A Novel Directional Light Dark Matter Detector Based on Vertically-Aligned Carbon Nanotubes, the Dark PMT

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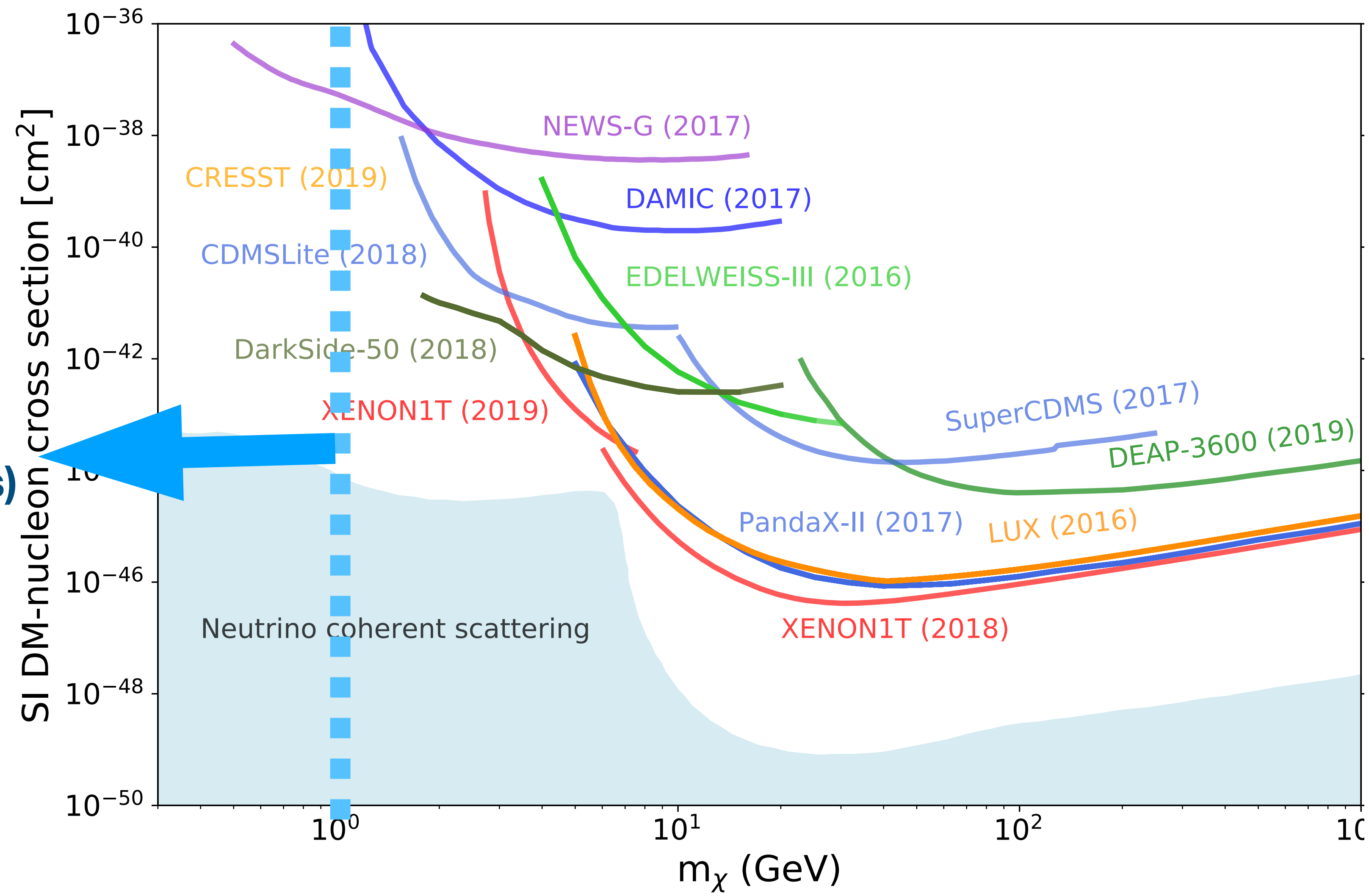
ANDROMEDA
Aligned Nanotube Detector for Research On MeV Darkmatter

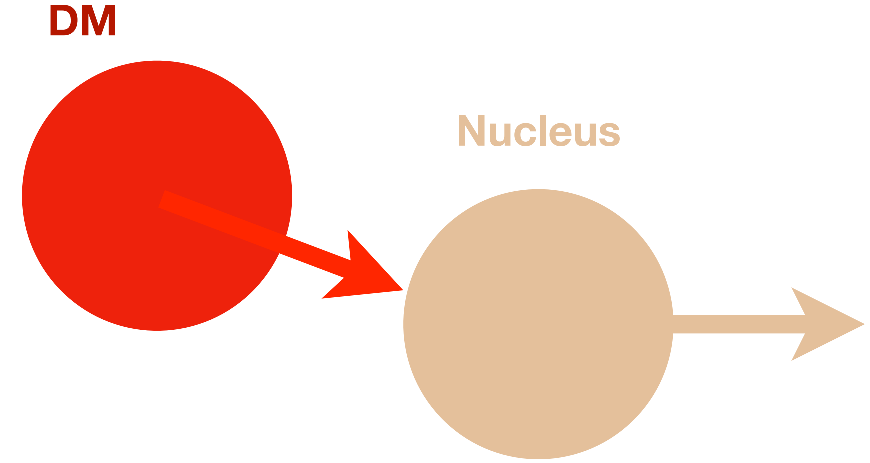
New mass range for dark matter, new experiments

- Look for a single **recoiling** particle
  - Nuclei too heavy for light DM

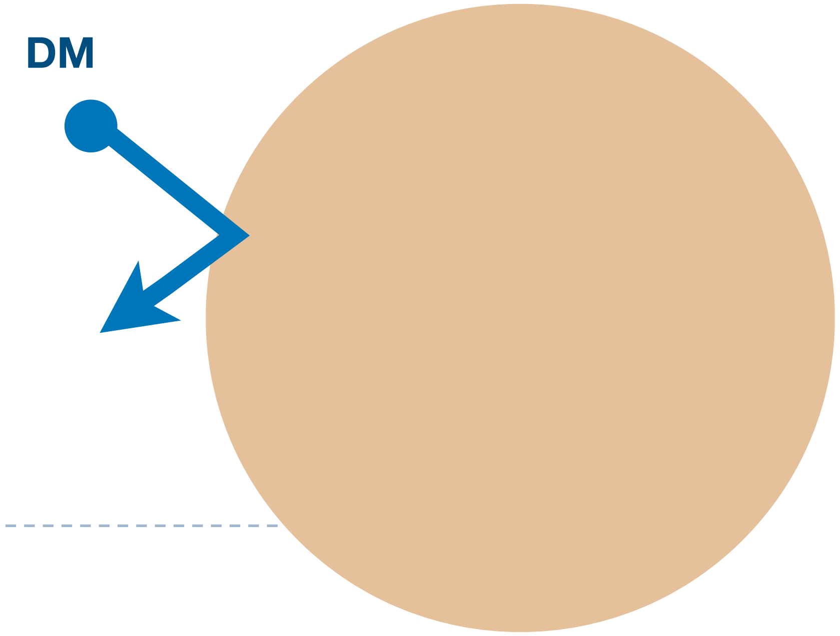
“light” DM (SIMPSs)



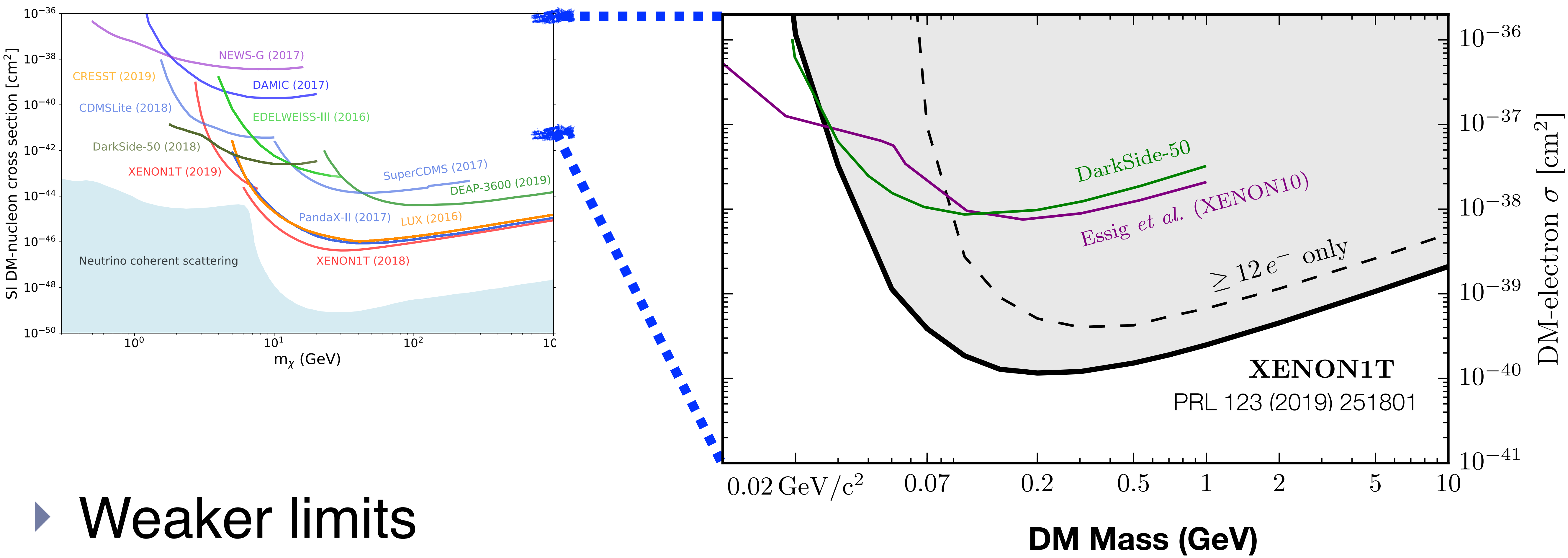
m_{DM} ~ 10 GeV



m_{DM} ~ 10 MeV



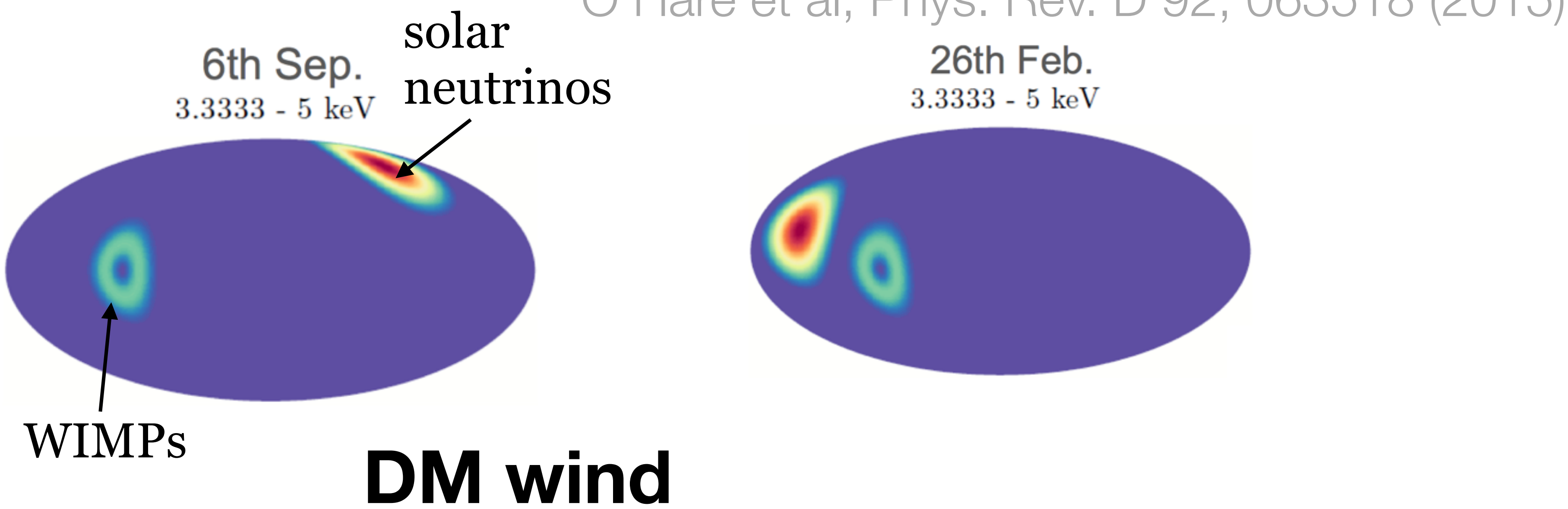
Electron recoils are (much) better

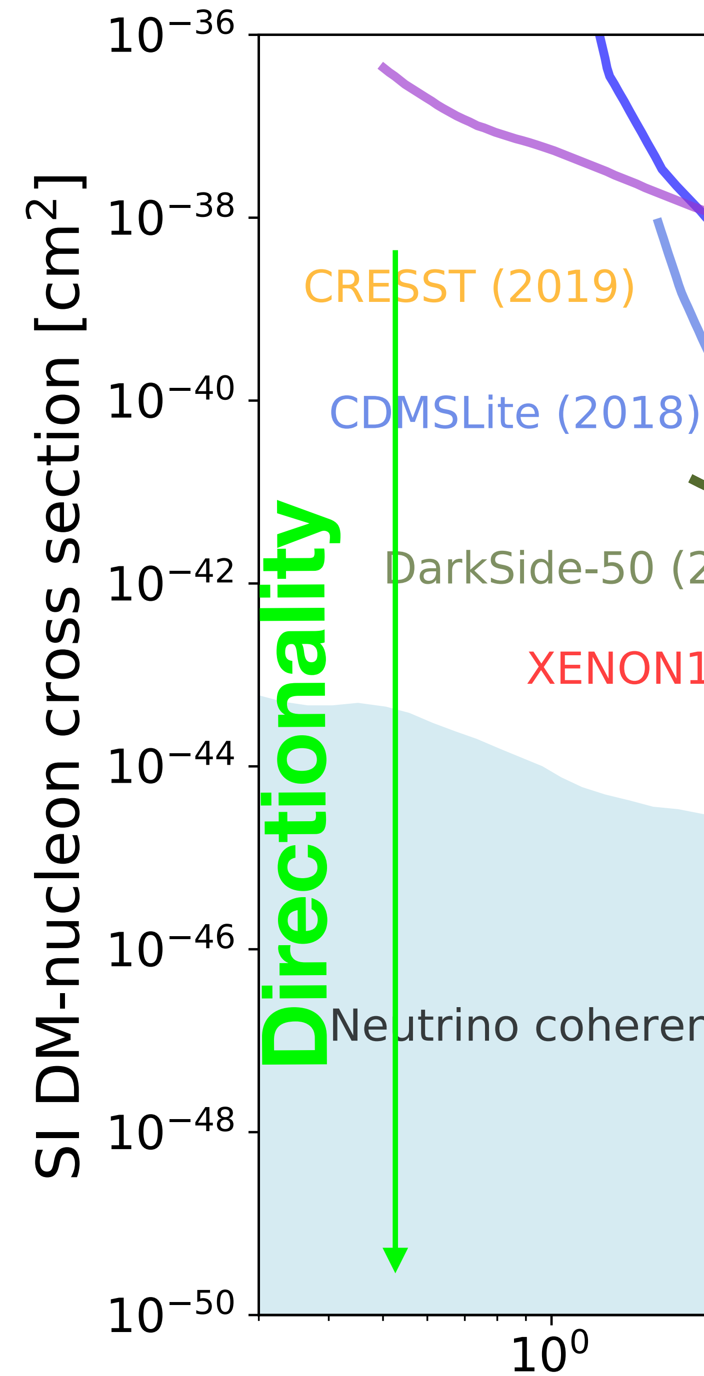


- Weaker limits
  - $m_{DM} < 100$ MeV very poor limits

Window of opportunity for gram sized targets ?

Neutrino floor exploration





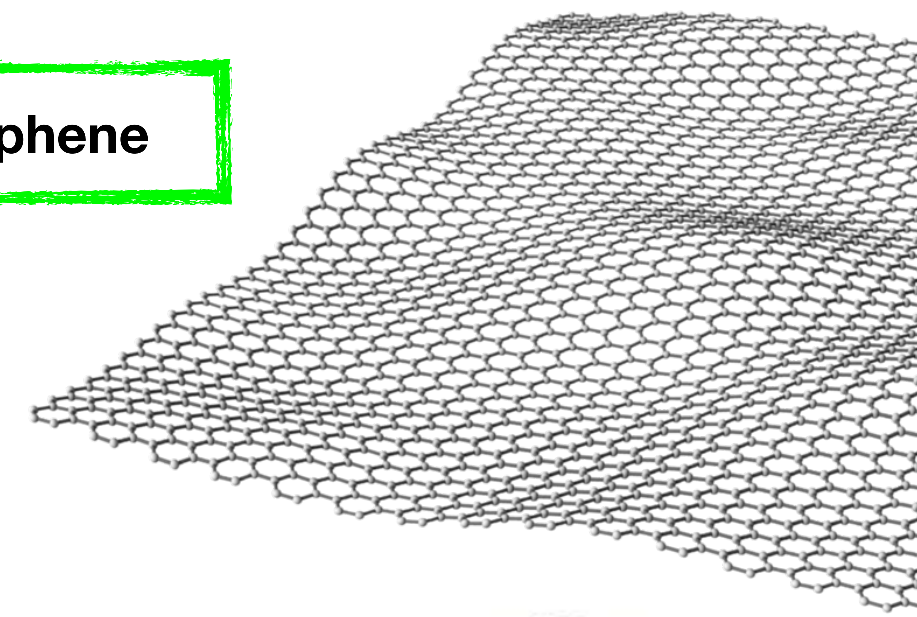
- Solar neutrinos direction never overlaps with DM wind
- In general a powerful tool to suppress any background (radioactivity)

A new detector: Light DM sensitivity and directionality in the same detector

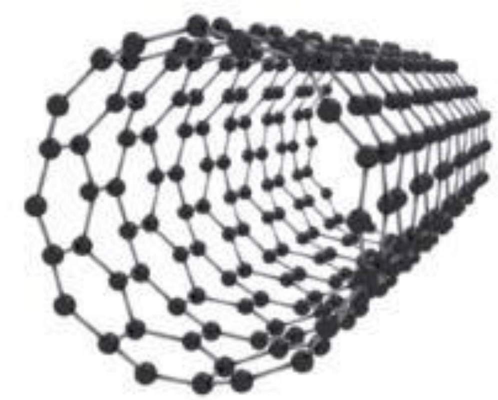
Solid state targets: 2D materials

- **Back of the envelope** calculation:
  K_{DM} = 5-50 eV (for m_{DM} = 10-100 MeV)
  - Assuming v_{DM} ~ 300 km/s
- **Enough** to extract an electron from carbon
  - Φ ~ 4.7 eV (work function) so K_e ~ 1-50 eV
  - Extremely **short** range in matter!
- 2D materials: electrons ejected **directly** into vacuum
  - **Graphene** and **carbon nanotubes**

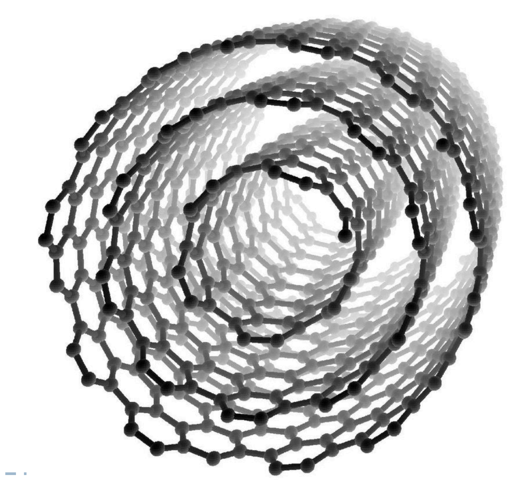
Graphene



Single-wall nanotube

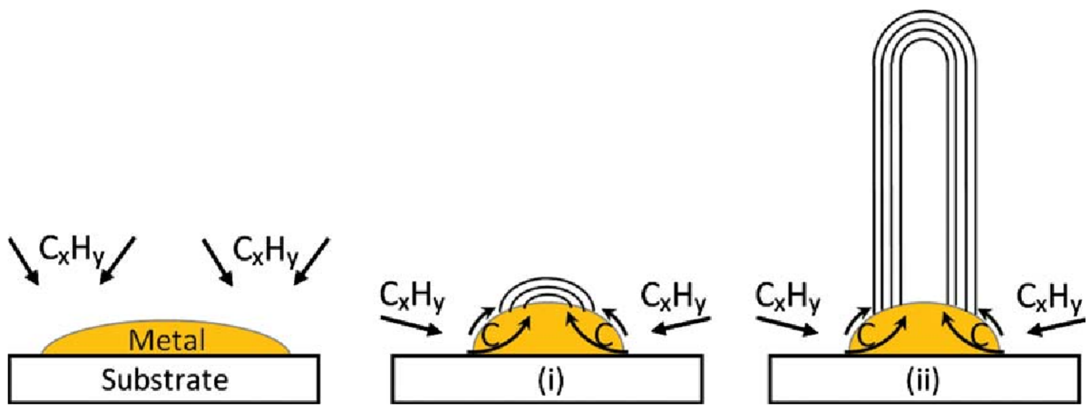


Multi-wall nanotube

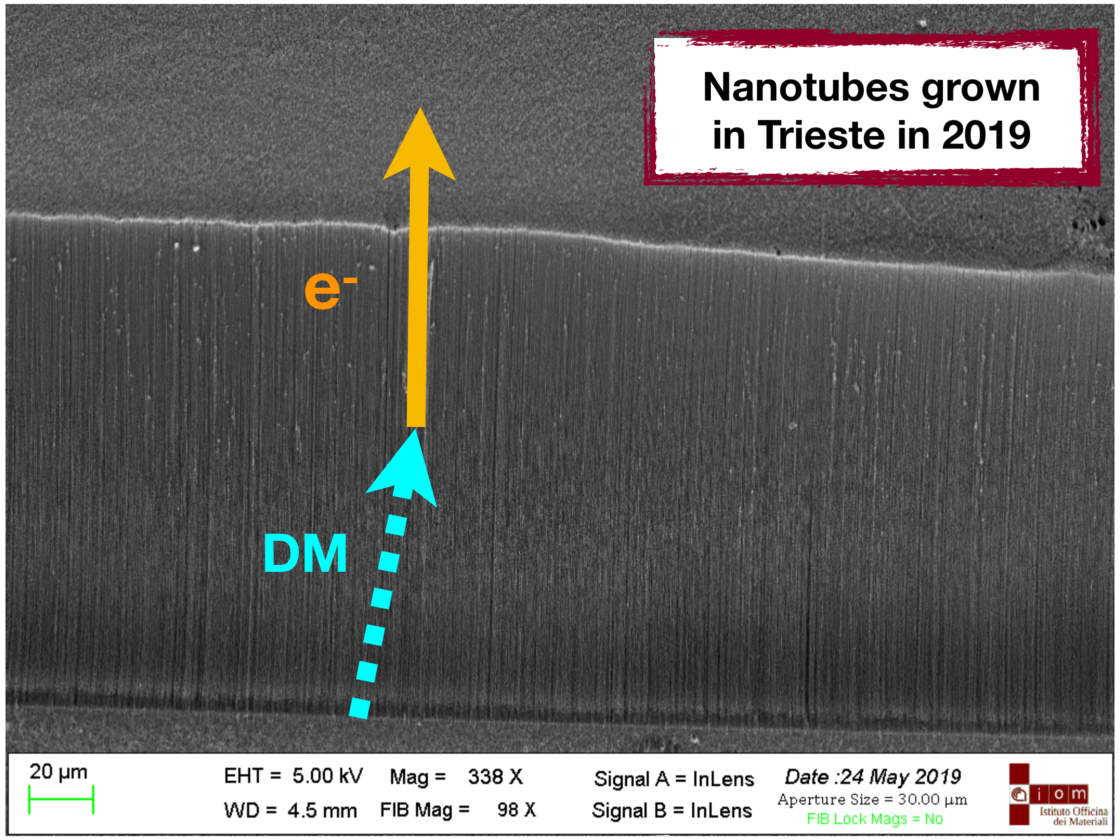


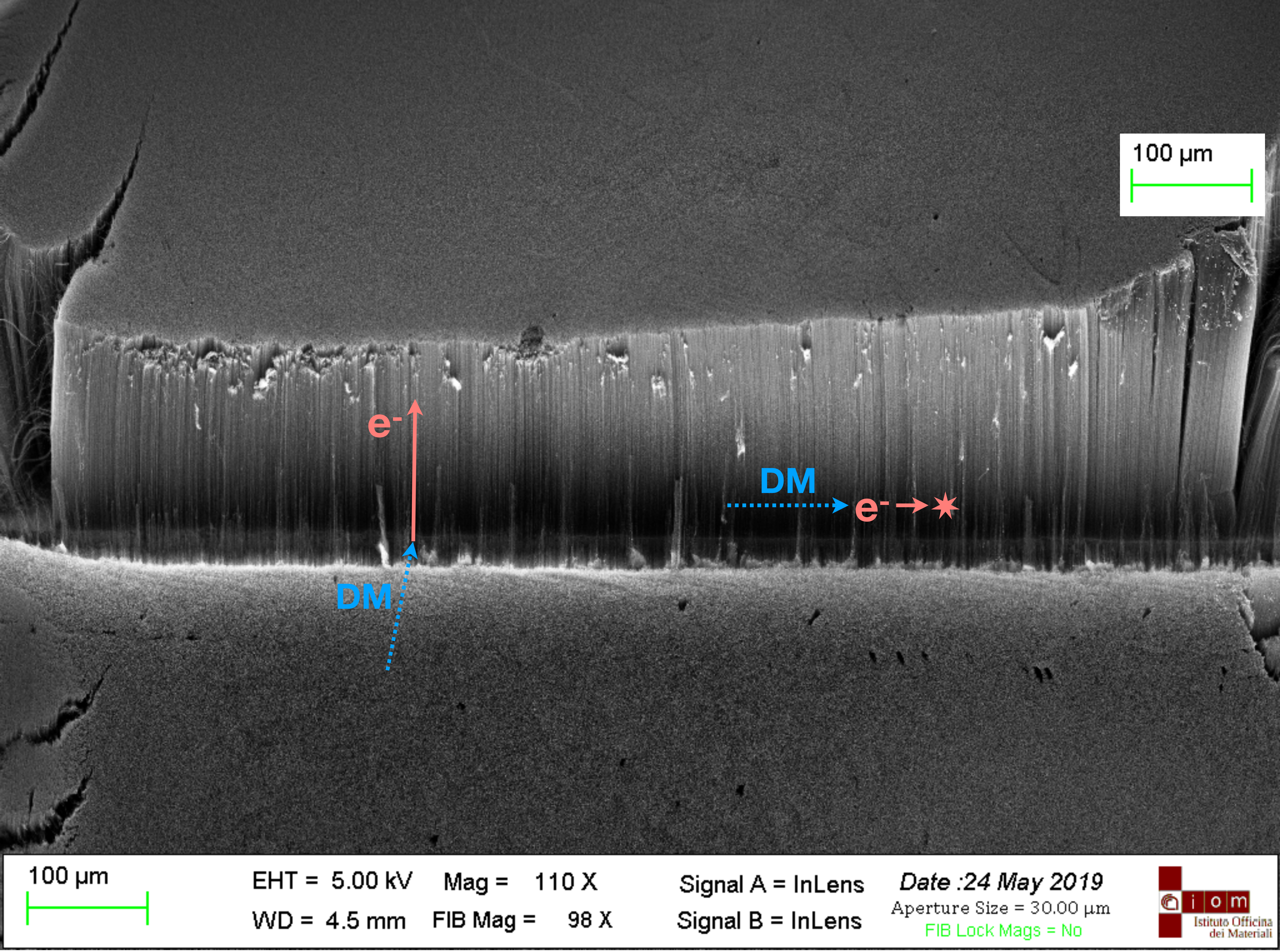
Growing vertically aligned CNT

- **Carbon nanotubes** synthesized through Chemical Vapor Deposition (CVD)
  - Internal diameter ~5 nm, length up to 300 µm
  - Single- or multi-wall depending on growth **technique**



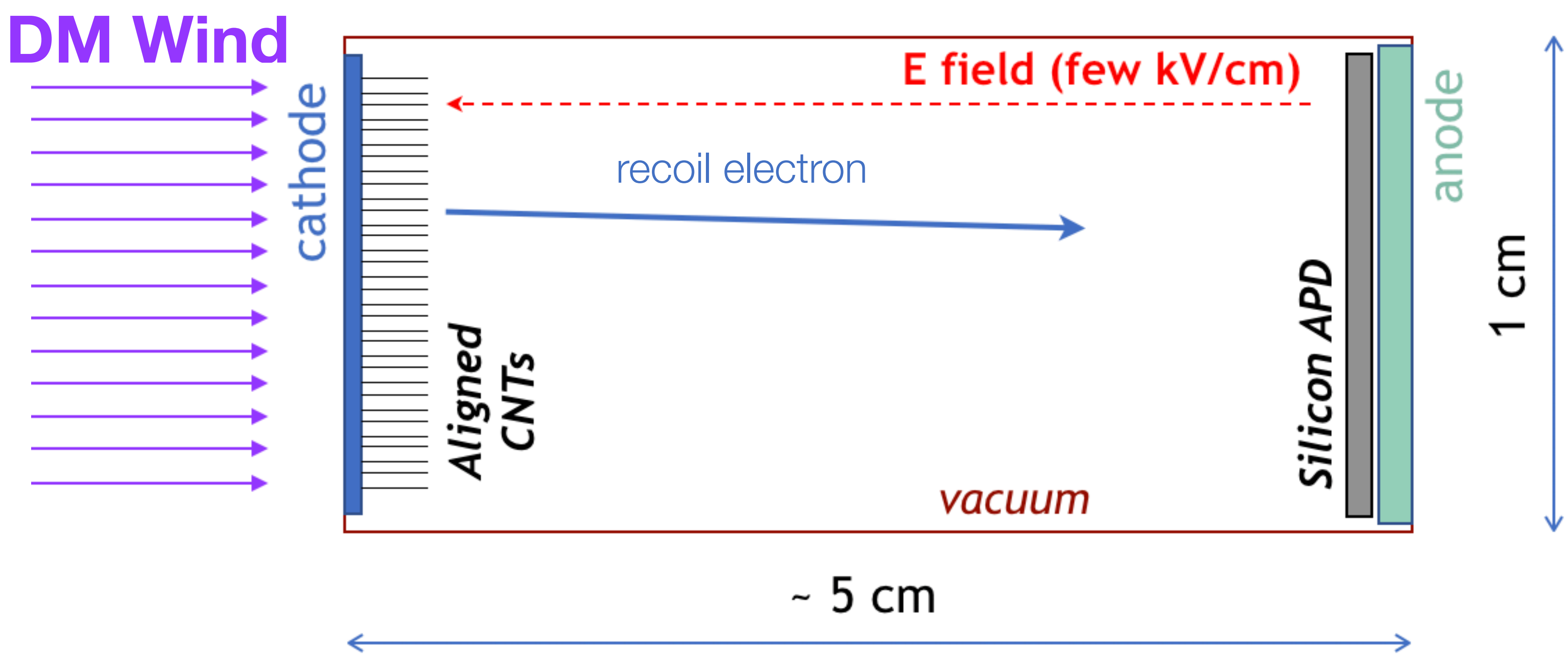
- Result: vertically-aligned nanotube 'forests' **(VA-CNT)**
  - **'Hollow'** in the direction of the tubes
  - Electrons can **escape** if **parallel** to tubes
  - Makes it an **ideal** light-DM target




100 µm
e-
DM
e- → ✶
DM
100 µm
EHT = 5.00 kV
WD = 4.5 mm
Mag = 110 X
FIB Mag = 98 X
Signal A = InLens
Signal B = InLens
Date :24 May 2019
Aperture Size = 30.00 µm
FIB Lock Mags = No
i o m
Istituto Officina dei Materiali

L.M. Capparelli, et al., Phys. Dark Universe, 9-10 (2015) 24
G.Cavoto, et al., EPJC 76 (2016) 349
G. Cavoto, et al., PLB 776 (2018) 338

The Dark PMT



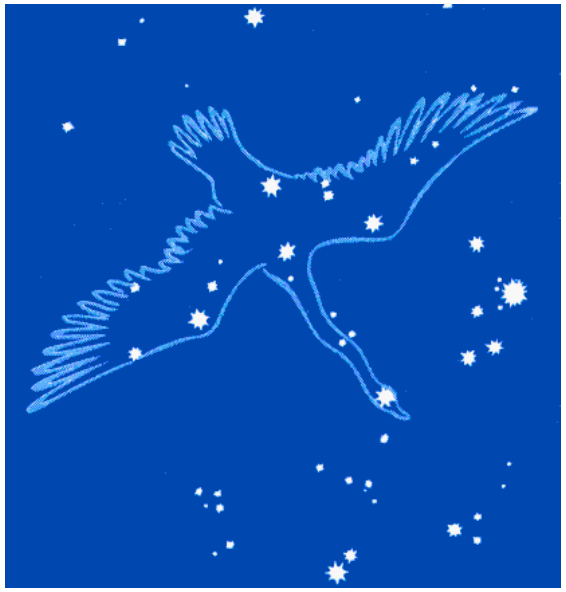
- ‘Dark-photocathode’ of aligned **nanotubes**
  - Ejected e^- accelerated by electric field
  - Detected by solid state **e^- counter**

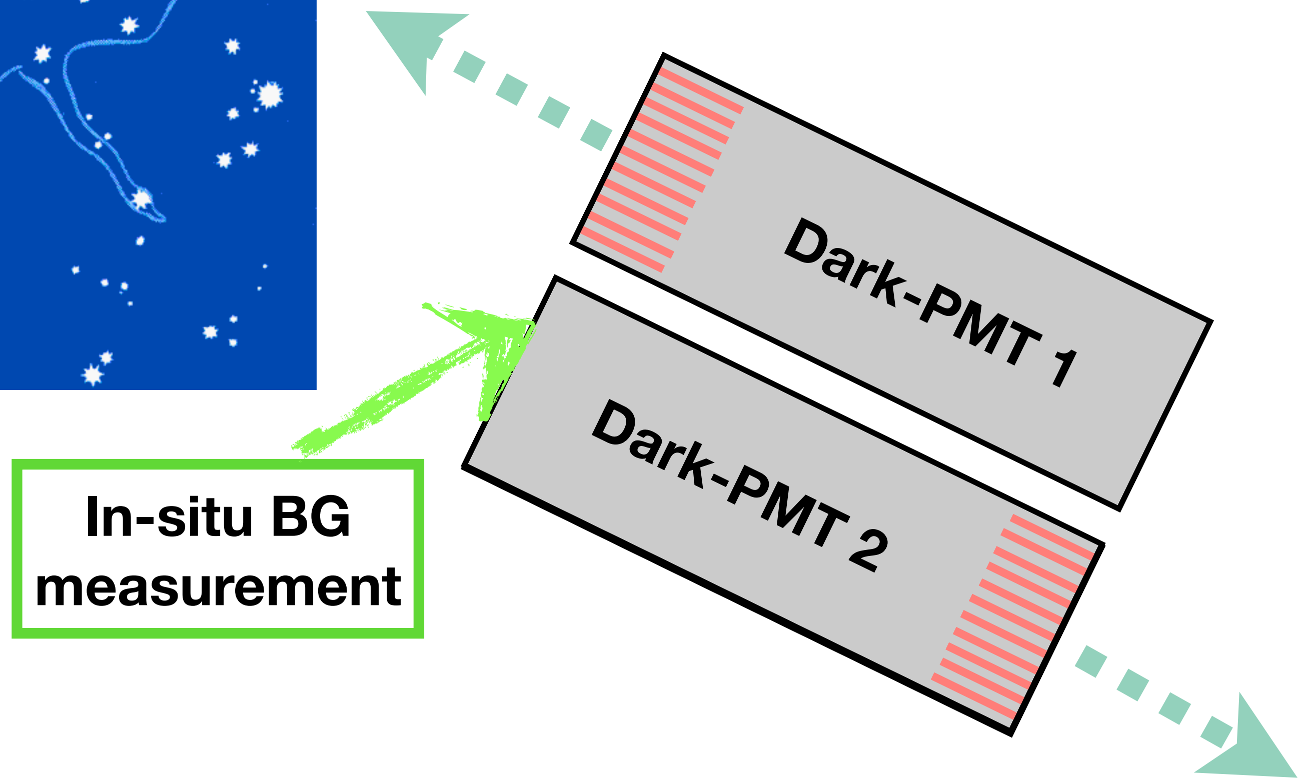
Dark-PMT features:

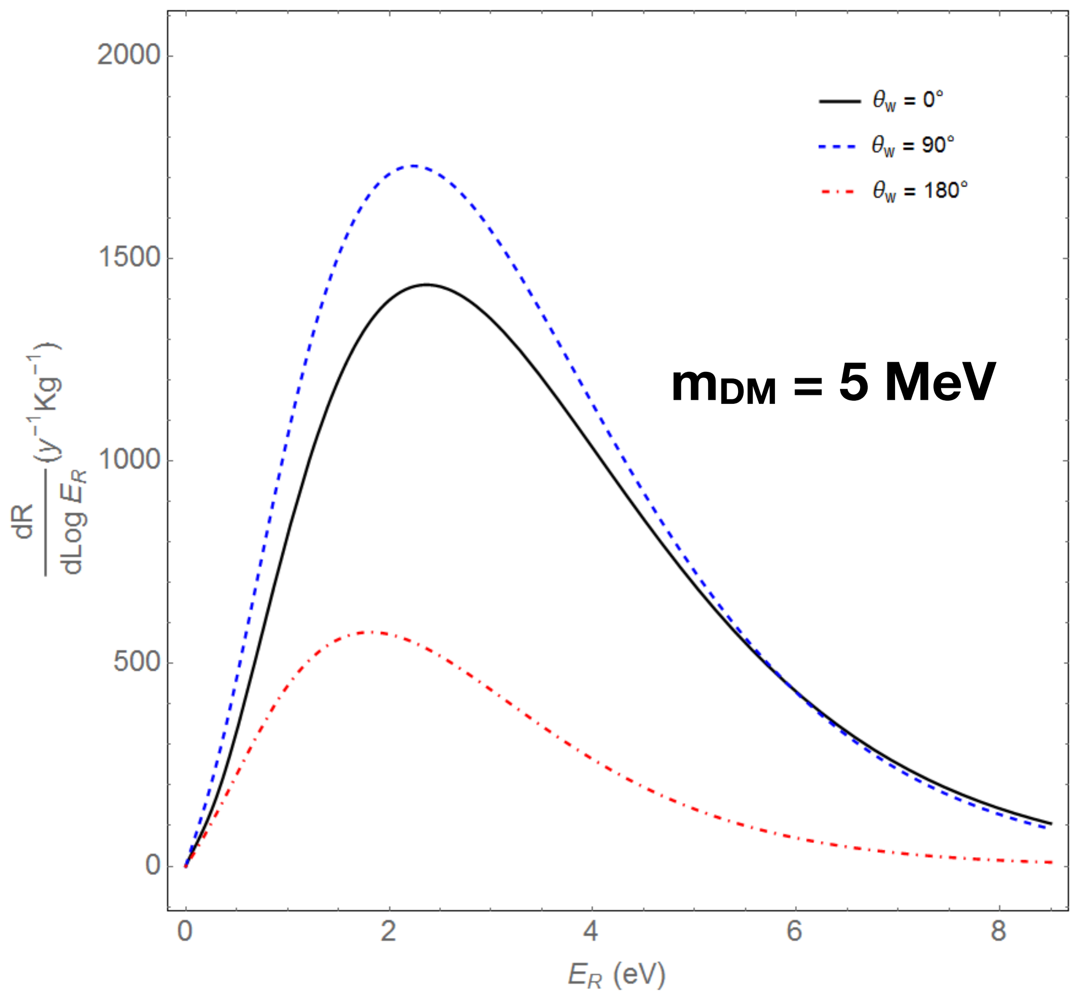
- **Portable, cheap, and easy to produce**
- **Unaffected by thermal noise (Φ_e = 4.7 eV)**
- **Directional sensitivity**

A telescope of dark PMT

G. Cavoto, et al., PLB 776 (2018) 338





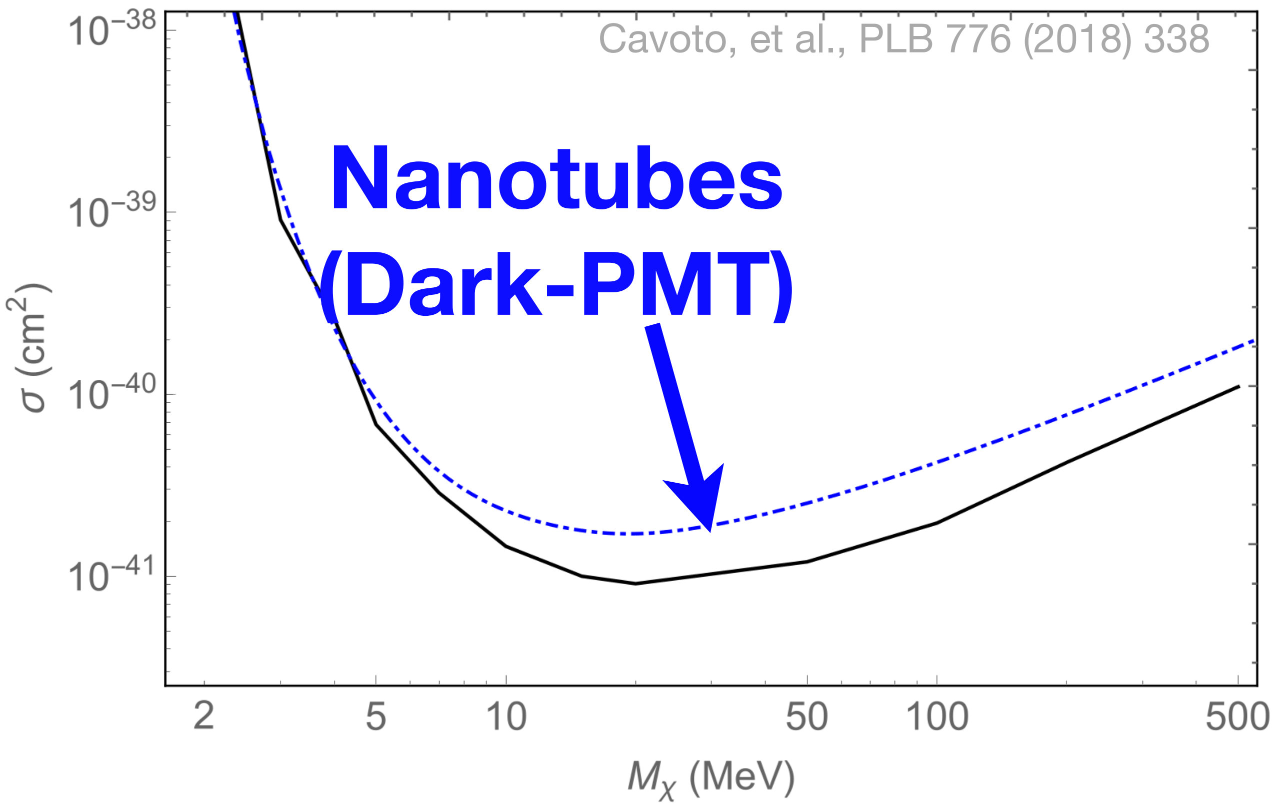


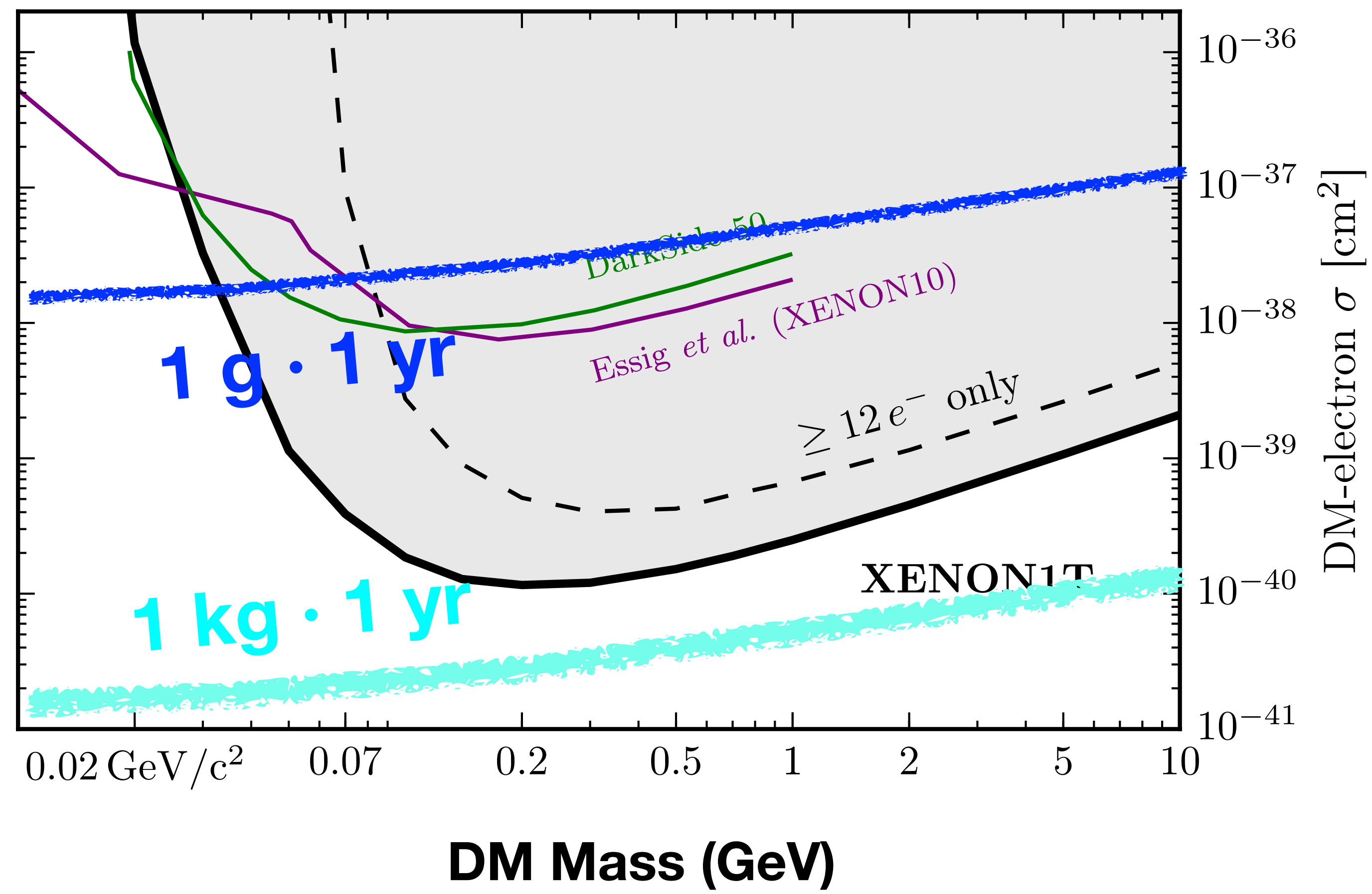
- **Two** sets of detectors: pointing towards Cygnus, and in **orthogonal** direction
  - Search variable: N_1-N_2

In principle sensitive to eV electrons!

Sensitivity down to 2 MeV DM

Exposure = 1 kg · 1 year



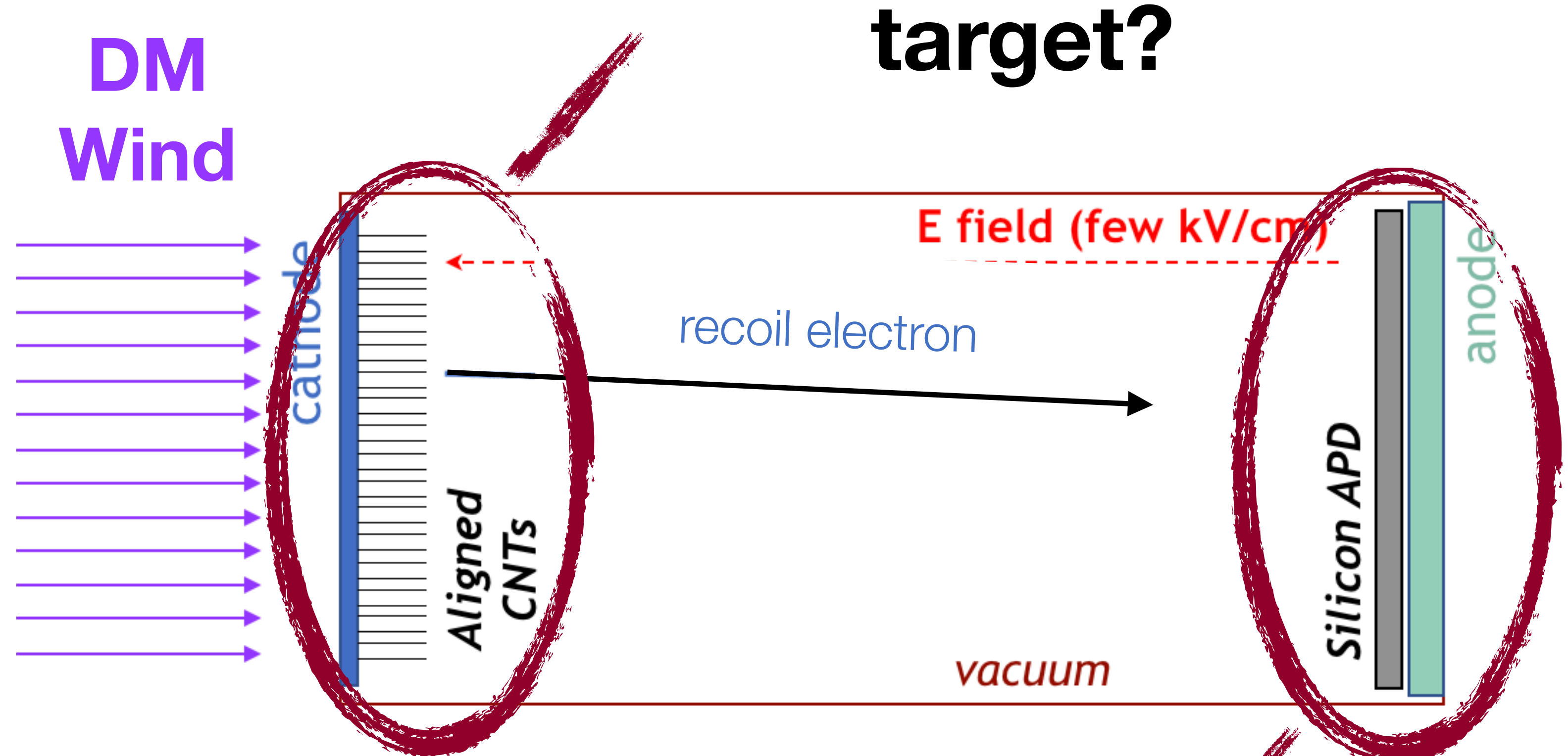


- Competitive searches with gram target mass.

The Andromeda project

- **Main objective:** have a working dark-PMT protoype by end of project (3 years)
  - Challenges on **both sides** of detector

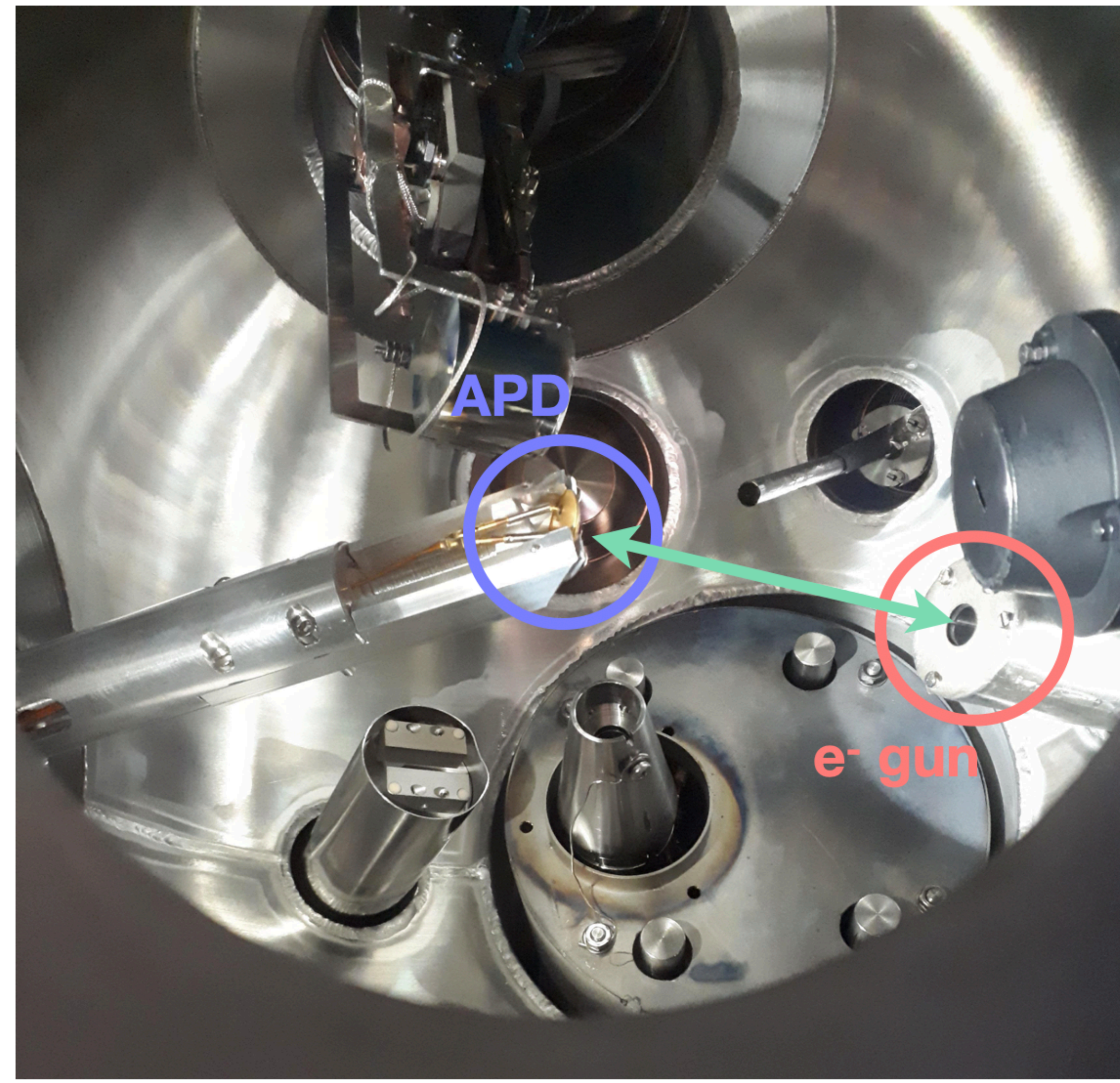
Ideal nanotubes for DM target?



Best detector for keV electrons?

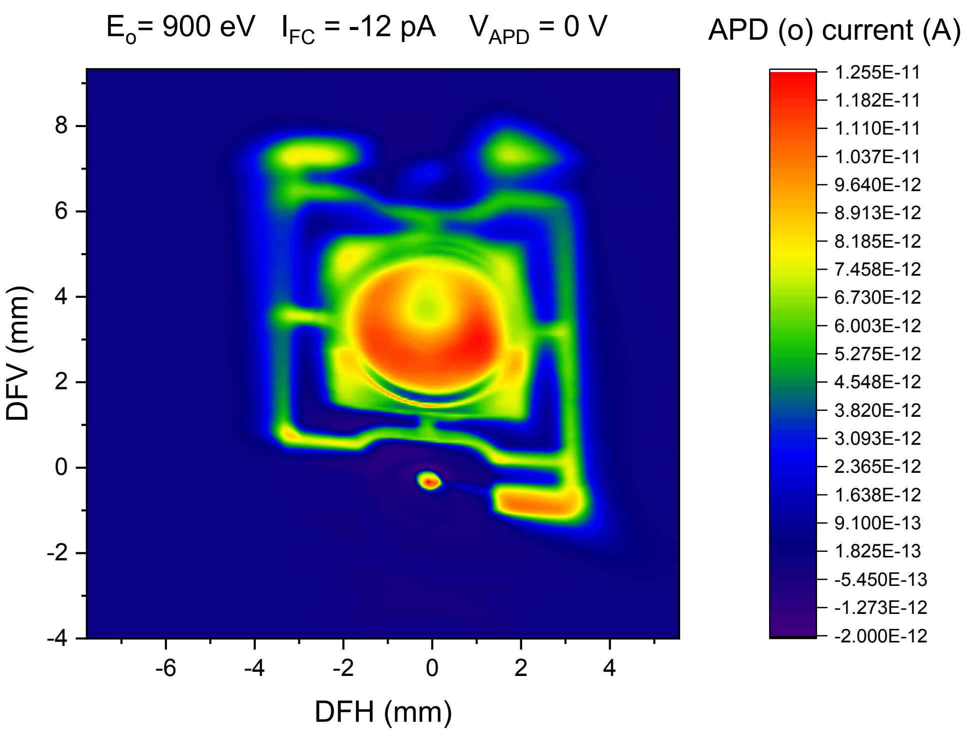
APD Characterization

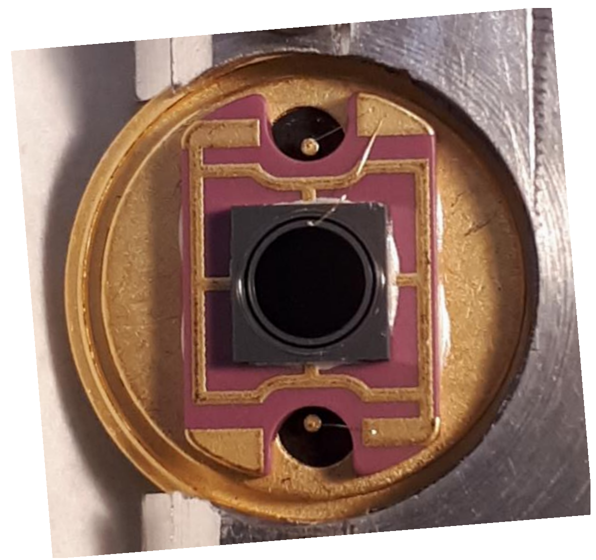
- State-of-the-art e⁻ gun @ LASEC Labs (Roma Tre)
  - Electron **energy**: 30 < E < 1000 eV
  - Energy uncertainty < 0.05 eV
- Gun **current** as low as a few fA
  - i.e. electrons at ~10 kHz (not bunched)
  - Can probe **single-electron** regime
- Beam profile ~ 0.5 mm
  - Completely **contained** on APD (⌀ = 3 mm)

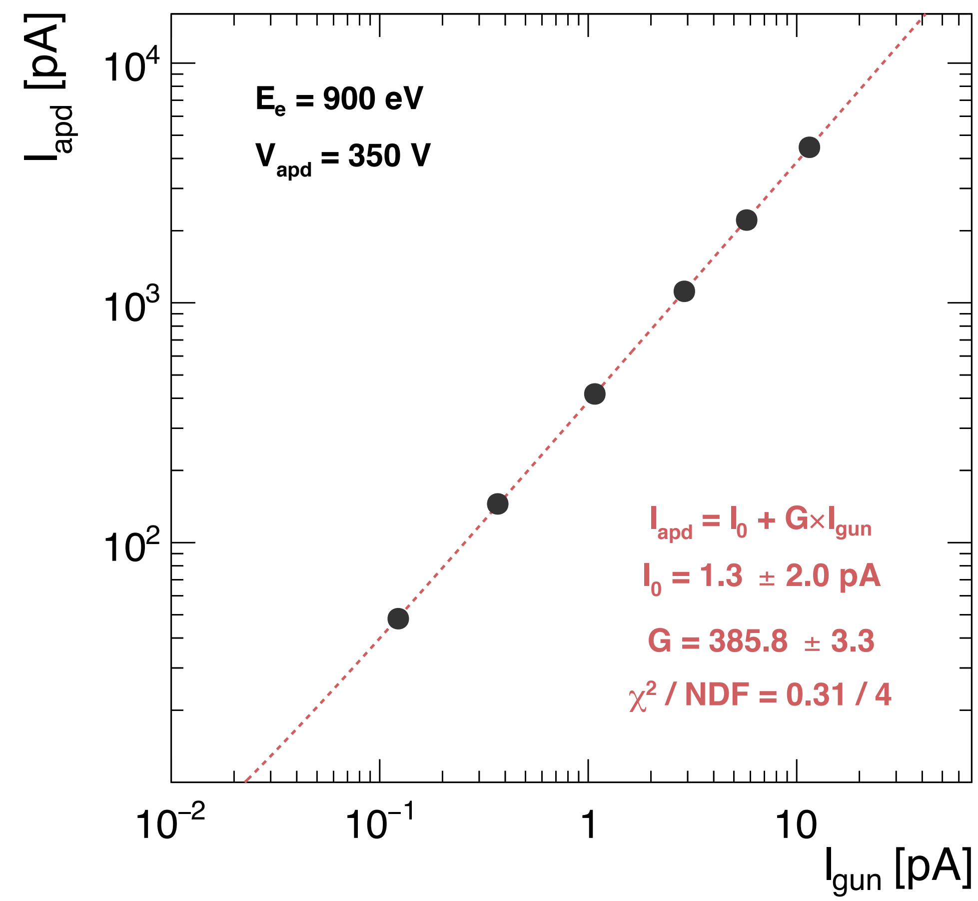


APD and 900 eV electrons

A. Apponi et al 2020 JINST **15** P11015

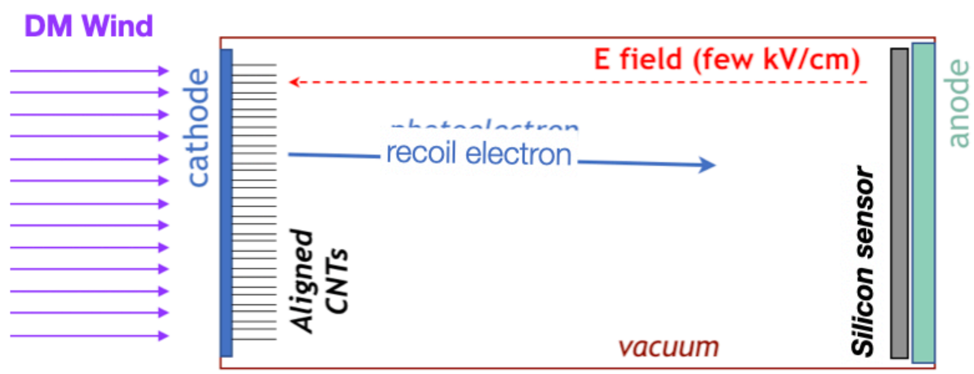


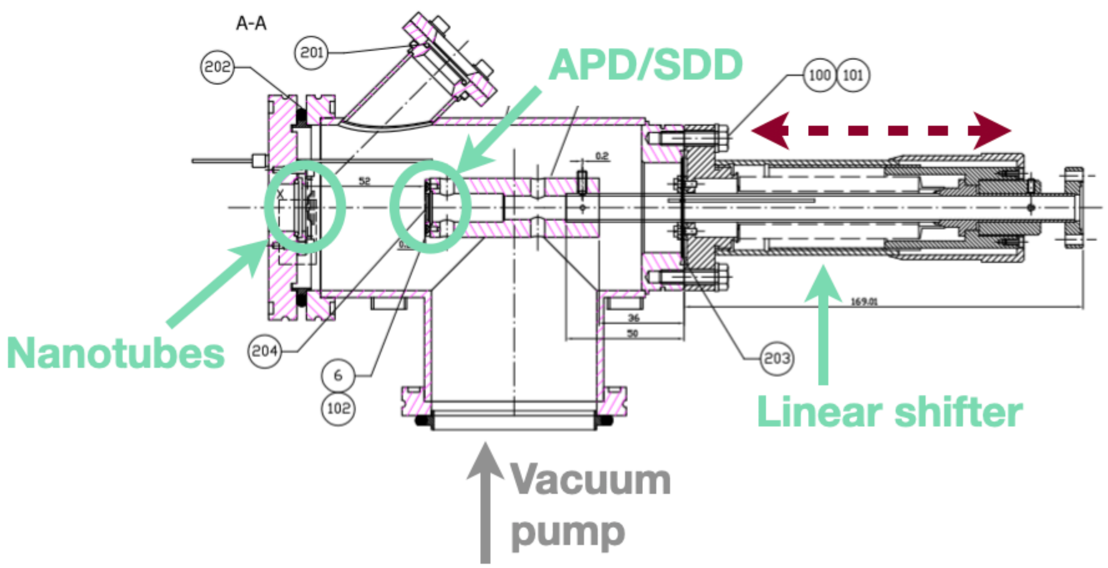


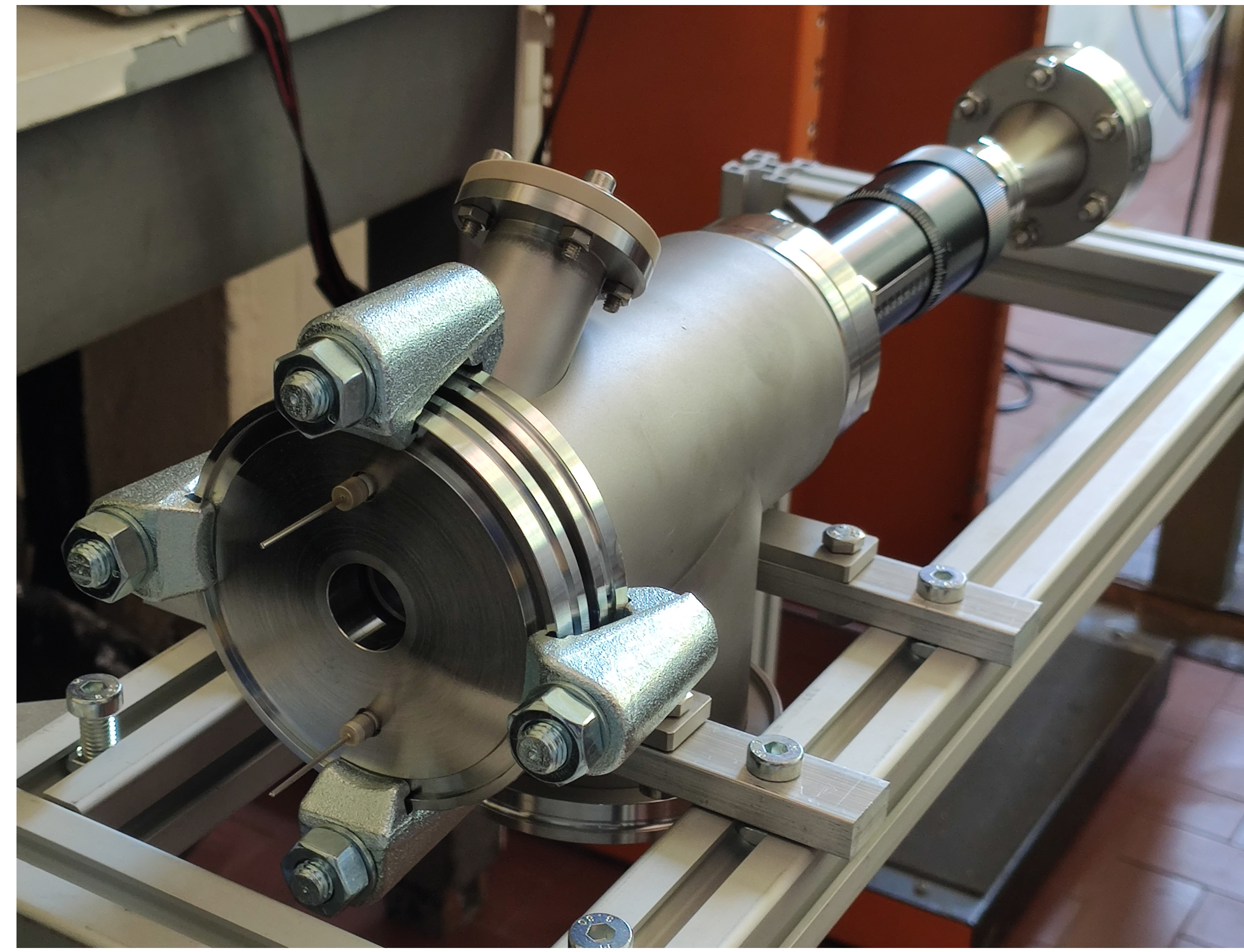


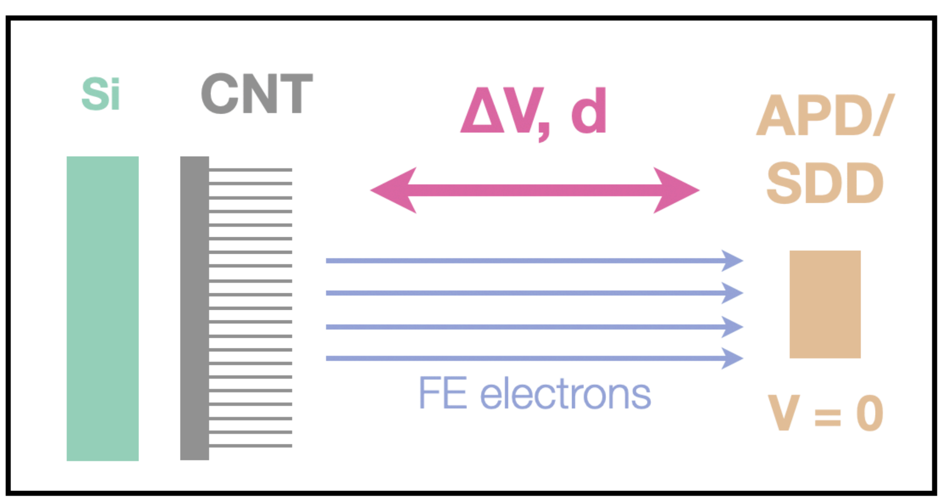
- Reading APD bias current when shooting gun on it
  - $V_{apd} = 0$: electronic 'image' of APD
  - $V_{apd} = 350$ V: I_{apd} **proportional** to I_{gun}

Dark PMT prototype-0: Hyperion







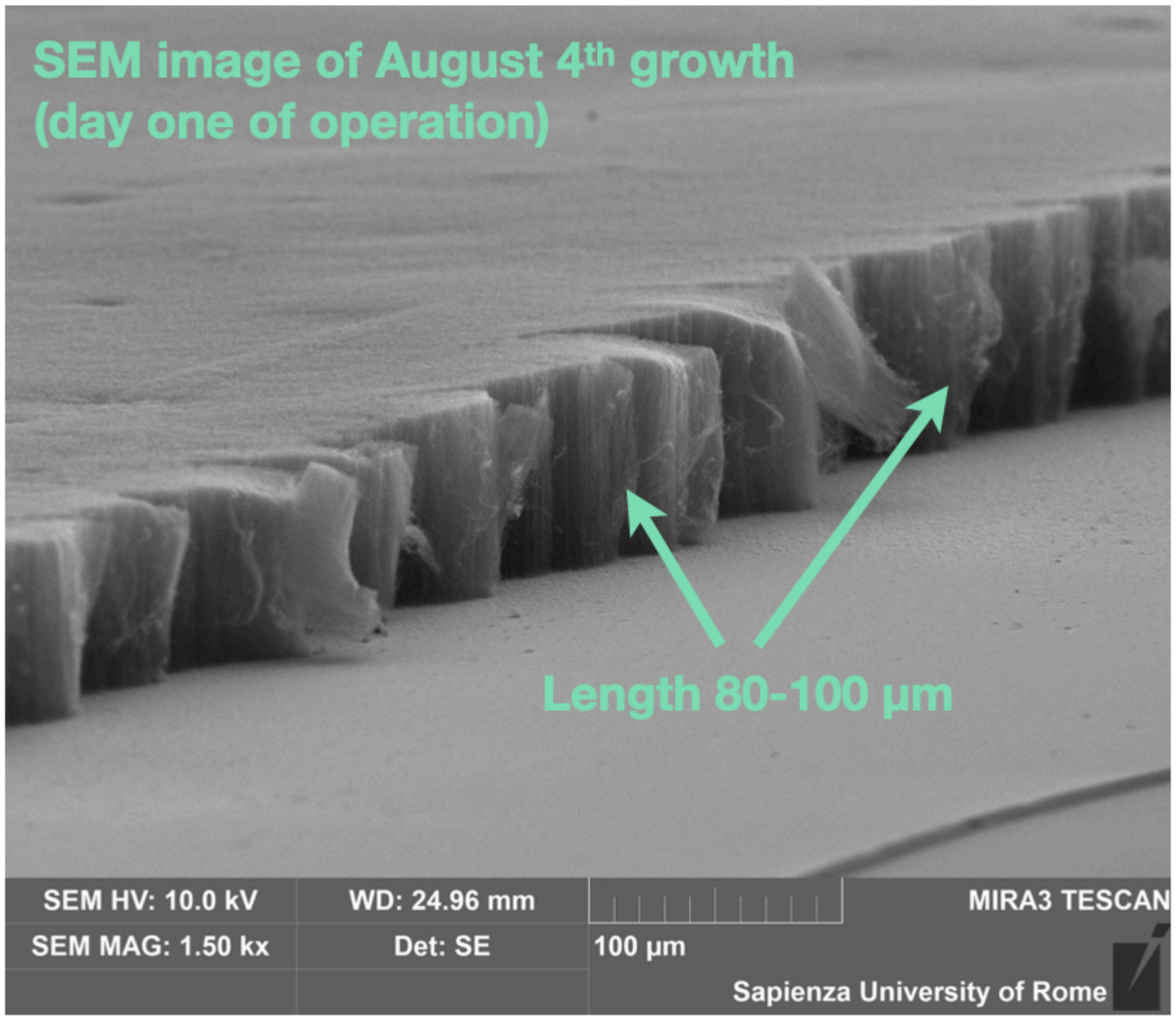


Hyperion Prototype

Instrumented also With silicon drift detector

Field emission electron observed!

VA CNT synthesis at Roma

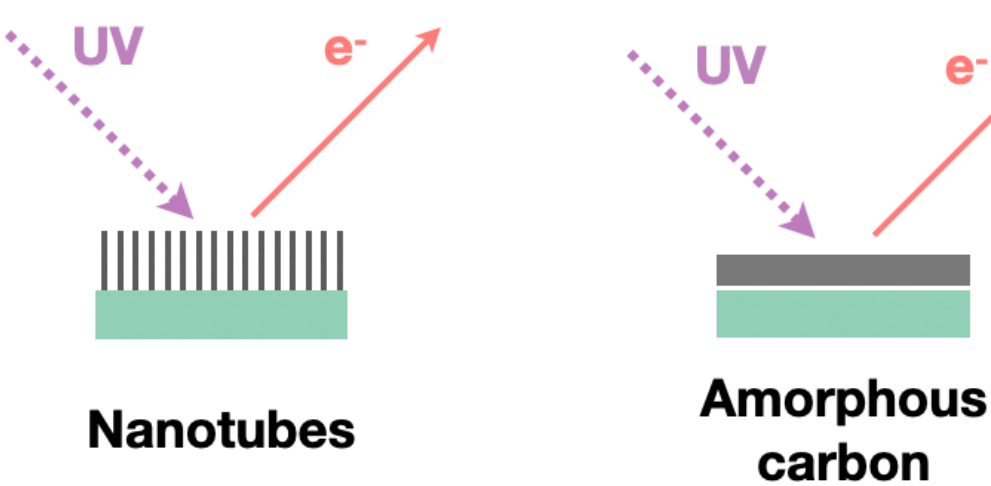


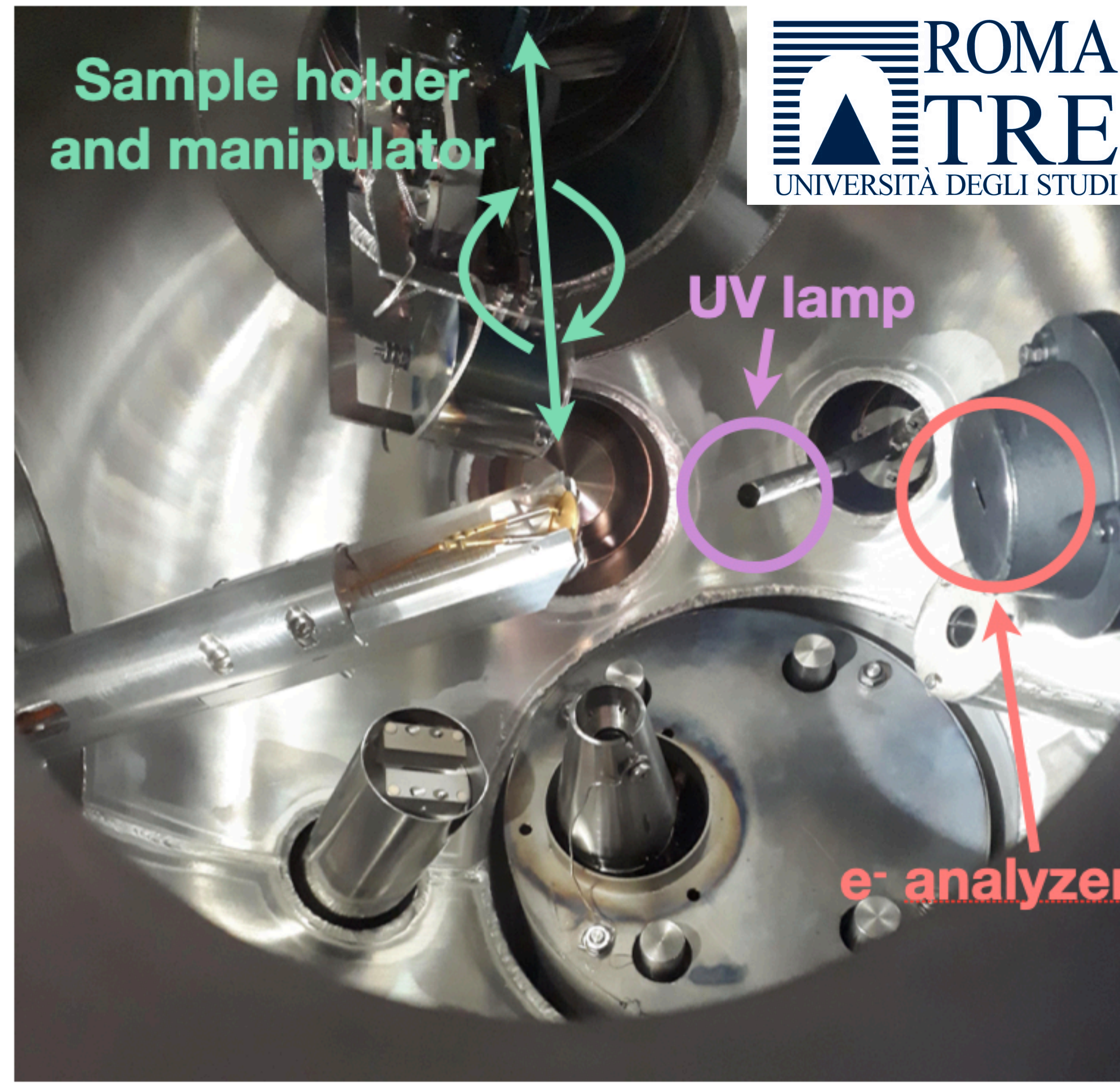
- Successfully synthetized multi-wall nanotubes with Chemical Vapour deposition
- Growing nanotubes on a **number** of subtrates:
  - ☑ Silicon
  - ☑ Fused silica
  - ☑ Basalt fibers
  - ☑ Quartz fibers
  - ☑ Carbon fibers
  - ☐ Metallic supports (Cu)

Very fast process, growing 10 mg over ~1x1 cm^2 support in ~10 minutes
100 cm^2 detector for 1 gram

CNT characterisation with photons and electrons

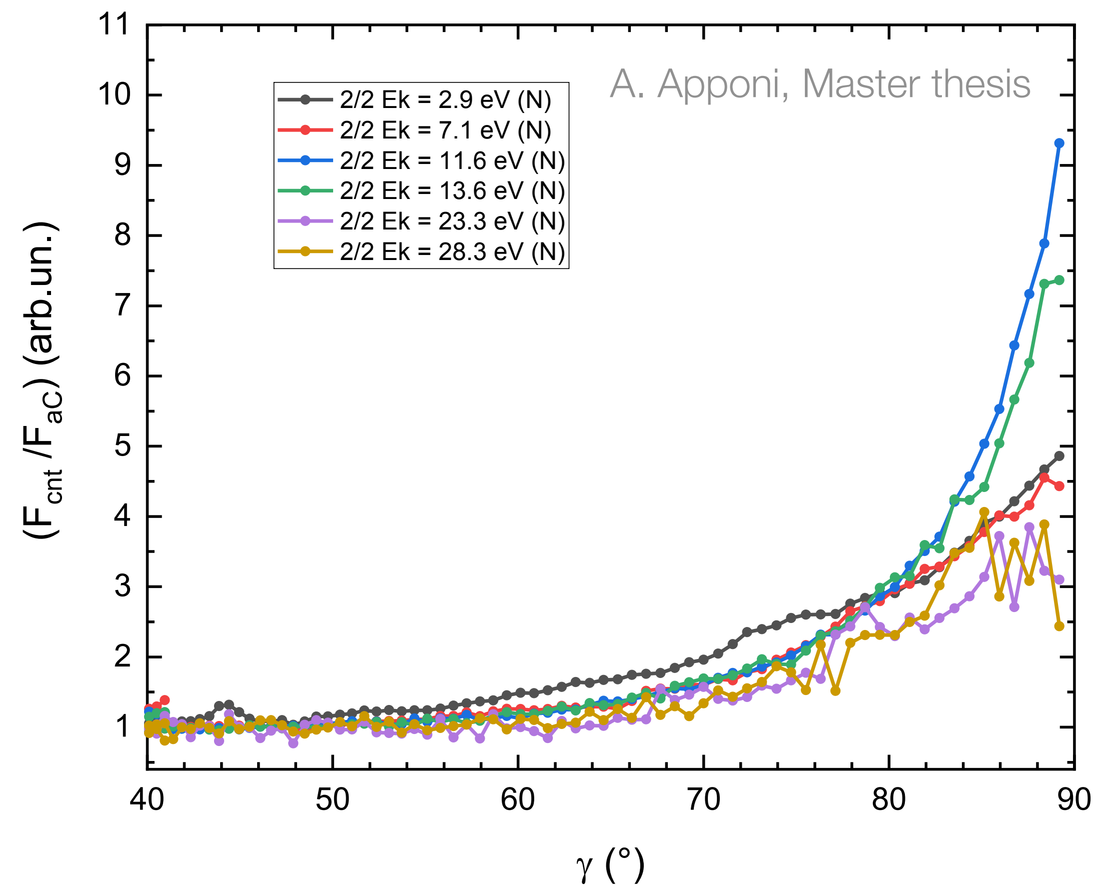
- Large UHV chamber at Roma Tre LASEC labs
  - Equipped with UPS, XPS, e⁻ energy loss analysis
- Performed UPS characterization of **nanotubes**
  - And compared them to **amorphous carbon**

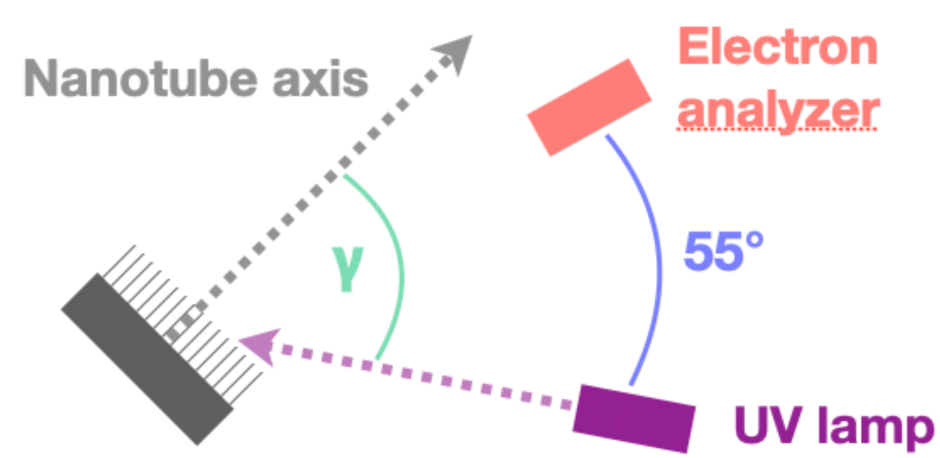




Anisotropic electron emission (?)

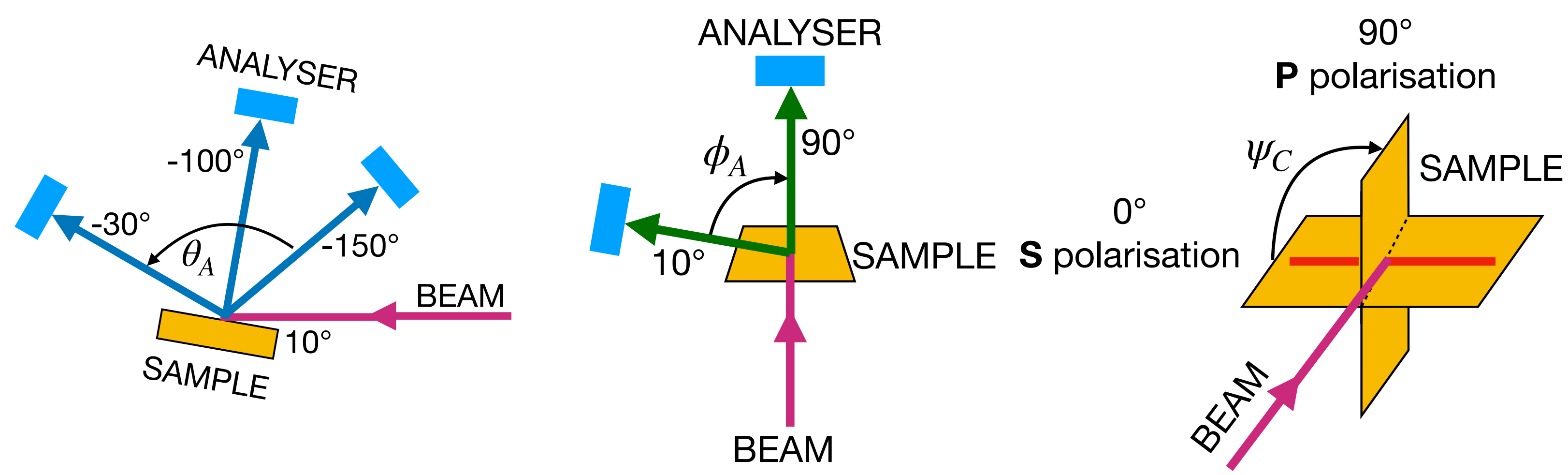
- Using He (I+II) UV lamp
  - hν = 21.2 eV and 40.8 eV
- Studied electron flux ratio F_{cnt}/F_{aC}
  - vs angle γ between nanotube axis and UV light
  - Normalized so that $F_{cnt}/F_{aC} = 1$ @ γ = 40°
  - CNT variation **up to 10x larger** than aC @ γ = 90° (grazing angle)
  - Further proof of **anisotropy** of nanotubes

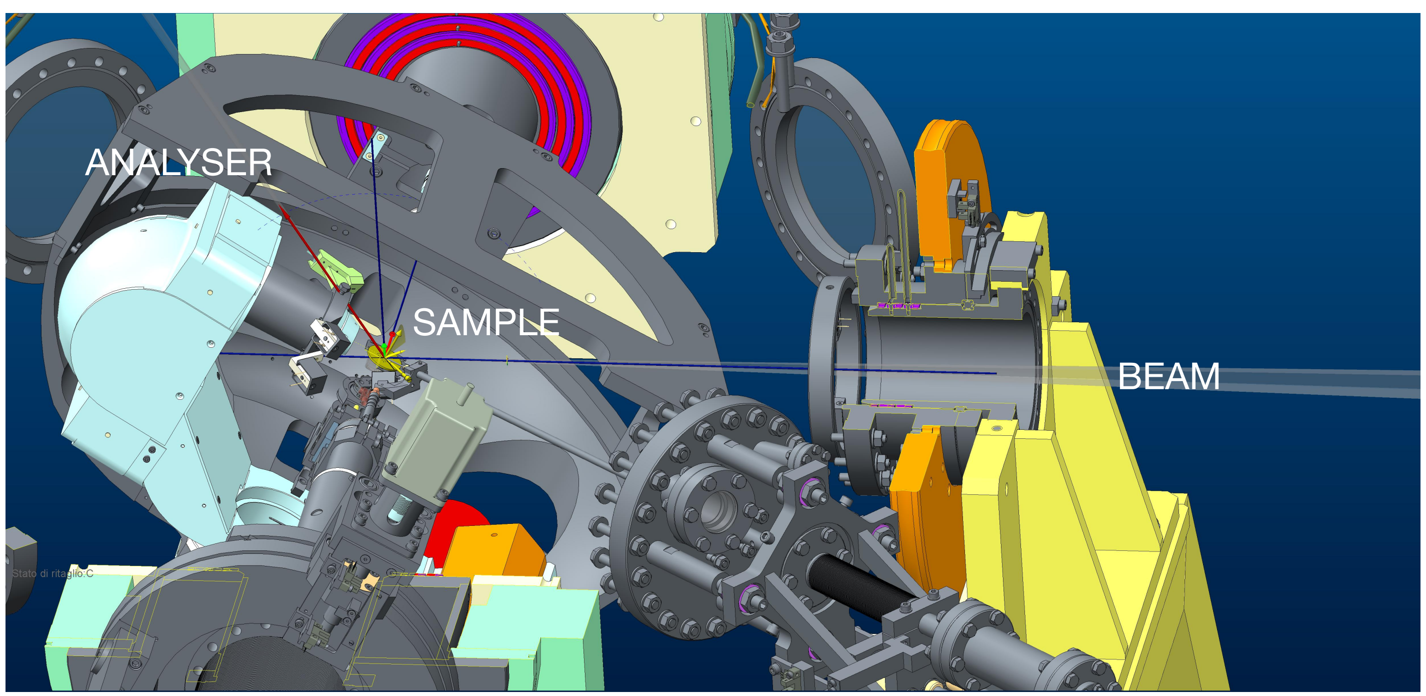




VA-CNT at synchrotron

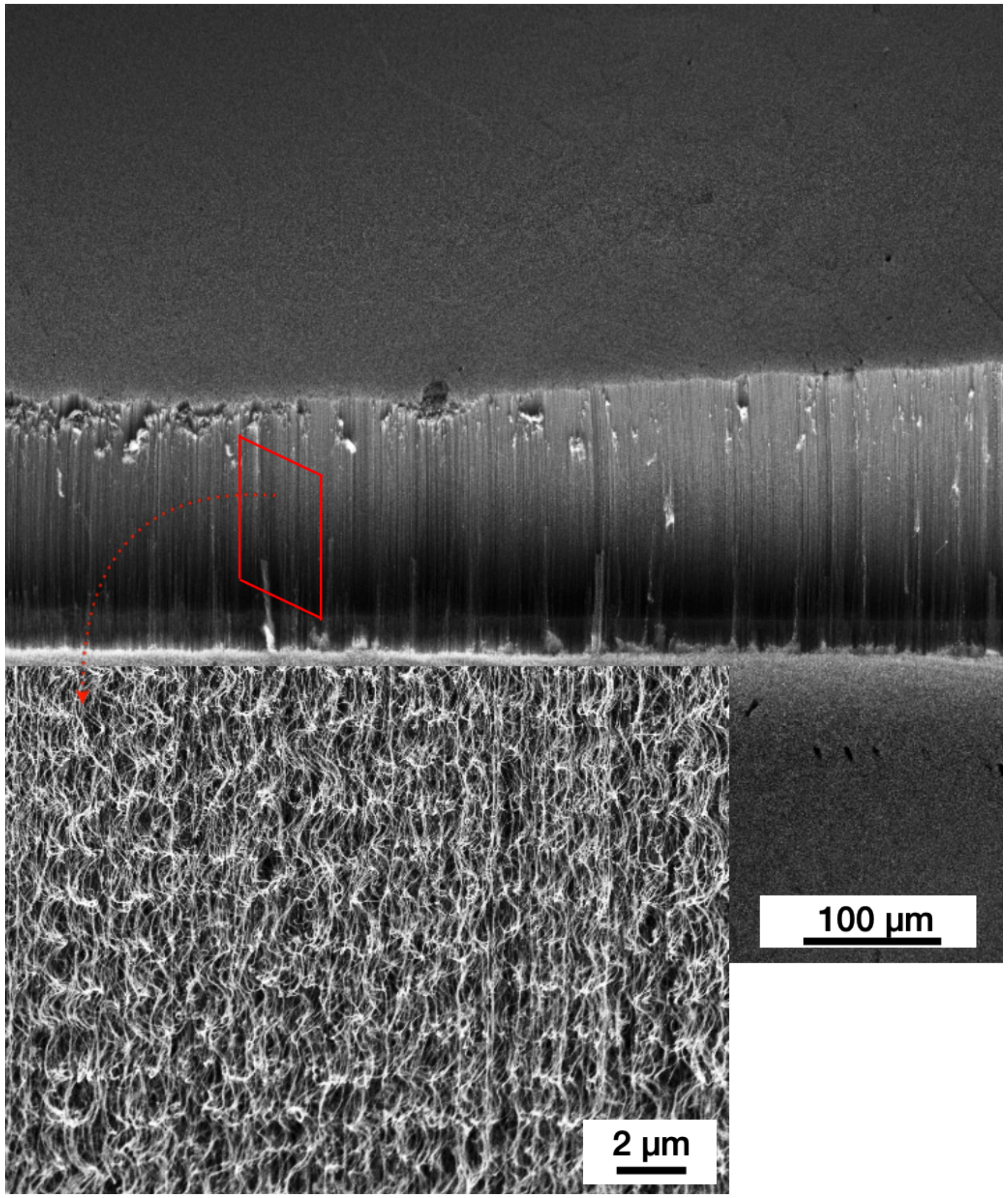
- BEAR beamline: 2.8-1600 eV photons
  - Selectable polarization
  - ‘Everything’ can rotate



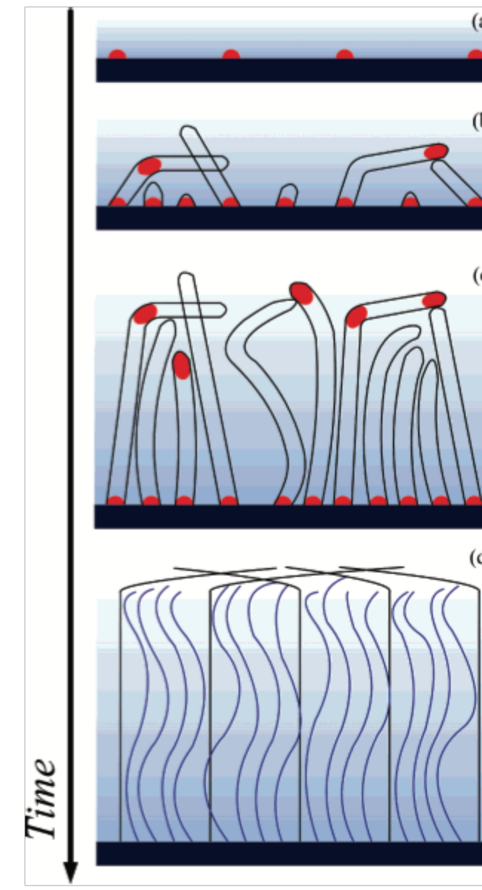


- **Rich** characterization program **underway**
  - Valence band analysis
  - Angular scans
  - Drain current analysis

Aiming at ultimate parallelism at nanoscale



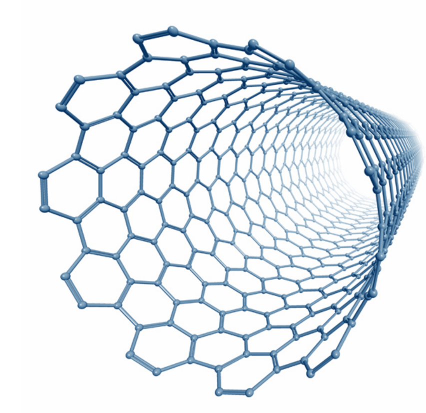
- Nanotube waviness caused by **two** factors:
  - Non-uniformity of catalyst seed **size**
  - Low **density** of seeds
- Seeds of different **size** grow nanotubes at different **rates**
  - Interaction between **fast and slow** lead to waviness
- Parallelism due to van der Waals **tube-tube interactions**
  - **Denser** seeds
    → stronger interaction
    → **straighter** tubes

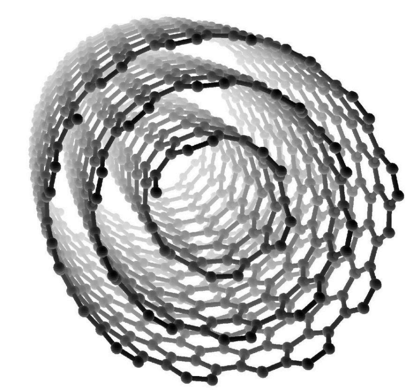


	Current	Goal
Seed density (cm^{-2})	10^{10}-10^{11}	> 10^{12}
Seed size (nm)	15-30	5 (±20%)

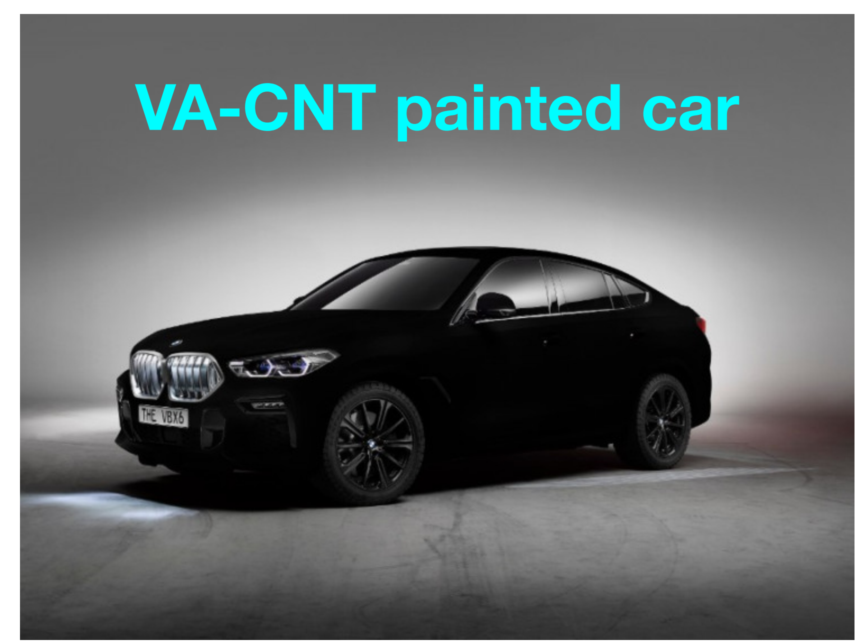
Conclusion and outlook

- **Light DM** direct detection prefers **electrons** as target
  - Hollow VA-CNT structures:
    - emission of ~eV electron into vacuum
    - Anisotropy: correlation with DM wind possible
  - **A light DM directional detector**



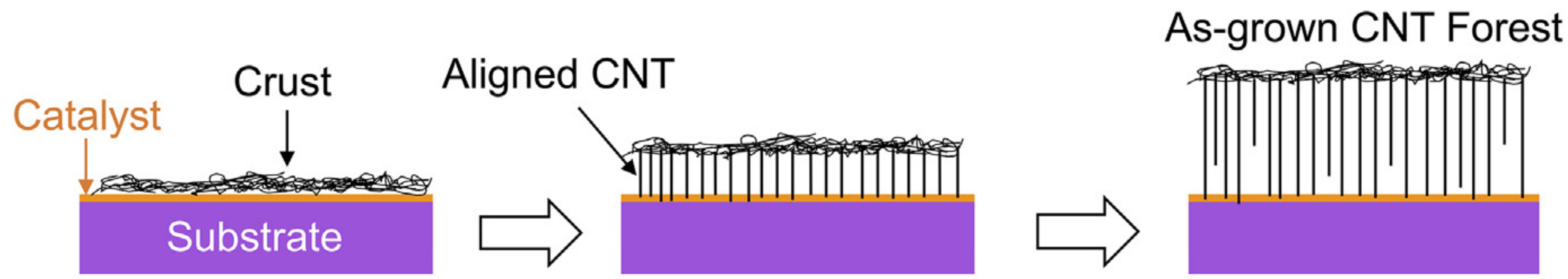


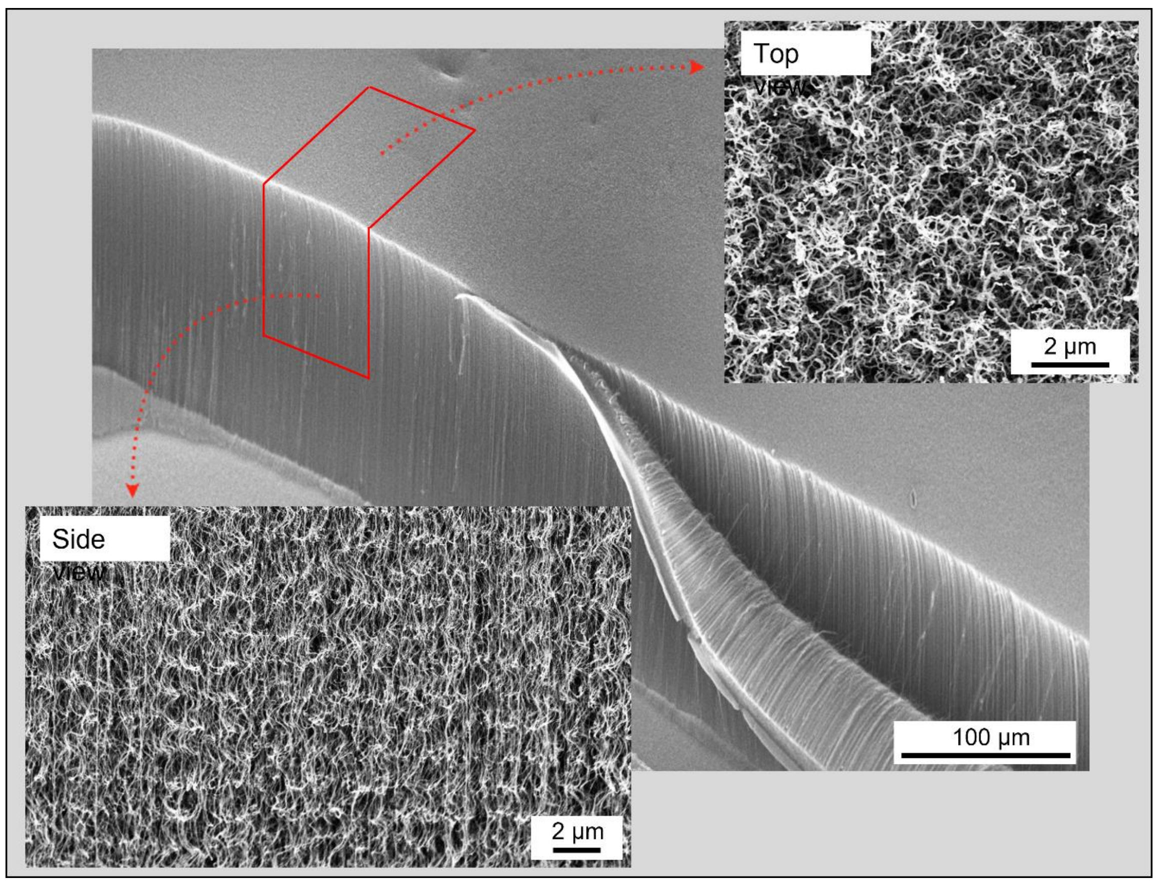
- Andromeda is exploring a **hybrid** configuration (CNT + silicon detectors)
  - Relying on keV electron detection
  - Easily scalable (in principle) to large mass.
    - Need an optimised synthesis and advanced characterisation of the target



Backup

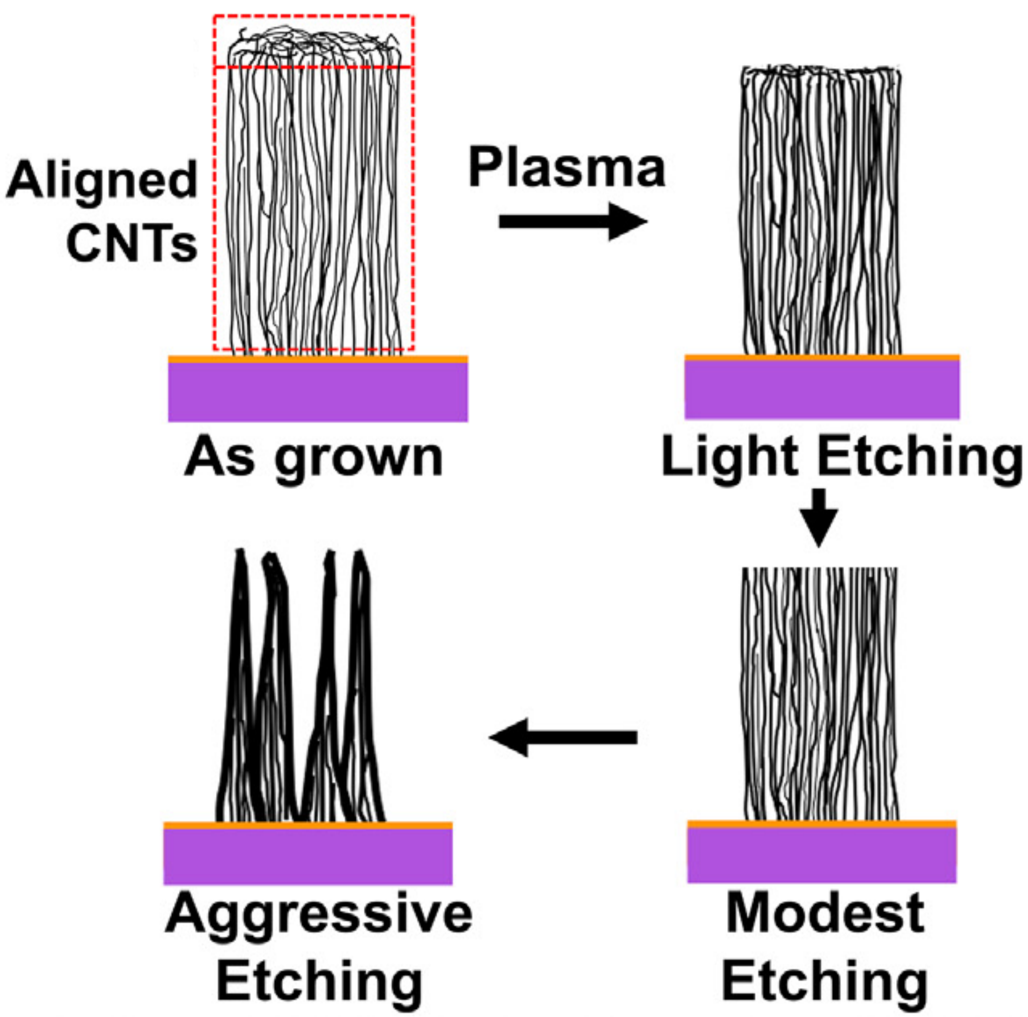
VA-CNT feature to be corrected

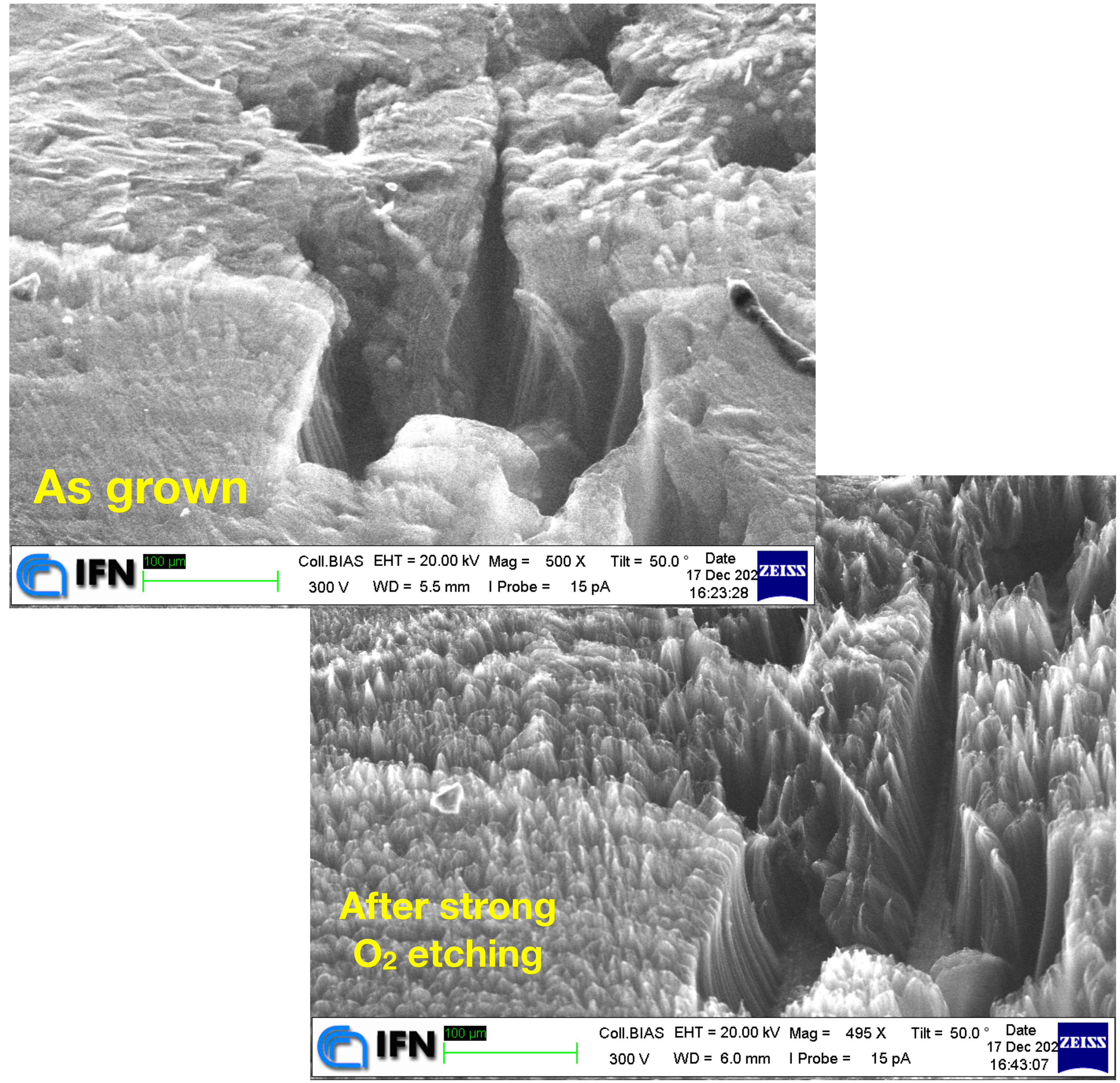




- **Traditional** CVD synthesis produces nanotubes straight at the µm-scale, but:
  - Non-aligned (spaghetti-like) **top layer**
  - Side **'waviness'** at the nanoscale
- **Both** hamper electron transmission
  - Need to **minimize** both effects for ideal DM target

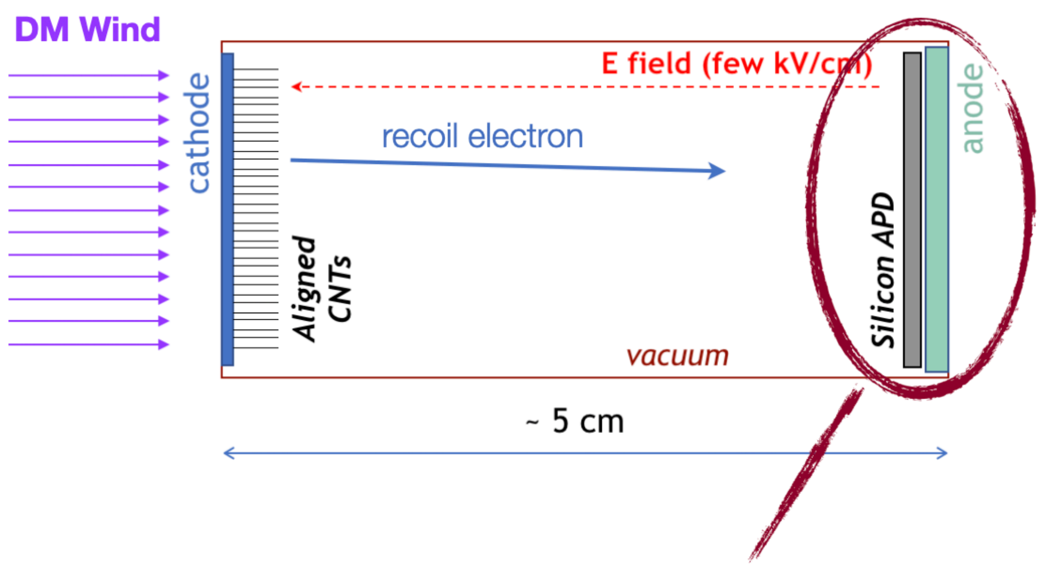
Plasma etching to remove crust





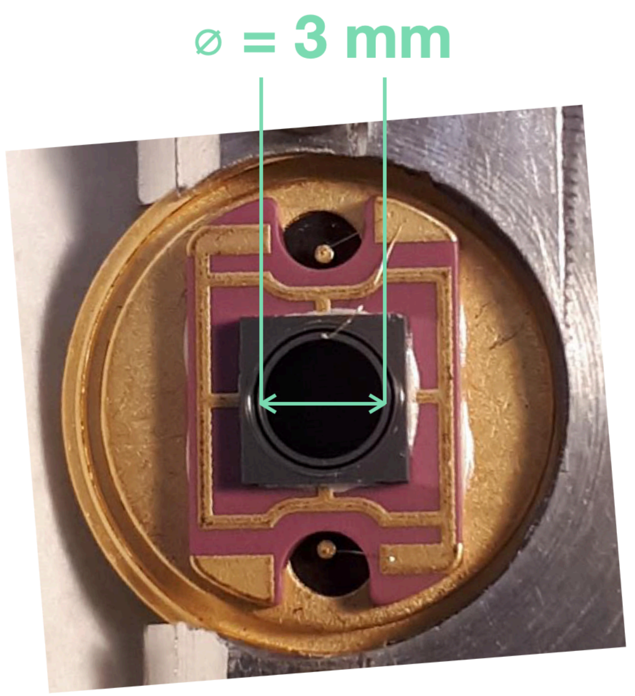
Silicon detectors for keV electrons

APDs and SDDs 'born' as photon detectors

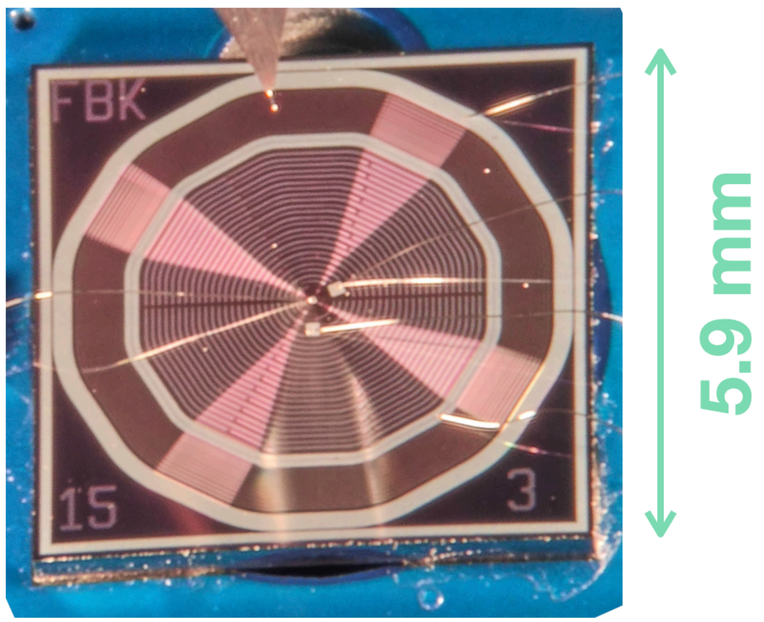


Challenge: detect keV electrons (with high efficiency)

- Benchmark: **Avalanche Photo-Diodes**
  - Simple, cost-effective
  - Hamamatsu windowless APD

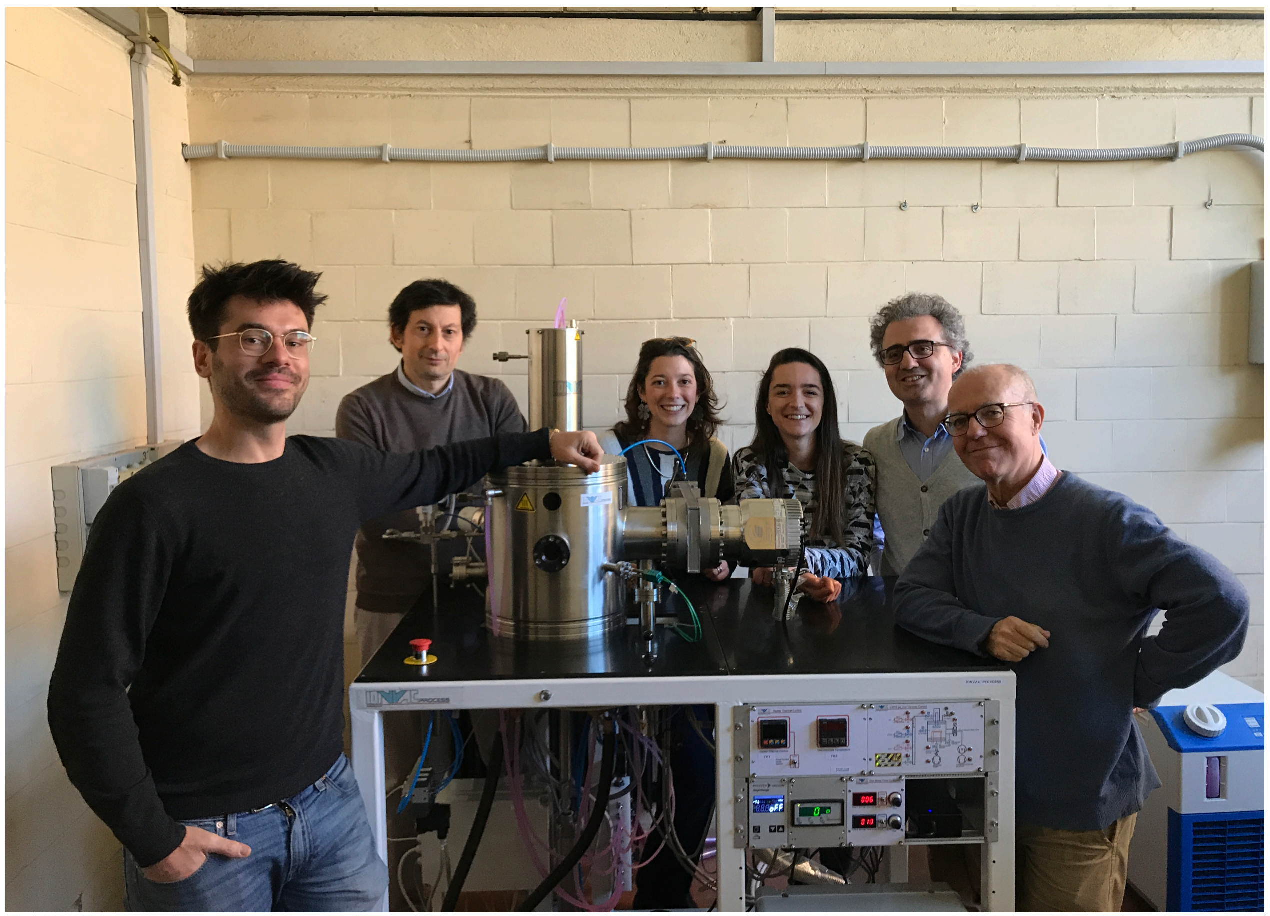


- Possible upgrade: **Silicon Drift Detectors**
  - Ultimate resolution
  - FBK (SDD) + PoliMi (electronics)



Chemical Vapour Deposition chamber for CNT

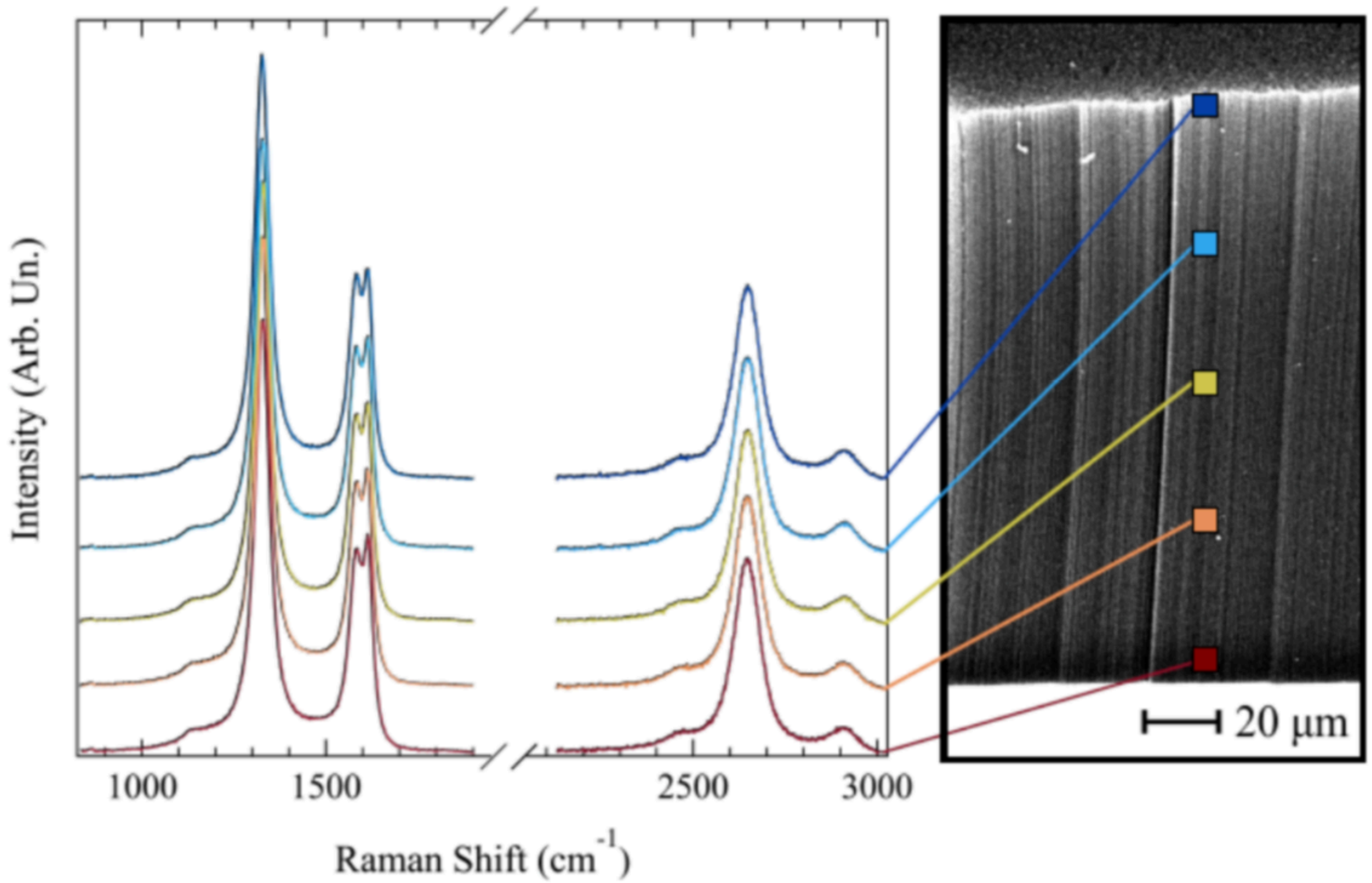
ATTRACT



- Start to develop a novel **UV light** detector made with carbon nanotubes

- CVD chamber Equipped with **Plasma-Enhanced** technology
  - Capable of **single-wall** nanotubes
- **Operational** (in few weeks) since August 2020 (despite COVID)
- Being upgraded with metal evaporator

Raman Scattering of CNT



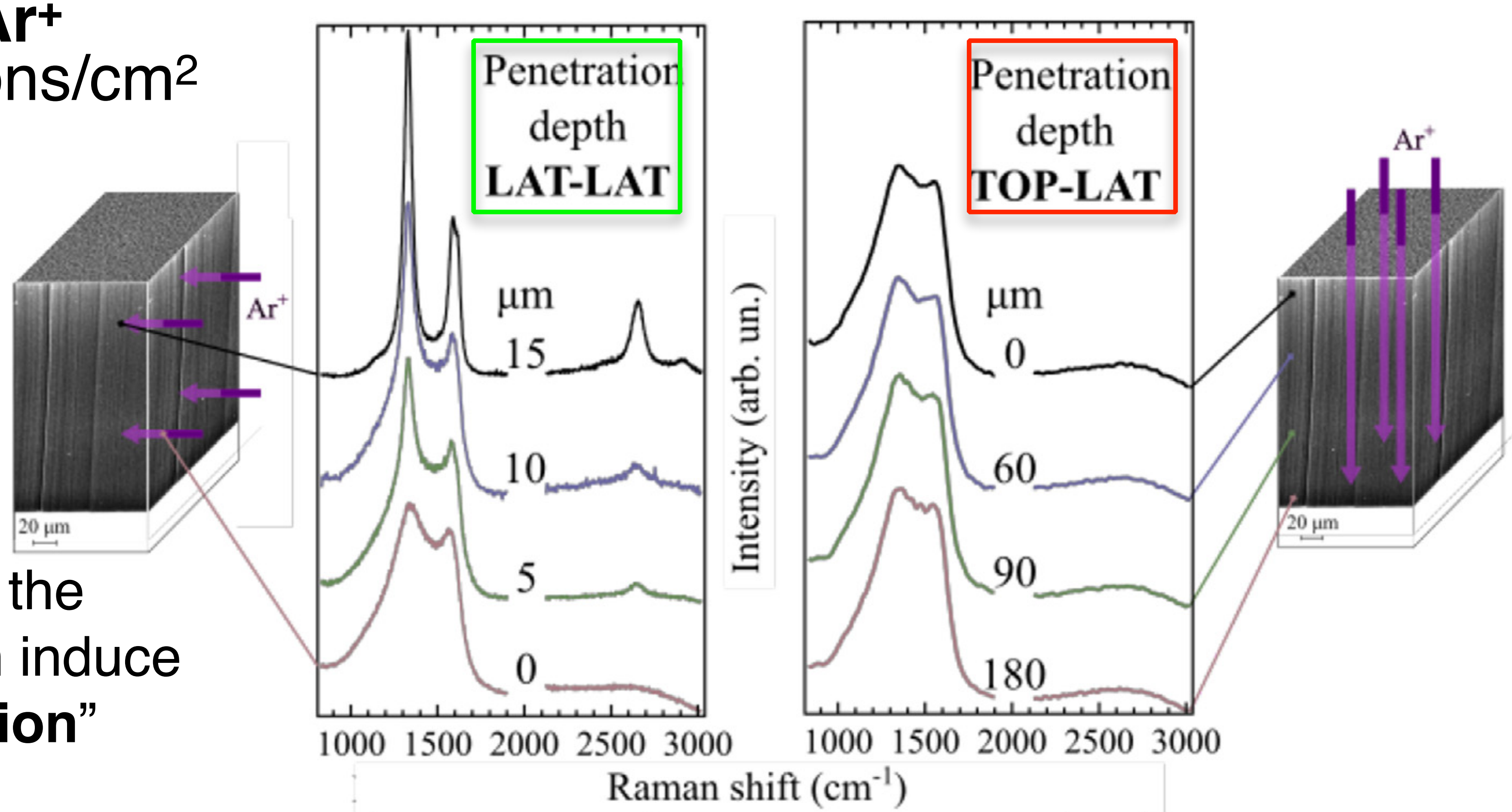
- Spatially resolved, can assess quality of the CNT bonds at various **height** of the VA-CNT
- Light can be focused at various **depth** in the interior of the CNT (up to few µm)

G.D'Acunto et al, Carbon, 139 (2018) 768

Bombarding MW-CNT with Ar^+

The CNT forest appears '*opaque*' to ions if bombarded from the side
very '*porous*' if bombarded from the top.

5 keV Ar^+
at 1.5 10^{17} ions/cm^2

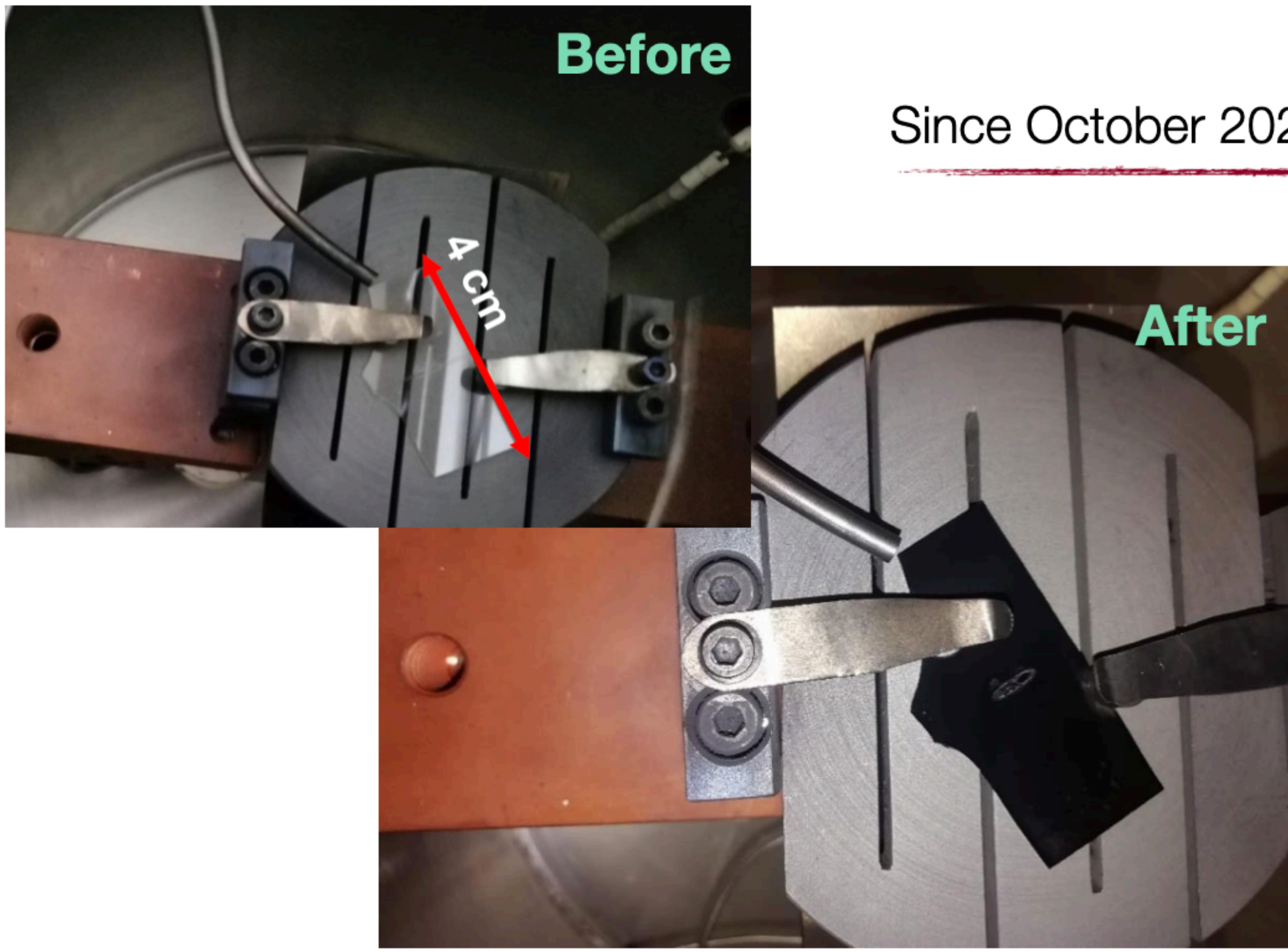


When Ar ion hits the CNT surface can induce an "**amorphization**"

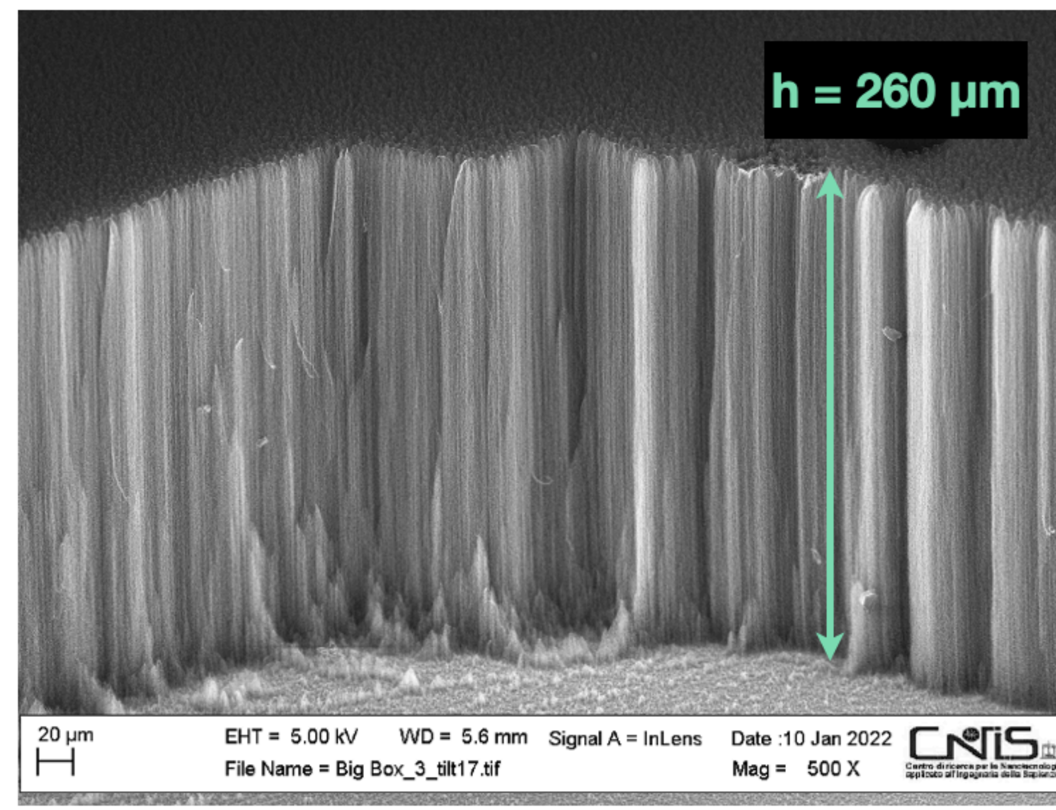
LAT bombardment: Raman spectrum unchanged 15 µm lateral depth.
No amorphization at 15µm.

TOP bombardment: amorphization from top to bottom (at any height)

Optimizing CNT growth process



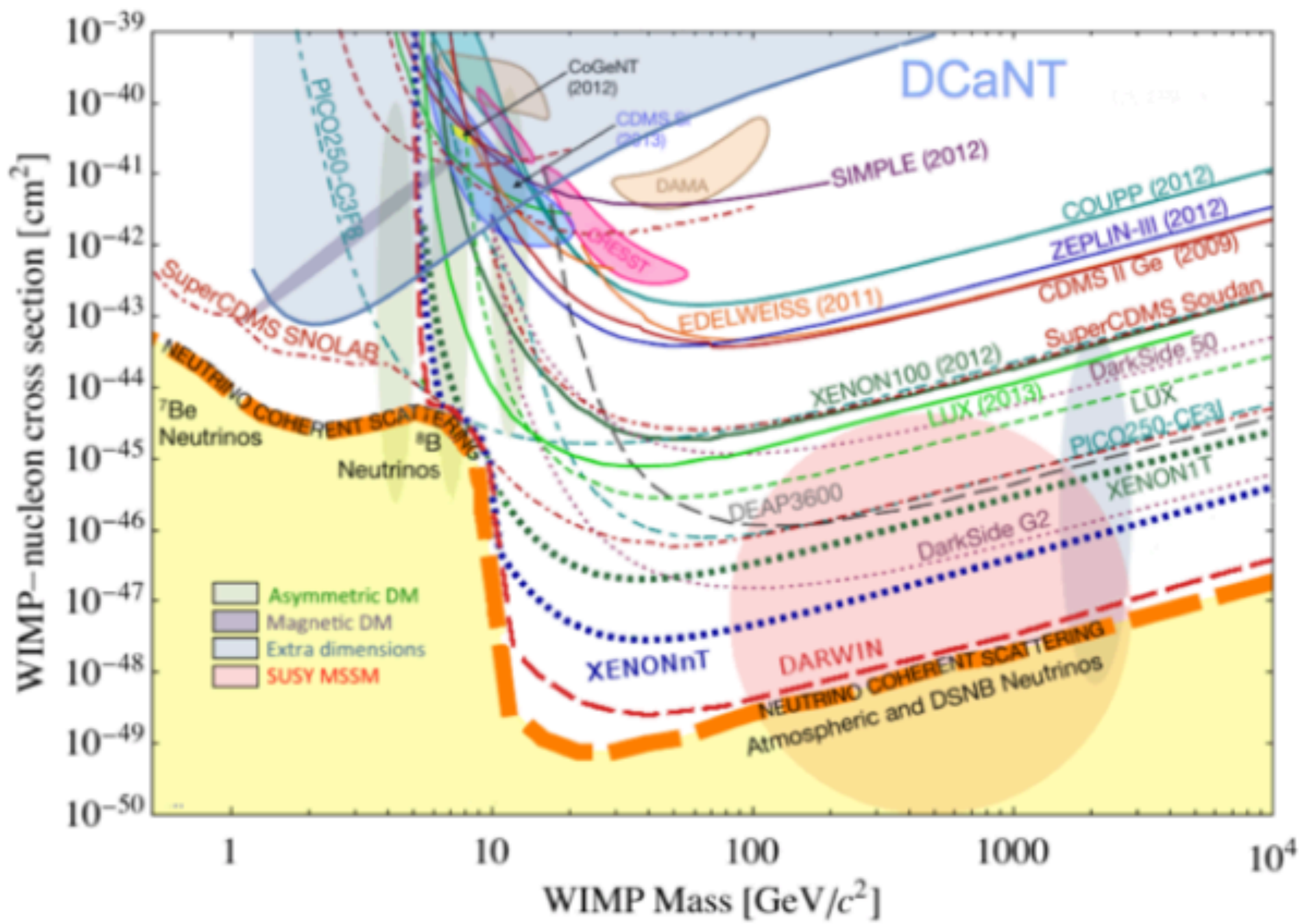
Since October 2020 achieving **uniform** growths over 4x2 cm^2



Sensitivity to low mass WIMP

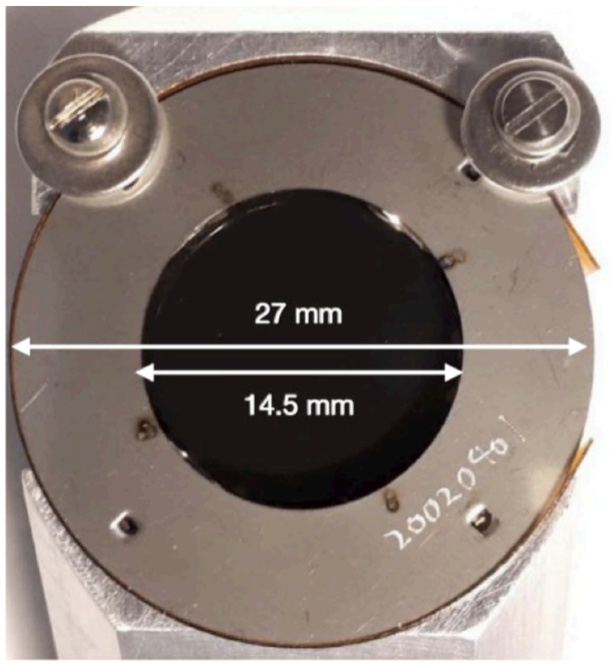
- Positive **C** ion recoiling against DM
- If ***C*** ion detected (threshold at 1 keV)

Exposure: 0.4 Kg year

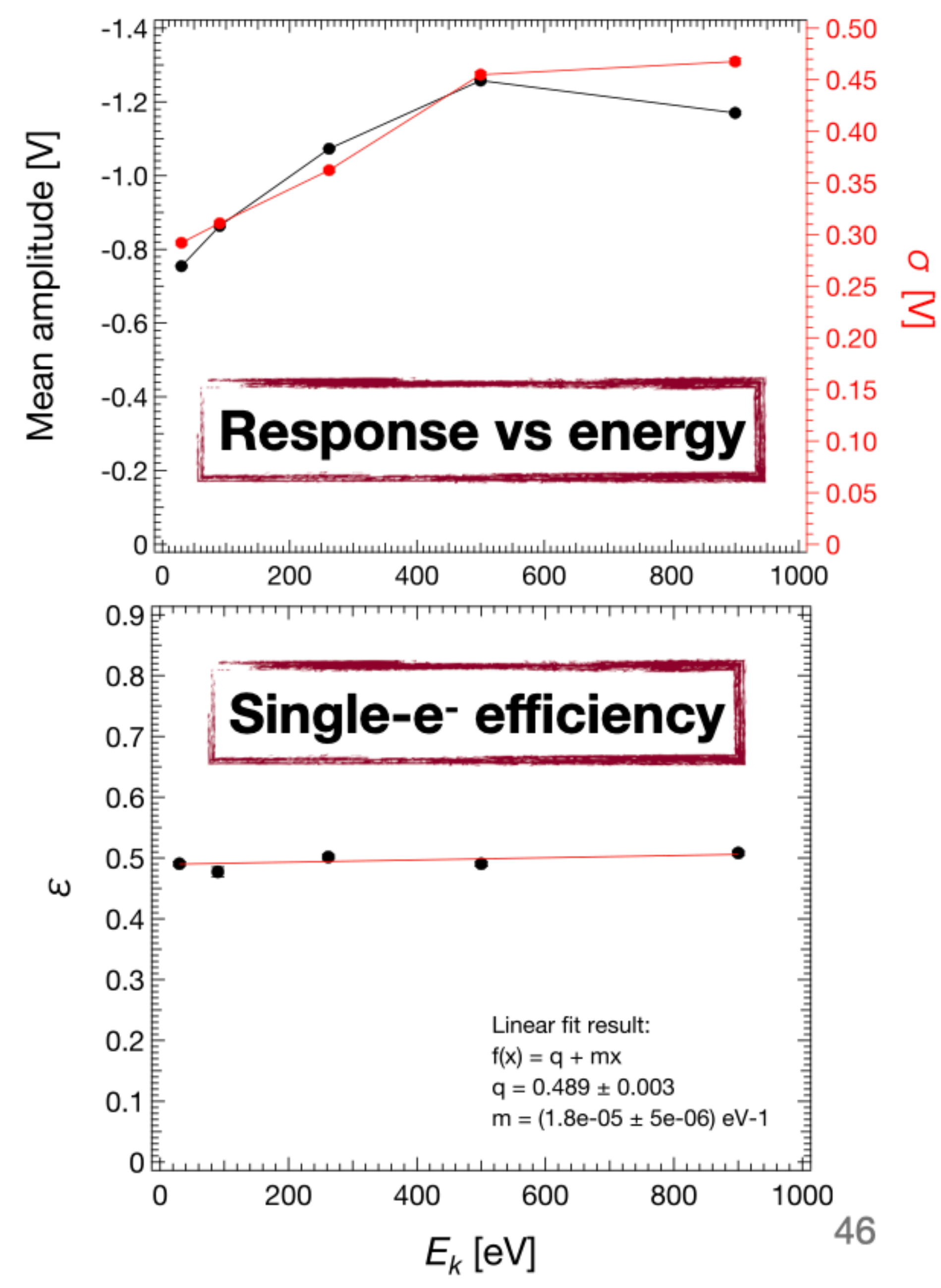


A. Apponi et al, Meas. Sci. Technol. **33** (2022) 025102

Alternative to silicon: Multi-channel plates

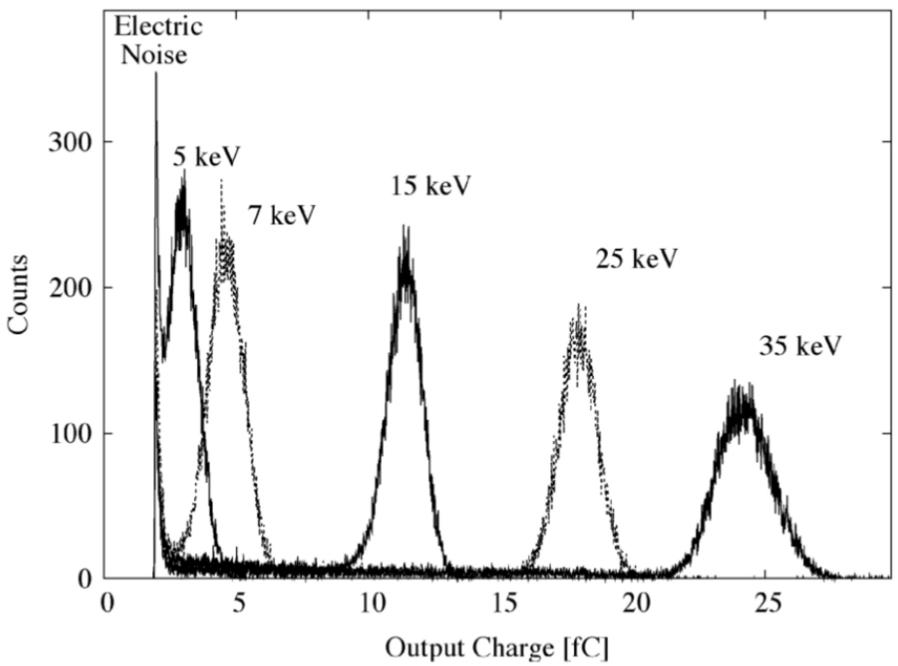


- **Established** detector for low-energy electrons
  - But **bad** energy resolution
- **Extensive** MCP characterization @ LASEC
  - $30 < E_e < 900$ eV
  - Very **mild** energy dependance
  - Single-e^- absolute **efficiency** ~ 49%

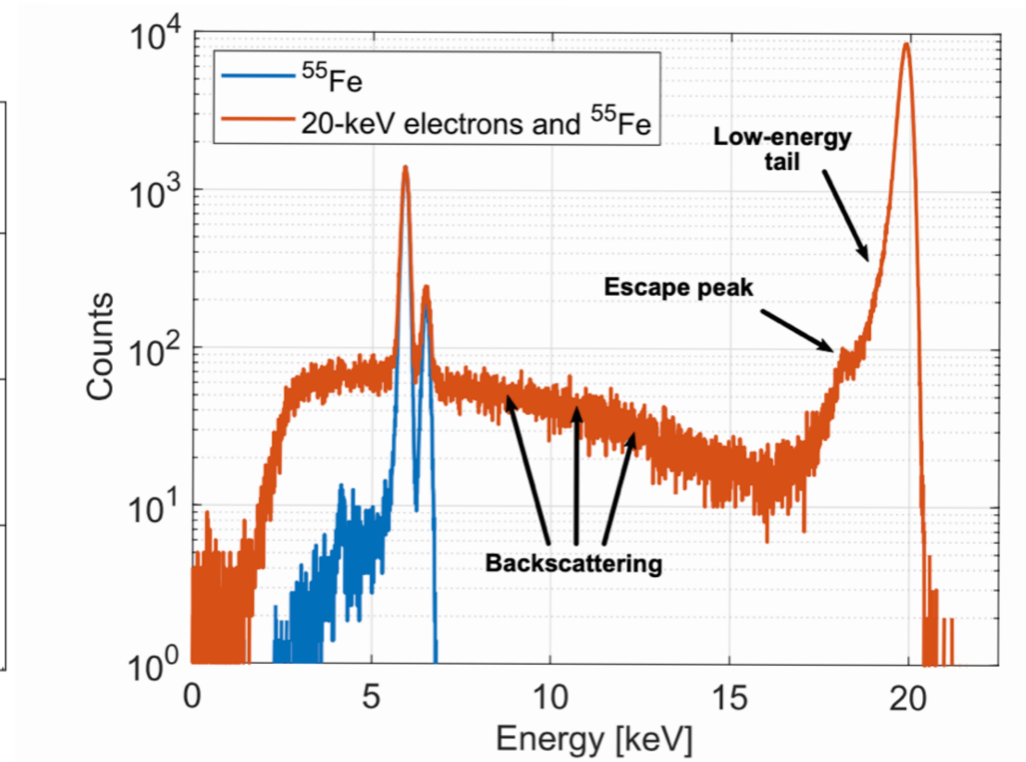


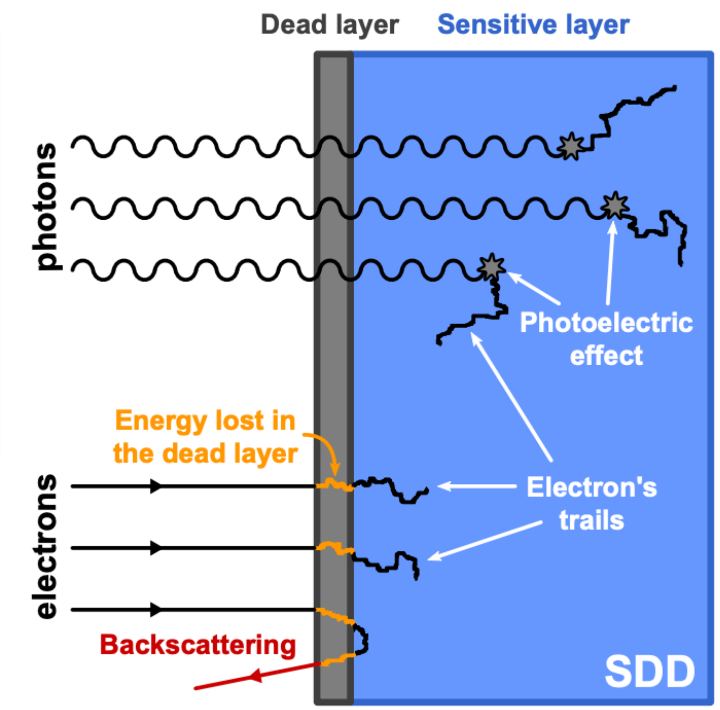
Single electron detection with silicon detectors

S. Kasahara, et al.,
IEEE Trans. Nucl. Sci. **57** (2010) 1549



G.Gugiatti, et al.,
NIM A **979** (2020) 164474

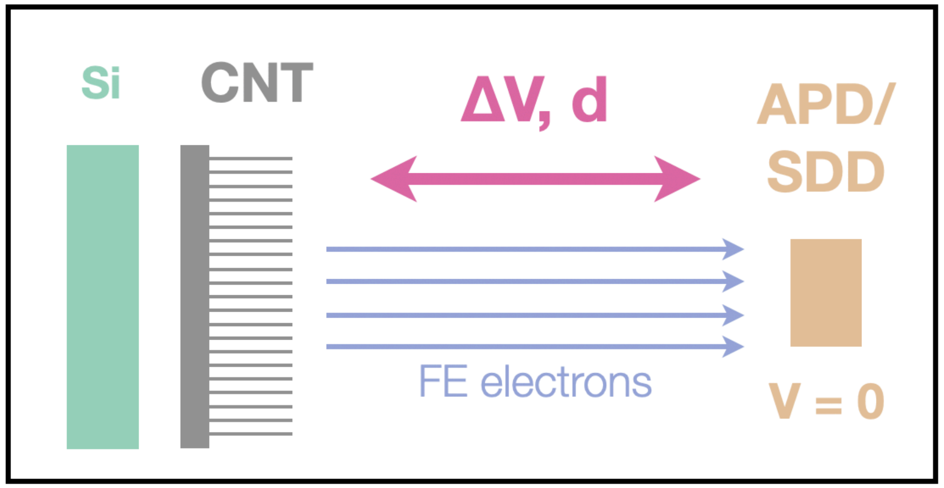




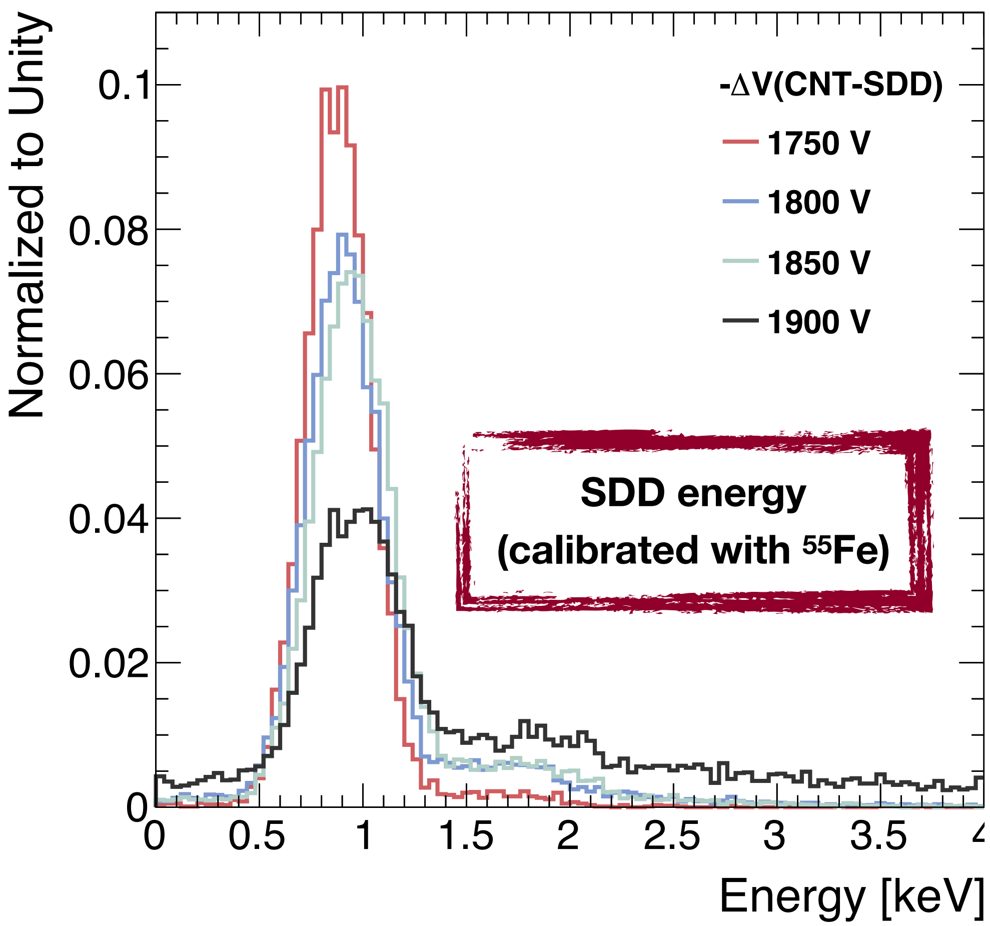
- APD can measure single e-
  - But only if $E_e > 5$ keV
- SDD: excellent resolution
  - But higher cost/complexity

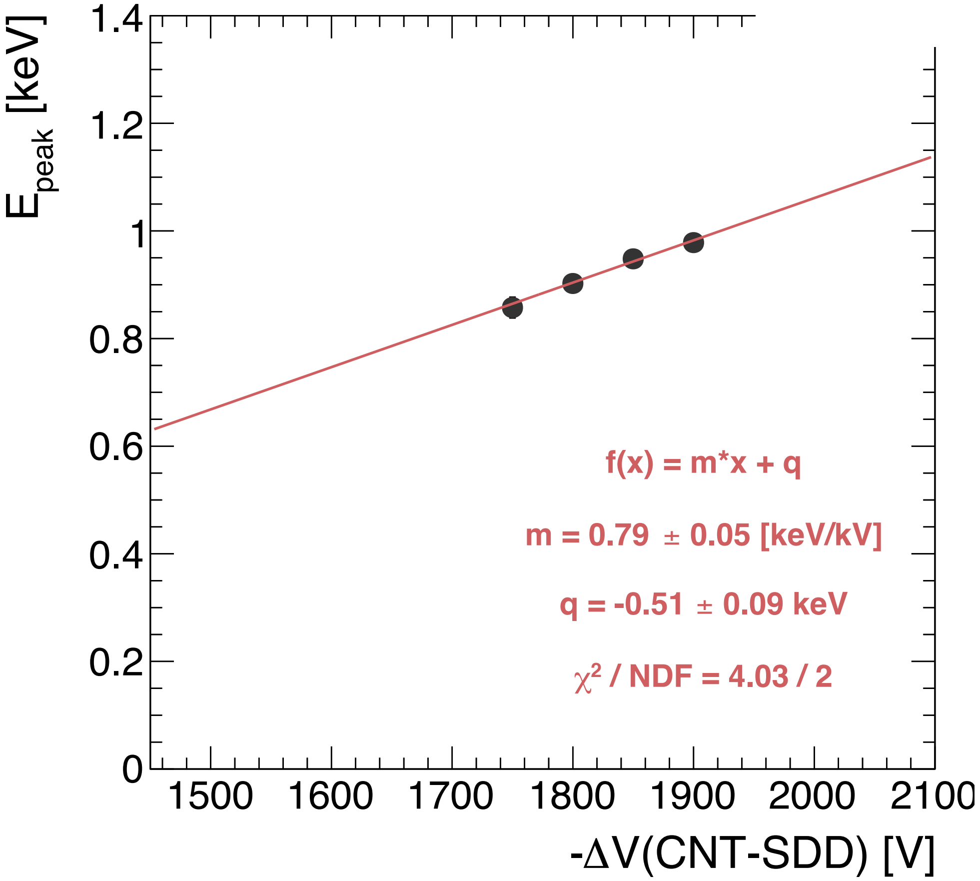
Field emission from CNT

- Observed **field electron emission** from CNTs
  - For high ΔV / small d(CNT-SDD)
  - Well-documented effect   eg Carbon 45 (2007) 2957



Hyperion Prototype

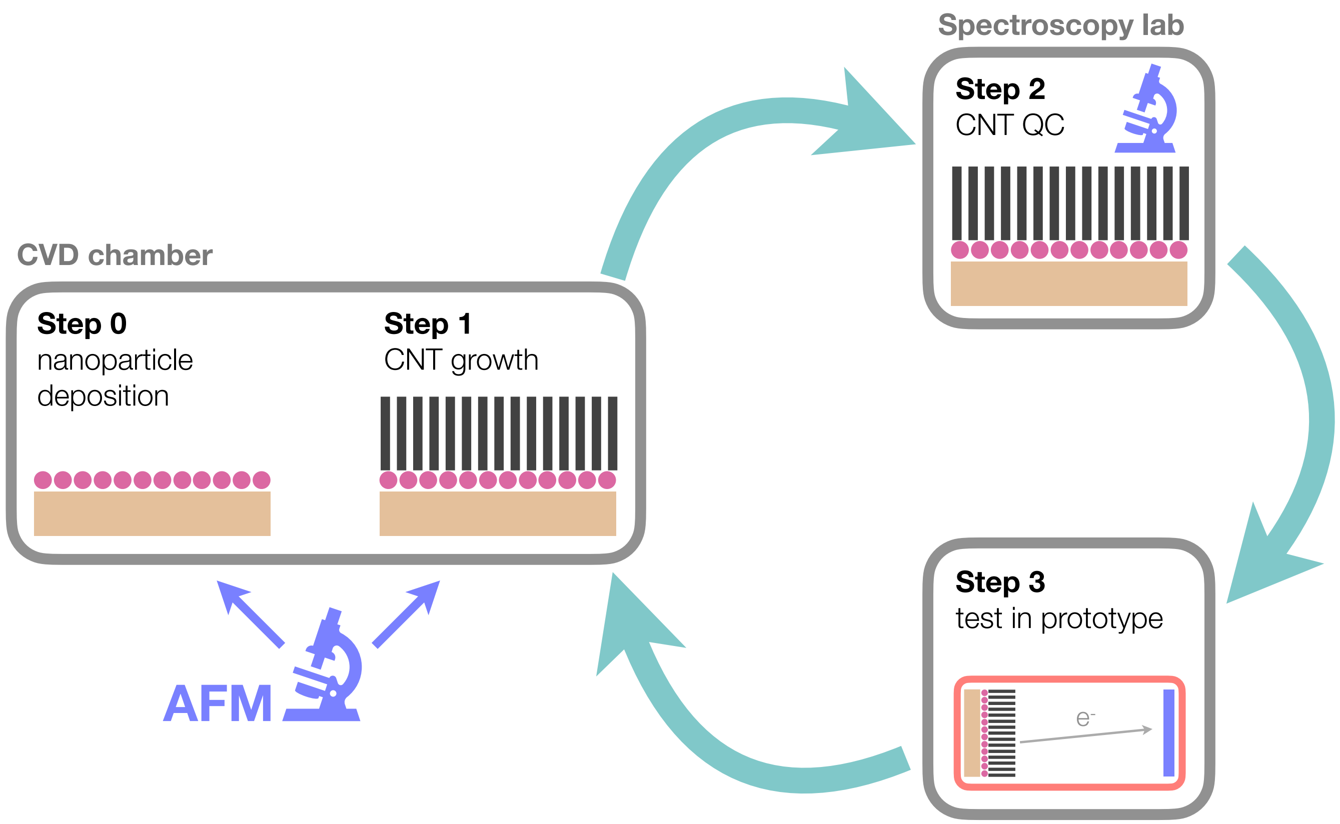




We can measure ~2 keV electrons emitted by CNTs

Controlling this effect critical to avoid background in DM searches

Planned upgrade of VA-CNT synthesis



- Seed deposition will be done in **same vacuum volume** as synthesis
  - **Control** over seed uniformity/ density
  - **No oxidation**
- Atomic force microscope (AFM) will check nanoparticle density/ uniformity
  - Quick feedback → quick optimization

Beyond DM

- **UV light** detector based on VA-CNT (NanoUV)
  The calibration technique for dark PMT, in fact

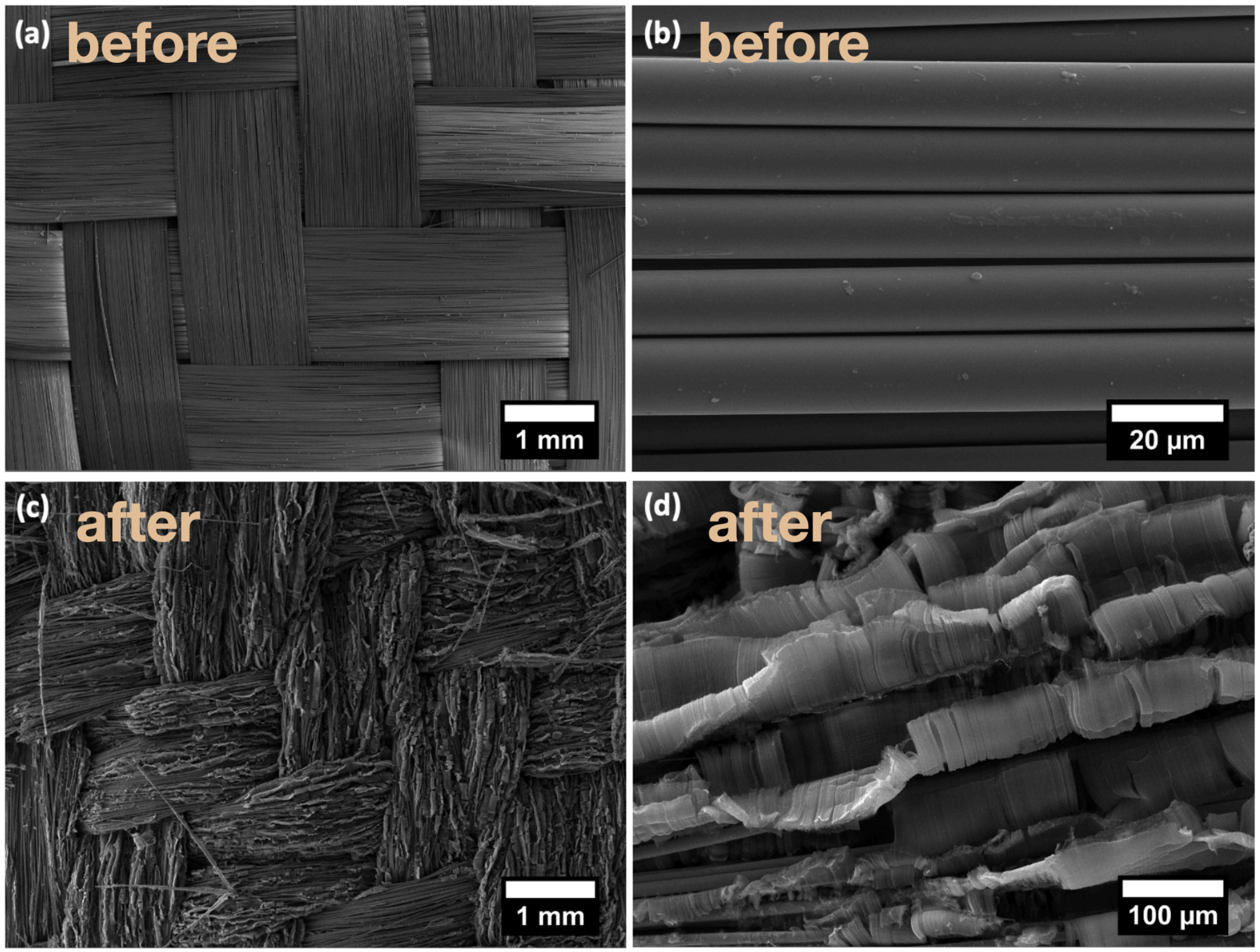
- VA-CNT for **bio**sensor or anti-microbial surfaces (collaboration with Biology department)

- CNT in novel **composite** materials
  Additive manufacturing

- Use of CNT to host tritium atoms for the Ptolemy target
  See hep/ph/…

Basalt fiber enhanced with CNT

in collaboration with Sapienza DICMA

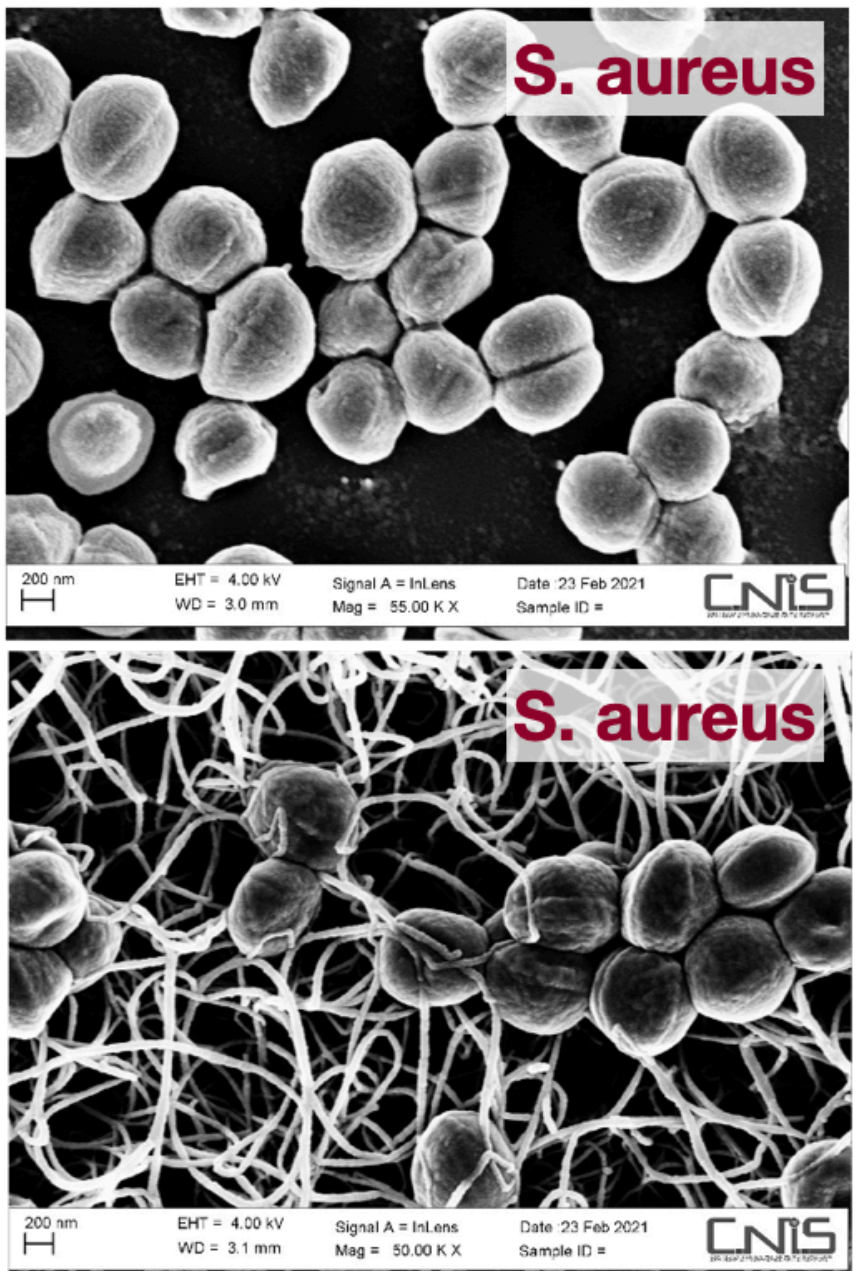


Paper submitted to Nano Today

- **Basalt fibers**: exciting new 'green' material
  - **Excellent** mechanical properties
  - Much **cheaper** than carbon fibers
- We grew nanotubes **directly** on the fibers
  - **Without** catalyst (world first!)
- Fibers become **highly** conductive (>250 S/m)
  - (Normally basalt is insulator)
  - Applications: EM shielding, smart textiles

in collaboration with D. Uccelletti (Sapienza Biology)

Bactericidal films made of CNT



- Nanotubes have **bactericidal** properties
  - Bacteria **‘skewered’** by nanotubes
- Could lead to development of bactericidal films
  - **Self-cleaning** surfaces
- First results are **encouraging**