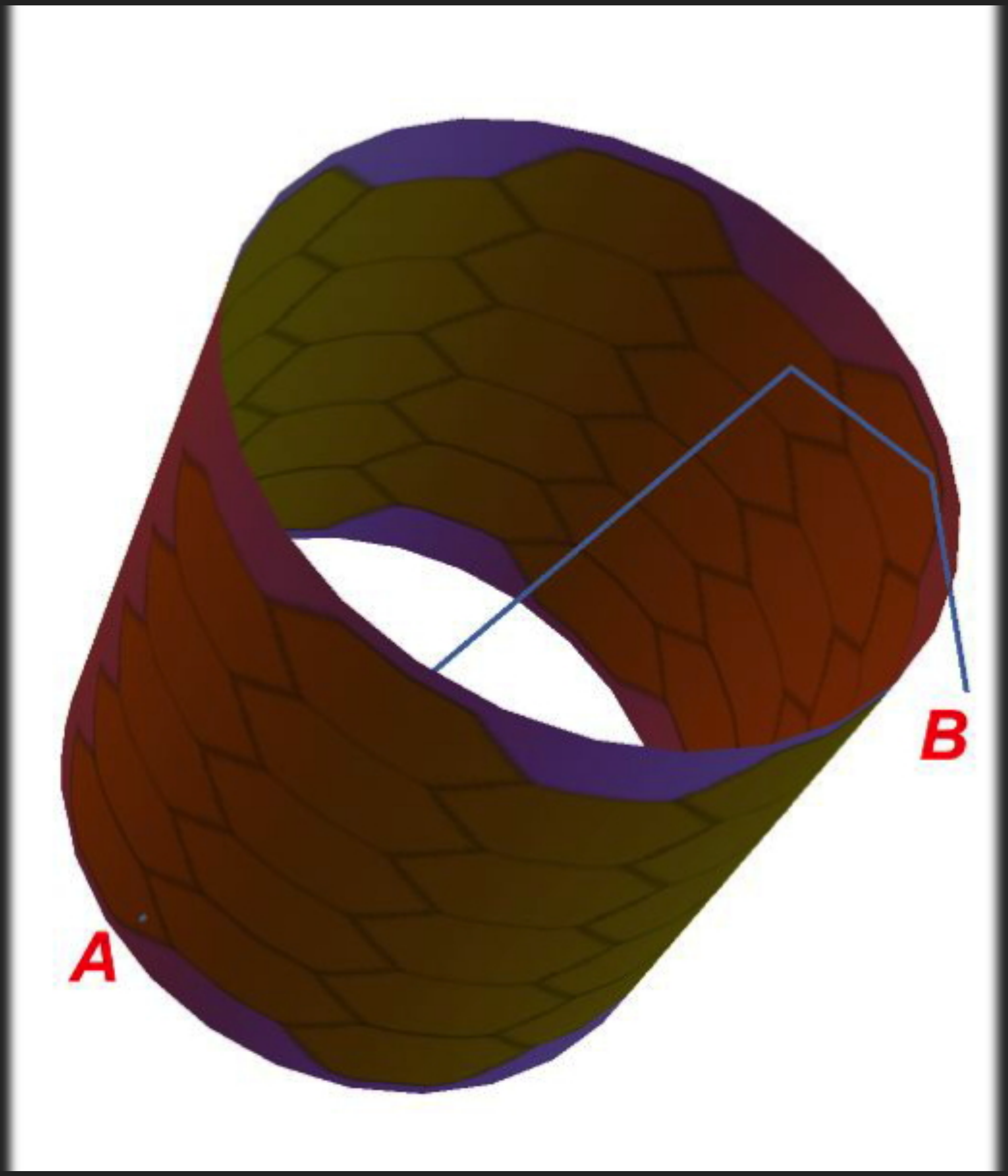
AD POLOSA, SAPIENZA UNIVERSITY OF ROME

CARBON NANOTUBES AND GRAPHENE AS DIRECTIONAL DETECTORS OF LIGHT DM

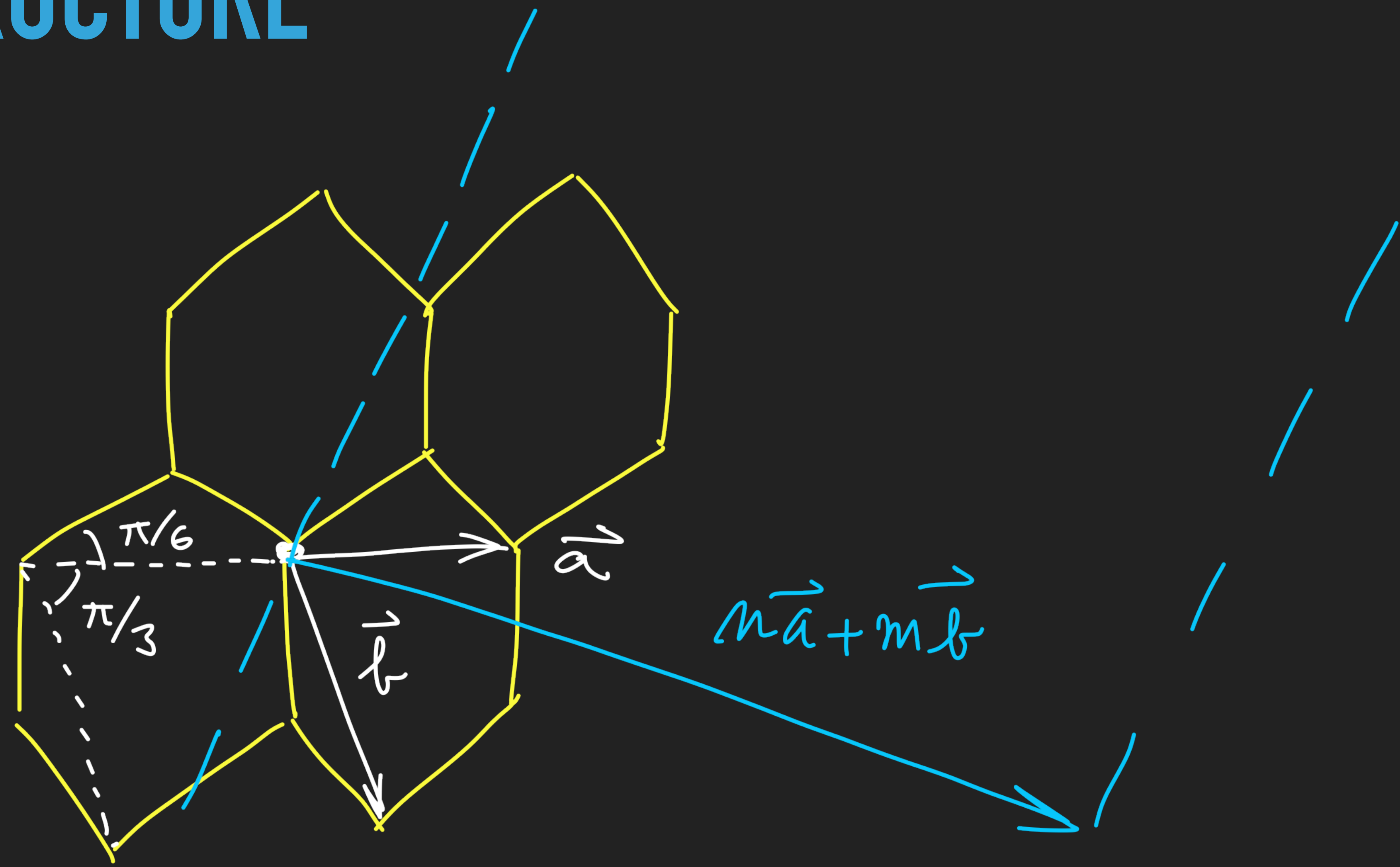
CNT AS IONS CHANNELS

- The surface of a single wall CNT can repel positive ions with very low transverse kinetic energy (< 300 eV)
- A *channeling* phenomenon could be at work if the colliding WIMP, with a mass ~10 GeV, is coaxial with the tube axis. The inner volume is void of electrons and much larger than typical channels in crystals.
- At 10 GeV the neutrino floor is higher and a directional detector would be particularly useful in that region.



Capparelli et al. Phys. Dark Univ. 9-10 (2015) 24, ibid. Phys. Dark Univ. 11 (2016) 79;
Cavoto et al. Eur. Phys. J. C76 (2016) 349;

CNT STRUCTURE



ℓ (bond length) $\cong 0.14$ nm

$|\vec{a}| = |\vec{b}| = \ell\sqrt{3}$

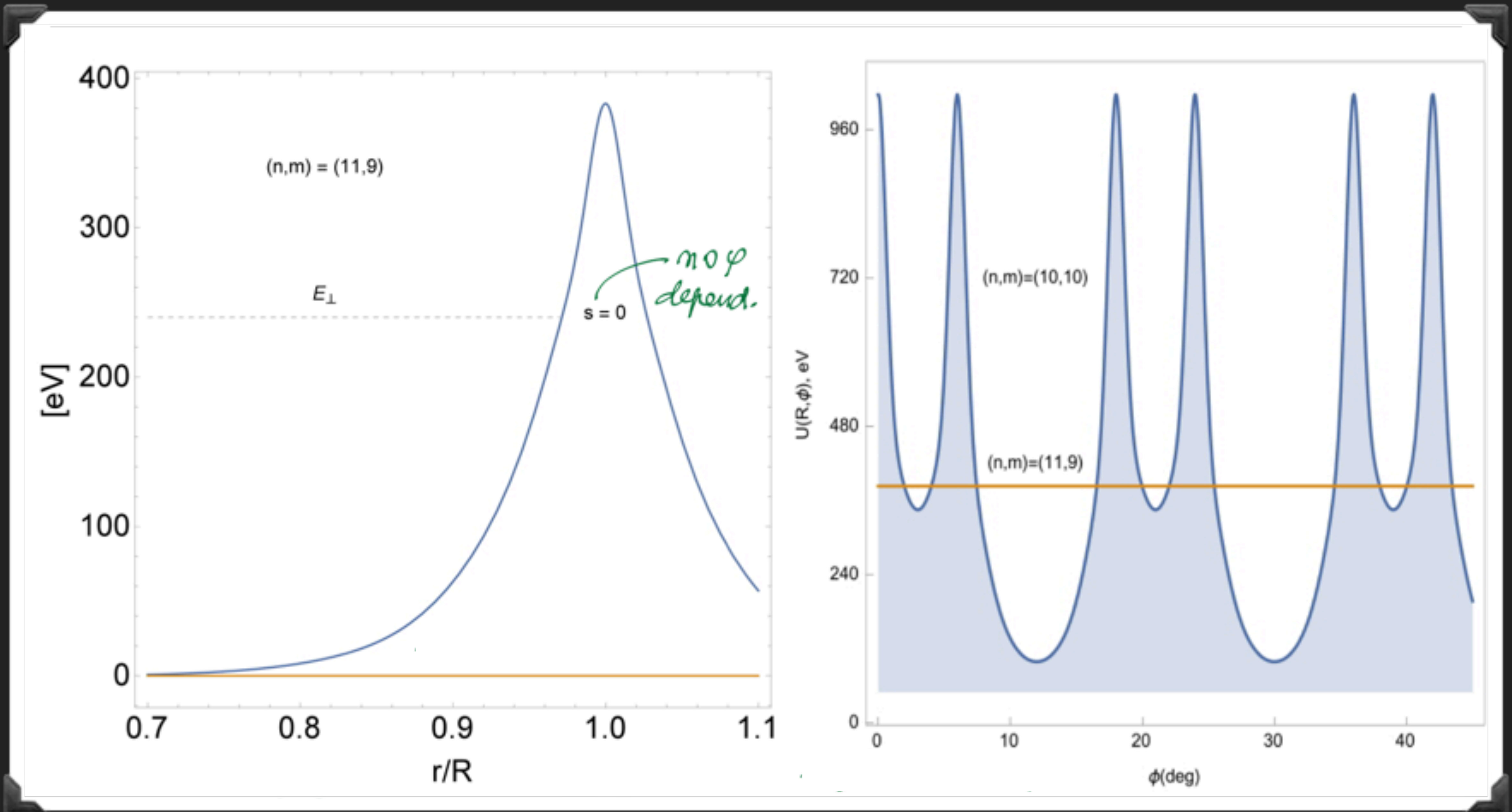
$$R_{CNT} = \ell\sqrt{3(n^2+nm+m^2)}$$

(n,n) METALLIC

(n,m) w/ n−m multiple of 3
SEMICOND.

(n,0) ZIG-ZAG HYBRID

SURFACE POTENTIAL FOR A POSITIVE ION

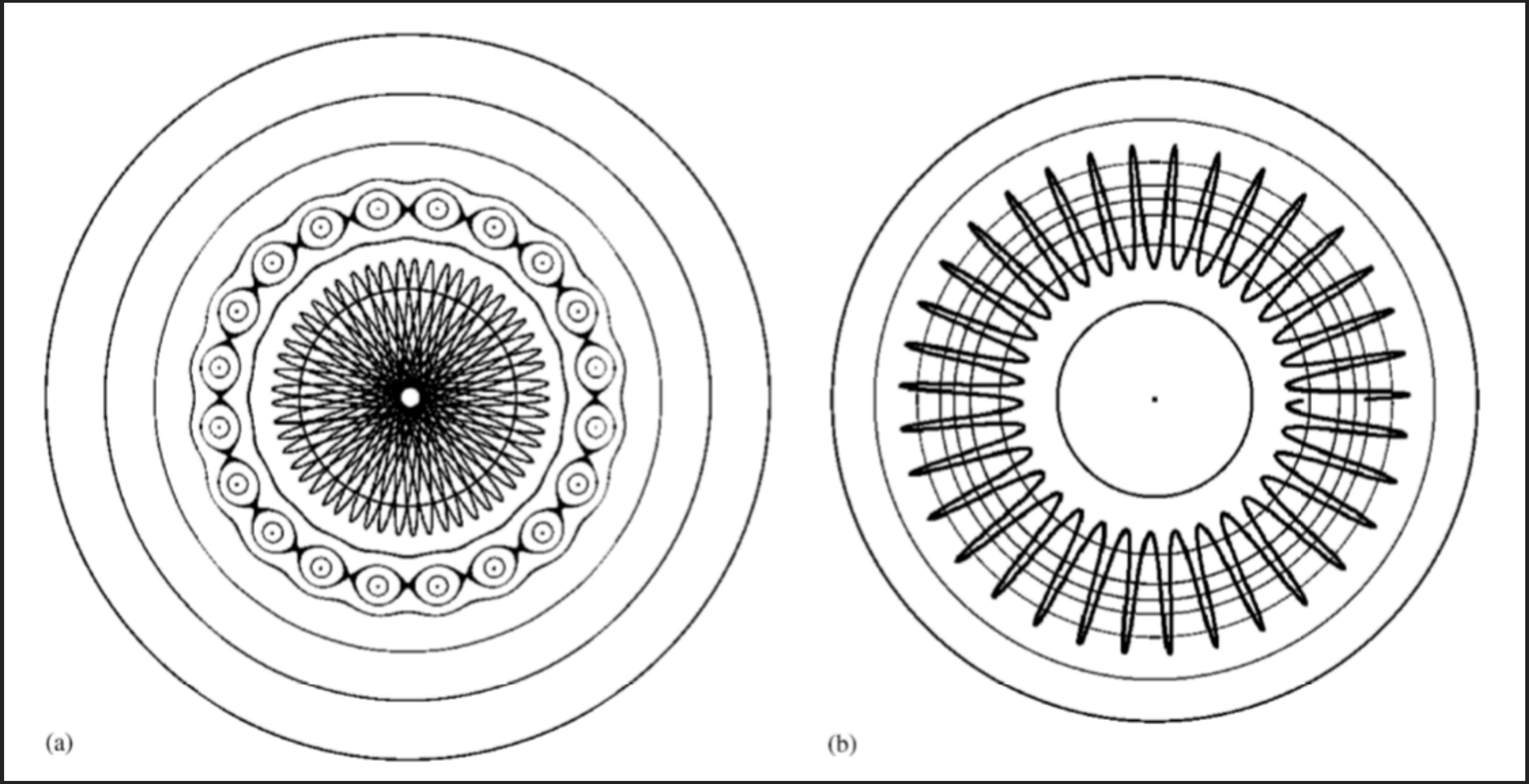


For a C^{6+}

The extraction price of a C atom is less than 20 eV. Making a C^{4+} costs extra ~ 147 eV. Similarly C^{5+} costs extra ~ 539 eV and C^{6+} ~ 1024 eV. $T_{N\ recoil}$ ~ O(1) keV.

Artru et al. Phys. Repts. 412 (2005) 89

SURFACE POTENTIAL FOR A POSITIVE ION

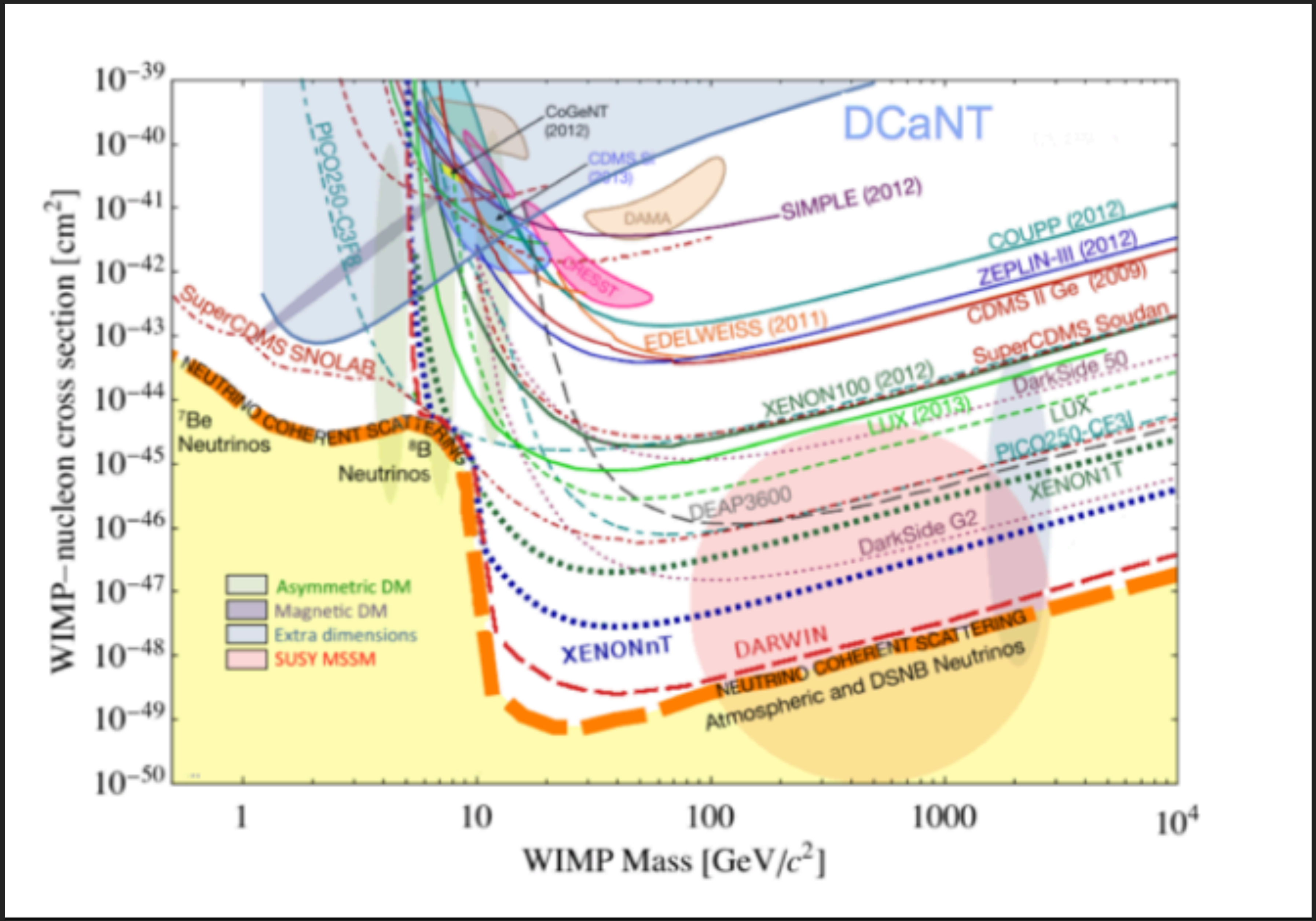


Typical *transverse* trajectories of *channeled* positive (a) and negatively (b) charged particles in an axially symmetric nanotube field (*L* integral of motion).
Positive particles are processing around the *tube axis* while moving longitudinally. Negative particles *nutate near the nanotube surface*. Frequencies of radial oscillations and nutations can be estimated in simplified conditions (potentials). Otherwise dynamic chaos conditions set in.

Artru et al. Phys. Repts. 412 (2005) 89

SENSITIVITY

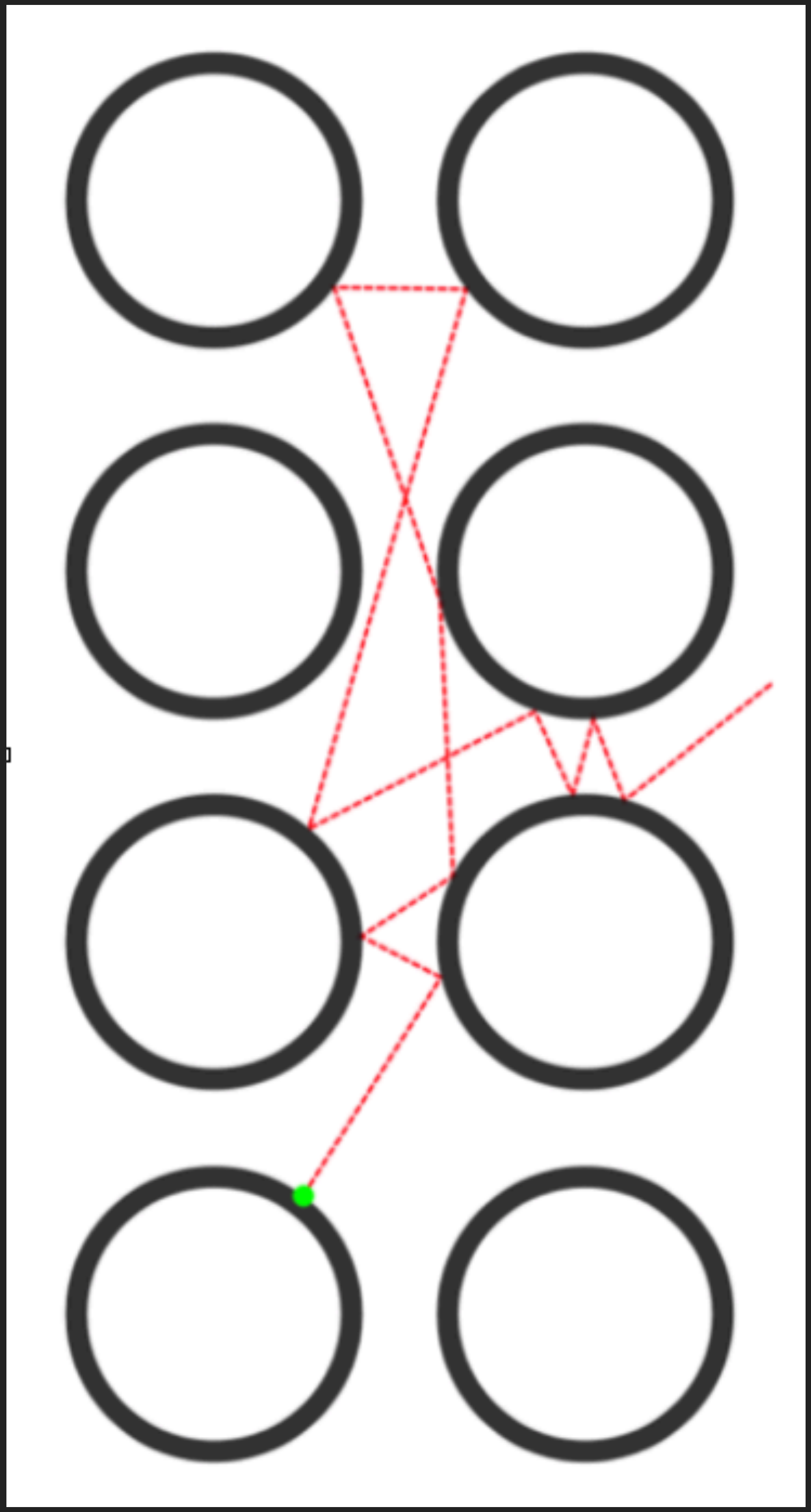
Directionality gives a better control on backgounds.

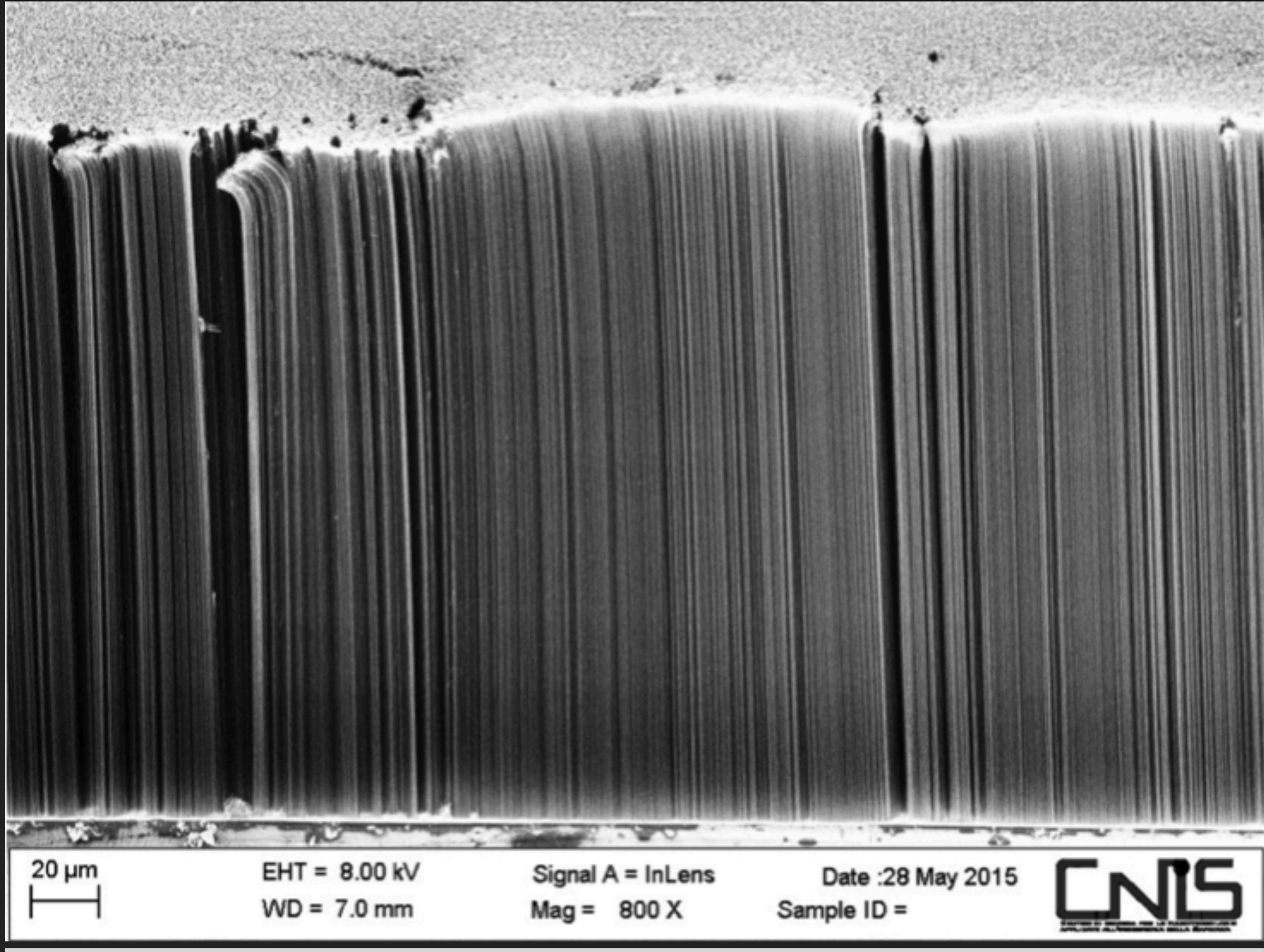


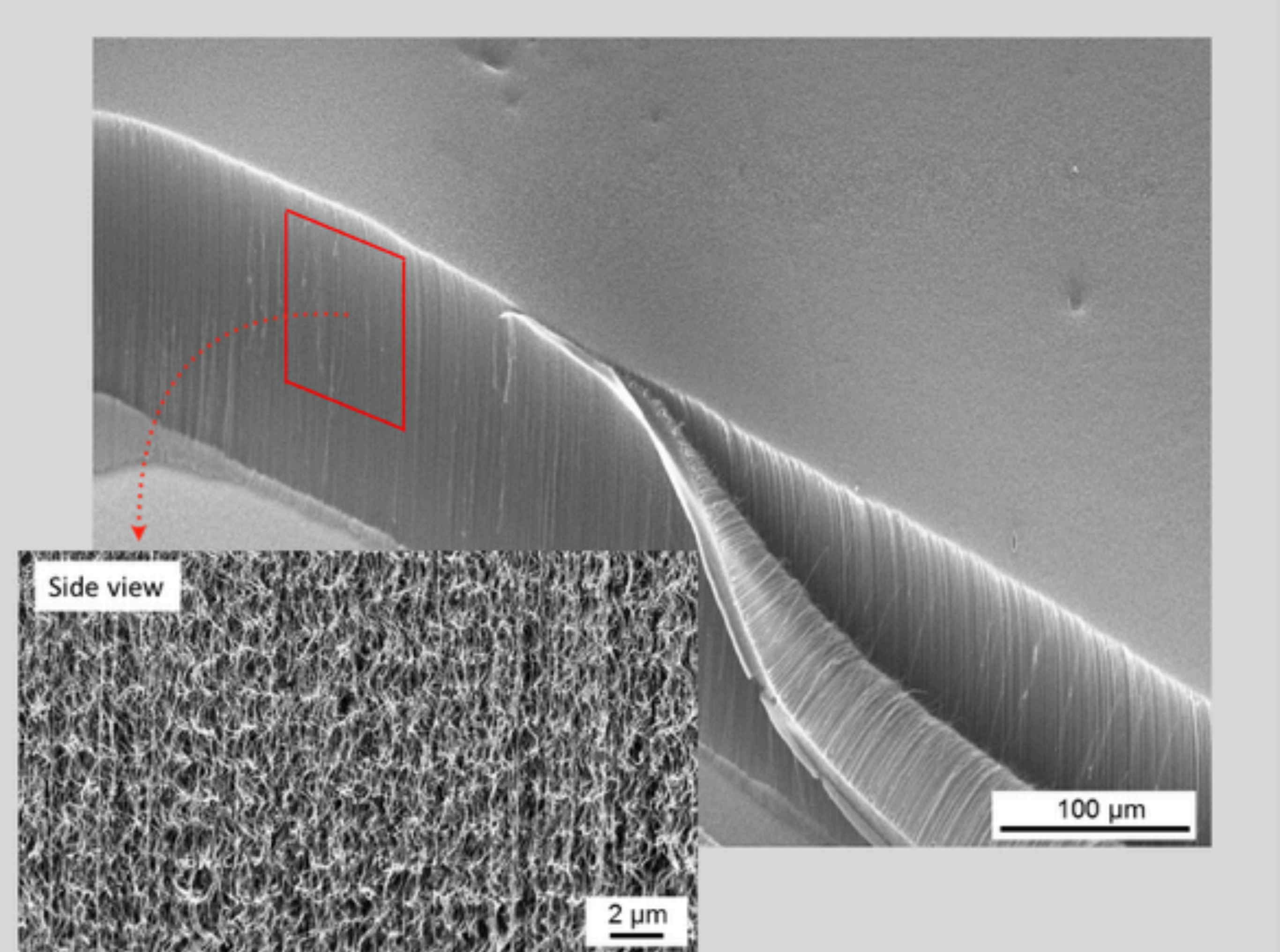
Exposure 0.4 * Kg * 1 year – output ions @ 1 keV

Capparelli et al. Phys. Dark Univ. 9-10 (2015) 24, ibid. Phys. Dark Univ. 11 (2016) 79;

INTERSTICES



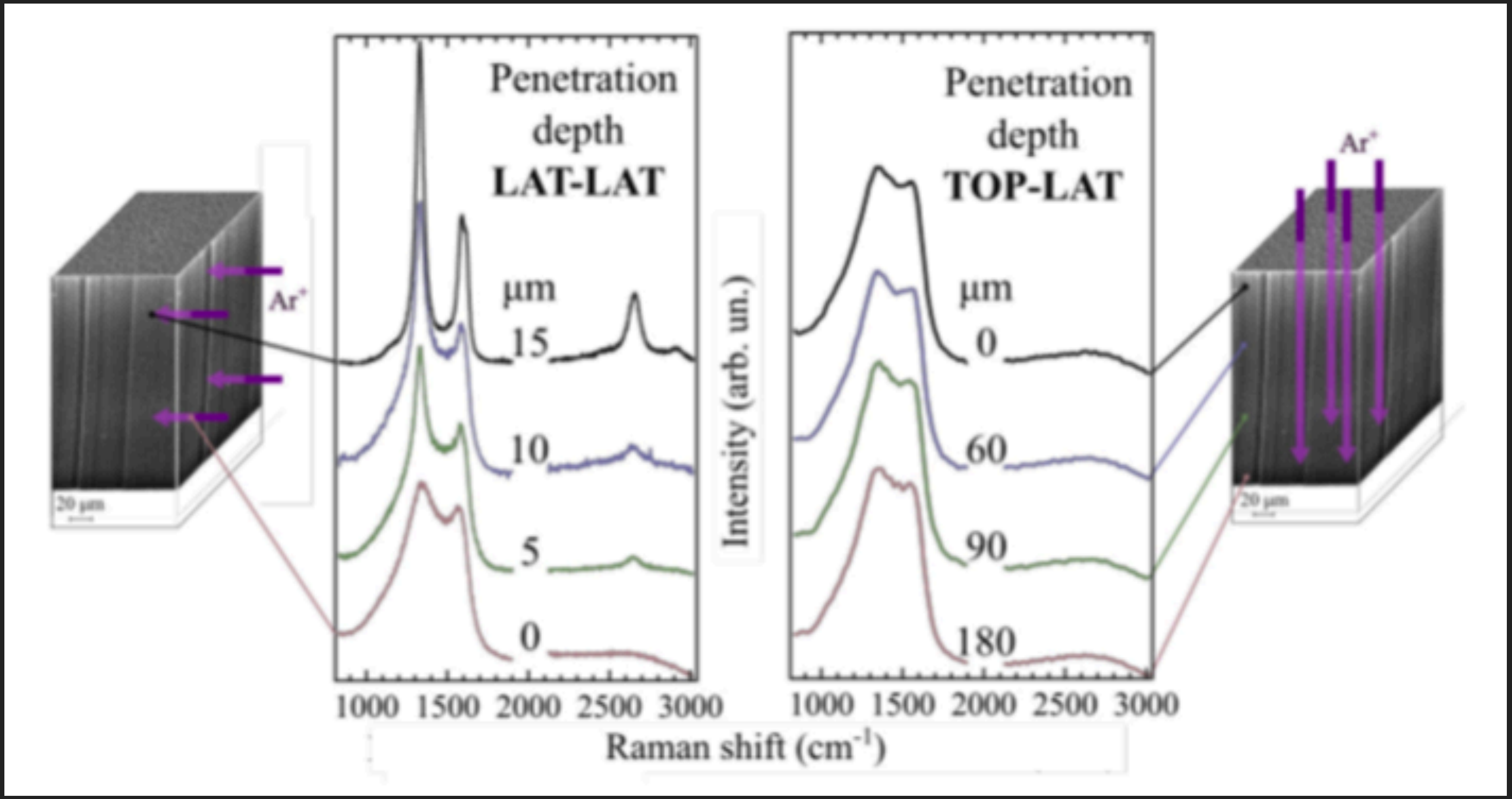




Cavoto et al. Eur. Phys. J. B776 (2018) 338
Interstices are more important than tubes.

BOMBARDMENT OF MWCNT WITH AR IONS

The CNT forest appears 'opaque' to ions if bombarded from the side and very 'porous' if bombarded from the top.



Bombardment of MWCNT with 5 keV Ar^+ and 1.5 x 10^{17} ions/cm^2

(LAT) The damage due to bombardment is arrested at about 15 *10^{-6} m where the Raman spectrum of the pristine smaple is found again. (TOP) Partial 'amorphization' from top to bottom.

D'Acunto et al. Carbon 139 (2018) 768-775

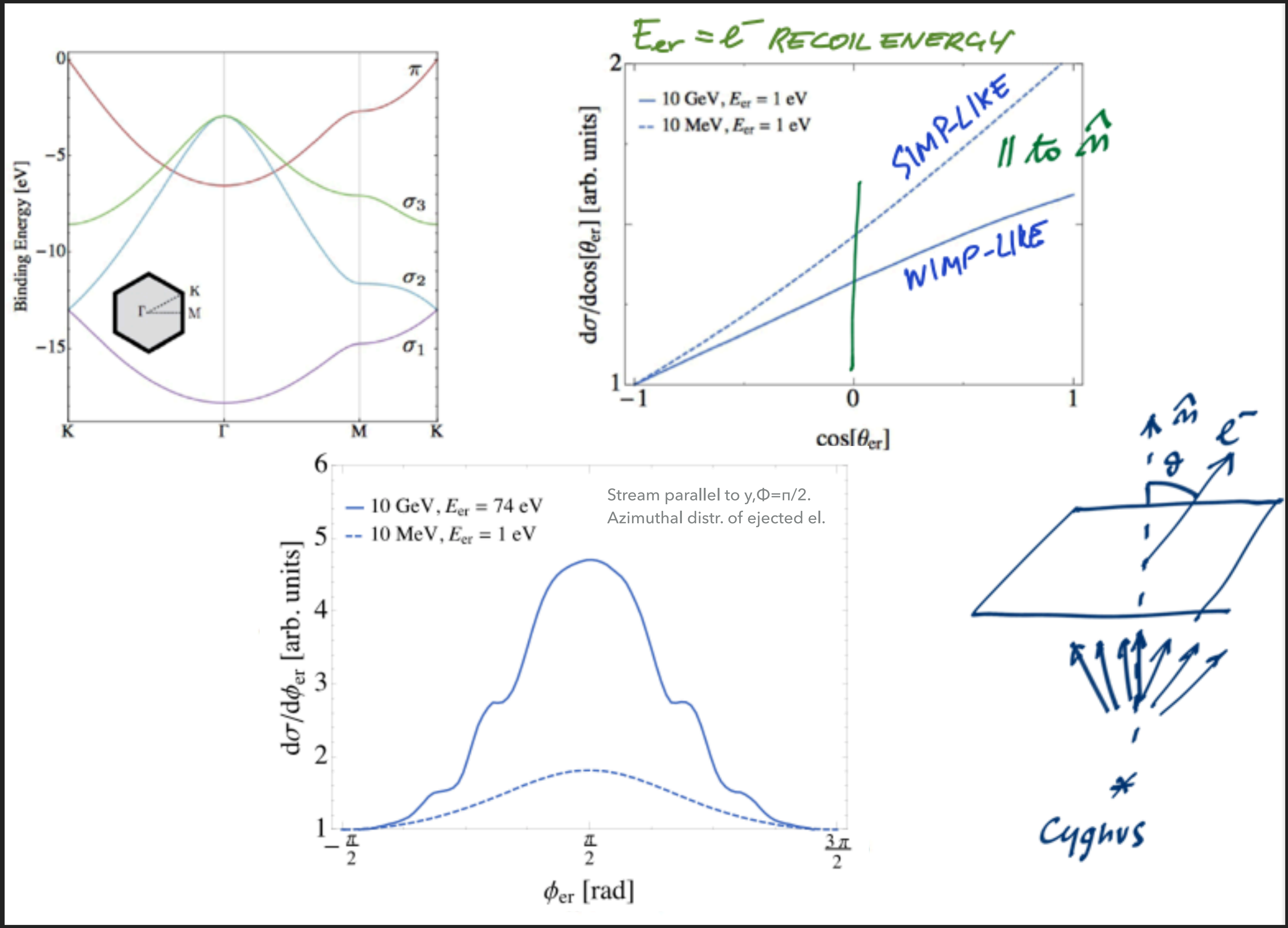
RAMAN SPECTROSCOPY OF CNTS

- Visible laser light shined on CNTs carries an electric field E_{ext} which locally induces a dipole momentum in the material through the polarizability (tensor) α. The material shines back light.
- The spectrum of back-scattered light has a central "elastic" peak, which is filtered, and two side-bands *shifted* by ~$\omega_{vibr.}$ The most intense one gets analyzed.
- Pristine nanotubes show a marked peak (absent in graphene) in the sideband, which is found to be gradually attenuated upon the passage of Ar^{+} ions. The second peak in intensity is related to the exagon 'breathing' modes.
- Different depths are reached using "confocal microscopy" techniques – the back scattered light will be less and less intense, but this did not prevent to reach the conclusions stated above.
- LAT–TOP. e.g., means bombarded from the side – Raman analyzed from the side, etc.

(P. Postorino and collabs.)

D'Acunto et al. Carbon 139 (2018) 768-775

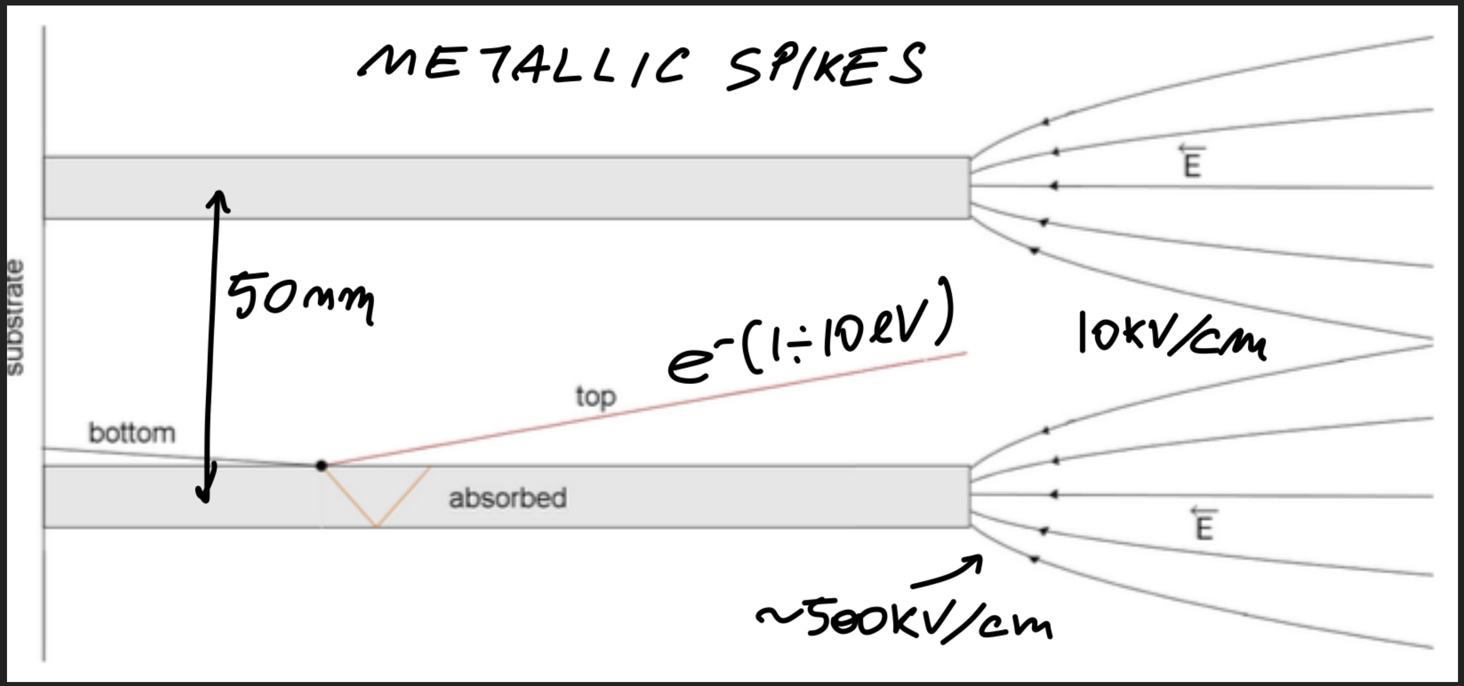
GRAPHENE: FROM IONS TO ELECTRONS



Hochberg, Kahn, Lisanti, Tully, Zurek Phys. Lett. B772 (2017) 239

ELECTRONS FROM CNTS

Look at the space among CNTs and at very low energy electrons from MeV DM.
Consider CNTs as metallic spikes – conducivity 6 orders of magnitude higher than copper.



$$j(\mu A) \simeq 7.5\frac{E}{\phi^{1/2}}\exp\left(-6.83\frac{\phi^{3/2}}{E}\right)\coth\left(5.6\frac{\phi^{1/2}}{2ER}\right) \approx \exp(-10^3)\ \mu A\ \text{(with } E \sim 500\ \text{kV/cm)}$$

Thanks to the the high work function (~4 eV) in nanotubes of radius R

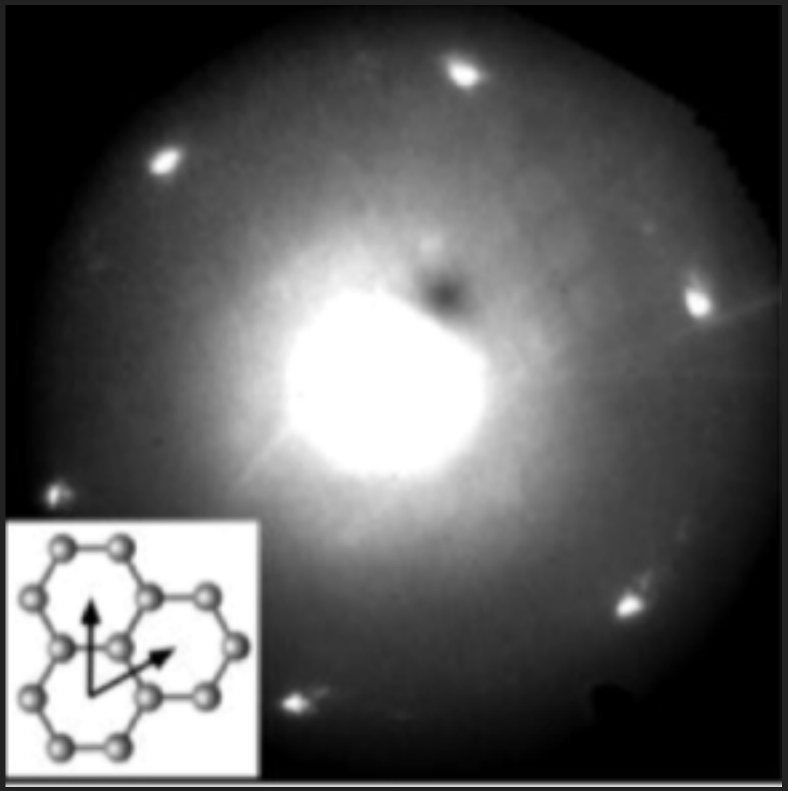
Cavoto, Luchetta, ADP Phys. Lett. B776 (2018) 338
S-D. Liang and L. Chen, Phys Rev. Lett. 101 (2008) 027602

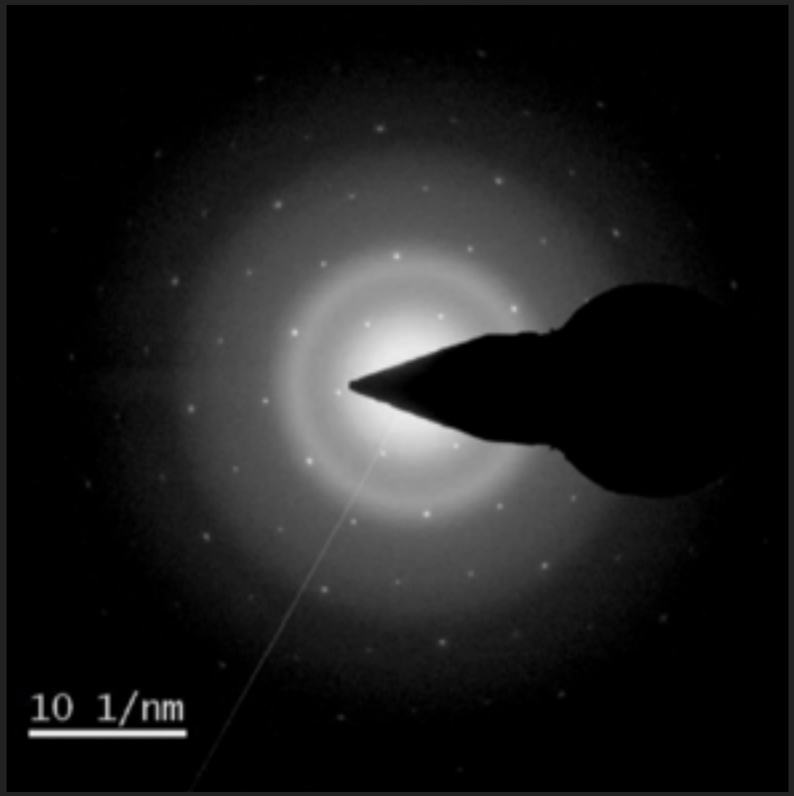
TRANSMISSION OF LOW ENERGY ELECTRONS FROM GRAPHENE

Low energy electrons (1–10 eV) produce a diffraction pattern with the largest intensity in the fwd peak. Secondary maxima are are at angles ϑ

$$\sin\theta/2 = \frac{\lambda}{3\ell}(m_1^2 + m_2^2 + m_1 m_2)^{1/2}$$

$$\ell = 0.14 \text{ nm}, \quad \text{T} \sim 5 \text{ eV}, \quad \lambda = \frac{\text{h}}{\text{p}} \simeq \frac{4\times10^{-15} \text{ eV sec}}{2236 \text{ eV/c}} = 5.3 \text{ Å}, \quad \frac{\lambda}{3\ell} \approx 1.3$$

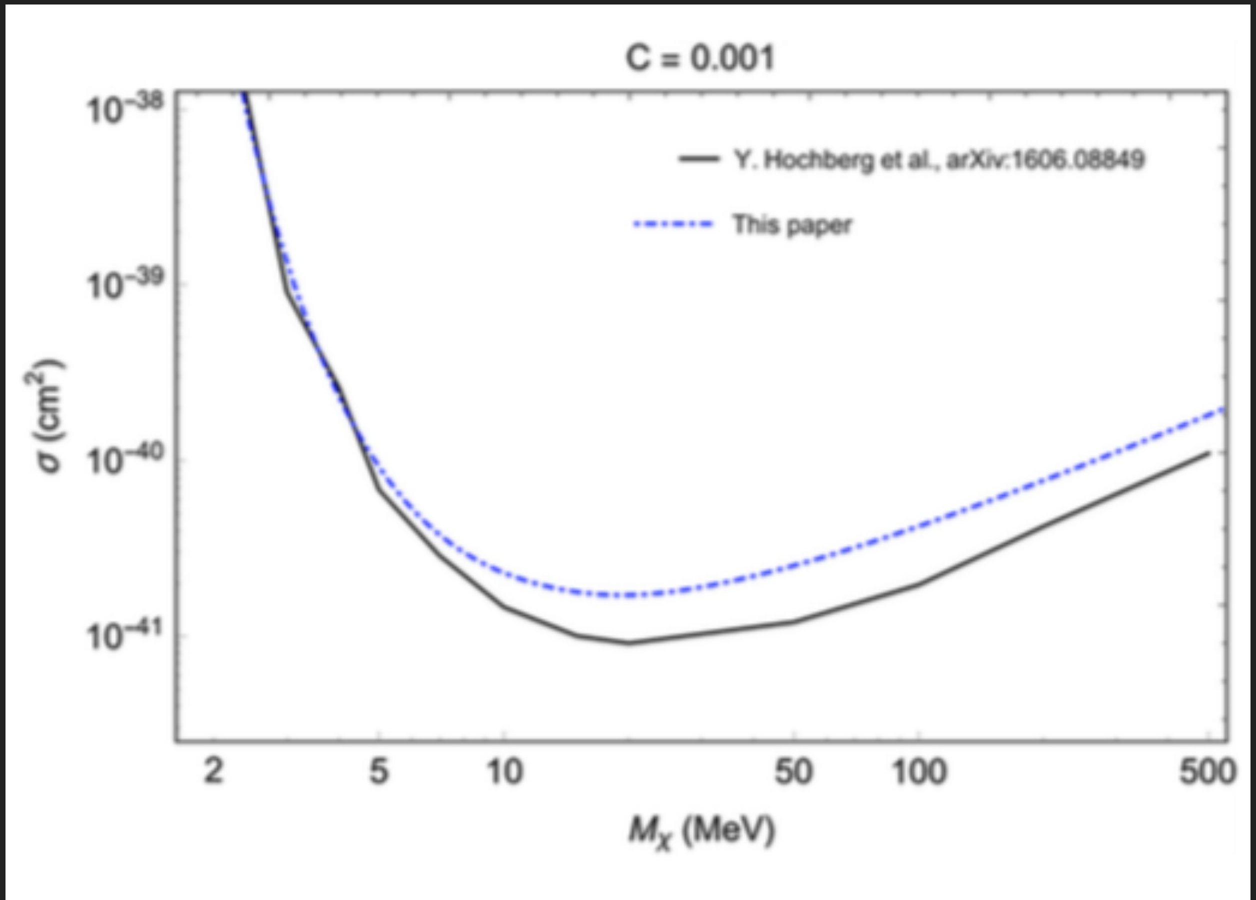




Muller et al. Nature Comm. 5 (2014) 5292

ELECTRONS FROM CNTS

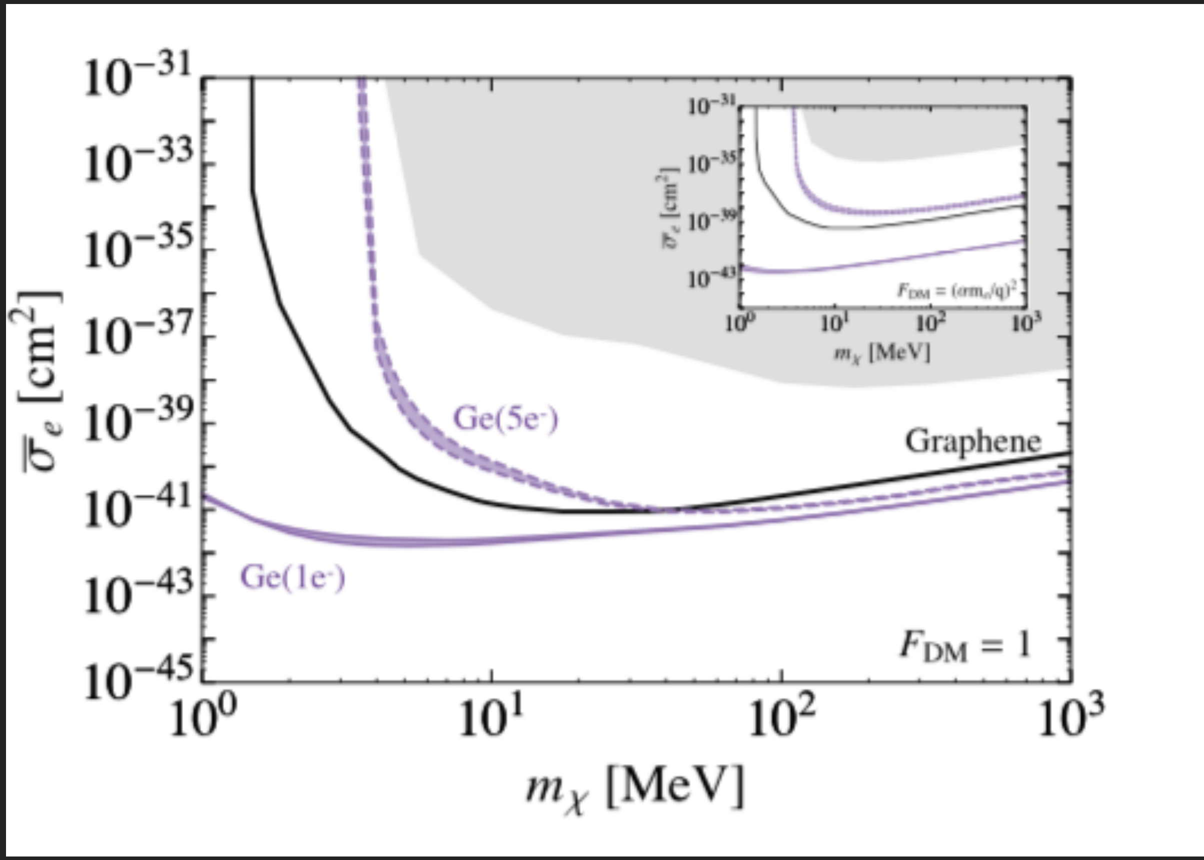
- The exclusion plot is made including both electrons from *sp*² orbitals and π, the more sensitive to lighter dark matter hits.
- This also depends on the absorption coefficient (C=1-T-R~10^{-3}). The exclusion line will shift upwards for higher values of C.
- Exposure: 1kg x Year



Cavoto, Luchetta, ADP, Phys. Lett. B776 (2018) 338

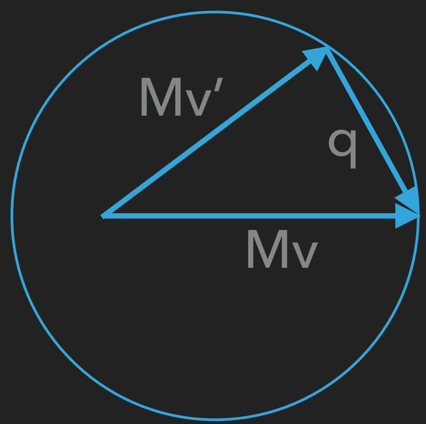
ELECTRONS FROM CNTS

- The exclusion plot is made including both electrons from *sp*^{2} orbitals and π, the more sensitive to lighter dark matter hits.
- The inset is made considering a light mediator exchange in addition to the heavy mediator.
- Esposure: 1kg x Year for graphene black curve.



Hochberg, Kahn, Lisanti, Tully, Zurek Phys. Lett. B772 (2017) 239
Lee, Lisanti, Mishra-Sharma, Safdi, Phys. Rev. D92 (8) (2015) 083517
Essig, Volansky, Yu, arXiv:1703.00910

ELECTRONS FROM CNTS



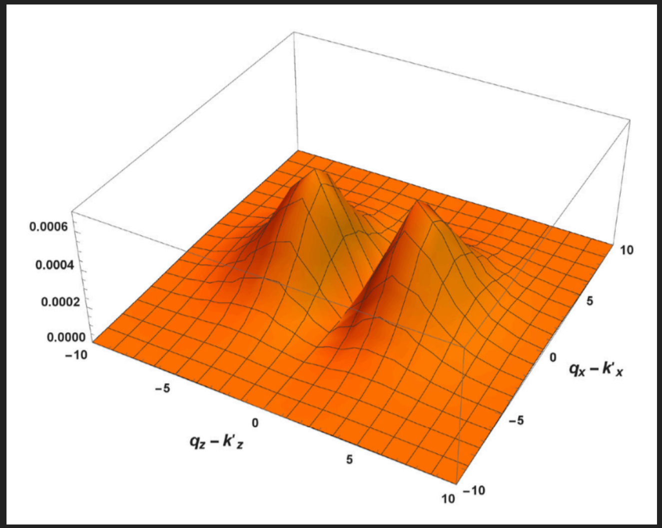
q and k′ however are *independent* since the bound state wf is a energy eigenstate, not a mom. eigenstate

$$\Delta E = E_i(\ell) + \phi_{\rm wk} + \frac{k'^2}{2M_\chi}$$

$$\Delta E = \frac{(M_\chi \mathbf{v})^2}{2M_\chi} - \frac{(M_\chi \mathbf{v} - \mathbf{q})^2}{2M_\chi} = \mathbf{v}\cdot\mathbf{q} - \frac{\mathbf{q}^2}{2M_\chi}$$

(The prob. of the recoiled e to have k′ with q and l fixed)

$$d\sigma(\ell) \propto \frac{1}{F}\sigma_{e\chi}\frac{d^3p'}{(2\pi)^3 2\varepsilon'}\frac{d^3k'}{(2\pi)^3 2E}\,|\tilde{\psi}(\mathbf{q}-\mathbf{k}',\ell)|^2\,\delta(v_{\rm min}|\mathbf{q}| - \mathbf{v}\cdot\mathbf{q})$$



$|\psi(q\text{-}k',0)|^2$ for a π orbital with Mv along z.
If qz is large and qx,qy are small, then k′z tends to be large as well, whereas k′x, k′y are small too.

Hochberg, Kahn, Lisanti, Tully, Zurek Phys. Lett. B772 (2017) 239

Cavoto, Luchetta, ADP, Phys. Lett. B776 (2018) 338

ELECTRONS FROM CNTS

$$v_{\min} = \frac{\Delta E}{|\mathbf{q}|} - \frac{|\mathbf{q}|}{2M_\chi}$$

$$\frac{\Delta E}{|\mathbf{q}|} \approx v_{\min} < v_{esc} + v_0 \Rightarrow |\mathbf{q}| > \frac{4.3\text{eV}}{550 + 220\ \text{km/sec}} \simeq 1.7\ \text{KeV}$$

$$R \propto \frac{\#(C)}{1\text{Kg}} \frac{\rho_\chi}{M_\chi} \int_{\ell \in B_1} \frac{d^2\ell}{(2\pi)^2} d^3v\, f(\mathbf{v})\, \mathbf{v}\, \sigma(\ell)$$

(Total rate per unit time and detector mass; in the first Brillouin zone of the reciprocal lattice.)

$$\exp(i(x + 2\pi r)\ell_x) = \exp(ix\ell_x)$$

(if x is the coordinate along the nanotube, at fixed r and z)

$$\int d^2\ell \to \sum_n \int d\ell_y \quad (\ell_x = n/r)$$

Hochberg, Kahn, Lisanti, Tully, Zurek Phys. Lett. B772 (2017) 239

Cavoto, Luchetta, ADP, Phys. Lett. B776 (2018) 338

ATTEMPTS TOWARDS A 'DARK-PMT'

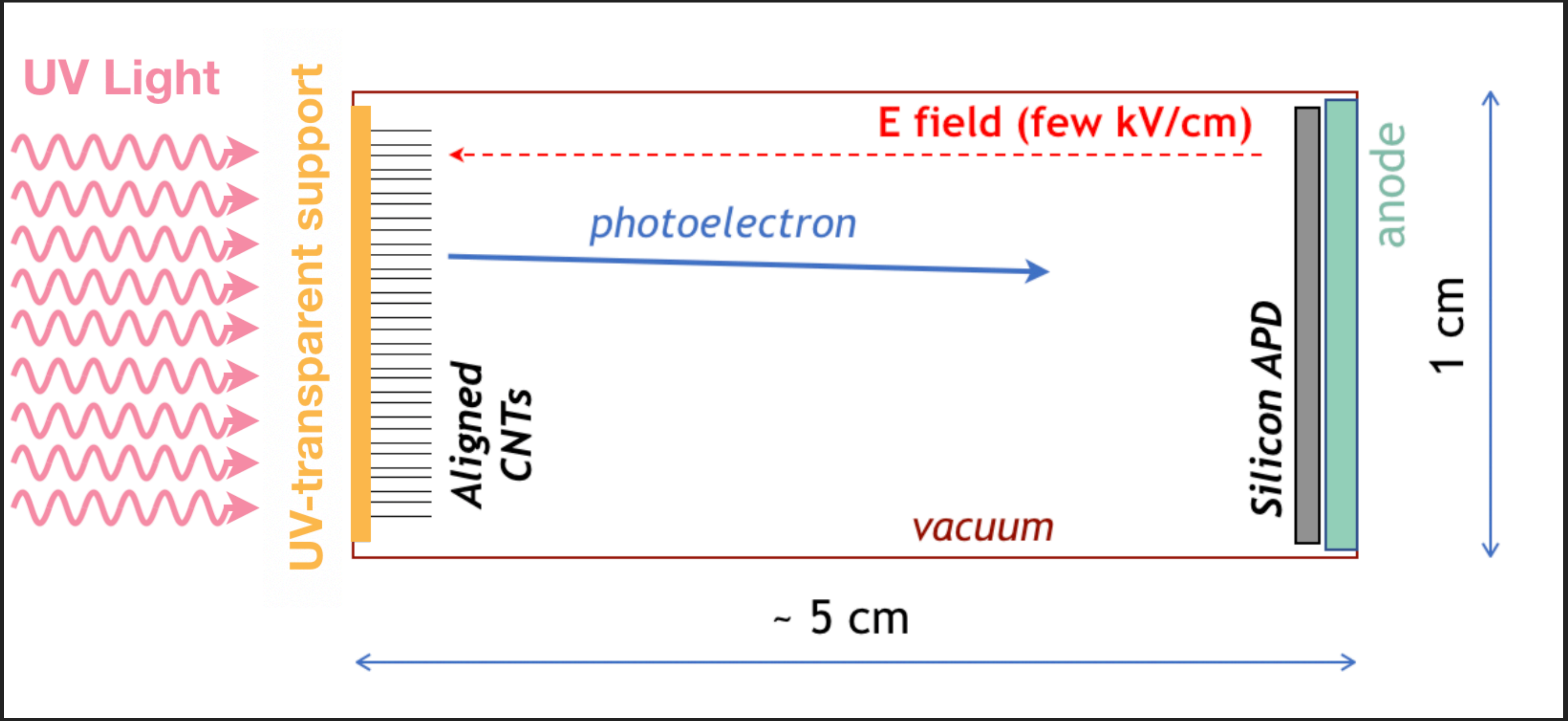
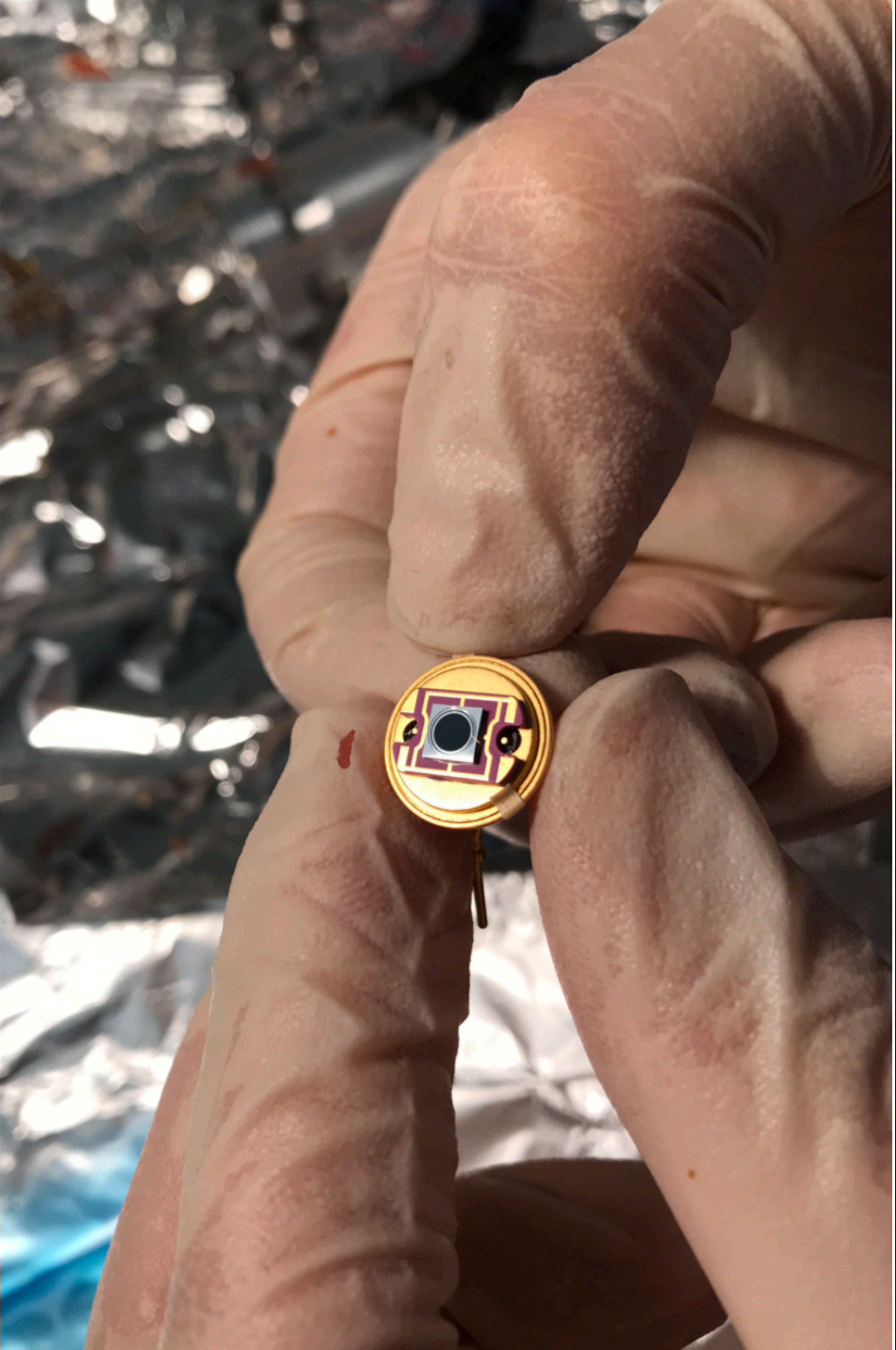
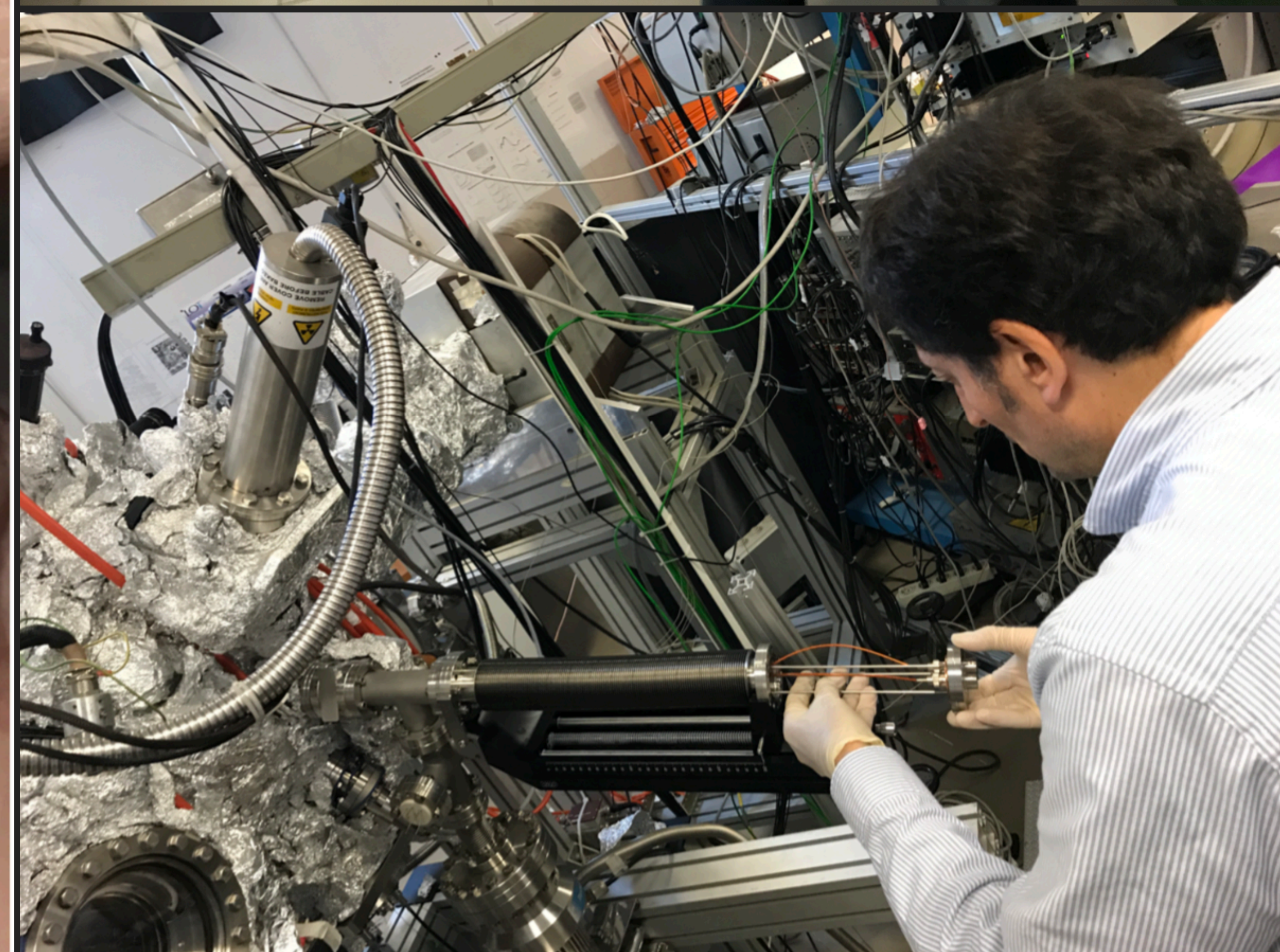


Photo-electrons are emitted along the direction of light polarization.

The commercial silicon APD is optimized for *photons* – have a protetctive window covering silicon. However we need to *detect low energy electrons* (down to eV!) which would get absorbed by the protective window. Ordered windowless (bare silicon) models by Hamamatsu.

Funded by EU (attract-eu.com)
Proposed by F. Pandolfi (INFN-Rome)



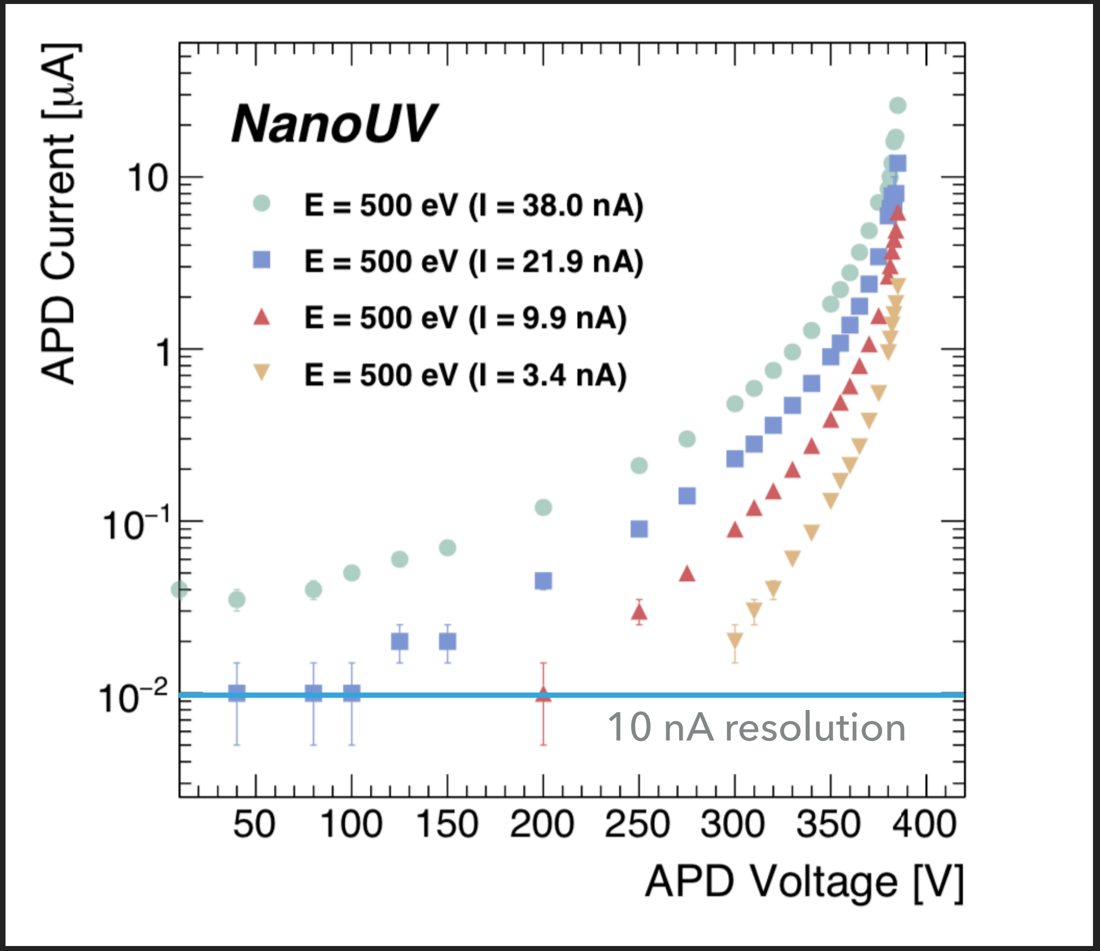


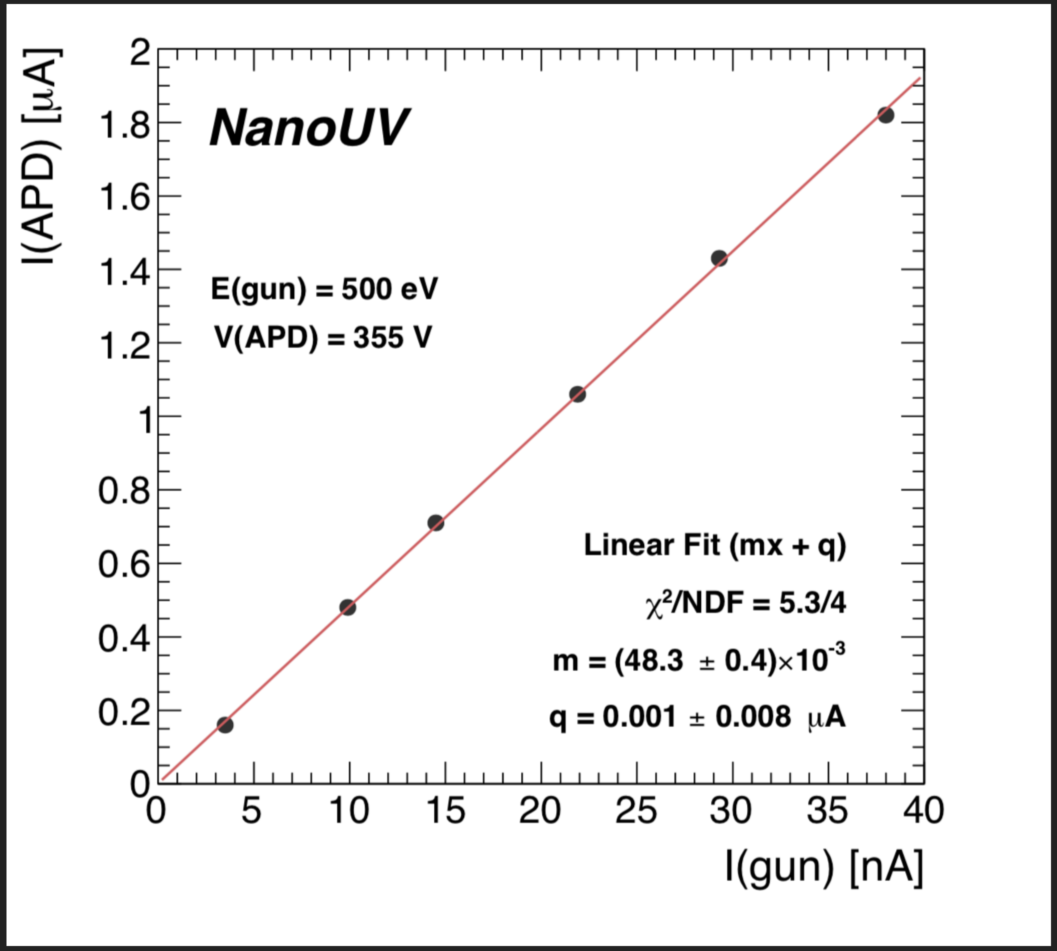
APD CHARACTERIZATION WITH THE ELECTRON GUN

APD = Avalanche-*Photo*-Diode to be used as a *Electron*-Diode

We started a collaboration with Rome3 (A. Ruocco) using an electron gun able to go down to energies below 500 eV. Currents as low as 0.01 uA can be measured.

(G. Cavoto, F. Pandolfi, A. Ruocco)





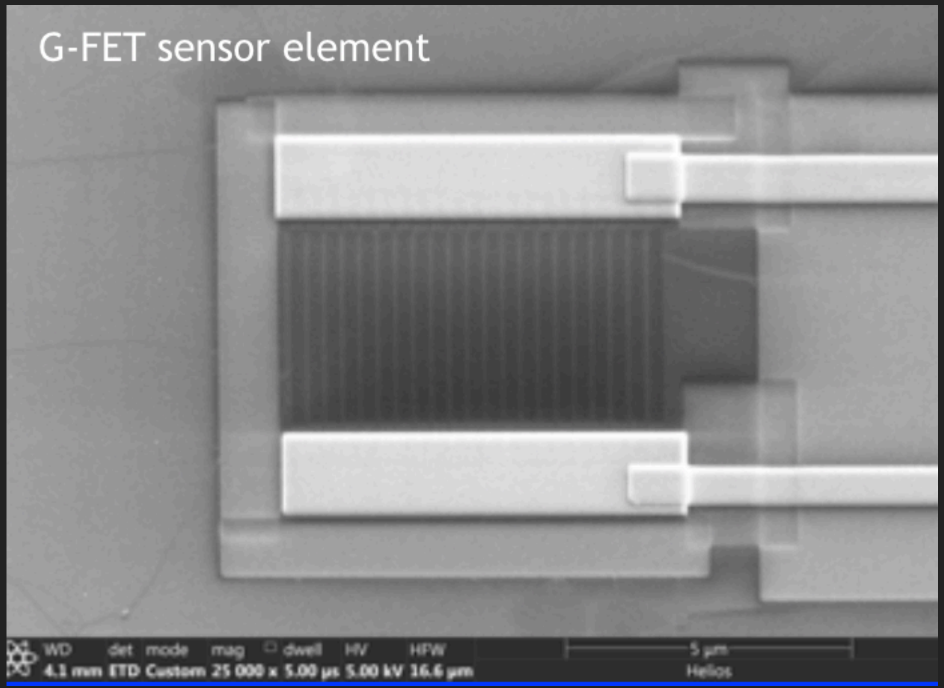
Correnti with ~ 10 e-/psec. Quantum efficiency with photons is ~0.6; to be understood with electrons.

The V(APD) field is *inside* the APD device. Above a certain voltage (~380 V) the proportional regime is lost – Geiger regime. We plan to study the potentiality of *single electron countings* exploting the electric field between CNTs and the anode. Confirmed linear response.

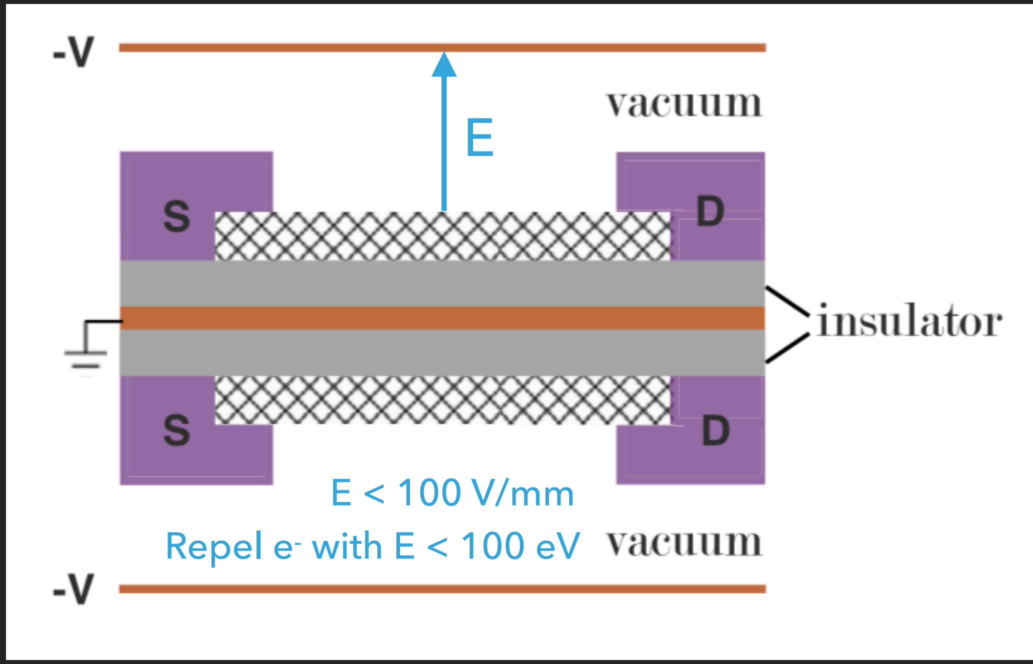
GRAPHENE-FET IN PTOLEMY

The addition or removal of *single electrons* in graphene can cause large measurable changes in the conducivity (effect larger by a factor of ~10 at cryogenic temperatures), with consequent macroscopic charge flow from S to D (read out at regular intervals). Coincidence measurements in two FET are required.

(Ptolemy collaboration)



Nanoribbons (Princeton U.)

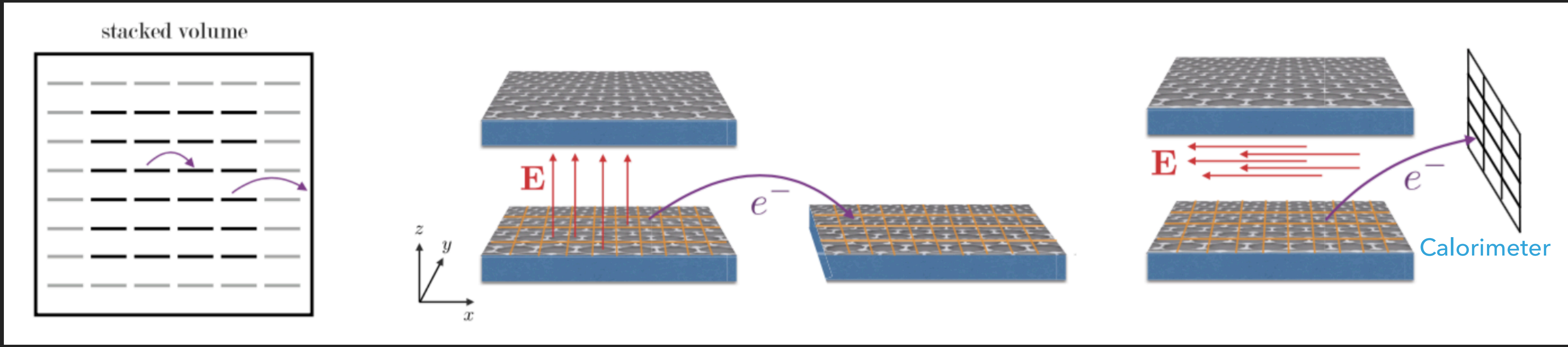


A single electron charge on the finite capacitance of the ribbon produces a voltage step, which increases the conducivity of the ribbon by many orders of magintude. The 4.3 eV work function of graphene helps to suppress dark counts from ejected electrons.

Schwierz, Graphene Transistors, Nat. Nanotechnol 5 (7) (2010) 487
Hochberg, Kahn, Lisanti, Tully, Zurek Phys. Lett. B772 (2017) 239

GRAPHENE-FET IN PTOLEMY

Electrons are ejected in vacuum (10^{-7} torr; mfp 500 m; @ 4K) where their trajectories are shaped with electric fields. High energy events may trigger many FETs at once (background). Vertical sep. ~ mm. Pixel area 1 mm^2. 10^4 pixels per sheet. Target mass of 0.5 kg fit in a compact volume of 10^3 m^3. Maximum *E* of 100 V/mm, sufficient to repel electrons below 100 eV. The calorimeter at the boundary allows to measure electron energy.



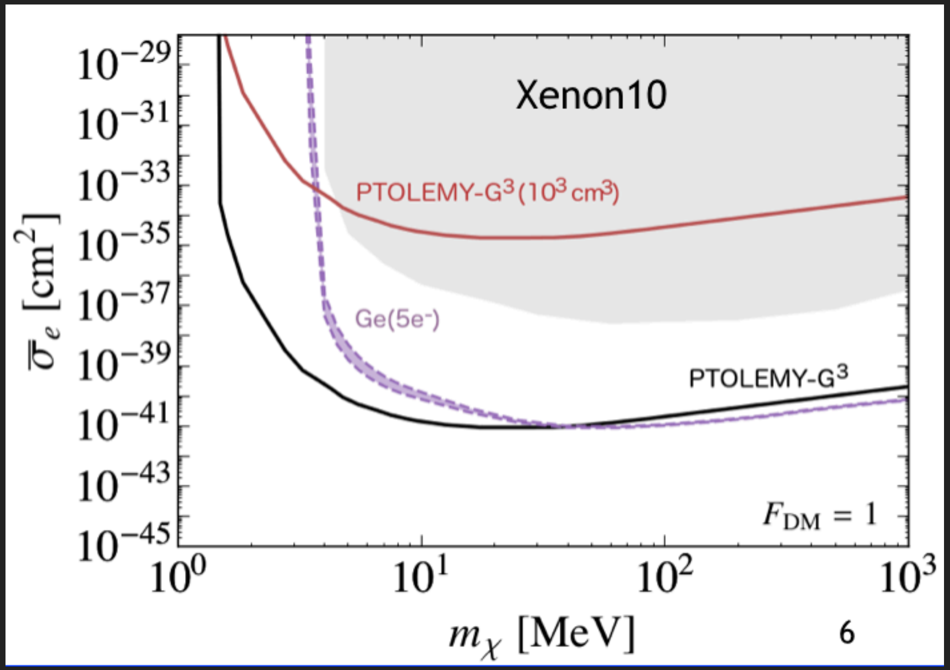
If the DM wind is directed along z, coincidence events will be registered from the top FET layers. Twelve hours later coincidence signals will be from the bottom layer (separated by a grounded electrode). Electrons will be recoiled with velocities of 10^6-10^7 m/s. TOF can be measured and v reconstructed

$$-1/2\,|e|\,E/m(\Delta t)^2 + v_z \Delta t = \Delta z = 0$$

$$v_x = \Delta x/\Delta t \quad v_y = \Delta y/\Delta t$$

Hochberg, Kahn, Lisanti, Tully, Zurek Phys. Lett. B772 (2017) 239

GRAPHENE-FET IN PTOLEMY : BACKGROUNDS



At LNGS the total flux of muons across the graphene target falls below 10^{-1} sec^{-1}. However, any incident particle with sufficient energy poses a background: environmental radioactivity can be limited by shielding and the use of highly radiopure materials. The substrate itself can be source of radioactive backgrounds – can be mitigated by atomic thin substrates.

Main irreducible background is ^{14}C. The fraction of ^{14}C can be reduced from 10^{-18} (achieved in Borexino) to 10^{-21}. This eventually would allow to have ~10^4 atoms of ^{14}C in 0.5 Kg target mass: 1-2 events per year.

Betas emitted almost coplanar with graphene will likely pose *irreducible* backgrounds: need to reach 10^{-21}.

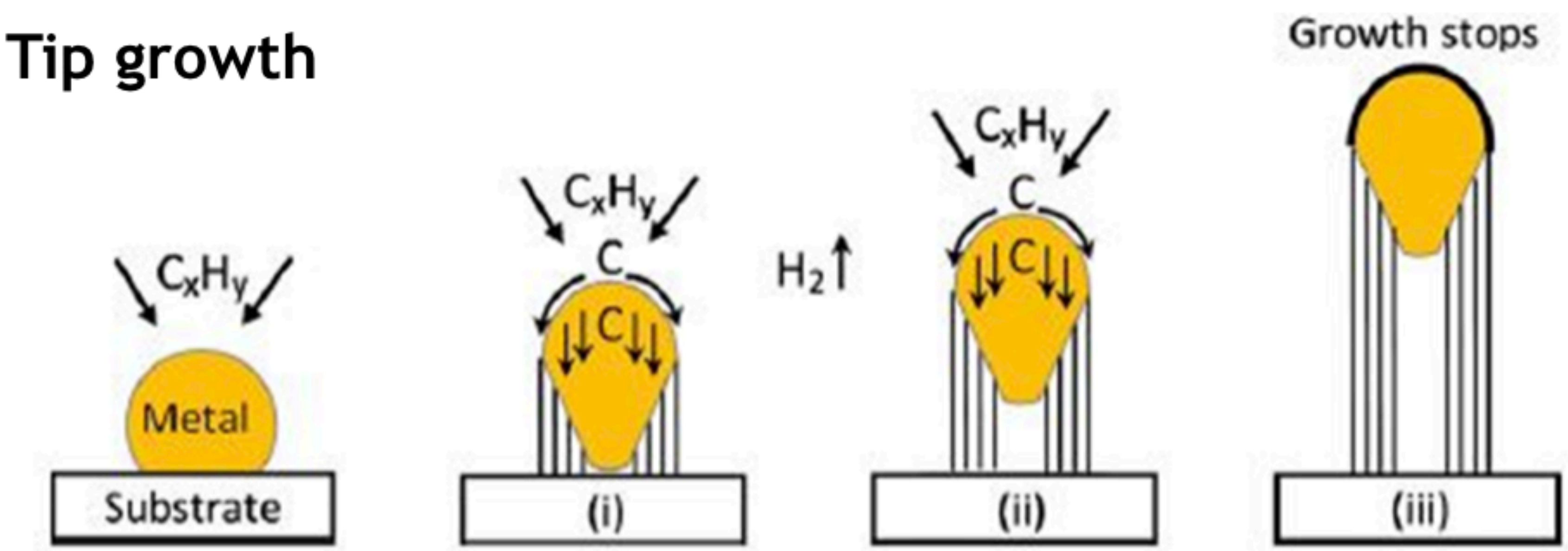
Hochberg, Kahn, Lisanti, Tully, Zurek Phys. Lett. B772 (2017) 239

CNTs growth mechanism

Courtesy of I. Rago

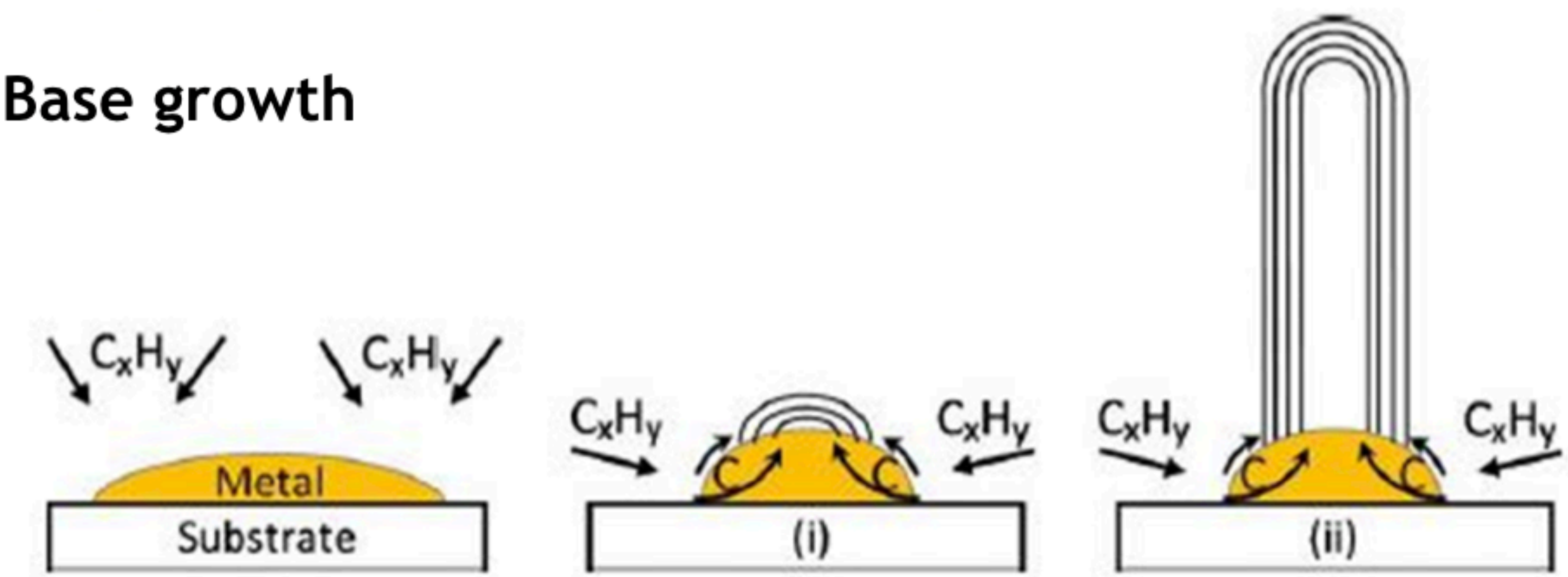
Metallic nanoparticles (Fe, Co, Ni) are required to enable hydrocarbon decomposition. Relationship between CNT morphology and hydrocarbon molecular structure/decomposition temperature. E.g. SWCNT produced at high temperatures ~ 900-1200 C.

Tip growth



The catalyst is lifted off from the supporting surface during nanotube's growth

Base growth



CNT grows up with the catalyst particle rooted on its base

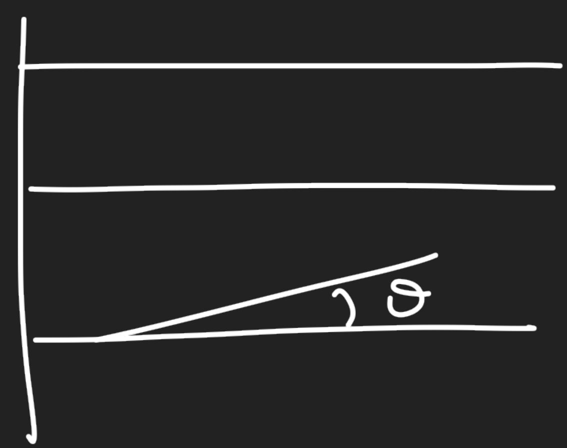
Growth time ~ 10 min.

M Kumar and Y. Ando, J. Nanosc. Nanotec. (2010)

BACKUP

ASYMMETRY

N_-



$N_+ = N(\theta)$

$$A(\theta) = \frac{N(\theta) - N_-}{N(\theta) + N_-} \simeq 0.4 \text{ for } \theta \simeq 0$$

SOME INDICATIONS THAT $C = 1 - T - R \approx 10^{-4}$

WITH $C \sim 10^{-4}$, $0 \leq \theta \leq 10^\circ$ THE RECOILED e^- TRAVELS SEVERAL HUNDREDS μm.

C NEEDS TO BE MEASURED AT LOW ENERGIES.

Cavoto, Luchetta, ADP, Phys. Lett. B776 (2018) 338

ELECTRONS FROM CNTS

- Larger cross sections for e^- recoils orthogonal to the graphene layer (see Hochberg et al.) but we need small ϑ angles.
- At the e^- energies of interest (λ of a few Angstroms) and for a R=10 nm, electrons should `see` locally flat graphene.

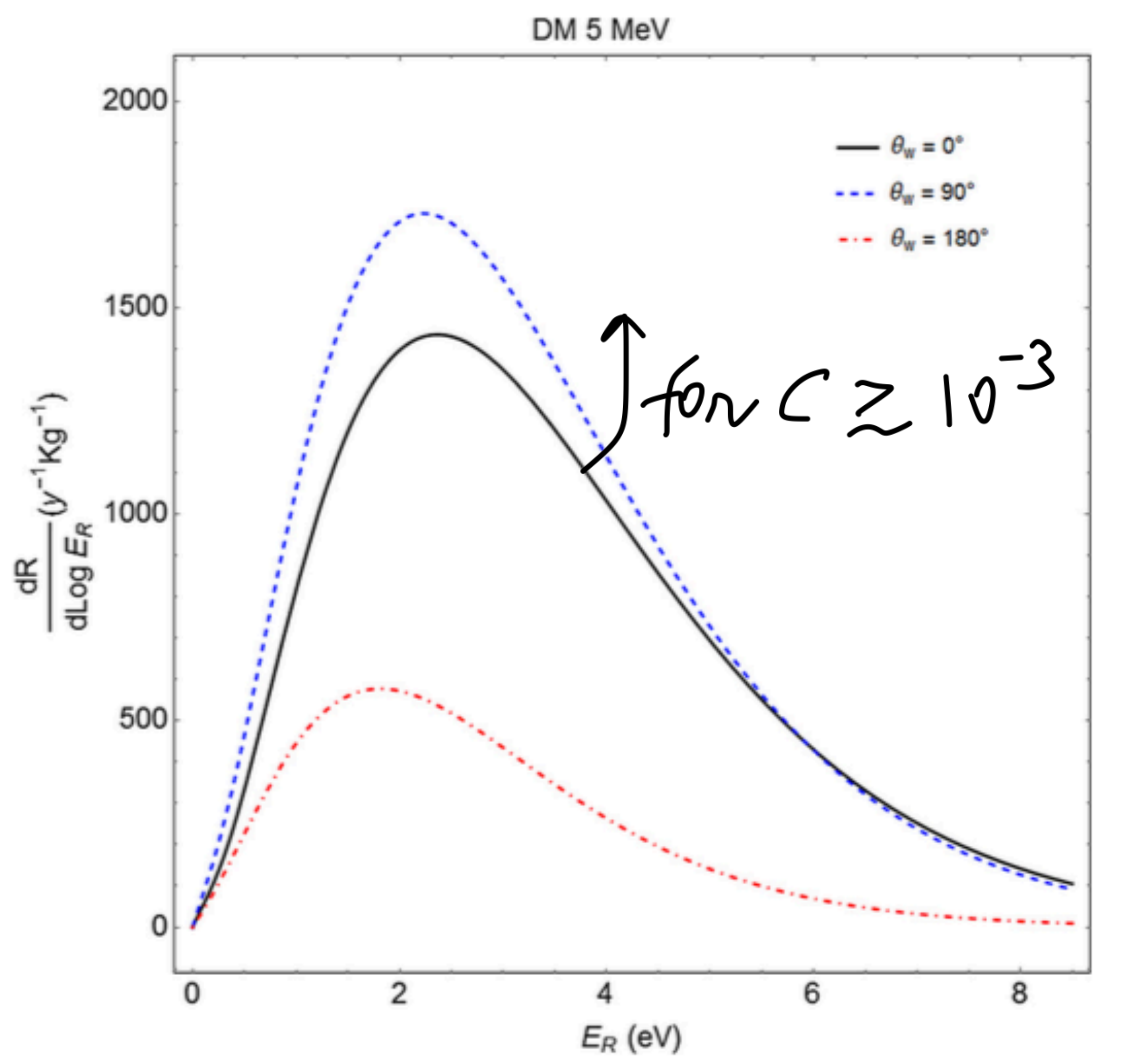


Fig. 2. Differential rates of ejected electrons per year per kg, distributed in the recoil energy E_R for $M_\chi = 5$ MeV. We include both sp^2 and π-orbital electrons. The three curves reported are relative to three different orientations of the DM wind main direction with respect to the carbon nanotube parallel axes. The plot reported here is found with Eq. (23) and the addition of the absorption probability at every hit with the CNT. E_R corresponds to the kinetic energy of the electrons emitted from the surface of the CNTs, having overcome the work function $\phi_{\rm wf}$.

Cavoto, Luchetta, ADP, Phys. Lett. B776 (2018) 338

CNT REPULSIVE POTETIALS

$$U(r,\varphi) = 3^{-3/2} 32\pi\, Ze^2 l^{-2} R \sum_{j=1}^{4} a_j b_j^2 \exp[-b_j^2(r^2+R^2)] I_0(2b_j^2 r R)$$

Axially symmetric potential for a CNT

$$a_j = \{3.222, 5.270, 2.012, 0.5499\} \times 10^{-4}\,\text{nm}^2\ ,$$
$$b_j = \{10.330, 18.694, 37.456, 106.88\}\,\text{nm}^{-1}$$

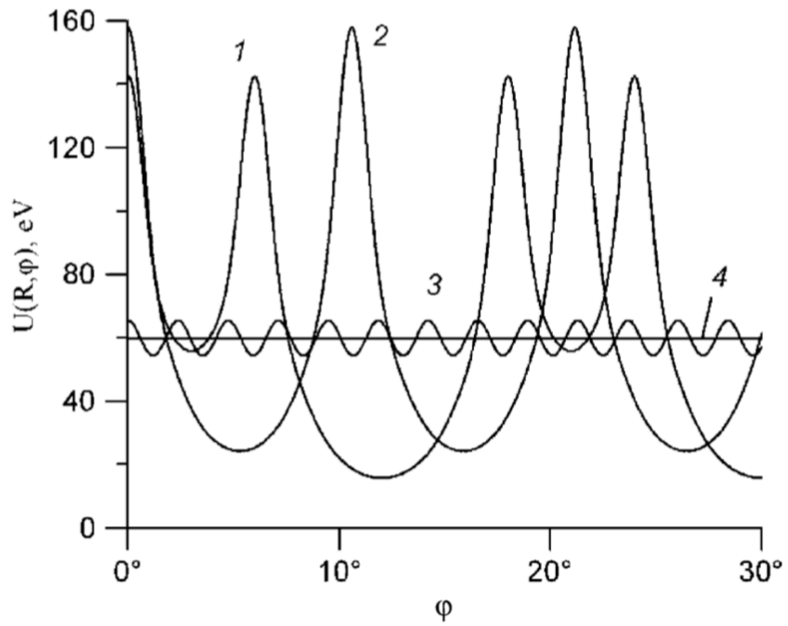


Fig. 3. Azimuthal profile of the potential barrier $U(R,\varphi)$ of nanotubes with various indices (n,m). The curves correspond to different indices: curve 1—(10, 10), 2—(17, 0), 3—(12, 8). The horizontal straight line 4 corresponds to nanotubes with intermediate helicity, for example, (11, 9).

Artru et al. Phys. Repts. 412 (2005) 89