3D Electric Field Simulations for XENONnT

Zurich PhD Seminar

University of Zurich[UZH]

Department of Physics

8 September 2020

Ricardo Peres

The XENON Colaboration (2020 edition)

28
Institutions
worldwide

150+
members

The XENON Colaboration (2020 edition)

Columbia RPI Nikhef Muenster KIT Stockholm Mainz MPIK, Heidelberg Freiburg

Chicago

UCSD

Rice

Purdue

Zurich

Tokyo

Nagoya

Coimbra Subatech LPNHE IJCLab L'Aquila Bologna LNGS Torino Napoli Weizmann NYUAD Kobe

The XENON detectors

XENON10
Target mass: 14kg
2005-2007

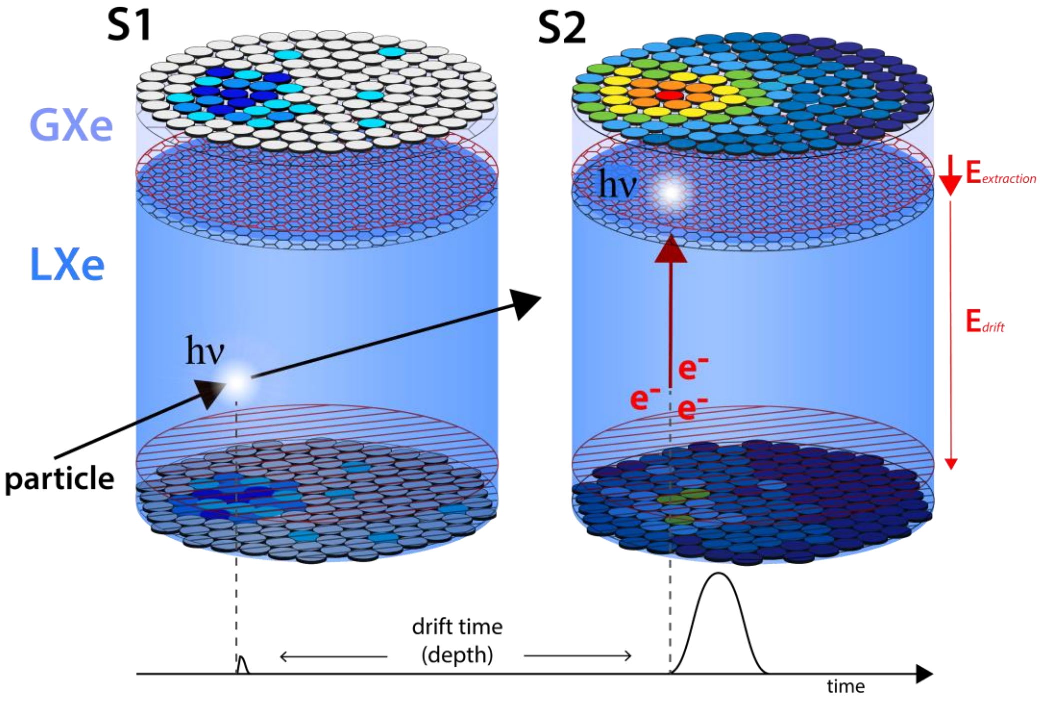
XENON100
Target mass: 62kg
2008-2016

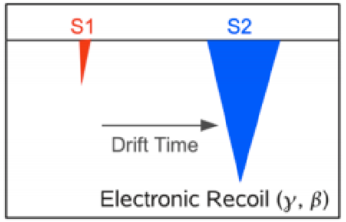
XENON1T
Target mass: 2000kg
2013-2018

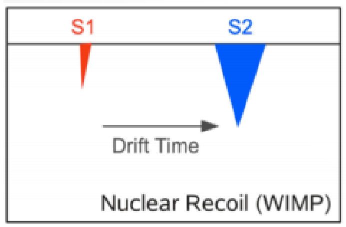
XENONnT
Target mass: 6000kg
2020 - 2025

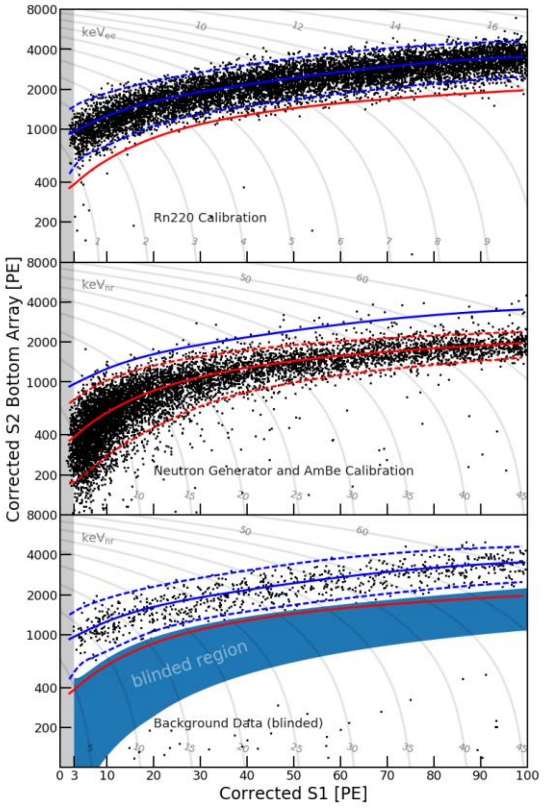
Detection principle

- Two-phase Time Projection Chamber (TPC)
  - Energy calculation
  - 3D event reconstruction
  - Type of recoil discrimination (ER or NR)





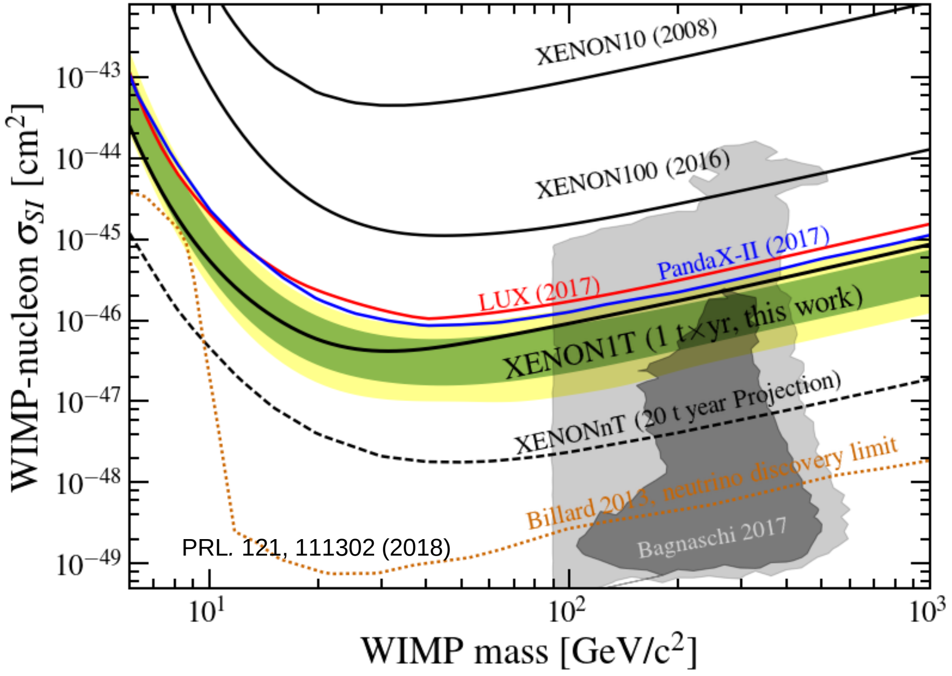


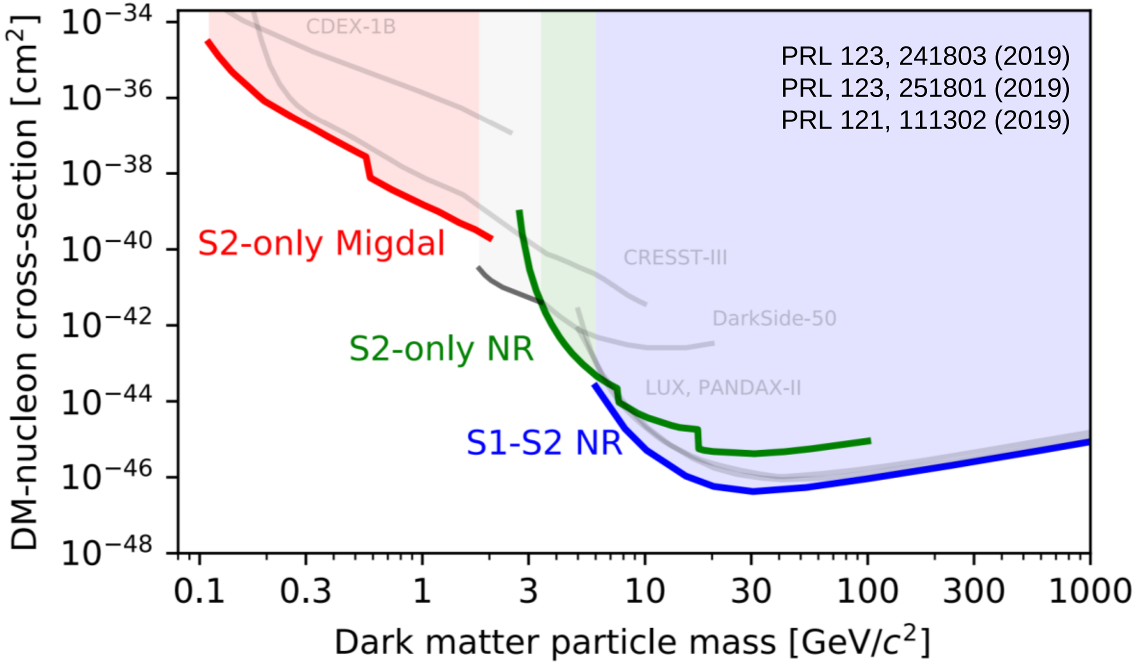


PRL 119.181301 (2018)

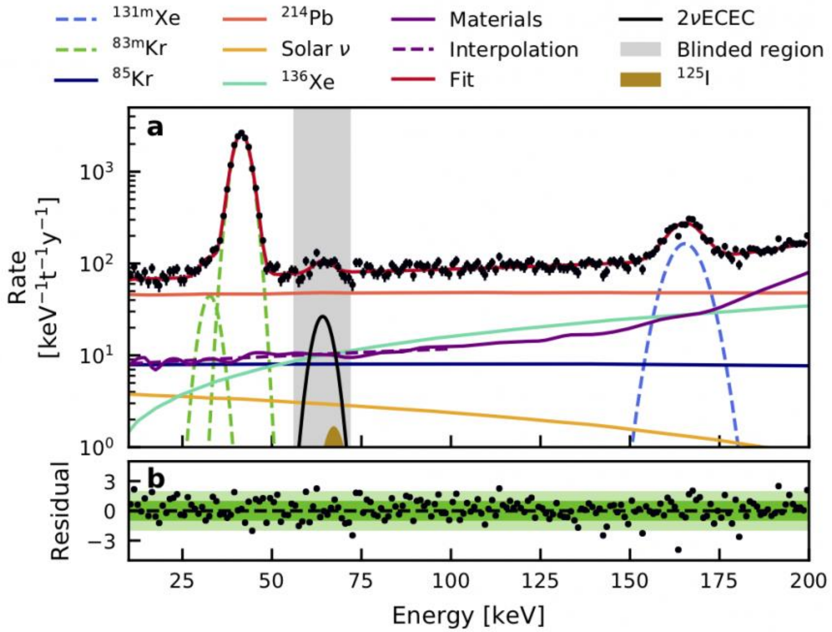
XENON1T, the most sensitive DM detector

SI WIMP-nucleon cross section



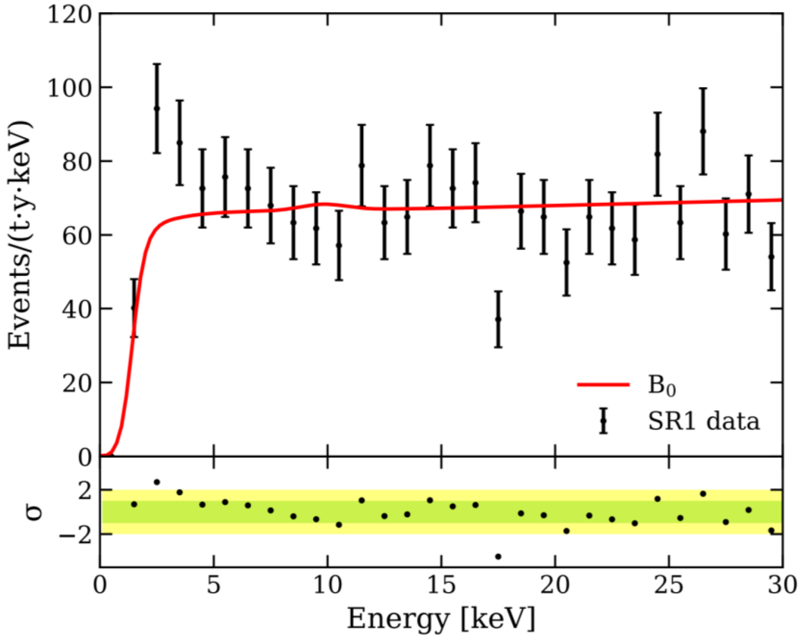


XENON1T, beyond DM searches



First observation of two-neutrino double electron capture in Xe124.

Nature volume 568, pages 532–535 (2019)



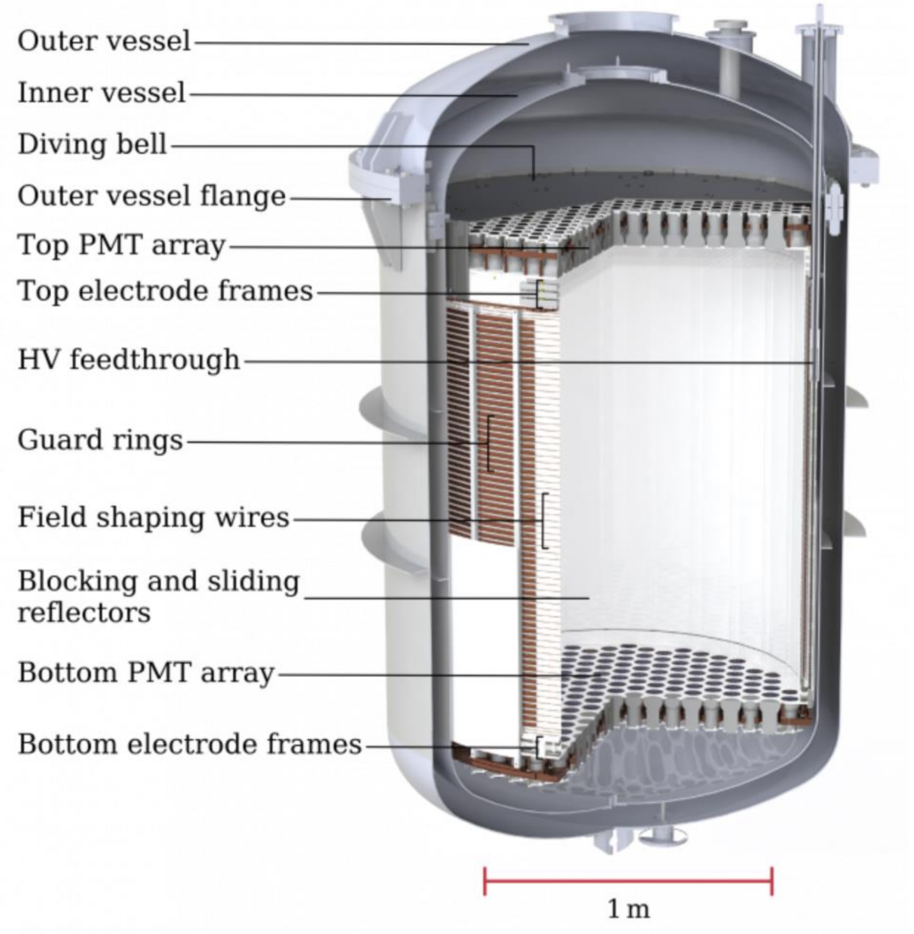
Reported excess in Low-ER background data.

arXiv 2006.09721 (2020)

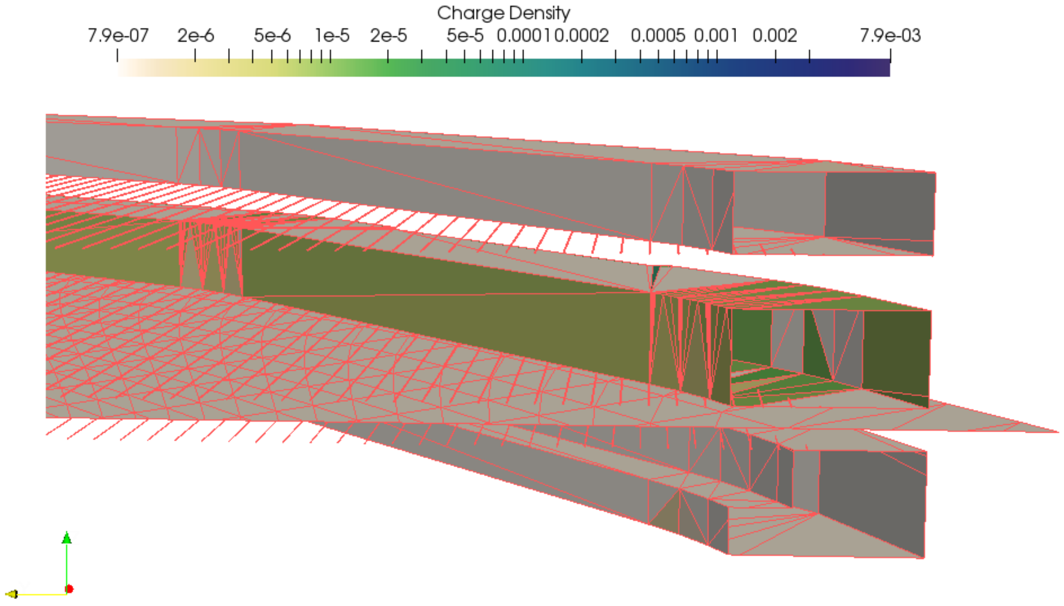
Onwards to XENONnT

- Upgrade from XENON1T
- From 2 to 5.9 t active volume of LXe
- 1.5 m height x 1.5 m diameter TPC
- 253 PMTs on Top Array
- 241 PMTs on Bottom Array
- Two different field shaping elements:
  - Wires
  - Guards

See Giovanni Volta's talk
Tomorrow @ 13:30

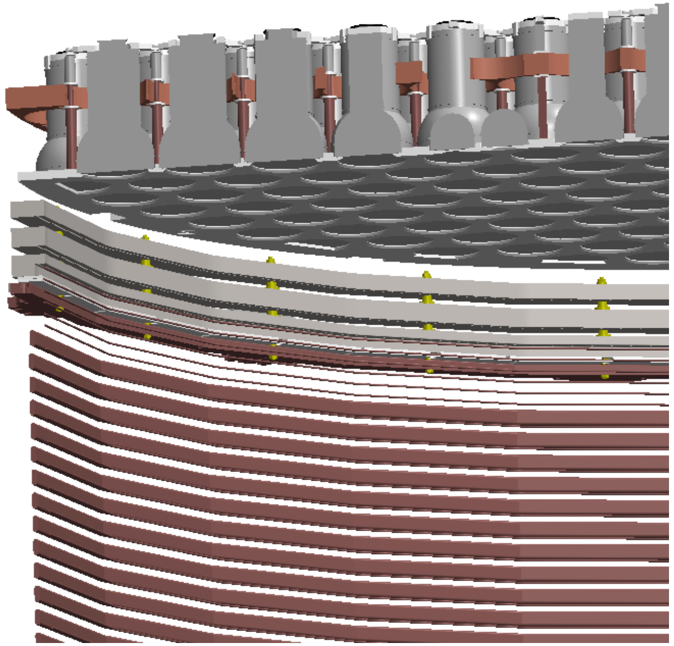


XENONnT electrodes



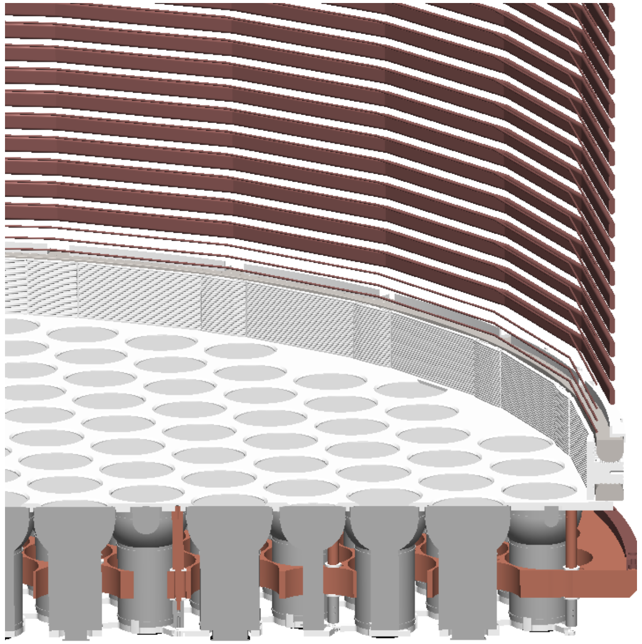
Electrode	Voltage (V)	Wire diameter (mm)	Wire pitch (mm)	Z position (mm)
Top screening	-1500	0.216	5	+36
Anode	+4500	0.216	5	+8
Gate	-2000	0.100	5	0
Cathode	-30k	0.216	7.5	-1501
Bottom screening	-1500	0.216	7.5	-1536
Perpendicular Wires				
Anode	+4500	0.304	--	+8
Gate	-2000	0.304	--	0

XENONnT electrodes



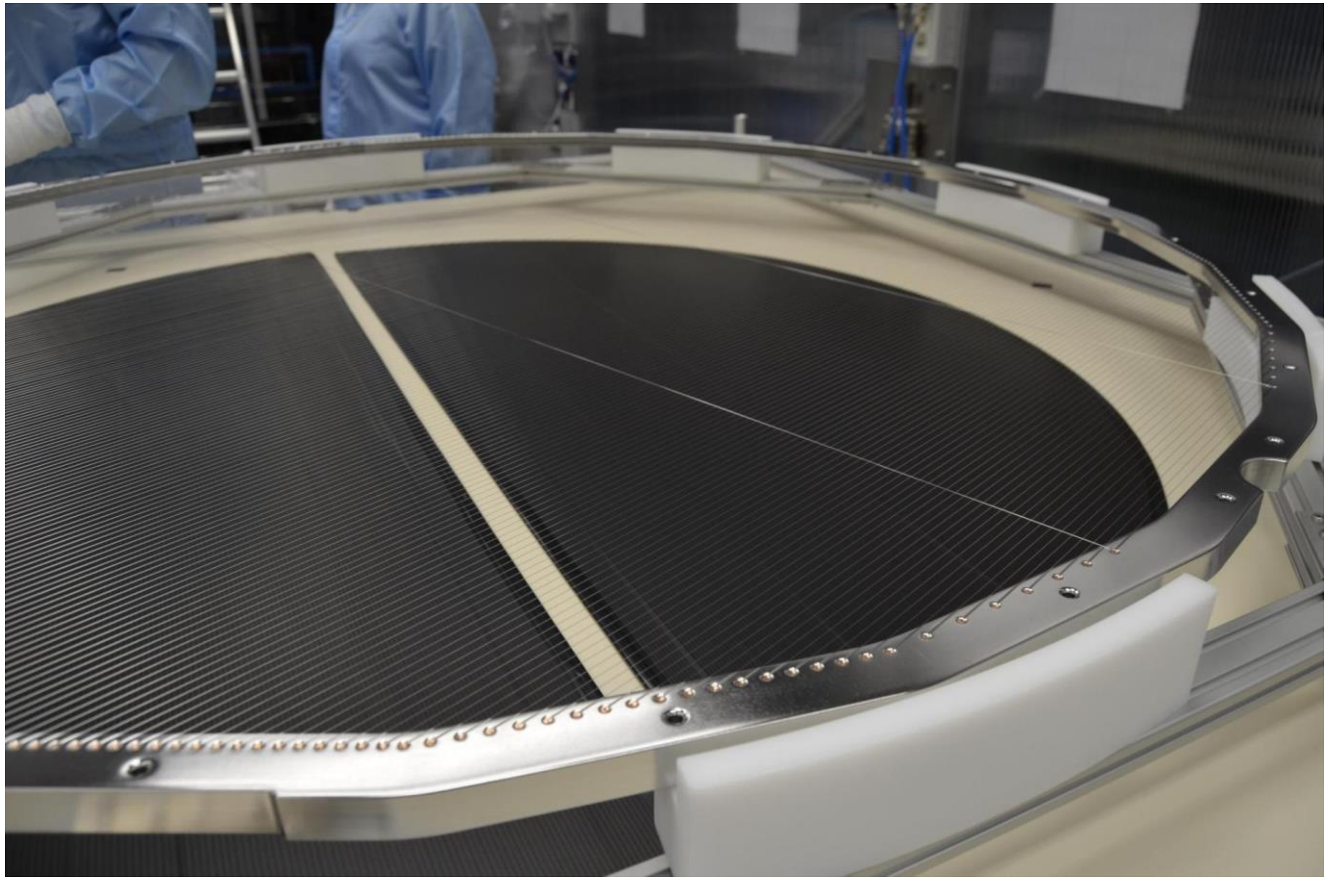
Drift field: 186.5 V/cm
Extraction field: 8 kV/cm

71 wires
64 guards



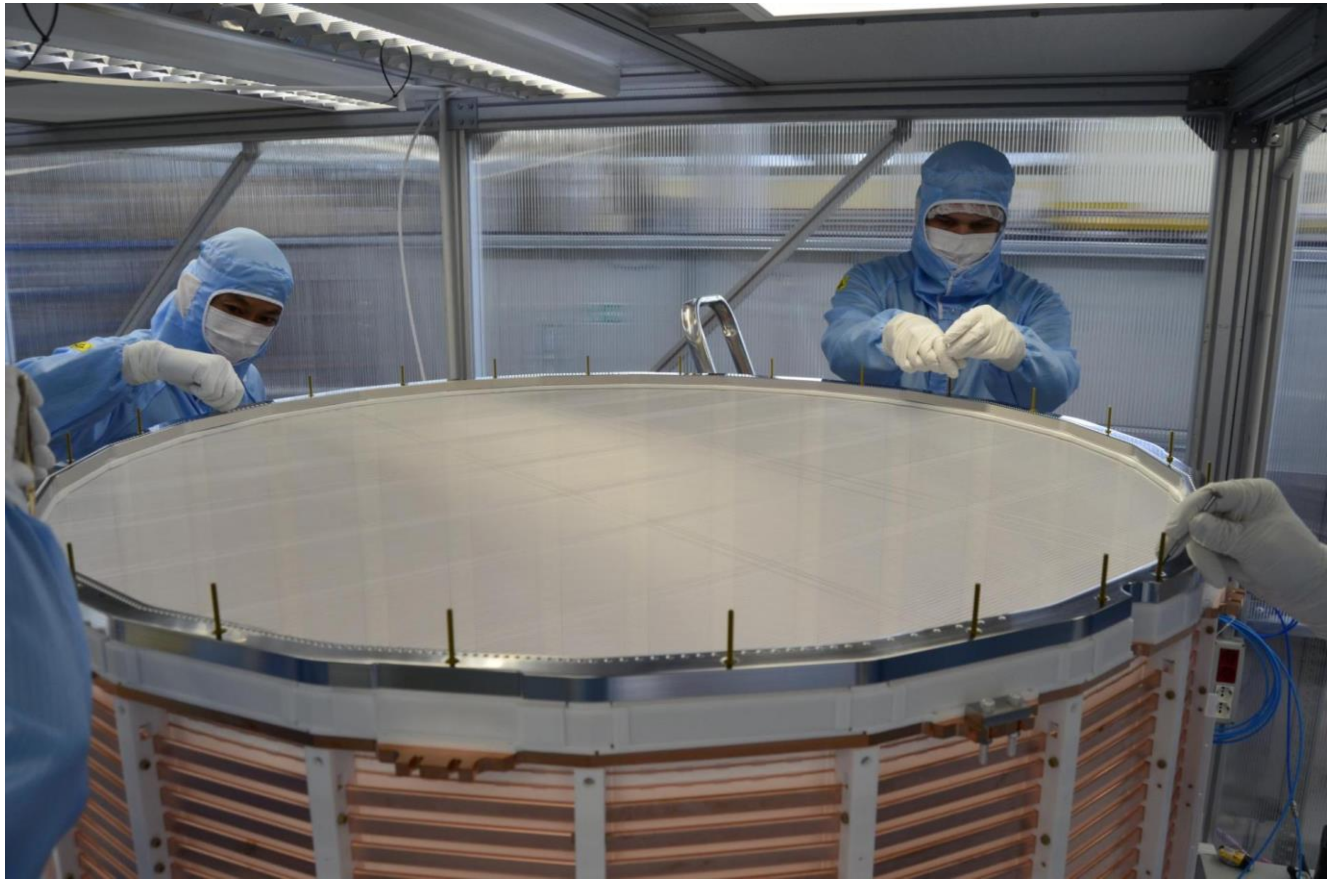
XENONnT electrodes

Gate electrode during assembly



XENONnT electrodes

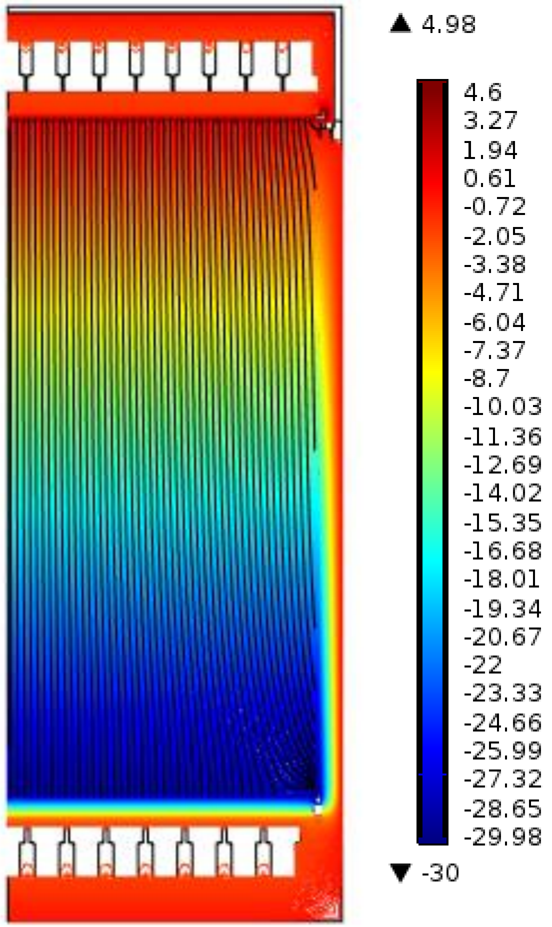
Top stack electrodes during assembly



See Giovanni Volta's talk for more in depth assembly procedures Tomorrow @ 13:30

Electric field simulations for XENOnT

- A well understood electric field is of major importance for proper analysis of our data:
  - Electron drift velocity and time;
  - Electron extraction efficiency;
  - Streamlines and electron drift;
  - Charge and light yield 3D map;
  - Electron loss on the PTFE walls;
  - Simulation driven field corrections;



EF simulation - methods

Finite Element Method

- Pros
  - Commercially available (COMSOL Multipyshics) - less steep learning curve
  - Less steep learning curve
  - Better for non-linear problems
  - Applicable to dynamic problems
- Cons
  - Scales with volume
  - Requires large computational power

Boundary Element Method

- Pros
  - Open regions are not a problem
  - Very accurate for field solutions
  - Can run in parallel in GPU clusters.
  - Faster to reach same level of accuracy.
- Cons
  - Not so common or commercially available – steeper learning curve

BEM for Electrostatic fields

- Only surface of electrodes and dielectrics need to be meshed into sub-elements.

$$S = \sum_{j}^{N} S_j$$

- Each sub-element has a constant charge density homogenously distributed.
  - In KEMField these sub-elements can triangles, rectangles or wires.
  - Each element is defined by its shape, coordinate and voltage.

$$U_i = \sum_{j}^{N} C_{ij}\sigma_j$$

U_i - Electric potential
σ_j - Charge density
C_{ij} - Coulomb-matrix element

$$C_j(\vec{r_i}) = \frac{1}{4\pi\epsilon_o}\int_{S_j} \frac{1}{\vec{r_i} - \overrightarrow{r_{S_j}}}\, d^2\overrightarrow{r_{S_j}}$$

For dielectric sub-elements: $\epsilon_i^+ E_i^+ n_i + \epsilon_i^- E_i^- n_i = 0$

BEM for Electrostatic fields

- Given the calculated Coulomb-matrix elements and the set applied voltage on the sub-element, the charge densities, σ_j, can be found.

$$\sigma_i = \left(U_0 - \sum_{j \neq i}^{N} C_{ij} \sigma_j \right) / C_{ii}$$

- KEMField solves the matrix equation with the iterative Robin-Hood method
  - Scales with O(N) memory-wise.
  - Can be highly parallelized.
  - In each iteration finds the sub-element which differs the most from the equipotential surface and recalculates its charge density.

$$U_i = \sigma_i C_{ii} + \sum_{j \neq i}^{N} C_{ij} \sigma_j \qquad U_i = \sum_{j}^{N} C_{ij} \sigma_j \qquad \theta = \frac{U_0 - U_i}{U_0} < \theta_{max}$$

BEM for Electrostatic fields

- Computing the charge densities of all the sub-elements marks the first and most demanding part of the simulations.

$$U(\vec{r}) = \frac{1}{4\pi\epsilon_o}\sum_{j}^{N}\sigma_j\int_{S_j}\frac{1}{\vec{r}-\overrightarrow{r_{S_j}}}\,d^2\overrightarrow{r_{S_j}}$$

- The electric potential and field can be calculated at any given point by the superposition of the individual contributions of the sub-elements.

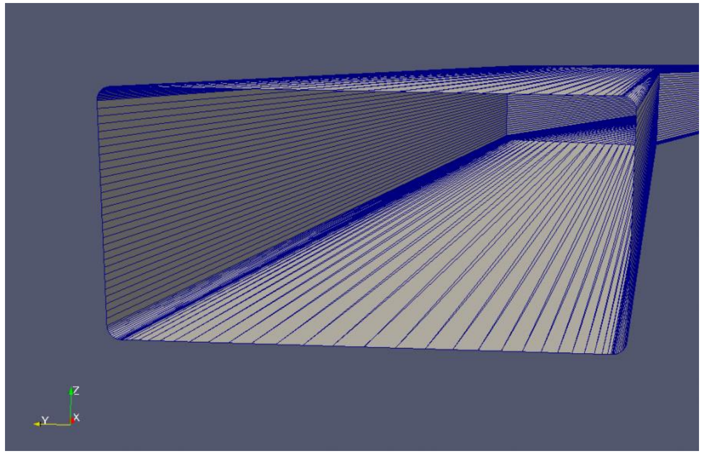
$$E(\vec{r}) = \frac{1}{4\pi\epsilon_o}\sum_{j}^{N}\sigma_j\int_{S_j}\frac{\vec{r}-\overrightarrow{r_{S_j}}}{\left(\vec{r}-\overrightarrow{r_{S_j}}\right)^3}\,d^2\overrightarrow{r_{S_j}}$$

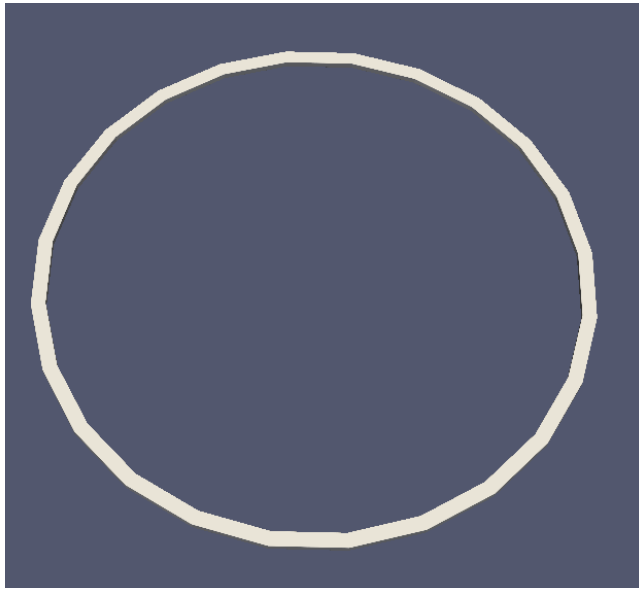
Xenon Simulation and Analysis Package

- Repo on github.com/Physik-Institut-UZH/XSLAP
- Custom adaptation of the KEMField software developed by Katrin for EF simulation (github.com/KATRIN-Experiment/Kassiopeia);
- Core and computation in C++ and OpenCL/MPI for use in GPUs
- Output to .stl and .root files
- Python scripts and jupyter notebooks for analysis
  - Field mapper + streamline calculation
  - Drift of electrons in Xenon
  - Electron multiplication *

Simulating the detector's geometry

- All the geometry elements must be meshed with triangles, rectangles and/or wires.
  - By coding the distribution of the sub-elements

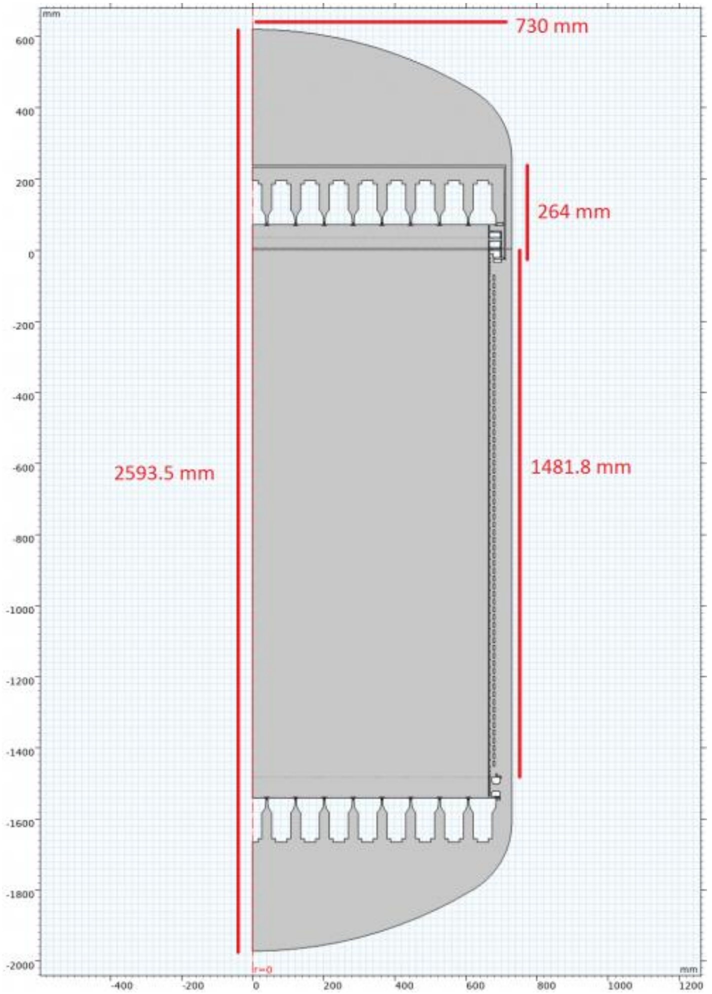




  - By importing a converted version of the CAD drawing of the part

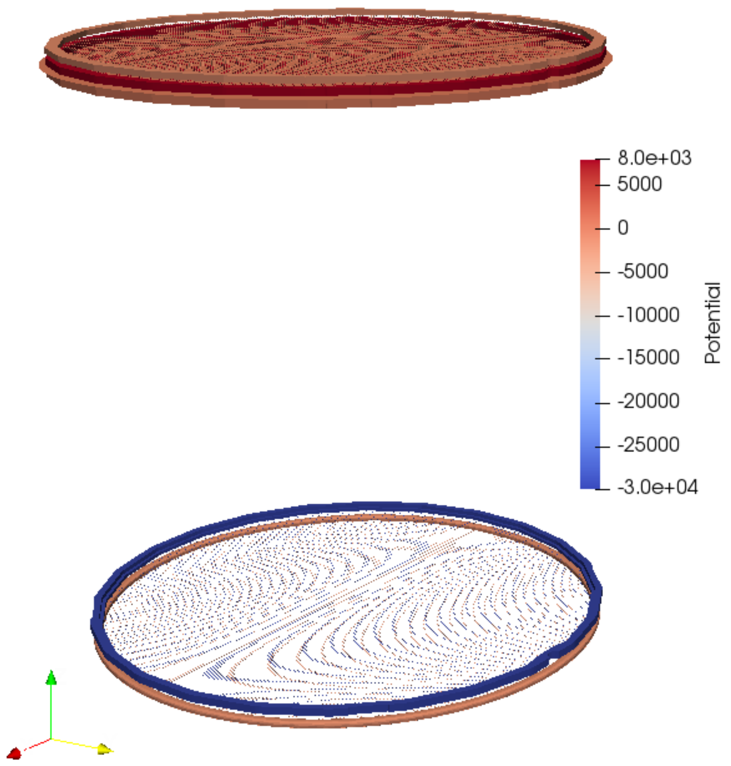
XENONnT simulations

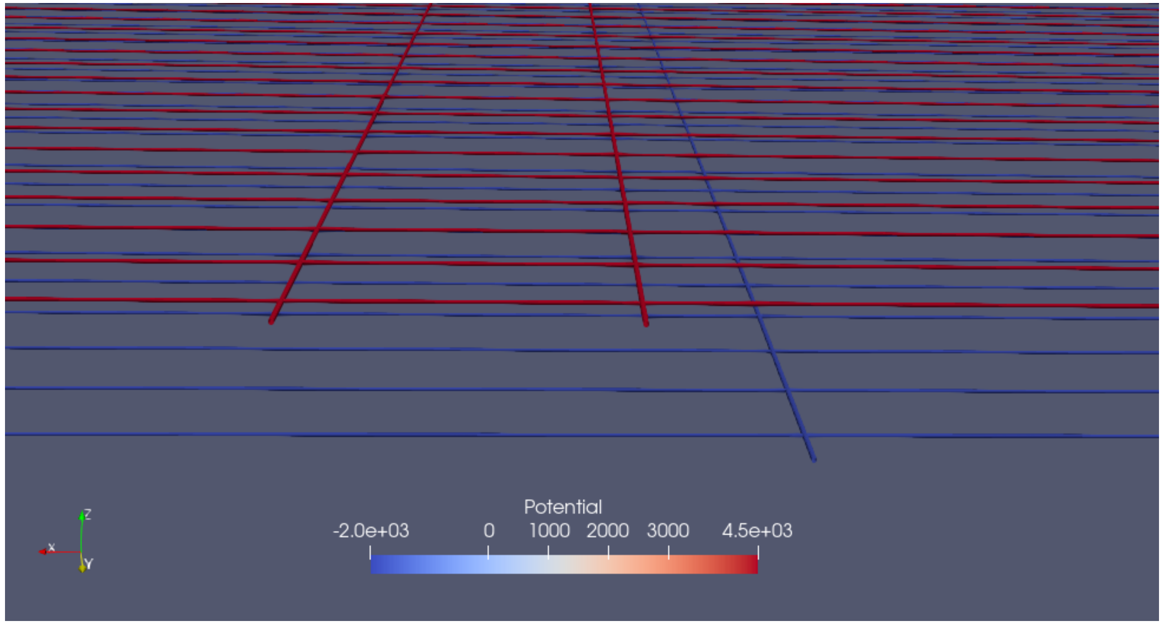
- Electrodes (+holders):
  - Top screening
  - Anode
  - Gate
  - Cathode
  - Bottom screening
- Field shaping elements:
  - Wires
  - Guards
- Cryostat (inner)
- Bell
- PMTs



From CAD to KEMField

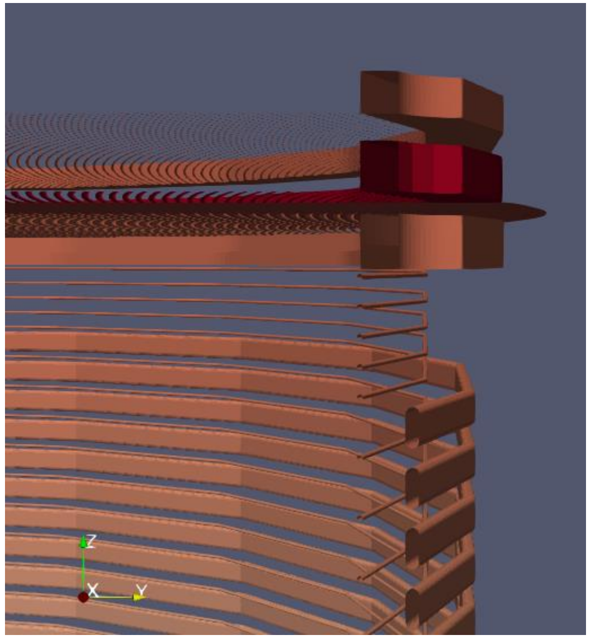
- All electrodes (wires + holders + perpendicular wires)

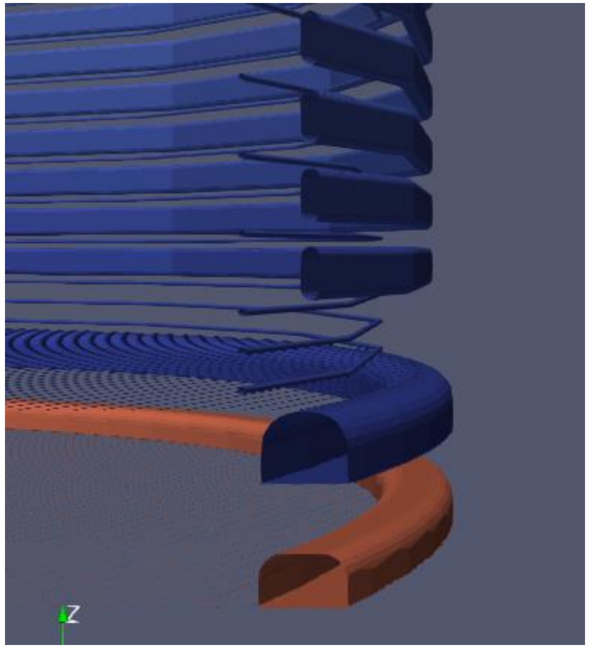




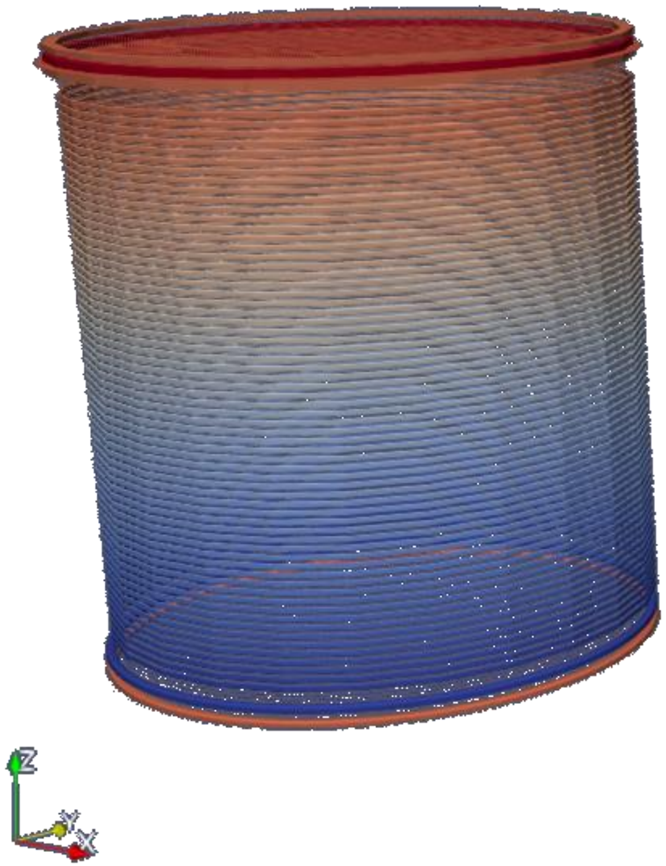
Field Shaping Elements

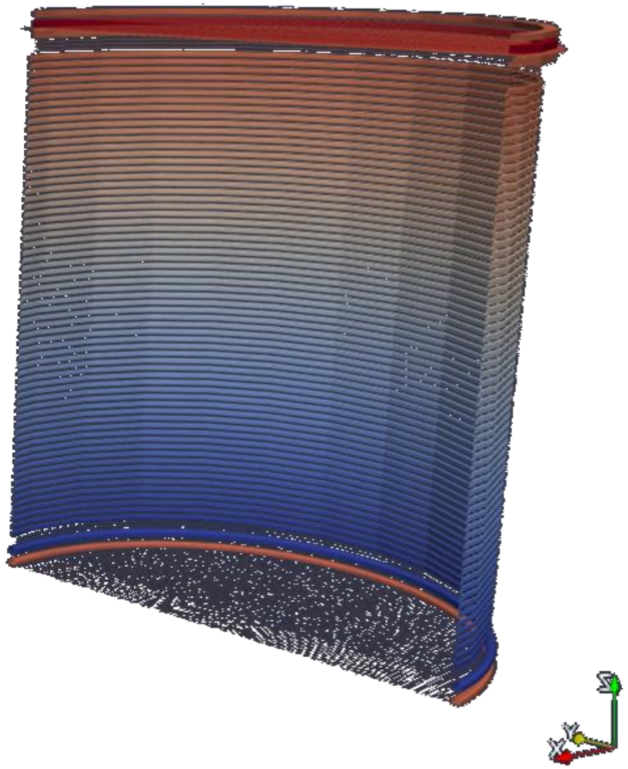
- XENONnT has two different types of shaping elements:
  - Wires – flushed with the PTFE pannels
  - Guards – 1 cm outwards from wires





XENONnT - full model

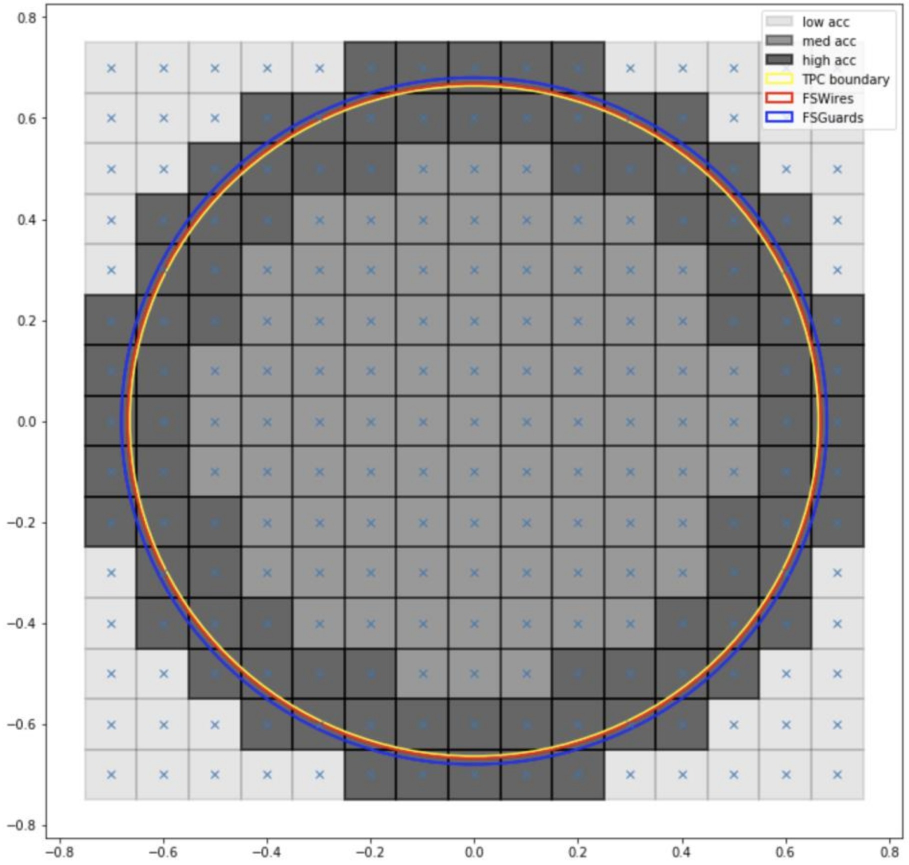




Computing the Electric Potential and Field

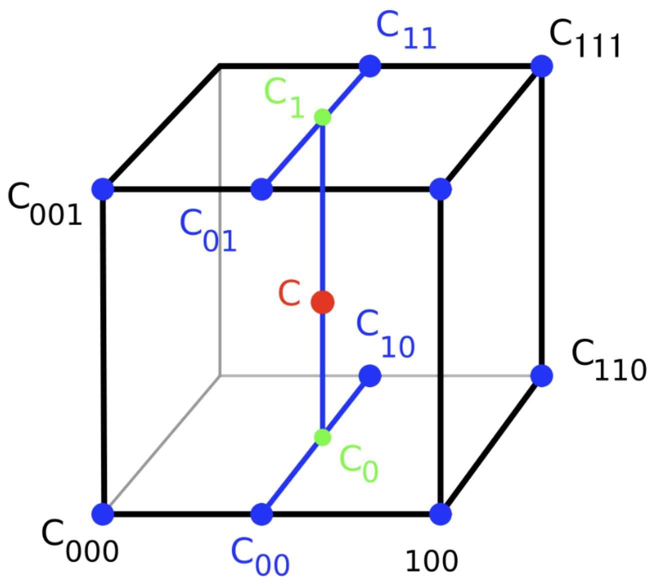
- Batch submission at UZH GPU cluster.
- 3D space points divided between high, medium and low accuracy regions for more efficient computation

High accuracy	Medium accuracy	Low accuracy
1 mm	8 mm	50 mm
48 cubes	89 cubes	88 cubes
1M elements/ cube	1728 elements/ cube	8 elements/ cube



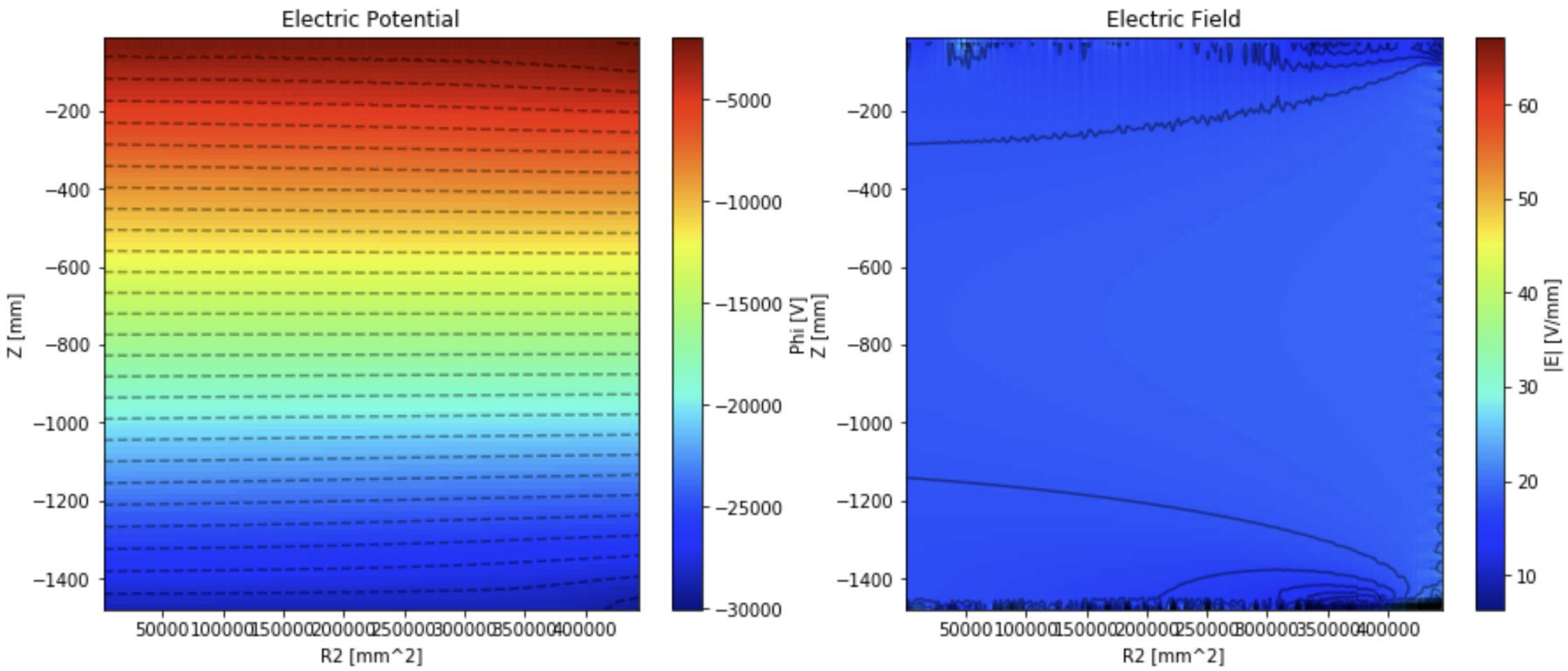
Interpolating field between points

- Using XSLAP to compute all the required electric field points has proven a risk (crash, full sets with NaNs, availability of cluster...)
- From a set of computed points, any other in between can be 3D interpolated.
- scipy.interpolate.RegularGridInterpolator
  - Fast
  - Requires regular grid



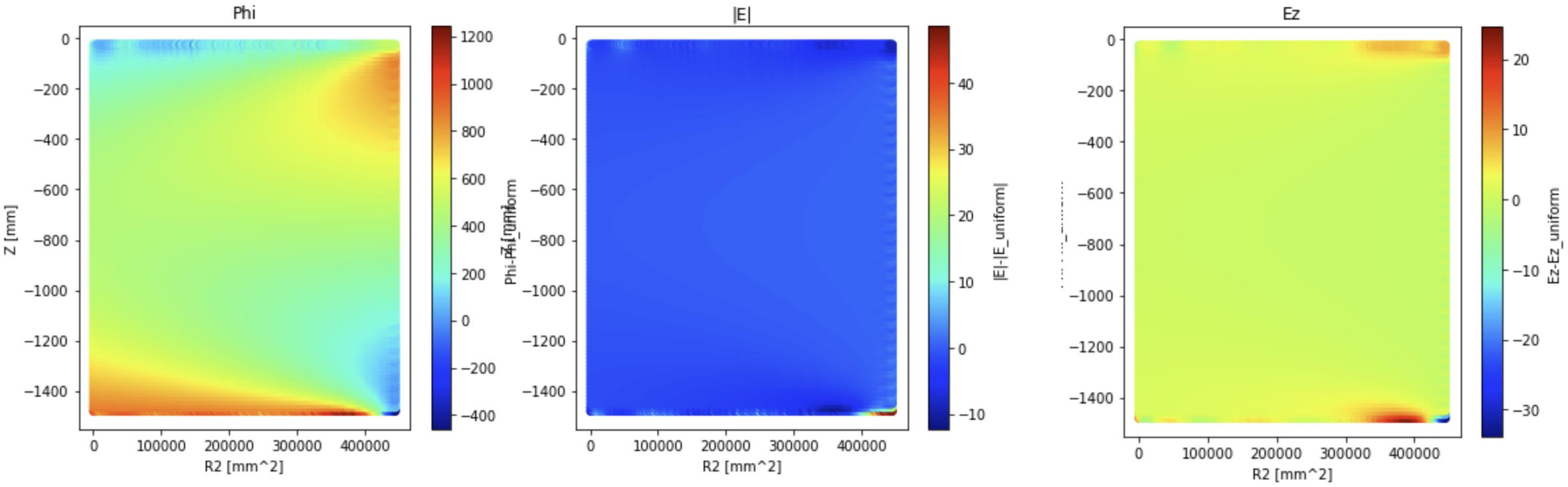
Results for the drift field

- 2D projection (averaged over the full azimotal angle).
- Distributions of Ex and Ey average zero, as expected.



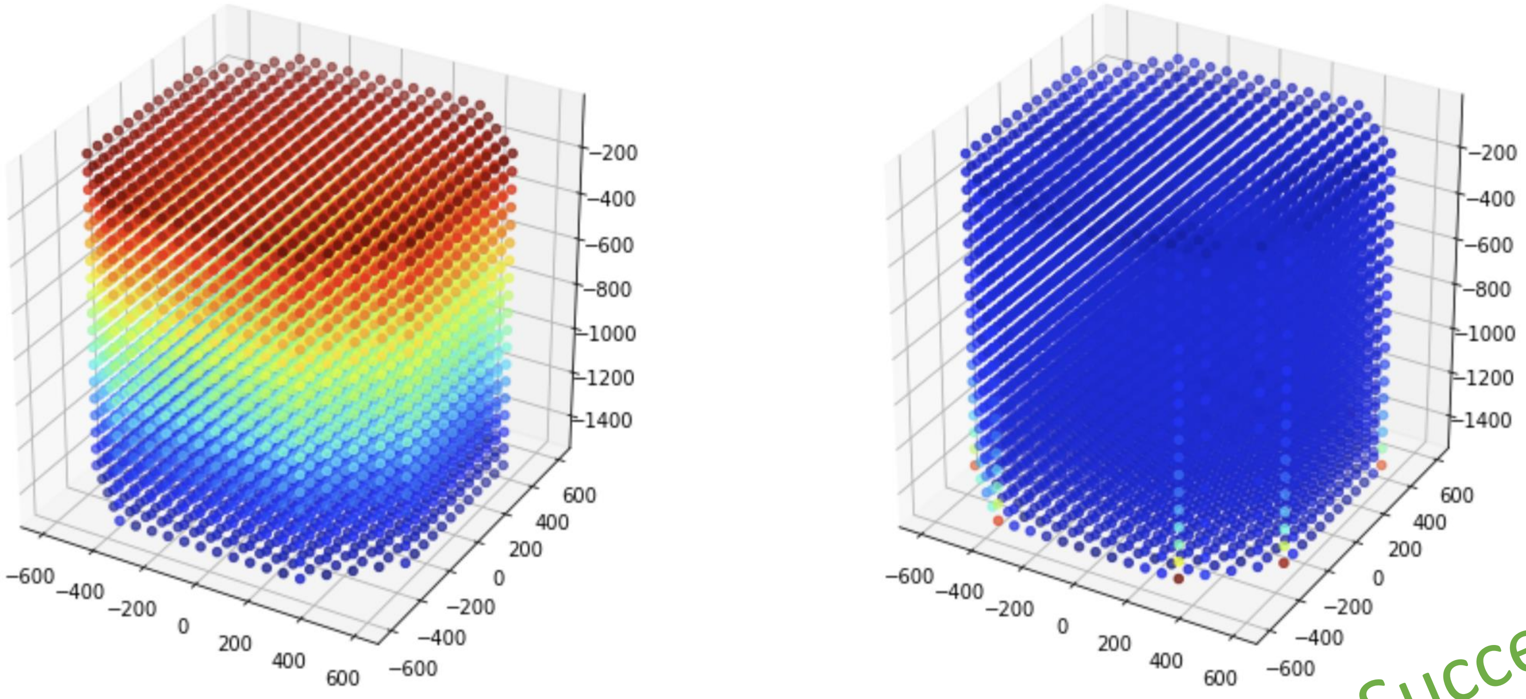
Results for the drift field

- How far from nominal value? (186.5 V/cm)
  - Potential: mostly on an offset
  - Efield: very close to nominal



Results for the drift field

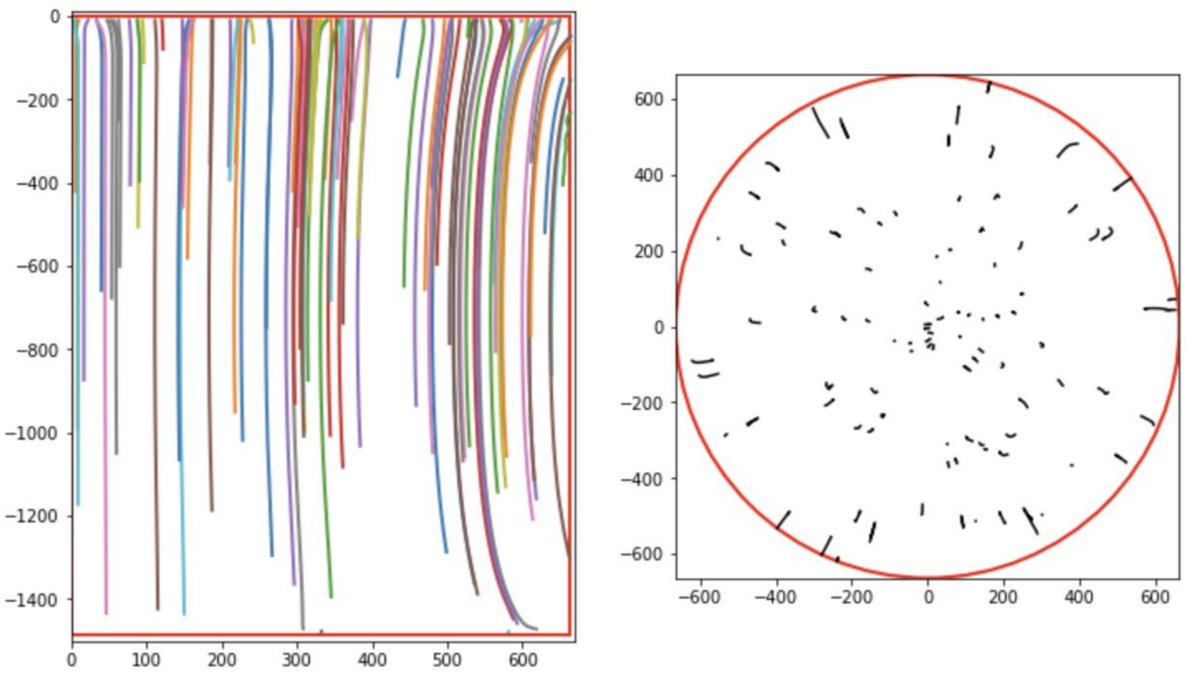
- Overall 3D prespective of electric drif field on a regular grid



Success!

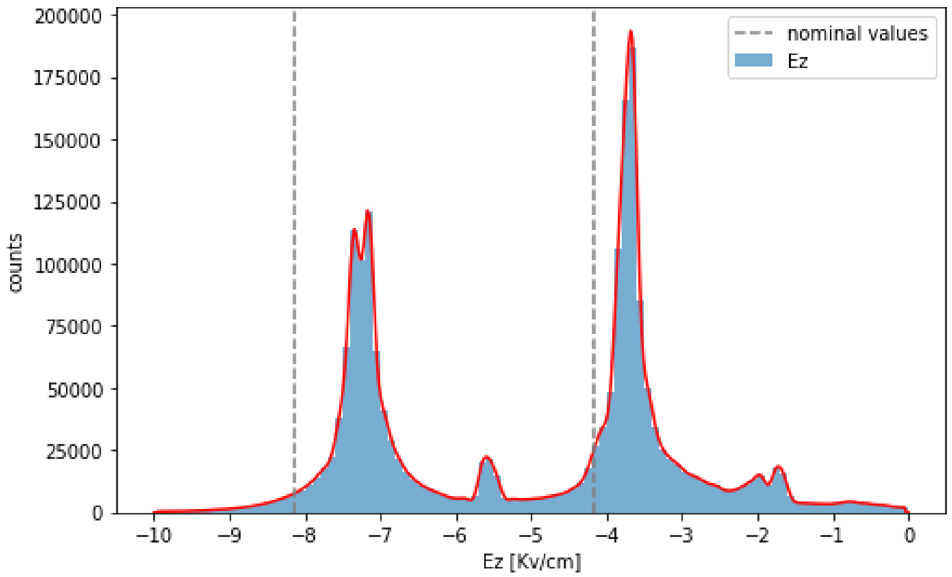
Results for the drift field

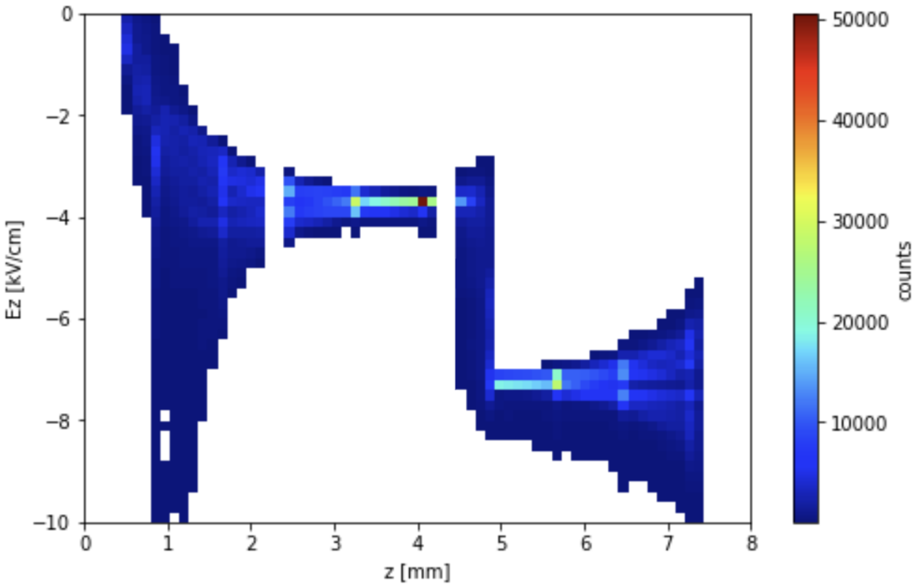
- Streamline of the field == path of the extracted electrons
- Vital for an accurate and truthful 3D position reconstruction near the wall
- Predicts the active volume lost due to charges ending on the PTFE panels



Results for the Gate-Anode region

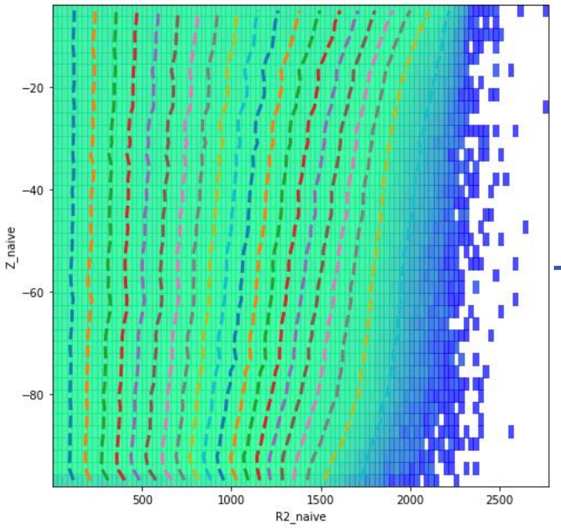
- Between the gate and the anode the field is order of magnitude stronger
- At 4mm above the gate (z=0mm) stands the liquid-gas boundary.
- Secondary scintillation signals (S2s) are produced in the GXe region between 4 and 8mm.



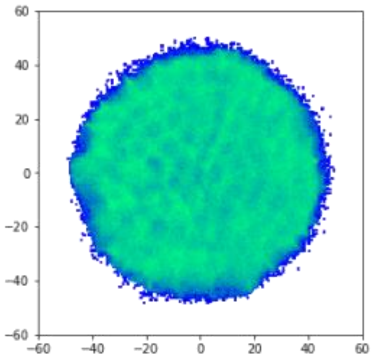


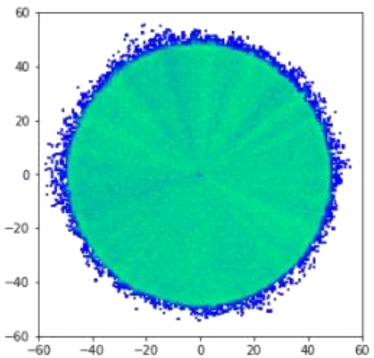
Data-driven corrections of field distortion

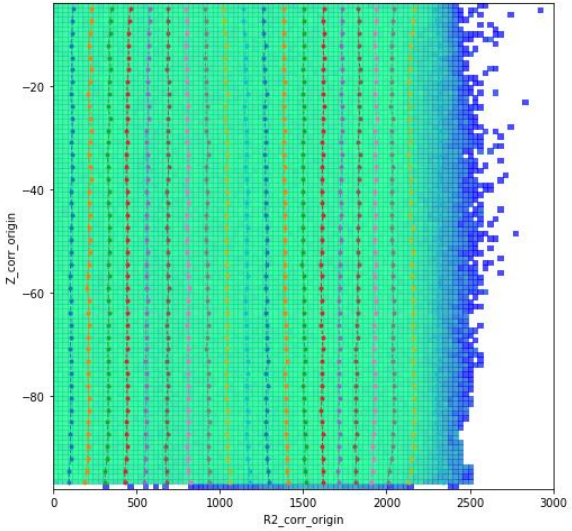
- Some distortion may be present in the drift field due to the finite geometry and over time charge accumulation on the walls.
- A pseudo-3D data-driven correction method is commonly applied to handle such distortion using Kr83m calibration data.



Making the P_{98} be on the wall (known radius of the TPC) per z slice and per azimuthal slice







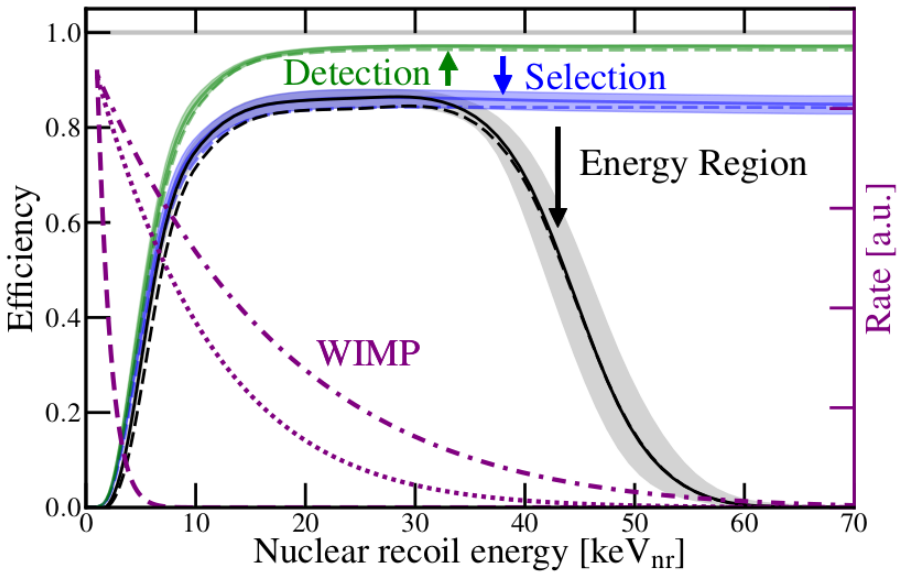
Conclusions

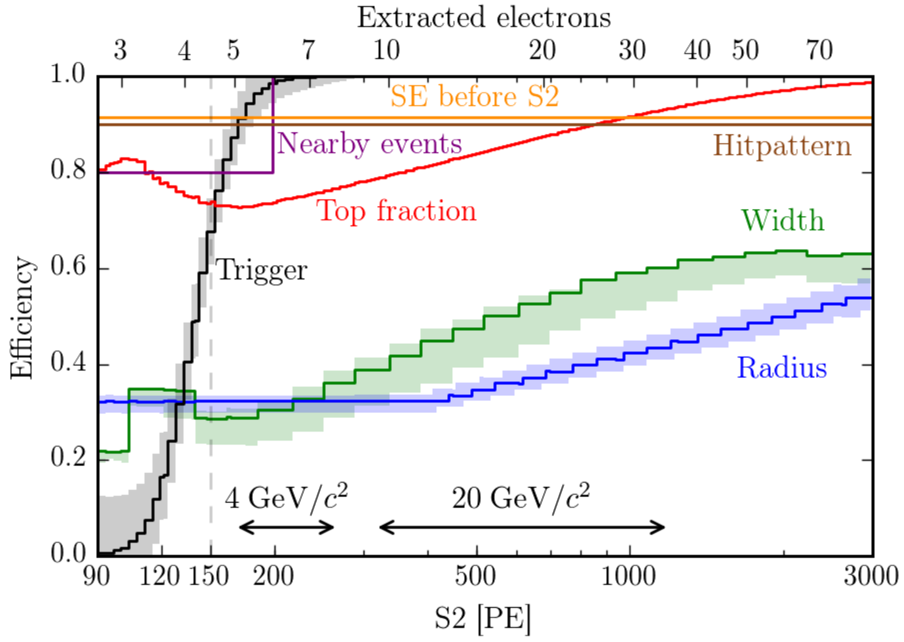
- To prepare the analysis of XENONnT data and its corrections, a 3D simulation of its expected electric field was performed;
- The drift field is very close to the previous 2D studies;
- The accurate representation in the (x,y,z) space of the field streamlines is of great use to properly reconstruct events;
- Overall, the extraction field region behaves as expected, reaching magnitudes of the field where the extraction efficiency is ~99%;
- A data-driven approach to field distortion correction, such as done previously, has also been prepared under the XENONnT analysis framework.

Thank you!

Backup Slides

Efficiency and event acceptance in XENON1T (S1+S2 vs S2-only)





ER and NR light and charge yields