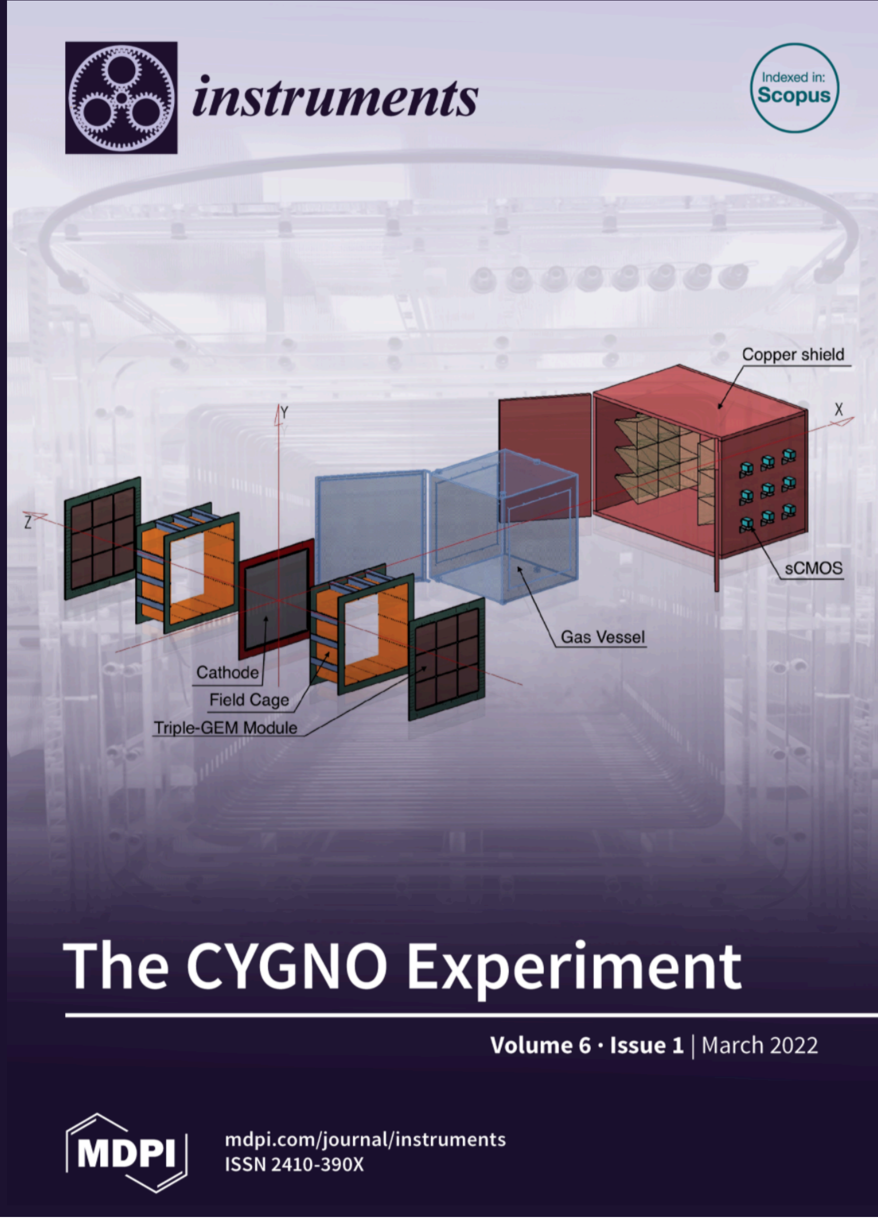


Fernando Domingues Amaro [1], Elisabetta Baracchini [2,3], Luigi Benussi [4], Stefano Bianco [4], Cesidio Capoccia [4], Michele Caponero [4,5], Danilo Santos Cardoso [6], Gianluca Cavoto [7,8], André Cortez [2,3], Igor Abritta Costa [9], Rita Joanna da Cruz Roque [1], Emiliano Dané [4], Giorgio Dho [2,3], 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] **B. P. Gelli, E. Kemp**

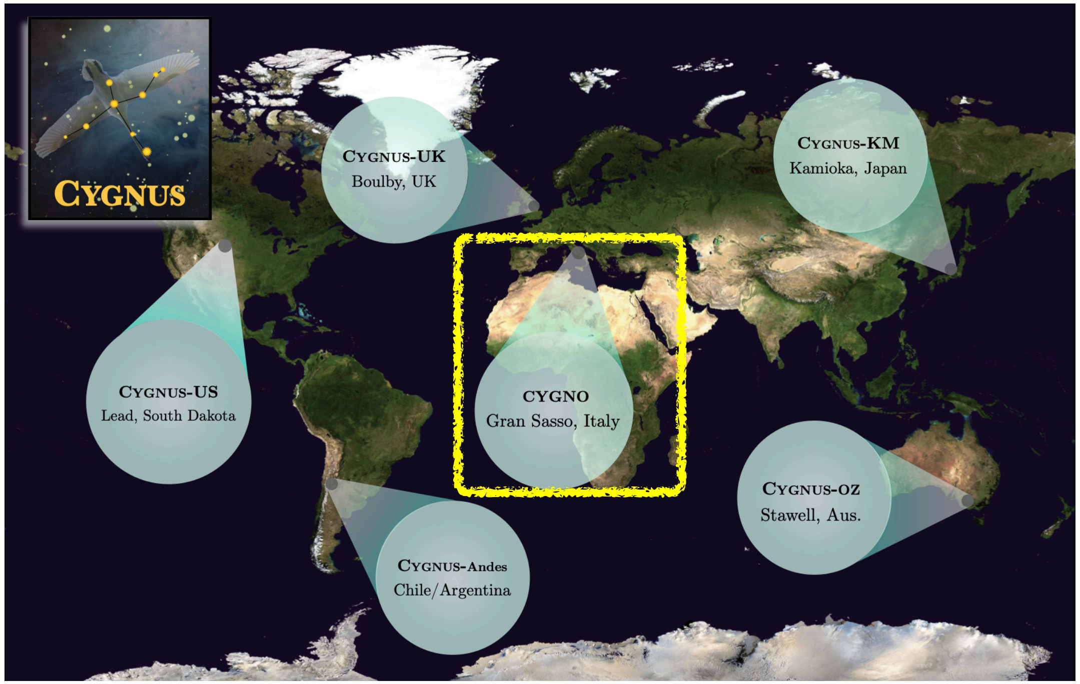
CYGNUS proto-collaboration vision

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]

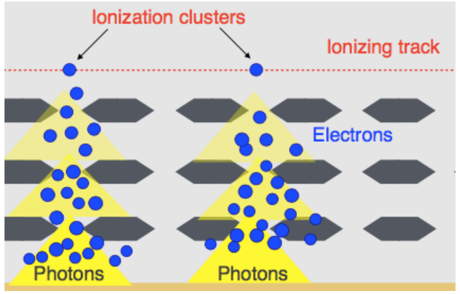
arXiv:2008.12587



- 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)**

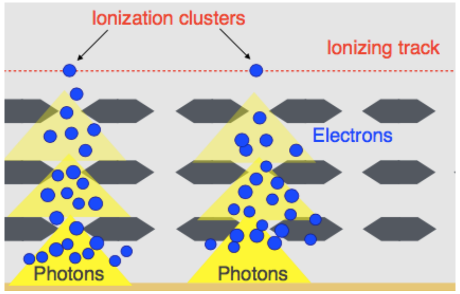
CYGNO: 3D optical readout with sCMOS & PMT

JINST 13 (2018) no.05, P05001



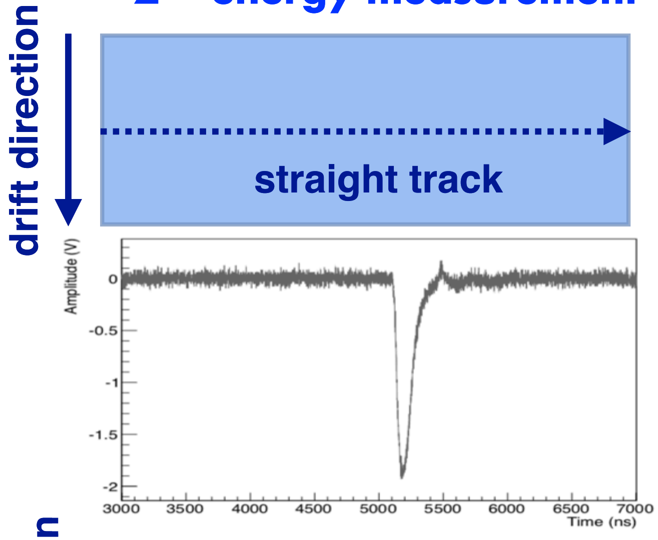
CYGNO: 3D optical readout with sCMOS & PMT

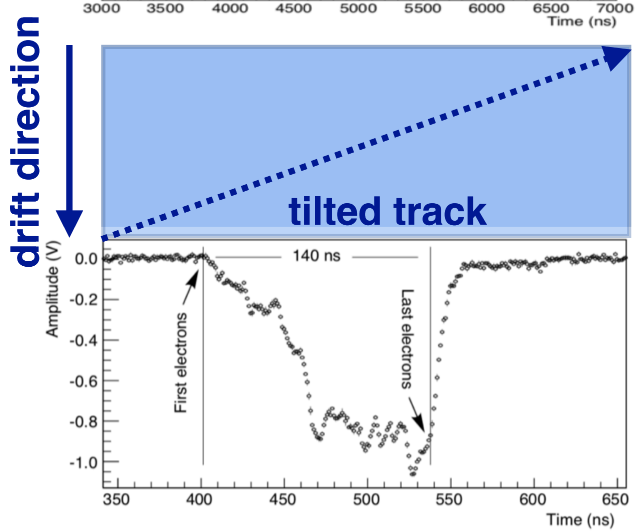
JINST 13 (2018) no.05, P05001



PMT:

integrated
Z + energy measurement



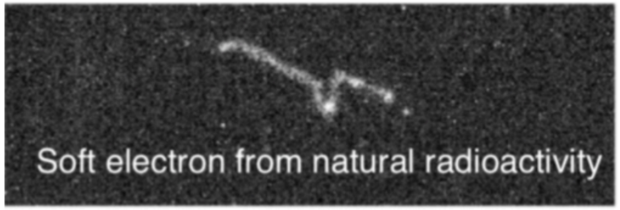


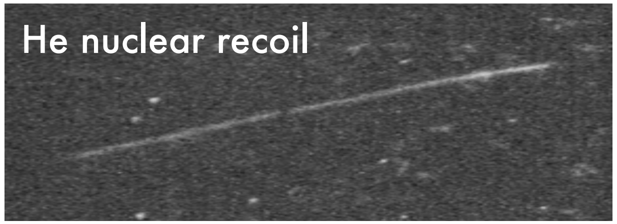
CYGNO: 3D optical readout with sCMOS & PMT

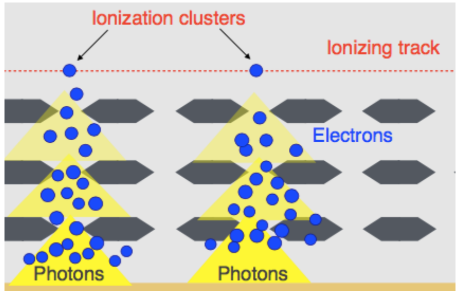
JINST 13 (2018) no.05, P05001

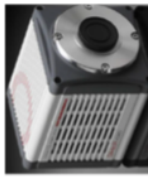
sCMOS:

high granularity
X-Y + energy measurements



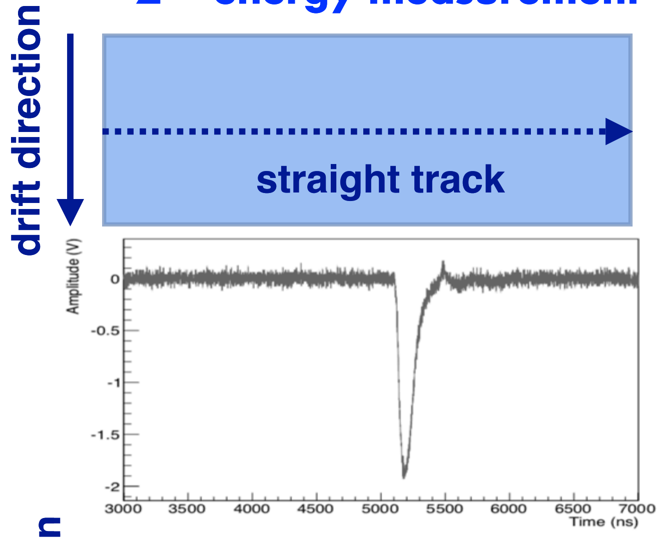


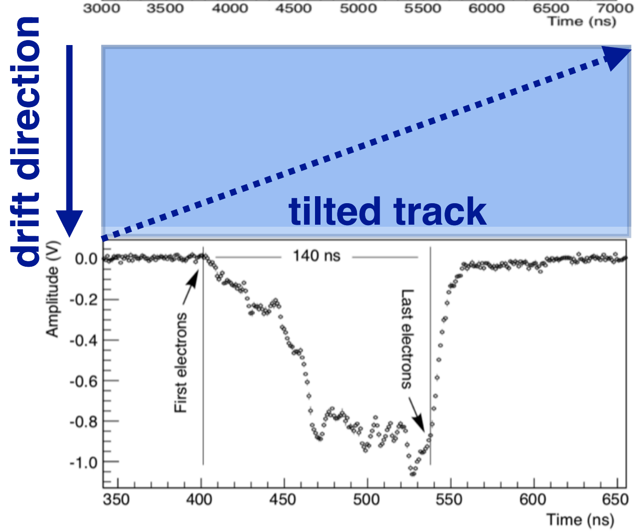




PMT:

integrated
Z + energy measurement





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

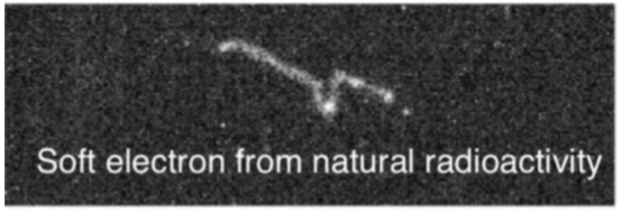
CYGNO: 3D optical readout with sCMOS & PMT

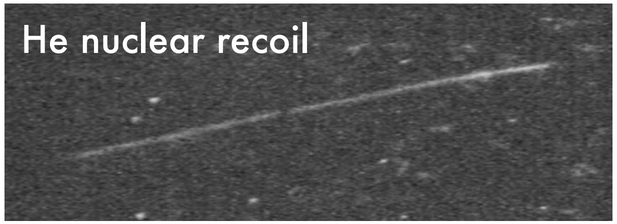
He:CF_4 @ 1 atm

JINST 13 (2018) no.05, P05001

sCMOS:

high granularity
X-Y + energy measurements





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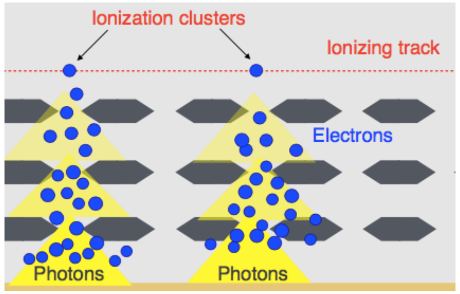
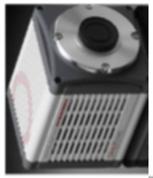
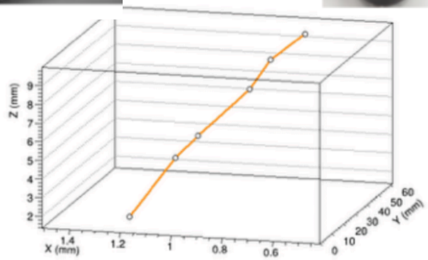
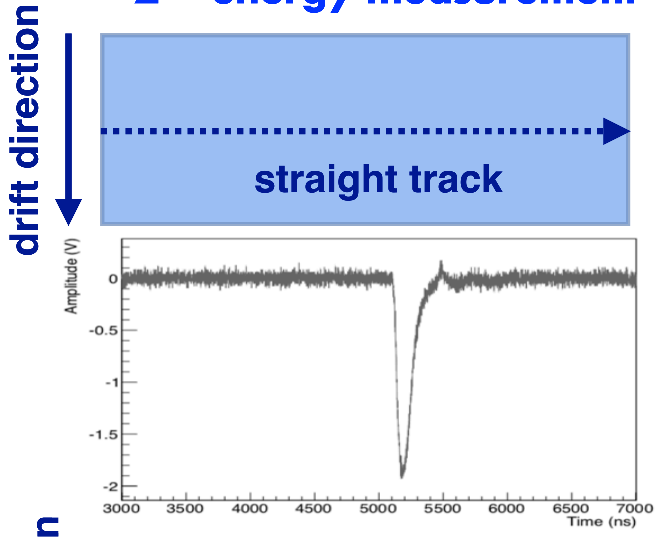


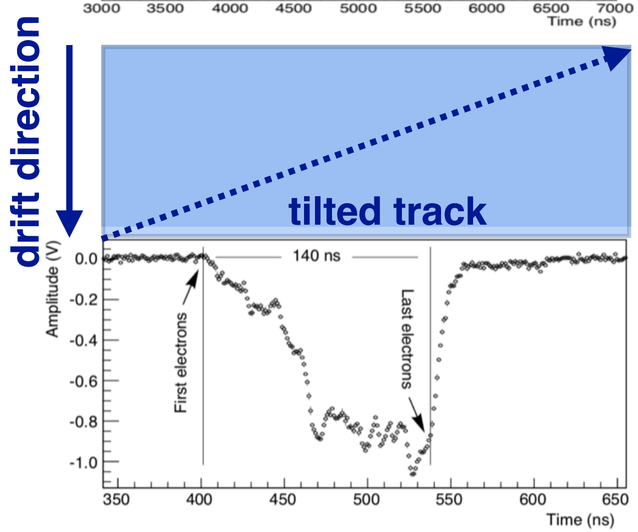




PMT:

integrated
Z + energy measurement





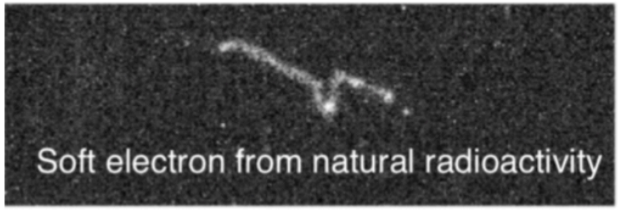
CYGNO: 3D optical readout with sCMOS & PMT

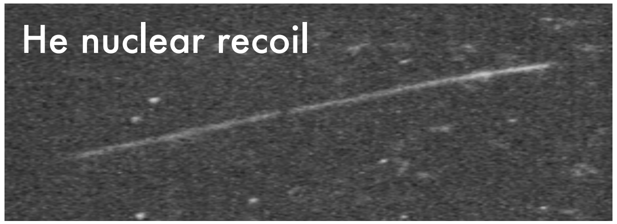
JINST 13 (2018) no.05, P05001

sCMOS:

high granularity

X-Y + energy measurements





- **1/3 noise w.r.t. CCDs**
- **Market pulled**
- **Single photon sensitivity**
- **Decoupled from target**
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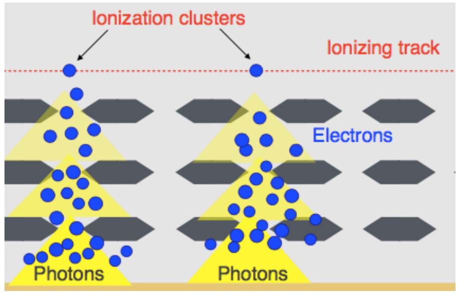
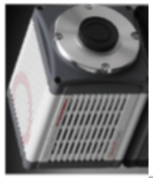
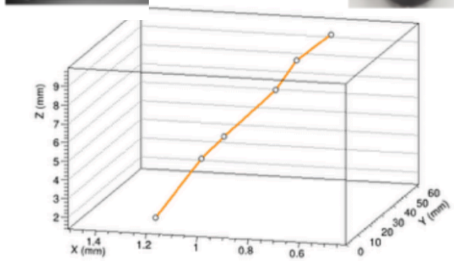






+ SF_6 for negative ion drift

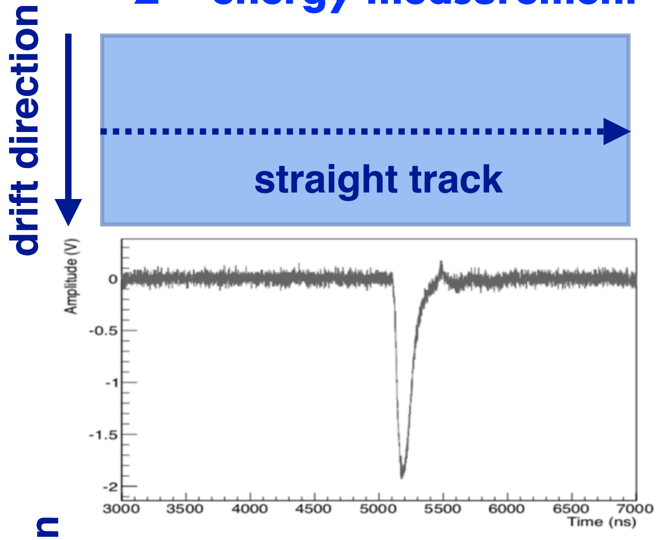
European Research Council

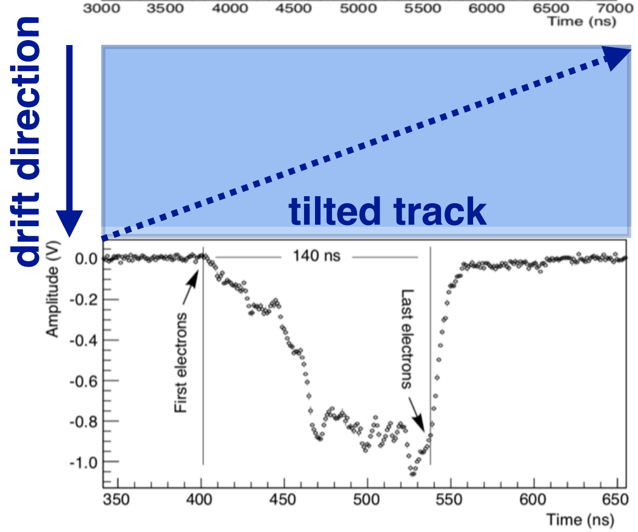
INITIUM

PMT:

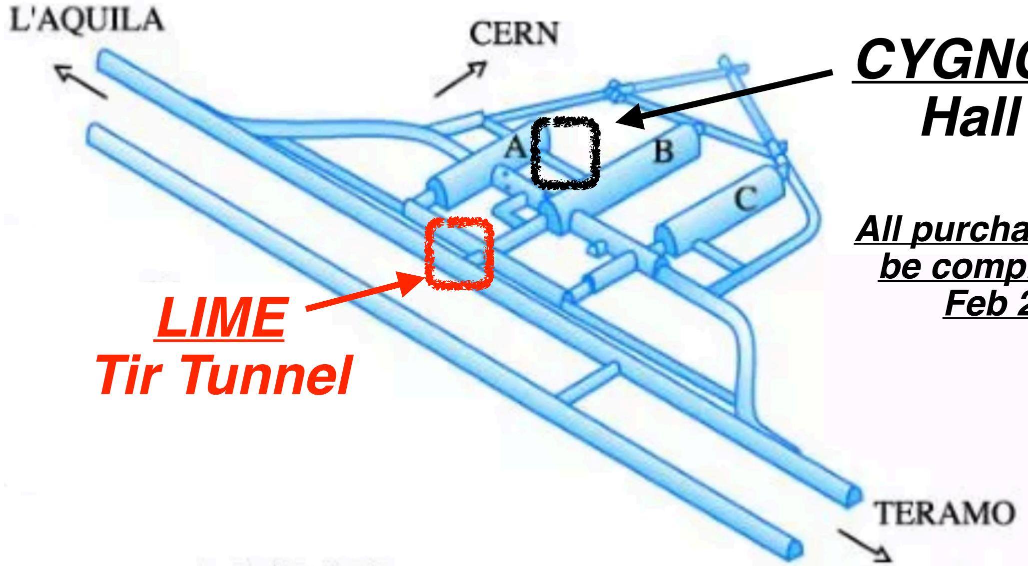
integrated

Z + energy measurement





CYGNO timeline

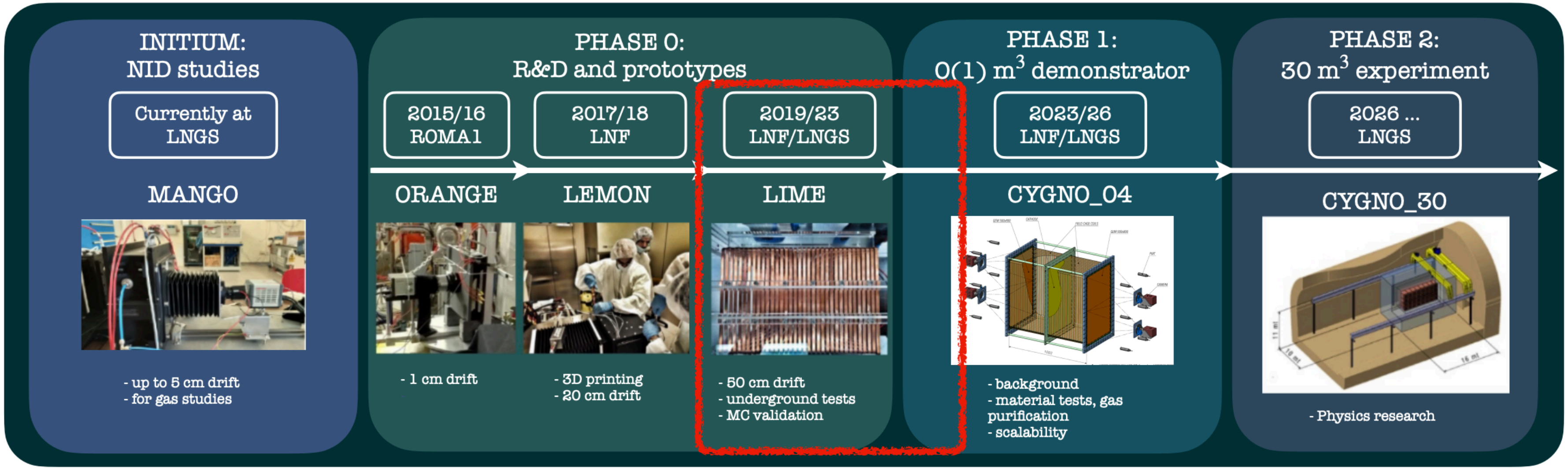


CYGNO-04
Hall F

LIME
Tir Tunnel

No interference with LNGS PNRR thanks to Hall F location

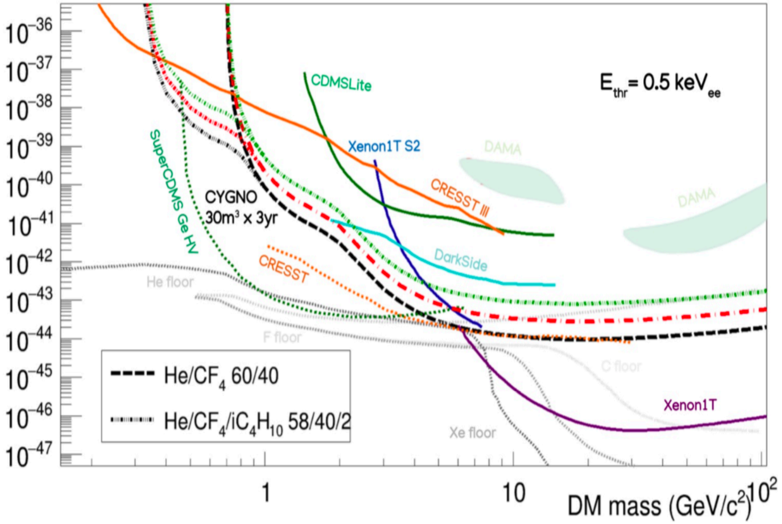
All purchases must be completed by Feb 2025

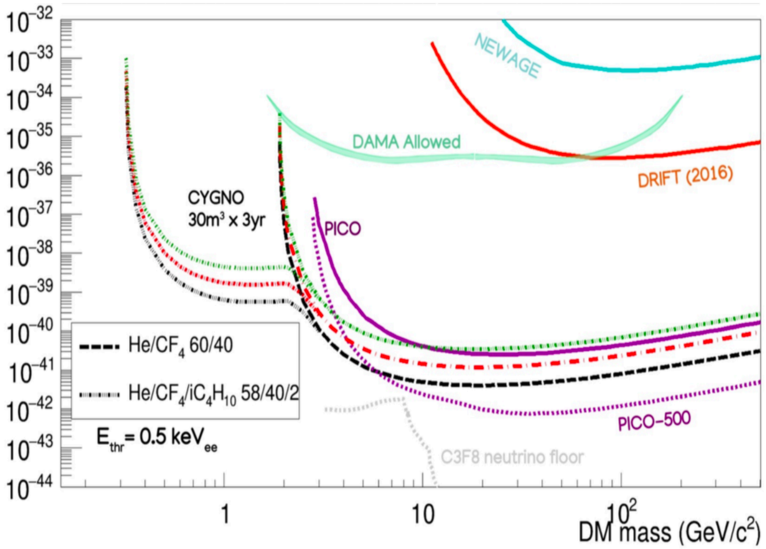


PHASE-1 fully funded through ERC Grant

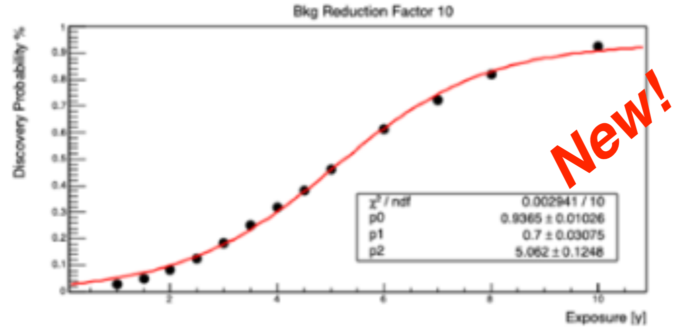
Physics goals for CYGNO-30

Direct DM searches

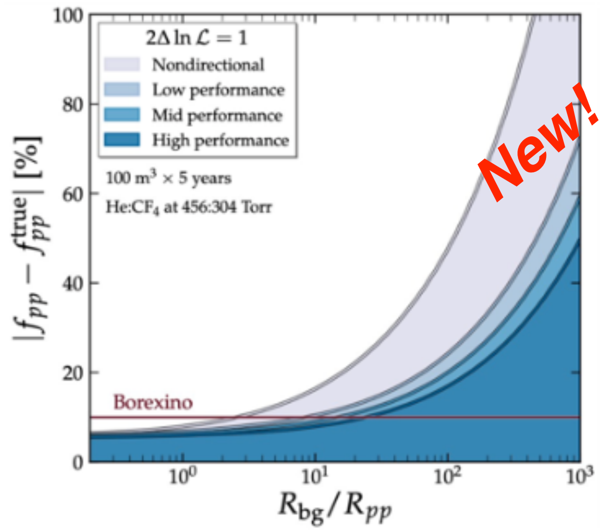




Solar neutrino spectroscopy



3 sigma pp cycle observation with CYGNO-30 x 3 years with a neutrino energy threshold of ± 50 keV (N.B. Borexino 300 keV)



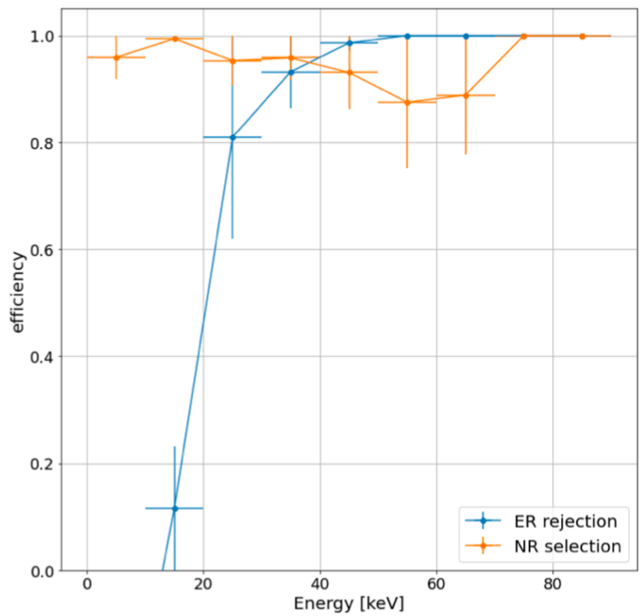
Possibility to improve precision over Borexino with CYGNO-100 for 5 years

PHASE-0 achievements

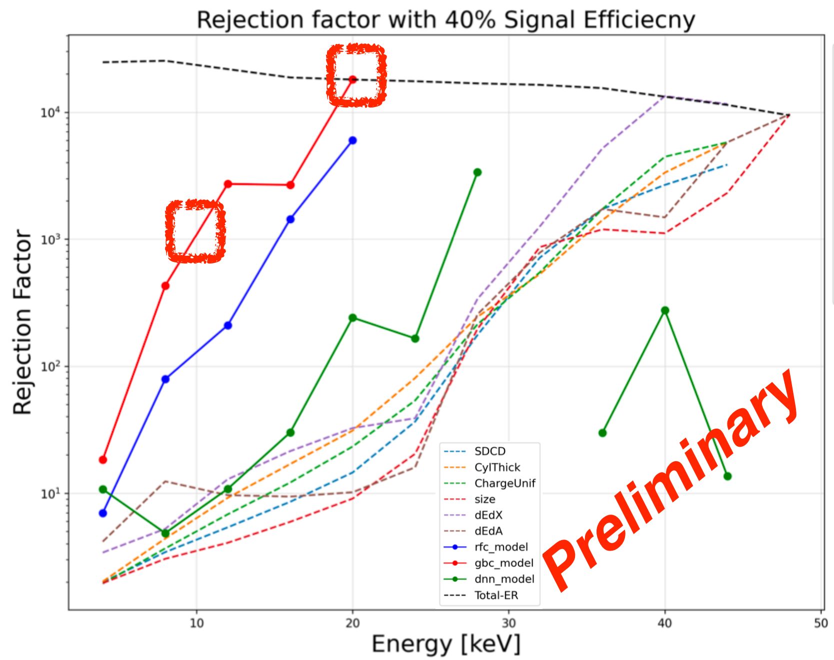
PHASE 0 has been successful in realising its goals

- LIME underground operation proceeding since > 1 year
- Auxiliary systems improved and validated
- Computing infrastructure realised and validated
- External shielding effect on backgrounds validated
- MC simulation validated and unforeen background contamination likely identified
- Preliminary ER/NR discrimination >80% at 20 keV with >90% NR efficiency (LIME AmBe data sample)
- Ongoing work with ML approach indicating possibility of achieving >10^4 ER background rejection at 20 keV with 40% NR efficiency (LIME MC simulation)
- Stable and high quality detector operation achieved with full auxiliary systems configuration

Standard cut on single variable

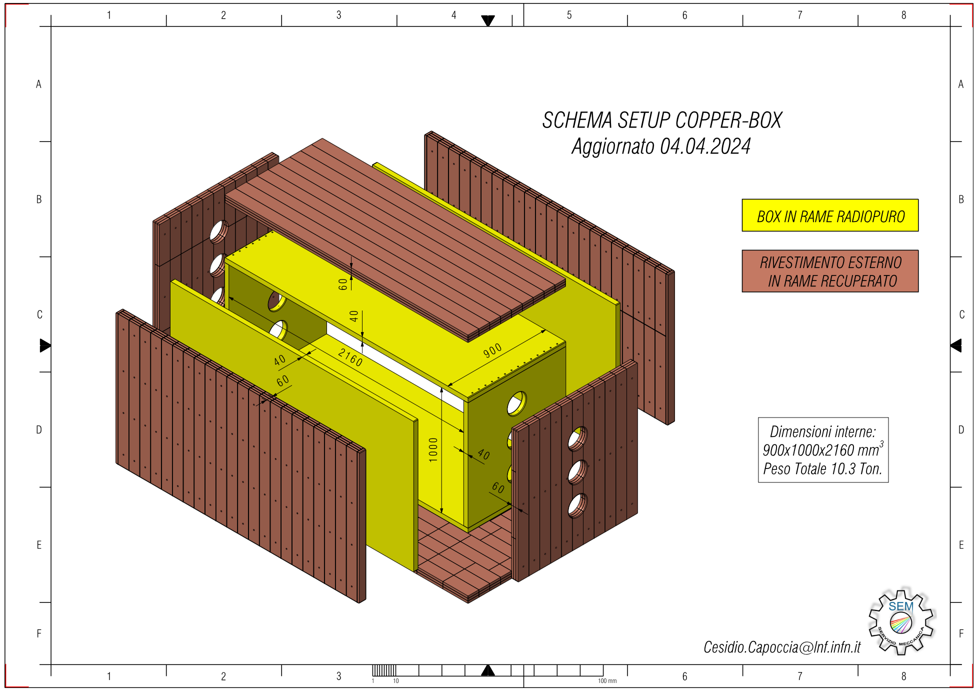


ML techniques



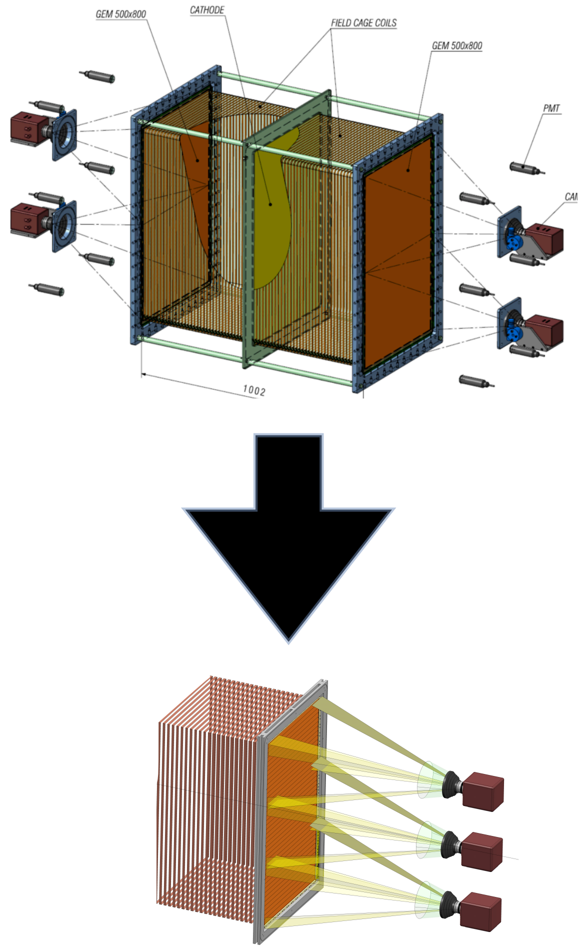
Towards finalisation of CYGNO-04 detector and Cu shielding technical design

Shielding foreseen to include an internal 4 cm "clean" Cu + 6 cm external "standard" Cu to minimise shielding radioactivity contribution as indicated by preliminary GEANT-4 simulation results



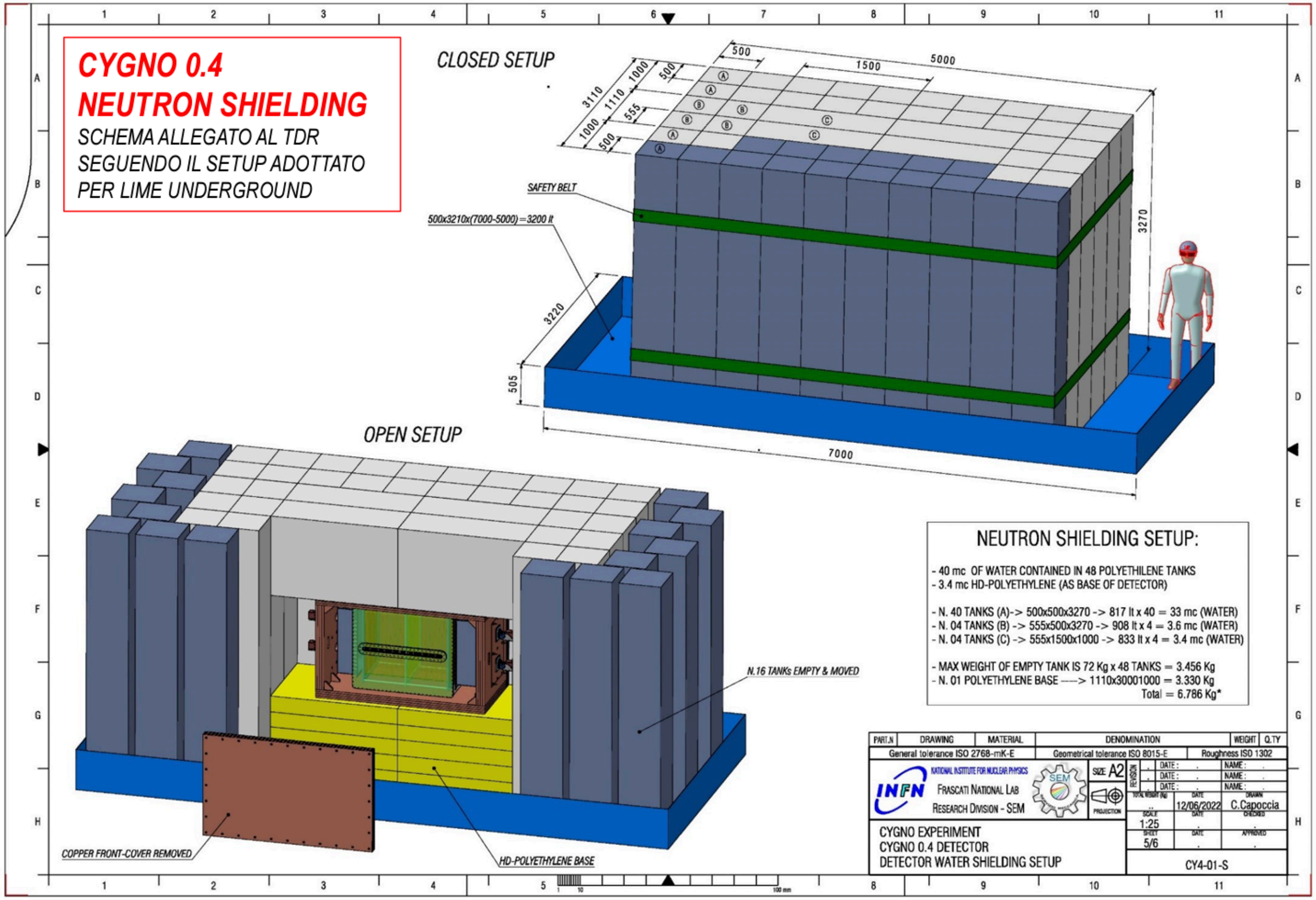
External standard Cu from dismissed Opera Cu (already secured)

For "clean" Cu two companies already contacted, final choice depending on actual costs and final results of GEANT-4 simulation



From 2 to 3 cameras per side to maximise LY and granularity while still matching the available fundings

Towards finalisation of technical design of water shielding tanks



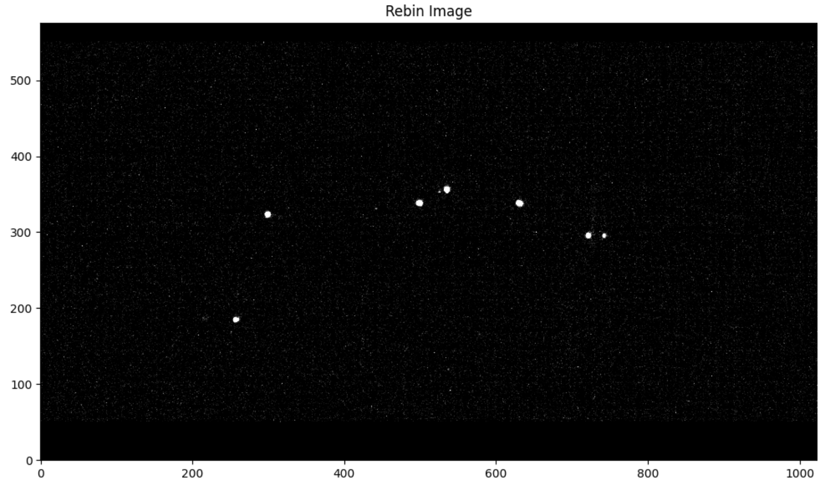
Cygno 15.01.2023 Cesidio.Capoccia@lnf.infn.it

Same company that provided LIME water shielding to be used

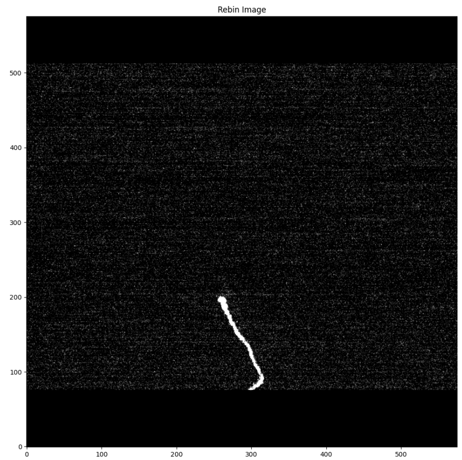
CYGNO-04 components: sCMOS camera

Preliminary comparison with standard reconstruction code optimised on Orca Quest (i.e. CYGNO-04 sCMOS camera)

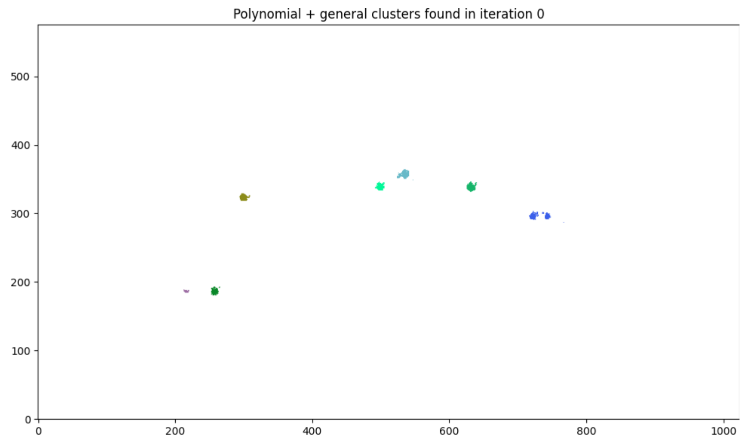
Orca Quest

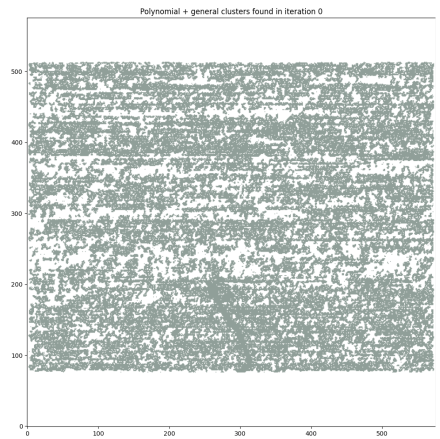


Orca Fusion



Original image



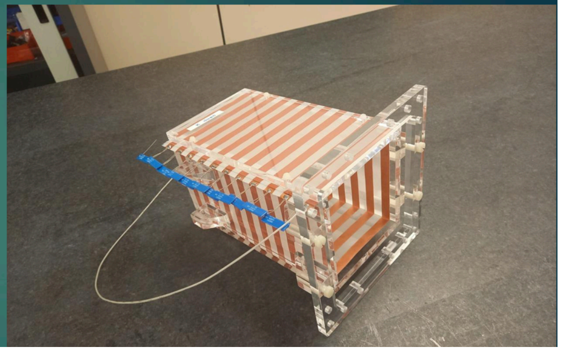


Clusters found by reconstruction code

CYGNO-04 components: field cage (FC) and cathode

“Glued” FC + Cu cathode

- **FC Characteristics:**
  - Glued on PVC
  - Four indepent panels glued (one per side)
  - Electric contact when glued toghether
- **Cathode Characteristics:**
  - Made of well-levigated Copper
  - Simple construction



Field cage 100 um PET substrate (70 um) with circuit printed copper bands (30 um)

- **Highly unstable operations**
- **Sparking and luminous spots along FC**
- **Degradation of performances with time**

CYGNO-04 components: field cage (FC) and cathode

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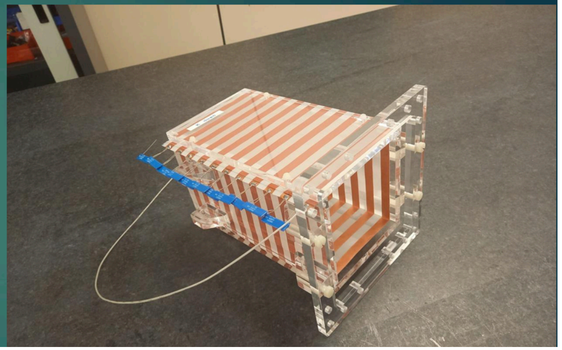
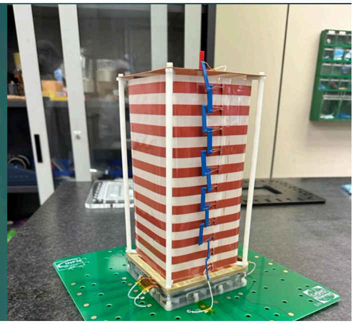


"Ethereal" FC + Cu cathode

- **FC Characteristics:**
  - Rolled up on DELRIN Pillars
  - Glued to itself
  - Not connected to PVC
- **Cathode Characteristics:**
  - Made of well-levigated Copper
  - Simple construction



Field cage 100 um PET substrate (70 um) with circuit printed copper bands (30 um)

- **Highly unstable operations**
- **Sparking and luminous spots along FC**
- **Degradation of performances with time**

- **Drift field up to 1.5 kV/cm achieved with no performance issue**
- **Long term stability test with 2 kV/cm field ongoing**
- **Full performance evaluation ongoing**

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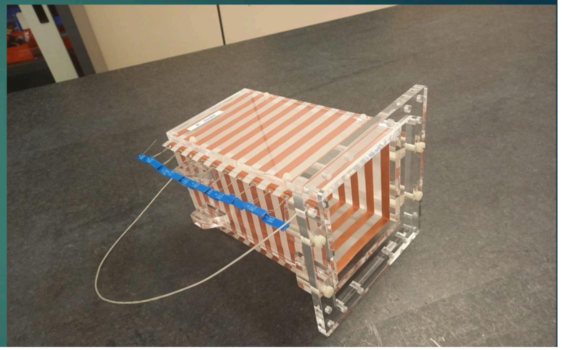

"Ethereal" FC + Cu cathode

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  - Not connected to PVC
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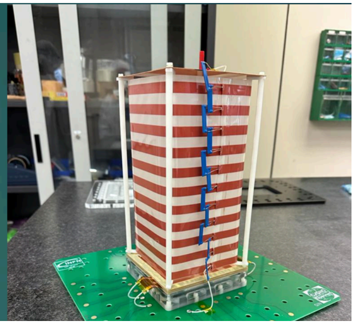
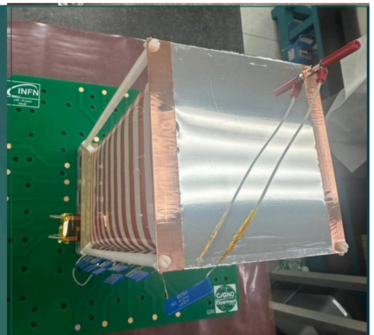
  - Simple construction



"Ethereal" FC + 0.9 um aluminised mylar cathode

- **FC Characteristics:**
  - Rolled up on DELRIN Pillars
  - Glued to itself
  - Not connected to PVC
- **Cathode Characteristics:**
  - Thin Aluminium film over a Copper Landing strip
  - Well-streched aluminium film
  - Copper tabs for electric contacts



Field cage 100 um PET substrate (70 um) with circuit printed copper bands (30 um)

- **Highly unstable operations**
- **Sparking and luminous spots along FC**
- **Degradation of performances with time**

- **Drift field up to 1.5 kV/cm achieved with no performance issue**
- **Long term stability test with 2 kV/cm field ongoing**
- **Full performance evaluation ongoing**

- **Operated for 10 days with drift field at 1.3 kV/cm with no performance issue**
- **Full performance evaluation ongoing**

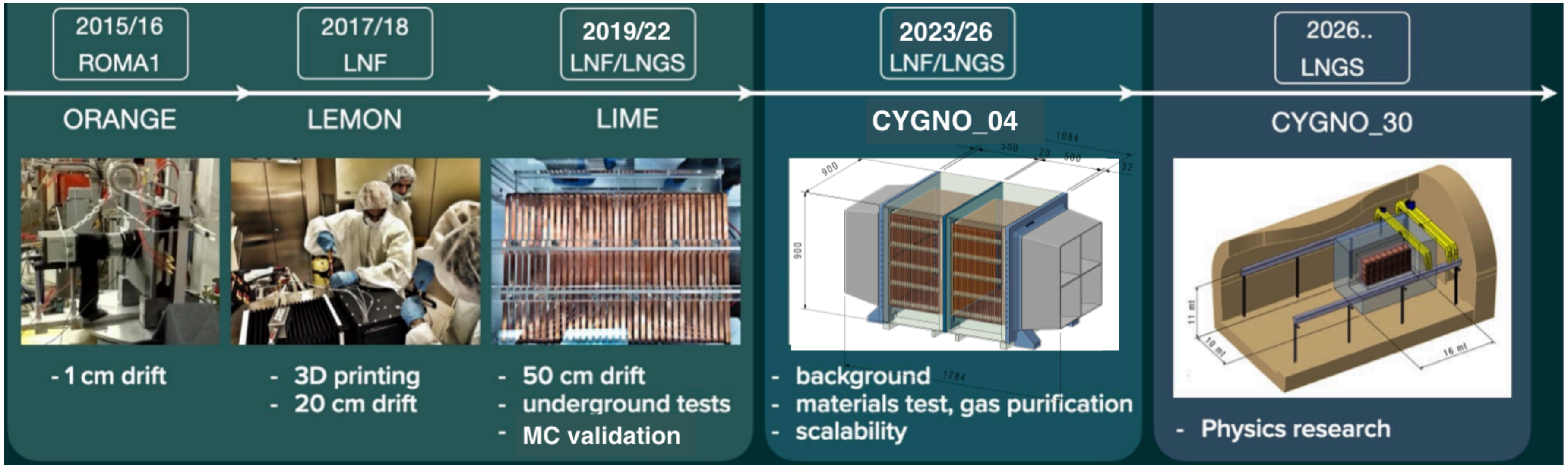
CYGNO personnel & team

- Including ERC & PRIN project, a total of 24.25 FTE
- 4 italian istitutions
- 5 foreigner institutions from 3 countries

	Institution	Qualification	FTE CYGNO	FTE INITIUM	FTE PRIN
Baracchini E.	GSSI & INFN LNGS	Professore Ord.	0.2	0.6	0.1
D'Astolfo M.	GSSI & INFN LNGS	PhD	1		
Di Giambattista F.	GSSI & INFN LNGS	PhD	0.7		0.3
Fiorina D.	GSSI & INFN LNGS	Postdoc	0.2		
Islam Z. U.	GSSI & INFN LNGS	Postdoc	0.5		
Marques D.	GSSI & INFN LNGS	PhD		1	
Prajapati A.	GSSI & INFN LNGS	PhD		1	
Torelli S.	GSSI & INFN LNGS	PhD		1	
Benussi L.	INFN LNF	Ricercatore	0.2		
Bianco S.	INFN LNF	Primo Ricercatore	0.2		
Capoccia C.	INFN LNF	Tecnico	0.3		
Caponero M.	INFN LNF	Primo Ricercatore	0.2		
Dané E.	INFN LNF	Tecnologo	0.2		
Dho G.	INFN LNF	Postdoc		0.2	
Maccarrone S.	INFN LNF	Primo Ricercatore	0.4		
Mazzitelli G.	INFN LNF	Primo Ricercatore	0.5	0.4	
Menguccі A.	INFN LNF	Tecnico	0.1		
Orlandi A.	INFN LNF	Tecnico	0.1		
Paoletti E.	INFN LNF	Tecnico	0.5		
Piccolo D.	INFN LNF	Primo Ricercatore	0.2		
Pierluigi D.	INFN LNF	Tecnico	0.2		
Rosatelli F.	INFN LNF	Tecnico	0.3		
Russo A.	INFN LNF	Tecnico	0.2		
Saviano G.	INFN LNF	Tecn. Ricercatore	0.2		
Tesauro R.	INFN LNF	Tecnico		1	
Tomassini S.	INFN LNF	Primo Tecnologo	0.2	0.1	
Cavoto G.	La Sapienza & INFN Roma1	Professore Ass.	0.3	0.1	
D'Imperio G.	INFN Roma1	Ricercatore	0.5		
Di Marco E.	INFN Roma1	Ricercatore	0.2		
Iacoangeli F.	INFN Roma1	Tecnologo	0.3		
Messina A.	La Sapienza & INFN Roma1	Professore Ass.	0.6		
Piacentini S.	La Sapienza & INFN Roma1	Postdoc	0.5		
Pinci D.	INFN Roma1	Ricercatore	0.5	0.1	
Renga F.	INFN Roma1	Ricercatore	0.3	0.1	
Abritta Costa I.	Roma3 & INFN Roma3	Postdoc	0.5		
Antonietti R.	Roma3 & INFN Roma3	PhD	1		
Meloni P.	Roma3 & INFN Roma3	PhD	1		
Petrucci F.	Roma3 & INFN Roma3	Professore Ass.	0.4		
Gregorio R.	University of Sheffield	PhD	0.2		
McLean A.	University of Sheffield	PhD	0.15		
Spooner N.	University of Sheffield	Professore Ord.	0.1		
Amaro F. D.	Universidade de Coimbra	Ricercatore	0.4		
Dos Santos J. M. F.	Universidade de Coimbra	Professore Ord.	0.3		
Mano R. D. P.	Universidade de Coimbra	PhD	0.4		
Monteiro C. M. B.	Universidade de Coimbra	Professore Ord.	0.4		
Roque R. J. C.	Universidade de Coimbra	PhD	1		
Lopes Junior A.	Universidade Juiz de Fora	MSc	0.5		
Migliorini M. L.	Universidade Juiz de Fora	MSc	0.2		
Nobrega R. A.	Universidade Juiz de Fora	Professore Ass.	0.6		
Pains I. F.	Universidade Juiz de Fora	BSc	0.5		
Pinero Lopes G. S.	Universidade Juiz de Fora	MSc	0.2		
Cardoso D. S.	Centro Brasileiro de Pesquisas Fisicas	MSc	0.1		
Lima Junior H. P.	Centro Brasileiro de Pesquisas Fisicas	Primo Tecnologo	0.4		
Oliveira T. A. B.	Centro Brasileiro de Pesquisas Fisicas	MSc	0.1		
Gelli B. P.	Universidade Estadual de Campinas	PhD	0.25		
Kemp E.	Universidade Estadual de Campinas	Professore Ass.	0.25		
Total			**18.45**	**5.4**	**0.4**

Conclusions & Outlook

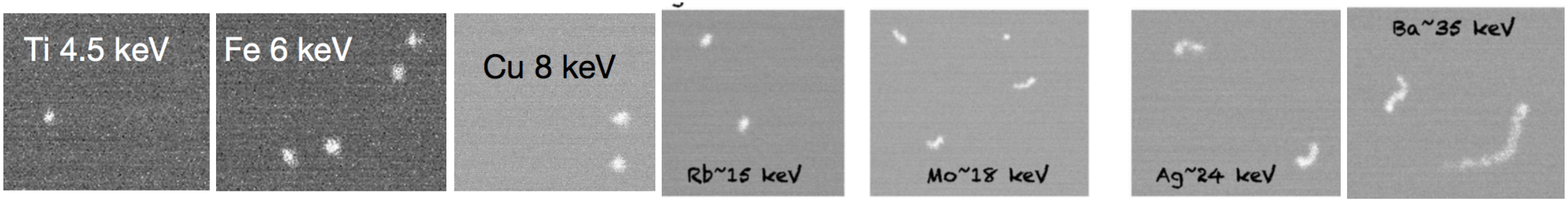
- Development towards CYGNO-04 realisation advancing
  - Infrastructures to be completed in a couple of months
  - Detector and shielding design under finalisation
  - Main detector materials and components identified and construction procedures under test
  - Full background simulation ongoing
  - Detector underground installation foreseen starting from Spring 2025
  - Advancements consistent with TDR schedule



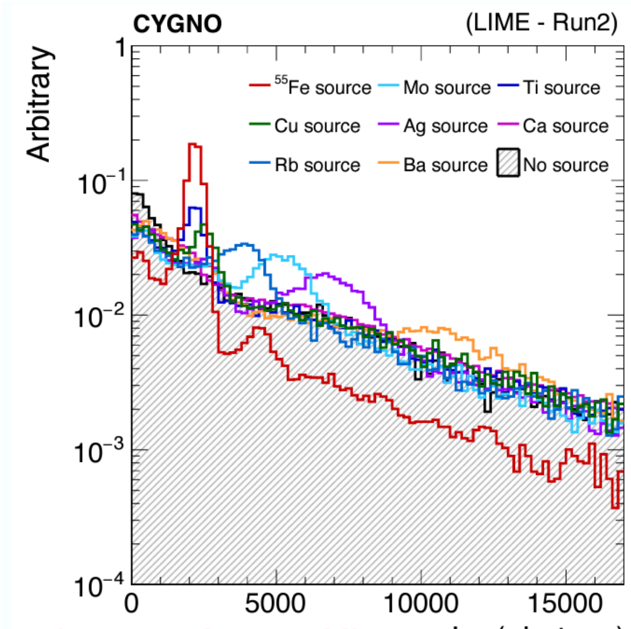
BACKUP

LIME overground commisioning @ LNF

Electron recoils calibration

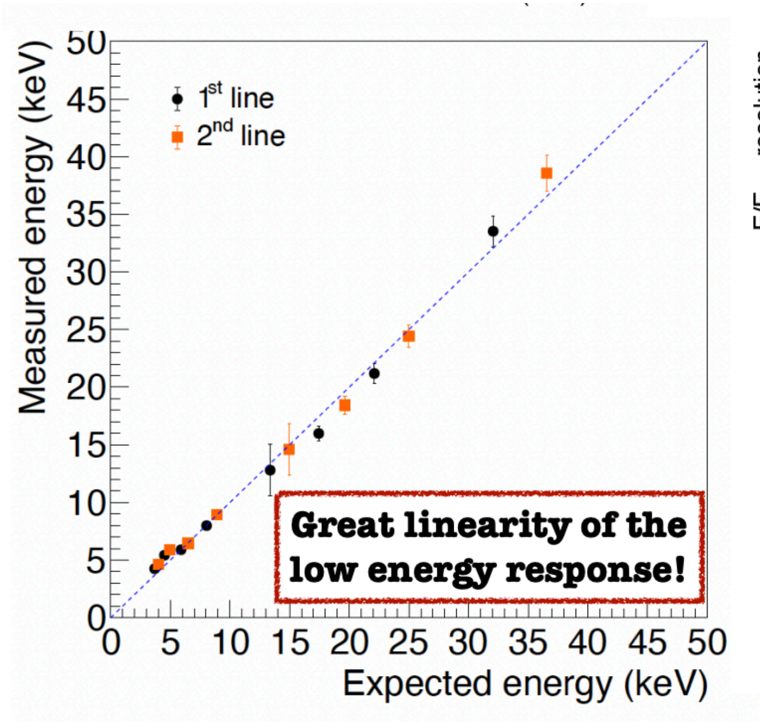


Multi-source + bkg spectrum

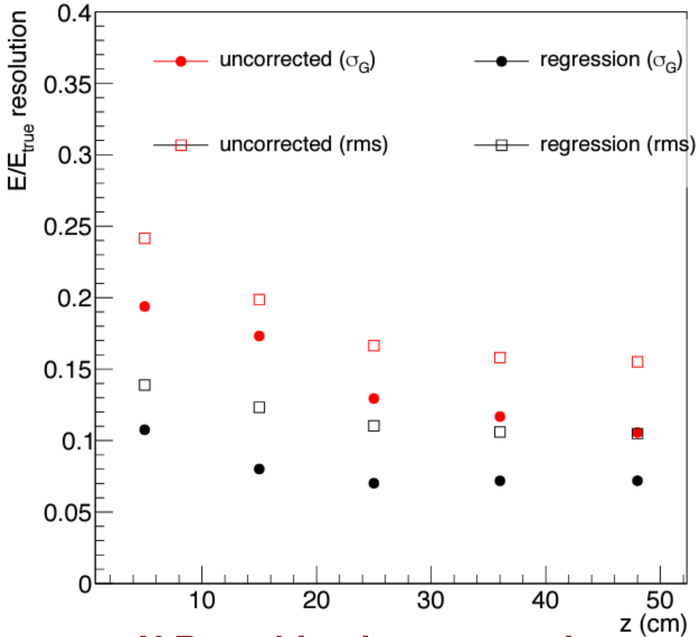


Muti-target observed lines

Energy response linearity

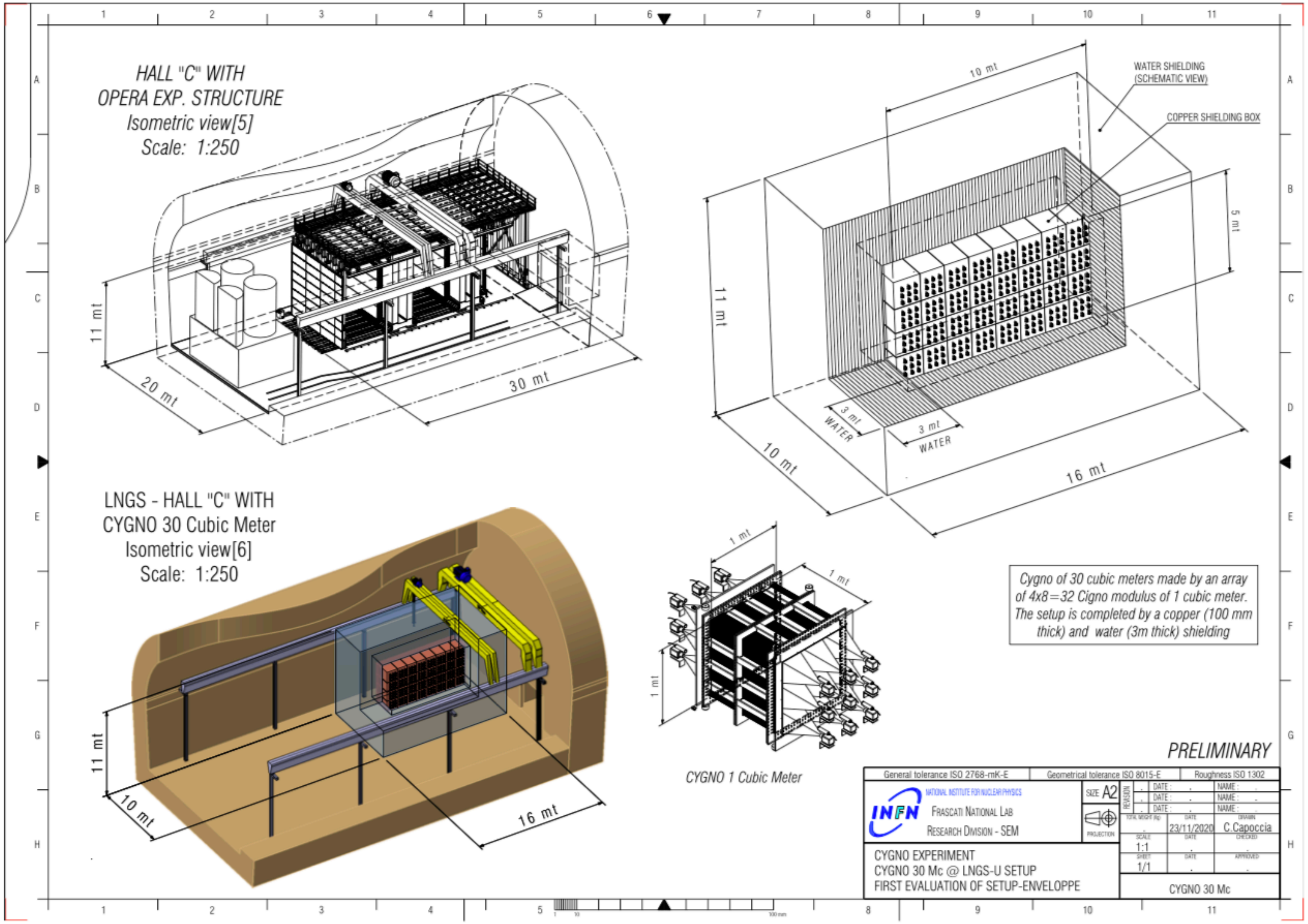


Energy resolution



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

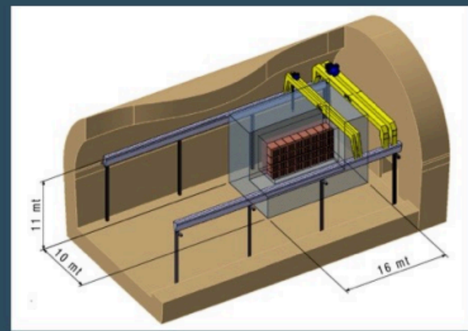
CYGNO future



PHASE 2:
30 m³ Experiment

2026..
LNGS

CYGNO_30

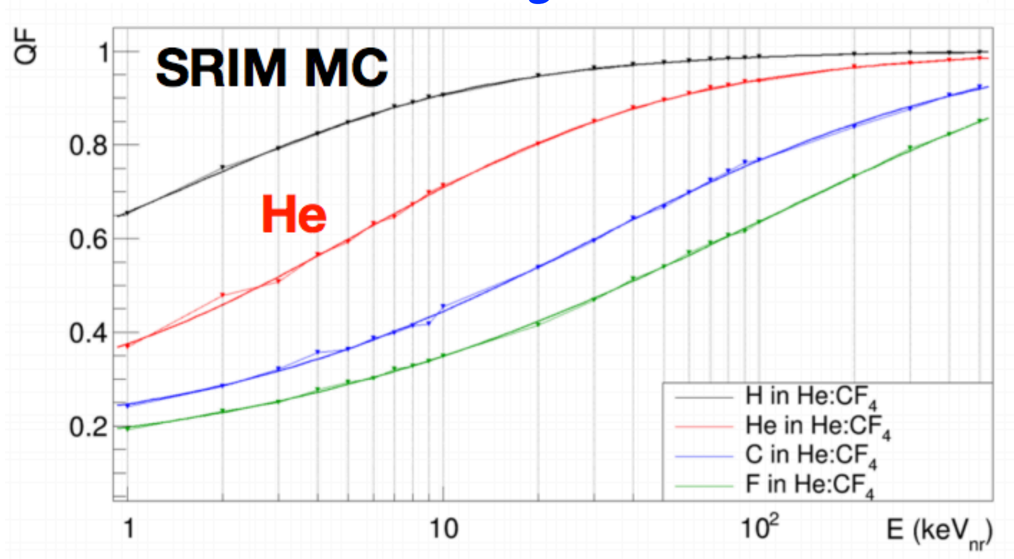


- **Physics research**

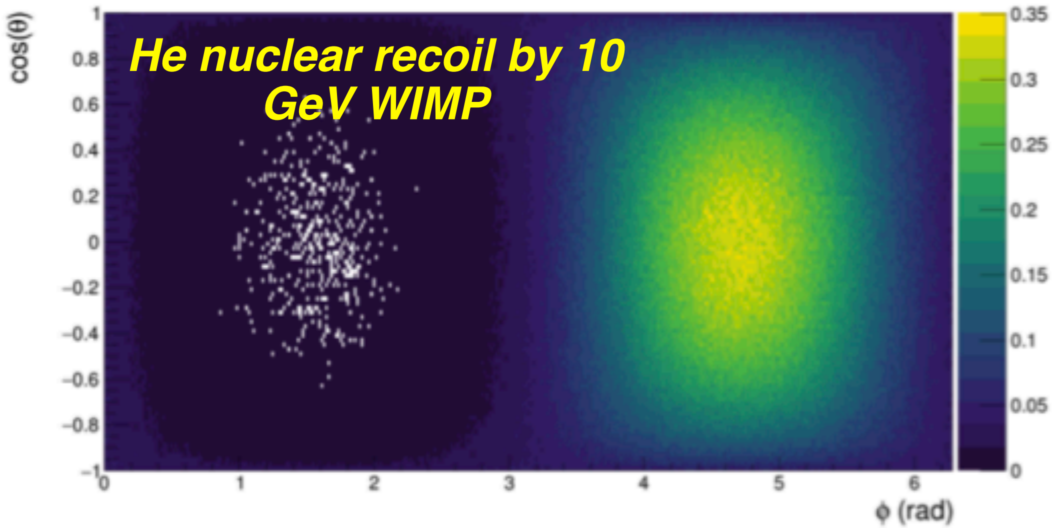
CYGNO PHASE 2 sensitivity evaluation

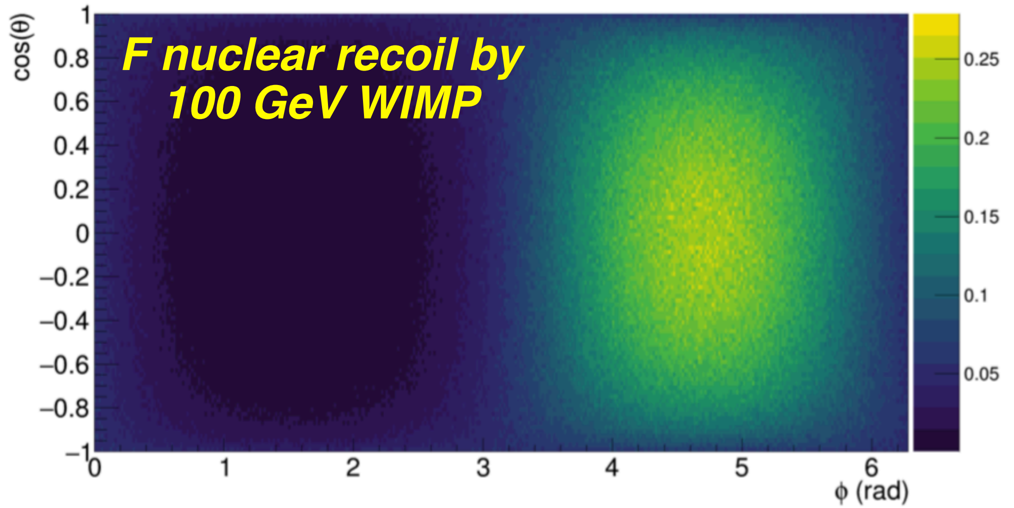
- Use 1 keV_{ee} threshold
- Evaluate QF with SRIM
- Introducing **angular distribution** as discriminating
- Full head/tail recognition
- Using a 30 deg resolution

Quenching Factor



Examples of expected measured angular distribution in Galactic coordinates





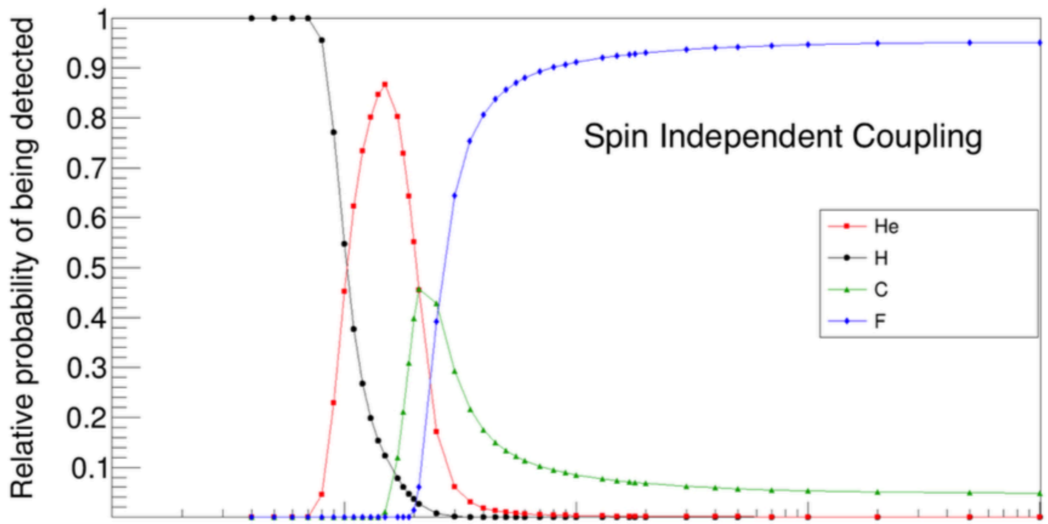
CYGNO PHASE 2 sensitivity evaluation

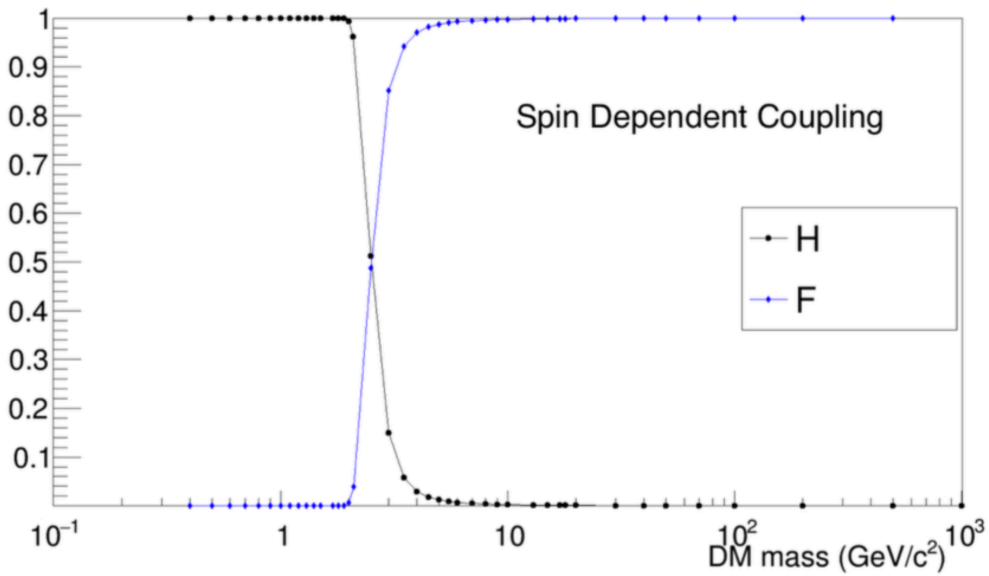
CYGNO Experiment

- **Since CYGNO is a multi-target DM experiment, both the kinematics of the expected DM-nucleus interaction and the expected rate calculation influence the probability of each element to be detected differently as a function of the DM mass**

- **The region of the DM velocity distribution accessible to detection is limited at lower values by the energy threshold and at higher values by the local escape velocity (here taken as 544 km/s)**

	Minimum detectable DM mass for 0.5 keV_{ee} energy threshold	Minimum detectable DM mass for 1 keV_{ee} energy threshold
H	300 MeV/c^2	500 MeV/c^2
He	700 MeV/c^2	1 GeV/c^2
C	1.4 GeV/c^2	1.9 GeV/c^2
F	1.9 GeV/c^2	2.5 GeV/c^2

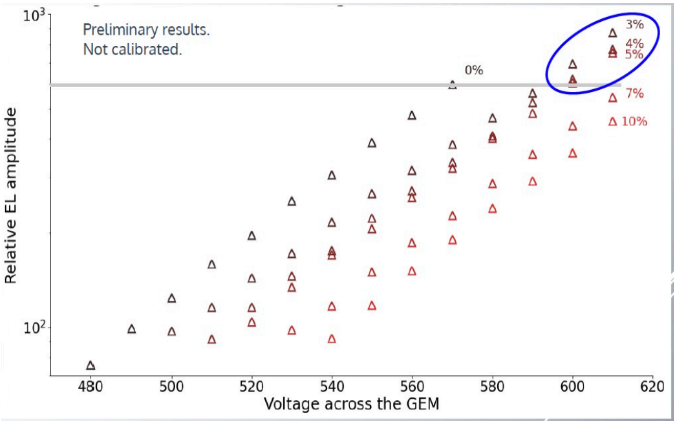




Target nuclei relative probability of being detected for 1 keV_{ee} energy threshold

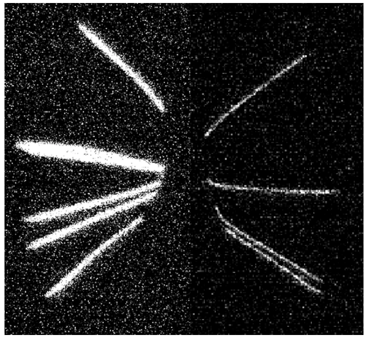
R&D developments towards CYGNO 30 m^3

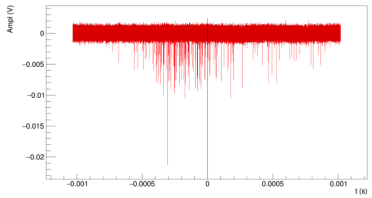
Improve sensitivity at low < 1 GeV WIMP masses by means of Hydrogen target



- **R&D with iC_4H_{10} and CH_4 demostrated good light yield achievable**
- **Future studies on Fluorine-based molecule with H (CHF_3, CH_2F_2)**
- **R&D work on eco-friendly gas mixture as substitute to CF_4** (doi: 10.1109/NSS/MIC42101.2019.9059721)

Improve tracking by means of Negative Ion Drift operation





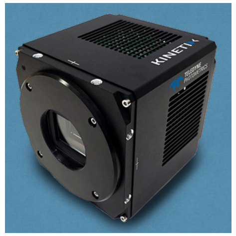
$He:CF_4:SF_6$ 59:39.4:1.6

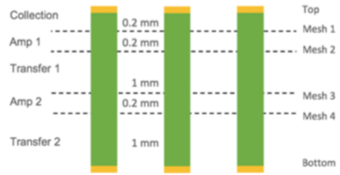
European Research Council

INITIUM

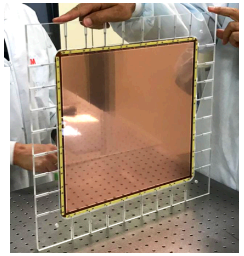
- **First ever demonstration of NID operation at atmospheric pressure with optical readout of both sCMOS and PMT**
- **5 MeV alpha particles and possibly Ba133 observed**
- **Opens a completely new window of possibility of optimisation of the gas mixtures**
- **Systematics studies ongoing**

Minimise internal radioactivity and optimise optical system & amplification





(a) Cross-section of the MMThGEM detector with the field names (left), plane names (right) and the gap widths (centre-left)



- **Develop custom sCMOS sensor with photon sensitivity & radioactivity budget optimised for CYGNO**
- **Realisation of custom lens with large aperture & low radioacitivity**
- **Optimisation of amplification structures in terms of gain and radioacitivty budget**

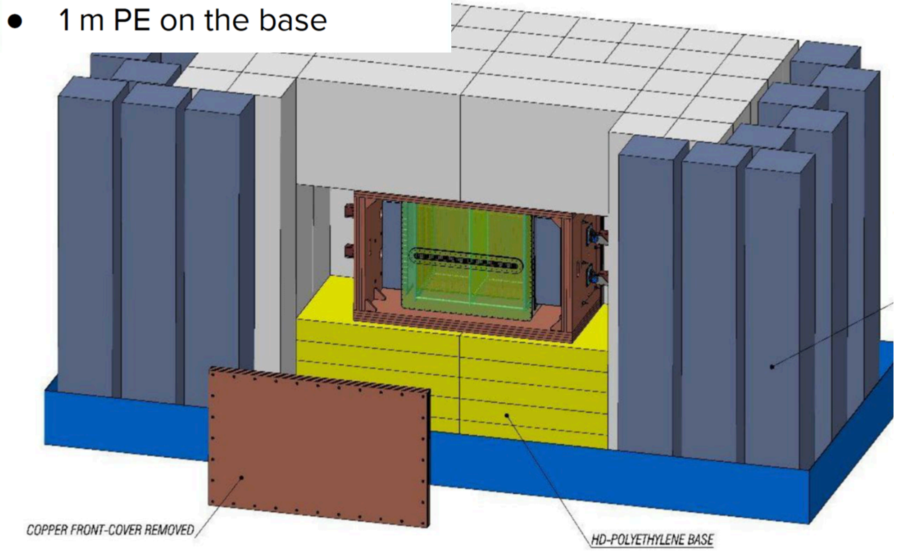
SWOT analysis

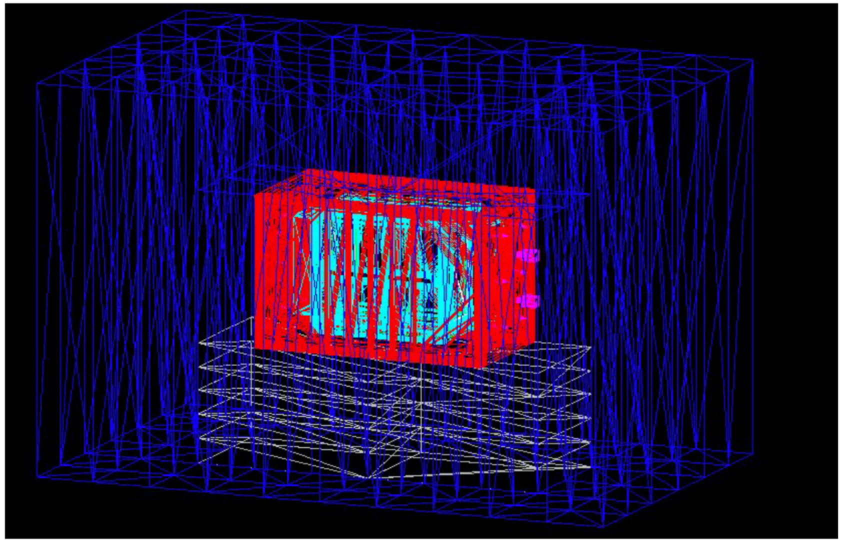
Strength		Weakness	
CYGNO-04	CYGNO-30	CYGNO-04	CYGNO-30
• Technology develop by INFN • Large international interest • Threshold and granularity never obtained with other technology • Core costs covered by European fundings already secured • Limited costs for INFN • Demonstrate the feasibility of large TPC without huge investment	• Explore yet uncharted DM mass versus coupling parameter space • Different approach to DM/SN discover/measurements • Boost of high granularity TPC technology • Imaging and tracking of ER and NR down to keV energies • No need for cryogenics	• DM sensitivity significantly below current limits • High risk technology • Complex Design due to space constraint • Need for significant internal background reduction w.r.t. current know-how	• DM sensitivity and directionality limited to 1 GeV/c2 in DM masses • Low ratio mass/volume due to gaseous target • No self-shielding due to gaseous target • Need for gas purification plant • High costs with today knowhow • Need for significant internal background reduction w.r.t. current know-how

Opportunity		Threat	
CYGNO-04	CYGNO-30	CYGNO-04	CYGNO-30
• International leadership • Realize the most sensitive directional DM detectors • Investigate new technological scenarios • Directional and spectral precise measurement of LNGS underground neutron flux with a innovative technology • Contribute to the investigation of DAMA puzzle with directionality	• International leadership • Realize the most sensitive directional DM detectors • Discover DM • Make DM astronomy by means of directionality • Demonstrate directional solar neutrino detection with TPC technology • Measure solar neutrino pp chain to lower energy threshold w.r.t. Borexino	• Demonstration of better directional DM search performances with alternative (i.e. charge readout based) technology	• All parameter space accessible to CYGNO-30 in both SI and SD couplings already excluded by other experiments • Demonstration of better directional DM search performances with alternative (i.e. charge readout based) technology • Demonstration of DM nature different from the one testable with nuclear recoil in the energy range accessible by the experiment

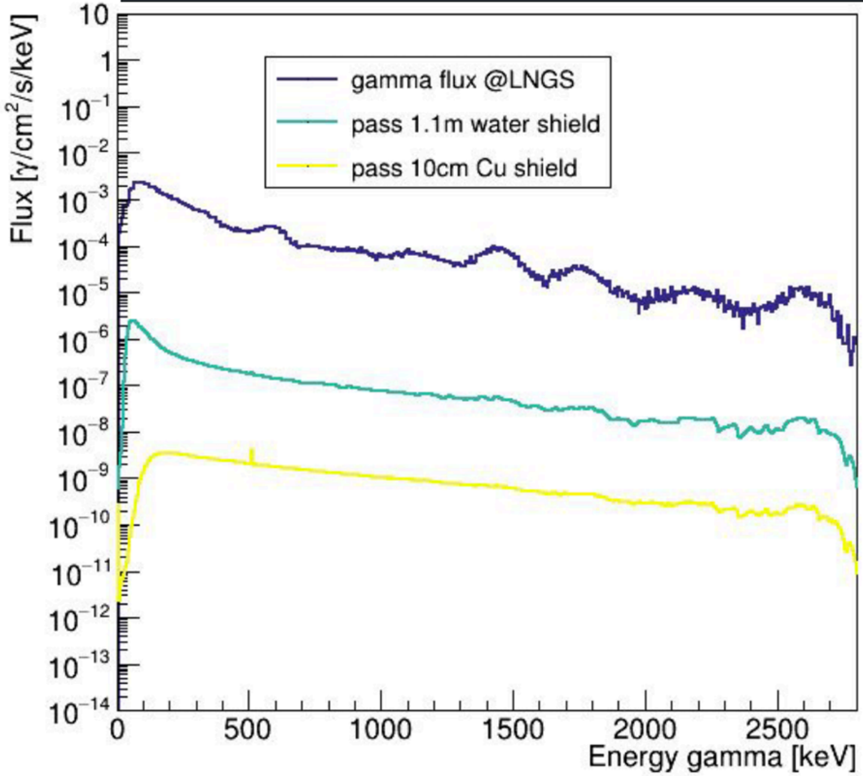
(nearly) final CYGNO-04 design implemented in GEANT4, prelminary evaluation of external gammas

- 10 cm copper on all sides
- 1 m water on sides and top
- 1 m PE on the base





gamma flux entering shield: 2.4×10^{-6} cm^{-2}s^{-1}

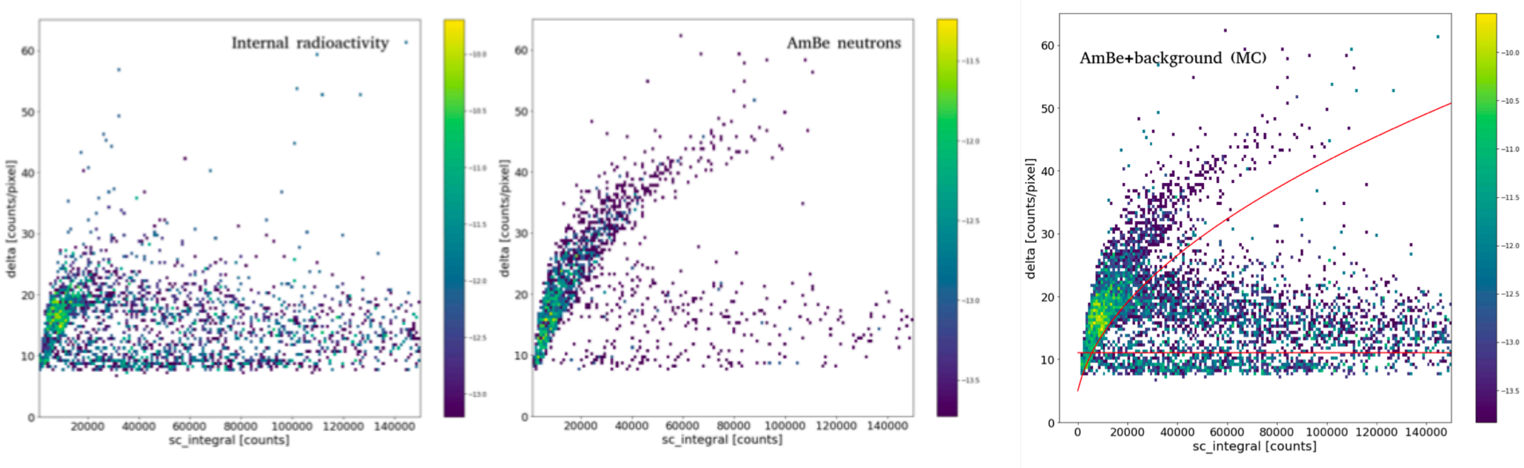


External gammas contribution subdominant (order 10^{-9} ev/s/keV) with current shielding foreseen scheme

Full simulation of all internal backgrounds (including shielding contribution) with final design on-going

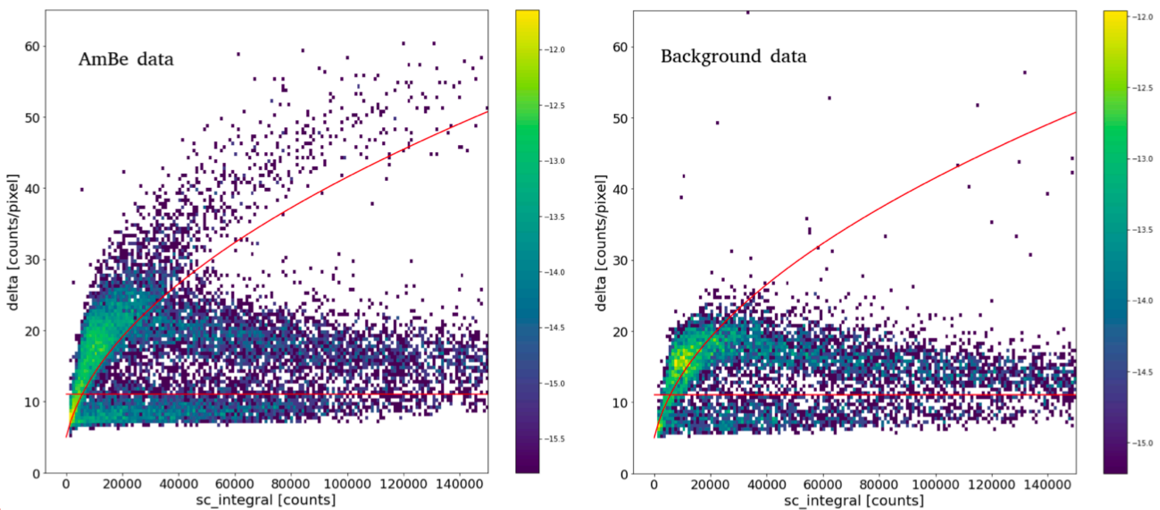
AmBe data: NR identification/ER rejection with classical approach

Same energy calibration, time normalisation and quality and selection cuts as background analysis, except for delta < 40 to not remove NR



MC simulation

uncalibrated dE/dx versus uncalibrated E



LIME AmBe/ background data

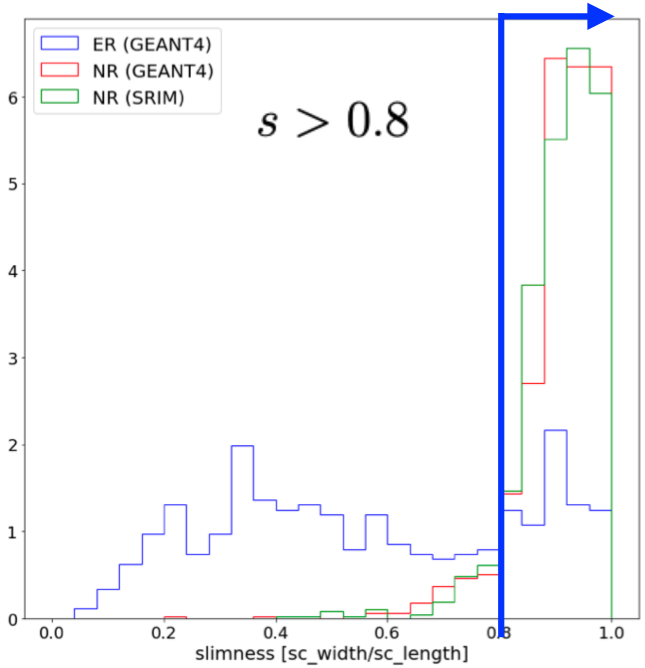
$$\delta > \sqrt{a + bI}$$

$$a = 25 \text{ and } b = 0.017$$

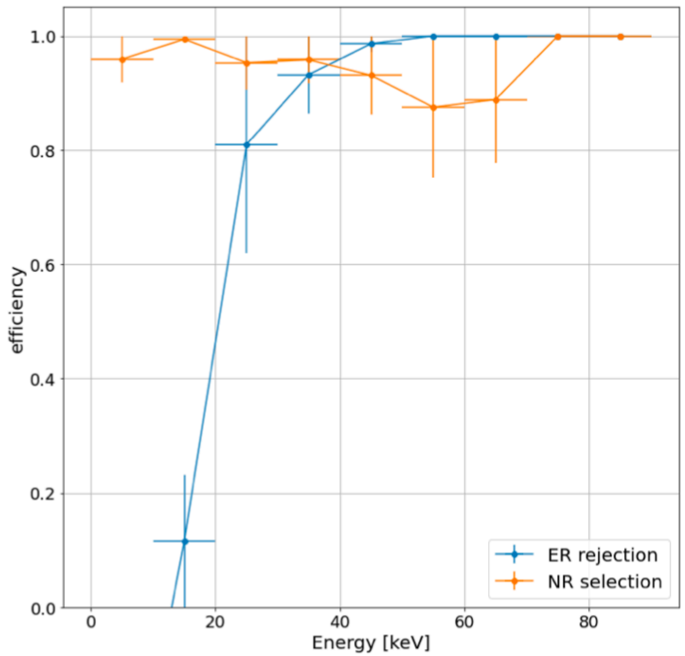
NR selection cut optimised on MC simulation

AmBe data: NR identification/ER rejection with classical approach

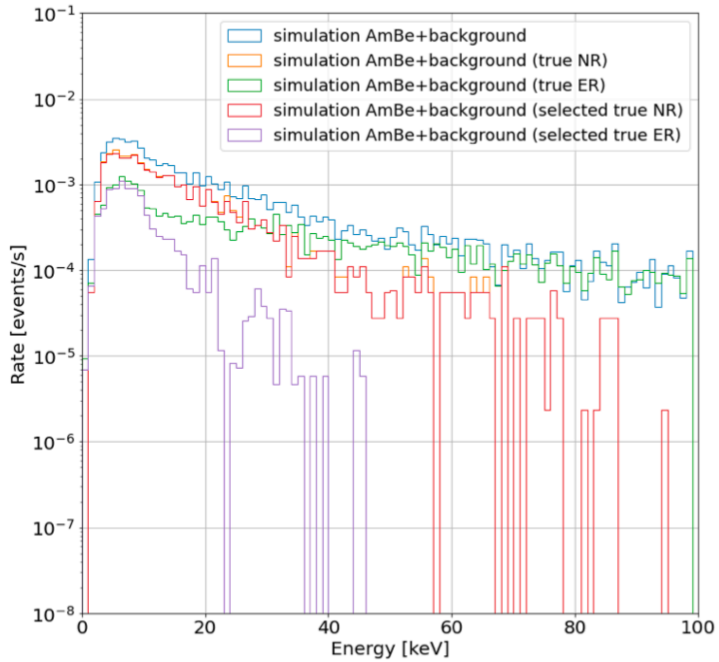
Ratio minor/major track axis



NR efficiency/ER rejection



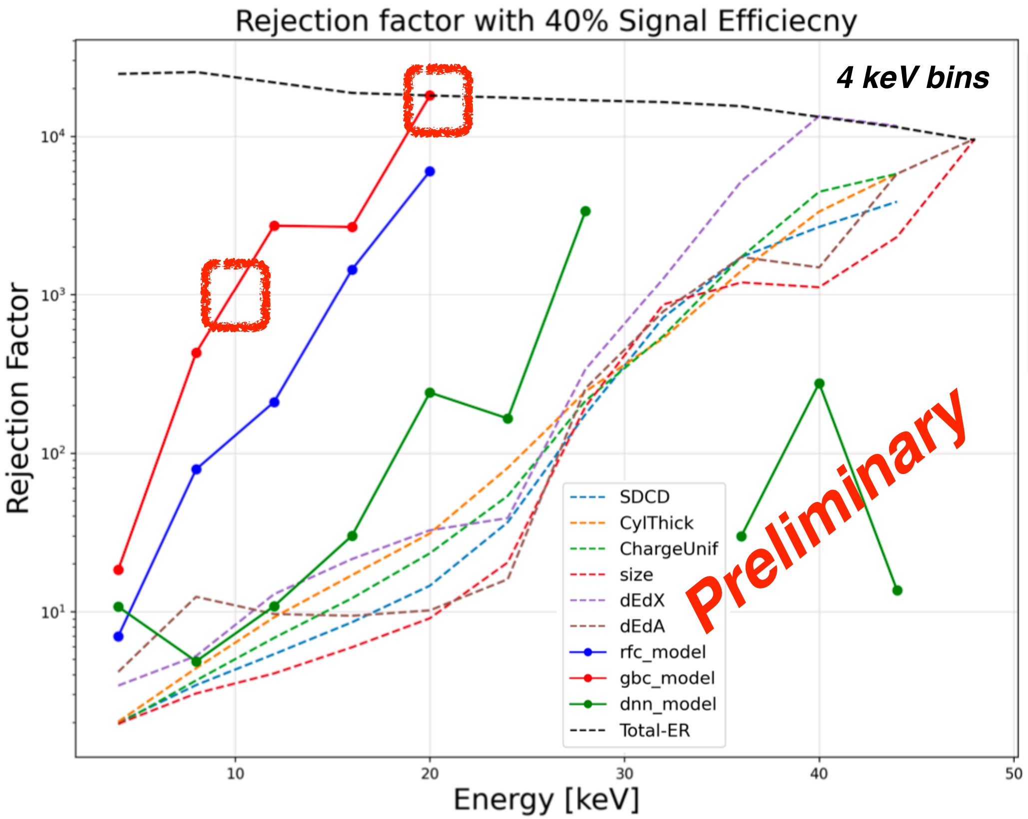
AmBe spectrum after selection



- Simple selection optimized on MC, cut on **track energy density** and **slimness** yields good **ER rejection** (>80% at 20 keV)
- Preliminary demonstration of feasibility of neutron flux measurement (Run 5)
- ML algorithm developments ongoing for ER/NR discrimination

Preliminary results from ML techniques

Rejection factor on MC full simulation

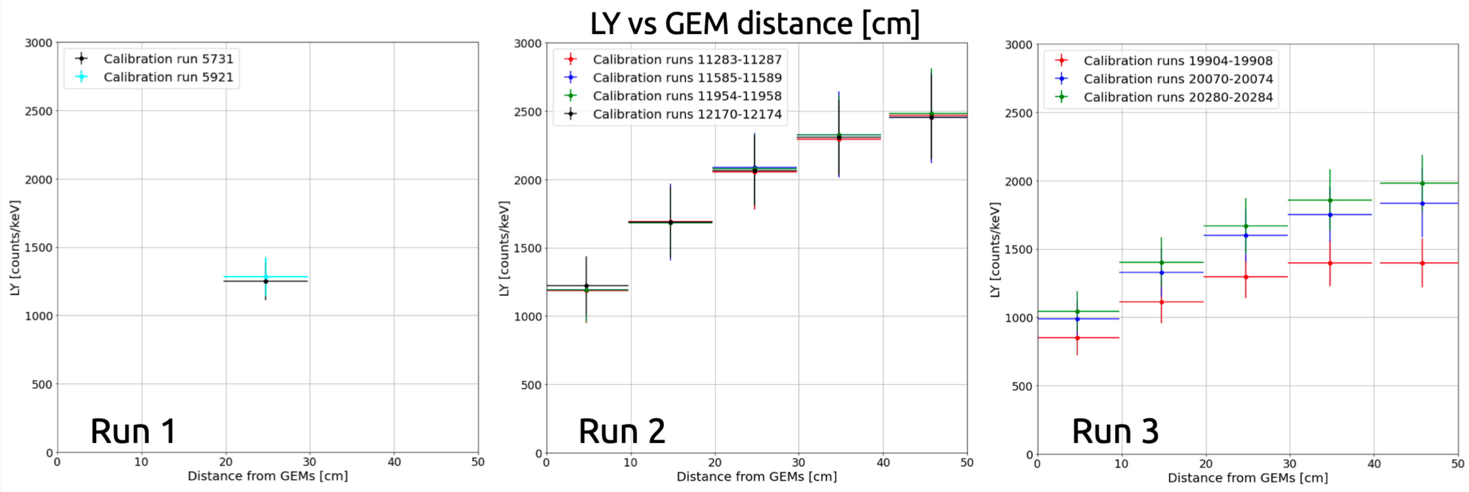


3 deep lerning models developed and compare with classical analysis on track shape variable

indication of background rejection > 10^4 @ 20 keV

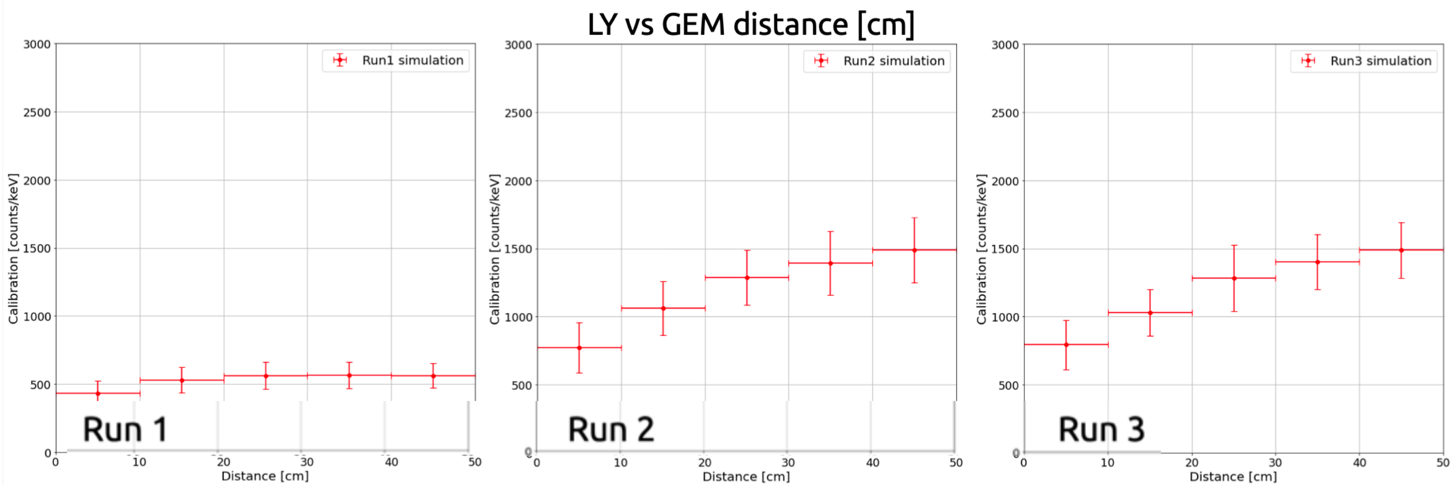
Energy calibration with ^{55}Fe

Run1, Run2 and Run3 data energy calibration



- **LY depends on distance from GEM (Z)**
- **Event Z position evaluation still preliminary and not precise enough yet (about 10 cm resolution) to correct data**
- **Random uniform Z extraction, random Gaussian LY extraction, bootstrap sampling**

Run1, Run2 and Run3 MC energy calibration



- **LY from MC sample with energy between 2 and 10 keV**
- **Same method used for data, except for LY variation over time**
- **Lower LY observed in MC (optimised on overground data), strongly dependent on specific data conditions**