Electron transport measurements in Xenoscope, a DARWIN Demonstrator

10.1140/epjc/s10052-023-11823-1

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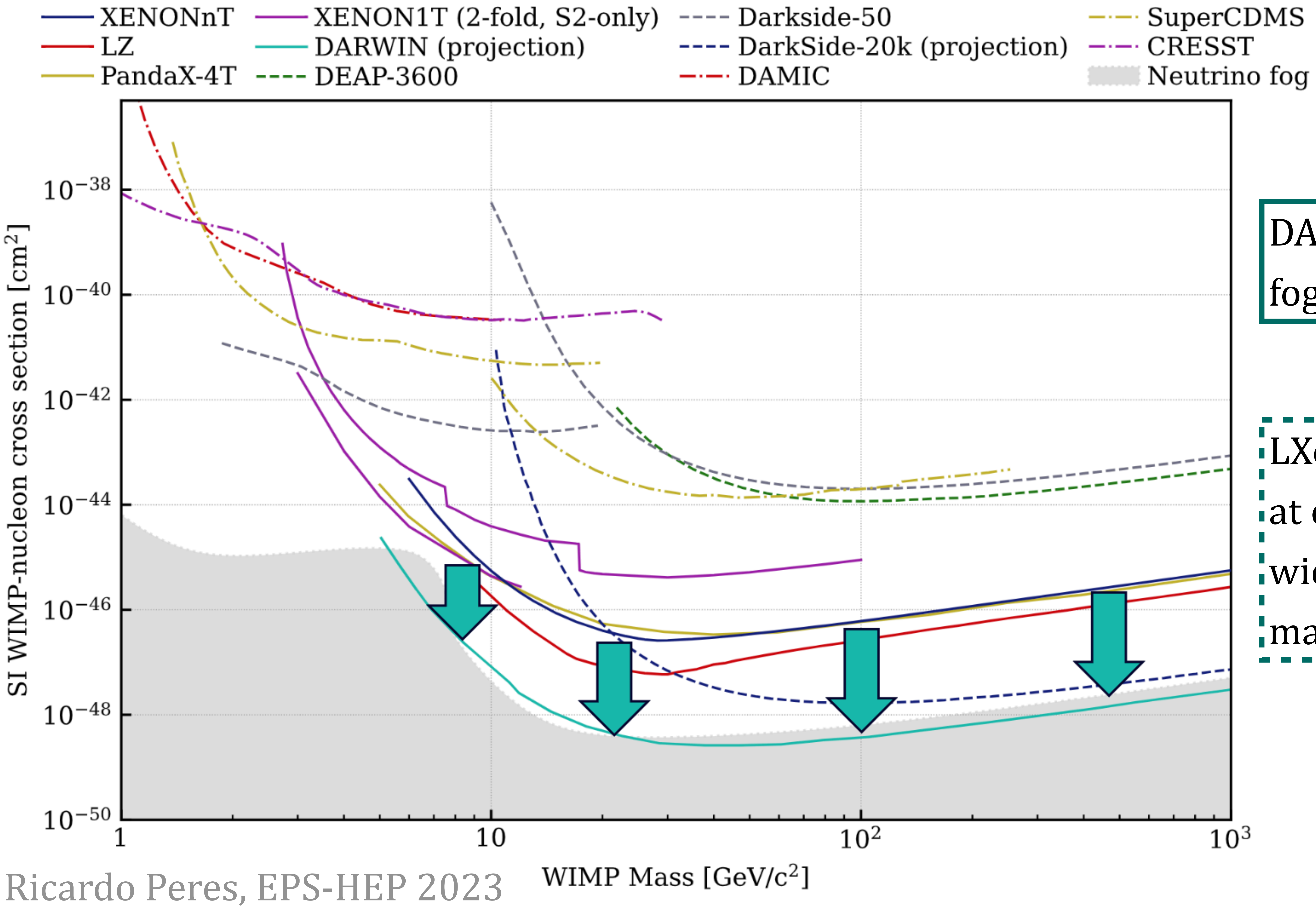
Karlsruhe Institute of Technology,
on behalf of the Xenoscope team at the Universität Zürich

TIPP Conference, 6th September 2023

Liquid Xenon Time Projection Chambers



Ricardo Peres, EPS-HEP 2023

DARWIN Goal: Reach the neutrino fog

LXe experiments were successful at establishing limits spanning a wide range of WIMP candidate masses

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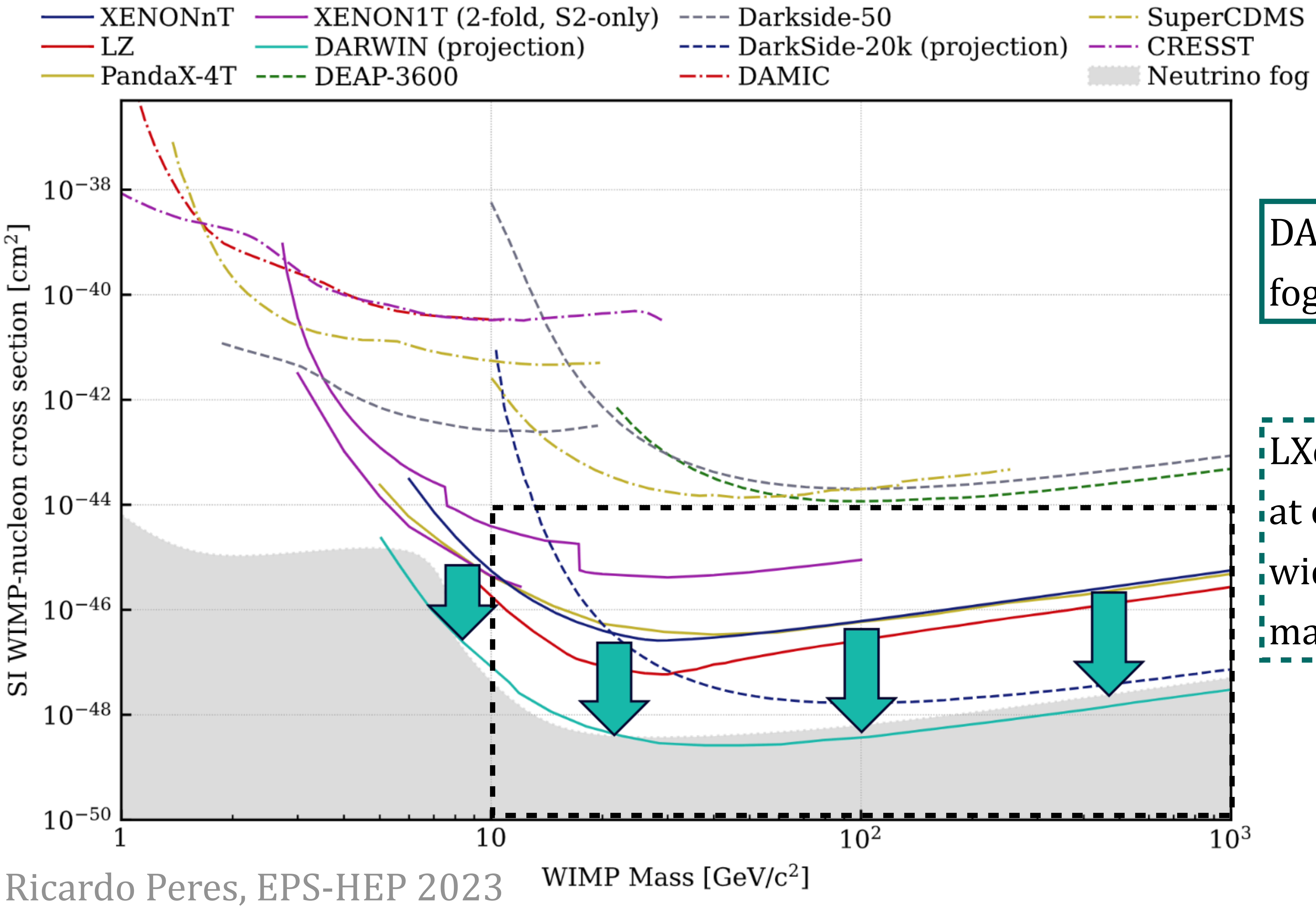

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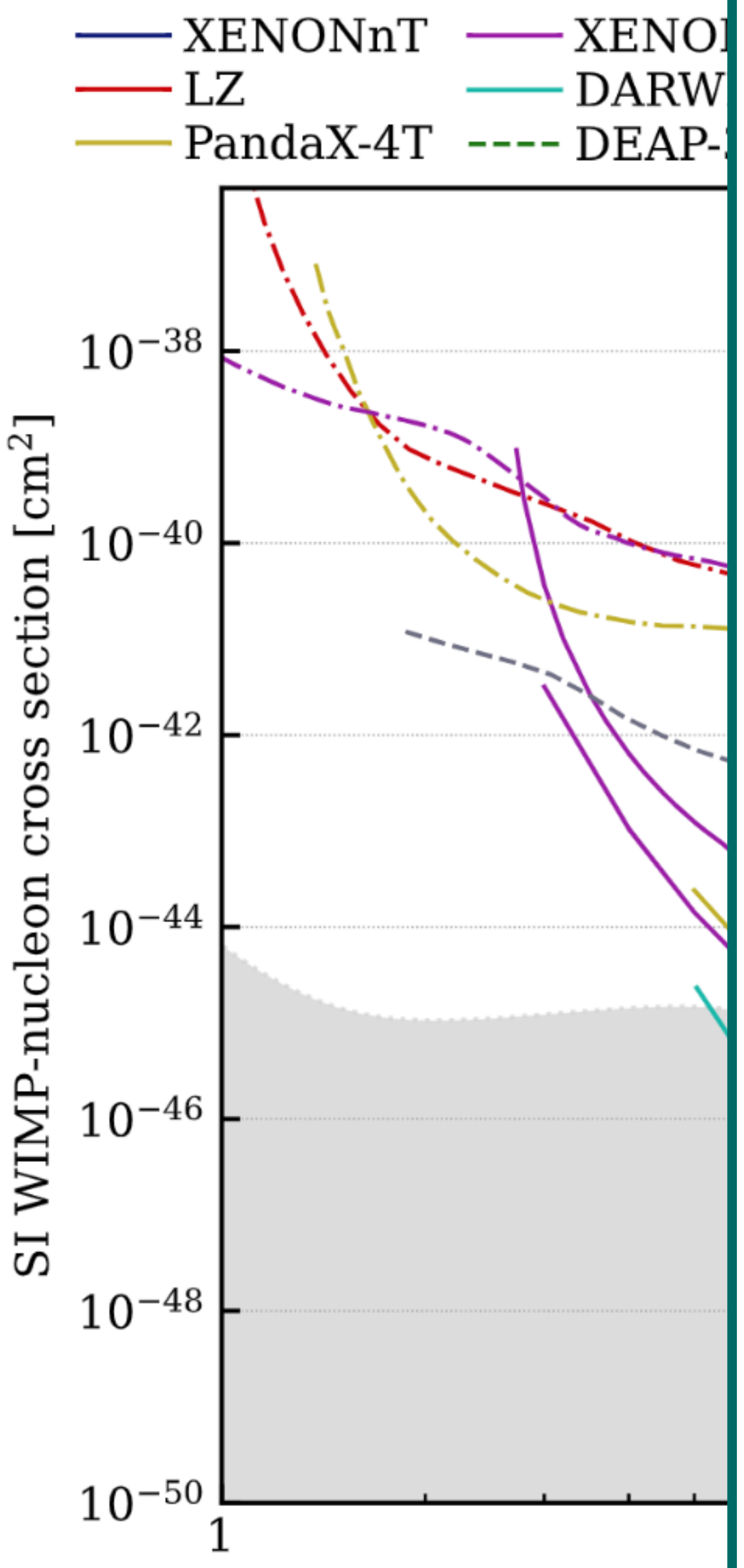

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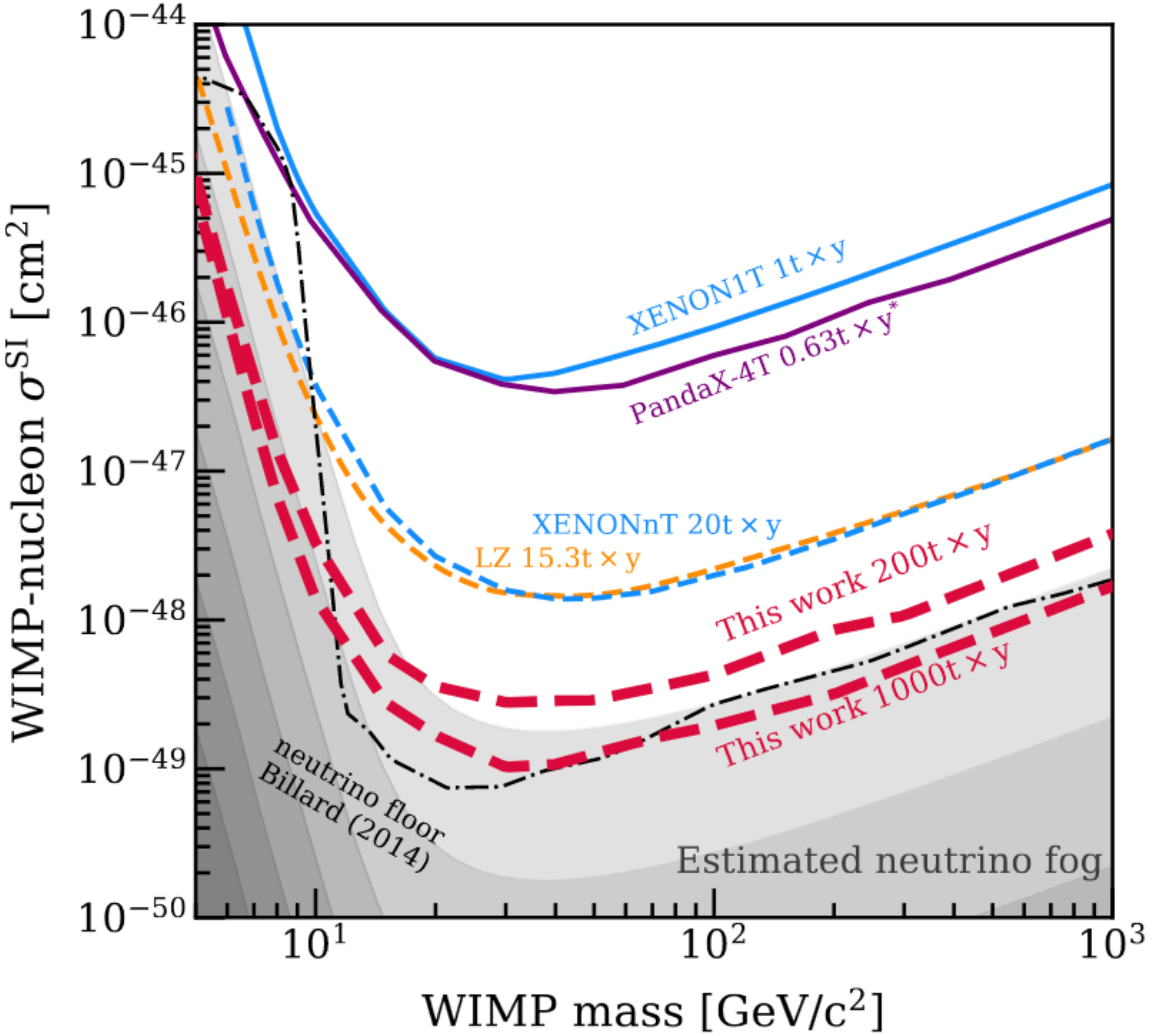

A next-generation liquid xenon observatory for dark matter and neutrino physics, Community paper (XENON+LZ+DARWIN), 2023, J. Phys. G: Nucl. Part. Phys. 50 013001

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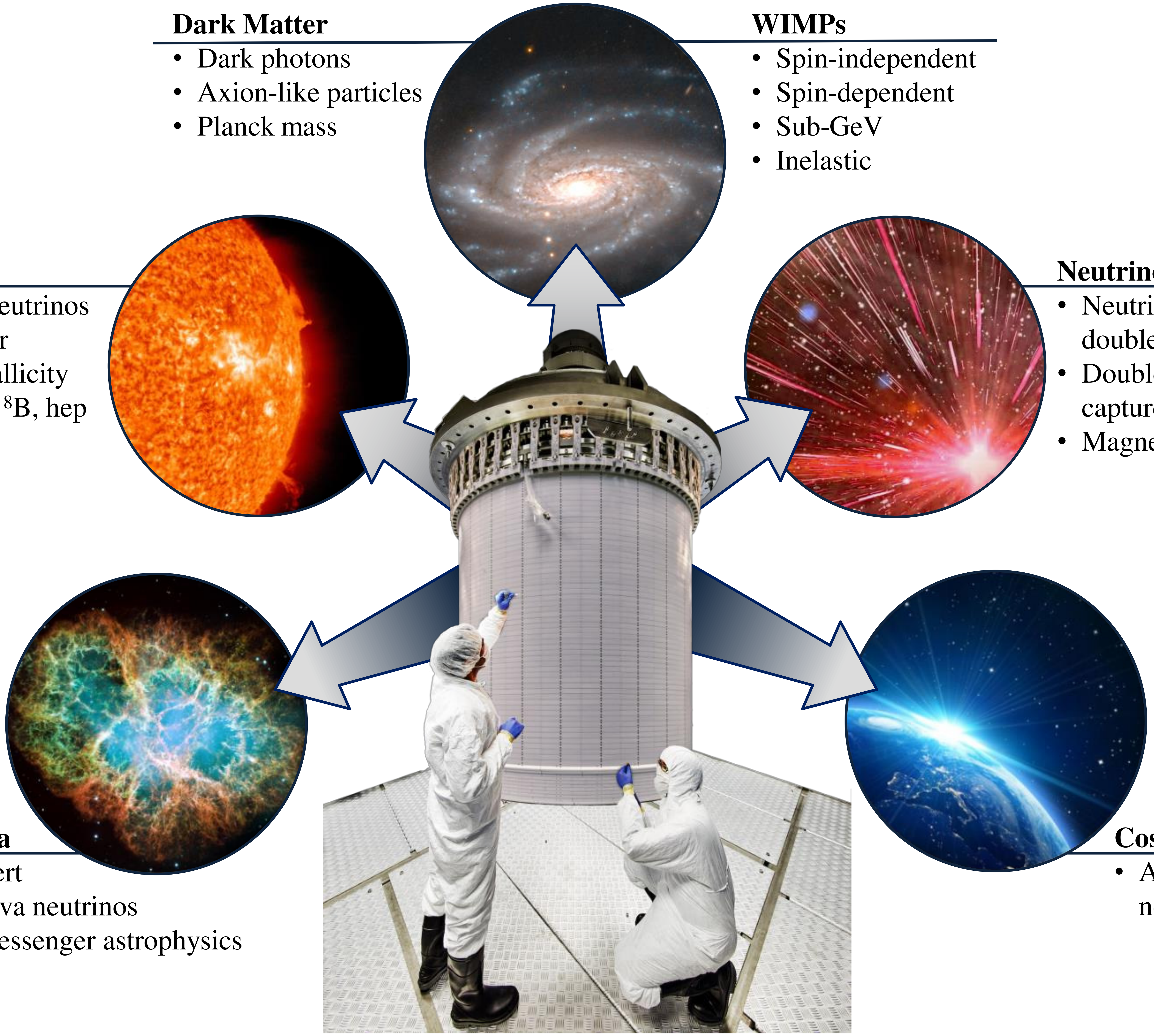
Next Generation LXe TPCs



Dark Matter
- Dark photons
- Axion-like particles
- Planck mass

WIMPs
- Spin-independent
- Spin-dependent
- Sub-GeV
- Inelastic

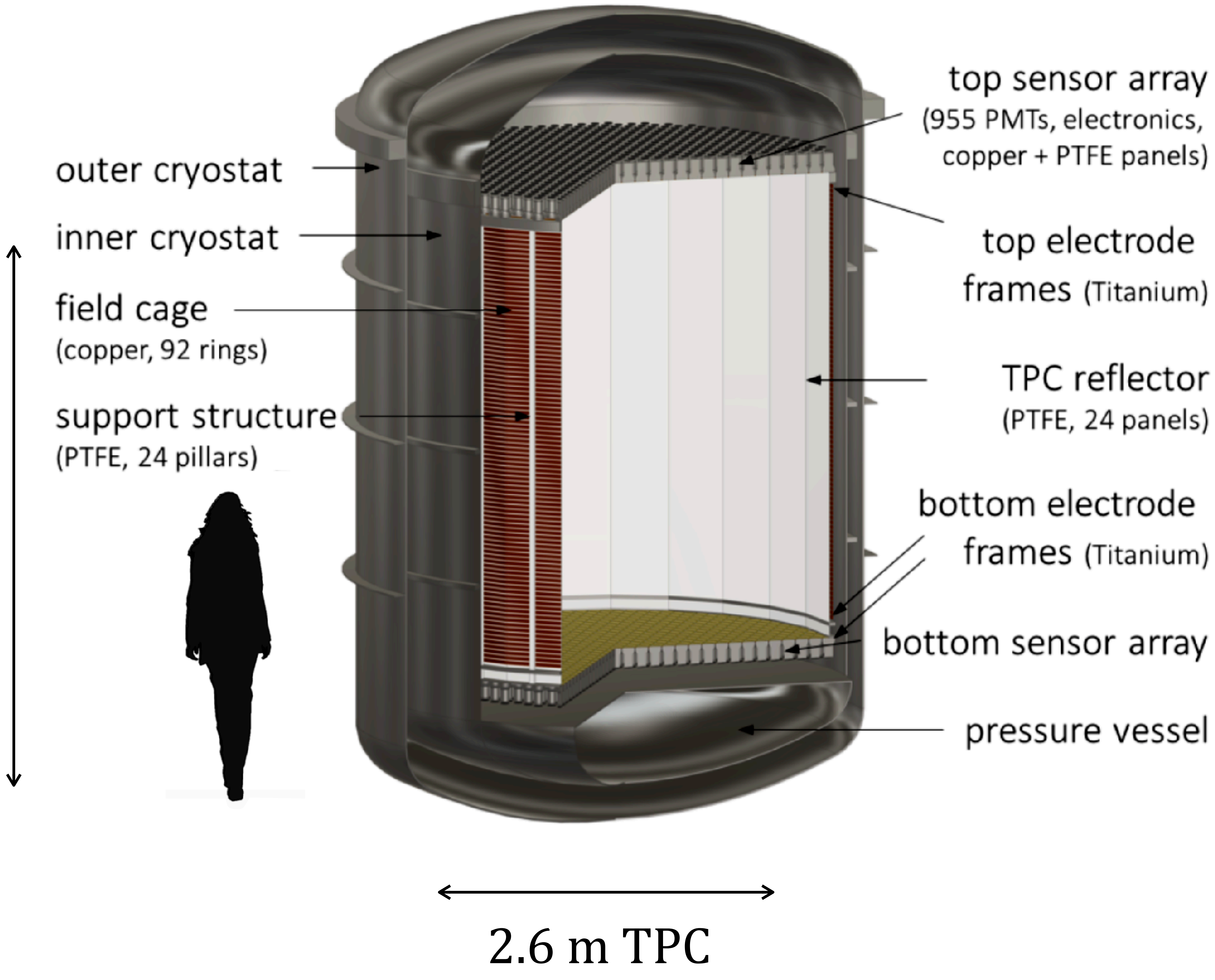
Sun
- pp neutrinos
- Solar metallicity
- ^{7}Be, ^{8}B, hep

Neutrino Nature
- Neutrinoless double beta decay
- Double electron capture
- Magnetic Moment

Supernova
- Early alert
- Supernova neutrinos
- Multi-messenger astrophysics

Cosmic Rays
- Atmospheric neutrinos

The DARWIN Observatory



DARWIN: towards the ultimate dark matter detector

[JCAP 11, 017 (2016)]

Dual-phase Time Projection Chamber (TPC)

50 t total (40 t active) of liquid xenon (LXe)

Drift field 200 V/cm

Drift time = distance/velocity

Drift time ↑ Accidental coincidences ↑

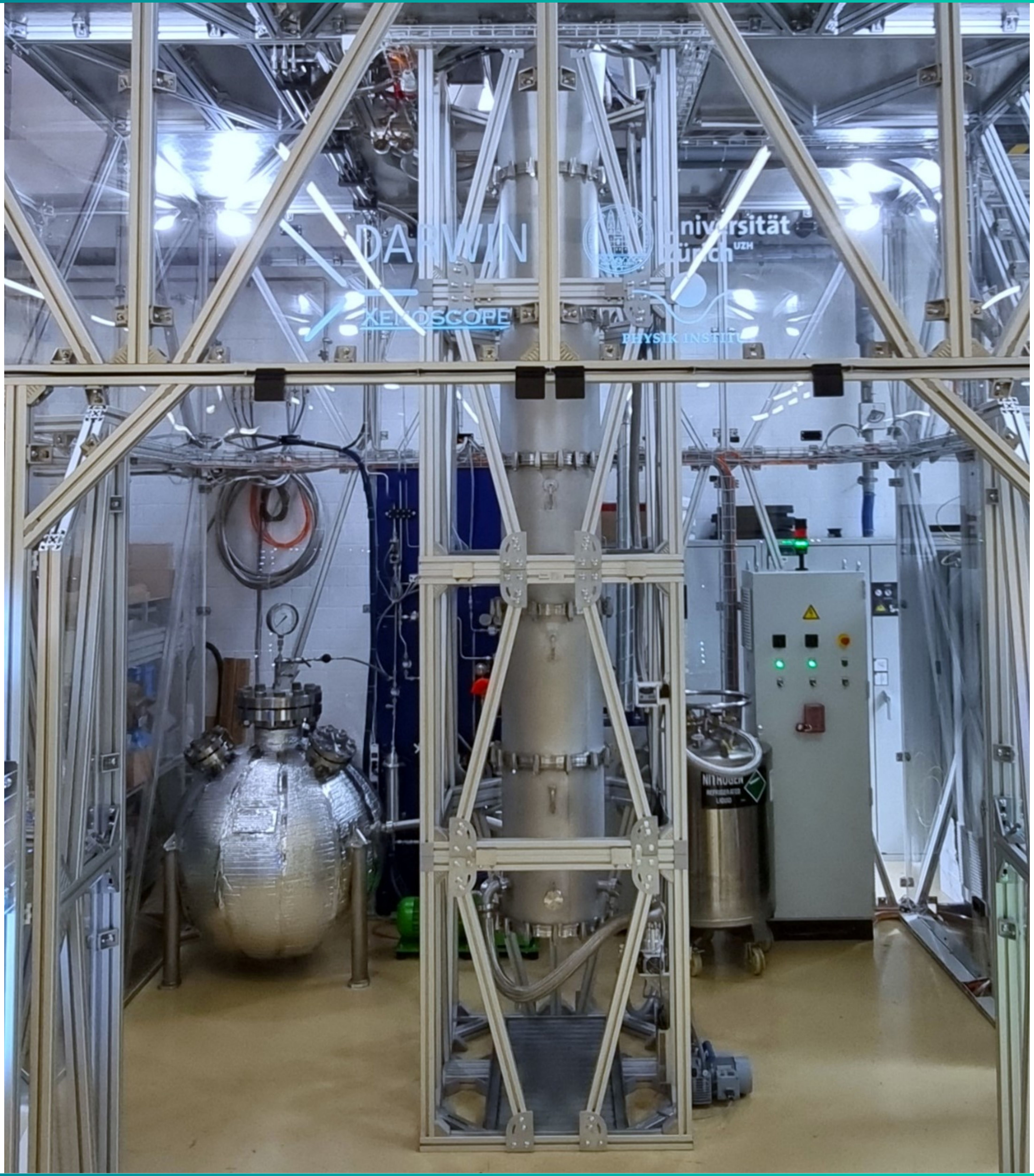
Single vs multi site discrimination

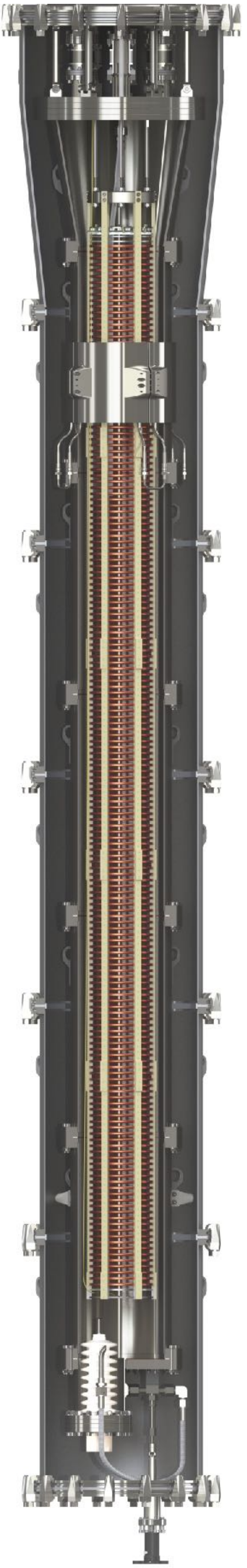
Drift time ↑ Diffusion ↑ Discrimination power of energy depositions ↓

Precise models of electron transport in liquid xenon

Xenoscope, a demonstrator for DARWIN

- Facility located at the University of Zurich
- 400 kg of LXe
- Drift electrons over 2.6 metres
- Study properties such as electron transport and light attenuation in LXe
- Test different photosensor technologies

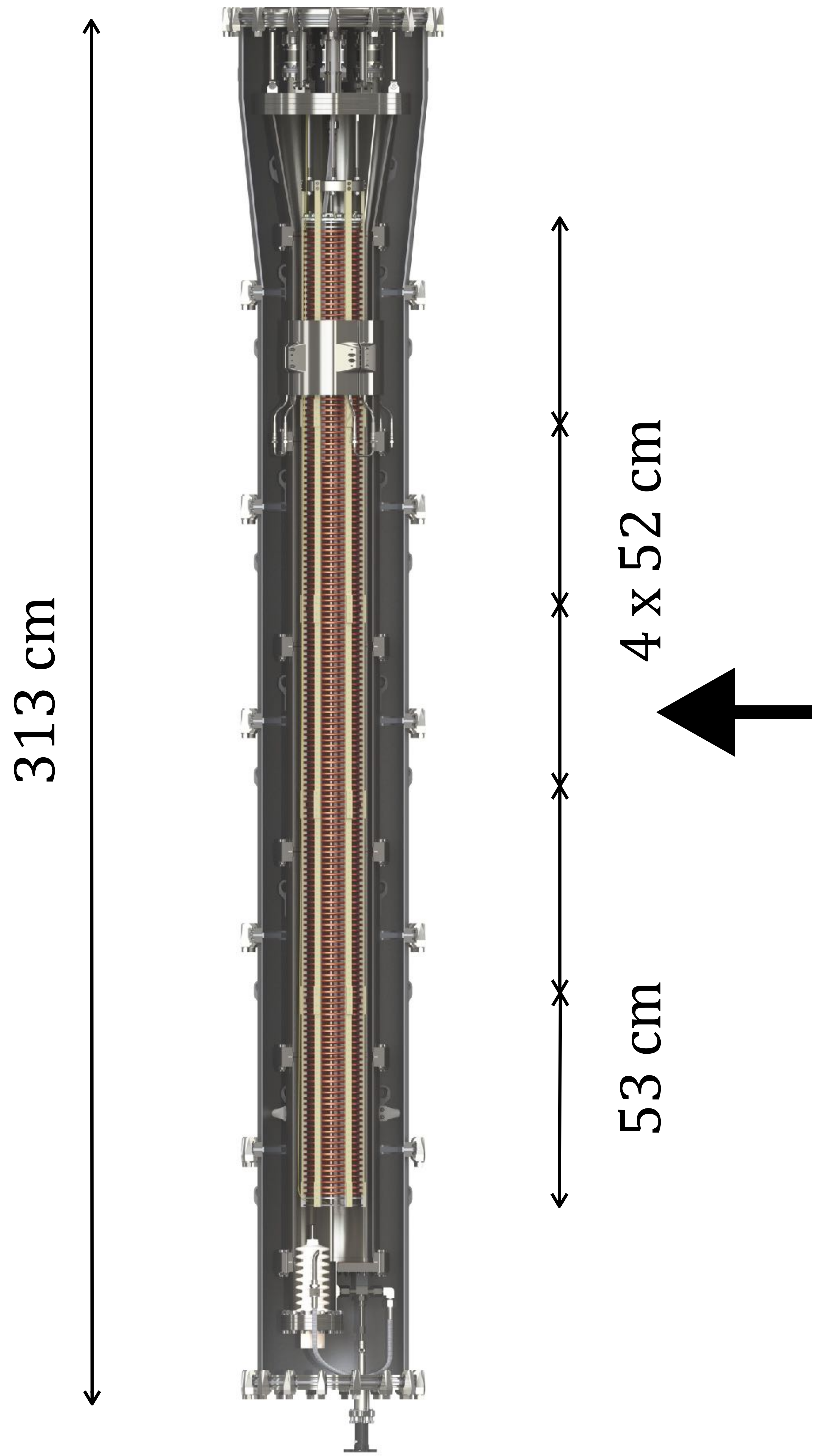




First phase: operation of a 53 cm Purity Monitor

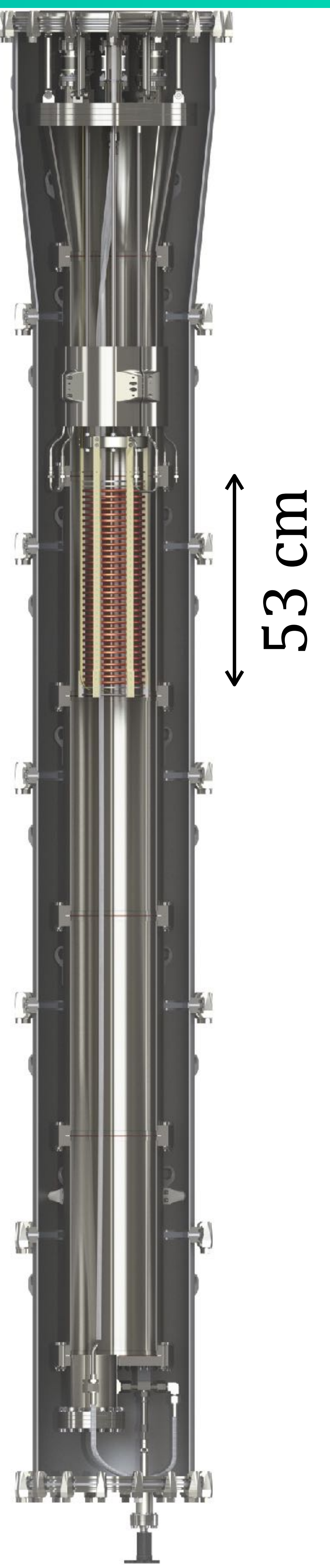
TPC phase

- Field cage of five modules
- Stainless steel ring supports six PAI pillars that hold the field-shaping rings in place
- 173 oxygen-free copper rings
- Photosensor array



Purity monitor phase

- Measures the concentration of electronegative impurities diffused in the LXe
- No photosensor instrumentation
- Troubleshooting the purification system
- Benchmark the facility sub-systems

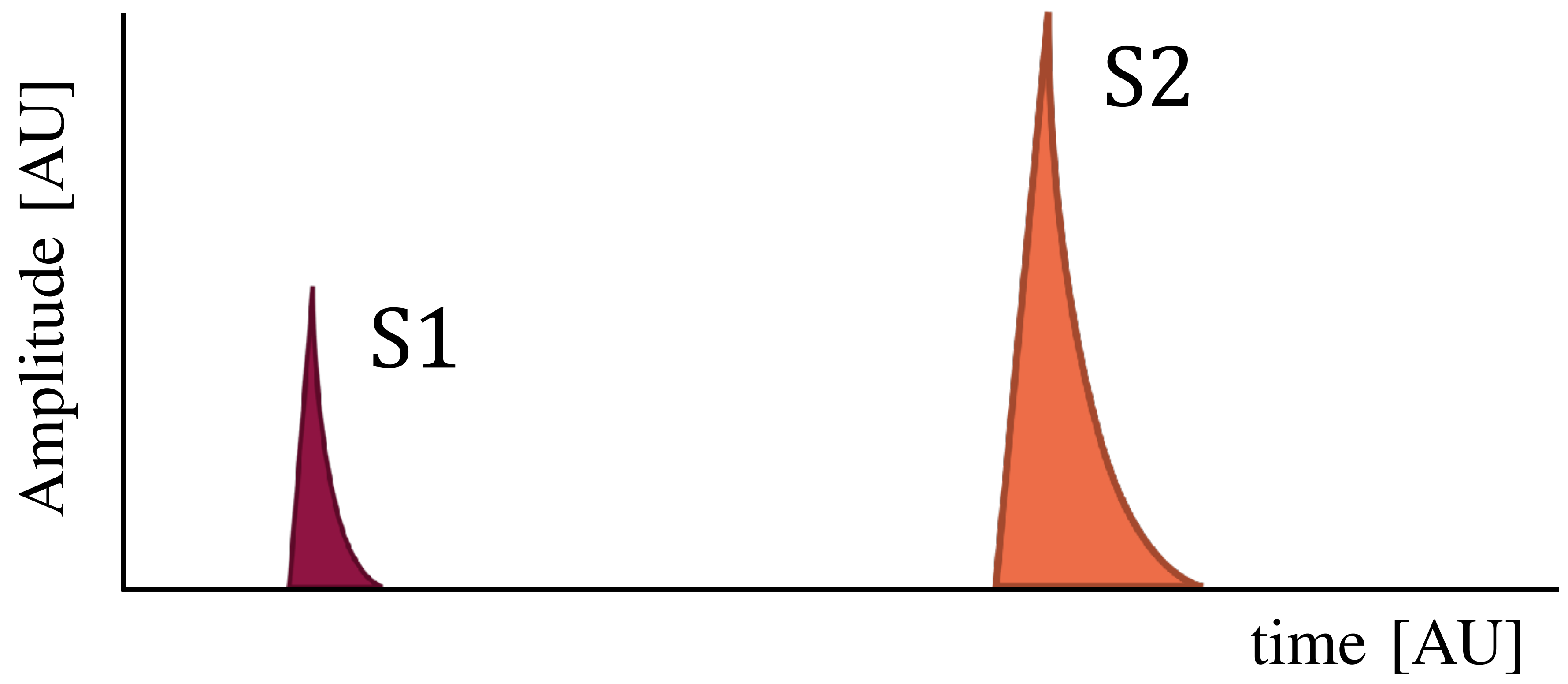


Electron lifetime in LXe TPCs

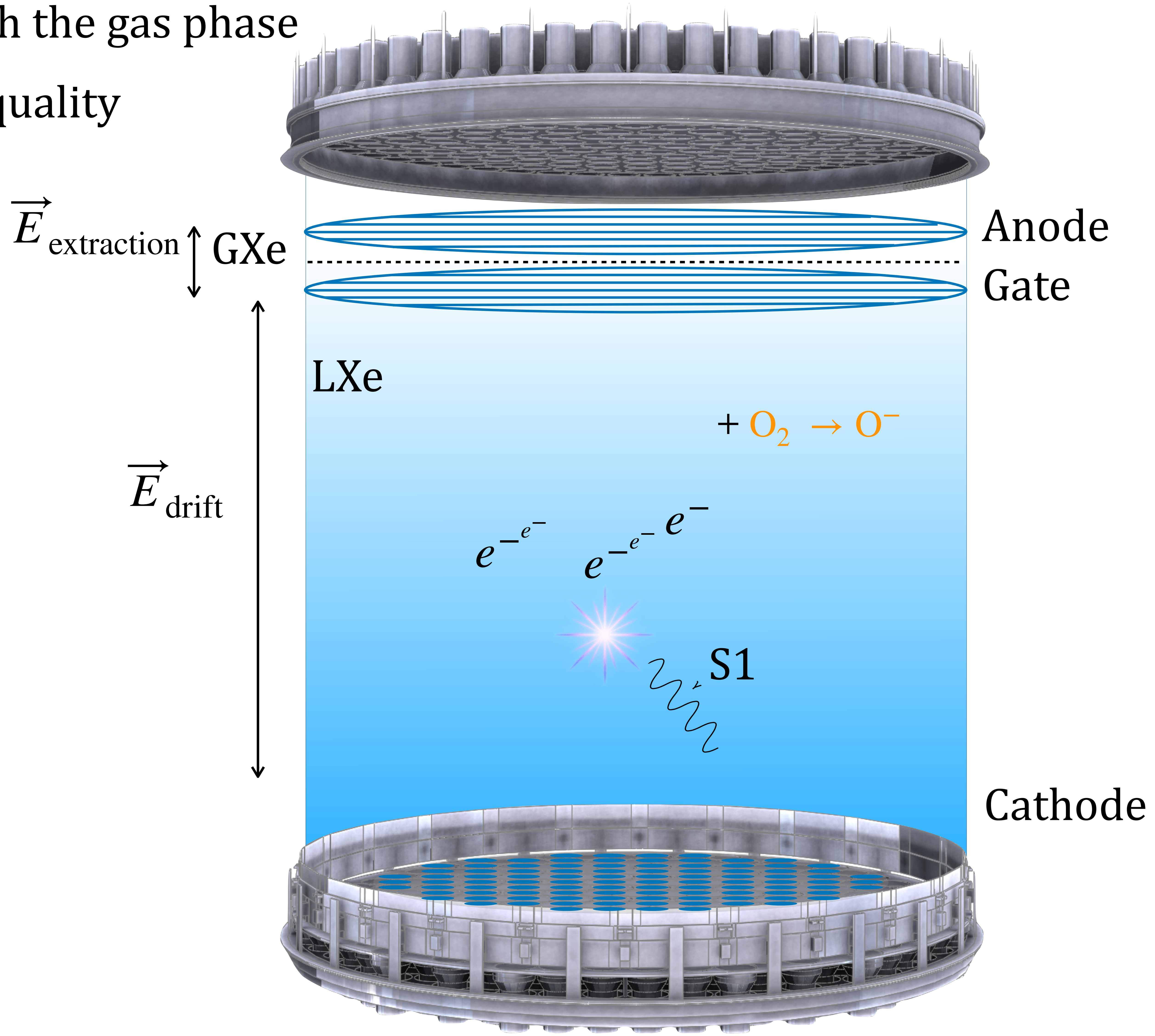
- The electrons produced in the interaction might not reach the gas phase
- Impurities diffused in the xenon compromise the signal quality

$$N(t) = N_0\ e^{-t/\tau}$$

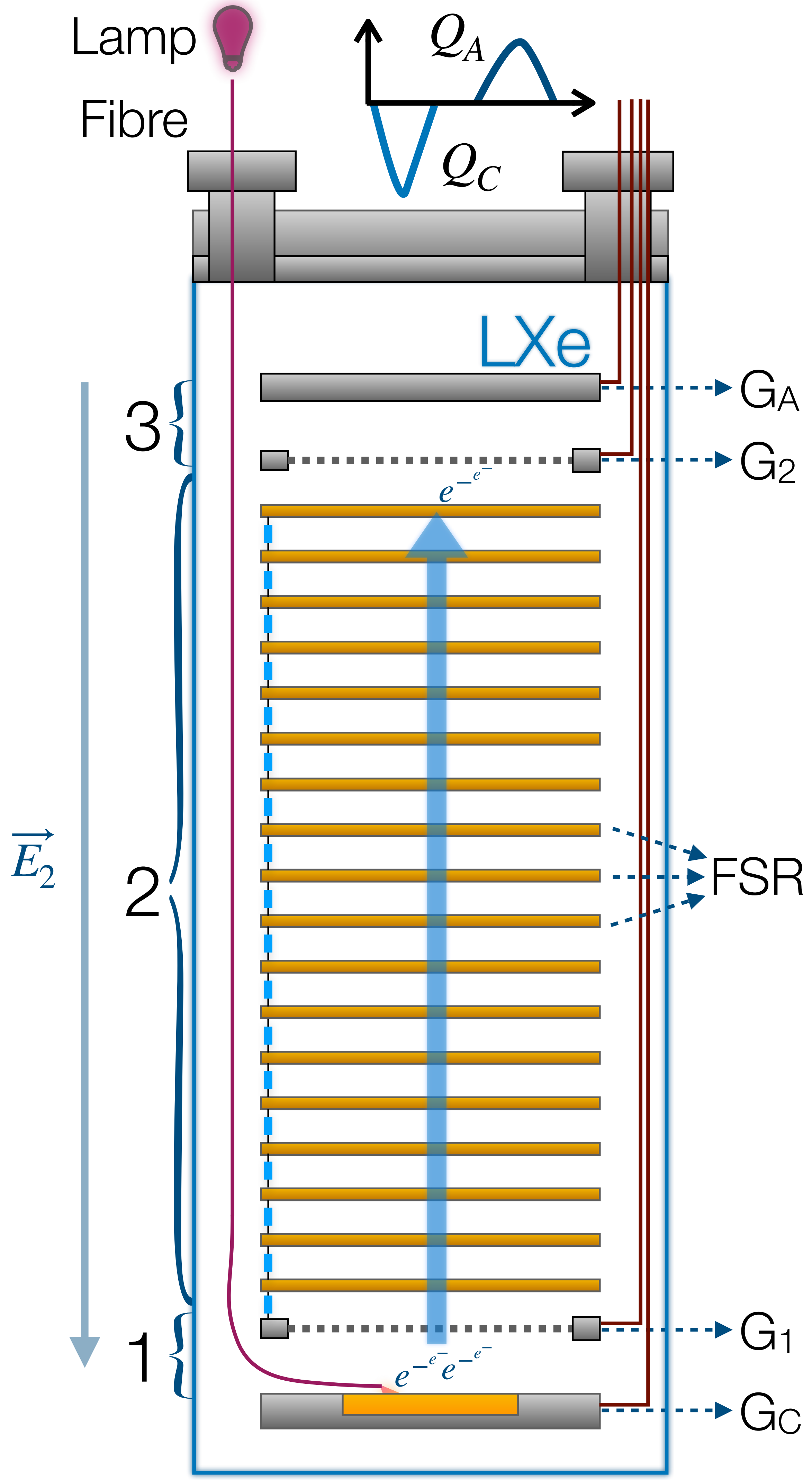
τ : electron lifetime



LXe needs to be continuously purified

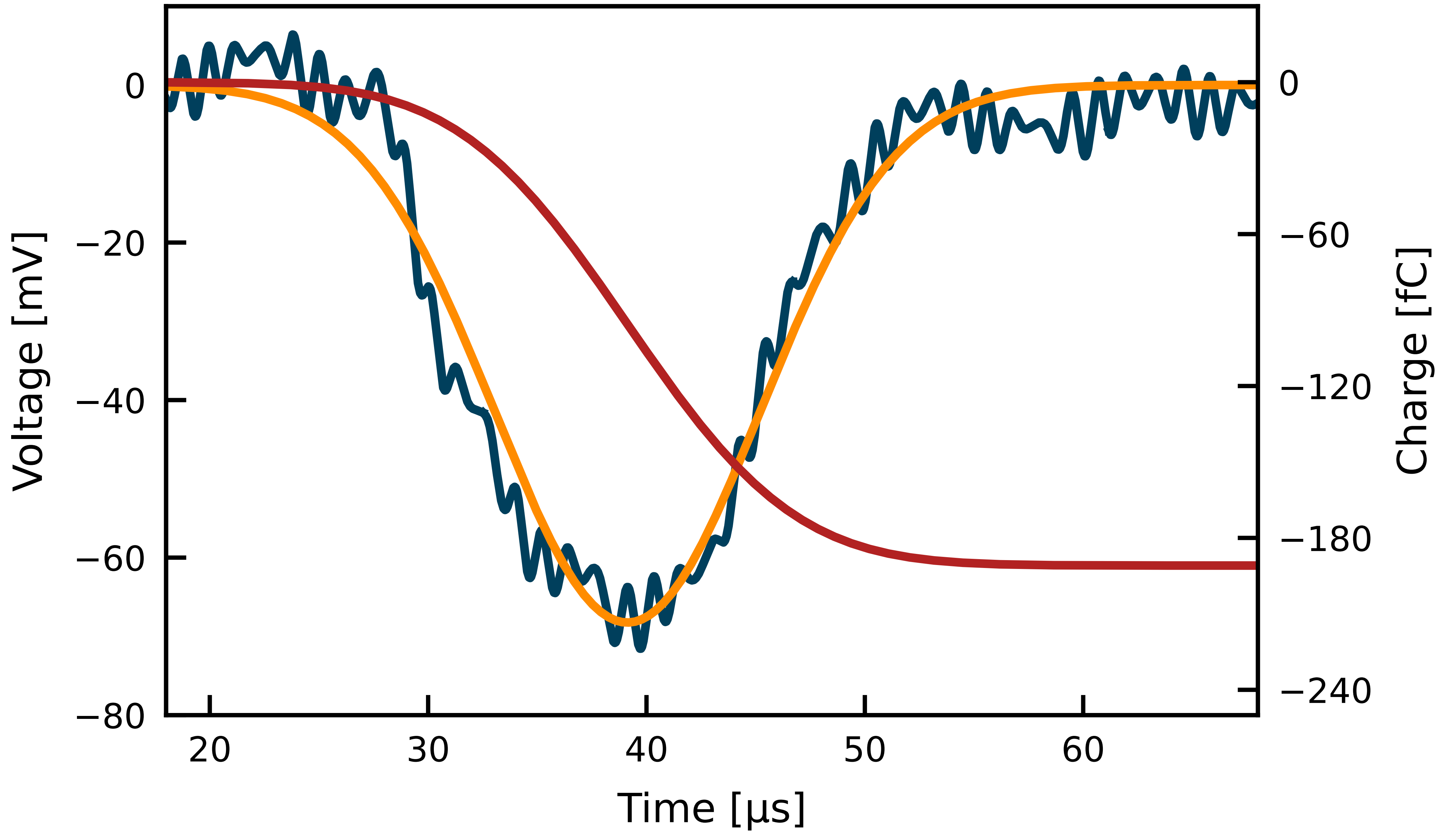


Purity monitor concept

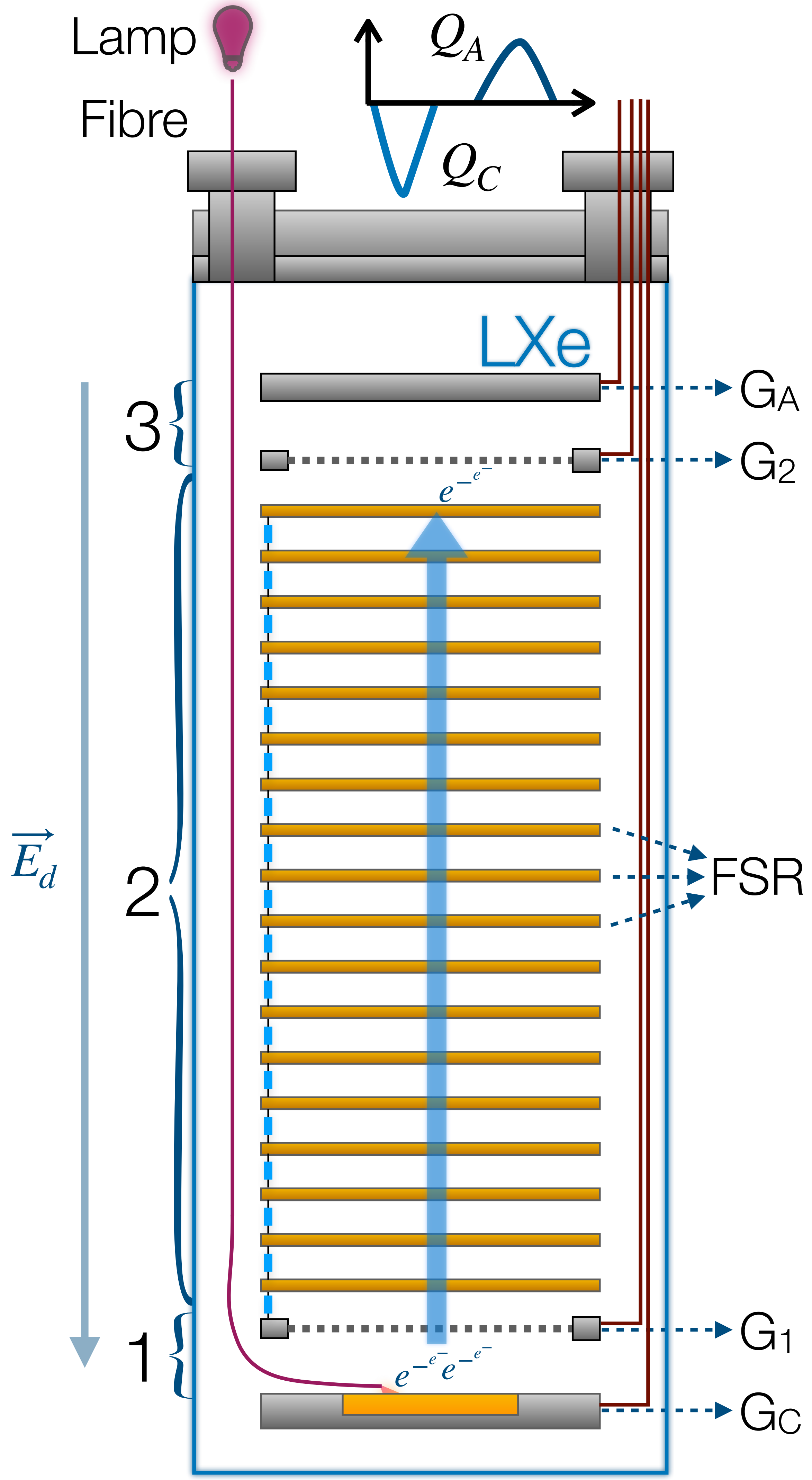


The path of electrons in a purity monitor:

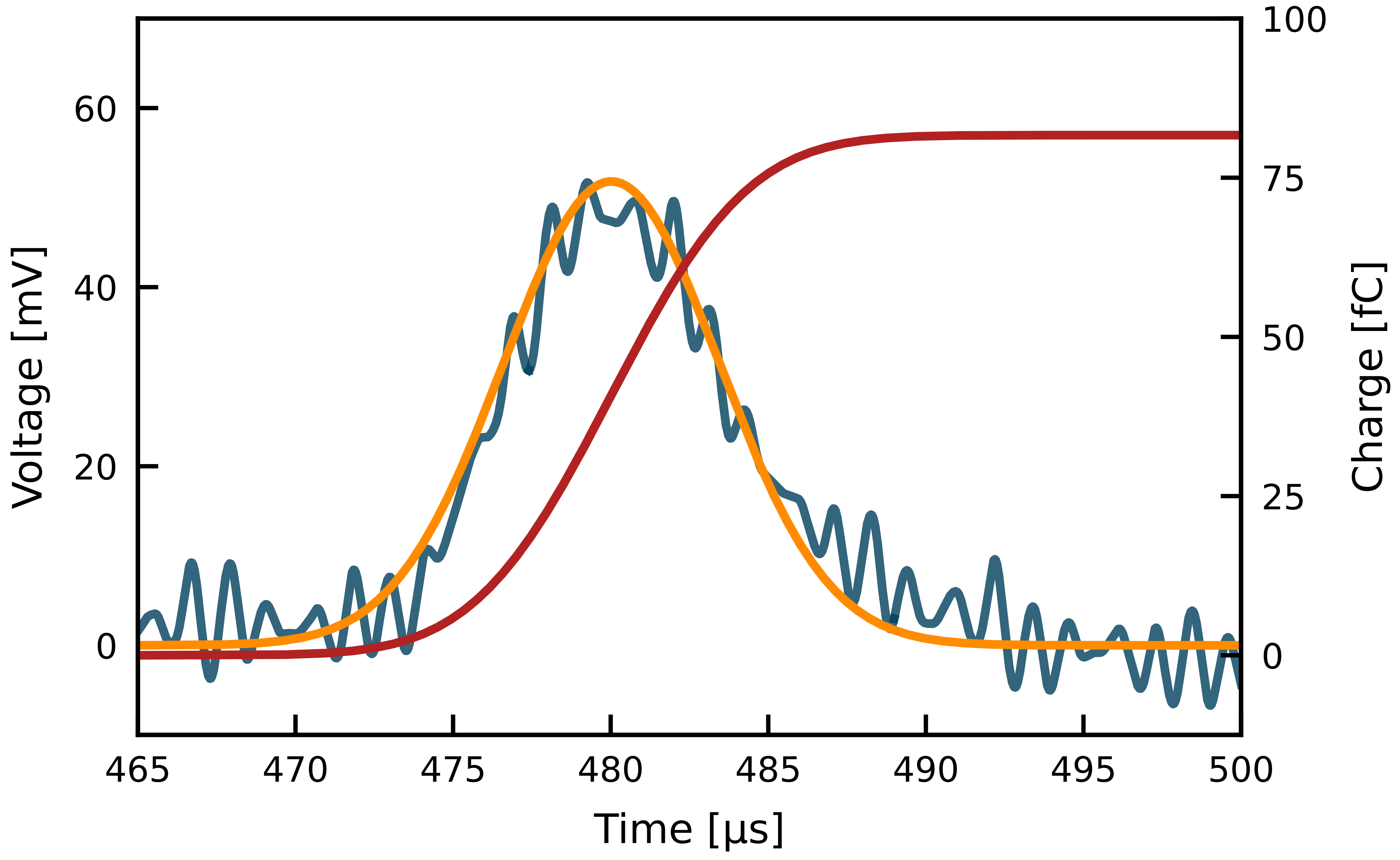
- Photons are generated via the photoelectric effect with a width proportional to the lamp's pulse
- The electrons drift from G_C to G_1 by an extraction field, $\vec{E}_1$
- Their drift induces a current in G_C



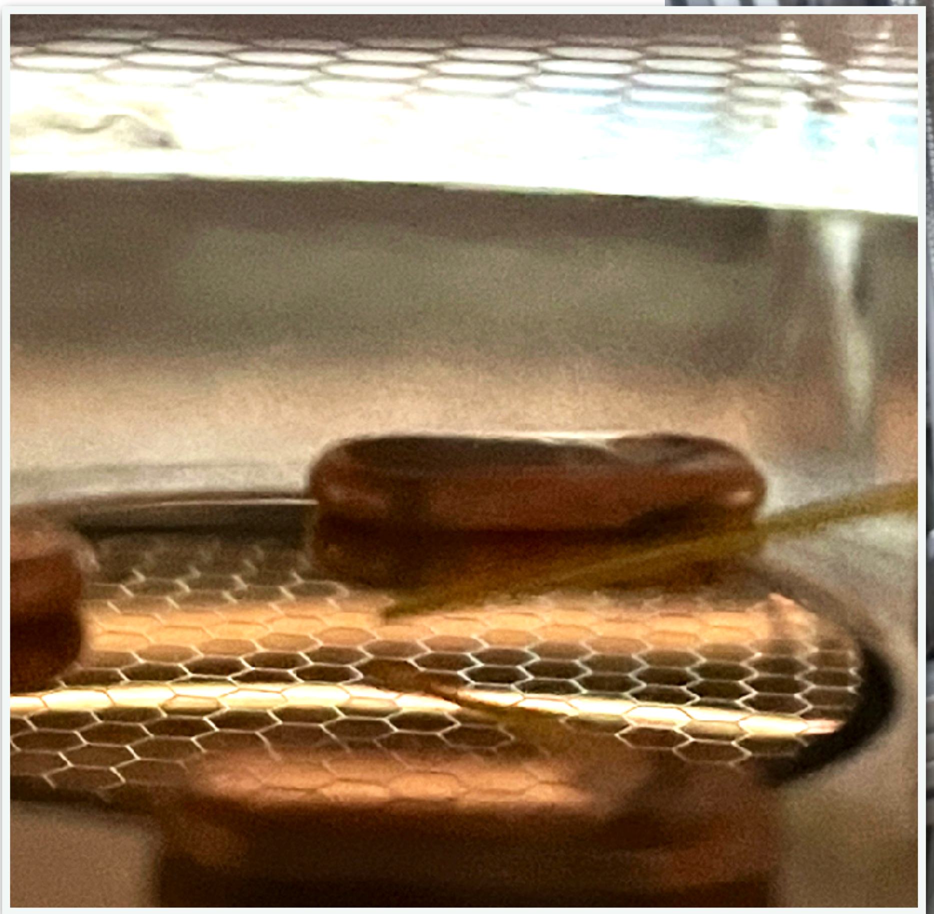
Purity monitor concept

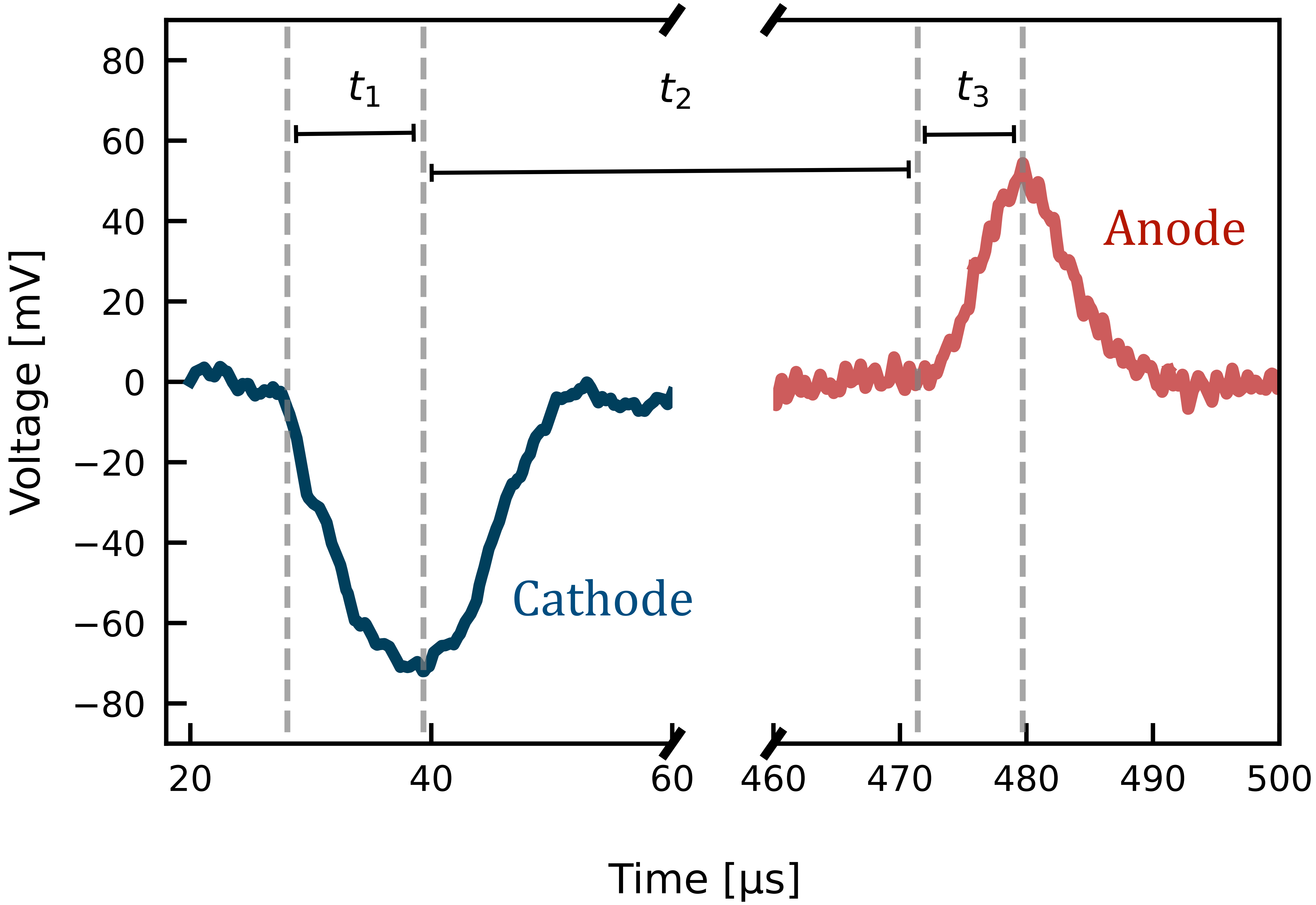


- They traverse the screening grid G_1 and stop inducing a current on G_C
- Drifted towards G_2 with the drift field, $\vec{E}_2$
- Some electrons are captured by electronegative impurities
- Electrons traverse the screening grid G_2 and are accelerated towards G_A with the collection field $\vec{E}_3$



Purity monitor in Xenoscope

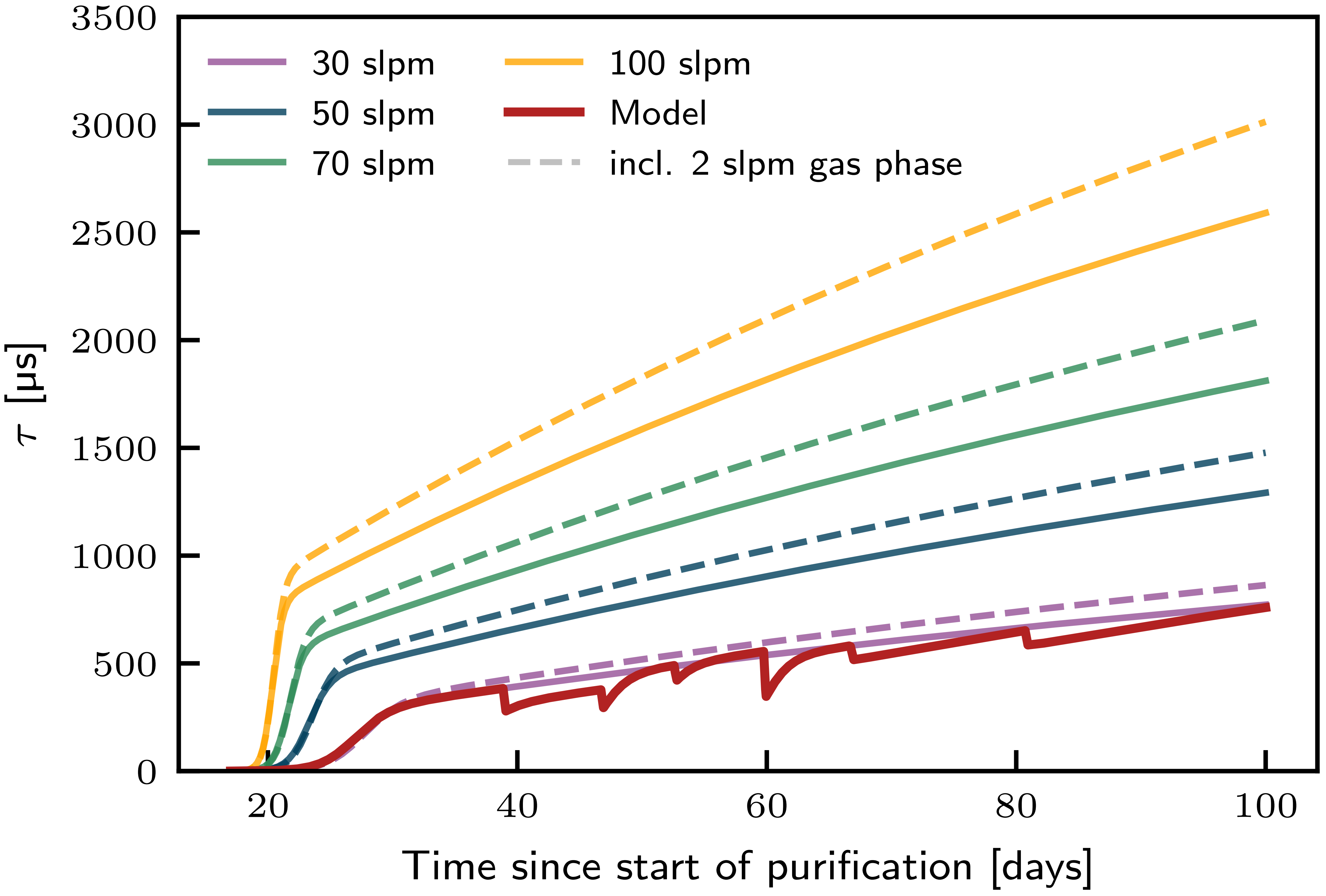


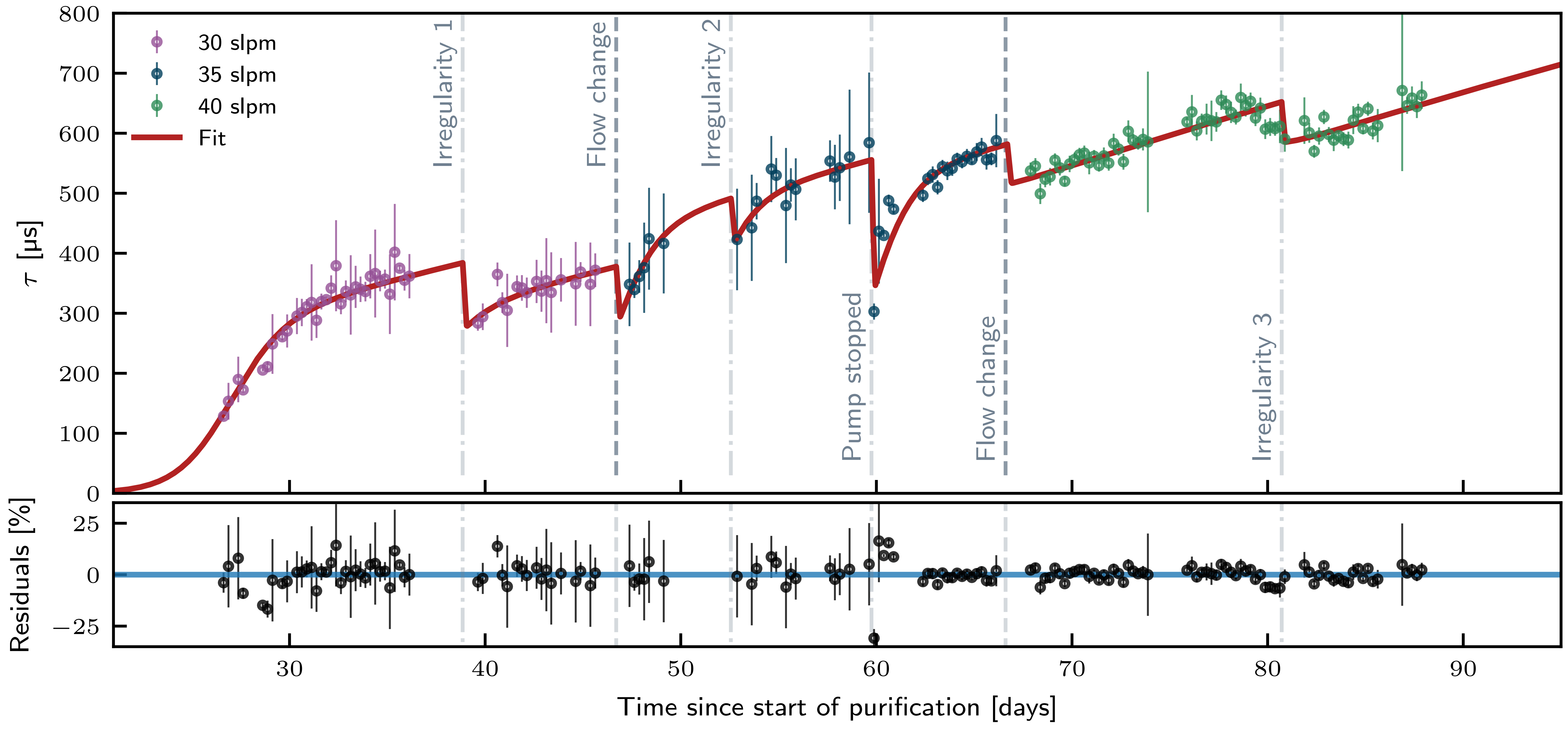


Electron lifetime results

Data acquired at 177 K with three gas speeds in the recirculation loop: 30, 35 and 40 slpm for 343 kg of xenon over 88 days

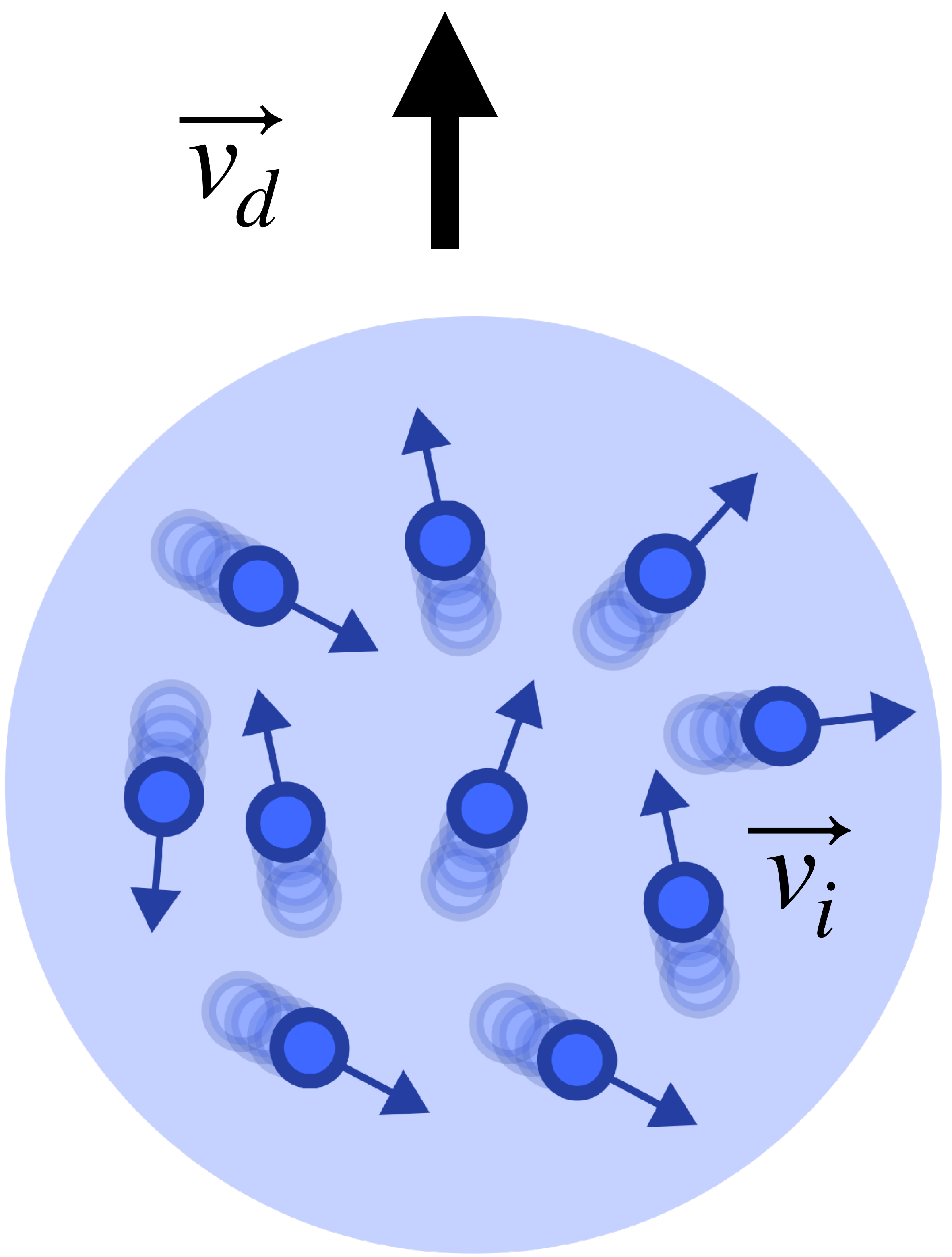
Model of the impurity concentration in the gas and liquid phase adapted [1,2]





Prediction with higher recirculation speeds and purification of the gas phase

Electron transport: Drift velocity



From our experimental data we can obtain the drift velocity, as

$$v_\mathrm{d} = d_2/t_2$$

And the dependence on the electric field is usually included in the electron mobility term μ

$$v_\mathrm{d} = \mu E_\mathrm{d}$$

But what behaviour should we expect? Can we learn something about systematics and dependences from transport models?

Results on drift velocity

Two different regimes:

mean free path

$$\mu_{\text{cold}} = \frac{2}{3}\left(\frac{2}{\pi\, m_e\, k_B\, T}\right)^{\frac{1}{2}} e\,\frac{\lambda}{v}$$

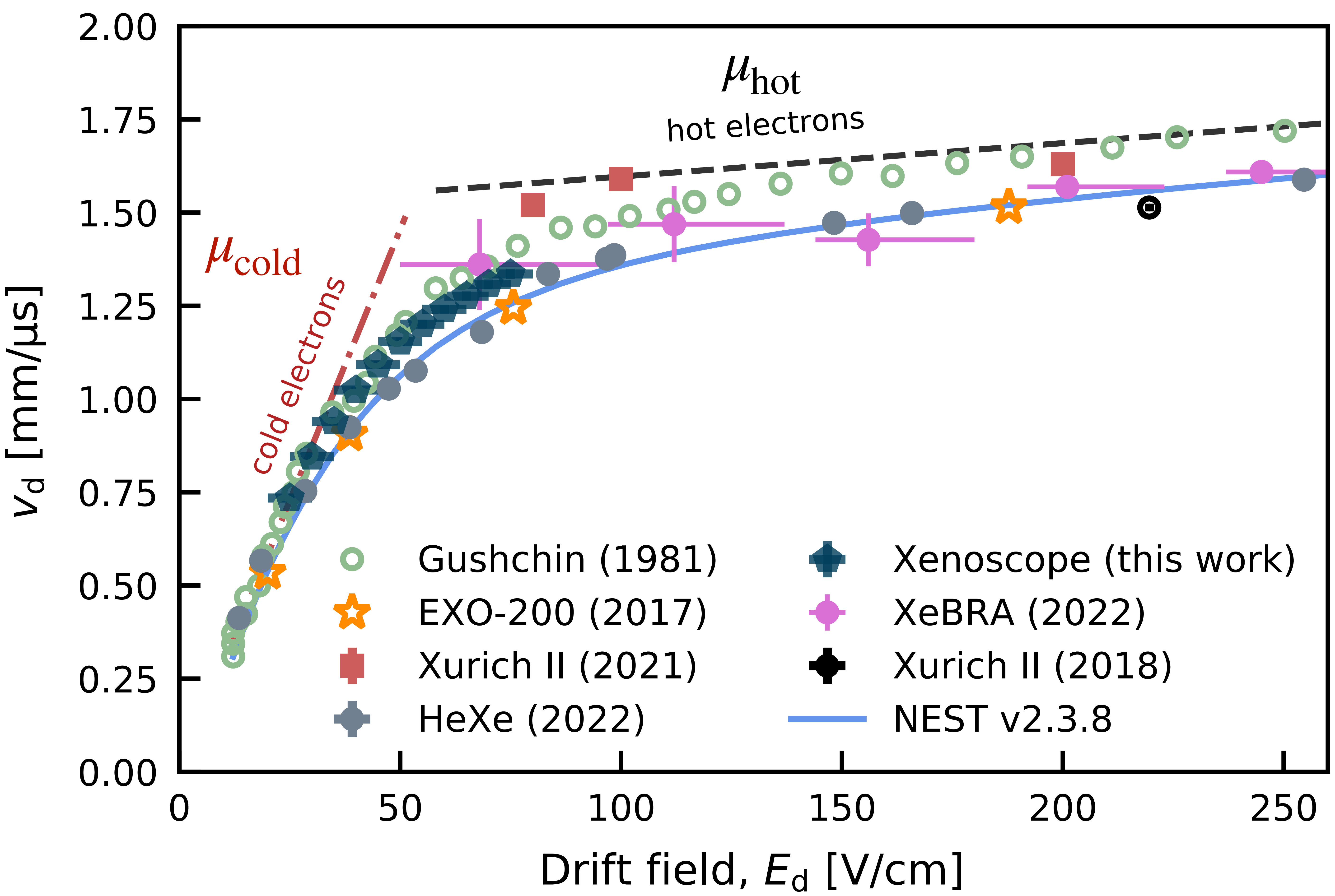
$$\mu_{hot} = \frac{4\,e\,\lambda}{3v\pi^{1/2} m_e^*}$$

electron effective mass in the liquid

$$\lambda = \frac{1}{\sum_i \sigma_i(\epsilon)\frac{n_i}{N}}$$

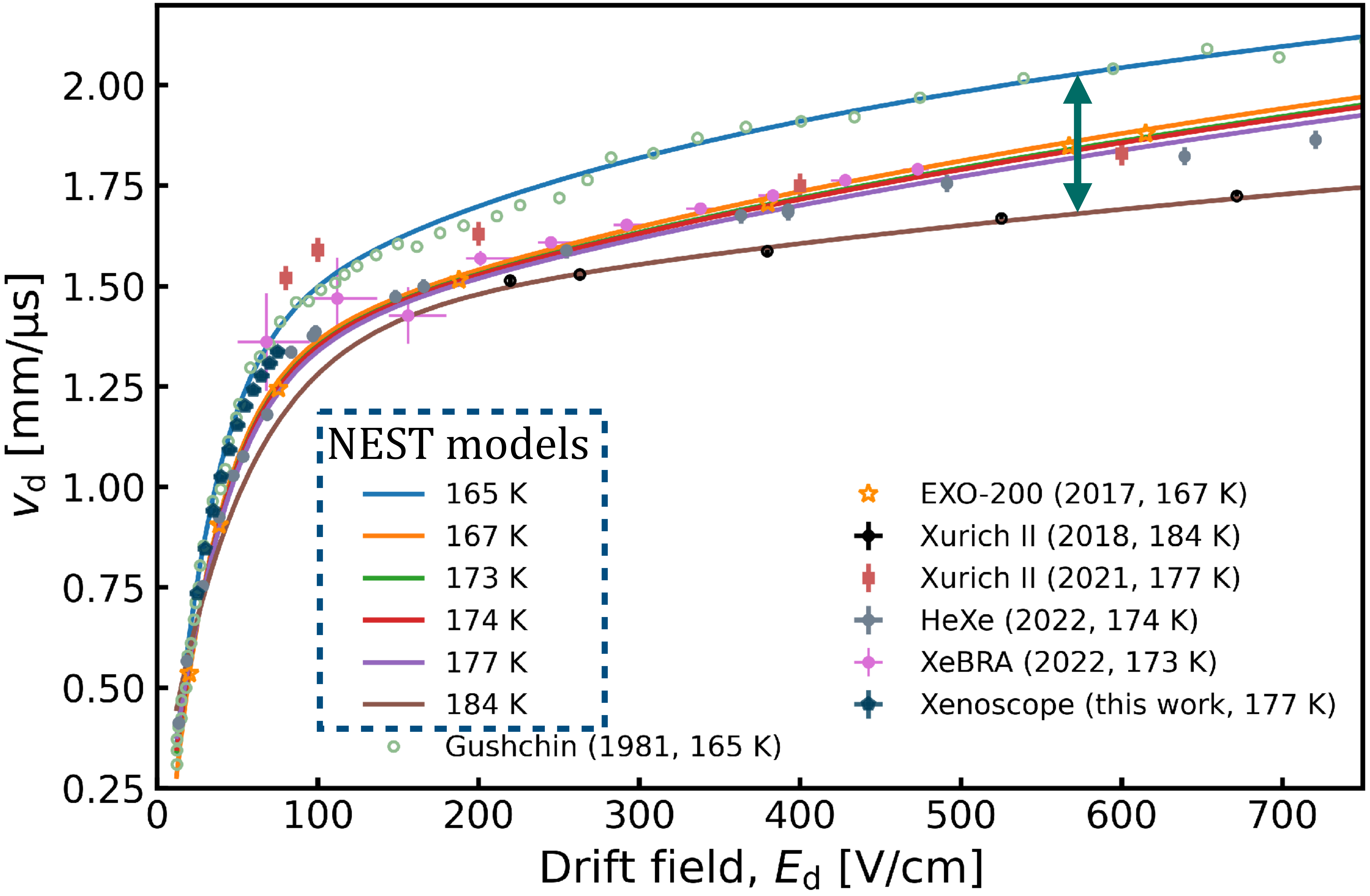
cross section with particles in the liquid

$$v_\text{d} = \mu E_\text{d}$$



Interpretation of drift velocity values

No clear trend on the dependence with temperature, only parametrising previous measurements



- Molecular solutes introduce scattering centres
- Electrons can lose energy by inelastic collisions more efficiently than with xenon atoms

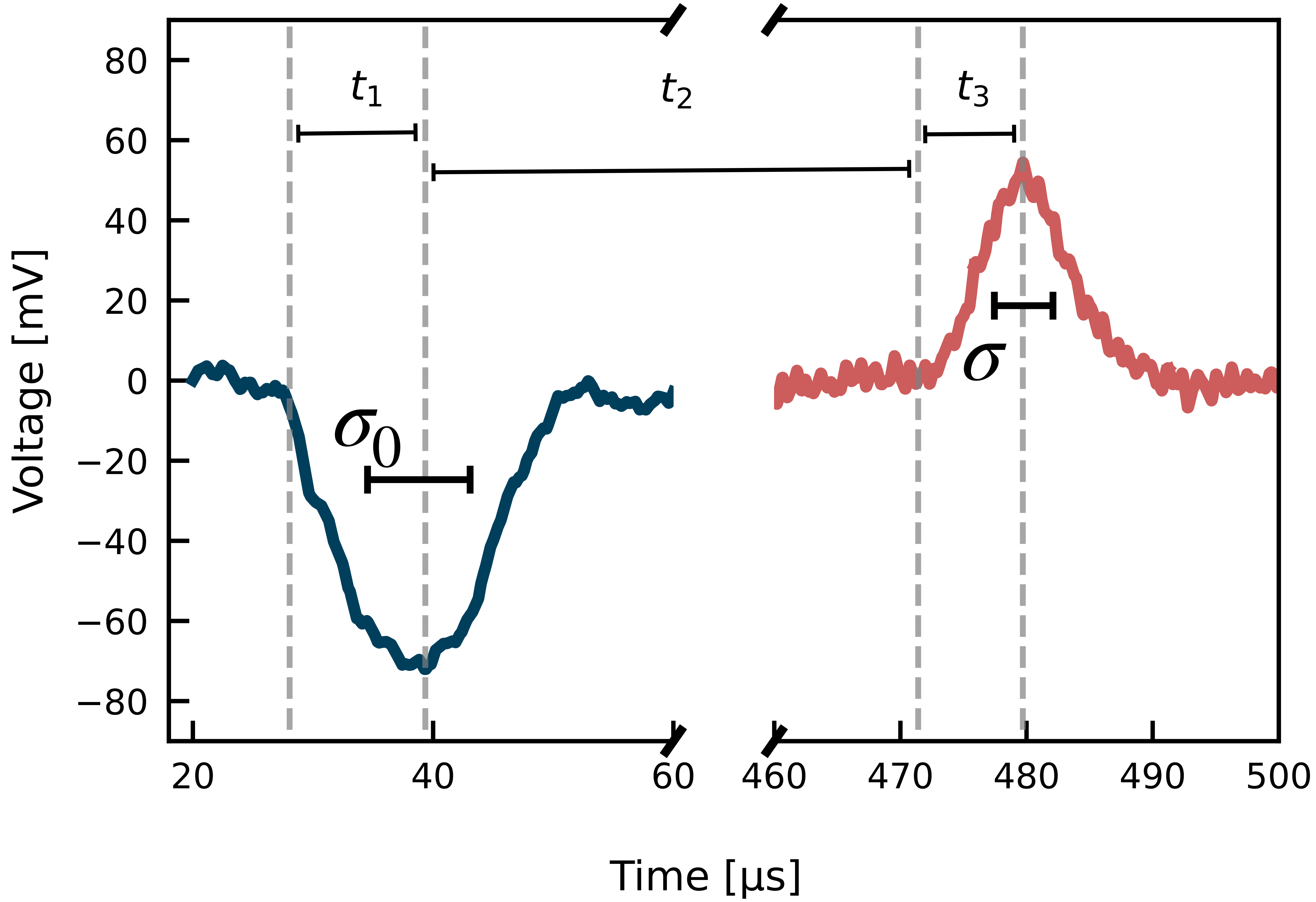
Momentum transfer

$$v = \sqrt{\frac{2eEv_d}{m_e v \boxed{\sum_i n_i \sigma_i(\epsilon)\Lambda_i(\epsilon)}} + \frac{3kT}{m_e}}$$

$$v_d = \frac{eE}{mv}\frac{1}{\sum n_i \sigma(\epsilon)_i}$$

Results on longitudinal diffusion

Fast response of the trans-impedance preamplifiers allow us to measure precisely the spread in time of the signals



t_1: extraction region

t_2: drift region

t_3: collection region

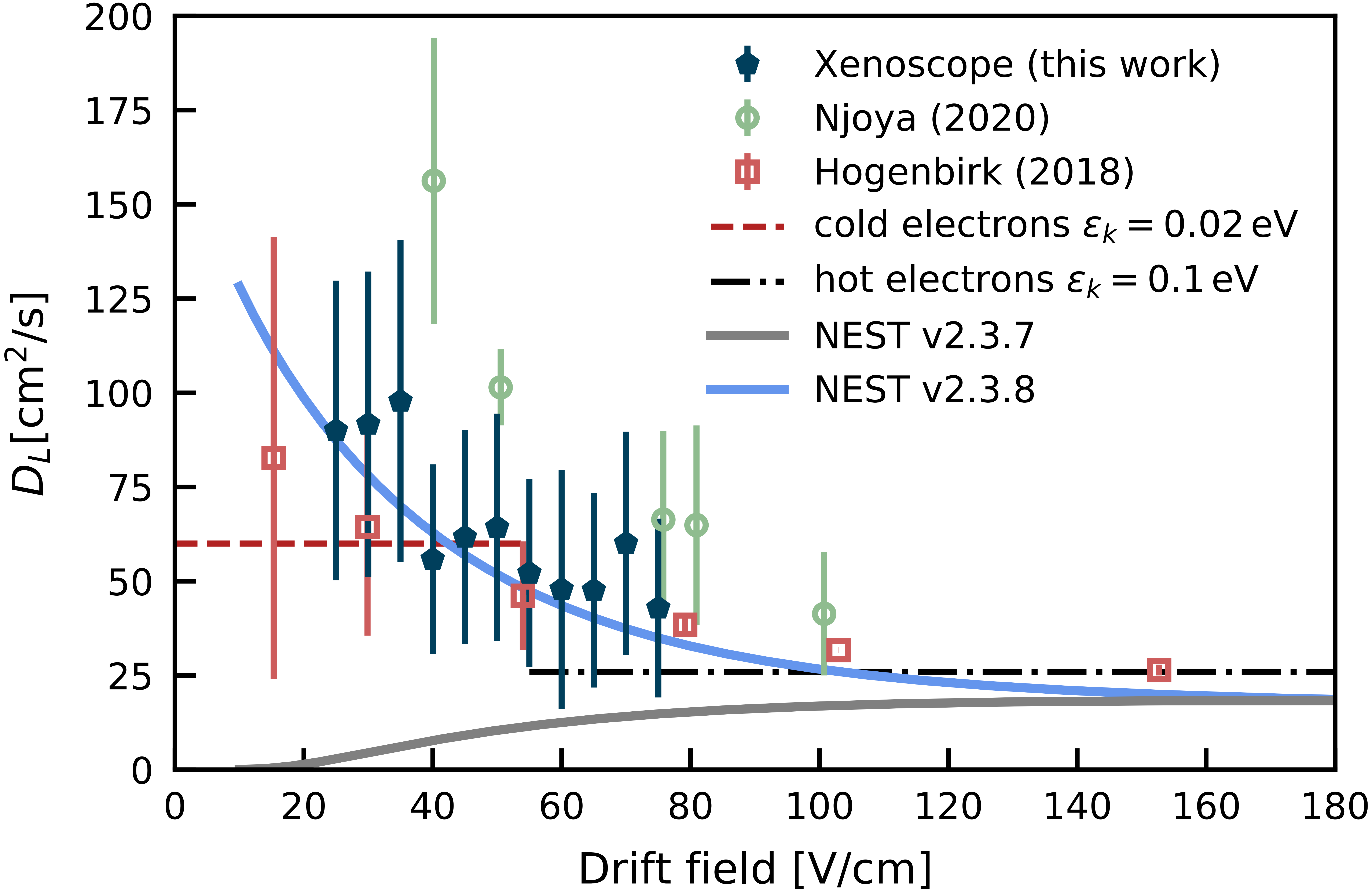
From here we can extract:

$$\sigma_L^2 = \sigma^2 - \sigma_0^2$$

$$D_L = \frac{d^2 \sigma_L^2}{2t^3}$$

Longitudinal diffusion

Results on longitudinal diffusion



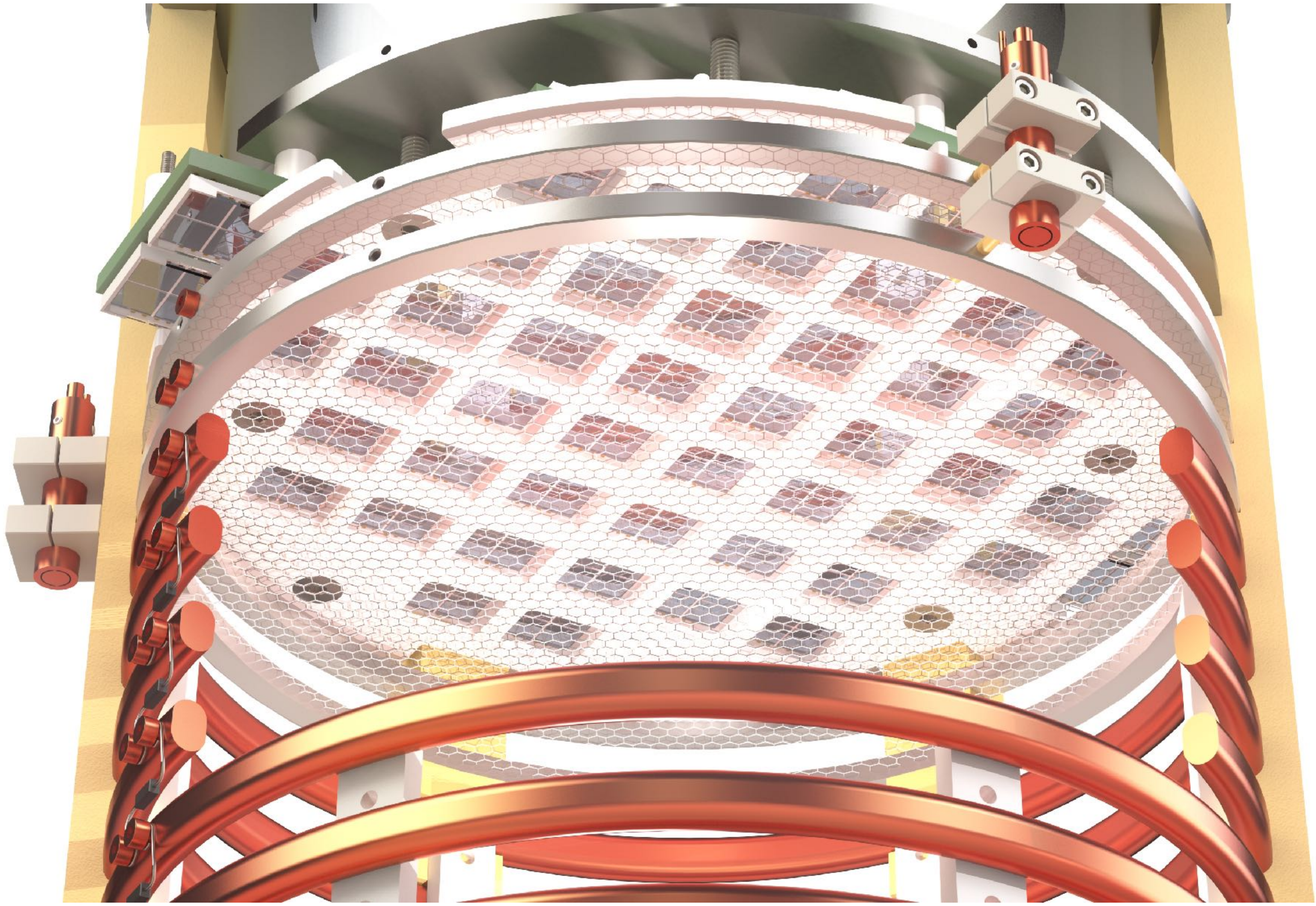
Thermal

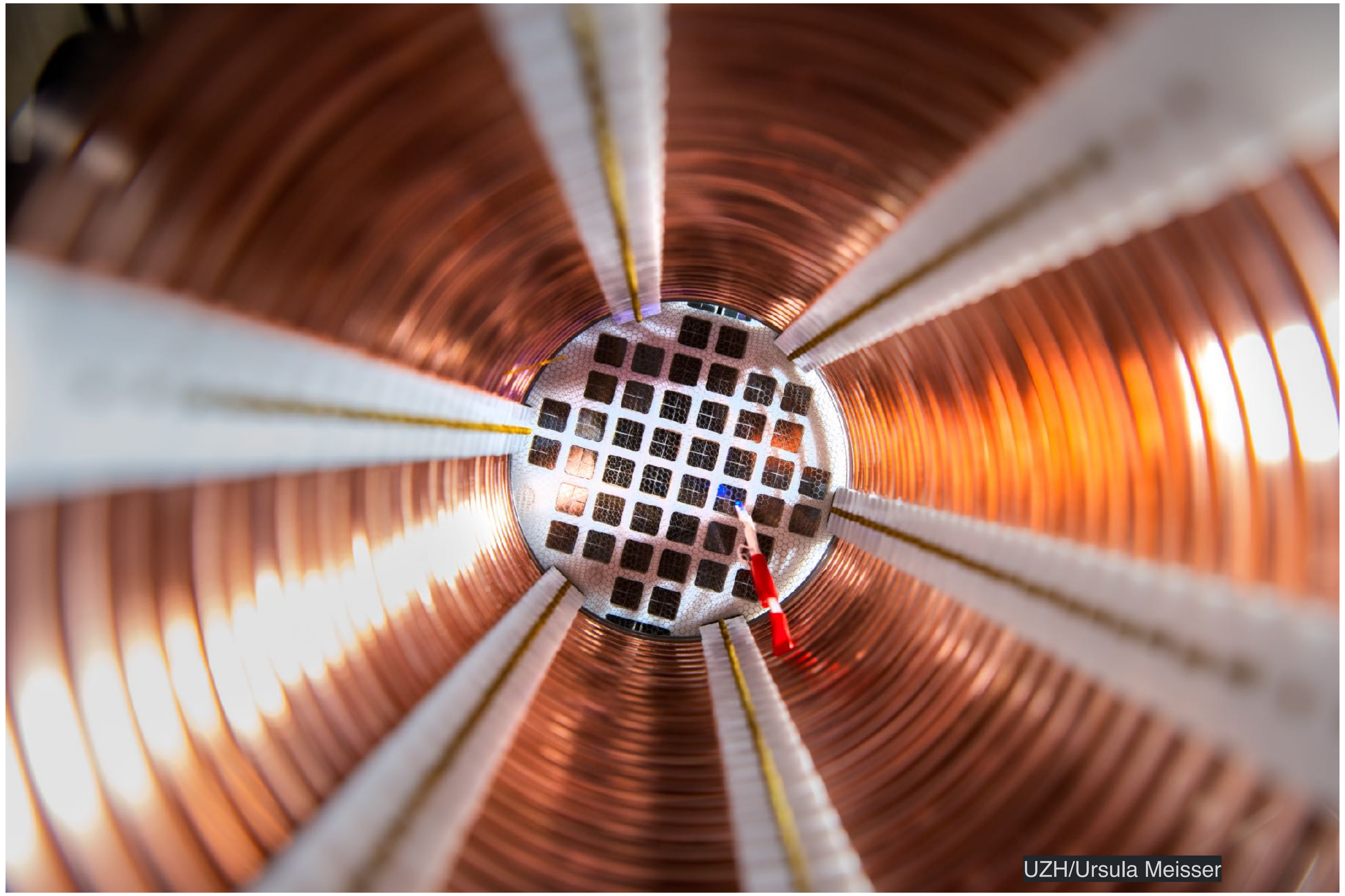
$$D_L = \frac{kT}{e}\left(\mu + E\frac{\partial \mu}{\partial E}\right)$$

Field dependent

$$\frac{D_L}{D_T} = 1 + \frac{E}{\mu}\frac{\partial \mu}{\partial E}$$

Upgrade and future plans





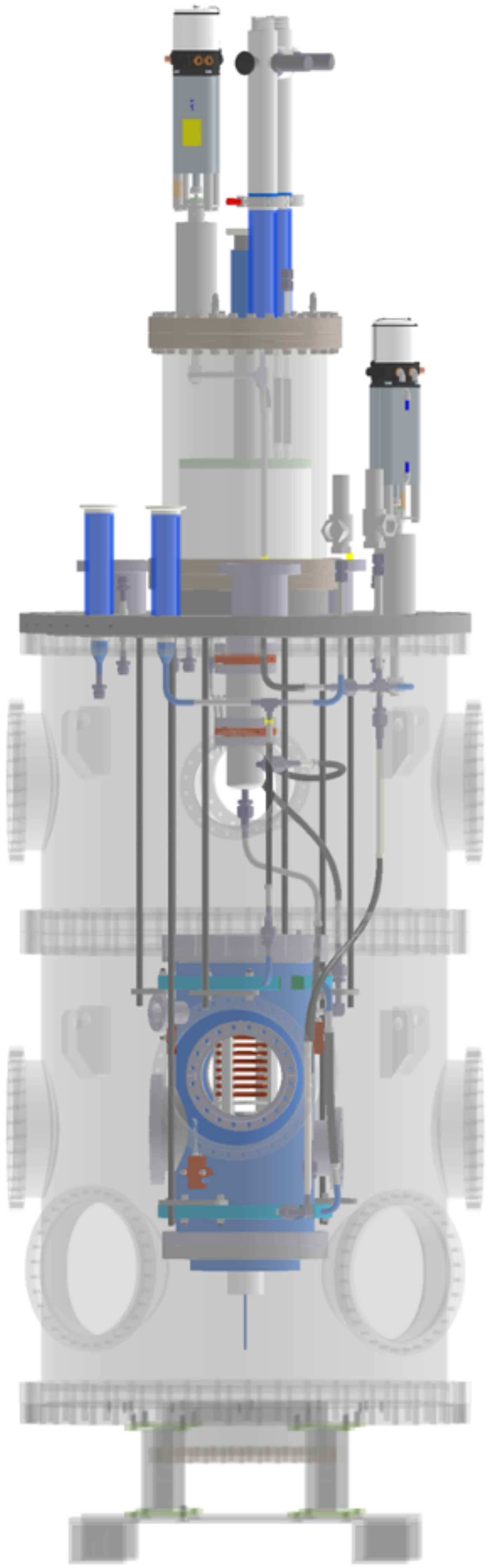
Extension to a 2.6 m TPC, Light readout with a top array comprised of tiles of SiPM,

Transversal diffusion measurements, where literature is scarce

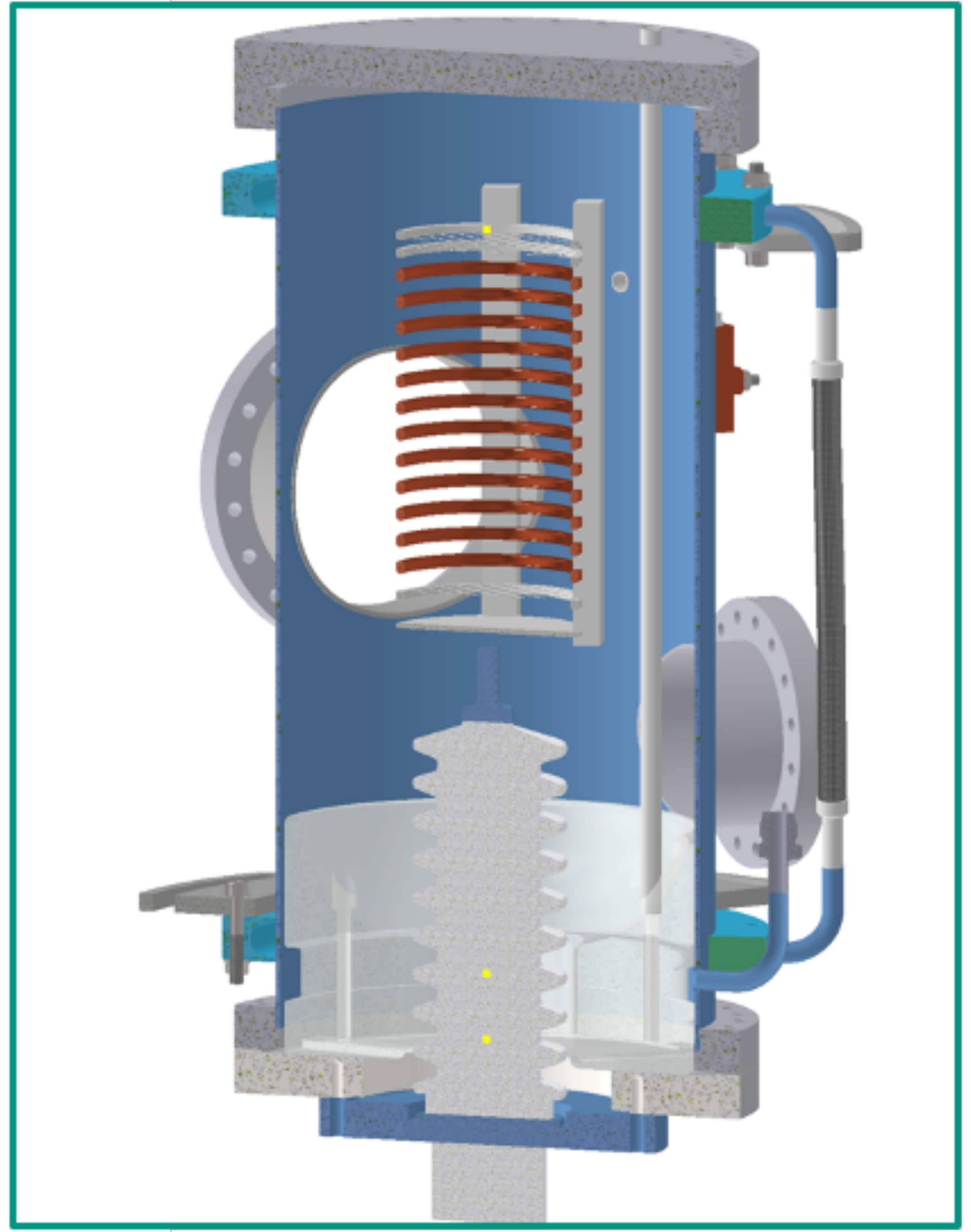
SiPM array of Xenoscope, a full-scale DARWIN vertical demonstrator,
R. Peres on behalf of Xenoscope team

Upgrade and future plans

- TPC for studies of liquid xenon properties and high voltage delivery in liquid xenon
- Study of type of discharge: bubble streamers, cosmic rays
- Continue studies on liquid xenon properties and their relation with thermodynamical parameters and purity composition
- Synergies with different institutes inside KIT and universities (University of Zürich, University of Freiburg)



Karlsruhe Institute of Technology



XLZD Consortium

101 PIs from XENON + LZ + DARWIN signed MoU, July 2021

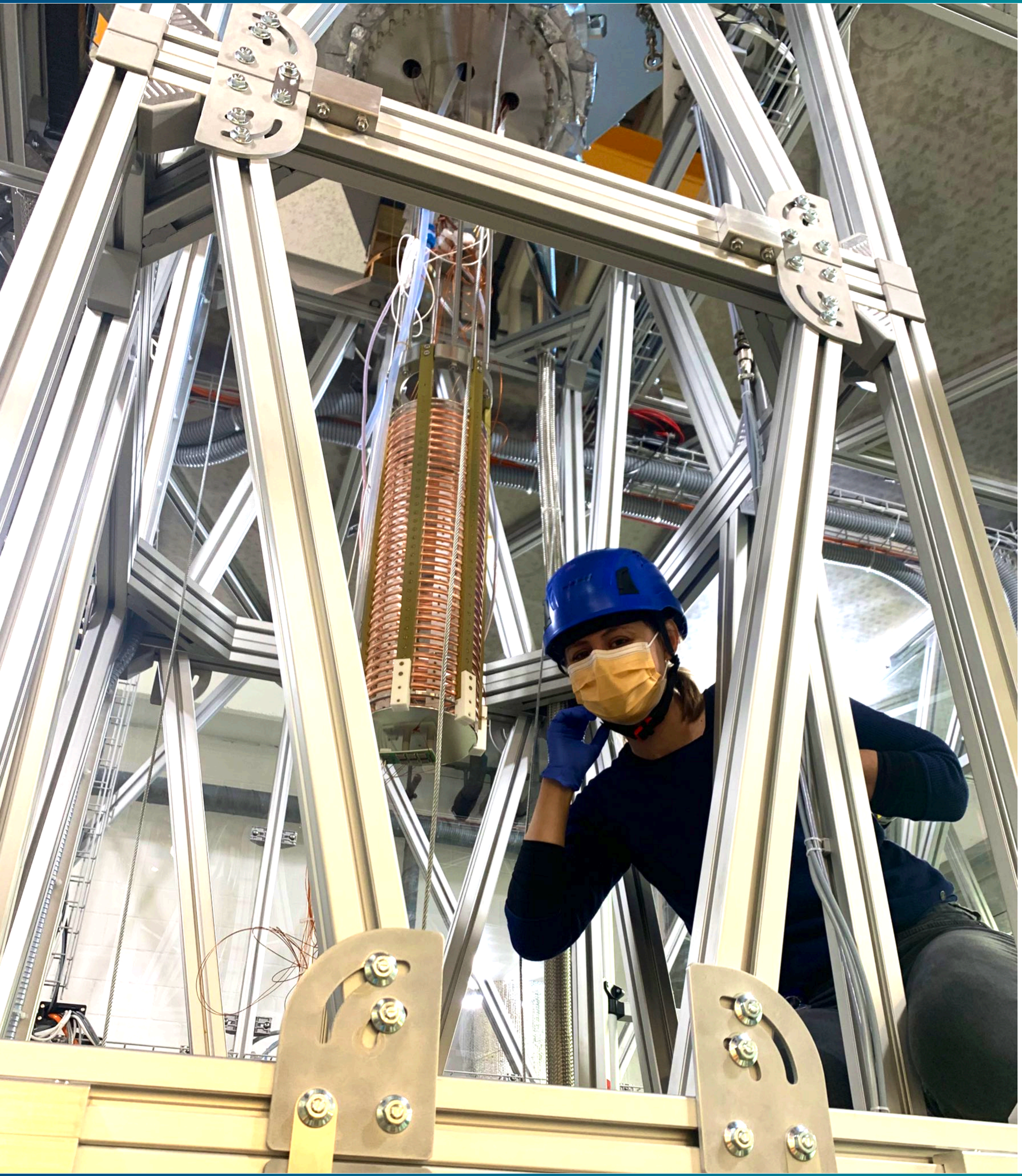
To become formal collaboration in case of positive P5 funding decision in US

- We aim to design and build a **single**, common **multi-ton** experiment.
- Current detectors LZ and XENONnT have the same goals but differ in some technologies
- Explore and select the best option from both worlds, **strengthening** our R&D efforts by **combining** ideas and resources

Conclusions

- Successfully operated a 53 cm purity monitor in Xenoscope filled with 343 kg of xenon
- Continuously purification over 88 days, which allowed electron transport measurements, i.e. drift velocity and longitudinal diffusion
- Our results and feedback prompted a drastic change in the way NEST was modelling diffusion, and their models were updated
- Can temperature effects alone explain the differences in the acquired drift velocity data between experiments?
- The ‘cold’ and ‘hot’ benchmarks are starting to appear in the discussion for models in NEST
- Future upgrades of the detector and newer setups can provide more information on liquid xenon properties relevant to large-scale TPCs

Conclusions



Thank you for your attention!

References

[1] Z. Greene, The XENON1T Spin-Independent WIMP Dark Matter Search Results and a Model to Characterize the Reduction of Electronegative Impurities in its 3.2 Tonne Liquid Xenon Detector. PhD thesis, Columbia University, 2018. 10.7916/D87M1RTN.

[2] G. Plante, E. Aprile, J. Howlett and Y. Zhang, Liquid-phase purification for multi-tonne xenon detectors, Eur. Phys. J. C 82 (2022) 860, [2205.07336].