Searching for Dark Matter with Carbon Nanotubes: the ANDROMeDa Project

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INFN Rome

The Low-Energy Frontier of Particle Physics

LNF, 11.02.2025

ANDROMeDa

Aligned Nanotube Detector for Research On MeV Darkmatter

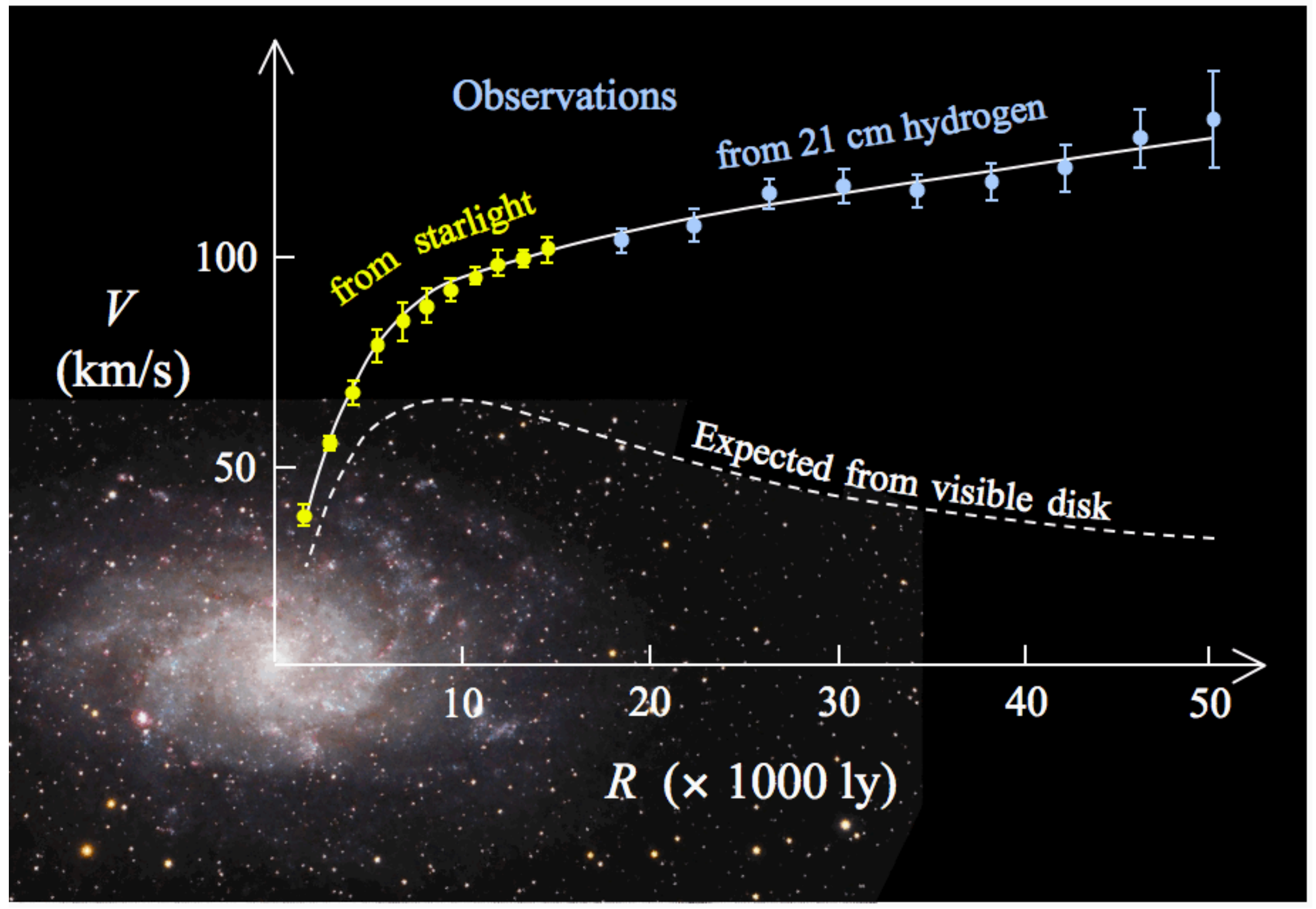
INFN Istituto Nazionale di Fisica Nucleare

ROMA TRE UNIVERSITÀ DEGLI STUDI

85% of the Matter of the Universe Unaccounted For

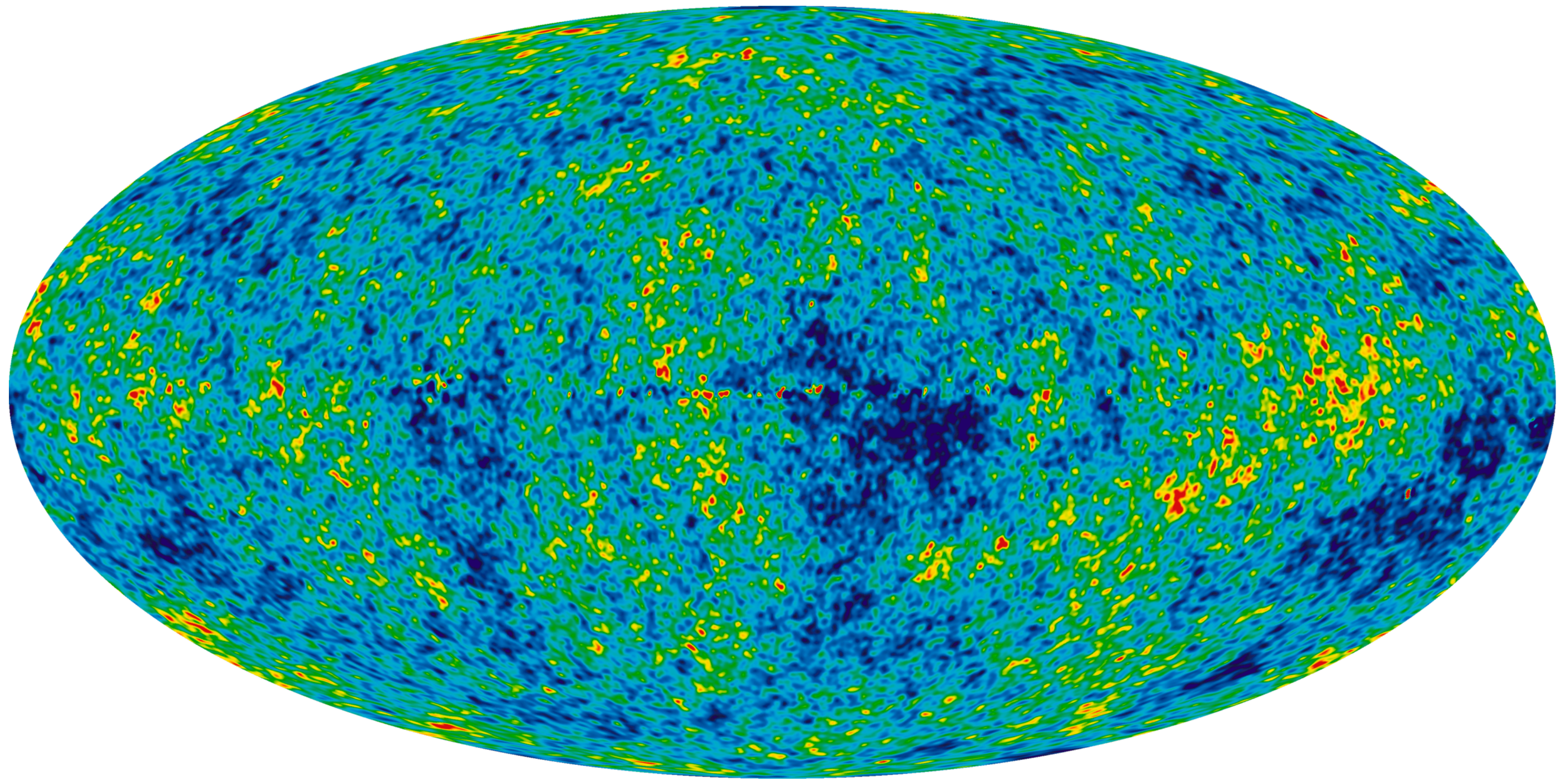
- **Overwhelming** evidence for large mass of non-baryonic matter

Rotation curves



Bullet cluster

CMB



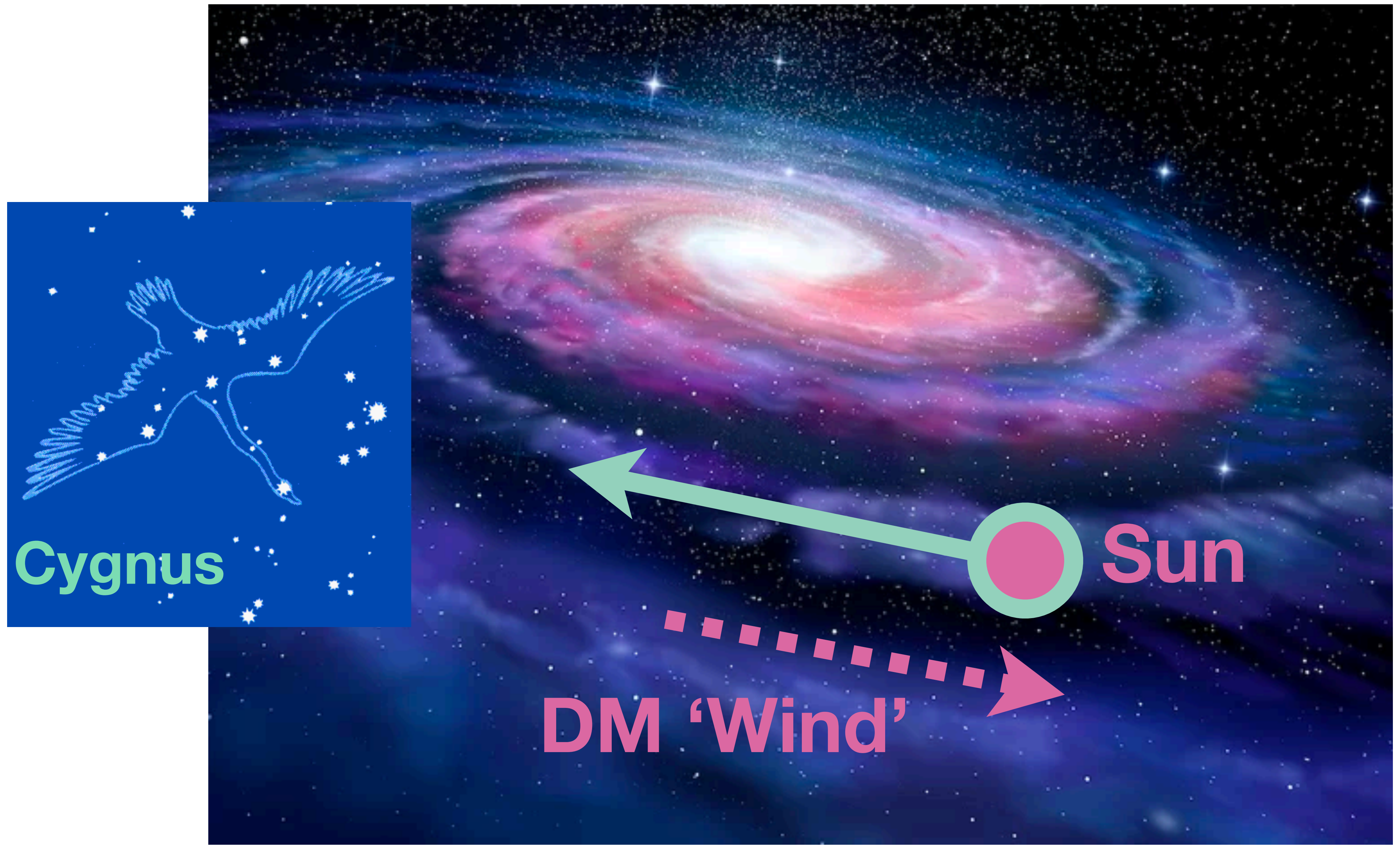
The Rise of the ΛCDM Model

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

	Ω	Ω·h²
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)

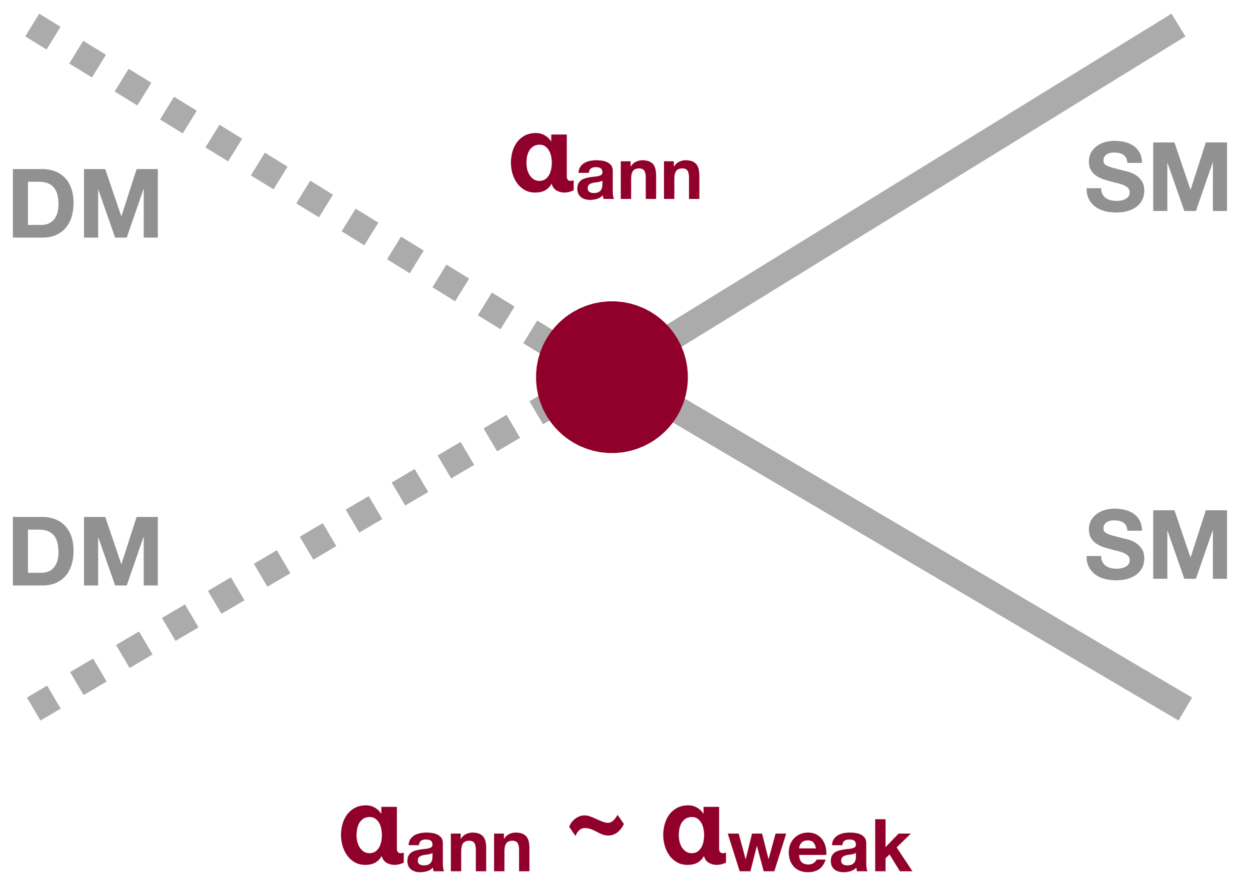


The WIMP and Its ‘Miracle’

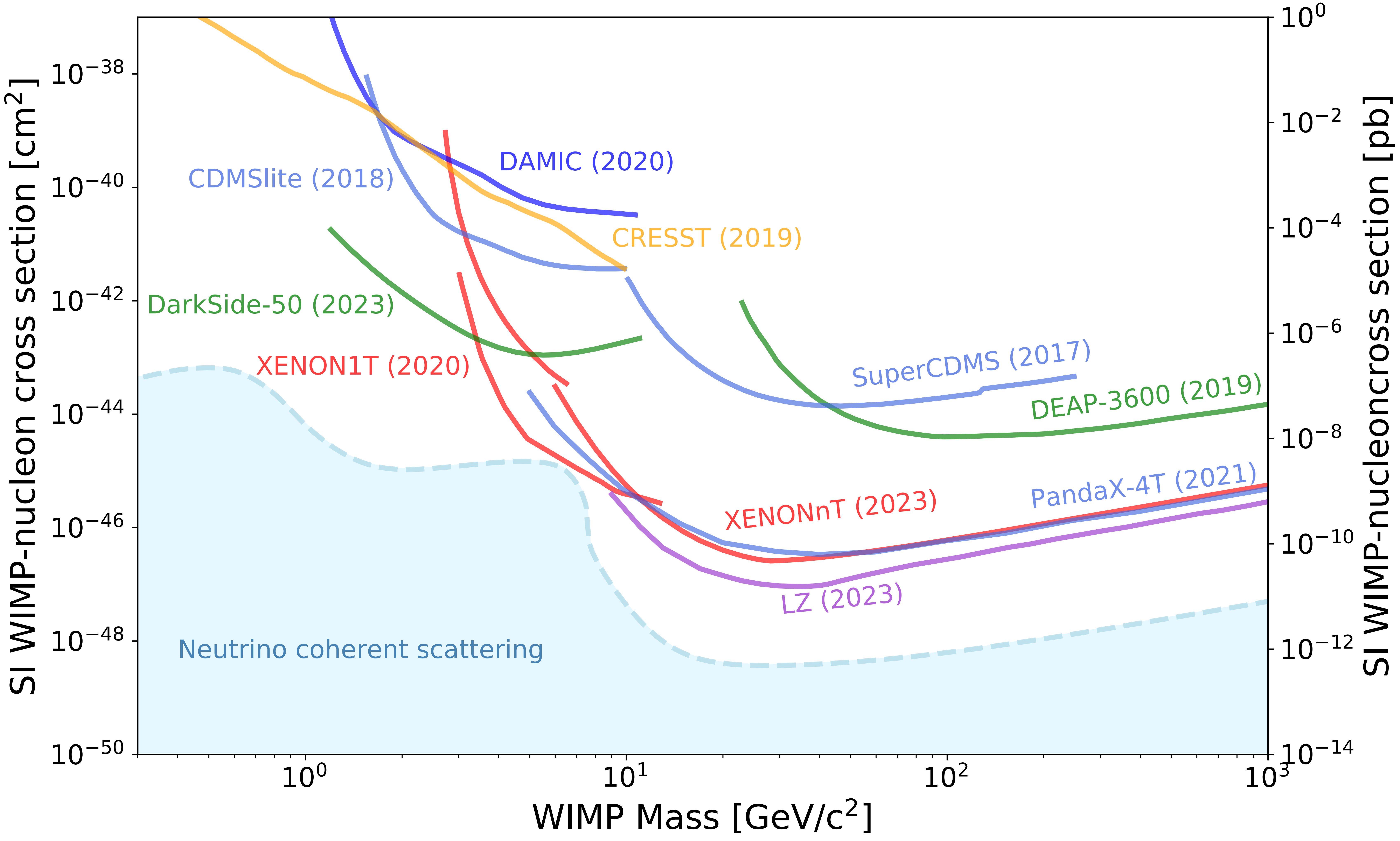
- For correct relic abundance $\Omega_d \sim 0.12$ after ‘freeze-out’, one needs: $\langle \sigma v \rangle \sim 1$ pb
  - Which is **exactly** what one gets for a 100 GeV particle with **electroweak** couplings

- 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



… 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 (1 Mpc)
- **Problems** arise when describing structures at **sub-galactic** scale (<1 Mpc)
  - Cusp/core
  - Missing satellites
  - Too-Big-to-Fail

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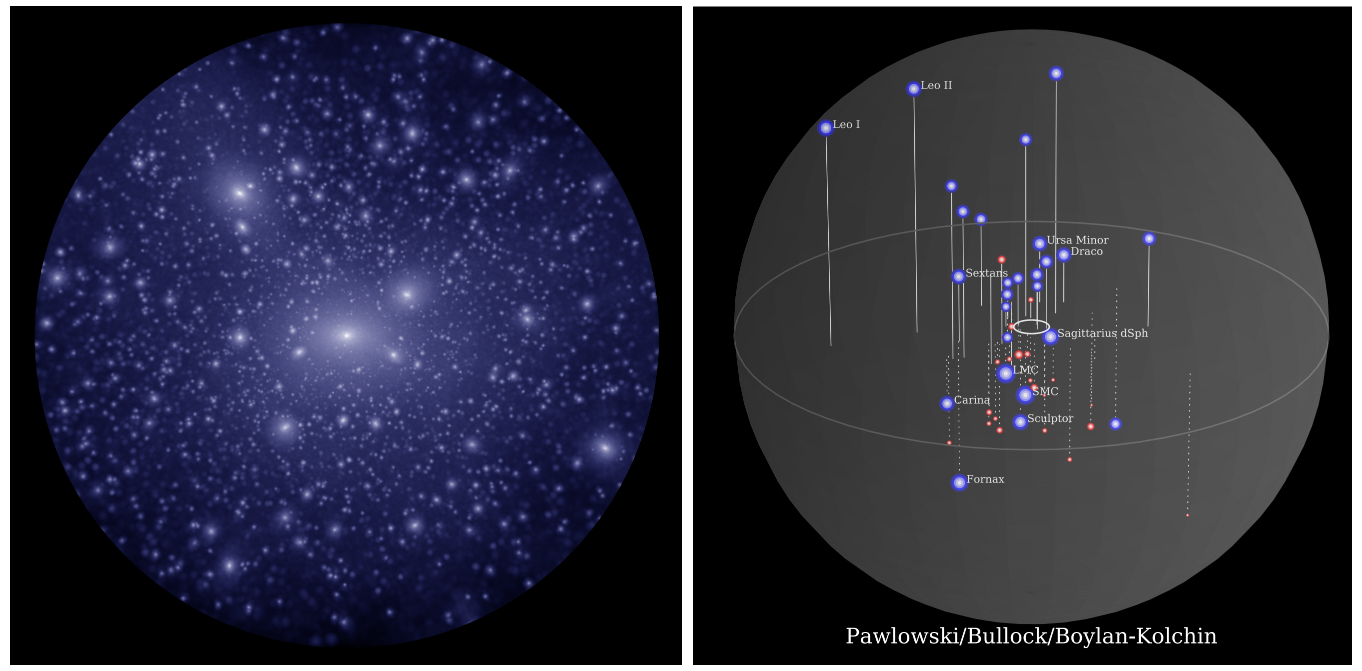
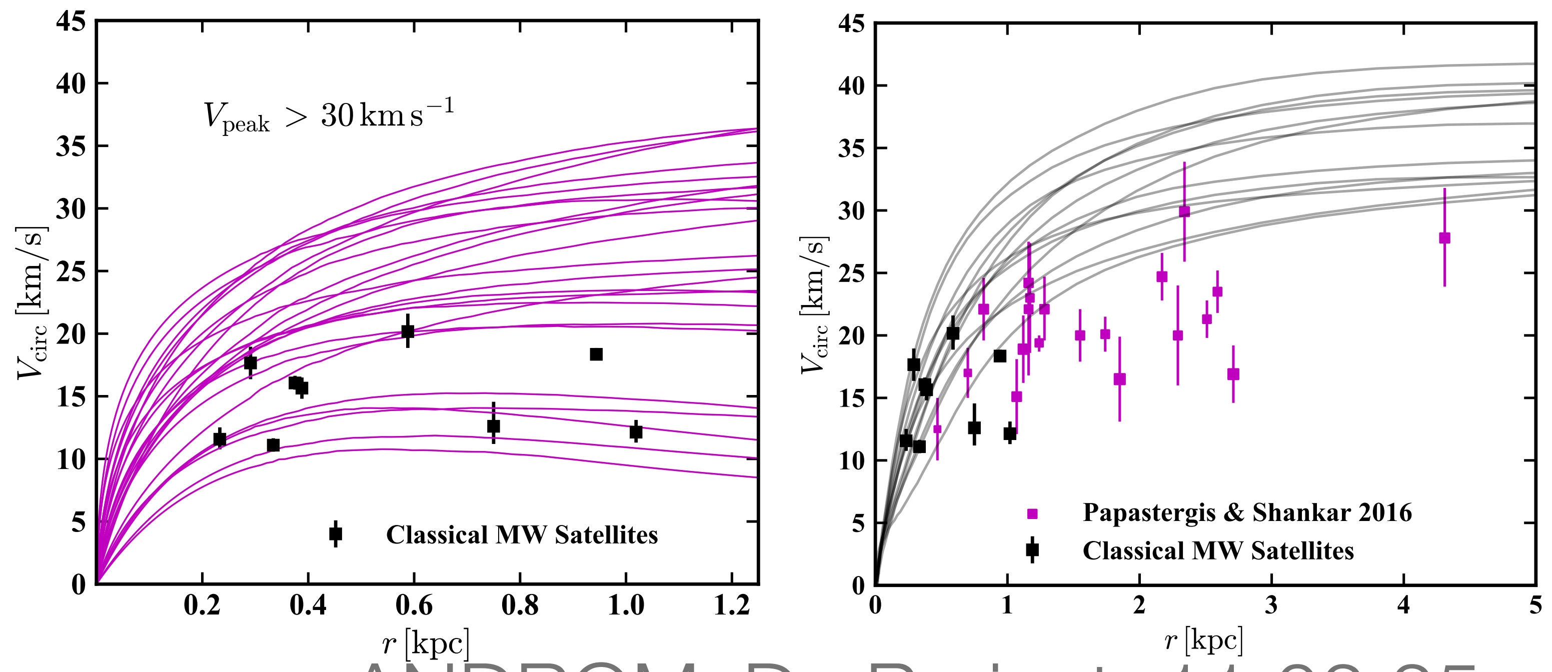
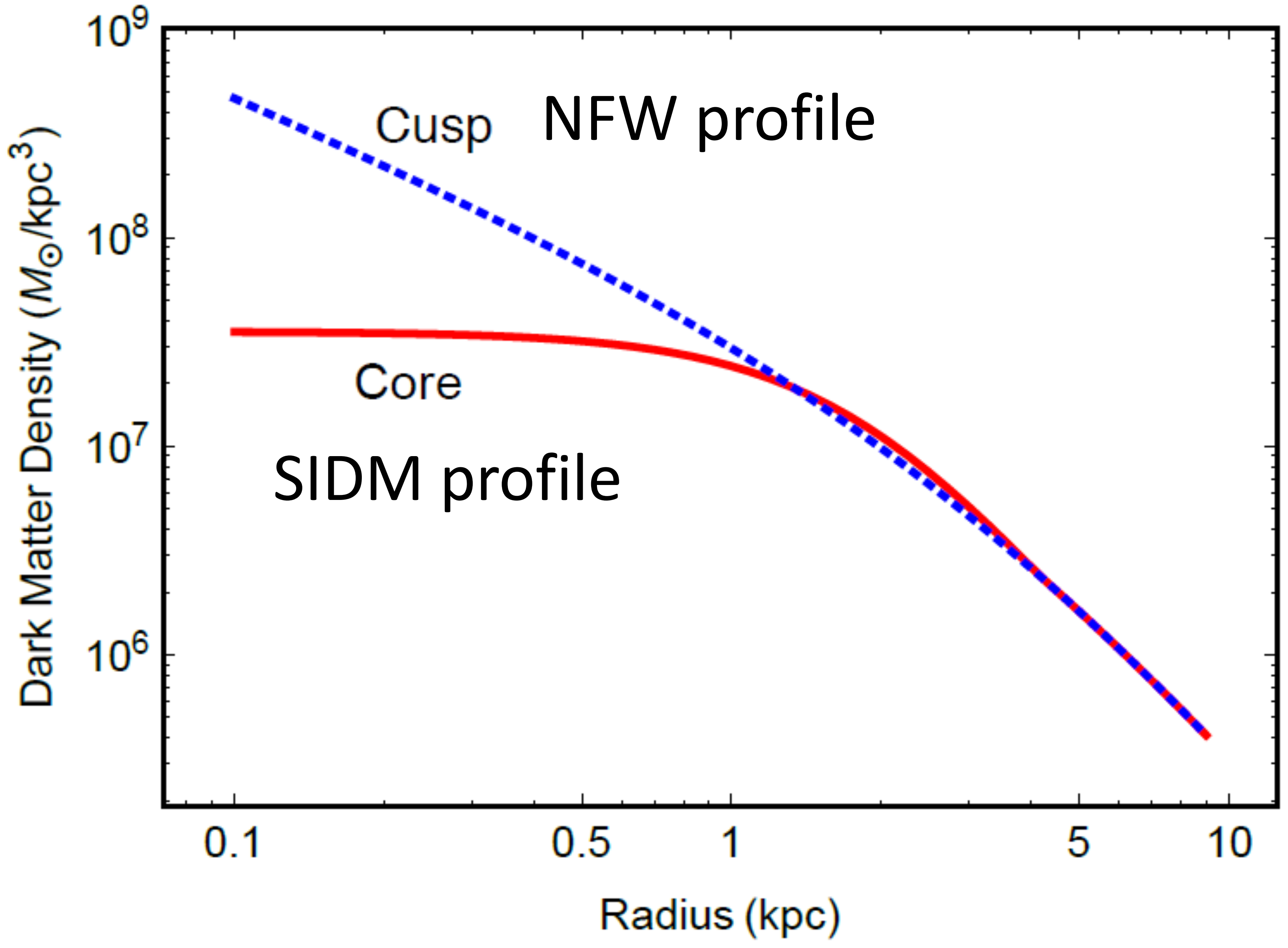


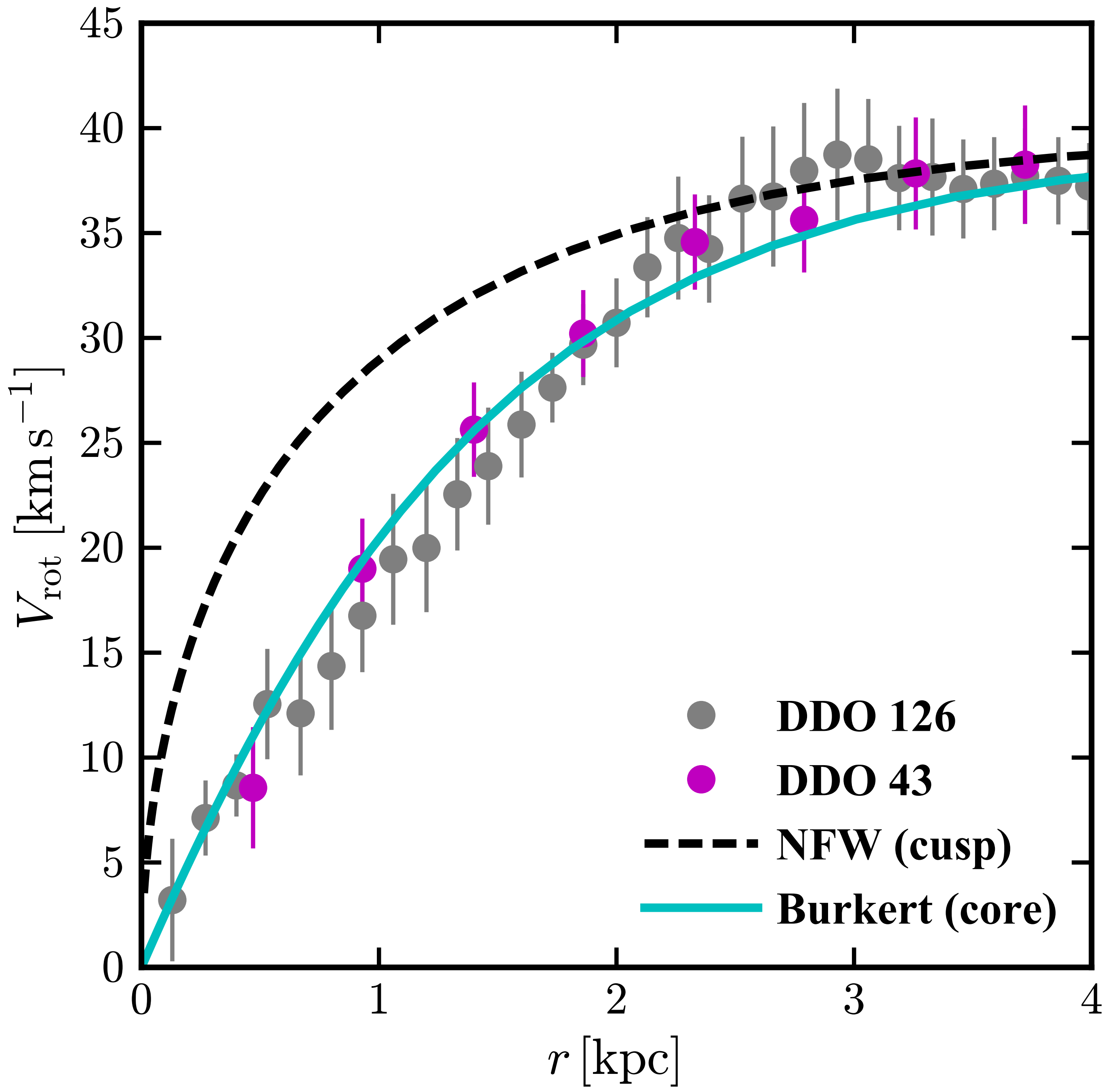


Not covering these two, for comprehensive review see arXiv:1707.04256

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')

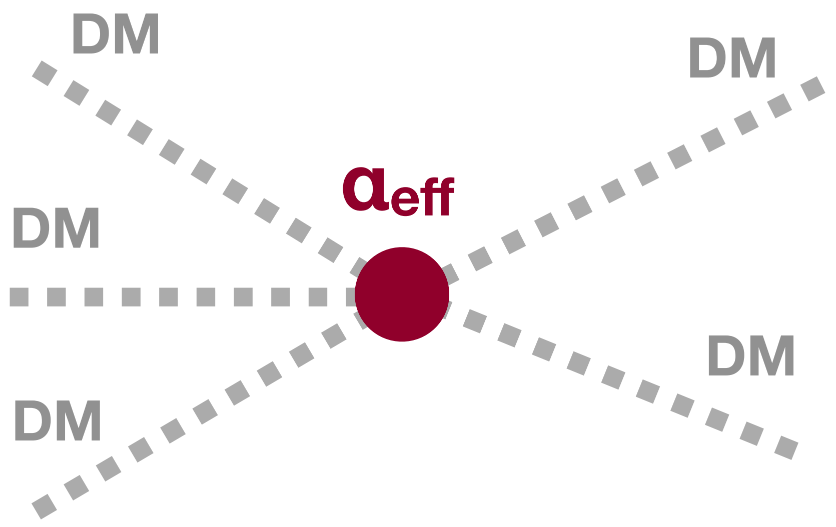
The SIMP Paradigm (in a Nutshell)

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)

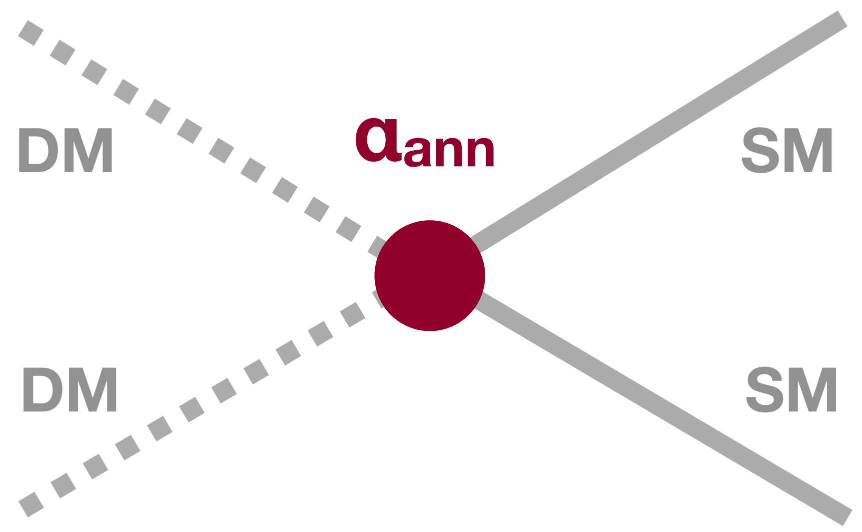
→ **1 MeV < m_{DM} < 1 GeV**

3→2 scattering heats up DM



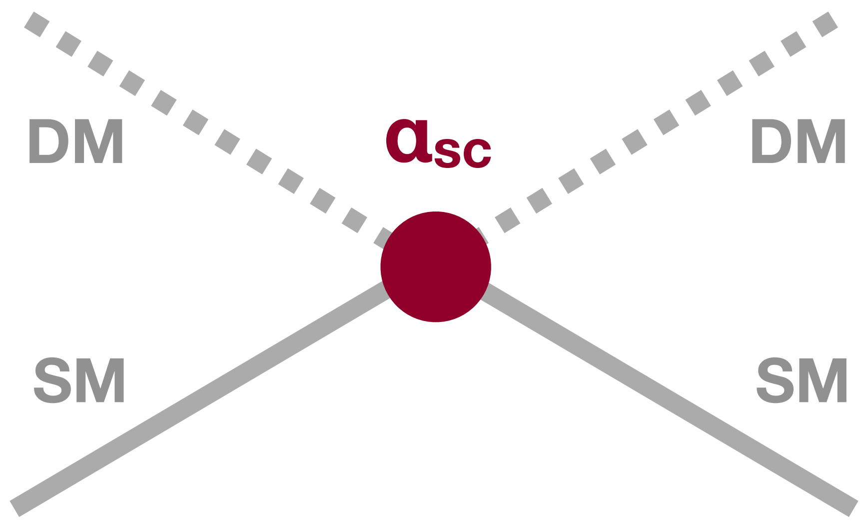
$\alpha_{eff} \sim 1$

No more DM → SM annihilation



$\alpha_{ann} \sim 0$

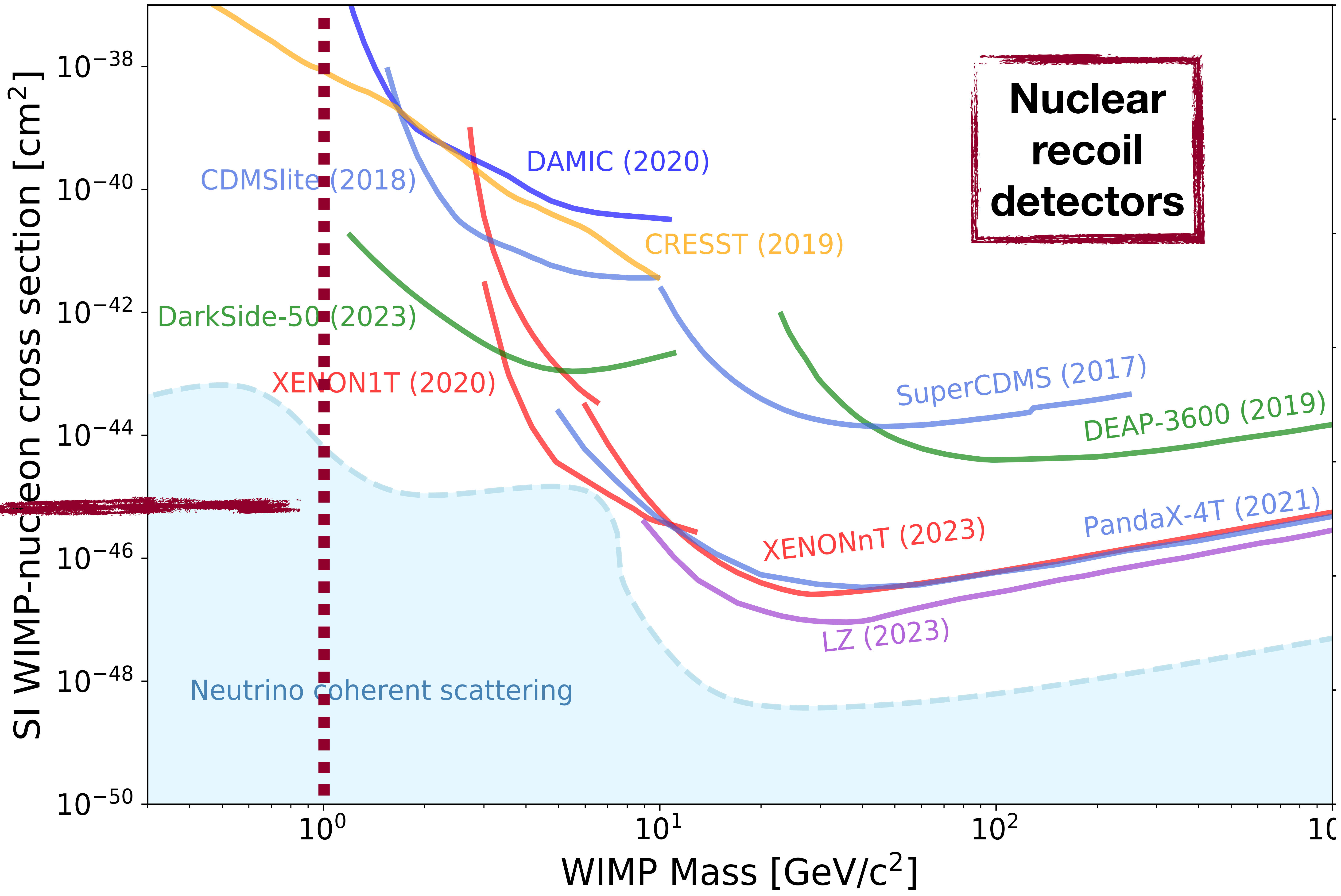
DM-SM scattering



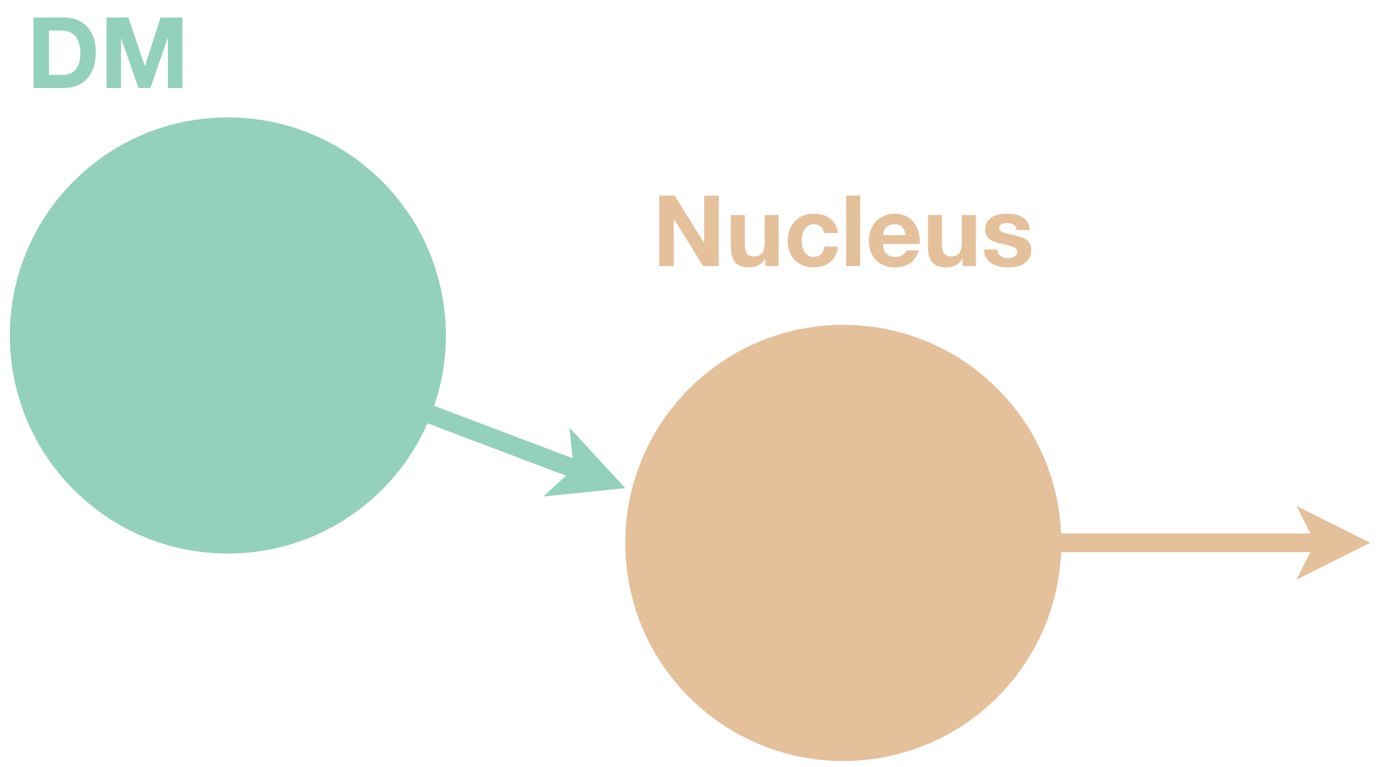
(for thermal equilibrium)

Most Experiments Not Too Sensitive to Sub-GeV DM

Sub-GeV DM (eg. SIMPs)



m_{DM} ~ 10 GeV



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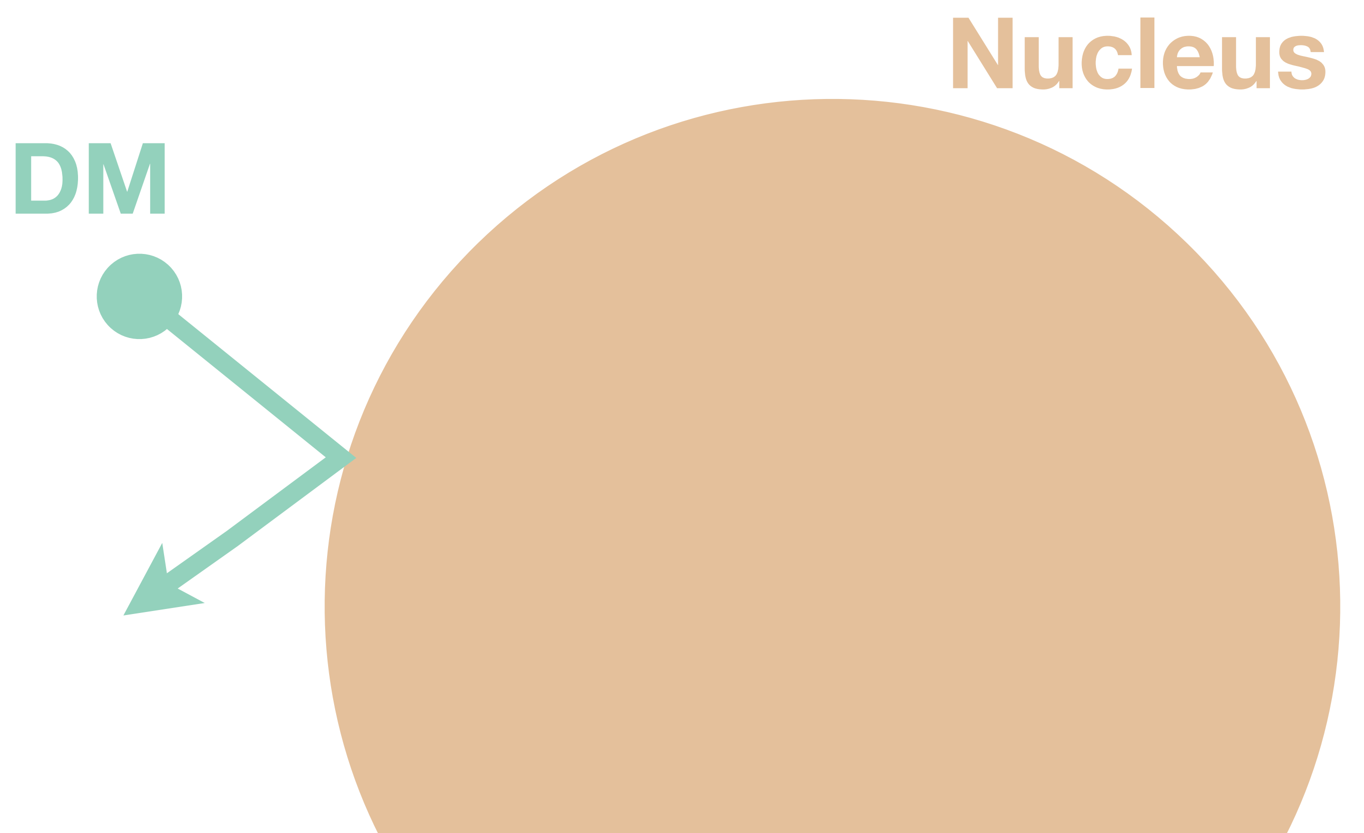
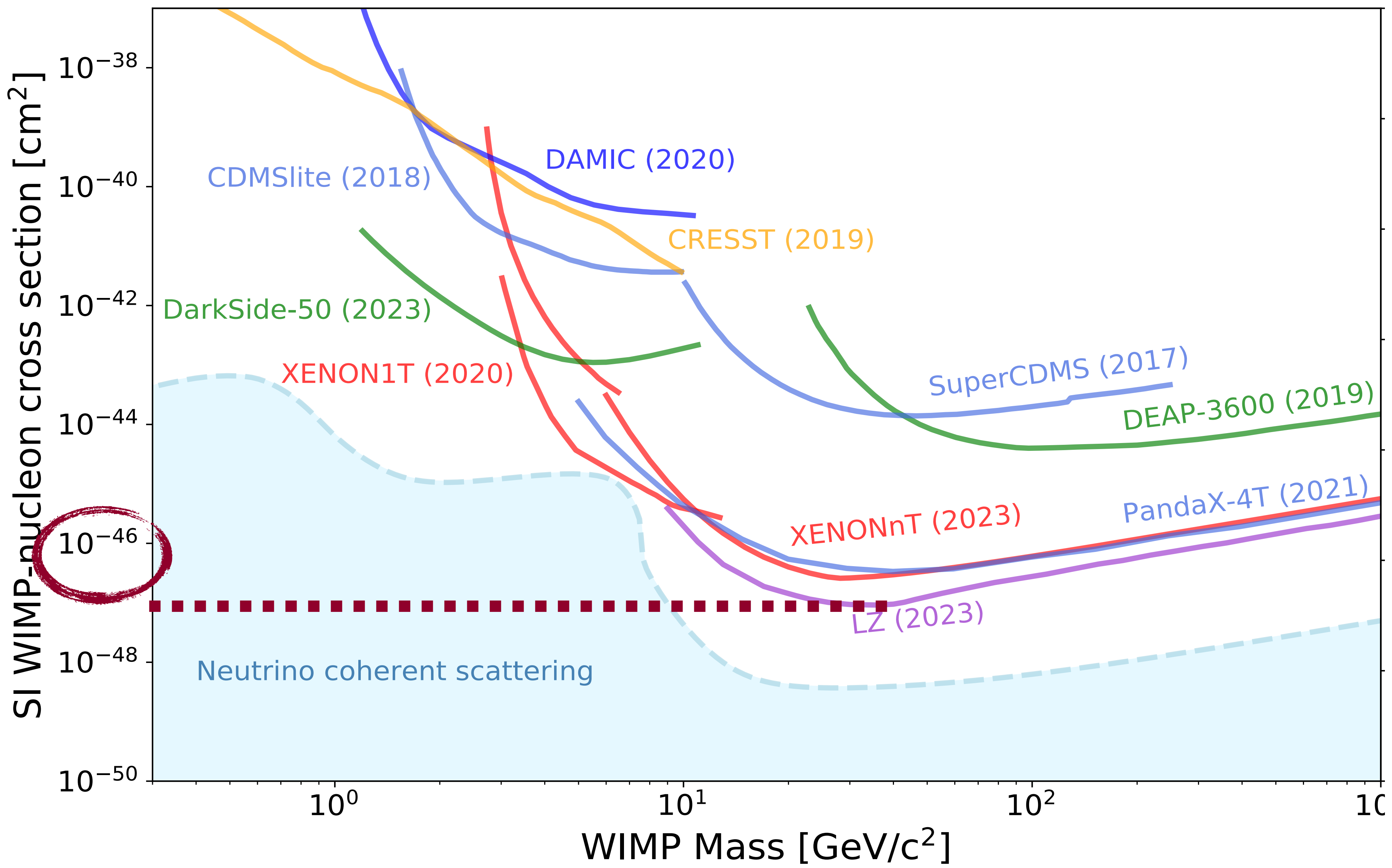
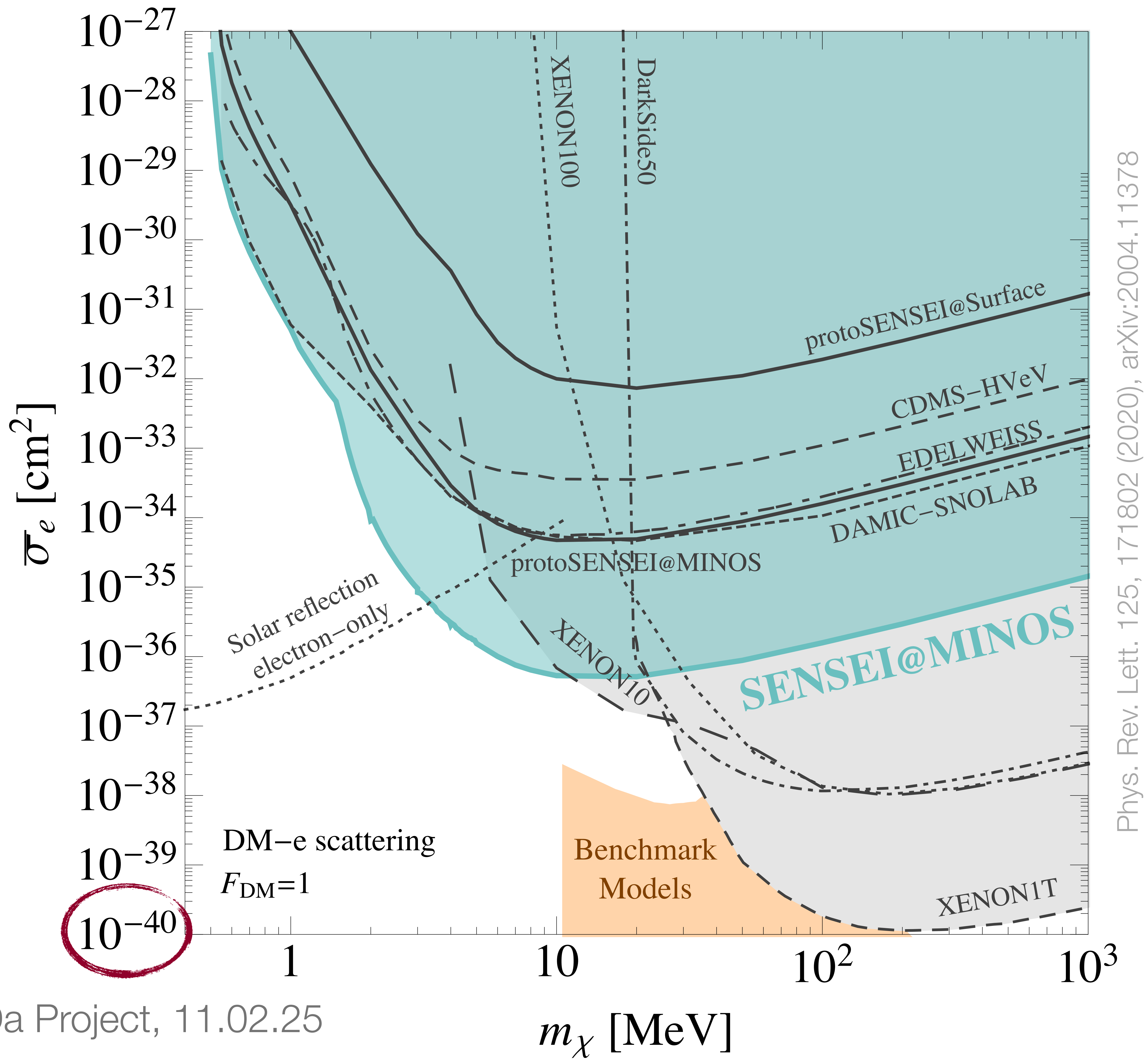


For Light Dark Matter Better to Use Electron Recoils





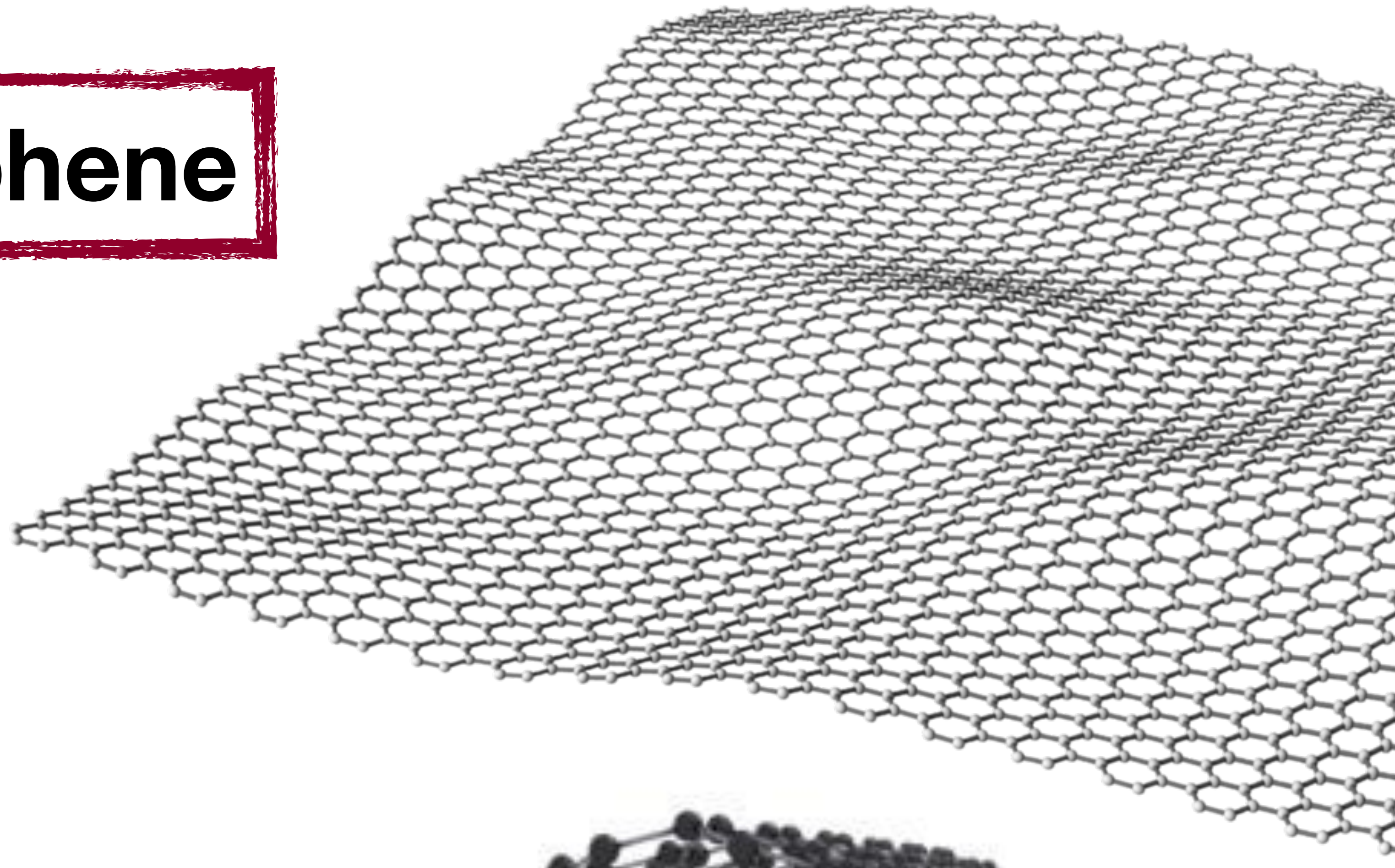
Phys. Rev. Lett. 125, 171802 (2020), arXiv:2004.11378

- Much **weaker** limits (10^{-6})
- From ton-targets to **gram**-targets?
- m_{DM} < 100 MeV: sensitivity **drop** for ionization detectors (reconstruction thresholds)

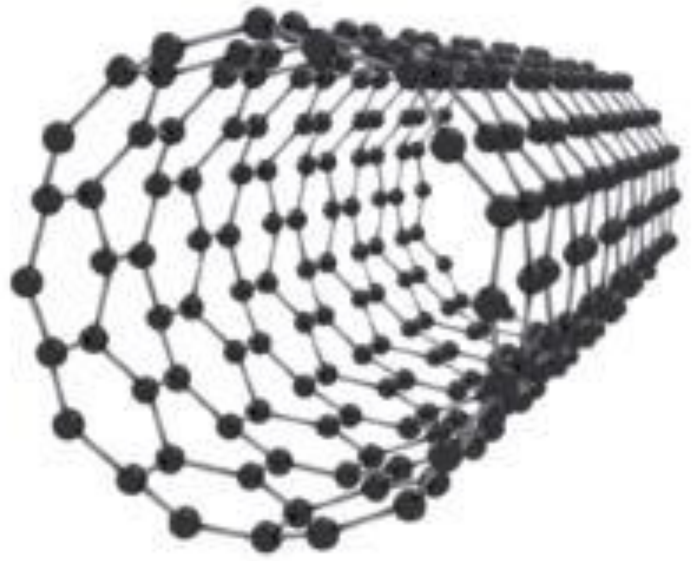
Solid State Targets: The Advantage of 2D Materials

- **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**

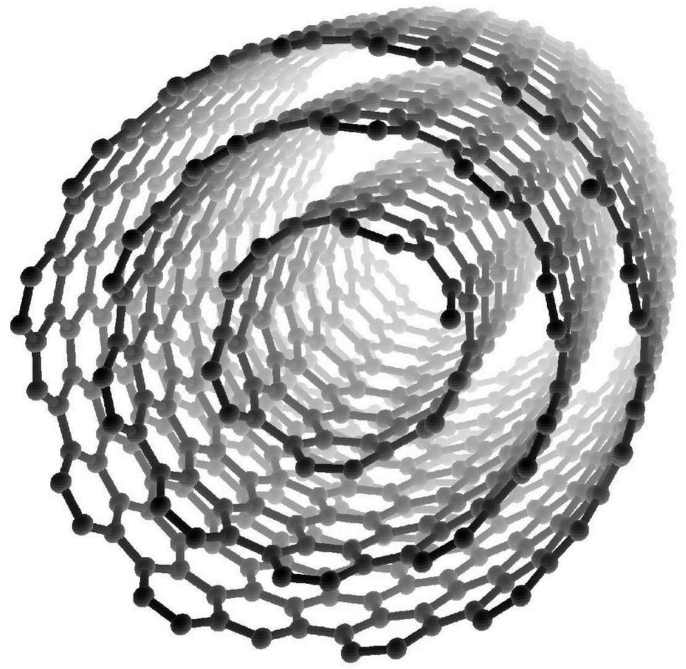
Graphene



Single-wall nanotube



Multi-wall nanotube

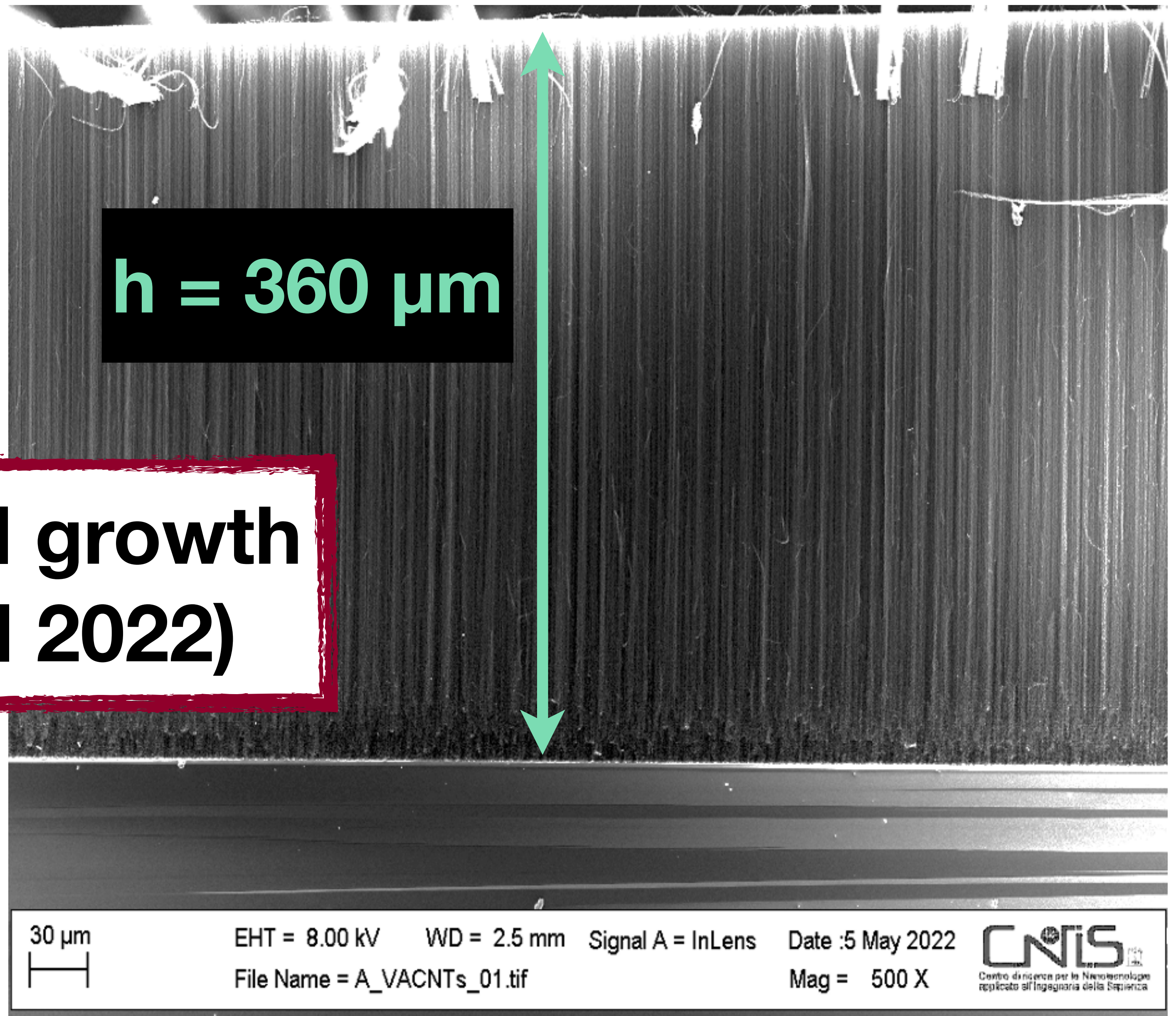


Growing Aligned Carbon Nanotubes in TITAN Lab

- **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

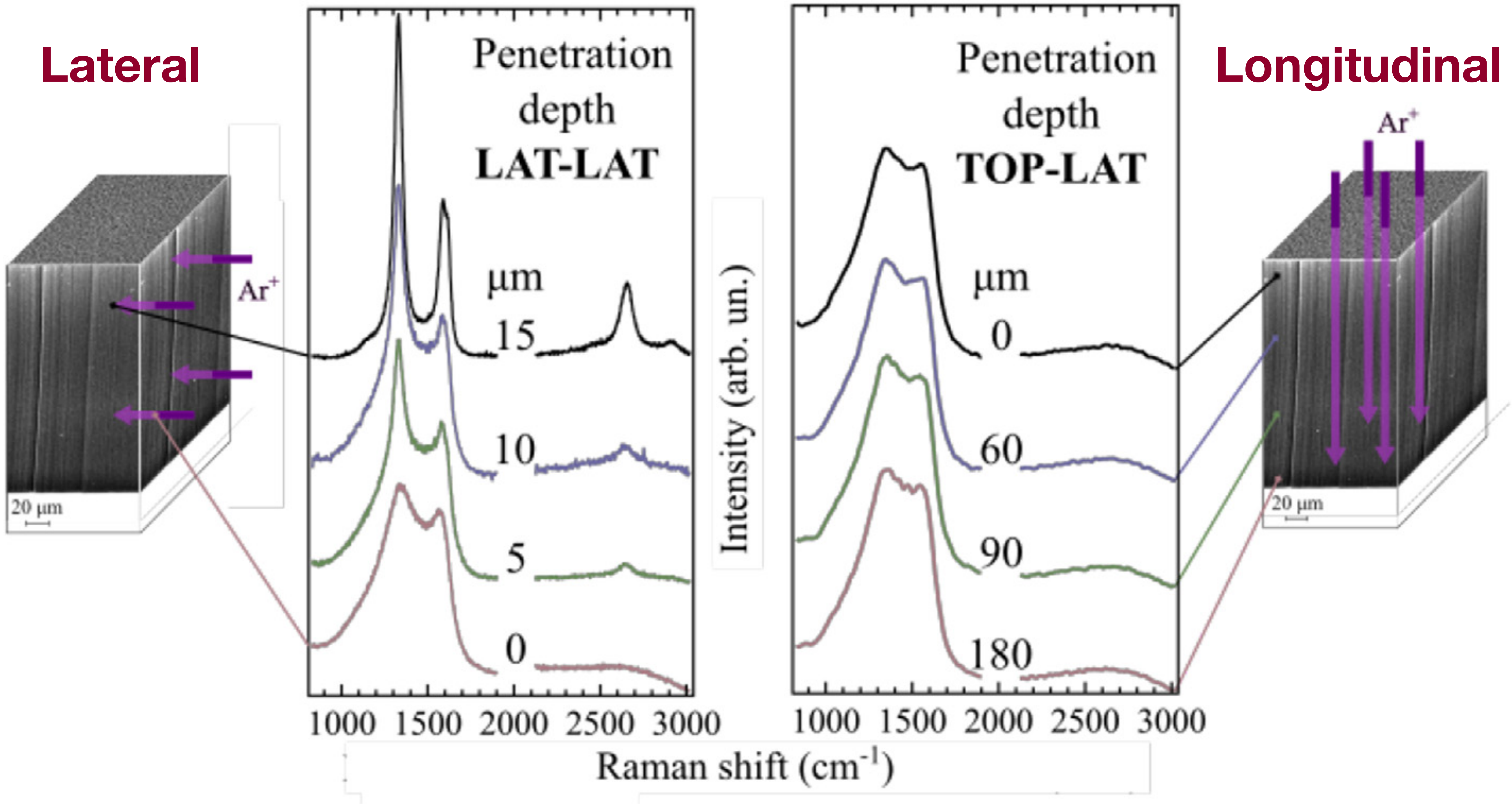
Installing the CVD chamber (Summer 2020)

Typical growth (April 2022)



Aligned Nanotubes: a Highly Anisotropic Target

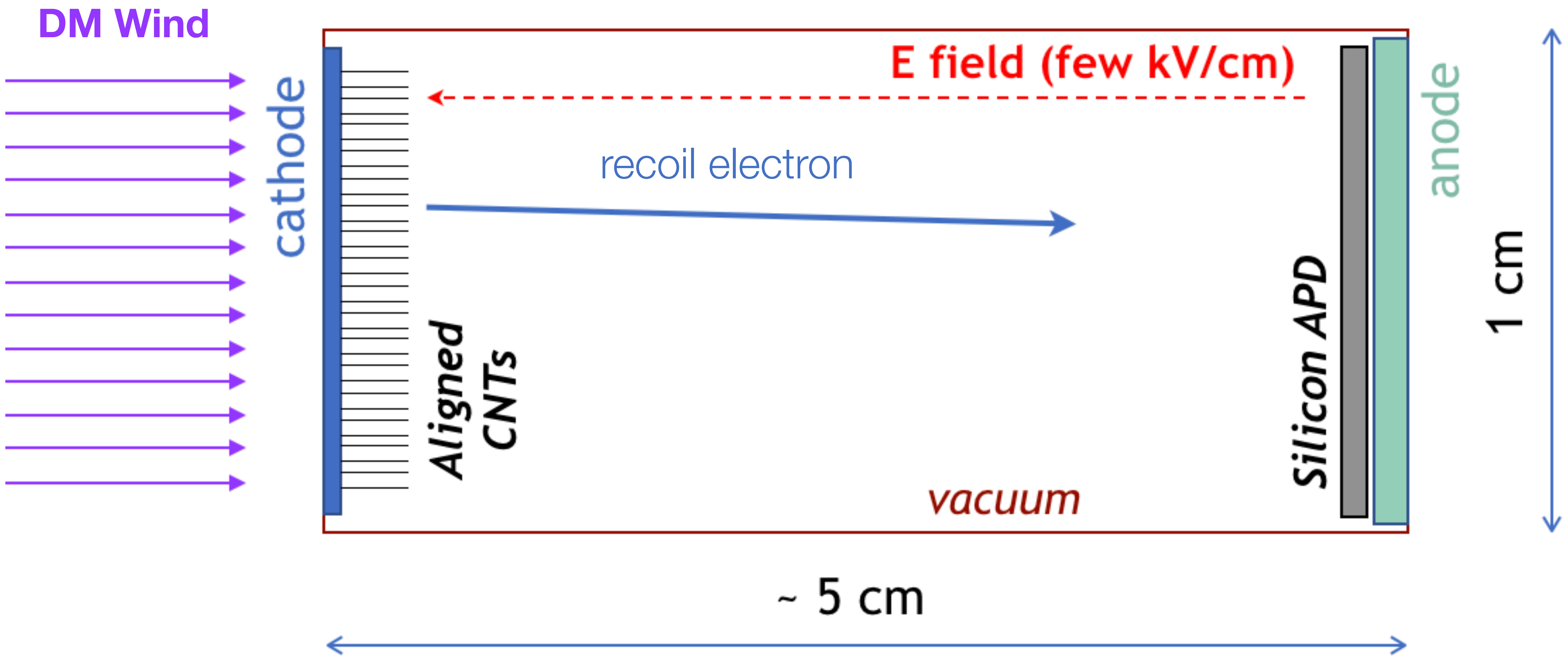
G. D'Acunto, et al., Carbon 139 (2018) 768



- **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'

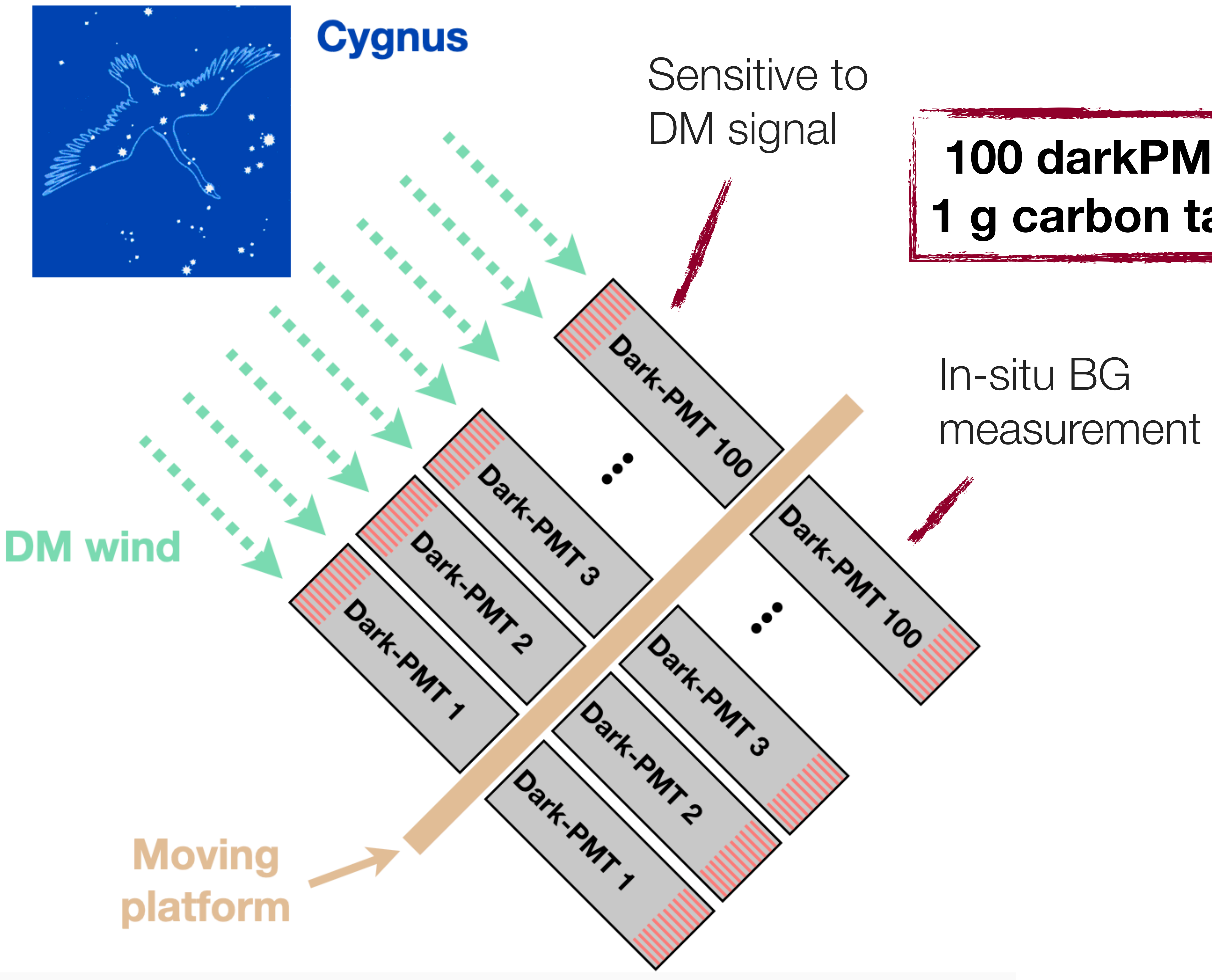


- 'Dark-photocathode' of aligned **nanotubes**
  - Ejected e^- accelerated by electric field
  - Detected by solid state **e^- counter**

Dark-PMT features:

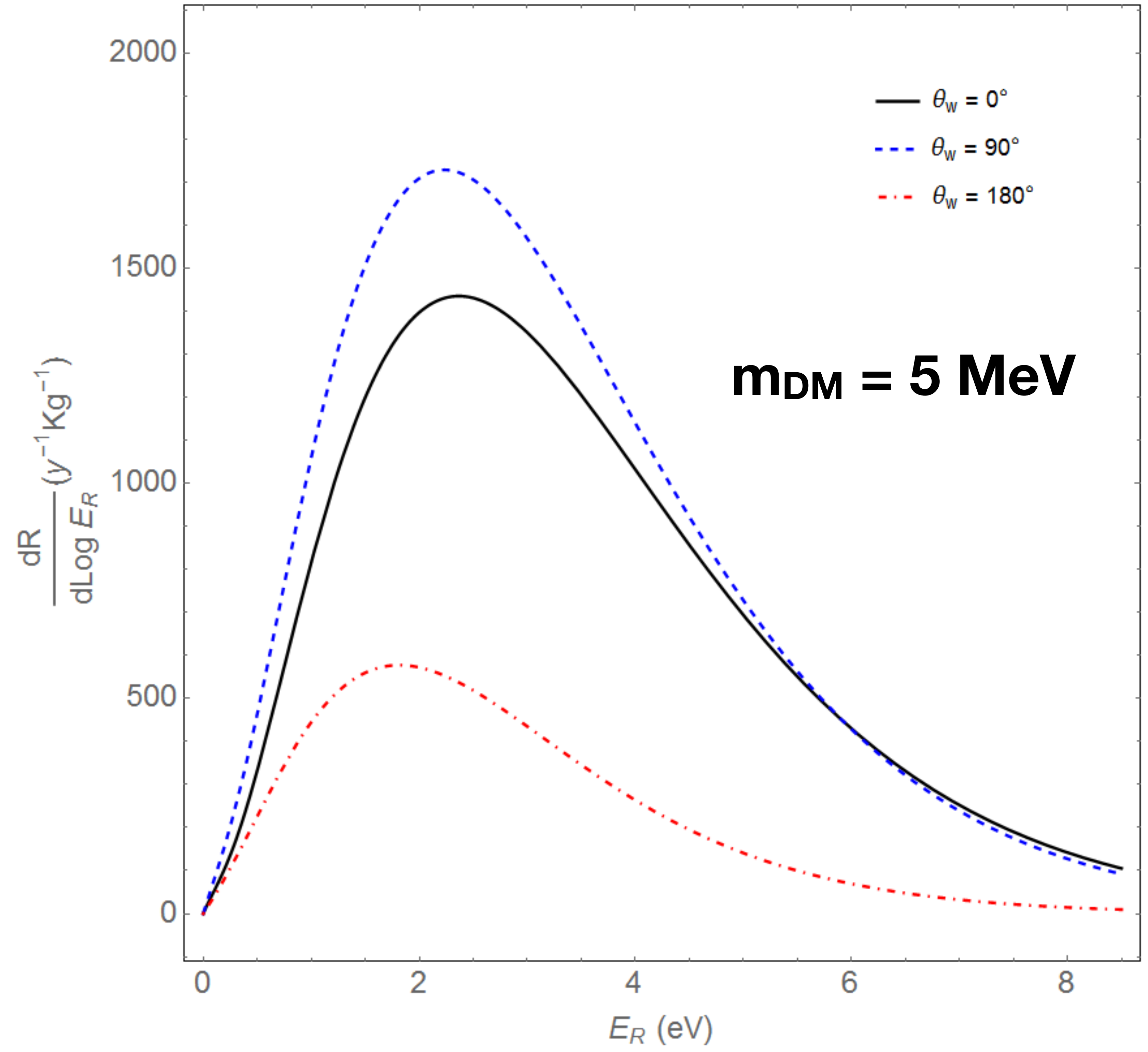
- **Portable, cheap, and easy to produce**
- **Unaffected by thermal noise (Φ_e = 4.7 eV)**
- **Directional sensitivity**

Two Arrays of Dark-PMTs to Search for Dark Matter



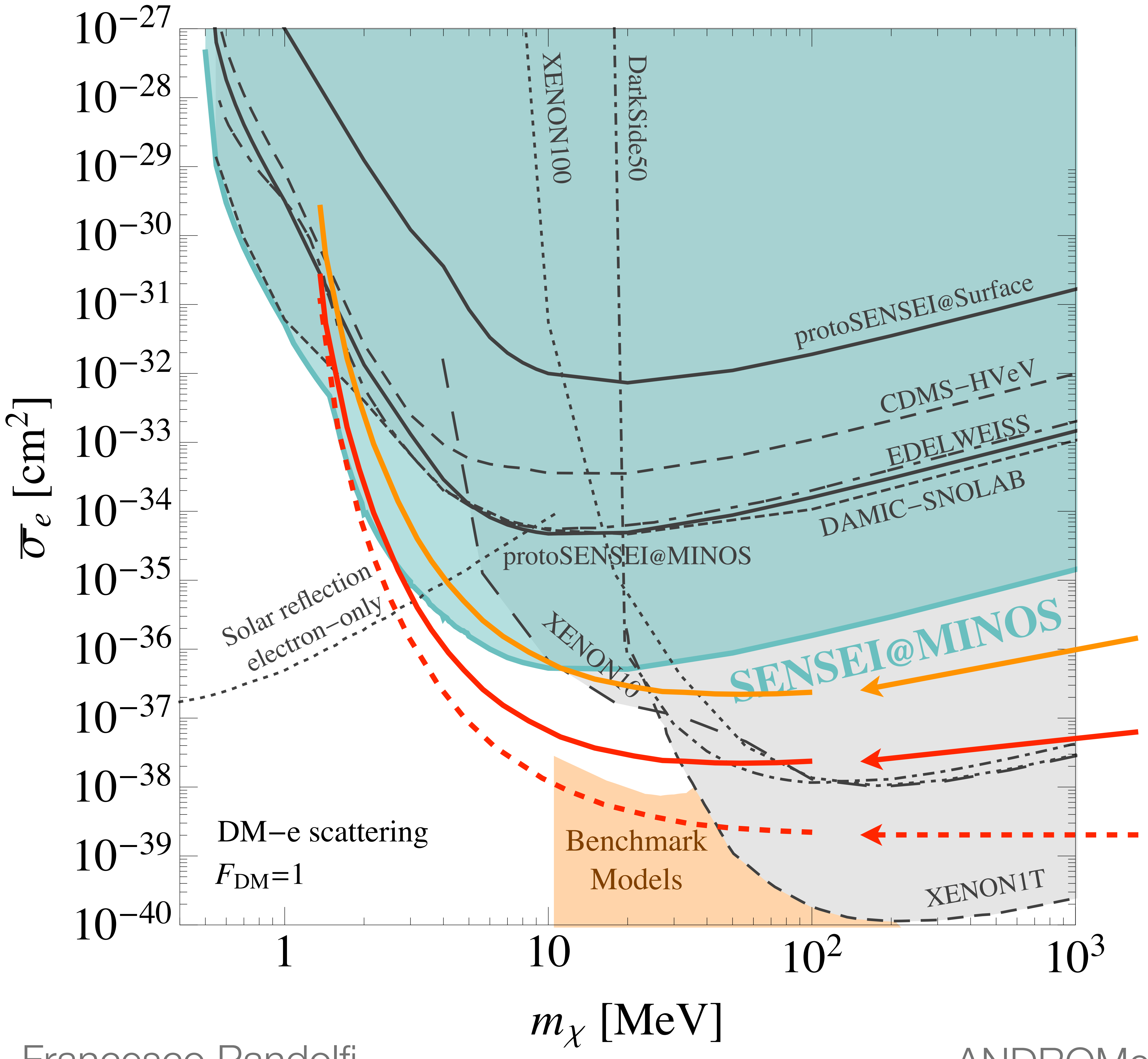
100 darkPMTs = 1 g carbon target

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



In principle sensitive to eV electrons!

Background Minimization Will Be Essential



- Need < 1 BG event per year per Dark-PMT
  - To **extend** current limits
  - With only 1g·yr !

<u>Projected Sensitivity</u>
(Exposure = 1 g·yr)

1 BG ev yr^{-1} darkPMT^{-1}

0.01 BG ev yr^{-1} darkPMT^{-1}

0 BG

R. Catena will give a seminar in Rome on 26/5

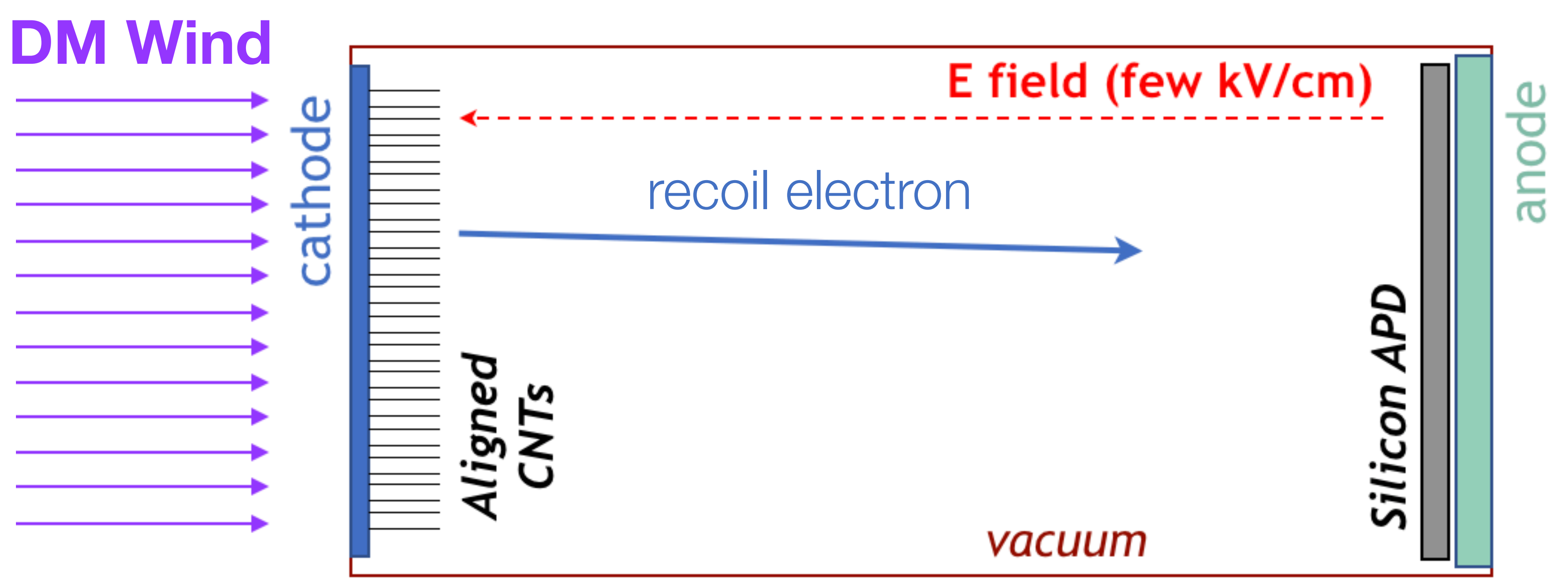
(curves adapted from R.Catena, et al., arXiv:2303.15509)

The ANDROMeDa Project

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

ANDROMeDa
Aligned Nanotube Detector for Research On MeV Darkmatter

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



The ANDROMeDa Project

PRIN 2020

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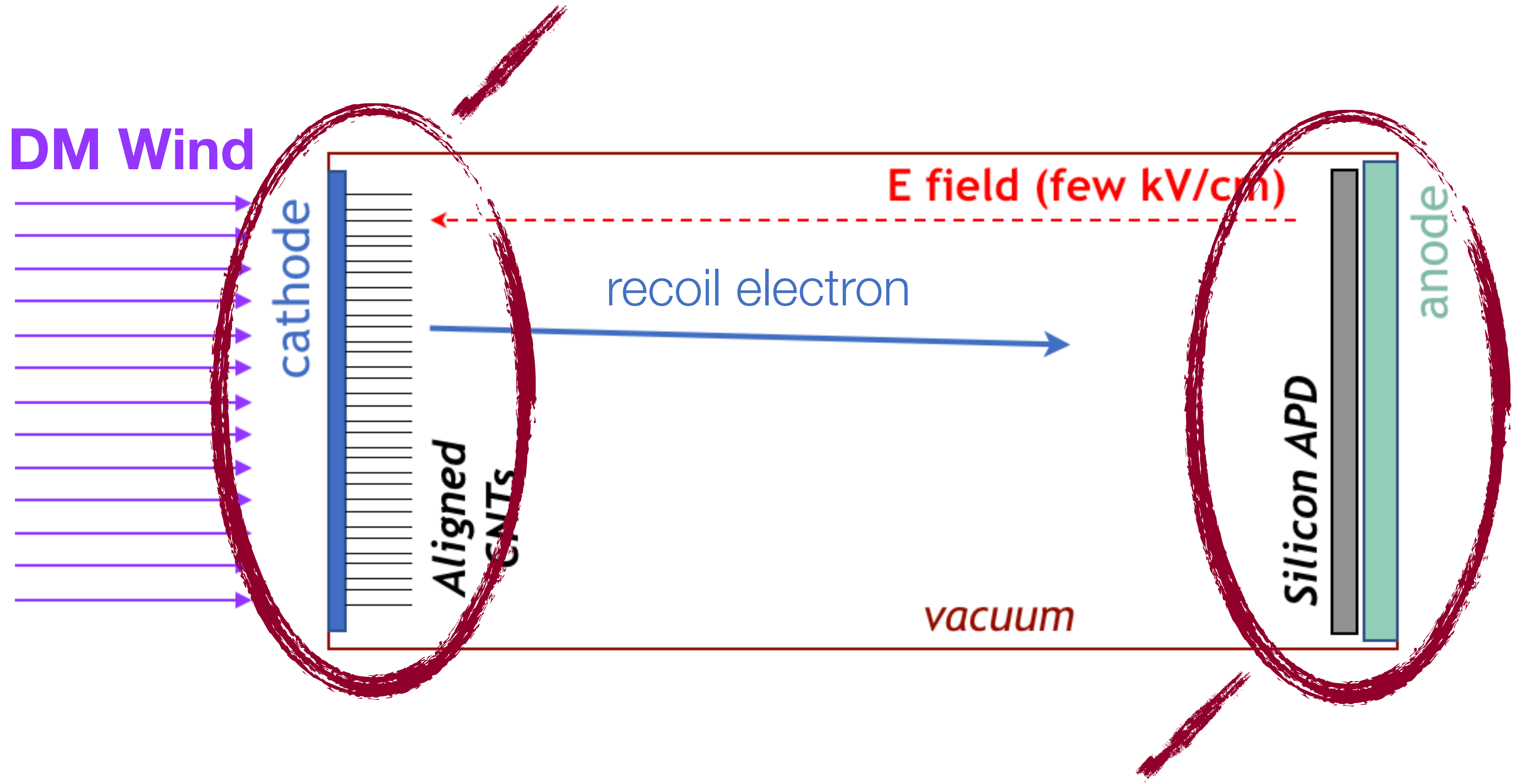
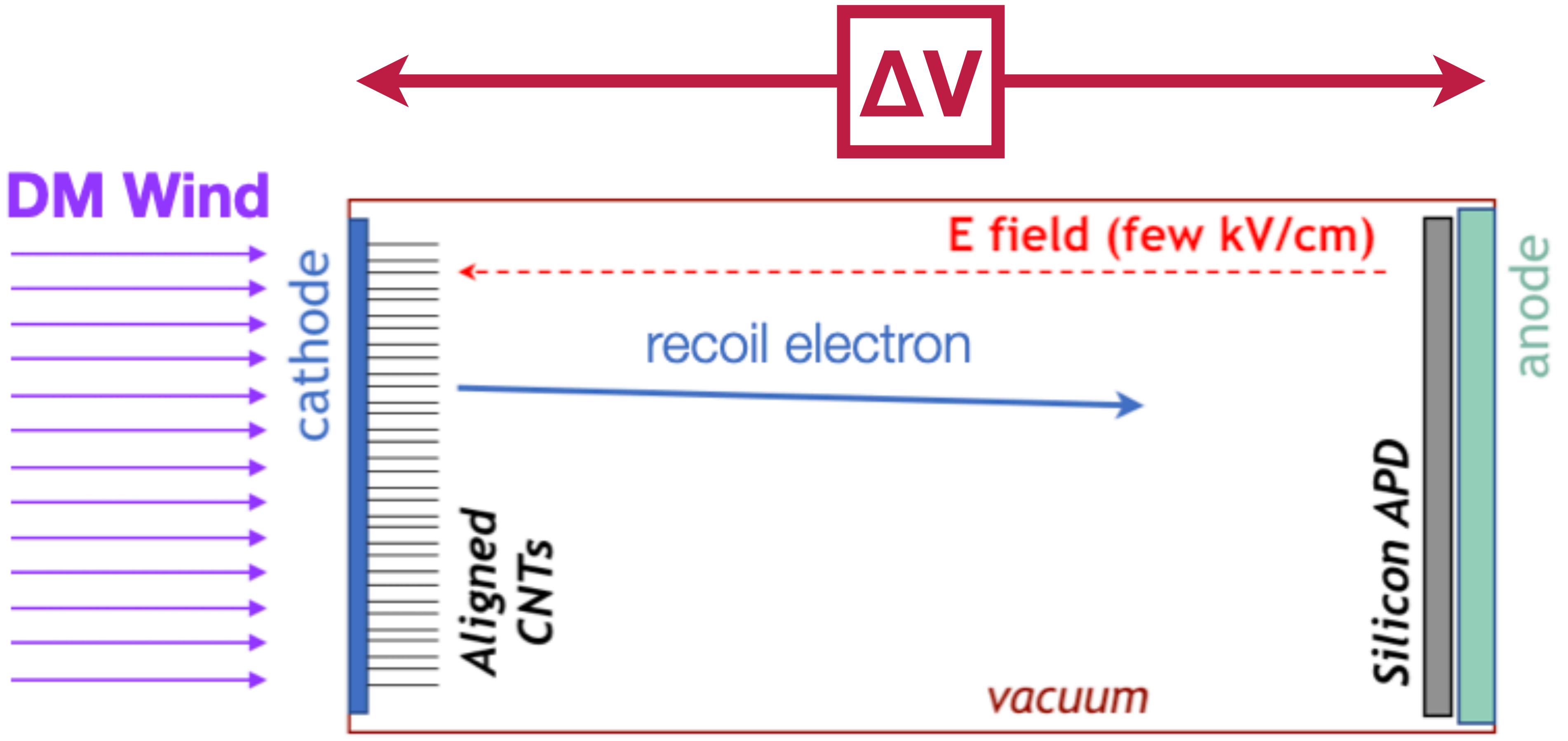
Ideal nanotubes for DM target?

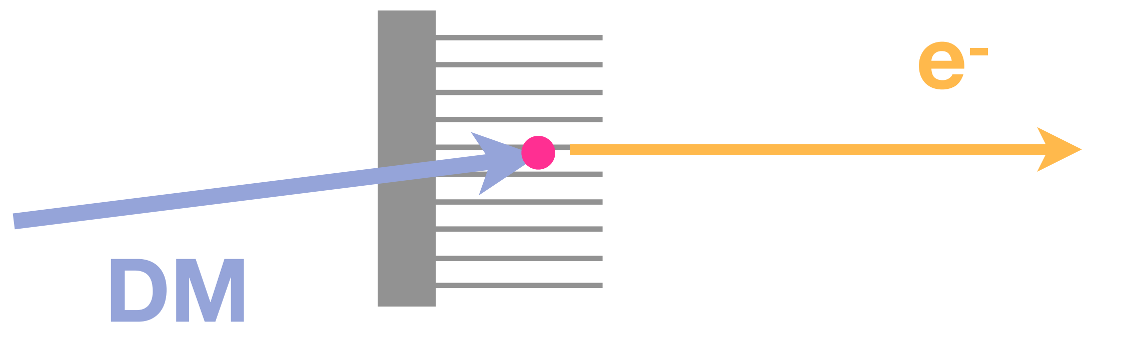


Best detector for keV electrons?

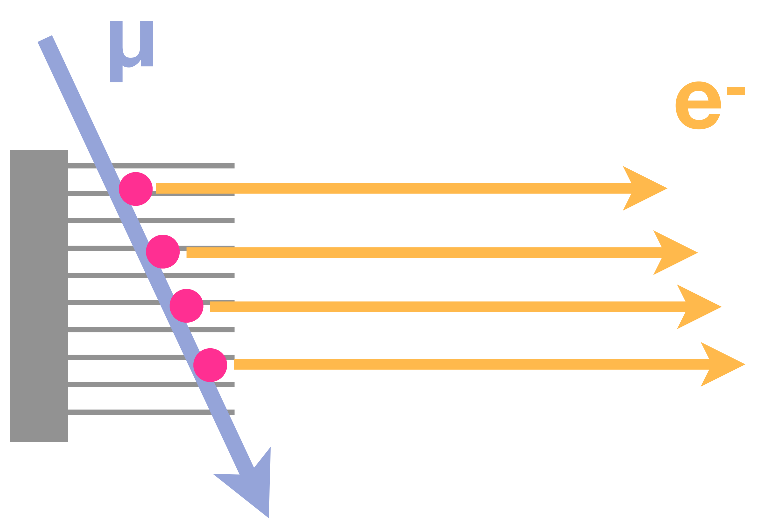
Requirements on Detecting keV Electrons



signal:



background:

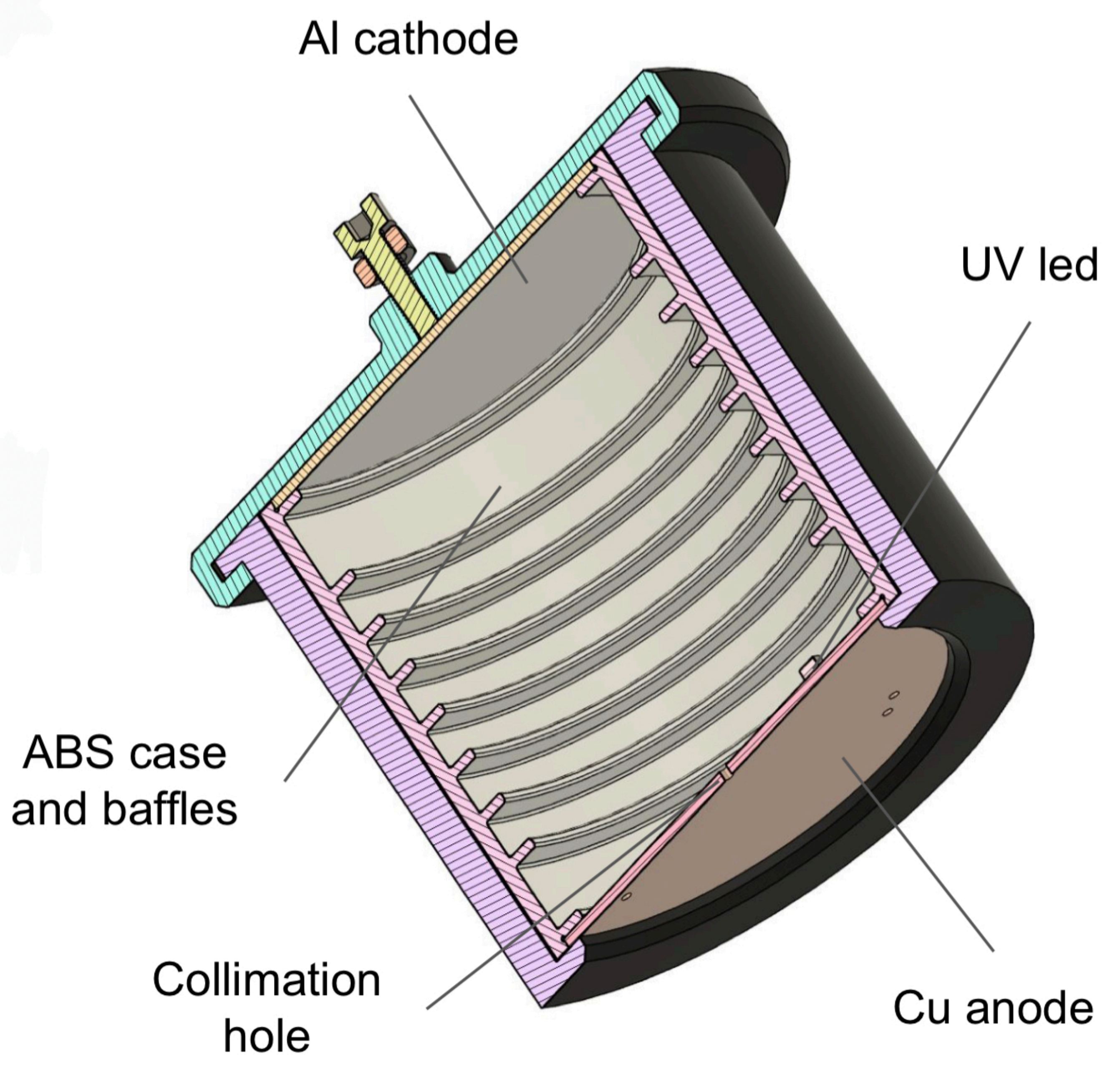


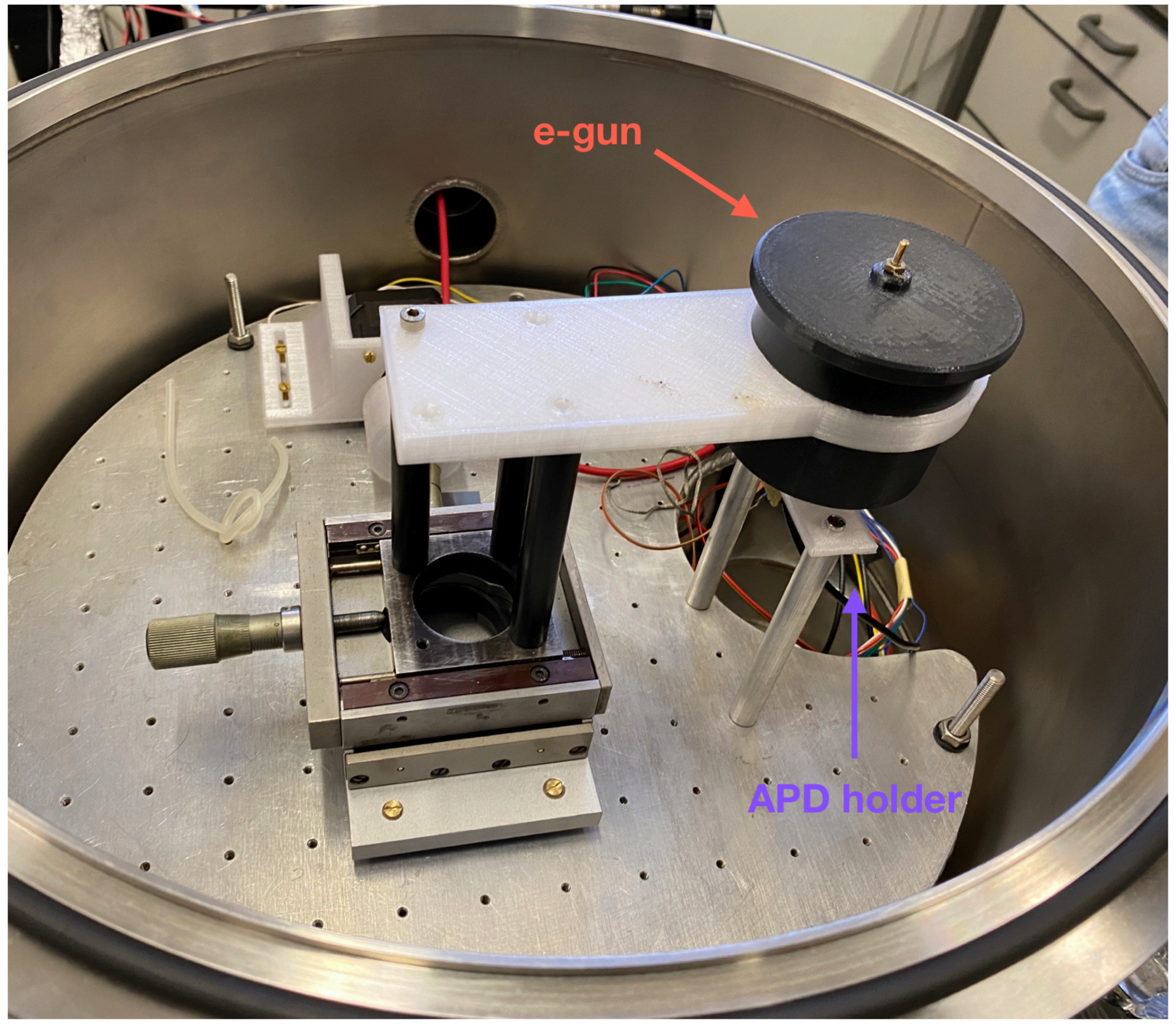
- Electron energy = ΔVe (initial energy negligible)
  - ΔV ~ 5 keV
- DM signal: **single** electron with E = ΔVe
  - Ionizing backgrounds: **multiple** electrons
- Electron detector <u>requirements</u>:
  - High (>95%) **efficiency**
  - Energy **resolution**: good enough to separate 1e$^-$ vs 2e$^-$ @ 5σ

APDs: Not Enough Resolution

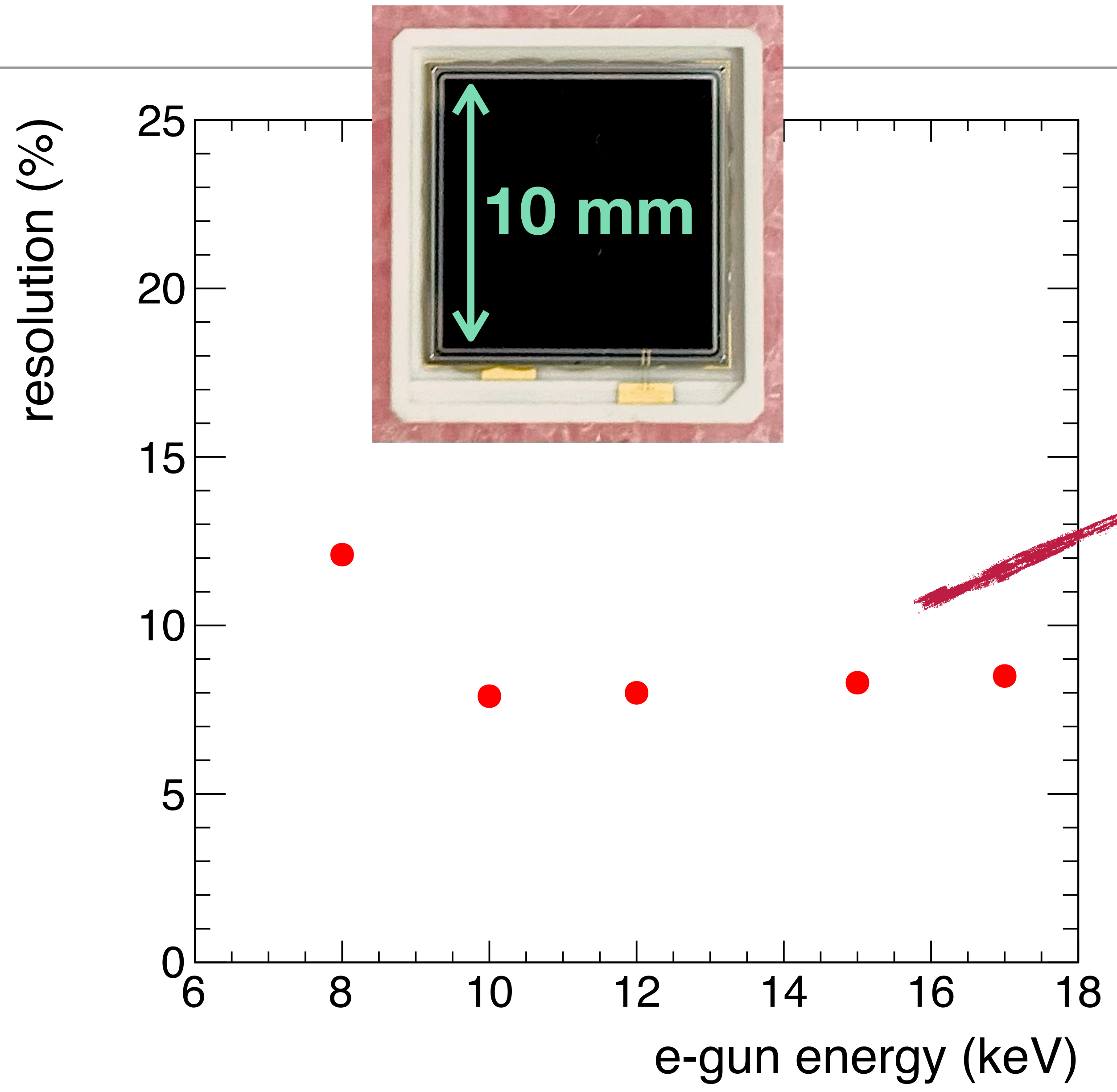
A. Apponi, et al., JINST 15 (2020) P11015

2023 Data Taking @ Milano Bicocca e-Gun (M. Biassoni)

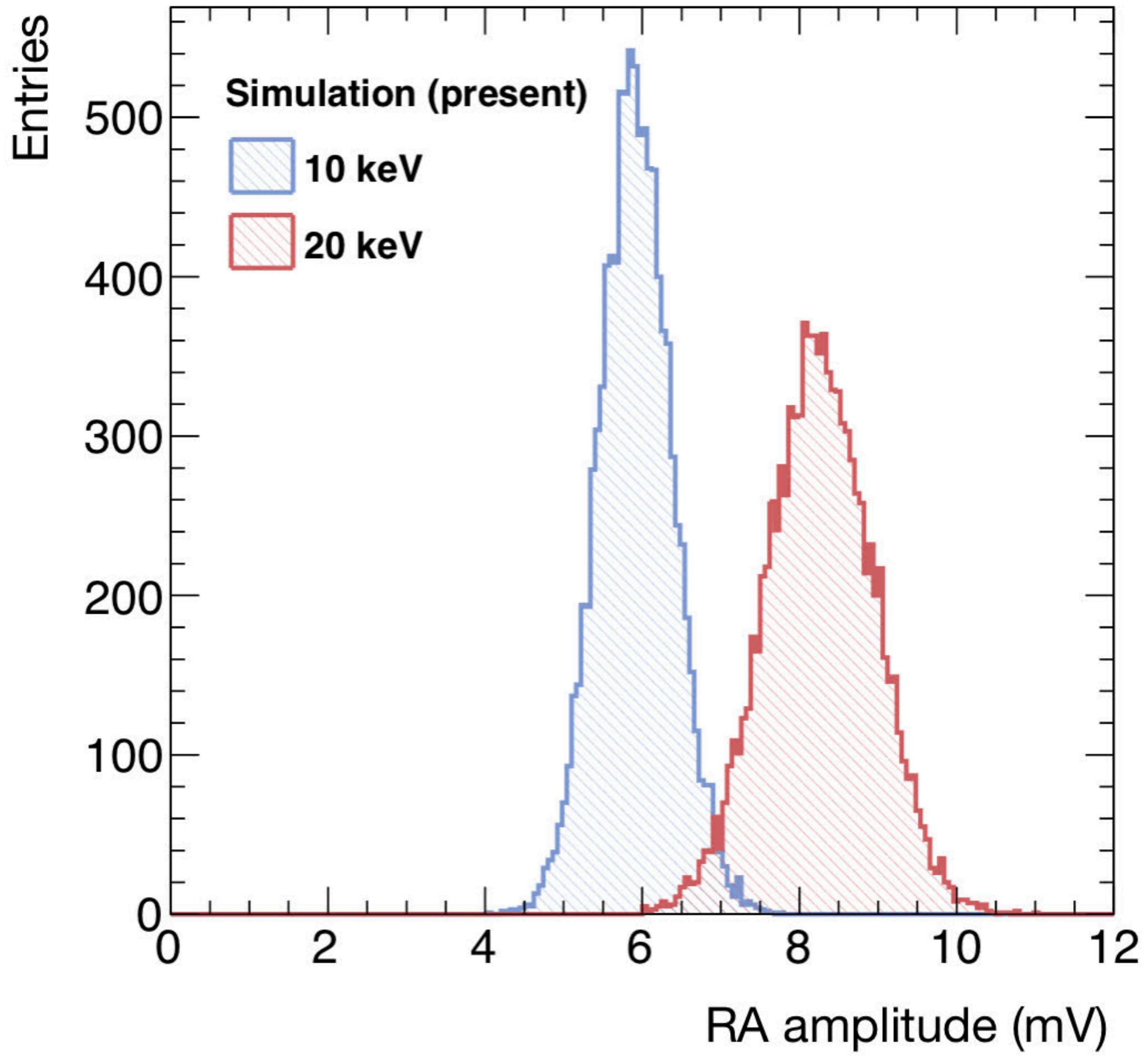




Hamamatsu windowless APD



Electron energy resolution

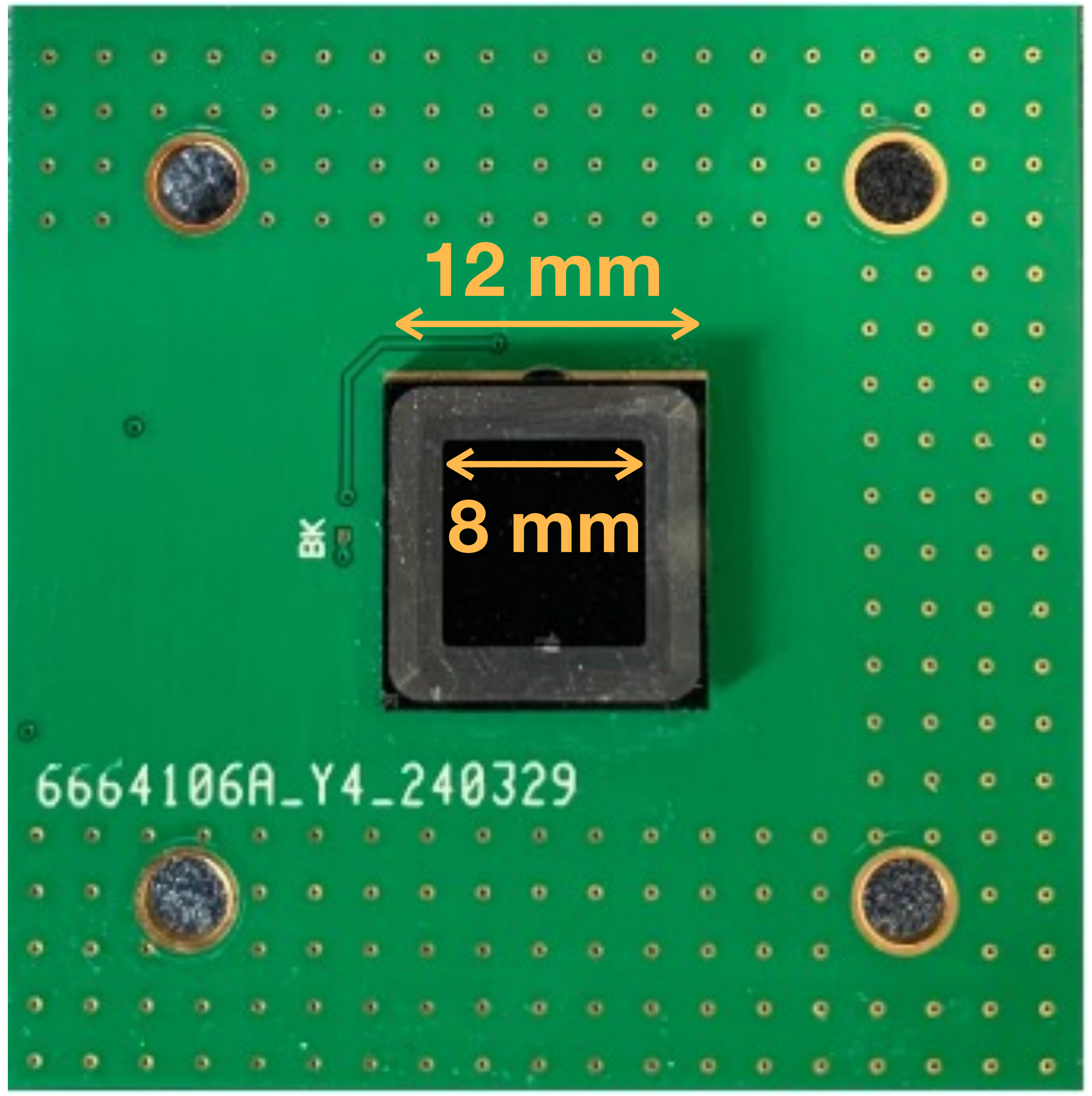


~3σ separation between 10 keV (data) and 20 keV (simulated)

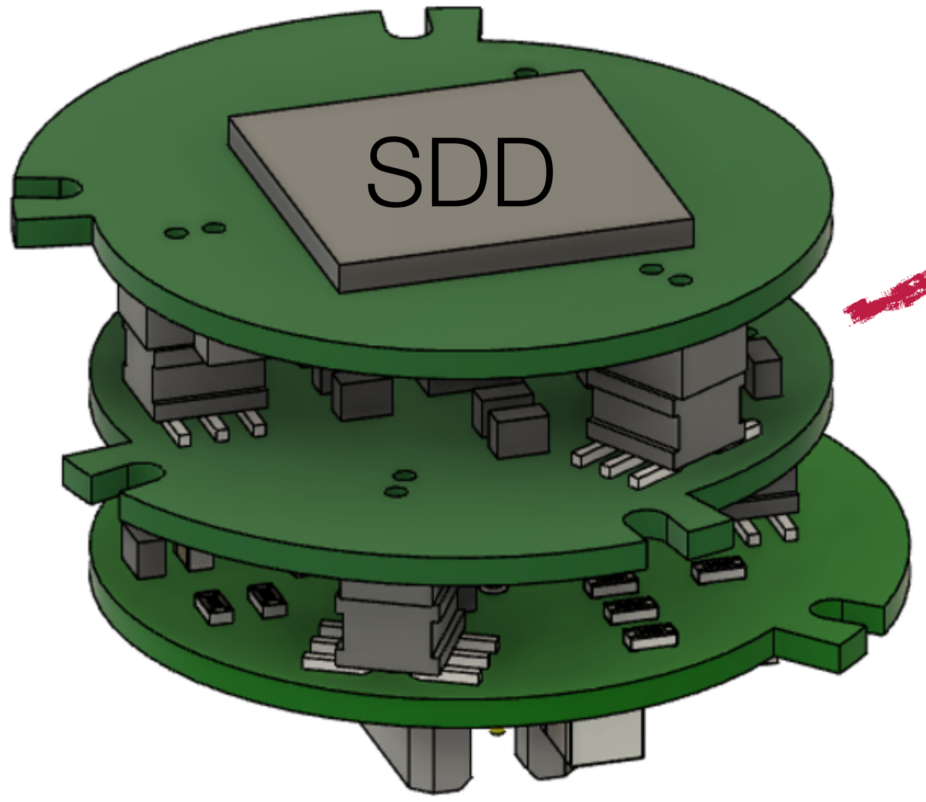
Not enough

Chosen Technology: Silicon Drift Detectors

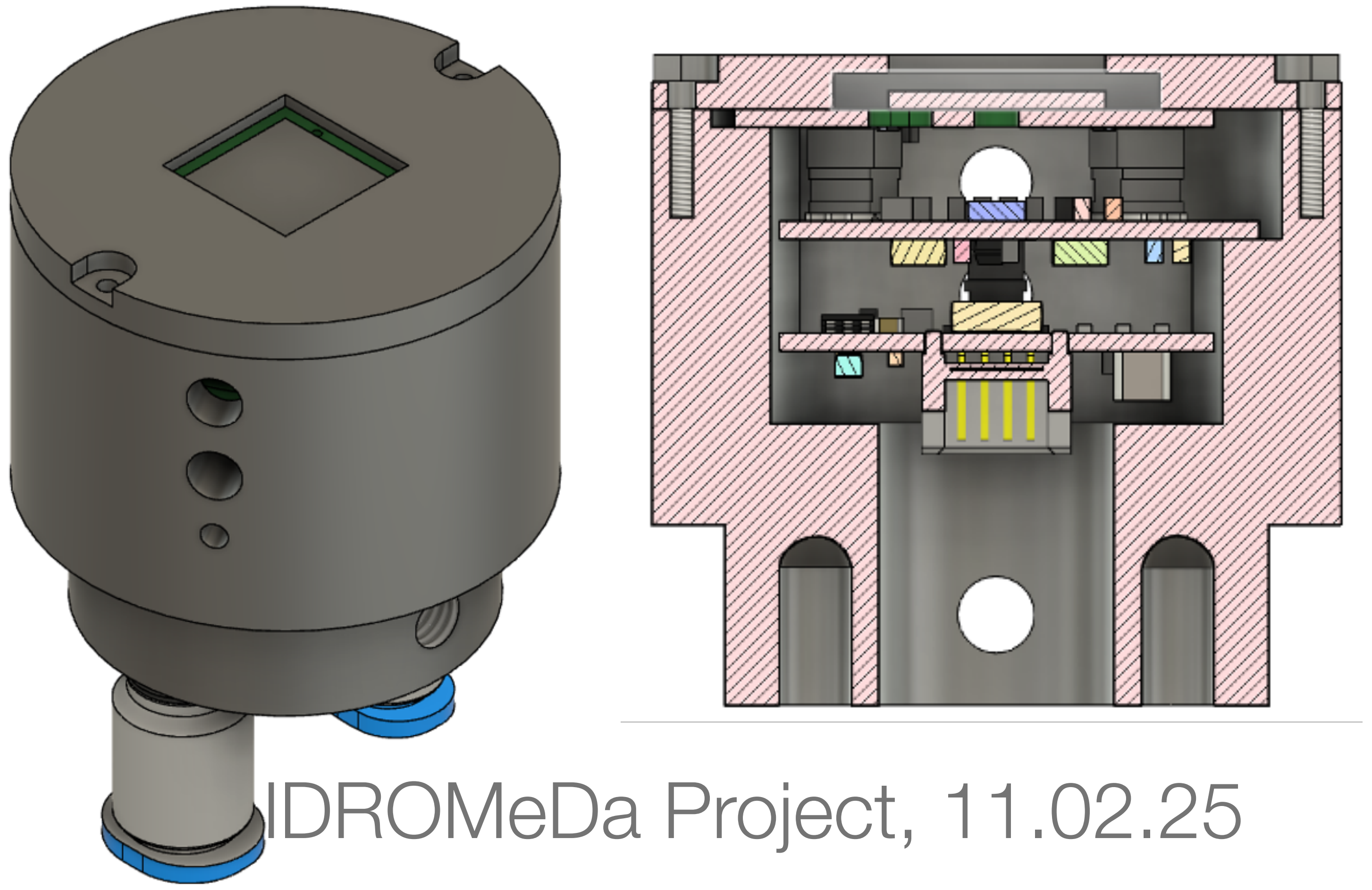
SDD produced by FBK



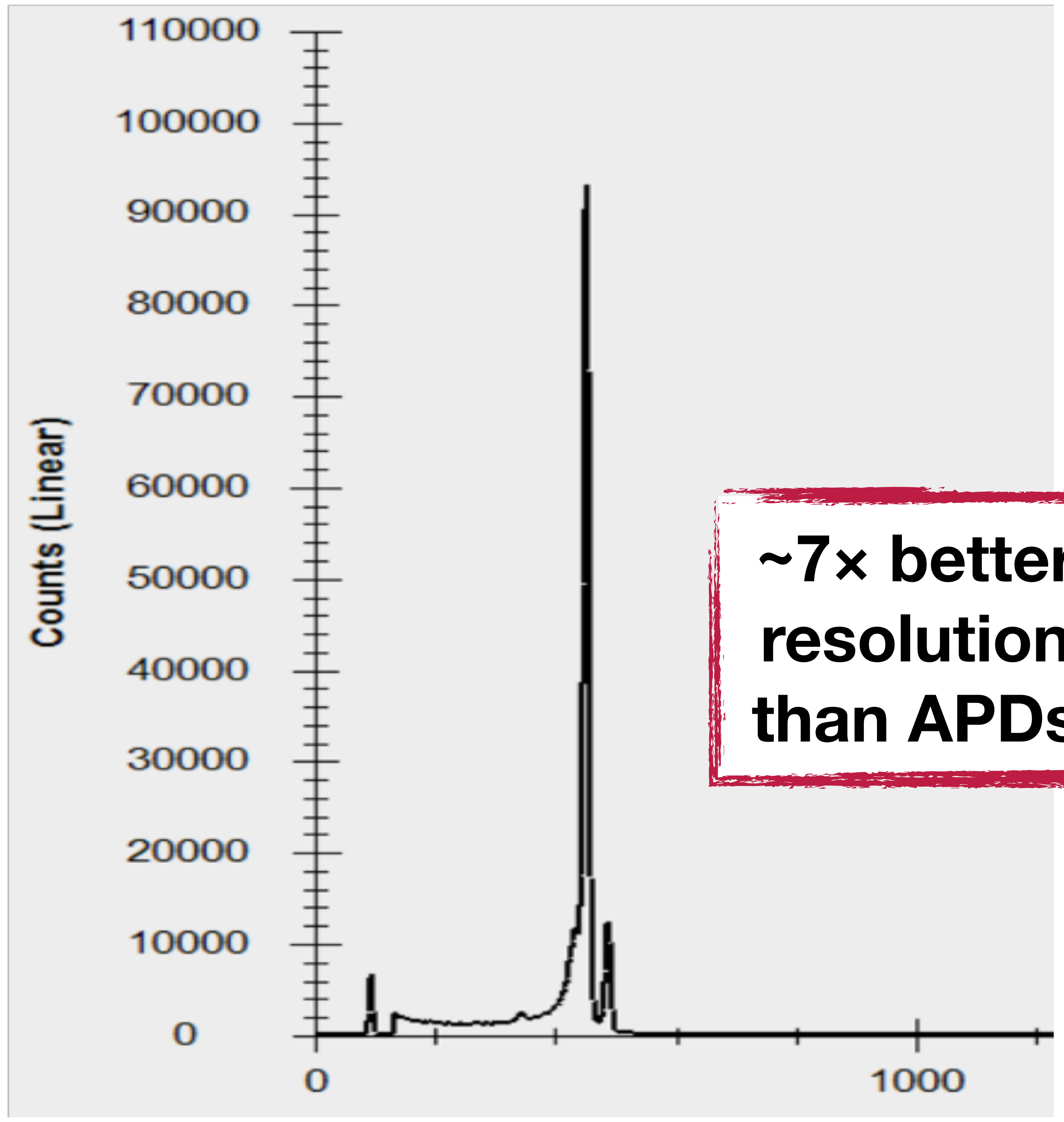
Holder and electronics by PoliMi



gain stage (G=3)

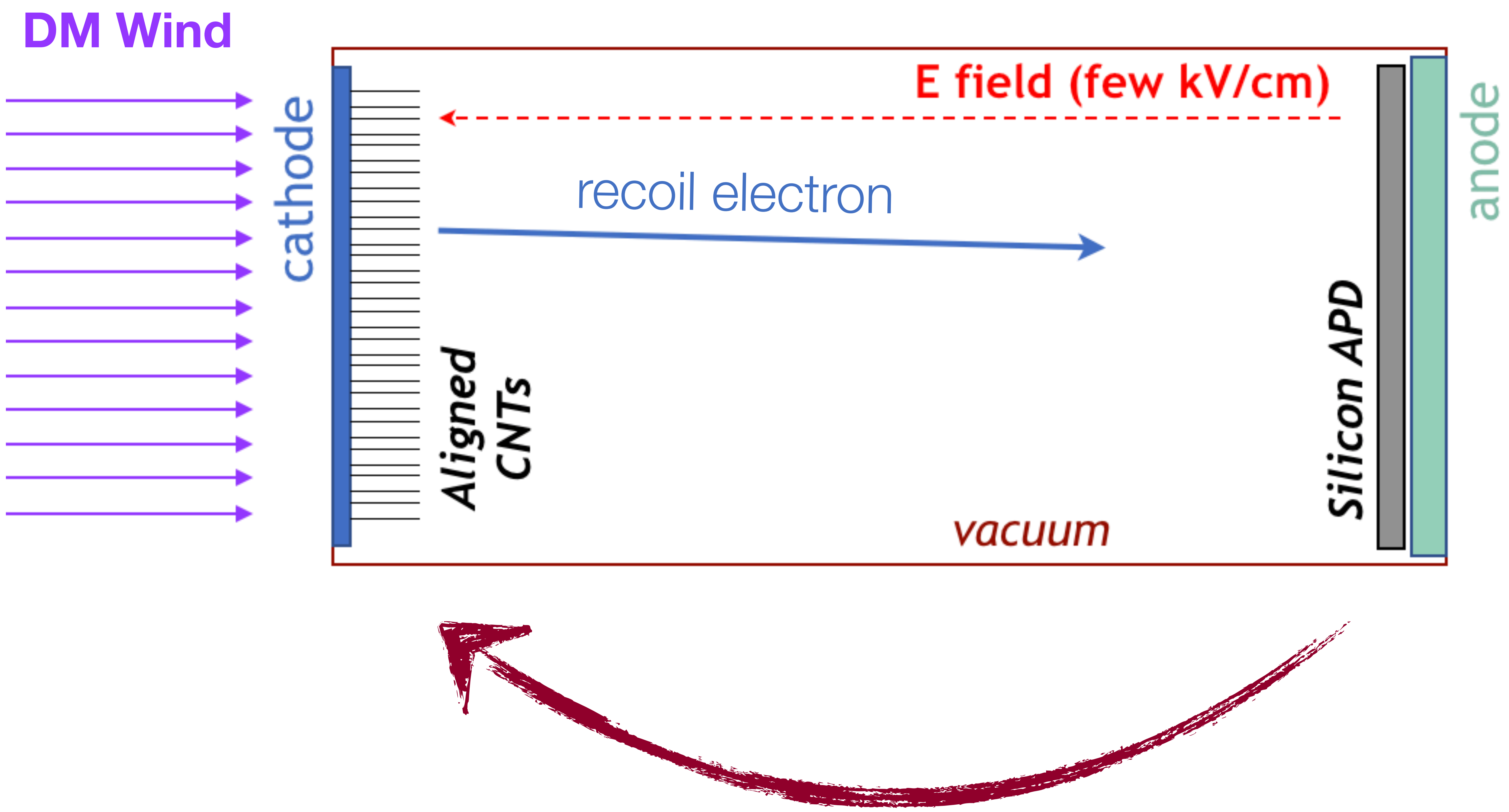


Fe55 Kα peak (5.9 keV) FWHM ~ 170 eV

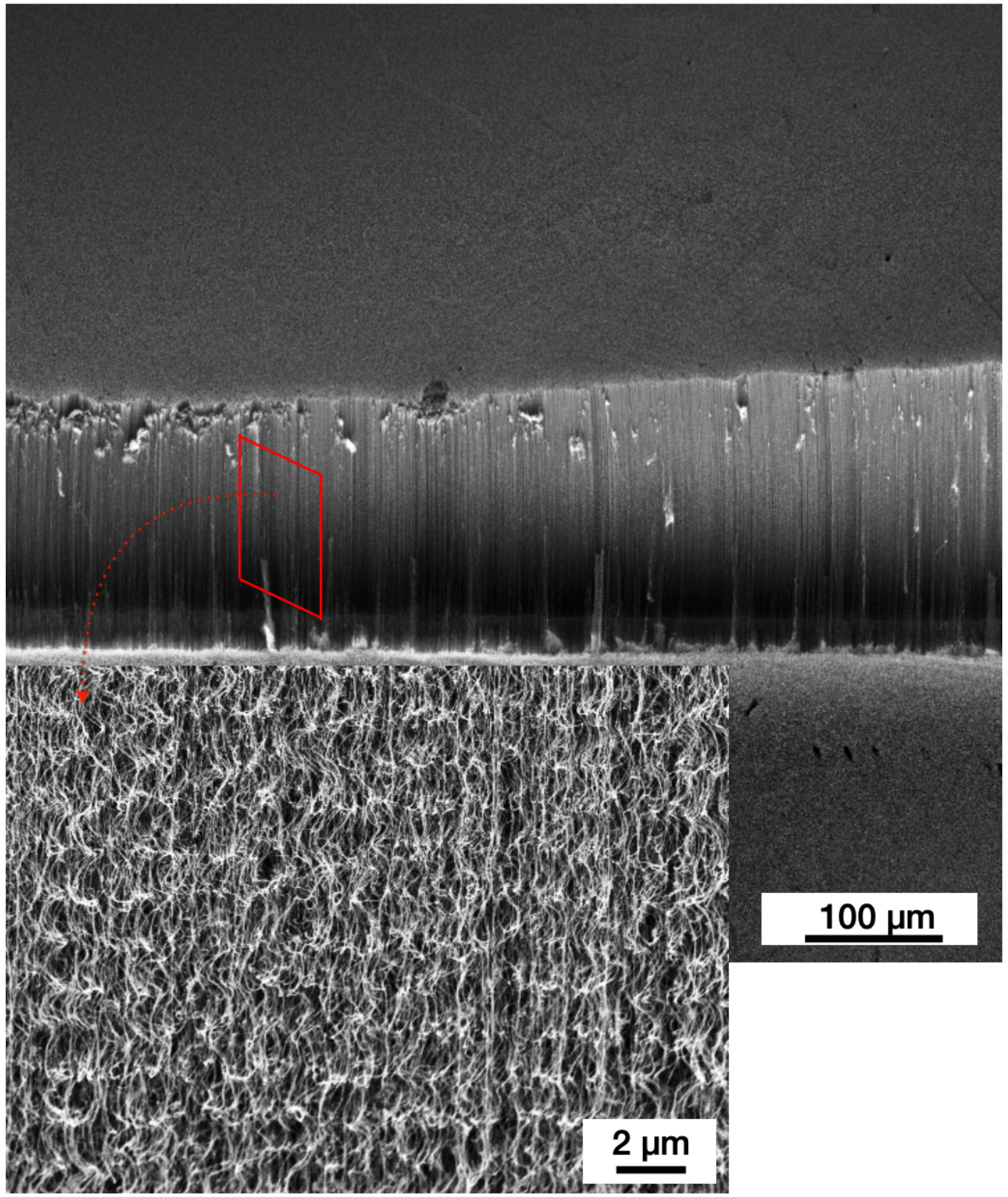


~7× better resolution than APDs

currently assembling in Milano…


DM Wind
cathode
E field (few kV/cm)
anode
recoil electron
Aligned CNTs
Silicon APD
vacuum

Aiming for Ultimate Parallelism at the Nanoscale



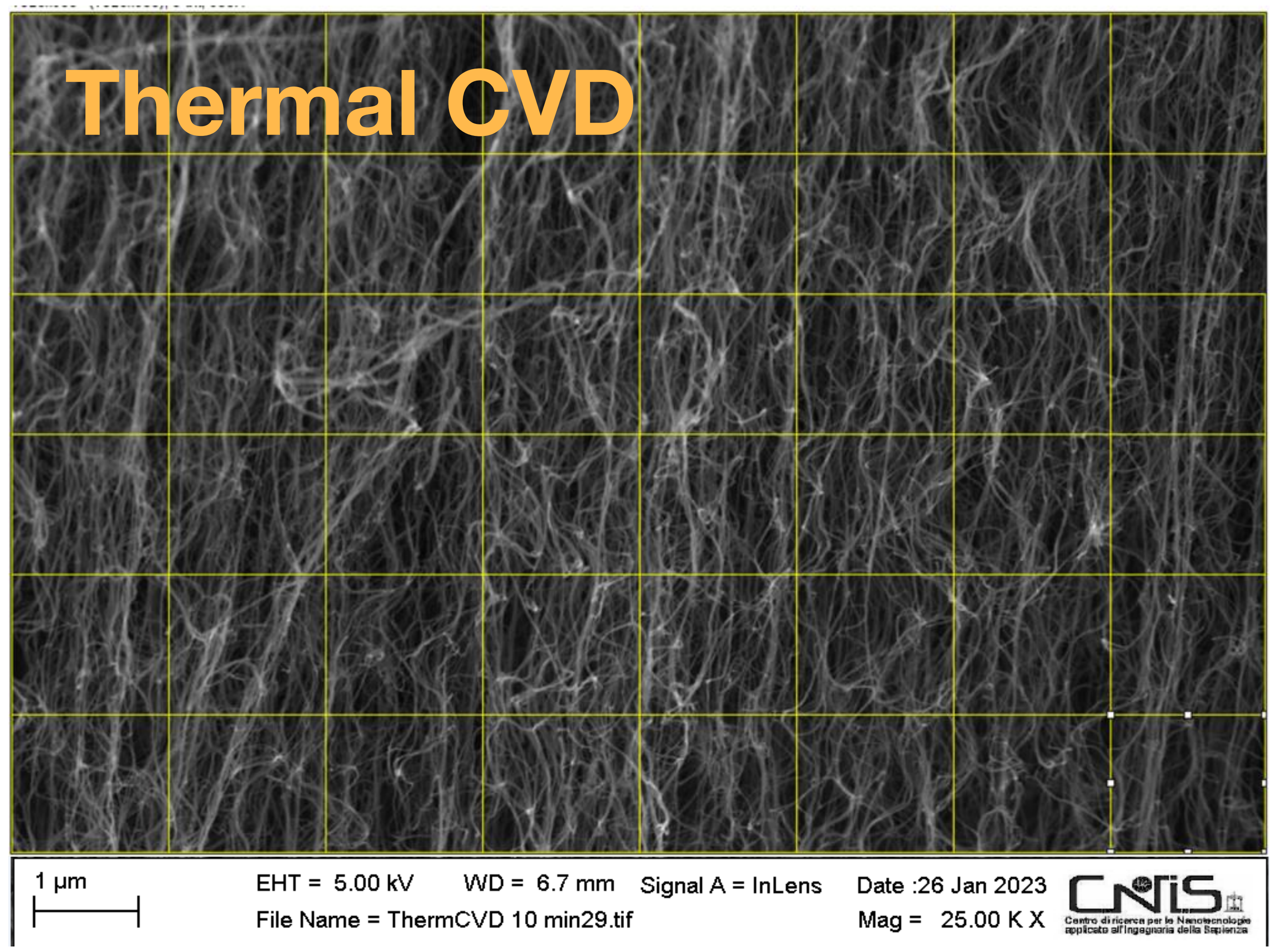
- Parallel at microscale, **waviness** at nanoscale
  - Can hinder electron transmission

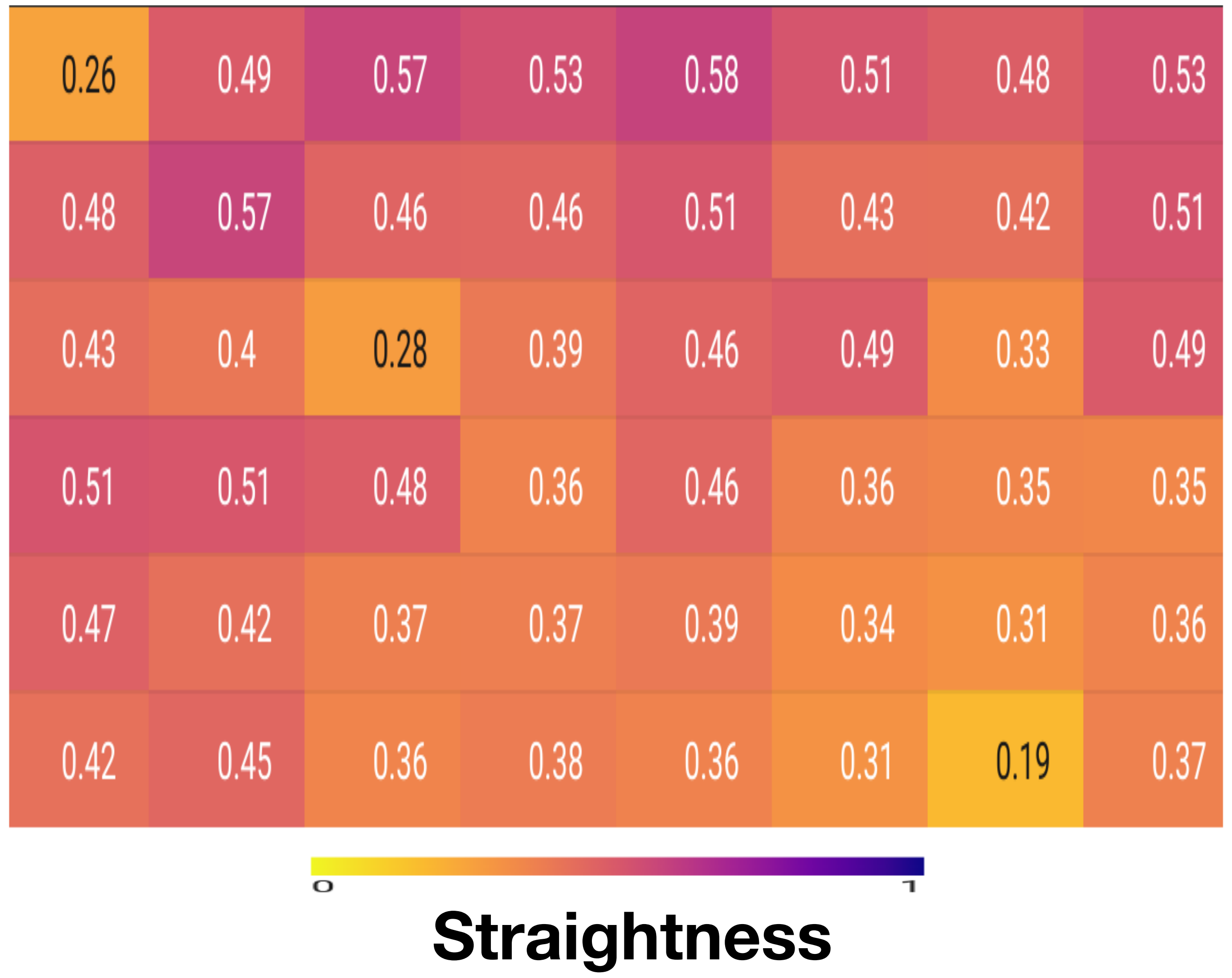
- **Two strategies** to straighten nanotubes
  - Add **electric field** during growth
  - Optimize catalyst **seeds**

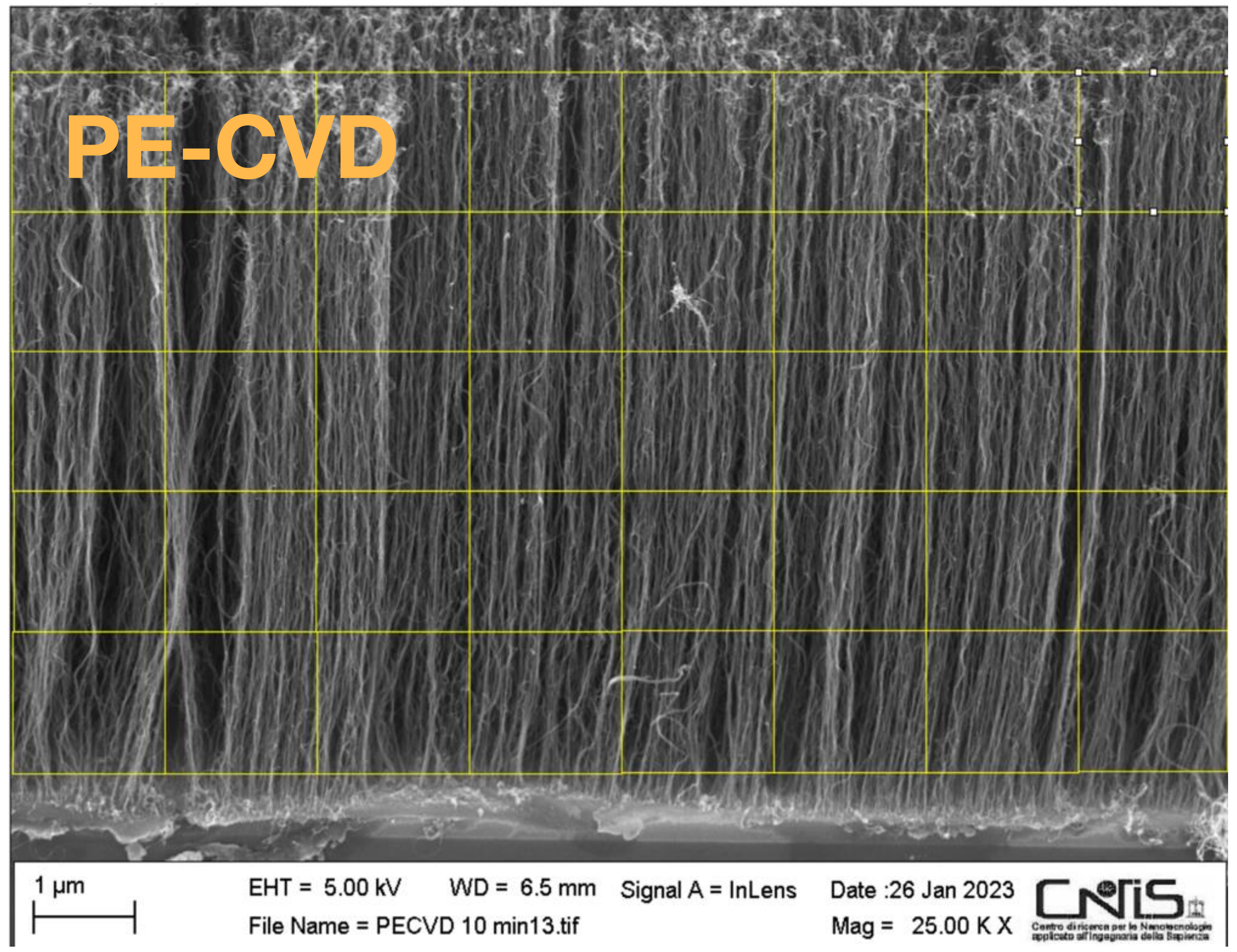
Plasma-Enhanced Growth Straightens Nanotubes

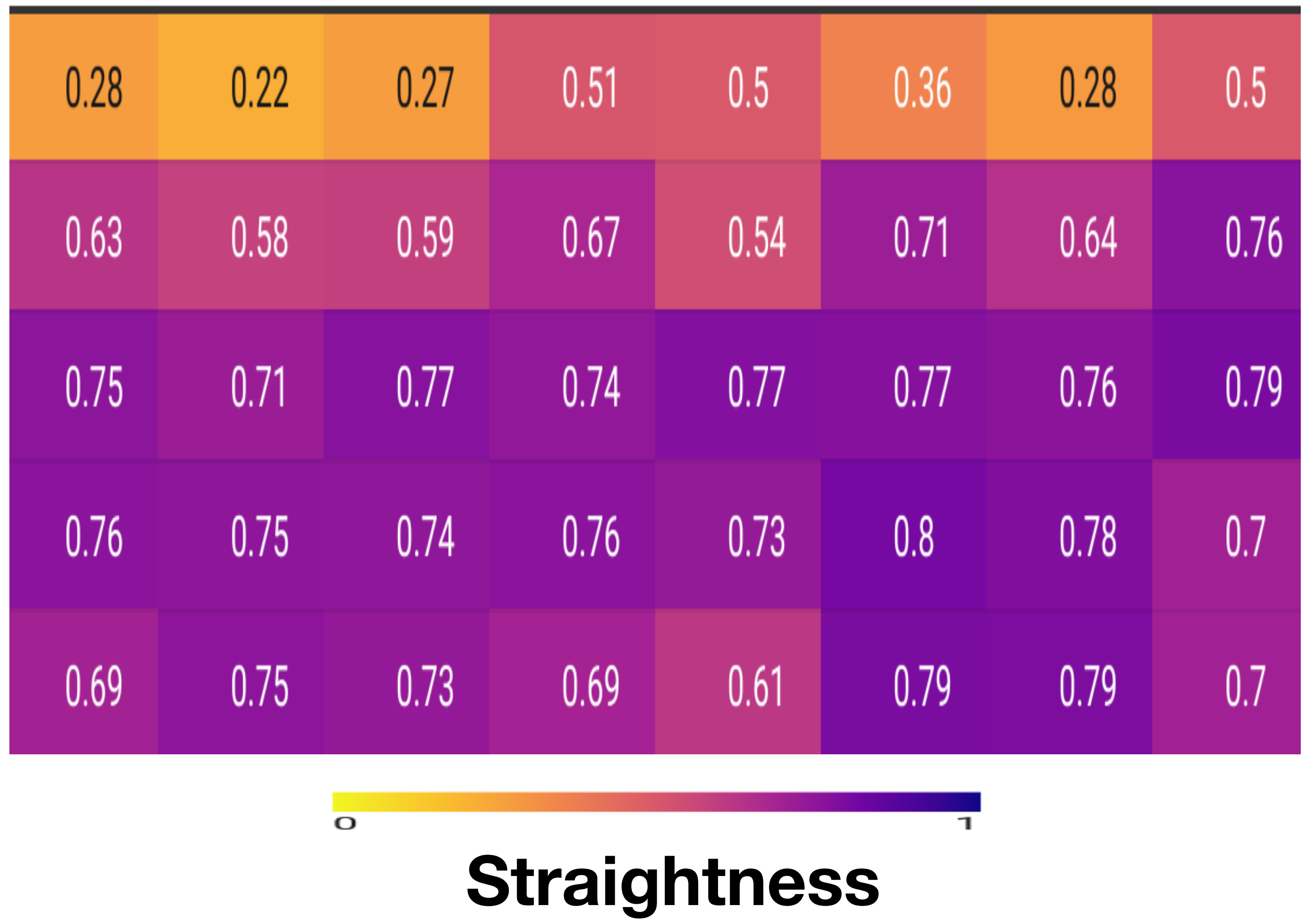
R. Yadav, et al., NIMA 1060 (2024) 169081

- September 2022: **added RF** to CVD chamber
  - 'Thermal' CVD: high **temperature** breaks C_2H_2
  - 'Plasma-Enhanced' CVD: RF **electric field** does the job
- Nanotubes grown with plasma: significantly **straighter**
  - Straightness defined from image gradient (R. Yadav)

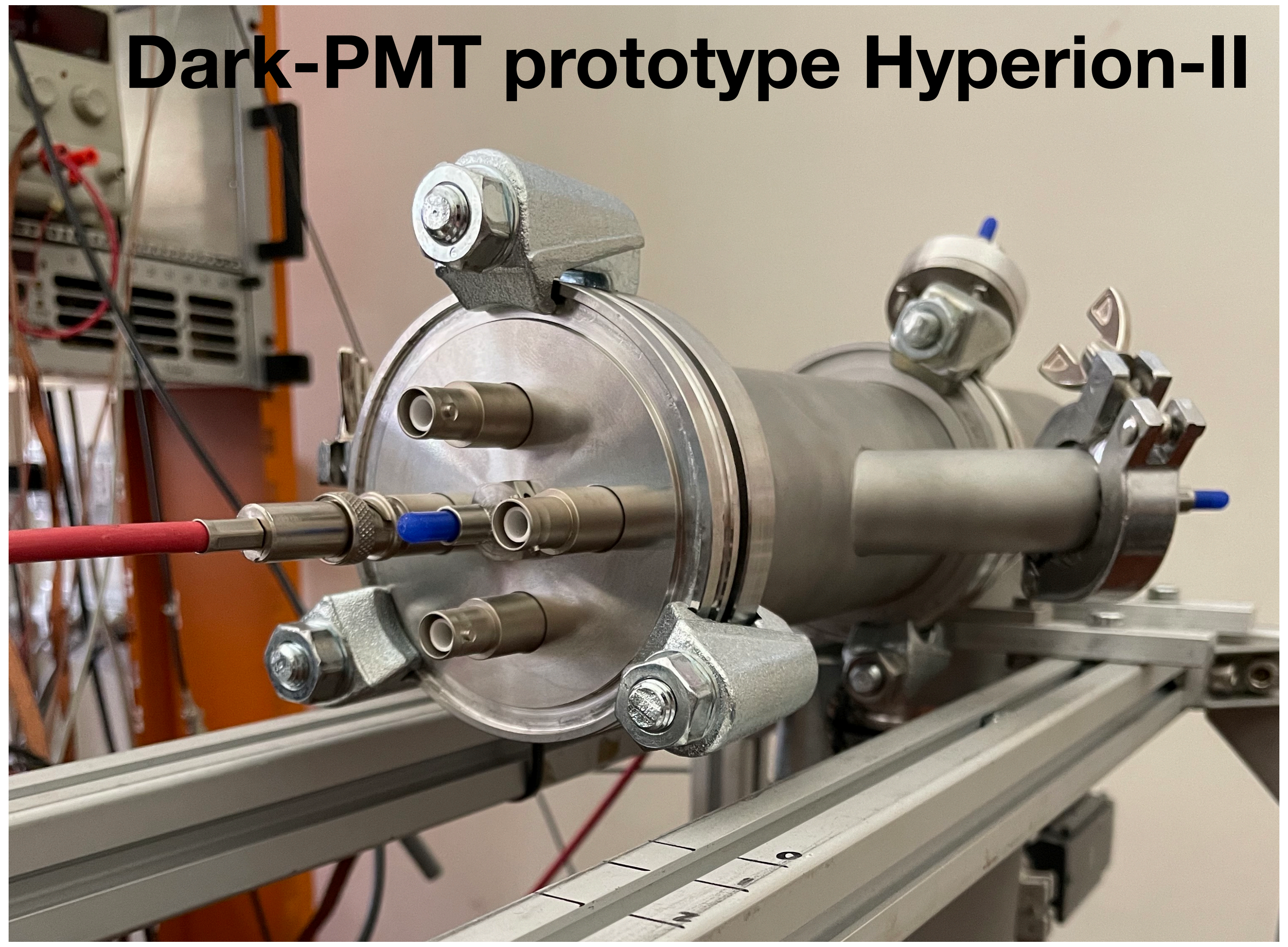


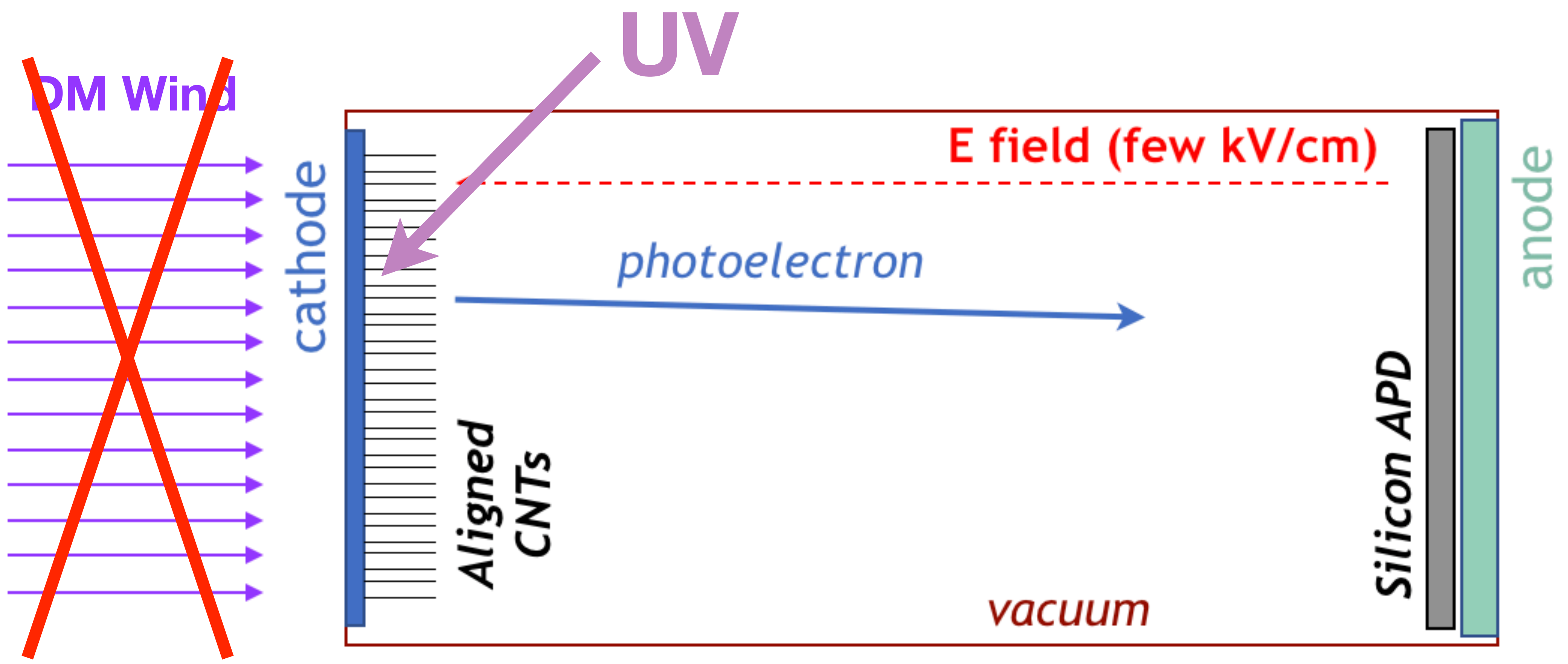




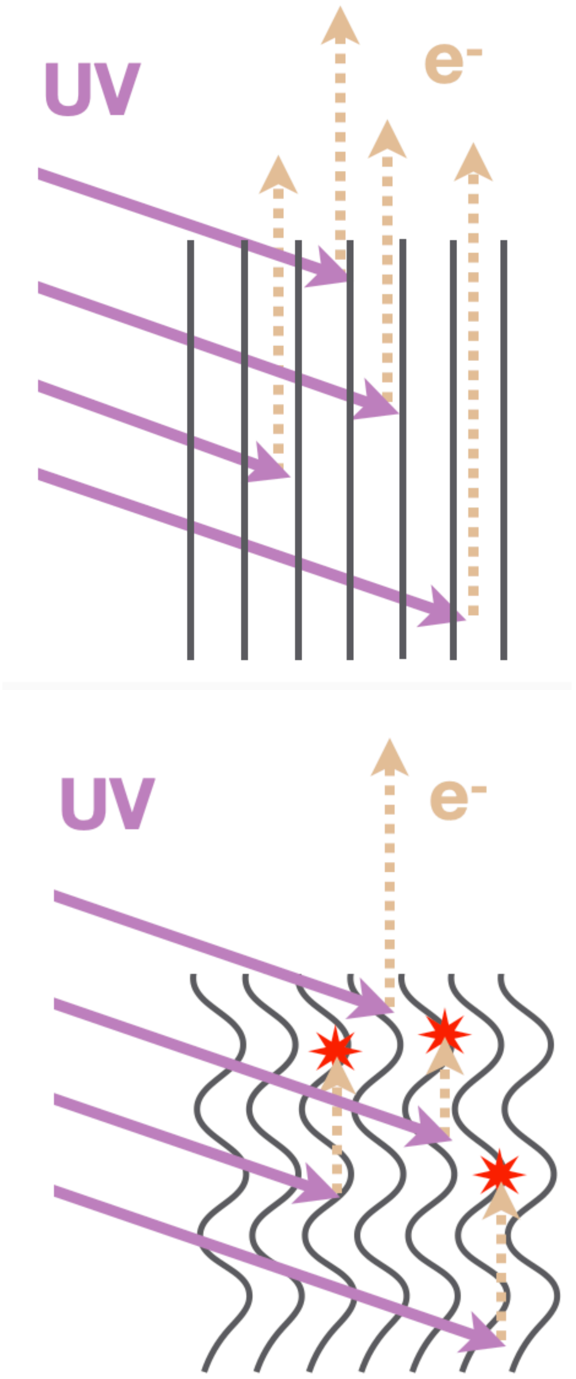


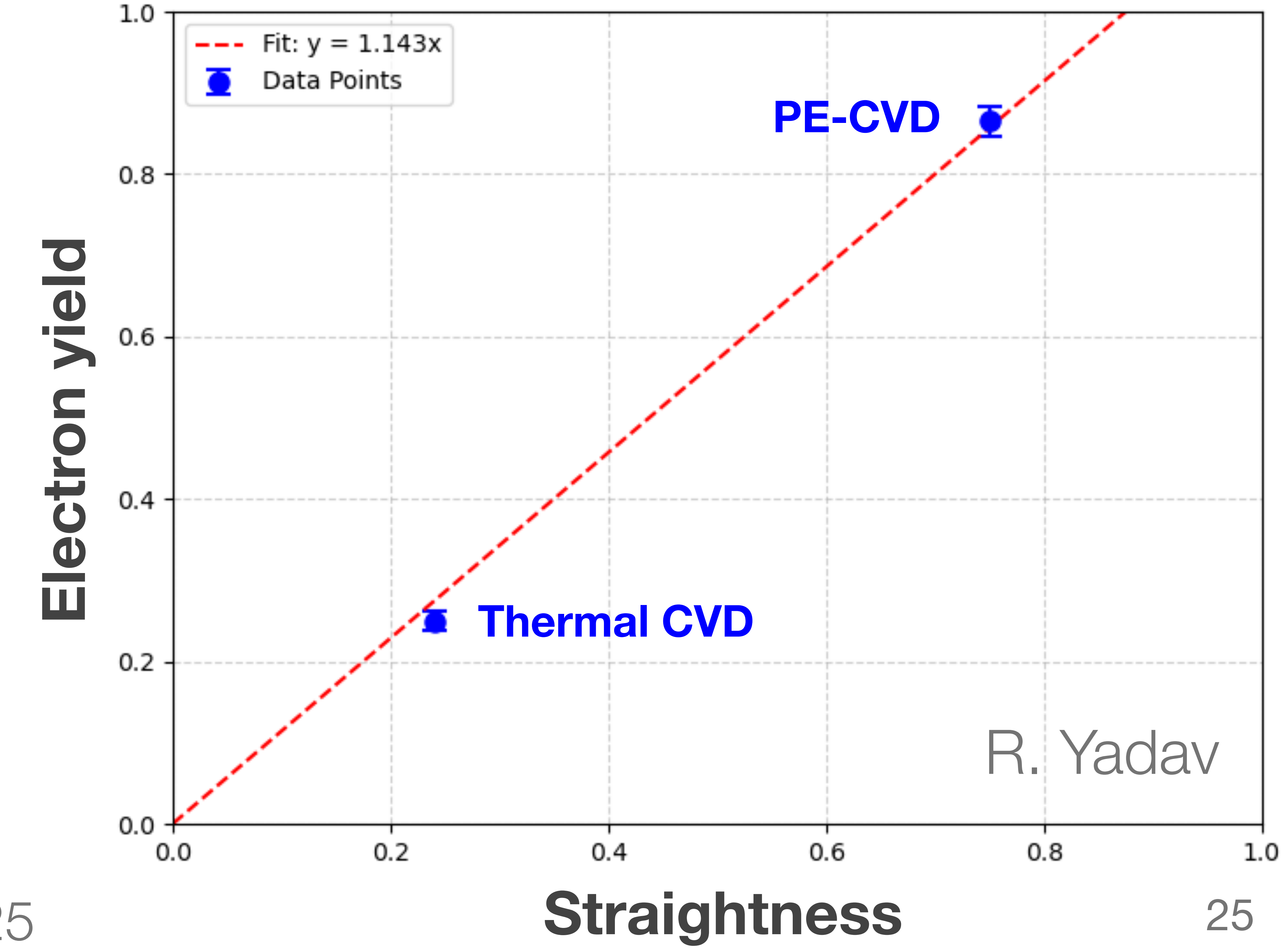
Results Confirmed by UV Photoemission





- Shooting UV photons on nanotubes
  - $E_\gamma = 5$ eV $> \phi_{cnt} = 4.7$ eV
  - **More electrons** extracted from **straighter** tubes





New Evaporation Chamber (Finally) Operational

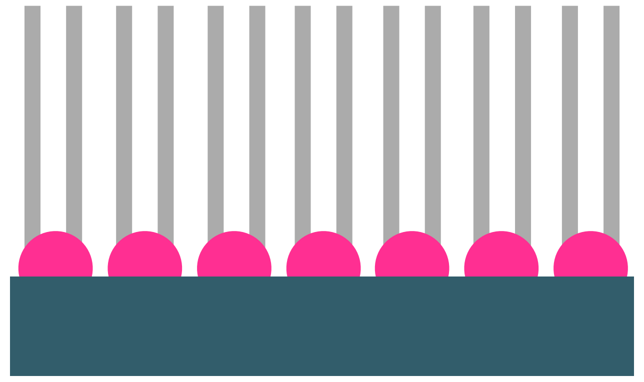
Previously done by PoliFab (Milano)

Evaporation

A nanolayer of iron deposited on substrate

Annealing at 720 °C

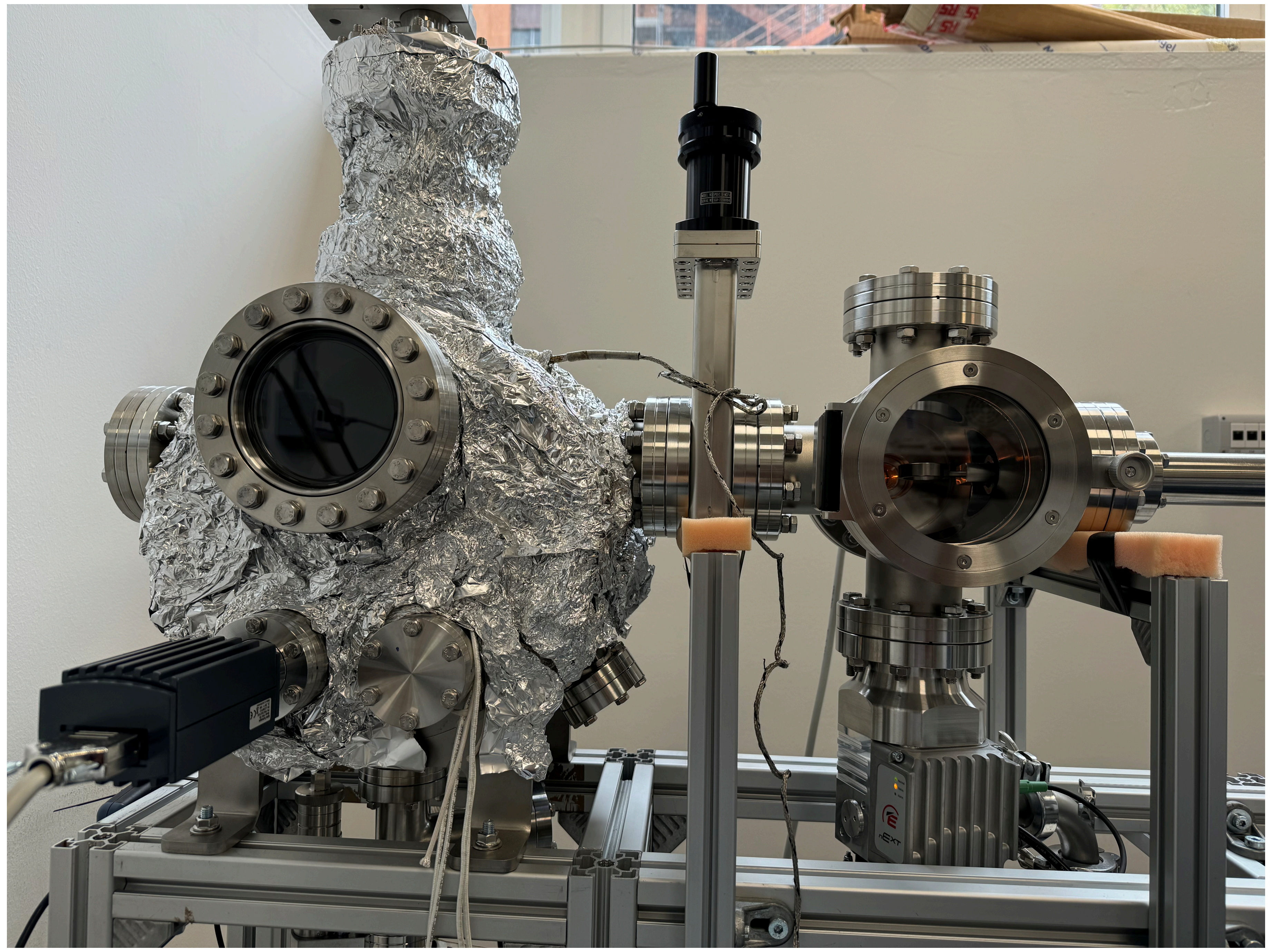
Nanoparticles are formed



CVD Synthesis

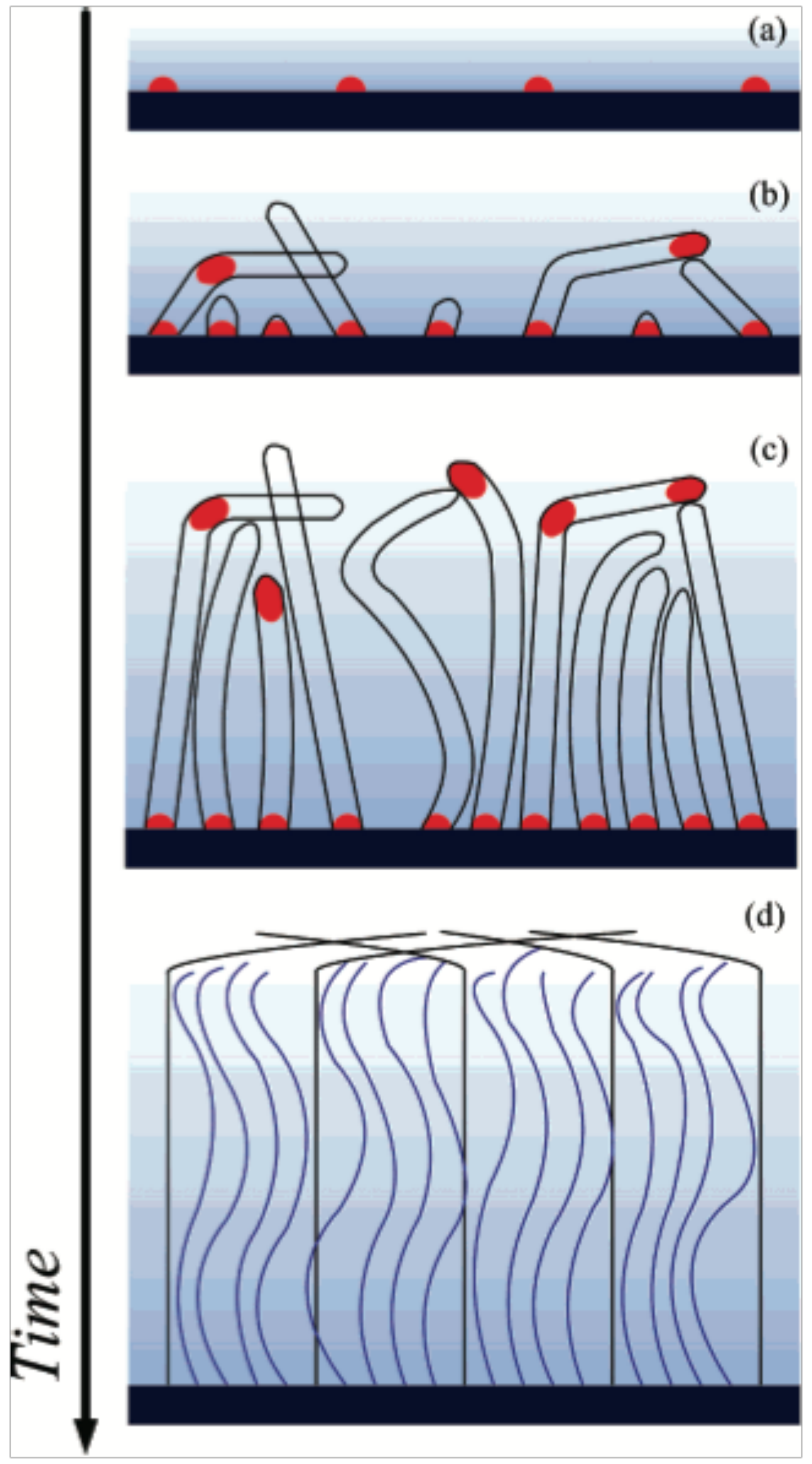
Nanoparticles function as catalyst seeds

New evaporation chamber @ TITAN Lab

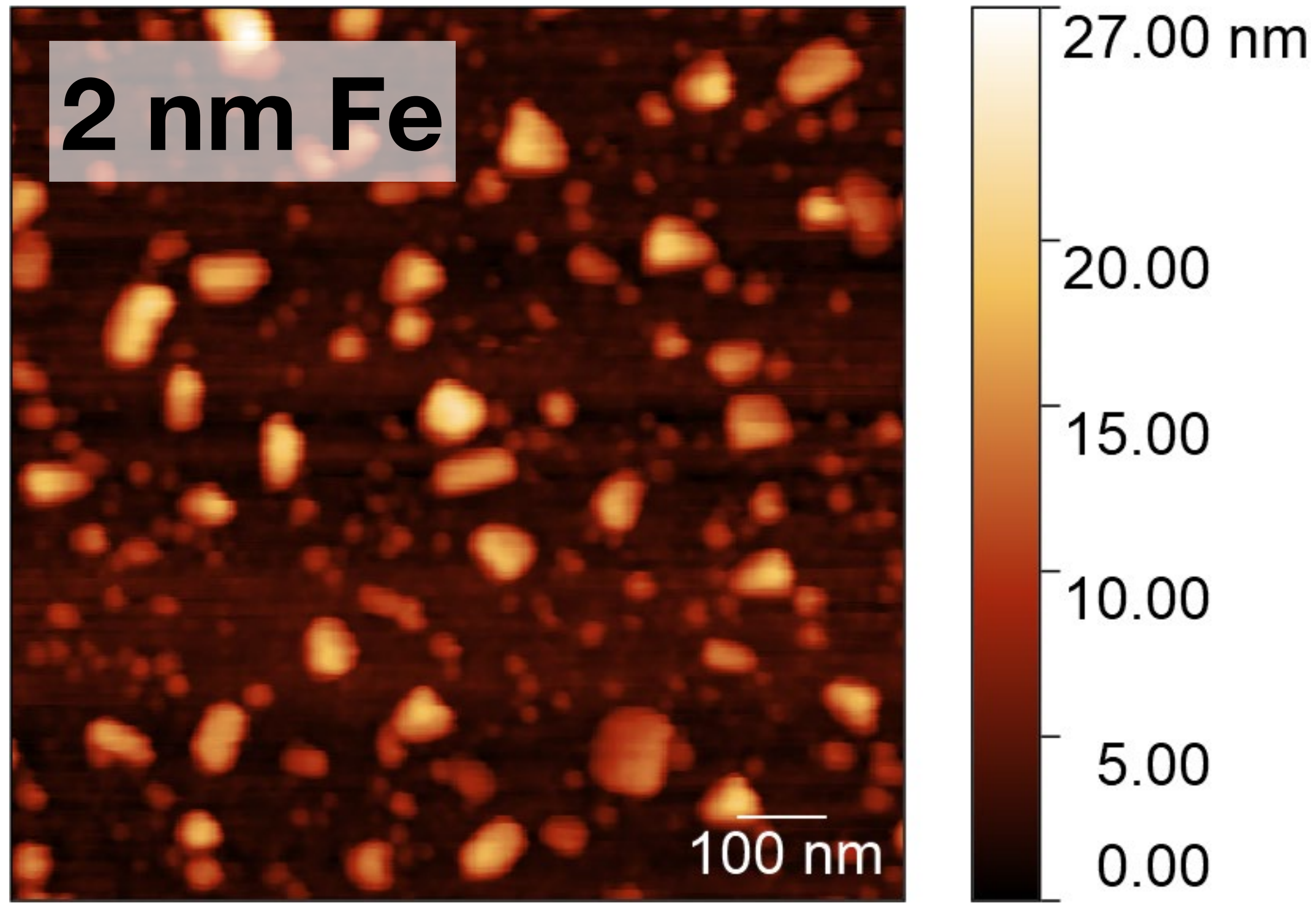


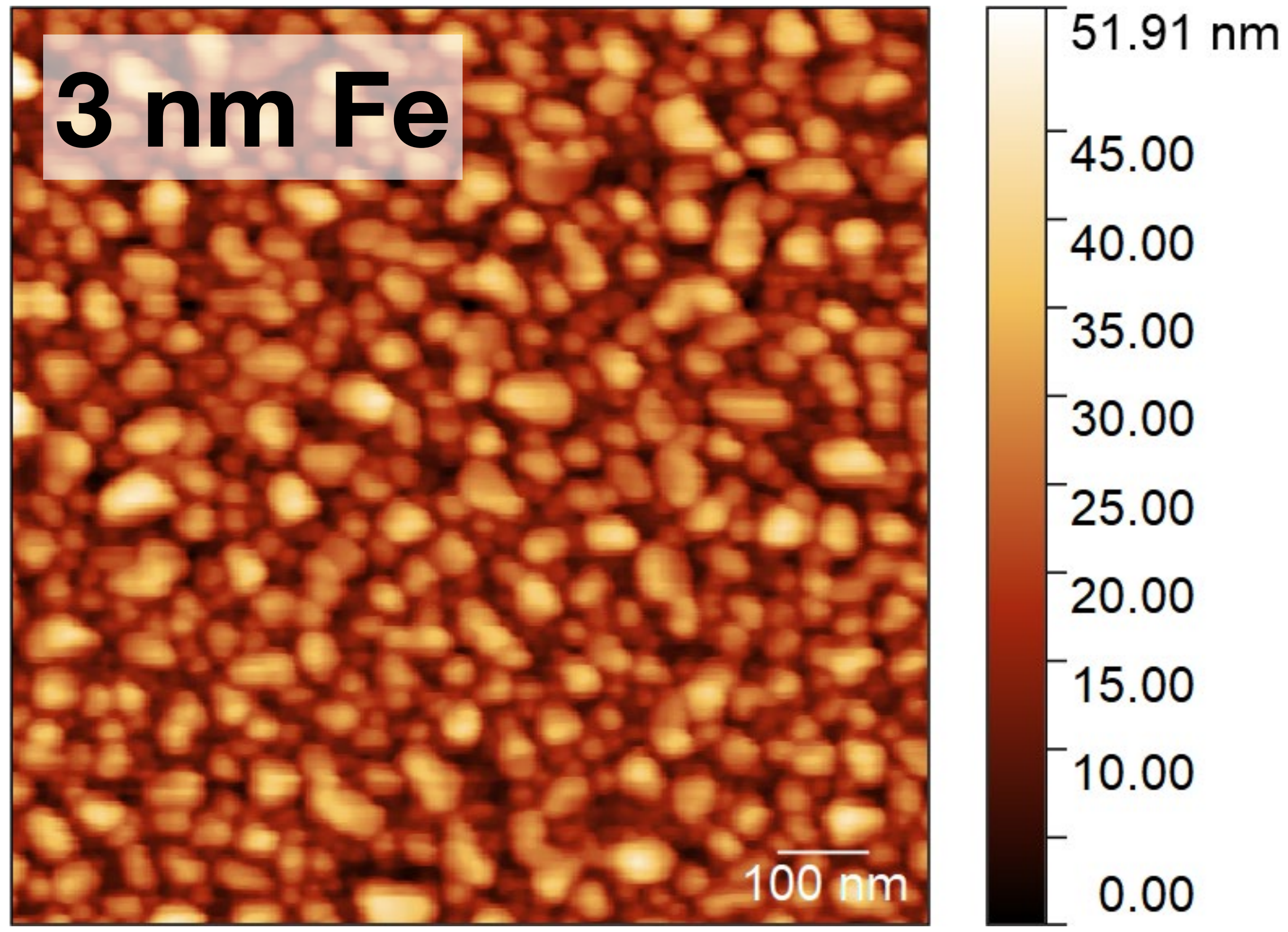
First successful evaporation on January 16th!

Optimizing Nanoparticles for Nanotube Straightness

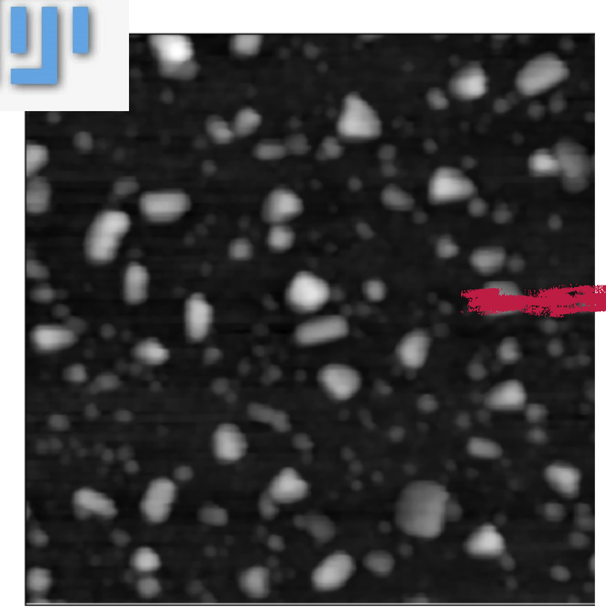


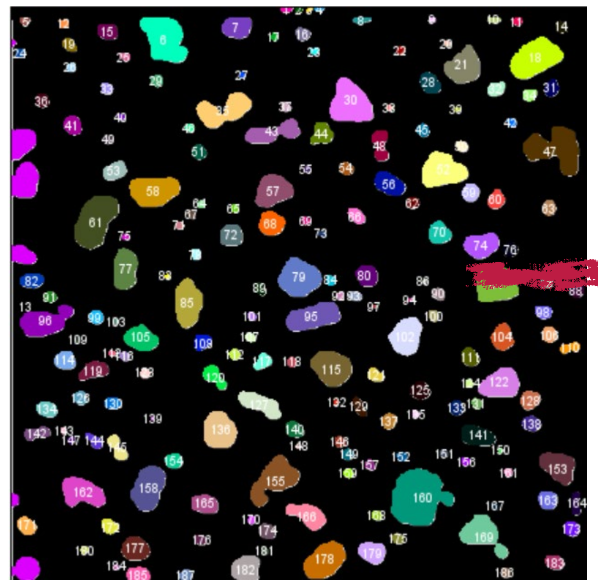
- Nanoparticle **size** and **uniformity** strongly influence nanotube **straightness**
  - Non-uniform seeds → **different** growth rates → **wavy** nanotubes
  - Nanoparticle size depends on evaporated nanofilm **thickness**
  - Studying nanoparticle size with atomic force microscope (AFM)

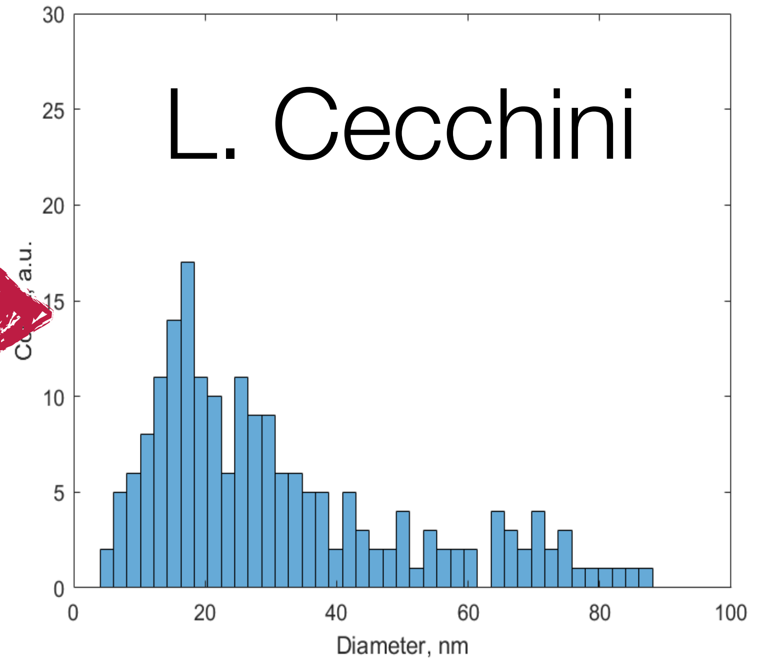




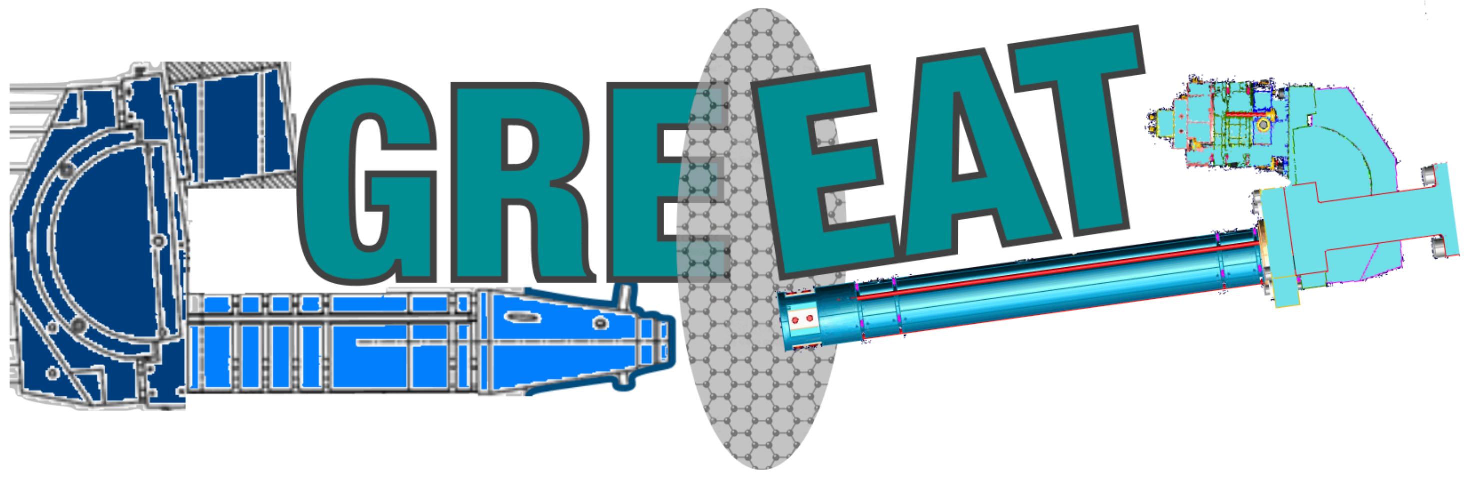
Quantitative image analysis with Fiji:





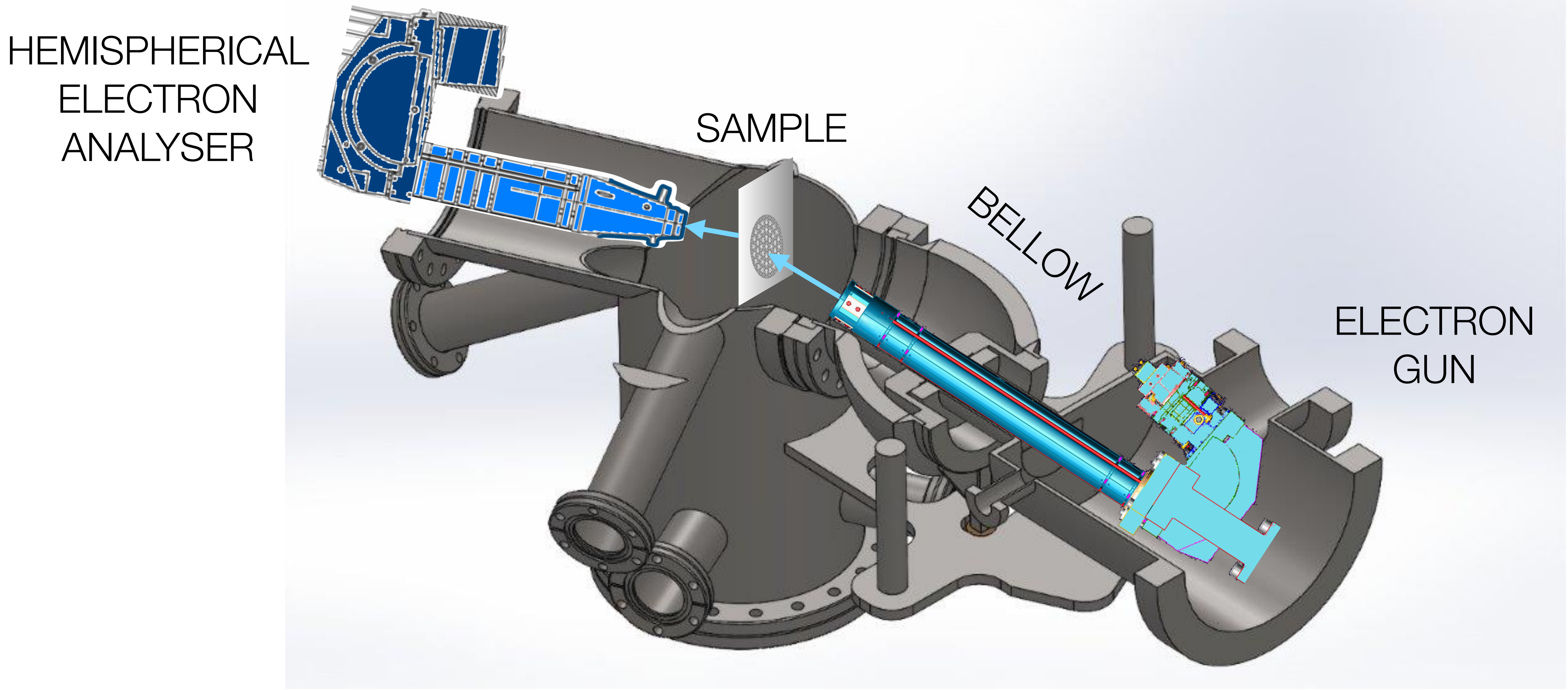


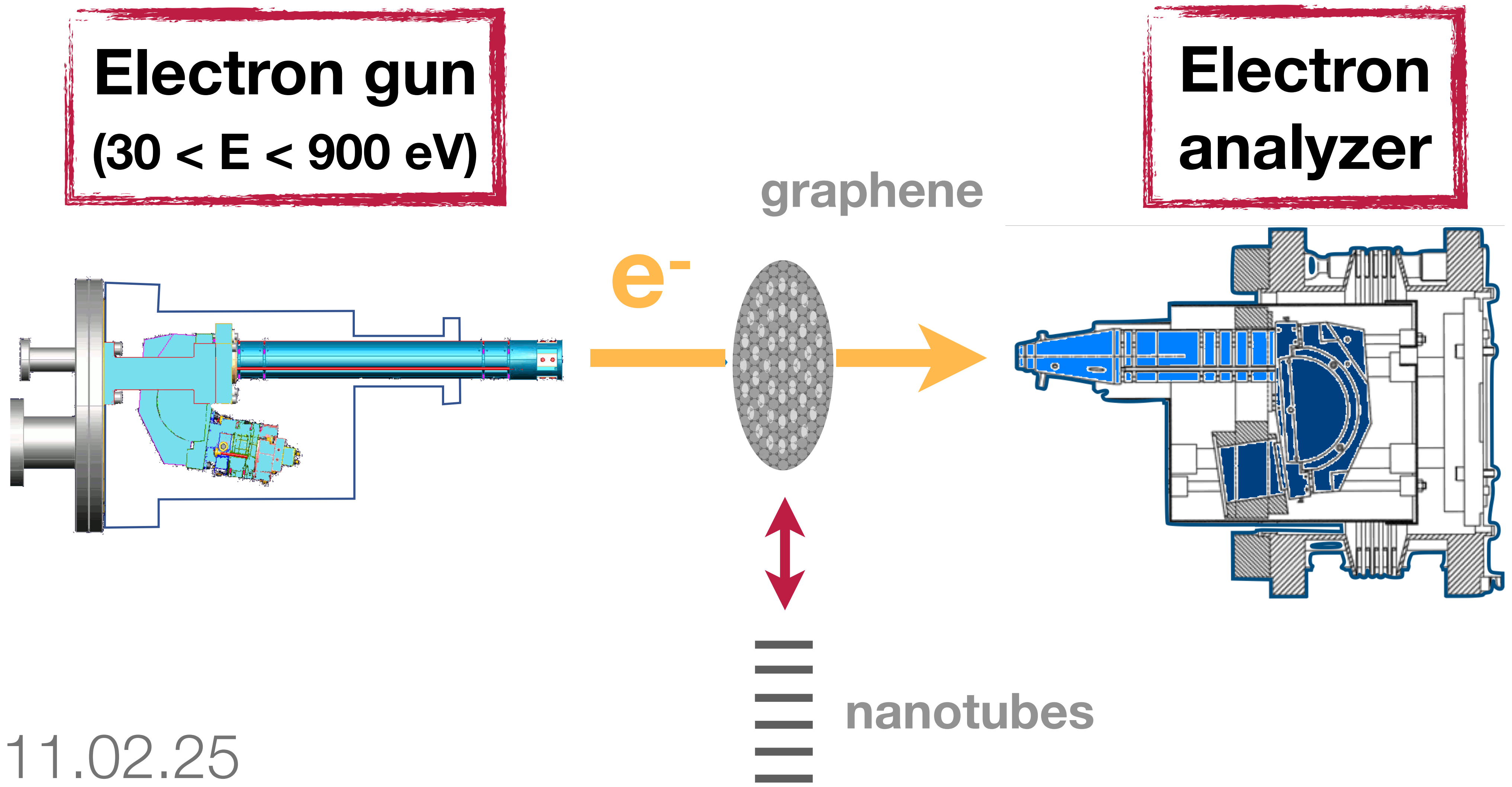
GREEAT Project Started in Roma Tre (P.I.: A. Apponi)



GRaphene to Electrons:
Energy and Angular resolved Transmission

- Young Researcher Grant CSN5 26724/2024
  - 145 k€ over 2 years (2025-26)
- **Aim**: measure interaction cross section of electrons through graphene
  - Will study also electron transmission in **nanotubes**

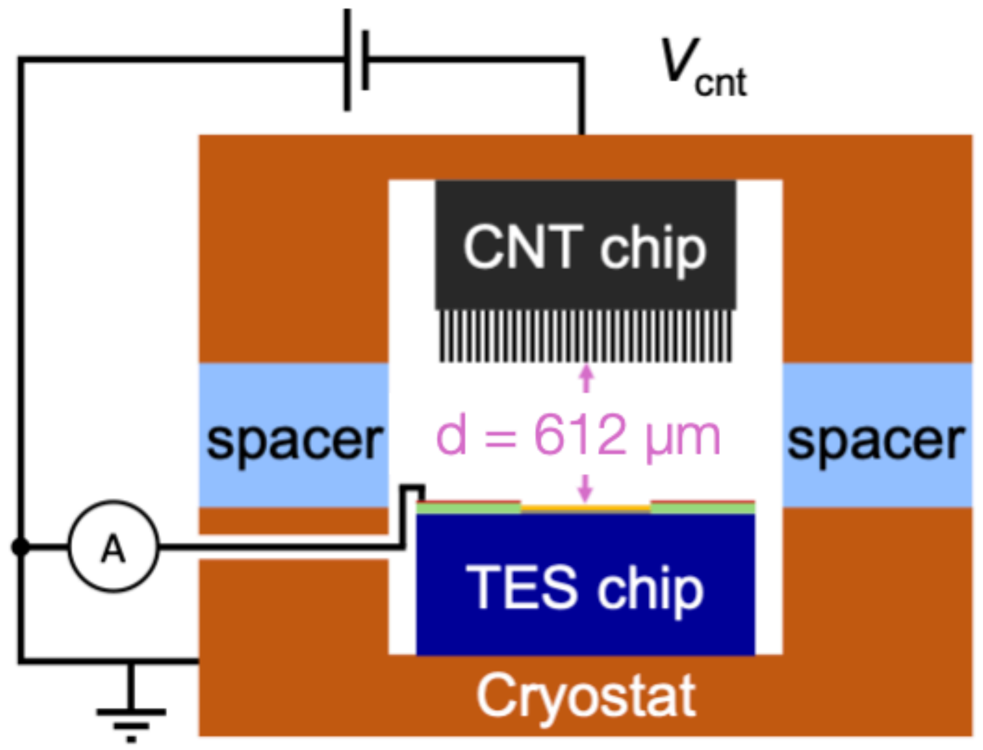


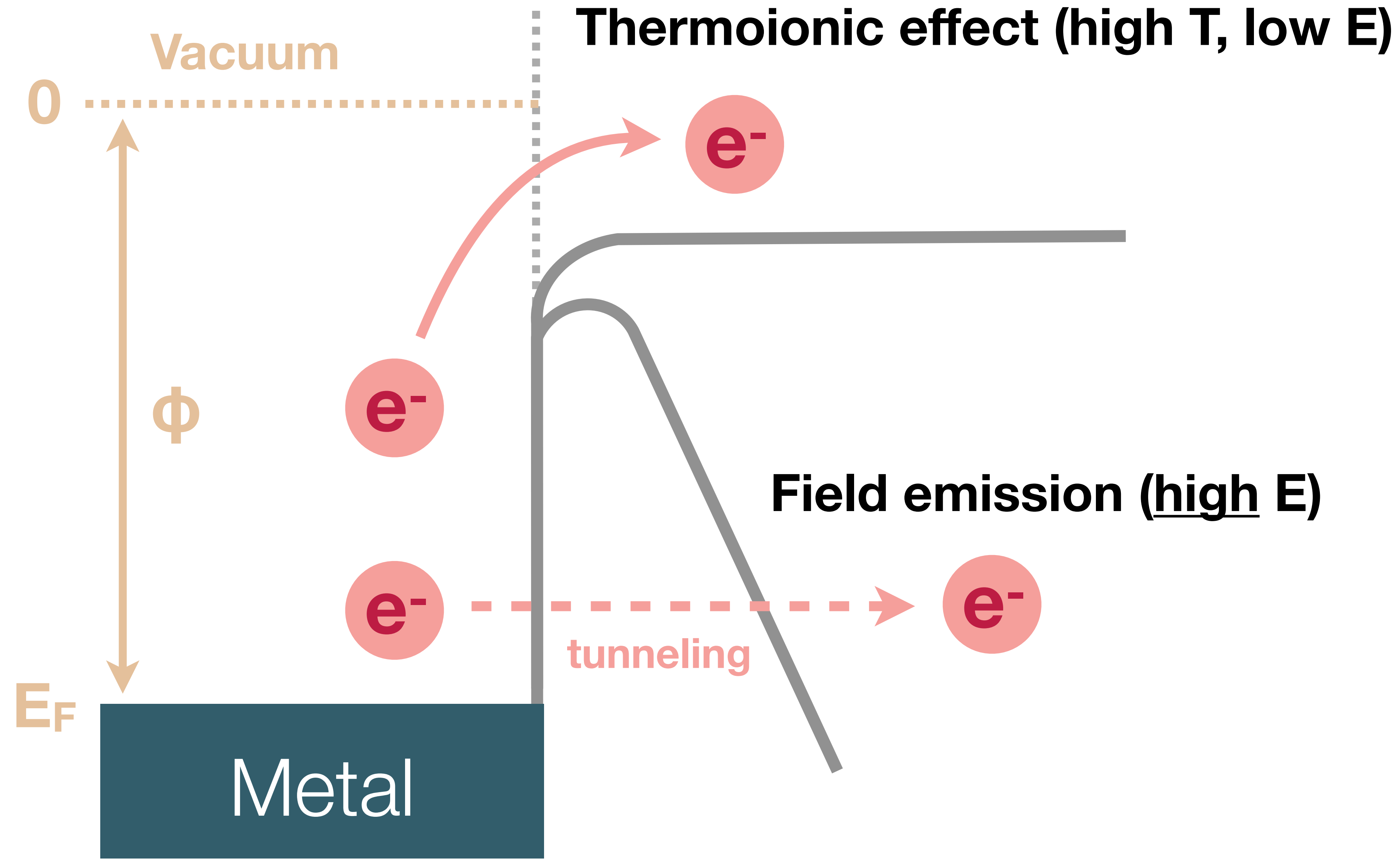


Nanotubes as Cryogenic Electron Source

Phys. Rev. Applied 22 (2024) L041007

- **Field emission** from nanotubes
  - Quantum effect: **no heating**
  - Local E field **amplified** (tip effect)

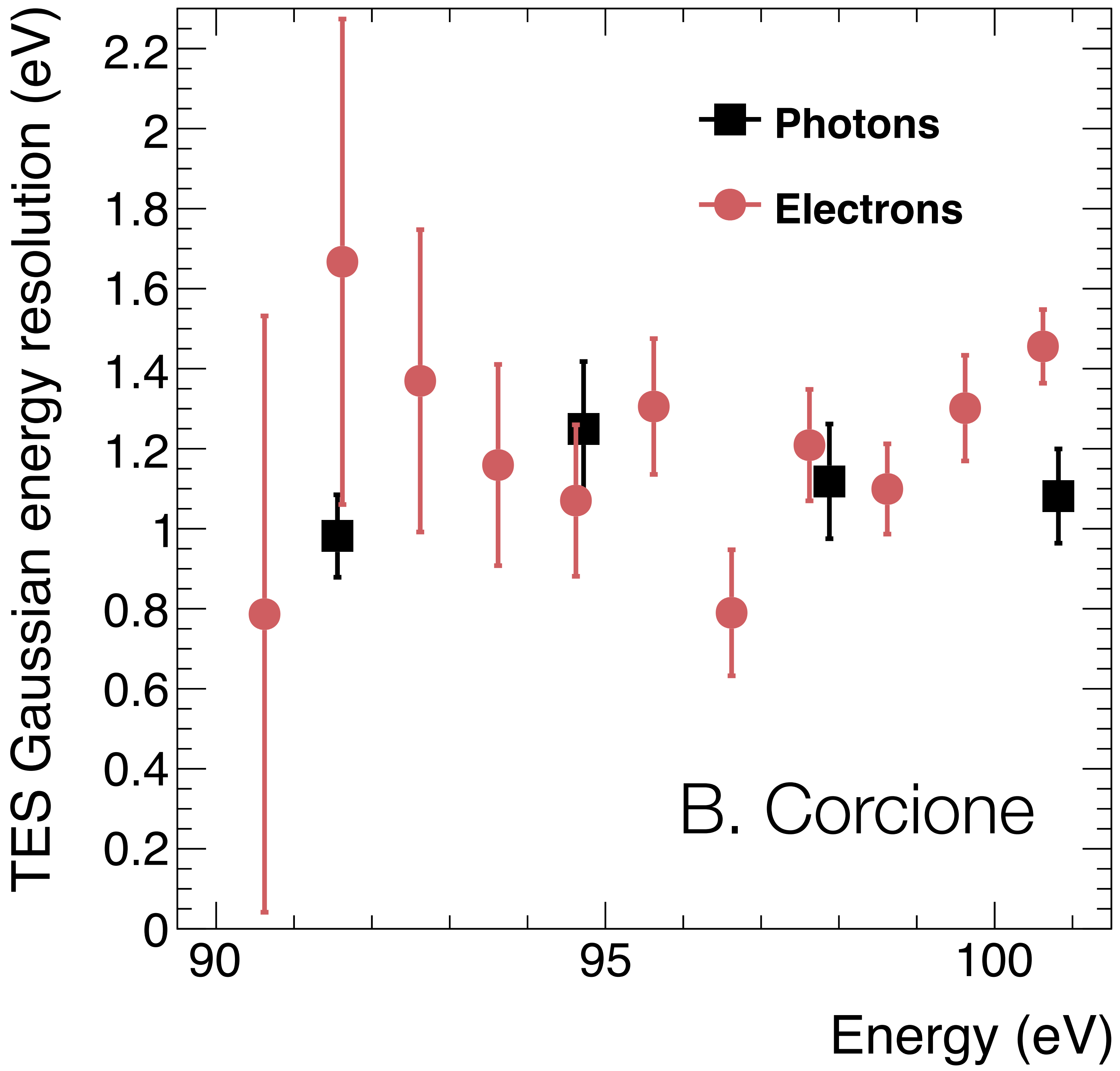




Nanotube chip installed in 30 mK plate of cryostat @ INRiM (Torino)

In context of PTOLEMY project

PTOLEMY



- Measured 100 eV e^- with TES detector!
  - $\sigma_e(E) \sim 1$ eV $= \sigma_\gamma(E)$

ANDROMEDA

Aligned Nanotube Detector for Research On MeV Darkmatter

ROMA TRE

UNIVERSITÀ DEGLI STUDI

PTOLEMY

Strong **in-department** synergies (SMART Lab, LOTUS...)

S. Tayyab, et al., Nanomaterials 14 (2024) 77

V. Ficca, et al., Adv. Func. Mat. 35 (2025) 2413308

TITAN LAB

TECHNOLOGY INNOVATION THROUGH ADVANCED NANOSTRUCTURES

INRiM

ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Dragon Copper

INFN Istituto Nazionale di Fisica Nucleare

Novel nanocomposite material
Copper reinforced with nanotubes

International patent deposited

Collaboration with Biologia

antibacterial and antifungal properties of nanotubes

Nanomaterials 13 (2023) 1081

Collaboration with Engineering

nanotubes to reinforce basalt and quartz fibers

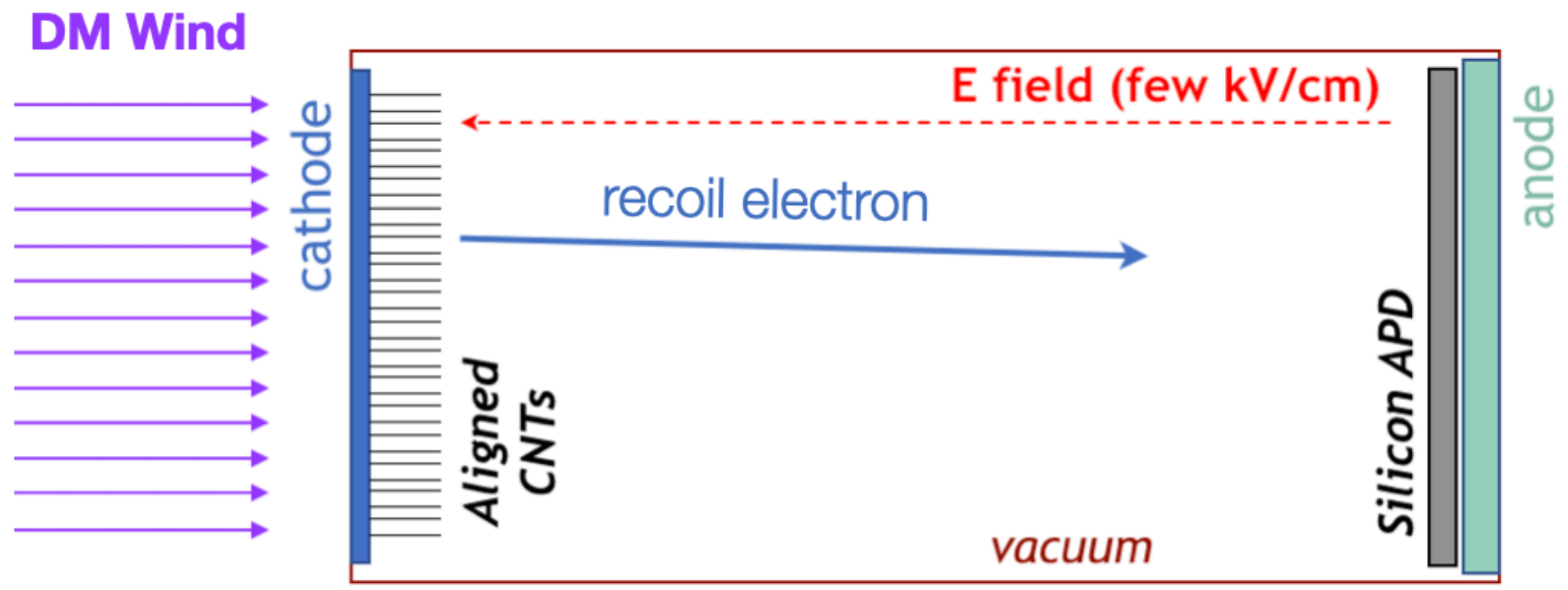
Comp. B 243 (2022) 110136

+ submitted to Comp. Part B

Conclusions

❖ **ANDROMeDa**: aiming to build light DM detector **Dark-PMT**

- DM-electron recoil inside aligned carbon **nanotube** target
- **Features**: portable, no thermal noise, directional sensitivity
- Need nanotubes with unprecedented **parallelism**



❖ **TITAN** @ Segre: state-of-the-art nanostructure lab

- Synthesis of high-quality **nanotubes**
- New evaporator chamber **operative**
- Many **synergies** and **collaborations**

TITAN LAB
TECHNOLOGY INNOVATION THROUGH ADVANCED NANOSTRUCTURES