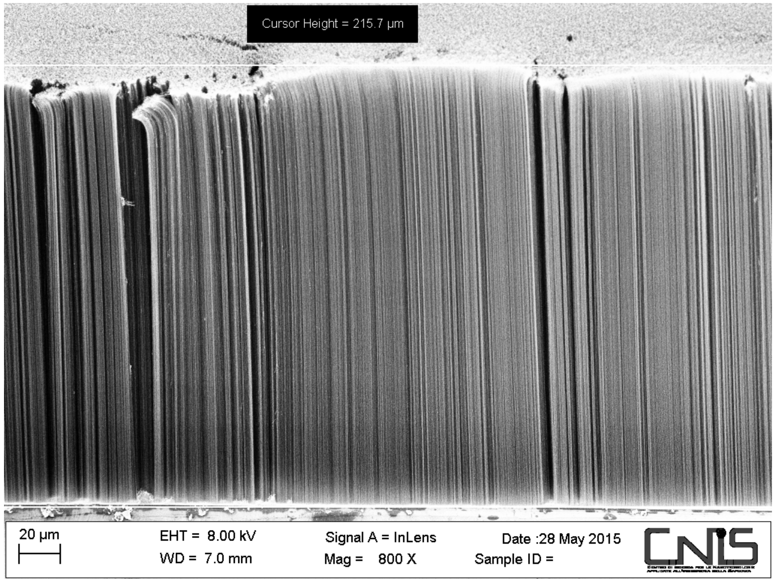


Novel technologies for direct dark matter detection

Gianluca Cavoto (Sapienza Univ. Roma and INFN)
GEMMA workshop, Univ Salento Lecce
4 Jun 2018

Outline

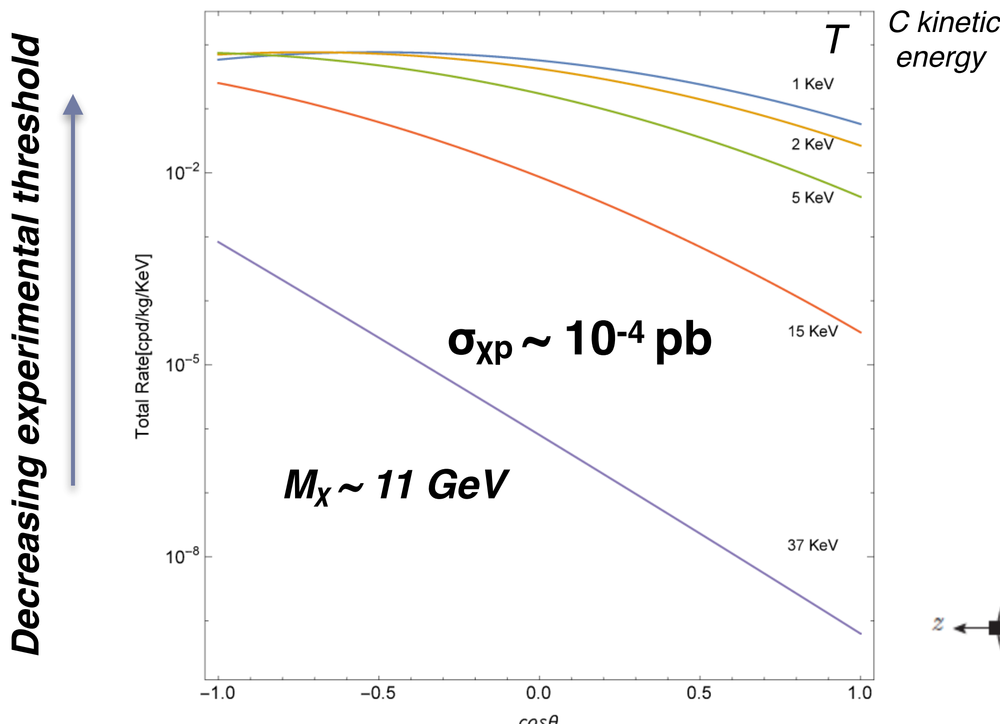
Not a review, but a (very) personal view

- **Directionality** - a tool to reject background
  - low density gas detector
  - anisotropic targets (CNT)
- **Sub-GeV** dark matter
  - detecting electrons

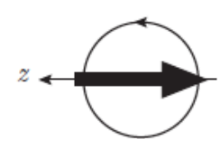
Direct detection: the name of the game

- No-one knows ***what*** a dark matter particle is
- **WIMP** model: non relativistic 10-1000 GeV particles with cross section much larger than solar neutrino weak cross section

ELASTIC scattering of a WIMP χ on a C ion



We ***move*** with the Sun in a galactic halo of DM particles



$\theta = \pi$

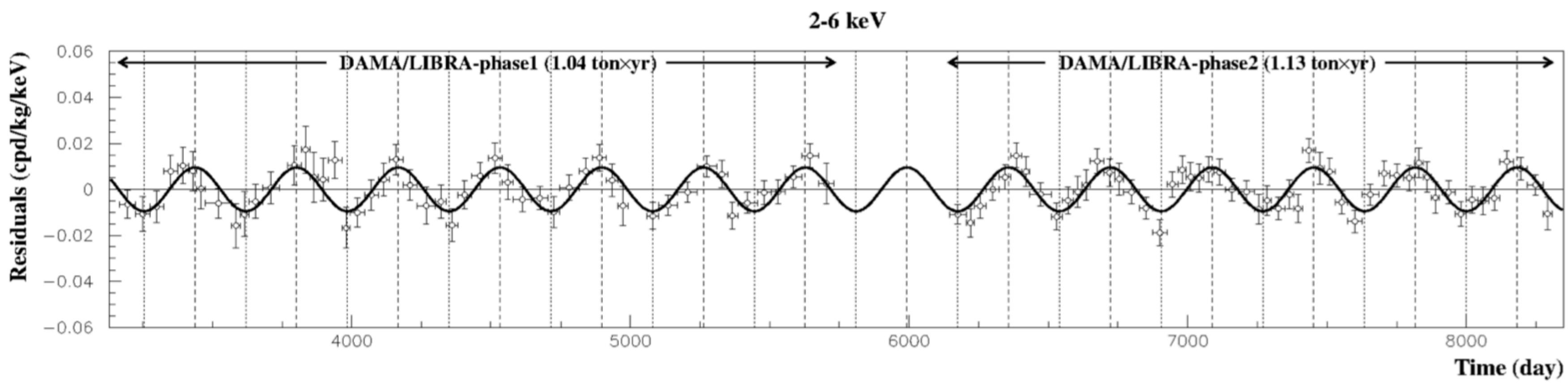
WIMP "wind"

Anisotropic distribution: background rejection

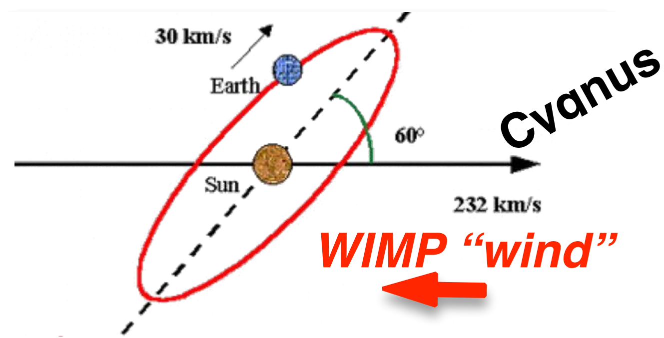
DAMA/Libra new results

- Year-modulated signal in **NaI crystal** target (ton-y exposure)
- **Confirmed in phase 2 data**
- All the interpretation in terms of background not convincing so far.

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton × yr)

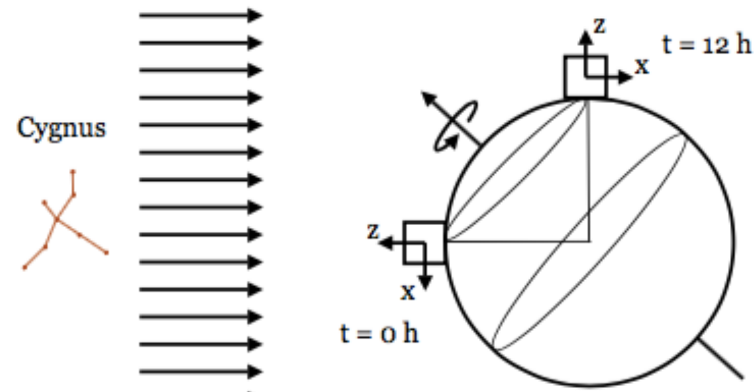


Preferred values for
$\sigma_{\chi p} \sim 10^{-40}$ - 10^{-41} cm^2
with $M_\chi \sim$ 10 - 100 GeV

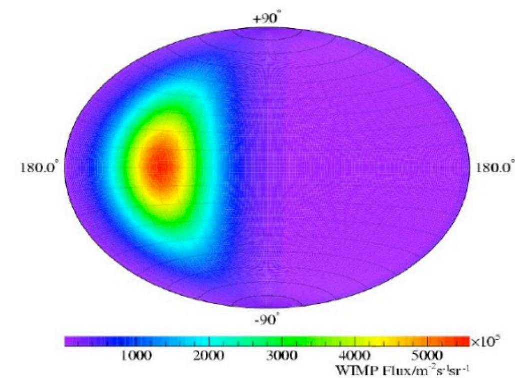


Directionality

- **WIMP** must appear as coming from **CYGNUS**



- Nuclear recoils must reflect this feature (*dipole* distribution)



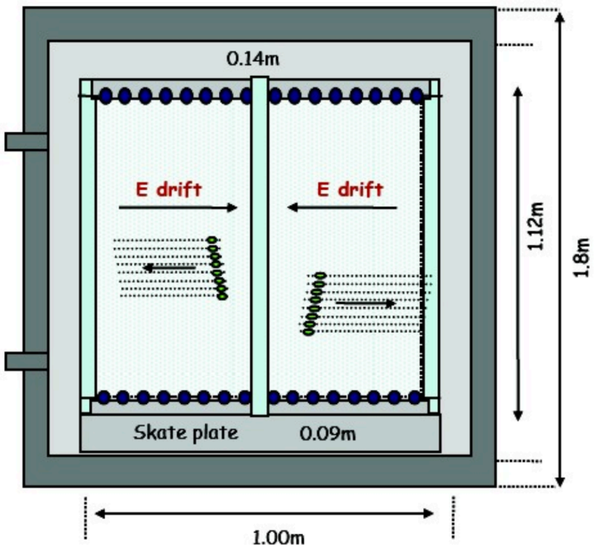
- Radioactive background is isotropic

- Solar **neutrinos** comes from the **Sun**!

One m^3 low pressure gas TPC

- The DRIFT detector (Boulby)

Astropart.Phys. 91 (2017) 65-74

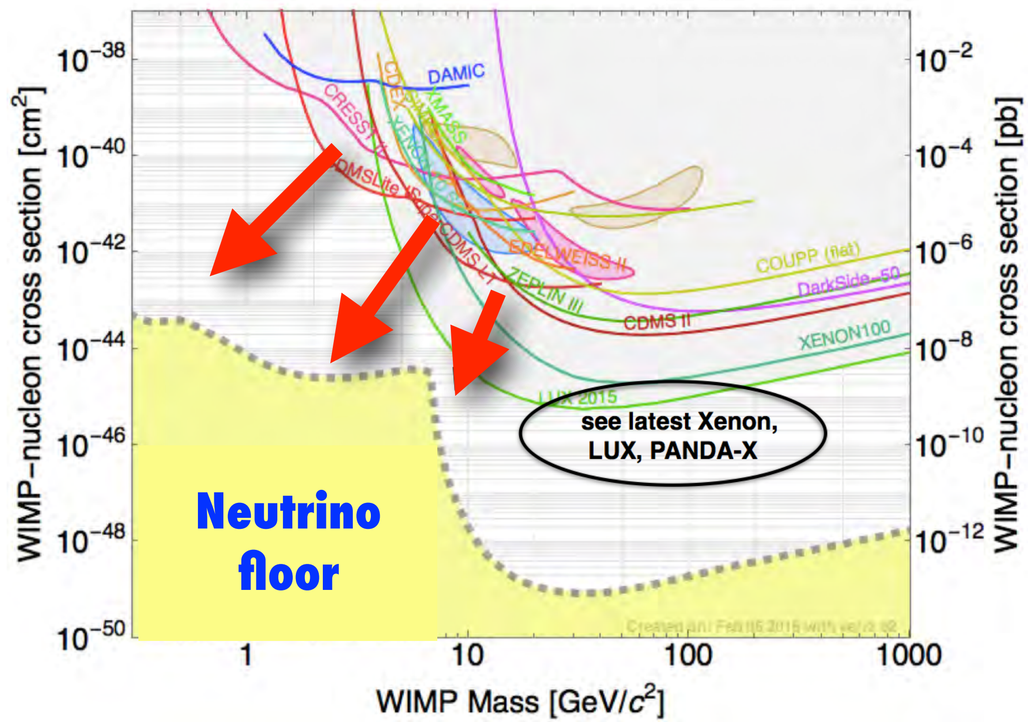


- Measuring **Head-tail of the recoiling nuclei**

- Very small mass: gas mixture CS_2 : CF_4 : O_2 (30-10-1 torr) amplification with wires
- Full electron rejection up to 30 keV_{ee}
- Negative ion drift, reduced diffusion
- Fiducialization with multiple charge carries

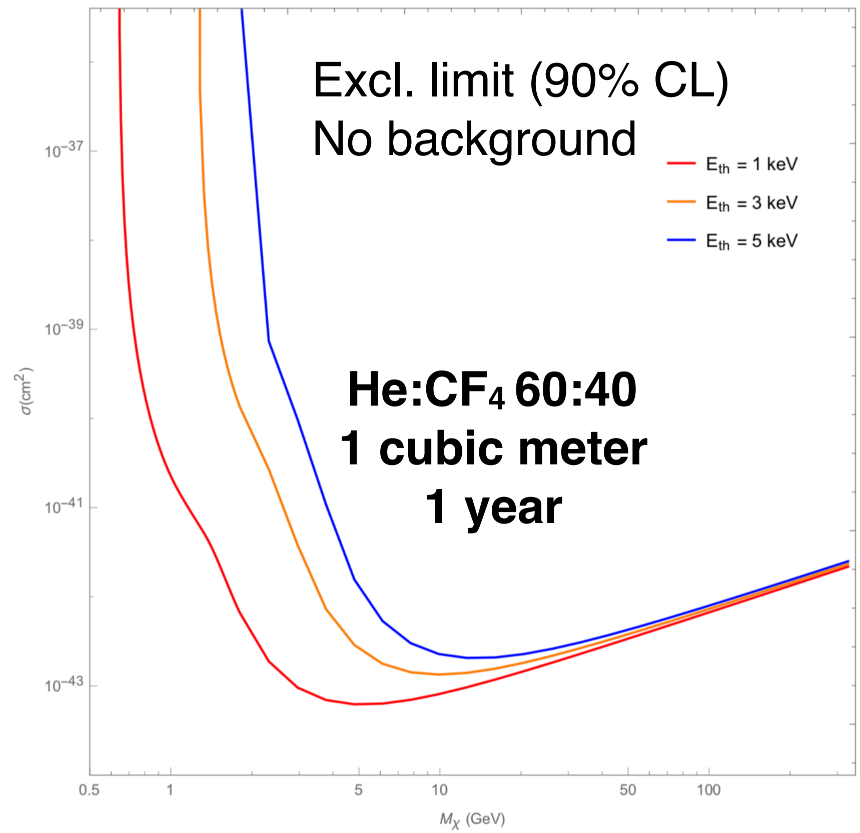
Low mass WIMPs (still wiMps??)

- Lowering **threshold** in cryogenic detectors (CRESST, CDMS, DAMIC)
- Lowering **mass** of the target nucleus
- **Gamma rejection difficult at low WIMP masses: new techniques ?**

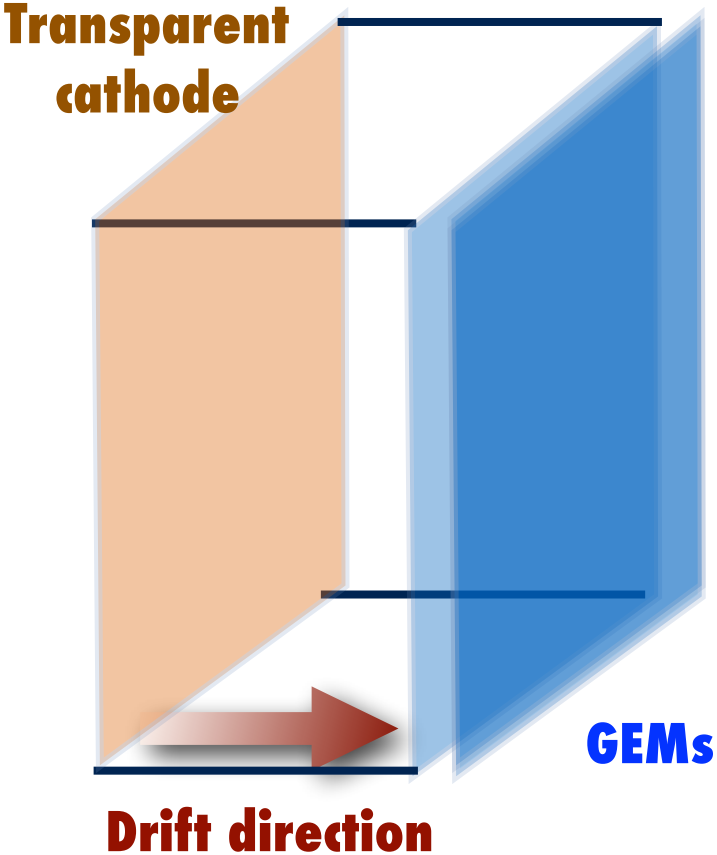


He based detector: CYGN-O

- ***Atmospheric*** pressure gas TPC (He:CF4)
- ***He*** recoils, more sensitive to low masses
- Amplification with ***GEM***
- High resolution ***Optical*** readout
- Aim at very **low** threshold (~ keV)



CYGNO detector concept

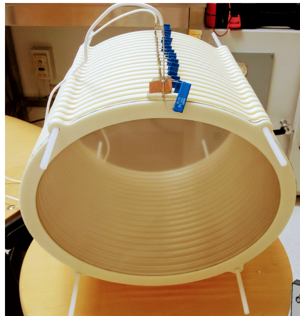


- Read the **light from the GEM** discharge with a low noise s**CMOS camera**
  - 2D X-Y resolution at 100 µm
  - No interference with gas
- ***Use PMT as trigger***
- ***Combine PMT and camera for directionality***

Can actually "image" the recoiling particles

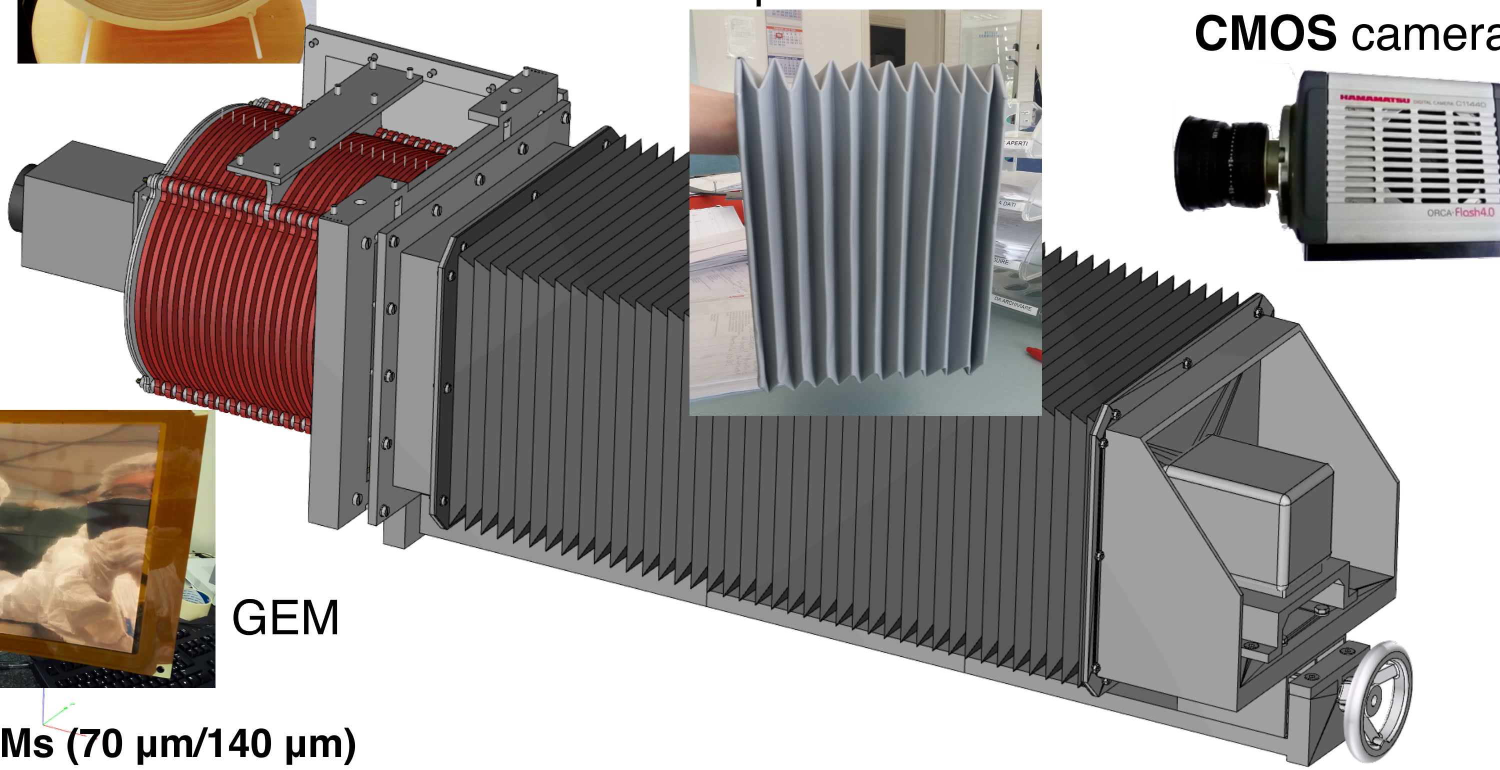
R&D, CYGNUS - 10 liter prototypes

PMT



Field cage with semi-transparent cathode (20 cm drift space)

Optical bellow



CMOS camera

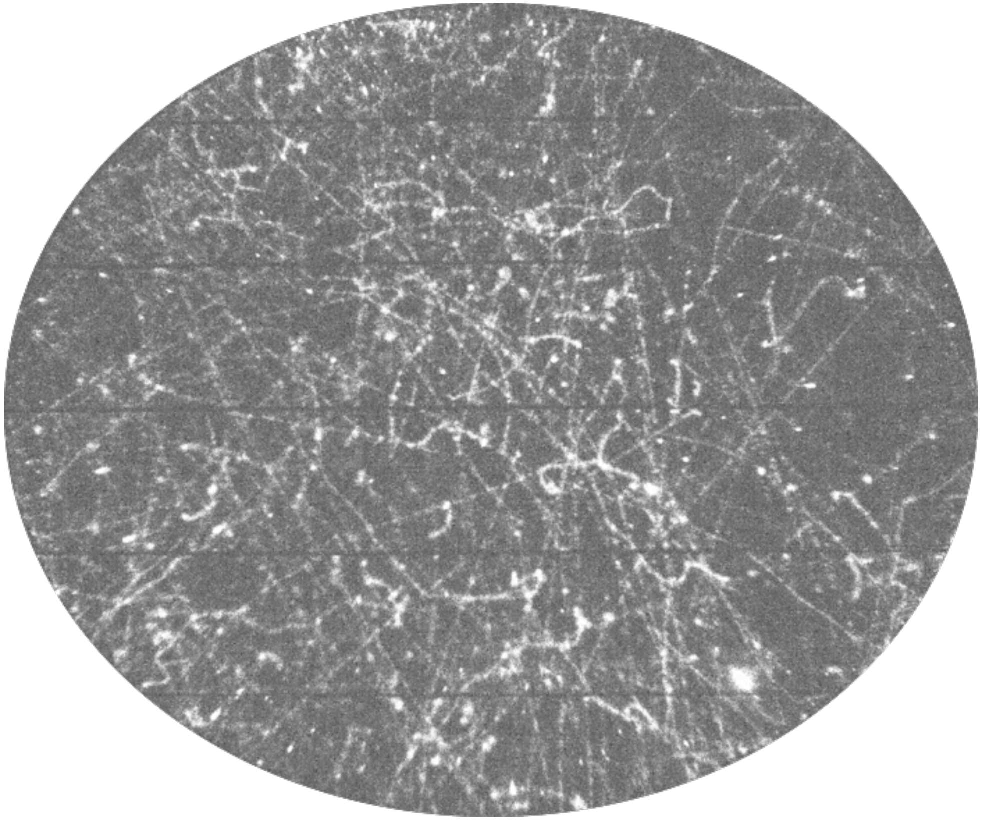
GEM

24x20 cm² GEMs (70 μm/140 μm)

A snapshot of radioactivity

TPC with **electron** drift in He-CF_4 (60-40) gas mixture

- Use 2D projection to separate *electron recoils* from *nuclear recoil* (specific ionisation)

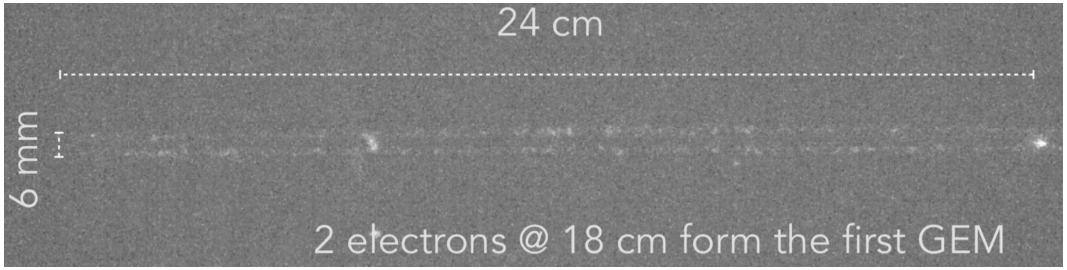


5 sec of natural background

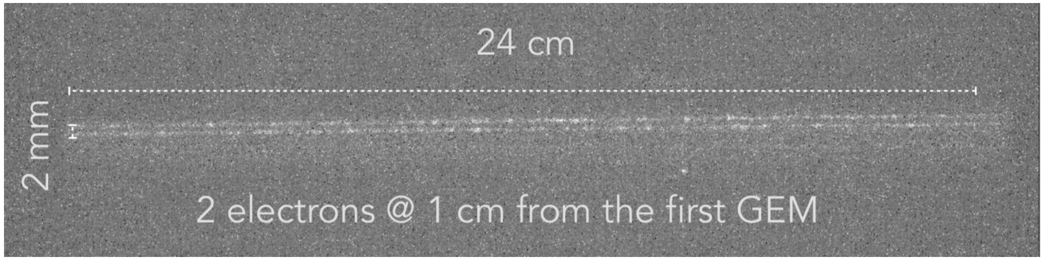
Electron mip tracks

- *450 MeV electron tracks producing ionisation cluster, drifting to GEM, flash of lights during GEM discharge*

$HeCF_4$(60/40)
by Garfield simulation



dE/dx @ 400 MeV = 0.23 keV/mm
about ~ 7 primary e^- / mm
V_{drift} = 4.5 cm/μs @ 640 V/cm

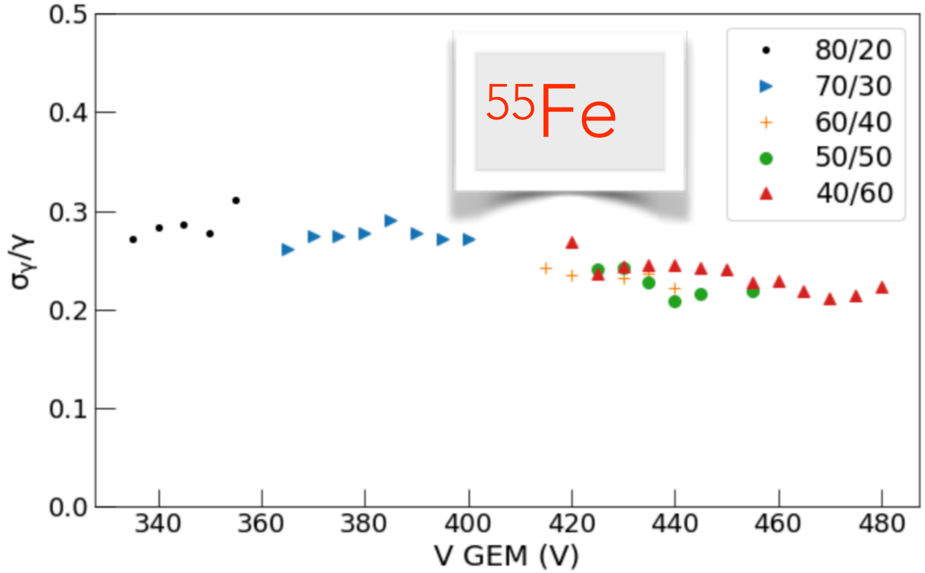


Resolution for a high energy electron track is 30-60 μm

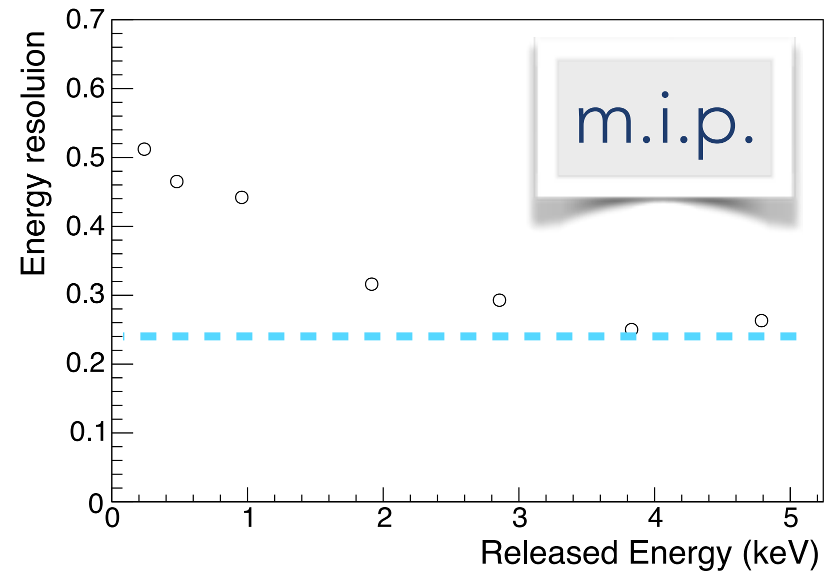
D.Pinci et al., PoS EPS-HEP2017 (2017) 077

Energy resolution

Small prototype 1cm drift gap exposed to **5.9 keV** (^{55}Fe) gamma rays and relativistic electrons (**2.3 keV/cm**)



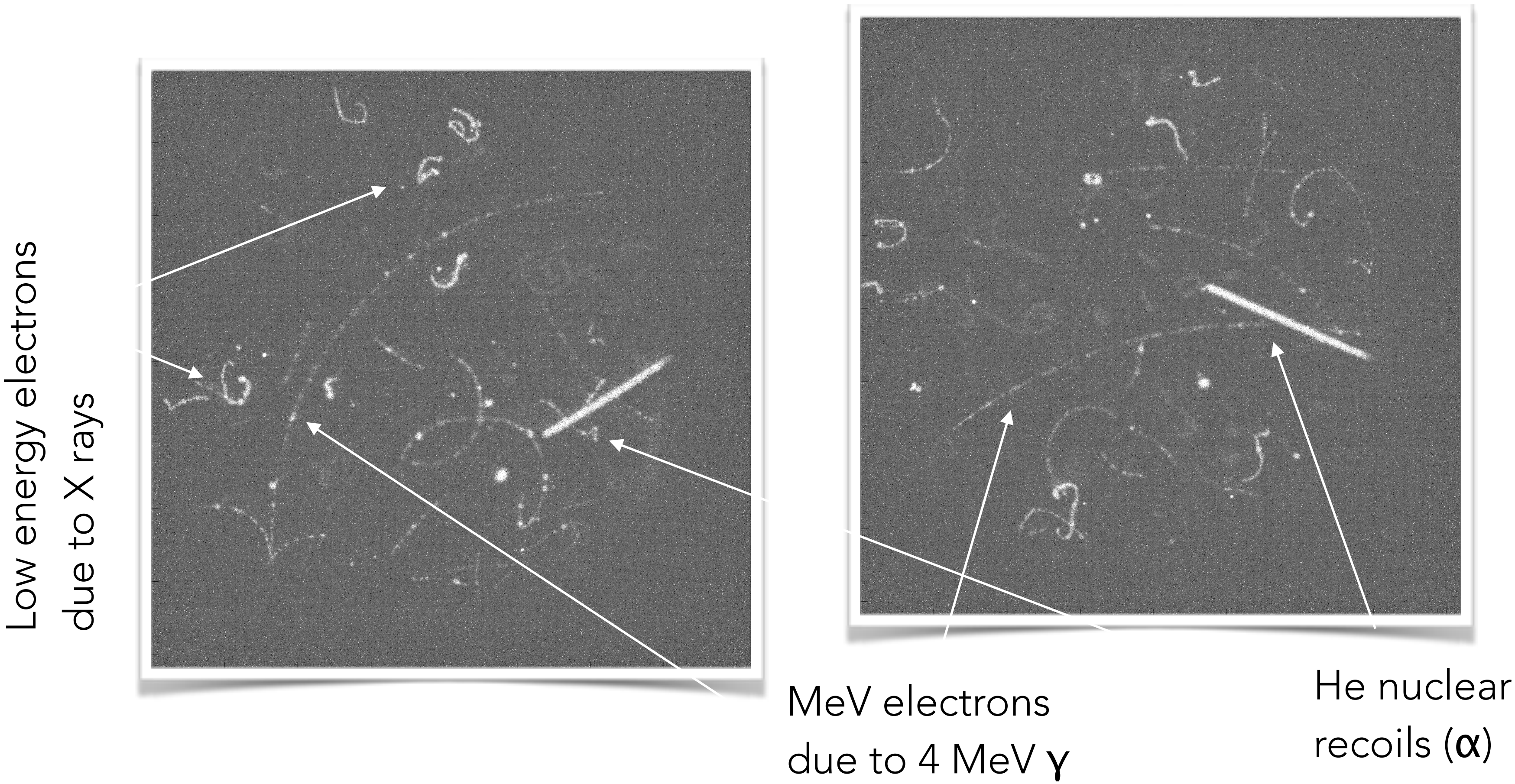
Resolution limited by intrinsic gain fluctuation



Promising results for reaching a low energy threshold

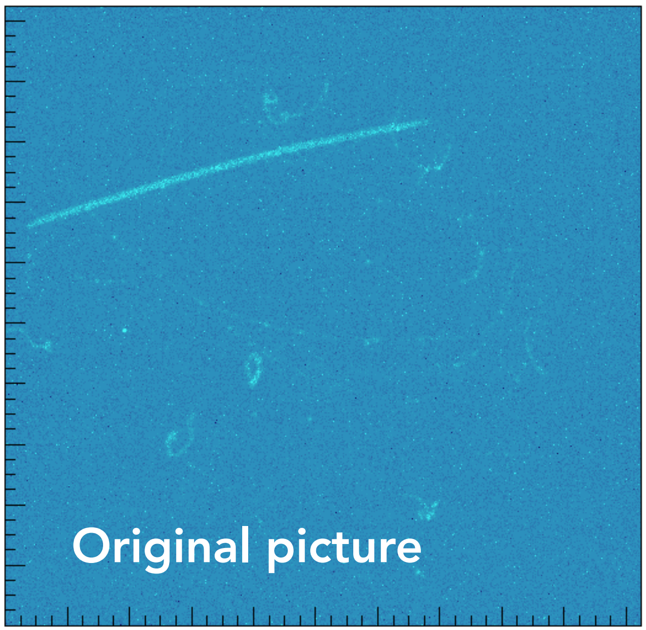
Measurements with neutrons

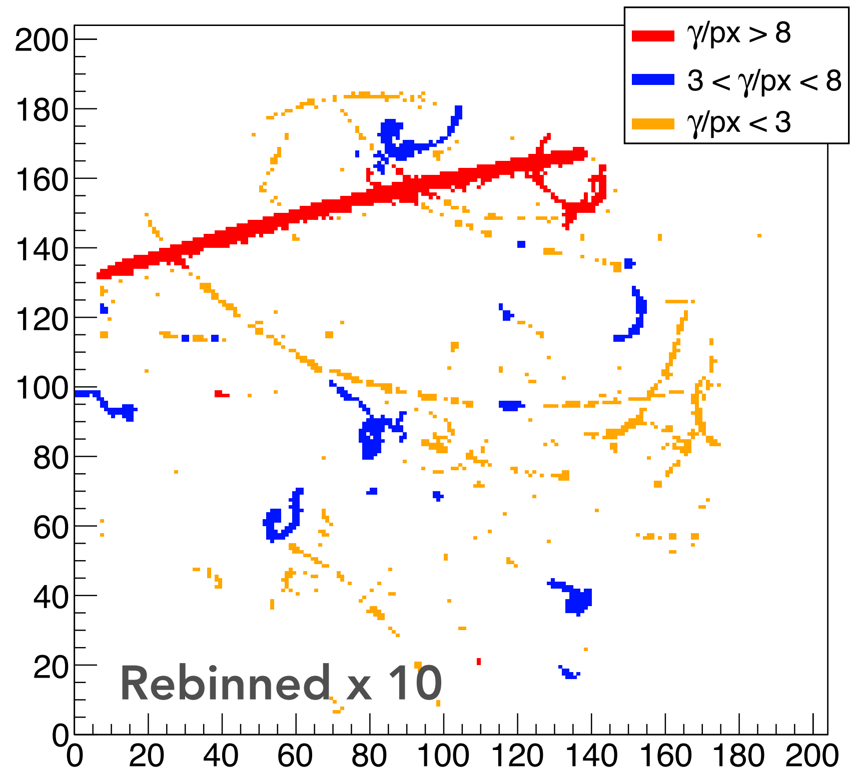
Small prototype exposed to an Am-Be source:
1-10 MeV neutrons along with 4 MeV and 60 keV photons.
A 0.2 T magnetic field within the drift field (a permanent magnet).



Particle identification

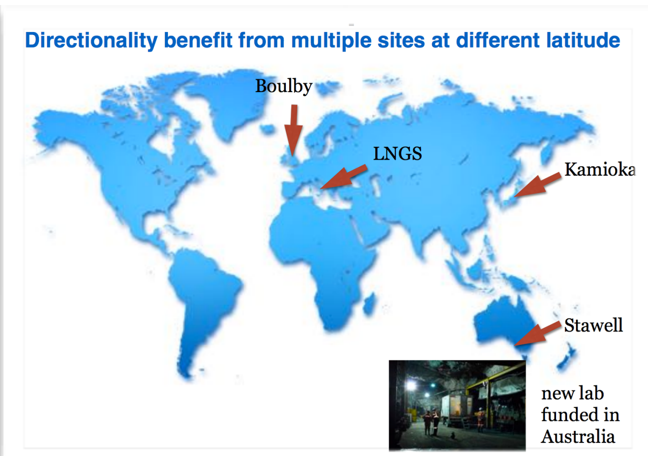
- Ionization density
  measured by counting photons per unit length/area





Towards a large volume DM detector ?

- Optical readout of large surface seems promising
  - Exploiting GEM high gain
  - Large market of cameras,
    higher resolution and lower prices in the future ?
- Need to address key points
  - Low radioactive material
  - Fiducialization (possible use of negative ion drift ? add SF_6?)
- *An innovative fast neutron detector (measure background at LNGS)*

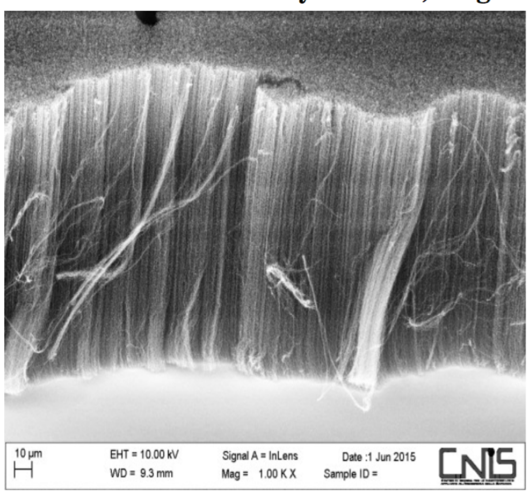


Building a collaboration for CYGNO, a demonstrator in the context of the CYGNUS-TPC collaborative network towards a 1000 cubic meter multi-site nuclear recoil observatory

Solid target: CNT

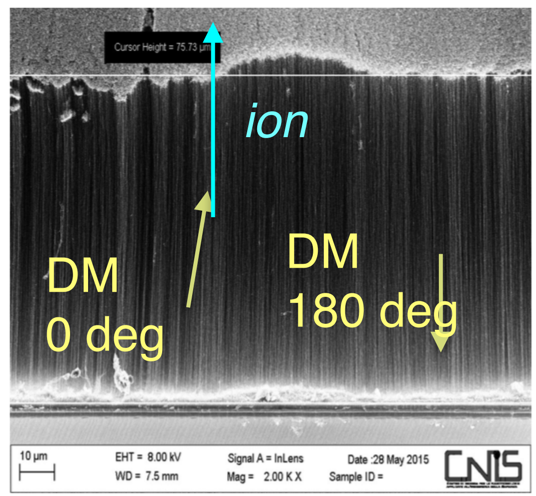
- Idea: WIMP scatters on a ***anisotropic*** target as ***aligned*** carbon nanotubes.
- Nuclear recoils are **exiting the target only** when along the CNT axis - otherwise, absorbed!

collaboration University of Mons, Belgium



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

commercial



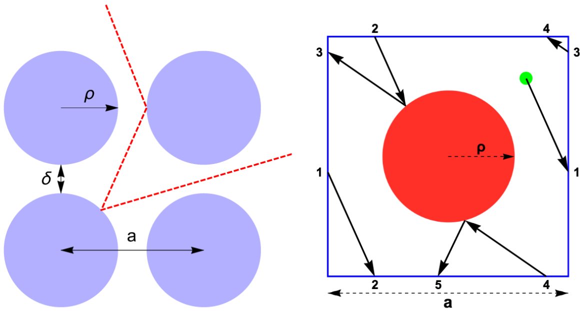
detector side

absorbing substrate

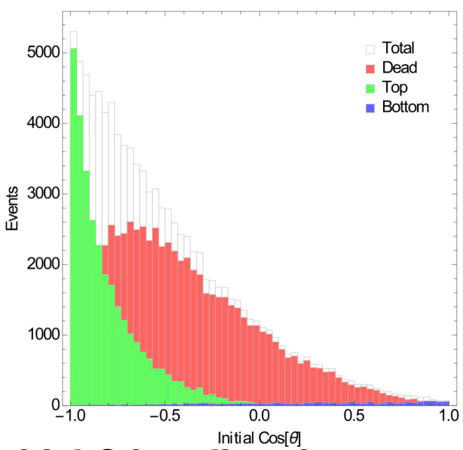
length: 75 ***µm***
ext. diameter: ***(13 ± 4) nm***
aspect ratio: 0.6 ***x10⁴***

C ion moving within the array

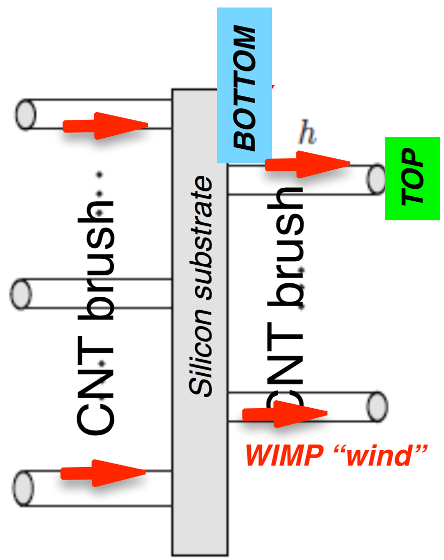
G.Cavoto et al., Eur.Phys.J. C76 (2016) no.6, 349
L.M.Capparelli et al., Phys.Dark Univ. 9-10 (2015) 24-30



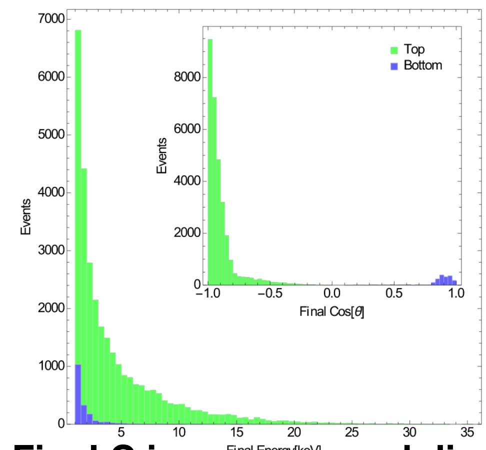
- *C* ion extracted by the WIMP feels a repulsion at the CNT wall
- Being “channeled” ?



Initial C ion direction



Double CNT brush



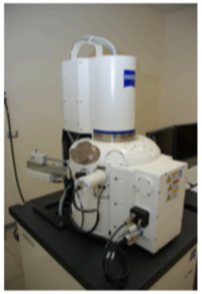
Final C ion energy and direction

A prediction for an “acceptance” channeling angle of 35 deg is made

Investigating CNT structure

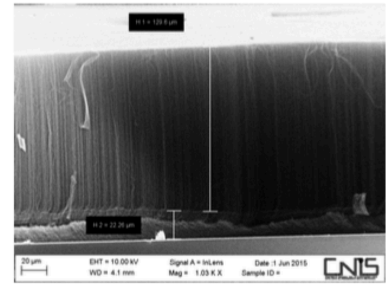
AMALDI RESEARCH CENTER

erc European Research Council



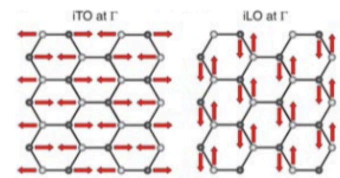
Scanning Electron Microscopy (SEM) at sub-μm scale

CNIS lab. @ Sapienza

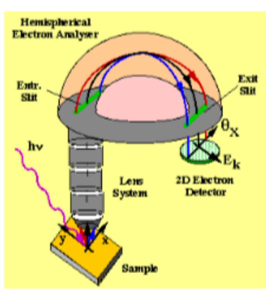


Raman spectroscopy at sub-μm scale

Phys. Dept. @ Sapienza

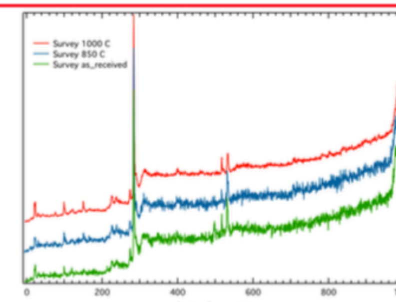


IR inelastic scattering: vibrational structure of the carbon lattice, defects, ...



X-ray Photoelectron Spectroscopy (XPS)

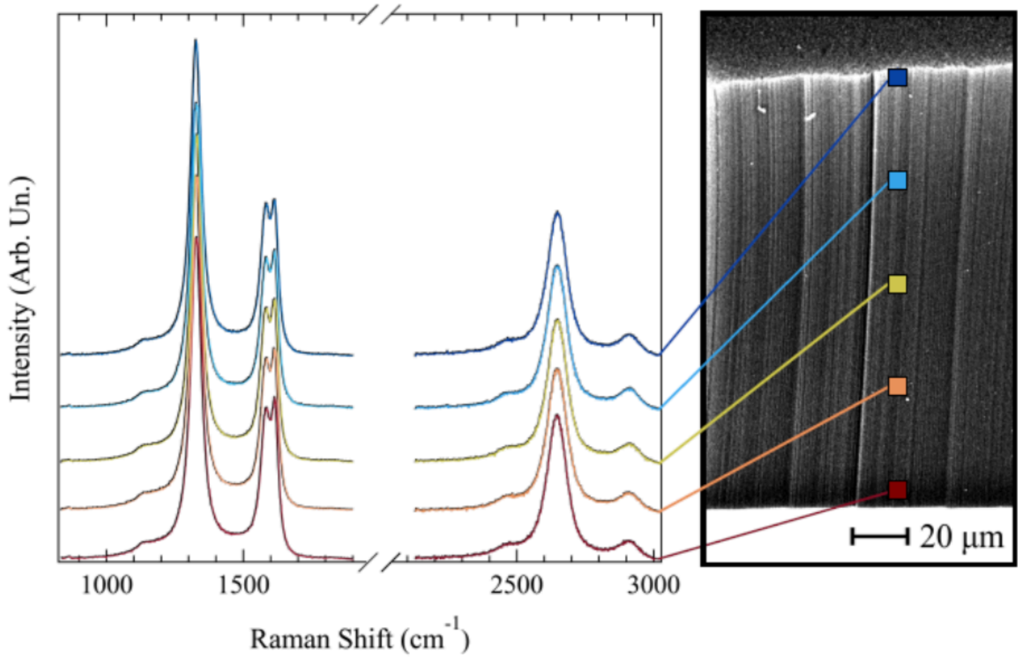
Phys. Dept. @ Sapienza and @ Univ. Mons



spectral density of electronic states: C chemical state, bonding, defects, ...

SAPIENZA UNIVERSITÀ DI ROMA

Raman scattering characterisation

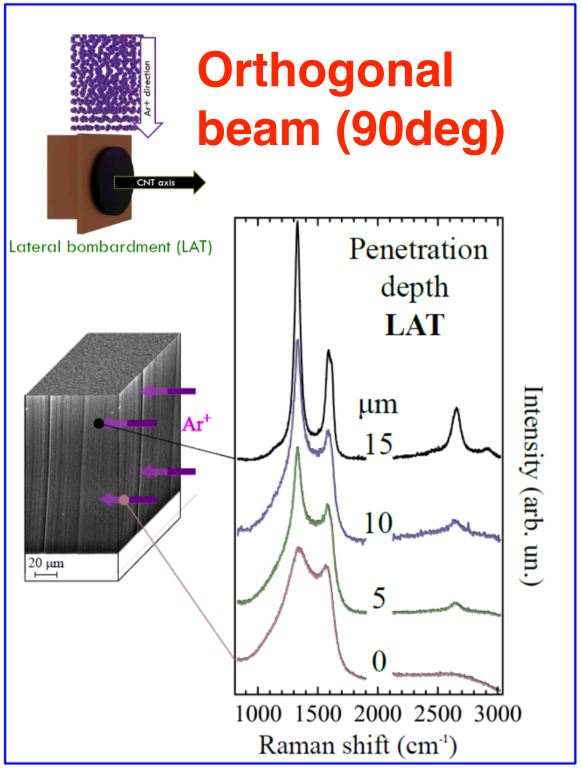


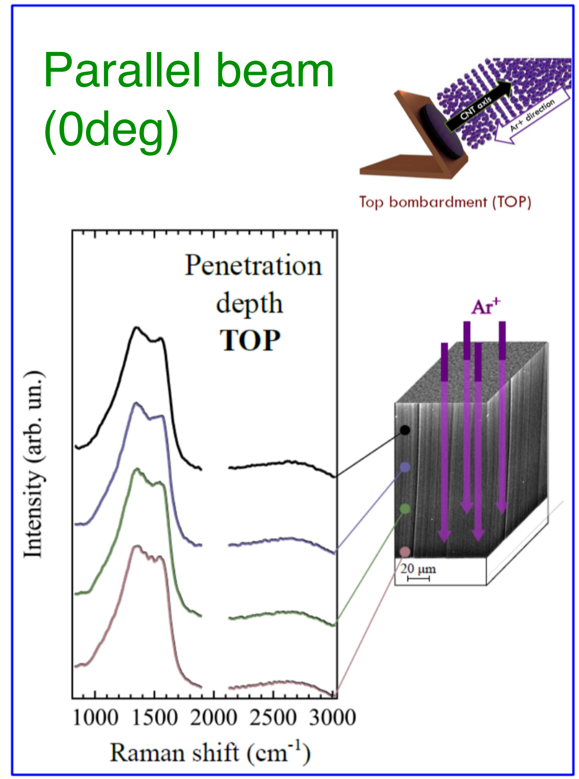
Very good quality CNT

- Spatially resolved, can asses the quality of the CNT bonds at **various heights** of the target
- Light can be focused at **various depths** in the interior of the target (up to few 10 μm)

Ar$^+$ ion beam on CNT

- 5 keV Ar$^+$ beam onto a CNT at ***different*** angles with respect to CNT axis





Number of **defects** measures the **penetration** of Ar ions
When Ar beam **aligned** with CNT, defects present **at all the heights**
When Ar beam **orthogonal** to CNT, defects present **only on the surface**

Towards a prototype detector

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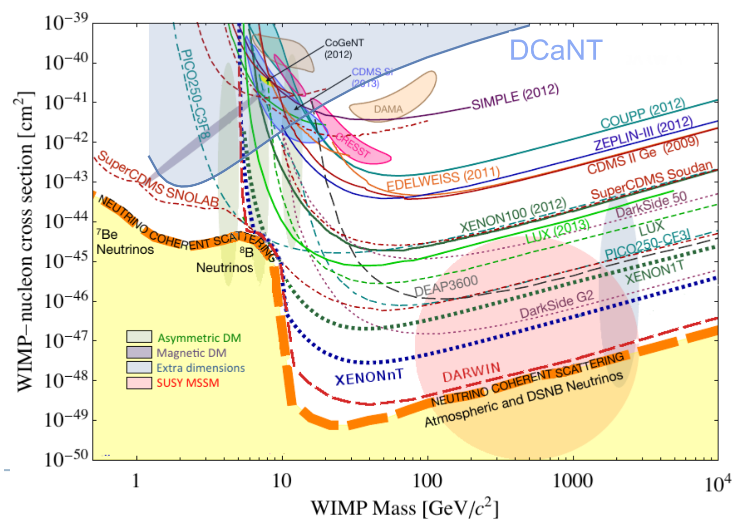
erc European Research Council

- Indications that low energy Ar ion might be "**channeled**" in CNT
  - More tests going-on, different beam intensity, different kinetic energy (< 1 keV)
  - Try to confirm the **prediction of 35 deg critical angle** for channeling (ion trapped within the interstices among CNT)

- If confirmed, try to detect a **single scattered C ions**
  - use a relativistic electron beam to scatter C out of the CNT

- Eventually, build a prototype DM detector *exploiting rate asymmetry*



Sensitivity for a 0.4 kgy exposure

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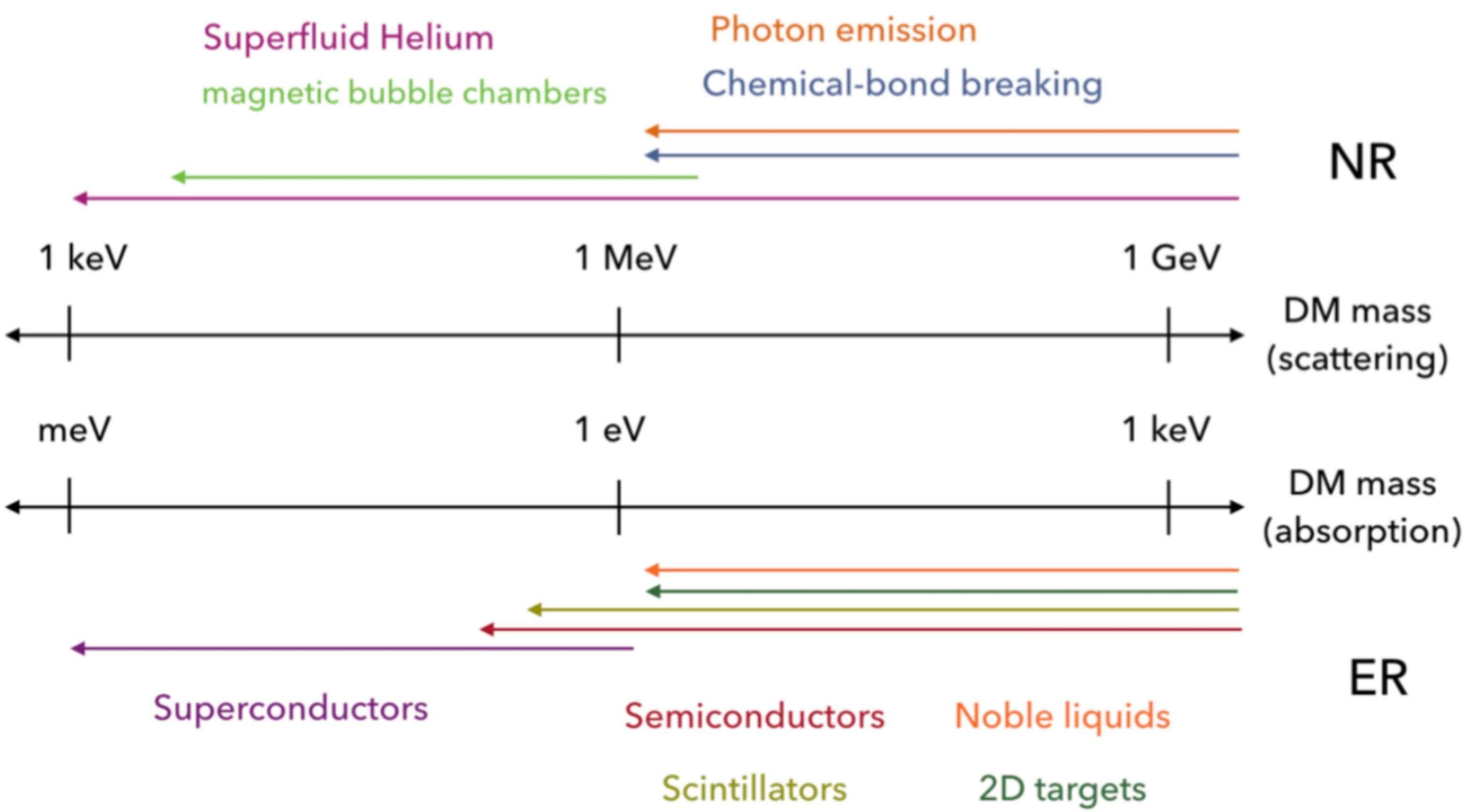
- What if dark matter is not so massive ? Scattering over the target ***electrons***

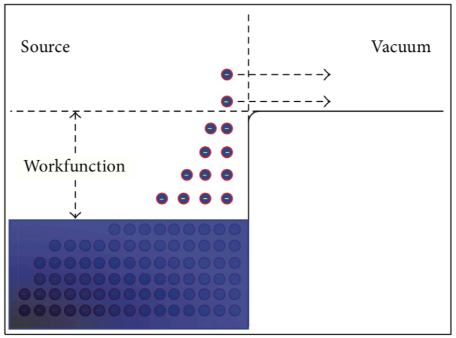
Sub-GeV dark matter



[US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report : https://arxiv.org/abs/1707.04591](https://arxiv.org/abs/1707.04591)

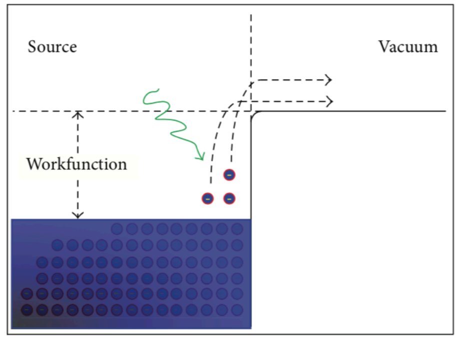
Electron emission from a cathode

Thermoionic emission

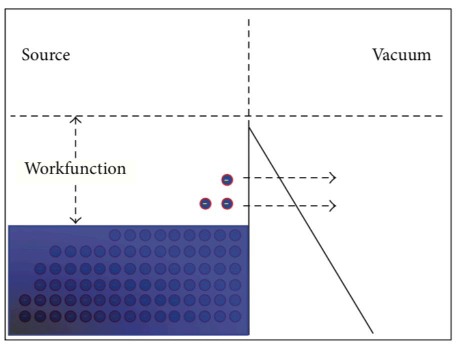


(a)

Photoelectric emission



(b)



(c)

Field emission

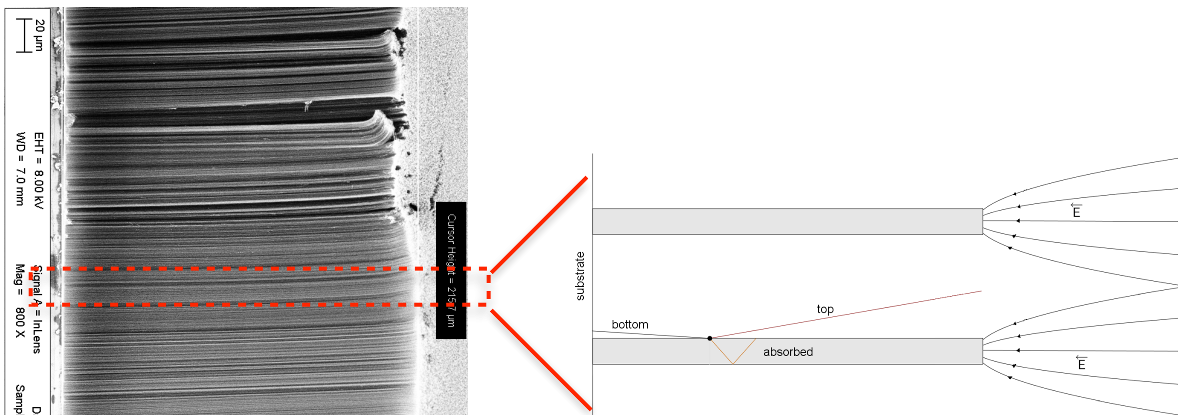
What about a DM particle scattering off an electron ?
*a **dark-cathode** ?*

Work function of CNT is > 4 eV

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

Electron emitted from aligned CNT

- Electron extracted by a DM scattering
  - ***Few eV energy*** electrons are recoiling off

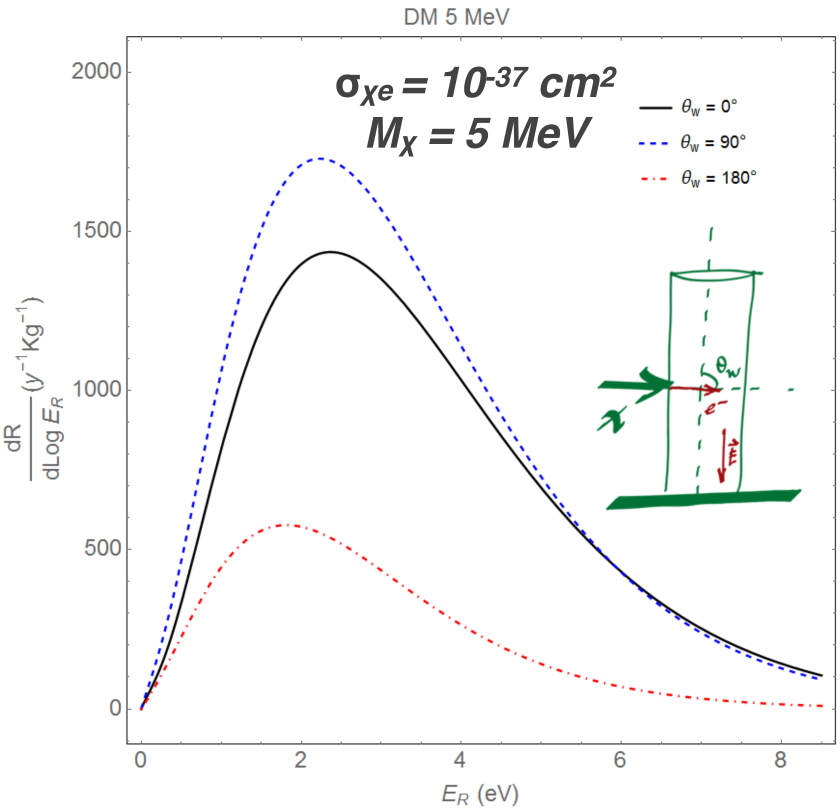


Electron collected by an external electric field ***E***

- **Inelastic** electron - graphene interactions are **suppressed** at this energy (compare ***e*** wavelength)

- electrons can be *transmitted*, *reflected* *absorbed* by a graphene sheet
- absorption ~ 10^{-3} (but no good data available)

Directionality



Different rate at different angles $\boldsymbol{\theta_w}$

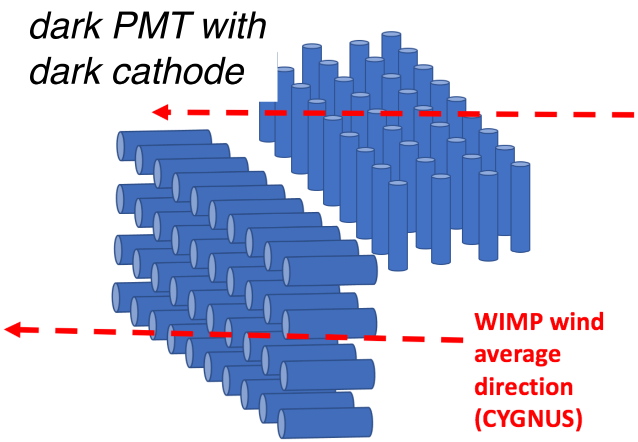
$\theta_w \sim 90$ preferred by graphene electron wave function

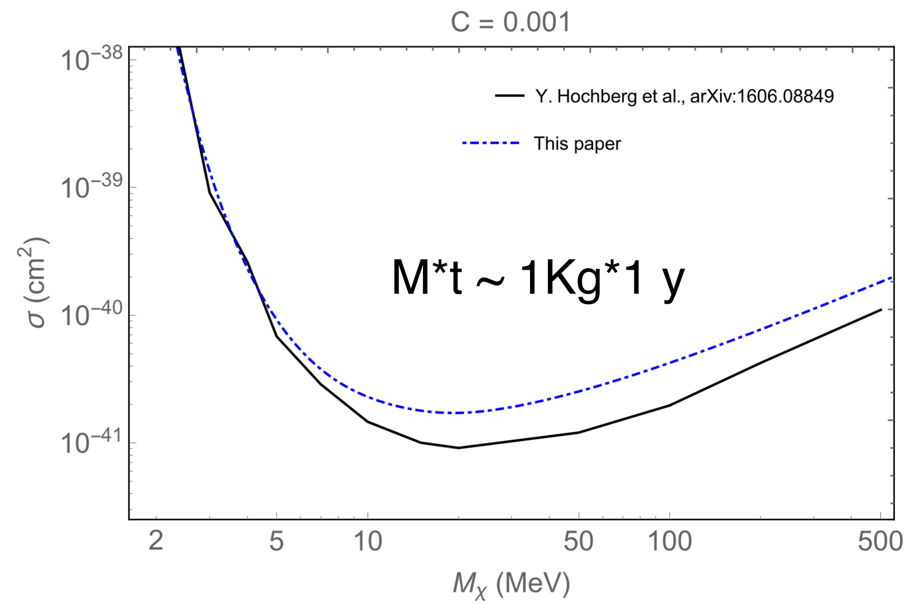
- A rate **asymmetry** can be measured by comparing two CNT target orientation

With an exposure of 100g * 200 day a 5σ non null asymmetry can be measured

Sensitivity region

G.Cavoto et al, Phys.Lett. B776 (2018) 338-344





- Two arrays of *dark PMT*
  (~10^4 units, 10mg dark cathode mass each)

Towards a dark PMT demonstrator

- Build a dark PMT prototype out of a CNT as a cathode, an electric field and an electron sensors (an avalanche photodiode in vacuum).
  - ***A few eV single electron detector***

- **Synergy** with **PTOLEMY**
  (PonTecorvo Observatory for Light Early universe Massive neutrino Yield).
    - *PTOLEMY's concept uses a target of tritium doped graphene layers for relic neutrinos*
  - Need to asses the **radioactivity of graphene based structure:** a dark PMT could be a tool for it
  - Electron - graphene interactions must be studied.

My conclusion (for direct searches)

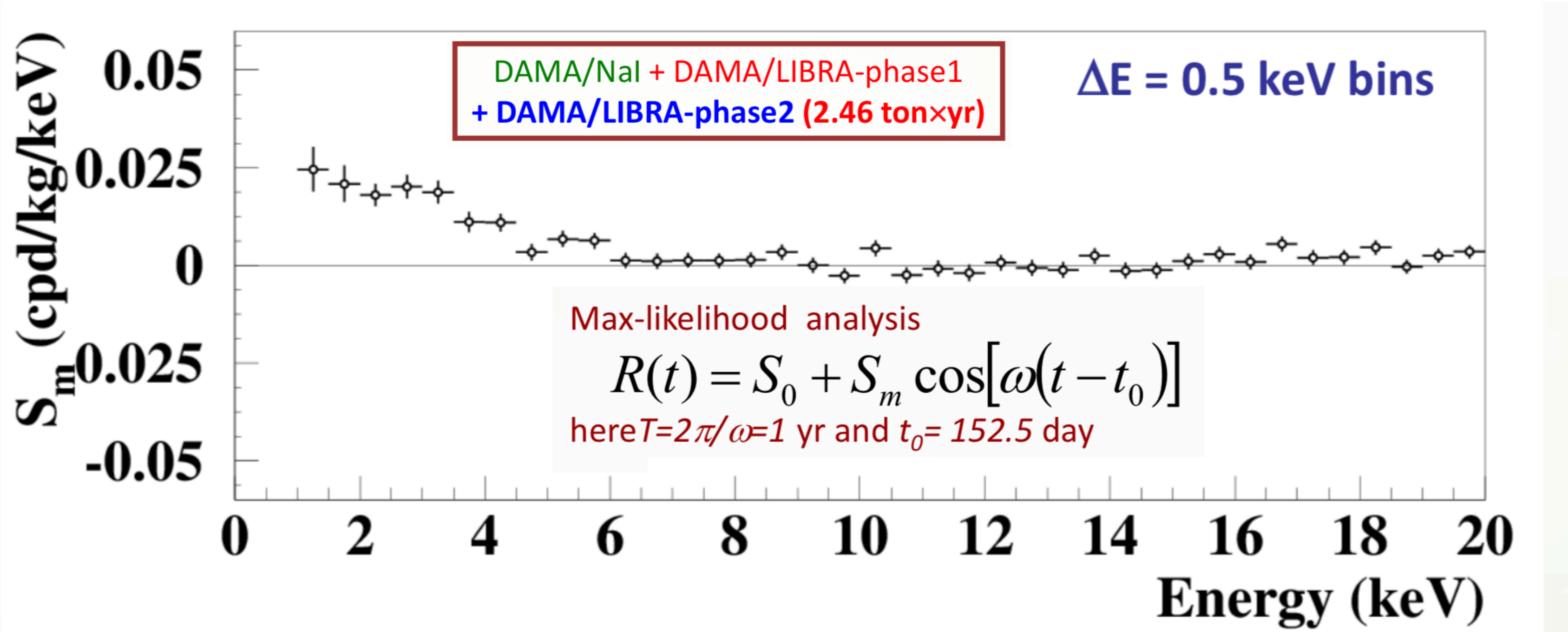
- **WIMP** is a **great** paradigm, but no firm experimental evidence so far.
  - DAMA/LIBRA result yet **unconfirmed with different target nuclei**.
  - "**Several ton-year** "is the new frontier in the high mass (> 10 GeV) region
- Need to prepare to dig into the **neutrino floor**
  - directional tools need to be explored now
    (anisotropic targets, low density gas and large volume)
- Look in other mass range, well below GeV
  - **electron** recoils

Besides brute force, we (desperately?) need
some brave (experimental) idea.

And - possibly - some luck
(since nobody really knows where exactly to look).

Back-up slides

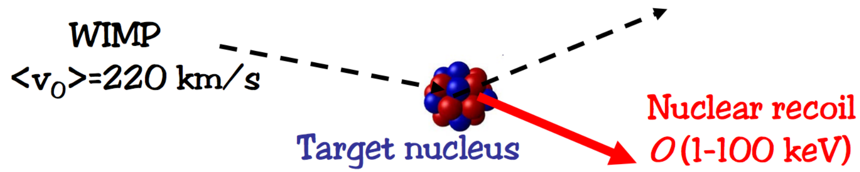
Energy spectrum of modulation



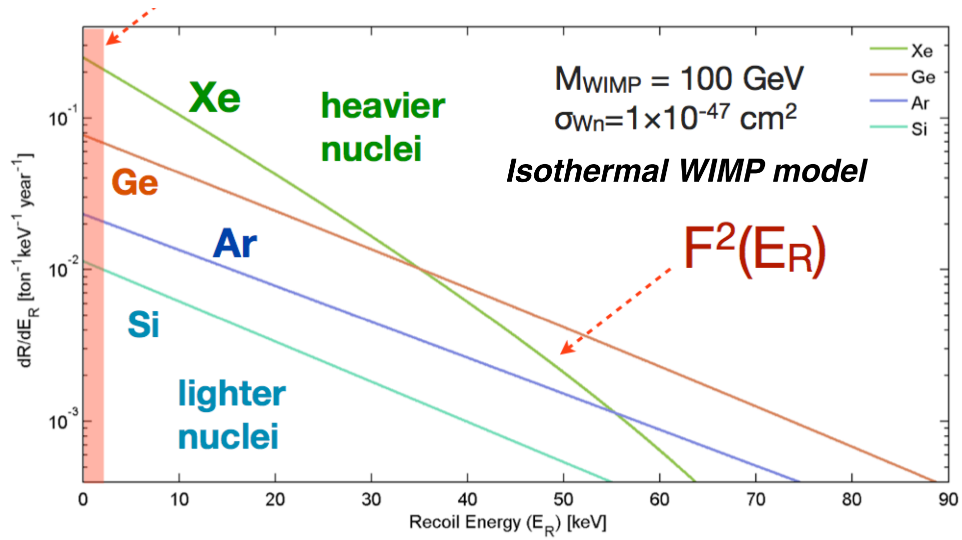
- **Lower** PMT threshold (higher Q.E. PMT) can shed light on **different models** of the WIMP distributions (halo, stream, etc.)
- Diurnal modulation might be investigated (large exposure)

If an anisotropic scintillation crystal is found(**ZnWO**?), measure the WIMP direction!

Response to elastic scattering



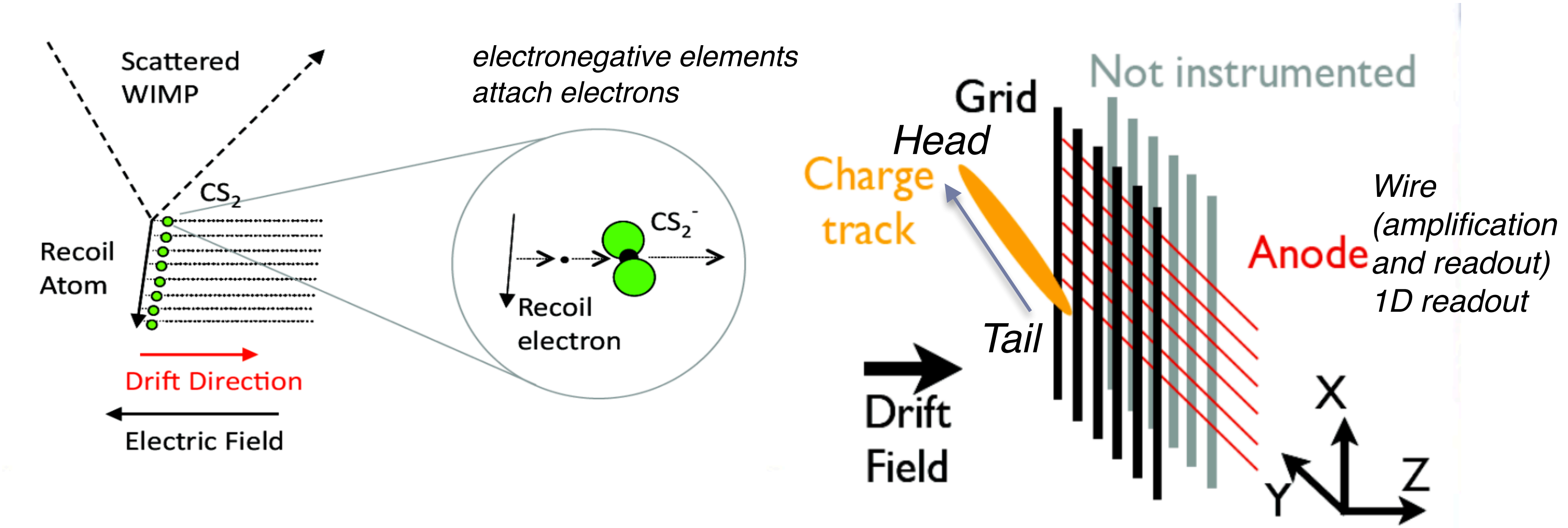
- WIMP (and neutrinos) interact **coherently** with a nucleus
- Energy release is **tiny**
- Rate is **few** events/Kg/year



- Interaction might be **spin**-*independent* or spin-*dependent* (not all the nuclei are equivalent)
- Some effect of the **nuclear form factor**

*But other scheme are possible, interaction with **electron**, **inelastic** interaction…*

DRIFT: negative ion drift TPC

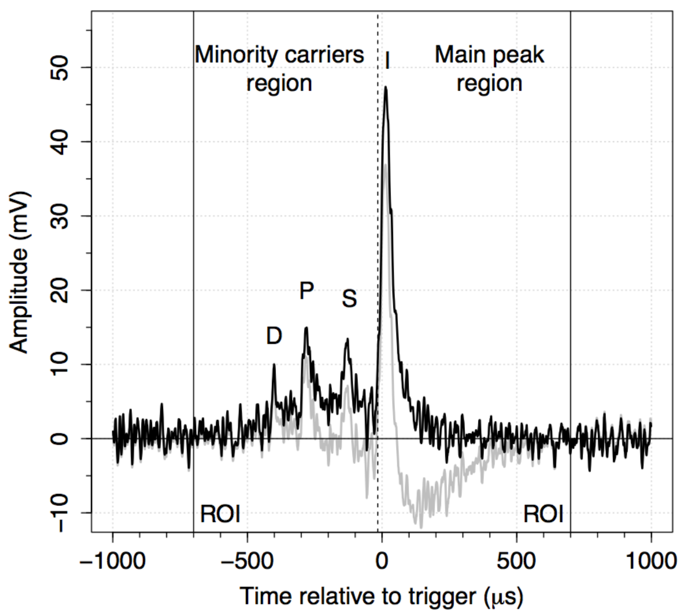


- Limited diffusion ever over long drift distance (<0.5mm on 0.5m)
- If anode segmented, a "ion recoil track" can be reconstructed: **direction**
- **Head-tail** information is valuable as well (might be enough for discrimination)

DRIFT fiducialization

- TPC with no external trigger.
  - Multiple negative ions drifting!

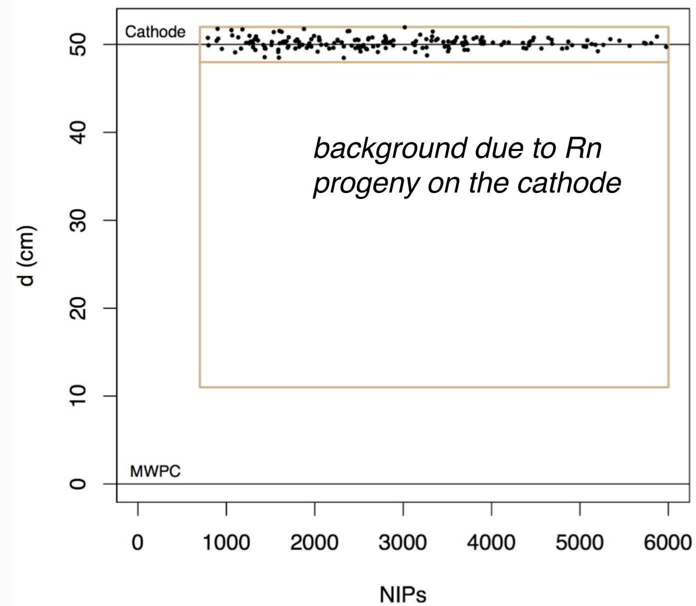
Signal on one wire



$$v_d = \left(\frac{1}{m} + \frac{1}{M}\right)^{1/2} \left(\frac{1}{3kT}\right)^{1/2} \frac{eE}{N\sigma},$$

ion ***gas***

Astropart.Phys. 91 (2017) 65-74



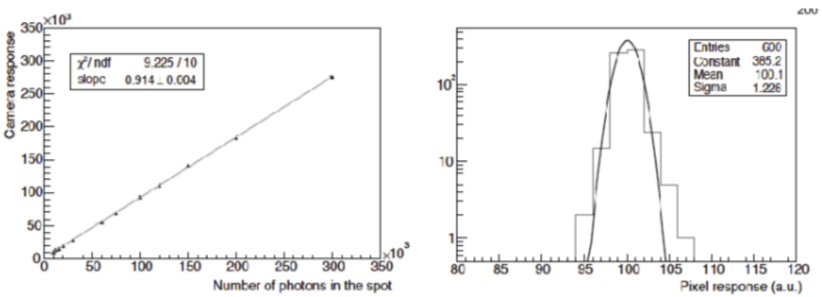
Z position measurement

$$\boxed{z = (t_m - t_p)\frac{v^m_{drift} v^p_{drift}}{v^m_{drift} - v^p_{drift}}}$$

Light readout

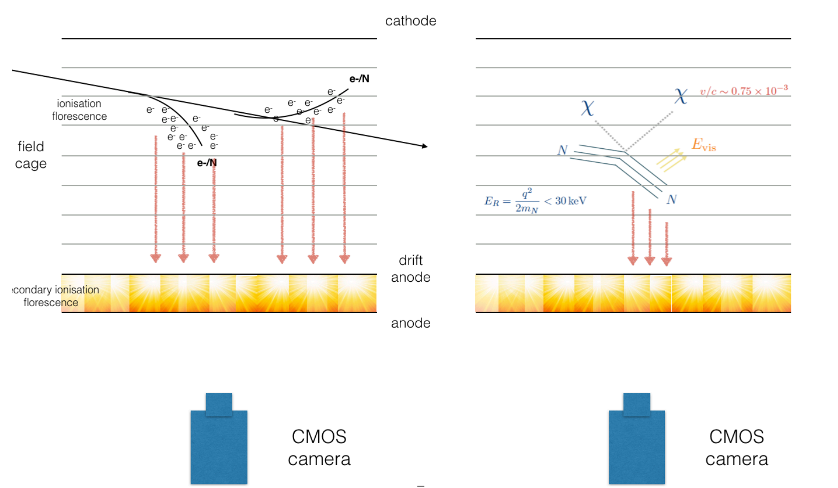
- Light production in a GEM discharge readout with low noise CMOS camera

For a m.i.p. track we predict (Garfield)
~ $7e^{-}$/mm (primary ionisation electrons)
For a m.i.p. track we **measure**
~ 1000 photons/mm
that means
~150 photons/primary electron



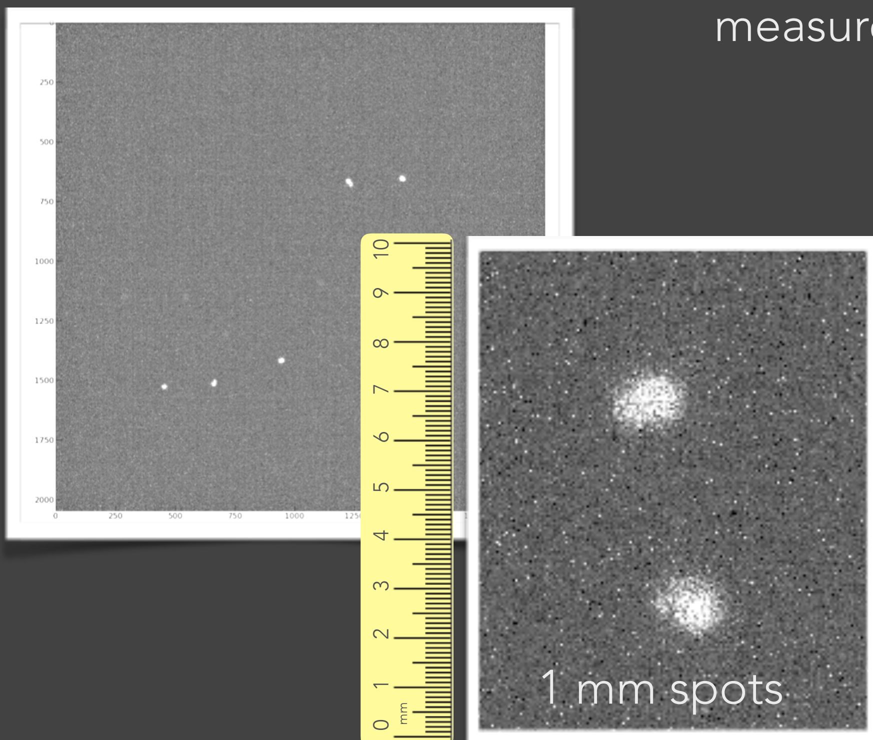
Camera calibration, pedestal is less than ***2*** photon per pixel (***"photon" noise equivalent***)

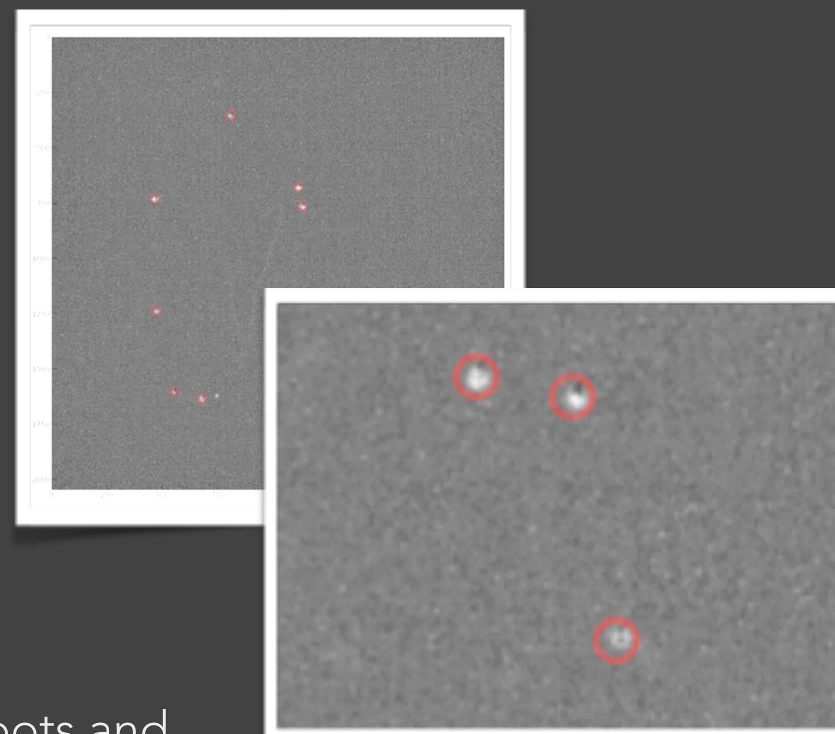
- Very good signal to noise ratio!



X-RAYS FROM A ^{55}FE SOURCE

The light response to 5.9 keV photons from a ^{55}Fe was measured for several He/CF_4 mixtures.

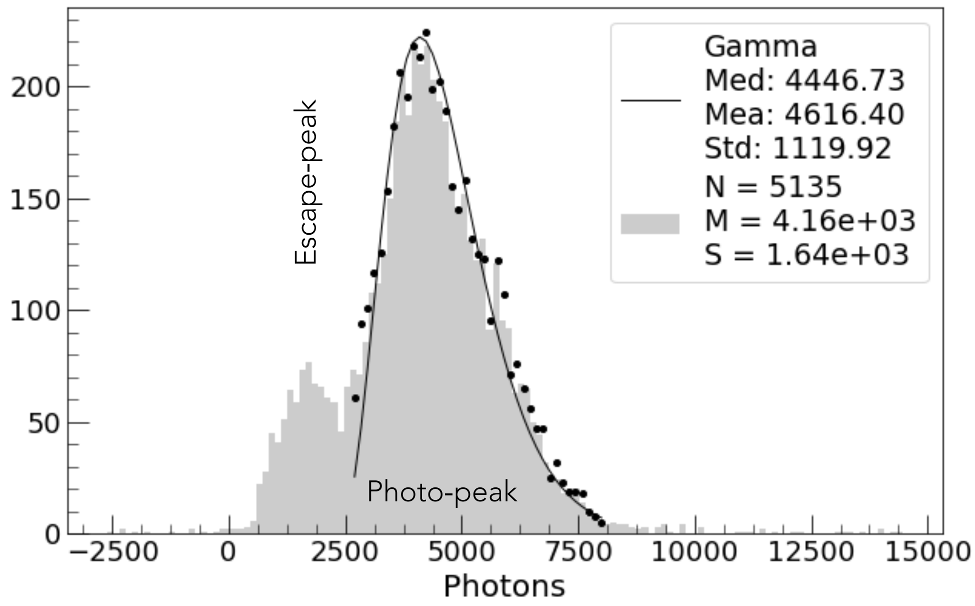




We used a Hough transform to individuate spots and measure their dimension and light yield.

X-RAYS FROM A ^{55}FE SOURCE

Light yield distributions were studied as a function of the mixture and the to the GEM voltages

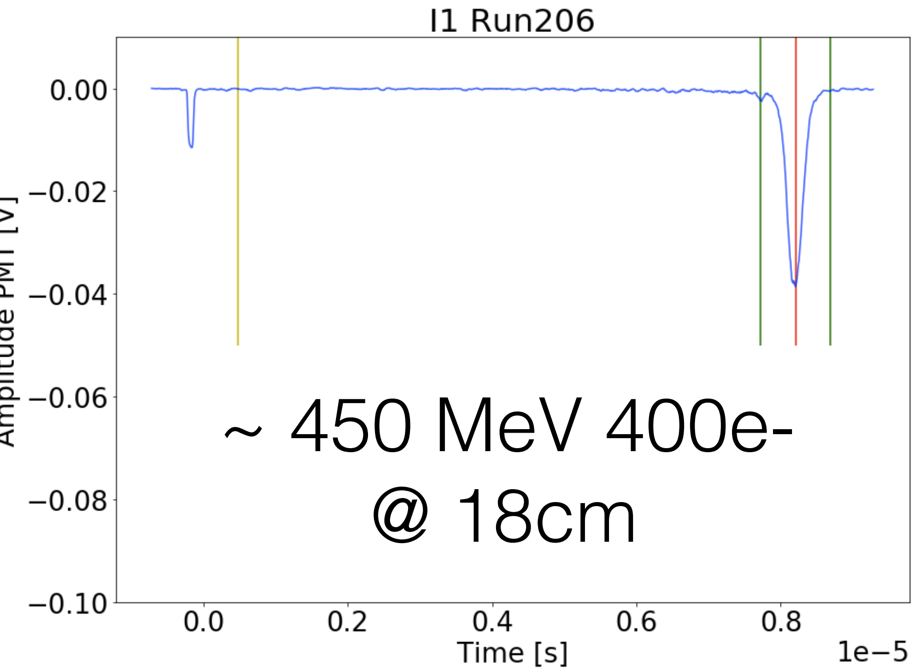


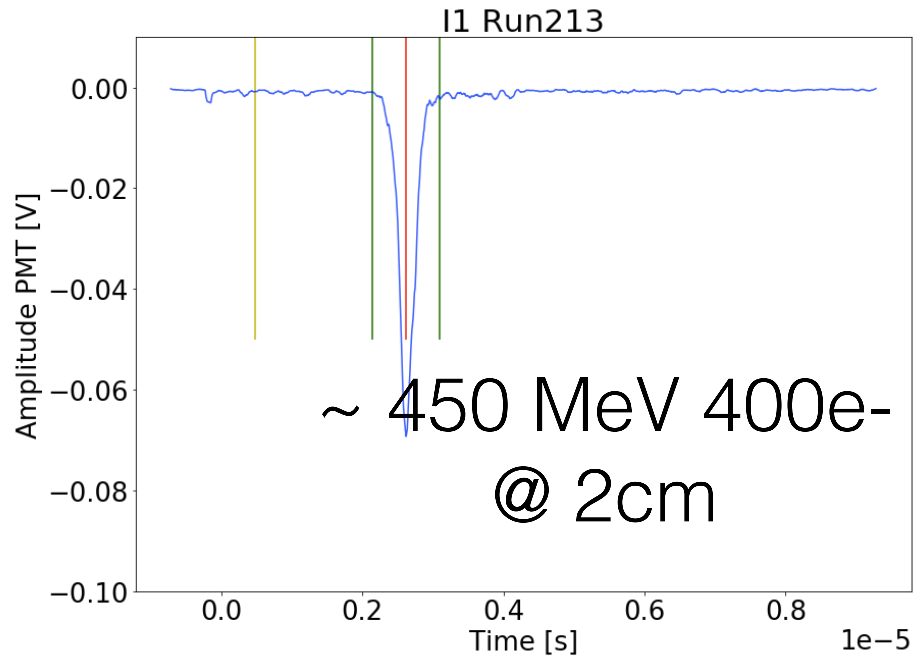
Peak positions and widths were evaluated by a Polya fit

By means of an X-ray tube, electron yield was also studied for different mixtures and different voltages.

Primary light

Primary (from e track) and secondary (first GEM) light signals

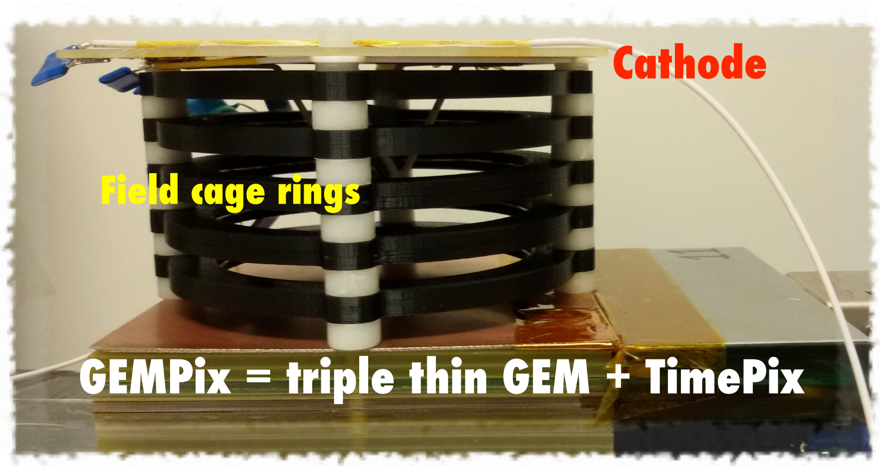




Still very far from being useful for full fiducialization
(but we used sub-optimal Q.E. PMT and limited light collection)
It might be good to reject cathode events anyway!

R&D NITEC

NITEC: Negative Ion Time Expansion Chamber



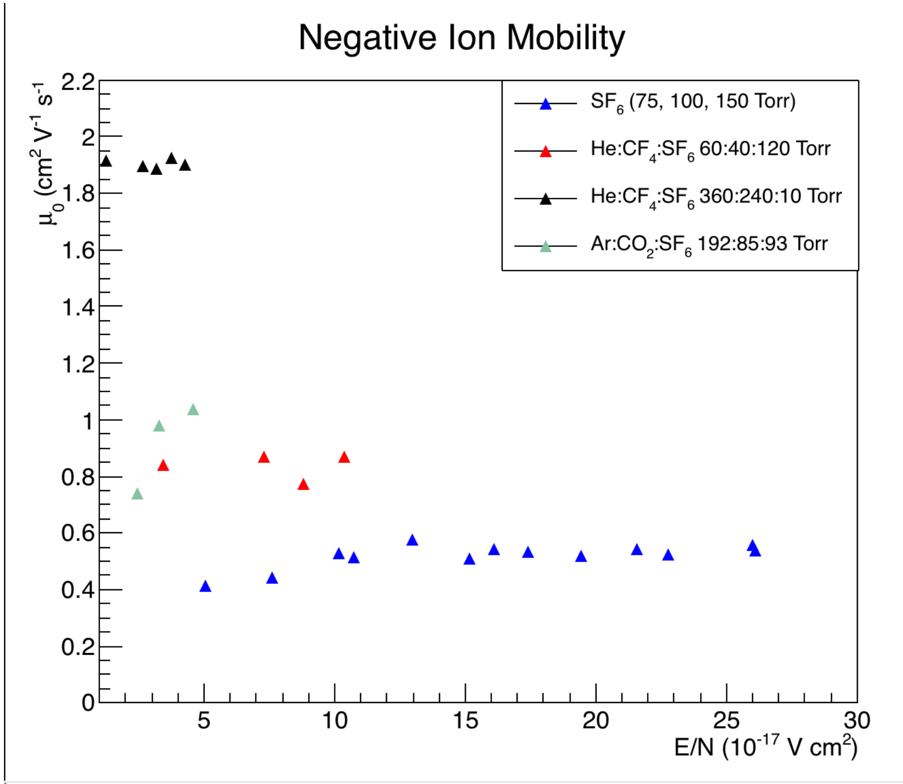
3 x 3 x 5 cm^3
0.045 Liters
Triple thin GEMs
Timepix pixel charge readout

- Small gas volume to study gas properties
- Operation in pure SF_6 at low pressure
- Operation with gas mixture
- GEM pixelated charge readout

SF_6 negative ion drift

E.Baracchini et al.JINST 13 (2018) no.04, P04022

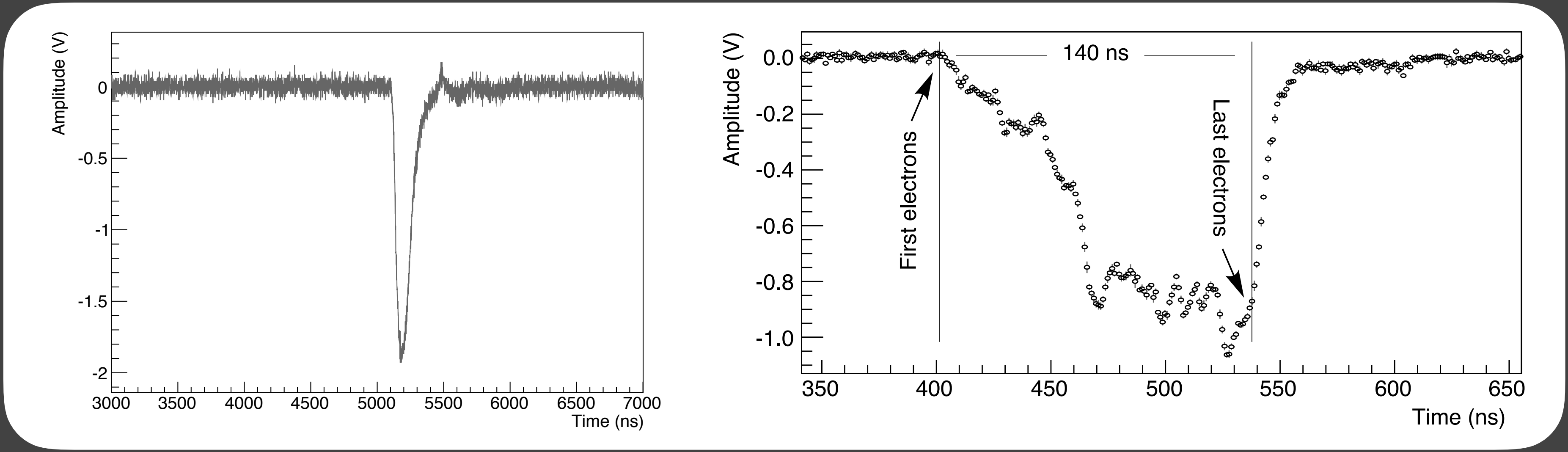
- Measured ion mobility in SF_6 based gas mixture at 600 torr.
  (from drift velocity of negative ions generated by the 45 MeV BTF electron beam)



- Need to understand the "**light**" **gain** of gas mixture with SF_6
- Hope to see signal of **minority** carriers (SF_5, SF_4, etc.)

COMBINED LIGHT READOUT

JINST 13 (2018) no.05, P05001

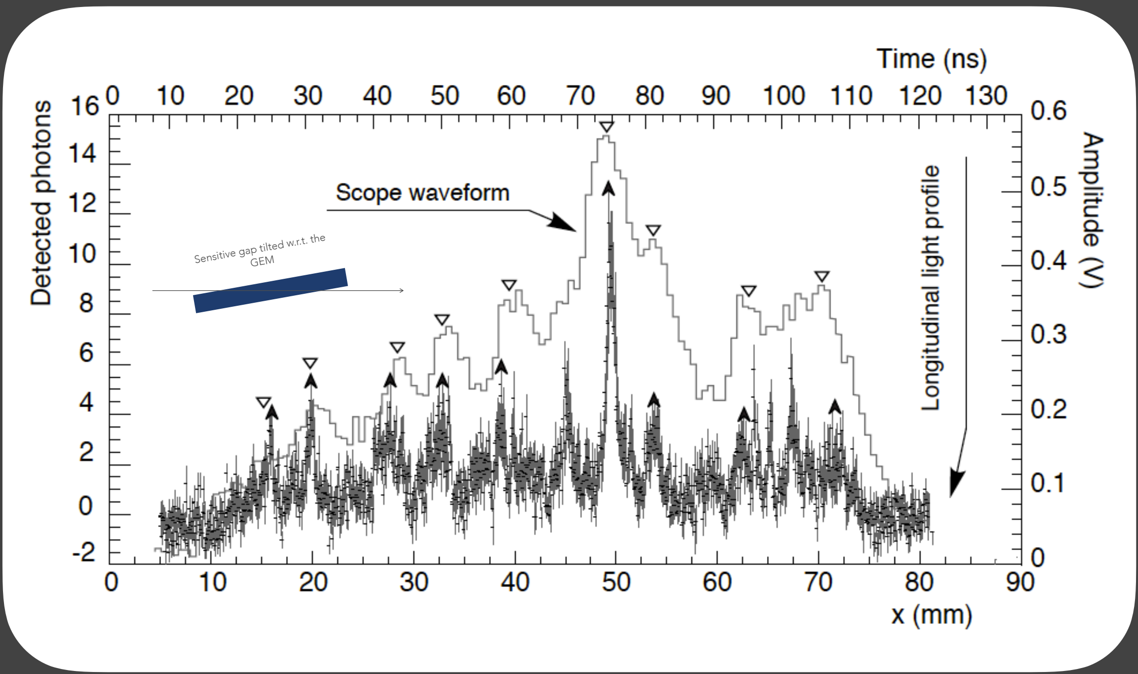


1 cm in 140 ns => drift velocity 7.2 cm/μs in agreement with Garfield expectation of 7.3 cm/μs.

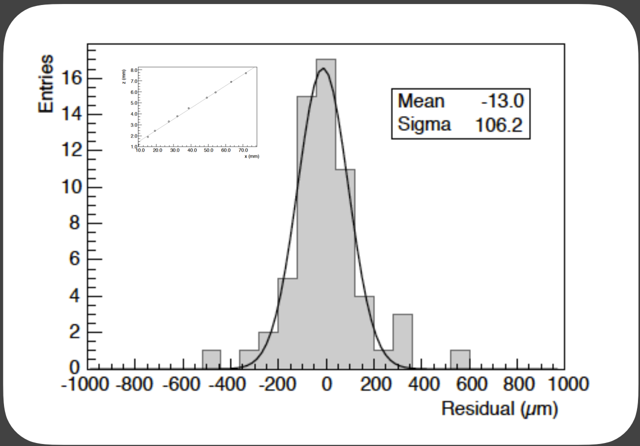
PMT+CMOS COMBINED READOUT

Single cluster 3D position reconstruction can be obtained by comparing the light profile along the track (X, Y) and the PMT waveform (t);

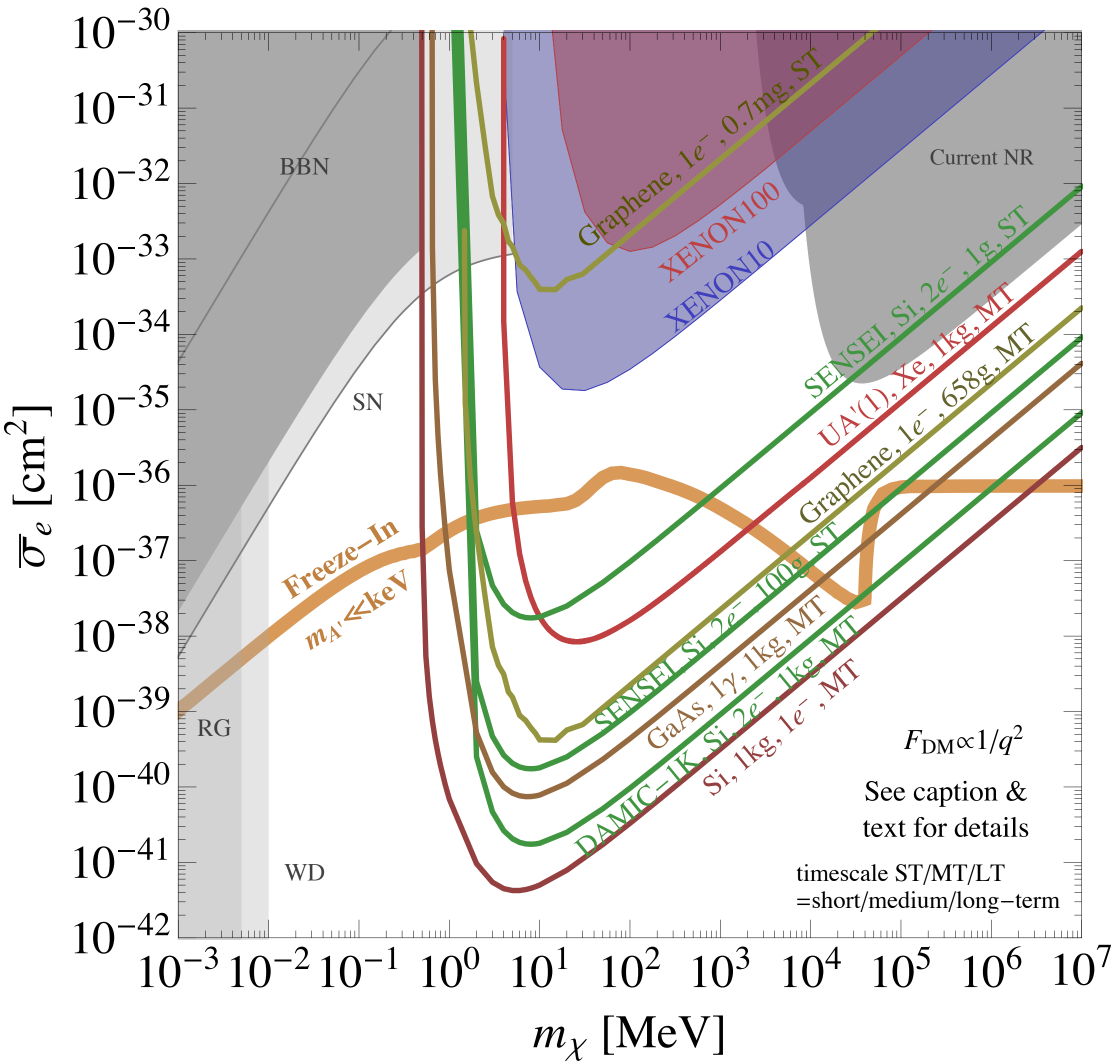
A peak finding algorithm was used to highlight the main cluster signals;



By means of the measured drift velocity, Z coordinate was evaluated;



Residual distribution to a 3D fit allows to compute a resolution on Z of 100 μm.

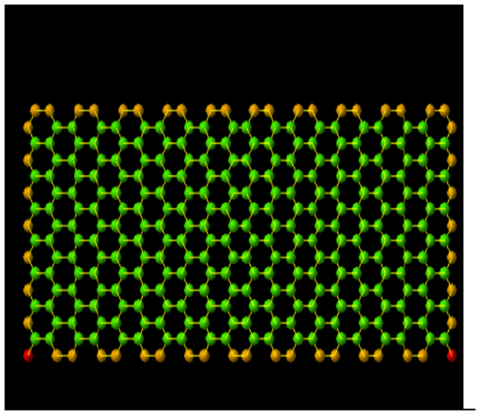


Near-term results for MeV Dark Matter expected with 2e– thresholds in Si (DAMIC/ SENSEI/SuperCDMS)

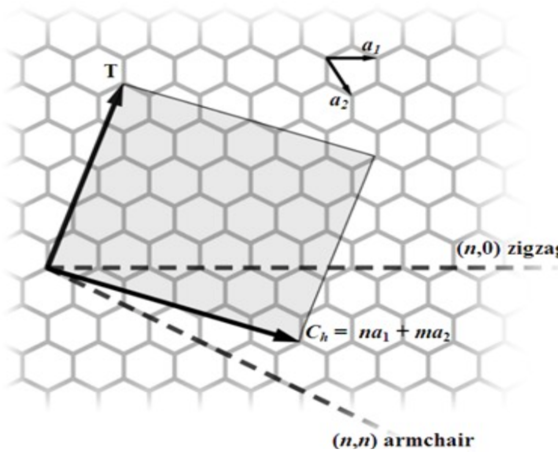
→Significant overlap in sensitivity to follow up with **Directional Detection (PTOLEMY-G³)**

Carbon nanotubes

Structure: Imagine wrapping a sheet of graphen into a nanotube



Shigeo MARUYAMA, Univ. Tokyo

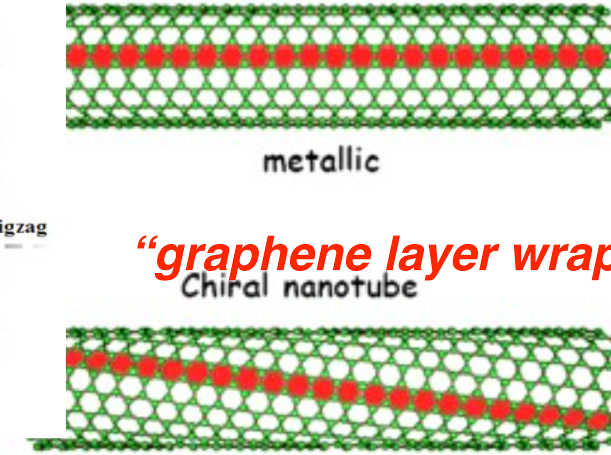


$$R = \frac{l\sqrt{3}}{2\pi}\sqrt{n^2 + m^2 + nm} \qquad l = 0.14nm$$

n=m → metallic

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

Nonchiral ('armchair') nanotube

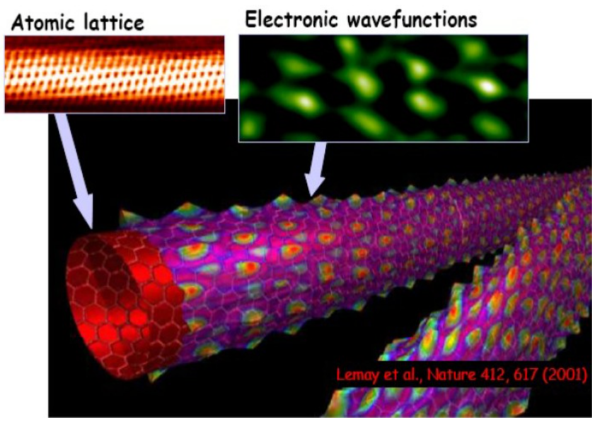


metallic

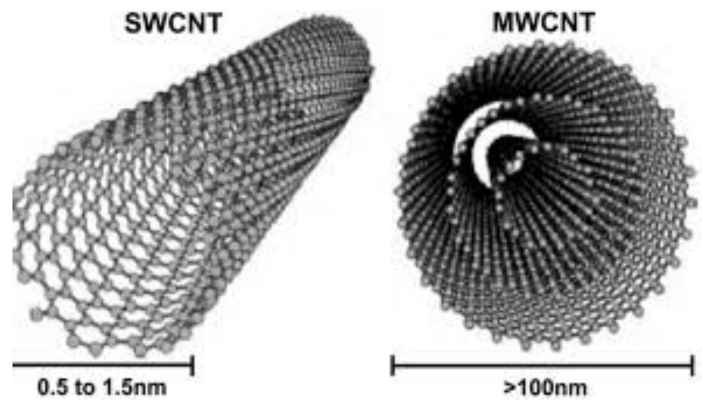
"graphene layer wrapping"

Chiral nanotube

semiconducting *or* metallic



Electron orbitals on CNT surface

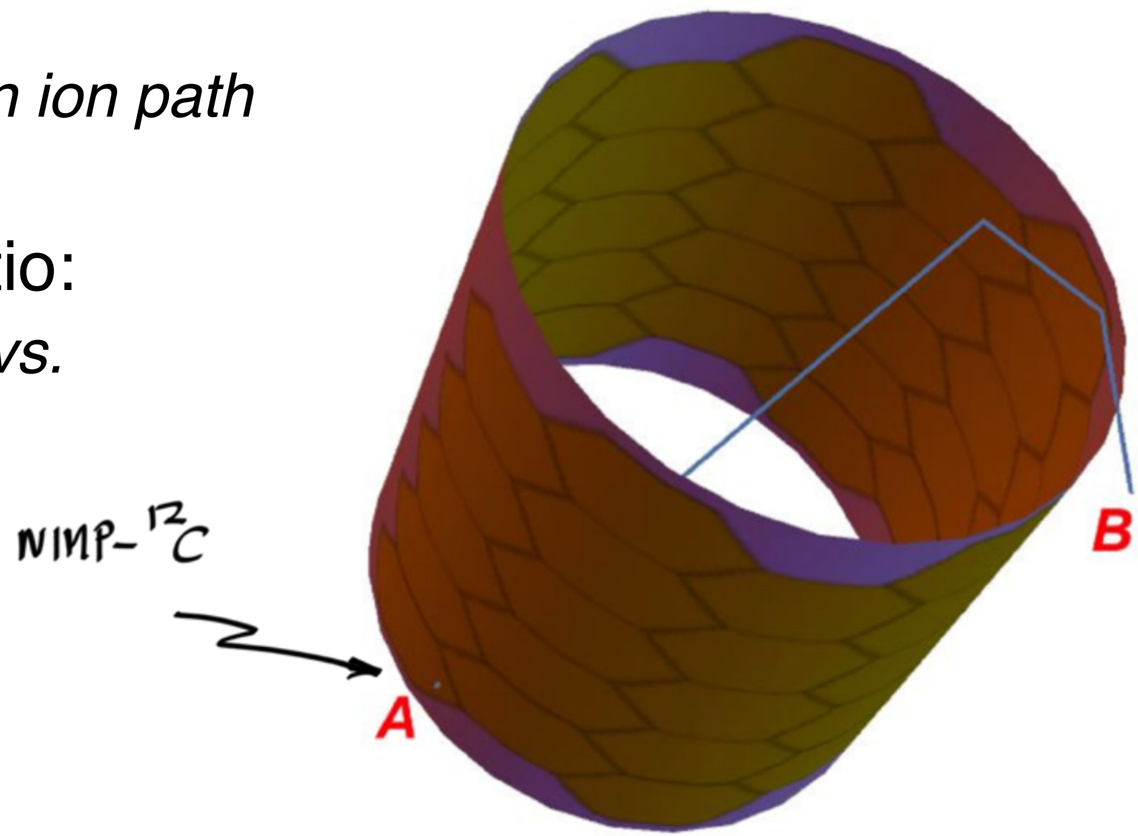


Scattering on a carbon nanotube

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

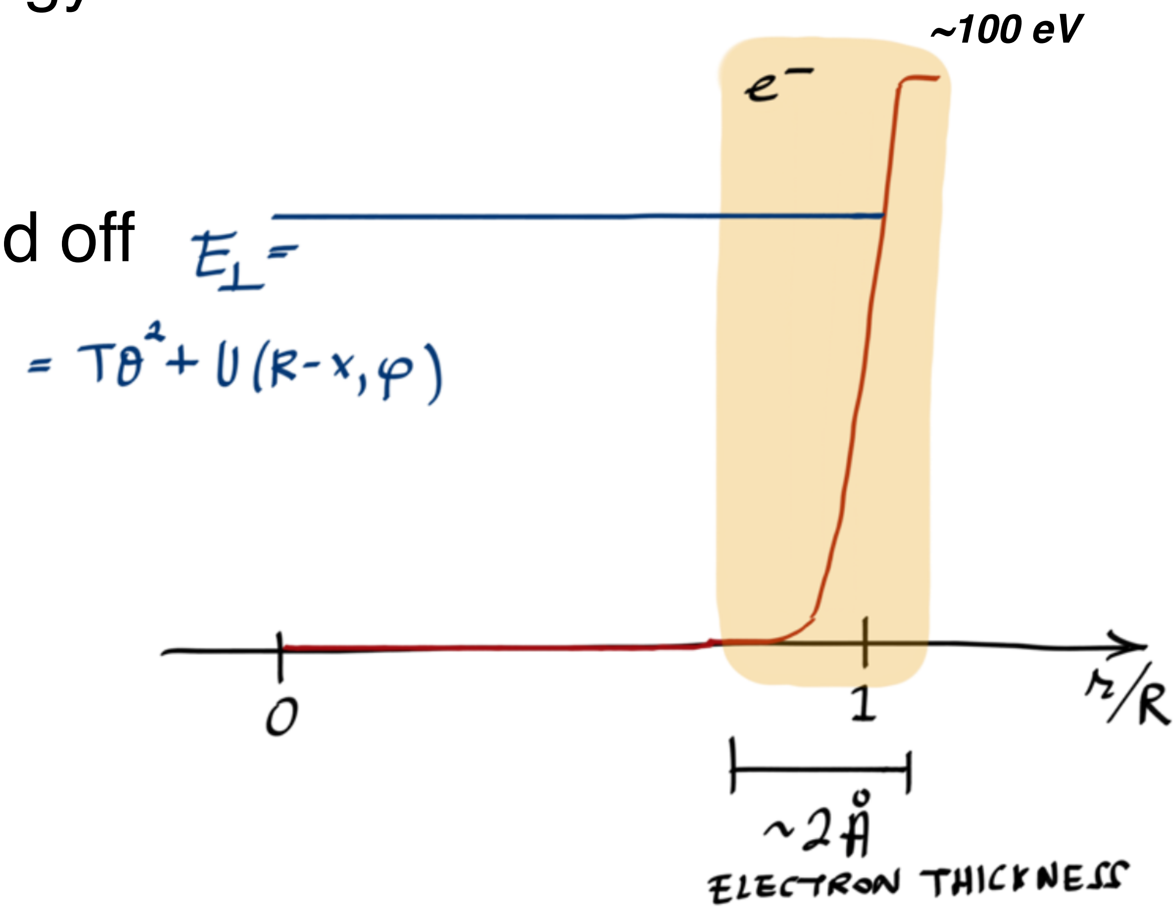
- Large aspect ratio:
  ~10 nm diameter vs.
  ~100 µm height

- ***“target”** mass*
  on the CNT
  surface



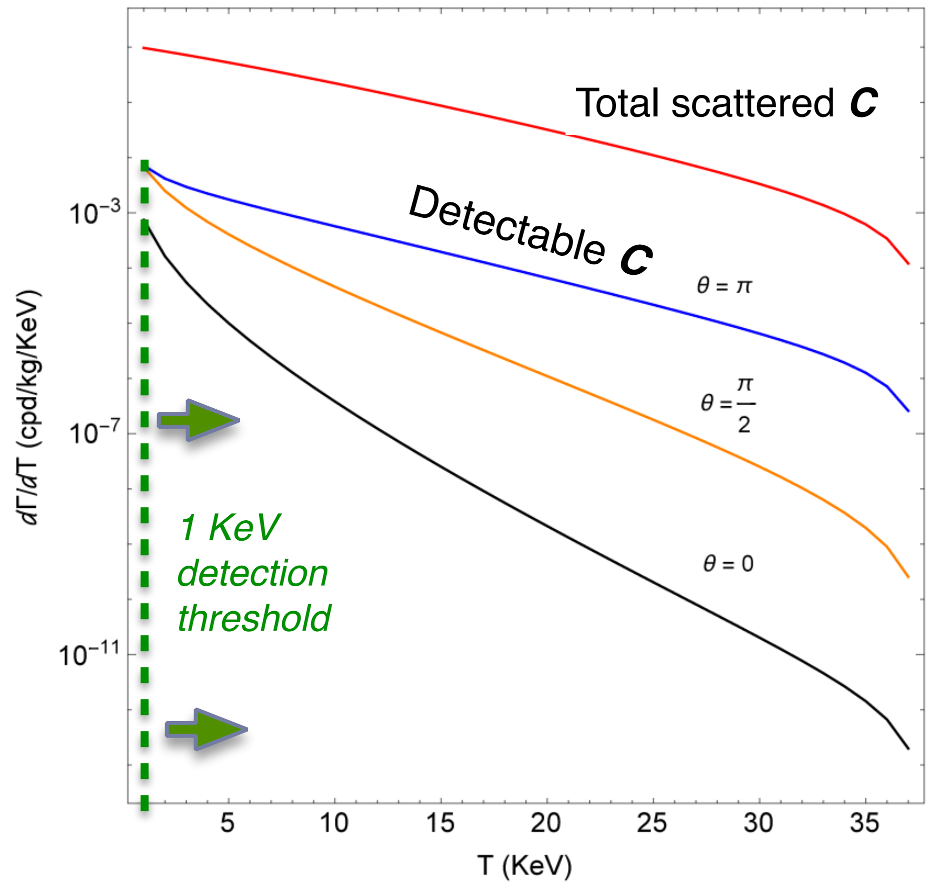
CNT as a potential well

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



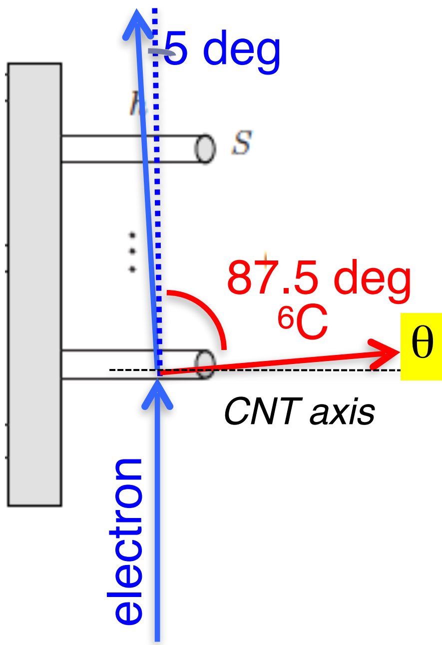
CNT anisotropic medium

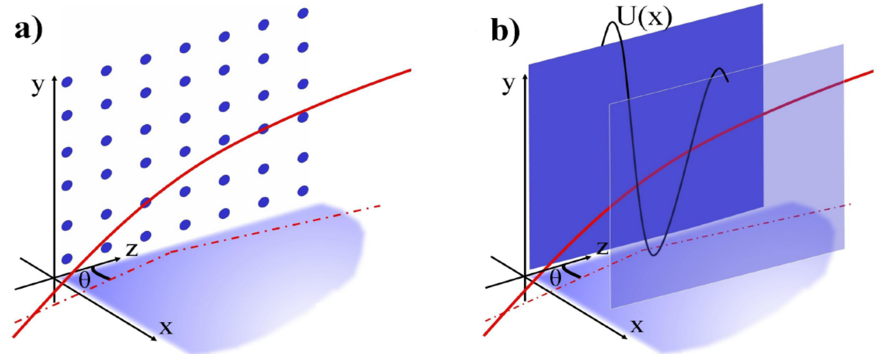
- **Aligned and oriented CNT "brush"**
  - *Recoiling **C** ions are emerging from CNTs with different rates* **depending** on CNTs **orientation.**
  - When ***C*** ions are **not channeled** they are **absorbed** within the brush
- Effect of rechanneling or **inter-CNT trapping** NOT included HERE



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 ^6C channeling

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

Functionalization

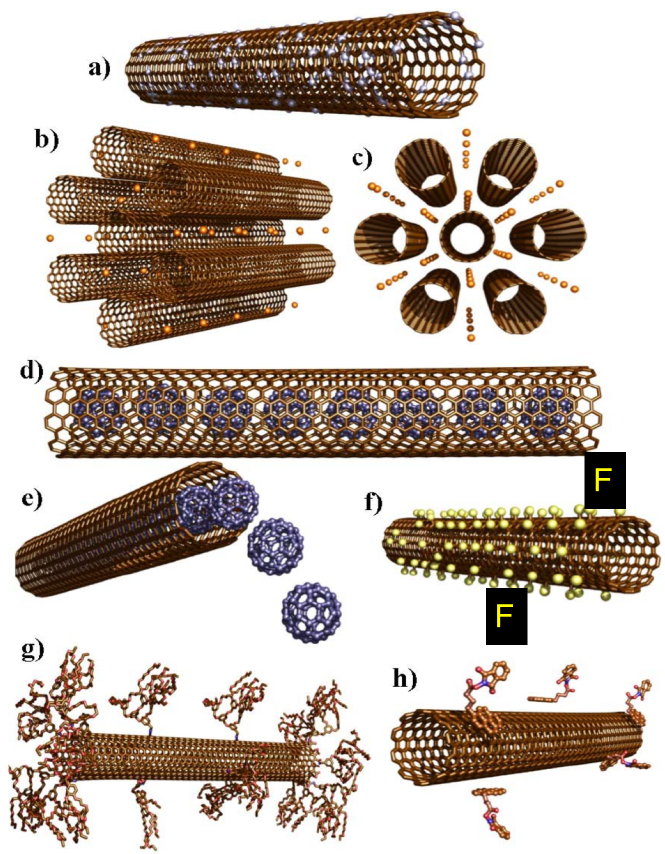
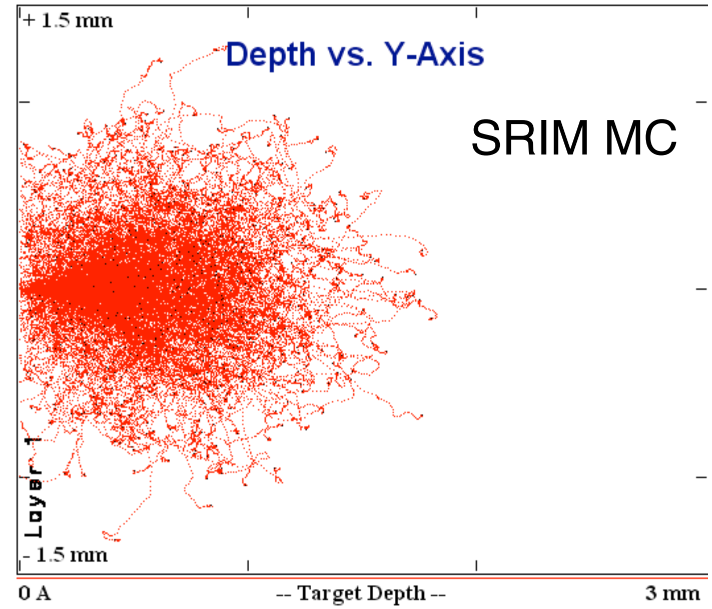


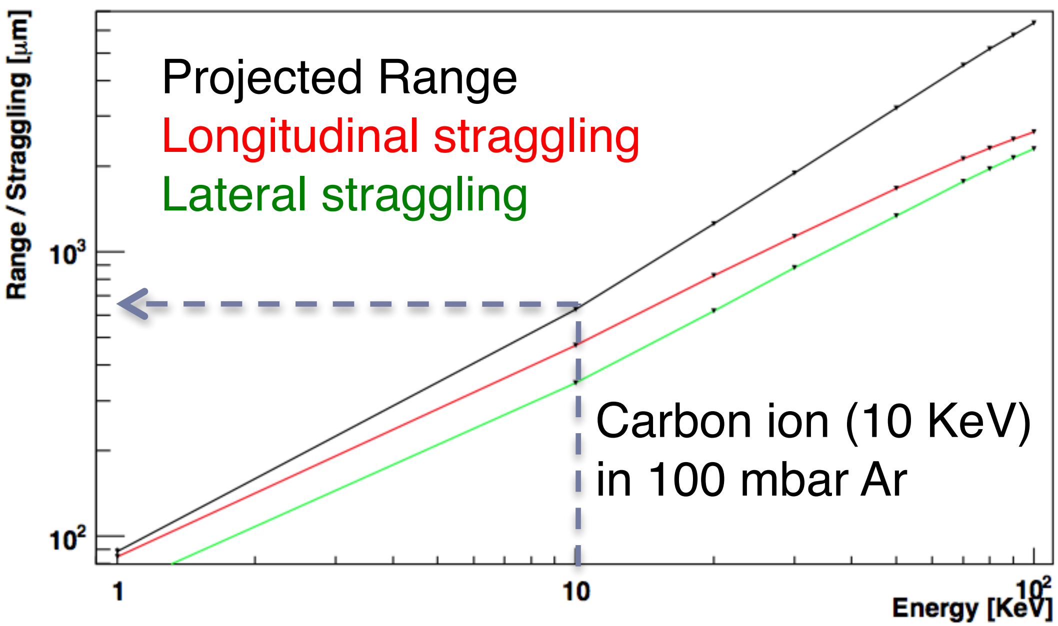
Figure 8. Different approaches to chemical modification of carbon nanotubes. (a) substitutional doped single-walled nanotubes (either during synthesis or by post-growth ion-implantation), (b,c) nanotube bundles intercalated with atoms or ions, (d,e) peapods: SWNTs filled with fullerenes (other endohedral 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

Range of few KeV ion in Ar

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

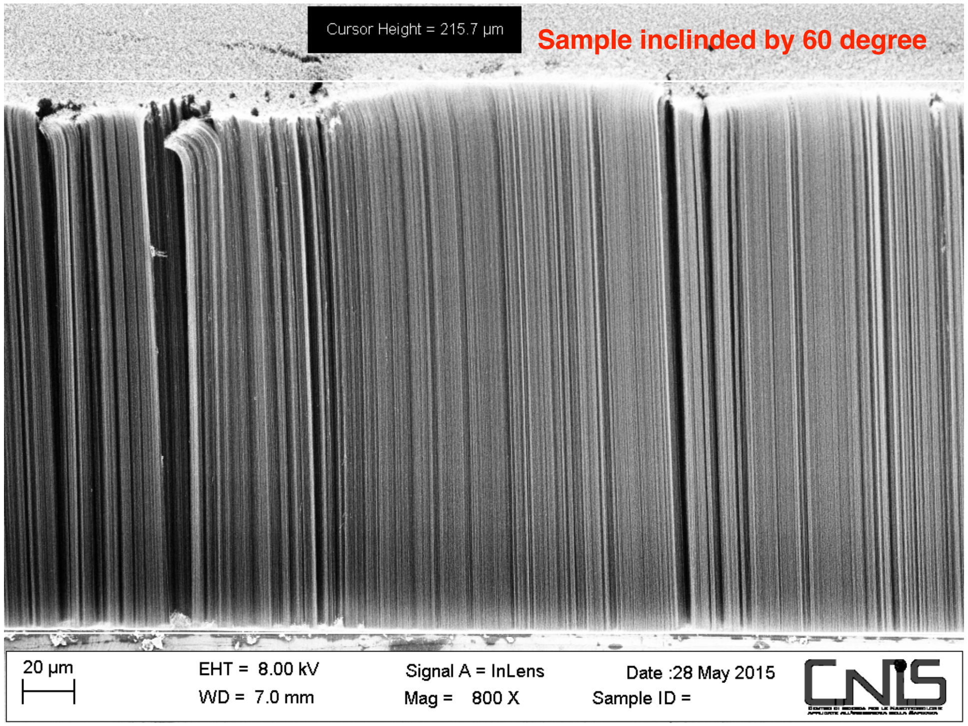




Even with large spread of ionization, the range measurement might help to identify the signal

 G.Cavoto

How to pack enough mass ?



SEM image of NanoLab aligned CNT on mm Si substrate

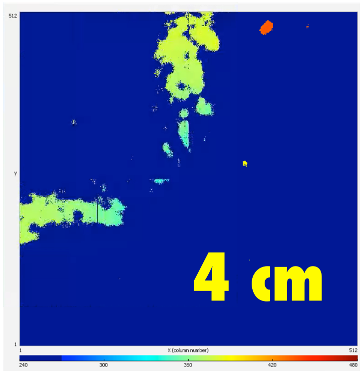
First test shows $<10^{-3}$ contamination of Fe (“seed”) and O.

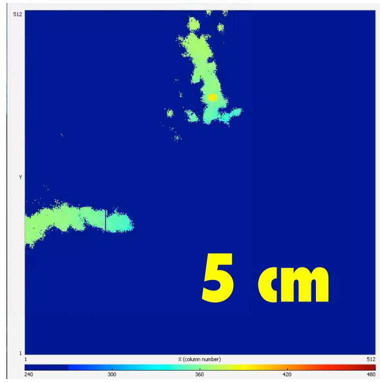
- Simple-man calculation for 1 m^2 layer - 100 layers detector
- ρ=5 nm and h =300 µm
- number CNT per layer (single wall) ~ 2 m^2/a^2
- Surface density of a graphene layer: 1/1315 g/m^2

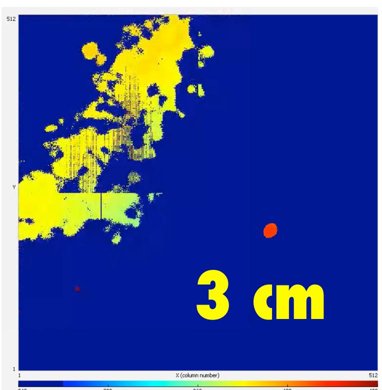
a [nm]	CNT detector mass [kg]
11	11.8
30	1.6
45	0.7
58	0.4

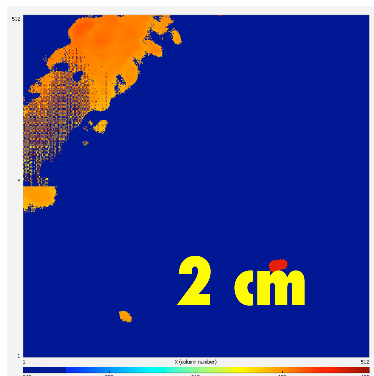
First look at CNT

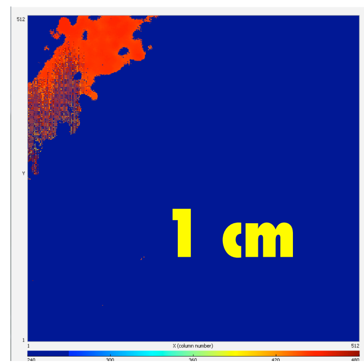
$Ar:CO_2:CF_4$ TOA data @ 300 Torr
(confirmed with pure SF_6 @ 150 Torr)

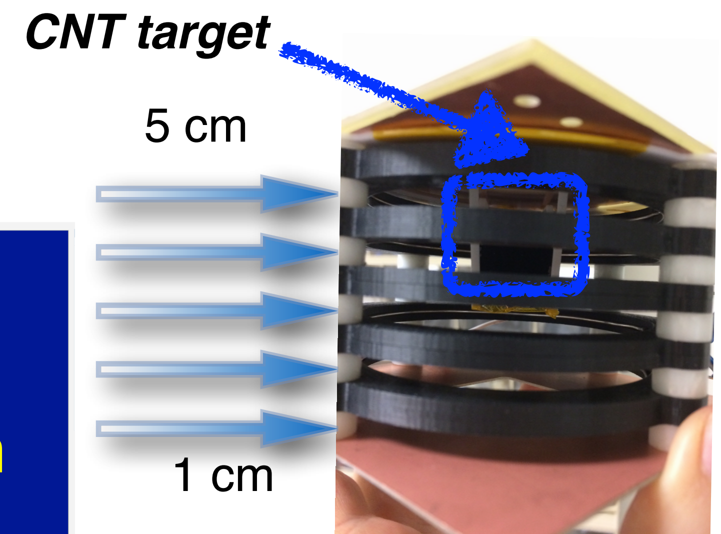












Color is drift time (along Z) for different Z position (X-Y projection)

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