Part of this project has been funded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 657751

Seminario di Dipartimento

Universita' di Roma La Sapienza

Negative Ion Time Projection Chambers for very rare events searches

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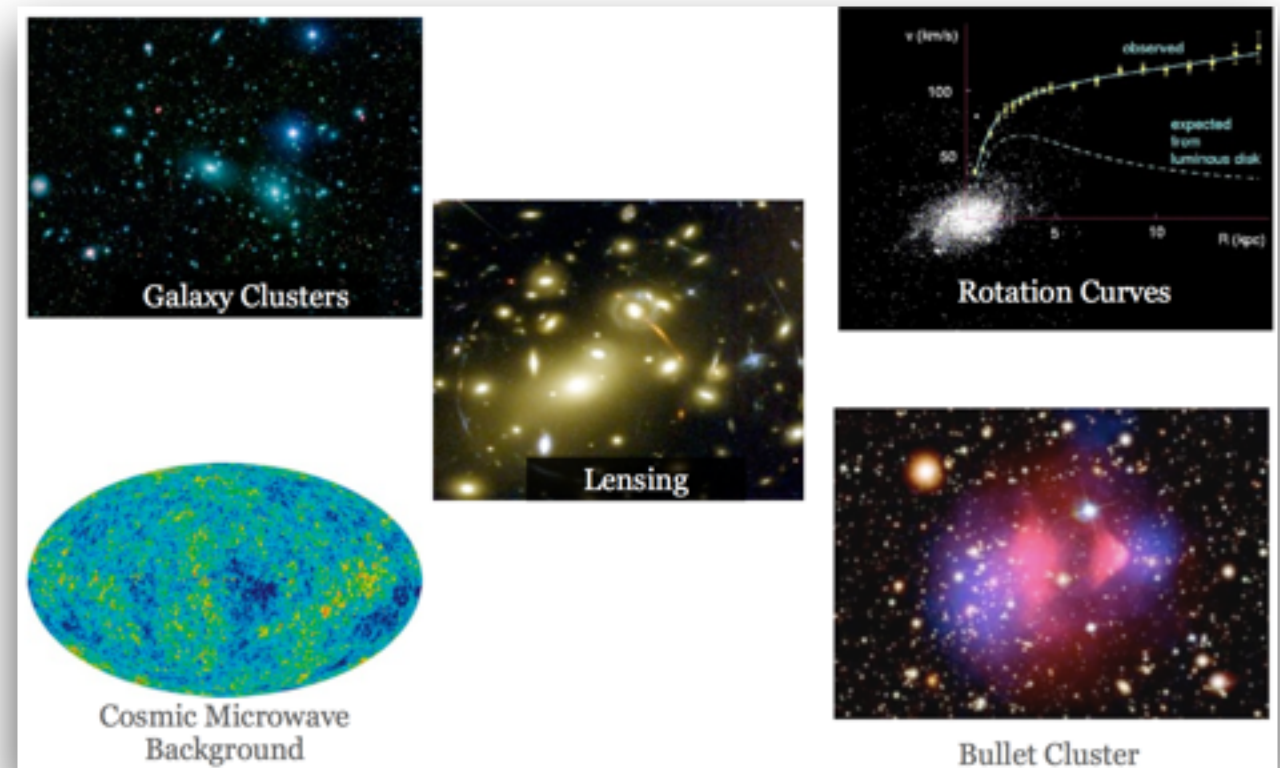
In collaboration with C. Antochi, G. Cavoto, E. Di Marco, M. Marafini, G. Mazzitelli, F. Murtas, D. Pinci, F. Renga, A. Tomassini, C. Voena

Outline

- **Very rare events searches today** and the need for large volume, background-free experiments
- **The choice:** track topology and fiducialization with negative ion gaseous TPC approach
- **R&D efforts** in Italy
  - **NITEC**
  - **DCANT**
  - **CYGNUS R&D**
- The **CYGNUS-TPC** project
- The **UNDER** project

Fundamental physics unsolved enigmas

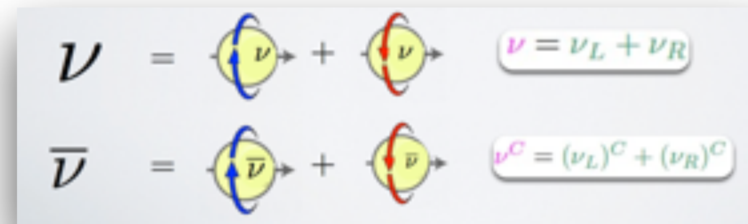
Dark Matter Identity



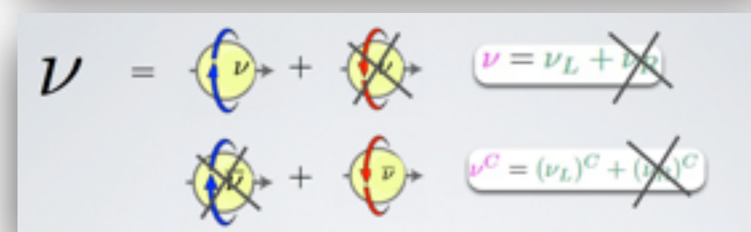
Dark Matter existence is an established and yet mysterious paradigm

What exactly is Dark Matter?

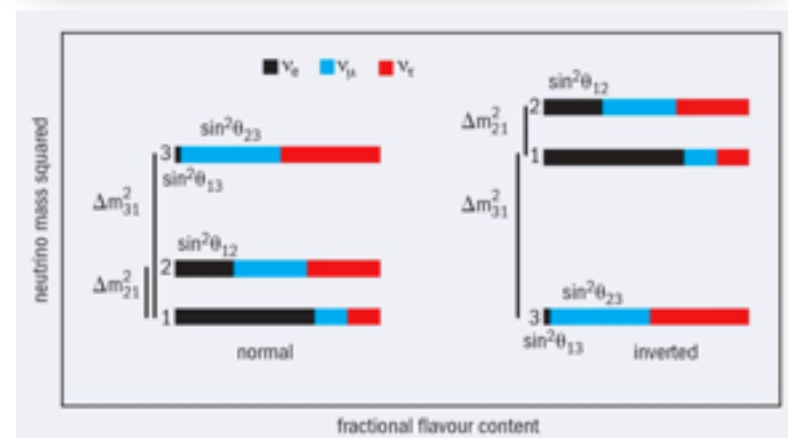
Neutrino Properties



Dirac neutrino?



Majorana neutrino?



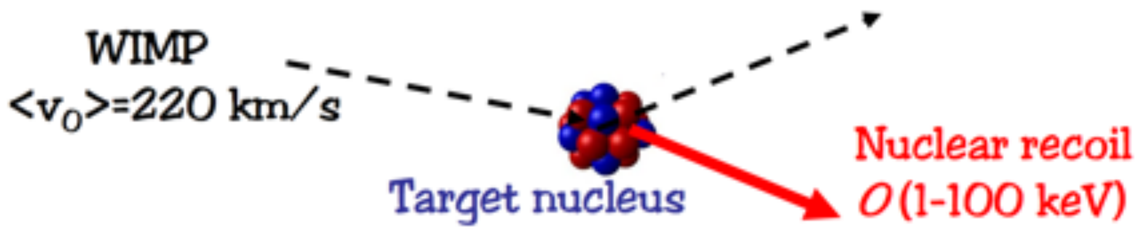
Neutrino mass scale?

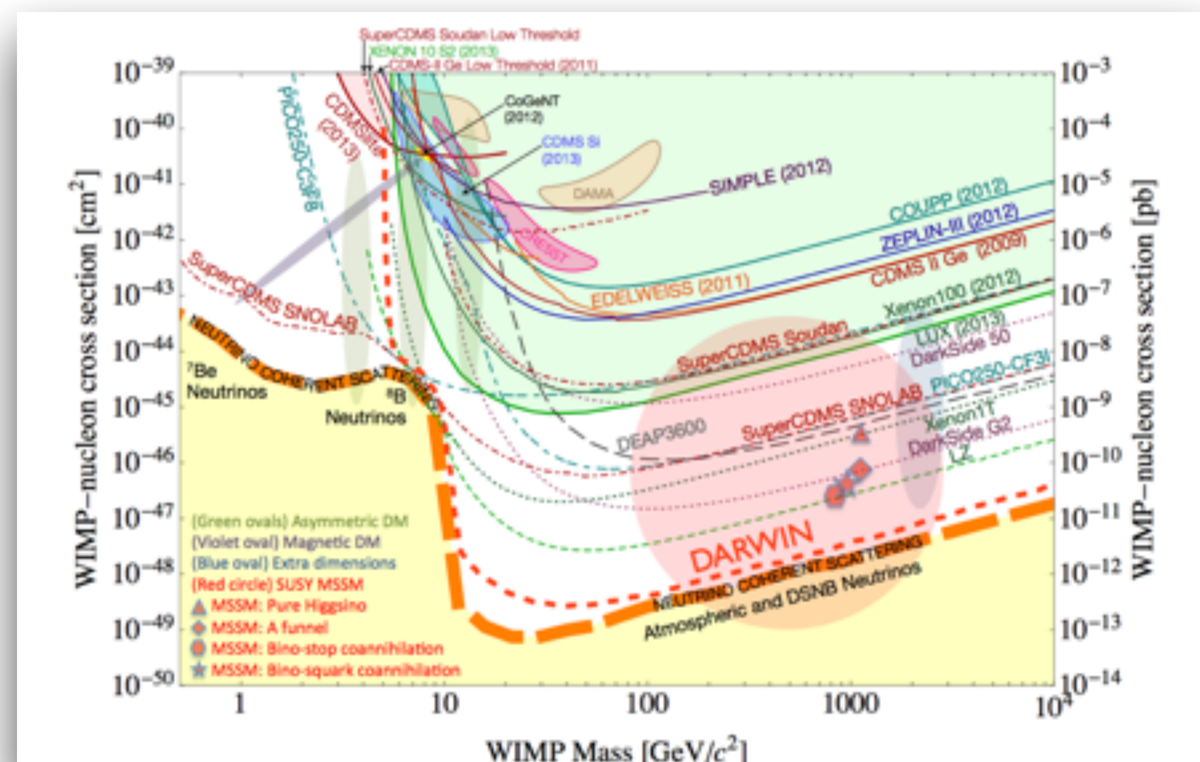
A Majorana neutrino would represent a NEW form of matter

Is the neutrino is own anti-particle?

How we try to tackle them

Direct Dark Matter Searches

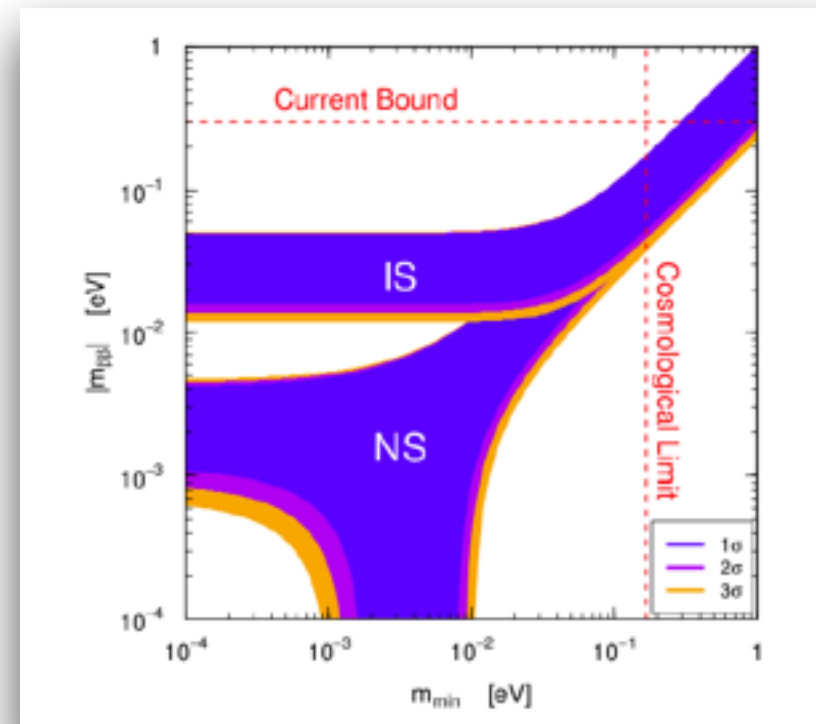




Neutrino-less Double Beta Decay Searches

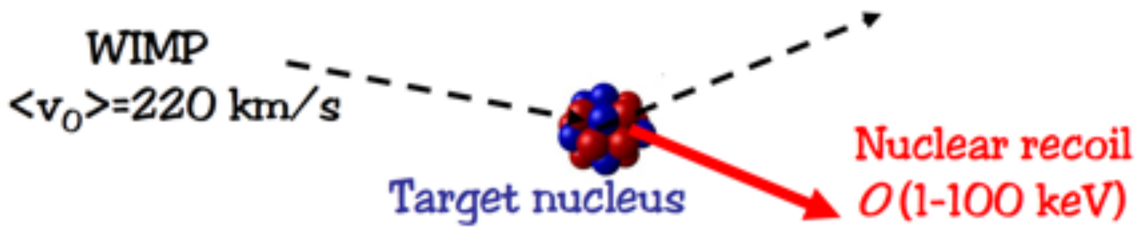
Observed

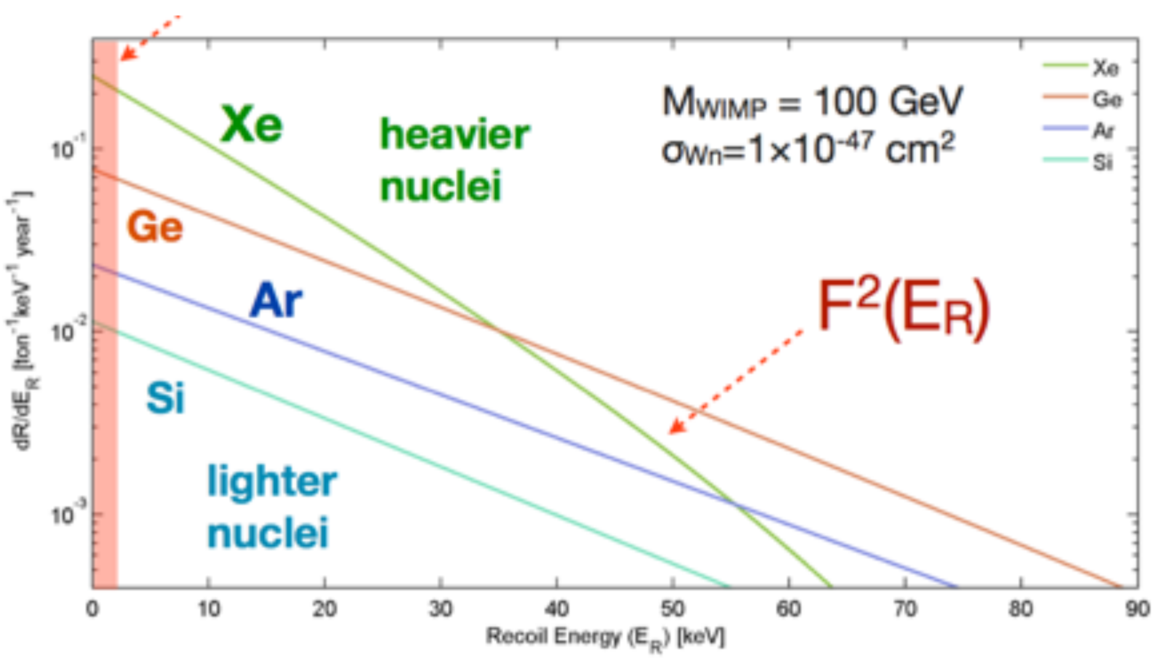
only if Majorana neutrino



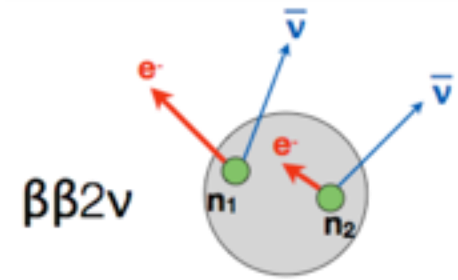
How we try to tackle them

Direct Dark Matter Searches

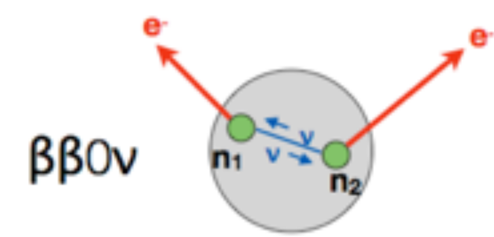




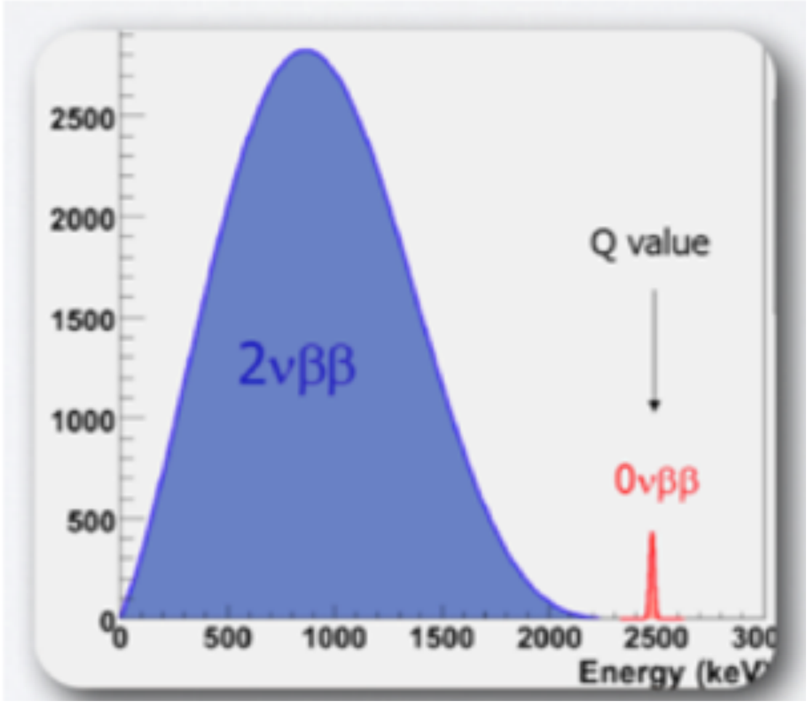
Neutrino-less Double Beta Decay Searches



Observed

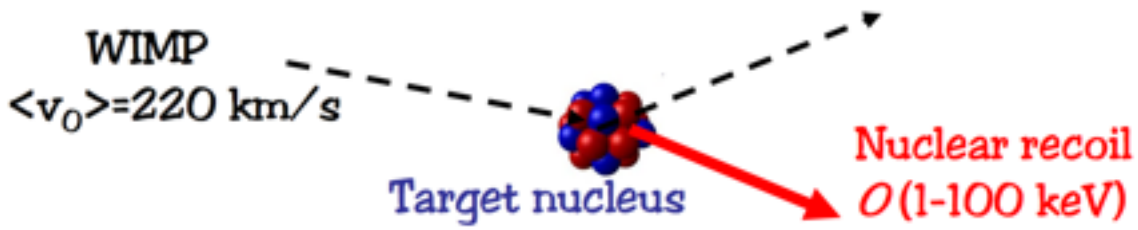


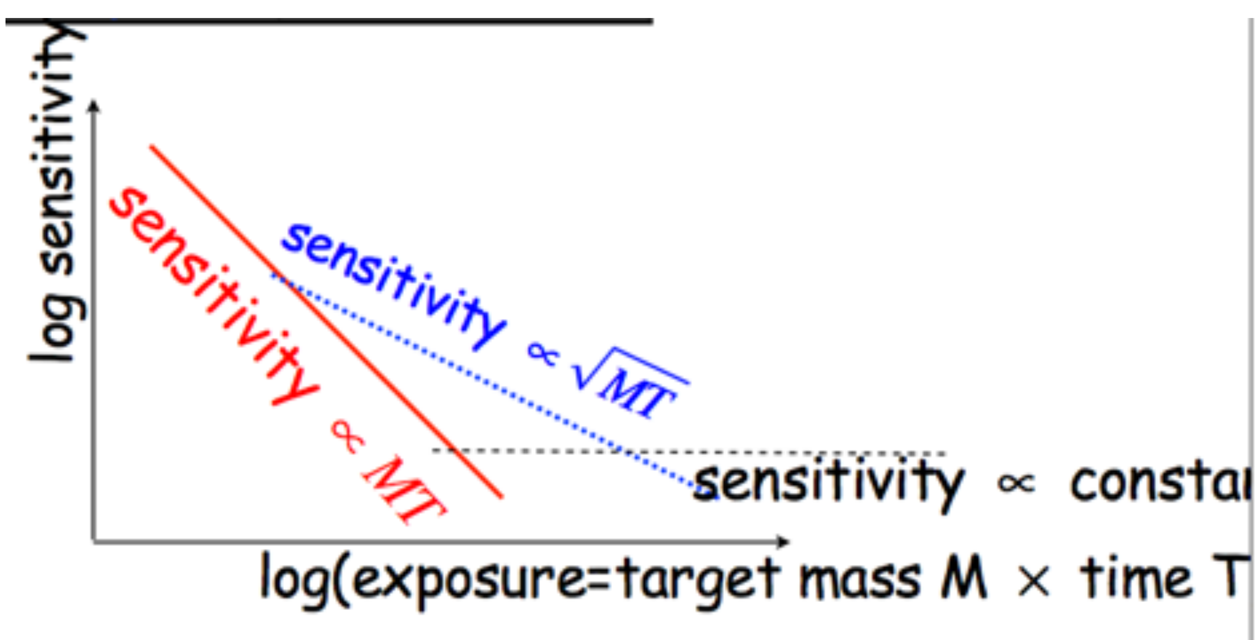
only if Majorana neutrino



How we try to tackle them

Direct Dark Matter Searches





Neutrino-less Double Beta Decay Searches

Observed

only if Majorana neutrino

Nb>>1

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A}\sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

Nb ≤ O(1) → "zero background"

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

→ ($\langle m_{ee} \rangle$)

$$S^{0\nu}_{1/2}(m_{ee}) \propto \epsilon \frac{i.a.}{A} \frac{1}{\sqrt{G^{0\nu}}|M^{0\nu}|}\sqrt[4]{\frac{bkg \cdot \Delta E}{M \cdot t_{meas}}}$$

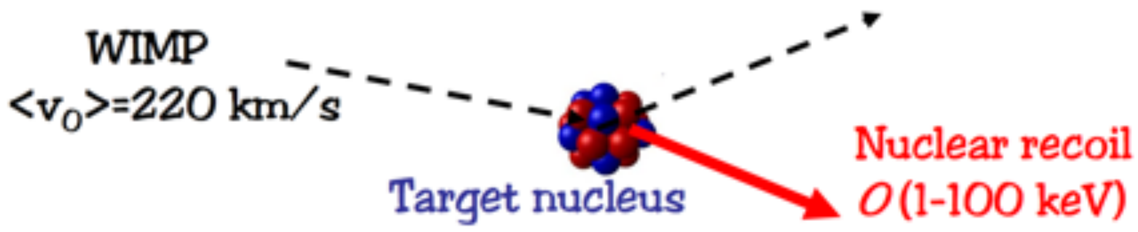
- Isotope choice

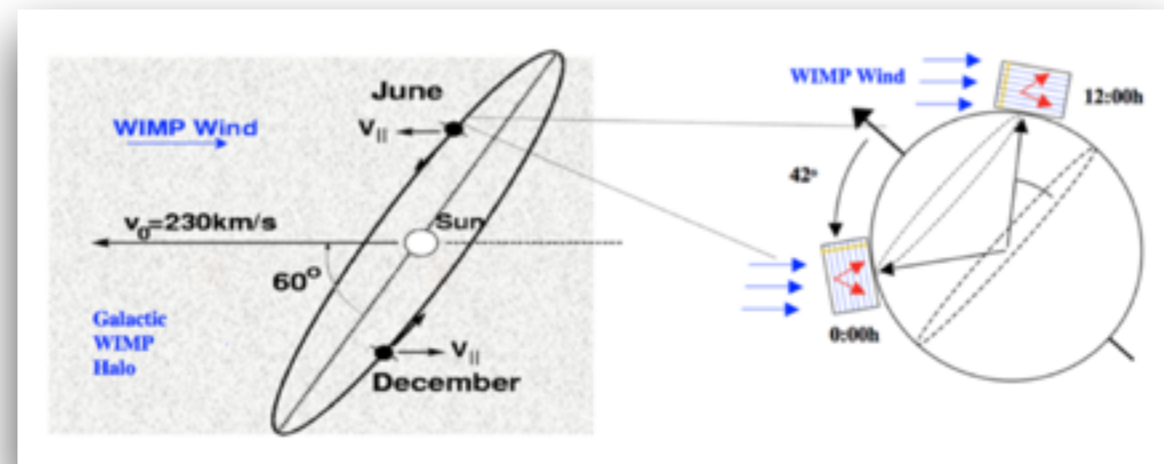
- Isotopical abundance
- Mass
- Energy resolution
- Background level

Next-generation experiments share the need for a background-free large volume detector

The chosen approach

Direct Dark Matter Searches



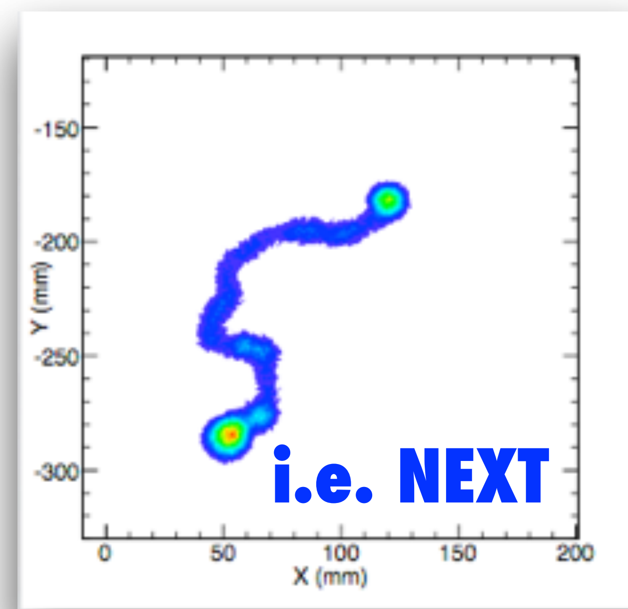


Energy measurement +
Detection of Dark Matter incoming direction

Neutrino-less Double Beta Decay Searches

Observed

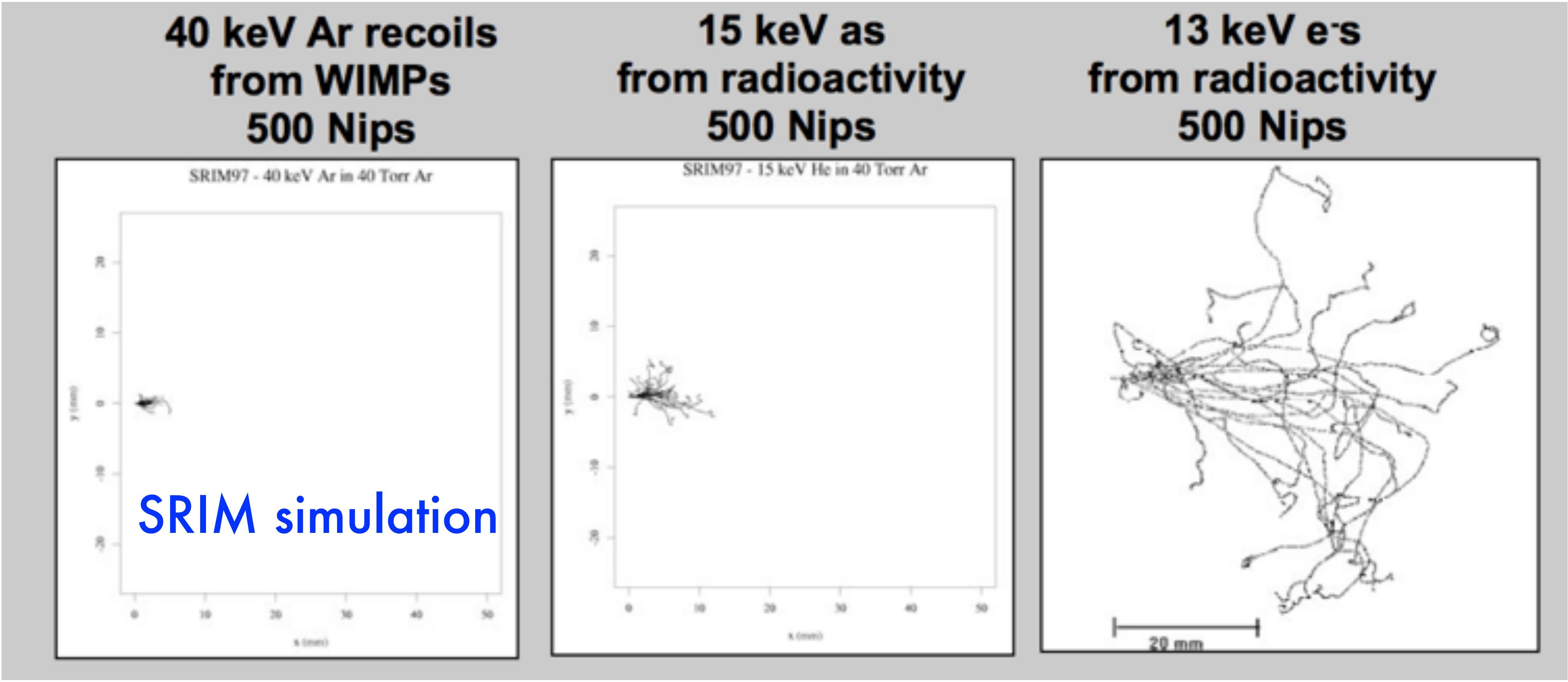
only if Majorana neutrino



Energy measurement +
Topological identification of back-to-back electrons

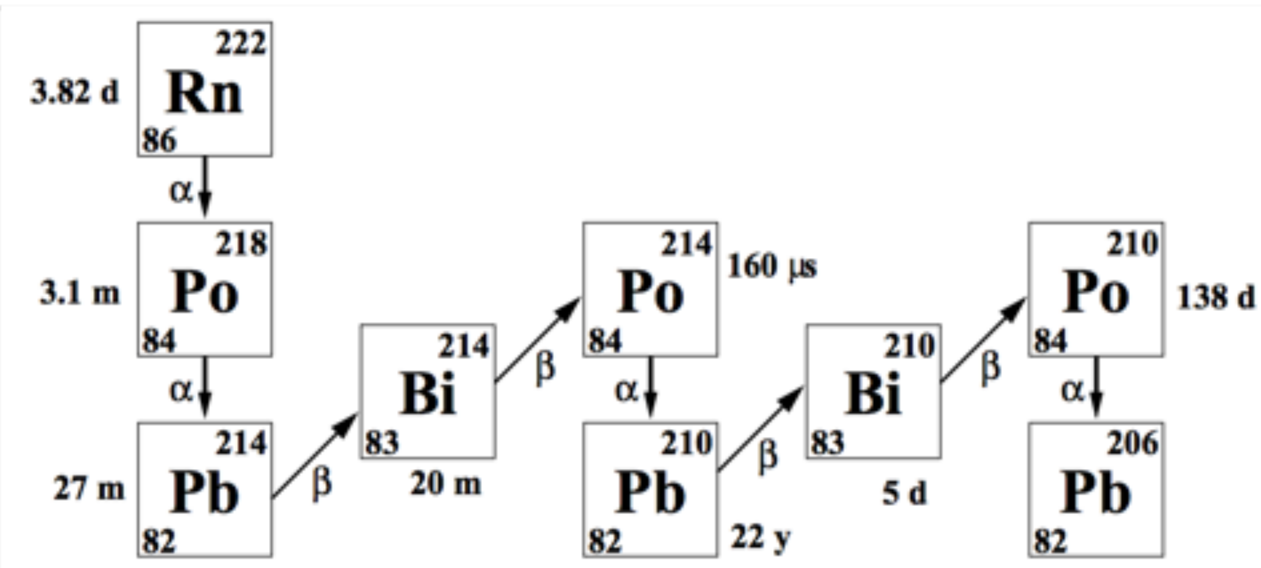
The choice: exploit track directional information and fiducialization

Gaseous TPC approach



- **Gaseous TPCs potentially provides the best observables for very rare search experiments:**
  - Total charge/light collected indicates energy of the event
  - Comparison b/w track path and energy provide excellent rejection of alphas and electrons
  - The track itself indicates the axis of the recoil —> **topology, not available in denser media**
  - Measurement of charge/light (and dE/dx) along the path allows to infer the sense of direction
  - **Very high particle identification/background rejection capabilities w.r.t. other approaches**
- **Drawback:**
  - Total active mass less w.r.t. liquid or solid approaches

Fiducialization with TPC



After classical background minimization (underground lab, active & passive shielding and radio-pure detector components), Radon progeny from deposit on detector surfaces can still produce signal-like tracks

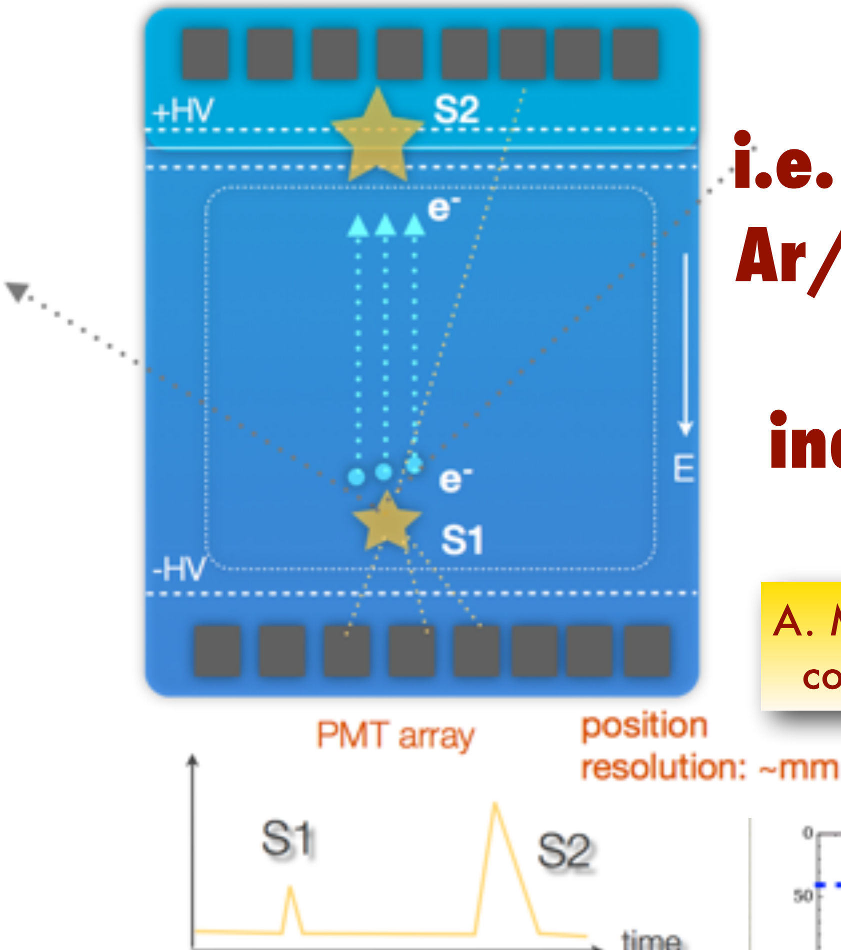
Measurement of the position of the event, including drift direction, allows to remove this remaining background

Fiducialization

- **Through detection of primary scintillation light**, that provide the start t_0 of the event
  - Difficult, very few photons, used in liquid Ar/Xe double phase TPCs
- **Through ionization cloud profile**, from the fit to the transverse diffusion
  - Possible, but need a high resolution/high granularity readout, demonstrated by D^3
- **Through minority carriers arrival time difference**
  - Possible with negative ion drift and low resolution/low granularity readout, demonstrated by DRIFT

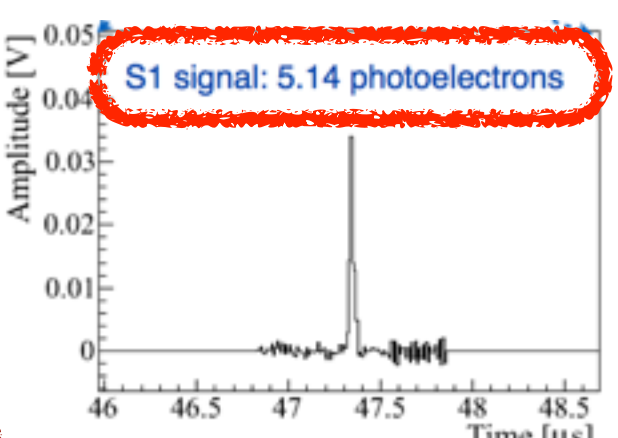
Fiducialization with TPC

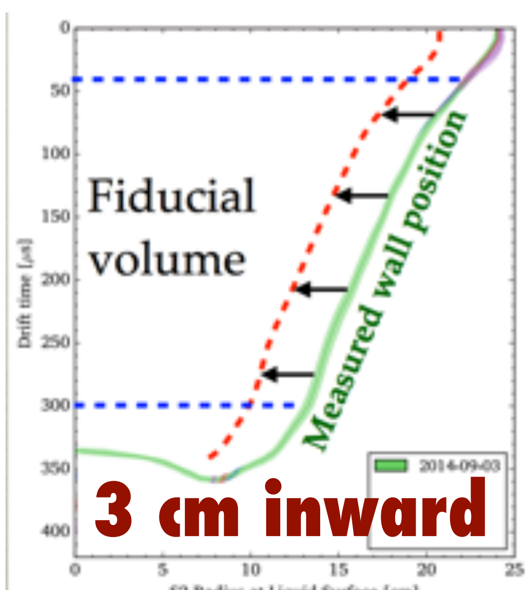
Through primary ionization light



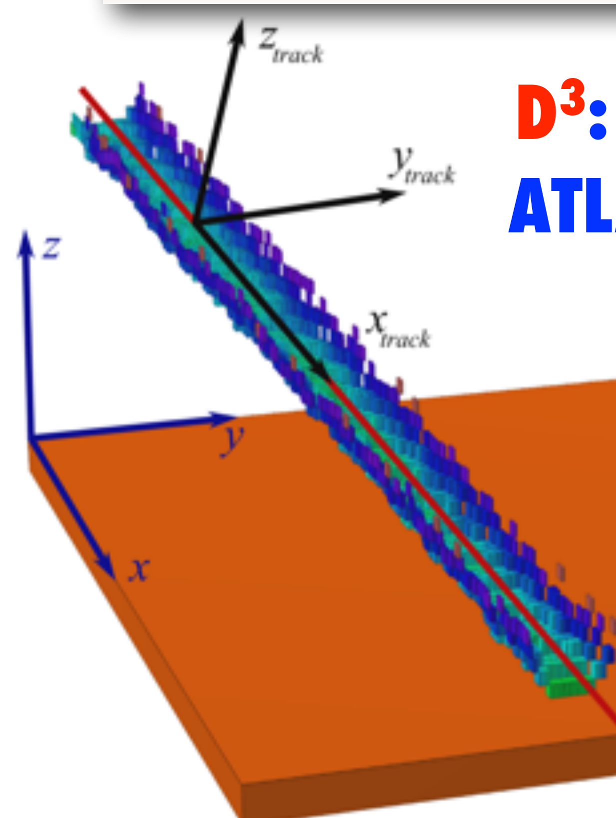
i.e. Double phase Ar/Xe liquid TPC: drift time indicates depth

A. Manalaysay talk for LUX collaboration, IDM 2016





Through ionization cloud profile



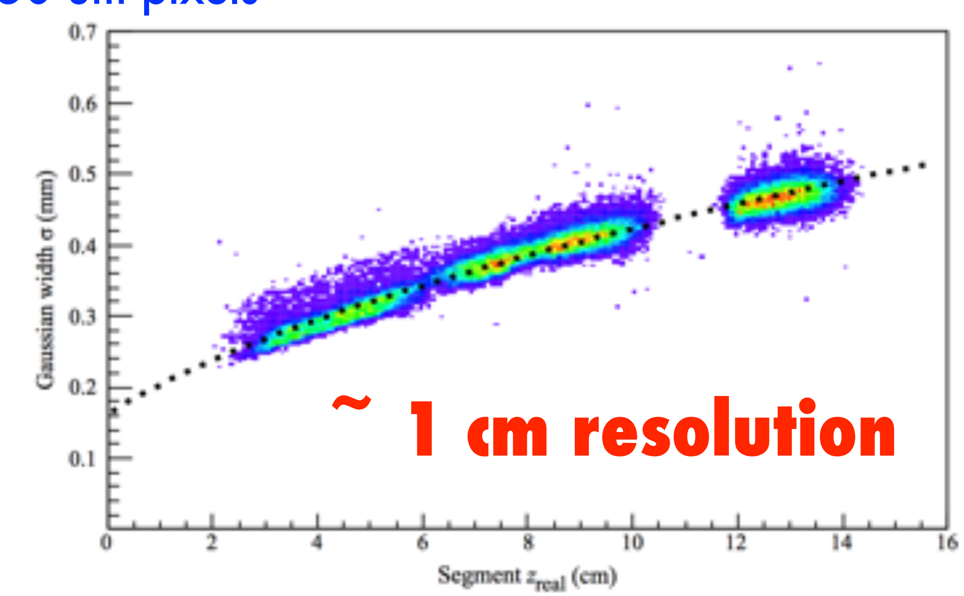
D^3: double thin GEMs + ATLAS FE-I4B pixels chip $He:CO_2$ 70:30

P. Lewis et. al, Nucl. Instrum. Meth. A 789 (2015) 81-85

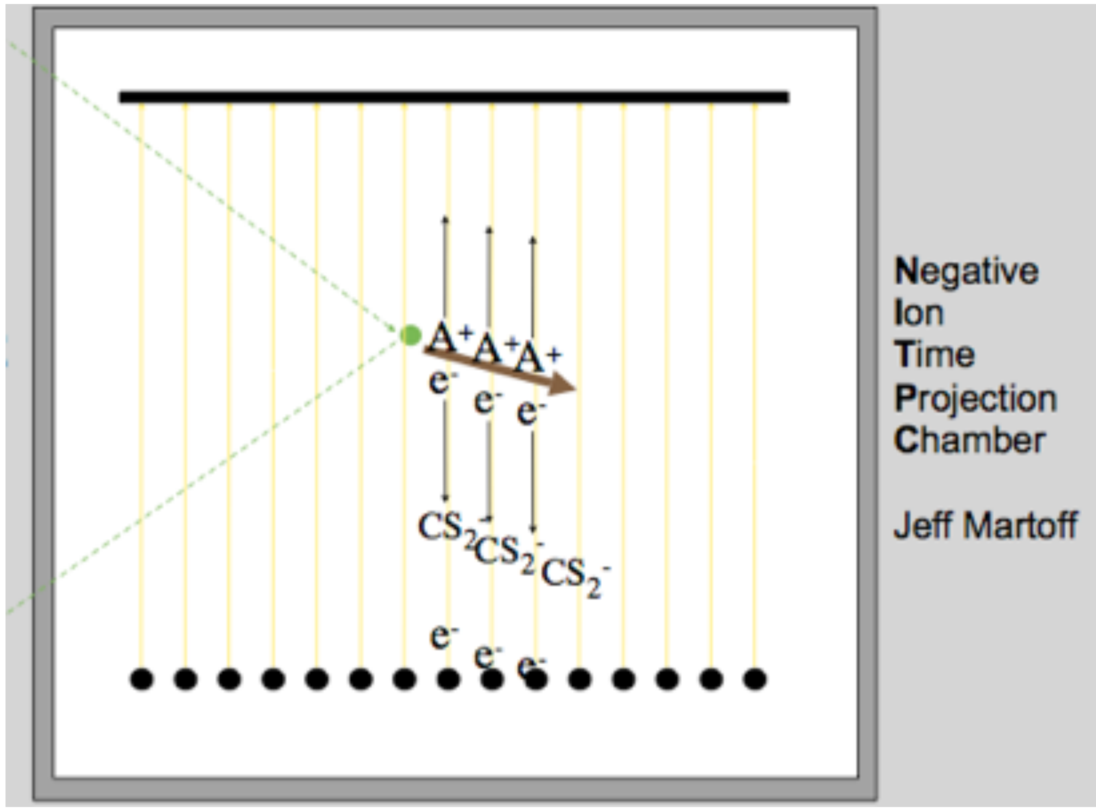
$$\sigma(z) = \sqrt{A^2 + B^2 z}.$$

$A = 180 \pm 20\ \mu m$ and $B = 123 \pm 7\ \mu m$.

50 x 250 um pixels



Negative Ions Drift



- Mixture of target gas + electronegative gas (typically CS_2)
- Primary ionization electrons are captured by the electronegative molecules at O(100) um
- Anions drift to the anode acting as the effective image carrier instead of the electrons
- Thanks to the much higher anions mass w.r.t. electrons, longitudinal and transversal diffusion is reduced to thermal limit w/out any magnetic field
- At the anode, the electron is stripped from the anion and normal electron avalanche occurs

< 0.5 mm diffusion achieved over 0.5 m drift length w.r.t. 10 mm obtained with electrons (no magnetic field)

$$\sigma^2 = \frac{4\varepsilon_k L}{3eE}$$

$$\epsilon_k \sim k_B T$$

for ions

$$k_B T \leq \epsilon_k \leq O(eV)$$

for electrons

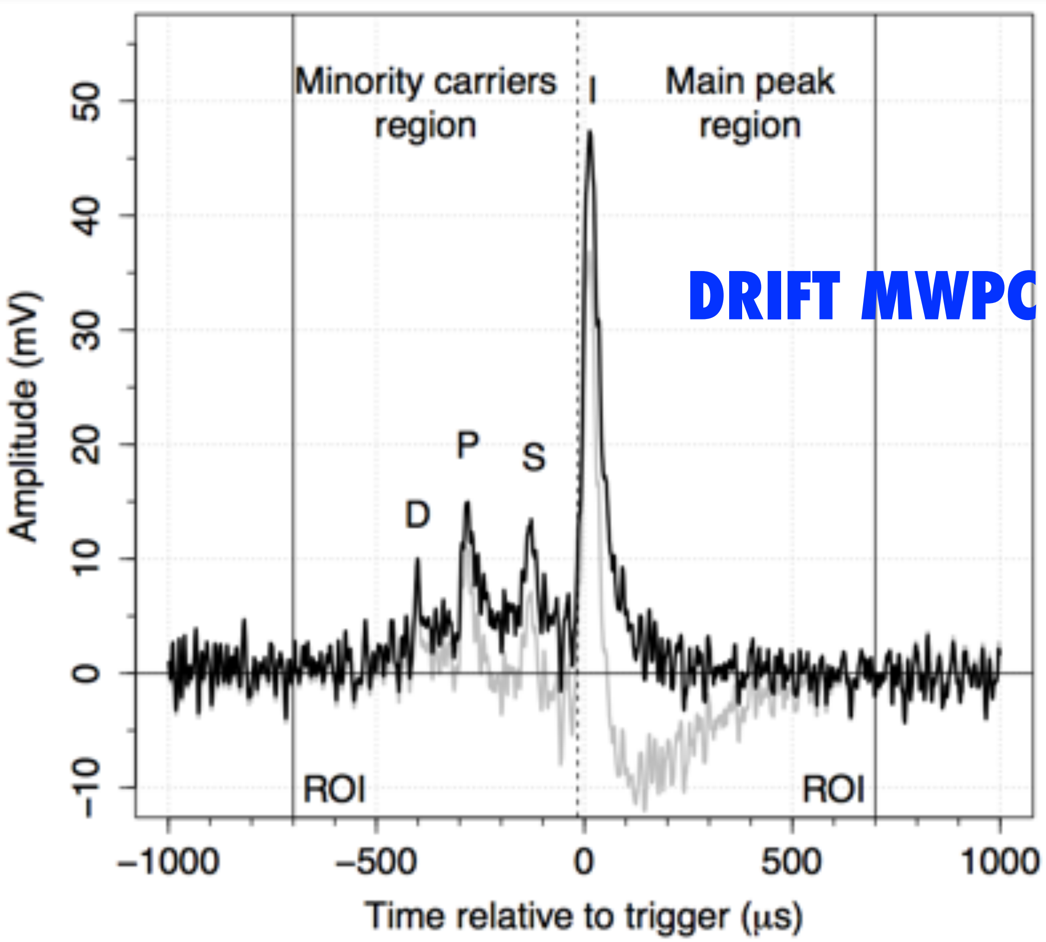
J. Martoff et al., NIM A 440 355

T. Ohnuki et al., NIM A 463

Address TPC typical volume limitations

Fiducialization with Negative Ions TPCs

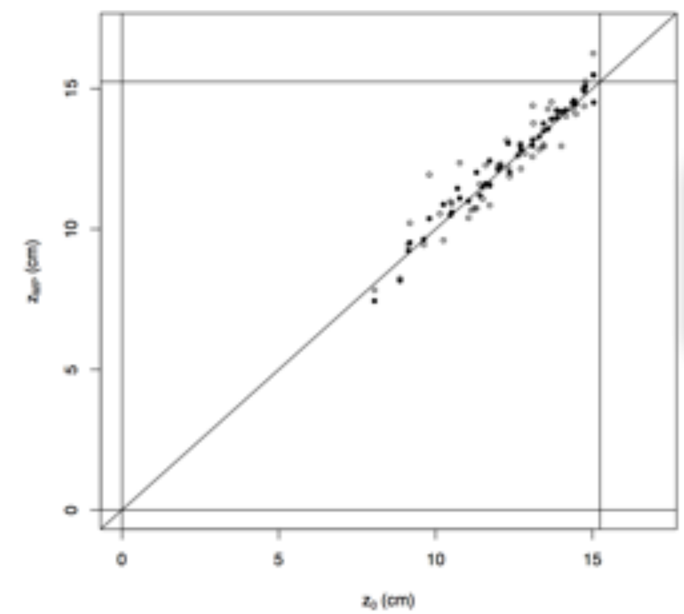
NEW (2013): discovery of fiducialization through minority carriers, allowed DRIFT to achieve zero background



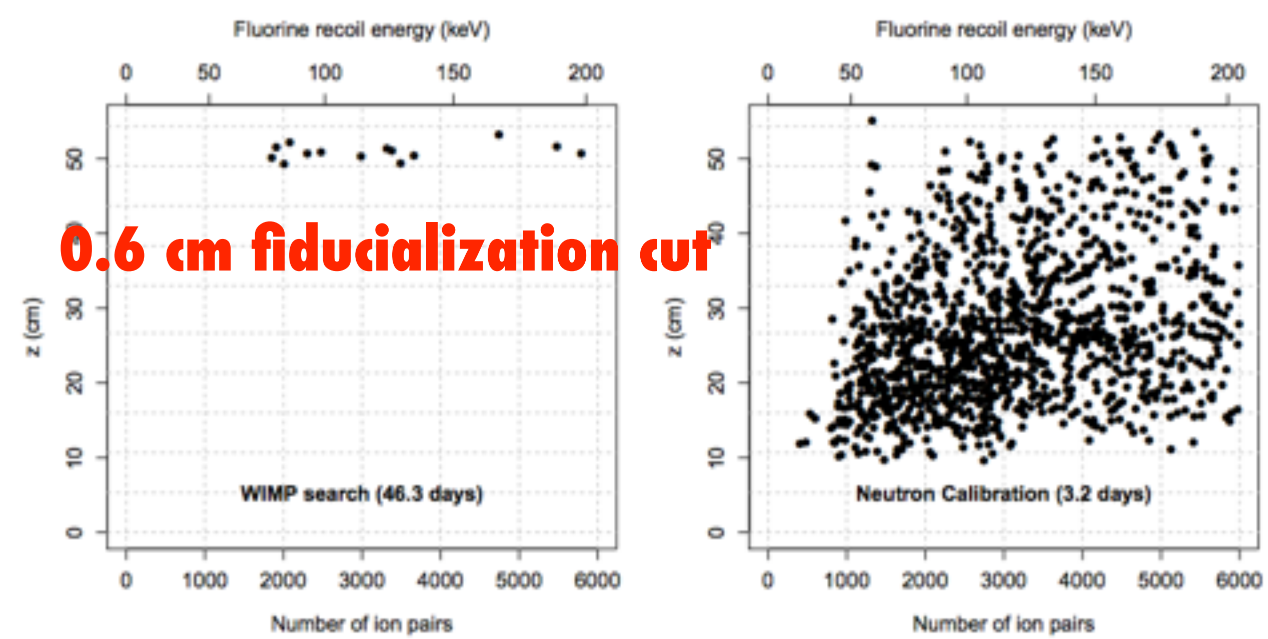
$$v_d = \left(\frac{1}{m_{ion}} + \frac{1}{M_{gas}}\right)^{1/2} \left(\frac{1}{3kT}\right)^{1/2} \frac{eE}{N\sigma},$$

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

Triggerless fiducialization



D. Snowden-Ifft, Rev. Sci. Instrum. 85 (2014) 013303



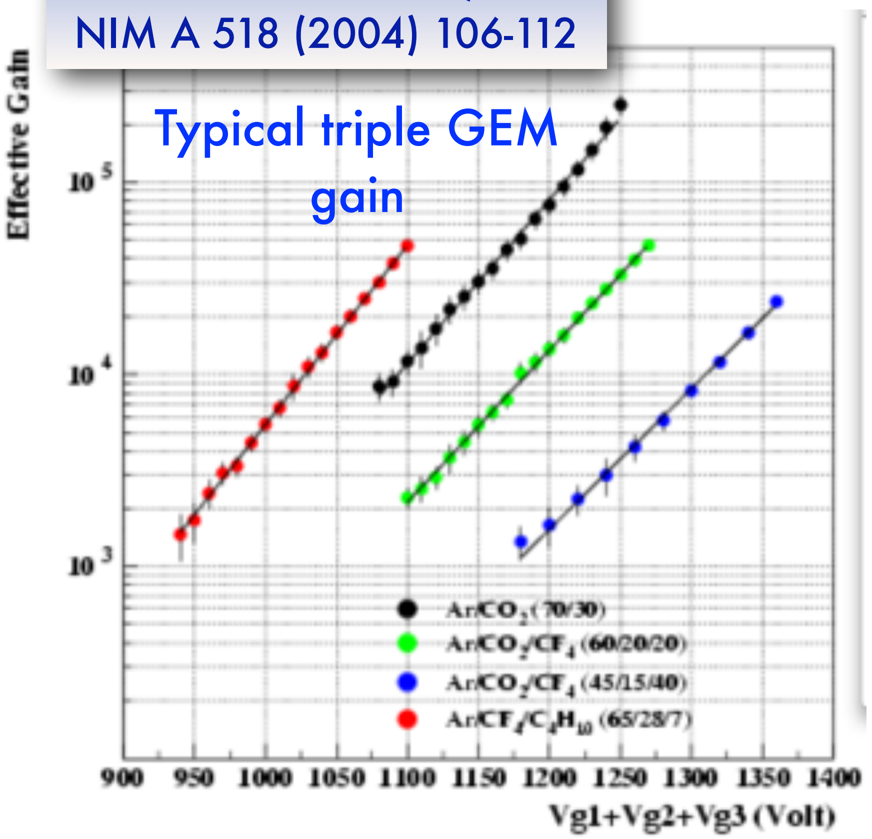
J. B. R. Battat et al., arXiv:1701.00171 [astro-ph.IM].

New R&D efforts in Italy

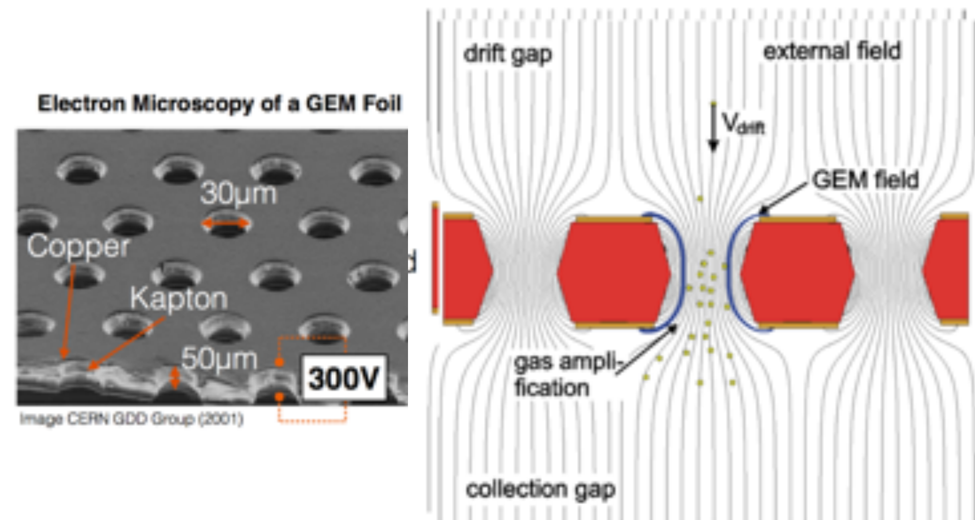
- **NITEC** EU HORIZON 2020 — May 2015- May 2017
  - NITPC with triple thin GEM amplification (3 x 3 cm^2) + pixel charge/time readout
- **DCANT** INFN CSN5 — 2016
  - Low pressure TPC to detect C ions channeled by carbon nanotubes
- **CYGNUS-RD** INFN CSN5 — 2017-2018
  - NITPC with triple thin GEM amplification (10 x 10 cm^2) + CMOS + PMT optical readout

Thin GEM Amplification

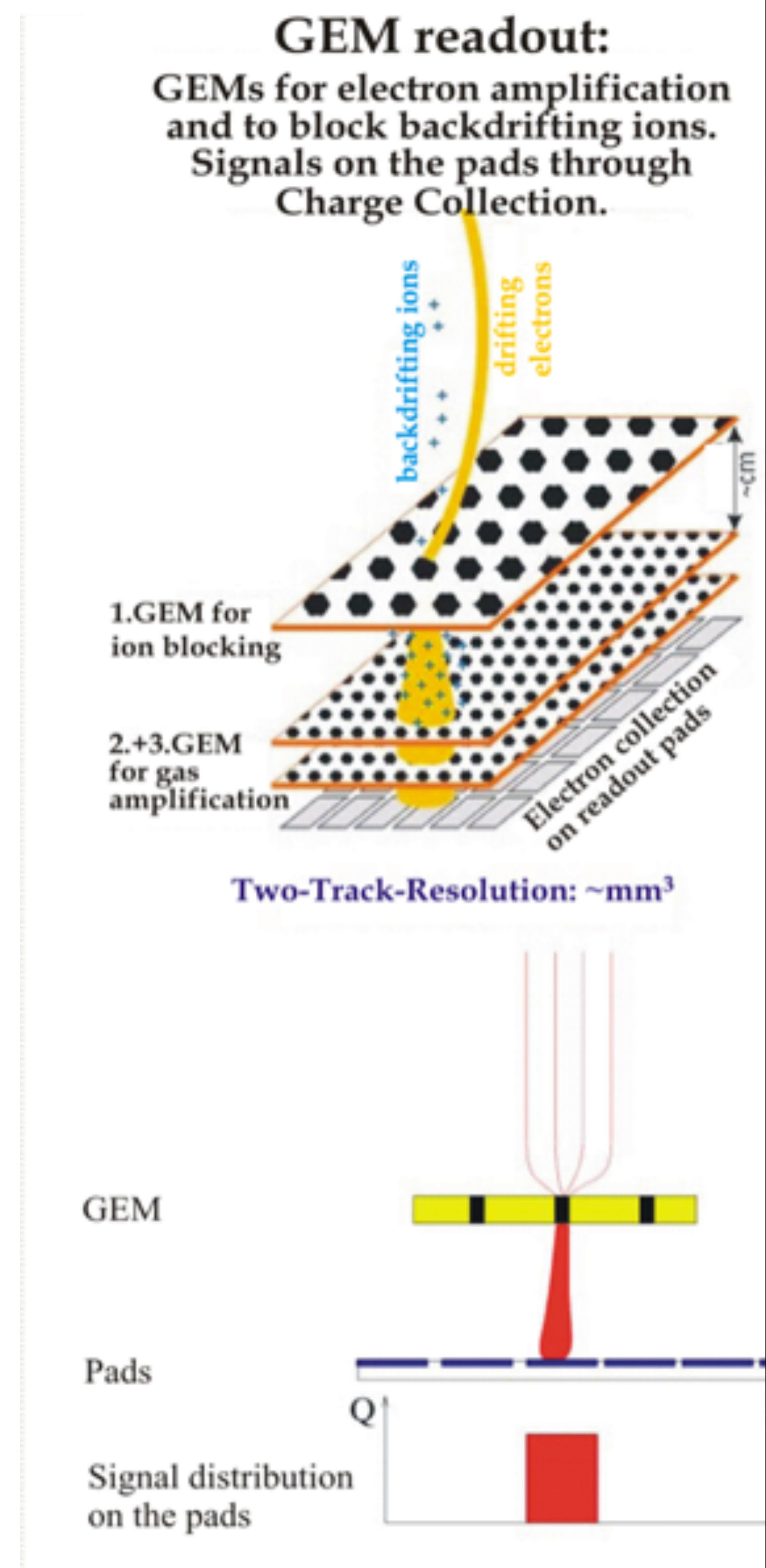
M. Alfonsi et al.,
NIM A 518 (2004) 106-112



- Particle conversion, charge amplification and signal induction zones are physically separated
- Large dynamic range: from 1 to 10^8 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

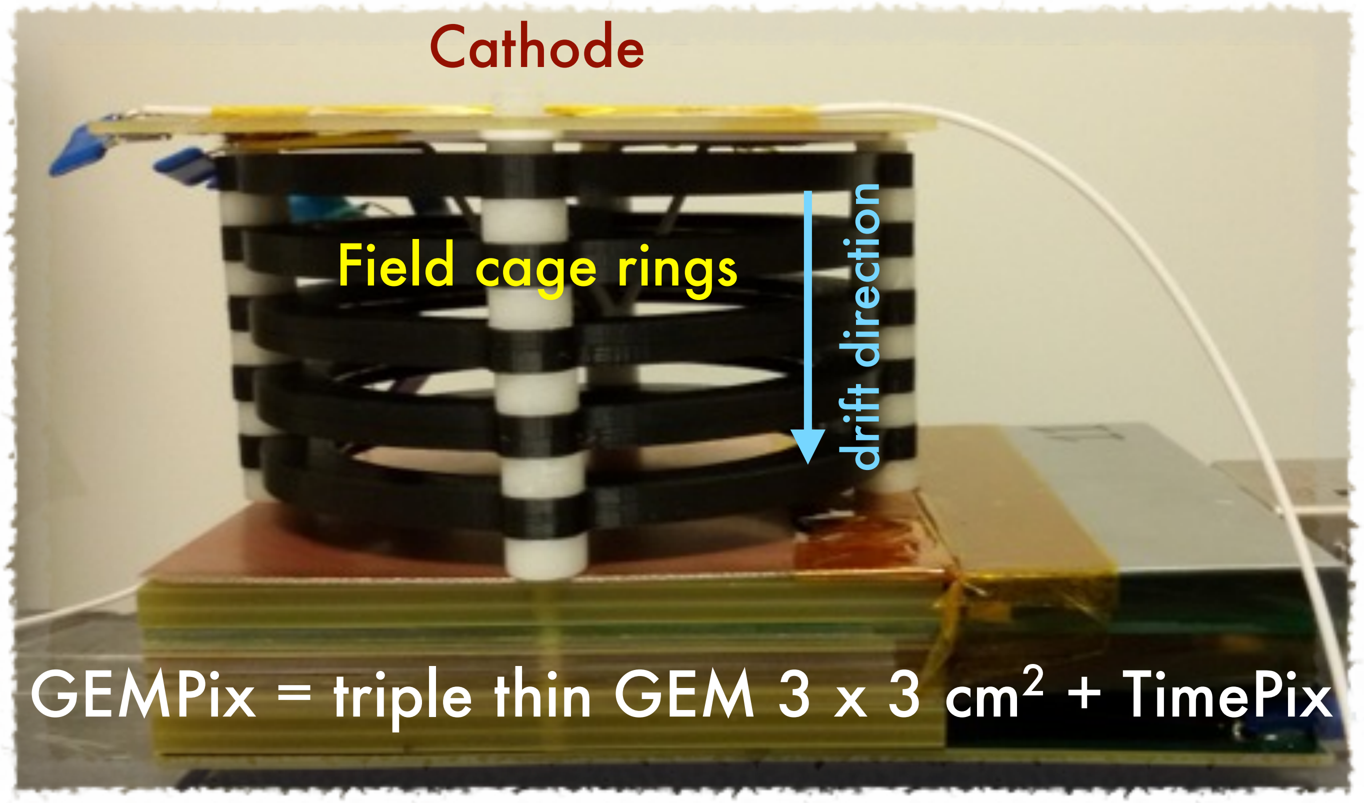


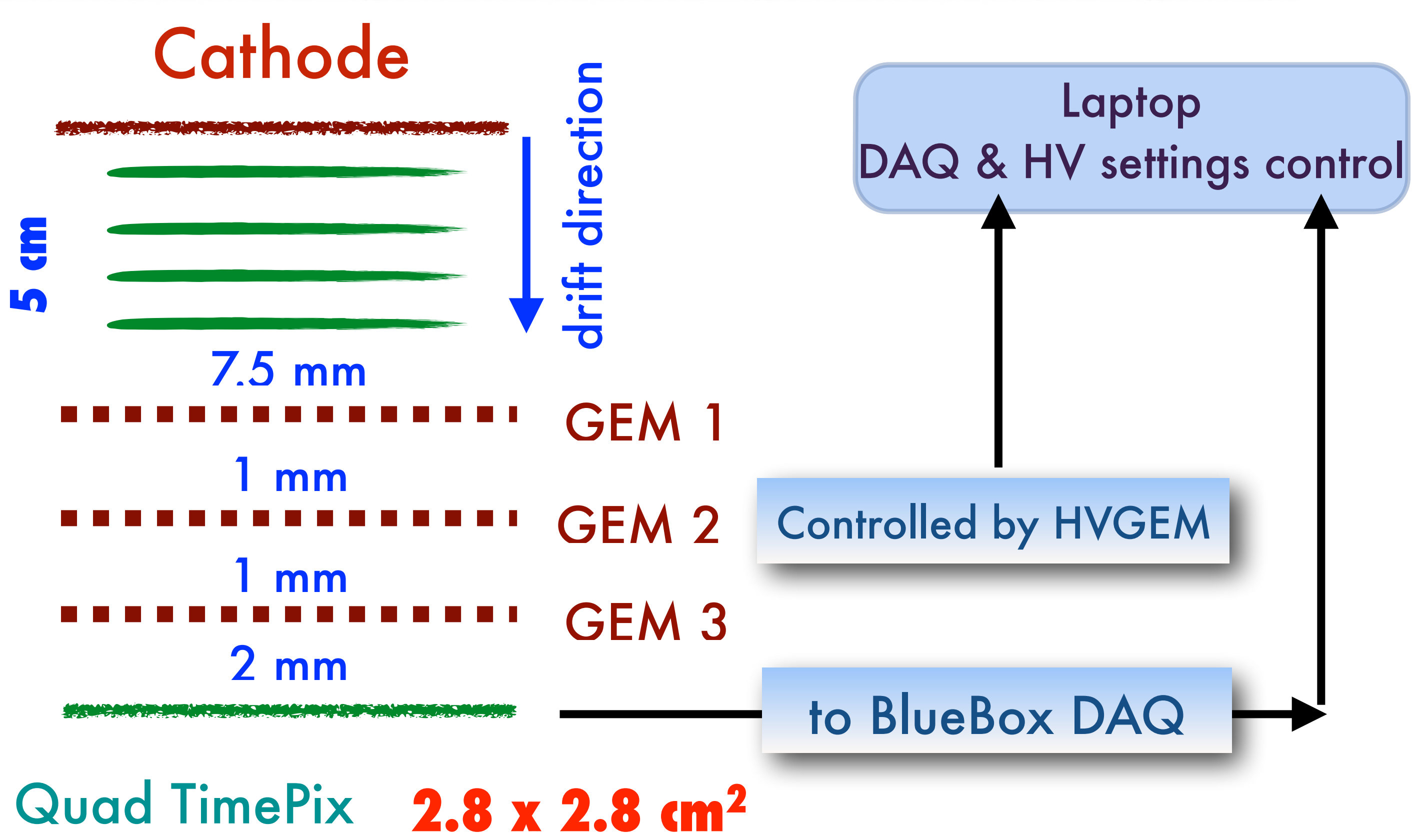
NITEC

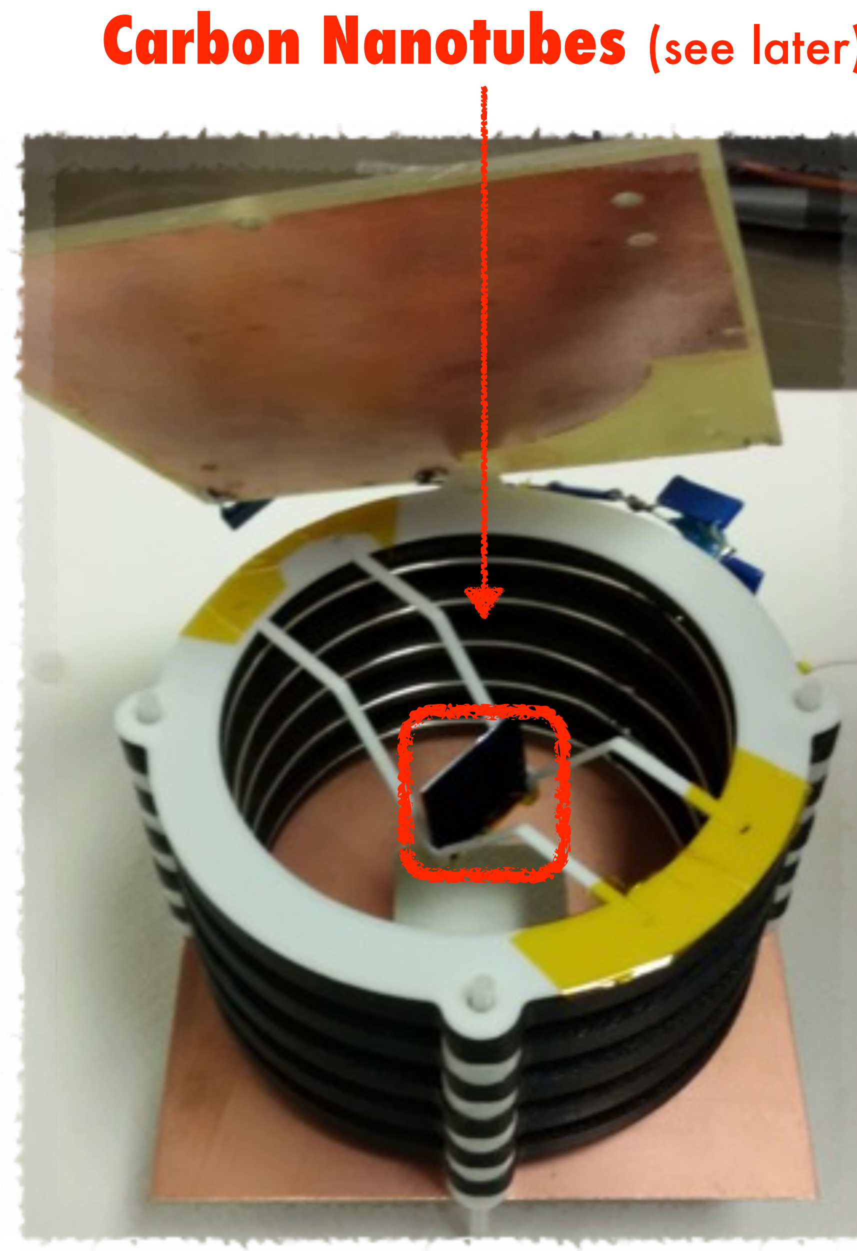
a Negative Ion Time Expansion Chamber for directional Dark Matter searches

This project has been fully funded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 657751

NITEC detector





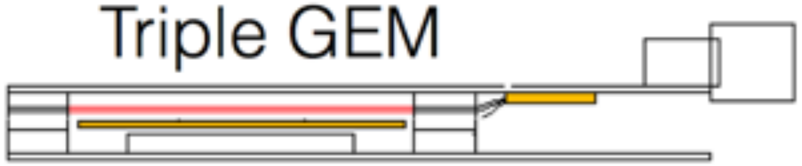


Field cage: rings support structure (in black in the picture) manufactured with 3D printer at LNF

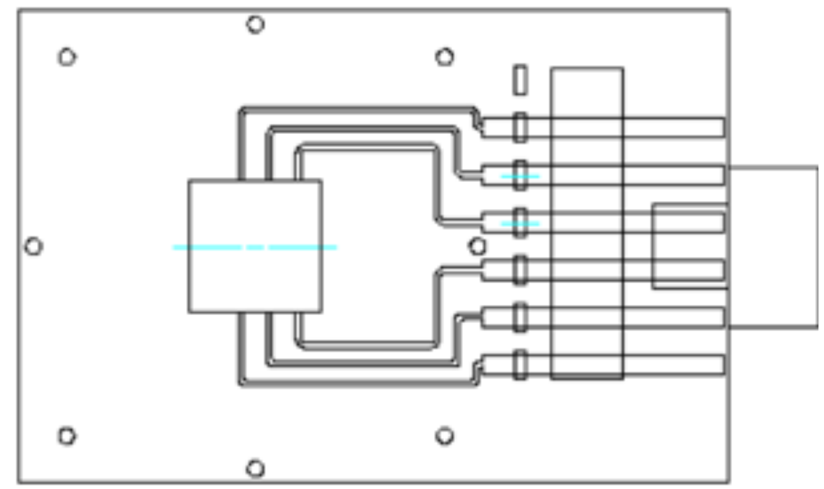
GEMPix

Developed by LNF in collaboration with CERN

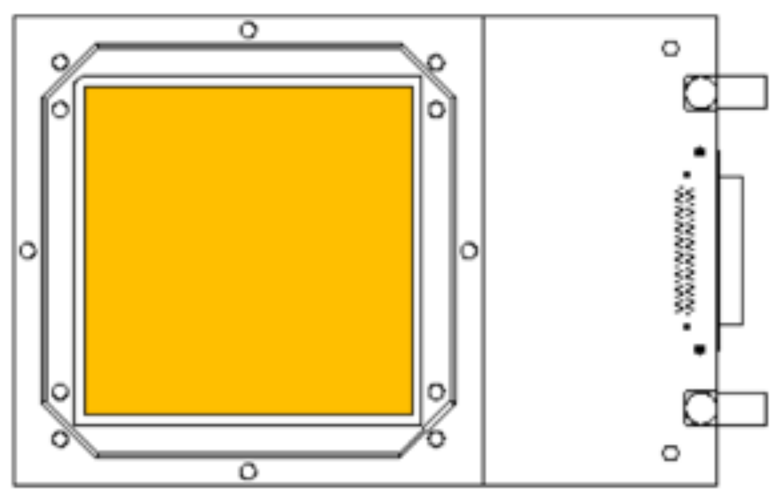
Triple GEM detector with HV filters and connector



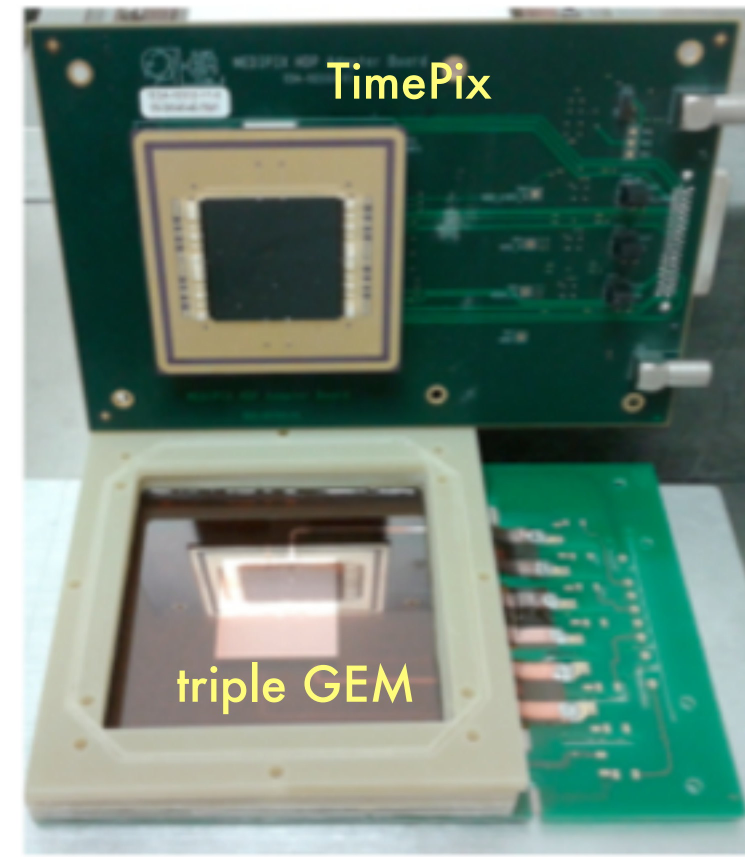
Quad Timepix ASIC board with naked devices (i.e. no silicon)



top view



side view



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

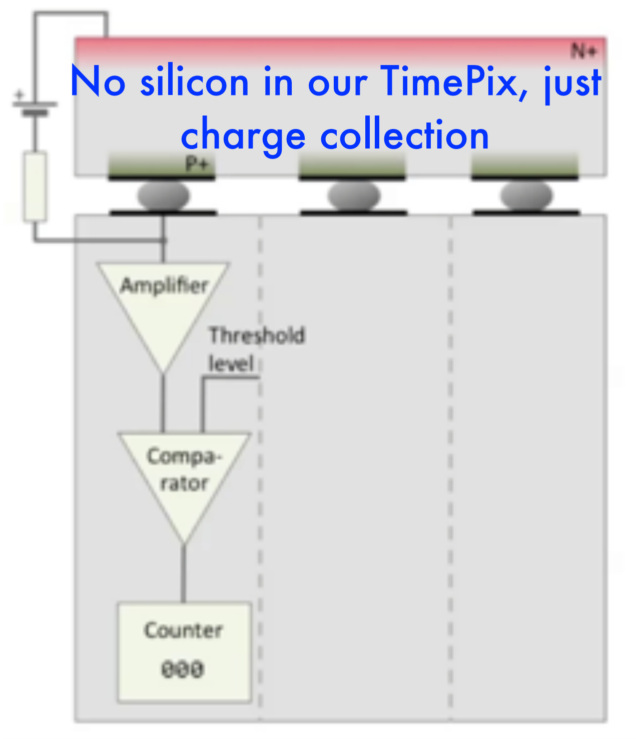
pixel size 55 x 55 um

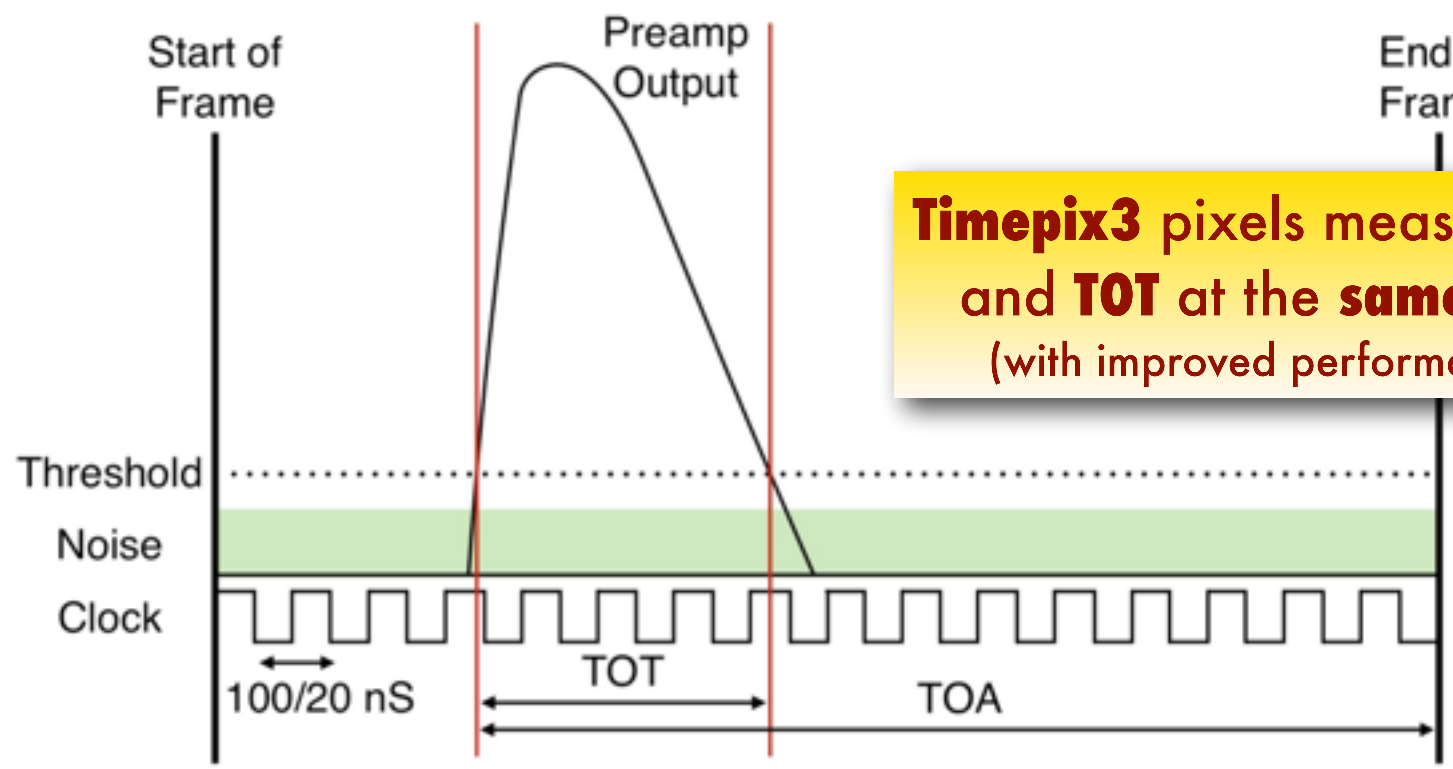
Quad Timepix (512 x 512 pixels) = 4 Timepix chips

$2.8 \times 2.8\ cm^2$

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**

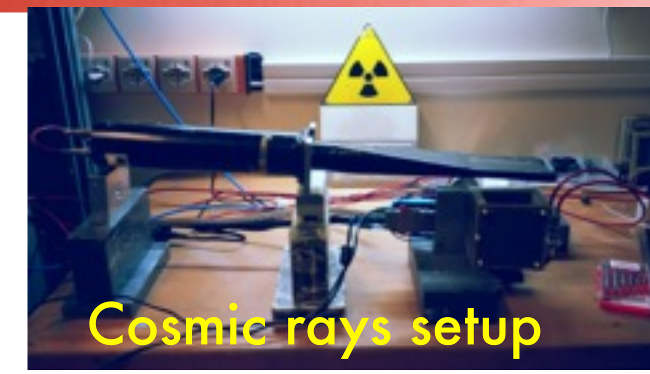
NITEC activities 2015-2016

- 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

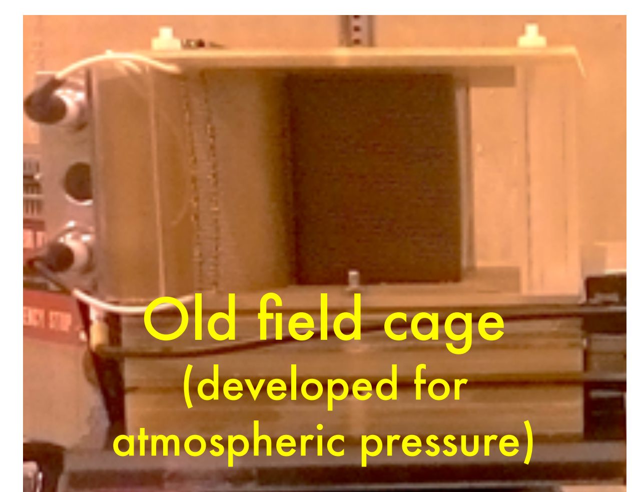
- Old prototype tests with SF_6 negative ion mixtures
  - pure SF_6, $Ar:CO_2:SF_6$ (atmospheric pressure)

May 2016

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

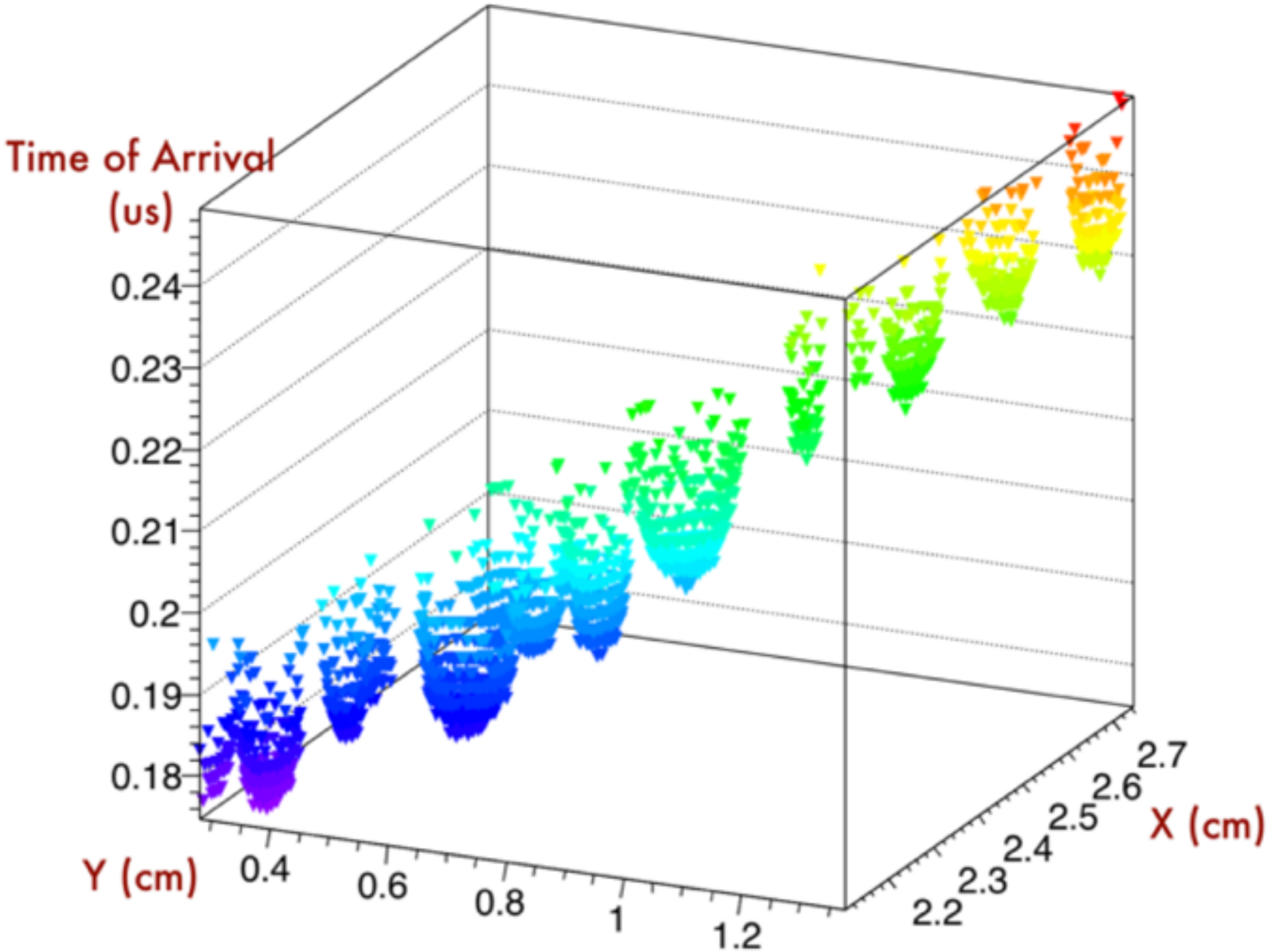
Dec 2016

Single track data analysis still on going



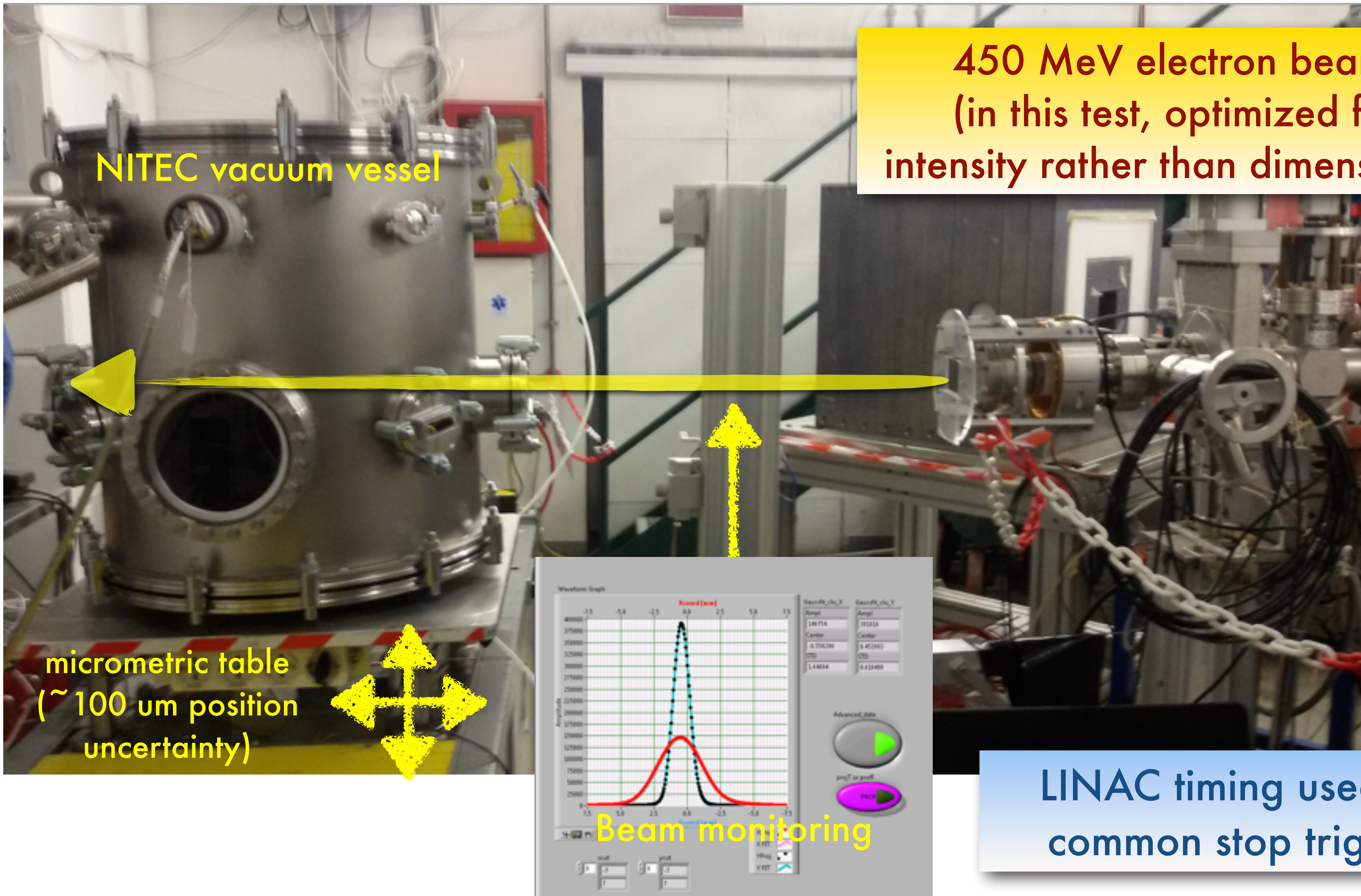
A NITEC event

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

BTF measurements (TOA)

Apr 2016

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

total GEM HV gain	1480 V		

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

total GEM HV gain	1140 V	1240 V	1440 V

Dec 2016

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

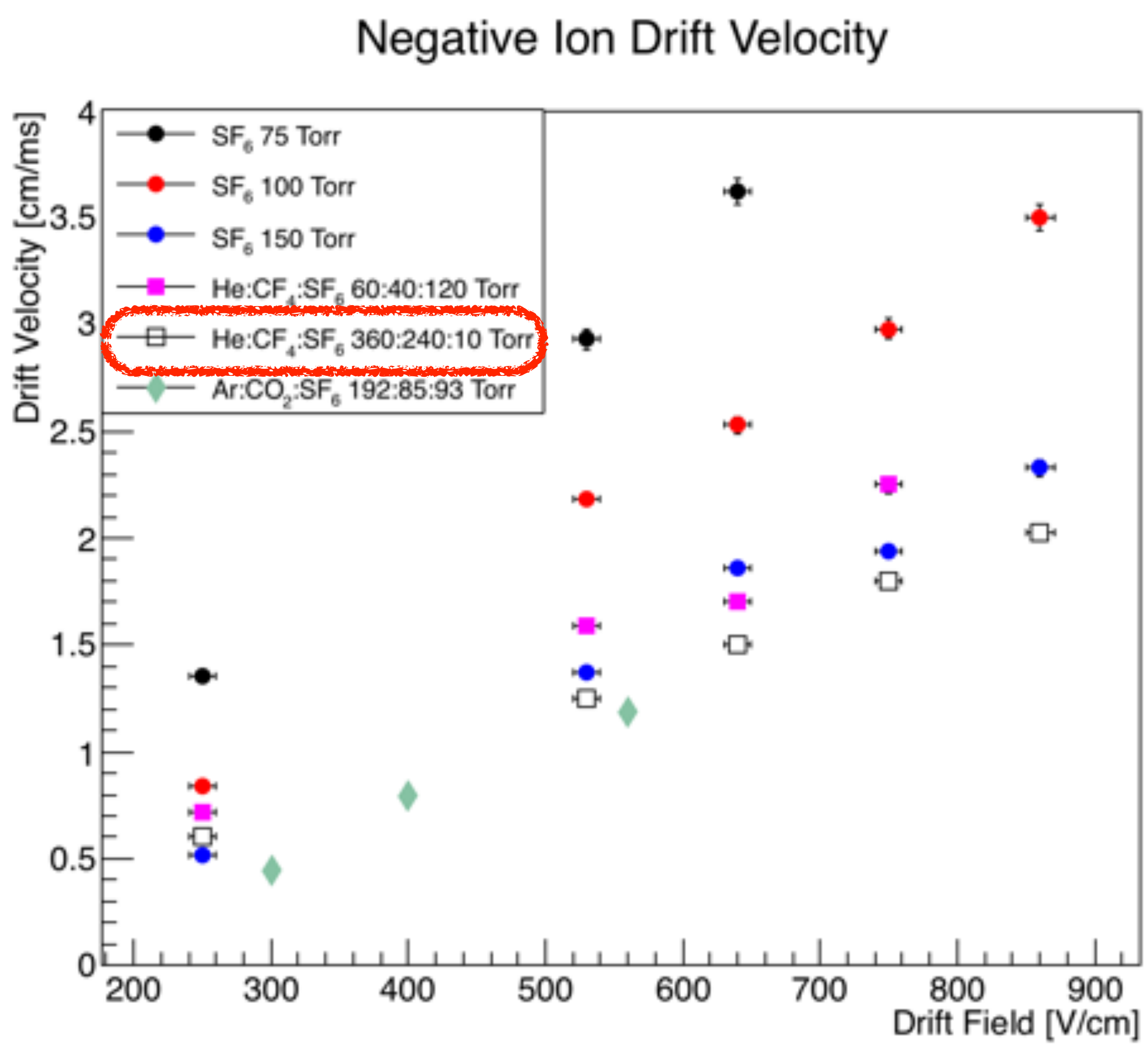
total GEM HV gain	1460 V	1640 V

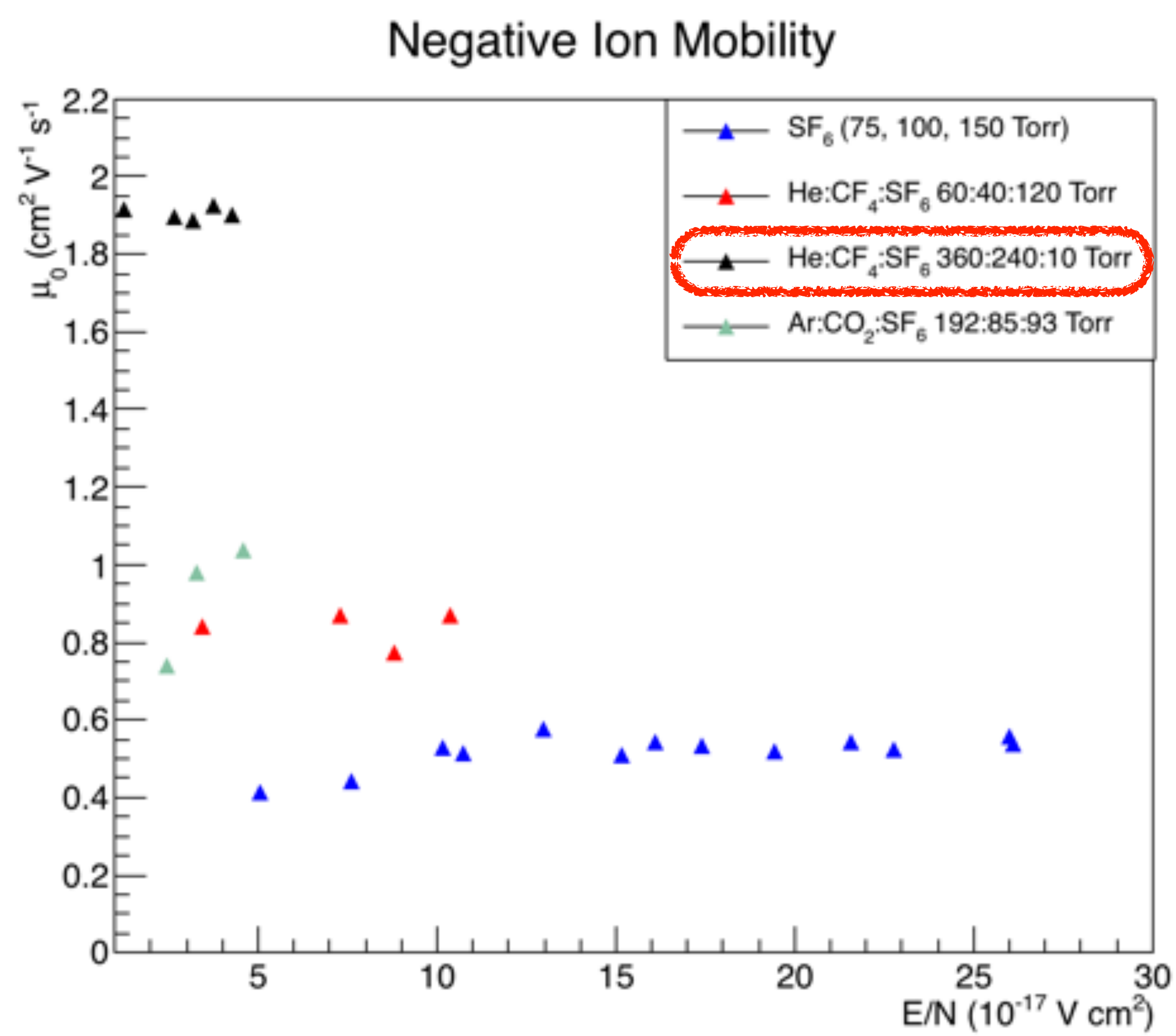
We measured the Time Of Arrival for 5 different drift distances @ 250, 530, 640, 750 and 860 V/cm for each configuration

(less points in Apr 2016 data)

Drift velocity & mobility measurements

First operation EVER of SF_6 negative ion mixture at nearly atmospheric pressure





Pure SF_6 results in agreement with published data

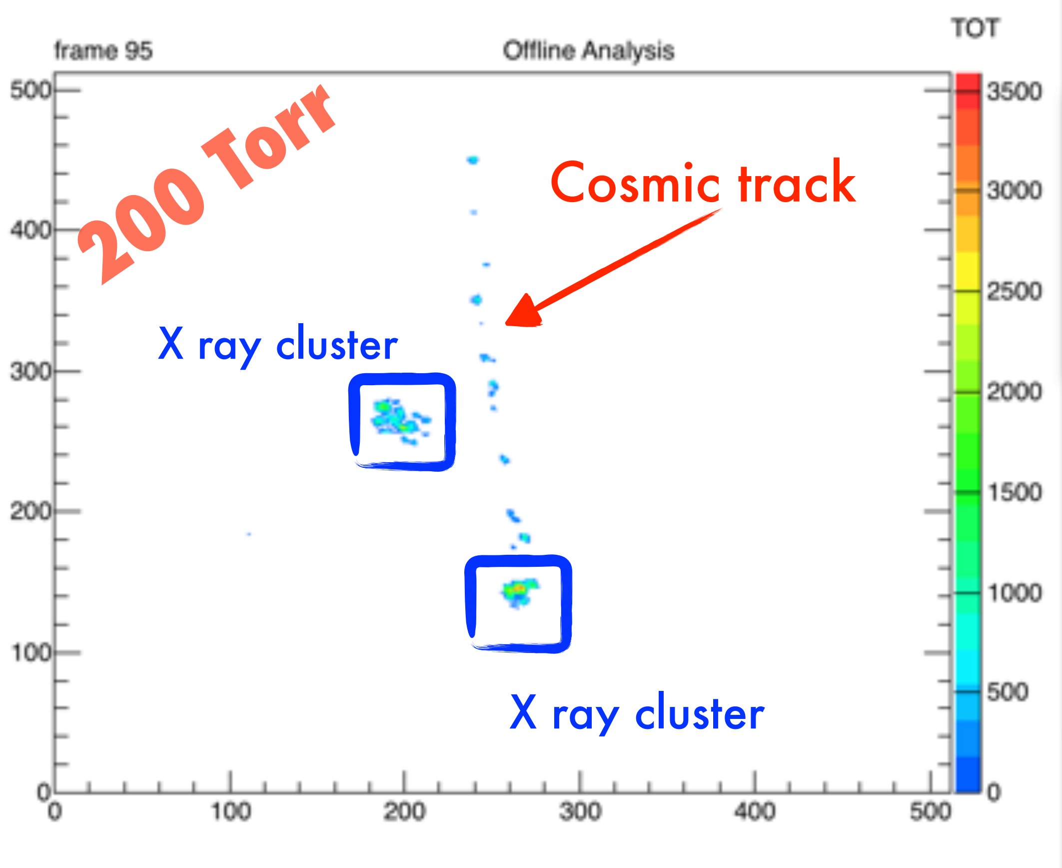
N.S.Phan et al, arXiv:1609.05249

PRELIMINARY

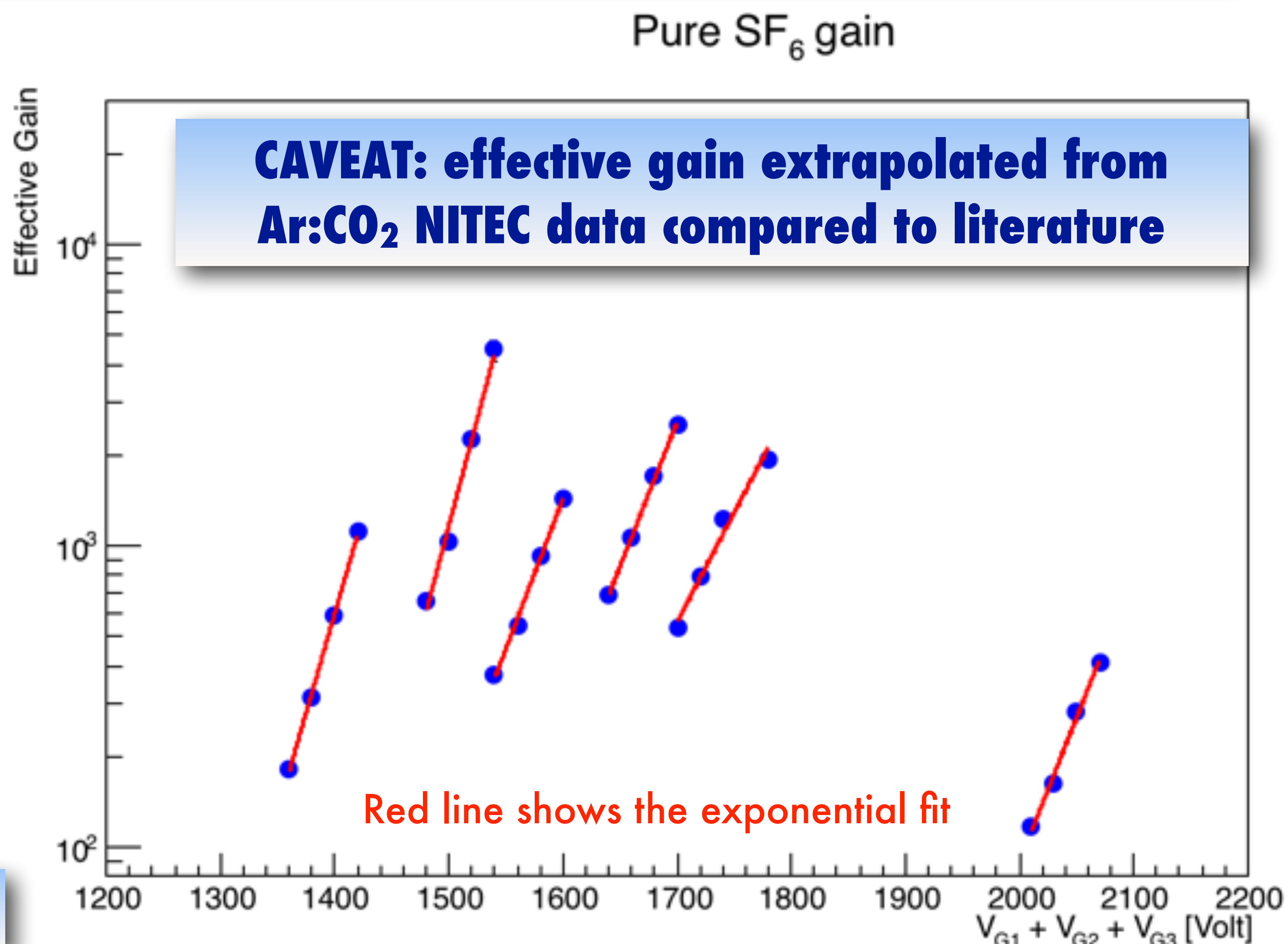
Paper in preparation

Pure SF_6 gain measurements with ^{55}Fe

The higher effective gain EVER obtained with pure SF_6, thanks to triple thin GEMs and dedicated HVGEM



a NITEC event a 200 Torr of pure SF_6



PRELIMINARY

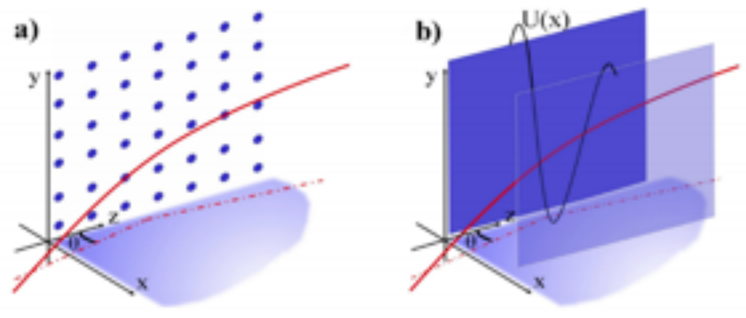
Paper in preparation

DCANT

Carbon Nanotube for for Dark Matter directional searches

DCANT Concept

Channelling concept



Critical (Lindhard's) angle

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

Potential well depth (U_0)

Particle energy (E)

~ 8 deg for ^{6}C at 10 KeV

Detector concept

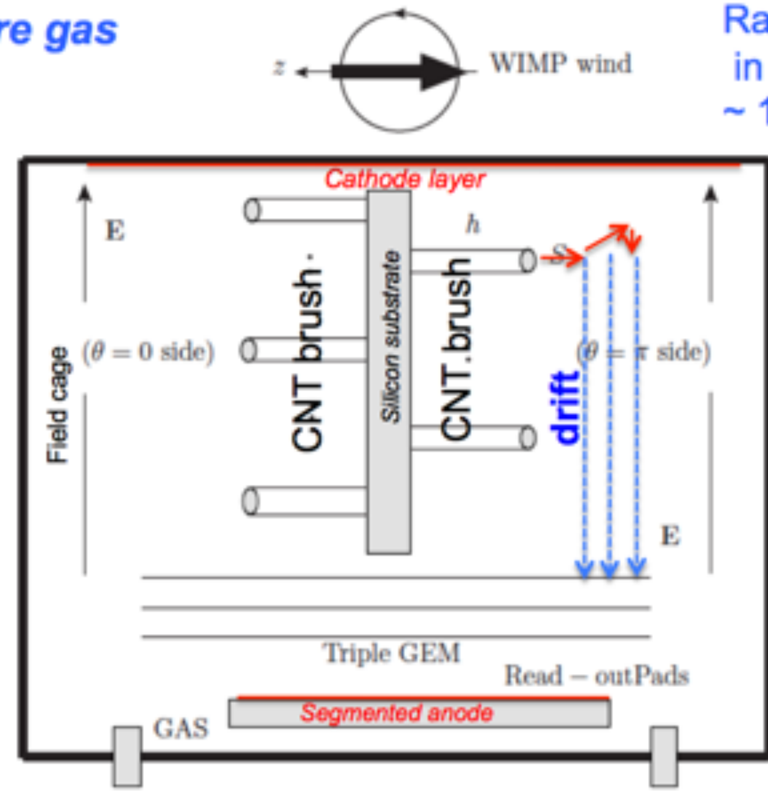
Low pressure gas (0.1 bar)

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

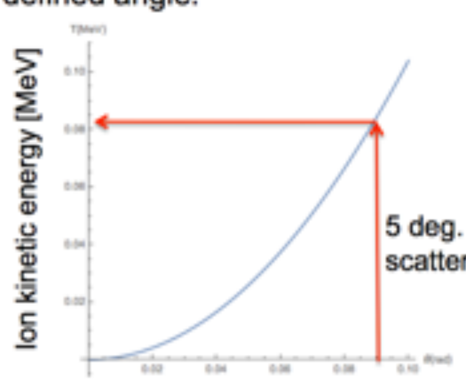


Carbon ions **ranging out** In the gas

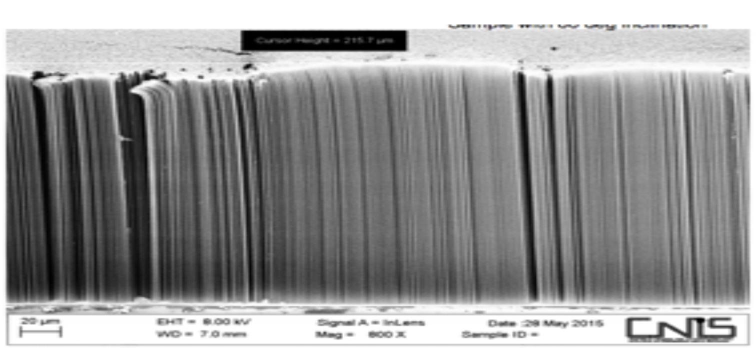
Electrons from ionized gas atom **drift** towards anode

Need to be tested:

- 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



Could allow an integrated gas + solid DM target experiment WITH DIRECTIONAL SENSITIVITY

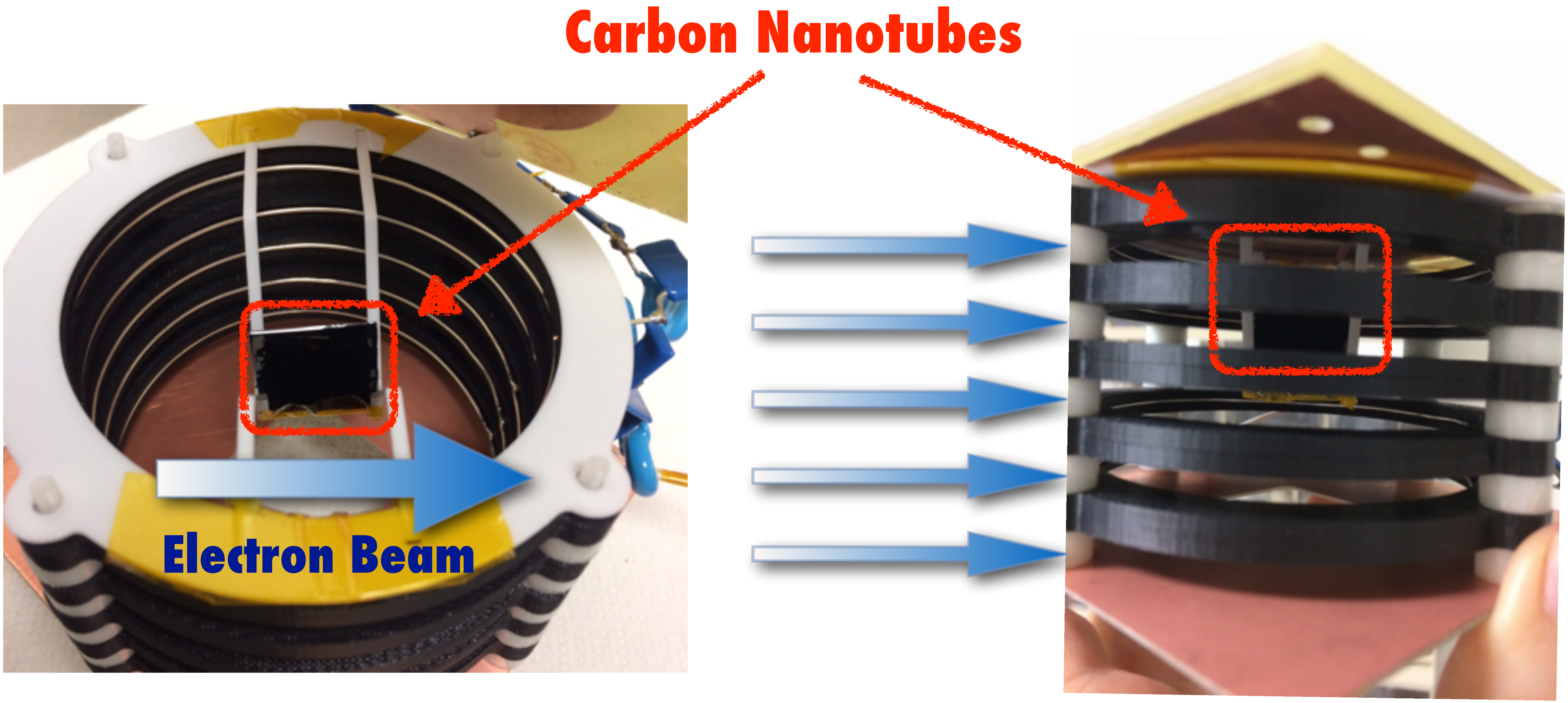


- About 10^{16} 1nm diameter SWCNT can fit on a 10x10 cm^2 substrate
- Surface density of a graphene layer: 1/1315 g/m^2
- About 2 g CNT on 100cm^2
  - ***CNT ropes?***

C. Capparelli et. al, Phys. Dark Univ. 11, 79 (2016)

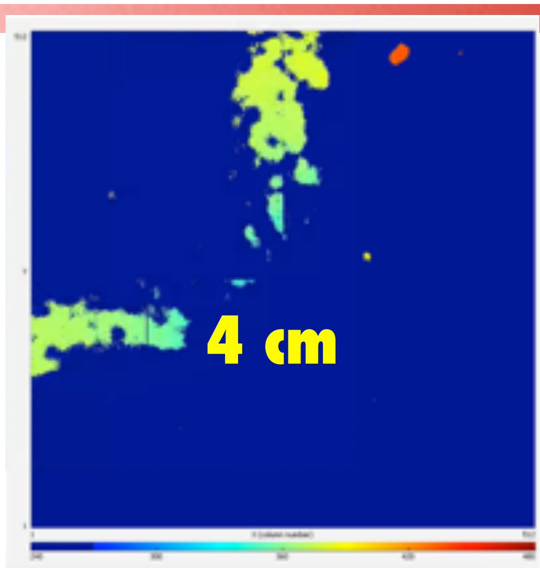
G. Cavoto et. al, Eur. Phys. J C 76 (2016) no.6, 349

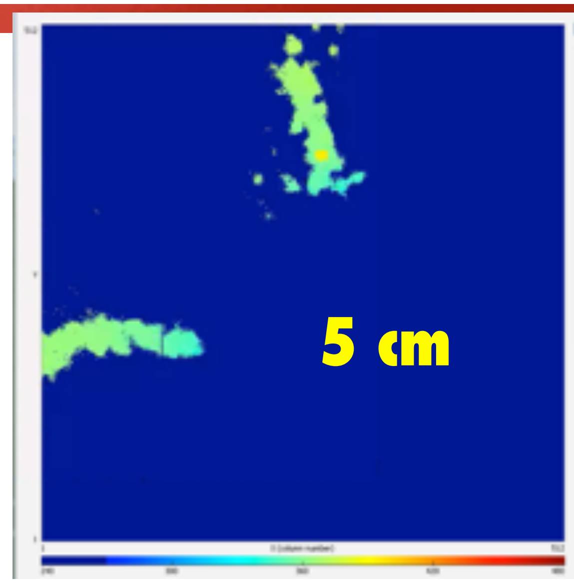
NITEC tests with carbon nanotubes

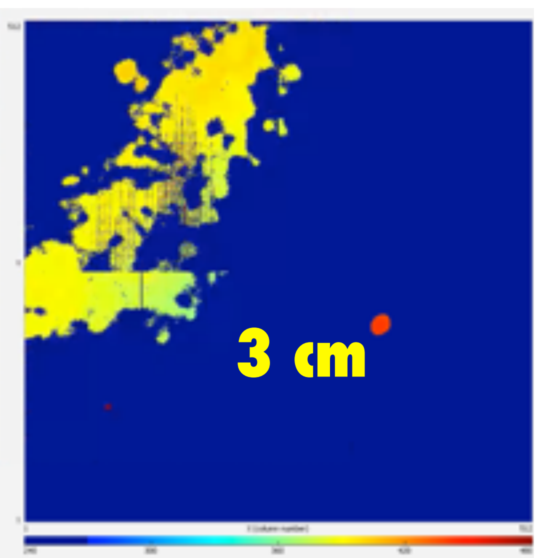


Beam on the side of nanotubes at various heights to study modification of the drift field

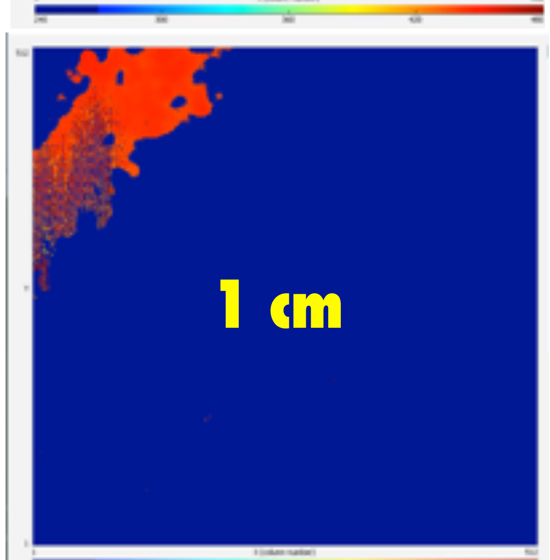
NITEC tests with carbon nanotubes

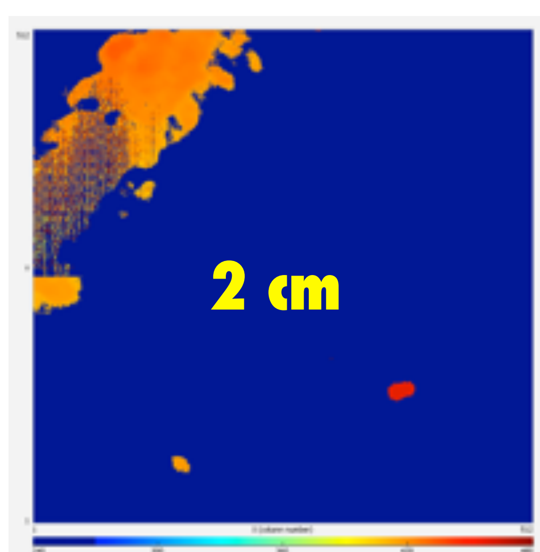




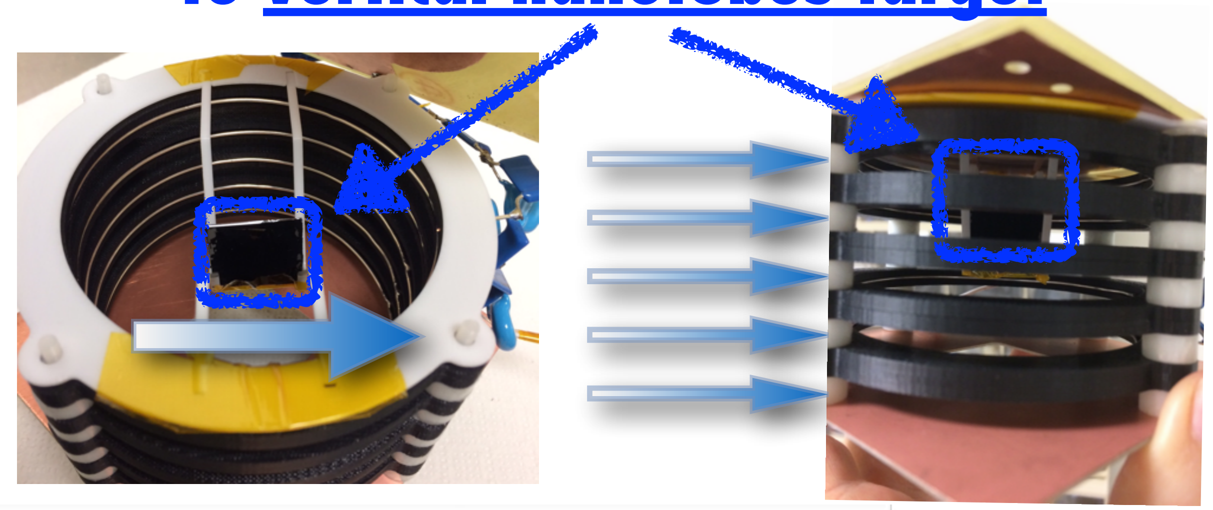


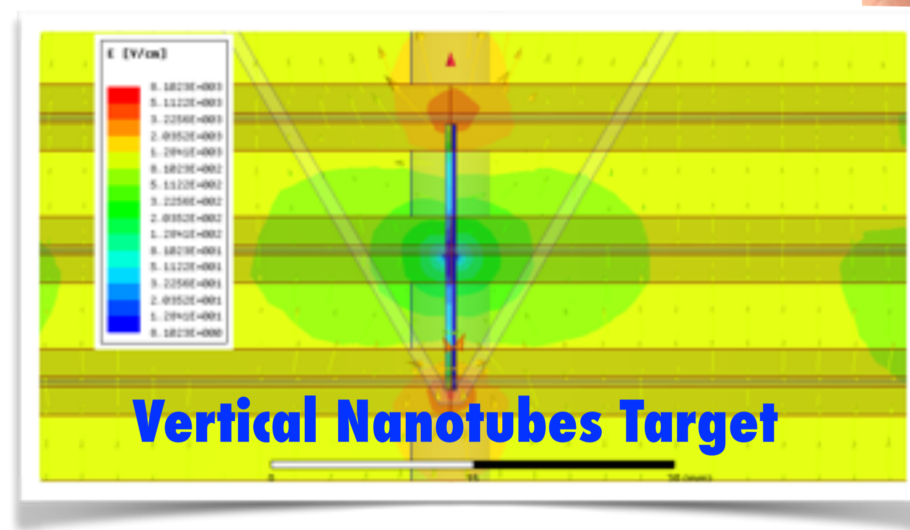
$Ar:CO_2:CF_4$ TOA data @ 300 Torr
(confirmed with pure SF_6 @ 150 Torr)



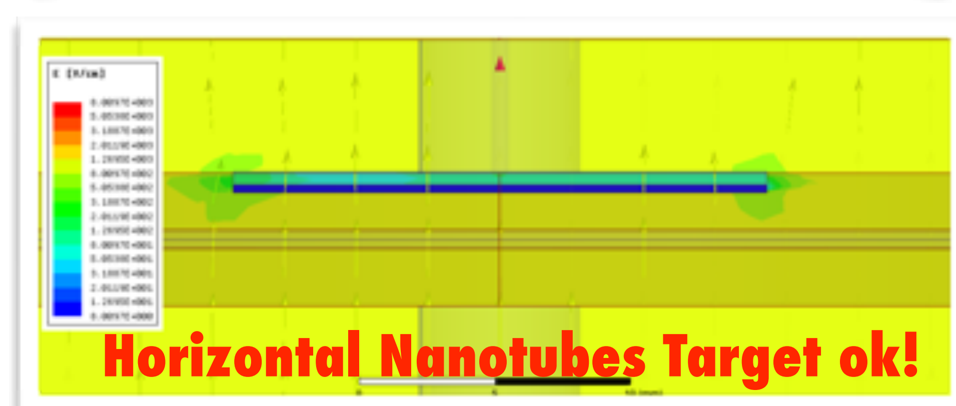


Test of drift field modification in NITEC due to vertical nanotubes target





ANSYS Maxwell simulation

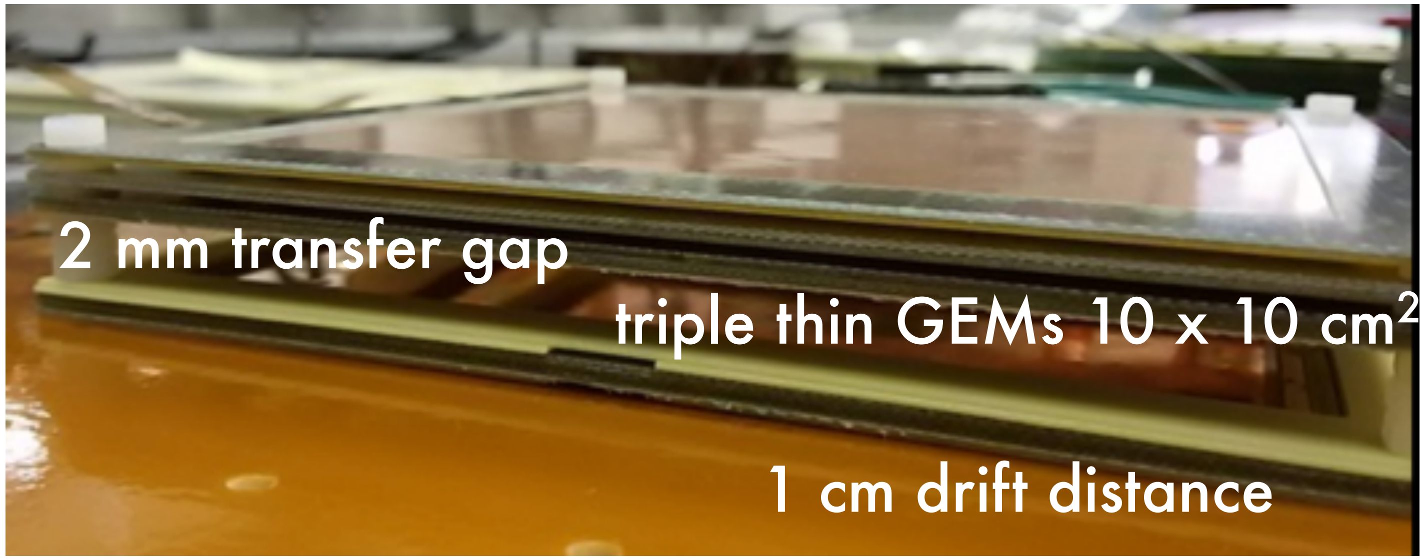


Horizontal Nanotubes Target to be tested at BTF in June

CYGNUS-RD

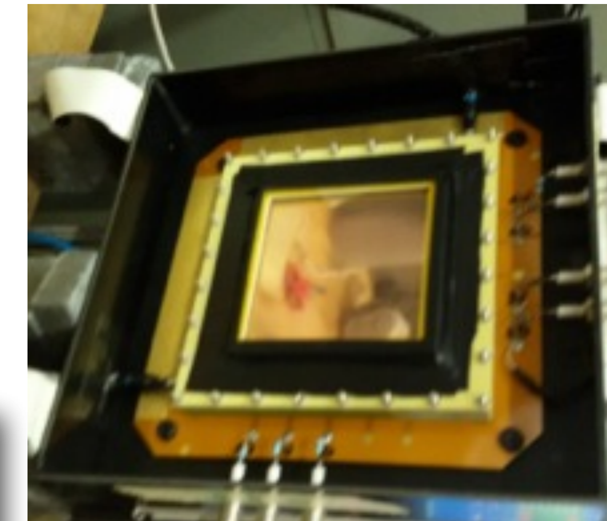
Optical readout for a Negative Ion Time Projection Chamber

CYGNUS-RD Detector

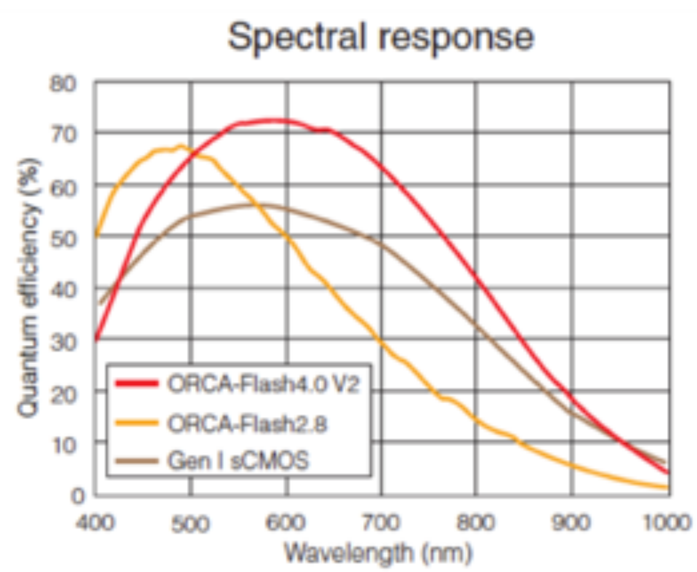


M. Marafini et al., NIM A 824 (2016) 562

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



+



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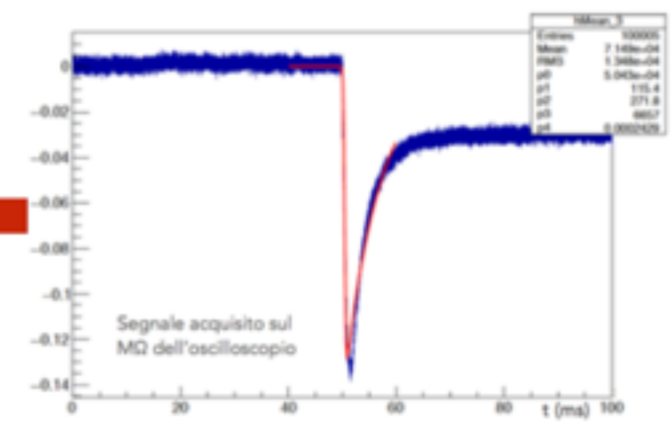
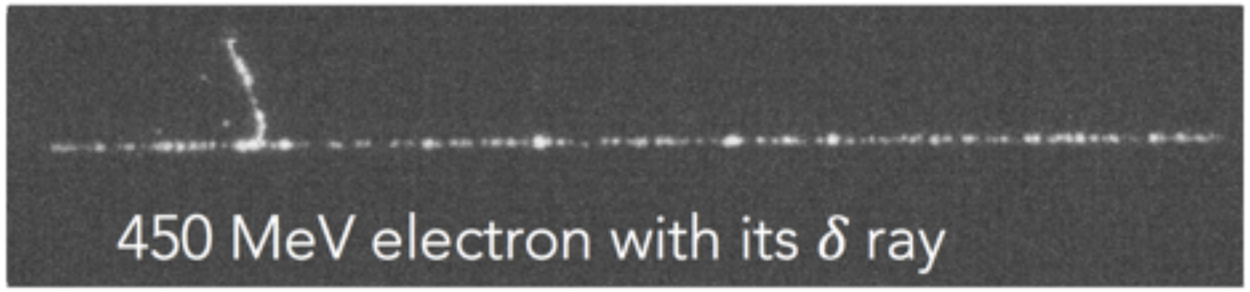
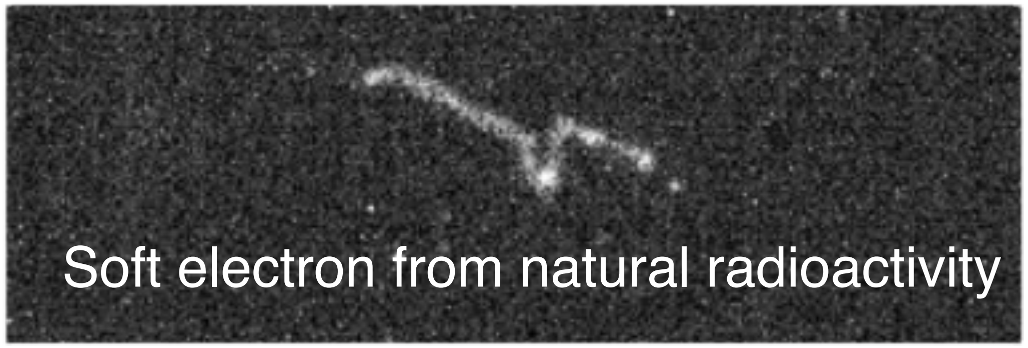


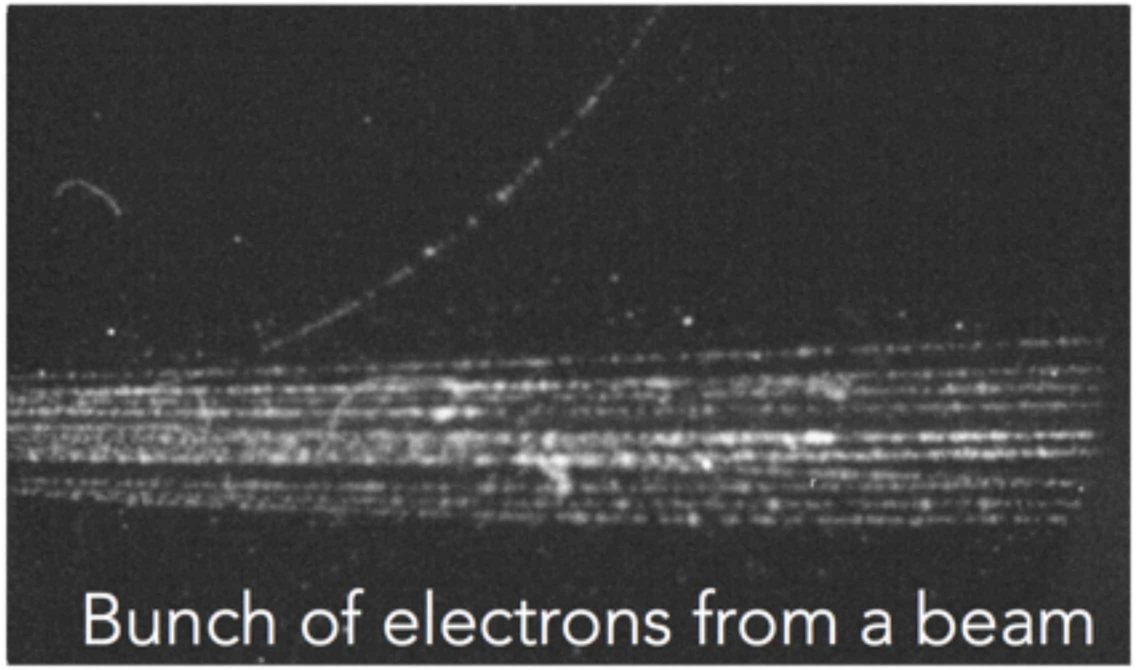
GEM signal readout

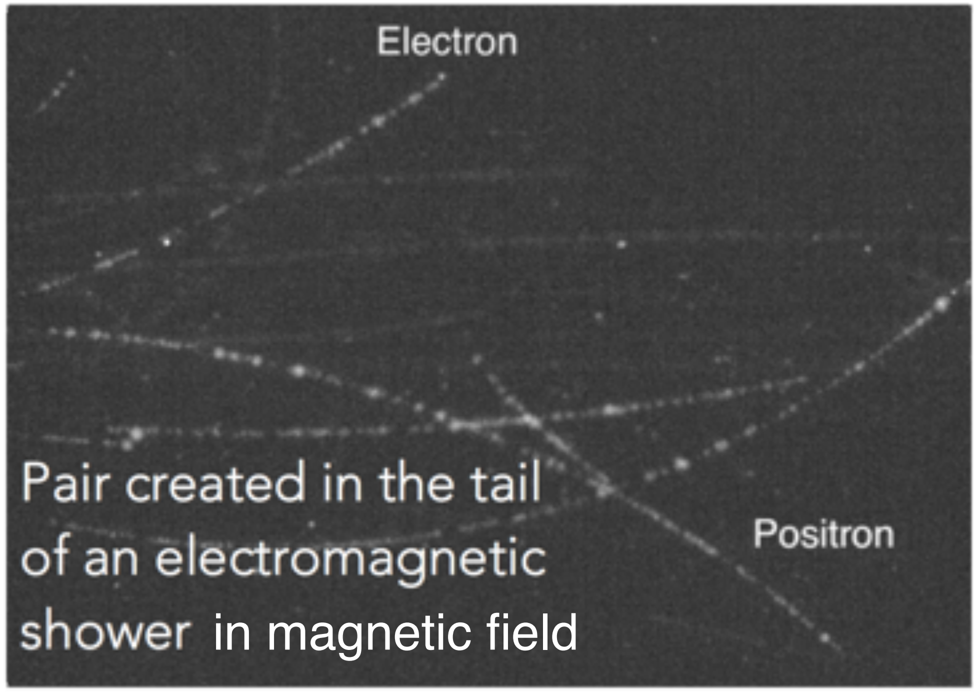
light or charge?

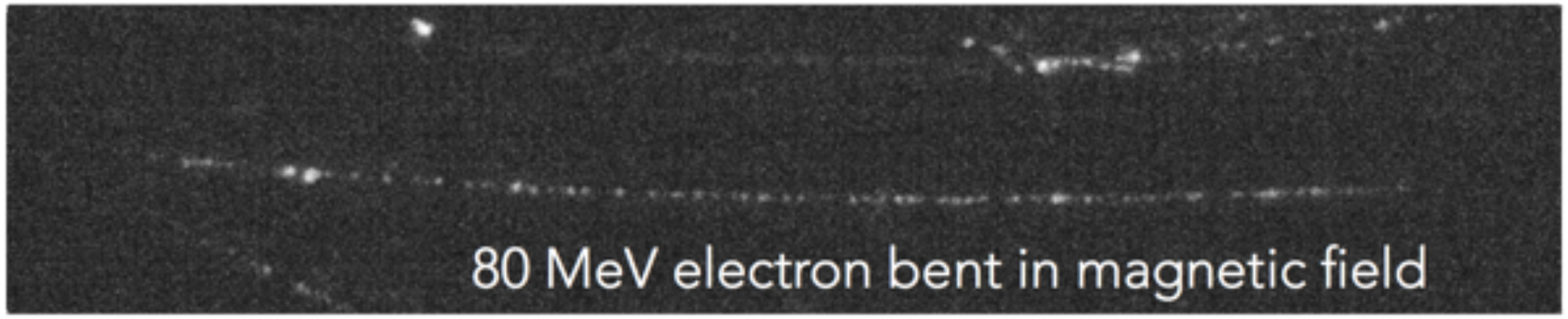
CYGNUS-RD events (with electron drift)







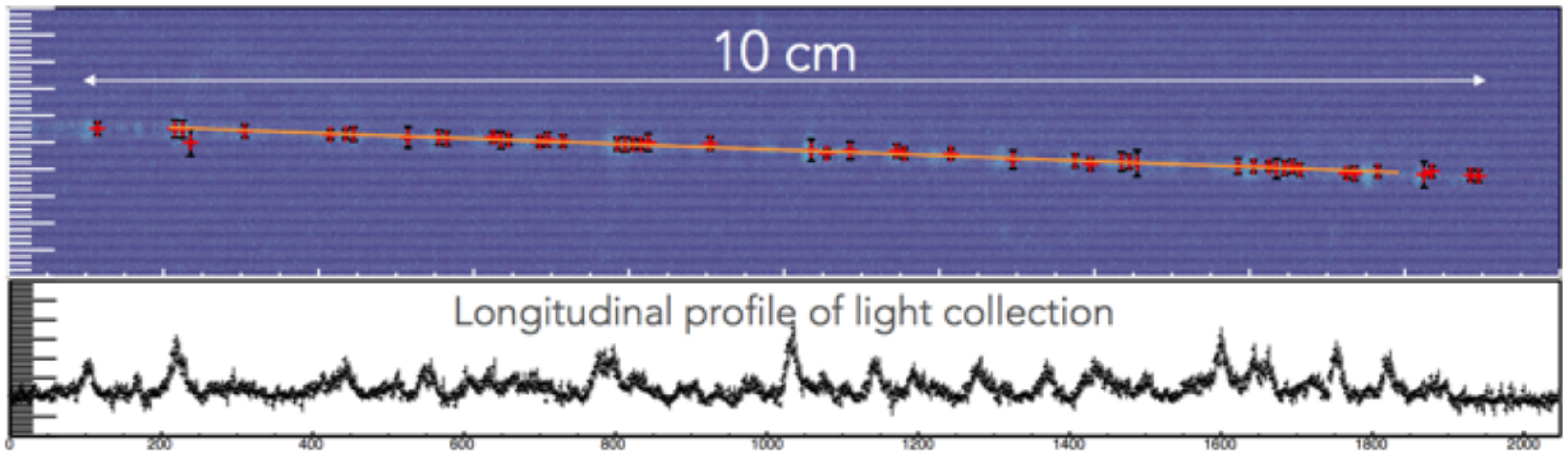


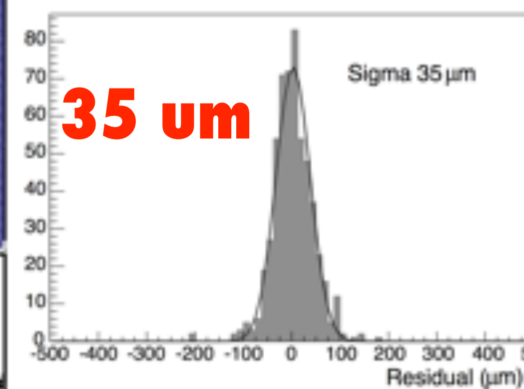


CYGNUS-RD potentialities

May 2016, electron drift

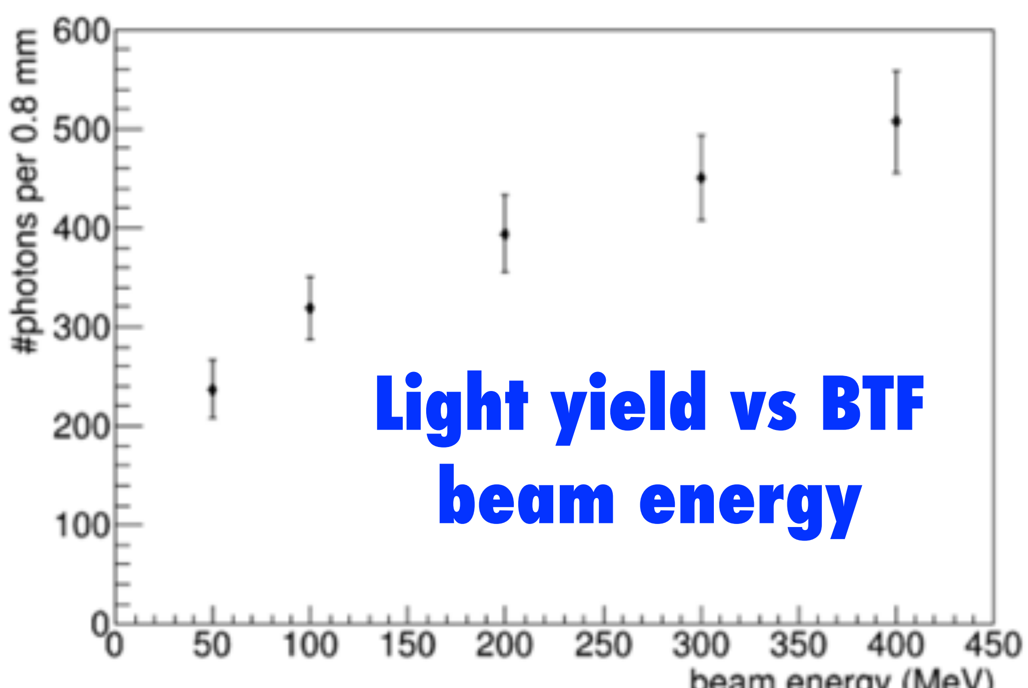
1) Tracking

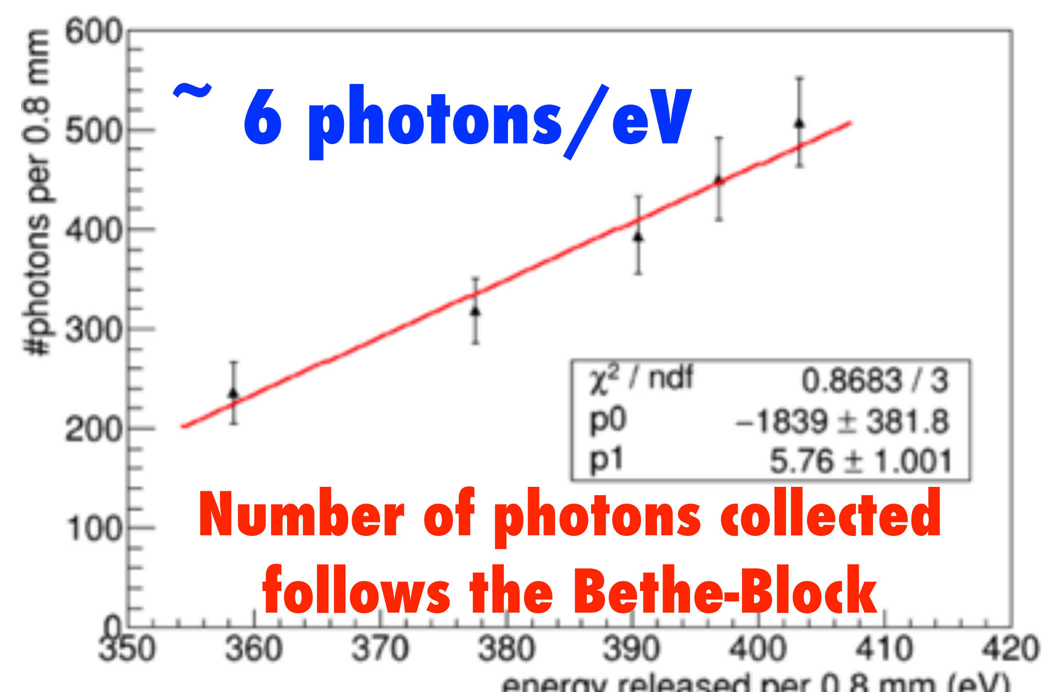




~ 1000 photons/track mm, ~35 um track residuals, cluster structures visible

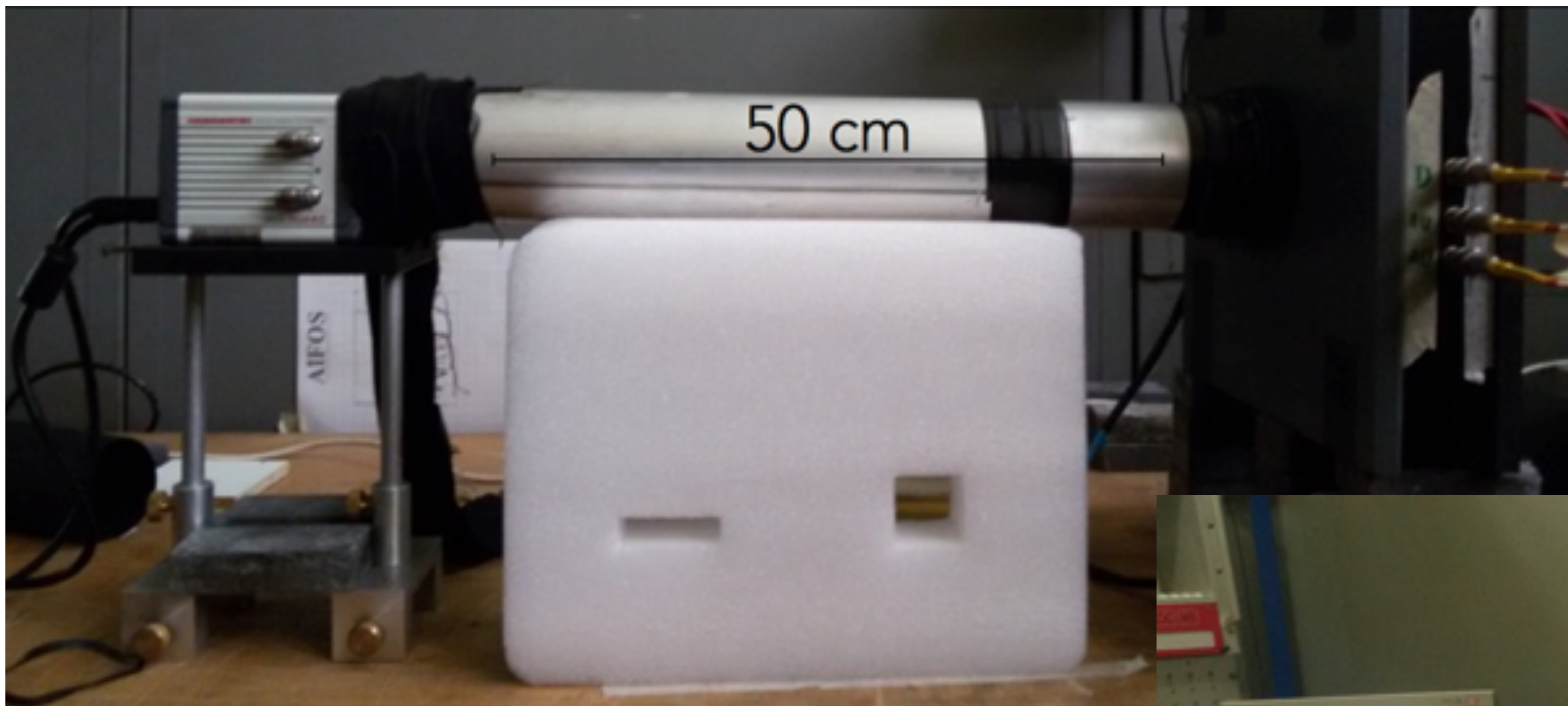
2) Ionization density (can be used to extrapolate track direction/sense)

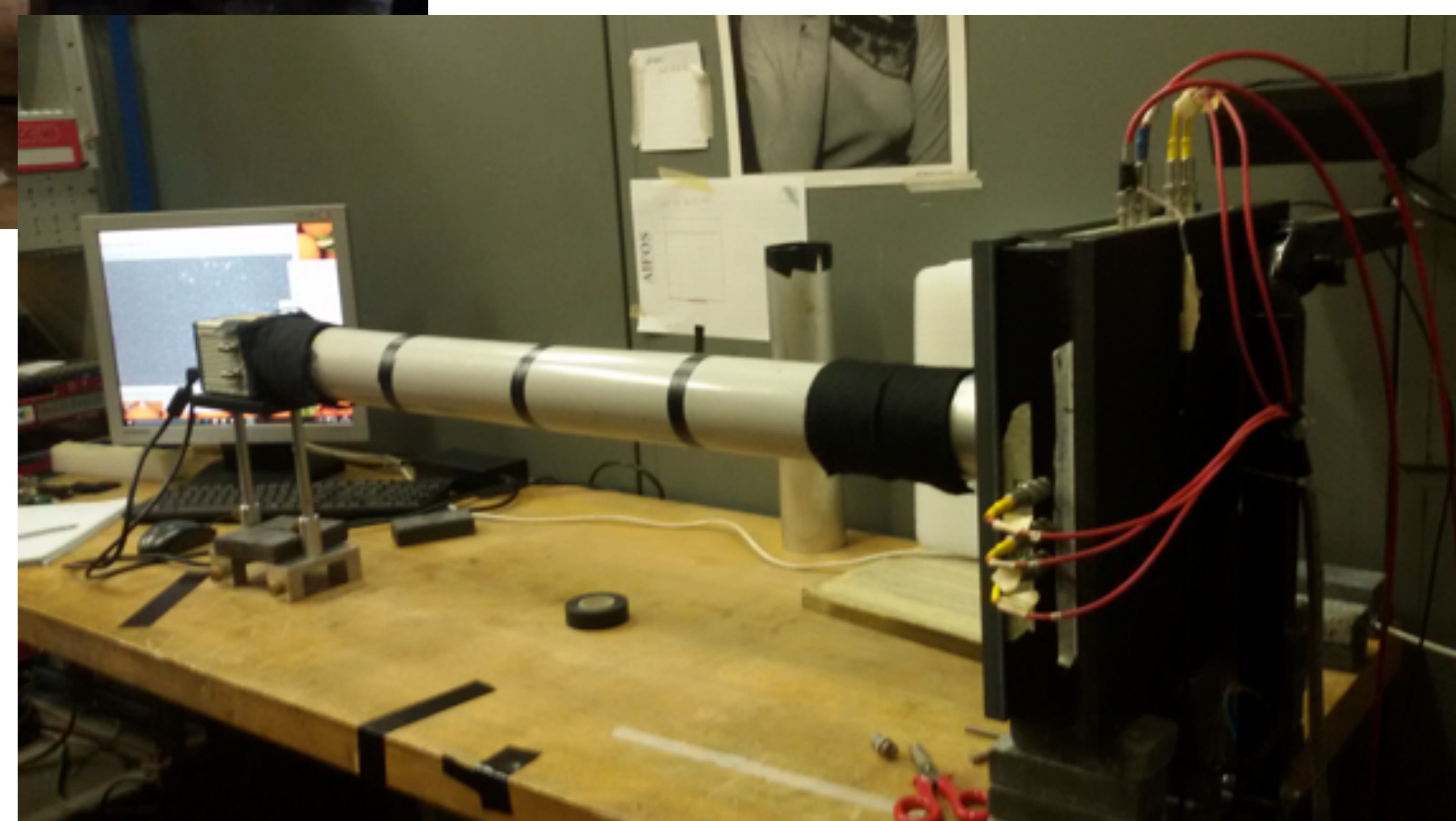




Light collection study with CR

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





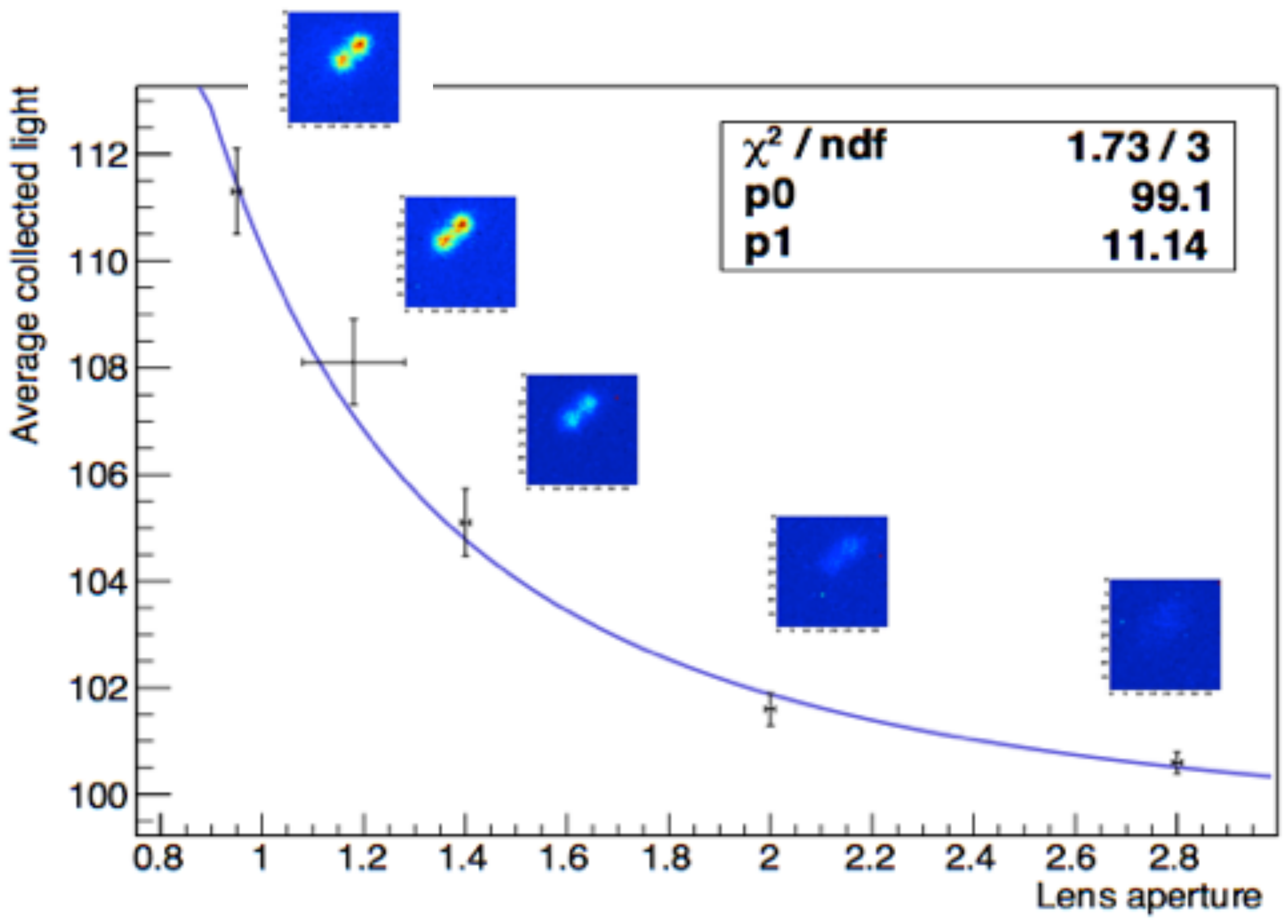
Is the light produced by the GEMs isotropic or collimated?

Light collection study with CR

Dec 2016, electron drift

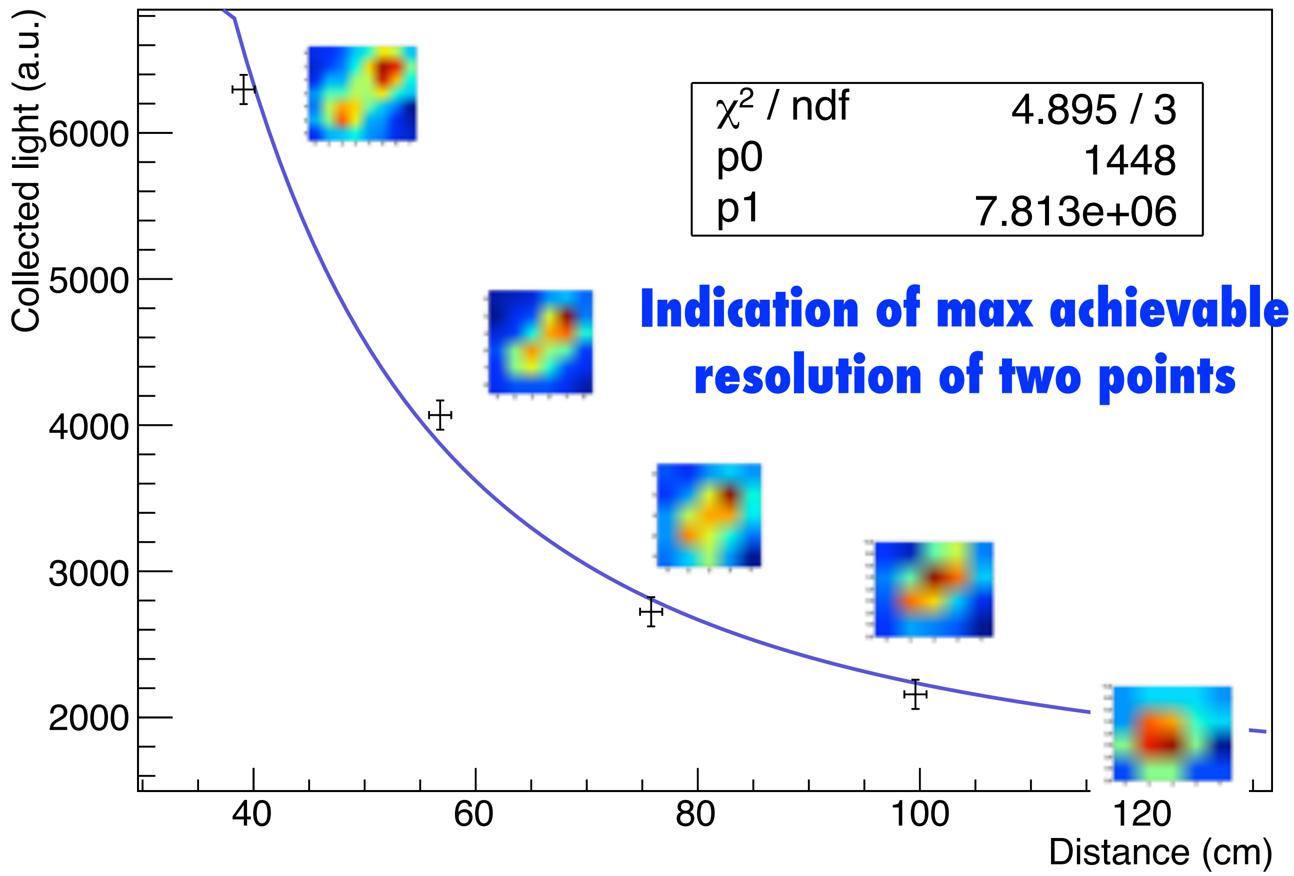
little sparks from GEM holes used to study light collection

Light vs Lens Aperture



@ 20 cm distance 50 um pixels equivalent

Light vs Distance

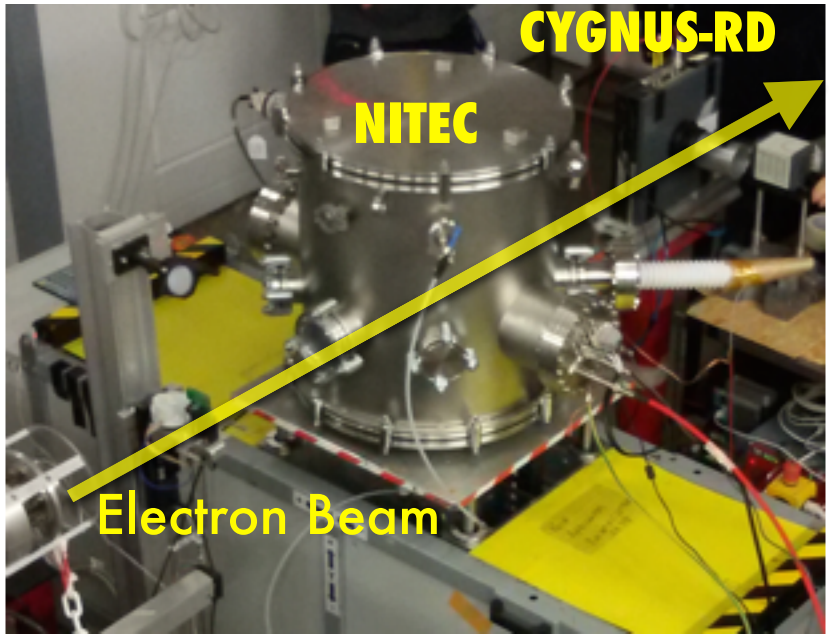


Indication of max achievable resolution of two points

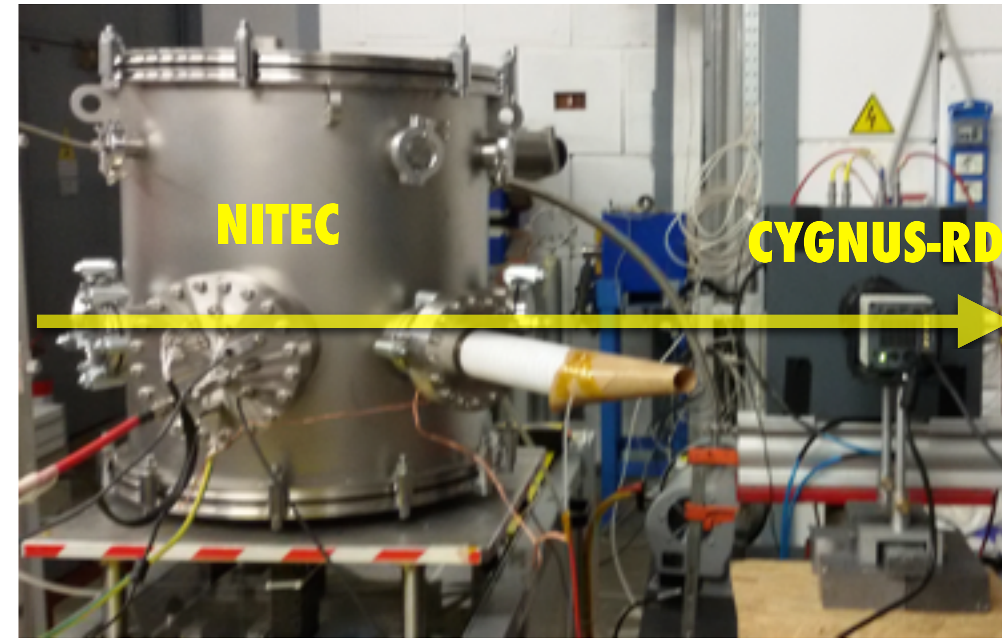
@ 60 cm we cover a 30 x 30 cm^2 area

Both light vs lens aperture and light vs distance indicate isotropic light production

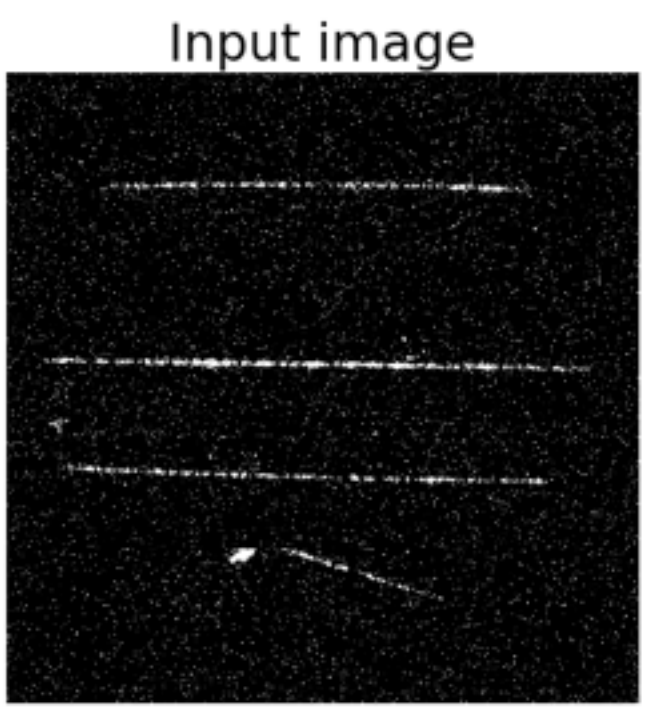
CYGNUS-RD @ BTF

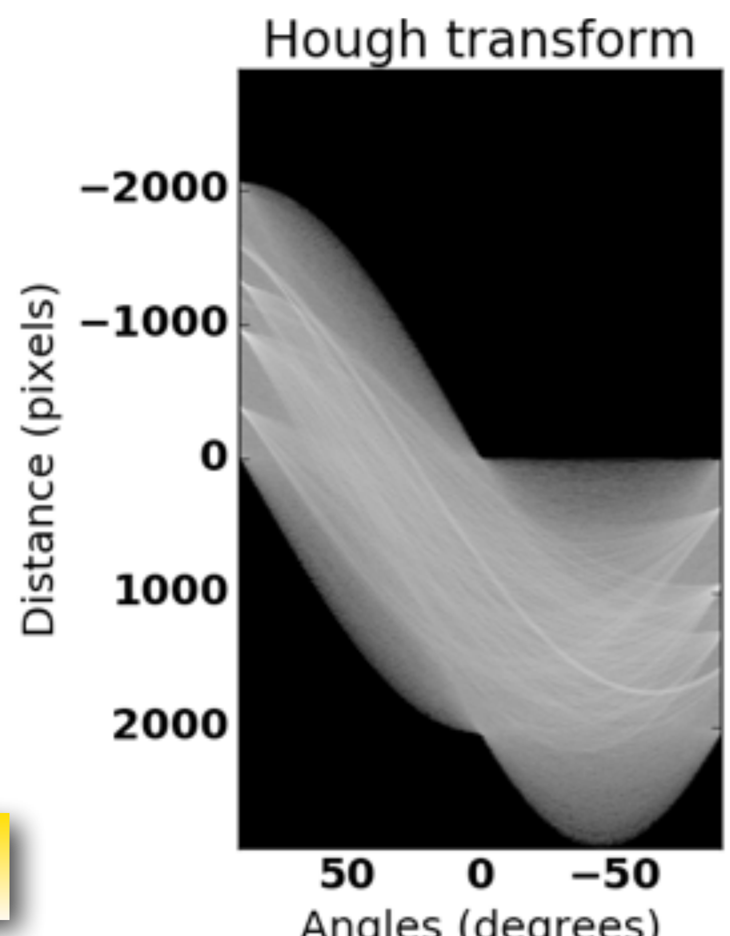


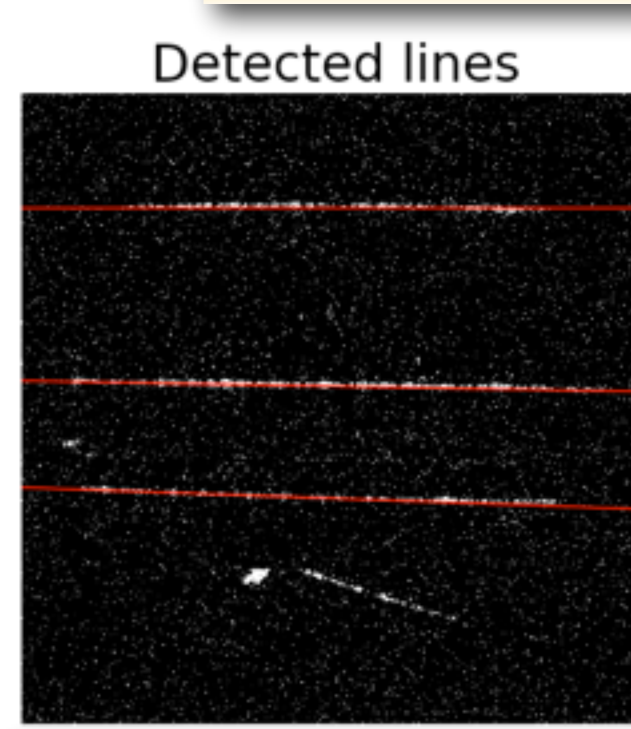
+ PMT to read last GEM light
+ last GEM waveform readout



Dec 2016, electron drift



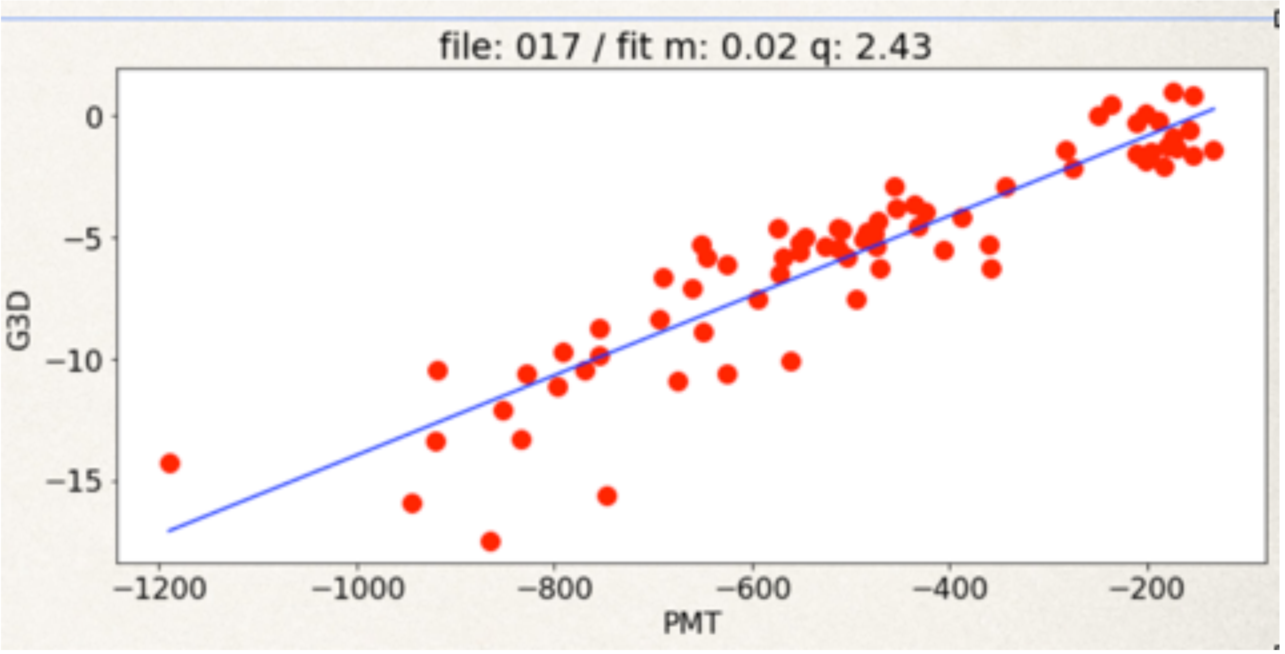


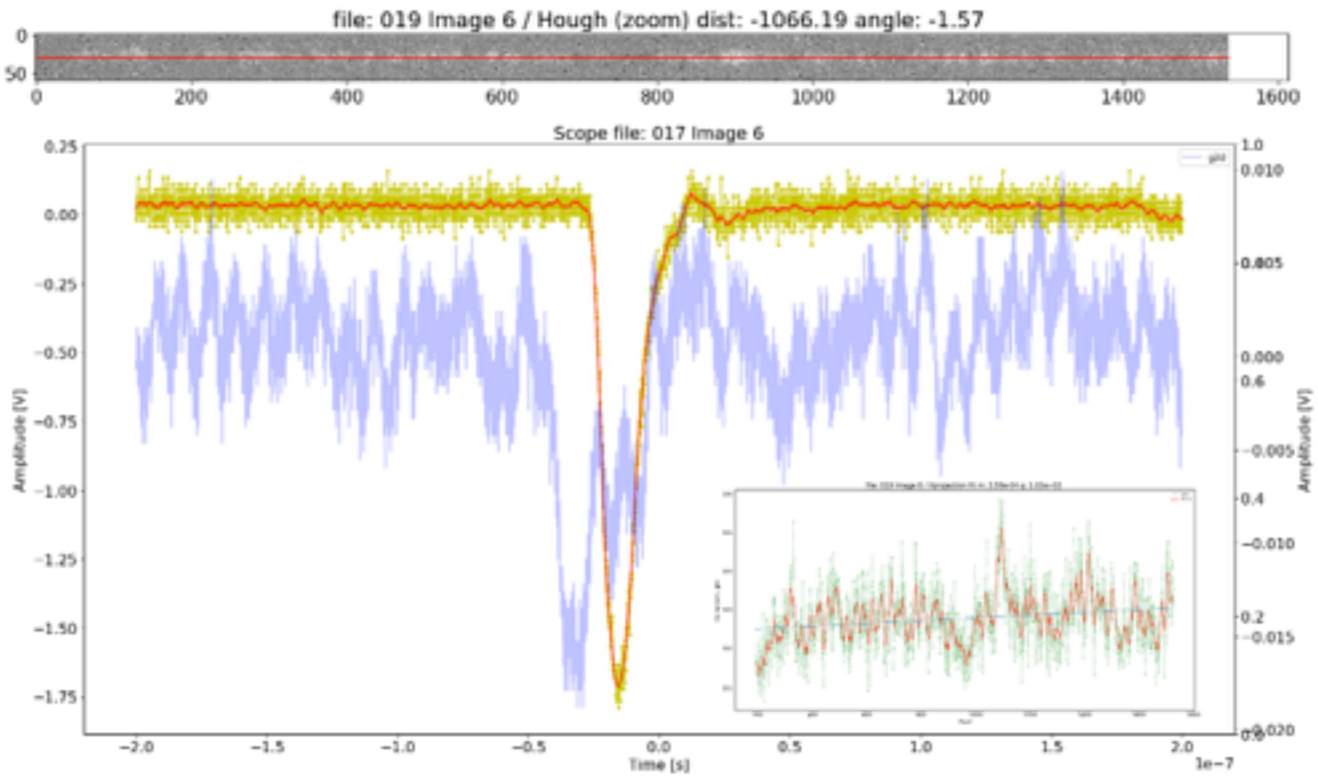


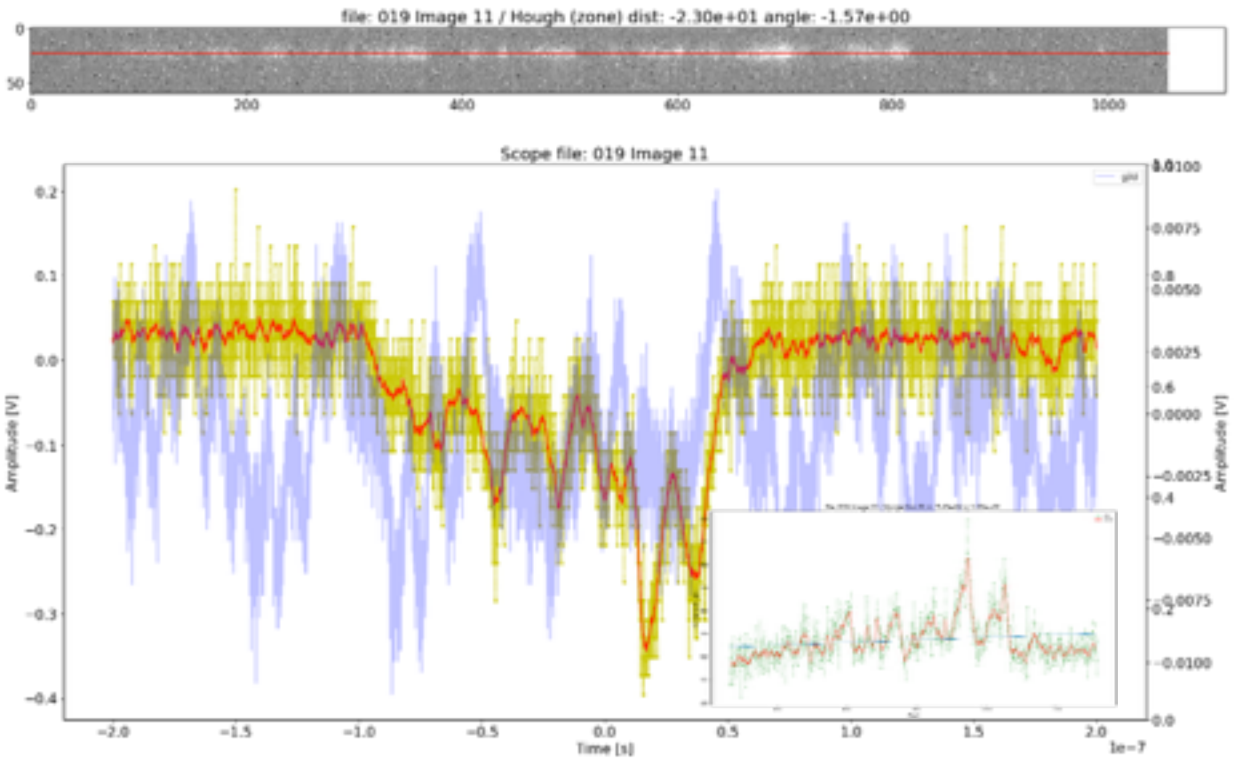
Data analysis on-going

450 MeV electron beam

PMT and last GEM correspondence

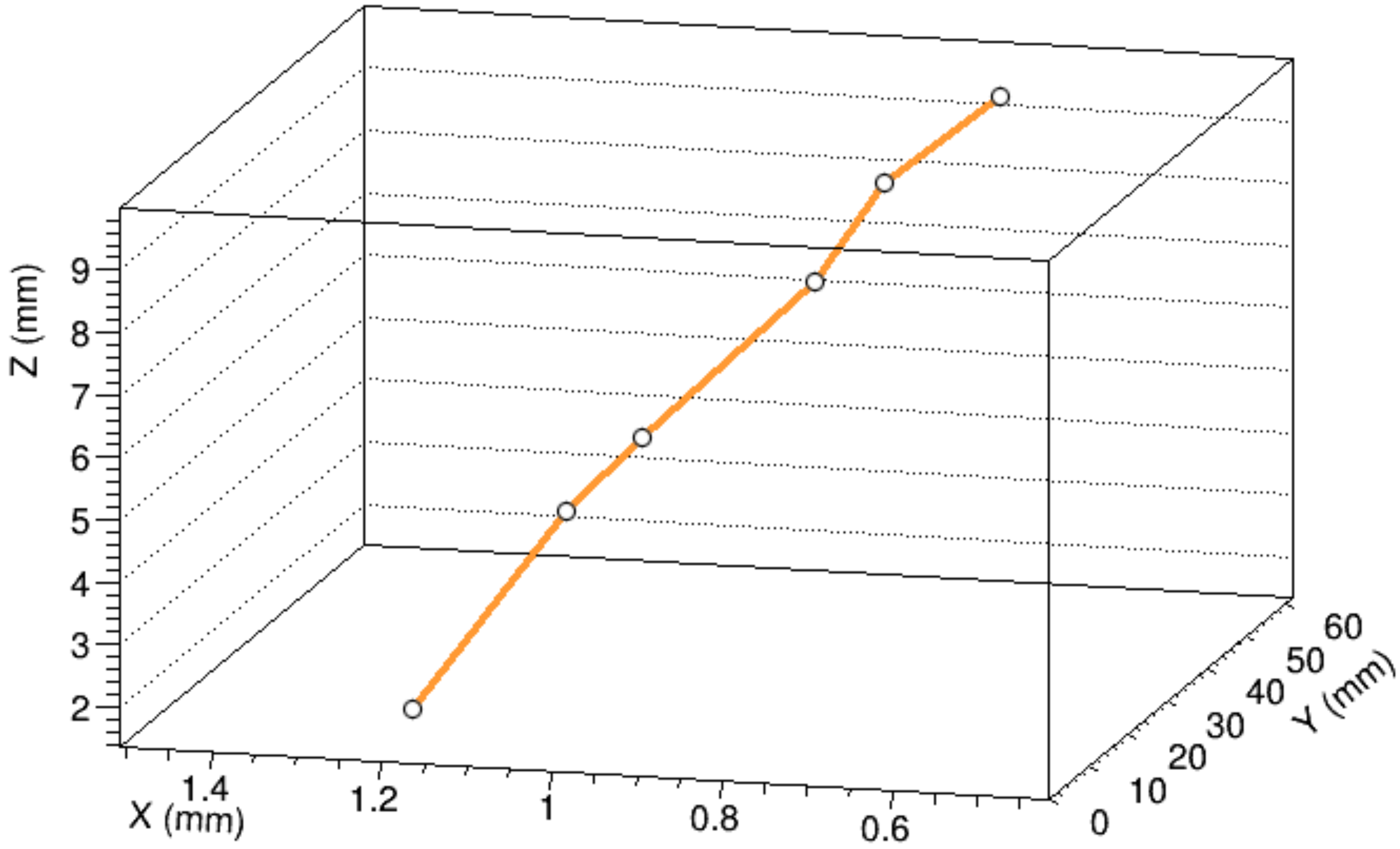






straight track **tilted track**

CYGNUS-RD @ BTF preliminary results

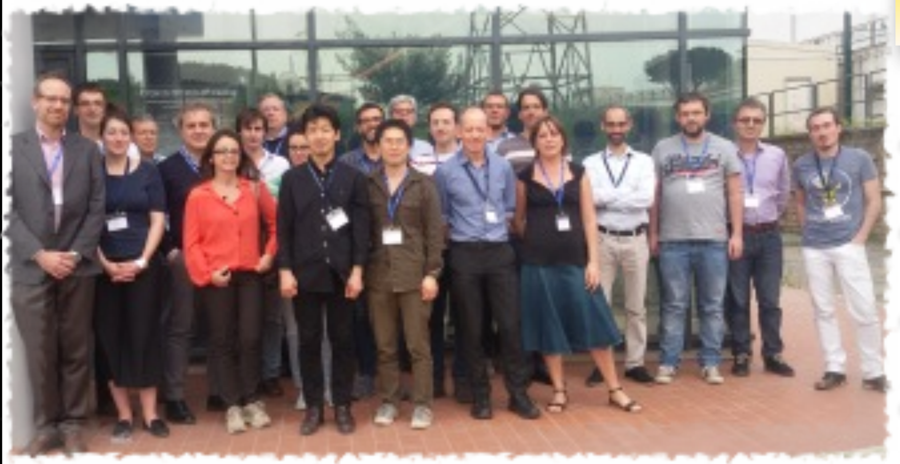


with clusters time from PMT

The CYGNUS-TPC project

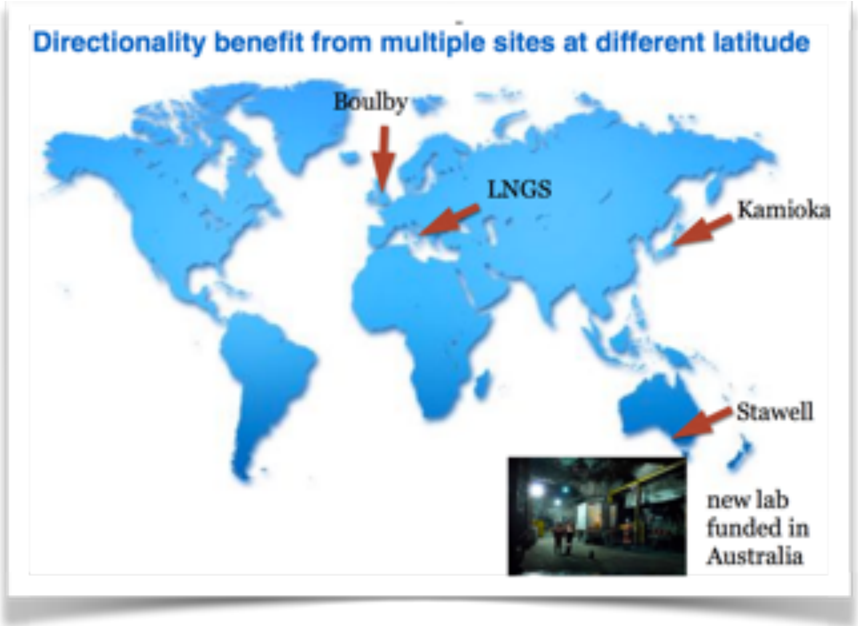
- Proto-collaboration agreement 50 signatures
- Coordinated R&D and simulations through regular meetings
- 2 related papers, 1 ongoing
- Kick-off meeting at LNF

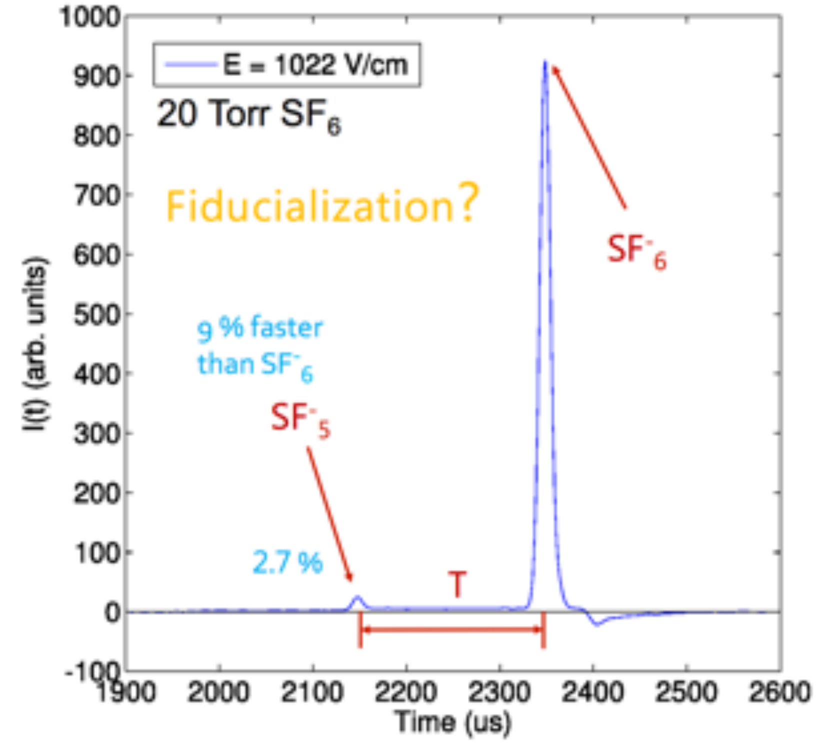
J. Battat et. al, Phys. Rept. 662 (2016) 1-46



CYGNUS-TPC key elements:

- Recoil sensitive TPCs with negative ions drift
- SF_6 gas mixture (possibly with He @ atmospheric pressure)
- Fiducialization with minority carriers
- Multiple underground sites





UNDER

Underground Neutron DEtection through nuclear Recoils @ LNGS

Motivations

Fast neutrons

E interval (MeV)	Fast Neutron Flux (10^{-6}cm^{-2}s^{-1})					
Detector		Liquid scintillator	BF_3	^{3}He		^{3}He
	Ref. [5]	Ref. [6]	Ref. [2]	Ref. [1]	Ref. [7]	Ref. [8]
0.1 – 1			0.54±0.01			
1 – 2.5		0.14±0.12	(0.53±0.08)			
2.5 – 3		0.13±0.04	0.27±0.14			
3 – 5			(0.18±0.04)			2.56±0.27
5 – 10		0.15±0.04	0.05±0.01 (0.04±0.01)	3.0±0.8	0.09±0.06	
10 – 15	0.78±0.3	$(0.4 \pm 0.4) \cdot 10^{-3}$	$(0.6 \pm 0.2) \cdot 10^{-3}$ ($(0.7 \pm 0.2) \cdot 10^{-3}$)			
15 – 25	UL		$(0.5 \pm 0.3) \cdot 10^{-6}$ ($(0.1 \pm 0.3) \cdot 10^{-6}$)		UL	

Measurement of fast neutron flux are more than 20 years old!

Thermal neutrons

E interval (eV)	Thermal Neutron Flux (10^{-6}cm^{-2}s^{-1})			
Detector	^{3}He	BF_3	^{3}He	^{3}He
	Ref. [1]	Ref. [2]	Ref. [3]	Ref. [4]
0 - 0.05	5.3 ± 0.9	1.08 ± 0.02 (1.07 ± 0.05)	0.54 ± 0.13	0.32 ± 0.09
0.05 - 1000		1.84 ± 0.20 (1.99 ± 0.05)		

[1] Bellotti 1985
[2] Belli 1989
[3] Debicki 2009
[4] Best 2015
[5] Aleksan 1989
[6] Arneodo 1999
[7] Cribier 1995
[8] Rindi 1988

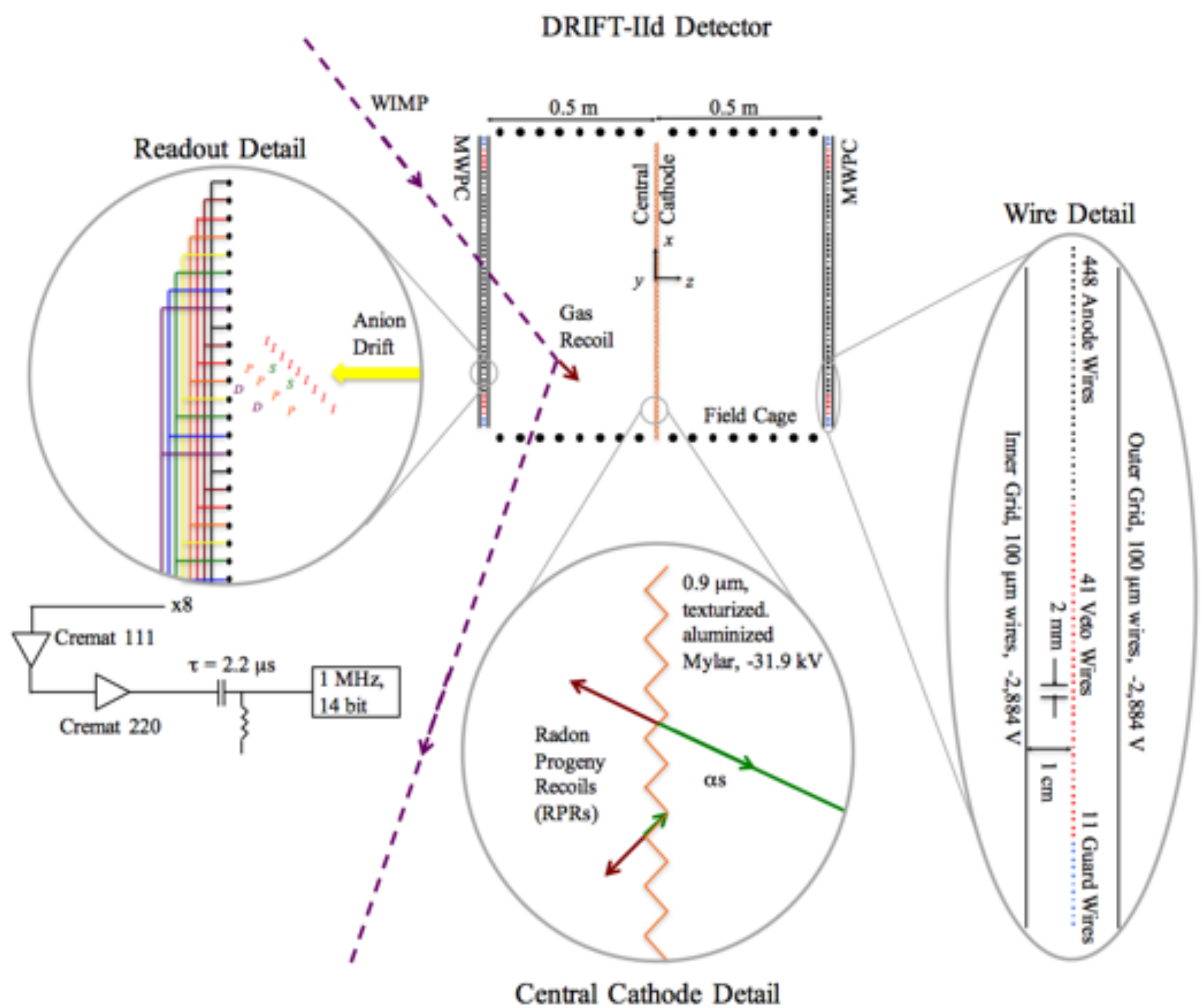
Both fast and thermal flux measurements varying widely

- **Neutron background limits the maximum achievable sensitivity in most deep underground nuclear, astroparticle and double-beta decay experiments**
  - Fast neutrons background to current experiments
  - Thermal neutrons: able to activate detector material, background for future large volume experiments
- **At a typical depth of 3000-4000 m.w.e. neutron flux from the environment is about 2-3 order of magnitude larger than from cosmogenic muon activation**
  - Dominant source from ^{238}U fission from rocks, (alpha,n) reaction on light nuclei and experimental setup activity

DRIFT background free measurement @ Boulby

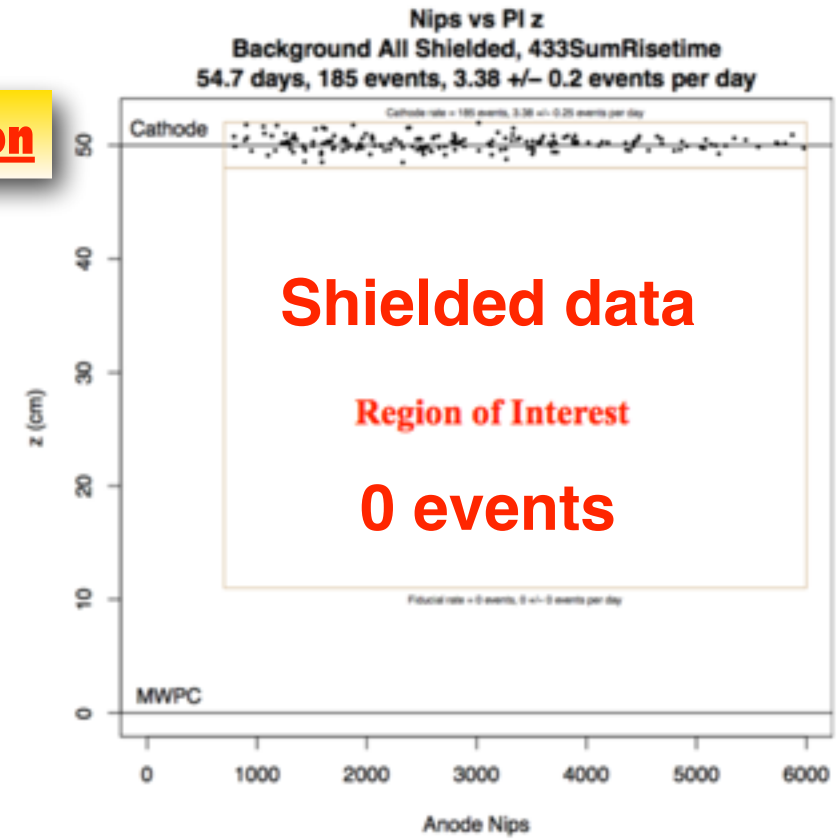
J. Battat et al., [DRIFT]
arXiv: 1701.00171

$CS_2:CF_4:O_2$
30:10:1 Torr
(low pressure)

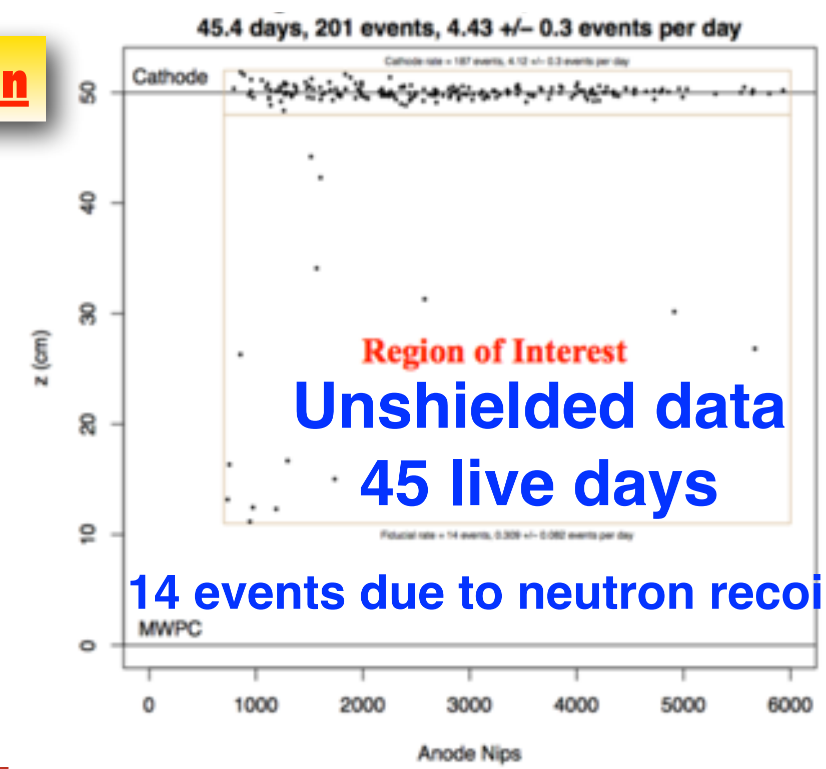


1.98 x 10^{-7} gamma rejection factor

Fiducialization

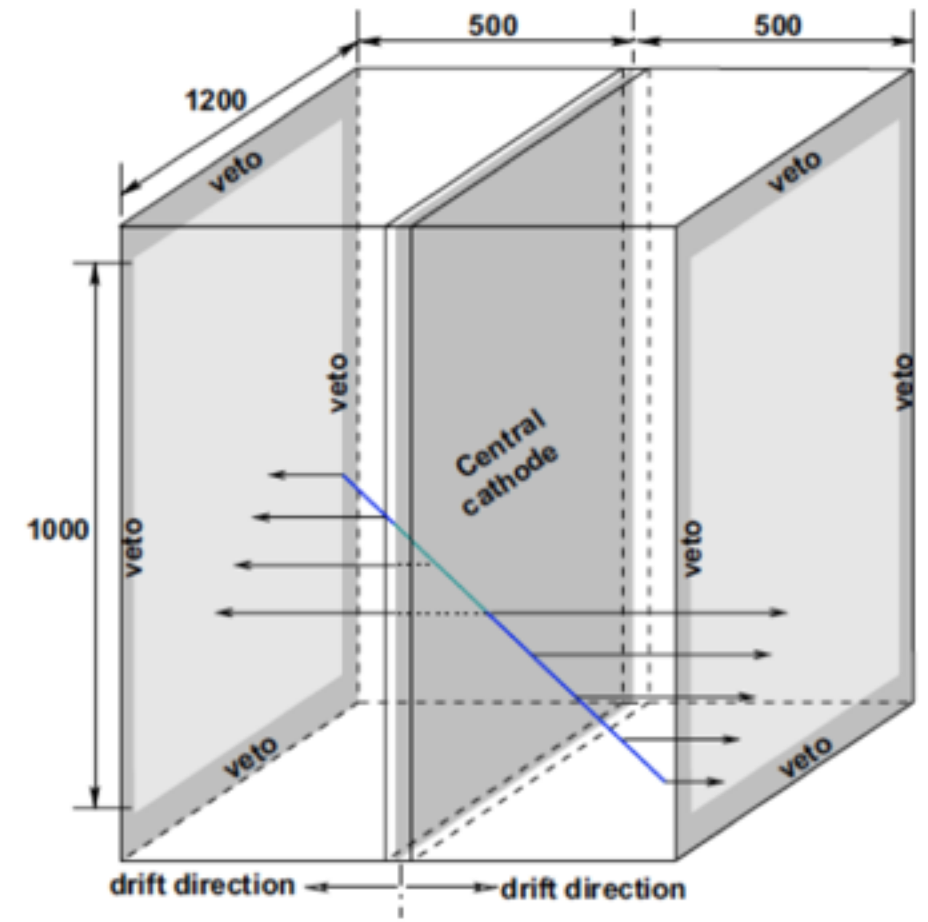


Fiducialization

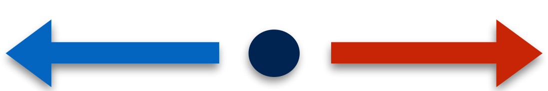


The UNDER project

- **Two 50 cm back-to-back Negative Ion TPC with triple thin GEMs amplification for a one-year measurement in Hall B to check for seasonal variations**
  - Charge readout (through amplifiers connected to last GEM) or light readout (through PMTs) under discussion —> see CYGNUS-RD results



- **He:^{3}He:SF_6 gas mixture (atmospheric pressure)**
  - Fast neutron flux measurement with zero background through usual nuclear recoil technique (as demonstrated by DRIFT)
  - Thermal neutron flux measurement through ^{3}He capture
  - Fiducialization through minority carriers



$$n + {}^3He \longrightarrow p + {}^3H + 764keV$$

- **CYGNUS-TPC demonstrator**
  - Close collaboration and synergy with CYGNUS-TPC, signed letter of support

The UNDER strategy

- **Two-fold strategy:**
  - High yield without directionality **$He:^3He:SF_6$ 659:1:100 Torr**
  - If inconsistencies are found, lower partial SF_6 content to investigate observed flux with directionality down to low threshold **$He:^3He:SF_6$ 749:1:10 Torr**

Expect at least same number of thermal neutrons events ($He:^3He$ 600:1 ratio)

From F. Mouton, University of Sheffield

He:	Rock neutrons rate	Concrete neutrons rate	Recoils due to fast neutron/month
659:1:100	2.93 x 10	3.6 x 10	9330
749:1:10	< 8.22 x 10	3.1 x 10	800

- From the simulation developed for the DRIFT measurement @ Boulby (SOURCES + GEANT4)
- LNGS Hall B dimensions, rock and concrete U and Th content (40 cm concrete)

Wulandari et. al., Astropart.Phys. 22 (2004) 313-322

- Assume same performance as DRIFT with $CS_2:CF_4:O_2$ 30:10:1 Torr (including fiducialization)
- Rate includes fiducial cuts and 30 keV energy threshold (as in DRIFT)
- Simulation reproduces neutron flux in agreement with Belli et al.

Conclusions & Outlook

Data shown today are part of papers in preparation

- **NITEC**
  - Study gain, energy threshold, minority carriers and gamma rejection with $He:SF_6$ 660:100 gas mixture from the charge collected by the last GEM (no pixels)
  - Perform tests with alphas and neutrons
  - Finalize analysis of collected data (preliminary single track reconstruction for BTF data nearly ready)
- **CYGNUS-RD**
  - Operate with negative ions
  - Study gain, energy threshold, minority carriers and gamma rejection with $He:SF_6(:CF_4)$ gas mixtures
    - With the CMOS camera
    - From the charge collected by the last GEM
    - From the light produced in the GEM and collected by a PMT (no CMOS/low granularity optical readout)
- **CYGNUS-TPC Project**
  - Finalize R&D work on SF_6 with a variety of amplifications & readout devices (thin and thick GEMs, muPIC, Micromegas, MWPC)
  - Finalize simulations and physics case potentialities
  - Next meeting: Xichang, Sichuan, China June 2017

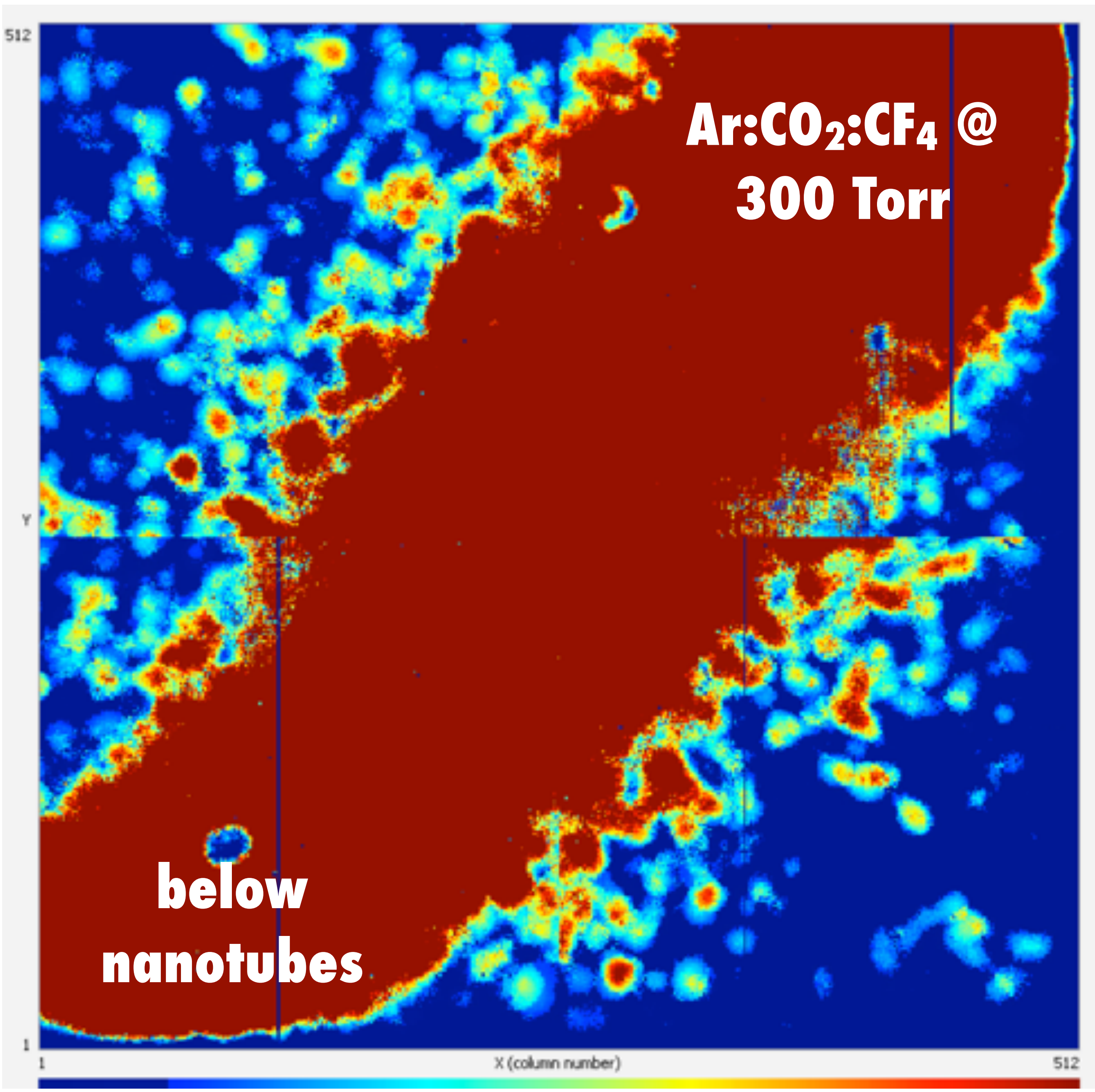
CYGNUS-TPC Whitepaper in preparation (target summer 2017)

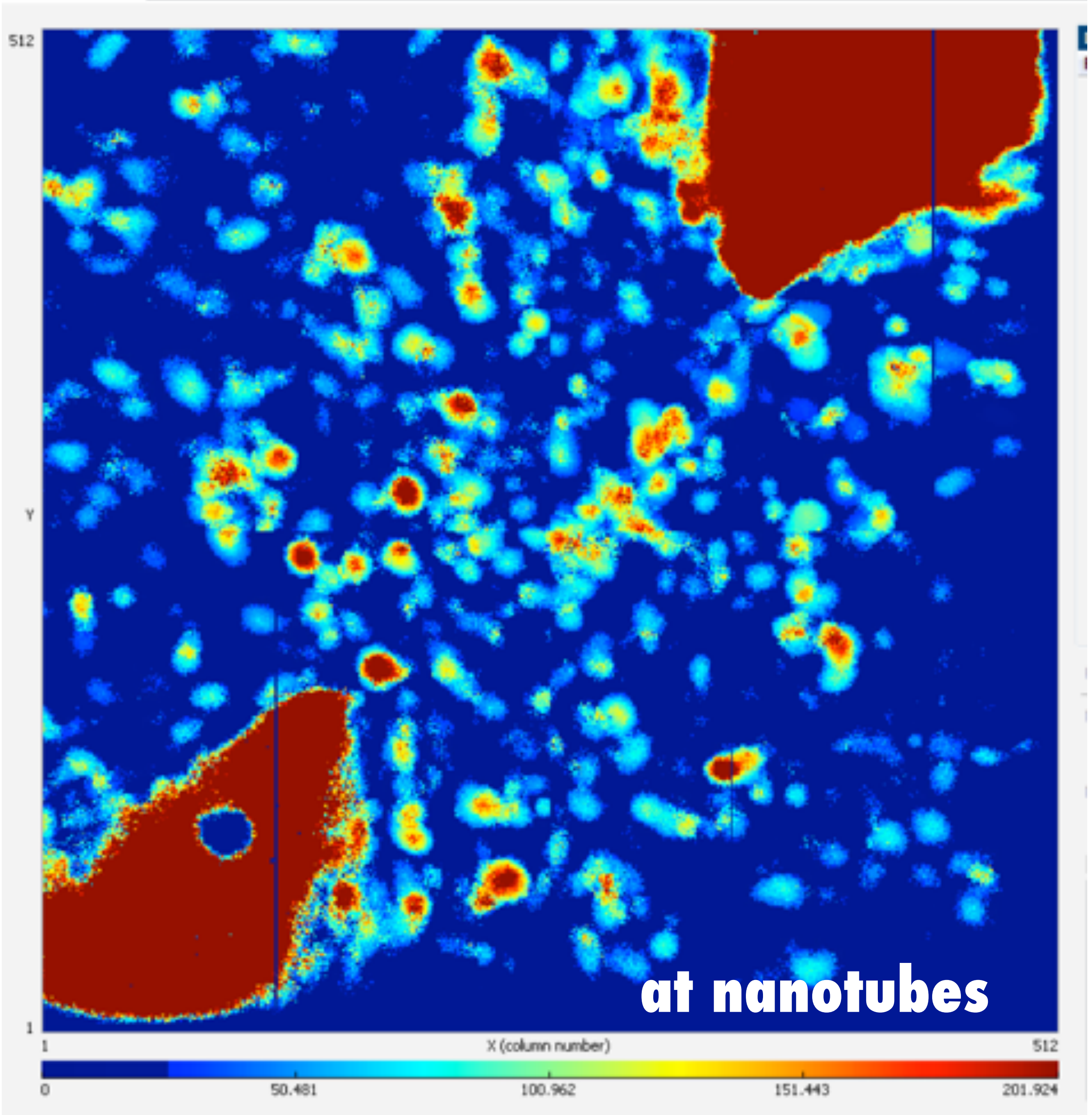
- **UNDER Project**
  - Present to CSN2 at April meeting and hopefully to LNGS SC at October meeting
  - Readout simulation work on going

UNDER Conceptual Design Report in preparation (target summer 2017)

Backup

Carbon Nanotubes





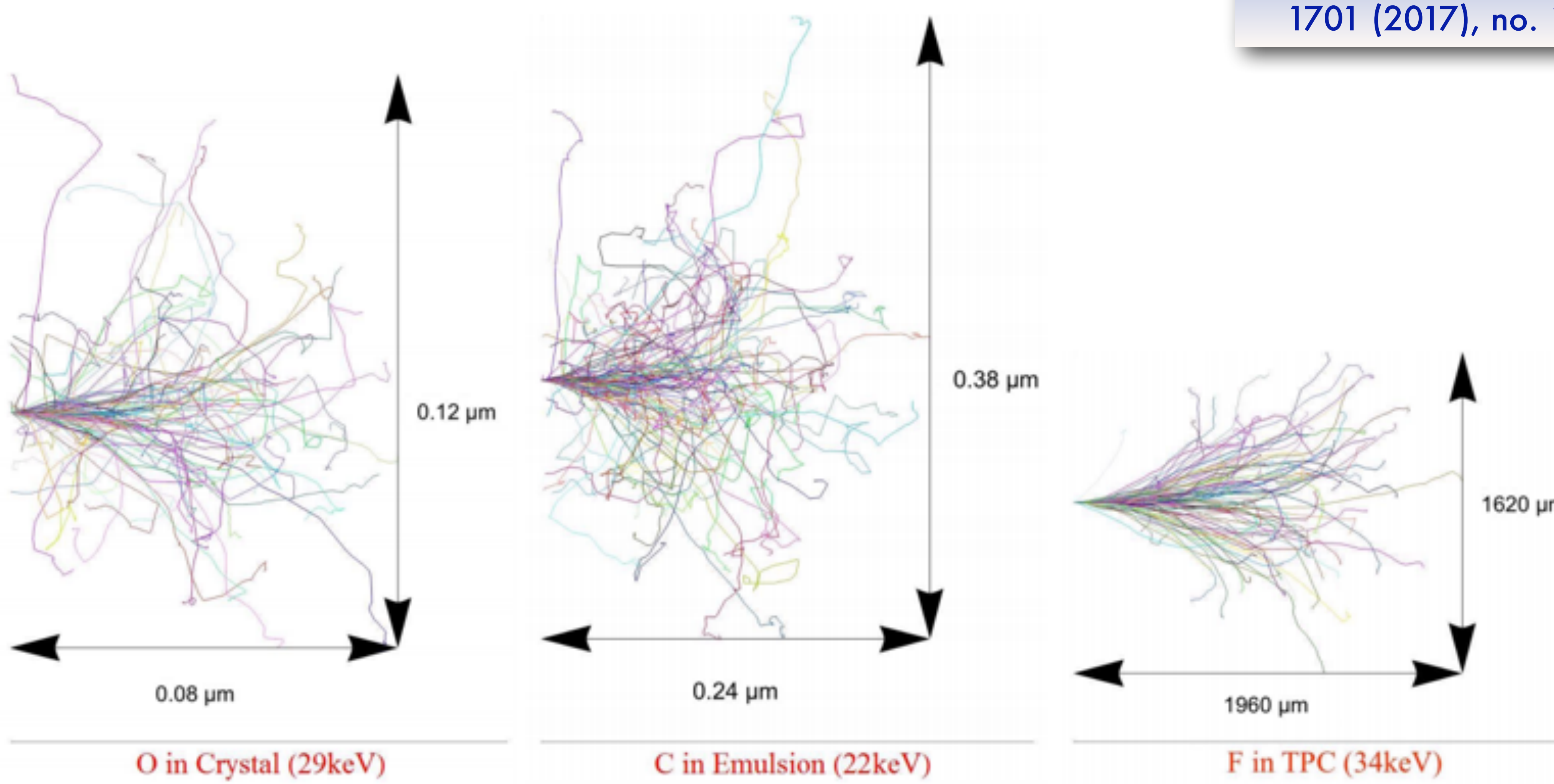
GEMPix + NITPC: A Time Expansion Chamber

- 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)

Directionality

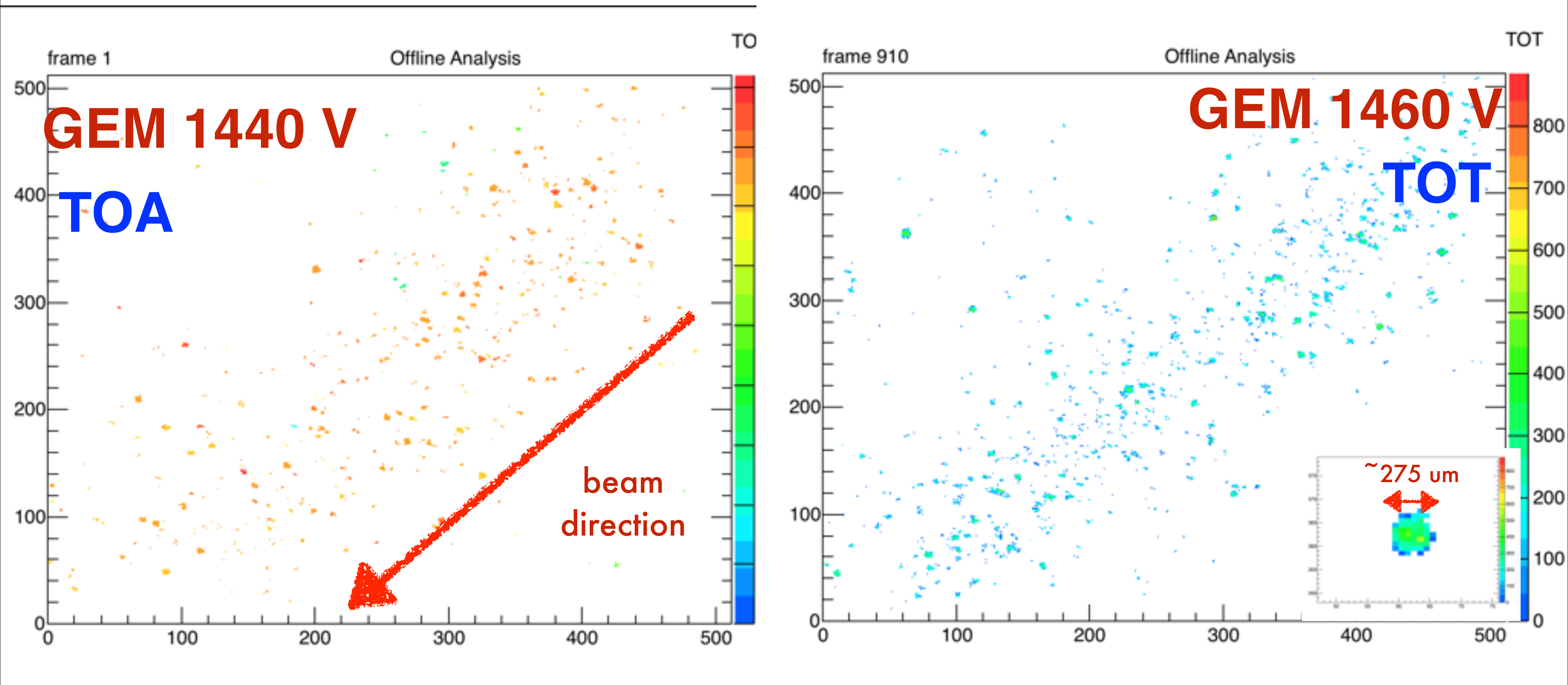
C. Couturier et al., JCAP 1701 (2017), no. 1, 027



	^{16}O in Crystal	^{12}C in Emulsion	^{19}F in TPC
WIMP Mass (GeV/c^2)	Mean range ± std. deviation (μm)		
1	$(1.78 \pm 0.92)\ 10^{-3}$	$(4.15 \pm 1.93)\ 10^{-3}$	13 ± 6
10	$(8.64 \pm 4.49)\ 10^{-3}$	$(3.25 \pm 1.73)\ 10^{-2}$	170 ± 70
100	$(3.65 \pm 1.64)\ 10^{-2}$	$(9.46 \pm 4.57)\ 10^{-2}$	800 ± 300
1000	$(4.41 \pm 1.89)\ 10^{-2}$	$(1.11 \pm 0.54)\ 10^{-1}$	1040 ± 360

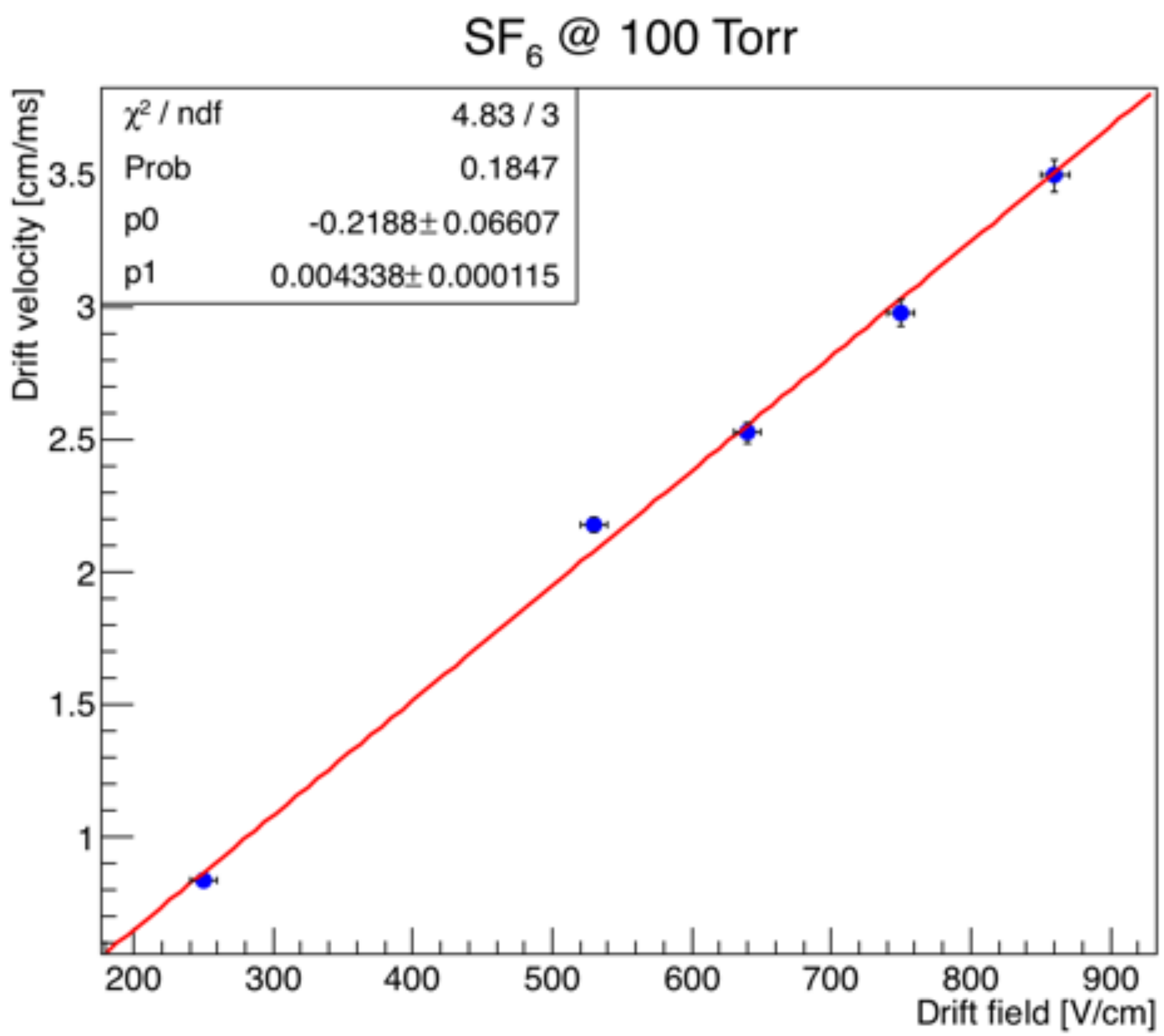
SF_6 @ 150 Torr

Dec 2016



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

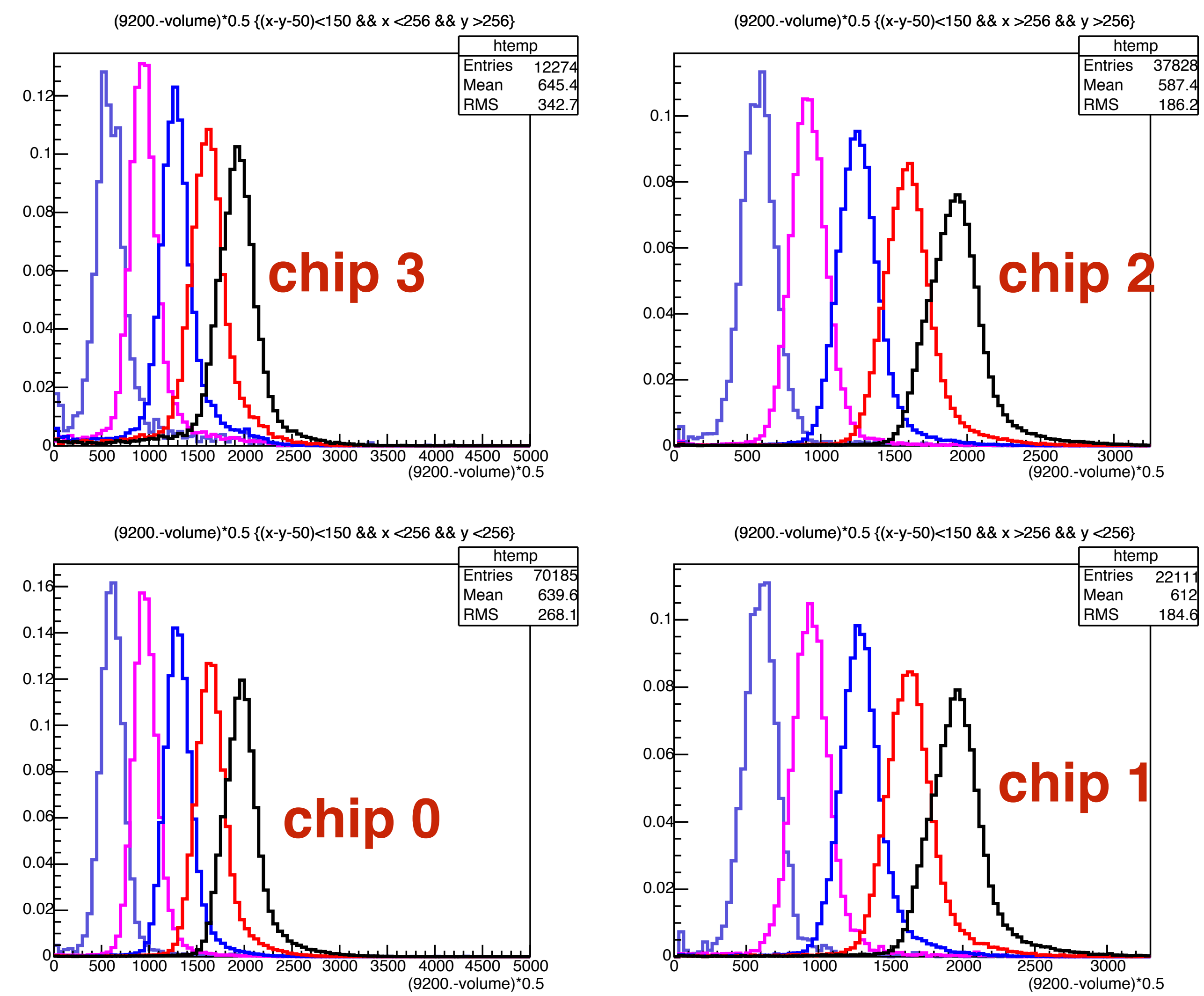
SF_6 @ 100 Torr TOA analysis



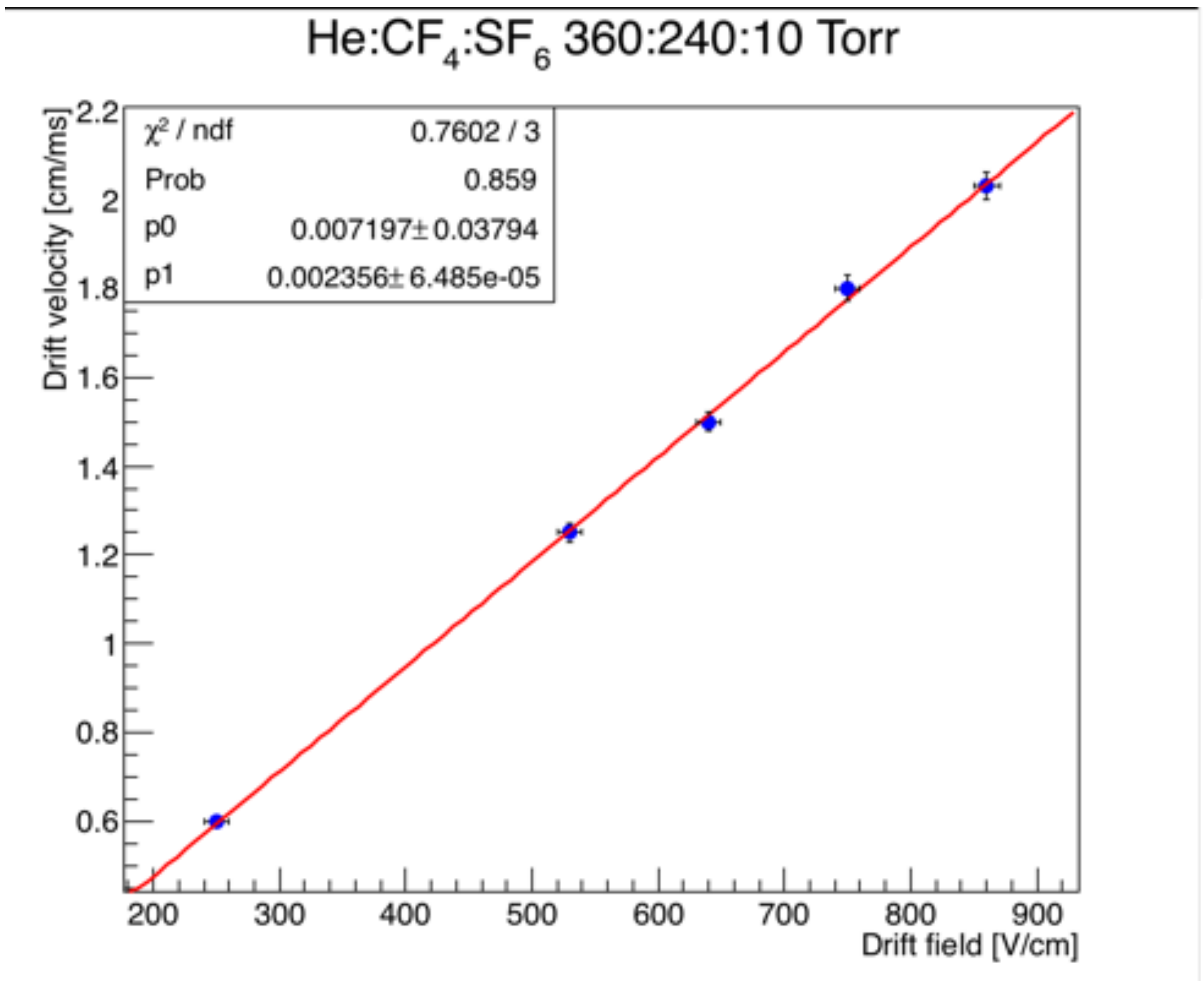
750 V/cm

```
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



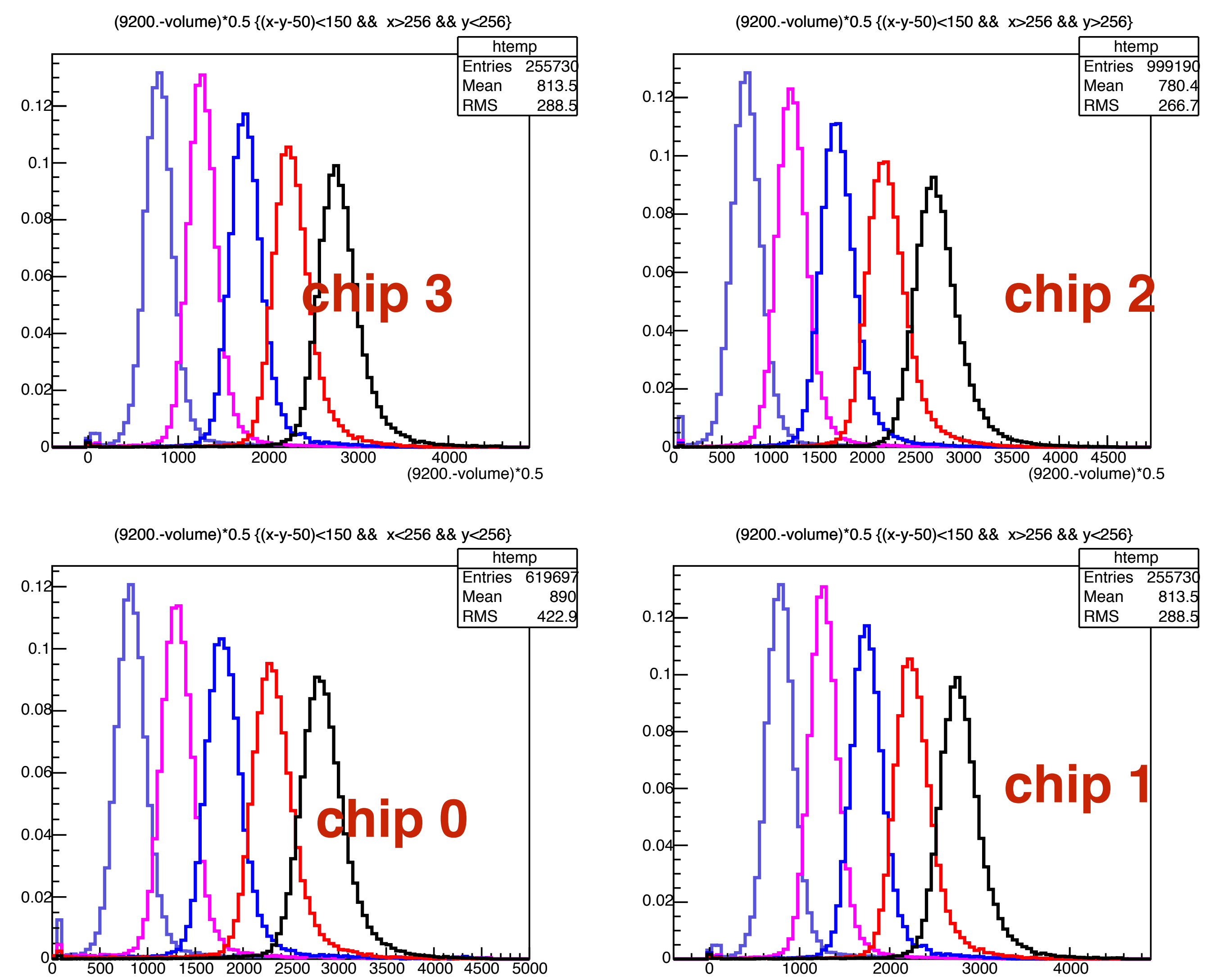
He:CF_4:SF_6 360:240:10 Torr TOA analysis



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



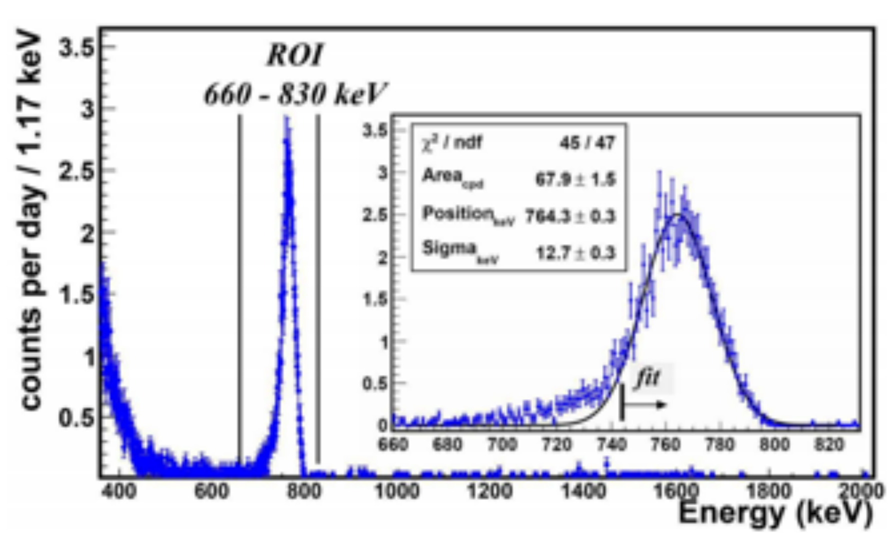
Nearly atmospheric operation!

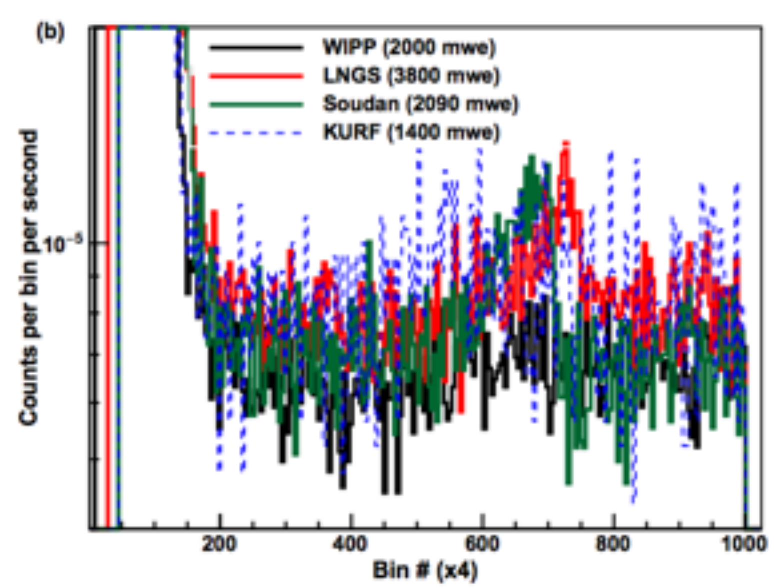
^{3}He and BF_3 counters technique

- **^{3}He and BF_3 measurements**
  - Thermal neutron through capture: a peak over a large background of internal radioactivity (alphas mainly), to be estimated and subtracted to obtain the final result
    - NOTE that several other laboratories felt the need to perform ^{3}He measurements with low-radioactivity background detectors
  - Fast neutron (Belli, Bellotti): only through Cadmium and Polyethylene moderators, complicating detector efficiency and introducing additional uncertainty on yield and energy range

Best et al., ^{3}He at LNGS (2016) (only thermal neutrons)

Edelweiss He3 at LMS (2012)





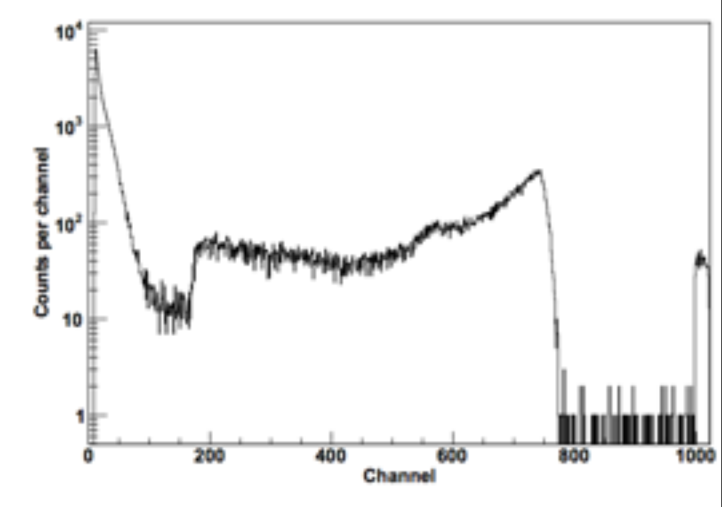
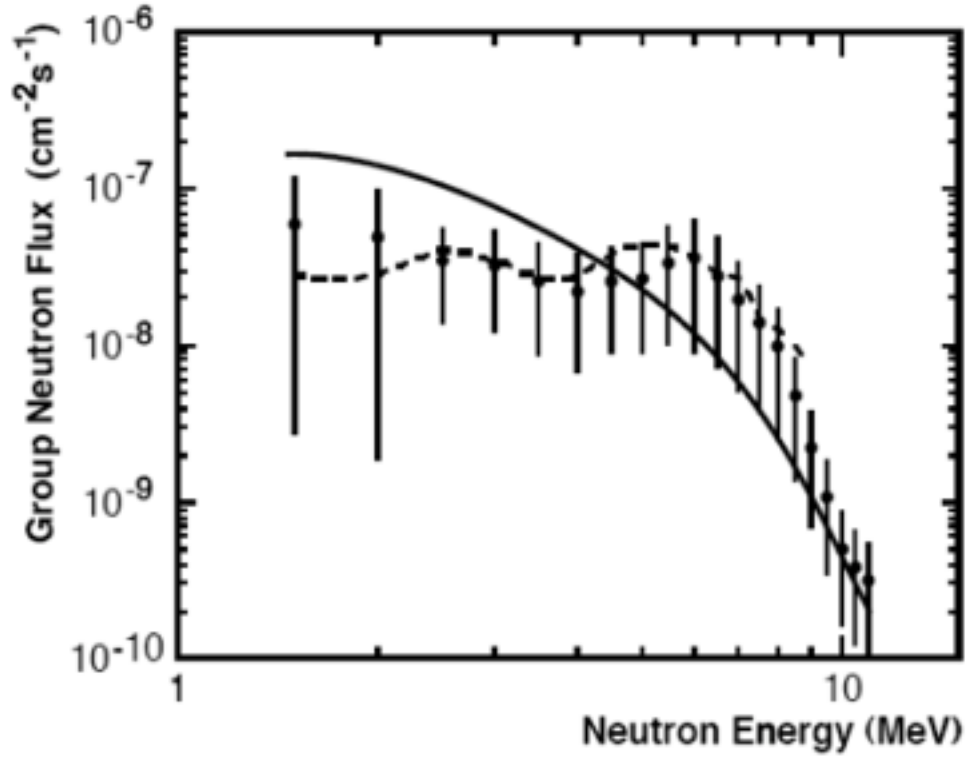


Figure 1: Typical spectrum from a ^{3}He counter (1 channel ≈ 1 keV). A neutro generates a signal between channels ~200 and 800. Signals above and belo this region are due to alpha particles and electronic noise, respectively.

Proton recoil technique

- **Scintillator with proton recoil technique [6] (1999)**
  - Proton recoil technique is similar to nuclear recoil
  - Authors recognize energy calibration with external gamma source was complicated and used internal alpha particles from internal radioactivity but had to estimate the contaminants from simulation (unable to resolve alpha lines)
  - Alphas were also background to proton recoils

Neutron spectrum at Gran Sasso - Arneodo et al. Nuovo Cimento, A112 (1999) 819.



LNGS Hall A, Hall B and Hall C

Wulandari et. al.,
Astropart.Phys. 22 (2004) 313-322

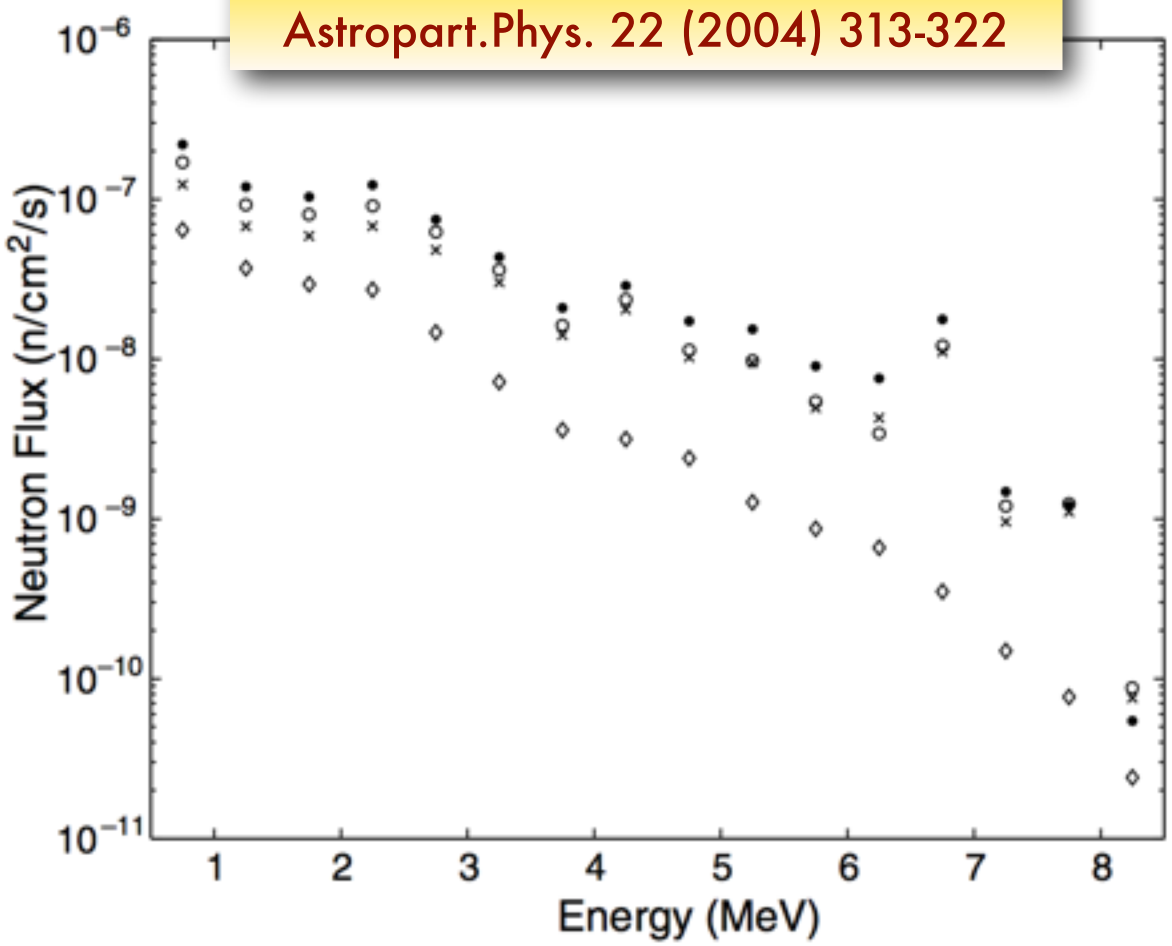


Fig. 3. Neutron flux at the Gran Sasso laboratory, ●: hall A, dry concrete, ×: hall A, wet concrete, ◇: hall A, dry concrete, fission reactions only and ○: hall C, dry concrete. Each point shows the integral flux in a 0.5 MeV energy bin.

The flux is dominated by neutrons produced in the concrete layer and therefore does not vary much from hall to hall

At higher energies, the contribution of (alpha,n) reaction becomes larger introducing the difference

emitted per fission [11]. The total number of neutrons produced by fission and (α,n) in the rock/concrete at the Gran Sasso laboratory depends eventually on the ^{238}U and ^{232}Th contamination.

Table 3
^{238}U and ^{232}Th activities in LNGS rock

Hall	Activities (ppm)	
	^{238}U	^{232}Th
A	6.80 ± 0.67	2.167 ± 0.074
B	0.42 ± 0.10	0.062 ± 0.020
C	0.66 ± 0.14	0.066 ± 0.025

NEUTRON BACKGROUND HIGHLY DEPENDENT ON CONCRETE WATER CONTENT!!!

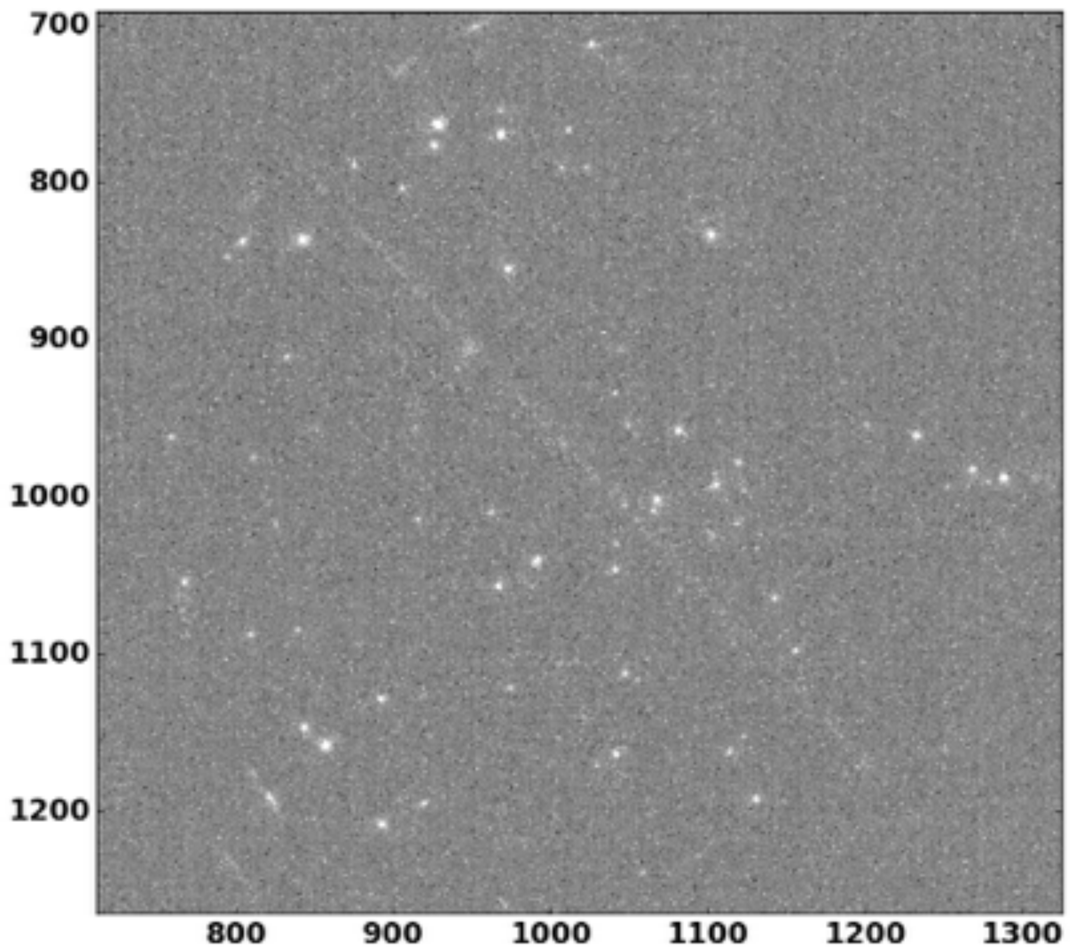
..something that can change over a year…

	Hall A	Hall B	Hall C
rock	3.54	0.22	0.34
concrete	0.55	0.55	0.55

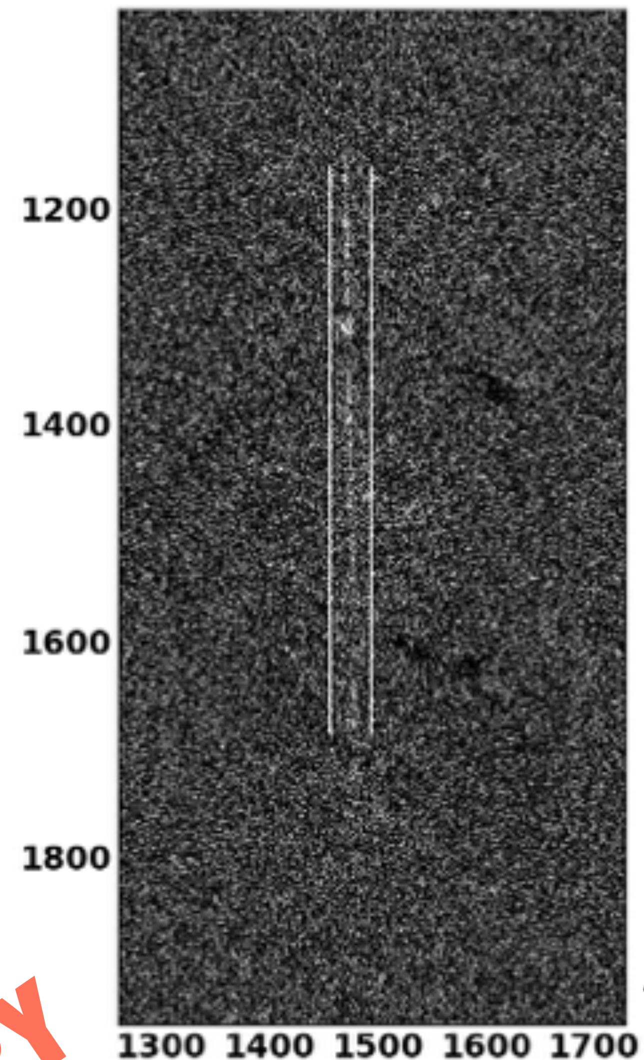
n/year/g

Example of cosmic track @ 60 cm

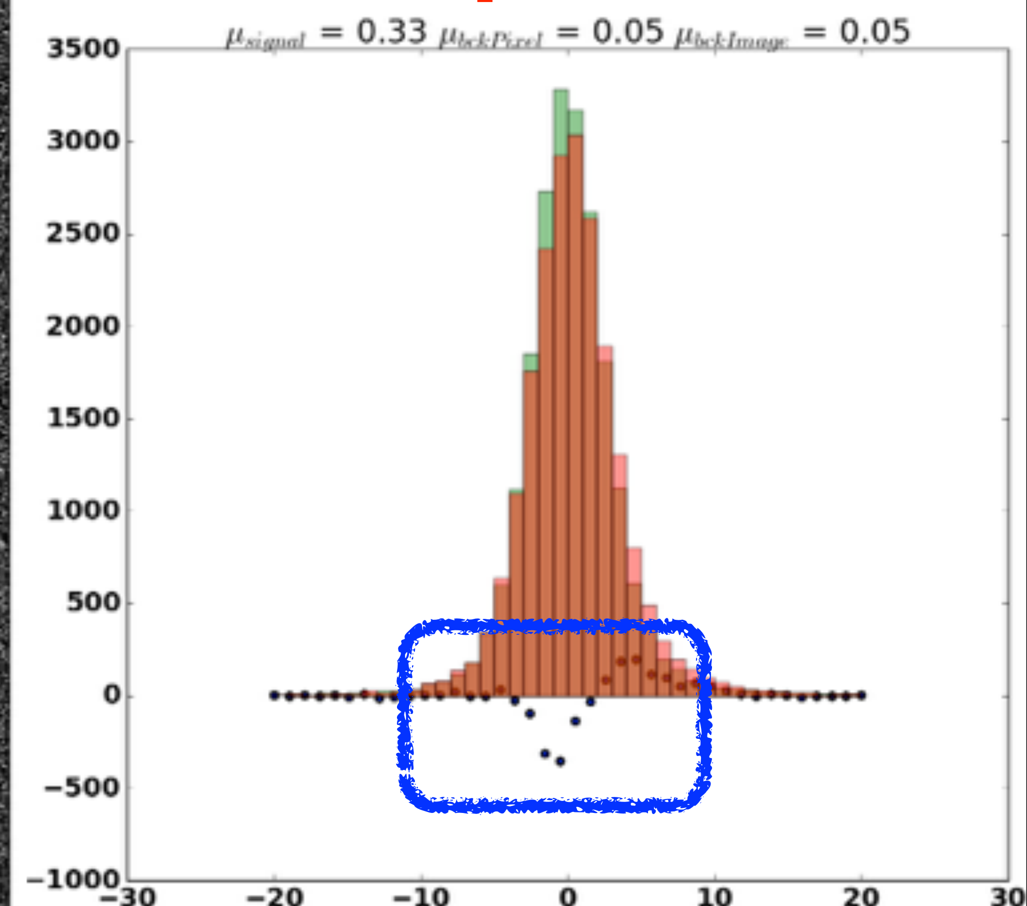
Cosmic track raw data as seen by the CMOS



Background subtracted & rotated



Signal (red)/ noise (green) comparison



PRELIMINARY

After noise subtraction, signal is clearly visible