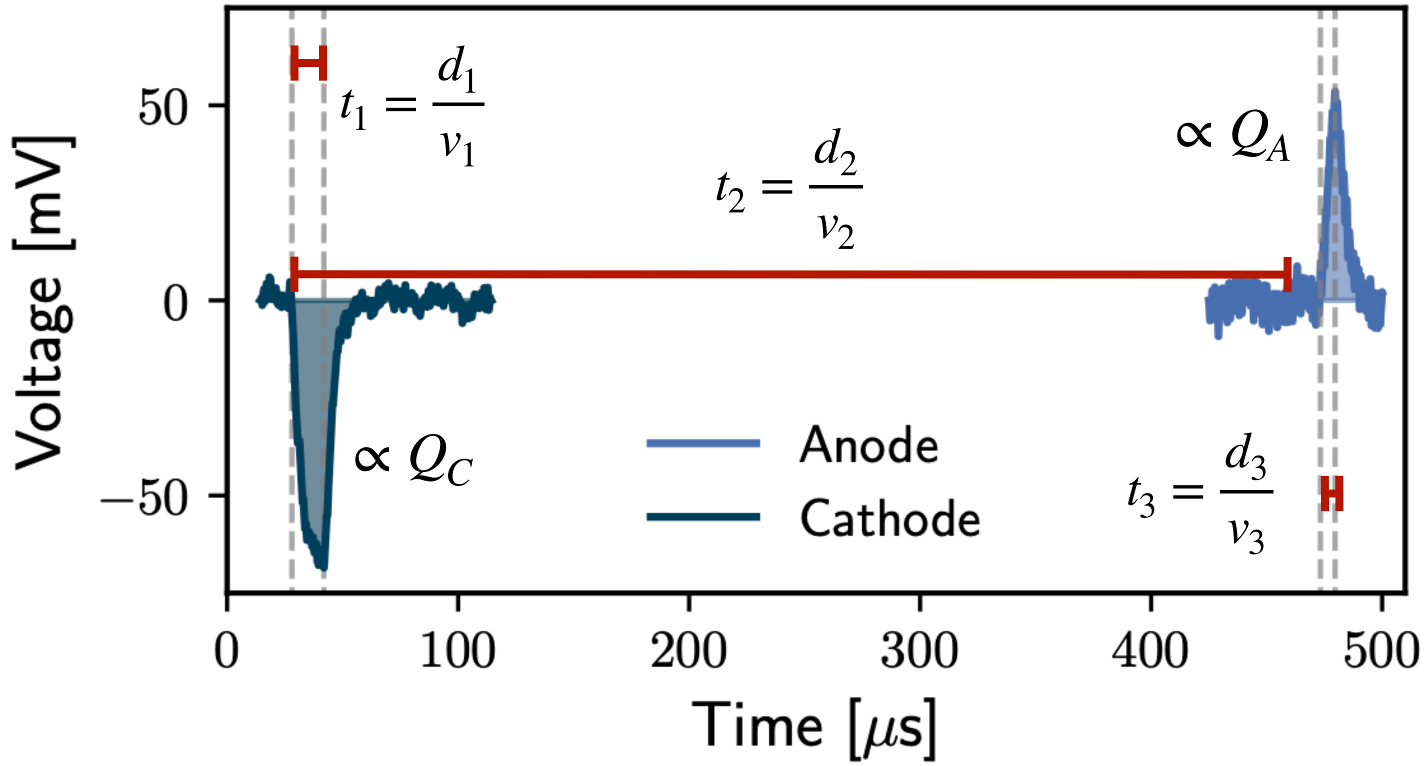
Waveform filtered for low noise

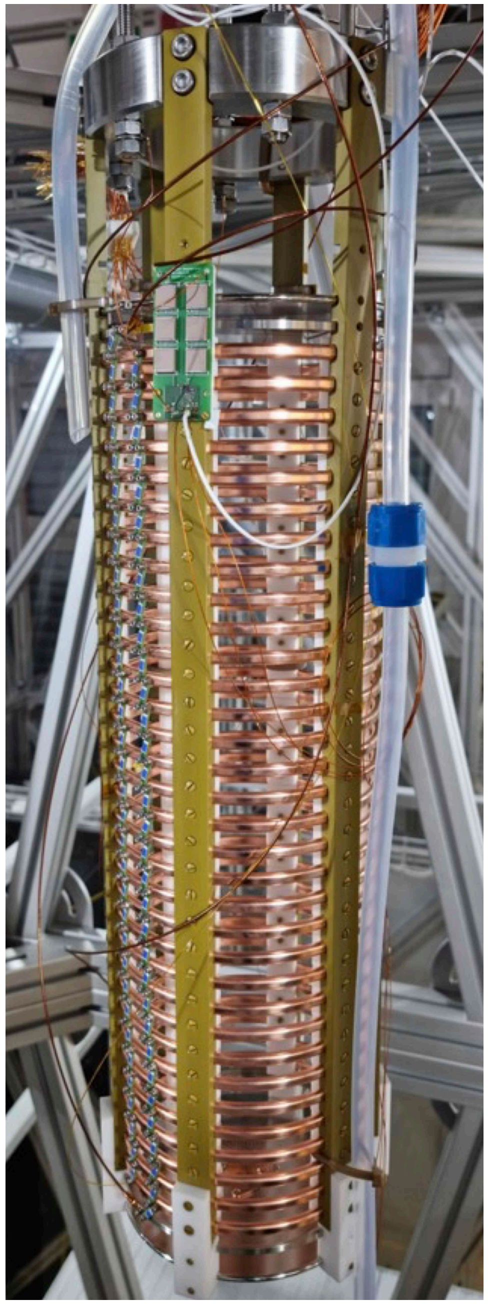
Integral ⇒ charge measured in the drift regions

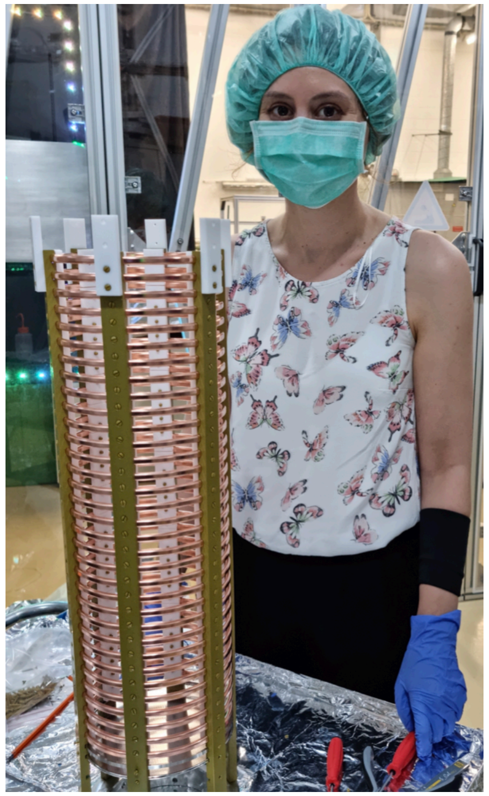




The purity monitor: e⁻-lifetime determination





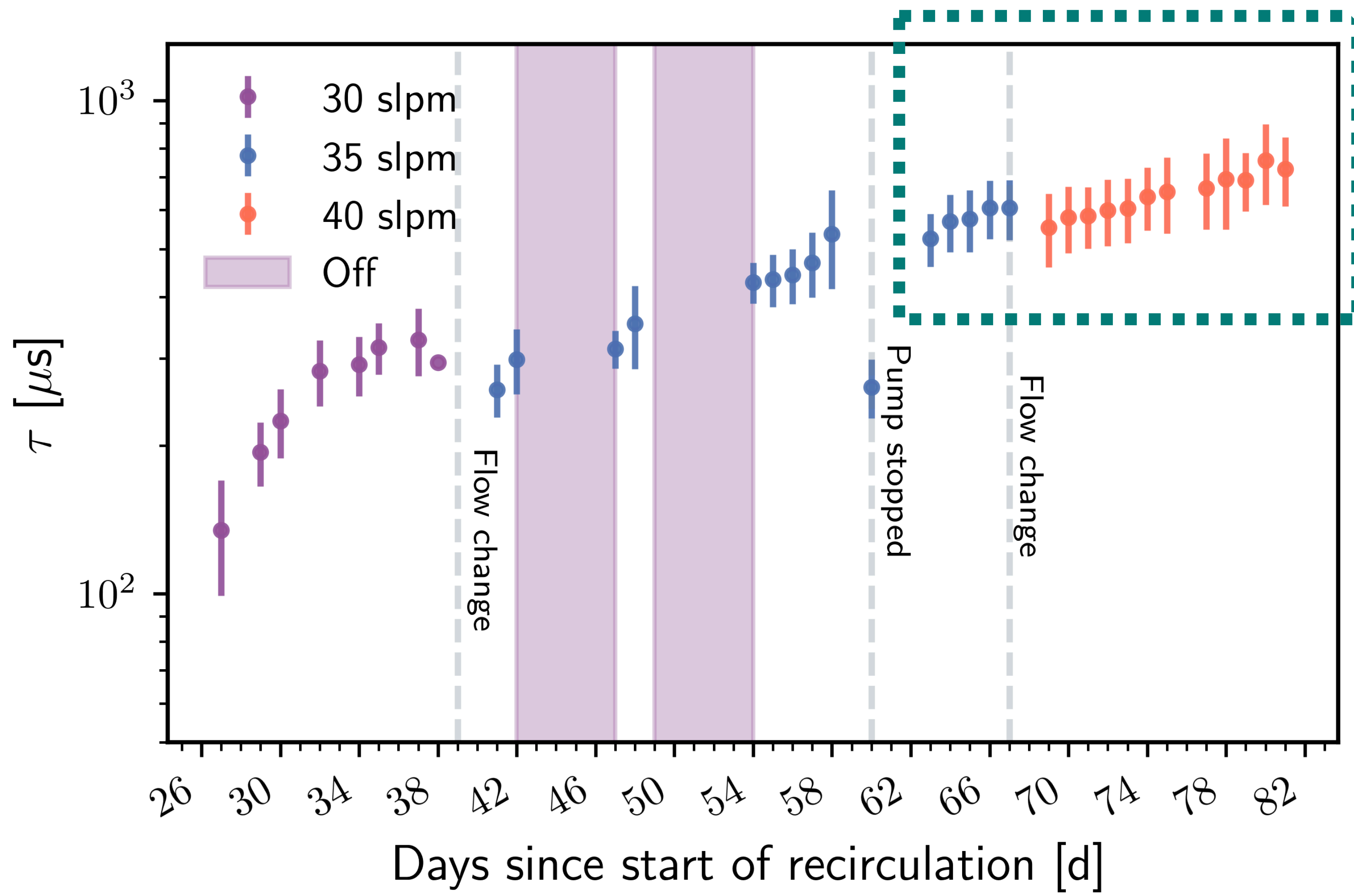


- Waveforms: acquired by oscilloscope and ADC
- Charges: integrals of the current pulses
- The e-lifetime (with $\Delta t = t_2$, rise times t_1, t_3)*

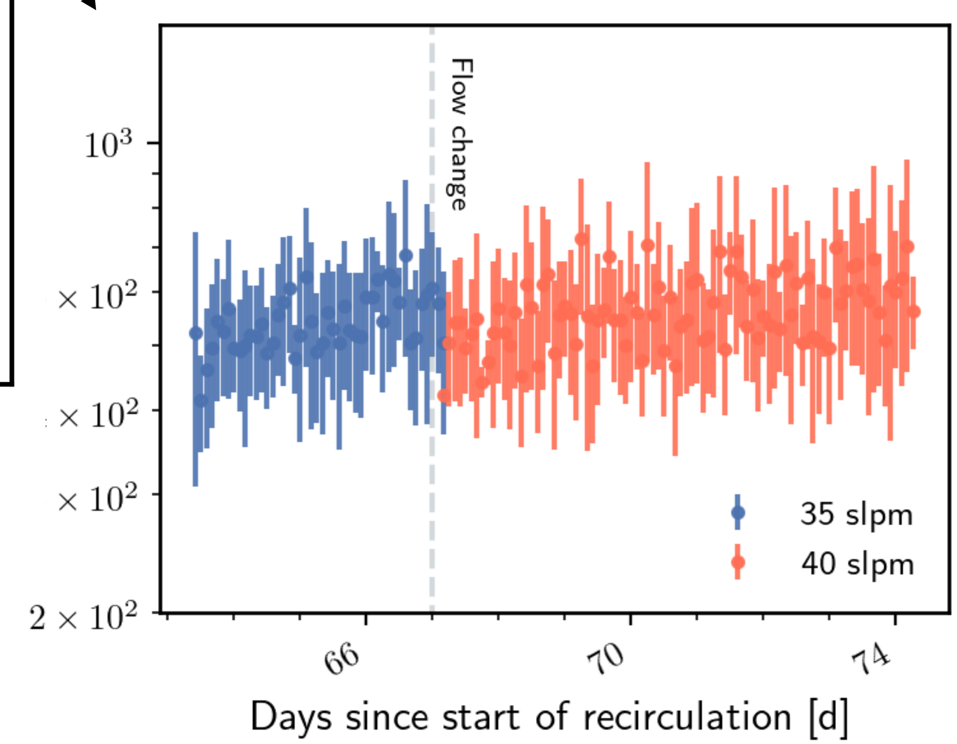
$$\tau_e \approx \frac{1}{\ln(Q_A/Q_C)}\left(t_2 + \frac{t_1+t_3}{2}\right)$$

*L. Manenti et al., JINST 15, 2020

The purity monitor: results so far

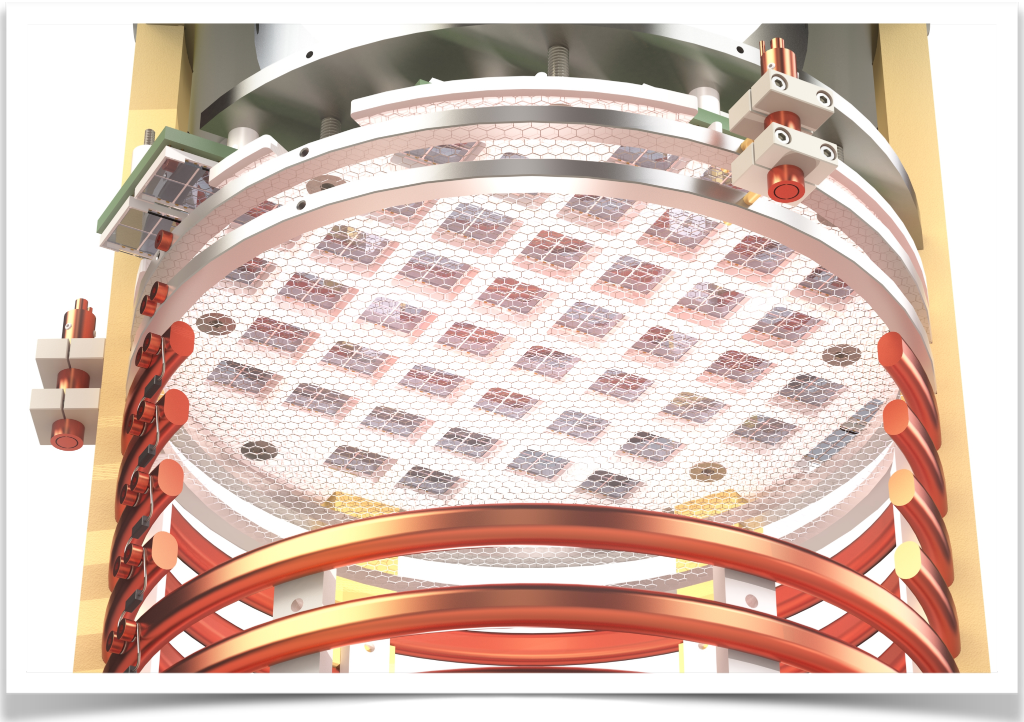


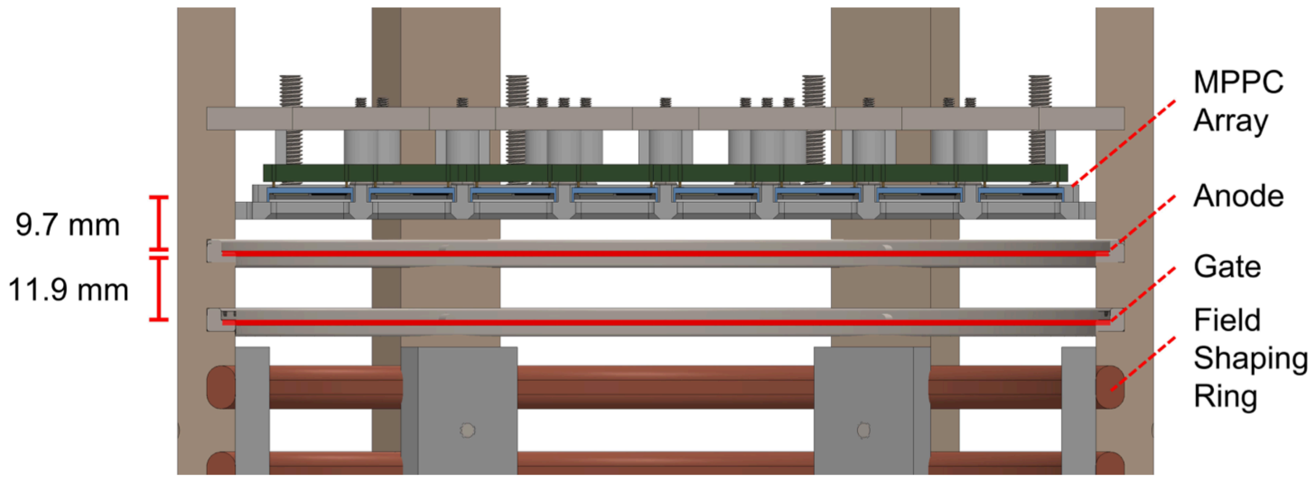
Stable operation since noise troubleshooting, one data point every 15 minutes



Two-phase TPCs

- Top charge readout replaced by SiPM array
- Bottom: Ag-photocathode first, later eventually PMT arrays
- Liquid level adjustment: weir attached to motion feed-through (in production)
- Three capacitive level meters to determine LXe level: concentric cylinders of 4 mm inner, 4.5 mm outer Ø, 30 mm length (already produced)
- Operational modes
    - triggered e^- production on photocathode
    - triple coincidence between muons (2 plastic scintillators, currently being tested) and S2 signal in TPC



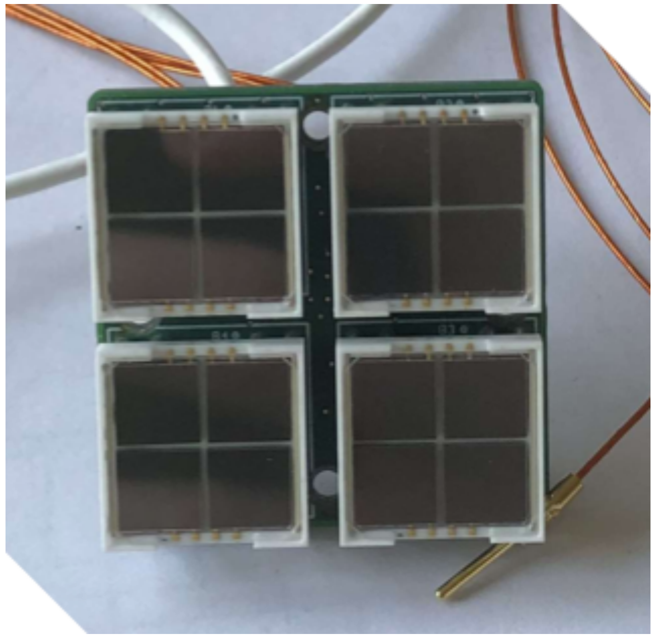


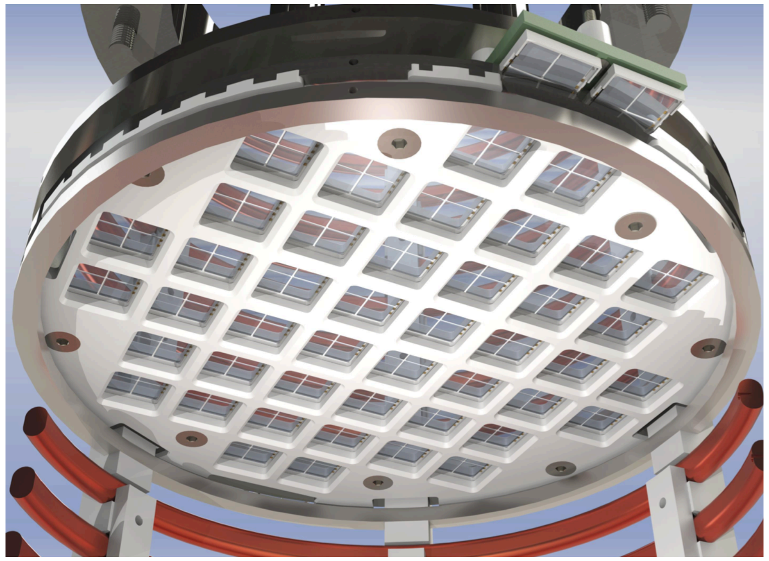
Top section of TPC: 0.1 mm thick gate & anode, with liquid/gas interface in between

The SIPM array

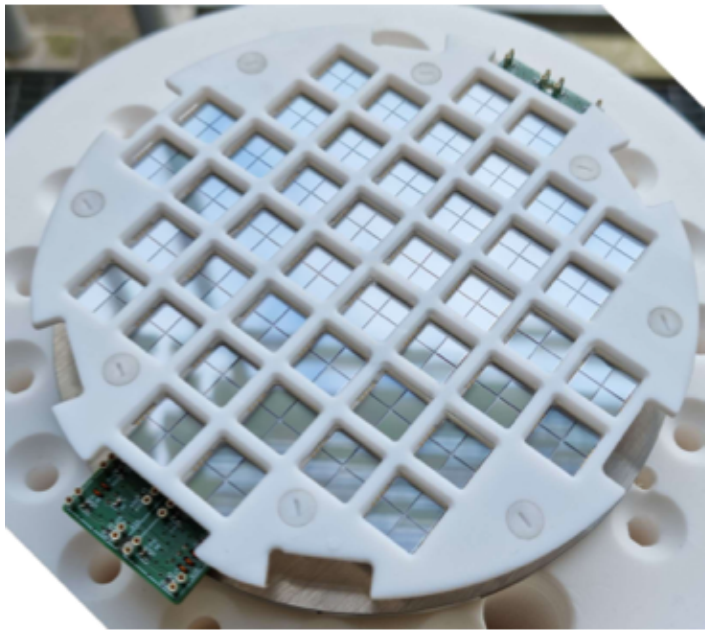
- Tiles made out of 4 Hamamatsu VUV4 12×12 mm² units each; 12 tiles in total
- Onboard $\times$ 10 pre-amplifier
- Very good single photo-electron resolution; DCR: ~ 4 kHz/tile at 190 K (gaseous Xe)
- Same type operated in Xurich top TPC array*
    - see talk by Ricardo Peres

One channel: 24 x 24 mm² tile





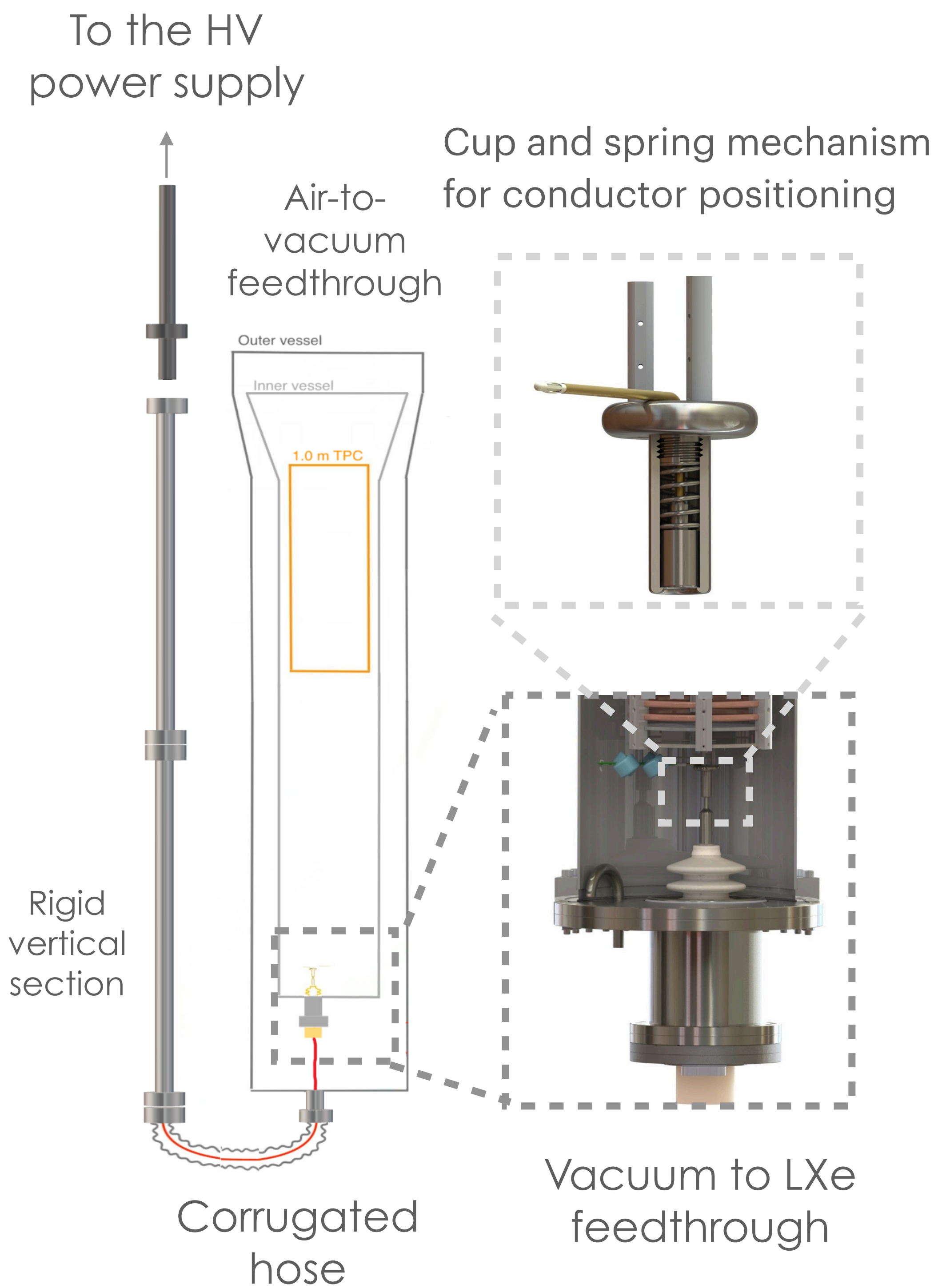
TPC diameter: 16 cm



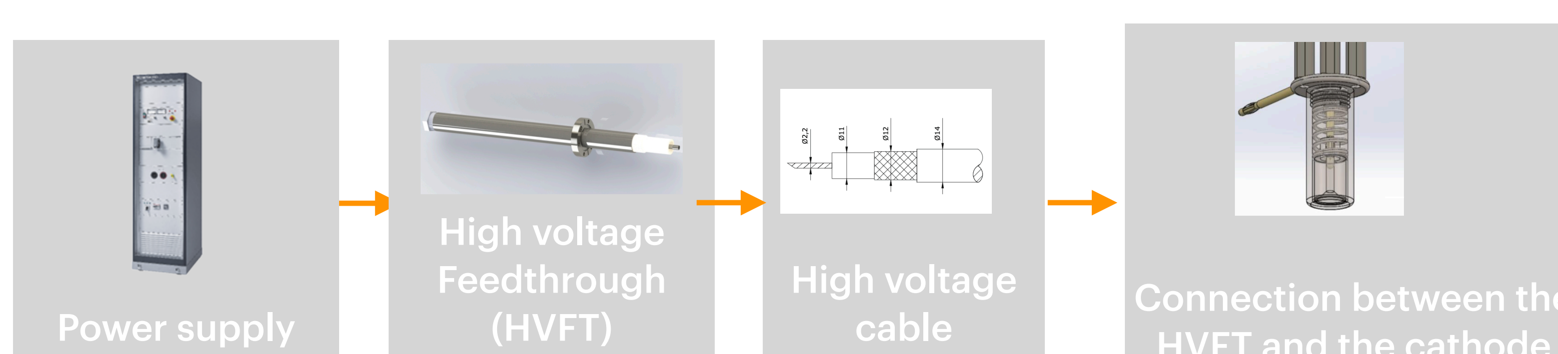
12 channel array

* L. Baudis et al., Eur. Phys. J. C 80 (2020) 477

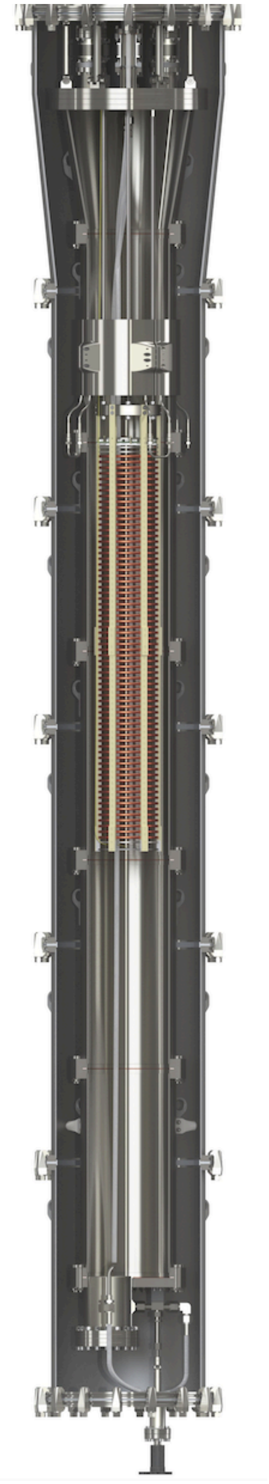
The HV distribution



- **HV system**: generation of the nominal voltage & safe transmission from the power supply to the cathode
  - Heinzinger power supply rated up to 100 kV
  - HV transmitted via a Heinzinger HV cable
- Air-to-vacuum FT: custom-made, cryo-fitted rod
- Rigid vertical section connected to a corrugated vacuum hose that bends the cable towards the bottom flange of outer vessel.
- Vacuum-to-LXe FT: ceramic FT (*CeramTec 304*) entering the LXe volume via the bottom flange of inner vessel
- Spring & cup mechanism ensures good electrical contact in the rod-cup union



Toward the 1 m + 2.6 TPCs



Summary and Outlook

- **Strong physics case for a large xenon observatory** in astroparticle physics, as advocated by DARWIN *(and by DARWIN/XENON-LUX-ZEPLIN)*
- Due to the much larger scale compared to current-generation detectors we need
  - large, full-scale demonstrators in the *z*, and *x-y* dimensions
- **Xenoscope: a full-scale, 2.6 m TPC demonstrator constructed at UZH**
  - Main goals: e^--drift over large distances, e^--cloud diffusion, photosensor and HV R&D, light attenuation measurements
  - Also, test platform for the collaboration & new ideas are welcome :-)
  - Run with 525 mm purity monitor ongoing, current e^--drift lifetime >720 μs
  - Next runs: 1.0 m two-phase TPC with SiPM S2-readout, then 2.6 m TPC
- **Stay tuned!**

The Xenoscope Team

Slide thanks to Frédéric Girard



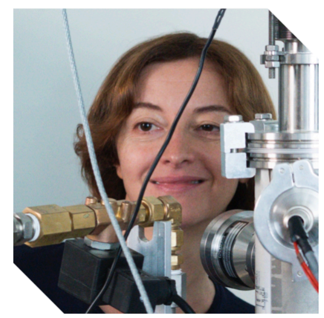




DARWIN

XENOSCOPE

Universität Zürich[UZH]



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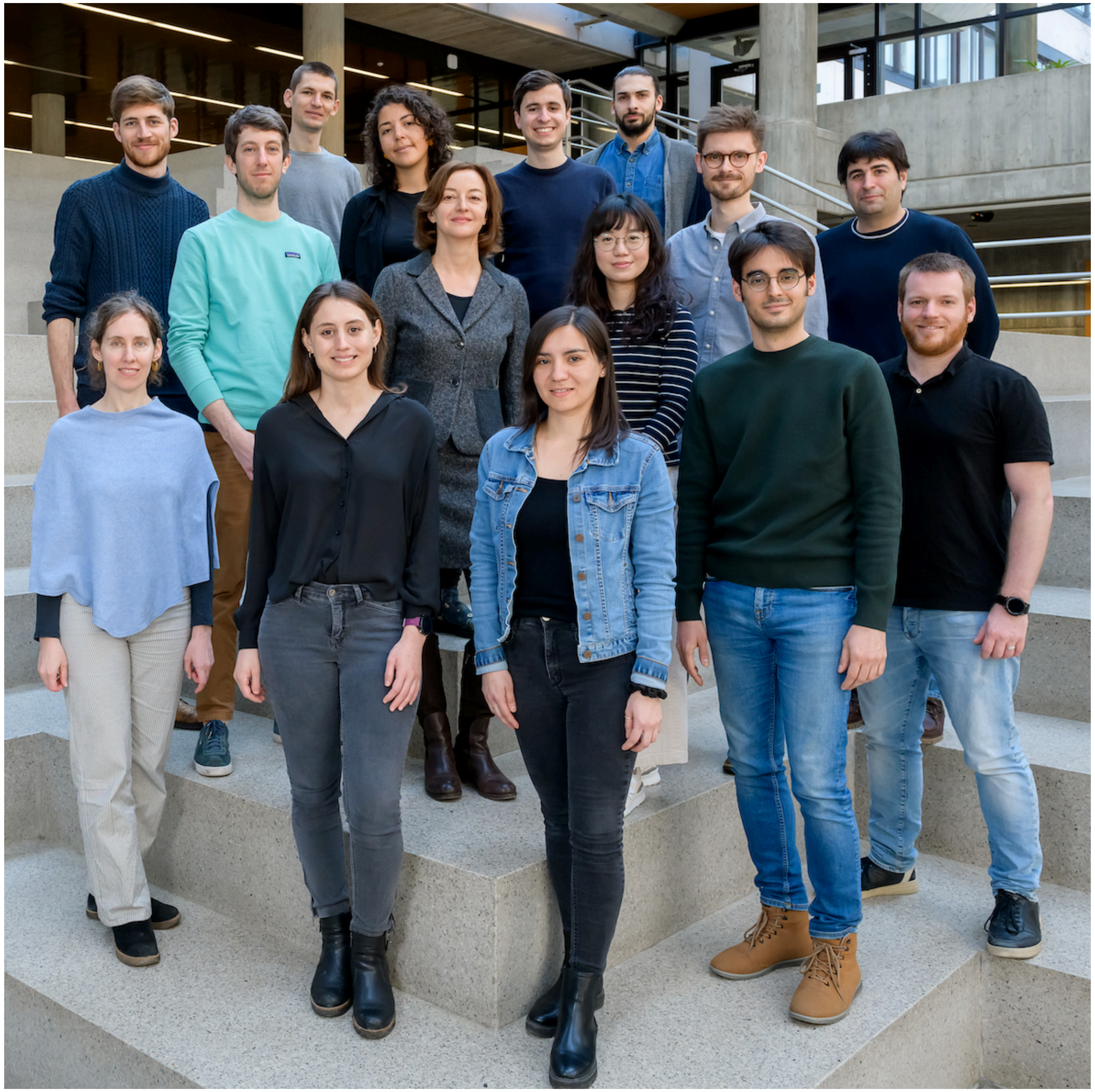
* Former members

Further reading: PhD thesis of Kevin Thieme, "The Low-Energy and Large-Scale Frontier of Dual-Phase Xenon Time Projection Chambers for Dark Matter Search", UZH 2022

The astroparticle physics group

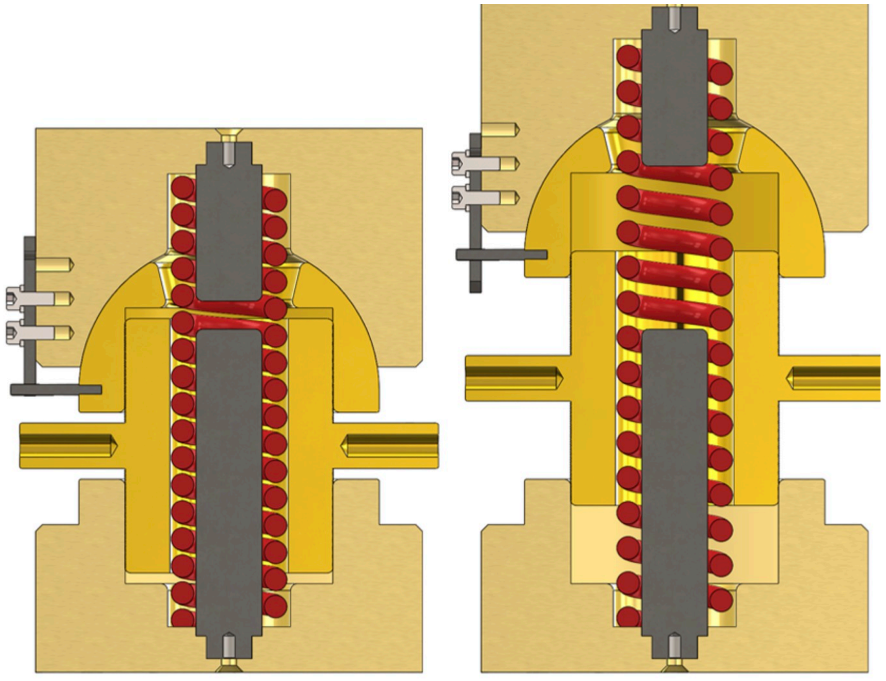


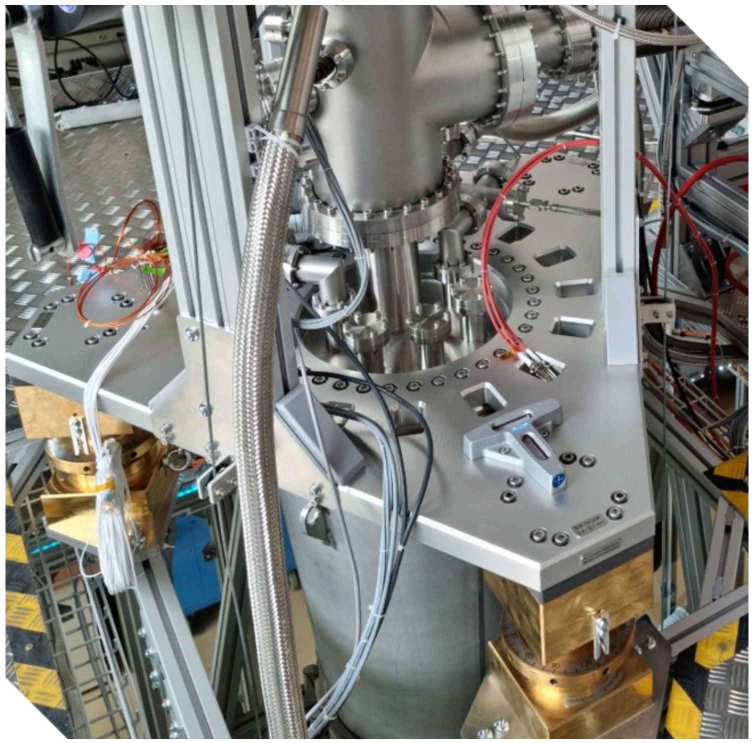
The end

Backup slides

The levelling system

- For uniform amplification signal and to prevent large radial forces on cryostat & flanges
  - liquid-gas interface must be parallel to gate and anode meshes
- Fine adjustment system: 40 mm AlMg alloy triangular plate supported by 3 levelling legs
  - dual counter-rotating M92 fine thread screw
  - central spring bears most of the weight
  - equilateral geometry for even weight distribution (can level masses up to 700 kg/leg)
- Adjustment of the x-y level: < 60 μm/m





Xe optical properties measurements

Motivation: experimental values for LXe optical properties poorly known. Measurements can be performed at density, temperature, wavelength and length scales relevant for DARWIN.

Measurement of xenon group velocity:

- Hodoscope construction using external muon detectors as trigger
- Measure difference in arrival time and path lengths to photosensors at various heights
- Scintillation light group velocity (v_g) extracted from linear fit
- refractive index (n) of LXe derived from parameterisation at 178 nm:

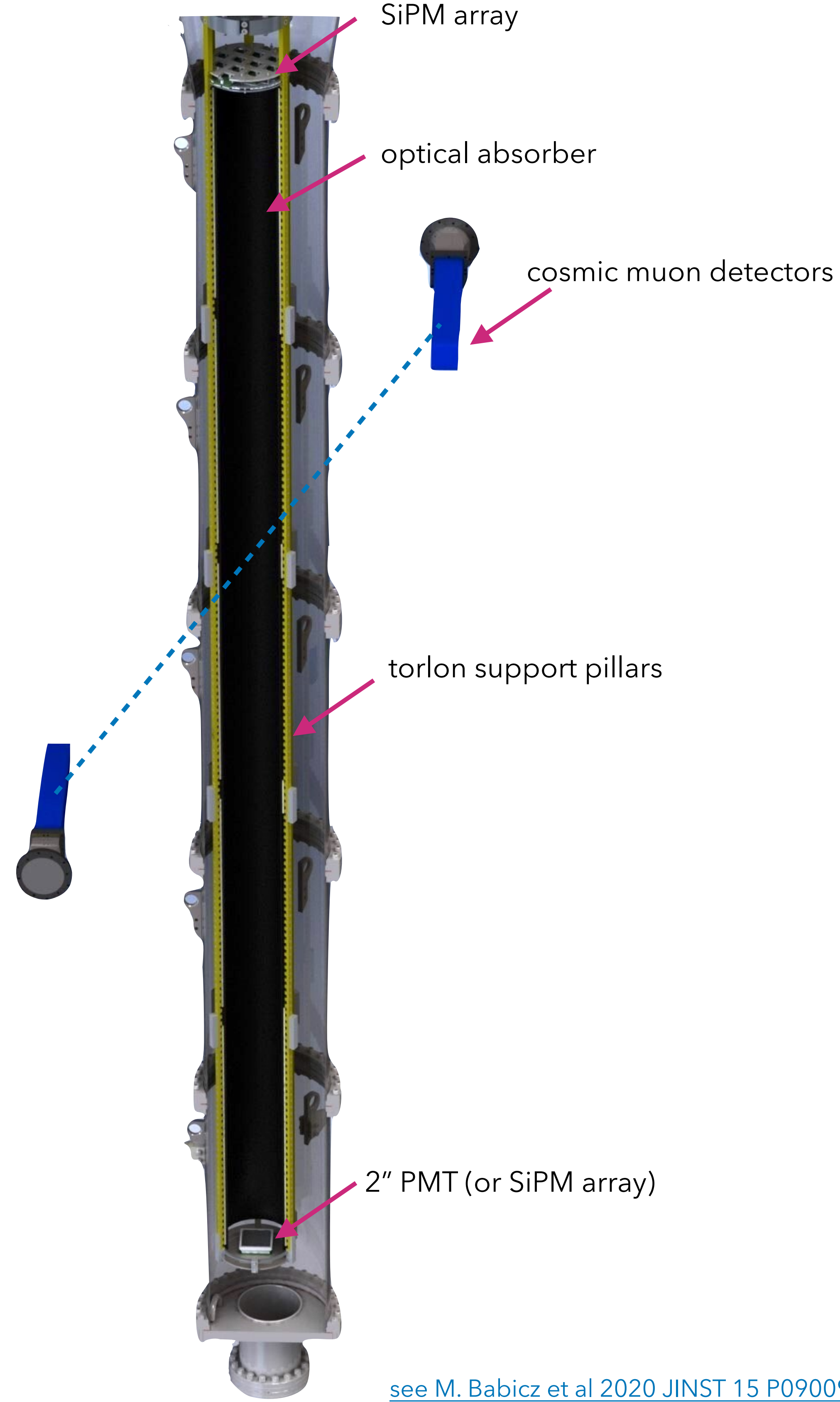
$$v_g = \frac{c}{n - \lambda \frac{dn}{d\lambda}}$$

- Rayleigh scattering length: can be deduced from n, where k_B is the Boltzmann constant and ω the angular frequency :

$$\frac{1}{L_R} \propto \frac{\omega^4}{c^4} k_B T \, (n^2-1)^2 (n^2+2)^2$$

Dependence on xenon purity level, temperature, density

- monitoring of H_2O content with Tiger Optics HALO monitor
- obtain results at various temperature, density, purity
- benchmark and deduce uncertainties with MC simulations



see M. Babicz et al 2020 JINST 15 P09009

Xe optical properties measurements

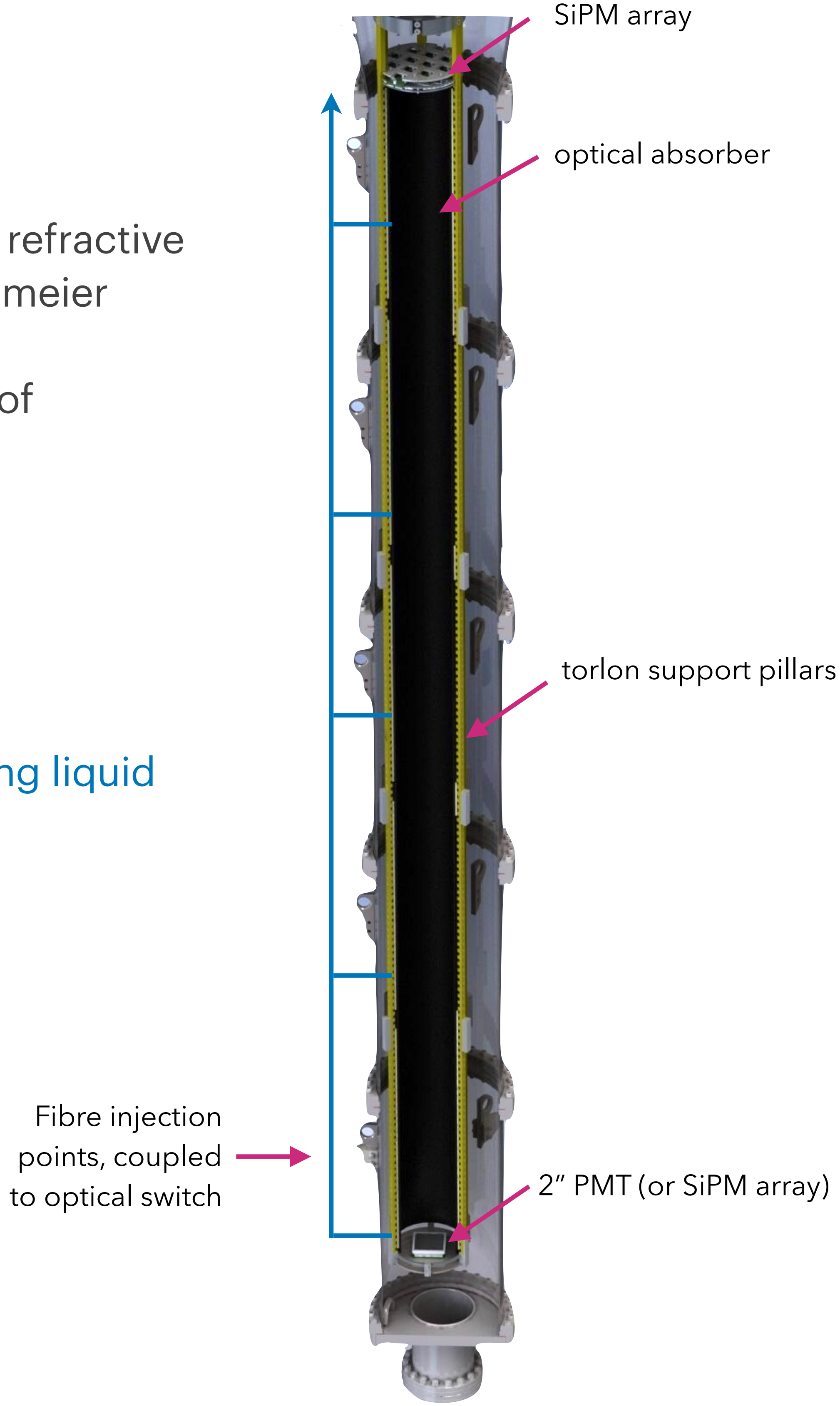
Other possible measurements:

- Varying injected wavelength allows parametrisation of refractive index, extraction of Rayleigh scattering length (via Sellmeier coefficients)
- Deduce xenon absorption length from measurements of attenuation length up to 2.6 m*

$$\frac{1}{L_{\mathrm{att}}} = \frac{1}{L_{\mathrm{abs}}} + \frac{1}{L_{\mathrm{R}}}$$

- Independent measurement of refractive index by varying liquid level in TPC

- injection of light source at various heights via fiber optics.
- photon source down to 170 nm and bandpass filters currently under investigation.



* current measurements only to 1 m, see A. Baldini et al 2005 NIM A 545

The P&ID for Xenoscope