Discoverying supernova-produced light dark matter with directional detectors like CYGNO

International Conference on Supernovae Neutrino Detection 2023

Elisabetta Baracchini
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in collaboration with W. DeRocco
&
on behalf of CYGNO collaboration

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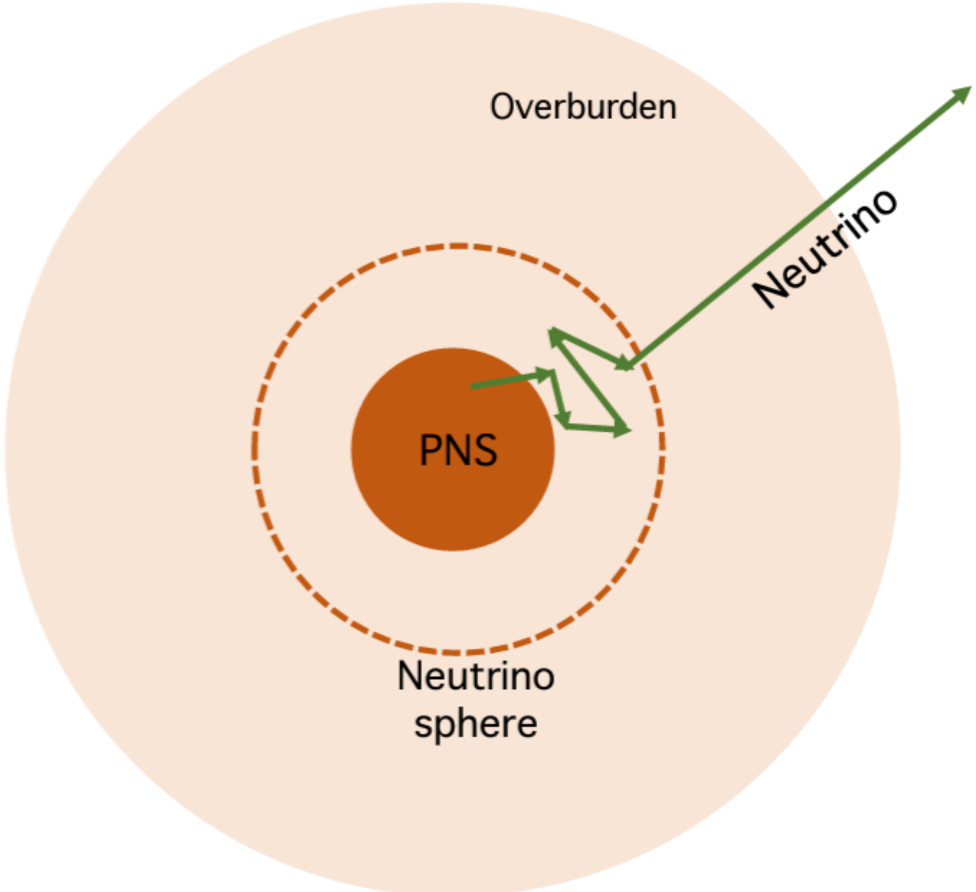
Outline

- Supernova (SN) production of MeV-scale particles is large well below cooling bound
- SN-produced MeV dark matter is detectable in existing WIMP detectors
    - How DM detectors can discriminate MeV SN-produced DM from classical WIMP-DM?
- Directional searches with CYGNO

Protoneutron star

- Core-collapse of massive star releases **>10^{53} erg**
- Protoneutron star (PNS) has temperature ~**30 MeV**
- Neutrinos diffuse inside "neutrino sphere" then free-stream, cooling PNS

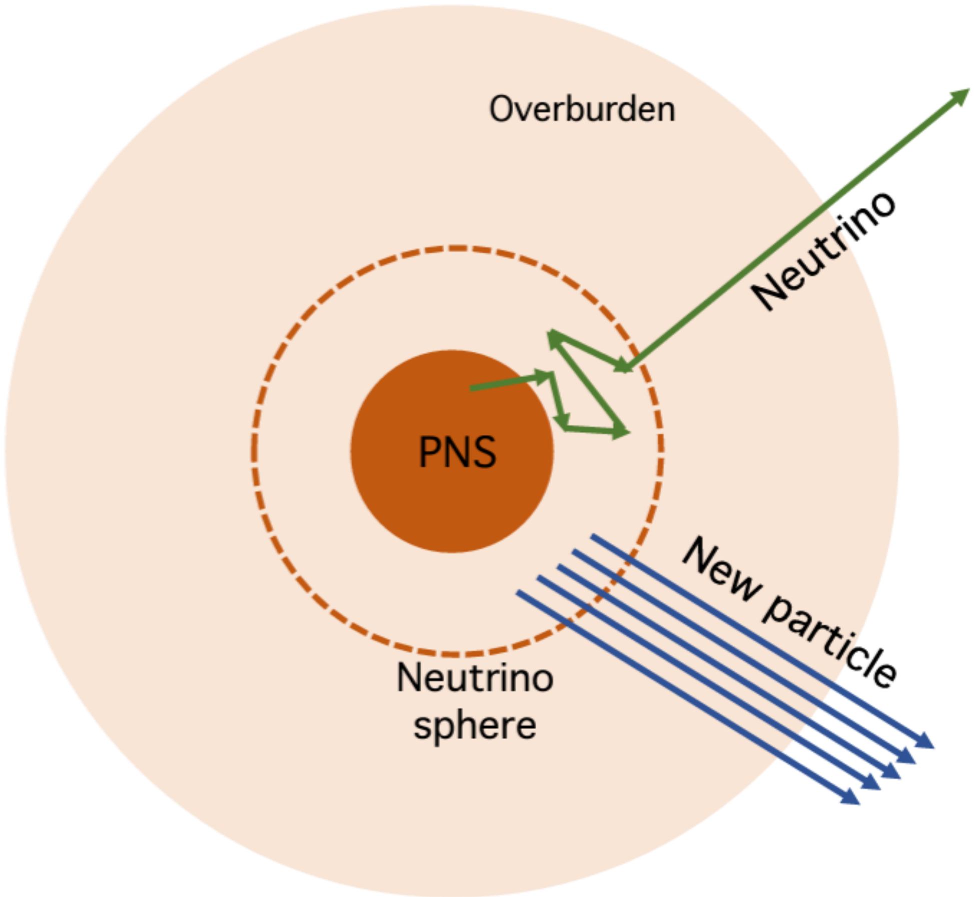


From the talk by W. DeRocco
Supernova signals of light dark matter in directional detectors

W. DeRocco,[1] P. Graham,[1] D. Kasen,[2] G. Marques-Tavares,[3] S. Rajendran[2]

Protoneutron star cooling constraints

- Core-collapse of massive star releases **>10^{53} erg**
- Protoneutron star (PNS) has temperature ~**30 MeV**
- Neutrinos diffuse inside "neutrino sphere" then free-stream, cooling PNS
- 10-second cooling timescale observed during SN1987a
- **Cooling constraint:** new particle cannot transfer more energy than neutrinos



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Supernovae can produce MeV Dark Matter!

PHYSICAL REVIEW D **100,** 075018 (2019)

Supernova signals of light dark matter

William DeRocco,[1] Peter W. Graham,[1] Daniel Kasen,[2,3] Gustavo Marques-Tavares,[1,4] and Surjeet Rajendran[2]
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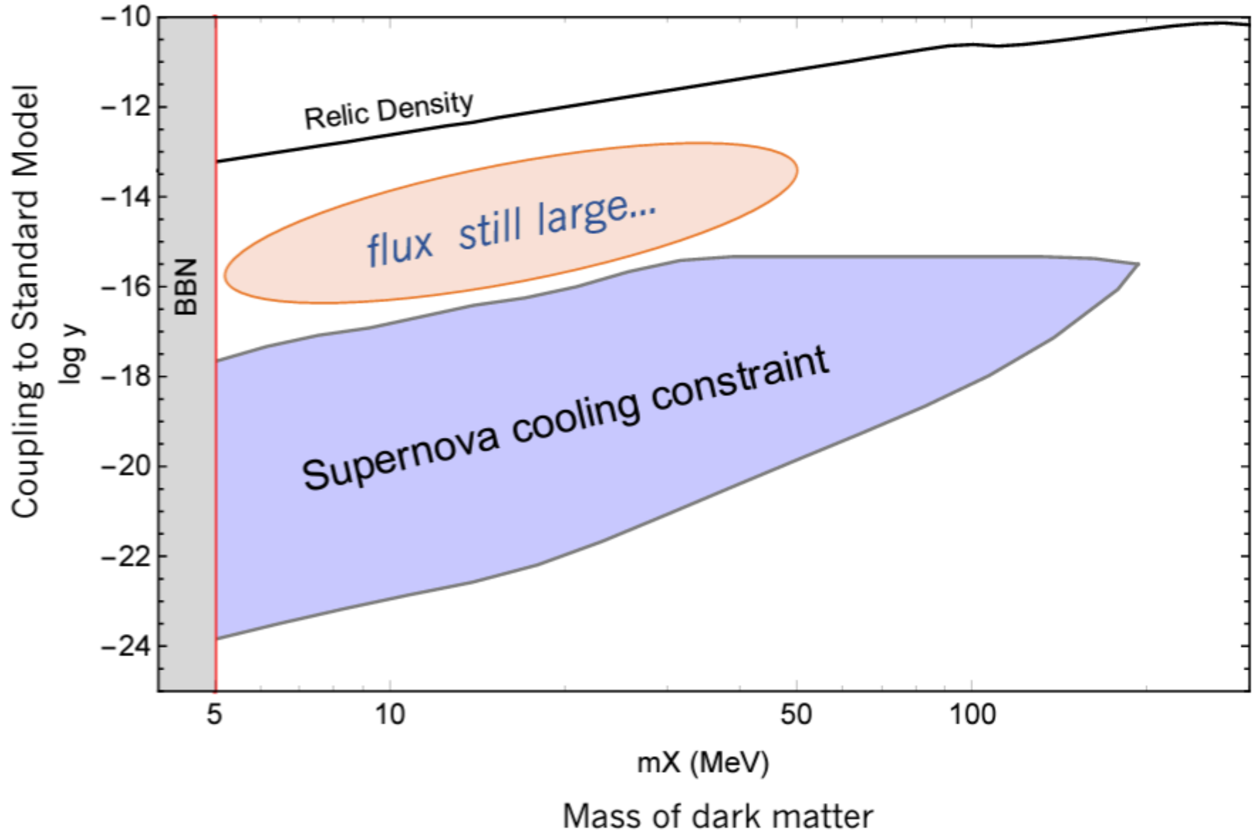
[2]*Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*

- Near cooling limit, flux of MeV-scale particles can still be very large
- **Direct observation can constrain where cooling bound fails!**

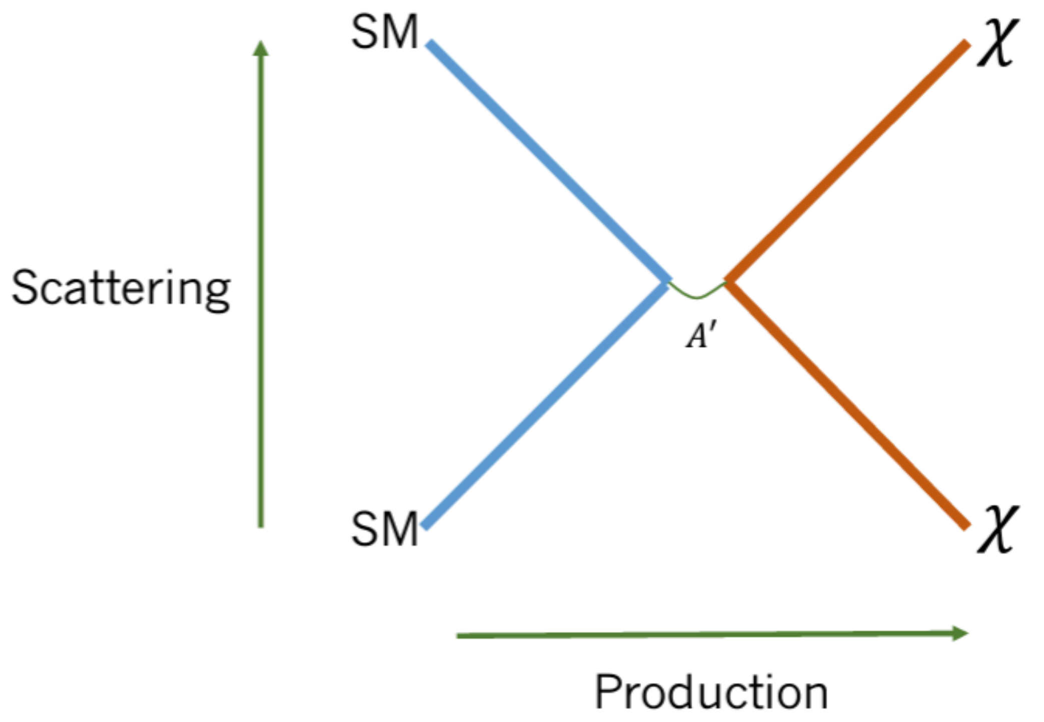


Dark Fermion scenario

- Dark sector with stable fermion (χ)
- DM-SM coupling through heavy dark photon (A')

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon_Y}{2}F'_{\mu\nu}B_{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu + \bar{\chi}(i\not{\partial} - m_\chi)\chi$$

- **Results apply to large class of models**



MeV DM production through diffusive trapping

- **Above cooling bound, particles diffusively trapped by SM scattering**
- Spectrum set by radii at which interactions decouple

Production/annihilation

$$\chi\ \bar{\chi} \longleftrightarrow e^{+}\ e^{-}$$

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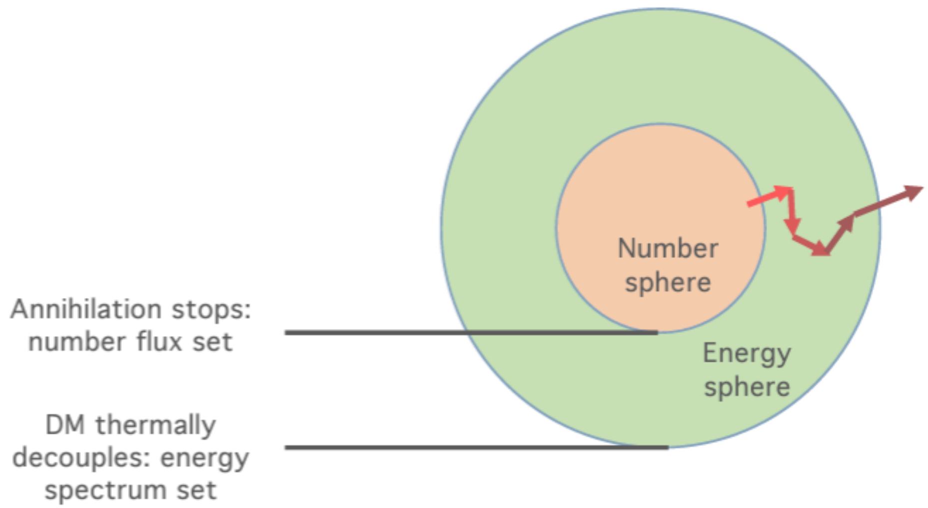
Energy transfer

$$\chi\ e \longrightarrow \chi\ e$$



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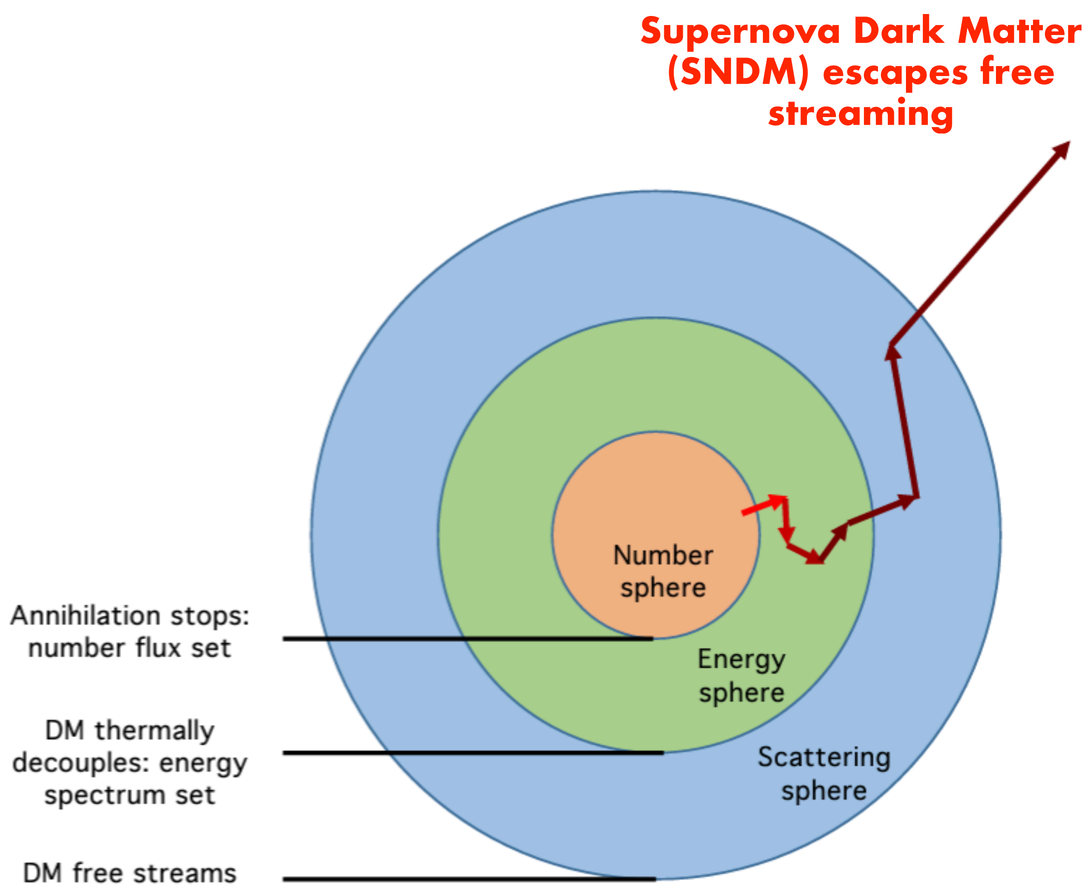
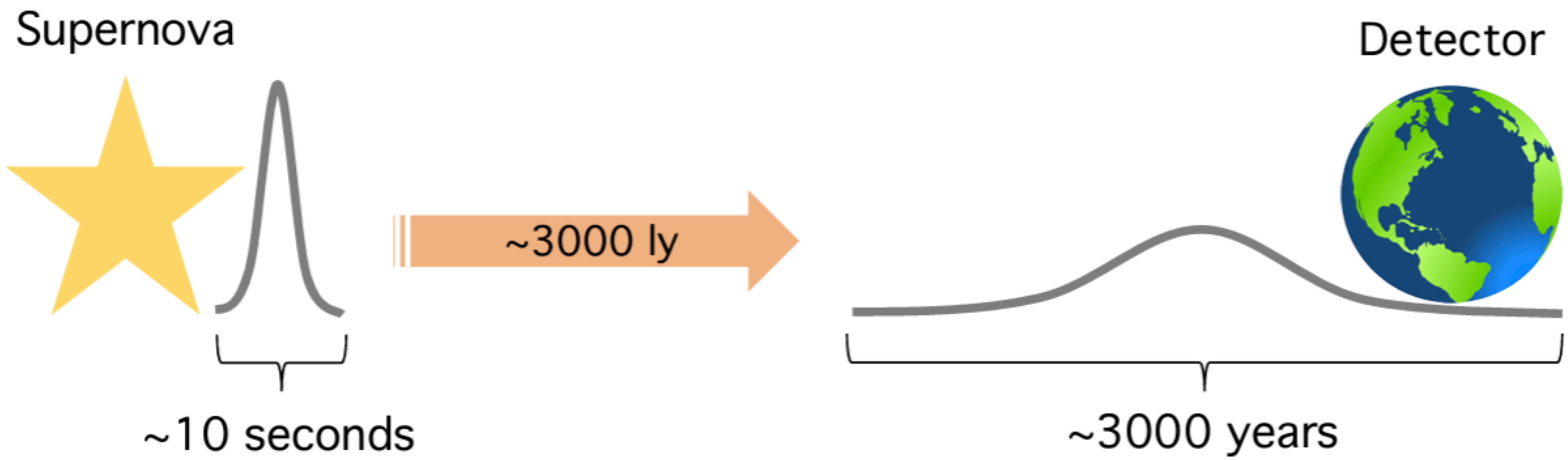


SNDM diffuse galactic flux

- Dark fermions escape at semirelativistic velocities
- Arrival times at Earth spread by light travel time
- **Emissions from several SN overlap to form diffuse flux**



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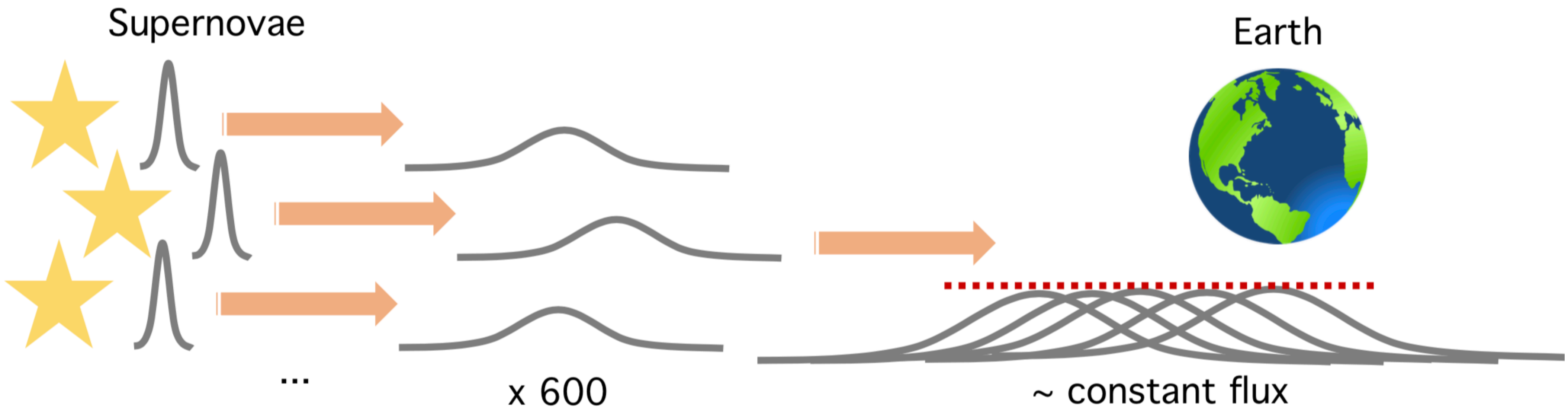

SNDM versus WIMP induced recoil momentum

Phys.Rev.D 102 (2020) 7, 075036

Target (i.e. nuclei) recoil momentum

$$|\vec{k}| = \frac{2m_A(\sqrt{p_0^2+m_X^2}+m_A)p_0\cos\theta_r}{(\sqrt{p_0^2+m_X^2}+m_A)^2 - p_0^2\cos^2\theta_r}$$

non-relativistic O(GeV) masses

$$|\vec{k}^{\rm WIMP}_{\rm nuc}| \approx 2p_0\cos\theta_r\left(\frac{m_A}{m_A+m_X}\right). \longrightarrow 2v_0\mu\cos\theta_r$$

$$|\vec{k}^{\rm SNDM}_{\rm nuc}| \approx 2p_0\cos\theta_r. \longrightarrow 2E_0v_0\cos\theta_r,$$

semi-relativistic O(MeV) masses

For $E_0 \simeq \mu_0$ **then** $|\vec{k}^{\rm WIMP}_{\rm nuc}| \simeq |\vec{k}^{\rm SNDM}_{\rm nuc}|$

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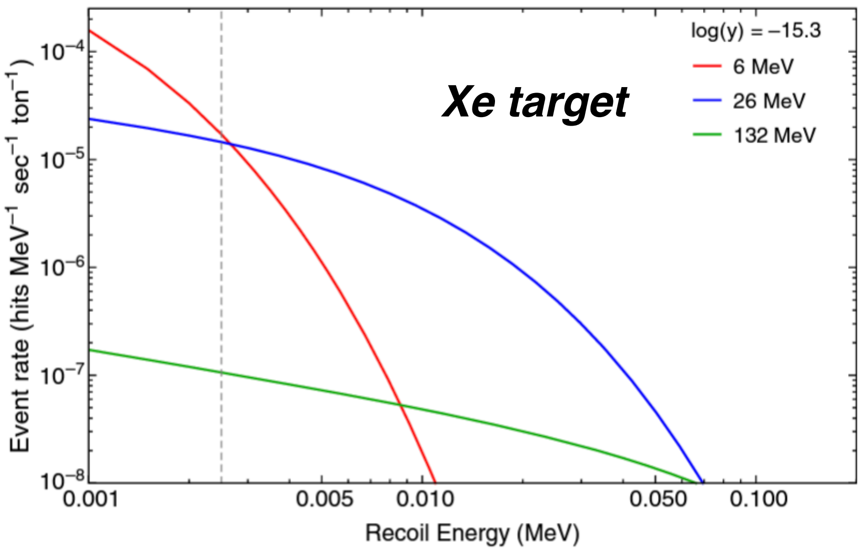
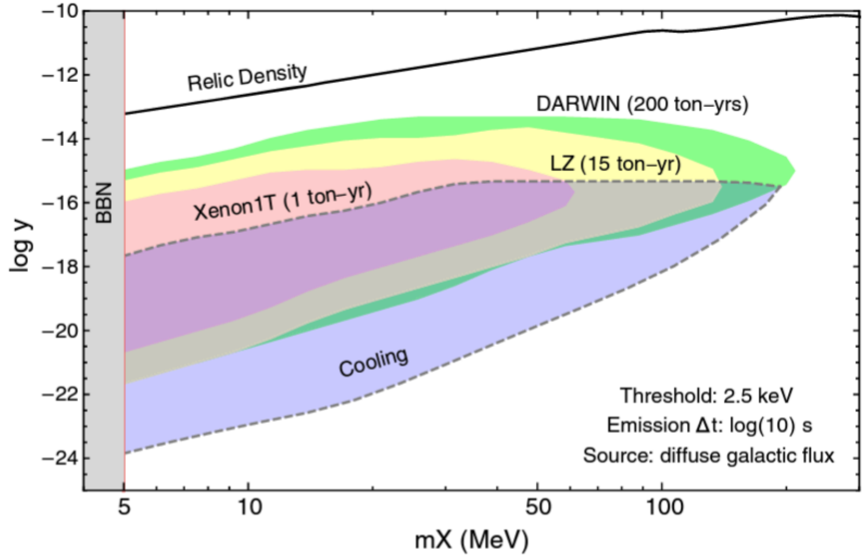
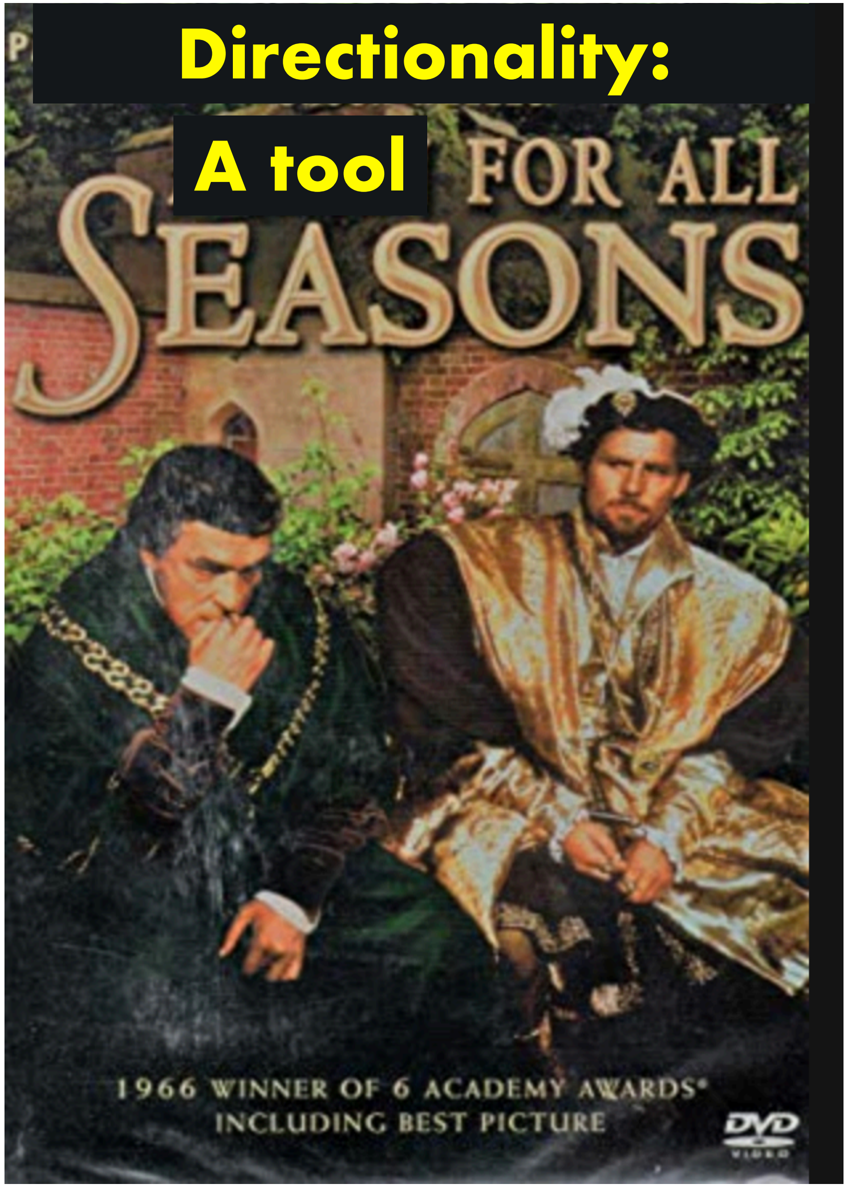




The issue

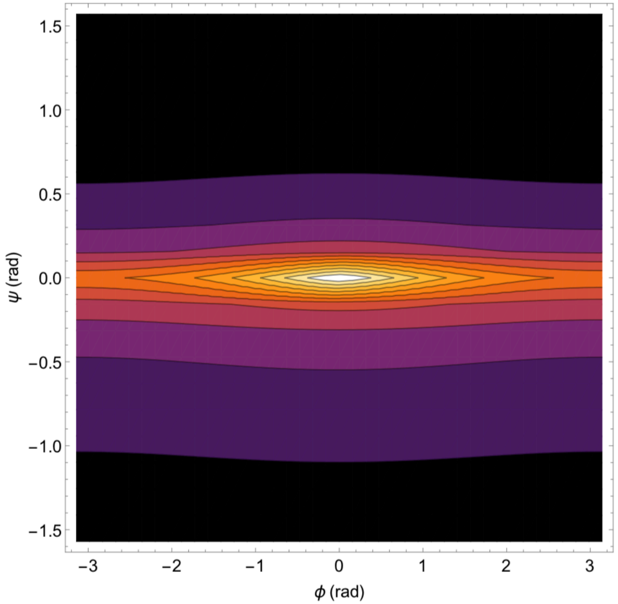
If a DM detector observes an O(keV) nuclear recoil signal, how can we tell if is WIMP or SNDM?

Directionality: a tool for all season



Directionality saves the day!

- **Diffuse flux strongly peaked towards Galactic center**
- Isotropic intergalactic contribution highly subdominant



$m_χ$ = 11 MeV
y = 1e-16

All-sky flux:
~10^4 cm^{-2} s^{-1}

$\log_{10} \Phi$ (cm^{-2} s^{-1} sr^{-1})

4.25
4.00
3.75
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75

Note: 100 GeV WIMP
~ 10^5 cm^{-2} s^{-1}

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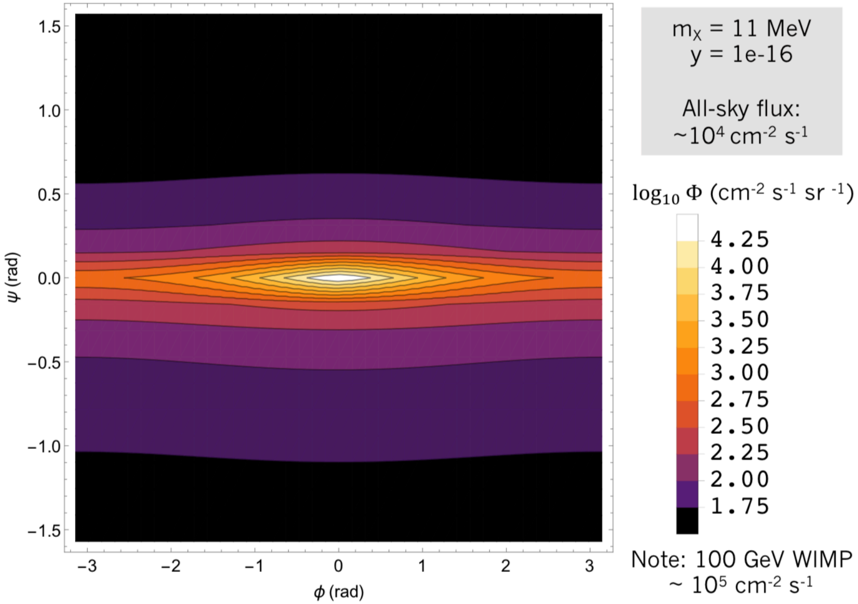
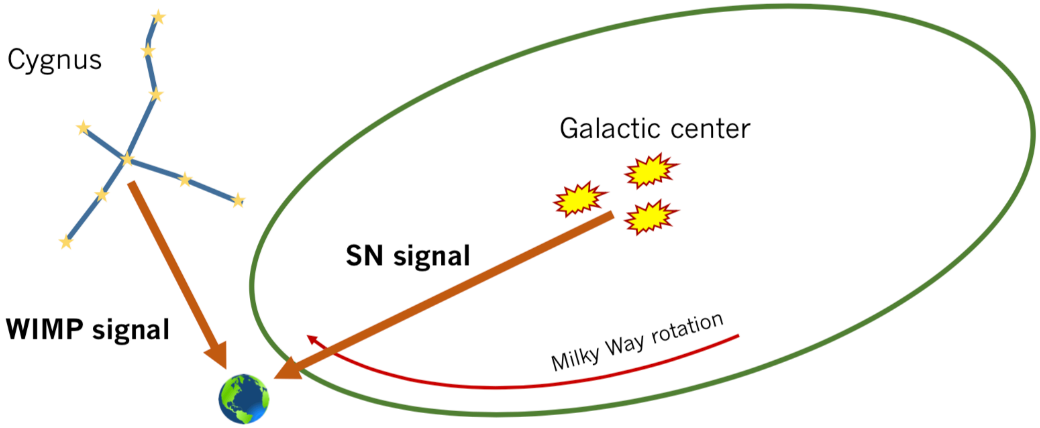


- **SN signal is perpendicular to WIMPs!**
- Directional detectors are necessary for discrimination of future signal



SN-produced MeV DM versus WIMPs scenarios

Discovering supernova-produced dark matter with directional detectors

Elisabetta Baracchini,[1,2] William DeRocco,[3] and Giorgio Dho[1,2]

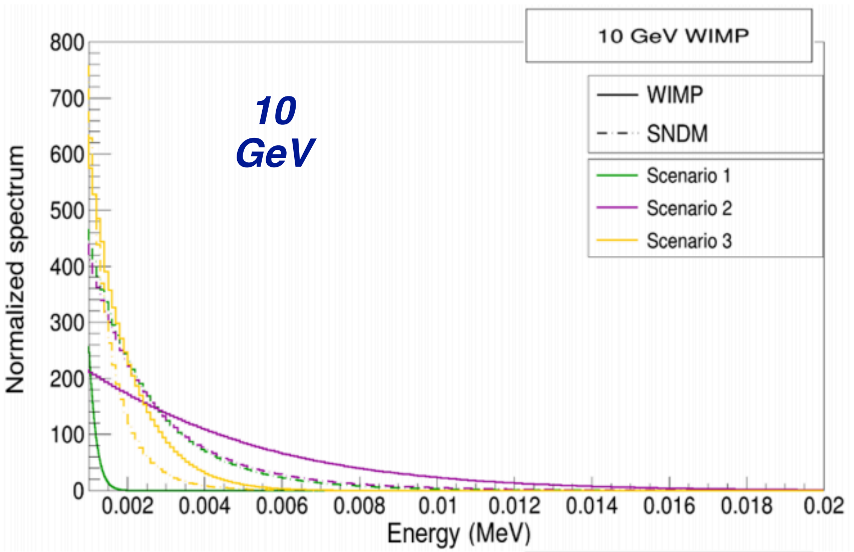
Phys.Rev.D 102 (2020) 7, 075036

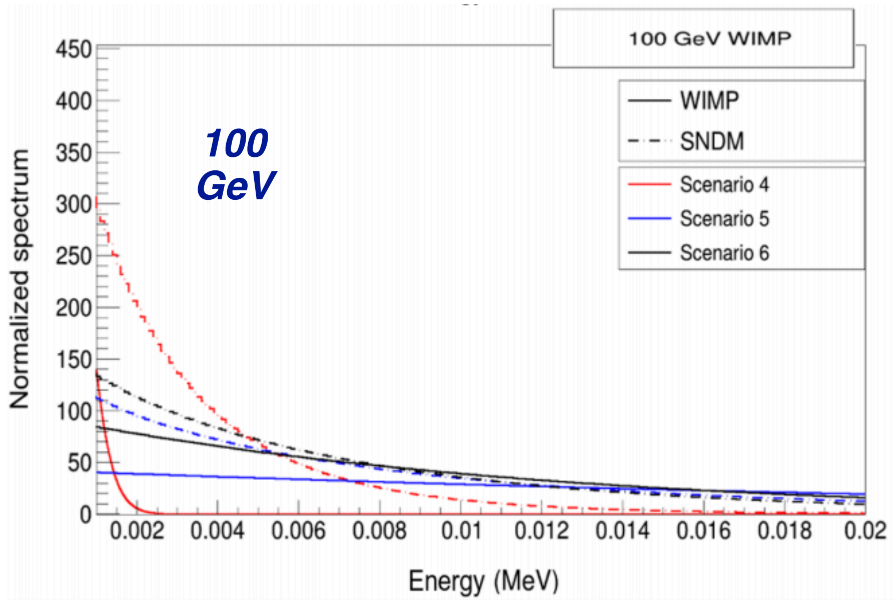
- **Light, medium and heavy target: He, F, Xe**
- **Light (10 GeV) and heavy (100 GeV) WIMP masses**
- **Six SNDM scenarios producing similar energy deposition in the detector**

T = Temperature of energy sphere
y = SNDM to SM coupling
Φ = related to the radius of energy sphere

Scenario	Target	WIMP Mass [GeV]	SNDM Mass [MeV]	T [MeV]	$\log_{10} y$	Φ
1	^{4}He	10	5	0.31	−13.3	0.006
2	^{19}F	10	7	1.0	−14.3	0.02
3	^{131}Xe	10	9	1.6	−14.6	0.03
4	^{4}He	100	5	0.52	−14.0	0.01
5	^{19}F	100	14	3.0	−15.0	0.07
6	^{131}Xe	100	38	13.4	−16.0	0.1

Energy spectra





Experimental toy setup

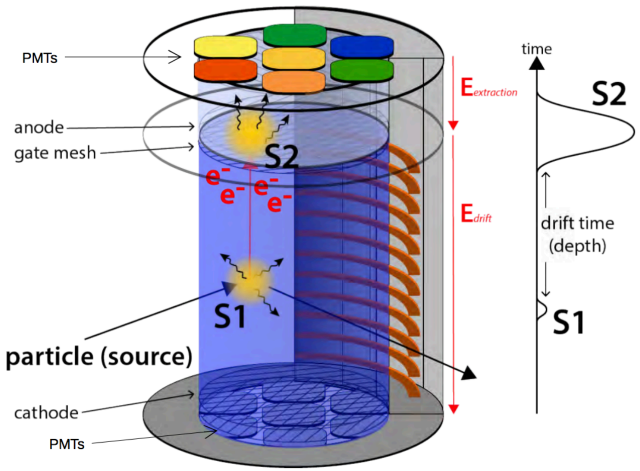
Since the interest is in quantifying the capability to discriminate between two models (and not in the discovery), perfect background rejection is assumed in both cases

LXe TPC

Energy ROI [4.9, 40.9] keV$_{nr}$

Realistic energy resolution from measurements

Energy only information

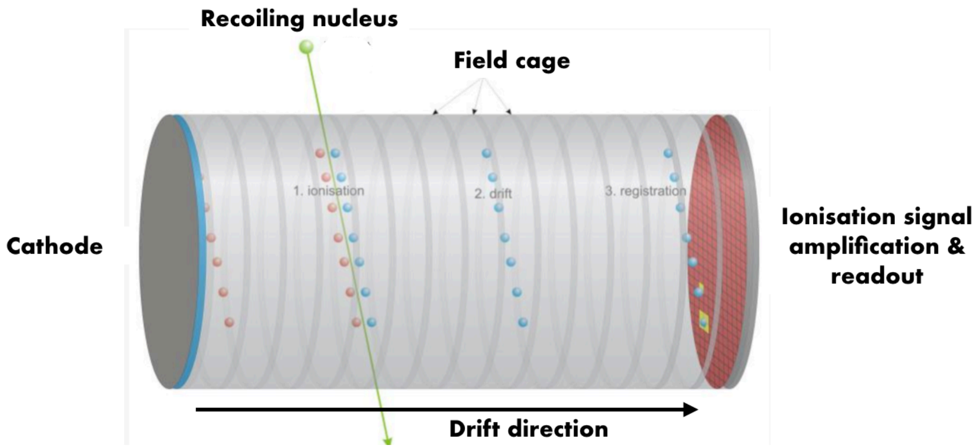


He:CF$_4$ gas TPC

Energy ROI [5.9, 100] keV$_{nr}$

Realistic energy resolution extrapolated from measurements

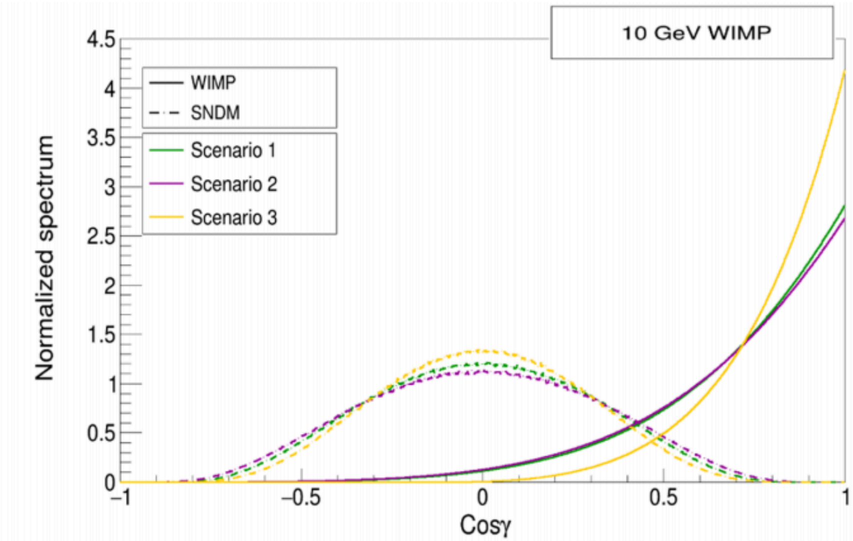
Energy + Angular information



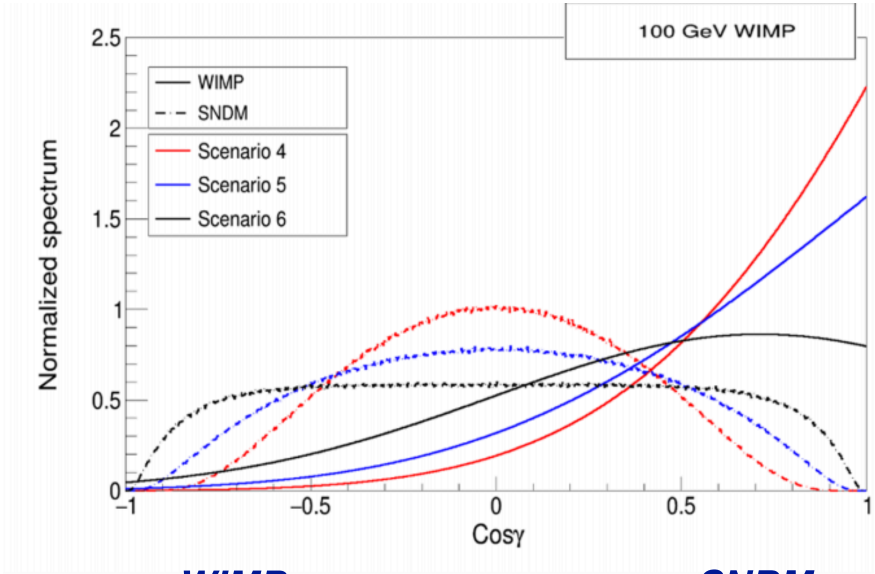
SN-produced MeV DM versus WIMPs angular distributions

1D angular

10 GeV WIMP

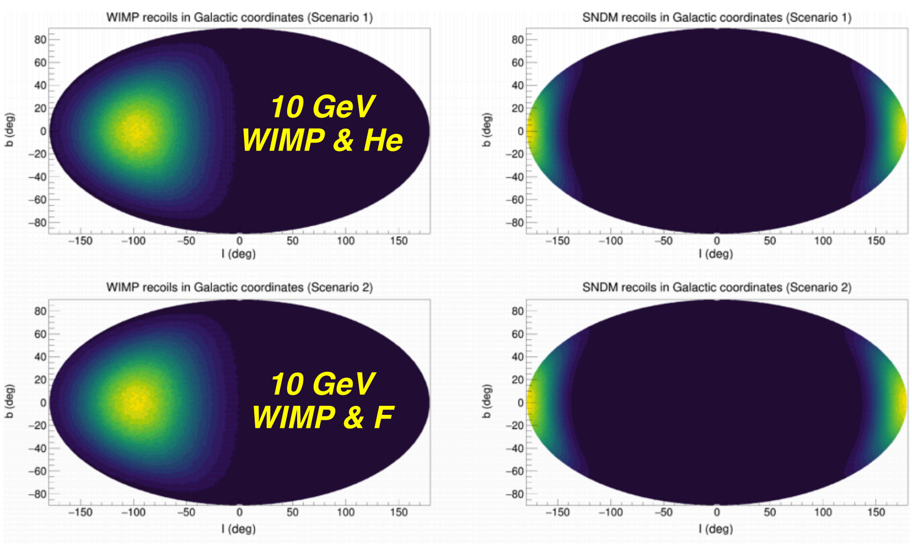


100 GeV WIMP

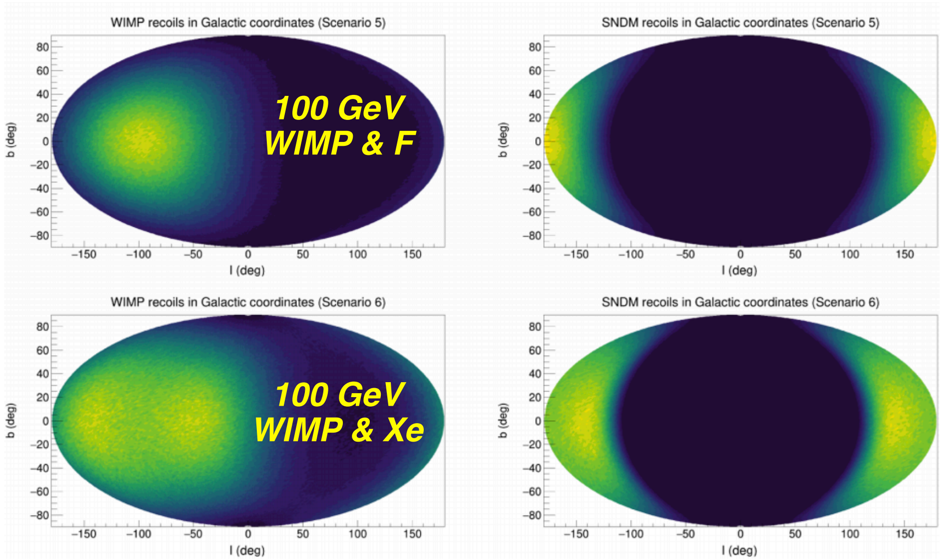


2D angular

WIMP **SNDM**

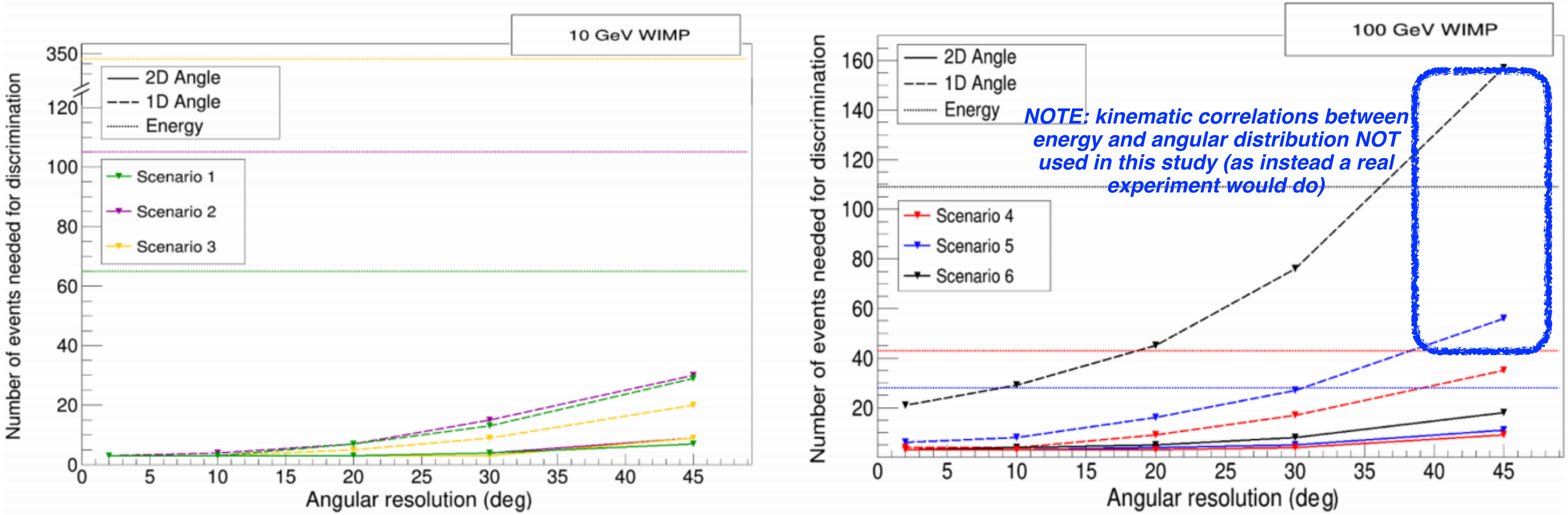


WIMP **SNDM**



Results within realistic experimental scenarios

Number of detected signal events in the ROI needed to distinguish WIMP from SNDM scenarios

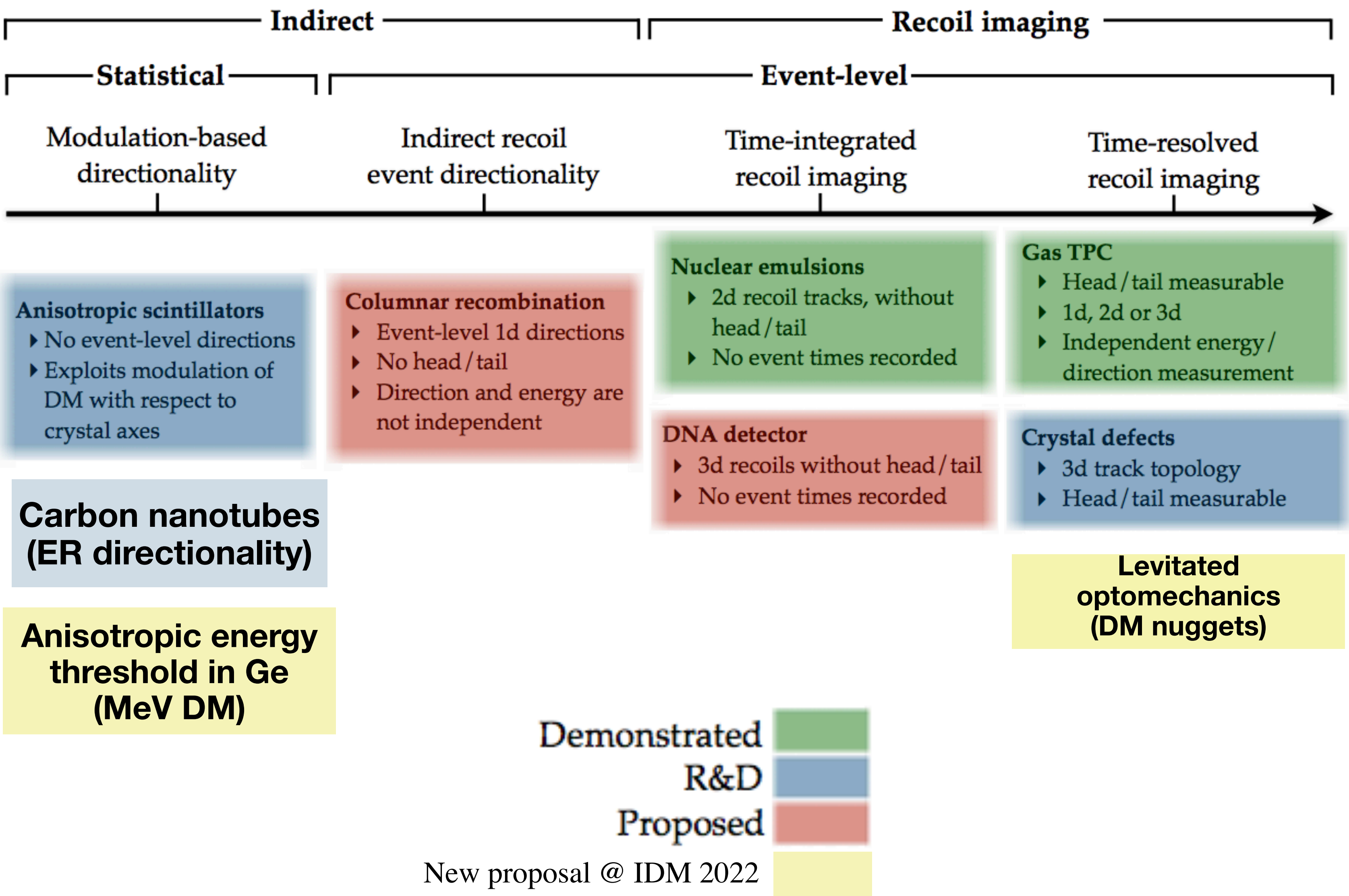


Directionality can reduce of <u>1-2 order of magnitude</u> the number of detected events to discriminate WIMPs from SNDM

How to make a directional detector of O(keV) energy recoils?

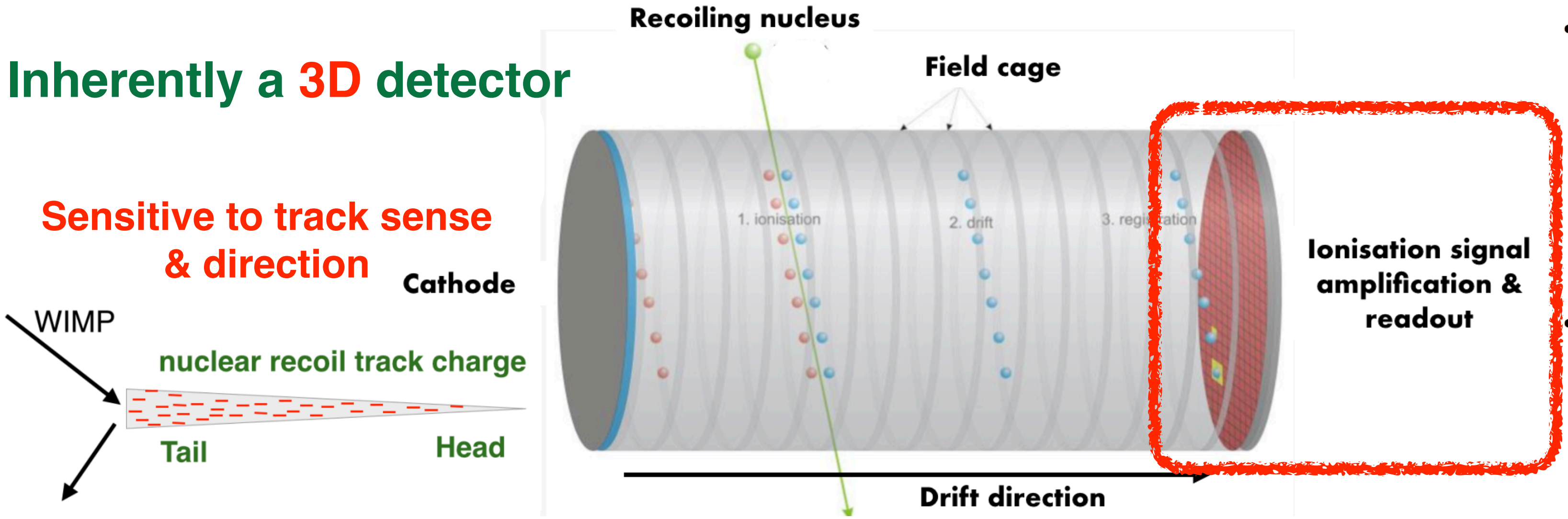
Detector classes by directional information

[Liberally adapted from S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224]



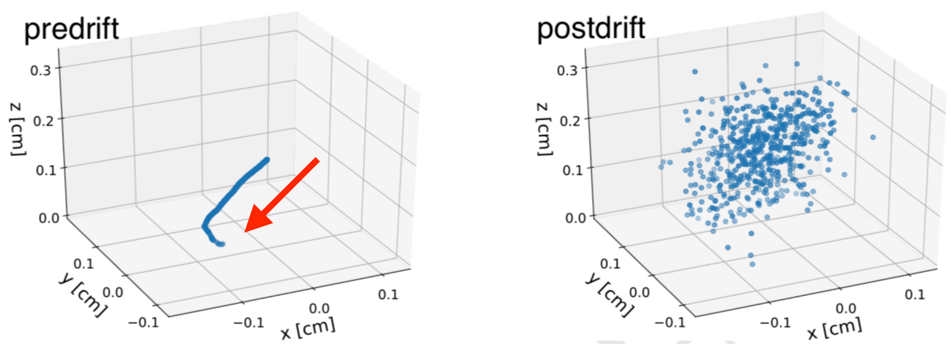
Gaseous TPC experimental approach

Inherently a 3D detector

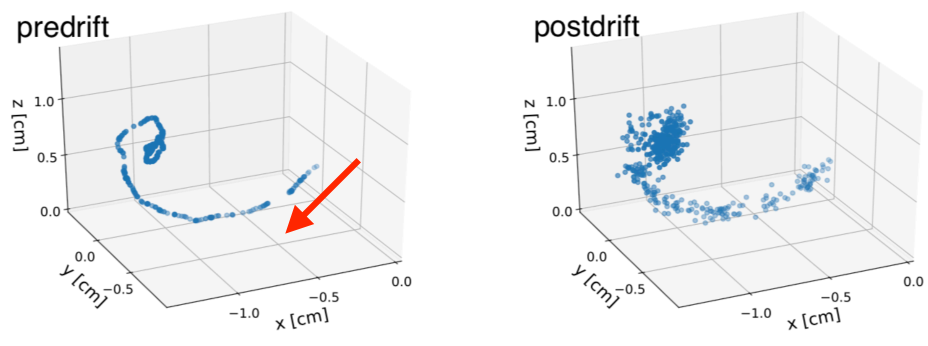


- Advantages:
  - Axial Directionality
  - **Head/tail**
  - Background rejection
  - Particle ID
  - 3D fiducialization
- Technologically challenging, but now achievable via multiple technologies

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

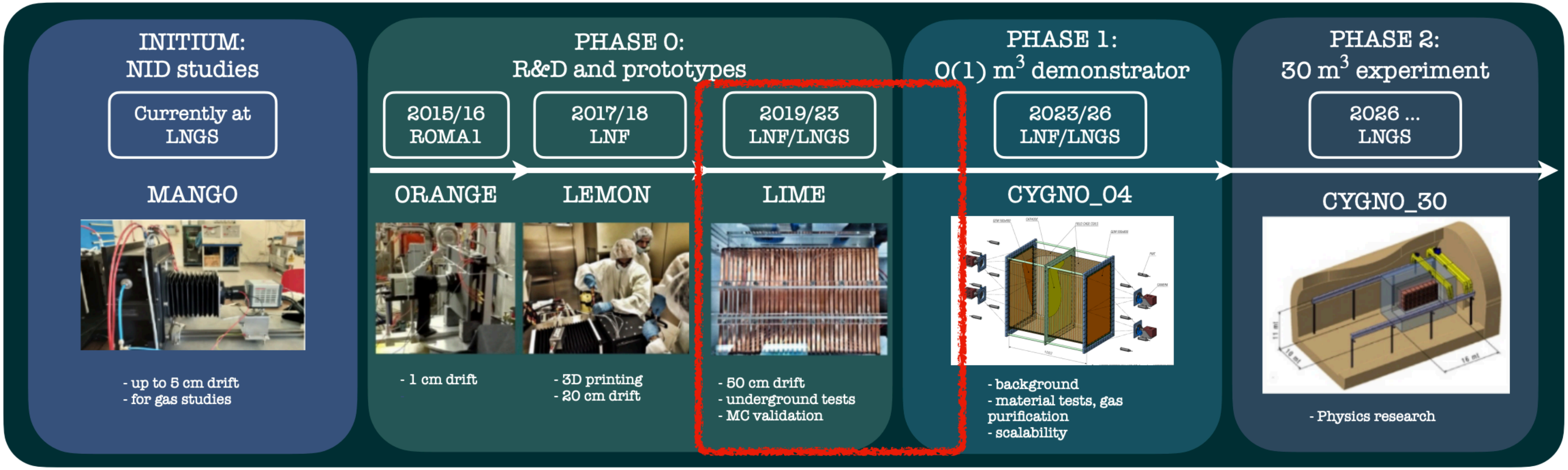


25 keV_{nr} nuclear recoil in He:SF_6 755:5 Torr



20 keV_{ee} electron recoil in He:SF_6 755:5 Torr

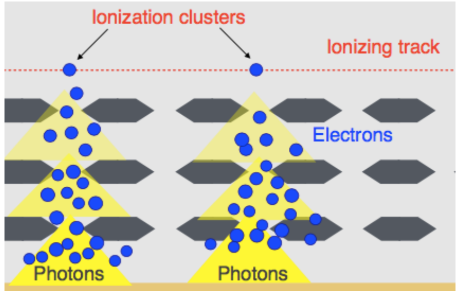
CYGNO timeline



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

CYGNO: GEMs + sCMOS + PMT

JINST 13 (2018) no.05, P05001



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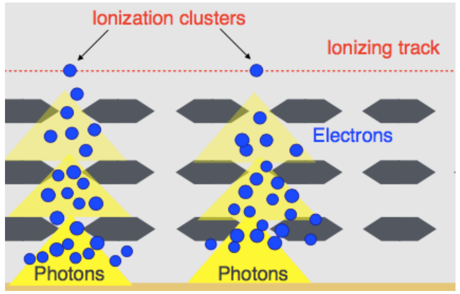
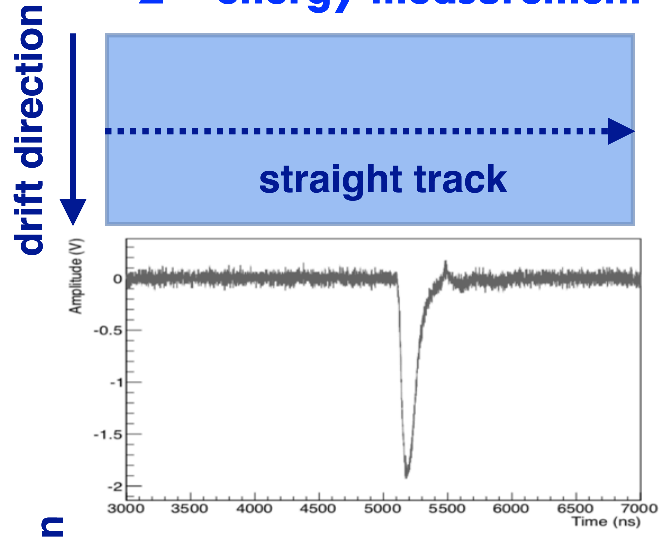
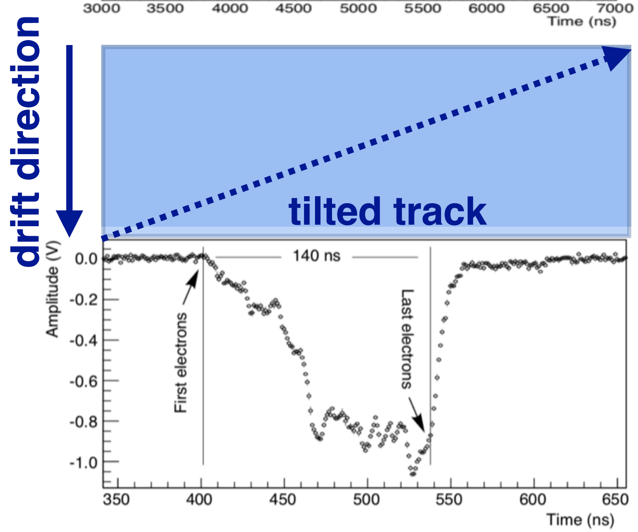


PMT:

integrated
Z + energy measurement





3D optical readout — *He:CF_4 @ 1 atm*

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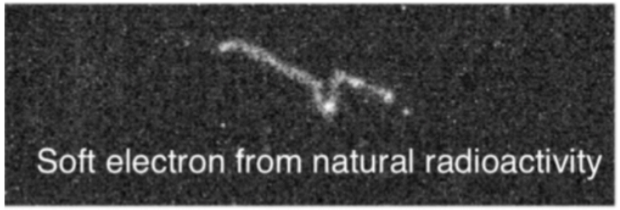
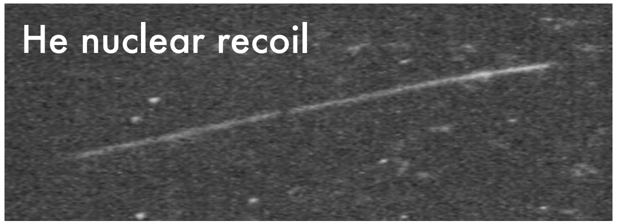
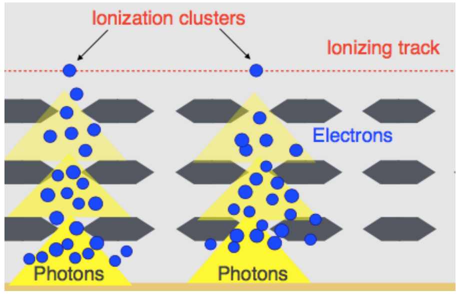
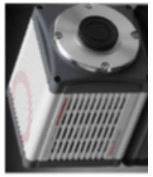
sCMOS:

high granularity
X-Y + energy measurements





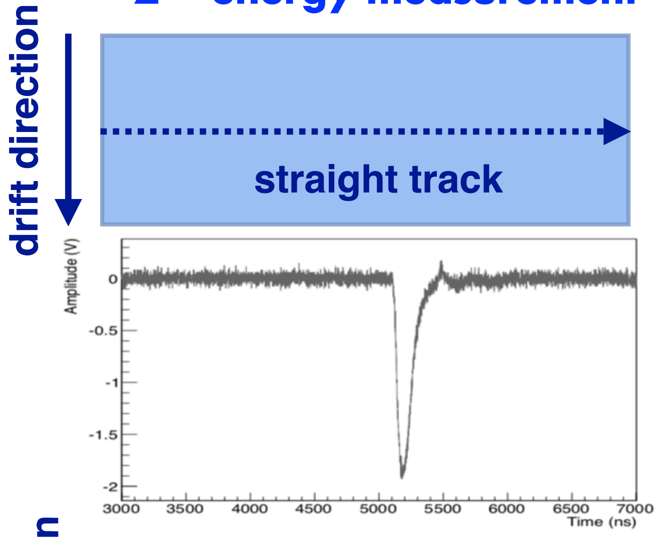


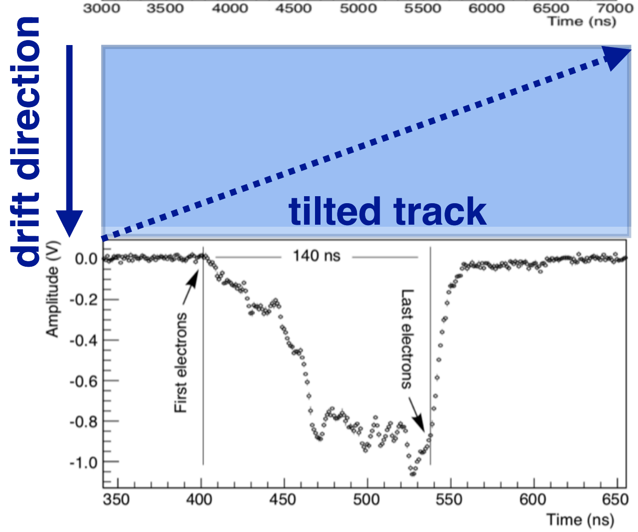


- **1/3 noise w.r.t. CCDs**
- **Market pulled**
- **Single photon sensitivity**
- **Decoupled from target**
- **Large areas with proper optics**

PMT:

integrated
Z + energy measurement





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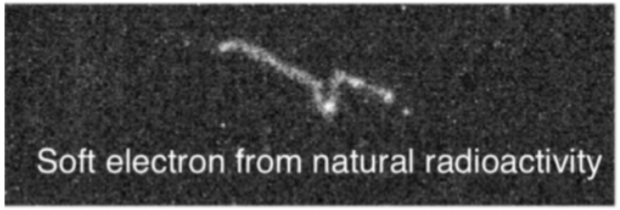

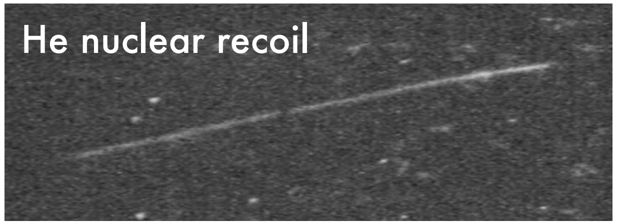

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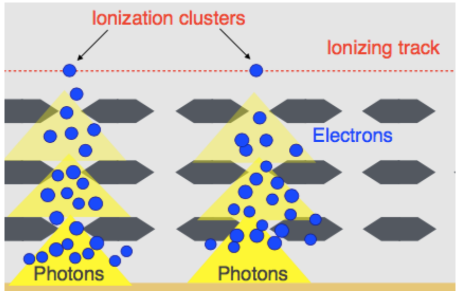

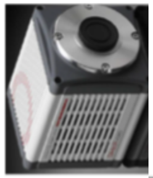

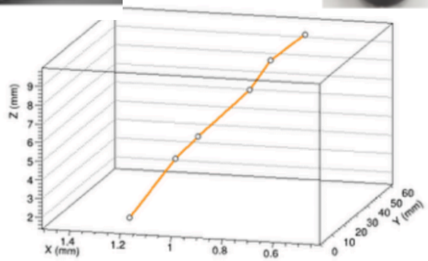

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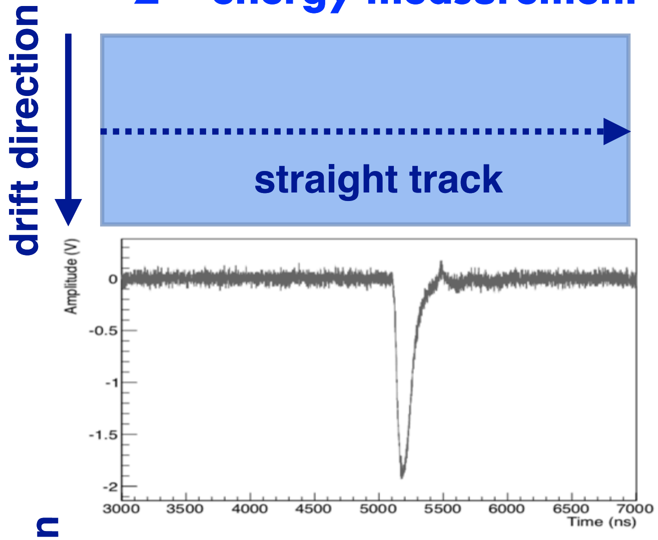

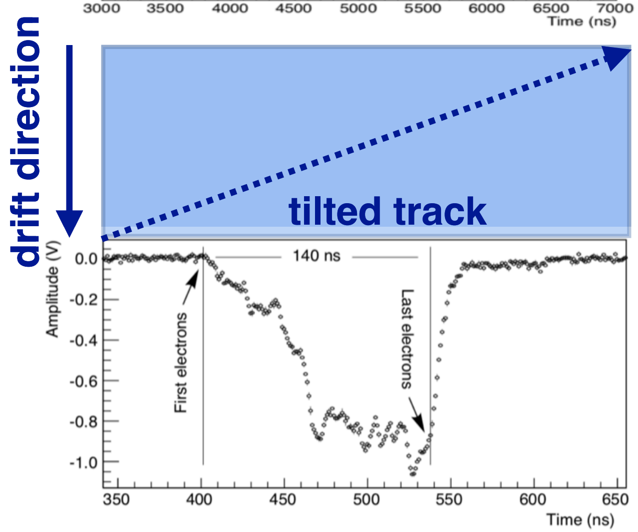

GSSI

3D optical readout

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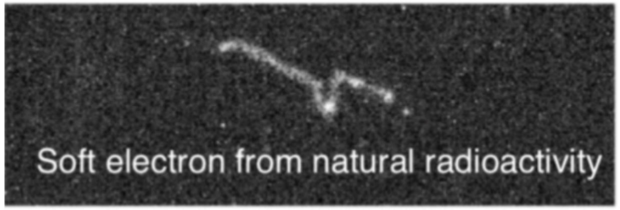
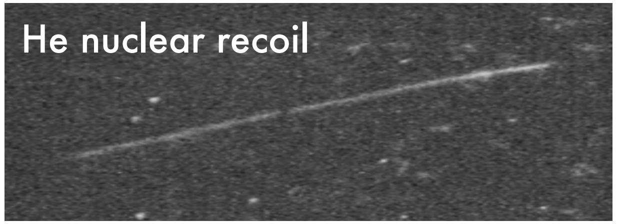
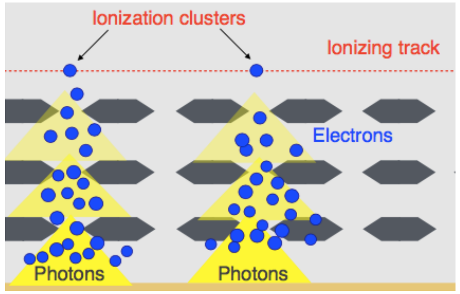
X-Y + energy measurements

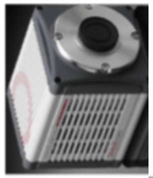


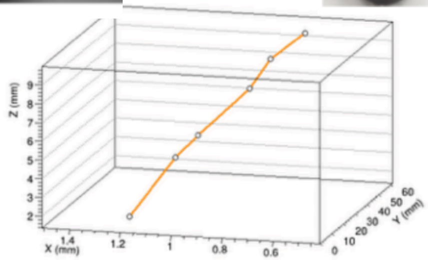


1/3 noise w.r.t. CCDs

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





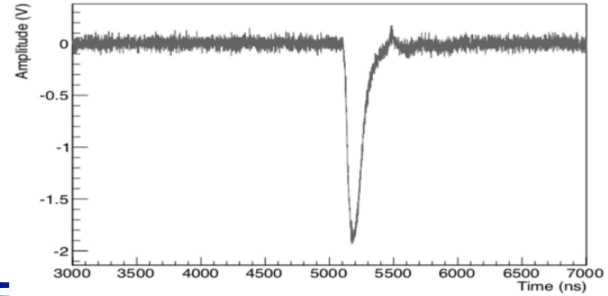


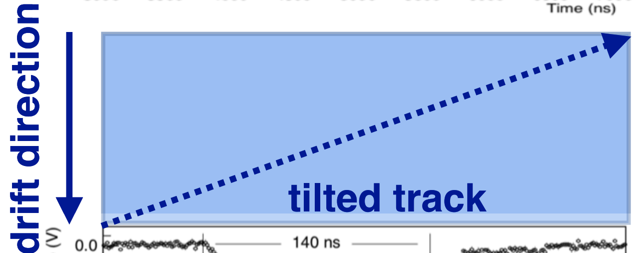
+ SF_6 for negative ion drift

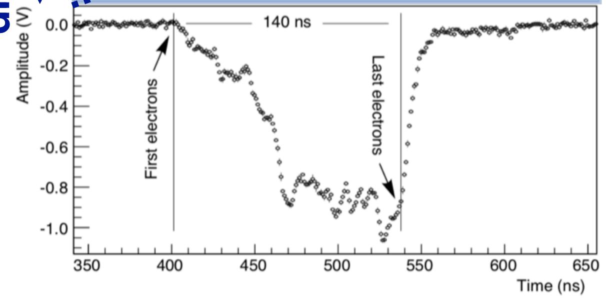
erc
European Research Council
INITIUM

PMT:

integrated
Z + energy measurement

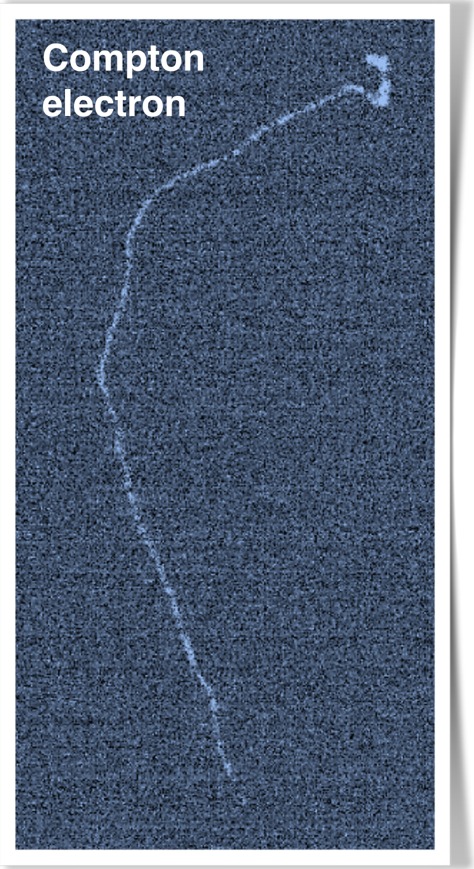


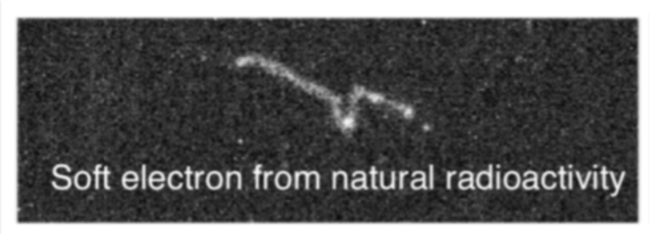


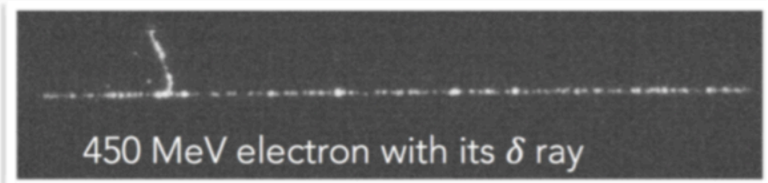


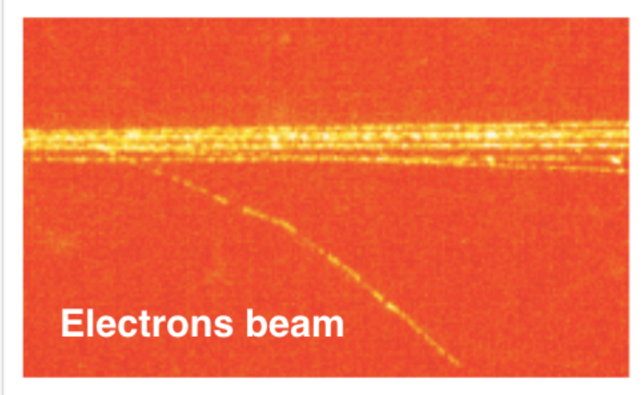
CYGNO:photographing tracks

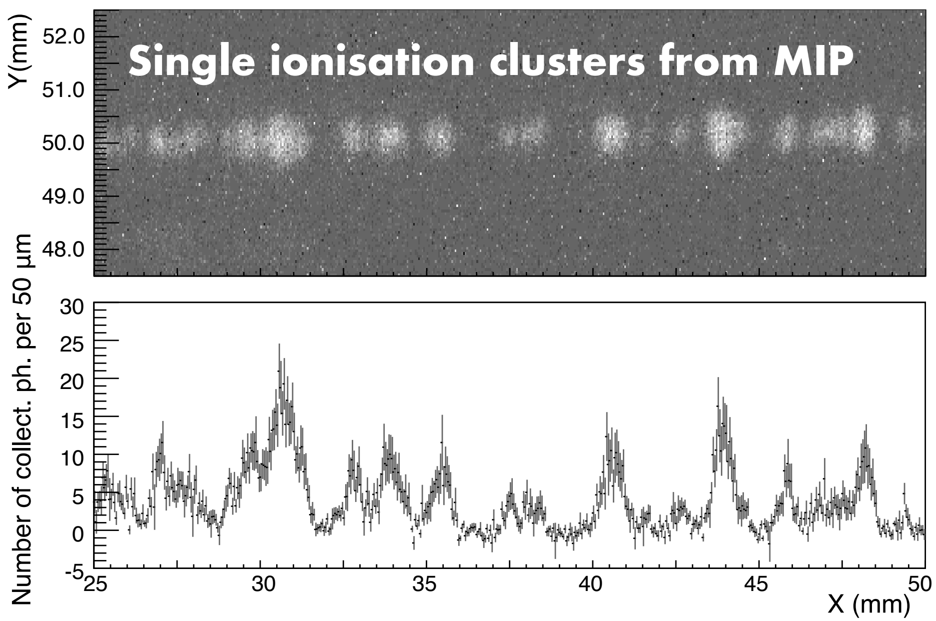
$He:CF_4$ @ 1 atm

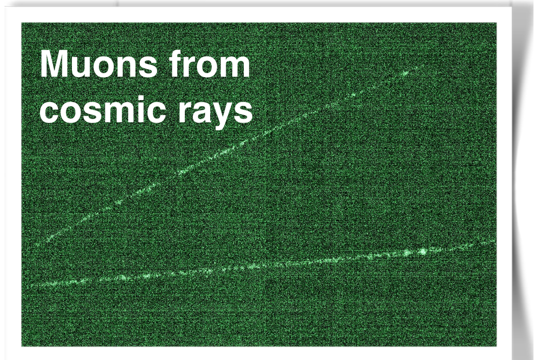


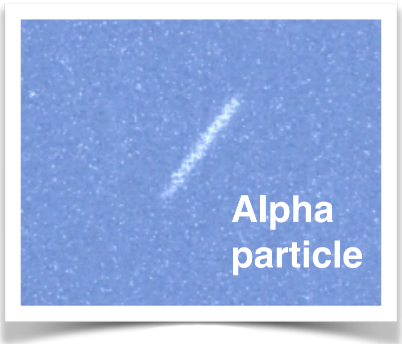


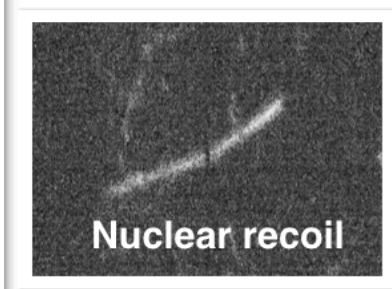












Optical readout: details

The CYGNO optical readout

- **CMOS** sensor noise:
  - ➡ Readout noise of 0.7 e^-/px ~ 0.9 γ/px
  - ➡ Dark current of 0.2 e^-/px/s ~ 0.25 γ/px/s
  - ➡ Acquisition time ~ 30-300 ms

- **Camera** Hamamatsu Orca-Fusion:
  - ➡ 80 % QE at 600 nm
  - ➡ 2304x2304 pixels
- 4 Hamamatsu R7378 **PMTs**:
  - ➡ 22 mm diameter
  - ➡ ~ns time response
- **Lens**: Schneider Xenon with 25.6 mm focal length and 0.95 aperture

Imaging a 33 x 33 cm² readout area

- Camera **geometrical acceptance** for light emitted on the GEM plane:

$$\epsilon_\Omega = \frac{1}{\left[4\,(1/\delta + 1) \times a\right]^2} = 1.2 \times 10^{-4}$$

De-magnification: $\delta = \frac{f}{d-f}$ with $f = 25.6$ mm [focal length], $d = 623$ mm [distance from GEMs]

Aperture = 0.95

- PMTs **geometrical acceptance:**
  - ➡ critically **depends** on the **position** of the emission on the GEM plane w.r.t. the PMT position
  - ➡ Empirical measured scaling:

$$L_i = \frac{L}{R_i^{\alpha}}$$

Light collected by the PMT #i (L_i); Total light emitted (L); Distance from the light emission (R_i); We measured $\alpha \sim 4$

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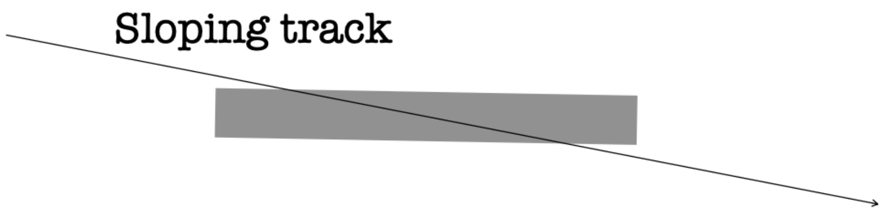
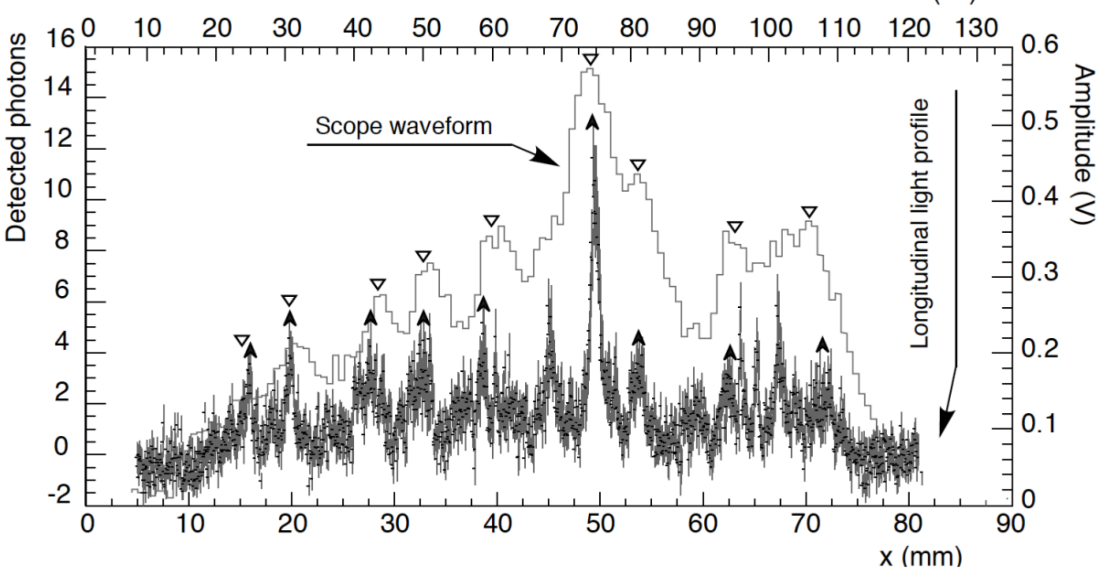
CMOS combined with Photomultipliers

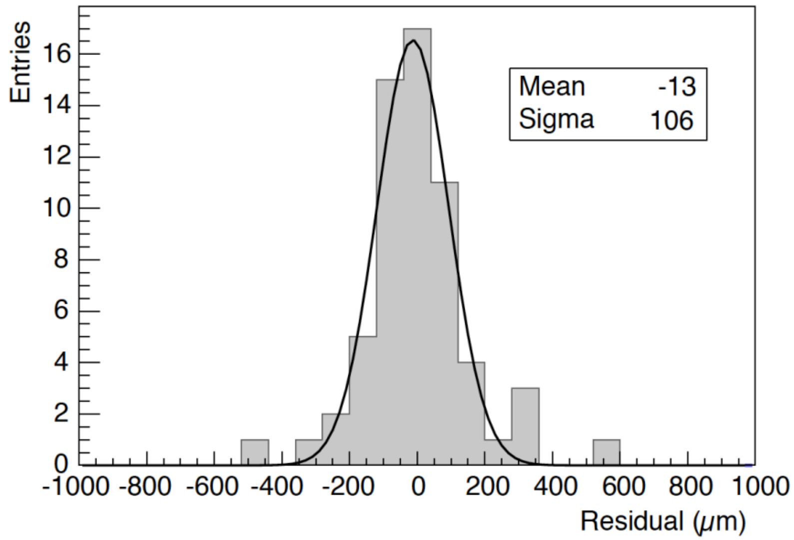
- Fast photosensors (**PMTs**) to get the **time** information ⇒ reconstruct **z inclination**



Antochi et al, 2018 JINST 13 P05001



Time + drift velocity ⇒ relative z coordinate



100 μm resolution on relative cluster **z**

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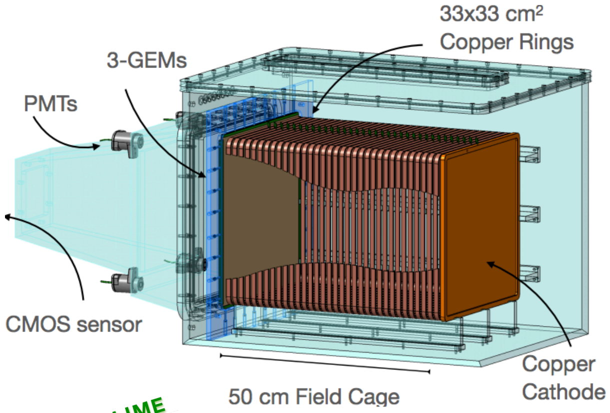
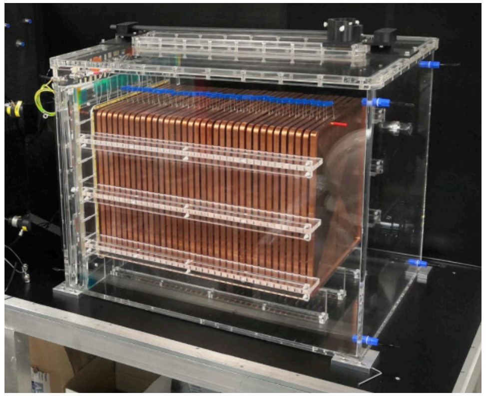
CYGNO PHASE 0: the LIME detector

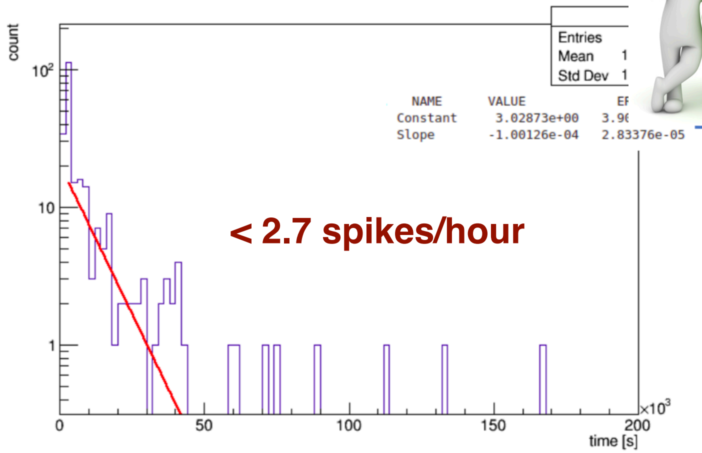




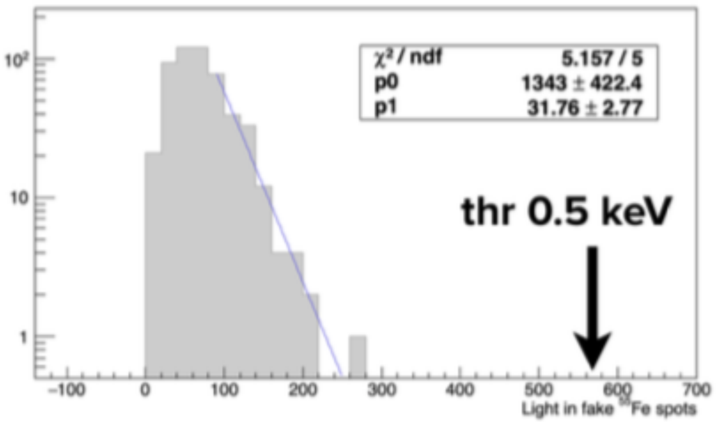
He:CF4
@ 1 atm

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

Stability



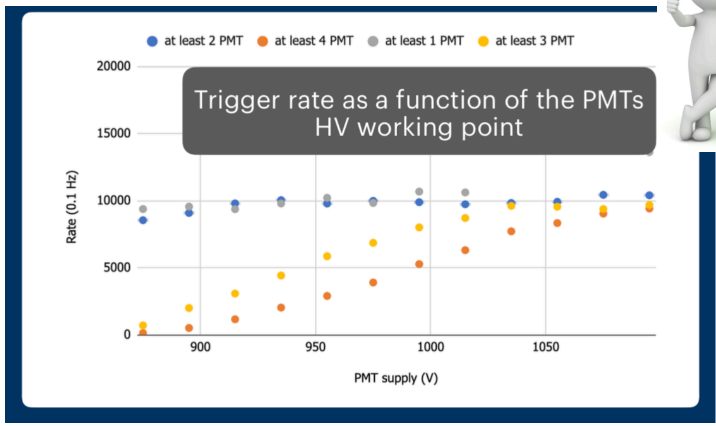
sCMOS fake clusters threshold



ORCA-Fusion

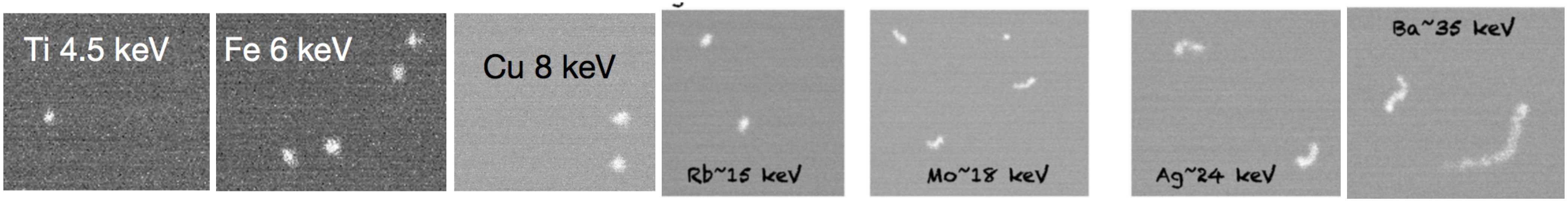
1 keV = 1200 photons

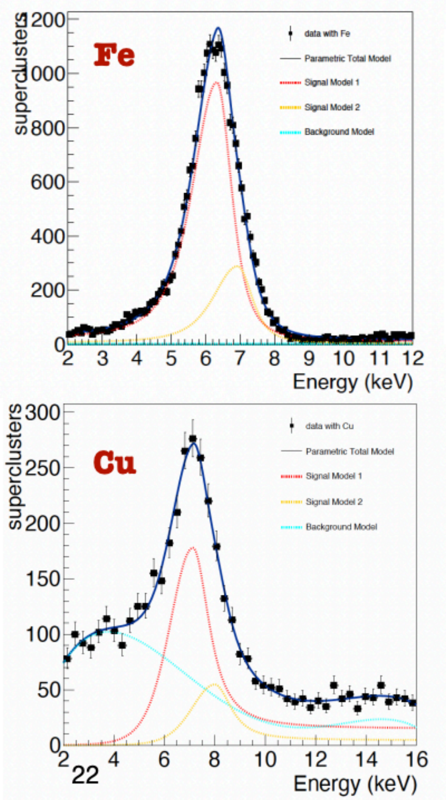
PMT trigger rate

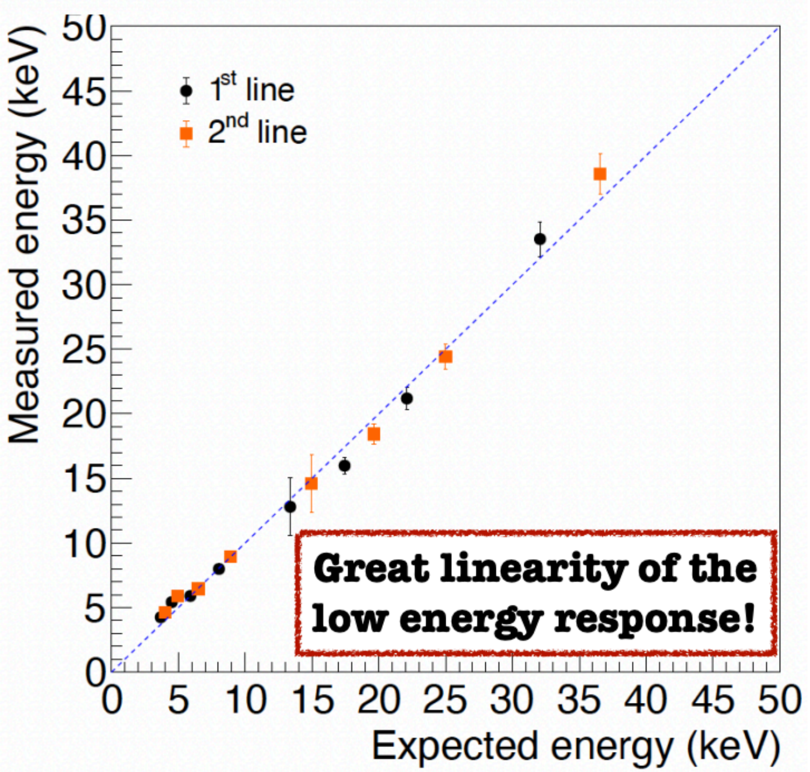


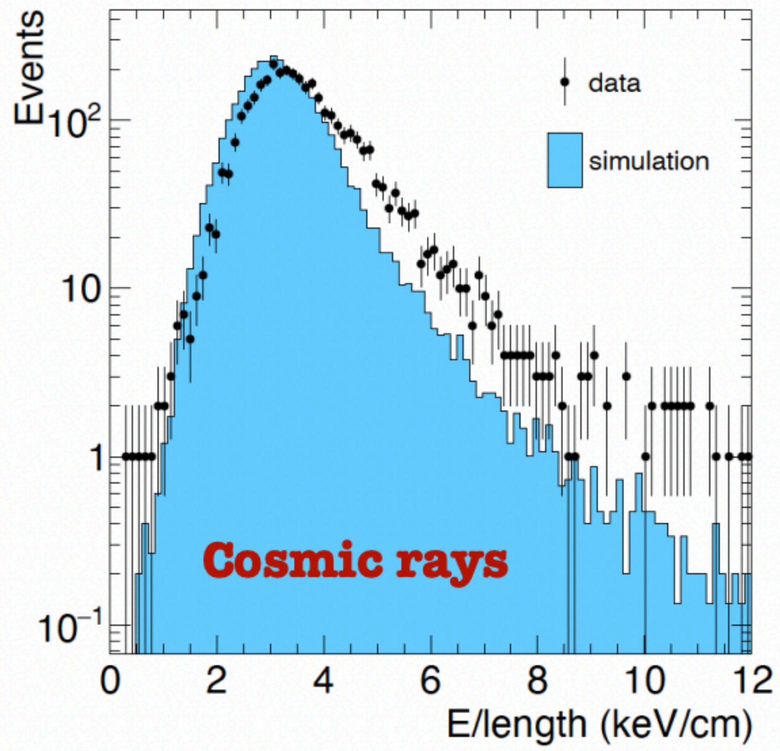
Different Trigger logics were tested with ^{55}Fe;
All of them converge to the same rate of 1 kHz

Electron recoils calibration



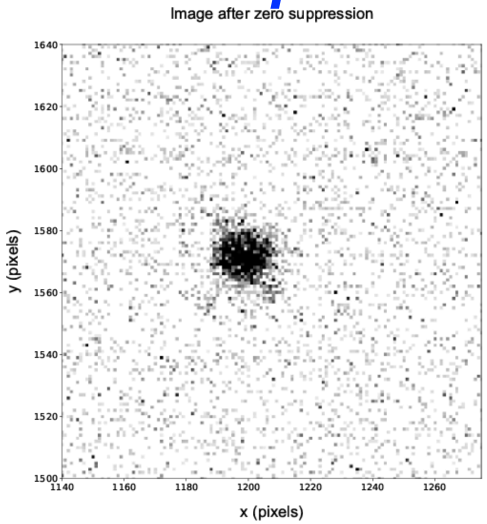




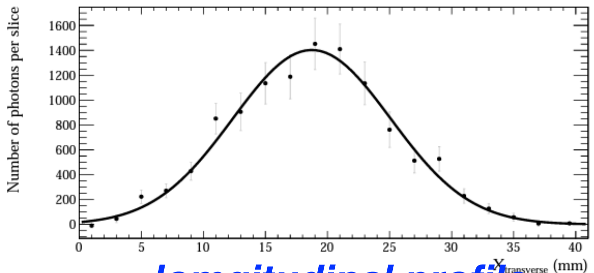


Fiducialization @ 5.9 keV_{ee}
(i.e. absolute Z coordinate)

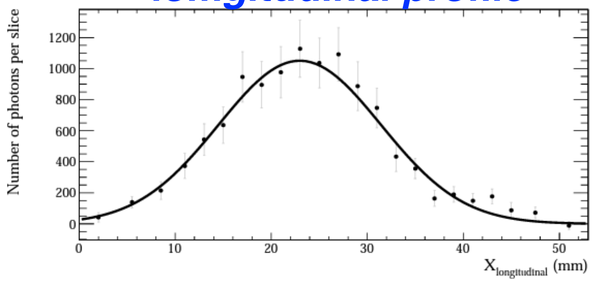
Iron spot



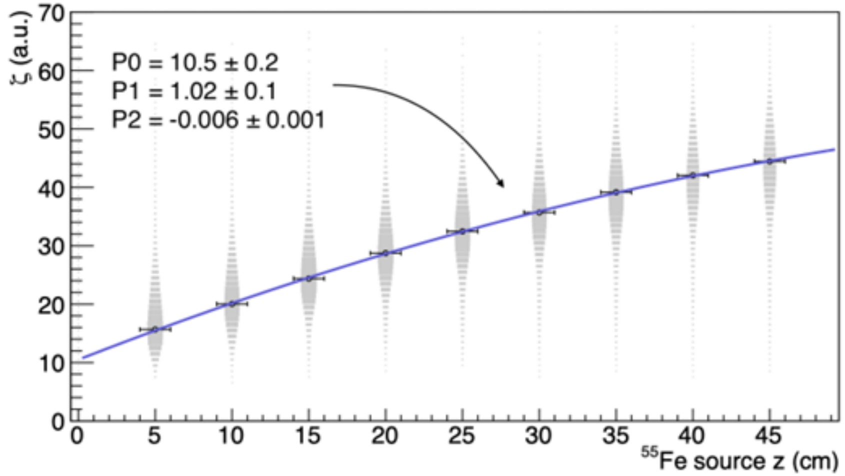
transverse profile



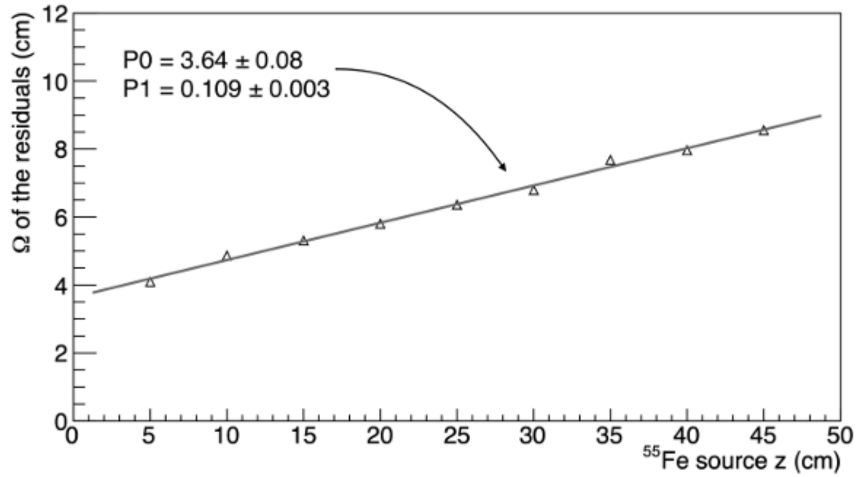
lomgitudinal profile



ζ = sigma of transverse profile x RMS of # pixels inside the spot

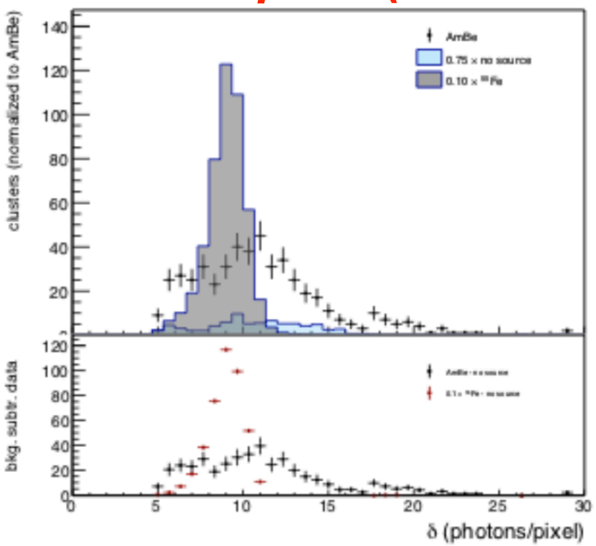


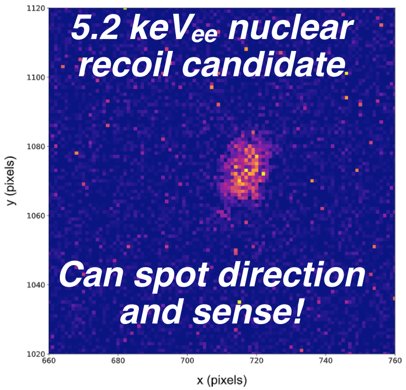
ζ residuals



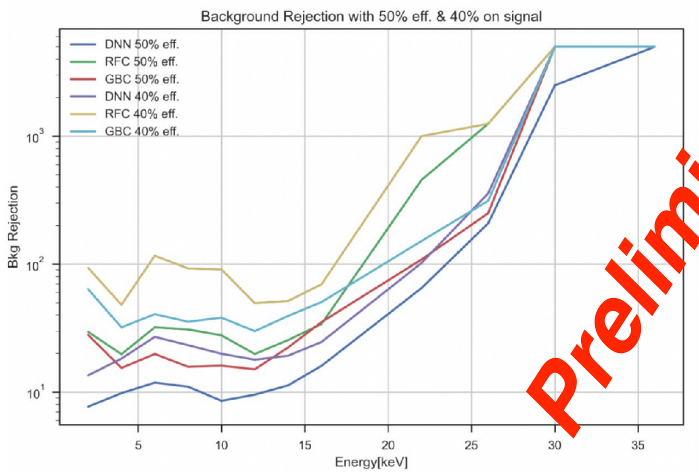
ER/NR discrimination

#counts/pixel (i.e dE/dx)





On going work on ML techniques



A. Prajapati PhD Thesis

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

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

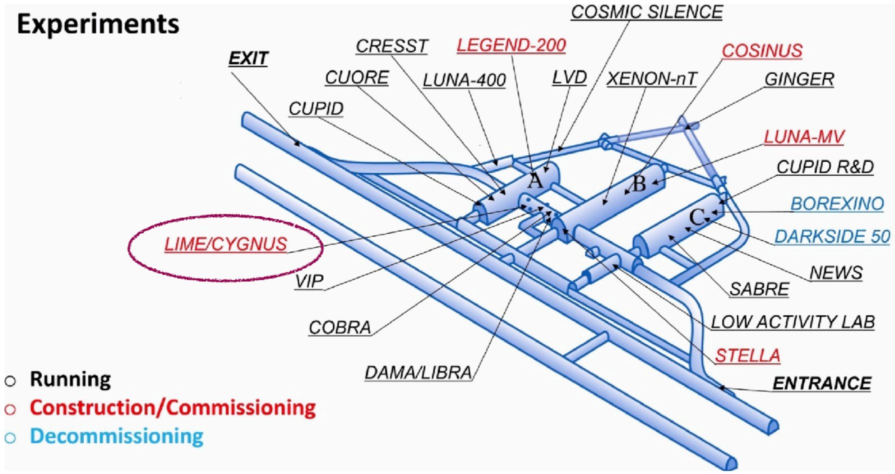
Reconstruction based on custom multiple iteration of IDBSCAN + morphological geodesic active contours (GAC)

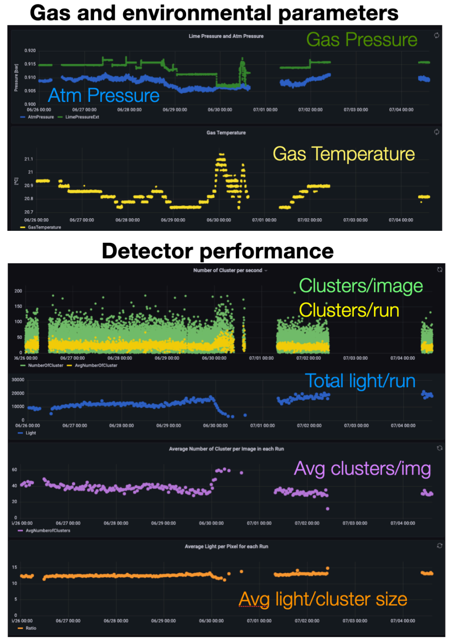
Measur.Sci.Tech. 32 (2021) 2, 025902

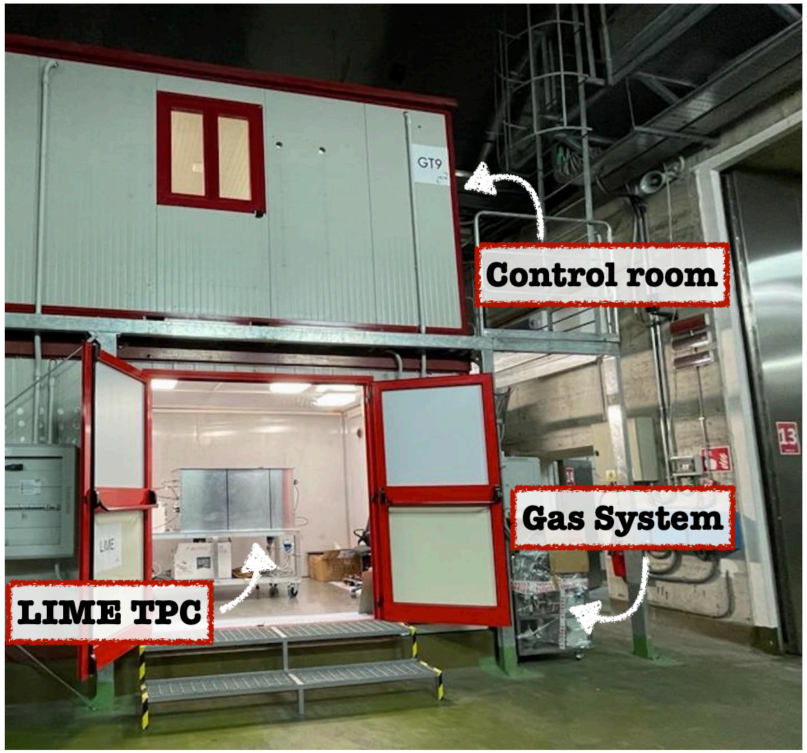
Models	Signal Efficiency [ϵ^S]%	Bkg. Rej. Efficiency [1-ϵ^B]%
RFC	40	99.1
	50	97.5
GBC	40	98.3
	50	96.5
DNN	40	96.6
	50	93.5

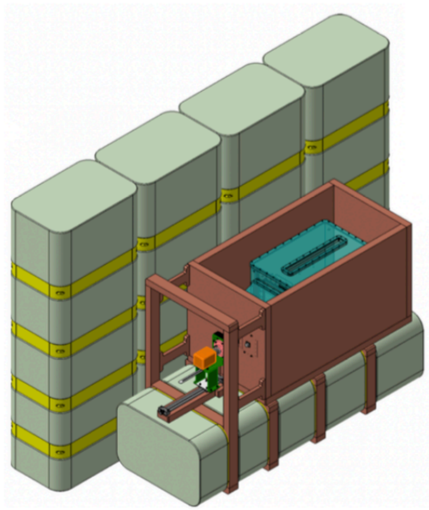
For the full 1-35 keV energy range

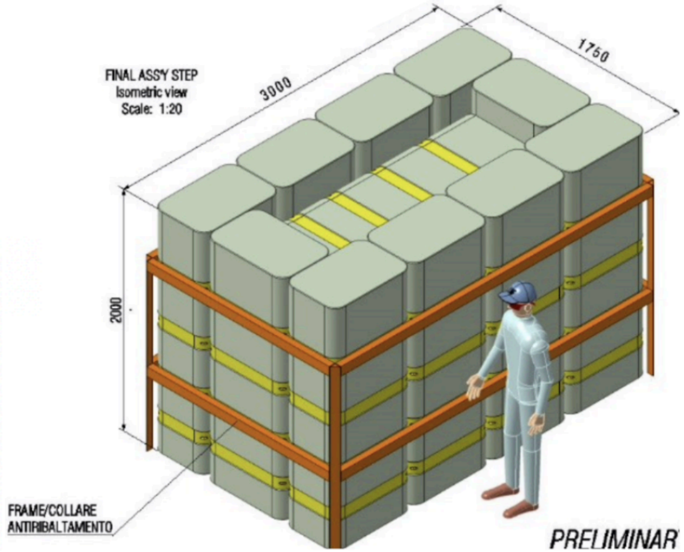
LIME underground installation @ LNGS









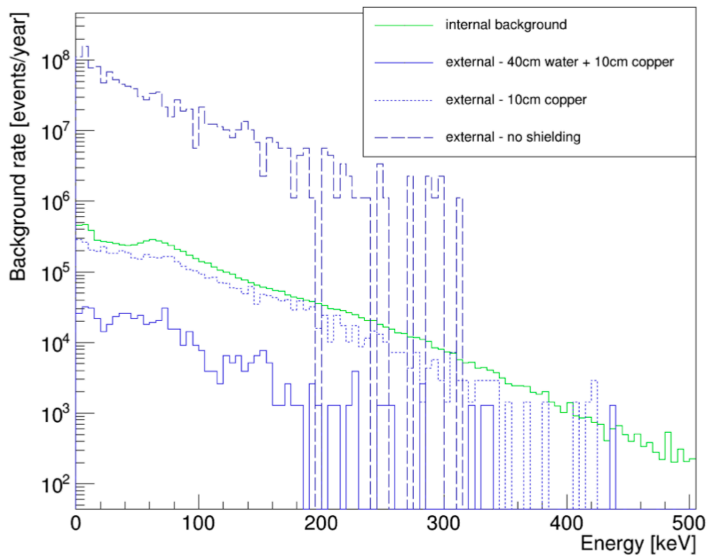


LIME underground program

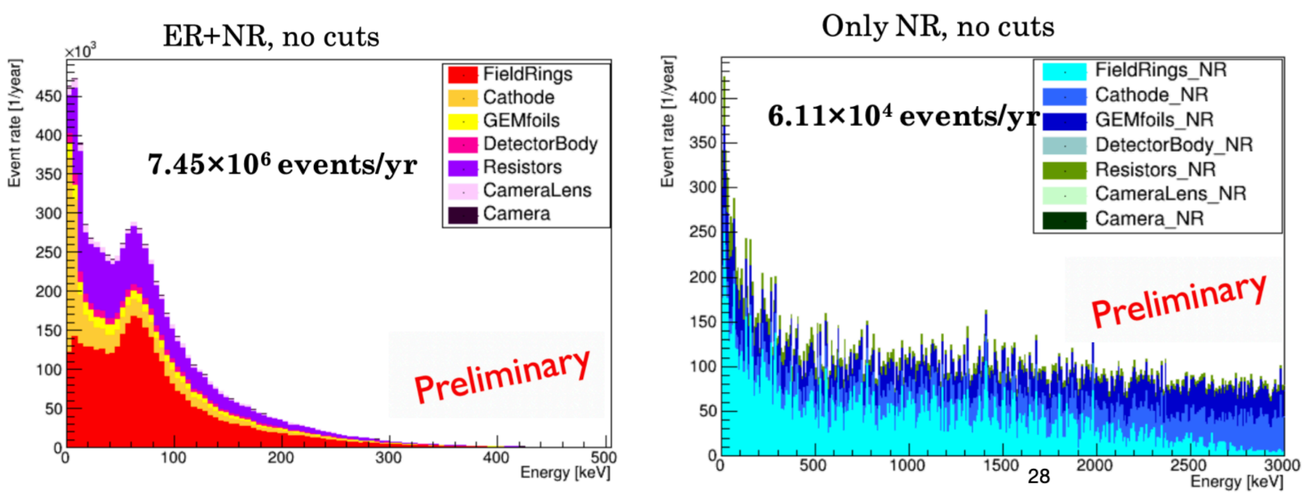
- **Unshielded:**
  - Detector characterisation with ^{55}Fe
  - External background study with periodic ^{55}Fe calibrations
- **4 cm Cu shield**
  - External background study with periodic ^{55}Fe calibrations
- **10 cm Cu shield**
  - Detector response to nuclear recoil measurement with AmBe source
  - Background study with periodic ^{55}Fe calibrations
  - Spectral measurement of underground neutron flux. About 200 NR events from neutron interaction expected in 4 months in the 20-100 keV range
- **10 cm Cu + 40 cm H_2O**
  - Study of internal backgrounds and validation of MC simulation. Expect to suppress all external neutral background and reduce external gamma background to the same level of internal one.

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

NOTE: internal background can be reduced of 96% (99.97% for NR) with fiducial cuts



ER and NR internal background

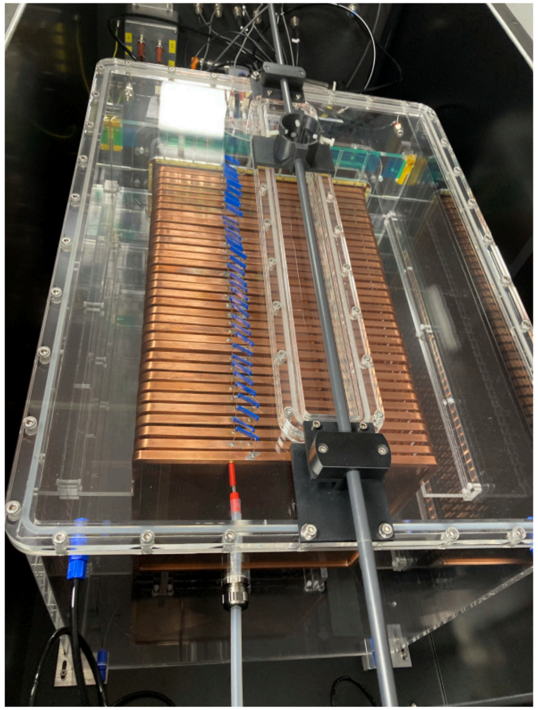


Underground data so far

RUN 1: No-shielding

- **From Oct 8, 2022 to Dec 6, 2022**
- Some numbers:
  - ➡ Integral number of **BKG pictures**: $\sim 4 \times 10^5$
  - ➡ Background **observed event rate**: (33.88 ± 0.58) Hz
  - ➡ Background **expected** event **rate** (from MC): ~37 Hz

~ 4.0 x 10^6 events in ~ 33 h cam exposure



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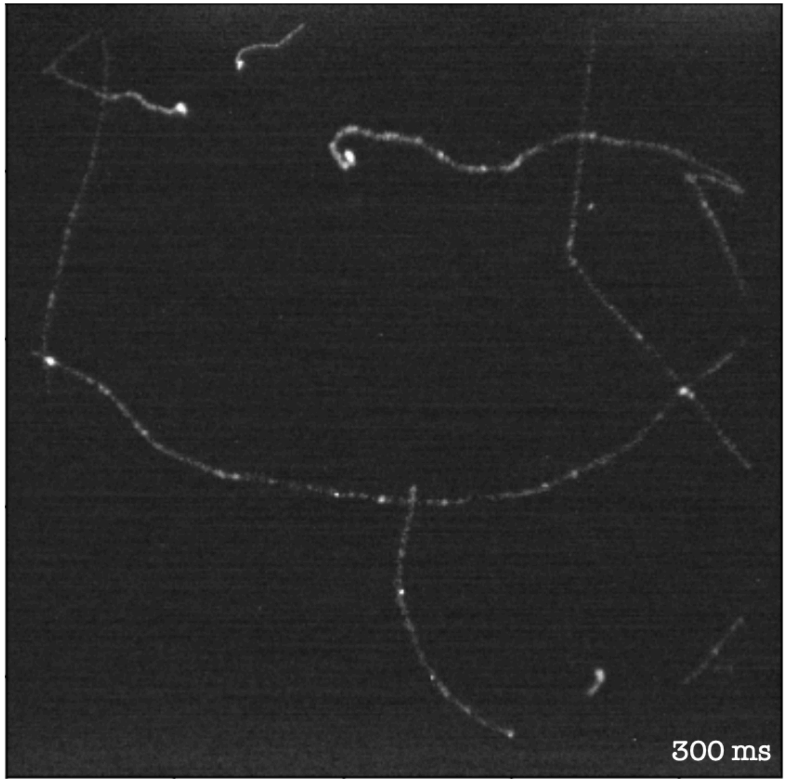
RUN 2: 4 cm Cu shielding

- **From Feb 15, 2023 to Mar 9, 2023**
- Some numbers:
  - ➡ Integral number of **BKG pictures**: $\sim 4.5 \times 10^5$
  - ➡ Background **observed event rate**: ~ 3.5 Hz (data not fully analyzed)
  - ➡ Background **expected** event **rate** (from MC): ~ 1.1 Hz

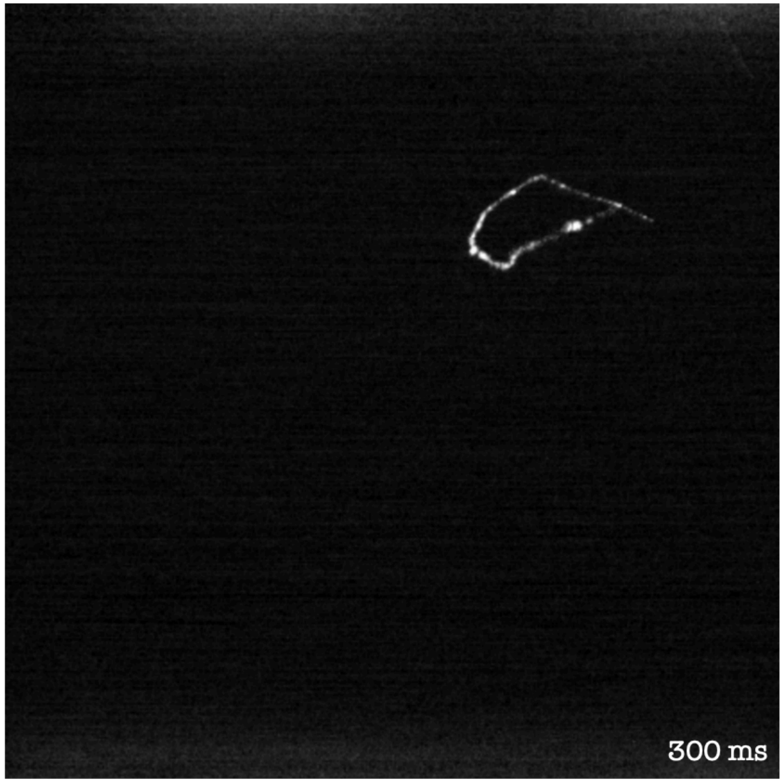
~ 0.48 x 10^6 events in ~ 38 h cam exposure

Underground data so far

RUN 1: No-shielding



RUN 2: 4 cm Cu shielding



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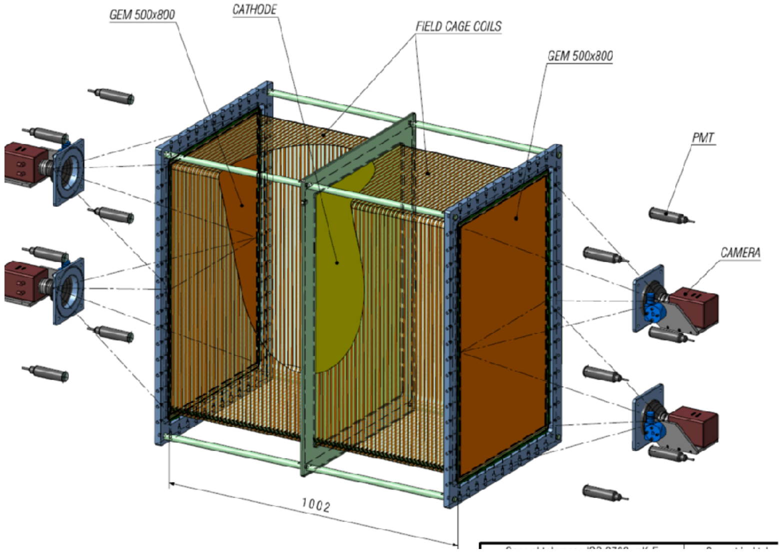
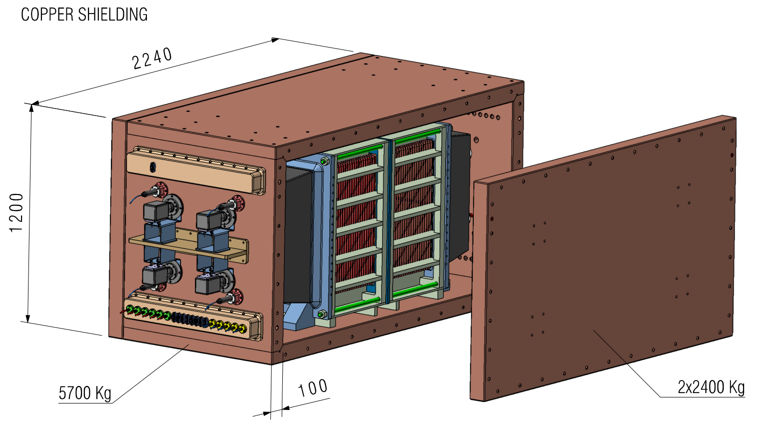
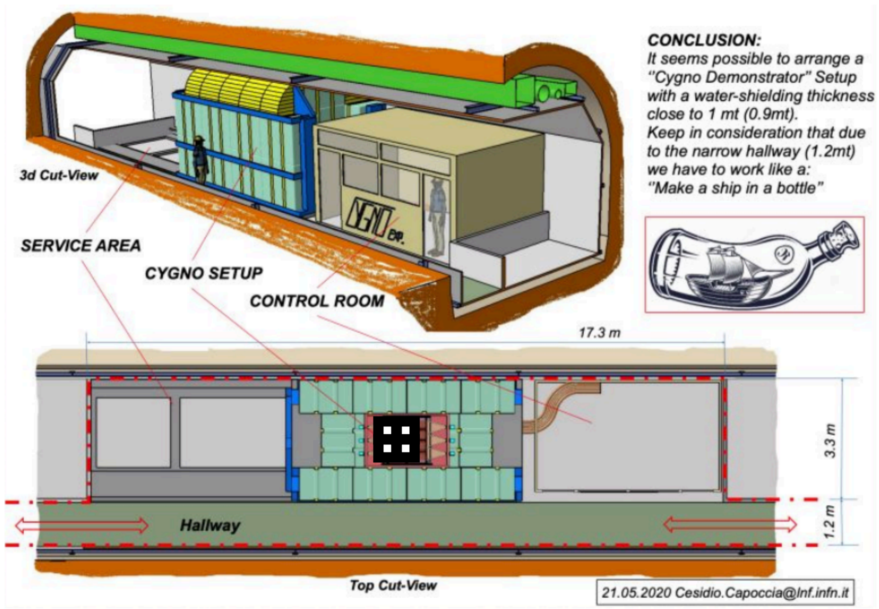
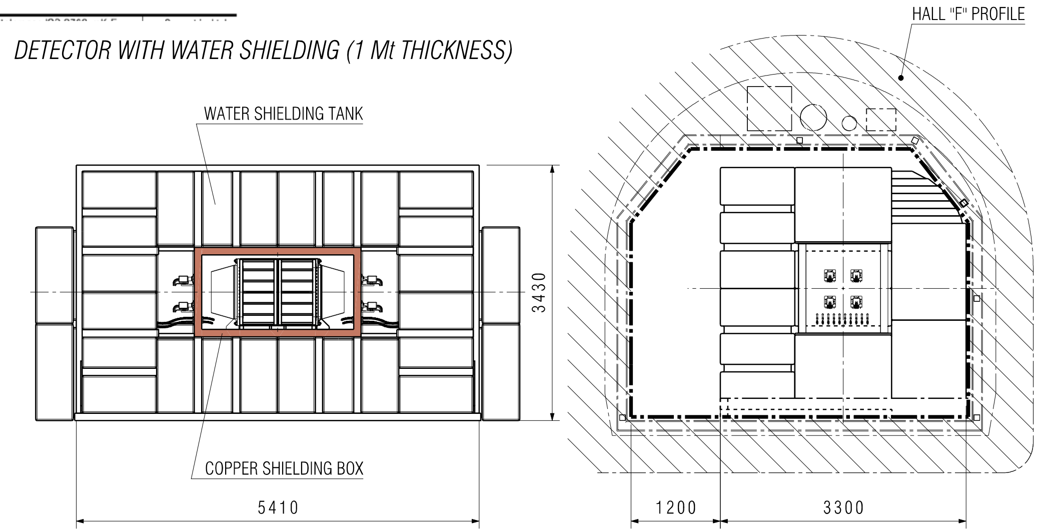
PHASE 1: CYGNO_04 design in Hall F

- **Preliminary design:**
  - TPC made of **2 chambers** with a **common cathode.**
  - Closed by 2 sets of **50 cm x 80 cm triple GEMs**
  - **Readout** of each GEM side: 2 cameras with rectangular sensors (ORCA Quest) + 6 PMTs
  - **Vessel:** low radioactivity PMMA
  - **Shielding:** 10 cm copper + 100 cm water with a polyethylene base





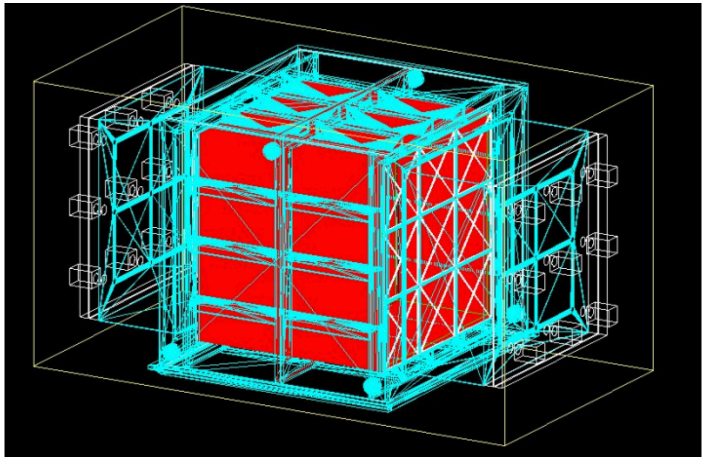




Preliminary shielding configuration:
110 cm H_2O + 10 cm Cu
Optimization ongoing

PHASE 1 background simulation

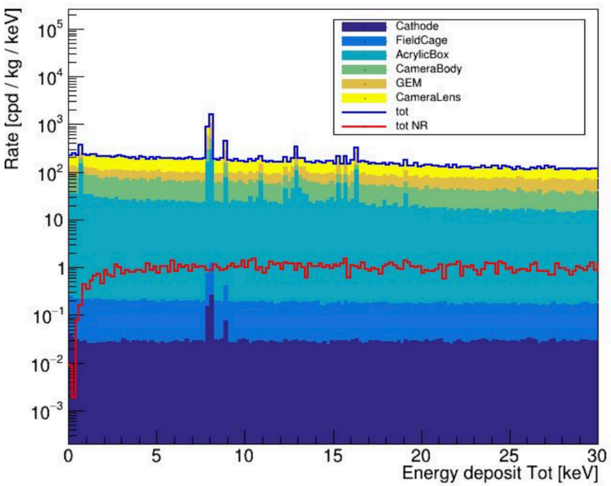
Full background simulation study done for 1 m³ detector



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

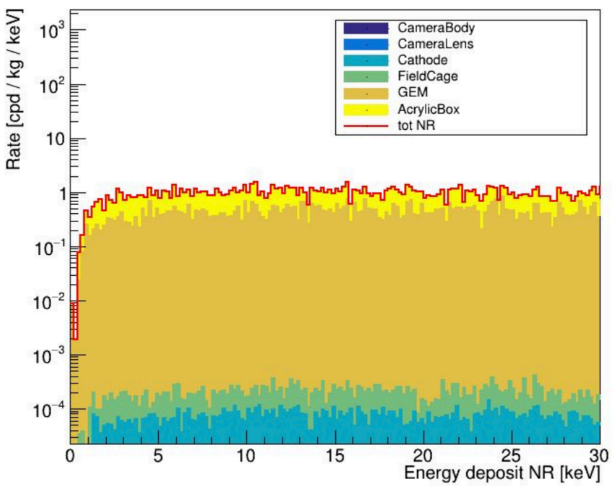
- For external background
  - flux entering the shielding for CYGNO_04 option (110 cm water + 10 cm Cu)
  - energy deposits in the CYGNO gas 1 m^3
  - number of events is scaled by 0.44 (sensitive volume factor)
- For internal background
  - assign material radioactivity and calculate background for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

- **CYGNO: ER rate [1-20] keV = 2.3×10^6 cts/yr**
- **CYGNO_04: ER rate [1-20] keV = 4.9×10^5 cts/yr**



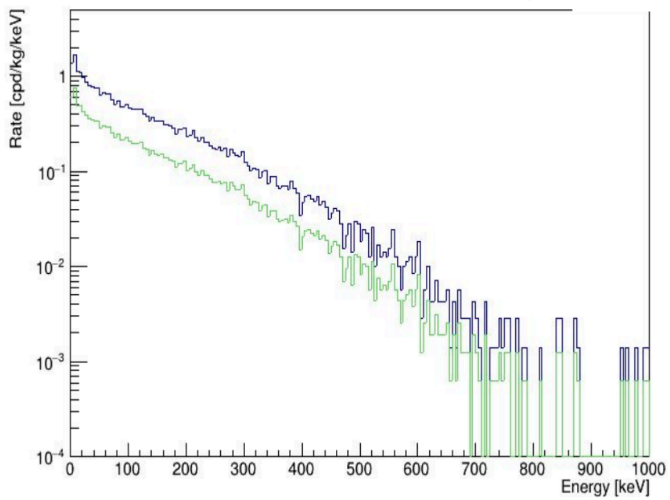
Internal ER background

- **CYGNO: NR rate [1-20] keV = 1.1×10^4 cts/yr**
- **CYGNO_04: NR rate [1-20] keV = 2.6×10^3 cts/y**



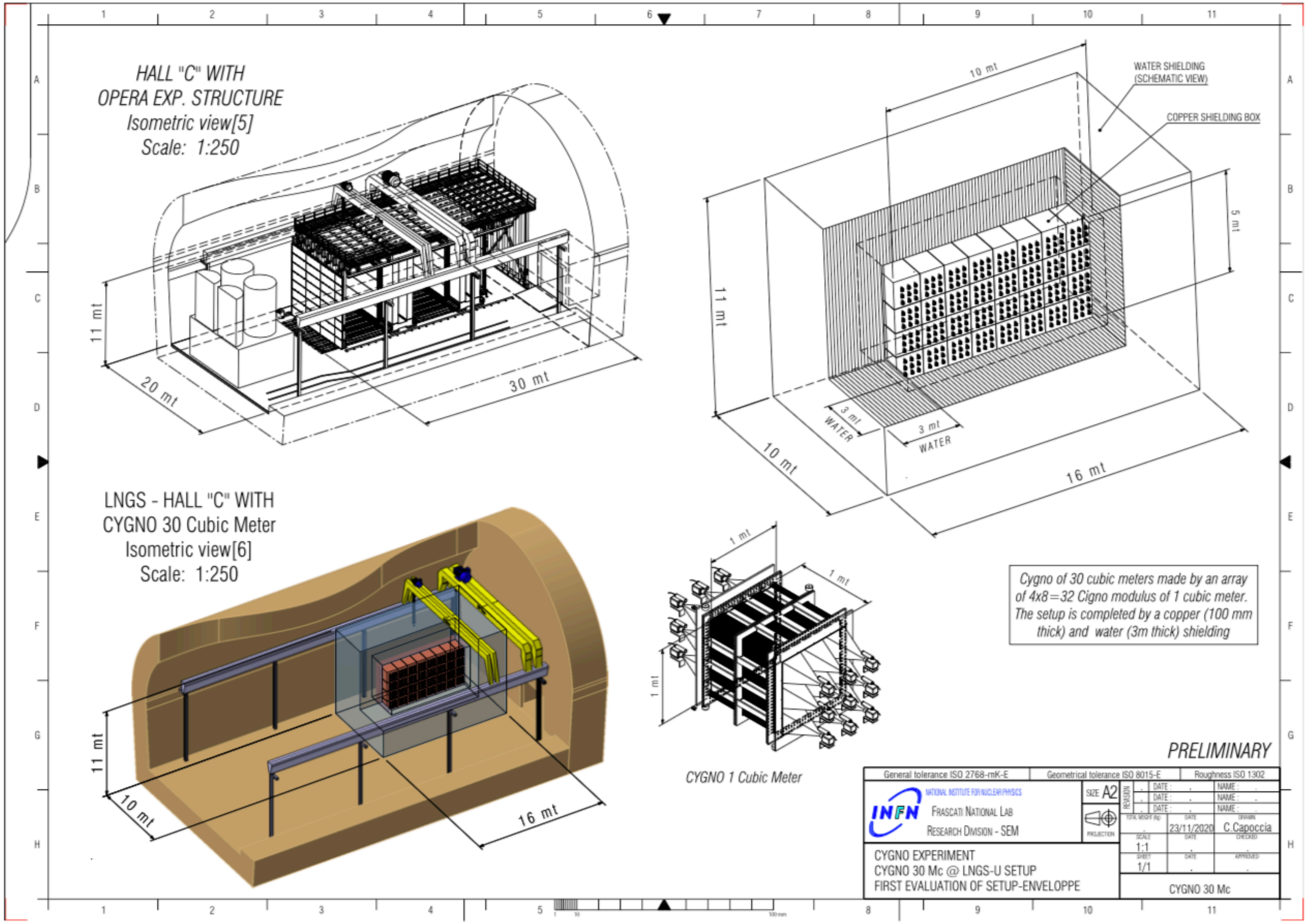
Internal NR background

- **Rate [1-20] keV = 1.4×10^4 cts/yr (CYGNO)**
- **Rate [1-20] keV = 6.4×10^3 cts/yr (CYGNO_04)**



Total external background

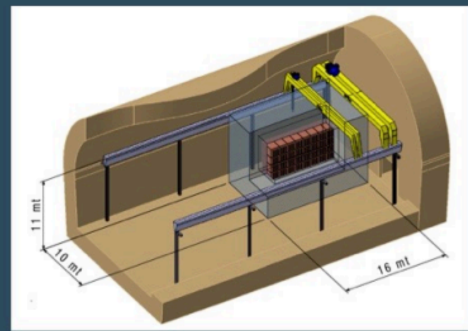
CYGNO future



PHASE 2:
30 m³ Experiment

2026..
LNGS

CYGNO_30

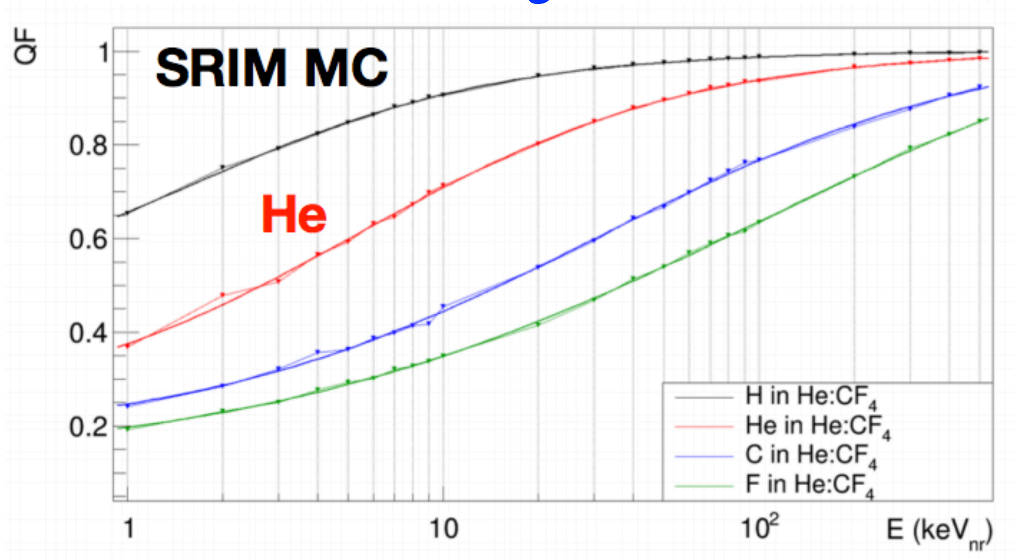


- **Physics research**

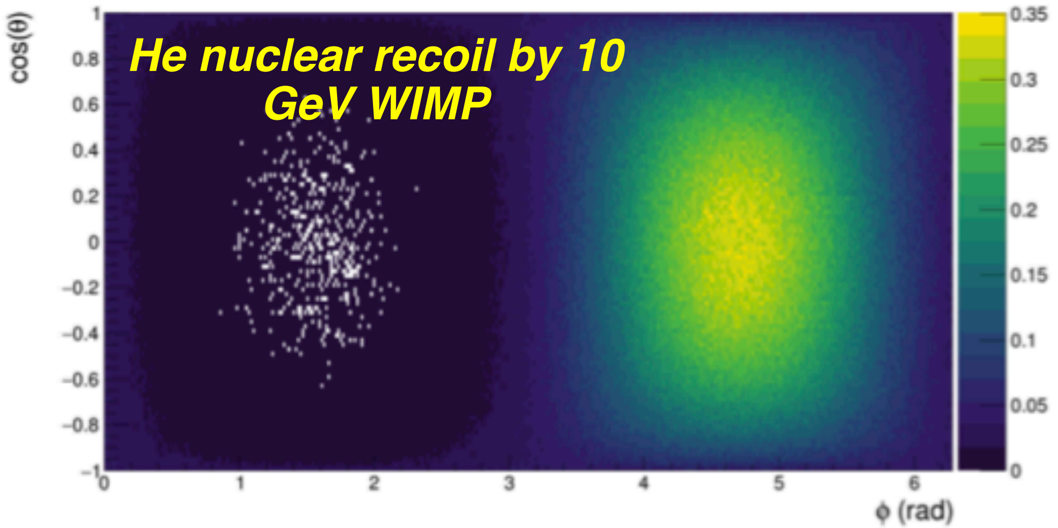
CYGNO PHASE 2 sensitivity evaluation

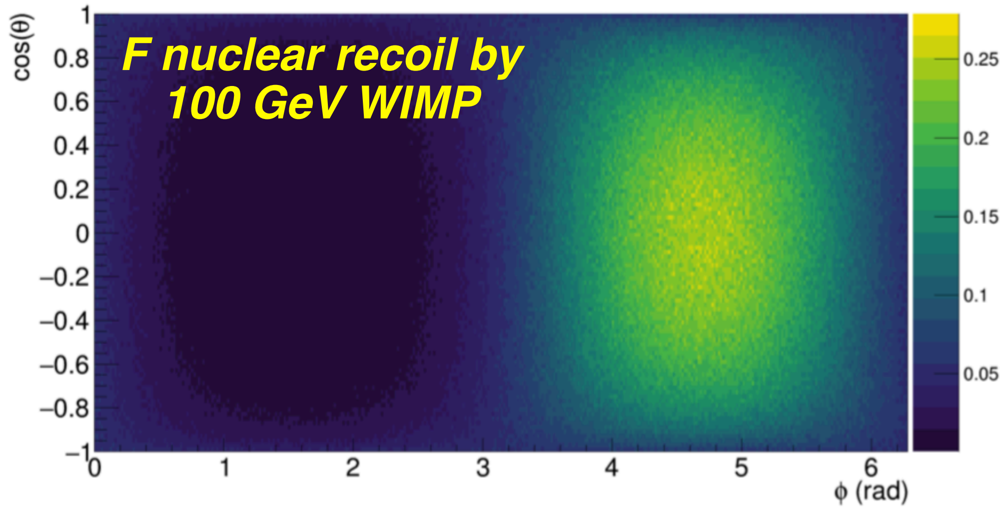
- Use 1 keV_{ee} threshold
- Evaluate QF with SRIM
- Introducing **angular distribution** as discriminating
- Full head/tail recognition
- Using a 30 deg resolution

Quenching Factor



Examples of expected measured angular distribution in Galactic coordinates



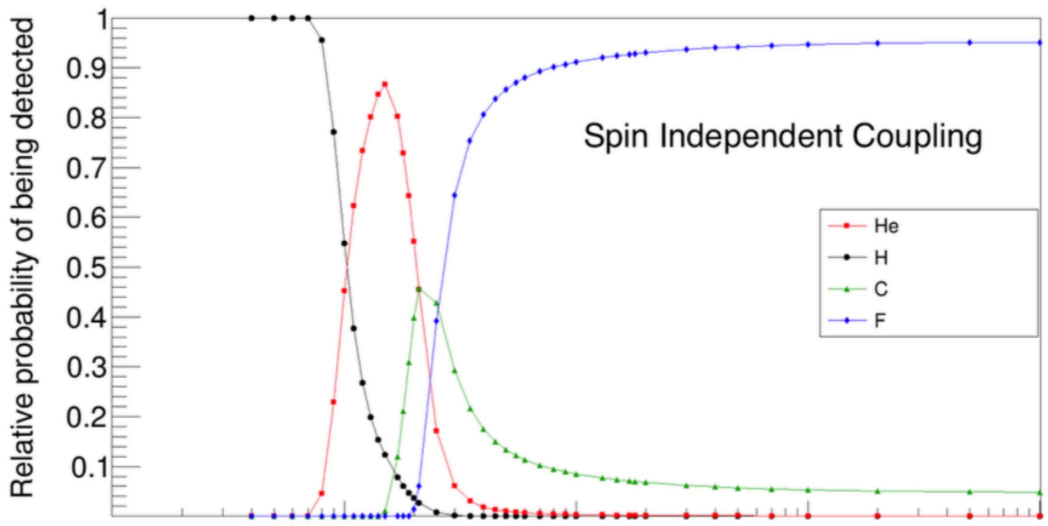


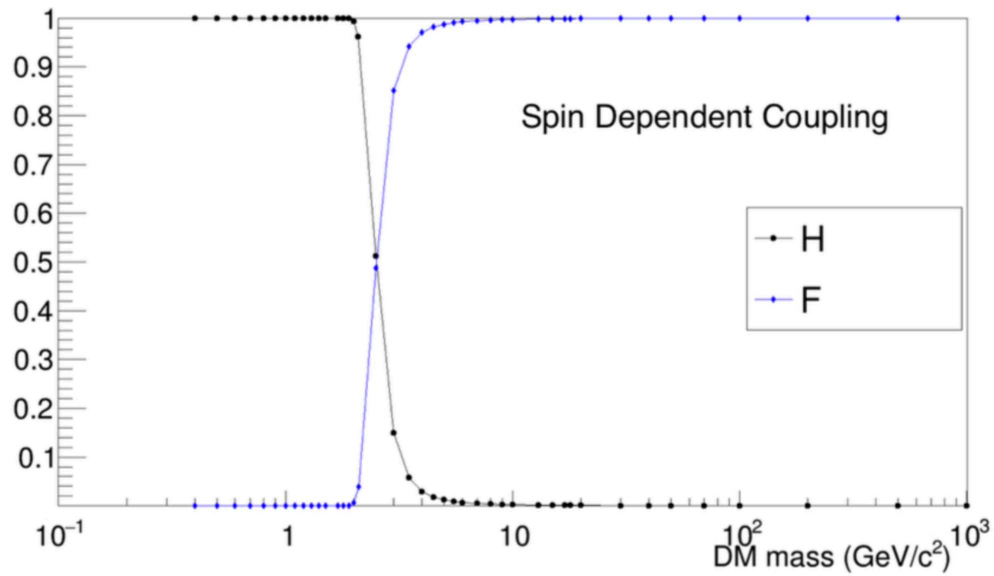
CYGNO PHASE 2 sensitivity evaluation

- **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

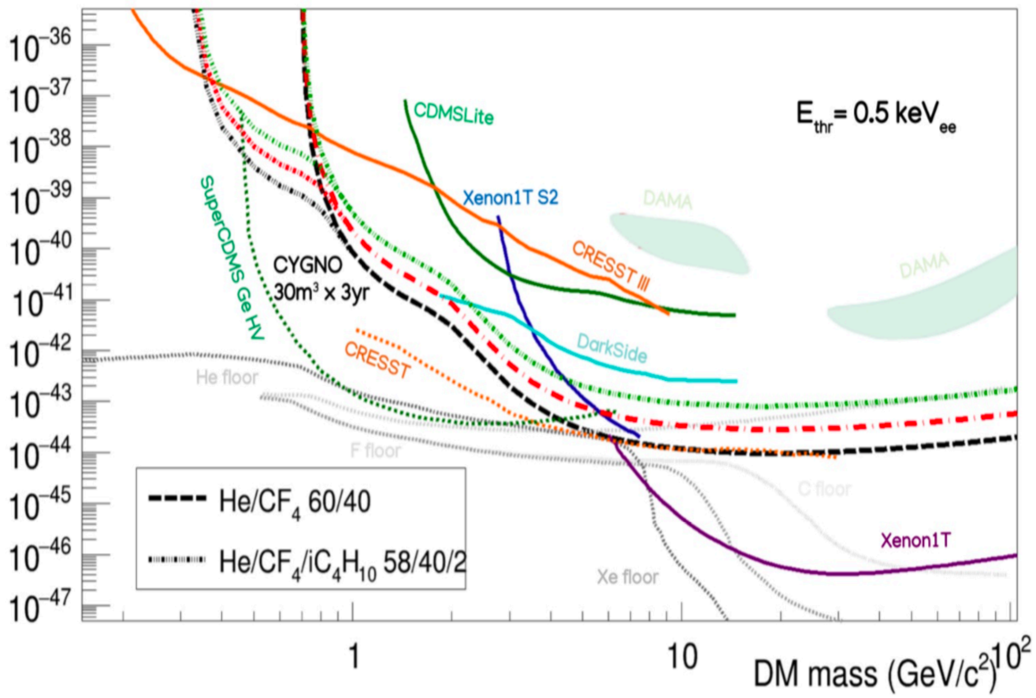




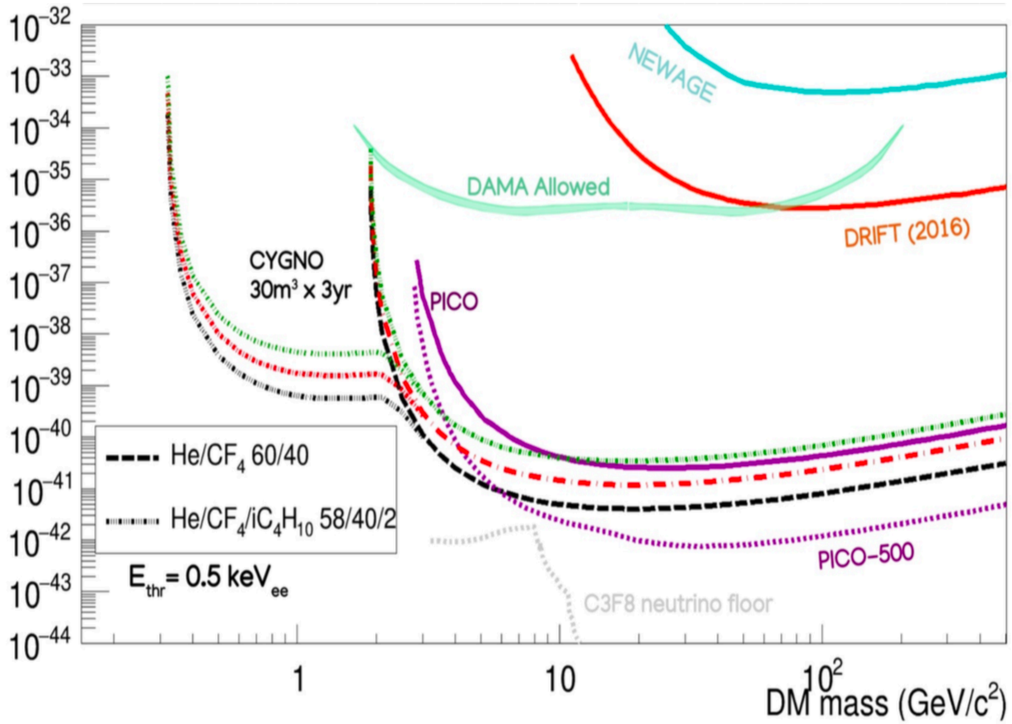
Target nuclei relative probability of being detected for 1 keV_{ee} energy threshold

CYGNO 30 m³ preliminary sensitivity studies

Spin Independent



Spin Dependent



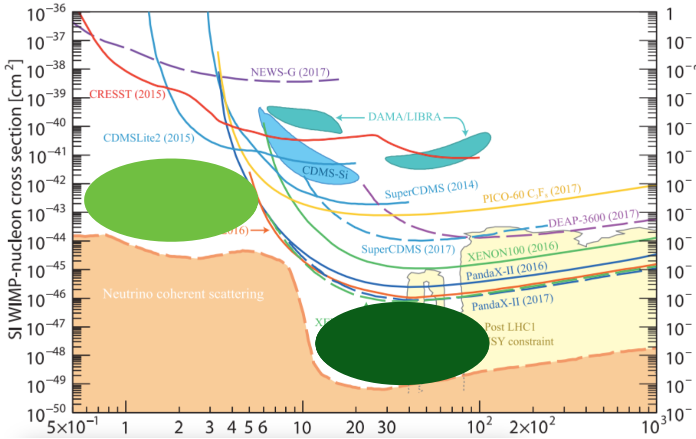
$n_{BKG} = 10^2$

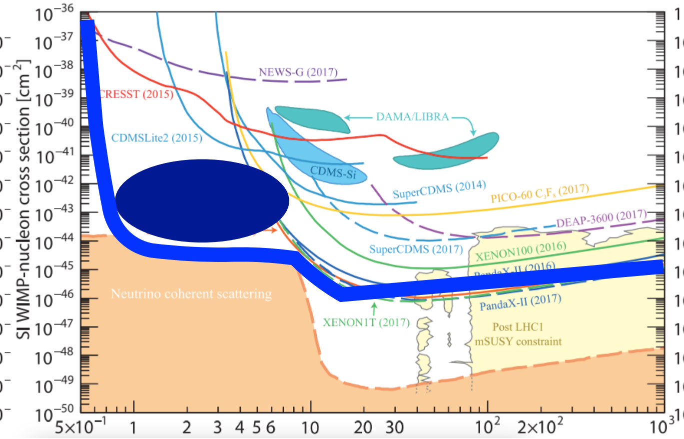
$n_{BKG} = 10^3$

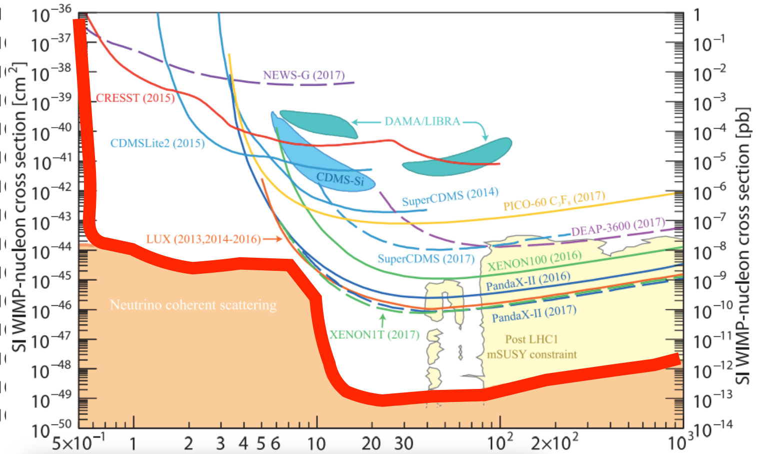
$n_{BKG} = 10^4$

Direct DM search future

Old limits, only illustrative purpose







DM is claimed:
only a directional experiment can confirm the galactic origin of the observed signal and identify DM properties

Incompatible results:
only a directional experiment can test the galactic origin of the observed signal

DM is excluded to the Neutrino Fog:
only a directional experiment can continue DM searches and study neutrinos

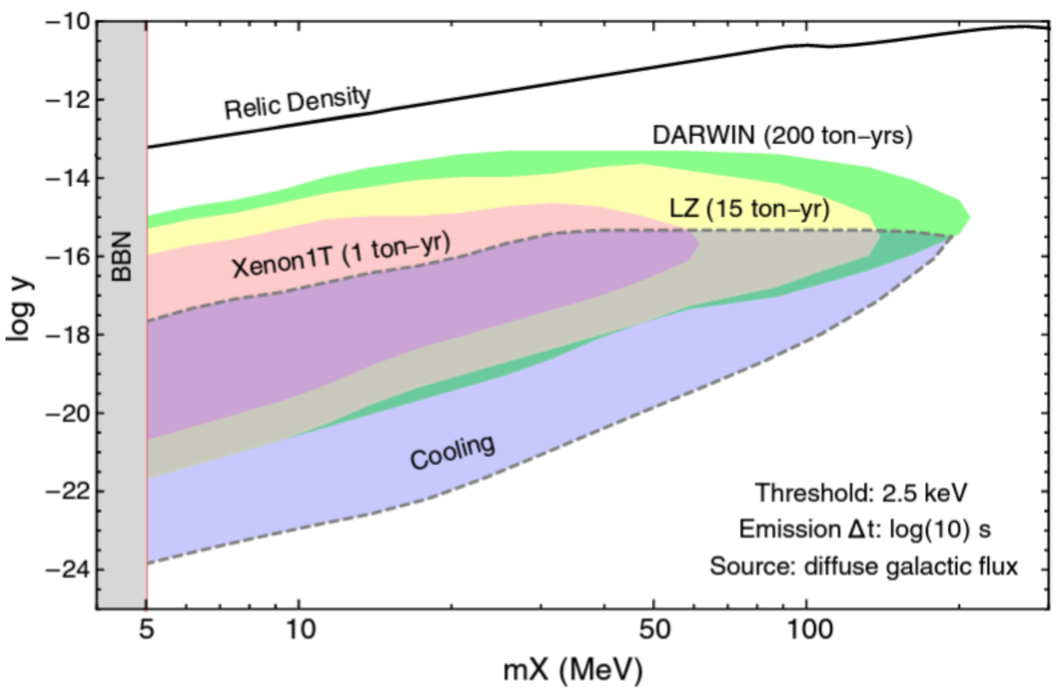
*Or we "hit" some new other irreducible background

Backup slides

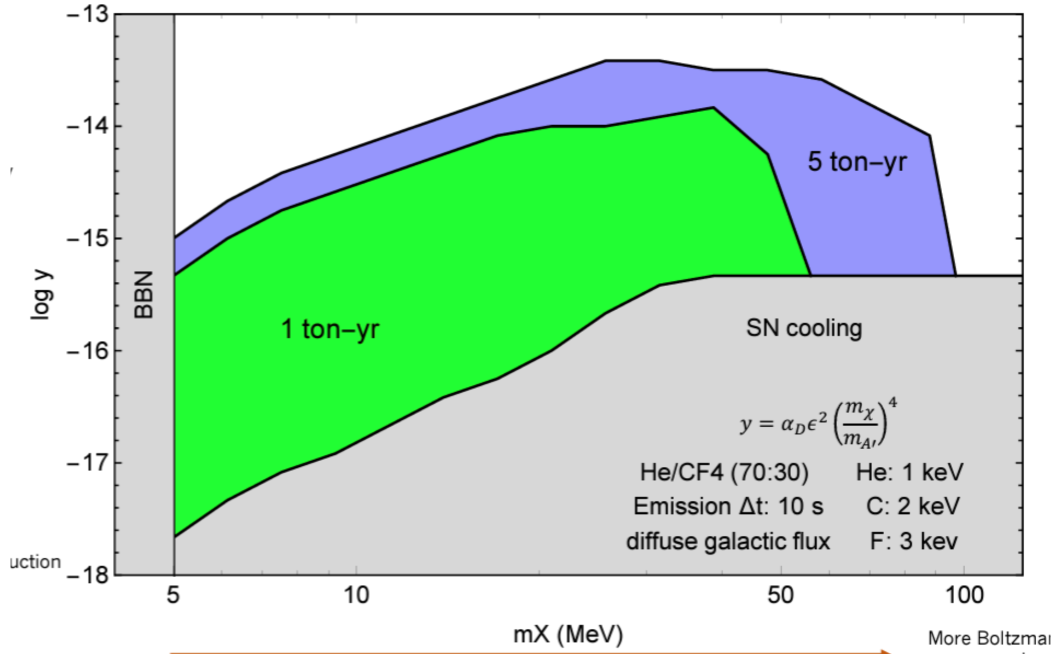
Sensitivity Xe vs He:CF_4

Low y == weaker coupling, hence less production
High y == stronger coupling, more diffusively trapped

Xe target



He:CF_4 target



the larger m_X, the more Boltzmann suppressed

PHYSICAL REVIEW D **100,** 075018 (2019)

MeV DM production through diffusive trapping

Radius of each sphere defined as the one at which the optical depth associated with a particular interaction becomes O(1)

Optical depth at r_0 = $\int_{r_0}^{\infty} \lambda^{-1}(r)dr$

Production/annihilation

$\chi\,\bar{\chi} \longleftrightarrow e^+\,e^-$

$$\lambda_{\chi\chi}(r) = (n_\chi \sigma_{\chi\chi\to ee})^{-1},$$

Energy transfer

$\chi\,e \longrightarrow \chi\,e$

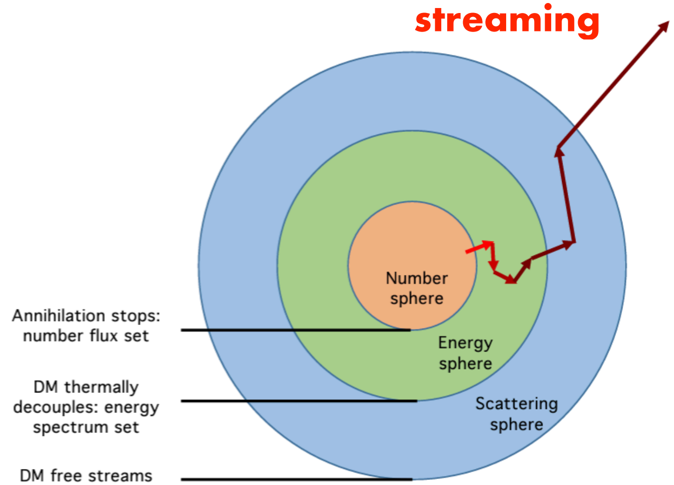
$$\lambda_{\chi e^\pm}(r) = \langle v_\chi \rangle (n_{e^\pm}\sigma_{\chi e\to\chi e} v_{\rm rel})^{-1},$$

Diffusive scattering

$\chi\,p \longrightarrow \chi\,p$

$$\lambda_{\chi p}(r) = (n_p \sigma_{\chi p\to\chi p})^{-1},$$

Supernova Dark Matter (SNDM) escapes free streaming



The analytic estimate proceeds as follows:

(1) Treat the protoneutron star as a blackbody of radius r_N with a diffusive envelope. The number flux at the blackbody surface is given by

$$\Phi_{r_N} = g_\chi \int \frac{d^3k}{(2\pi)^2} \frac{1}{e^{E_k/T_N}+1} \frac{k\cos\theta}{E_k}\Theta(\cos\theta)$$
$$= \frac{1}{2\pi^2}\int dE \frac{E^2-m_\chi^2}{e^{E/T_N}+1}, \qquad (8)$$

where $g_\chi = 4$ is the number of degrees of freedom (d.o.f.) in DM and $T_N \equiv T(r_N)$ is the temperature at the number sphere. To obtain an energy flux one can just multiply the integrand by the DM energy.

(2) Multiply this total flux by a normalized differential energy spectrum set by assuming a Fermi-Dirac distribution at T_E, the temperature at the energy sphere:

$$\frac{\partial\Phi_{r_E}}{\partial E} = \Phi_{r_N}\left(\frac{E^2-m^2}{\exp(E/T_E)+1}\right) \times \left(\int_{m_\chi}^{\infty}\frac{E^2-m^2}{\exp(E/T_E)+1}dE\right)^{-1}. \qquad (9)$$

(3) Even though the number changing reactions are frozen out at $r > r_N$, some particles emitted from that radius can bounce back and return to the region $r < r_N$ as they are trying to diffuse out of the streaming sphere. Therefore one must include a transmission factor to account for the losses due to this effect (see Ref. [32] for details),

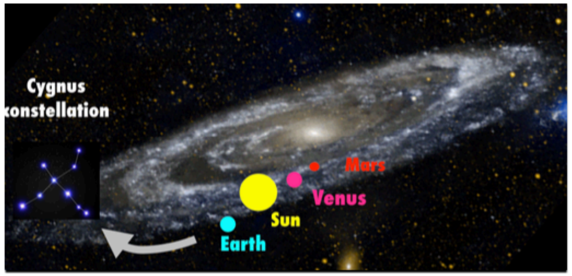
$$\frac{\partial\Phi_\chi}{\partial E} = \frac{\partial\Phi_{r_E}}{\partial E}\left(1+\frac{3}{4}\tau_{r_N}\right)^{-1}, \qquad (10)$$

As before, we take the temperature at thermal decoupling to be $T(r_E)$. We then enforce that the DM energy spectrum take the form of a Fermi-Dirac distribution at this temperature, but with normalization set by the number flux determined via the MC simulation. Hence, we have the following differential flux:

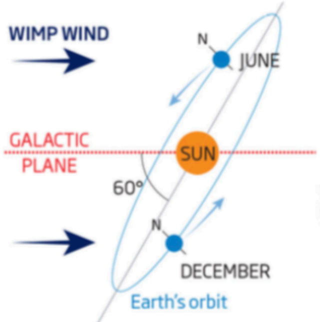
$$\frac{\partial \dot{N}_\chi}{\partial E} = \dot{N}_\chi^{\rm MC}\left(\frac{E^2-m^2}{\exp(E/T)+1}\right)\left(\int_{m_\chi}^{\infty}\frac{E^2-m^2}{\exp(E/T)+1}dE\right)^{-1}, \qquad (14)$$

where $\dot{N}_\chi = \frac{\partial N_\chi}{\partial t}$ denotes the total DM flux in number per second and $\dot{N}_\chi^{\rm MC}$ denotes the total number of DM particles escaping the PNS per second as computed with the simulation.

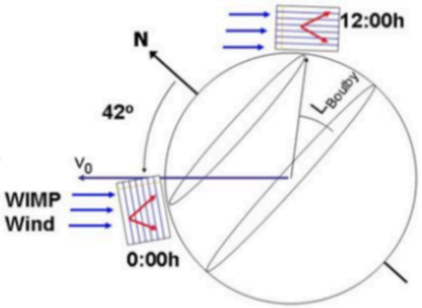
DM induced events have a specific direction in space



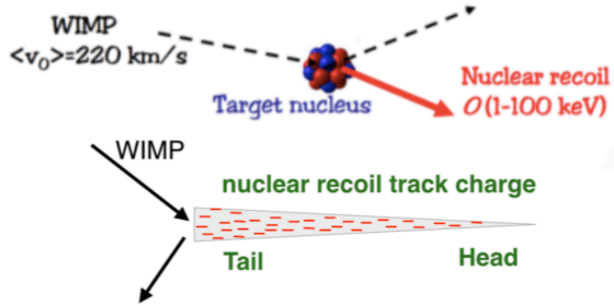
Our Galaxy



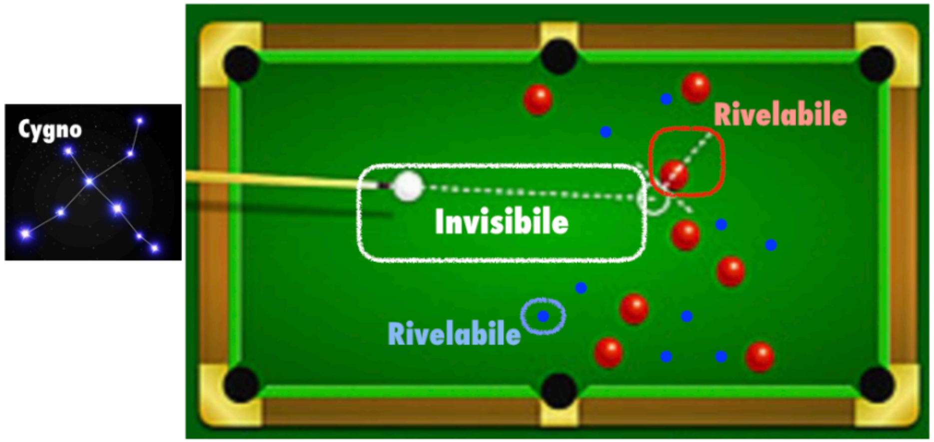
Solar system

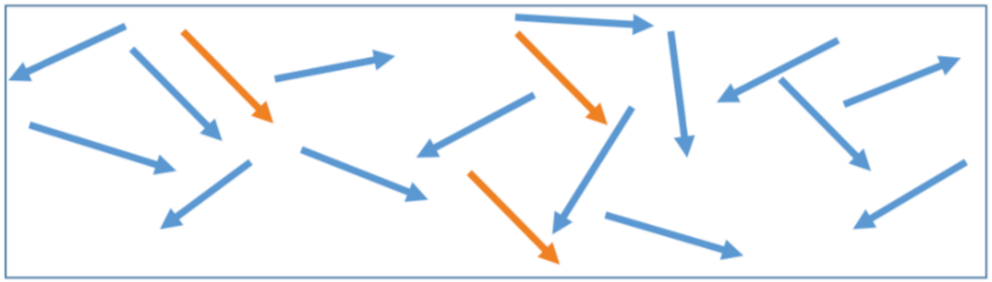


Earth



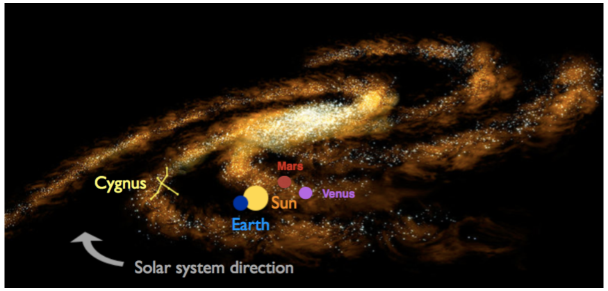
Detector target

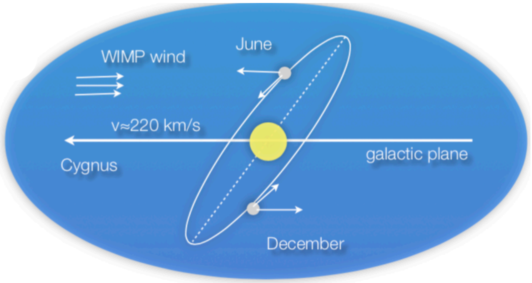


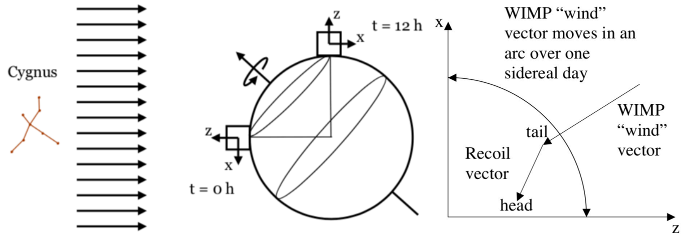


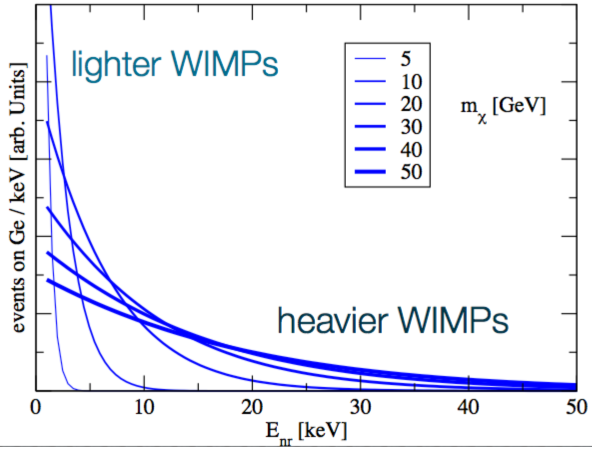
Directionality as key for unambiguous identification of DM

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

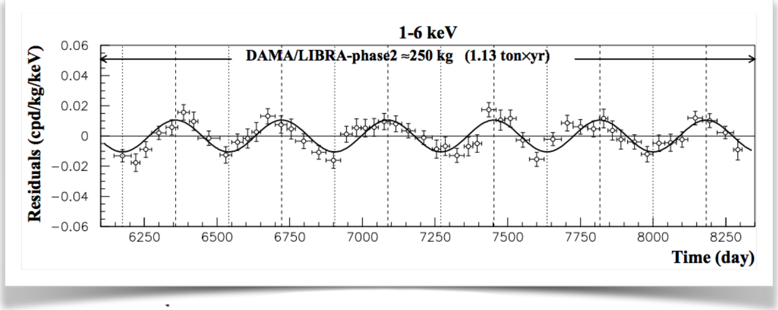




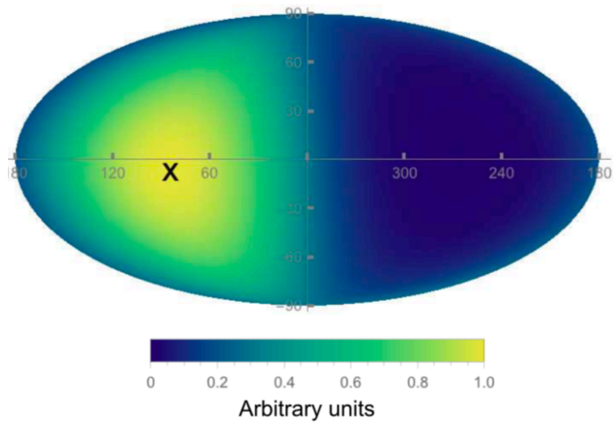




DAMA/LIBRA Collaboration



Universe 4 (2018) no.11, 116



Energy dependence: a falling exponential with no peculiar features

Temporal dependence: a few % annual modulation

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

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

Directionality as tool for background rejection,

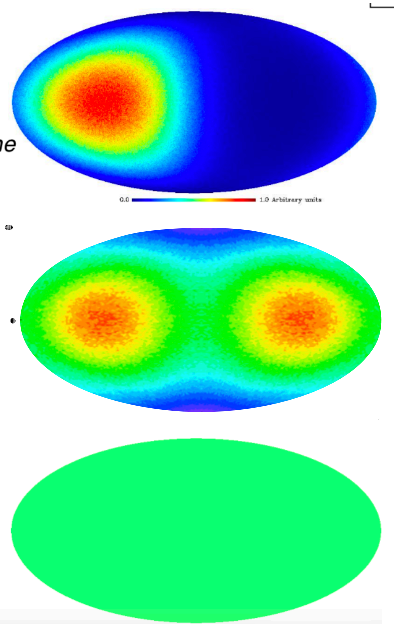
Capability to confirm galacitc orgin == reject isotropy

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

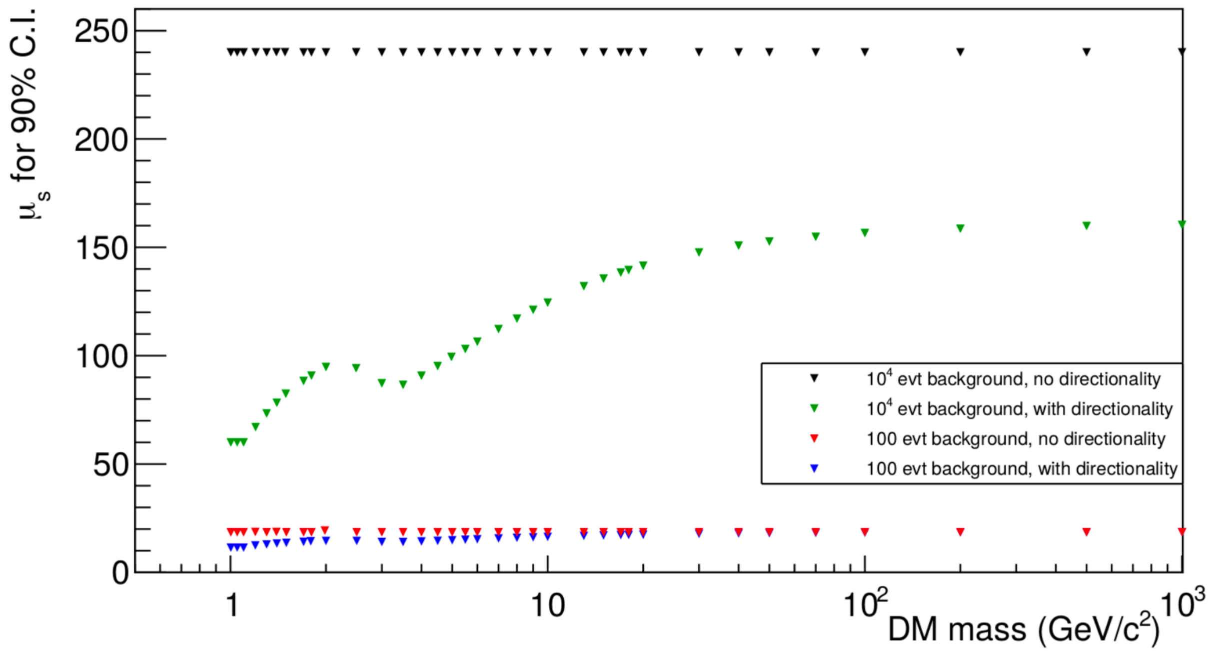
WIMP signal (recoil map)
with sense

WIMP signal (recoil map)
without sense
(the importance of head-tail)

Background



From G. Dho thesis



Stronger effect when the angular distribution is more peaked

Directional detector can tolerate unknown backgrounds, including neutral, because they will all be isotropic in galactic coordinates!

Direction more effective with more background

↓

For directional detectors, sensitivity improves with backgrounds

Directionality as tool for background rejection, including neutrinos

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

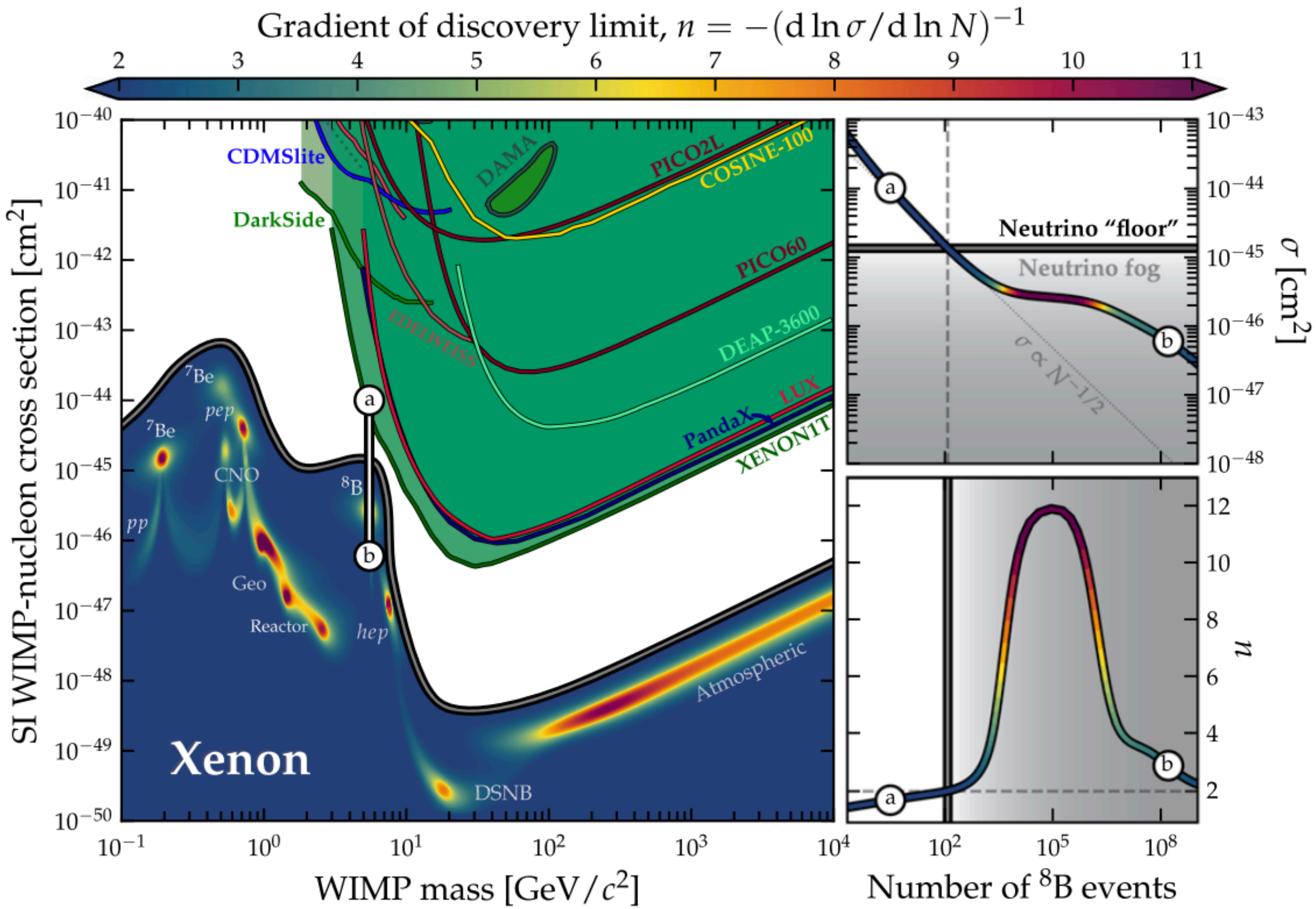
$$N\delta\Phi^2 \ll 1, \sigma \propto 1/\sqrt{N}$$

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

Directionality as tool for background rejection, including neutrinos

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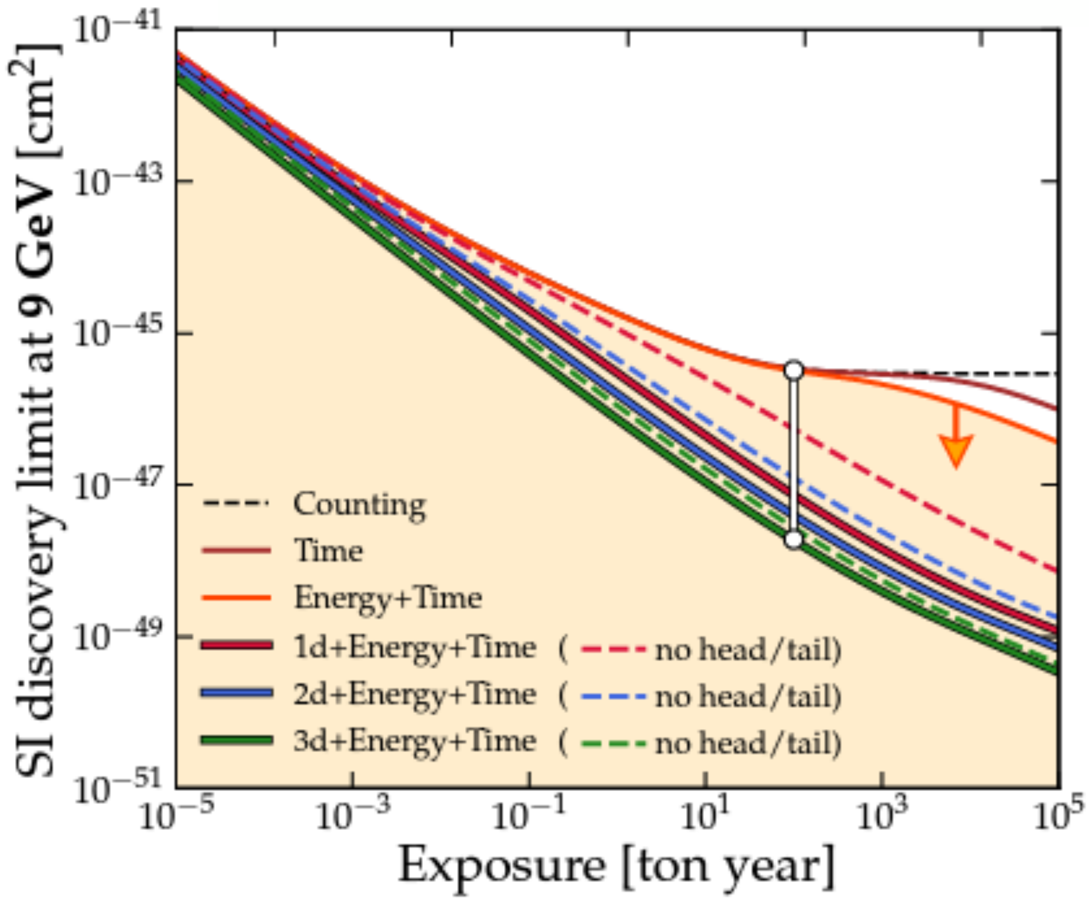

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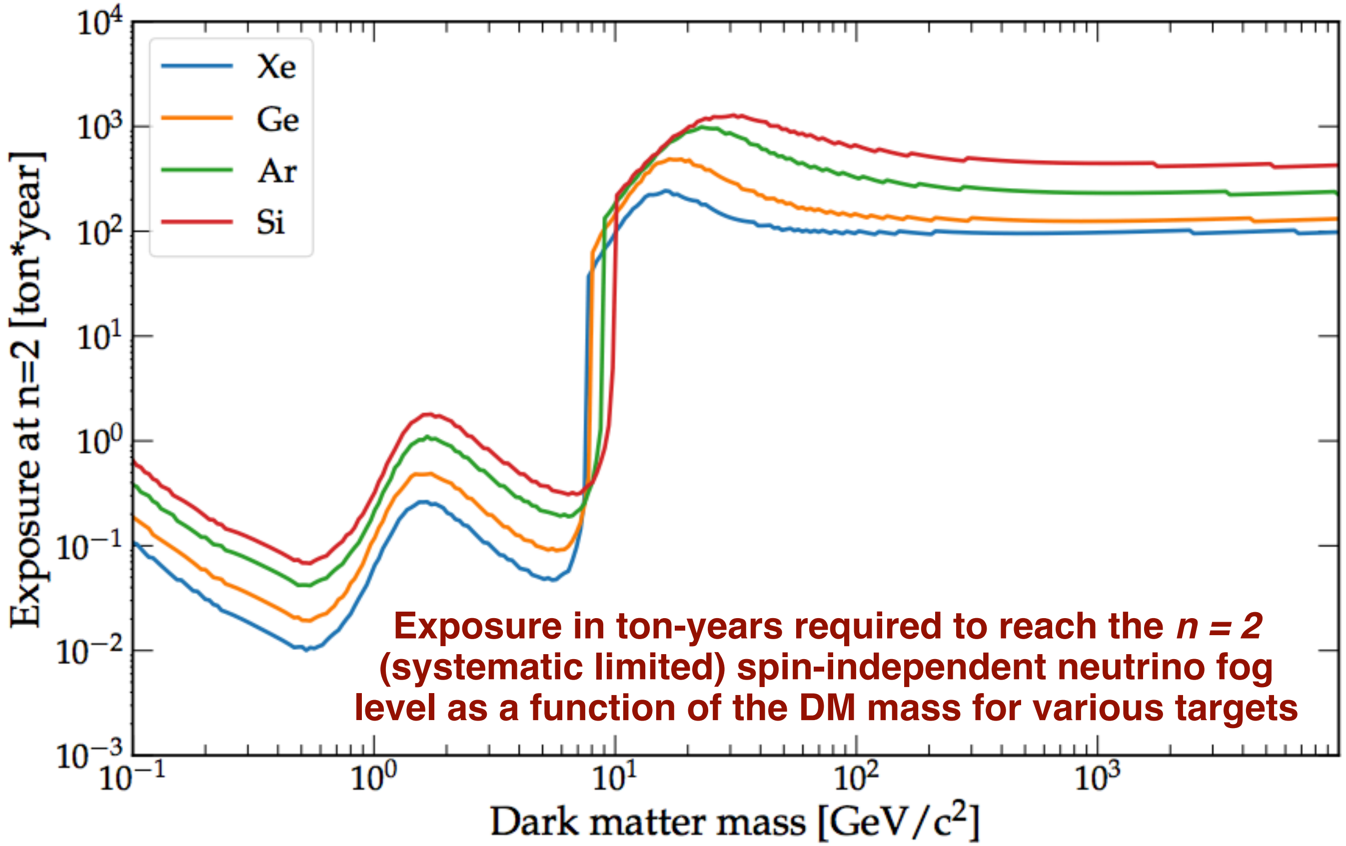
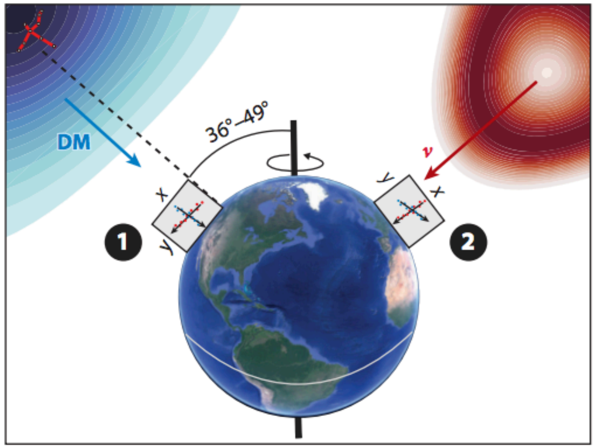
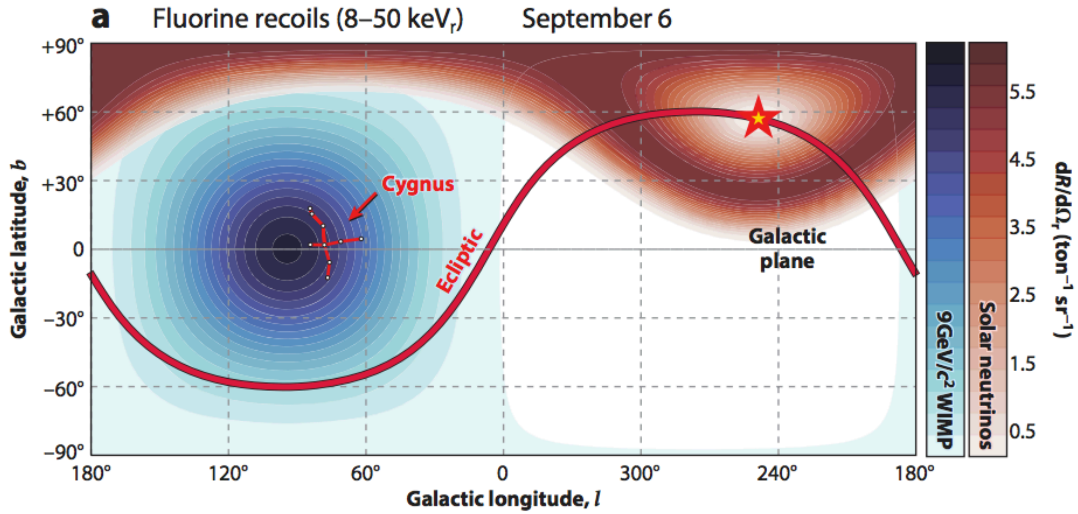


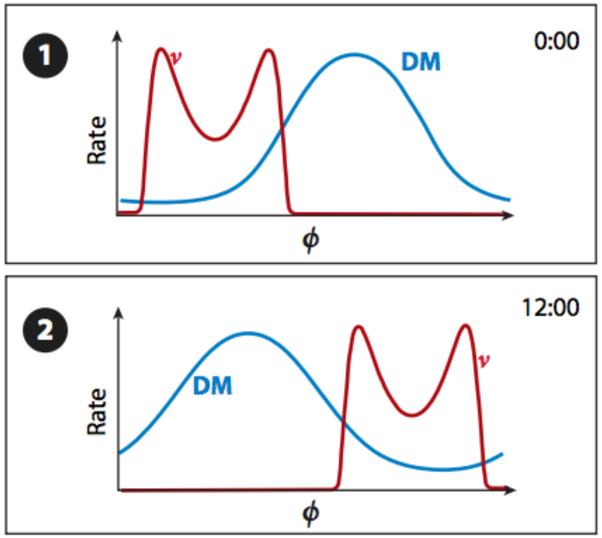
Reducing the sensivity of an experiment by a factor x requires an increas in the exposure by *at least x^n*

S. Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224

How to see through the neutrino fog?







DM and solar neutrinos event rate as a function of some angle ϕ on a two-dimensional readout plane at 12 h time distance or 180º of longitude

What is required to clear the neutrino fog?

(see our review [2102.04596] and Snowmass WP [2203.05914] for reasoning)

- Angular resolution **<30˚**
- Correct head / tail **>75%** of the time
- Fractional energy resolution < 20%

If you don't achieve these then directionality adds nothing to the sensitivity (in the context of the ν fog)

And achieved…

- At the level of individual events
- In as high a density target as possible
- Below <10 keVr
- With a timing resolution better than a few hours

Can this be done? Maybe, but the way to go seems to be "recoil imaging"

Gaseous TPCs

	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)

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