# Design and performance of the XENONnT TPC electric field

**Francesco Toschi**

**14.02.2024 – Nagoya (online)**

***Nagoya Workshop on Technology and Instrumentation in Future Liquid Noble Gas Detectors***

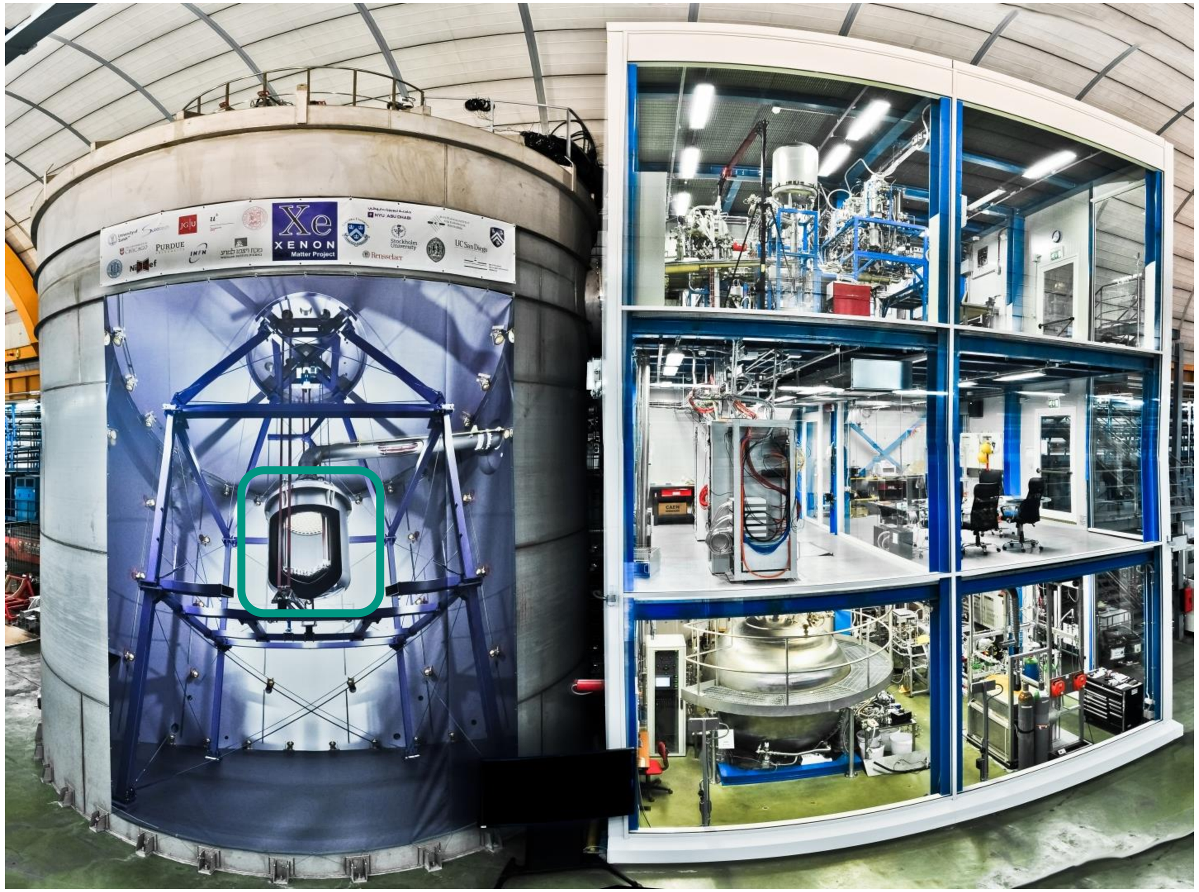
*Eur. Phys. J. C* **84**, 138 (2024)

# The XENONnT experiment

- Located at LNGS (~3600 mwe overburden)
- Nested detector:
  - active muon Cherenkov veto (MV);
  - active neutron Cherenkov veto (NV);
  - dual-phase time projection chamber (TPC)
- Unprecedented low ER background in ROI
  - (15.8 ± 1.3) events/(t·y·keV)
- Gas + liquid purification system
  - talk by Prof. Yamashita, Friday @ 10:30

Phys. Rev. Lett. 131, 041003 (2023)

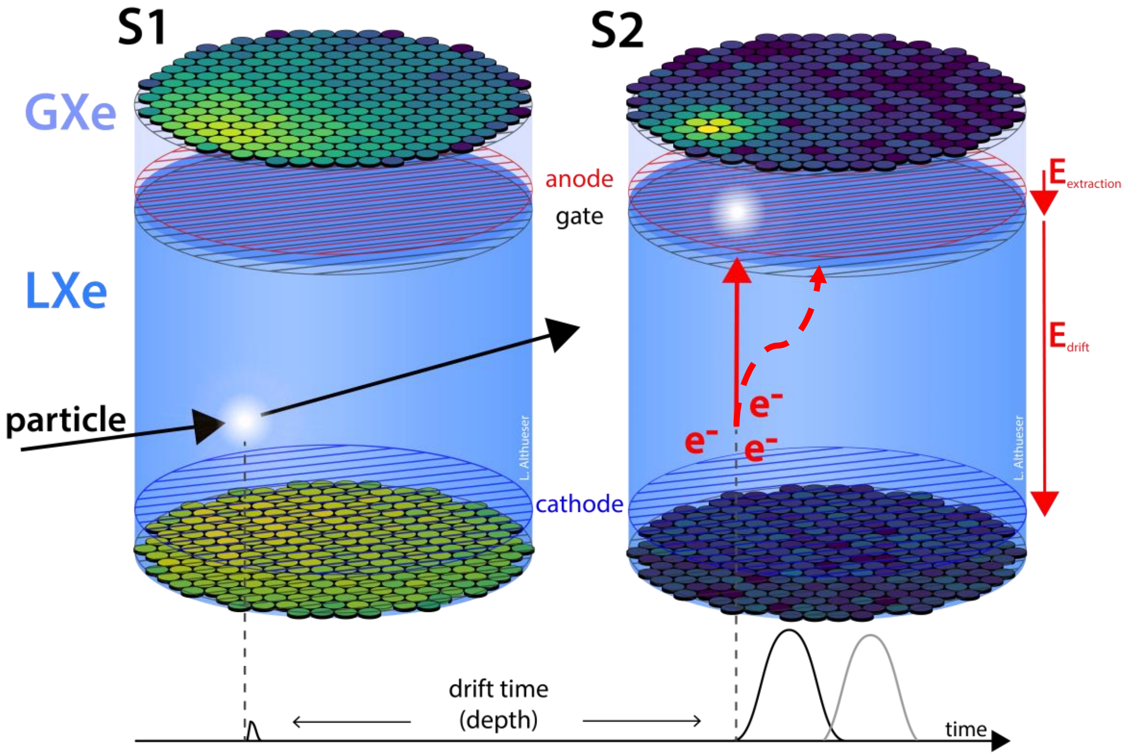
# The XENONnT experiment



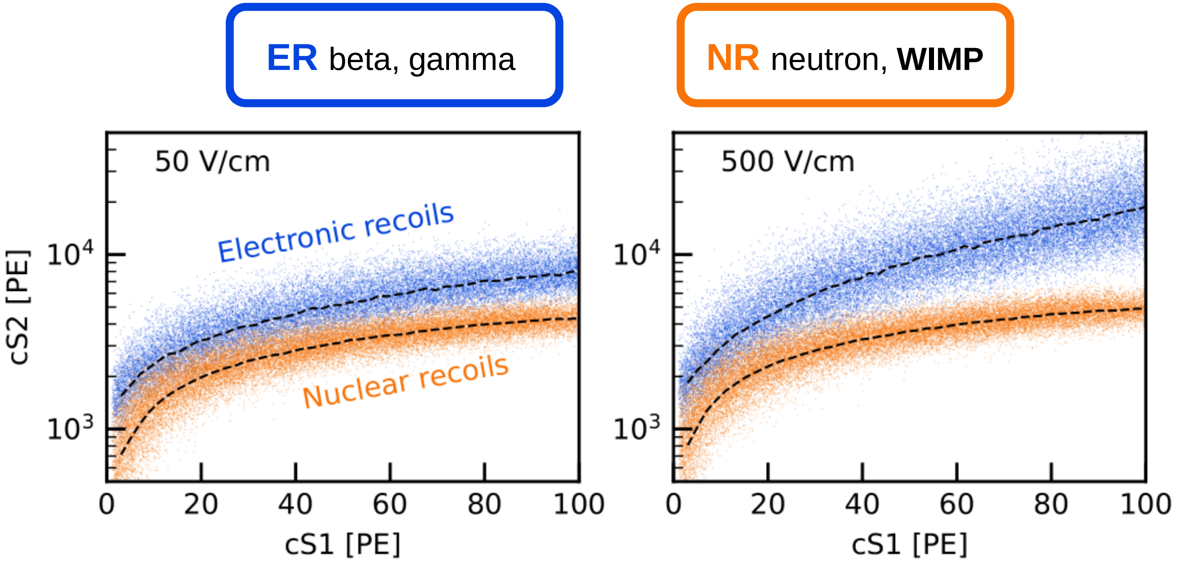
- Located at LNGS (~3600 mwe overburden)
- Nested detector:
  - active muon Cherenkov veto (MV);
  - active neutron Cherenkov veto (NV);
  - dual-phase time projection chamber (TPC)
- Unprecedented low ER background in ROI
  - (15.8 ± 1.3) events/(t·y·keV)
- Gas + liquid purification system
  - talk by Prof. Yamashita, Friday @ 10:30

Phys. Rev. Lett. 131, 041003 (2023)

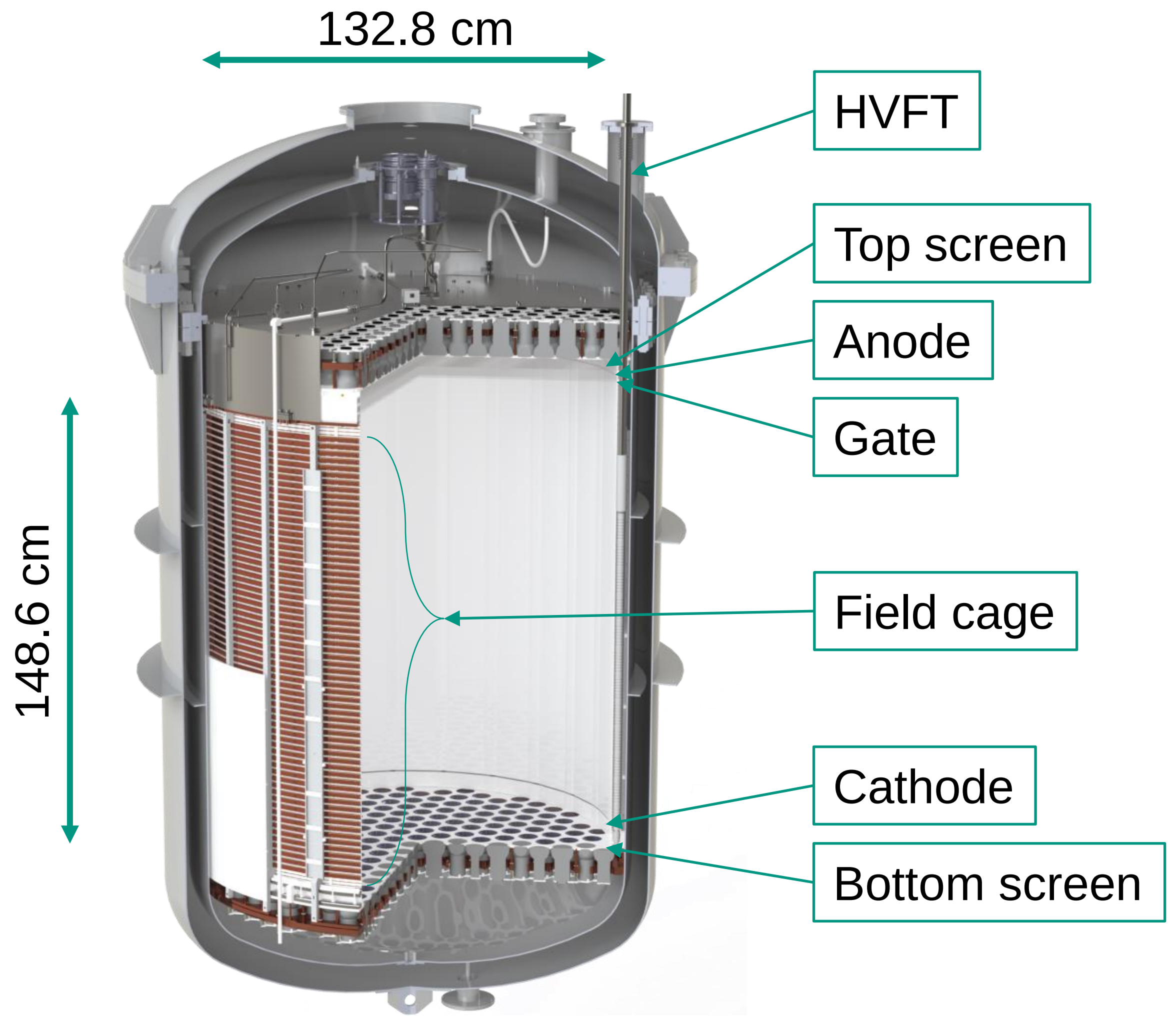
# Impact of the electric drift field



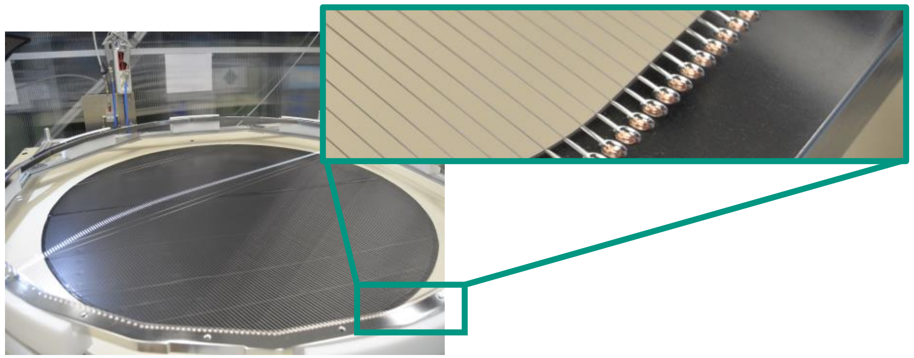

- S2 top hit pattern → (x,y) position
- Drift time → z position
- S2 multiplicity → multi-scatter rejection
- S2/S1 ratio → recoil type discrimination



# The XENONnT TPC electric field

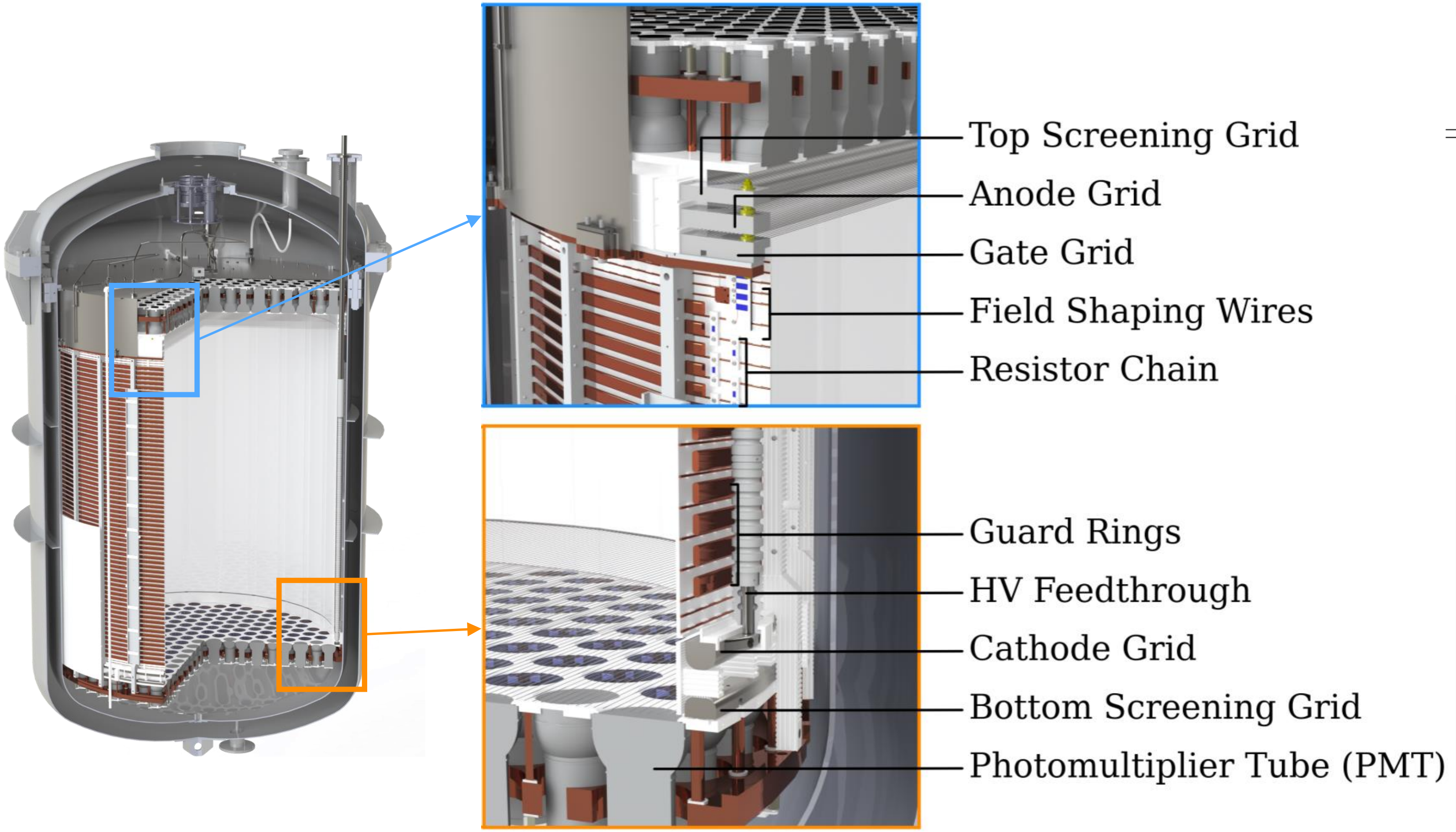



- Five electrodes divided into top and bottom stacks;
- HVFT from XENON1T (tested up to -110 kV);
- Parallel wire grids electrodes:
  - SS wires (Ø216 µm, but Ø304 µm cathode),
  - wires are connected via copper pins.

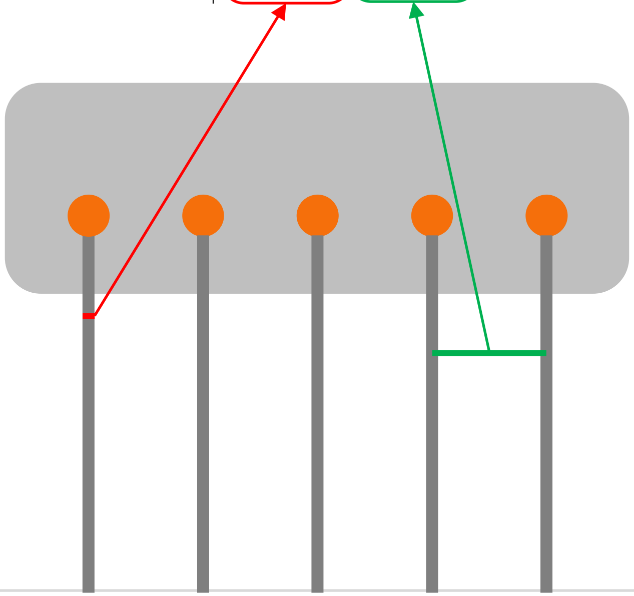


# The XENONnT TPC electrodes

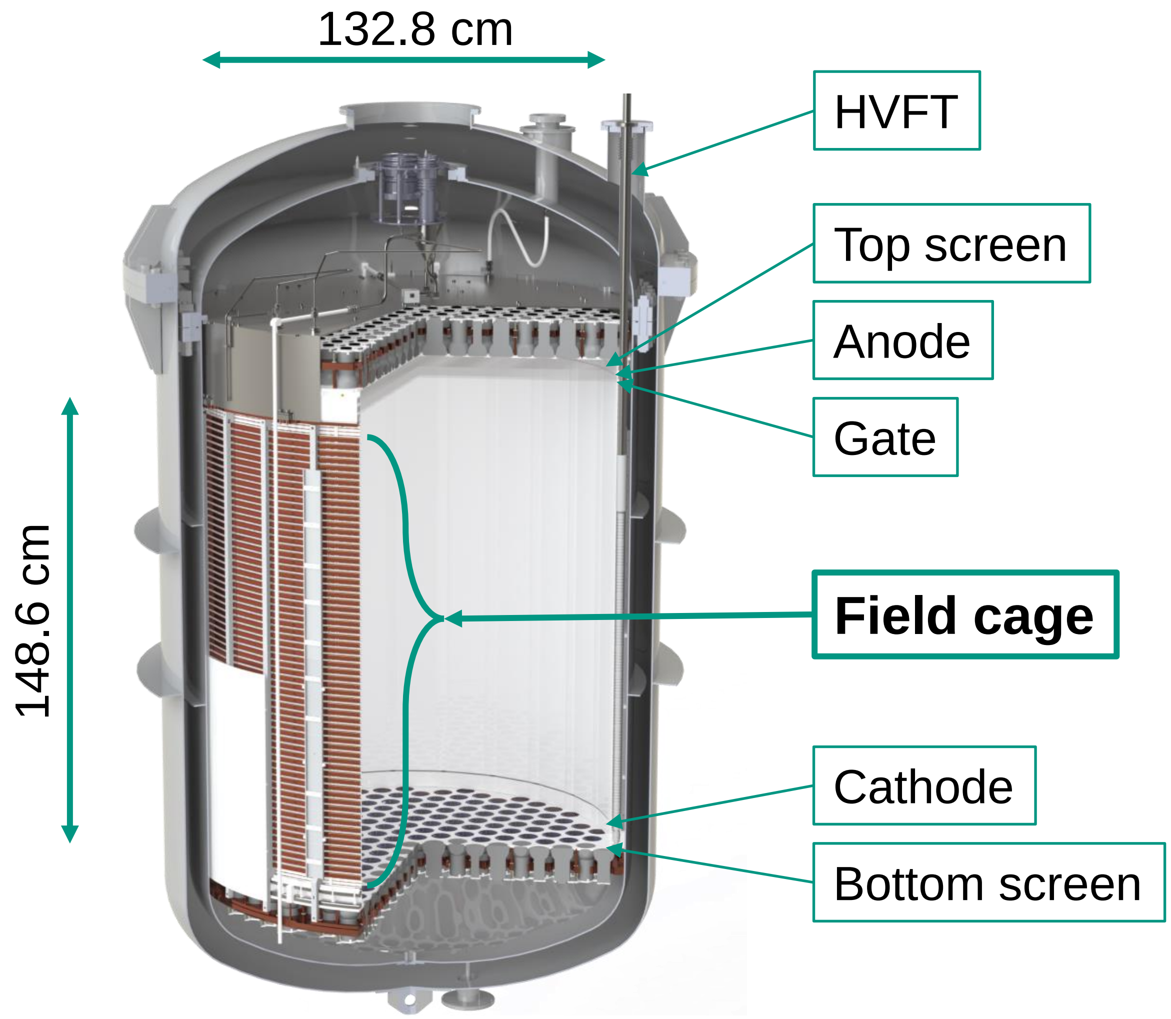




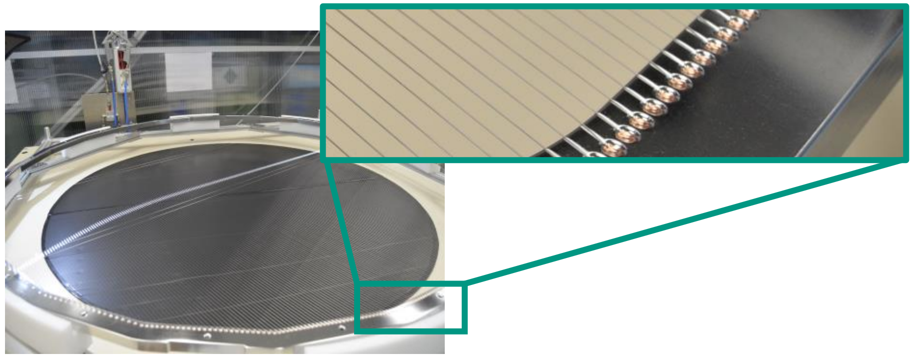

| | $d_{\mathrm{wire}}$ [µm] | $p$ [mm] | Shape |
|---|---|---|---|
| **Top screen** | 216 | 5 | 24-pol. |
| **Anode** | 216 | 5 | 24-pol. |
| **Gate** | 216 | 5 | 24-pol. |
| **Cathode** | 304 | 7.5 | circ. |
| **Bottom screen** | 216 | 7.5 | circ. |



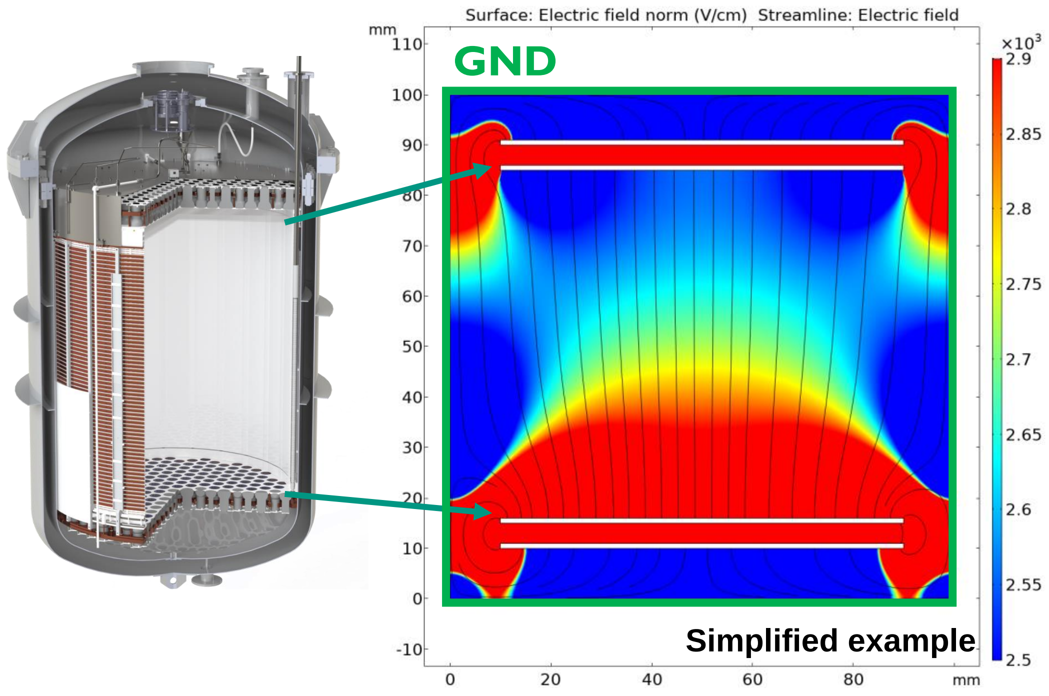
# The XENONnT TPC electric field




- Five electrodes divided into top and bottom stacks;
- HVFT from XENON1T (tested up to -110 kV);
- Parallel wire grids electrodes:
  - SS wires (Ø216 µm, but Ø304 µm cathode),
  - wires are connected via copper pins.

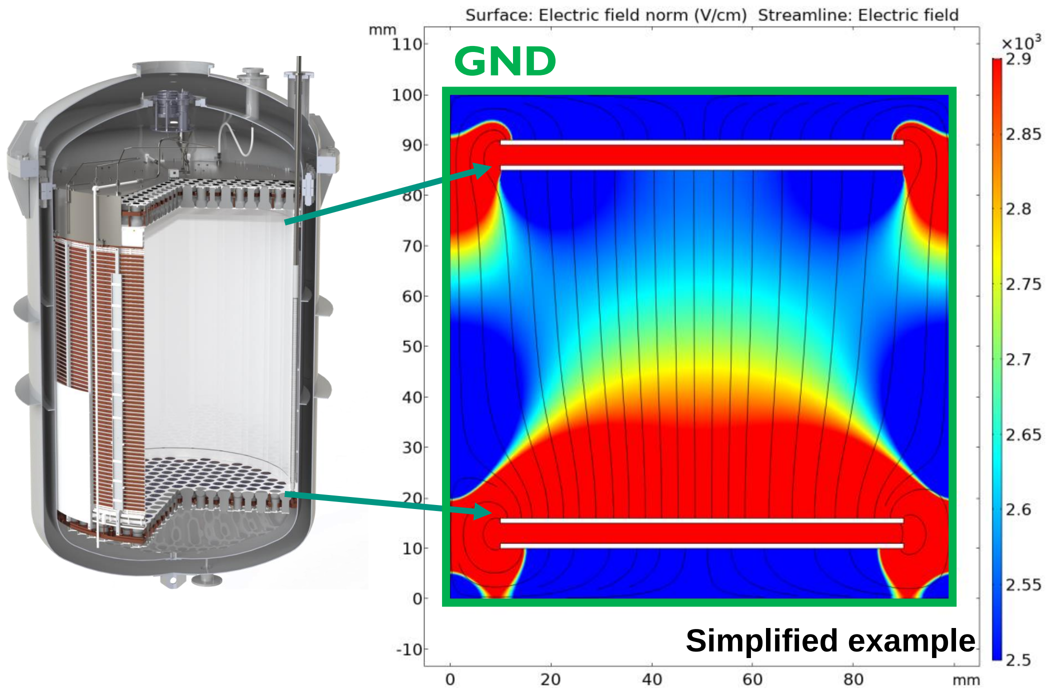


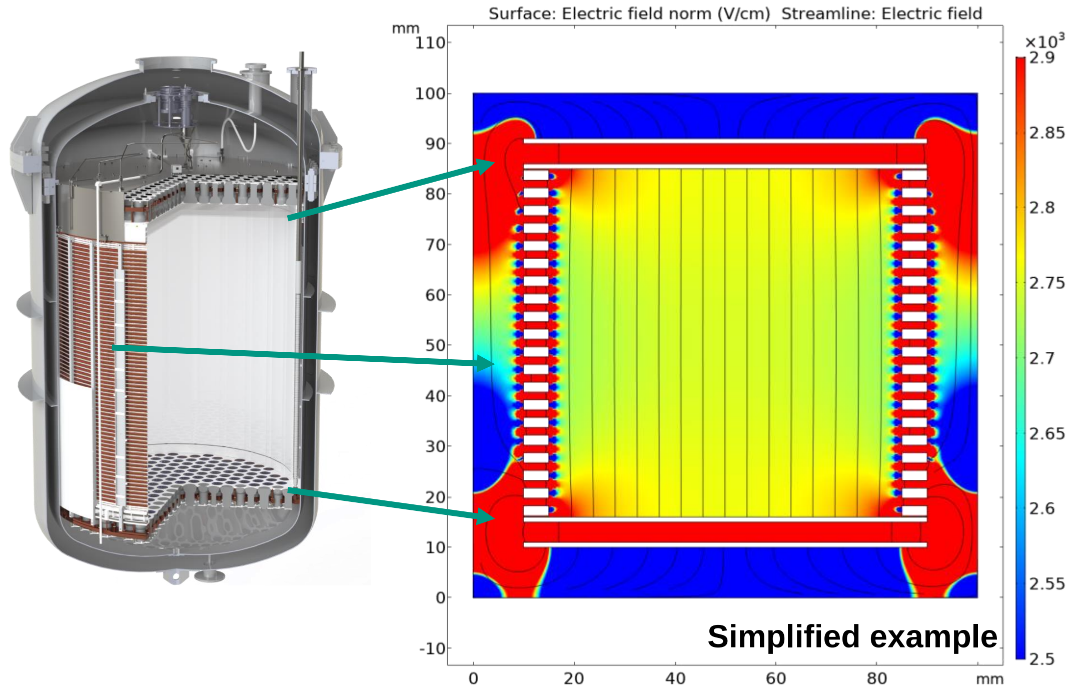
# Why a field cage?



# Why a field cage?

Field cage = field shaping elements + resistive chain

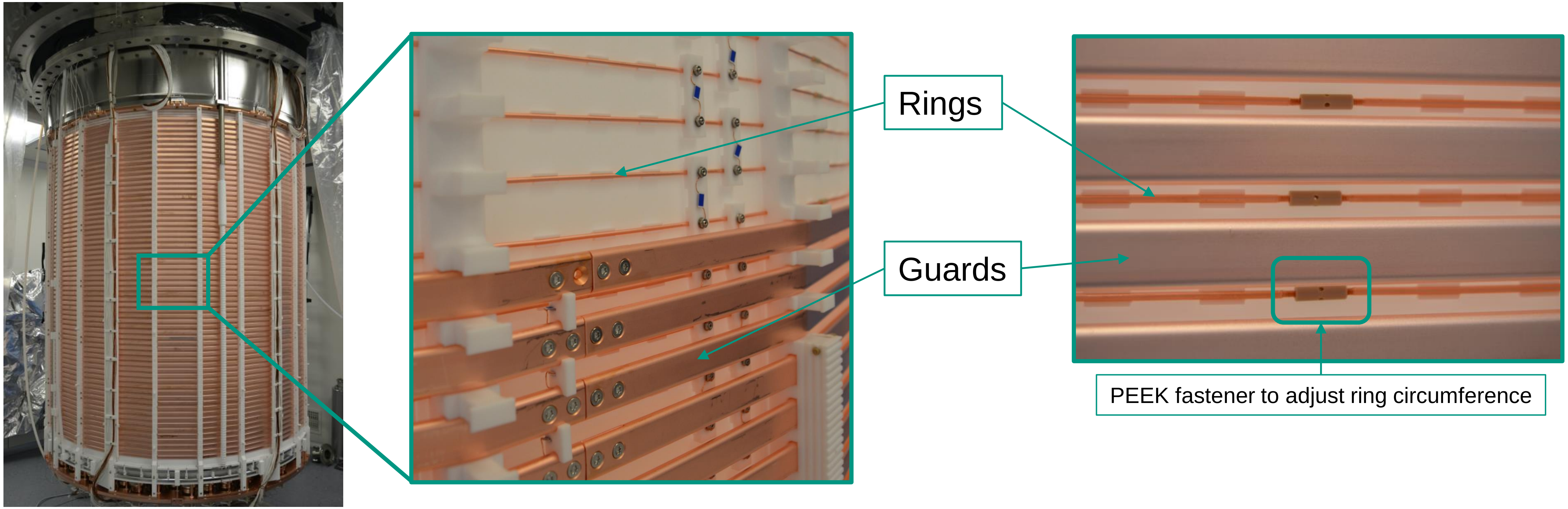


# The XENONnT field cage

Two nested arrays of copper electrodes:

- ***Guards*** (5 mm x 15 mm), two icositetragonal halves connected at the resistive chain location;
- ***Rings*** (Ø 2 mm), touching the PTFE walls thanks to notches on the sliding reflectors.



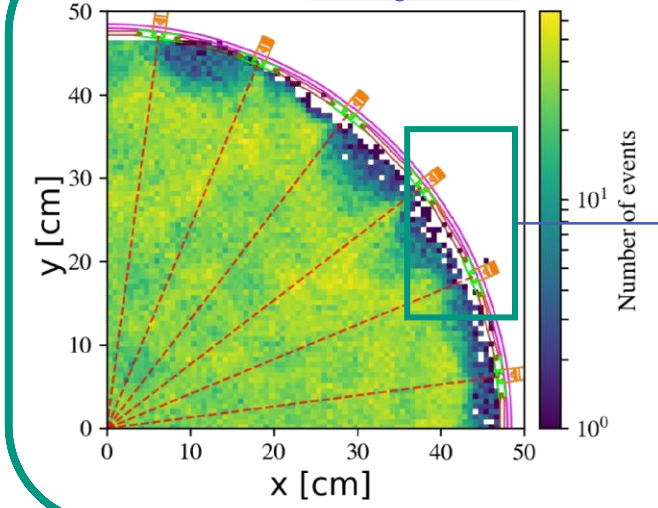
# The XENONnT field cage

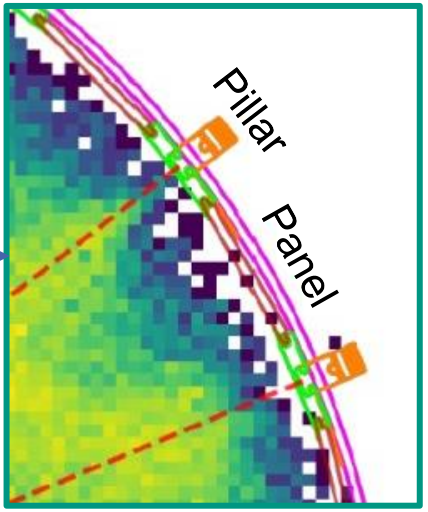
Two nested arrays of copper electrodes:

- ***Guards*** (5 mm x 15 mm), two icositetragonal halves connected at the resistive chain location;
- ***Rings*** (Ø 2 mm), touching the PTFE walls thanks to notches on the sliding reflectors.

„Bite-structure“

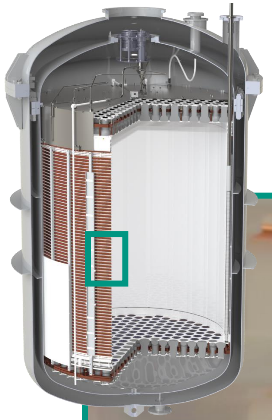
From M. Vargas thesis



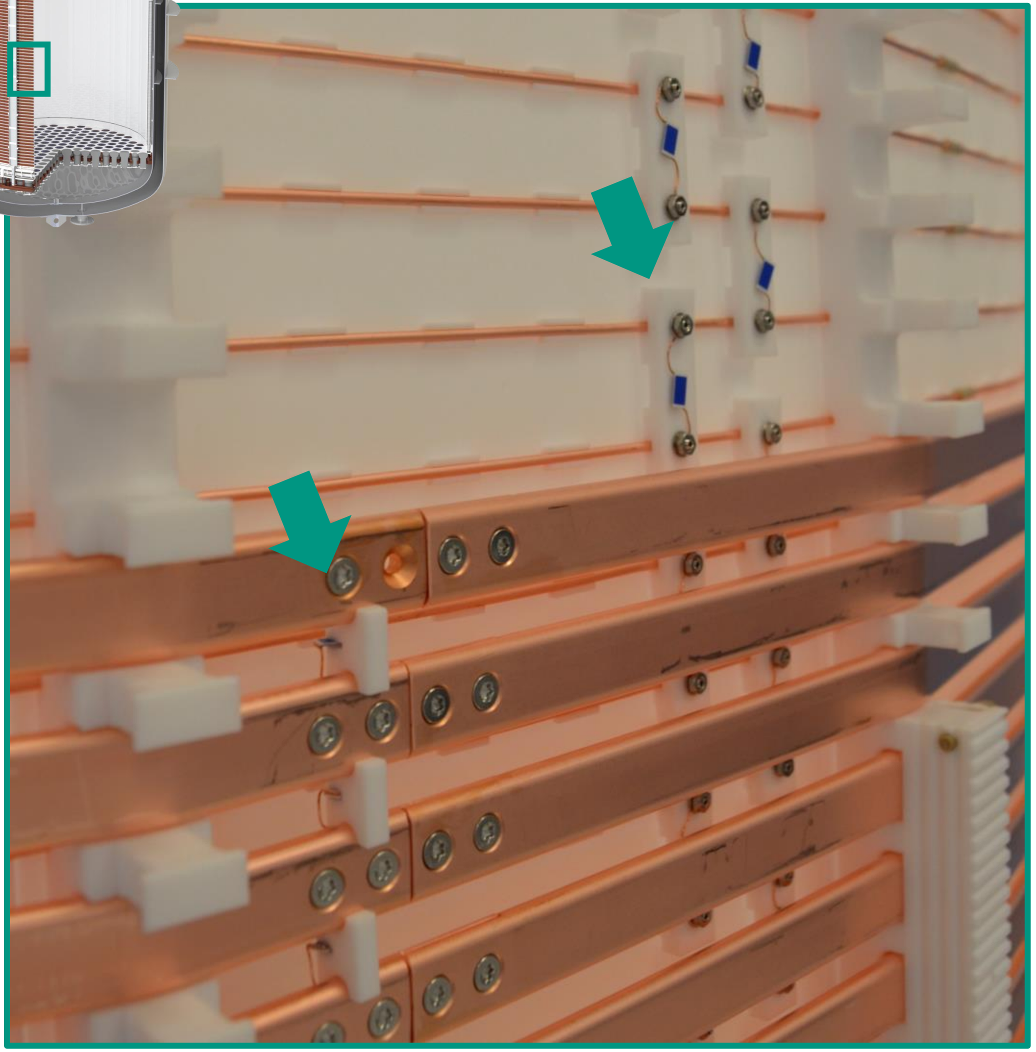

- Charge-up observation from XENON1T: inward push at panels, less at pillars;
- Field cage is in contact with pillars, not with panels;
- Conclusion: contact with copper helps reducing charge-up effect.

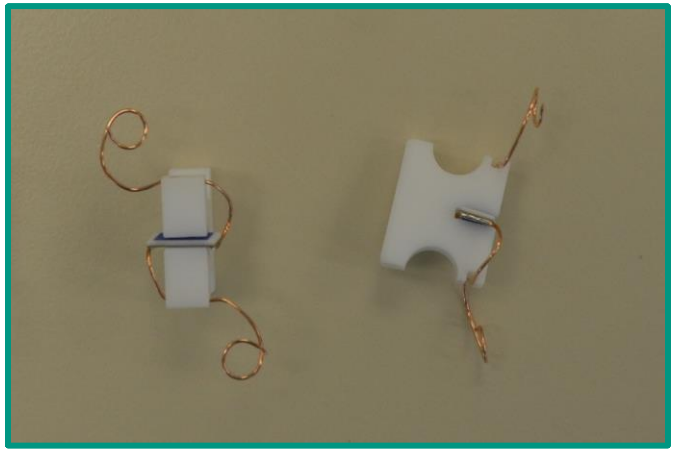
# The XENONnT resistive chain

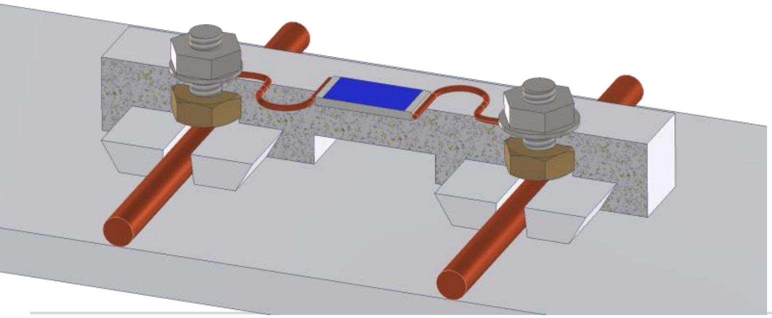


Field shaping elements are connected by 5 GΩ resistors (two redundant resistive chains):

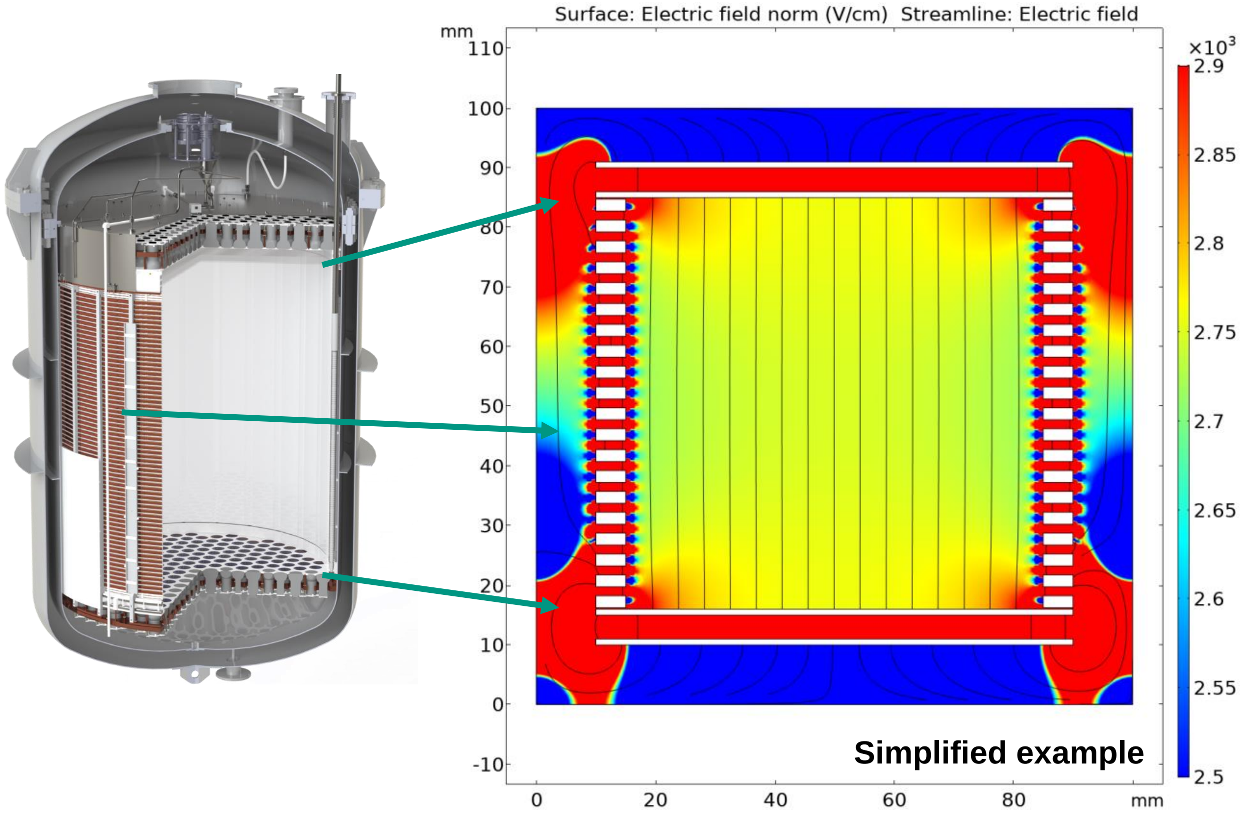
- guards‘ chain is based on „sandwiching“ the resistors‘ connectors between a nut and the guard‘s copper;
- rings‘ chain is based on spring-loaded connections using PTFE elements fixed by special notches on the panels.



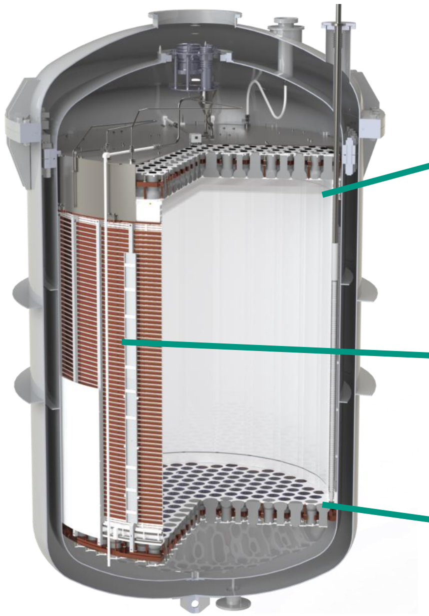


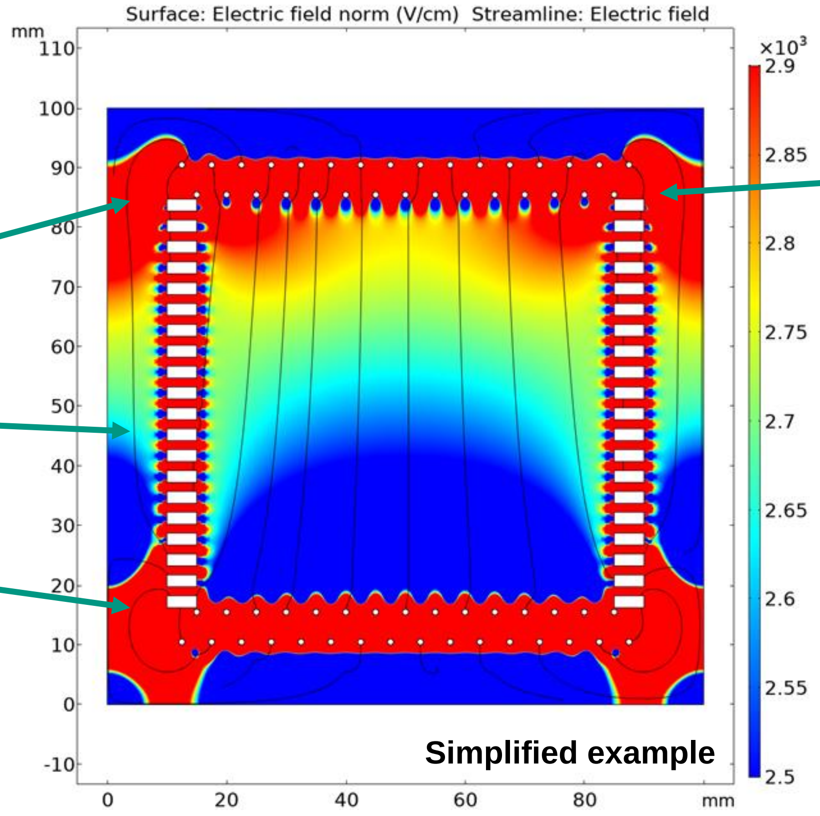


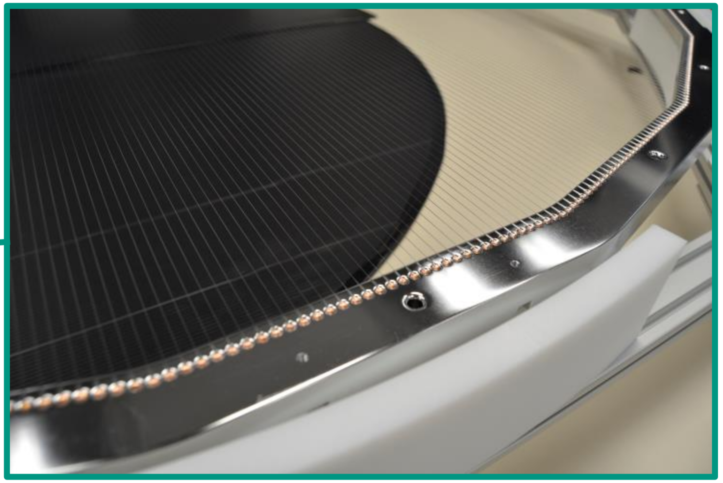
# Field leakage through the electrodes



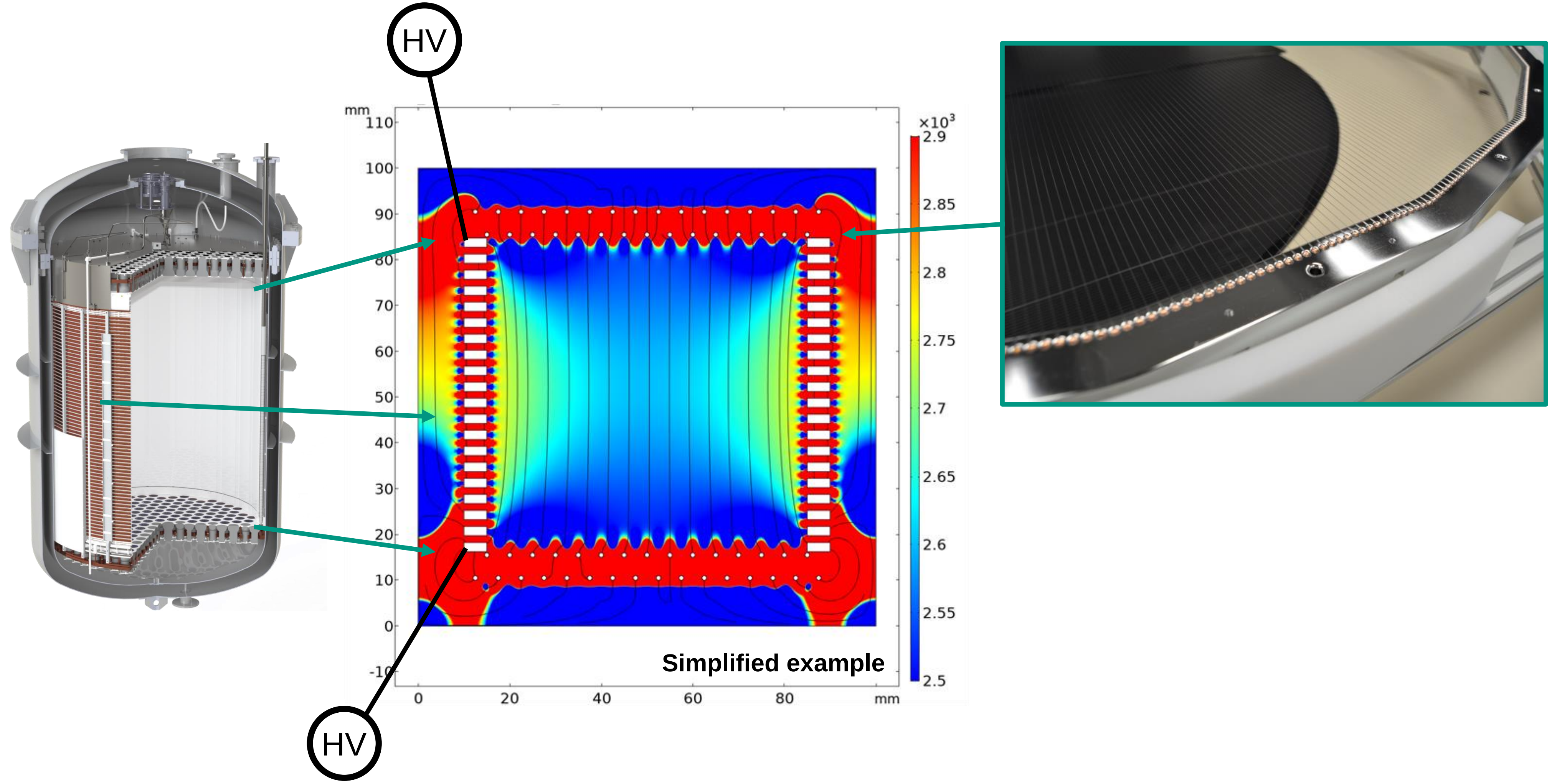
# Field leakage through the electrodes





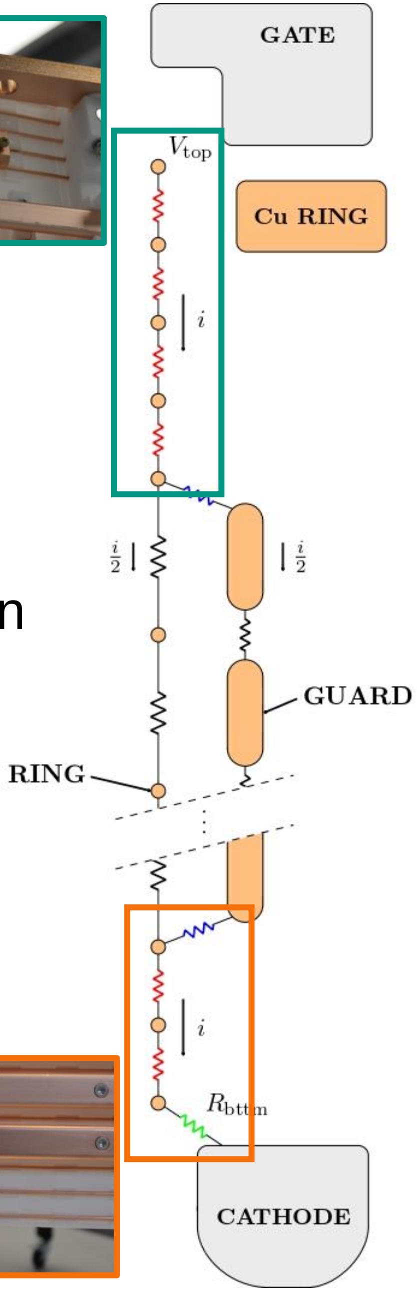



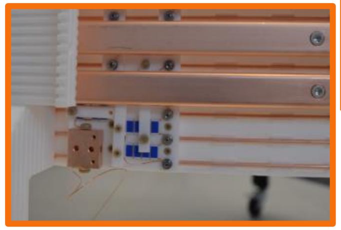
# Field leakage through the electrodes



# The degrees of freedom of the field cage

- Geometry defined by mechanical constraints (e.g., HVFT position);
- Voltage partitioner (resistive chain) ensures linear potential drop;
- The field can be **optimized** thanks to the 2 degrees of freedom of the resistive chain



### Top voltage - $V_{top}$

- Independent HV power supply;
- tunable voltage during detector operation (no need to access the field cage).

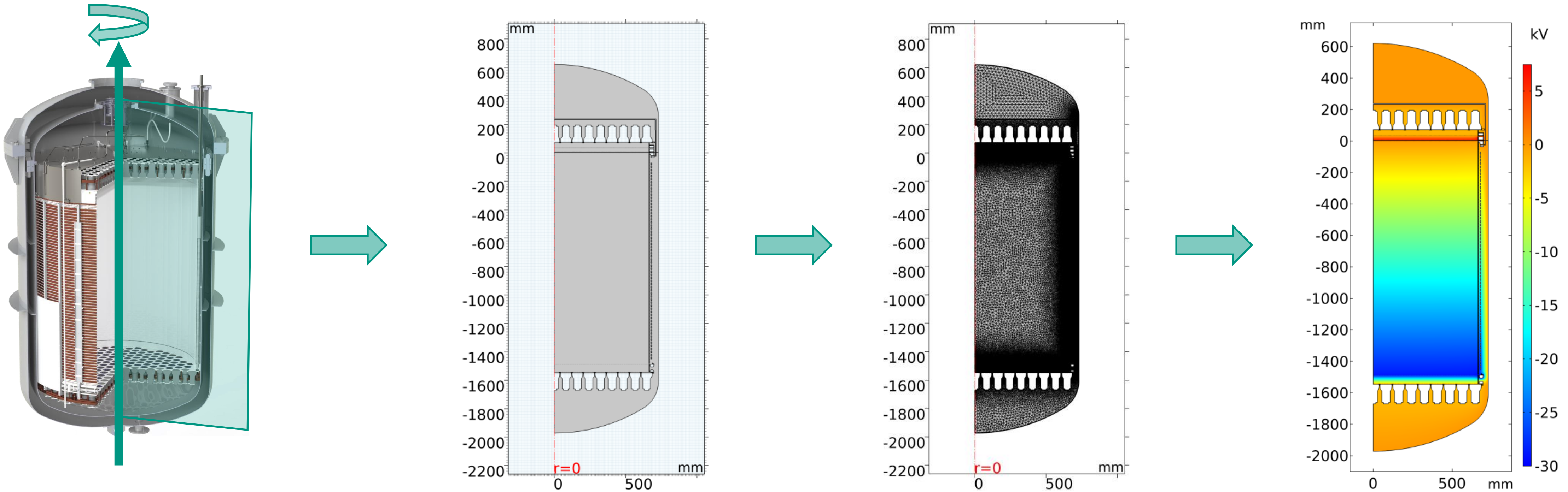
### Bottom resistor - $R_{bttm}$

- HV power supply required new feedthrough;
- effective potential achieved by selecting proper resistance;
- fixed at design phase.

# Finite element method – COMSOL

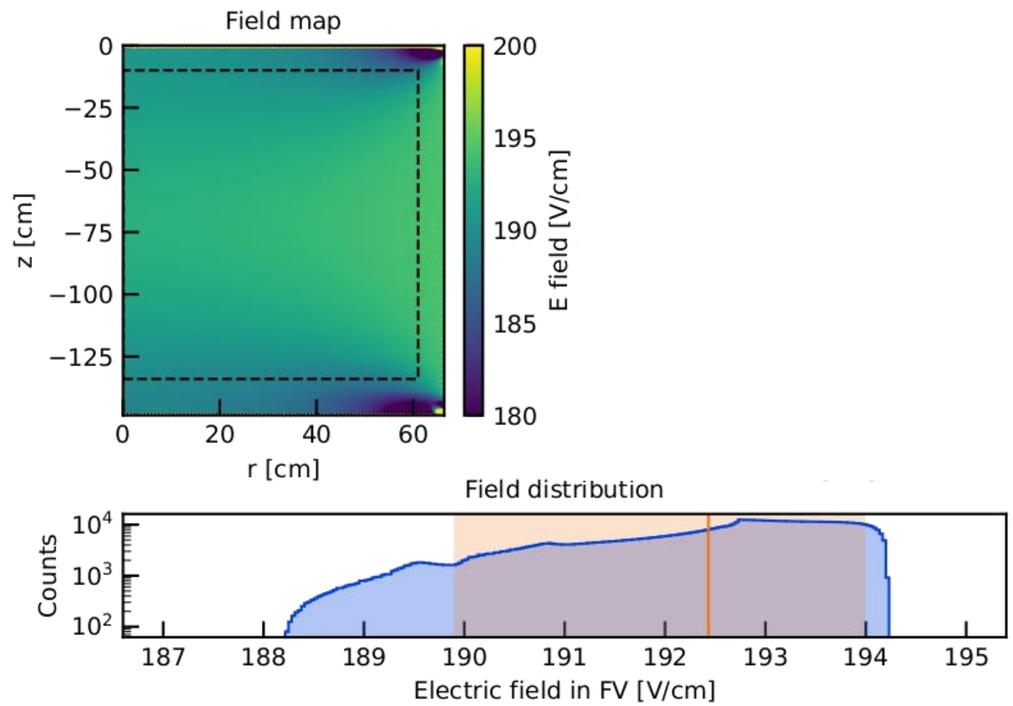
- The simulations were performed using the finite element method (FEM) software **COMSOL Multiphysics v5.4** on a 32 GB machine;

- exploiting 2D-axysimmetry of the detector (custom mesh of ~5 million elements).



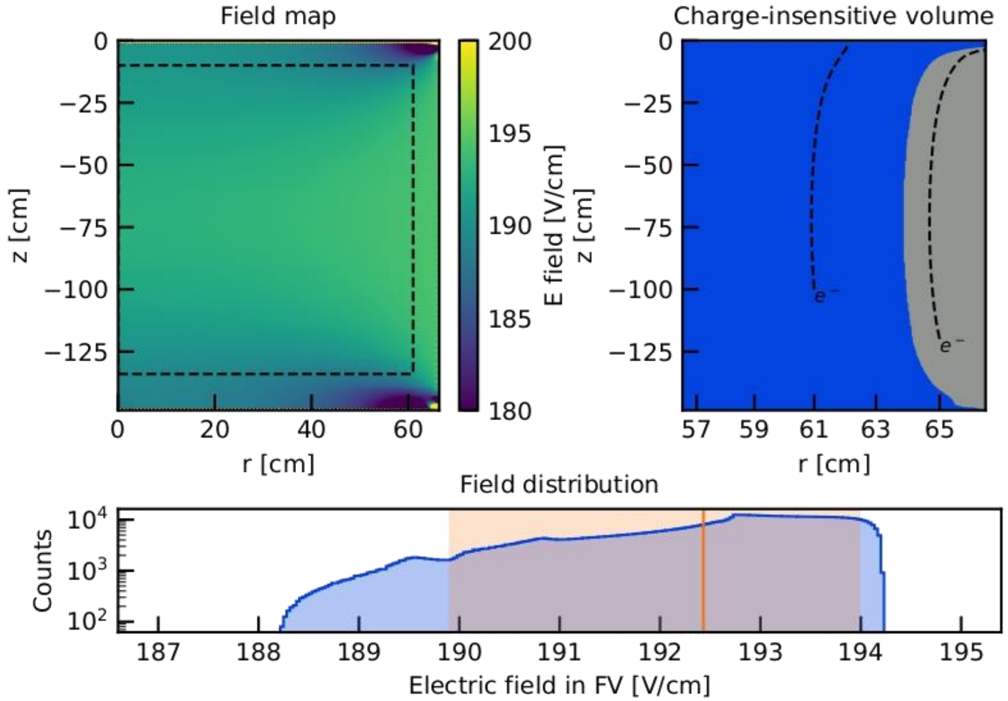
# Optimization of the electric field

- Two figures of merit:
    - **Field spread** inside a fiducial volume;



# Optimization of the electric field

- Two figures of merit:
  - **Field spread** inside a fiducial volume;
  - **Charge insensitive volume** (CIV) estimated simulating the electrons' propagation.

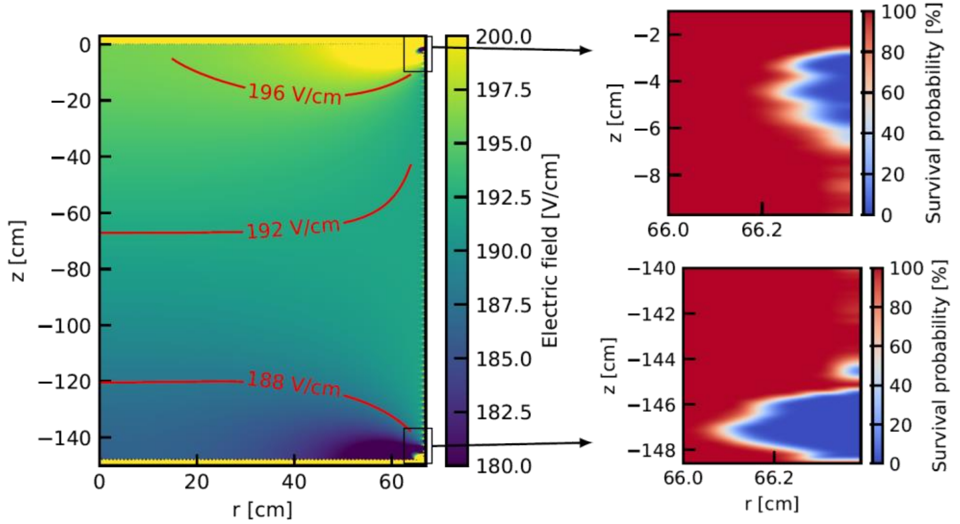


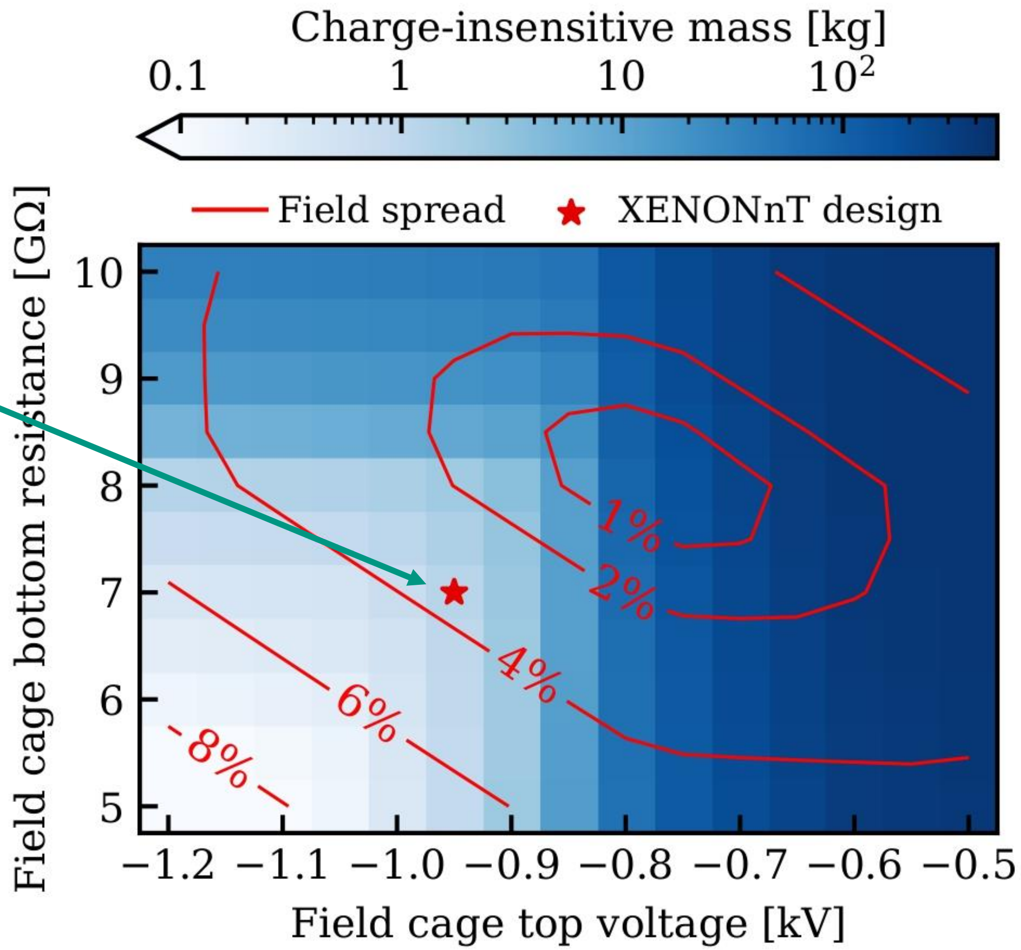
# The design electric field of XENONnT

| | V [kV] |
|---|---|
| Top screen | −1.5 |
| Anode | +6.5 |
| Gate | −1.0 |
| Cathode | −30.0 |
| Bottom screen | −1.5 |

- Best-performing configuration for field spread resulted in >300 kg of CIV.

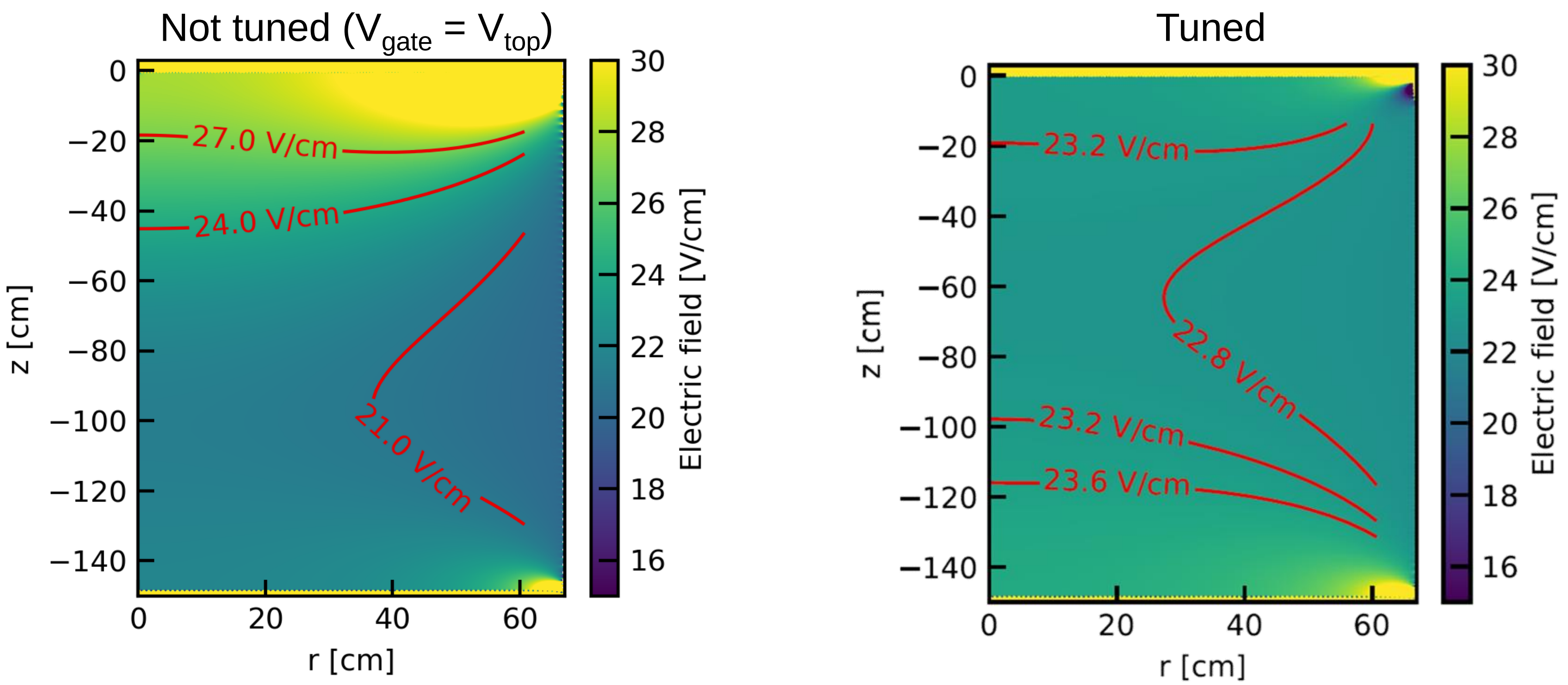
- Selected configuration:
  - -950 V top voltage (+50 V w.r.t. gate)
  - 7 GΩ bottom resistance (= -28.8 kV)



# XENONnT electric field during SR0

- Short-circuit between cathode and bottom screen limited cathode voltage to -2.75 kV;
- still possible to tune the electric field by changing the field cage top voltage!

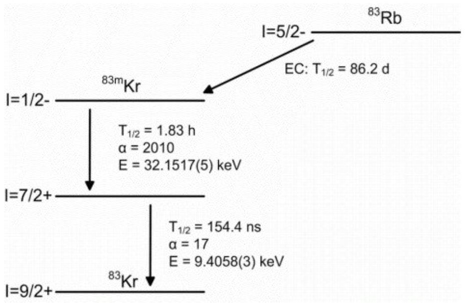


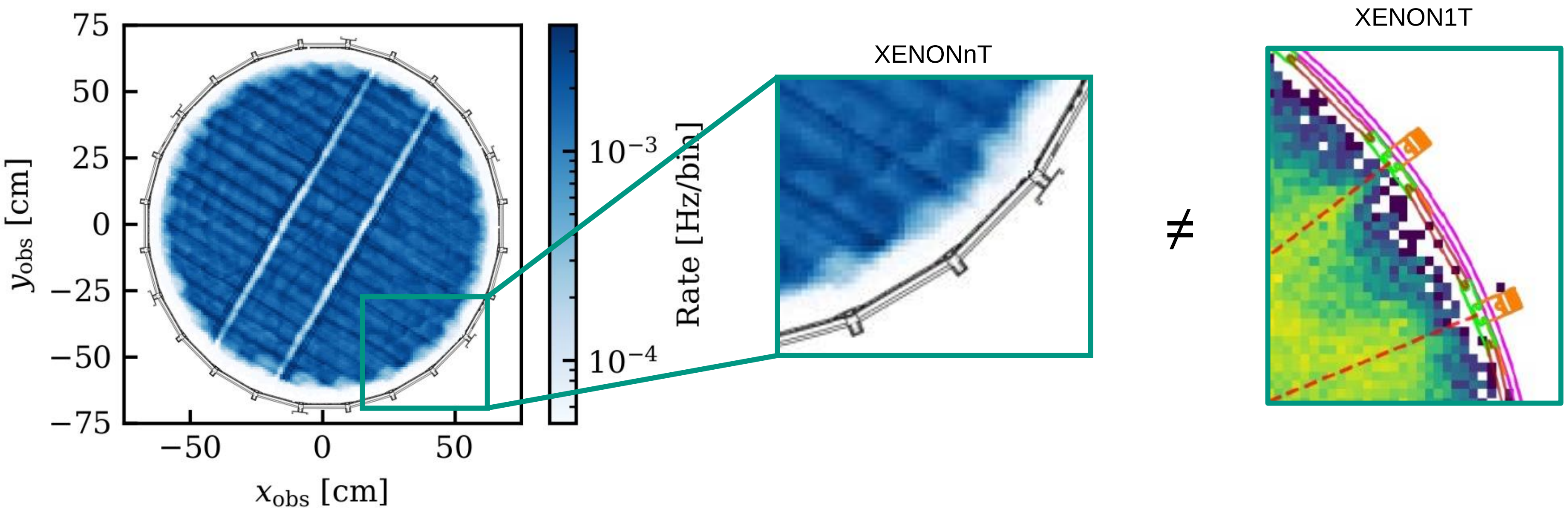

| | SR0 voltage [kV] |
|---|---|
| Top screen | −0.9 |
| Anode | +4.9 |
| Gate | +0.3 |
| **Top field cage** | **+0.65** |
| Cathode | −2.75 |
| Bottom screen | −2.75 |

# $^{83m}$Kr calibration data: bite-structure

- $^{83m}$Kr is a homogeneously distributed calibration source in the active target:
  - ideal to study the electric field!

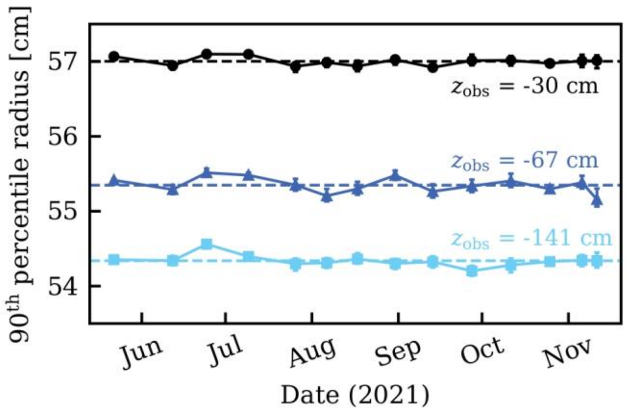
- First check: is the „bite-structure“ still there? Yes, but inverted!

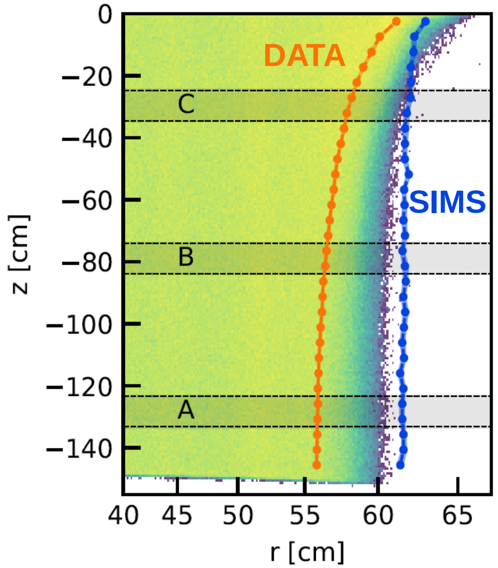


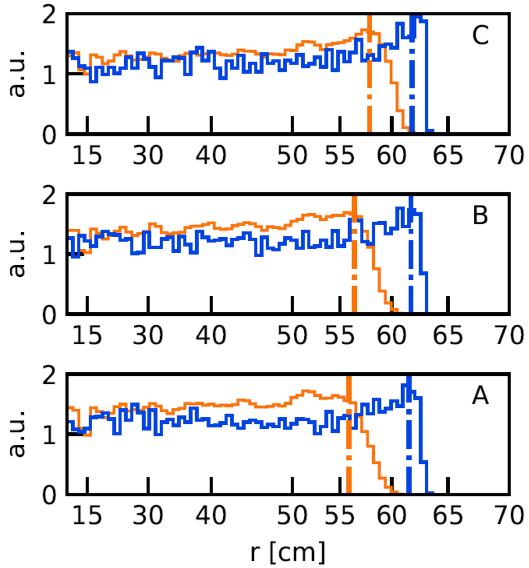



# Comparison $^{83m}$Kr - simulations

- Expected (r,z) distribution from uniformly distributed source can be simulated using the electric field map and literature values for diffusion and drift speed;
- comparison between data and simulation is done by comparing the radial distribution 90$^{th}$ percentile along the TPC height;
- no time evolution of the position distribution is observed in almost 6 months of data taking.



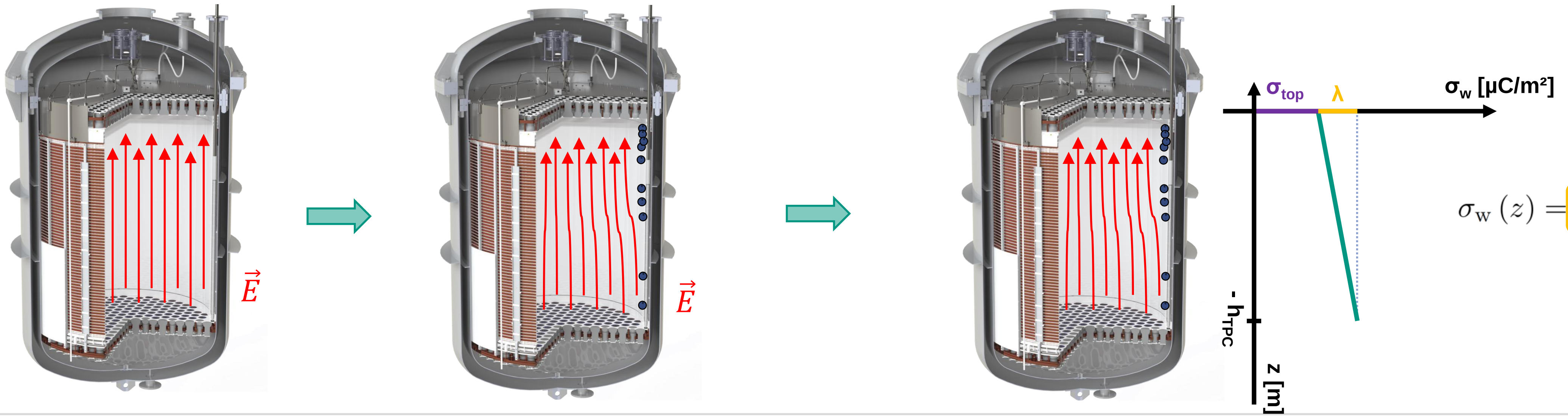




# Charge accumulation on PTFE walls

Karlsruher Institut für Technologie

- Mismatch could be due to charge accumulation on the highly electronegative PTFE walls
  - charge distribution already modelled by LUX with average 3-5 μC/m² and varying over time.
- Include **linear surface charge density distribution** on the PTFE walls in the simulation.
- Charge distribution parameters from chi-square minimization of radial 90$^{th}$ percentile distribution along z.

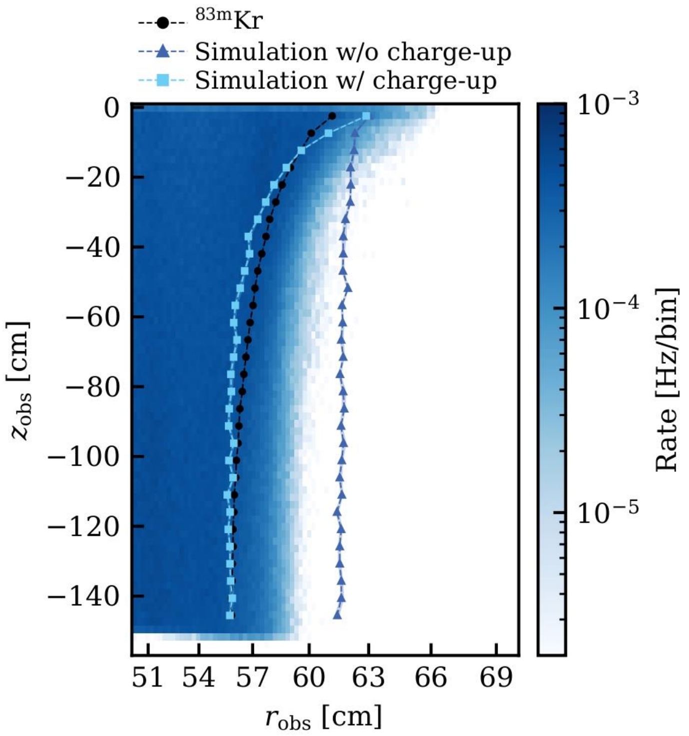



$$\sigma_w(z) = \lambda \cdot \frac{|z|}{h_{TPC}} + \sigma_{top}$$

JINST 12, no. 11, P11022 (2017)

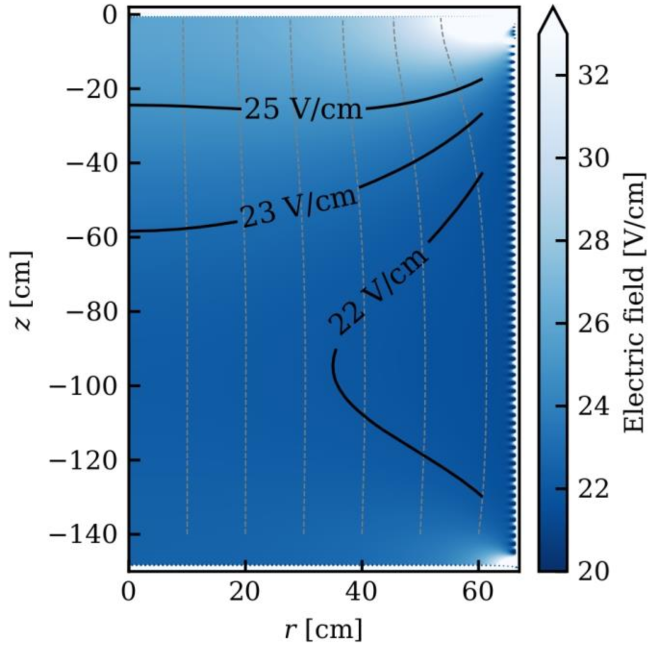
# Charge accumulation on PTFE walls

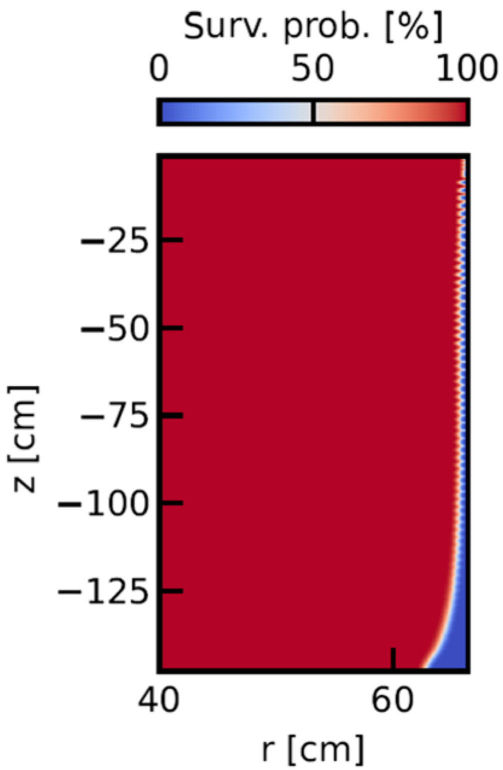
- Much better agreement between simulated (r,z) position distribution and observed one;
- new field map including linear charge accumulation along PTFE walls.




$$\sigma_{top} = (-0.50 \pm 0.05(\mathrm{sys}) \pm 0.02(\mathrm{stat}))\ \mu\mathrm{C/m^2}$$

$$\lambda = \left(0.40 \pm 0.15(\mathrm{sys})^{+0.20}_{-0.10}(\mathrm{stat})\right)\ \mu\mathrm{C/m^2}$$

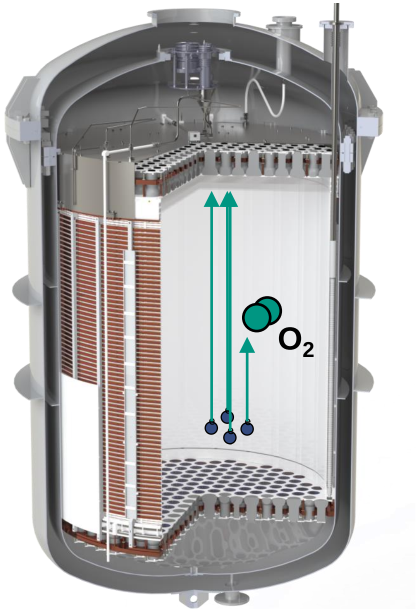


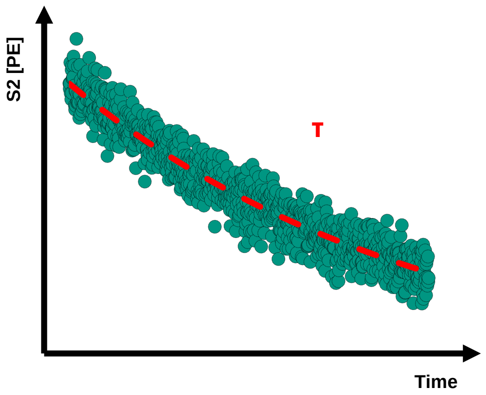




CIV = 112 kg

# Testing our field knowledge: e-lifetime

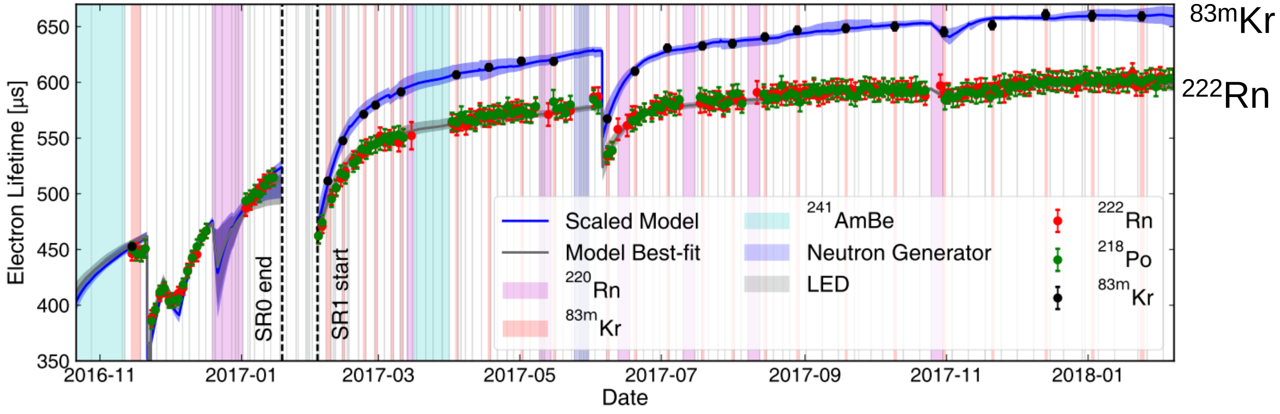
- In XENON1T the measurement of electron lifetime showed a dependence on the source;
- explained as an effect of the non-uniformity of the electric field + source dependence of charge yield.



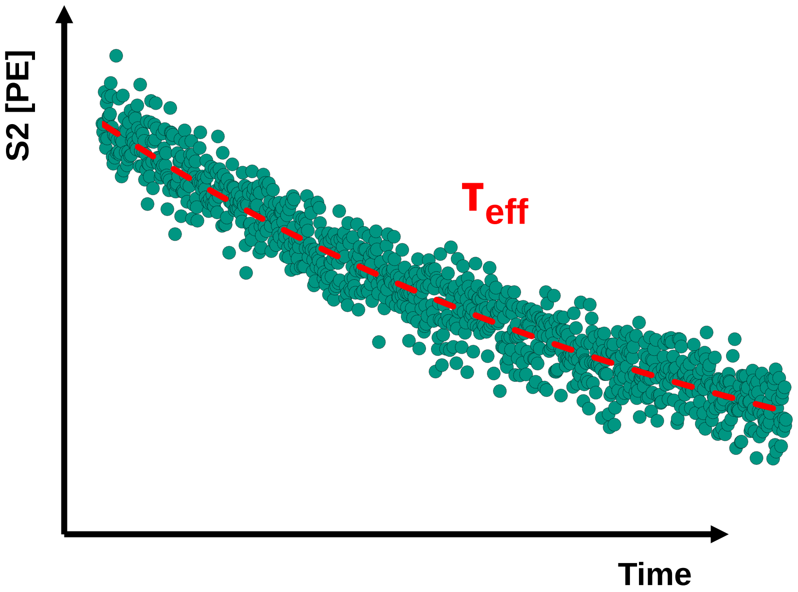

$$\mathrm{S2}\left(t\right)=\mathrm{S2}\left(0\right)e^{-t/\tau_{\mathrm{e}^-}}$$

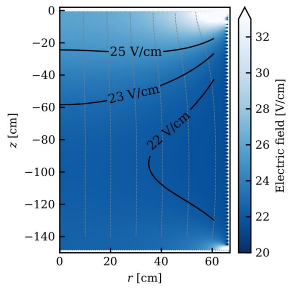
Phys. Rev. D 100, 052014 (2019)

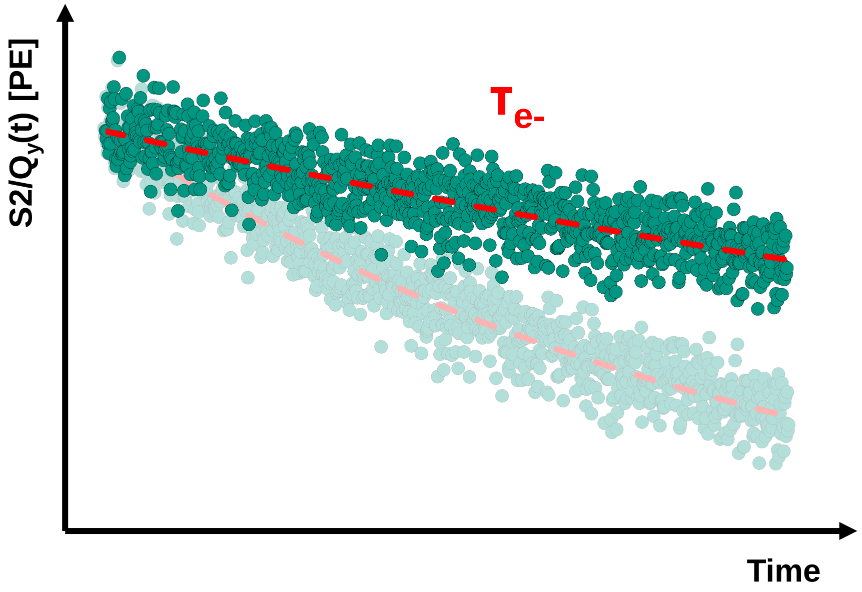


# Testing our field knowledge: e-lifetime

- We can use the field map and the charge yield $Q_y$ from NEST to obtain the physical e-lifetime.



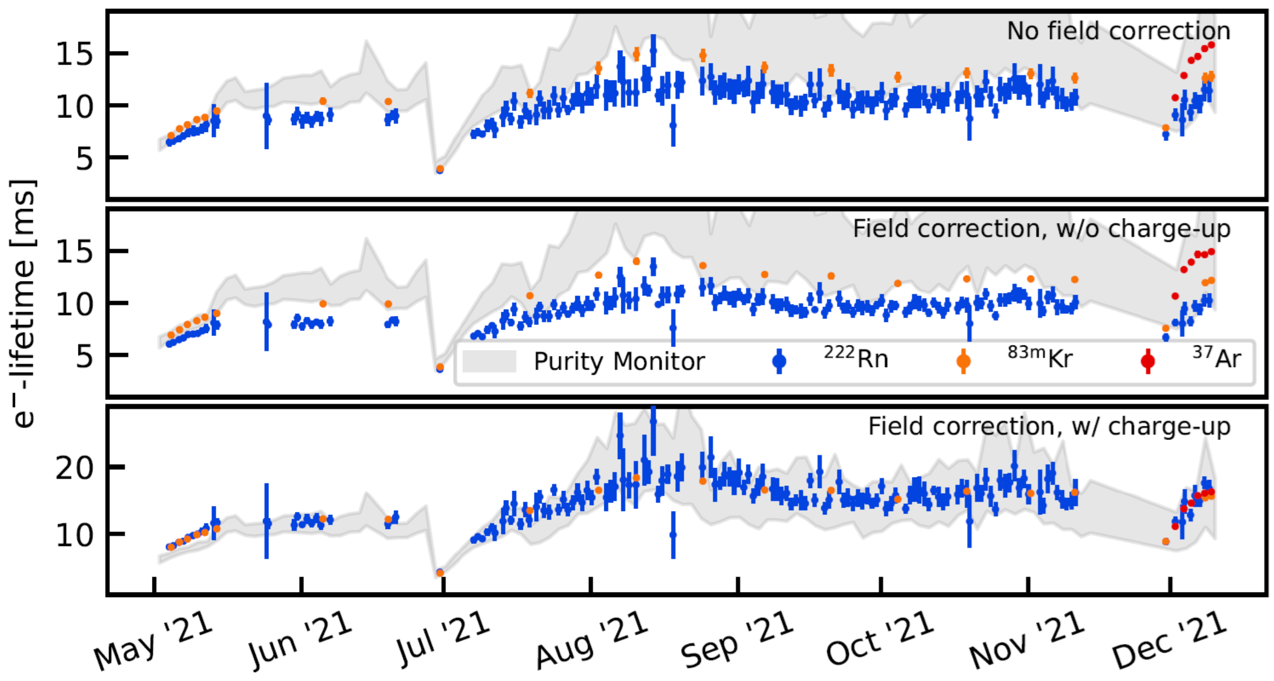




$$S2\,(t) = S2\,(0)\,e^{-t/\tau_{e^-}^{eff}} = S2\,(0)\,Q_y\,(t)\,e^{-t/\tau_{e^-}}$$

$$S2\,(t)/Q_y\,(t) = S2\,(0)e^{-t/\tau_{e^-}}$$

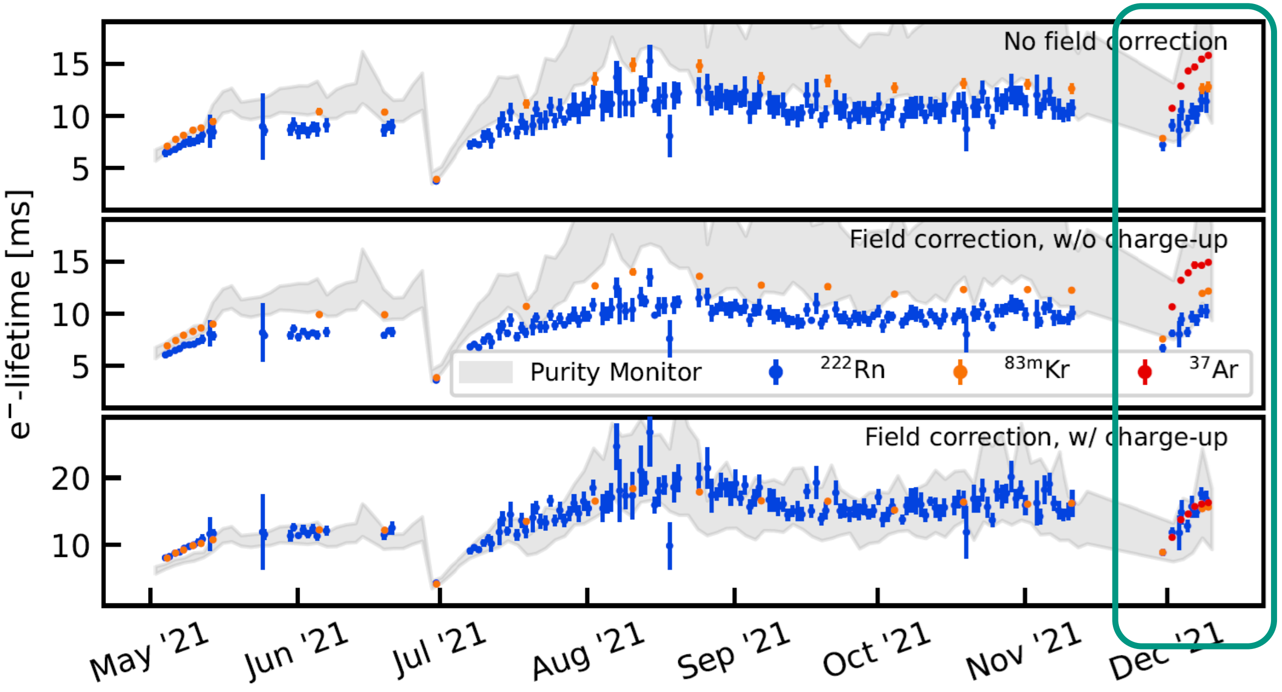
# Testing our field knowledge: e-lifetime

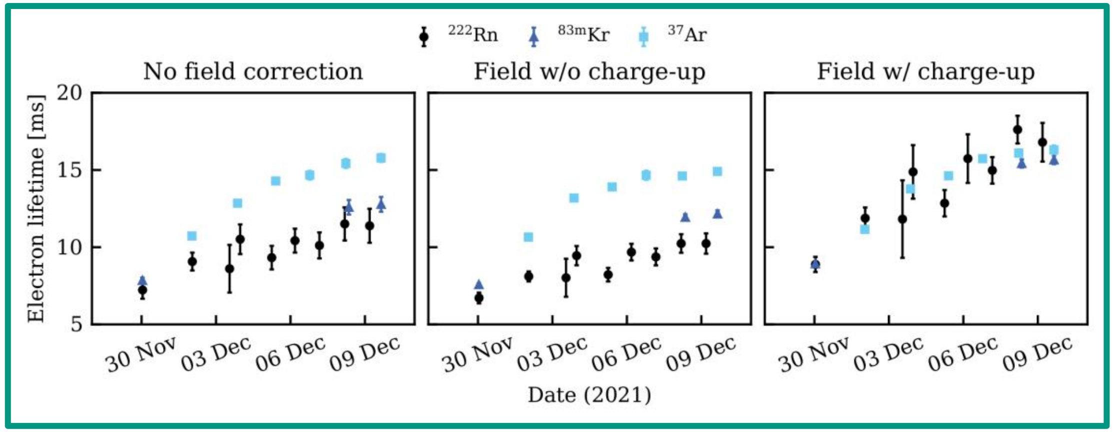
- Source-dependence both without field correction and using the field map w/o charge accumulation on the PTFE walls;
- good agreement among sources when using new field map!



# Testing our field knowledge: e-lifetime

- Source-dependence both without field correction and using the field map w/o charge accumulation on the PTFE walls;
- good agreement among sources when using new field map!



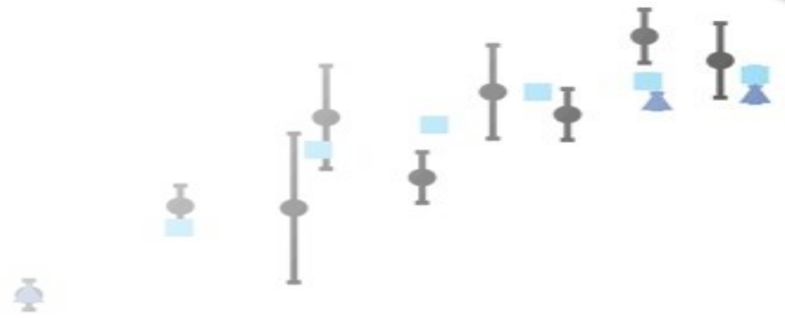
# Conclusion

## Innovative field cage design

- Dual-array for copper-PTFE contact
  - **no time evolution** of charge accumulation observed
- Independently biased field cage
  - **tuning** of the electric field

## Field understanding

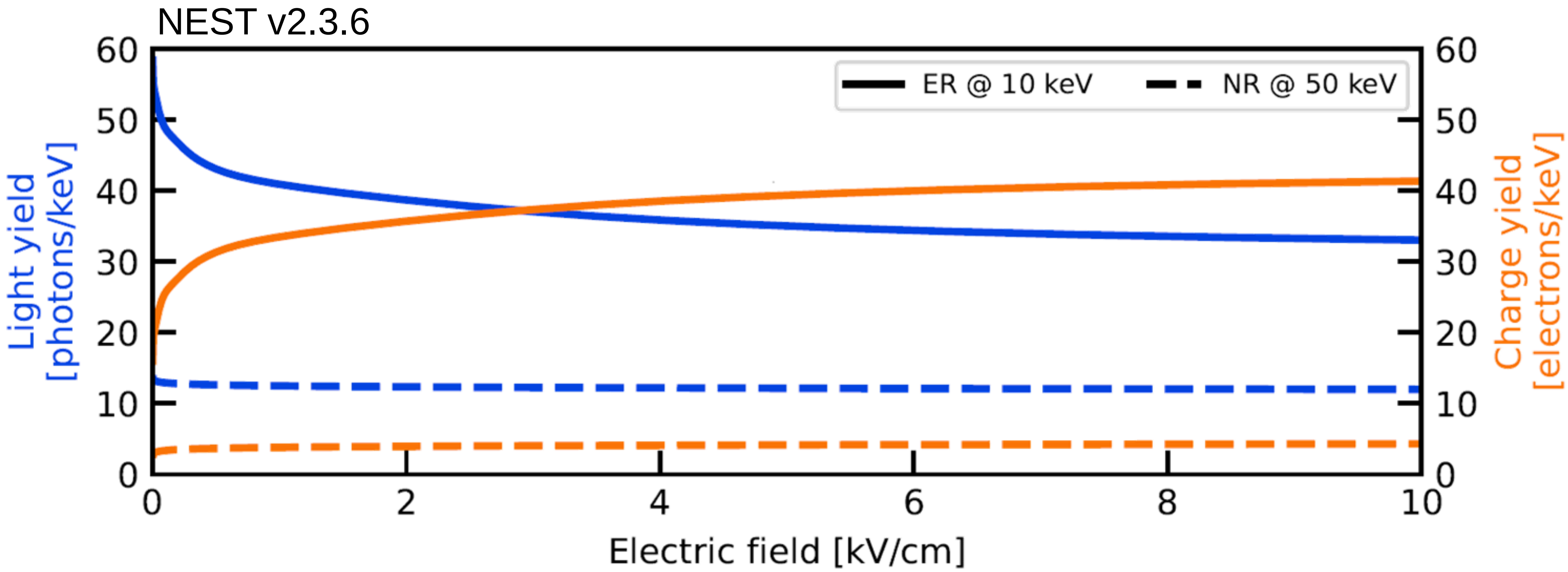
- **Charge accumulation** from comparison of simulations to $^{83m}Kr$ (r, z)-position distribution
- Resolved source-dependence of electron lifetime measurement



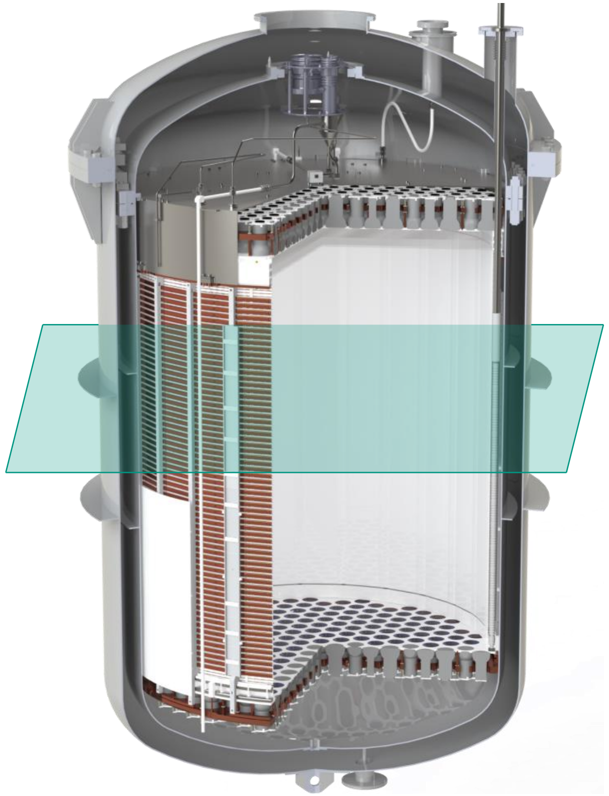
# Backup slides

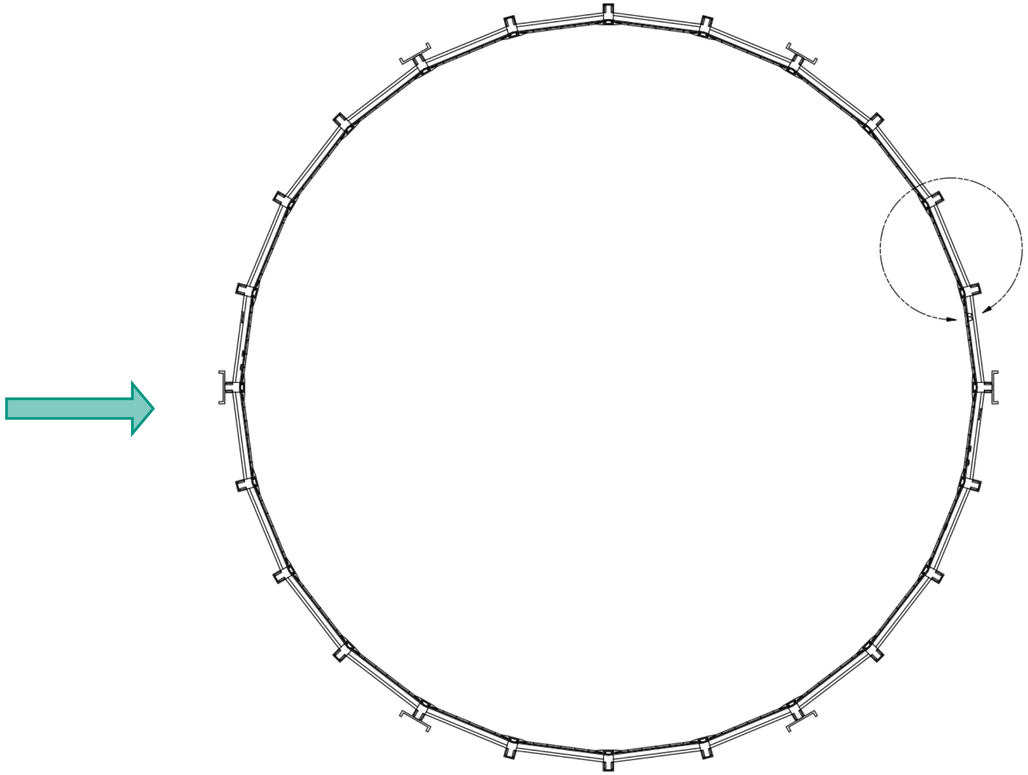
# Charge/light yield

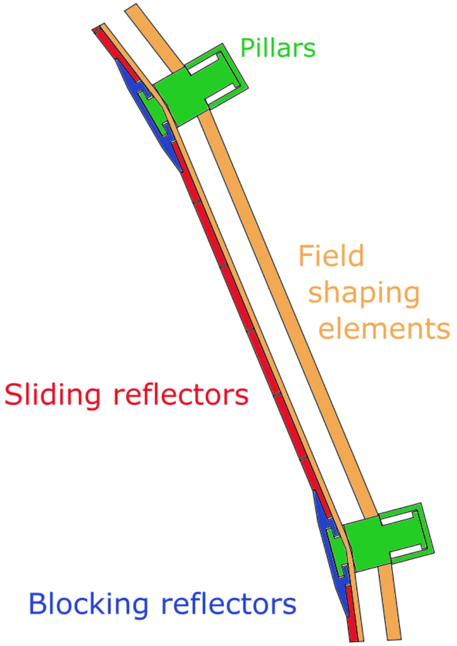
Recombination of electrons and ions leads to excited states, hence scintillation. A stronger electric field increases the charge yield (freed electrons) at the expenses of the light yield.



# Sectional view of the XENONnT field cage

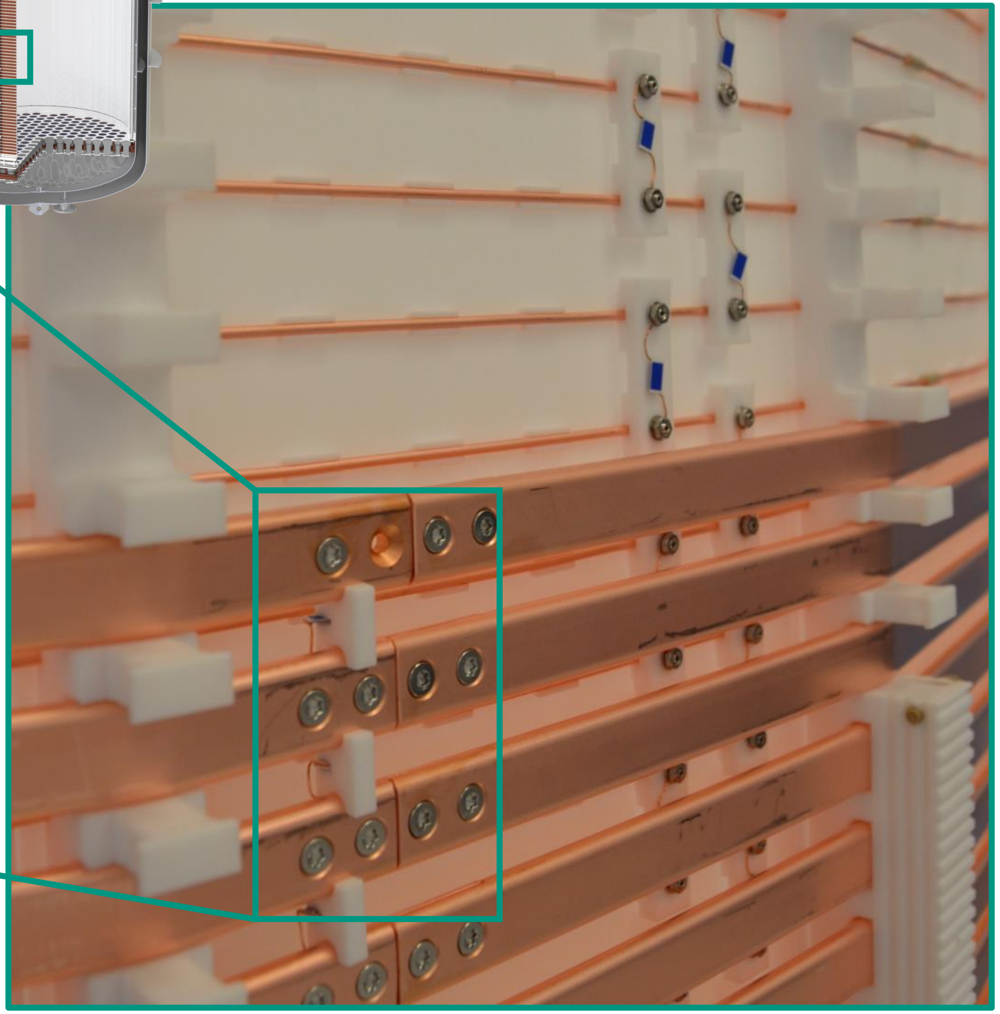







Icositetragon (24-gon) ≃ circle

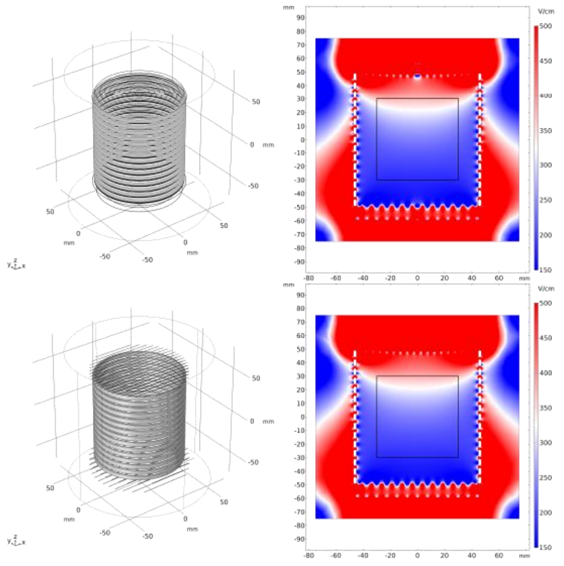
# The field cage of XENONnT

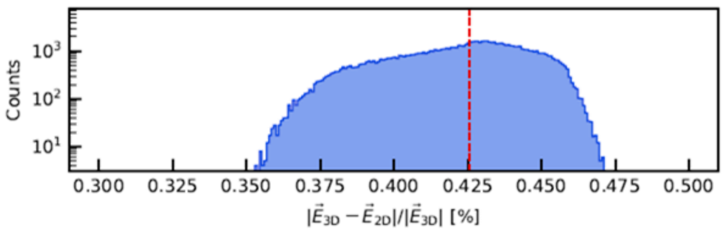


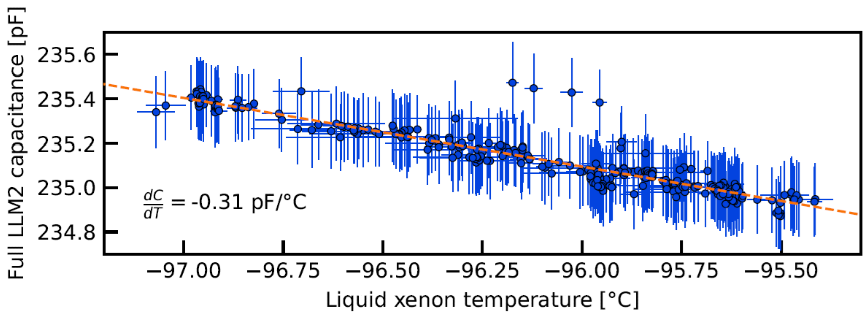
# Systematic checks of simulations

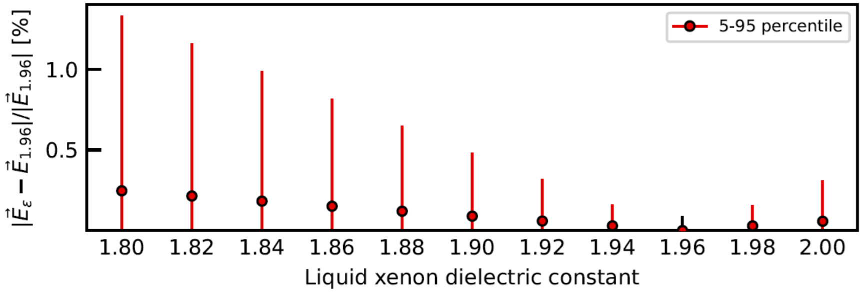
The impact of several effects was considered for the electric field simulations:

- **concentric wire grids**, with an effect of 0.4% within an arbitrary small FV;
- **polygonal TPC**, <1% effect when comparing different TPC radii;
- **LXe dielectric constant**, <1% when considering different literature values.

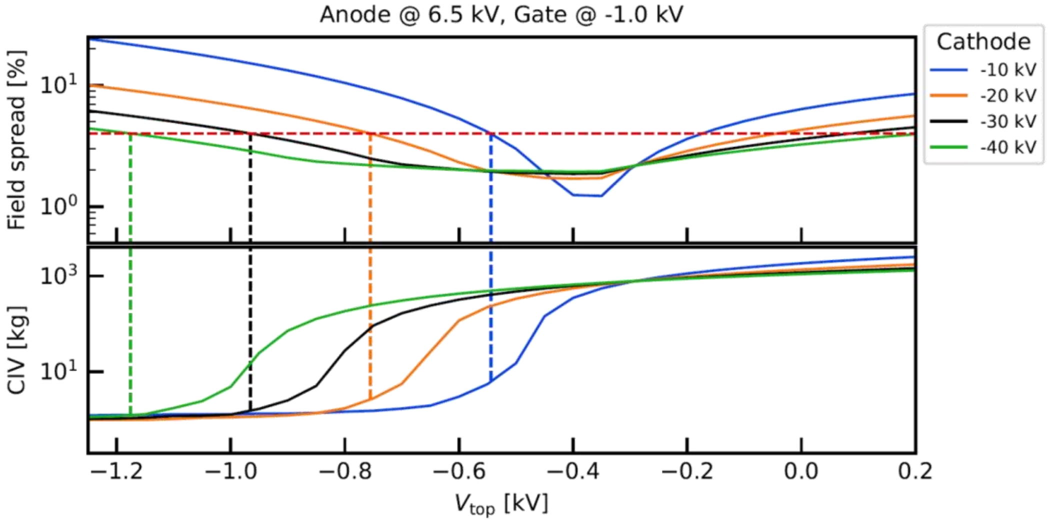




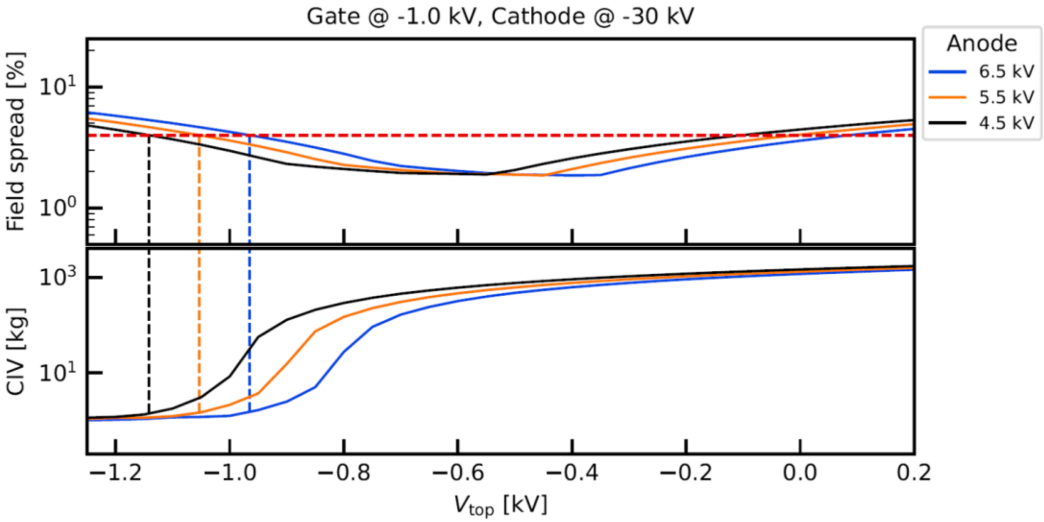



# Bottom resistance for different voltages



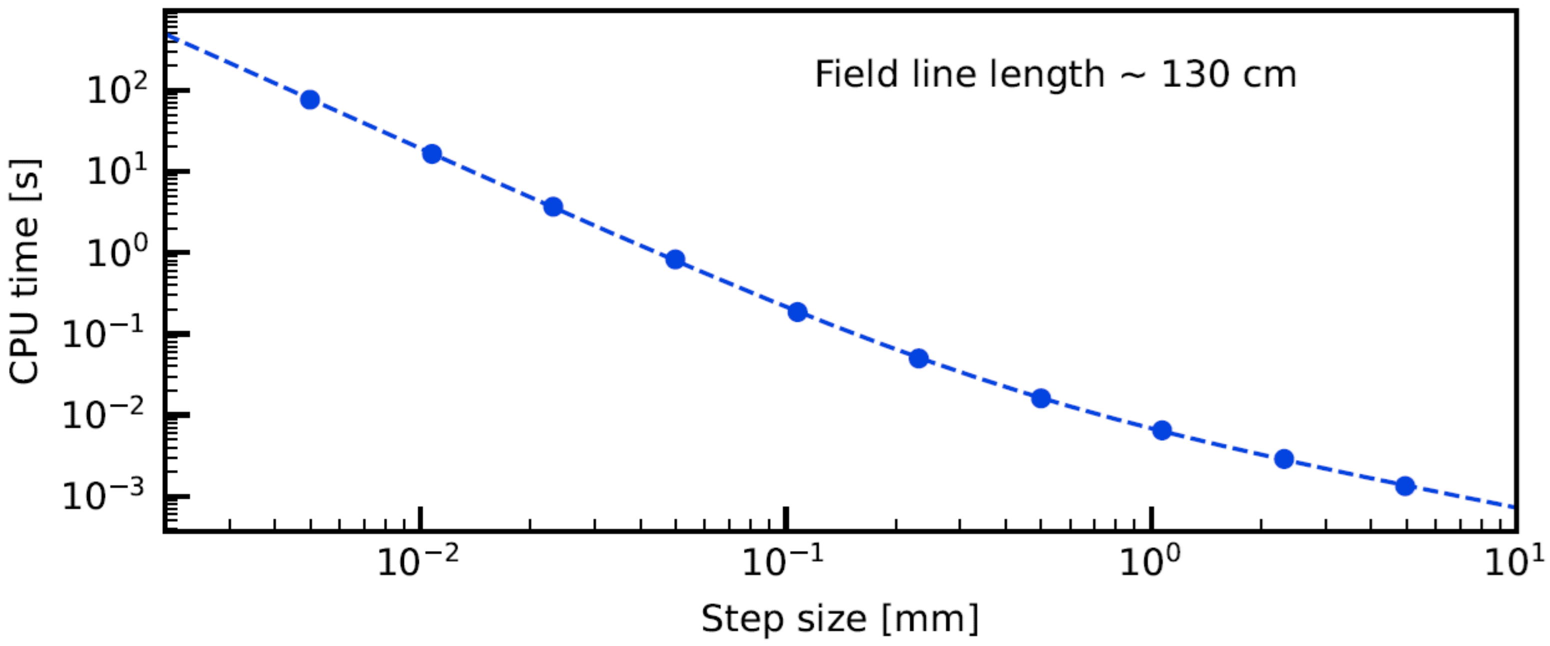

For lower absolute voltages at the cathode it is not possible to tune $V_{top}$ in order to recover the same field performance as for design voltage.

As the anode voltage changes, it is possible to tune $V_{top}$ and retrieve an almost identical performance of the field as for design.



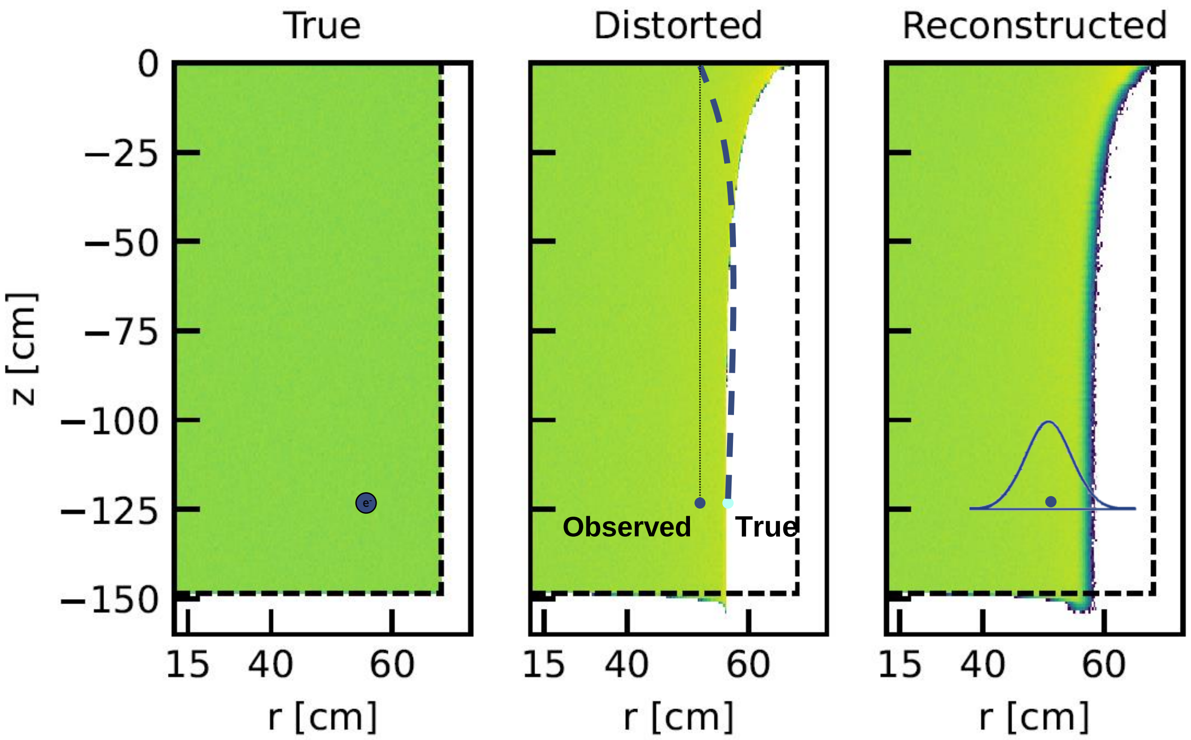
# PyCOMes

- Custom module
- Optimized with the „just-in-time“ compiler numba
- Diffusion coefficients and drift speed values from literature



# Simulation of position distribution

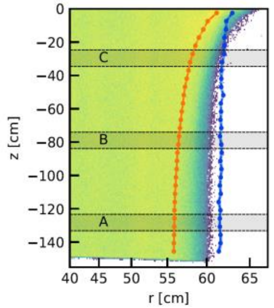
- Uniform distribution of initial positions of electrons within the TPC;
- propagate each electron following the drift field (***PyCOMes*** module) and including drift speed and diffusion;
- consider final radial position to determine (x, y) and drift speed as proxy for z;
- include position reconstruction resolution as gaussian smearing.



# Charge accumulation on PTFE walls

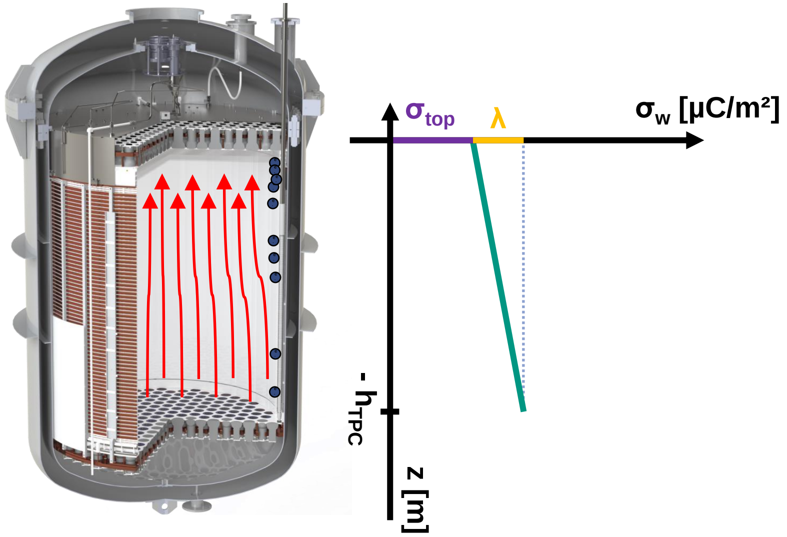
Karlsruher Institut für Technologie

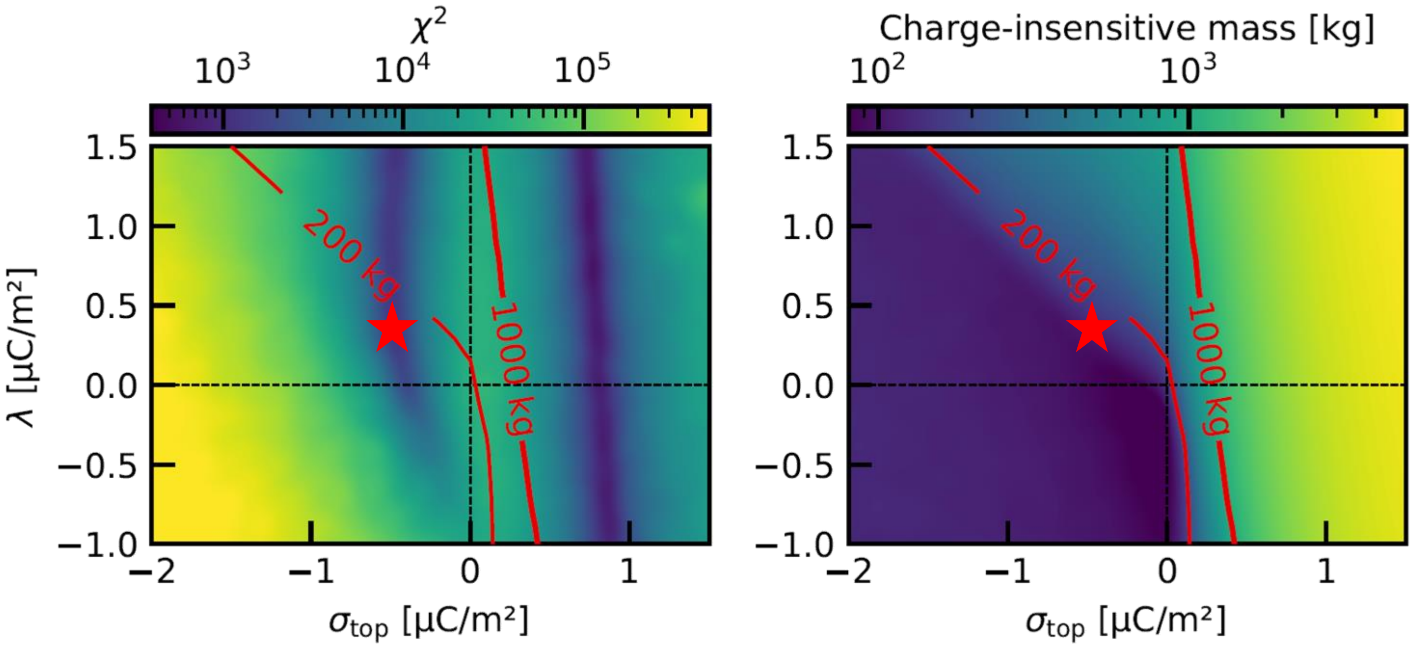
- The expected position distribution and associated 90th percentile along z is evaluated for different combinations of ($\sigma_{top}$, $\lambda$);



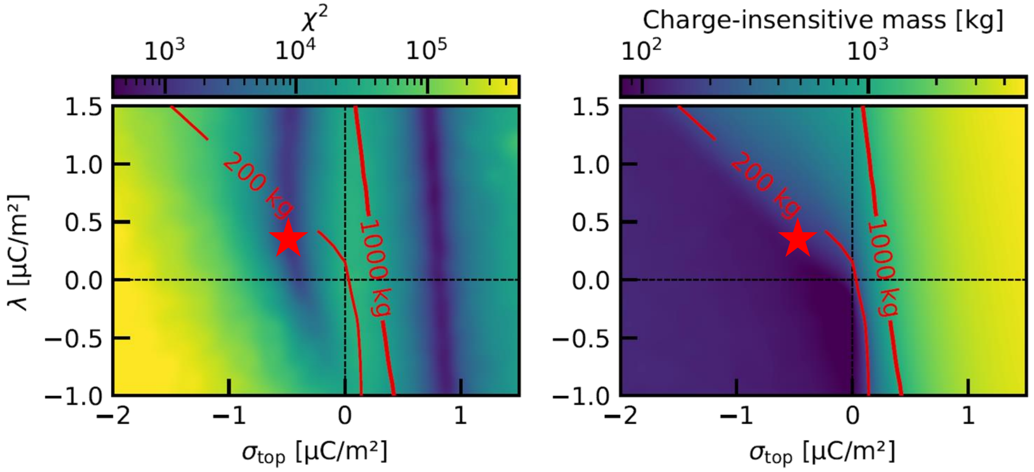

- Chi-square is calculated for each configuration

$$\chi^2 = \sum_{z_i} \frac{\left(r_{90p}^{z_i}\,(\text{data}) - r_{90p}^{z_i}\,(\text{sim})\right)^2}{\sigma_{z_i}^2}$$



# Charge accumulation on walls: uncertainties




$$\sigma_{top} = (-0.50 \pm 0.05(\text{sys}) \pm 0.02(\text{stat}))\ \mu\text{C/m}^2$$

$$\lambda = \left(0.40 \pm 0.15(\text{sys})^{+0.20}_{-0.10}(\text{stat})\right)\ \mu\text{C/m}^2$$

## Systematic uncertainties

- Change z-binning
- Change percentile

## Statistical uncertainties

For each combination ($\sigma_{top}$, λ) the simulated position distribution is resampled 1000 times and the $\chi^2$ distribution is newly estimated. The distribution of the best-matching configurations returns the uncertainty on each parameter.

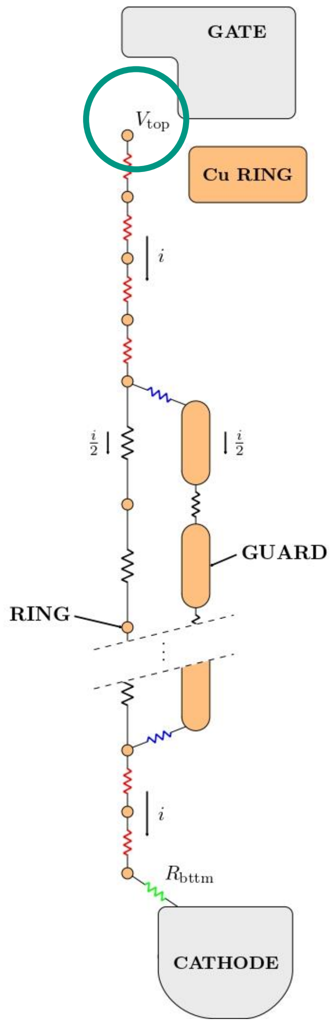
# Testing the field cage

After SR0 a dedicated test (< 1 day) of the bias voltage of the top of the field cage was carried on during a $^{83m}Kr$ calibration.

The bias voltage $V_{top}$ was changed from 300 V (gate voltage) up to 1000 V: this has a small impact on the intensity of the field, but a large impact on its spread.

We want to compare our predictions to the observations regarding:

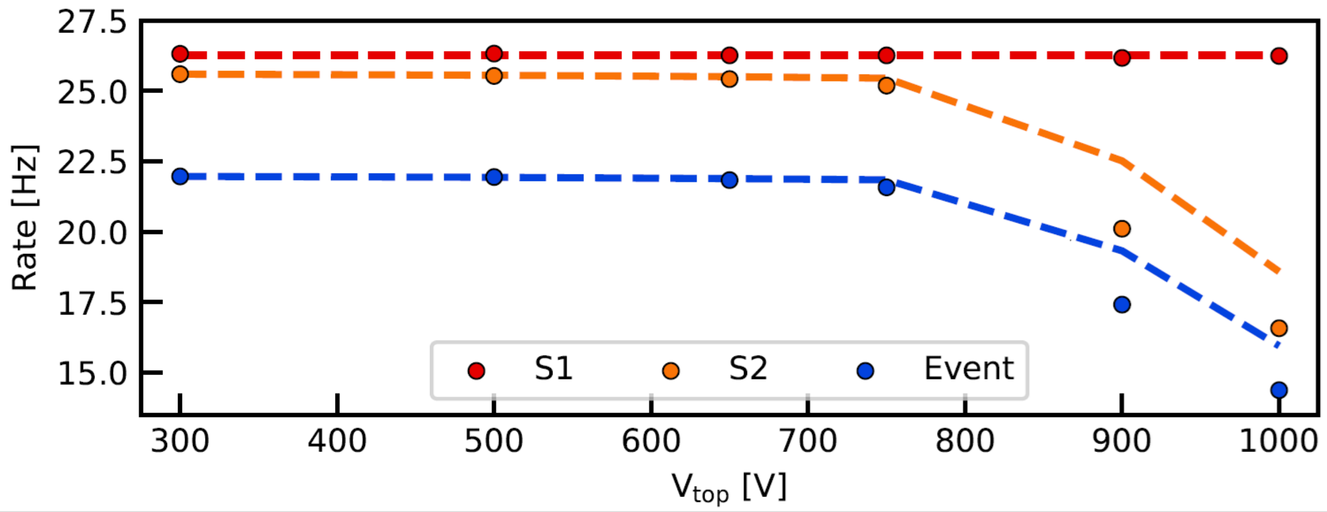
- charge-insensitive volume;
- position distribution;
- electron lifetime.

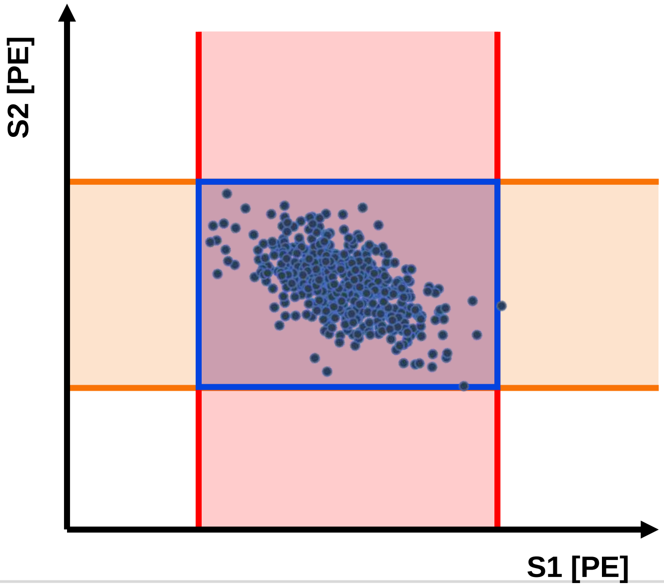


# Testing the field cage: CIV

- S1-, S2-, and event-rate (paired S1+S2) follow simulations:
  - as voltage increases, CIV increases keeping the S1 rate unaffected, while S2 rate decreases;

- disagreement with simulations above 750 V shows room for improvement, but overall understanding of detector physics.

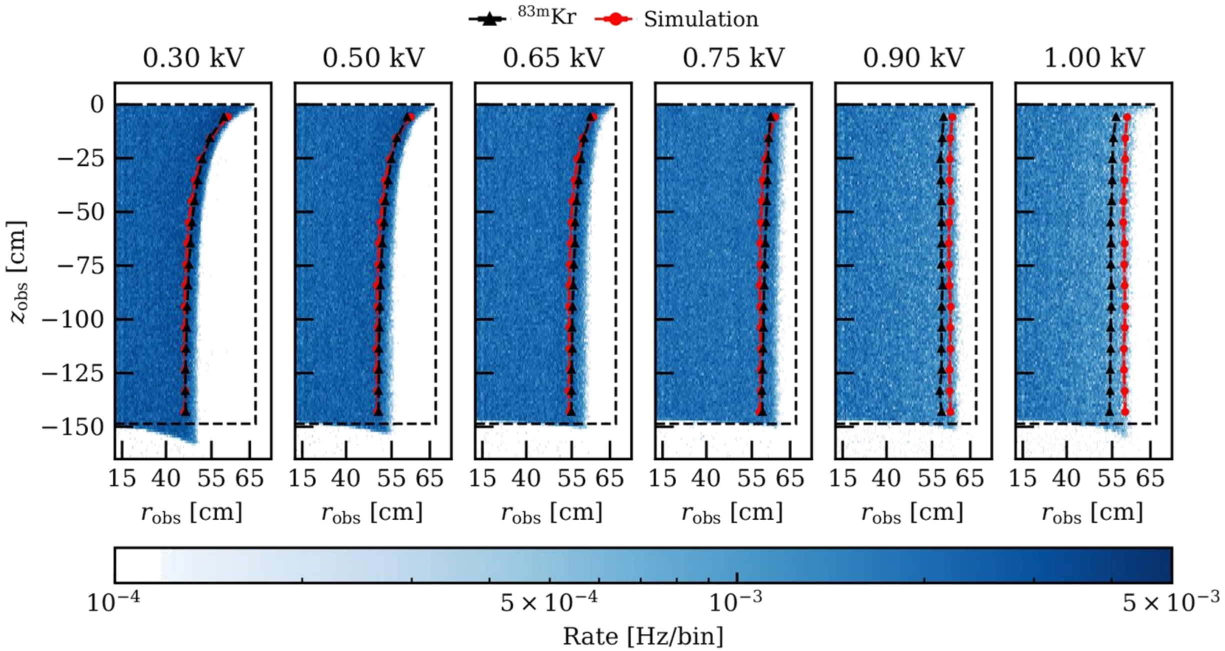


# Testing the field cage: position distribution

- Observed a change in the (r, z)-position distribution for different voltages;

- good agreement with simulations when including the same wall charge distribution from SR0:
  - surface charge density is not affected by field cage tuning;
  - agreement worsens above 750 V.




$$\sigma_{top} = (-0.50 \pm 0.05_{(sys)} \pm 0.02_{(stat)})\ \mu C/m^2$$

$$\lambda = \left(0.40 \pm 0.15_{(sys)}{}^{+0.20}_{-0.10}{}_{(stat)}\right)\ \mu C/m^2$$

# Testing the field cage: electron lifetime

- Measured electron lifetime clearly shows a dependence on the homogeneity of the electric field;
- when correcting for the corresponding field map, an agreement among different measurements is recovered: physical electron lifetime!