Carbon Nanostructures
for Directional Light Dark Matter Detection

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ROMA TRE
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University of Birmingham
20.01.2021

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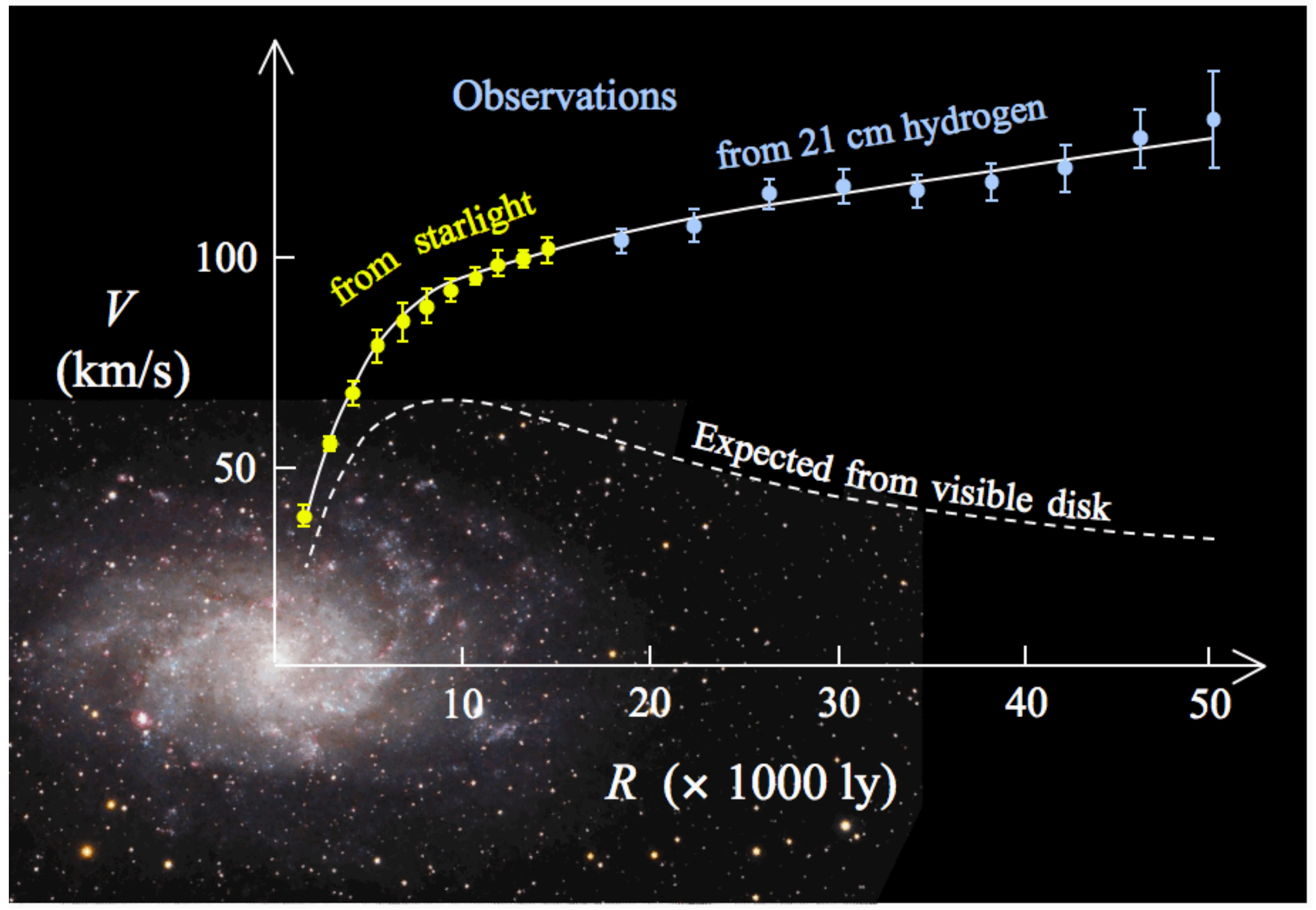
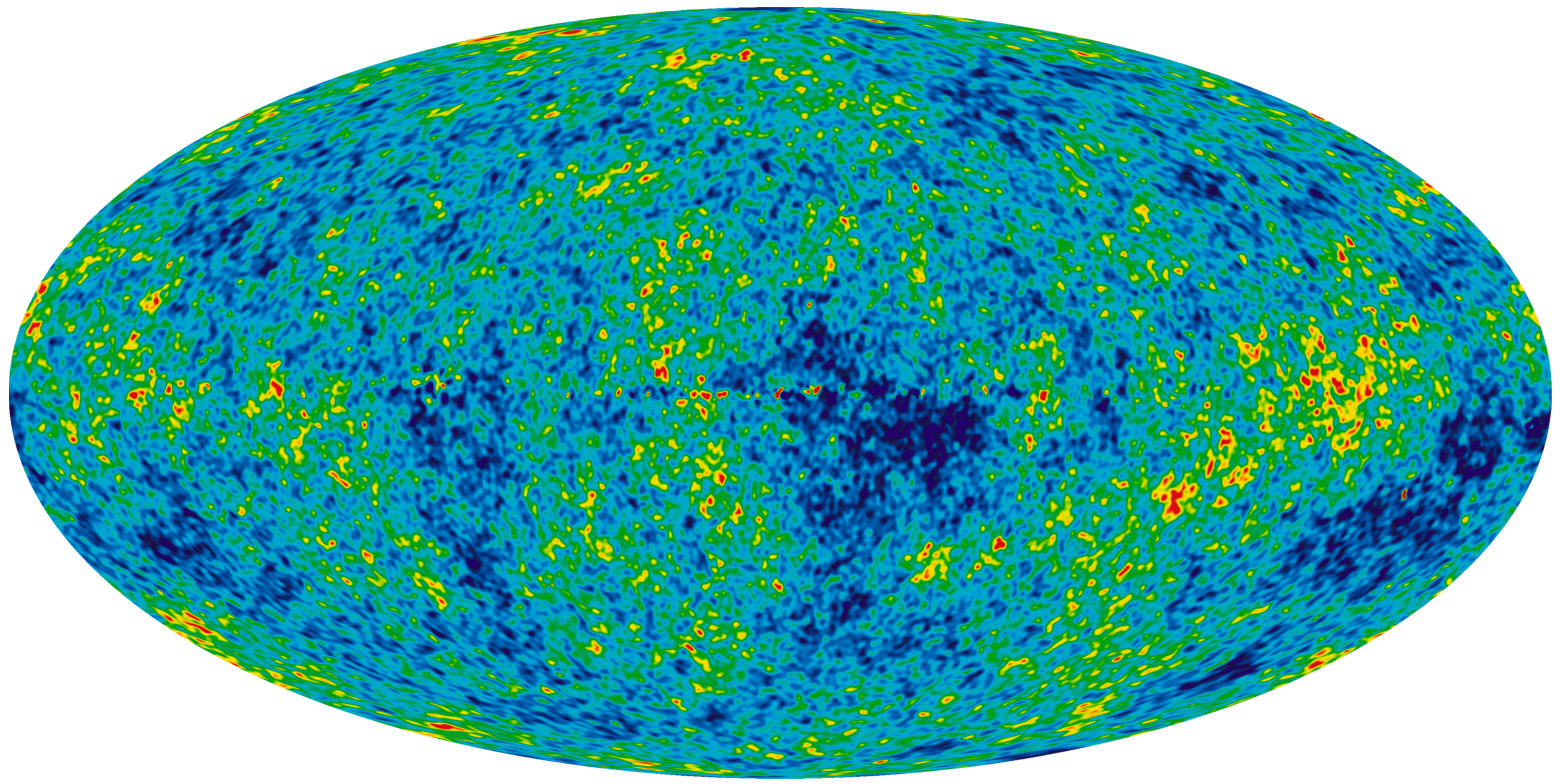
85% of the Matter of the Universe Unaccounted For

Rotation curves



Bullet cluster

CMB

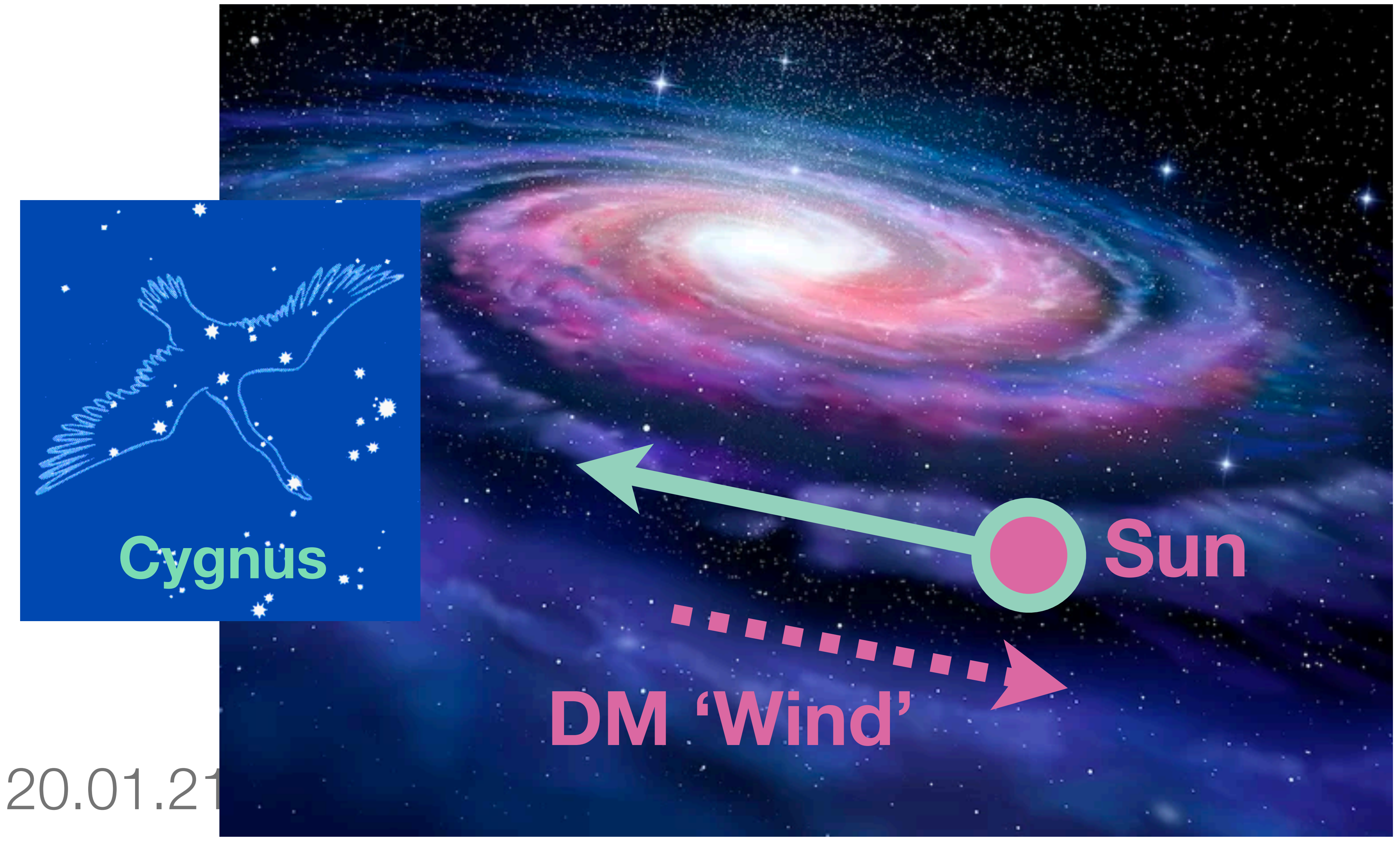


The Rise of the ΛCDM Model

- In ΛCDM, dark matter is:
  - Massive
  - Electrically neutral
  - Not self-interacting (‘cold’)
  - Gravitationally interacting with ordinary matter

	Ω	$\Omega \cdot h^2$
Atoms	0.048	0.022
Dark Matter	0.26	0.12
Dark Energy	0.69	—

- Primordial **fluctuations** in DM density → virial wells
  - ‘Seeds’ for galaxies
- On Earth: DM ‘wind’ from **Cygnus** constellation
  - Non-relativistic speed ($v_{DM} \sim 10^{-3}$ c)



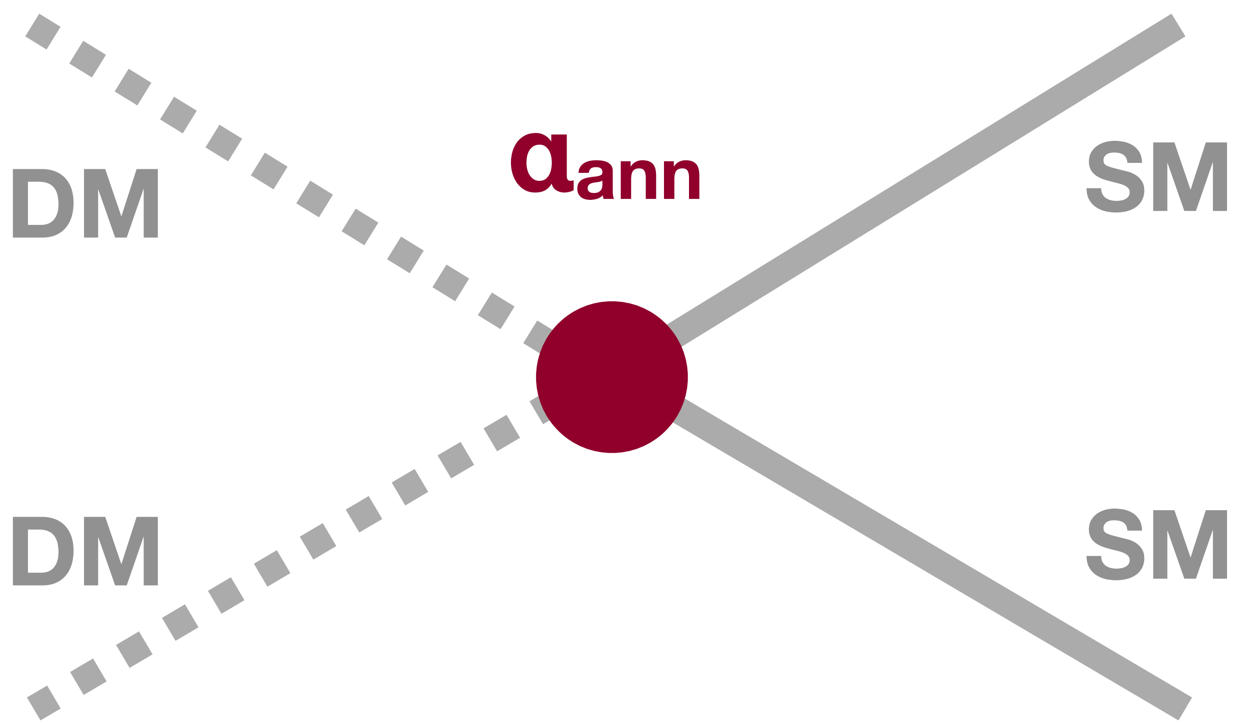
The WIMP and Its 'Miracle'

- For correct relic abundance $\Omega_d \sim 0.12$ after 'freeze-out', one needs: $\langle\sigma v\rangle \sim 1$ pb
  - Which is **exactly** what one gets for a 100 GeV particle with **electroweak** couplings

- In **WIMP** paradigm dark matter is:
  - Massive **(M ~ 100 GeV)**
  - Electrically neutral
  - Not self-interacting ('cold')
  - Gravitationally interacting with ordinary matter

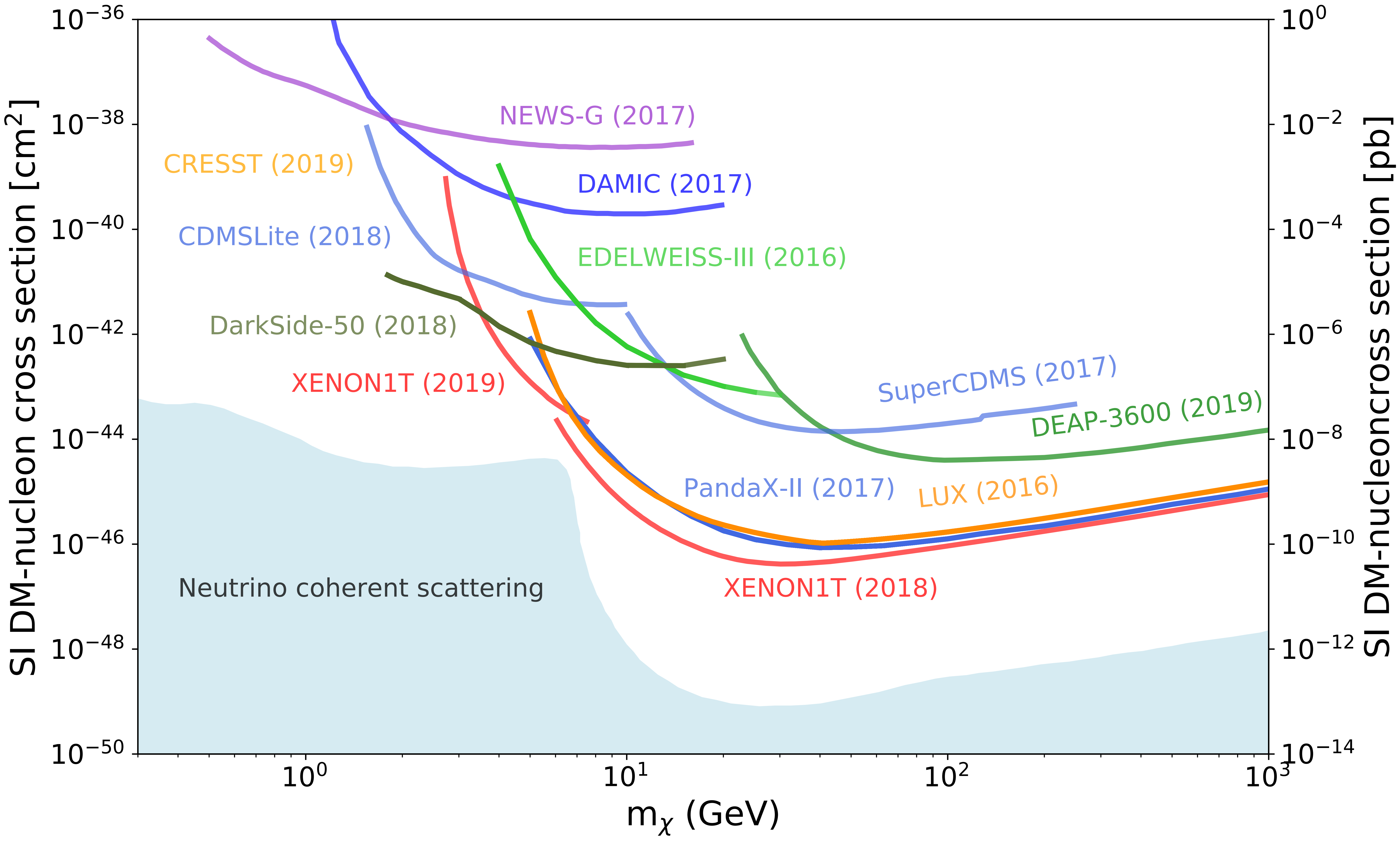
  ✓ **Weakly** interacting with ordinary matter

Freeze-out through 2→2 annihilation



$\alpha_{ann} \sim \alpha_{weak}$

… Yet We Didn't Find the WIMP



Problems with ΛCDM at Sub-Galactic Scale

- ΛCDM extremely **successful** in describing Universe at **large** scales
  - From horizon (15000 Mpc) to inter-galaxy distance (1Mpc)
- **Problems** arise when describing structures at **sub-galactic** scale (< 1Mpc)
  - Cusp/core
  - Missing satellites
  - Too-Big-to-Fail

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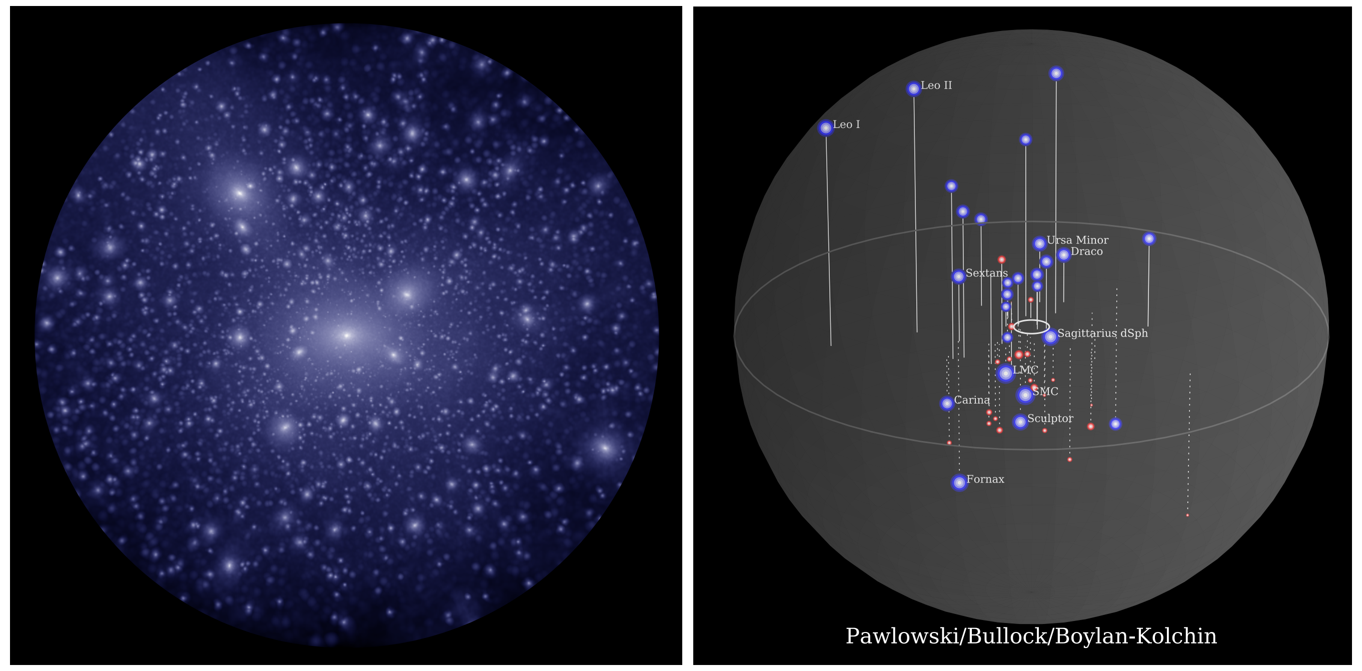
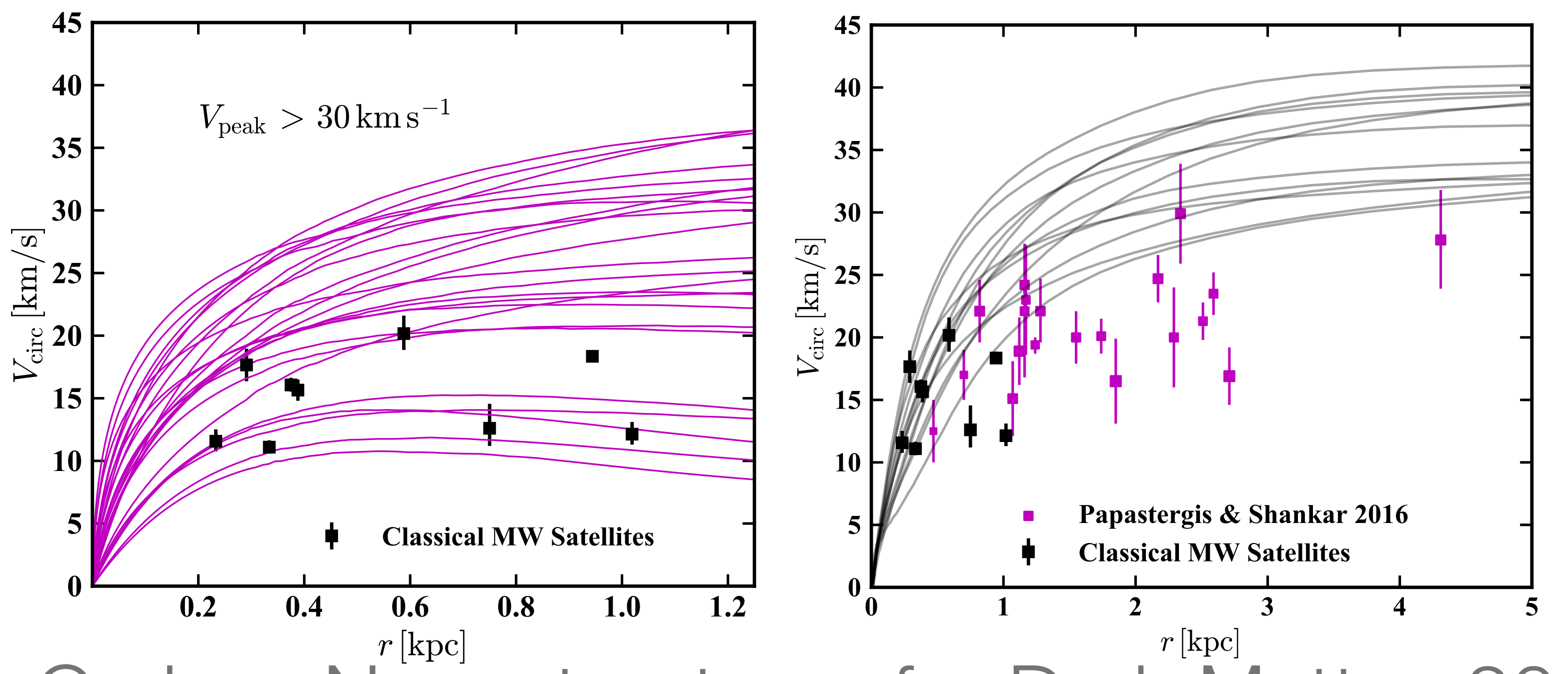


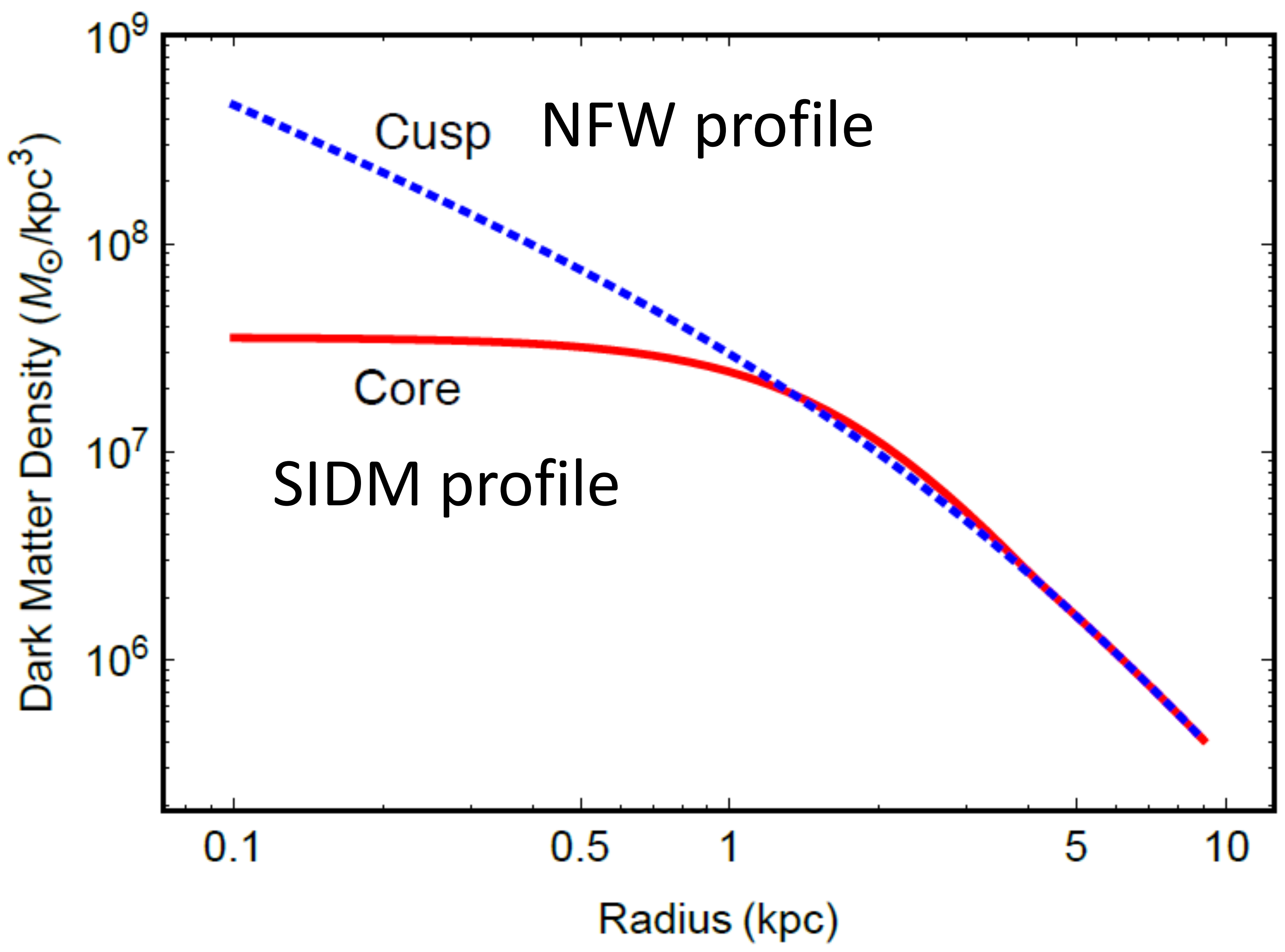


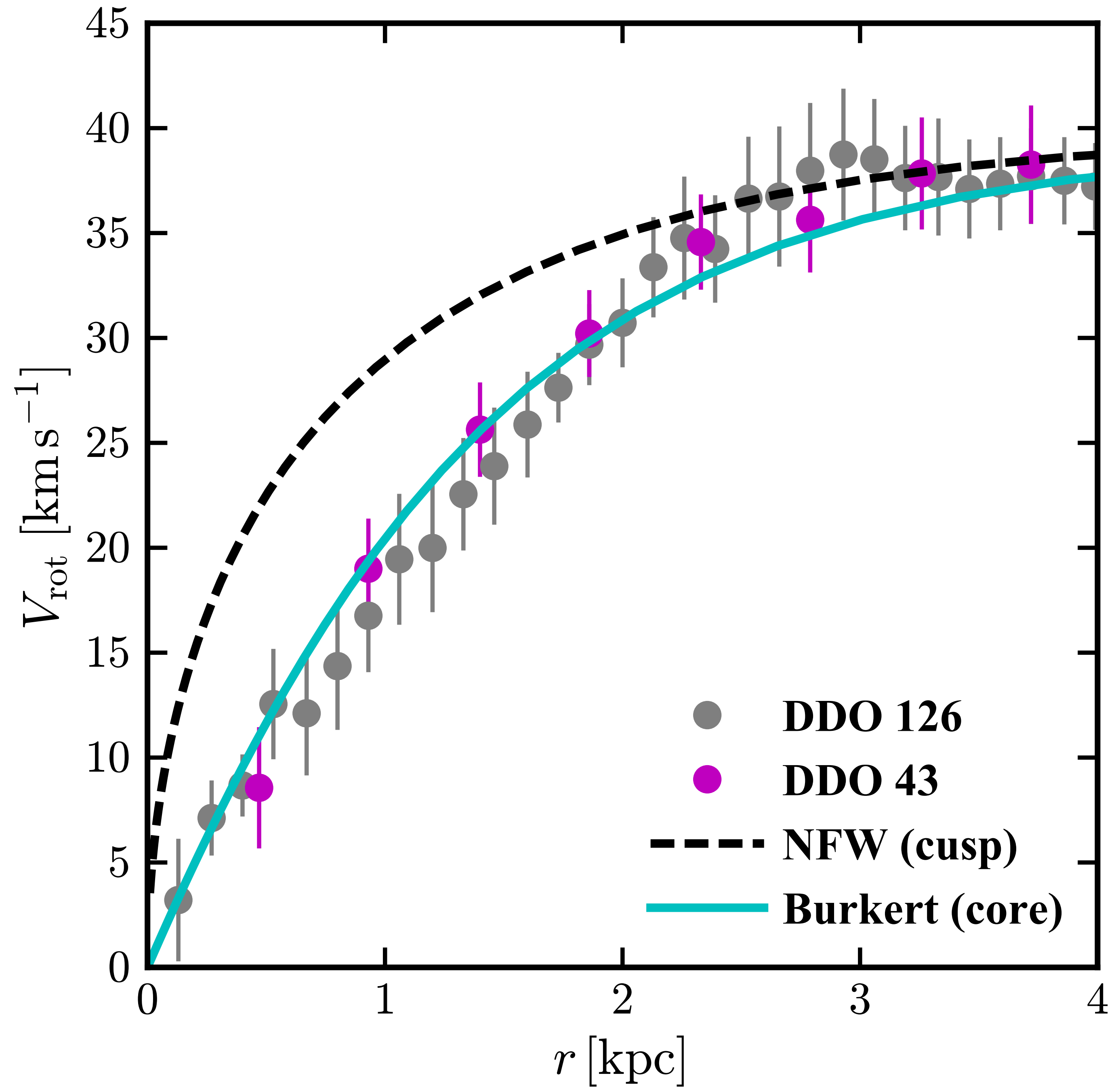
Not covering these two, for comprehensive review see arXiv:1707.04256

The Cusp/Core Problem

❖ Cold DM creates halos with **high** central density

- Density profile predicted to be **'cuspy'**: increases steadily at smaller radii (ρ ~ 1/r)





❖ **Fails** to describe rotation curves at low r

- Data supports **flatter** DM density profile ('core')

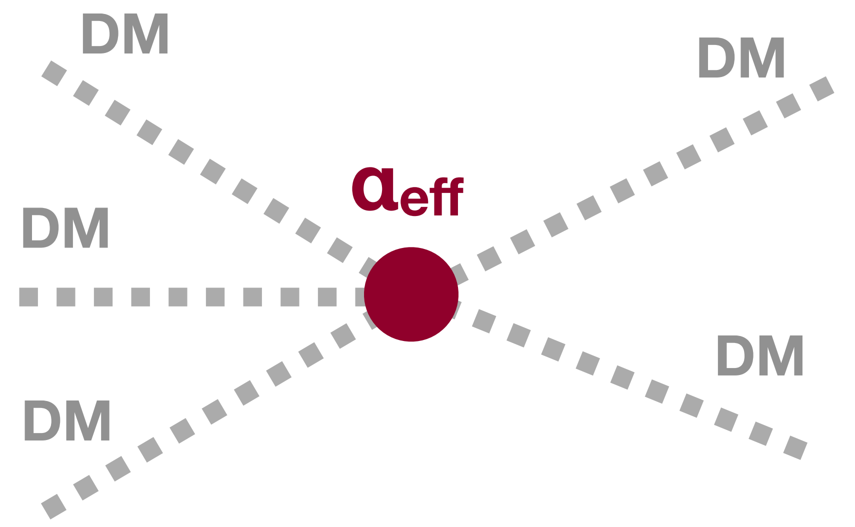
The SIMP Paradigm (in a Nutshell)

Hochberg et al., PRL 113 (2014) 171301

- Strongly Interacting Massive Particles (SIMP)
  - **Self-interacting** DM through 3 → 2 process
- Self-interaction **heats up** DM → **lowers** density
  - **Solves** cusp/core (and too-big-to-fail)
- SIMP predicts **sub-GeV** DM
  - $m_{DM} \sim \alpha_{eff} (T^2 M_{Pl})^{1/3}$ (eg $\alpha_{eff} = 1 \rightarrow m_{DM} = 100$ MeV)
  - α_{eff} constraints: not too **small** (wouldn't solve cusp/core) nor too **large** (wouldn't explain Bullet cluster)

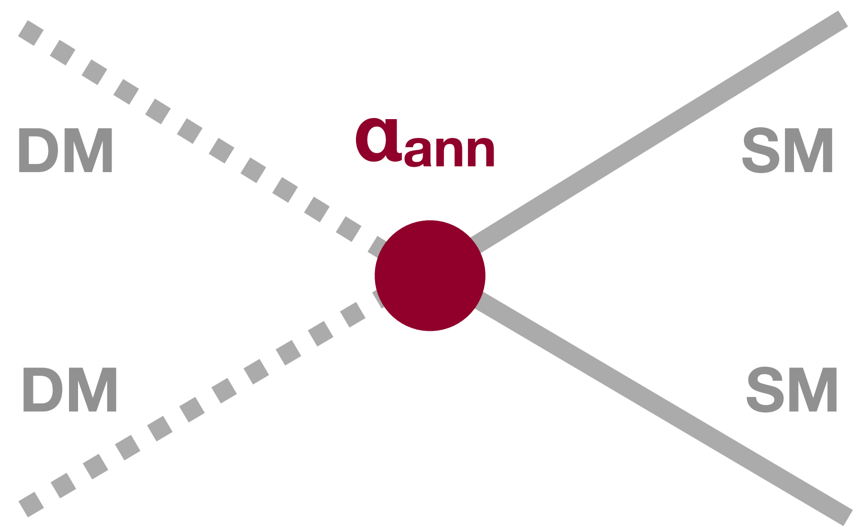
→ **1 MeV < m_{DM} < 1 GeV**

3→2 scattering heats up DM



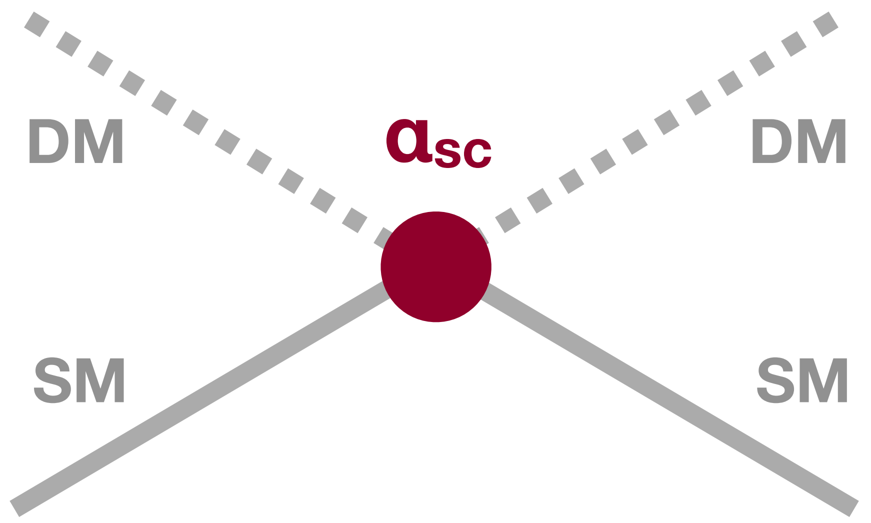
$\alpha_{eff} \sim 1$

No more DM → SM annihilation



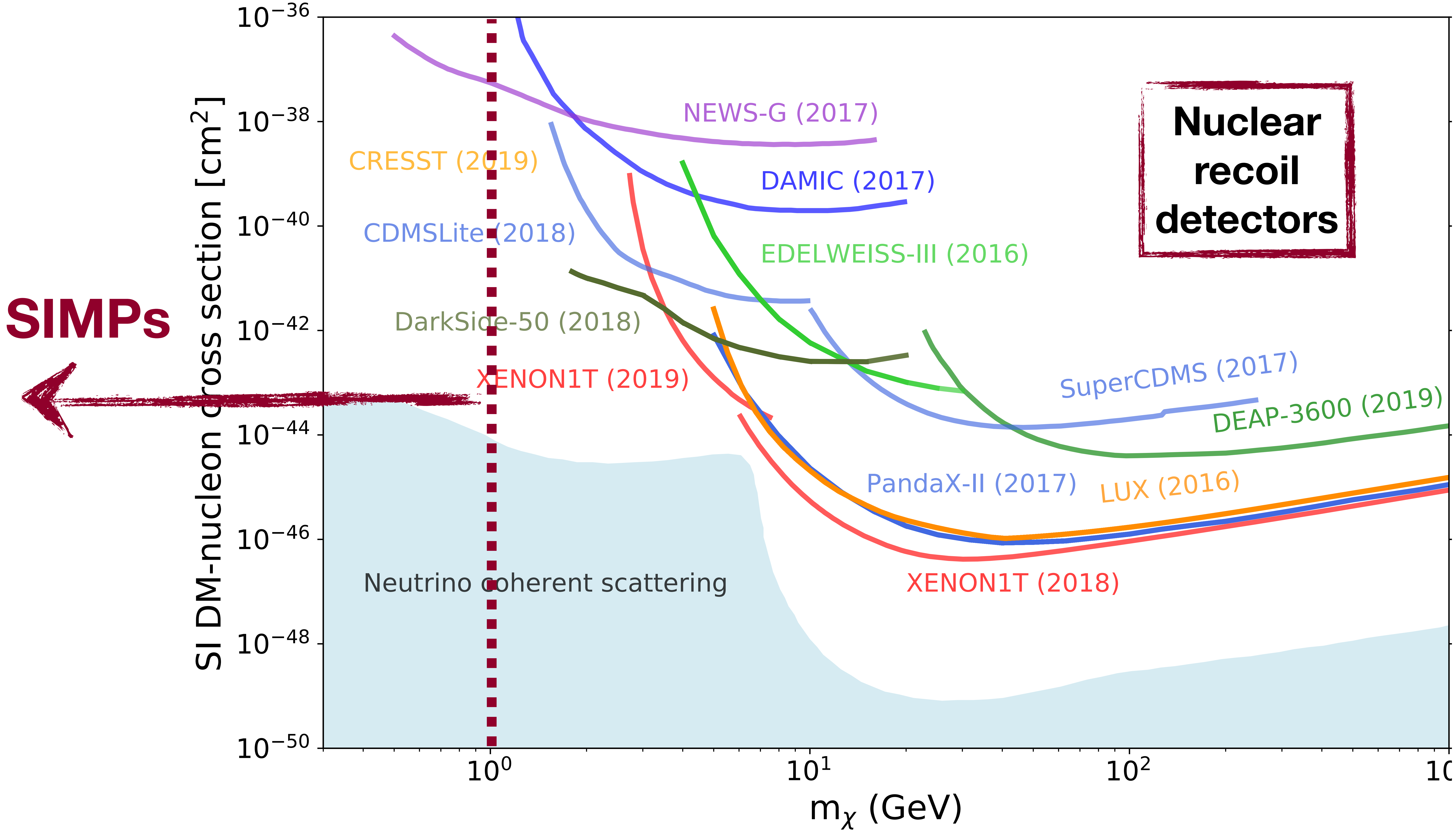
$\alpha_{ann} \sim 0$

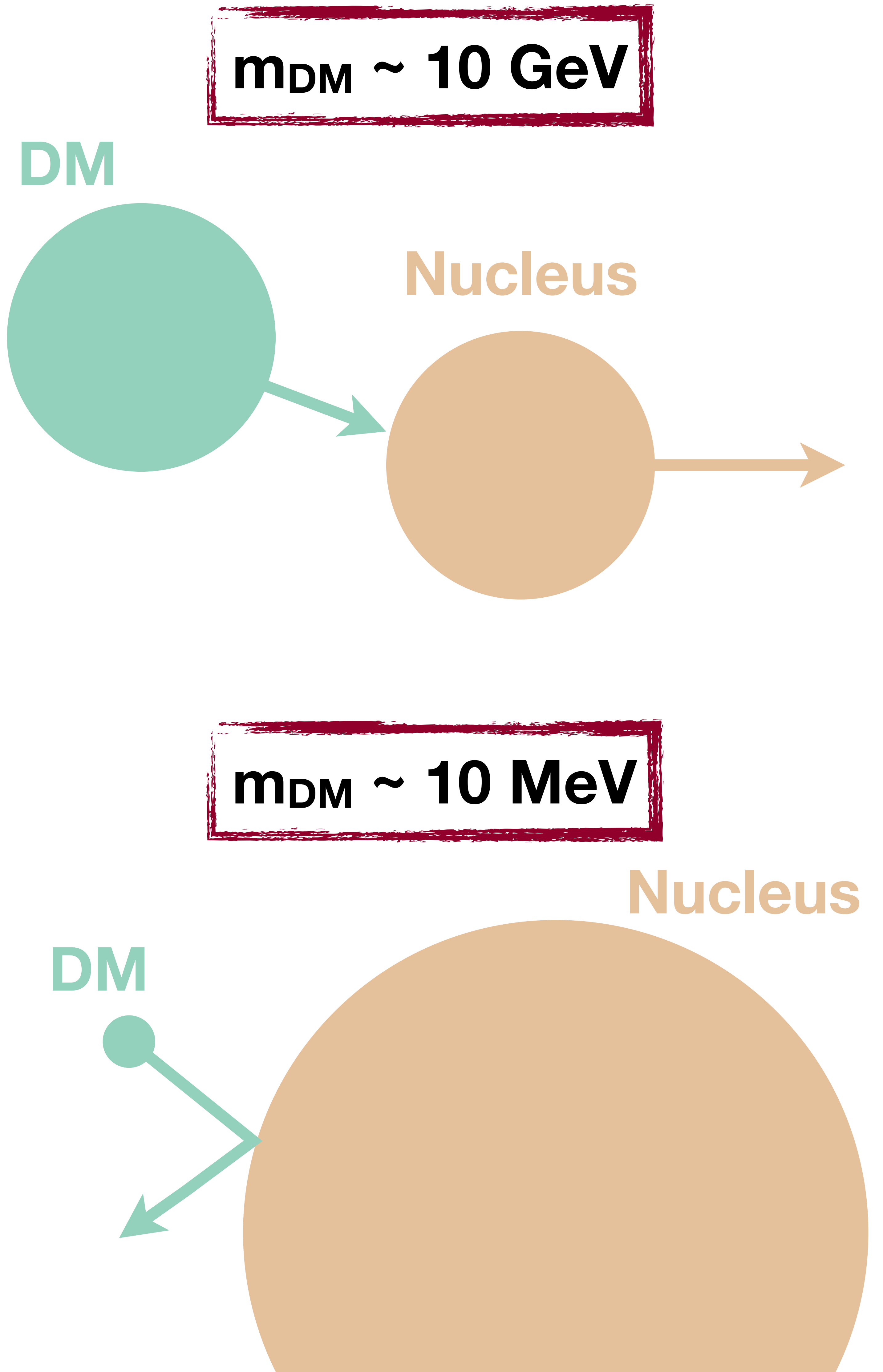
DM-SM scattering



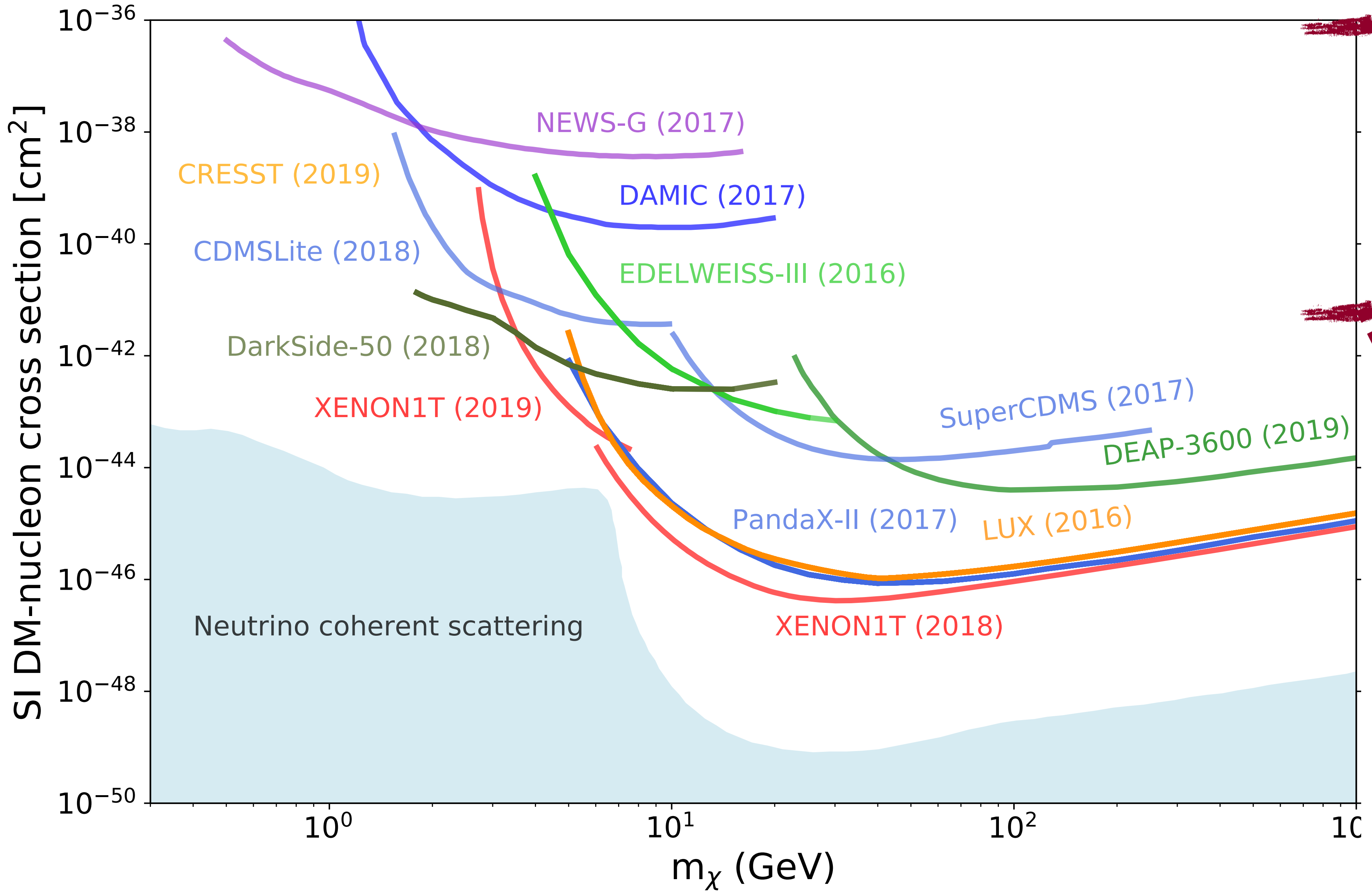
(for thermal equilibrium)

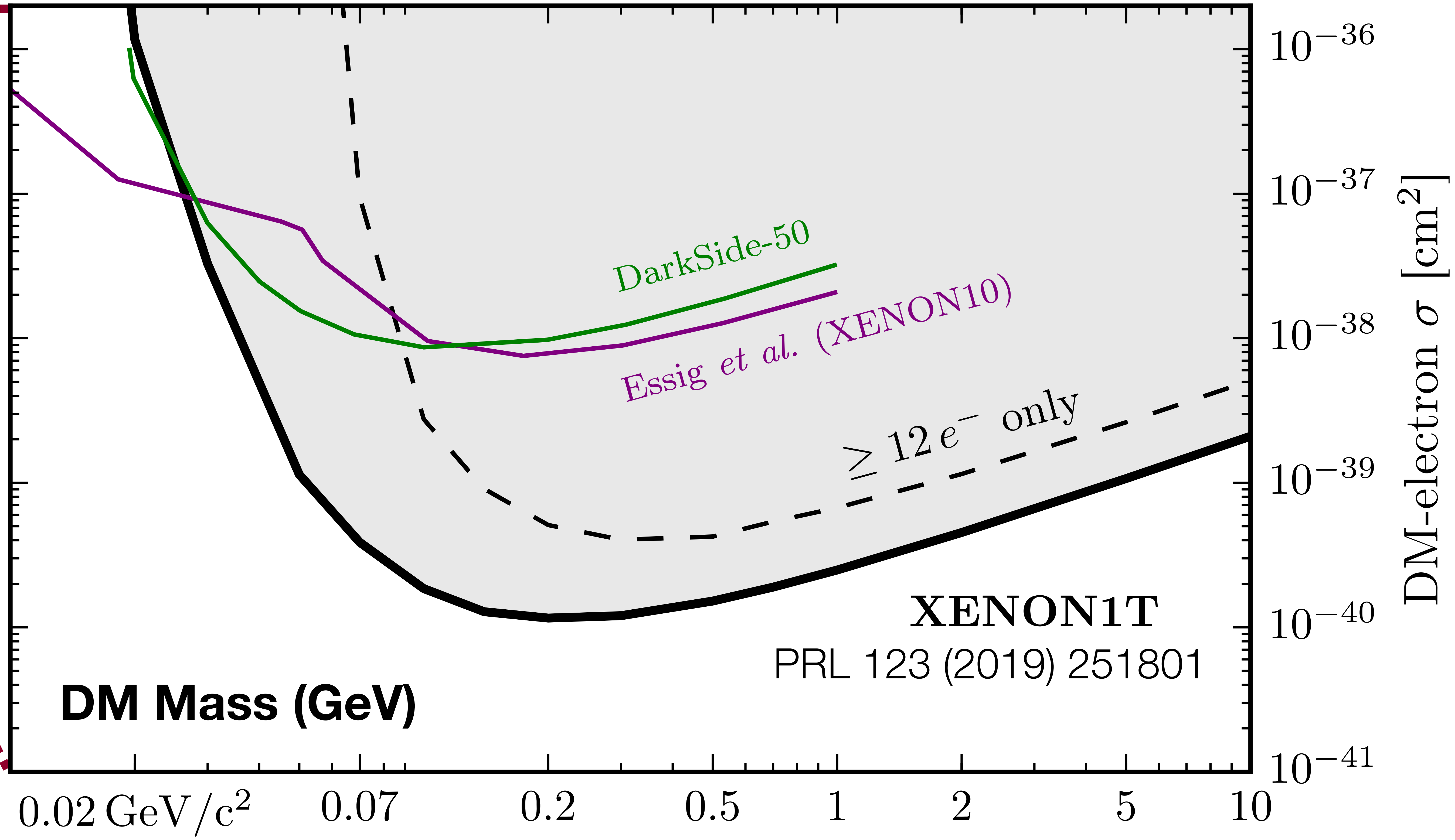
Current Experiments Not Sensitive to SIMP Mass Range





For Light Dark Matter Better to Look For Electron Recoils



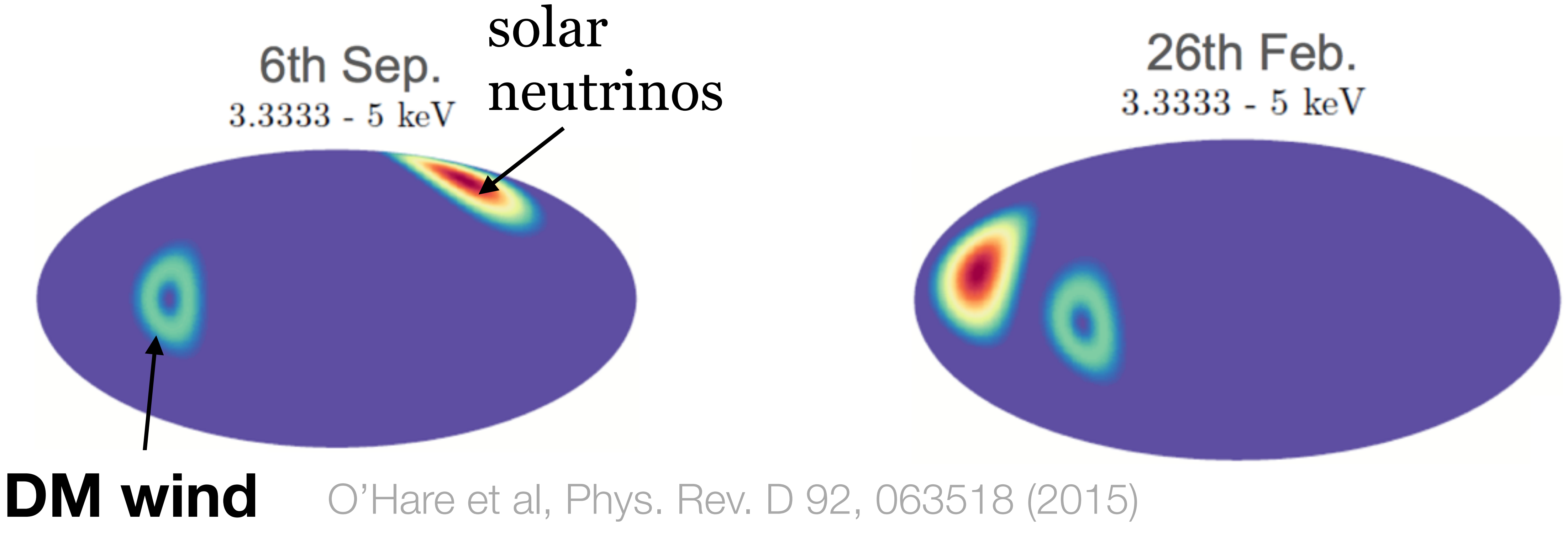


- Only a **few** experiments sensitive to electron recoils
  - Much **weaker** limits (10^{-6})
  - From ton-targets to gram-targets?

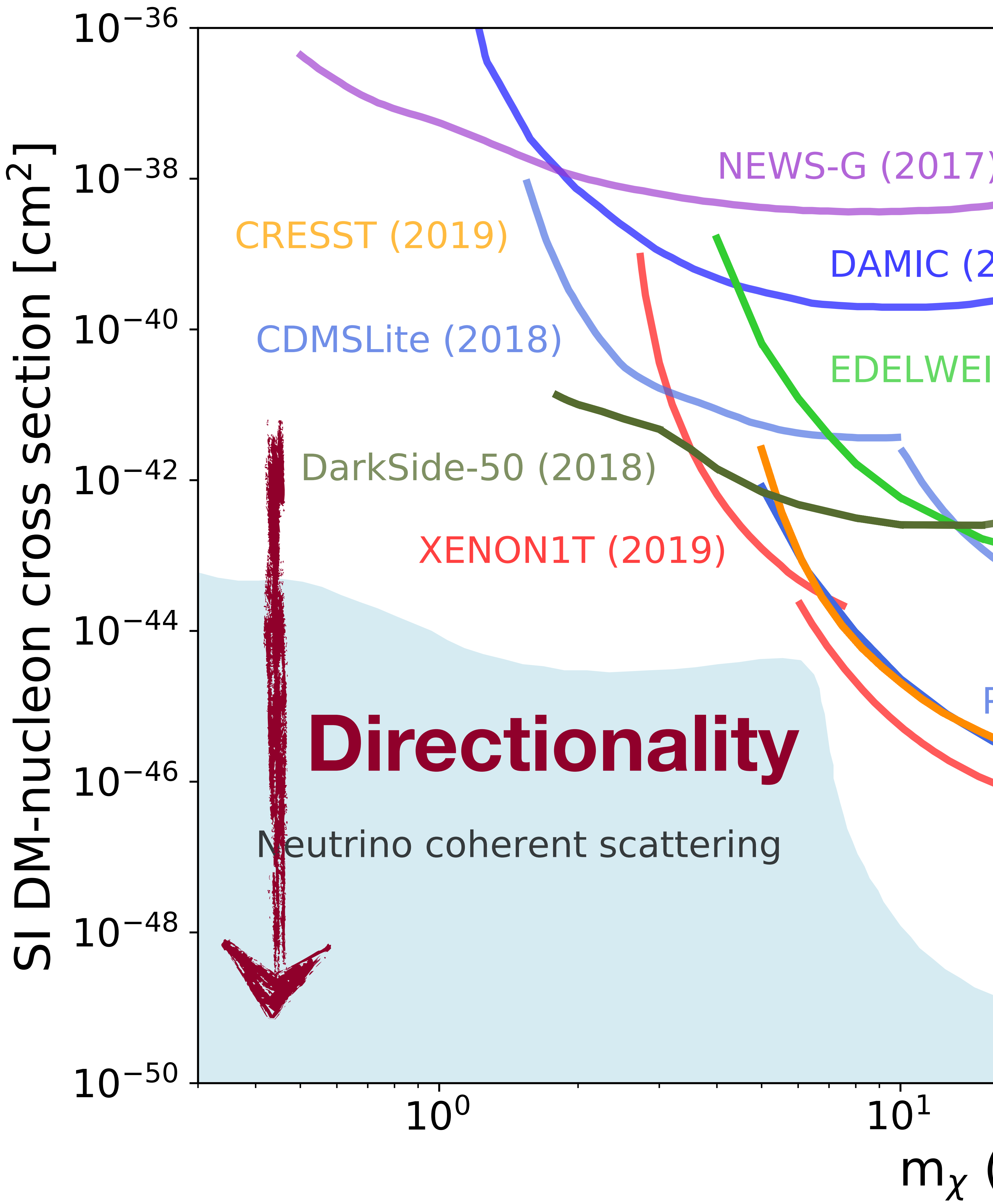
Sensitivity drops for m_{DM} < 100 MeV (electron reconstruction thresholds)

Directionality To (One Day) Pierce Neutrino Floor

- **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



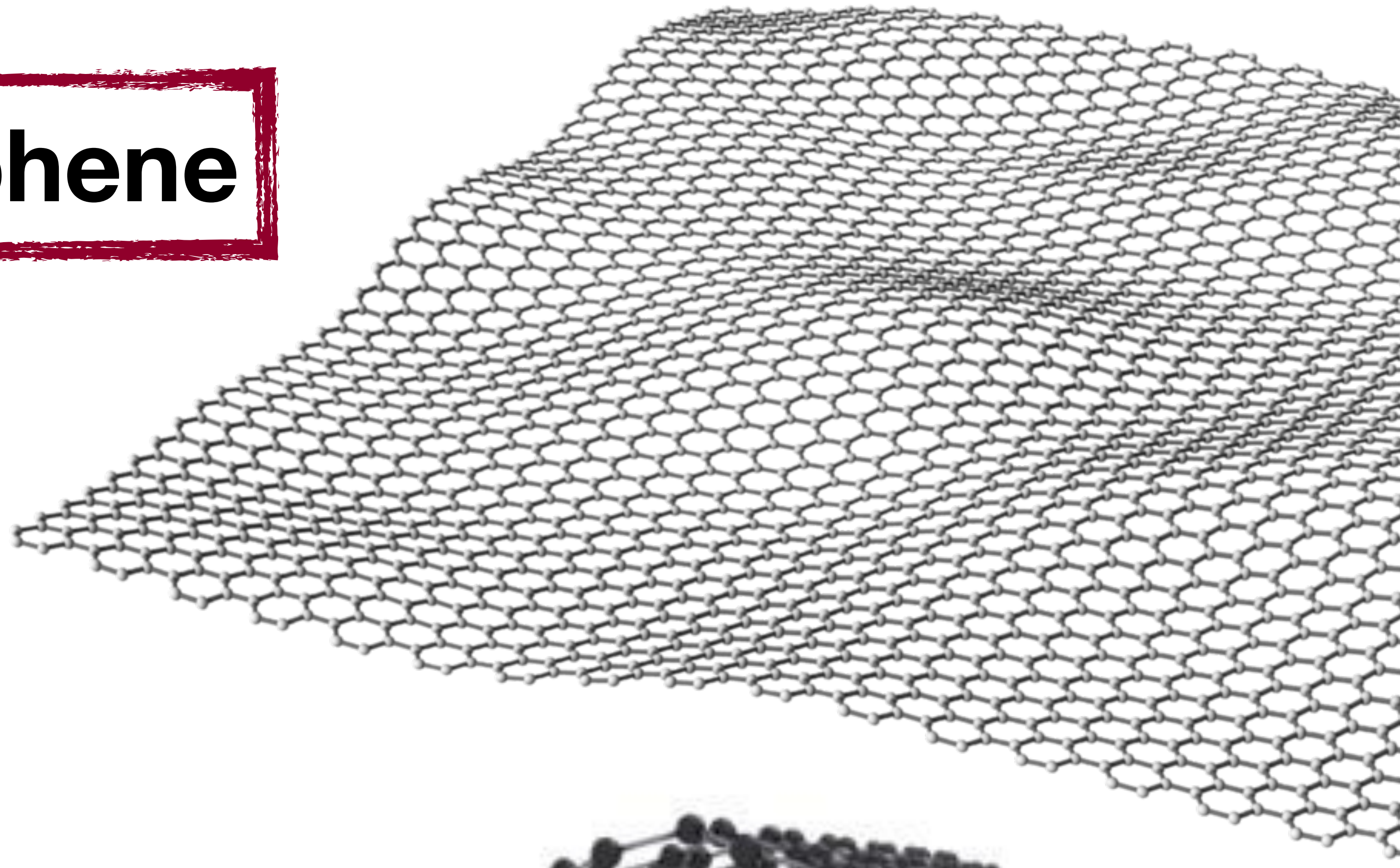
O'Hare et al, Phys. Rev. D 92, 063518 (2015)



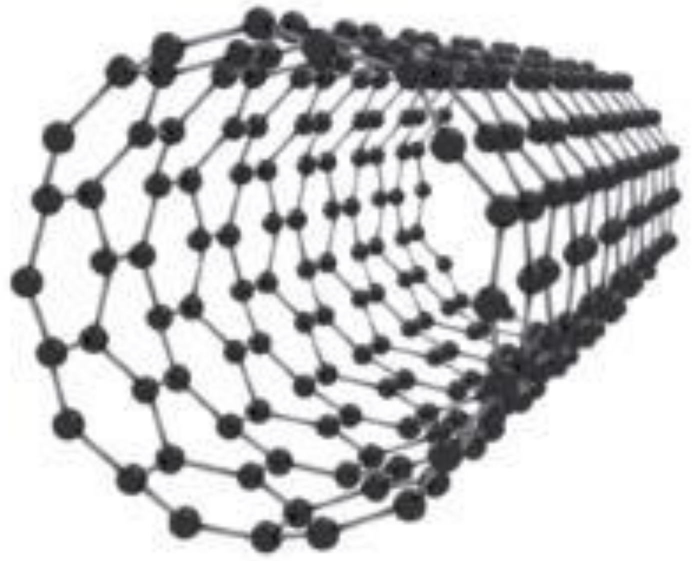
Solid State Targets: The Advantage of 2D Materials

- **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 ~ 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**

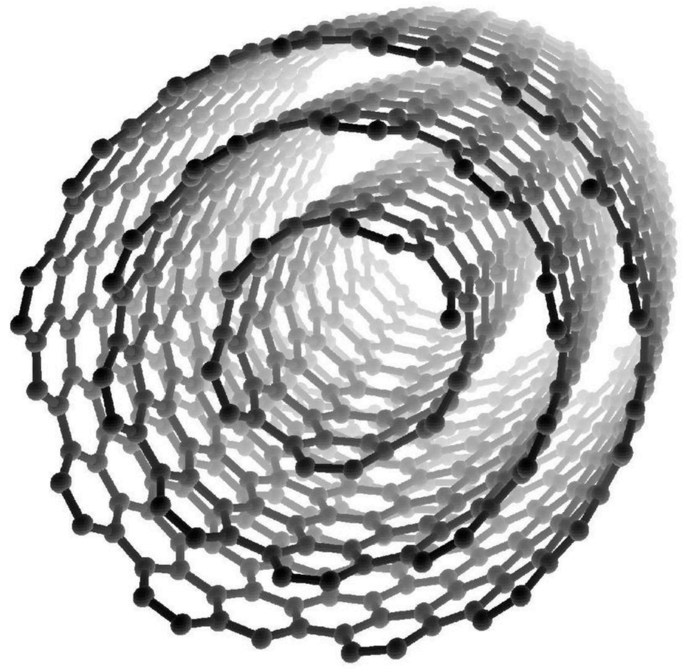
Graphene



Single-wall nanotube



Multi-wall nanotube



Sharing R&D on Graphene with PTOLEMY

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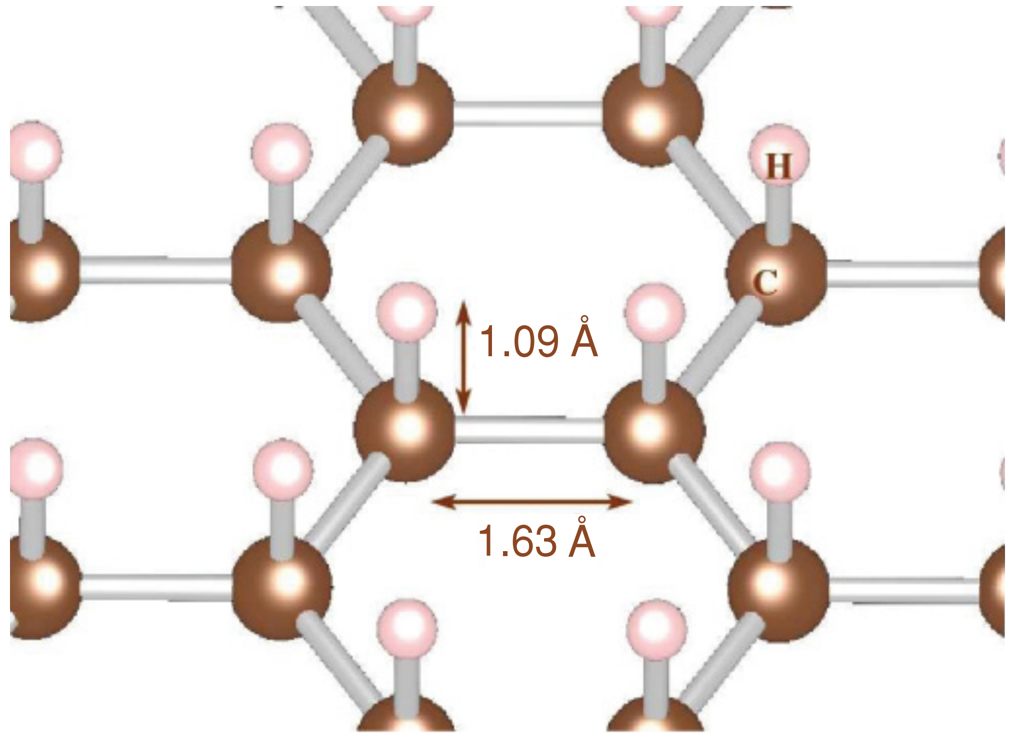
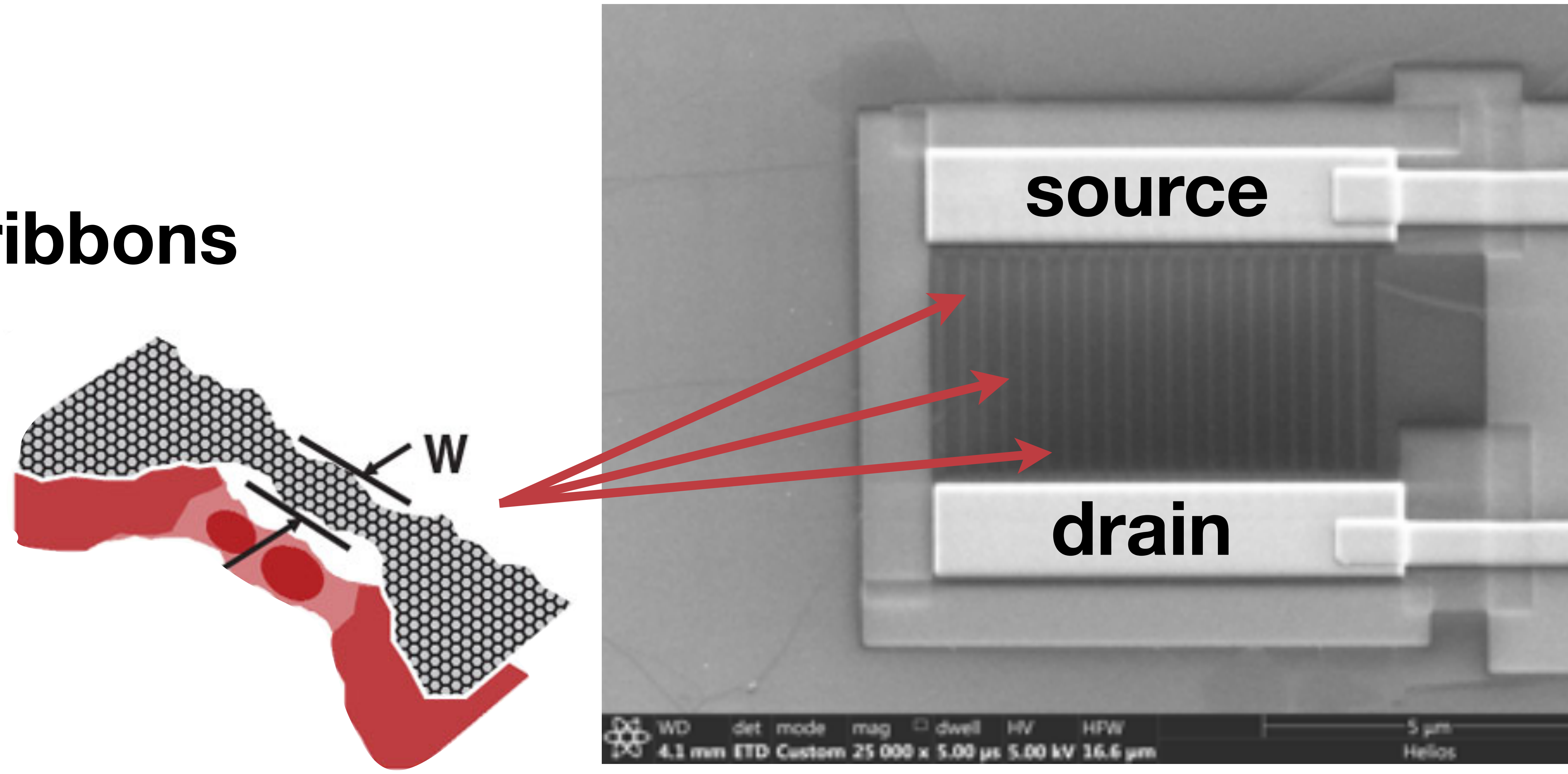
- PTOLEMY aims to measure Cosmic Neutrino Background
  - Tritiated **graphene** target (up to 0.5 kg, ~100 m^2)
  - R&D on graphene **also** aimed towards DM



- Graphene arranged in **Graphene-FETs (G-FET)**
  - Source and drain connected by graphene **nanoribbons**
  - **Quasi-1D** material, width W < 50 nm
  - Electrical properties depend on W



G-FET: Sensitive to Single Electrons

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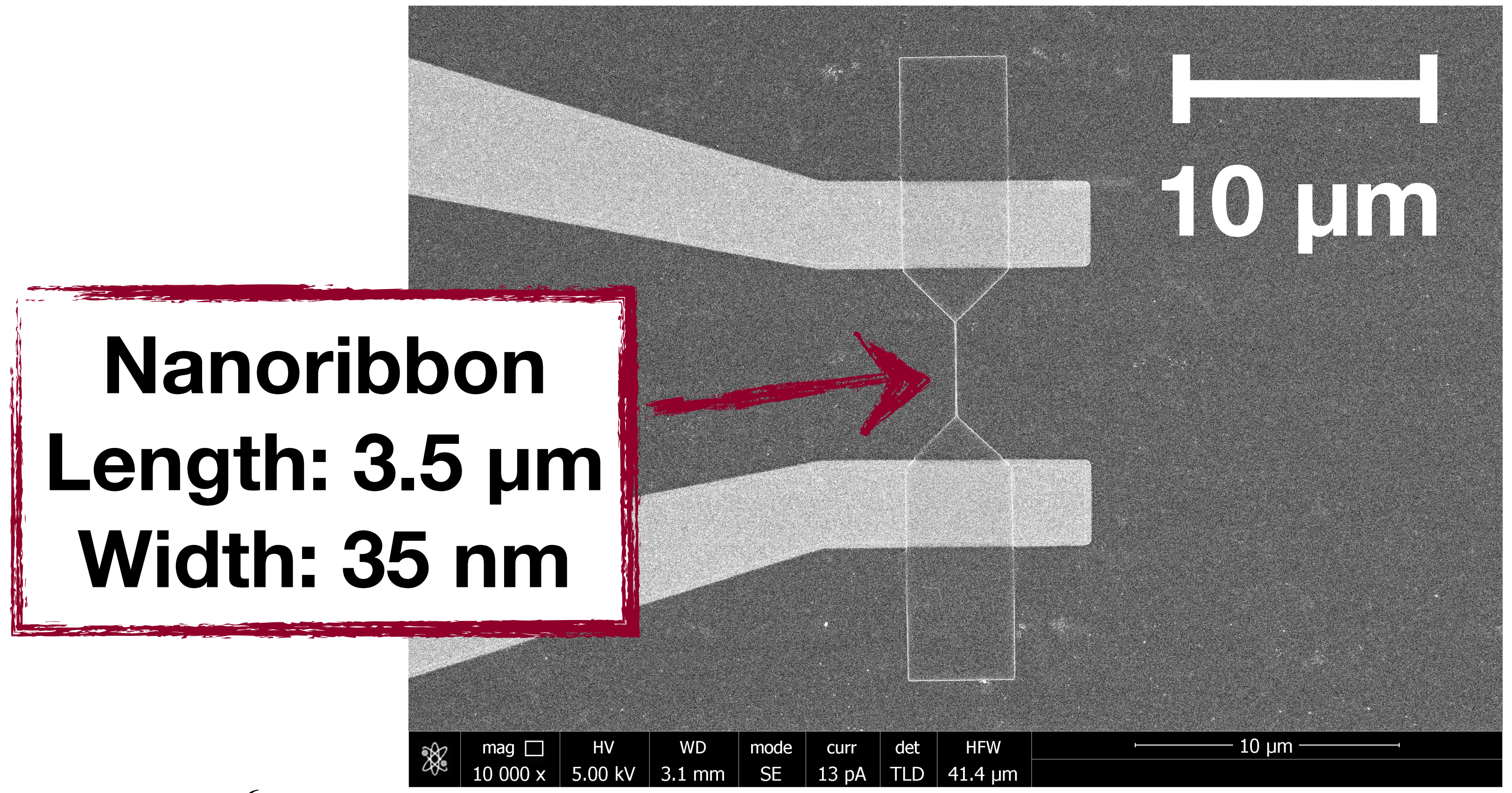
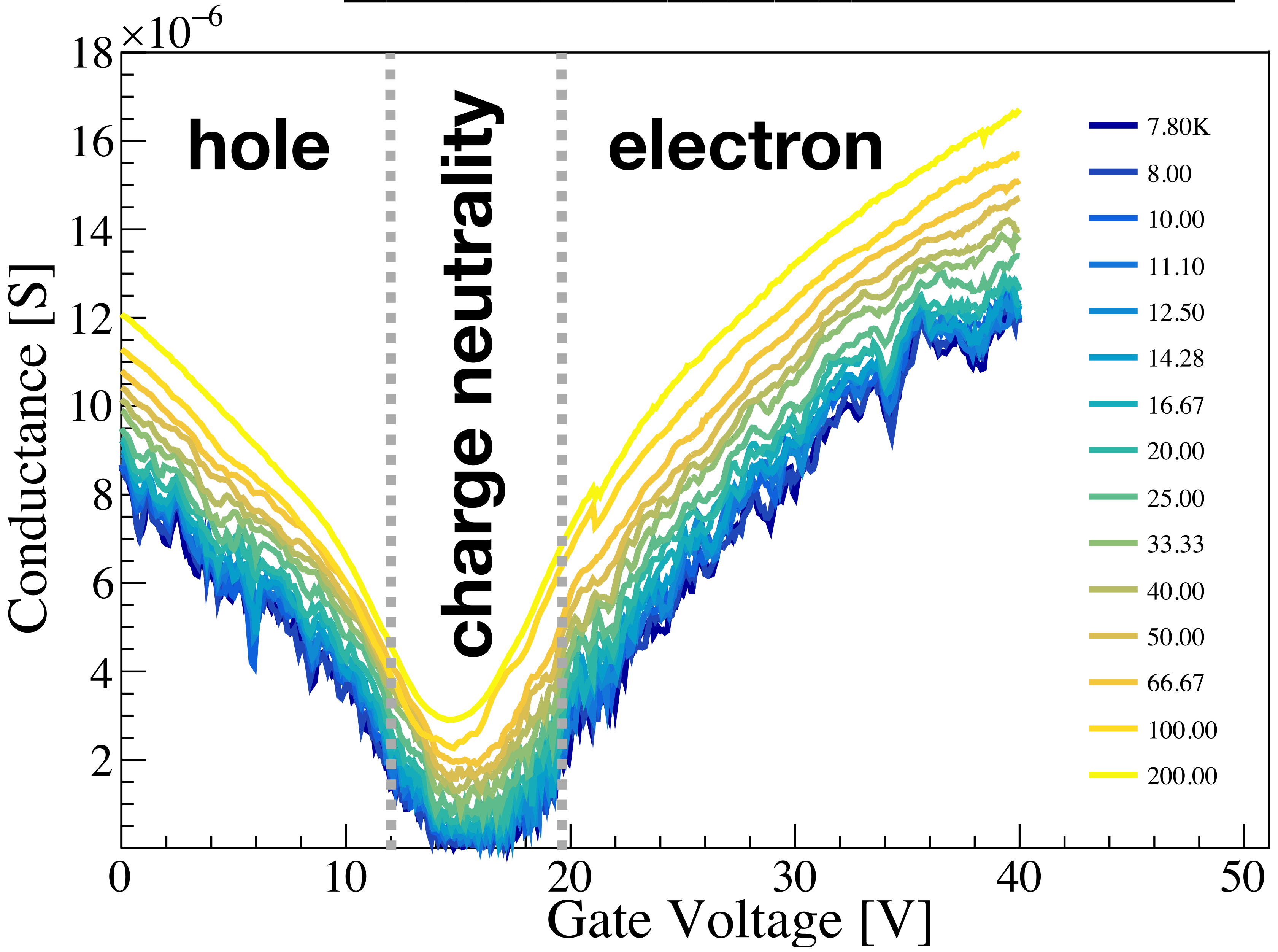
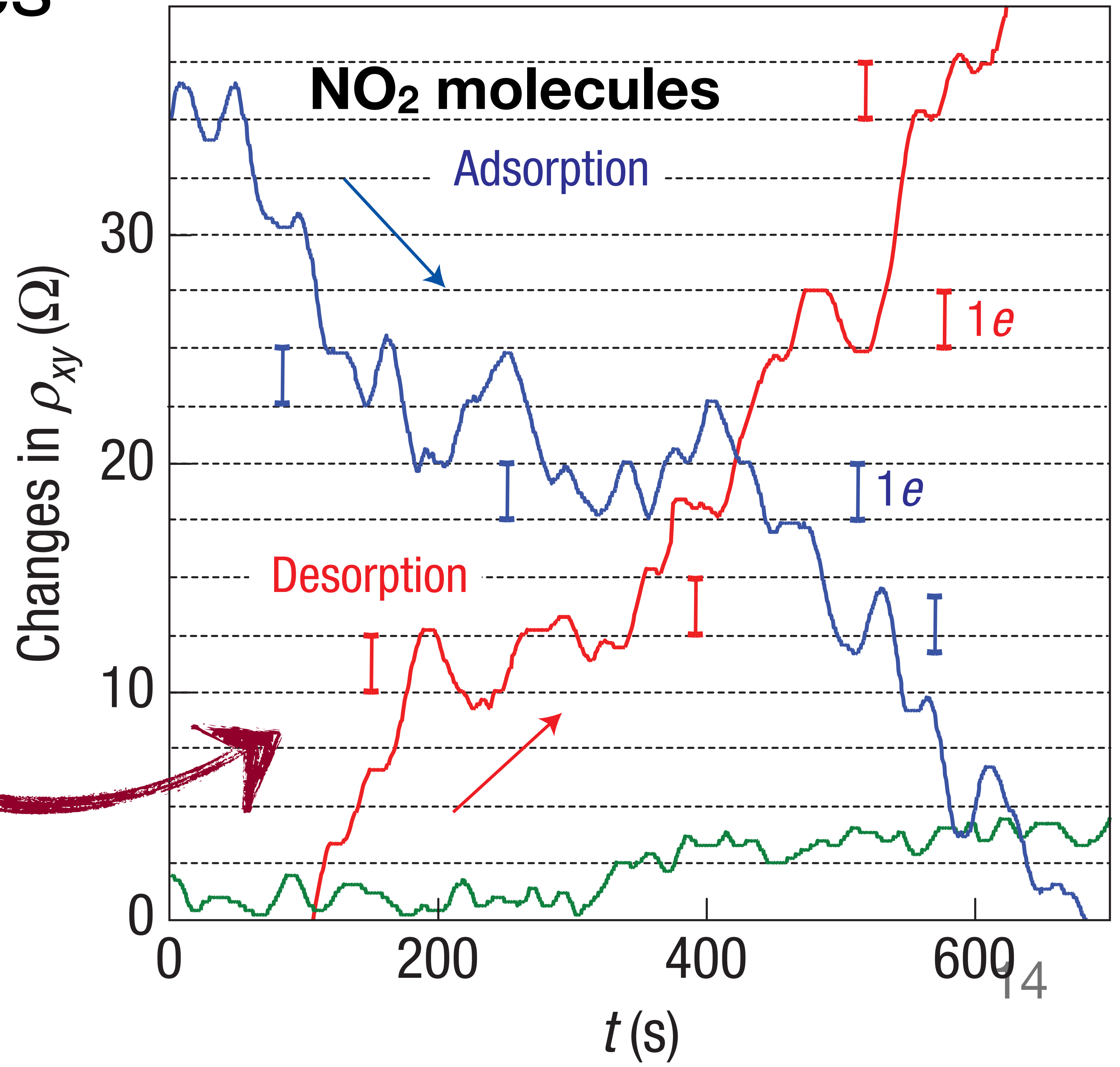




- ❖ **Conductance** depends on gate voltage and temperature
  - **Minimum** at neutrality point
  - **Semiconductor** behavior
  - $\times$**10** variation at cryo temperatures
- ❖ At minimum: sensitive to **single e$^-$**
  - **Absorption** or **emission**
  - **Measurable** jumps in resistivity

F. Schedin et al., Nat. Mater. 6 (2007) 652



Graphene-FETs as Directional Dark Matter Detectors

Hochberg, et al., PLB 772 (2017) 239

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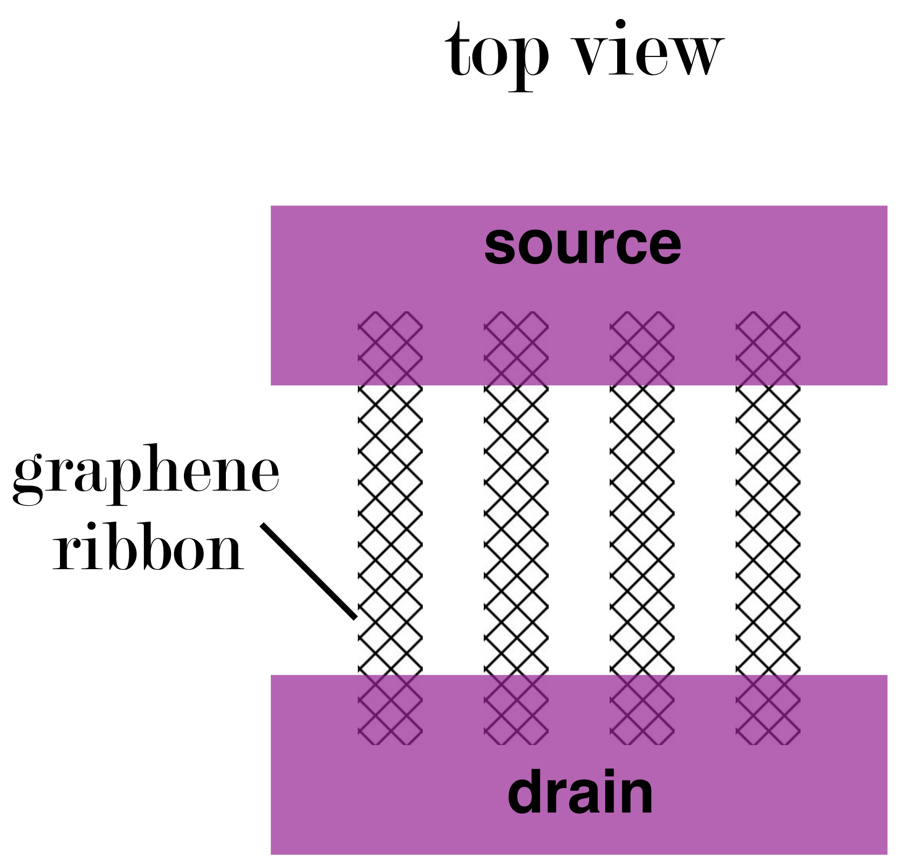
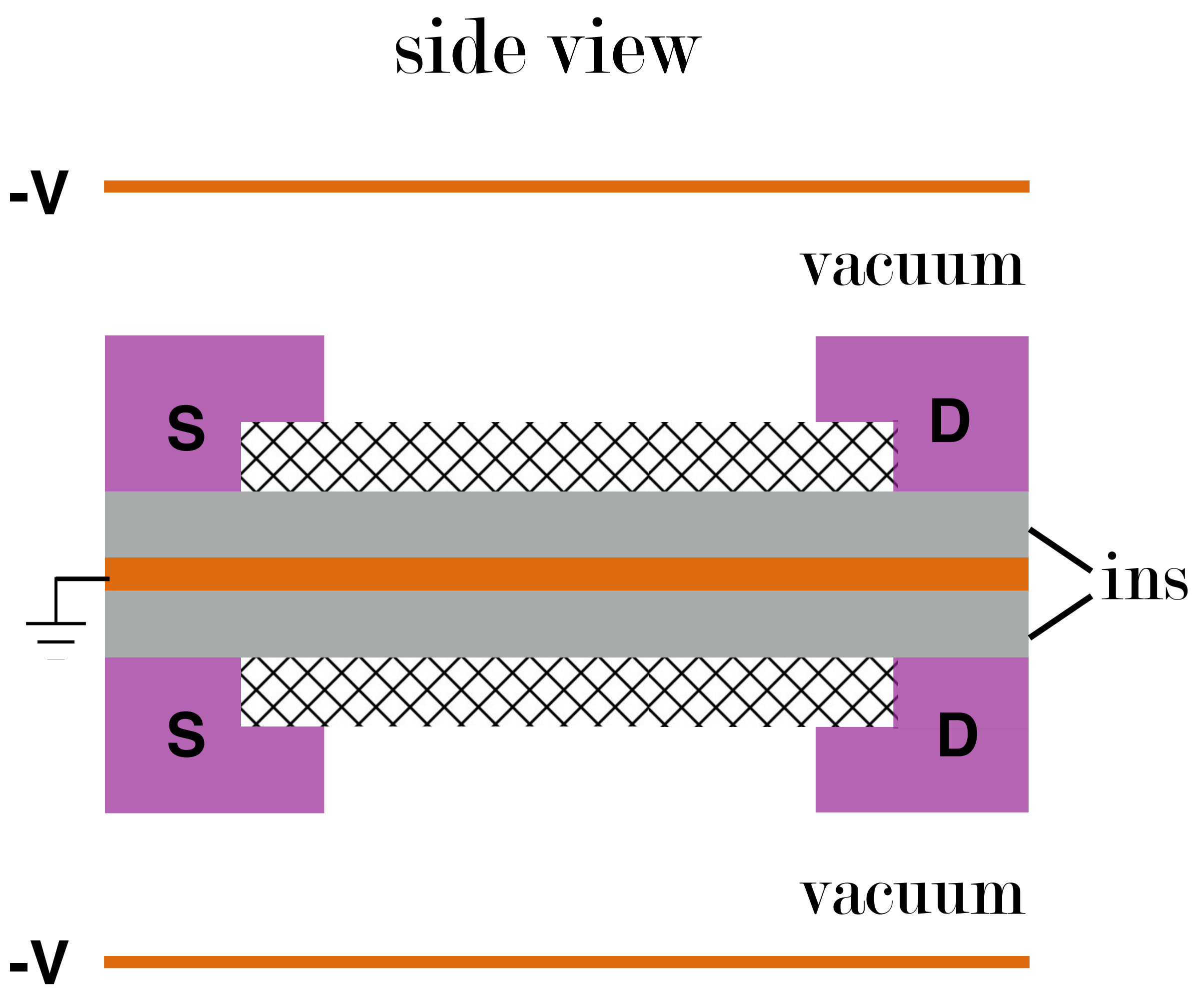
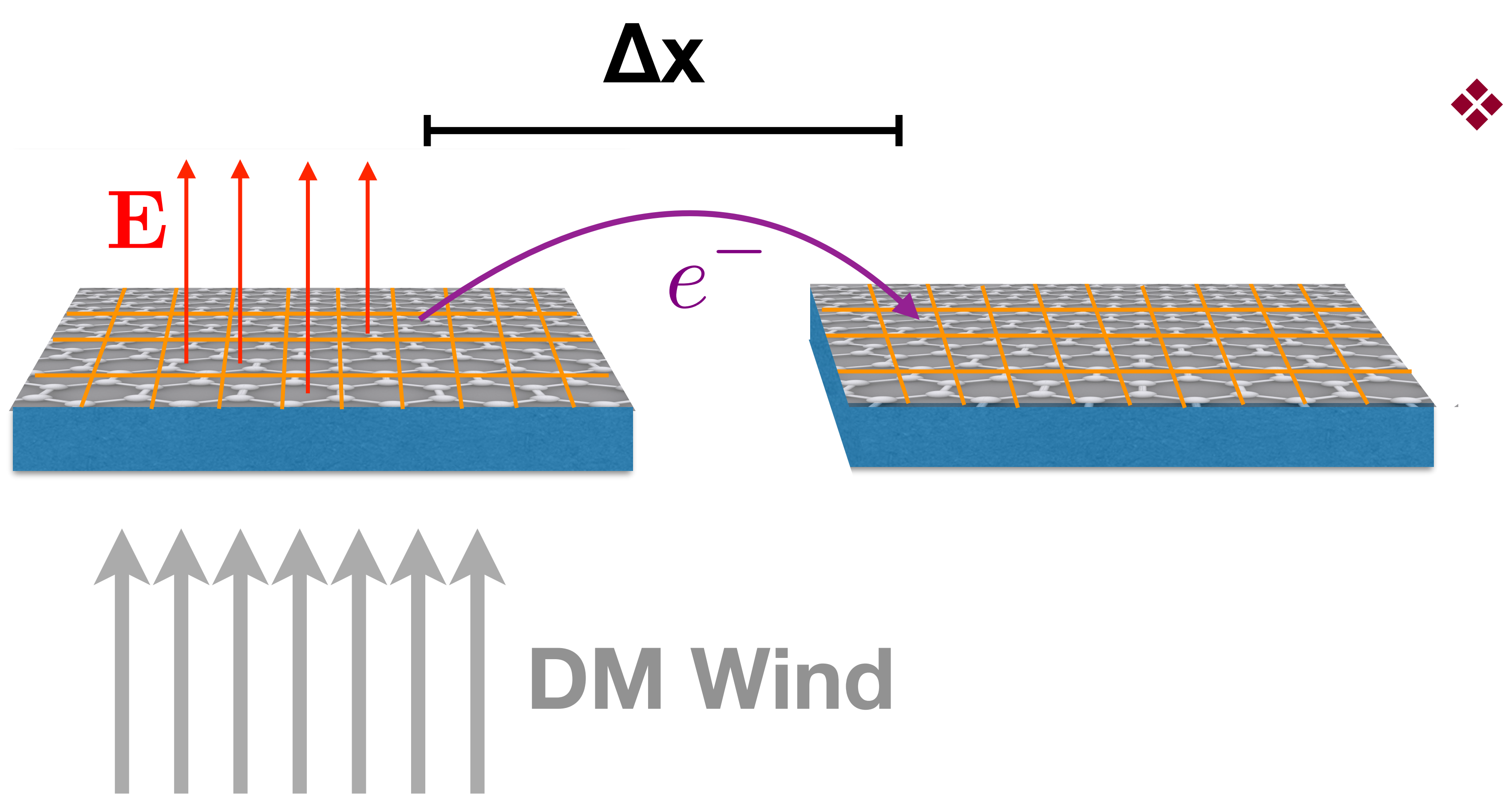




- Double-sided G-FET geometry, between two **electrodes** (V = -100 V)
  - To accelerate ejected electrons **back** towards graphene
- DM event: **coincidence** of two cells (departure and arrival)
  - Aligning towards Cygnus: excess of **top vs bottom** events



TOF

- Ballistic drift: knowing E, Δx **and Δt**
  → can **fully** reconstruct electron $\vec{v}_e$
  - $\vec{v}_e$ **correlated** to DM wind direction
  - Directionality

Progress on G-FETs: Reducing Conductance Spikes

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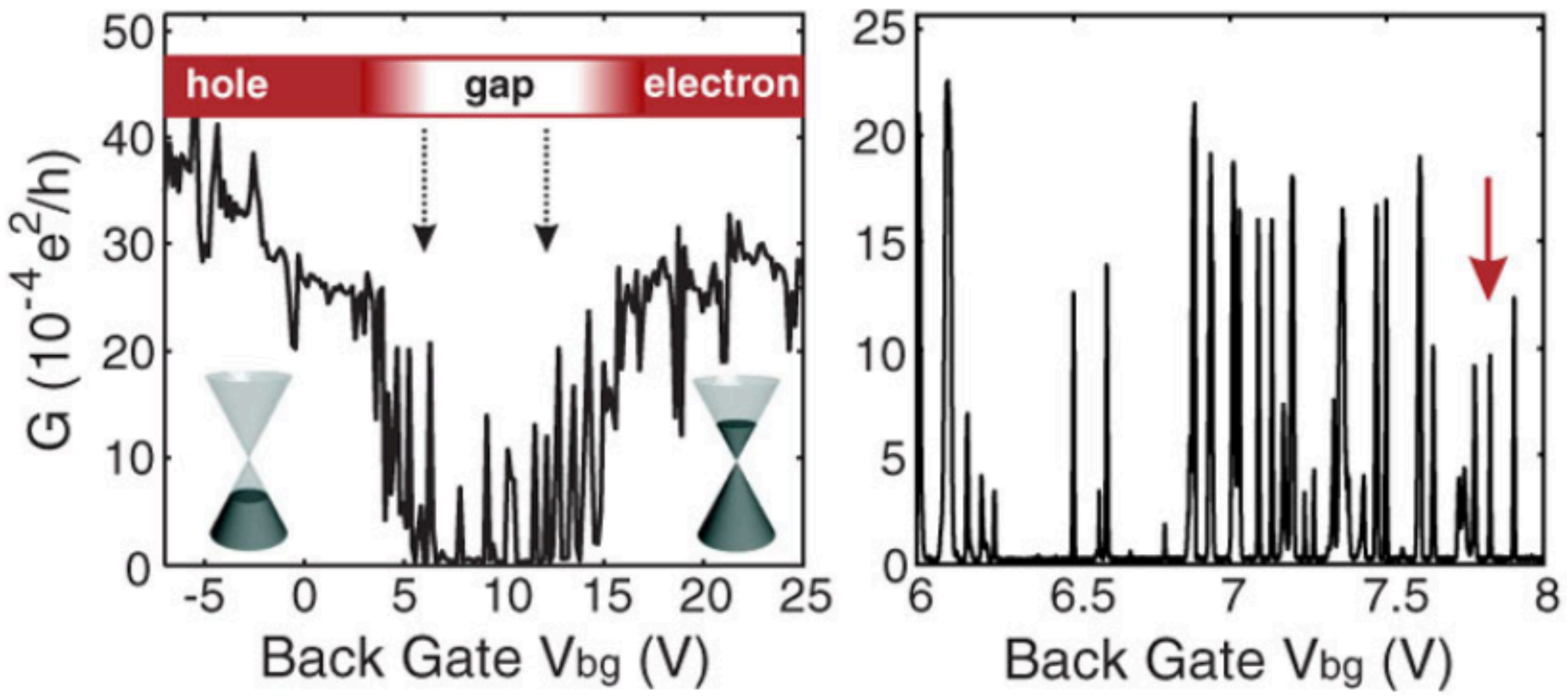
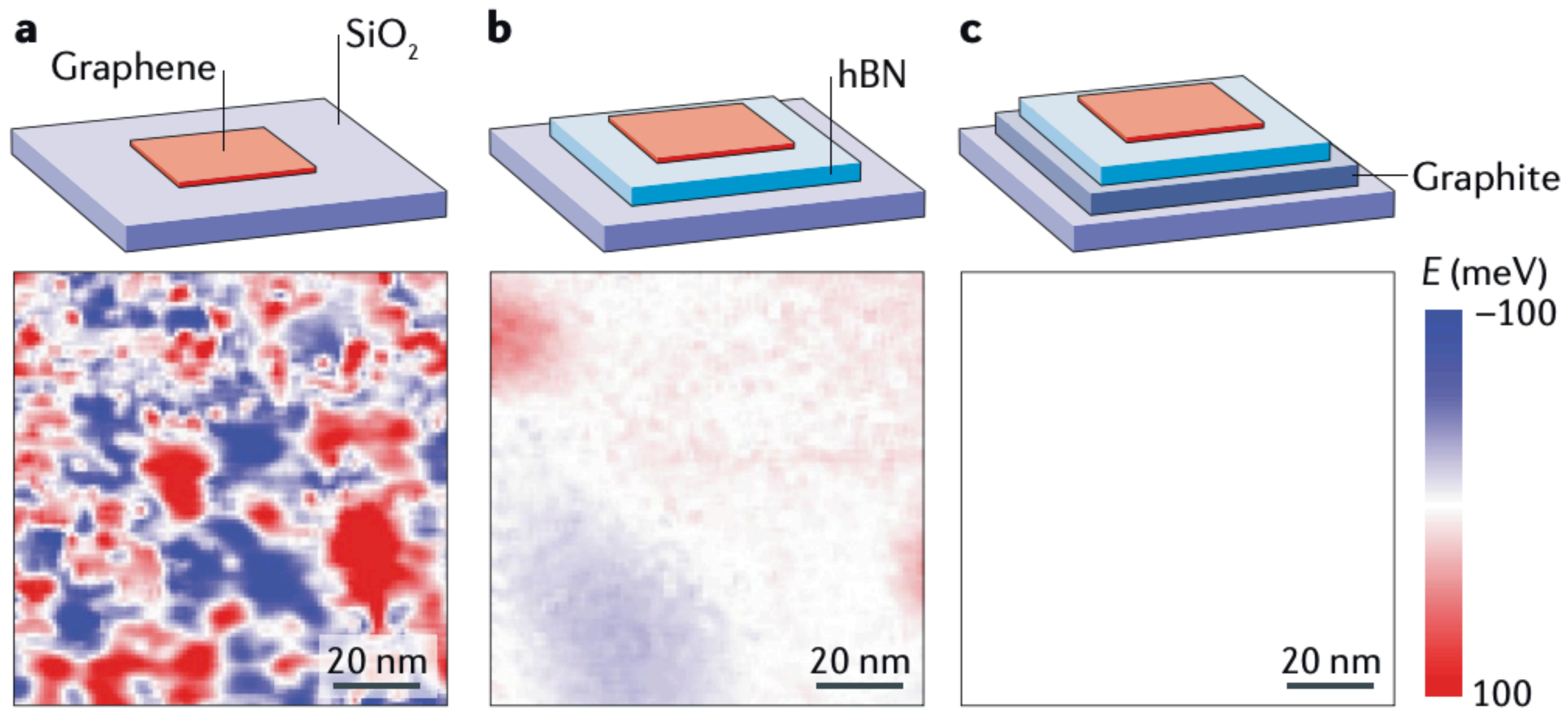
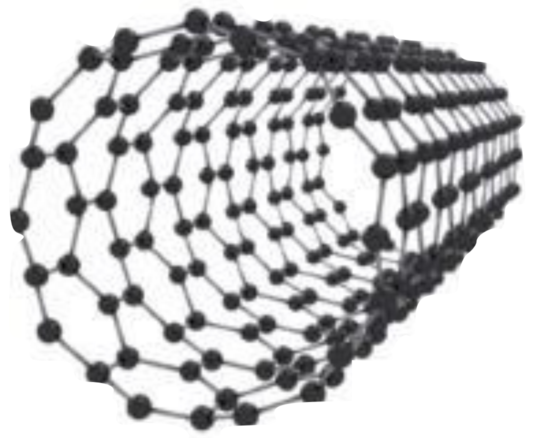
PRL 102 (2009) 056403



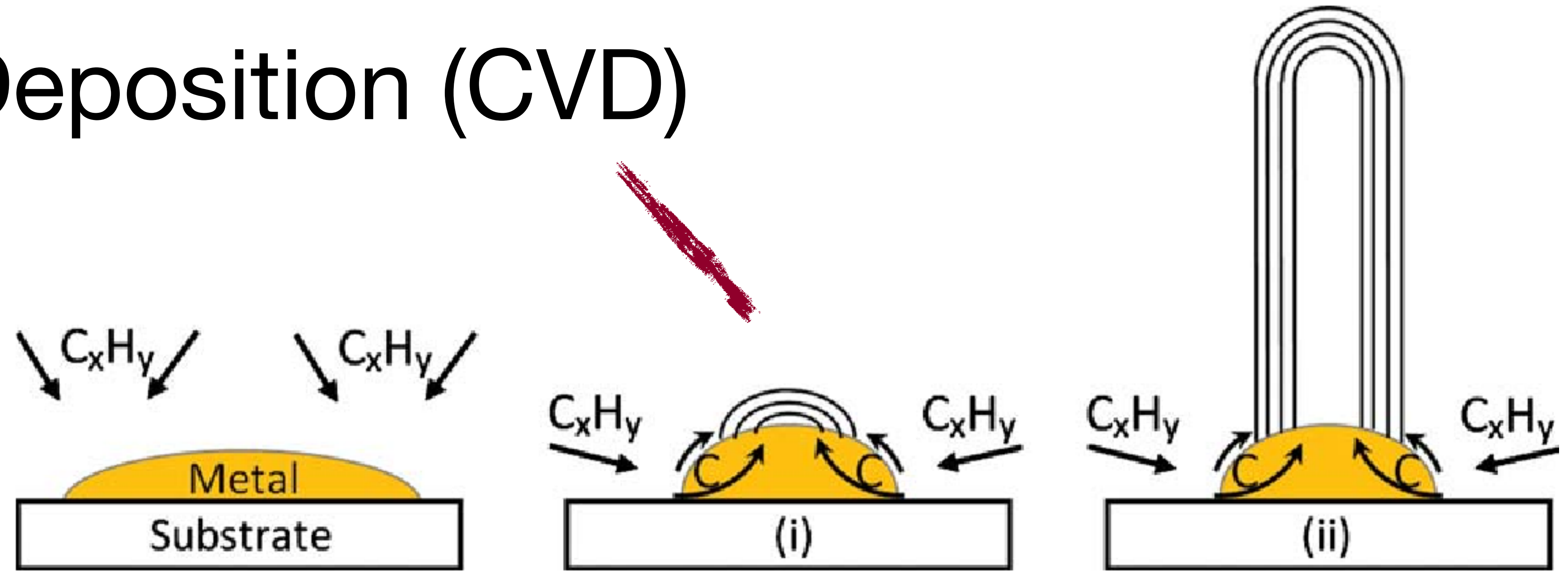


- Conductance **spikes** in transport gap
  - Mostly due to charge **impurities**
  - Coming from the Si/SiO_2 **substrate**
- **Isolating** graphene from SiO_2 substrate
  - **Greatly** reduces charge inhomogeneities
  - **x10** already with only hBN layer

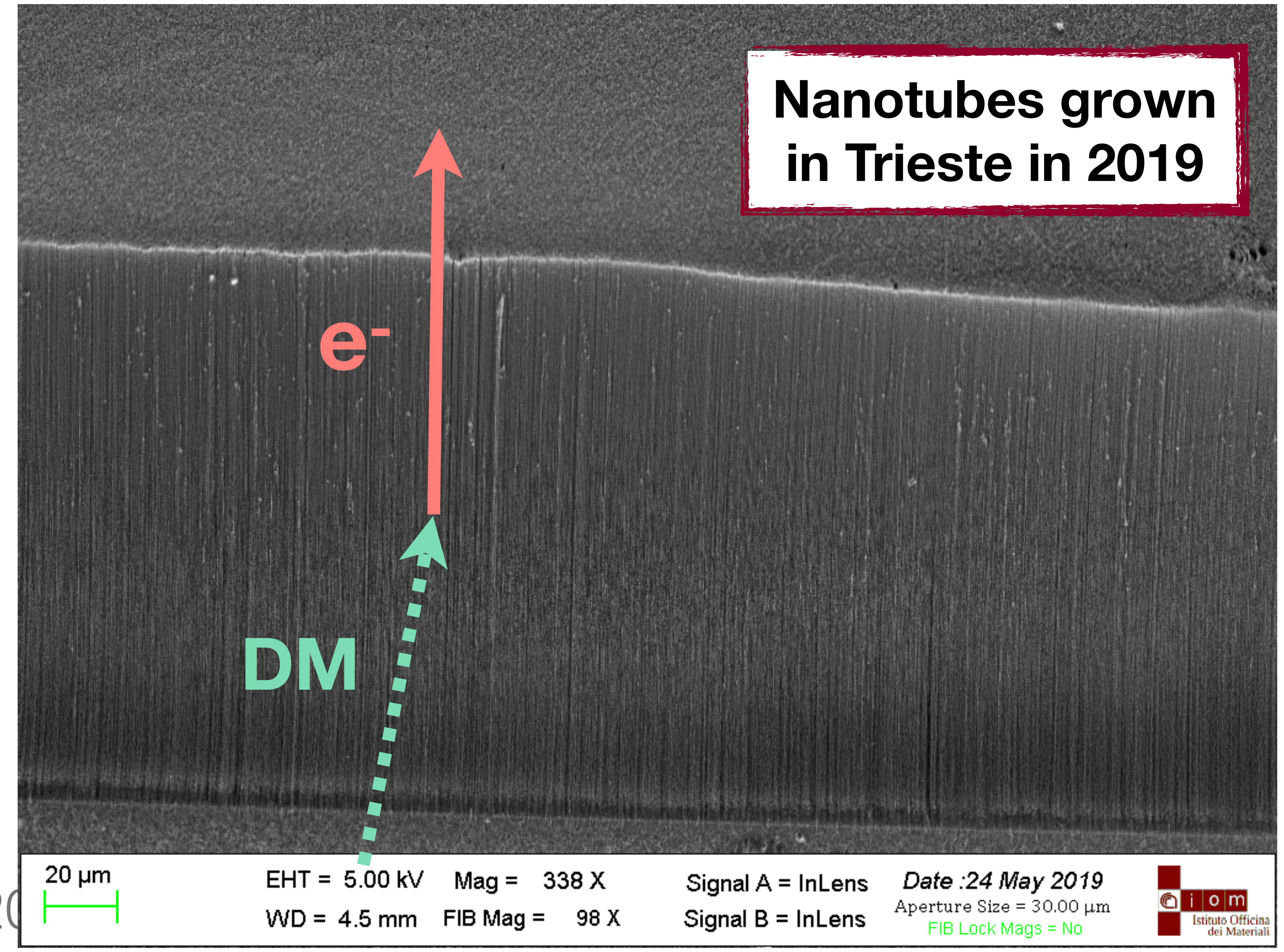
Growing Vertically Aligned Carbon Nanotubes in the Lab



- **Carbon nanotubes** synthesized through Chemical Vapor Deposition (CVD)
  - Internal diameter ~20 nm, length up to 300 μm
  - Single- or multi-wall depending on growth **technique**



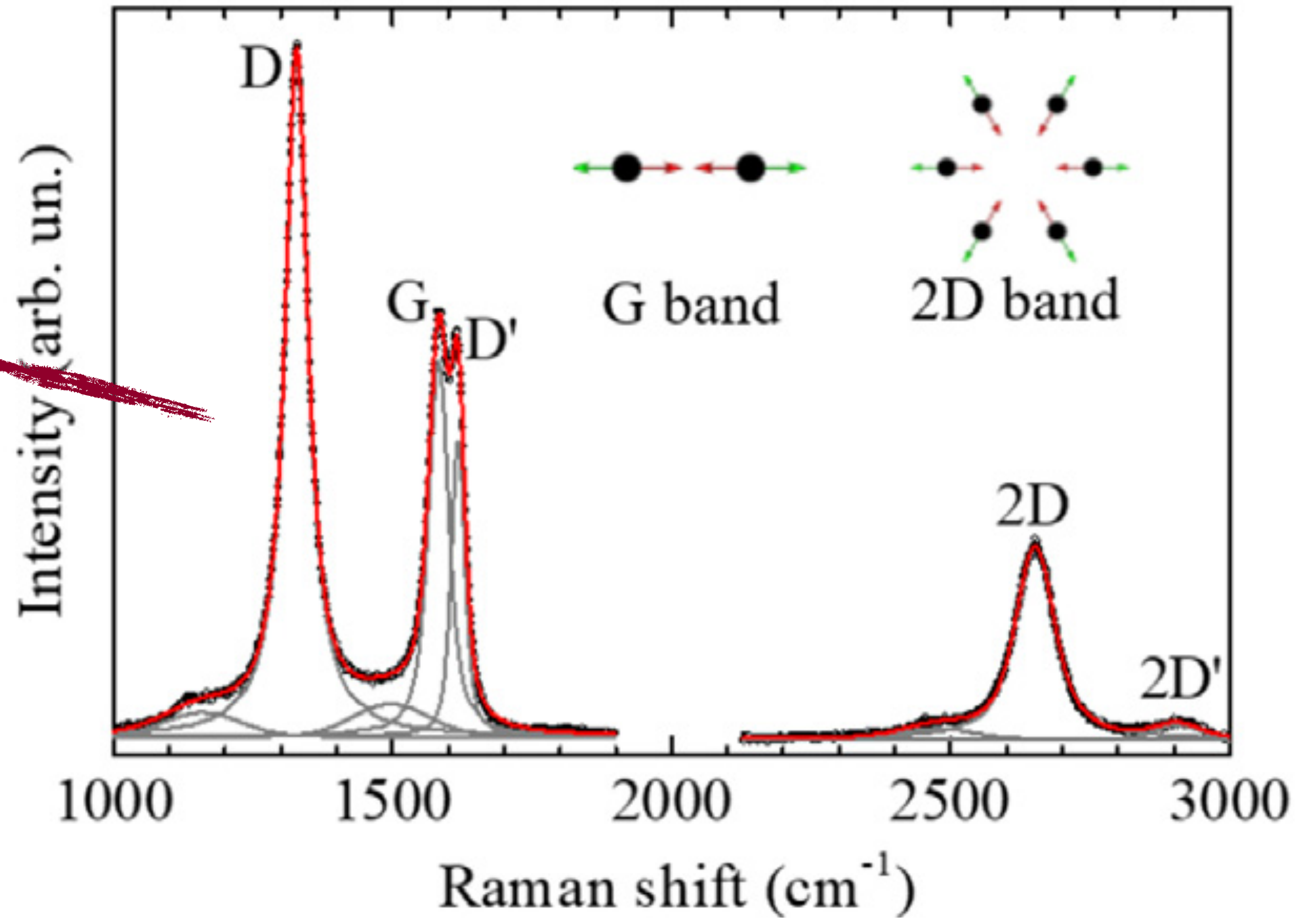
- Result: vertically-aligned nanotube 'forests'
  - **'Hollow'** in the direction of the tubes
  - Electrons can **escape** if // tubes
  - Makes it an **ideal** light-DM target



Raman Analysis: Nanotubes are Highly Anisotropic

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

Pristine spectrum



❖ **Raman** analysis: anelastic energy loss

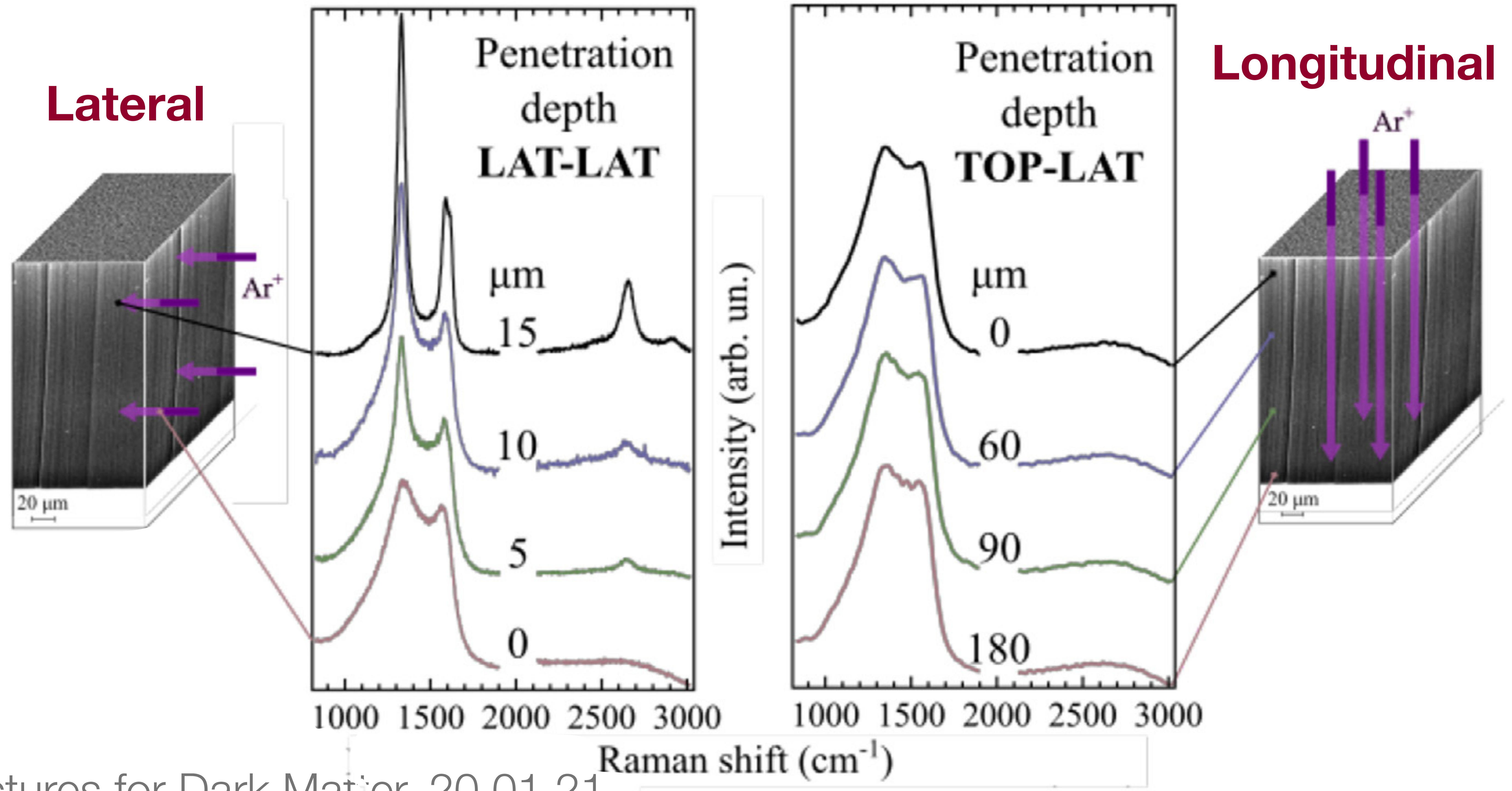
- **Vibrational** modes (G, 2D) of carbon
- D ‘defect’ peak **typical** of nanotubes (absent in graphene)

❖ After bombarding nanotubes with Ar+ ions

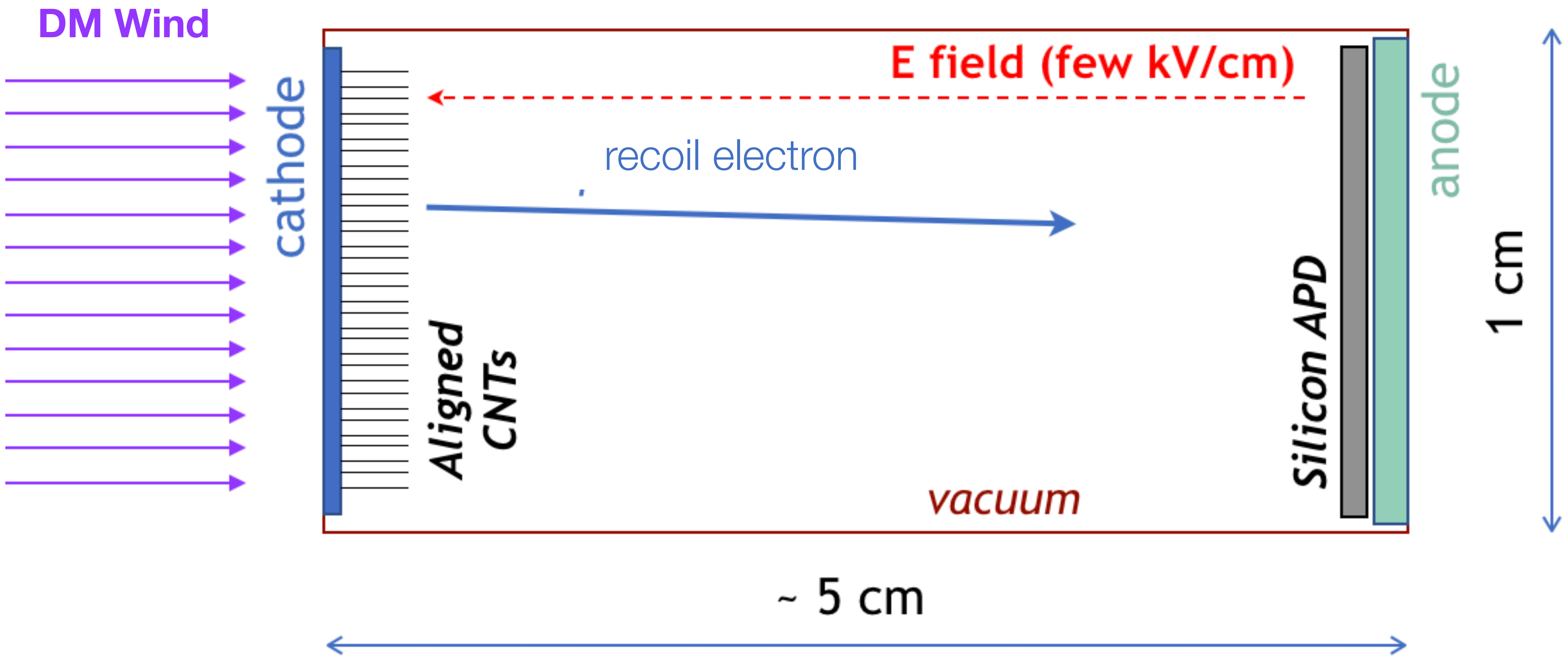
- **Lateral** penetration < 15 μm
- Longitudinal damage along **full** length (180 μm)

Lateral

Longitudinal



Nanotube Detector Concept: the 'dark-PMT'

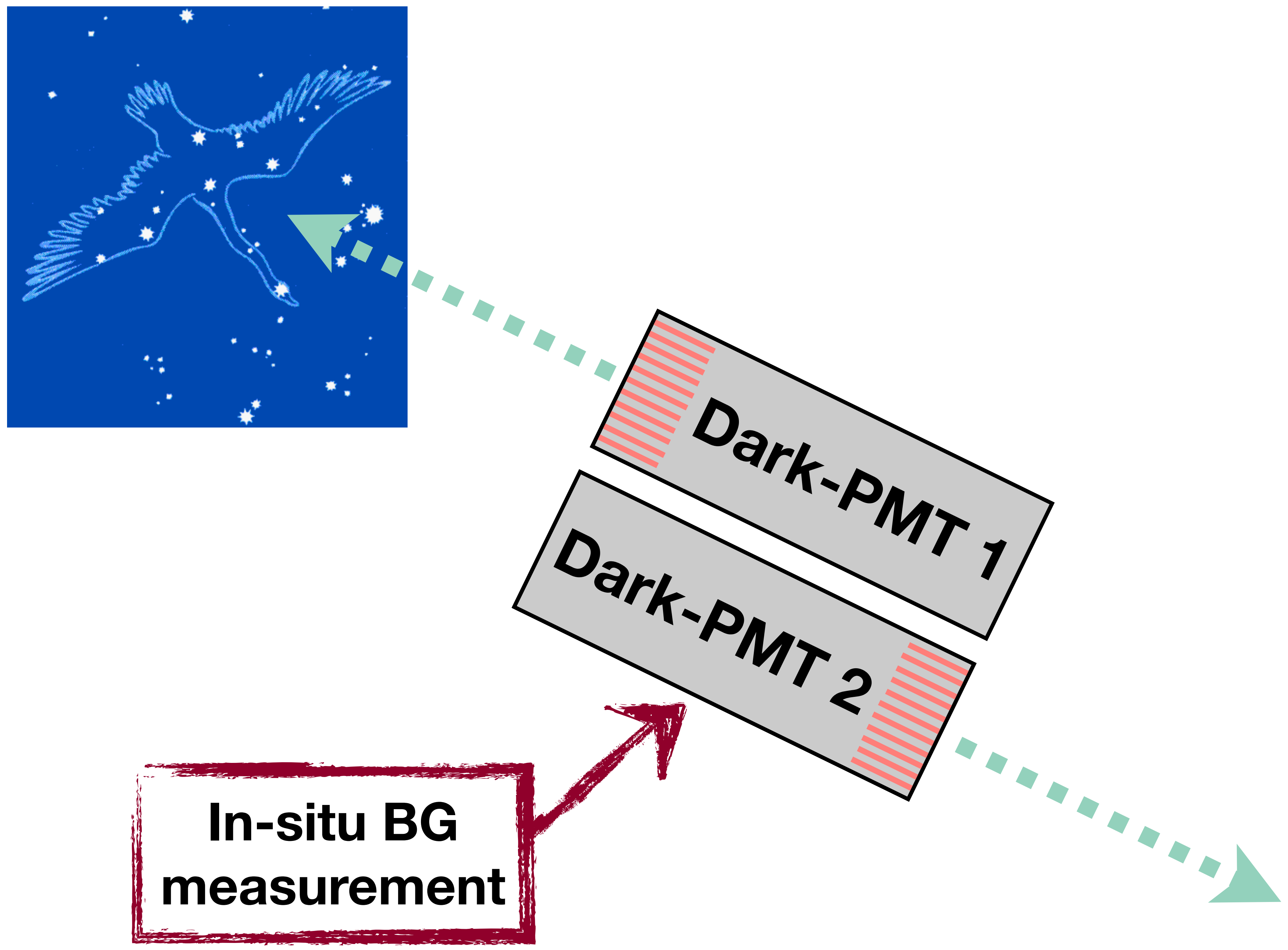


- 'Dark-photocathode' of aligned **nanotubes**
  - Ejected e^- accelerated by electric field
  - Detected by solid state **e^- counter**

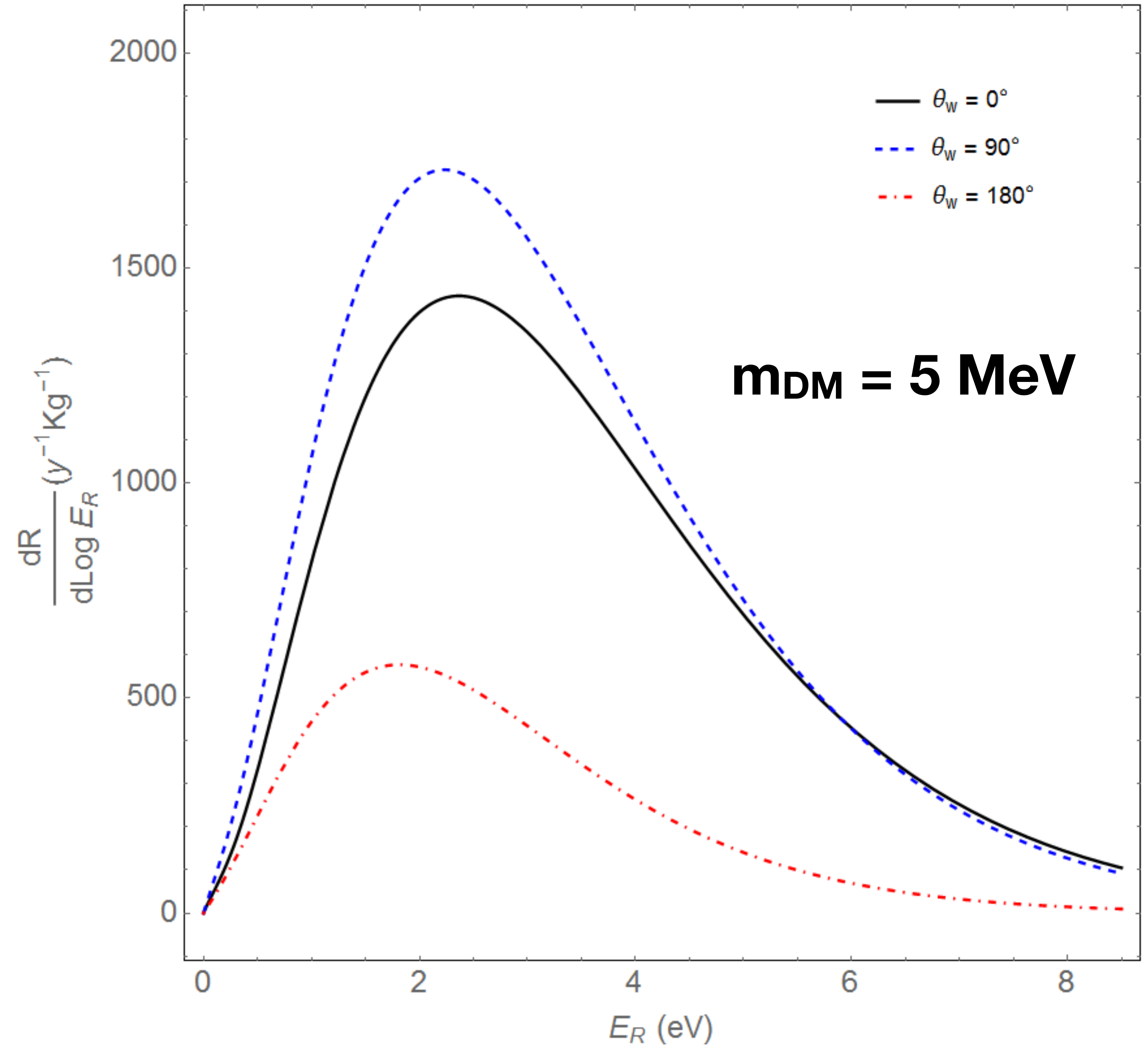
Dark-PMT features:

- **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



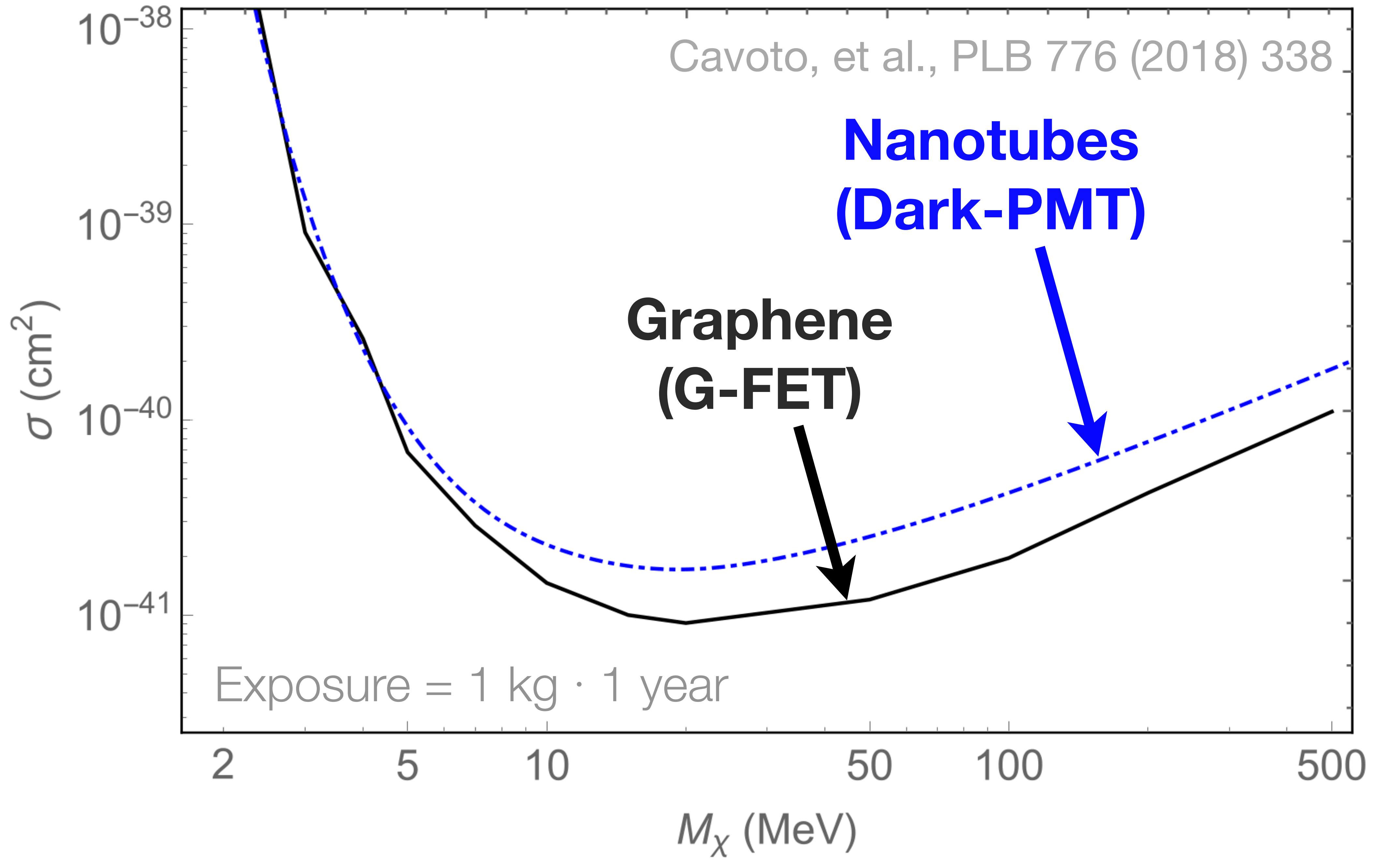
G. Cavoto, et al., PLB 776 (2018) 338

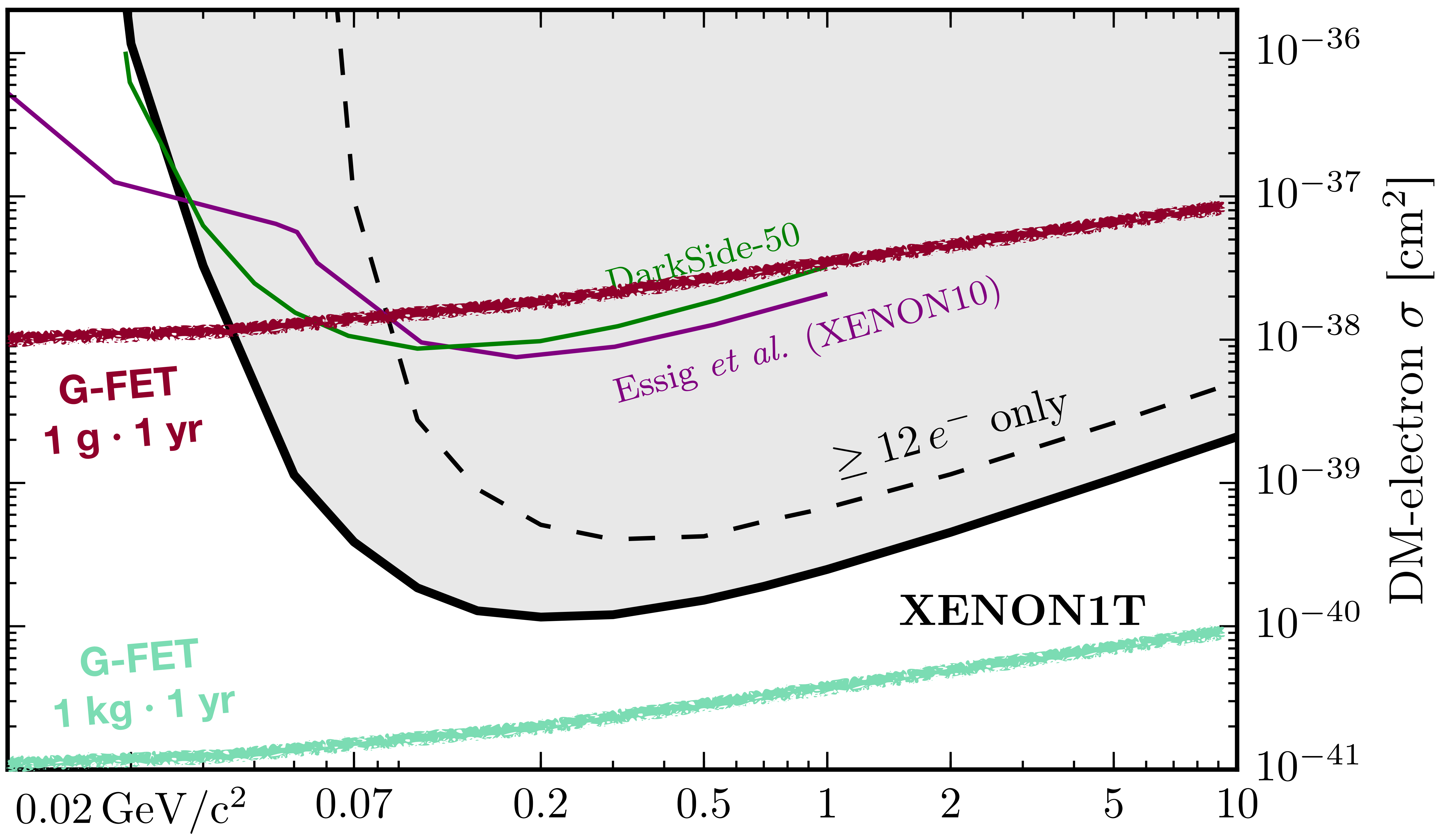


- **Two** sets of detectors: pointing towards Cygnus, and in **orthogonal** direction
  - Search variable: N_1-N_2

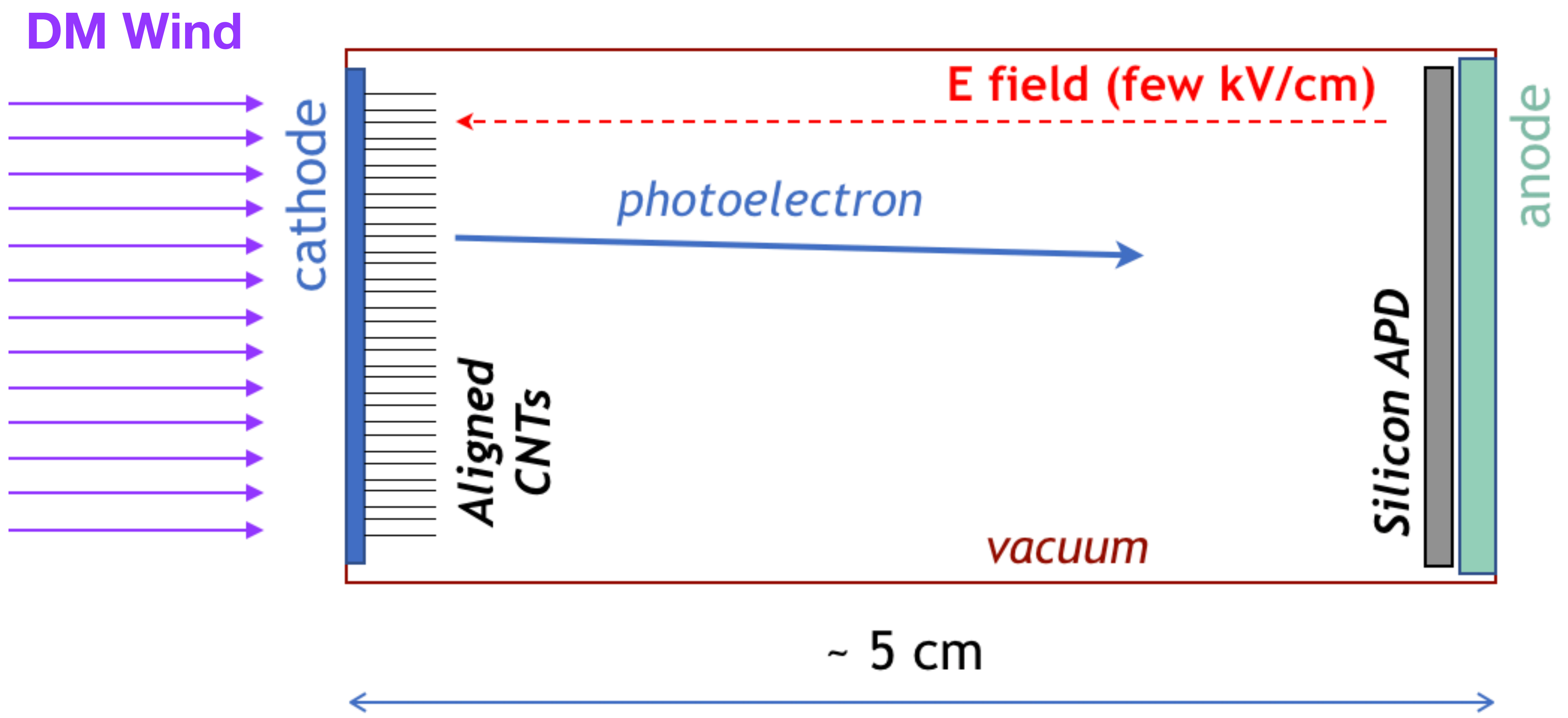
In principle sensitive to eV electrons!

Sensitive Down to DM Particles of 2 MeV!

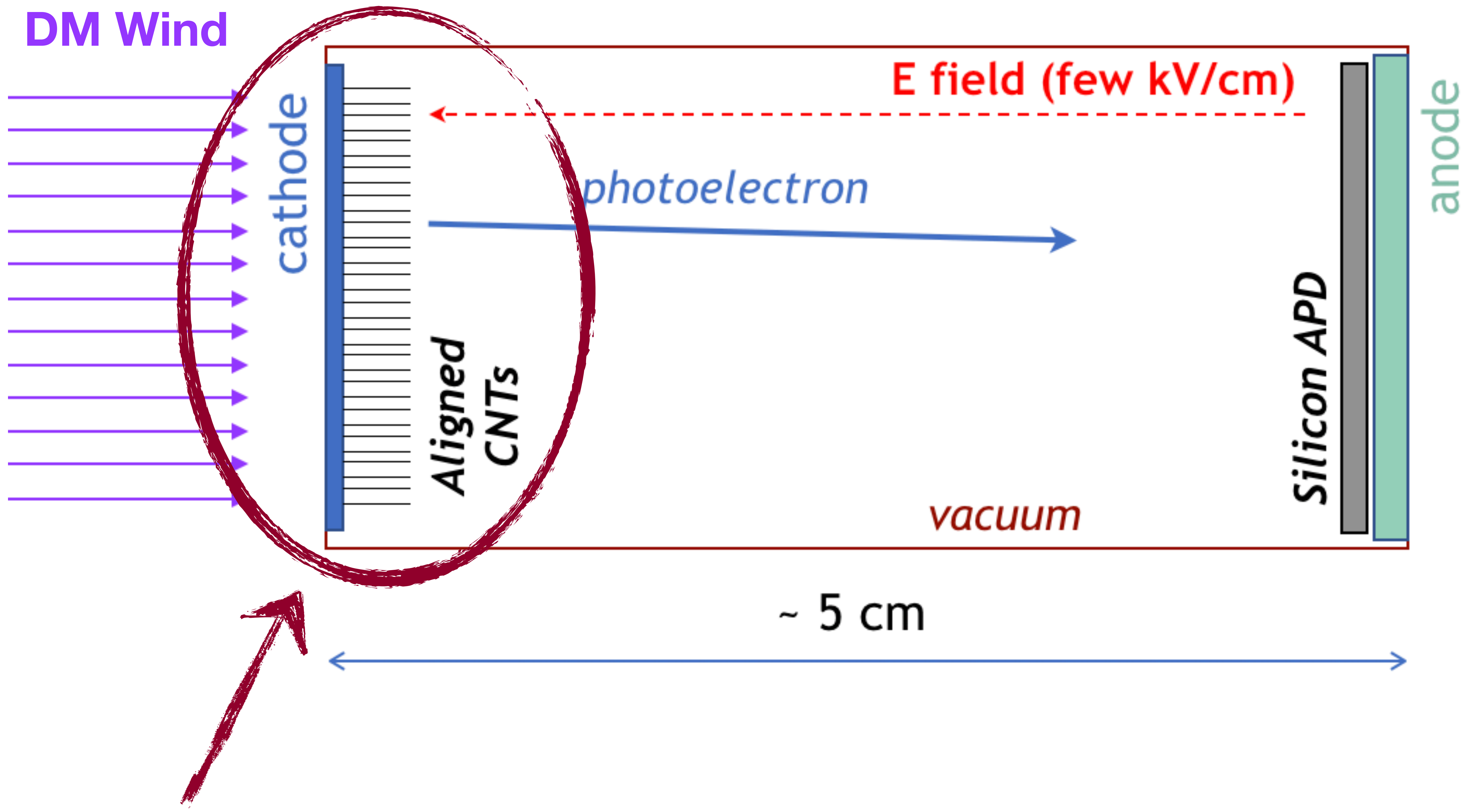




Optimizing the Two Sides of the dark-PMT



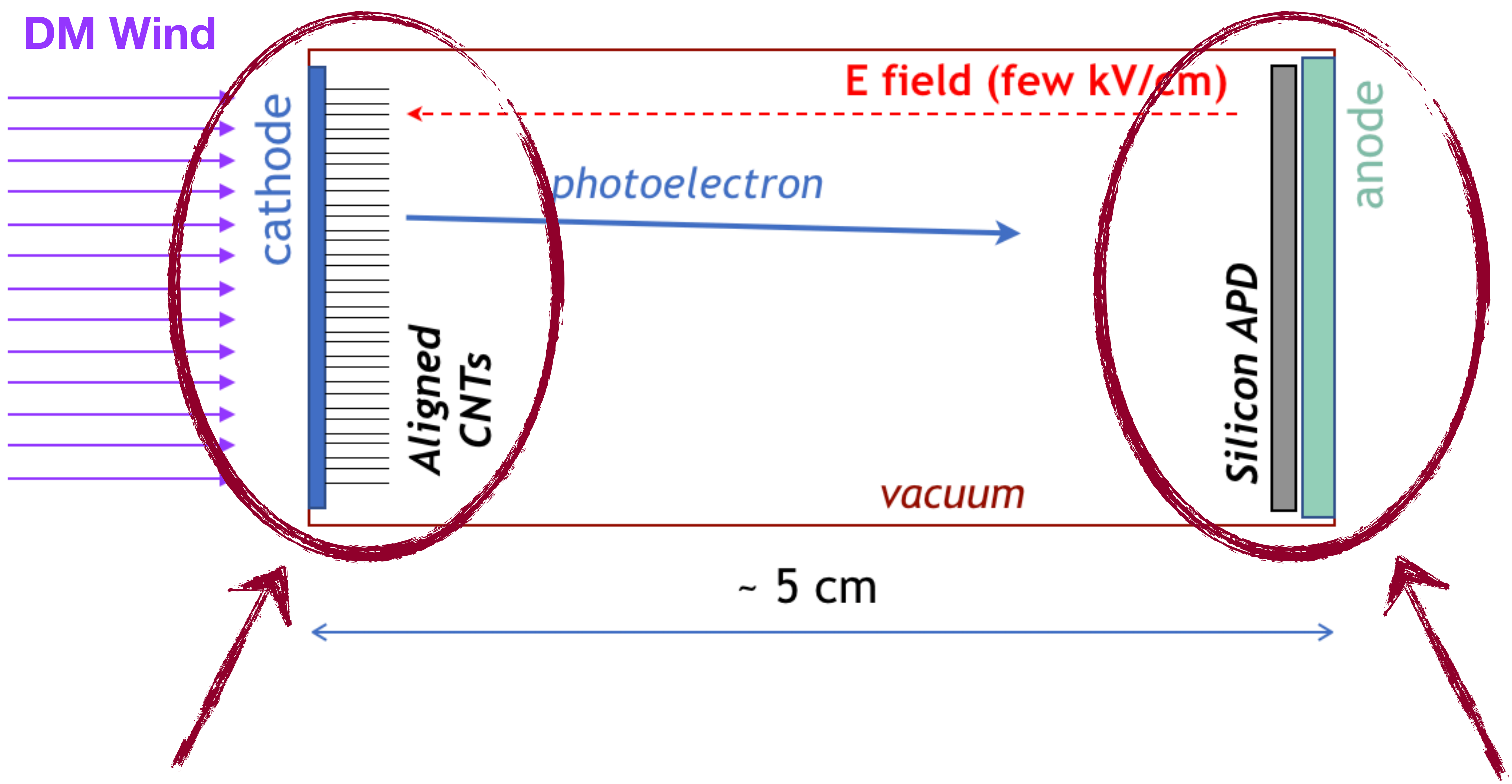
Optimizing the Two Sides of the dark-PMT



Aligned carbon nanotubes

Optimize: length, density, single-wall vs multi-wall

Optimizing the Two Sides of the dark-PMT



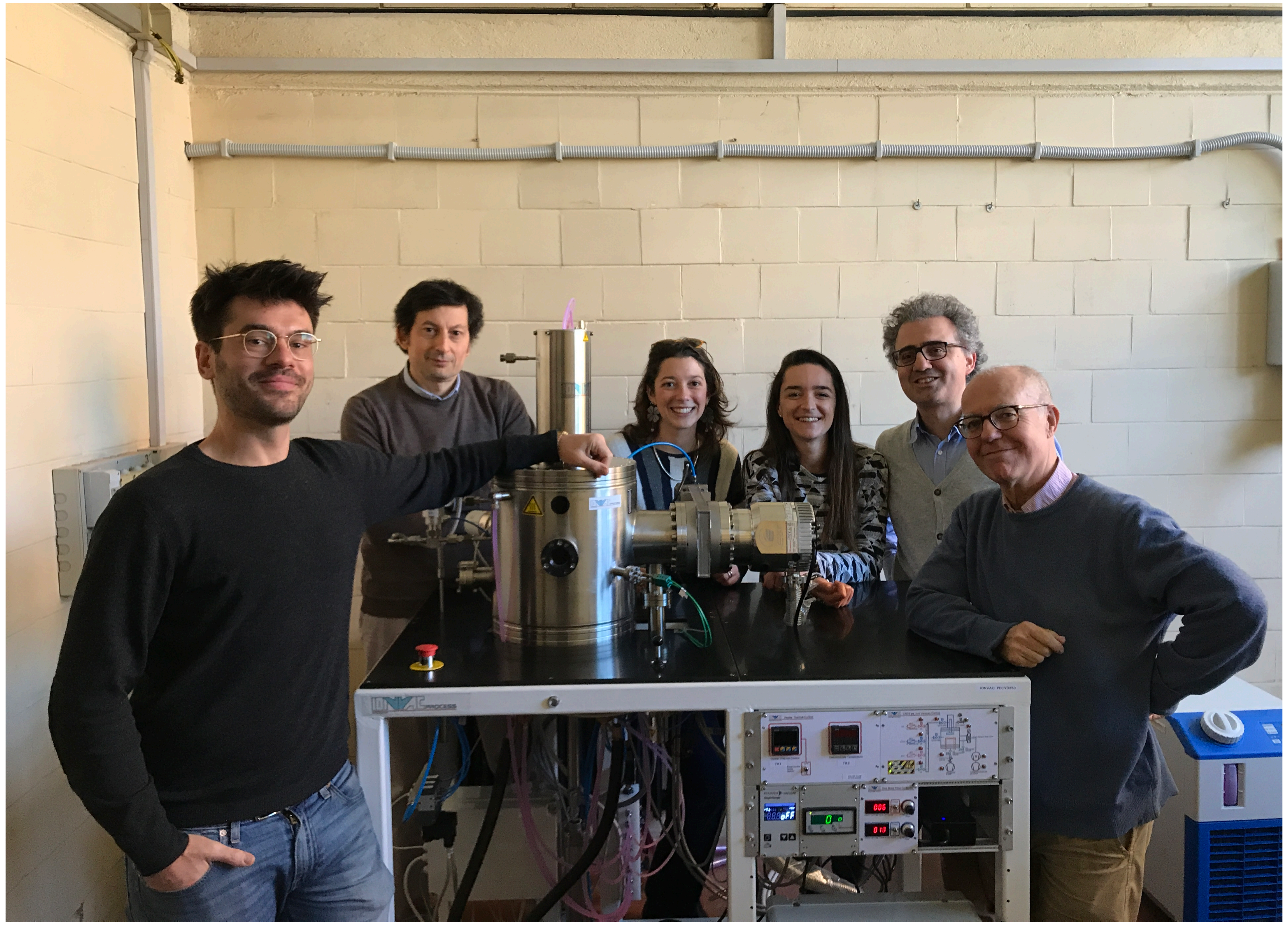
Aligned carbon nanotubes

Optimize: length, density, single-wall vs multi-wall

Silicon detector for keV electrons

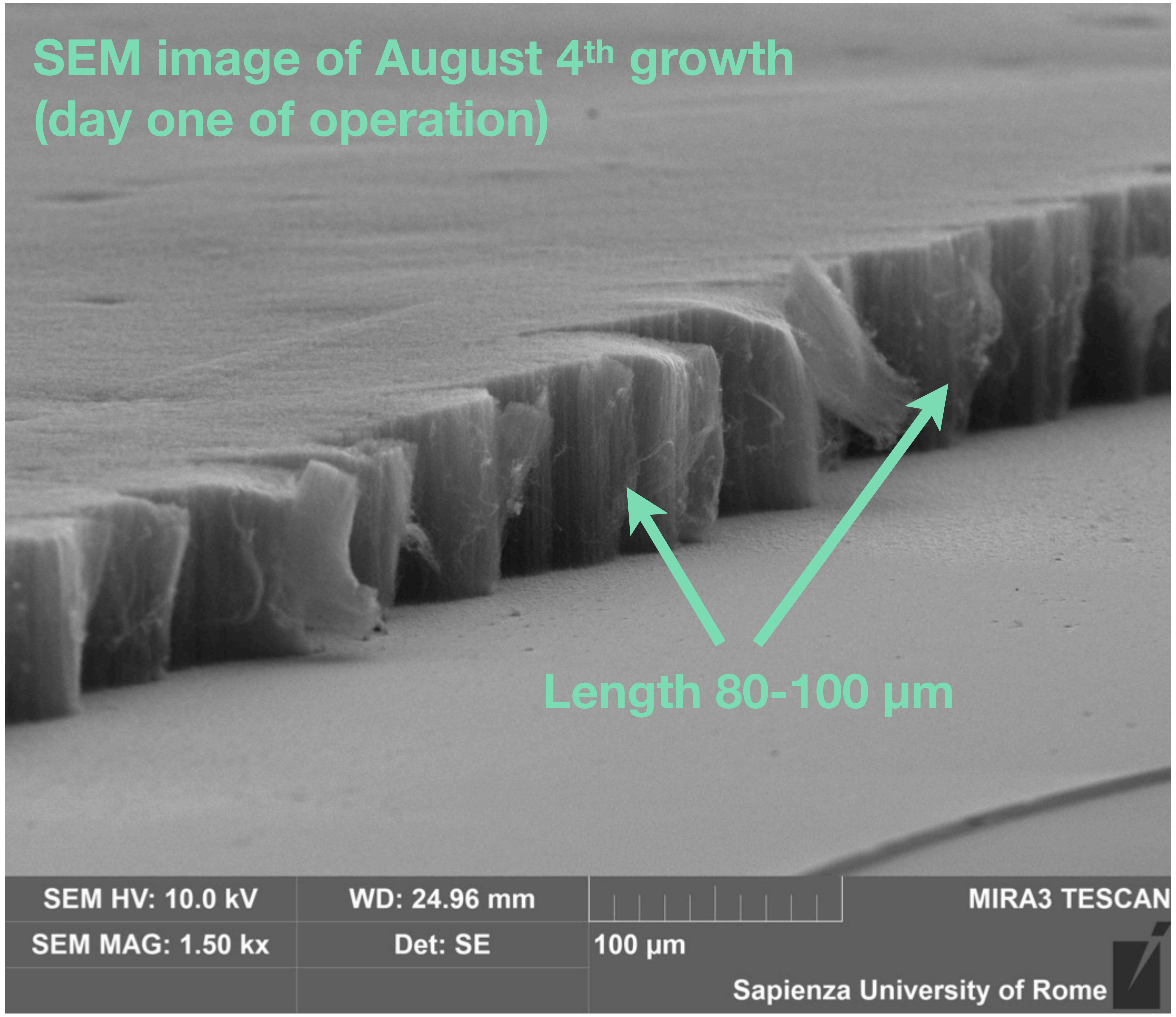
Optimize: technology, geometry, distance

A State-of-the-Art CVD Chamber in Rome



- Thanks to ATTRACT funding
  - To develop novel **UV light** detector made with carbon nanotubes
- Equipped with **Plasma-Enhanced** technology
  - Capable of **single-wall** nanotubes
- **Delivered** right before lockdown (March 2020)
  - Commissioning **finished** in July 2020
  - **Operational** since August 2020

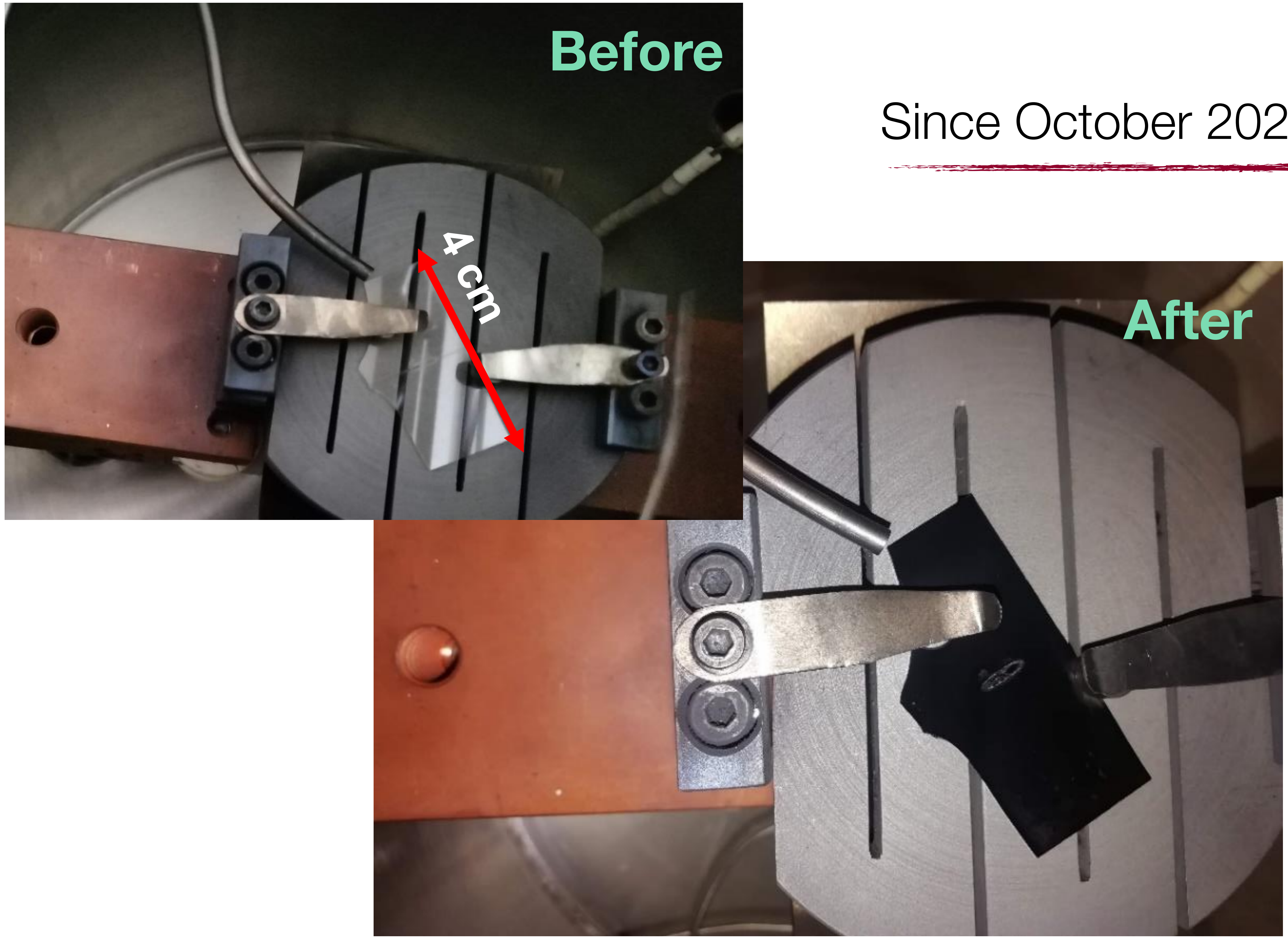
First Successful Growths on Day One!



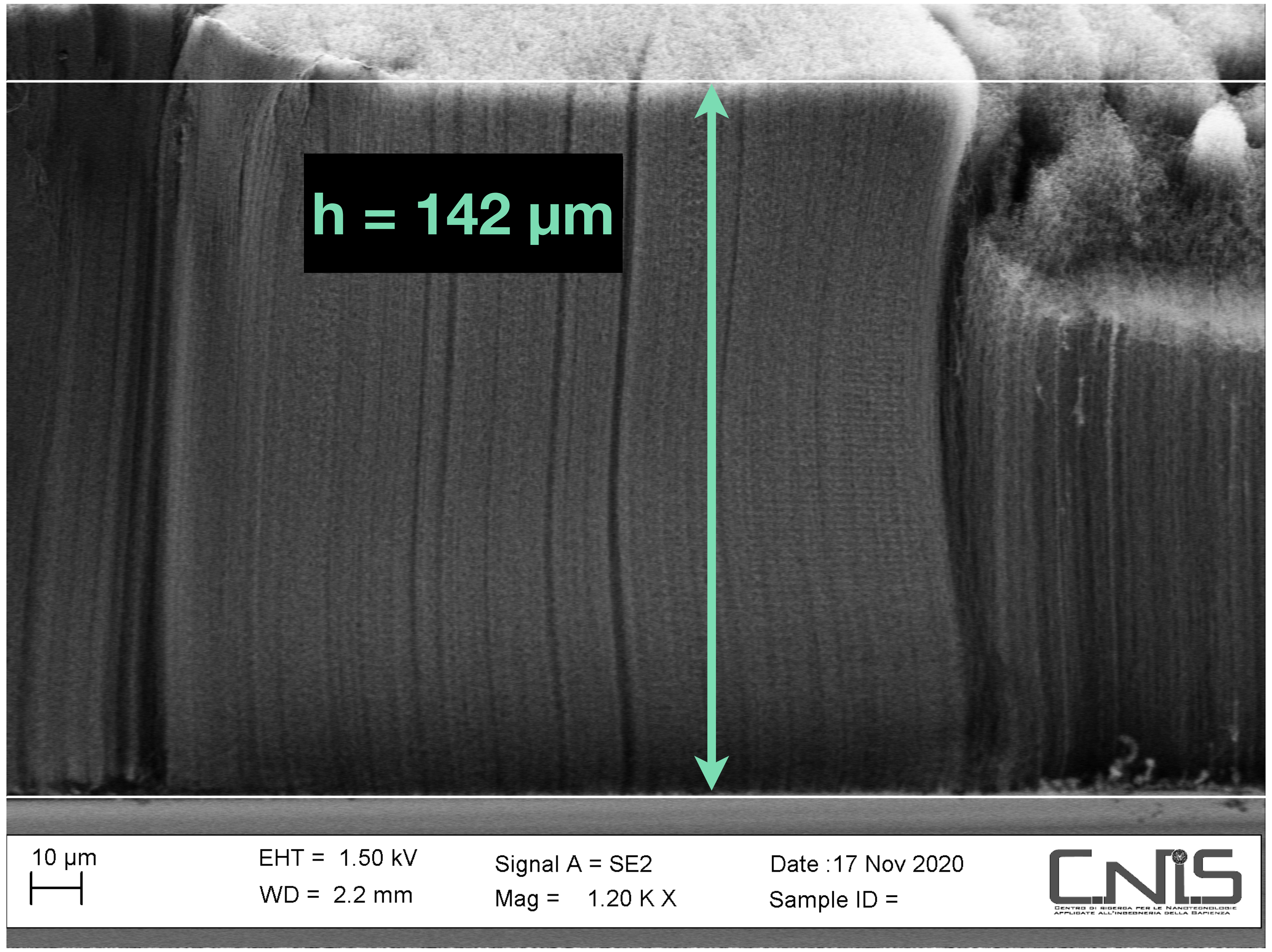
- Successfully synthetized nanotubes **on day one!**
  - Can take **months** to commission CVD
- Growing CNTs on a **number** of subtrates:
  - ☑ Silicon
  - ☑ Fused silica
  - ☑ Basalt fibers
  - ☐ Borosilicate glass

Not quite, yet

Optimizing the Nanotube Growth Process

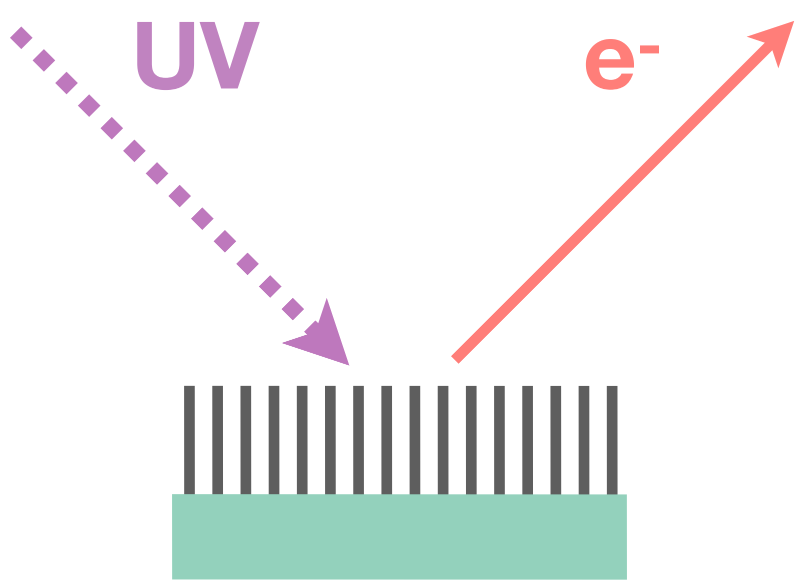


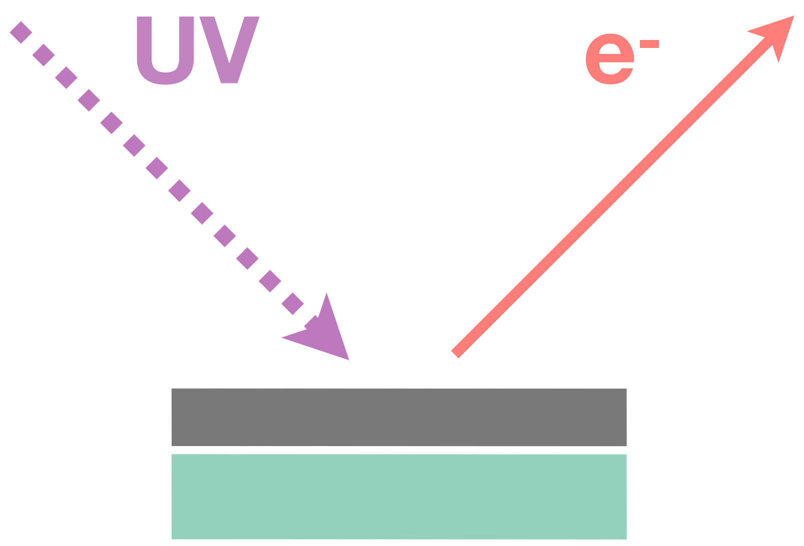
Since October 2020 achieving **uniform** growths over 4x2 cm^2

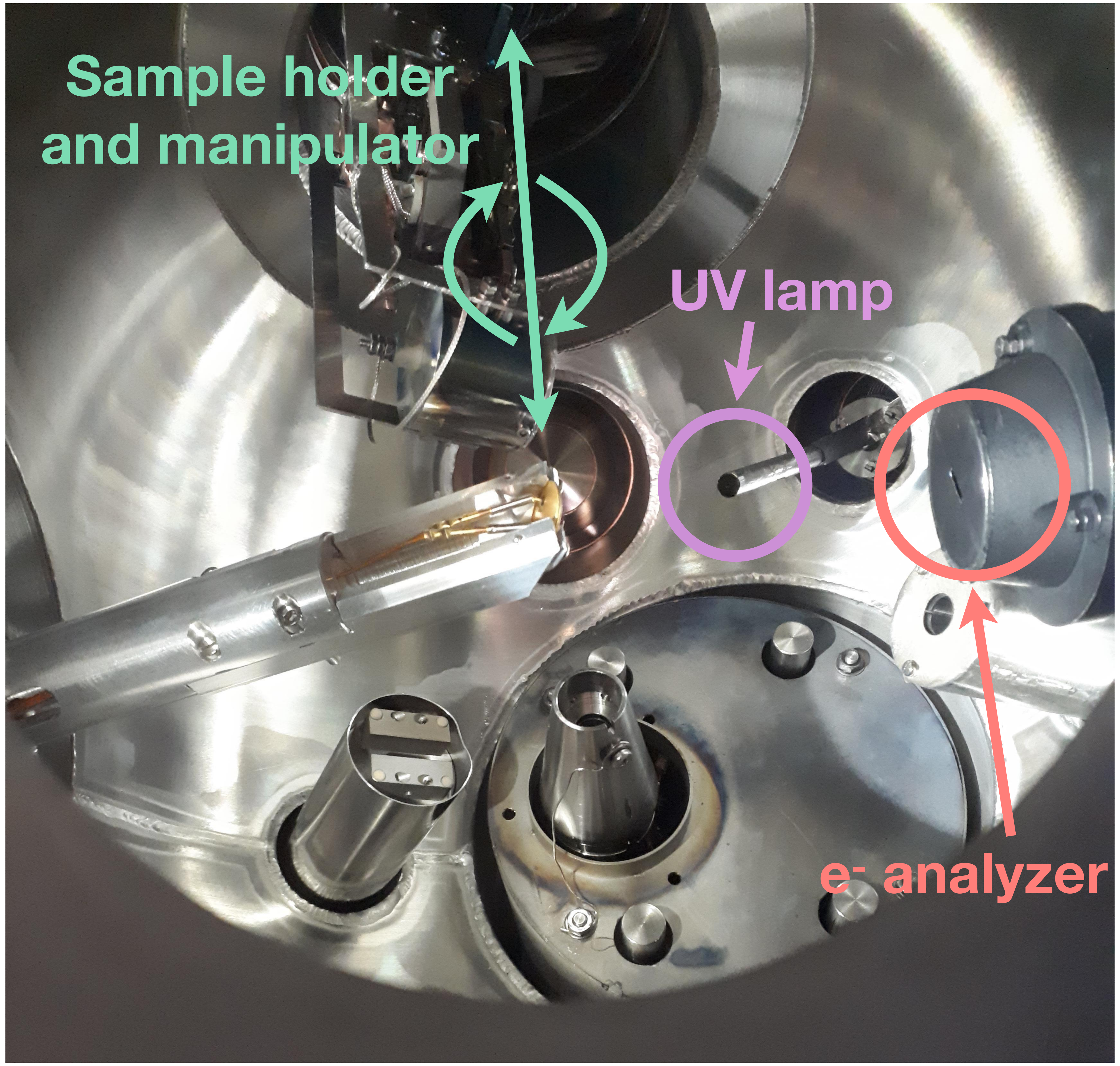


Nanotube Characterization at Roma Tre LASEC Labs

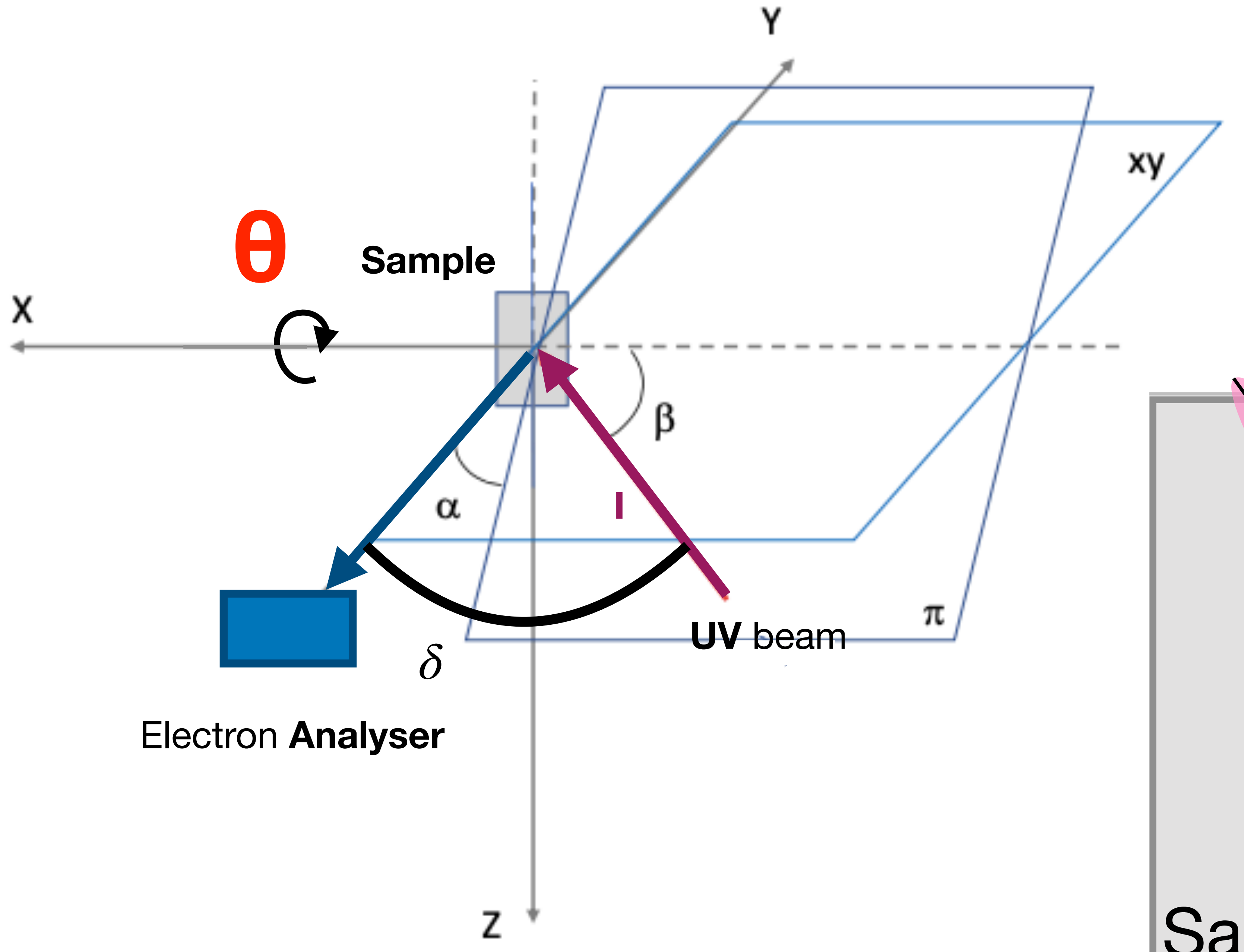
- Large UHV chamber at Roma Tre LASEC labs
  - Equipped with UPS, XPS, e^- energy loss analysis
- Performed UPS characterization of **nanotubes**
  - And compared them to **amorphous carbon**

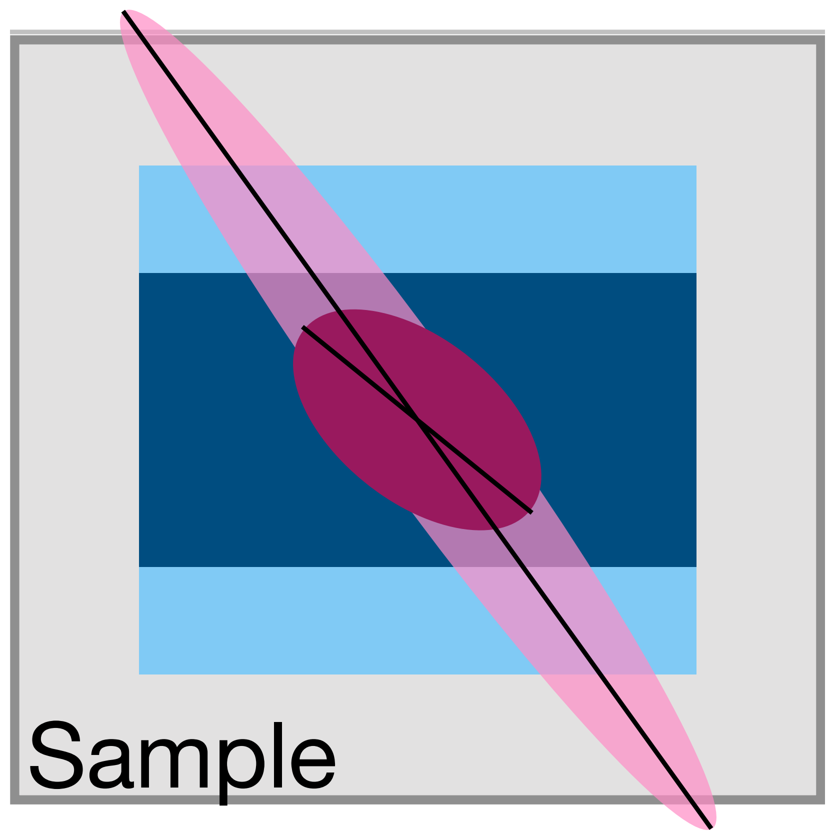






Non-trivial Geometry Needs to be Taken into Account

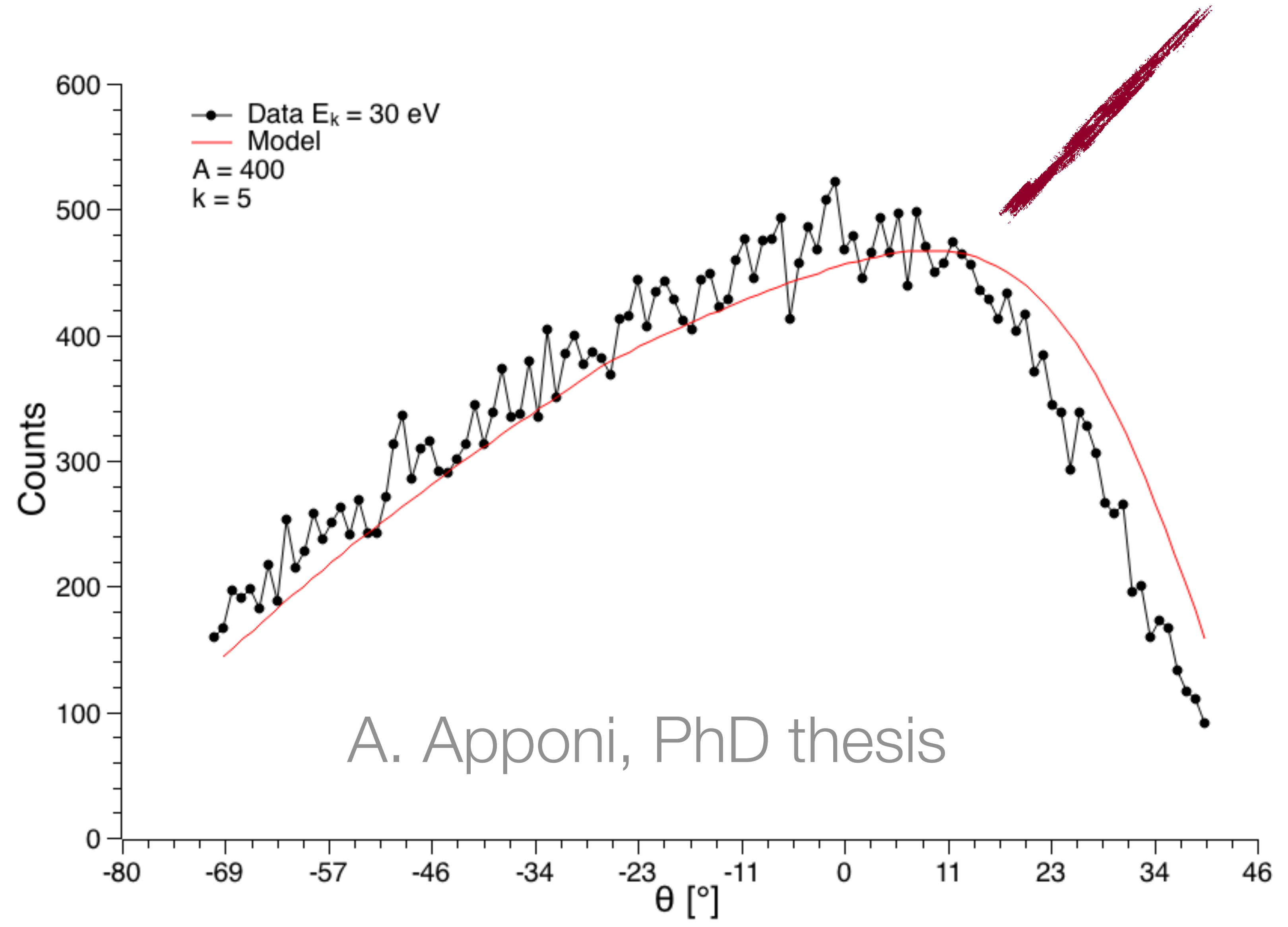




$$N(\theta) = A\left[\left(1 - \frac{1}{1+e^{-k(\theta-\theta_0)}}\right)\cos\theta + \frac{1}{1+e^{-k(\theta-\theta_0)}}\begin{cases}\dfrac{d_e^V}{\sin\left(tg^{-1}\left(tg\,\beta\,\sin(\alpha+\theta)\right)\right)}\,\dfrac{\sin\beta\,\cos(\alpha+\theta)}{d_{UV}\sin\beta\,\cos\alpha} & \theta > \theta_c\\[2ex] \dfrac{d_e^H\cos\theta}{\cos\left(tg^{-1}\left(tg\,\beta\,\sin(\alpha+\theta)\right)\right)}\,\dfrac{\sin\beta\,\cos(\alpha+\theta)}{d_{UV}\sin\beta\,\cos\alpha} & \theta \le \theta_c\end{cases}\right]$$

Geometrical model with only **one** free parameter

Satisfying description of amorphous carbon spectrum

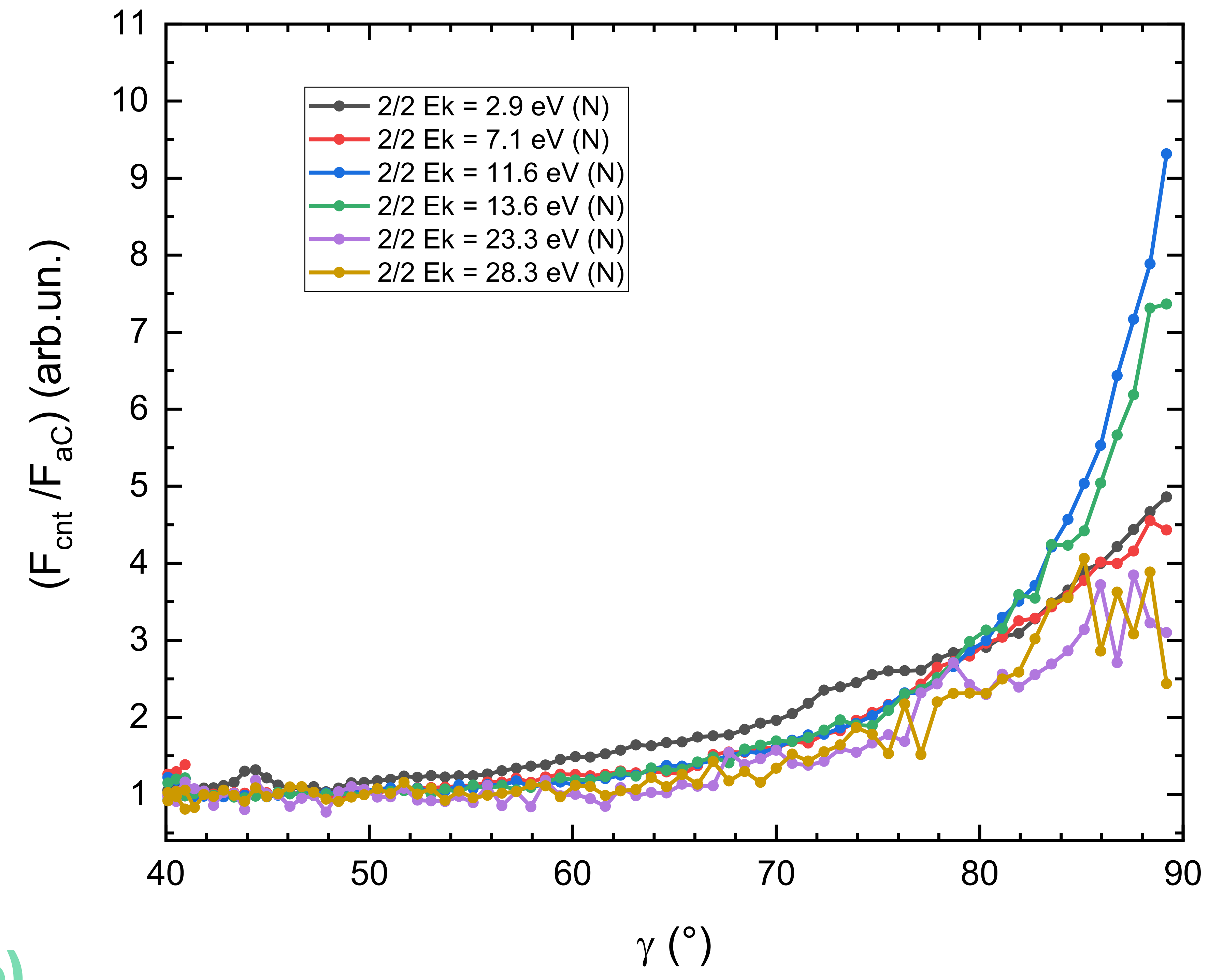


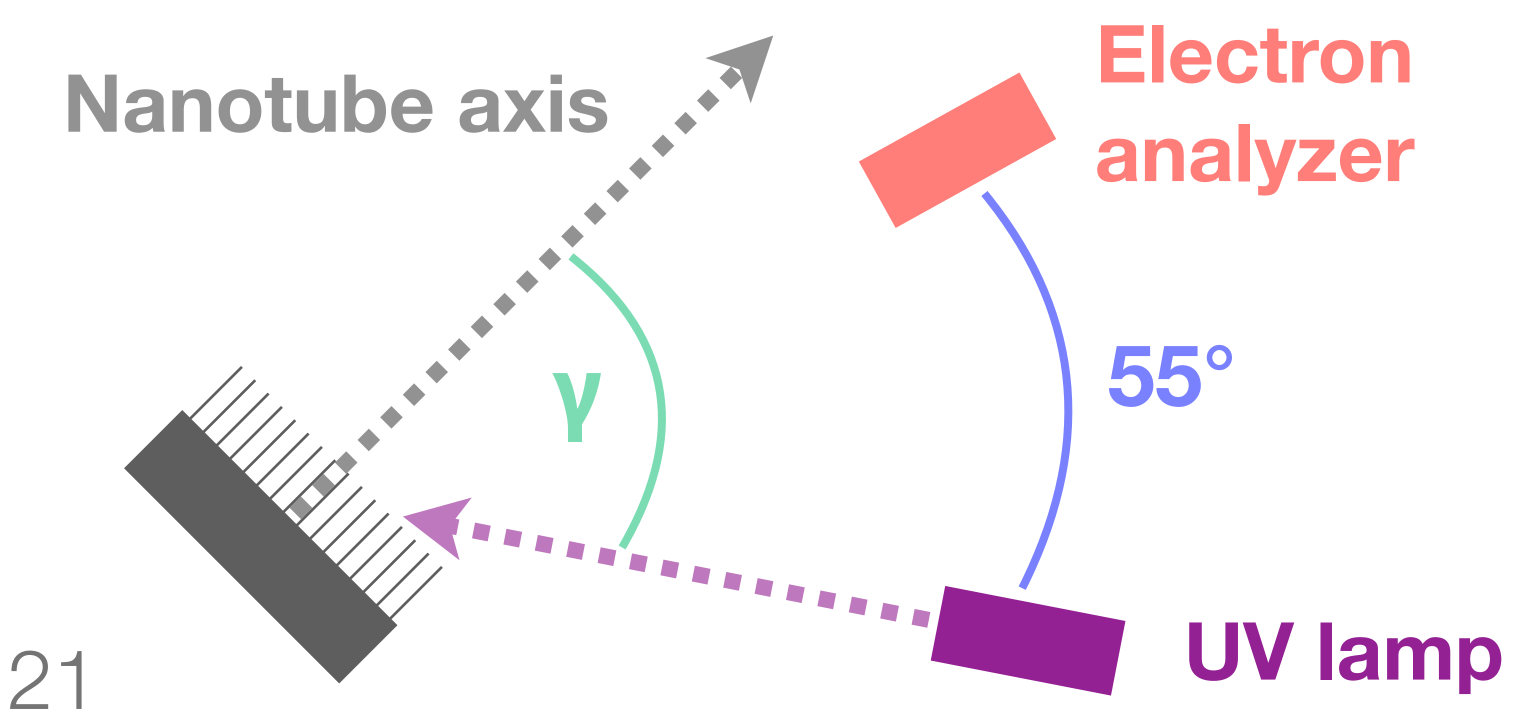
During rotation:

- **UV beam spot** turns and stretches
- **Analyzer field of view** shrinks

Enhanced Electron Emission by Nanotubes

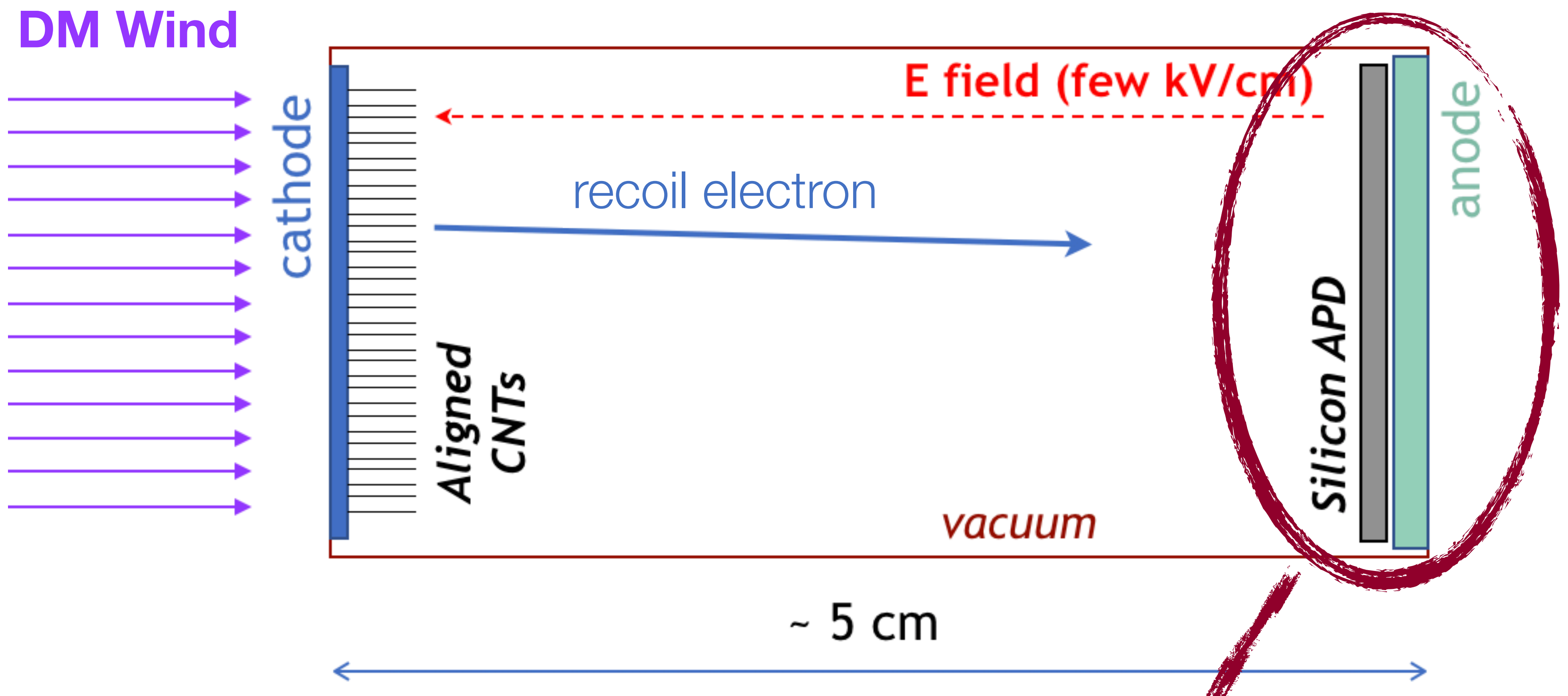
- Using He (I+II) UV lamp
  - hν = 21.2 eV and 40.8 eV
- Studied electron flux ratio F_{cnt}/F_{aC}
  - vs angle γ between nanotube axis and UV light
  - Normalized so that F_{cnt}/F_{aC} = 1 @ γ = 40° (grazing angle)
  - CNT variation **up to 10x larger** than aC @ γ = 90°
  - Further proof of **anisotropy**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





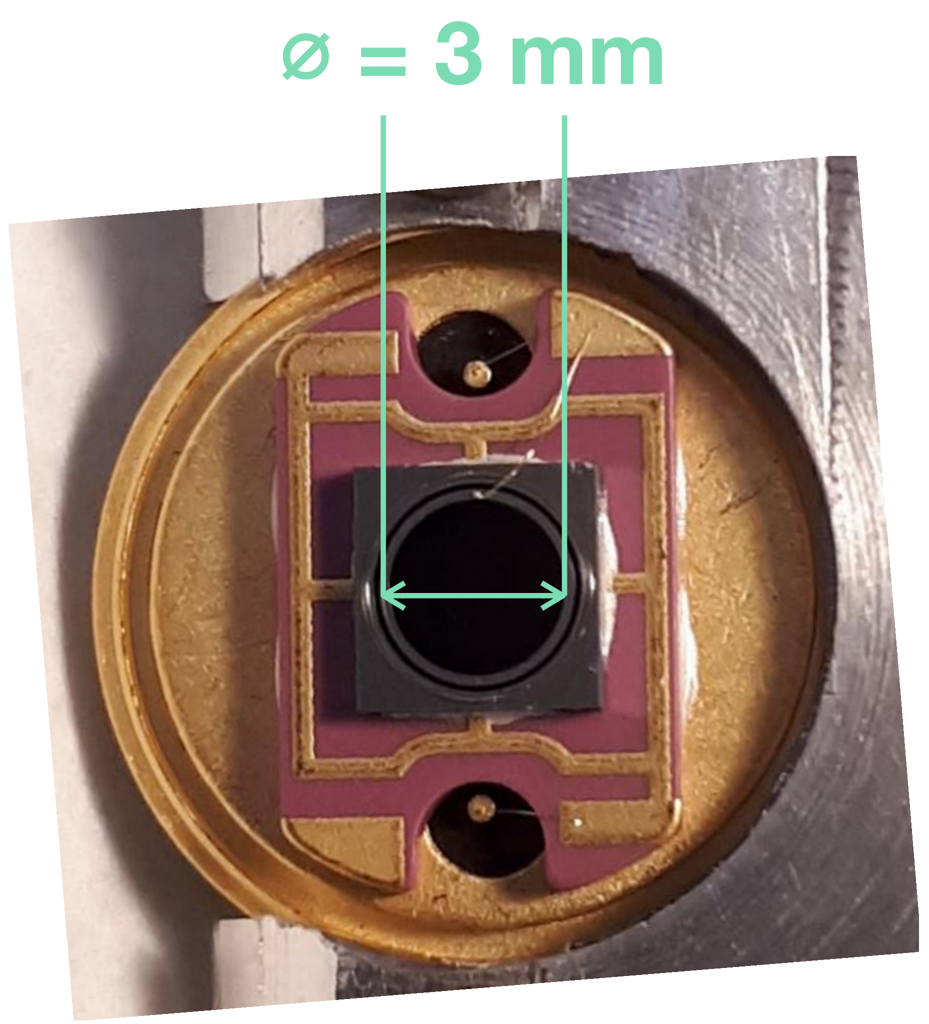
Silicon Detectors for keV Electrons

APDs and SDDs 'born' as photon detectors

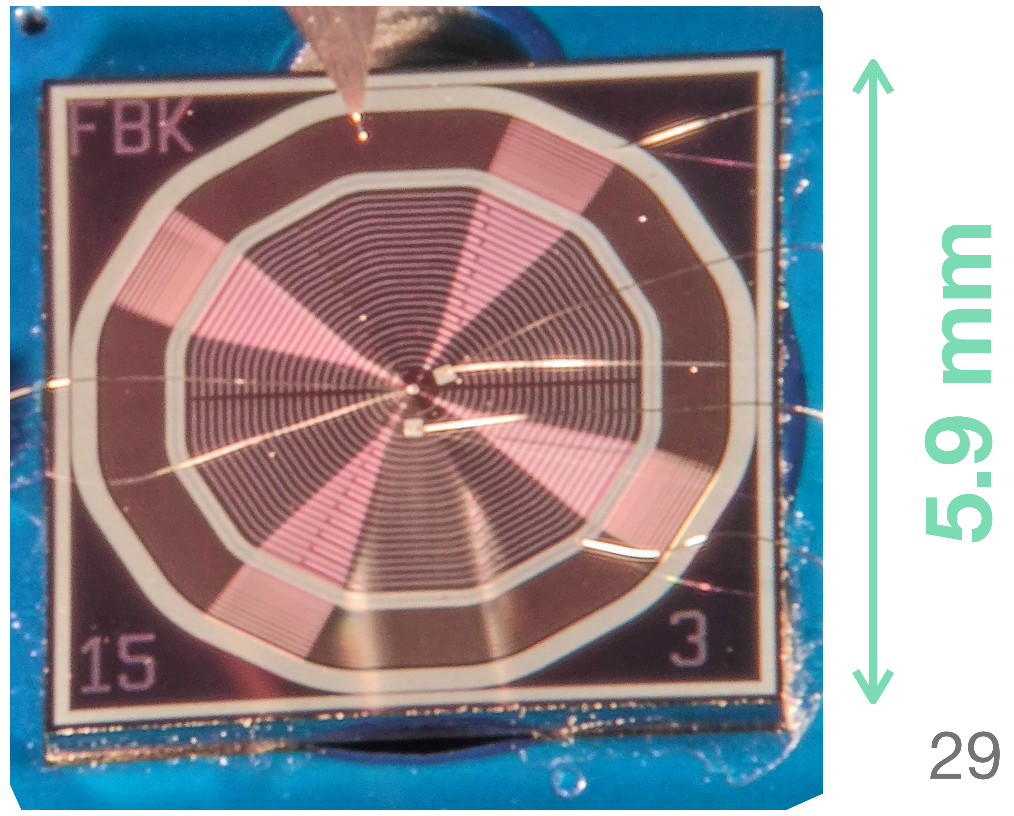


Challenge: detect keV electrons (with high efficiency)

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

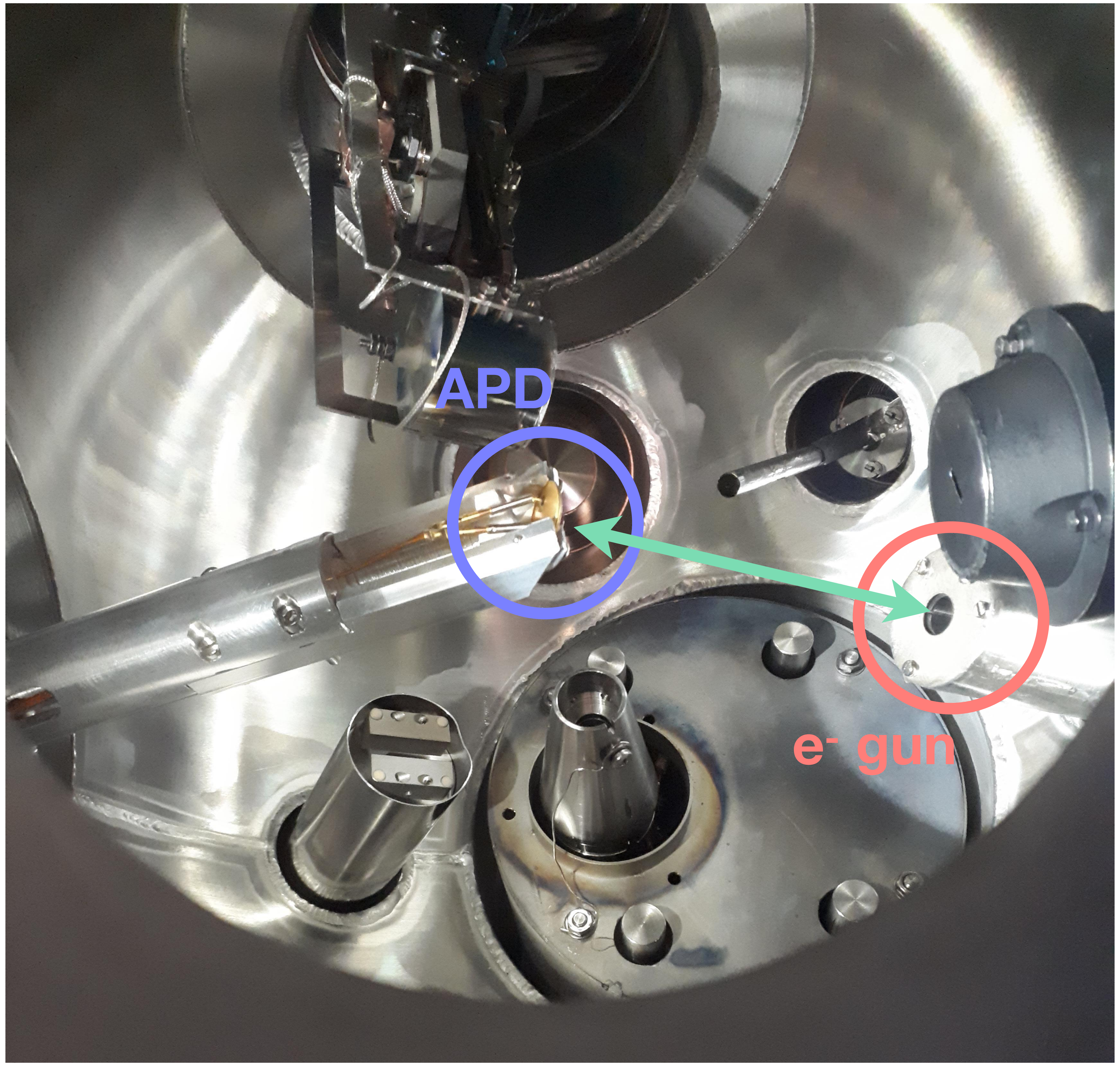


- Possible upgrade: **Silicon Drift Detectors**
  - Ultimate resolution
  - FBK (SDD) + PoliMi (electronics)

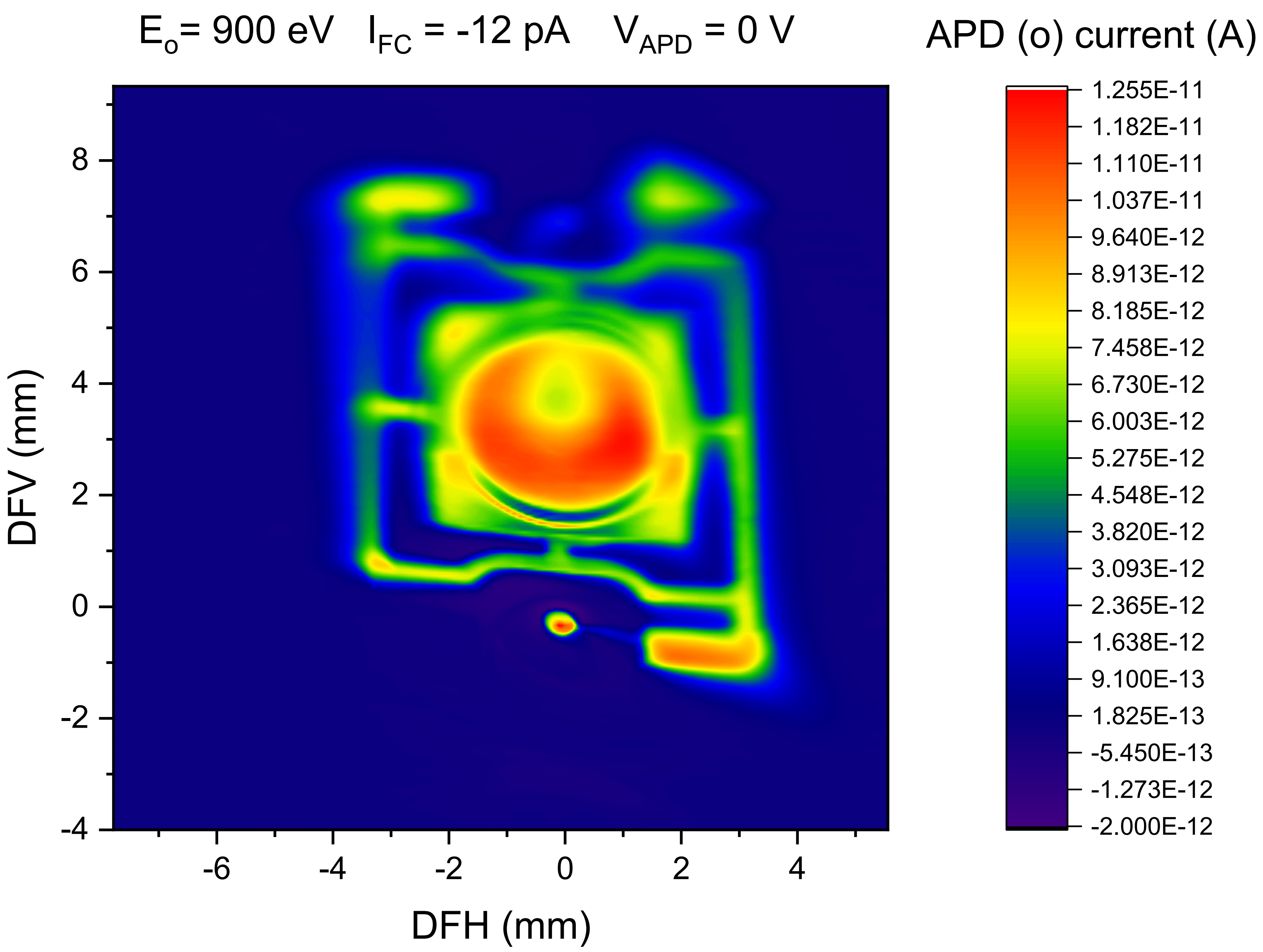


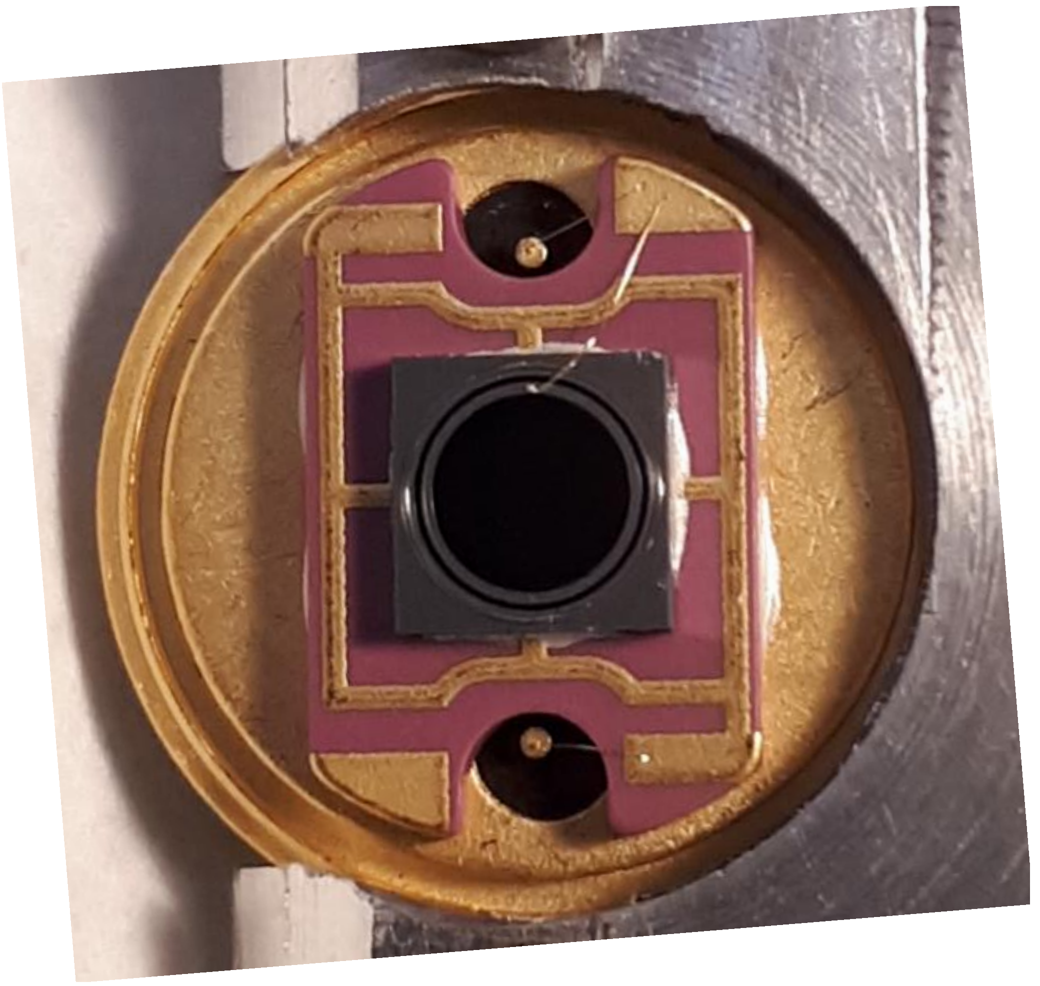
LASEC Labs Also Have State-of-the-Art e^- Gun

- Inside **same** UHV chamber as UPS
  - Electron **energy**: 90 < E < 1000 eV
  - Energy uncertainty < 0.05 eV
- Gun **current** as low as a few fA
  - i.e. electrons at ~10 kHz (not bunched)
- Beam profile ~ 0.5 mm
  - Completely **contained** on APD (⌀ = 3 mm)

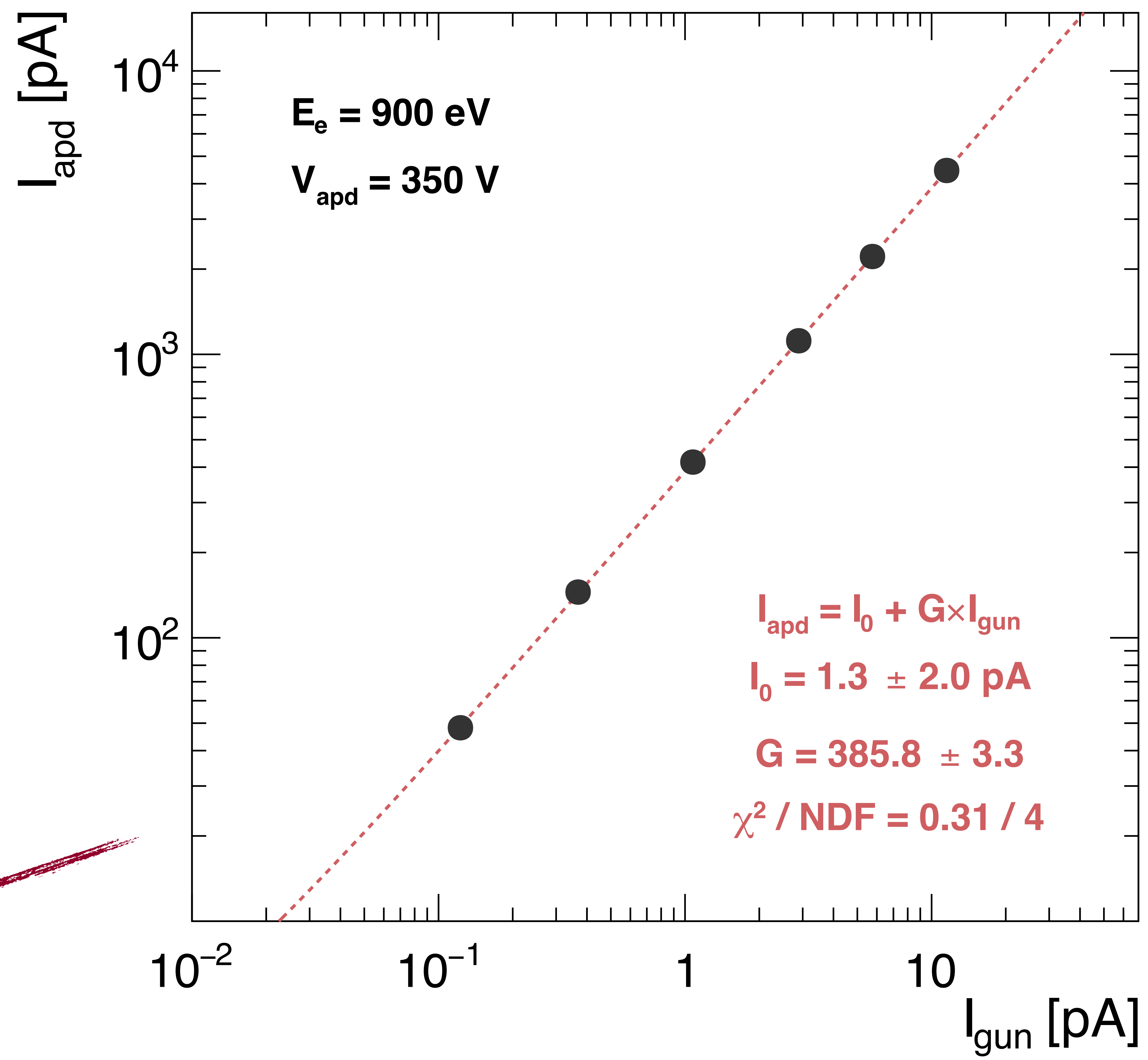


APD Characterization with 900 eV Electrons



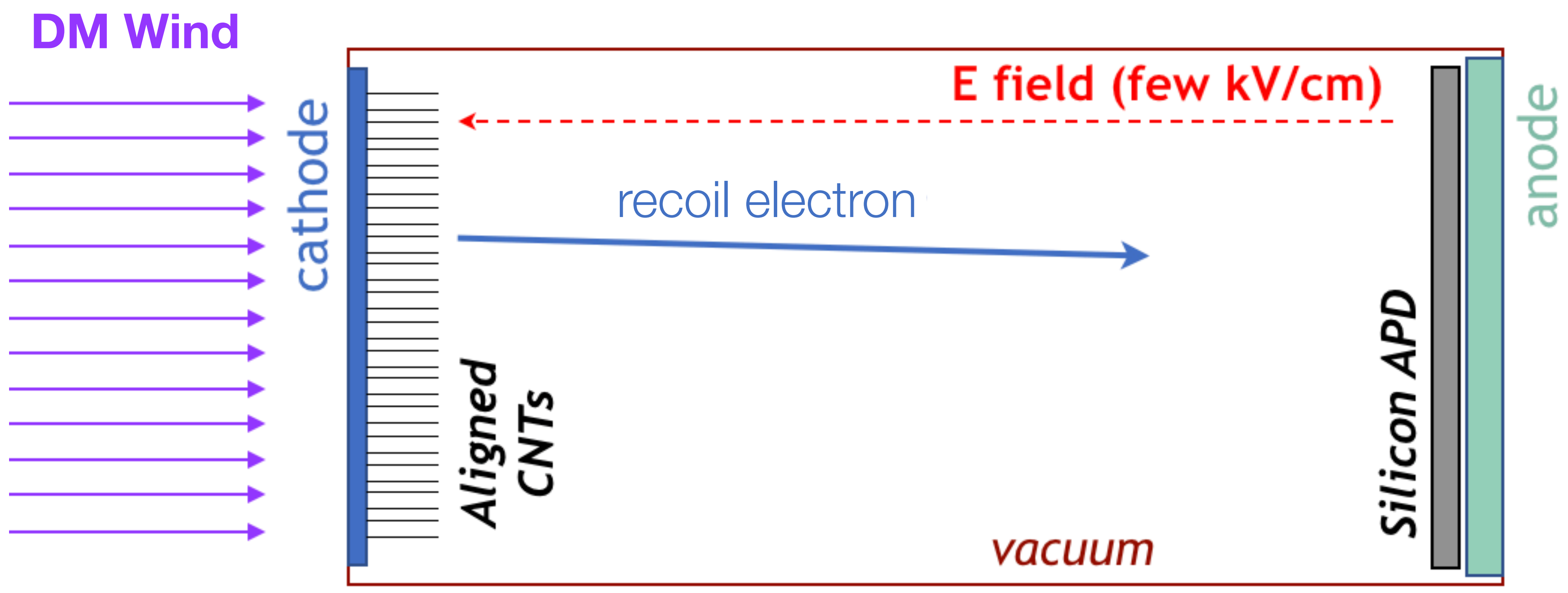


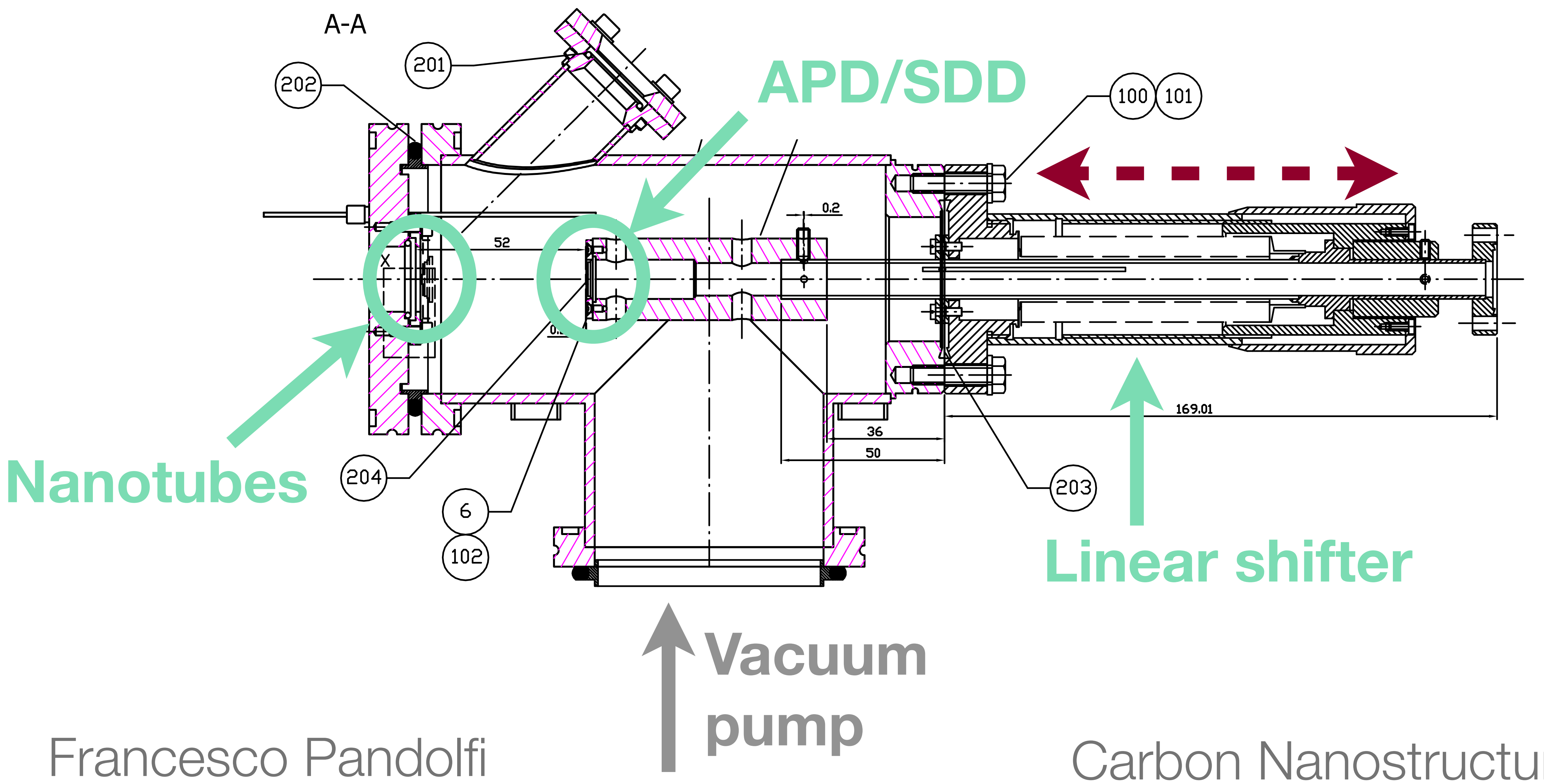
A. Apponi et al 2020 JINST **15** P11015

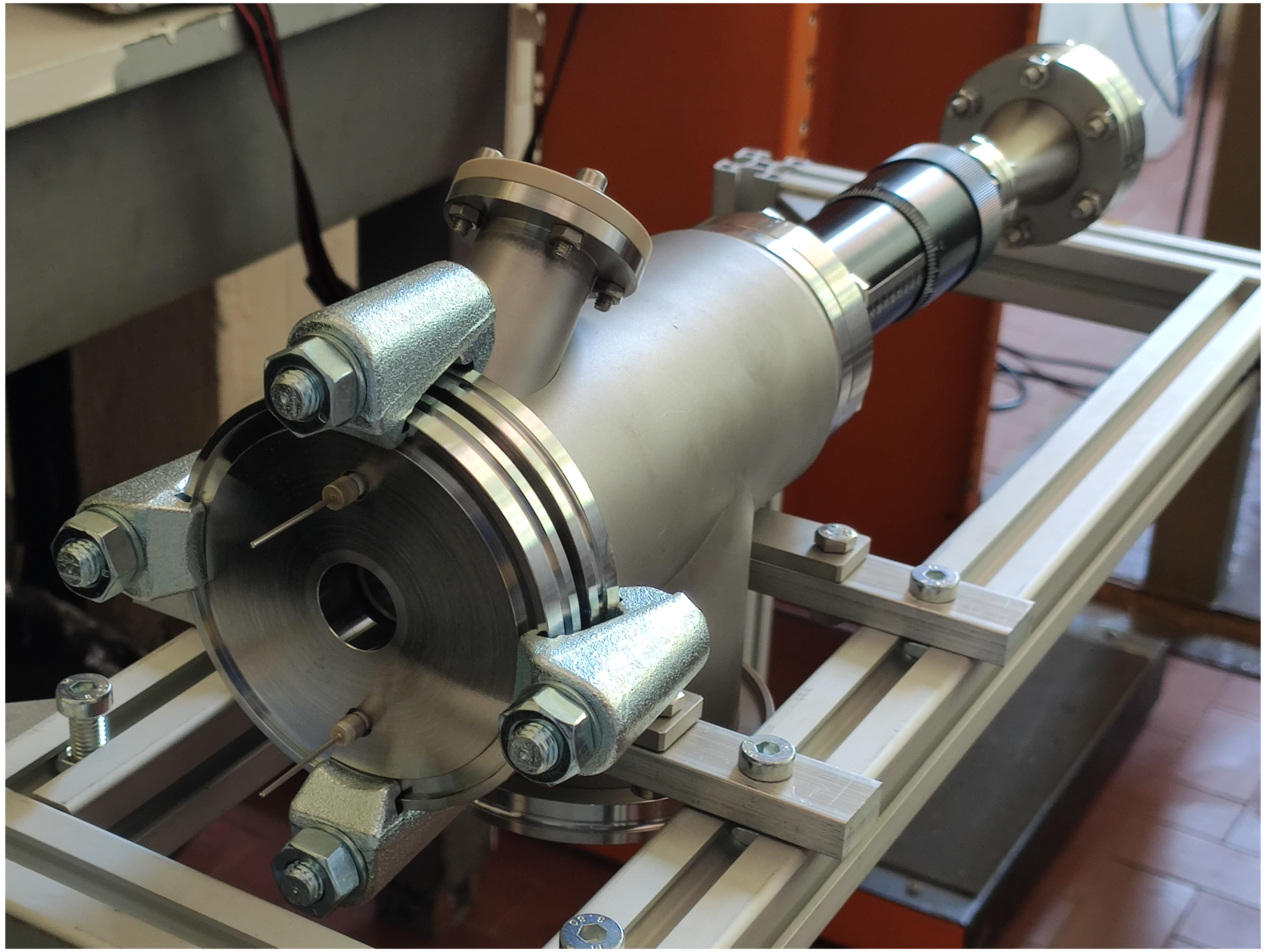


- Reading APD bias current when shooting gun on it
  - $V_{apd} = 0$: electronic ‘image’ of APD
  - V_{apd} = 350 V: I_{apd} **proportional** to I_{gun}

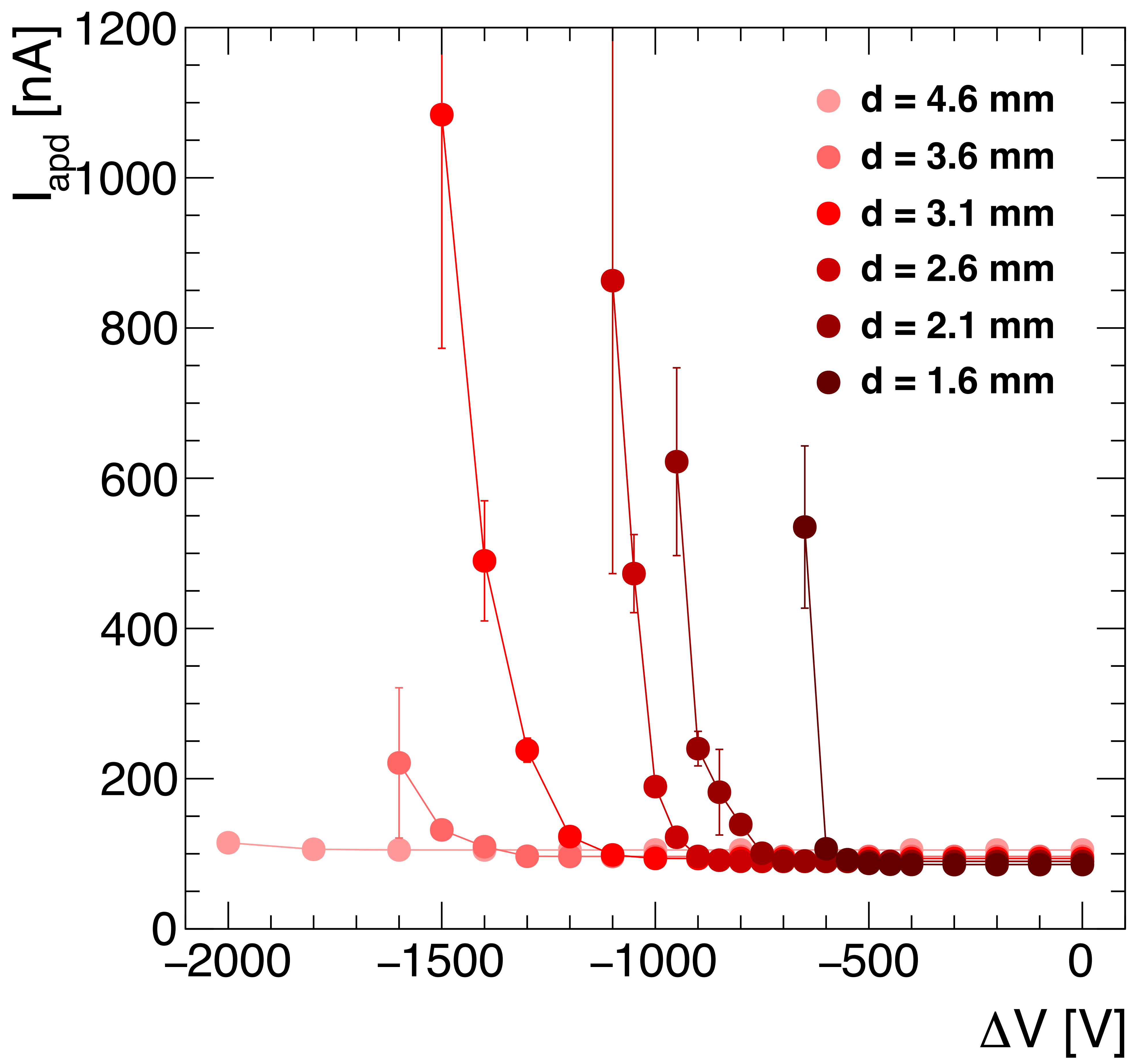
Dark-PMT Prototype ‘Hyperion’ Taking Data in Rome





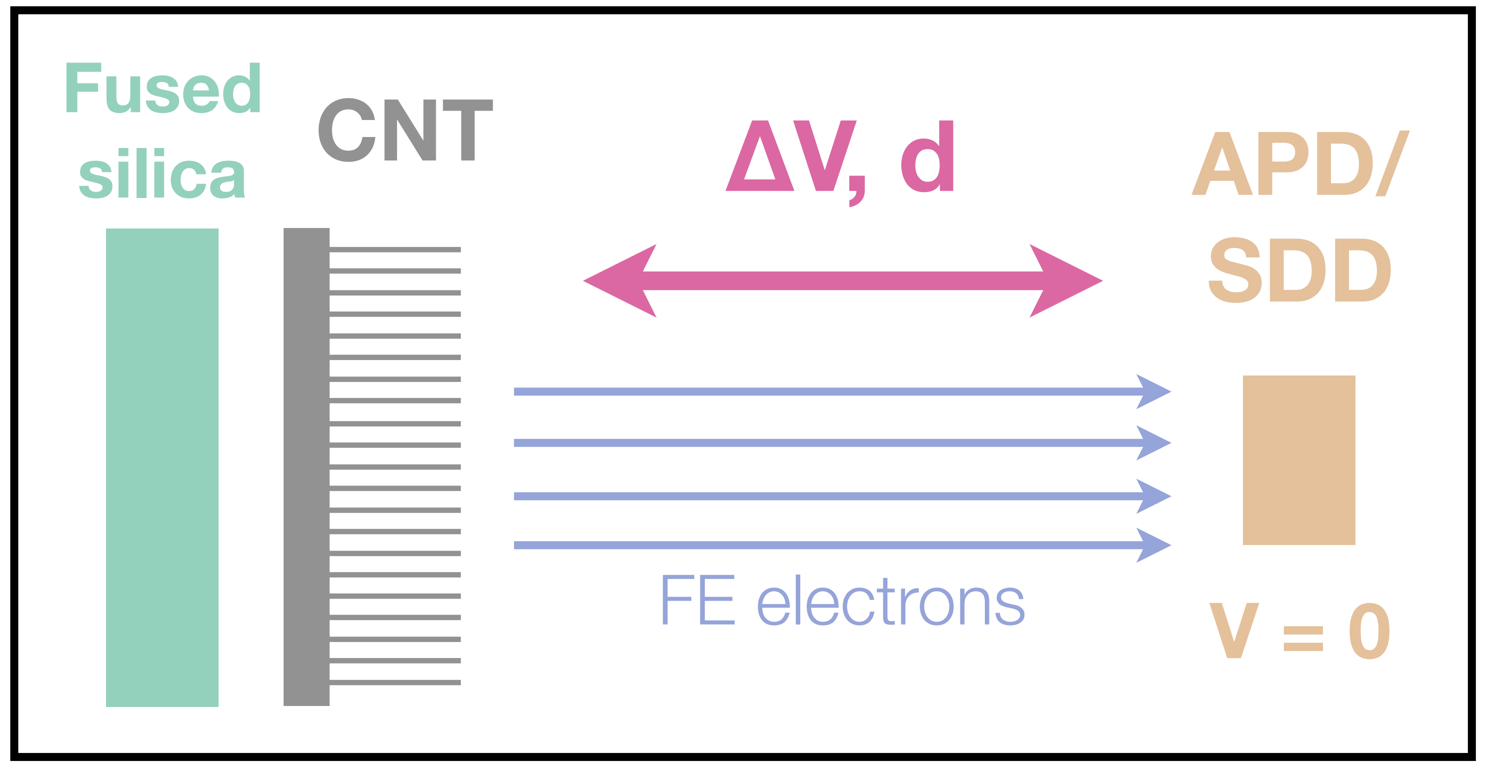


Field Electron Emission from Nanotubes?



- Observed **high I_{apd}** at high ΔV and small d(CNT-APD)
  - **Compatible** with field electron emission
  - Well-documented effect eg Carbon 45 (2007) 2957
- Checked that **no effect** with ΔV > 0
  - And with substrate **without** nanotubes

Proves that prototype can measure electrons emitted by CNTs



Hyperion Prototype

Not Limited to Dark Matter!

❖ Young but **ambitious** nanotube programme started in Rome

- 'NanoUV': **UV light** detectors based on carbon nanotubes

  100k€ ATTRACT grant

- 'NanoBio': nanotubes for **biosensors**

  13k€ Sapienza grant (collaborating with Biology department)

- Development of novel **composite materials** made with carbon nanotubes

  Collaborating with faculty of Engineering

Conclusions

- **Carbon nanostructures**: exciting new possibilities for light dark matter searches
    - **2D** materials: recoiling electrons ejected **directly** into vacuum
- Two detector concepts, both with **directional** sensitivity
    - ‘G-FET’: made of **graphene nanoribbons**
    - ‘Dark-PMT’: made of aligned **carbon nanotubes**
- Lots of **exciting** R&D ongoing both in Princeton and Rome!
    - Rome CVD chamber successfully synthesizing nanotubes since **day one**
    - Dark-PMT prototype ‘Hyperion’ currently being commissioned with APDs and SDDs

Some of this work has received funding
from the ATTRACT project funded by the EC
under Grant Agreement 777222

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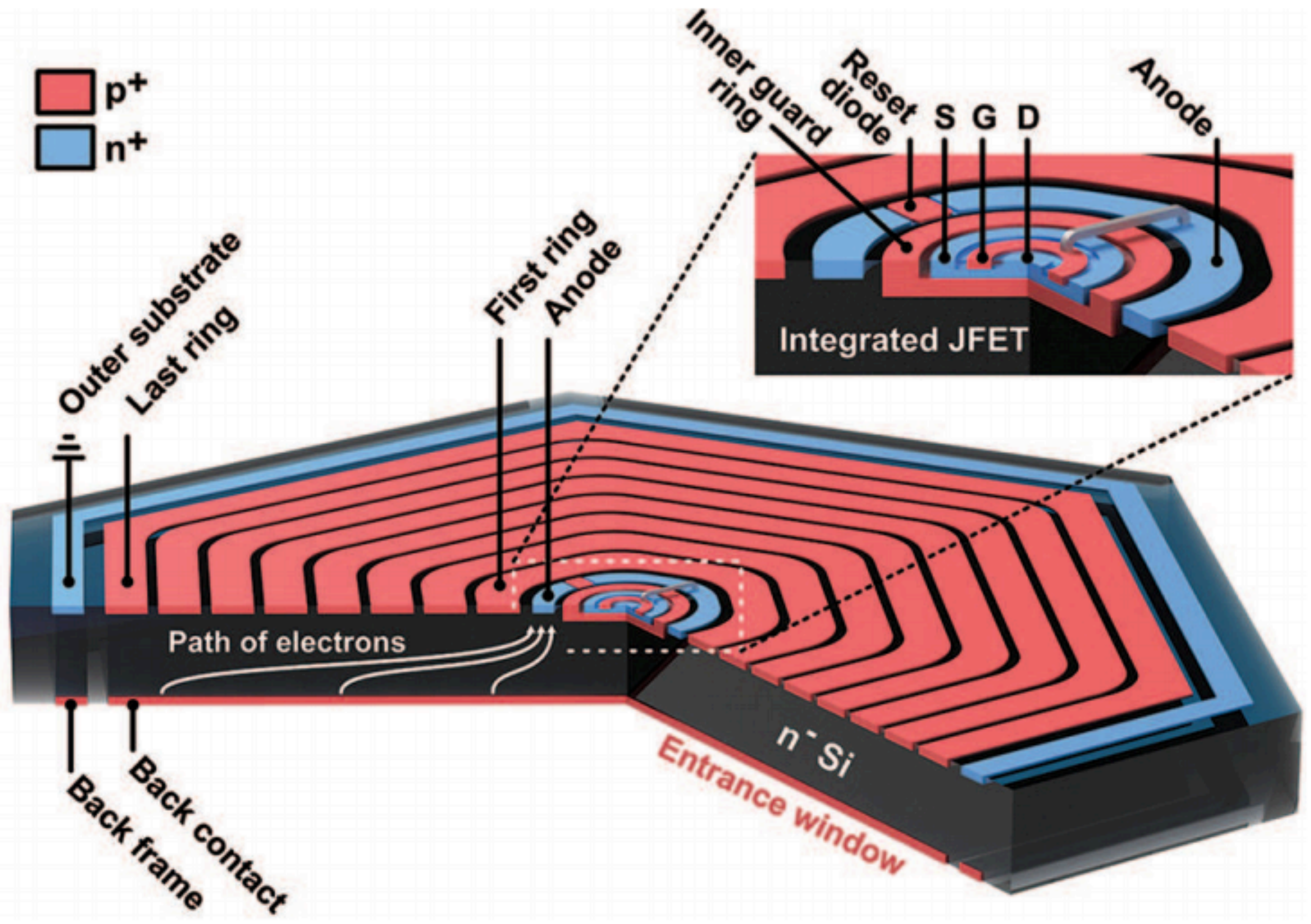
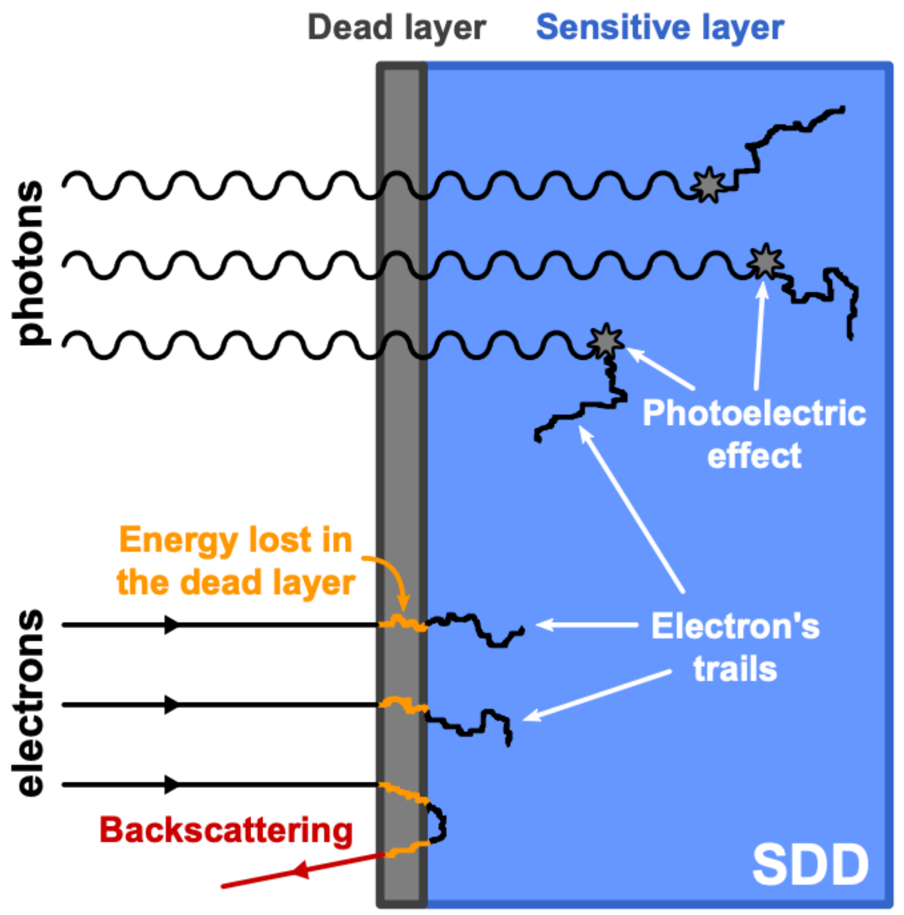
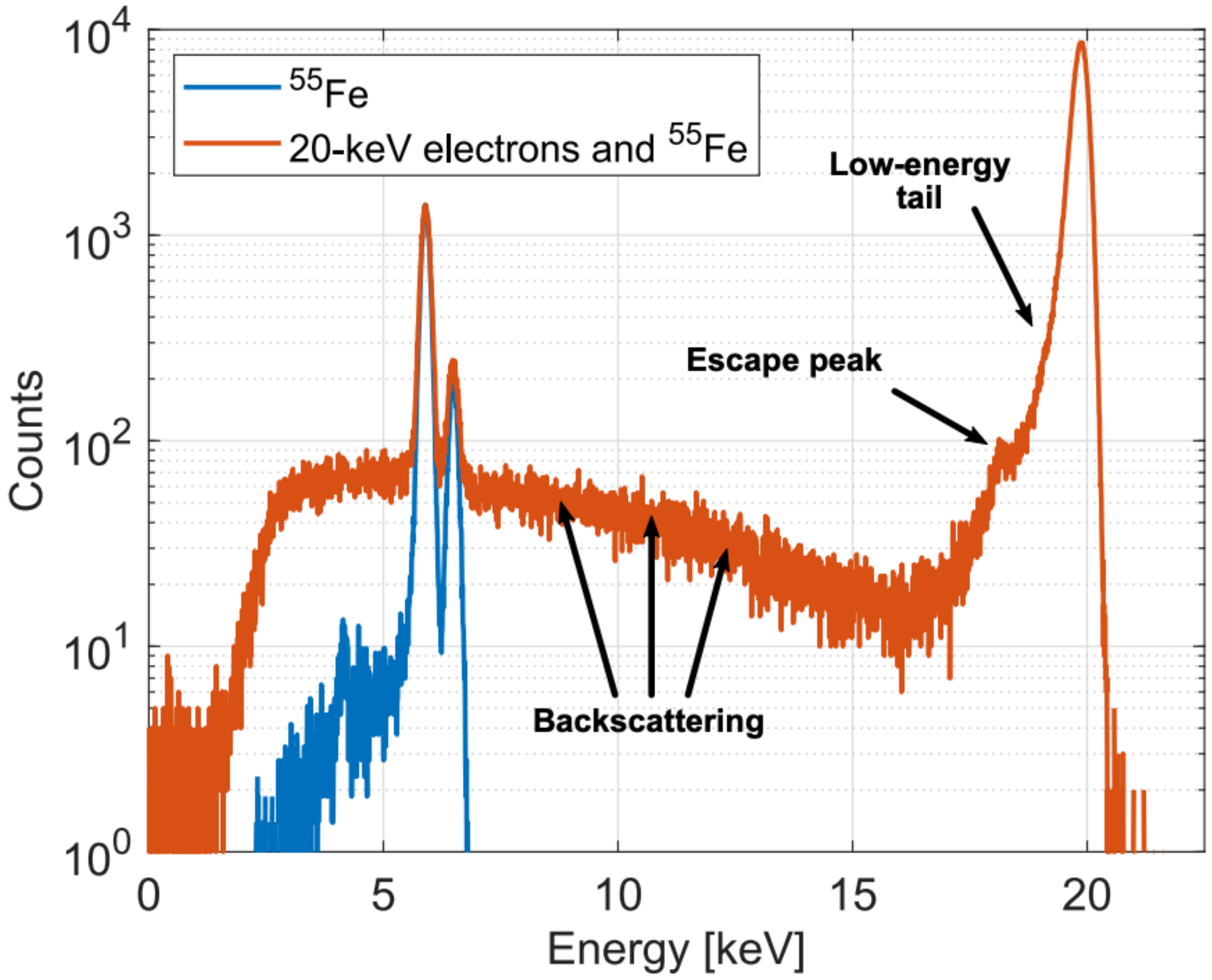
Additional Material

SDDs for High-Resolution Electron Spectroscopy





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



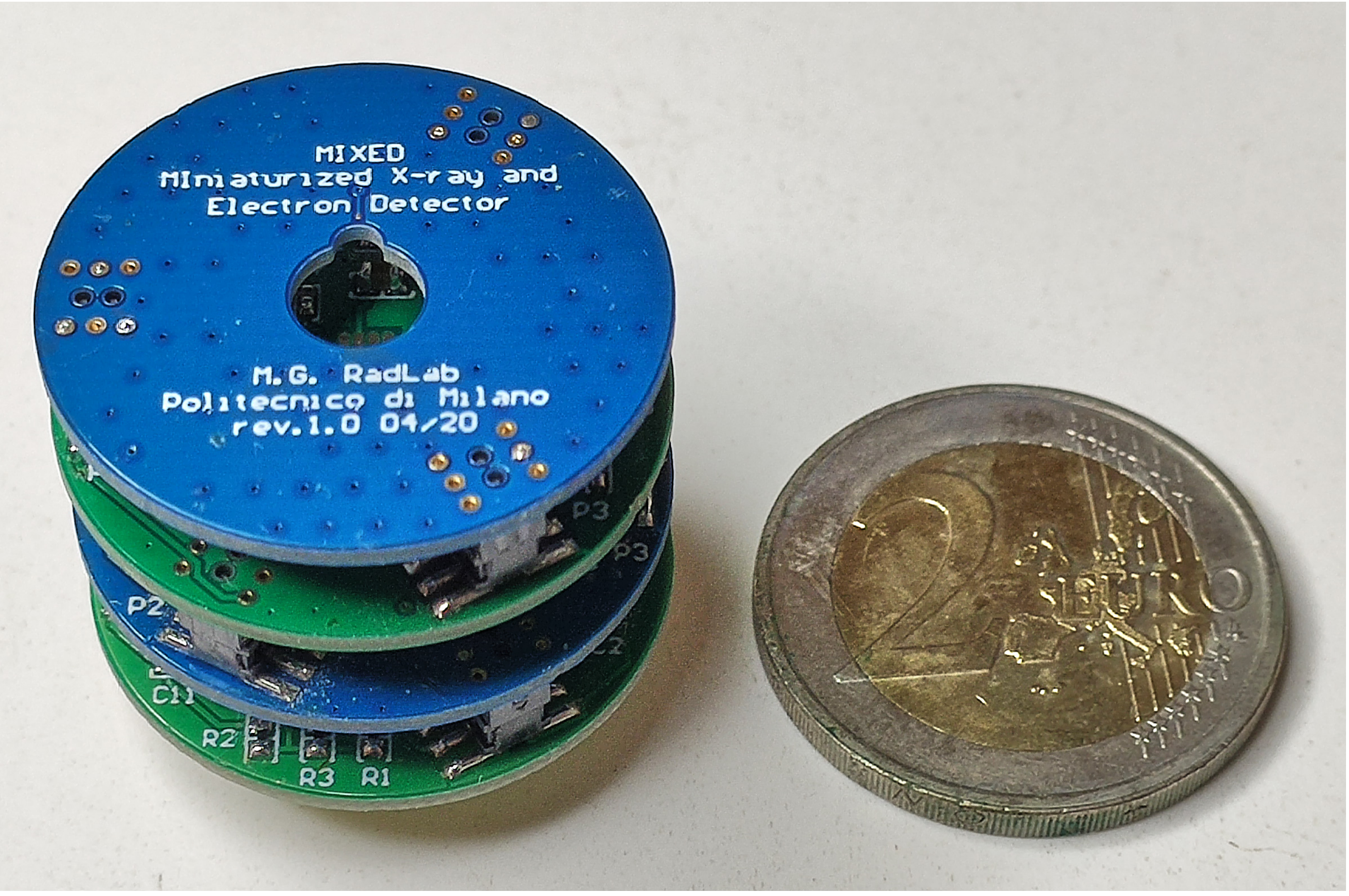
- Anode rings to guide electron drift to center
  - Lower gain (~10) wrt APDs (~100-300)
- Recently shown to be **excellent** electron detectors
  - In 5-20 keV energy range

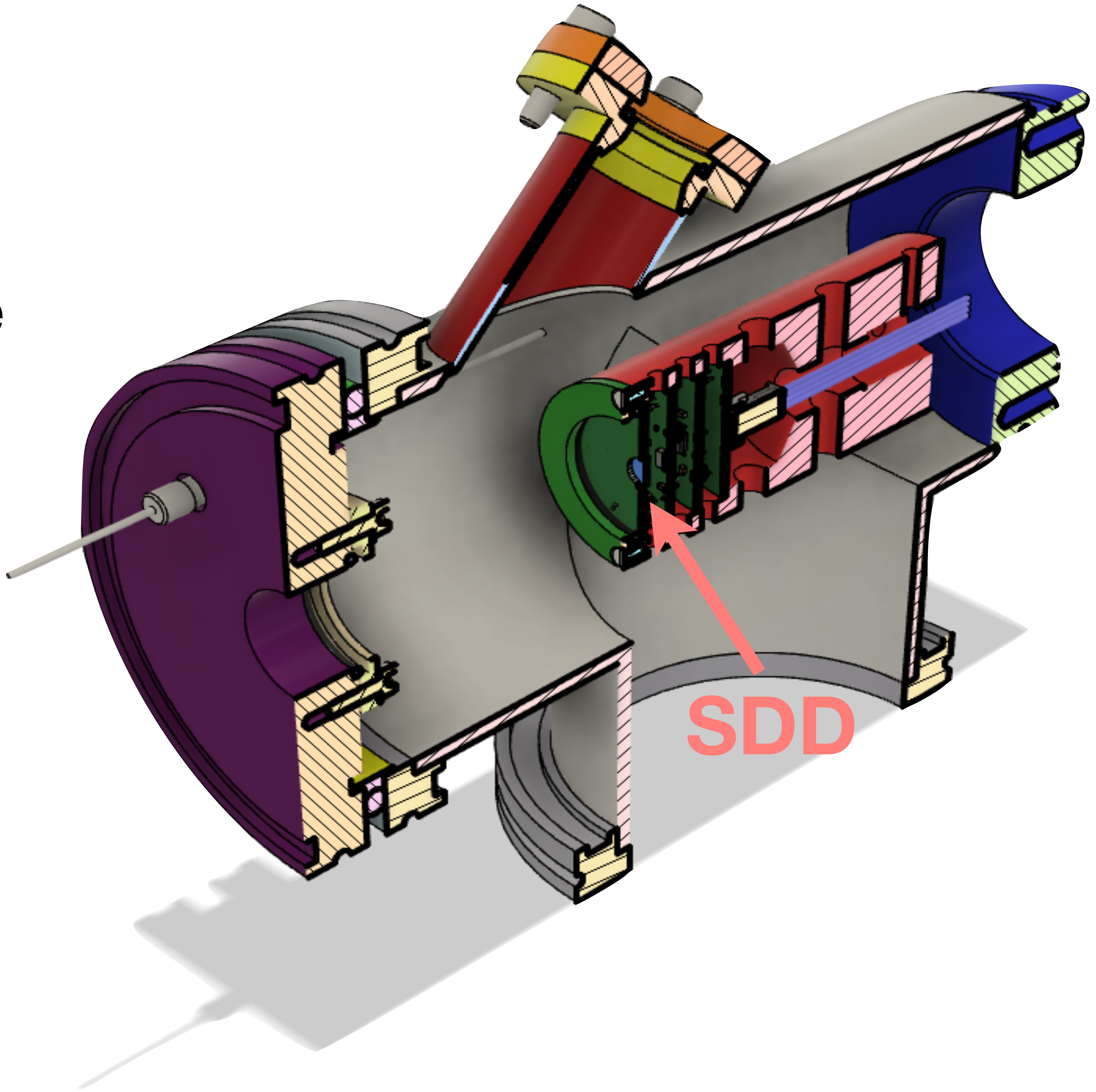
SDD Integration in Hyperion with MIXED Module

POLITECNICO
MILANO 1863

MIXED: MIniaturized X-ray and Electron Detector
M. Gugiatti, et al., Proc. IEEE ICECS 2020

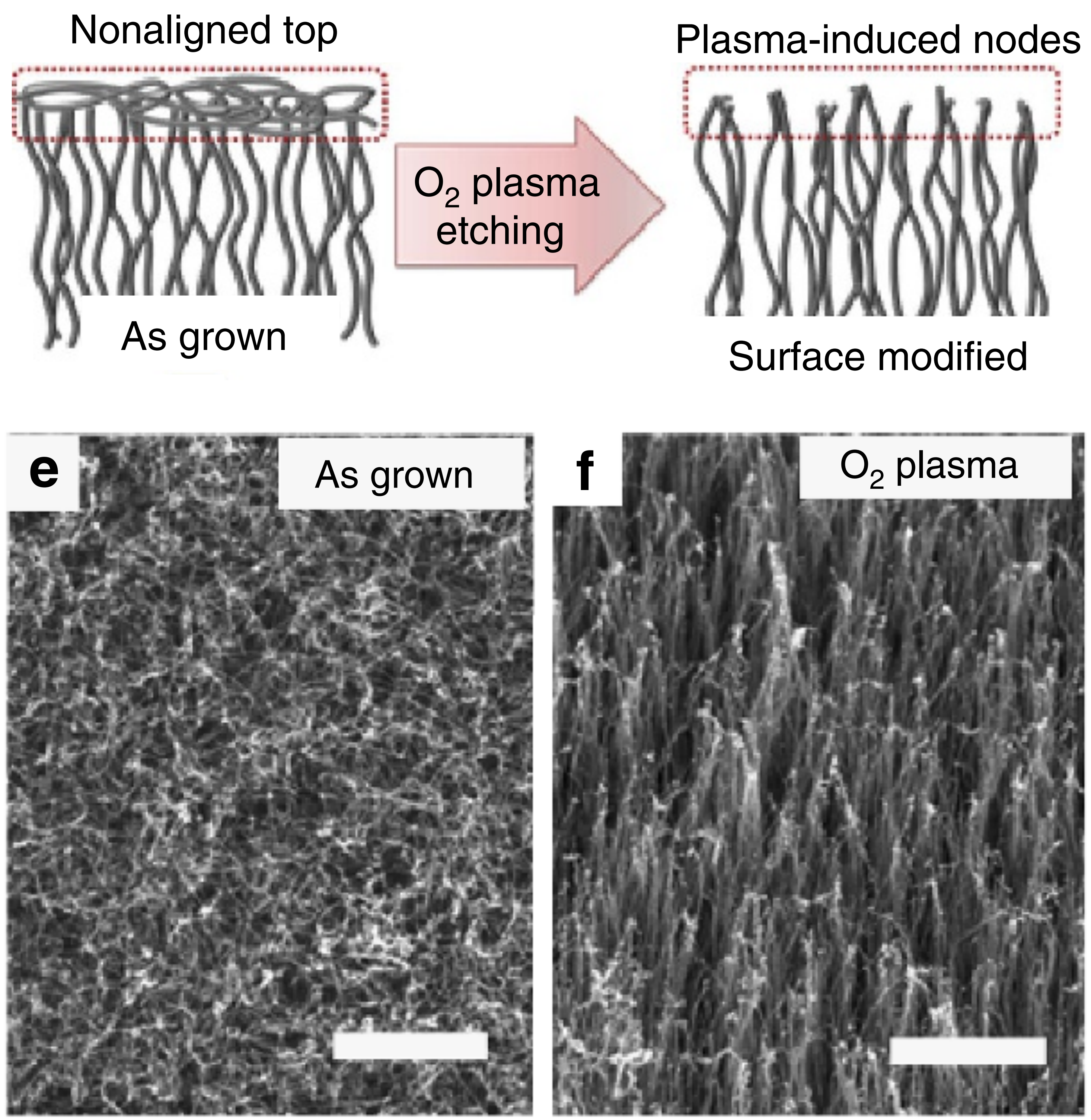
- Collaboration with PoliMi (Prof. C. Fiorini)
  - Leading **experts** on SDDs
- Designed SDD module 'MIXED'
  for integration in Hyperion prototype



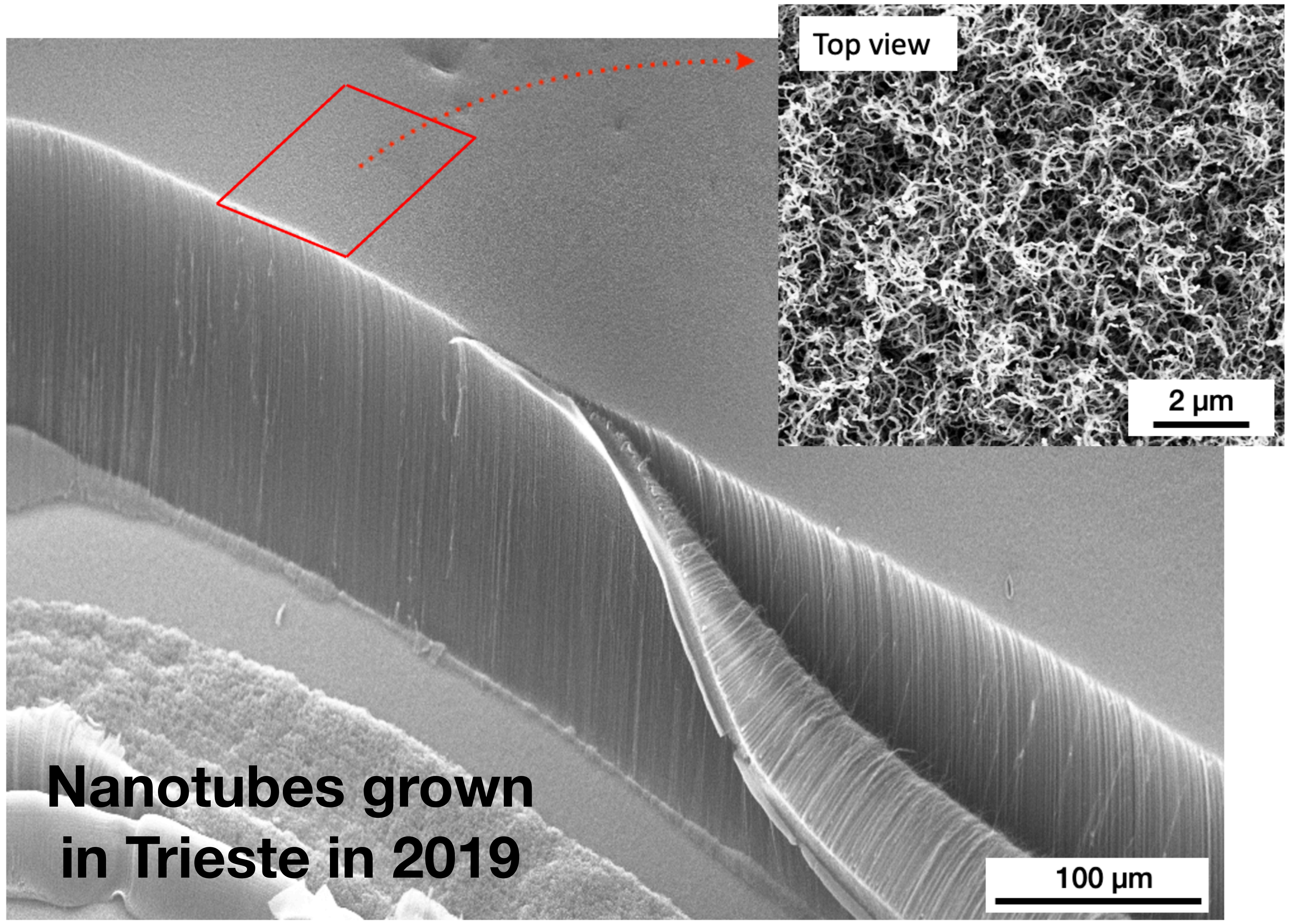


Non-Aligned Top Layer: A Problem?

Xu, et al., Nat Commun 7 (2016) 13450

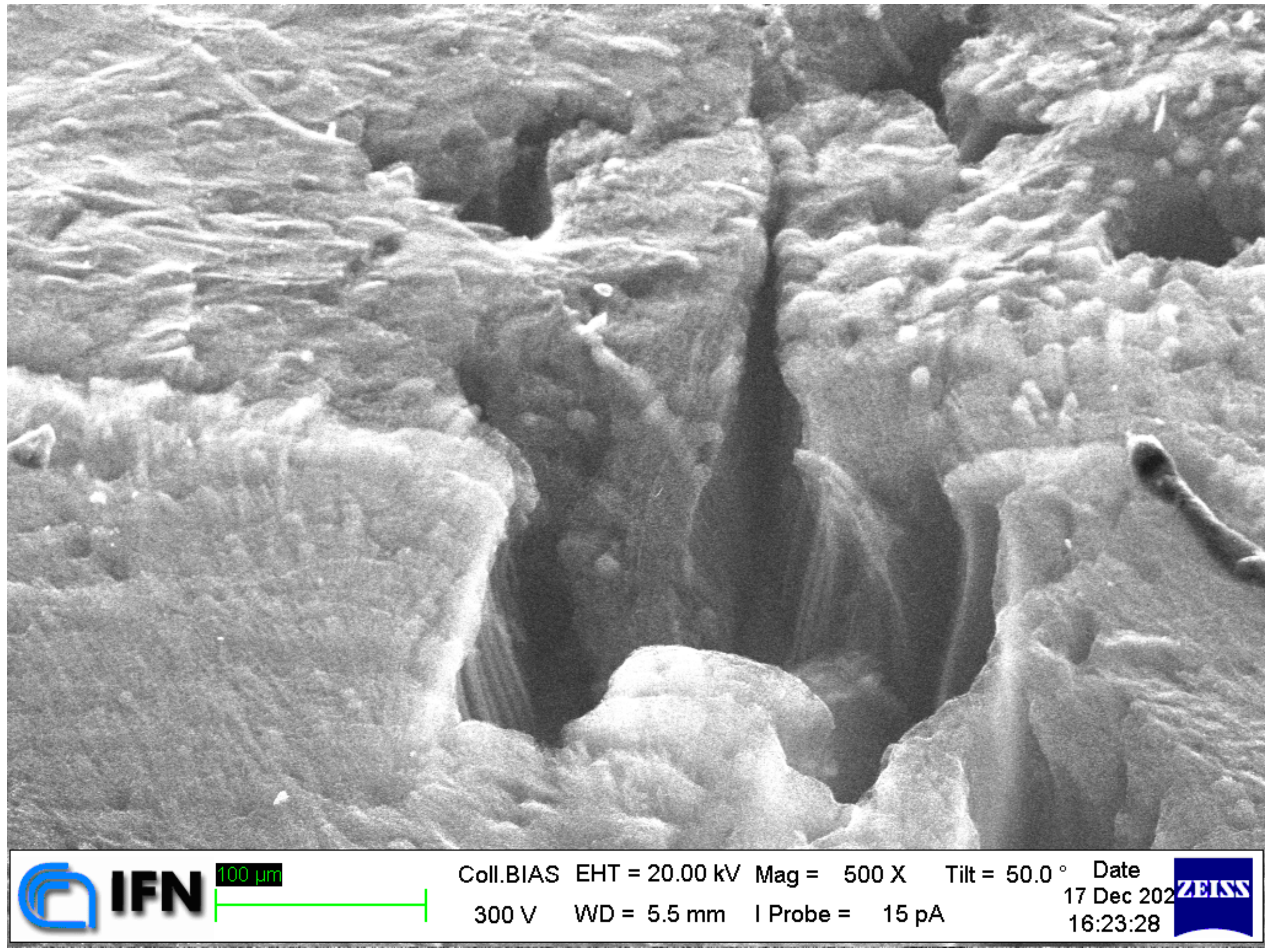


- Common effect of CVD growth: **non-aligned** top layer
    - Could be a problem for electrons (absorbed)

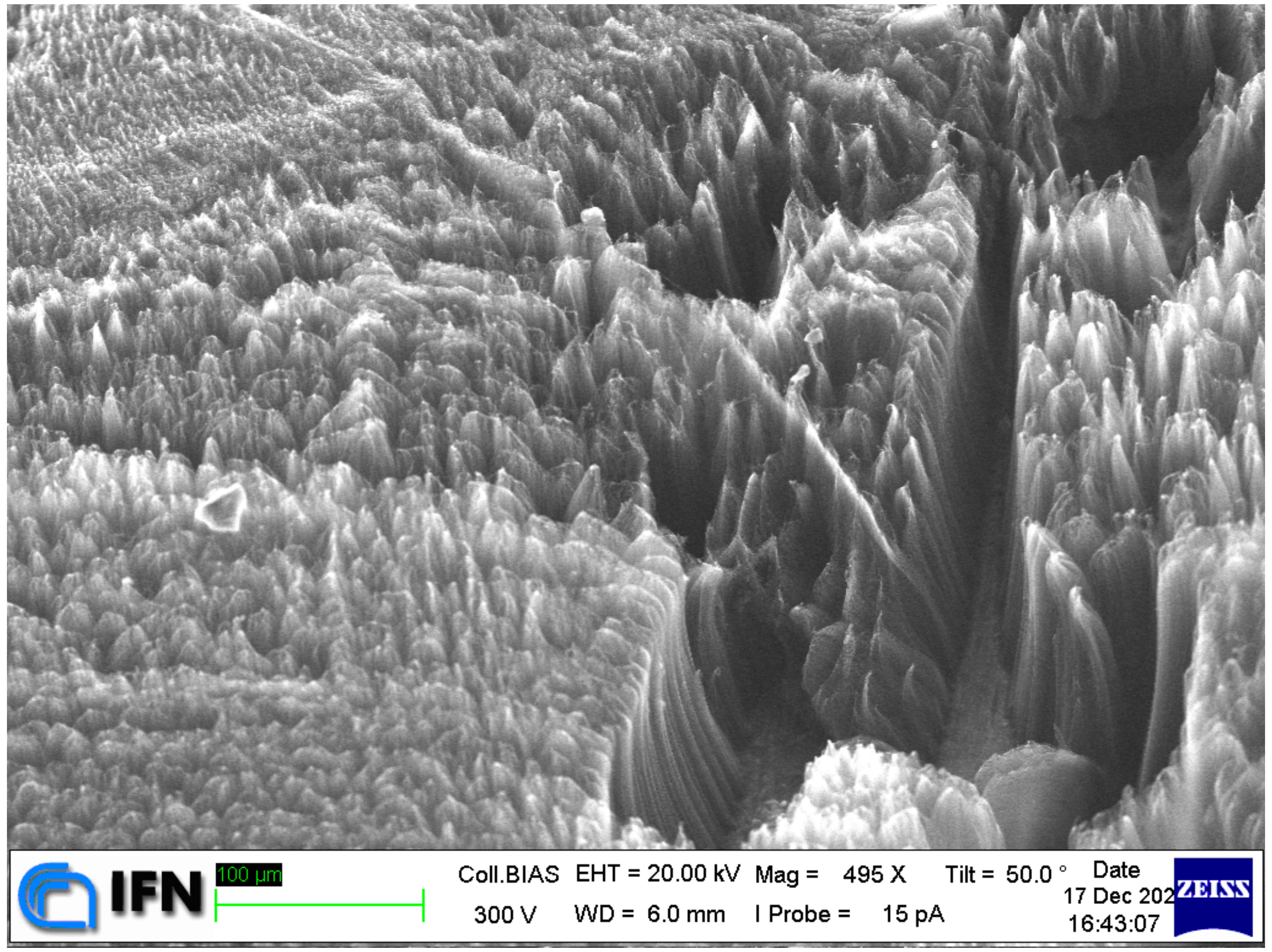


First Attempt with O_2 Plasma Etching Successful

As grown



After O_2 etching



- Visually, seems like it **worked**
- Will study effect on electron emission