Towards the next xenon filled dark matter experiment

Alexander Deisting

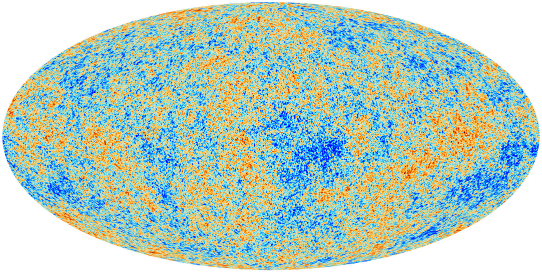
NQM seminar, 23rd of October 2023

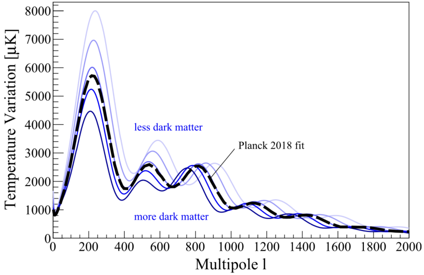
Outline

- Evidence for dark matter
- Dual-phase xenon time projection chambers (TPCs)
- XENONnT (and LZ) & some of their results
- Future experiments: Darwin (or XLZD)
- Development of new electrodes

Some evidence for the existence of dark matter

Evidence for dark matter: Cosmic microwave background





- ΛCDM (= cold dark matter) model fitted to the Planck data
- Planck's receipt for assembling our universe: 5 % ordinary matter, 26 % dark matter, 69 % dark energy

E.g.: ESA BR-347: Planck - Science and Legacy

Marc Schumann 2019 J. Phys. G: Nucl. Part. Phys. 46 103003

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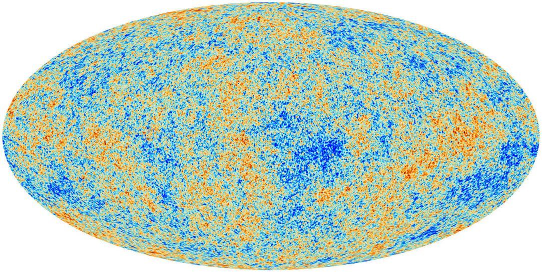

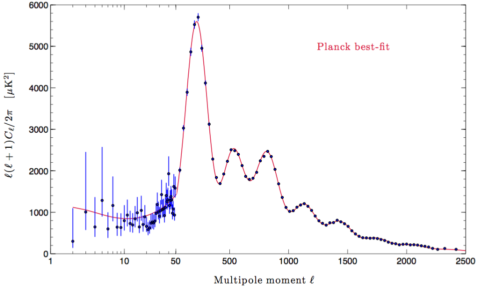

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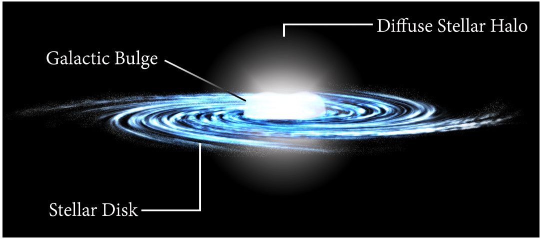
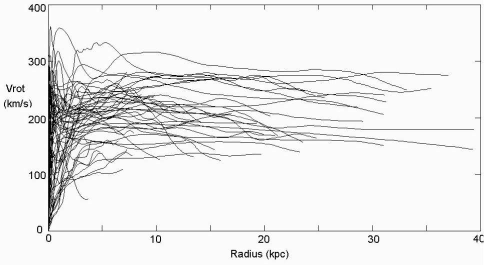
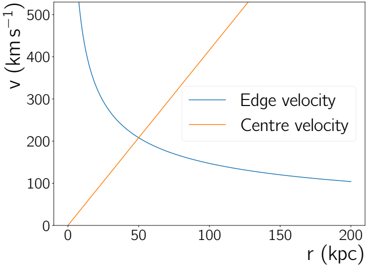
Evidence for dark matter: Rotation curves



[Springer Nature Astronomy: Behind the paper]



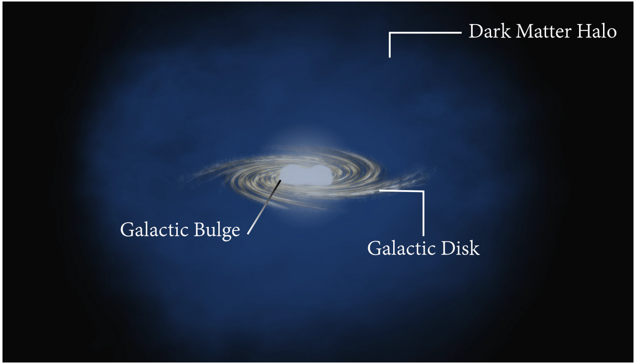
$$v_{\text{centre}} \sim d, \qquad v_{\text{edge}} \sim \frac{1}{\sqrt{d}}$$



→ Star velocities around their galactic centre do not follow the expectation based on the observed mass distribution

Introducing: The dark matter halo

Vera Rubin (1928 – 2016)

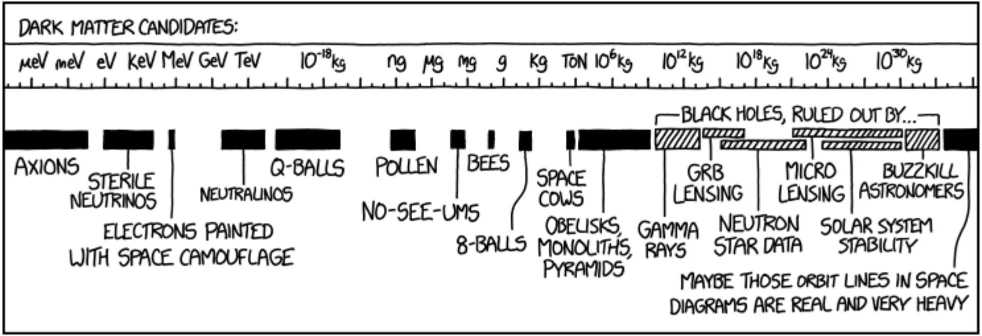


Springer Nature Astronomy: Behind the paper

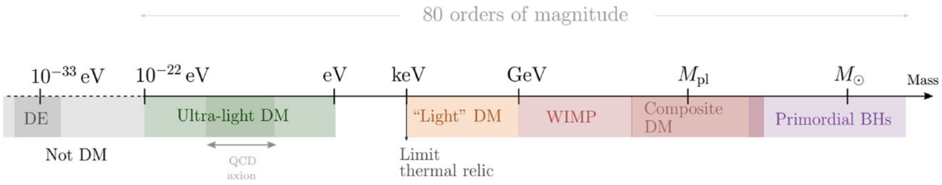
Properties of dark matter

Based on astronomical observations:

- Electrically neutral
- Small (self-)interaction cross section
- Either long-lived/stable or produced
- Must be cold/warm dark matter
- Must exist within galaxies (but not necessarily in all of them)

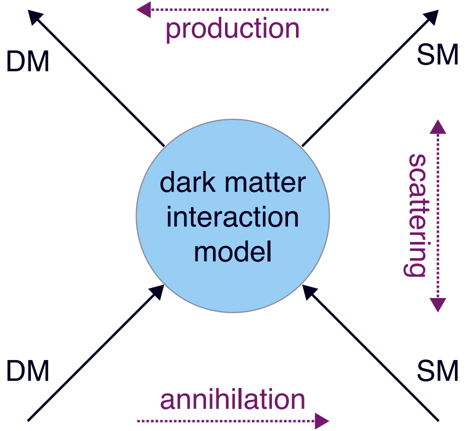

DARK MATTER CANDIDATES:
µeV meV eV KeV MeV GeV TeV 10^{-18}kg ng µg mg g kg TON 10^{6}kg 10^{12}kg 10^{18}kg 10^{24}kg 10^{30}kg
BLACK HOLES, RULED OUT BY...
AXIONS
STERILE NEUTRINOS
ELECTRONS PAINTED WITH SPACE CAMOUFLAGE
NEUTRALINOS
Q-BALLS
POLLEN
NO-SEE-UMS
BEES
8-BALLS
SPACE COWS
OBELISKS, MONOLITHS, PYRAMIDS
GAMMA RAYS
GRB LENSING
NEUTRON STAR DATA
MICRO LENSING
SOLAR SYSTEM STABILITY
BUZZKILL ASTRONOMERS
MAYBE THOSE ORBIT LINES IN SPACE DIAGRAMS ARE REAL AND VERY HEAVY

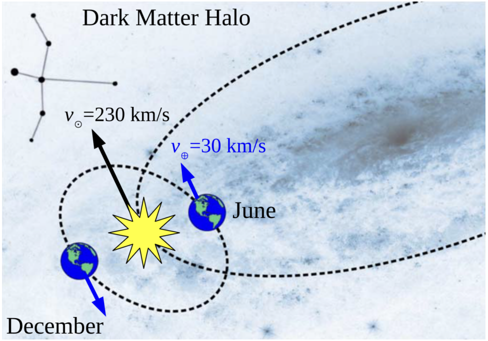
XKCD



Ferreira, E.G.M. Ultra-light dark matter. Astron Astrophys Rev 29, 7 (2021)

Dark matter searches

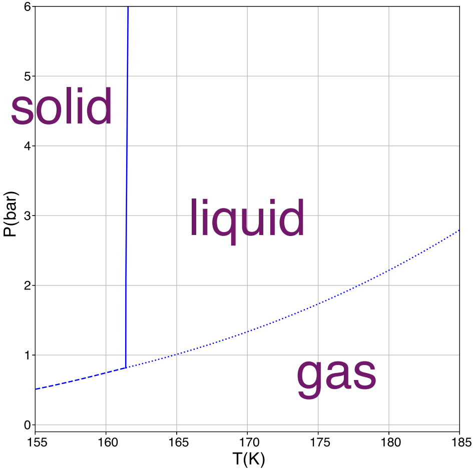


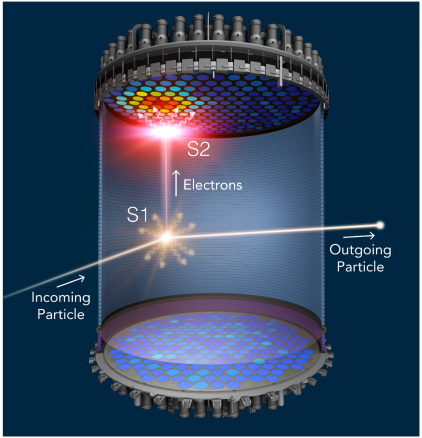


Marc Schumann 2019 J. Phys. G: Nucl. Part. Phys. 46 103003

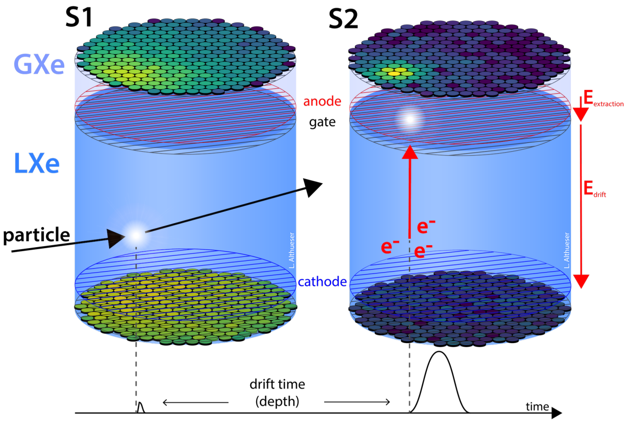
→ observe scattering events in a detector as the detector moves through the dark matter halo.

Dual-phase time projection chambers

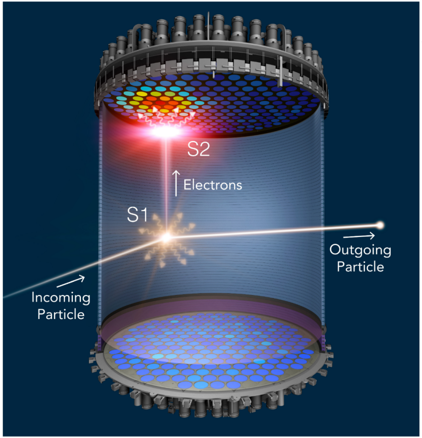




LZ (arXiv:1703.09144)



Lutz Althueser (XENONnT)



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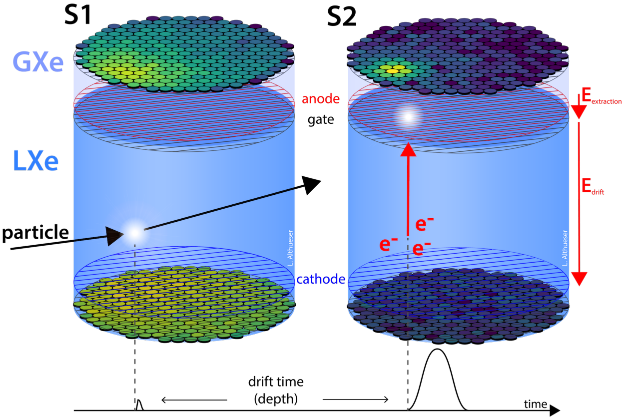


Lutz Althueser (XENONnT)

S1: Light produced during the primary ionisation and subsequent recombination

S2: Electrons liberated, drifted to the liquid-gas interface, extracted, and accelerated to the end of exciting electro luminescences

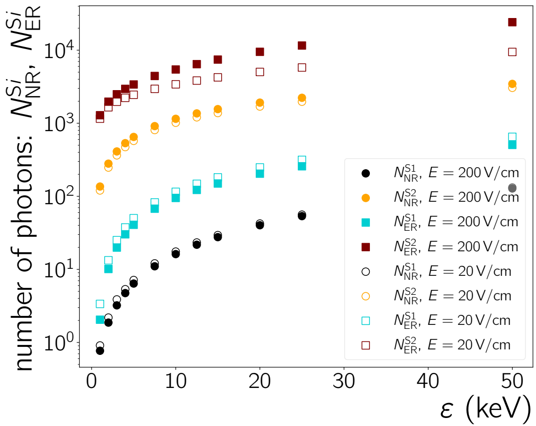
Nuclear recoil vs electronic recoil

Electronic recoil: Scattering events with the electron shell of the (xenon) atom.
$\rightarrow \beta$, γ, axions, neutrinos

Nuclear recoil: Scattering events with the atomic nucleus.
$\rightarrow$ neutrons, WIMPs, neutrinos

"Energy quenching" as compared to the electronic recoil – part of the collision energy is absorbed into motion of the nucleus

Electric fields matter for the (relative) size of S1 and S2 signal: drift field, extraction field, field for acceleration



Made using NEST with $\rho = 3\,g\,cm^{-3}$, $g_{S1} = 0.2$, $g_{S2} = 20$.

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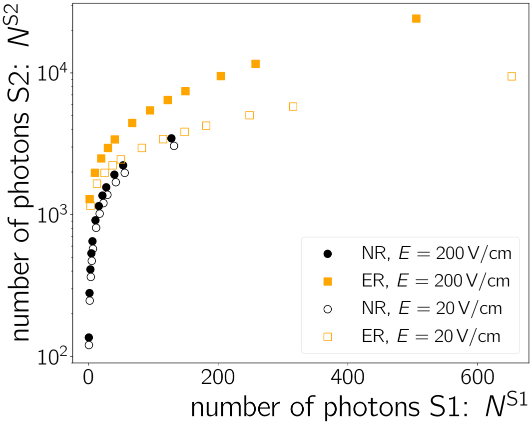

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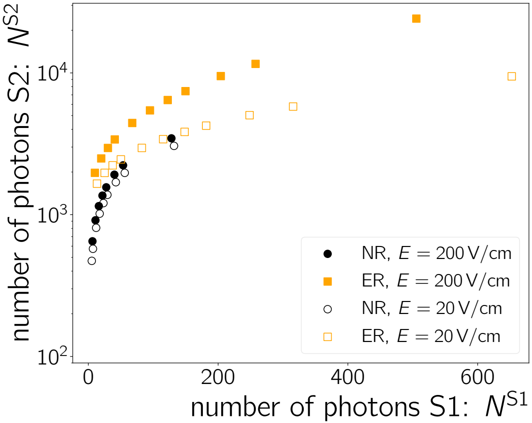

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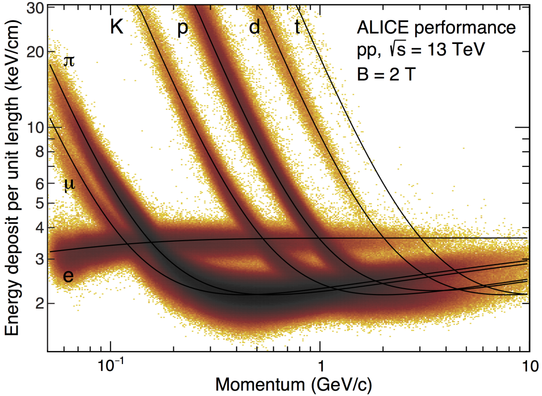
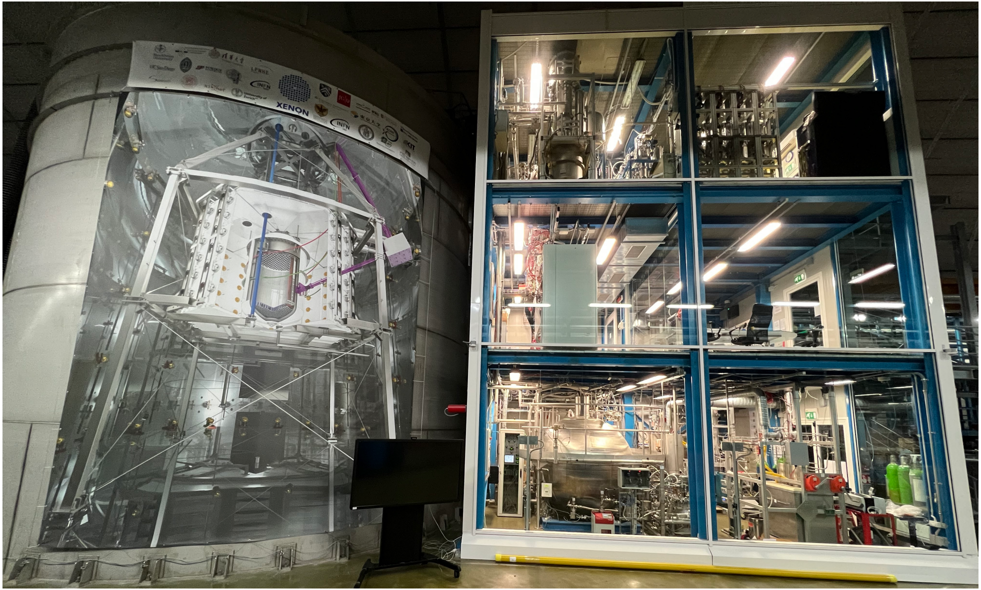
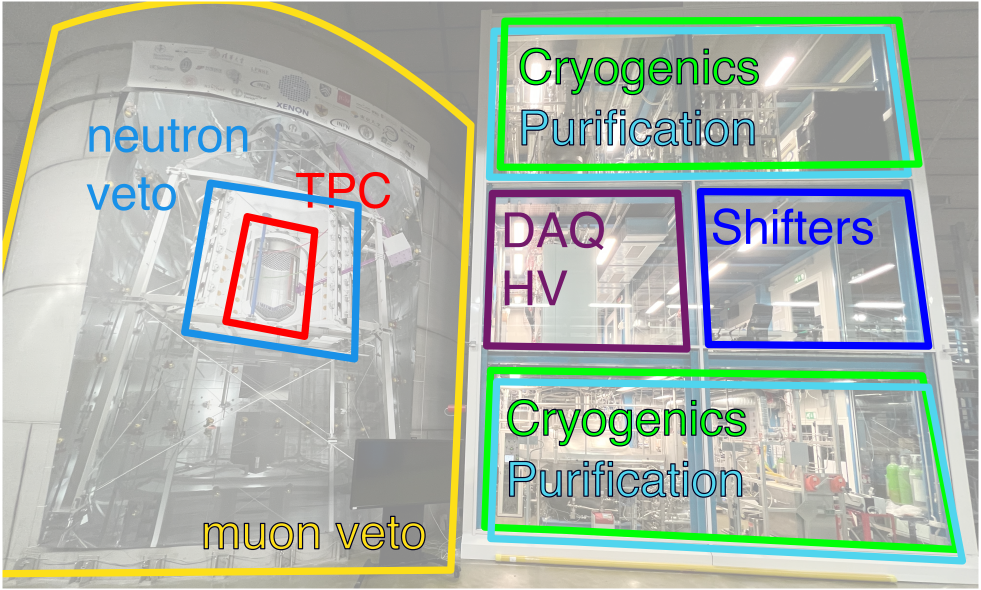


R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

XENONnT


XENON


neutron
veto
TPC
muon veto
Cryogenics
Purification
DAQ
HV
Shifters
Cryogenics
Purification

Muon veto:

- Water Cherenkov detector, vetos muons, shields the TPC

Neutron veto:

- World's first water Cherenkov neutron veto
- 120 8" PMTs facing the TPC cryostat
- Maximizes light-collection efficiency with highly reflective ePTFE walls and ultra-pure water
- Neutrons are tagged by the 2.22 MeV γ released by neutron-capture on hydrogen
- Gadolinium salt recently added. Increase the neutron capture cross-section and the energy released in γs to $\sim$8 MeV

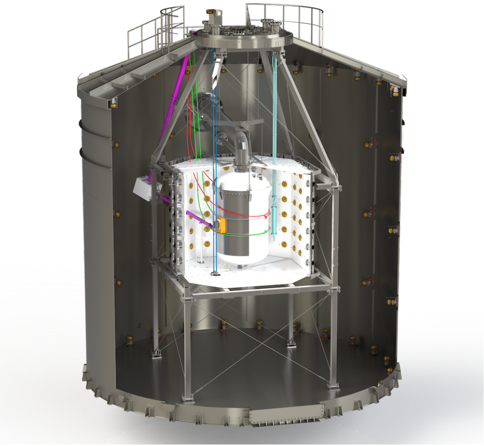


Image credit XENON collaboration

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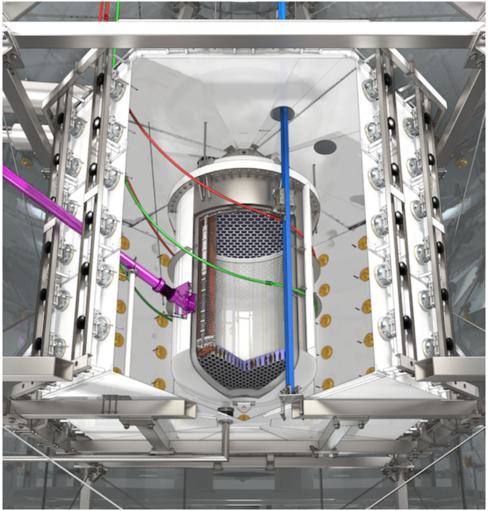


Image credit XENON collaboration

XENONnT TPC

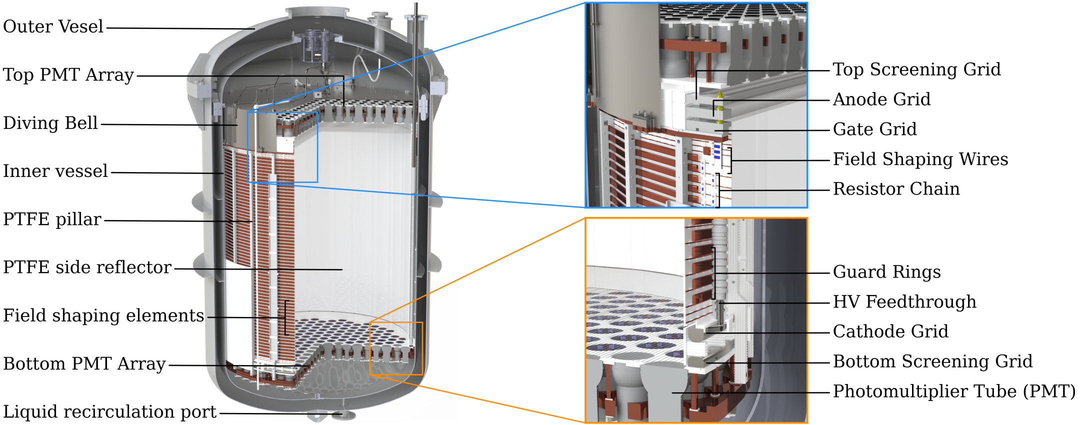
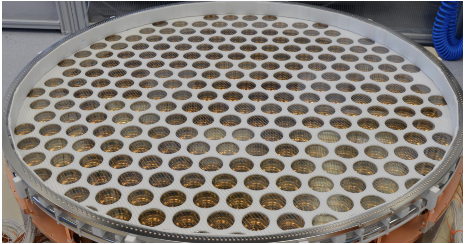


Image credit XENON collaboration

XENONnT TPC

- 494 3" PMTs in top and bottom array
- Cathode, gate and anode (as well as top and bottom screen) are wire grids with 200 m to 300 m of wire per grid
- Gate and anode have two additional "transverse wires"
- Wires are fixed with coper pins in specially screened and selected stainless steel frames
- Cylindrical PTFE walls for high reflectivity
- Drift field: $23\,\mathrm{V\,cm^{-1}}$; 2.2 ms electron drift time; ($>$ 15 ms electron life time due to excellent purity)



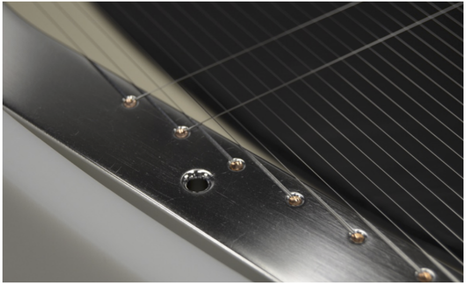
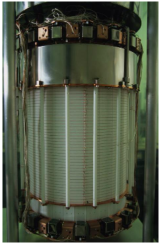
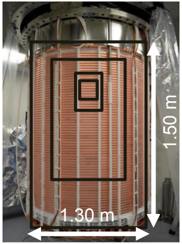


Image credit XENON collaboration

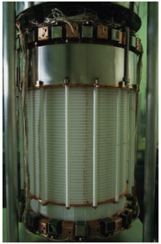
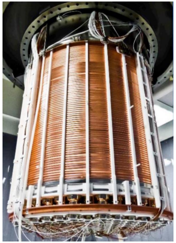
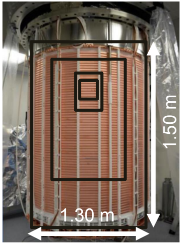
The XENON evolution



	XENON10	XENON100	XENON1T	XENONnT
	2005-2007	2008-2016	2012-2019	2020-2026
	14 kg Xe target	62 kg Xe target	2 t Xe target	5.9 t Xe target, 8.5 t total mass
	~10^{-43} cm^2	~10^{-45} cm^2	$4 \cdot 10^{-47}$ cm^2	$1.4 \cdot 10^{-48}$ cm^2 (projected for 20 t·y exposure) (Flea)
	~2M background ER / (keV· t·y)	1800 background ER / (keV· t·y)	82 background ER / (keV· t·y)	16.1 background ER / (keV· t·y)

The XENON evolution

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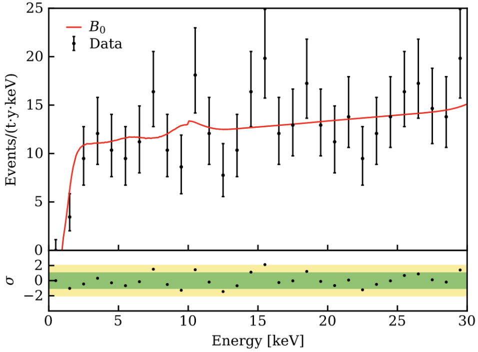
?

Electron and nuclear recoil results

Electron recoil



Phys. Rev. Lett. 129, 161805

WIMP

Electron and nuclear recoil results

Electron recoil

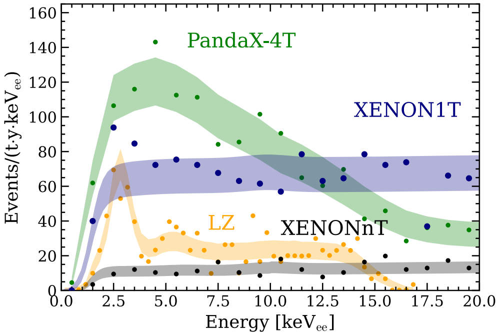


Image credit: XENON collaboration

WIMP

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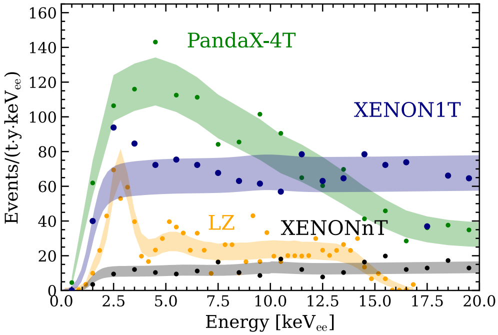

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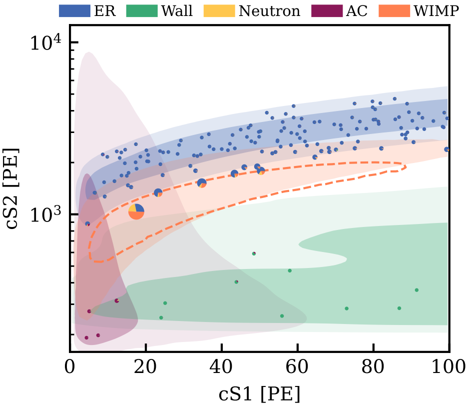

Image credit: XENON collaboration

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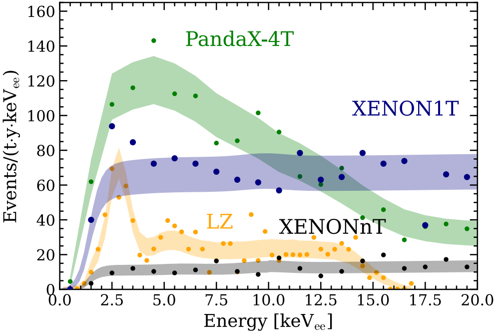

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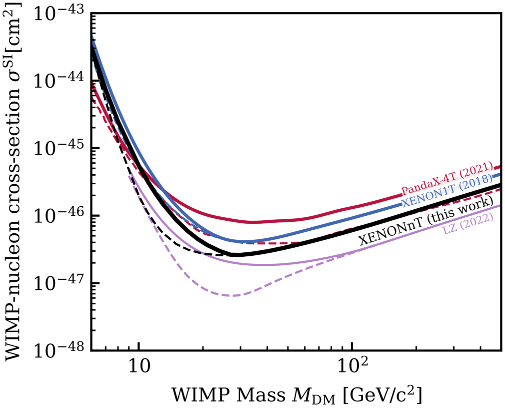


Phys. Rev. Lett. 131, 041003

Electrode stability's imprint on physics results

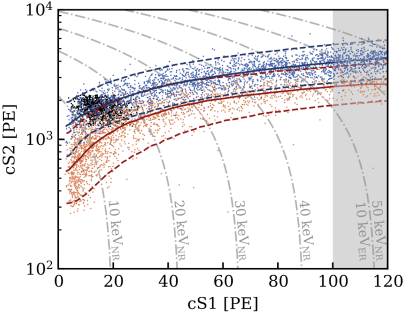


FIG. 1. NR and ER calibration data from ^{241}AmBe (orange), ^{220}Rn (blue) and ^{37}Ar (black). The median and the $\pm 2\sigma$ contours of the NR and ER model are shown in blue and red respectively. The gray dash-dotted contour lines show the reconstructed NR energy (keV$_{NR}$). Only not shaded events up to a cS1 of 100 PE are considered in the response model fits.

$$E_\mathrm{d} = 23\,\mathrm{V\,cm^{-1}}$$

Phys. Rev. Lett. 131, 041003

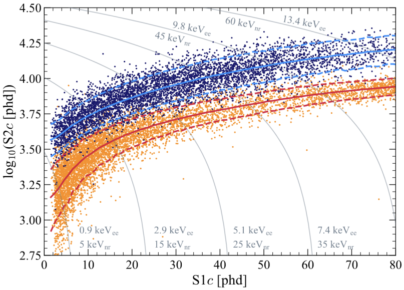


FIG. 1. Calibration events in $\log_{10}$S2c-S1c for the tritium source (dark blue points, 5343 events) and the DD neutron source (orange points, 6324 events). Solid blue (red) lines indicate the median of the ER (NR) simulated distributions, and the dotted lines indicate the 10 % and 90 % quantiles. Thin grey lines show contours of constant electron-equivalent energy (keV$_{ee}$) and nuclear recoil energy (keV$_{nr}$).

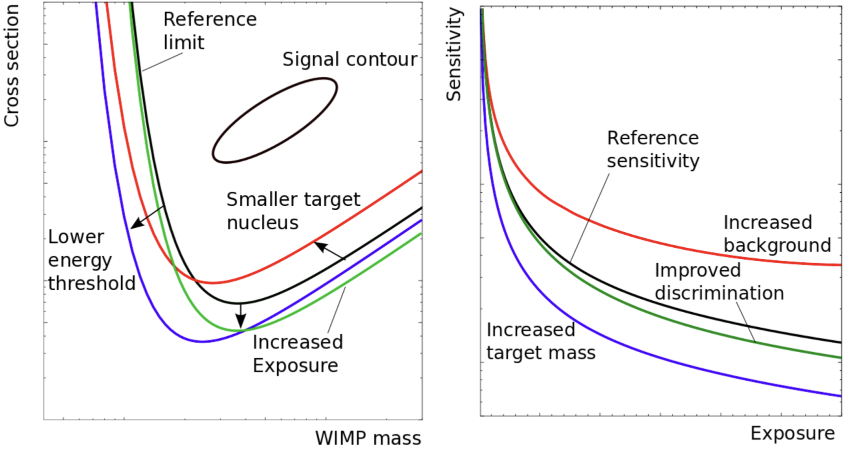
$$E_\mathrm{d} = 193\,\mathrm{V\,cm^{-1}}$$

Phys. Rev. Lett. 131, 041002

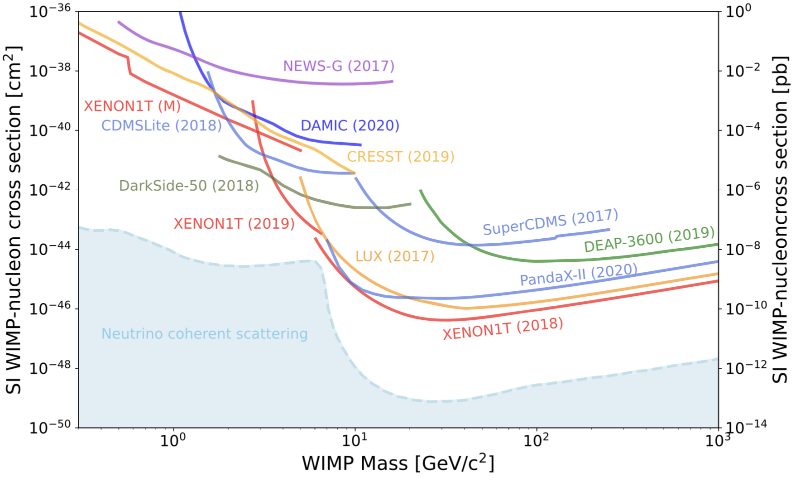
Future experiments: Darwin or XLZD

Darwin: $\sim$40 t liquid xenon target

XLZD: up to 100 t liquid xenon



J. Phys. G43 (2016) no.1, 013001



J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001

Current baseline approach: Make XENONnT / LZ bigger

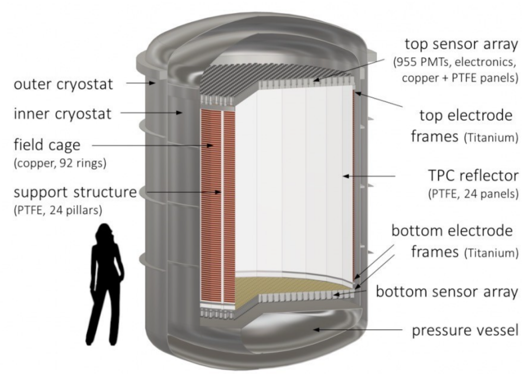
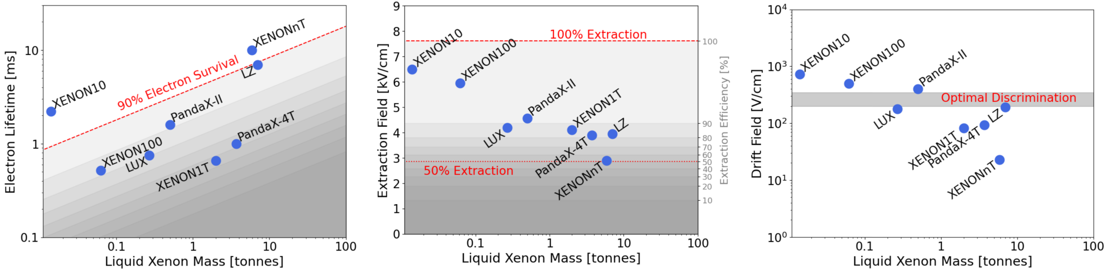


Image credit: Darwin collaboration

- 1910 3" PMTs: 955 in top and bottom array each
- 50 t liquid xenon
- Background target: 0.1 μBq kg^{-1} ^{222}Rn
- 2.6 m drift length, 2.6 m electrode diameter
- XLZD: Consortium formed by XENONnT, LZ, Darwin to work together for the next generation experiment

What if we just made XENONnT / LZ bigger ?

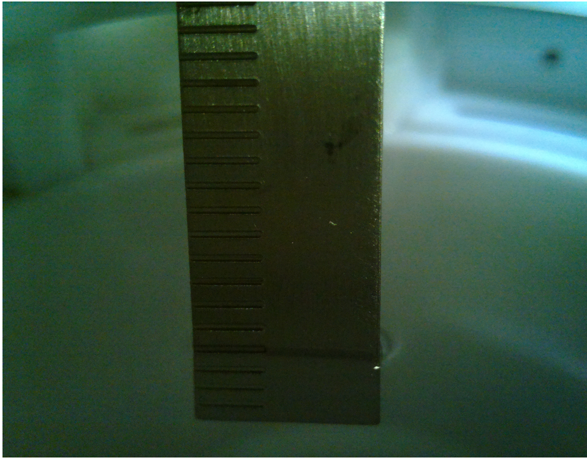


arxiv:2310.00722

- Today's xenon purification techniques already allow a much larger detector
- Other challenges I won't talk about: Accidental coincidences, backgrounds in general, calibration
- Field stability challenging: LZ's design field $E_\mathrm{d} = 300\,\mathrm{V\,cm^{-1}}$, has $193\,\mathrm{V\,cm^{-1}}$; XENONnT's design field: $E_\mathrm{d} = 200\,\mathrm{V\,cm^{-1}}$, has $23\,\mathrm{V\,cm^{-1}}$

Single phase: Removing the phase boundary

- TPC geometry no longer dictated by gravity
- Potentially getting rid of “hot spots”
- No longer the need to ensure a careful spacing between liquid level and two electrodes
- Need fields between 400 $\mathrm{kV\,cm^{-1}}$ and 700 $\mathrm{kV\,cm^{-1}}$ to produce S2
- Unfortunately nothing to report yet … but we had the first liquid xenon after lock-down this month



Video, GIF

Development of electrode screening techniques

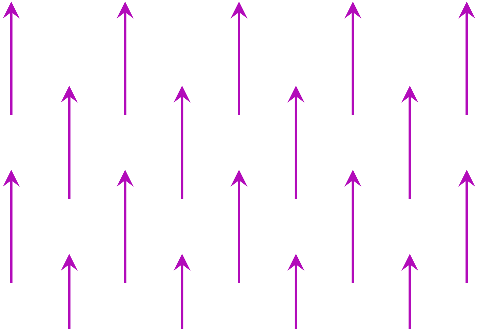
$\rightarrow$ Identifying regions which may emit electrons and create backgrounds or induce breakdown

Field emission

Fowler-Nordheim field emission current density:

$$J = \frac{c_1}{\phi} \cdot 10^{\frac{c_2}{\sqrt{\phi}}} (\beta E)^2 \cdot \exp\left(\frac{-c_3 \sqrt[3]{\phi}}{\beta E}\right)$$

- β: **Field enhancement** factor
- ϕ: Work-function of steel in liquid xenon
- E: Electric field in the bulk



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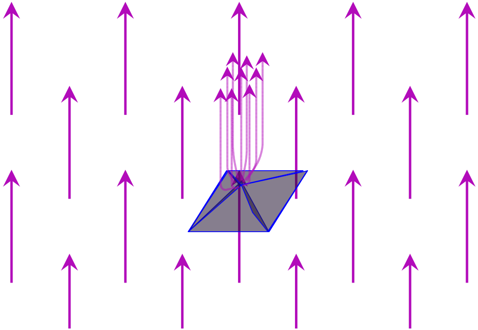

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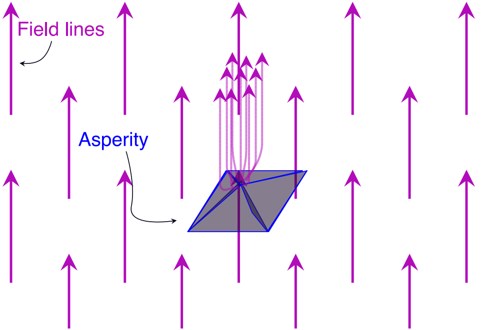

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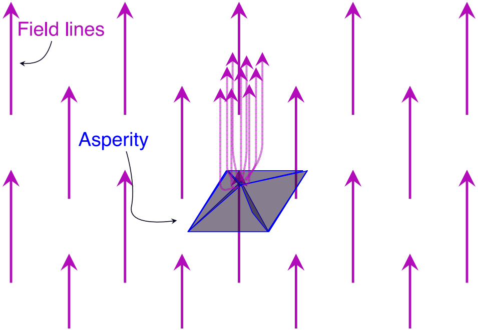
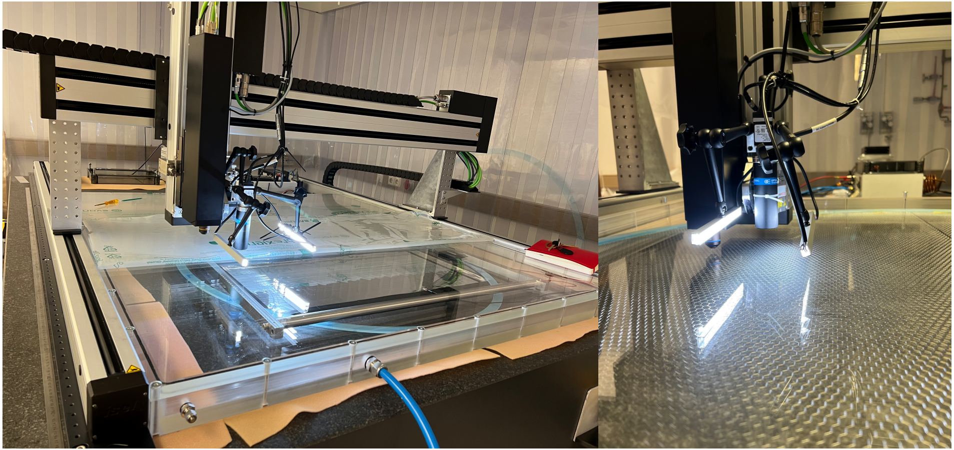
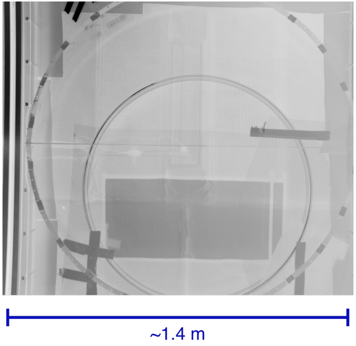


- Field enhancement created through (*e.g.*) asperities on the electrodes' surface
- Impurities may reduce the work-function ϕ
- Electrons emitted from cathodic surfaces, may not only lead to backgrounds but in the worst case to breakdown



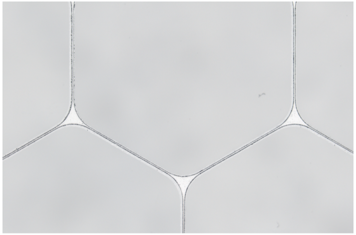
$\Rightarrow$ Objects with up to $2.0 \times 1.4\,\text{m}^2$ can be scanned fully automatically

Overview camera for $\sim 1.5 \times 1.5\,\text{m}^2$ imaging



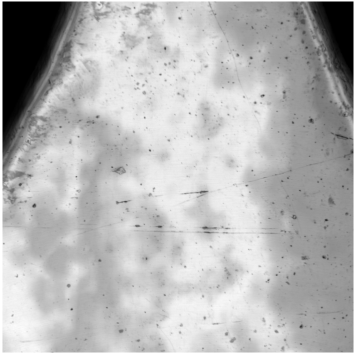
- 5 Mpixels, working distance ~ 1 m
- Resolution: $\sim 0.6 \times 0.6\,\text{mm}^2$ imaged in one pixel

High resolution camera for close-up inspection



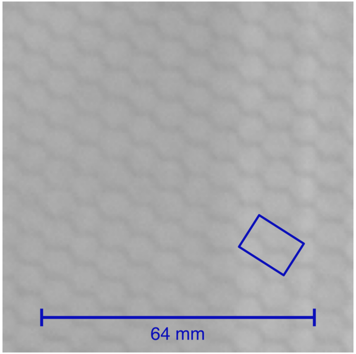
- ~ 15 Mpixels, working distance 43.1 mm
- Resolution: $\sim 1.4 \times 1.4\,\mu\text{m}^2$

3D confocal microscope



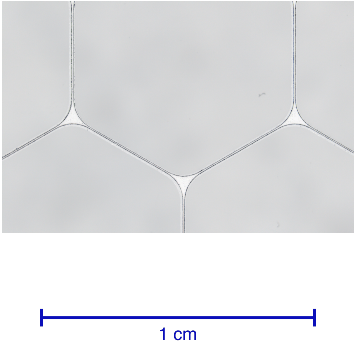
- $\times 10$, $\times 20$, $\times 50$ (photo)
- 1.4 Mpixels, working distance $\sim 11 - 1$ mm
- Res.: $\sim 0.96 \times 0.96\,\mu\text{m}^2$ to $\sim 0.3 \times 0.3\,\mu\text{m}^2$

Overview camera for $\sim$1.5 × 1.5 m^2 imaging



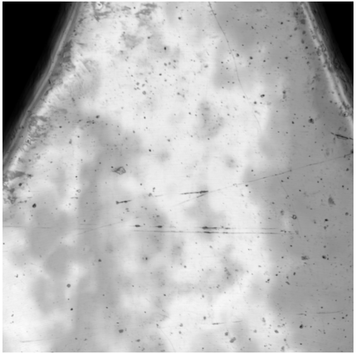
- 5 Mpixels, working distance $\sim$1 m
- Resolution: $\sim$0.6 × 0.6 mm^2 imaged in one pixel

High resolution camera for close-up inspection



- $\sim$15 Mpixels, working distance 43.1 mm
- Resolution: $\sim$1.4 × 1.4 µm^2

3D confocal microscope



- ×10, ×20, ×50 (photo)
- 1.4 Mpixels, working distance $\sim$11 − 1 mm
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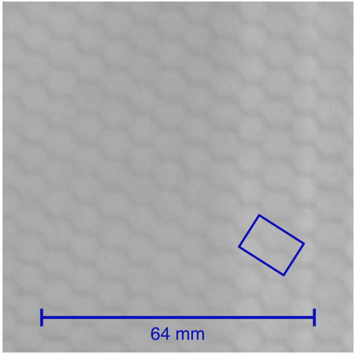
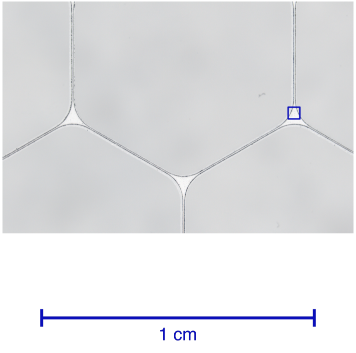
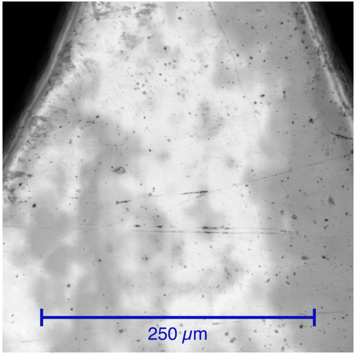
Overview camera for $\sim$1.5 $\times$ 1.5 m^2 imaging	High resolution camera for close-up inspection	3D confocal microscope
		

- 5 Mpixels, working distance $\sim$1 m
- Resolution: $\sim$0.6 $\times$ 0.6 mm^2 imaged in one pixel

- $\sim$15 Mpixels, working distance 43.1 mm
- Resolution: $\sim$1.4 $\times$ 1.4 µm^2

- $\times$10, $\times$20, $\times$50 (photo)
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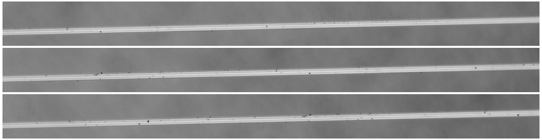
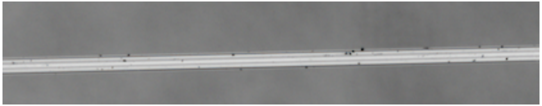
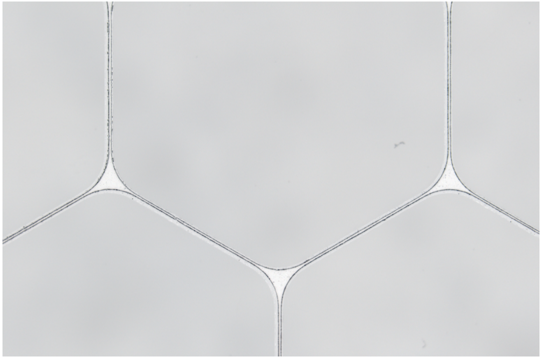


Zoomed wire:





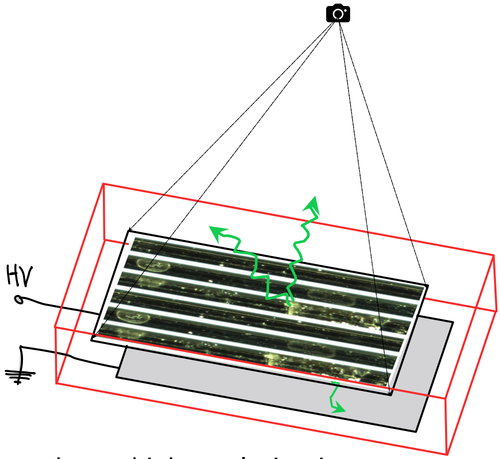
Zoomed leg:

- Various spots seen on wires and ledges
- Which would lead to local field enhancement and electron emission?

Challenge: Which of the many “spots” may enhance the local field and possibly lead to electron emission or even breakdown ?

Ansatz:

- Place an electrode on a ground plane and in an atmosphere of choice (air, argon…)
- Apply HV. If “spots” are defects which enhance the electrical field locally, they may seed corona discharges
- Image the light (electroluminescence) of the discharge



⇒ Such a measurement would also be much faster than a high resolution image scan

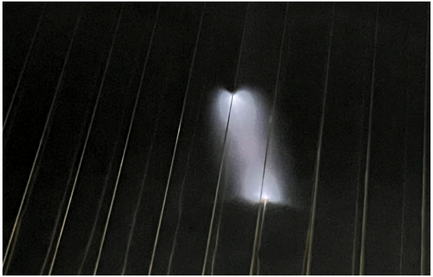
Corona discharges

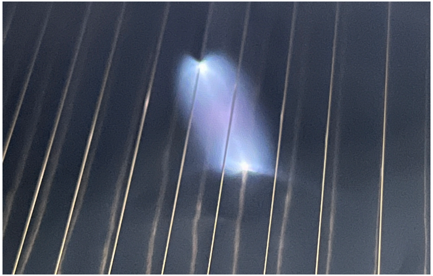
$$E_c = 31 \cdot \delta \cdot \left(1 + \frac{0.308}{\sqrt{\delta r\,[\mathrm{cm}]}}\right) \left[\mathrm{kV\,cm^{-1}}\right]$$

$$V_c \sim \frac{E_c}{2} r \cdot \ln\left(\frac{2d}{r}\right)$$

Using corona discharges for electrode tests:

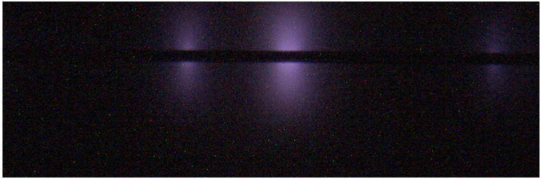
- Ideally: Keep the HV on the electrodes below the limit of corona discharges caused by the wire geometry itself
- Field enhancing defects on wires: $V_c^{\mathrm{defect}} < V_c$
- Corona emission below the wire in geometry: Ground plate – wire – camera





Preliminary correlation of defects and corona – 1/2

Example: Air, high resolution camera:



dark

- Scan wires (XENONnT quality) with the high resolution camera and measure argon corona
- Use corona and scanning images to train a binary class convolutional image classifier with dense processing layers (tensorflow sequential)
- The following is only based on ~60 cm of wire in the small scale, exploratory set-up

B.Sc. thesis work of S. Mitra

Preliminary correlation of defects and corona – 1/2

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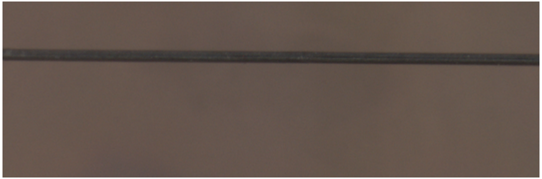

bright

- Scan wires (XENONnT quality) with the high resolution camera and measure argon corona
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B.Sc. thesis work of S. Mitra

Preliminary correlation of defects and corona – 1/2

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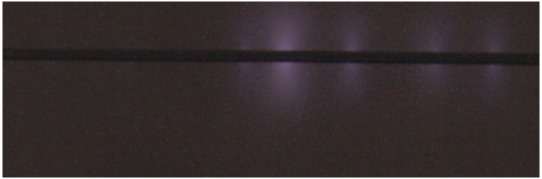

overlay

- Scan wires (XENONnT quality) with the high resolution camera and measure argon corona
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Preliminary correlation of defects and corona – 2/2

- Match coordinate system in high resolution images and corona images
- Label "spot" locations – *i.e.* potential defects – in images ($N_{\mathrm{d}}^{\mathrm{train}} = 675$), label corona locations ($N_{\mathrm{c}}^{\mathrm{train}} = 175$).
- Train the image classifier to predict *corona* or *no corona* based on a *spot*

⇒ The prediction power for *corona* is not great. (Some correlation between *spots* and *corona*)

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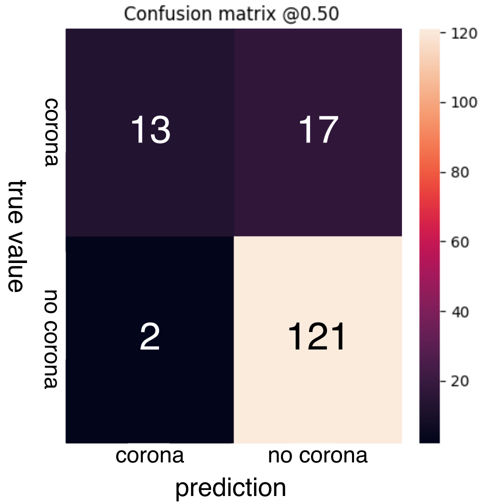

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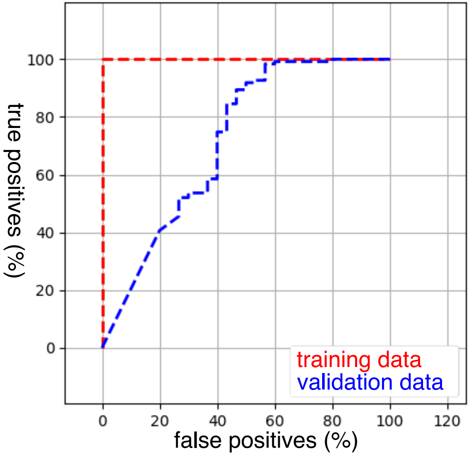

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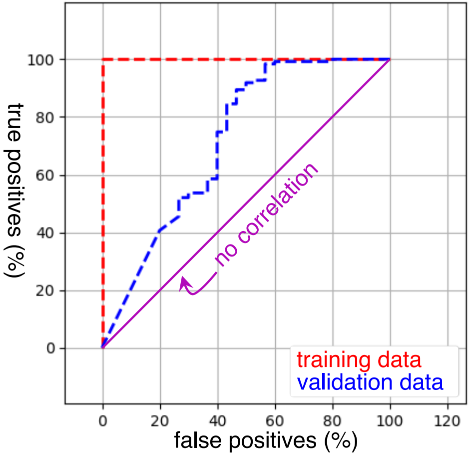
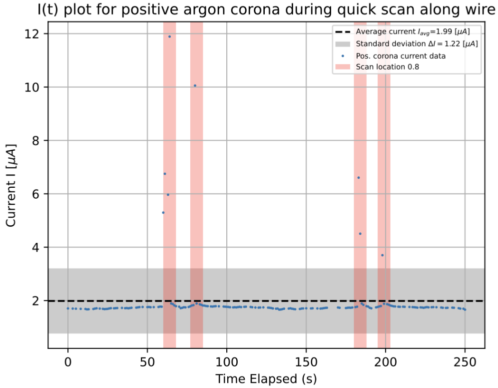


Scan a wire with a moving electrode



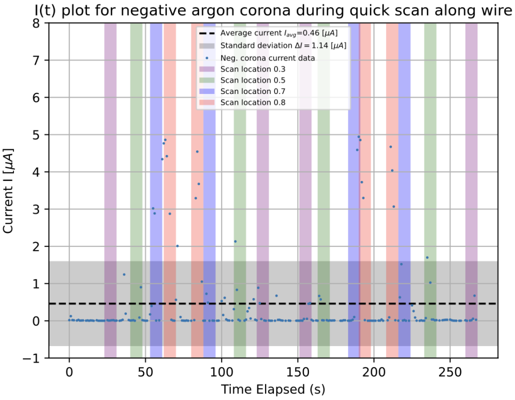


Image credit S. Mitra

→ Current increase measured with a moving electrode might be a better tool for defect detection

Summary & Outlook

- The hunt for dark-matter continues; xenon filled experiments are currently leading the way
- A next generation xenon observatory for dark matter will aim at filling the gap to the "neutrino fog"
- Reaching the design fields has already been proven challenging for the current generation of TPCs
- Electrodes of a next generation experiments will have $\sim$60 % larger radius
- Work on new electrodes, assay methods for the current style of electrodes, and different concepts is on the way
- In Mainz we are working on (semi-) automatic identification of defects on electrodes
- Tools based on a moving "scanning an electrode" seem the most promising so far