The ANDROMeDa Project

Searching for Dark Matter with Vertically-Aligned Carbon Nanotubes

ANDROMeDa

Aligned Nanotube Detector for Research On MeV Darkmatter

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STVDIVM VRBIS

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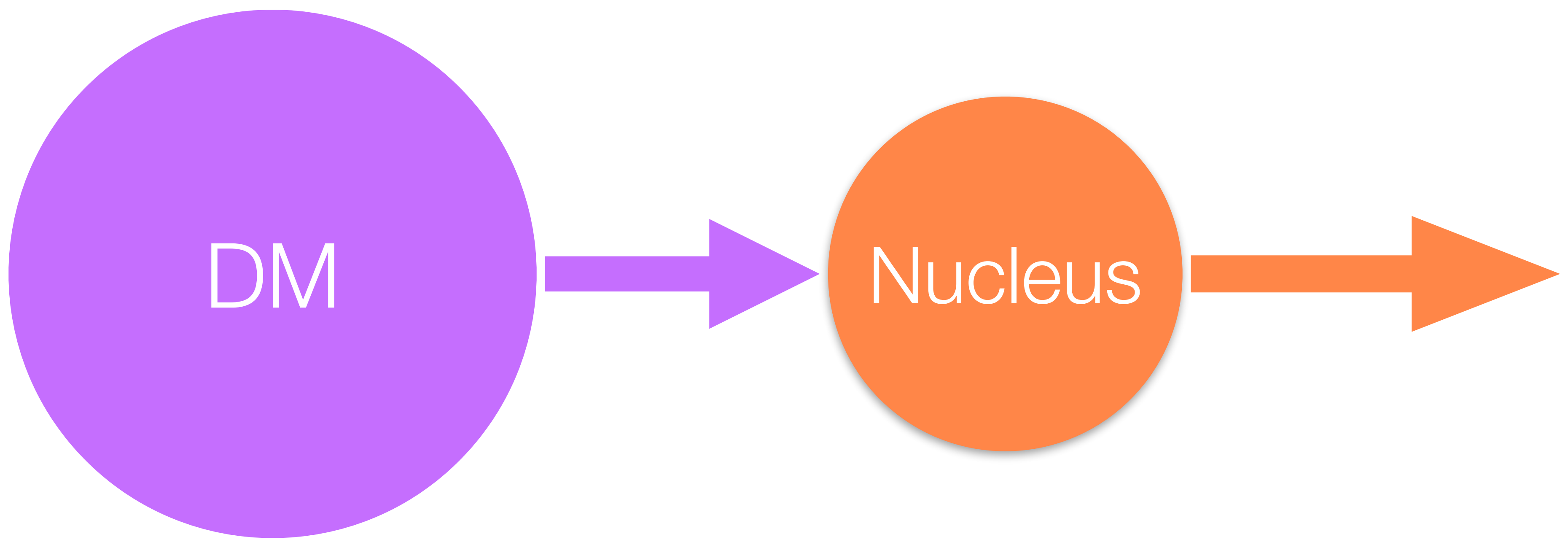
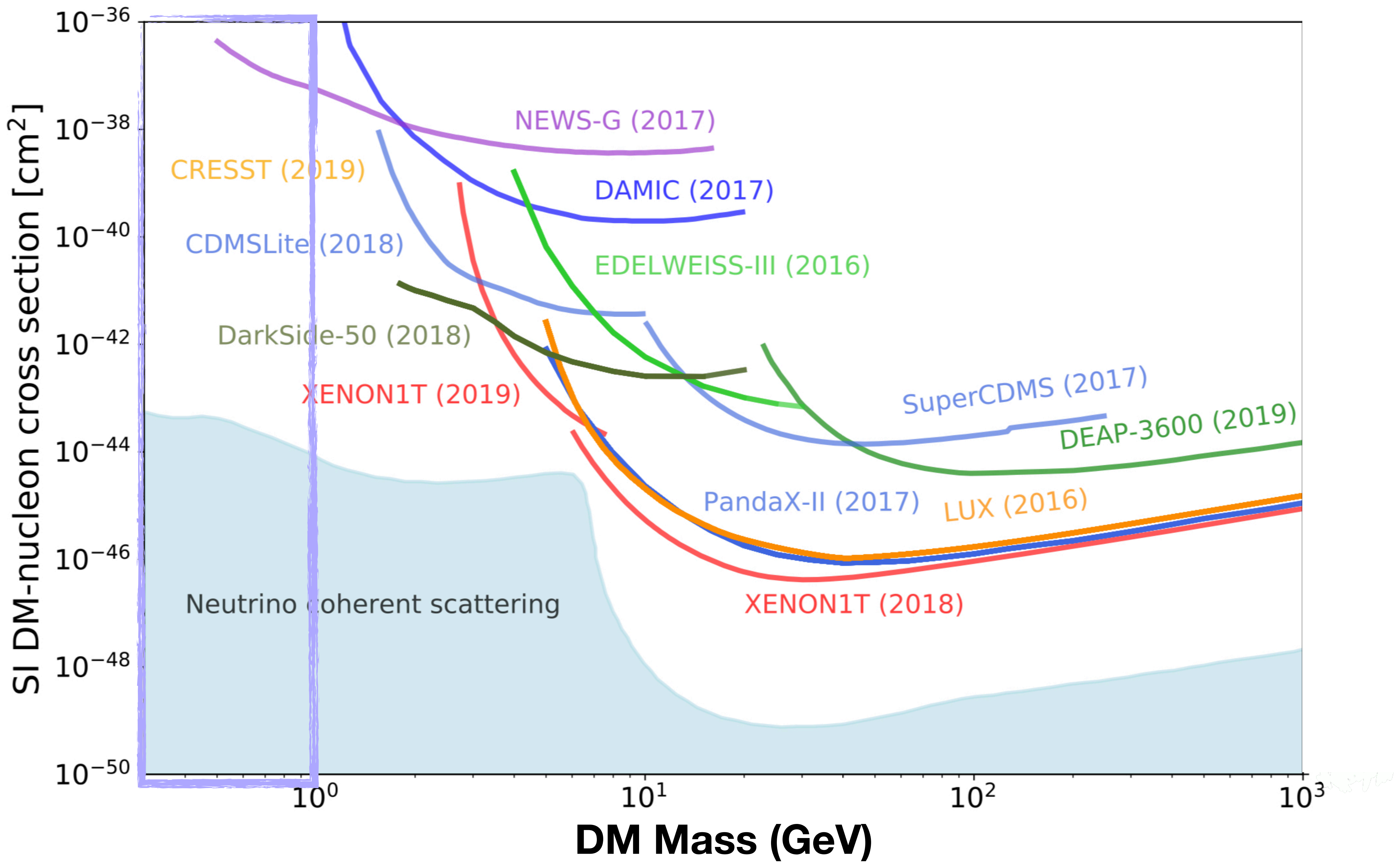
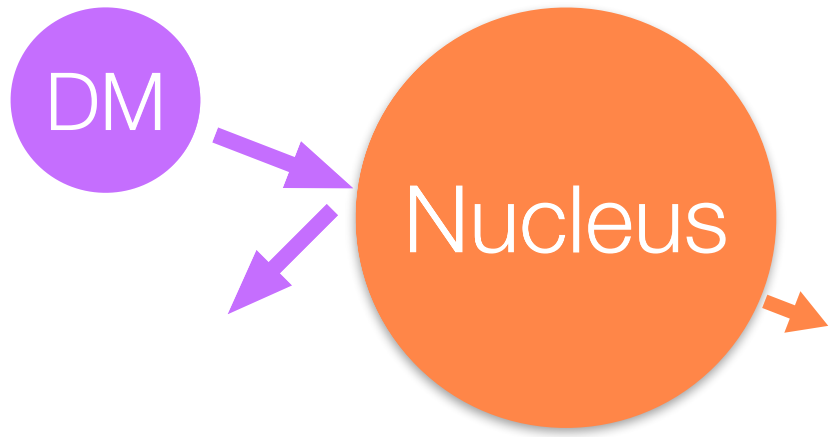
Poor Sensitivity for Dark Matter in Sub-GeV Range

- Current experiments mainly based on **nuclear recoil**





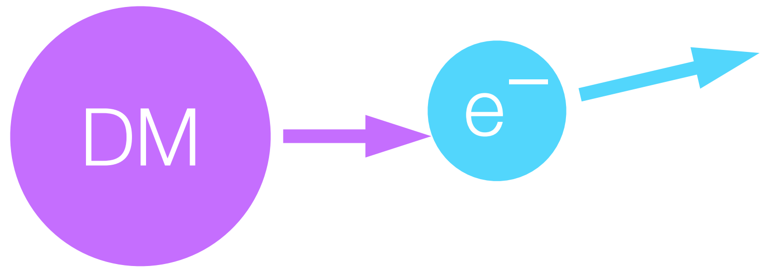
- If Dark Matter (DM) mass < GeV
  - no visible nuclear recoil



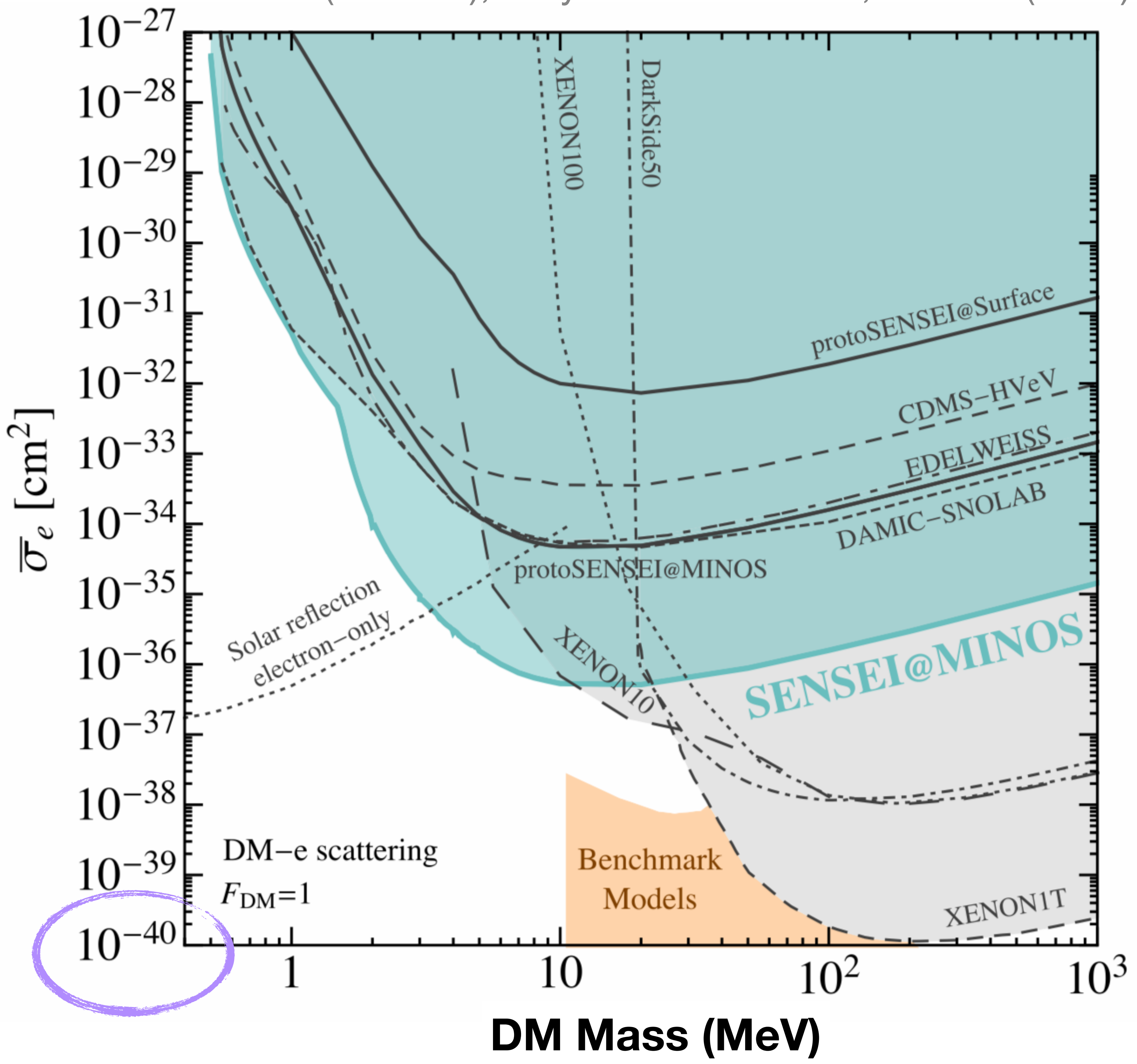
  - **lighter target needed**

Less Strict Limits Using Electron Recoil

- For Sub-GeV DM better look for **DM-electron scattering**
  - visible also with few MeV DM mass
- Few experiments sensitive to electron recoil
  - cross section limits 10^6 times weaker
  - sensitivity drop for mass < 100 MeV
- **New detection strategy** needed to go below 100 MeV



L. Barak et al. (SENSEI), Phys. Rev. Lett. 125, 171802 (2020)



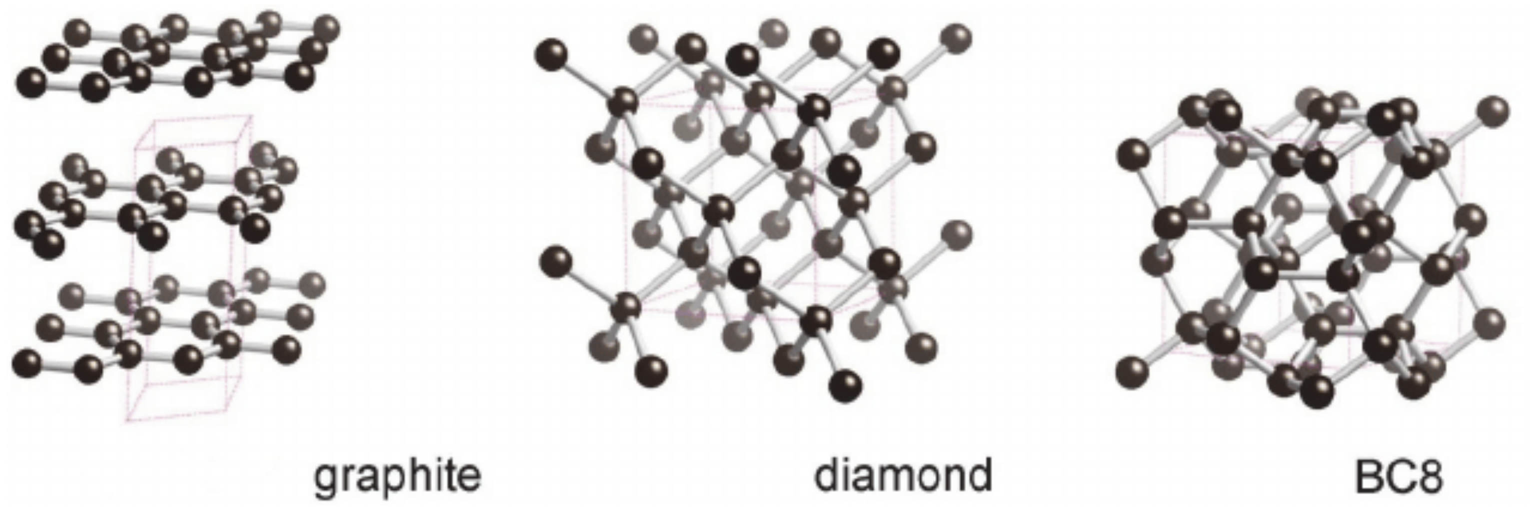
Electrons Directly Into Vacuum: 2D Materials

- Assuming $\begin{cases} v_{DM} = 300 \ \dfrac{km}{s} \\ m_{DM} = 10 - 100 \text{ MeV} \end{cases}$ For → $K_{DM} = 5 - 50$ eV

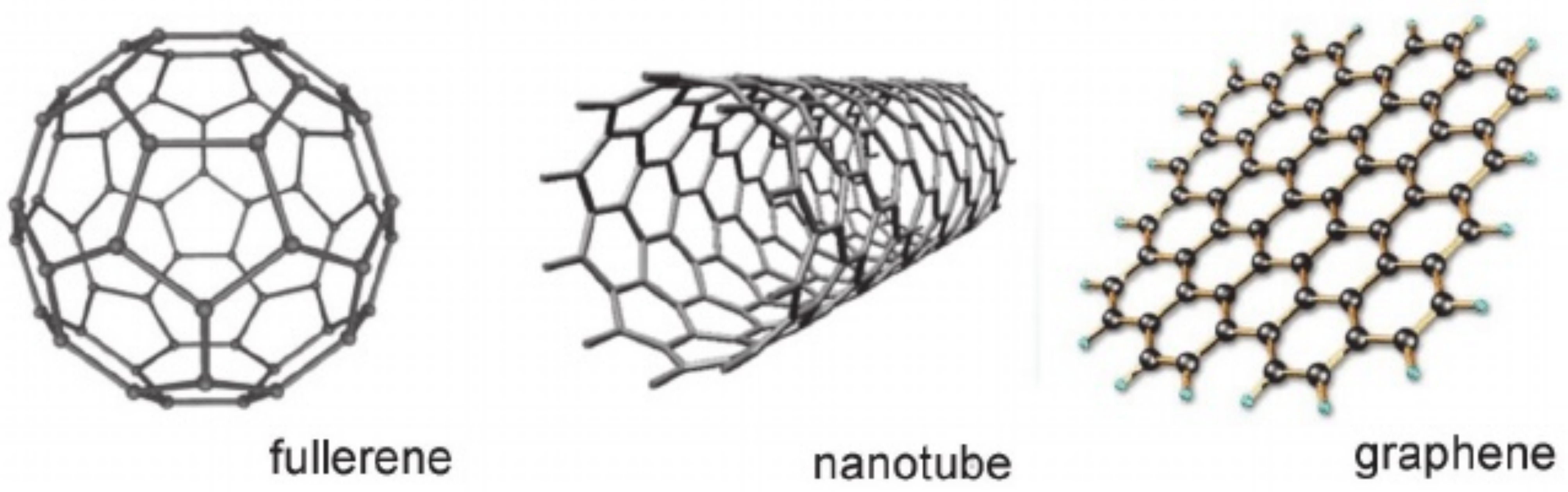
- Able to **extract electrons** from carbon ($\Phi_C = 4.7$ eV)

- Low energy electrons = extremely **short range** in matter

- Problem solved using **2D materials**:
    - electrons directly ejected <u>into vacuum</u>
    - no additional energy loss

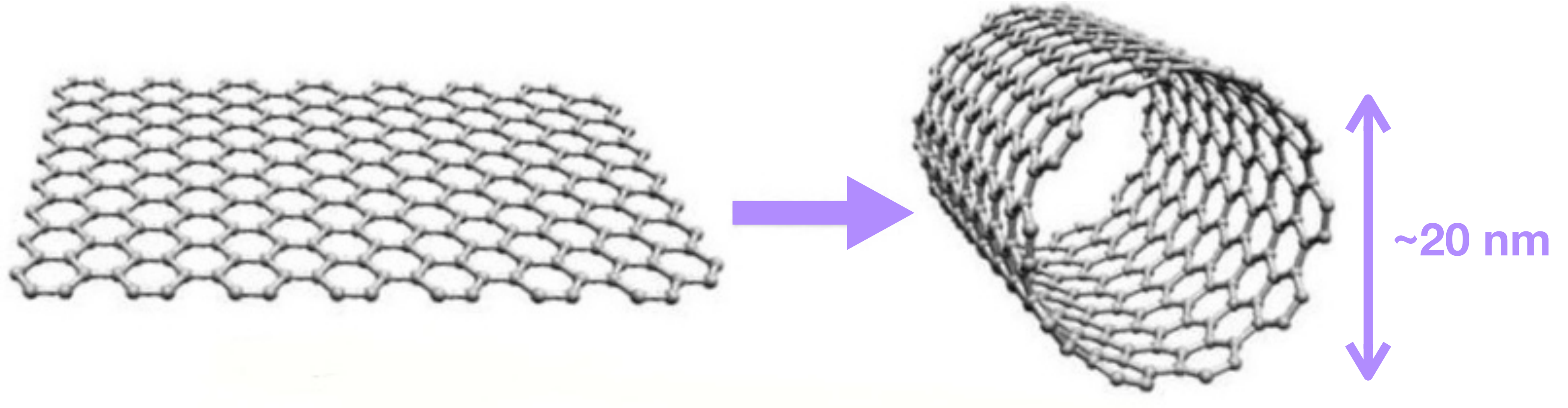


Low dimension

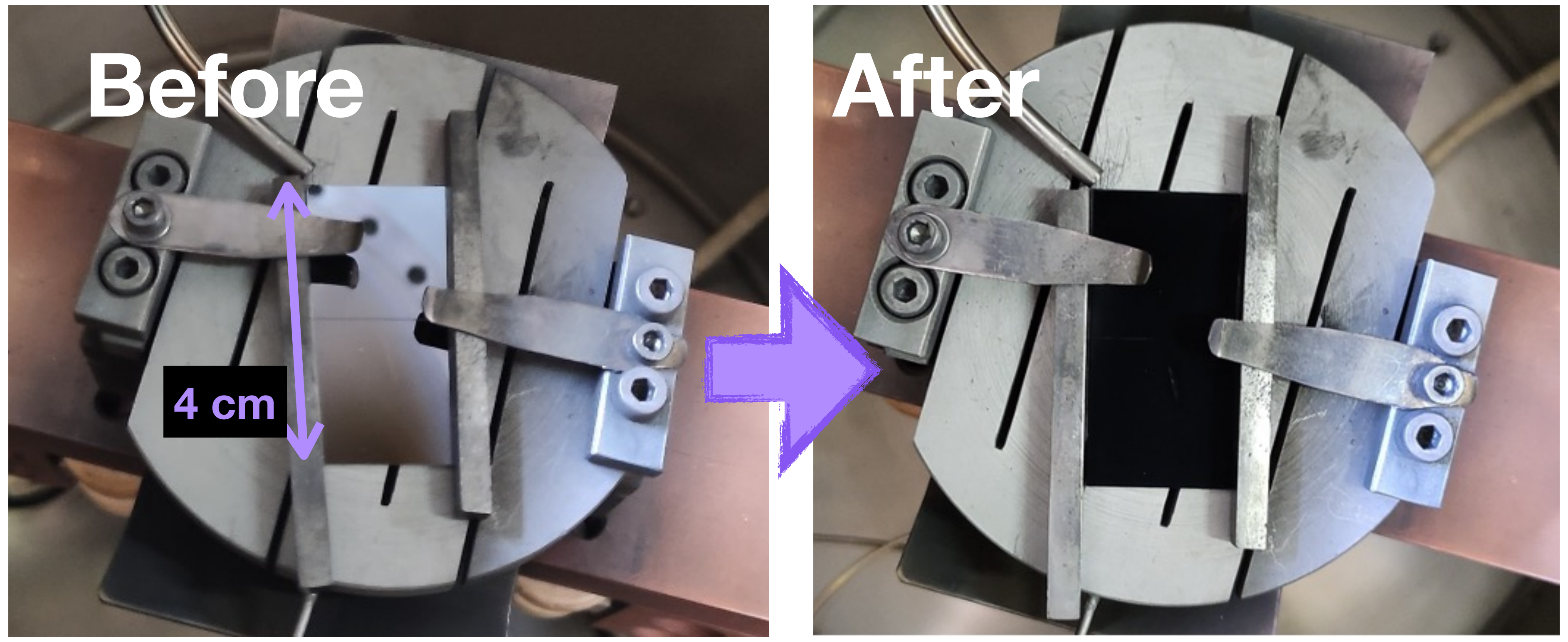


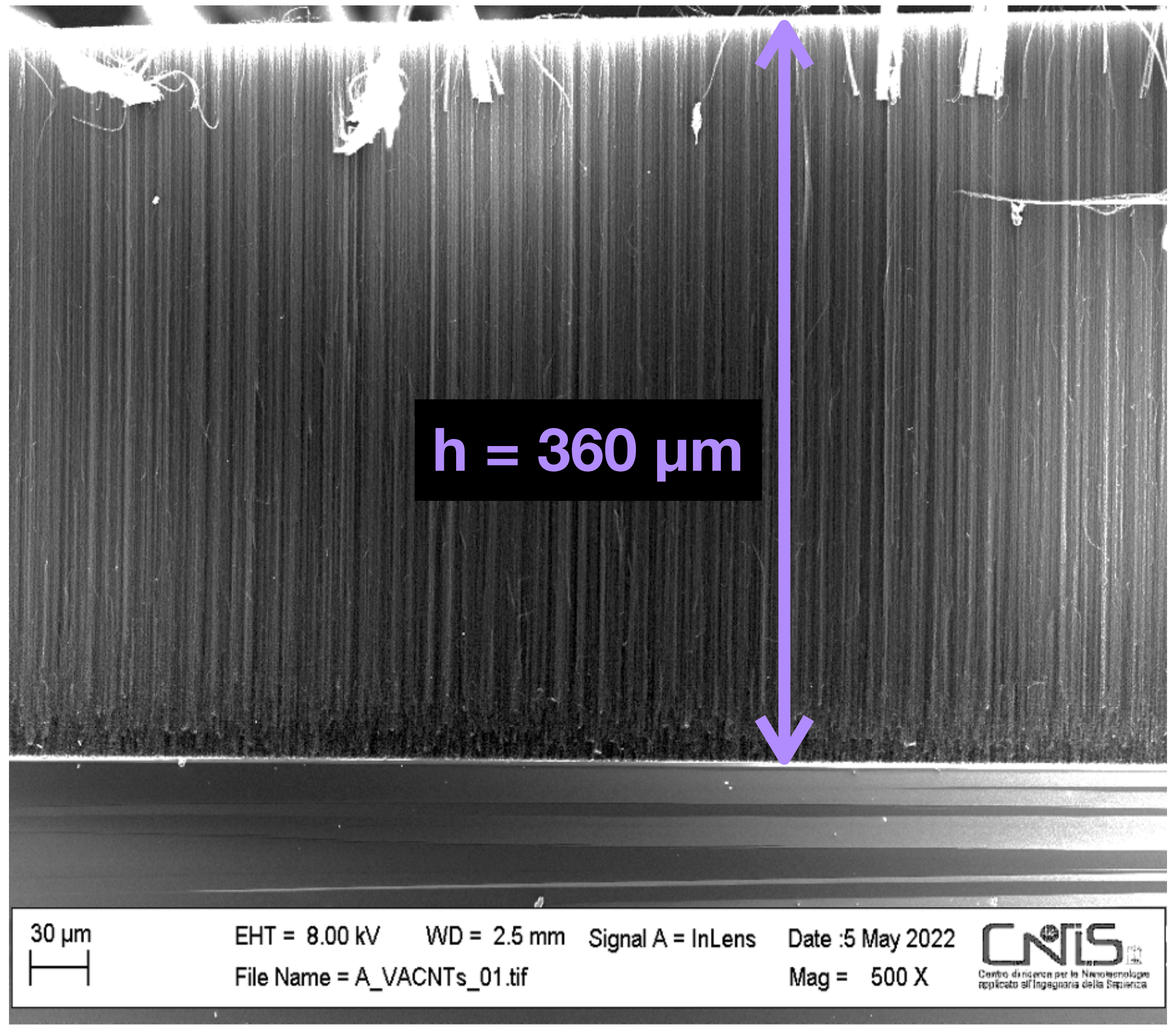
Growing Carbon Nanotubes Forests

- Idea:



- **State-of-the-art** nanotube facility in Rome Sapienza
  - Chemical Vapour Deposition (CVD) technique
  - Up to 8 cm^2 extension on various substrates
  - Diameter ~20 nm, length up to 400 µm
- **Result**: vertically-aligned nanotubes forests
  - Ideal target for DM search?

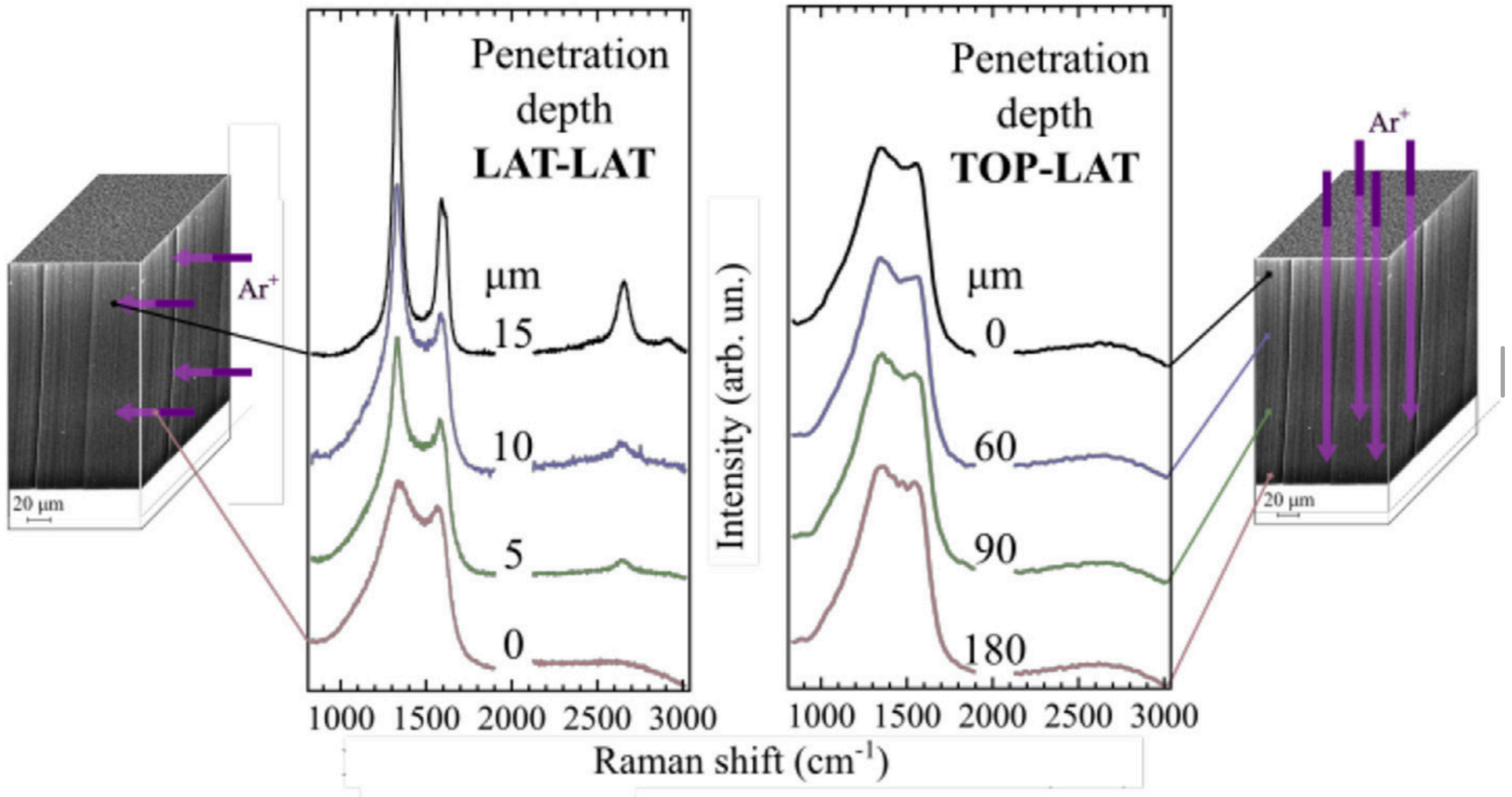




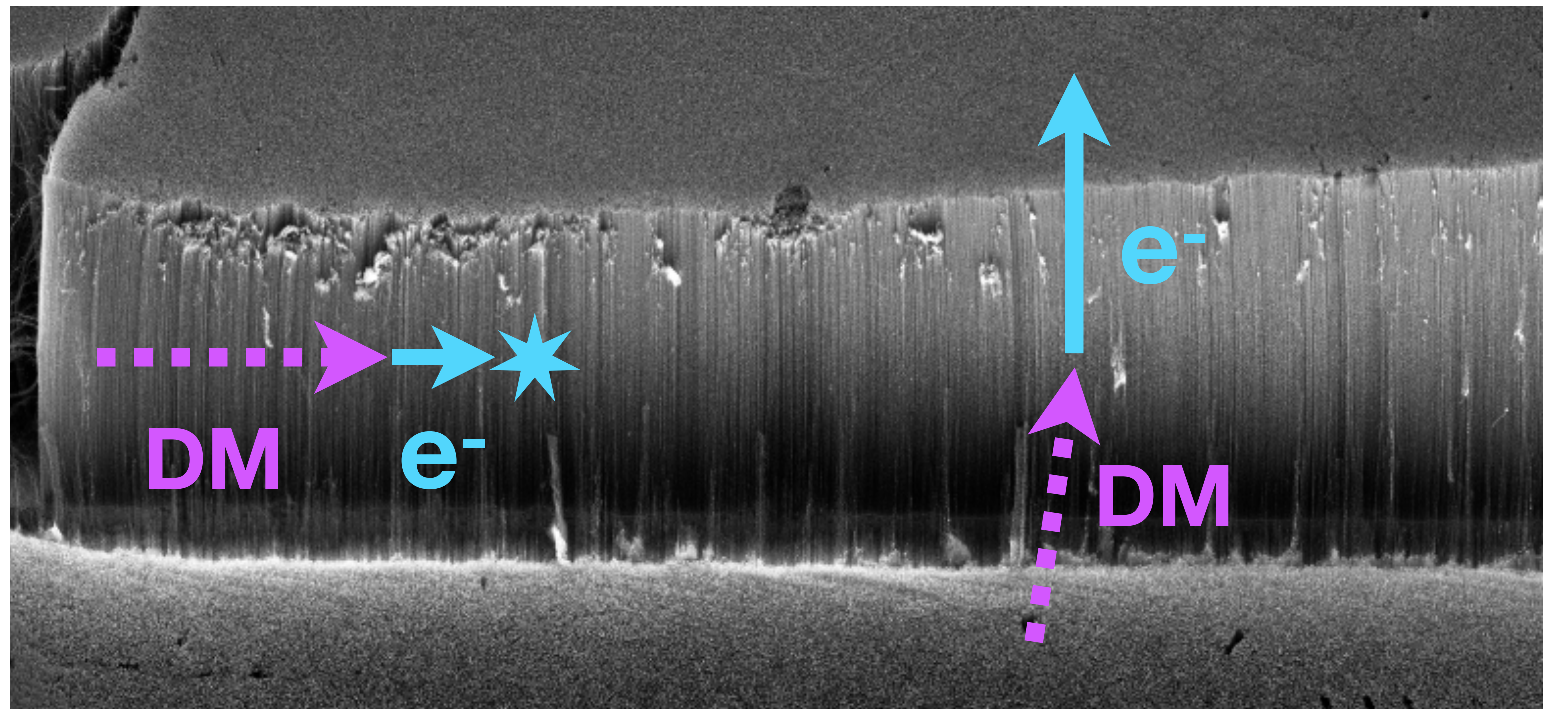
Directional Sensitivity with Carbon Nanotubes

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

- **Raman analysis** after Ar+ bombardment
  - Lateral penetration < 15 μm
  - Longitudinal damage along full length (180 μm)
  - **Highly anisotropic density**

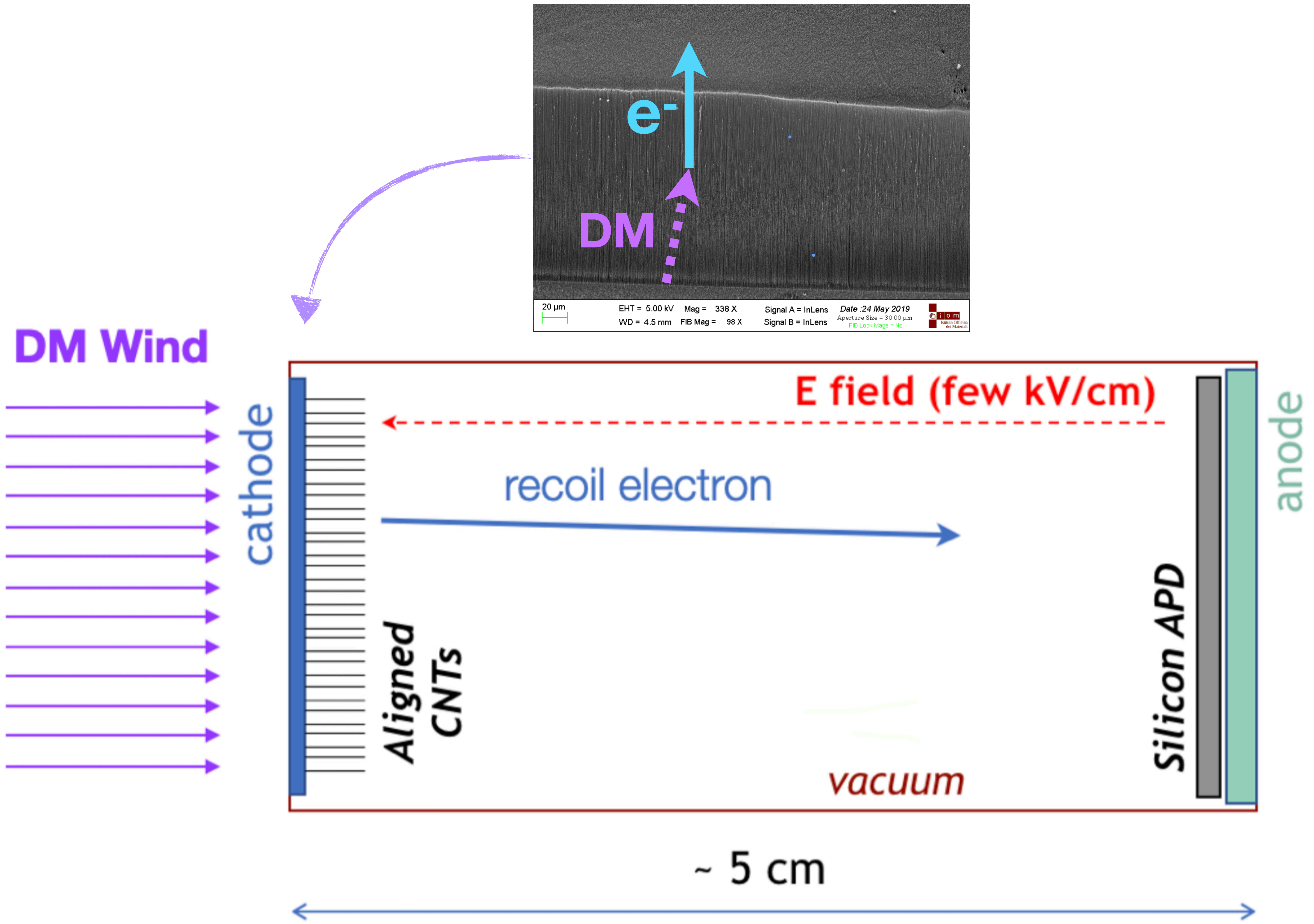


- CNTs as **target for DM-electron scattering**
  - ~vanishing density in tube axis direction
    - electron ejected **only if parallel to tubes**



A New Detector Concept: The Dark-PMT

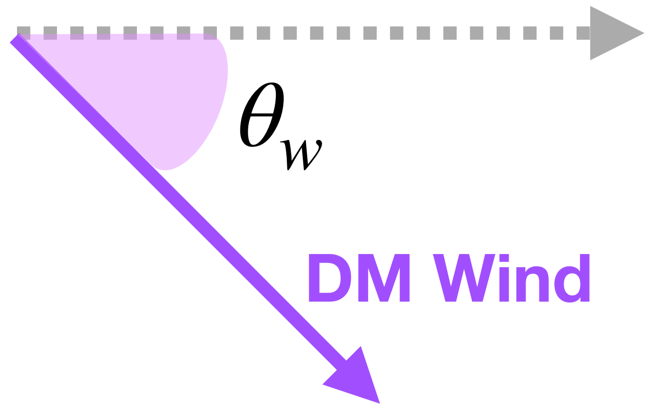
- **Working principle:**
  - DM-electron scattering on a target of VA-CNTs
  - Electrons out if tubes parallel to the DM wind
  - Acceleration up to keV
  - Detection by silicon sensor



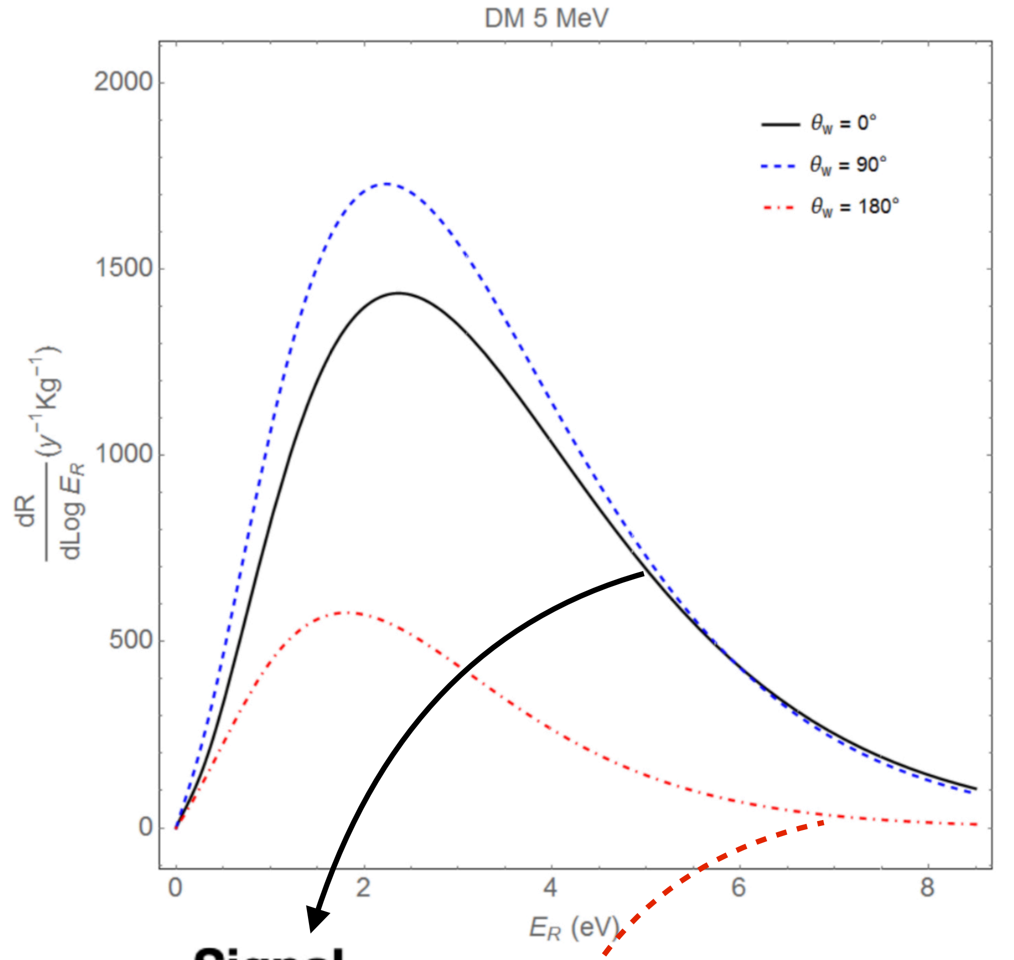
- **Key features:**
  - ☑ Directional Sensitivity
  - ☑ Sensitive to few eV electrons
  - ☑ ~Unaffected by thermal noise ($\Phi_C = 4.7$ eV) even at room temperature

Dark Matter Search with 2 Dark-PMT Arrays

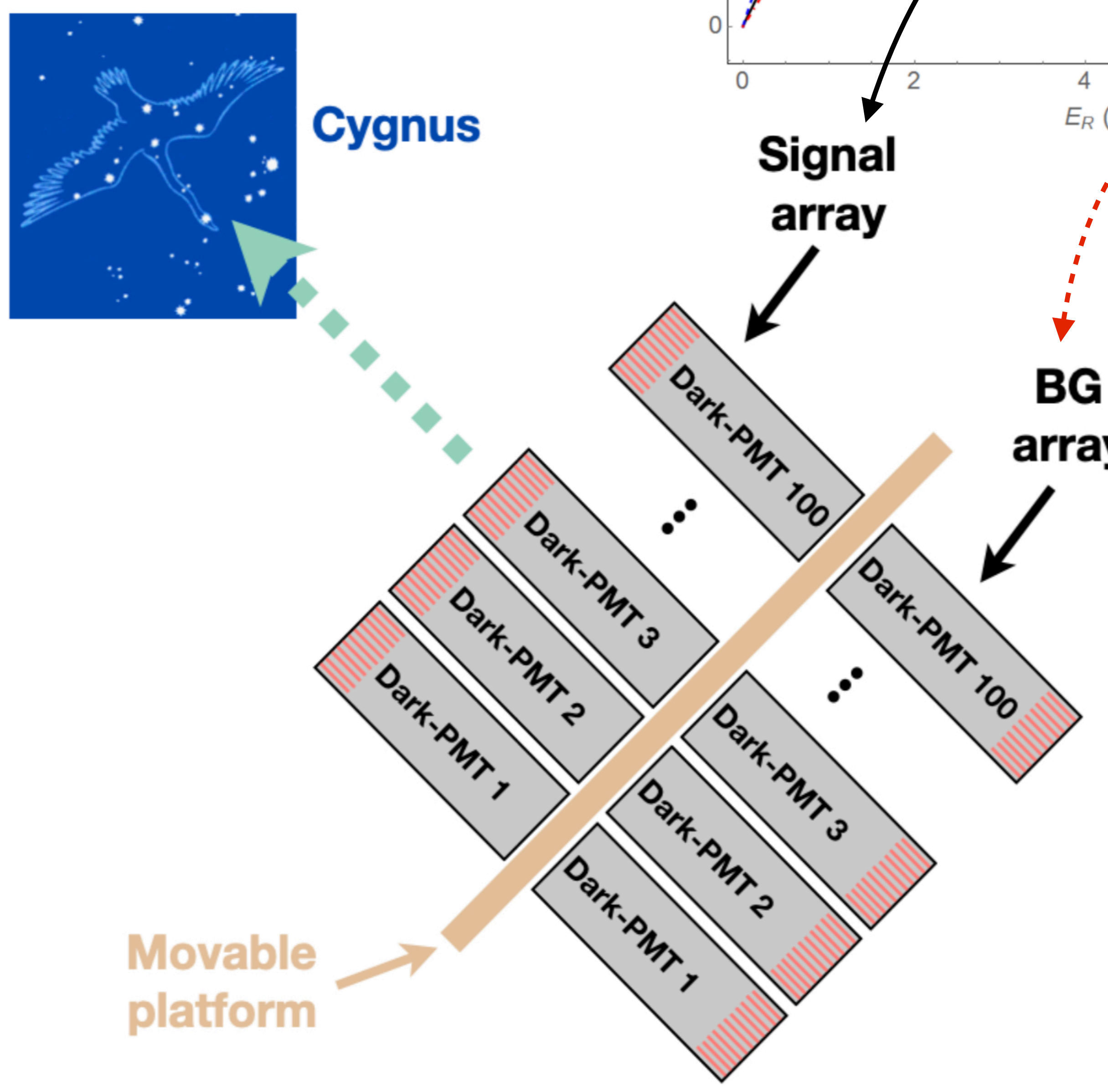
- Looking at expected rate of electrons ejected from VA-CNTs
  - rate for θ_w = 0° >> rate for θ_w = 180°
  - <u>counts excess</u> if dark-PMT pointed in DM wind direction



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



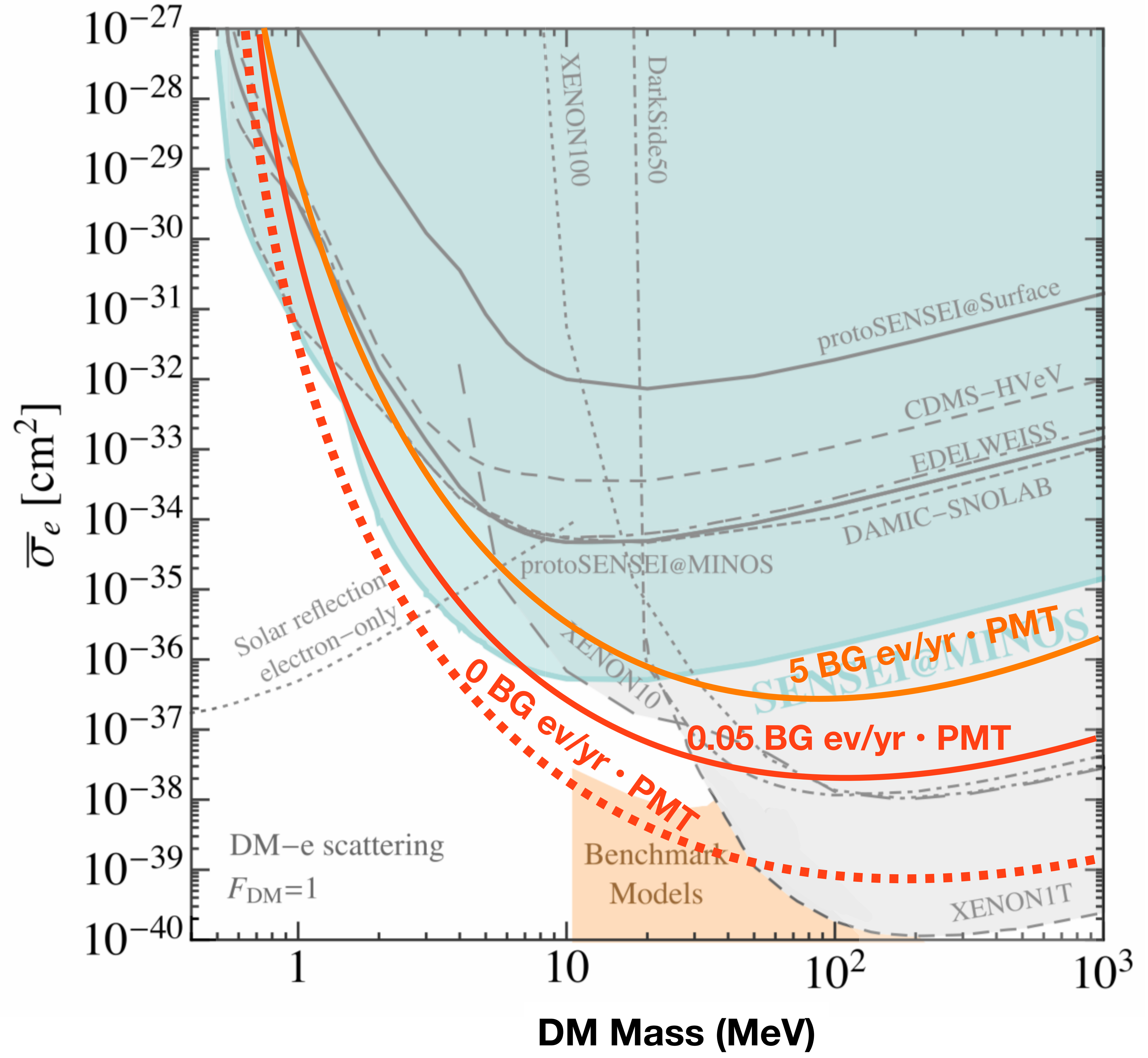
- two arrays of dark-PMTs on a moving platform
  - 1st pointed towards Cygnus → ***DM signal***
  - 2nd in opposite direction → *backgrounds*
  - $\geq$1 g mass for array so ~100 units with 10 cm^2 cathode area



Background Minimisation Will Be Essential

- Expected exclusion limits
  - For just 1 g x 1 year exposure
    - Using 2 arrays of 100 Dark-PMTs
- Performance **strongly depends** on BG event rate
  - BG rate < 0.05 events/year x dark-PMT needed to **extend current limits**

R. Catena et al., arXiv:2303.15509 [hep-ph]

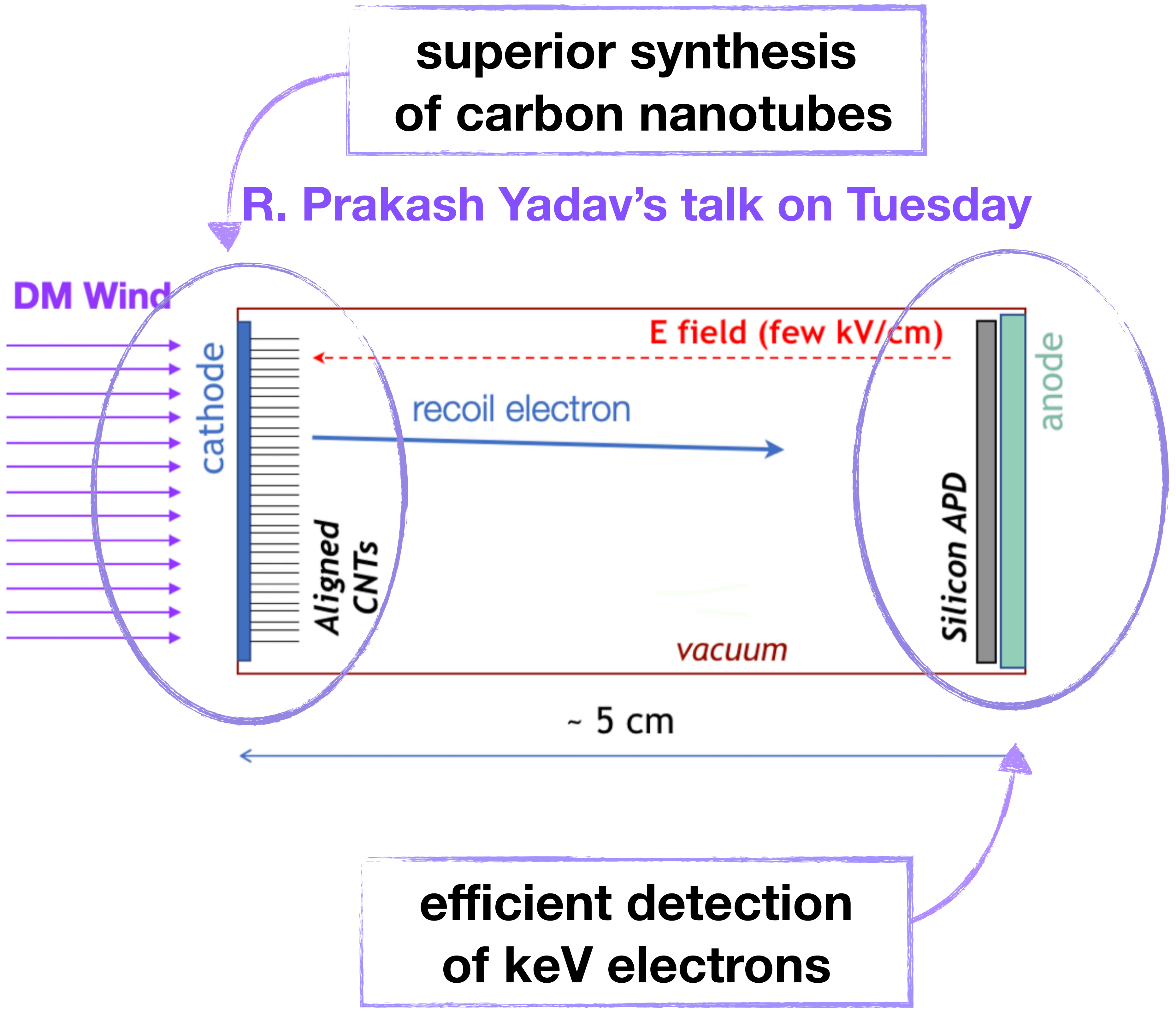


The ANDROMeDa Project

- Awarded PRIN2020 Grant (1M€)
  - 3 years project started in 2022
  - 3 units: INFN (F. Pandolfi - P.I.)
    Sapienza (G. Cavoto)
    Roma 3 (A. Ruocco)

PRIN 2020

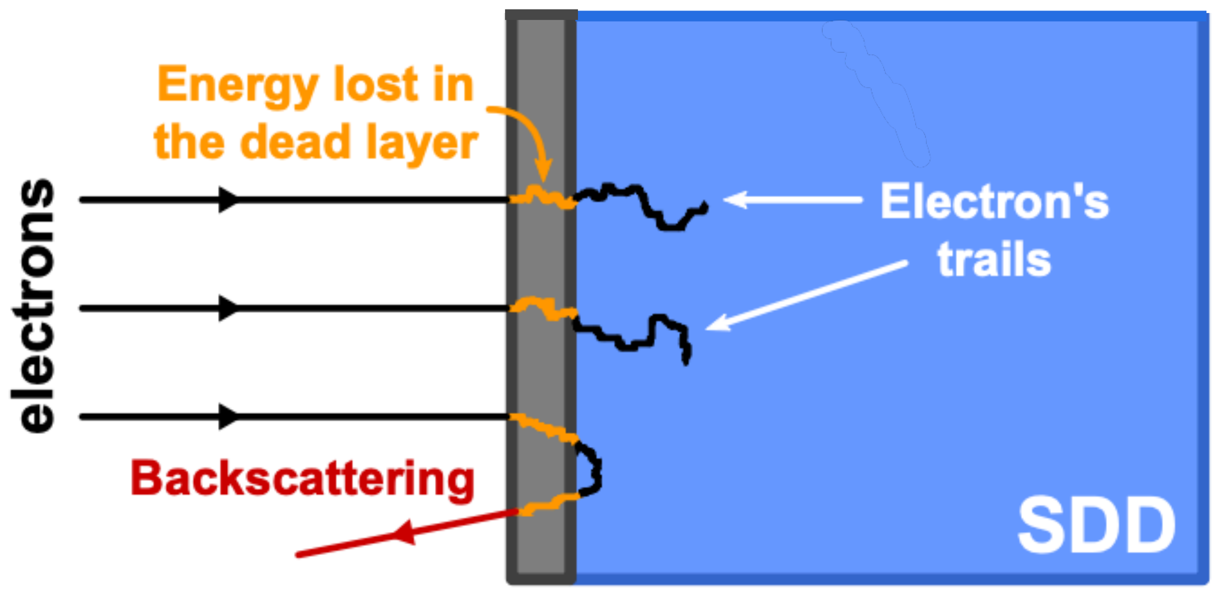
- **Main objective**: development & construction of a <u>dark-PMT prototype</u>
  - **challenges on both sides** of detector



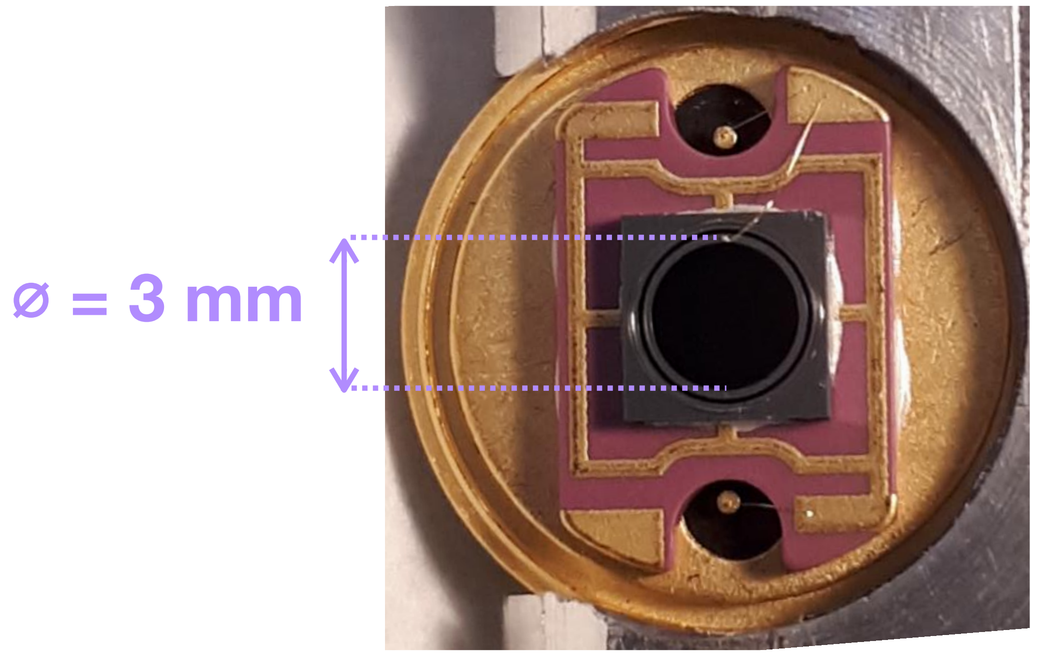
ANDROMEDA
Aligned Nanotube Detector for Research On MeV Darkmatter

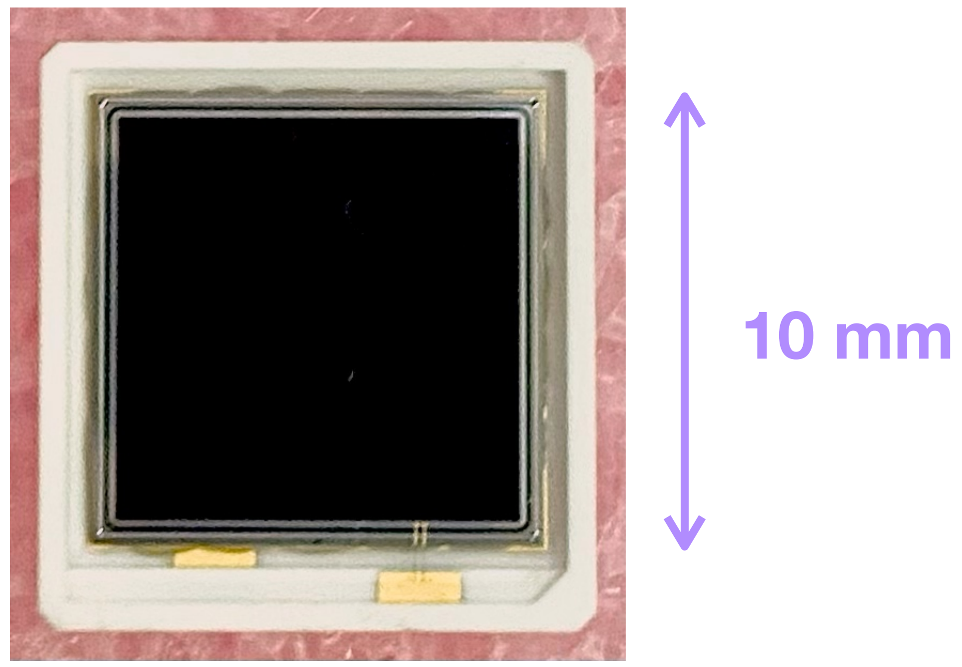
Detecting keV Electrons with Silicon Detectors

- SDDs & APDs born as photon detectors
  - with thick dead layer (Si oxidation) → able to **detect electrons**



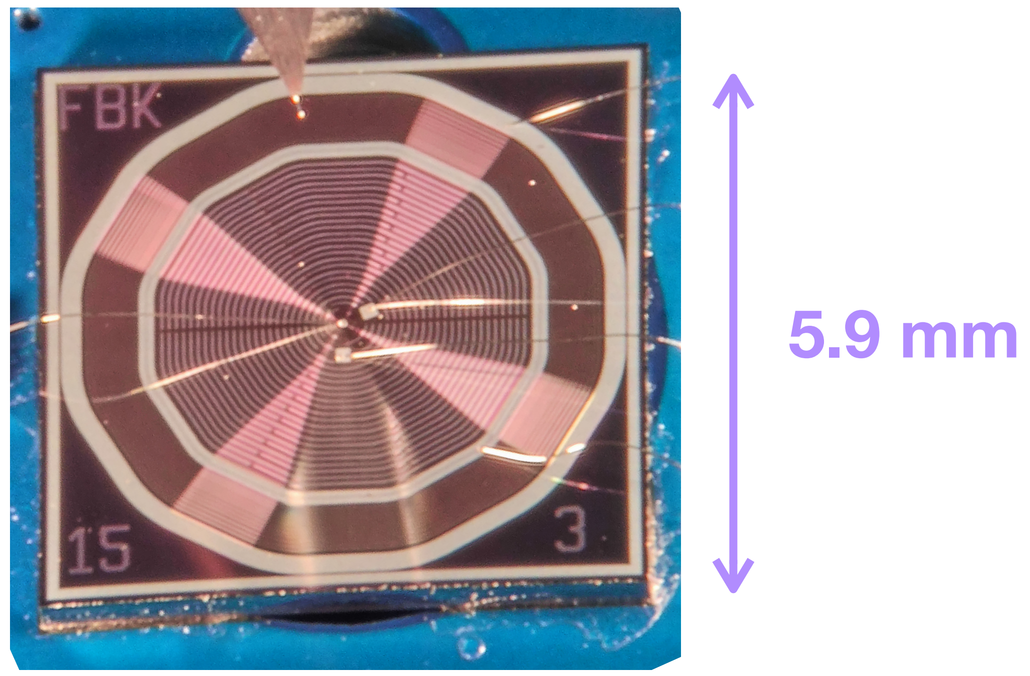
- Benchmark: **Windowless Avalanche Photodiodes**





  - simple, cost-effective
  - produced by Hamamatsu

- Backup: **Silicon Drift Detectors**

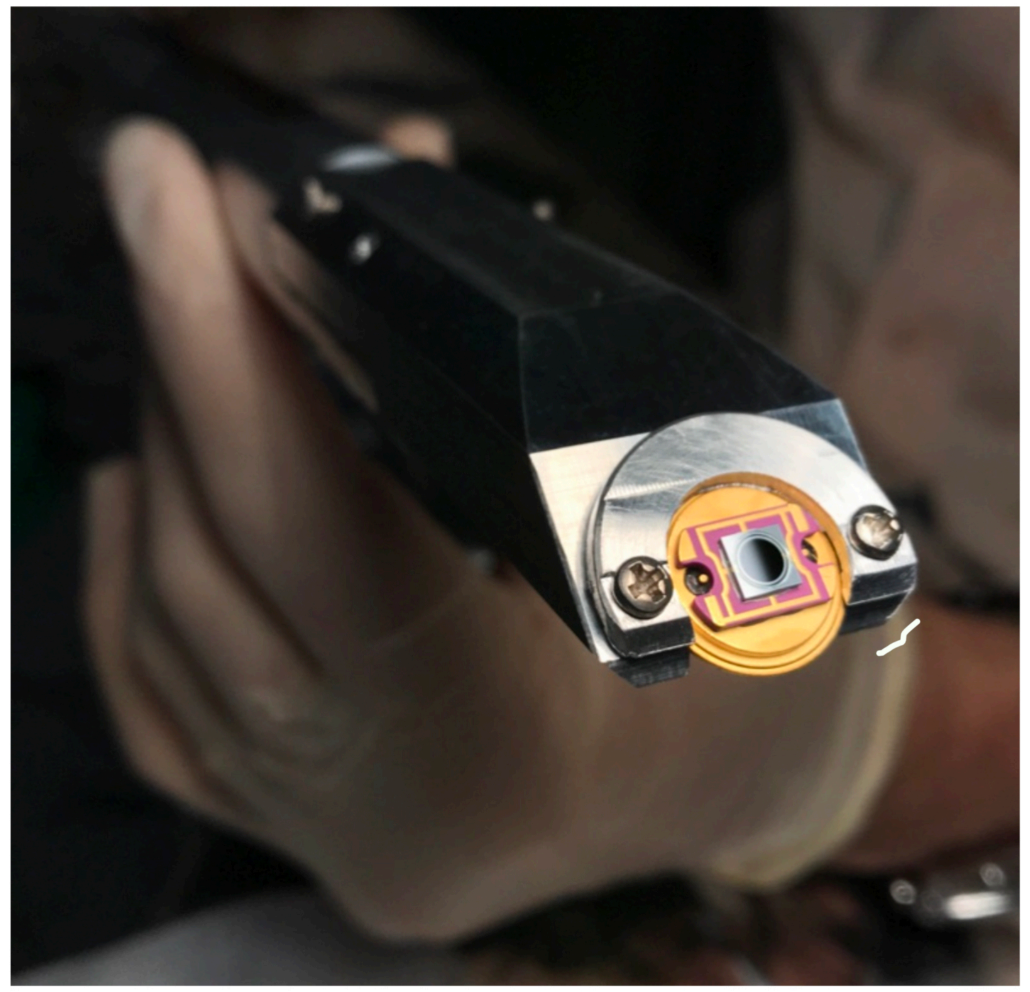


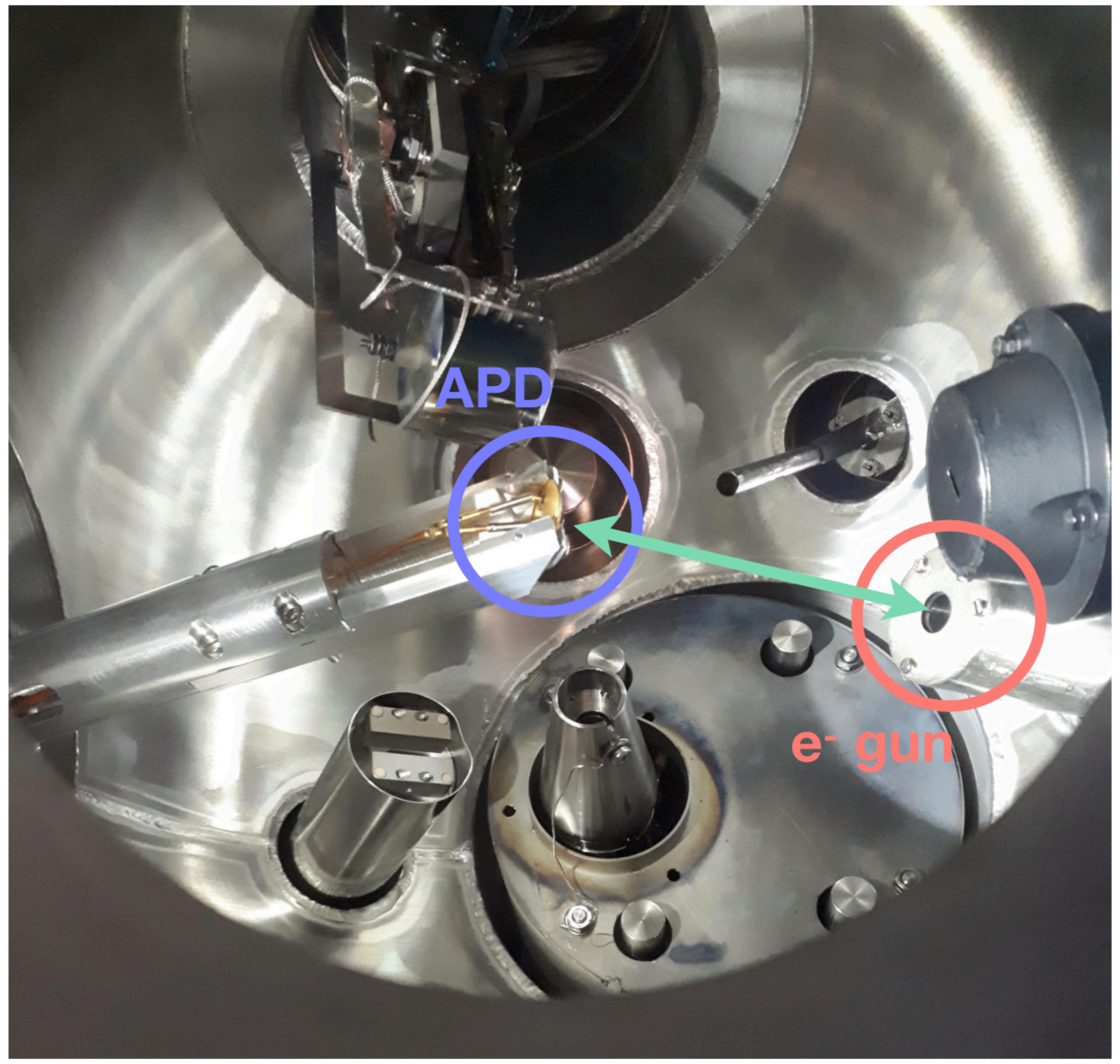
  - ultimate energy resolution
  - produced by FBK + electronics by PoliMi

APD Characterisation @ LASEC Labs (Roma Tre)

- Hot tungsten filament + electrostatic lenses

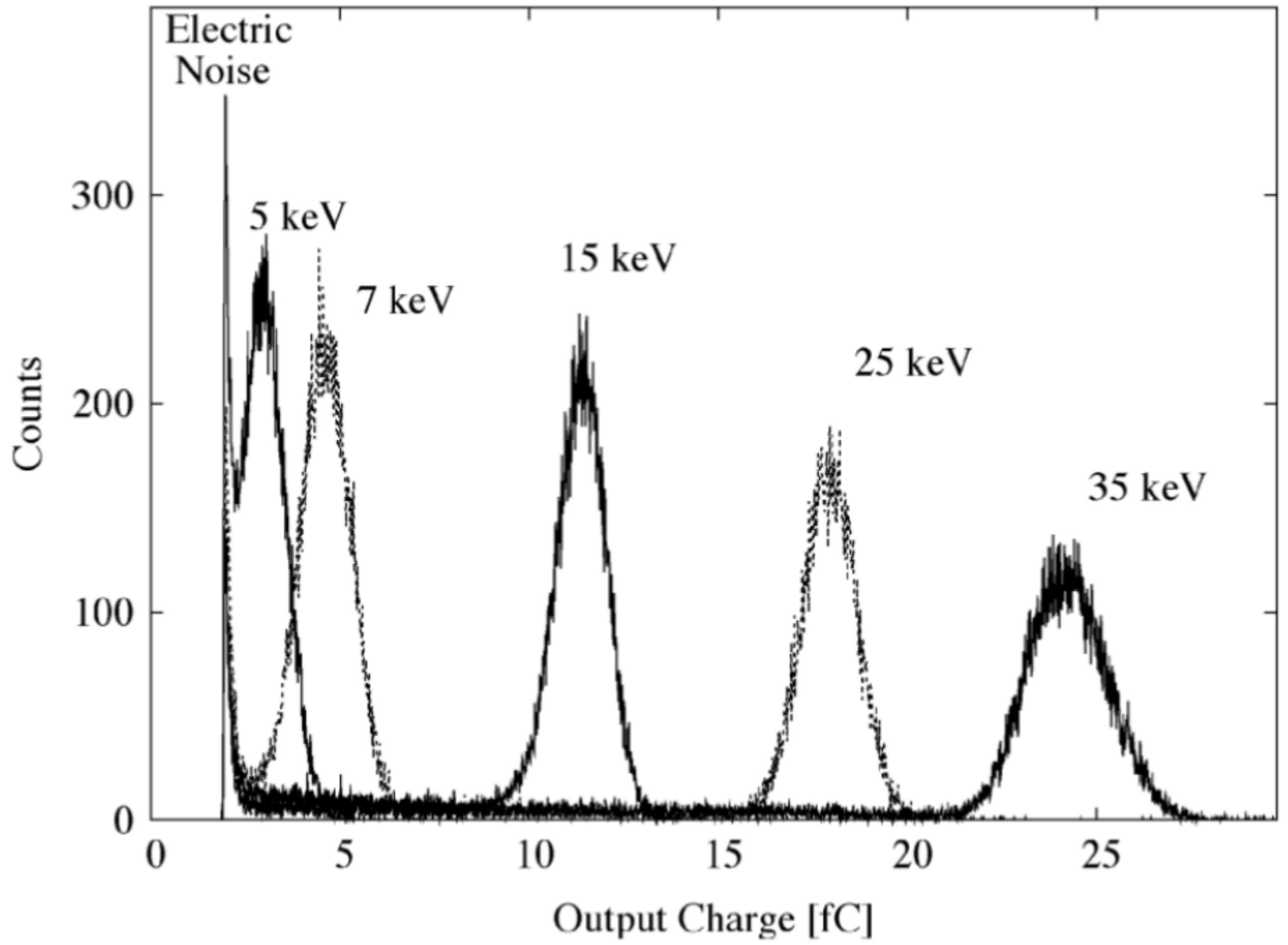
- **Key features**:
  - Electron energy: 30 < E < 1000 eV
  - Energy uncertainty < 0.05 eV
  - Beam spot ~ 0.5 mm
  - Current as low as a few fA
    - ☑ can probe **single electron regime**





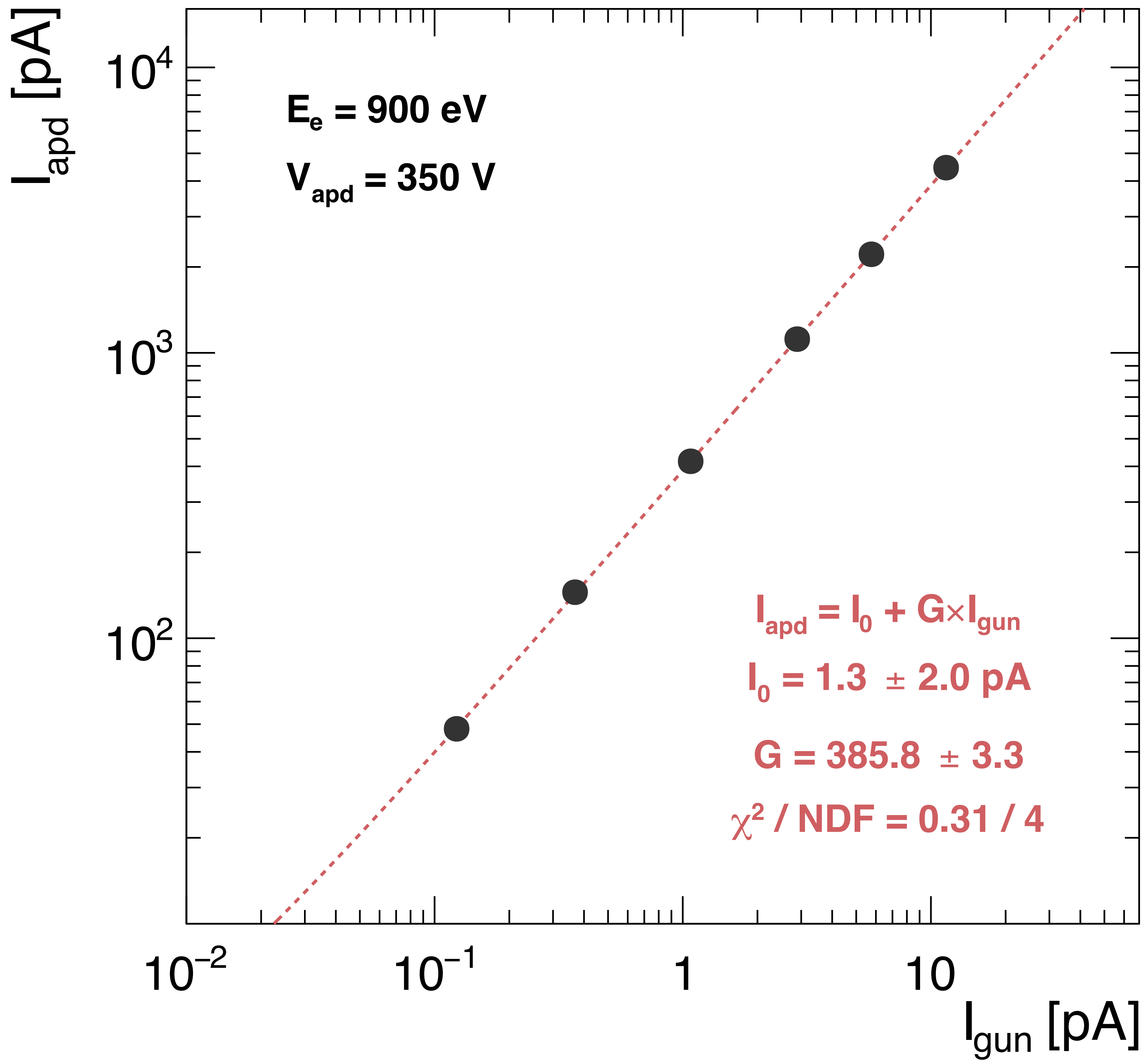
Linearity Between Gun and APD Currents

- Reading APD bias current when shooting gun on it
  - Clear **linear correlation** with gun current
- Not able to see single-electron pulses
  - from literature:
    $E \geq 5$ keV to see single-electron signals with APDs



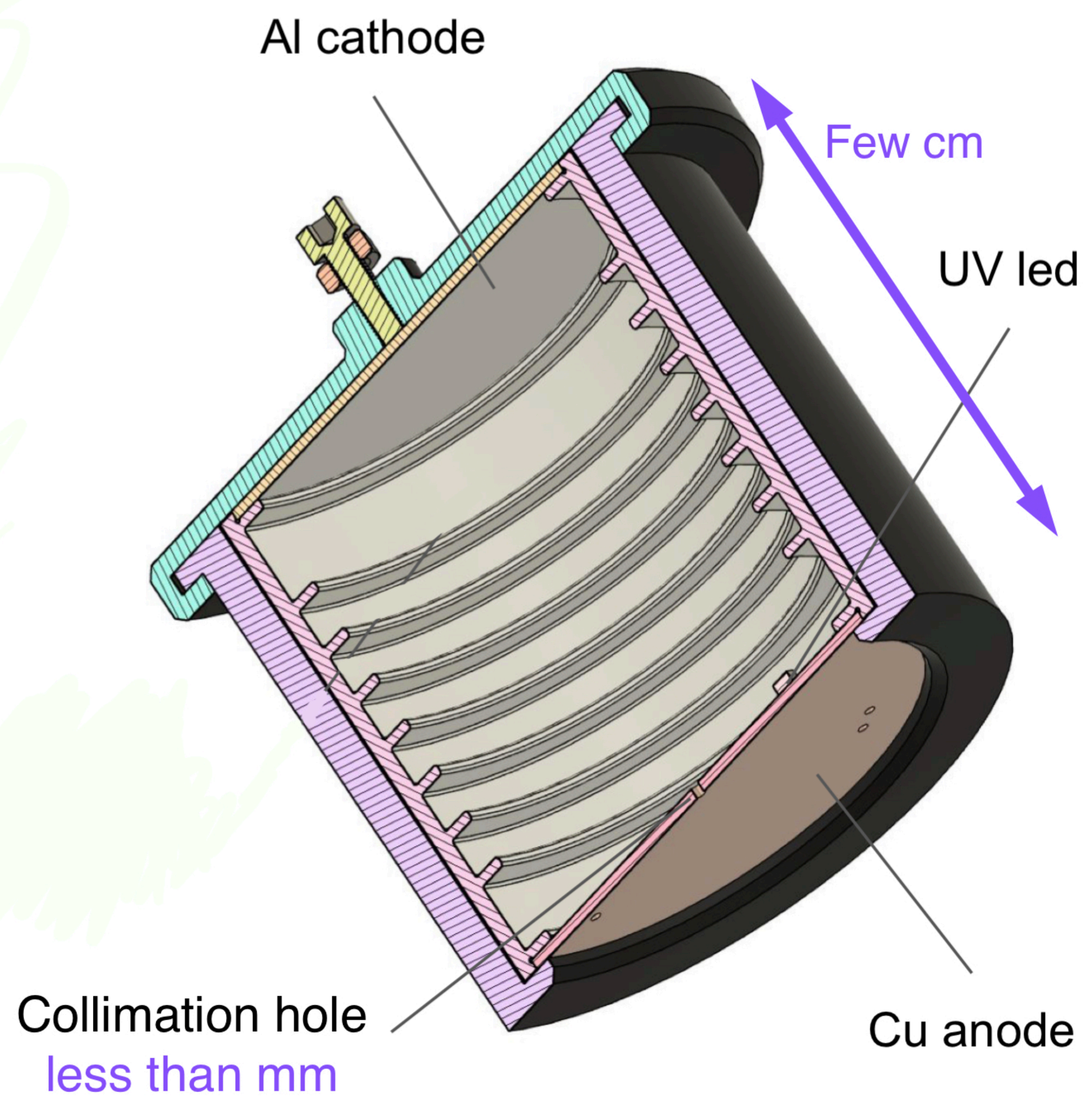
S. Kasahara, et al.,
IEEE Trans. Nucl. Sci. 57 (2010) 1549

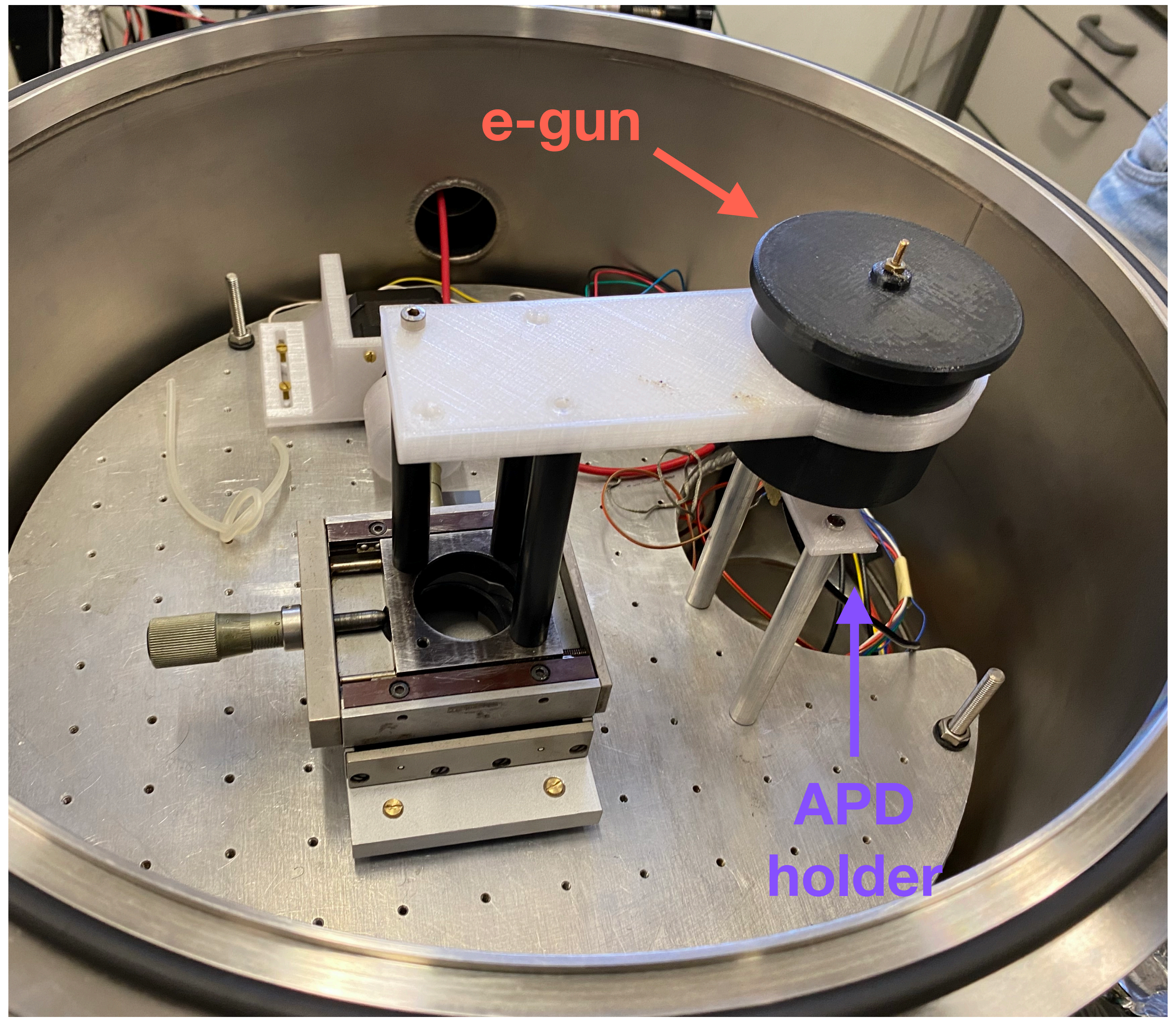
A. Apponi et al 2020 JINST **15** P11015



Electron Gun @ Milano Bicocca

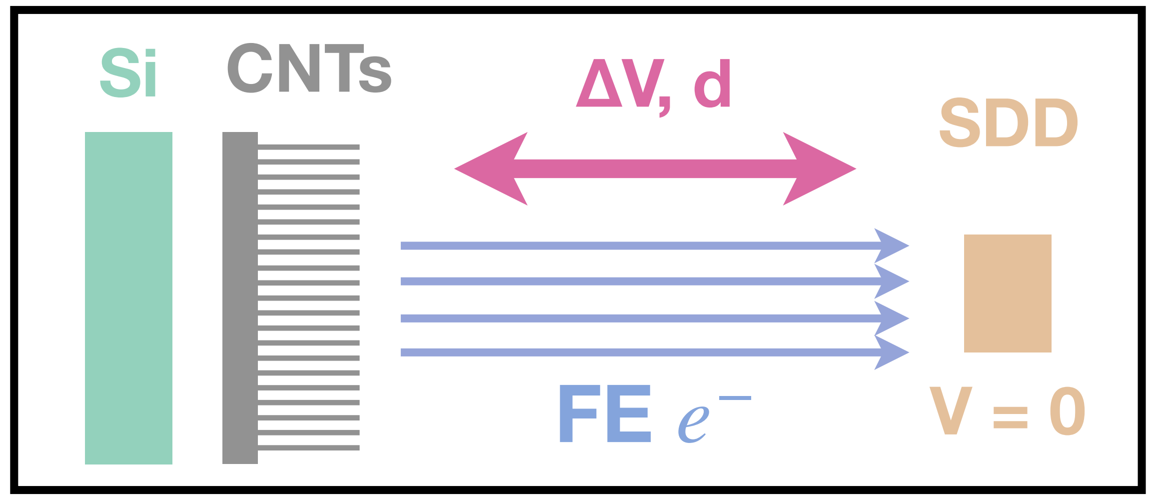
- UV led + metallic electrodes + electric field
- **Key features:**
  - Electron energy: 0 < E < 30 keV
  - Energy uncertainty < 2 eV
  - Beam spot < 1 mm
  - Current as low as a few fA
  - Compact & easy to move
- First measurements on APDs in Jan 2023 → **ongoing analysis** (my thesis work)

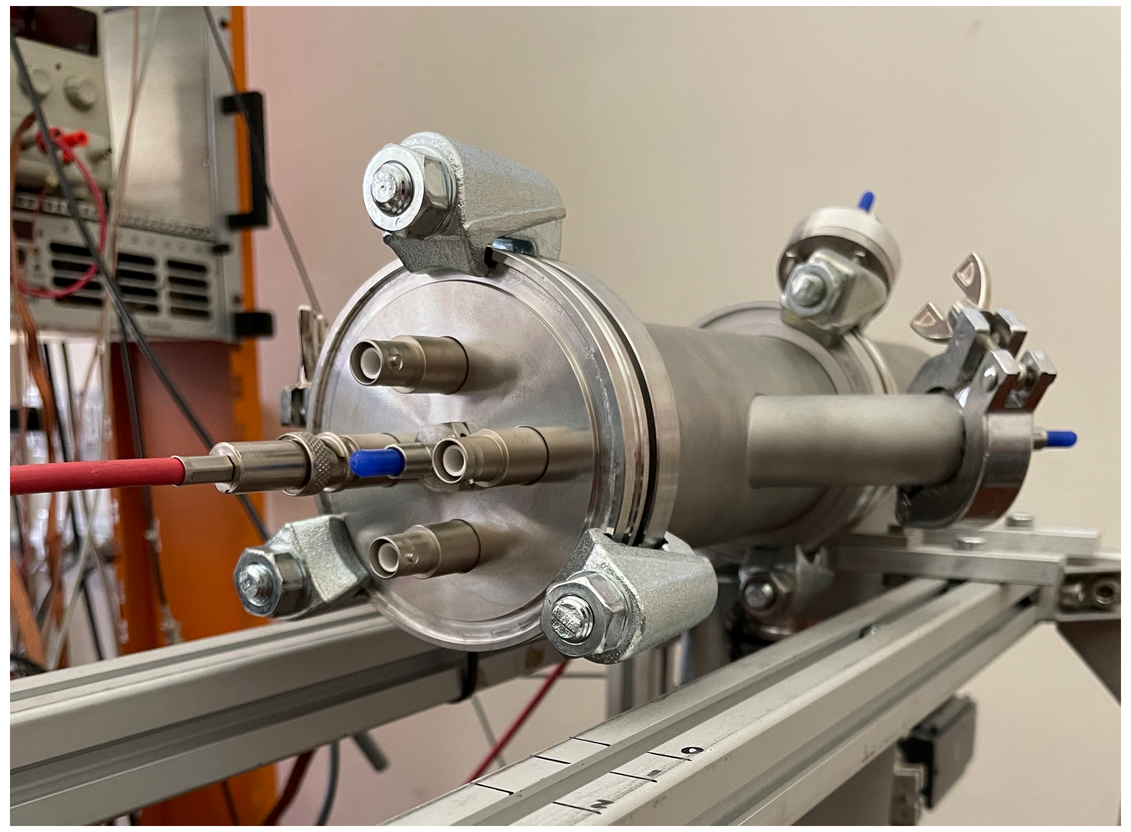




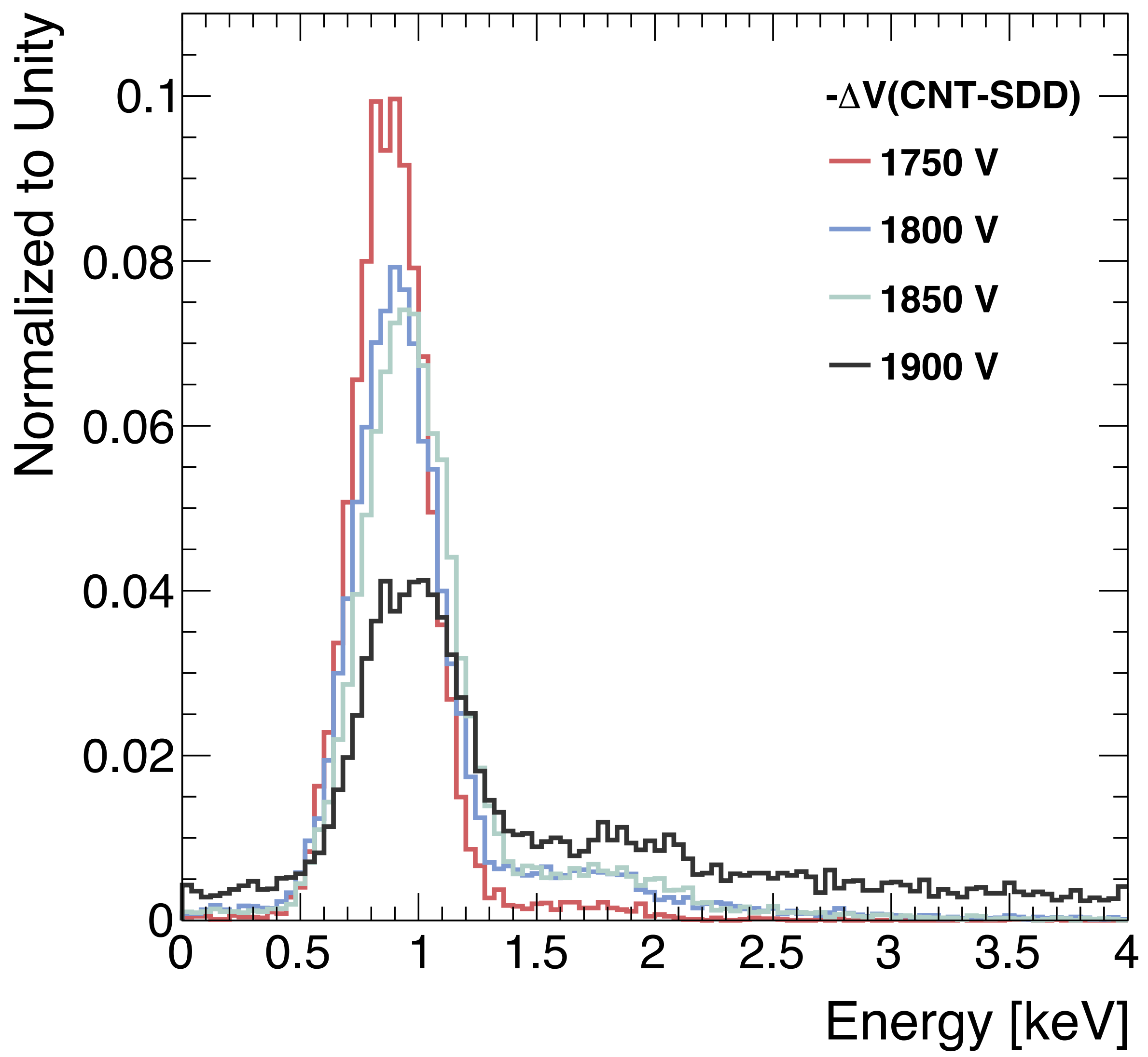
First Dark-PMT Prototype: Hyperion II

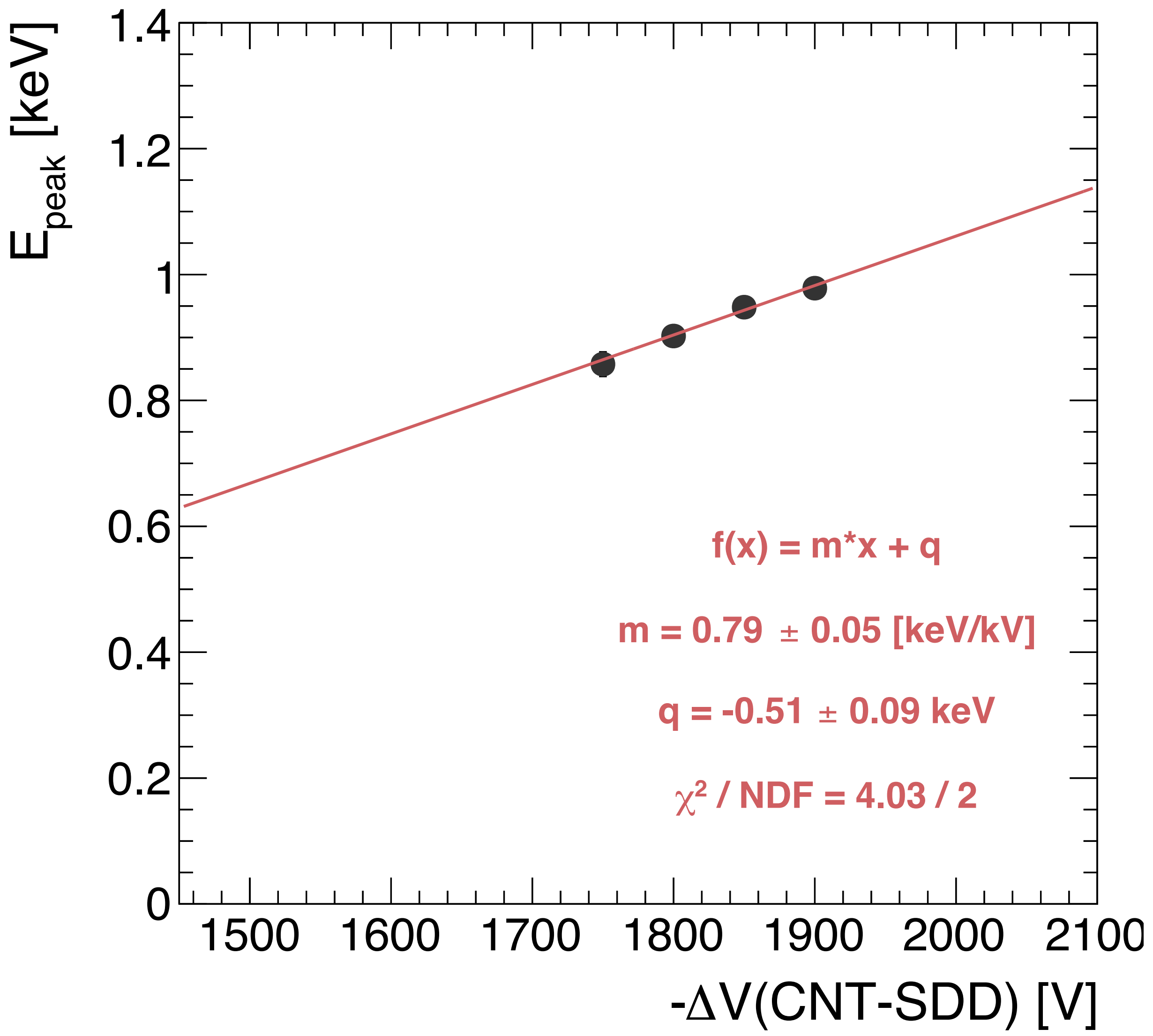
- Prototype-0 already taking data in Rome Sapienza
- Observed **field electron emission** from CNTs





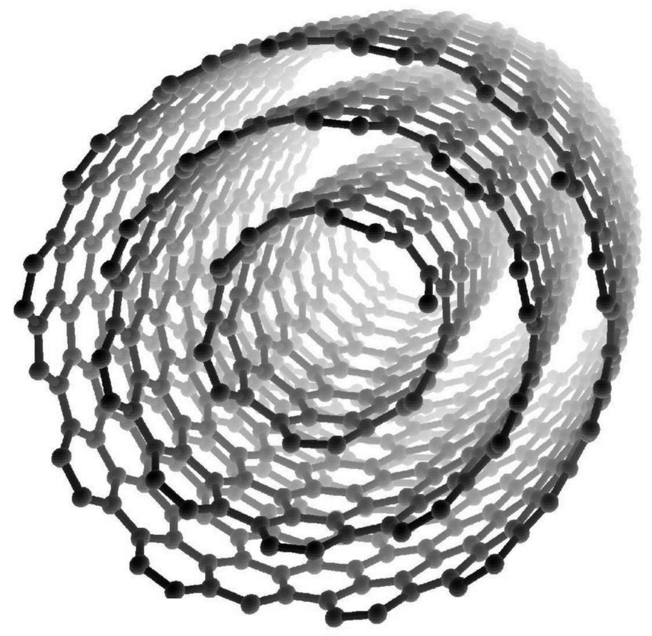
- Measurements with SDD
- For high ΔV / small d(CNT-SDD)
- ~2 keV electrons emitted by CNTs detected



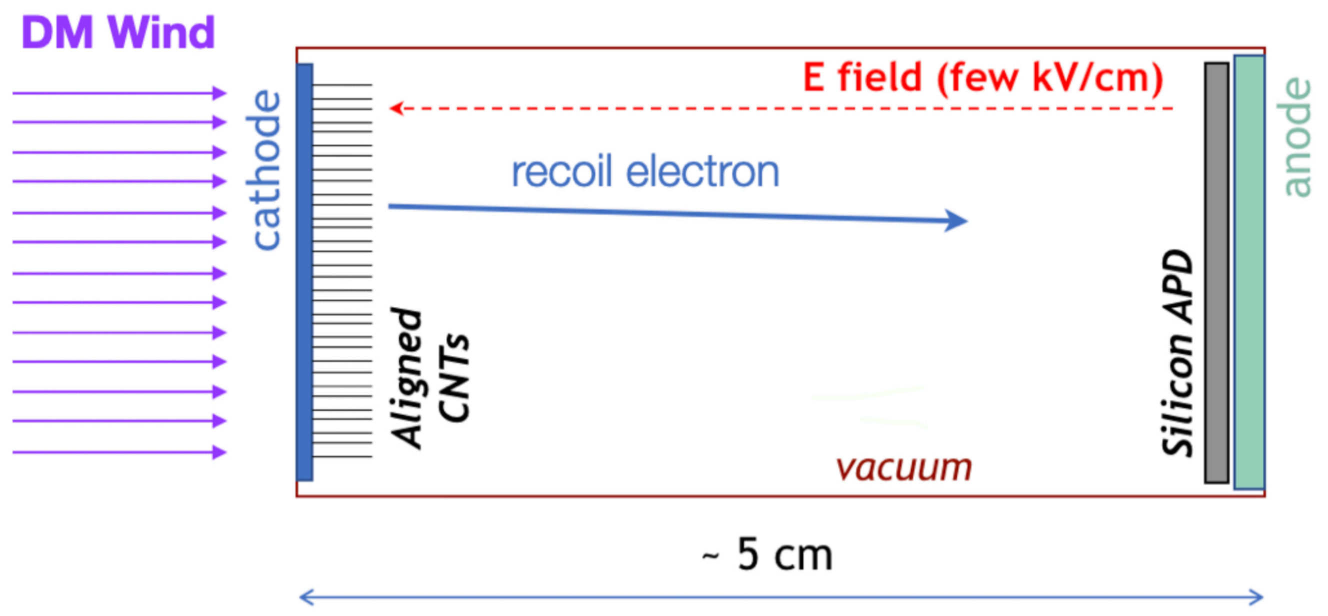


Conclusions

- **Carbon nanotubes:** exciting material for dark matter detectors
  - 2D material: electrons ejected directly into vacuum
  - density anisotropy



- **Dark-PMT:** a new dark matter detector concept
  - Portable, no thermal noise, directional sensitivity
  - Competitive with just 1 g target



- **ANDROMeDa:** a young and ambitious program in Rome
  - Aiming to build first working Dark-PMT prototype by 2025

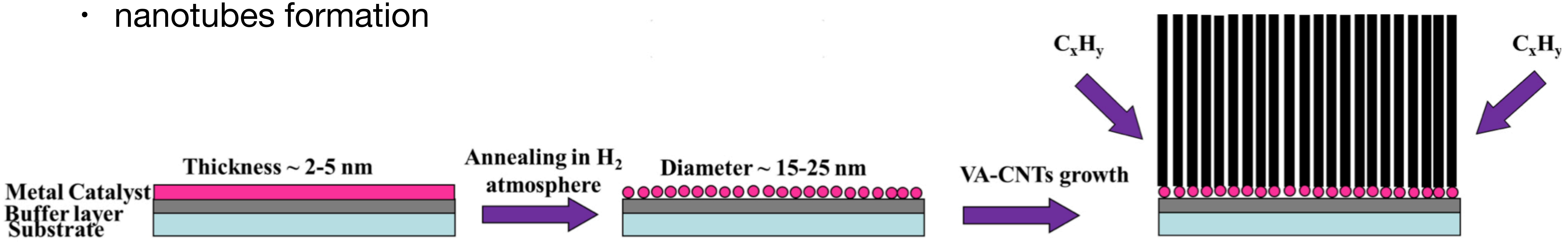
ANDROMeDA
Aligned Nanotube Detector for Research On MeV Darkmatter

Backup Slides

CVD: How Does It Works?

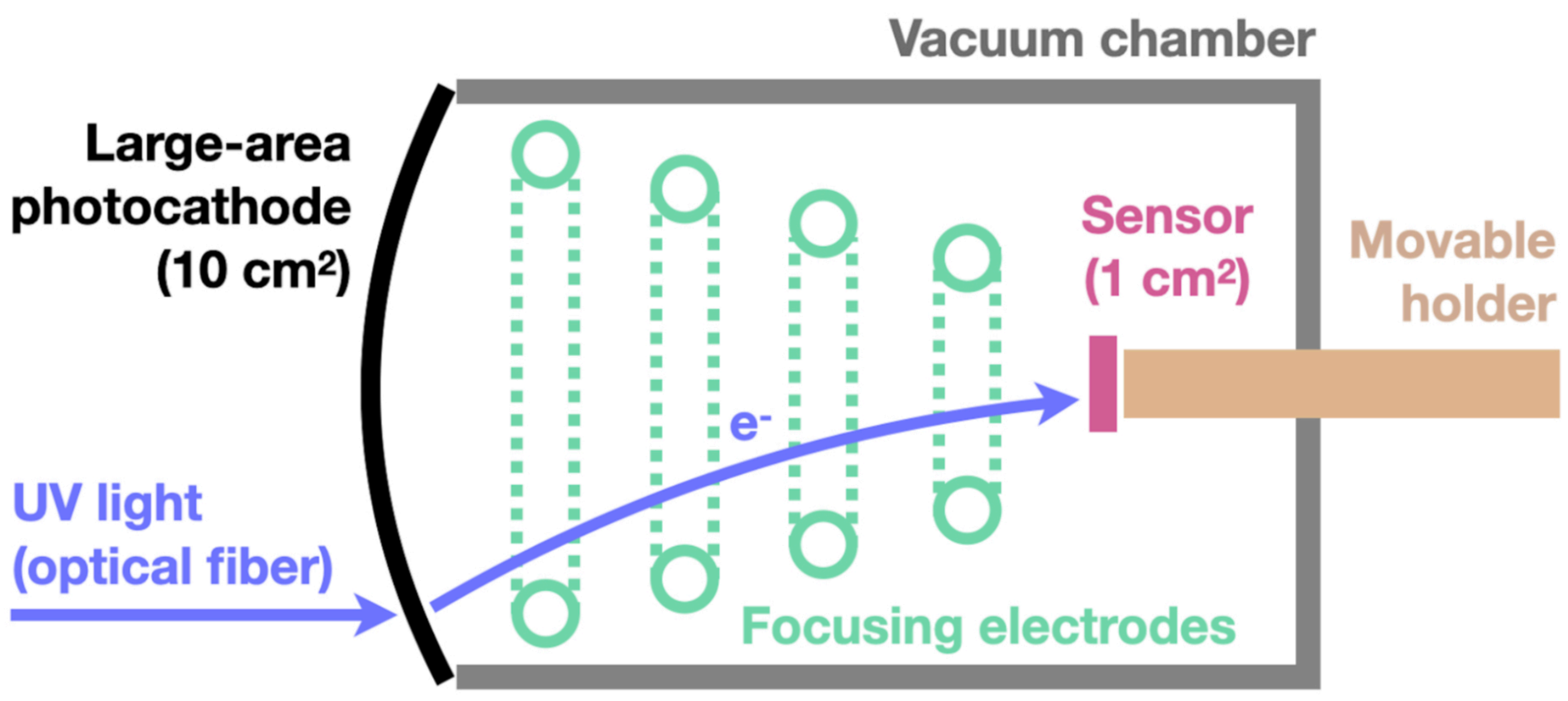
Main Steps:

1. metallic nanolayer (e.g. iron) deposited on the substrate
2. annealing at high temperature
   - nanolayer forms nanoparticles = catalyst seeds during synthesis
3. Carbon precursor gas (e.g. acetylene) oriented on nanoparticles at high temperature
   - nanotubes formation



From 10 cm^2 Cathode to 1 cm^2 Sensor

- To reach 1 g target with 100 dark-PMTs → 10 cm^2 cathodes
- Large Area Silicon Detectors → 1 cm^2 sensors



▷ 10:1 **electron focusing system** needed

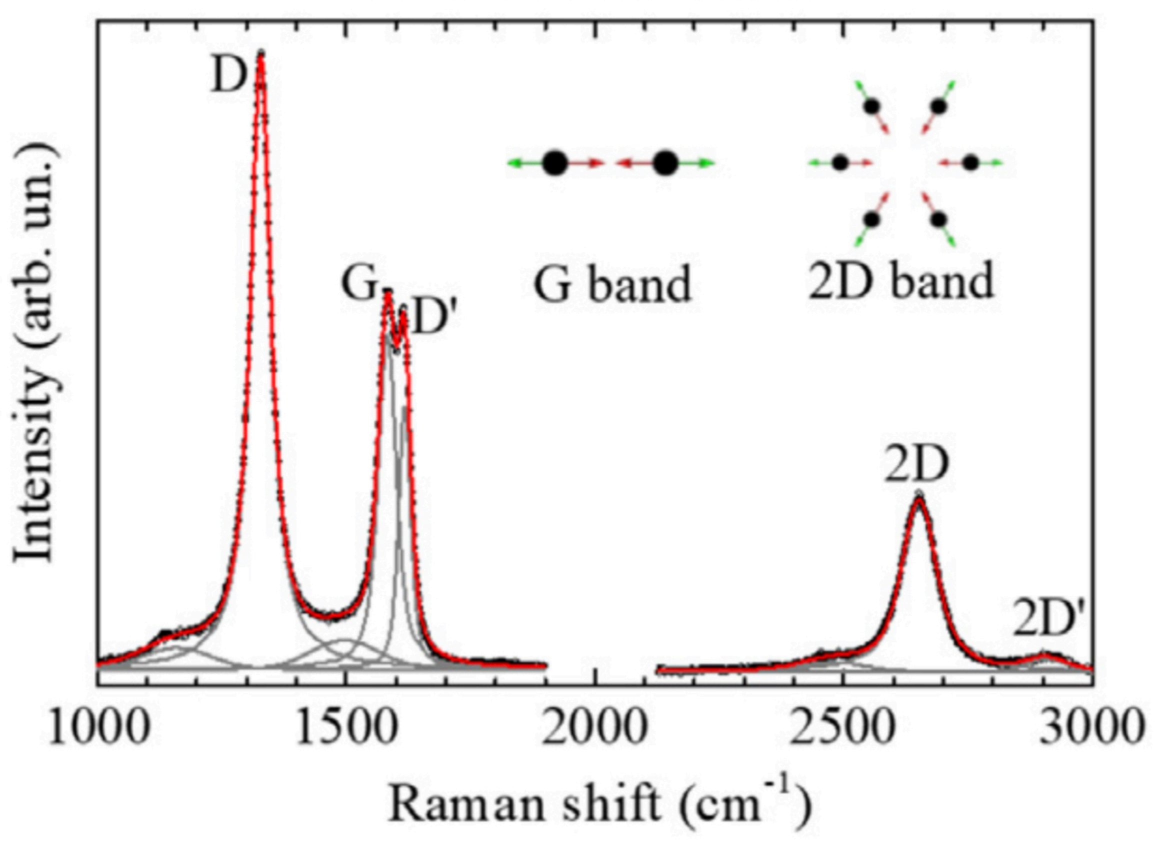
▷ Key parameter: **focusing efficiency**

- computed as $\dfrac{\#\ e^-\ detected}{\#\ e^-\ from\ cathode}$
- aim for efficiency **> 90%**
- can be optimised using UV light + standard photocathode

ONGOING:
Electron trajectories simulations with SIMION software

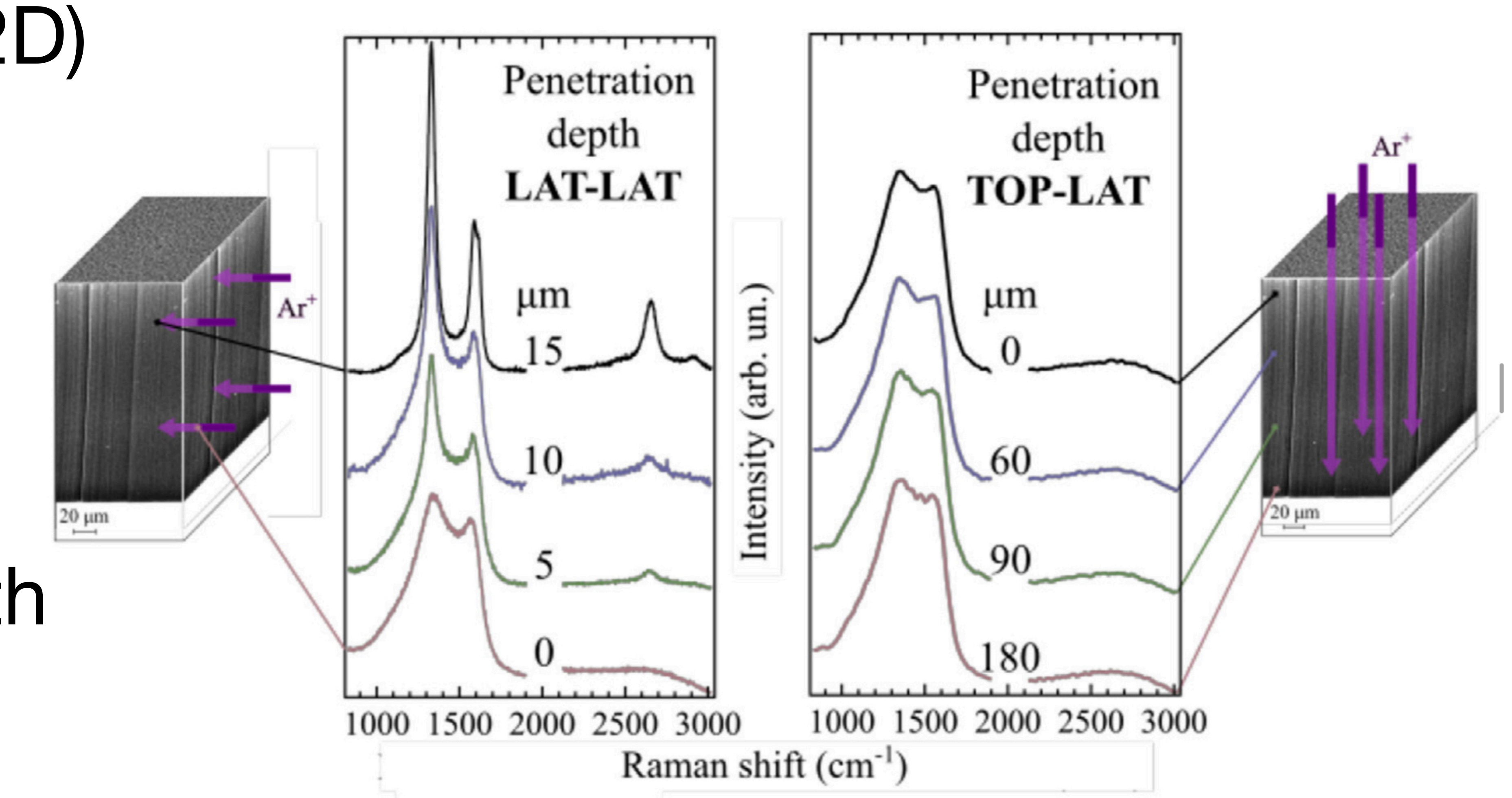
Going Into Detail on Raman Spectroscopy

- **Raman Spectroscopy** used to determine vibrational modes
  - can assets quality of chemical bondings
  - can be focused at various depth and coordinates of the sample

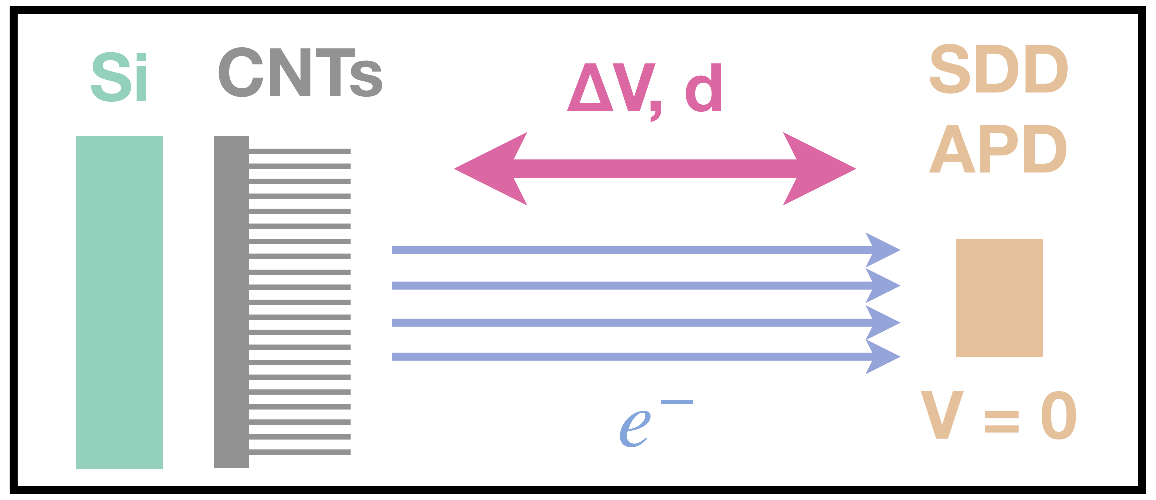


- on pristine sample:
  - excitation of vibrational modes of the carbon lattice (G and 2D)
  - prominent 'defect' (D) peak

- after Ar ions bombardment (5 keV at 1.5 x 10^{17} ions/cm^2)
  - LATERAL: Raman spectrum unchanged at 15 μm lateral depth
  - TOP: amorphization from at any height



Electron Detection: Main Challenges

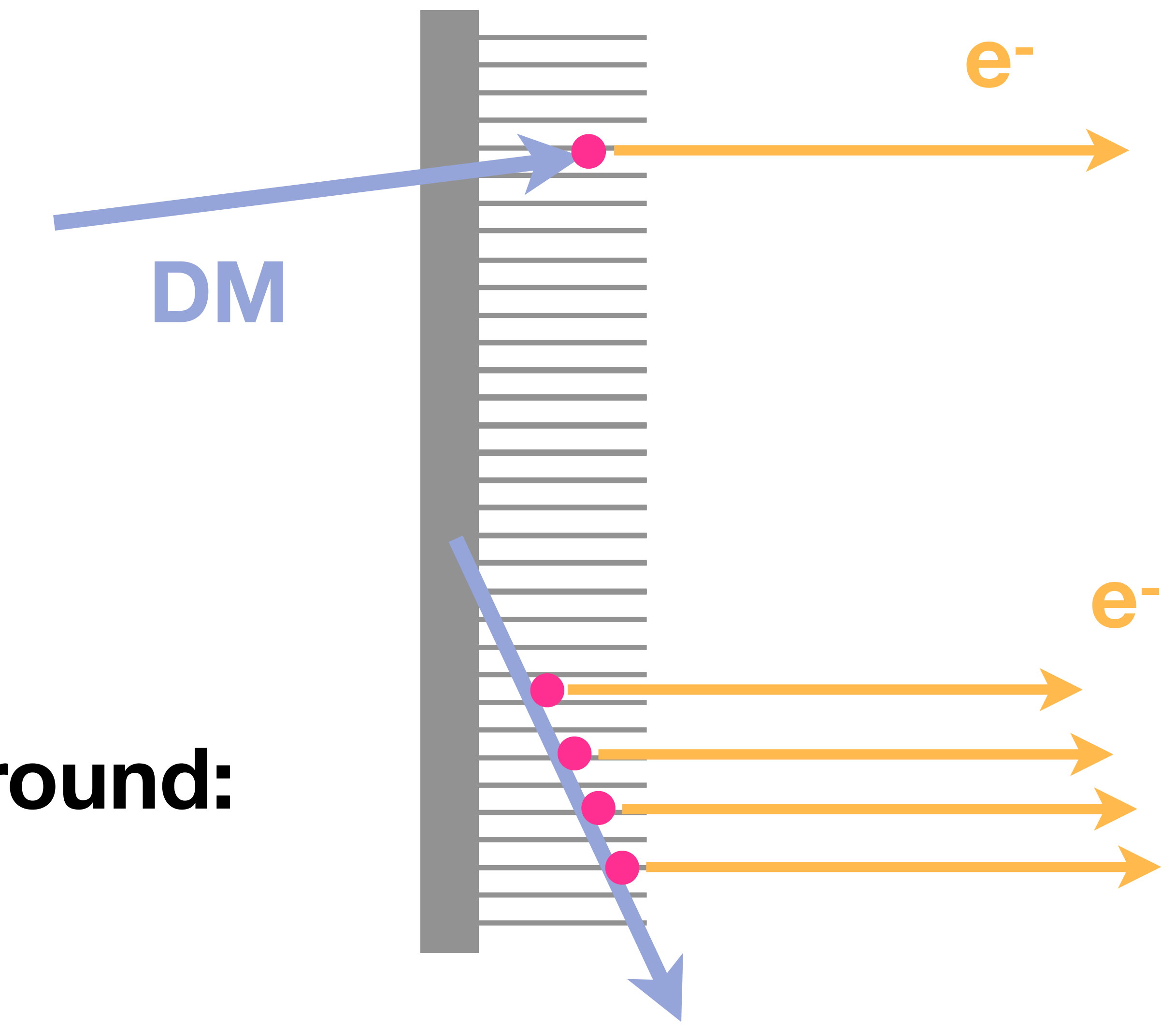


- Electron energy = ΔV(anode-cathode) to keep < 10kV

- **Key parameters :**

1. **compactness** to have a portable dark-PMT detector;
2. high (>90%) **efficiency** on single e^- detection in keV energy range;
3. percent-level **discrimination** between $1e^-$ and $2e^-$ events
4. **suppression** at permil level of fake single e^- signals due to noise

signal:

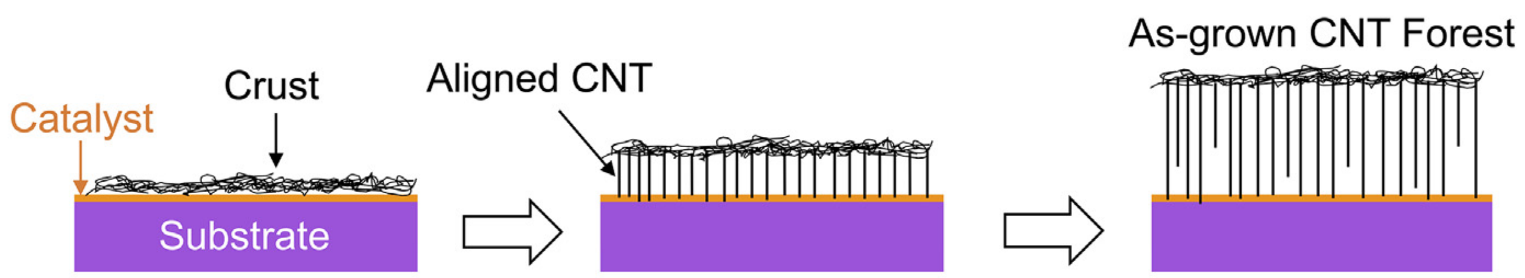


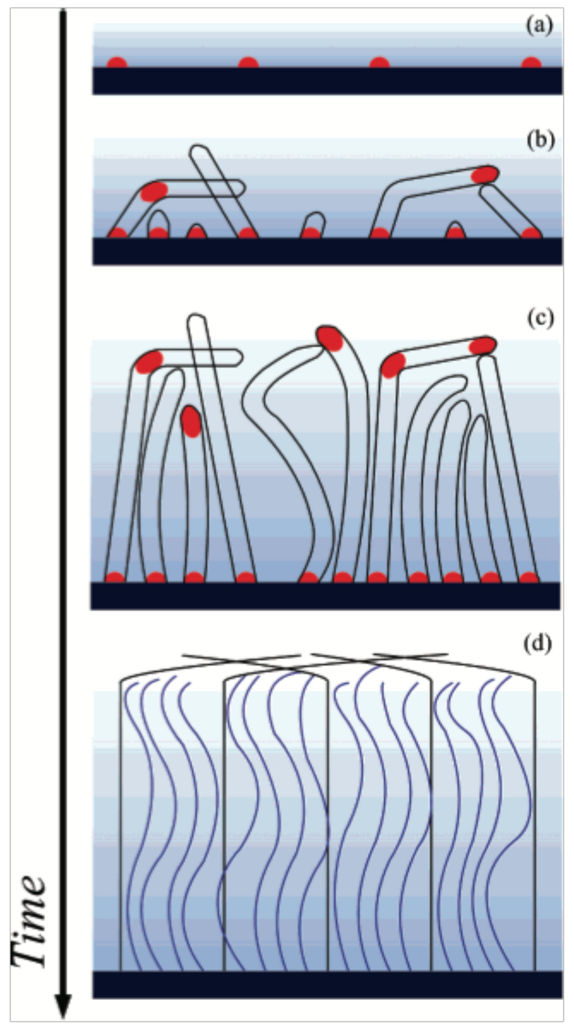
background:

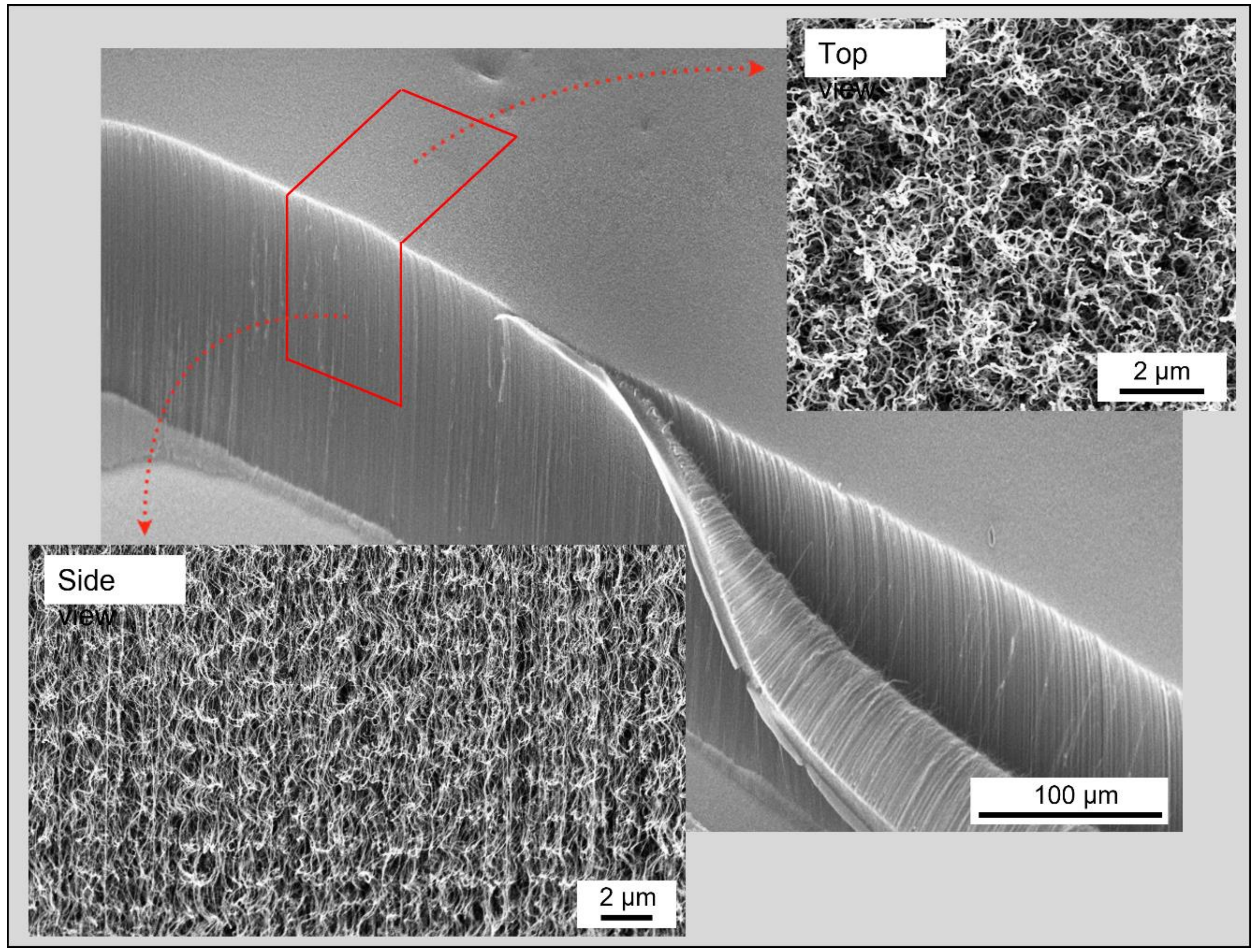
Unwanted Features of Carbon Nanotubes

- Two **problems** with as-grown nanotubes forests:

    1. non-aligned **top crust** layer
        - due to initial growth instabilities
    2. side **waviness** at the nanoscale
        - due to different growth rates



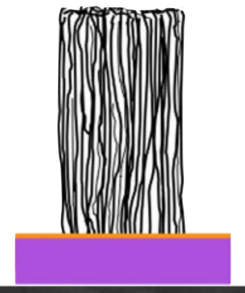




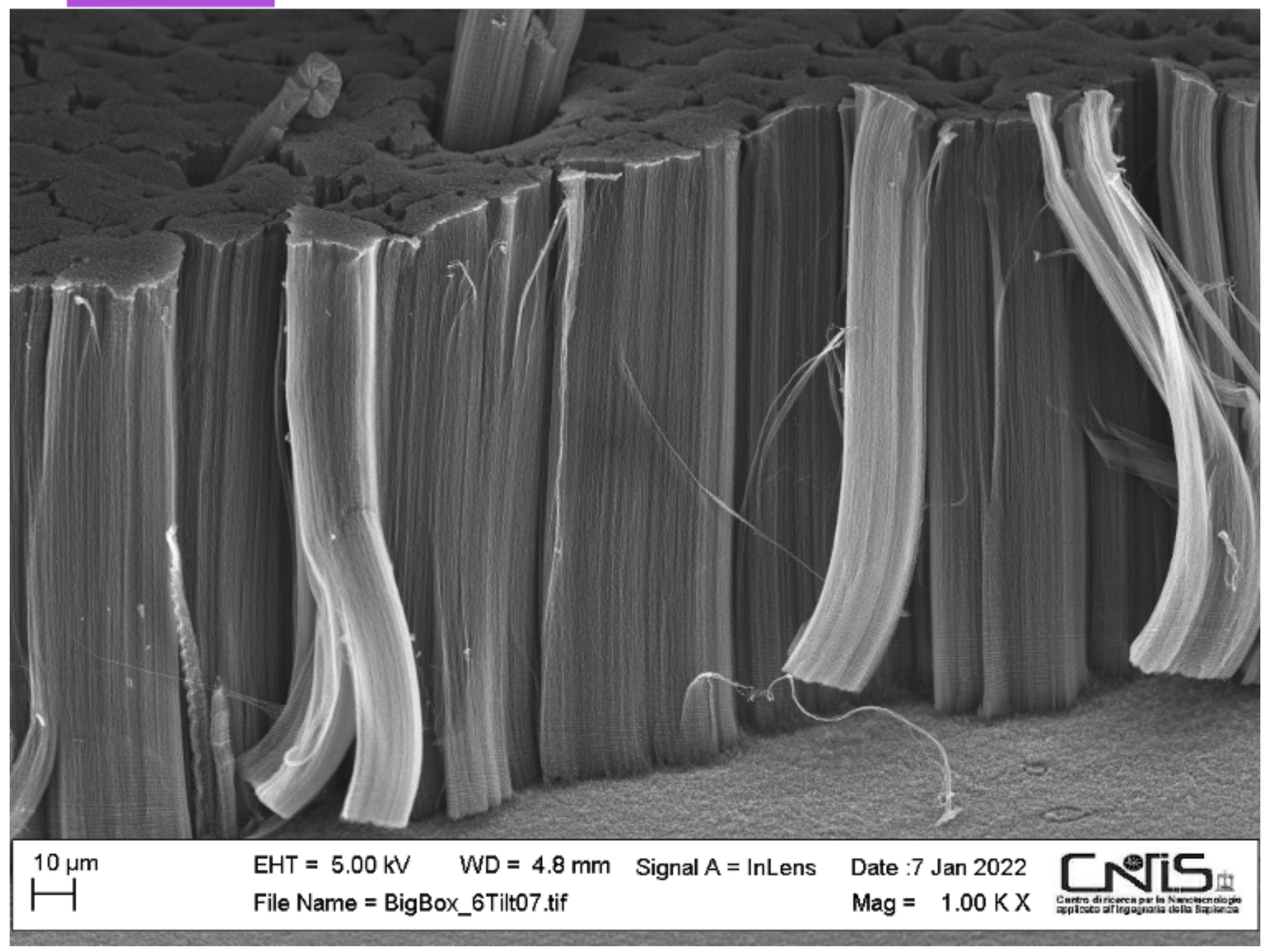
- Both hamper electron transmission
    - **minimisation** needed for ideal DM target

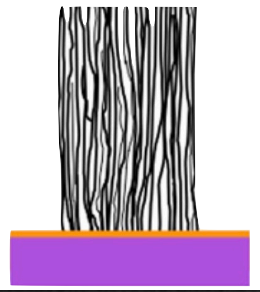
Plasma Etching to Remove Crust

- **Optimisation** of Ar_2/O_2-plasma etching parameters (e.g. time, plasma power, frequency, pressure)
  - measuring morphology (SEM), roughness (AFM) and electron emission

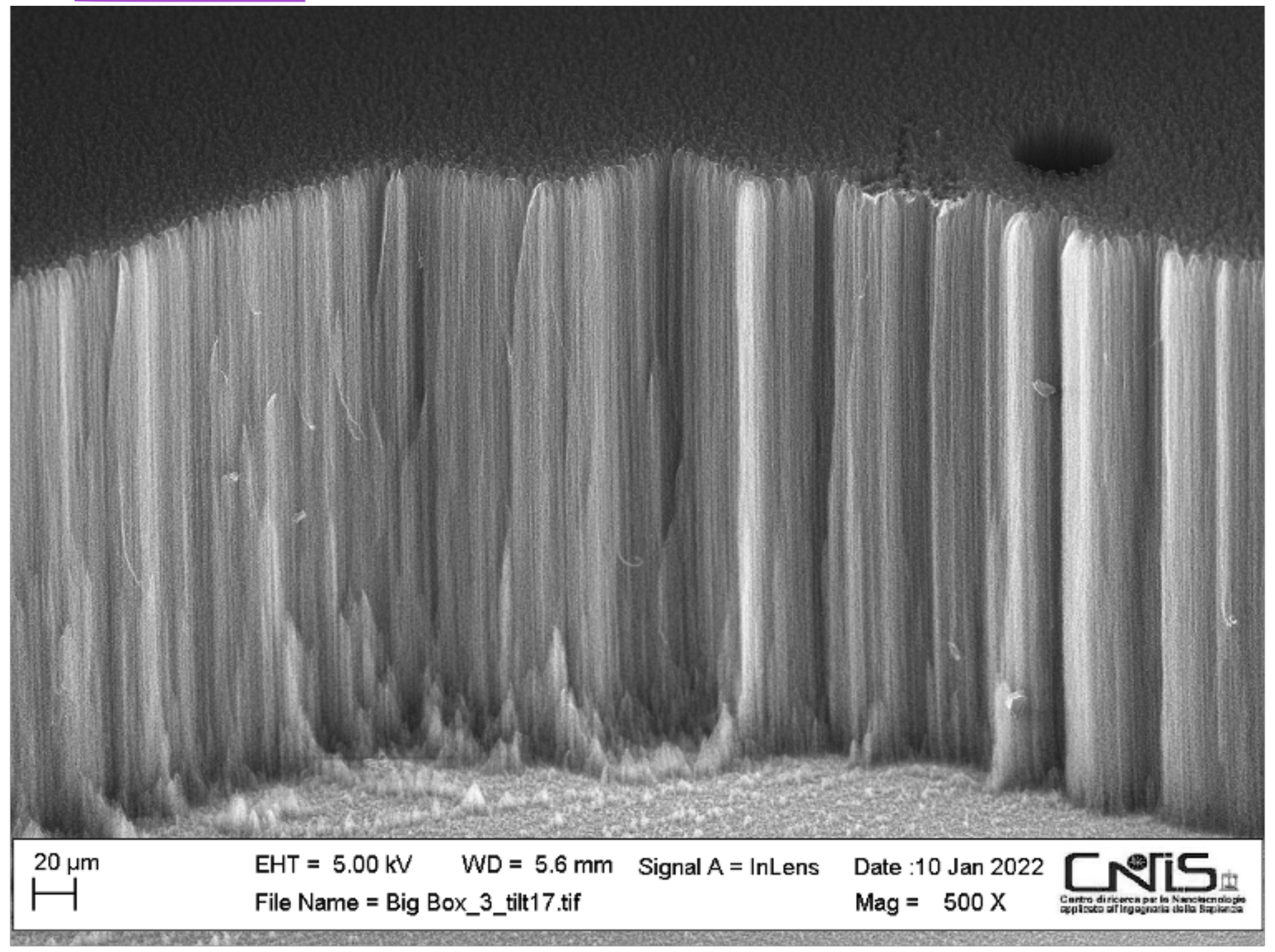


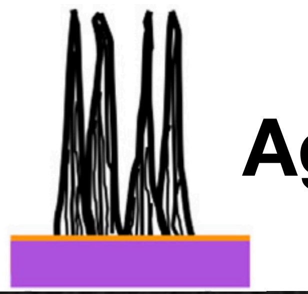
Light etching (35 W)



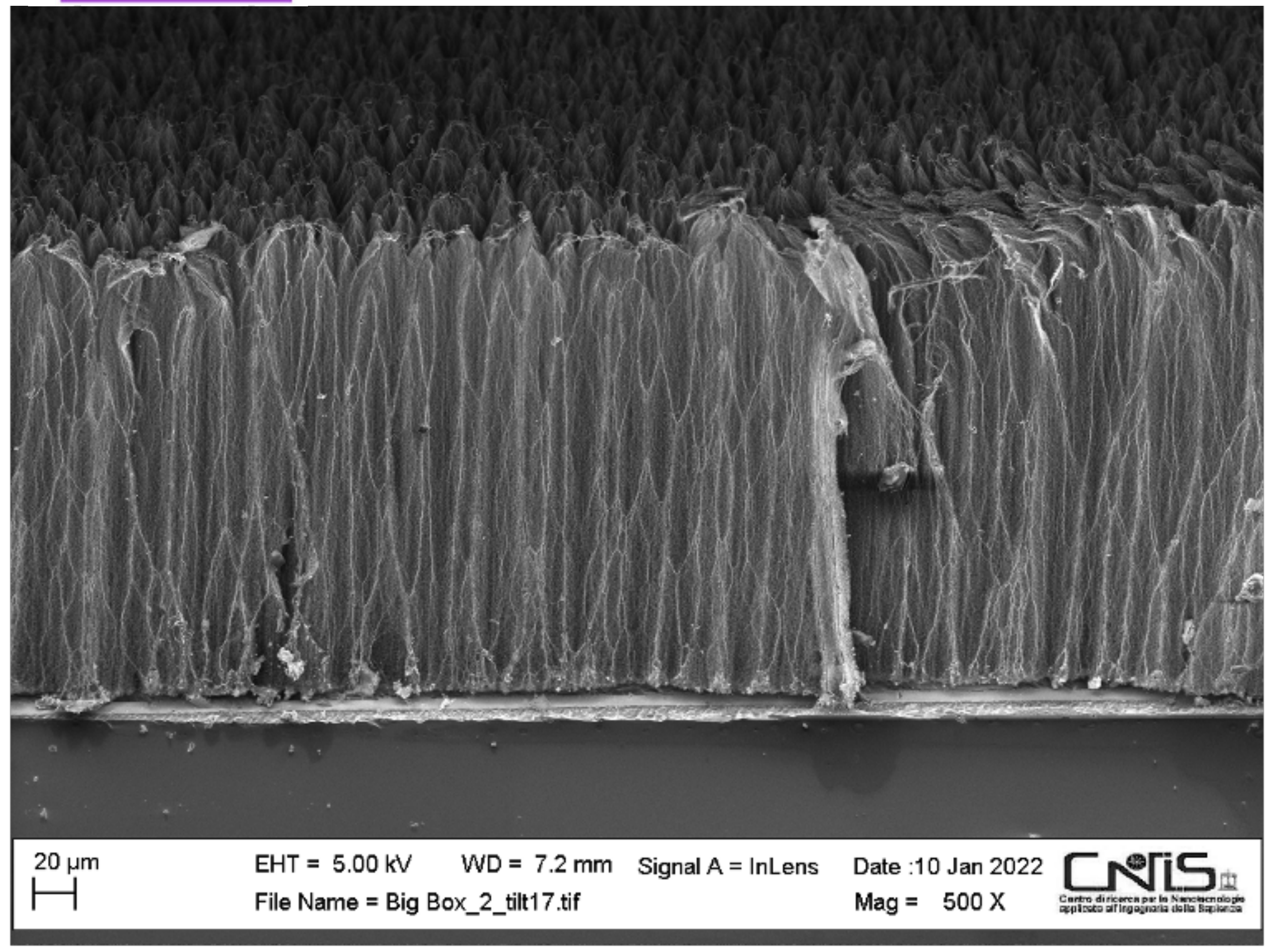


Modest etching (50 W)





Aggressive etching (80 W)



Aiming for Ultimate Parallelism at the Nanoscale

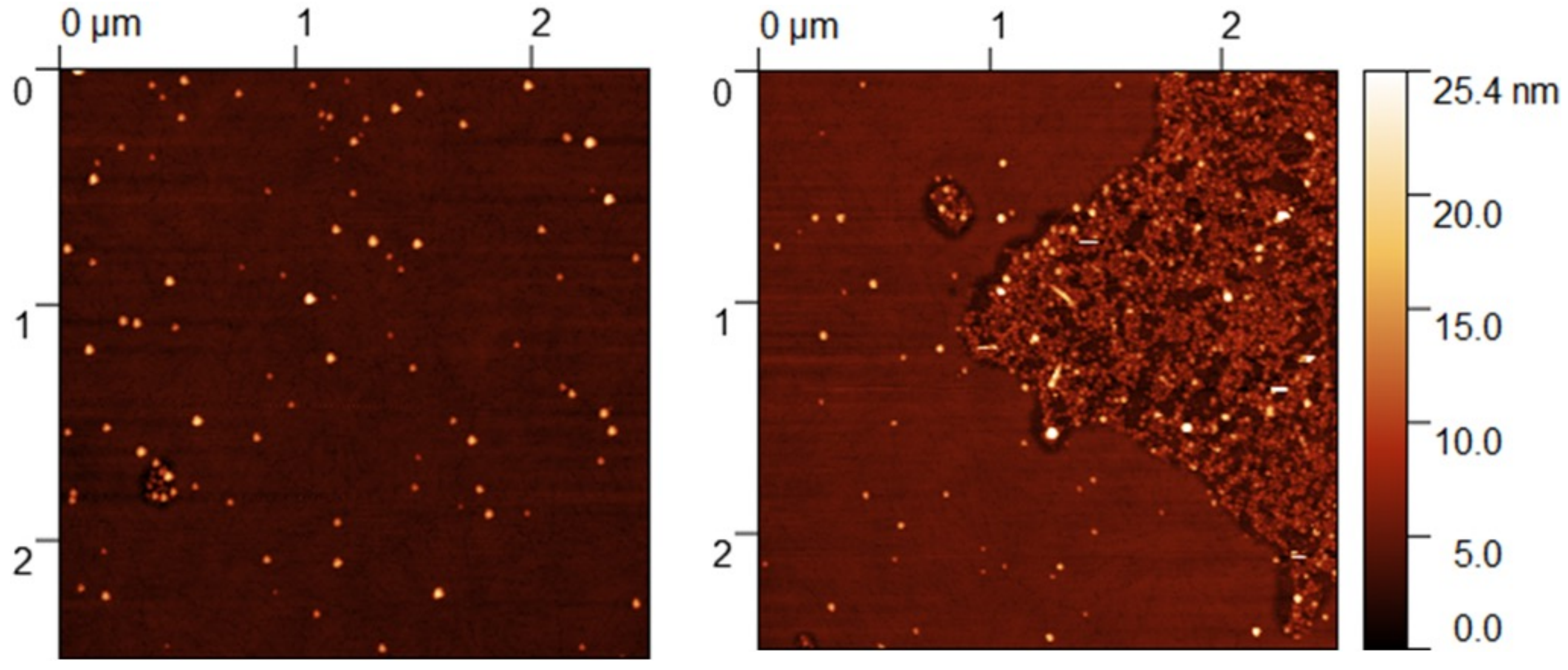
- Parallelism strongly influenced by iron **catalyst seeds**

  1. **non-uniformity** in seeds size
     - leads to different growth rates
  2. **density** of seeds
     - farer seeds = weaker interaction between tubes

- Evaporation chamber being built in Rome

  - aim for seed density > 10^{12} cm^{-2}
  - **AFM** to check seeds size, density and distribution
  - **iterative optimisation** of nucleation parameters

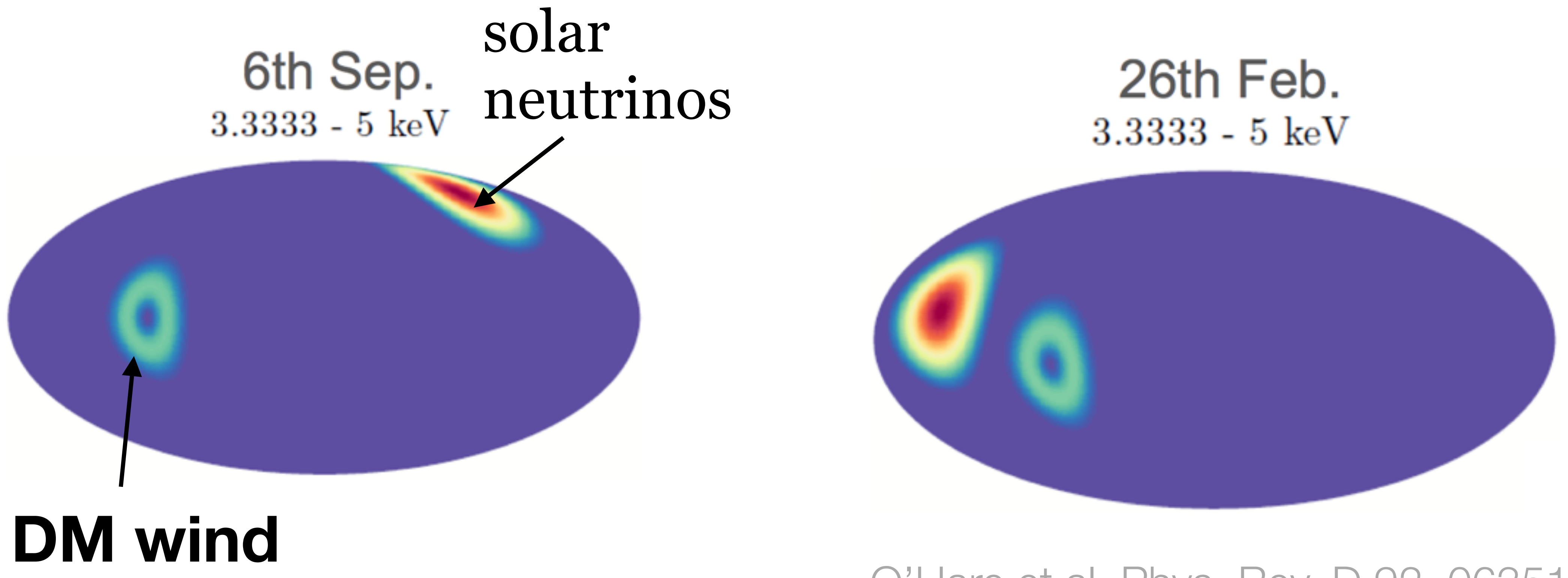
AFM scans



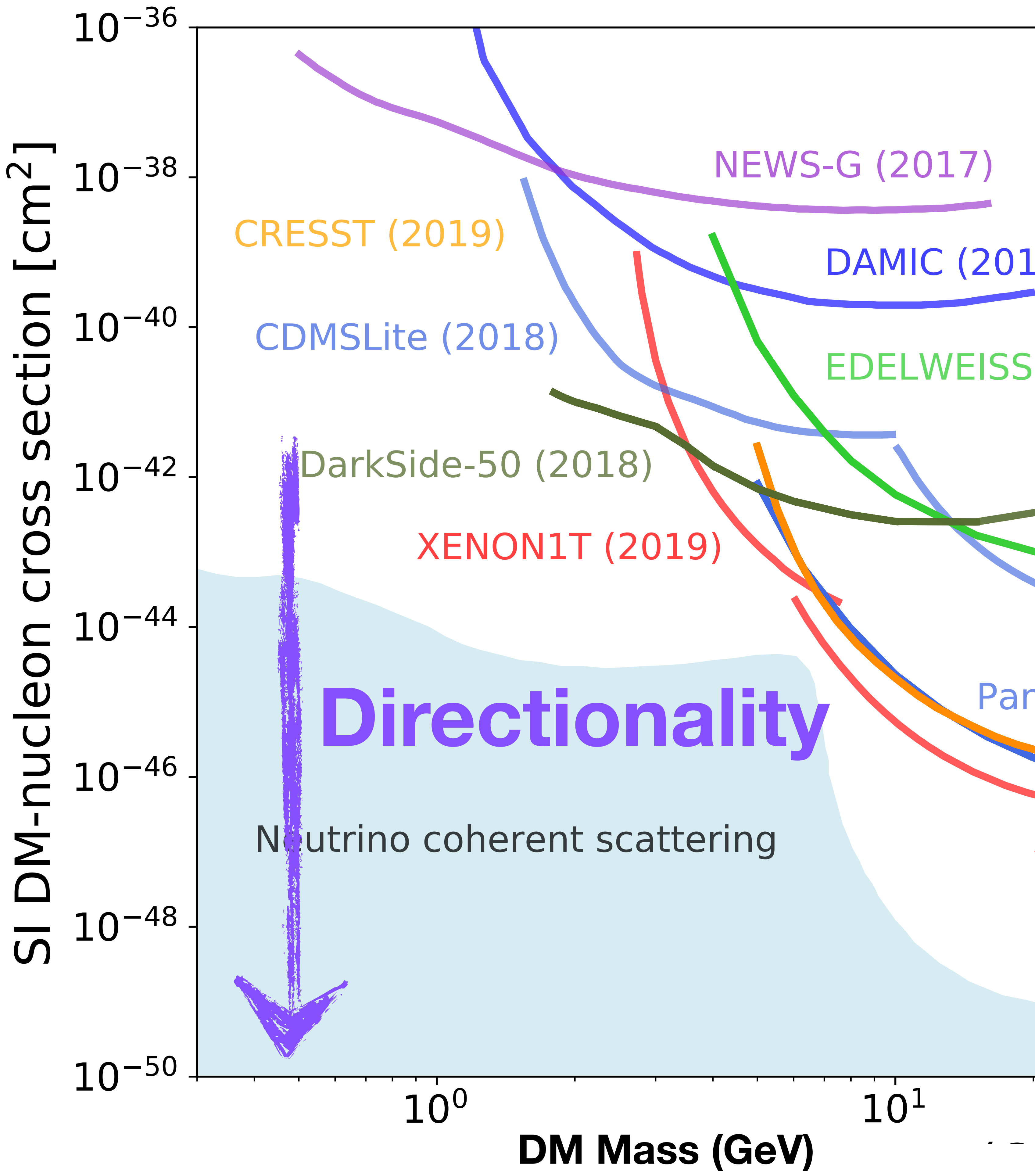
	Now	Goal
seeds density [cm^{-2}]	10^{10}-10^{11}	> 10^{12}
seeds size [nm]	15-30	5 (±20%)

Avoiding Neutrino Background with Directionality

- **Directionality**: link a signal with region of the sky
  - DM ‘wind’ expected to come from Cygnus constellation
- But also to be **insensitive to neutrino floor**
  - Low mass neutrino floor mostly from solar neutrinos
  - Cygnus **never overlaps** with Sun



O’Hare et al, Phys. Rev. D 92, 063518 (2015)



World-Leading Sensitivity Below 30 MeV?

- **Competitive** with other light DM searches
  - with just 1 year exposure
  - using 1 kg target

- In principle **sensitive to few MeV DM**
  - **extend search** below 30 MeV
  - using just 1 g target

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