# Carbon Nanotubes as Anisotropic Target for Dark Matter Experiments

Francesco Pandolfi
INFN Rome

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# Aiming for the 'Why Not' Region

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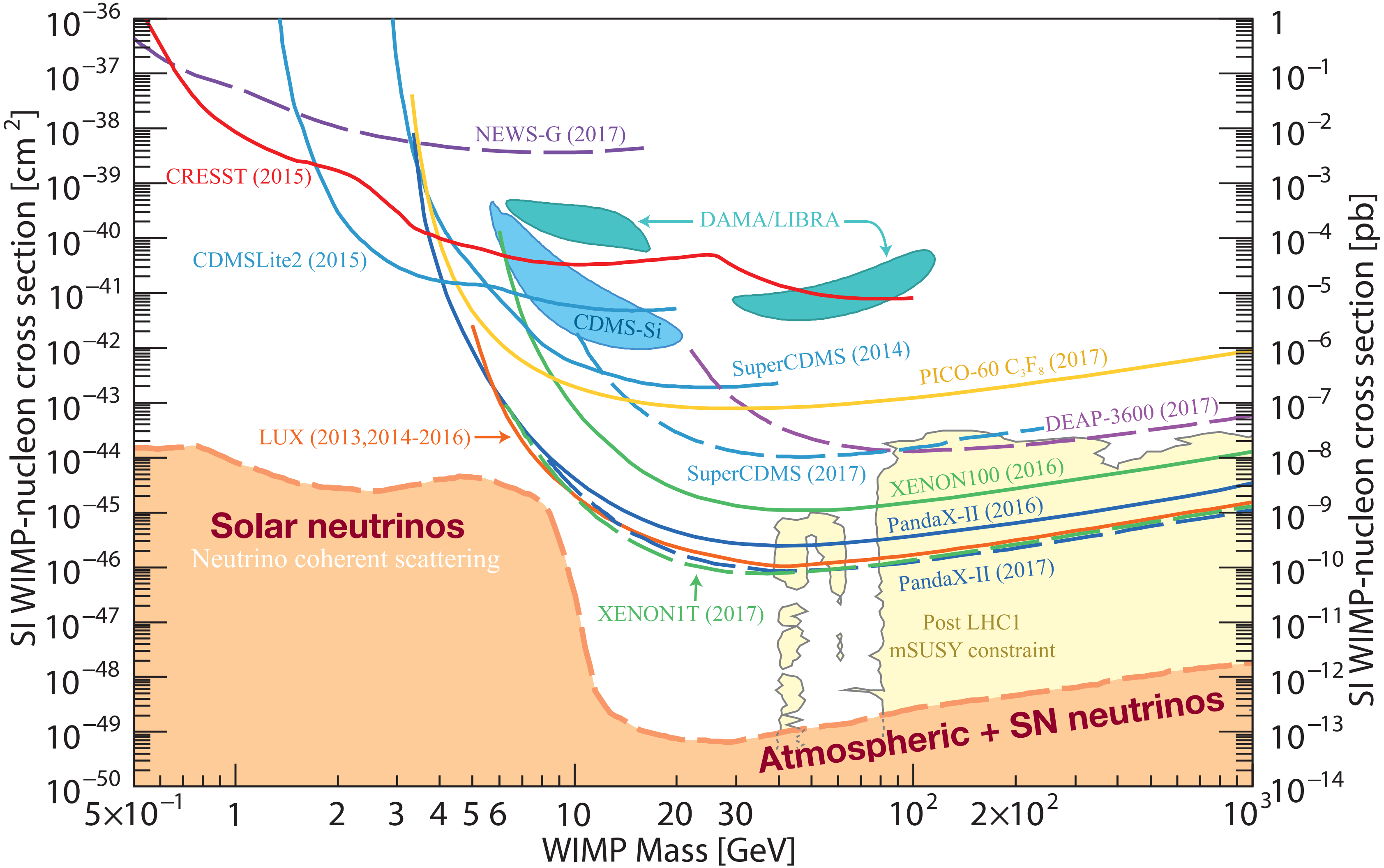
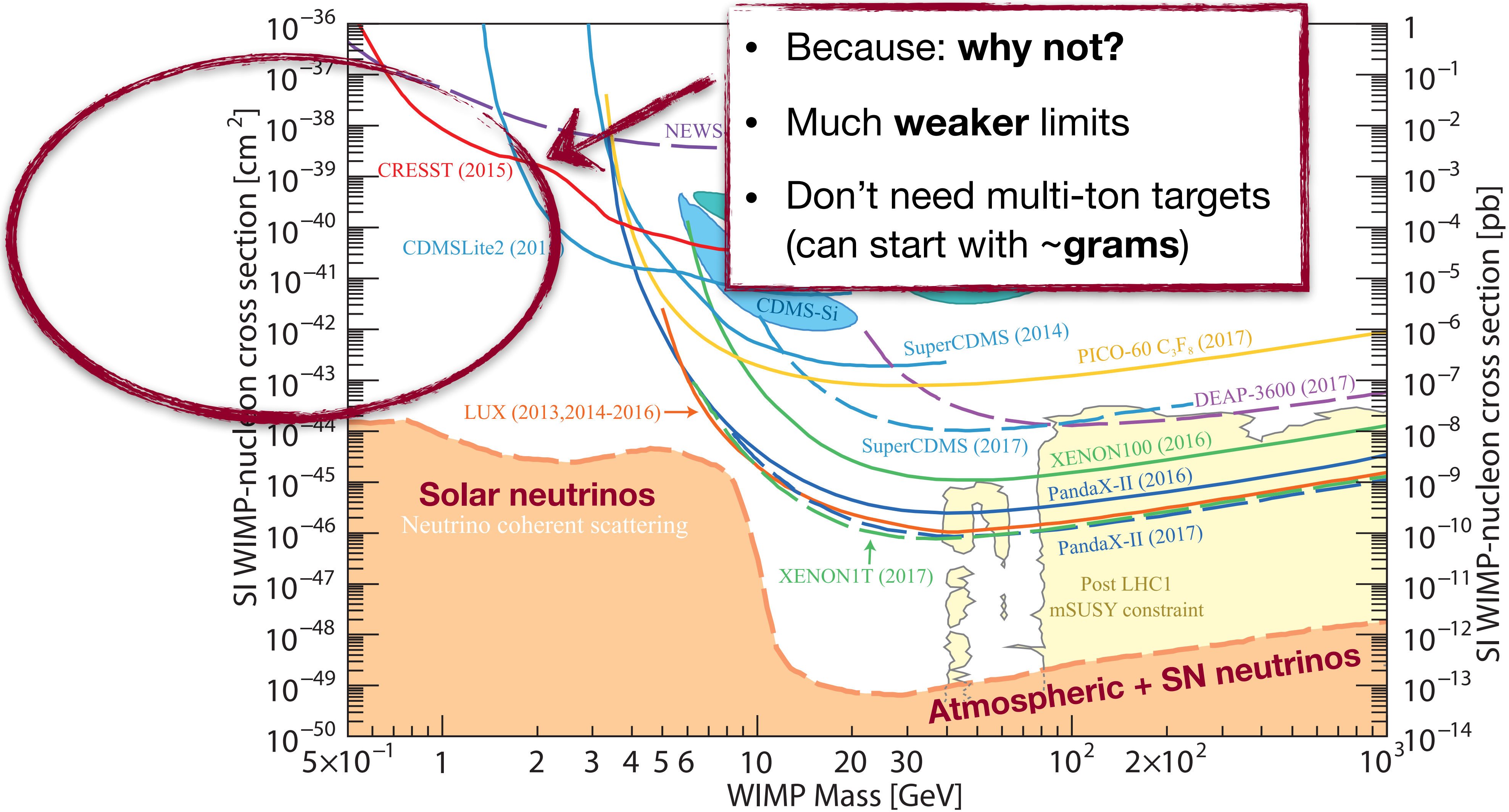


# Aiming for the 'Why Not' Region

- Because: **why not?**
- Much **weaker** limits
- Don't need multi-ton targets (can start with ~**grams**)



# Our Idea: A Carbon Nanotube Target

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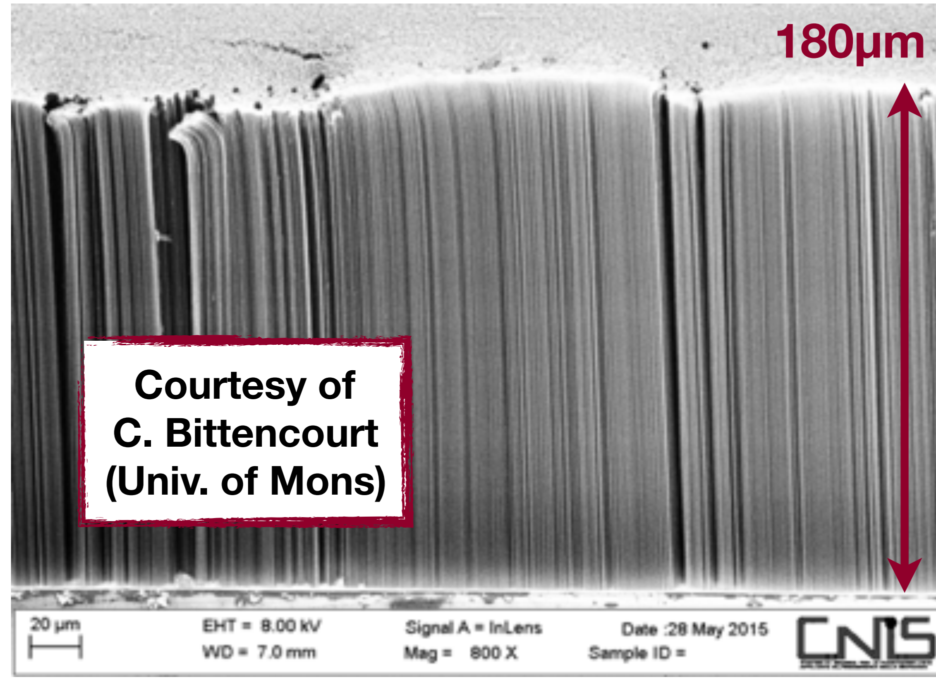
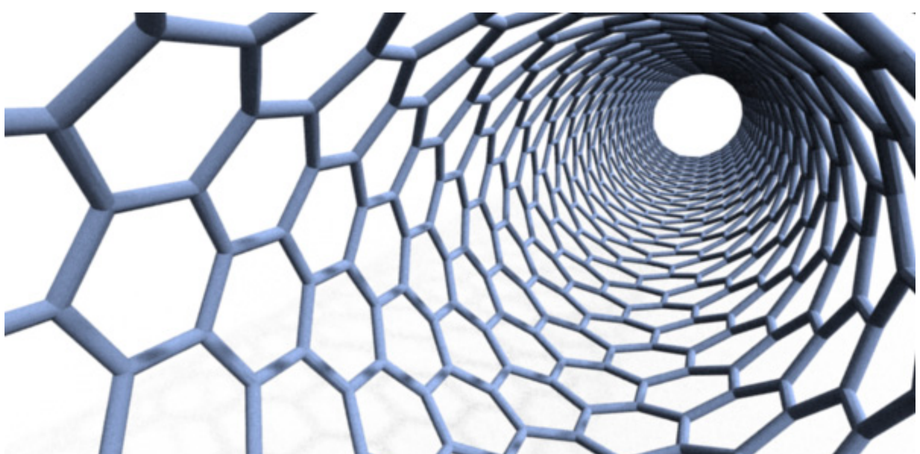
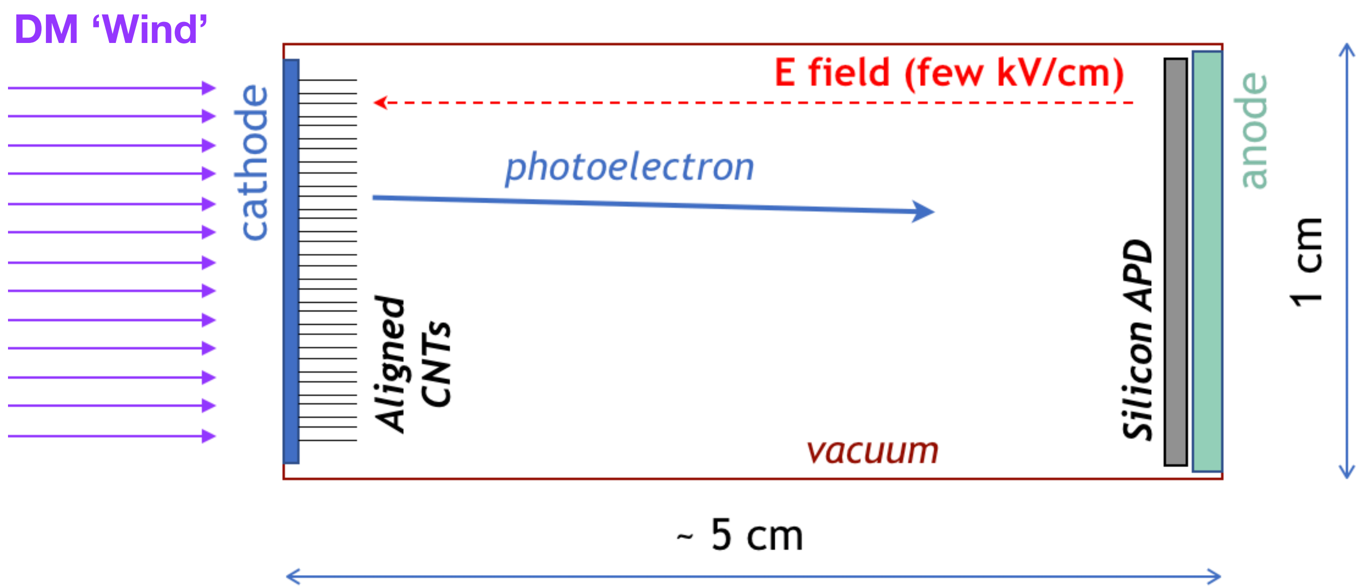
- Arrays of **carbon nanotubes** (CNTs)
  - Diameter: 20 nm
  - Length: up to ~ 300μm
- **Highly anisotropic** material
  - 'Hollow' in tube direction



- Carbon **work function**: 4.3 eV
  - **Unaffected** by thermal noise
  - Sensitive to UV light (λ < 290 nm)

# We Want to Develop a 'Dark-PMT'




- 'Dark-photocathode' made of **aligned CNTs**
  - DM extracts **photoelectron** of few eV
  - $e^-$ escapes **only** if in direction of tube axis

**Directionality by design**

# Directionality Serves Two Purposes

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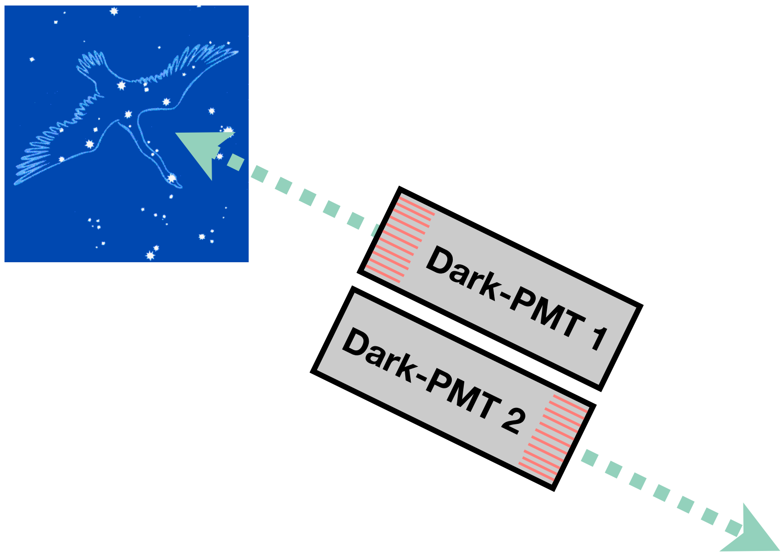
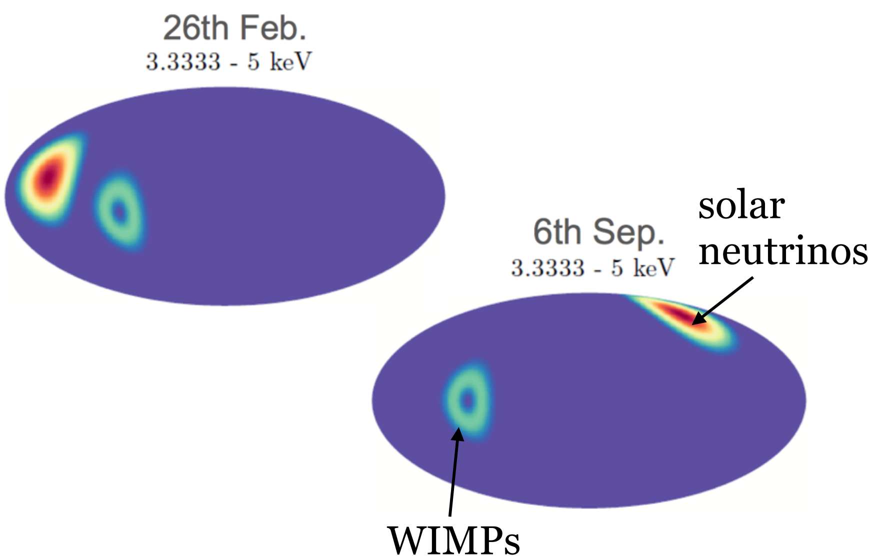
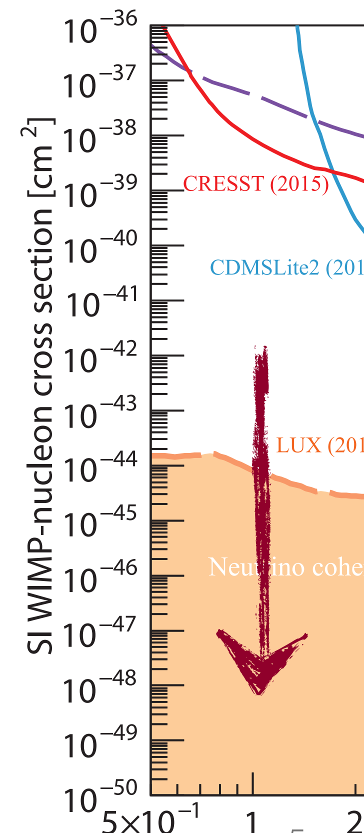



- **Easy** in-situ background measurement
  - Build **two** detectors
  - One pointing to Cygnus, one in **orthogonal** direction
  - Search variable: $N_1$-$N_2$



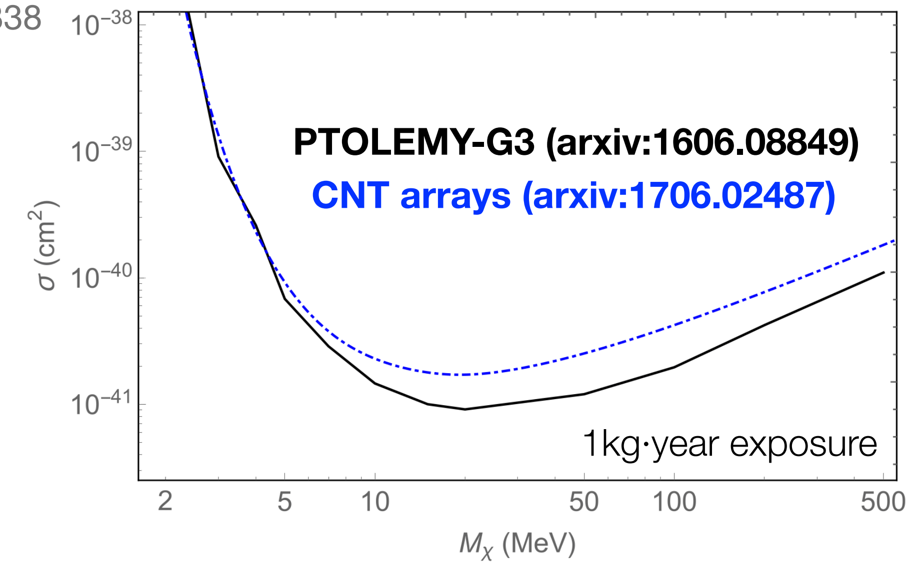

- **Insensitive** to neutrino floor
  - Solar neutrinos never overlap with Cygnus

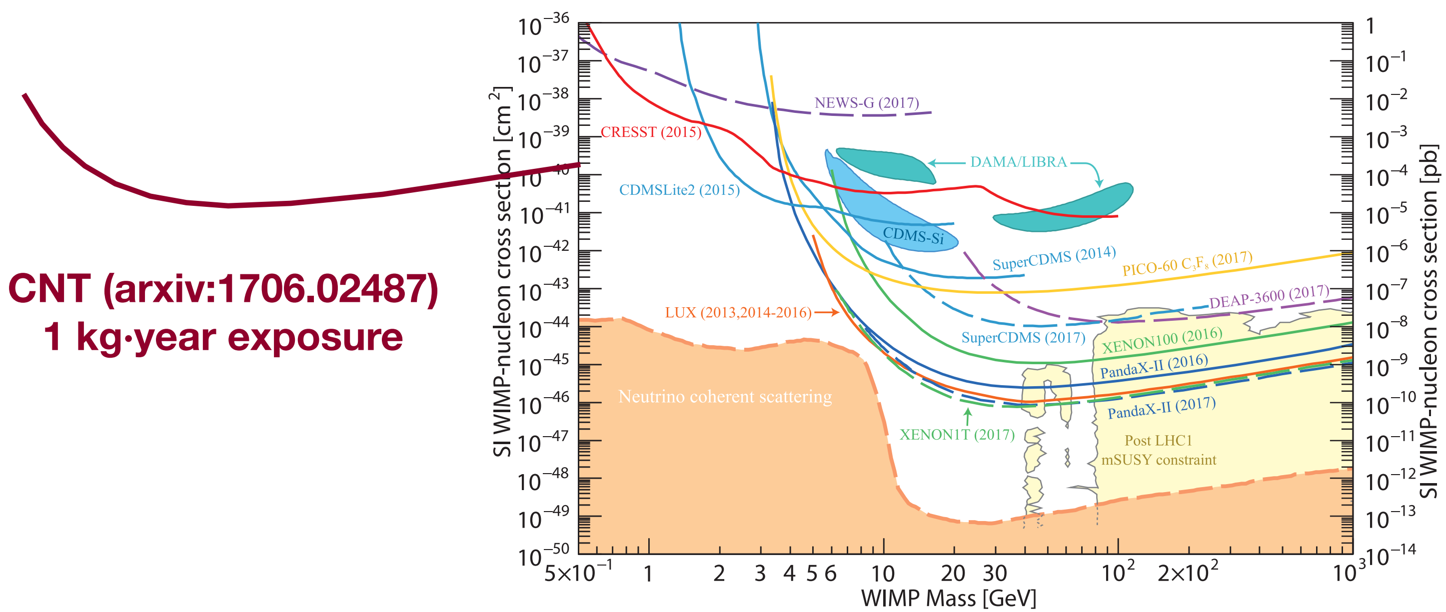


# In Principle It Should Work!

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

- Simple model: idea **should work**
  - Electrons should travel **through** CNTs
  - 1 kg·year exposure: **competitive** limits



# Nanotubes: Wrapped-Up Graphene

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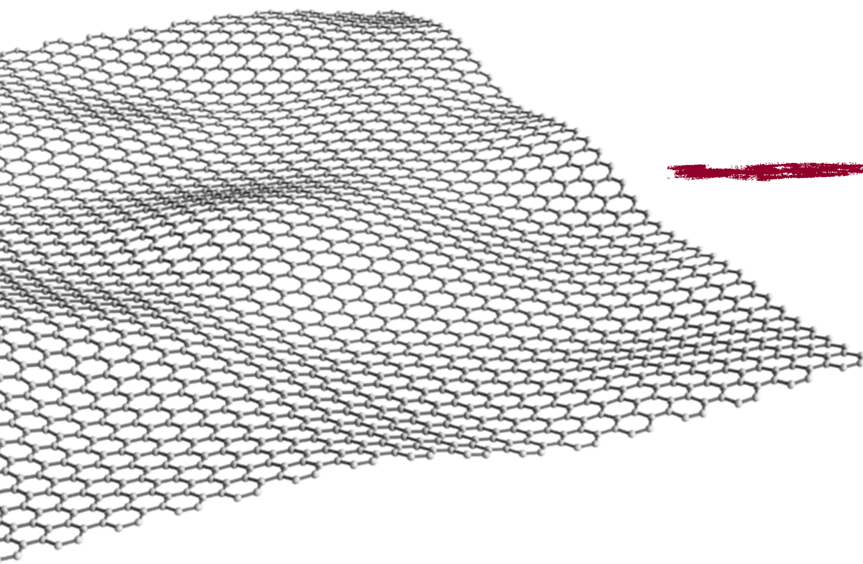
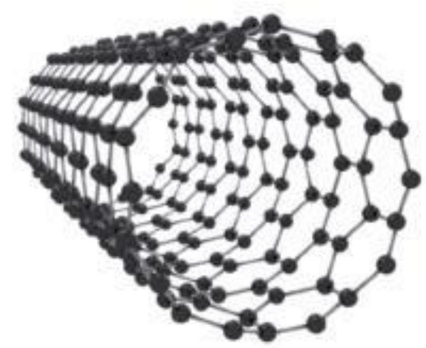
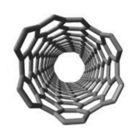
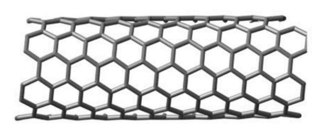
**Graphene**



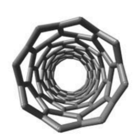
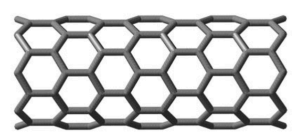
**Single-Wall CNT**



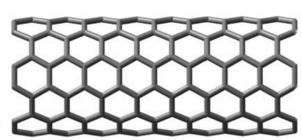
**Metallic or semiconductor depending on lattice structure**

**Chiral**

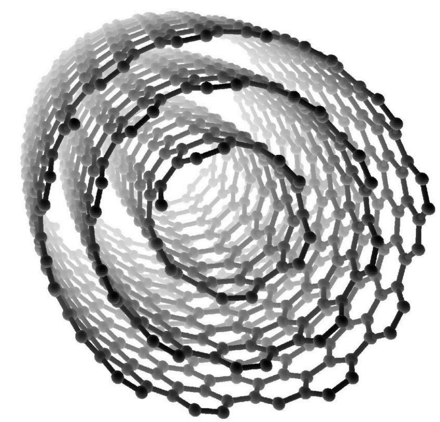
 

**Zig-zag**

**Armchair**

**Multi-Wall CNT**



**Always metallic**

**This talk**

# Aligned CNTs Can Be Grown in Vacuum

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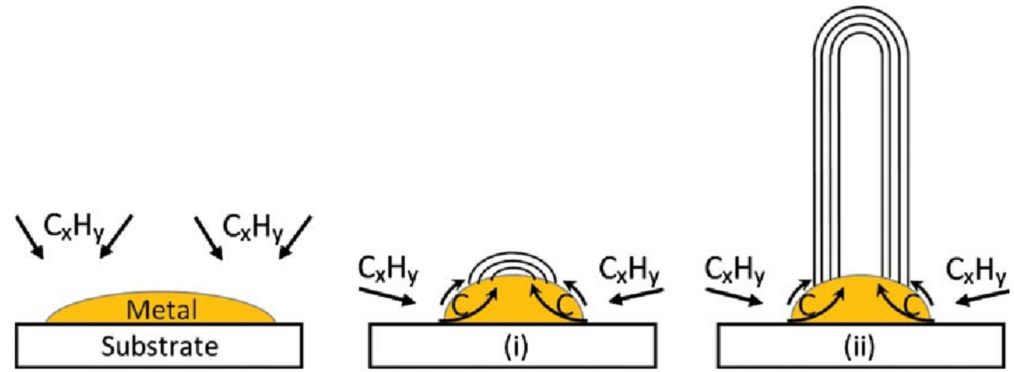
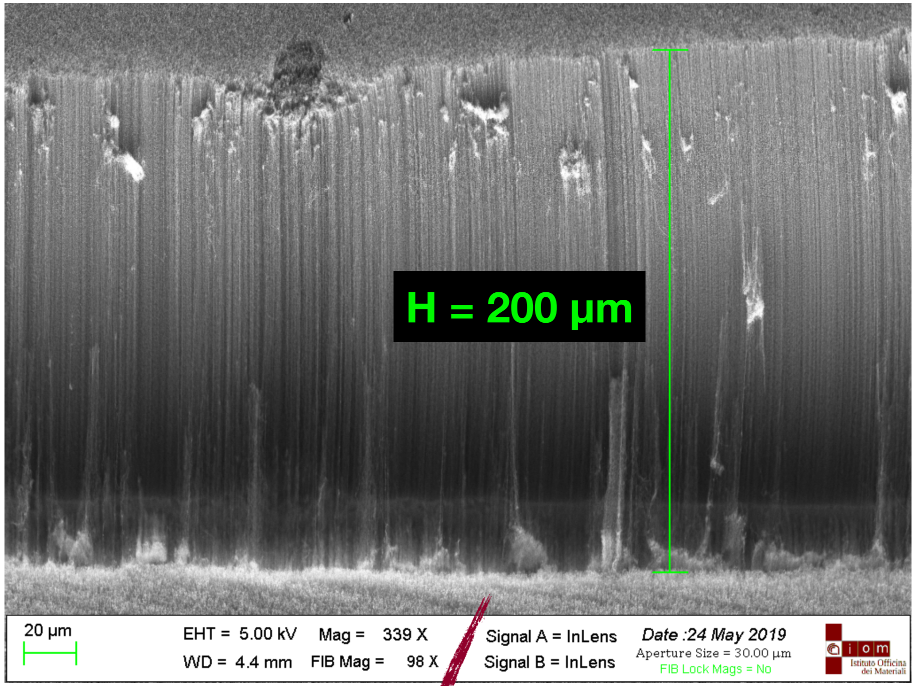
**The CVD chamber at Elettra (Trieste)**

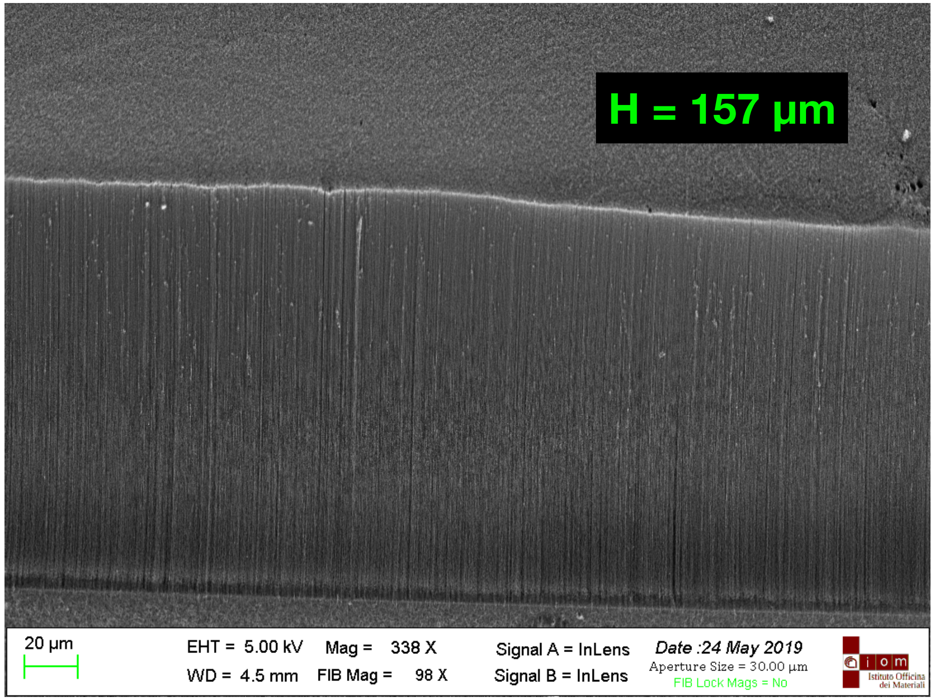



- **Chemical Vapor Deposition** (CVD) growth process
  - In high-vacuum reaction chamber
  - **Catalyst** nanoparticles deposited on substrate
  - **Precursor** gas ($C_2H_2$) injected
  - $C_2H_2$ **decomposed** by catalyst (Fe, Co, Ni)
  - Nanotube grows, catalyst rooted at **base**

# 2019 Growth: We Broke Some Records

- Had access to Trieste CVD chamber
  - Produced **new** batch of CNTs



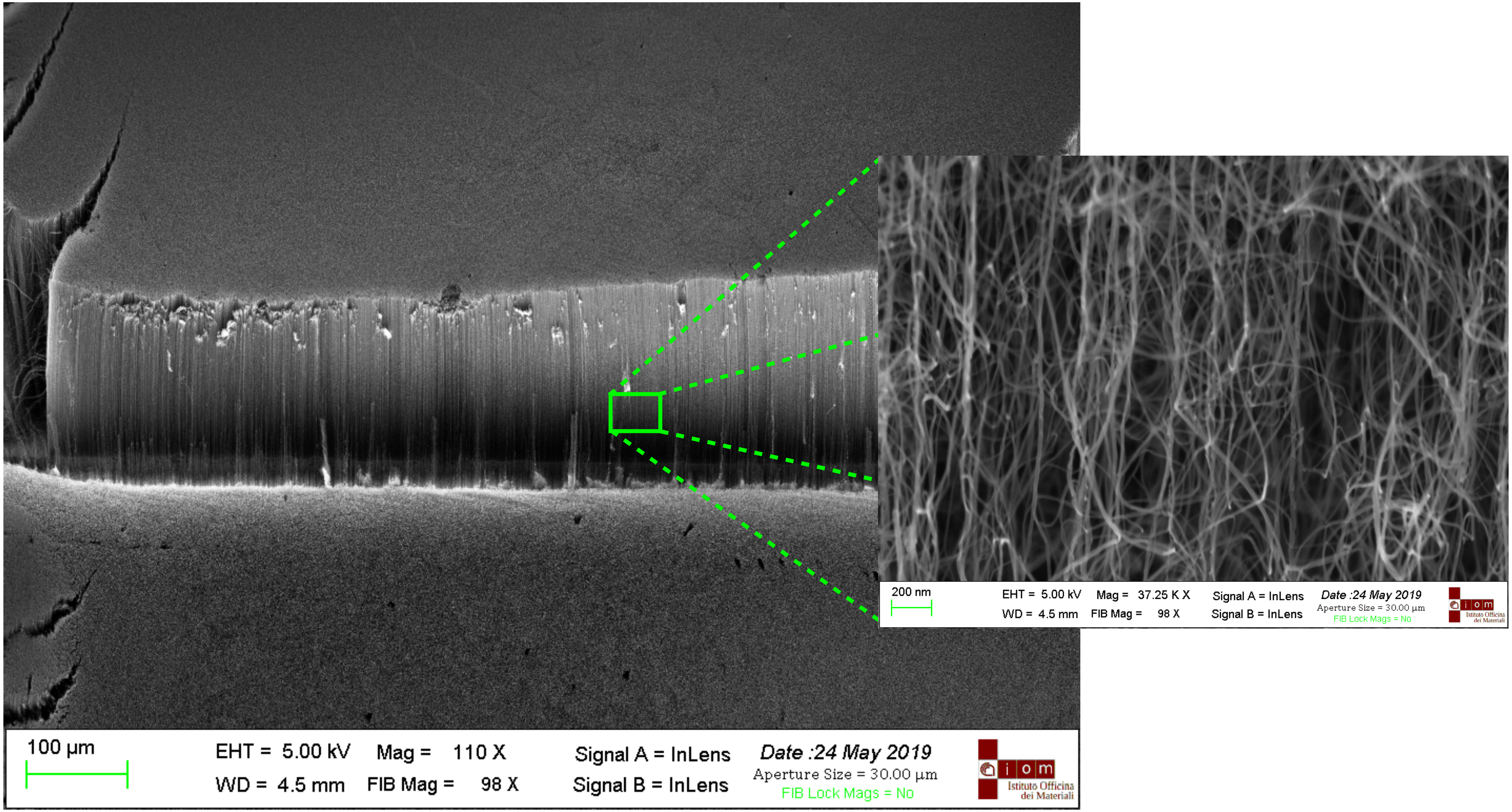




**Silicon substrate**

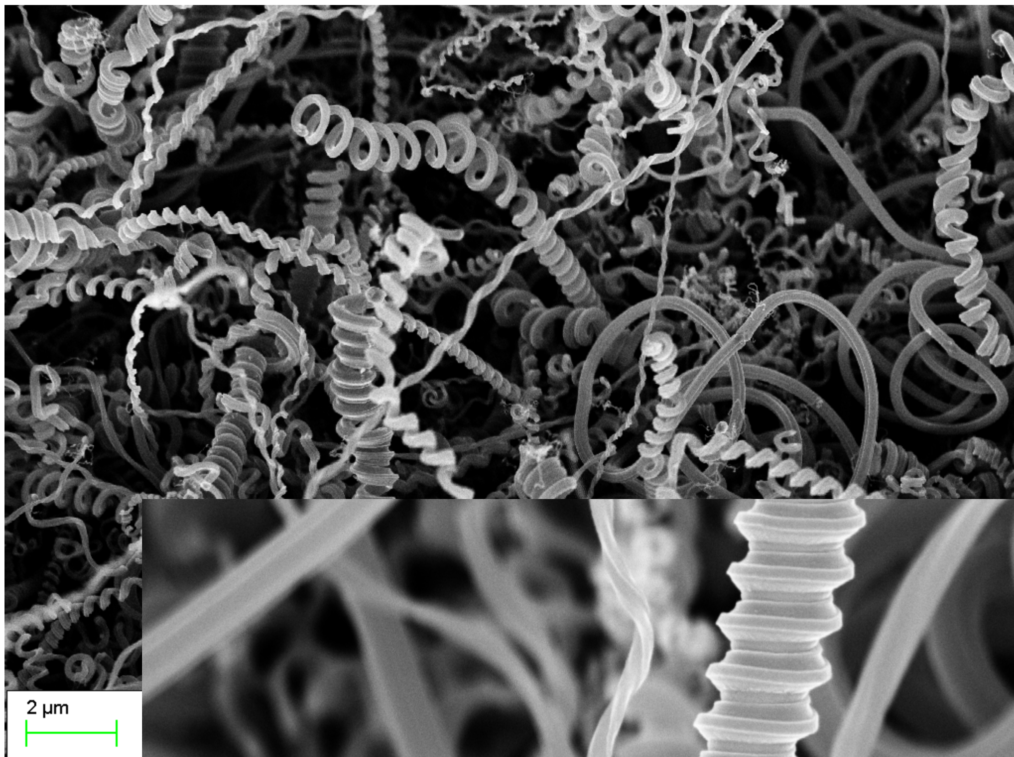
**Fused silica substrate**

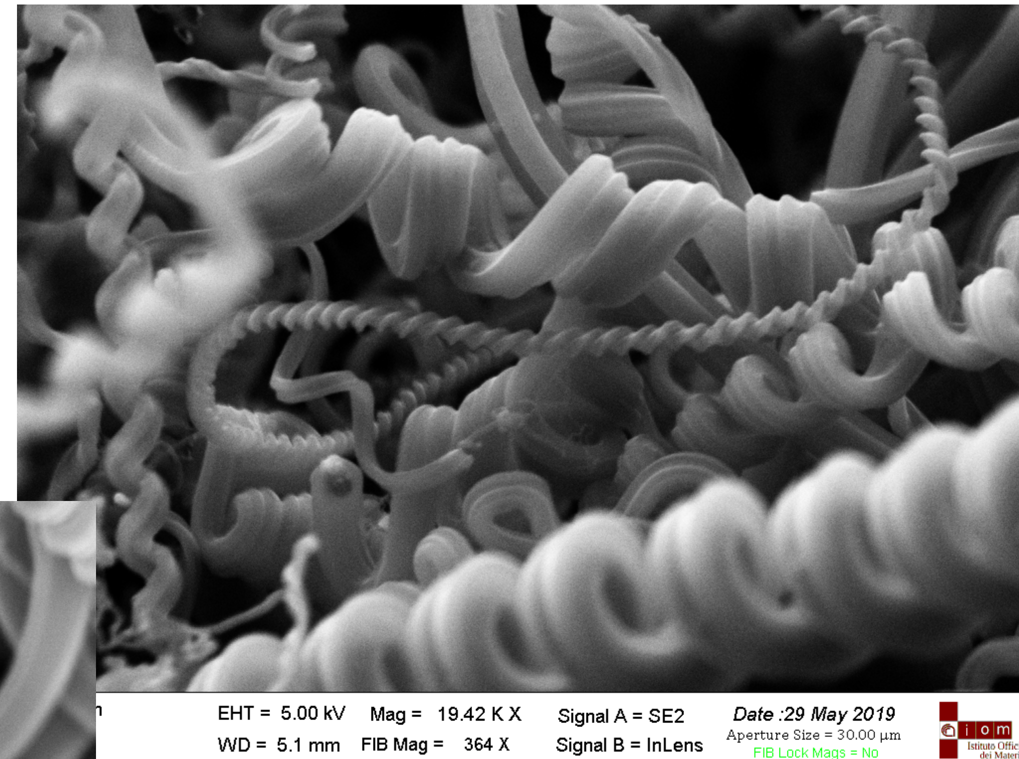
**(Longest CNTs ever grown on fused silica)**

# Zooming On the Sides: There's Structure



# We Also Tried to Grow Tubes on ITO





**…and we got nano-fusilli**

**(also a record?)**

# Anisotropy Observed with $Ar^+$ Ions

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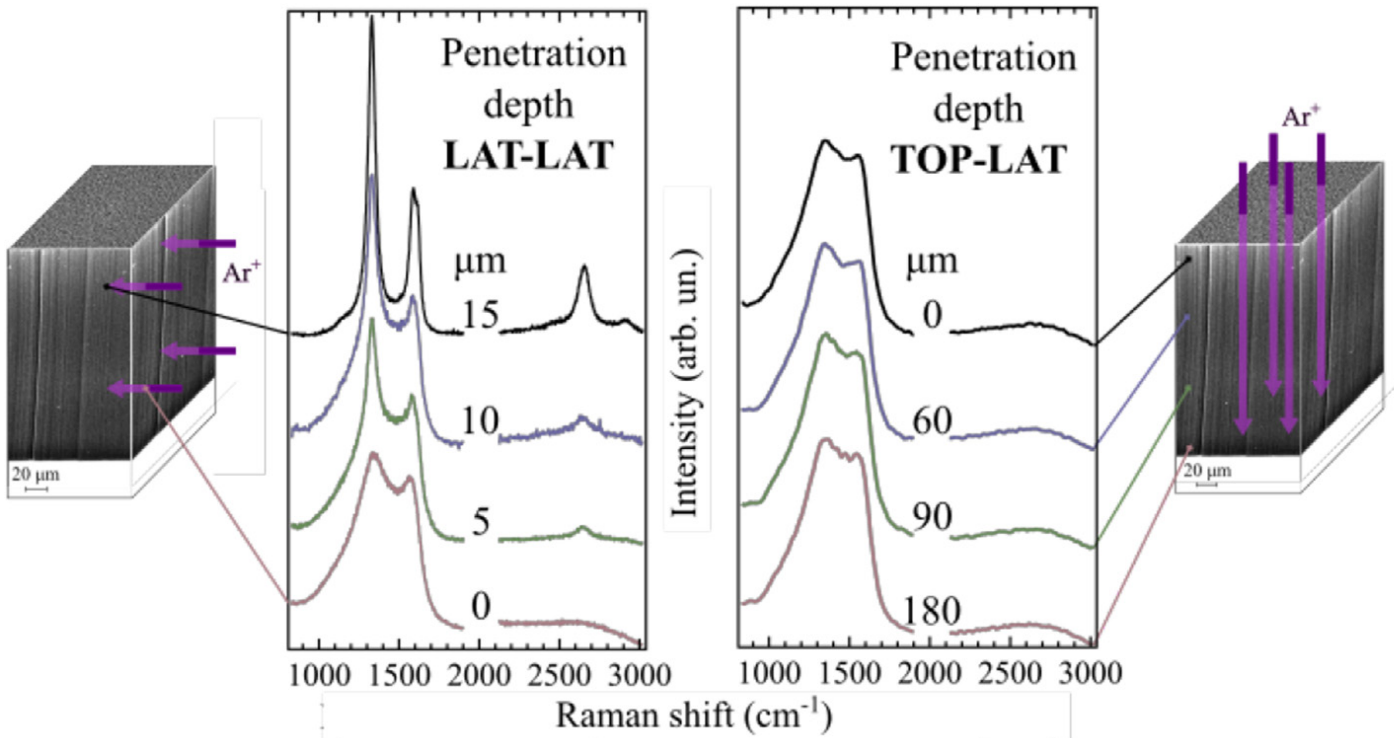
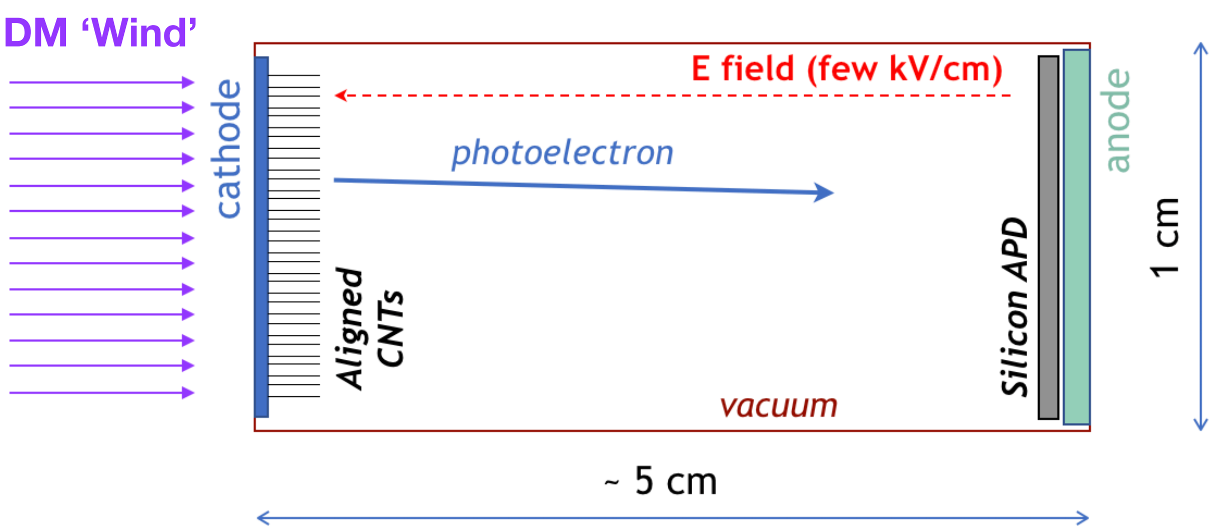
G. D'Acunto, et al., Carbon 139 (2018) 768

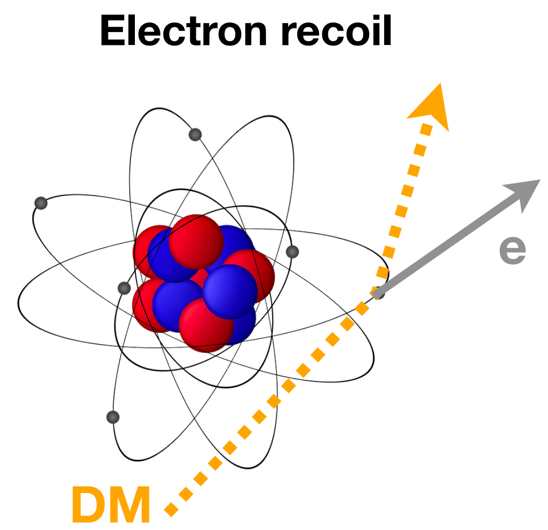



**See talk by F. Ripanti**

- ❖ **Raman** analysis after $Ar^+$ bombardment
  - **Side** penetration < 15 µm
  - Longitudinal damage along **full** CNT length (180 µm)
- ❖ Filtering for **electrons** yet to be proven
  - **Aim** of 2019-20 R&D

# What About the Other Side?



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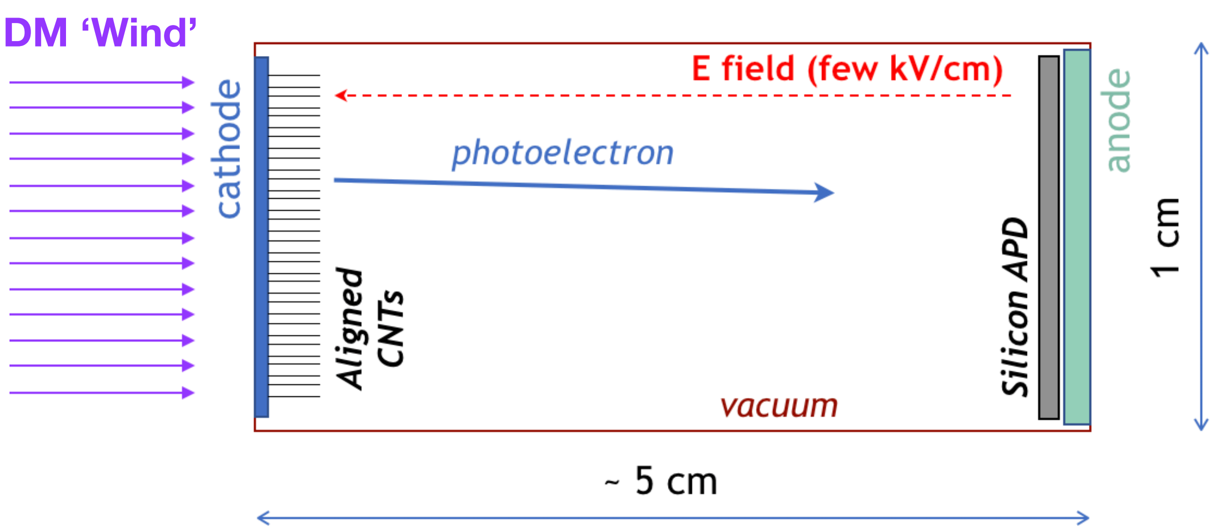


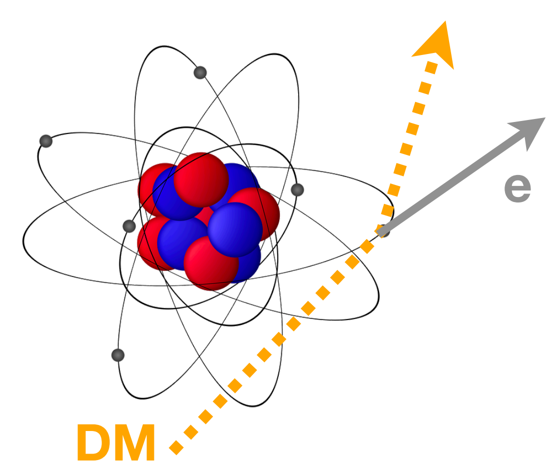


- **Classical** approx: $E_{DM} \sim 1/2\ M_{DM}\ (v/c)^2$
  - with v = 300 km/s:
    $E_{DM} \sim 0.5\ (M_{DM}/\text{MeV})$ [eV]
  - so if **all** E transfered to $e^-$:
    $E_e \sim 5\text{-}50$ eV (for $M_{DM}$ = 10-100 MeV)

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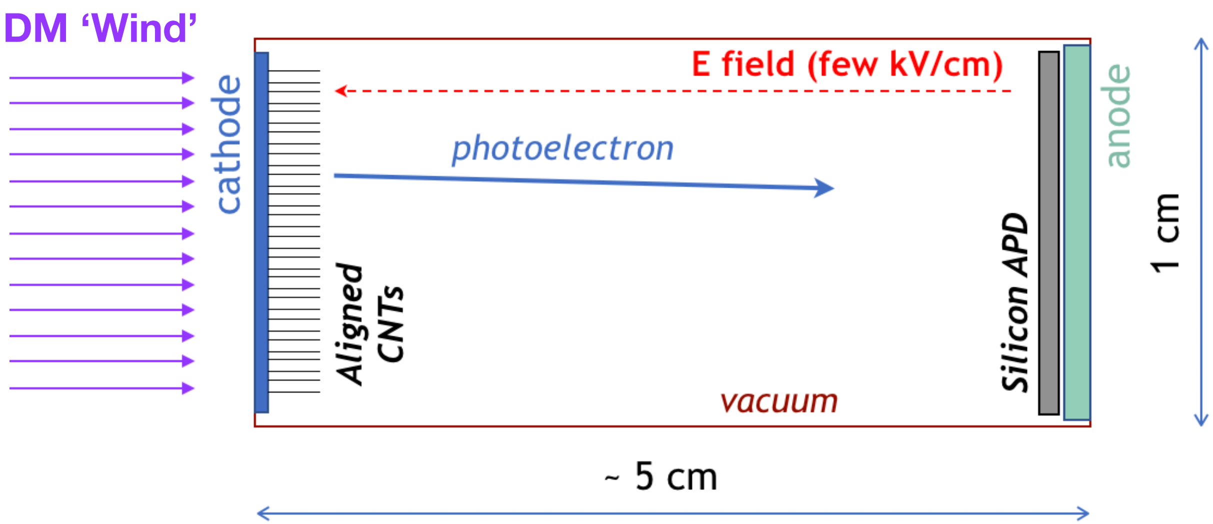


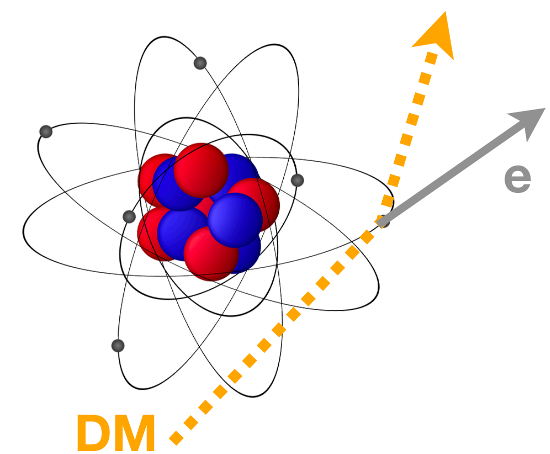


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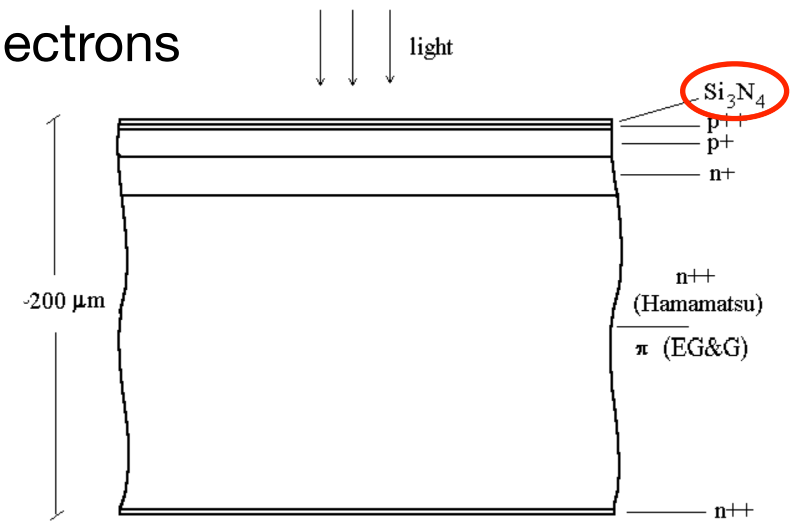
❖ With field of few kV/cm: electrons accelerated to **few keV**

- Need to detect them (with high efficiency)
- Not a **completely** trivial task

# Using APDs for Low-Energy Electrons

- Commercial APDs designed for **photons**, not electrons
  - Protective **'window'** covers silicon
  - Serves as **photocathode**
  - **Absorbs** low-energy electrons



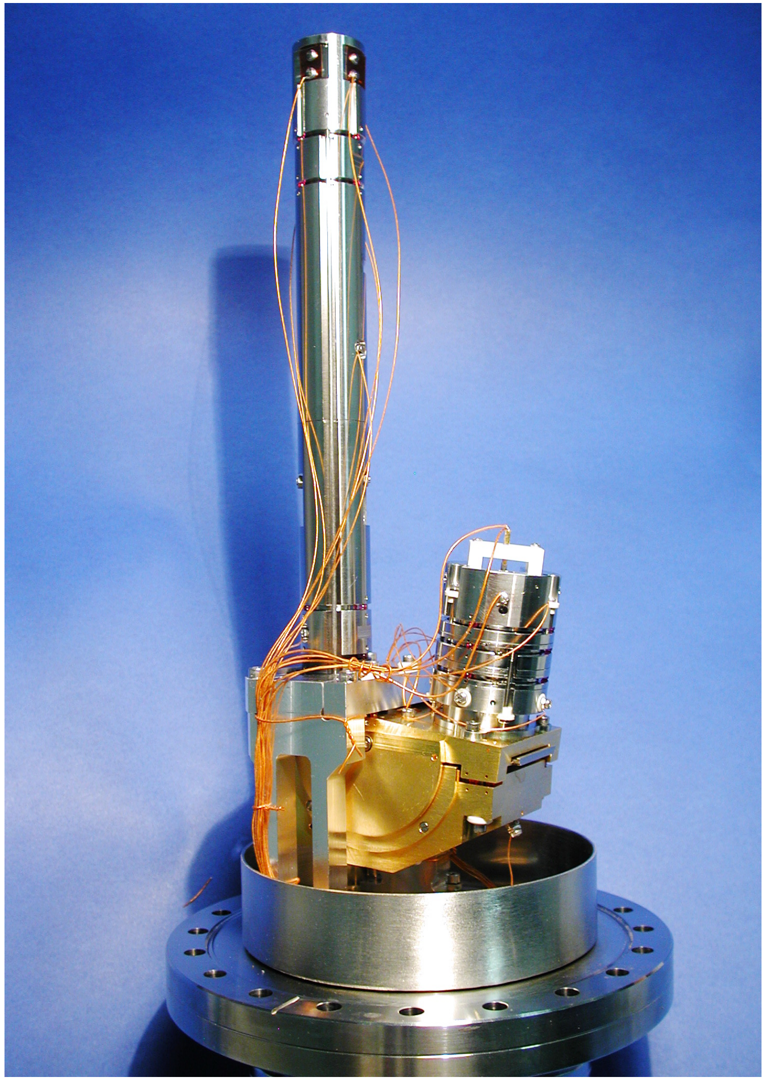

- **Windowless** APDs from Hamamatsu
  - Sensitive area ⌀ = 3 mm

- **Challenge**: measure single-e⁻ efficiency

$$\epsilon = \frac{N^e_{detected}}{N^e_{onTarget}}$$

# The Rome-3 Electron Gun Facility

- Electron **energy**: 90 < E < 500 eV
  - Uncertainty on E: 45 meV
  - Will **upgrade** to reach 1 keV
- Gun **current**: 3 < I < 38 nA
  - Could go down to ~ 10 fA
- Beam profile < 1 mm
  - Completely **contained** on APD ($\varnothing$ = 3 mm)



# In-Situ Beam Profile Measurement

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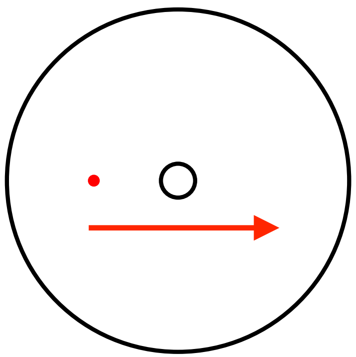
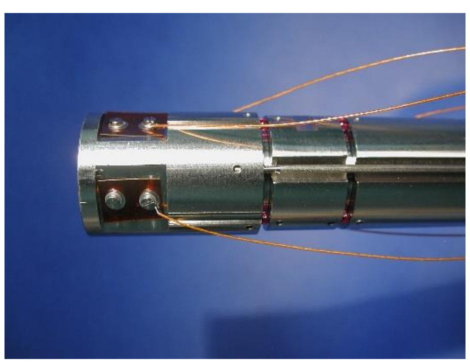
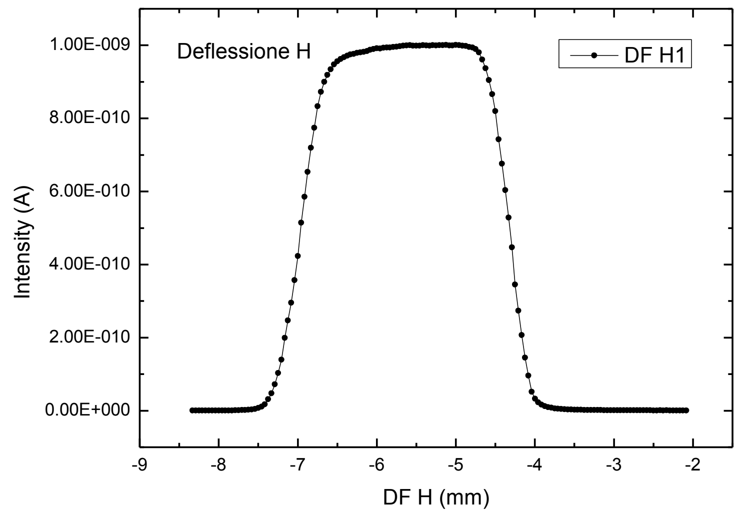
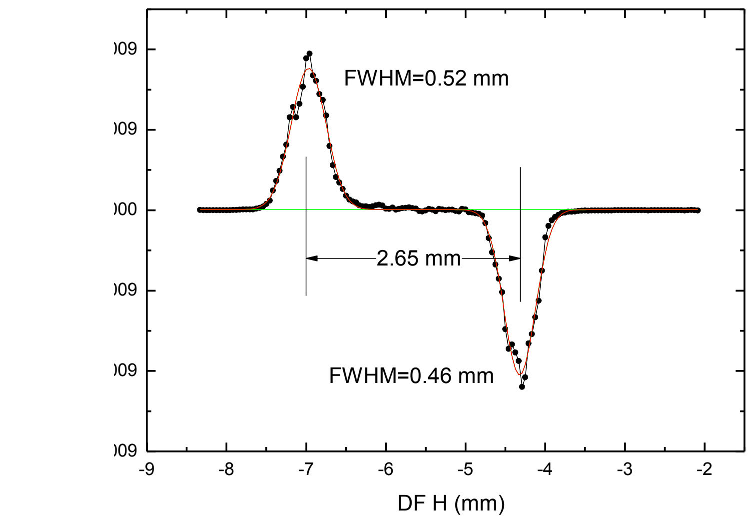
## e-beam on Faraday cup

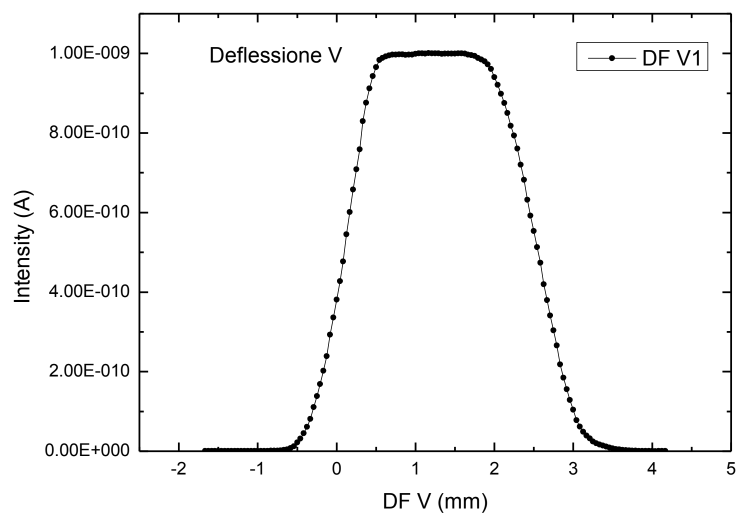


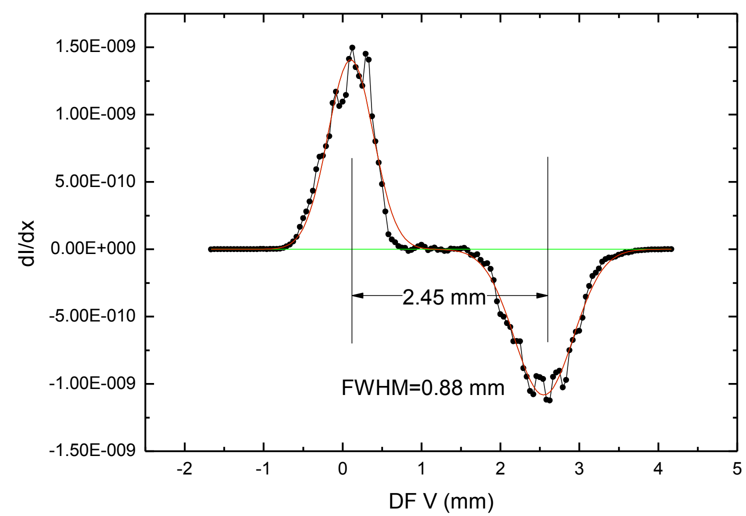
## Deflection plates





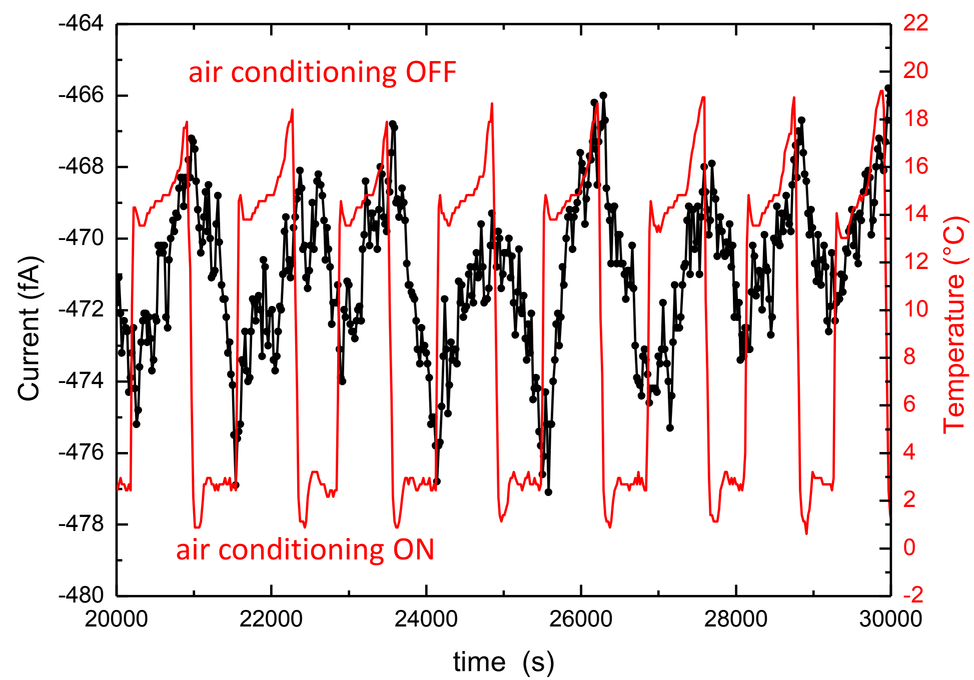



# Can Probe the Single-Electron Regime

- Keysight B2987A picoamperometer
  - Can measure down to 0.01 fA
- Allows to **lower** gun current
  - **Lowest** measurement:
    I(gun) = 8.6 fA ± 310 aA (!)
- Apparatus so **sensitive** that we saw ~10 fA fluctuations
  - **Linked** to AC cycle
  - Now **fixed**



# Inserting the APD in the Vacuum Chamber

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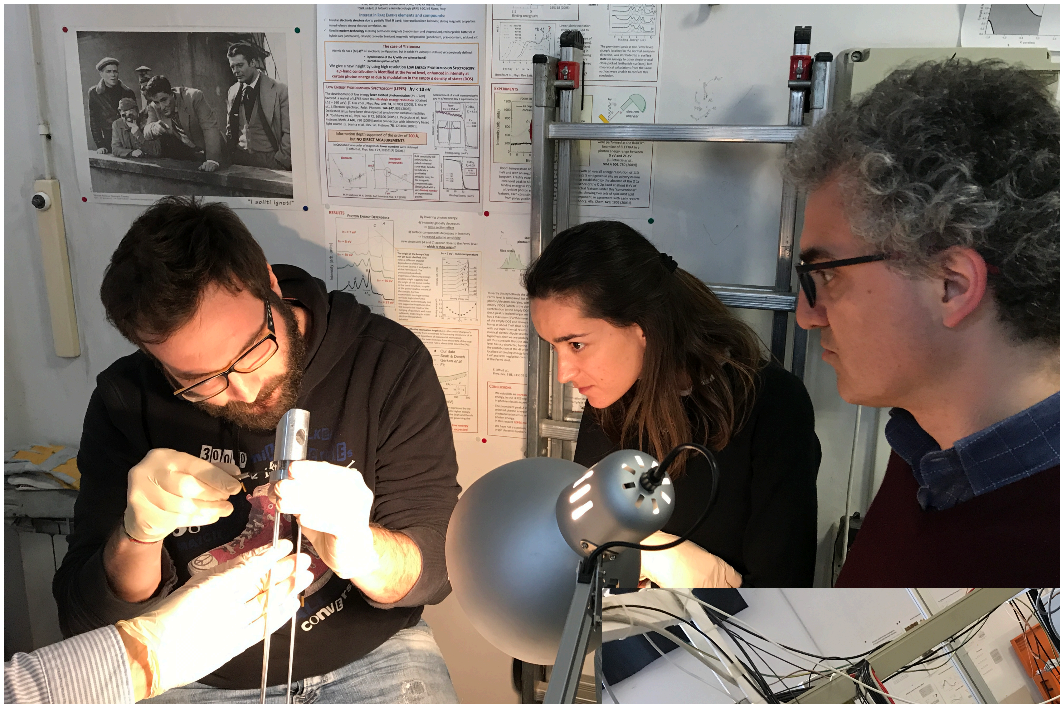

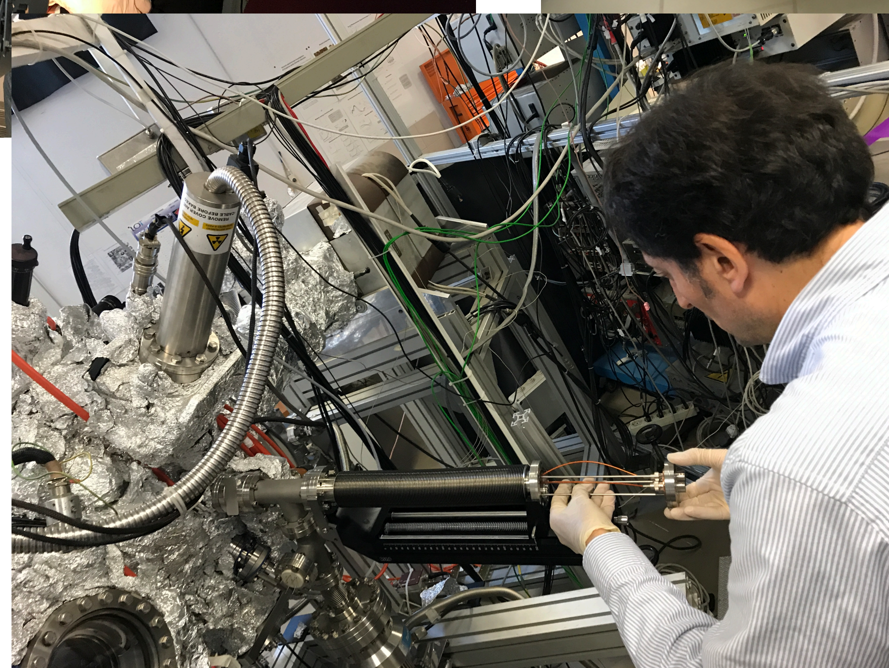

# Aiming the Gun on the APD

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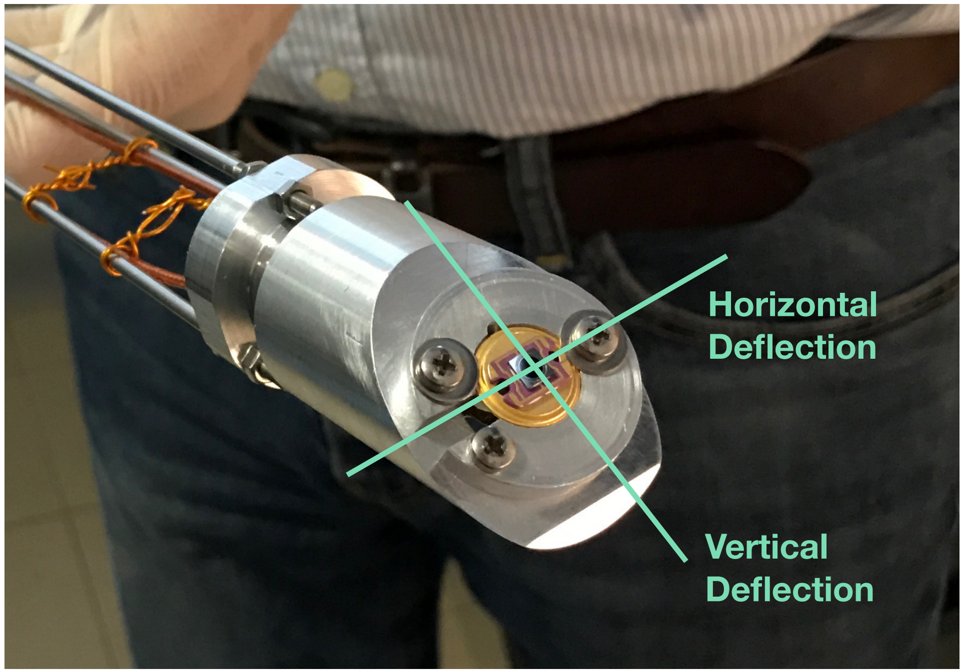
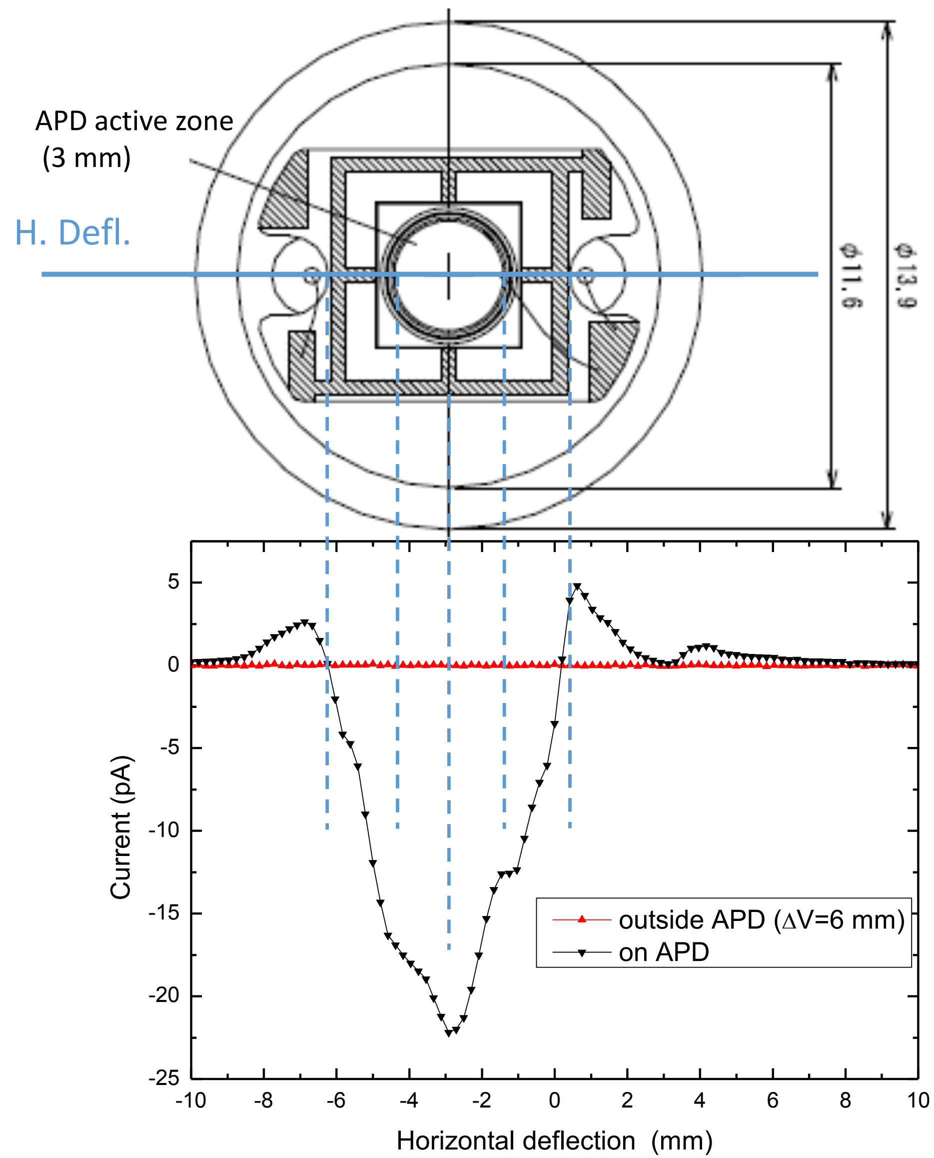
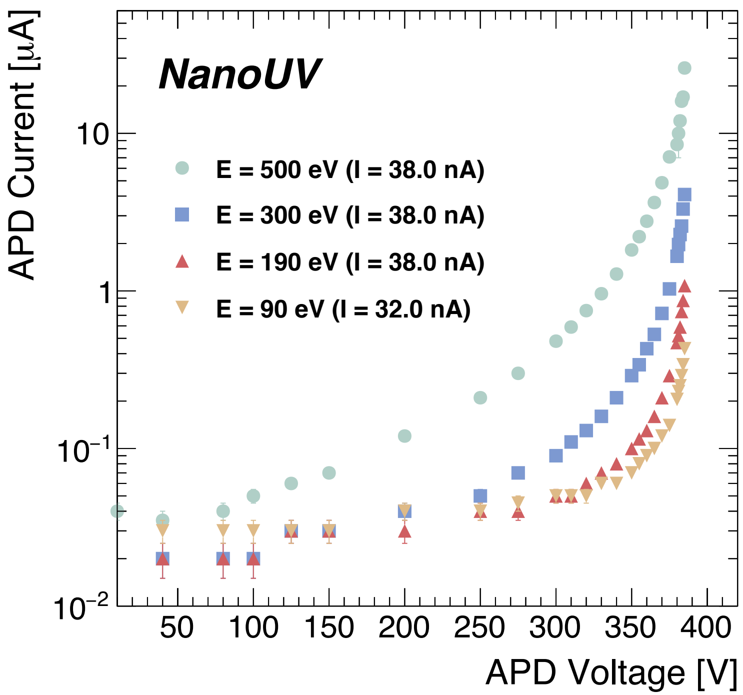


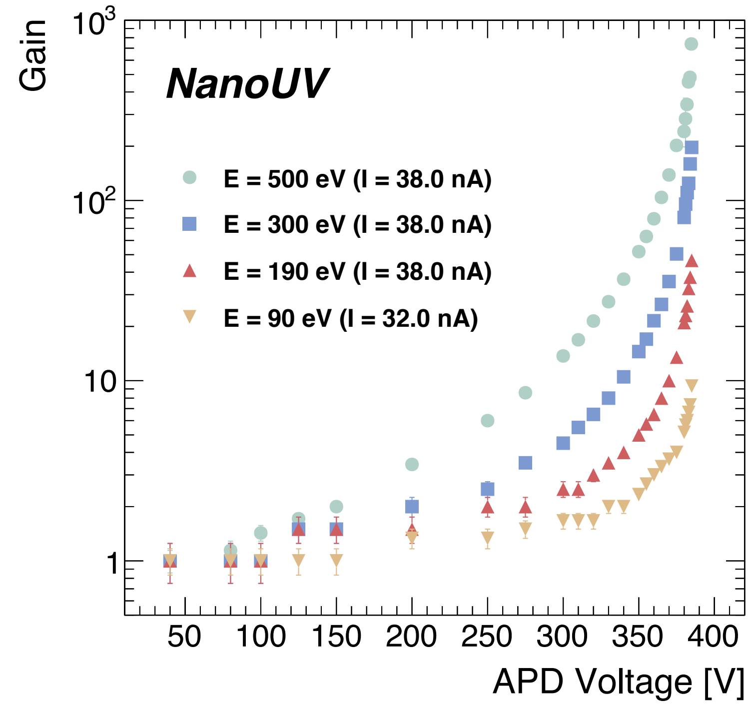

- ❖ Scanning gun position (V and H)
  - Reading APD with picoamperometer
  - Can **clearly** see APD structure

# We're Able to See 90-500 eV Electrons (!)

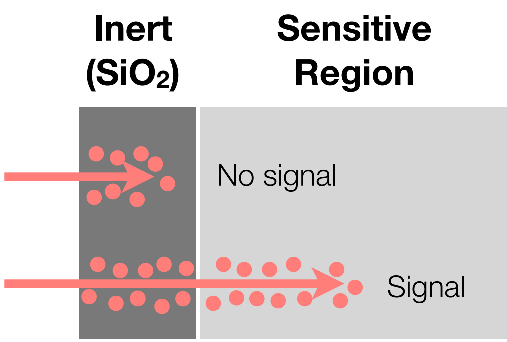
**I-V Curve**




**Gain**

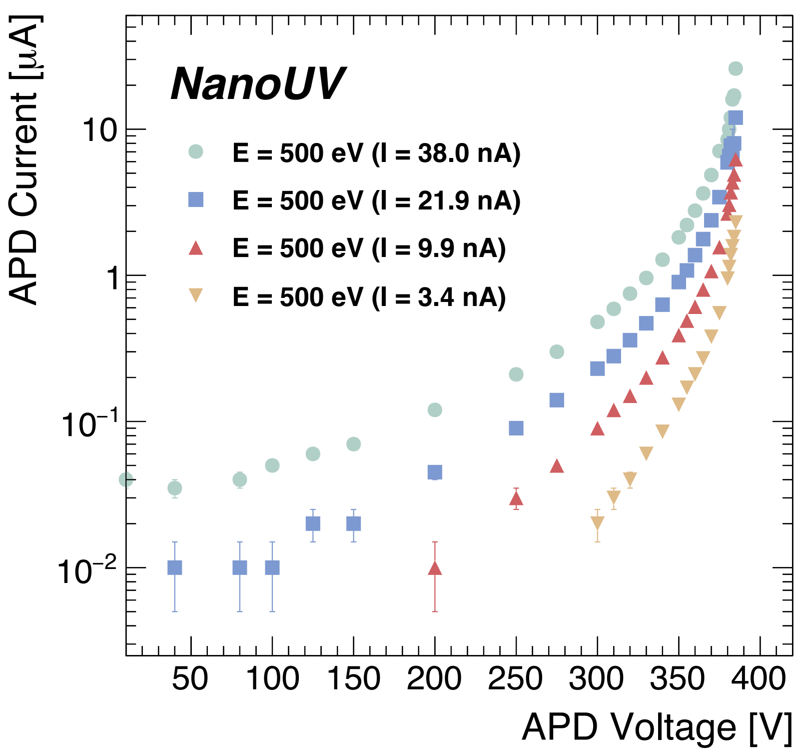



- Still **only** at I-V level (not pulses)
  - Upgrading electronics: new gun test **soon**

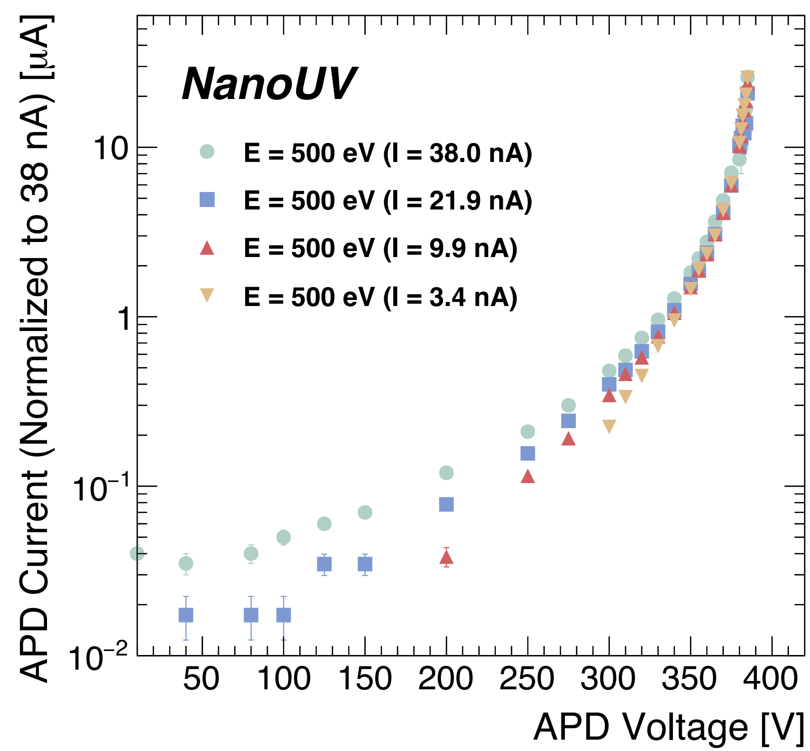


# APD Current Scales with Gun Current

**I-V curves for different I(gun)**




**Normalized to 38 nA**




**… proving that we are indeed seeing the gun electrons**

# First Step: Building a 'Dark-PMT$_{UV}$'

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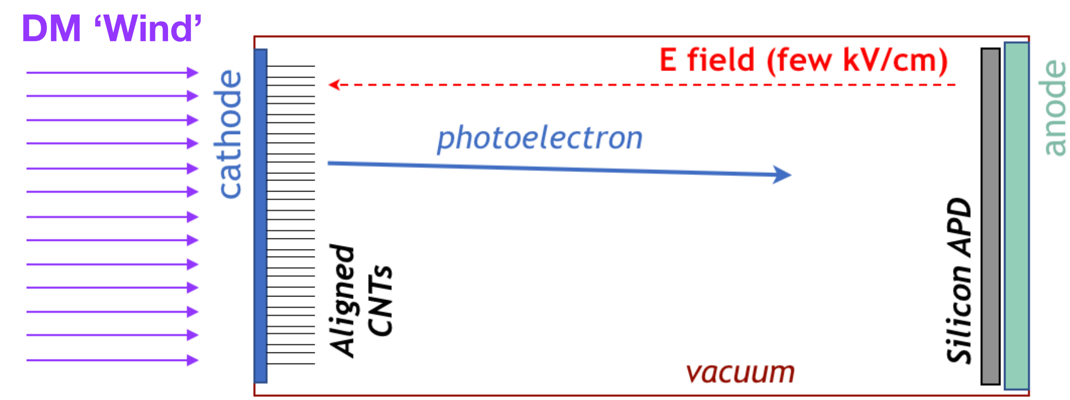


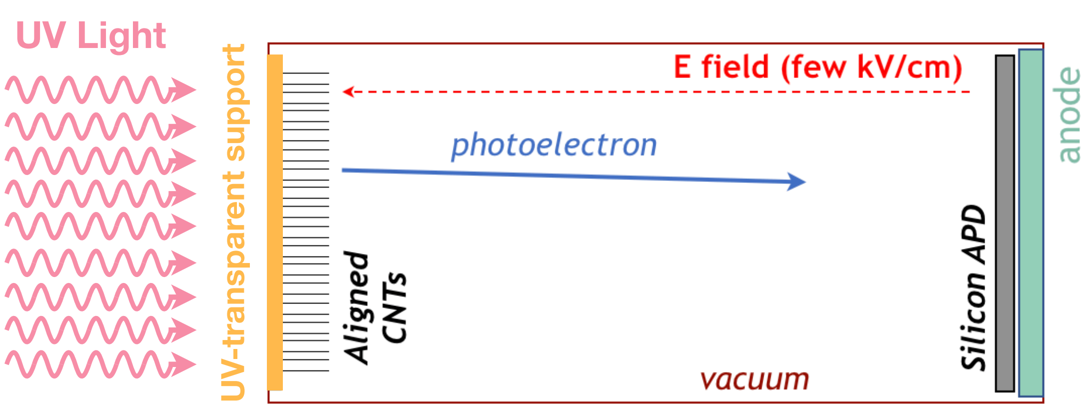


- **Same** operating principle
  - Instead of DM → UV photons
  - UV-transparent support (eg fused silica)
- Important **benchmark**
  - **Proof** that can extract electrons from nanotubes
- **Same** challenge for APDs
  - Detect 1-10 keV electrons

# The ‘Side Project’ Got Traction

- **NanoUV**: development of a high-efficiency photocathode for UV light detection

- One of 170 conceptual breakthrough ideas funded by **ATTRACT** (attract-eu.com/)
    - 100k EUR for **1 year** (May 2019 - May 2020)
    - Aim: build a **working demonstrator**
    - If successful, might obtain larger funding (1.7M) next year (only 10 projects)


- Will build **CNT growing facility** at Sapienza

# The Next 10 Months Will Be Intense

- By May 2020 we intend to:
  - **Finalize** APD characterization with low-energy electrons
  - Design and construct a NanoUV **demonstrator**
  - Demonstrate that UV photons **eject electrons** from nanotubes
  - Build a fully operational **CNT growing facility** in Sapienza
- It's an ambitious program, it's going to be **hard**
  - But: *We choose to go to the Moon, **not** because it's easy…*
  - And we're having **loads** of fun

# Conclusions

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- We want to build a DM detector based on **carbon nanotubes**: ‘Dark-PMT’
  - Electron recoil: sensitive to **sub-GeV** Dark Matter
  - **Directionality** by design (in-situ background estimation)
- **Succesful** CNT growing campaign in 2019
  - Already some **record-breaking** growths
- APD **characterization** with low-intensity electron gun
  - Seeing electrons with $90 < E < 500$ eV
- ATTRACT **funding** to develop a CNT-based UV light detector
  - Will build a **CNT growing facility** in Sapienza