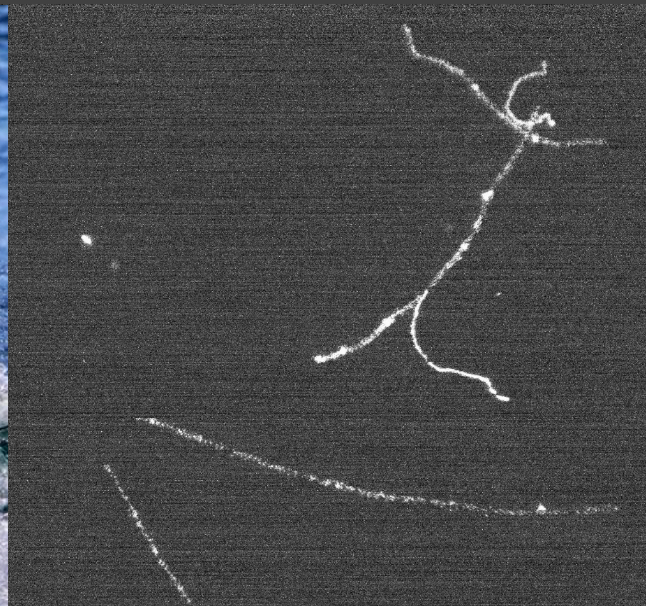
High precision recoil imaging TPC for directional searches even beyond Dark Matter

An Elisabetta surfing (for the first time)



Soft electrons measured by LIME at underground LNGS

Or how to surf through multiple physics cases with the same experimental approach

European Research Council
Established by the European Commission

G S
S I

Elisabetta Baracchini, Gran Sasso Science Institute & INFN

INFN

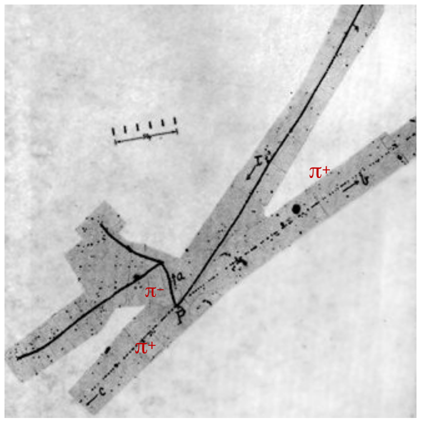
Imaging detectors: history

Photographic emulsions

Cecil Frank Powell
Nobel Laureate 1950

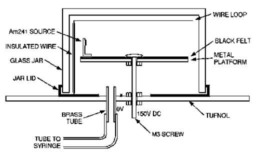
DISCOVERY OF THE τ (K^+) *Brown et al, 1948*

$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$

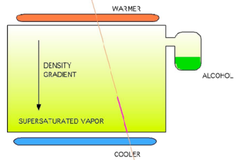


Cloud chamber

Expansion



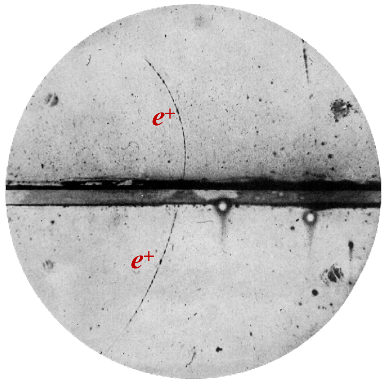
Diffusion



Charles Thompson Wilson (1911)

C. T. Wilson, A. Compton, Nobel Laureates 1927

DISCOVERY OF THE POSITRON

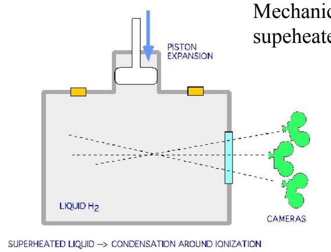


A COSMICCHARGED PARTICLE (1) ENTERS THE DETECTOR, LOSES ENERGY IN A METAL PLATE AND CONTINUES WITH LOWER ENERGY (2). THE CURVATURE IN MAGNETIC FIELD IDENTIFIES ITS SIGN AND MASS.

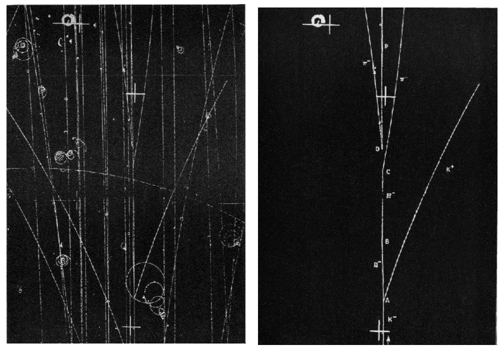
Carl Davis Anderson. Nobel Laureate 1936

Bubble chamber

Mechanical expansion of supeheated liquid (H_2)



Donald Arthur Glaser
Nobel Laureate 1960



$K^- + p \rightarrow K^+ + \Omega^- + K^0$

$\hookrightarrow \Xi^- + \pi^0$

$\hookrightarrow \Lambda + \pi^-$

$\hookrightarrow p + \pi^-$

GSSI

Imaging detector today: (gaseous) TPC

*my favourite, others exists

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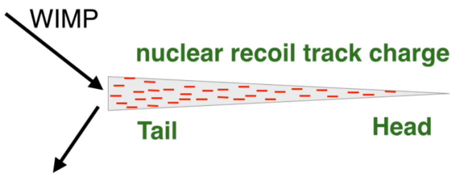
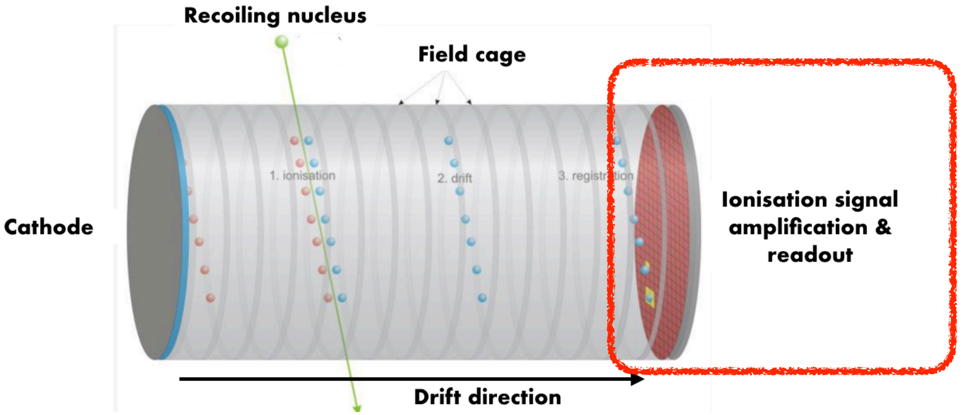
Inherently a 3D detector

Sensitive to track sense & direction

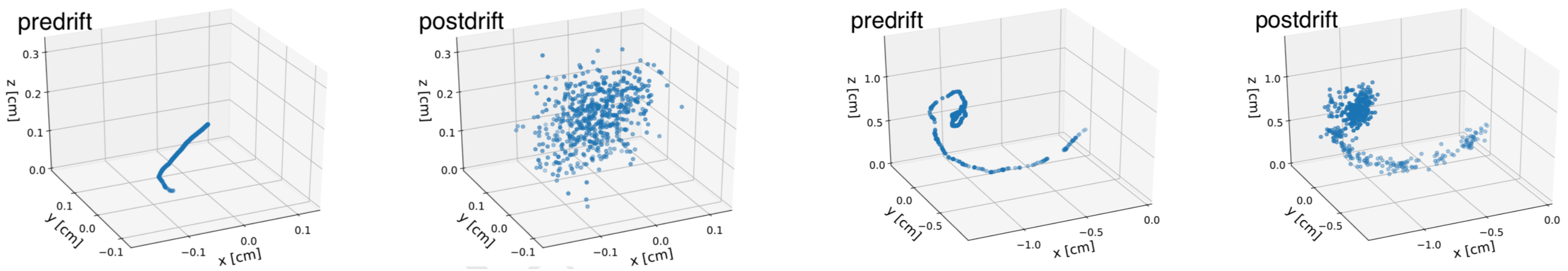




- Advantages:
  - Axial Directionality
  - **<u>Head/tail</u>**
  - Background rejection
  - Particle ID
  - 3D fiducialization

Energy loss and track topology to efficiently reject background at O(keV) energy threshold

NOTE: in this talk we talk about (relatively) low rate environments



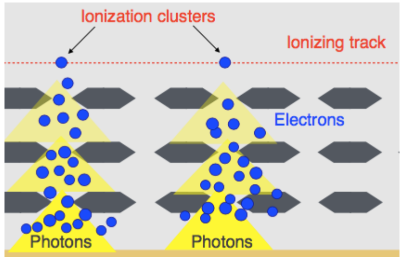
25 keV$_{nr}$ nuclear recoil in He:SF$_6$ 755:5 Torr

20 keV$_{ee}$ electron recoil in He:SF$_6$ 755:5 Torr

The issue: how to make a detector big enough for the physics case of your choice without spoiling tracks imaging by diffusion or readout granularity?

Optical readout TPC with sCMOS + PMT readout

JINST 13 (2018) no.05, P05001



Optical readout TPC with sCMOS + PMT readout

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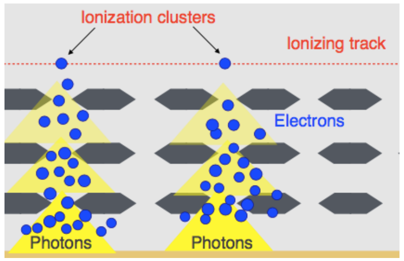
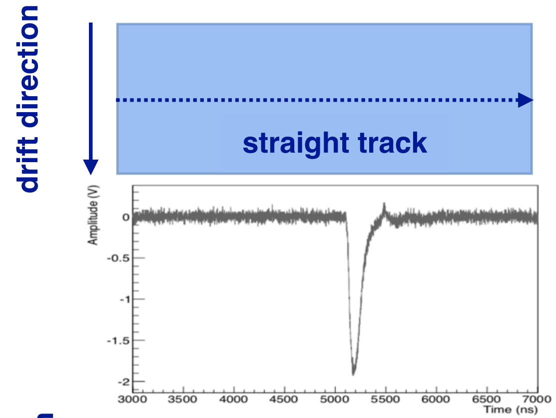
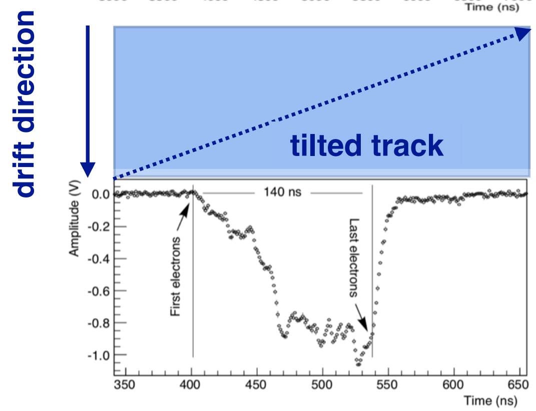


PMT:

integrated
Z + energy measurement

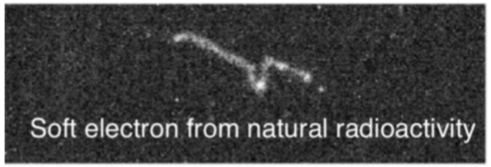




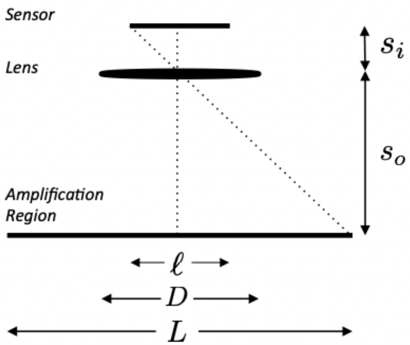
Optical readout TPC with sCMOS + PMT readout

sCMOS:

high granularity
X-Y + energy measurements

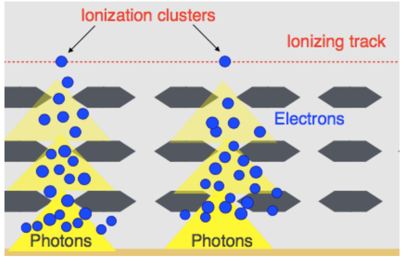


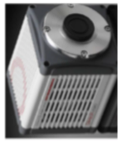
- **Market pulled**
- **Single photon sensitivity**
- **Decoupled from target**
- **Large areas with proper optics**



A single cameras can image a 36 x 36 cm² area with an effective pixel size of 160 x 160 um² (see later)

JINST 13 (2018) no.05, P05001





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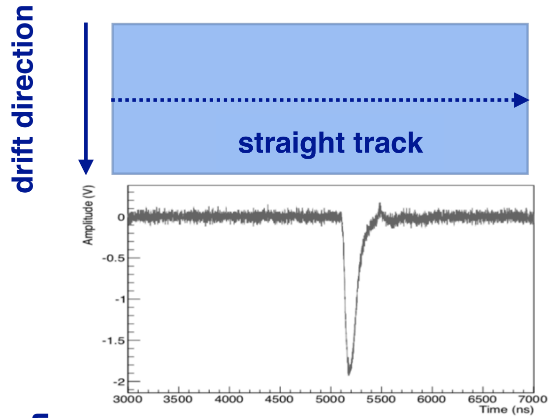

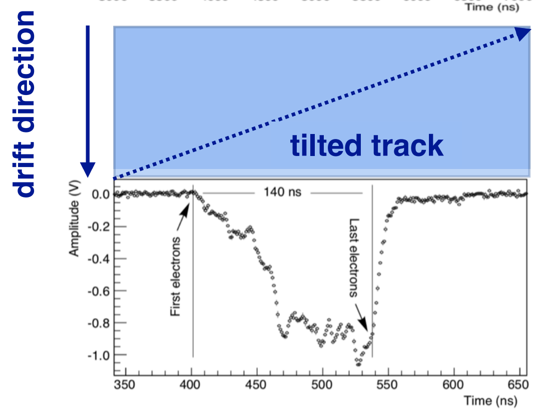

Optical readout TPC with sCMOS + PMT readout

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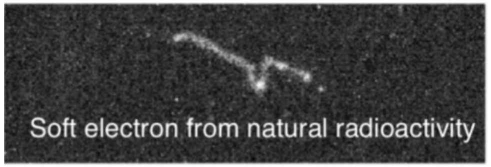

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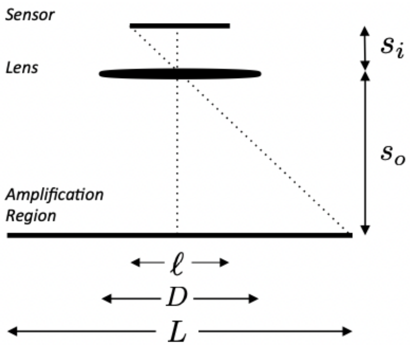

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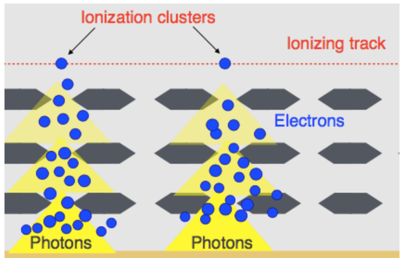

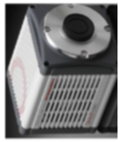

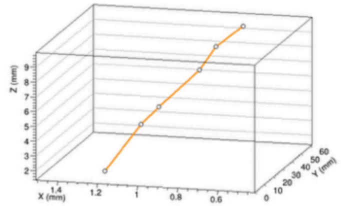

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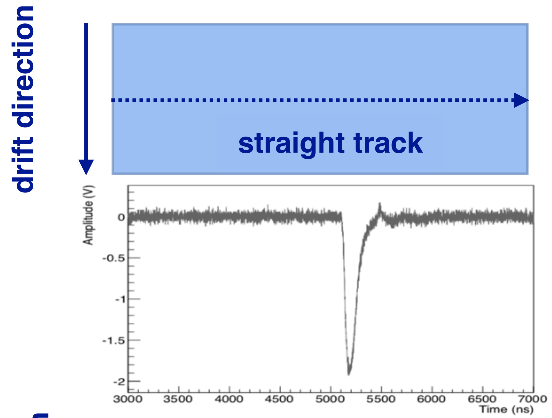
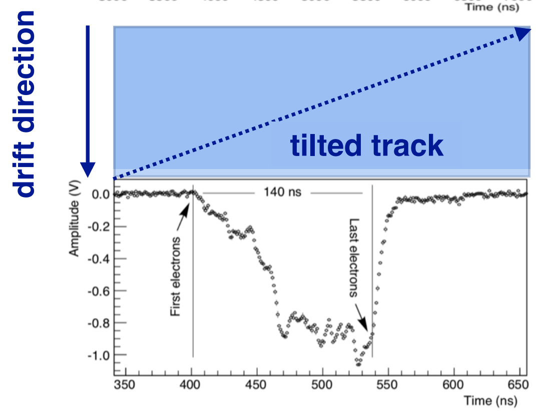
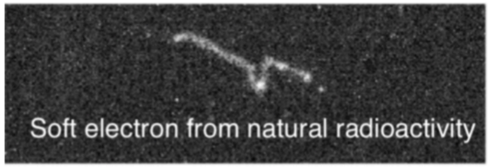




Optical readout TPC with sCMOS + PMT readout

sCMOS:
high granularity
X-Y + energy measurements



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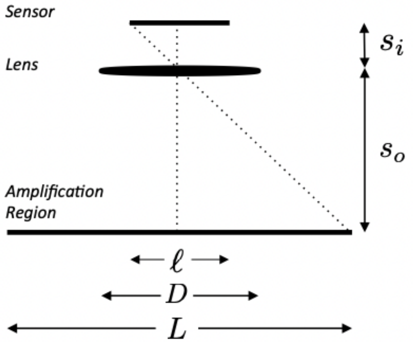
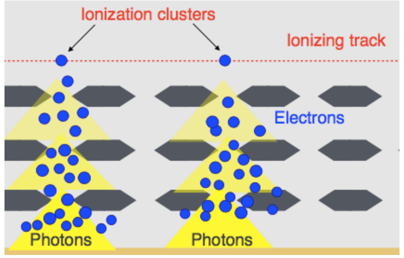
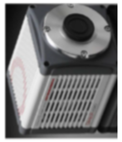
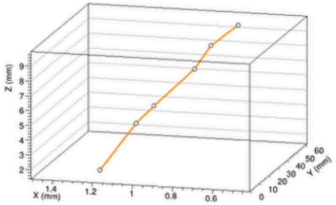


A single cameras can image a 36 x 36 cm^2 area with an effective pixel size of 160 x 160 um^2 (see later)

JINST 13 (2018) no.05, P05001

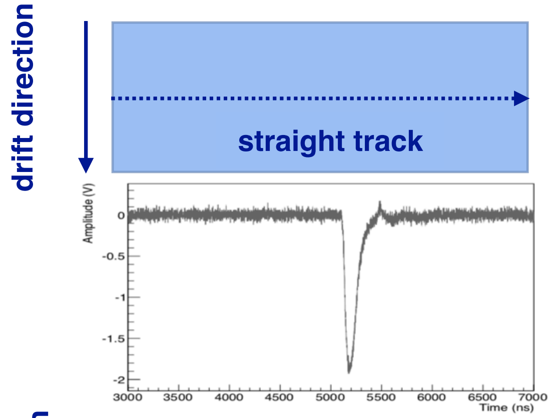


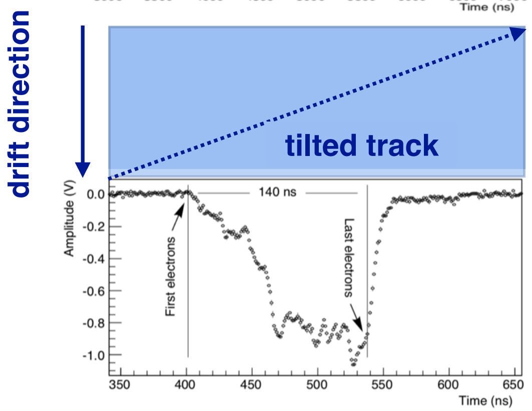




+ SF_6 for negative ion drift (see later)

PMT:
integrated
Z + energy measurement

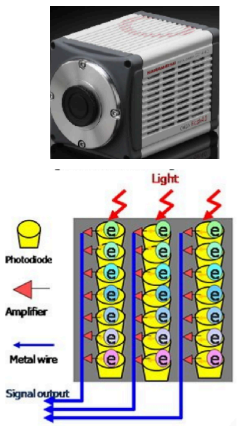




sCMOS characteristics & gas emission spectra

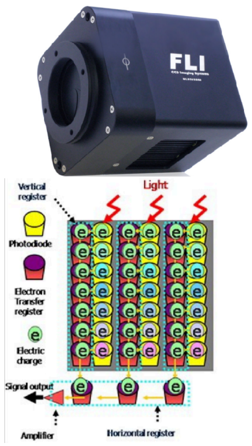
https://www.hamamatsu.com/eu/en/product/cameras/cmos-cameras.html

sCMOS



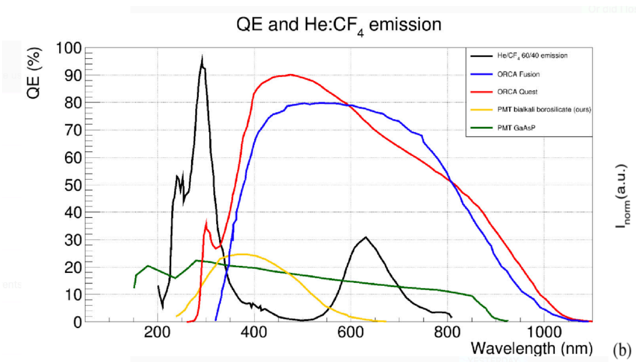
Lower light yield
Lower noise
Lower power consumption
Cheaper than CCD
Under rapid developments

CCD

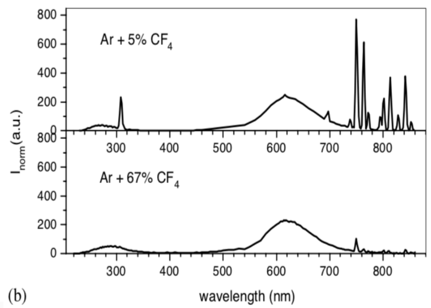


Larger light yield
Crispier images
Higher uniformity
Larger noise
Larger power consumption

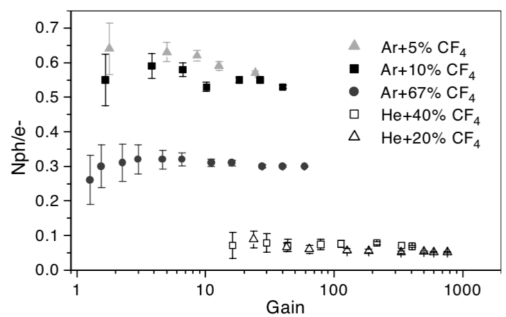
HAMAMATSU	# of pixels	pixel size [um²]	sensor area [cm²]	dynamic range	readout noise (fast scan)	Exposure time (fast)
Orca Flash	2048 x 2048	6.5 x 6.5	1.33 x 1.33	37000:1	1.4 (1.6) rms	33 (10) us
Orca Fusion	2304 x 2304	6.5 x 6.5	1.498 x 1.498	21400:1	0.7 (1.4) rms	280 (17) us
Orca Quest	4096 x 2304	4.6 x 4.6	1.884 x 1.060	25900:1	0.27 (0.43) rms	200 (7.2) us



Ar:CF4 spectra



Ar:CF4 & He:CF4 photon production

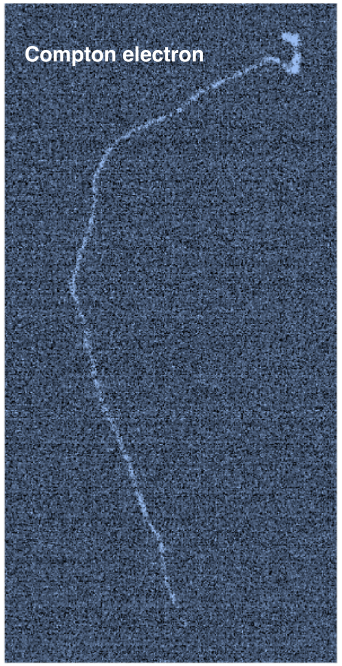


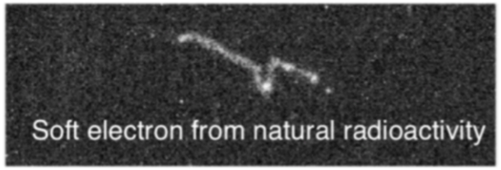
NIM A 504 (2003) 88-92

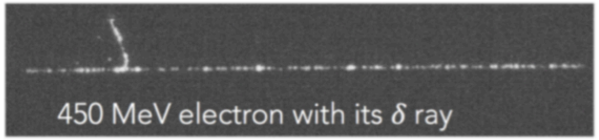
Photographing tracks

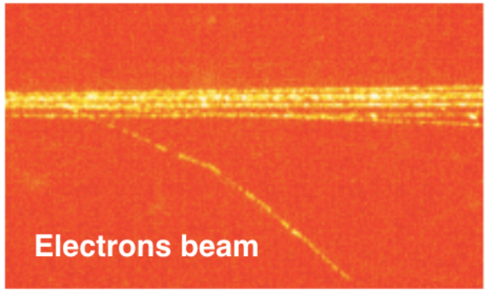
https://web.infn.it/cygnus/

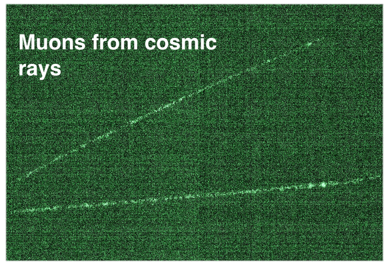
He:CF_4 @ 1 atm

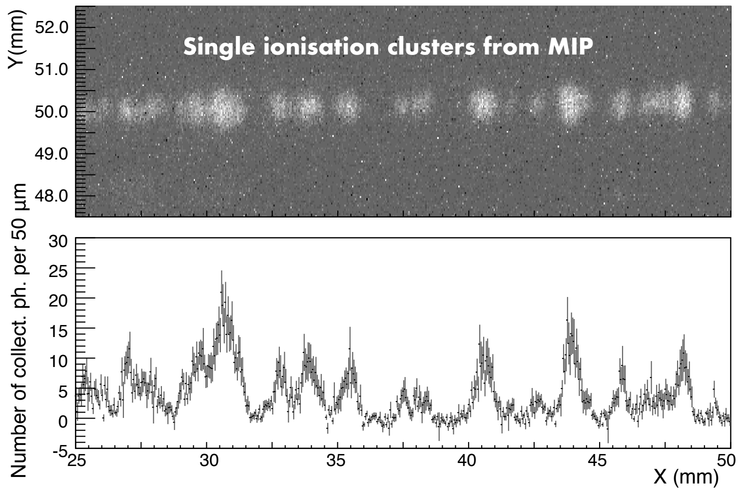


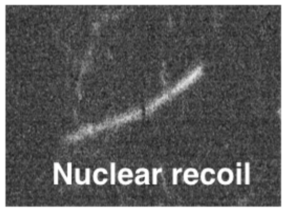






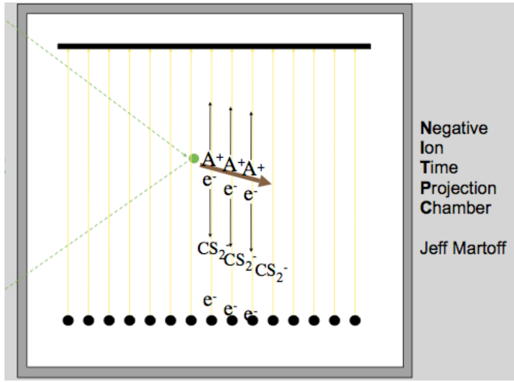






TPC with Negative Ion Drift (NID) operation

Reduced diffusion = improved tracking



- Electronegative dopant in the gas mixture (CS_2, SF_6, CH_3NO_2, ...)
- Primary ionization electrons captured by electronegative gas molecules at O(100) um
- Anions drift to the anode acting as the effective image carrier instead of the electrons and reducing both longitudinal and transverse diffusion to thermal limit

$$\sigma = \sqrt{\frac{2kTL}{eE}} = 0.7\,\mathrm{mm}\left(\frac{T}{300\,\mathrm{K}}\right)^{1/2}\left(\frac{580\,\mathrm{V/cm}}{E}\right)^{1/2}\left(\frac{L}{50\,\mathrm{cm}}\right)^{1/2}$$

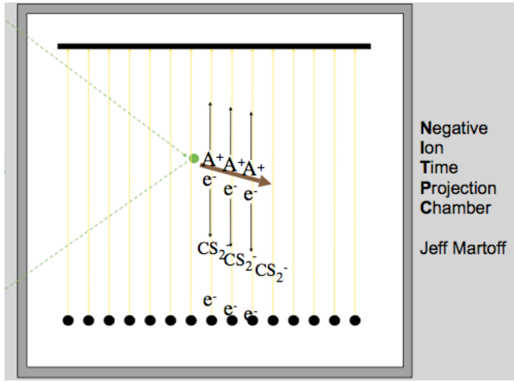
low diffusion increases active volume per readout area

T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

TPC with Negative Ion Drift (NID) operation

Reduced diffusion = improved tracking



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T. Ohnuki et al., NIM A 463

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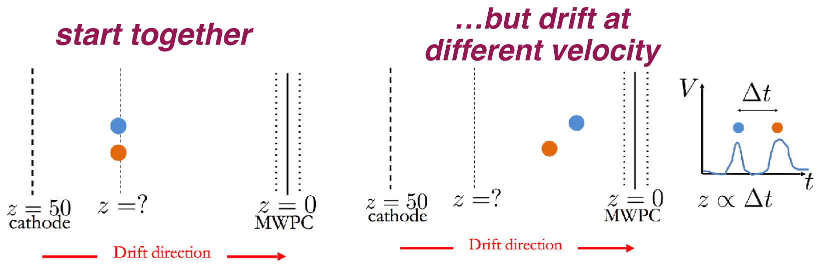
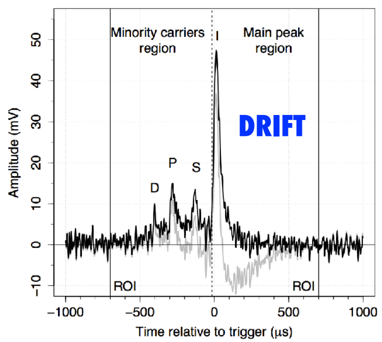
Multiple charge carriers = fiducialization!!

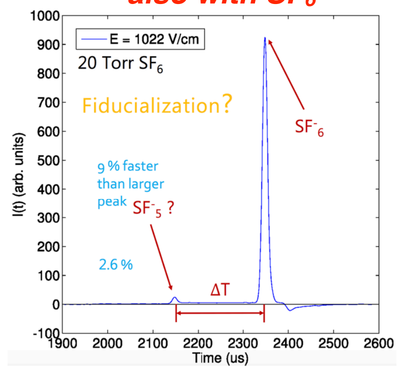


$$z = (t_m - t_p)\frac{v^m_{drift}v^p_{drift}}{v^m_{drift} - v^p_{drift}}$$

- CS_2:CF_4:O_2 30:10:1 Torr



From 2015 demonstrated also with SF_6



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

N.S.Phan et al., JINST 12 (2017) no.02, P02012

Negative ion drift: history & status

G S S I

INFN Istituto Nazionale di Fisica Nucleare

Charge Readout

Low pressure

- Concept demonstrated in 2000 at 40 Torr CS_2 with MWPC [1]
- Pioneered in a actual experiment by DRIFT with $CS_2:CF_4:O_2$ at 40 Torr with MWPC [2]
- 20-40 Torr pure SF_6 in 2017 with THGEM [3]
- 20 Torr pure SF_6 with THGEM-multiwire [4] and muPIC in 2020 [5]

(nearly) Atm pressure

- Demonstrated in 2010's in $He:CS_2$[6] and $CO_2:Ne:CH_3NO_2$[7] with GEMs and MWPC
- In 2017 at 610 Torr of $He:CF_4:SF_6$ with GEMs and TimePix2 [8]
- In 2021 in $Ar:iC_4H_{10}:CS_2$ with GridPix (Ingrid + Timepix3) [9]

Optical Readout

- 50-150 Torr $CF_4:CS_2$ with glass GEM and CMOS [D. Loomba, talk at RD51 June 2022 meeting]

THIS TALK

[1] C. J. Martoff et al. NIM A 440 335
[2] G. J. Alner et al., NIM A 535
[3] N. S. Phan et al, *JINST* 12 (2017) 02, 02
[4] A. C. Ezeribe NIM A 987
[5] T. Ikeda et al, *JINST* 15 07, P07015
[6] C. J. Martoff et al, NIM A 555
[7] C. J. Martoff et al, NIM A 598
[8] E. Baracchini et al, *JINST* 13 04, P04022
[9]C. Ligtenberg et al, NIM A 1014 165706

*Detector operated at LNGS (900 m): atm pressure is 880 mbar

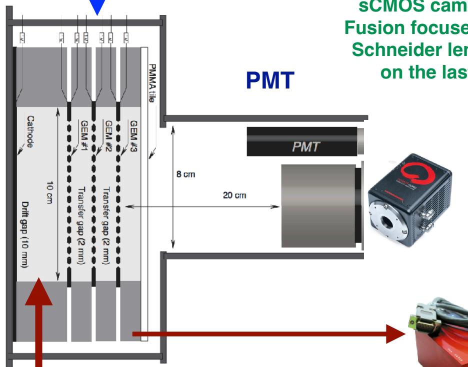
Negative ion drift at atmospheric pressure with optical readout

NEW! Data analysis on going and paper in preparation

MANGO

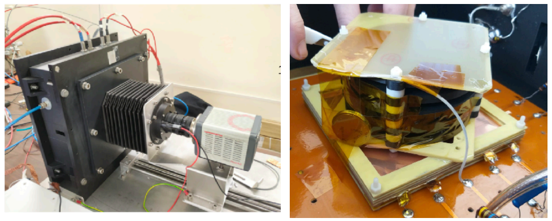
- Imaging 10 x 10 cm^2 area
- Effective pixel granularity 45 x 45 um^2
- From 5 to 15 cm drift gap
- Sensor geometrical acceptance 1.1 x 10^{-3}

Triple thin 50 um GEM stack 10 x 10 cm^2



PMT

sCMOS camera Orca Fusion focused through Schneider lens (f/0.95) on the last GEM

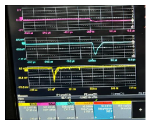


Acquire sCMOS images, PMT & GEM waveforms with ^{241}Am source

Drift gap (variable from 5 to 15 cm)

Charge sensitive preamplifier
300 us decay time
0.113 mV/fC

Shaper amplifier
shaping time
0.5 us (ED)/ 10 us (NID)



Oscilloscope
Trigger on GEM preamp output

This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the Marie Sklodowska-Curie grant agreement No 657751 and from the European Research Council (ERC) grant agreement No 818744

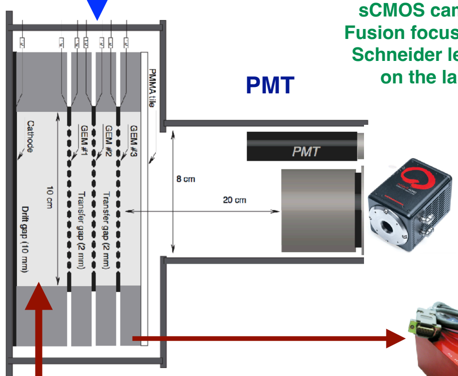
Negative ion drift at atmospheric pressure with optical readout

NEW! Data analysis on going and paper in preparation

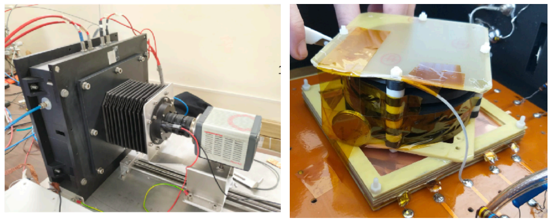
MANGO

- Imaging 10 x 10 cm^2 area
- Effective pixel granularity 45 x 45 um^2
- From 5 to 15 cm drift gap
- Sensor geometrical acceptance 1.1 x 10^{-3}

Triple thin 50 um GEM stack 10 x 10 cm^2



sCMOS camera Orca Fusion focused through Schneider lens (f/0.95) on the last GEM

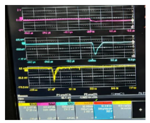


Acquire sCMOS images, PMT & GEM waveforms with ^{241}Am source

Drift gap (variable from 5 to 15 cm)

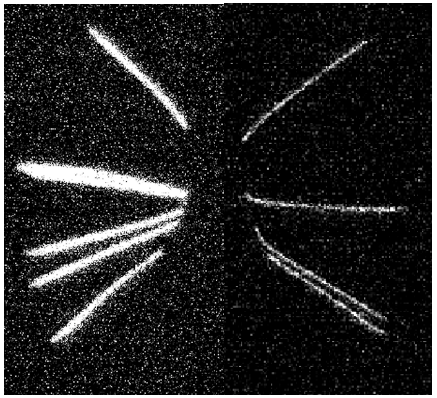
Charge sensitive preamplifier
300 us decay time
0.113 mV/fC

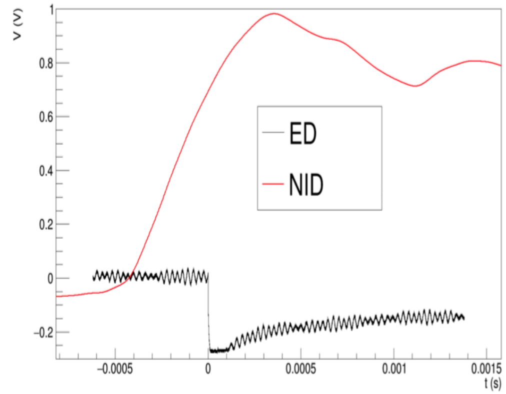
Shaper amplifier
shaping time
0.5 us (ED)/ 10 us (NID)



Oscilloscope
Trigger on GEM preamp output

Eyes (and waveforms) can't lie!





He:CF_4	He:CF_4:SF_6
60:40	59:39.4:1.6
1 kV/cm	0.4 kV/cm
(ED)	(NID)

GEM preamp output
O(us) rise for ED
O(ms) rise for NID

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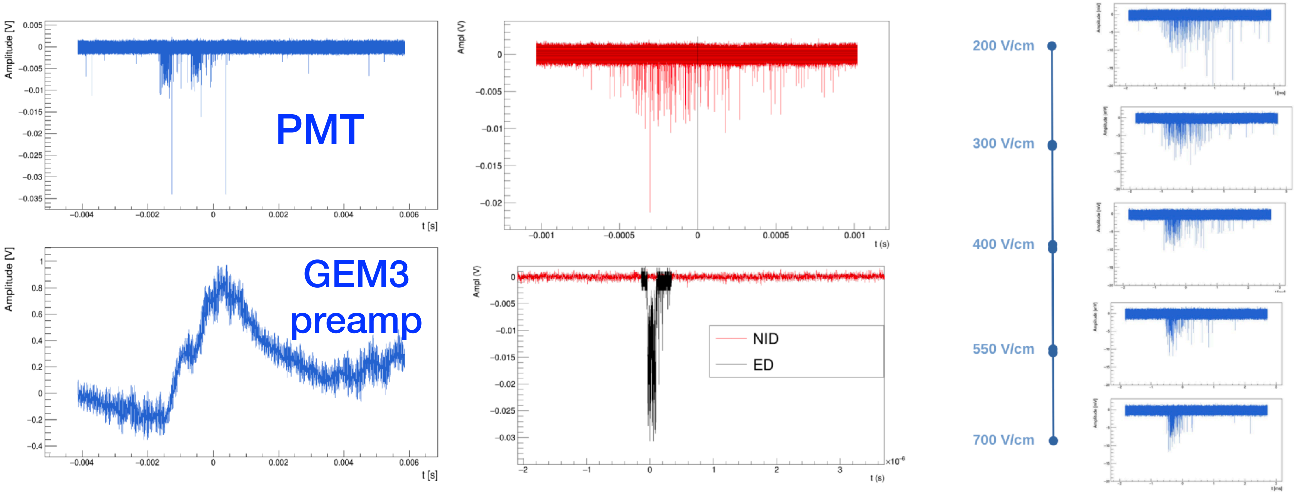
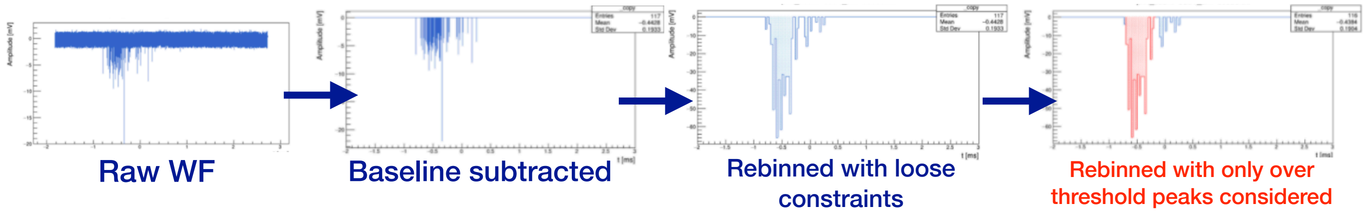
Negative ion PMT waveforms & analysis

*First time NID are observed with PMTs!



Given the PMT sampling and the "slow" arrival of charge carriers, individual clusters are visible in the PMT signal --> WF analysis requires proper rebinning (not trivial)



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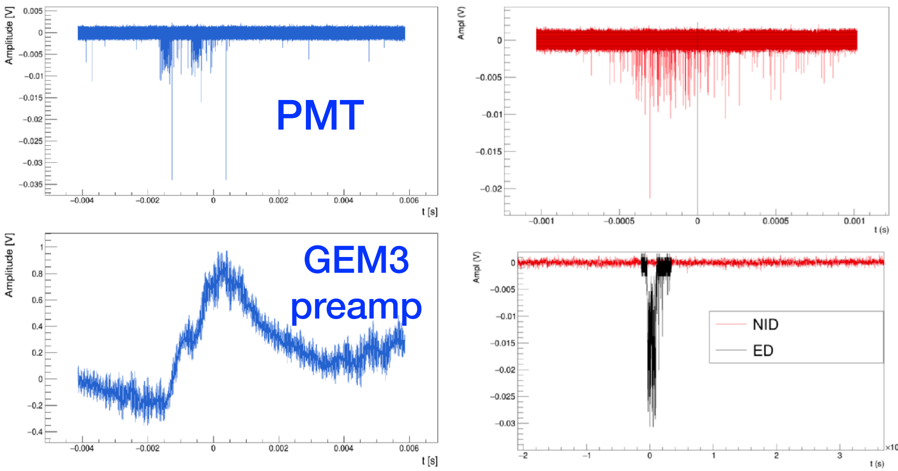

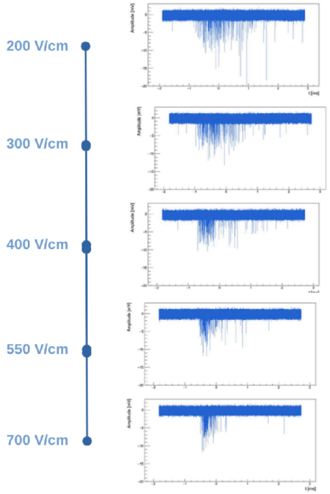

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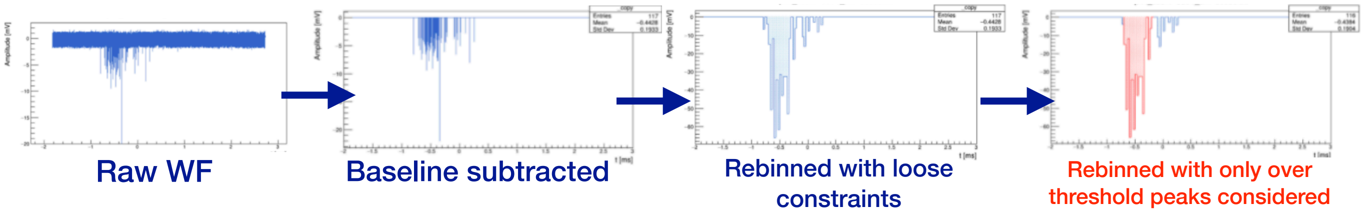
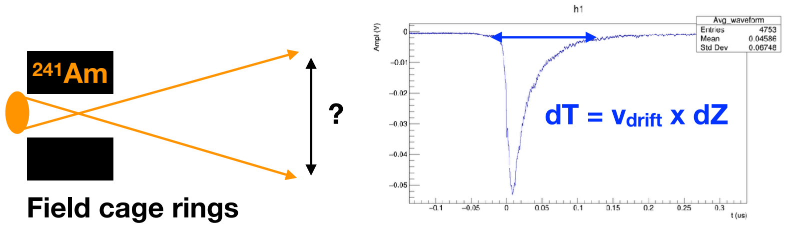
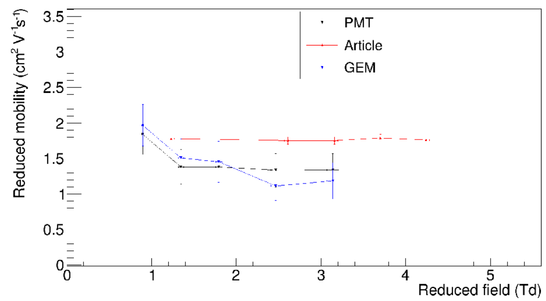




From ED PMT signal, given the known drift velocity, we estimate the alpha dZ spread (? == 7 mm)

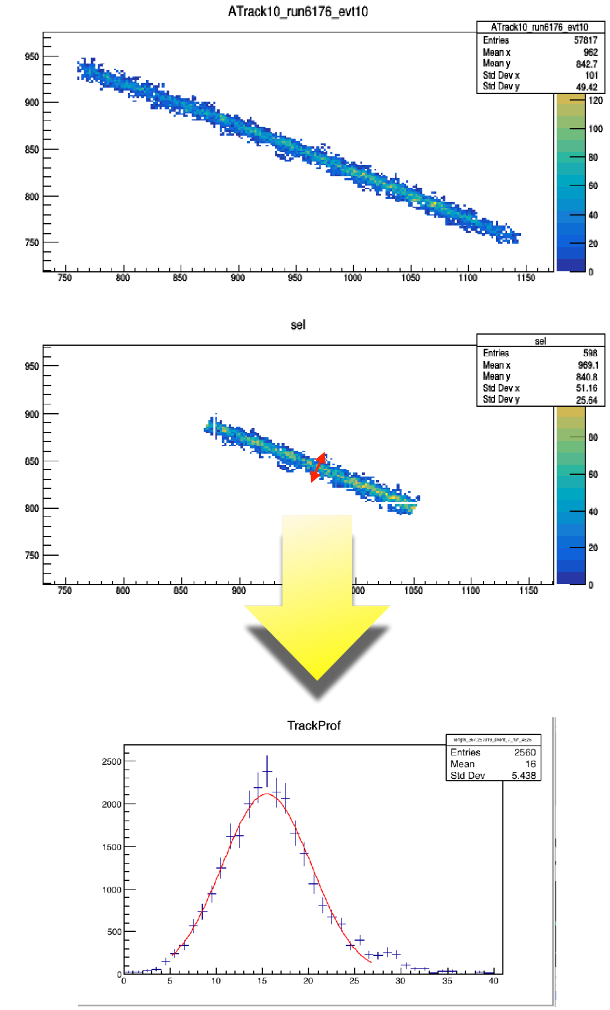
Given the alpha dZ spread estimated from ED (7 mm), estimate NID drift velocity:

- From GEM preamp output rise time
- From PMT waveforms time window extension, after proper WF rebinning



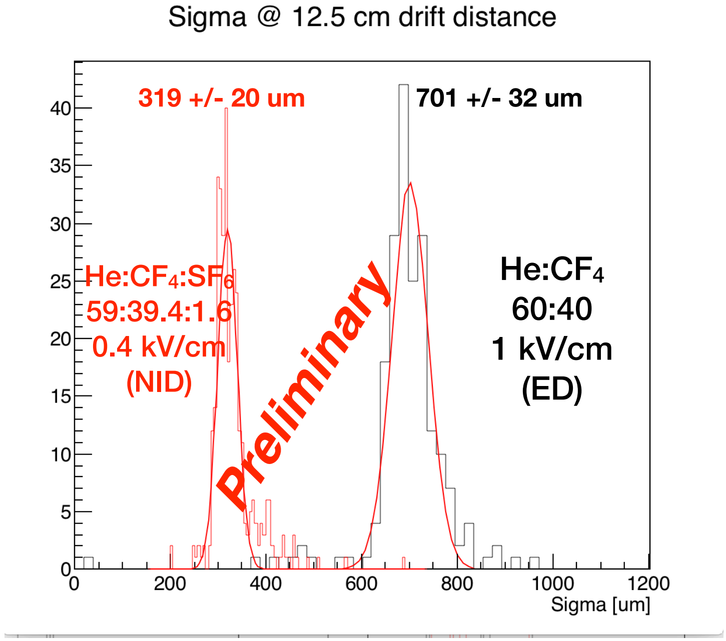
Measured mobility consistent with NID published data [8]

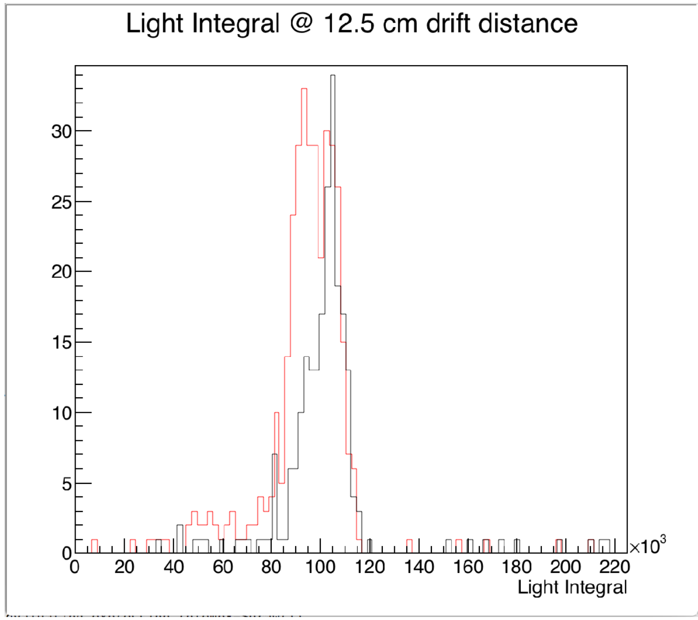
Negative ion sCMOS images analysis



Diffusion & intergral @ 12.5 cm drift distance

0.65 atm 300 V/cm drift field



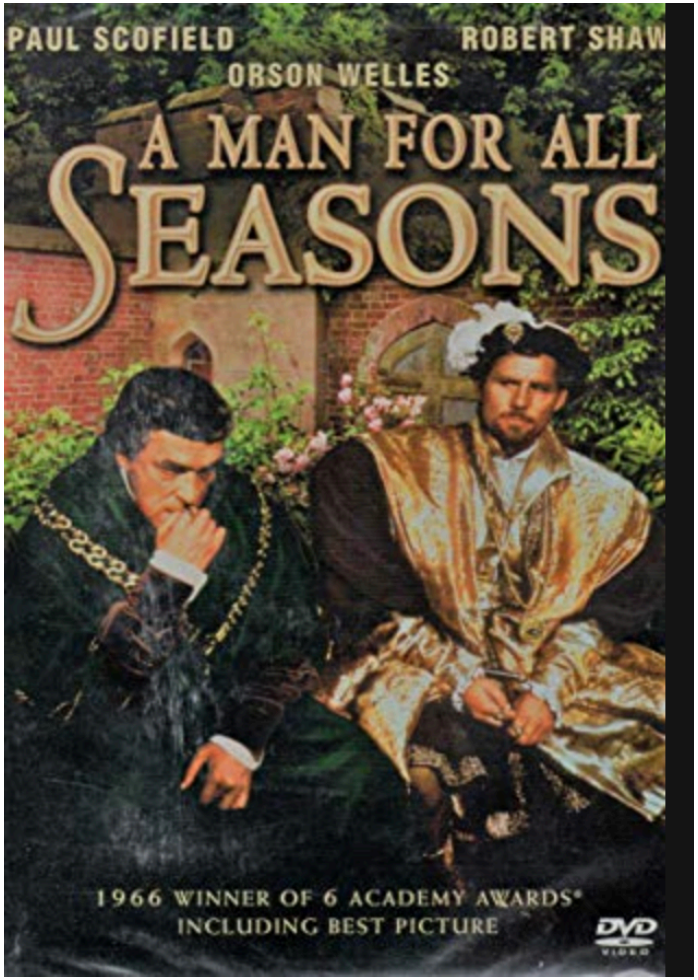


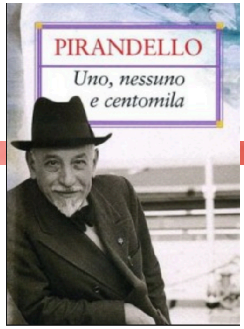
ED diffusion @ 12.5 drift distance is twice NID diffusion, with same track light integral!

for the paper in preparation!

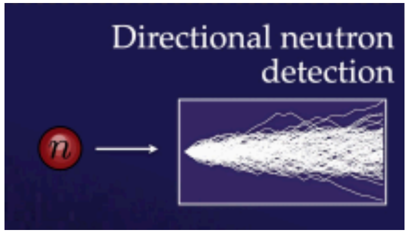
Directionality: "a tool for all season"

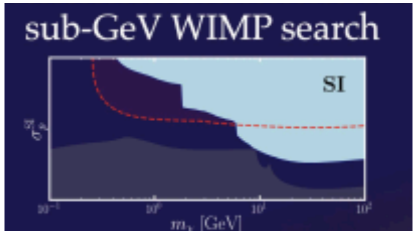
High imaging capabilities of today's Time Projection Chamber, including but not limited to directional capability, can open the doors to many physics cases beyond Dark Matter searches

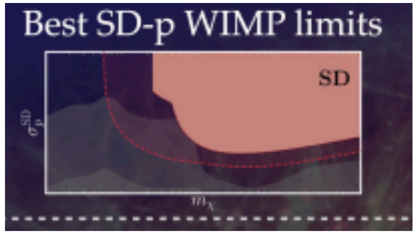


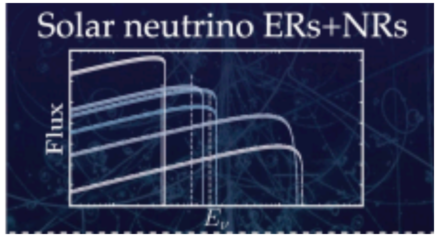


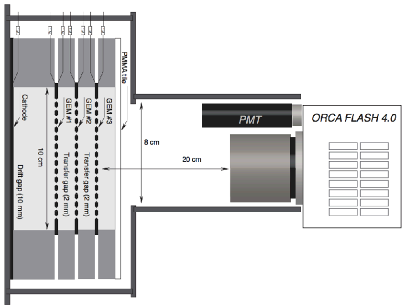
One, no one and one hundred thousand optical imaging TPC applications



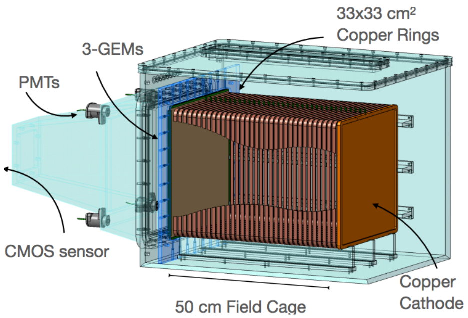




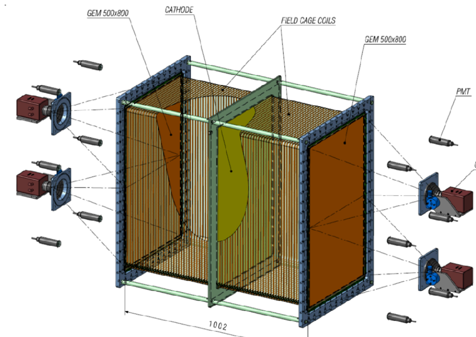




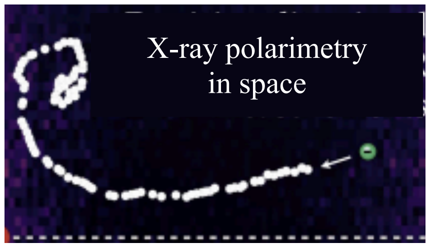
Small O(1) L

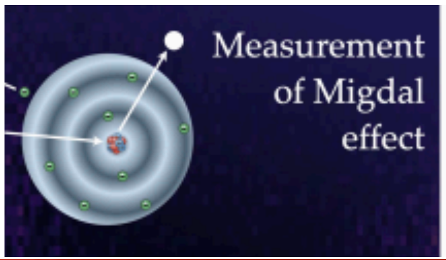


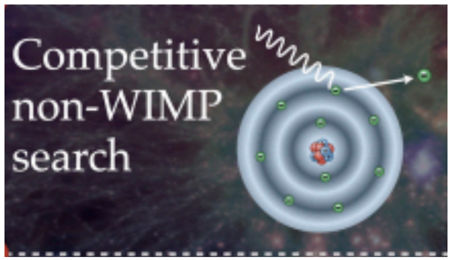
Medium O(50) L

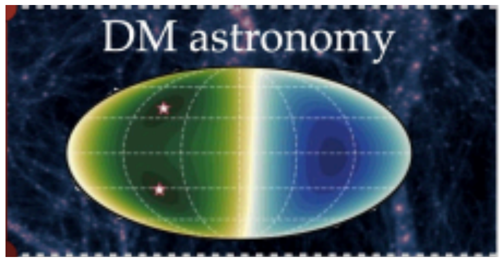


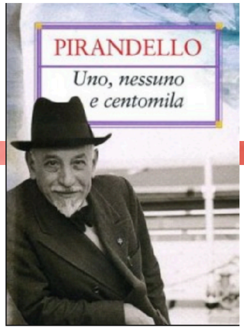
Large O(500) L - 1 Ton



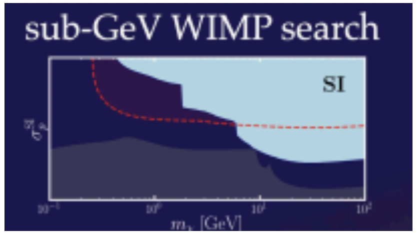


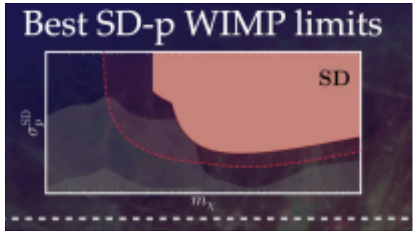


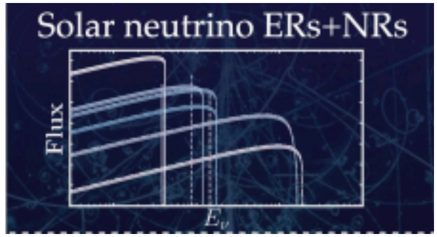


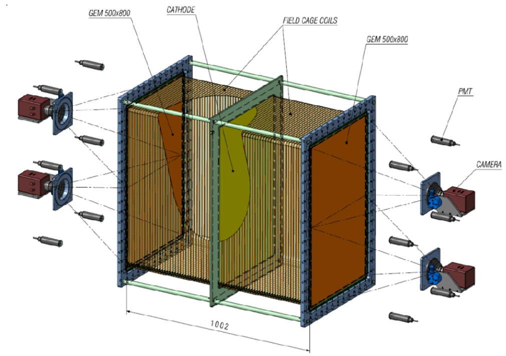


One, no one and one hundred thousand optical imaging TPC applications

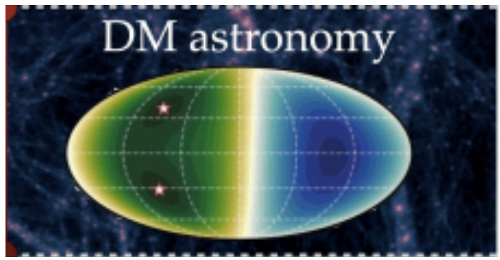








Large O(500) L - 1 Ton



Directional Dark Matter searches

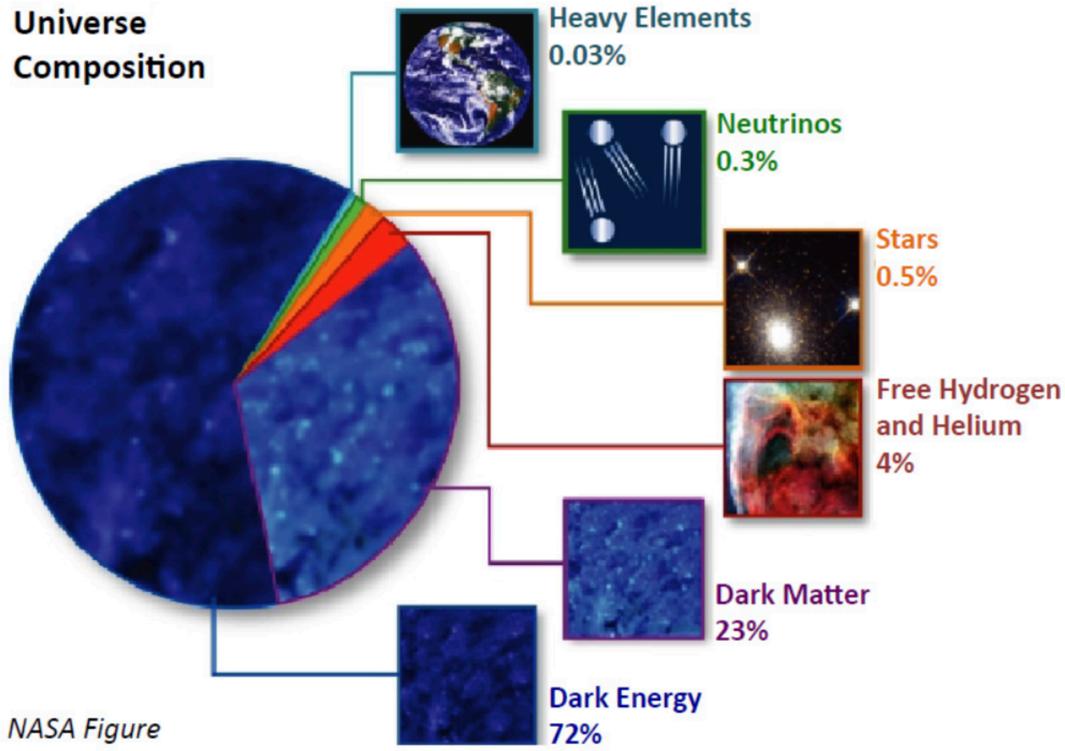
(and solar neutrino spectroscopy)

The CYGNO/INITIUM experiment

Fernando Domingues Amaro [1], Elisabetta Baracchini [2,3], Luigi Benussi [4], Stefano Bianco [4], Cesidio Capoccia [4], Michele Caponero [4,5], Danilo Santos Cardoso [6], Gianluca Cavoto [7,8], André Cortez [2,3], Igor Abritta Costa [9], Rita Joanna da Cruz Roque [1], Emiliano Dané [4], Giorgio Dho [2,3], Flaminia Di Giambattista [2,3], Emanuele Di Marco [7], Giovanni Grilli di Cortona [4], Giulia D'Imperio [7], Francesco Iacoangeli [7], Herman Pessoa Lima Júnior [6], Guilherme Sebastiao Pinheiro Lopes [9], Amaro da Silva Lopes Júnior [9], Giovanni Maccarrone [4], Rui Daniel Passos Mano [1], Michela Marafini [10], Robert Renz Marcelo Gregorio [11], David José Gaspar Marques [2,3], Giovanni Mazzitelli [4], Alasdair Gregor McLean [11], Andrea Messina [7,8], Cristina Maria Bernardes Monteiro [1], Rafael Antunes Nobrega [9], Igor Fonseca Pains [9], Emiliano Paoletti [4], Luciano Passamonti [4], Sandro Pelosi [7], Fabrizio Petrucci [12,13], Stefano Piacentini [7,8], Davide Piccolo [4], Daniele Pierluigi [4], Davide Pinci [7,*], Atul Prajapati [2,3], Francesco Renga [7], Filippo Rosatelli [4], Alessandro Russo [4], Joaquim Marques Ferreira dos Santos [1], Giovanna Saviano [4,14], Neil John Curwen Spooner [11], Roberto Tesauro [4], Sandro Tomassini [4] and Samuele Torelli [2,3]

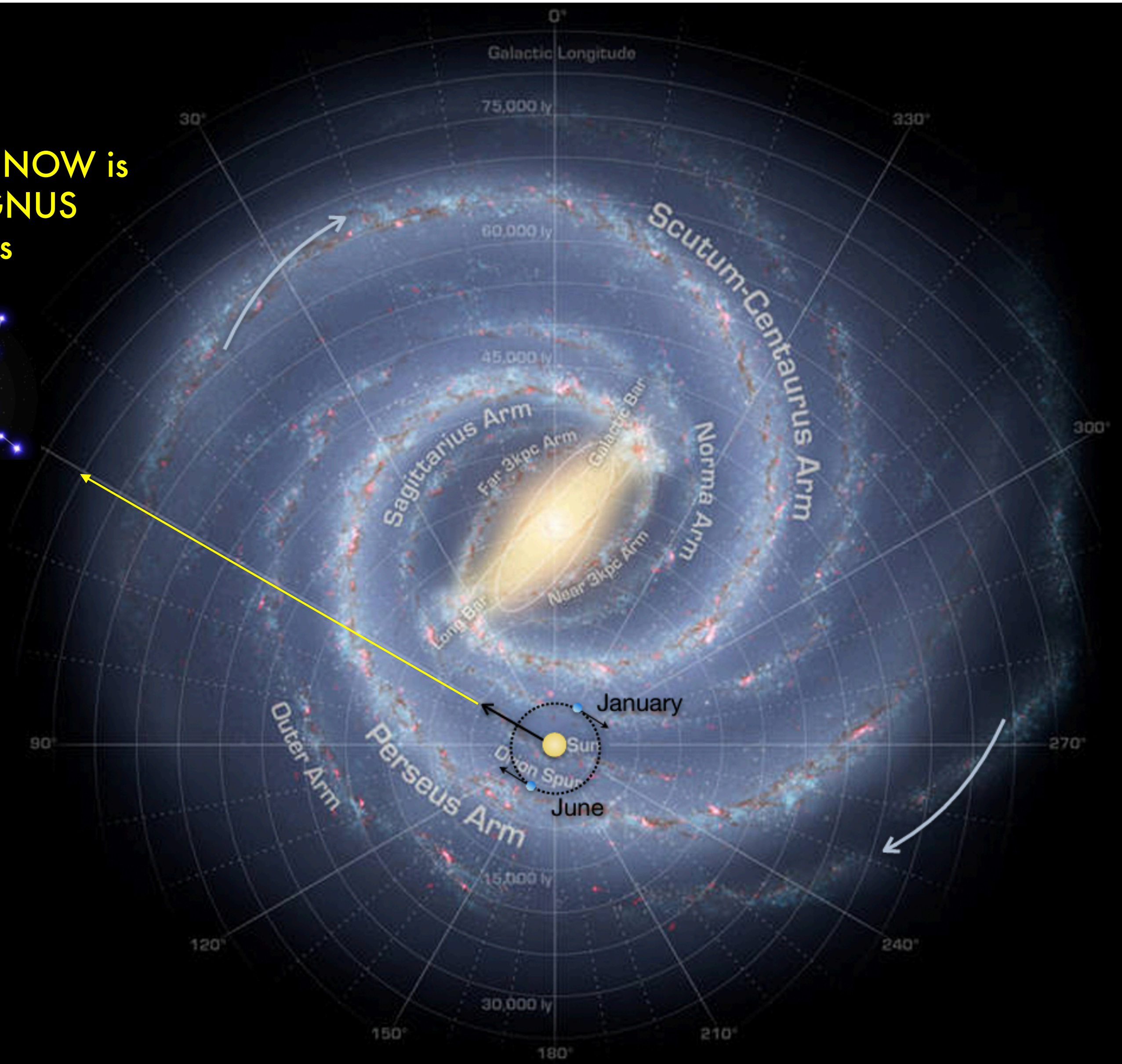
This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the European Research Council (ERC) grant agreement No 818744

It's a Dark Universe

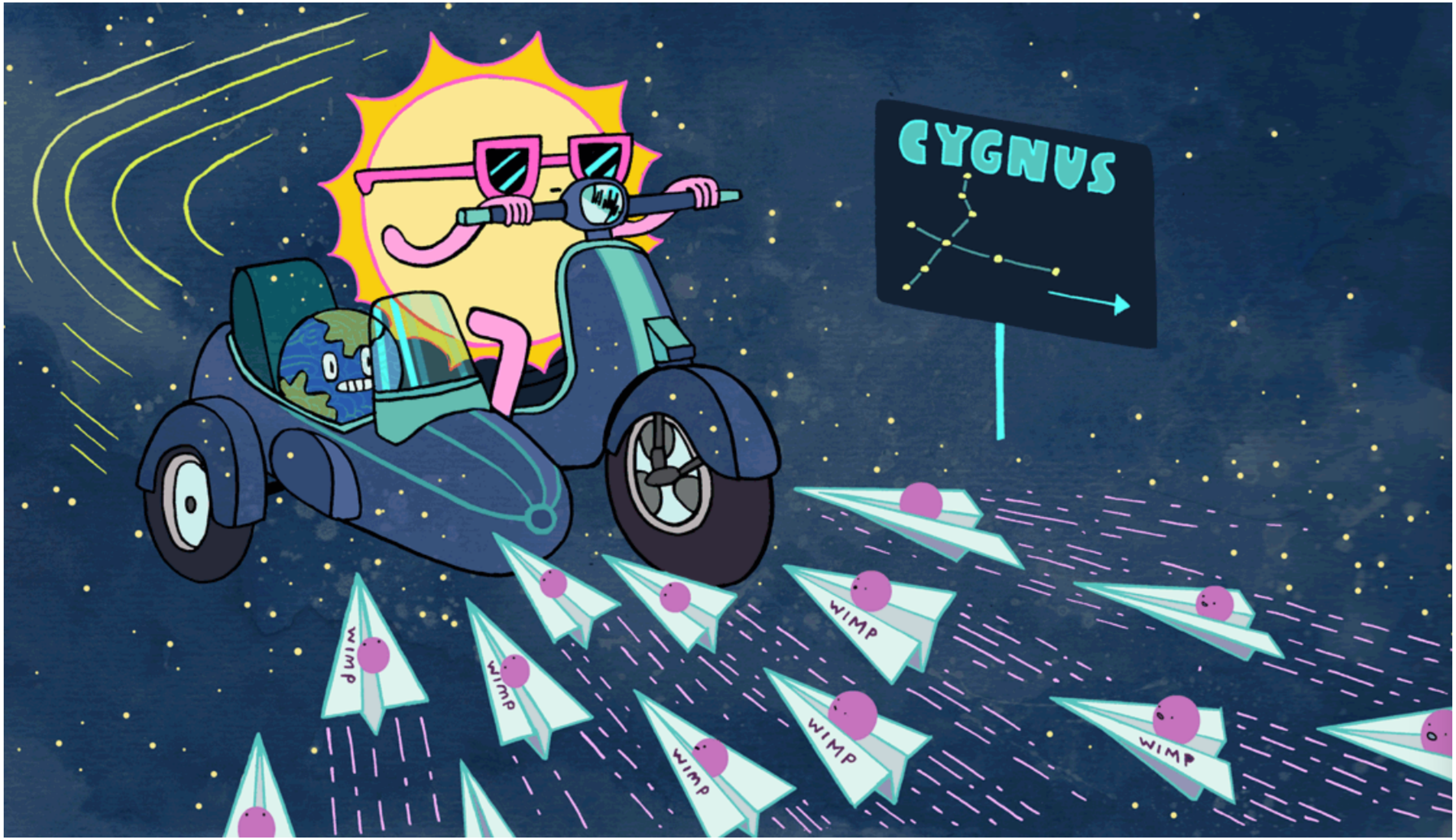


The Universe we observe is gravitationally dominated by an obscure and unknown kind of matter, that behaves differently with respects to the common matter we experience every day

Appartent direction NOW is
towards the CYGNUS
constellations

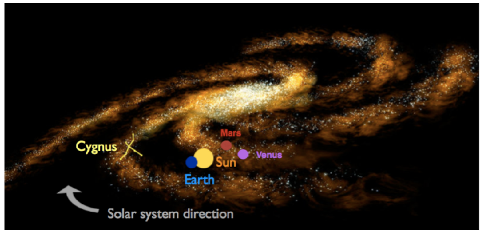


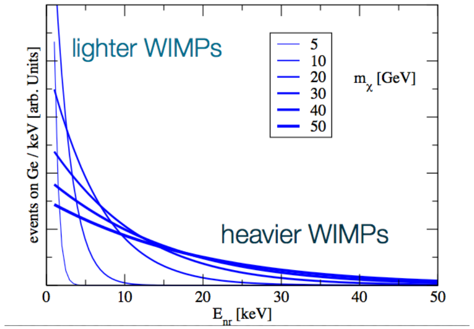
Driving towards CYGNUS with a Dark Matter wind blowing in your hair



Directionality as key for an unambigous identification of a DM signal

Increasing reliability of any observed signal, increasing difficulty in the experimental technique





Energy dependence:
a falling exponential with
no peculiar features

Directional correlation with an astrophysical source is the only available POSITIVE identification of a DM signal

Directionality as key for an unambigous identification of a DM signal

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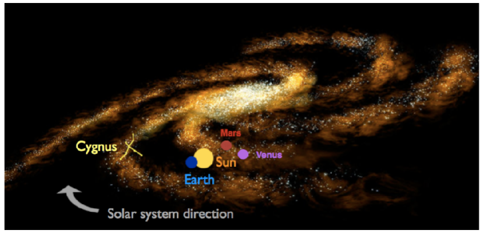

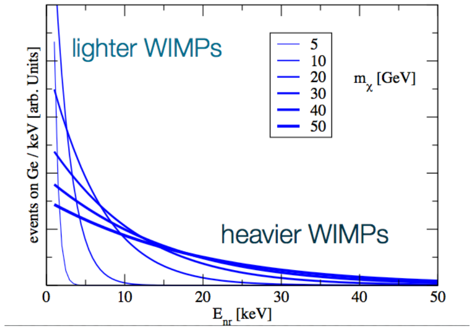

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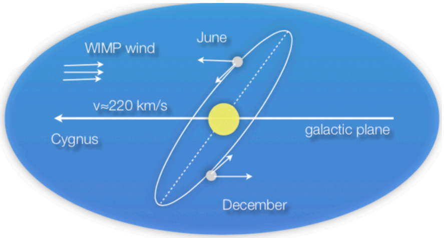
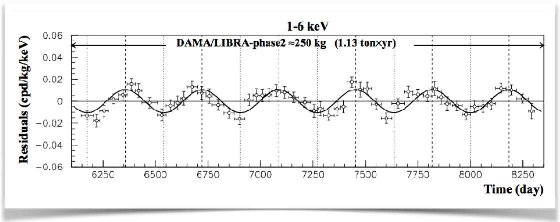


DAMA/LIBRA Collaboration



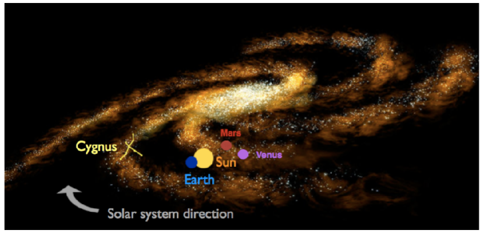
Universe 4 (2018) no.11, 116

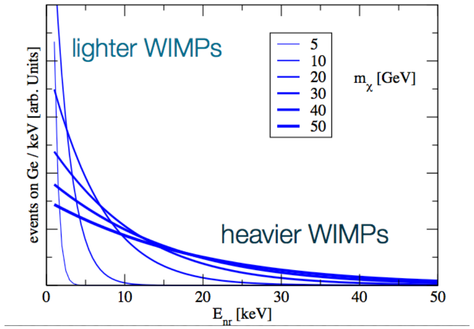
Temporal dependence:
a few % annual modulation

Directional correlation with an astrophysical source is the only available POSITIVE identification of a DM signal

Directionality as key for an unambigous identification of a DM signal

Increasing reliability of any observed signal, increasing difficulty in the experimental technique





Energy dependence:
a falling exponential with
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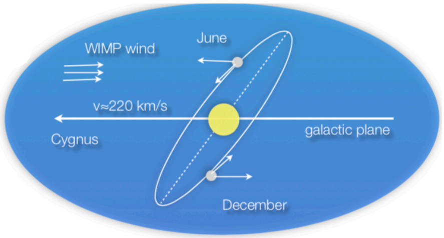
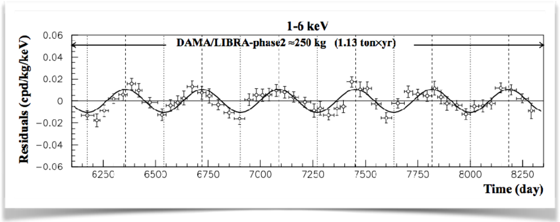


DAMA/LIBRA Collaboration



Universe 4 (2018) no.11, 116

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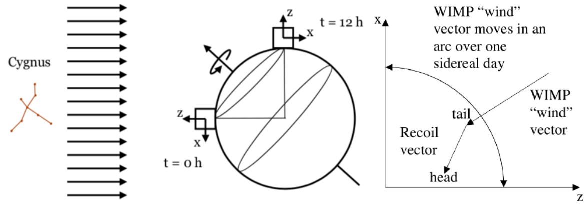
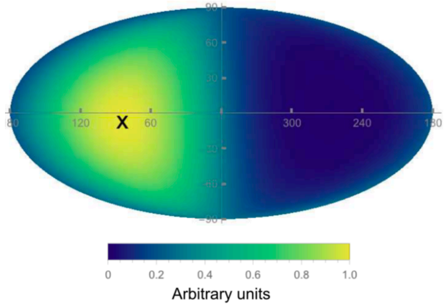




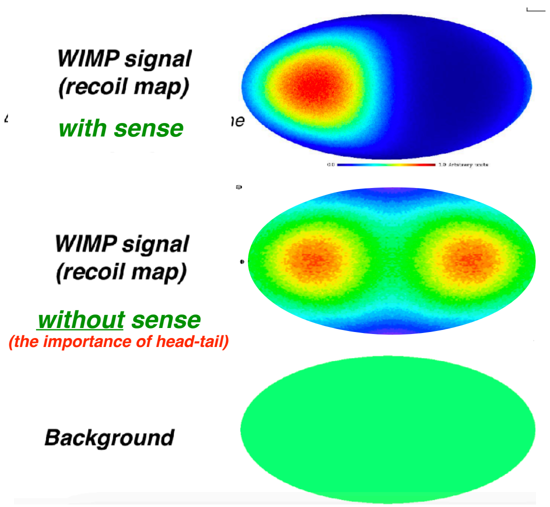
Directional dependence:
an O(1) effect that no background
whatsoever can mimic

Directional correlation with an astrophysical source is the only available POSITIVE identification of a DM signal

Directionality as a tool for background rejection, neutrino physics and DM astronomy

Capability to reject isotropy

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



Directional detector can tolerate
unknown backgrounds, including neutral

WIMP signal in principle detectable with O(10) 3D events

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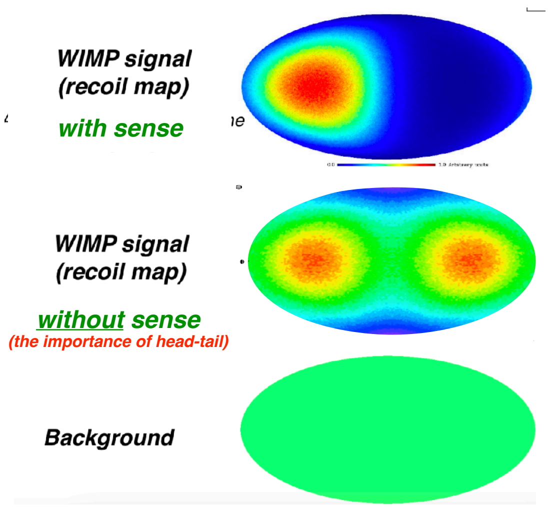
A. M. Green et. al, Astropart. Phys. 27 (2007) 142



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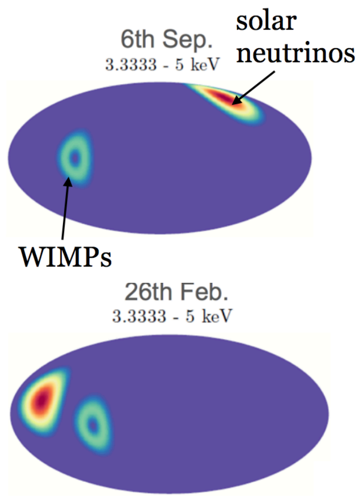
Capability to discriminate neutrinos from WIMPs

C. O'Hare et al, Phys. Rev. D 92 063518 (2015)



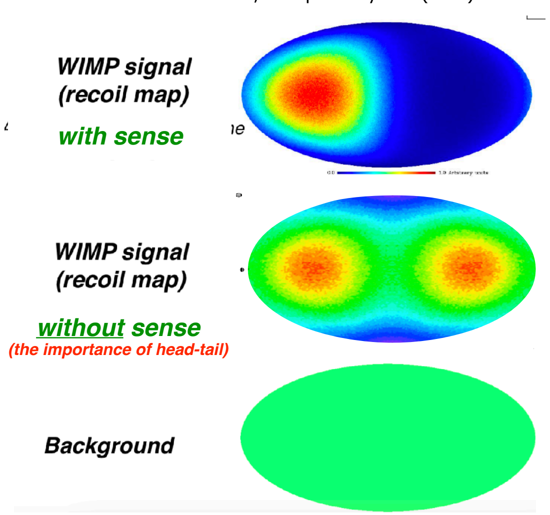
The Neutrino Floor is an opportunity, not a limit

Sun neutrinos physics

Directionality as a tool for background rejection, neutrino physics and DM astronomy

Capability to reject isotropy

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



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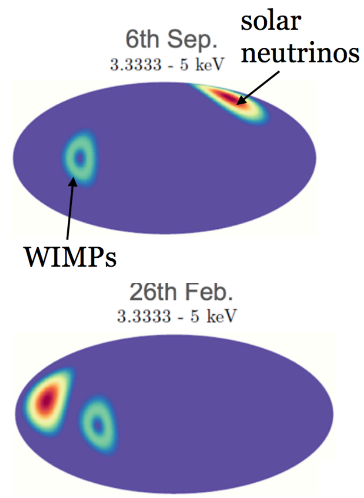
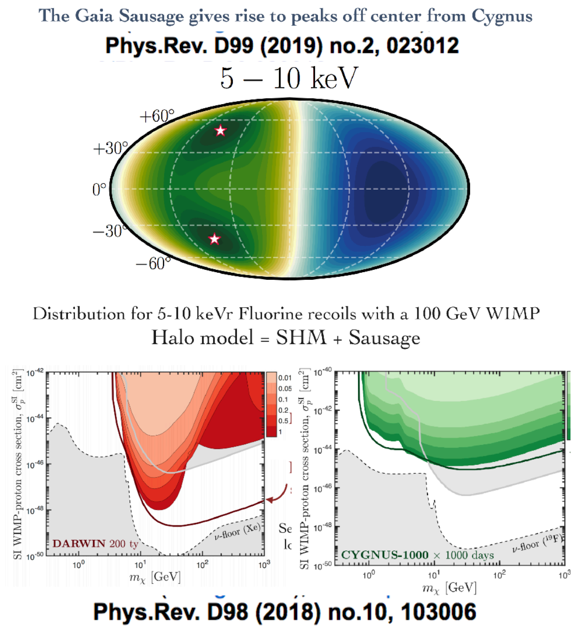


The Neutrino Floor is an opportunity, not a limit

Sun neutrinos physics

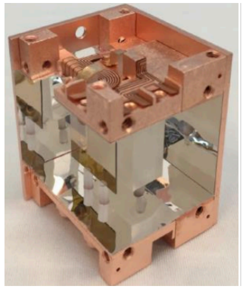
Capability to probe DM nature

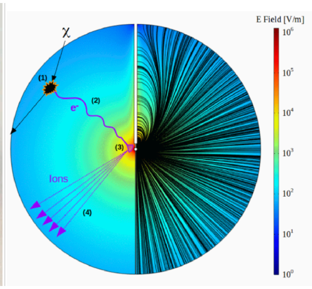


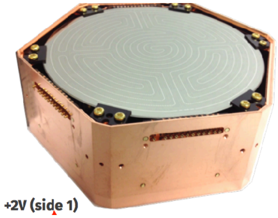
WIMP & halo properties unbiased constrained with a single measurement

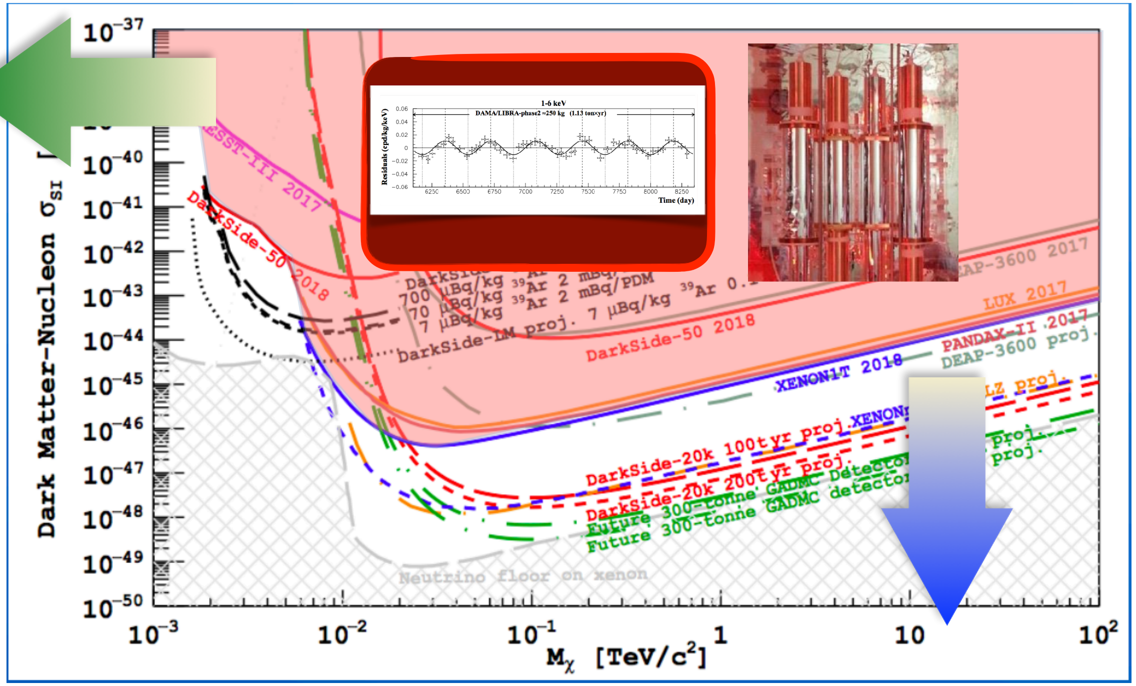
DM astronomy & DM interactions

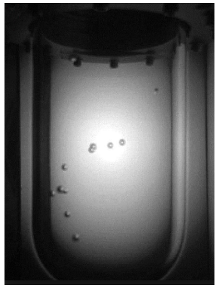
Directional Dark Matter search context

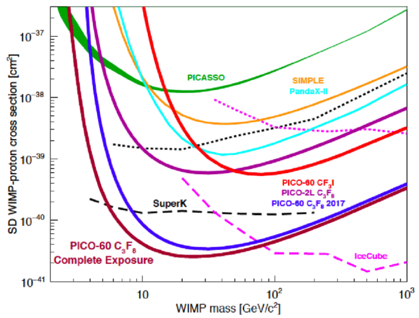


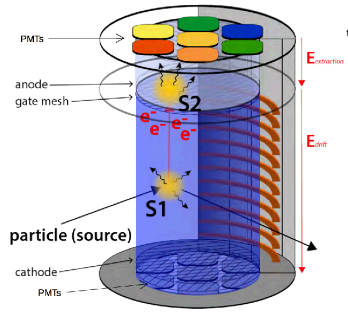




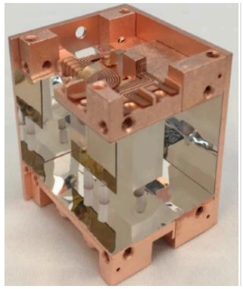


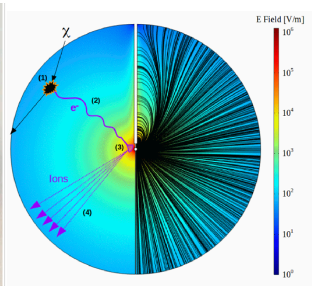


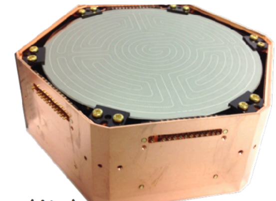


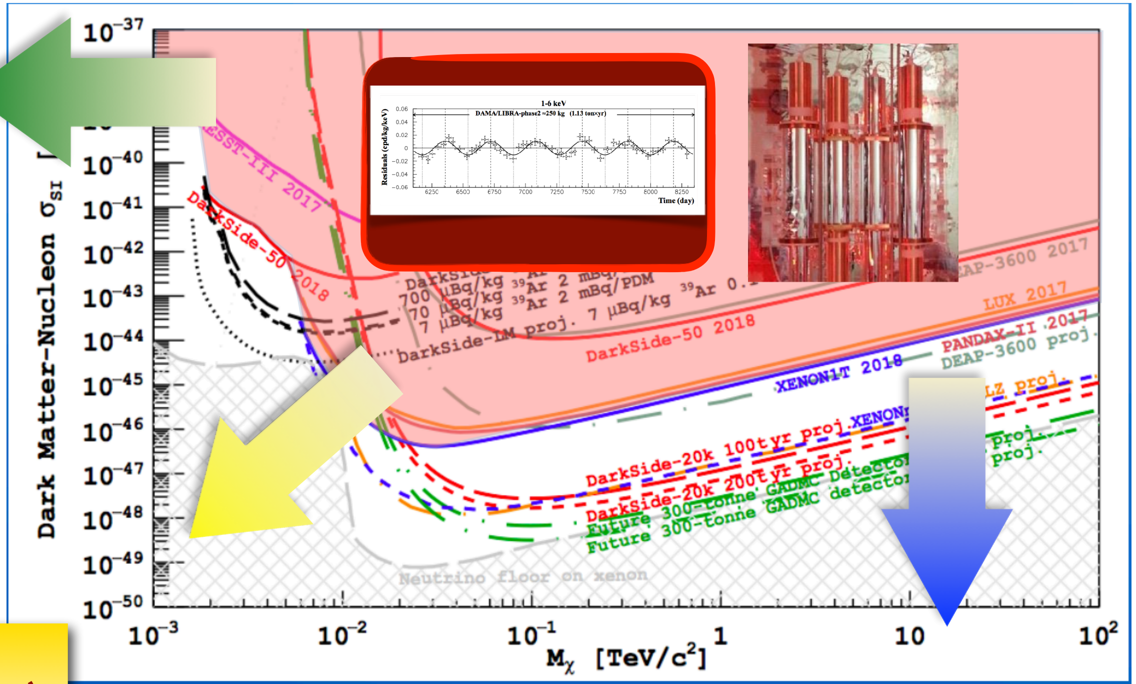


Directional Dark Matter search context

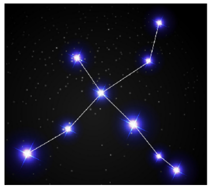


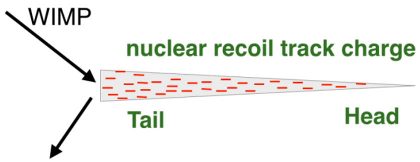


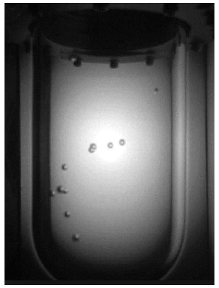


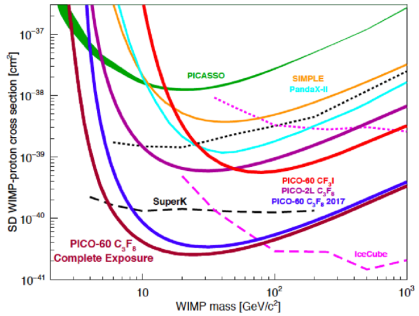


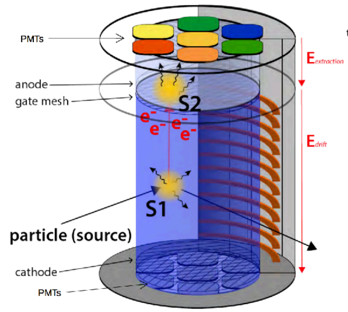
The "third way": directionality (for both SI and SD) through the Neutrino floor







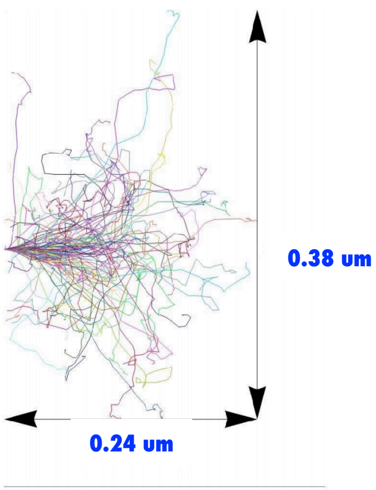




Directionality: how well preserved in nuclear recoils?

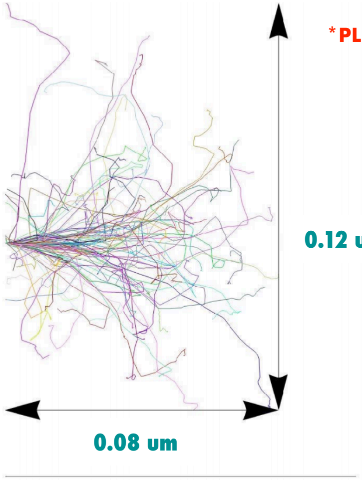
Choose your target material & WIMP mass region

- Emulsion layers



C in Emulsion (22keV)

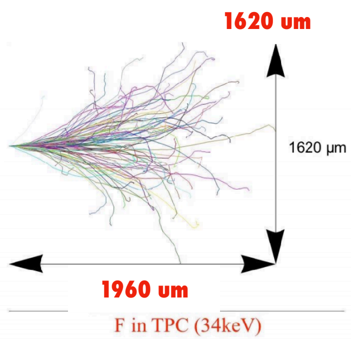
- Crystals scintillators



O in Crystal (29keV)

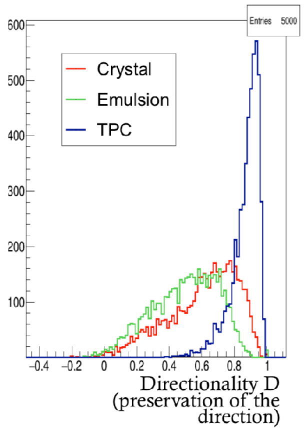
- Low pressure TPCs *

*PLEASE NOTE: what matter is the target density, not the gas pressure



F in TPC (34keV)

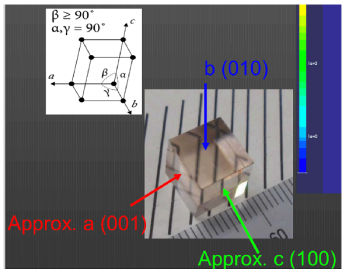
From SRIM software simulation



JCAP 1701 (2017) no.01, 027

NEWS-DM (emulsions)

Anisotropic crystals



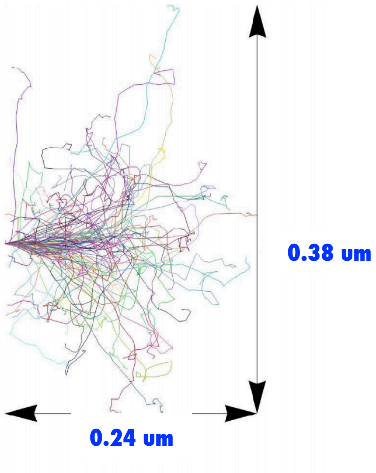
Directionality: how well preserved in nuclear recoils?

Choose your target material & WIMP mass region

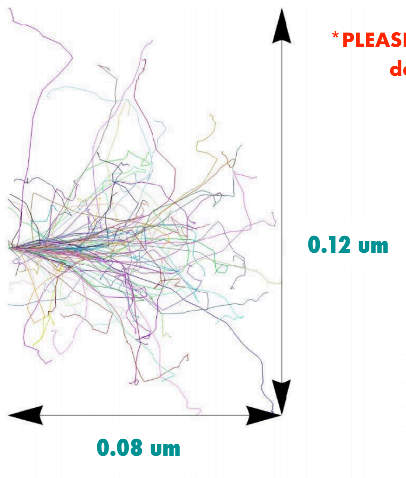
- Emulsion layers
- Crystals scintillators
- Low pressure TPCs *

*PLEASE NOTE: what matter is the target density, not the gas pressure

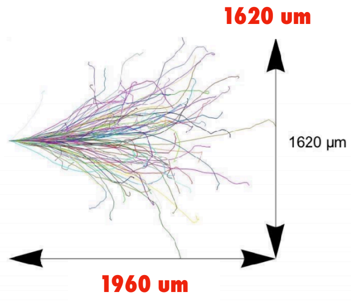
From SRIM software simulation



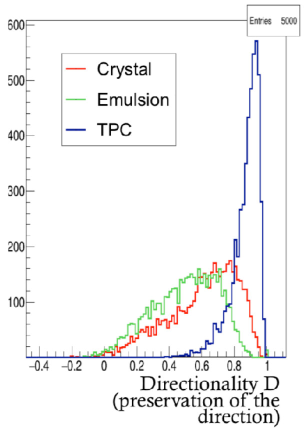
C in Emulsion (22keV)

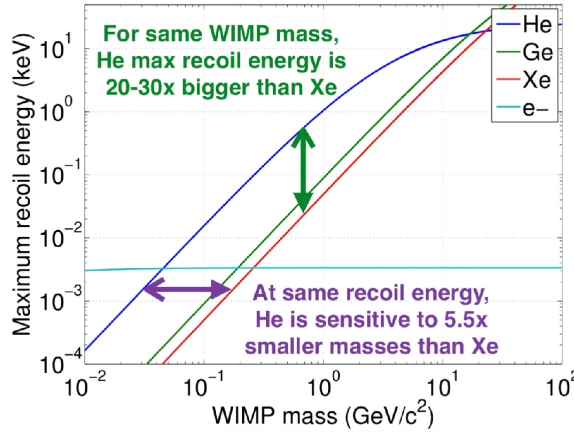


O in Crystal (29keV)

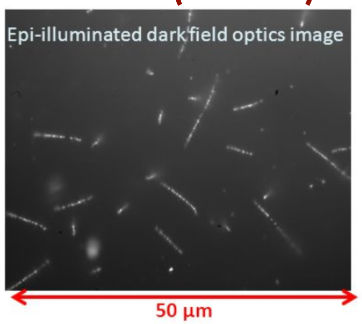


F in TPC (34keV)

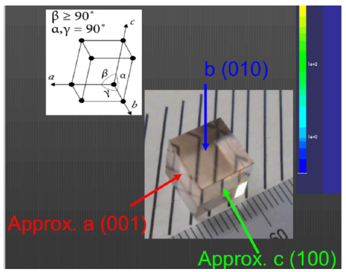




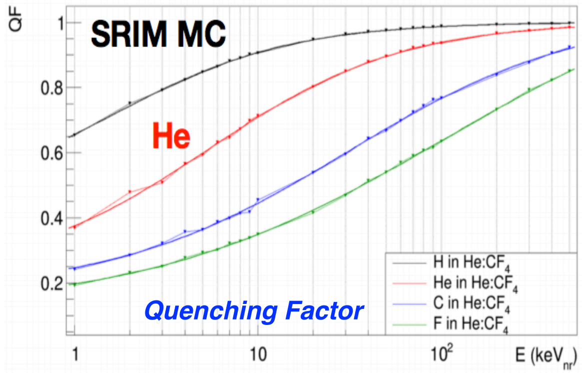
NEWS-DM (emulsions)



Anisotropic crystals

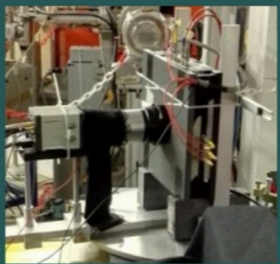
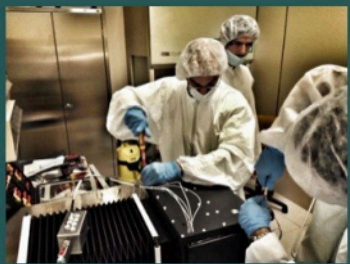
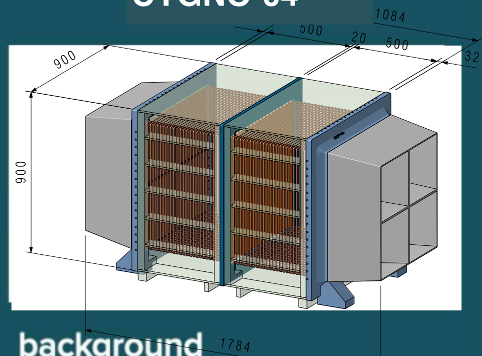
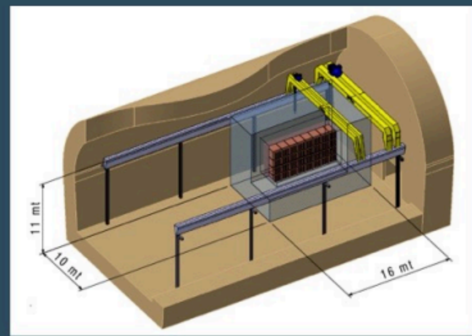


JCAP 1701 (2017) no.01, 027



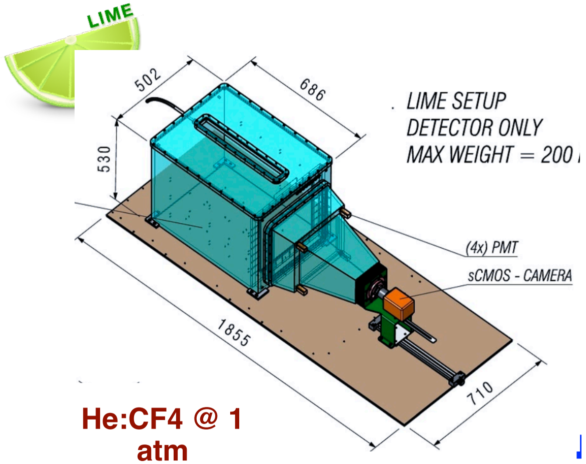
The CYGNO experiment

Timeline & Detectors

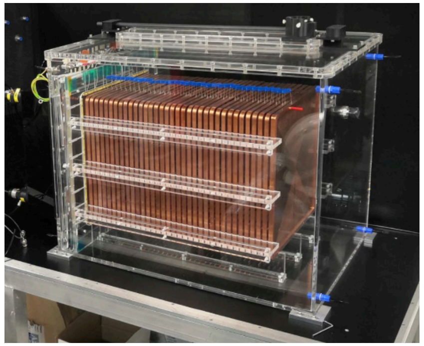
PHASE 0: R&D and prototypes			PHASE 1: O(1) m³ Demonstrator	PHASE 2: 30 m³ Experiment
2015/16 ROMA1	2017/18 LNF	2019/22 LNF/LNGS	2023/26 LNF/LNGS	2026.. LNGS
ORANGE	LEMON	LIME	CYGNO-04	CYGNO_30
				
- 1 cm drift	- 3D printing - 20 cm drift	- 50 cm drift - underground tests - MC validation	- background - materials test, gas purification - scalability	- Physics research

0.0001 m³ **0.01 m³** **0.05 m³** **0.4 m³** **30 m³ ?**

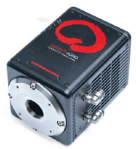
LIME: the Long Imaging ModulE



He:CF4 @ 1 atm

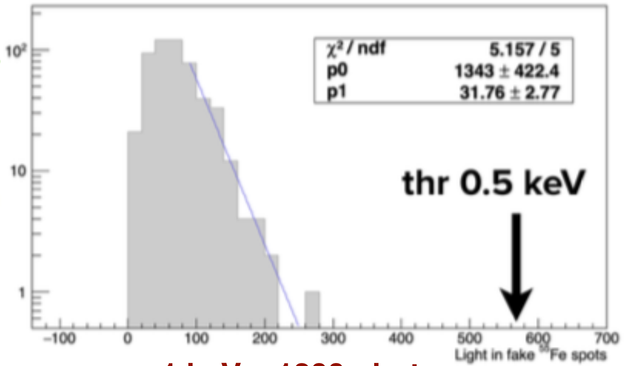


sCMOS + 4 PMT + 3 GEMs
33 x 33 cm² area
50 cm drift, 50 L active volume
Base module of PHASE 1 design



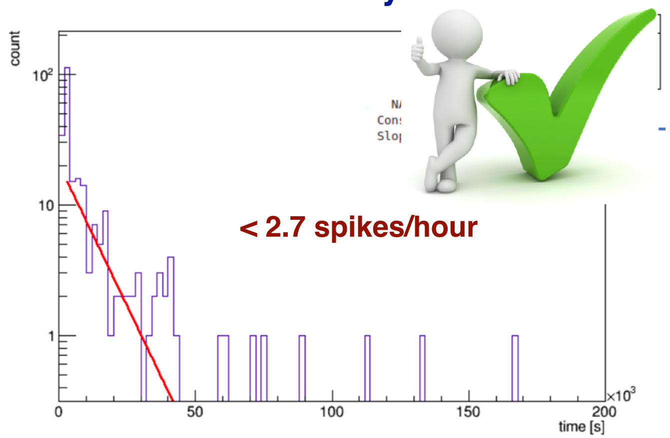
ORCA-Fusion

sCMOS fake clusters threshold



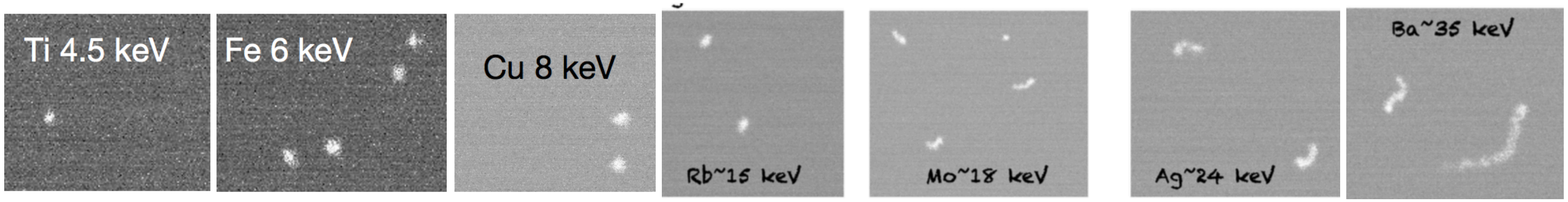
1 keV = 1200 photons

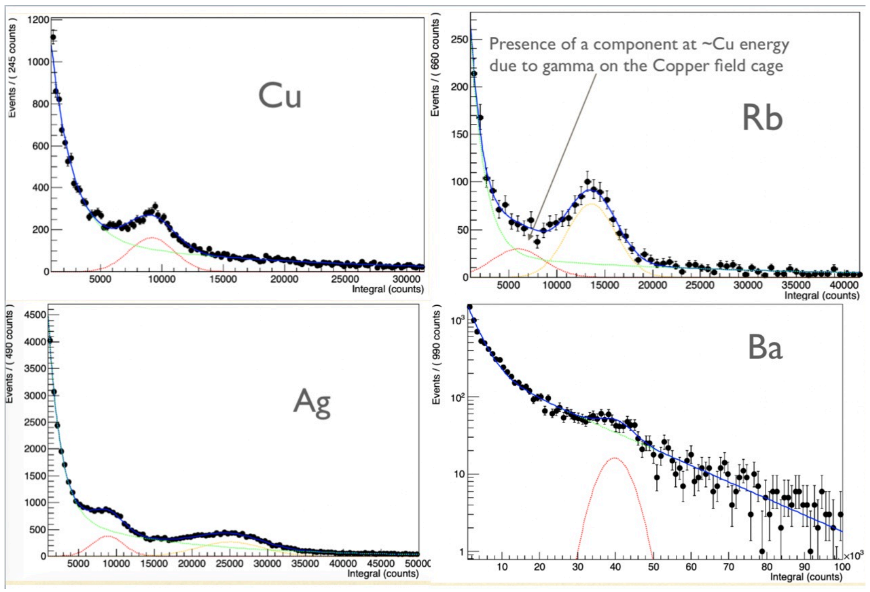
Stability

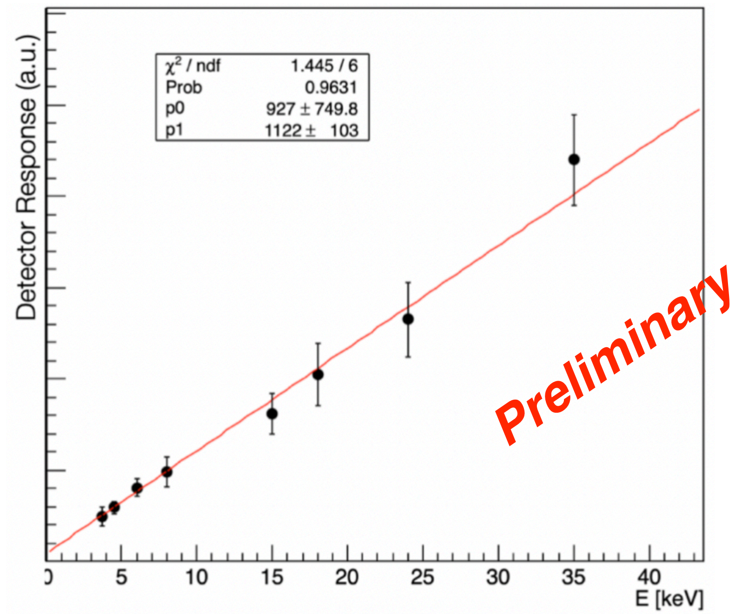


- 1.498 x 1.498 cm² sensor
- 6.5 x 6.5 um² pixels
- 2304 x 2304 pixels
- Schneider lens, 25 mm FL, f/0.95
- Imaging 36 x 36 cm² area
- Effective pixel granularity 160 x 160 um²
- Sensor geometrical acceptance Ω =1.1 x 10^{-4}

Energy threshold and energy response



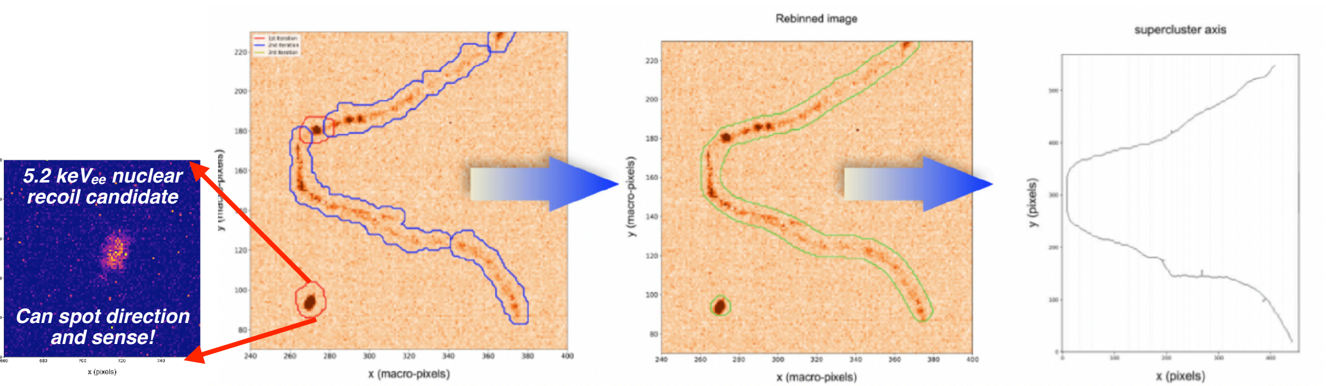




- Very good energy response linearity between 3.5 and 35 keV
- About 13% energy resolution (σ) along the whole volume

Nuclear recoil efficiency reconstruction & background discrimination

JINST 15 (2020) 12, T12003

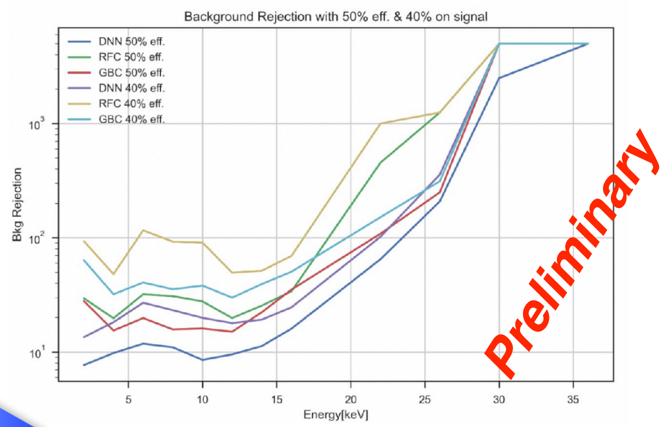


Multiple DBSCAN iteration to select different ionisation patterns

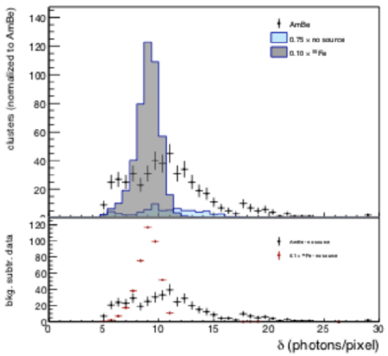
Morphological geodesic active contours (GAC) to connect long tracks

Iterative morphological thinning for actual track length

On going work on ML techniques



A. Prajapati PhD Thesis



energy deposit density

40% nuclear recoil efficiency for energies < 20 keV$_{ee}$, with 99% ^{55}Fe events rejected @ 5.9 keV

Signal efficiency			Background efficiency		
ε_S^{presel}	ε_S^{δ}	ε_S^{total}	ε_B^{presel}	ε_B^{δ}	ε_B^{total}
0.98	0.51	0.50	0.70	0.050	0.035
0.98	0.41	0.40	0.70	0.012	0.008

Measur.Sci.Tech. 32 (2021) 2, 025902

Models	Signal Efficiency $[\epsilon^S]$%	Bkg. Rej. Efficiency $[1-\epsilon^B]$%
RFC	40	99.1
	50	97.5
GBC	40	98.3
	50	96.5
DNN	40	96.6
	50	93.5

For the full 1-35 keV energy range

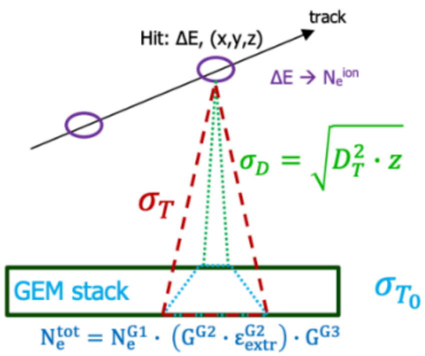
MC simulation & data/MC agreement

- Electron tracks generated with GEANT4, nuclear tracks with SRIM
- Quenching factor from SRIM, soon to be experimentally measured
- # of primary ionisation electrons Poisson distribution with mean $N_e = \Delta E / W_i$ with $W_i = 46.2$ eV/pair
- Primary ionisation electron diffused longitudinally and transversally with $\sigma_T = \mathrm{sqrt}(\sigma^2_0 + D^2_T\, z)$ with σ_0 & D_T from measurements
- Electron avalanche fluctuation taken into account for the first GEM foil, with an effective gain to reproduce gain dependence on the charge density as observed in data

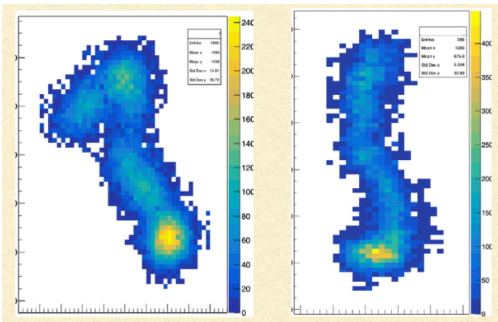
$$G = A\frac{g}{1 + n\beta(g-1)}$$

- Gain parameters extensively optimised on data
- Mean total number of photon N^{tot}_{γ} from Poisson distribution with mean $N^{mean}_{\gamma} = 0.07$ γ/e
- Number of photon hitting the sensor $N_{\gamma} = N^{tot}_{\gamma} \cdot \Omega$
- sCMOS sensor noise from real data

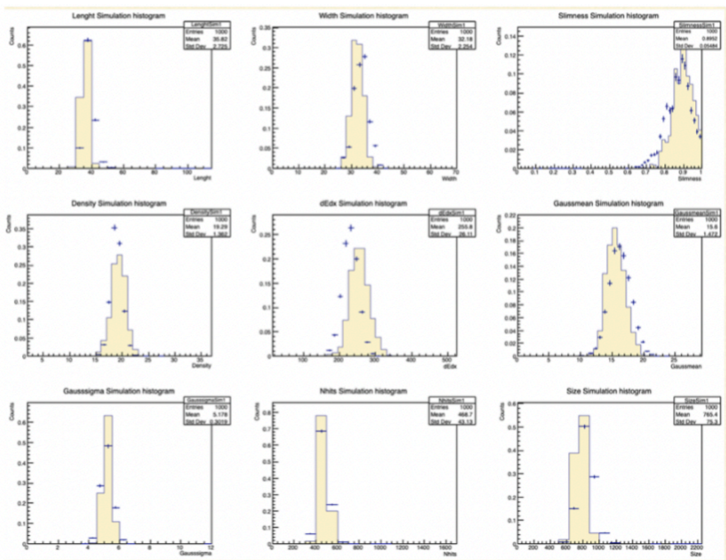
$$\Omega = \frac{1}{(4(1/\delta + 1) \times a)^2} \qquad \delta = \frac{f}{d - f}$$

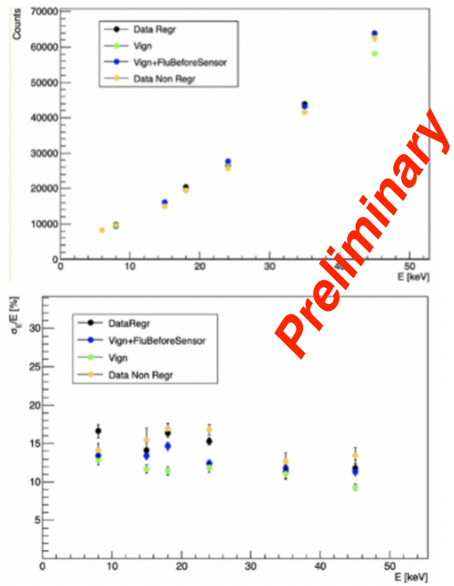


30 keV electron

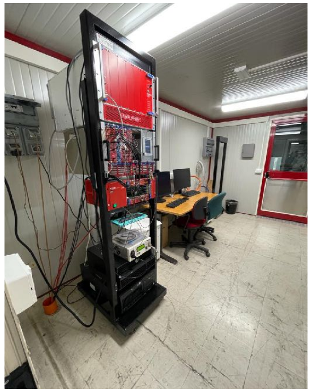


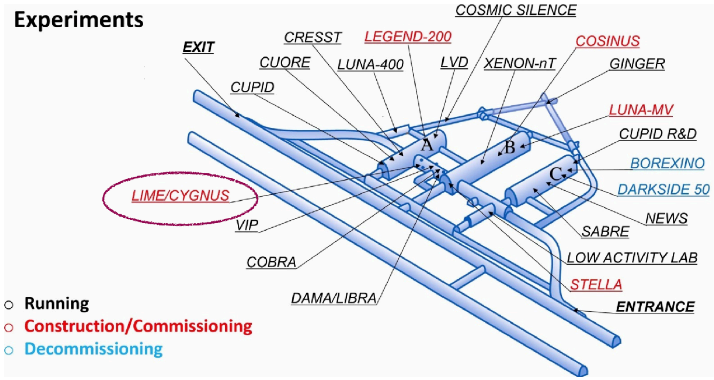
Simulation   Data



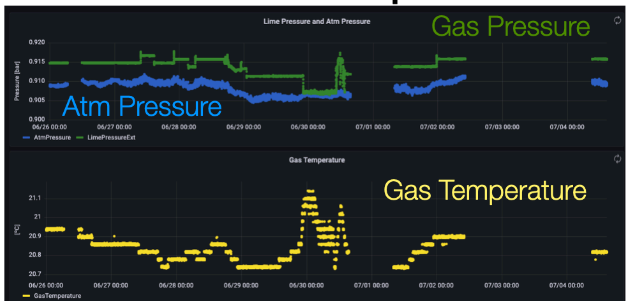


LIME at underground Laboratori Nazionali del Gran Sasso

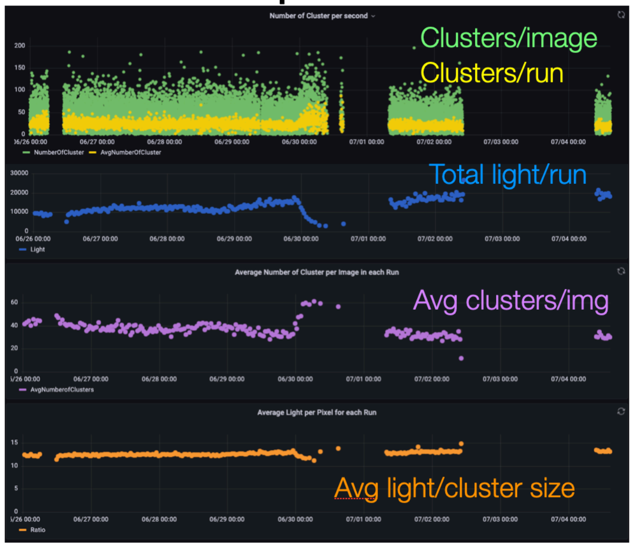




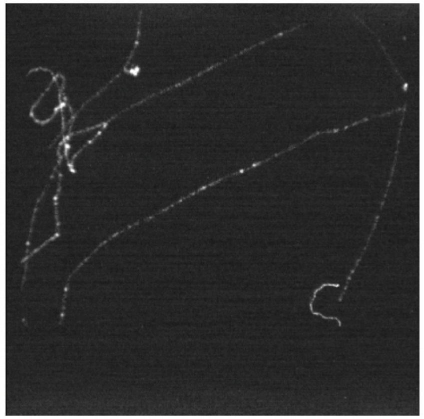
Gas and environmental parameters



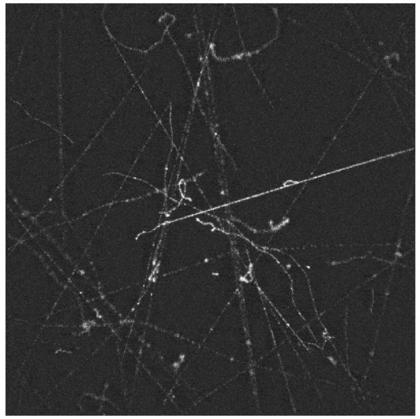
Detector performance



Underground reduction of CR as expected

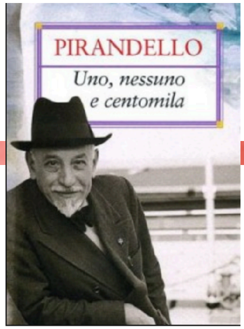


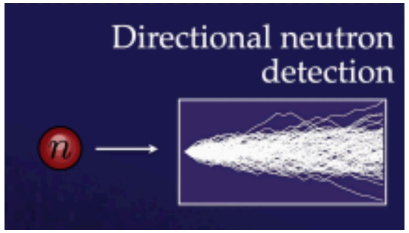
LNGS

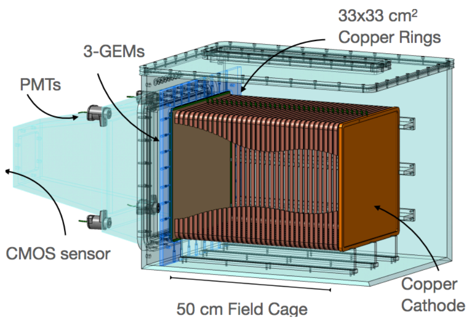


LNF

One, no one and one hundred thousand optical imaging TPC applications





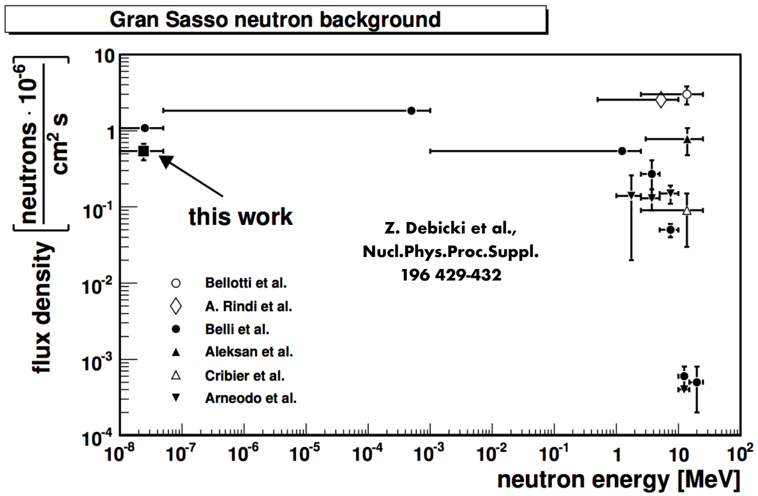


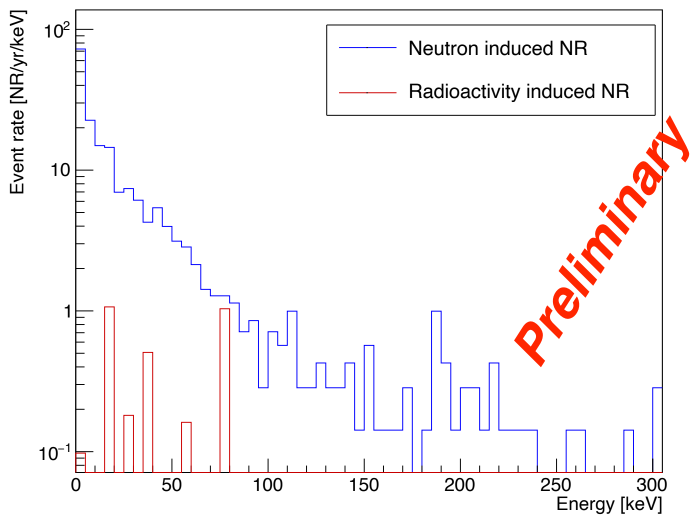
Medium O(50) L

LIME as a directional fast and thermal neutrons detector

Prin 2017

This project has been funded by the Italian Ministry of Education, University and Research through the project PRIN: Progetti di Ricerca di Rilevante Interesse Nazionale "Zero radioactivity in future experiment" (Prot. 2017T54J9J)





F. Di Giambattista PhD Thesis

+ 0.5% ^{3}He

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

With 0.5% of ^{3}He, same rate of fast and thermal neutrons in LIME

Nitrogen as target

$^{14}N + n \rightarrow {}^{14}C + p + 625$ keV, $\sigma_{th} = 1.83$ b

$^{14}N + n \rightarrow {}^{11}B + \alpha - 159$ keV, thres=1.7 MeV

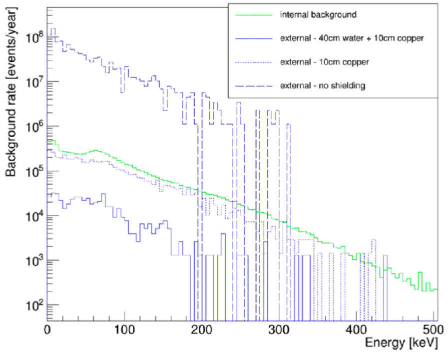
Test the use of N as alternative thermal neutron capture agent (from I. Manthos talk @ ICHEP 2022)

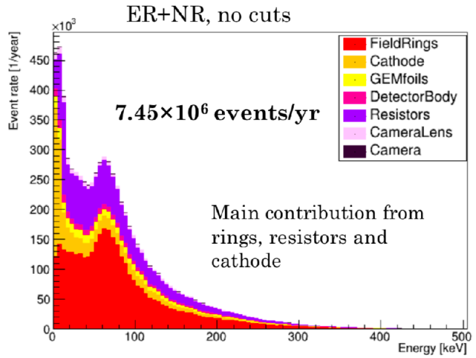
	Energy range	ER+NR rate [events/year]	NR rate [events/year]
10 cm copper 	1-20 keV	8.86(1)×10^5 + 1.383(7)×10^5*	447.2(6)
	1-50 keV	2.024(2)×10^6 + 2.95(1)×10^5*	638.2(7)
	total	4.810(3)×10^6 + 5.41(1)×10^5*	1089(1)

LIME underground goals & program

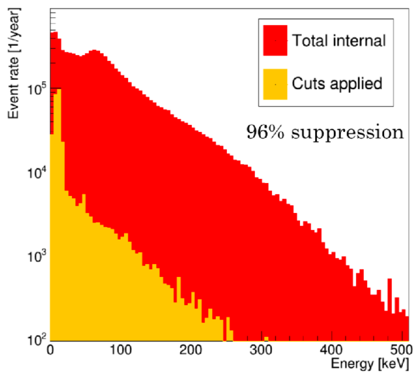
- **Unshielded:**
  - Detector characterisation with ^{55}Fe and AmBe sources
  - External background study with periodic ^{55}Fe calibrations
- **6 cm Cu shield**
  - External background study with periodic ^{55}Fe calibrations
- **10 cm Cu shield**
  - Background study with periodic ^{55}Fe calibrations
  - Spectral measurement of underground neutron flux. About 300 NR events from neutron interaction expected in 4 months
- **10 cm Cu + 40 cm H_2O**
  - Study of internal backgrounds and validation of MC simulation. Expect to suppress all external neutral background and reduce external gamma background to the same level of internal one.

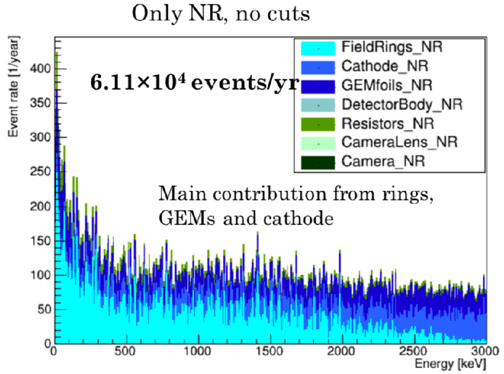
Shielding	Internal [ev/yr] (1-20 keV)	External* [ev/yr] (1-20 keV)
No shield	$1.5344(7)\times10^6$	$4.061(8)\times10^8$
5cm copper	$1.5344(7)\times10^6$	$1.90(2)\times10^7$
10cm copper	$1.5344(7)\times10^6$	$1.024(2)\times10^6$
40cm water + 10cm copper	$1.5344(7)\times10^6$	$2.46(1)\times10^5$



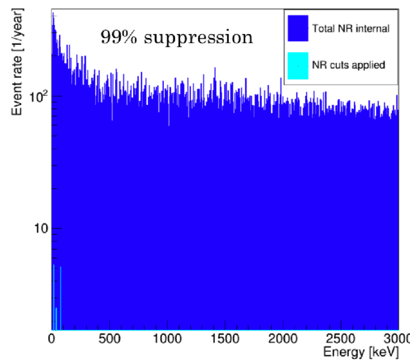


ER + NR after fiducial cuts





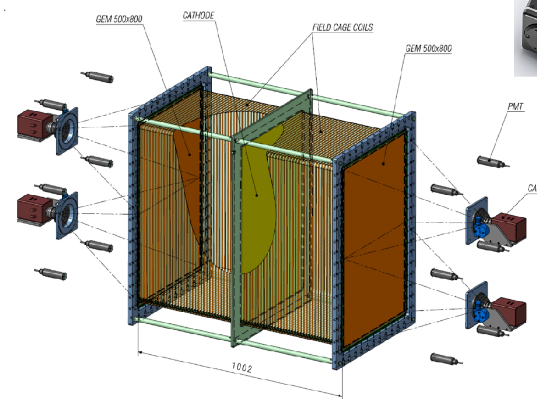
NR only after fiducial cuts



Fiducial cuts have 83% efficiency on nuclear recoils coming from the environmental flux (or Dark Matter…)

CYGNO PHASE 1 demonstrator: CYGNO-04

ORCA QUEST

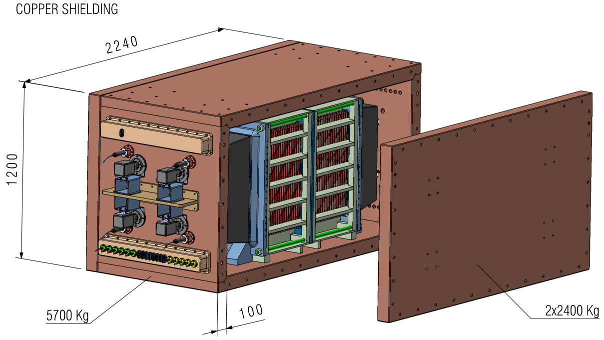


(2 sCMOS + 6 PMT + 3 GEMs) x 2
(50 x 80 cm^2 area) x 2
central cathode
0.4 m^3 active volume

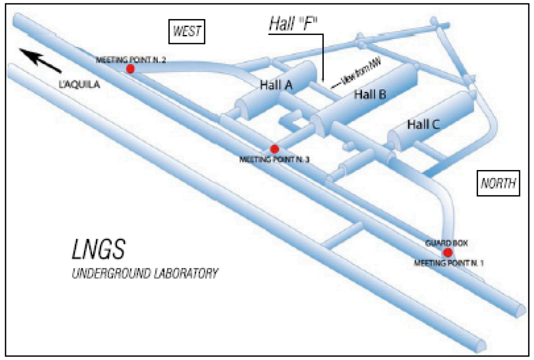
Reduction of **internal background**:

- use of **radio-pure** PMMA for **vessel**;
- **DRIFT**-like **field cage**: copper strips on plastic sheet;
- **DRIFT**-like **cathode**: **0.9 µm** thick **aluminum** foil in shared between 2 TPC, to **remove** events in **coincidence**;
- **low** radioactive **optical** systems;

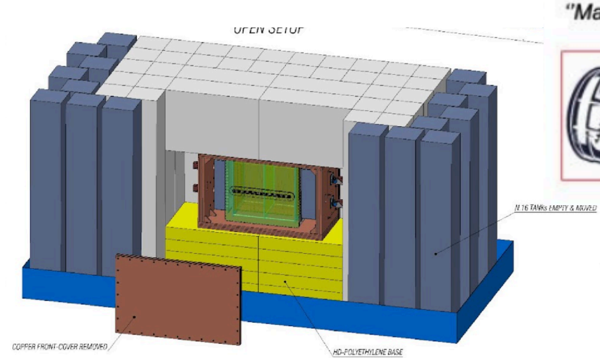
A CYGNO in a bottle



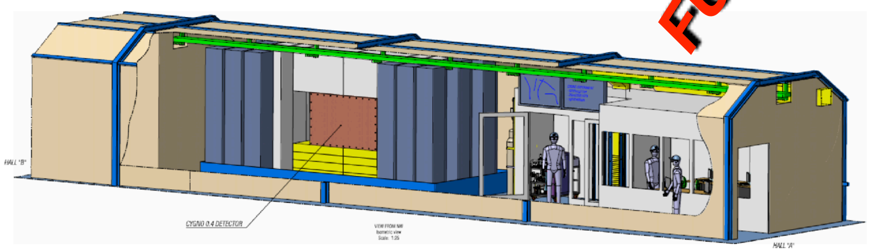
Preliminary shielding configuration:
110 cm H_2O + 10 cm Cu
Optimization ongoing

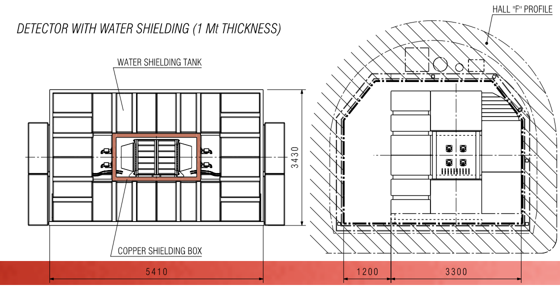


Keep in consideration that due to the narrow hallway (1.2mt) we have to work like a: "Make a ship in a bottle"



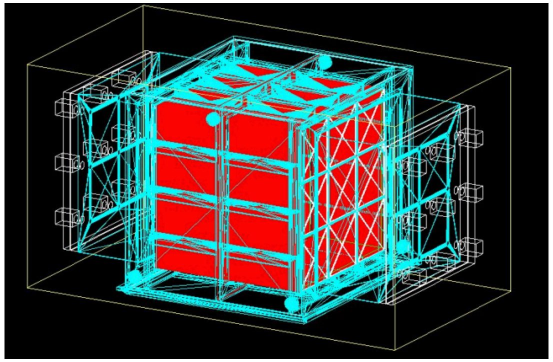
FUNDED!





CYGNO-04 expected backgrounds

Full background simulation study done for 1 m³ detector

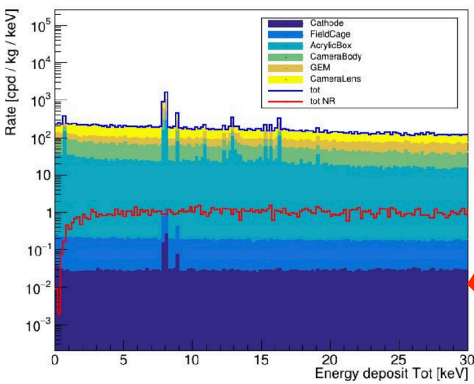


Preliminary CYGNO_04 background evaluation through scaling (full background simulation ongoing)

- For external background
  - flux entering the shielding for CYGNO_04 option (110 cm water + 10 cm Cu)
  - energy deposits in the CYGNO gas 1 m^3
  - number of events is scaled by 0.44 (sensitive volume factor)
- For internal background
  - assign material radioactivity and calculate background for CYGNO 1 m^3
  - scaling for less material (approximately 0.44 factor)
  - scaling for sensitive volume factor 0.44

Internal ER background

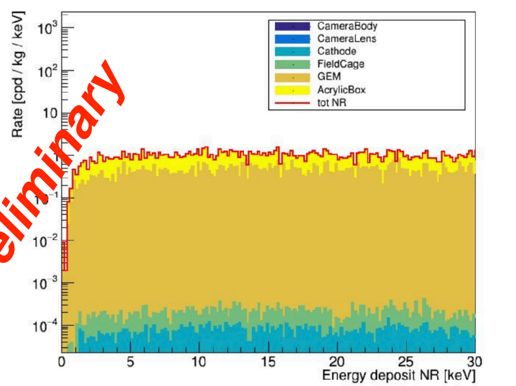
- **CYGNO: ER rate [1-20] keV = 2.3x10^6 cts/yr**
- **CYGNO_04: ER rate [1-20] keV = 4.9x10^5 cts/yr**



Internal ER background

Internal NR background

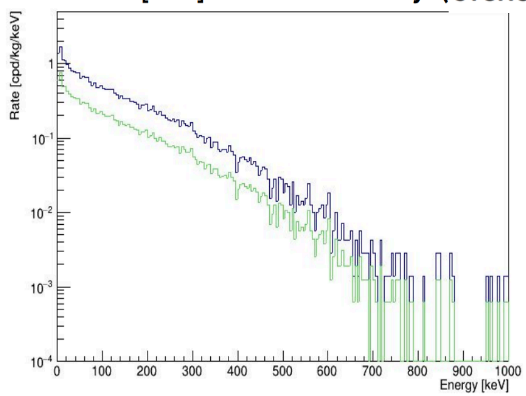
- **CYGNO: NR rate [1-20] keV = 1.1x10^4 cts/yr**
- **CYGNO_04: NR rate [1-20] keV = 2.6x10^3 cts/y**



Internal NR background

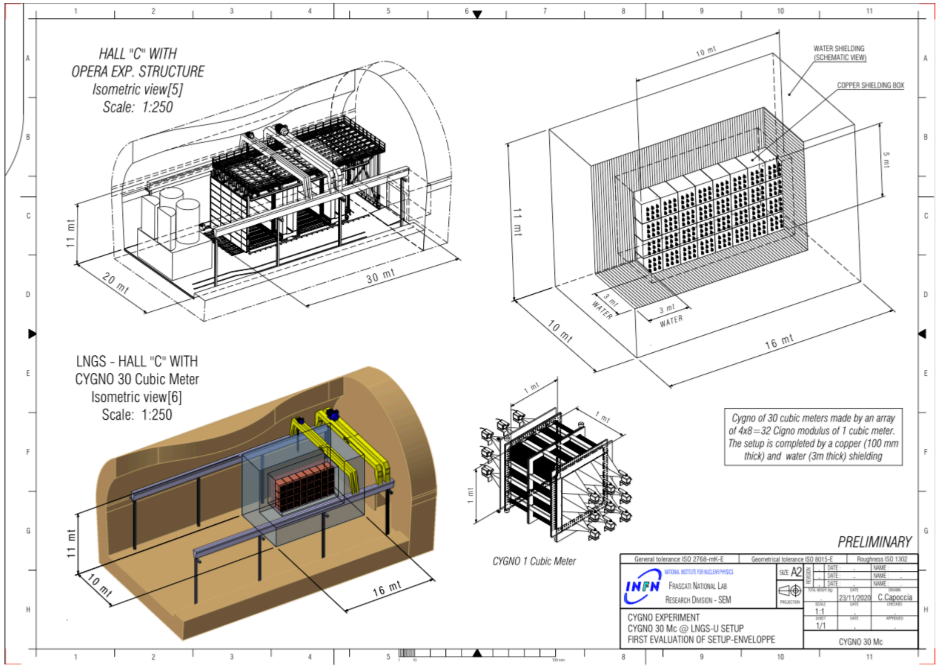
Total external background

- **Rate [1-20] keV = 1.4x10^4 cts/yr (CYGNO)**
- **Rate [1-20] keV = 6.4x10^3 cts/yr (CYGNO_04)**

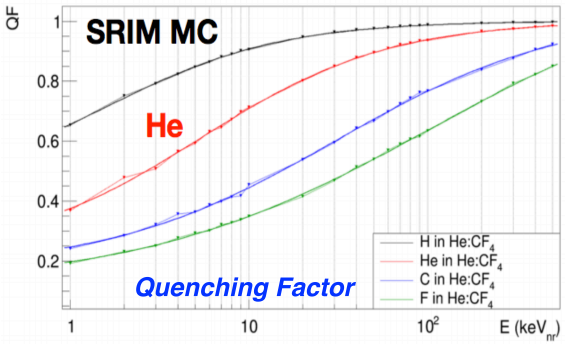


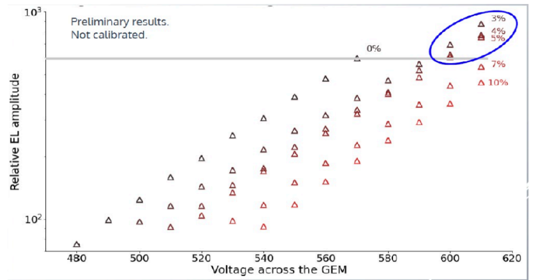
Total external background

CYGNO realistic dream: a O(30) m³ experiment

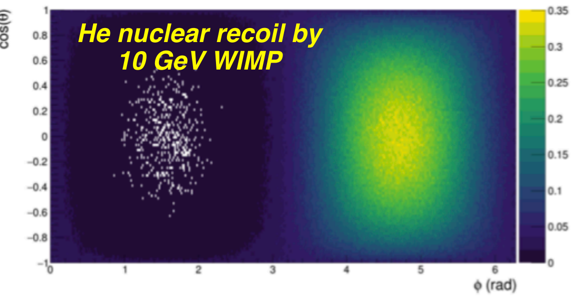


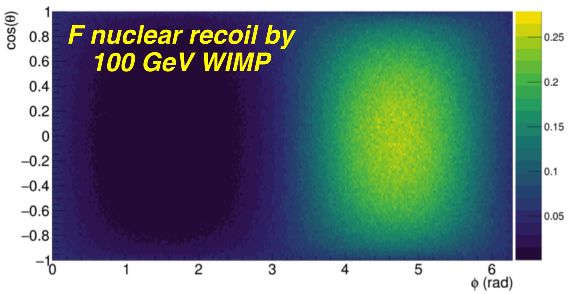
	Minimum detectable DM mass for 0.5 keV_{ee} energy threshold	Minimum detectable DM mass for 1 keV_{ee} energy threshold
H	300 MeV/c²	500 MeV/c²
He	700 MeV/c²	1 GeV/c²
C	1.4 GeV/c²	1.9 GeV/c²
F	1.9 GeV/c²	2.5 GeV/c²



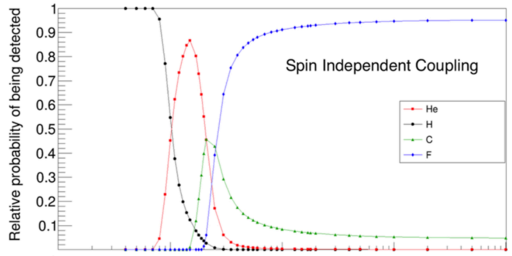


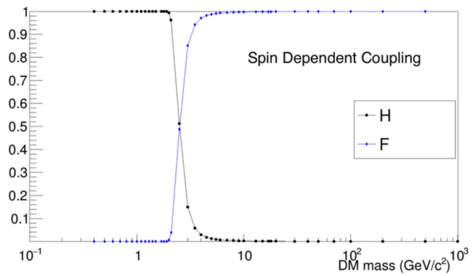
Tests with Hydrogen target ongoing to improve sensitivity at low < 1 GeV WIMP masses





Examples of expected WIMP measured angular distribution in Galactic coordinates

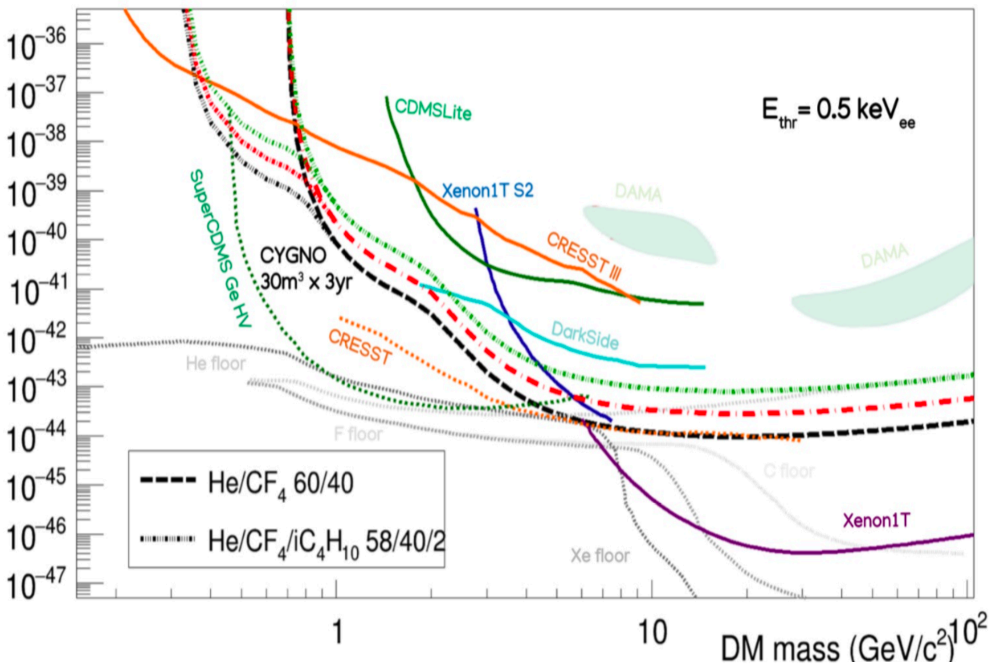




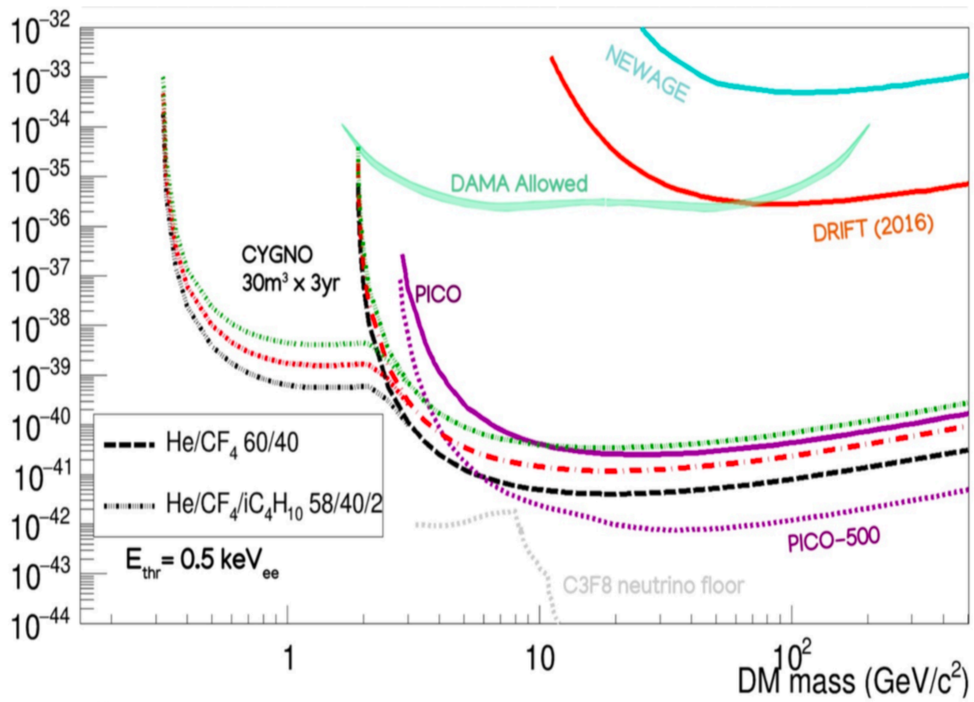
Target nuclei relative probability of being detected for 1 keV_{ee} energy threshold

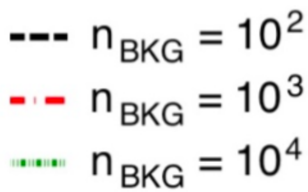
CYGNO 30 m³ preliminary sensitivity studies

Spin Independent

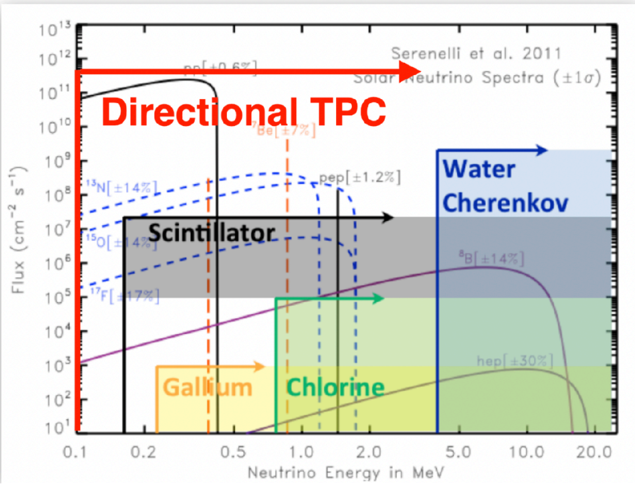


Spin Dependent

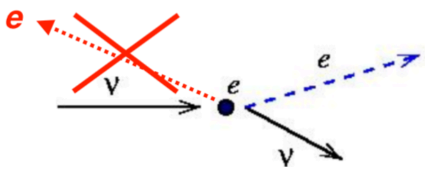




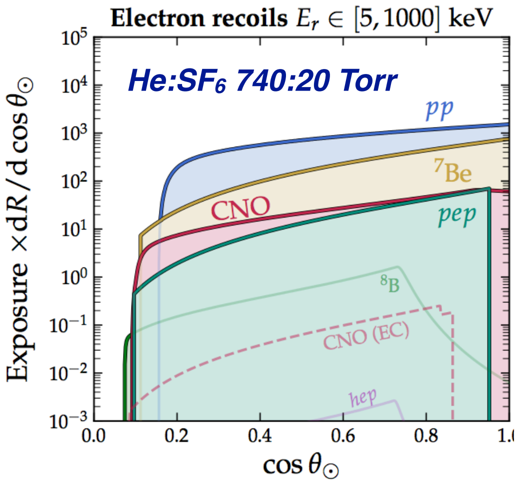
CYGNO 30 m³ as solar neutrino detector

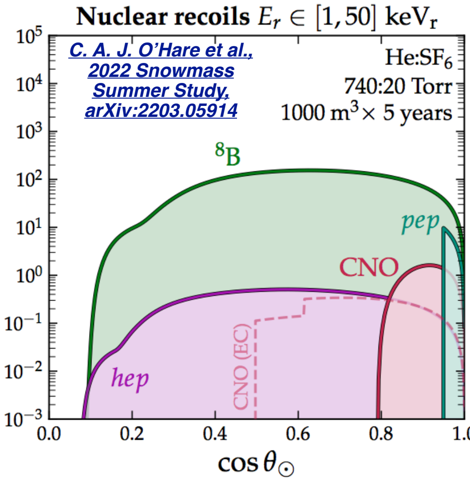


Given the Sun position, recoils in opposite direction are kinematically forbidden

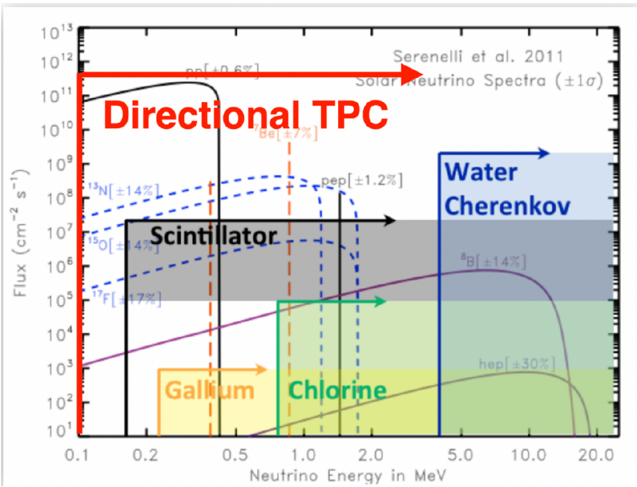


Differently from WIMPs, background can be __measured__ on sidebands data

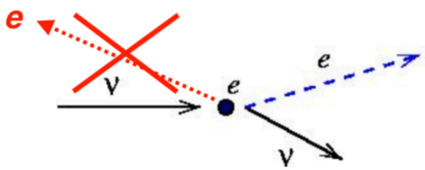




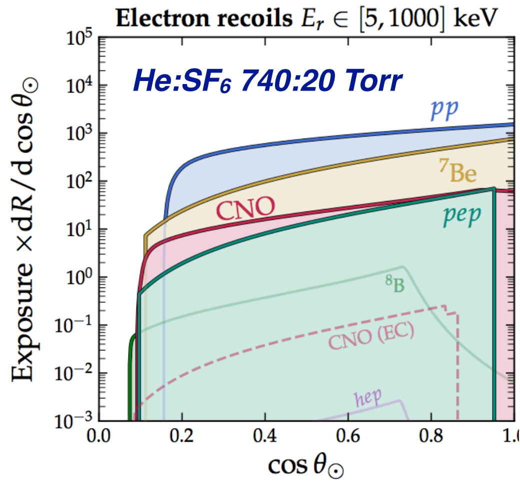
CYGNO 30 m³ as solar neutrino detector

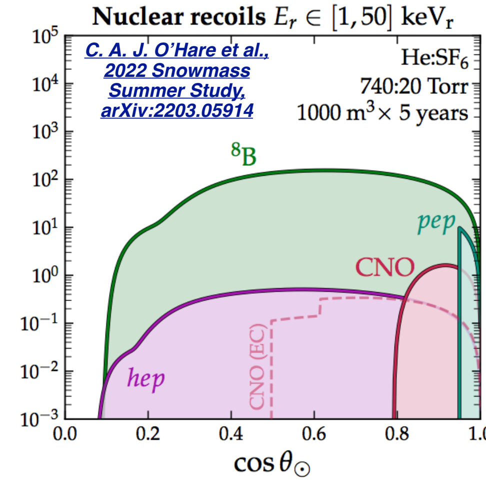


Given the Sun position, recoils in opposite direction are kinematically forbidden



Differently from WIMPs, background can be measured on sidebands data

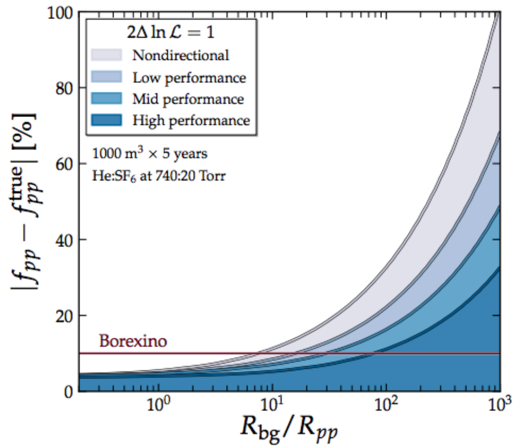




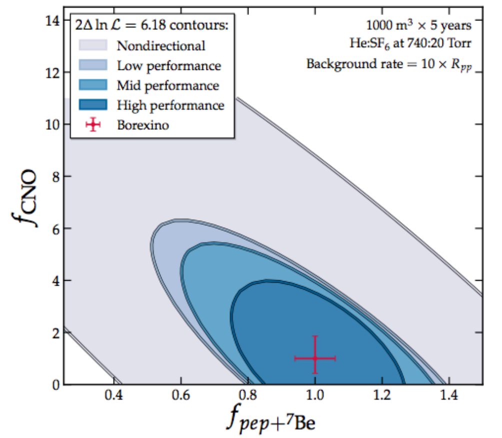
- ***Electron recoils directionality enables solar neutrino spectroscopy through neutrino-electron elastic scattering on an event-by-event basis***
  - **An O(10) m³ ER directional detector could extend Borexino pp measurement to lower energy**
  - **A O(1) ton could measure the CNO cycle by breaking the degeneracy with pep + ⁷Be fluxes through directionality**

For 1 m³ of He:CF₄ 60:40 with 20 keV threshold

$$R = N_e \cdot \int_{E_{min}}^{E_{max}} w(E)\varphi_{ppI}(E)\sigma(E)dE \qquad R = 2.9 \cdot 10^{-8}\,\frac{events}{s \cdot m^3} = 0.9\,\frac{events}{y \cdot m^3}$$



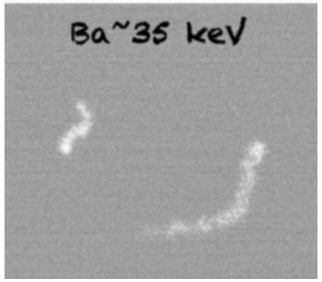
1 σ sensitivity to pp flux as a function of the total non-neutrino ER background



2 σ sensitivity to combined measurement of the CNO and pep + ⁷Be pp fluxes, fixing the background rate to 10 times the pp electron recoil rate

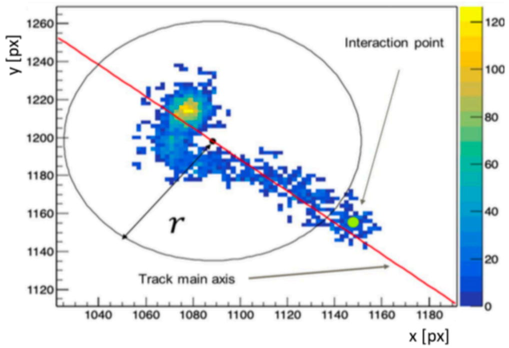
Low energy electrons directionality: not trivial

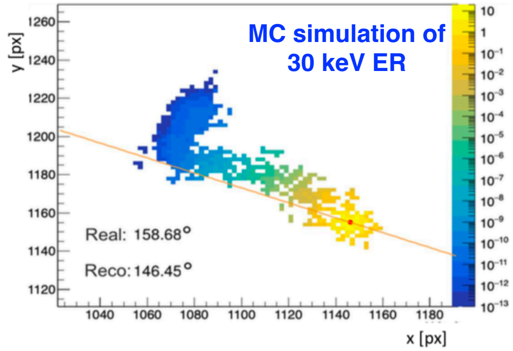
Evaluated on CYGNO simulated sCMOS images as expected in LIME (50 L volume)



S. Torelli PhD Thesis

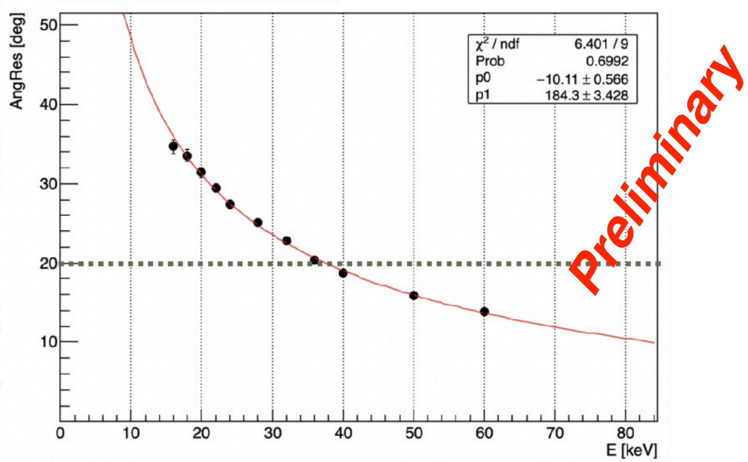
X-ray data in LIME: low energy ERs suffer large multiple scattering and have low dE/dX at the beginning of the track:
not trivial to measure the initial ER direction





- First part of the algorithm: search for the beginning of the track with:
  - Skewness
  - Distance of pixels from barycenter (farthest pixels)
- Second part of the algorithm aims to find the direction:
  - Track point intensity rescalad with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the the main axis of the rescaled track passing from the interaction Point
  - Orientation given following the light in the Pixels
- Algorithm adapted from X-ray polarimetry:

"Measurement of the position resolution of the Gas Pixel Detector"
Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105



Fit expectation for 70 keV ER compatible with prediction from previous slide and in the "Mid-perfornance" range

G S
S I

Getting bigger and bigger

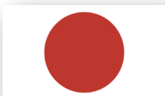
INFN
Istituto Nazionale di Fisica Nucleare

The CYGNUS project

The CYGNUS proto-collaboration

- About 70 members
- Steering group:
  - Elisabetta Baracchini (GSSI/INFN, Italy)
  - Greg Lane (Canberra, Australia)
  - Kentaro Miuchi (Kobe, Japan)
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)




A multi-site, multi-target Galactic Nuclear and Electron Recoil Observatory at the ton-scale to probe Dark Matter below the Neutrino Floor and measure solar Neutrinos <u>with directionality</u>

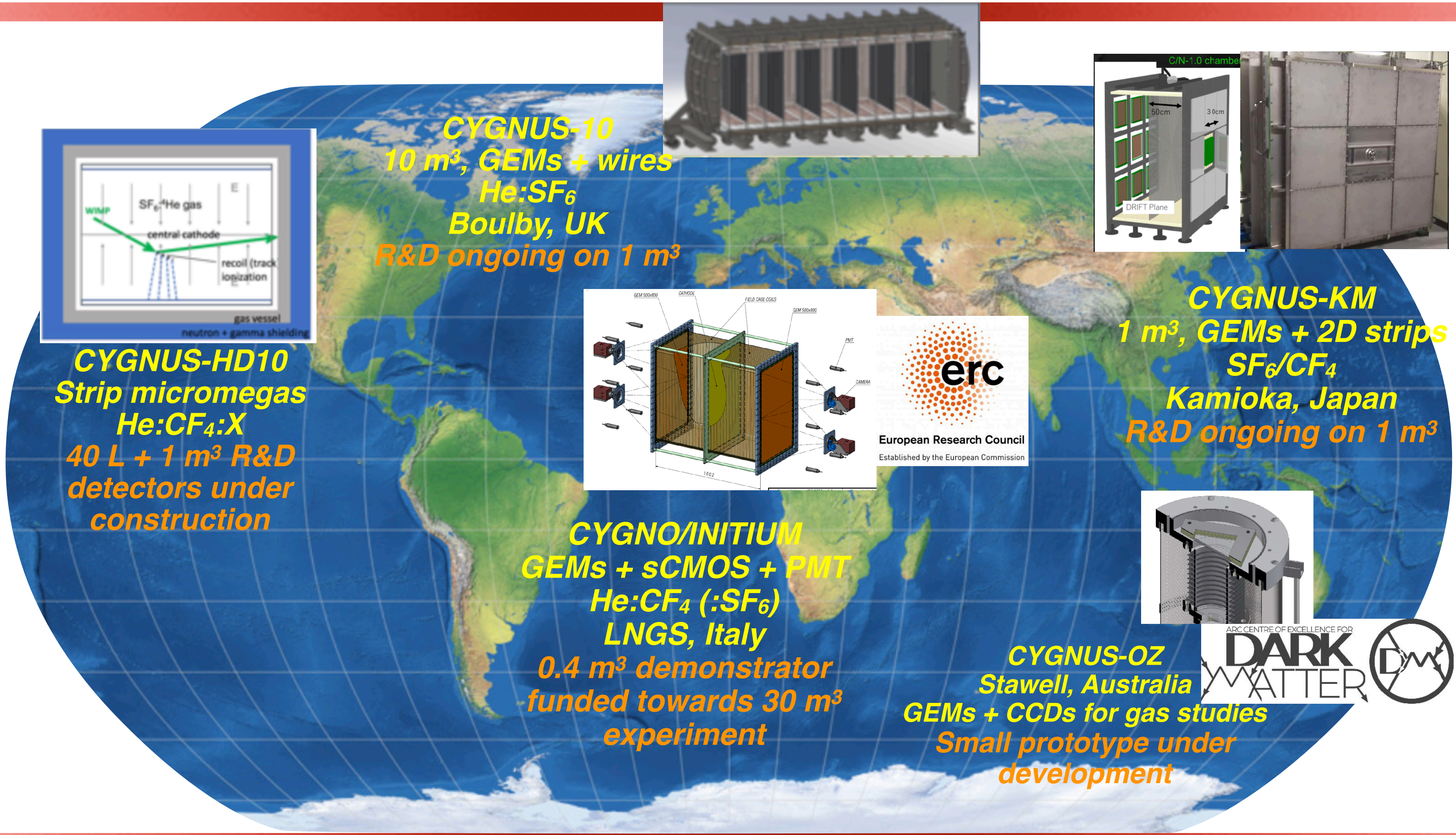
CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

S. E. Vahsen,[1] C. A. J. O'Hare,[2] W. A. Lynch,[3] N. J. C. Spooner,[3] E. Baracchini,[4,5,6] P. Barbeau,[7] J. B. R. Battat,[8] B. Crow,[1] C. Deaconu,[9] C. Eldridge,[3] A. C. Ezeribe,[3] M. Ghrear,[1] D. Loomba,[10] K. J. Mack,[11] K. Miuchi,[12] F. M. Mouton,[3] N. S. Phan,[13] K. Scholberg,[7] and T. N. Thorpe[1,6]

arXiv:2008.12587

- **Helium/Fluorine gas mixtures at 1 bar**
  - **Sensitivity to O(GeV) WIMP for both SI & SD couplings**
  - **Possibility of switching between higher (search mode) and lower gas densities (improved directionality) for signal confirmation**
- **Reduced diffusion**
  - **Through negative ion drift or "cold" gases (CF_4)**
- **3D fiducialization**
  - **Through minority carriers or fit to diffusion**
- **Directional threshold at O(keV)**
- **Full background rejection at O(keV)**
- **Both electronic and optical charge readout investigated**

CYGNUS multi-site network



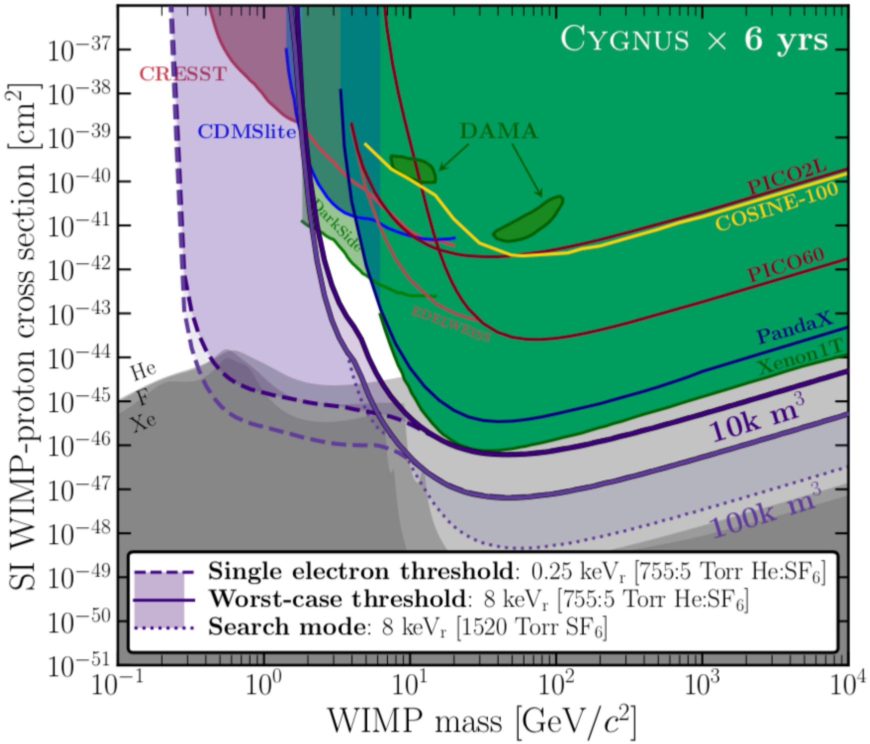
CYGNUS R&D landscape

	Established readout & directionality	Established gas	R&D readout	R&D gas	Largest detector realised	Detector under development
DRIFT	MWPC 1.5 D	$CS_2:CF_4:O_2$ @ 0.05 bar	THGEM + wire/ micromegas	$SF_6:(CF_4)$ @ 0.05 bar	1 m^3 (underground)	10 m^3 (under study)
NEWAGE	GEM + muPIC 3D	CF_4 @ 0.1 bar	GEM + muPIC	SF_6 @ 0.03 bar	0.04 m^3 (underground)	1 m^3 (vessel funded)
D^3/CYGNUS-HD	2 GEMs + pixels 3D	$Ar/He:CO_2$ @ 1 bar	Strip micromegas	$He:CF_4:X$ @ 1 bar	0.0003 m^3	0.04 m^3 (under construction)
New Mexico	THGEM + CCD 2D	CF_4 @ 0.13 bar	THGEM + CMOS	$CF_4:CS_2/SF_6$ @ 0.13 bar	0.000003 m^3	
CYGNO	3 GEMs + CMOS + PMT 2D + 1 D	$He:CF_4$ @ 1 bar	3 GEMs + CMOS + PMT	$He:CF_4:SF_6$ @ 0.8-1 bar	0.05 m^3 (underground)	0.4 m^3 (under development)
CYGNUS			All of the above	Helium-Fluorine @ 1 bar		1000 m^3

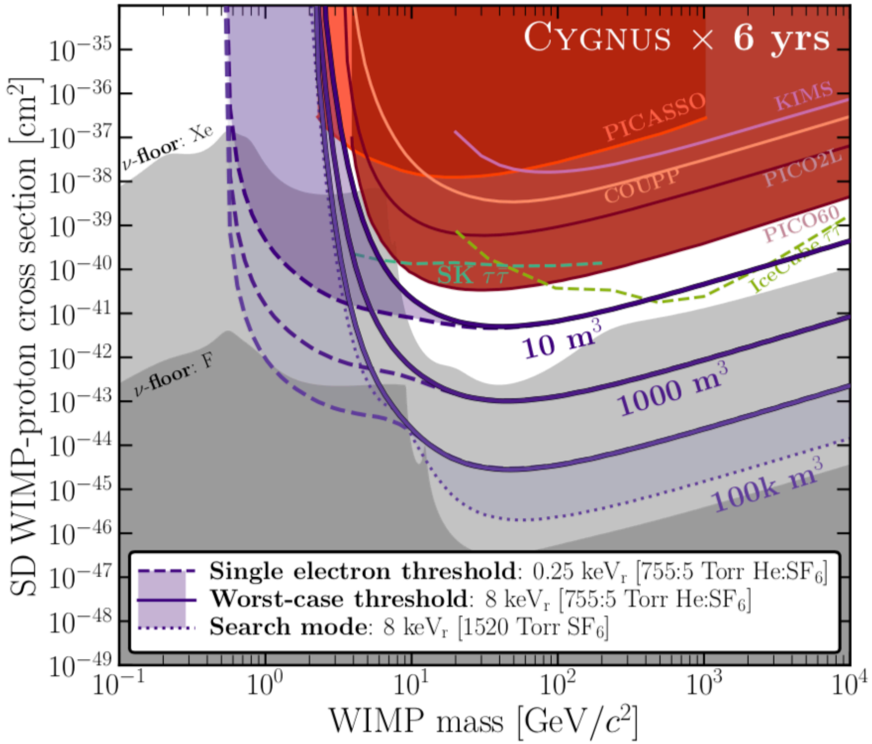
Electron drift ***Negative ion drift*** ***Charge readout*** ***Optical readout***

CYGNUS 1 ton WIMP reach (i.e. nuclear recoils)

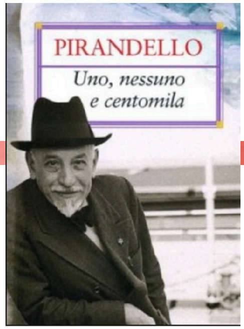
on going work on electron recoil physics cases (i.e. solar neutrino)



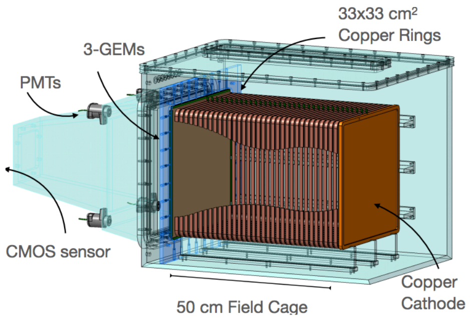
Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events



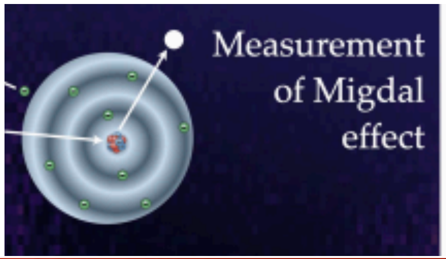
Significant improvement in SD reach over existing experiments for all WIMP masses, a 10 m³ detector can already breach the Xe neutrino floor



One, no one and one hundred thousand optical imaging TPC applications



Medium O(50) L

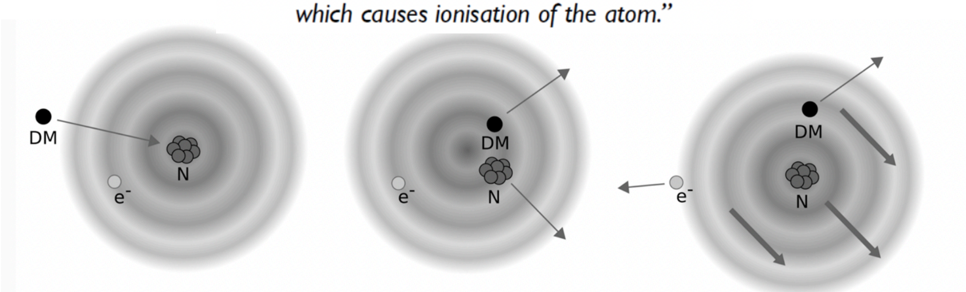


The Migdal effect

or how to lower the WIMP mass reach of DM experiment without modifying your detector

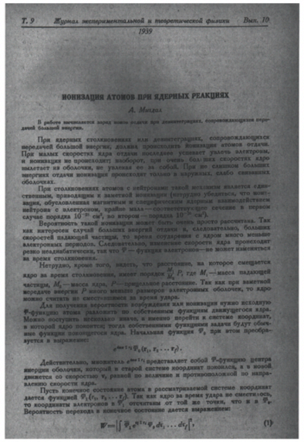
- For sub-GeV dark matter nuclear recoil signals become challenging
  → sensitivity can be lowered by looking for inelastic processes
  [e.g., Essig, Mardon, Volansky – PRD 2012, 1108.5383; Kouvaris, Pradler – PRL 2017, 1607.01789]
- One such process is the Migdal effect

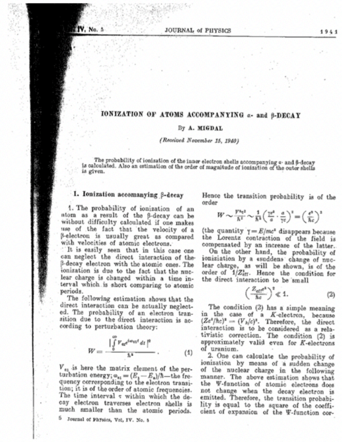
"...it takes some time for the electrons to catch up, which causes ionisation of the atom."



Migdal Effect - nucleus moves relative to the electron cloud. Individual electron might be ejected leading to ionisation.

$$E_R = \frac{\mu_N^2}{2m_N} v_{DM}^2 \left(\left(1-\sqrt{1-\frac{2\Delta E}{\mu_N v_{DM}^2}}\right)^2 + 2(1-\cos\theta_{CM})\sqrt{1-\frac{2\Delta E}{\mu_N v_{DM}^2}} \right)$$




JOURNAL of PHYSICS

IONIZATION OF ATOMS ACCOMPANYING α- and β-DECAY

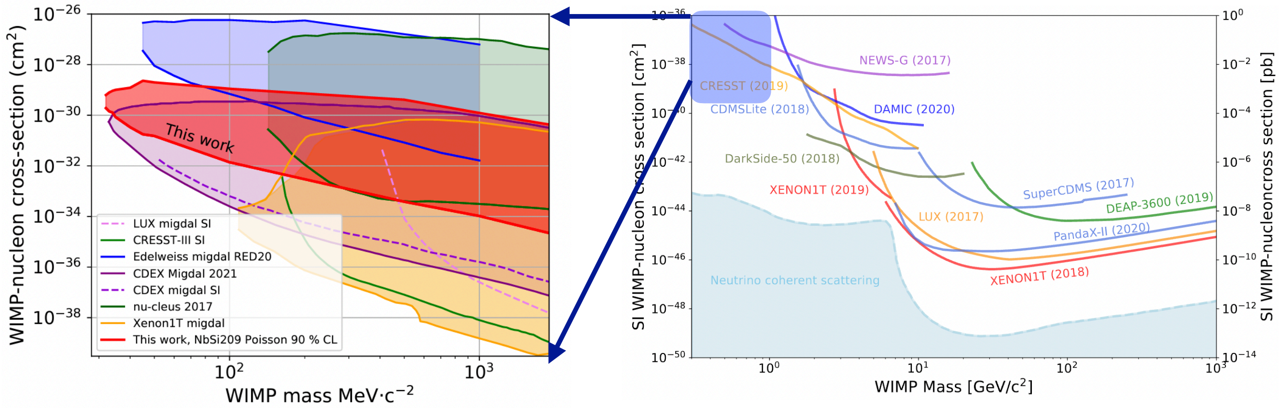
By A. MIGDAL

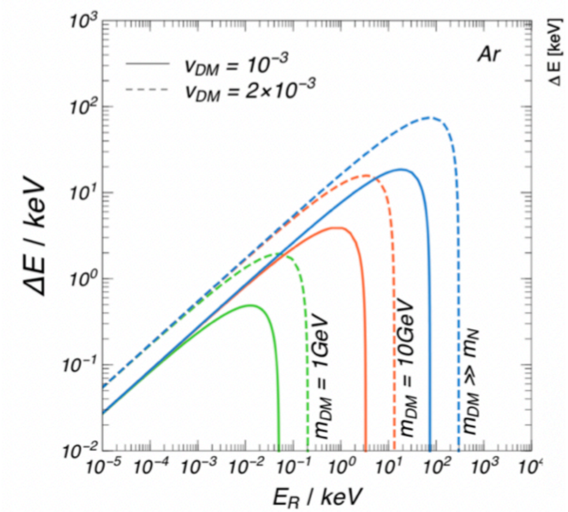
[1] A. Migdal *Ionizatsiya atomov pri yadernykh reaktsiyakh, ZhETF, 9, 1163-1165 (1939)*
[2] A. Migdal *Ionizatsiya atomov pri α- i β- raspade, ZhETF, 11, 207-212 (1941)*

....but never experimentally observed yet!

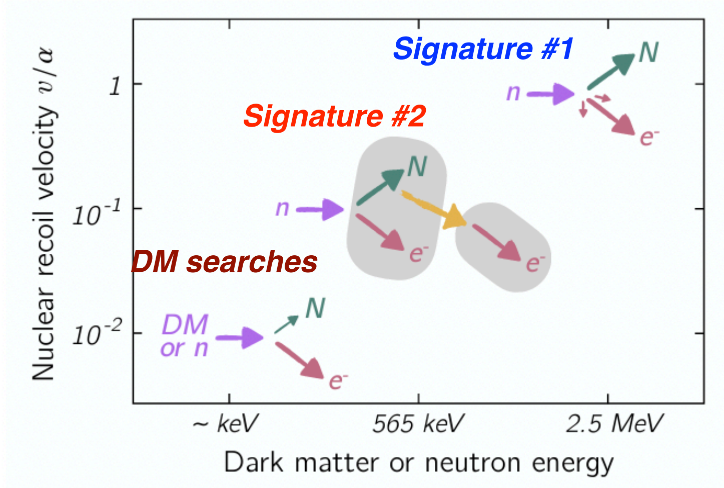
Migdal effect in DM searches

….and yet used by everbody to put contrains on WIMPs!





Kinematically allowed region for NR and ER in a Migdal event with different DM mass hypothesis



Schematic representation of the different regimes for DM and neutron induced Migdal processes

FINEM: Full Imaging of Nuclear recoils for Experimental Migdal measurement

FARE RICERCA IN ITALIA
FRAMEWORK PER L'ATTRAZIONE E IL RAFFORZAMENTO DELLE ECCELLENZE PER LA RICERCA IN ITALIA

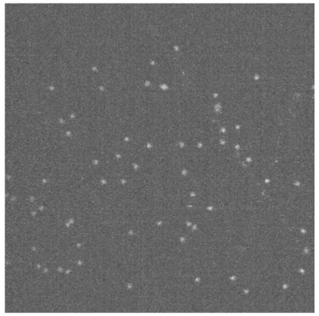
This project has been funded by the Italian Ministry of Education, University and Research through the project FARE: Framework per l'Attrazione e il Rafforzamento delle Eccellenze in Italia "FINEM: Full Imaging of Nuclear recoils for Experimental Migdal measurement" (Prot. R208LP3A4C)

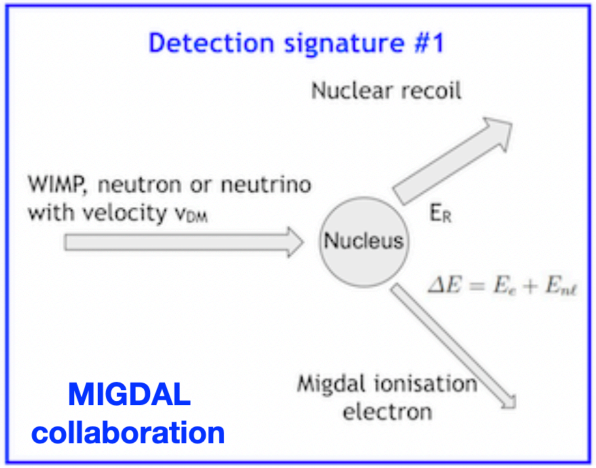
PLEASE NOTE: signature #1 is ALWAYS present (no X-ray needed) but might be difficult to distinguish ER + NR from same vertex

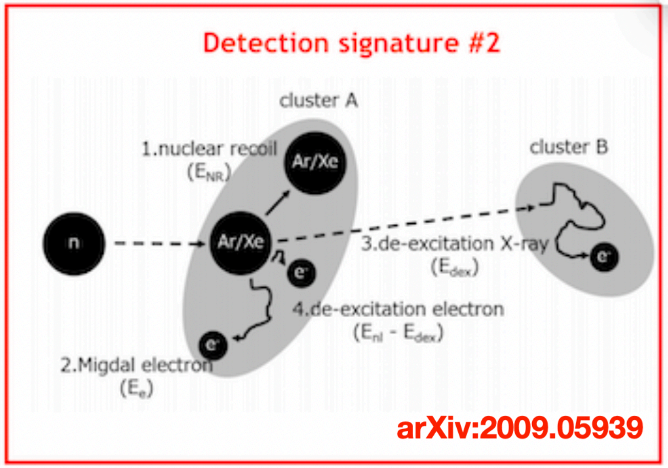
PLEASE NOTE: signature #2 is required for high density mixtures/low granularity readout BUT need an atom that makes X-ray

5.9 keV from ^{55}Fe in LIME

He/CF_4 (60/40)

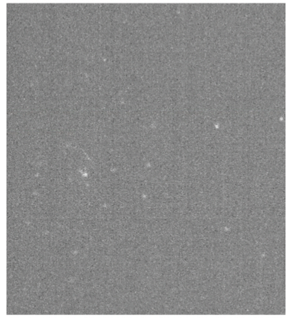


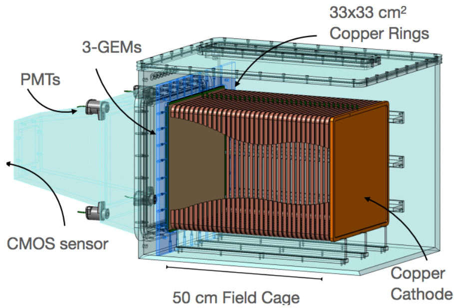




5.9 keV from ^{55}Fe in LIME

Ar/CF_4 (80/20)





FINEM GOAL: measure Migdal effect in He, CF_4 and Ar!

Exploiting signature #1 with $He:CF_4$

Exploiting signature #2 with $Ar:CF_4$

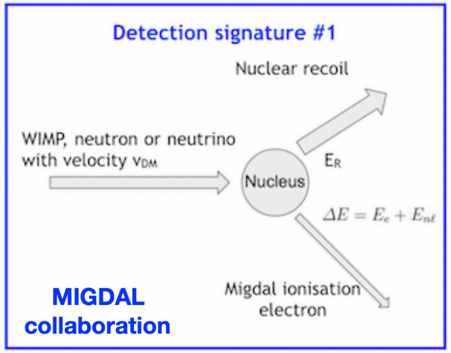
with a LIME-like detector

Preliminary studies towards MIGDAL measurements with FINEM

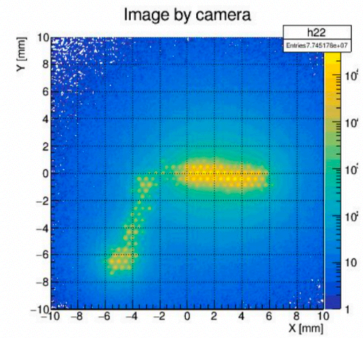
The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter

H.M. Araújo (Imperial Coll., London), S.N. Balashov (Rutherford), F.M. Borg (Imperial Coll., London), J.E. Brunbauer (CERN), C. Cazzaniga (Rutherford) et al. (Jul 17, 2022)

e-Print: 2207.08284 [hep-ex]

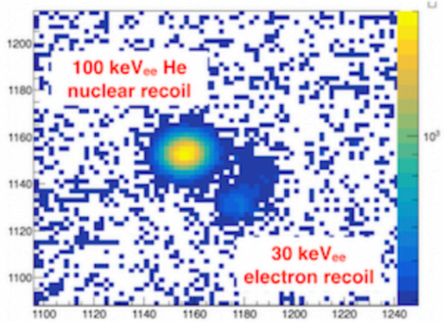


Migdal collaboration CF_4 100 Torr 1 cm drift



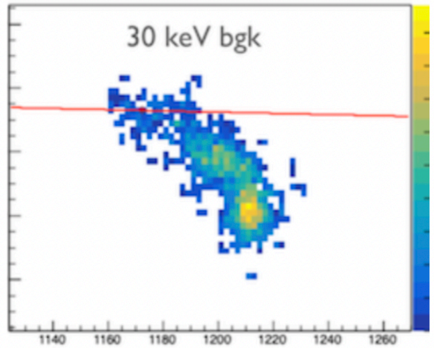
Compare to 200 keV F + 10 keV ER at 50 Torr & 1 cm drift

LIME simulated data @ 30 cm drift



Example of signature #1 at 30 cm drift in He:CF_4 1 atm

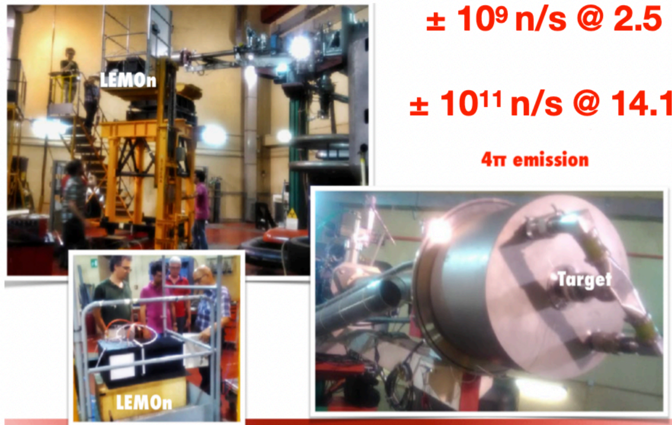
ER Angular resolution



±20° achievable @ 20 keV @ 30 cm

See S. Torelli

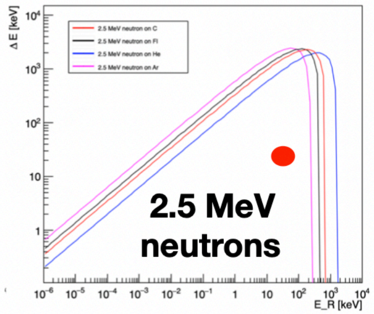
FNG @ Frascati

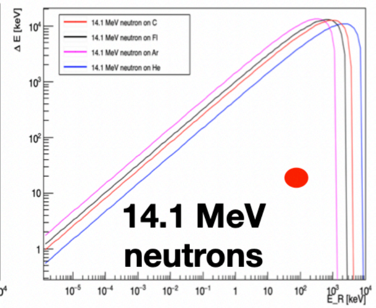


± 10^9 n/s @ 2.5 MeV

± 10^{11} n/s @ 14.1 MeV

4π emission

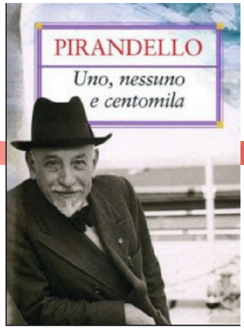


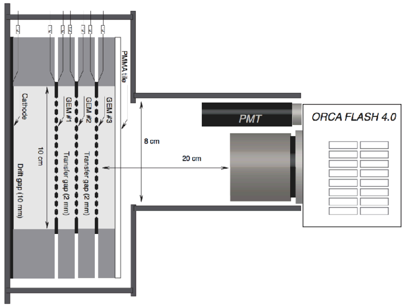


$f(E_n = 14\ \text{MeV}) = 72.4$

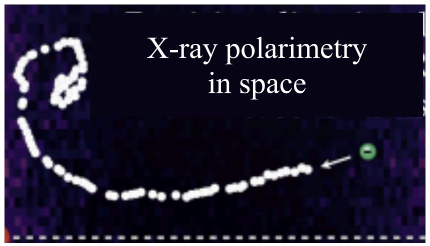
$f(E_n = 2.5\ \text{MeV}) = 12.9$ → O(3000 ev/day) @ 265 cm

One, no one and one hundred thousand optical imaging TPC applications

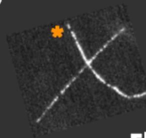




Small O(1) L



*Cosmic ray + low energy electron in LIME detector



ray-CMOS: a wide field of view X-ray polarimeter

*N.B project started on 29 May 2022

Elisabetta Baracchini[1,2*], Enrico Costa[3], Giorgio Dho[1,2], Flaminia di Giambattista[1,2], Alessandro Di Marco[3], Emanuele Di Marco[4], David Marques[1,2], Giovanni Mazzitelli[5], Fabio Muleri[3], Atul Prajapati[1,2], Paolo Soffitta[3], Samuele Torelli[1]

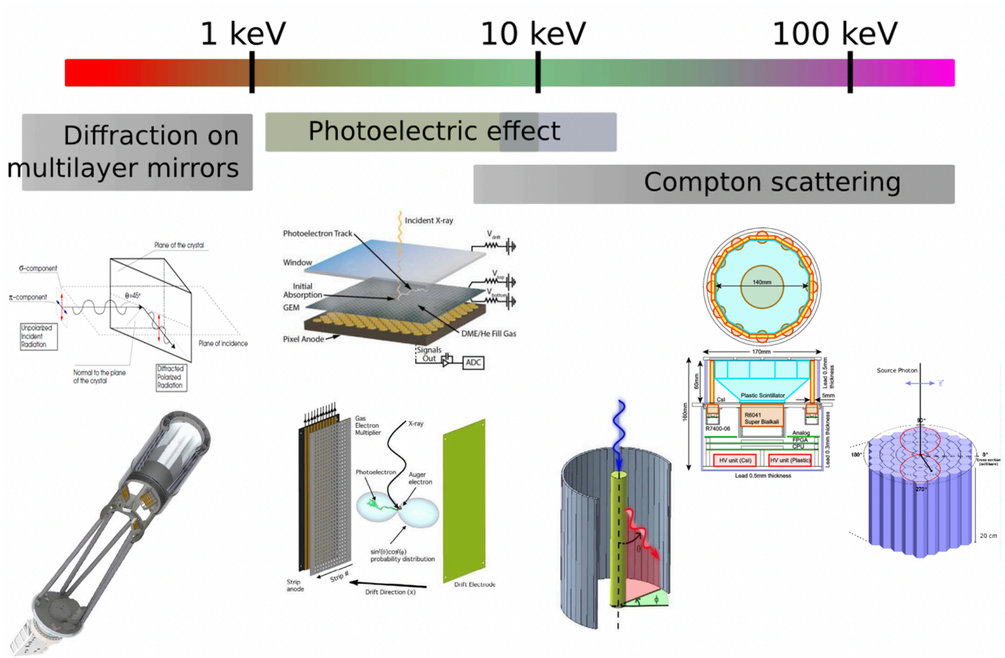
PRIN 2020

[1] Gran Sasso Science Institute, 67100 L'Aquila, Italy
[2] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, 67100 Assergi, Italy
[3] Istituto di Astrofisica e Planetologia Spaziali di Roma, Via Fosso del Cavaliere 100, I-00133 Roma, Italy
[4] Istituto Nazionale di Fisica Nucleare, Sezione di Roma1, 00185, Rome, Italy
[5] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, 00044, Frascati, Italy

This project has been funded by the Italian Ministry of Education, University and Research through the project PRIN: Progetti di Ricerca di Rilevante Interesse Nazionale "HypeX: High Yield Polarimetry Experiment in X-rays " (Prot. 2020MZ884C)

Polarimetry basics

Experimental techniques vs energy range



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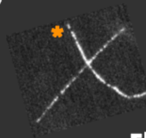

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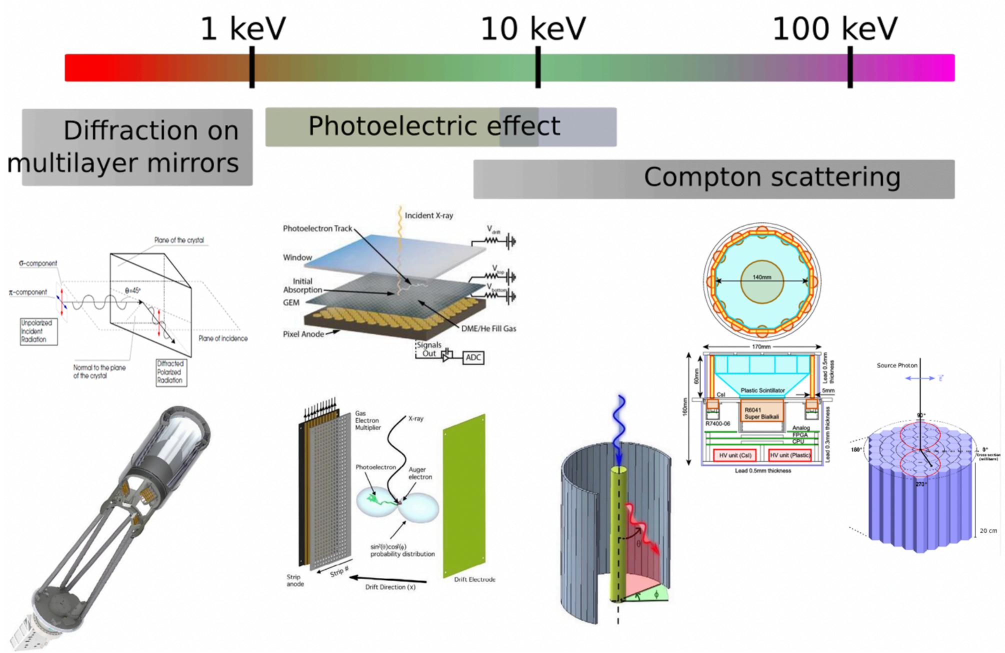


Physics cases vs energy range

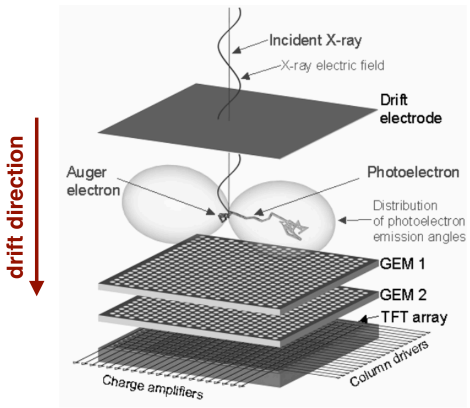
Scientific goals	Sources	< 1 keV	1-10	> 10 keV
Acceleration phenomena	PWN	yes (but absorp.)	yes	yes
	SNR	no	yes	yes
	jet (μQSO)	yes (but absorp.)	yes	yes
	jet (Blazars)	yes	yes	yes
Emission in strong magnetic fields	WD	difficult	yes	yes (difficult)
	AMS	no	yes	yes
	X-ray pulsator	difficult (absorp.)	yes (no cyclotron ?)	yes
	Magnetar	yes (better)	yes	no
Scattering in a-spherical geometries	Corona in XRB & AGNs	yes (but absorp.)	yes	difficult
	X-ray reflection nebulae	no	yes (long exposure)	yes
Fundamental Physics	QED (magnetar)	yes(better)	yes	no
	GR(BH)	no	yes	no
	QG (Blazars)	difficult	yes	yes
	Axions (Blazars, Clusters)	yes ?	yes	difficult

Galaxies 2018, 6(2), 54

X-ray polarimetry through photoelectric effect

Current detector approaches for X-ray polarimetry with photoelectric effect

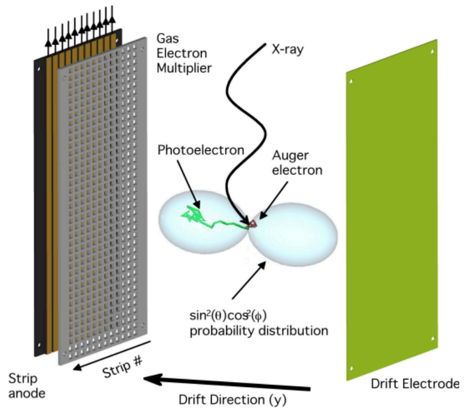
Incident X-ray perpendicular to readout plane



Costa et al. 2001
Bellazzini et al 2006, 2007

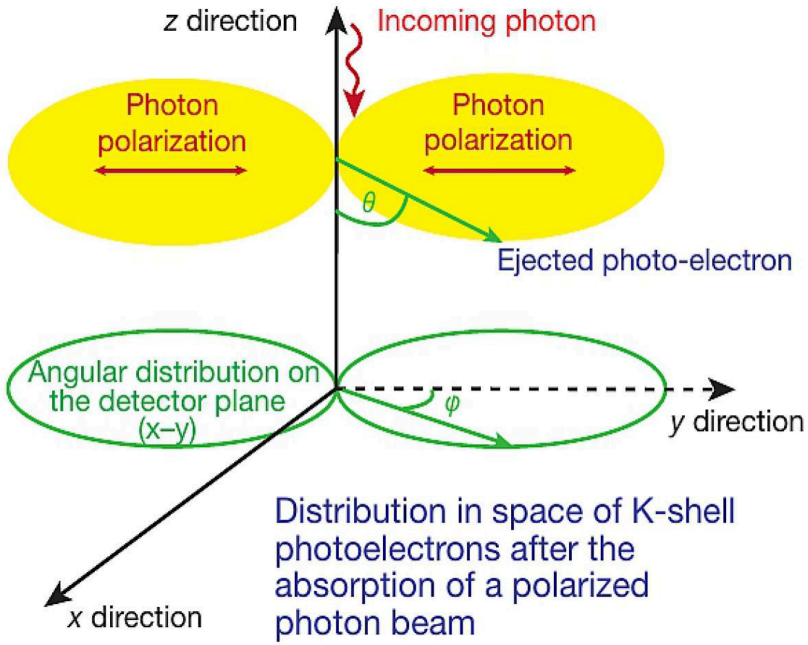
1.5 x 1.5 x 1 cm³ GDP with 50 x 50 um² pixels currently flying on IXPE and already providing physics results!

Incident X-ray parallel to readout plane



Black et al. 2007

Both configuration provide imaging, timing and spectroscopy

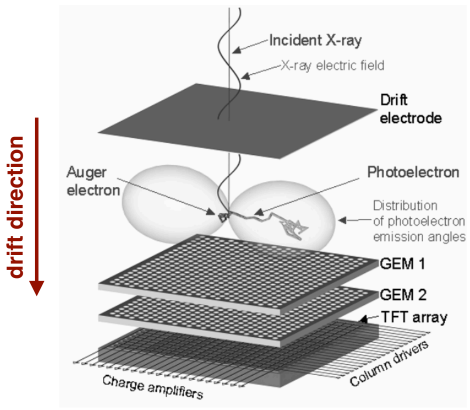


$$\frac{d\sigma_{ph}}{d\Omega} = \frac{\sigma_{ph}^{tot}}{4\pi}\left[1 + \frac{b}{2}\left(\frac{3\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4} - 1\right)\right]$$

IXPE mission: launched 11th December 2021

Until IXPE, only a single positive detection of X-ray polarisation from Crab Nebula in 1972

Incident X-ray perpendicular to readout plane



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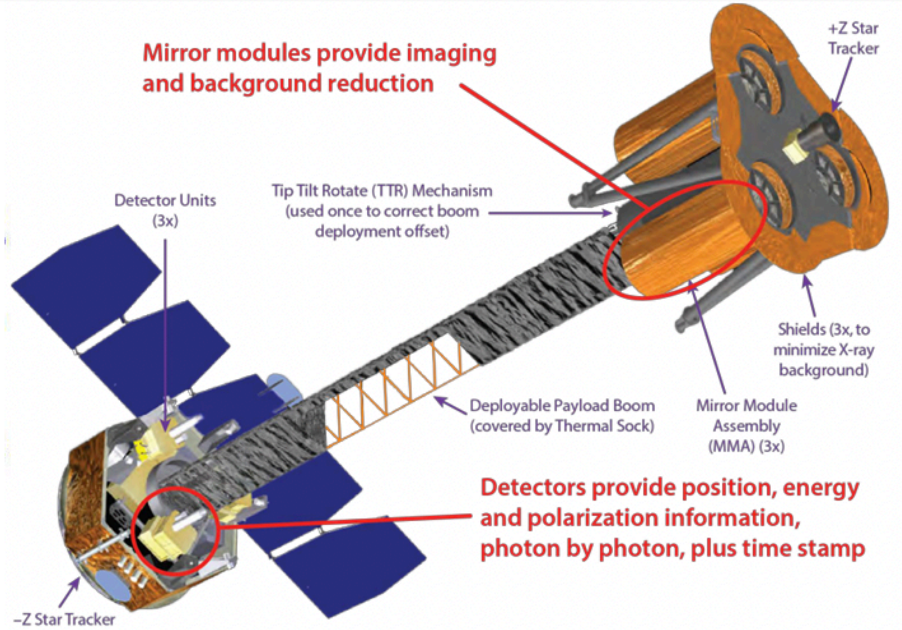
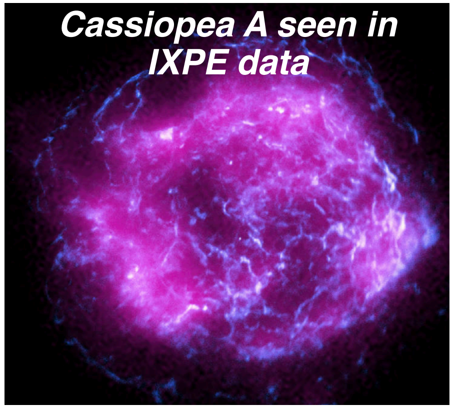


- What is the spin of a black hole?
- What are the geometry and magnetic-field strength in magnetars?
- Was our Galactic Center an Active Galactic Nucleus in the recent past?
- What is the magnetic field structure in synchrotron X-ray sources?
- What are the geometries and origins of X-rays from pulsars (isolated and accreting)?

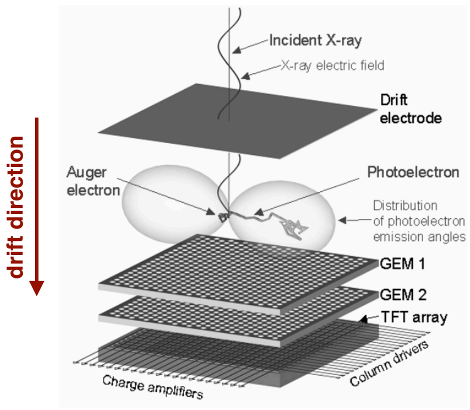


X-ray CMOS beyond current polarimetric techniques

GSSI | INFN Istituto Nazionale di Fisica Nucleare

Current detector approaches for X-ray polarimetry with photoelectric effect

Incident X-ray perpendicular to readout plane



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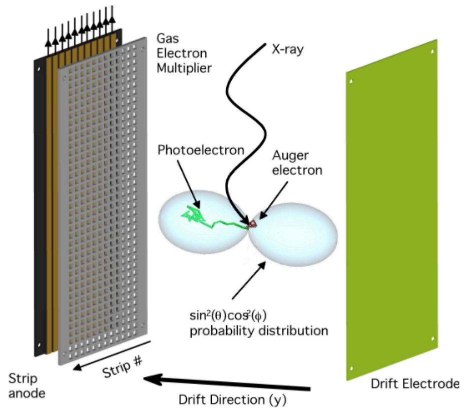
1.5 x 1.5 x 1 cm^3 GDP with 50 x 50 um^2 pixels currently flying on IXPE and already providing physics results!

Incident X-ray parallel to readout plane



Black et al. 2007

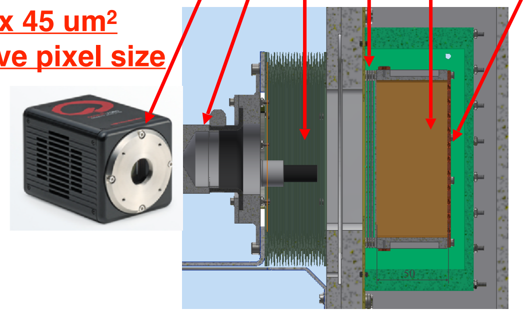
Both configuration provide imaging, timing and spectroscopy

X-ray CMOS project: large field of view optical TPC

<u>No requirements</u> on X-ray orientation

<u>45 x 45 um^2 effective pixel size</u>

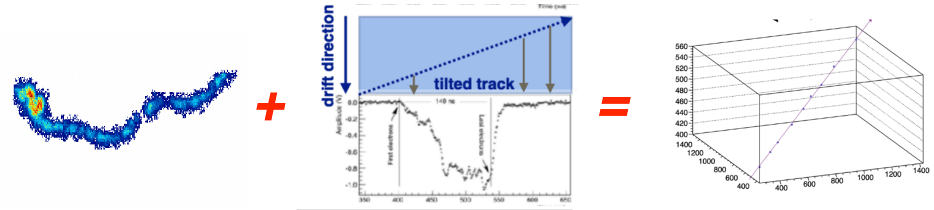
<u>1 L active volume</u>



1) Hamamatsu Orca sCMOS camera
2) Schneider lens f/0.95
3) PMT
4) GEM 10 x 10 cm^2
5) 10 cm drift gap
6) cathode

+ low diffusion gas:

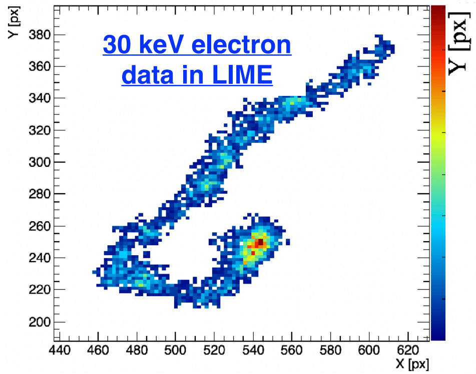
a) He:CF_4 with D_T =120 um/sqrt(cm)
b) Negative ion drift (see E. Baracchini talk on Thursday)

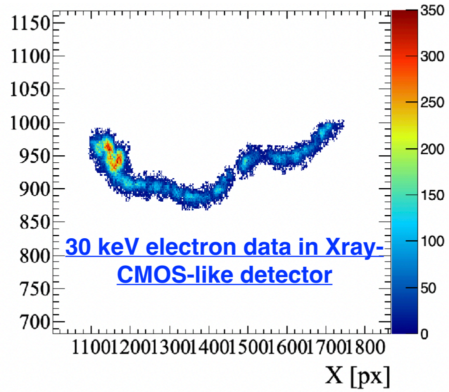


X-Y sCMOS image | *Z profile from PMT* | *3D track*

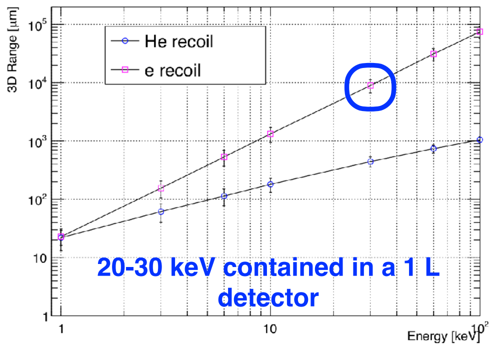
<u>JINST 13 (2018) no.05, P05001</u>

Very preliminary studies towards X-ray CMOS development

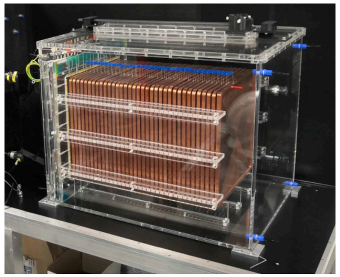


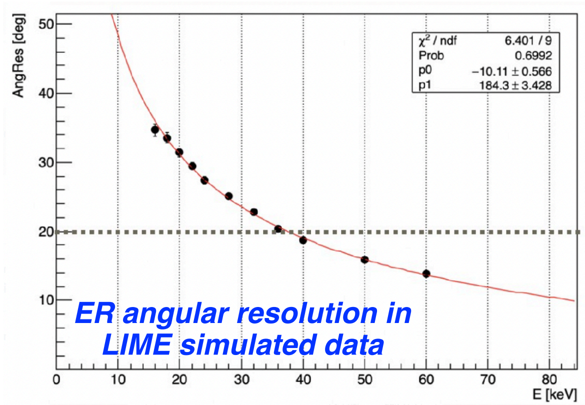


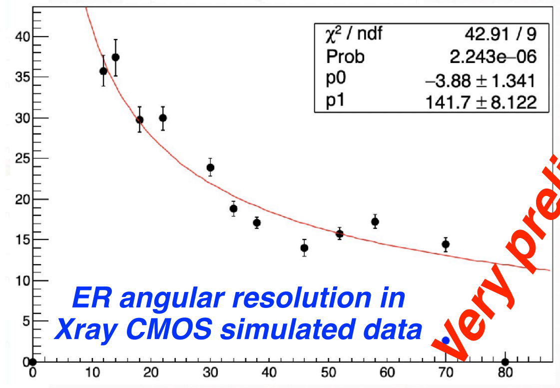
Particles range in He:CF_4



1 sCMOS + 4 PMT
33 x 33 cm^2 readout
50 cm drift length
50 L volume

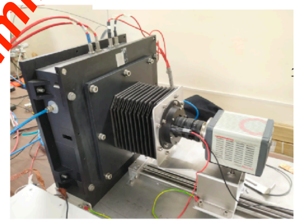


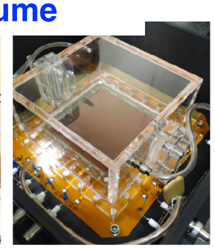




very preliminary

1 sCMOS + 1 PMT
10 x 10 cm^2 readout
10 cm drift length
1 L volume





From J. Vink & P. Zhou, Galaxies 6 (2018) 2, 46

$$\Delta\alpha = 5^o + 35^o\sqrt{\frac{4\text{keV}}{E}}$$

21^o @ 20 keV
16^o @ 60 keV

Parameterisation developed for a IXPE-like detector, i.e. 1.5 x 1.5 x 1 cm^3 consistent with preliminary X-ray CMOS simylation!

Conclusions & Outlook

- Recoil imaging TPCs (not only with optical readout) have nowadays reached a level of maturity that allows to employ them in many physics cases
- Recoil imaging implies the possibility of providing directional informations about recoils from a range of different particles and energies, and for enabling the recoiling particle identification capabilities
- Directionality is a "tool for all season"
  - Directional Dark Matter searches is only one of the many interesting physics cases that can be sought after with recoil imaging TPCs
    - Solar neutrinos
    - Precise neutron measurement
    - Nuclear physics (i.e. Migdal)
    - X-ray polarimetry
    - ...and many more I did not had time to discuss here
- We don't know where particle physics discoveries will lead us....hence we must always keep an open mind on how to better exploit the detectors or experimental techniques we might have developed for other applications

arXiv:2203.05914

Recoil imaging for dark matter, neutrinos, and physics beyond the Standard Model

Snowmass 2021 inter-frontier white paper:
IF5: Micro-pattern gas detectors
CF1: Particle-like dark matter
NF10: Neutrino detectors

I am looking for 2 Postdocs/Fixed Term Researcher for the FINEM & Xray CMOS projects

elisabetta.baracchini@gssi.it