This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 657751

Started on 4 May 2015

LNF Mini-Workshop Series: development of novel detectors at LNF

NITEC

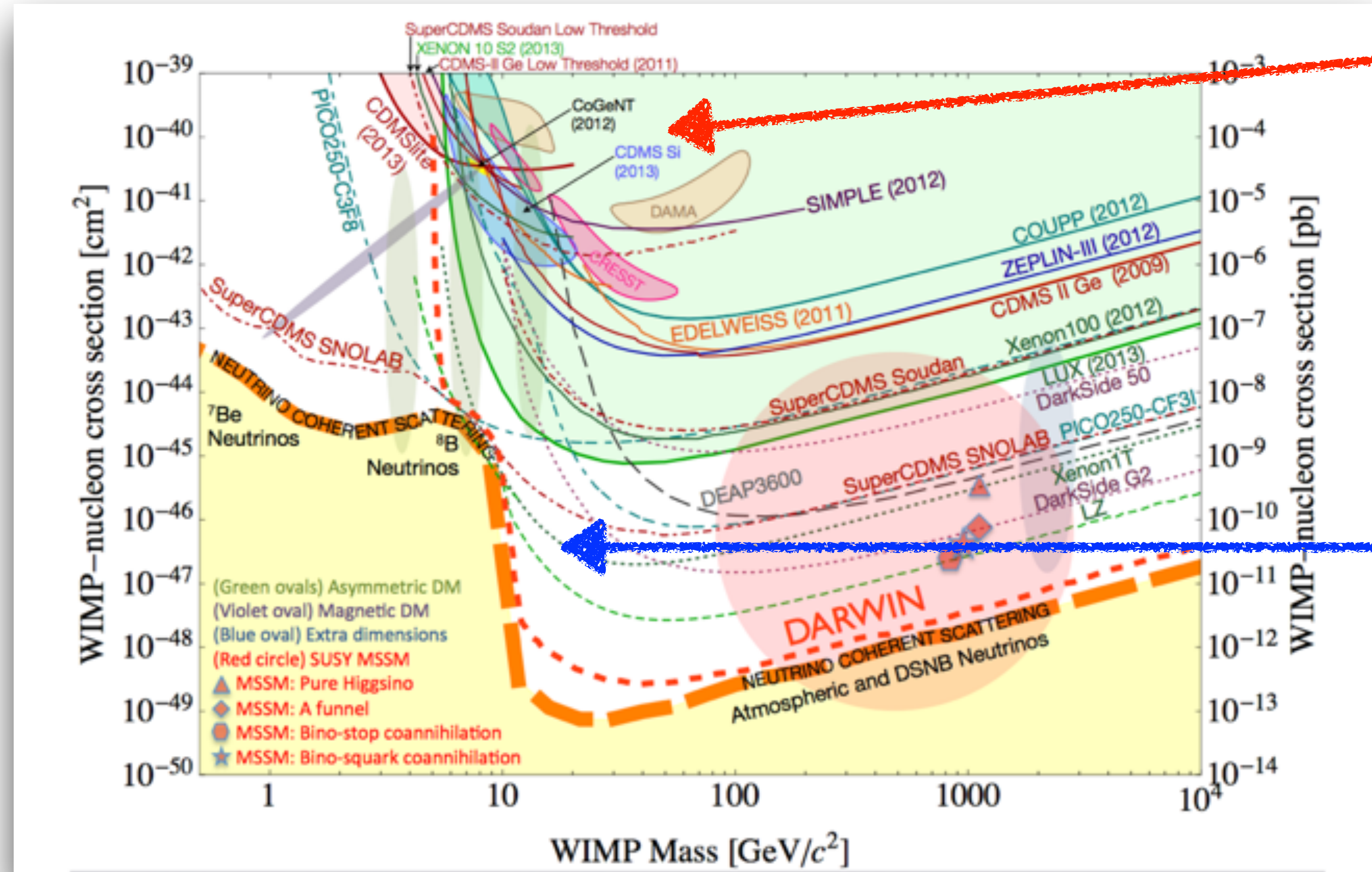
a Negative Ion Time Expansion Chamber for directional Dark Matter searches

Elisabetta Baracchini

Istituto Nazionale di Fisica Nucleare INFN, Laboratori di Frascati

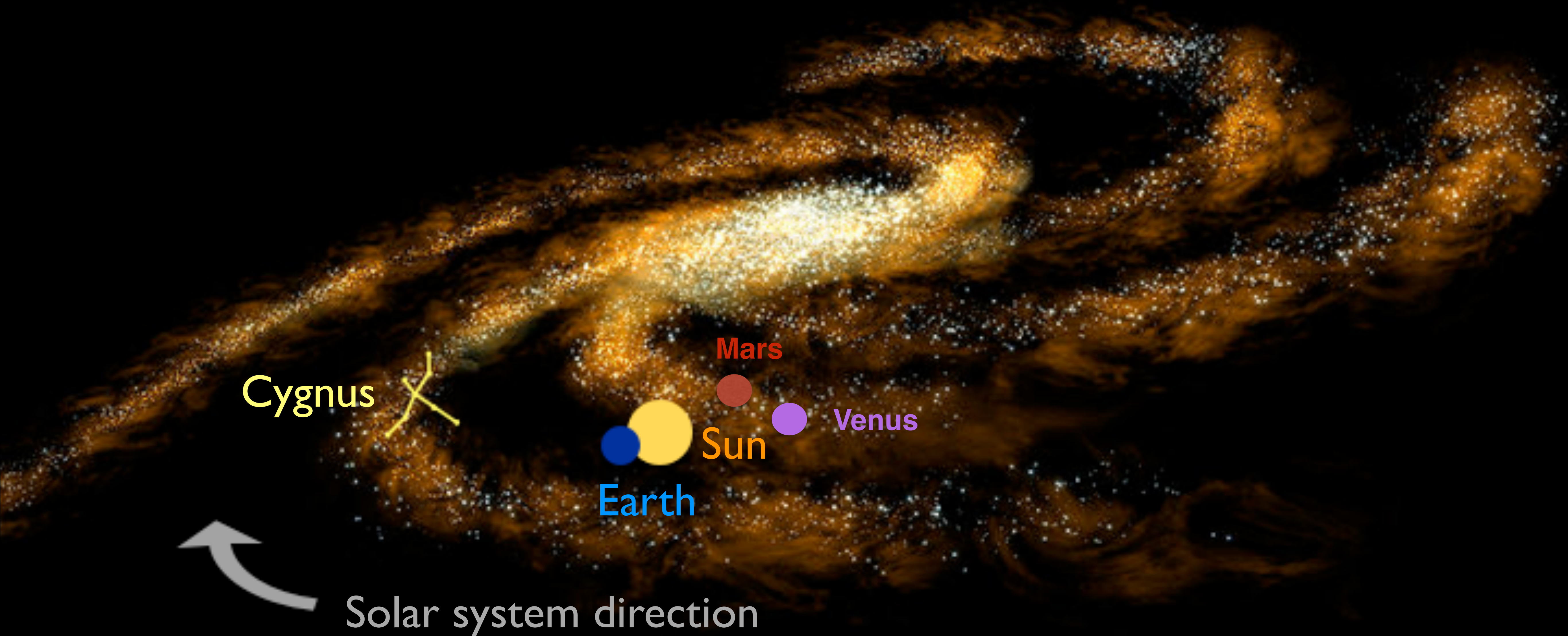
In collaboration with G. Bencivenni, G. Cavoto, F. Murtas, F. Renga, D. Tagnani

Direct Dark Matter Searches



- Claims for detection inconsistent with exclusions limits
- Neutrino Floor: DM experiments sensitive to solar and diffuse neutrinos background, that gives EXACTLY same response as signal

Next generation experiments will need an additional handle on top of rate and energy to discriminate signal from background: DIRECTIONALITY

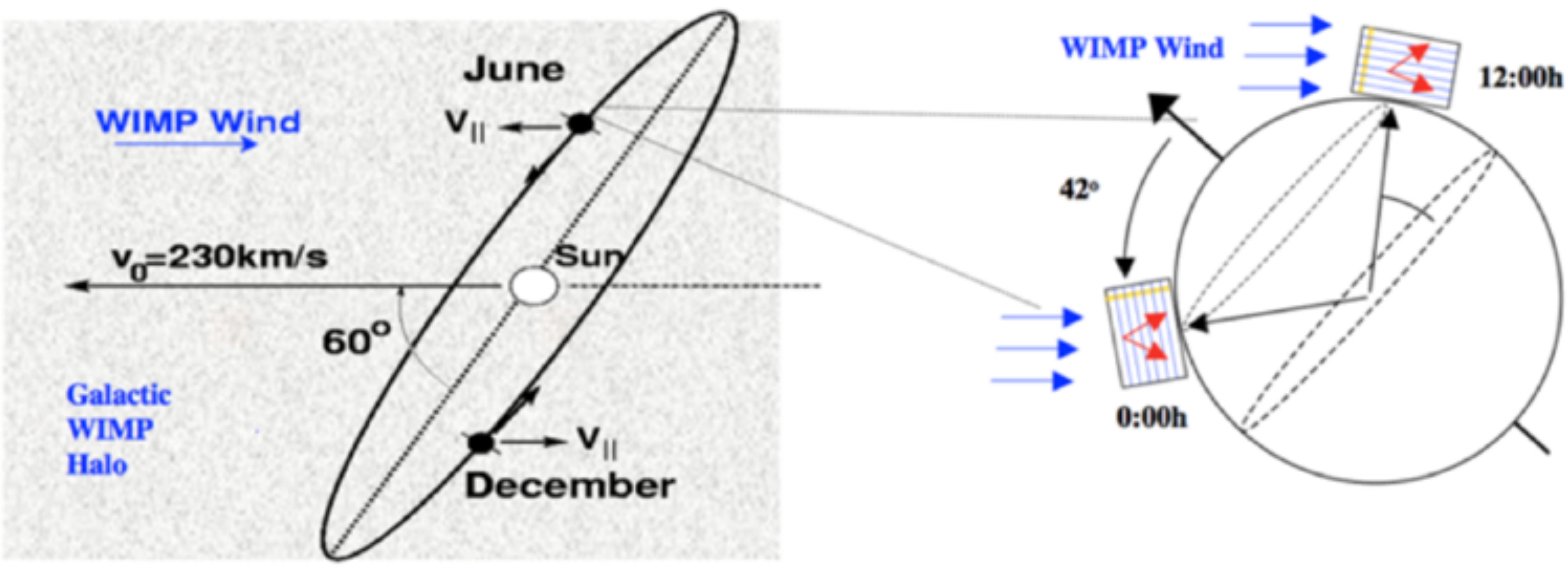


Men are from Mars, Women are from Venus
.....and WIMPs are from Cygnus :)

The power of direction

- *Annual Modulation:* as a result of Earth motion relative to WIMP halo; rate modulation with a period of 1 year and phase ~2 June; large mass required (~2% effect)

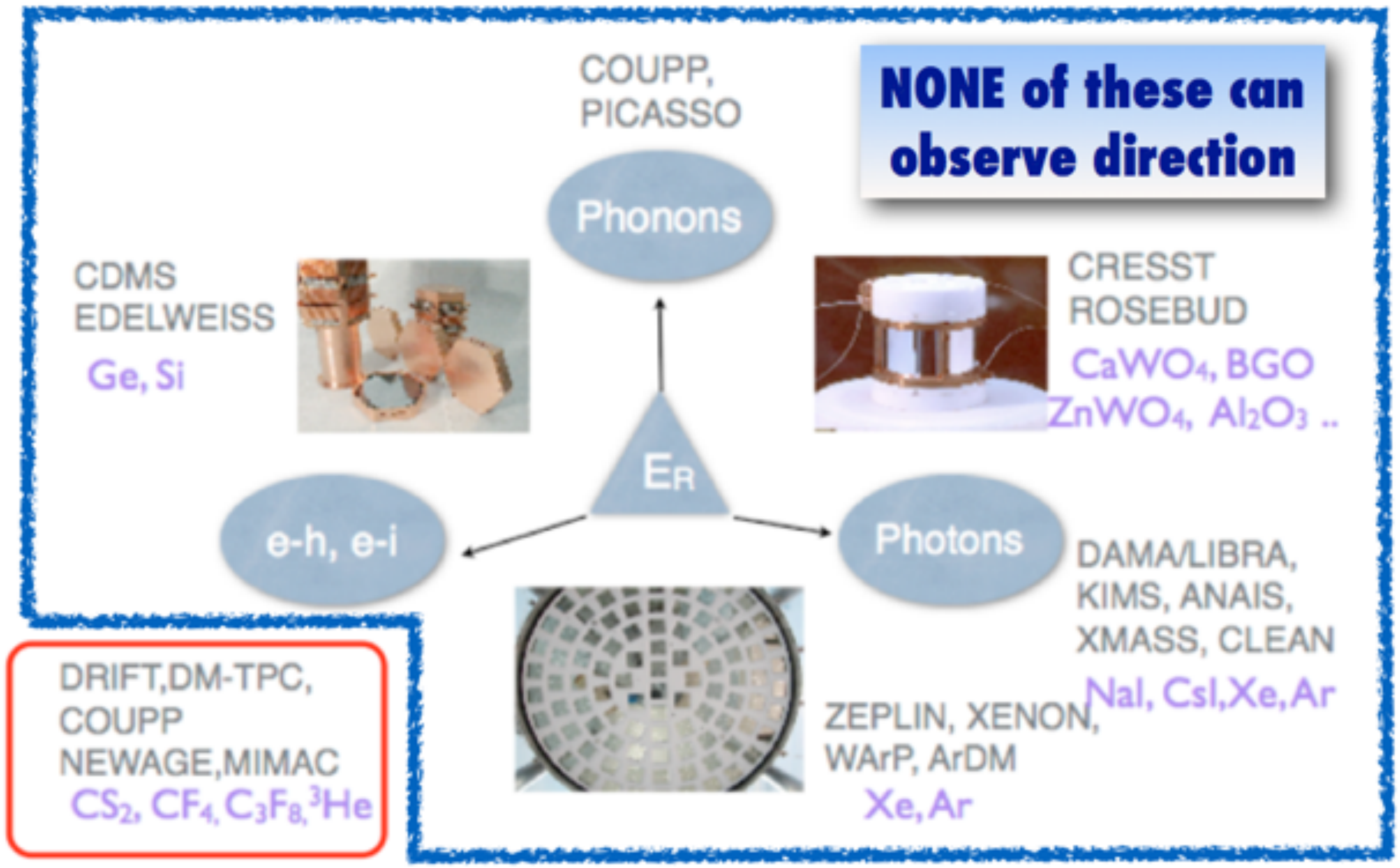
- *Diurnal Direction Modulation:* Earth rotation about its axis, oriented at angle w/respect to WIMP "wind", change the signal direction by 90 degree every 12 hrs. ~30% effect.



No background <u>whatsoever</u> can mimic a directional correlation with an astrophysical source

<u>PLUS: directionality is the only tool that allows to reject the neutrinos background from the Sun</u>

DM Direct Detection Experiments



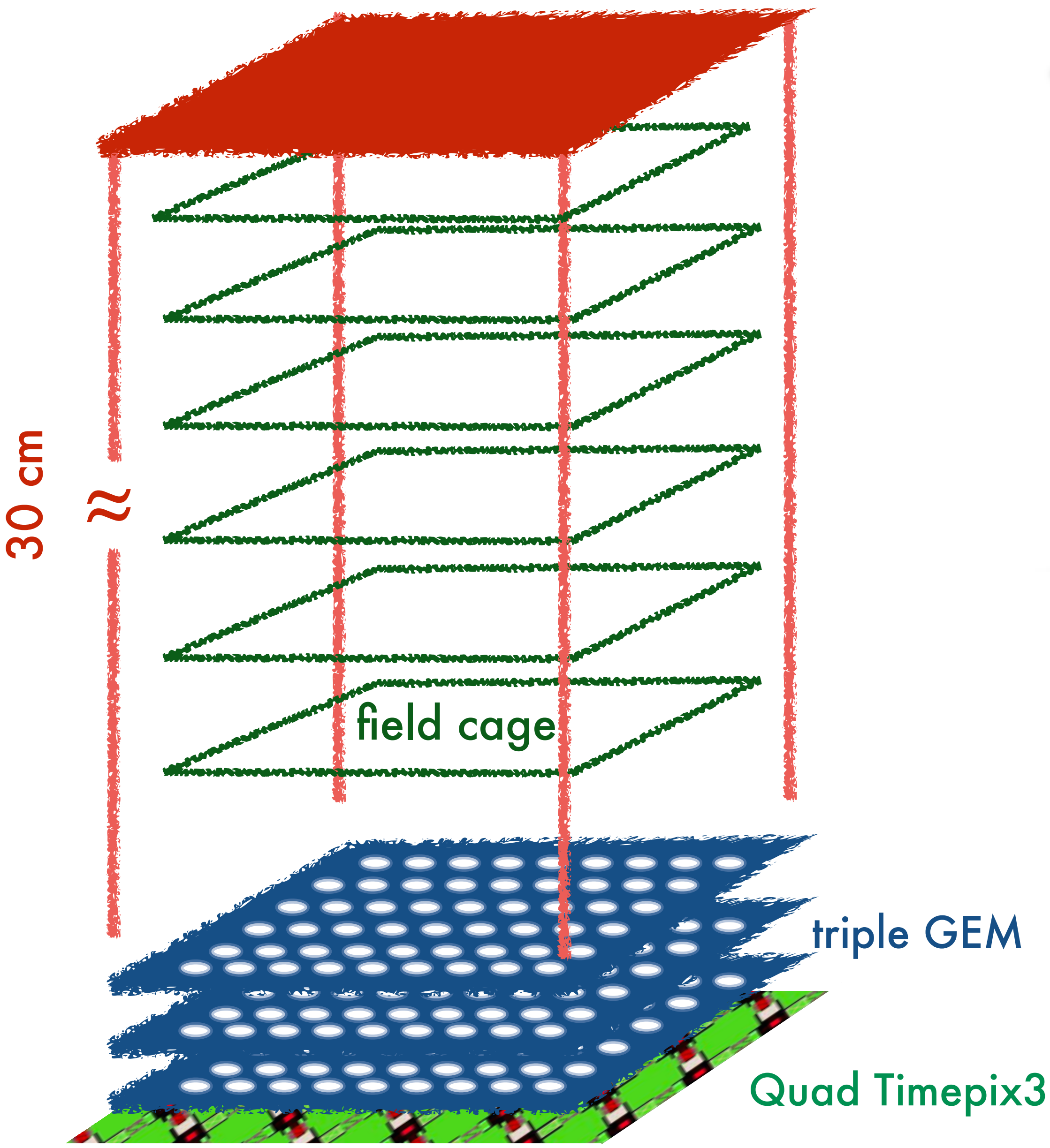
DRAWBACK: small masses

Low pressure gas detector in order to observe direction at these energies

- Directional gaseous detectors potentially provide the best observables of any DM experiment:
  - total charge collected indicates energy of the recoil
  - comparison b/w track path and energy provide excellent rejection of alphas and electrons
  - the track itself indicates the axis of the recoil
  - measurement of charge (and dE/dx) along the path allows to infer the sense of direction

All these information offer much more efficient means to actively suppress background than any other experimental approach

NITEC project



3 x 3 cm^2

Started on 4/5/2015

MARIE SKŁODOWSKA-CURIE ACTIONS
 # 657751
Individual Fellowships (IF)
Call: H2020-MSCA-IF-2014

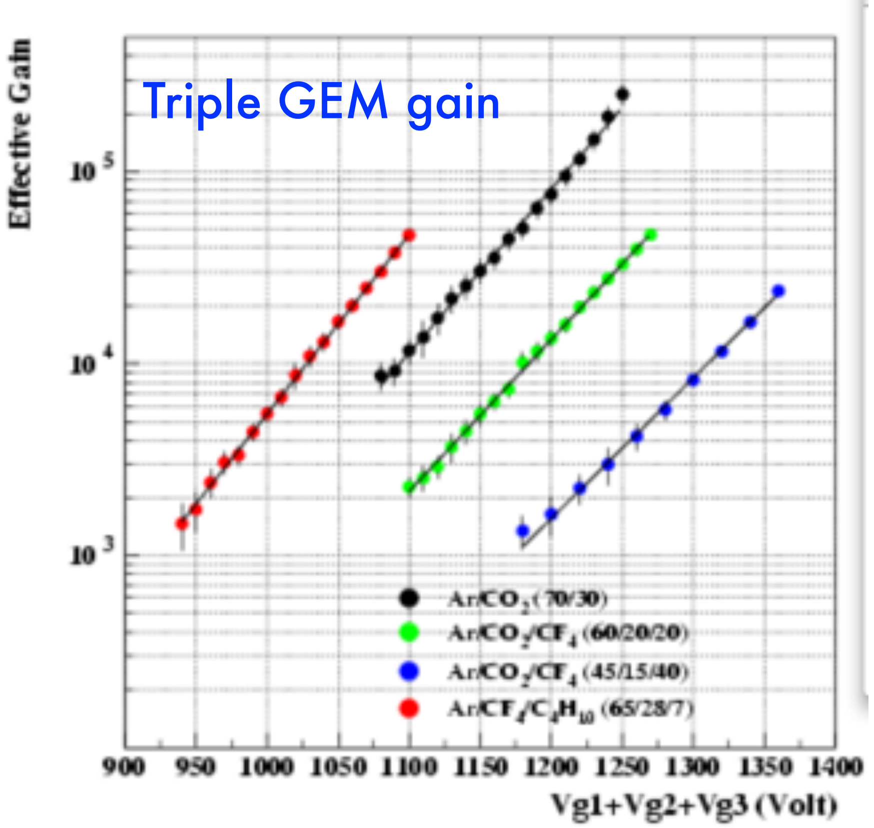
- A Negative Ion Time Expansion Chamber for very rare event searches
  - Negative ions as image carrier
  - 30 cm drift distance
  - Triple GEM amplification
  - CMOS pixel readout

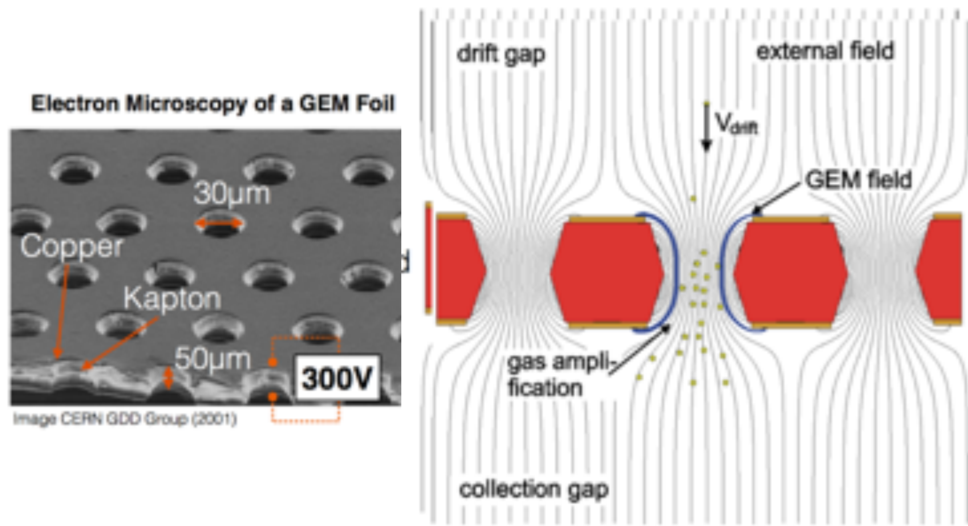
GEMPix

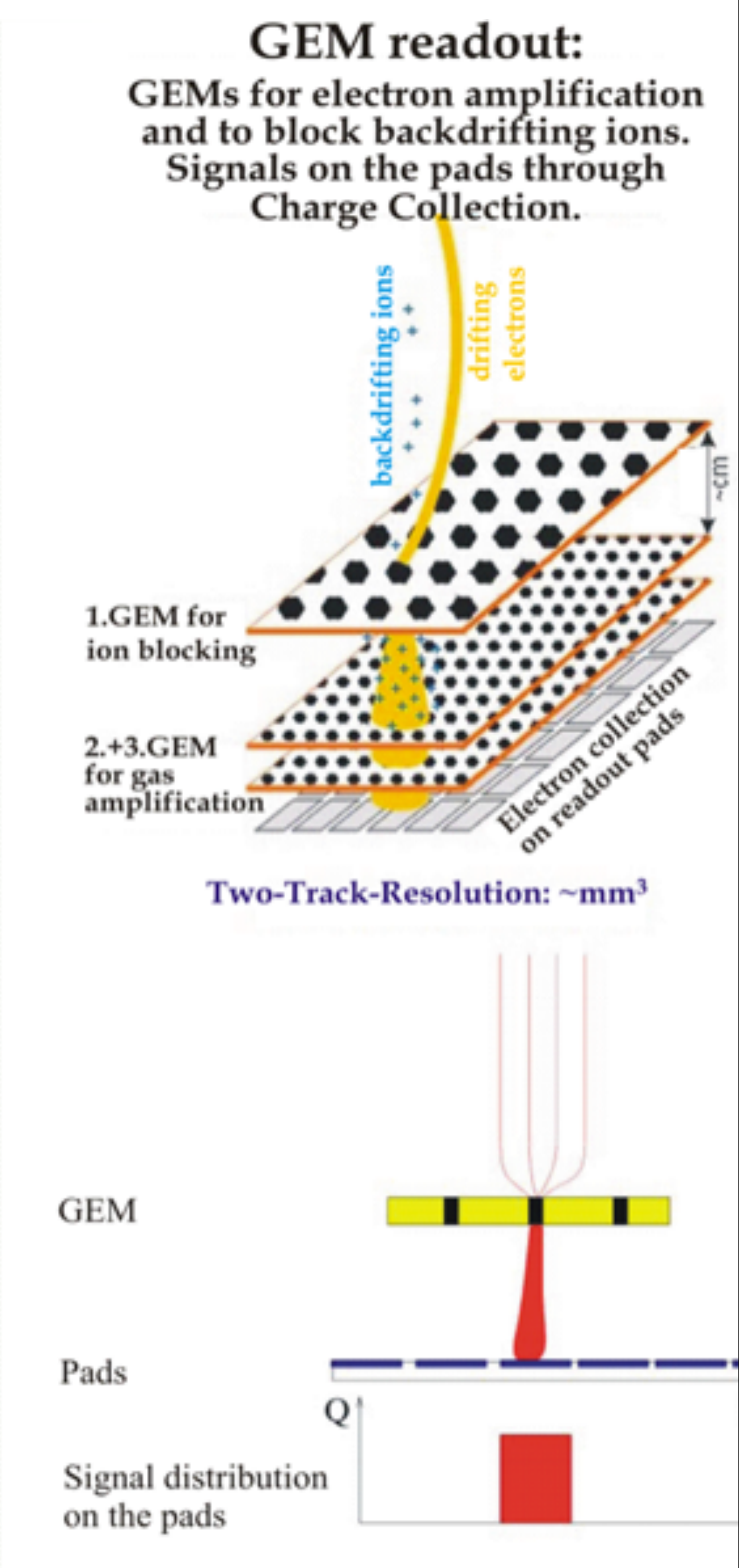
Innovation: first combination of negative ion concept with GEM amplification and CMOS pixel readout

- Prove capability of:
  - 3D reconstruction of the recoiling track with O(200) um spatial resolution
  - Low energy threshold with signal/background discrimination below 50 keV
  - Sense ("head-tail") discrimination down to about 50 keV
  - 30 cm drift distance with very small disruption of performances due to diffusion

GEM Amplification





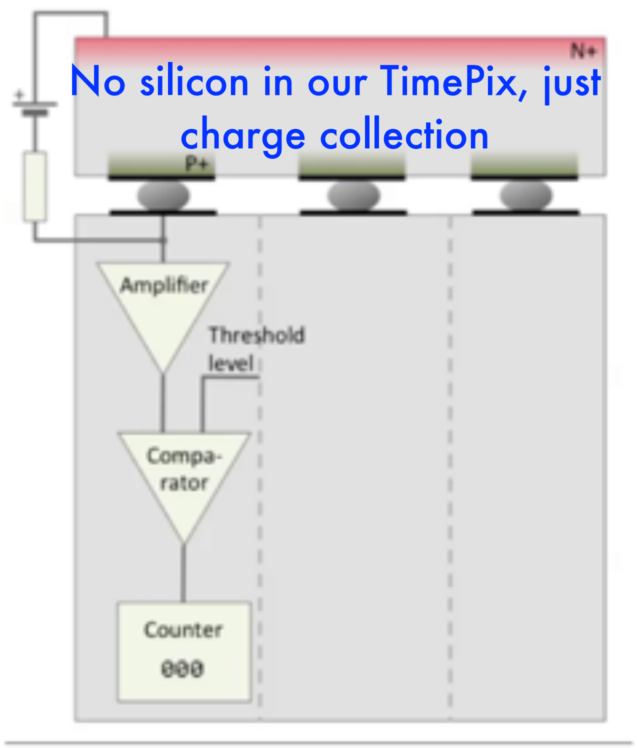


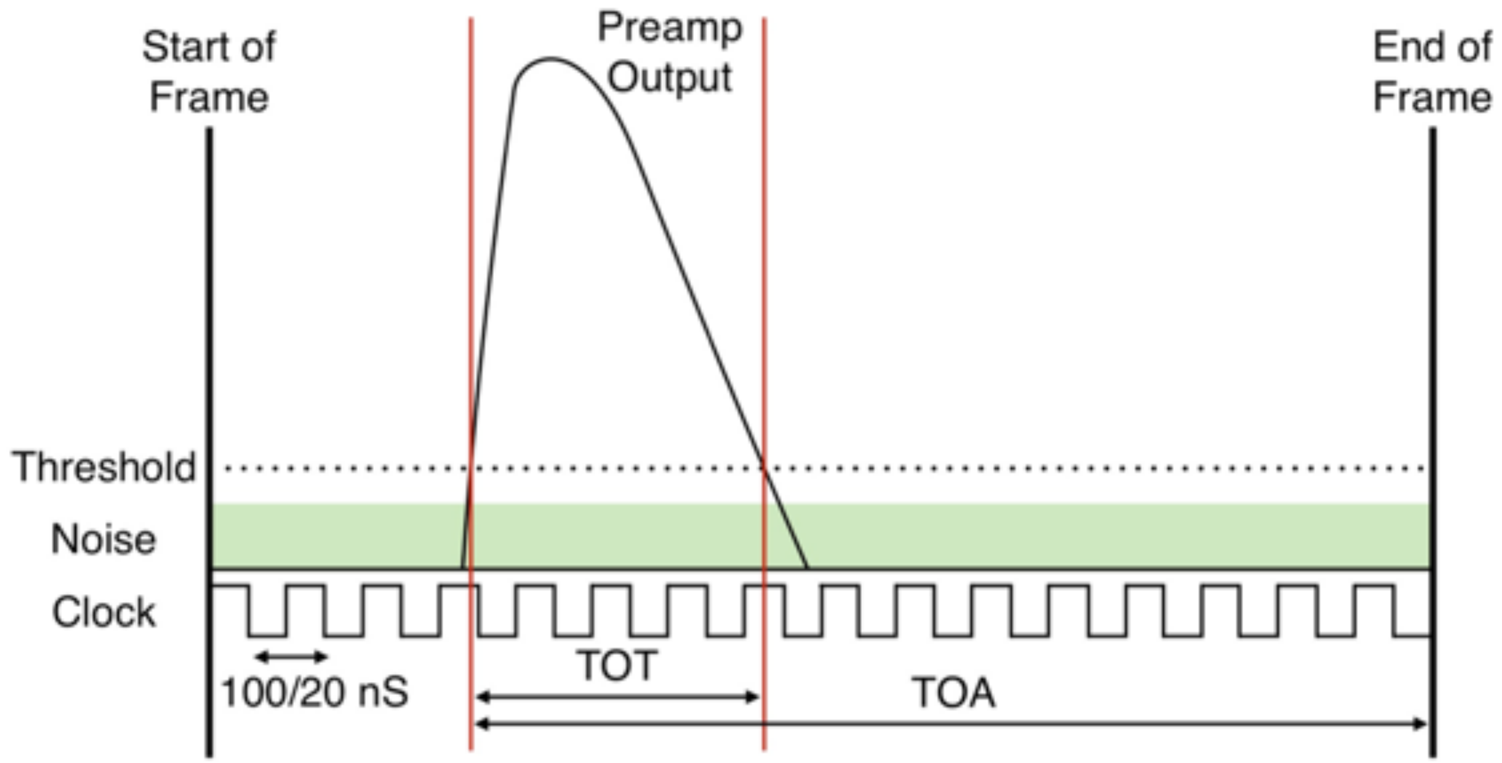
- Particle conversion, charge amplification and signal induction zones are physically separated
- Large dynamic range: from 1 to 10^8 particle/cm^2 /s
- Gain up to > 10^4
- High stability/granularity

- 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

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





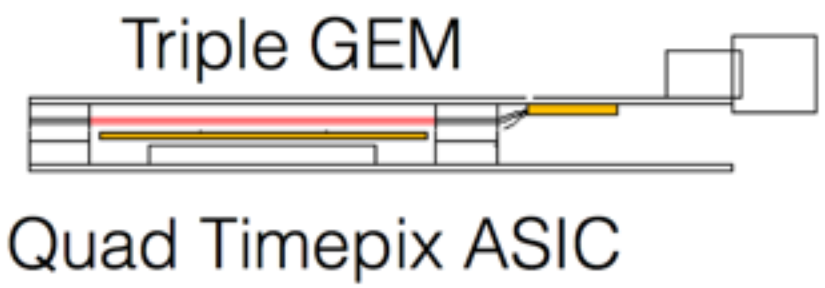
- Timepix clock can run from <1 MHz up to 100 MHz
- Timepix counter depth is 11810 —> limits total acquisition time —> ok for negative ion slow drift as well

TimePix vs Timepix3

	Timepix (2006)	Timepix3 (2013)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 μm^2	
Technology	250nm CMOS - 6Metals	130nm CMOS - 8Metals
Acquisition modes	1) Charge (iTOT) 2) Time (TOA) 3) Event counting (PC)	1) Time (TOA) AND Charge (TOT) 2) Time (TOA) 3) Event counting (PC) AND integral charge (iTOT)
Readout Type	1) Full-Frame	1) Data driven (DD) 2) Frame (FB)
Zero suppressed readout	NO	YES
Dead time per pixel	> 300μs readout time of one frame	> 475ns **~600x** Pulse measurement time + packet transfer time
Minimum timing resolution	10ns	1.562ns **6.4x**
On-chip Power pulsing (PP)	NO	YES
Minimum detectable charge	~750e-	>500e- **1.5x**
Output bandwidth	1 LVDS ≤200Mbps 32 CMOS ≤3.2Gbps	1 to 8 SLVS @640Mbps DDR ≤5.2Gbps **1.6x**

GEMPix

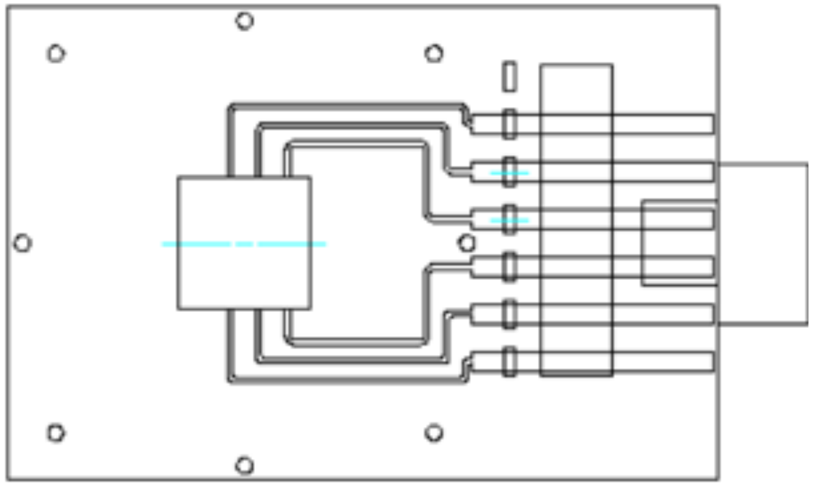
Triple GEM detector with HV filters and connector



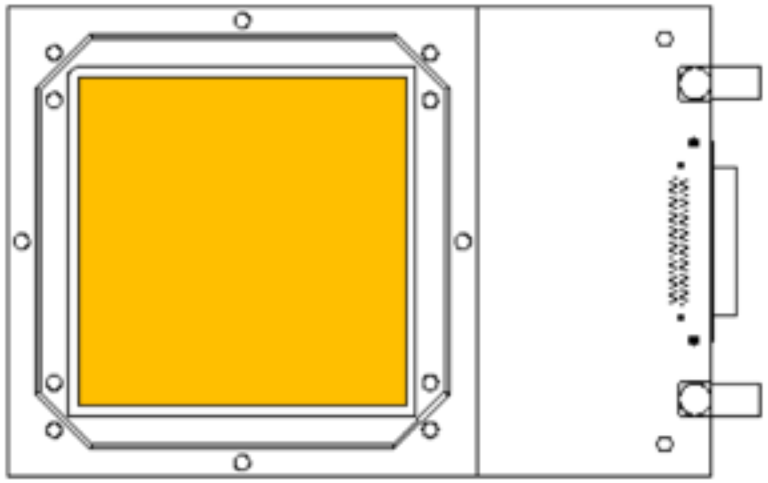
Quad Timepix ASIC board with naked devices (i.e. no silicon)

A dedicated GEM HV

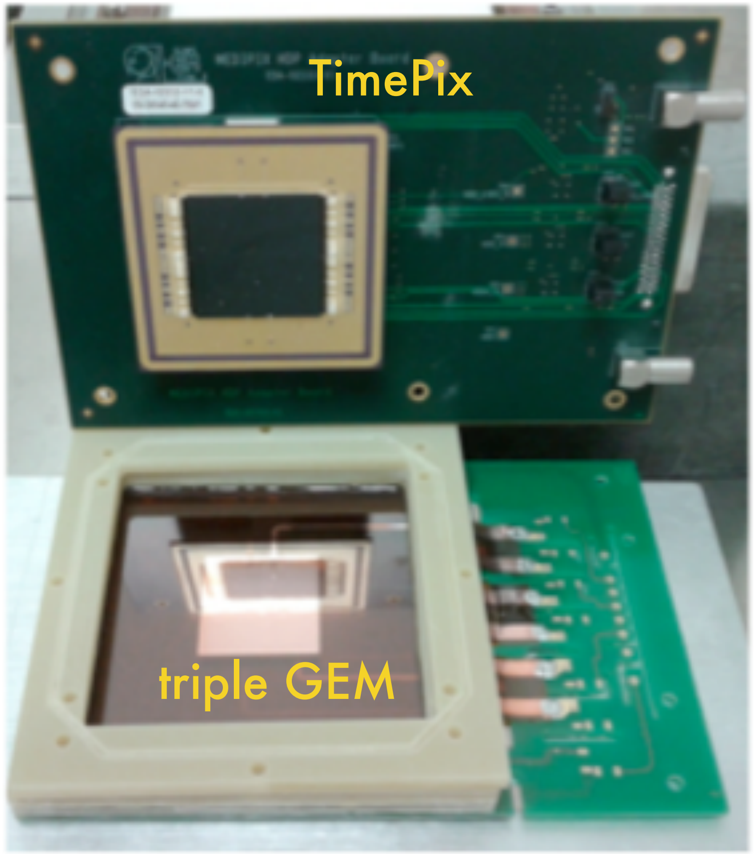
Developed by LNF **(F. Murtas)** in collaboration with CERN



top view



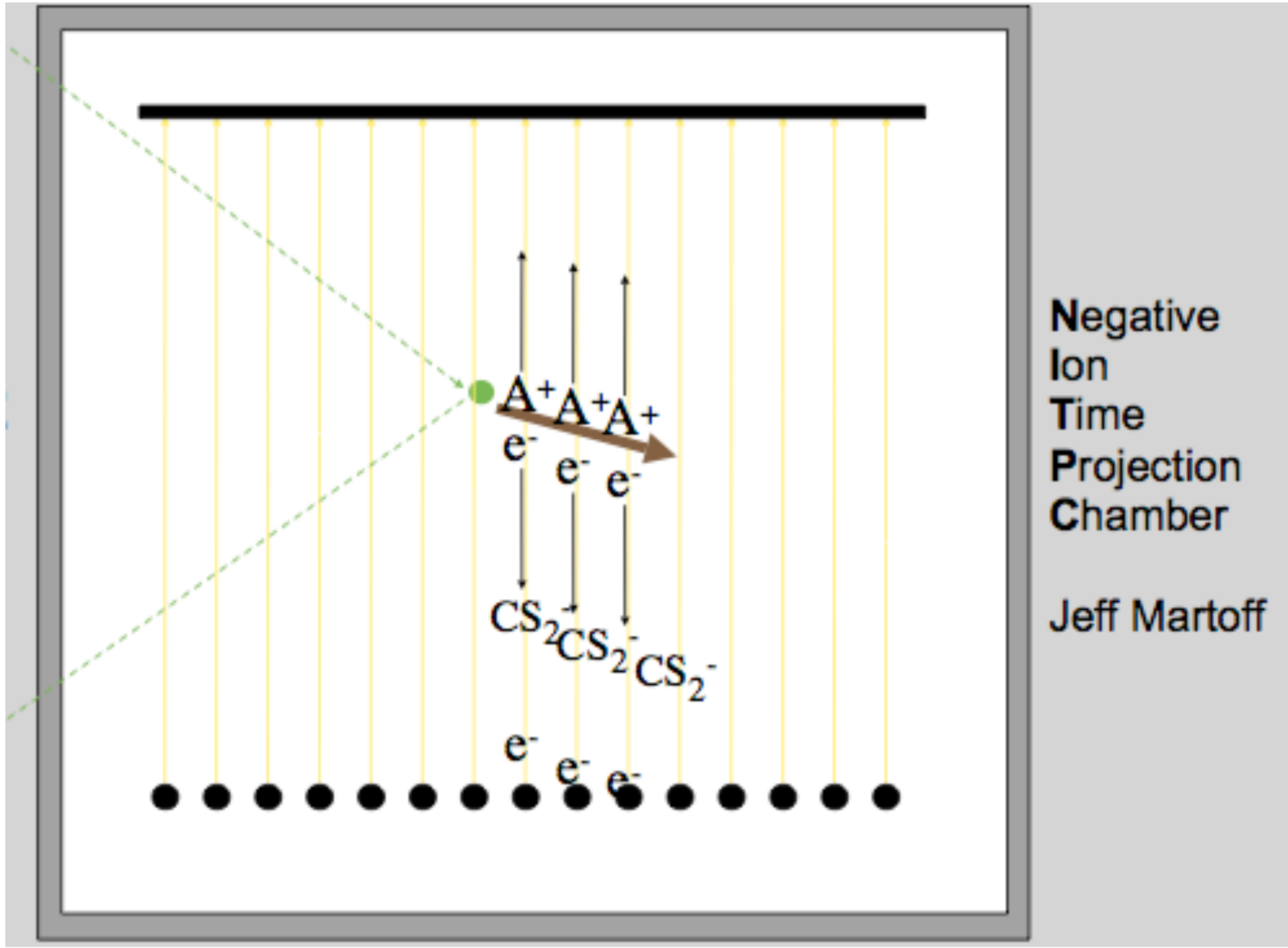
side view



pixel size 55 x 55 um

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

Negative Ion drift



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

J. Martoff et al., NIM A 440 355

T. Ohnuki et al., NIM A 463

- 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

Address TPC typical volume limitations

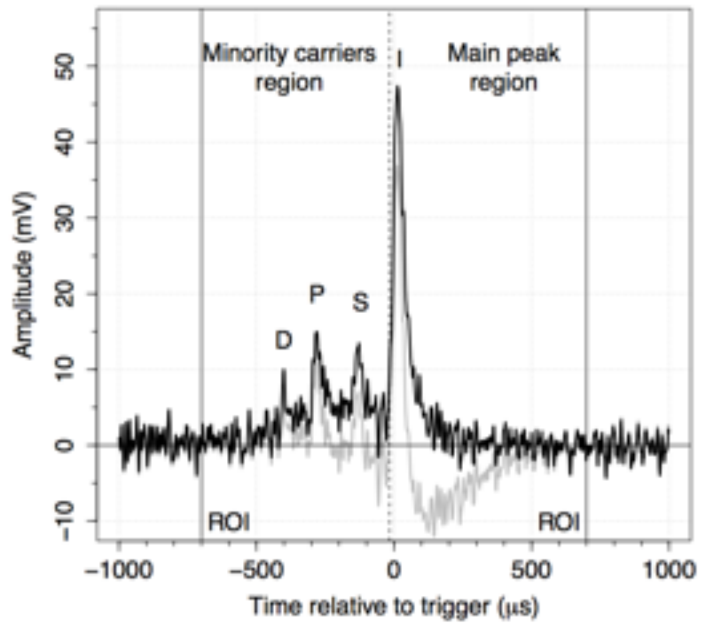
Negative Ions & Fiducialization

Fiducialization is **paramount** in Dark Matter search experiments to suppress radioactive background from detector materials

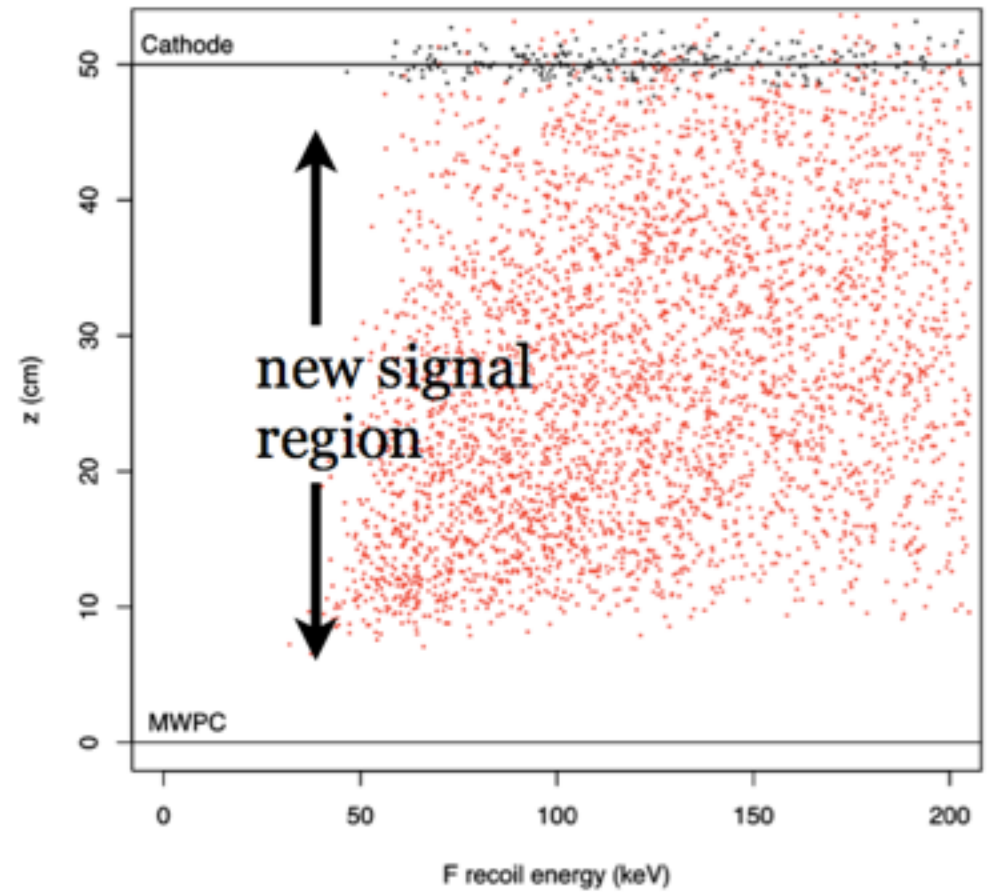
e.g. XENON100 use LXe as self-shielding, with a "fiducialized" target mass that is only ~ 35% of the total mass

Recently, the DRIFT experiment:

- **1% oxygen** added to normal 30:10 Torr CS_2: CF_4 mixture
- Appearance of "minority carrier" peaks **earlier** than the "majority" peak, carrying ~1/2 of the total charge (see Snowden-Ifft Rev. Sci. Instr. 85 (2014))
- Timing between main peak and minority peaks gives **absolute Z information** on events



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



Allowed to simplify cuts & enlarge signal region: **from ~5% to ~90%** signal efficiency

FEATURE AVAILABLE ONLY WITH NEGATIVE IONS DRIFT

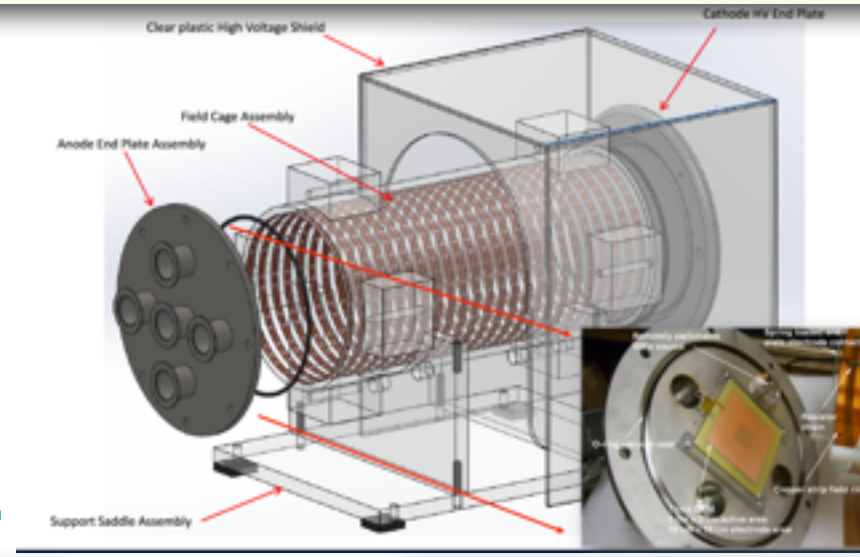
SF_6: a new player in the game

electron gas features | negative ion gas features

- Example: CF_4
  - Larger diffusion -> smaller detector length
  - Spin target -> no sacrifice of volume -> higher target density at same pressure -> can operate at shorter drift lengths.
  - Benign
  - Good scintillator -> allows for optical readouts
  - Fiducialization?

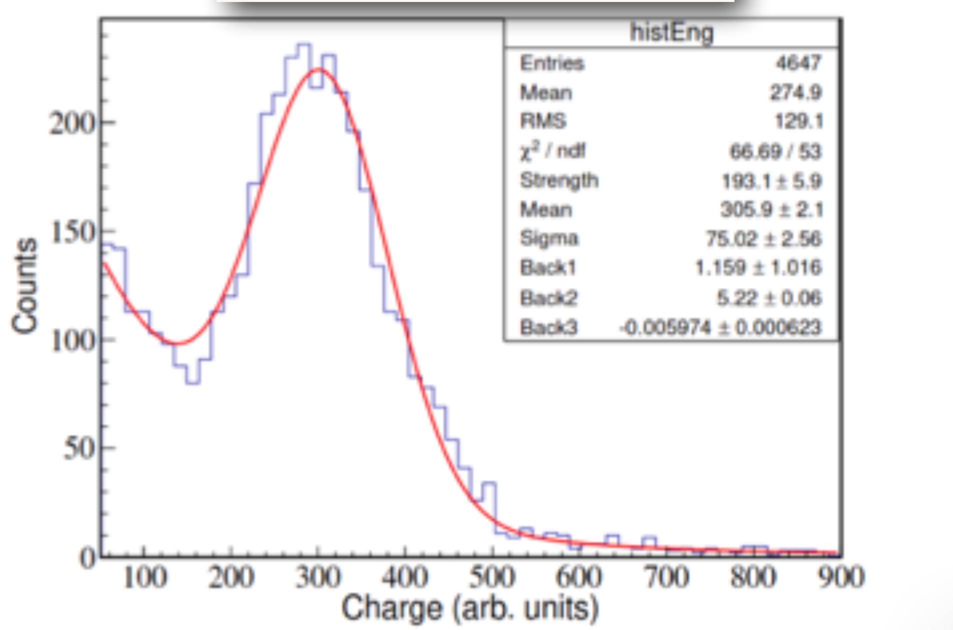
- Example: CS_2
  - Low diffusion -> large detector length
  - Good high voltage operation at low pressures
  - Demonstrated fiducialization
  - Lack spin-dependent content -> sacrifice detector volume to enable negative ion operation with a spin target
  - Toxic **TOXIC**

<u>ONLY ONE</u> measurement exists, with <u>thick GEMs</u>



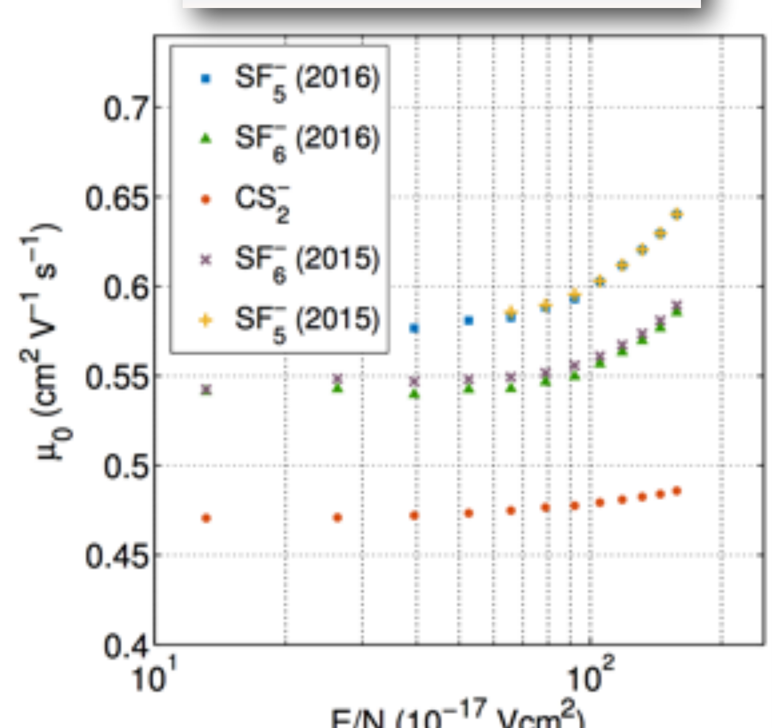
Could SF_6 have only nice features of both???

Gas gain proved

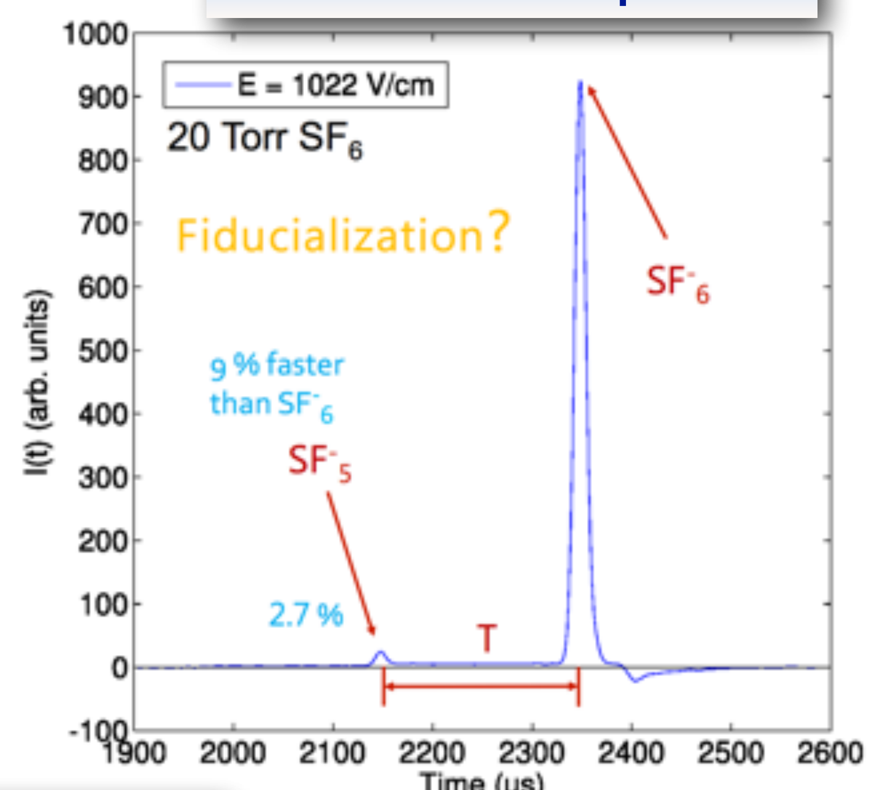


(a) ^{55}Fe energy spectrum in 30 Torr SF_6 using 0.4 mm THGEM

Mobility



Fiducialization proved



<u>From D. Loomba talks (2015-2016), not yet published</u>

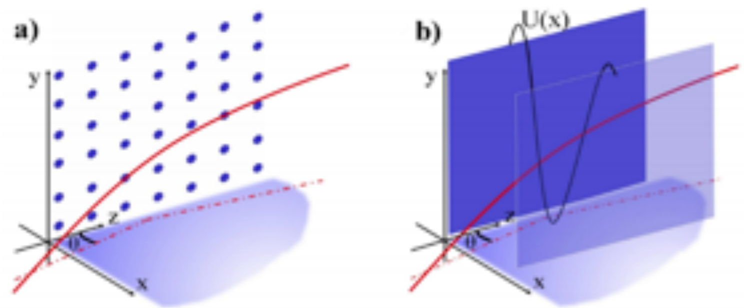
GEMPix + NITPC: A Time Expansion Chamber

- 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)

NITEC synergy: DCANT

Channelling concept



Critical (Lindhard's) angle

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

$2U_0$: Potential well depth

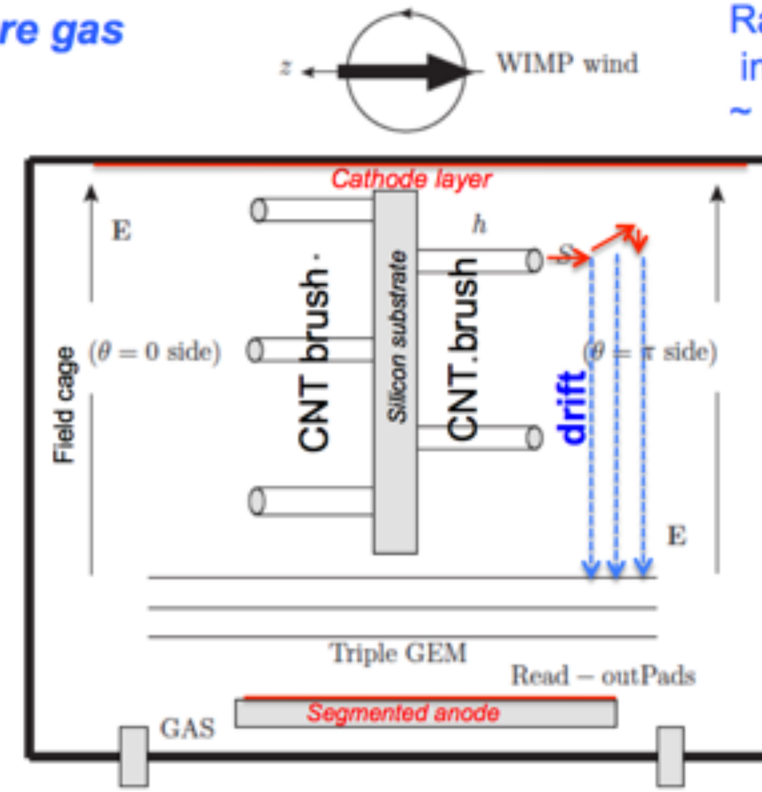
E: Particle energy

~ 8 deg for ^6C at 10 KeV

Detector concept

Low pressure gas (0.1 bar)

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



Not to scale!

h ~100 μm

S ~ $\pi(5)^2$ nm^2

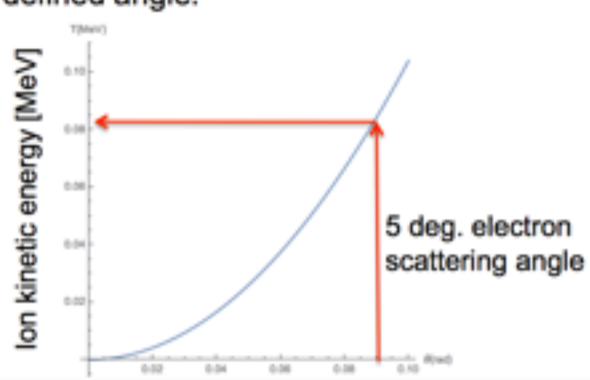
Drift distance can be 10 cm

Carbon ions **ranging out** In the gas

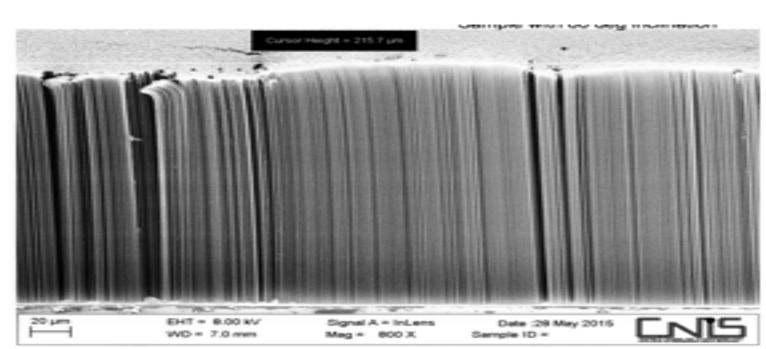
Electrons from ionized gas atom **drift** towards anode

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 <u>WITH DIRECTIONAL SENSITIVITY</u>

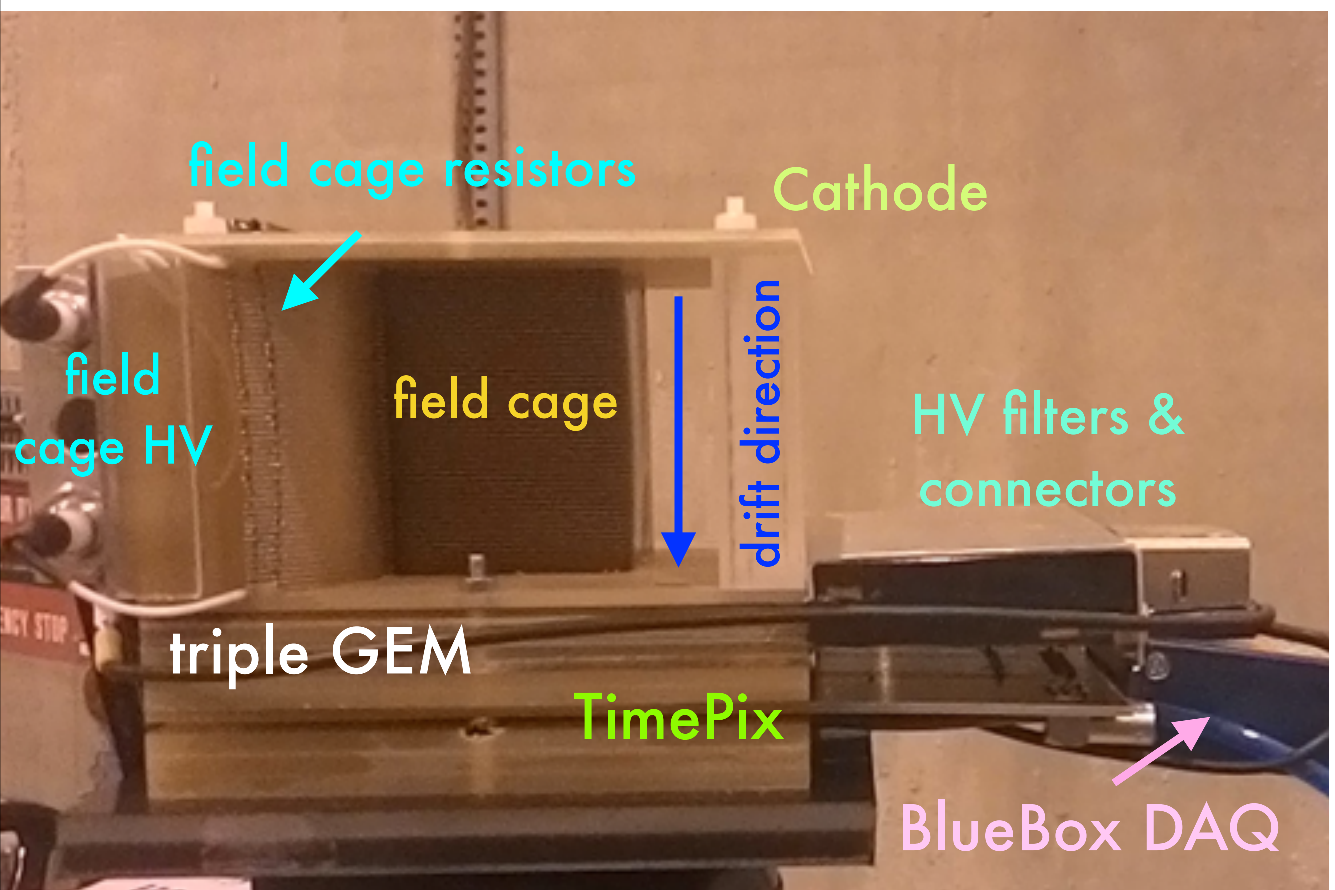


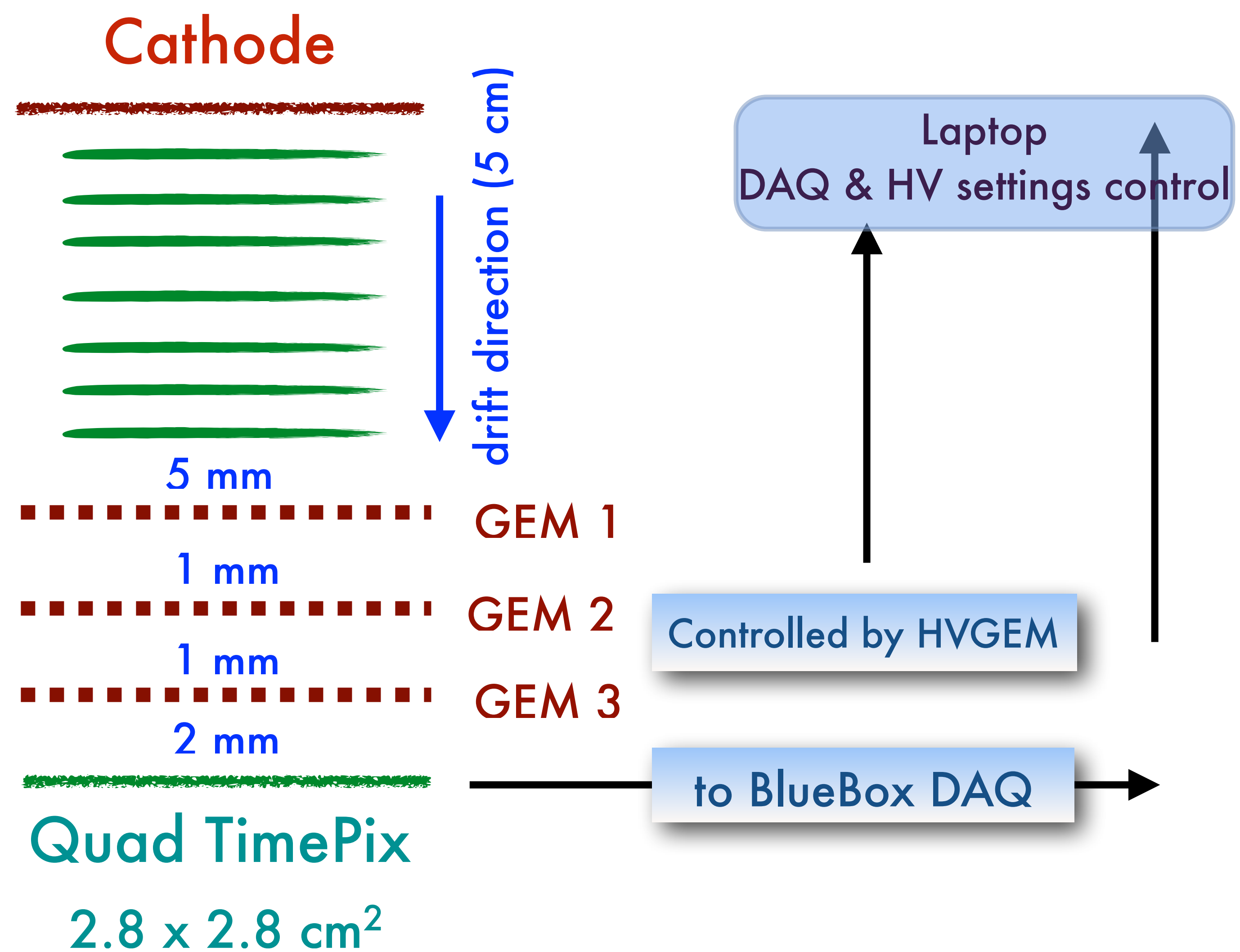
- About 10^{16} 1nm diameter SWCNT can fit on a 10x10 cm^2 substrate
- Surface density of a graphene layer: 1/1315 g/m^2
- About 2 g CNT on 100cm^2
  - ***CNT ropes?***

Developed an active and fruitful collaboration with DCANT group @ Roma1

The first NITEC prototype

This is the first 5 cm drift distance TPC ever realized with GEMPix readout





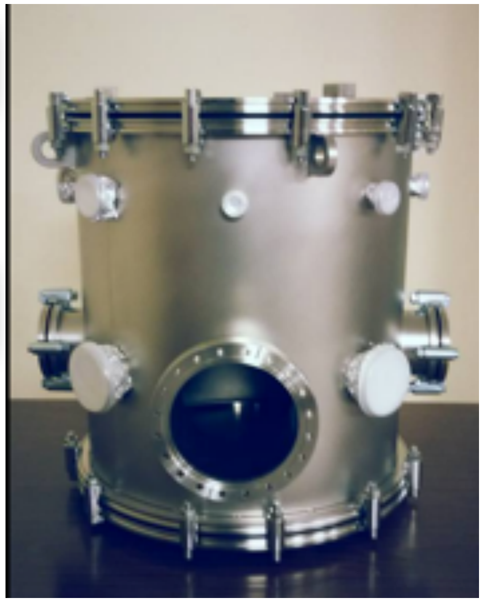
NITEC activities @ LNF

- Characterization of the small prototype with Ar:CO_2 and Ar:CO_2:CF_4 mixtures in traditional electron carrier configuration with:
  - Cosmics
  - ^{55}Fe spectrum
  - Electrons at BTF

Jul-Sep 2015

Oct 2015/Apr 2016

- Design and procurement of vacuum vessel to operate below atmospheric pressure



- First tests of the small prototype with SF_6 mixtures

Nov 2015 - Apr 2016

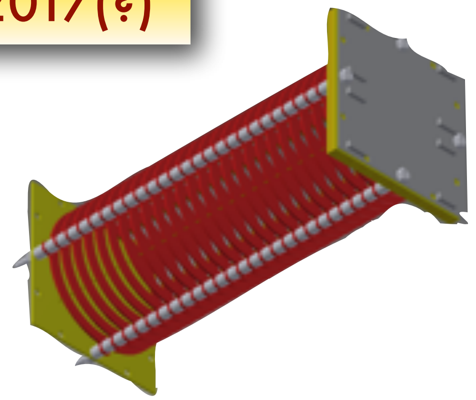
- Design, development and manufacturing of large prototype

May 2016

May 2016 - ???

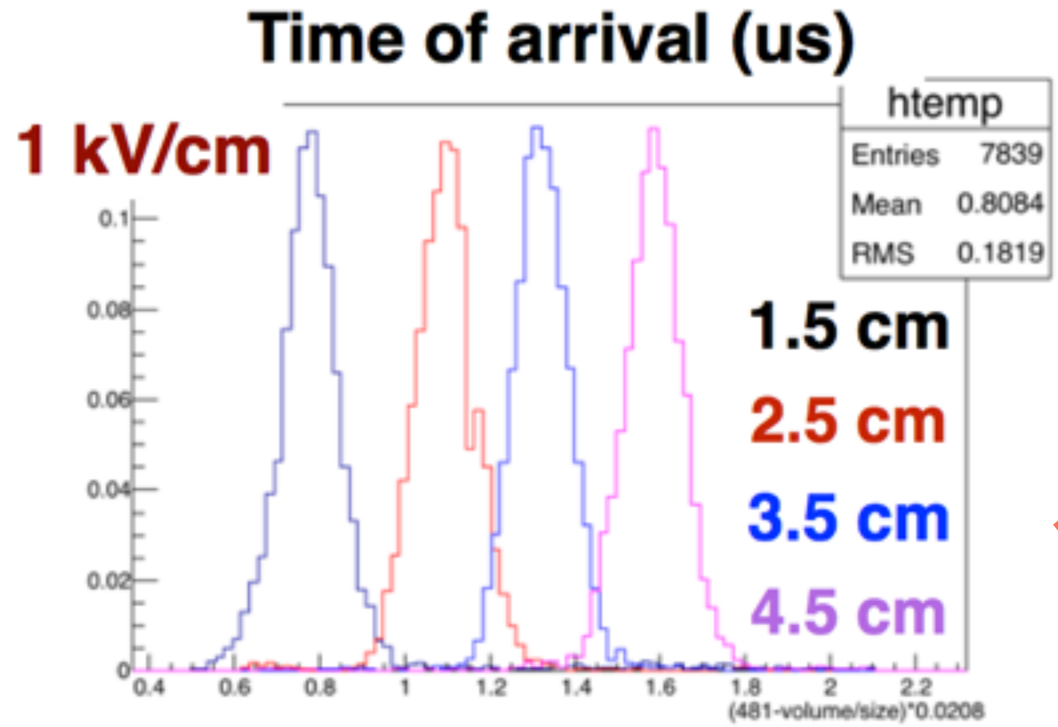
- Characterization of the large prototype with SF_6 and CS_2 mixtures
  - Synergically with the DCANT project to test anysotropic response of carbon nanotubes for directional DM searches

(?) Nov 2016 - Mar 2017(?)

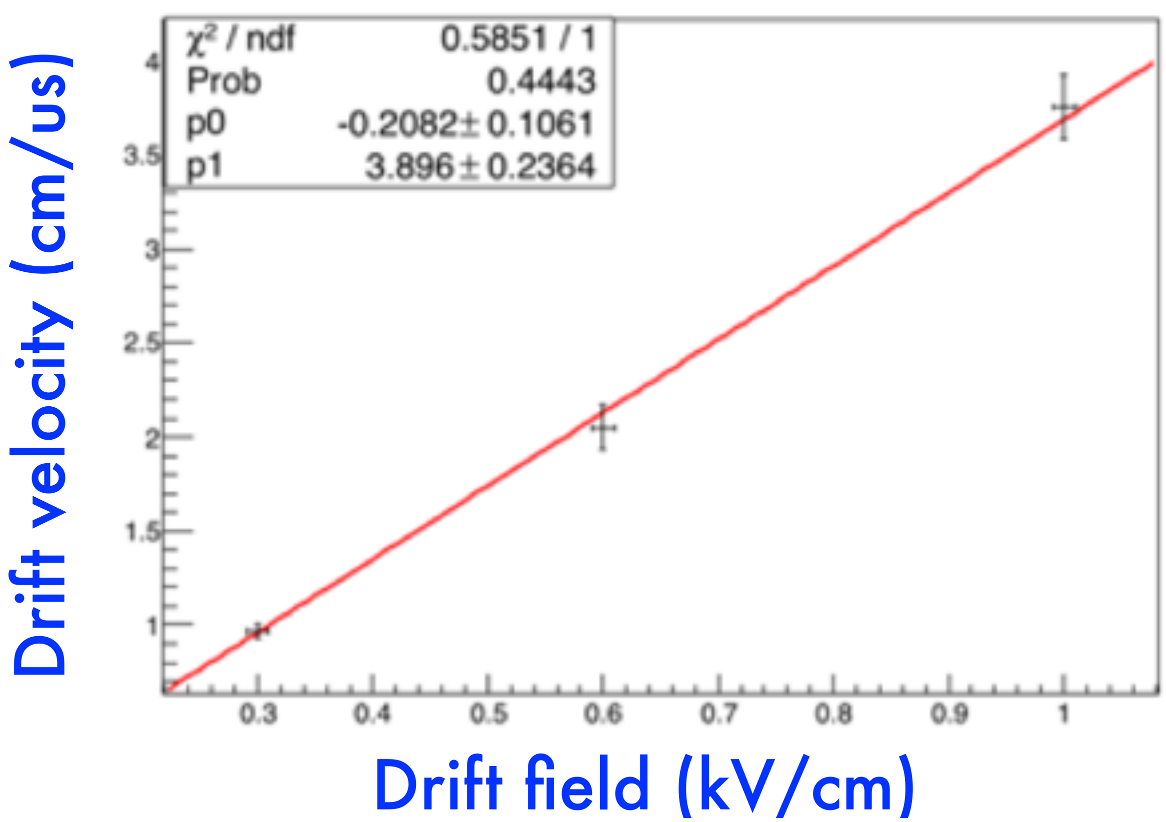


NITEC characterization with Ar:CO_2:CF_4

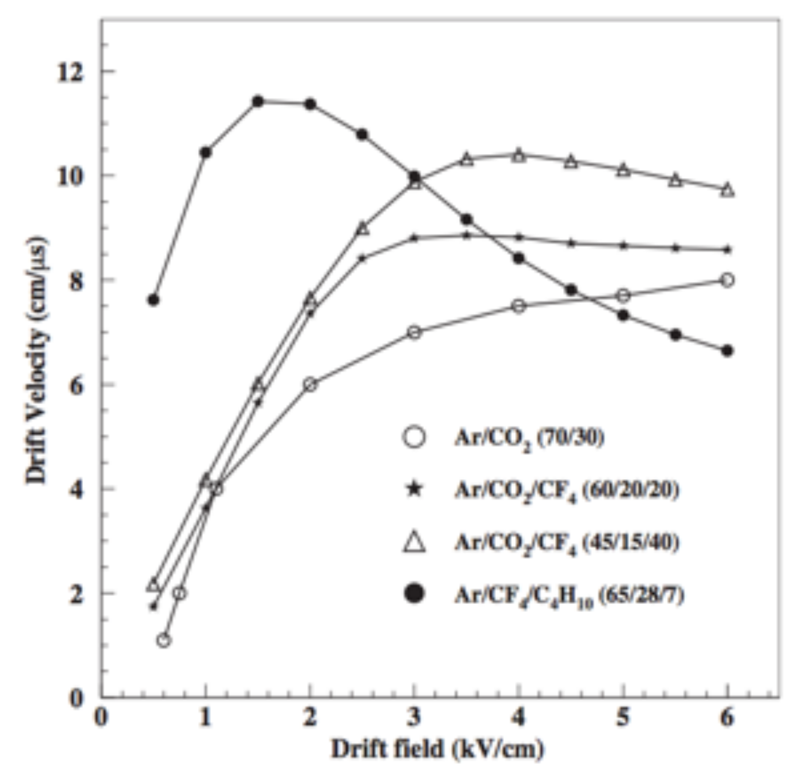
450 MeV electron beam data @ BTF



PRELIMINARY



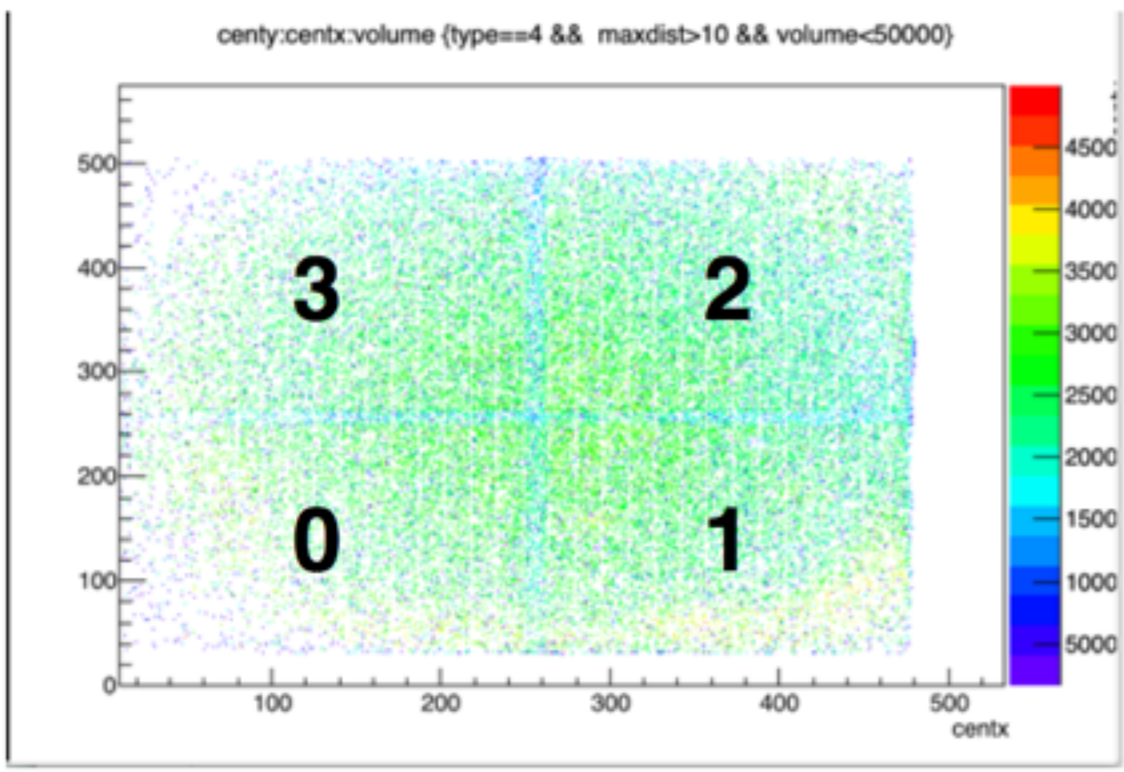
Consistent with published measurements

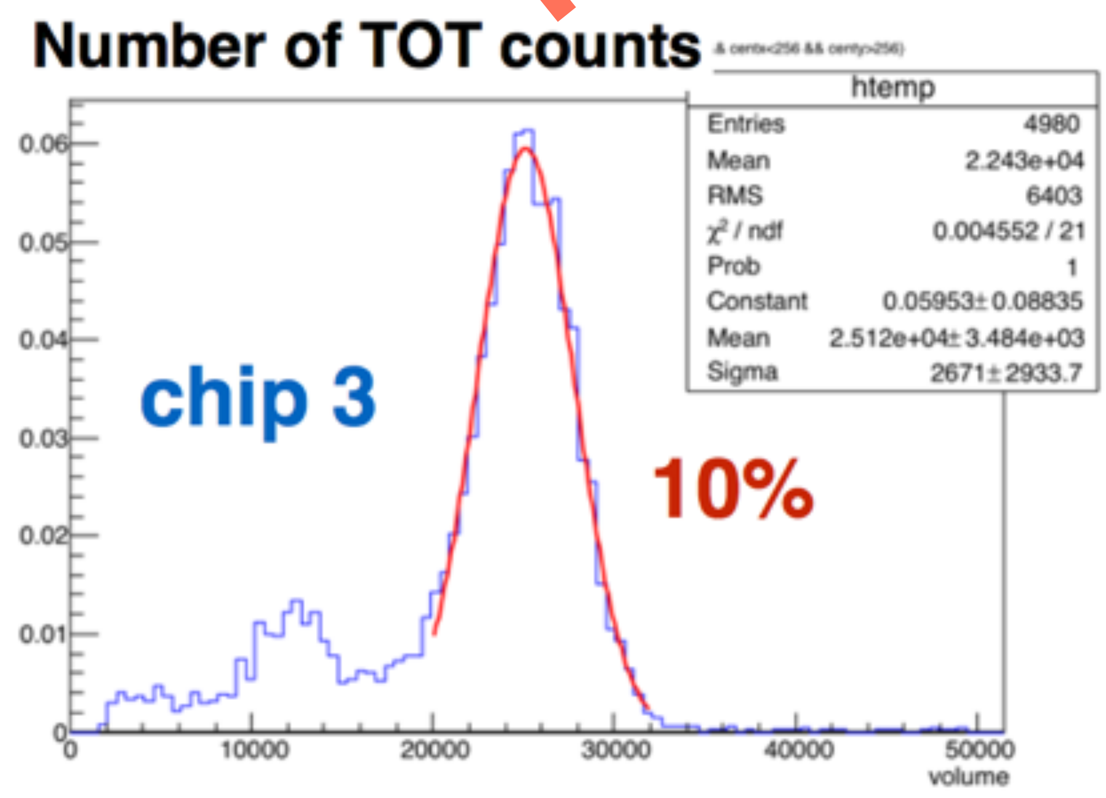


NITEC characterization with Ar:CO_2:CF_4

^{55}Fe radioactive source

PRELIMINARY

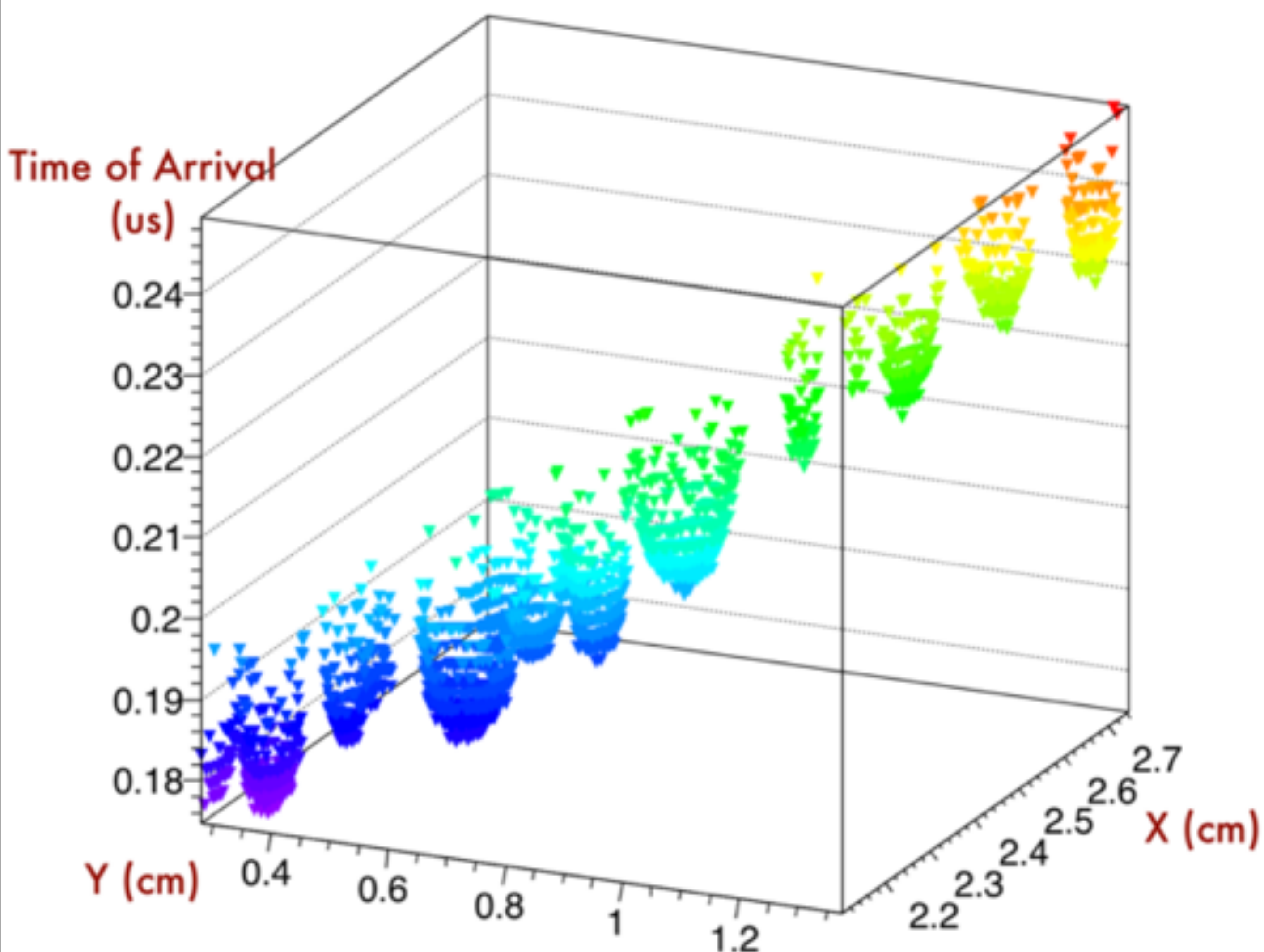




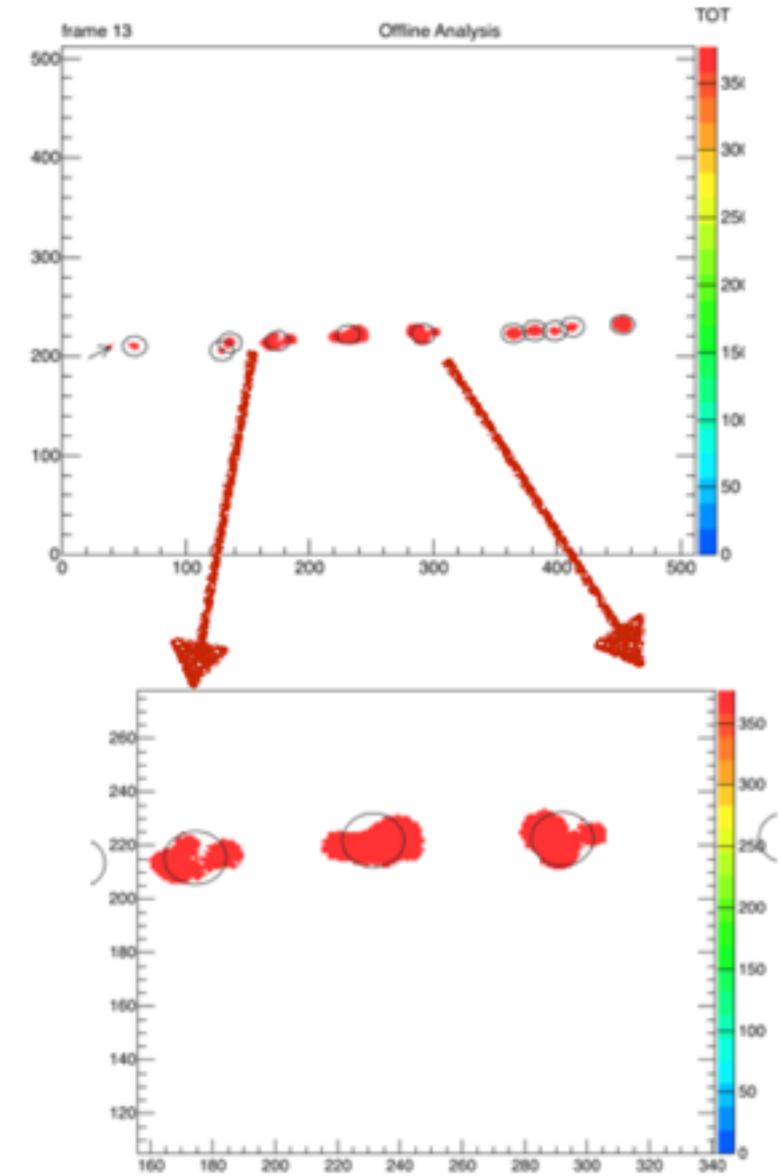
10% - 12% energy resolution with non-optimized calibrations

Cluster Counting with Ar:CO_2:CF_4

A cosmic ray recorded track
(raw data)



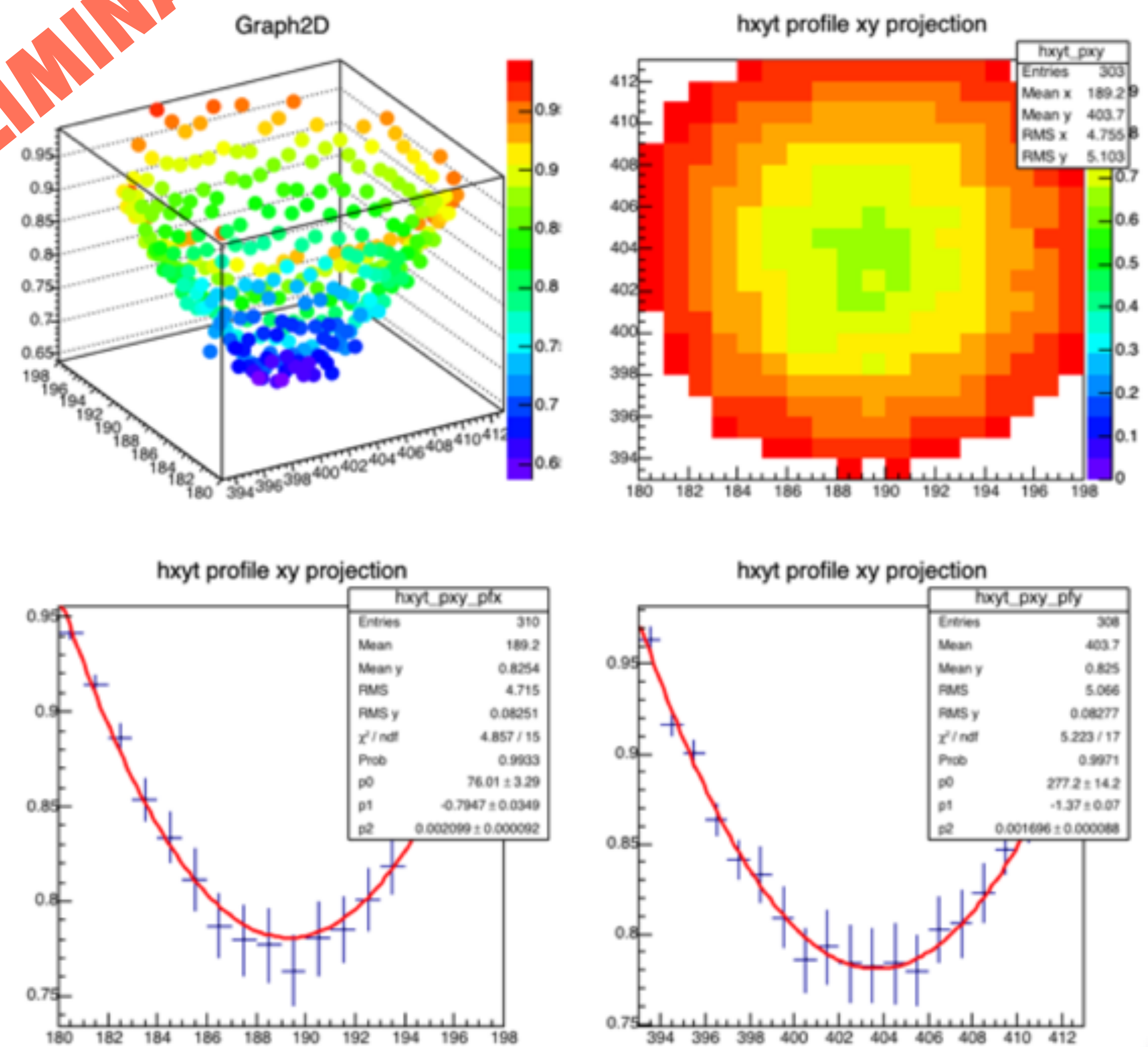
Standard GEMPix code
(MAFalda) cluster finding output



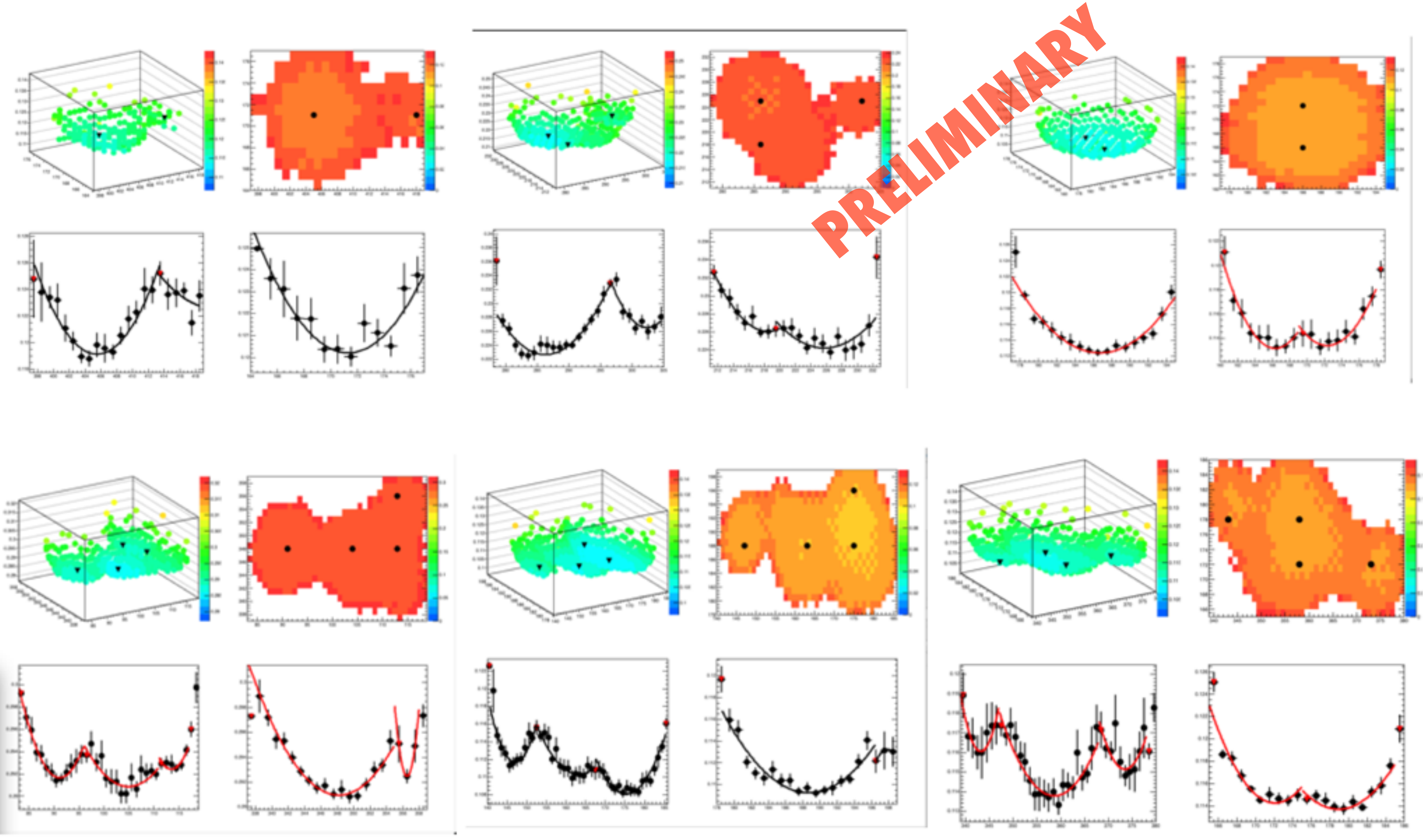
Cluster Counting with Ar:CO_2:CF_4

PRELIMINARY

- Start from BlobsFinder output and see if found blobs represent more than one cluster
- Tune the logic on ^{55}Fe data where only single clusters are present
- Extremely simple strategy for the moment
    - Look at xy, xt and yt projection
    - if single cluster, xt and yt projection can be fitted by pol2
- More complex strategy to be developed



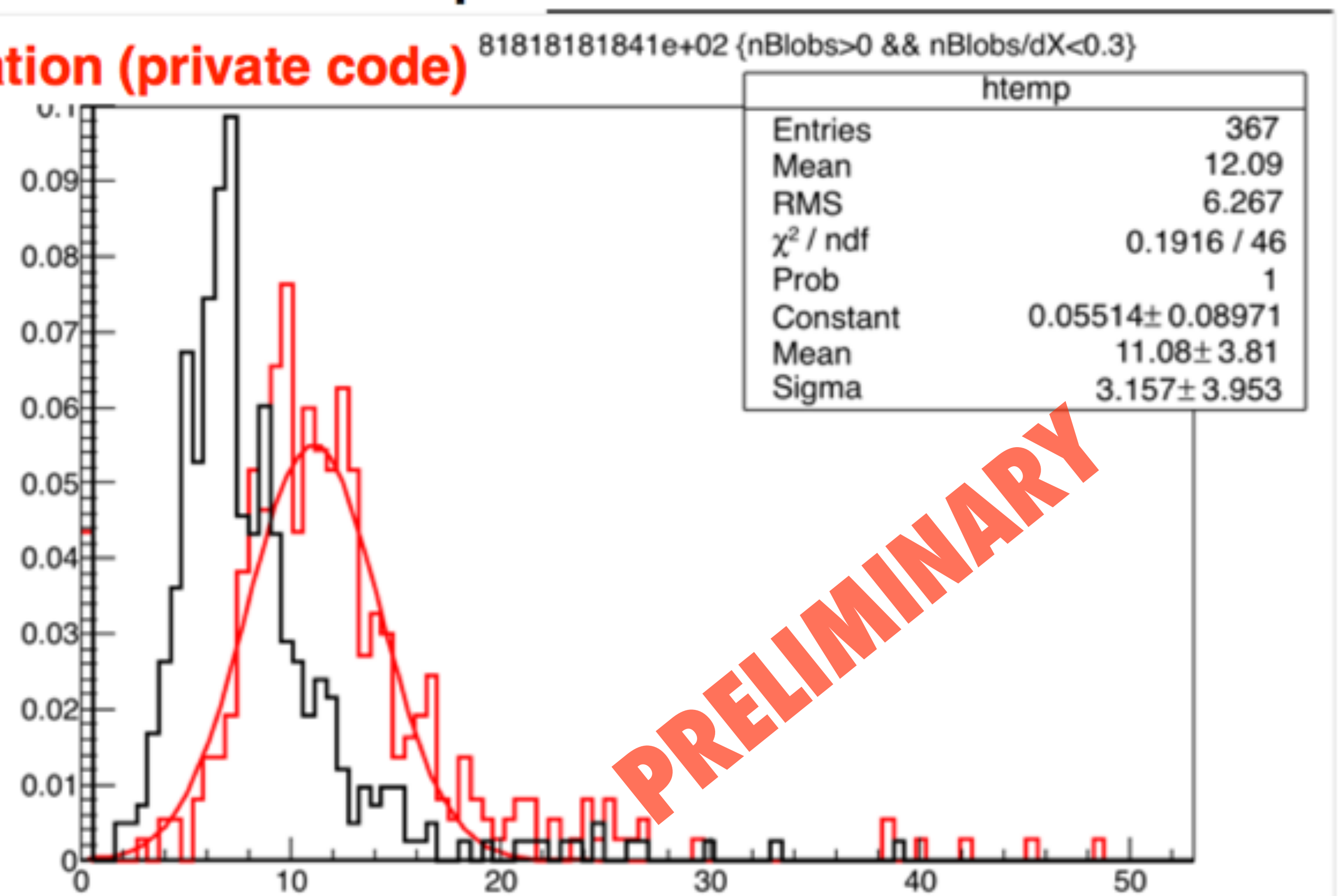
Cluster Counting with $Ar:CO_2:CF_4$



Cluster Counting with Ar:CO_2:CF_4

BlobsFinder MAfalda framework output

All pixels information (private code)



#of clusters/cm expected ~ 25

more work needed but already very encouraging (~50% efficiency)

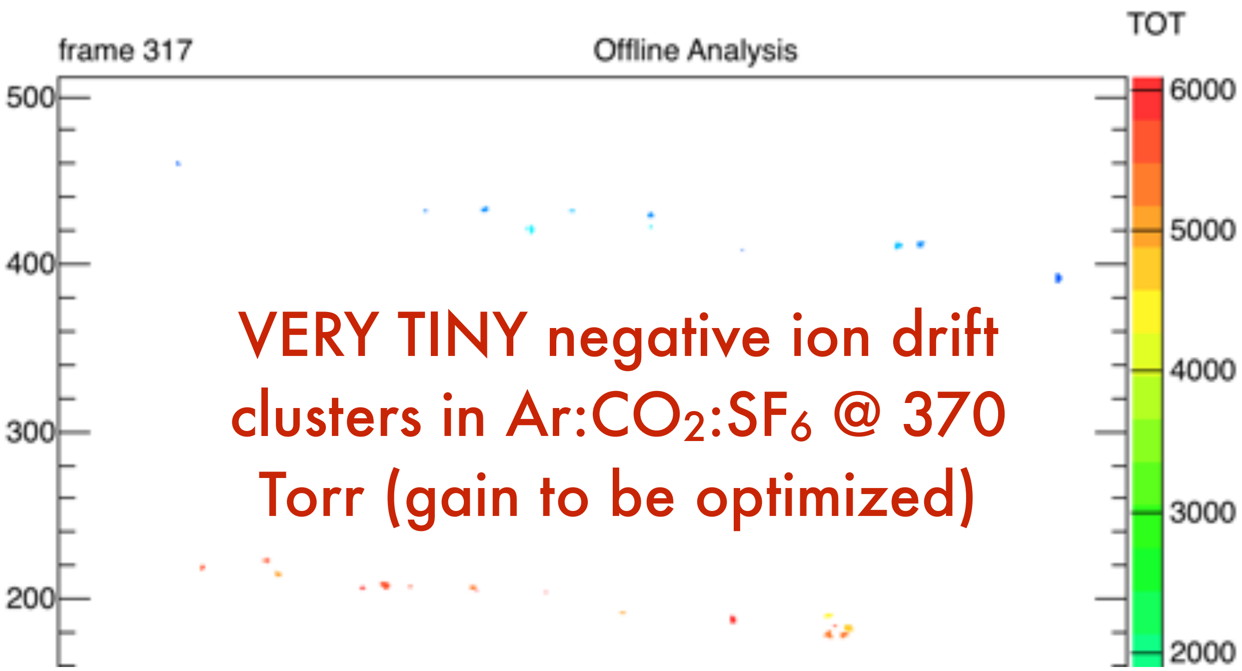
From Nygren's paper it appears that, even if the counting efficiency is significantly less than 100%, the energy resolution can still remain close to the intrinsic resolution. The reason for this is that if the fraction of counts lost is not large, the level of fluctuations in the lost counts is small relative to the intrinsic fluctuations in the number of electron/ion pairs in the total track. This assertion implicitly assumes

NITEC negative ion operation with SF_6

~1 month ago!!!!

FIRST EVER negative ion operation with SF_6 and thin GEMs

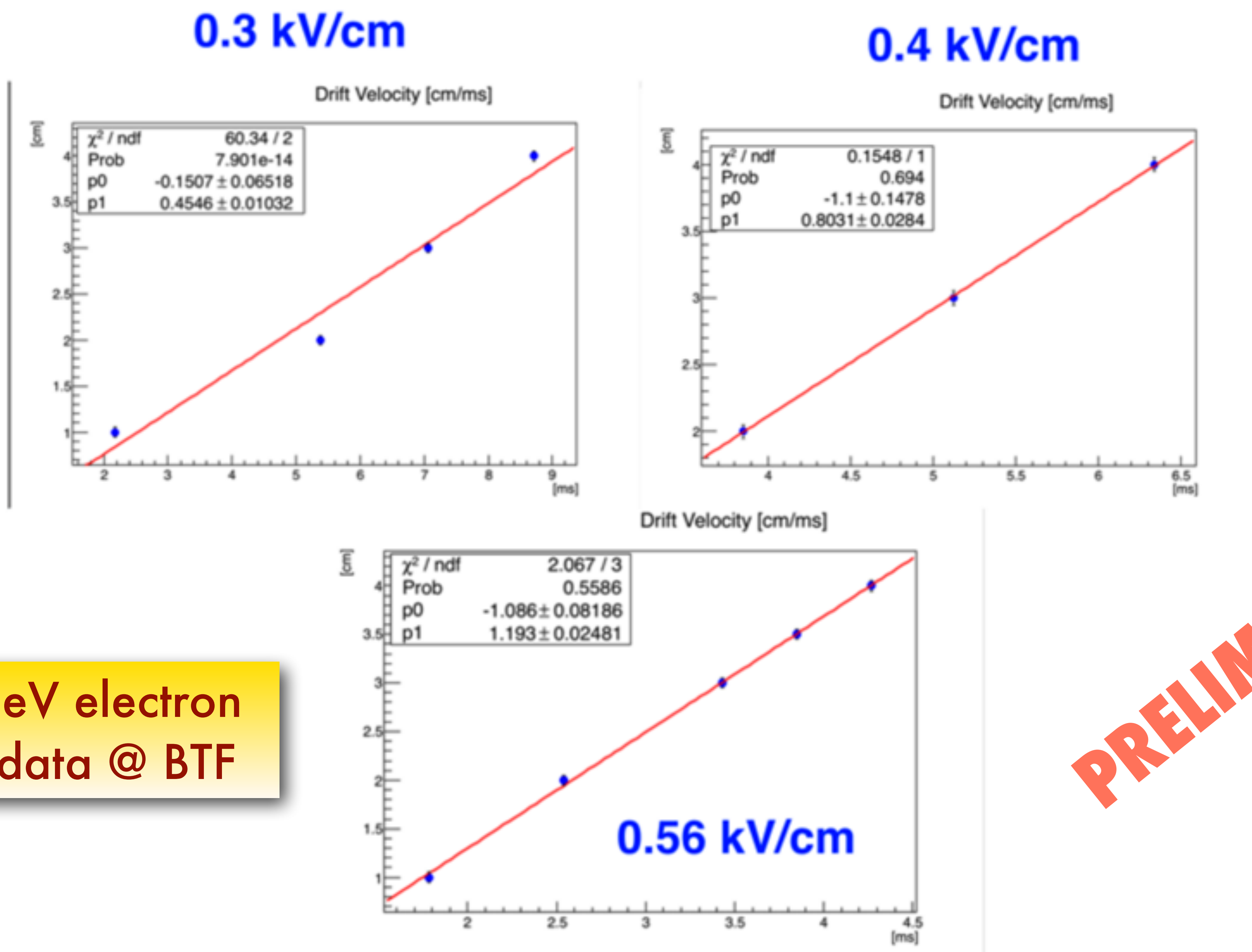
FIRST EVER negative ion operation with $Ar:CO_2:SF_6$ mixture 58:15:27



electron drift clusters in $Ar:CO_2$ @ 740 Torr

- Encountered several operating issues for the TPC due to the low pressure regime (worst part of the Paschen curve)
  - Field cage built by Nikhef before the NITEC start for proton tomography and to be operated at atmospheric pressure
- Pressure and drift field strongly limited by this
  - Data taken at 370 Torr with ~0.3-0.6 kV/cm drift field
- Thanks to this experience, we are carefully designing the large prototype and performing preliminary tests on each component in order to solve all these issues

Negative ion drift velocity measurement in Ar:CO_2:SF_6



450 MeV electron beam data @ BTF

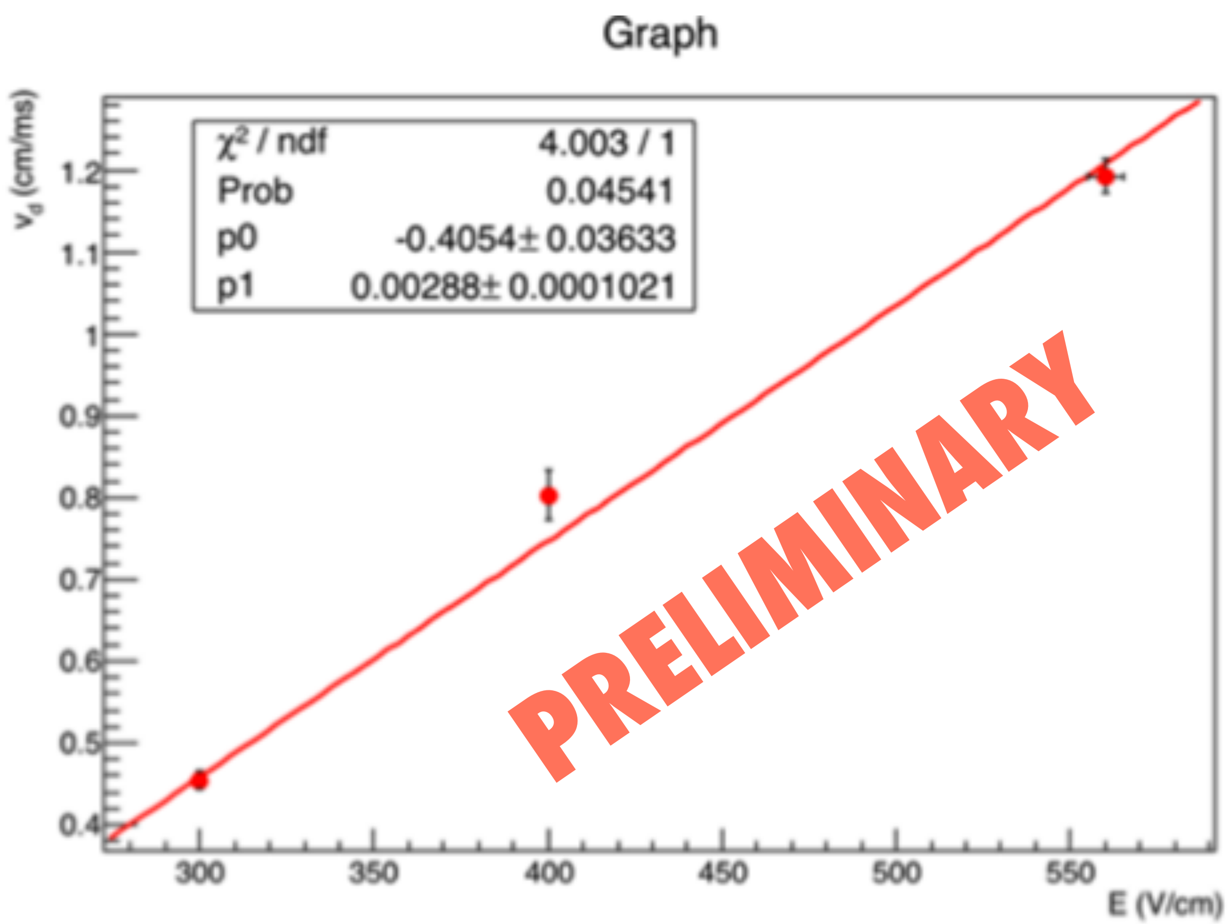
PRELIMINARY

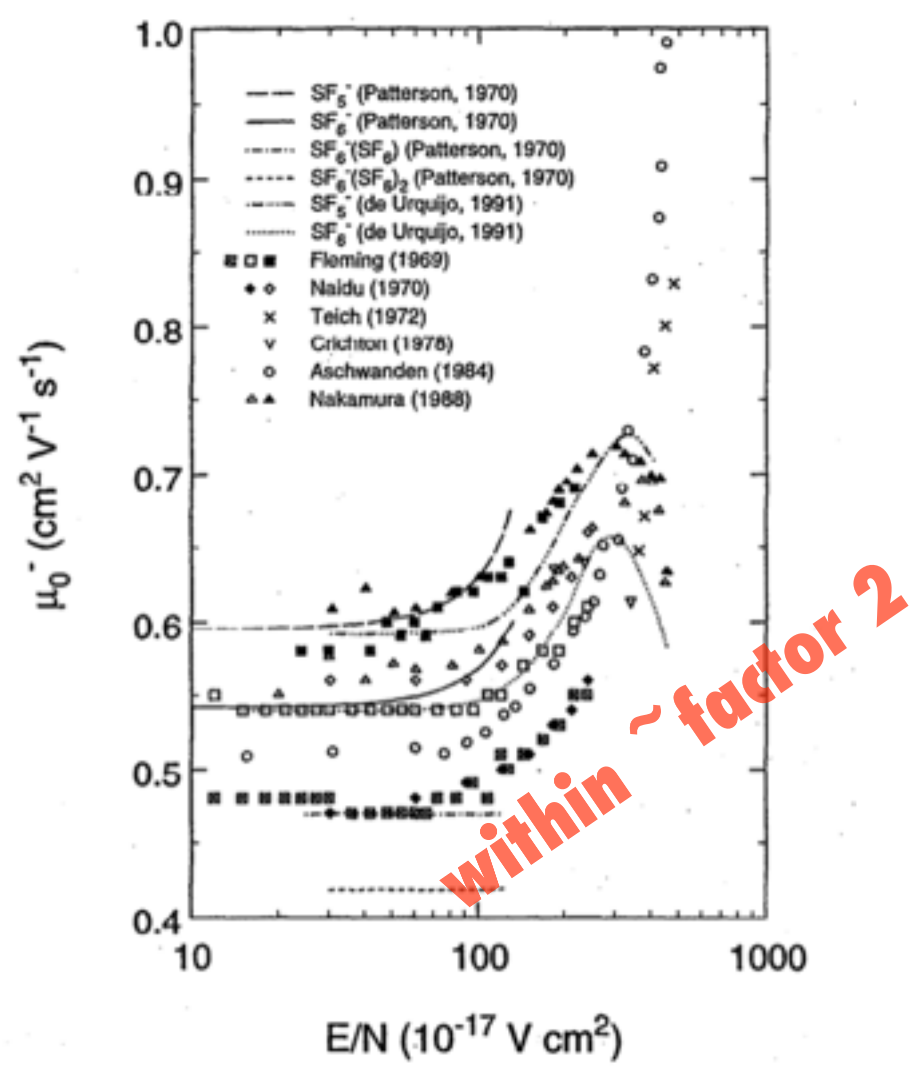
Negative ion drift velocity measurement in Ar:CO_2:SF_6

Drift velocity compatible with negative ions
(need to understand and prove which ion species is drifting)

L. Christophorou & J. Olthoff
J. Phys. Chem. Ref. Data, Vol 29, No. 3, 2000

BTF measurement of "allegedly" SF_6^- drifting in Ar:CO_2:SF_6 (58:15:27)





with the large prototype we are designing we will be able to test lower pressures and higher drift fields

~ 0.5 cm/ms @ 0.3 kV/cm @ 220 Torr for SF_6^- drifting in SF_6
(expected higher in lower density gases)

NITEC in the context of CYGNUS-TPC

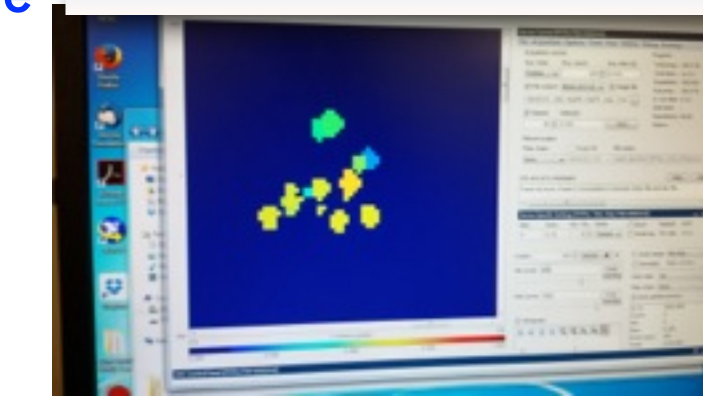
- NITEC is among the main actors of directional DM search working for the formation of a new international collaboration for the development of a multi-ton directional DM experiment
    - CYGNUS-TPC kick-off meeting organized here at LNF in April 2016
    - CYGNUS-TPC officially recognized in WhatNext white paper
    - Managed to gathered the interest of part of the italian neutrino community
- NITEC SF_6 studies and measurement will be fundamental for the development of CYGNUS-TPC proposal and CDR

Anybody interested is more than welcomed to join!!!!

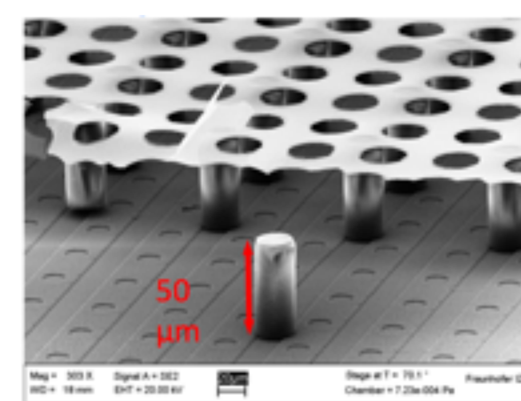
NITEC to do (on going)

- **With the small prototype:**
  - Measure gain in pure SF_6 data between 150 and 340 Torr with ^{55}Fe radioactive source (data analysis on going)
  - Verify the presence of minority carriers with different mobilities for fiducialization
  - Measure gain in $Ar:CO_2:SF_6$ (58:15:27) at 340 Torr
  - Improve single ionization cluster identification and measurement
- **With the large prototype:**
  - Gain and drift velocity measurements of pure and mixtures of SF_6
  - Test of carbon nanotubes anysotropic response at the BTF
  - Identification of the minority carriers for fiducialization
  - Gain and drift velocity measurements of pure and mixtures of CS_2 at DRIFT colleagues lab in Sheffield University
  - Test of NITEC large prototype read & amplified by the GridPix readout from our colleagues at Bonn University

Hint of different minority carriers



The University Of Sheffield.



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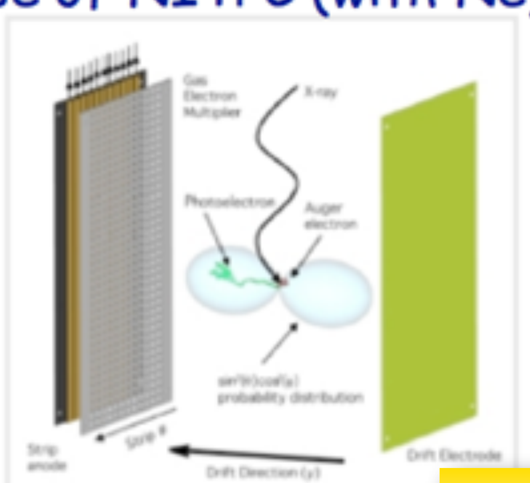
Backup

Not only DM: Alternative Applications

X ray polarimetry

- A photoelectron is emitted preferentially aligned with the electric field of the incident photon
  - Measurement of photoelectron direction provide information on photon polarization state
- Very few measurements of X ray polarization
- Can probe exotic astrophysical processes with the strongest gravitational and magnetic fields
- The community has just started to explore the use of NITPC (with Ne) [arXiv:1107.3079]



Neutrinoless double beta decay searches

with light readout

- A NITEC capable of counting each primary free electron liberated in a Xe gas by an ionizing event, will approach the intrinsic fluctuations in the conversion of energy to ionization [D.Nygren, JPCS 65 012003]
- Even with counting efficiency significantly less than 100%, a 5×10^{-3} FWHM energy resolution could be achieved
- First tests with a 17 bar Xe conventional TPC show very encouraging results (1% FWHM) [A. Goldschmidt et al, IEEE NSSCR 1409]

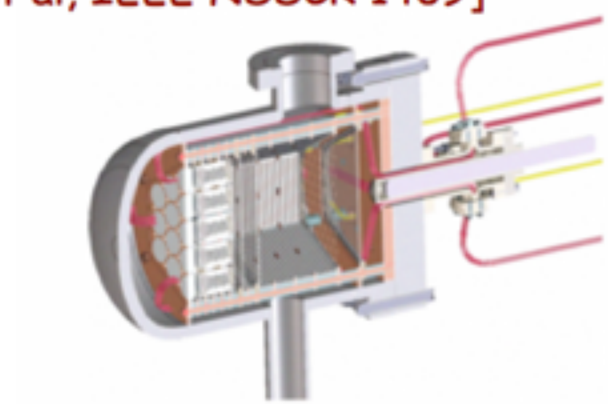


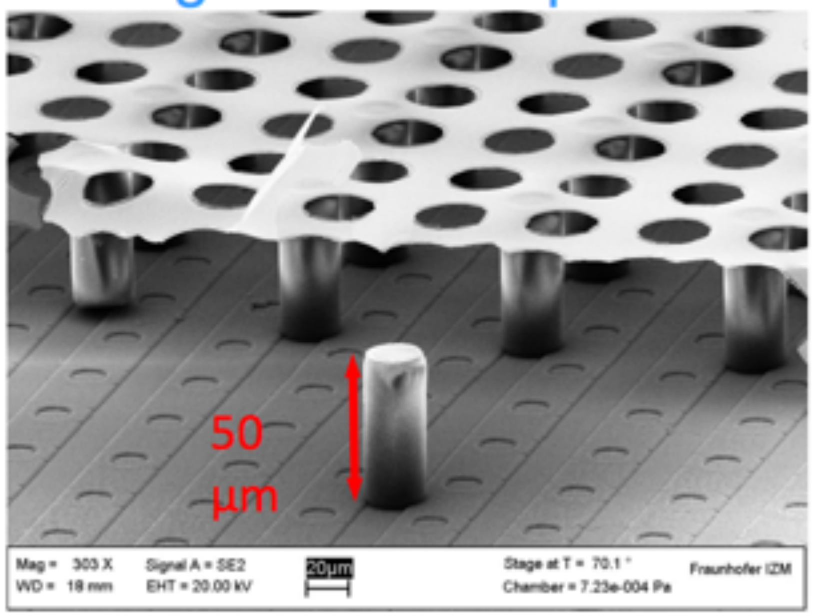
Fig. 1. Cross section of the TPC. Wire meshes separate the 19-PMT array from several regions, beginning at the mesh in front of the PMT array, from left to right: a 5 cm buffer region, an 8 cm drift region, a 3 mm EL gap, and [illegible] region. (Drawing by Robin LaFever.)

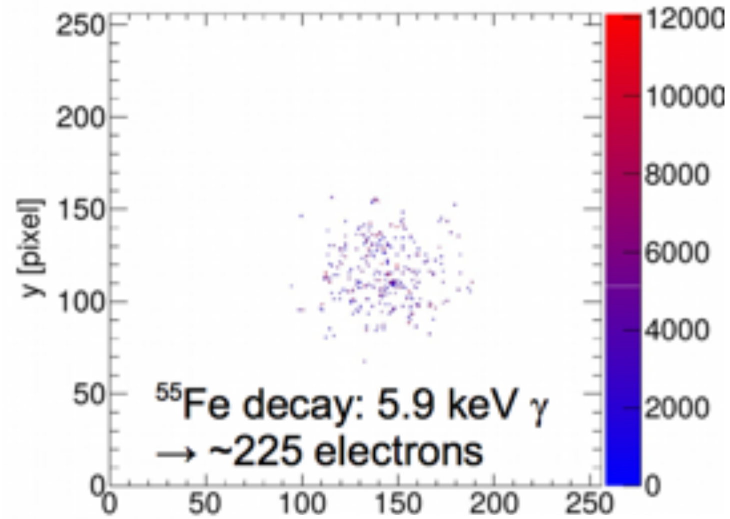
both with CH_3NO_2 as capture agent

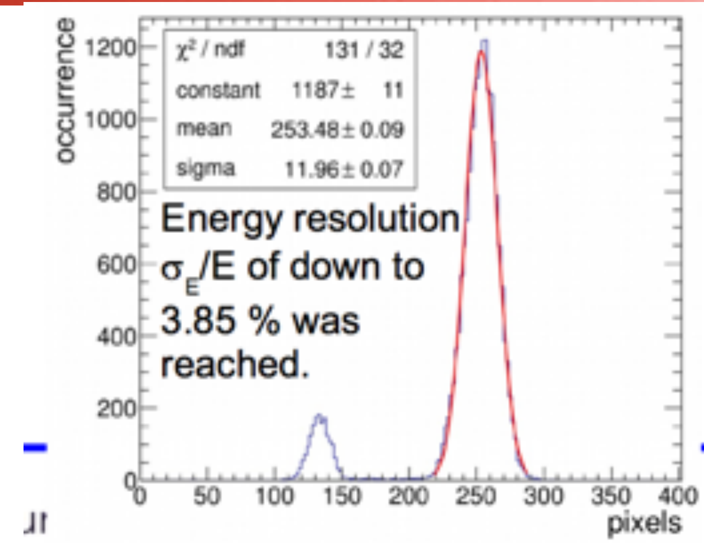
GridPix

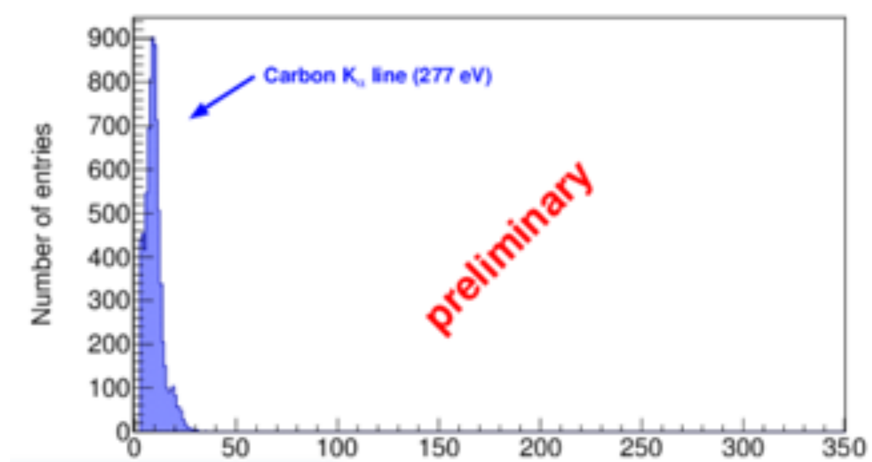
Standard charge collection:
- Pads of several mm²
- Long strips (l~10 cm, pitch ~200 μm)

Instead: Bump bond pads are used as charge collection pads.









pixel TPC is not a crazy idea anymore, but it is realistic.

160 GridPix with an active area of 320 cm^2