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

Laboratori Nazionali del Gran Sasso
Scientific Committee Open Session

UNDER:
Underground Neutral particles DEtection through nuclear Recoils

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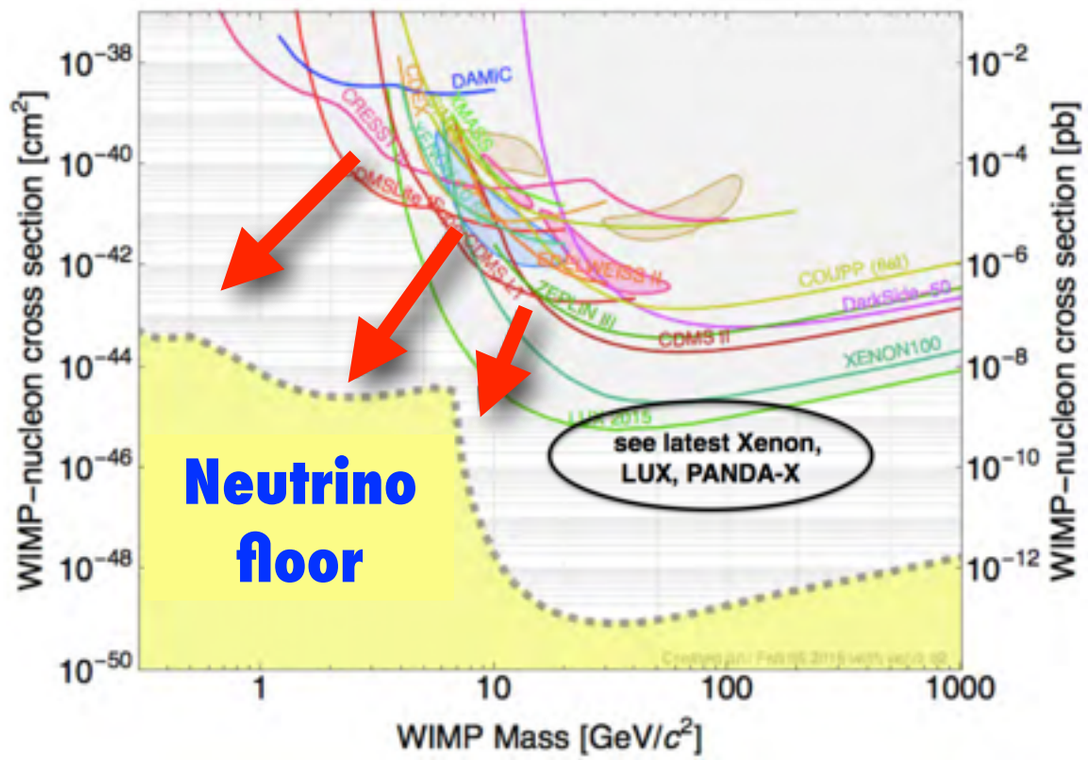
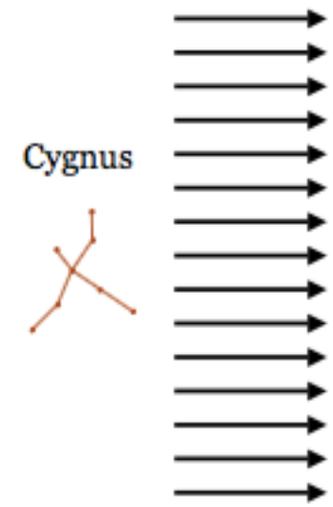
[2] INFN Laboratori Nazionali di Frascati

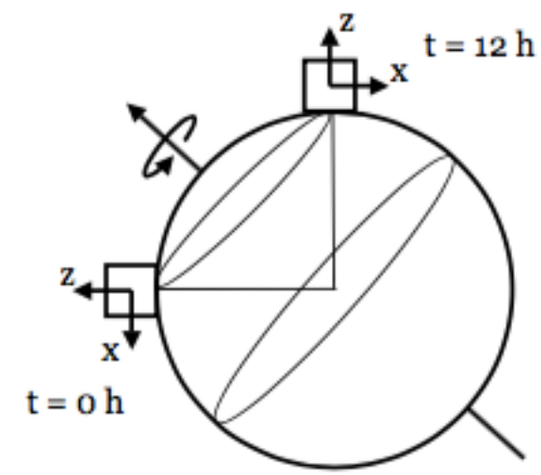
Outline

- Directional DM searches at the ton-scale: the CYGNUS project
- CYGNUS multi-site modular development: the UNDER project
- R&D efforts and results towards UNDER realization:
  - NITEC — Horizon 2020 2015-2017
  - CYGNUS RD — INFN CSN5 2016-2018

Dark Matter Searches



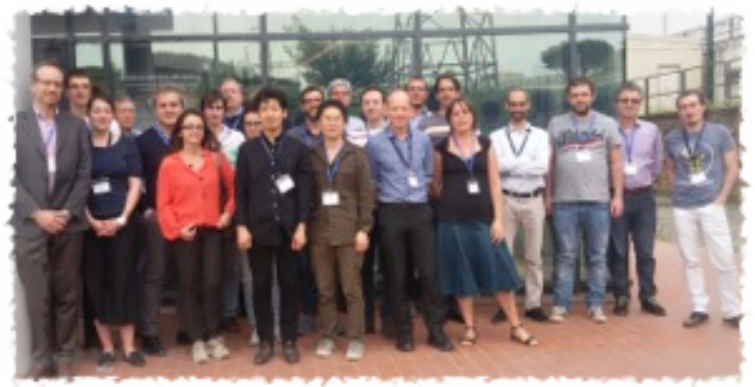




Strength and timeliness of directional DM searches

- **Unambiguous positive identification of Dark matter even in presence of unknown amounts of background**
  - Able to reject neutrons and neutrinos through directional information
- **Technology now mature to go for the ton-scale**
  - Zero-background operation established on 1 m^3 (DRIFT)
  - Several recent development in directional DM searches R&Ds

CYGNUS: Directional DM Searches at the Ton-Scale



CYGNUS key concepts

- Galactic Directional Recoil Observatory at the ton scale
- Gaseous TPC in multiple underground sites
- Negative ion drift in He
- Goal of zero background operation after electron/gamma rejection and fiducialization
- Directional and gamma/electron rejection thresholds at O(keV)

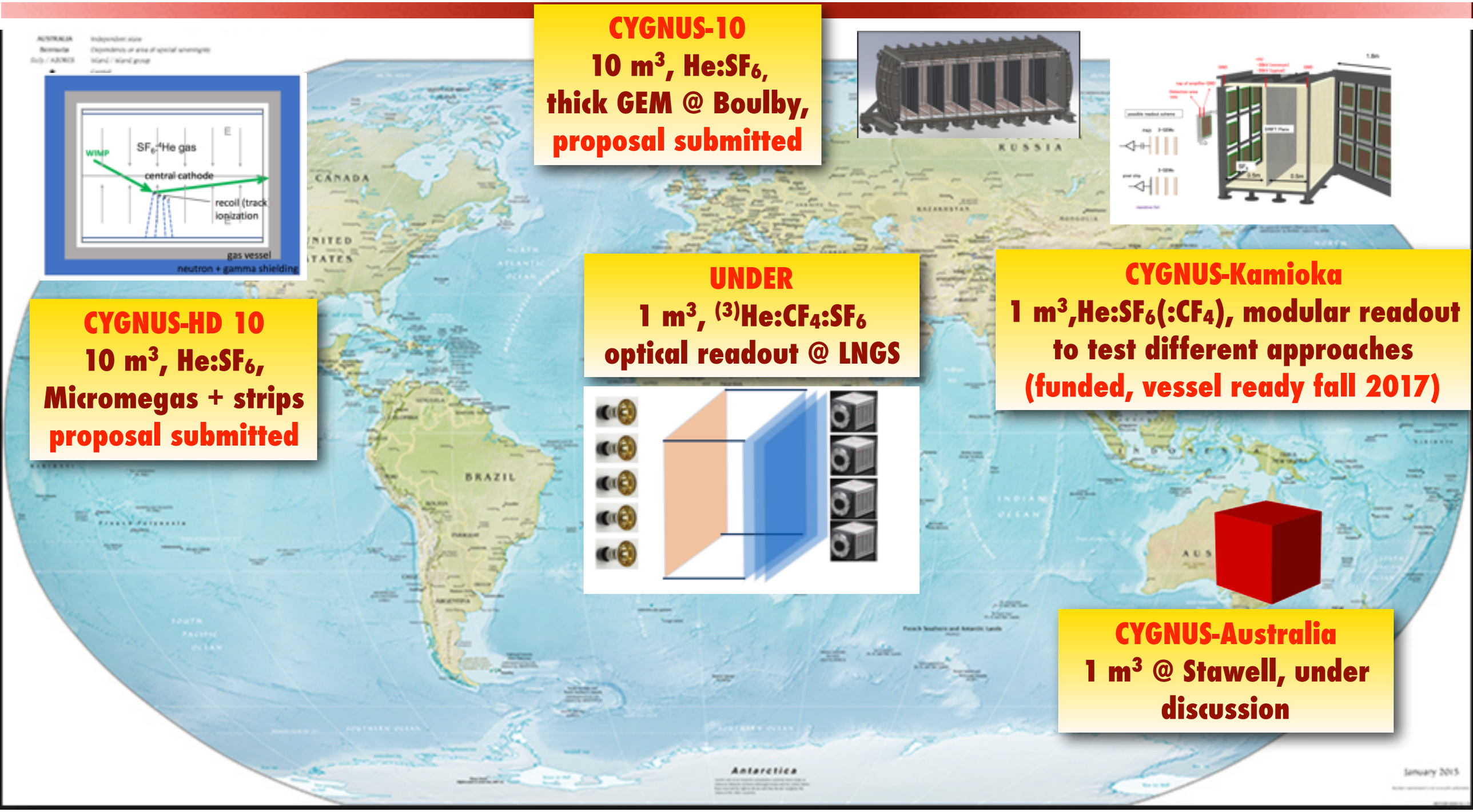
For DM search and neutrino physics

Easier deployment and reduced systematics

Reduced diffusion and fiducialization

Competitive with non-directional approaches in the low mass WIMP region

UNDER in the context of CYGNUS



CYGNUS-10
10 m³, He:SF₆, thick GEM @ Boulby, proposal submitted

CYGNUS-HD 10
10 m³, He:SF₆, Micromegas + strips proposal submitted

UNDER
1 m³, $^{(3)}$He:CF_4:SF_6 optical readout @ LNGS

CYGNUS-Kamioka
1 m³,He:SF_6(:CF_4), modular readout to test different approaches (funded, vessel ready fall 2017)

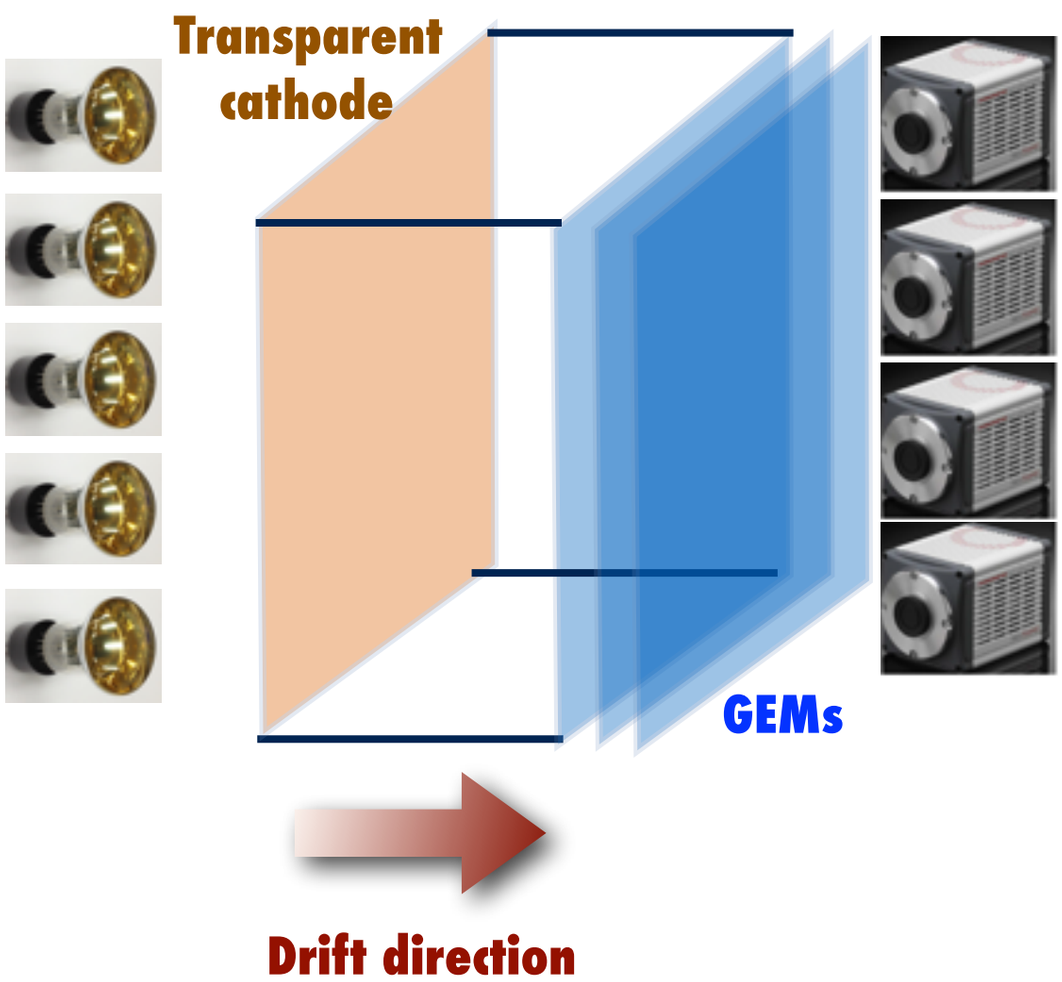
CYGNUS-Australia
1 m³ @ Stawell, under discussion

UNDER Detector Concept

1 m^3 TPC $^{(3)}He:CF_4:SF_6$

Triple thin GEMs

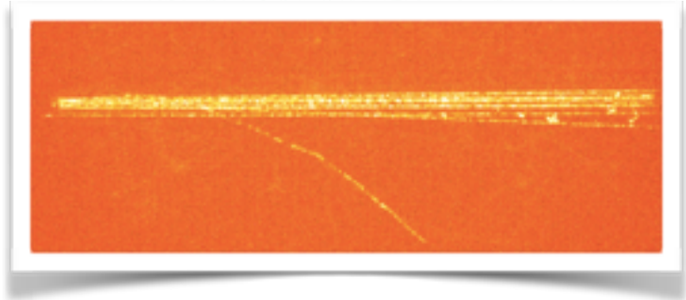
CMOS + PMT



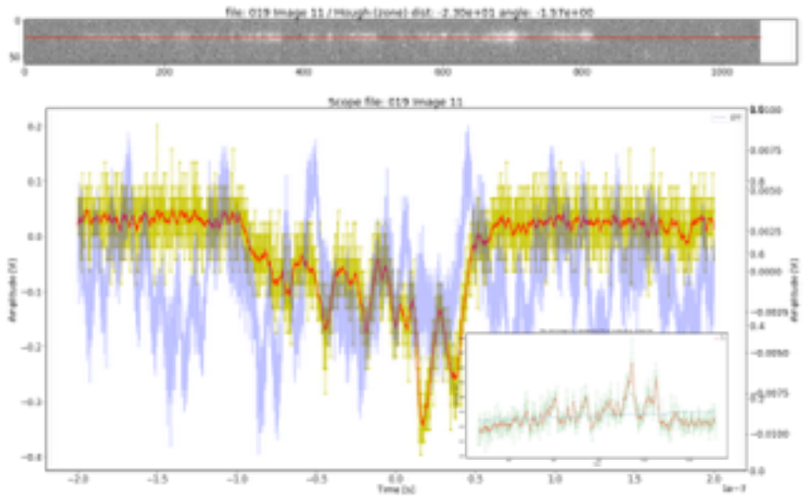
- He for low mass WIMP sensitivity and atmospheric pressure with low density
- ^{3}He for thermal neutron capture
- CF_4 for improved scintillation and minority carriers amplitude
- SF_6 for reduced diffusion and fiducialization with negative ion drift

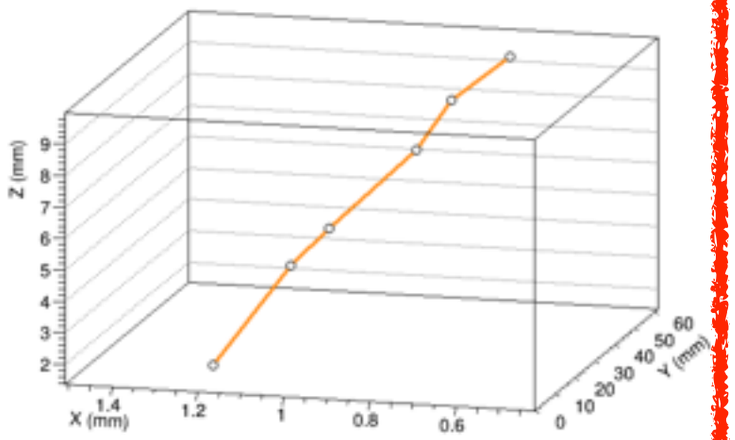
UNDER Detector Key Features

Low energy threshold capability thanks to GEMs high gain + CMOS high sensitivity

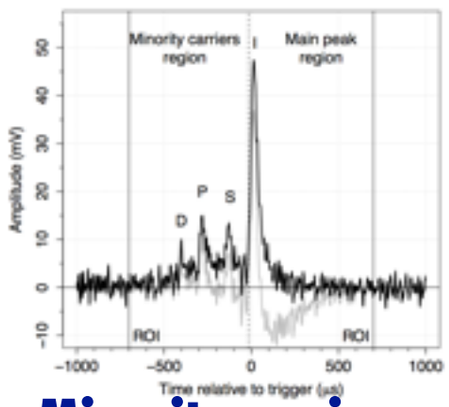


3D tracking with CMOS (x,y,dE/dx,E) + PMTs (t,z,E)

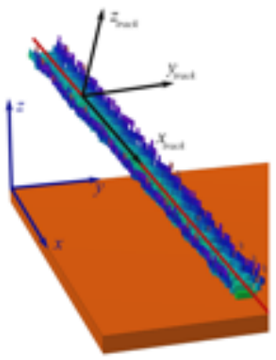




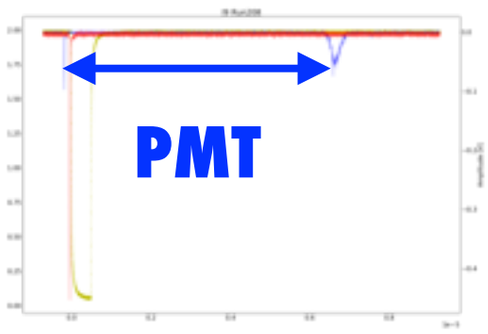
Full fiducialization, including drift direction



Minority carriers



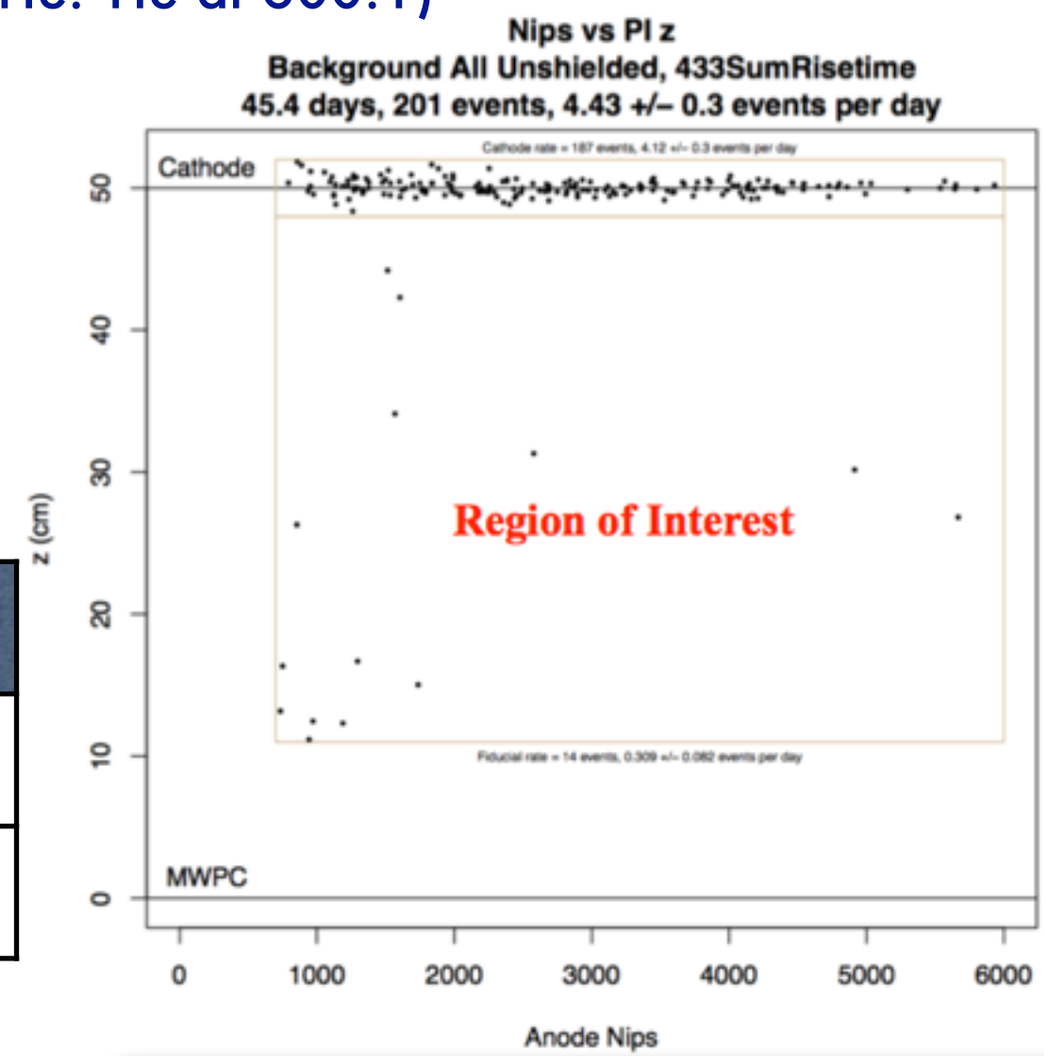
Charge cloud



Primary/secondary scintillation

UNDER Neutron Flux Measurement @ LNGS

- **Unshielded run to test proof-of-principle on 1 m³ and to provide a precise measurement of thermal and fast neutron flux in Hall B of LNGS**
  - $He:^3He:SF_6:CF_4$ at (nearly) atmospheric pressure ($He:^3He$ at 600:1)
  - Fast neutron through nuclear recoil
  - Thermal neutron through capture on ^3He
  - Full fiducialization, including drift direction



Expected number of neutron recoils events in UNDER
(from F. Mouton, University of Sheffield)

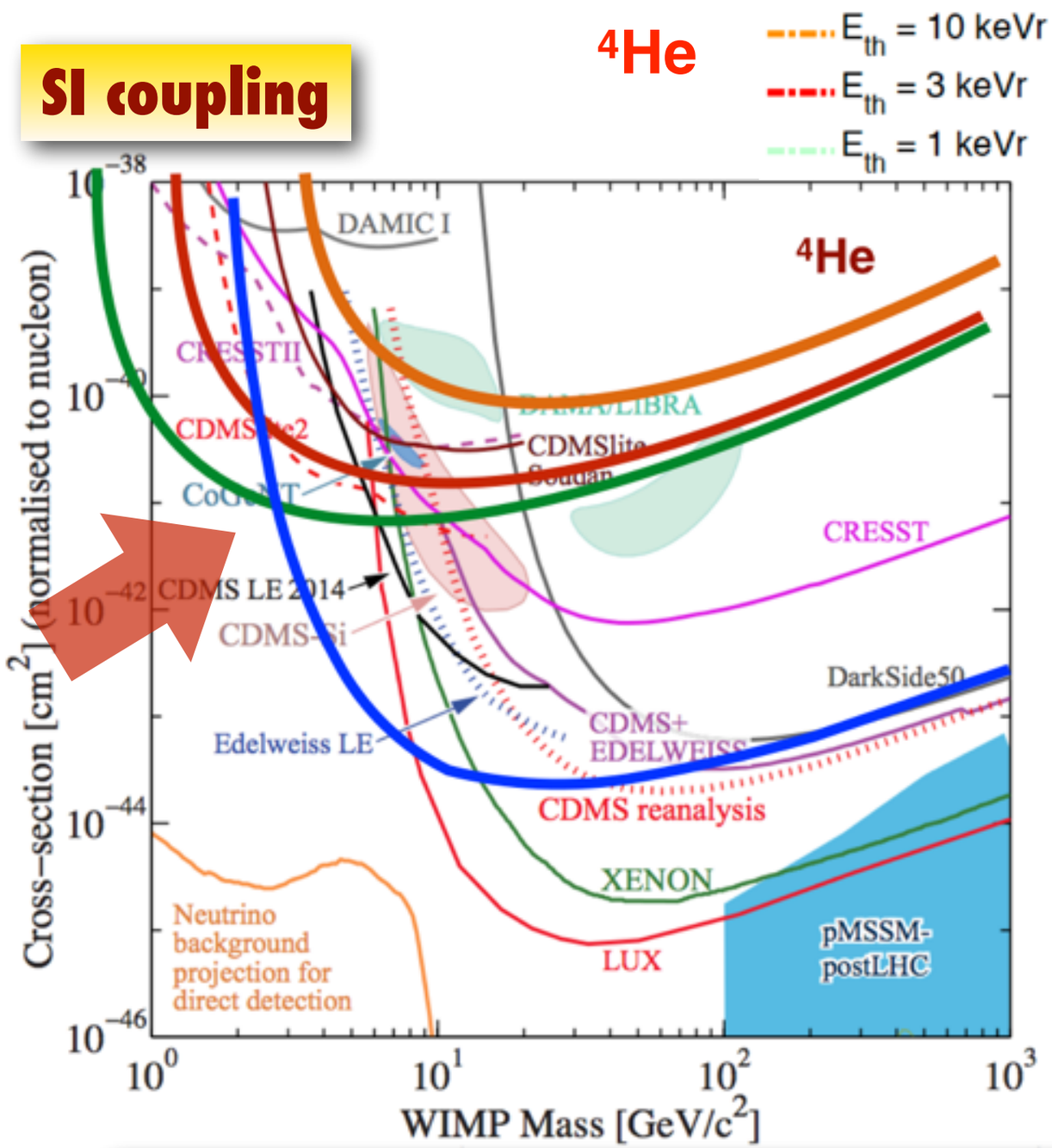
$He:^3He:SF_6$	Rock neutrons rate @ LNGS	Concrete neutrons rate	Recoils due to fast neutron/month
659:1:100	2.93×10^{-5}	3.6×10^{-3}	9330
749:1:10	$< 8.22 \times 10^{-5}$	3.1×10^{-4}	800

PRELIMINARY

Feasibility demonstrated by DRIFT @ Boulby with 1 m³ @ 41 Torr
(J. Battat et al. Atropart. Phys. 91 (2017) 65-74)

UNDER Potentialities on DM Limits

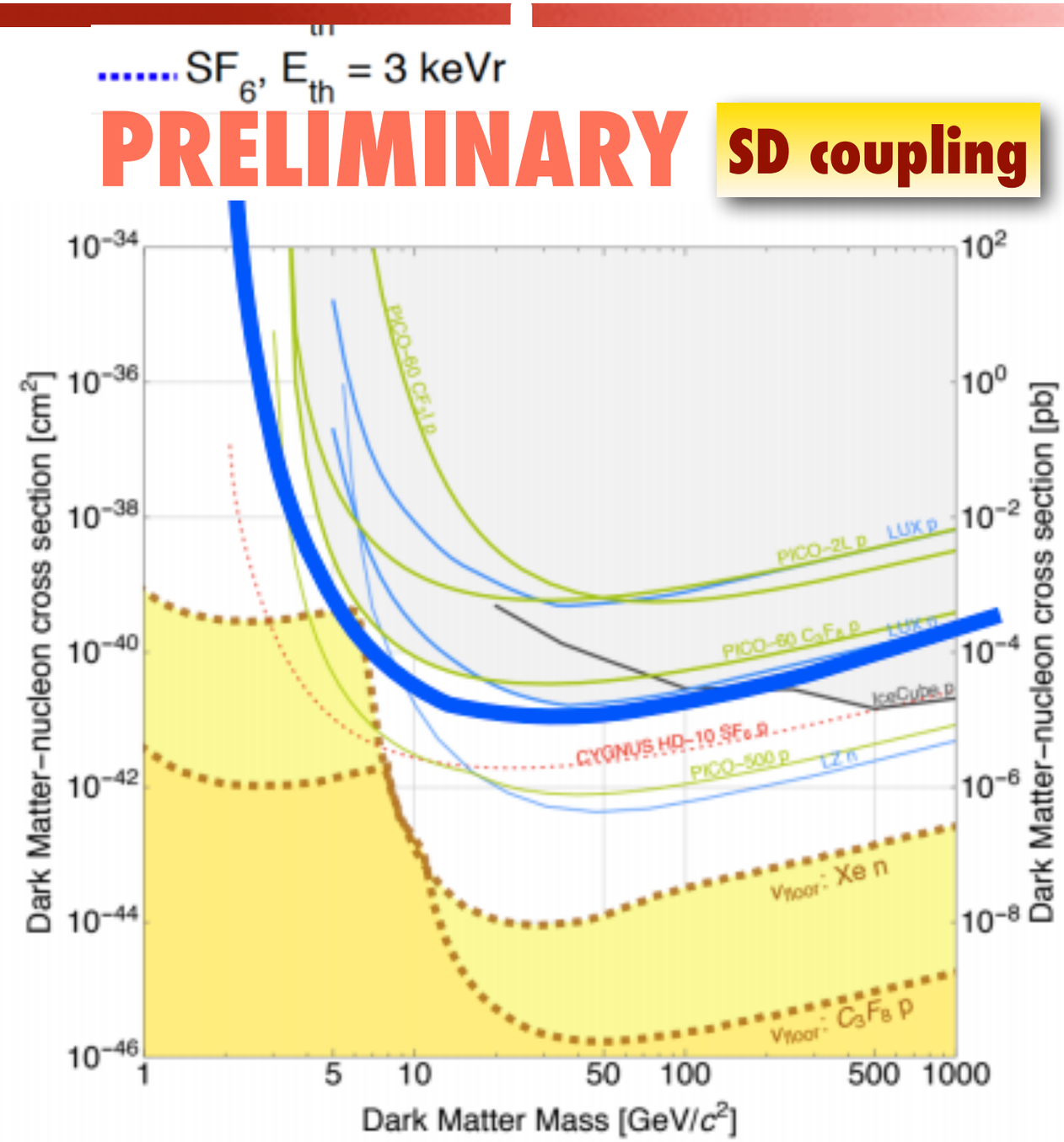
SI coupling



^{4}He:SF$_6$ 600:200 Torr
1 m^3 x 3 yrs is already competitive at low WIMP mass!

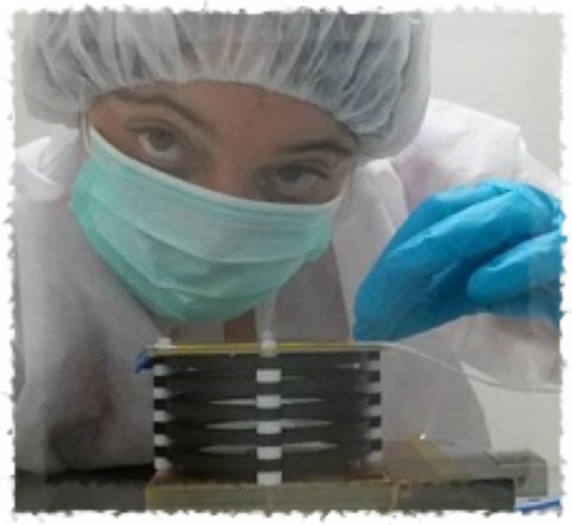
PRELIMINARY

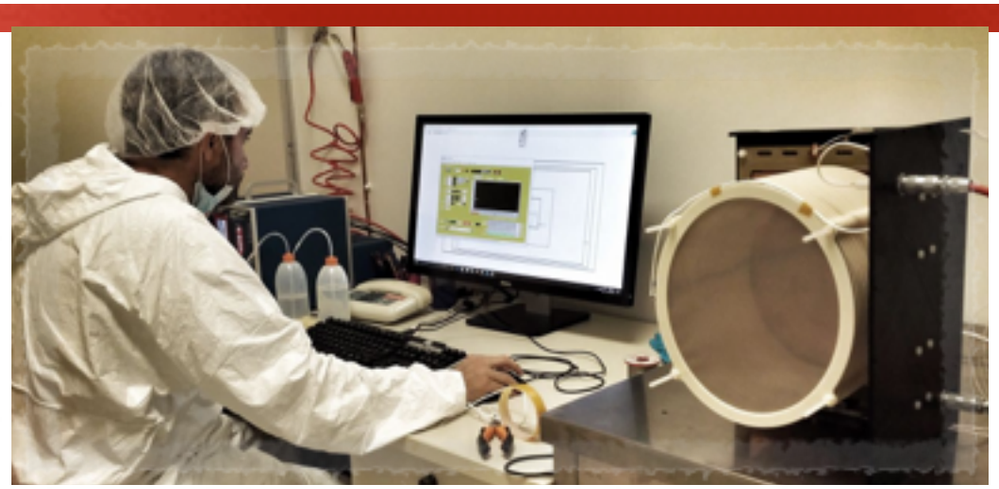
SD coupling

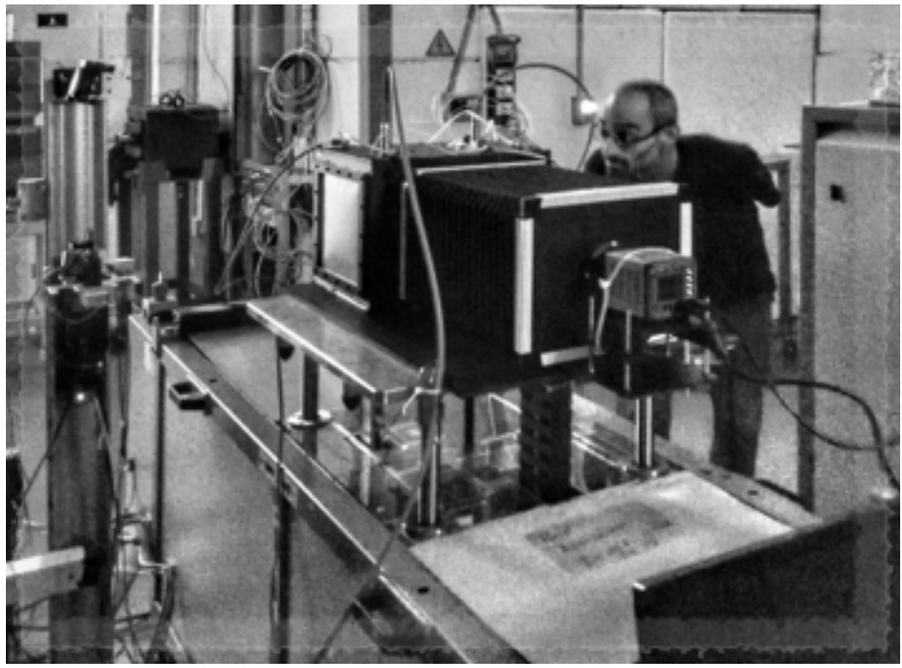


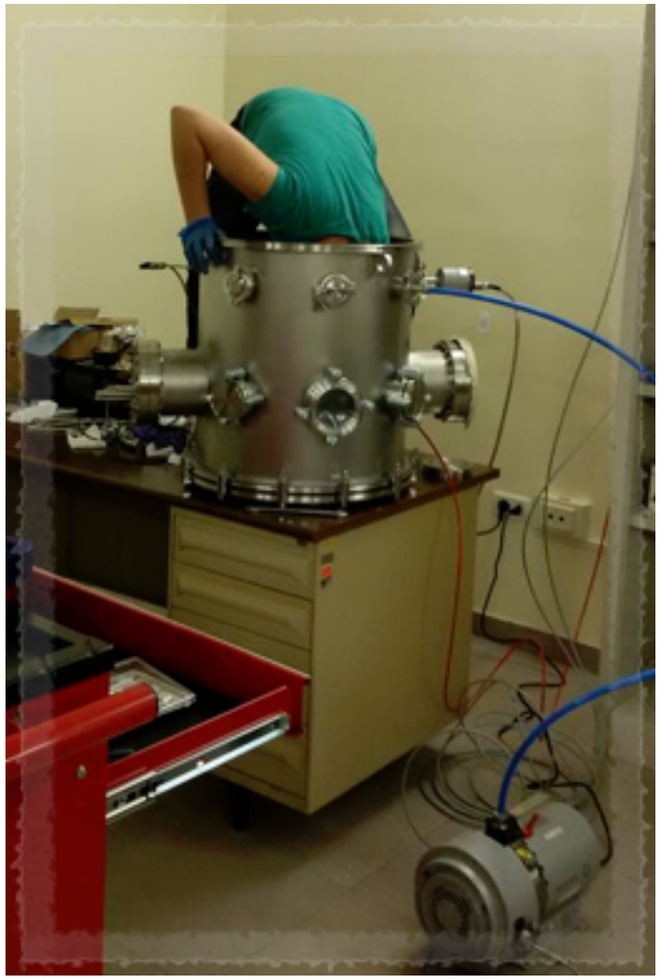
90% C.L. upper limit
Zero background

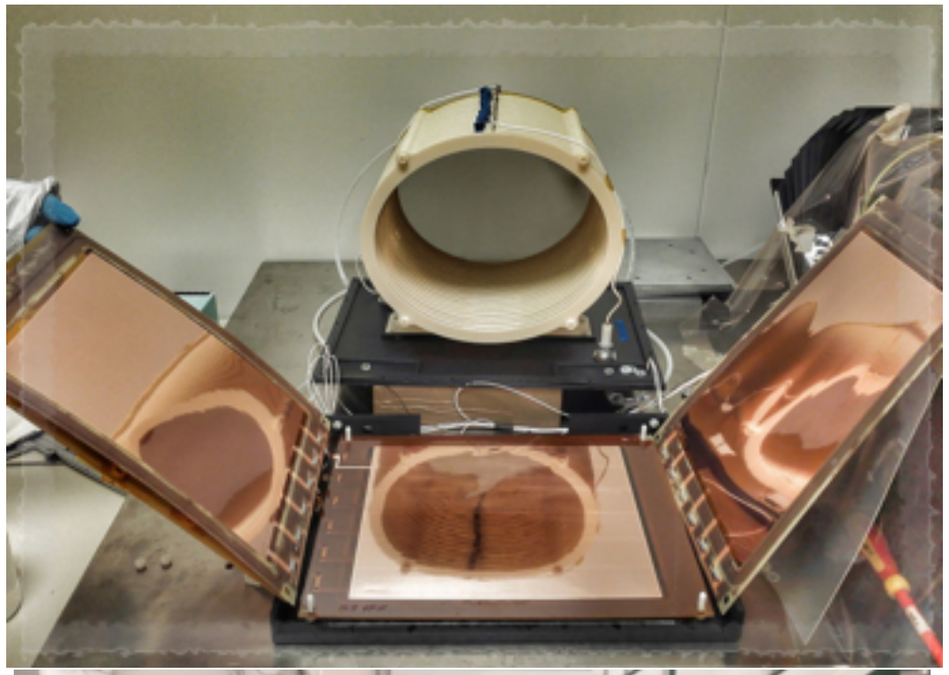
R&D efforts towards UNDER realization

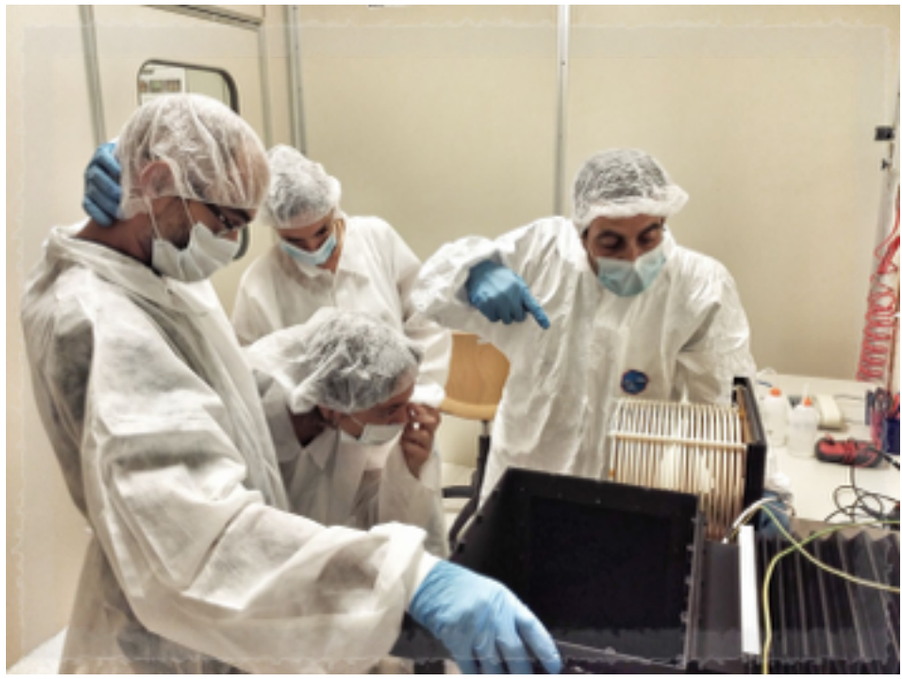








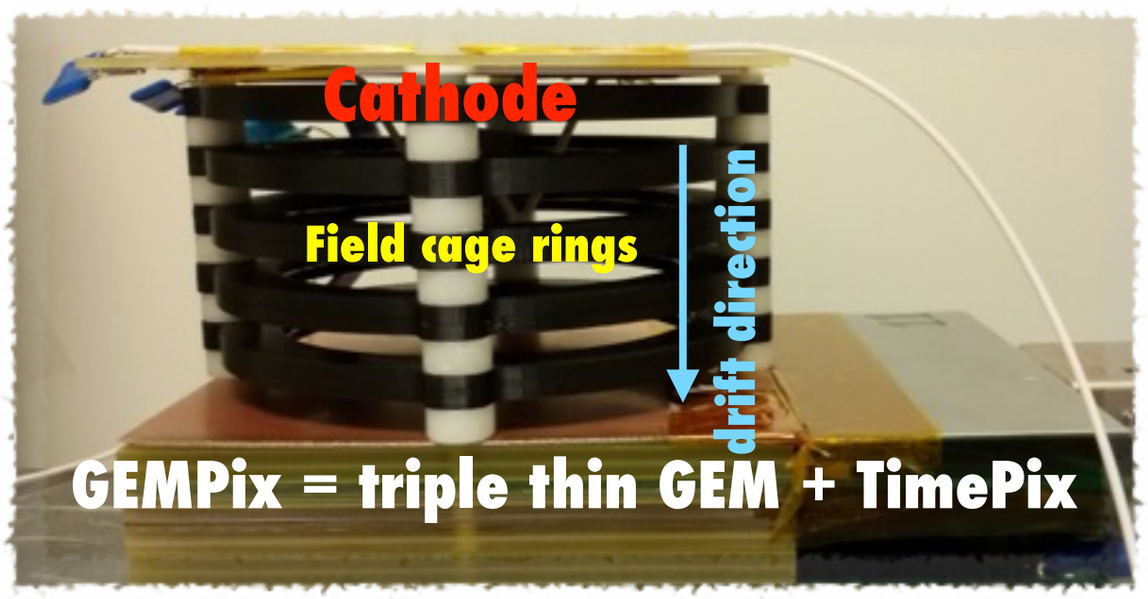




R&D detectors

2015

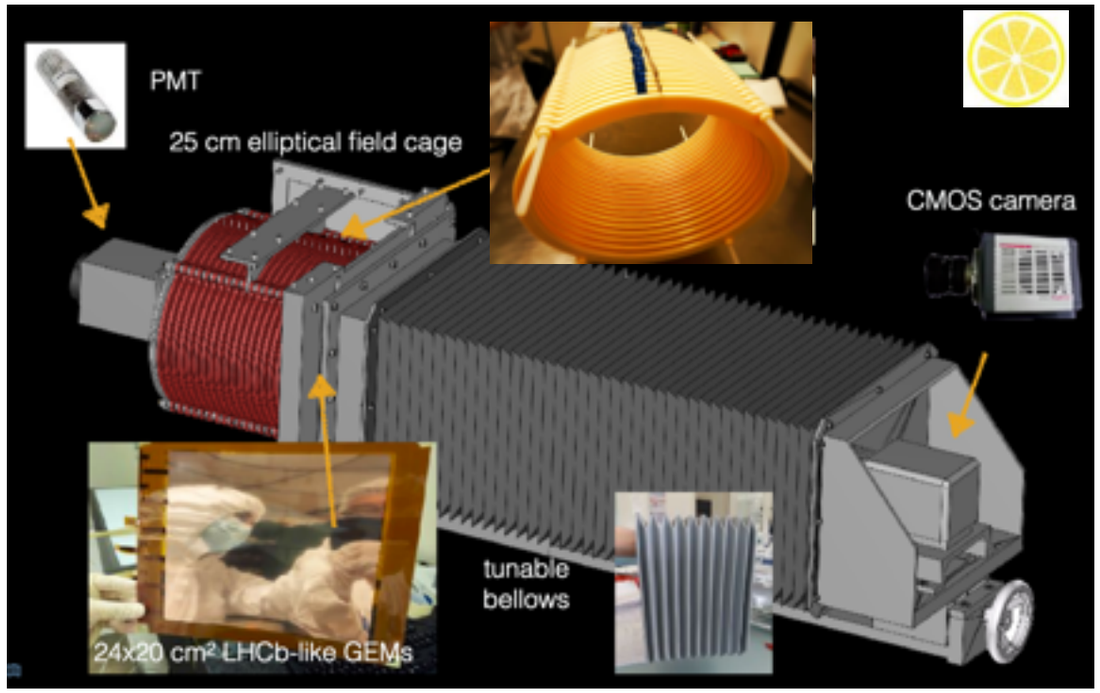
NITEC: Negative Ion Time Expansion Chamber



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

2017

LEMOn: Large Elliptic Module Optically readout

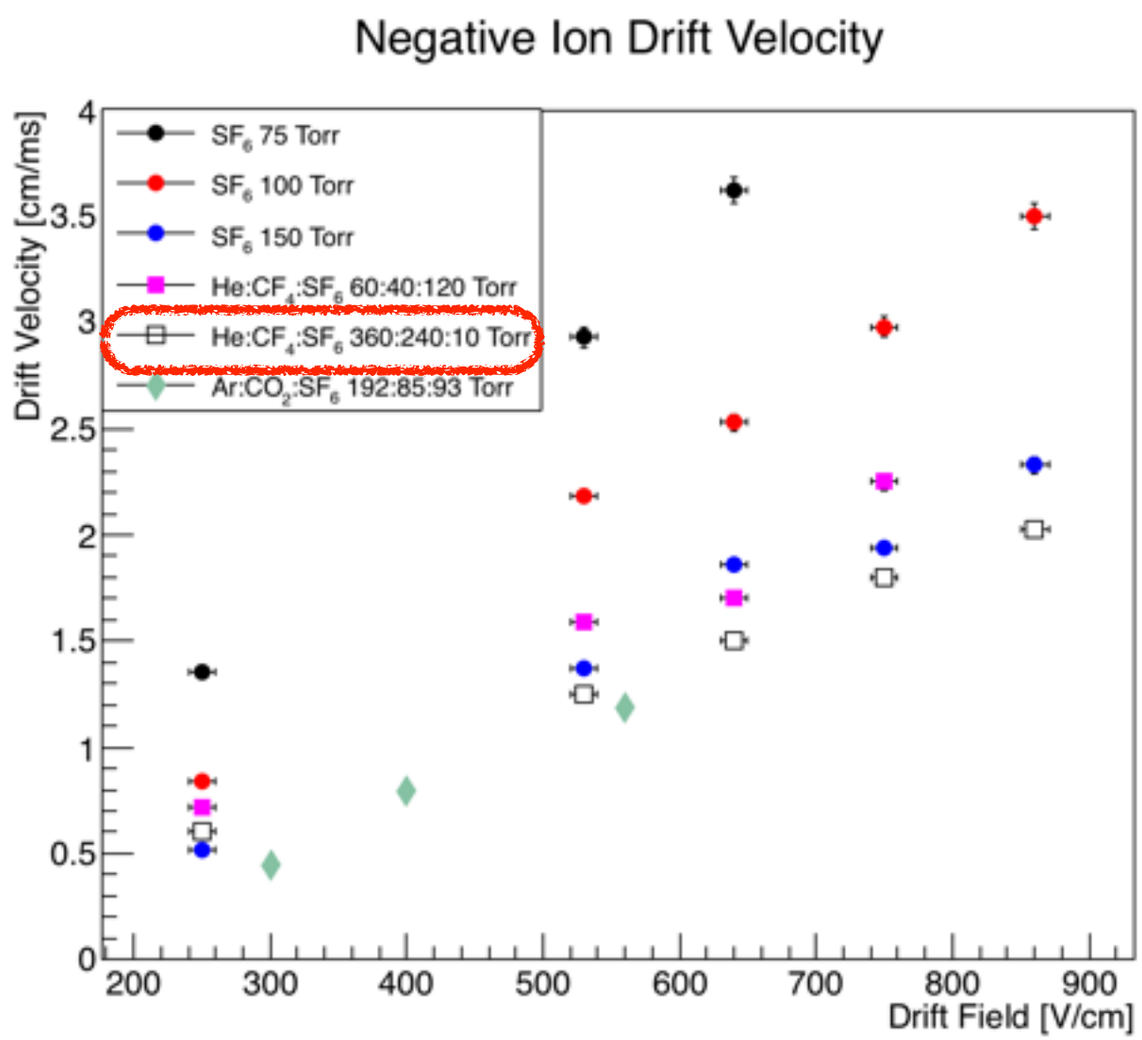


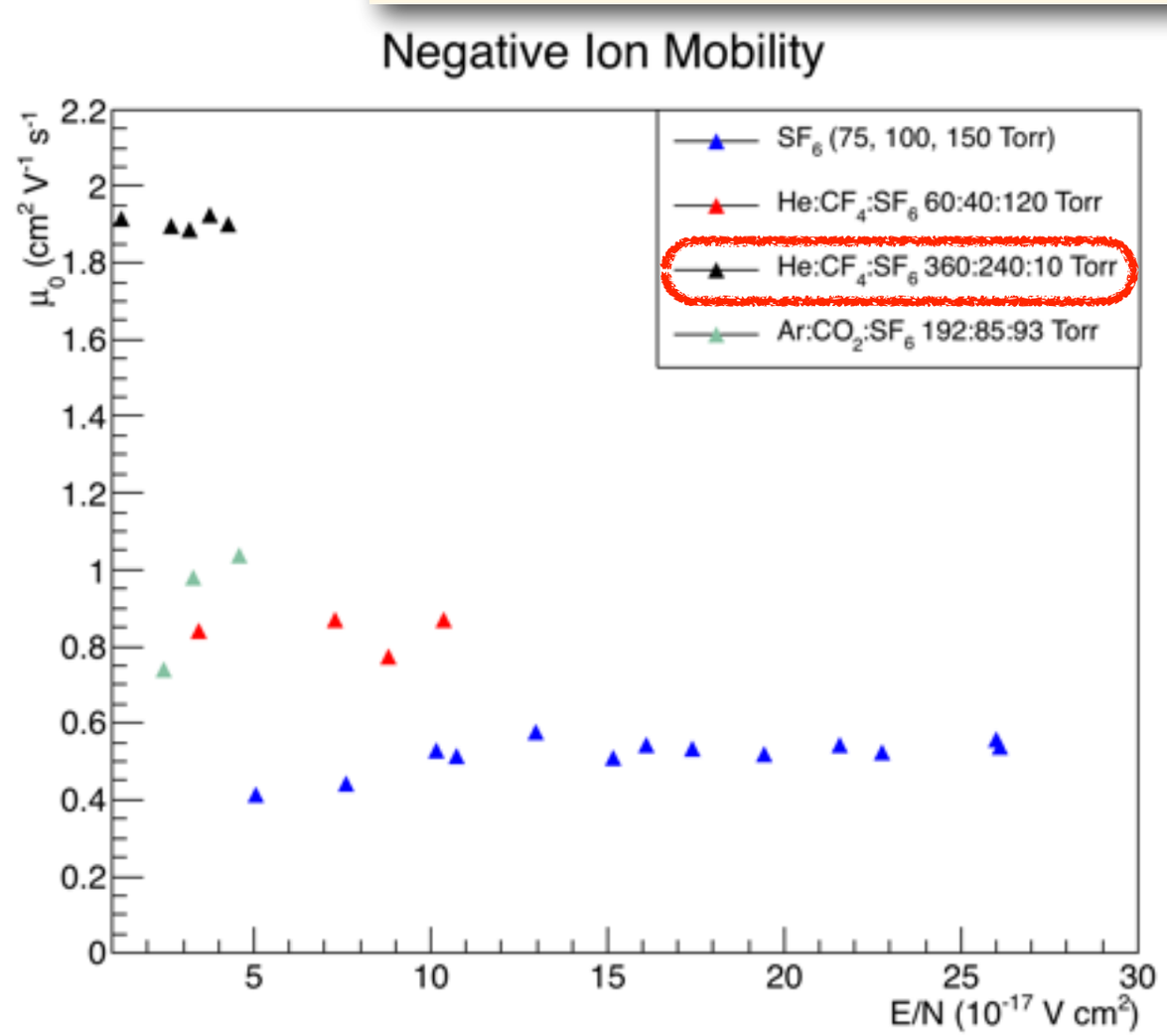
24 x 20 x 20 cm^3
9.6 Liters
Triple thin GEMs
CMOS & PMT optical readout

NITEC operation at nearly atm pressure

Measurements of drift velocity and mobilities of pure SF_6 and SF_6 mixtures up to 610 Torr

Jul 2016, 450 MeV e^- beam @ BTF



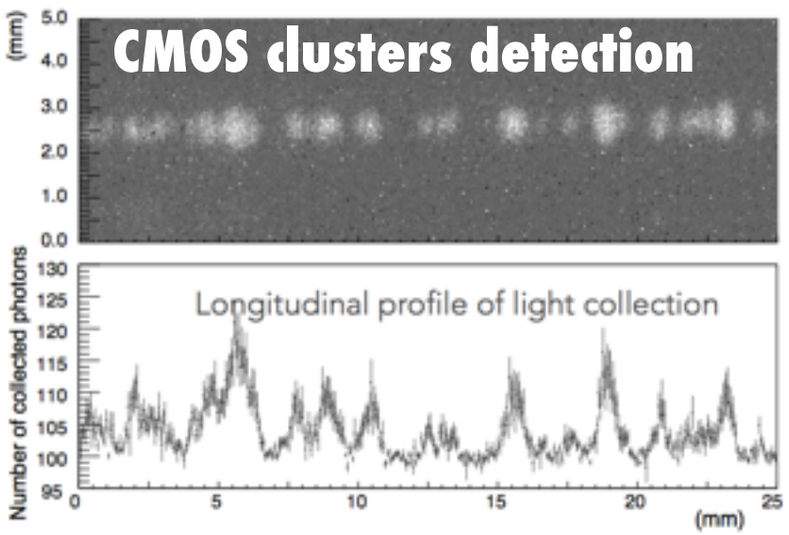


Pure SF_6 results in agreement with N. S. Phan et al, JINST 12 (2017) no. 02, P02012

Paper in preparation

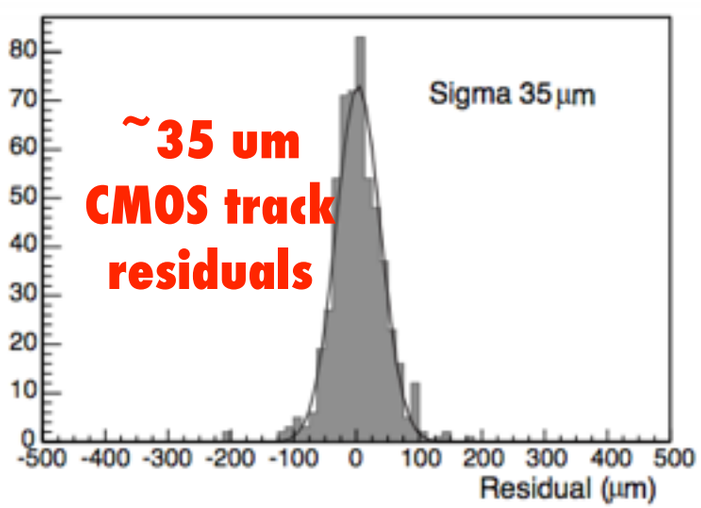
CYGNUS-RD preliminary results

Paper in preparation

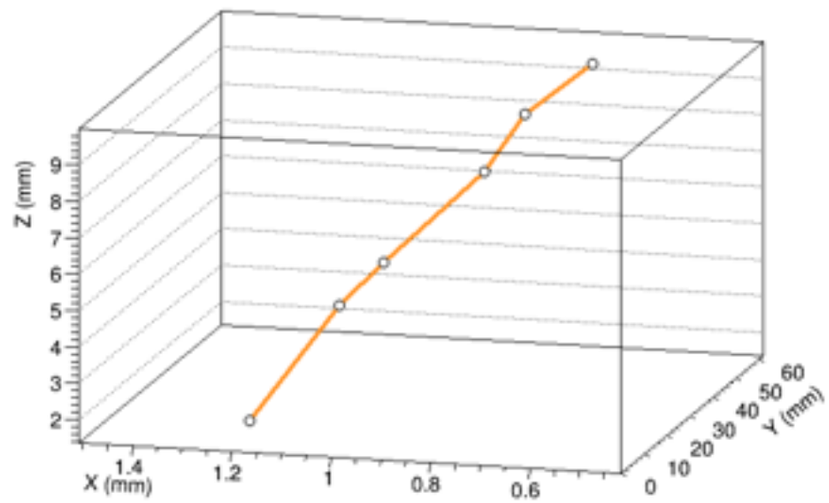


clear cluster structure

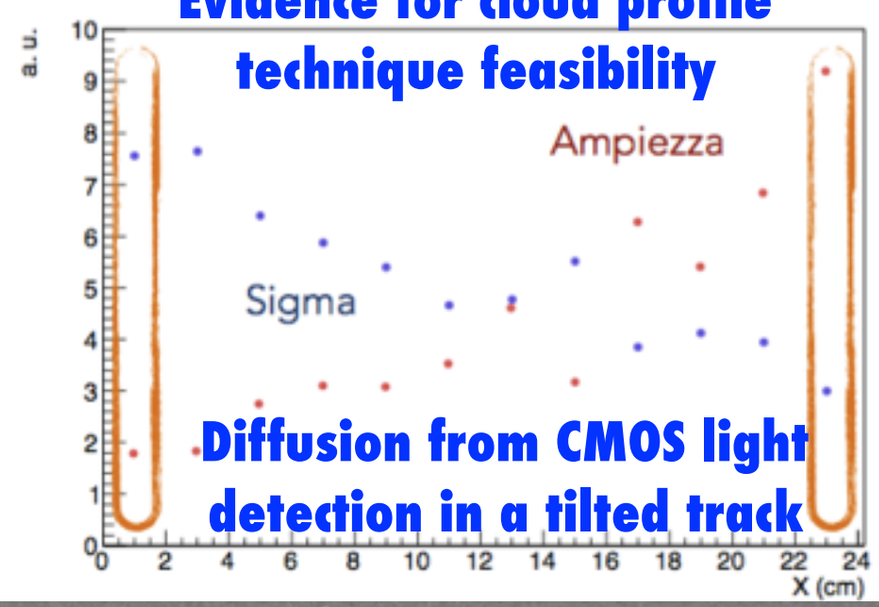
~150 ph/primary electron



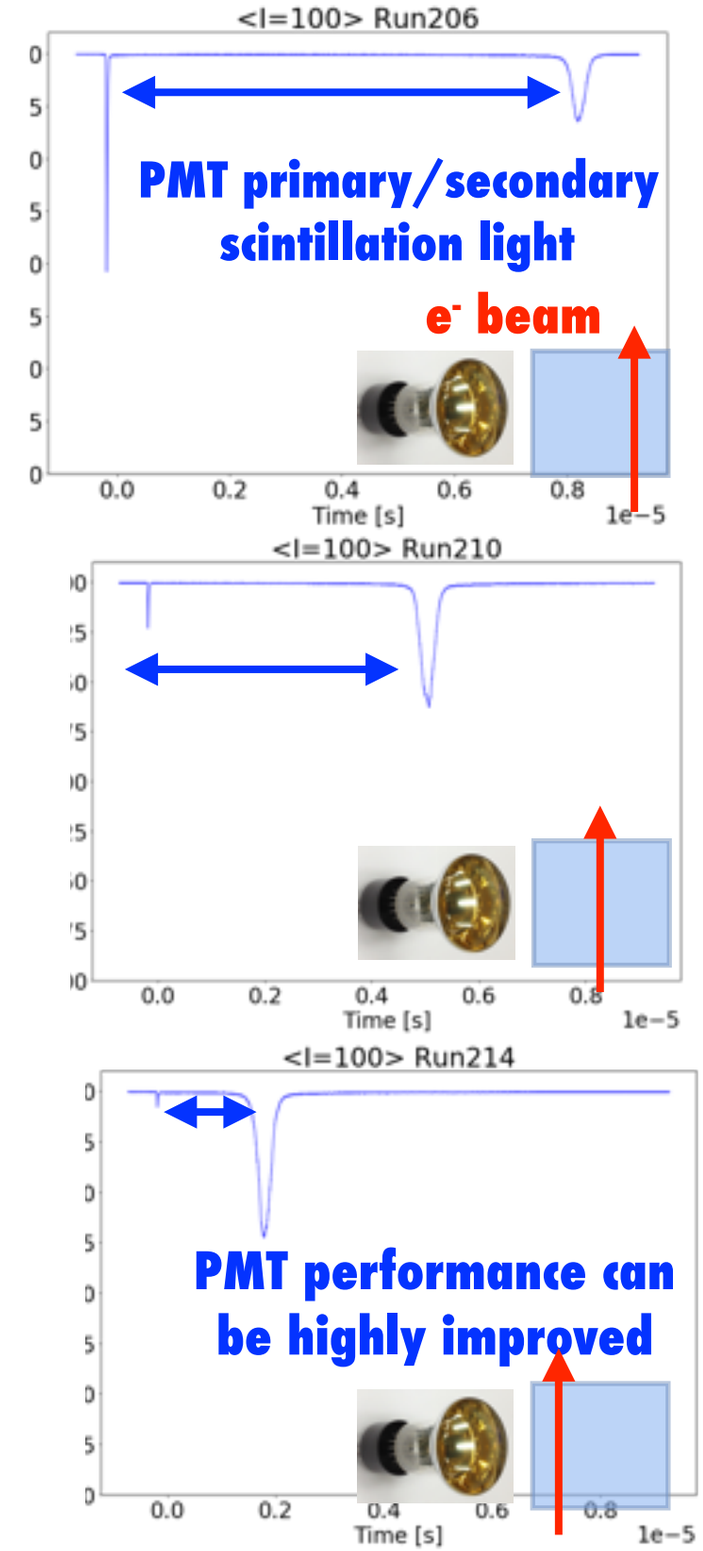
Highly performing 3D tracking with combined CMOS + PMT readout

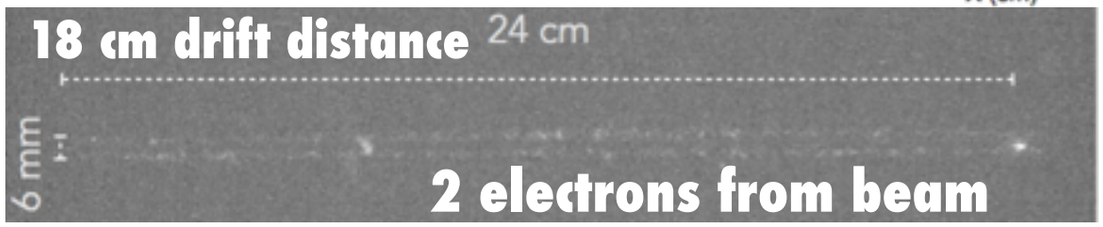


Evidence for cloud profile technique feasibility



Diffusion from CMOS light detection in a tilted track





Electron drift in He:CF_4, 450 MeV e^- beam @ BTF

Conclusions & Outlook

- **R&Ds towards UNDER achievements:**
  - Negative ion operation at 610 Torr with charge readout
  - Highly performing 3D tracking (on MIPs) with combined CMOS + PMT readout
  - Evidence for fiducialization capability (on MIPs) with ionization cloud profile and primary scintillation light

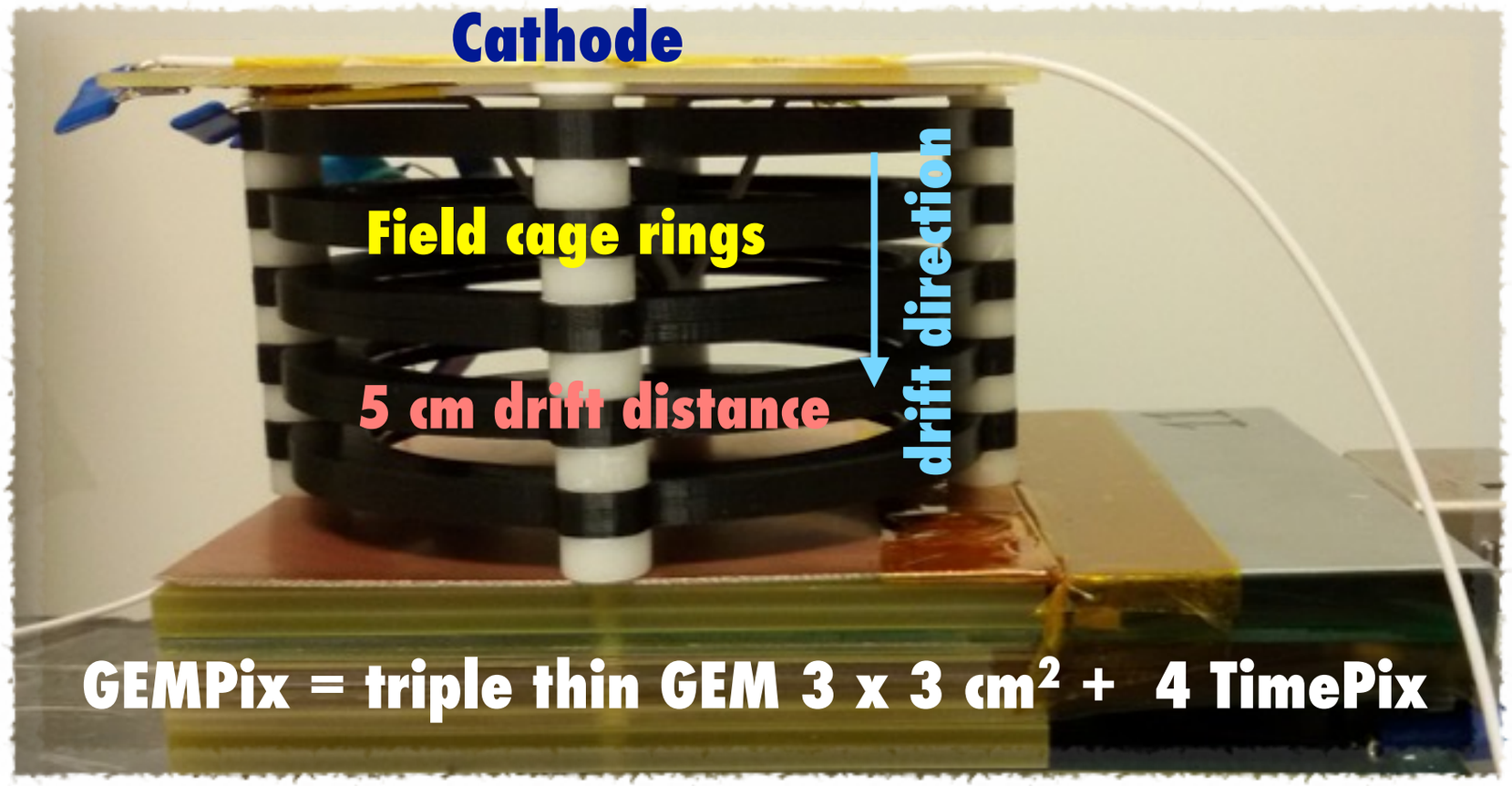
- **R&D steps to finalize:**
  - Negative ion operation at (nearly) atmospheric pressure with optical readout
  - Fiducialization capability over 50 cm drift distance
  - Directional energy threshold on nuclear recoils and gamma rejection

- **Full UNDER simulation under development to optimize detector design**

UNDER through the looking glass

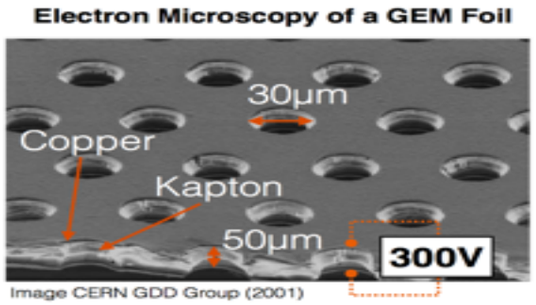
Backup

NITEC detector

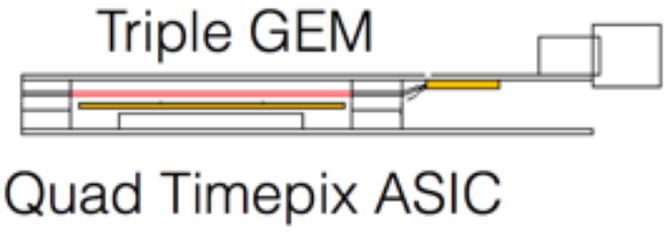


GEMPix = triple thin GEM 3 x 3 cm^2 + 4 TimePix

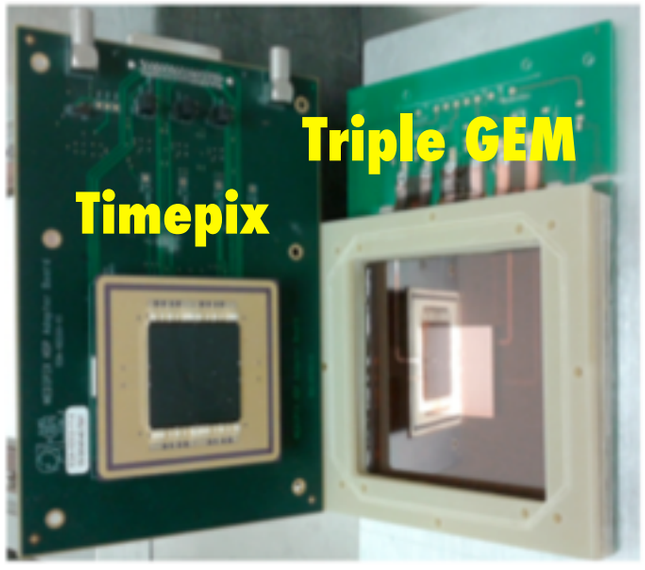
Triple Thin GEMs



High gain, high stability, high granularity

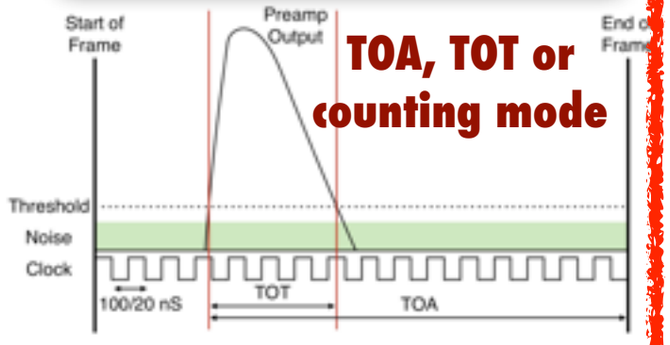


Developed at LNF in collaboration with CERN



Timepix

55 x 55 um^2 pixels

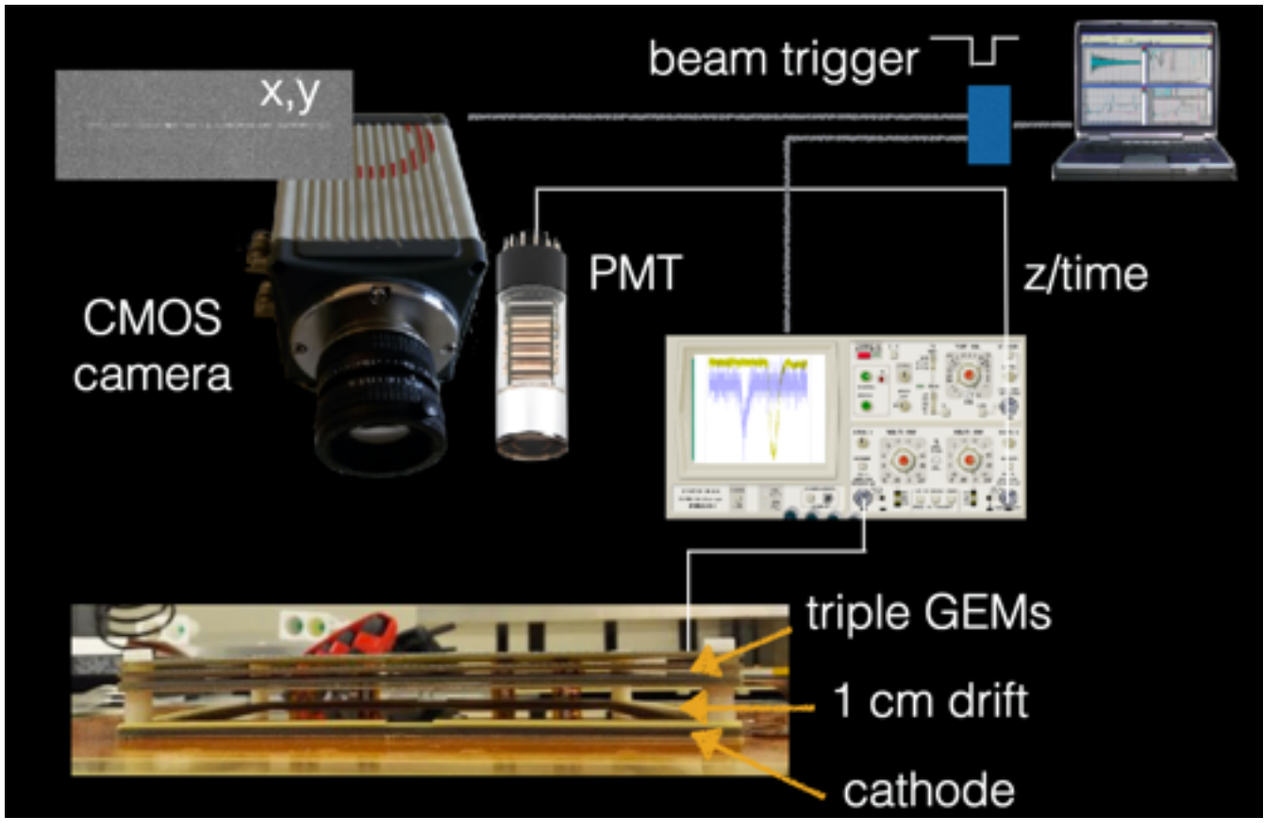


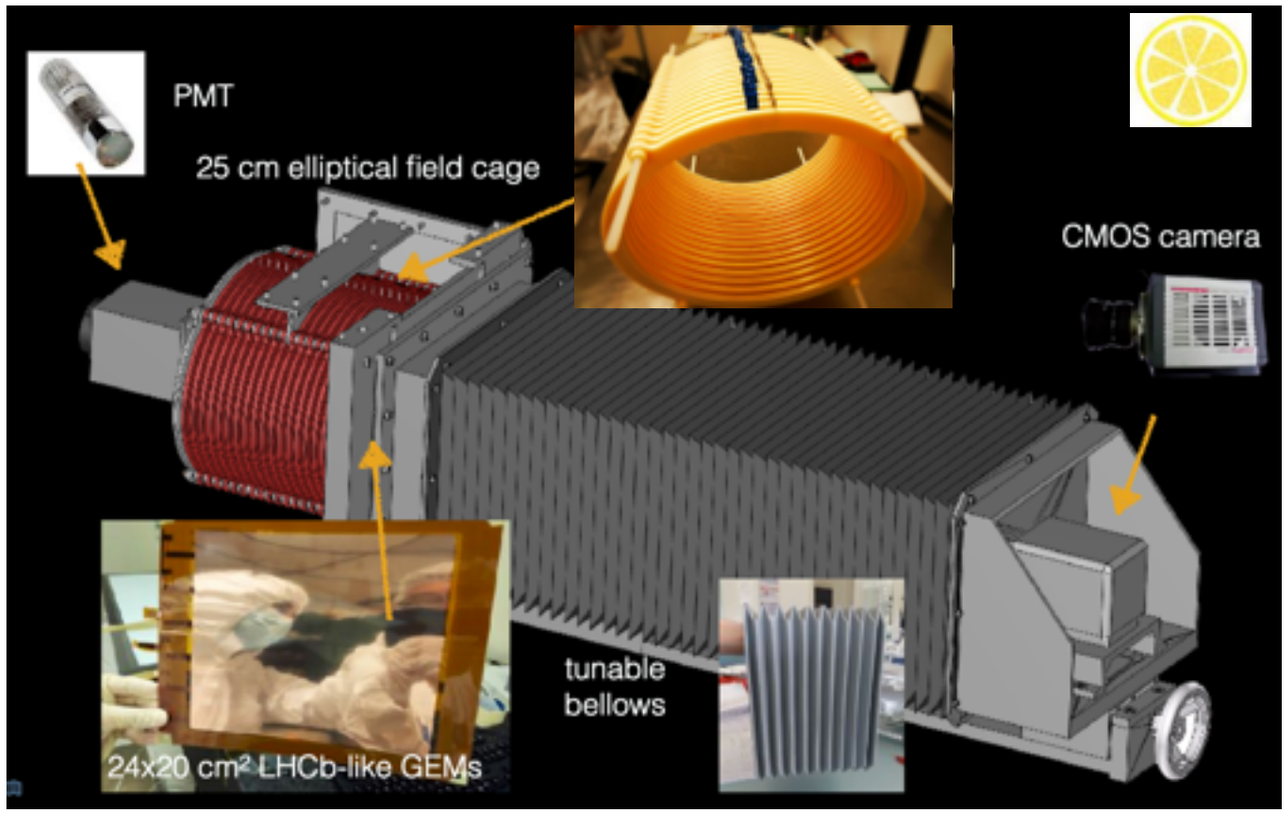
Adjustable clk from 50 kHz to 100 MHz SUITABLE for both electron and negative ion drift

CYGNUS-RD detectors

10 x 10 x 1 cm^3
0.1 Liters
Triple thin GEMs
CMOS & PMT on same side

24 x 20 x 20 cm^3
9.6 Liters
Triple thin GEMs
CMOS & PMT on opposite sides



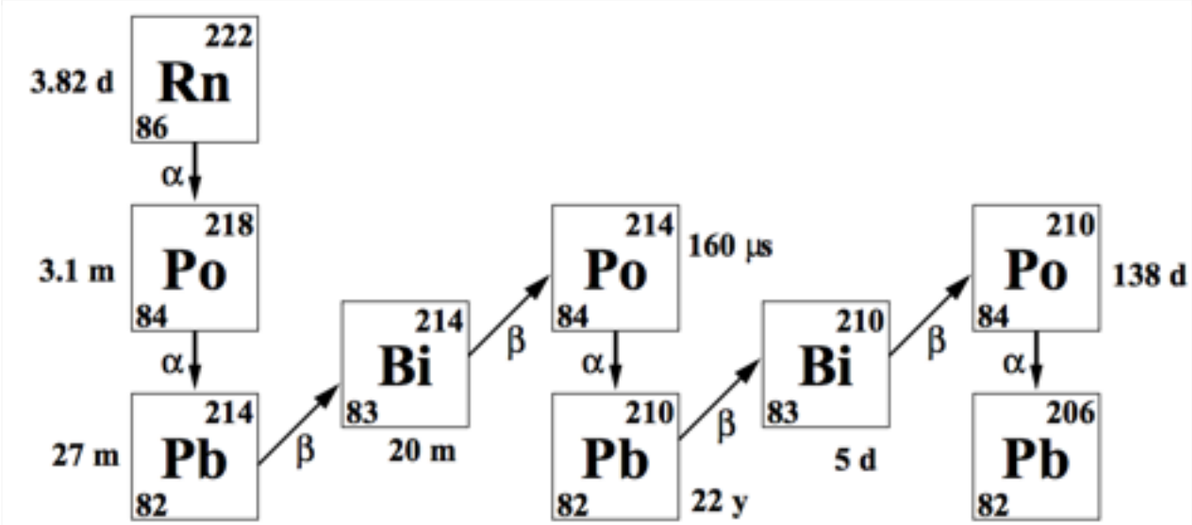


ORANGE: small prototype

LEMOn: large prototype

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

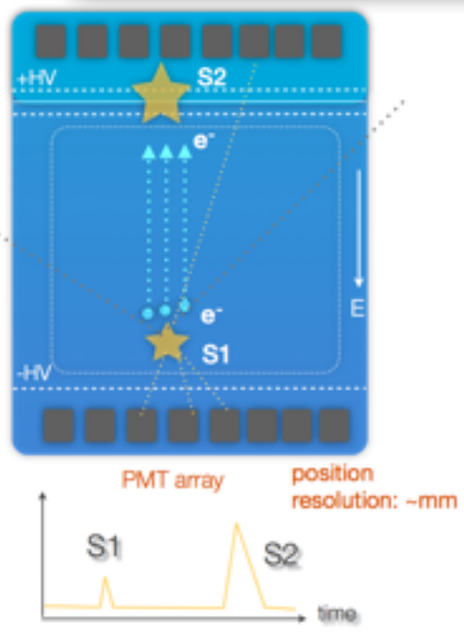
Neutron background in a TPC

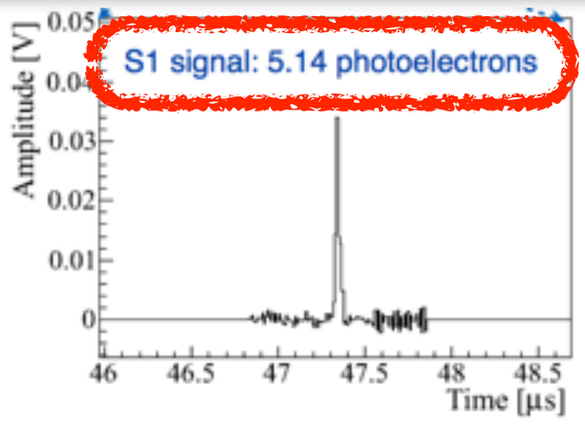


After classical background minimization (underground lab, active & passive shielding and radio-pure detector components), Radon progeny from deposit on detector surfaces can still produce signal-like tracks

Fiducialization allow to remove RPRs

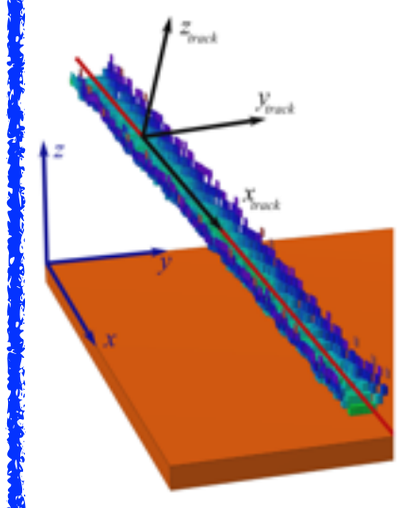
Through primary ionization light

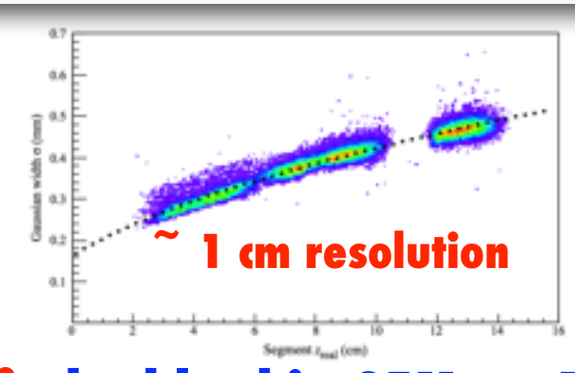




i.e. Double phase Ar/Xe liquid TPC: drift time indicates depth

Through ionization cloud profile



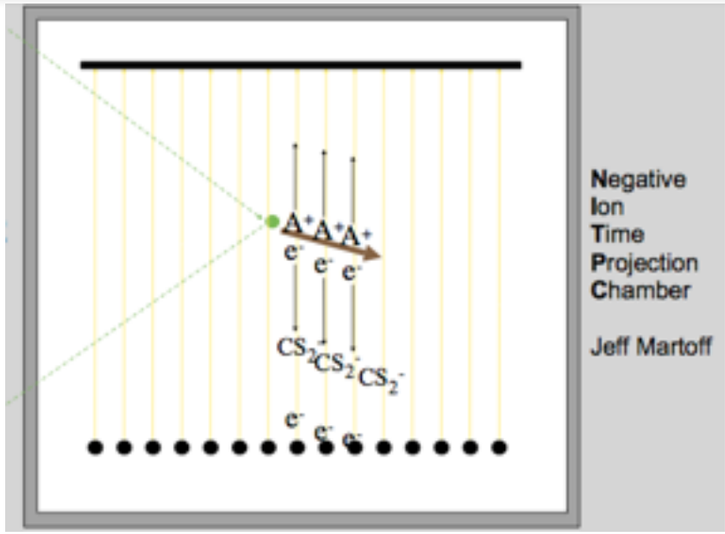


D^3: double thin GEMs + ATLAS FE-I4B pixels chip He:CO_2 70:30

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

Fiducialization with Negative Ions TPCs

Large volume fiducialized detector



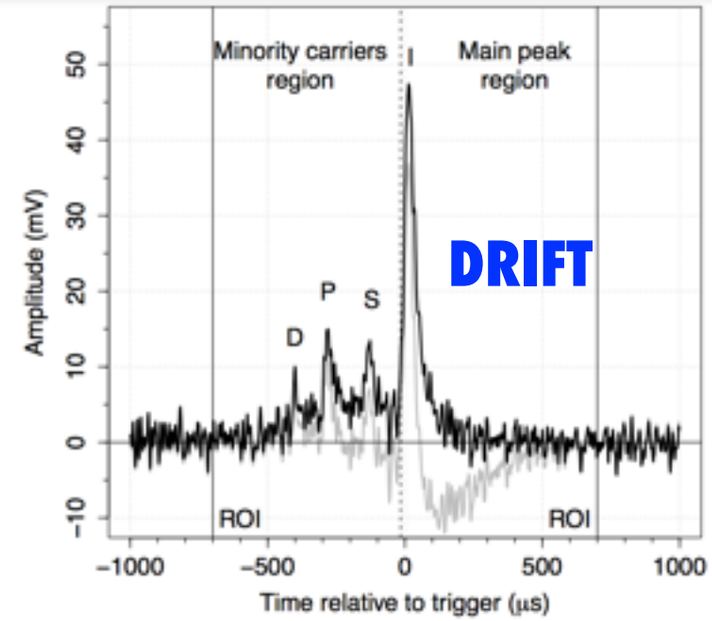
- Primary ionization electrons are captured by the electronegative gas molecules at O(100) um
- Anions drift to the anode acting as the effective image carrier instead of the electrons and reducing diffusion to thermal limit

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

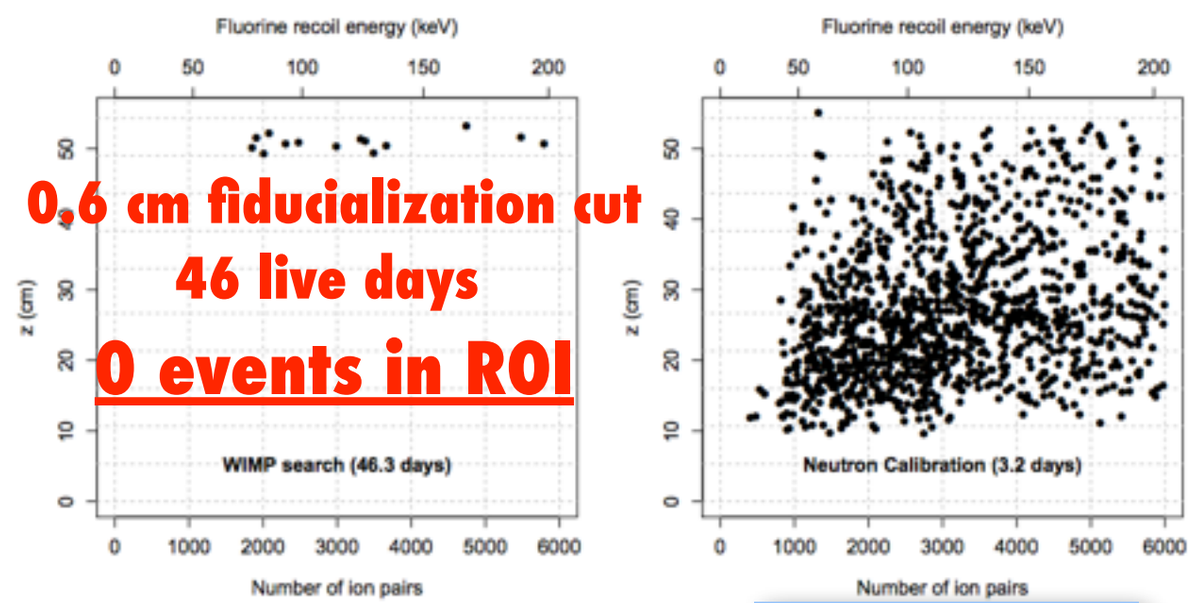
T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

NEW (2013): minority carriers



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

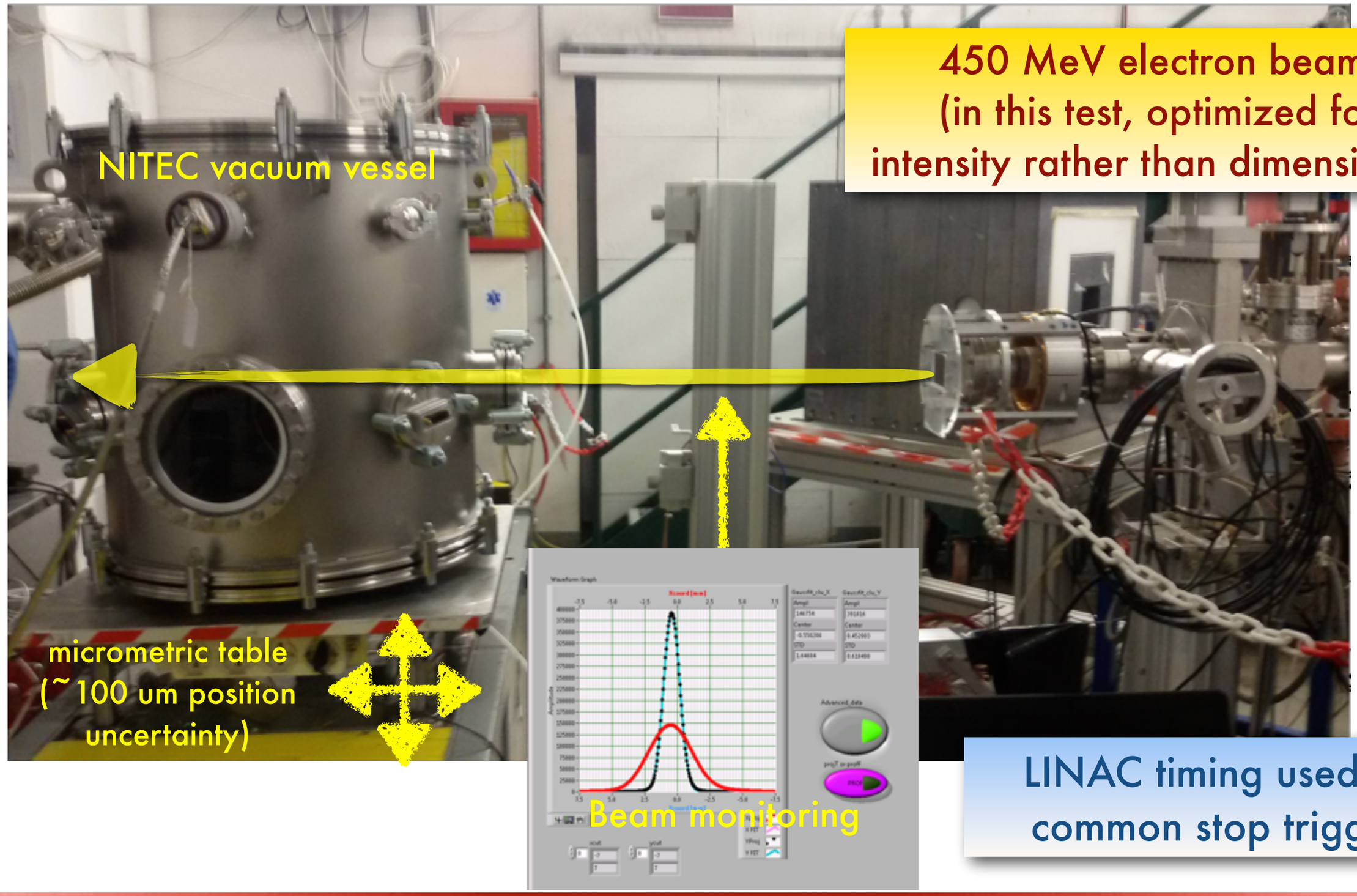


0.6 cm fiducialization cut
46 live days
0 events in ROI

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

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

Measurement @ Beam Test Facility



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

LINAC timing used as
common stop trigger

NITEC BTF measurements (TOA)

Apr 2016

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

total GEM HV gain 1480 V

Dec 2016

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

total GEM HV gain 1140 V 1240 V 1440 V

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

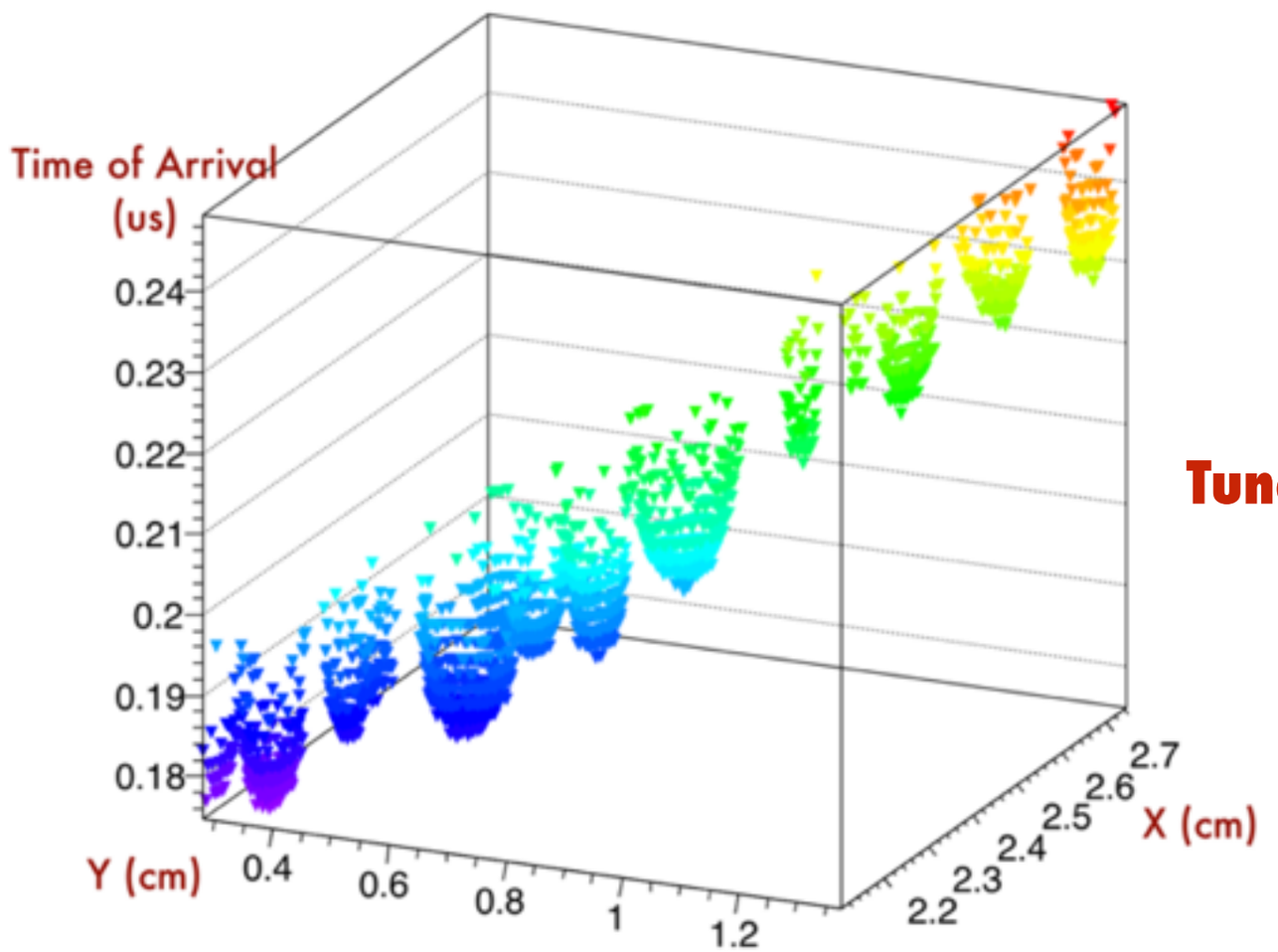
total GEM HV gain 1460 V 1640 V

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

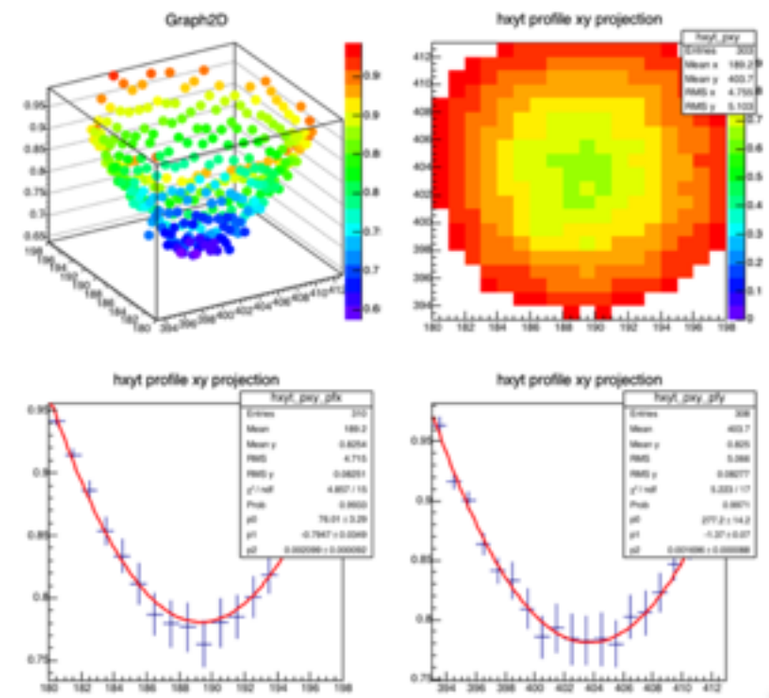
(less points in Apr 2016 data)

NITEC cluster counting

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

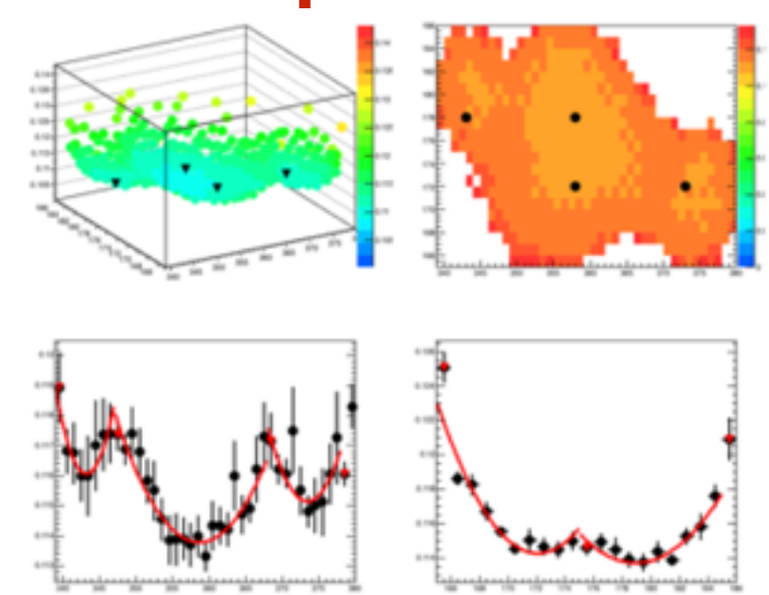


Ionization clusters structures clearly visible



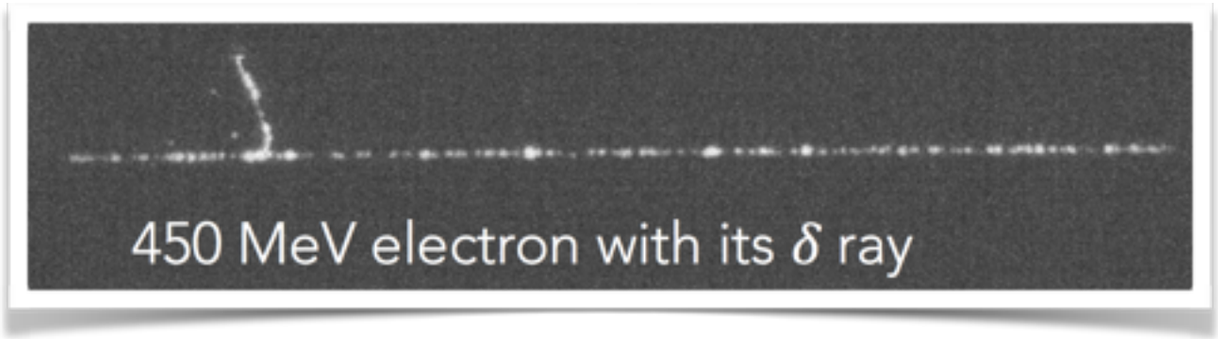
55Fe x-ray data

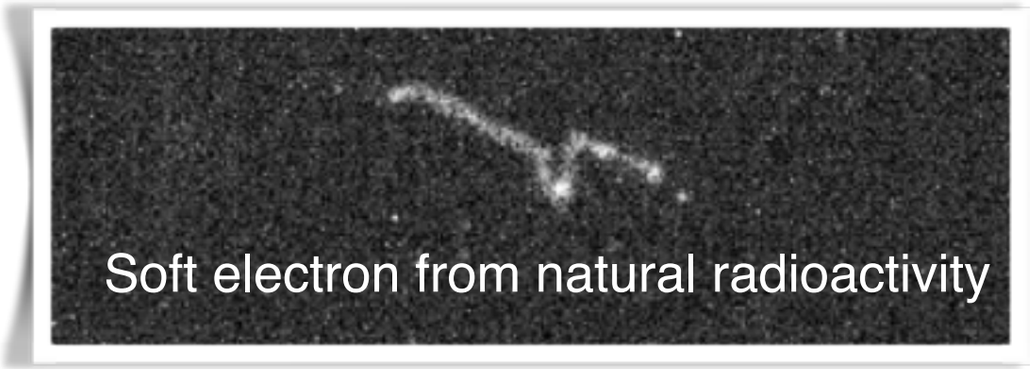
Tune the logic on ^{55}Fe single cluster x-ray to find multiple clusters blobs

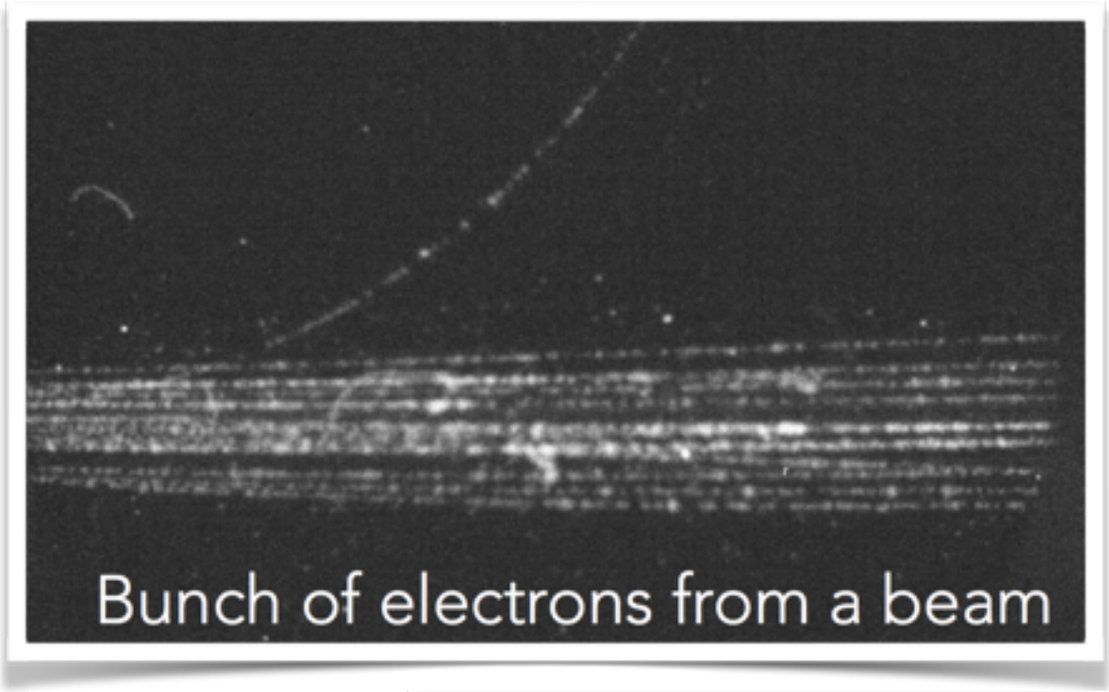


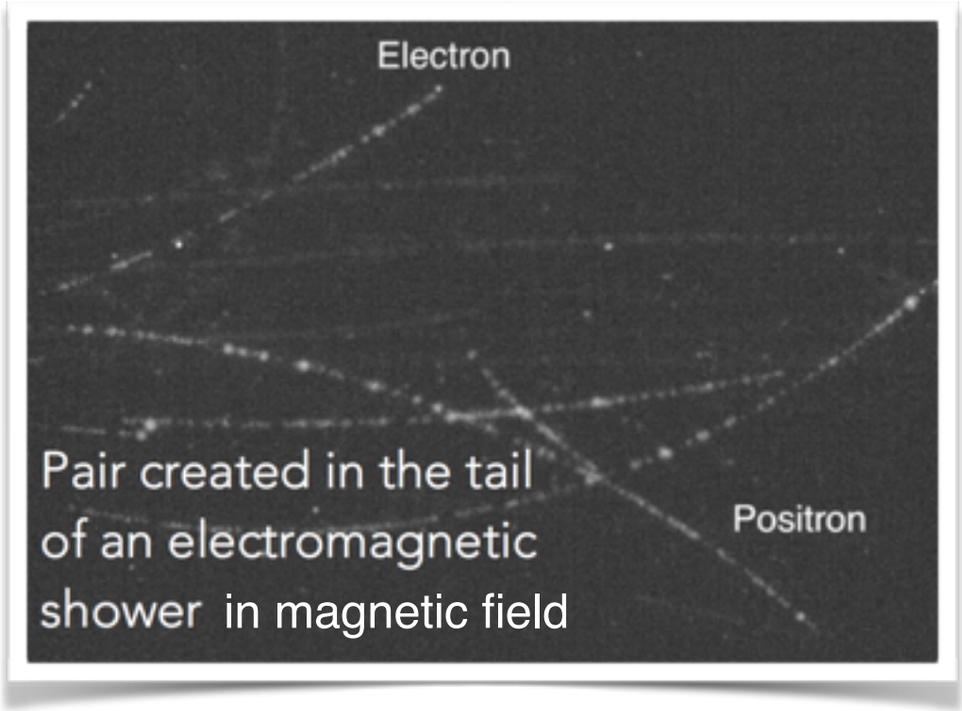
Cosmic ray data

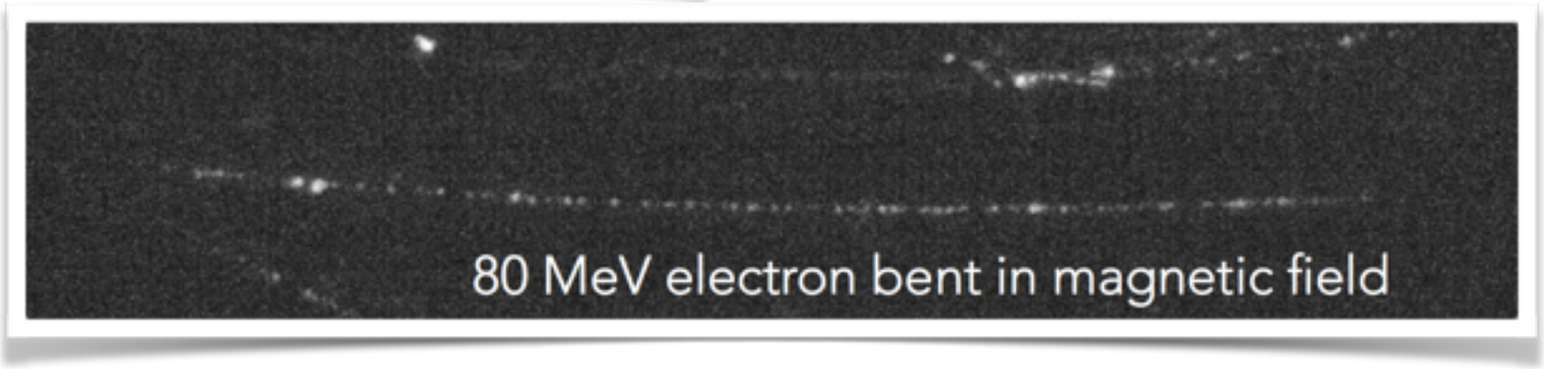
CYGNUS-RD events (with electron drift)



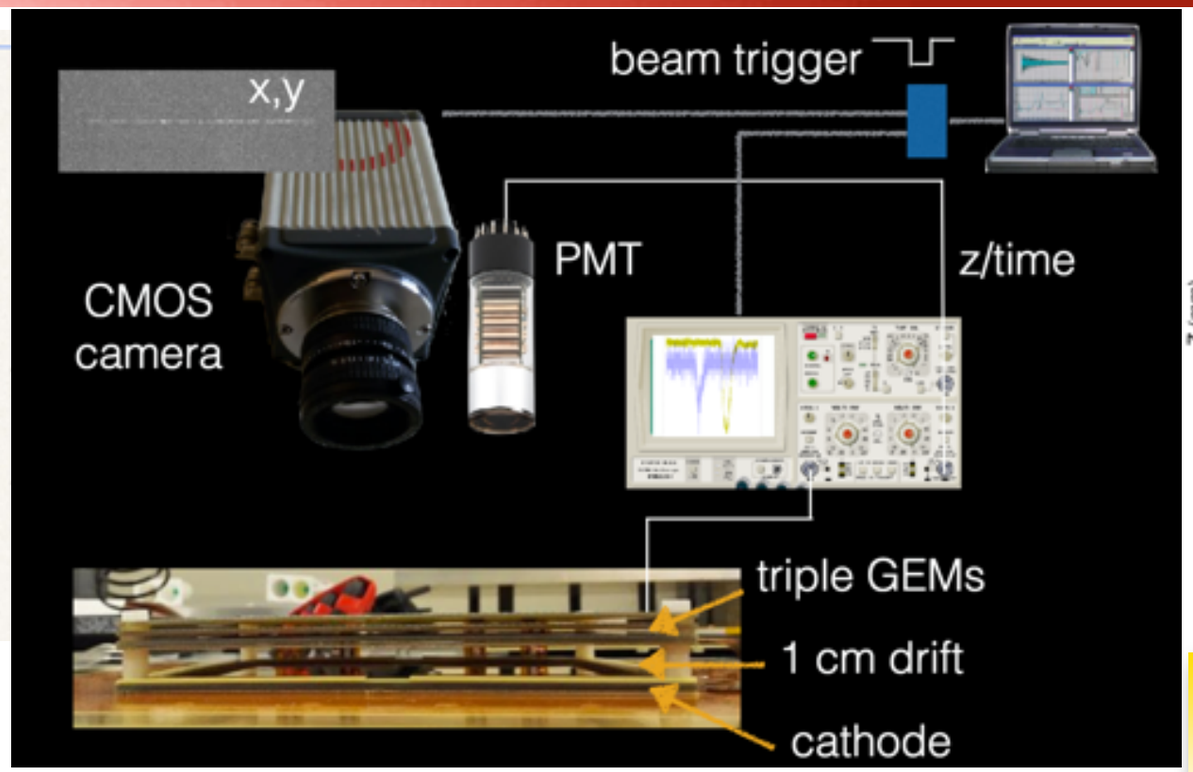




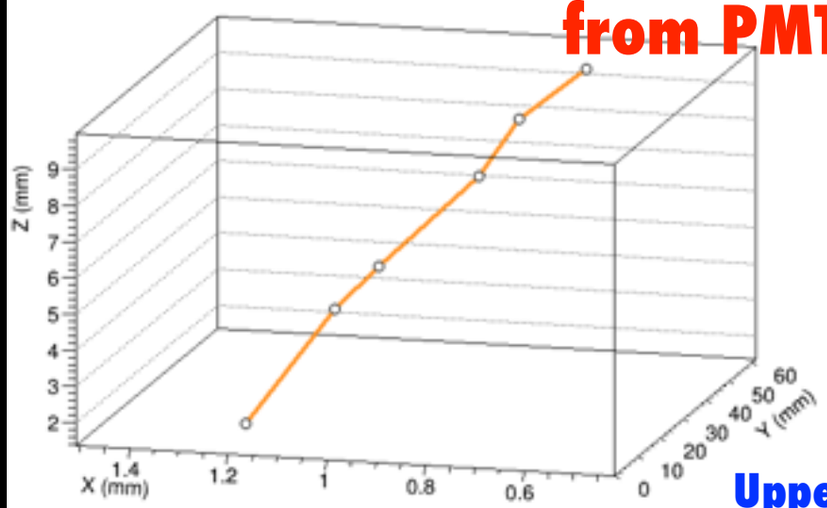


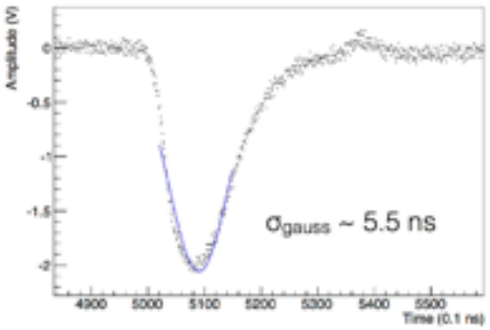


CYGNUS-RD 3D tracking



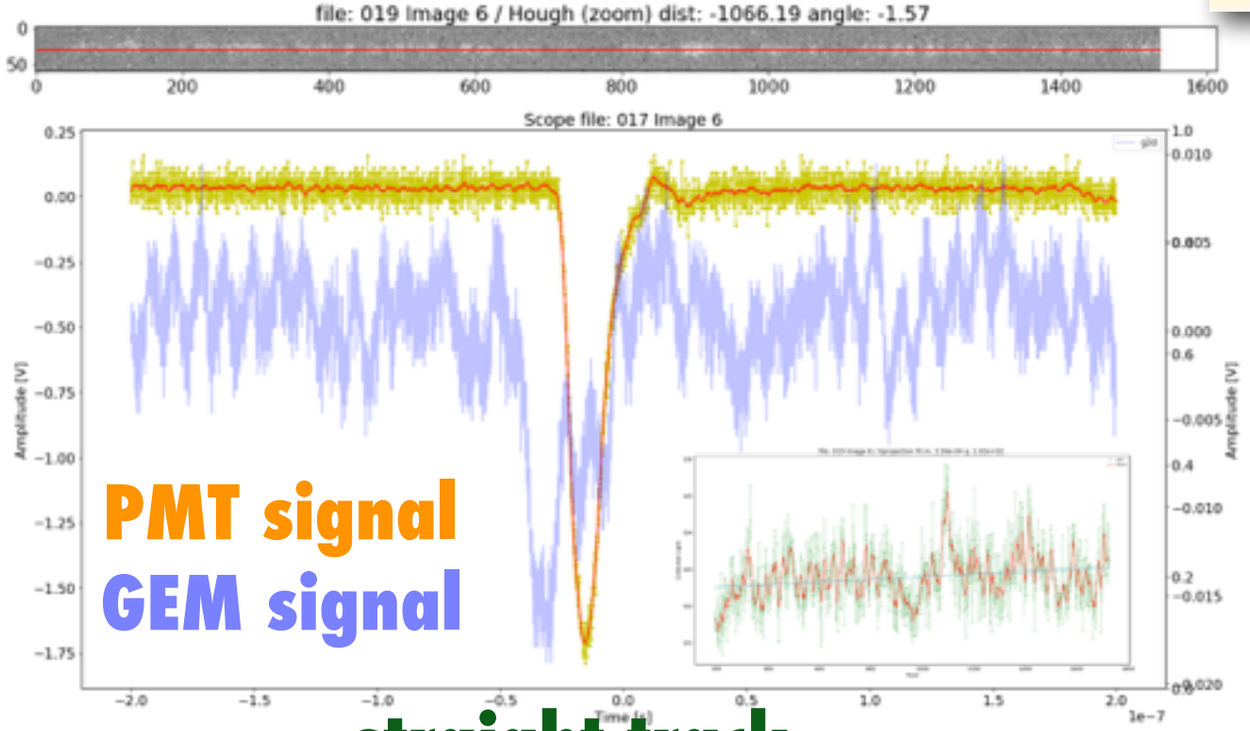
3D reconstructed track with clusters time from PMT



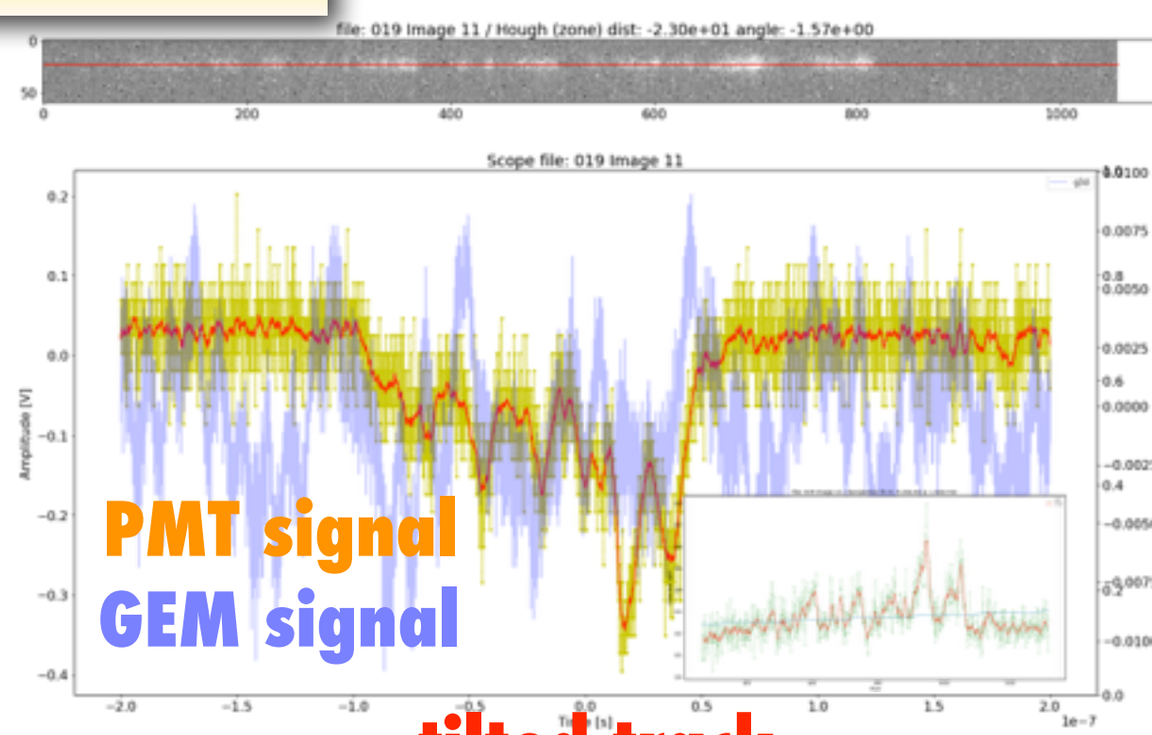


Upper limit on Z resolution (~400 um for 7.4 cm/us v_{DRIFT})

Feb 2017, electron drift in He:CF_4 @ BTF



straight track



tilted track

LNGS Neutron Flux Measurements

Fast neutrons

BF_3 ^3He ^3He

E interval (MeV)	Fast Neutron Flux ($10^{-6}cm^{-2}s^{-1}$)					
	Ref. [5]	Ref. [6]	Ref. [2]	Ref. [1]	Ref. [7]	Ref. [8]
0.1 – 1	Liquid scintillator		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

^3He BF_3 ^3He ^3He

E interval (eV)	Thermal Neutron Flux ($10^{-6}cm^{-2}s^{-1}$)			
	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