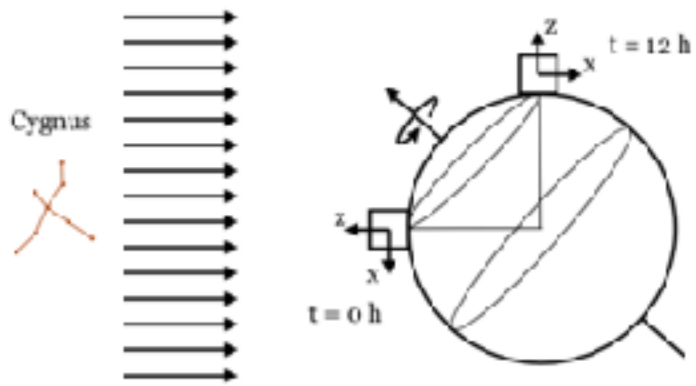
Elisabetta Baracchini
Gran Sasso Science Institute
On behalf of the CYGNO collaboration & D. Loomba

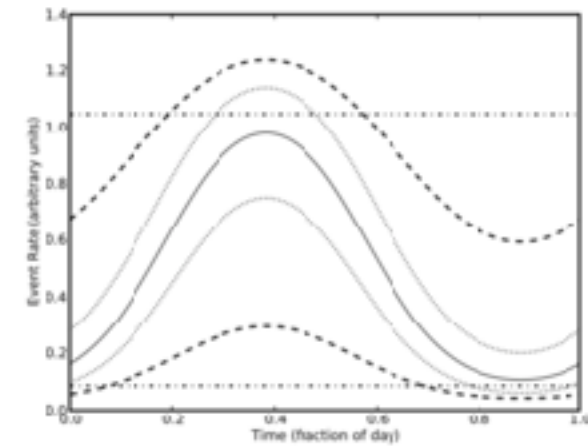
Directional Dark Matter search with optical readouts & the CYGNO project

Identification of Dark Matter 2018
Brown University, Providence, USA
23rd-27th July 2018

Why directional Dark Matter searches

The only approach able to unambiguously and positively identify a DM signal





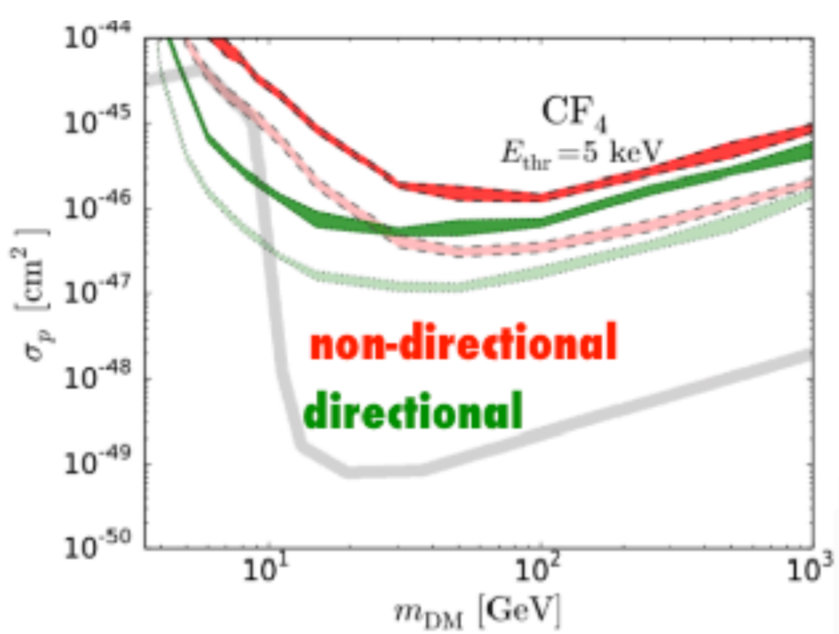
Review on directional direct dark matter search with gaseous detectors	Prof. Kentaro Miuchi
117, MacMillan	08.30 - 08.50
CYGNUS - a multi-latitude directional WIMP experiment	Prof. Neil Spooner
117, MacMillan	08.50 - 09.10

A. M. Green et. al, Astropart. Phys. 27 (2007) 142

difference from baseline configuration	N_{90}	N_{95}
none	7	11
$E_{TH} = 0$ keV	13	21
no recoil reconstruction uncertainty	5	9
$E_{TH} = 50$ keV	5	7
$E_{TH} = 100$ keV	3	5
$S/N = 10$	8	14
$S/N = 1$	17	27
$S/N = 0.1$	99	170
3-d axial read-out	81	130
2-d vector read-out in optimal plane, raw angles	18	26
2-d axial read-out in optimal plane, raw angles	1100	1600
2-d vector read-out in optimal plane, reduced angles	12	18
2-d axial read-out in optimal plane, reduced angles	190	270

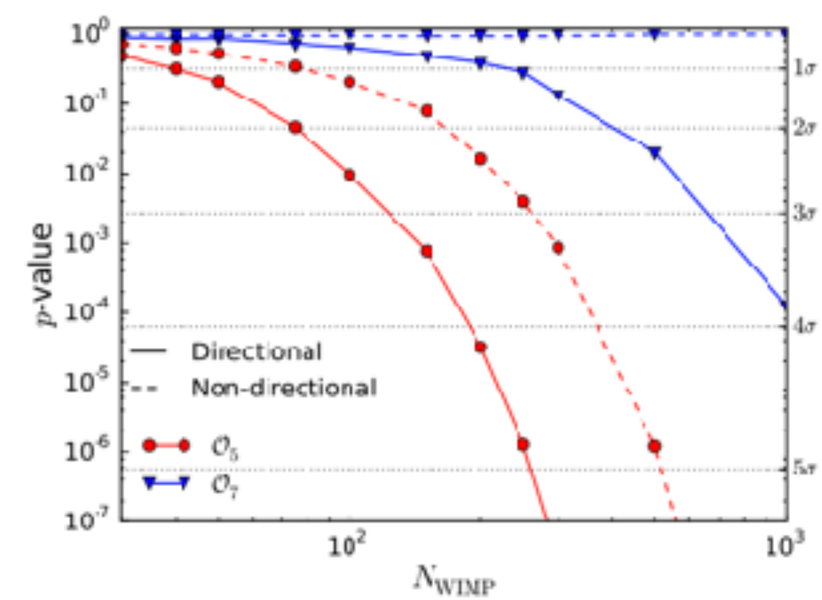
Capability to reject isotropy down to low threshold, i.e. to fight all backgrounds, including neutral

P. Grothaus, et al, Phys. Rev. D 90 (2014) no.5



Capability to leap beyond Neutrino Bound

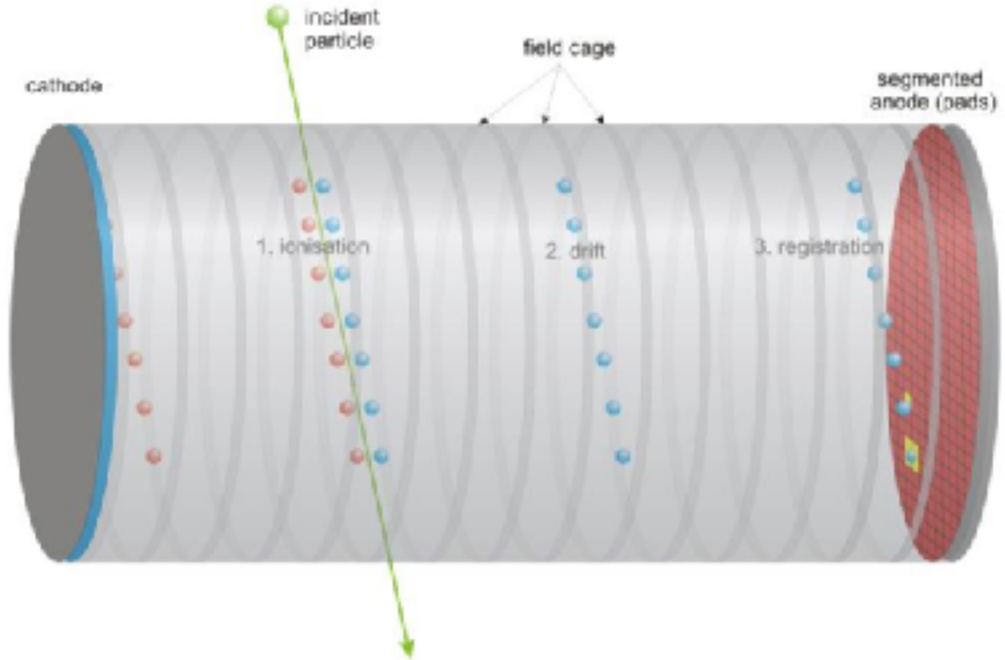
F. Mayet et al., Phys. Rept 627 (2016)



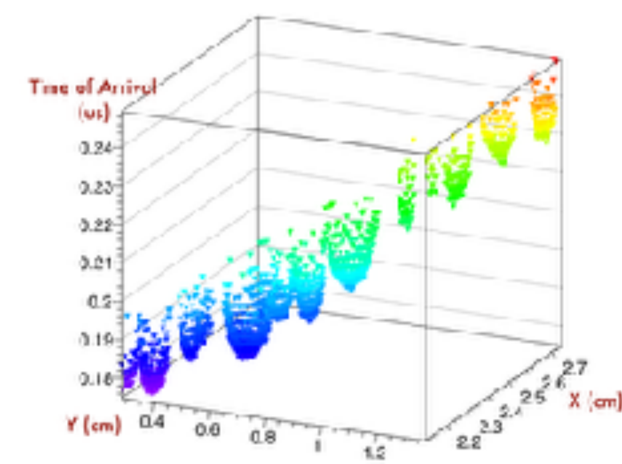
Capability to probe DM nature once discovered

Why gaseous TPC for (directional) DM searches

- TPCs are inherently a 3D detector, being able to measure position and direction, including sense
- TPCs can measure dE/dx for PID (read background rejection) and track sense determination
- TPCs allow to optimize pressure and gases content, to either increase exposure or track length
- Gas ionisation inherent energy threshold 20-40 eV
- Gas can be purified from Rn and other contaminants
- Gas TPCs do not need cryogenics, nor any other large service system like other DM searches approaches
- He (and H), the best kinematic matches nuclei for low mass WIMPs, are gaseous at STP

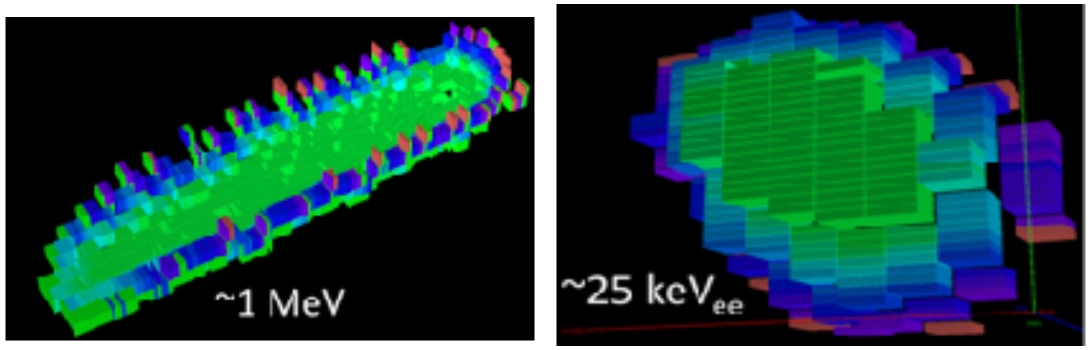


In a pixel readout TPC:

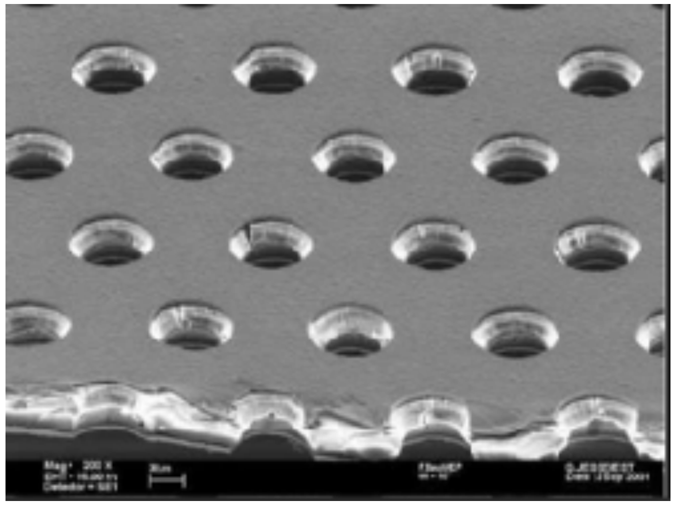


Cosmic ray

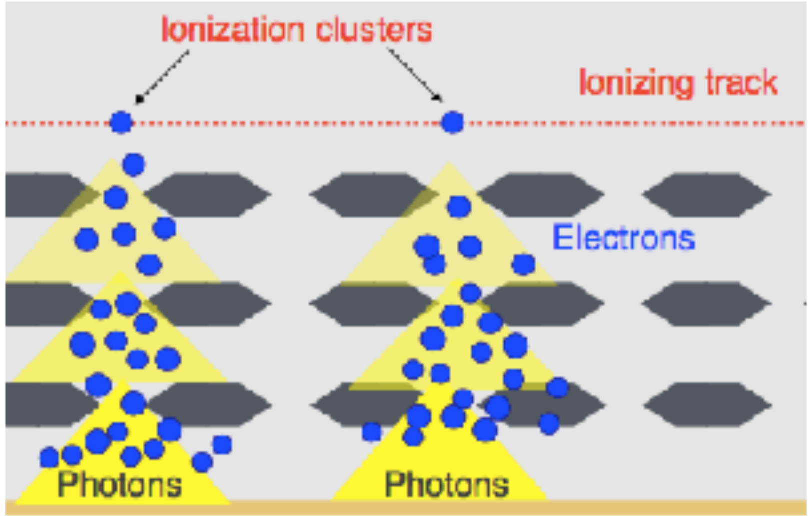
He recoils



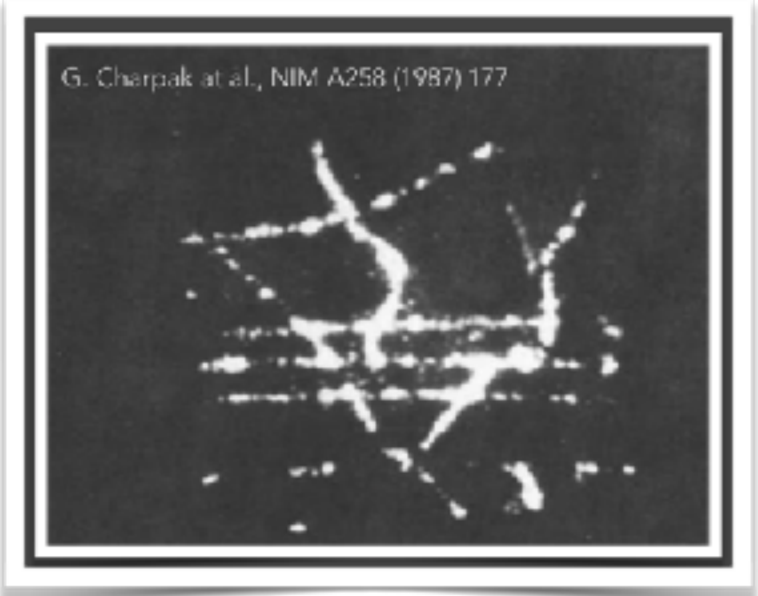
Gas amplification through GEMs and optical readout



Typical GEM charge gain 10^5-10^6



Photons are produced together with electrons in the amplification process



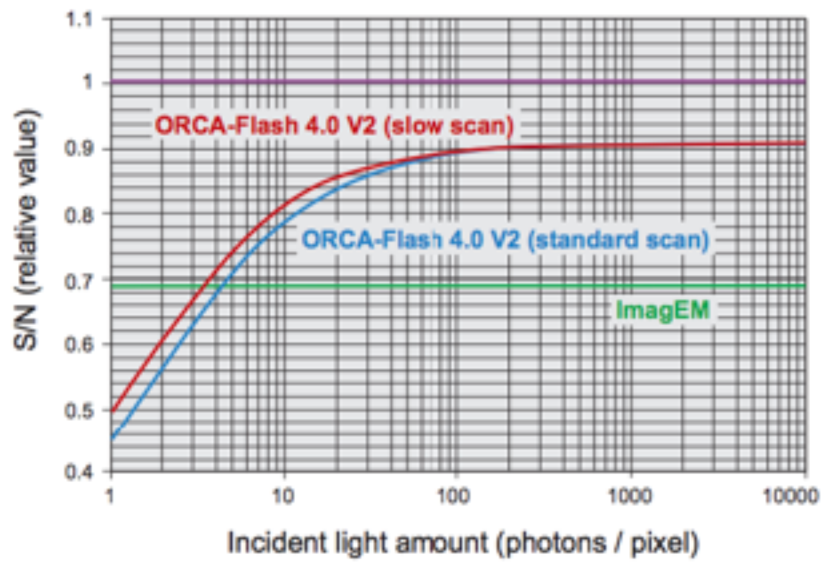
First realisation by Charpak in 1987

Optical readout advantages:

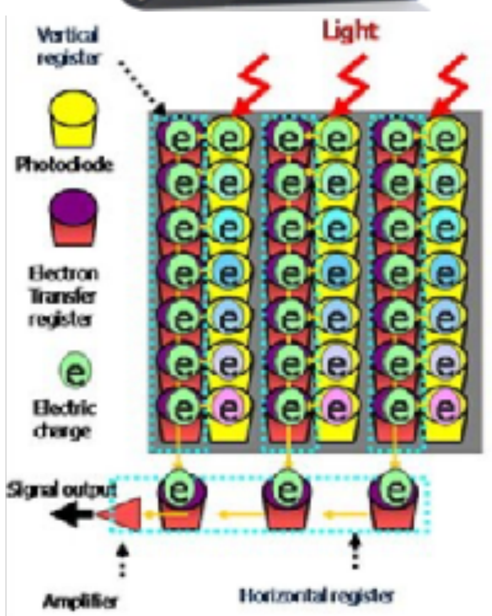
- High market availability & development, following **Moore law**
- **High integrated granularity** up to million of channels
- High sensitivity, down to **single photon**, hence low energy threshold
- **Decoupling** of sensors and electronic from target gas and high field drift region
- Possibility to image **large areas** with the proper optics

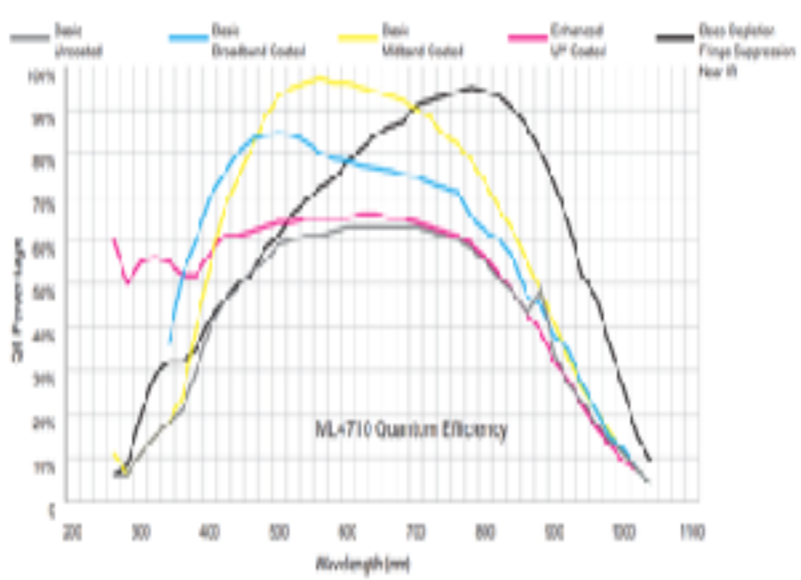
Imaging sensors: CCDs & sCMOS

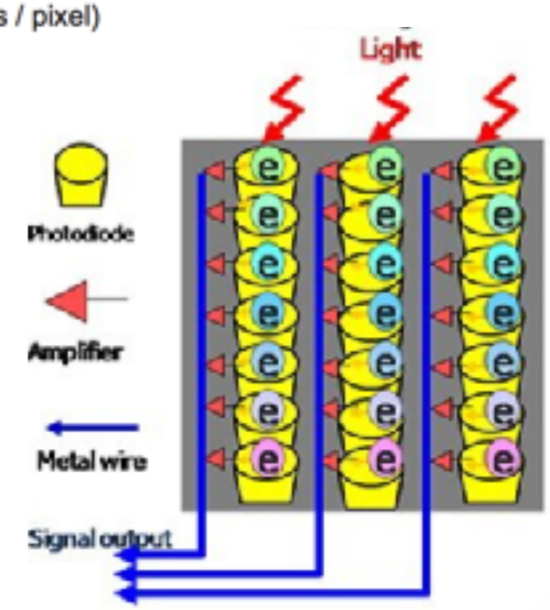
CCD

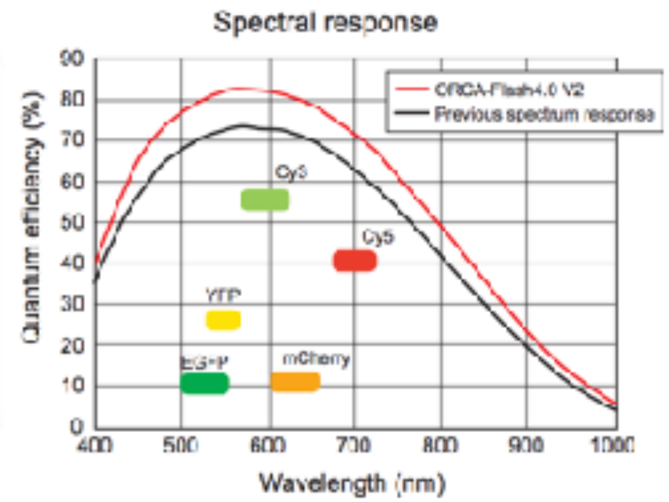


sCMOS









Larger light yield
Crispier images
Higher uniformity
Larger noise
Larger power consumption

	# pixels	Pixel size	Noise	Q.E. at peak
CCD ML4710	1024 x 1024	13 um	10 e- RMS	93%
CMOS Orca Flash	2048 x 2048	6.5 um	1 e- RMS	85%

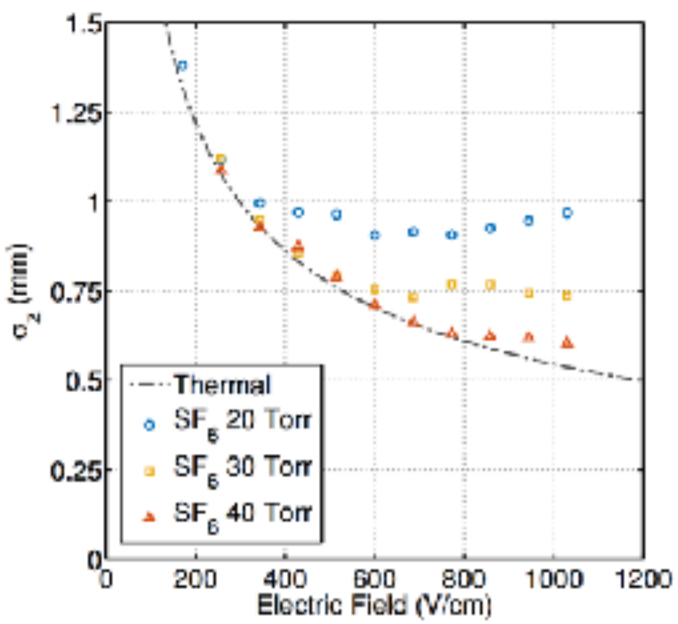
Lower light yield
Lower noise
Lower power consumption
Cheaper than CCD
Under rapid developments

CF_4-based gas mixtures

CF_4:(CS_2/SF_6)

100/150 Torr with CCD electron/negative ion drift

- **Diffusion reduced to thermal limit ± 1 mm/m**
- **Minority charge carriers for surface events rejection**
- **NI drift can be obtained with only ±1-2% CS_2/SF_6**

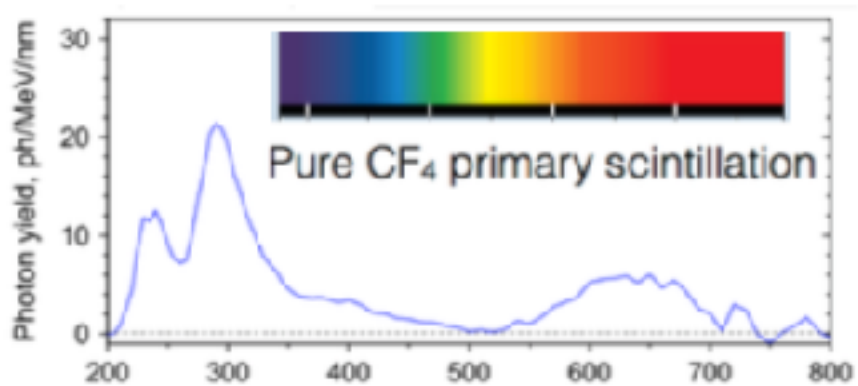


(a) SF_6 diffusion

SF_6 longitudinal diffusion

CF_4

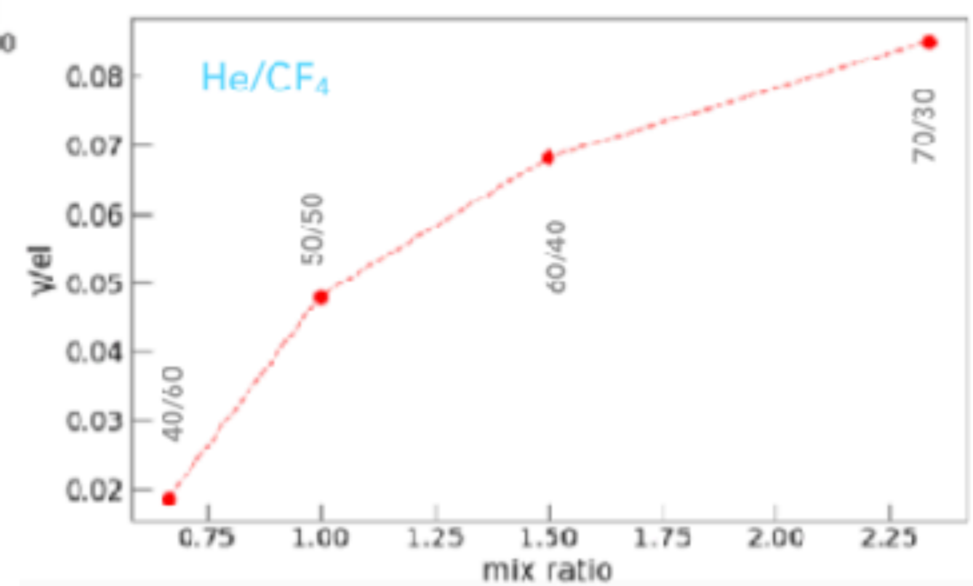
- **High light yield**
- **Spectrum matched to sensors**
- **Often used as quencher**



He:CF_4

740 Torr with sCMOS electron drift

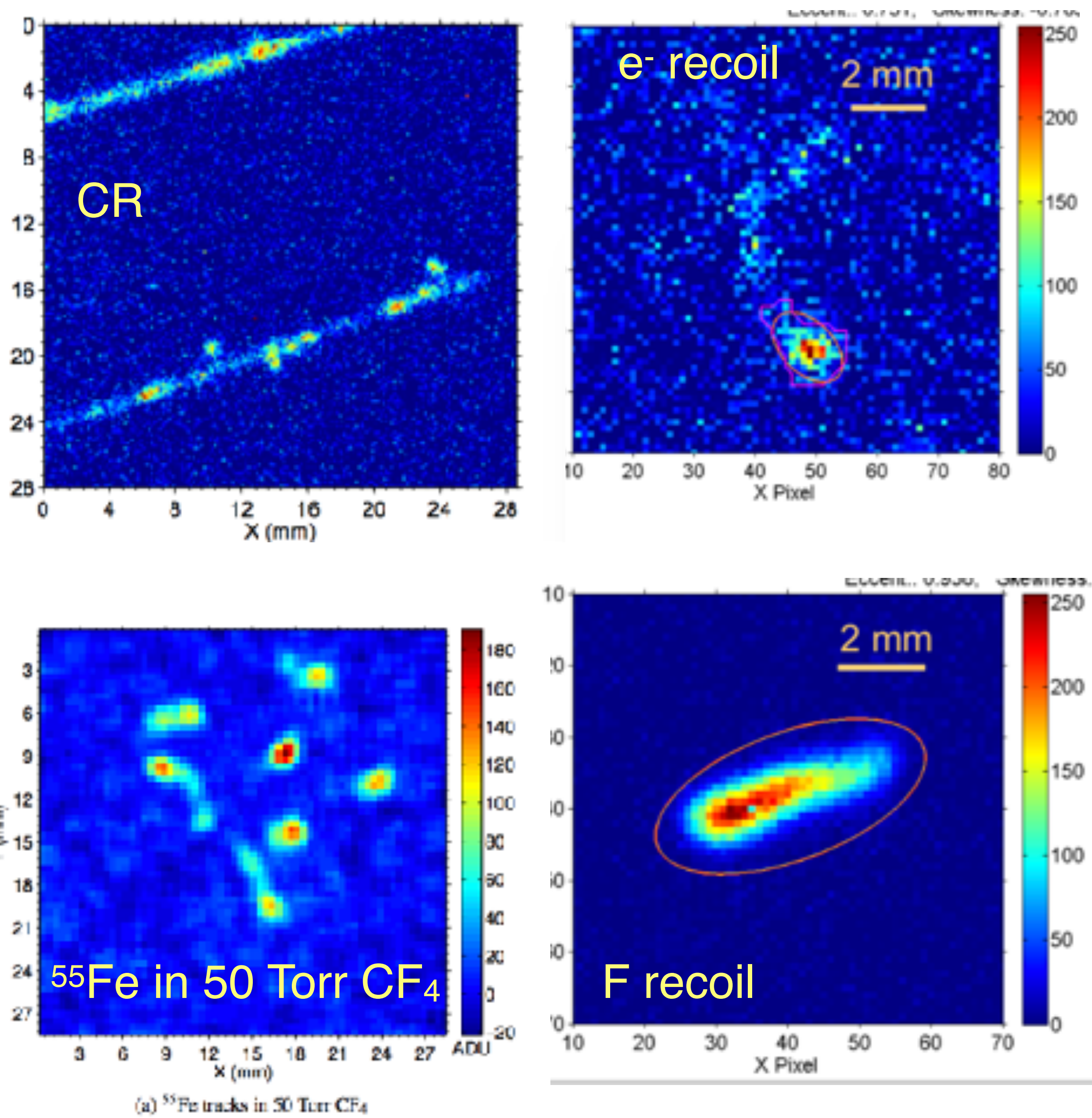
- **Atm operation while maintaining low target density (80:20 is only 20% denser than 150 Torr CF_4)**
- **SI sensitivity to low mass WIMP**
- **He increases γ/e⁻ ratio**



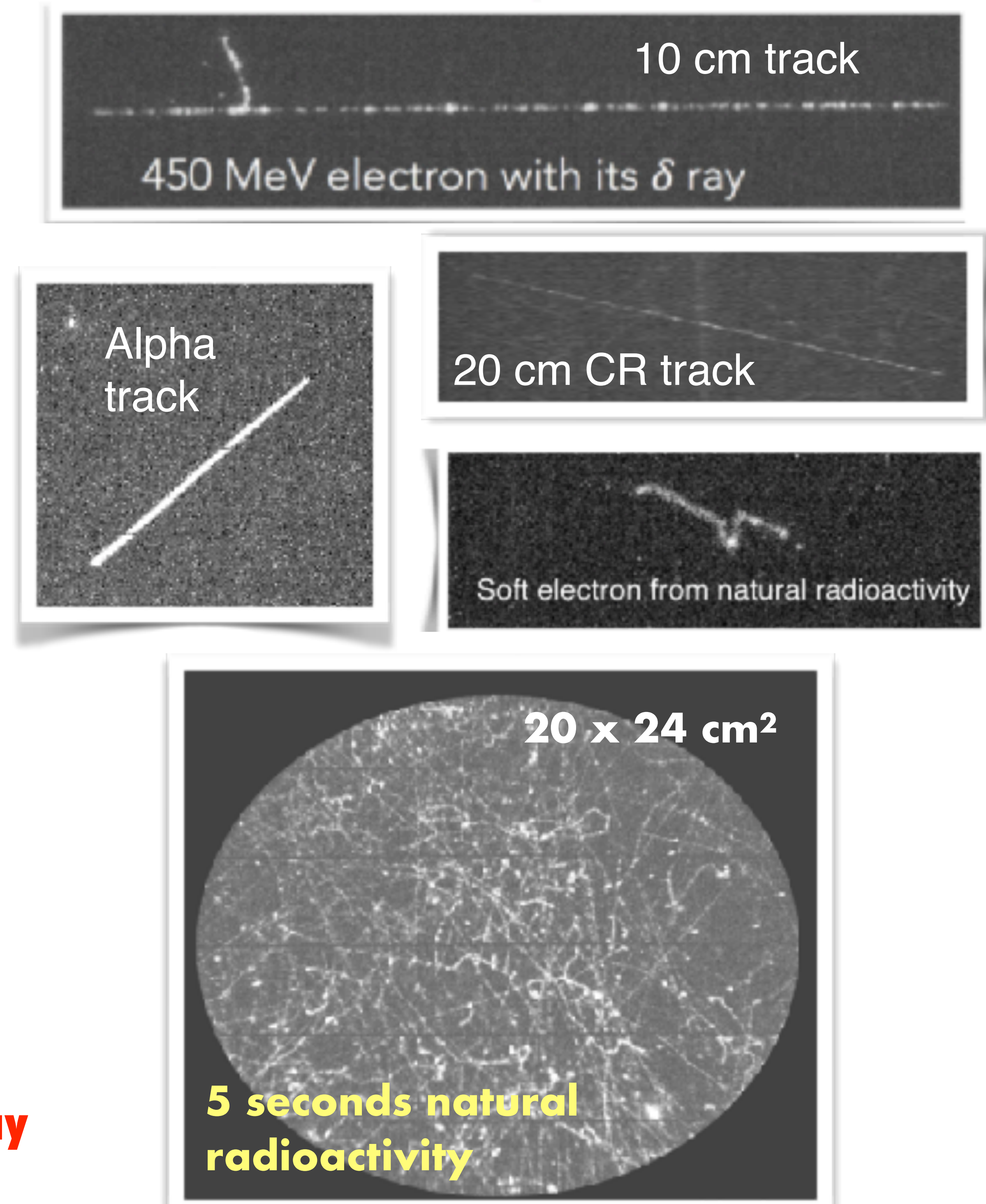
γ/e⁻ ratio as function of He/CF_4 ratio

Photographing tracks

CCD



sCMOS



***black & white/colours is simply the way we display data, not an intrinsic feature of the sensors ;)**

CCDs and negative ion gas mixtures

THE UNIVERSITY of NEW MEXICO

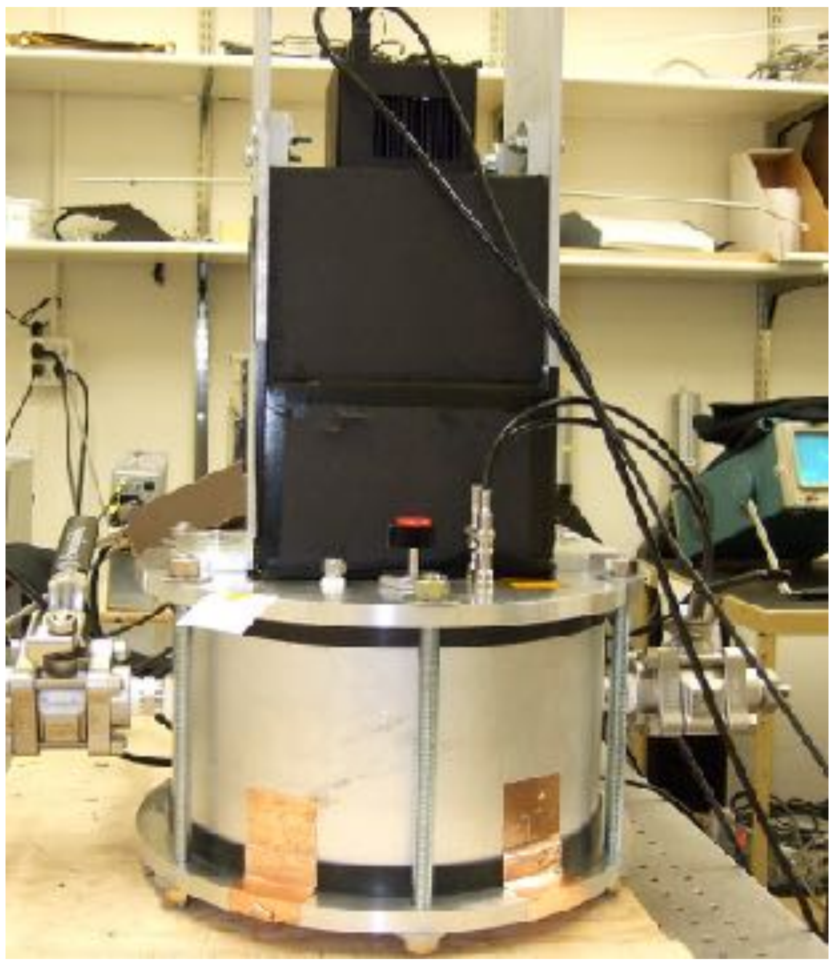
D. Loomba et. al

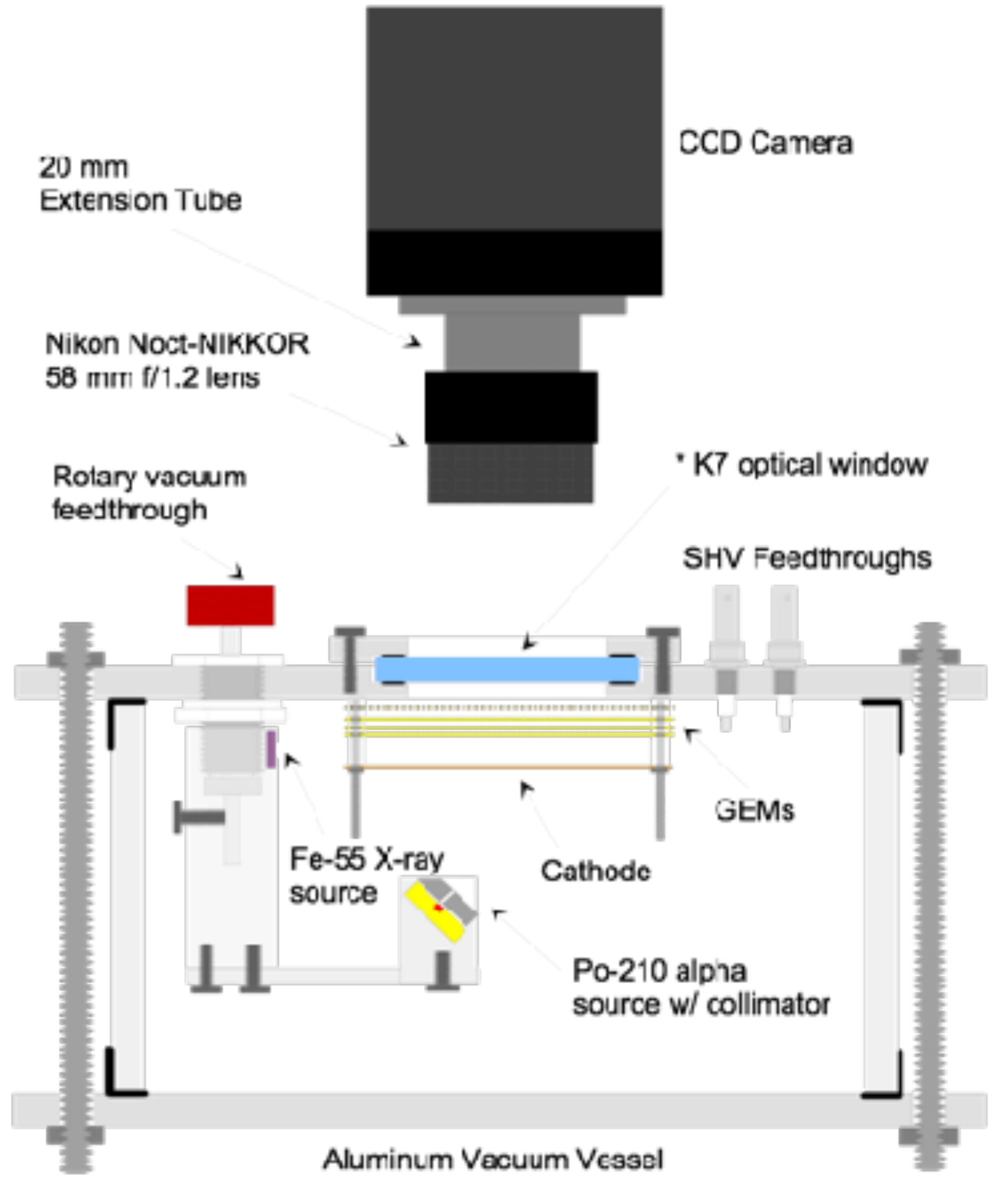
UNM prototype

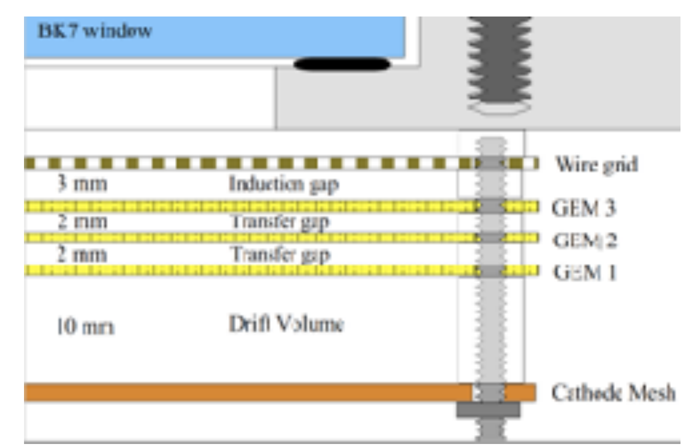
MicroLine ML4710-1-MB CCD camera

THE UNIVERSITY of NEW MEXICO

D. Loomba et. al





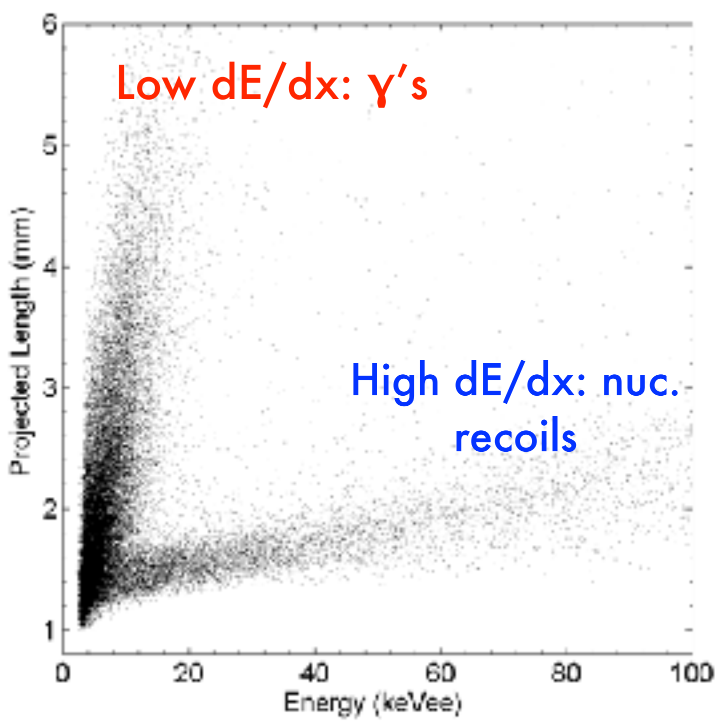


$3 \times 3 \times 1$ cm^3

- **Effective gain: ~ 200,000**
- **Energy resolution measured optically: 35 % (FWHM) at 5.9 keVee (CCD)**

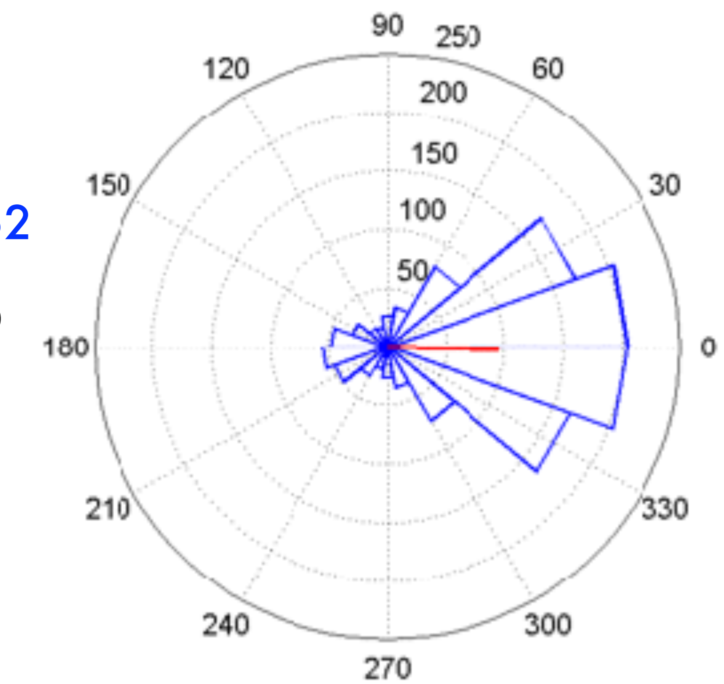
CCD in pure CF_4 100 Torr, e^- drift

Discrimination and Directionality demonstrated in 100 Torr CF_4:

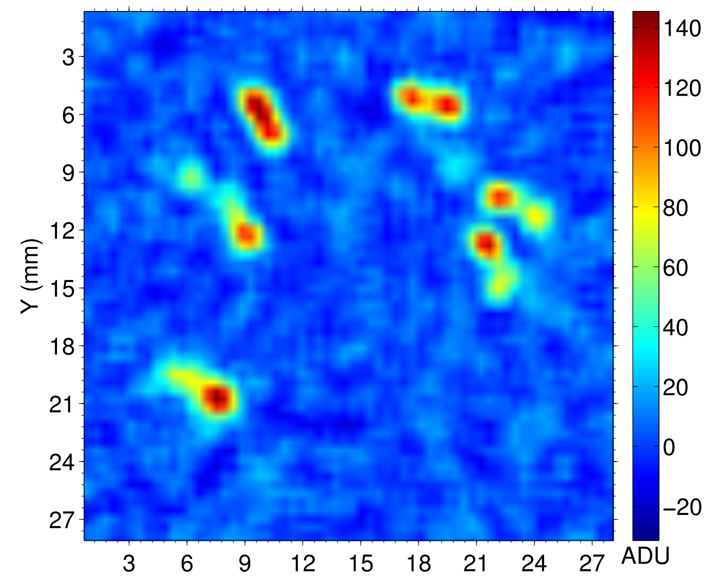


- 10^5 discrimination threshold ~ 10 keVee (~23 keVr).
- Directionality threshold ~40 keVr for axial, ~55 keVr for vector.
- Need ~50 events to rule out isotropy at 90% CL for 100 GeV WIMP.
- Both Discrimination and Directionality could extend to lower energies, and lower mass WIMPs. E.g. by reducing pressure and using light targets.
- Shown here are resolved Fe-55 electron tracks taken in 50 Torr CF_4, showing the direction of the emitted electrons

Cf-252



2D vector recoil directions



Phan, et al. Astro Part Phys. 84 (2016) 82-96

Phan, et al. arXiv: 1703.09883

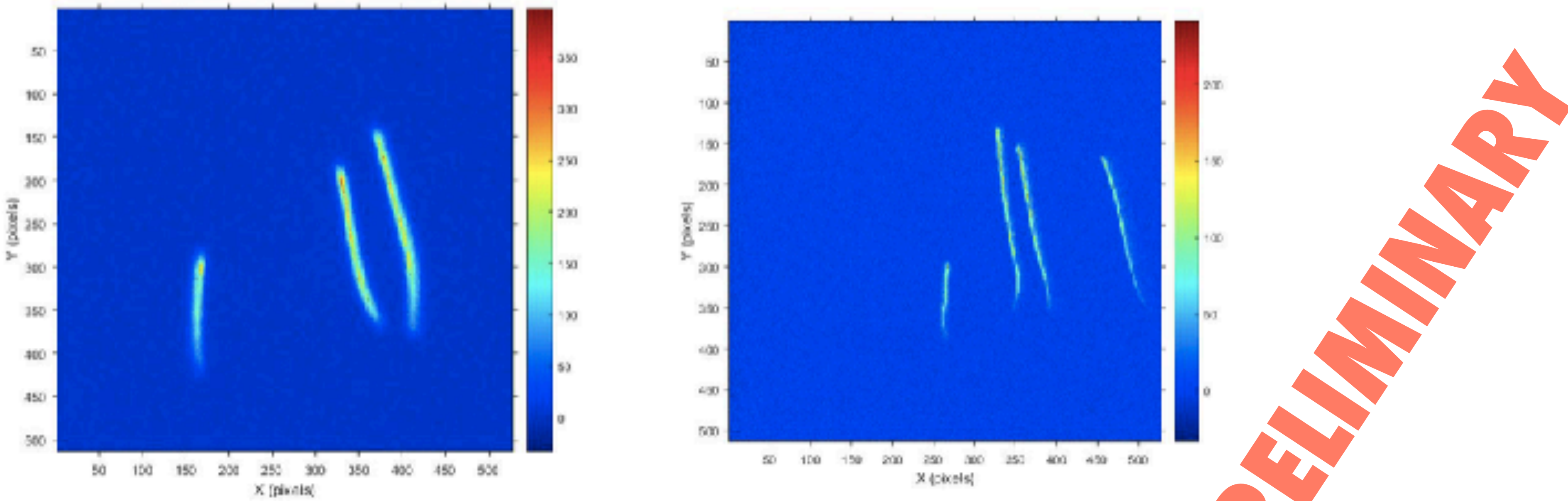
- For discriminating between electronic and nuclear recoils down to the lowest possible energies, high S/N is critical. 3D tracks would also help.

UNM R&D with CCD and NI drift

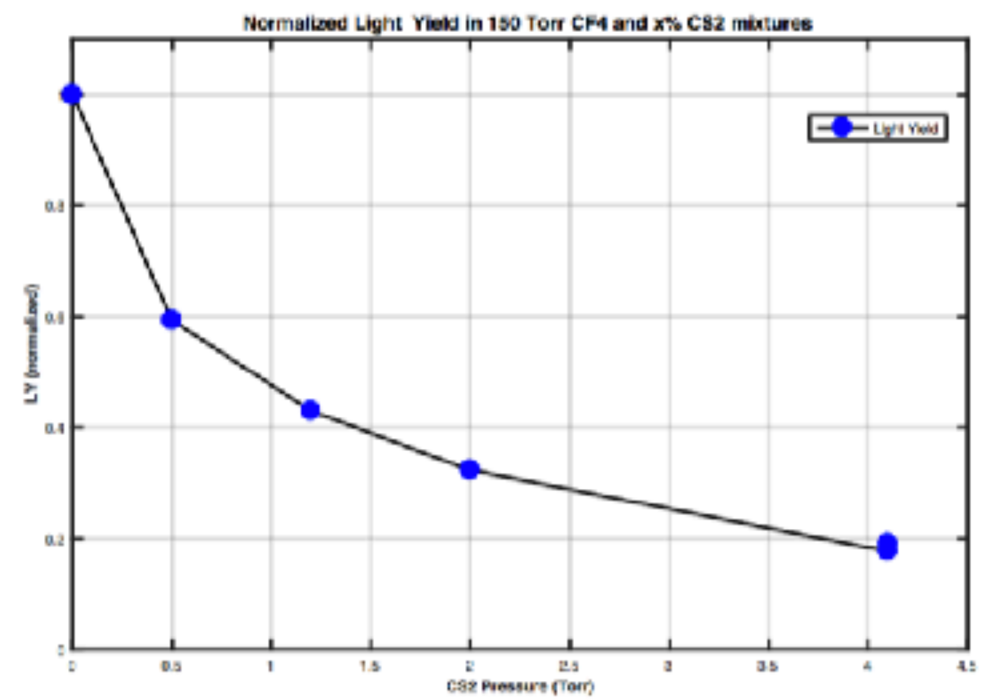
Investigate advantages/disadvantages of negative ion + CF_4 gas mixtures, such as CS_2/CF_4 and SF_6/CF_4.

- What is effect on diffusion? Results are for alpha tracks in 150 Torr CF_4 (left), plus ~4 Torr CS_2 (right).

  About 3.4X reduction In diffusion, determined using widths of alpha tracks.



- What is effect on light yield (LY)? About a factor 5X reduction in LY, measured using Fe-55 charge and optical spectra. If there is good S/N, this could bring benefits of NI to optical readout TPCs (LY == light/charge)



D. Loomba et. al

sCMOS and He-based gas mixtures at atmospheric pressure: CYGNUS-RD

E. Baracchini et. al

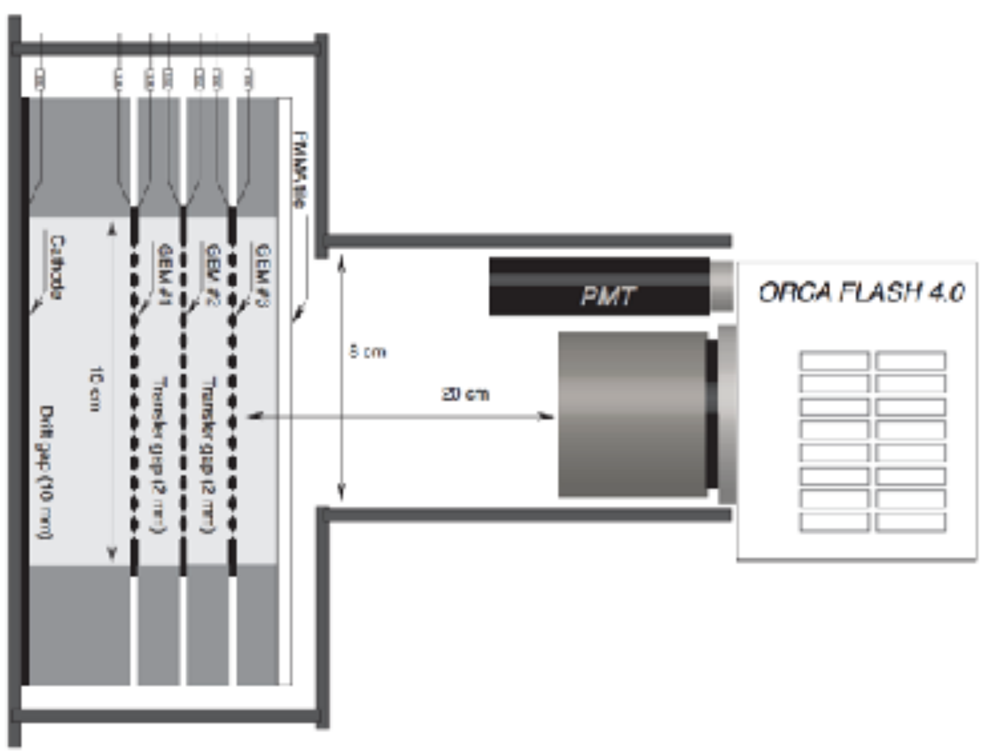
CYGNUS-RD project (2016-2018)

Hamamatsu Orca Flash 4 sCMOS camera

JINST 13 (2018) no.05, P05001

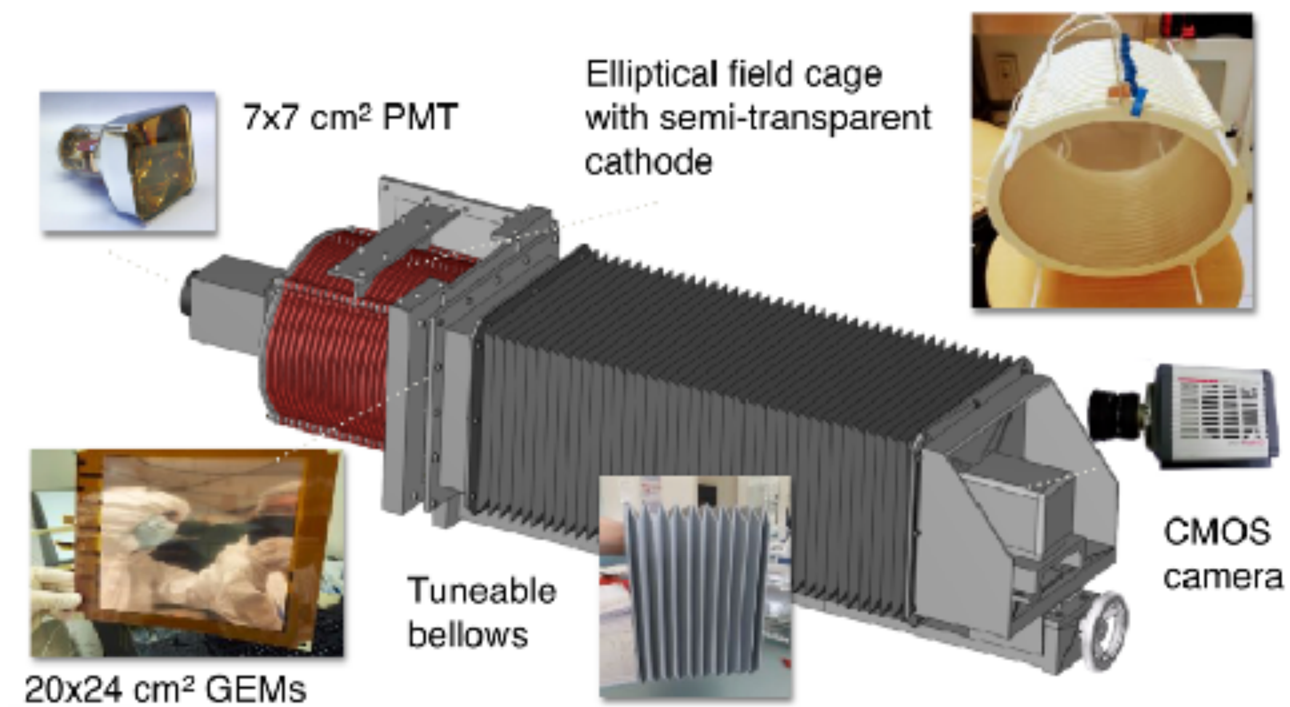
PoS EPS-HEP2017 (2017) 077

10 x 10 x 1 cm³
0.1 Liters
Triple thin GEMs
CMOS & PMT on same side



ORANGE: small prototype

24 x 20 x 20 cm³
9.6 Liters
Triple thin GEMs
CMOS & PMT on opposite sides



LEMOn: large prototype

CYGNUS-RD Italian collaboration - https://web.infn.it/cygnus/

CYGNUS-RD project (2016-2018)

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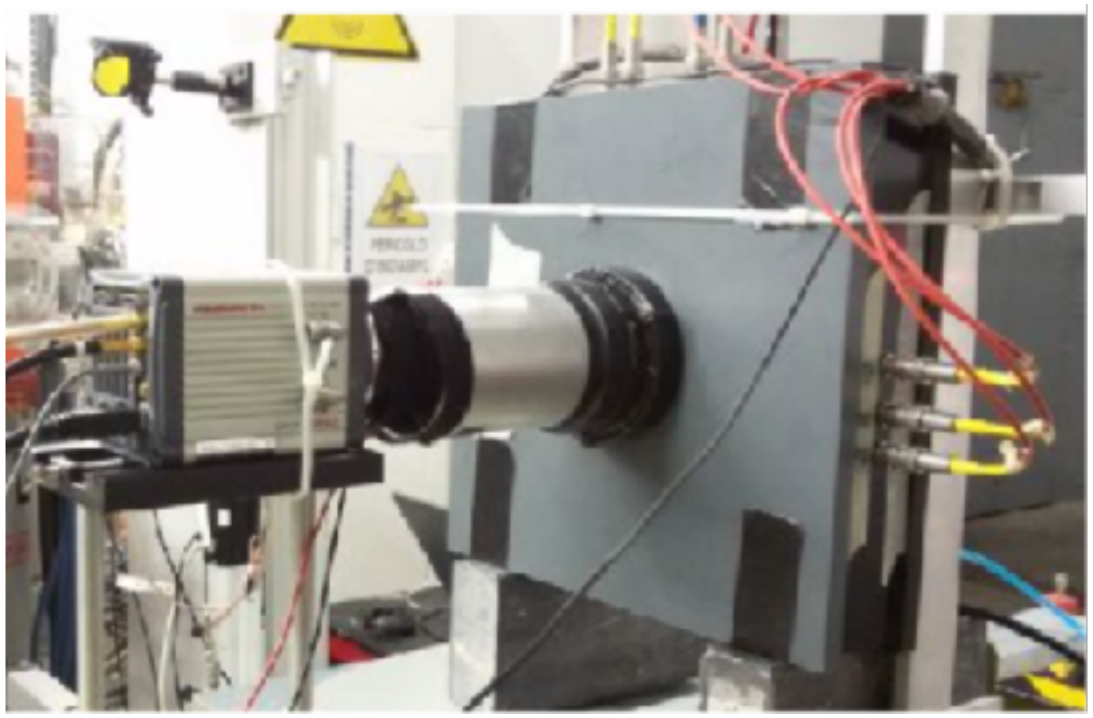
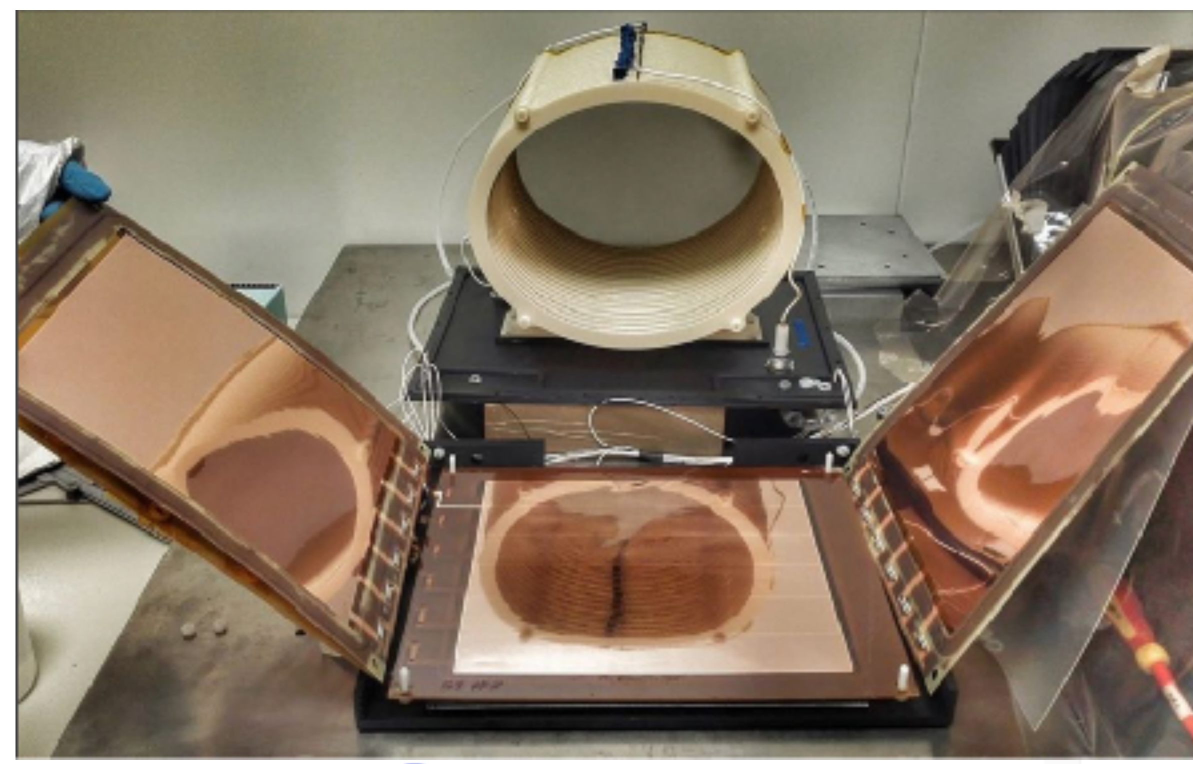


ORANGE: small prototype



LEMOn: large prototype

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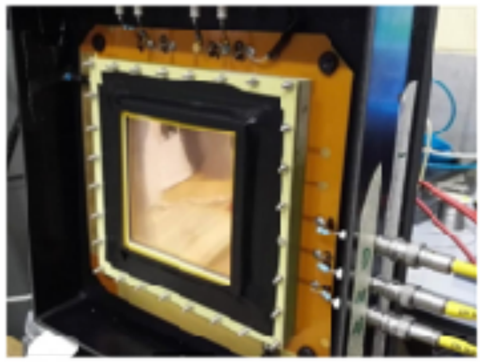
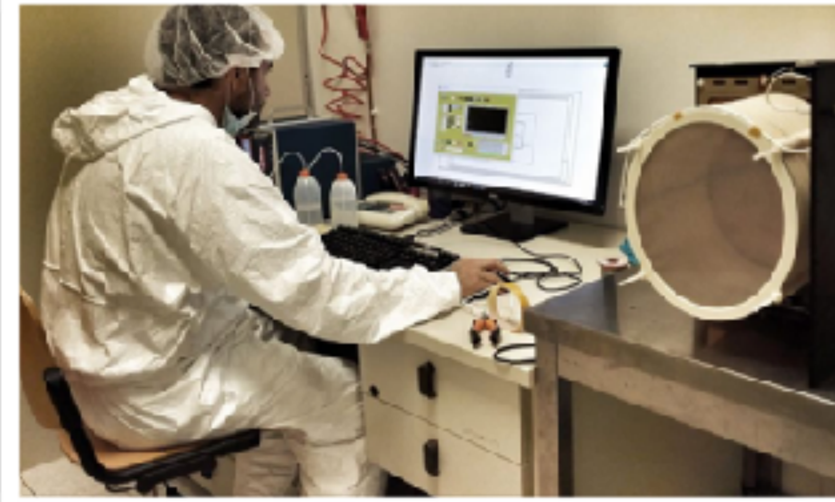
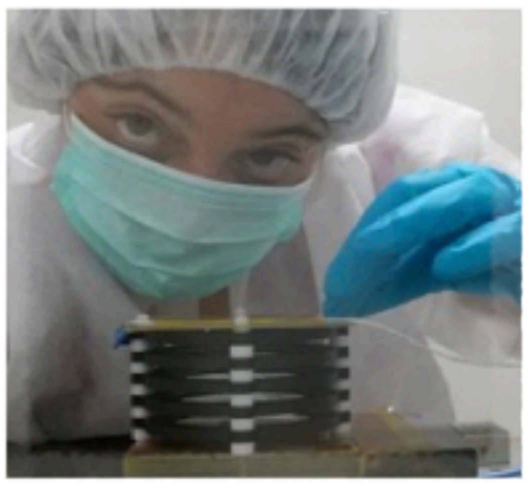
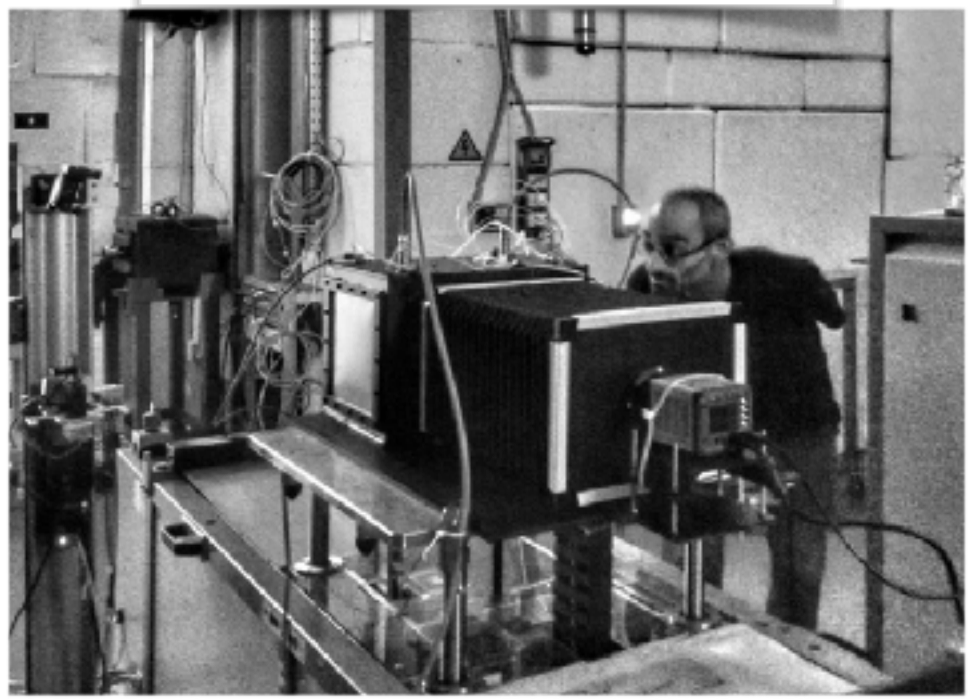
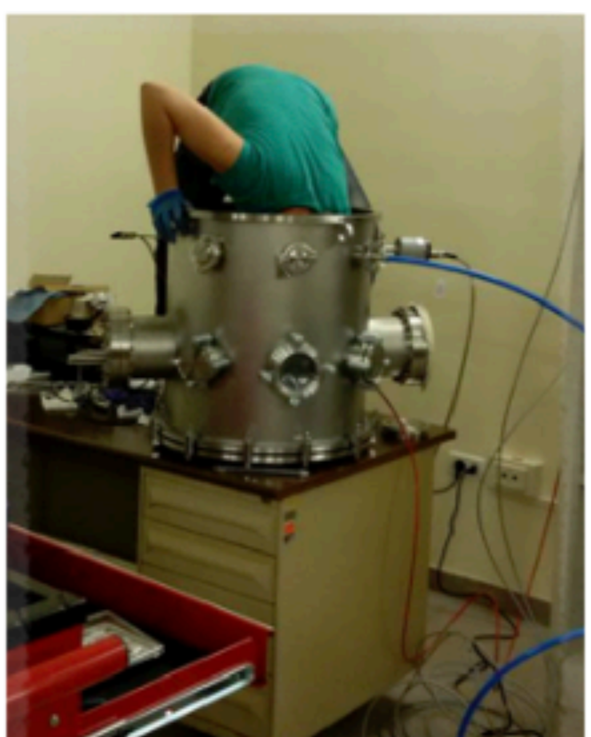
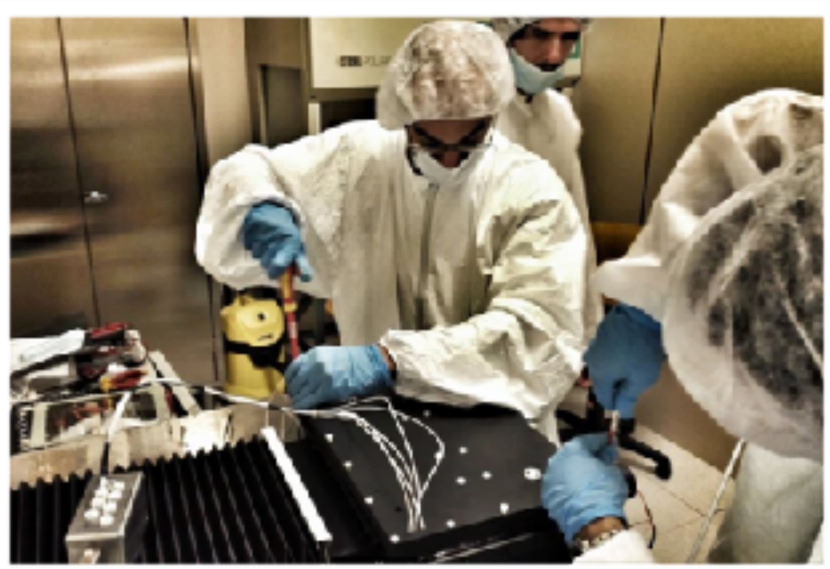
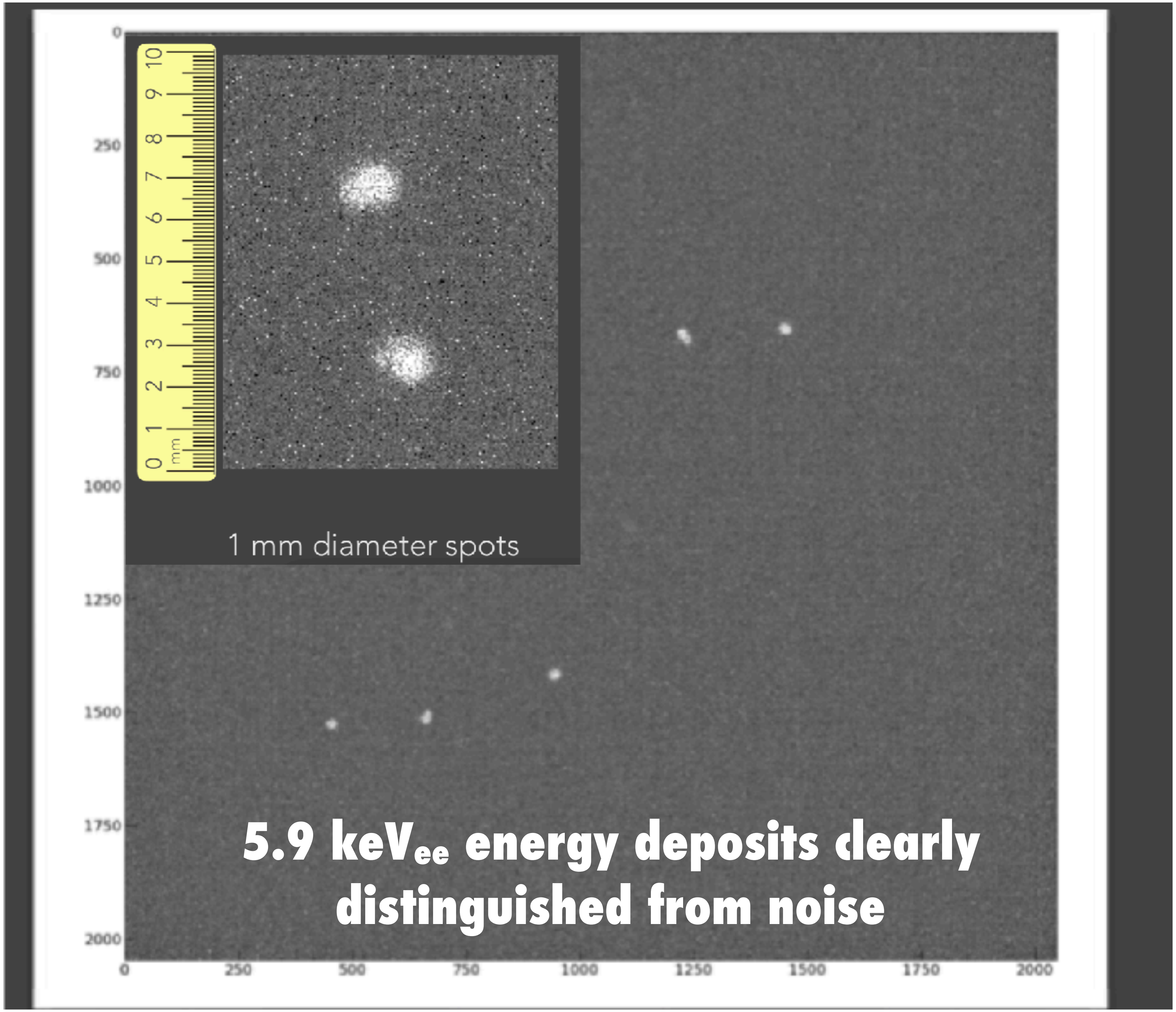
CYGNUS-RD in the making



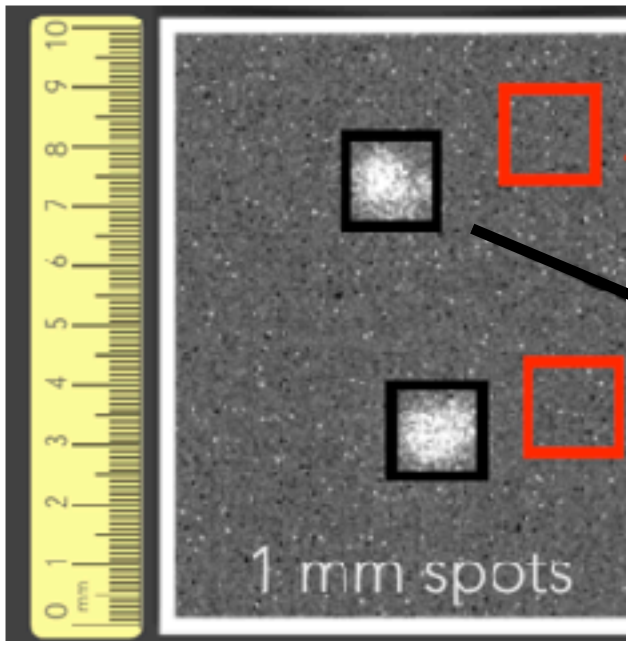



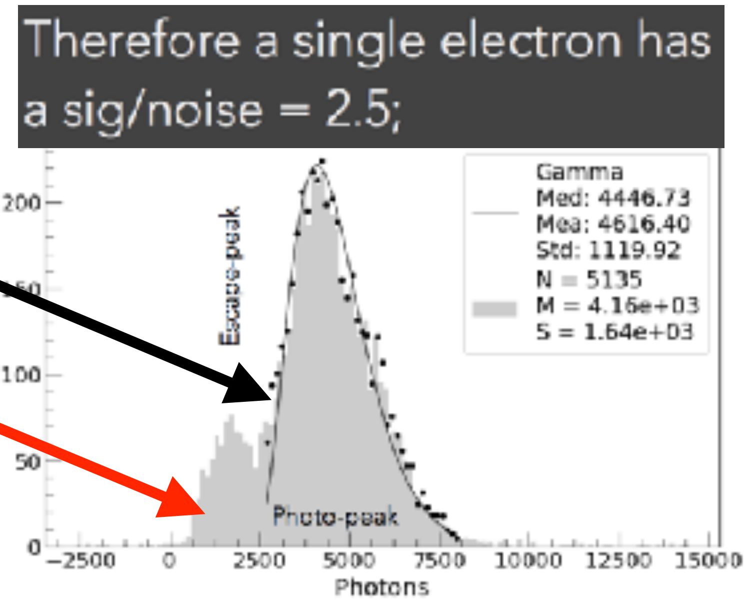

CYGNUS-RD ^{55}Fe events



CYGNUS-RD: energy threshold

O(keV$_{ee}$) energy threshold

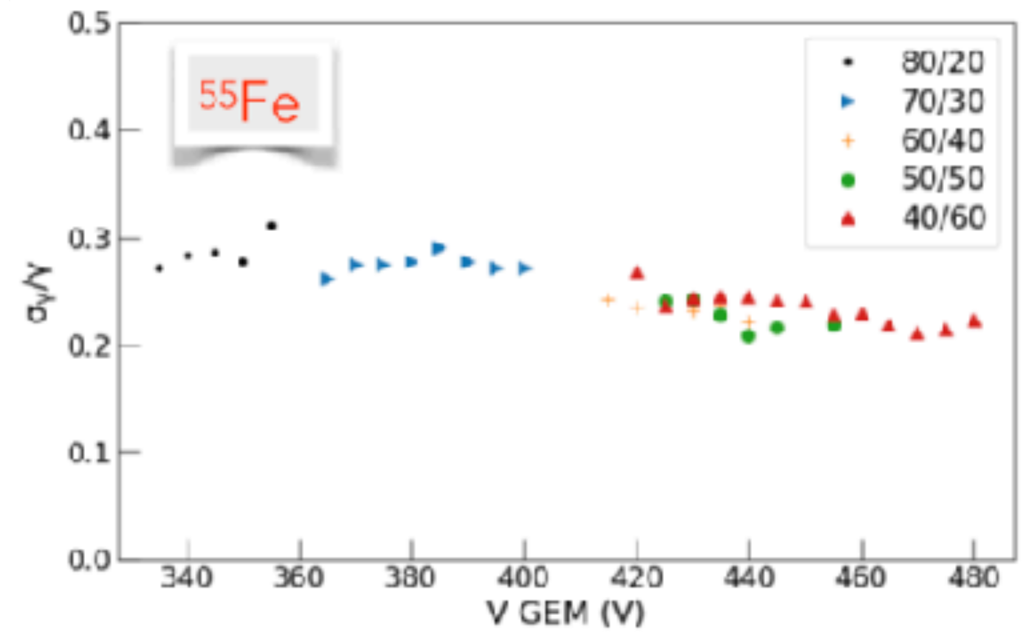


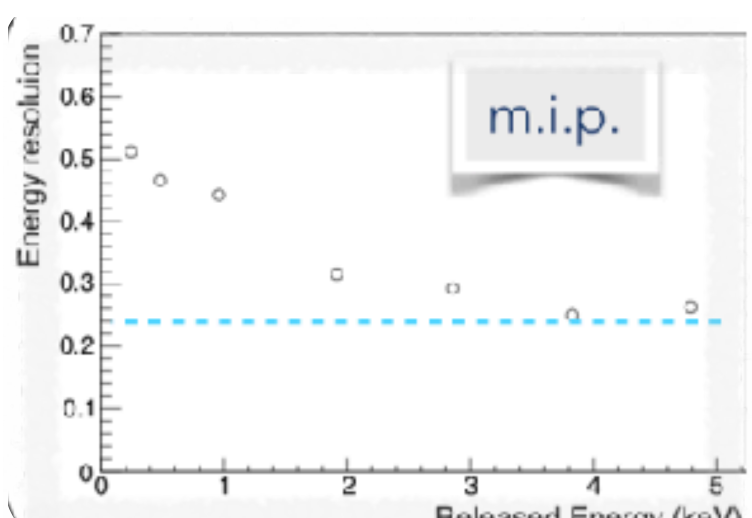


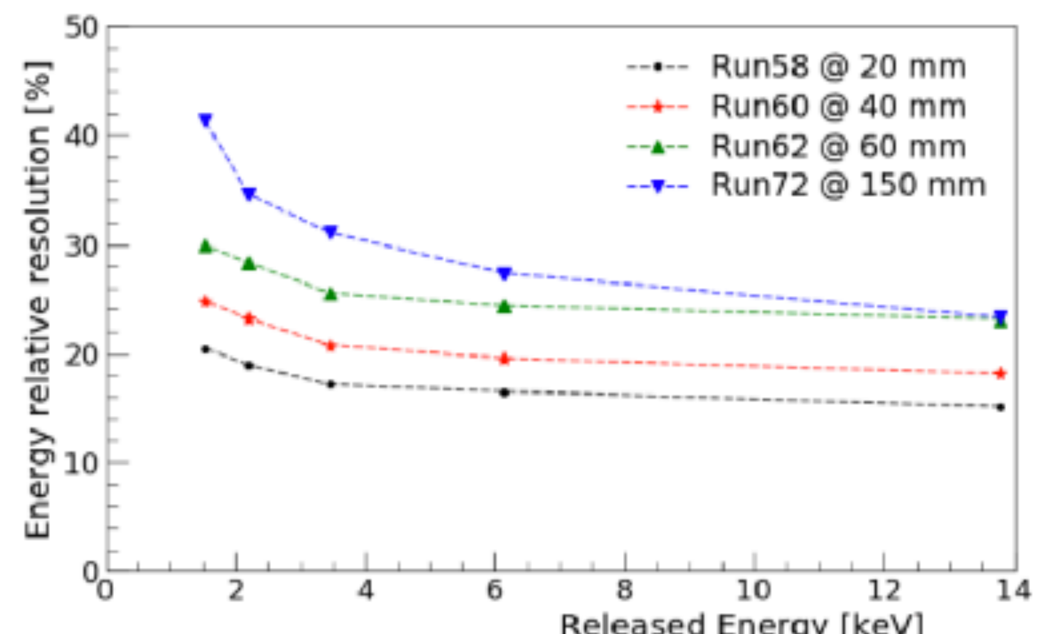
^{55}Fe events sCMOS image

^{55}Fe spectrum

± 20-30% resolution for ^{55}Fe





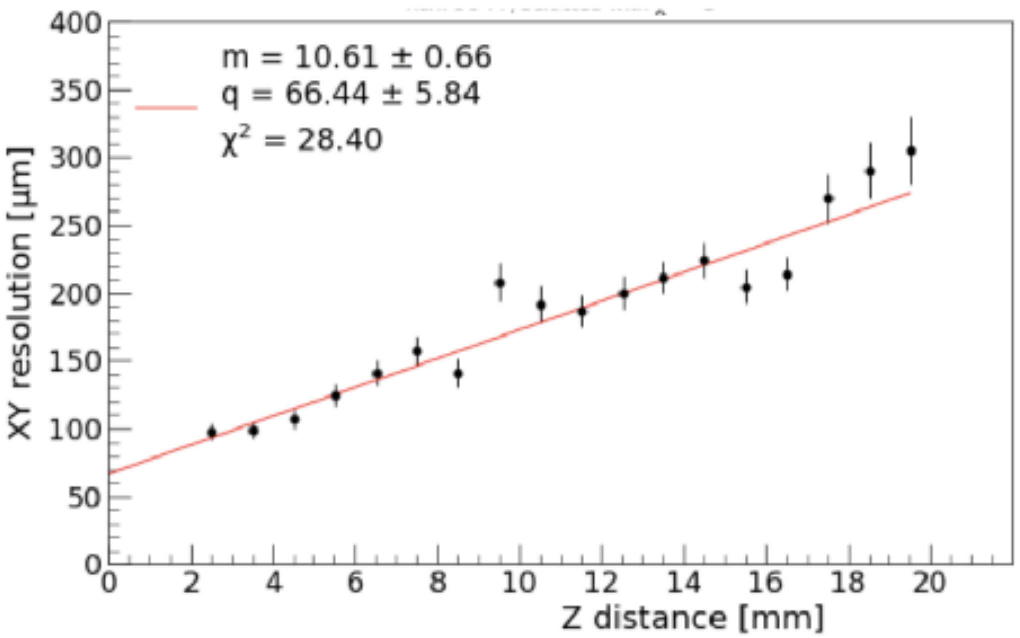


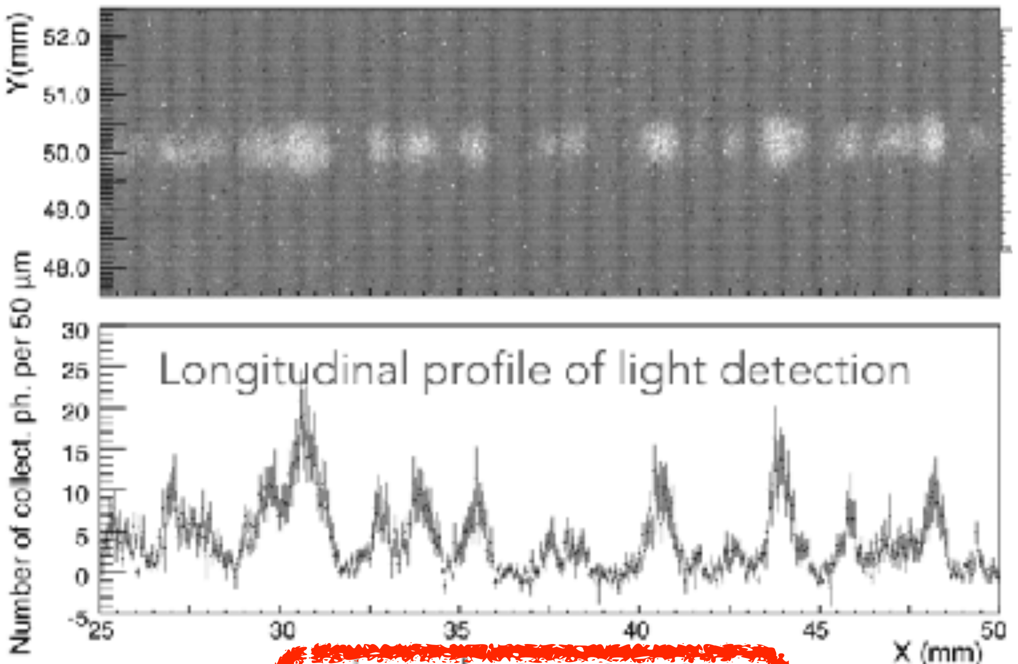
5 sigma threshold on detection in He:CF$_4$ = 200 eV

Nearly constant down to 5 keV$_{ee}$ over 20 cm drift distance

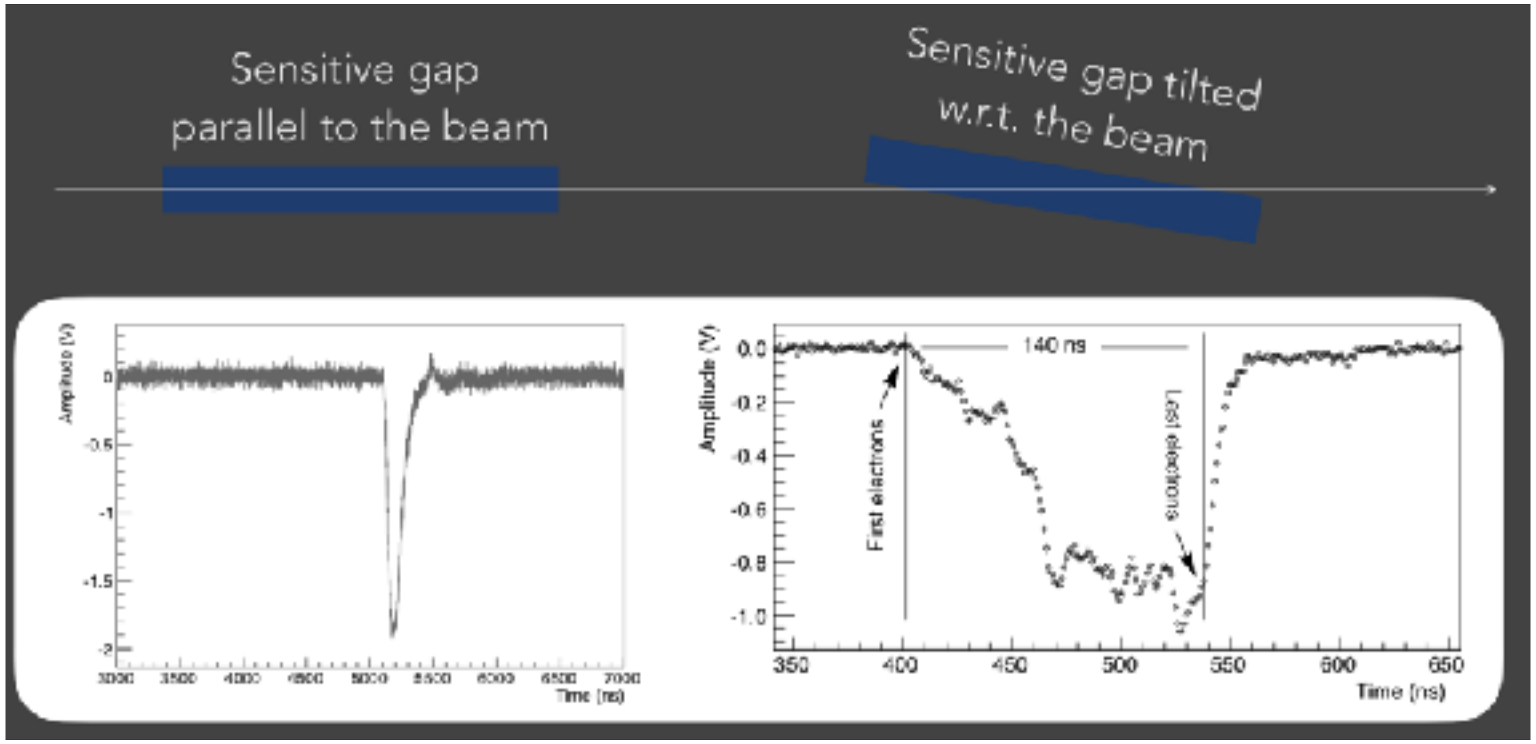
CYGNUS-RD: 2D & 3D tracking

O(100) um 2D X-Y resolution over 20 cm drift

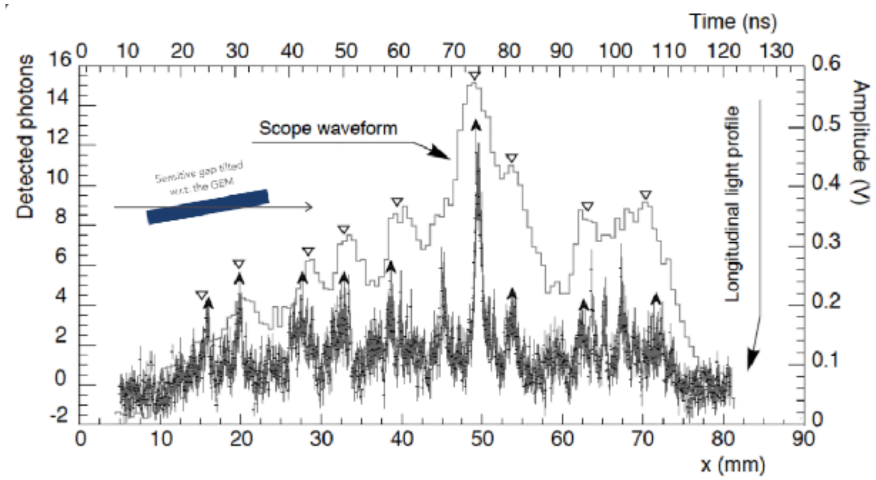


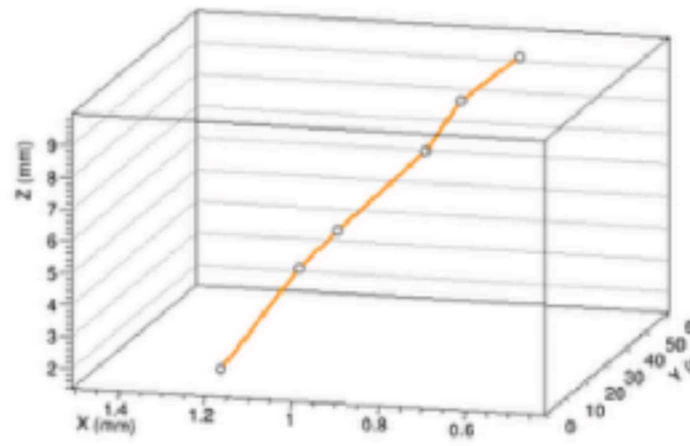


The PMT signal provides track profile in the 3rd direction



3D tracking with sCMOS + PMT

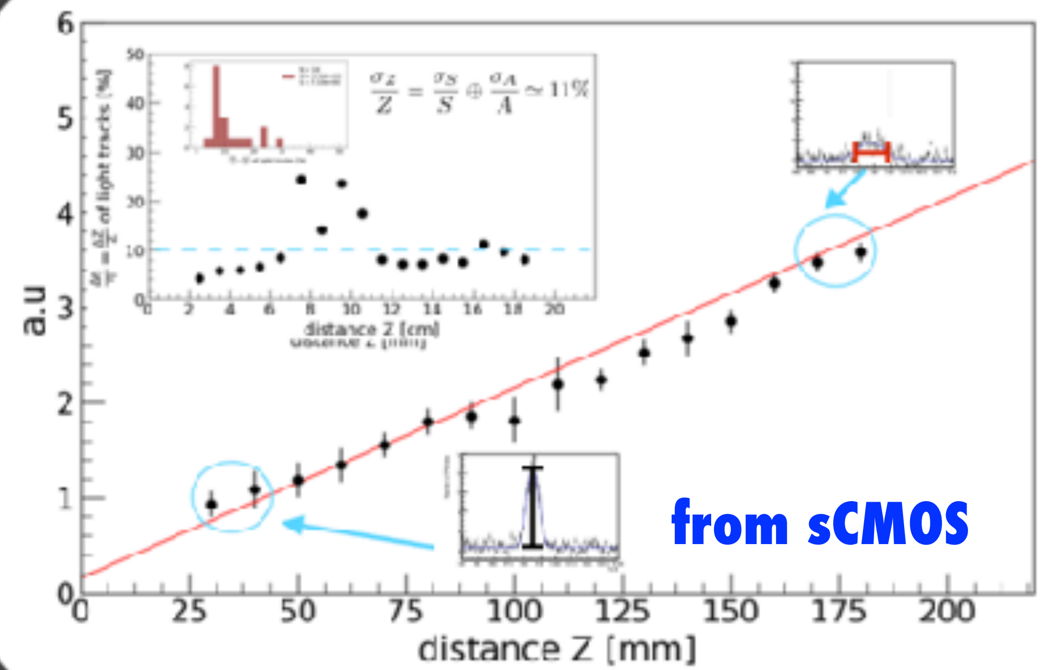


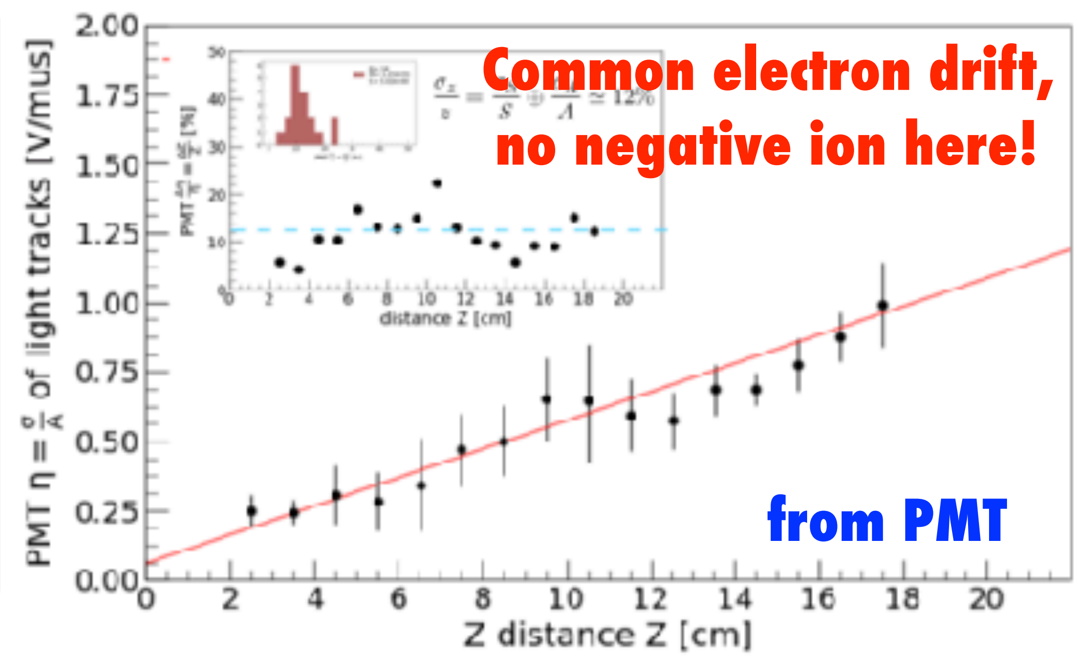


CYGNUS-RD: fiducialization along drift direction (i.e. z)

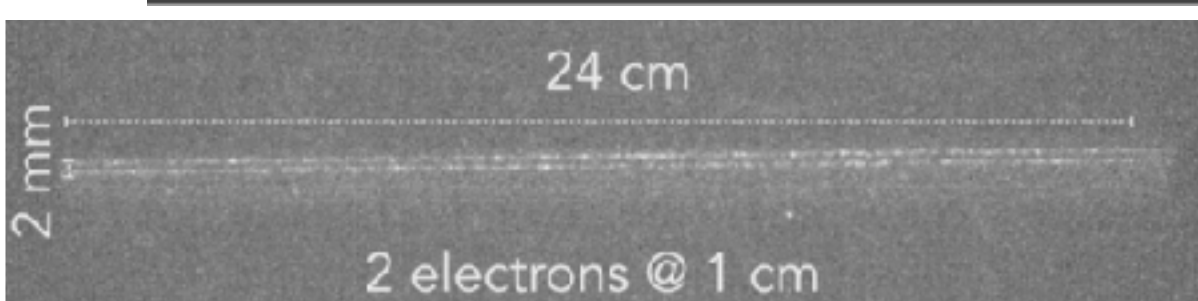
Electron diffusion in the drift gap can be exploited to evaluate the Z of the event The transverse light profile and the PMT signal waveform are expected to become lower and larger as long as the event is far from the GEM;

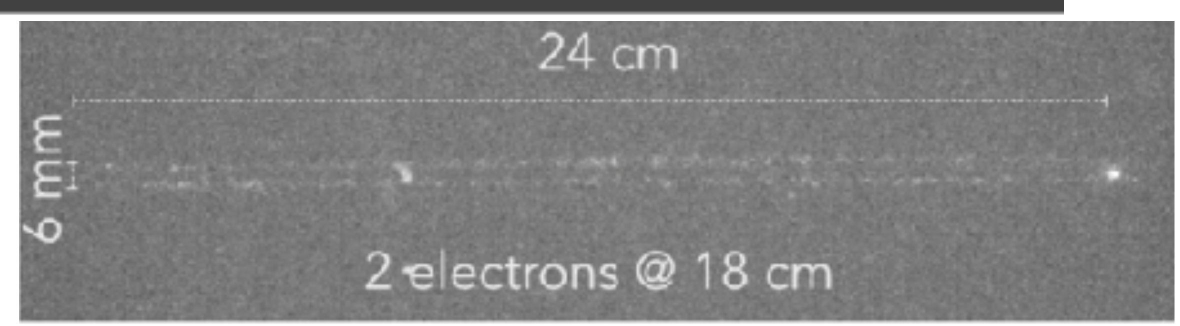
Since the amplitude (A) decreases and the width (S) increases with Z, their ratio η = S/A increases (independently from the amount of produced light);





Both methods gives 10% precision: σz ~ 2 cm @ 20 cm





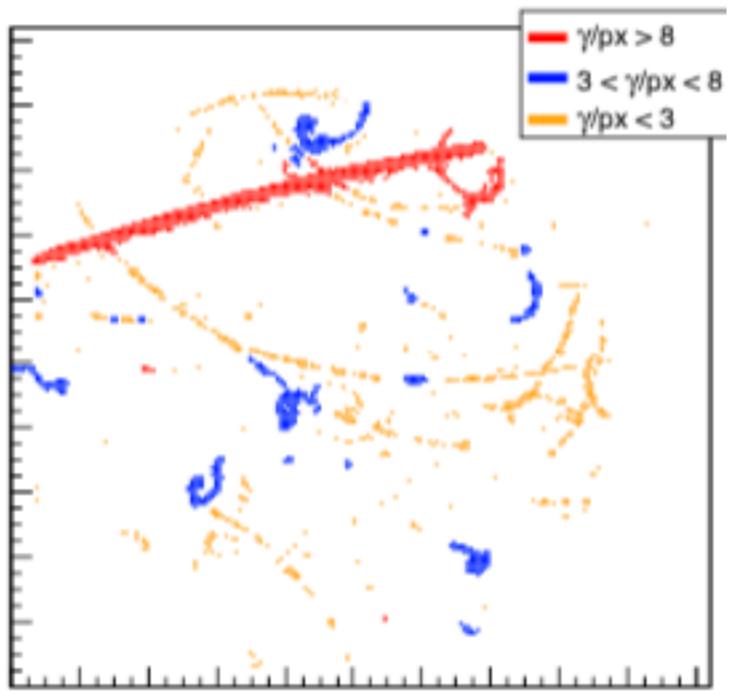
CYGNUS-RD: PID & ER rejection

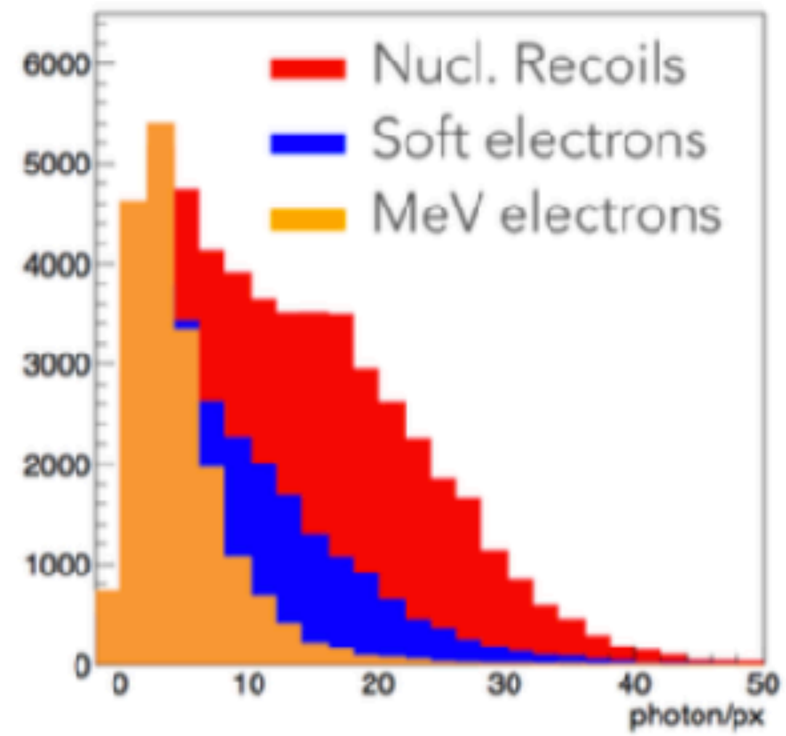
PID through dE/dx, i.e. # photons/pixel

PRELIMINARY

AmBe source event

0.2 T magnet to verify functioning, but curvature NOT used for PID

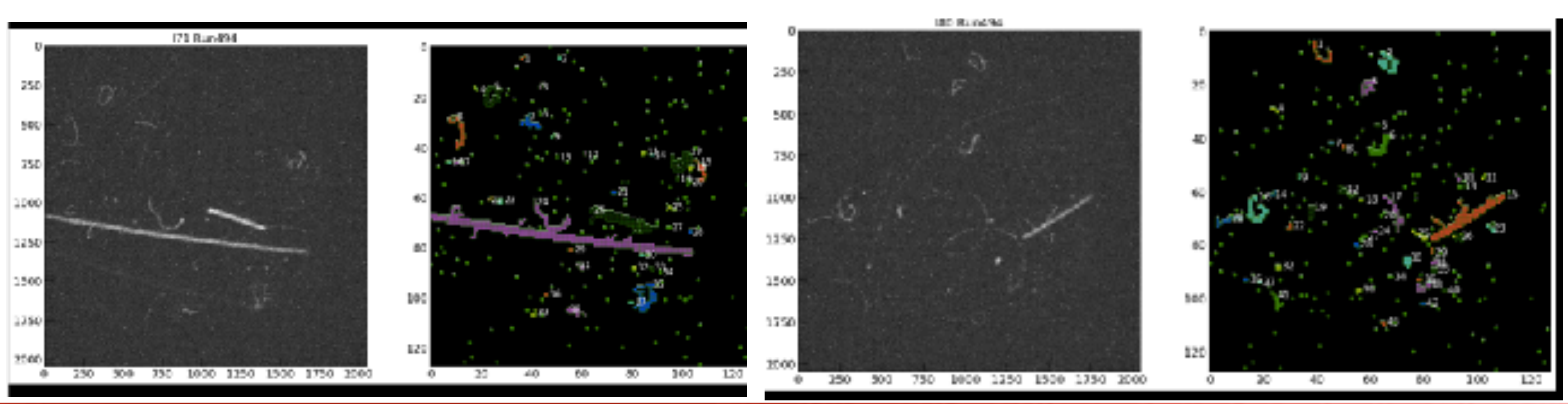




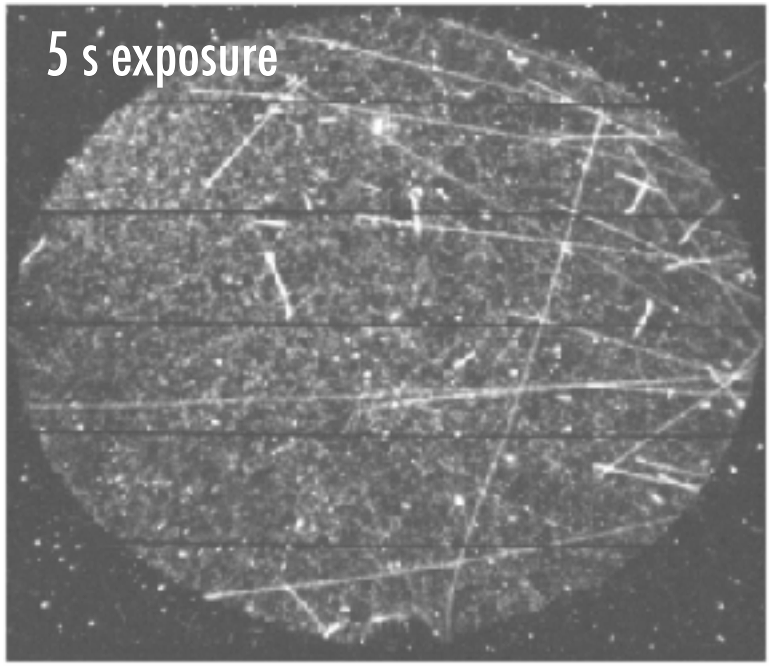
Fast PID through specific ionisation can easily distinguish between O(100) keV He nuclear recoils, 4 MeV and 60 keV electron recoils

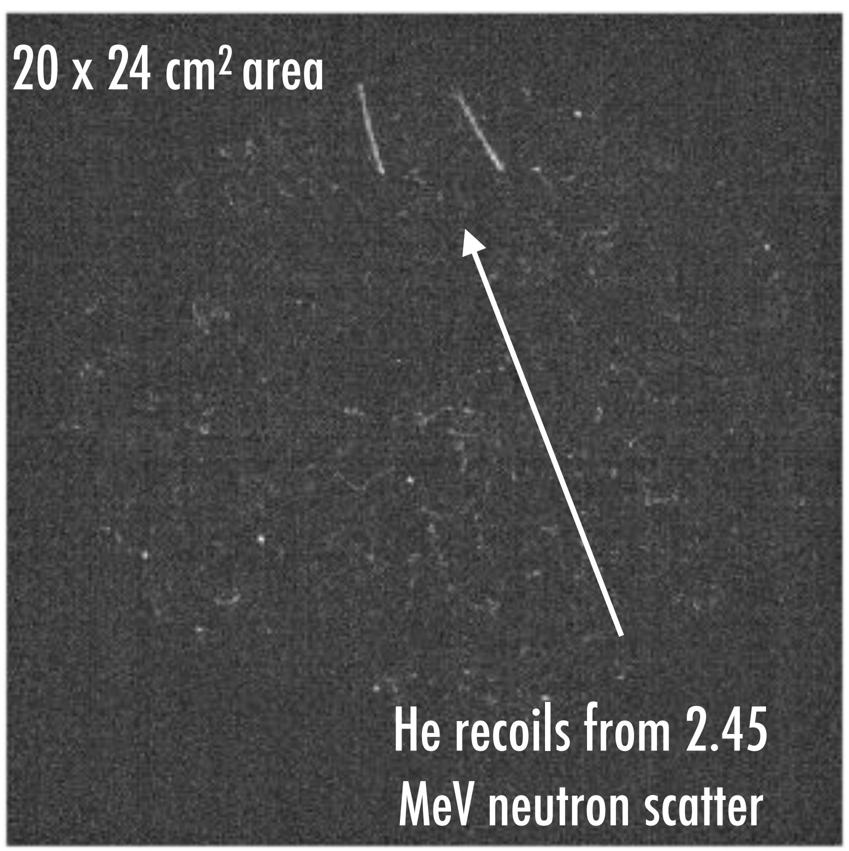
Rejection factor under evaluation

NOTE: PID can be complement and largely improved combining dE/dx with track topology and track length vs energy

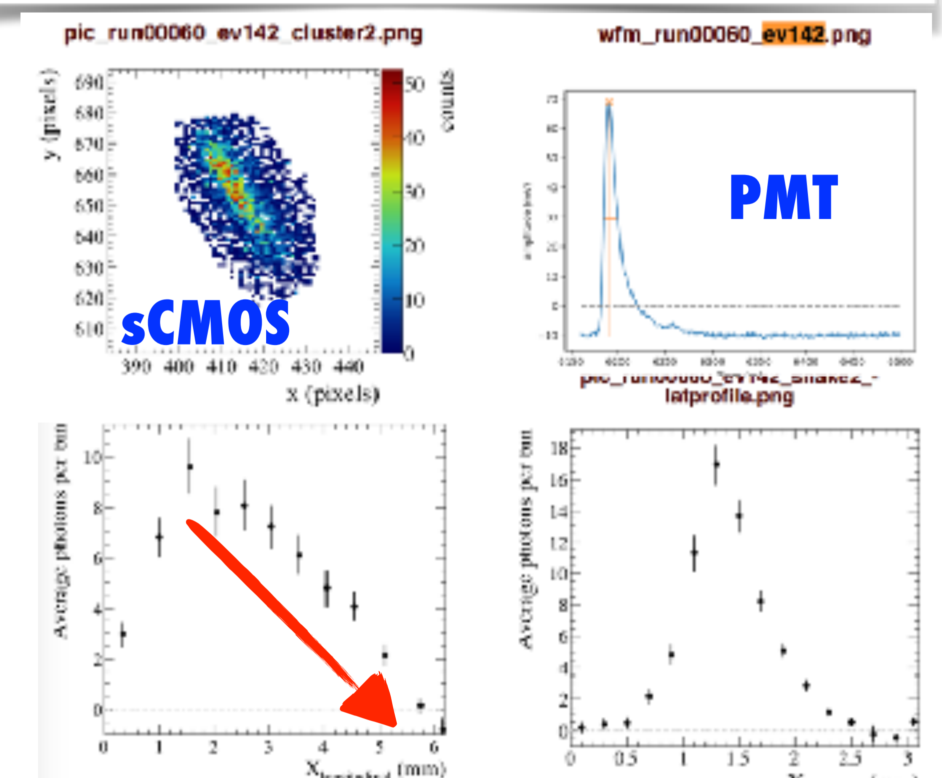


CYGNUS-RD: response to 2.45 MeV neutrons





Test with D-D source (2.45 MeV neutrons) at ENEA FNG June 2018, analysis on-going



longitudinal profile

head-tail!

lateral profile

PRELIMINARY

Successful PMT+CMOS signals DAQ!

GSSI

INFN

CYGNO

A CYGNus tpc module with Optical readout

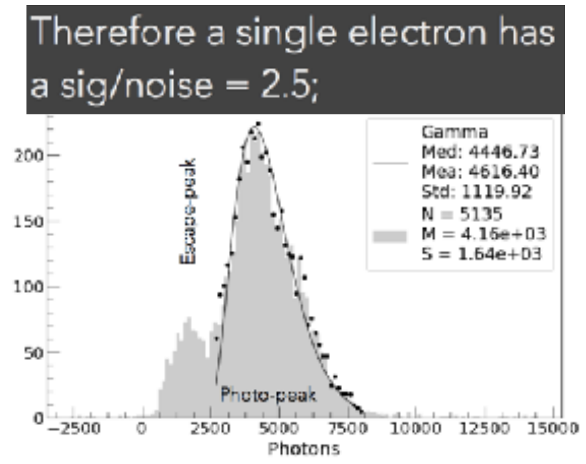
CYGNO concept

(3)He:CF$_4$ ±1 kg total mass **GEMs amplification** **combined PMT + sCMOS readout**

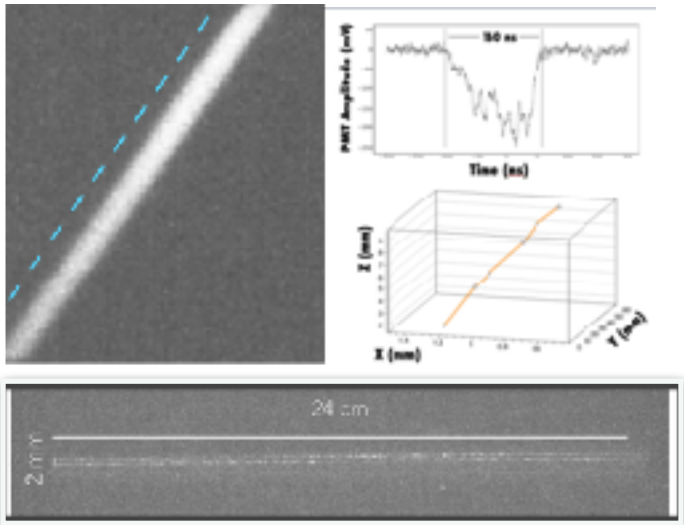
1 m³ target volume

Atmospheric pressure & room temperature

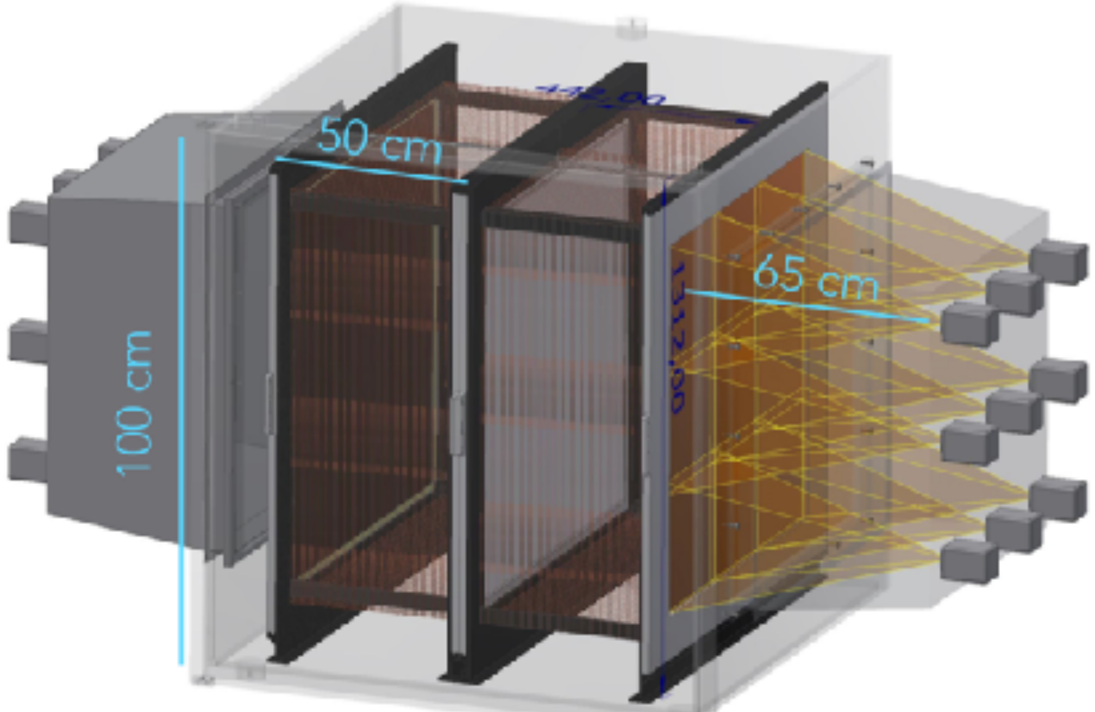
Aim: <u>zero background</u> over 1 yr and O(keV$_{ee}$) energy threshold



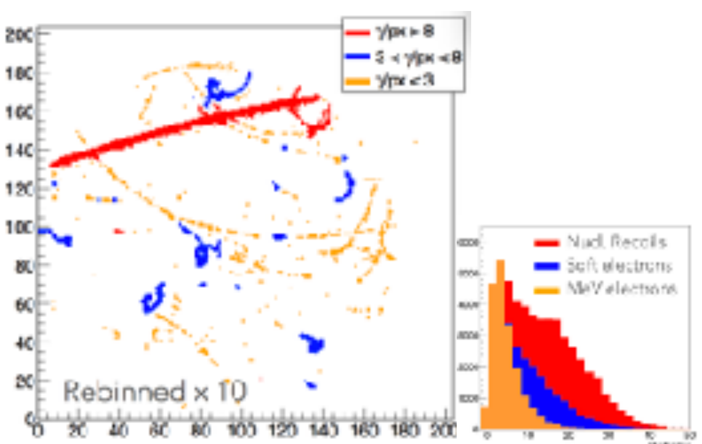
O(keV$_{ee}$) energy threshold



3D tracking with head-tail determination at O(keV$_{ee}$)

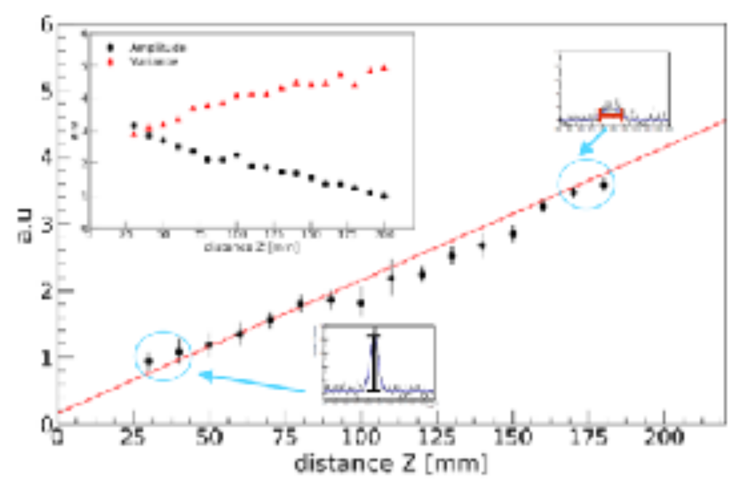


Quenching factor and track range measurements foreseen with LEMOn/LIME



10^5 ER rejection at O(keV$_{ee}$) to zero background goal

Combined low WIMP mass SI & SD sensitivity thanks to He & ^{19}F



Fiducialization in the drift direction at O(keV$_{ee}$)

CYGNO collaboration & proposal

Conceptual design of CYGNO

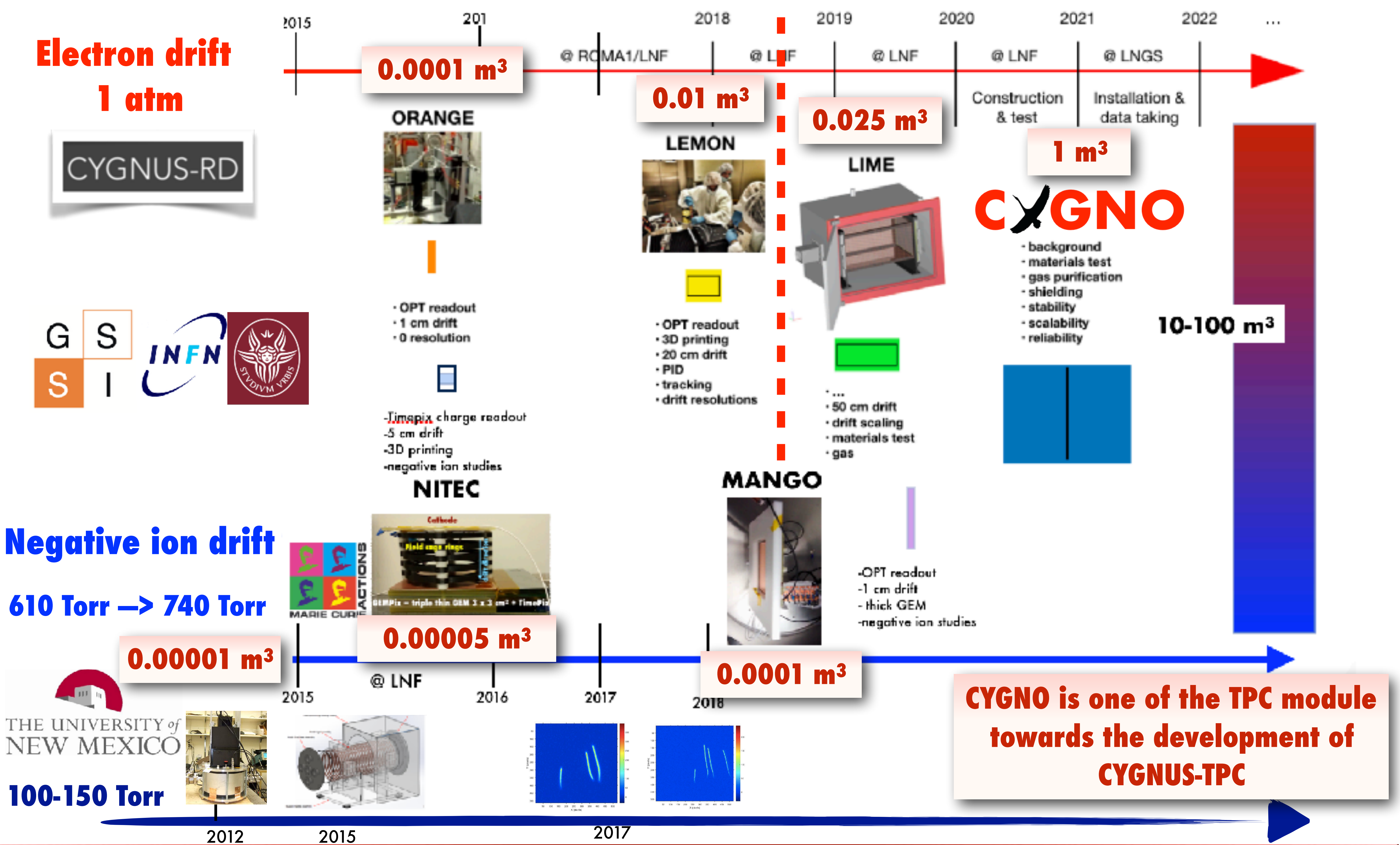
E. Baracchini[1], R. Bedogni[2], F. Bellini[3], L. Benussi[2], S. Bianco[2], L. Bignell[4], G. Cavoto[3], E. Di Marco[5], C. Eldridge[6], A. Ezeribe[6], R. Gargana[2], T. Gamble[6], R. Gregorio[6], G. Lane[4], D. Loomba[7], W. Lynch[6], G. Maccarrone[2], M. Marafini[8], G. Mazzitelli[2], A. Messina[3], A. Mills[7], K. Miuchi[10], F. Petrucci[11], D. Piccolo[2], D. Pinci[5], N. Phan[7], F. Renga[5], N. Spooner[6], T. Thorpe[9], S. Tomassini[2], and S. Vahsen[9]

[1] *Gran Sasso Science Institute L'Aquila, I-67100, Italy*
[2] *Istituto Nazionale di Fisica Nucleare , Laboratori Nazionali di Frascati, I-00040, Italy*
[3] *Dipartimento di Fisica, Sapienza Università di Roma, I-00185, Italy,*
[4] *Australian National University, Canberra ACT 0200, Australia*
[5] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma, I-00185, Italy*
[6] *University of Sheffield, S10 2TN, UK*
[7] *University of New Mexico, Albuquerque, NM 87131, USA*
[8] *Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi" , Piazza del Viminale 1, Roma, I-00184, Italy*
[9] *University of Hawaii, Honolulu, US*
[10] *Kobe University, Hyōgo Prefecture 657-8501, Japan*
[11] *Istituto Nazionale di Fisica Nucleare Sezione di Roma TRE, I-00154, Italy*

With contributions from CYGNUS-TPC collaborators on specific items:
D. Loomba (gas studies), N. Spooner (low radioactivity materials), S. Vahsen (detector simulation), K. Miuchi (gas purification & field cage), G. Lane (neutron measurement)

CYGNO request for funding presented to INFN by July 2018, decision by Sep 2018

CYGNO roadmap & future

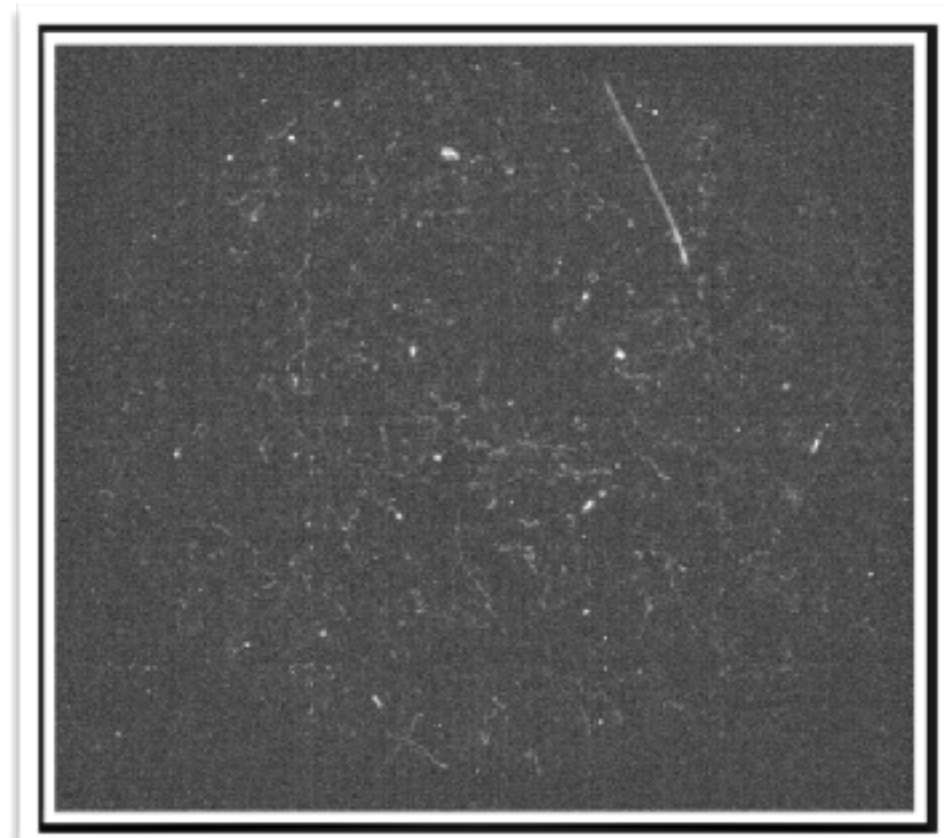


CYGNO 1m³ neutron flux measurement @ LNGS

- **Without passive neutron shielding**
- **Simultaneous sensitivity to thermal and fast neutron flux with $^3He:He:CF_4$ at atmospheric pressure**
  - Fast neutron through nuclear recoil
  - Thermal neutron through capture on ^3He (0.5% is enough thanks to the large capture cross section).
- **O(10 keV) threshold on fast neutrons**
- **Precise spectral measurement**
- **Directional measurement**
- **Seasonal measurement**
- **Background free measurement**
- **Hall B measurement**
- **Possibility to optimize pressure and gases content for higher yield or lower directional threshold**
- **Demonstrator for the DM search**

Proton 573 keV   Tritium 191 keV

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



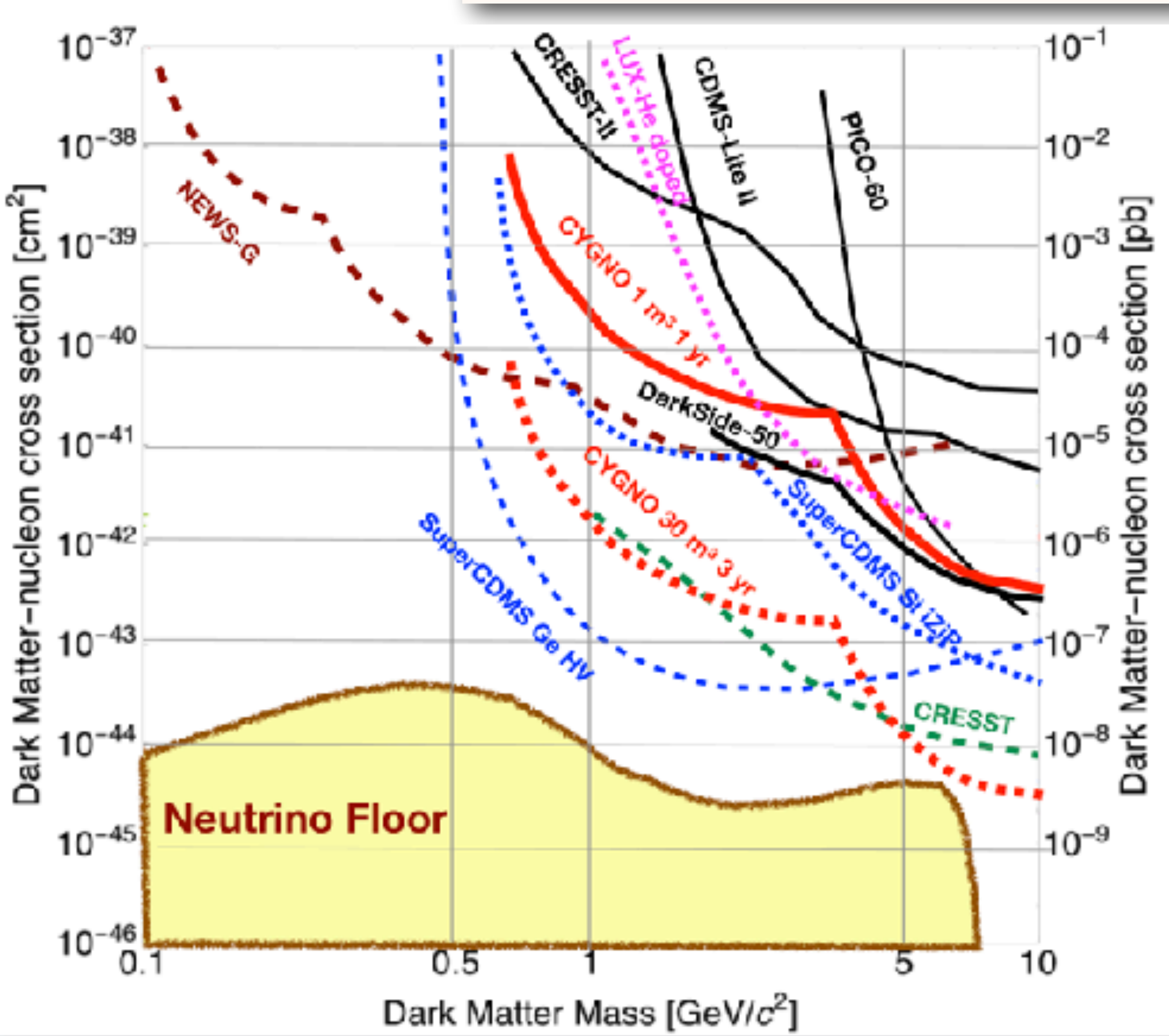
5000 detected nuclear recoils induced by fast neutrons/month
5000 detected thermal neutrons through capture/month

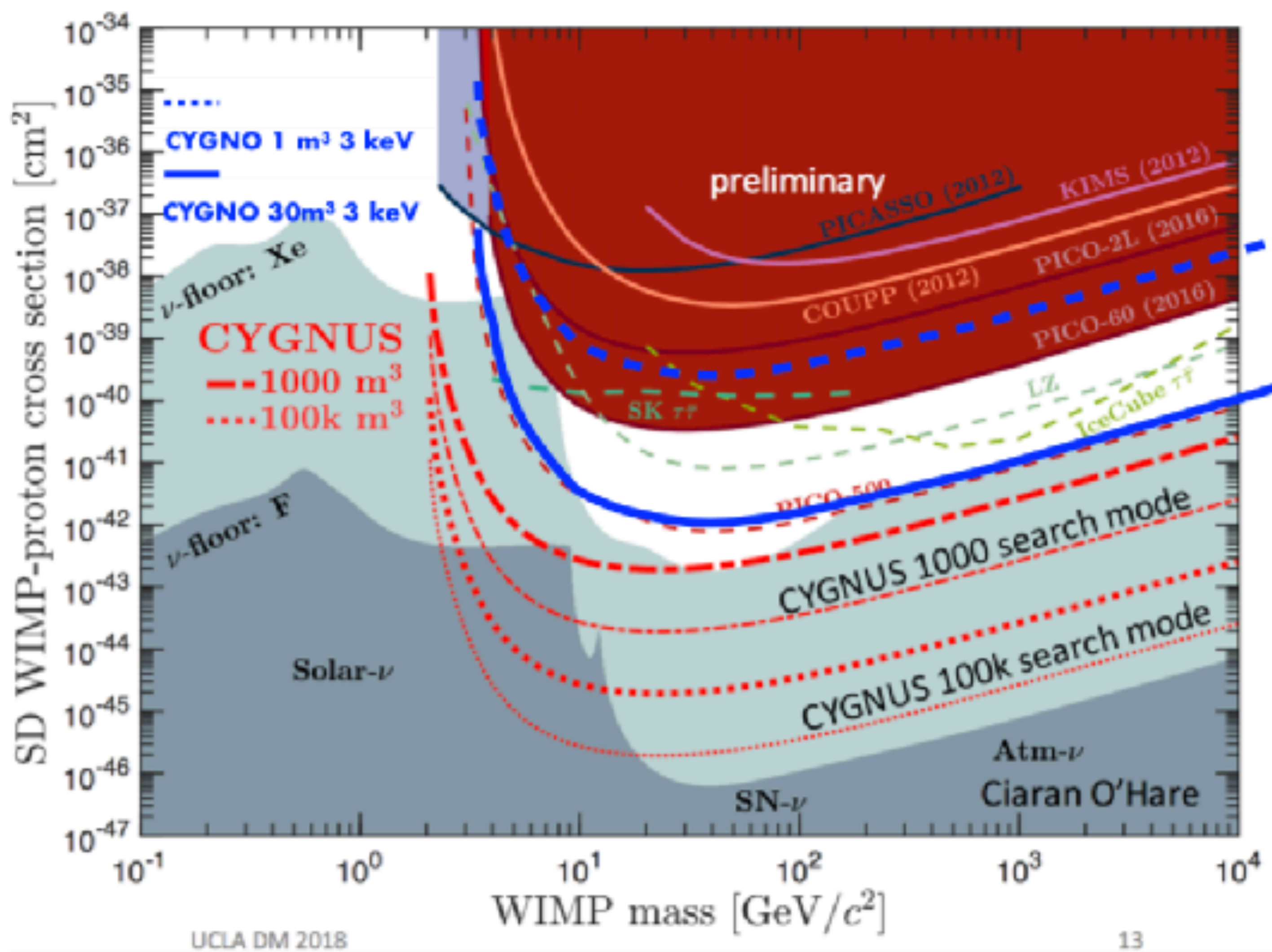
1 m³ sensitivity & future prospects

He:CF_4 80:20 @ 1 atm (±150 gr He + 800 gr CF_4)

1 keV_{ee} He/3 keV_{ee} F recoils threshold

Zero background over 1 year





Black lines: published limits

Coloured lines: future prospects

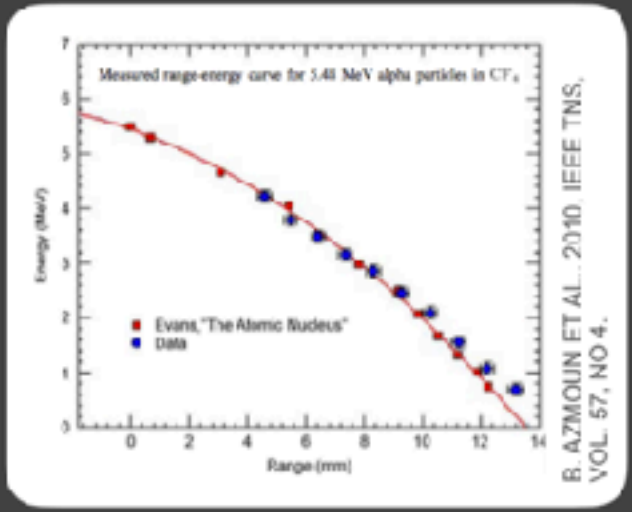
Backup slides

Track range in different gas mixtures

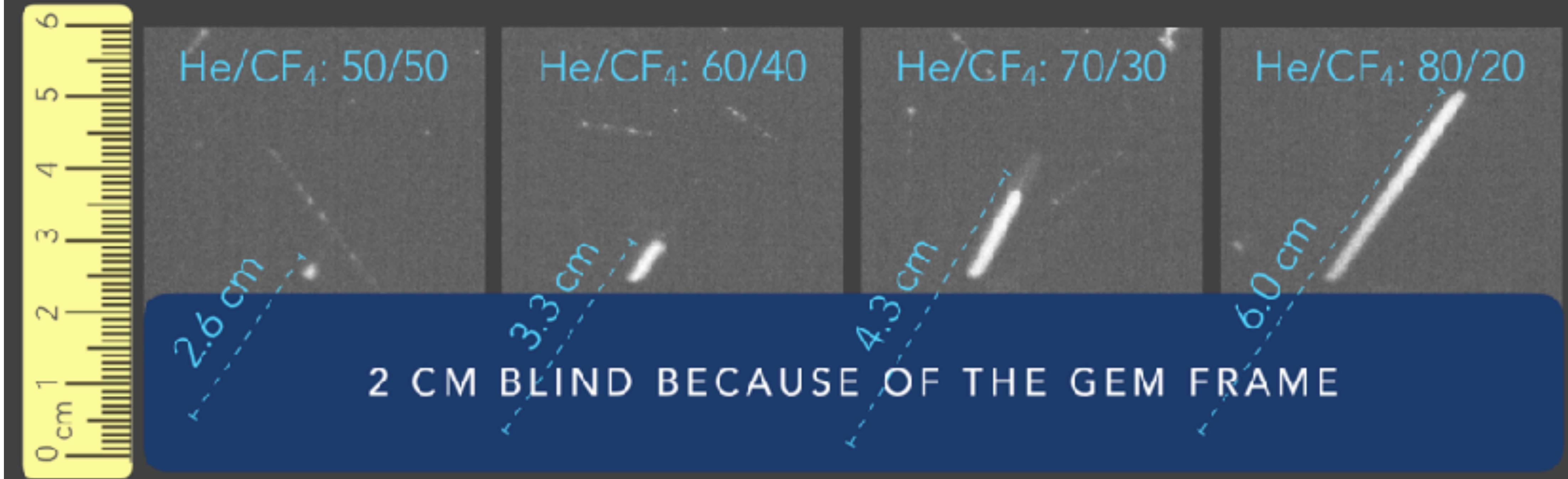
38

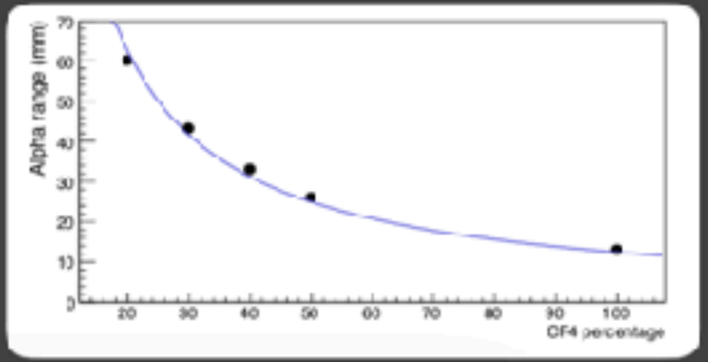
ALPHA TRACKS

5.48 MeV alpha particles have a range of 13 mm in pure CF_4;



B. AZMOUN ET AL., 2010 IEEE TNS, VOL. 57, NO 4.



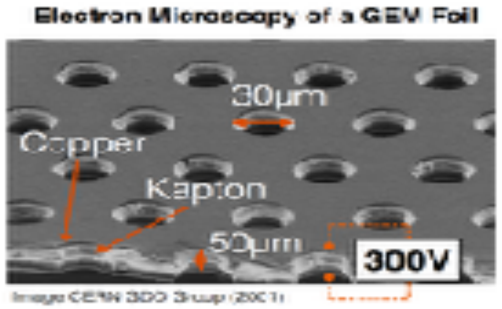


From preliminary measurements, alpha range seems to be "determined" only by CF_4 and to decrease linearly with its amount

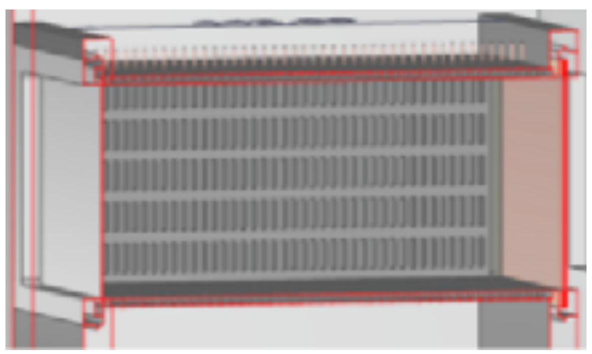
Davide Pinci - INFN Roma1 - CYGNO Proposal

CYGNO tentative radiation budget

~3.7 x 10^4 gamma/year between 1-100 keV
~2.6 x 10^3 gamma/year between 1-10 keV
~0.04 neutron recoils/year

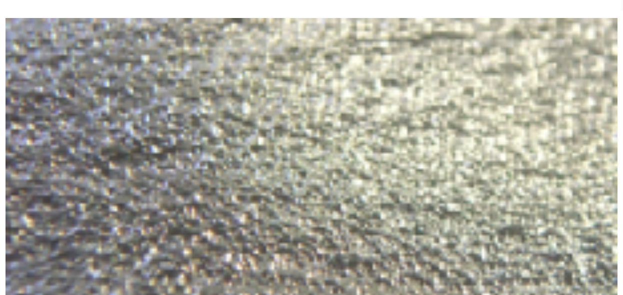


GEMs: Kapton + Cu, radioactivity from CYGNUS simulation, to be measured @ LNGS facility in next months

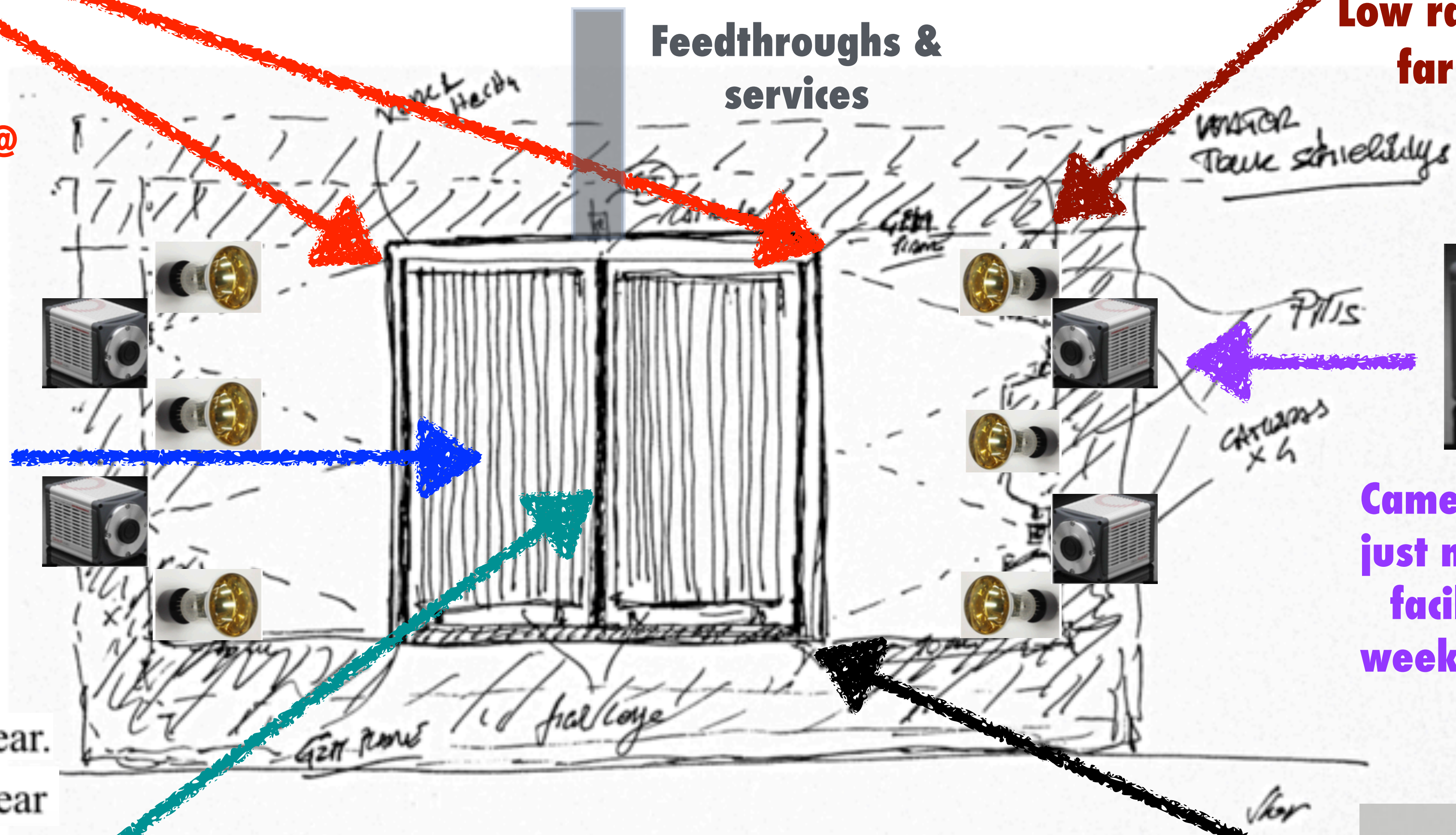


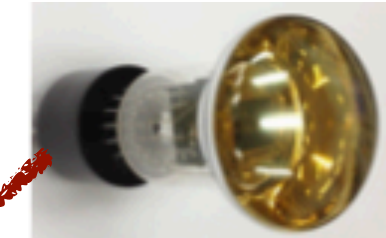
Field cage, Acrylic + Cu, low radioactivity

~1 x 10^2 electron recoils/year.
~1 x 10^{-6} neutron recoils/year



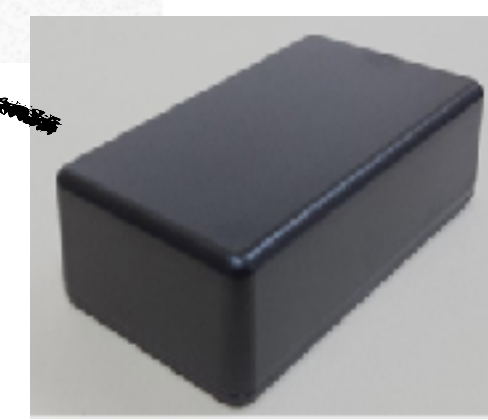
Transparent texturised mylar cathode a'la DRIFT





Low radioactivity PMTs, far & outside gas volume

Cameras: radioactivity just measured @ LNGS facility, results this week, can be partially shielded



Gas vessel: do not need to keep vacuum, i.e. not necessary steel, low radioactivity materials under evaluation

Neutron flux measurement @ LNGS

Both fast and thermal flux measurements varying widely

Thermal neutrons

^{3}He | BF$_3$ | ^{3}He | ^{3}He

E interval (eV)	Thermal Neutron Flux (10^{-6}cm^{-2}s^{-1}) Ref. [21]	Ref. [22]	Ref. [23]	Ref. [24]
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)		

Table 3: Thermal and epithermal (top) and fast (bottom) neutron flux measurements at the Gran Sasso laboratory reported by different authors. In analyzing their experimental data with Monte Carlo simulations, Belli et al. [22] have used two different hypothetical spectra: flat, and flat plus a Watt fission spectrum. This leads to the upper and lower data sets shown for ref.[22] respectively.

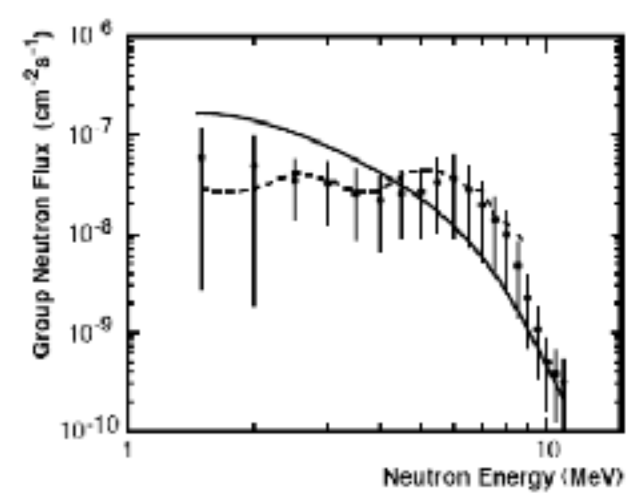
E interval (MeV)	Fast Neutron Flux (10^{-6}cm^{-2}s^{-1}) Ref. [25]	Ref. [26]	Ref. [22]	Ref. [21]	Ref. [27]	Ref. [28]
0.1 – 1	UL		0.54±0.01 (0.53±0.08)			UL 2.56±0.27
1 – 2.5		0.14±0.12				
2.5 – 3		0.13±0.04	0.27±0.14 (0.18±0.04)			
3 – 5						
5 – 10		0.15±0.04	0.05±0.01 (0.04±0.01)	3.0±0.8	0.09±0.06	
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			$(0.5 \pm 0.3)\cdot 10^{-6}$ ($(0.1 \pm 0.3)\cdot 10^{-5}$)			

Liquid scintillator | BF$_3$ | ^{3}He | ^{3}He

Fast neutrons

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

- **^{3}He and BF$_3$ measurements**
  - Thermal neutron through capture: a peak over a large background of internal radioactivity (alphas mainly)
  - Fast neutron (Belli, Bellotti): only through Cadmium and Polyethylene moderators, complicating detector efficiency and introducing additional uncertainty on yield and energy range
- **Scintillator with proton recoil technique**
  - Proton recoil technique is similar to nuclear recoil
  - Large backgrounds from alphas to proton recoils
  - Measurement from 1999



LNGS Hall A, Hall B and Hall C

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

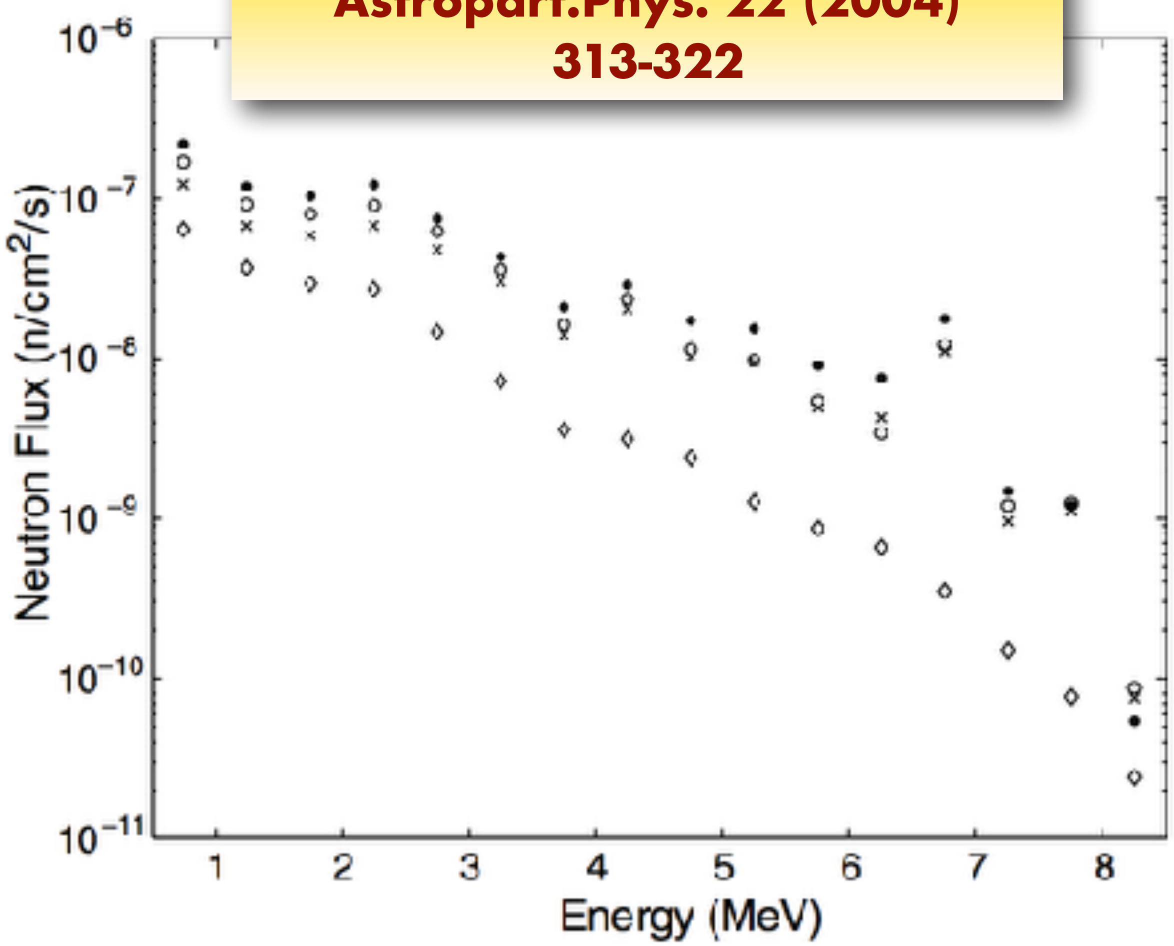


Fig. 3. Neutron flux at the Gran Sasso laboratory, ●: hall A, dry concrete, ×: hall A, wet concrete, ◇: hall A, dry concrete, fission reactions only and ○: hall C, dry concrete. Each point shows the integral flux in a 0.5 MeV energy bin.

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!!!

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

n/year/g

..something that can change over a year...