The Dark-PMT

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

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ANDROMeDa

Aligned **N**anotube **D**etector for **R**esearch **O**n **M**e**V** **Da**rkmatter

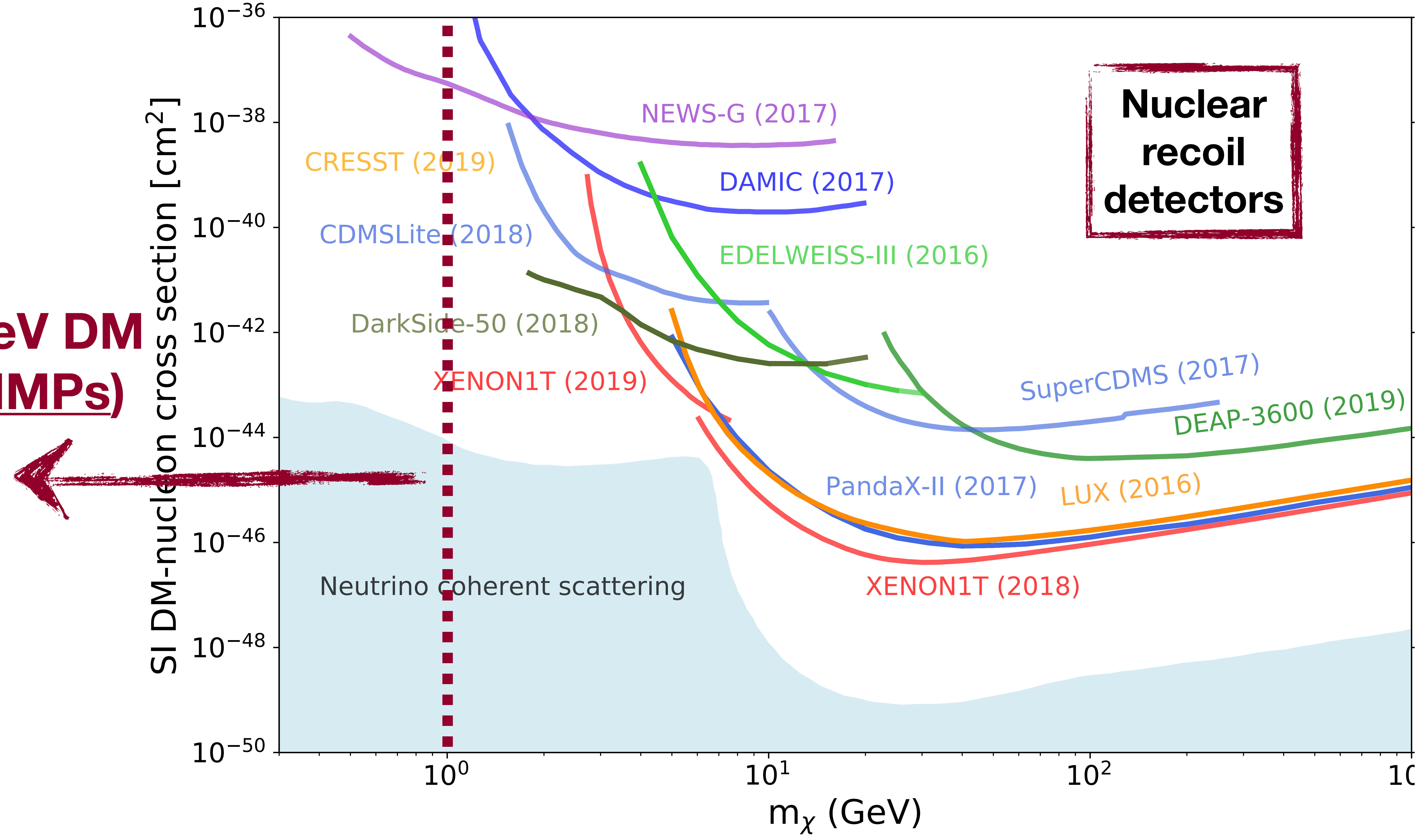
Istituto Nazionale di Fisica Nucleare

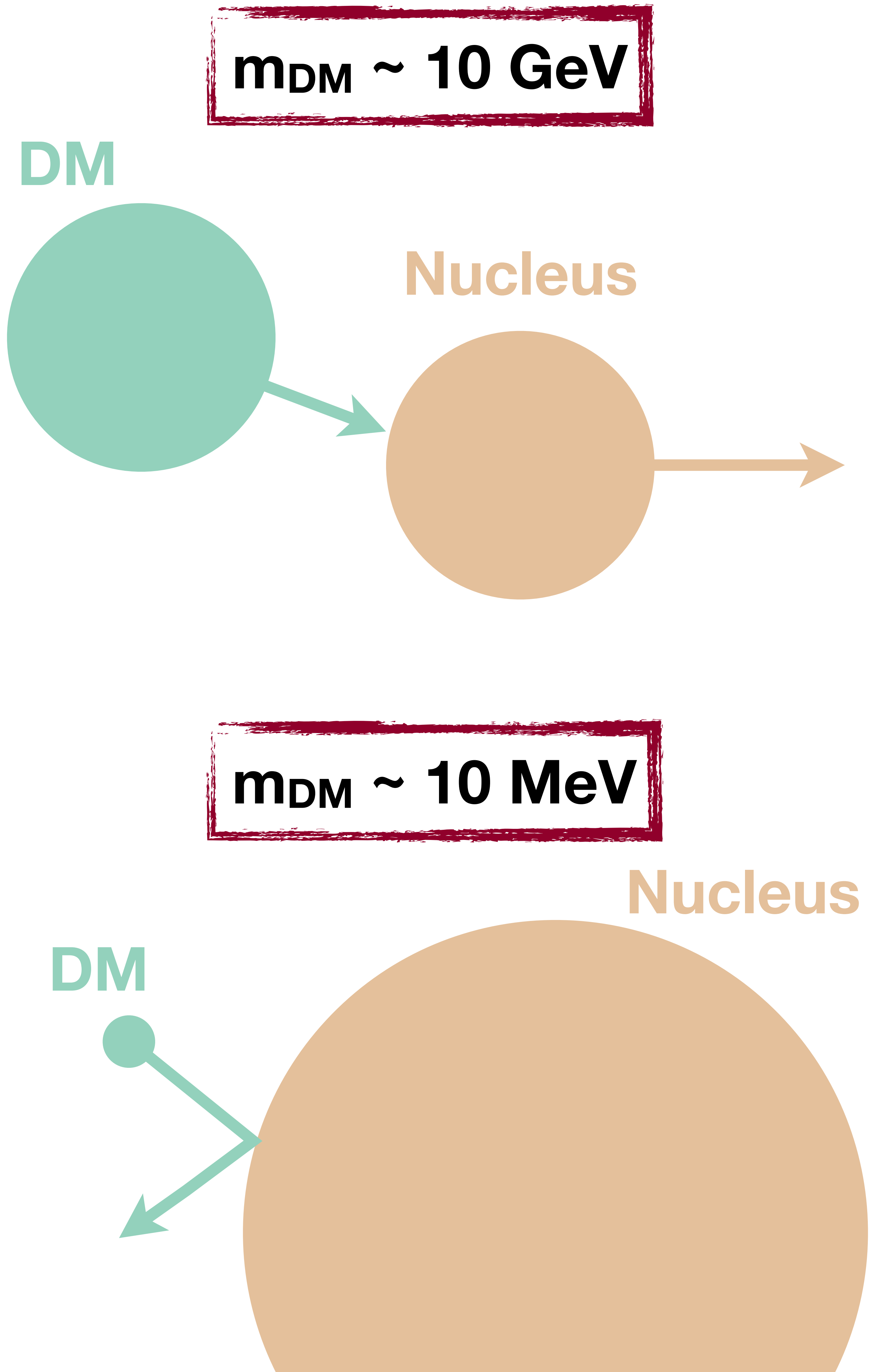
ROMA TRE UNIVERSITÀ DEGLI STUDI

15^{th} Pisa Meeting on Advanced Detectors, La Biodola, 26.05.2022

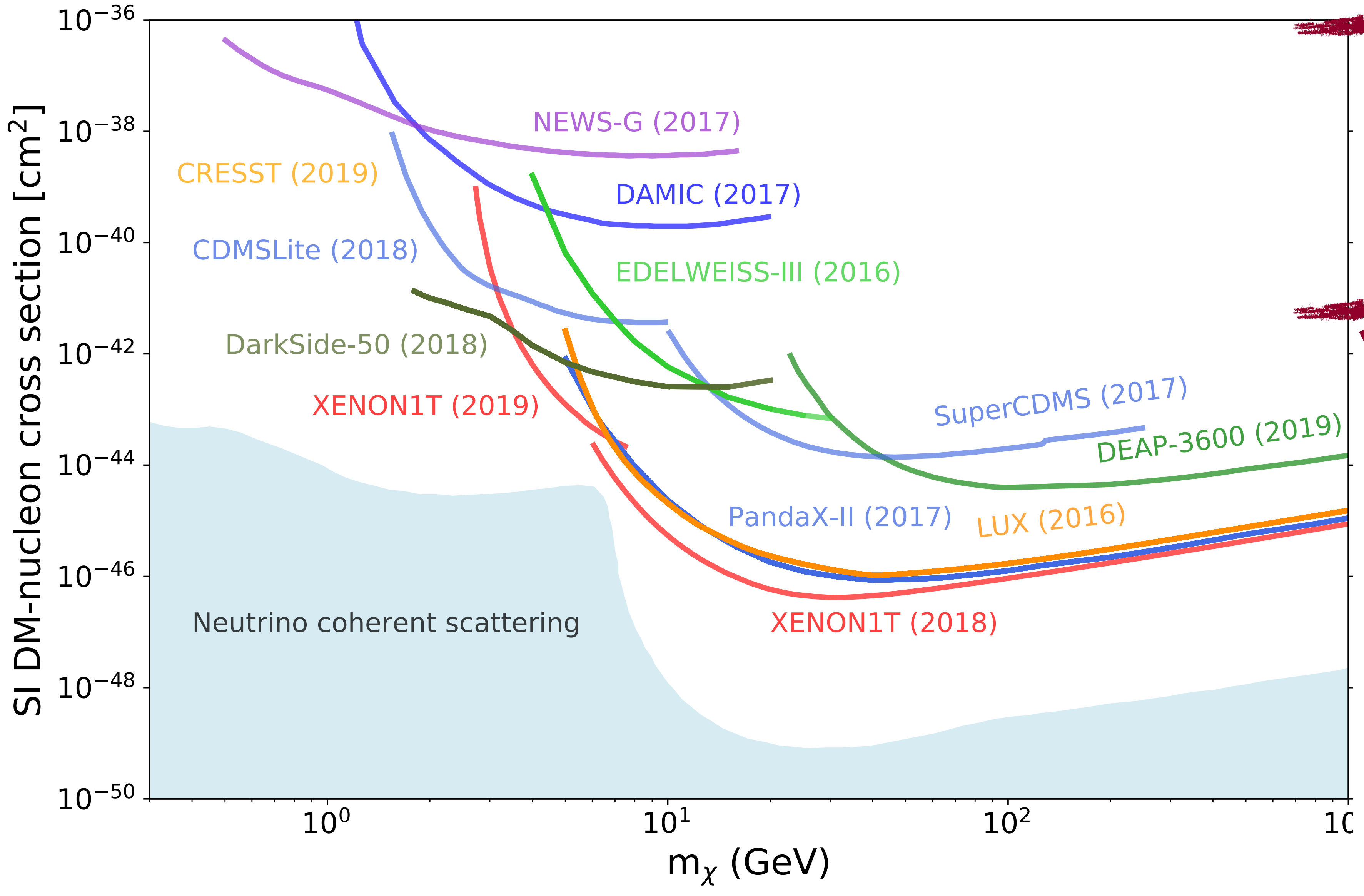
Current Experiments Not Too Sensitive to Sub-GeV DM

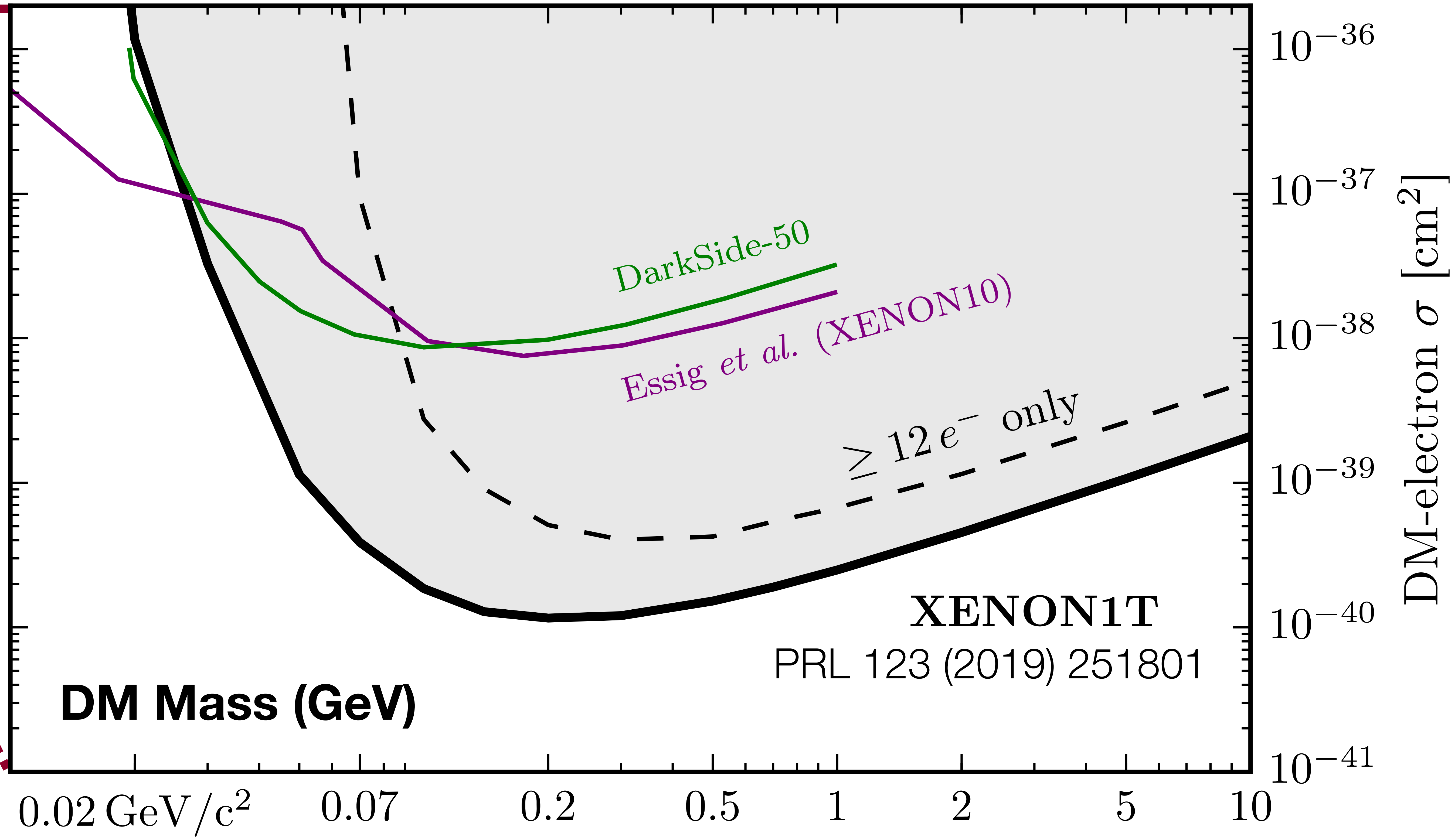
Sub-GeV DM (eg. SIMPs)





For Light Dark Matter Better to Look For Electron Recoils





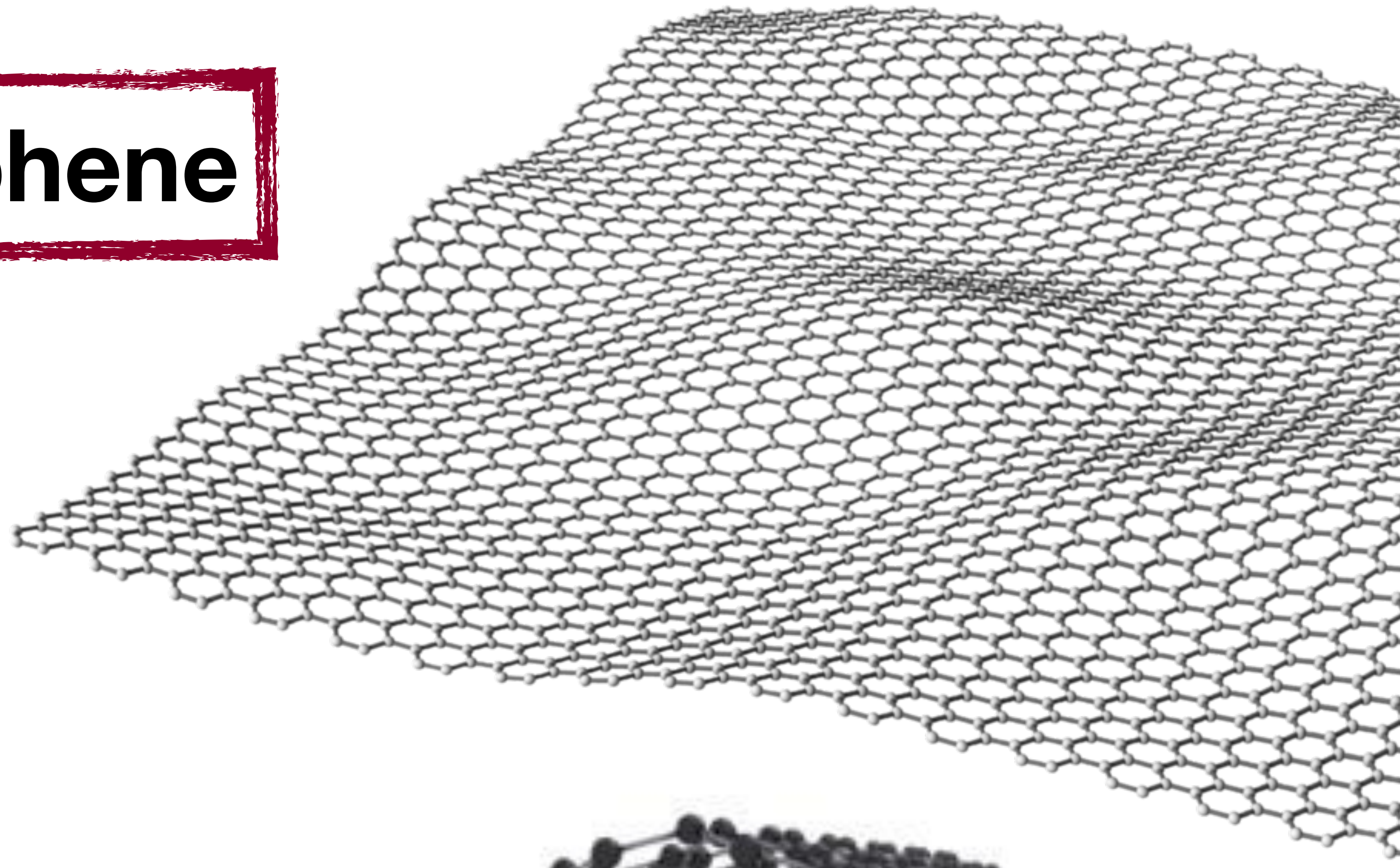
- Only a **few** experiments sensitive to electron recoils
  - Much **weaker** limits (10^{-6})
  - From ton-targets to **gram**-targets?

Sensitivity drops for m_{DM} < 100 MeV (electron reconstruction thresholds)

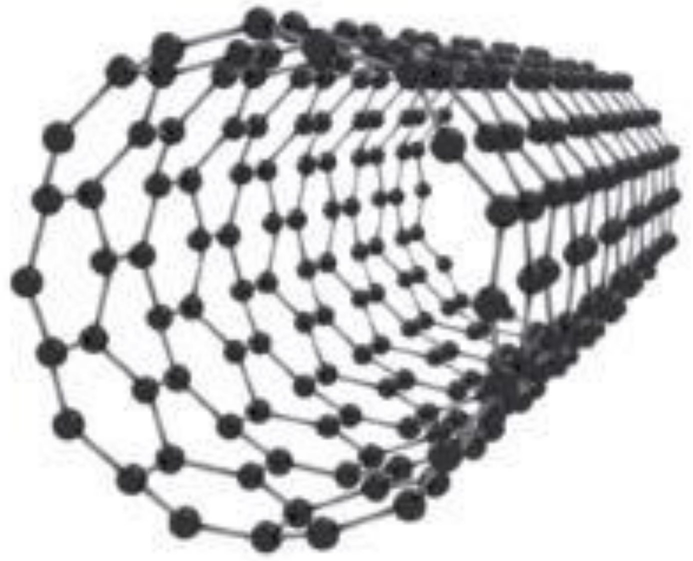
Solid State Targets: The Advantage of 2D Materials

- **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_e ~ 4.7 eV, so K_e ~ 1-50 eV
  - Extremely **short** range in matter!
- 2D materials: electrons ejected **directly** into vacuum
  - **Graphene** and **carbon nanotubes**

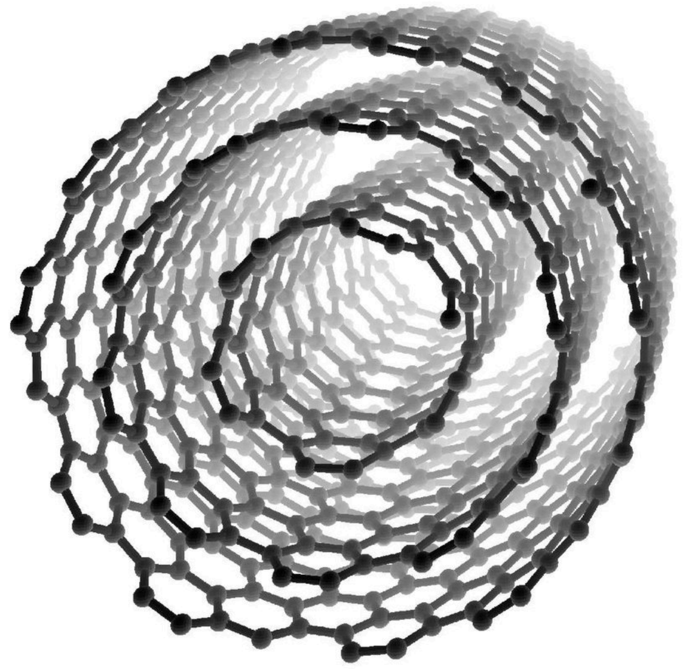
Graphene



Single-wall nanotube



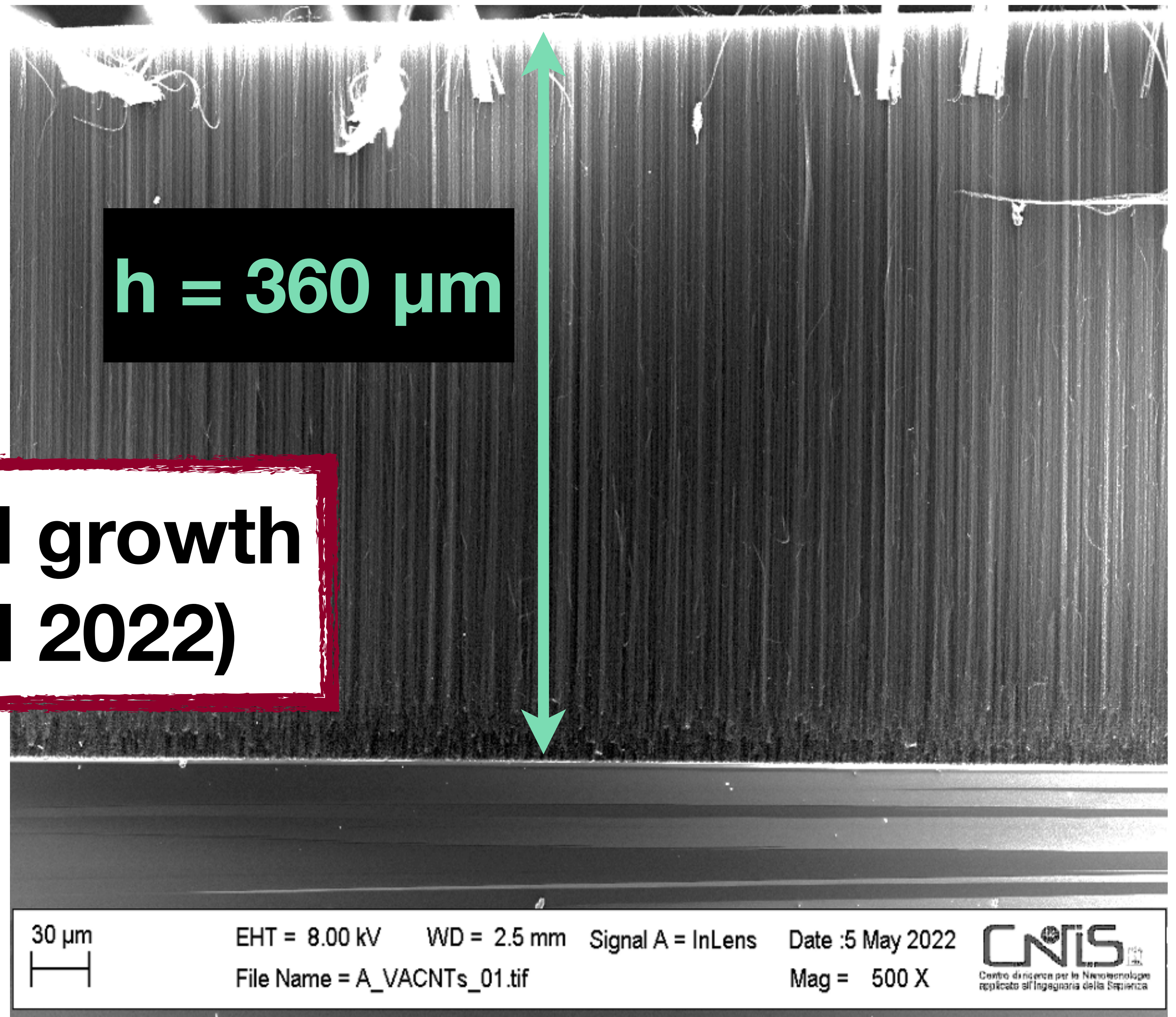
Multi-wall nanotube



Growing Vertically Aligned Carbon Nanotubes in the Lab

- New **state-of-the-art** nanotube facility in Rome Sapienza
  - Thanks to ATTRACT funding
  - Growing nanotubes with Chemical Vapor Deposition
  - Up to 400 μm in length, on different substrates

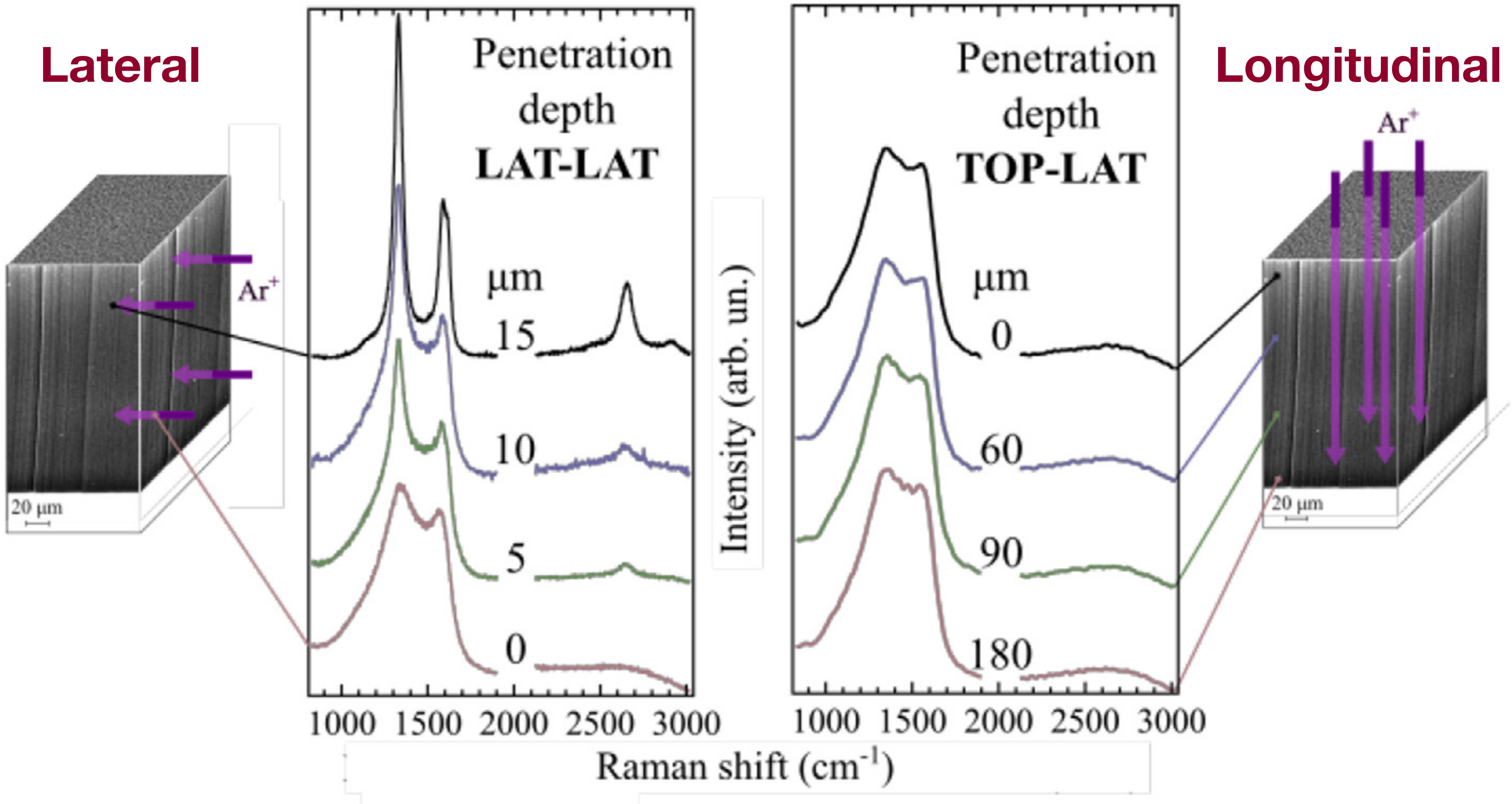
Installing the CVD chamber (Summer 2020)



Typical growth (April 2022)

Aligned Nanotubes: a Highly Anisotropic Target

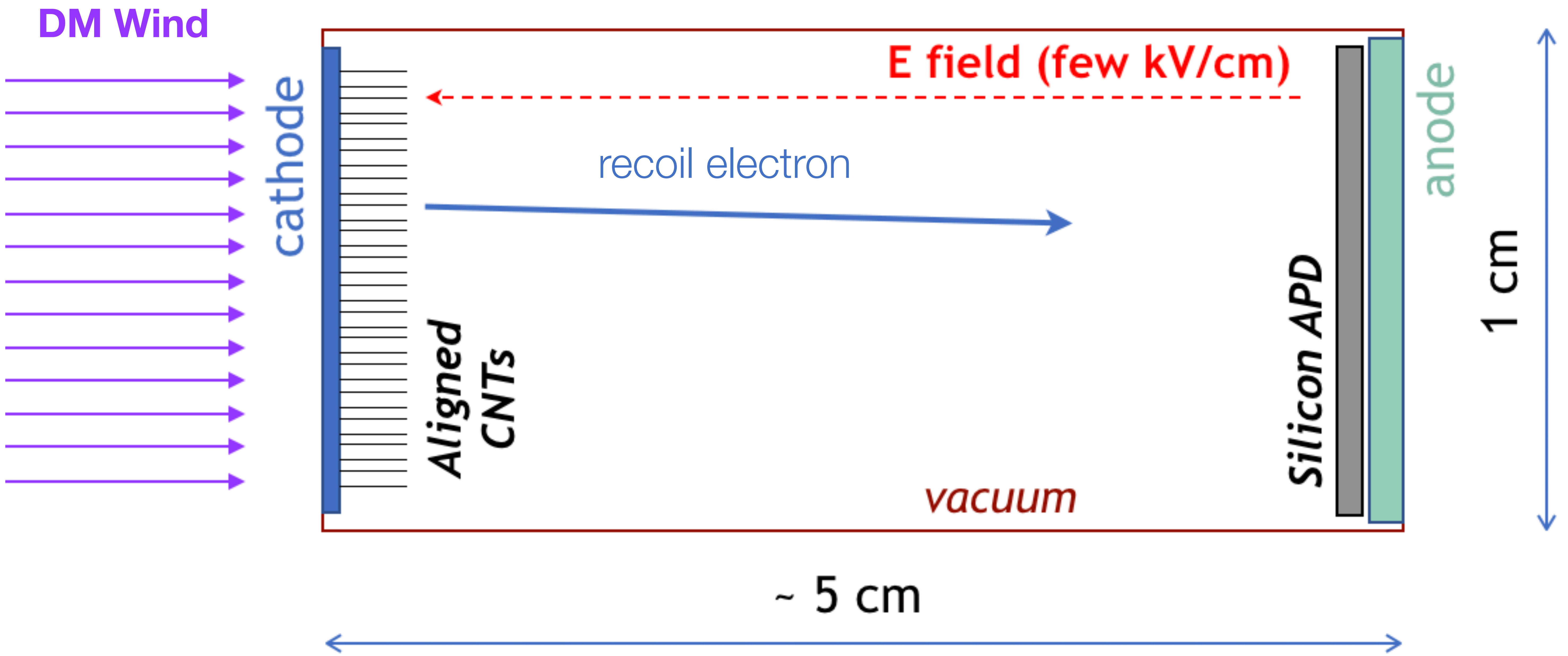
G. D'Acunto, et al., Carbon 139 (2018) 768



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


Directional sensitivity by design
100 µm
e-
DM
DM
e-

Nanotube Detector Concept: the ‘dark-PMT’

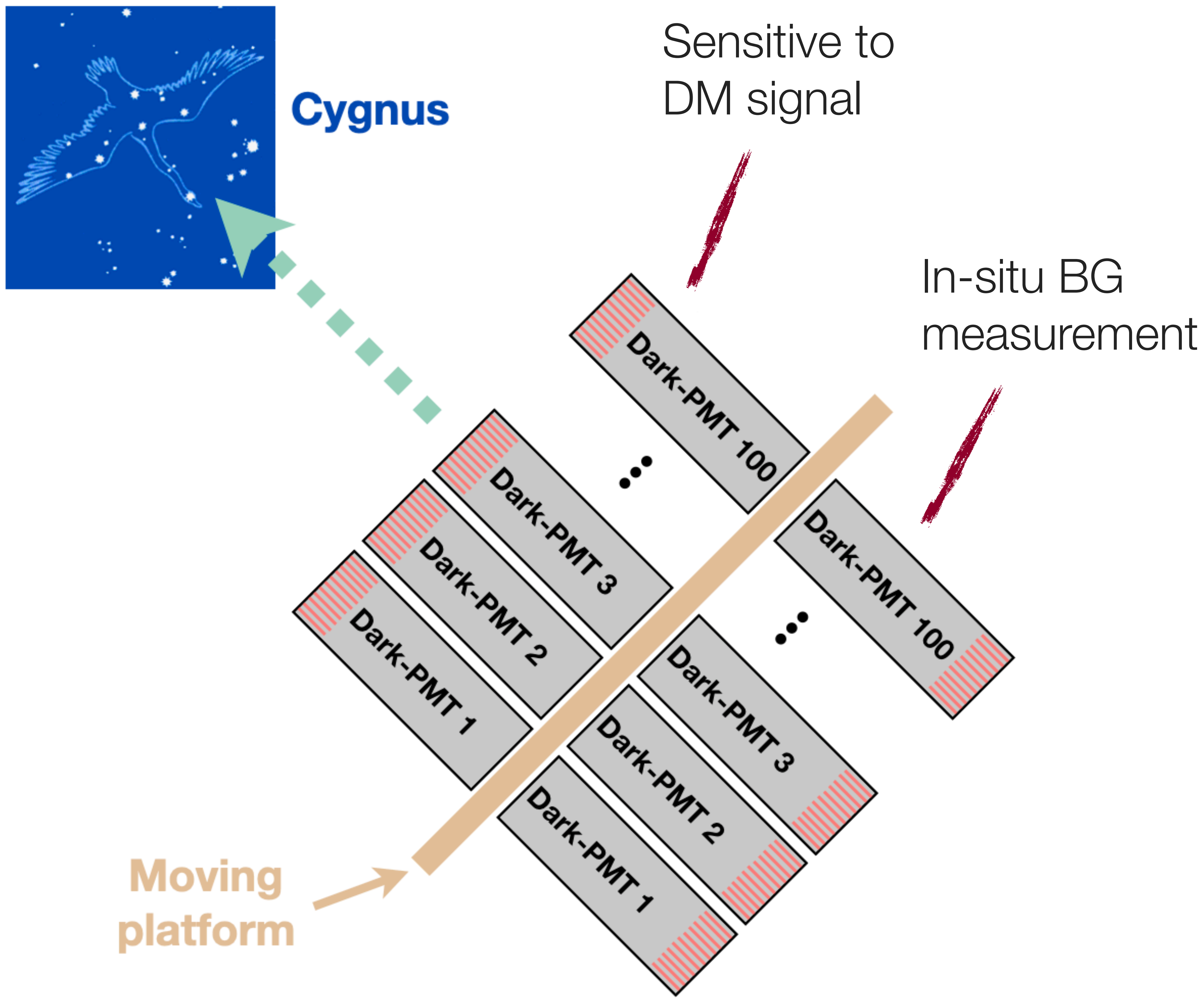


- ‘Dark-photocathode’ of aligned **nanotubes**
  - Ejected e⁻ accelerated by electric field
  - Detected by solid state **e⁻ counter**

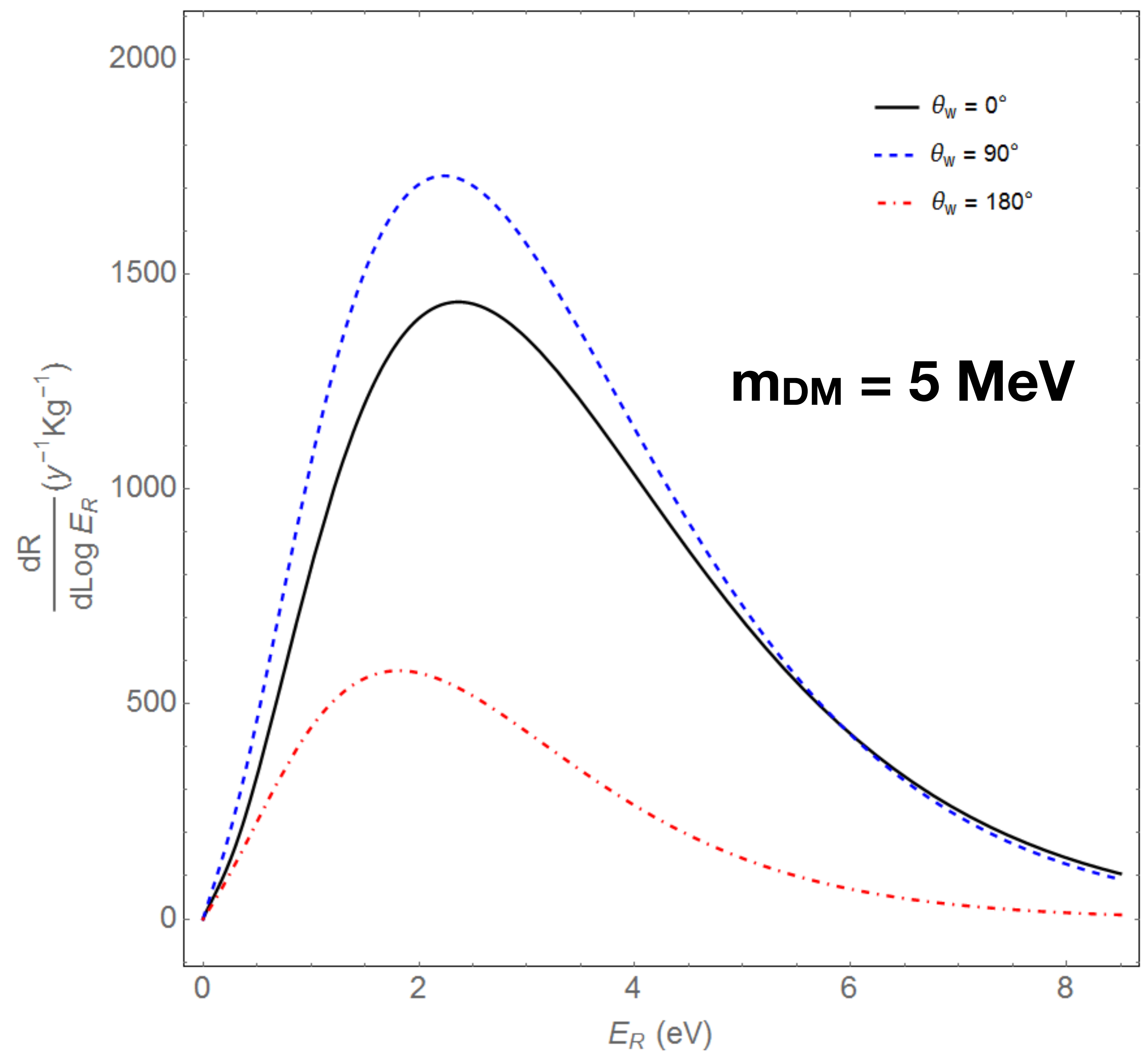
Dark-PMT features:

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

Two Arrays of dark-PMTs to Search for a Dark Matter Signal



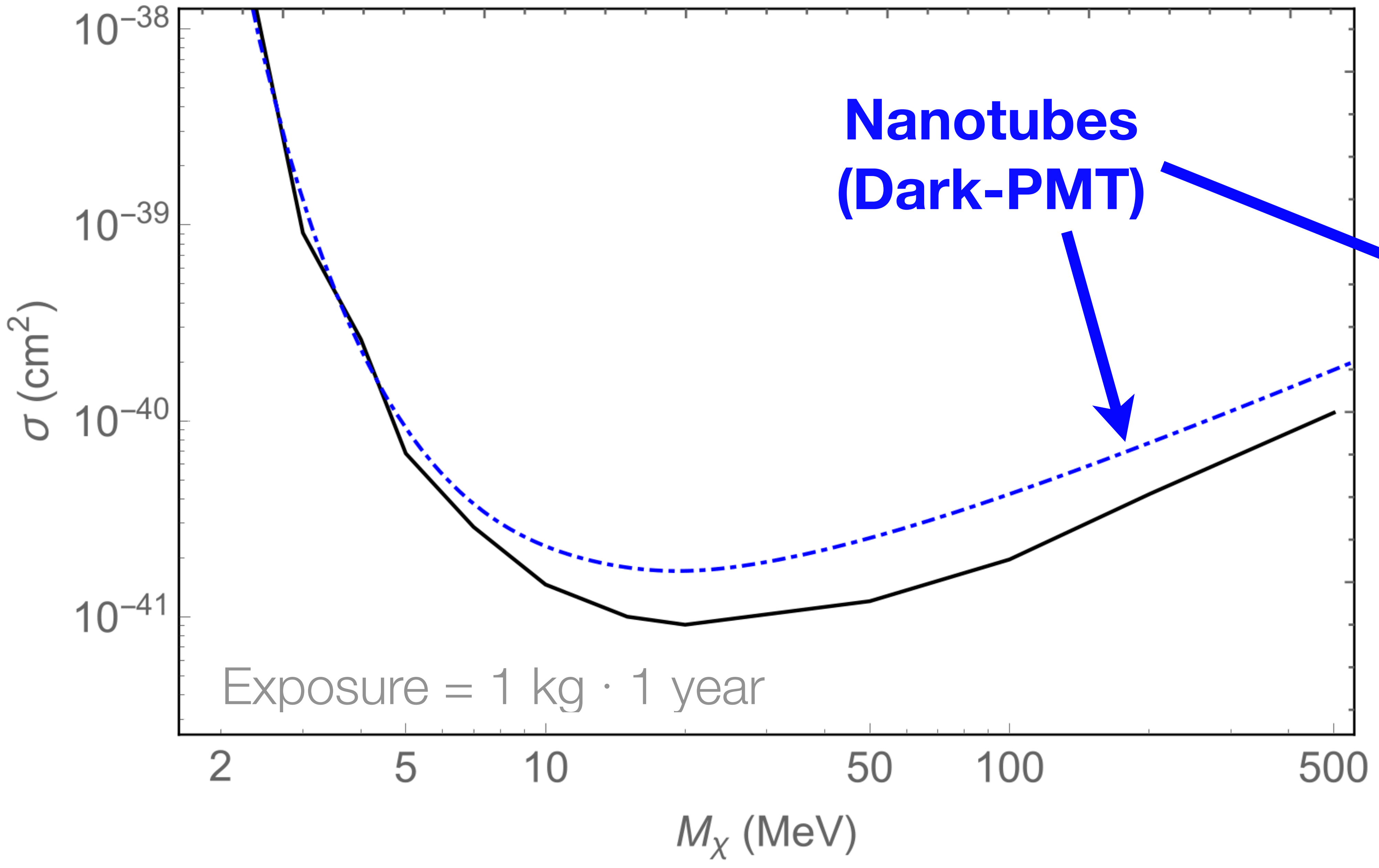
G. Cavoto, et al., PLB 776 (2018) 338

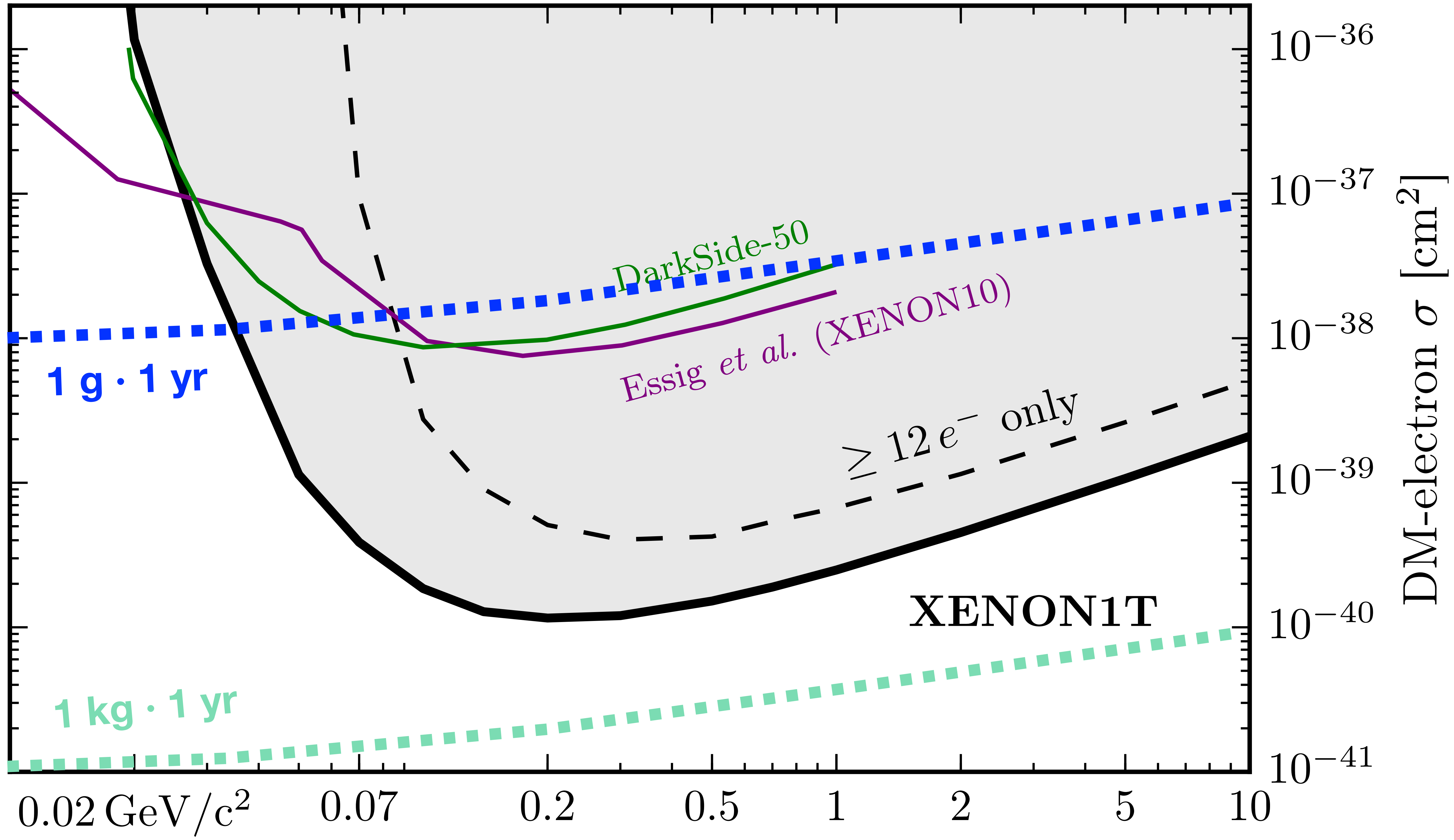


In principle sensitive to eV electrons!

Expected to Extend Reach Below 40 MeV

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





The ANDROMeDa Project

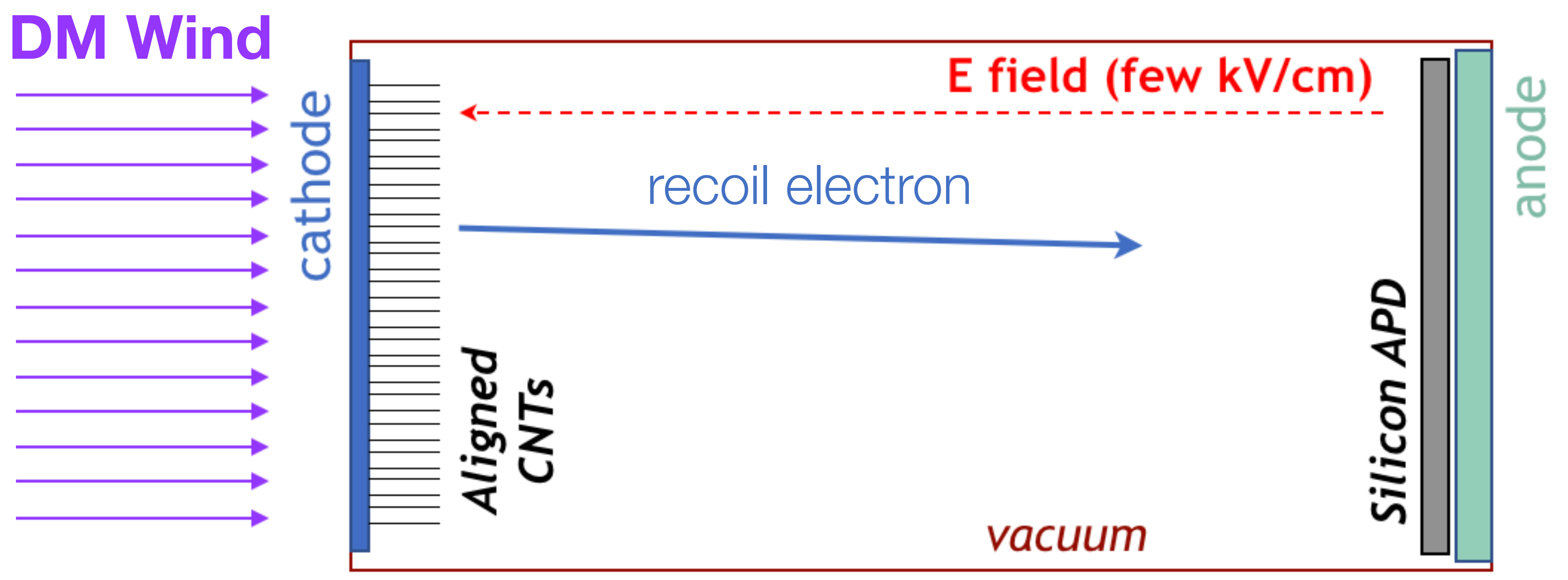
PRIN 2020

- ❖ Awarded PRIN2020 grant (1M€)
  - 3-year project, starting in 2022
  - 3 units: INFN (FP, P.I.)
Sapienza (G. Cavoto)
Roma Tre (A. Ruocco)

ANDROMeDa

Aligned **N**anotube **D**etector for **R**esearch **O**n **MeV** **Da**rkmatter

- ❖ **Main objective:** have a working dark-PMT prototype by end of project
  - Challenges on **both sides** of detector



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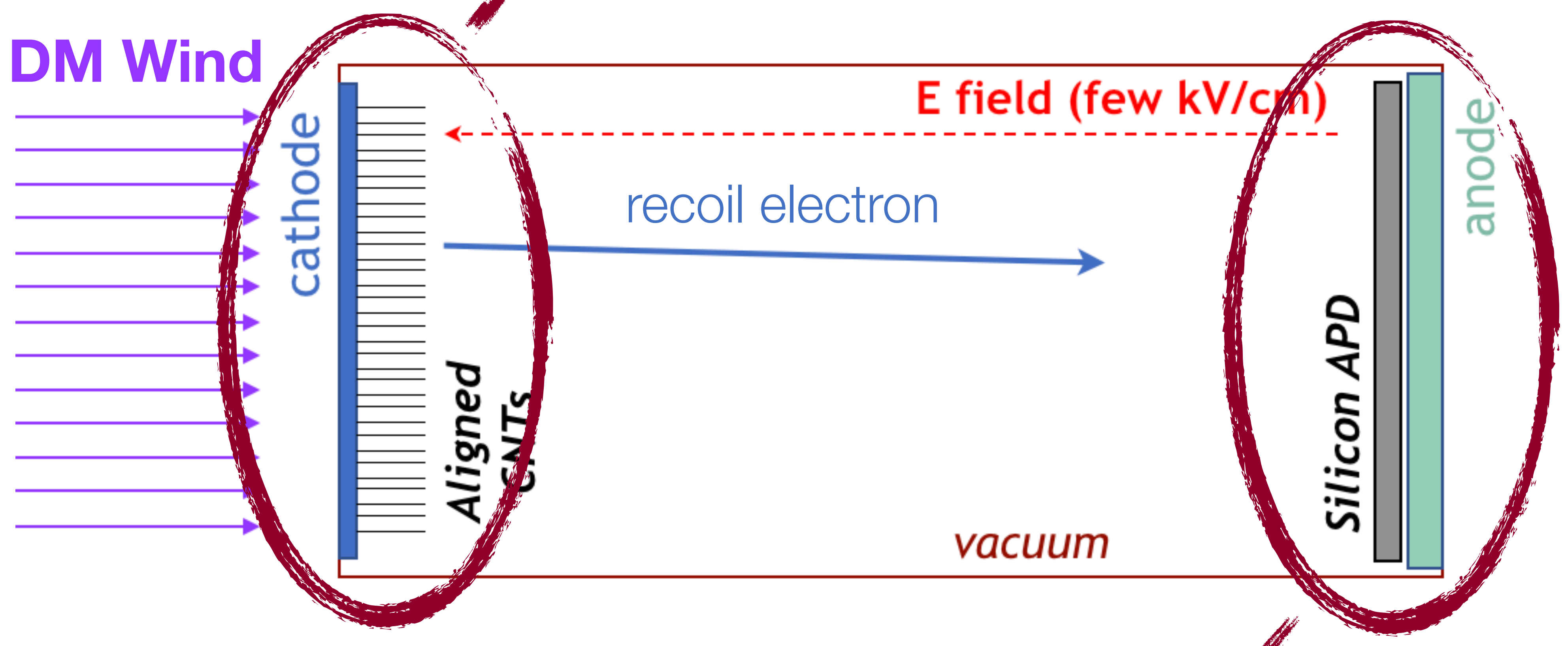
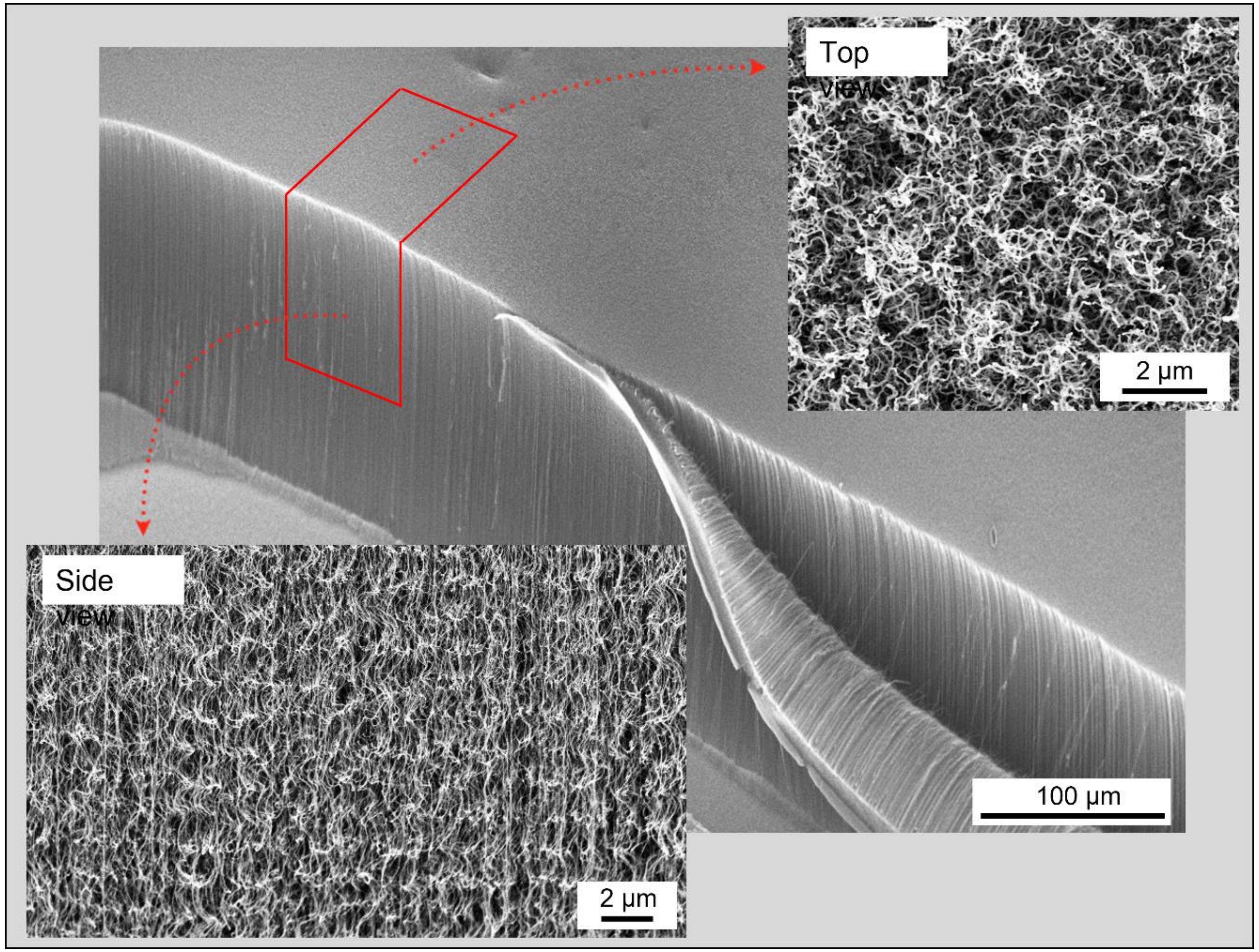
Ideal nanotubes for DM target?

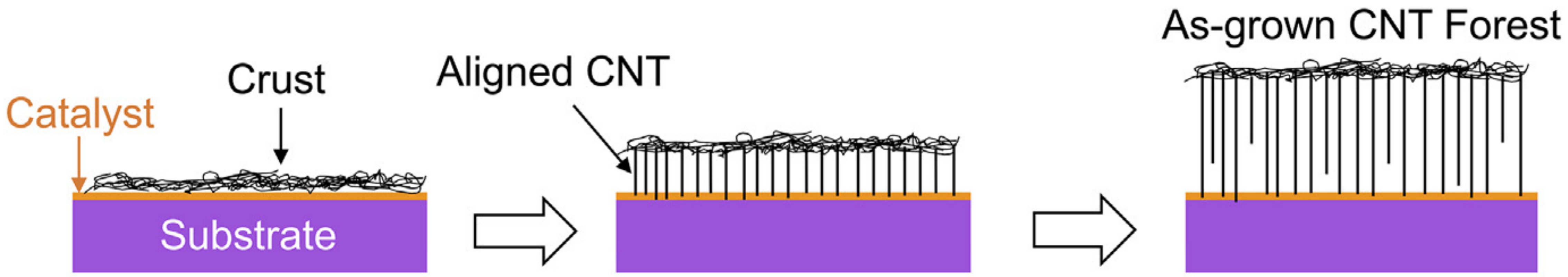


Best detector for keV electrons?

- **Main objective:** have a working dark-PMT prototype by end of project
  - Challenges on **both sides** of detector

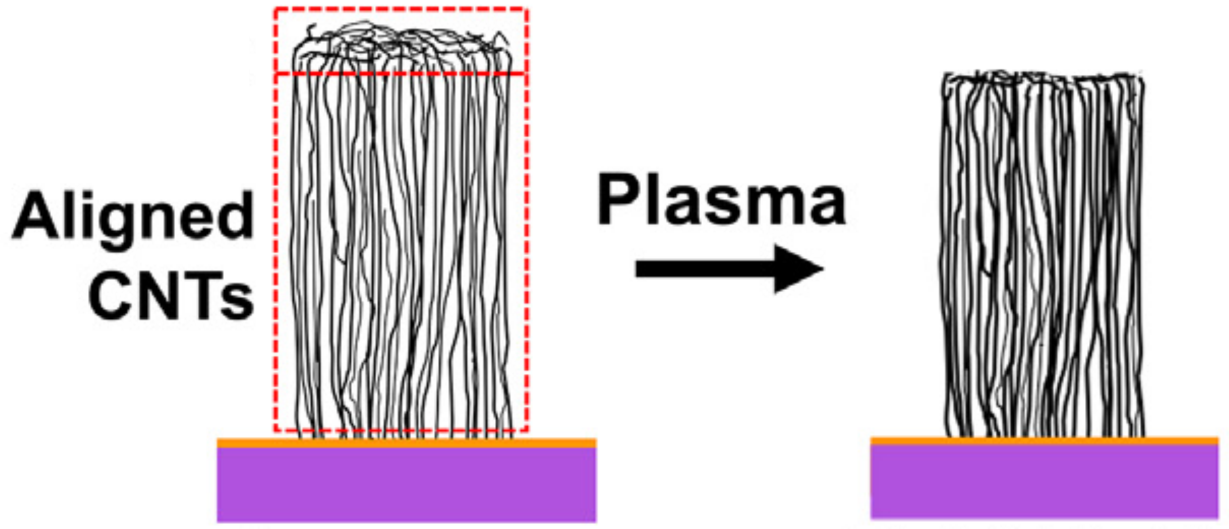
Two Unwanted Features of Carbon Nanotubes



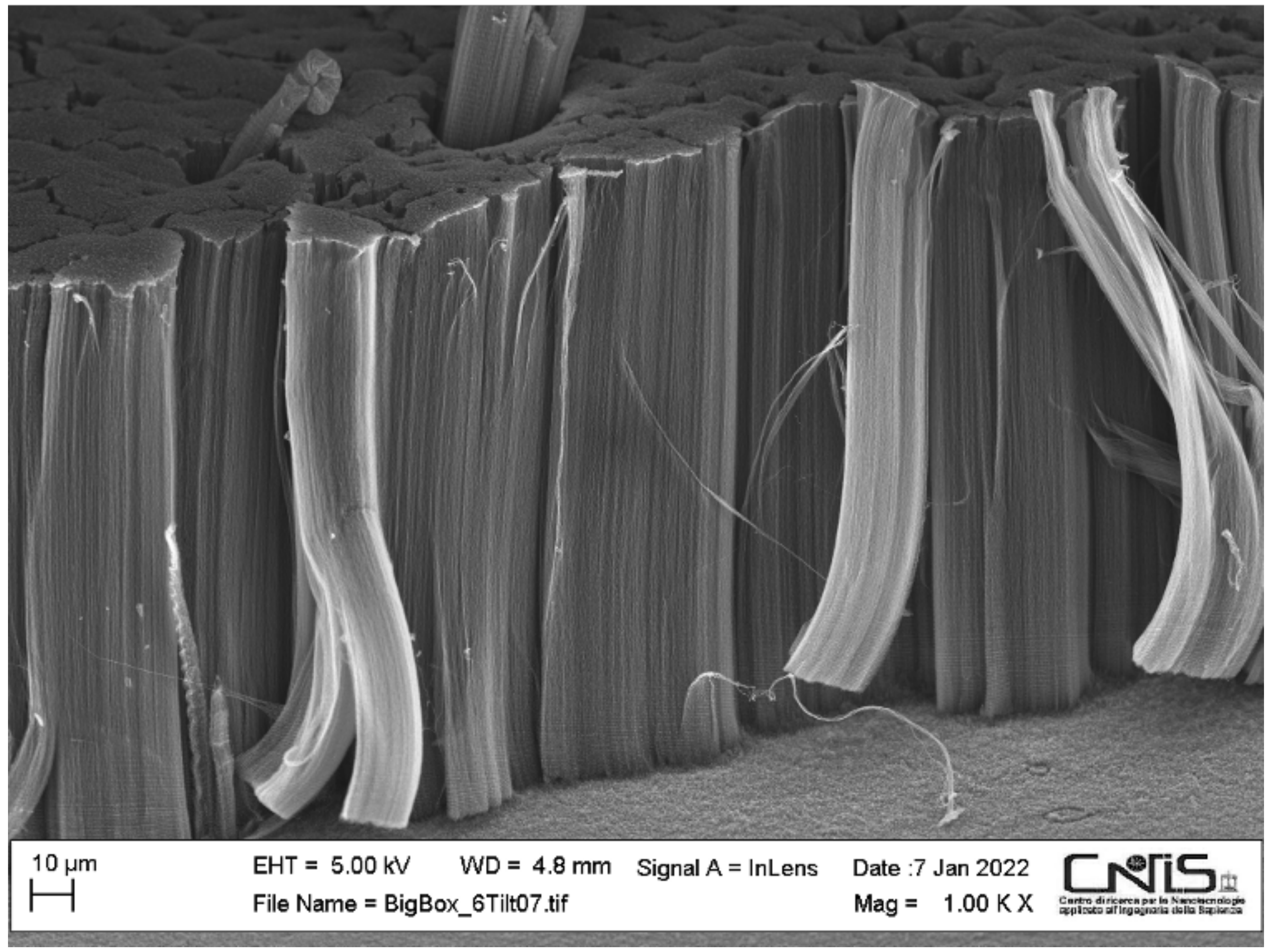


- **Two** problems with as-grown nanotubes:
  - Non-aligned **top crust layer**
  - Side **'waviness'** at the nanoscale
- **Both** hamper electron transmission
  - Need to **minimize** both effects for ideal DM target

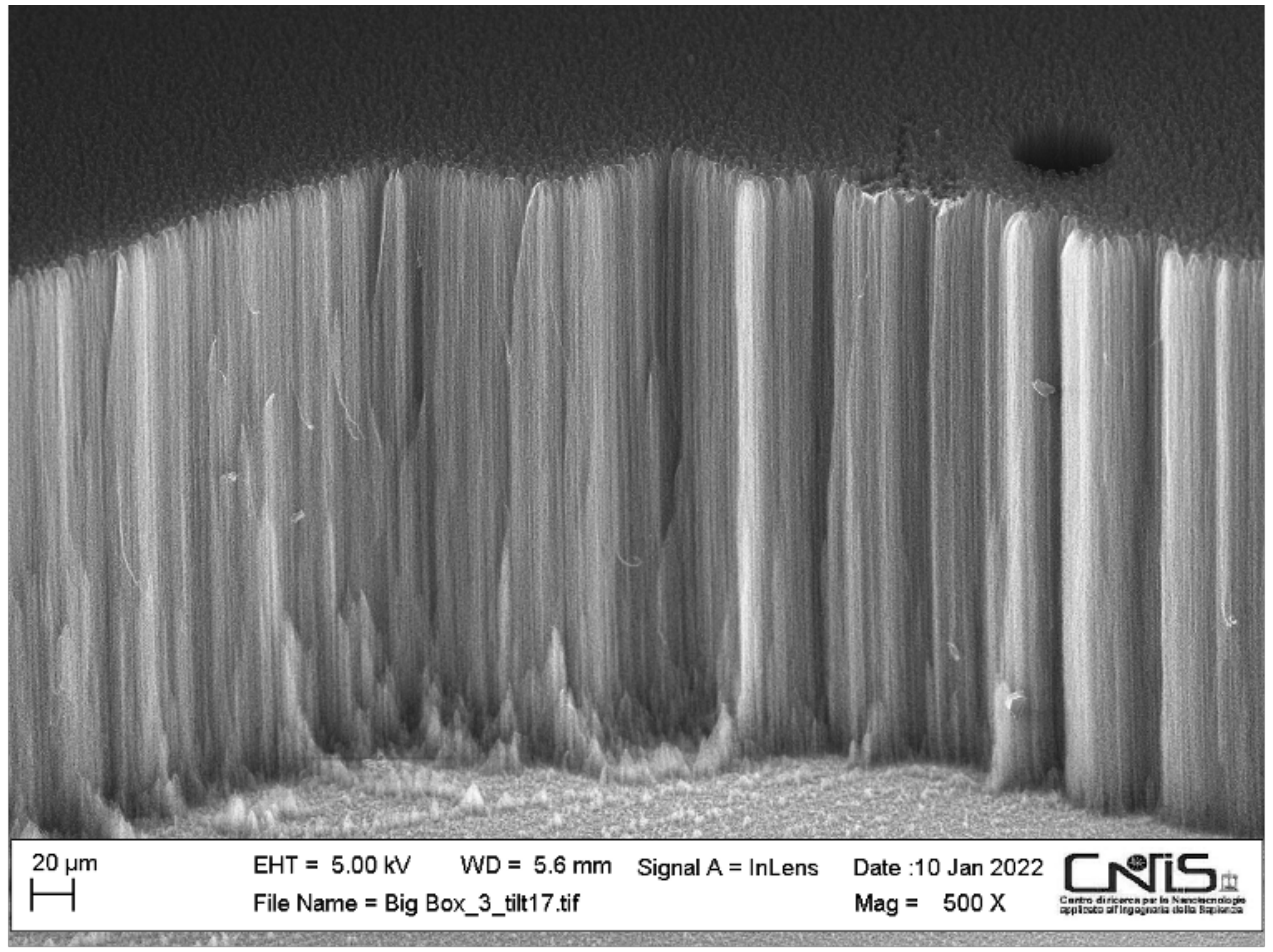
Plasma Etching to Remove Non-Aligned Top



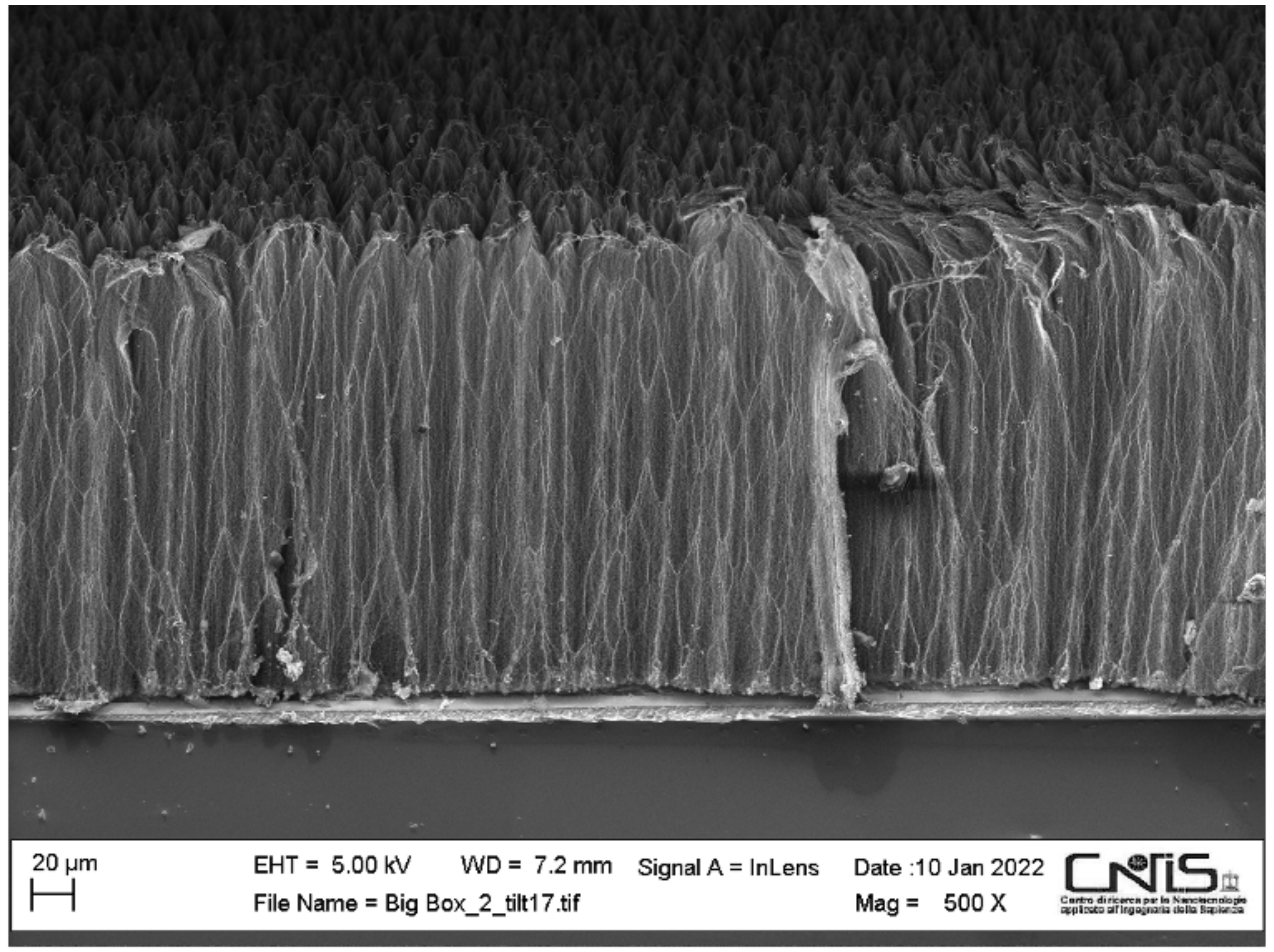
Mild Ar/O_2 etching → **Modest Ar/O_2 etching** → **Aggressive Ar/O_2 etching**



35 W



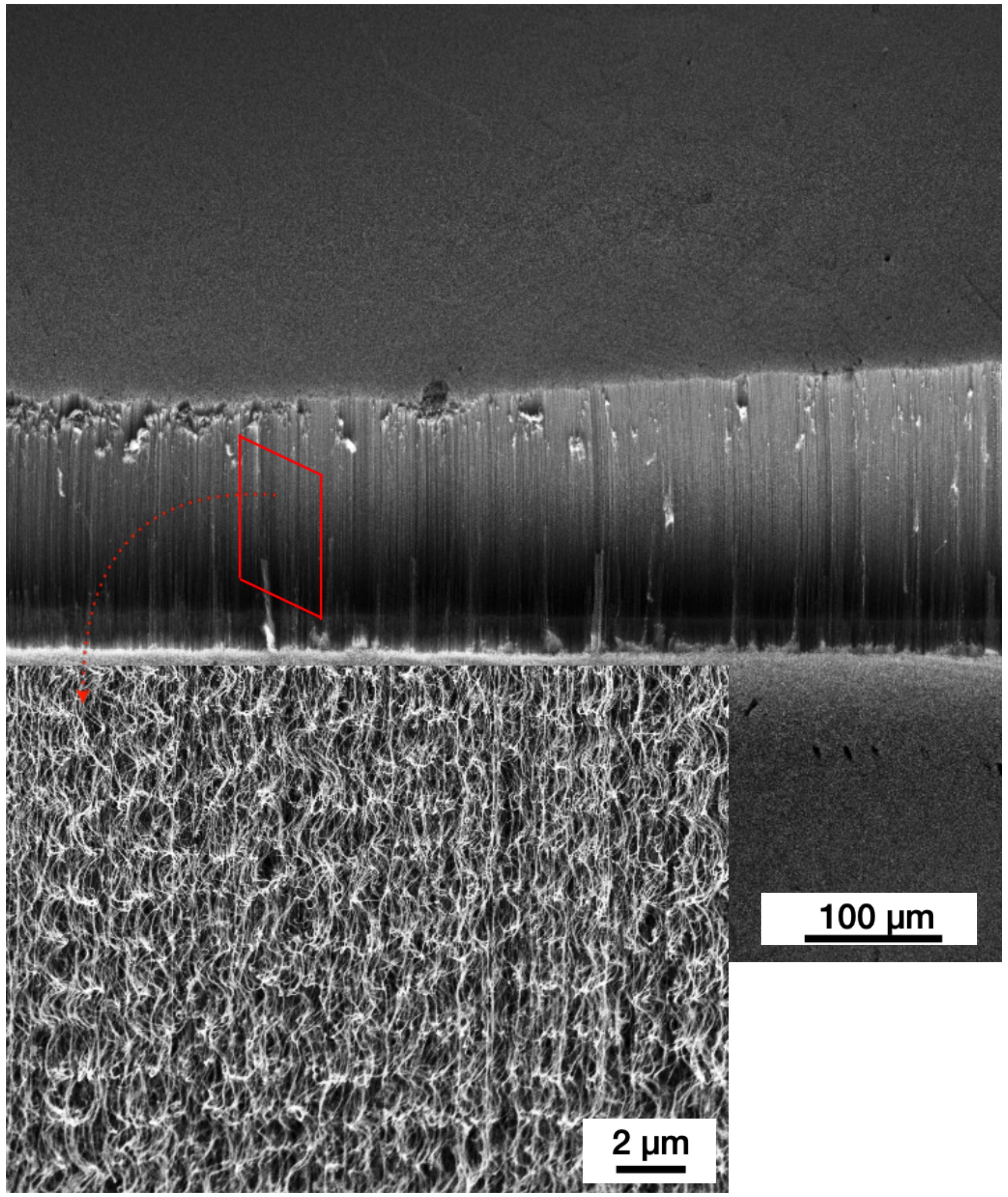
50 W



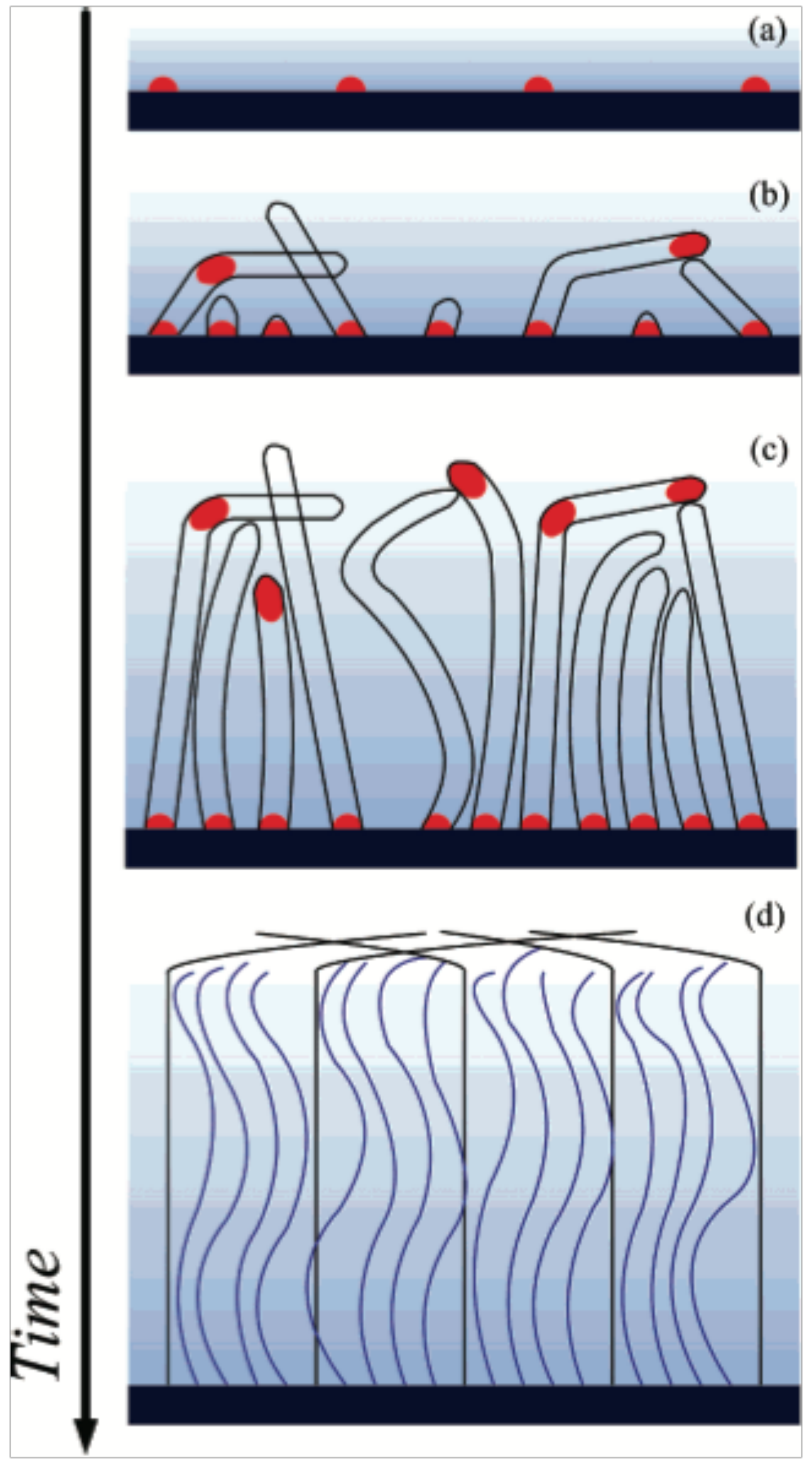
80 W

in collaboration with G. Pettinari (CNR-IFN)

Aiming for Ultimate Parallelism at the Nanoscale



- Parallelism strongly influenced by iron **catalyst seeds**
  - Density, uniformity and oxidation
- Building **evaporation chamber** in Rome
  - Will operate in 10^{-9} mbar to **minimize** oxidation
  - Aim for seed density $>10^{12}$ cm^{-2} with high **uniformity**
  - AFM to check seed size and density

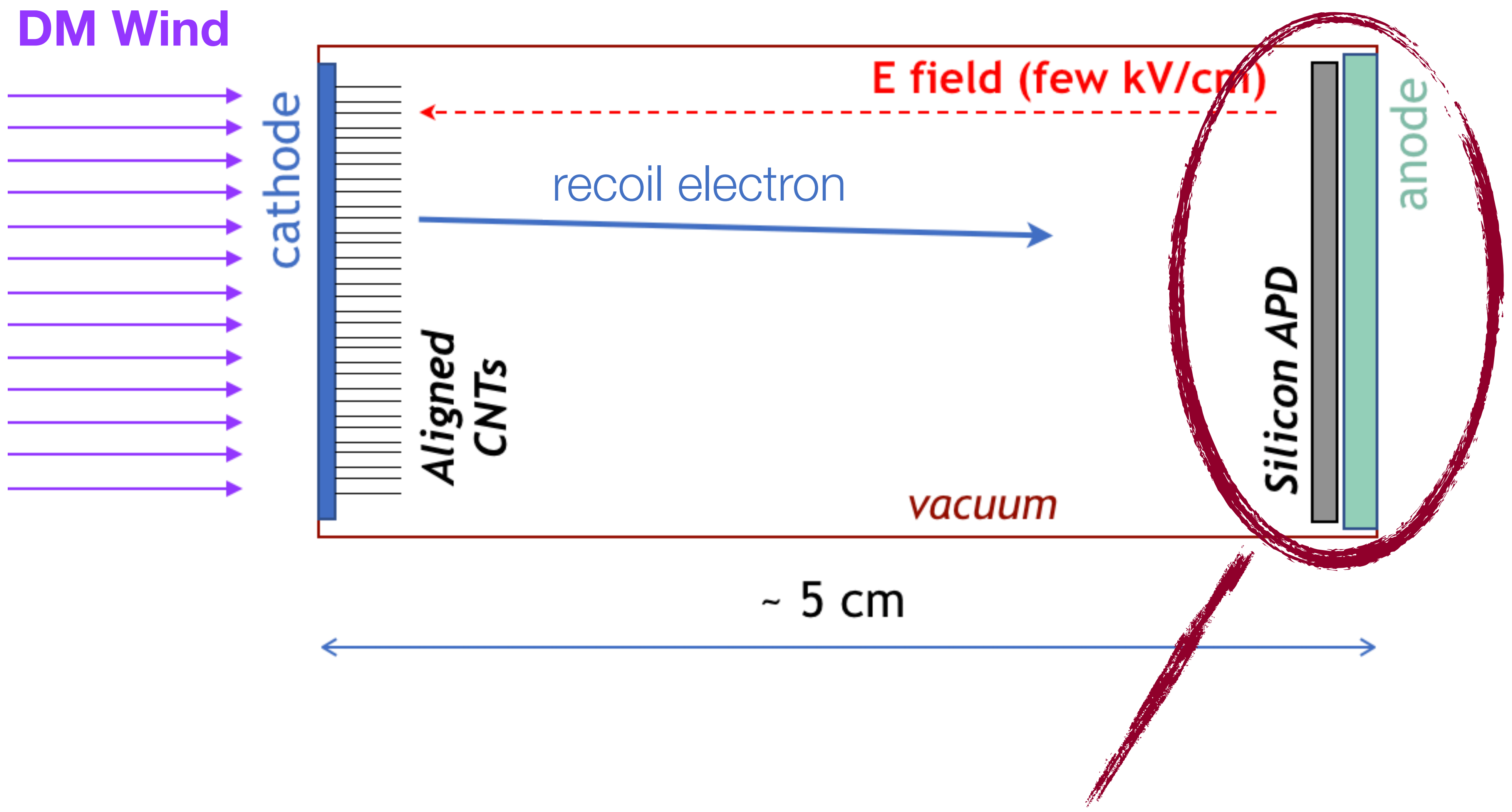


Non-uniform seeds
→ different growth rates
→ wavy nanotubes

APDs and SDDs 'born'
as photon detectors

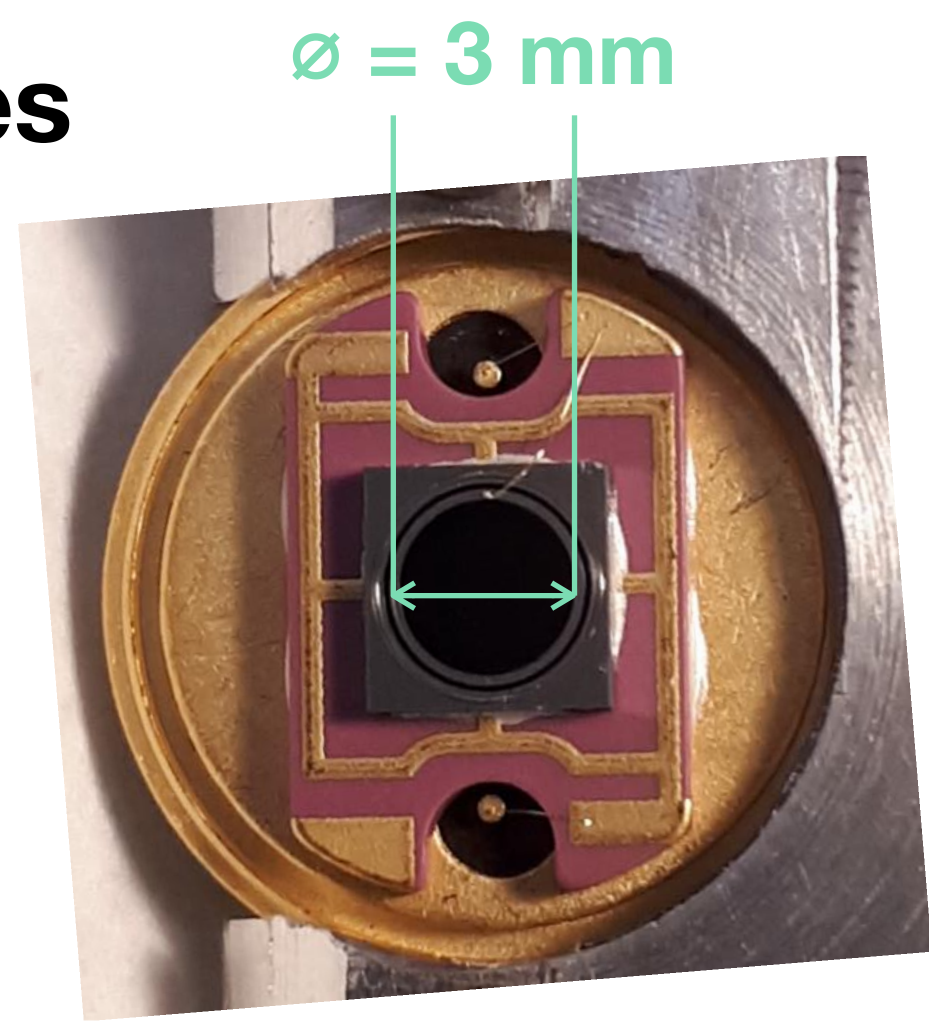
Silicon Detectors for keV Electrons

APDs and SDDs 'born' as photon detectors

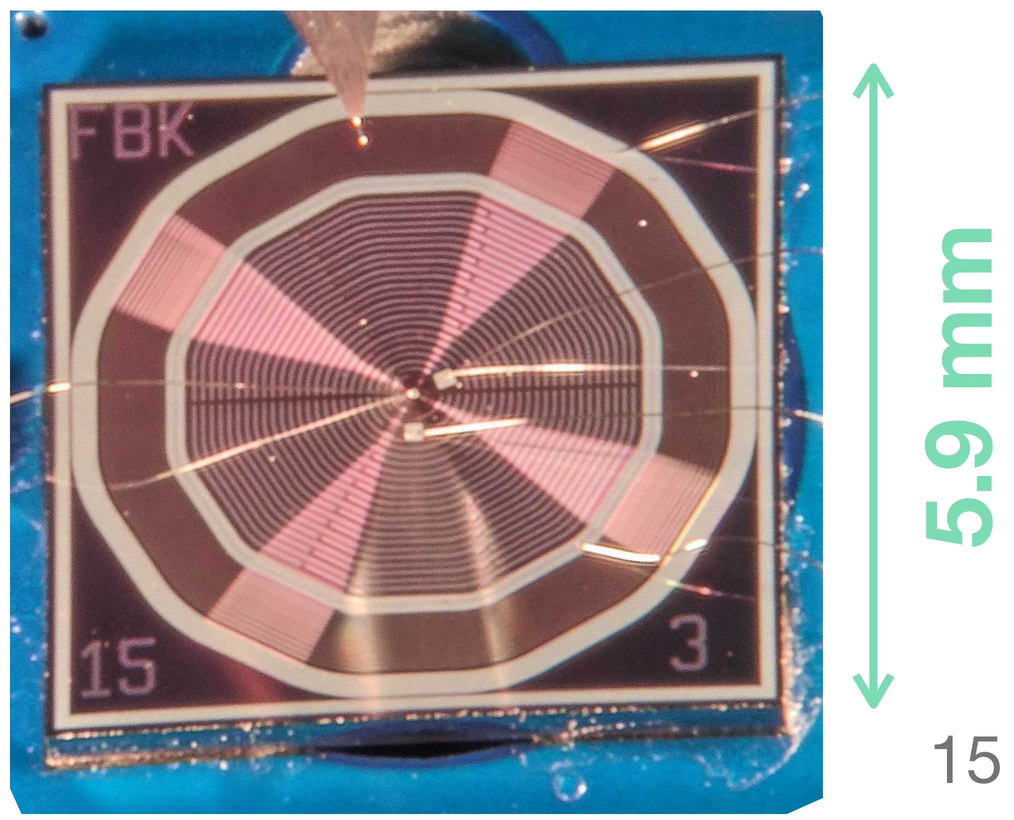


Challenge: detect keV electrons (with high efficiency)

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



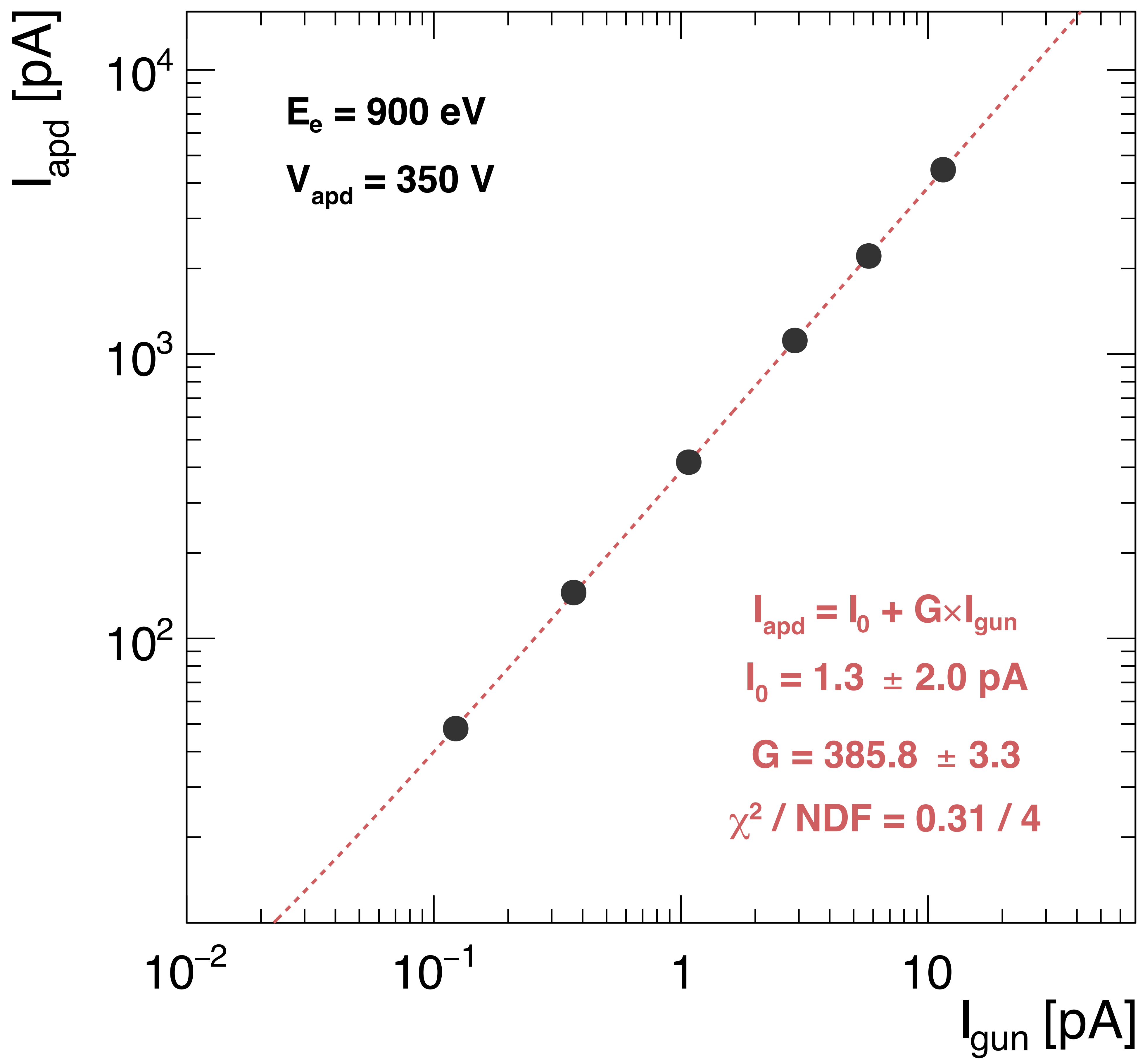
- Possible upgrade: **Silicon Drift Detectors**
  - Ultimate resolution
  - FBK (SDD) + PoliMi (electronics)



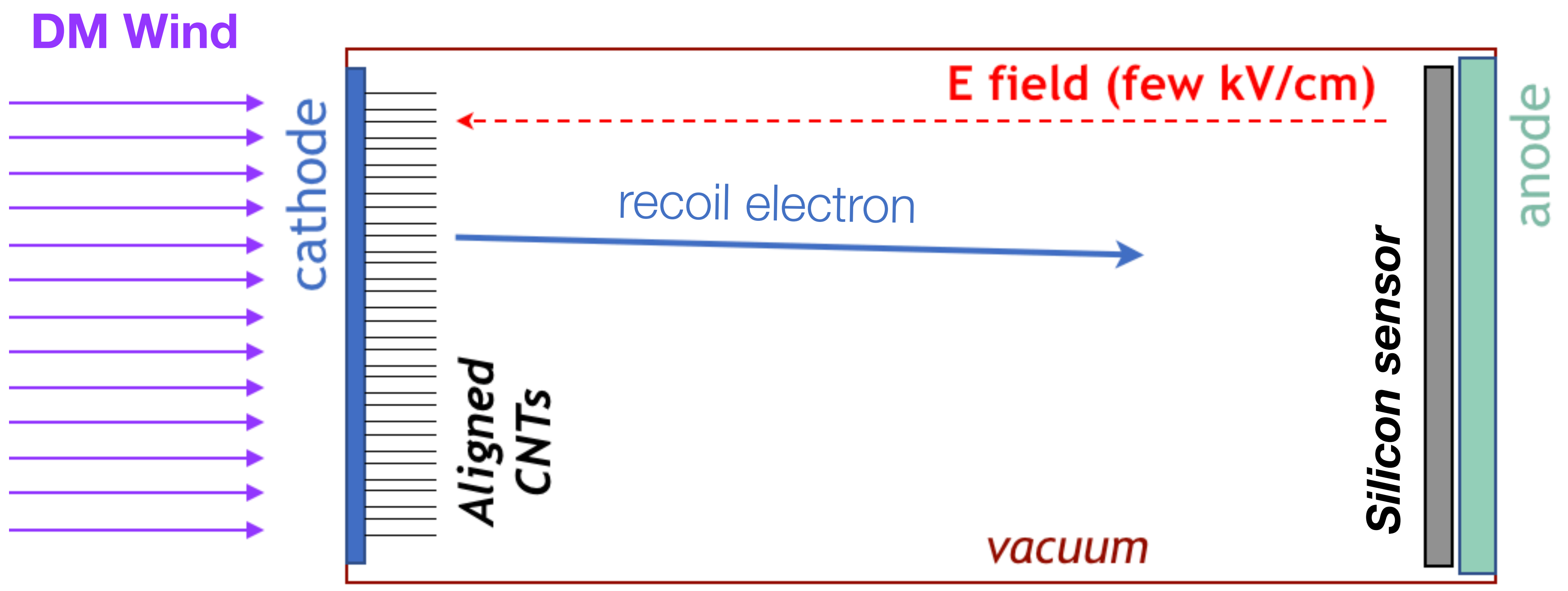
APD Characterization with 900 eV Electrons at Roma Tre

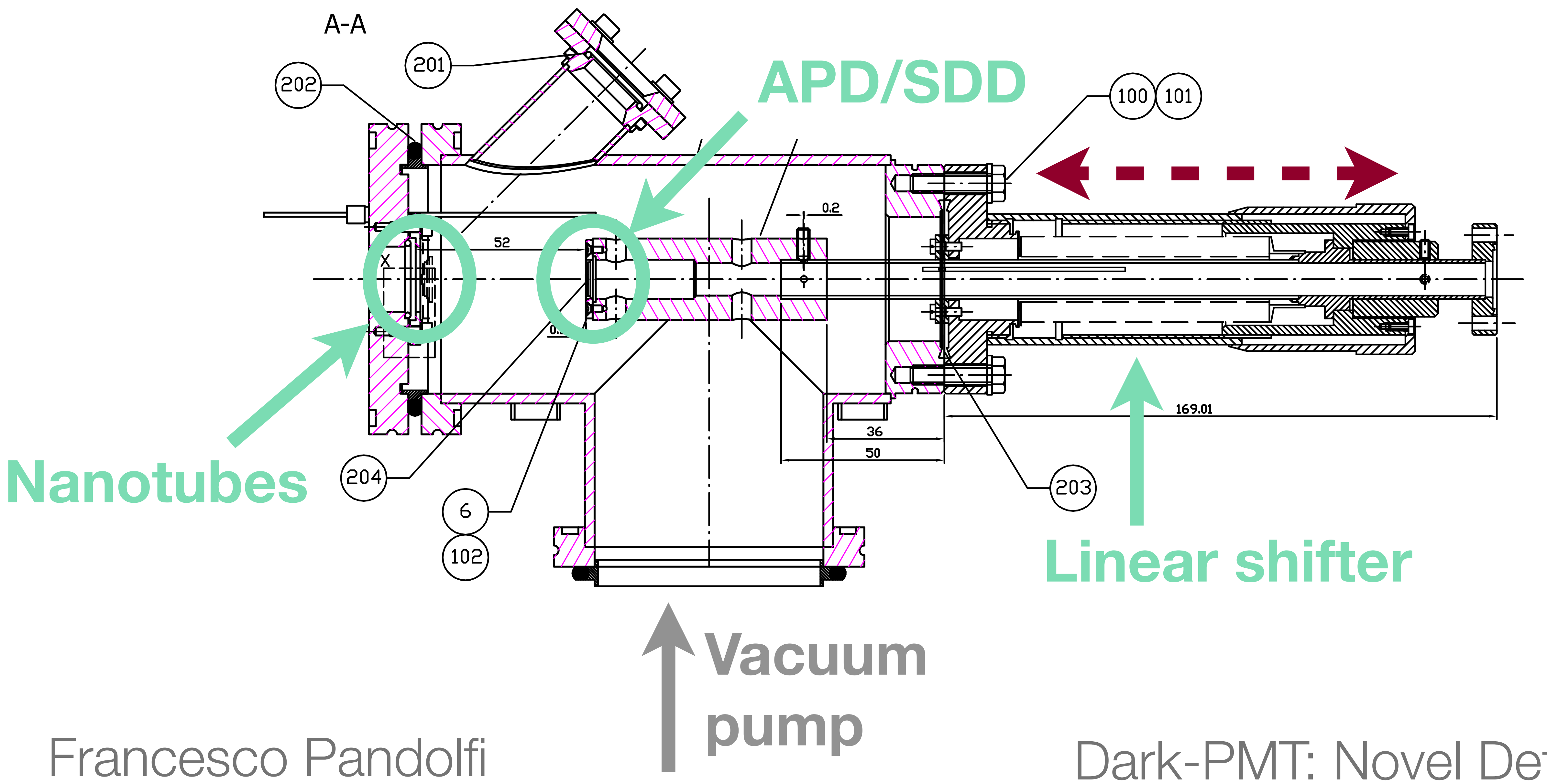
- **Electron gun** in LASEC Labs @ Roma Tre
  - Electron energy: 30 < E < 1000 eV
  - Energy uncertainty < 0.05 eV
  - Current as low as a **few fA**
  - Beam spot ~ 0.5 mm
- Reading APD bias current when shooting gun on it
  - Clear **linear correlation** with gun current

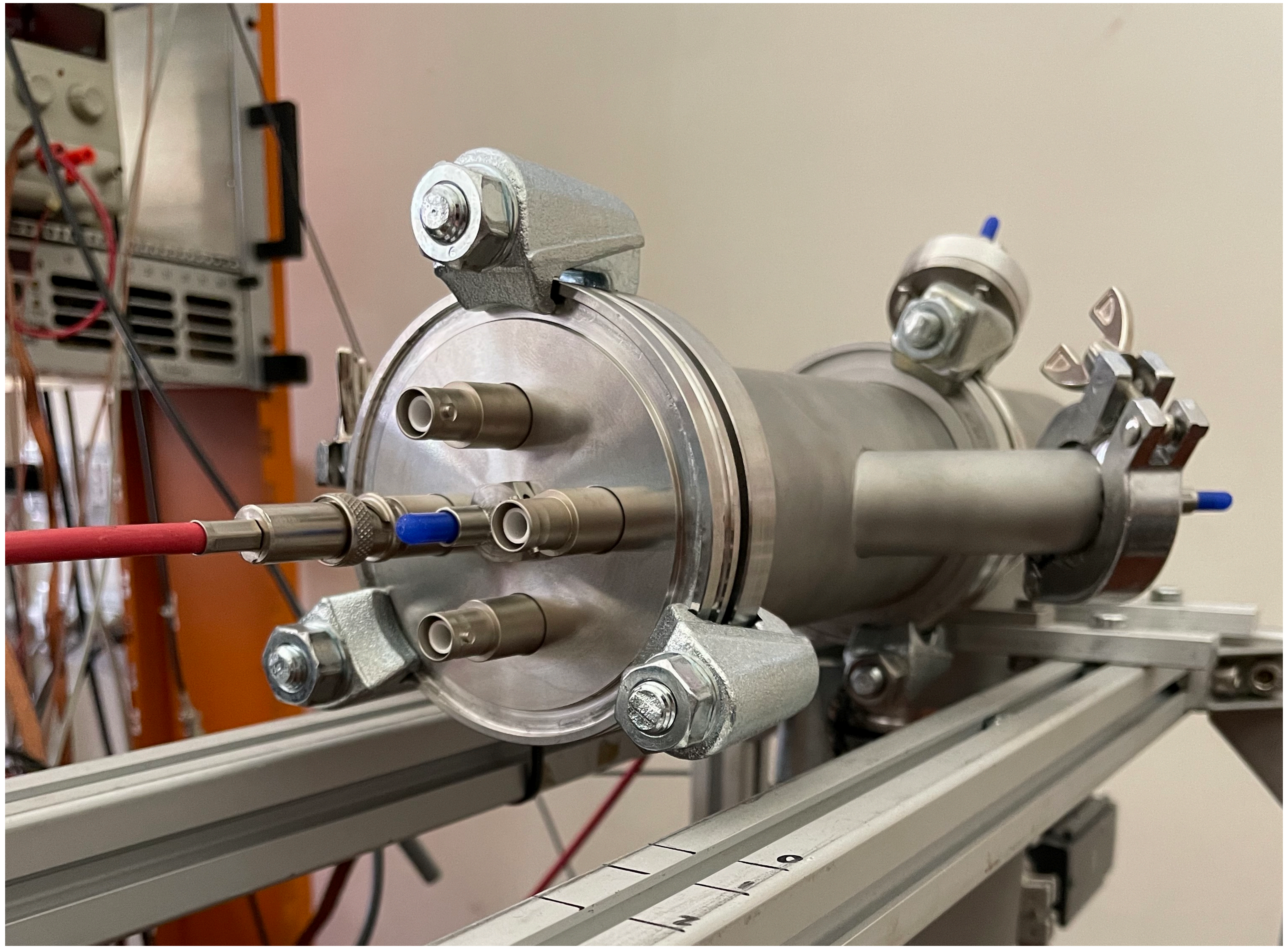
A. Apponi et al 2020 JINST **15** P11015



Dark-PMT Prototype ‘Hyperion-II’ Taking Data in Rome







Conclusions

- **Carbon nanotubes**: exciting new material for dark matter detectors
  - **2D** material: recoiling electrons ejected **directly** into vacuum
- **'Dark-PMT'** dark matter detector concept
  - Portable, no thermal noise, directional sensitivity
  - In principle sensitive to electron recoils of a **few eV**
  - Capable of extending reach to masses below 40 MeV
- ANDROMeDa: a **young** and **ambitious** program in Rome
  - Aiming to build **first** working Dark-PMT prototype by 2025

ANDROMeDa

Aligned **N**anotube **D**etector for **R**esearch **O**n **M**e**V** **D**ark matter