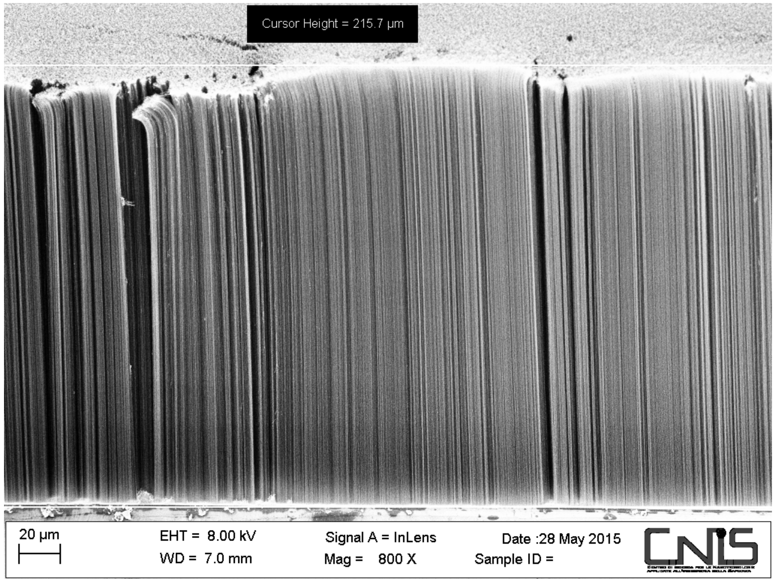


DCaNT: Directional WIMP detection with carbon nanotubes

Gianluca Cavoto INFN Roma

CYGNUS-TPC meeting

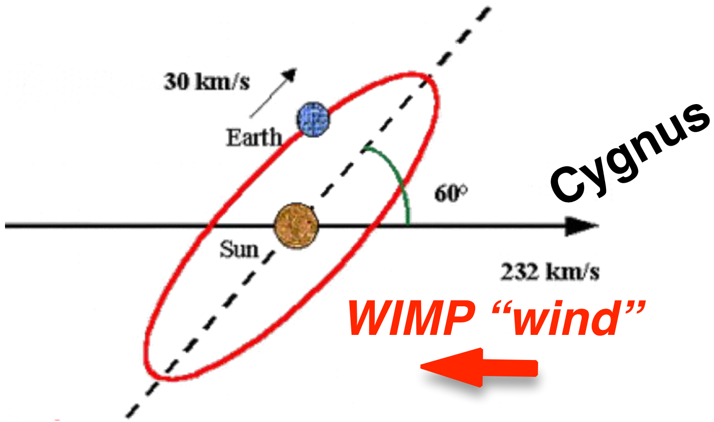
Apr 7th 2016

Laboratori Nazionali di Frascati

Outline

- WIMP directional searches

- Carbon Nanotubes (**CNT**)
  - **Aligned** CNT arrays as **anisotropic target**
  - *Ion channeling inside a CNT*
  - ***Ion trapping*** *in the CNT array*



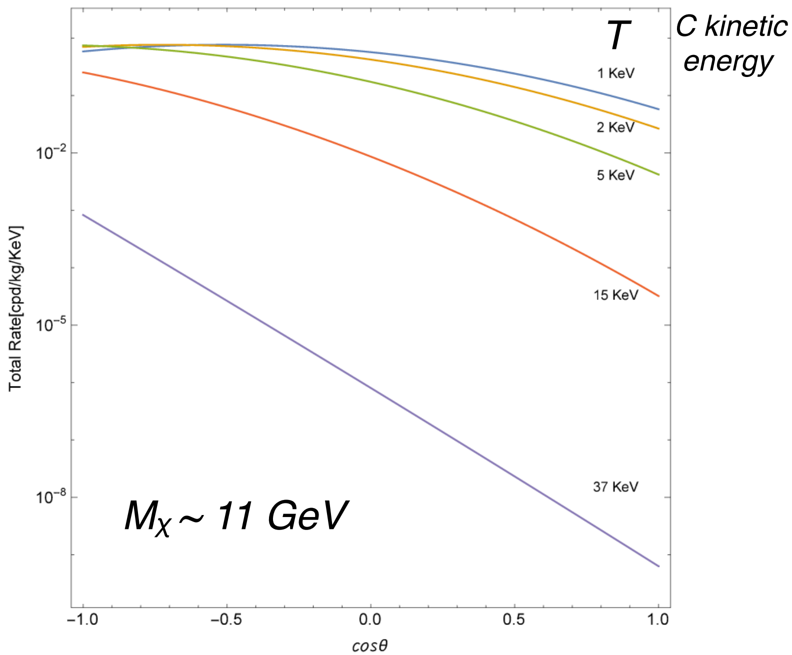
- **Detection of C ion**
  - In a Time Projection Chamber (*Triple-GEM TPC*)
  - Low threshold optimisation and large scale readout.

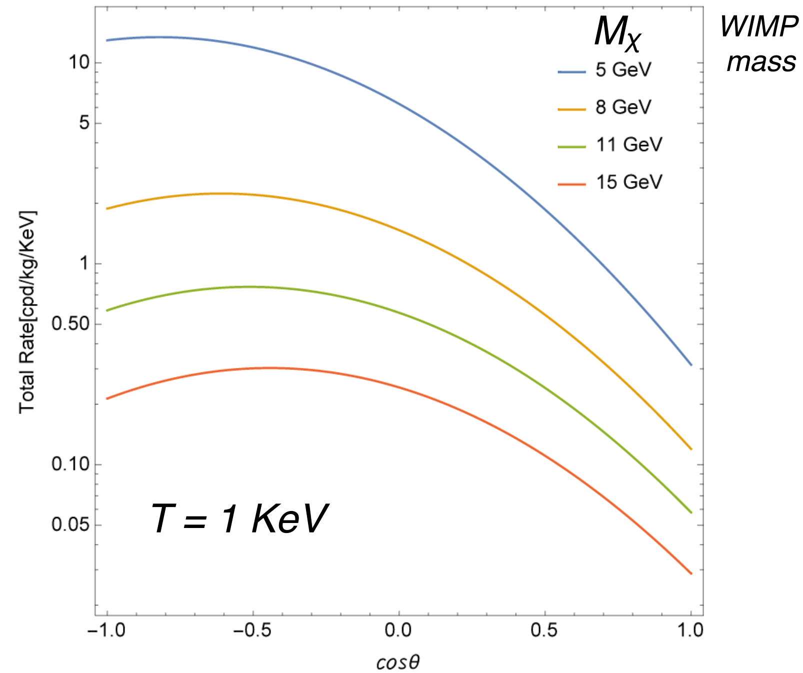
L.M. Capparelli, GC, D. Mazzilli, A.D. Polosa, ***Phys.Dark Univ.*** 9-10 (2015) 24-30, Phys.Dark Univ. 11 (2016) 79-80 (http://arxiv.org/abs/1412.8213)

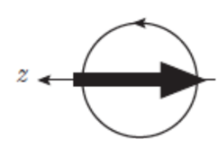
GC, E.N.M. Cirillo, F. Cocina, J. Ferretti, A.D. Polosa, subm. to **EPJC** (http://arxiv.org/abs/1602.03216)

Anisotropy in scattering rates

- Modelling based on elastic scattering of WIMP on ***C*** ions $\sigma_{\chi p} \sim 10^{-4}$ pb





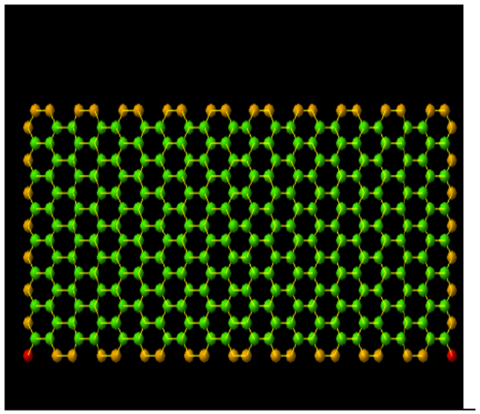


θ = π

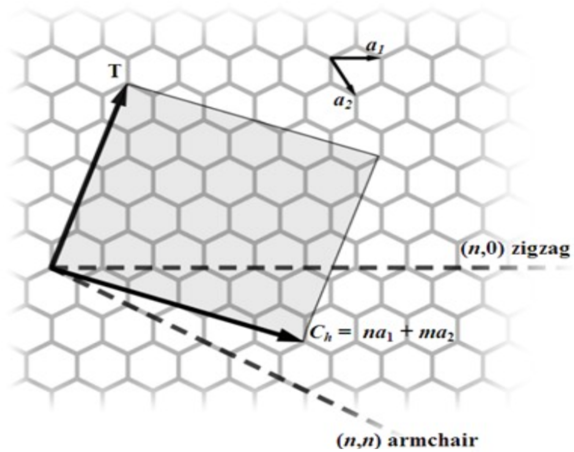
WIMP "wind"

Carbon nanotubes

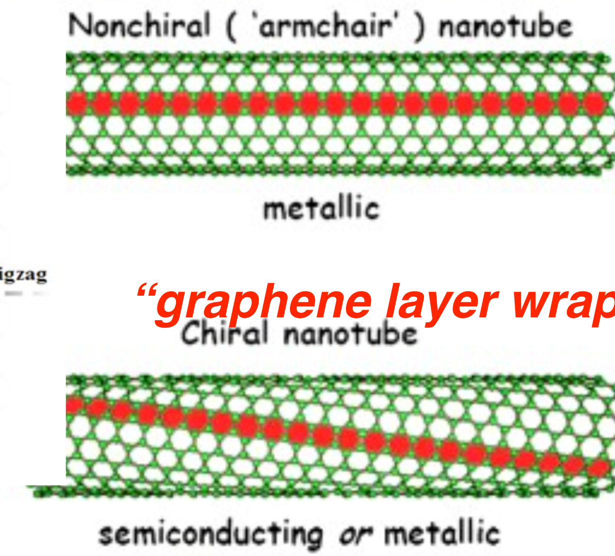
Structure: Imagine wrapping a sheet of graphen into a nanotube



Shigeo MARUYAMA, Univ. Tokyo



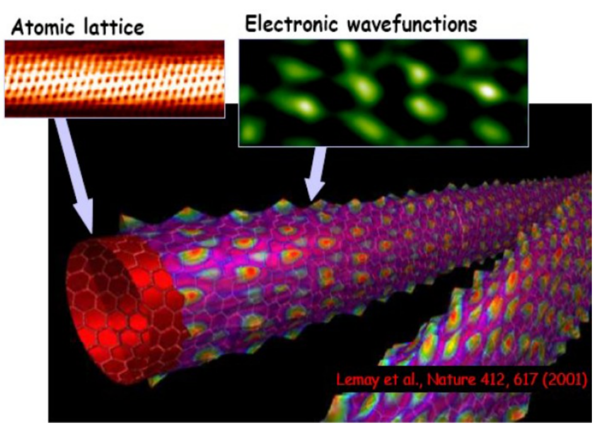
$$R = \frac{l\sqrt{3}}{2\pi}\sqrt{n^2+m^2+nm} \qquad l = 0.14nm$$



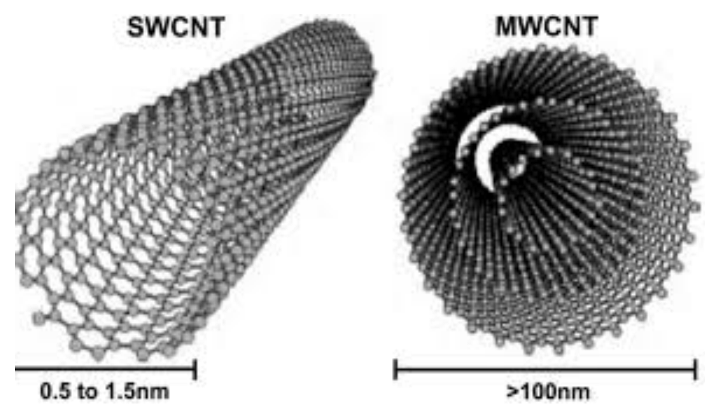
"graphene layer wrapping"

n=m → metallic

n – m= multiple of **3 → semiconducting**



Electron orbitals on CNT surface



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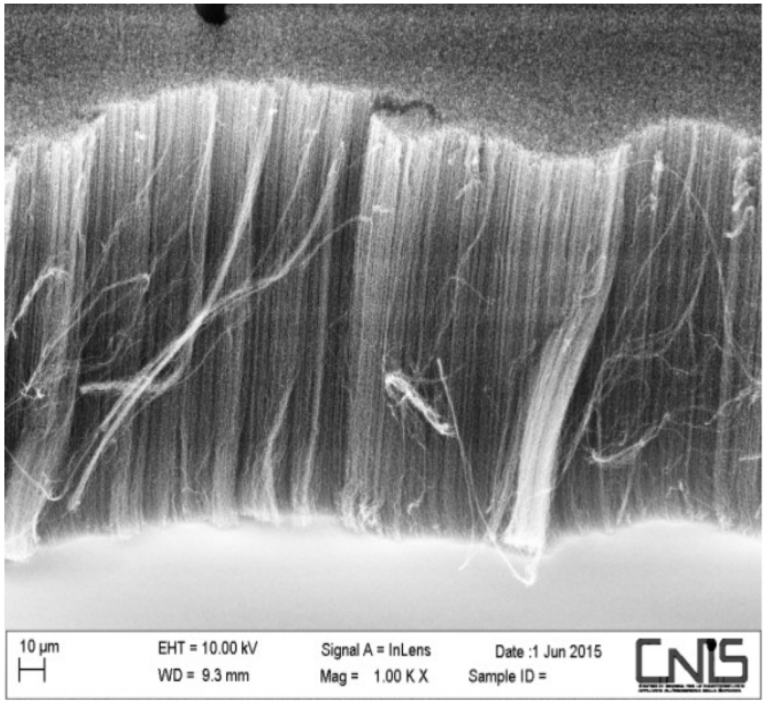
C.Mariani
Sapienza
Univ. Roma

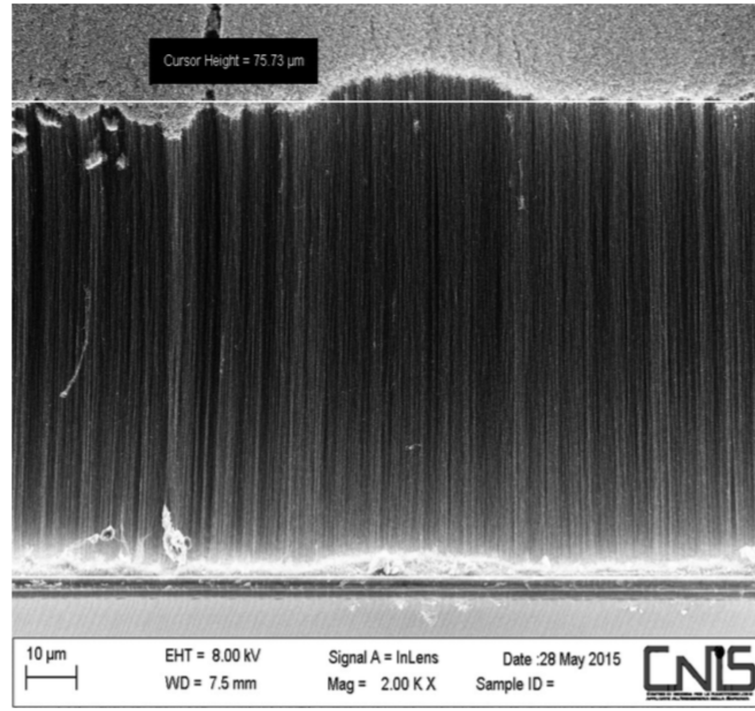
CNT with scattering electron microscope

collaboration University of Mons, Belgium



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

commercial



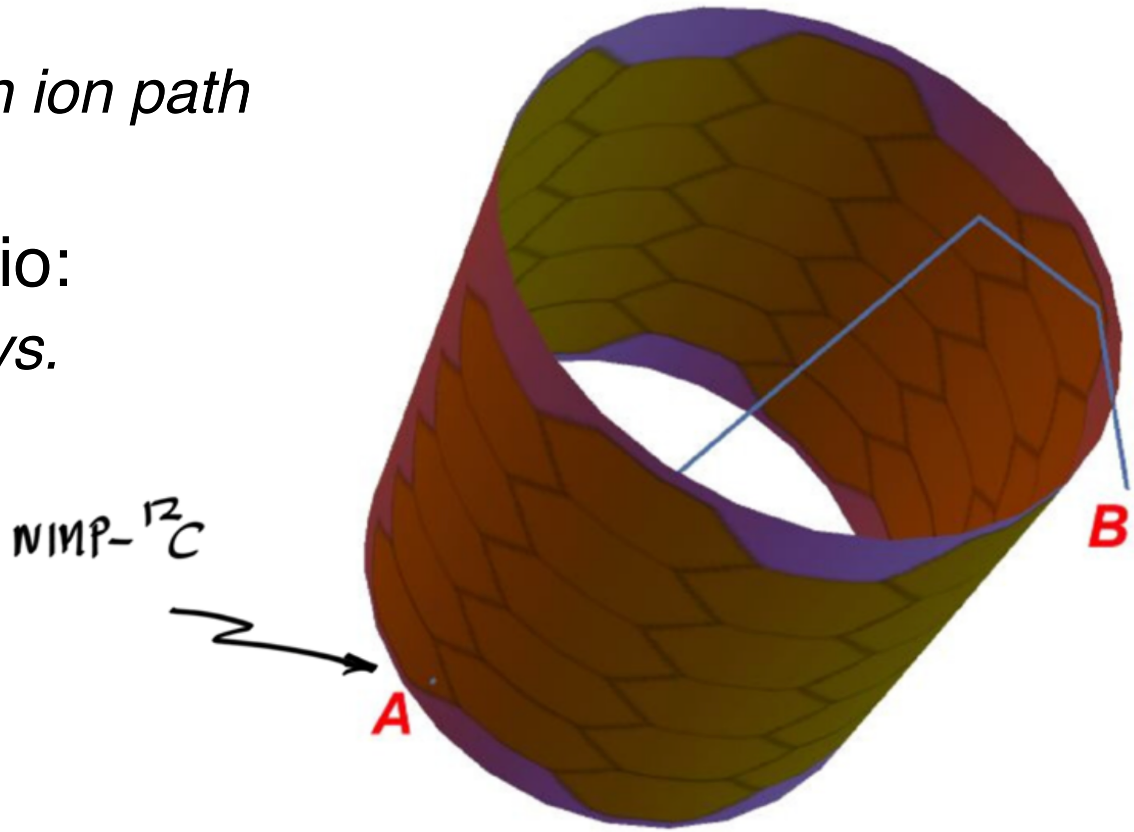
length: 75 ***µm***
ext. diameter: ***(13 ± 4) nm***
aspect ratio: 0.6 ***x10⁴***

Scattering on a carbon nanotube

- **CNT are "empty"**
  - *no electrons*
    along the carbon ion path

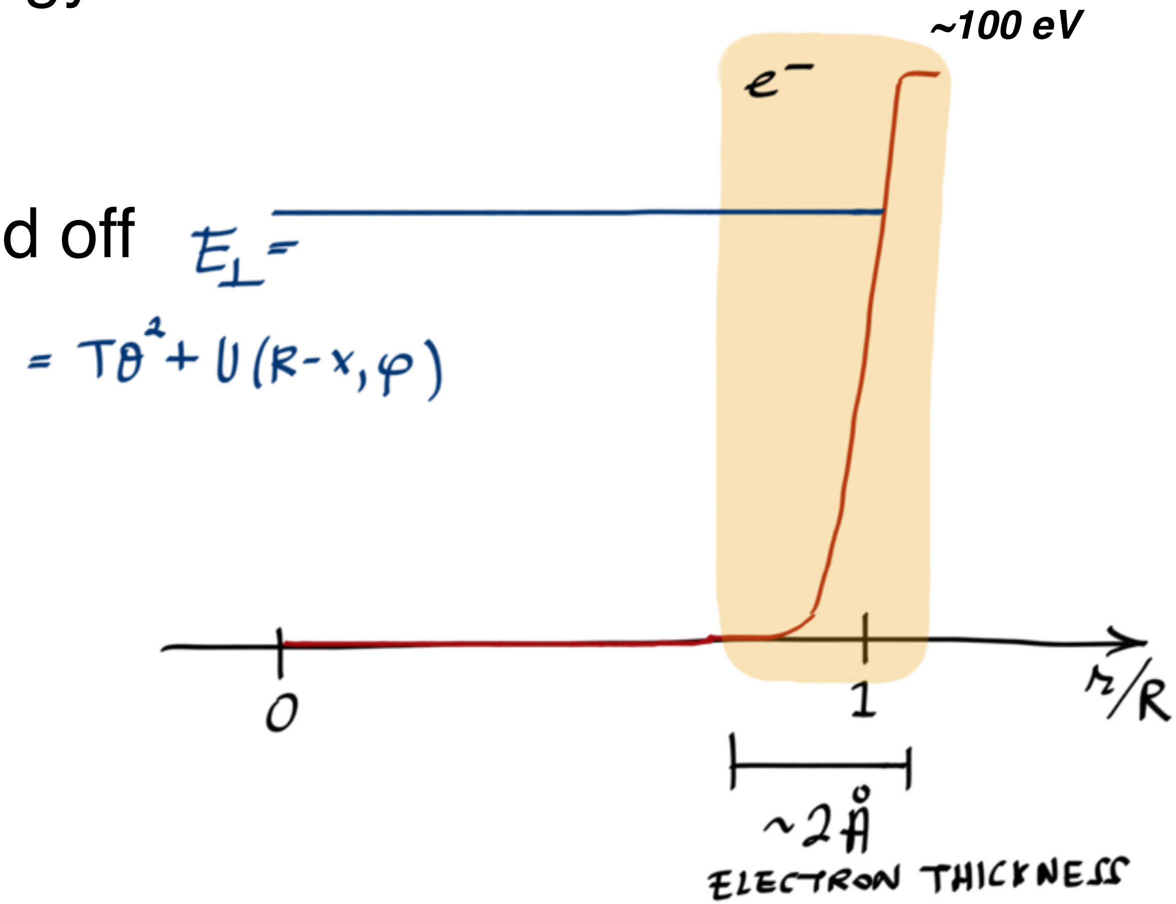
- Large aspect ratio:
  ~10 nm diameter vs.
  ~100 μm height

- *"**target**" mass*
  on the CNT
  surface



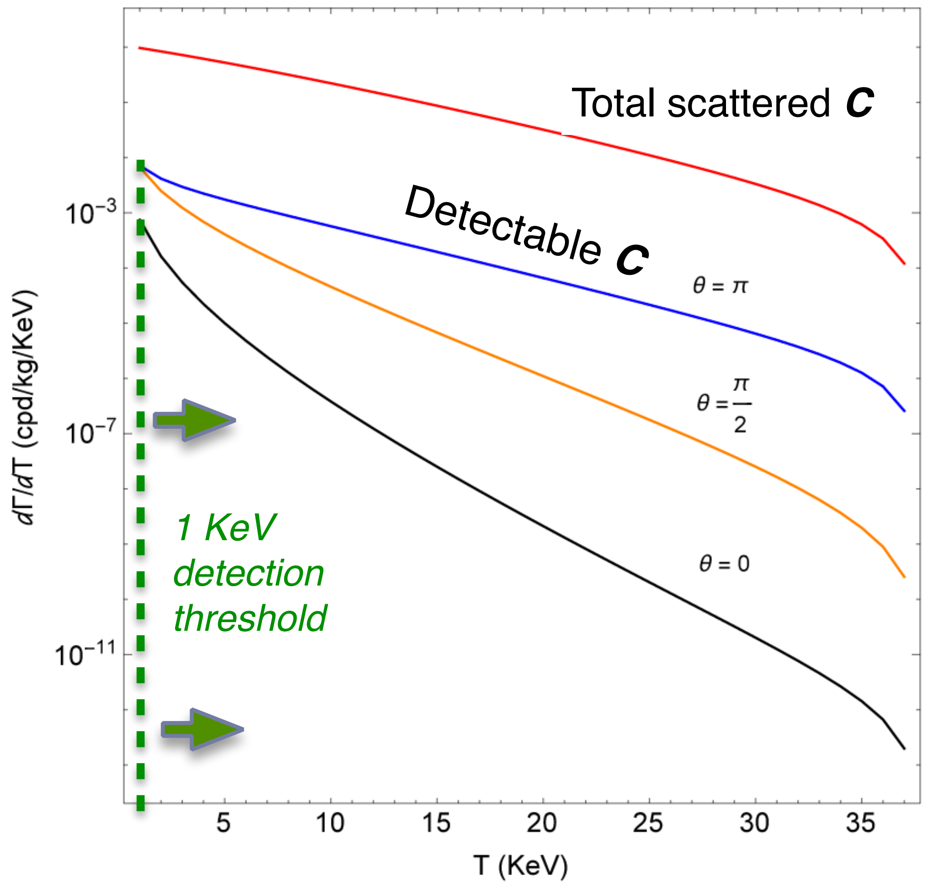
CNT as a potential well

- Transverse energy is **conserved**
- $^{6+}$***C*** ion scattered off the CNT are **channeled in the CNT**
- Little effect of electrons on CNT surface

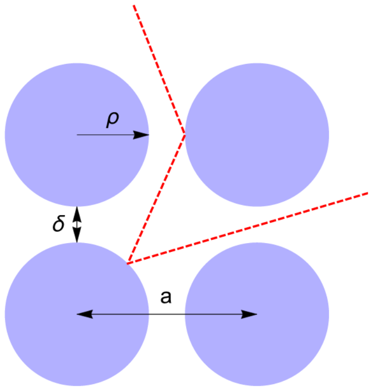


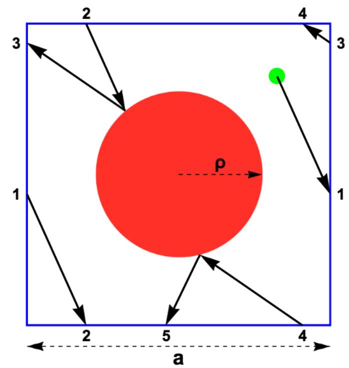
CNT anisotropic medium

- **Aligned and oriented CNT "brush"**
  - *Recoiling **C** ions are emerging from CNTs with different rates* **depending** on CNTs **orientation.**
  - When ***C*** ions are **not channeled** they are **absorbed** within the brush
- Effect of rechanneling or **inter-CNT trapping** NOT included HERE



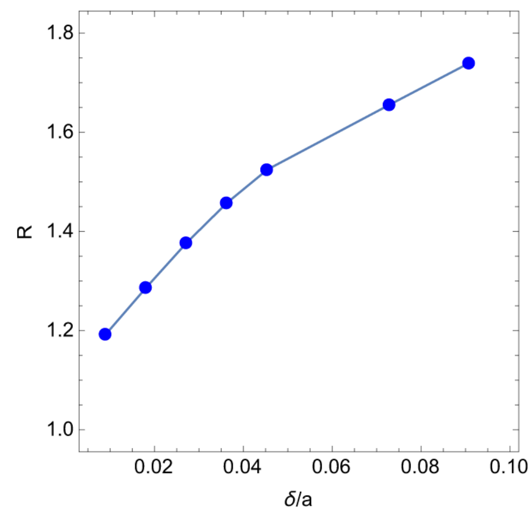
Infinite horizon billiard





- CNT brush as an array of cylindrical obstacles (LxL): ***trapping* within the inter-CNT space**
- *MC simulation of 2D motion (**C ions below energy barrier**)*

Ratio of our simulation to a semi-analytical result



Average **time** to **exit** the lattice from its **sides**

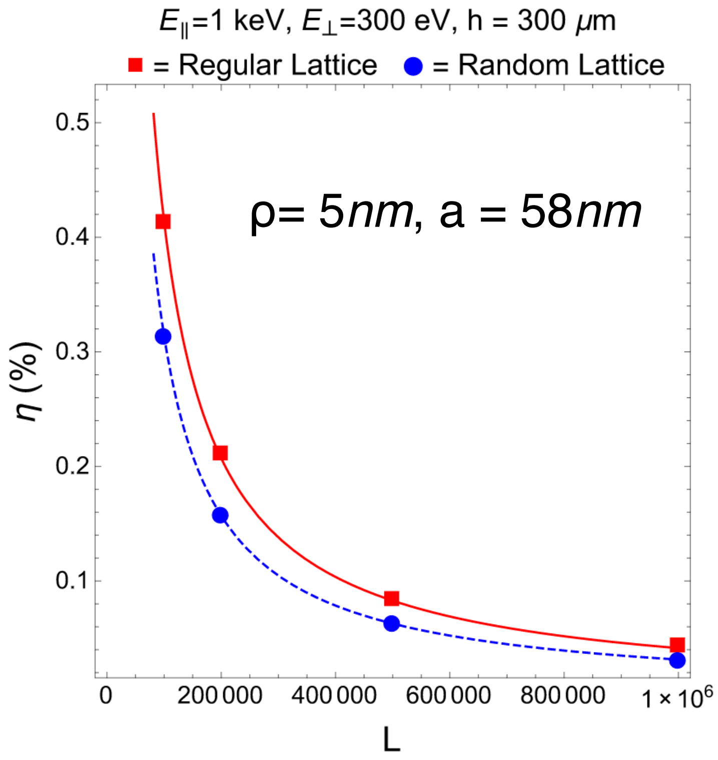
$$\langle \tau_{out} \rangle = \frac{L^2}{7} \tau_R \text{ with } \tau_R = \frac{\pi \left(a^2 - \pi \rho^2 \right)}{4 v_\perp \delta}$$

Small δ → Machta-Zwanzig regime

[1]J. Machta and R. Zwanzig, Phys. Rev. Lett. 50, 1959 (1983).

Lateral escapes of C ion

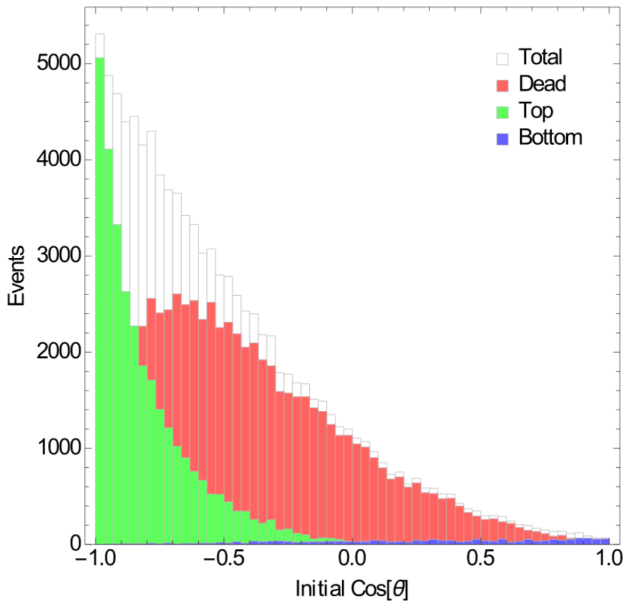
- C ion can leave the array at its top (*desired!*) or from the lateral sides (*avoid!*)
  - Fraction of particle leaving from the sides versus ***side length L***



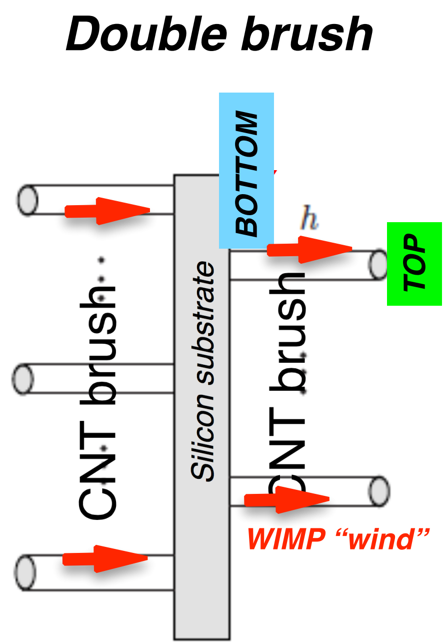
Lateral losses are negligible for realistic CNT brushes (L ~ 10^5)

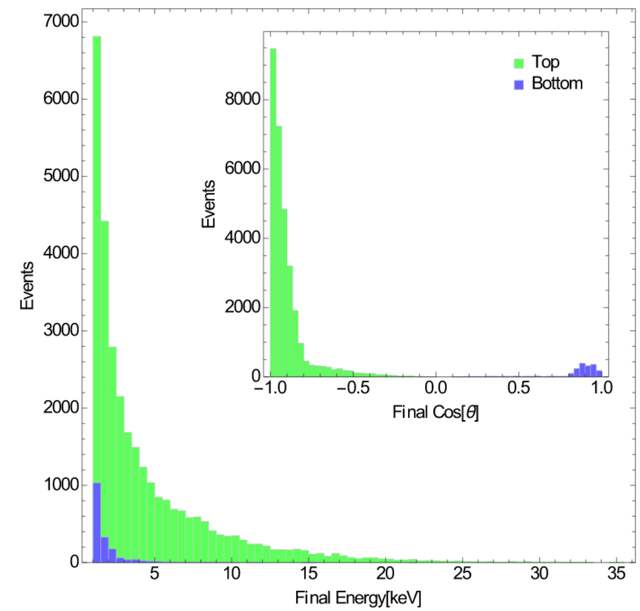
C ion moving within the array

- Simulation including energy losses and scattering on the CNT walls (***C ions can penetrate CNT***)
  - Initial kinematics according to WIMP-C scattering



Initial C ion direction





Final C ion energy and direction

Trapping efficiency much larger than single CNT channeling

Concept of detector for WIMP based on CNT

- Use **aligned CNT** as **target** mass (~few g/cm3 density possible)
- Aligned CNTs as an **anisotropic** medium: scattered ***C*** ions are escaping from the top of the array when emitted almost parallel to CNT axes.
- **Detect** the **channeled *C*** ion in a **very thin** (low pressure) gas chamber
- Escaping ***C*** ion **energy**, ***C*** ion **range** in gas and **direction** measurements should be possible

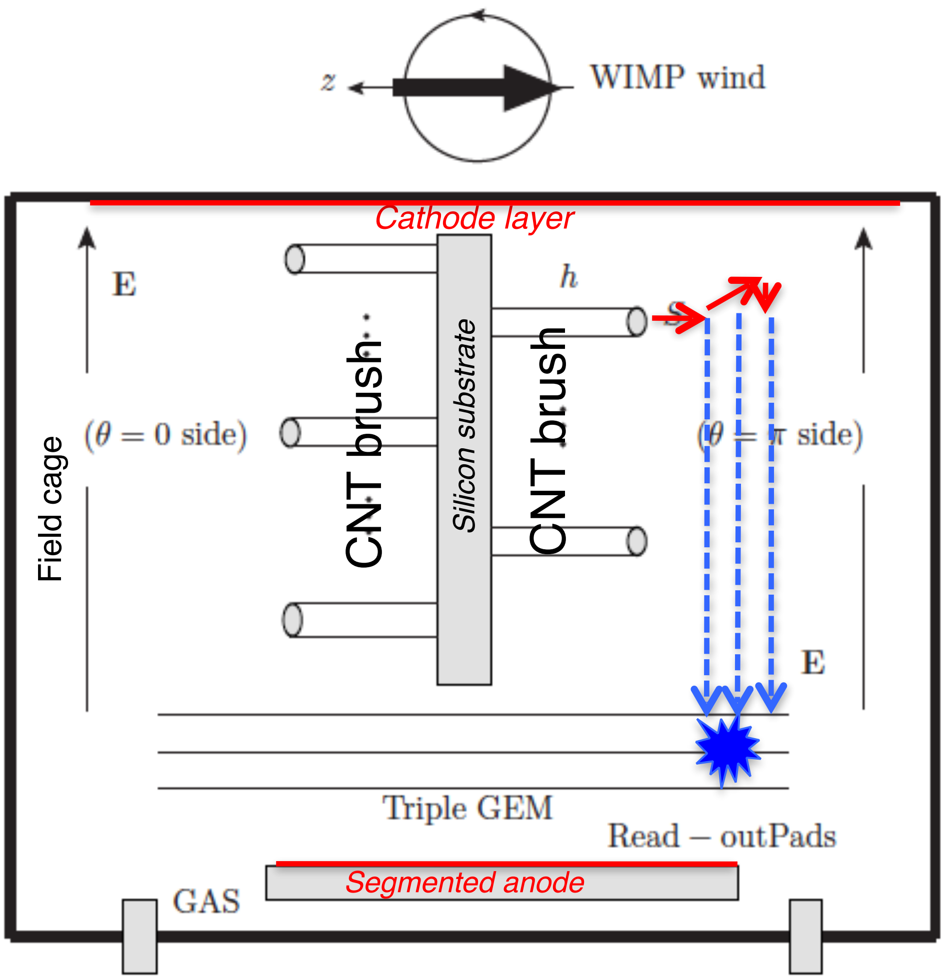
Clearly, demonstrating that a 1-100 KeV *C* ion is effectively channeled in CNT and then detectable is in order to advance with this detector concept

Scheme for detection of C ion

Low pressure gas TPC

Not to scale!

h ~100 μm
S ~ π(5)² nm²

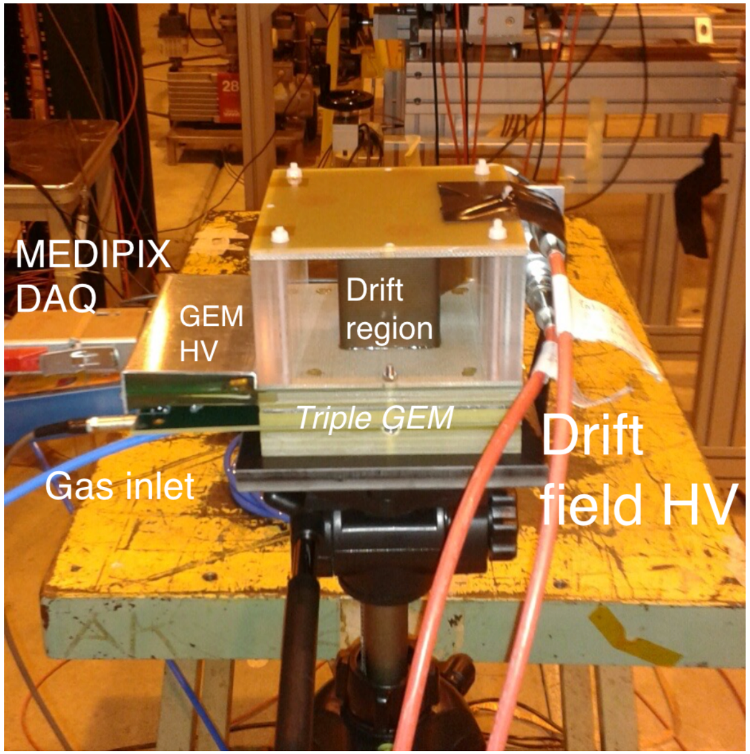


Must be able to measure:

- Kinetic energy (total ionization)
- **range (segmented anode)**
- **average direction (relative electrons time-of-flight)**

A TPC-GEM for the first test

- A time projection chamber with GEM amplification at anode



F.Murtas (LNF-CERN)

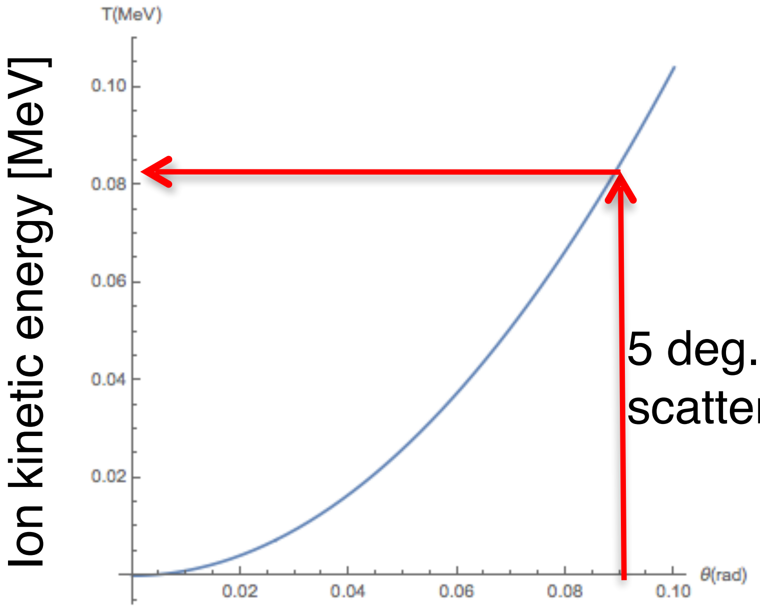
Anode is an ASIC used to read-out signals from **four** 512x512 **55μm** silicon pixel sensors (MEDIPIX)

In this configuration silicon pixels are removed: the **charge signal is generated in the Triple GEM**

Built at INFN LNF

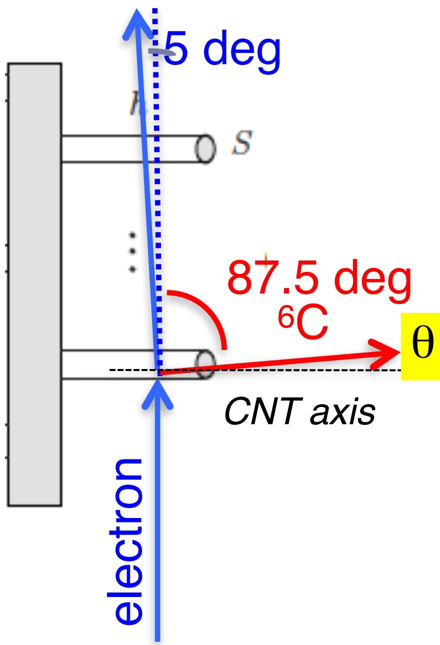
Experiment at Frascati BTF

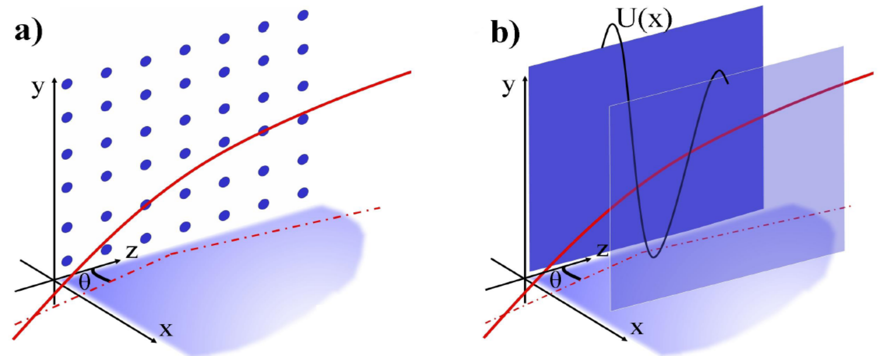
- Use electron beam at LNF BTF to "extract" carbon ions from CNT
  - One carbon ion elastically scattered by a 500 MeV electron
    - PRO: trigger on scattered electron at well defined angle: beam clearly visible
    - CON: electron beam can induce a sizeable background into TPC



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

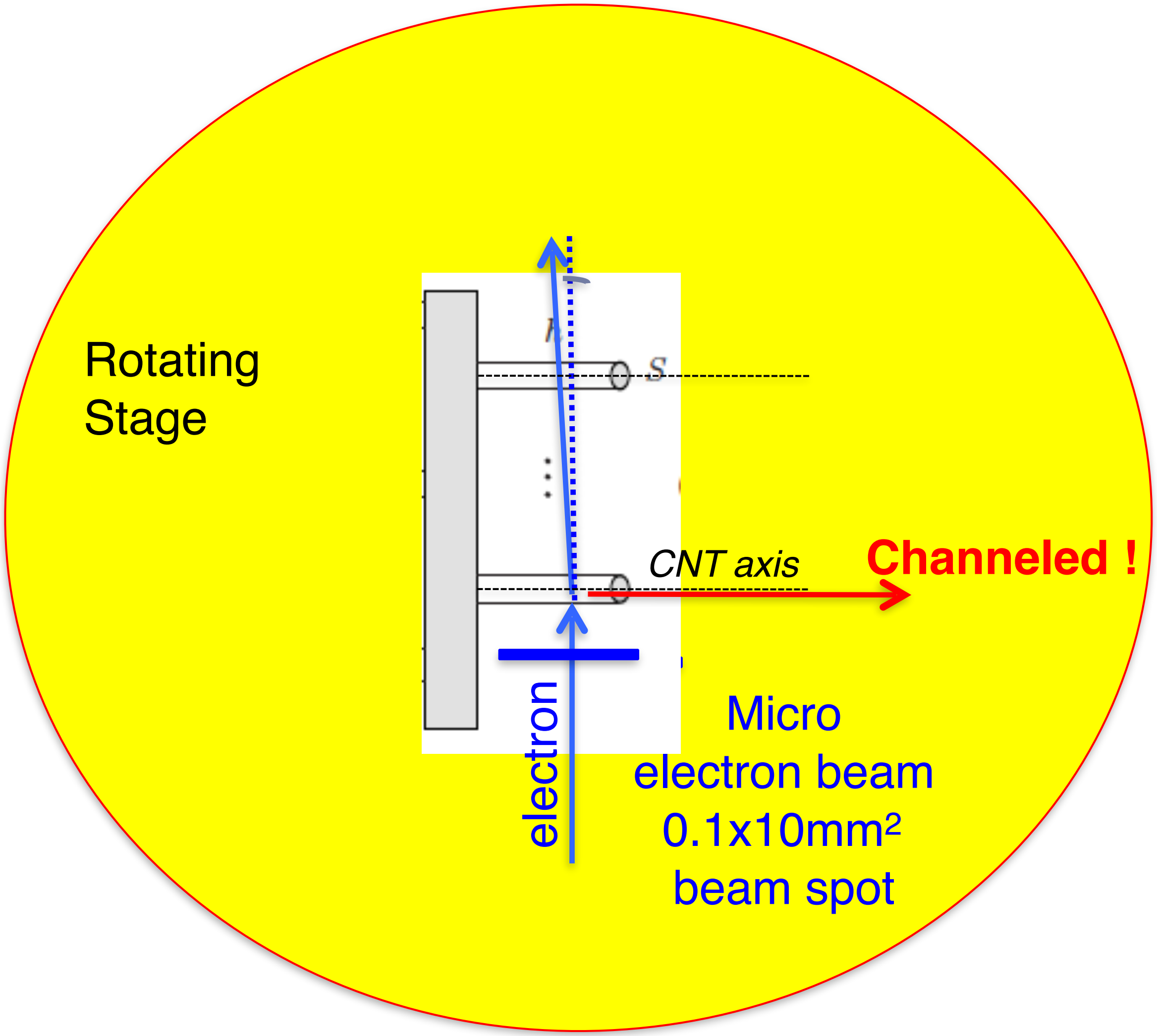
If $\theta < \theta_C$ ions are channeled!

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**

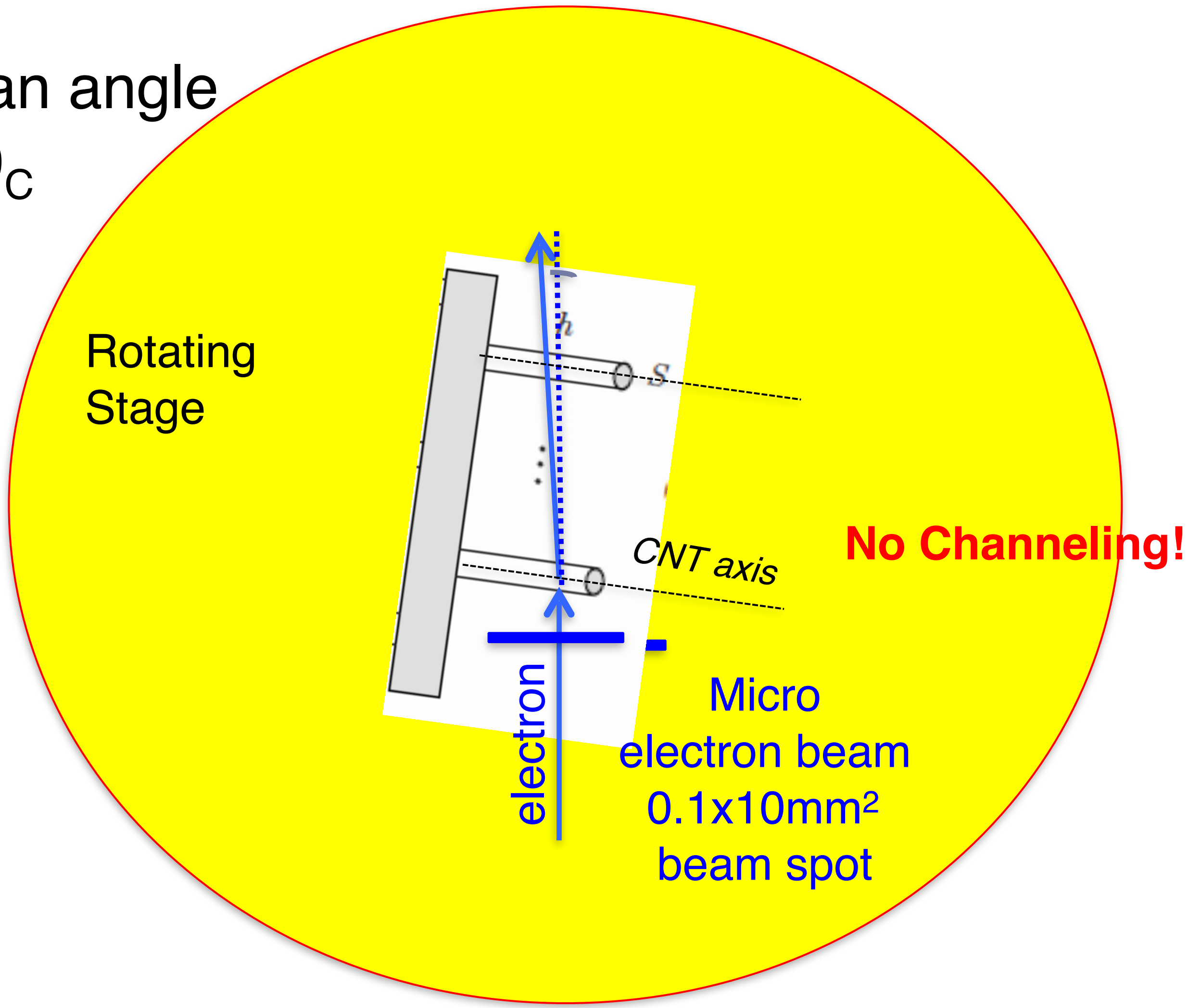
Experiment at BTF:channeling

$\theta < \theta_c$



Experiment at BTF

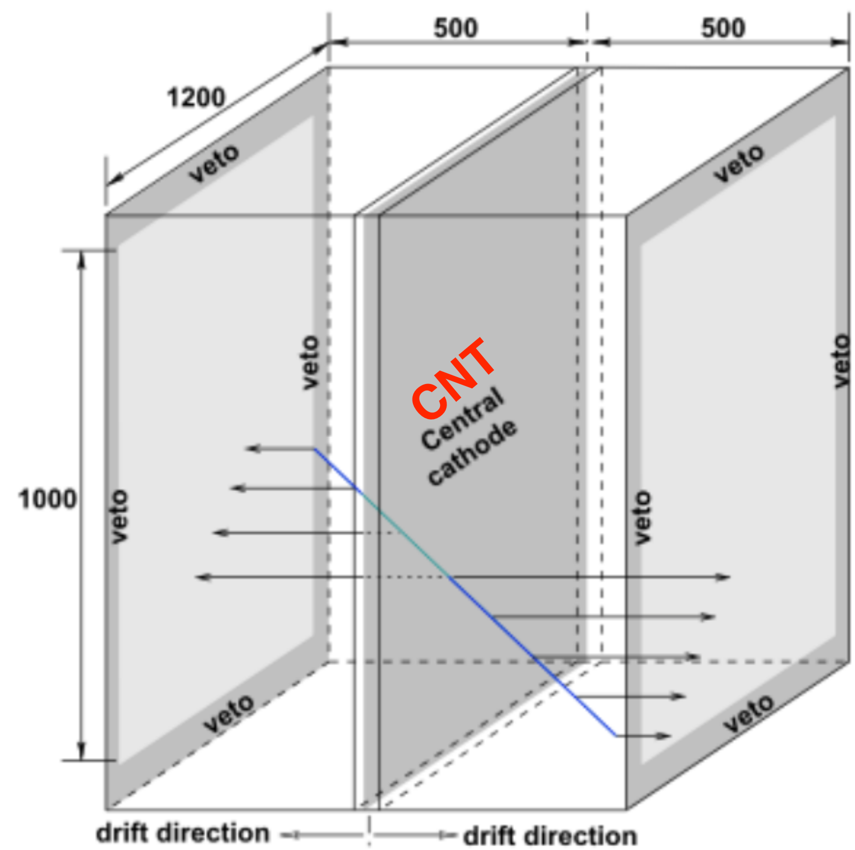
Rotation by an angle wider than θ_C



A prototype for a CNT DM detector

- If channeling of C ion is demonstrated,
  build a prototype for large scale readout

- Re-use the experience of directional DM low p gas detector (*DRIFT*)
  - ***Increase target mass putting CNT on the central cathode.***



Low threshold on C detection is the crucial limit

Functionalization

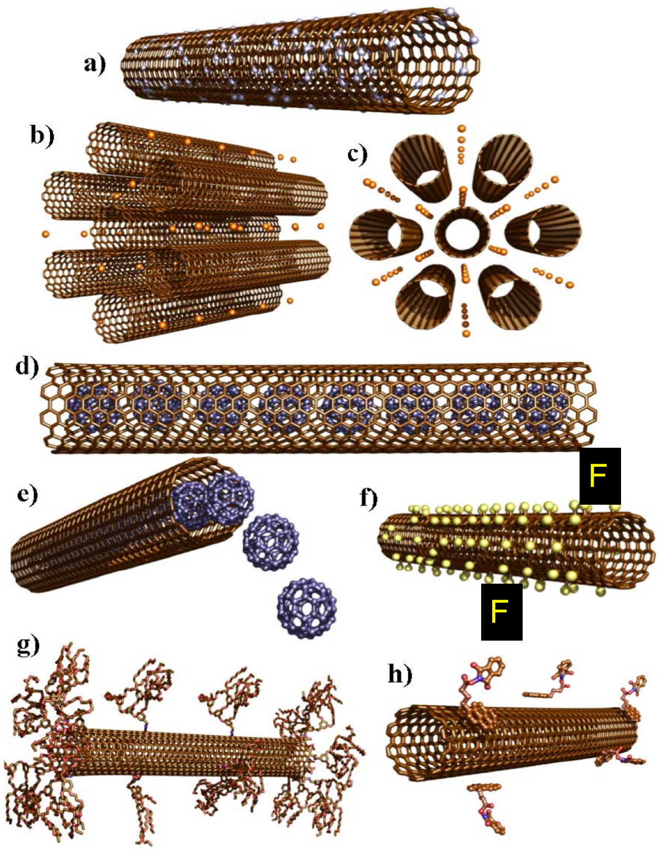


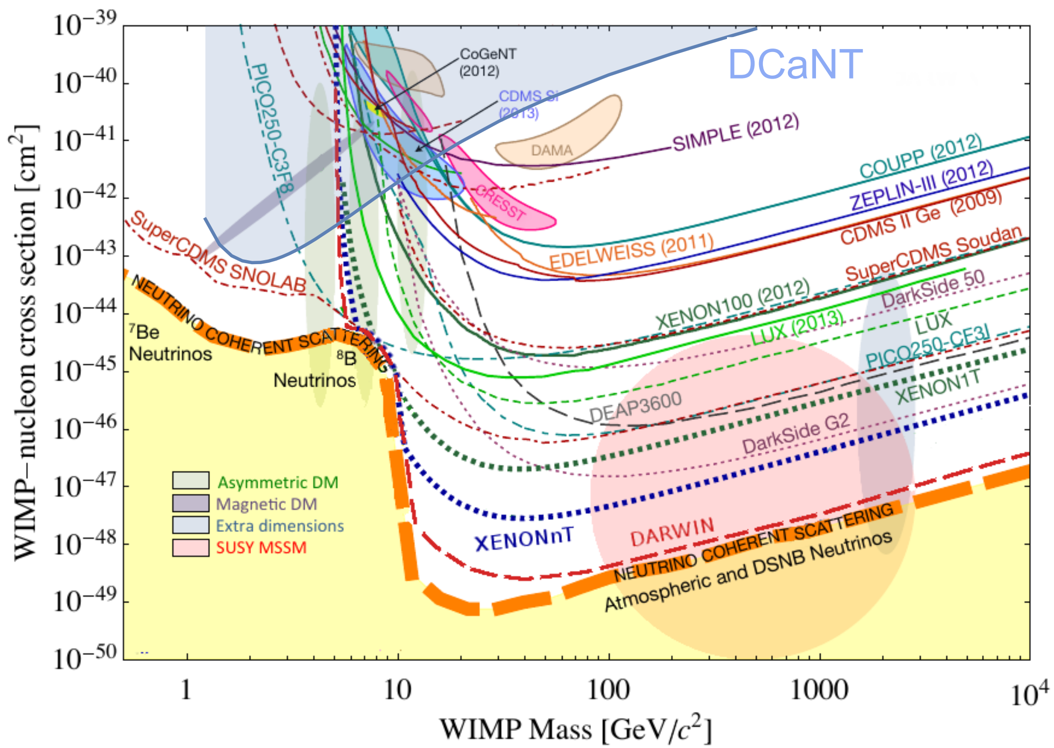
Figure 8. Different approaches to chemical modification of carbon nanotubes. (a) substitutional doped single-walled nanotubes (either during synthesis or by post-growth ion-implantation), (b,c) nanotube bundles intercalated with atoms or ions, (d,e) peapods: SWNTs filled with fullerenes (other endohedral fillings are possible), (f) fluorinated tubes, (g) covalently functionalised tubes and (h) functionalised nanotubes *via* π-stacking of the functionality and the tubes.

- CNT can be very efficiently **doped**
- **Alkali metal** can be bonded to CNT surface (Na,Cs,…) or F.
- WIMP can scatter on Na, Cs, … and these ions can then be channeled

Impact of a CNT based detector

- 100 layers, 1 m^2 each.
- With compact readout, it can have a few m^3 volume
- To be rotated tracking CYGNUS direction

Sensitivity for 0.4 kgy (CNT array trapping C ions detected downto 1 KeV)



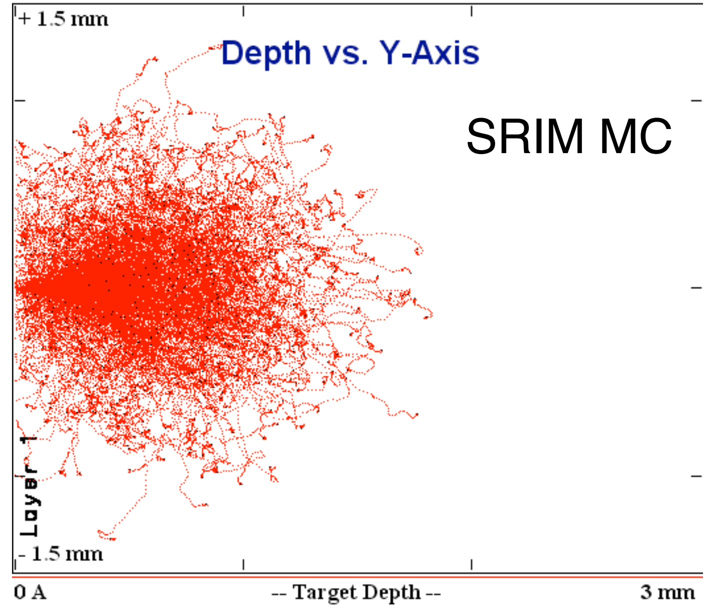
Observing C ion emerging from CNT arrays is the first step!

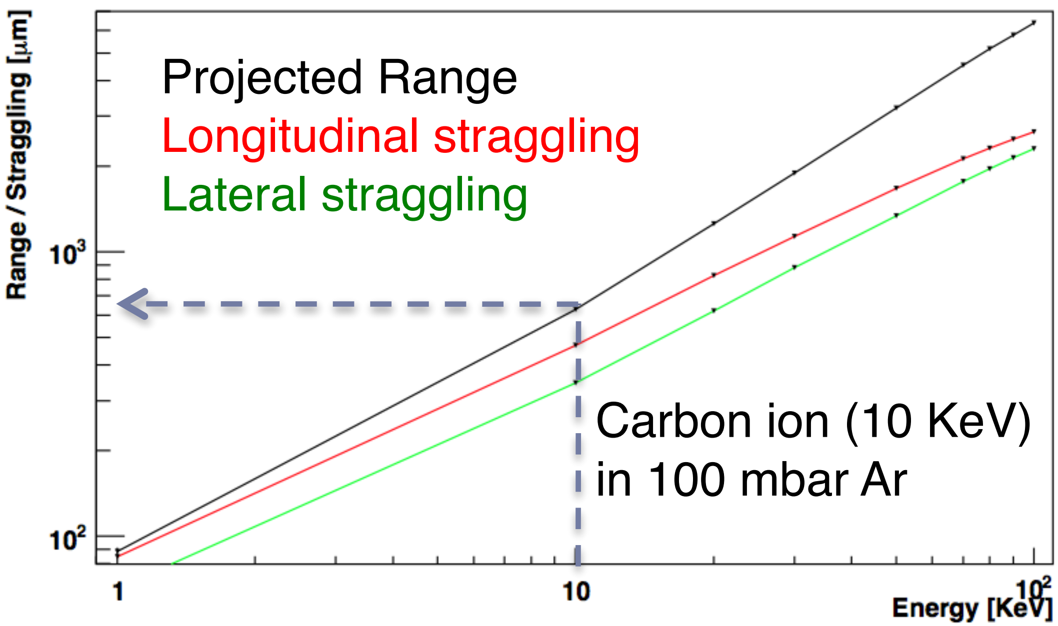
INFN CNS5 has financed it

Back-up slides

Range of few KeV ion in Ar

Carbon ion (10 KeV)
in 3mm thick 100 mbar Ar



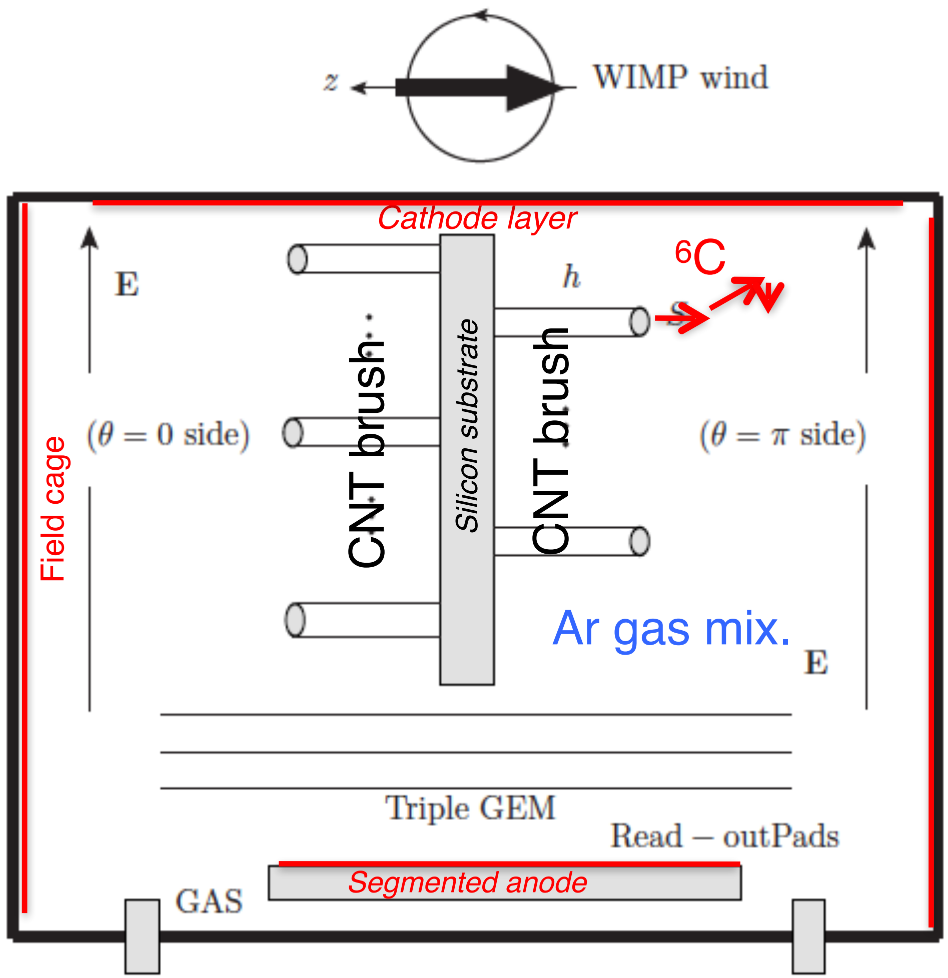


Even with large spread of ionization, the range measurement might help to identify the signal

Read-out scheme: exiting C ion

Not to scale!

h ~**100** μ**m**
S ~ π(**5**)^2 **nm^2**



Carbon ion (few KeV to few tens KeV kinetic energy) **emerging** from CNT "brush"

Carbon ions **ranging out** In the gas

Read-out scheme: electron drift

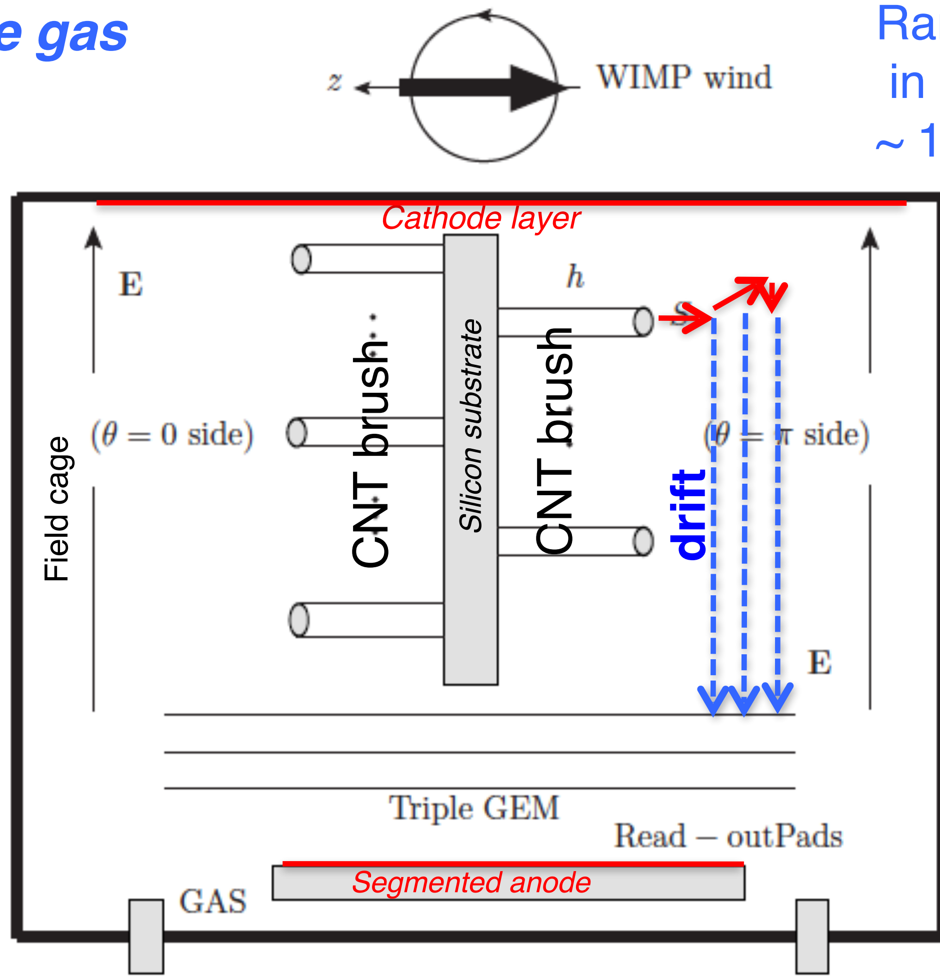
Low pressure gas (0.1 bar)

Range of 10 KeV ^{6}C in 0.1 bar Ar ~ 1mm (TRIM)

Not to scale!

h ~100 μm
S ~ $\pi(5)^2$ nm^2

Drift distance can be 10 cm



Carbon ions **ranging out** In the gas

Electrons from ionized gas atom **drift** towards anode

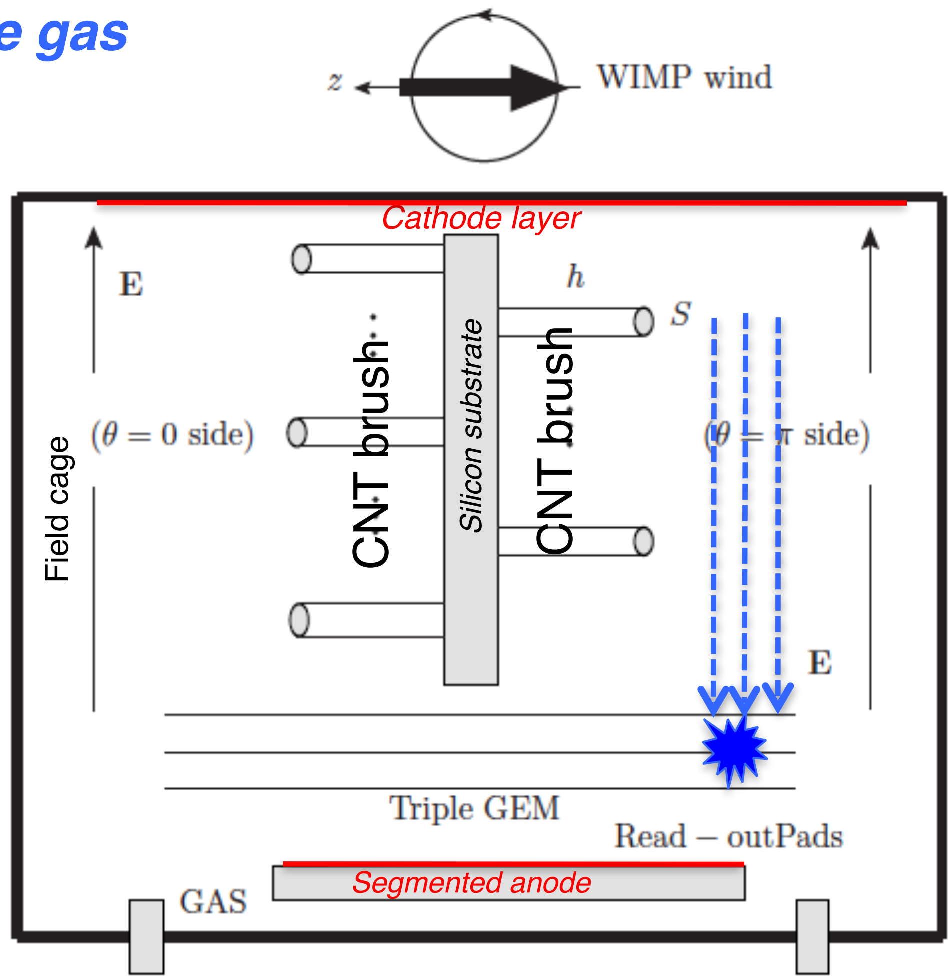
Read-out scheme: amplification

Low pressure gas (100 mbar)

Not to scale!

h ~100 μm

S ~ $\pi(5)^2$ nm²



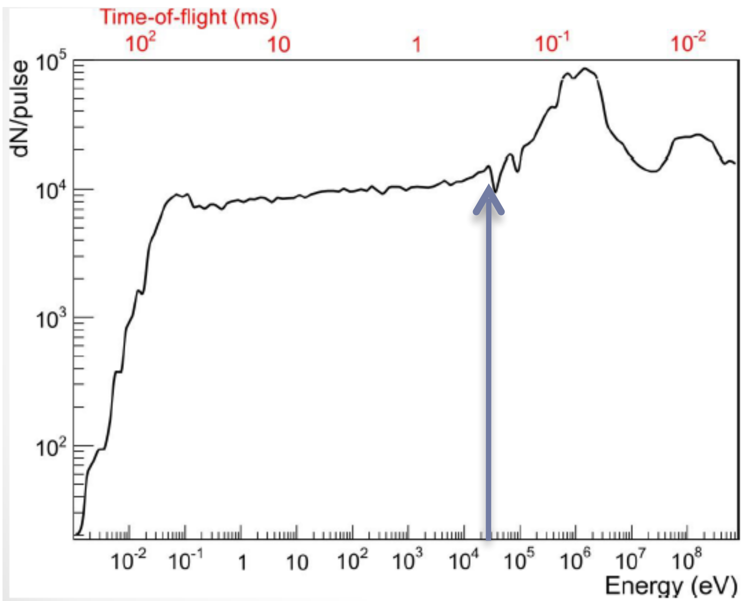
Triple GEM **amplification** stage

Electric signal **induced** on anode

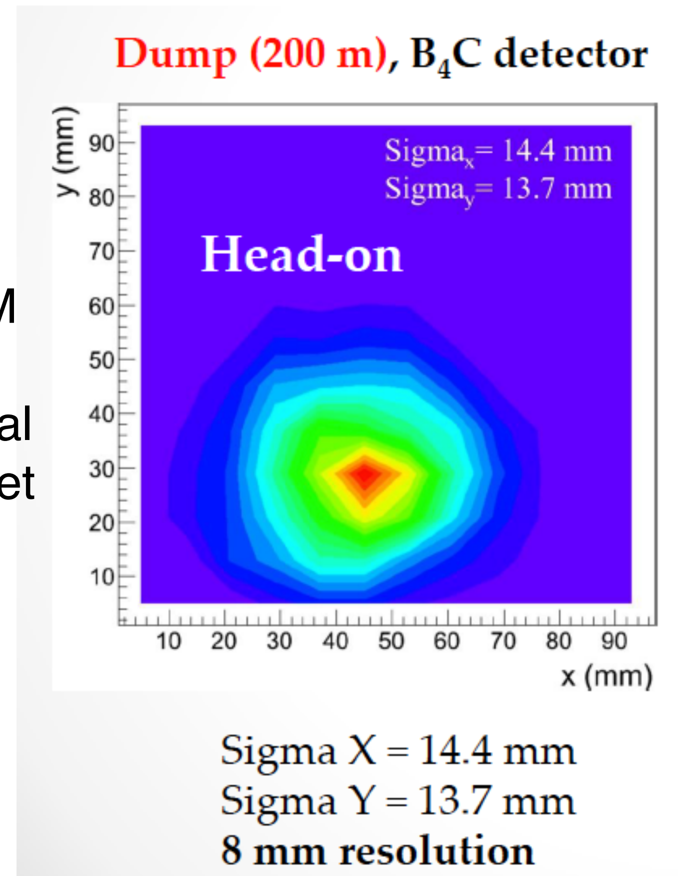
Experiment with nTOF neutrons

CERN ***nTOF*** facility: neutron from
PS 20 GeV protons
Energy measurement from time-of-flight
[precise proton extraction time]

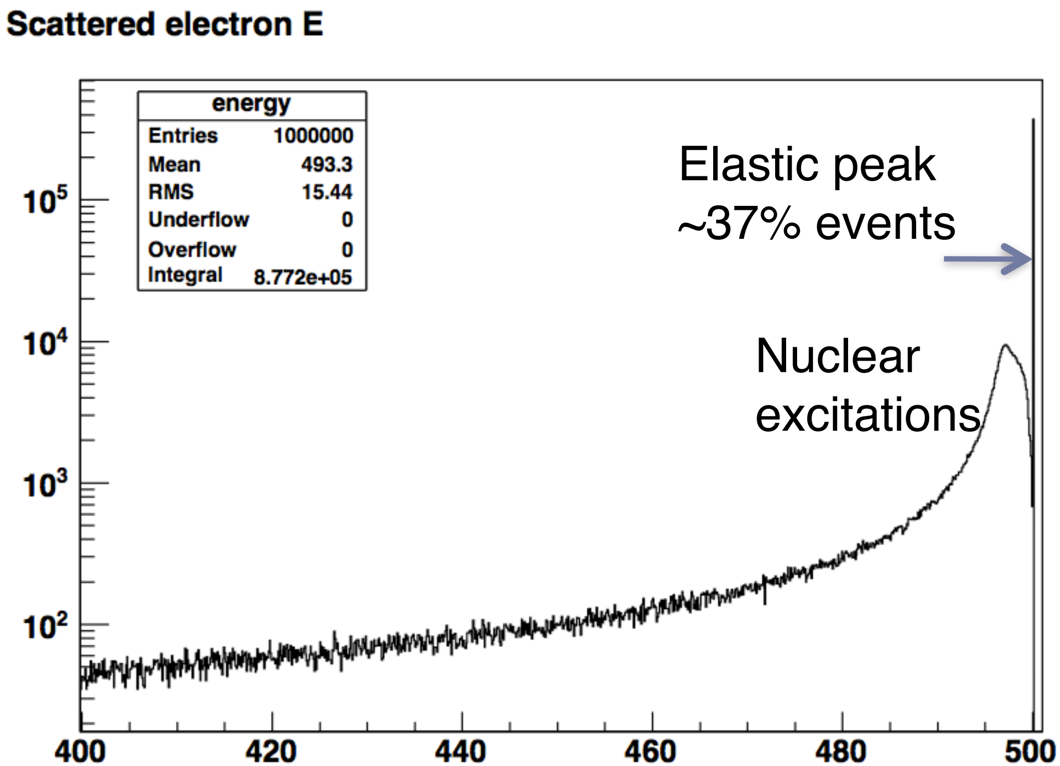
F.Murtas



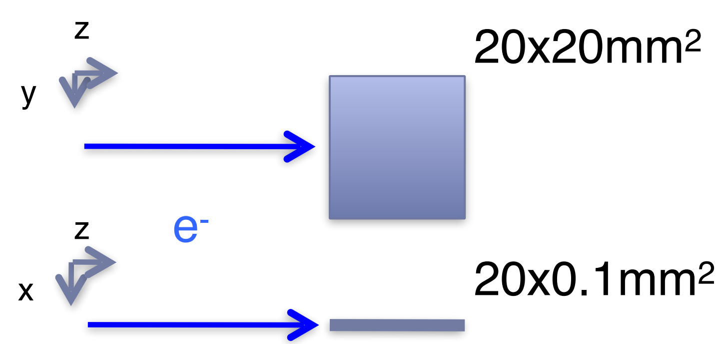
Triple GEM detectors with internal boron target



Elastically scattered ions



- Geant4 simulation of 500 MeV electron beam
  (no beam spread)



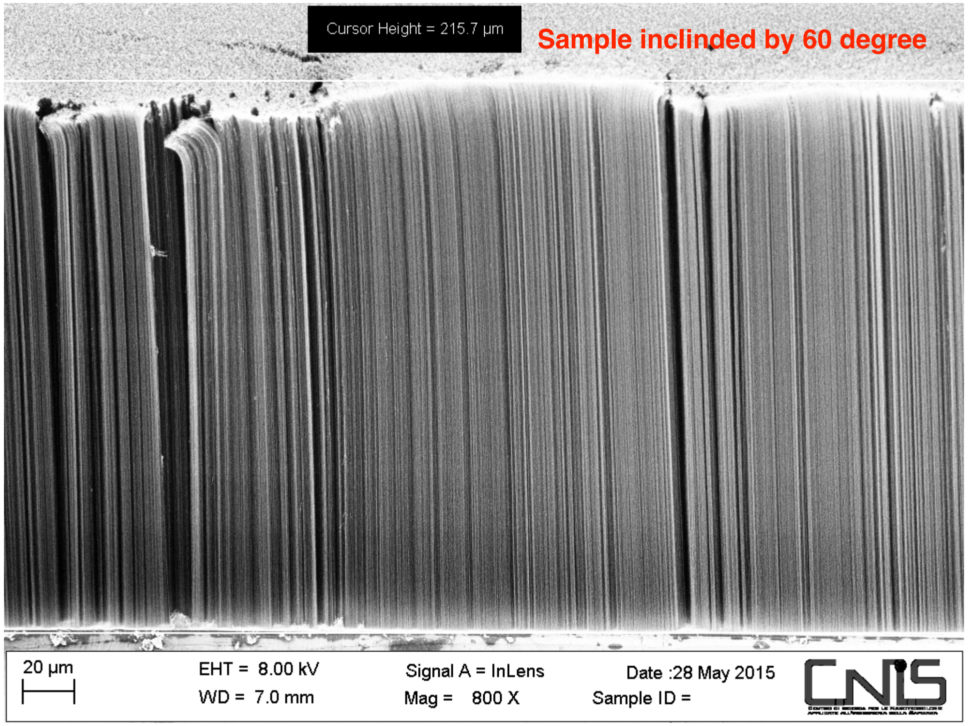
Electrons emerging from a 1 cm thick (amorphous) carbon target

Signature of ion channeling

- Intercept beam with CNT
  - Beam can be positioned by looking at scattering on silicon substrate
- Perform an angular scan
  - At each point of the angular scan record the number of ion tracks
- Distribution of ion track rate versus rotation angle should have a maximum when CNT axis is parallel to ion emission direction
  - Such distribution should have **width** of about θ_C

With a 5 10^4 electron per second on a 1 cm thick CNT brush
we should expect ~1 event per second

How to pack enough mass ?



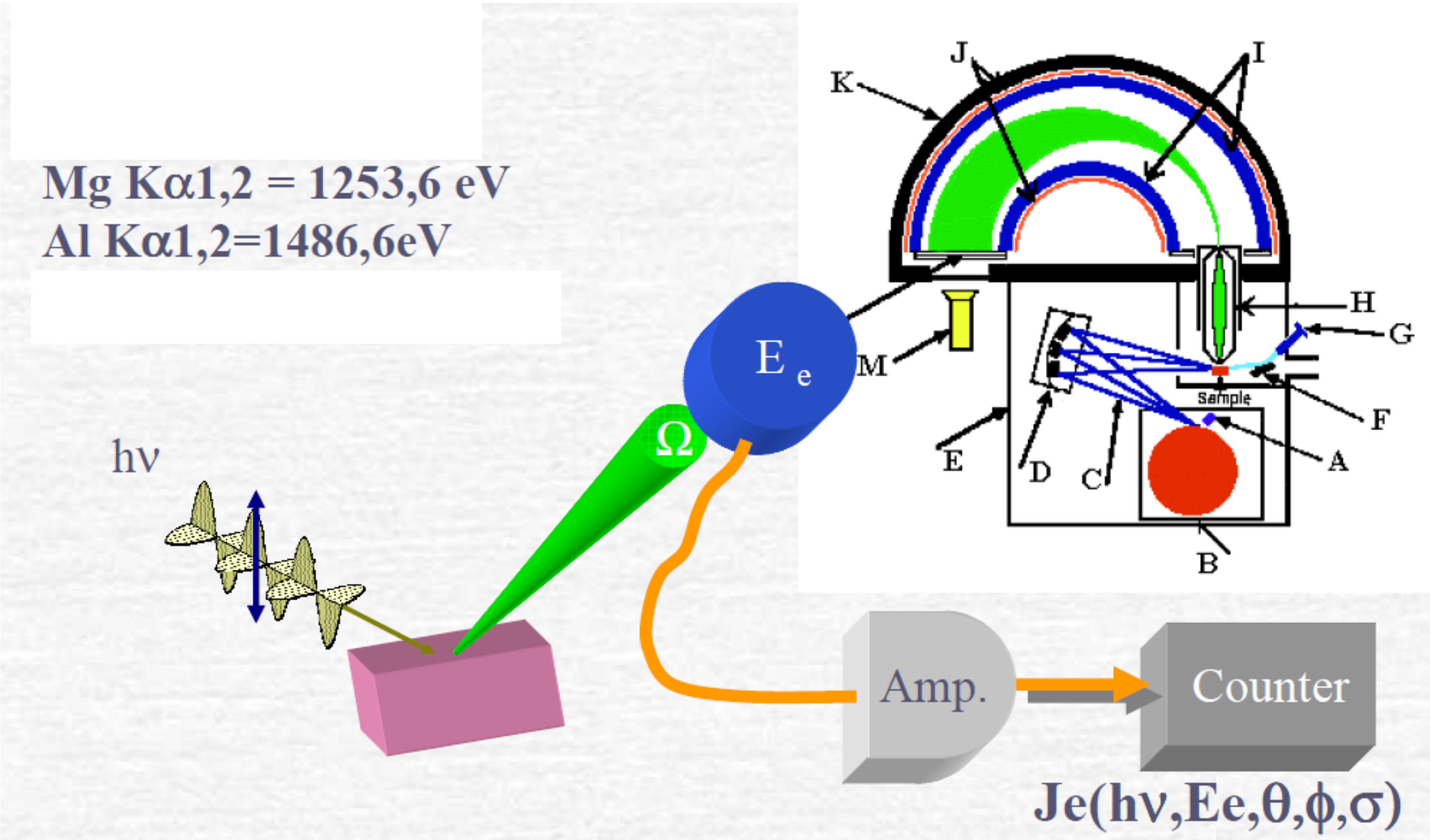
SEM image of NanoLab aligned CNT on mm Si substrate

First test shows $<10^{-3}$ contamination of Fe (“seed”) and O.

- Simple-man calculation for 1 m^2 layer - 100 layers detector
- ρ=5 nm and h =300 µm
- number CNT per layer (single wall) ~ 2 m^2/a^2
- Surface density of a graphene layer: 1/1315 g/m^2

a [nm]	CNT detector mass [kg]
11	11.8
30	1.6
45	0.7
58	0.4

XPS photon energy and e$^-$ analyser



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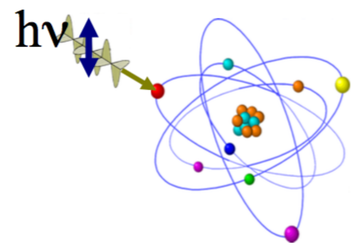
C.Mariani
Sapienza
Univ. Roma

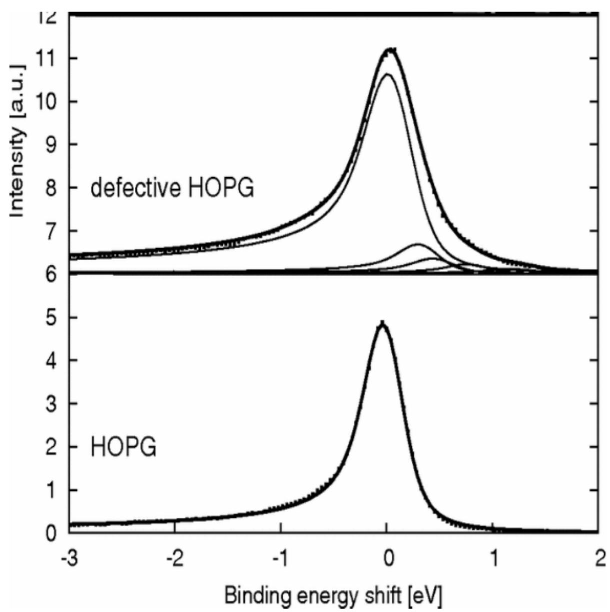
CNT characterization

Photoemission XPS Carbon 1s



$$E_e^{MAX} = h\nu - I$$

Effect of defects:
clean (bottom) and
ion-bombarded (top) graphite



Effect of doping:
Graphene flakes (left) after Li exposure (right)