Directional WIMP detection R&D

Gianluca Cavoto Sapienza Univ Roma and INFN

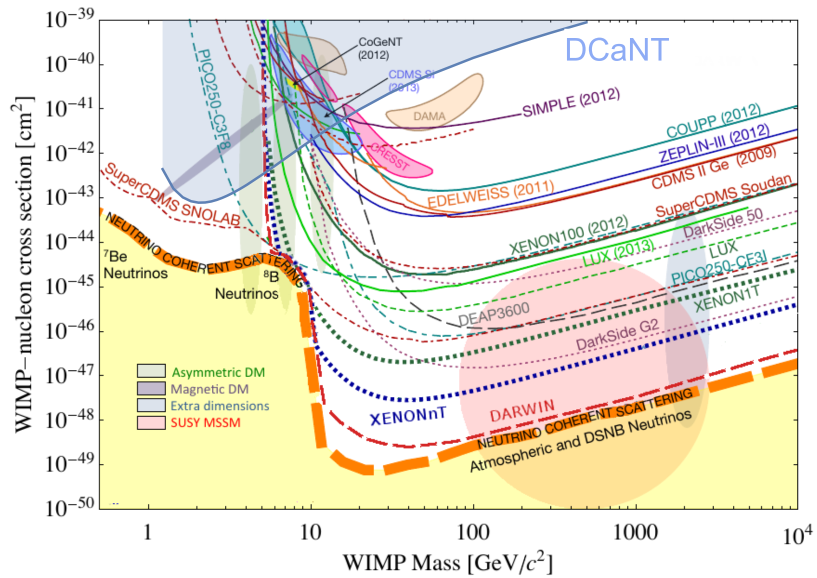
PIRE Workshop

Feb 5th and 6th 2017

Extending the reach

Low masses

Low cross sections

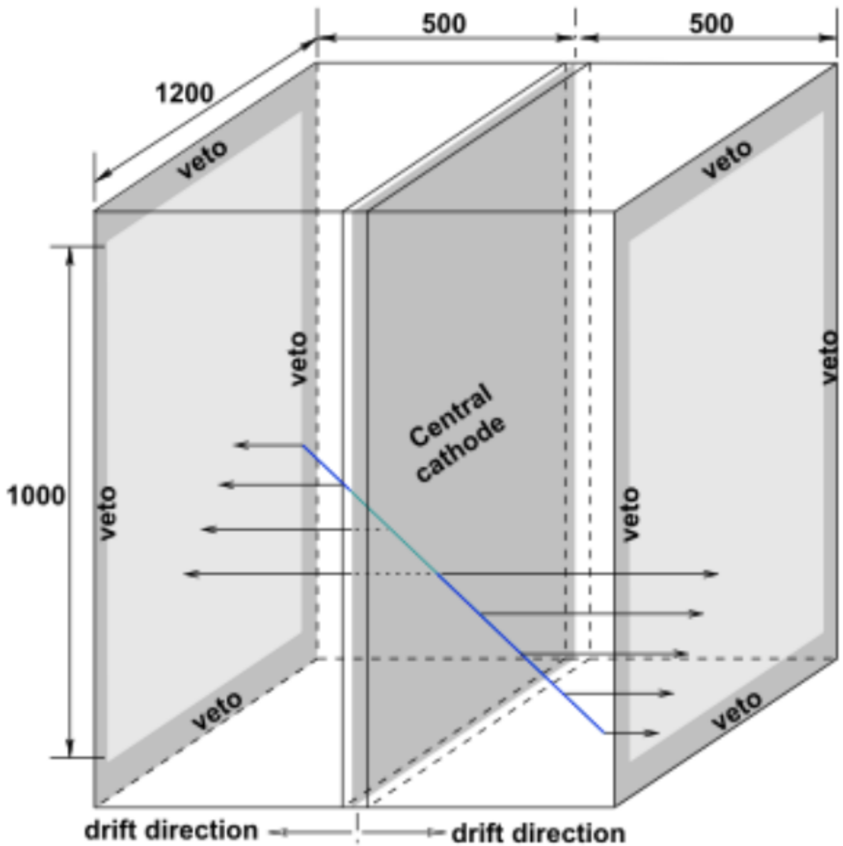


- **If** ton-scale dark matter detectors do **not** see anything, need to explore **lower cross section** (the **solar-atm neutrino** will be a background). Use **<u>direction</u>** of WIMPs to discriminate them

- **If** they do see **something**, study WIMP's **wind**

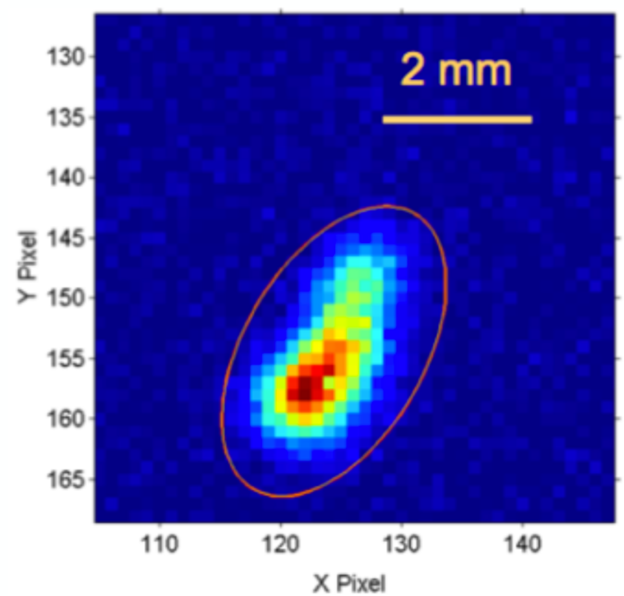
- Use smaller mass target (carbon, electrons) to go to **sub-GeV masses**

TPC concept for nuclear recoil



DRIFT detector (low pressure TPC with anode wire readout)

A nuclear recoil!



example high energy F recoil in optical TPC (D. Loomba et al.)

Activity in Italy - Roma and Frascati

- Various activities financed by INFN and EU
  (new detectors concepts, new target concepts, …)

  - **T**ime **P**rojection **C**hamber readout with GEM
    - Study negative ion drift
      (new gas mixture based on SF6, charge readout - **NITEC**)
    - Optical readout of large GEM surfaces - **CYGNUS-RD**
      (large surface detectors)
    - Carbon nanotubes as anisotropic target for WIMPs
      (demonstration of ion channeling) - **DCANT**

CYGNUS int'l proto-collaboration to create eventually a **multi-ton multi-site observatory**

Working on a proposal for measurement of neutrons flux
at INFN Gran Sasso underground labs

Sapienza and INFN

- Strong link between Sapienza Physics departments, INFN Roma division and INFN Frascati labs.

http://www.phys.uniroma1.it/fisica/en-welcome

http://www.roma1.infn.it/en/index.html

http://w3.lnf.infn.it/?lang=en

Access to Frascati **B**eam **T**est **F**acility
(50-500 MeV electron or positron beam from DAFNE LINAC
http://www.lnf.infn.it/acceleratori/btf/)

People involved

- People involved:
  - Sapienza and INFN Roma: C.Antochi (st.), GC, D.Pinci, E.Di Marco, M.Marafini, A.D.Polosa, F.Renga, C.Voena
  - INFN LNF (Frascati): E.Baracchini, G.Mazzitelli, F.Murtas, A.Tomassini.
- Sapienza and INFN have a strong link for Ph.D. student support
- Student academic training provided by Sapienza Ph.D. school(s)
- Access to laboratories granted by INFN

Projects & Concepts

FUNDING

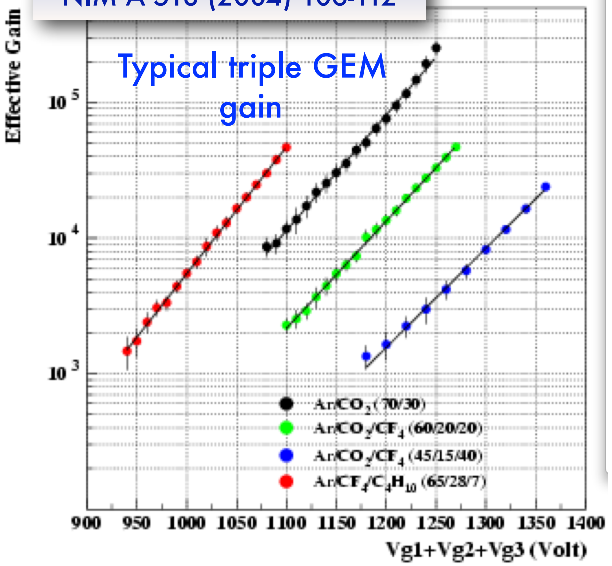
- **NITEC** — EU HORIZON 2020 — May 2015- May 2017
  - Triple thin GEM amplification (3 x 3 cm^2) + pixel charge/time readout
- **DCANT** — INFN CSN5 — 2016-2017
  - Carbon nanotubes with anisotropic directional response
- **CYGNUS-RD** — INFN CSN5 — 2017-2018
  - Triple thin GEM amplification (10 x 10 cm^2) + CMOS optical readout

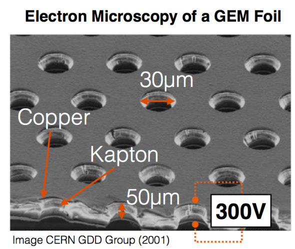
Dark Matter is very high in INFN priority list
Longer term support for investments might come from INFN if current R&D successful

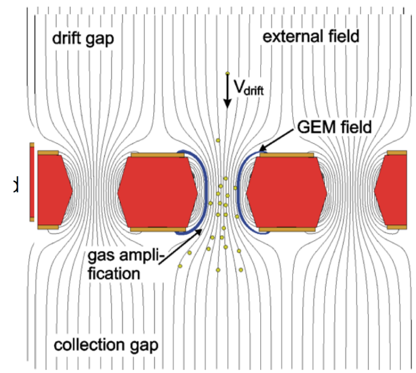
- In the following slides presented at two recent conferences
  - **E.Baracchini** at CAASTRO-CoEPP Joint Workshop, (Univ. Melbourne, Australia, Jan 2016)
  - **GC** at IDM 2016 (Univ Sheffield, UK - Jul 2017)

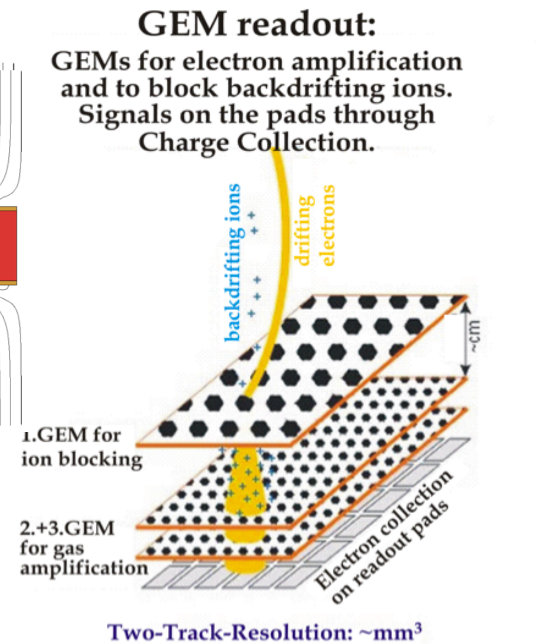
Thin GEM Amplification

M. Alfonsi et al., NIM A 518 (2004) 106-112



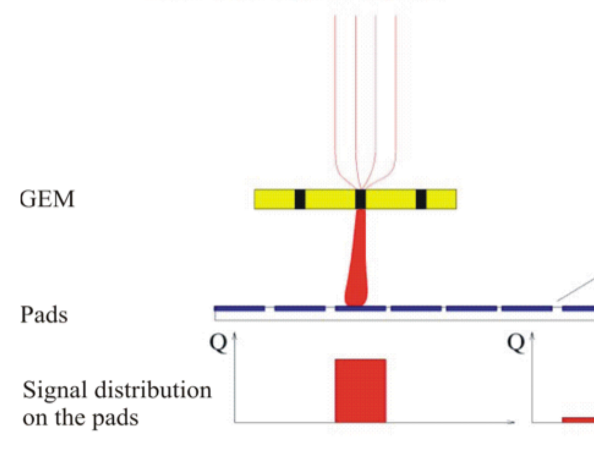






- Particle conversion, charge amplification and signal induction zones are physically separated
- Large dynamic range: from 1 to 10 particle/cm^2 /s
- Gain up to > 10^4
- High stability/granularity

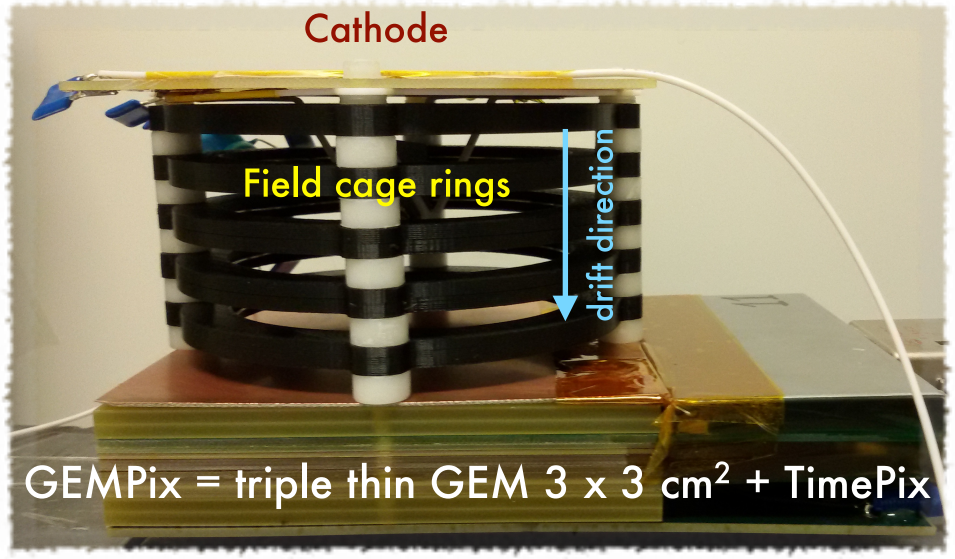
- Micro pattern gas detector
- Thin holes are etched in a metallised kapton foil and a potential is placed across it
- Very large electric field around the holes (40 kV/cm) which creates a localised electron avalanche

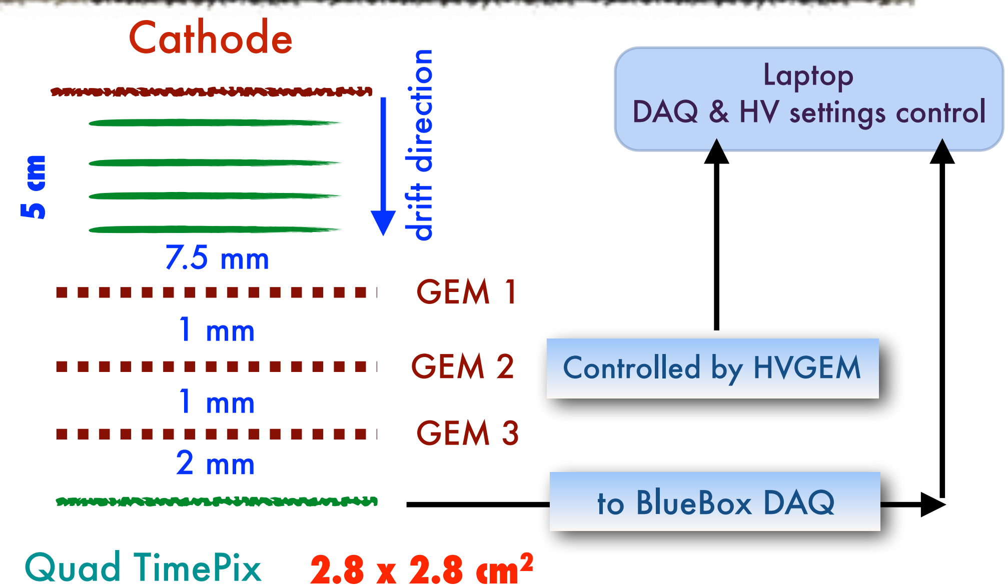


NITEC

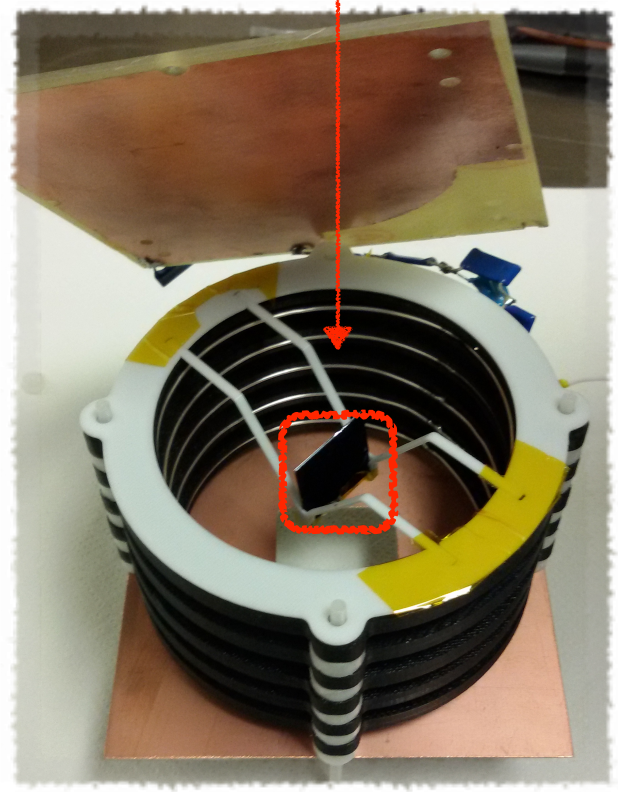
a Negative Ion Time Expansion Chamber for directional Dark Matter searches

NITEC detector





Carbon Nanotubes (see later)

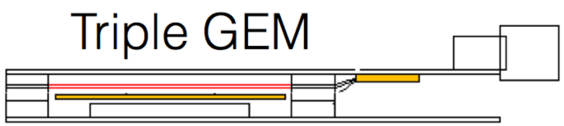


New field cage: rings support structure (in black in the picture) manufactured with 3D printer

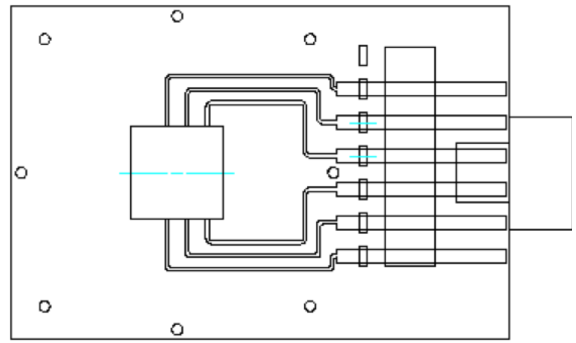
GEMPix

Developed by LNF in collaboration with CERN

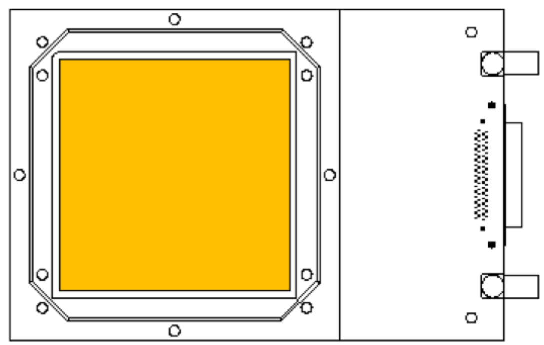
Triple GEM detector with HV filters and connector



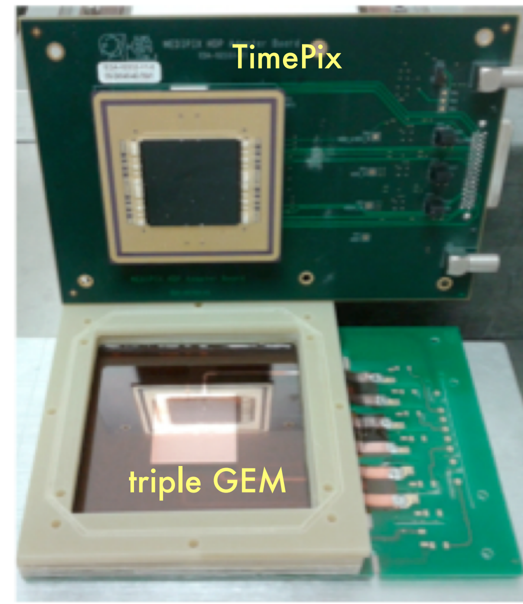
Quad Timepix ASIC board with naked devices (i.e. no silicon)



top view



side view



A dedicated, very stable GEM HV up to <u>700 V per GEM fully developed at LNF</u>

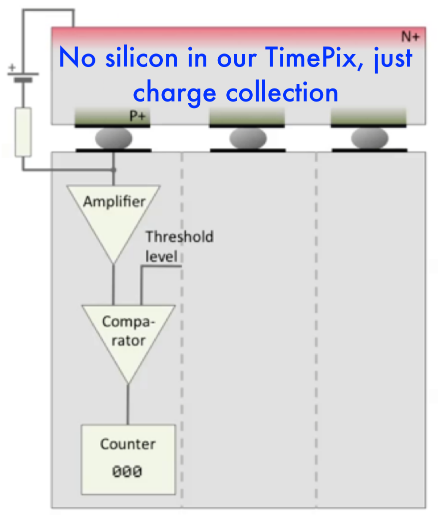
pixel size 55 x 55 um

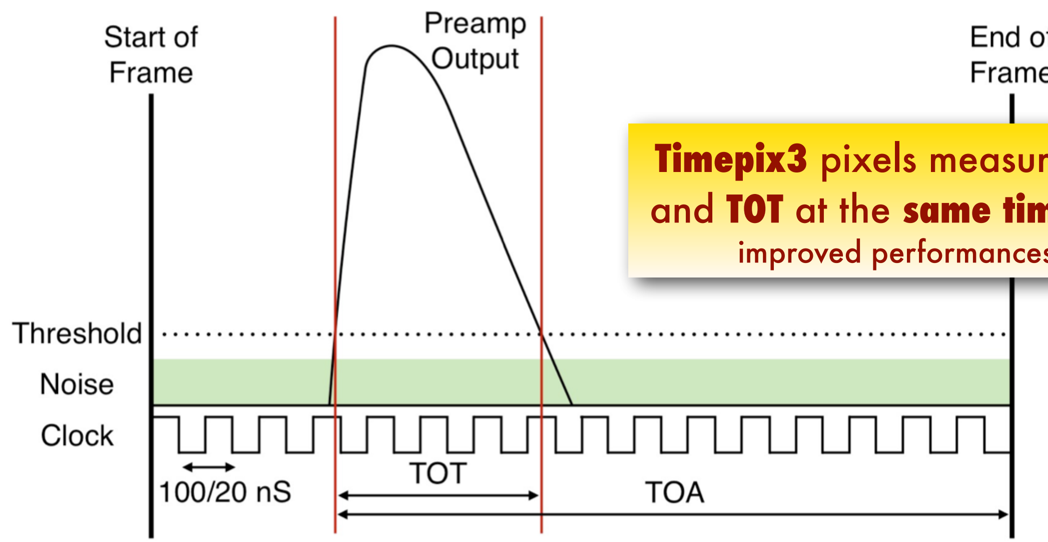
Quad Timepix (512 x 512 pixels) = 4 Timepix chips

2.8 x 2.8 cm^2

TimePix

- TimePix is a pixelated silicon detector developed by MediPix2 collaboration
- We use a 2x2 array for a total of 512x512 pixel of 55 um side WITHOUT silicon sensors
- Processing electronics, including preamplifiers, discriminator threshold and pseudo-random counter fit inside the footprint of the overlying semiconductor pixel.
- Can be operated in counting TOA, TOA and TOT mode but also *TOA/TOT MIXED mode*





Timepix3 pixels measure **TOA** and **TOT** at the **same time** (with improved performances)

- Timepix clock can run from <1 MHz up to 100 MHz
- Timepix counter depth is 11810, **SUITED FOR BOTH ELECTRONS and NEGATIVE IONS DRIFT**

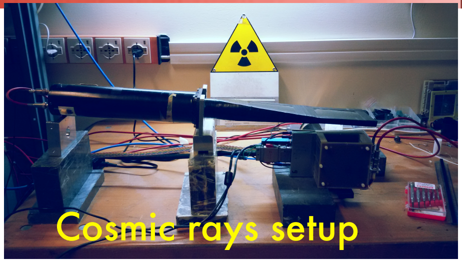
NITEC activities 2015-2016

- Characterization of old prototype with $Ar:CO_2$ and $Ar:CO_2:CF_4$ mixtures in traditional electron carrier configuration with:
  - Cosmics
  - ^{55}Fe spectrum
  - 450 MeV electrons at beam line (BTF)

On going work on single ionization cluster detection with electron drift

Jul-Sep 2015

Oct 2015/Apr 2016



- Design and procurement of vacuum vessel to operate below atmospheric pressure, design of new field cage

Nov 2015 - Apr 2016

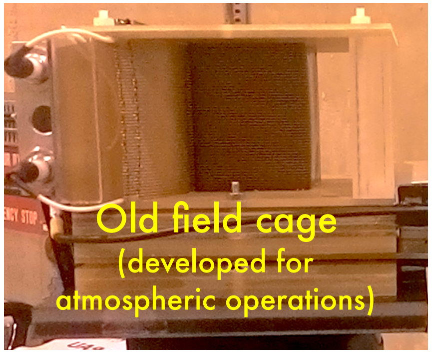
- Old prototype tests with SF_6 negative ion mixtures
  - pure SF_6, $Ar:CO_2:SF_6$ (high pressure)

May 2016

- New prototype tests with SF_6 negative ion mixtures
  - pure SF_6, $He:CF_4:SF_6$ (low pressure)

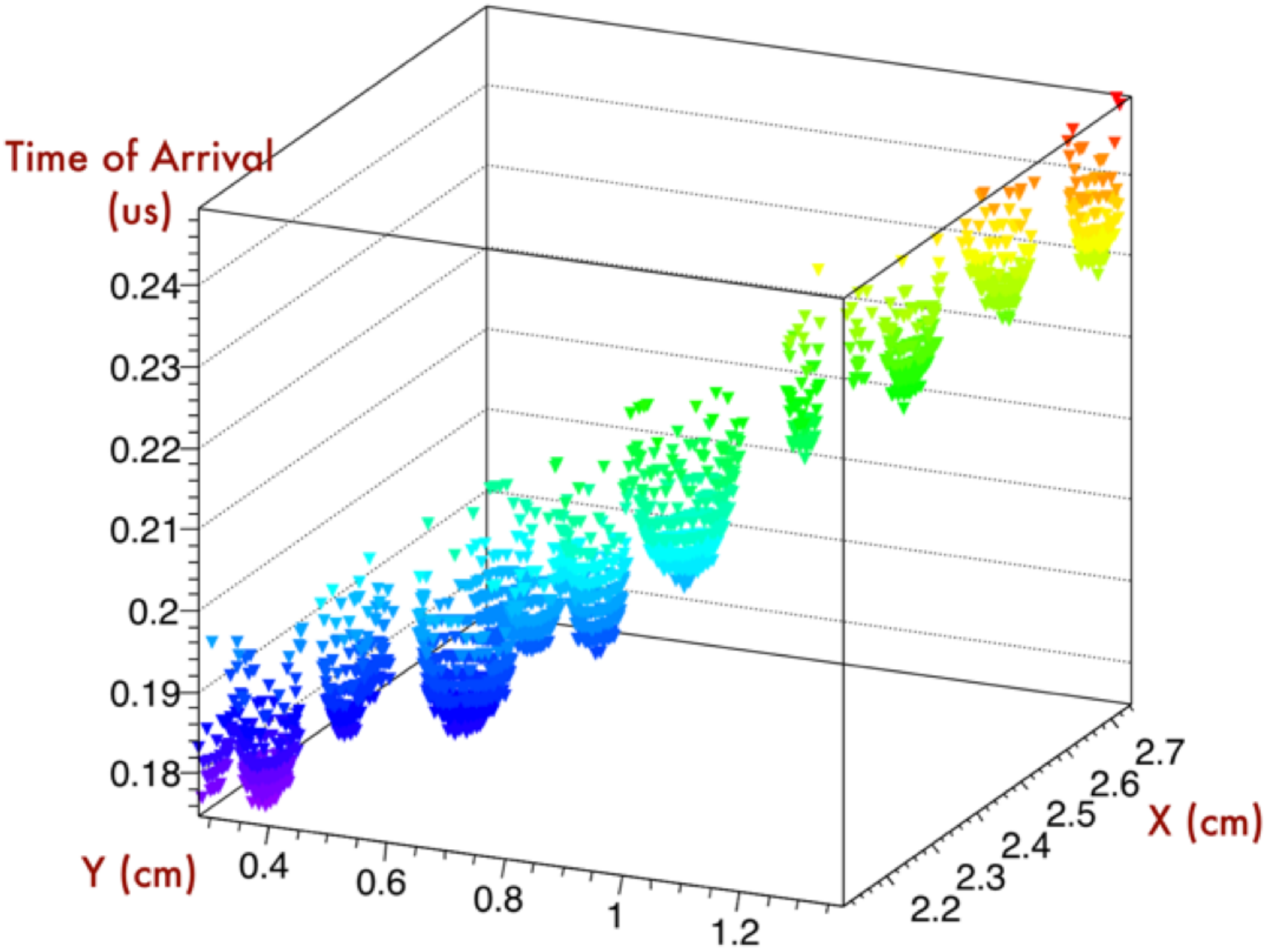
Dec 2016

Data analysis still on going



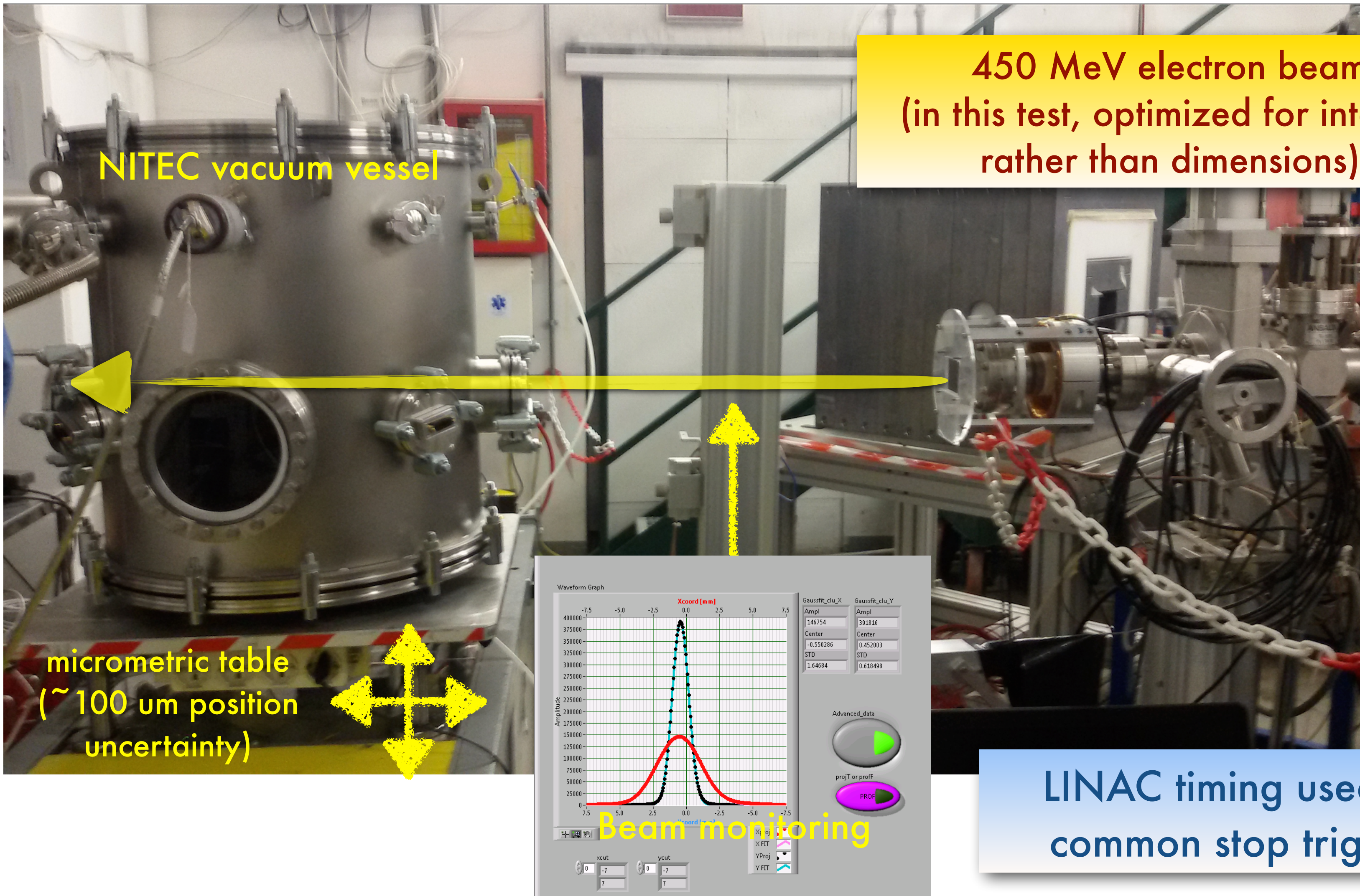
A NITEC event

A cosmic ray recorded track in $Ar:CO_2$
(electron drift)



Measurement @ Beam Test Facility

450 MeV electron beam
(in this test, optimized for intensity rather than dimensions)



LINAC timing used as common stop trigger

Time measurements (TOA)

Apr 2016

- $Ar:CO_2:SF_6$ 192:85:93 Torr

  GEM gain 1480 V

- Pure SF_6 at 75 Torr, 100 Torr, 150 Torr

  GEM gain 1140 V 1240 V 1440 V

Dec 2016

- $He:CF_4:SF_6$ 60:40:120 Torr, 360:240:10 Torr

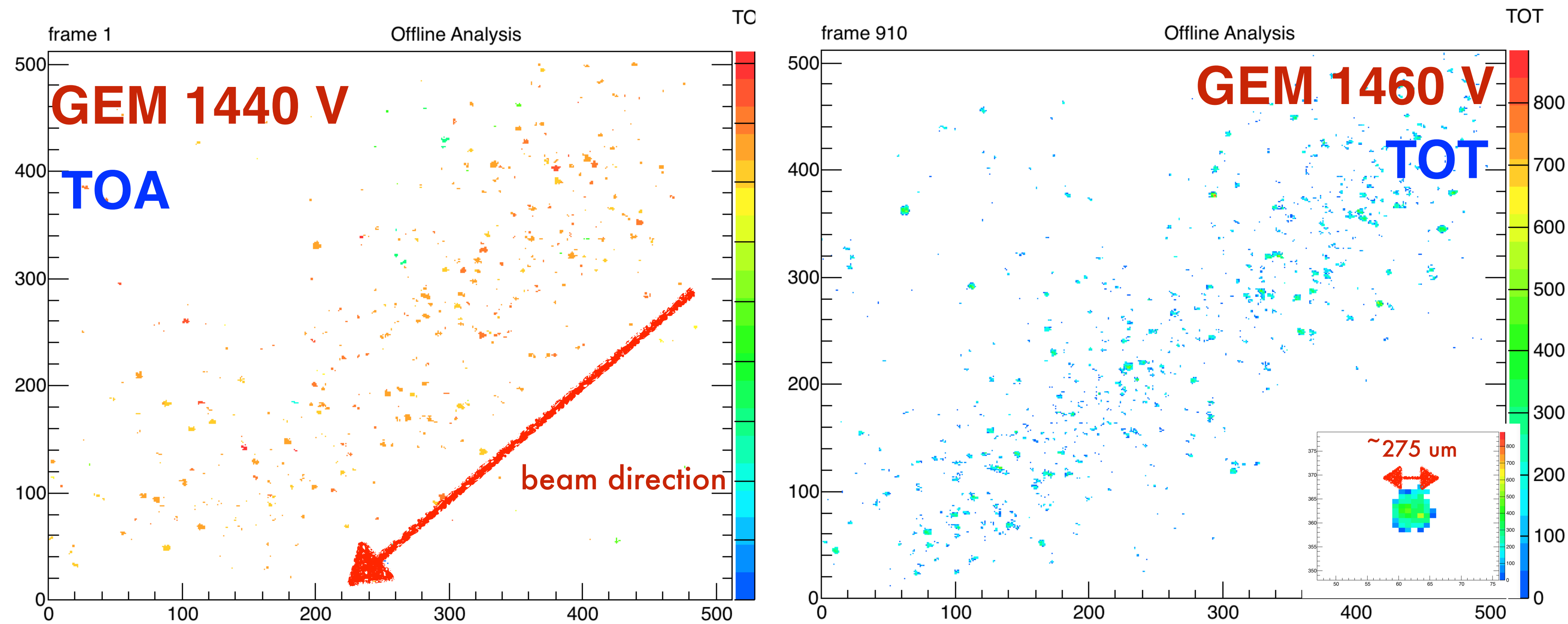
  GEM gain 1460 V 1640 V

We measured the Time Of Arrival for 5 different drift distances @ 250, 530, 640, 750 and 860 V/cm for each configuration

(less points in Apr 2016 data)

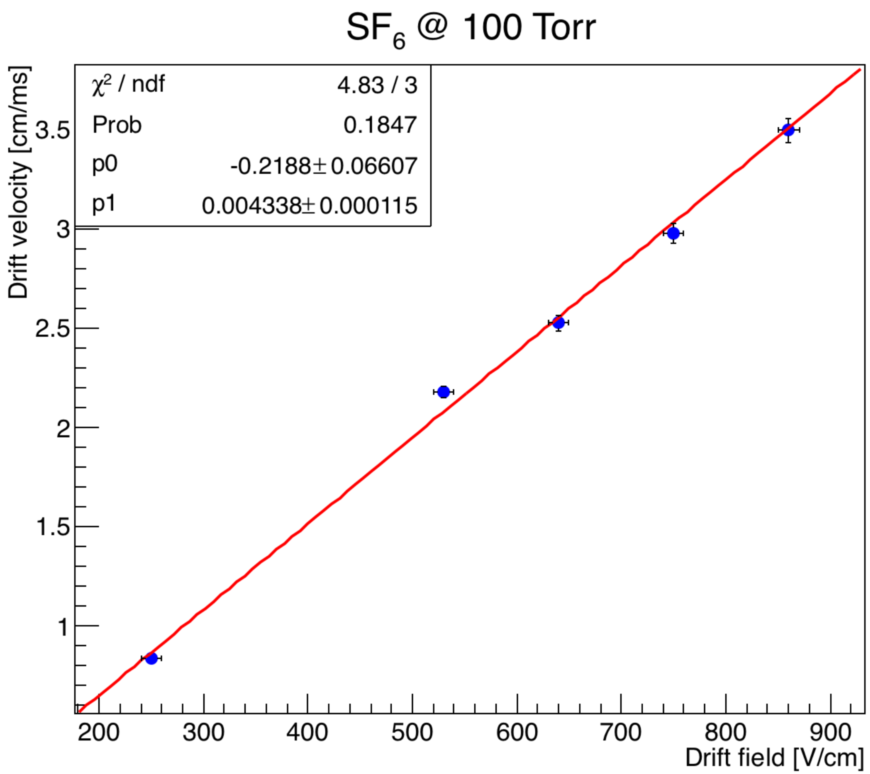
SF_6 @ 150 Torr

Dec 2016



Global quantities analysis shown in this talk. On going work on single track analysis.

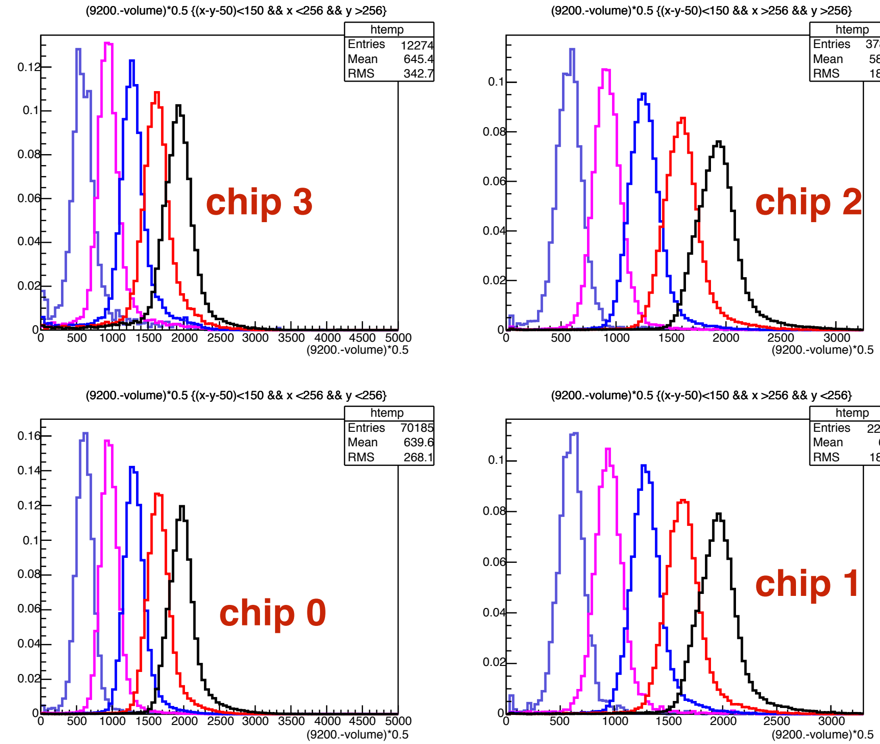
SF_6 @ 100 Torr TOA analysis



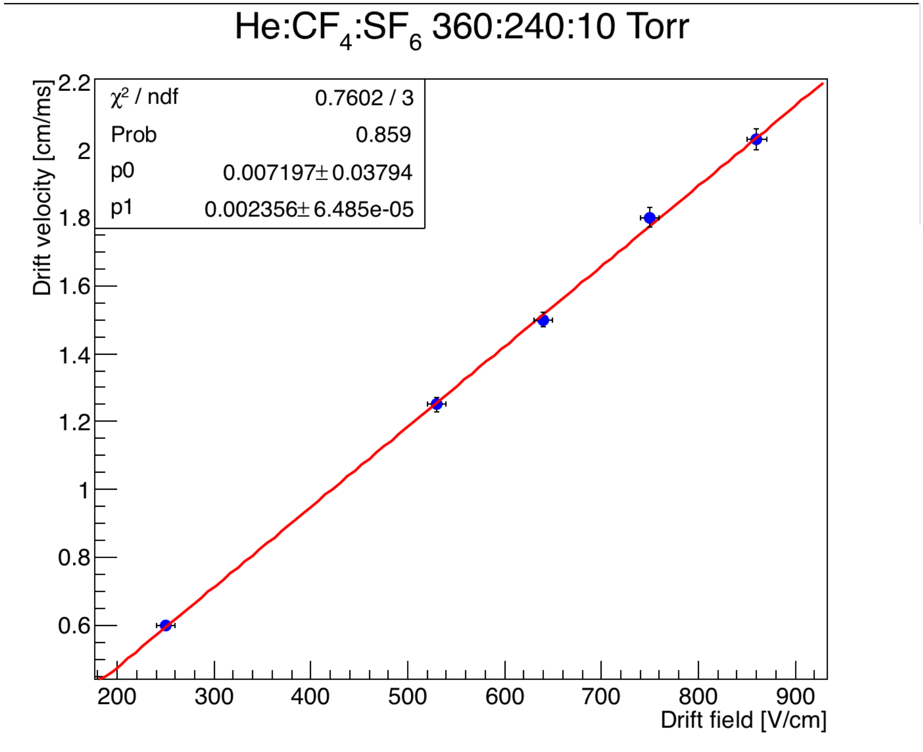
750 V/cm

```
vdrift chip 0 is 0.00295763 +/- 9.35414e-05
vdrift chip 1 is 0.00296488 +/- 9.37884e-05
vdrift chip 2 is 0.00299155 +/- 9.46174e-05
vdrift chip 3 is 0.00299736 +/- 9.48585e-05
```

Drift times



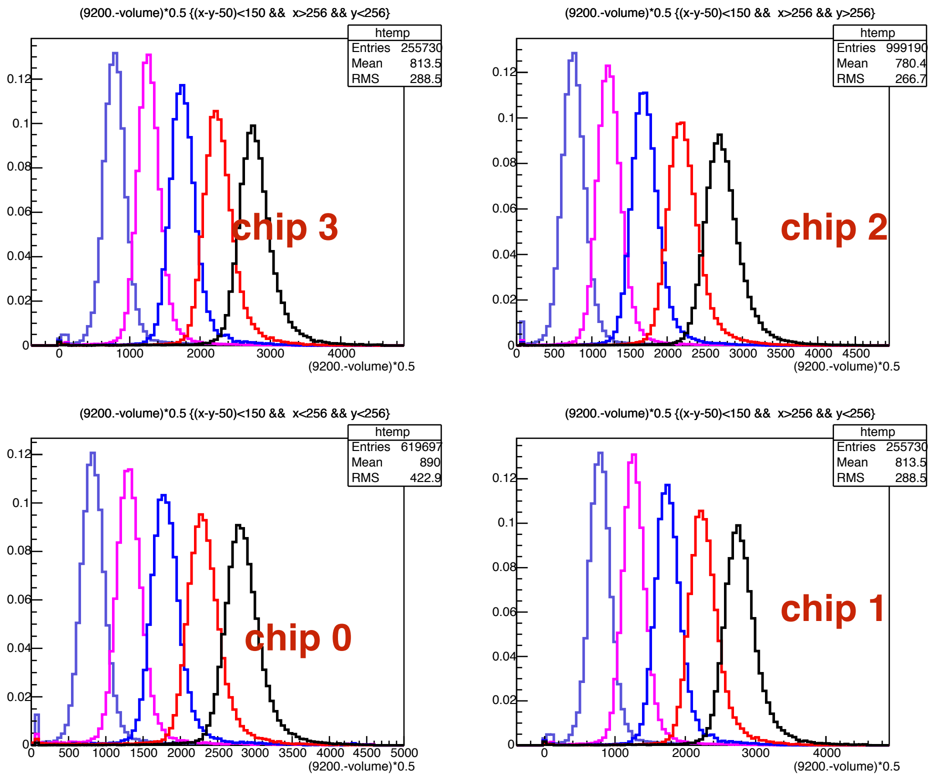
$He:CF_4:SF_6$ 360:240:10 Torr TOA analysis



860 V/cm

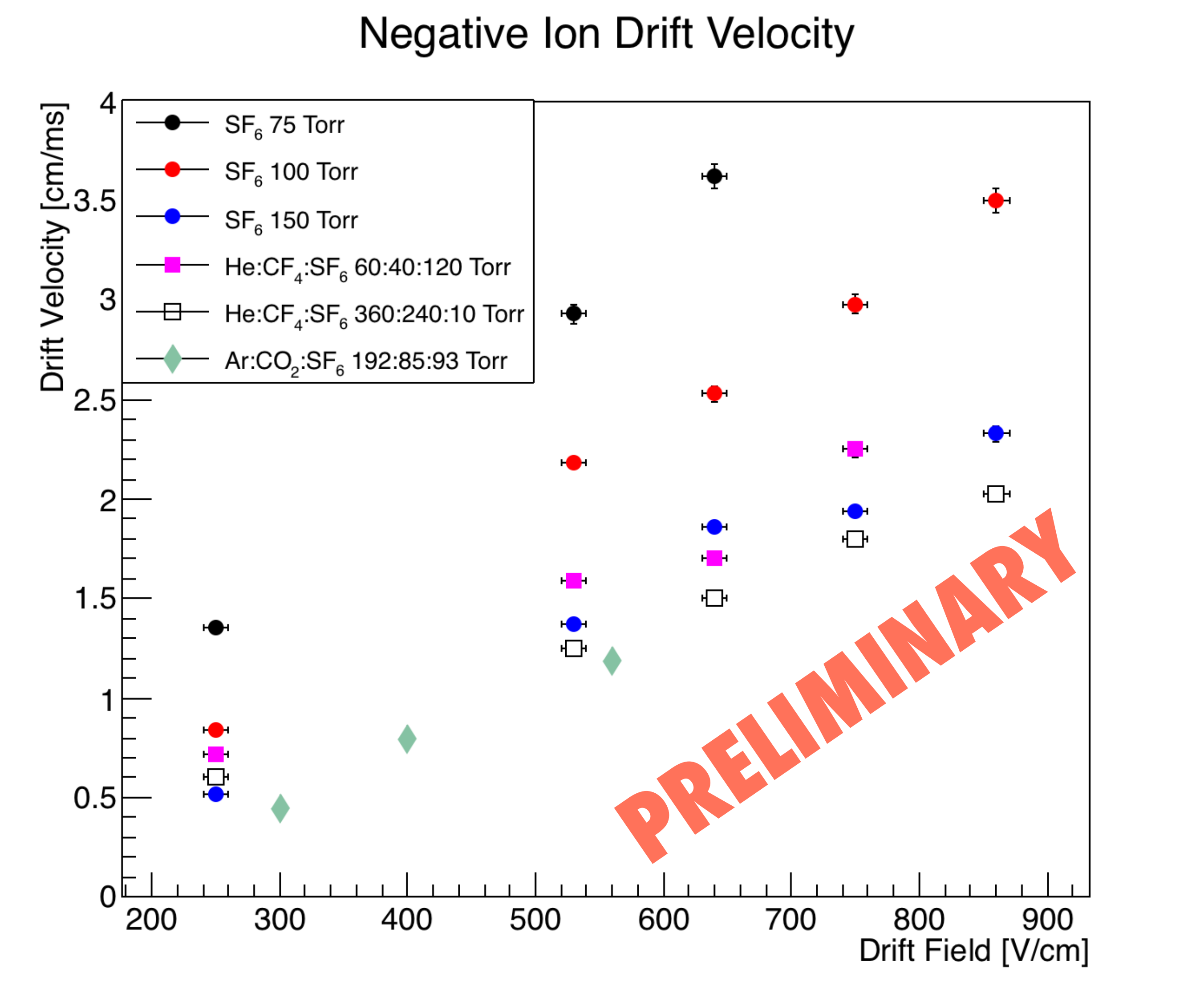
```
vdrift chip 0 is 0.0020193 +/- 6.38648e-05
vdrift chip 1 is 0.00203158 +/- 6.42549e-05
vdrift chip 2 is 0.00205442 +/- 6.49827e-05
vdrift chip 3 is 0.00203158 +/- 6.42549e-05
```

Drift times

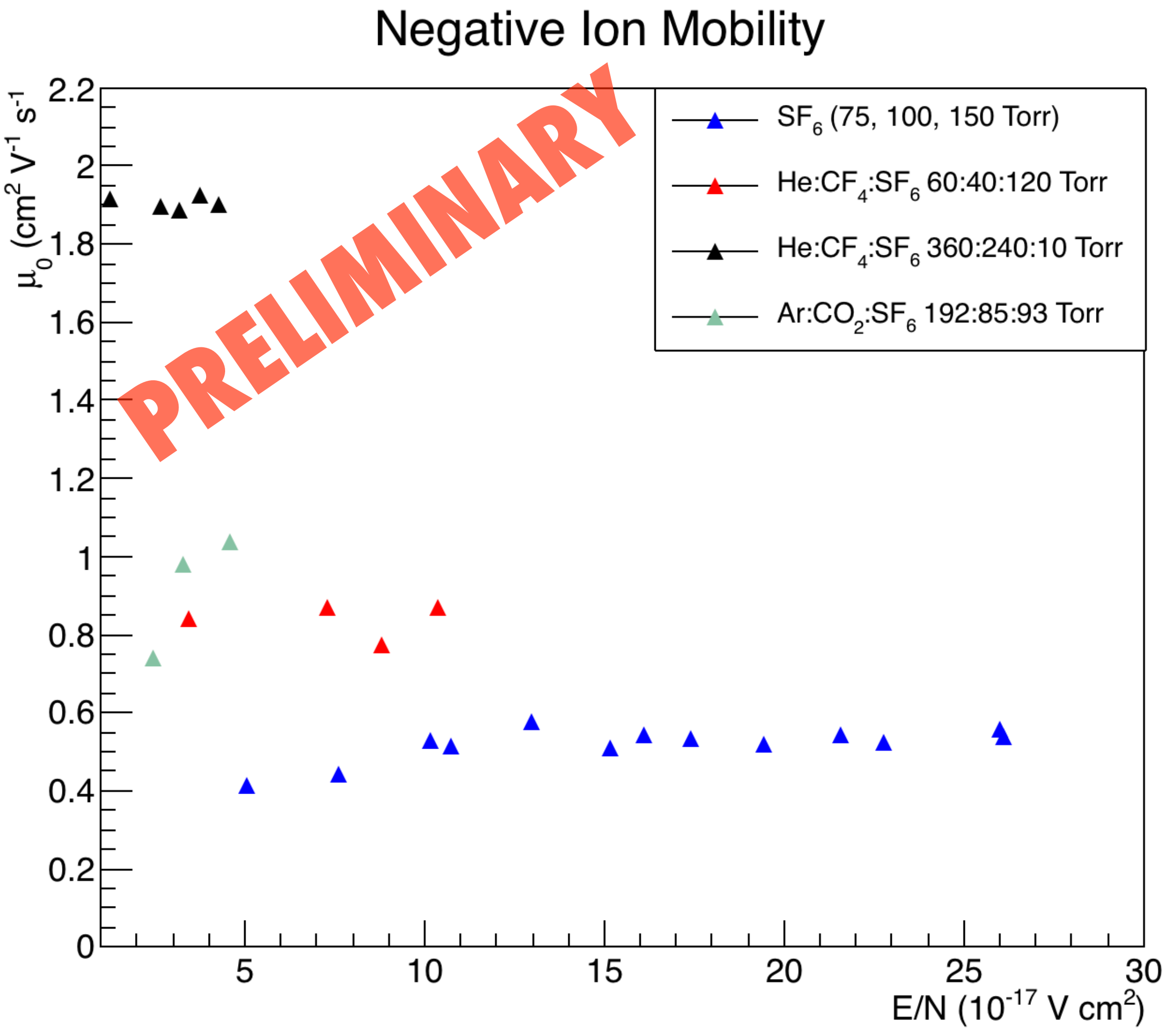


Nearly atmospheric operation!

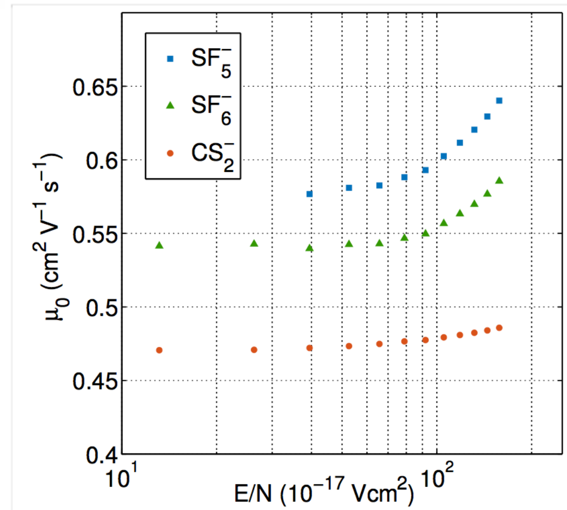
Drift Velocity Measurements



Mobility Measurements



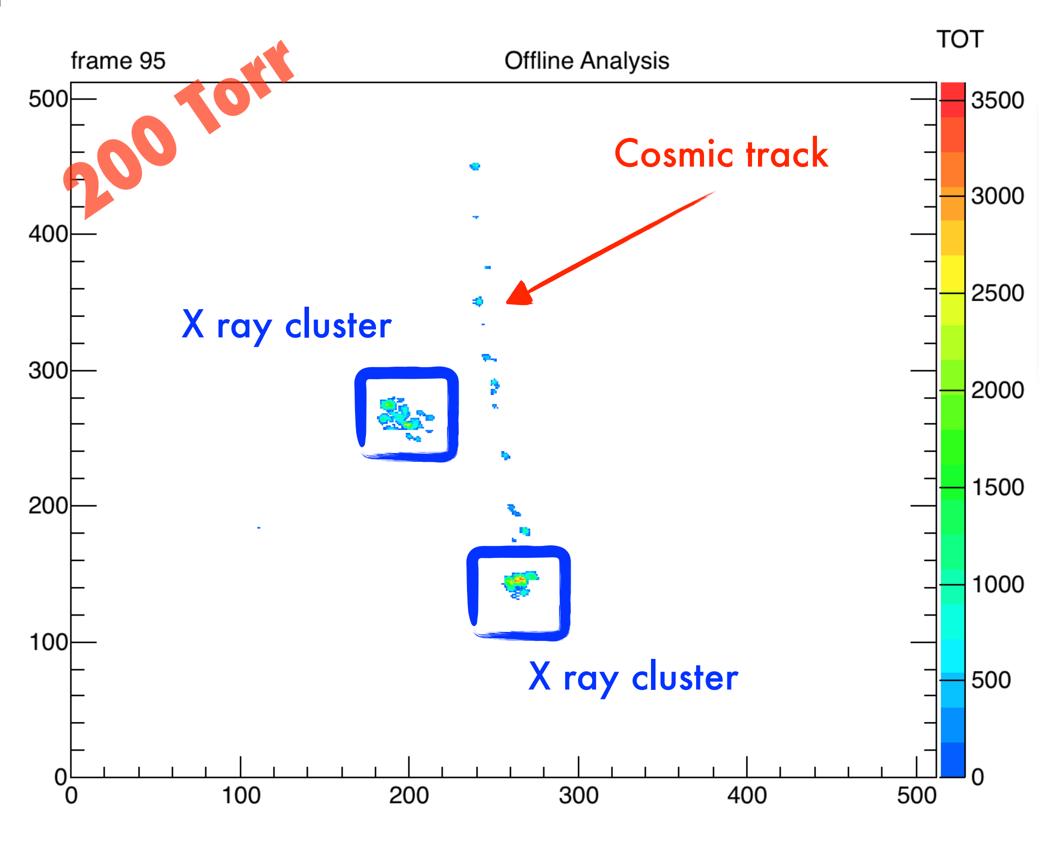
Pure SF_6 results in agreement with published data

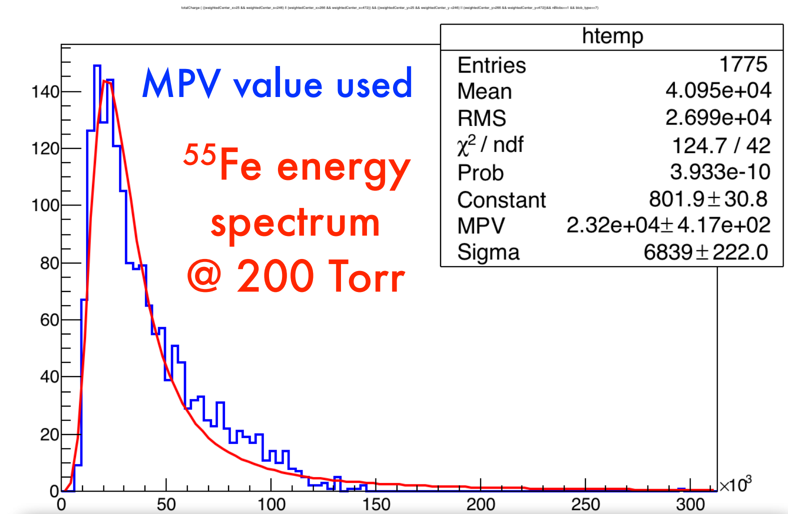


N.S.Phan et al, arXiv:1609.05249

NITEC gain (TOT) measurements in pure SF_6

^{55}Fe radioactive source





CAVEAT: **not completely understood** energy spectrum

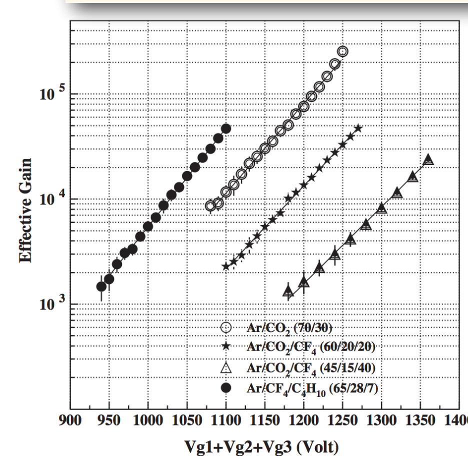
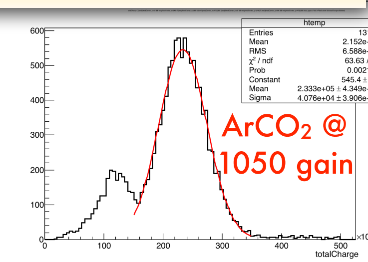


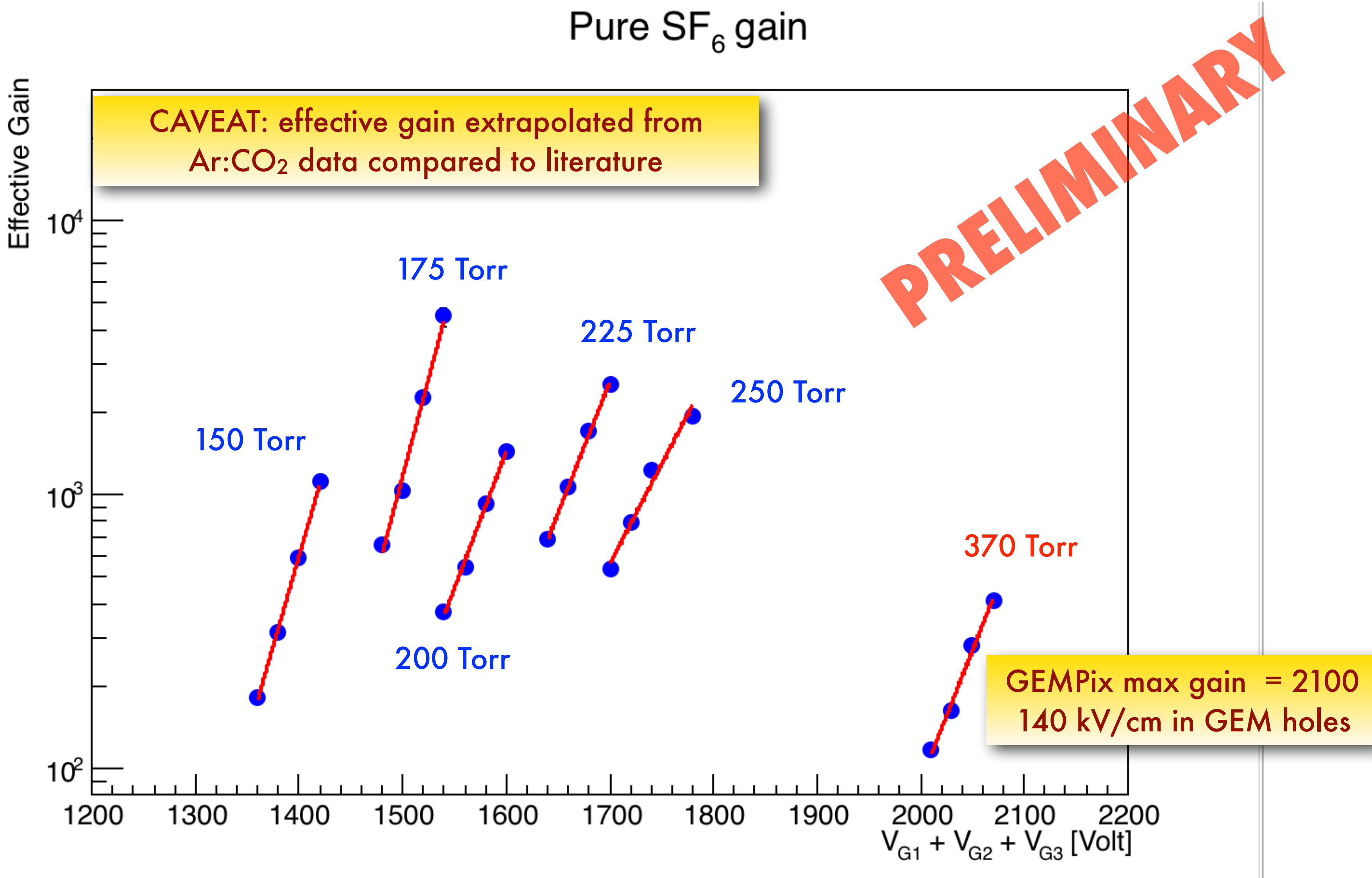
Fig. 3. Gas gain for the tested gas mixtures.



Effective gain extrapolated from Ar:CO_2 data compared to literature

June 2016

NITEC gain measurement in pure SF_6



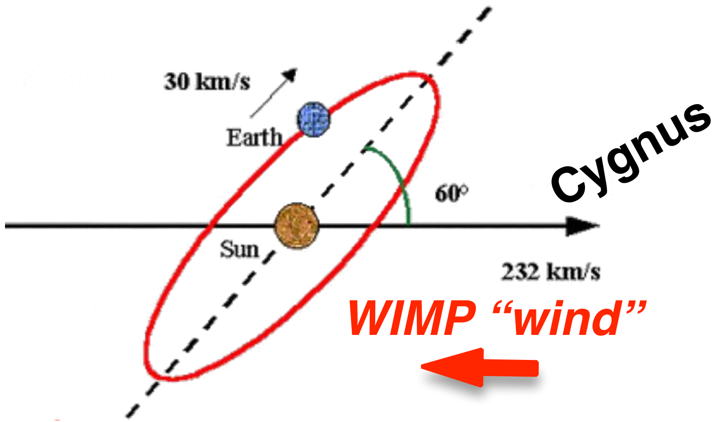
DCANT

Carbon Nanotube for for Dark Matter directional searches

Outline

- WIMP directional searches

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



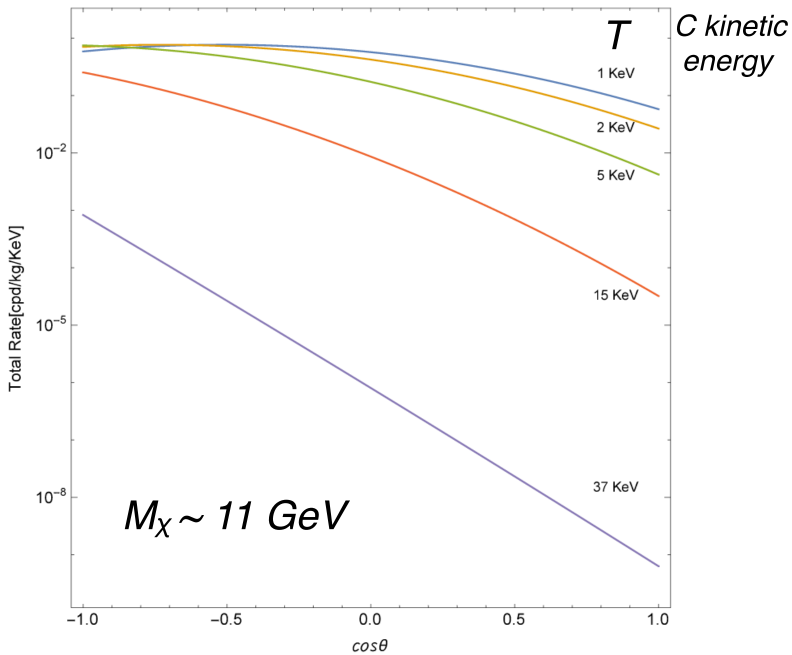
- **C ion channeling in CNT**
  - Use C ion in a Time Projection Chamber (*Triple-GEM TPC*) to demonstrate channeling is active

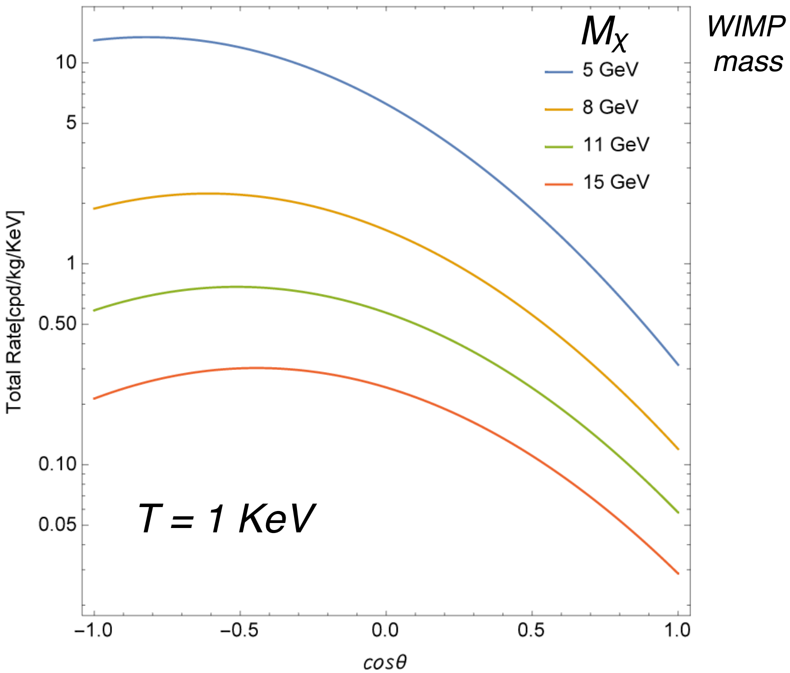
L.M. Capparelli, GC, D. Mazzilli, A.D. Polosa, ***Phys.Dark Univ.*** 9-10 (2015) 24-30,
Corrigendum: Phys.Dark Univ. 11 (2016) 79-80 (http://arxiv.org/abs/1412.8213)

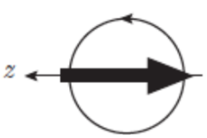
GC, E.N.M. Cirillo, F. Cocina, J. Ferretti, A.D. Polosa, **Eur.Phys.J. C** 76 (2016) no.6, 349
(http://arxiv.org/abs/1602.03216)

Anisotropy in scattering rates

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







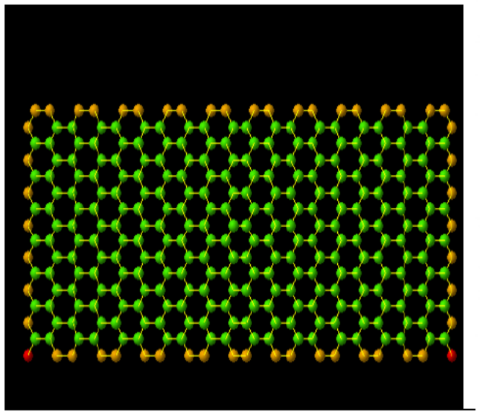
θ = π

WIMP "wind"

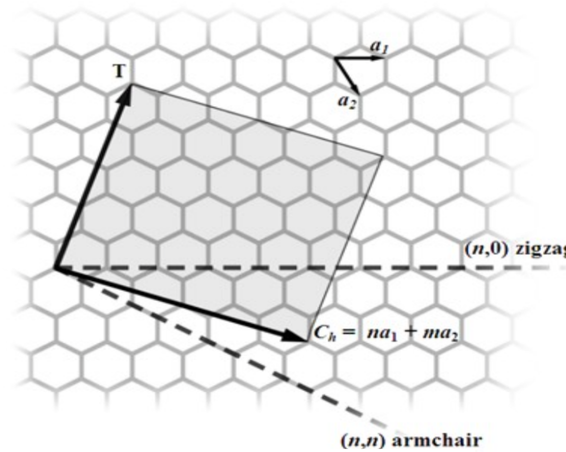
G.Cavoto

Carbon nanotubes

Structure: Imagine wrapping a sheet of graphen into a nanotube



Shigeo MARUYAMA, Univ. Tokyo

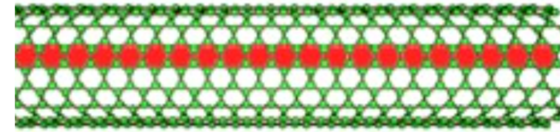


$$R = \frac{l\sqrt{3}}{2\pi}\sqrt{n^2 + m^2 + nm} \qquad l = 0.14nm$$

n=m → metallic

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

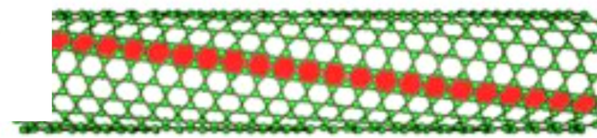
Nonchiral ('armchair') nanotube



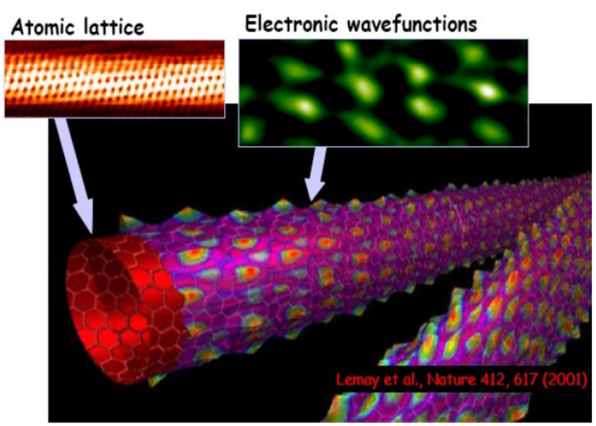
metallic

"graphene layer wrapping"

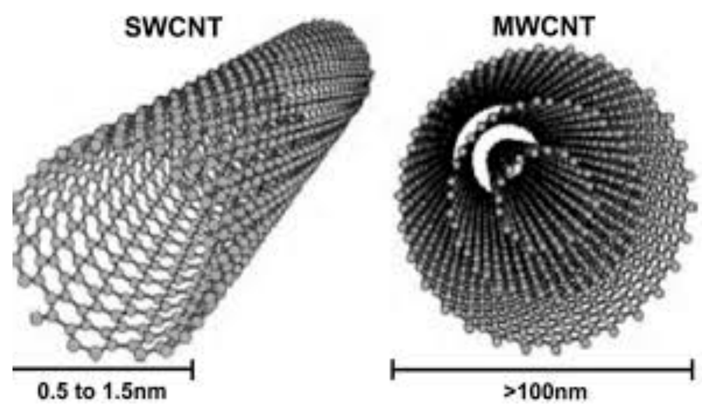
Chiral nanotube



semiconducting *or* metallic



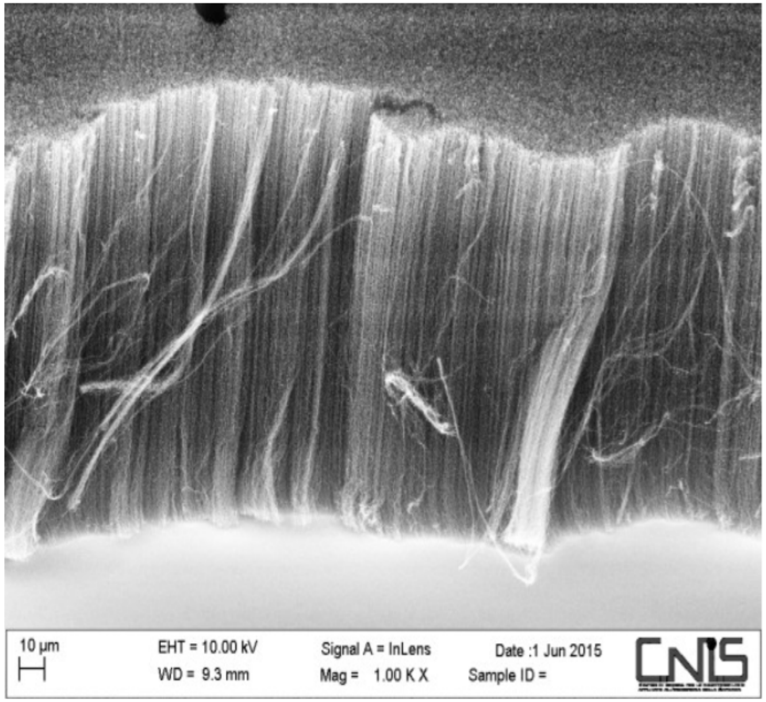
Electron orbitals on CNT surface



M.G.Betti,
C.Mariani
Sapienza
Univ. Roma

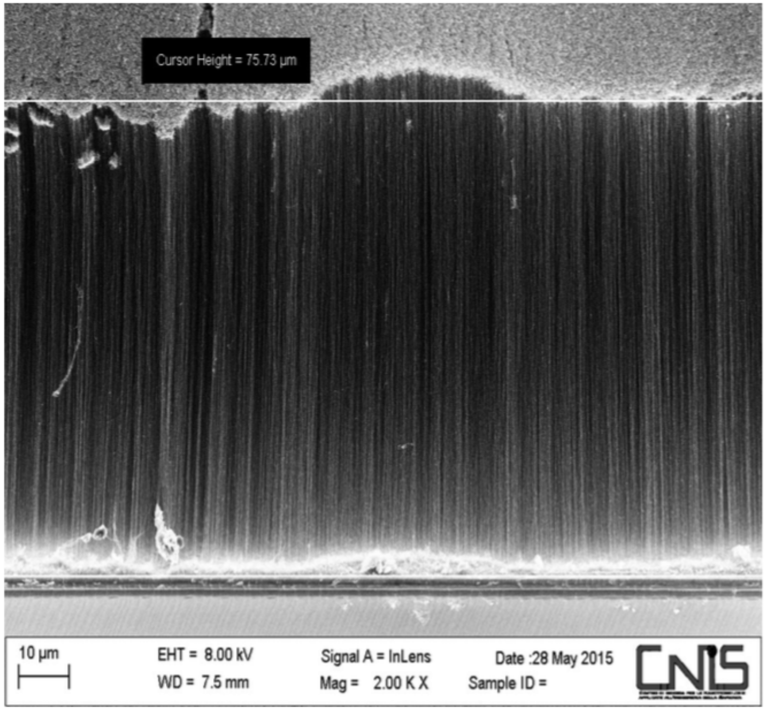
CNT with scattering electron microscope

collaboration University of Mons, Belgium



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

commercial



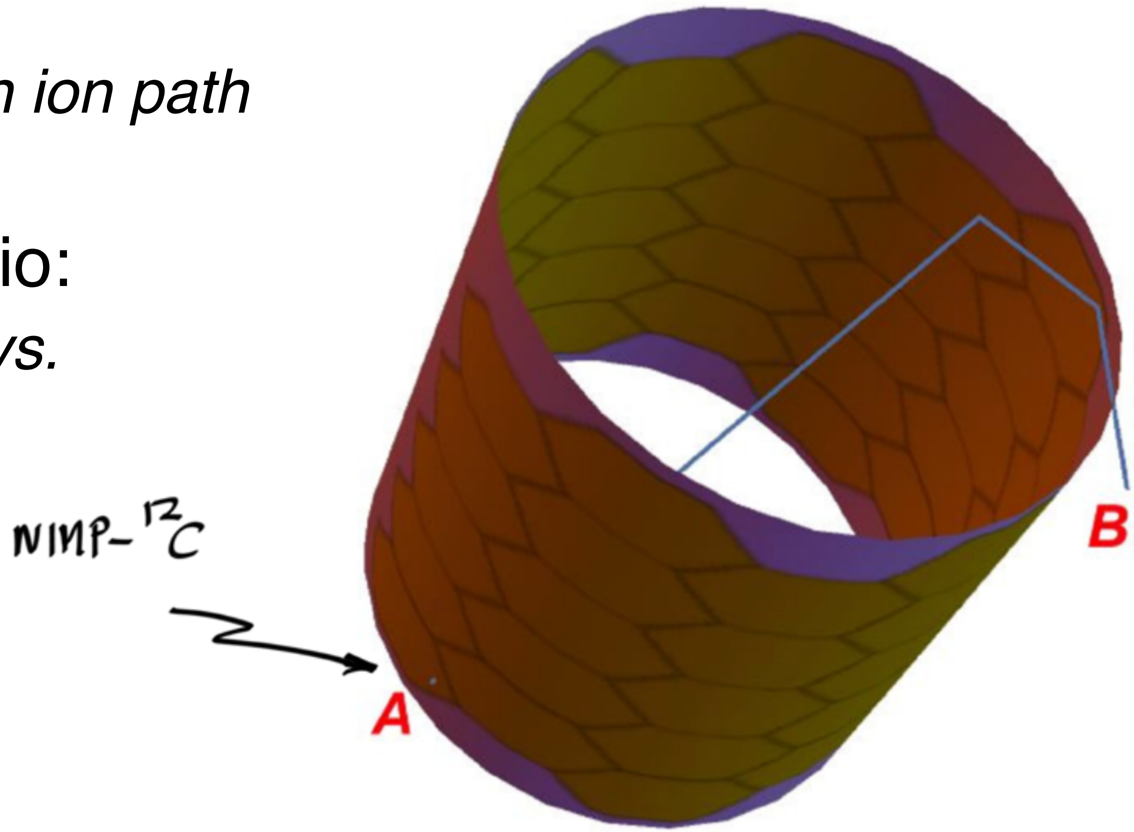
length: 75 ***µm***
ext. diameter: ***(13 ± 4) nm***
aspect ratio: 0.6 ***x10⁴***

Scattering on a carbon nanotube

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

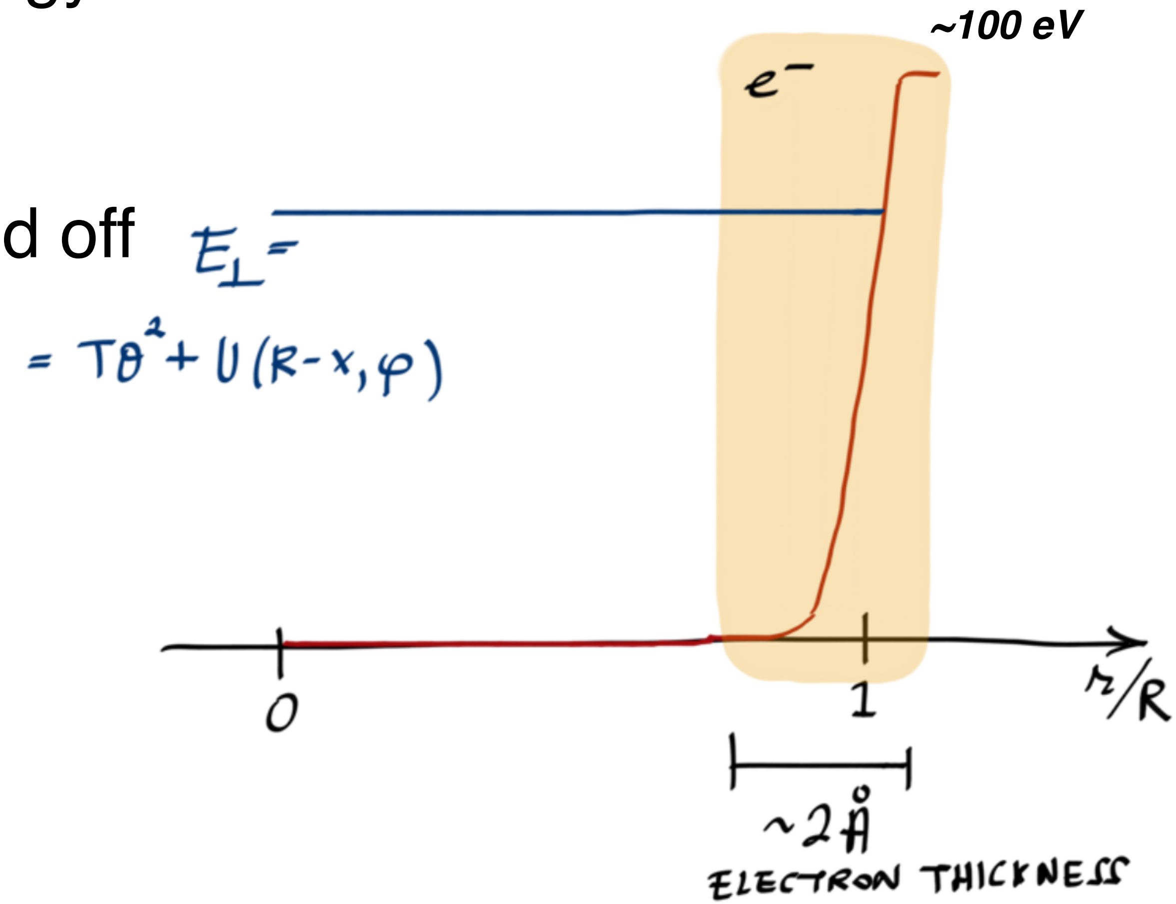
- Large aspect ratio:
  ~10 nm diameter vs.
  ~100 μm height

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



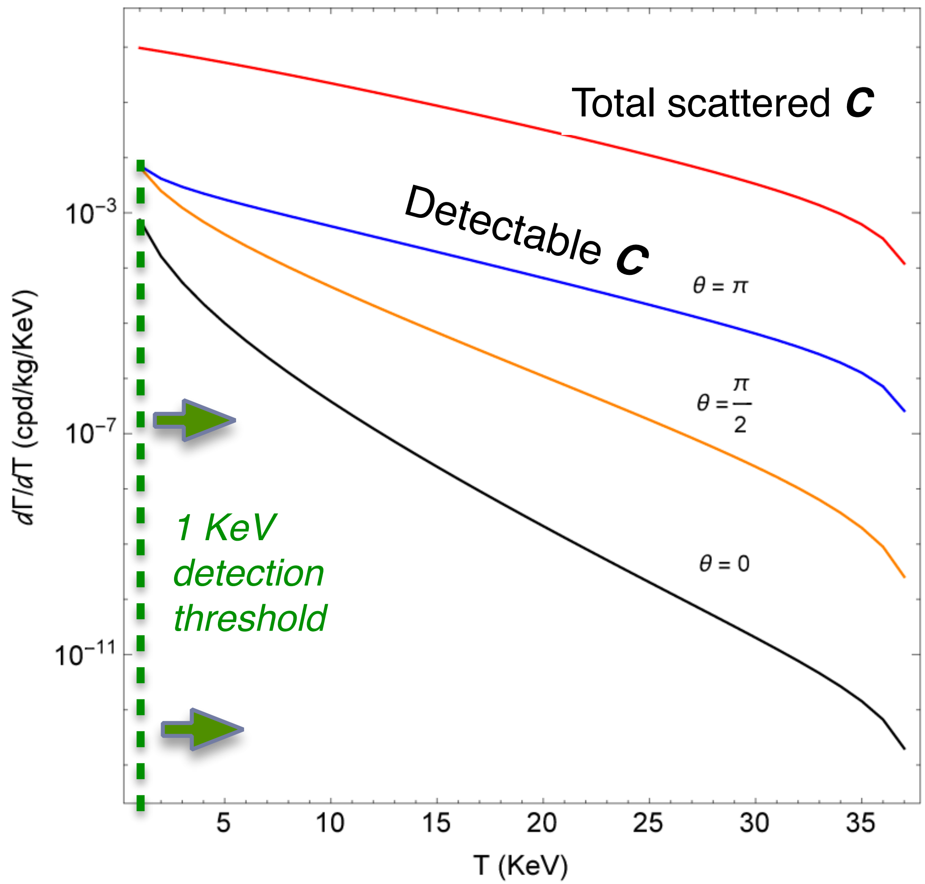
CNT as a potential well

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

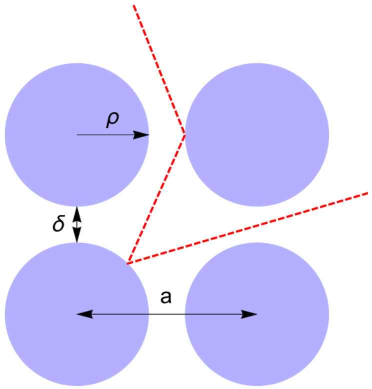


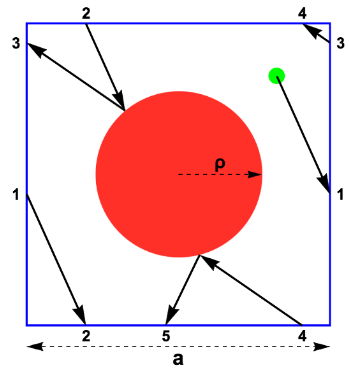
CNT anisotropic medium

- **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**)*

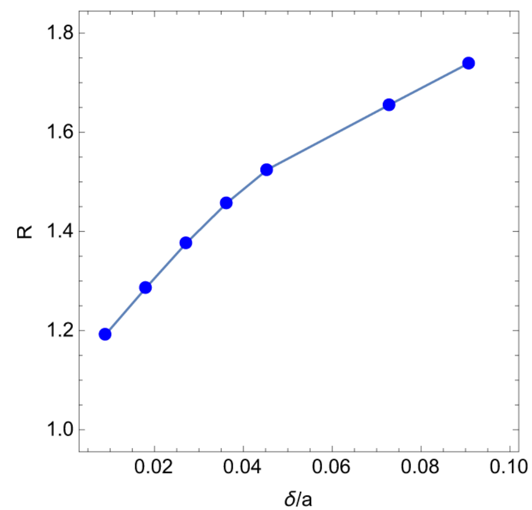
Ratio of our simulation to a semi-analytical result

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

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

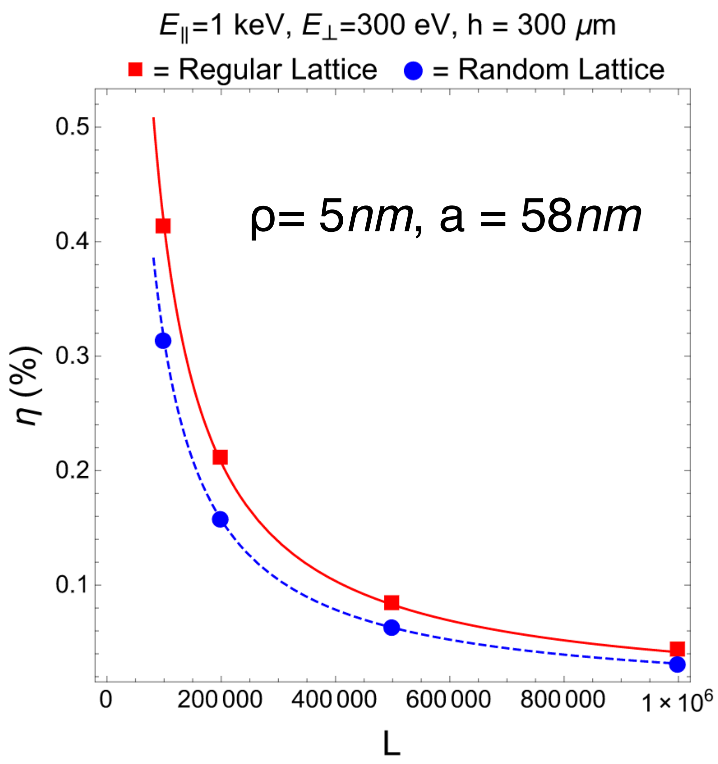
Small δ → Machta-Zwanzig regime

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



Lateral escapes of C ion

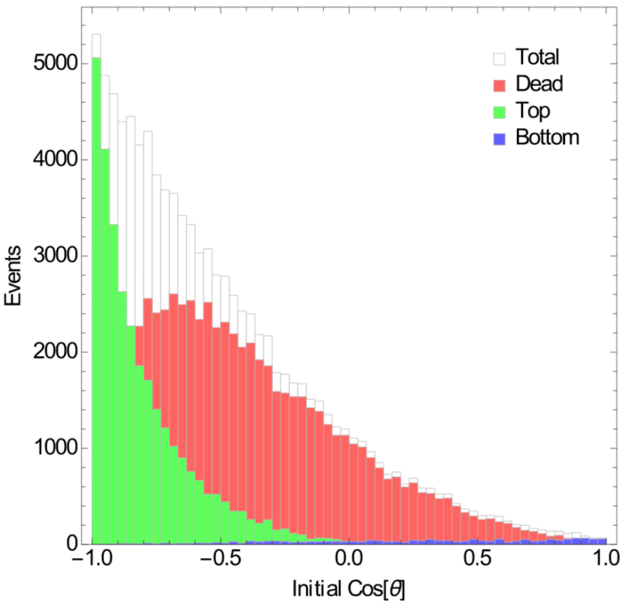
- C ion can leave the array at its top (*desired!*) or from the lateral sides (*avoid!*)
  - Fraction of particle leaving from the sides versus ***side length L***



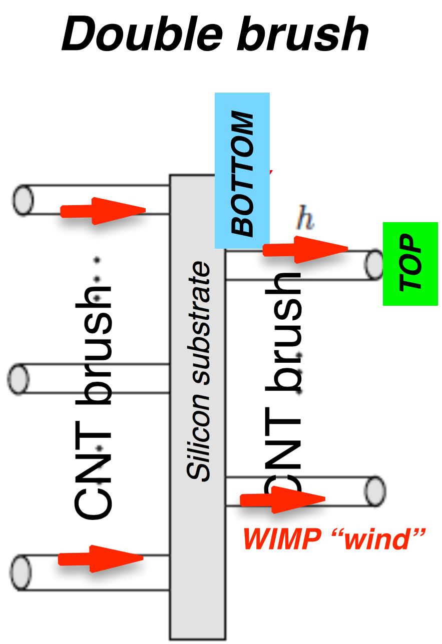
Lateral losses are negligible for realistic CNT brushes (L ~ 10^5)

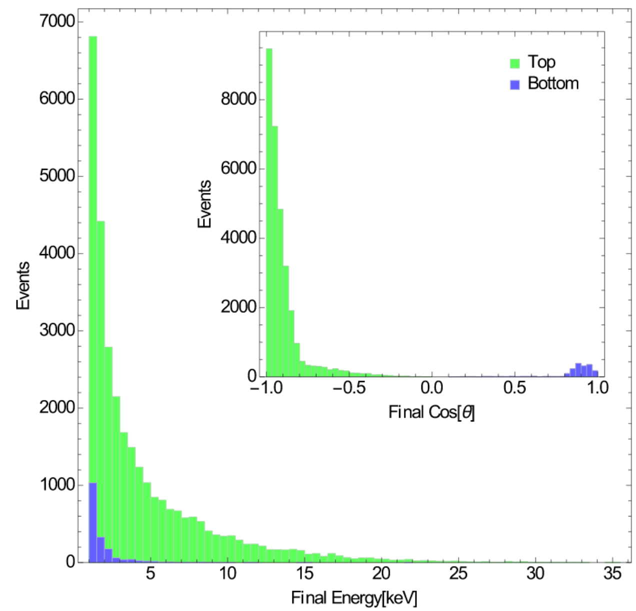
C ion moving within the array

- 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

Detecting C ion escaping CNTs

- 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

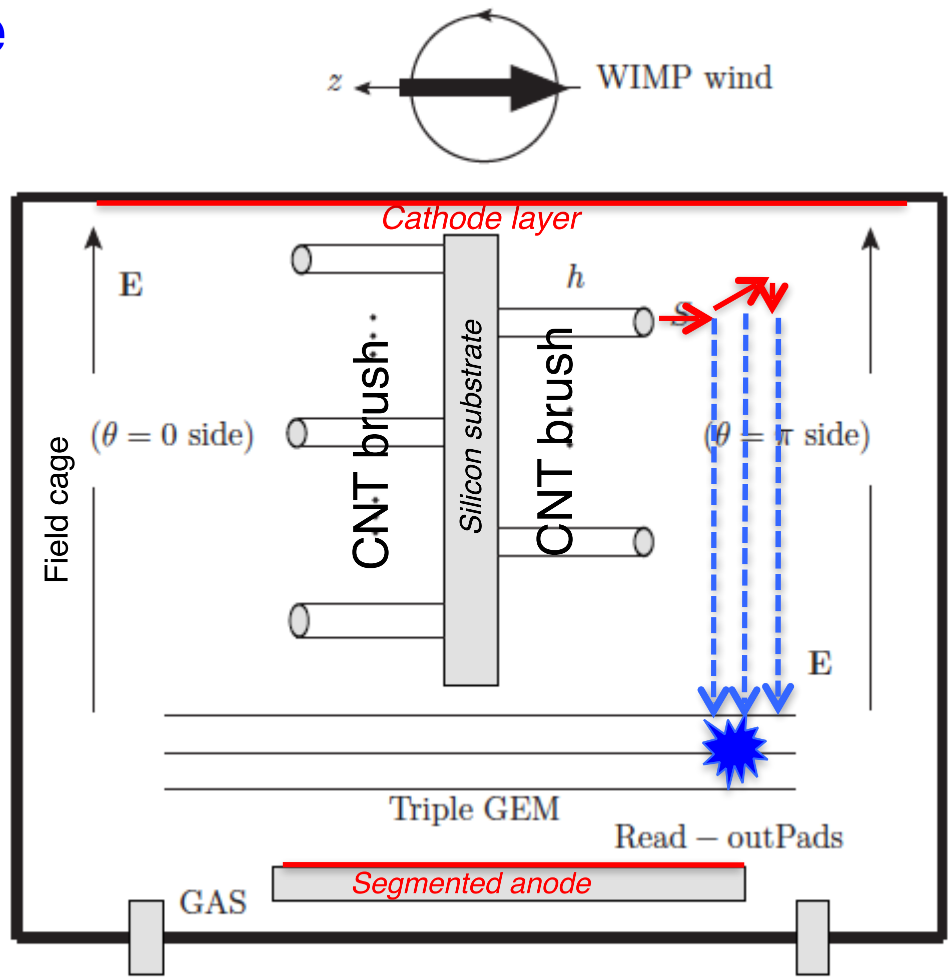
Demonstrating that a 1-100 KeV *C* ion is effectively channeled in CNT and then detectable

Scheme for detection of C ion

Low pressure gas TPC

Not to scale!

h ~100 μm
S ~ π(5)² nm²

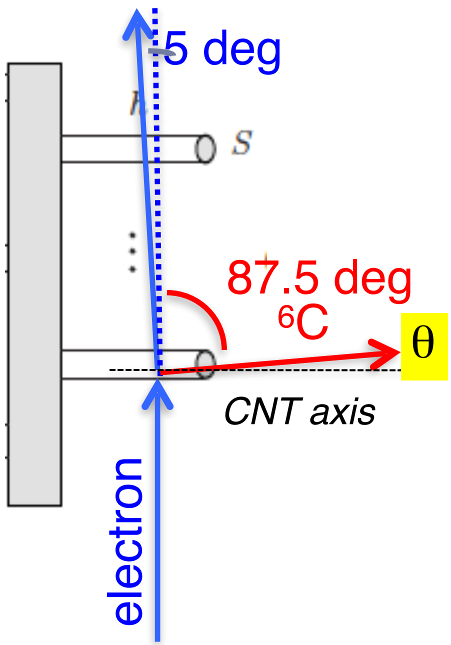


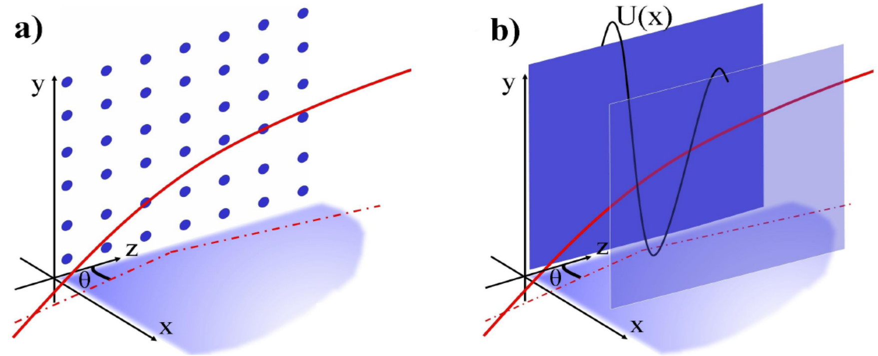
Must be able to measure:

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

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

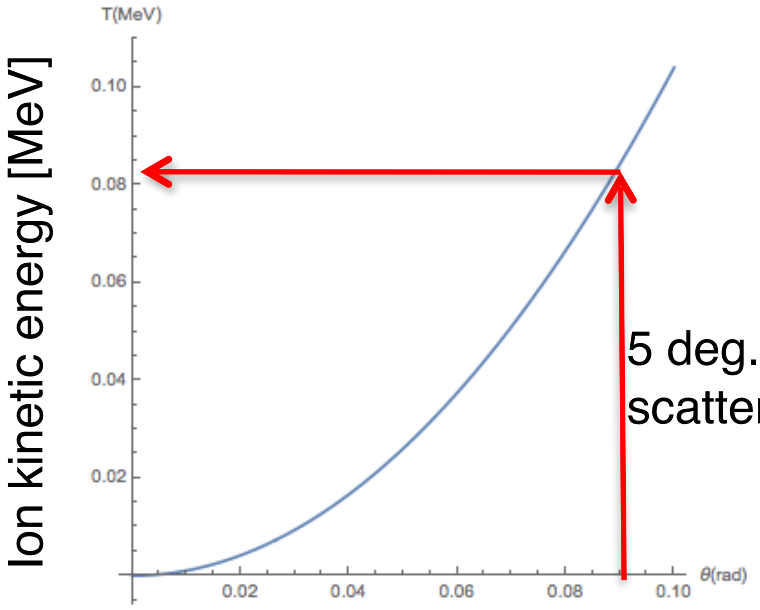
If $\theta < \theta_C$ ions are channeled!

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**

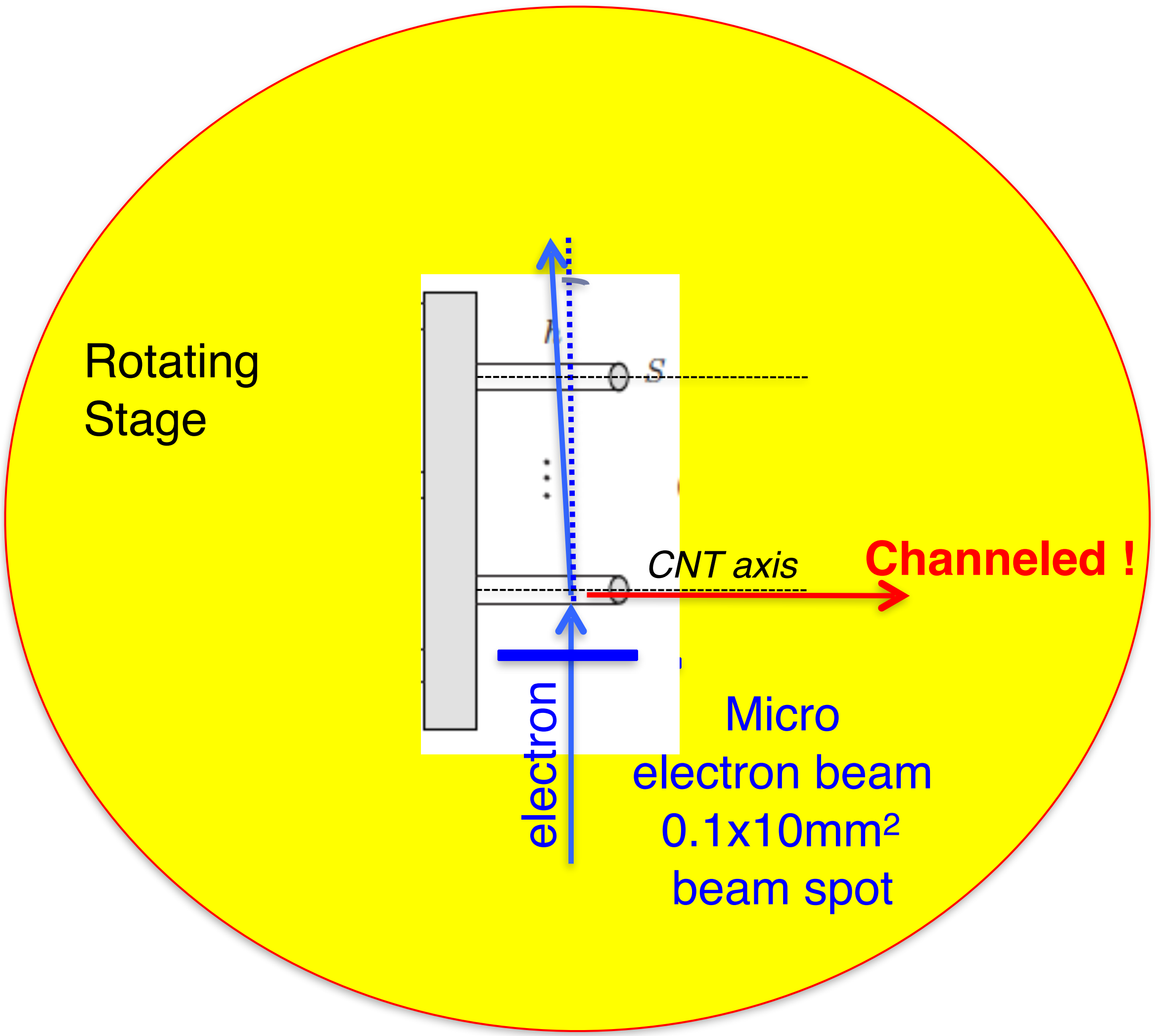
Experiment at Frascati BTF

- 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



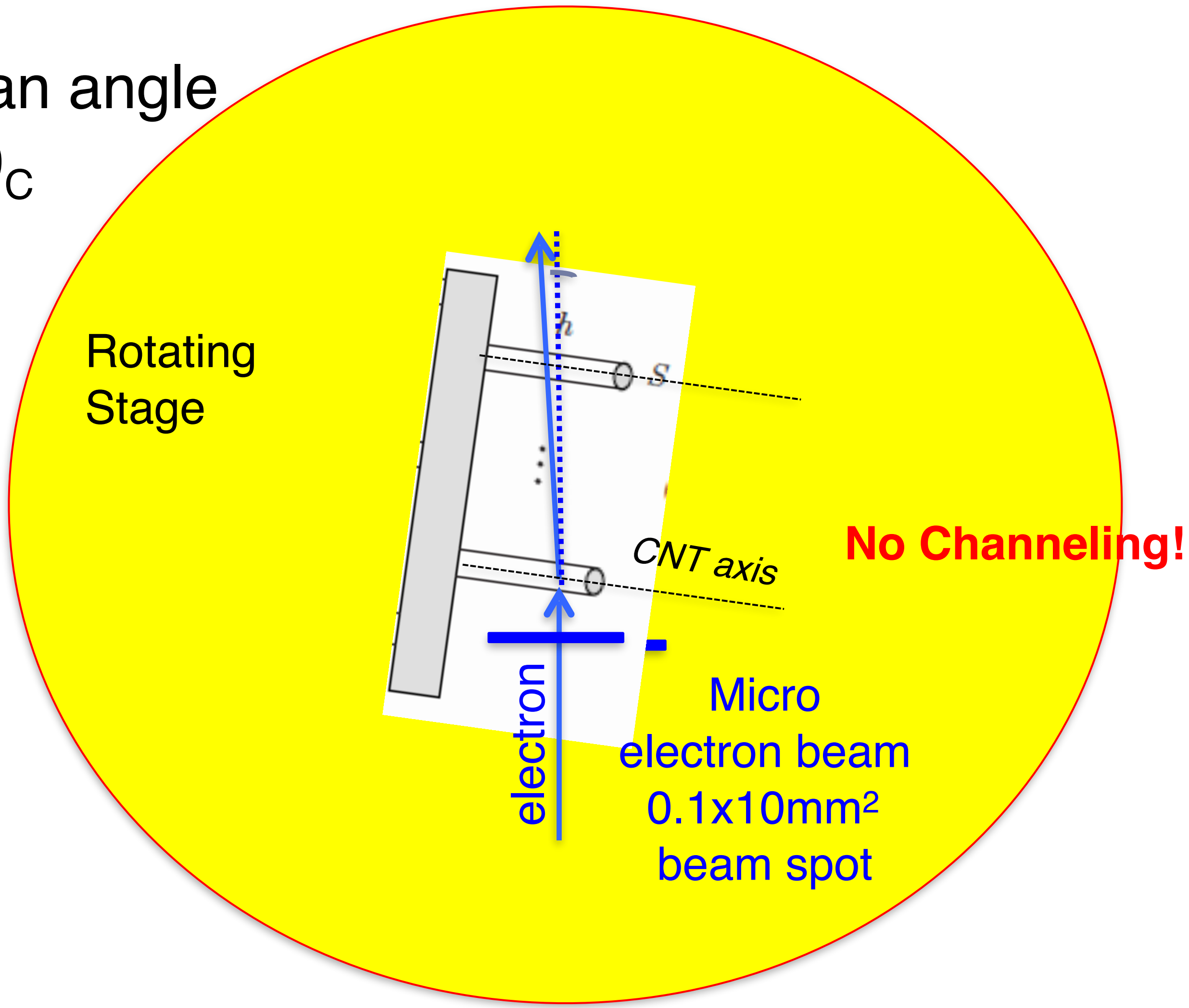
Experiment at BTF:channeling

$\theta < \theta_c$

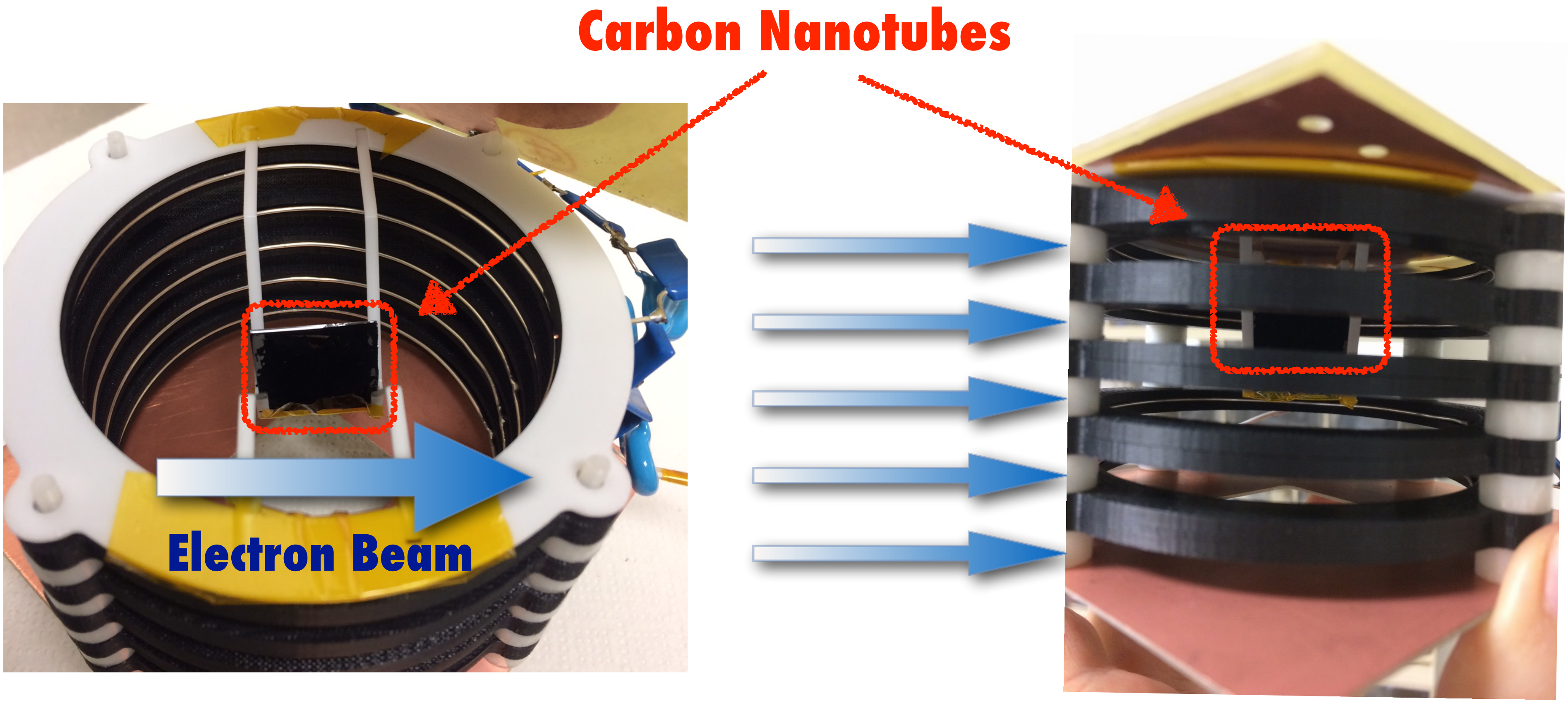


Experiment at BTF

Rotation by an angle wider than θ_C

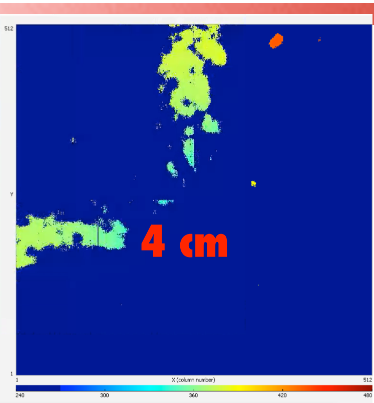


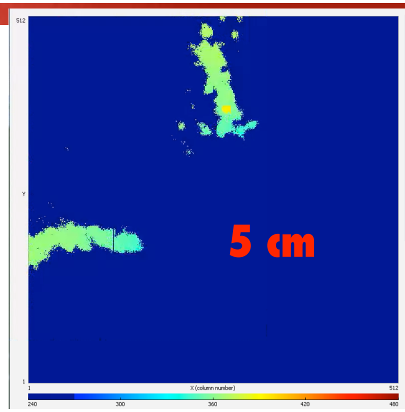
NITEC tests with carbon nanotubes

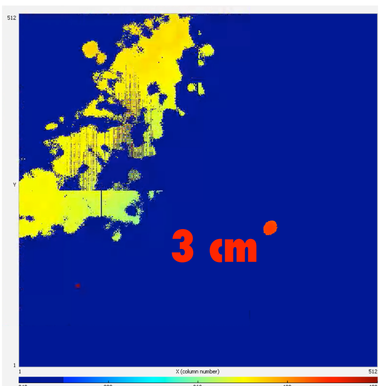


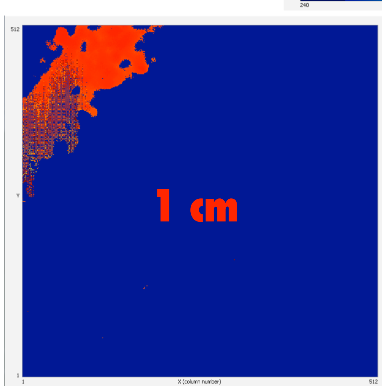
Beam on the side of nanotubes at various heights to study modification of the drift field

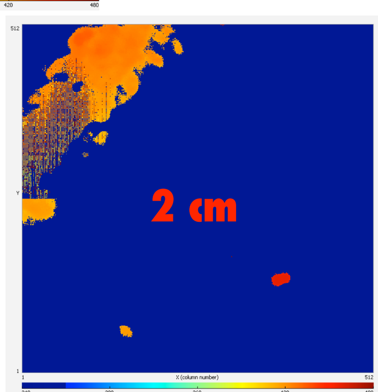
NITEC tests with carbon nanotubes

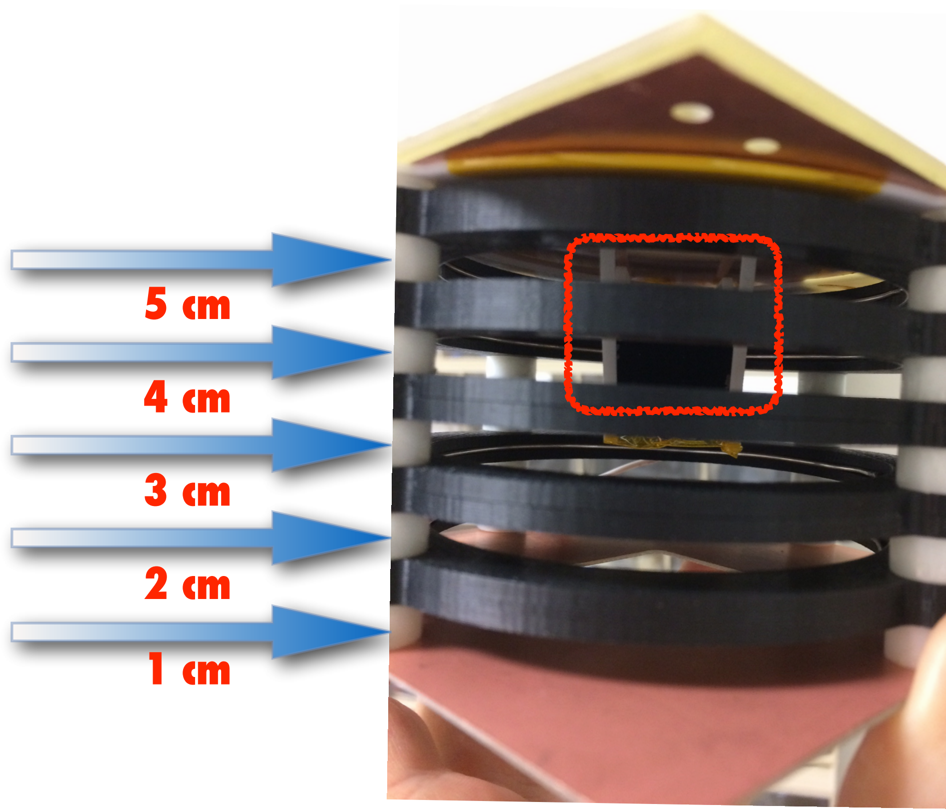






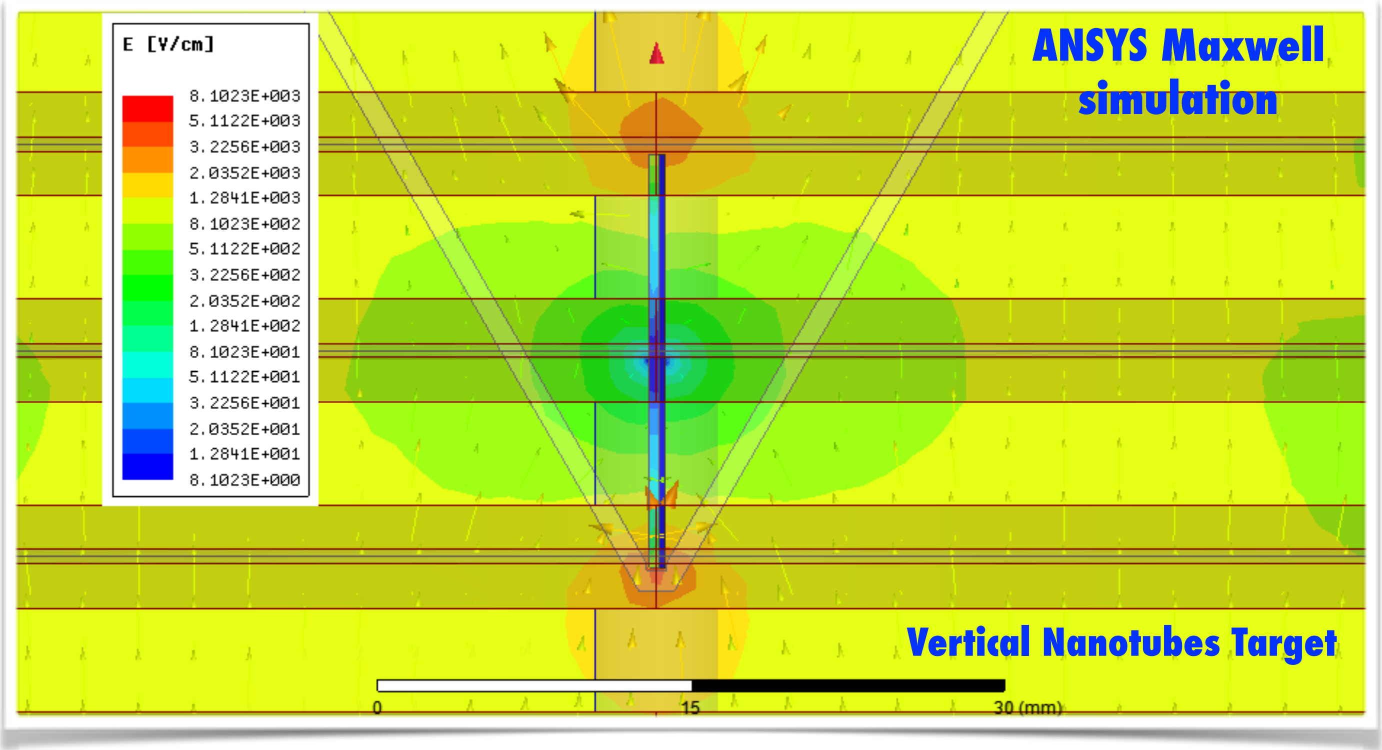




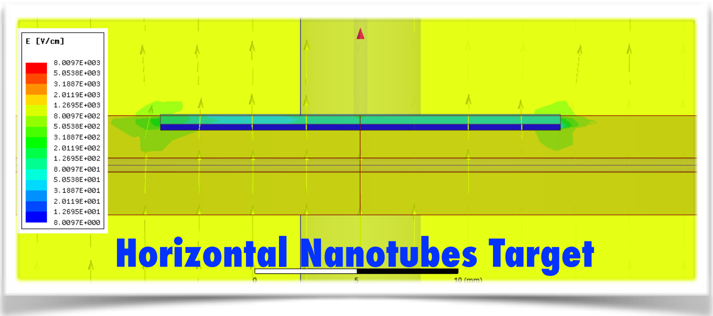


$Ar:CO_2:CF_4$ TOA data @ 300 Torr
(confirmed with pure SF_6 @ 150 Torr)

NITEC with carbon nanotubes



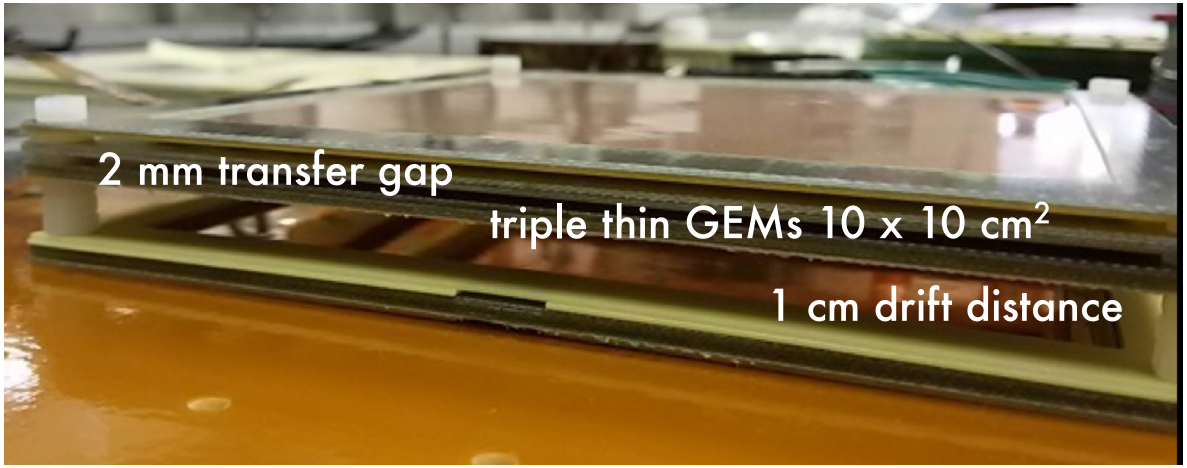
- **We observe a consistent modification of the drift field due to the introduction of nanotubes structure AND support**
  - Support, kapton scotch and nanotube get polarized
  - ANSYS simulation confirms observed results
  - On going work to develop suitable support and substrate

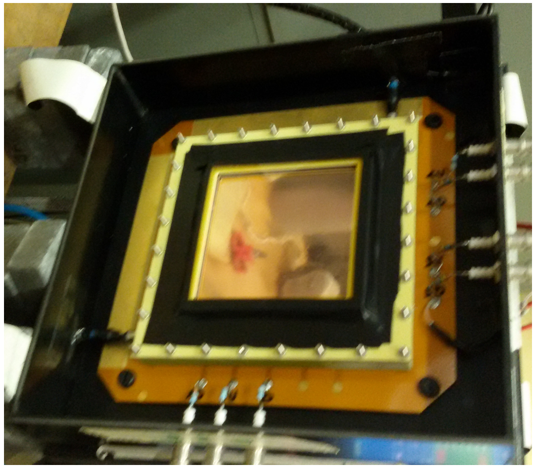


CYGNUS-RD

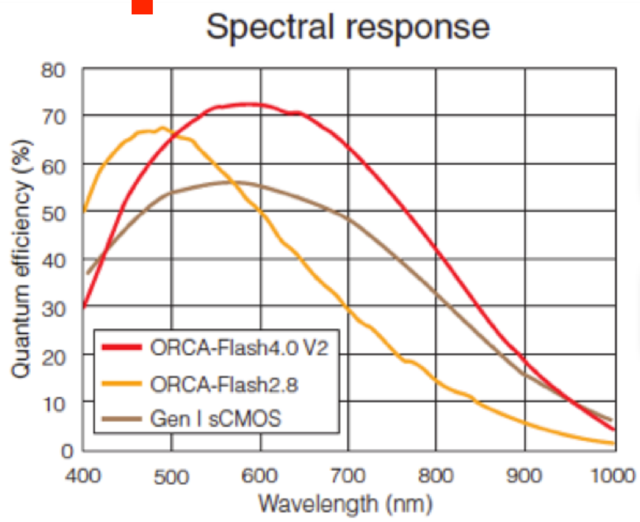
Optical readout for a Negative Ion Time Projection Chamber

CYGNUS-RD Detector





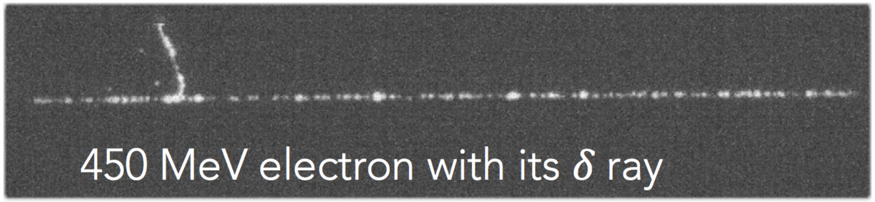
+

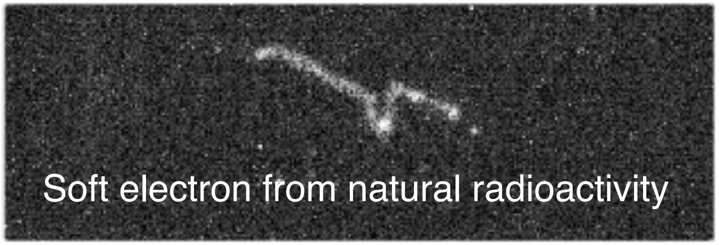


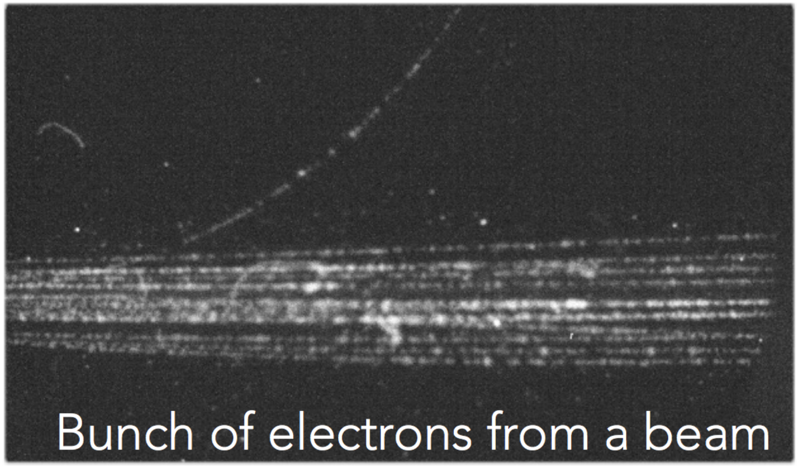
M. Marafini et al., JINST 10, P12010 (2005)

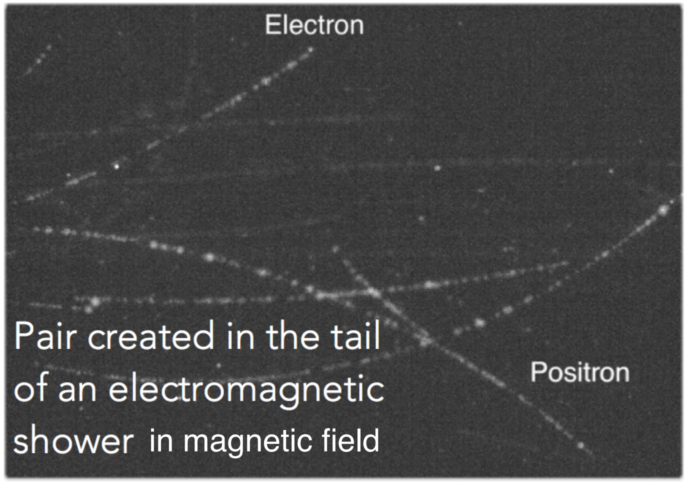
M. Marafini et al., NIM A 824 (2016) 562

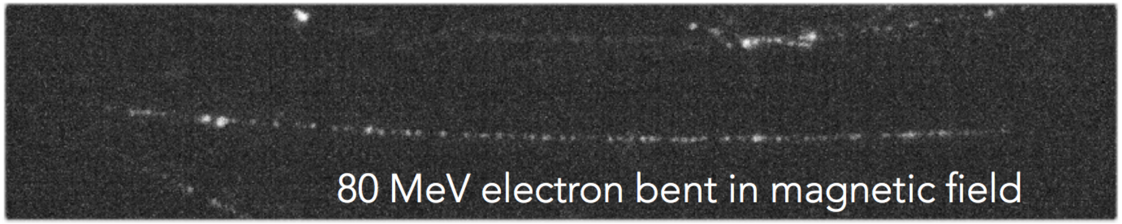
CYGNUS-RD events (with electron drift)







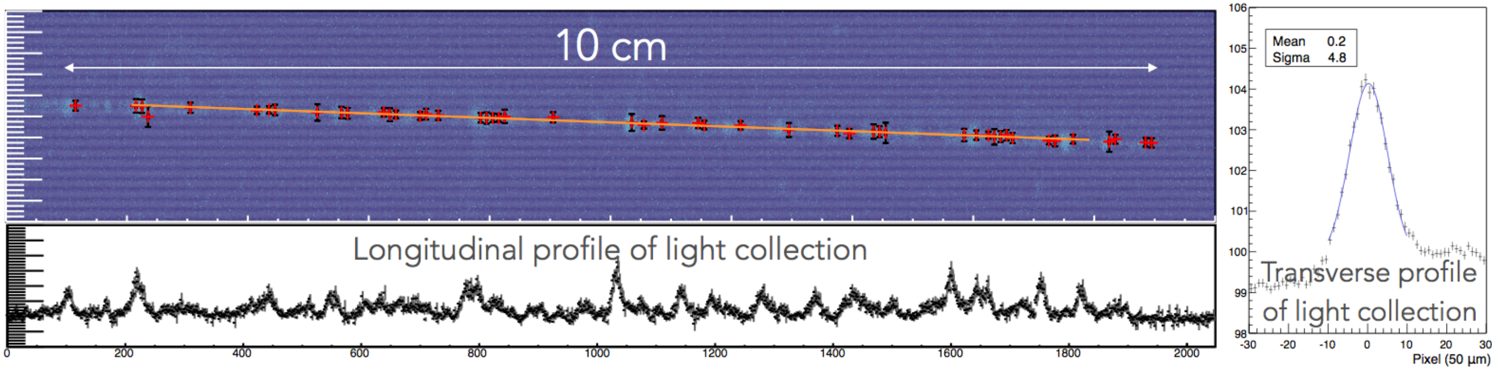




CYGNUS-RD potentialities

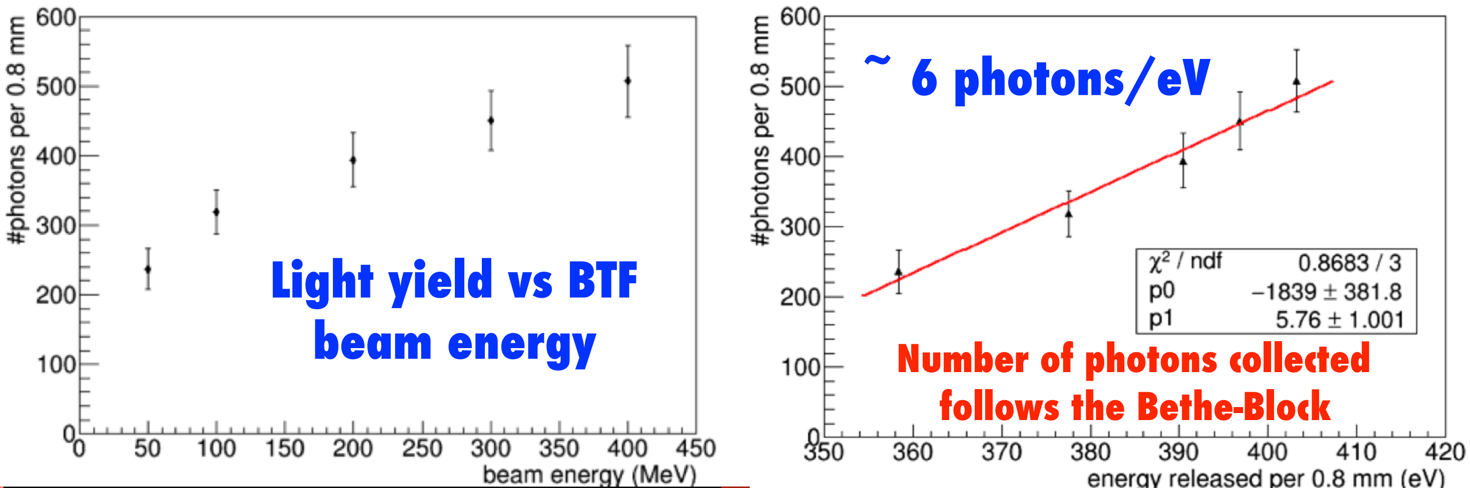
May 2016, electron drift

1) Tracking



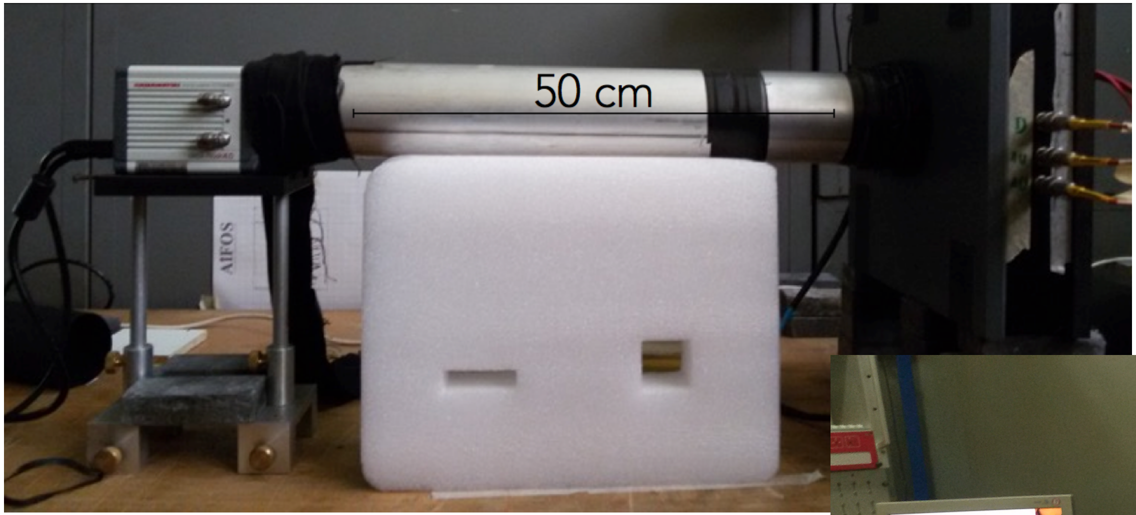
~ 1000 photons/track mm, ~70 um track residuals, cluster structures visible

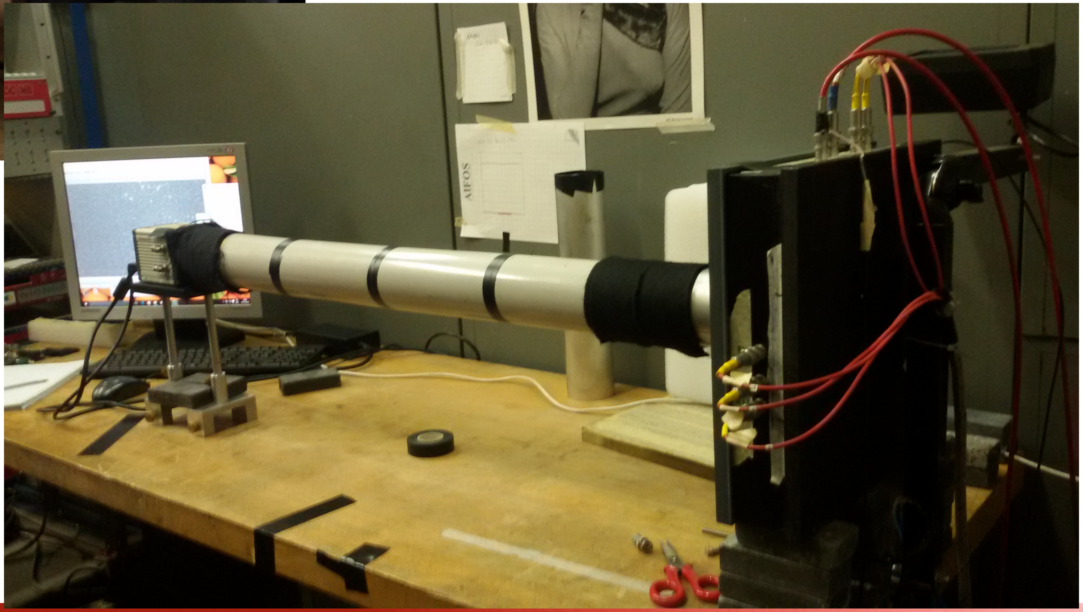
2) Ionization density (can be used to extrapolate track direction/sense)



Light vs Distance Study

How far can we go and still see light?
i.e. how large area can we cover with one CMOS camera?



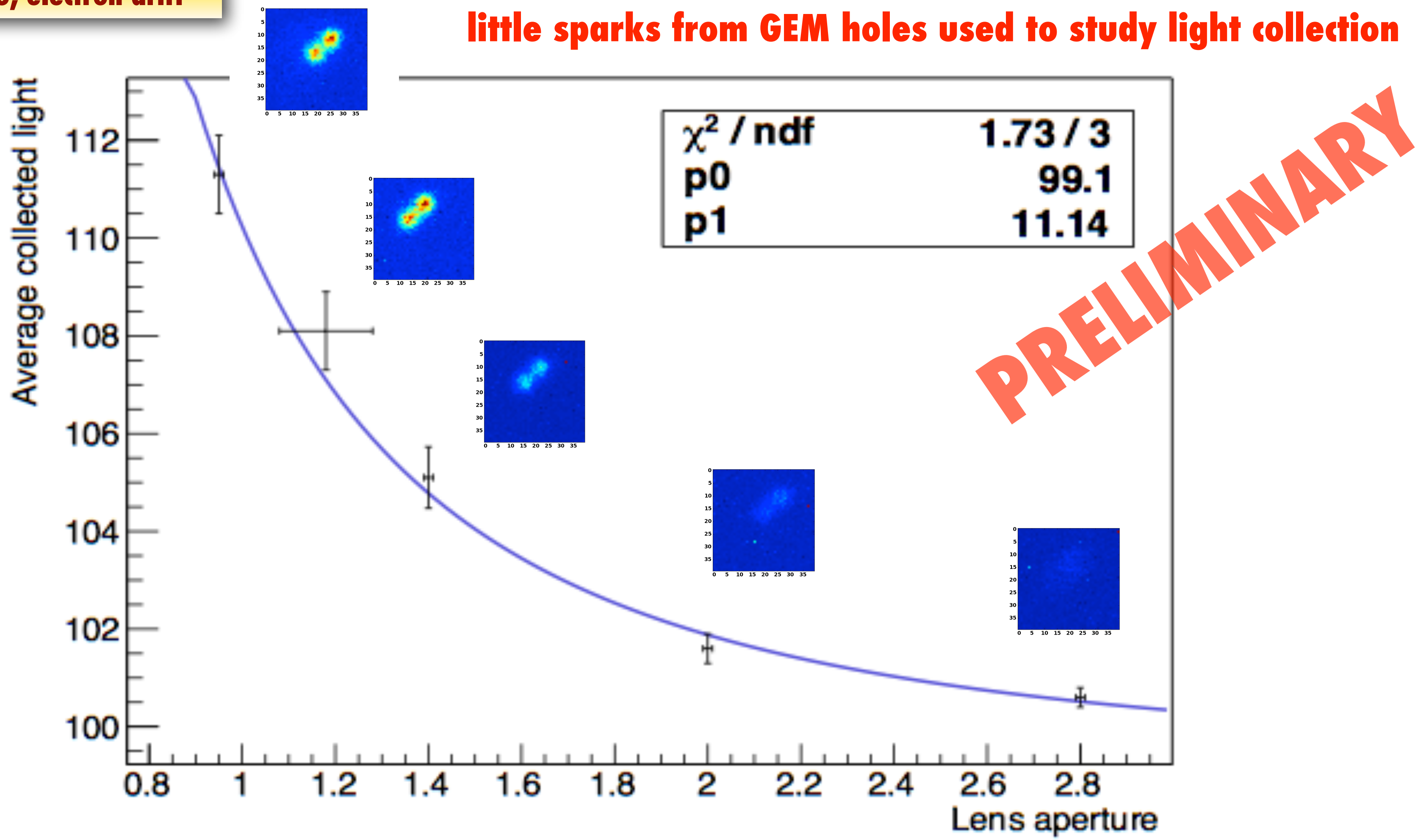


Is the light produced by the GEMs isotropic or collimated?

Light vs Lens Aperture

Dec 2016, electron drift

little sparks from GEM holes used to study light collection

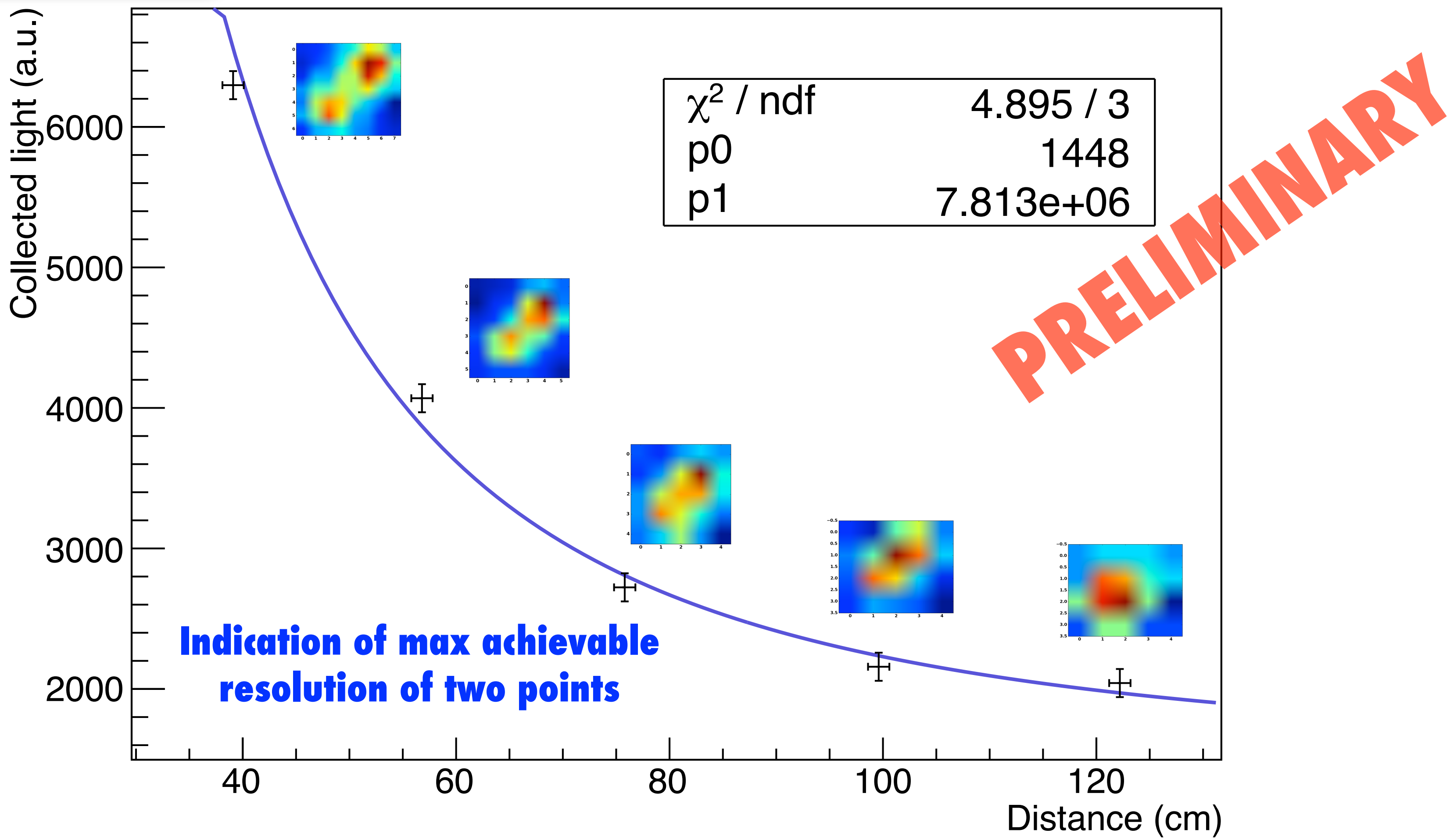


@ 20 cm distance 50 um pixels equivalent

Light vs Distance

Dec 2016, electron drift

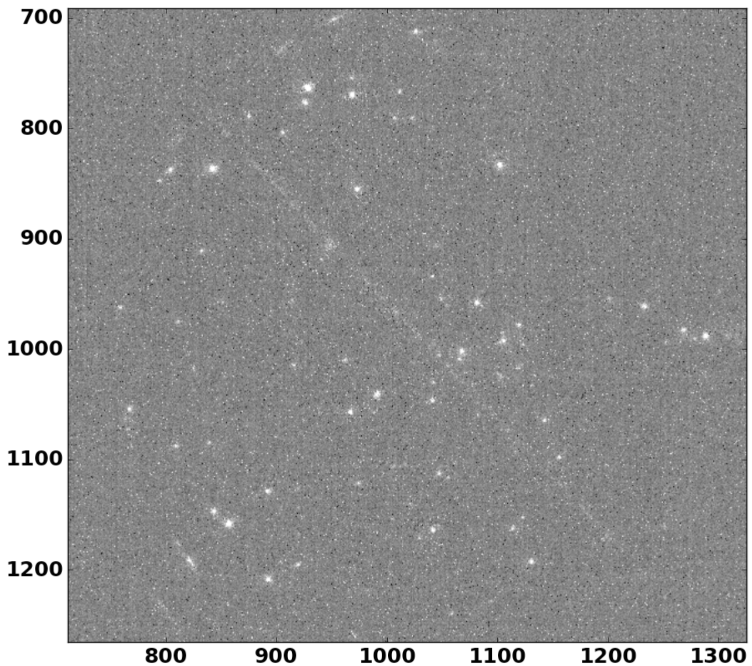
@ 60 cm we cover a 30 x 30 cm^2 area



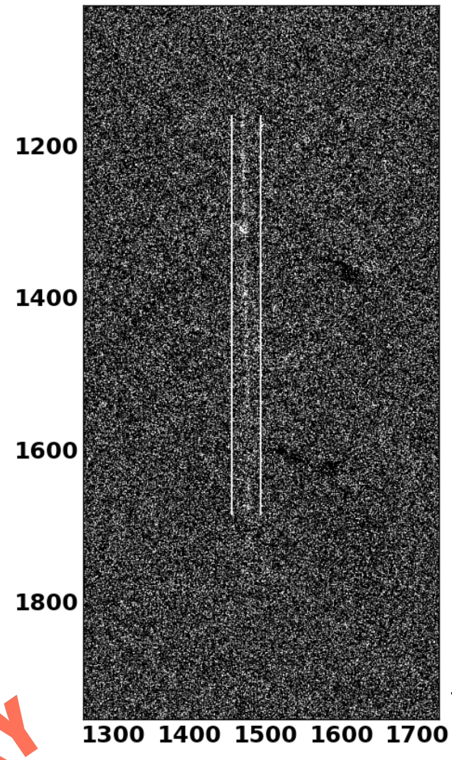
Both light vs lens aperture and light vs distance indicate <u>isotropic</u> light production

Example of cosmic track @ 60 cm

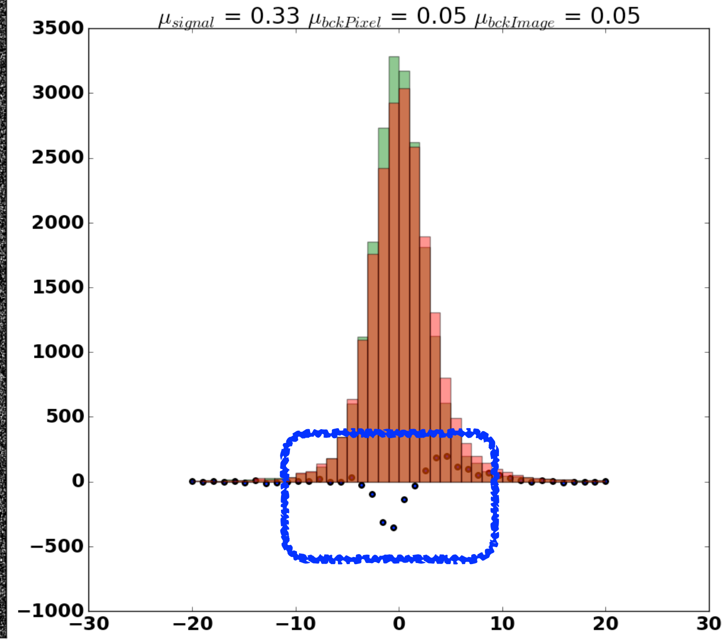
Cosmic track raw data as seen by the CMOS



Background subtracted & rotated



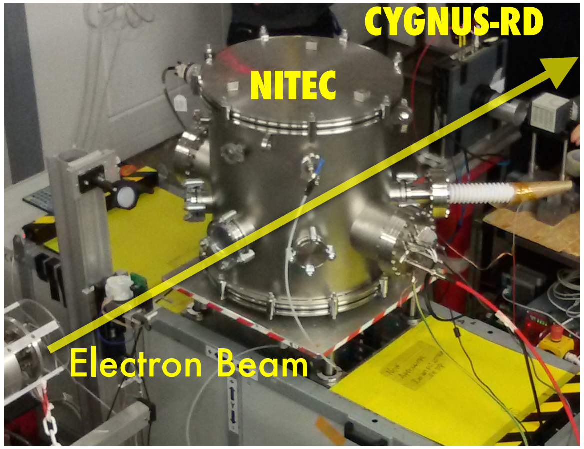
Signal (red)/noise (green) comparison

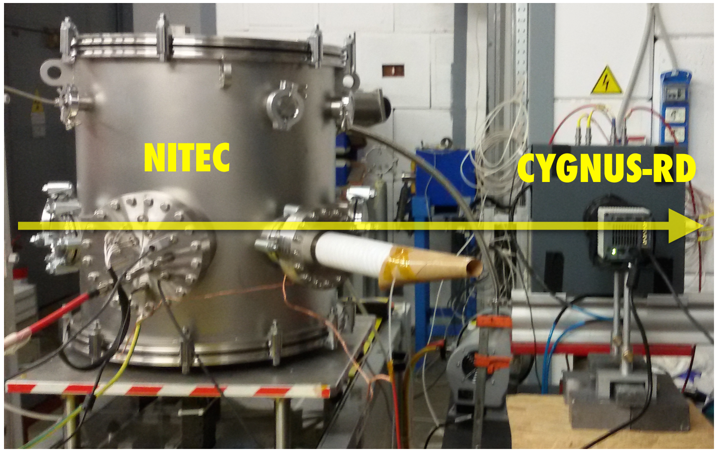


PRELIMINARY

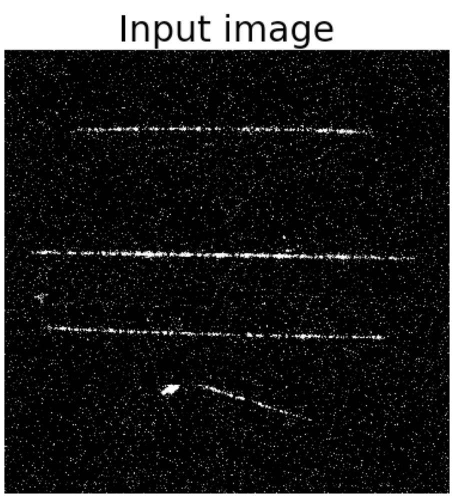
After noise subtraction, signal is clearly visible

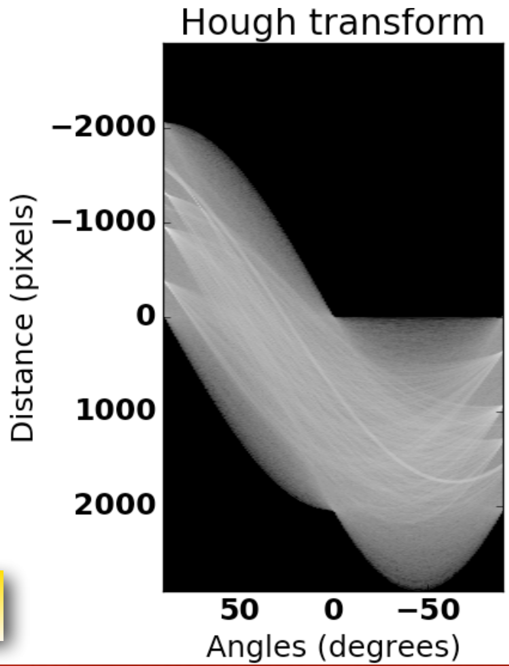
CYGNUS-RD @ BTF

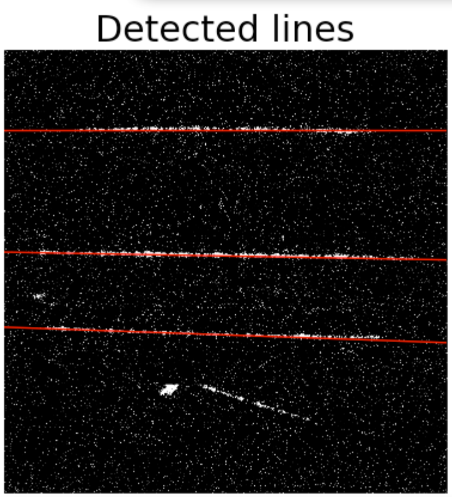




Dec 2016, electron drift







Data analysis on-going

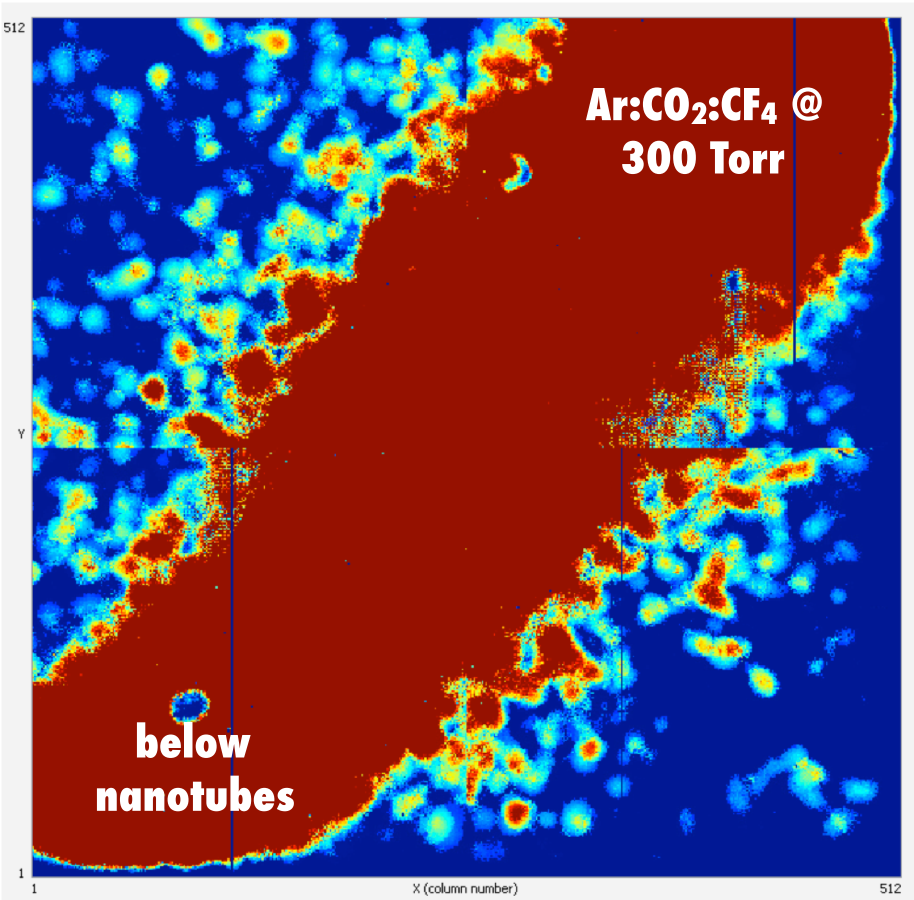
450 MeV electron beam

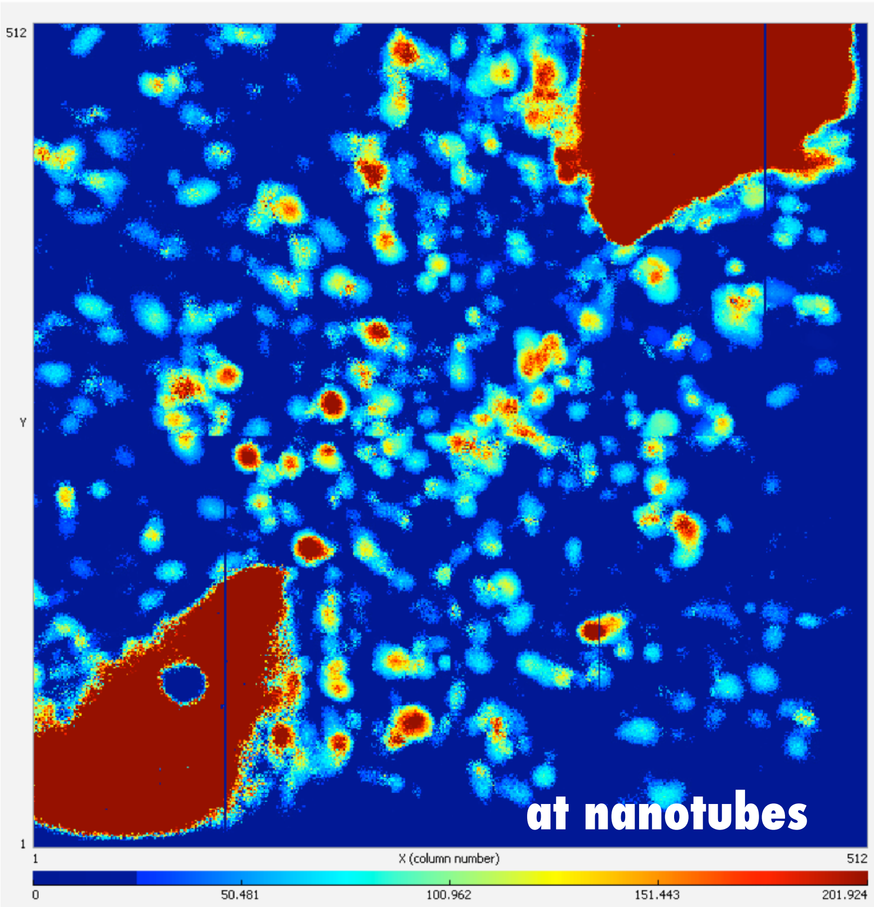
Conclusions & Outlooks

- **NITEC**
  - Innovative SF_6 based negative ion gas mixtures tested and operated nearly atmospheric pressure (610 Torr) with triple thin GEMs at electron beam line
  - Perform gain study with ^{55}Fe with the tested mixtures and explore new ones with higher He content (i.e. lower density)
  - Perform neutron run at the ENEA facility (under discussion)
- **DCANT**
  - Support and nanotubes observed to modify drift field
  - On going study to develop suitable support and substrate
- **CYGNUS-RD**
  - Verified isotropic emission of photons by the GEMs, implying that collected light follows optical rules (one over distance squared)
  - Cosmic tracks easy identified at 60 cm distance (i.e. 30 x 30 cm^2 area covered)
  - New beam test beginning Feb with attempt of atmospheric negative ion operation following gas mixtures tested by NITEC
  - Test of PMT inside TPC volume to measure times (minority carriers)

Backup

Carbon Nanotubes





GEMPix + NITPC: A Time Expansion Chamber

- At moderately high reduced fields, anions drift at about 100 m/s, compared to about 10^4 m/s for electron in typical atmospheric pressure drift chamber conditions
- Excellent GEMPix time, energy and spatial resolutions
- Slow anions speed + typical separation of primary ionization clusters in gas + GEMPix performances = Time Expansion Chamber
    - Single ionization clusters drift slowly and could be individually observed with high precision: a relative time expansion between ionization process and signal readout has effectively been achieved
- Single ionization cluster observation can provide excellent dE/dx information, improved position resolution and possibility of superior energy resolution for low energy radiation

"The Time Expansion Chamber and single ionization measurement" (A.H.Walenta, IEEE TNS 26 73)
"Suppressing drift chamber diffusion without magnetic field" (C.J.Martoff et al, NIM A 440)

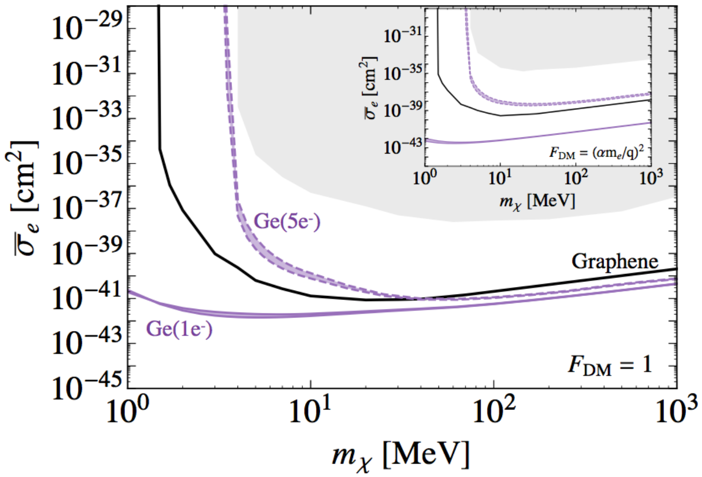
Also Graphene target !

http://arxiv.org/pdf/1606.08849.pdf

Directional Detection of Dark Matter with 2D Targets

Yonit Hochberg[1,2],* Yonatan Kahn[3],† Mariangela Lisanti[3],‡ Christopher G. Tully[3],§ and Kathryn M. Zurek[1,2]¶
[1] *Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720*
[2] *Department of Physics, University of California, Berkeley, CA 94720 and*
[3] *Department of Physics, Princeton University, Princeton, NJ 08544*

We propose two-dimensional materials as targets for direct detection of dark matter. Using graphene as an example, we focus on the case where dark matter scattering deposits sufficient energy on a valence-band electron to eject it from the target. We show that the sensitivity of graphene to dark matter of MeV to GeV mass can be comparable, for similar exposure and background levels, to that of semiconductor targets such as silicon and germanium. Moreover, a two-dimensional target is an excellent directional detector, as the ejected electron retains information about the angular dependence of the incident dark matter particle. This proposal can be implemented by the PTOLEMY experiment, presenting for the first time an opportunity for directional detection of sub-GeV dark matter.



Functionalization

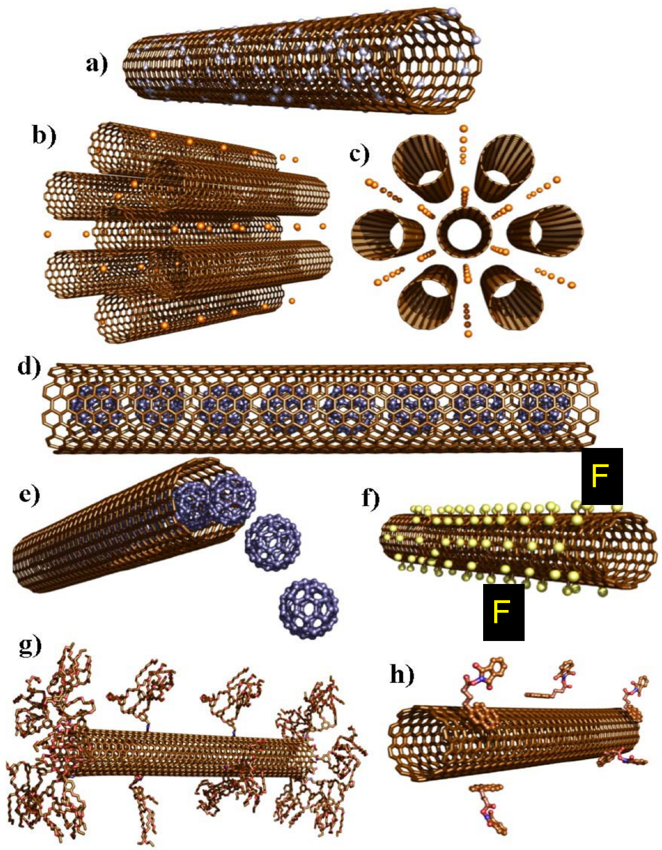


Figure 8. Different approaches to chemical modification of carbon nanotubes. (a) substitutional doped single-walled nanotubes (either during synthesis or by post-growth ion-implantation), (b,c) nanotube bundles intercalated with atoms or ions, (d,e) peapods: SWNTs filled with fullerenes (other endohedral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