SEARCHING FOR DARK PHOTONS USING A MULTILAYER DIELECTRIC HALOSCOPE

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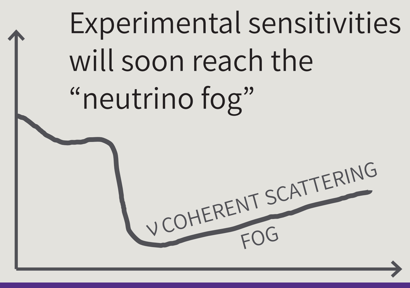
THE DARK PHOTON

85% Of the matter in the Universe is Dark Matter

Yet... it is still undiscovered

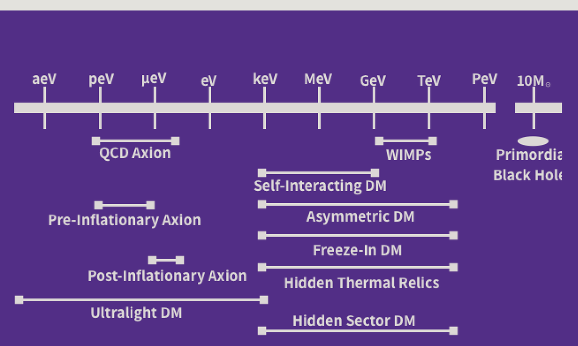
Among the most favourable DM candidates are WIMPs! Their electroweak cross section and a mass in the GeV-TeV range give the correct relic abundance—hence the so called "WIMP miracle"!

Experimental sensitivities will soon reach the "neutrino fog"



Alternative searches of dark matter are increasingly gaining traction.

Astrophysical and cosmological bounds are satisfied by a vast number of candidates that span over 30 orders of magnitude in mass: DM could be anywhere!



Axions and dark photons arise from sound theoretical frameworks and are the simplest among the alternative DM models.

EXPERIMENTS HAVE MAINLY FOCUSED ON THE DETECTION OF AXIONS AND DARK PHOTONS IN THE MICROWAVE RANGE, WHILE HIGHER MASSES REMAIN UNDEREXPLORED

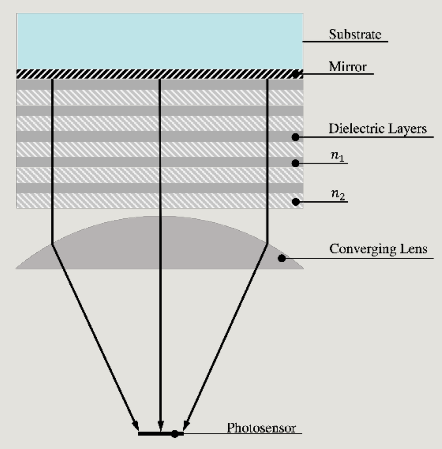
DIELECTRIC HALOSCOPES CAN BROADEN THIS SEARCH TO HIGHER MASSES IN THE RANGE FROM 0.1 TO 10 eV

This poster focuses on the detection of Dark Photons (DPs). The DP arises naturally in extensions of the SM by theorising the existence of an extra U(1) symmetry coupled to the U(1) gauge group of electromagnetism via kinetic mixing.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}(F'_{\mu\nu})^2 + \frac{\epsilon}{2}F'_{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2_{A'}(A'_\mu)^2$$

DIELECTRIC HALOSCOPE

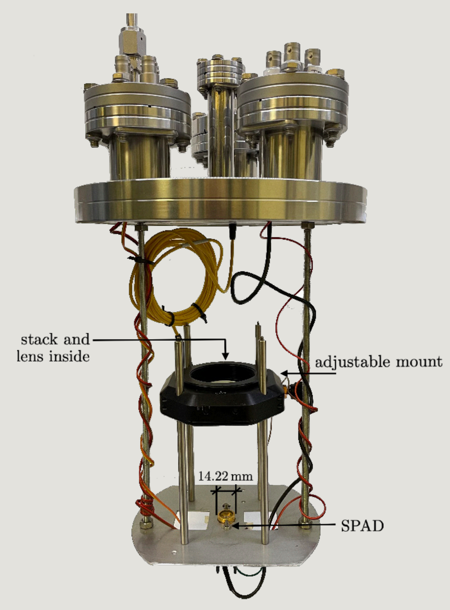
Dark photon to photon conversion is a promising experimental approach, transfering the entire rest mass energy of the DM particle to Standard Model photons.



The experimental setup consists of:

- A stack of dielectric bilayers with indices of refraction $n_1 >> n_2$ to allow for DP-photon conversion, which would otherwise be suppressed by energy-momentum conservation.
- Lens for focusing the converted dark photons onto the photosensor.
- Photosensor capable of single-photon detection, small active area, very low dark count rate and high detection efficiency.

At NYUAD we designed, built and operated MuDHI مضيء, a dielectric haloscope for the detection of DPs in the 1.5 eV mass range. MuDHI is also the first dark matter detector being operated in the Middle East.



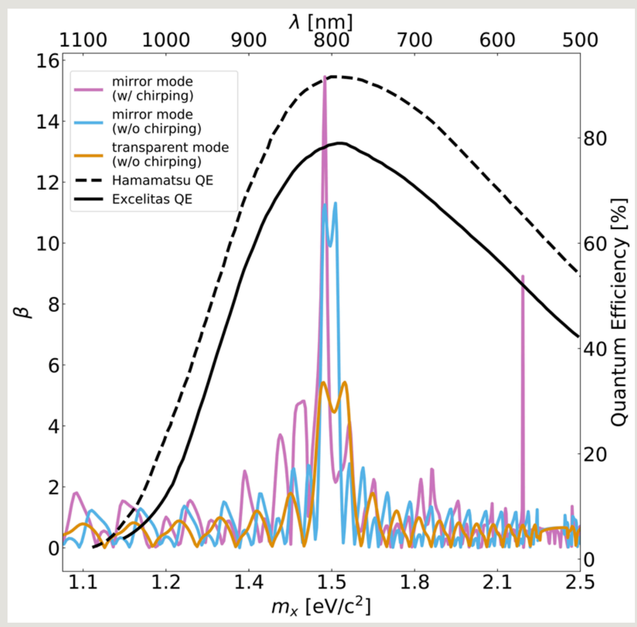
MuDHI مضيء (Multilayer Dielectric Haloscope Investigation)

- 23 bilayers of SiO_2 and Si_3N_4
- Optimisation of the number of layers and their thicknesses
- Deposition via plasma-enhanced chemical vapour deposition (PECVD)
- Measurement of thickness of the layers via Trasmission Electron Microscope

- Single-Photon Avalanche Diode: our choice of a low-cost and commercially available single-photon sensor.

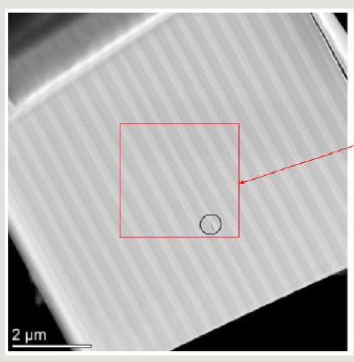
The boost factor of the stack can be described as the "conversion power" of the haloscope and is a function of the wavelength of the dark photon.

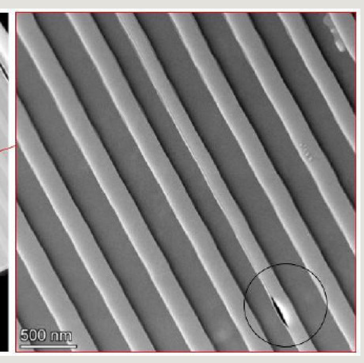
The plot to the right shows the expected boost factor spectra for different stack configurations. Each boost factor spectrum has been optimised to peak where the quantum efficiency of the photosensor is at its maximum. The solid black curve represents the QE of the Excelitas SPAD that was employed in the final configuration.

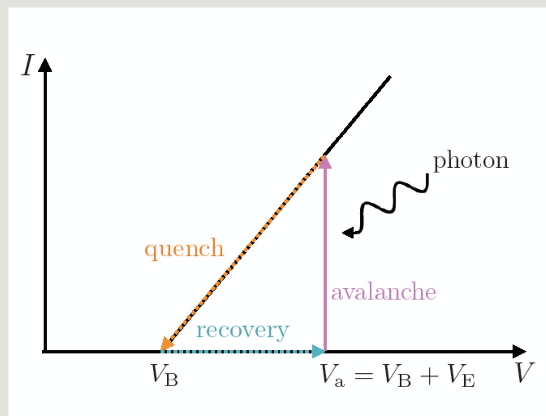


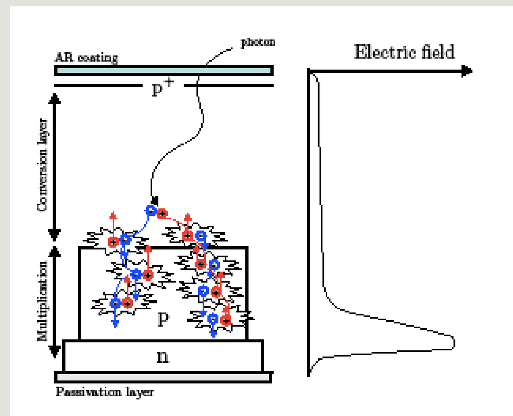
The actual boost spectrum depends on the measured thicknesses. We used the transmission electron microscopy (TEM) of the Analytical and Materials Characterization Core Technology Platform at NYUAD to analyse the stack samples prepared via focused ion beam (FIB) sample preparation procedures.

To the right, a TEM image of one of the samples extracted via FIB, the scale is shown on the bottom left corner. The photo on the right shows a zoomed-in section (the red square pointed by the arrow) of the lamella on the left.

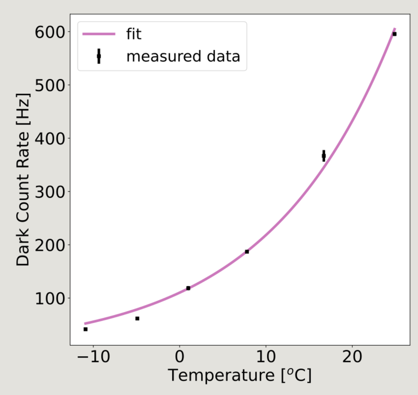


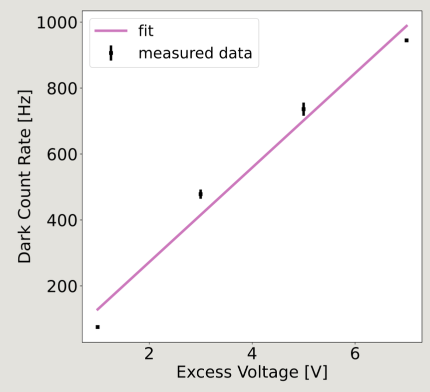


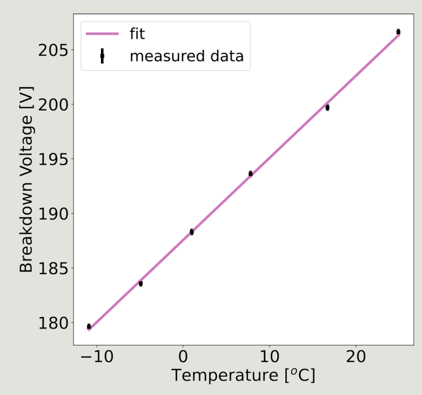




In its idle state, the SPAD is reverse-biased at a voltage V_a above the breakdown voltage V_B and no current is present. A photon impinging on the silicon can excite an electron from the valence band to the conduction band, leaving a hole behind. Thanks to the high electric field region, the electron-hole pair may trigger a diverging avalanche to produce a detectable electric pulse. Below our SPAD characterisation.







OBSERVED UPPER LIMITS

Experiment conducted in two phases.

"OFF MEASUREMENT" No stack present to measure the background

"ON MEASUREMENT" Stack present to measure signal + background

PLACE LIMITS

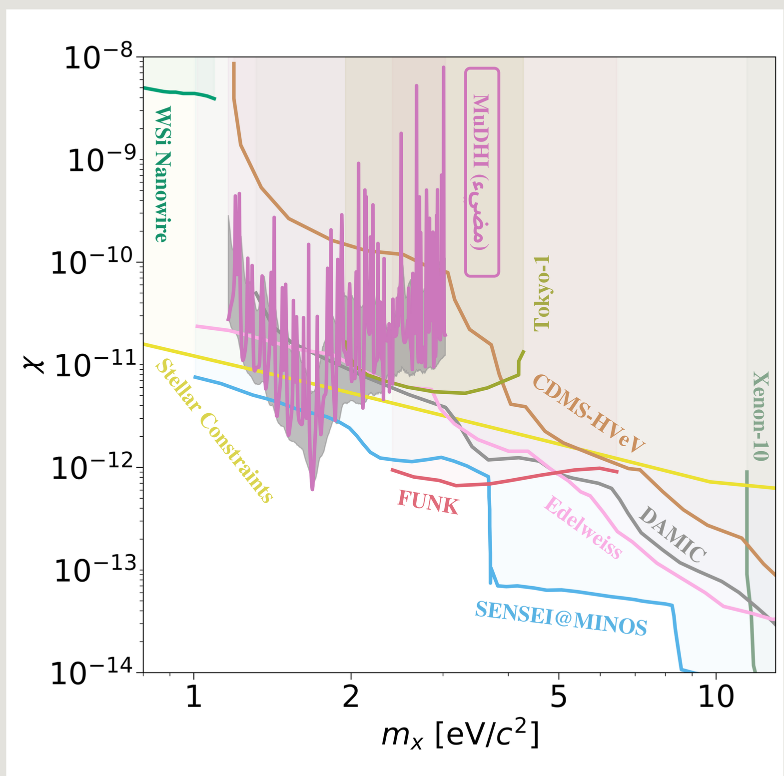
No significant signal excess is observed, so we compute the one-sided upper limit on the DP-photon coupling constant at 90% CL.

The measurements were taken at −5 o C and 1 V excess voltage.

The "on measurement" lasted two hours, while the "off measurement" lasted 30 minutes.

The final observed count rates were n_{on} = 98.6 Hz and n_{off} = 96.5 Hz, consistent with no signal observed. The corresponding 90% upper limit on the median observed dataset is 2.3 Hz.

The figure to the right shows the observed upper limit at 90% CL of the kinetic mixing parameter χ as a function of the dark photon energy using the measured boost factor. The same plot shows the most updated constraints using cosmological, experimental, and astrophysical bounds.



CONCLUSION

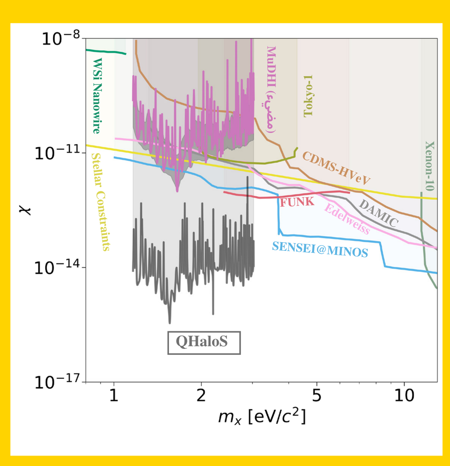
This work was published on March 30th 2022 on Physical Review D:
"Search for dark photons using a multilayer dielectric haloscope equipped with a single-photon avalanche diode" L. Manenti et al, Phys. Rev. D 105, 052010

CURRENTLY...

- Working on an axion prototype which will be operated in a 14 T magnet field.
- Characterising a new sensor equipped with a dual stage Peltier cell that allows to operate at colder temperatures and more stably.
- Fabrication of a new stack on a smoother substrate. Ex-situ ellipsometer measurements to evaluate the layer thicknesses.

THE FUTURE IS QUANTUM

The plan is to extend the search for DPs to weaker couplings by deploying a dielectric haloscope equipped with a **superconducting transition-edge sensor (TES)**. A TES is a photon number resolving quantum device with near-unity detection efficiency and very low dark count rate, exactly what is needed to greatly enhance the sensitivity to DP DM. Remarkably, with a TES, we can also explore the use of quantum sensors for particle physics. The experiment will be called QHaloS (Quatum Haloscope Search).



Current and projected constraints on the kinetic mixing parameter χ as a function of the dark photon mass mX . In magenta the result from MuDHI. In dark grey the conservative projected limits at 90% C.L. from QHaloS.