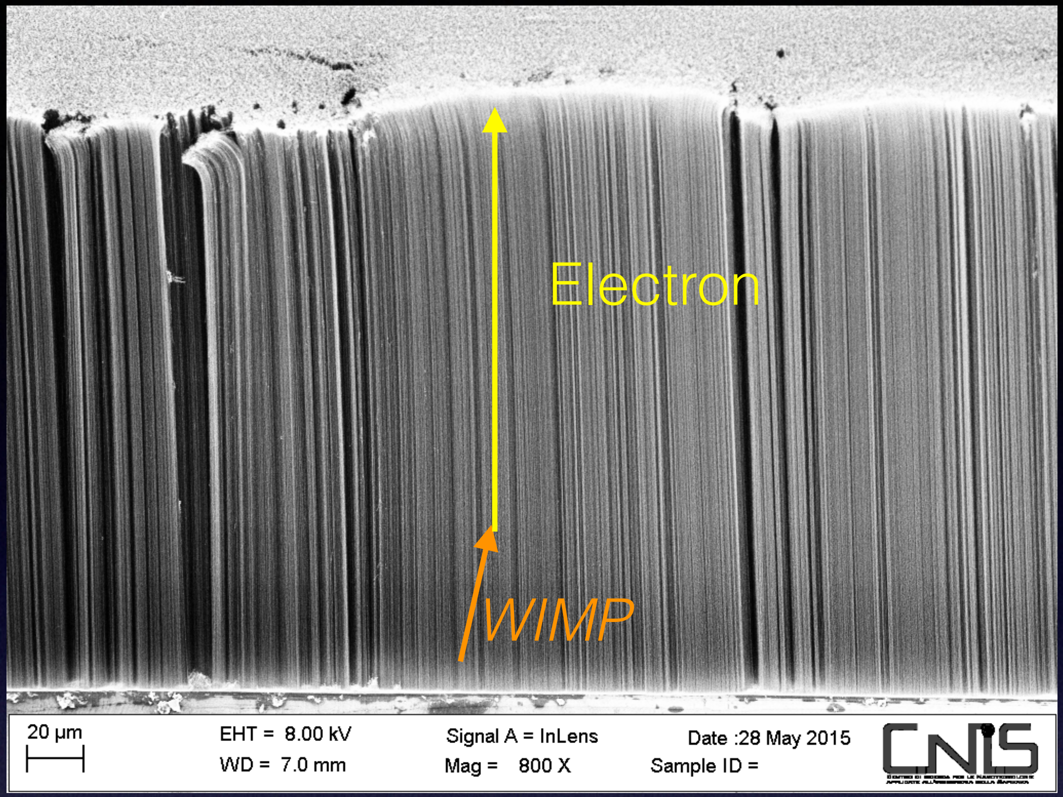


CARBON NANOTUBES FOR
DARK MATTER DIRECTIONAL SEARCHES

Sub-GeV Dark Matter Detection with Electron Recoils in Carbon Nanotubes

G.Cavoto, F.Luchetta, A.D.Polosa
(Sapienza - INFN Roma)

DM particles and CNT

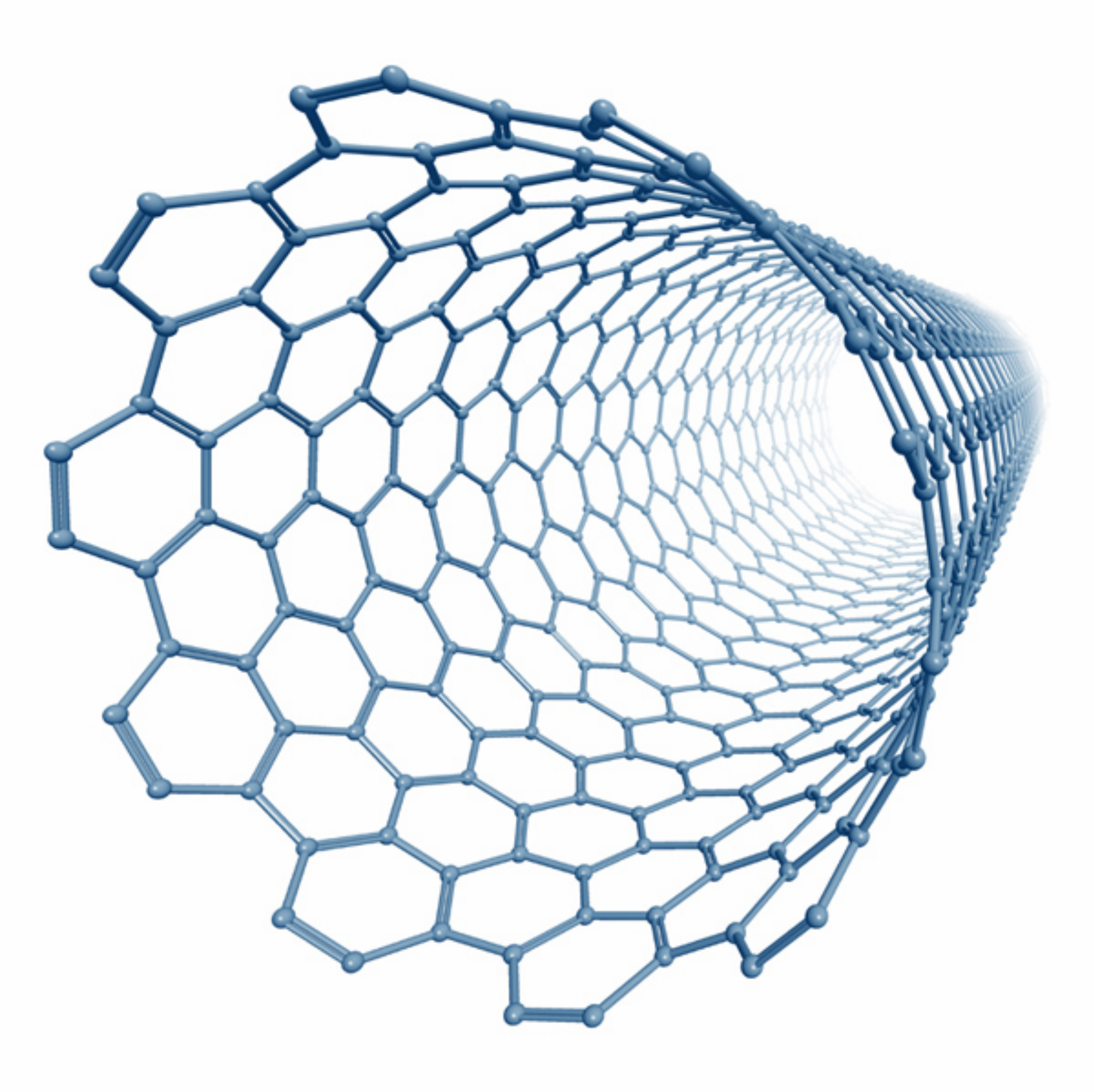
- **Carbon nanotubes can be an intrinsically anisotropic target for DM particles**
  - Ideas and simulation for WIMP-**nuclei** scattering
  - **Directional Dark Matter Searches with Carbon Nanotubes** L.M. Capparelli et al. **Phys.Dark Univ**. 9-10 (2015) 24-30, Erratum: **Phys.Dark Univ.** 11 (2016) 79-80
  - **WIMP detection and slow ion dynamics in carbon nanotube arrays** G. Cavoto etl al. **Eur.Phys.J. C76 (2016) no.6, 349**
- **Some experimental tests going on to prove the concept**

In this talk DM-**electron** scattering
in a CNT "brush"
(https://arxiv.org/abs/1706.02487 to appear in PLB)

DM mass is in the sub-GeV range
(DM not really WIMP…)

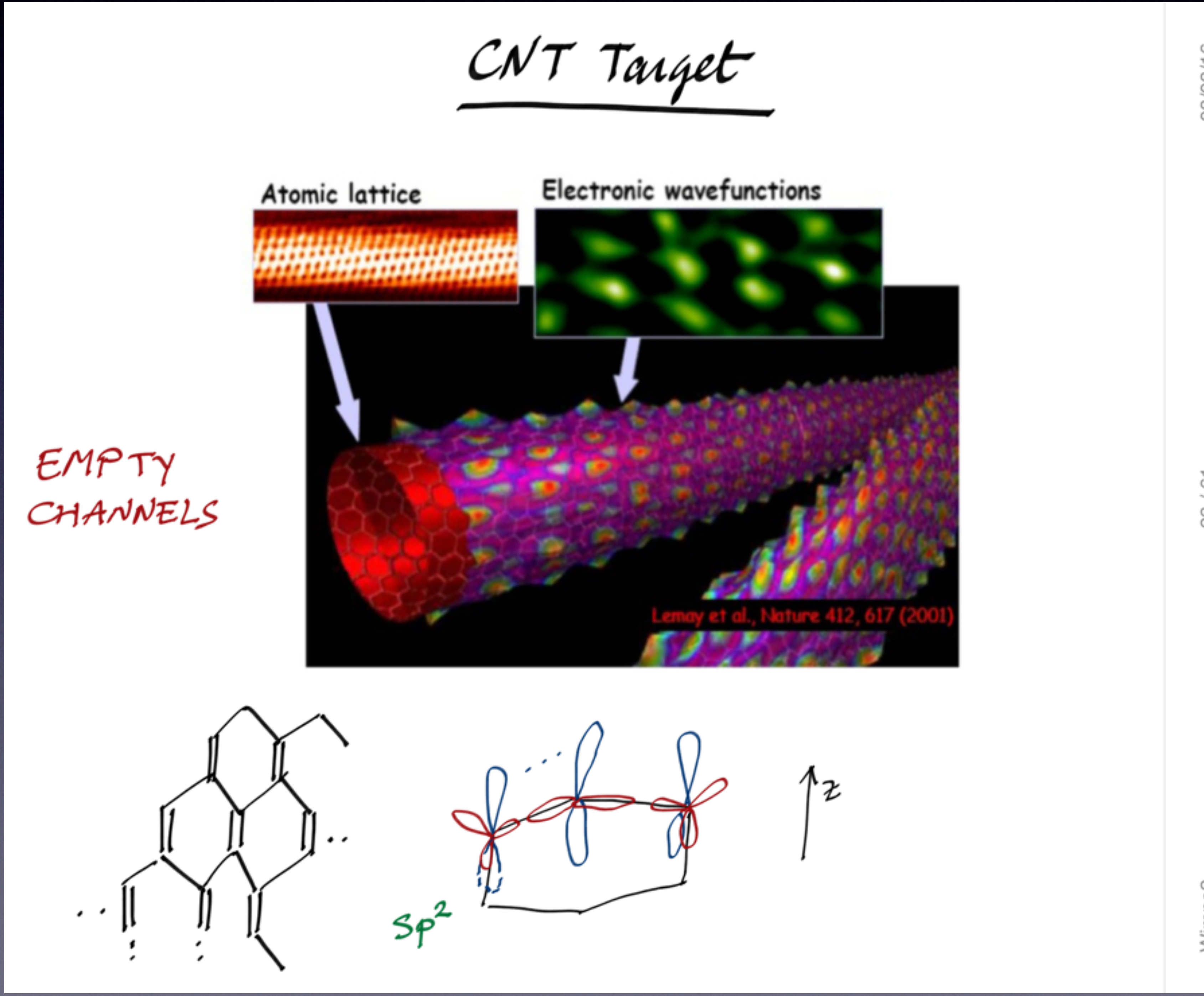
A single wall CNT

- A rolled-up graphene sheet (a single-atom surface)



Electrons on CNT

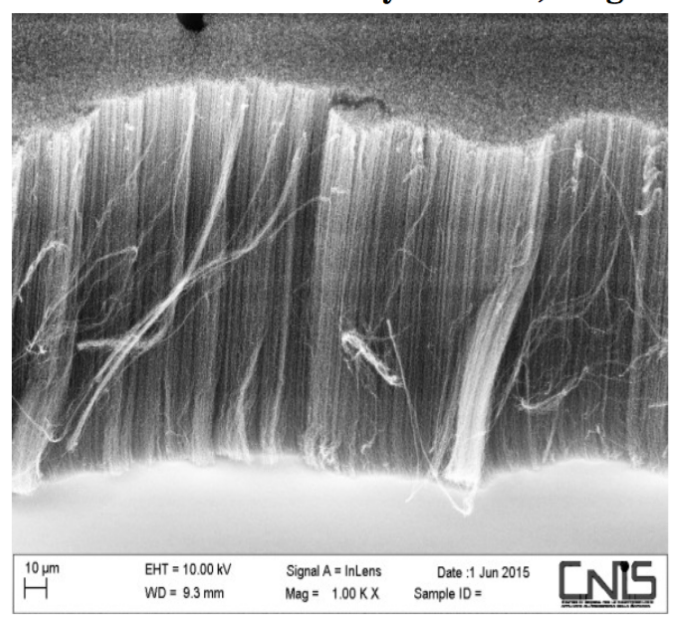
- CNT electrons are “confined” on the graphene sheet (π and sp^2 orbitals)
- Recoiling electrons (or ions) find an **empty** space
- Recoiling ions are **repelled** by the CNT surface (“channeling”)



A “brush” of CNT

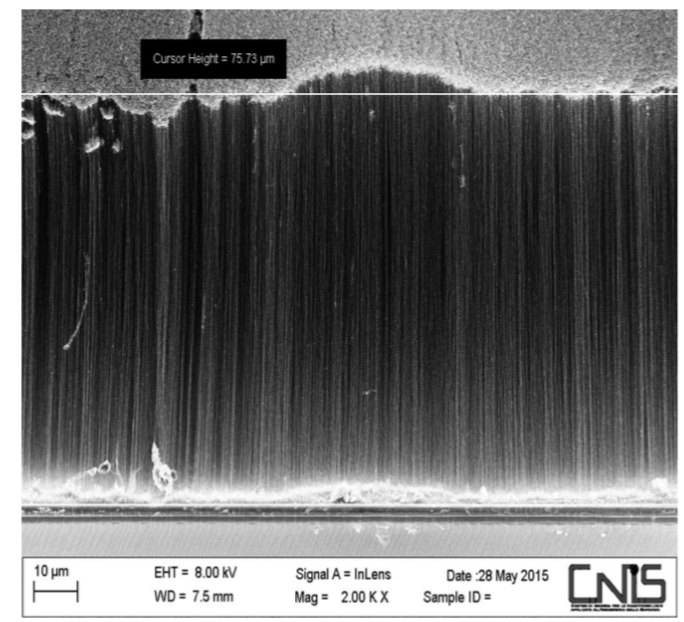
- **Aligned** (MW)-CNT (200 μm tall, 10nm diameter, 50 nm spaced one from the other)
- Grown on a substrate
- Free at the other end (can be “uncapped”)

collaboration University of Mons, Belgium



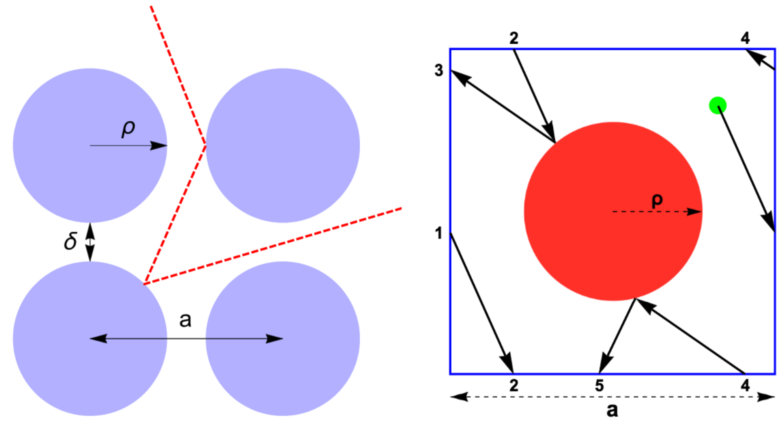
length: ***100 μm (can be increased)***
ext. diameter: ***(20 ± 4) nm***
aspect ratio: ***5x10⁴***

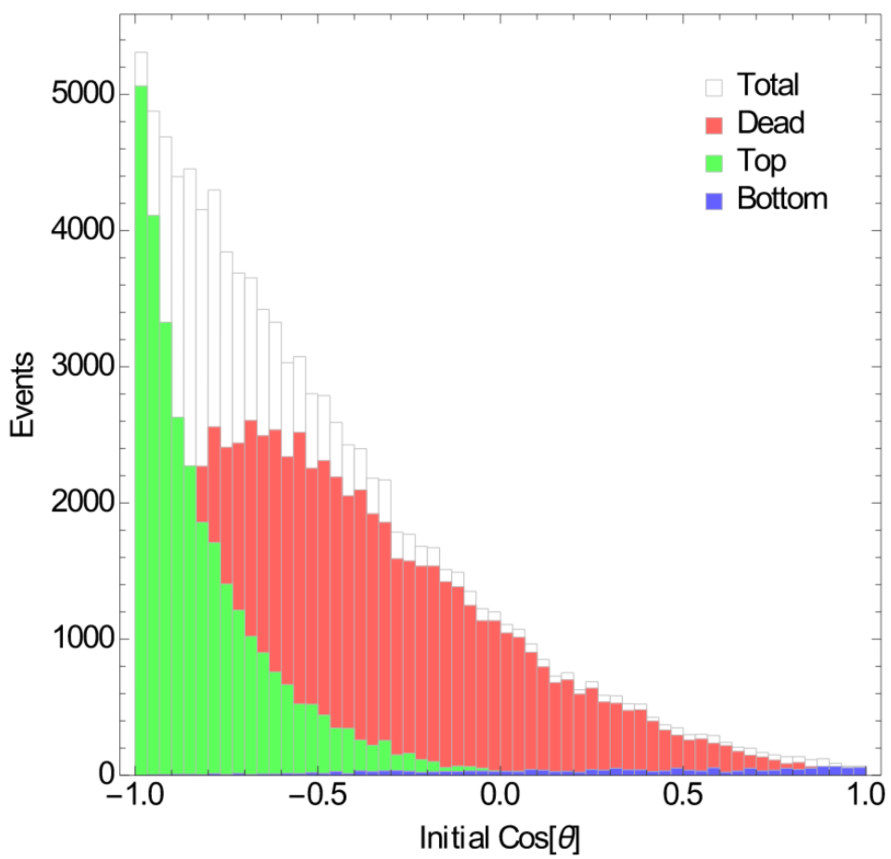
commercial



length: 75 ***μm***
ext. diameter: ***(13 ± 4) nm***
aspect ratio: 0.6 ***x10⁴***

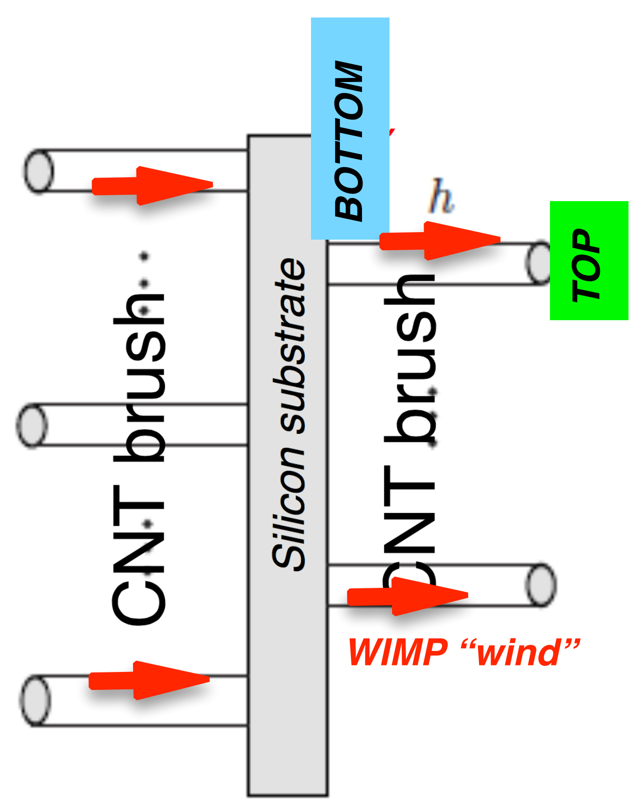
C ion moving within the array

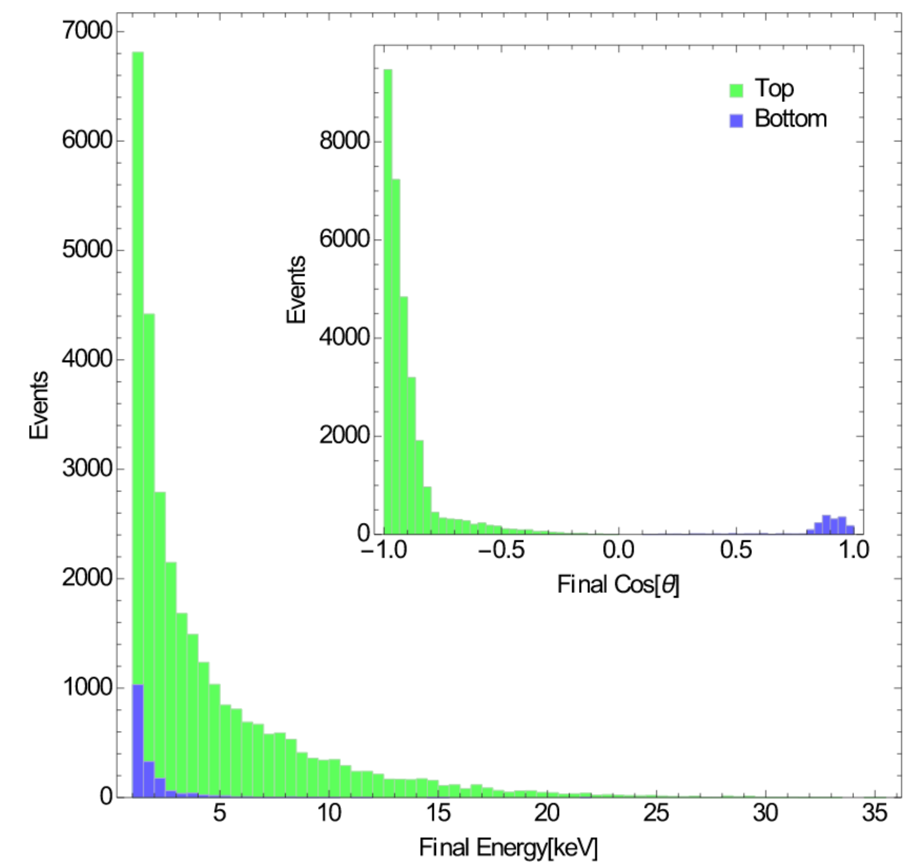




Initial C ion direction

Double brush

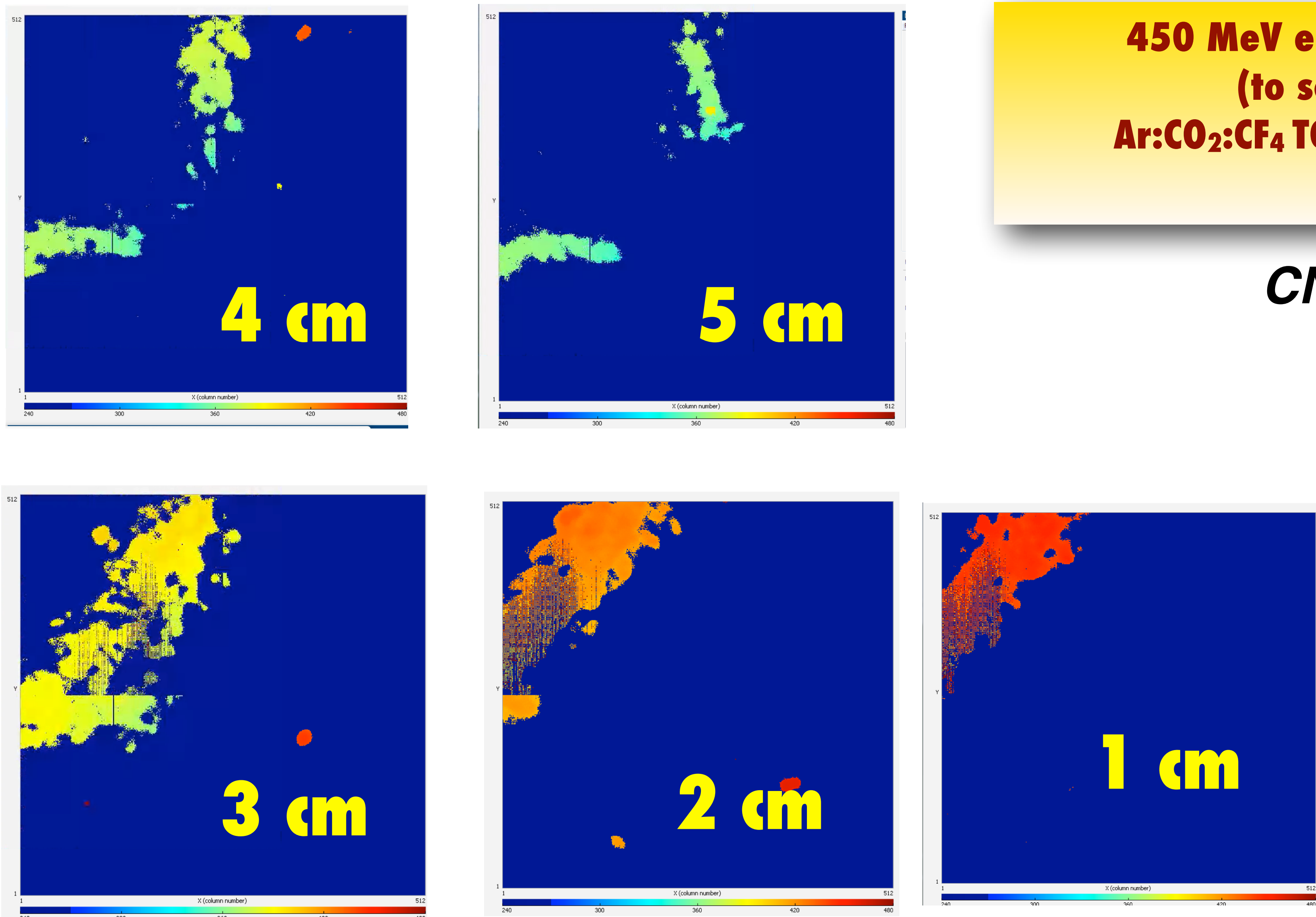


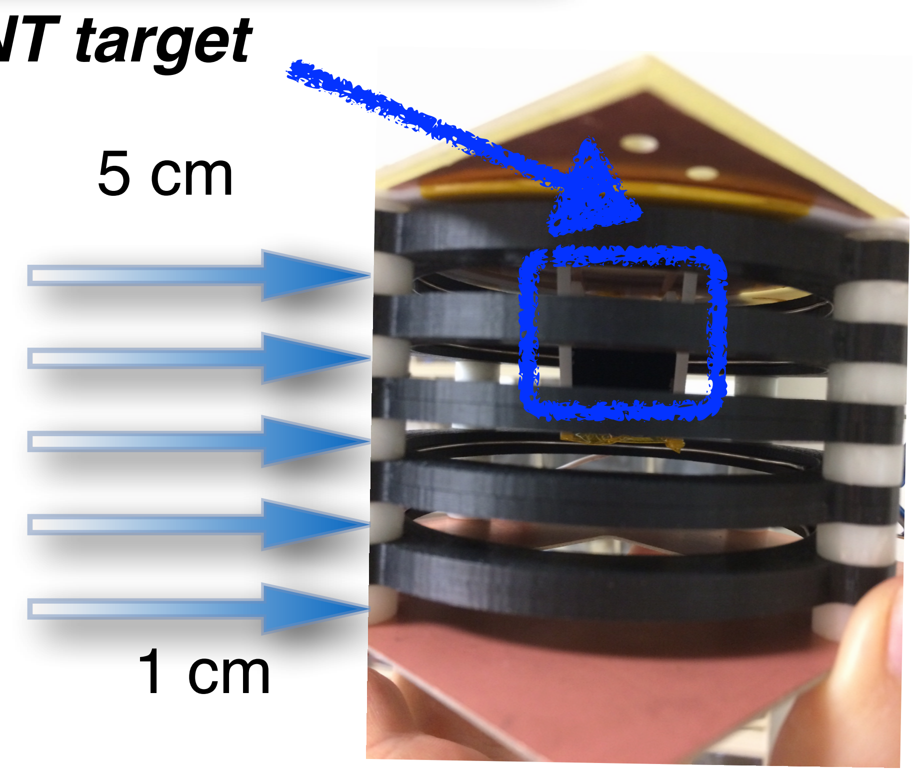


Final C ion energy and direction

First look at CNT with a beam

450 MeV electron at INFN LNF
(to scatter C ion)
Ar:CO_2:CF_4 TOA data @ 300 Torr





Color is drift time (along Z) for different Z position (X-Y projection)

*CNT are **good conductor**, modifying the field cage electric field.*
Different field configuration to be tried for the conceptual demonstration

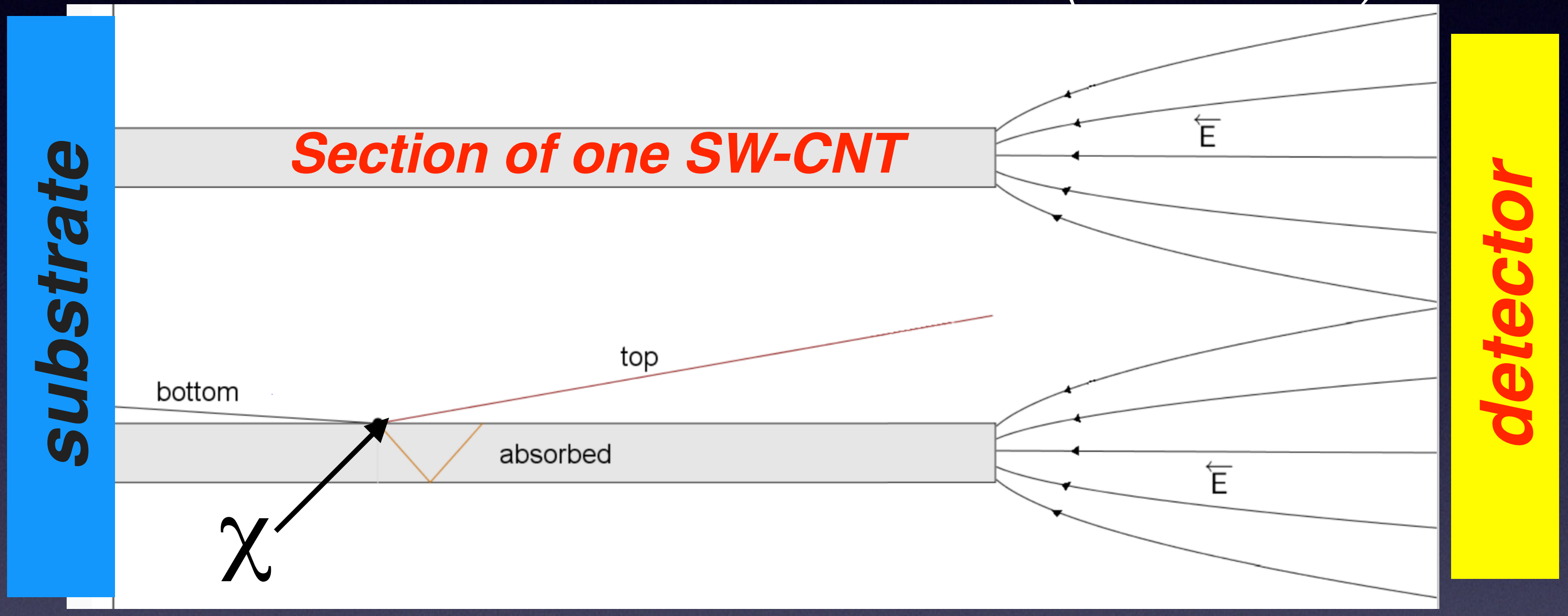
DM-electron scattering

DM-electron interaction

Assume all the CNT are conductors

- WIMP knocks out one electron
- Must pay: valence band energy and graphene work function (4.3 eV)

Acceleration field (in vacuum)

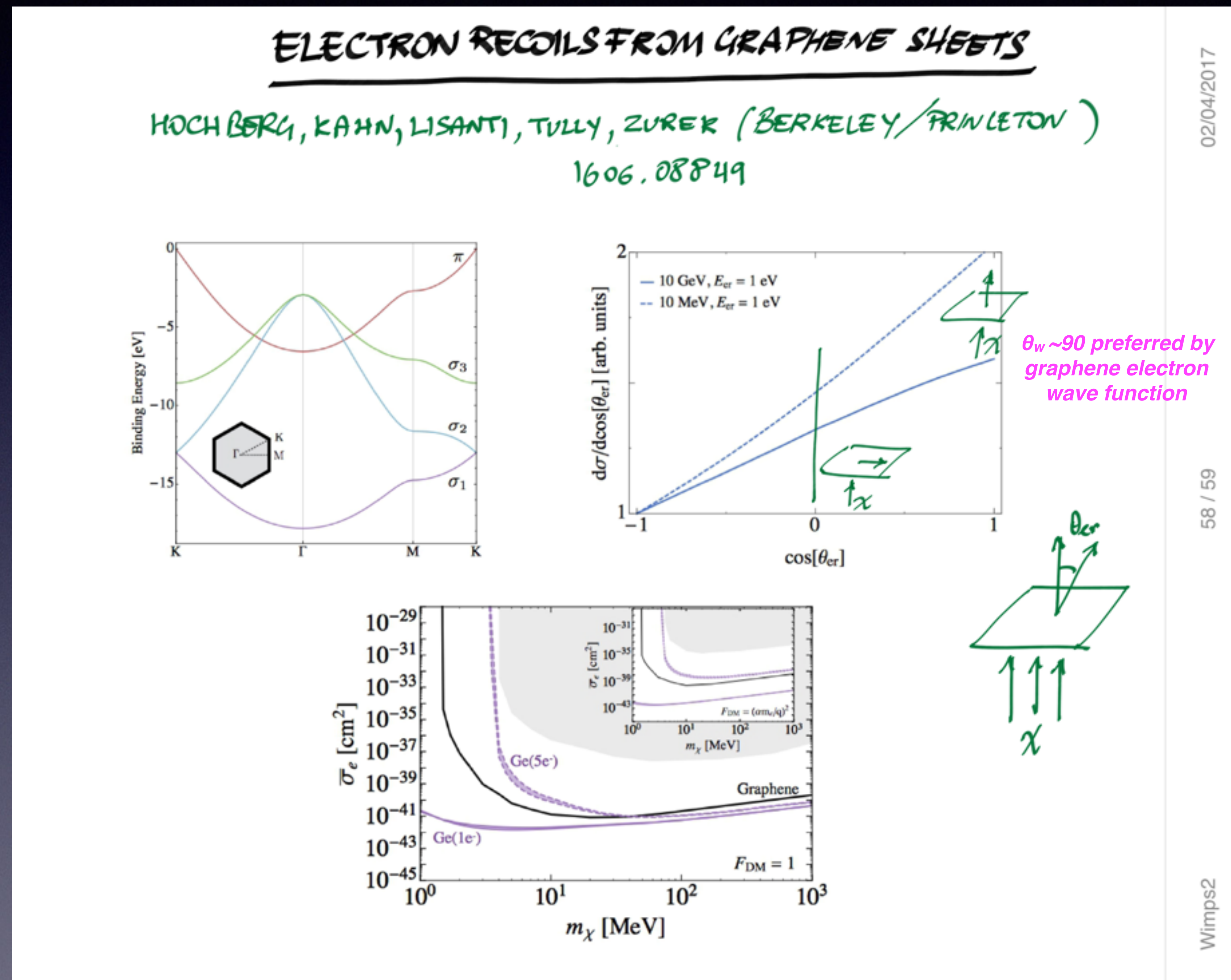


Top: ejected toward the open end (**detector**)
Bottom: absorbed in the **substrate**

Critical to know
Transmission+Reflection+Absorption =1
of a few eV electron through graphene sheets

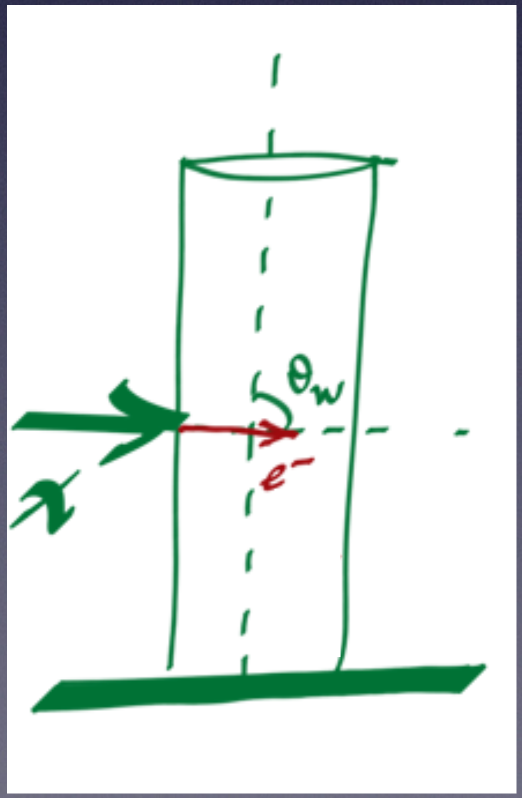
Use graphene sheet

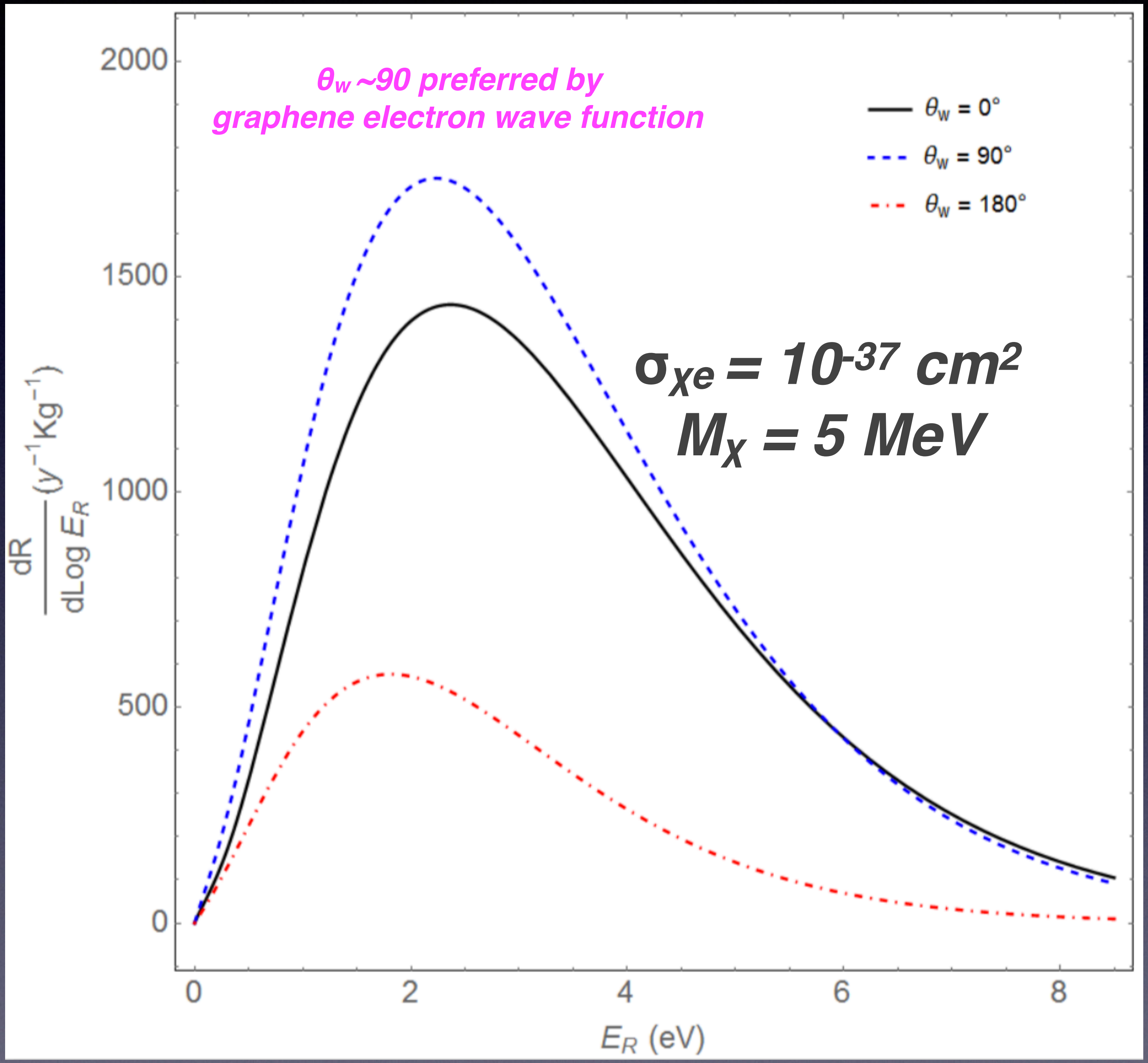
- Idea: use large area graphene sheets
- Band structure is such that emitted electrons have a **preferred direction**!



WIMP interaction rates

- Idea: wrap-up graphene into CNTs
- CNT axis at FIXED orientation $\boldsymbol{\theta_w}$

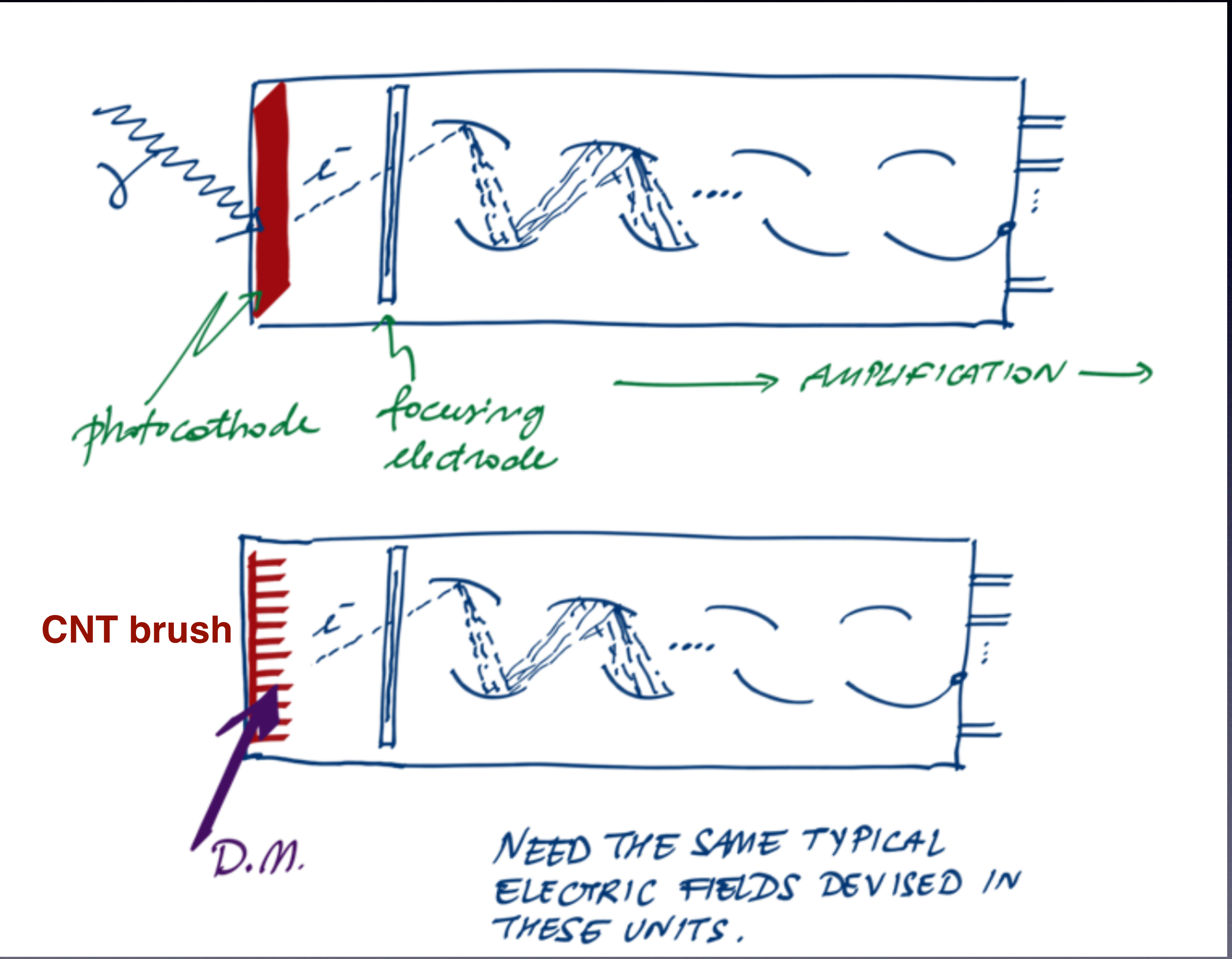




Emission rate from a CNT target at different angles $\boldsymbol{\theta_w}$

Conceptual detection

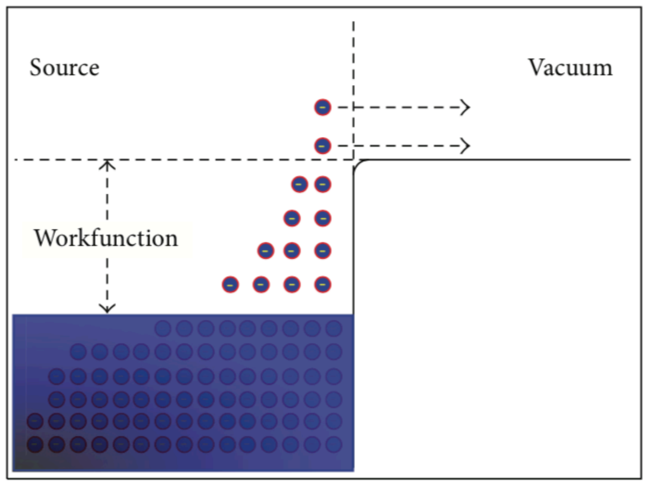
- Use a **CNT brush** as target for low mass **WIMP** (as photocathode does for photons)
- **Hybrid avalanche photodiode**
- **Does not measure E_R**



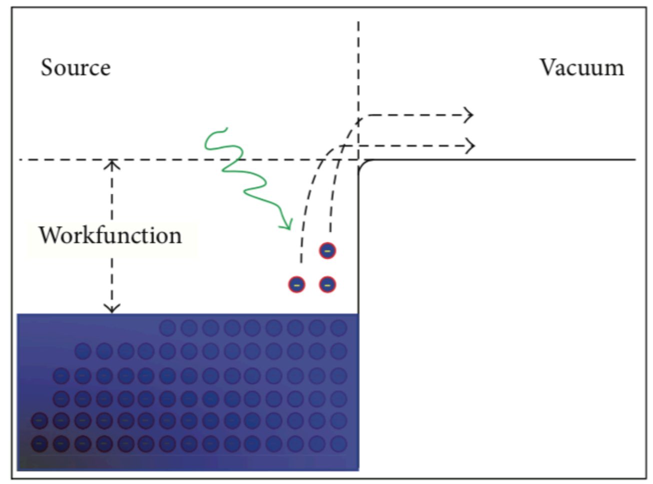
CNT brush as ***dark-cathode***

Electron emission from a cathode

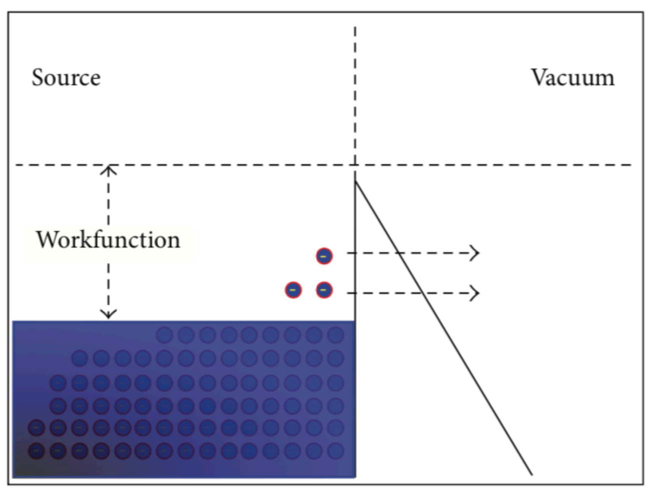
Thermoionic emission **Photoelectric emission**



(a)



(b)



(c)

Field emission

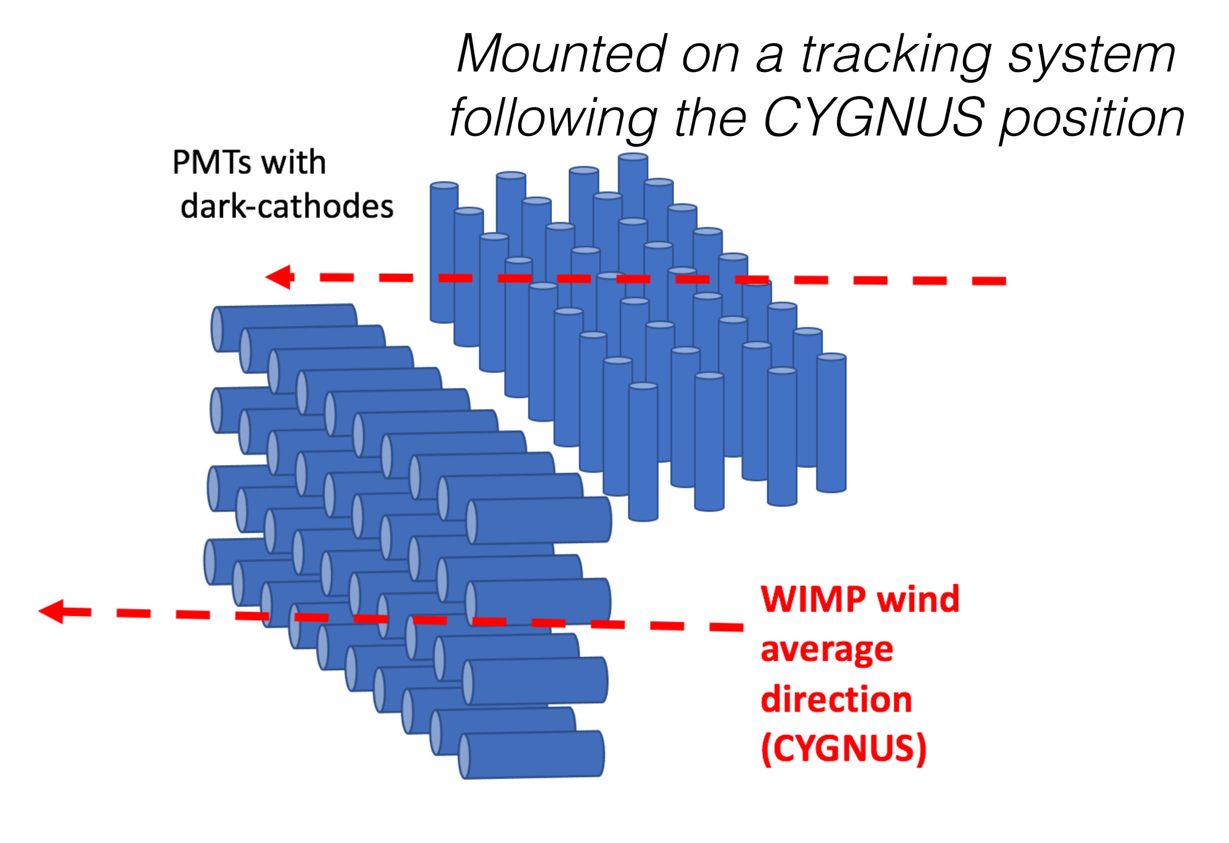
*Signal is **SINGLE ELECTRON** (assigned kinetic energy by the accelerating field)*

Work function of CNT is > 4 eV

*All these effects are suppressed: room temperature is already low enough, UV photon efficiently screened, **E field < 100 V/μm***

Conceptual apparatus

- Use **two** array of dark-HAPD at **two** fixed orientation



~10^4 units, each one with 10mg dark cathode mass

- Build an **asymmetry** out of these two count rates

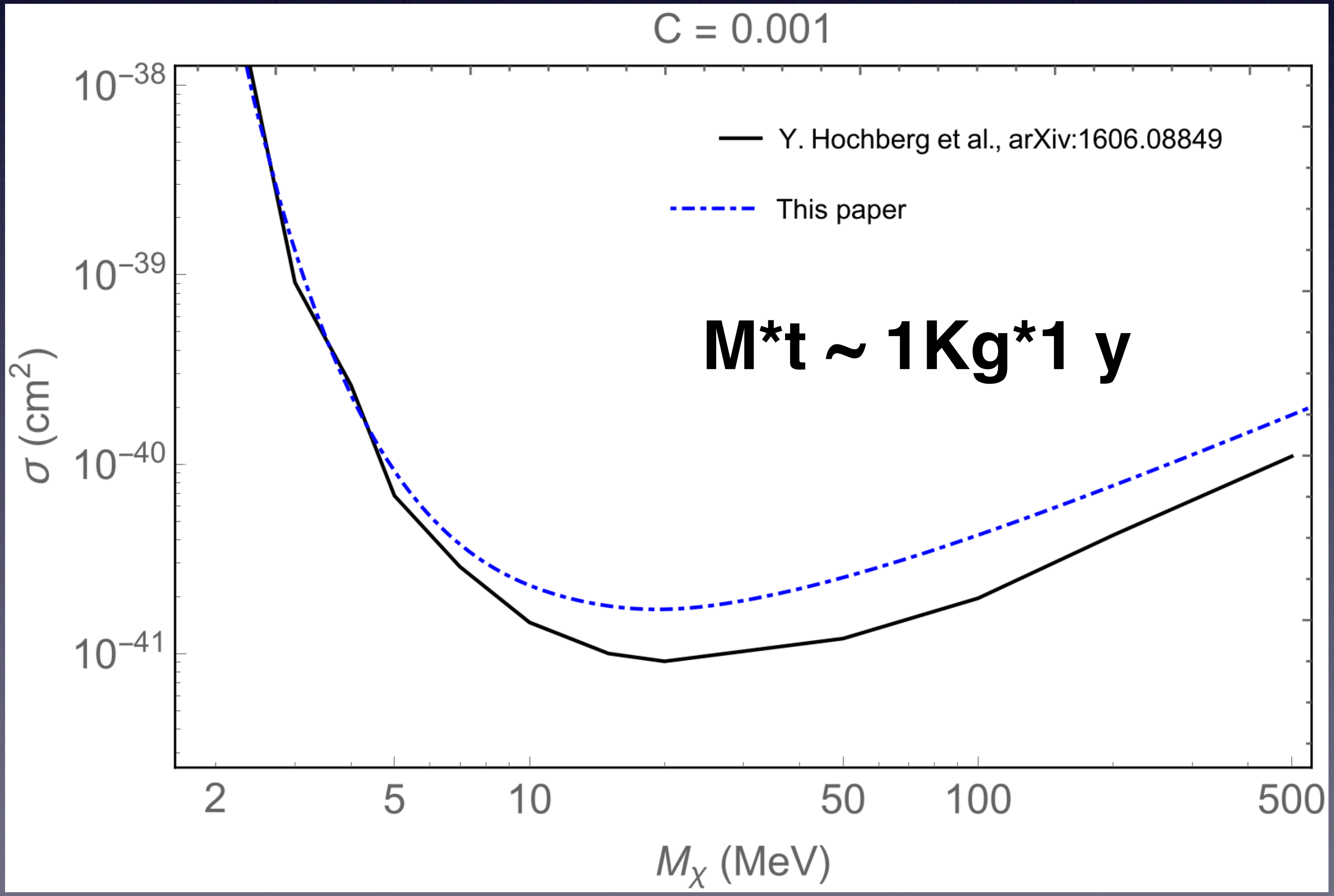
$$A(\vartheta_w) = \frac{N(\vartheta_w) - N(180)}{N(\vartheta_w) + N(180)}$$

Observation or exclusion

$\sigma_{\chi e} = 10^{-37}\ cm^2$
$M_\chi = 5\ MeV$

With an exposure of 100g * 160 day a 5σ non null asymmetry A(0) can be measured

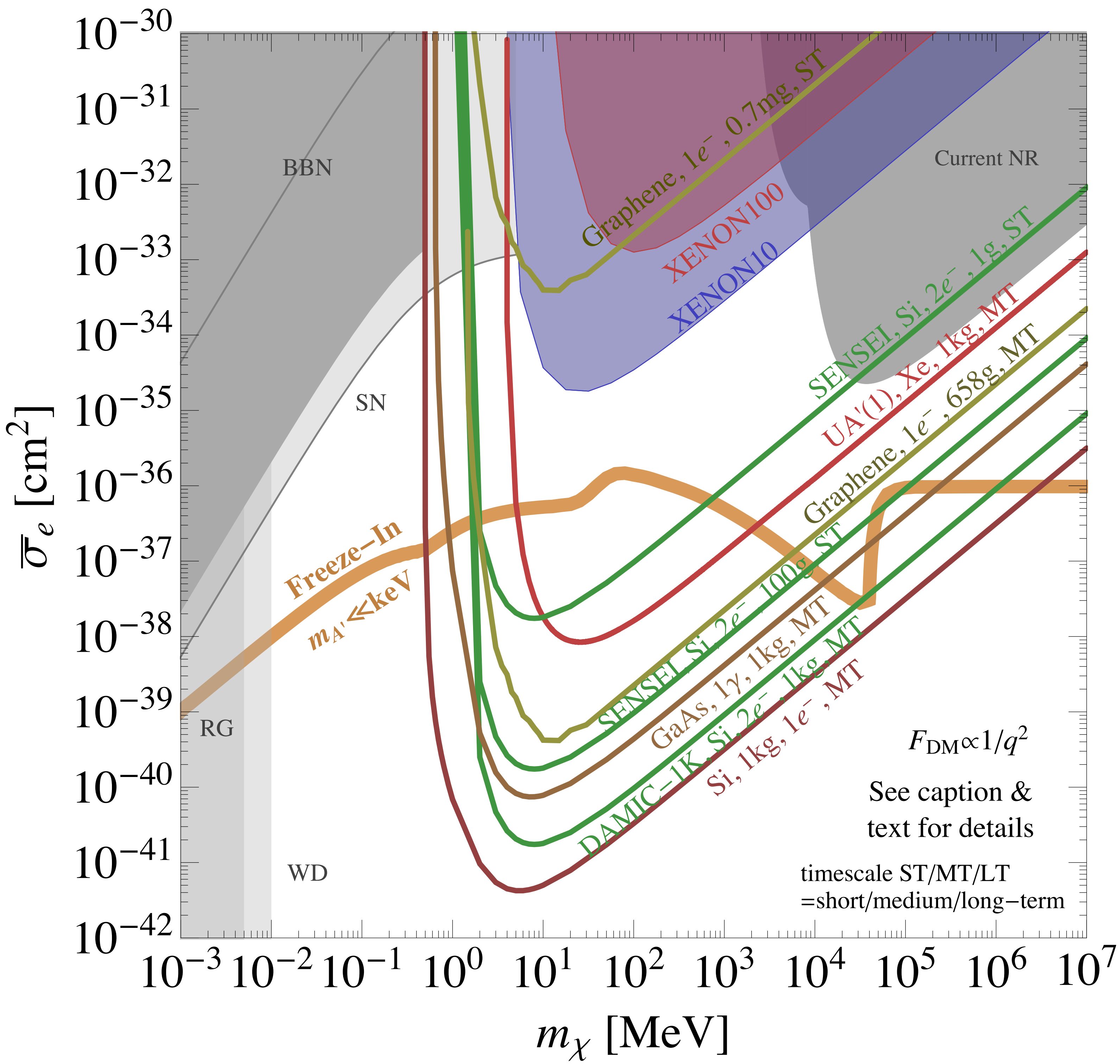
- Absorption coefficient **C = 10^{-3}**



Outlook

- WIMPs in the GeV-TeV range are much explored. Directionality might be the tool to go deeper (in the GeV mass range where the neutrino floor is much higher).
- DM-electron scattering can be relevant for other DM models with **masses in the MeV-GeV range**
- Graphene-based structures might offer **anisotropic target** for DM
- **CNT can help to pack more mass in less space**
- **Trying to follow up our ideas with experimental proof of the anisotropic behaviour and of the conceptual detection scheme**

Back-up

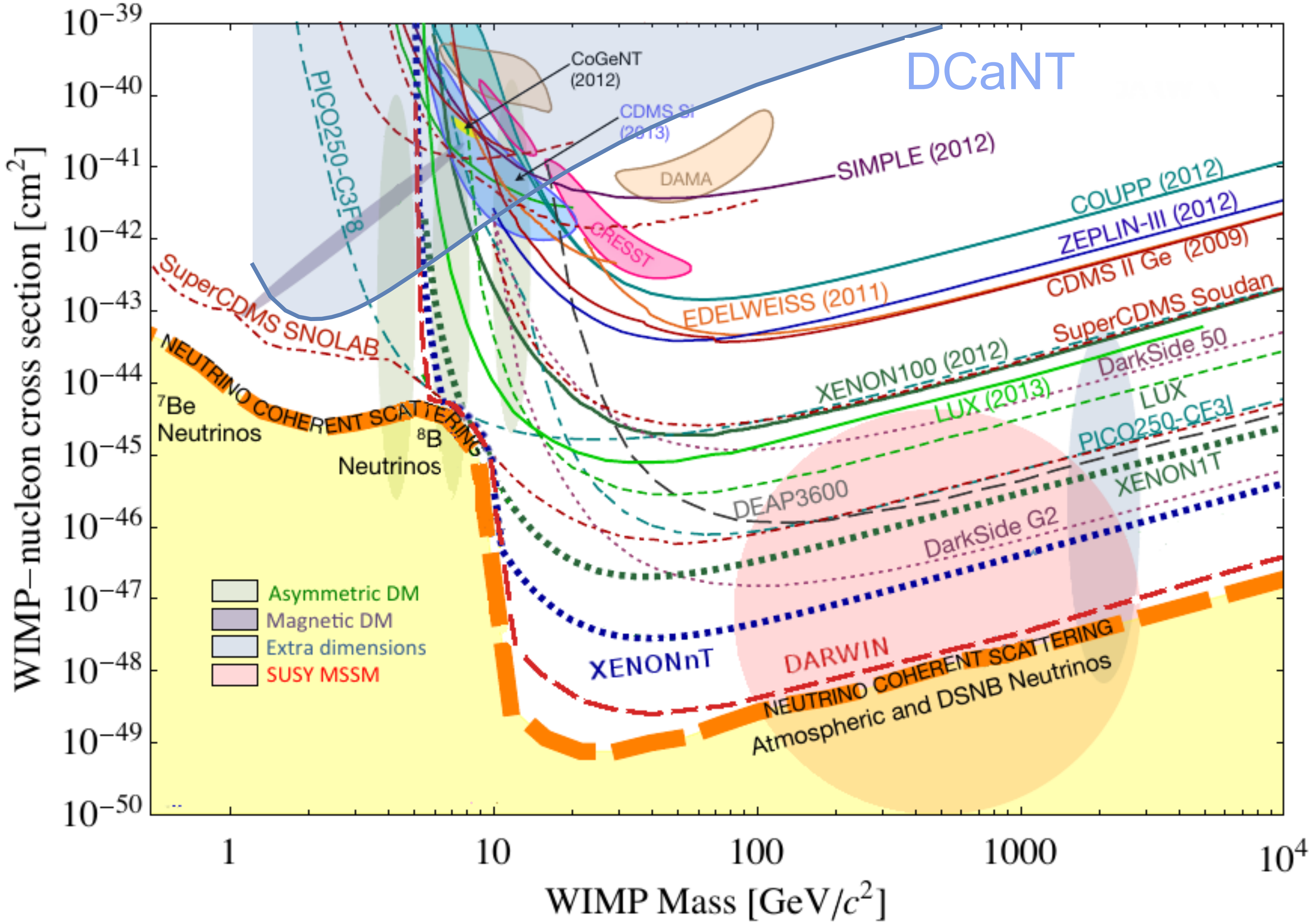


Near-term results for MeV Dark Matter expected with 2e⁻ thresholds in Si (DAMIC/SENSEI/ SuperCDMS)

→Significant overlap in sensitivity to follow up with **Directional Detection (PTOLEMY-G³)**

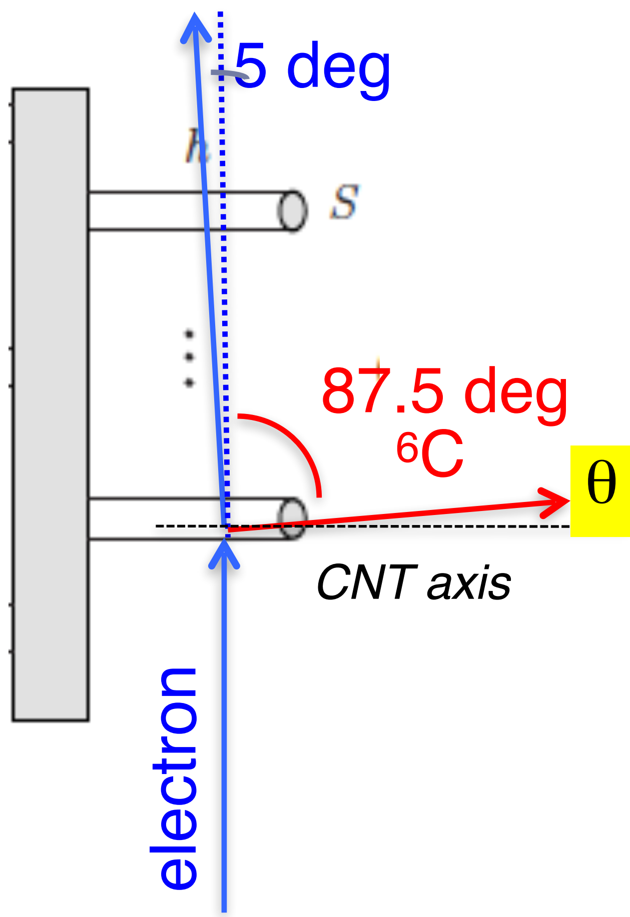
Looking for dark matter

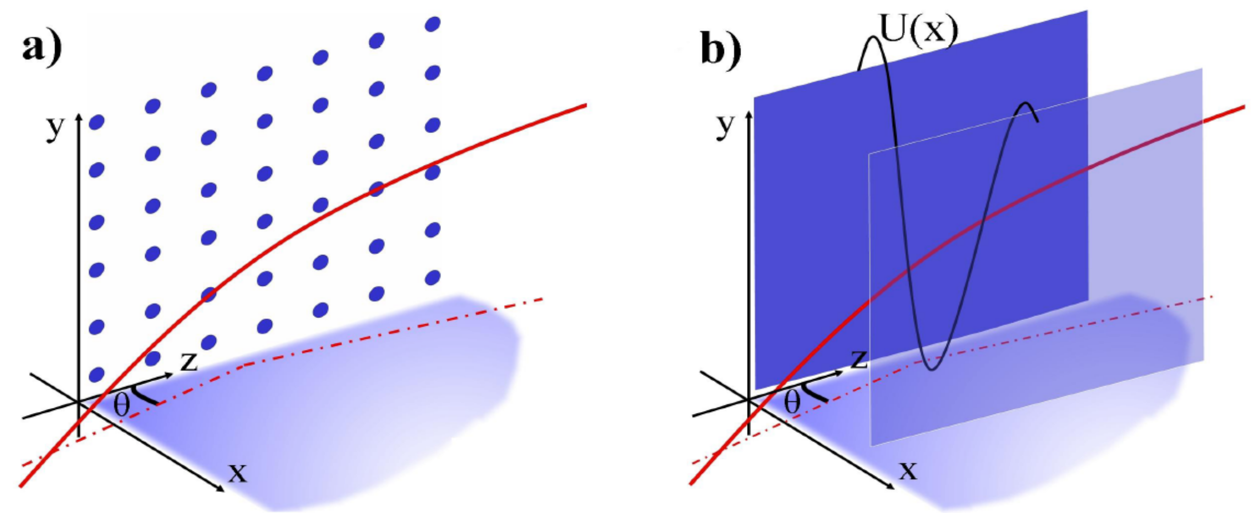
Sensitivity for an exposure of 0.4 kgy



Channeling of an ion

Ion elastically scattered almost at 90 degree





Critical (Lindhard's) angle

$$\theta_C = \sqrt{\frac{2U_0}{E}}$$

Potential well depth

Particle energy

If $\theta < \theta_C$ ions are channeled!

θ_C **~ 4 deg** for ^{6}C channeling

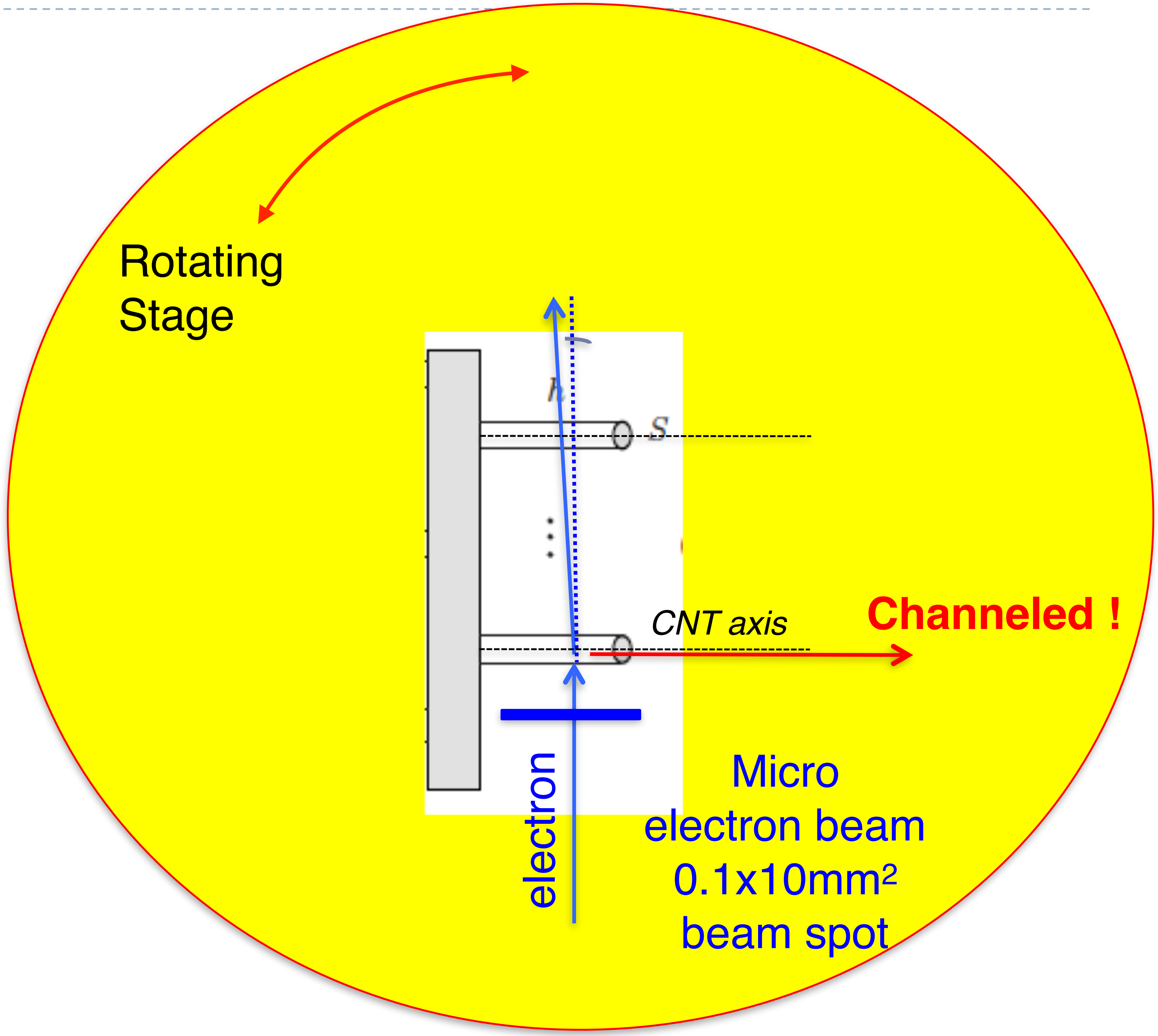
Demonstrate ~10-100 KeV C ions are trapped.
Trapping has a larger effective θ_C **~ 35 deg**

Experiment at BTF: CNT channeling

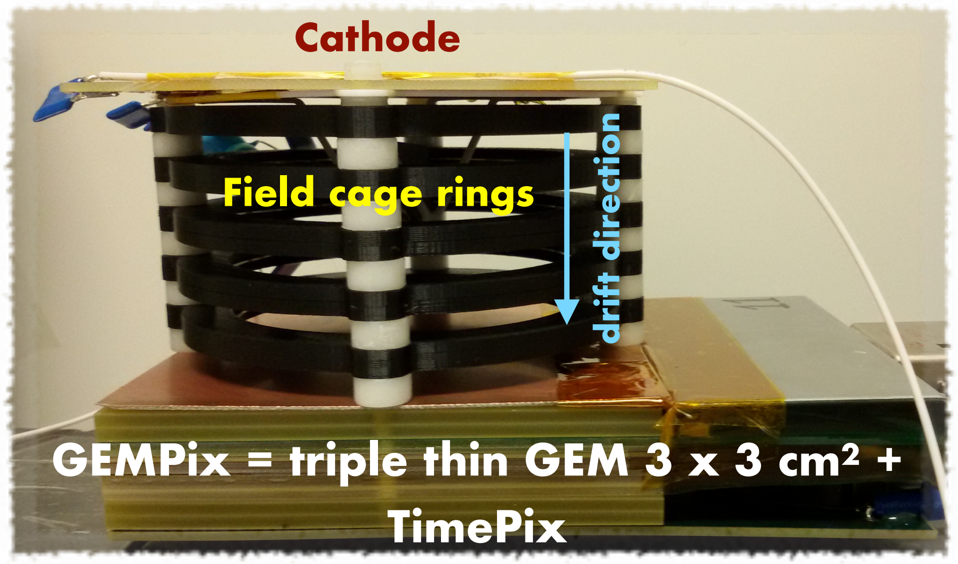
$\theta < \theta_C$

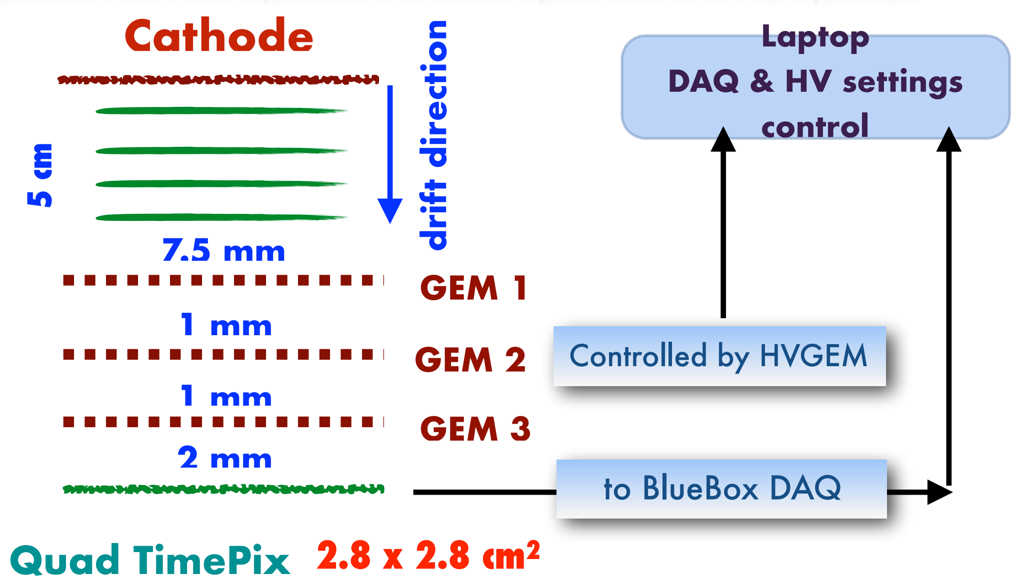
Need a ribbon-like beam

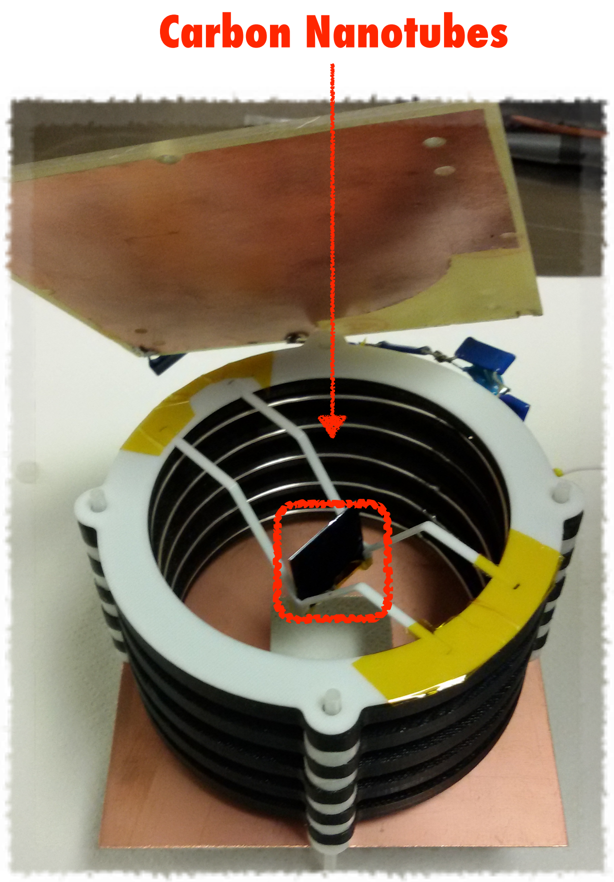
New collimators at BTF might be available later this year (June?)



New field cage (Fall 2016)



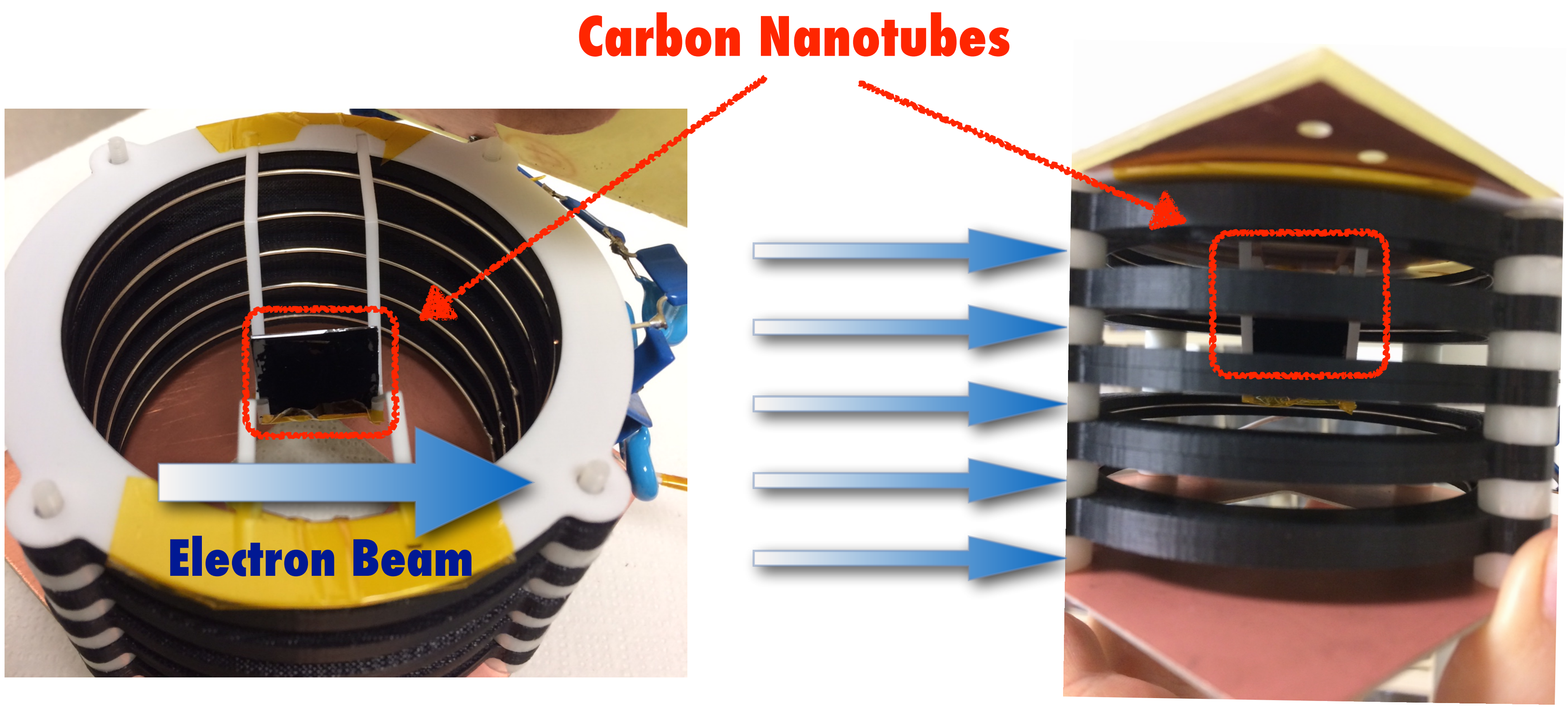




Rings support structure (black) and support for CNT (white) manufactured with 3D printer (LNF and RM)

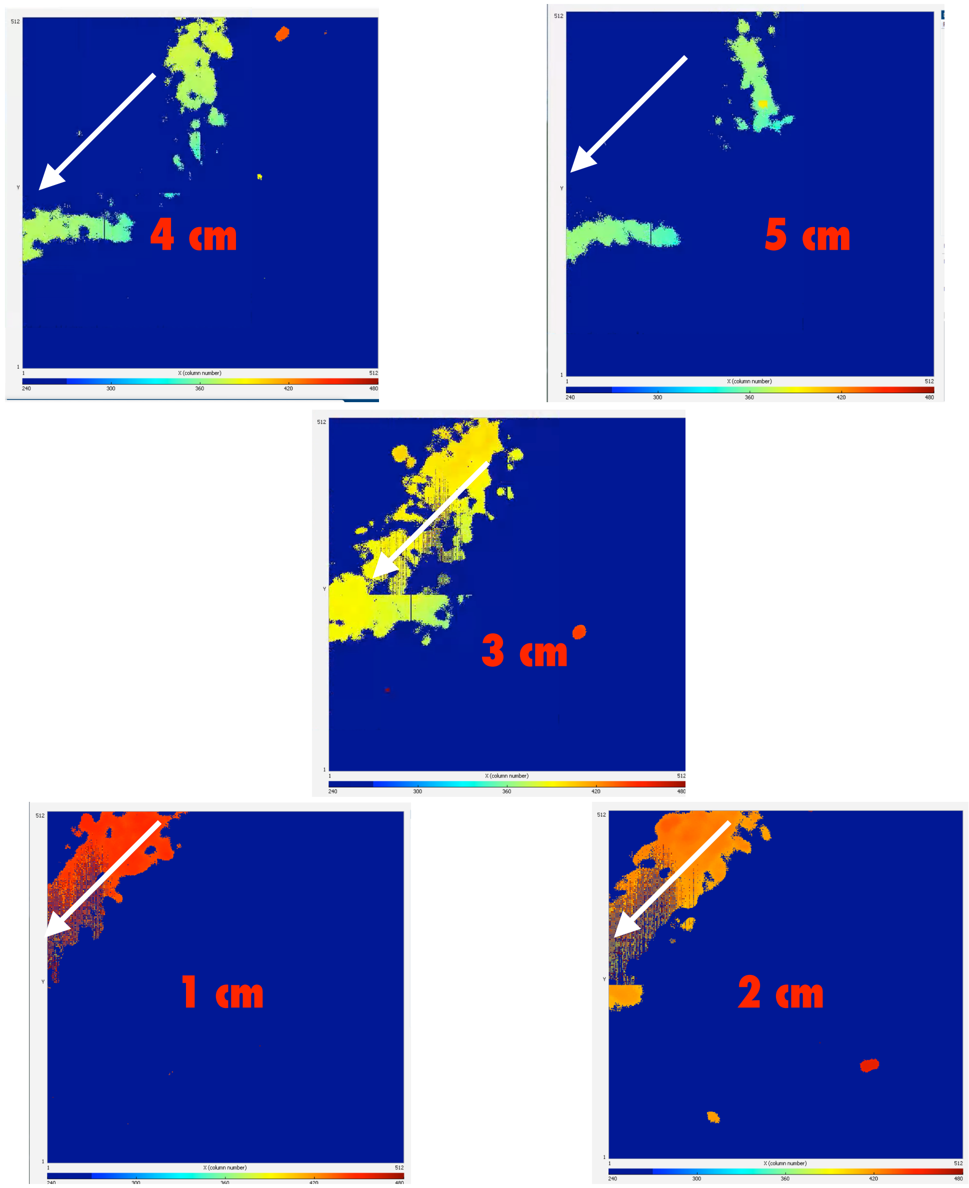
CNT target into the field cage

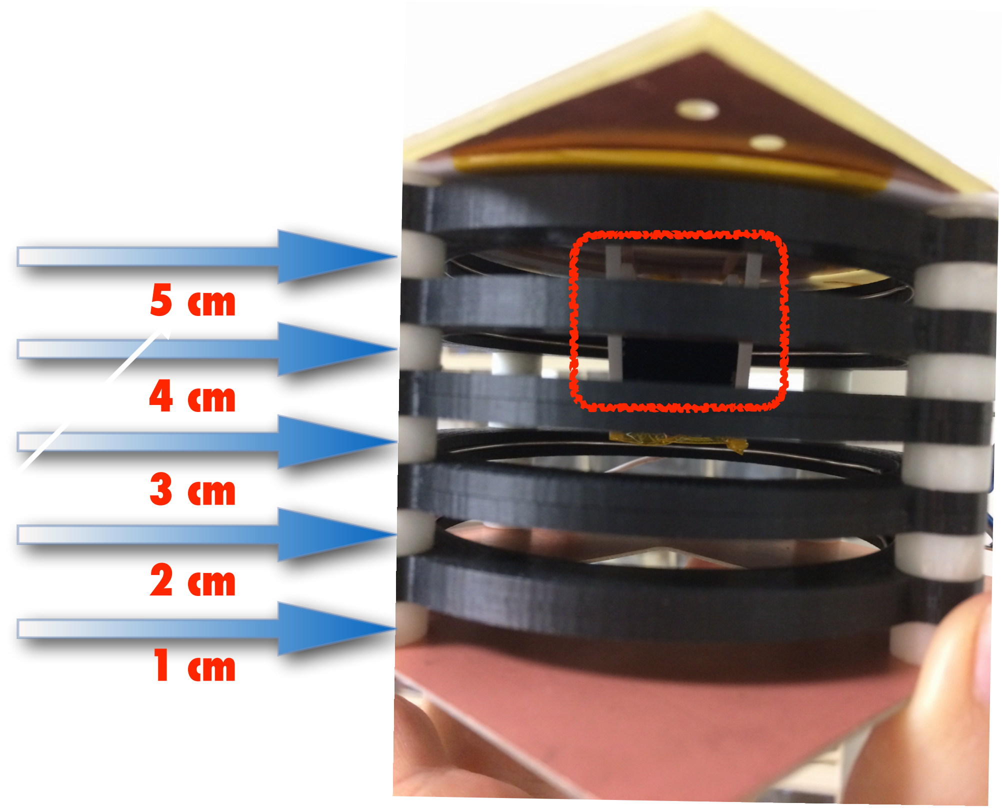
- BTF beam regulated at various heights
- Study effect of the target located into the E field



Drift field lines

- ***Color*** is **time of arrival** at each pixel
- Beam moved at different vertical position



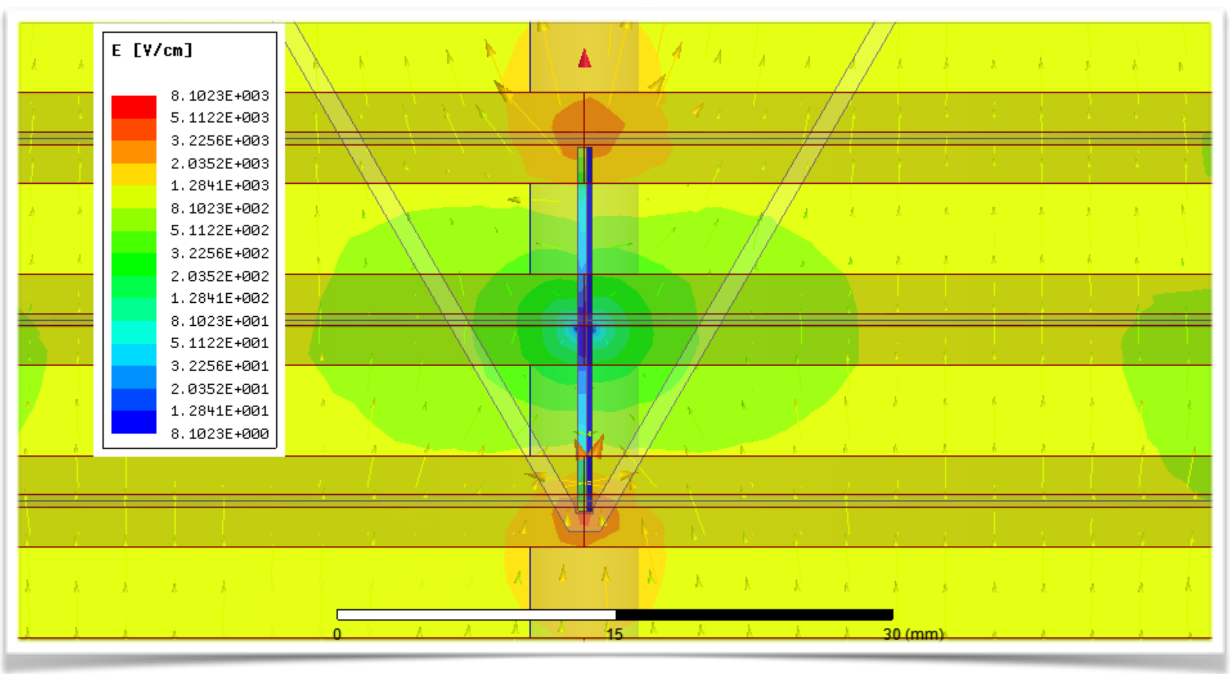


$Ar:CO_2:CF_4$ TOA data @ 300 Torr
(confirmed with pure SF_6 @ 150 Torr)

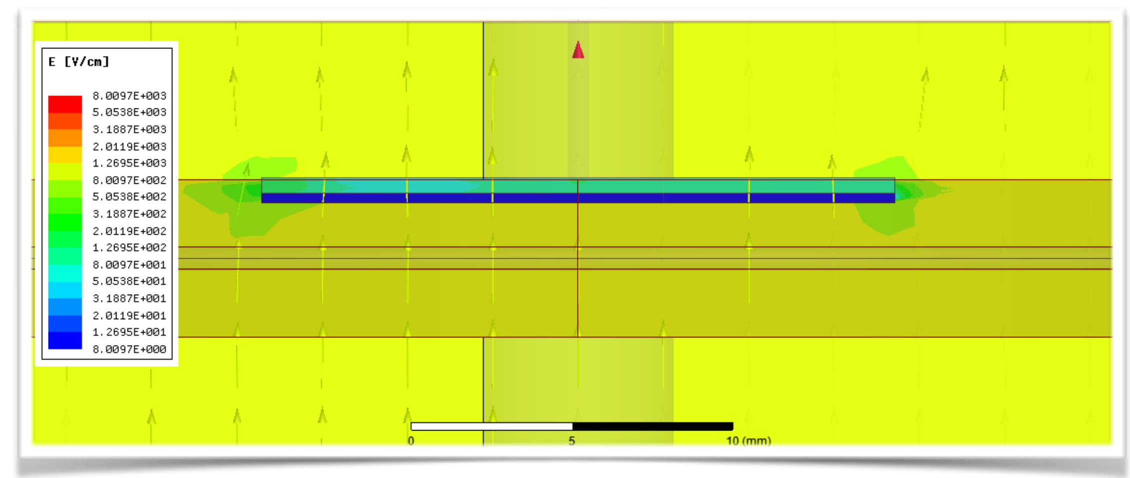
- When the beam is at the same height of the target
  the drifting electrons are “sucked” towards the CNT target…!

Drift field simulation

- Drift field lines deformed (ANSYS)
  - graphite conductive layer to mimic CNT



Vertical target
(CNT axis horizontal)



Horizontal target
(**CNT axis** vertical
and **parallel** to drift field lines)