Wire Electrode Test and Simulation for the DARWIN experiment

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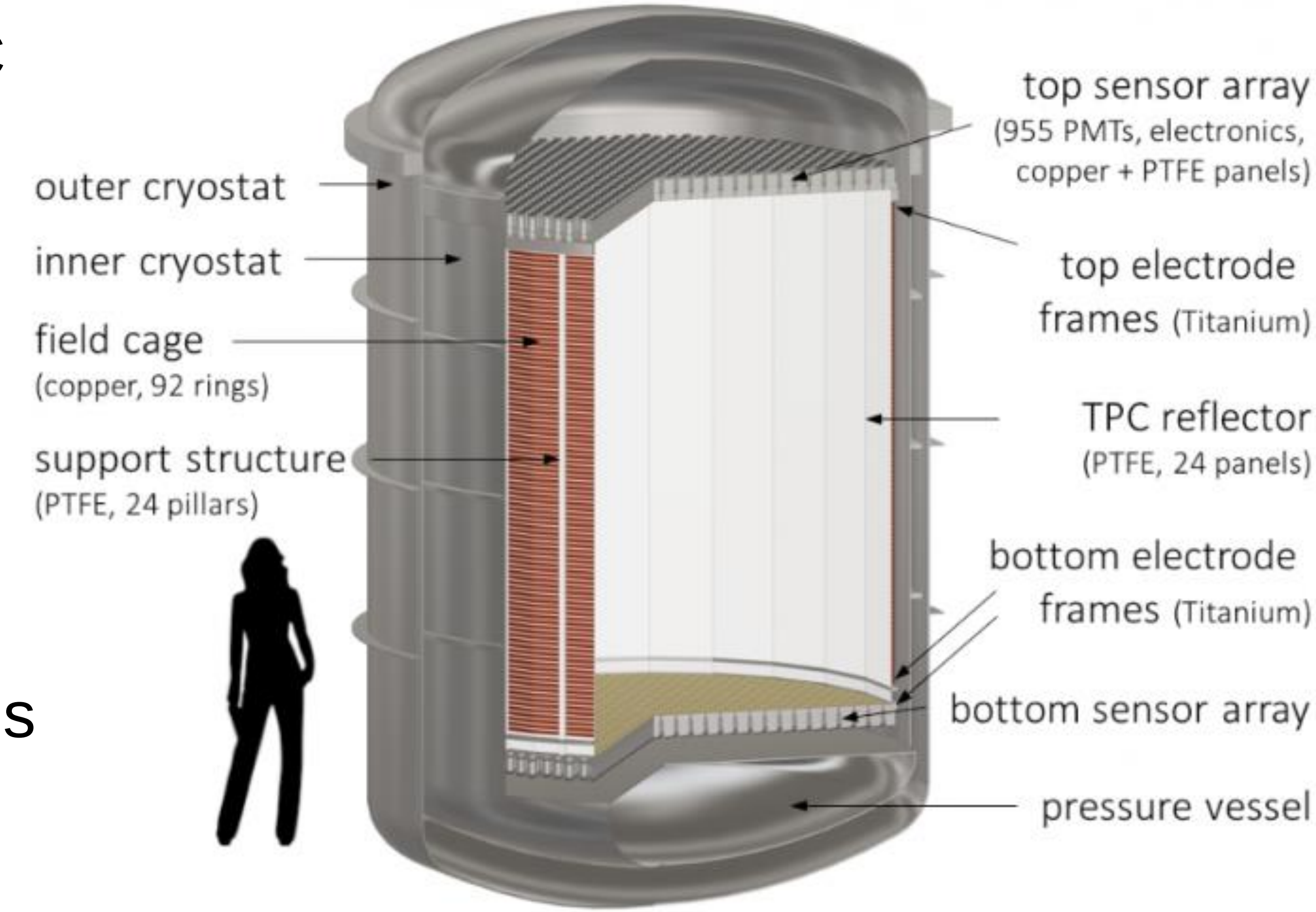
XeSAT 2022 - International Workshop on Applications of Noble Gas Xenon to Science and Technology

The DARk matter WImp search with liquid xenoN (DARWIN) observatory [1] See the talks from Laura and Igor

- Next generation liquid Xe **TPC** with 50 tons LXe
- Science goal:
  - WIMP (dark matter candidate)
  - coherent neutrino nucleus scattering,
  - solar axions,
  - others
- Projected sensitivity of WIMP is reaching the neutrino 'fog'



[1] J. Aalbers et al 2016 JCAP11(2016)017

Direct Detection with Time Projection Chamber (TPC)

When an interaction happens…

- Scintillation light (S1 signal) in LXe is detected.
- The electrons are drifted and extracted to GXe, electroluminescence (S2 signal) is induced.

-> event selection

Electrodes are important in TPC!

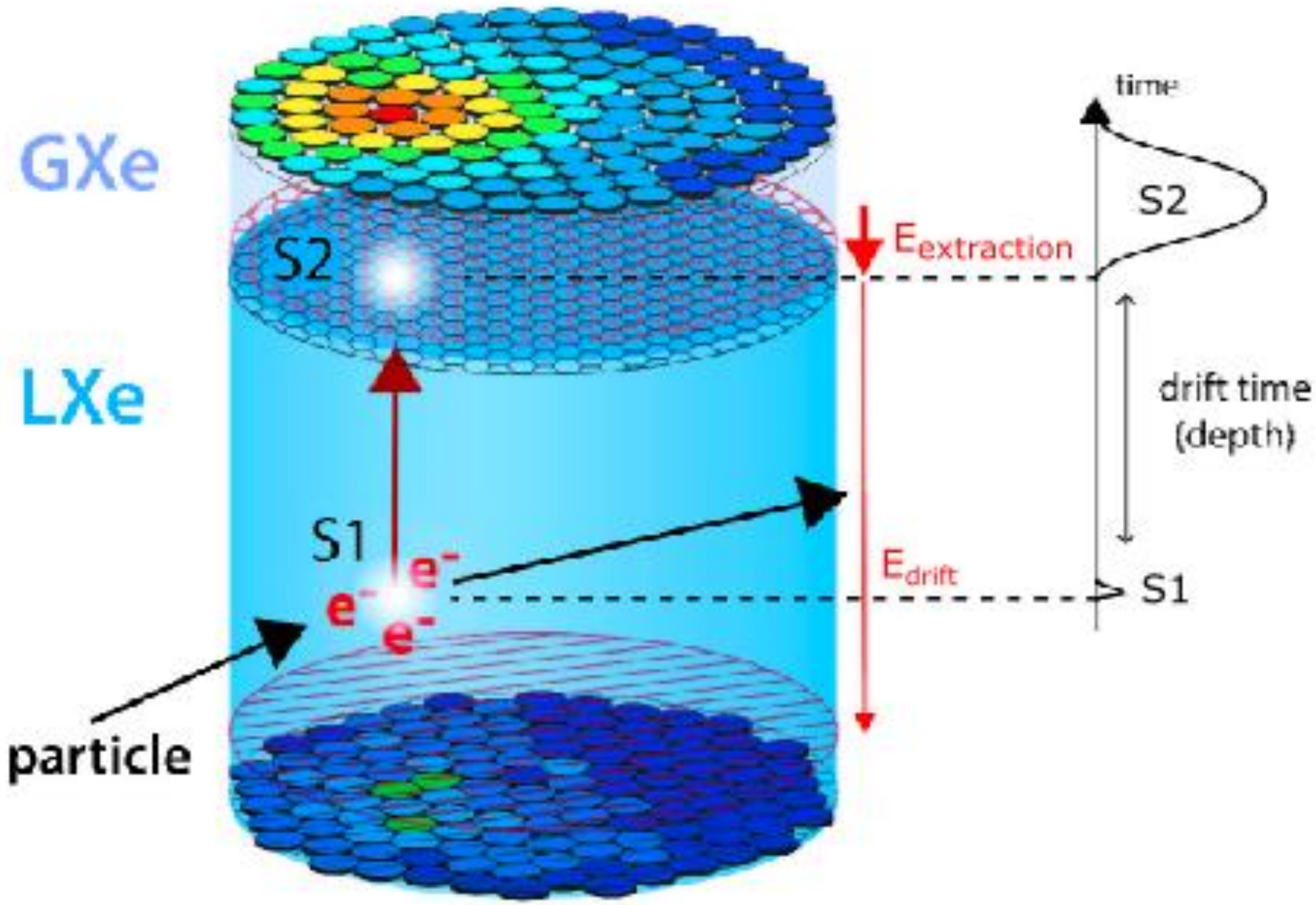
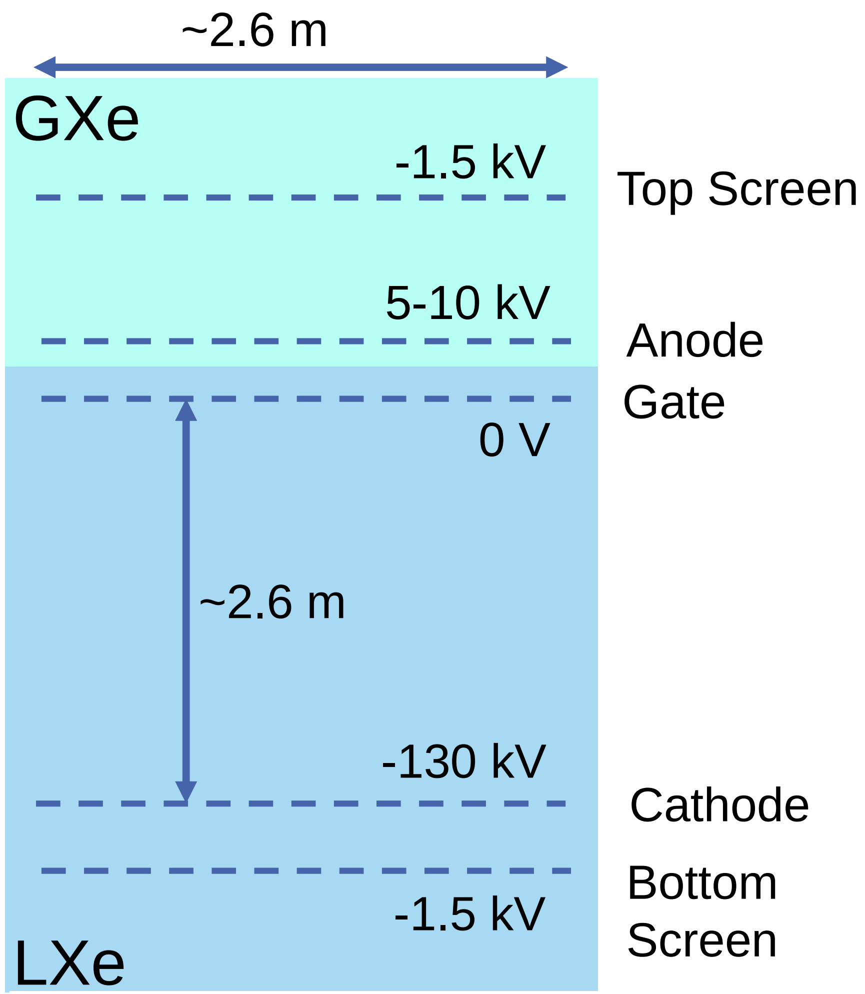


Figure from http://www.xenon1t.org/

Electric Field and Electrodes of the TPC [1]

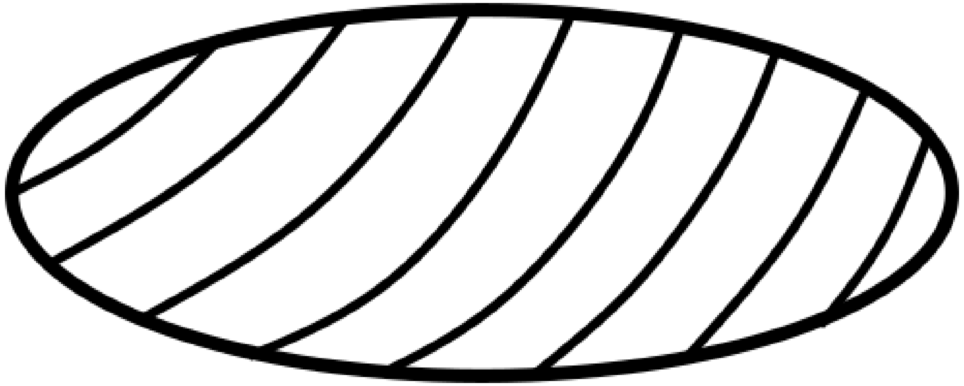
- Drift field: 3D position reconstruction
- Extraction field: Extracting electrons from LXe to GXe; signal amplification for the S2 signal (in GXe)
- Possibilities of electrode design:
  - Wire electrodes
  - Hexagonal mesh electrodes
  - Woven wire electrodes
  - Other novel techniques



position of the electrodes (not to scale)

[1] J. Aalbers et al 2016 JCAP11(2016)017

Sagging of the electrode



- The electrodes suffer from external forces during operation:
  - Electrostatic force (dominating)
  - Gravitational force (~ O(1) lower)
  - Buoyancy (~ O(2-4) lower)
- And during cooling: additional force due to temperature gradient

- The forces deform (up or down) the electrodes -> sagging

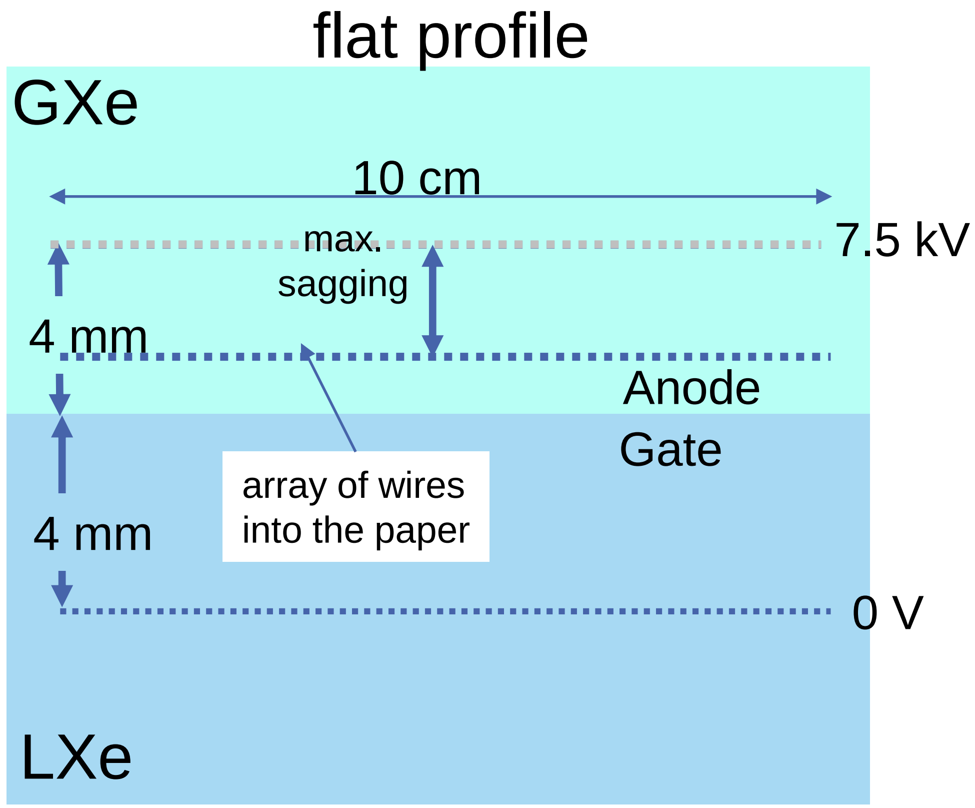
➢ Lower homogeneity of S2 response across x-y plane

➢ Coarser S2 resolution and, thus possibly reducing the background rejection ability with S2+S1 signal [1]

[1] J. Aalbers et al 2016 JCAP11(2016)017

Sagging and S2 signal

- Study focus on wire electrodes
- Simplified COMSOL 2D electrostatic simulation with **different sagging profile**



Sagging and S2 signal

- Study focus on wire electrodes
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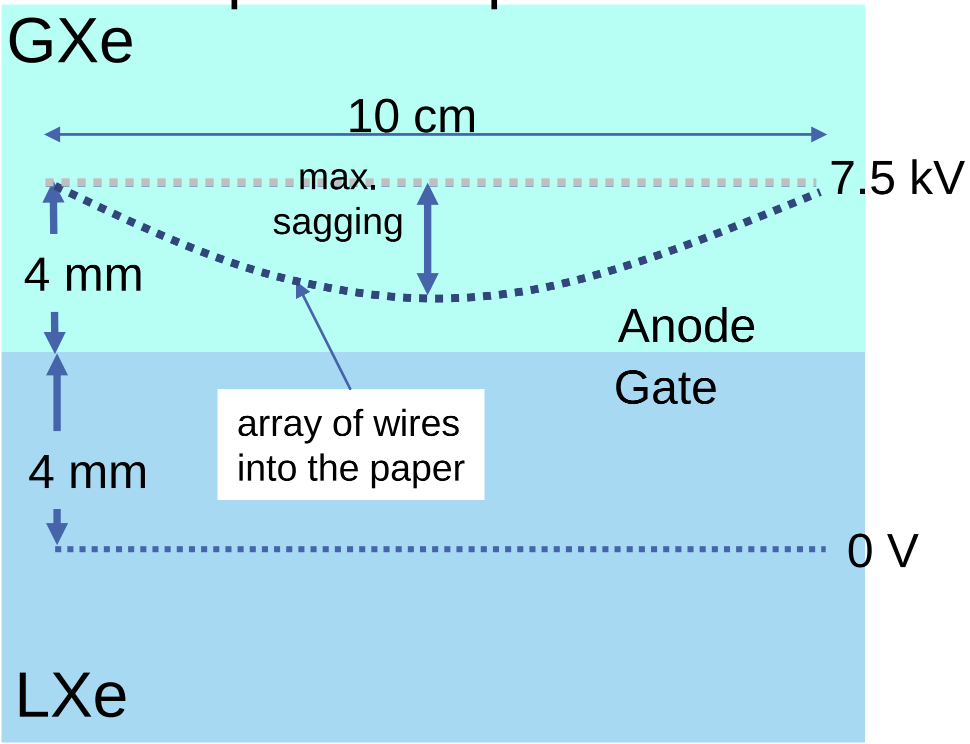
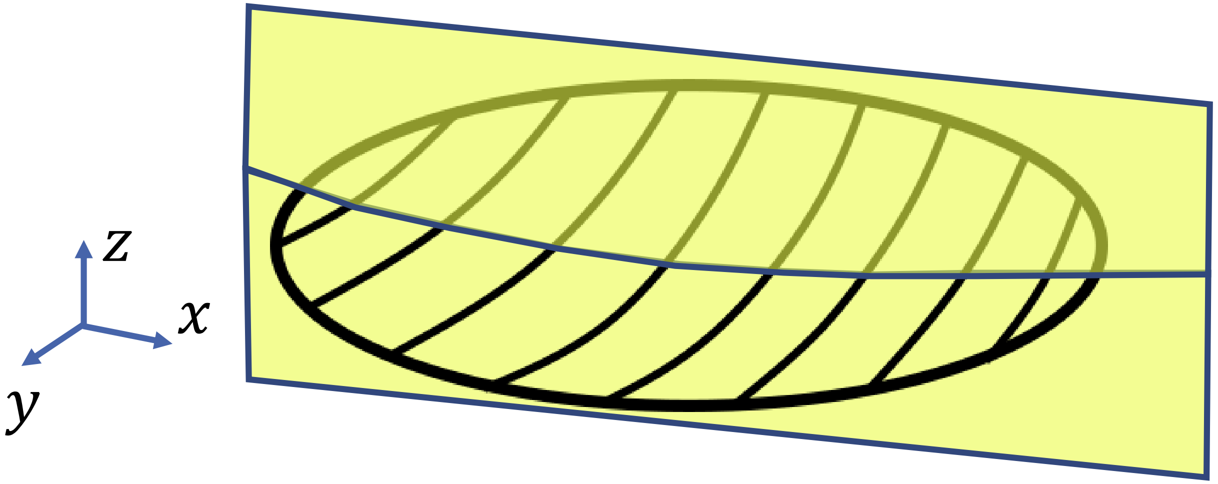
quadratic profile

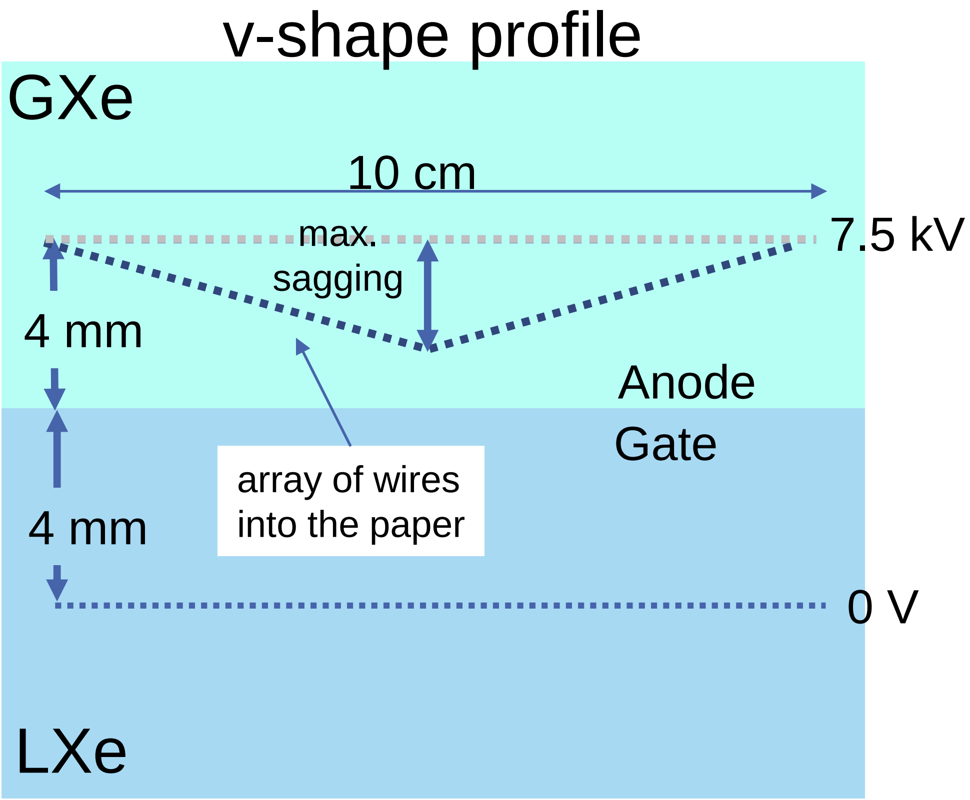


Sagging and S2 signal

- Study focus on wire electrodes
- Simplified COMSOL 2D electrostatic simulation with **different sagging profile**
  - Cutting the electrode along x-axis



  - Assuming the E-field along y direction is negligible
  - Avoid considering the edge and less computational time:
    zero charge boundary condition



Sagging and S2 signal

- For one electron path, the proportional S2 signal is estimated (1^{st} order):

1. Extraction efficiency (assume to be 1) [2]:

   portion of electrons extracted from LXe to GXe, depends on the field on the surface

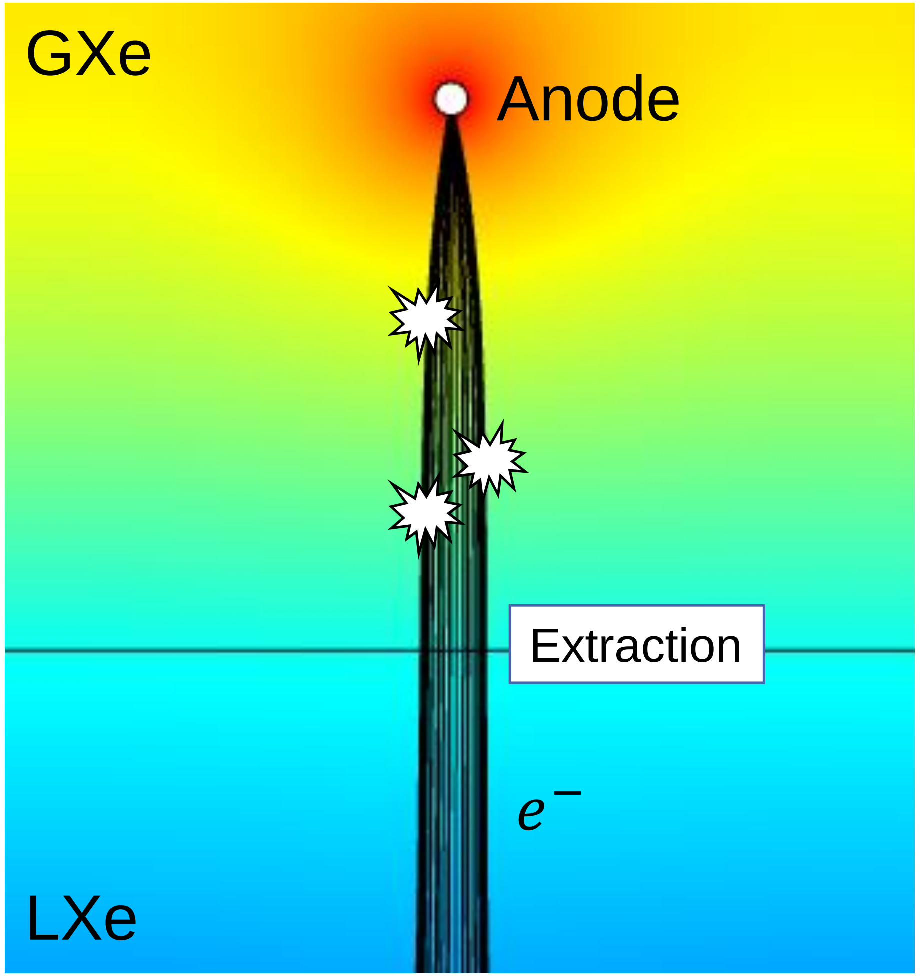
2. Electroluminescence due to excimers [3]

   electrons excite the Xe atom along the path from the surface to electrode, photons are generated

3. Townsend discharge at high E-field [4]

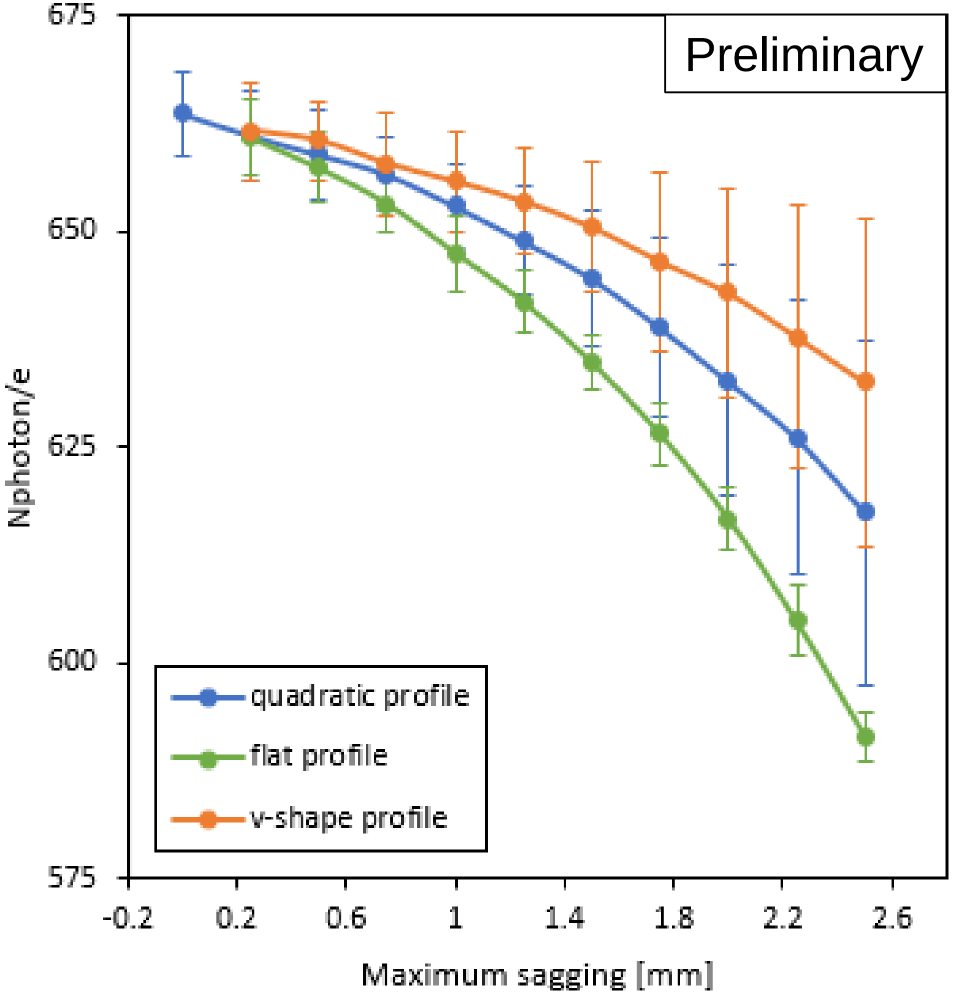
   avalanche of electrons in GXe

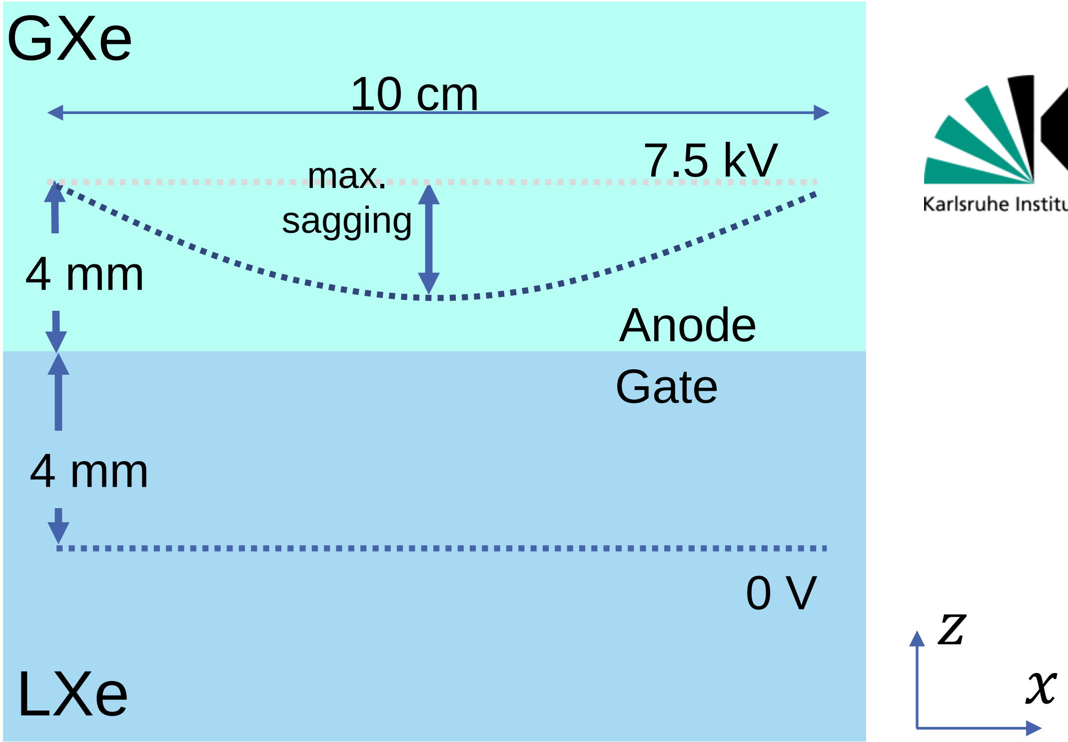
- 10000 electron paths are considered from the LXe surface -> mean & stdev



[2] E. Aprile et al 2004 IEEE Trans Nucl Sci 51(5) 1986-1990
[3] A. Buzulutskov 2020 Instruments 4(2) 16
[4] L Jacques et al 1986 J. Phys. D: Appl. Phys. 19 1731

Sagging and S2 signal





- The error bars are the stdev of the Nphoton/e among all the electron path.
- Large error bars --> inhomogeneous S2 signal amplification along x-axis

Sagging and Pre-tension in DARWIN dimension

Analytical calculation

To avoid sagging during operation, pre-tension is applied to the wire so that it is still straight under forces.

[5] T. Kleiner 2019 Master's Thesis (KIT)
[6] G. Hunziker 1942 Doctoral Thesis (ETH Zürich)

Sagging and Pre-tension in DARWIN dimension

Analytical calculation

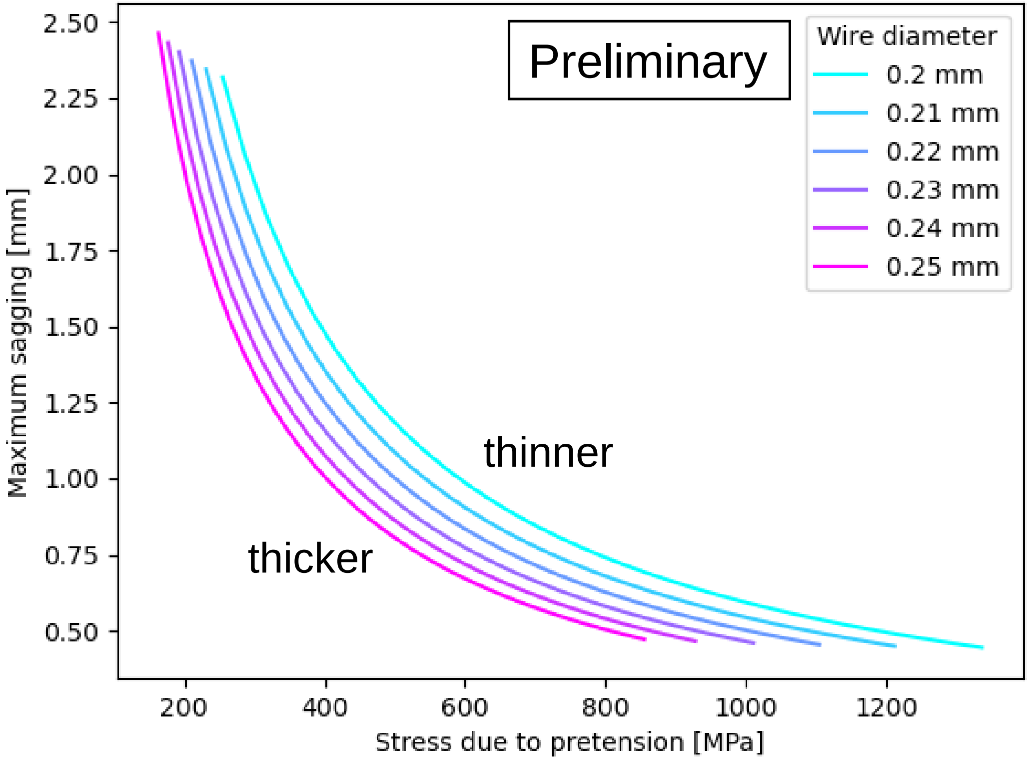
To avoid sagging during operation, pre-tension is applied to the wire so that it is still straight under forces.

Given:

- wire electrode geometry,
- ΔV = 7.5 kV,
- separation (anode and gate) = 8 mm
- wire pitch = 5 mm.
- wire length = 2.6 m (longest wire)

- Electrostatic attractive force per unit length $\sim 2 \times 10^{-5}$ N/mm [5]
- Weight is also added, ignore buoyancy

Pre-tension calculated for the corresponding sagging level [6]:



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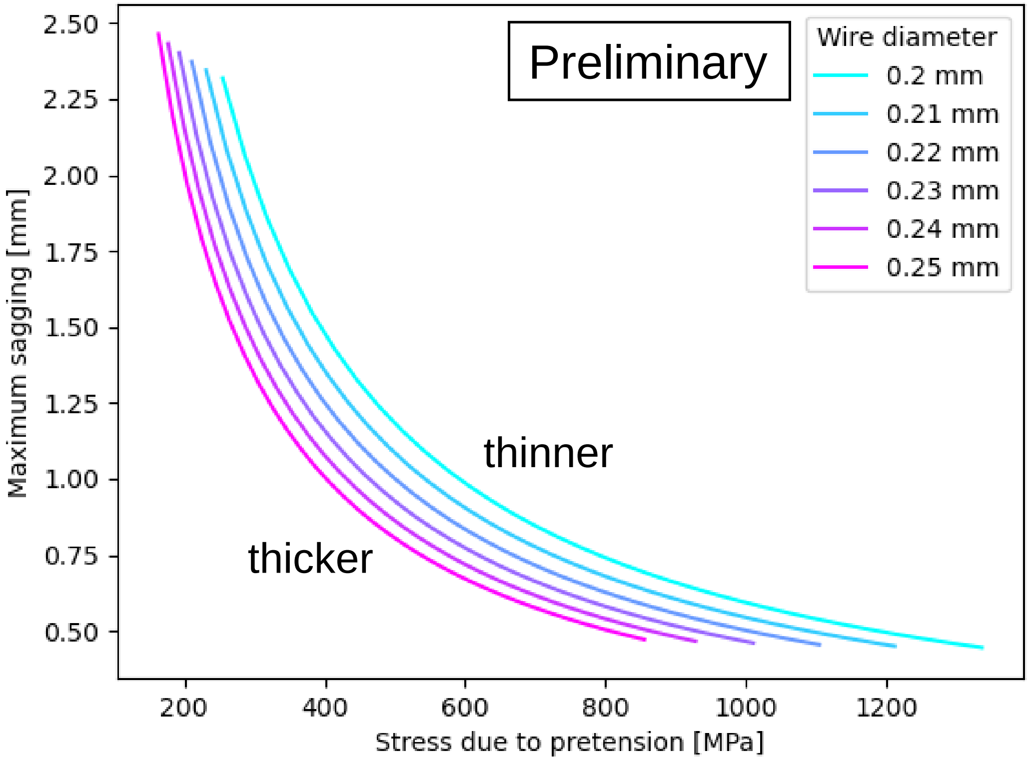

➢ Thicker wire requires less stress (F/A) due to pre-tension

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Mechanical Properties of the Candidate Material

Which material can withstand the pretension + thermal shrinkage?

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- Stainless steel
  - Cryogenic (LXe at 177 K)
  - Radioactively clean

Which material can withstand the pretension + thermal shrinkage?

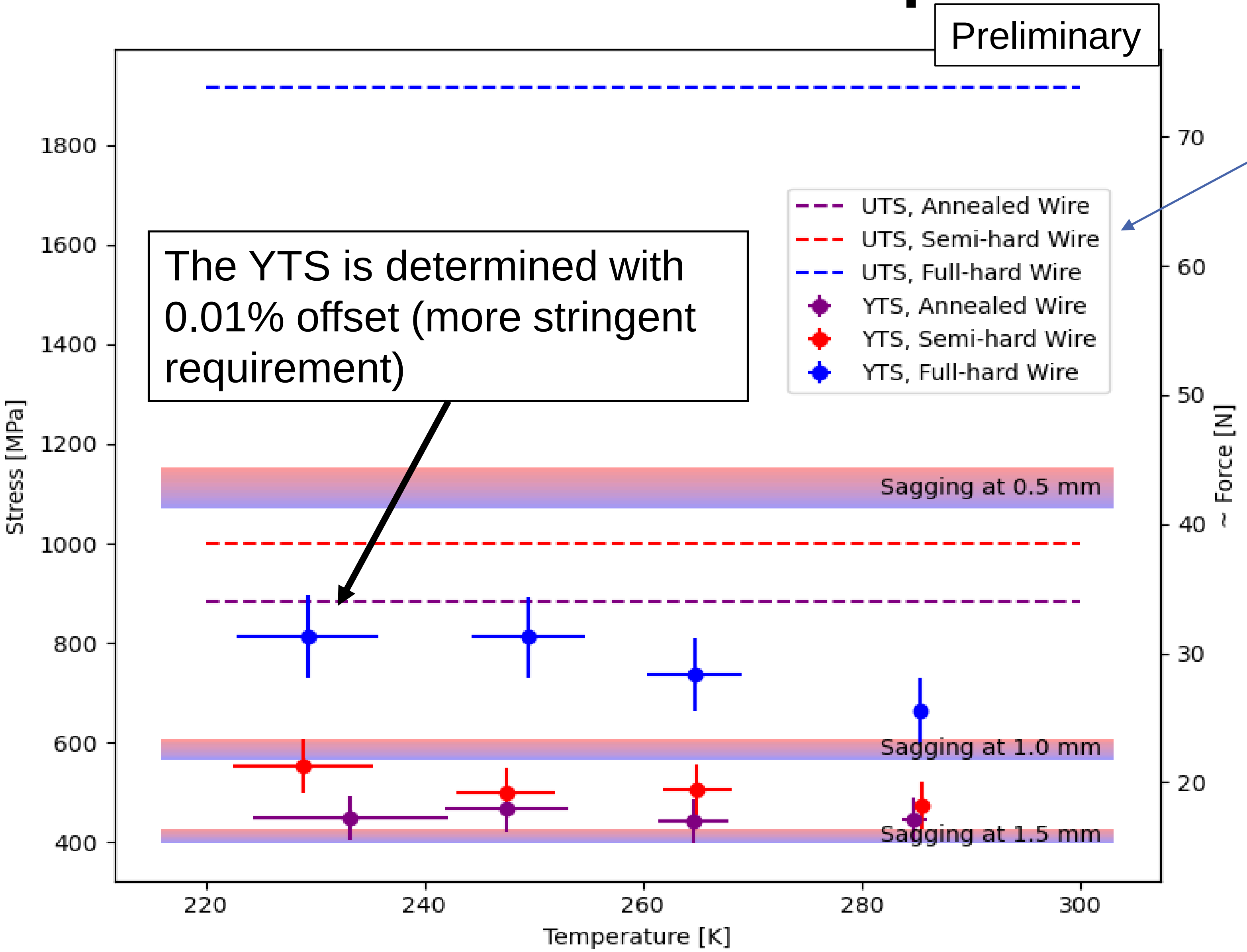
Mechanical Properties of the Candidate Material

- Stainless steel
  - Cryogenic (LXe at 177 K)
  - Radioactively clean
- Sample properties from data sheet
  - **YTS** (yield tensile stress): With an offset at strain (0.2% by convention) meaning that if the pressure on the sample surpassed the YTS, the sample permanently deforms by 0.2%.
  - **UTS** (ultimate tensile stress): the sample will break at UTS

Which material can withstand the pretension + thermal shrinkage?

Manufacturer	Diameter [mm]	Material (AISI)	UTS [MPa]	YTS at 0.2% offset [MPa]
California Fine Wire	0.216	316 annealed	884	725
Vogelsang	0.212	316 semi-hard	1000-1200	
Dahmen	0.221	316L full-hard	1916.5	1528.5

Tensile tests at various temperatures



The label refer to the specific samples we tested, not generic for the wire type

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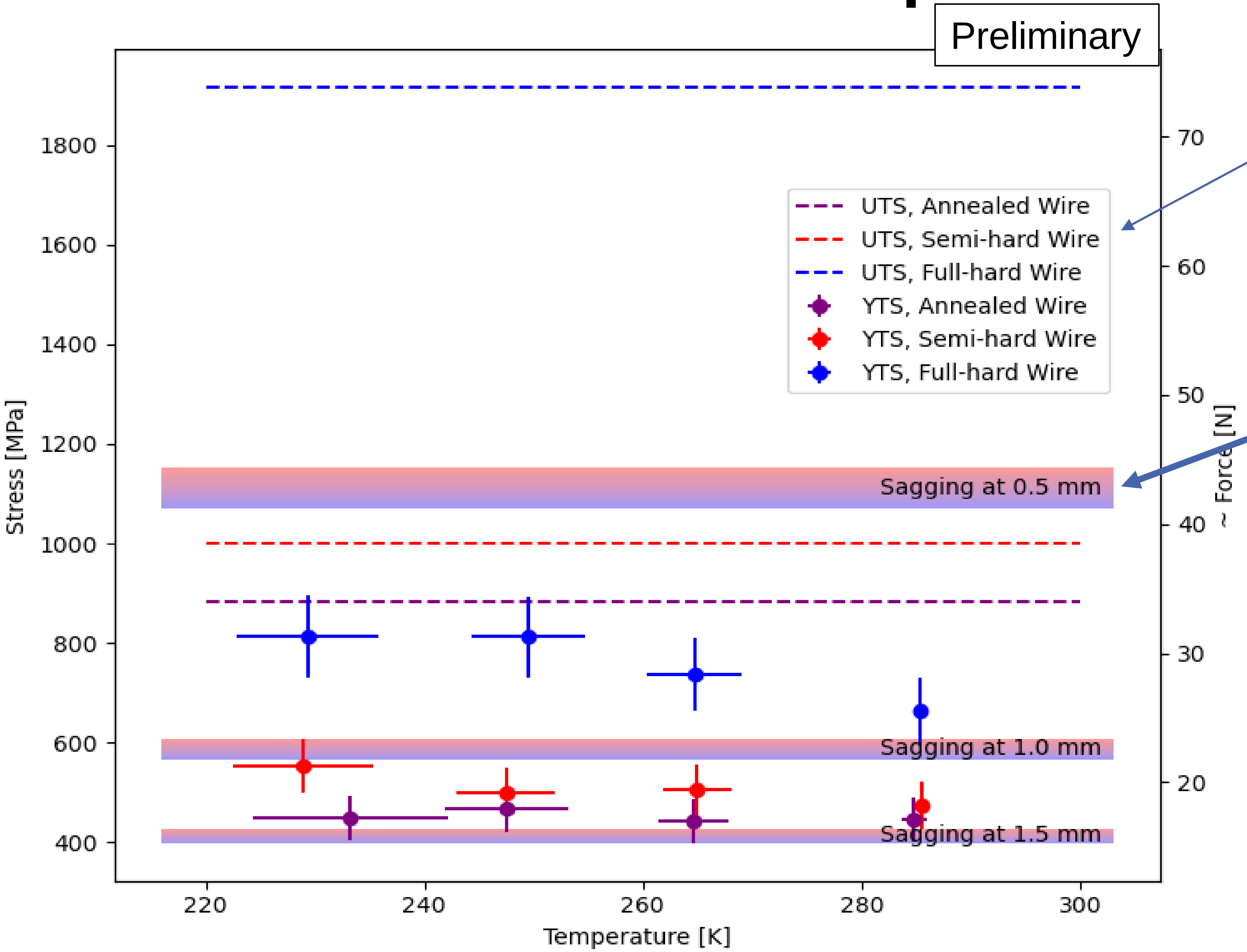

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Pre-tension (depends on wire diameter) + additional thermal stress (~ 65 MPa) during cooling ($\Delta T \sim 25K$)

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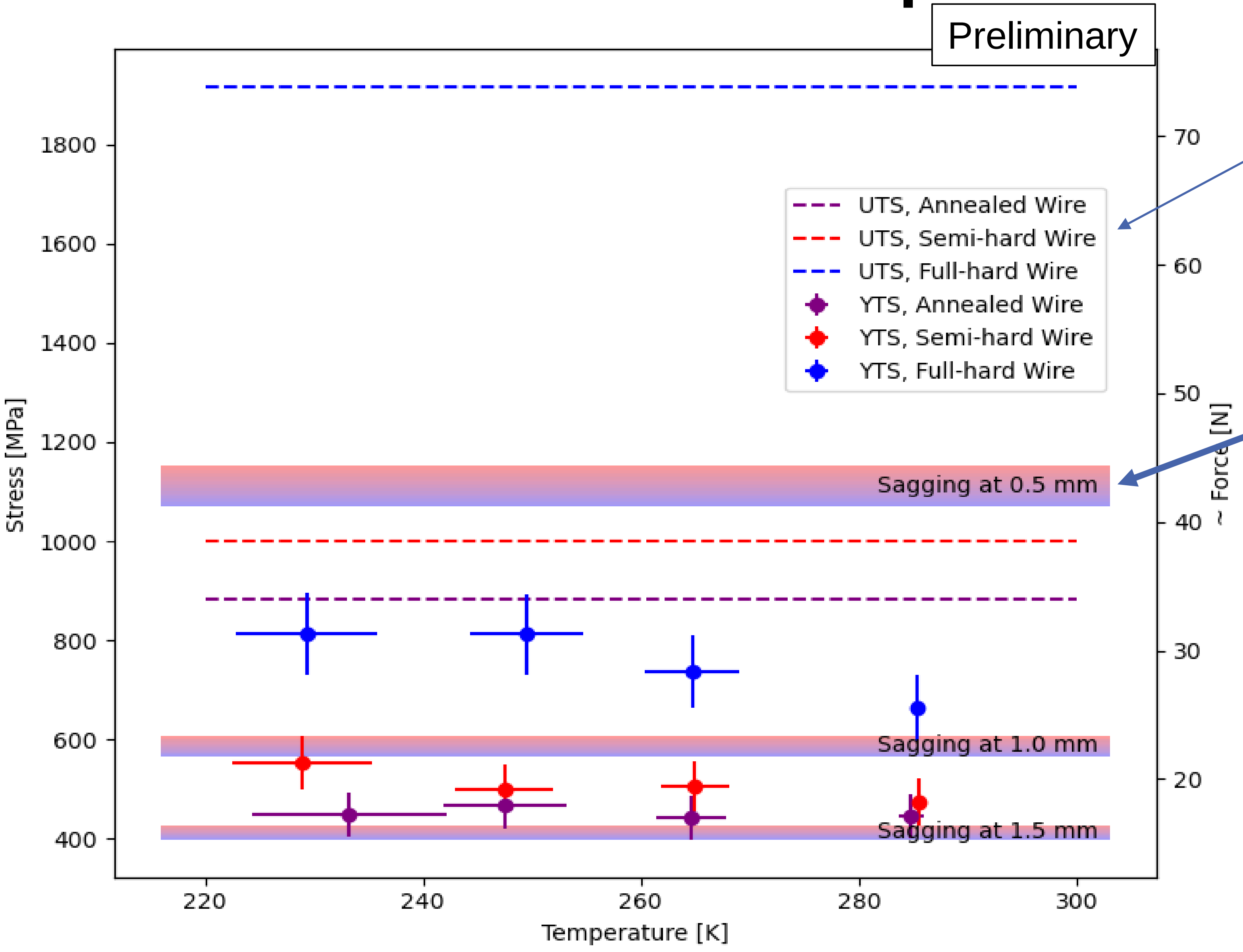

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Pre-tension (depends on wire diameter) + additional thermal stress (~ 65 MPa) during cooling ($\Delta T \sim 25 K$)

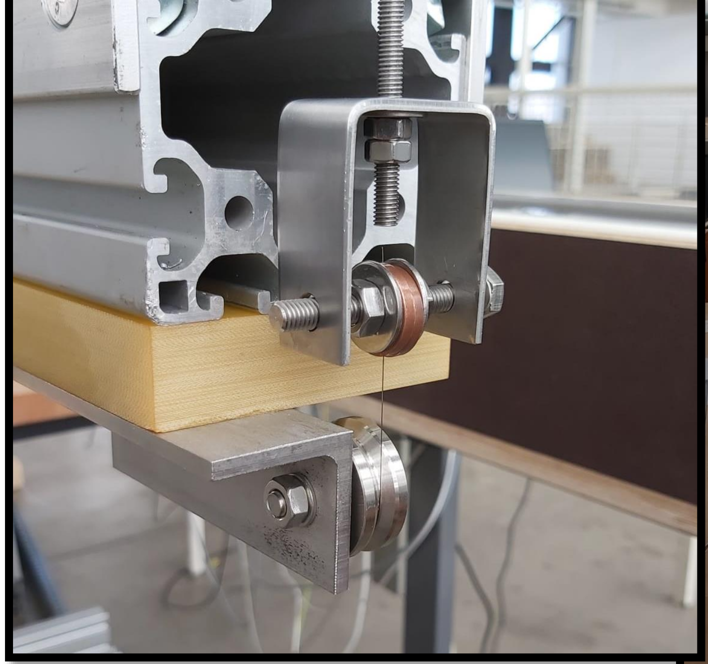
- Force on the wire surpass or are very close to the YTS of all the wire samples
- The full-hard wire might seem promising, but the elongation is not as good as other types

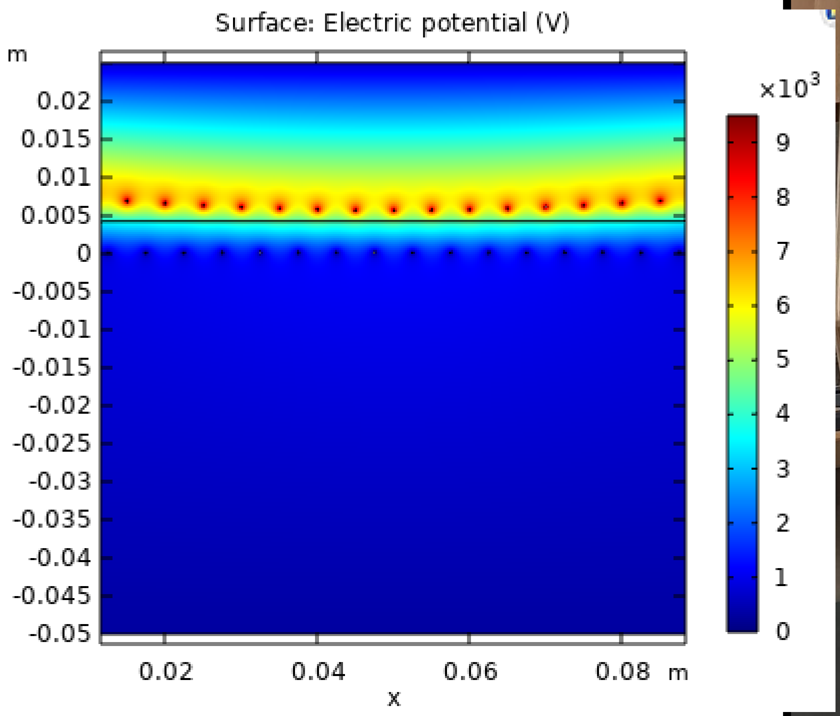
Conclusion

- Non-uniform sagging -> affect the homogeneity of S2 amplification
  - 3D sagging profile will come later
- The measured quantities (eMod, YTS, UTS) only depends on temperature/material/sample -> usable for other geometries
- Pre-tension is a limiting factor of the candidate wires
- Potential next steps:
  - Search for other materials
  - Thicker wires (optimization needed)
  - Increase the tolerance for sagging (optimization needed)
  - Use other geometry or novel electrode design

Acknowledgement

- Projects with bachelor students, Annabelle Engelhardt and Wenjun Li
- With the help from Klaus Müller for the pre-tension calculation; Michael Schrank for the wire test setup
- Supported by Klaus Eitel, Markus Steidl and Kathrin Valerius, for the ideas and discussions



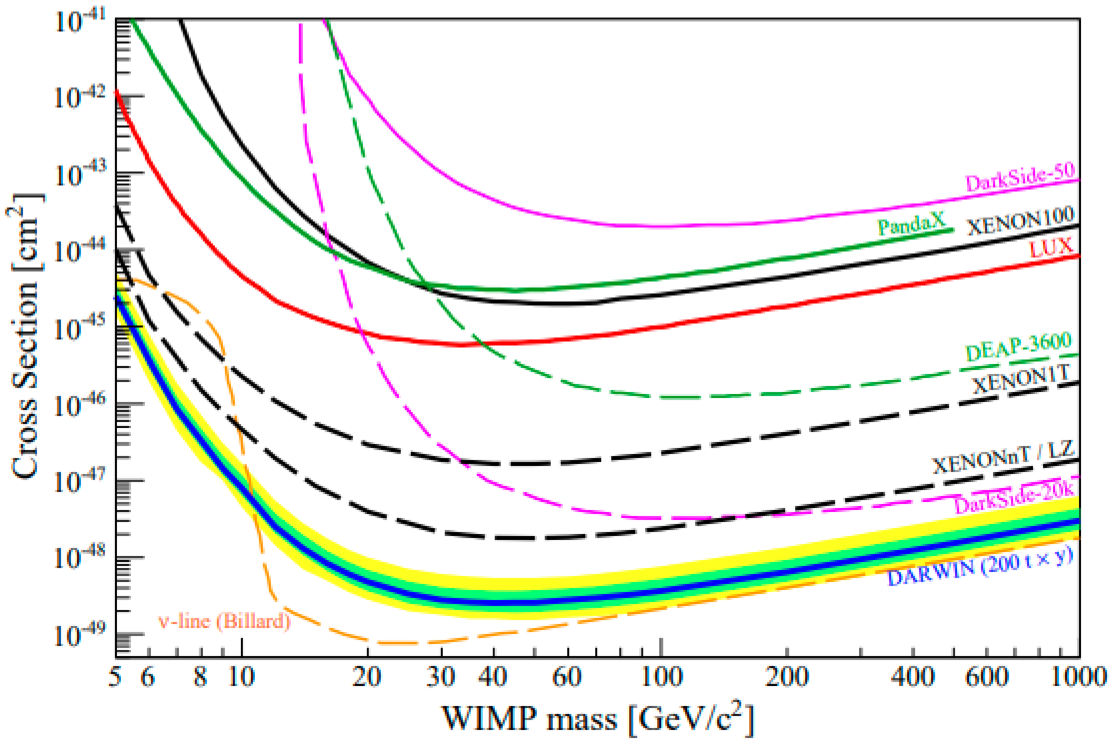


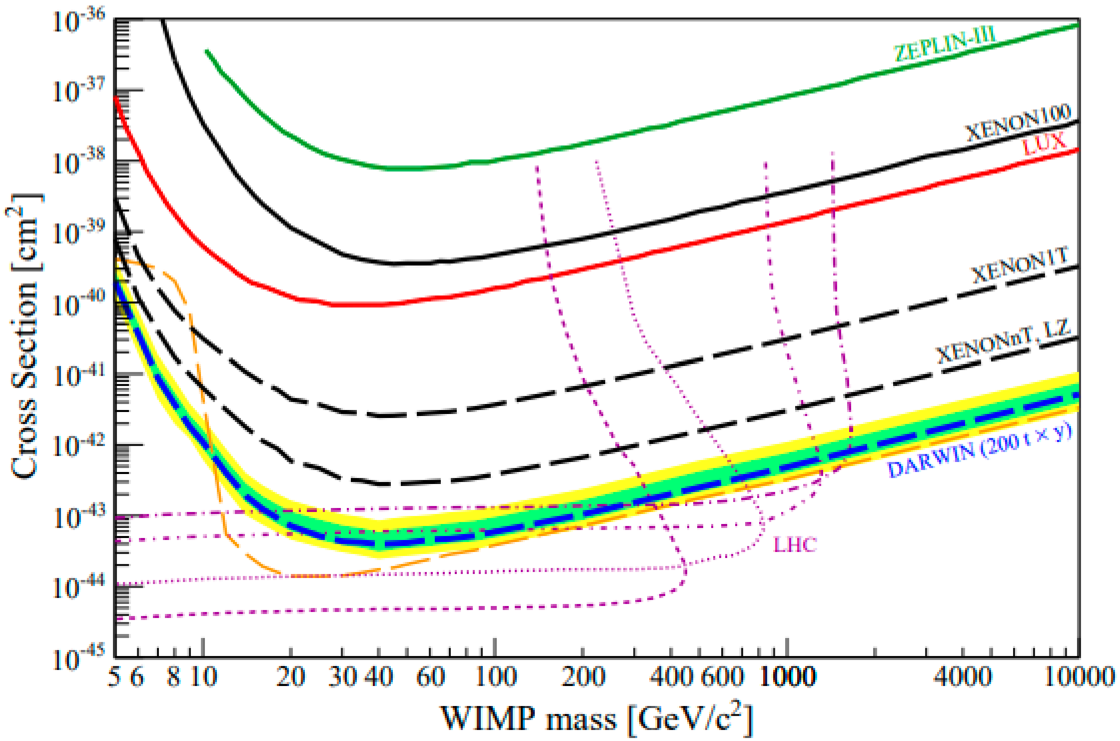
Backup

The DARk matter WImp search with liquid xenoN (DARWIN) observatory

J. Aalbers et al 2016 JCAP11(2016)017

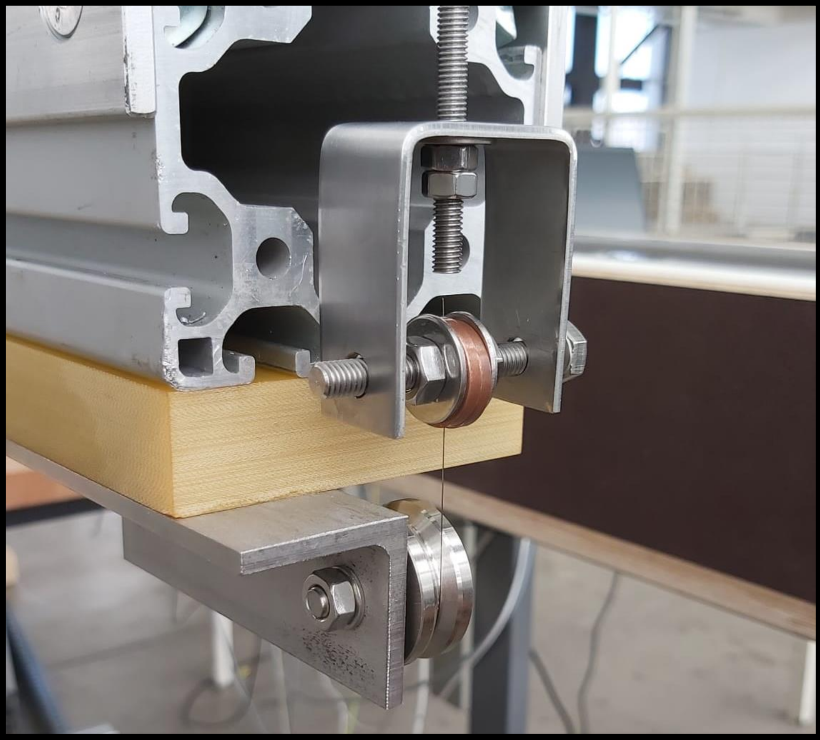
- Projected sensitivity on WIMP for different experiments, including DARWIN



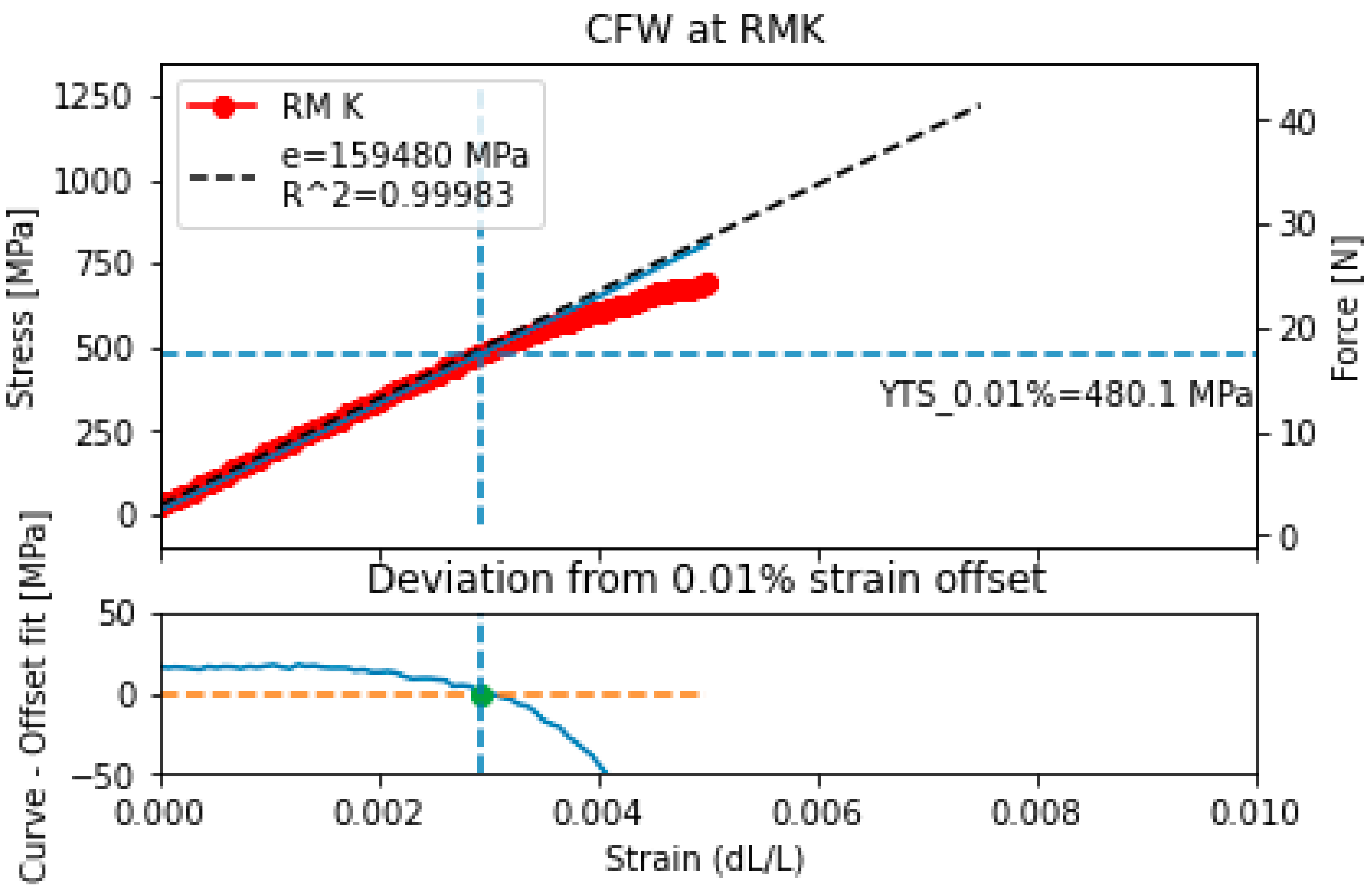


Tensile Test Setup

Cooling with dry ice + ethanol



Tensile Test Analysis

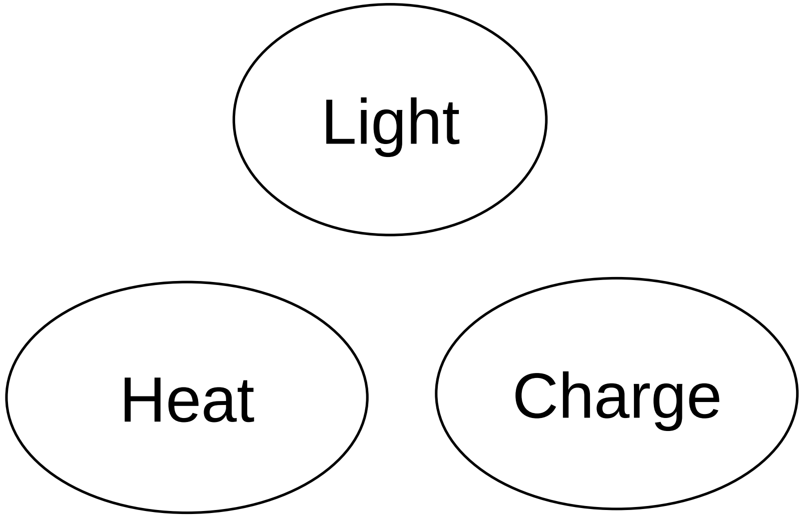


Detection with Xe

Why Xe among other noble gases?

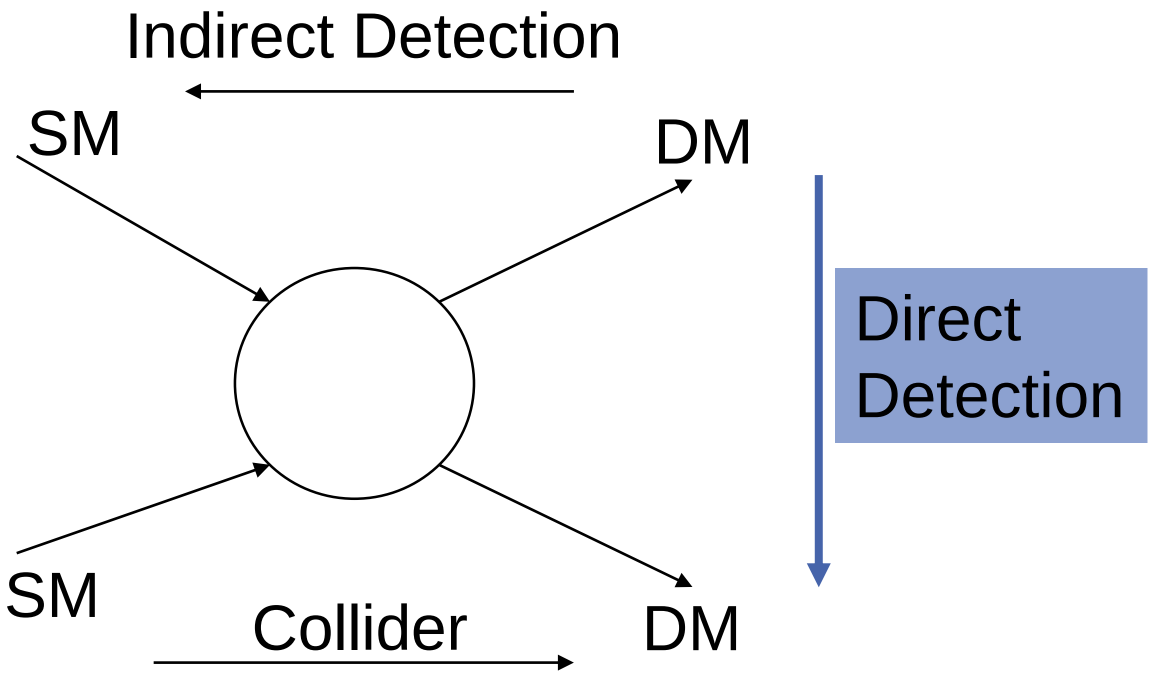
- Spin-independent scattering at few keV energy deposition: higher atomic mass -> higher scattering rate
- Stable isotopes
- High stopping power -> self shielding from background
- Higher boiling point -> more effective cooling

Energy deposition into Xe
in the form of:



Direct Dark Matter Search

- Evidence of dark matter and the incomplete standard model theory
  -> dark matter detection experiments



- Dark matter candidates
  - Weakly Interacting Massive Particle (WIMP)
  - Axion,
  - many more
- Direct detection: look for scattering with standard model praticles
  - Nuclear recoil
  - Electronic recoil

Direct Detection with Time Projection Chamber (TPC)

Energy deposition into Xe
in the form of:

Light
(S1)

Heat

Charge
(S2)

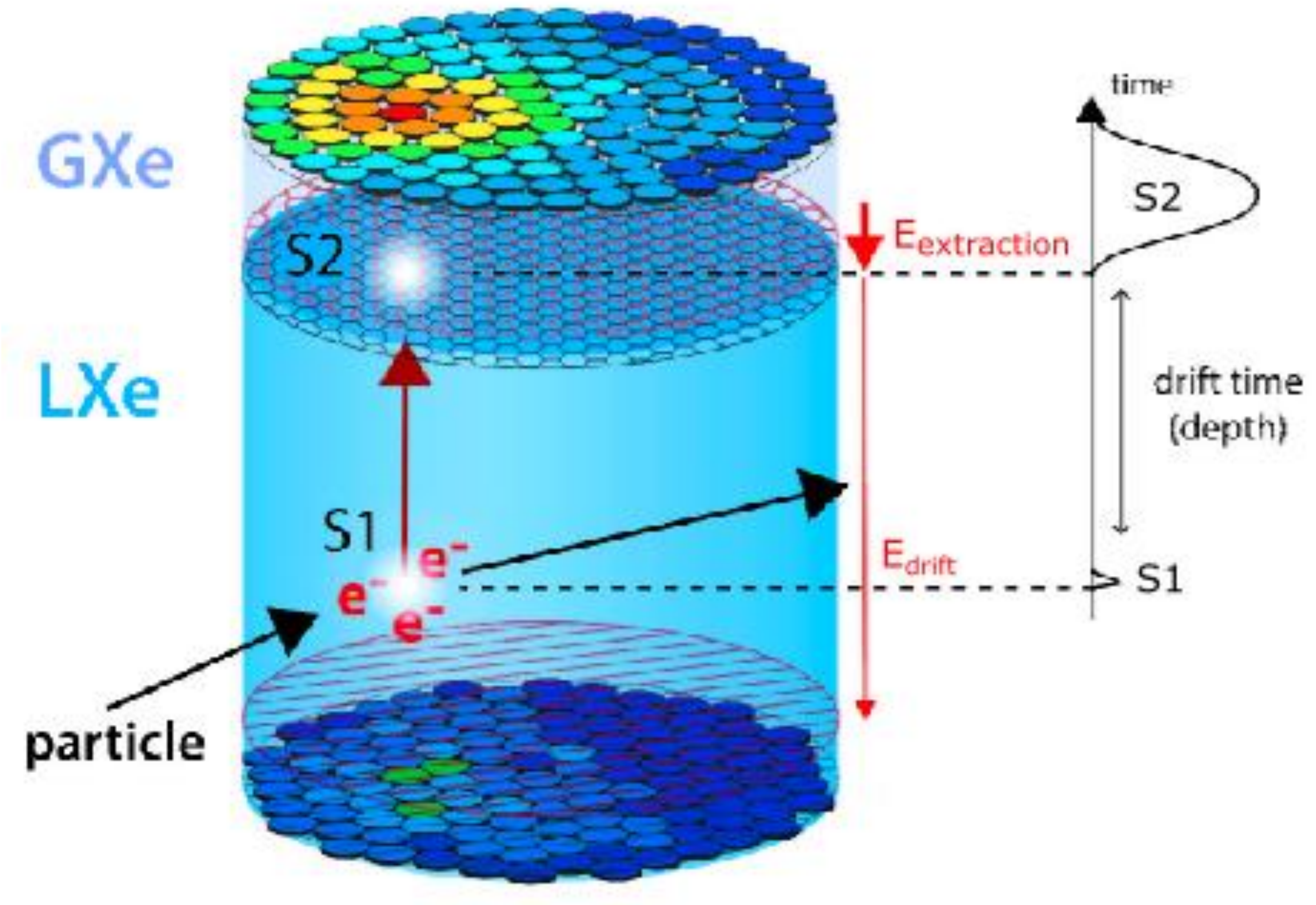


Figure from http://www.xenon1t.org/