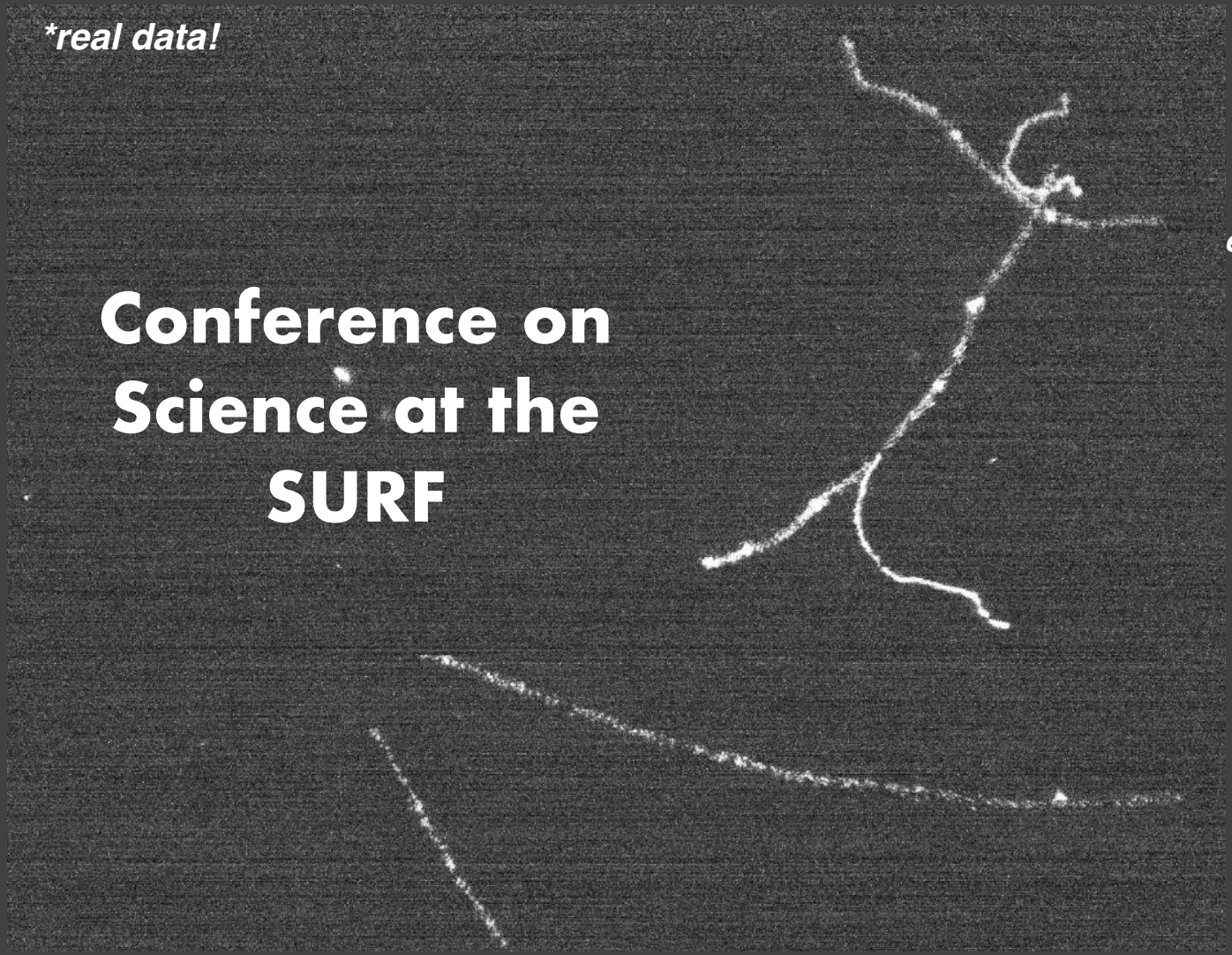
Directional Dark Matter searches with the CYGNO/INITIUM project



Low energy electrons in CYGNO 50 L detector

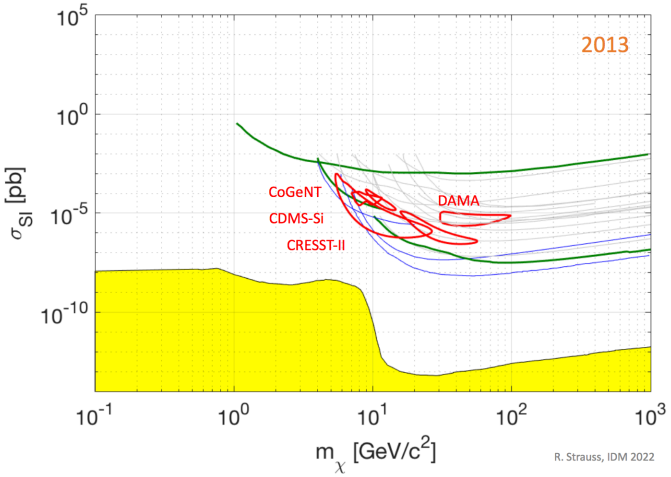
Elisabetta Baracchini
Gran Sasso Science Institute & Istituto Nazionale Fisica Nucleare

Dark Matter: a search hampered by many false promises

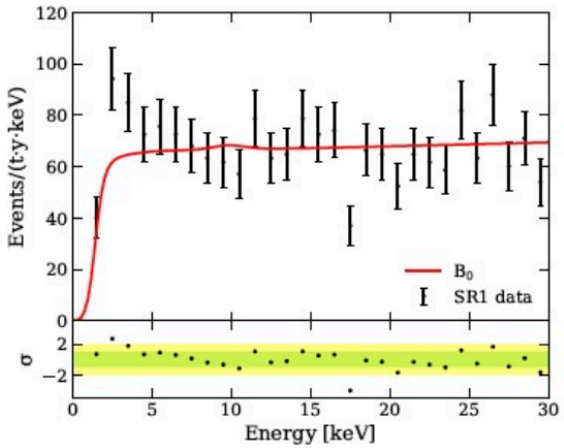
i.e. many things can look like a signal if you don't know where they are coming from

Direction is the only way

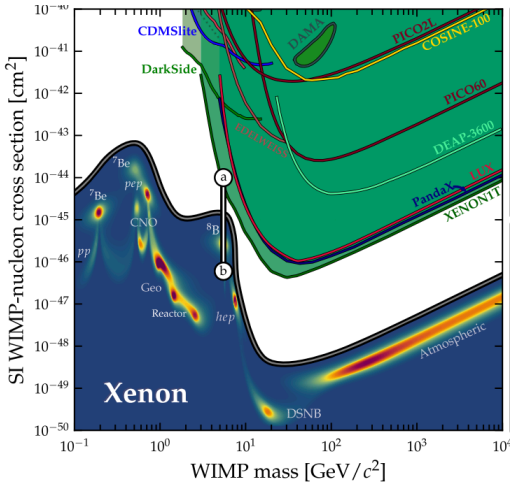
DAMA annual modulation + past Cogent-CDMS-CRESST claims at similar masses



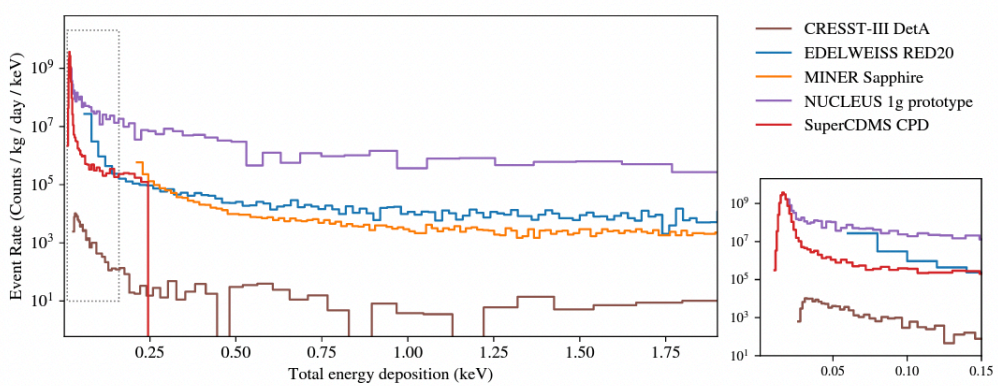
Low energy ER excess in Xenon1T

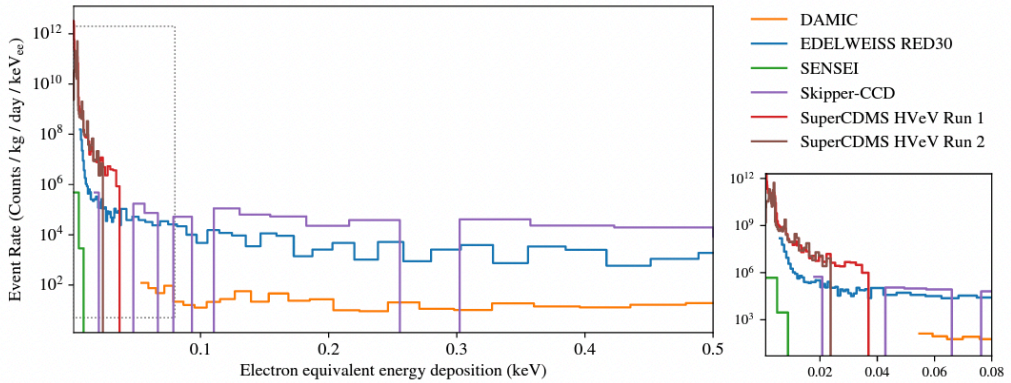


Neutrinos



The unexplained Low Energy Excess (LEE) appearing in many low threshold detectors (SciPost Phys.Proc. 9 (2022) 001)

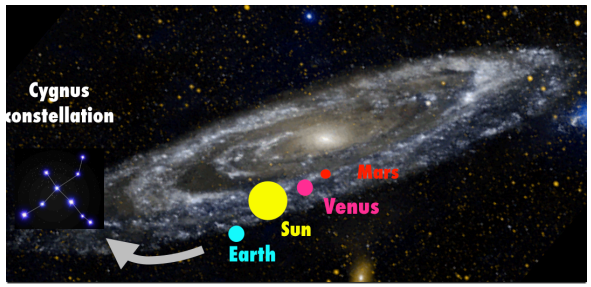




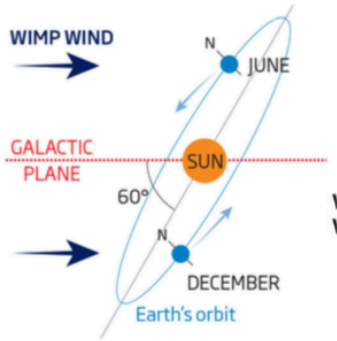
Directional DM searches

i.e. annual modulation of nuclear recoils rate

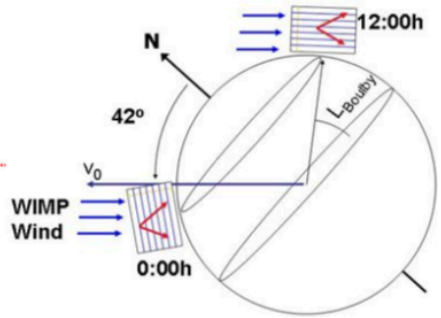
i.e. directional dependence of nuclear recoils



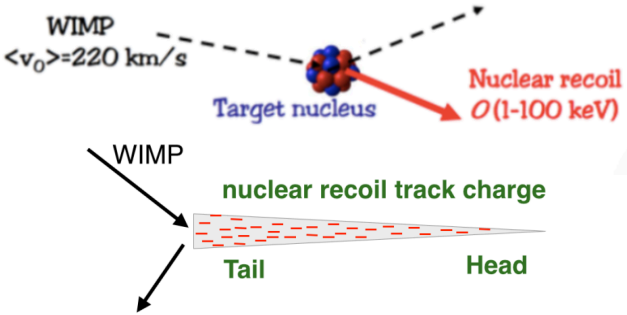
Our Galaxy



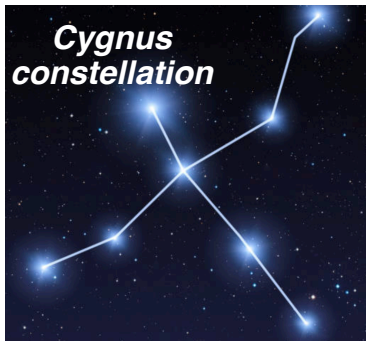
Solar system

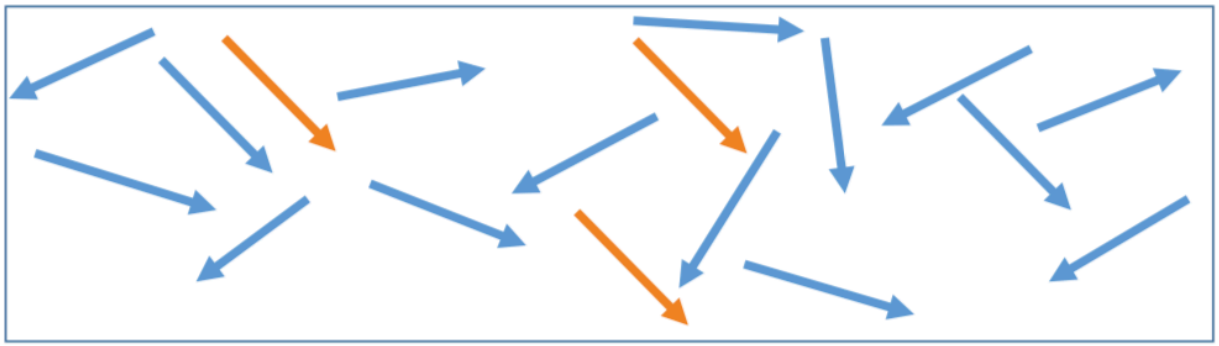


Earth



Detector target





background *signal*

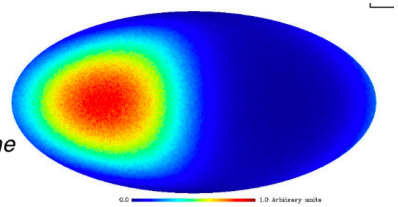
Directionality as tool for background rejection,

Capability to reject isotropy

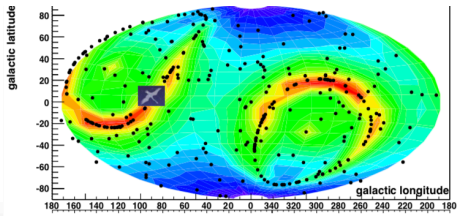
A. M. Green et. al, Astropart. Phys. 27 (2007) 142

WIMP signal (recoil map)

Angular distribution of Fluorine recoils [5;50] keV



Background



Directional detector can tolerate unknown backgrounds, including neutral

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

Directionality as tool for background rejection, neutrino physics

Capability to reject isotropy

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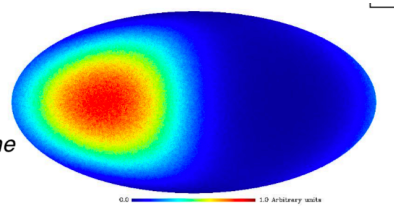
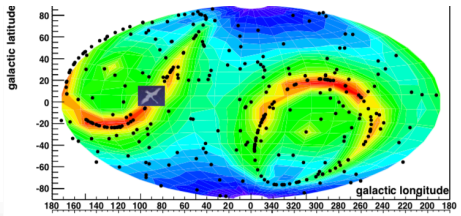


Background



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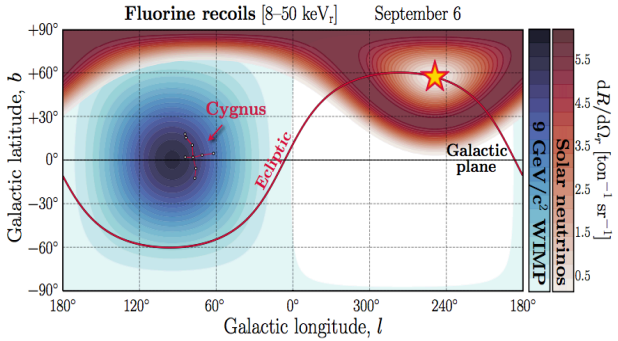
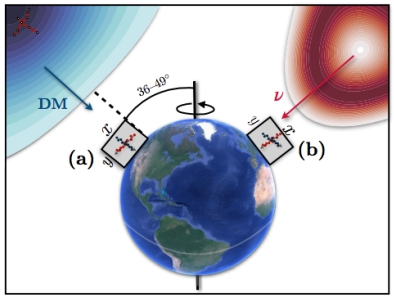
e-Print: 2102.04596





The Neutrino Floor is an opportunity, not a limit

Sun neutrinos physics

Directionality as 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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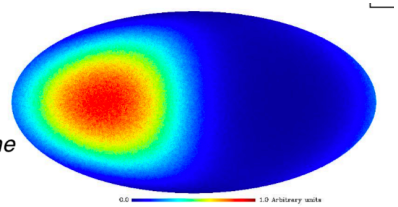
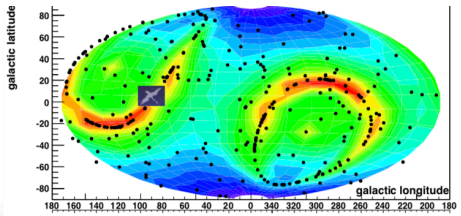


Background



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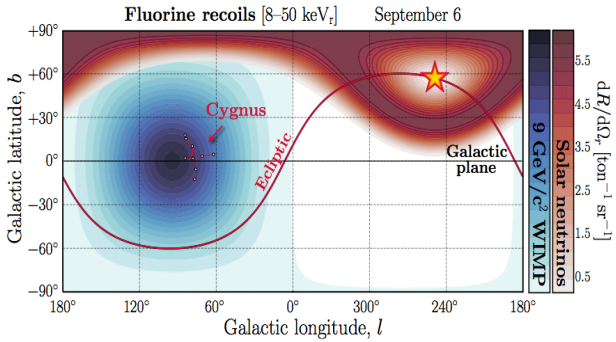
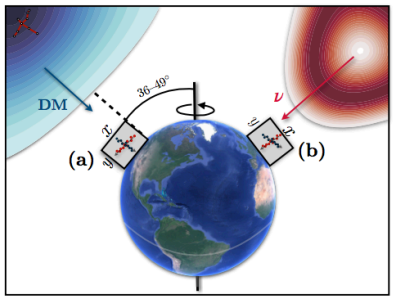


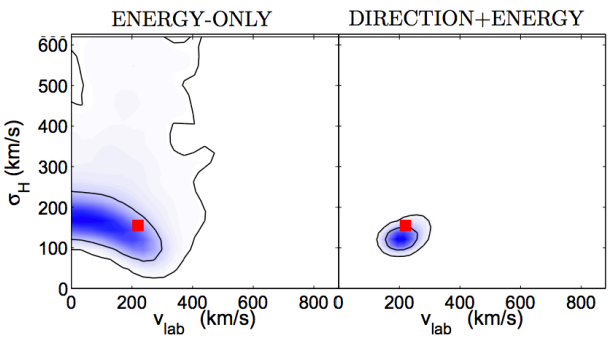


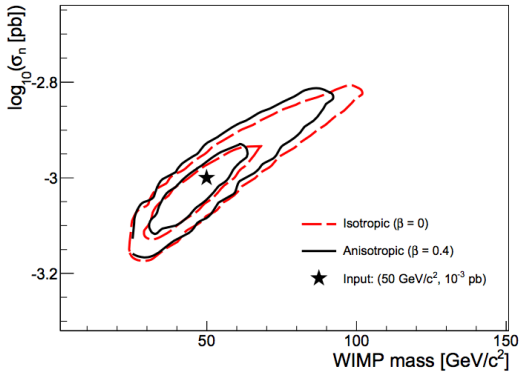
The Neutrino Floor is an opportunity, not a limit

Sun neutrinos physics

Capability to probe DM nature

Phys.Rept. 627 (2016) 1-49





WIMP & halo properties unbiased constraints with a single measurement

DM astronomy & DM interactions

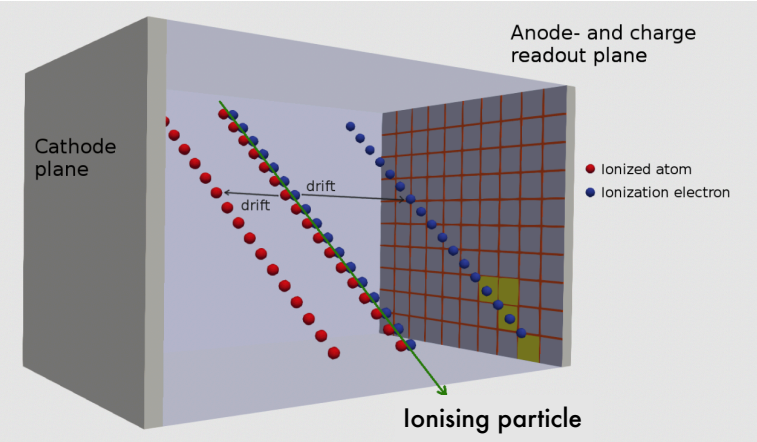
The CYGNO/INITIUM project

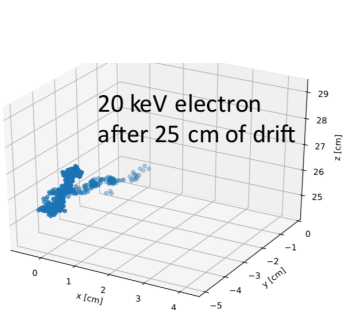
Fernando Domingues Amaro[1] Rita Antonietti[2,3] Elisabetta Baracchini[4,5] Luigi Benussi[6] Stefano Bianco[6] Francesco Borra[7,8] Roberto Campagnola[6] Cesidio Capoccia[6] Michele Caponero[6,9] Danilo Santos Cardoso[10] Gianluca Cavoto[7,8] Igor Abritta Costa[6] Emiliano Dané[6] Giorgio Dho[4,6] Flaminia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

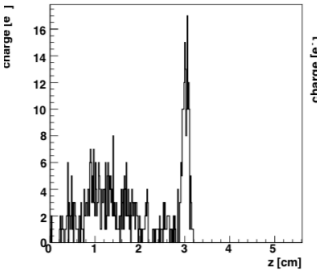
This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the European Research Council (ERC) grant agreement No 818744

Gaseous TPC experimental approach

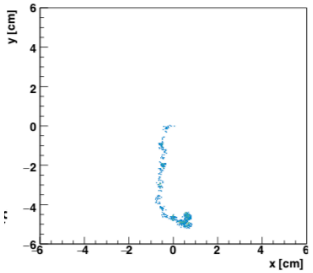
Depending on the anode segmentation (x-y) and time sampling (z), tracks can be reconstructed in 1D, 2D or 3D



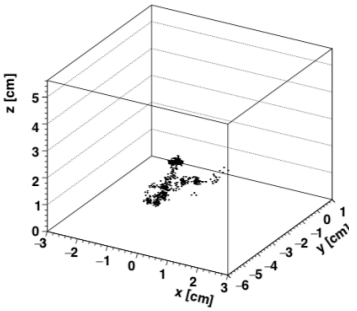




1D GEM



2D optical



3D pixels

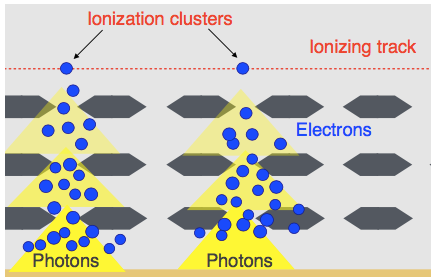
Energy + particle ID + 3D position + recoil angle + vector sense

Less event information → **More event information**

Improved background discrimination
More physics cases per exposure

CYGNO :3D TPC with optical readout via PMT + sCMOS

triple 50 um GEMs



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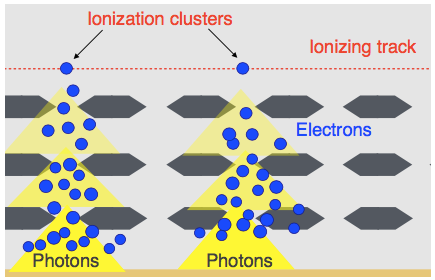
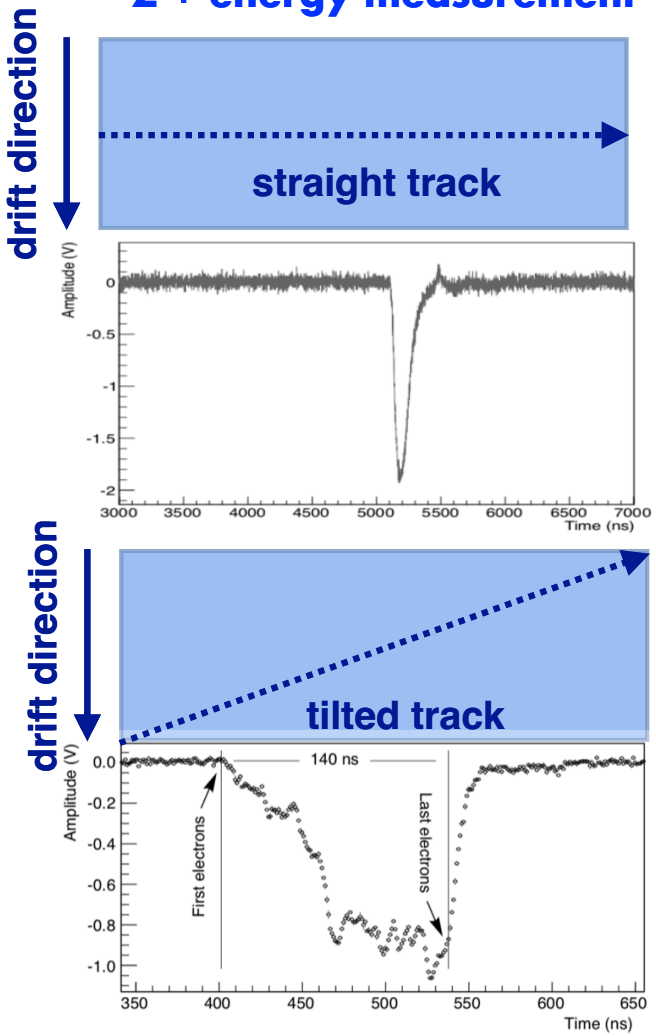


PMT:

integrated

Z + energy measurement

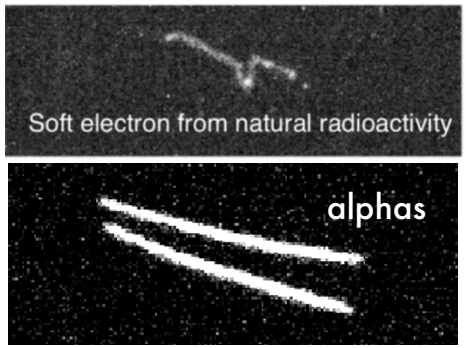


CYGNO :3D TPC with optical readout via PMT + sCMOS

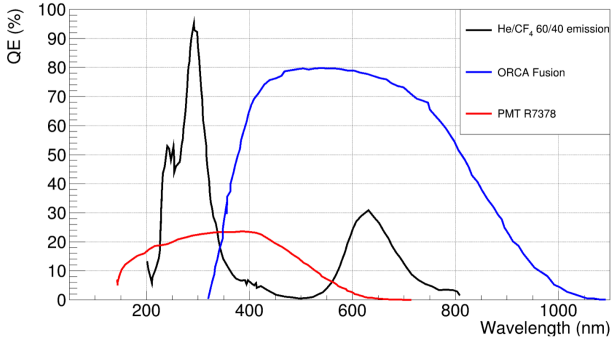
sCMOS:

high granularity

X-Y + energy measurements



- **1/3 noise w.r.t. CCDs**
- **Market pulled**
- **Single photon sensitivity**
- **Decoupled from target**
- **Large areas with proper optics**



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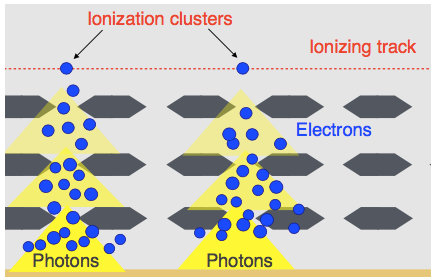

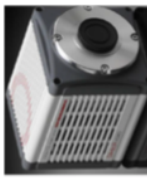

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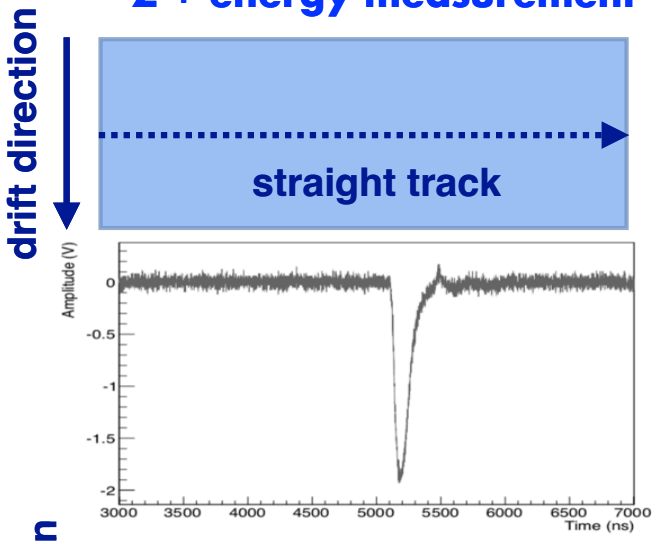
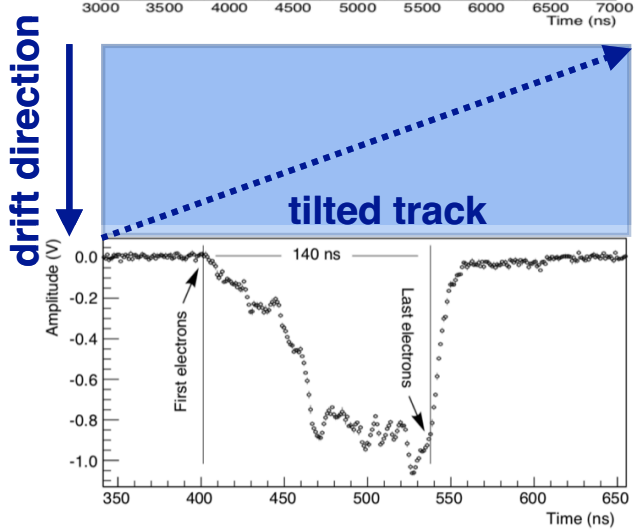




CYGNO :3D TPC with optical readout via PMT + sCMOS

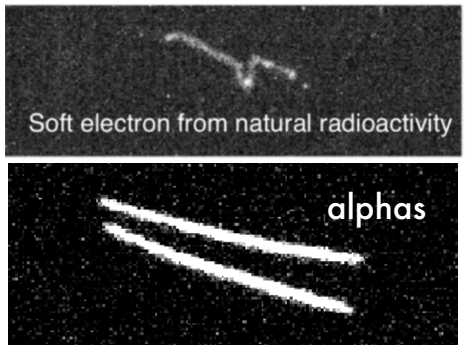
He:CF_4 @ 1 atm

JINST 13 (2018) no.05, P05001

sCMOS:

high granularity

X-Y + energy measurements



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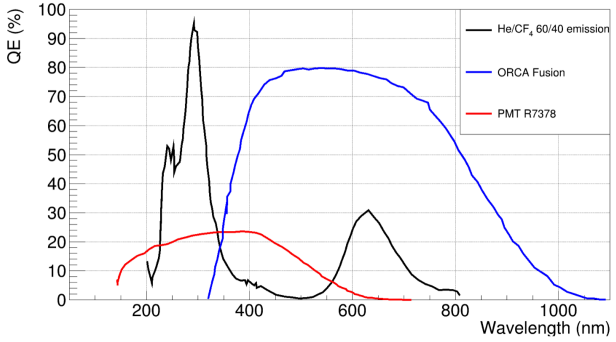

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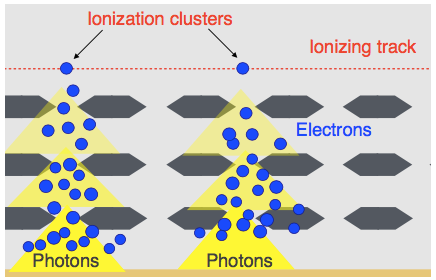

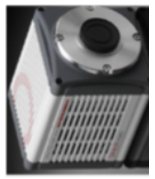

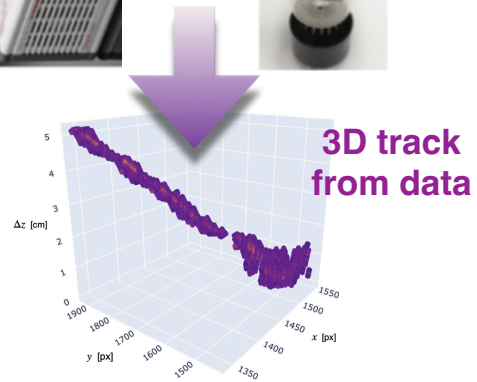

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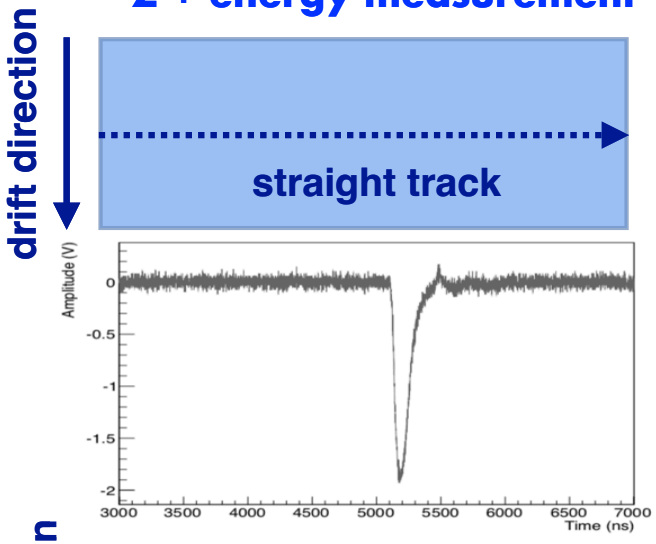

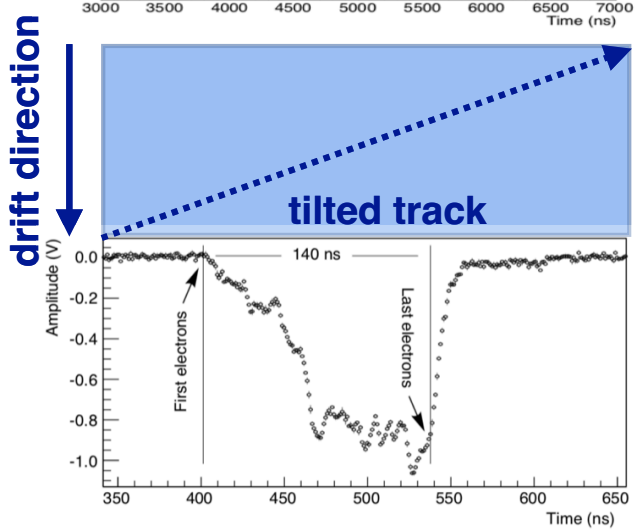

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He:CF_4 @ 1 atm

JINST 13 (2018) no.05, P05001

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high granularity

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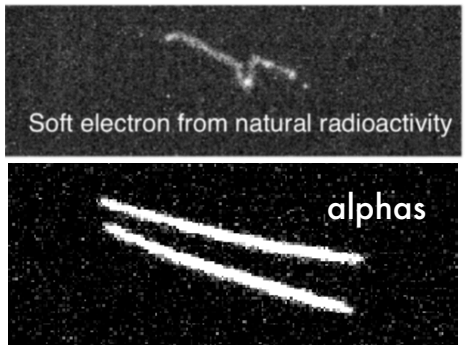

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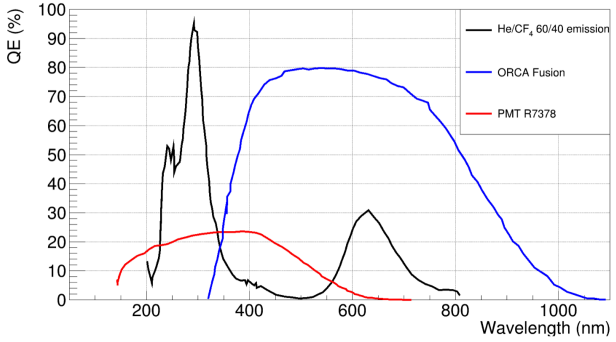
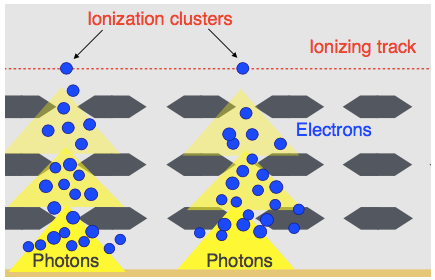
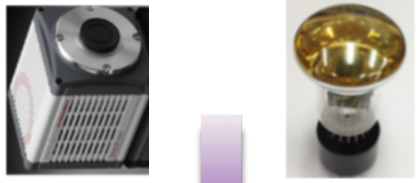
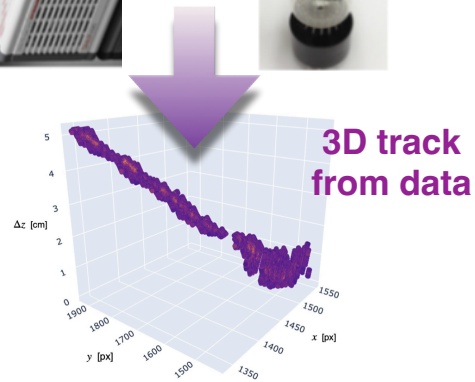


triple 50 um GEMs





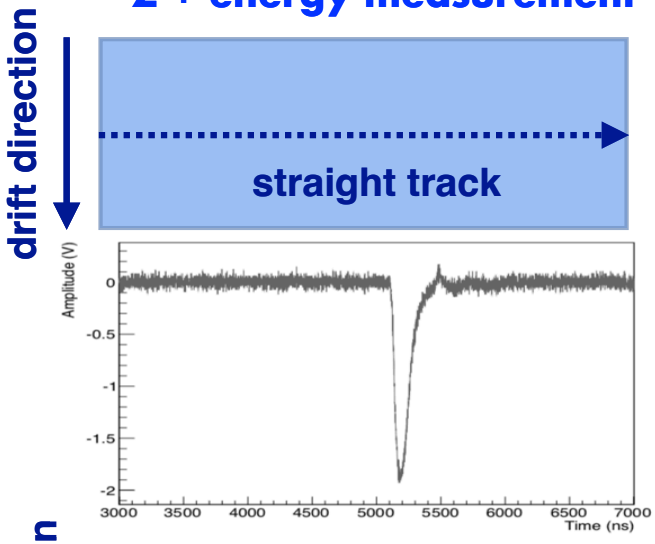


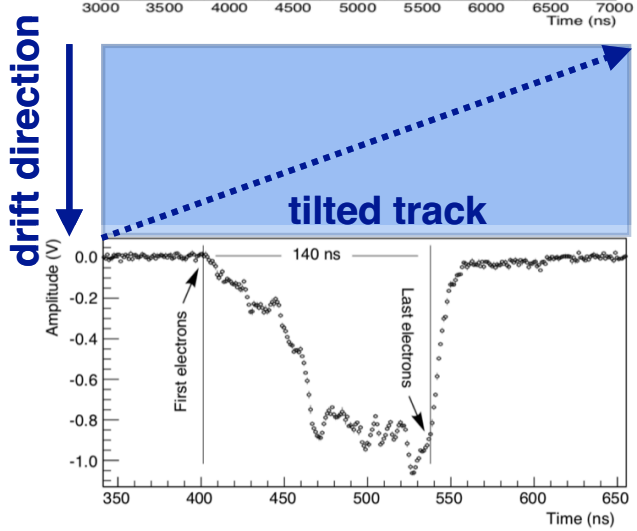
+ SF_6 for negative ion drift

PMT:

integrated

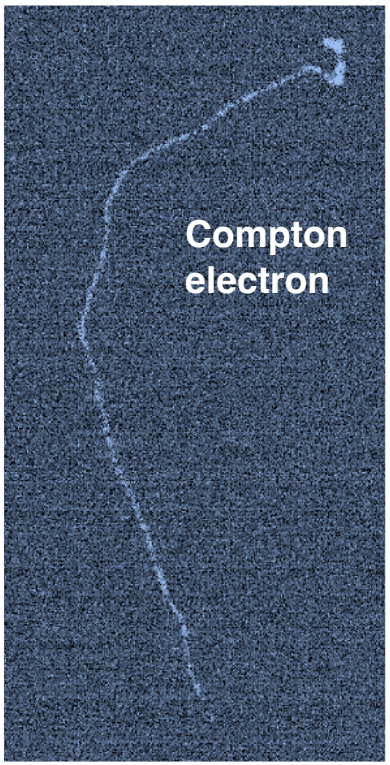
Z + energy measurement

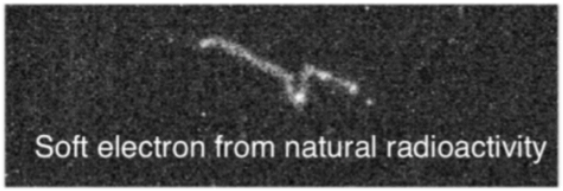


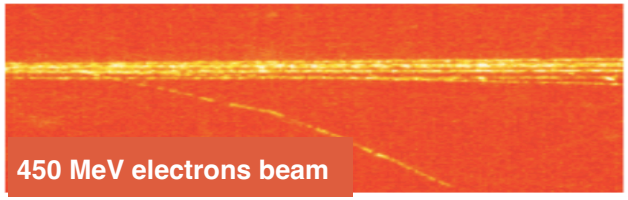


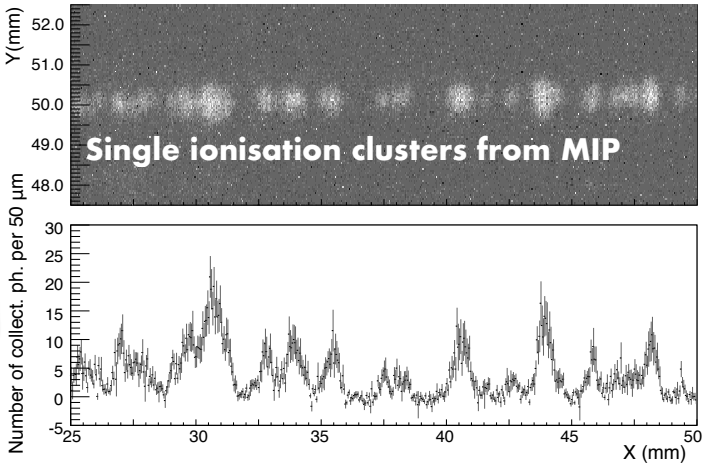
Photographing tracks with CYGNO

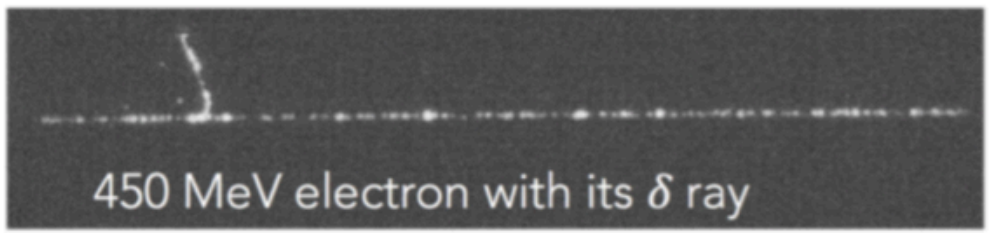
….with classical electron drift

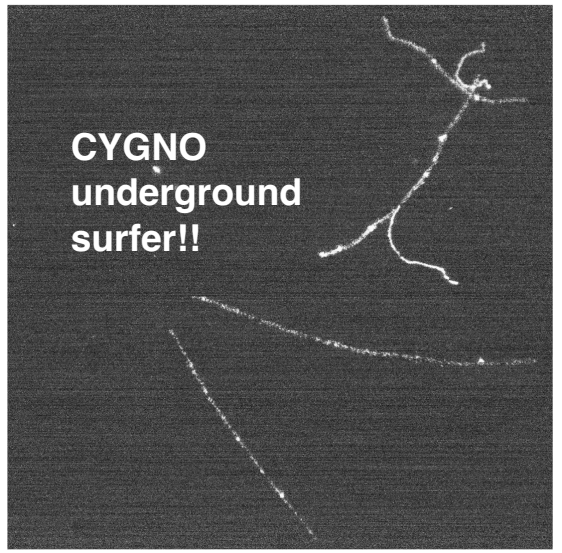


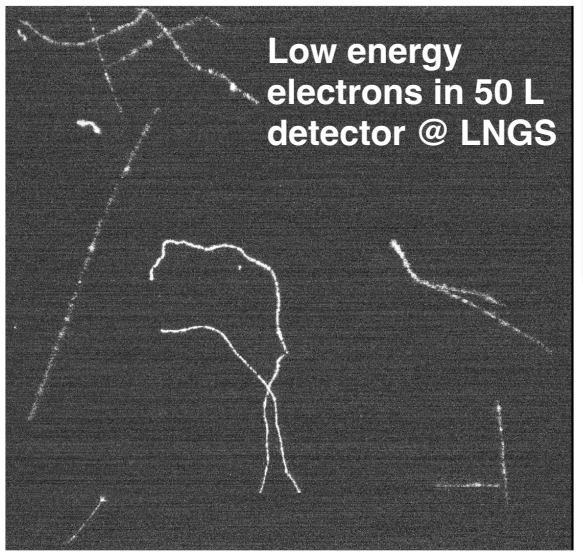


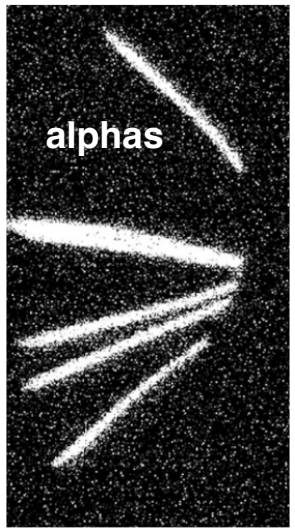












Optical readout features

- **Camera focused on last amplification stage**

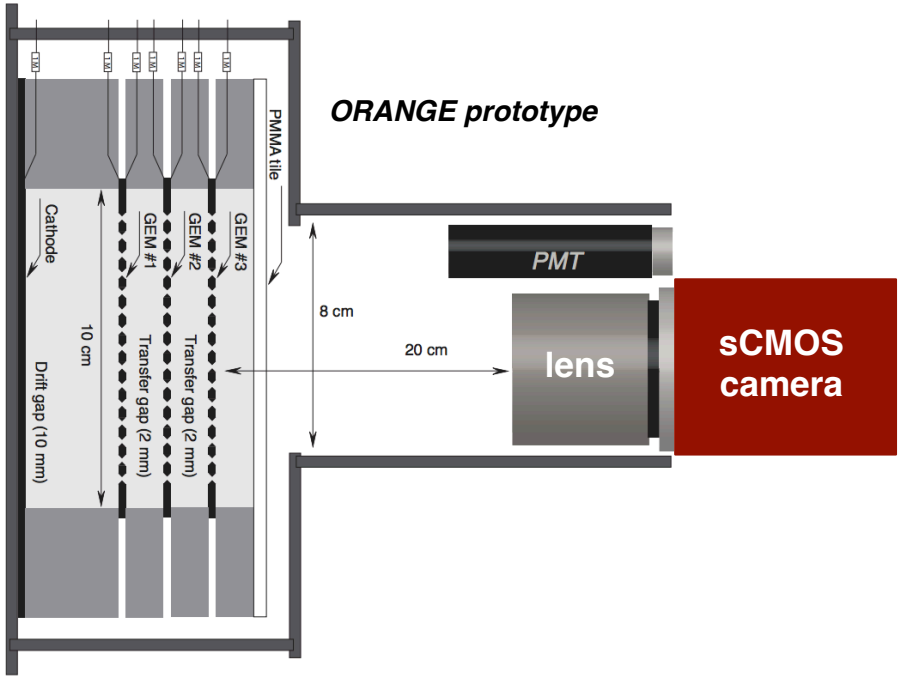
Lens de-magnification

$$\delta = \frac{f}{d - f}$$

sCMOS-GEM distance — **Focal lenght F.L.**

sCMOS sensor geometrical acceptance

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

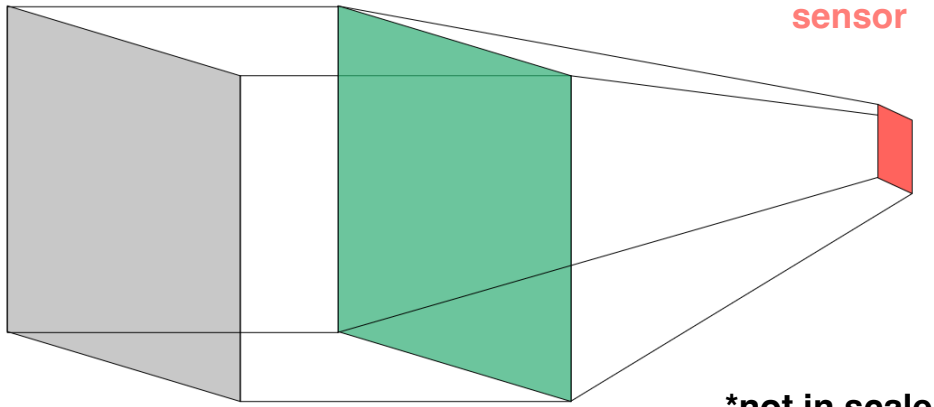


- **The further the camera, the larger the area it can image**
  - **a 36 x 36 cm² area with an effective granularity of 155 x 155 um² (large volume application)**
  - **a 10 x 10 cm² area with an effective granularity of 43 x 43 um² (small volume application)**
- **The further the camera, the lower the light yield detectable**
  - **± 1 x 10^{-4} coverage for large volume application**
  - **± 1 x 10^{-3} coverage for large volume application**

Camera electronics is integrated, the output is an USB plug

36 x 36 cm² imaged area

1.3 x 1.3 cm² sensor

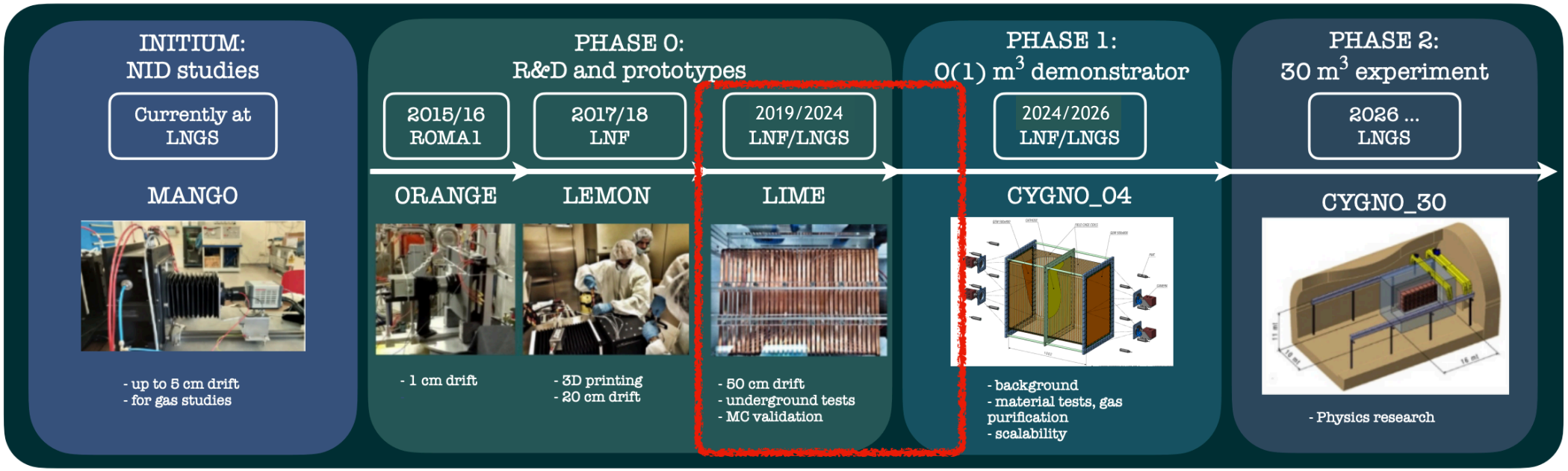


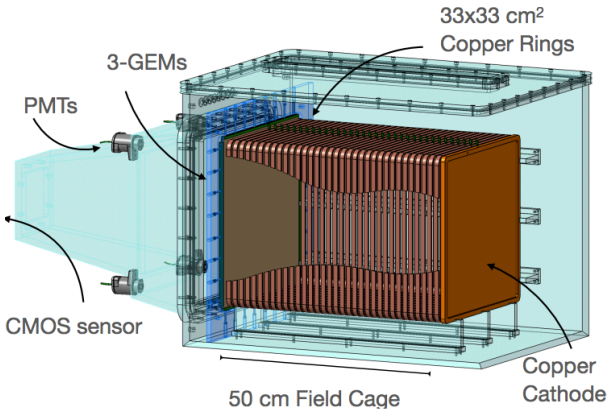
***not in scale**

CYGNO timeline

Instruments 6 (2022) 1, 6
JINST 15 (2020) 12, T12003
JINST 15 (2020) P08018
Measur.Sci.Tech. 32 (2021) 2, 025902

JINST 15 (2020) P10001
2019 JINST 14 P07011
NIM A 999 (2021) 165209



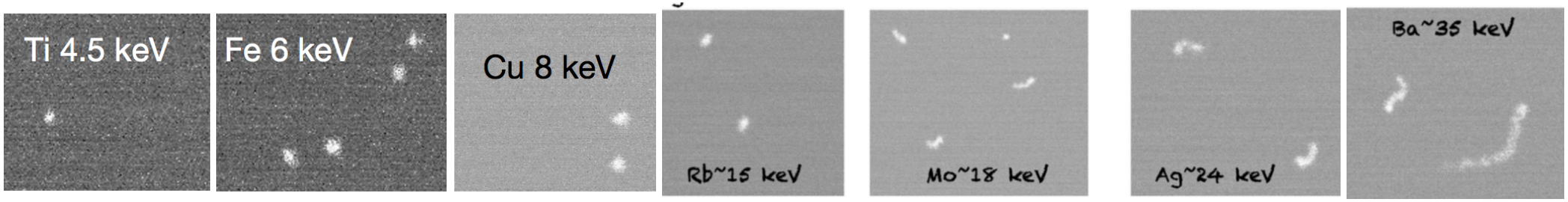


1 sCMOS + 4 PMT + 3 GEMs
33 x 33 cm² readout area
50 cm drift length
50 L active volume

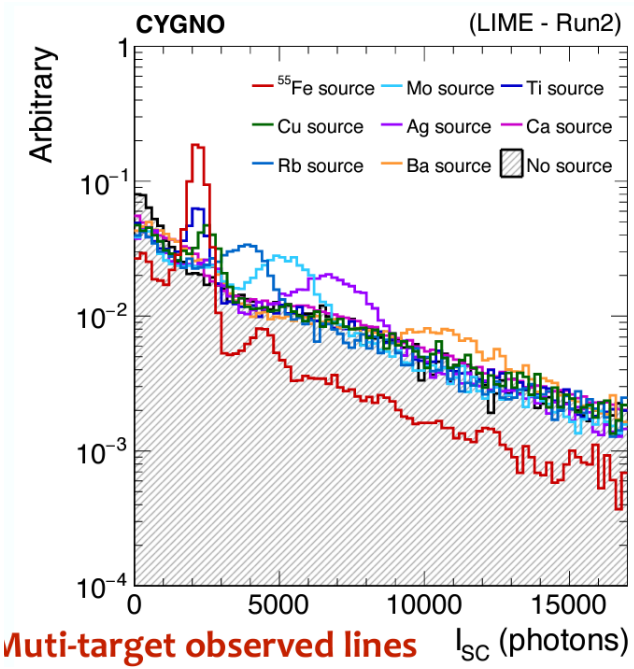
Eur. Phys. J. C 83 (2023) 10, 946

LIME overground commisioning @ LNF

Electron recoils calibration

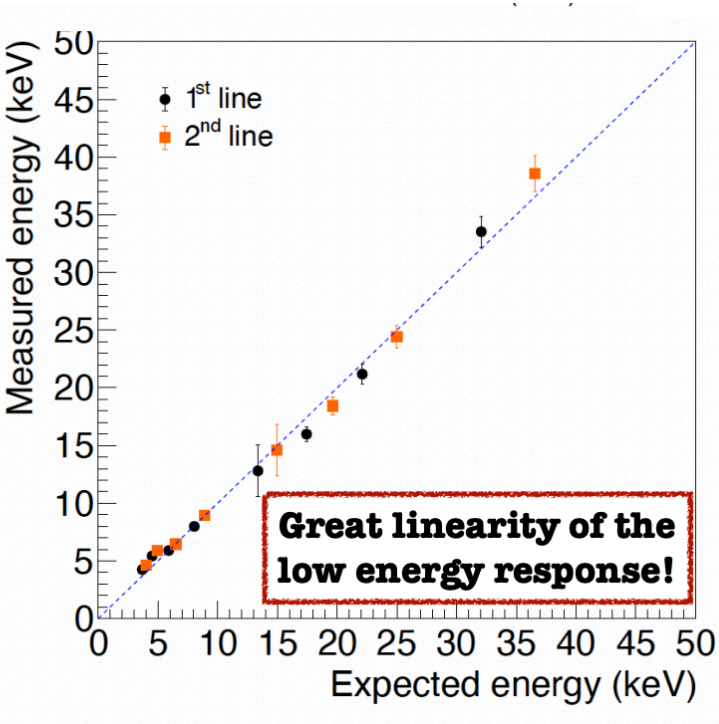


Multi-source + bkg spectrum

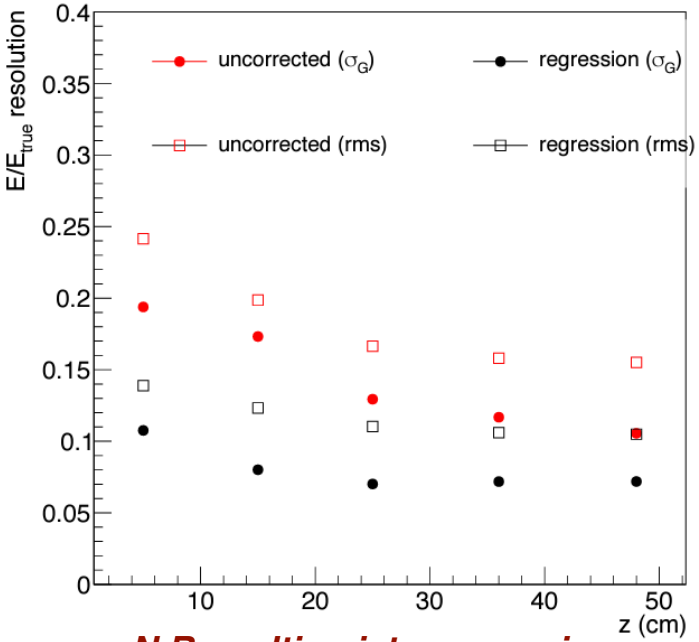


Muti-target observed lines

Energy response linearity



Energy resolution

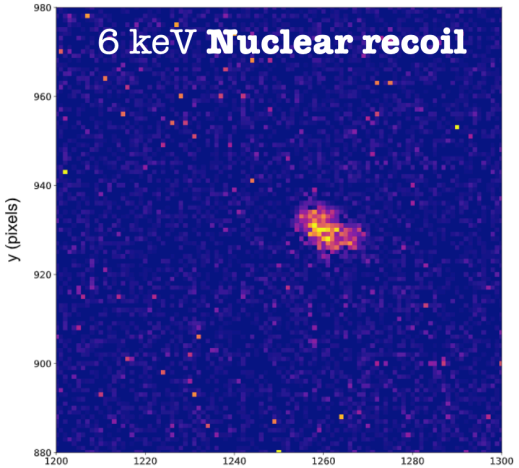


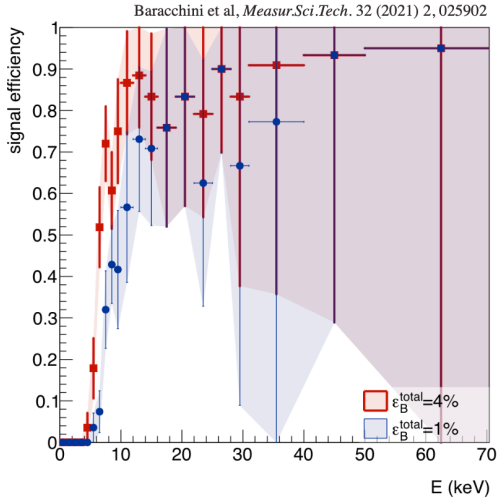
N.B. multivariate regression to correct for detector response disuniformities

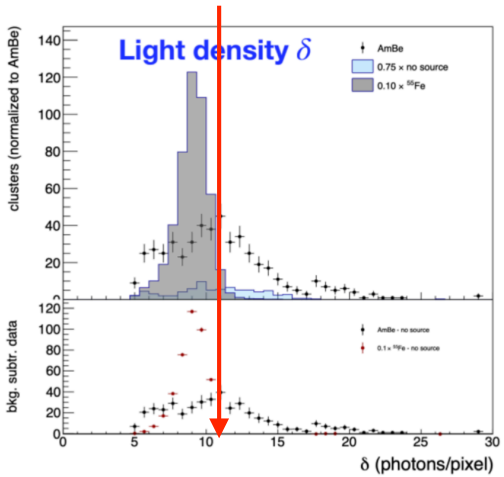
Measur. Sci. Tech. 32 (2021) 2, 025902

NR vs ER discrimination

- **AmBe neutron** source to induce NRs
- **Selection** based on **topological information** of the tracks (size, shape and light density)
- **Discrimination** based on single variable: **light density**







➡ **NR** detection efficiency over **40%** above 6 keV

➡ **96% rejection** power on the 6 keV ^{55}Fe **ERs**

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

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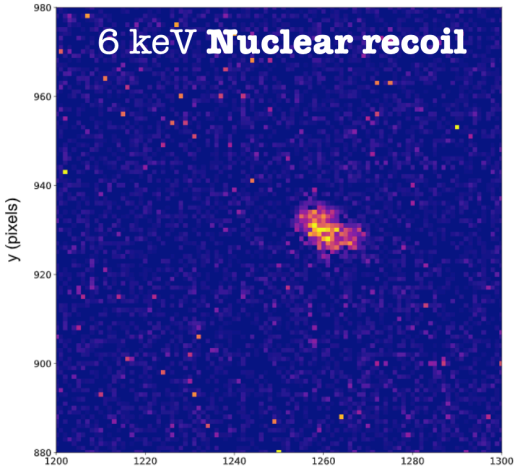

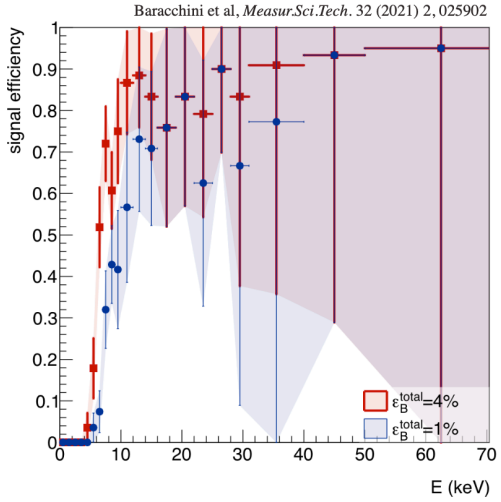

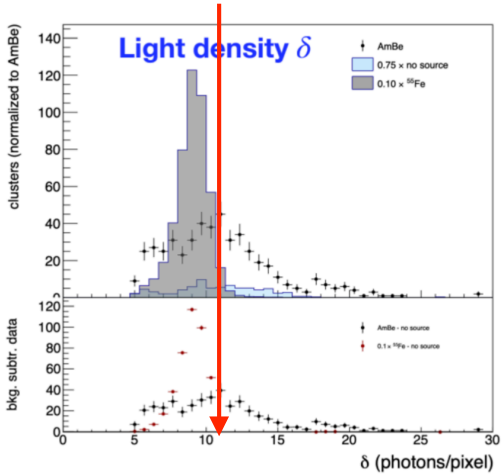

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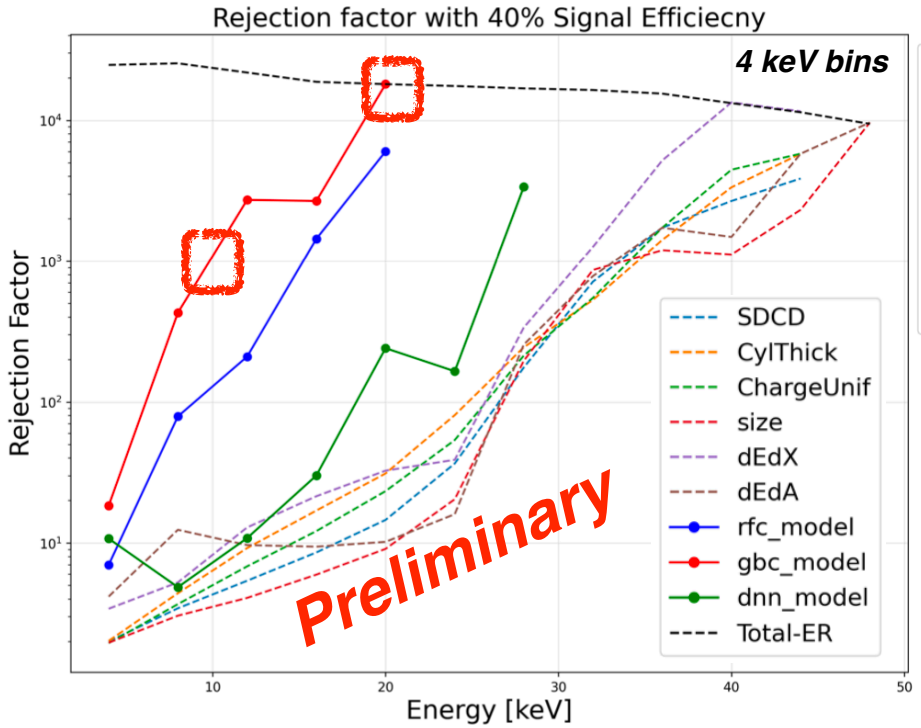
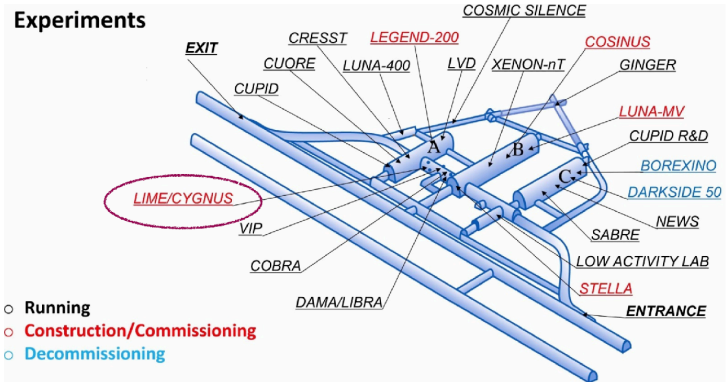
NEW!
ML techniques on full MC simulation

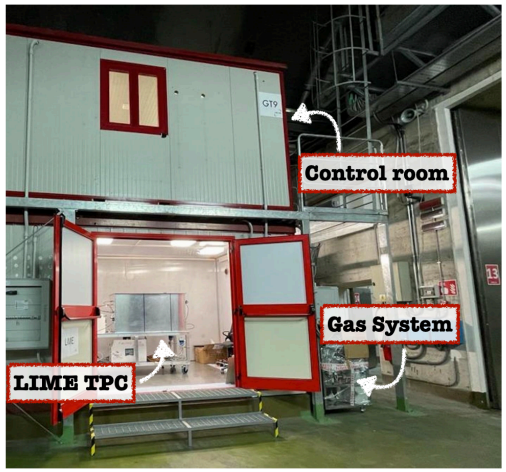


Indication of background rejection > 10^4/keV@ 20 keV

A. Prajapati PhD thesis

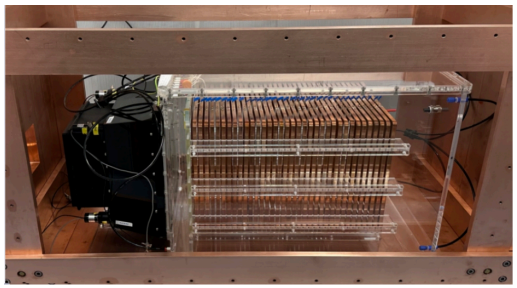
LIME underground campaign at LNGS

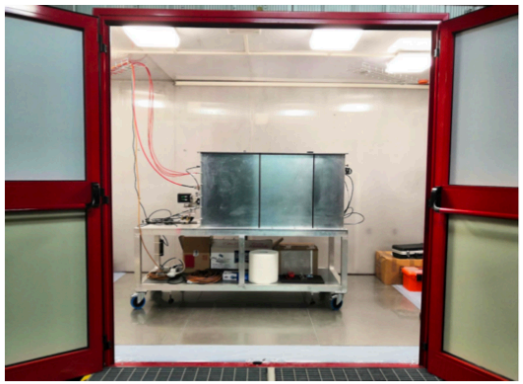


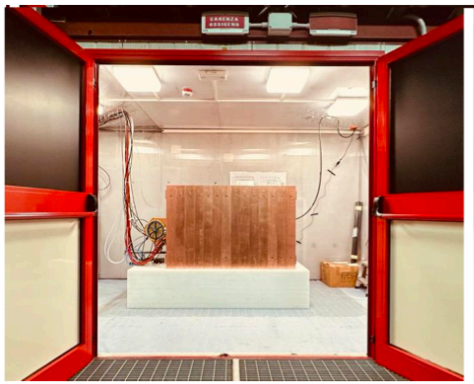


Underground installation with full axuliary systems

	Shielding	Number of bkg pictures	Event rate	Period
Run1	none	4×10^5	35 Hz	Oct 2022
Run2	4 cm Cu	4.5×10^5	3.5 Hz	Jan-Mar 2023
Run3	10 cm Cu	2.7×10^6	1.3 Hz	May-Nov 2023
Run4	10 cm Cu + 40 cm H_2O	2.8×10^6	0.9 Hz	Dec 2023-Apr 2024



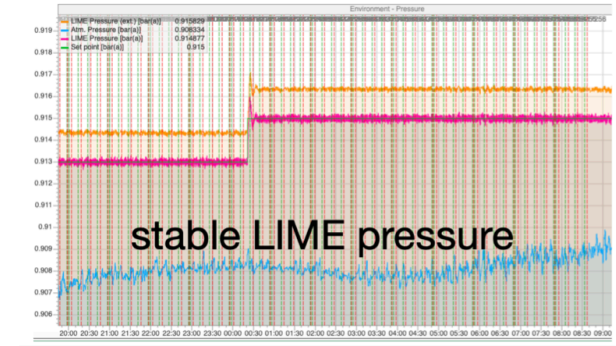


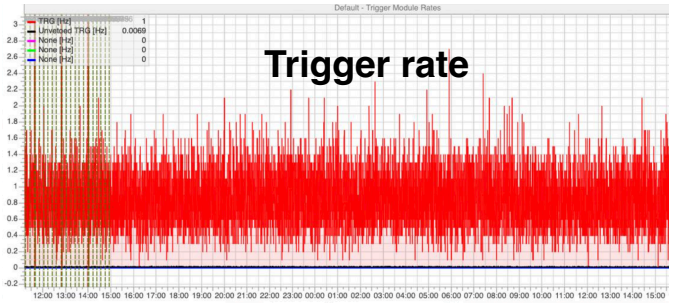


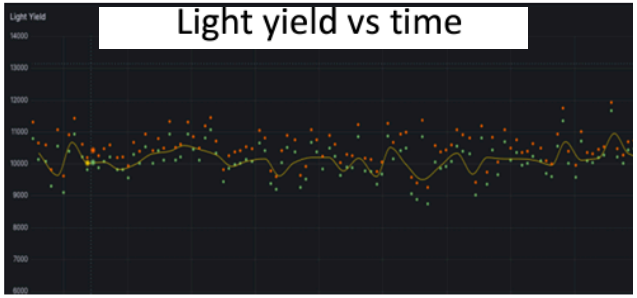
Run1 ***Run2 - Run3*** ***Run4***

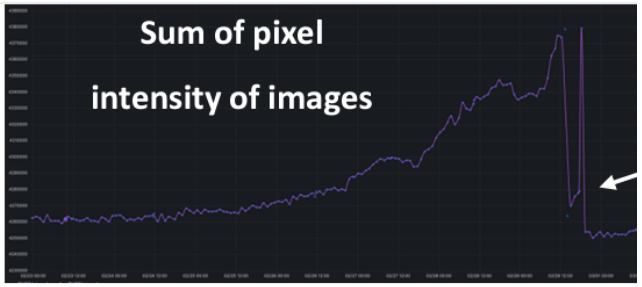
LIME underground operation with full auxiliary system configuration

- Automated system developed to control and monitor remotely HV, gas system, environmental parameters, DAQ, trigger rate, ^{55}Fe calibrations, detector conditions and data taking
- Automatic data reconstruction implemented
- Complementary Grafana online monitor for fast interventions to critical issues
- Fully remote shifts 24/7 from Run4





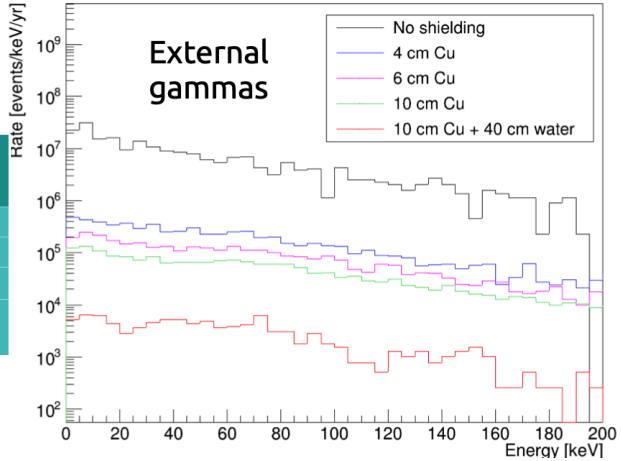




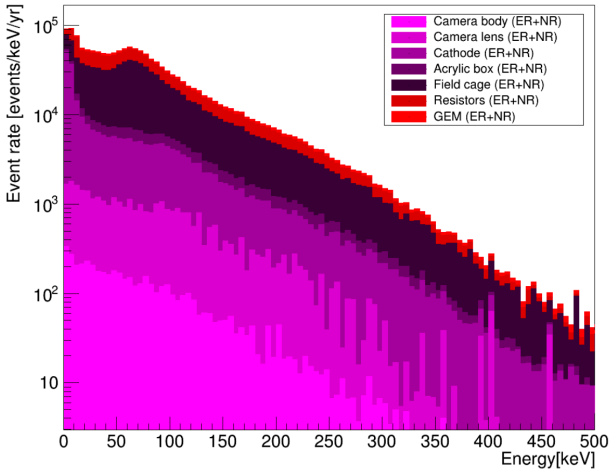
LIME expected backgrounds from MC simulation

External backgrounds

Shielding	Gamma background [10^6 ER yr^{-1}]	Neutron background [NR yr^{-1}]
Unshielded	(1140±30)	(1480±90)
4 cm Cu	(26.2±0.6)	(870±10)
6 cm Cu	(9.4±0.3)	(1000±30)
10 cm Cu + 40 cm H_2O	(0.5±0.2)	(2.0±0.2)



Internal backgrounds



Source	Event rate [10^6 yr^{-1}]
Field cage	(3.57±0.01)
Resistors	(1.873±0.006)
Cathode	(1.095±0.001)
GEMs	(0.3891±0.0002)
Vessel	(0.268±0.001)
Camera lens	(0.151±0.004)
Camera body	(0.0242±0.0005)
TOTAL	**(7.34±0.01)**

Please note LIME was NOT built with radioactive pure components

LIME expected backgrounds from MC simulation

External backgrounds

Shielding	Gamma background [10^6 ER yr^{-1}]	Neutron background [NR yr^{-1}]
Unshielded	(1140±30)	(1480±90)
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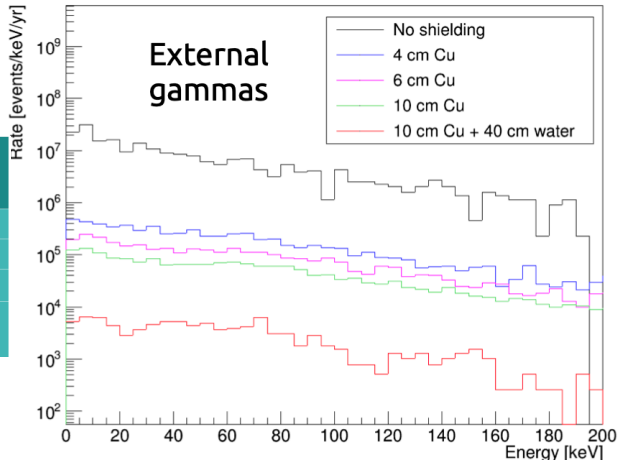
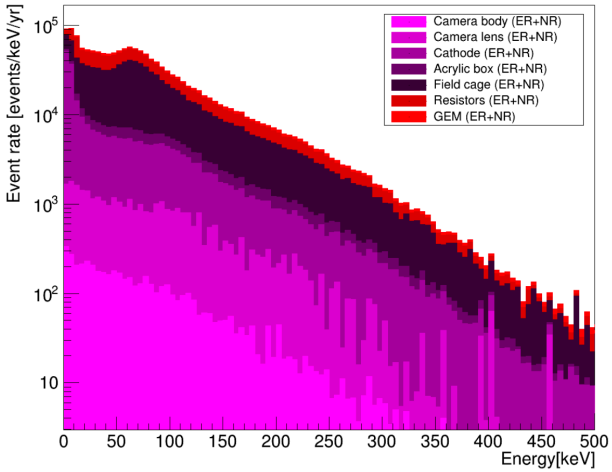


Internal backgrounds



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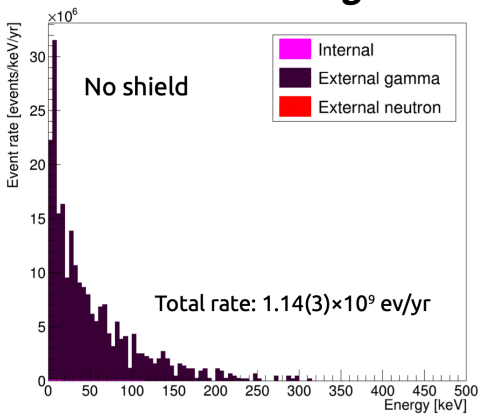
Total backgrounds

no shielding



internal/external bkg
0.6%

LIME expected backgrounds from MC simulation

External backgrounds

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Unshielded	(1140±30)	(1480±90)
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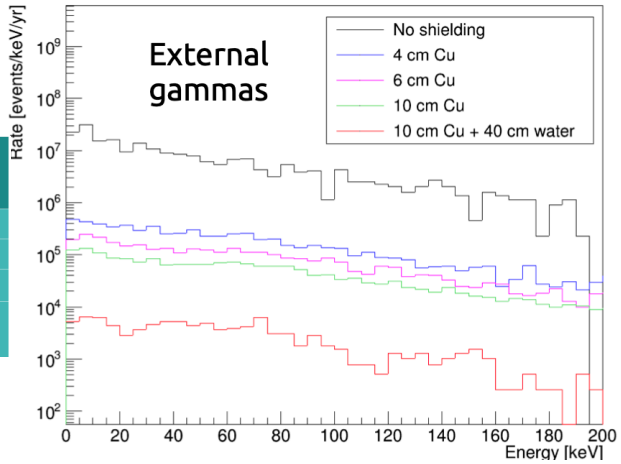
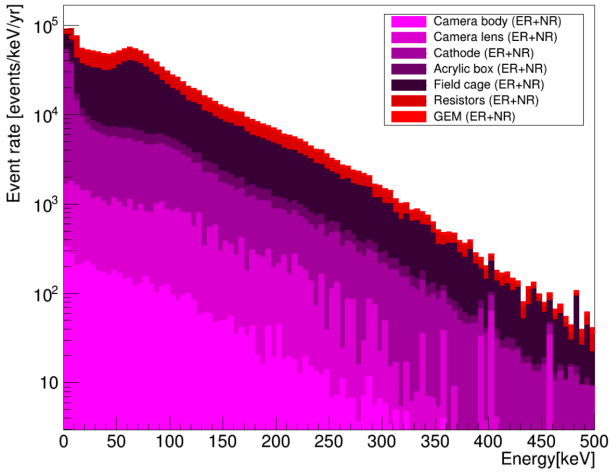
6 cm Cu	(9.4±0.3)	(1000±30)
10 cm Cu + 40 cm H_2O	(0.5±0.2)	(2.0±0.2)



Internal backgrounds



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TOTAL	**(7.34±0.01)**

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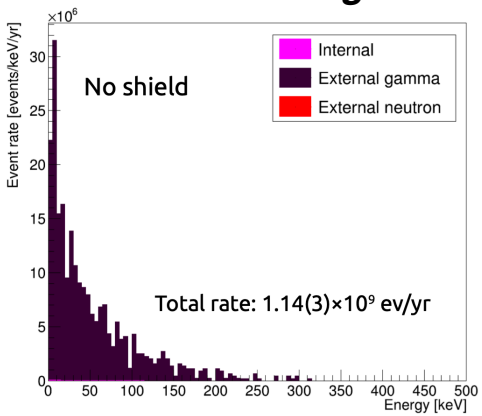
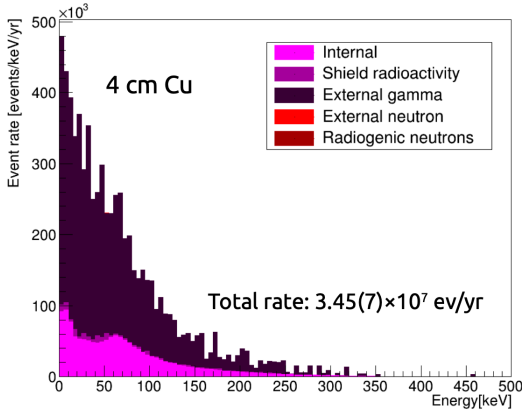
Total backgrounds

no shielding



internal/external bkg
0.6%

4 cm Cu



internal/external bkg
20%

LIME expected backgrounds from MC simulation

External backgrounds

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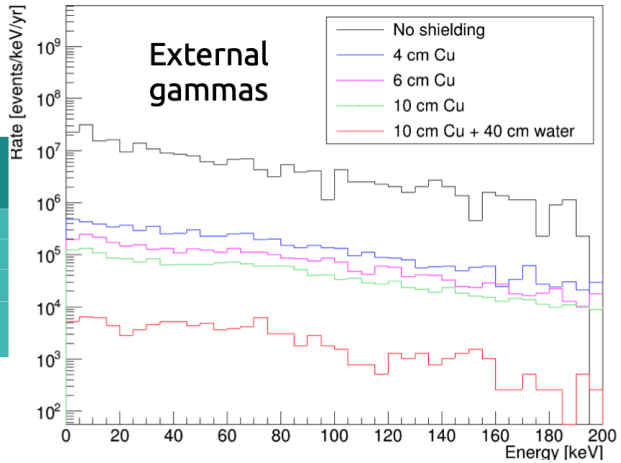
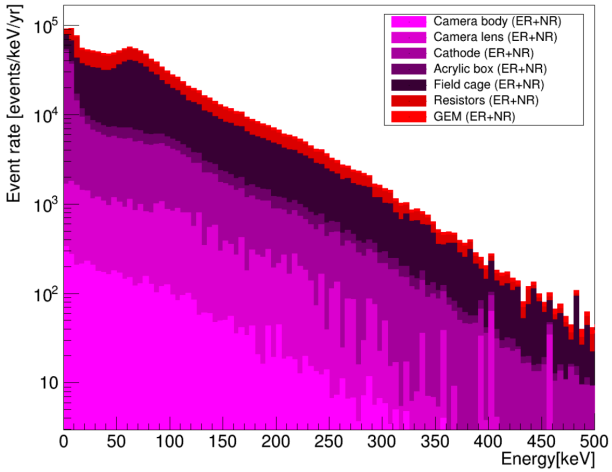
10 cm Cu + 40 cm H_2O	(0.5±0.2)	(2.0±0.2)



Internal backgrounds



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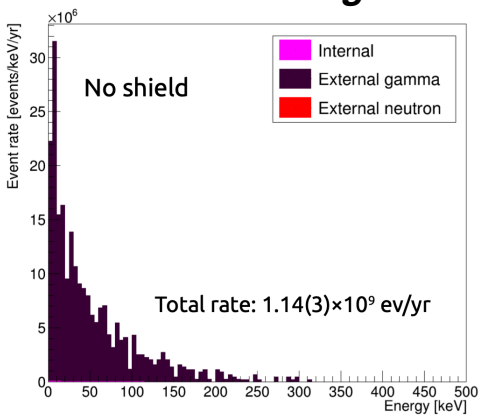
Field cage	(3.57±0.01)
Resistors	(1.873±0.006)
Cathode	(1.095±0.001)
GEMs	(0.3891±0.0002)
Vessel	(0.268±0.001)
Camera lens	(0.151±0.004)
Camera body	(0.0242±0.0005)
TOTAL	**(7.34±0.01)**

Please note LIME was NOT built with radioactive pure components

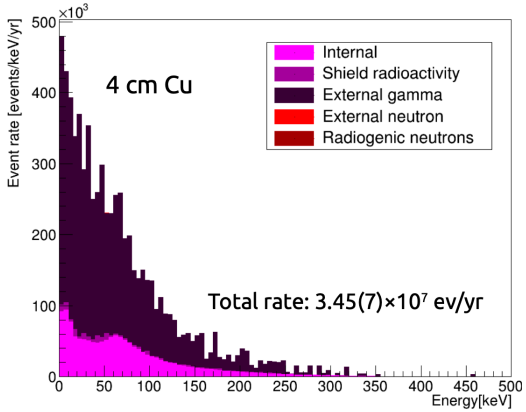
Total backgrounds

no shielding



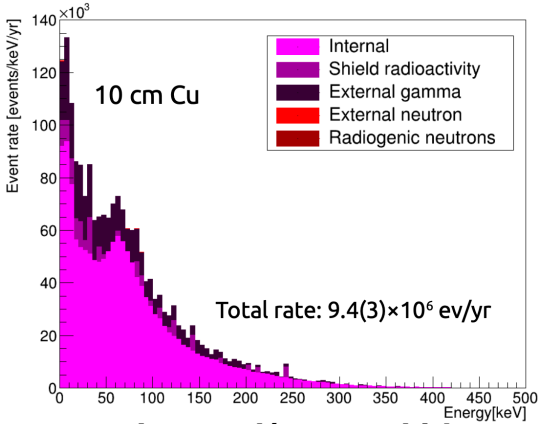
internal/external bkg
0.6%

4 cm Cu



internal/external bkg
20%

10 cm Cu

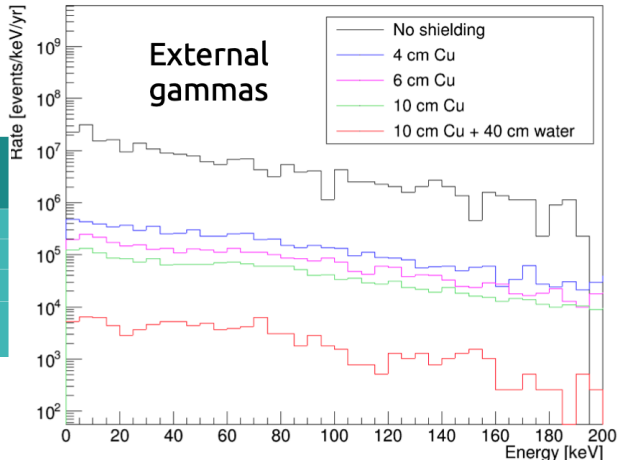


internal/external bkg
78%

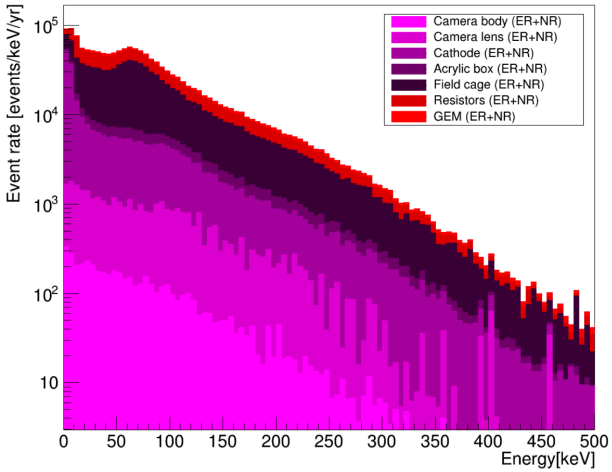
LIME expected backgrounds from MC simulation

External backgrounds

Shielding	Gamma background [10^6 ER yr^{-1}]	Neutron background [NR yr^{-1}]
Unshielded	(1140±30)	(1480±90)
4 cm Cu	(26.2±0.6)	(870±10)
6 cm Cu	(9.4±0.3)	(1000±30)
10 cm Cu + 40 cm H_2O	(0.5±0.2)	(2.0±0.2)



Internal backgrounds



Source	Event rate [10^6 yr^{-1}]
Field cage	(3.57±0.01)
Resistors	(1.873±0.006)
Cathode	(1.095±0.001)
GEMs	(0.3891±0.0002)
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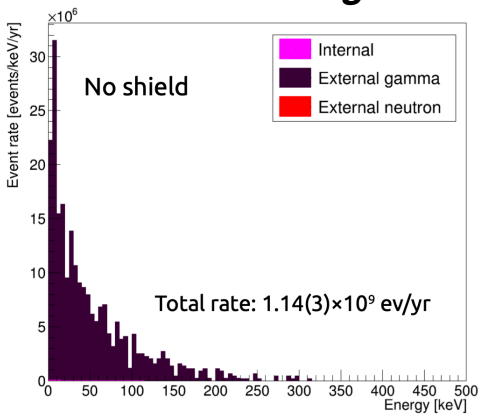
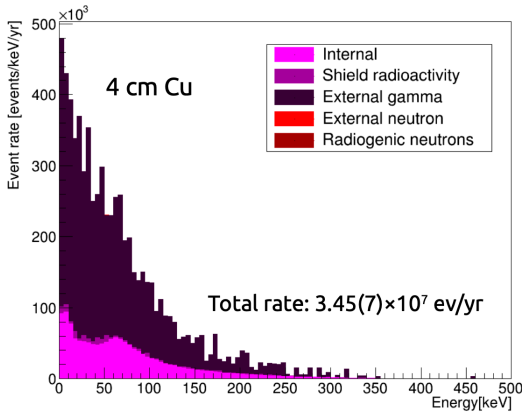


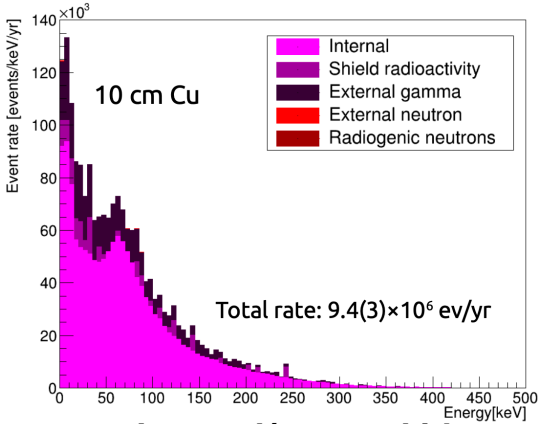
internal/external bkg
0.6%

4 cm Cu



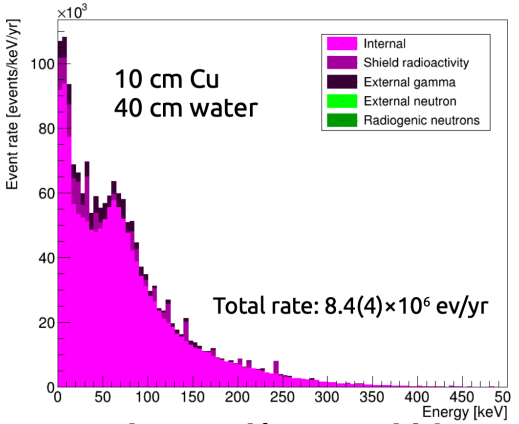
internal/external bkg
20%

10 cm Cu



internal/external bkg
78%

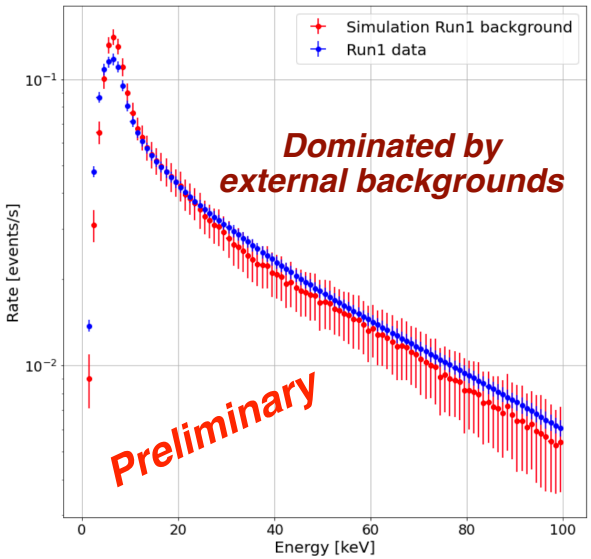
10 cm Cu + 40 cm H_2O

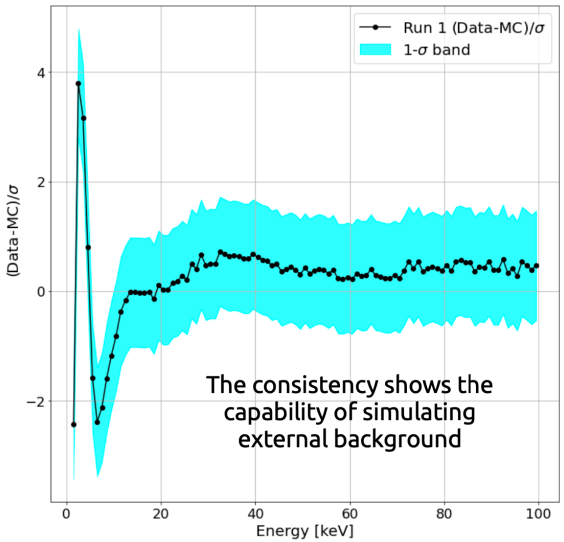


internal/external bkg
87%

LIME underground data/MC comparison results

Run1

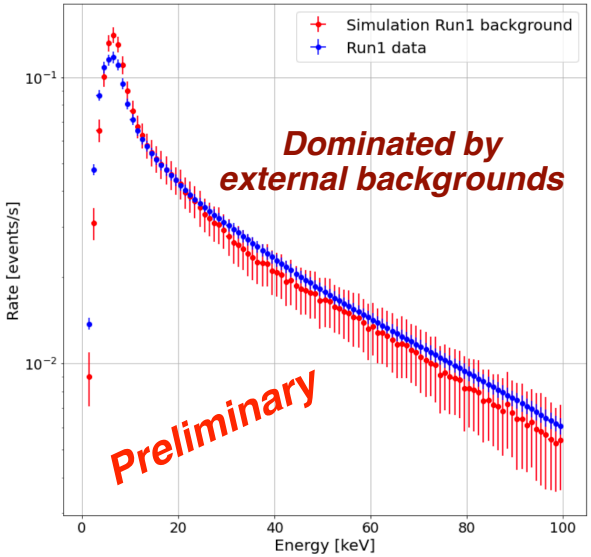


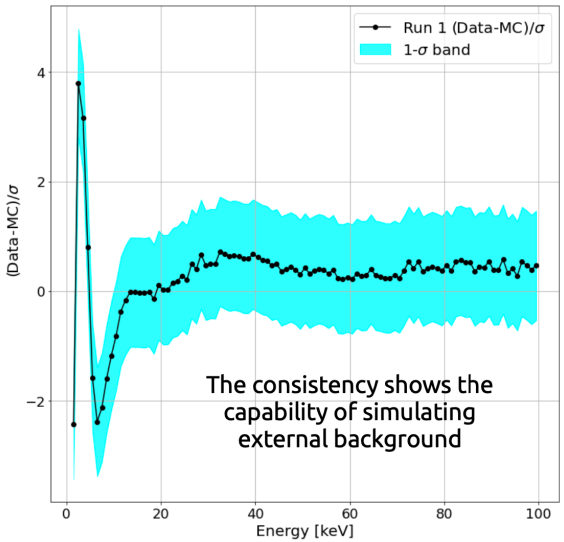


Data/MC agreement

LIME underground data/MC comparison results

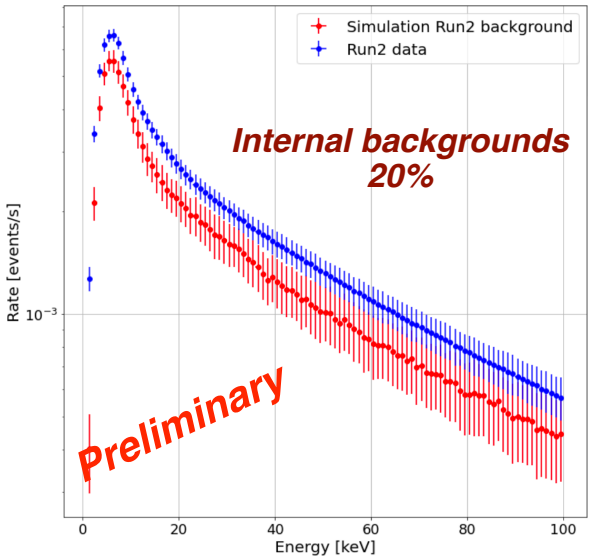
Run1

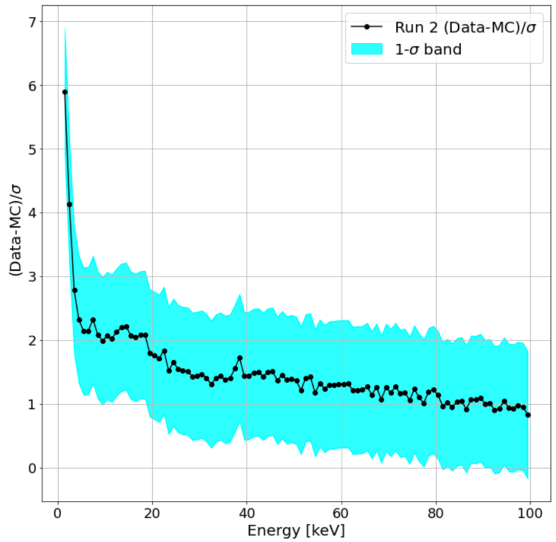




Data/MC agreement

Run2

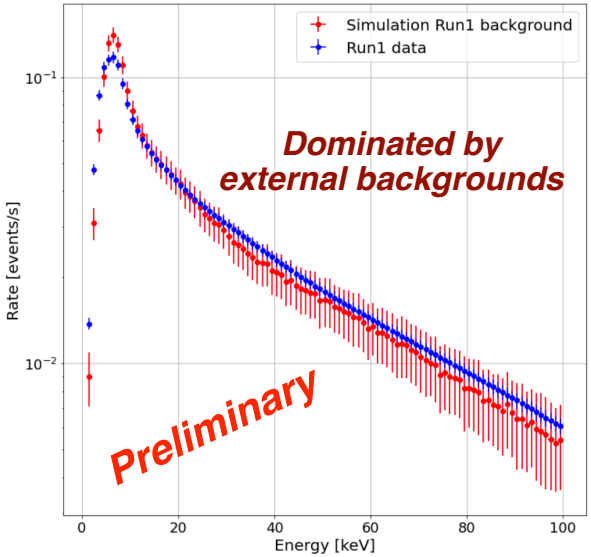


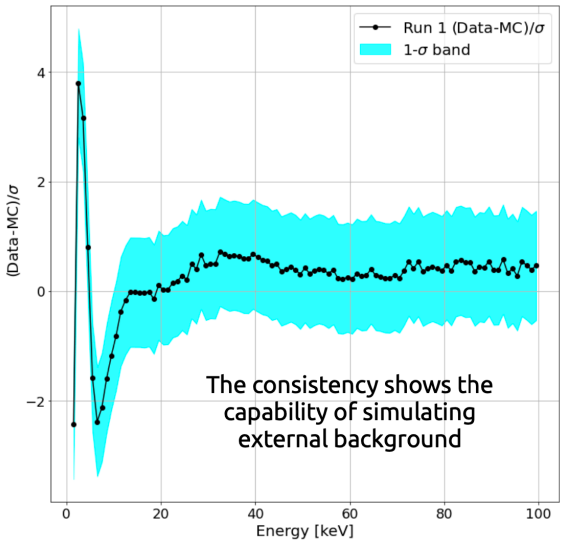


Data/MC difference ±22%

LIME underground data/MC comparison results

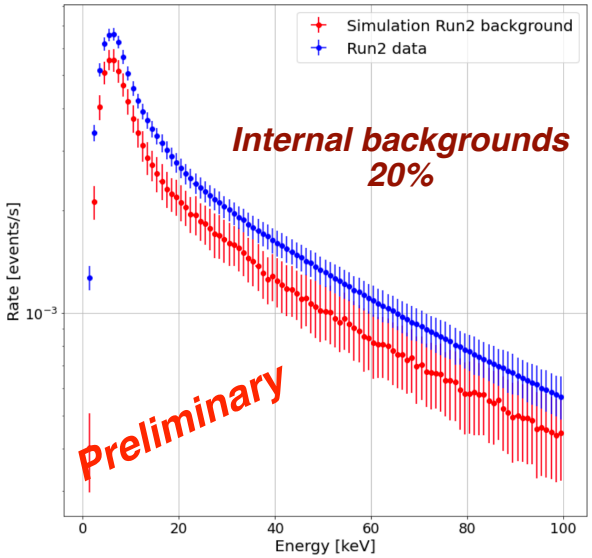
Run1

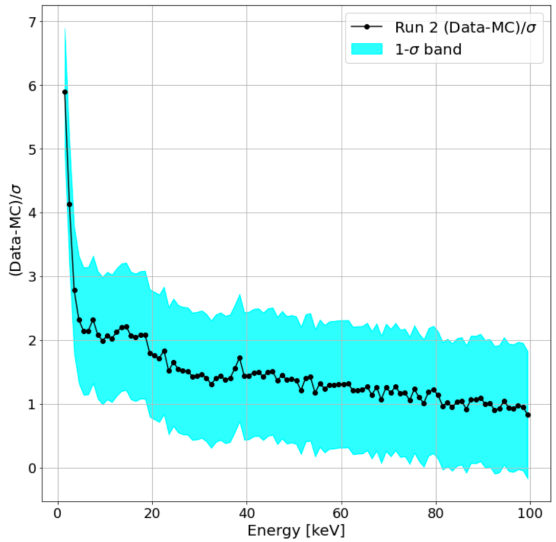




Data/MC agreement

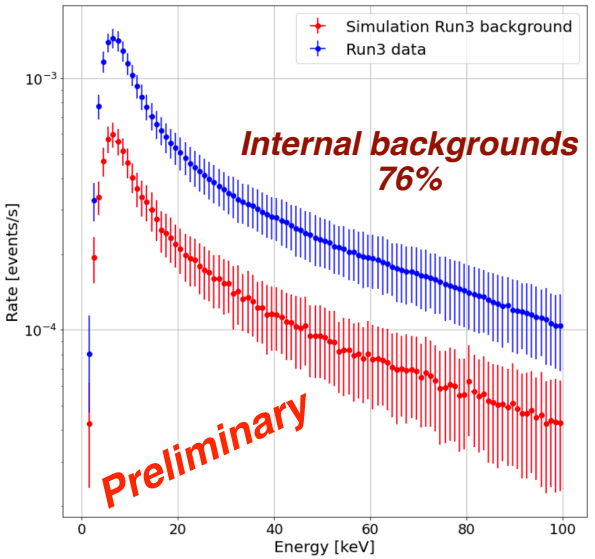
Run2

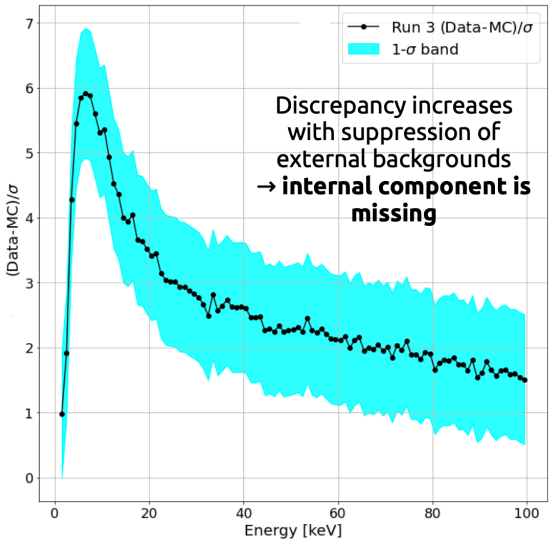




Data/MC difference ±22%

Run3

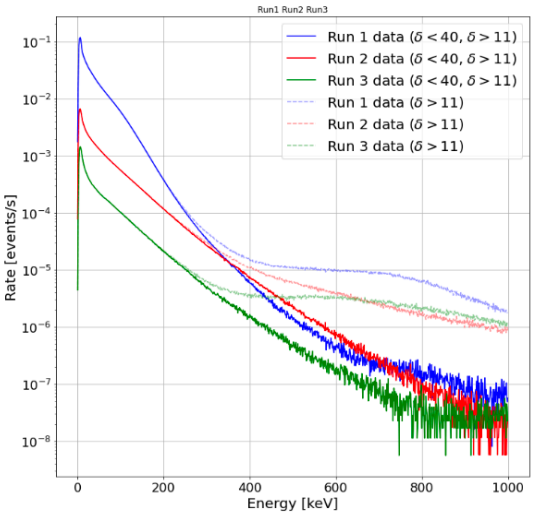




Data/MC difference ±60%

A closer look into the missing component

- **Excess of α** events in all runs (long, dense tracks)
  - Alphas from GEANT4 (not simulated) are not enough to explain the excess
- Due to gain saturation, alphas direct energy measurement not feasibile



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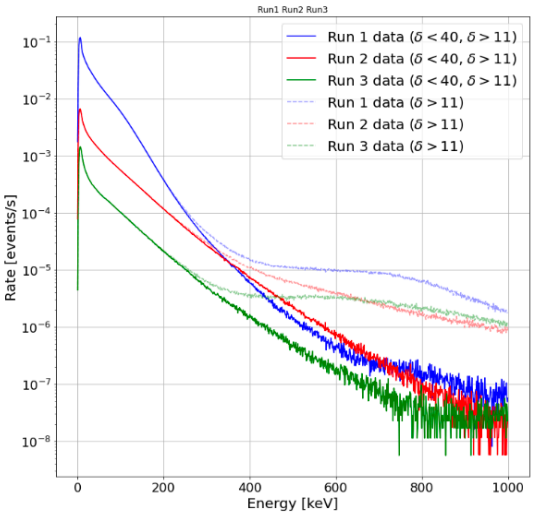
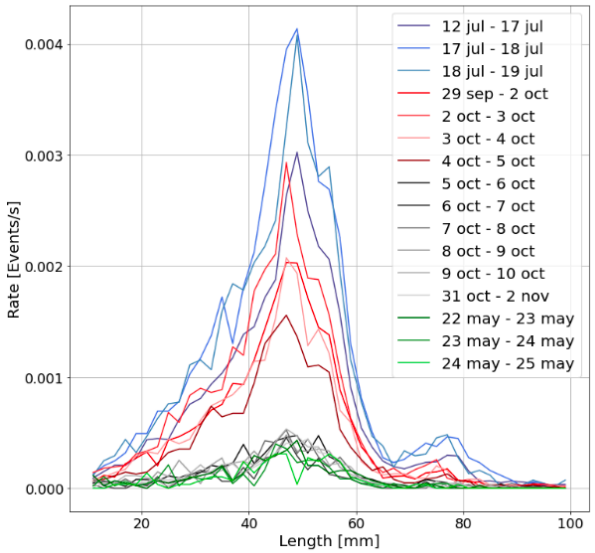
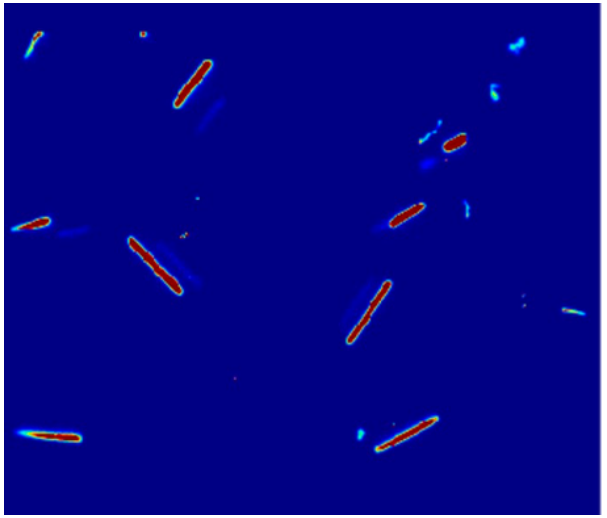


- **Length** distribution indicates peaks around 5.9 MeV, 6.6 MeV, 8.1 MeV peaks (might be ^{222}Rn)





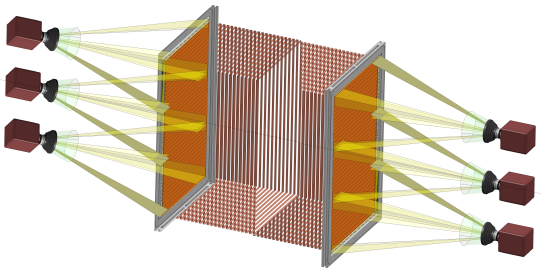
- Radioactive contamination might also induce beta and gamma events, populating the **low energy region**
- Further studies to identify the source (ongoing)

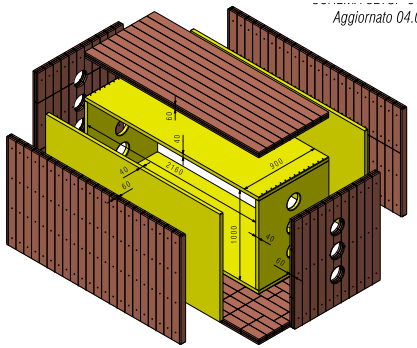
Low radioactivity Radon filter installed at the end of Run4!

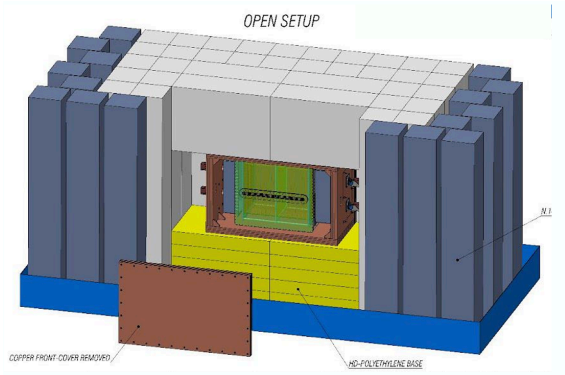
JINST 19 (2024) 03, P03012

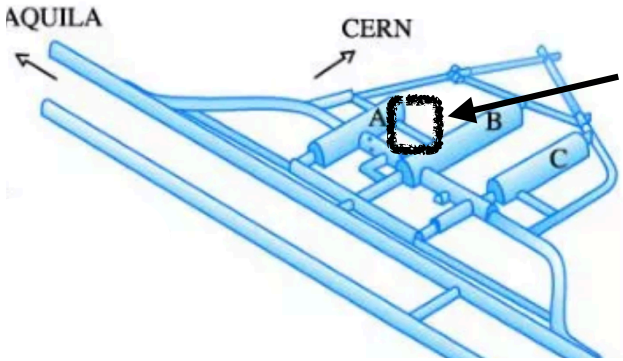
CYGNO TDR, DOI:10.15161/oar.it/76967

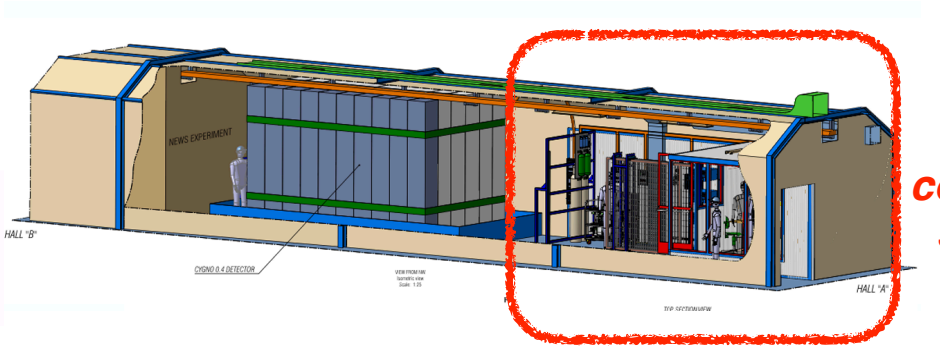
PHASE 1: CYGNO_04 design in LNGS Hall F





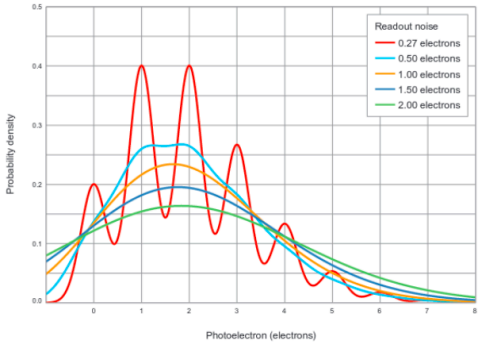


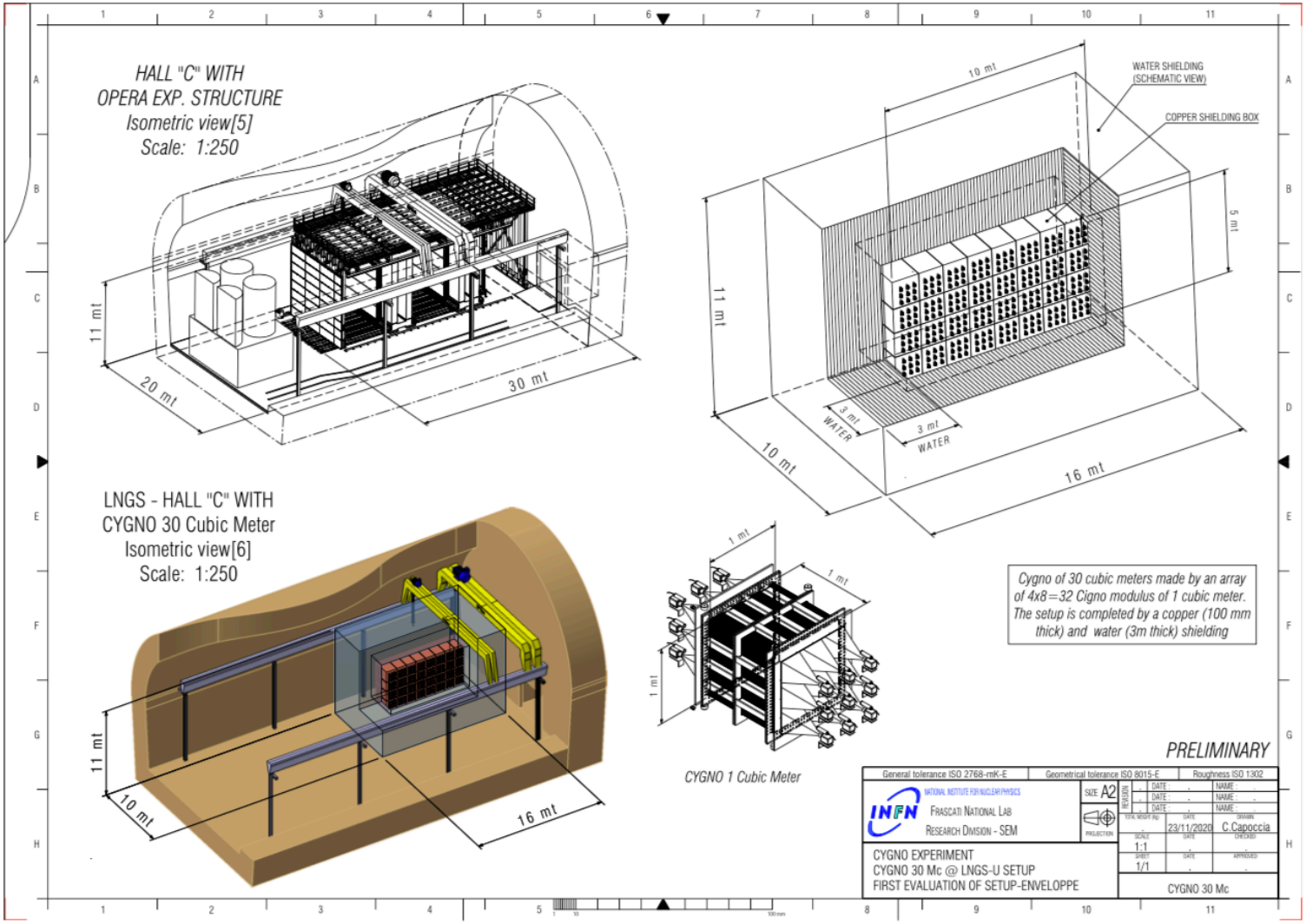




Infrastructure construction work starting in June

- 2 TPCs back to back, 50 cm drift, 0.4 m³ active volume
- 50 x 80 cm² readout area per side
- Triple 50 um GEMs amplification per side
- 3 sCMOS Orca Quest + 6 PMTs per side
  - Effective granularity 130 x 130 um² + 100 um along Z
- Goals:
  - Minimise internal radioactivity on a realistic experimental layout and scale
  - Assess actual potentialities of a large O(30) m³ PHASE 2 experiment to reach the expected physics goals

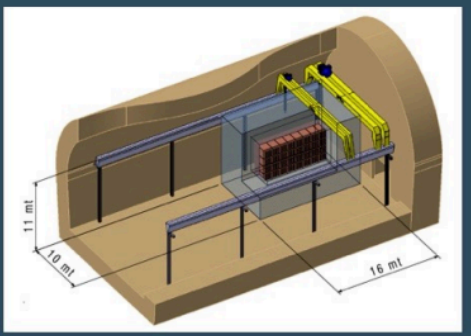




PHASE 2:
30 m³ Experiment

2026..
LNGS

CYGNO_30



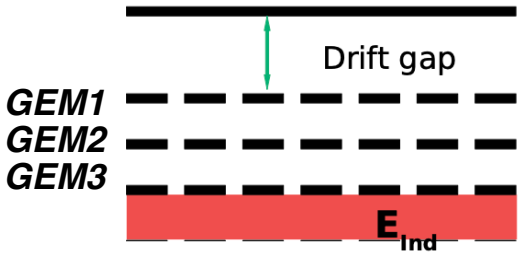
- Physics research

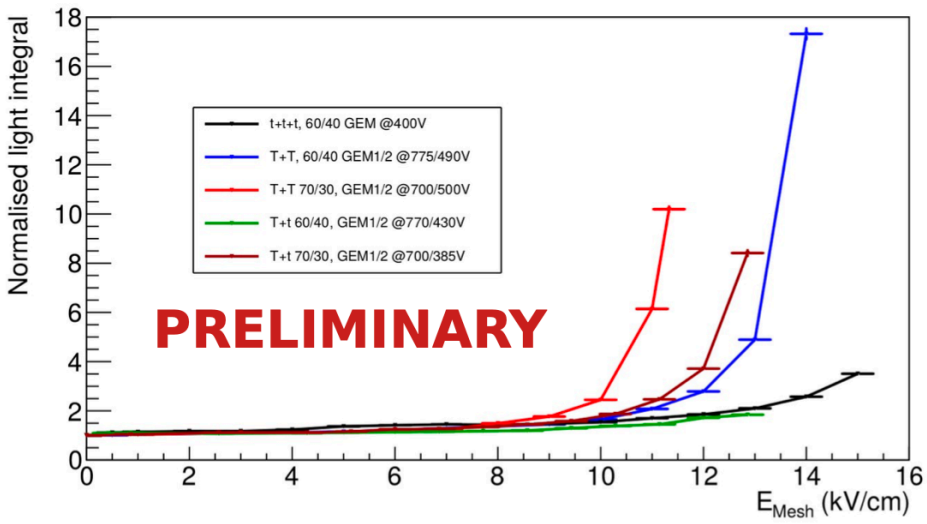
Multiple stacked CYGNO-04 like modules

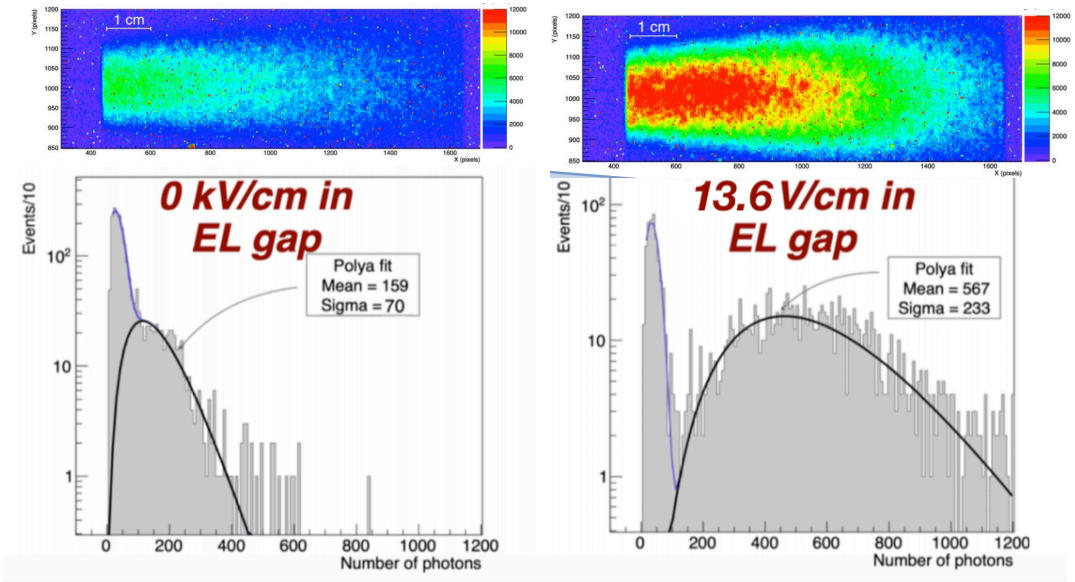
R&Ds towards CYGNO-30: lower the energy threshold

Paper on arXiv tomorrow!

- The possibility of increasing the light yield is under study to lower the energy threshold
- By applying a strong O(10) kV/cm induction field after the last GEM, additional secondary photon are produced
- Up to a factor 2 enhancement achieved for standard CYGNO amplification and gas mixture without any degradation in diffusion or resolutions
- Up to nearly a factor 20 enhancement achievable with altenative amplification strategies/gases fractions







^{55}Fe spectrum

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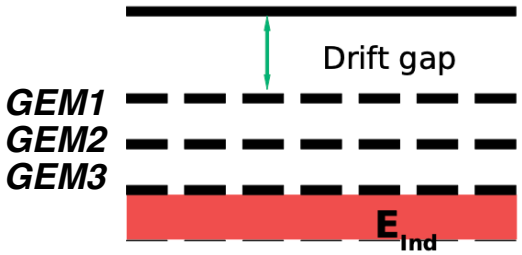
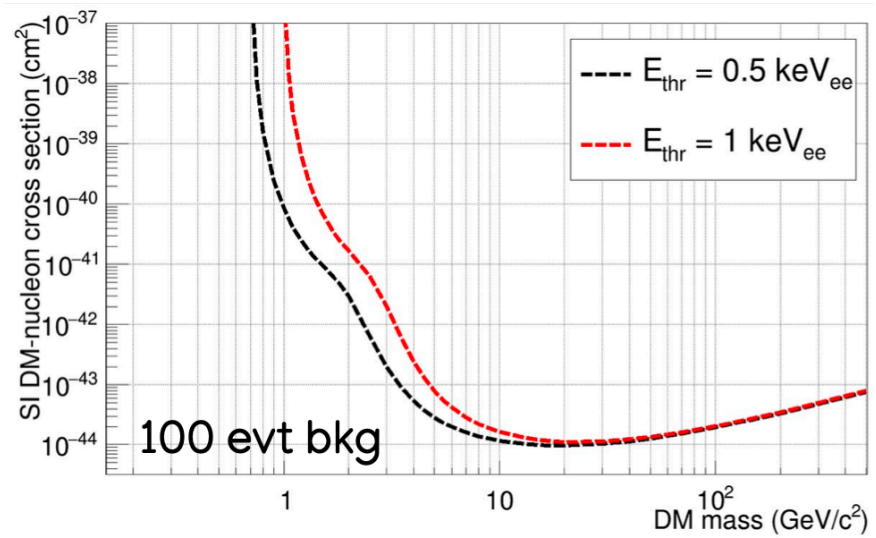
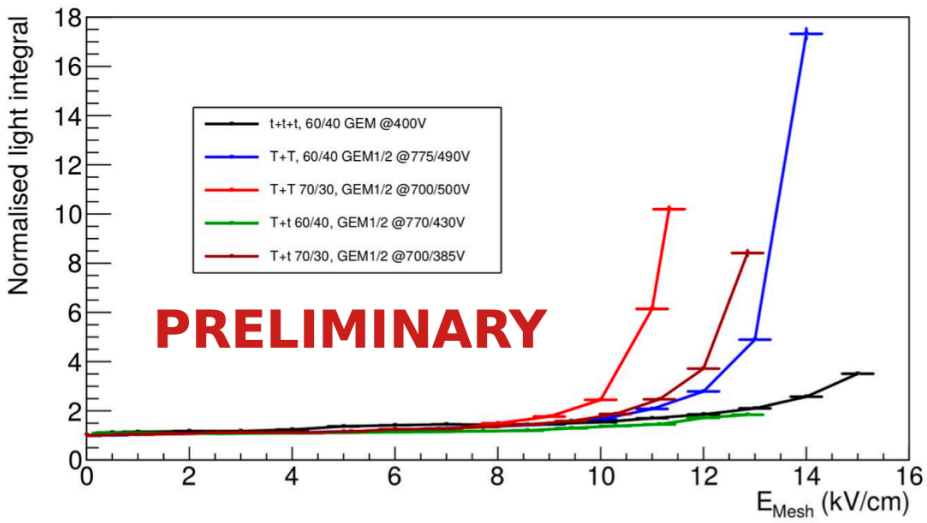
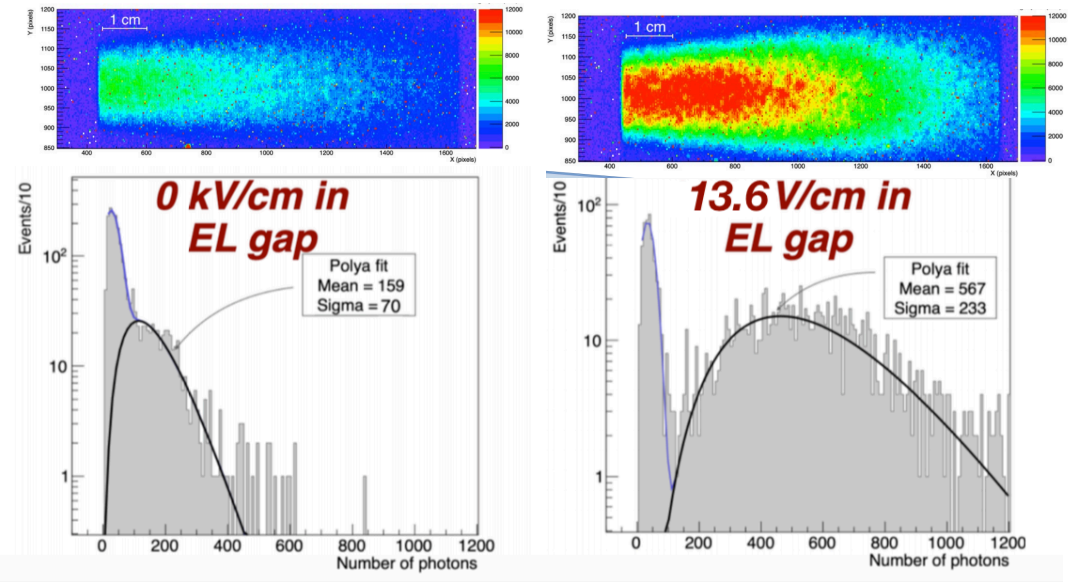






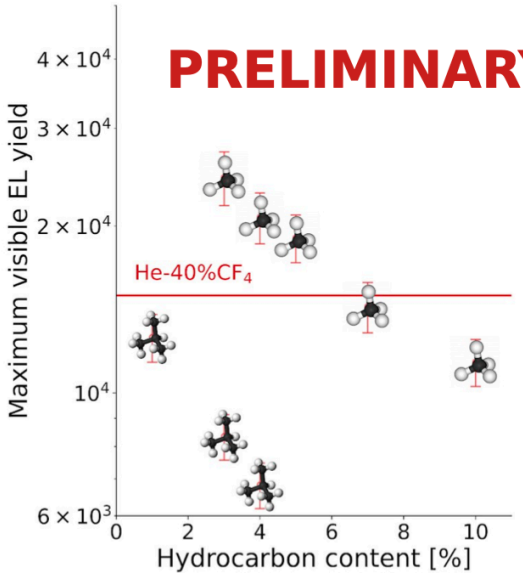


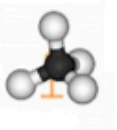
^{55}Fe spectrum

R&Ds towards CYGNO-30: increase sensitivity to O(GeV) WIMP masses

Paper under journal review

- Possibility of adding hydrogen-rich gases under study to increase sensitivity to lower WIMP masses
- Isobutane (iC_4H_{10}) and methane (CH_4) in < 10% concentration tested
- While overall light yield is quenched by hydrocarbons, the addition of methane allowed to reach higher gains effectively achieving higher LY





CH_4

iC_4H_{10}

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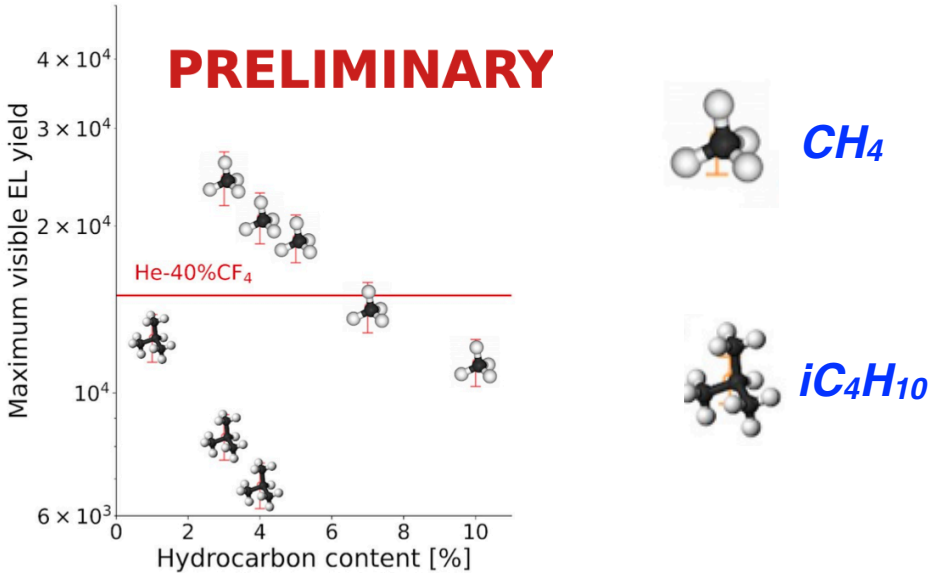
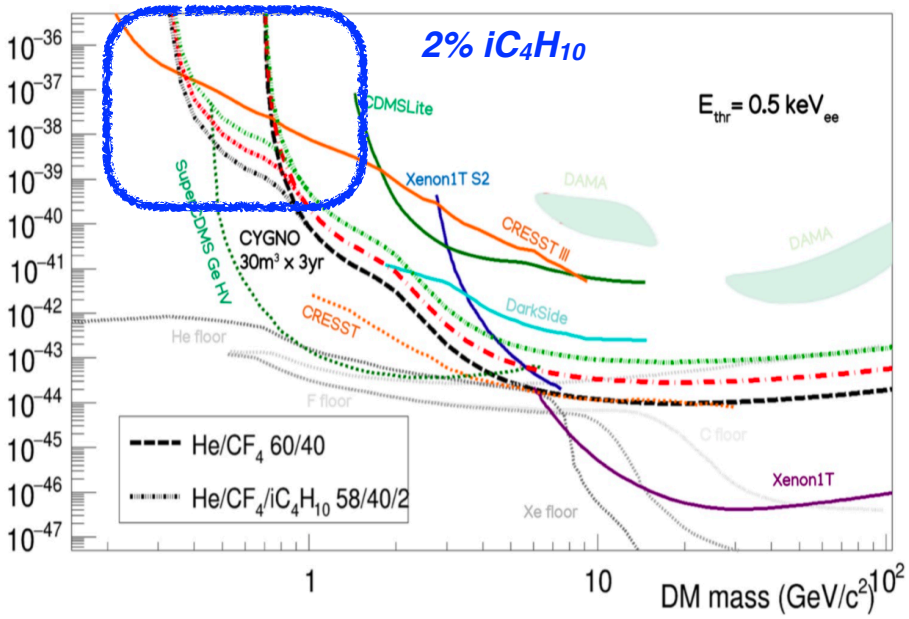
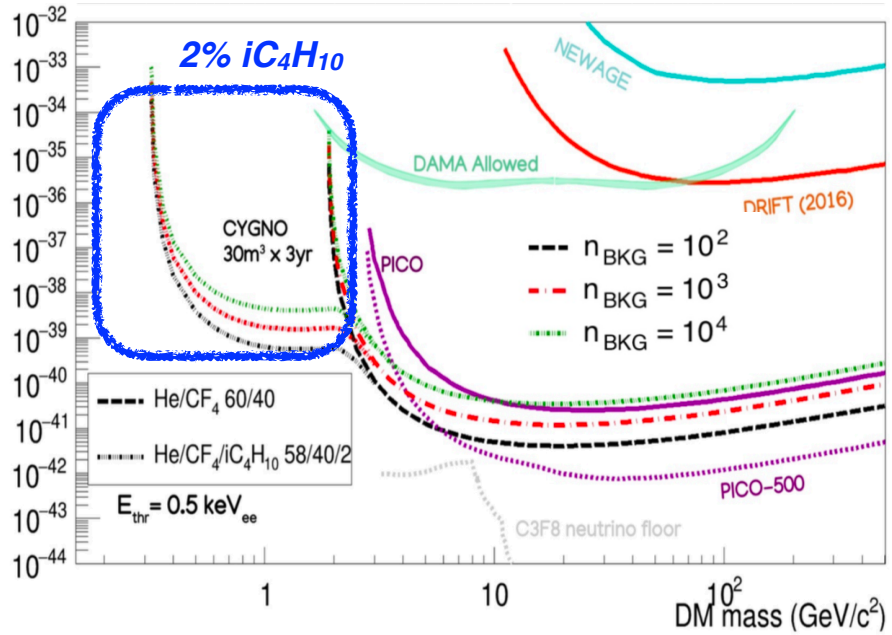


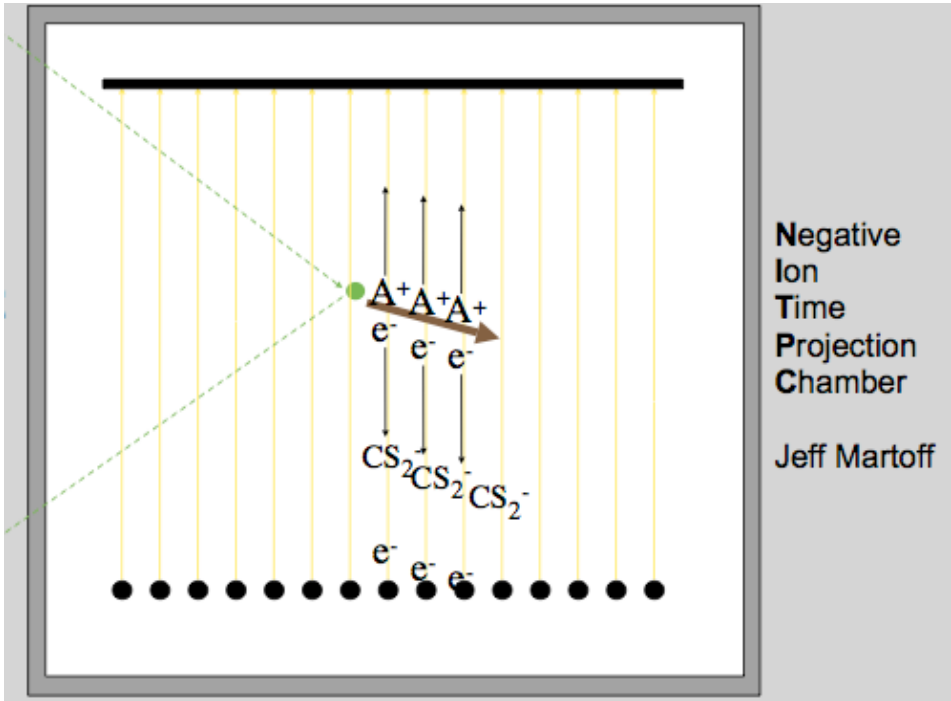




R&Ds towards CYGNO-30: improve tracking performances & scalability

T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355



- Electronegative dopant in the gas mixture (CS_2, 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
- Longitudinal and transverse diffusion reduced thanks to the large mass of the charge carrier
  - Allow for realisation of larger TPC volume with same (or improved) tracking performance
- Negative ion drift velocity is O(cm/ms), compared to O(cm/us) electon drift velocity because of larger mass
  - Significant improvement of resolution along drift direction thanks to slower image carriers for low rate applications

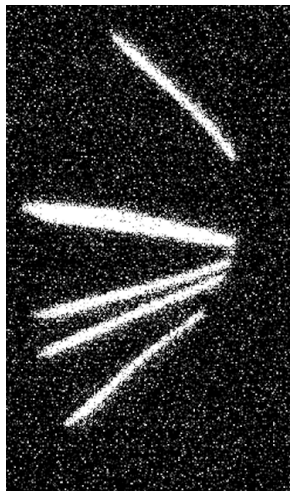
IN TIUM

INITIUM goal is to realise NID operation within the CYGNO approach

R&Ds towards CYGNO-30: improve tracking performances & scalability

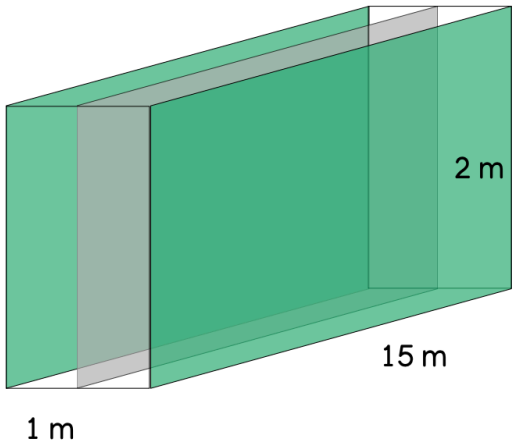
From this…. ***….to this with same experimental layout***

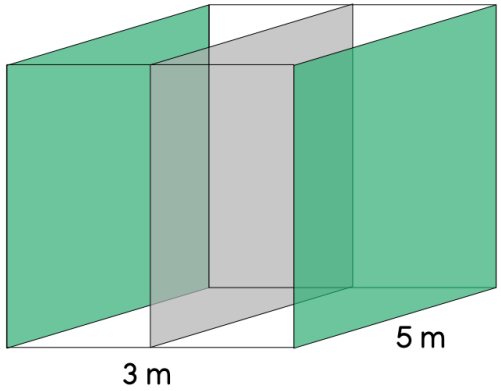
$He:CF_4$ 60:40



$He:CF_4:SF_6$ 59:39.4:1.6

From this…. ***….to this with same tracking performances***





30 m² less surface:
Less material (background)
Less redout sensors

Negative Ion Drift studies

0.90 atm
(LNGS atmospheric pressure)

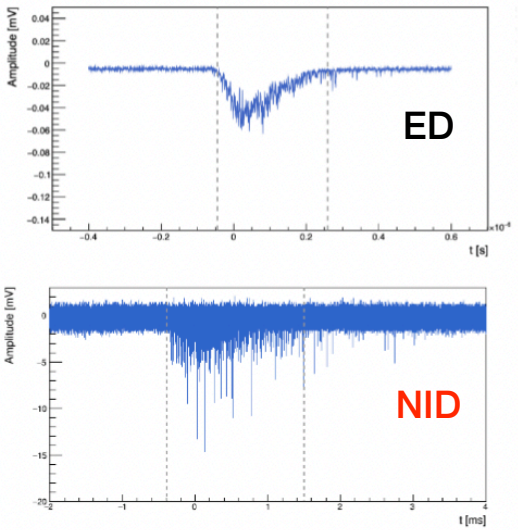
- **Negative Ion Drift studies: diffusion and mobility**
  - **Base mixture $He:CF_4:SF_6$**
  - **Multiple relative fraction of He/CF_4 tested with 1.6% of SF_6**
  - **Tranverse diffusion via sCMOS images analysis**
  - **Longitudinal diffusion via PMT waveform analysis**
  - **Finalisation of analysis and interpretation of the results on going**

To our knowledge,this is the first time ever NID operation at 900 mbar with optical readout is measured

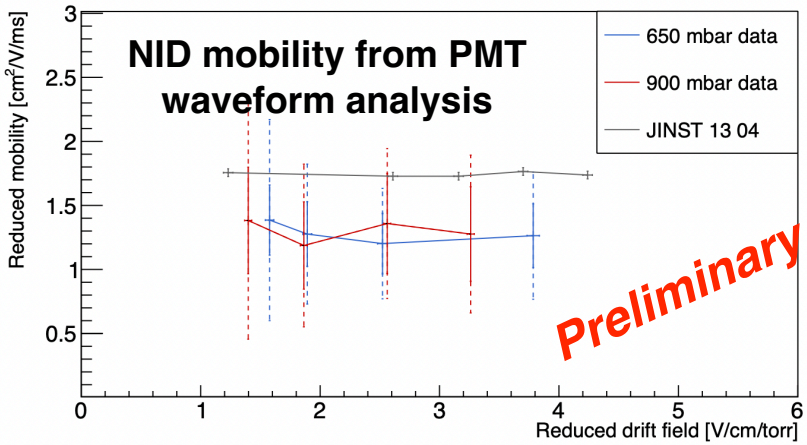
Gas	Diffusion @1 kV/cm [$\frac{\mu m}{\sqrt{cm}}$]
$Ar:CH_4$ (90/10):	600
$He:CF_4$ (60/40):	140
$He:CF_4:SF_6$ (59:39.4:1.6):	**35**

Preliminary

PMT waveforms



O(0.1 us) time extent for ED
O(10 ms) time extent for NID



Conclusions & outlook

- Directionality as a tool for positive DM signature identification
- Successful operation of 50 L detector underground for > 1 year
  - Stable and high quality operation achieved with full auxiliary system
  - High quality data and highly consistent MC simulation allowed to identify Radon contamination impossible to predict in advance
- Development towards CYGNO-04 realisation advancing
  - Construction expected to be completed by Fall 2025
- Several R&Ds under development towards CYGNO-30
  - First ever demonstration of NID operation at atmospheric pressure with 3D optical readout
  - Lowest measured diffusion ever reported to our knowledge

Conclusions & outlook

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- **Successful operation of 50 L detector underground for > 1 year**
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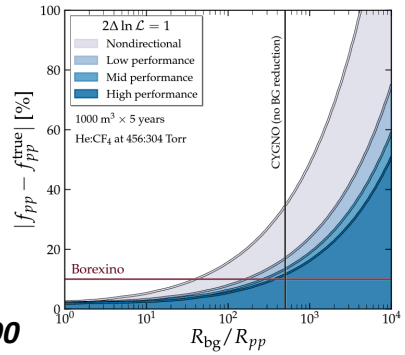
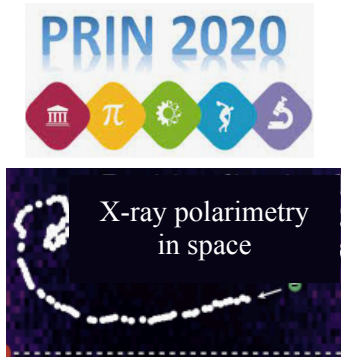
One, no one and one hundred thousand CYGNO/INITIUM approach applications!

Sun pp cycle



S. Torelli PhD thesis & arXiv:2404.03690

"Zero radioactivity in future experiments"



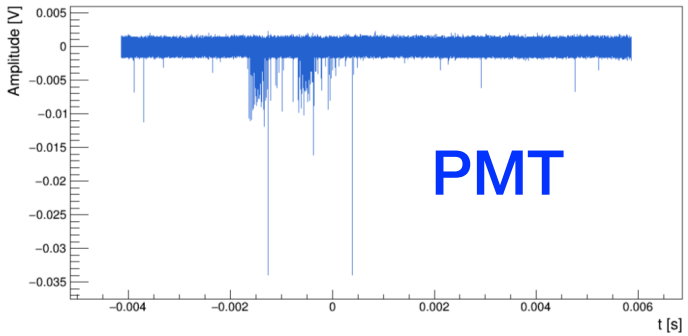
"HypeX: High Yield Polarimentry Experiment in X-rays"

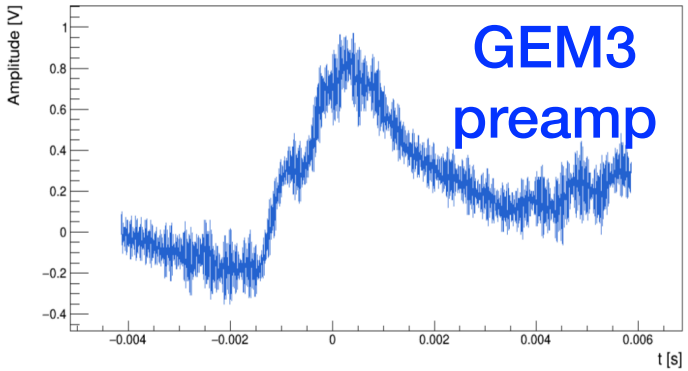
"FINEM: Full Imaging of Nuclear recoil for Experimental Migdal measurement"

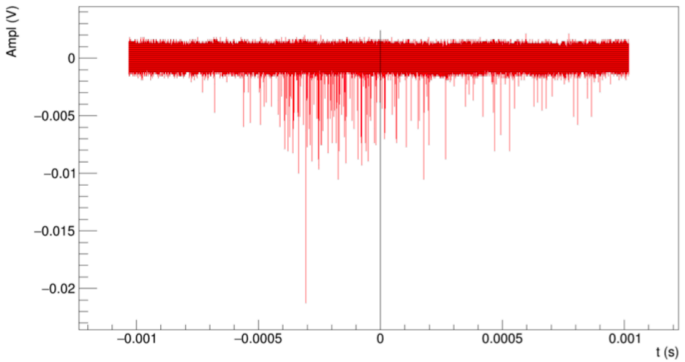
Backup slides

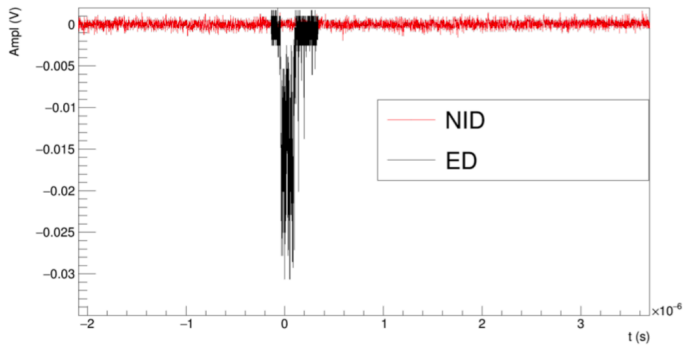
*First time ever NID are observed with PMTs!

NID PMT waveforms: how peculiar!

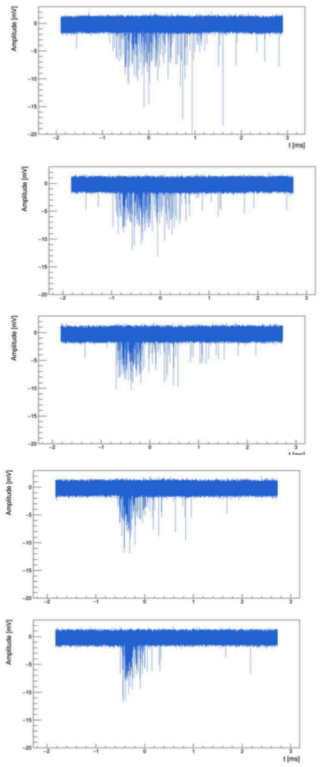




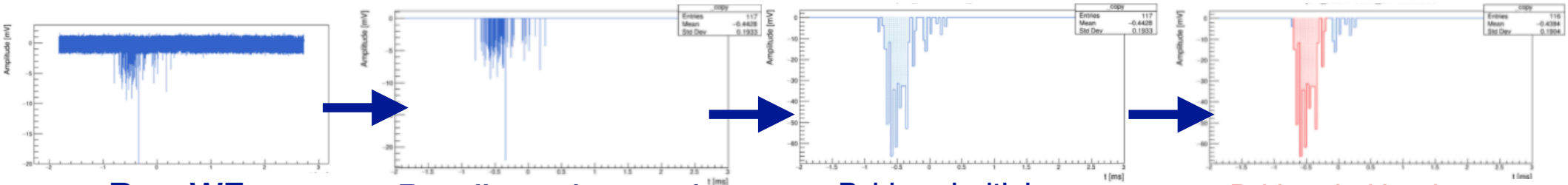




NID WF at varying drift field



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



Raw WF

Baseline subtracted

Rebinned with loose constraints

Rebinned with only over threshold peaks considered

From neutrino floor to neutrino fog

D. S. Akerib et al., 2022 Snowmass Summer Study, arXiv:2203.08084

C. A. J. O'Hare, Phys. Rev. Lett. 127 (2021) 25, 251802

- **Discovery limit as function of the observed *N* neutrino background events and uncertainty δΦ on neutrino fluxes**

Background free

$$N < 1, \sigma \propto 1/N$$

Poissonian background subtraction

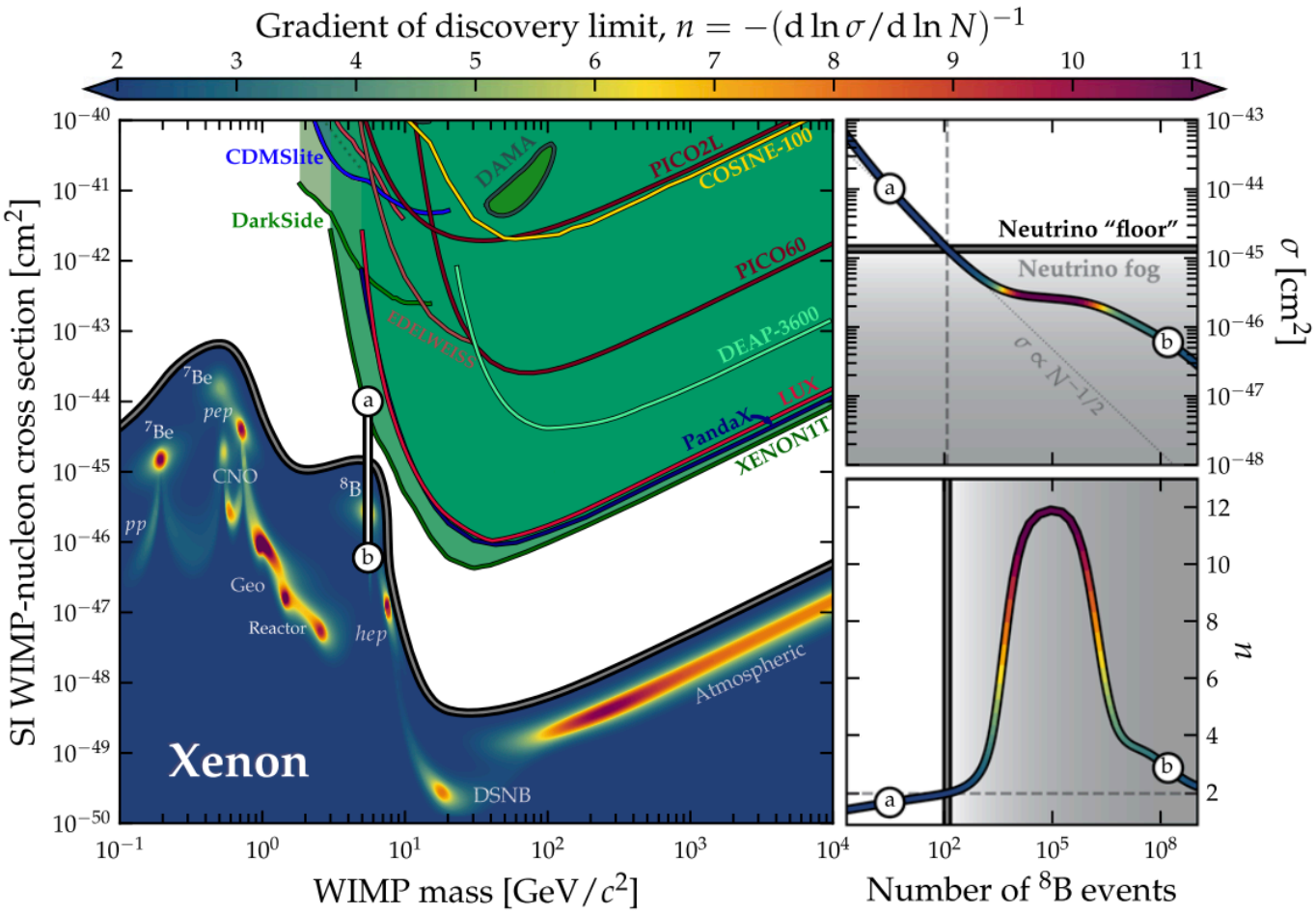
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

Purely dominated by systematics

$$N\delta\Phi^2 \gg 1, \sigma \propto \sqrt{(1+N\delta\Phi^2)/N}$$

- ***n* is defined so that *n = 2* under normal Poissonian subtraction, and *n > 2* when there is saturation**
  - **The value of the cross section *σ* at which *n* crosses 2 is defined as the neutrino floor.**

$$n = -\left(\frac{d\log\sigma}{d\log MT}\right)^{-1}$$



Reducing the sensivity of an experiment by a factor *x* requires an increas in the exposure by *at least* x^n

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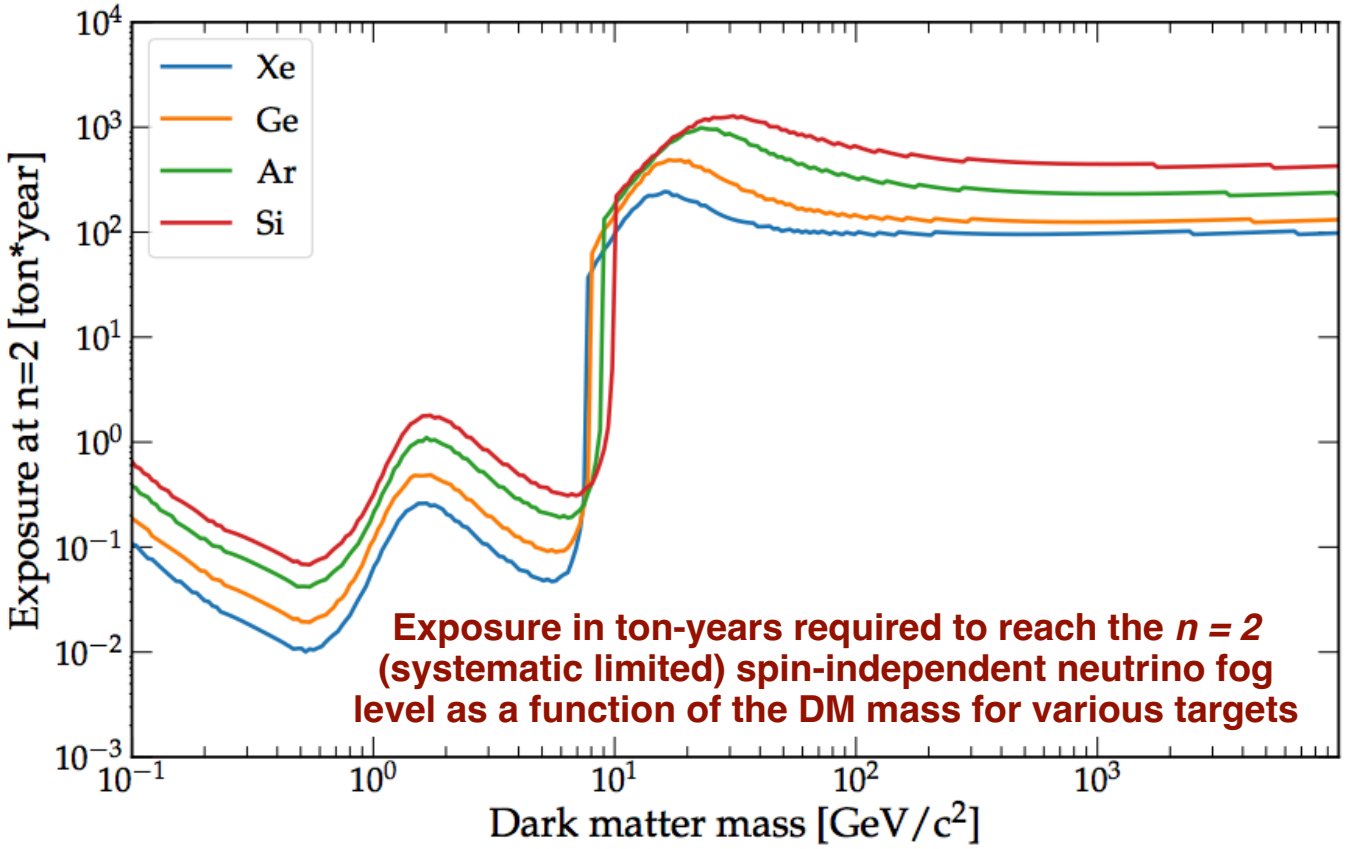


Exposure in ton-years required to reach the *n = 2* (systematic limited) spin-independent neutrino fog level as a function of the DM mass for various targets

Reducing the sensivity of an experiment by a factor *x* requires an increas in the exposure by *at least* x^n

Gaseous TPCs landscape

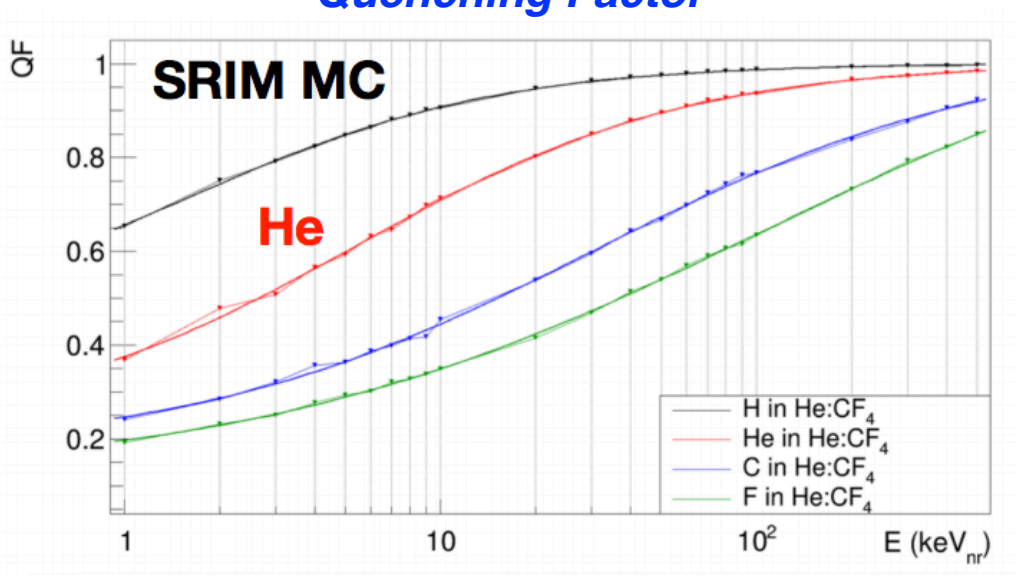
	Established readout & directionality	Established gas	R&D readout	R&D gas	Largest detector realised	Detector under development
MIMAC	Micromegas + FADC 3D	CF_4:CHF_3:C_4H_{10} @ 0.05 bar			0.05 m^3 (underground)	1 m^3 (under study)
DRIFT	MWPC 1.5 D	CS_2:CF_4:O_2 @ 0.05 bar	THGEM + wire/ micromegas	SF_6:(CF_4) @ 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 (funded)
CYGNUS			All of the above	Helium-Fluorine @ 1 bar		1000 m^3

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

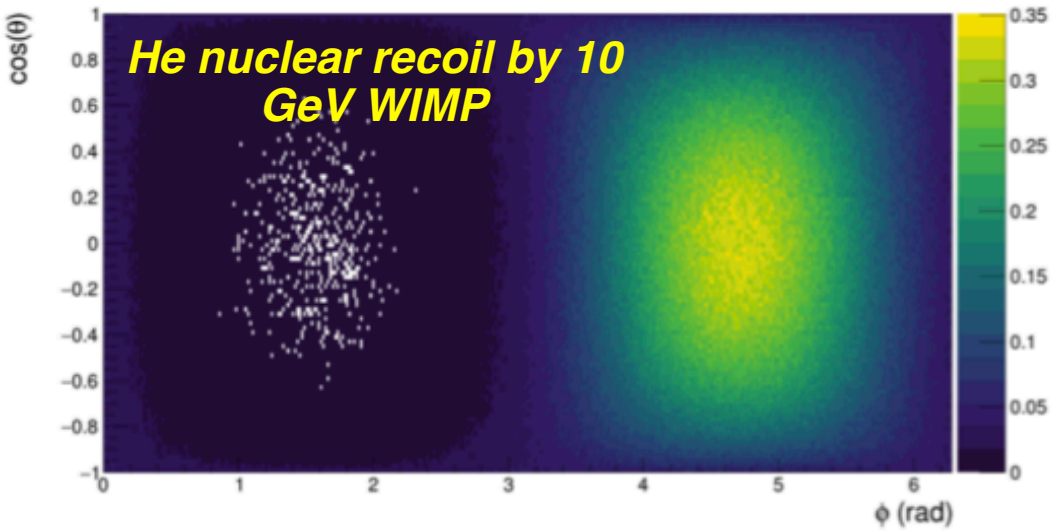
CYGNO PHASE 2 sensitivity evaluation

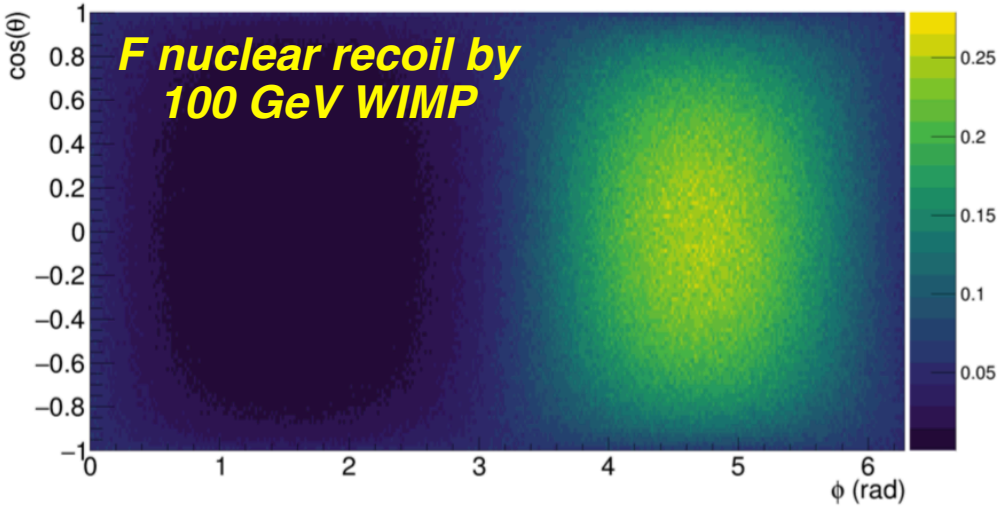
- Use 1 keV_{ee} threshold
- Evaluate QF with SRIM
- Introducing **angular distribution** as discriminating
- Full head/tail recognition
- Using a 30 deg resolution

Quenching Factor



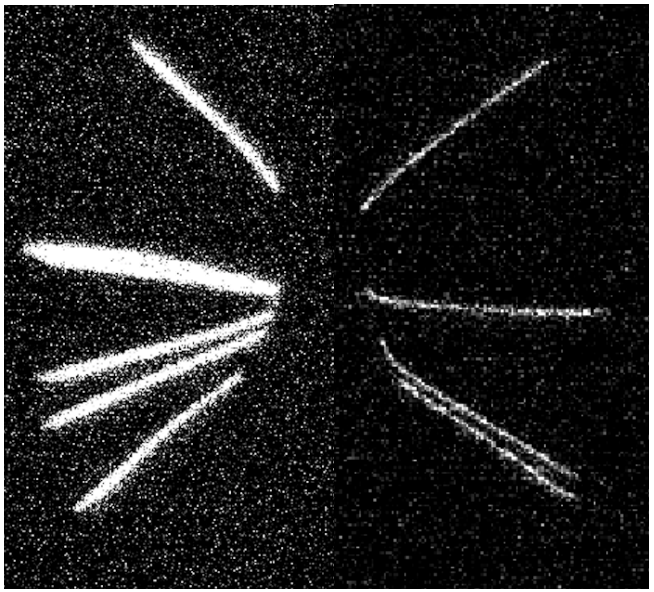
Examples of expected measured angular distribution in Galactic coordinates



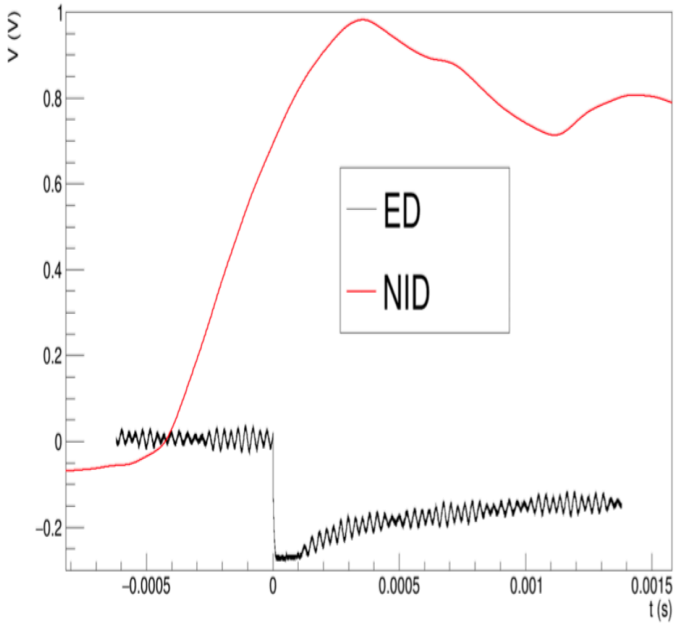


Eyes (and waveforms) can't lie

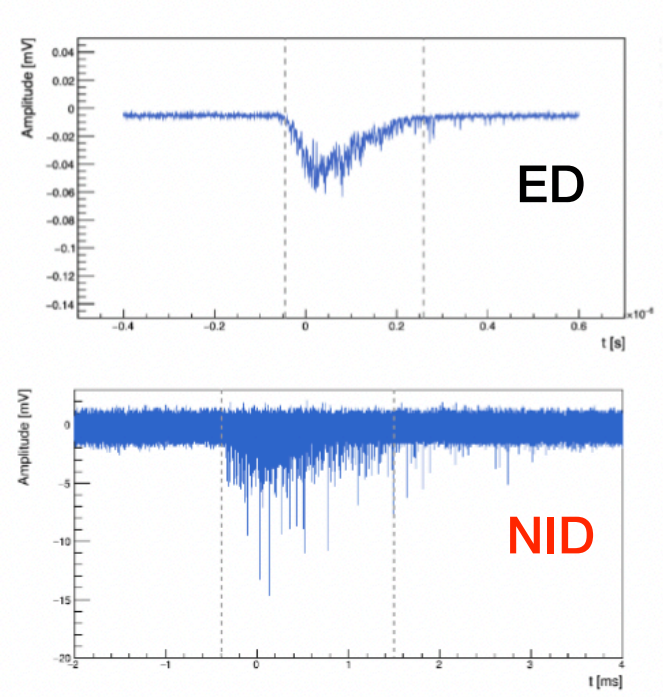
sCMOS image



GEM preamp output



PMT waveforms



$He:CF_4$
60:40
1 kV/cm
(ED)

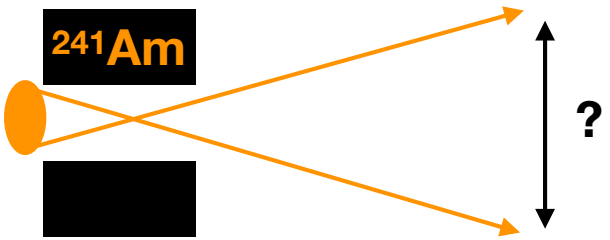
$He:CF_4:SF_6$
59:39.4:1.6
0.4 kV/cm
(NID)

O(us) rise for ED
O(ms) rise for NID

O(0.1 us) time extent for ED
O(10 ms) time extent for NID

0.90 atm
(LNGS atmospheric pressure)

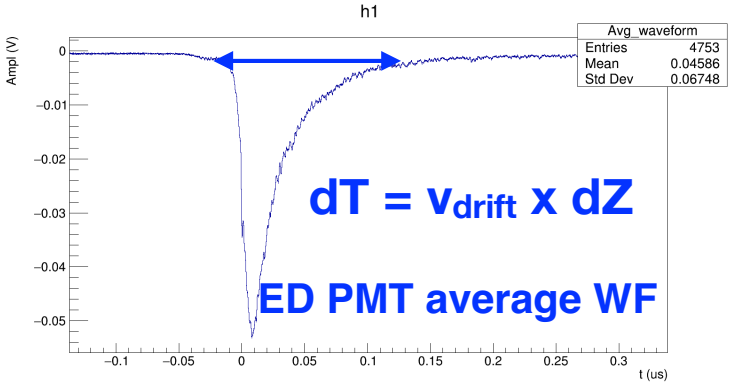
NID drift velocity and mobility from PMT WF analysis



Field cage rings

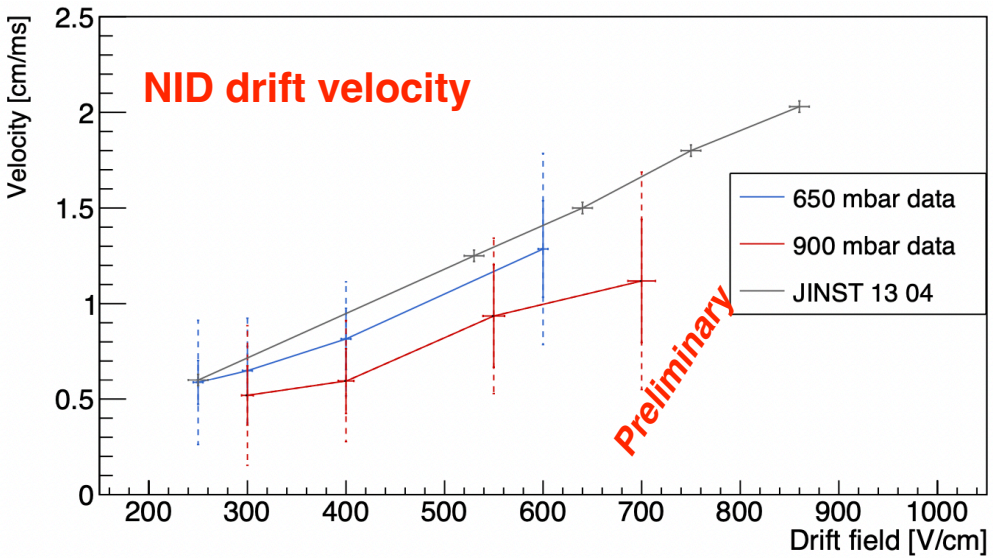
From ED PMT signal, given the known drift velocity, we estimate the alpha dZ spread (? == 7 mm)

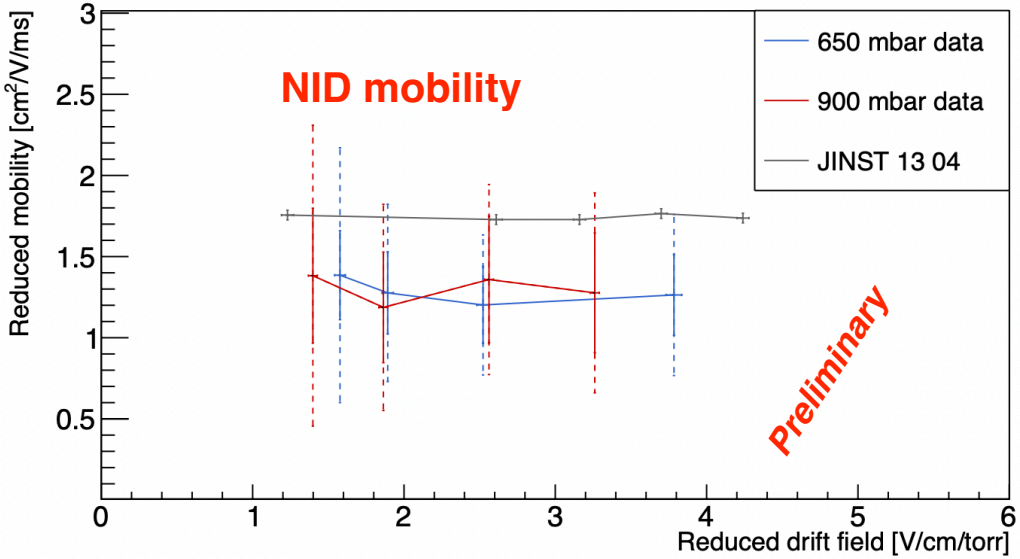
0.90 atm
(LNGS atm pressure)



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





Black points from published data with pixel charge readout and same mixture at 610 Torr [8]

CYGNUS proto-collaboration vision

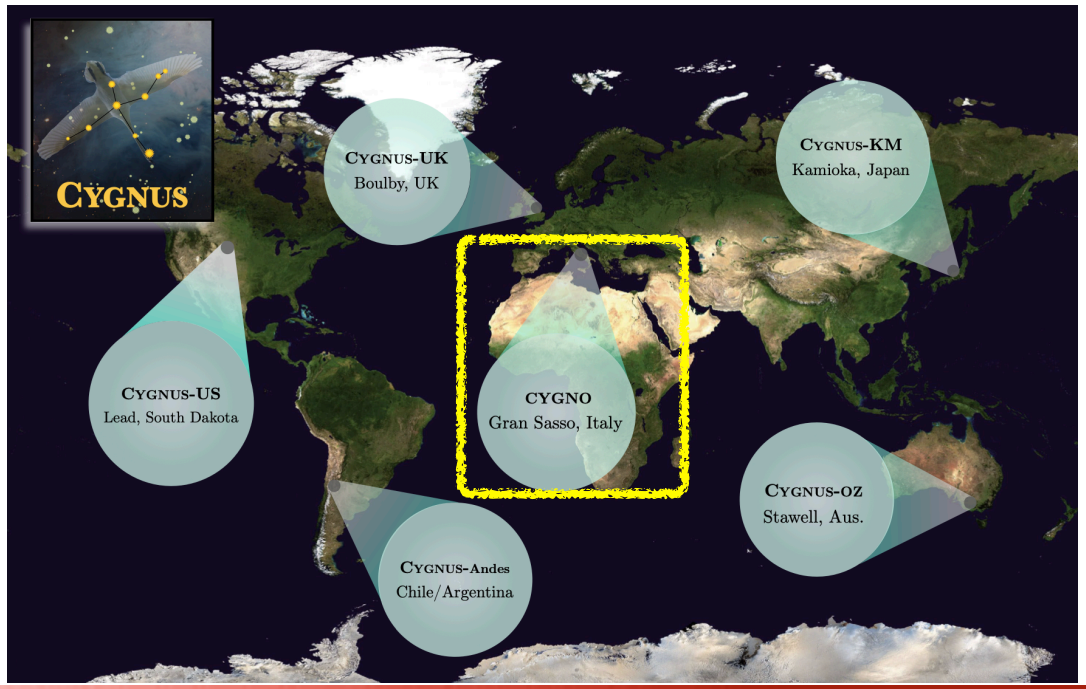
Since fall 2016

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

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]

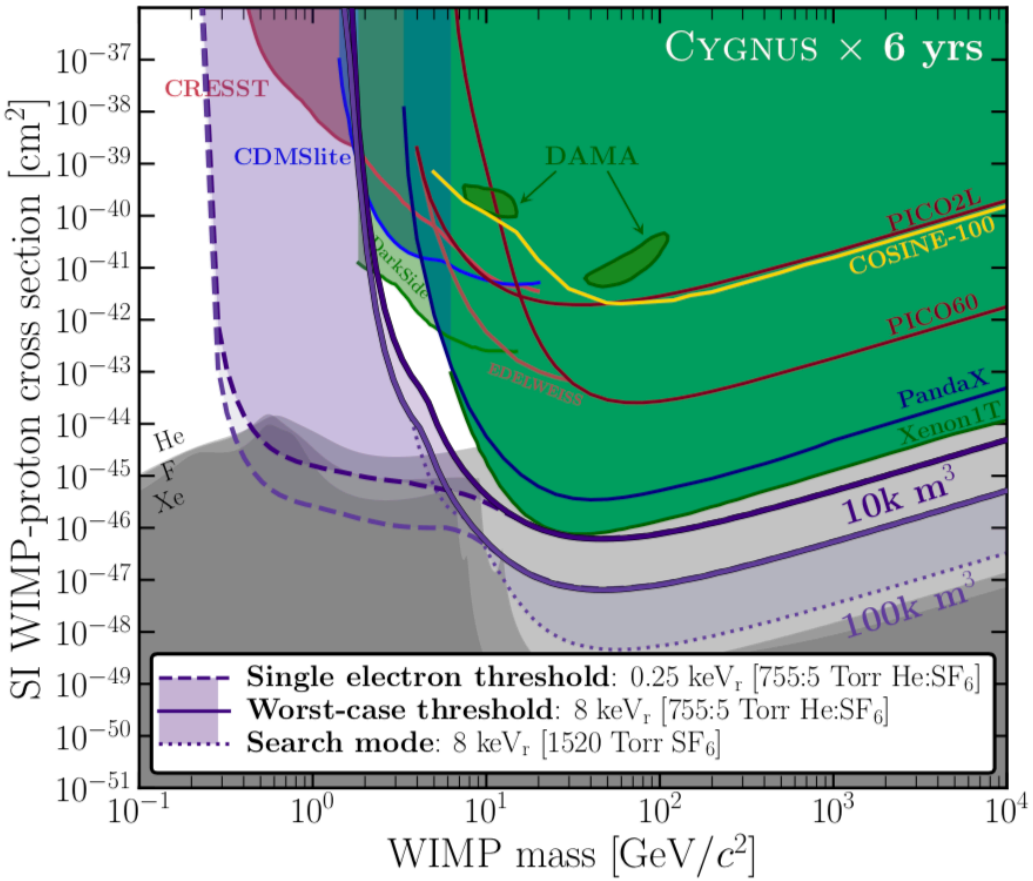
arXiv:2008.12587

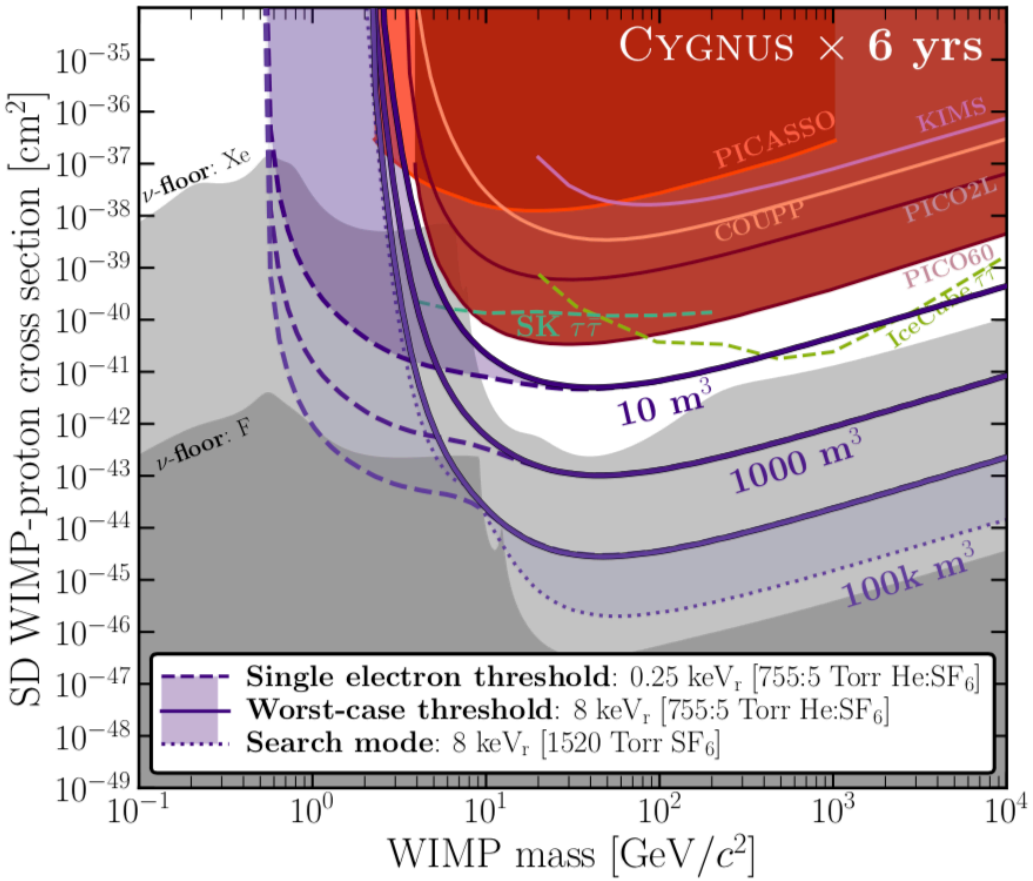


- **Helium/Fluorine gas mixtures at 1 bar**
  - **Sensitivity to O(GeV) WIMP for both SI & SD couplings**
  - **Possibility of switching between higher (search mode) and lower gas densities (improved directionality) for signal confirmation**
- **Reduced diffusion**
  - **Through negative ion drift or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

CYGNUS 1 ton WIMP searches expected sensitivity

He:SF_6 755:5





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 m^3 detector can already breach the Xe neutrino floor