*He recoils in CYGNO
10 L prototype

D RECTIONAL DIRECT DARK MATTER SEARCHES & THE CYGNO/INITIUM PROJECT

Elisabetta Baracchini

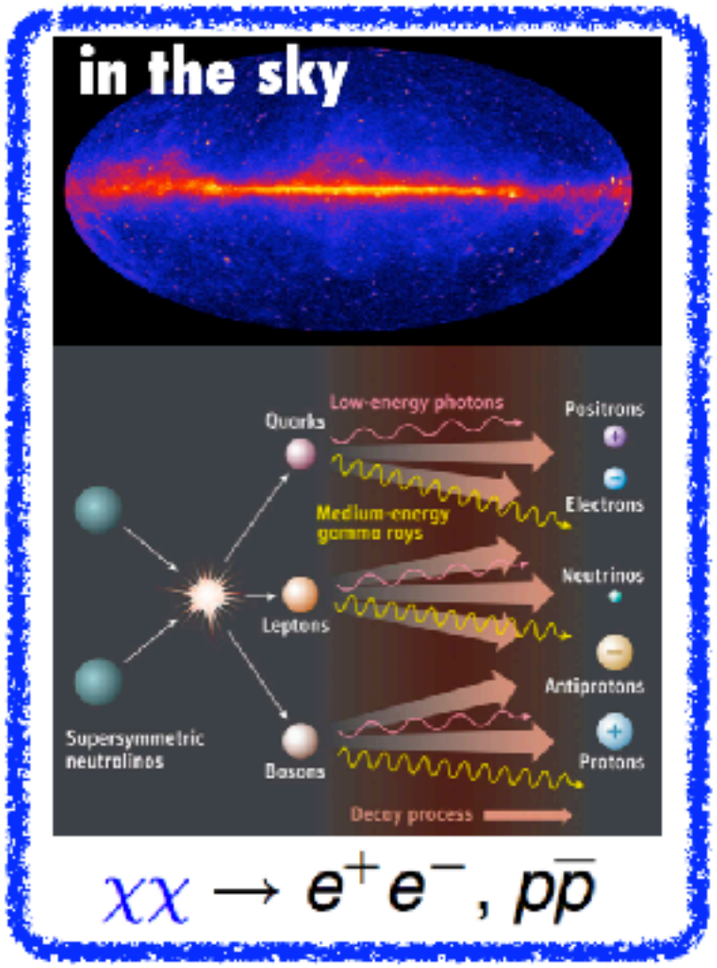
Gran Sasso Science Institute

On behalf of the CYGNO collaboration

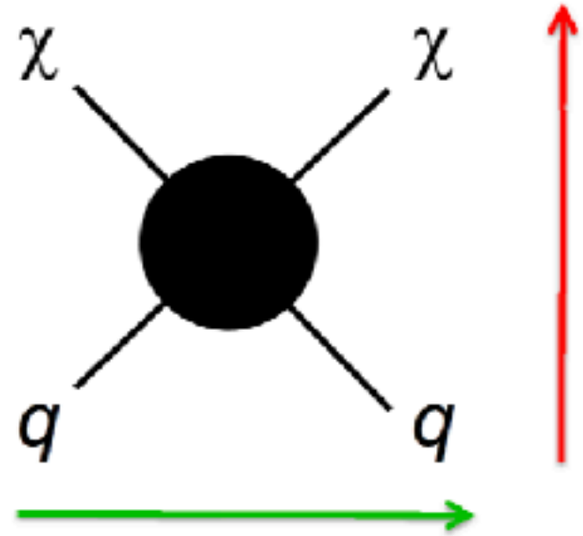
New Frontiers in the Search of Dark Matter 2019
Galileo Galilei Institute, Florence, Italy

European Research Council
Established by the European Commission

Searching for DM: complementarity is the key

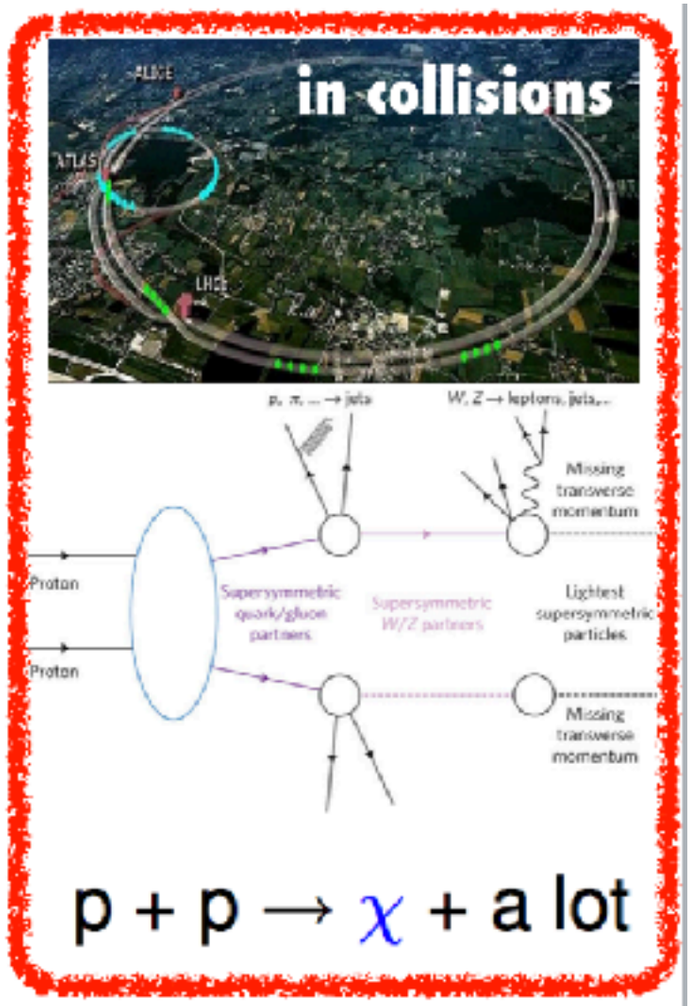


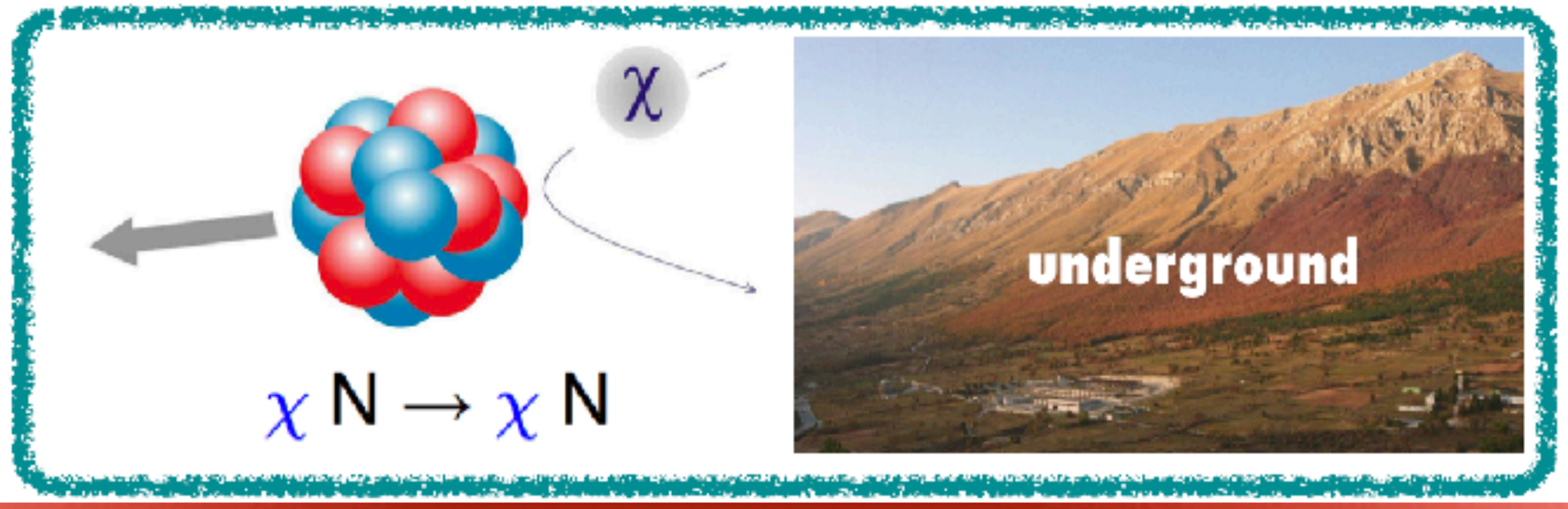
Efficient annihilation now
(Indirect detection)



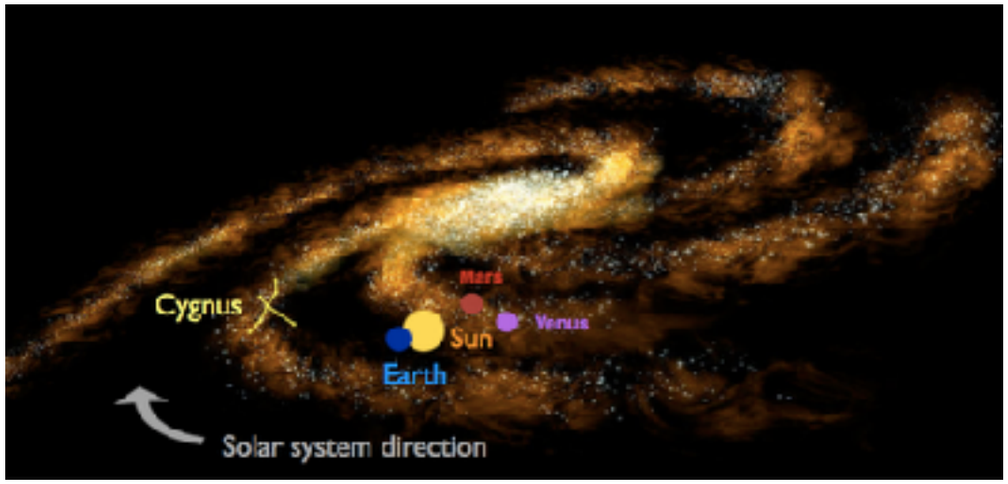
Efficient scattering now
(Direct detection)

Efficient production now
(Particle colliders)





Direct DM searches in a nutshell



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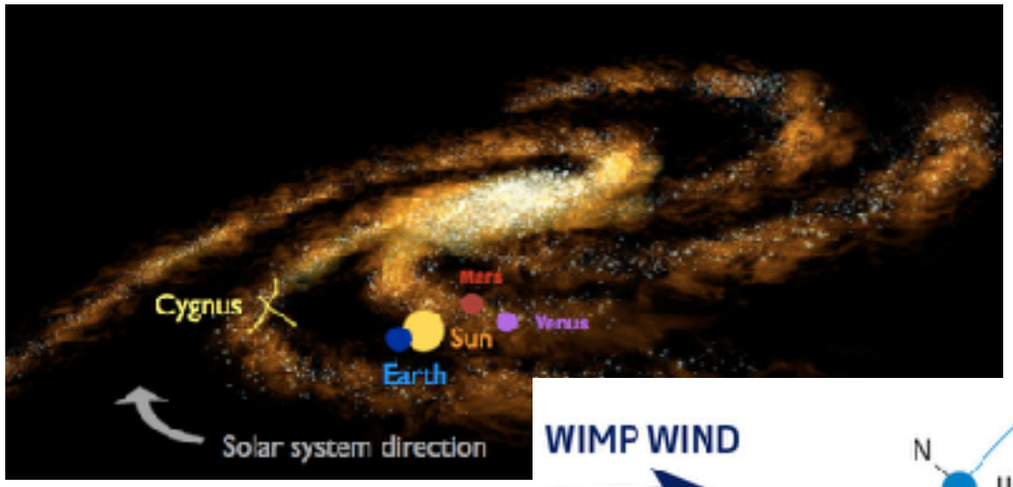

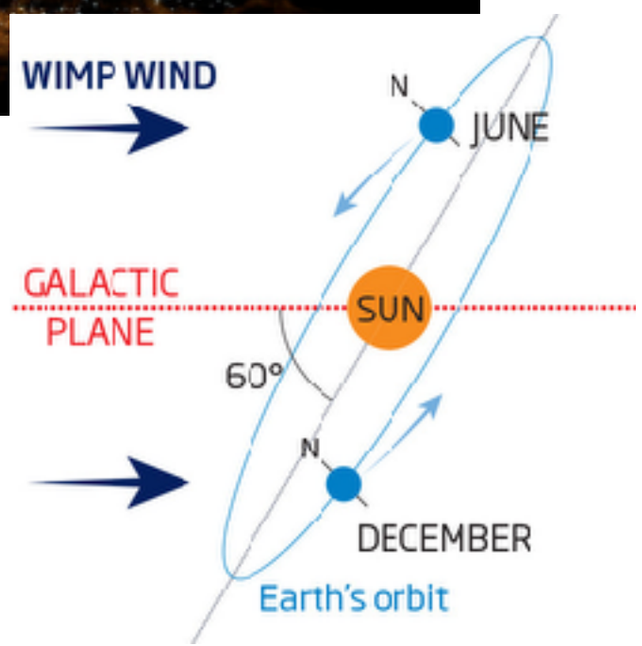

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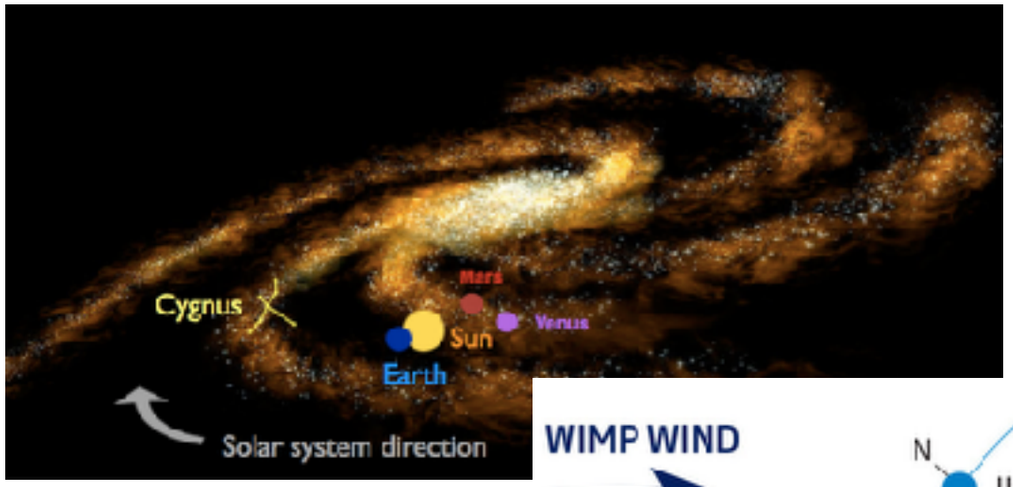

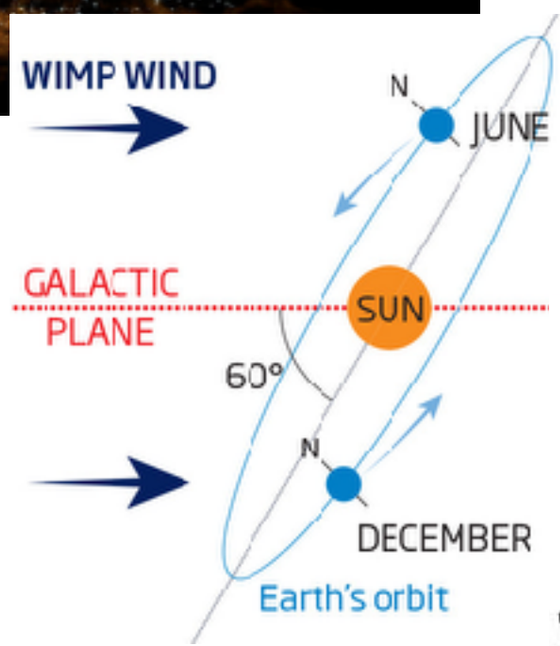

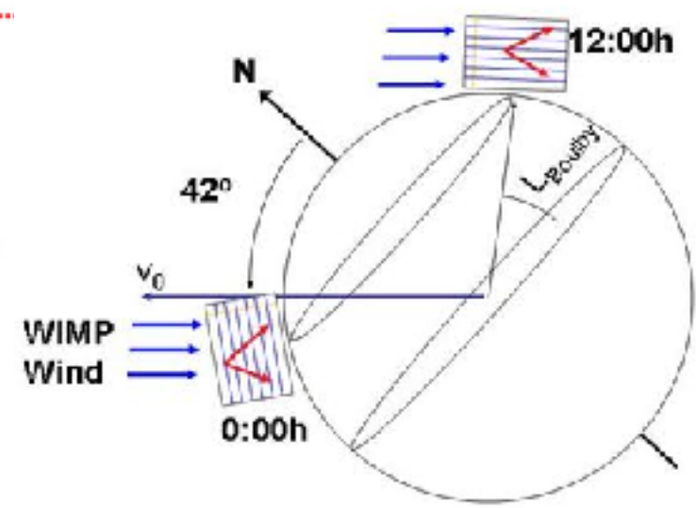

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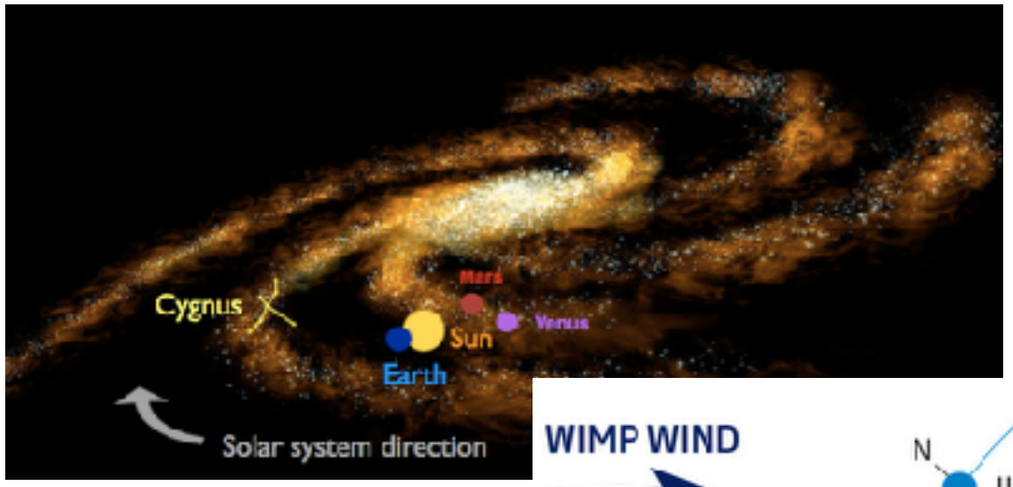
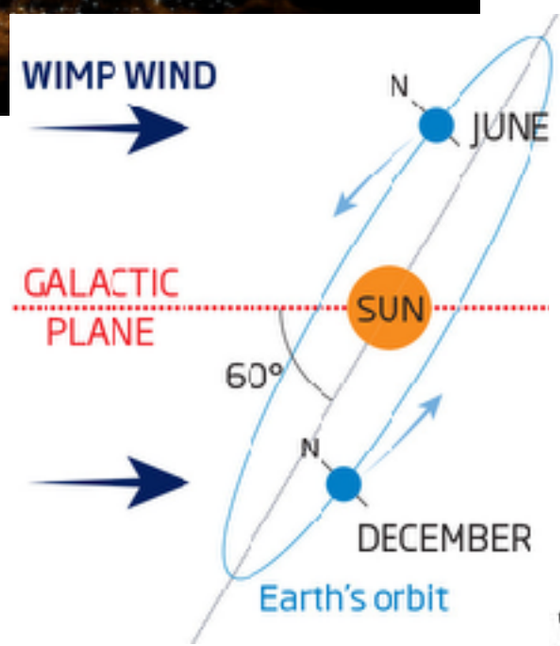
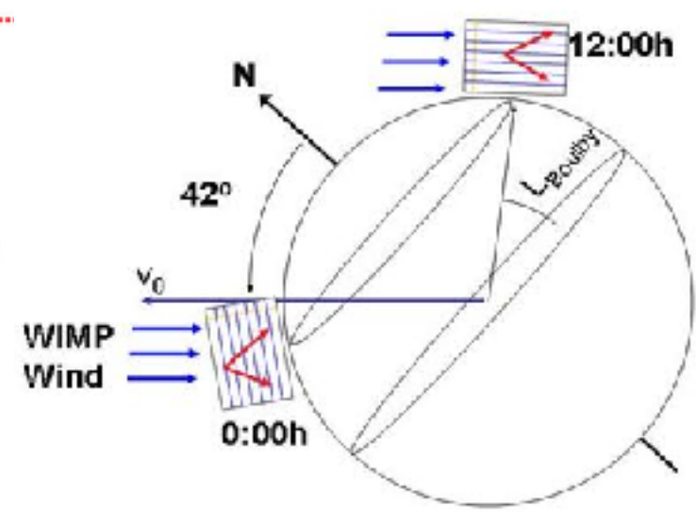
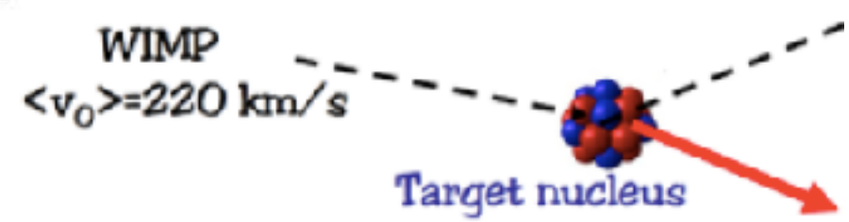


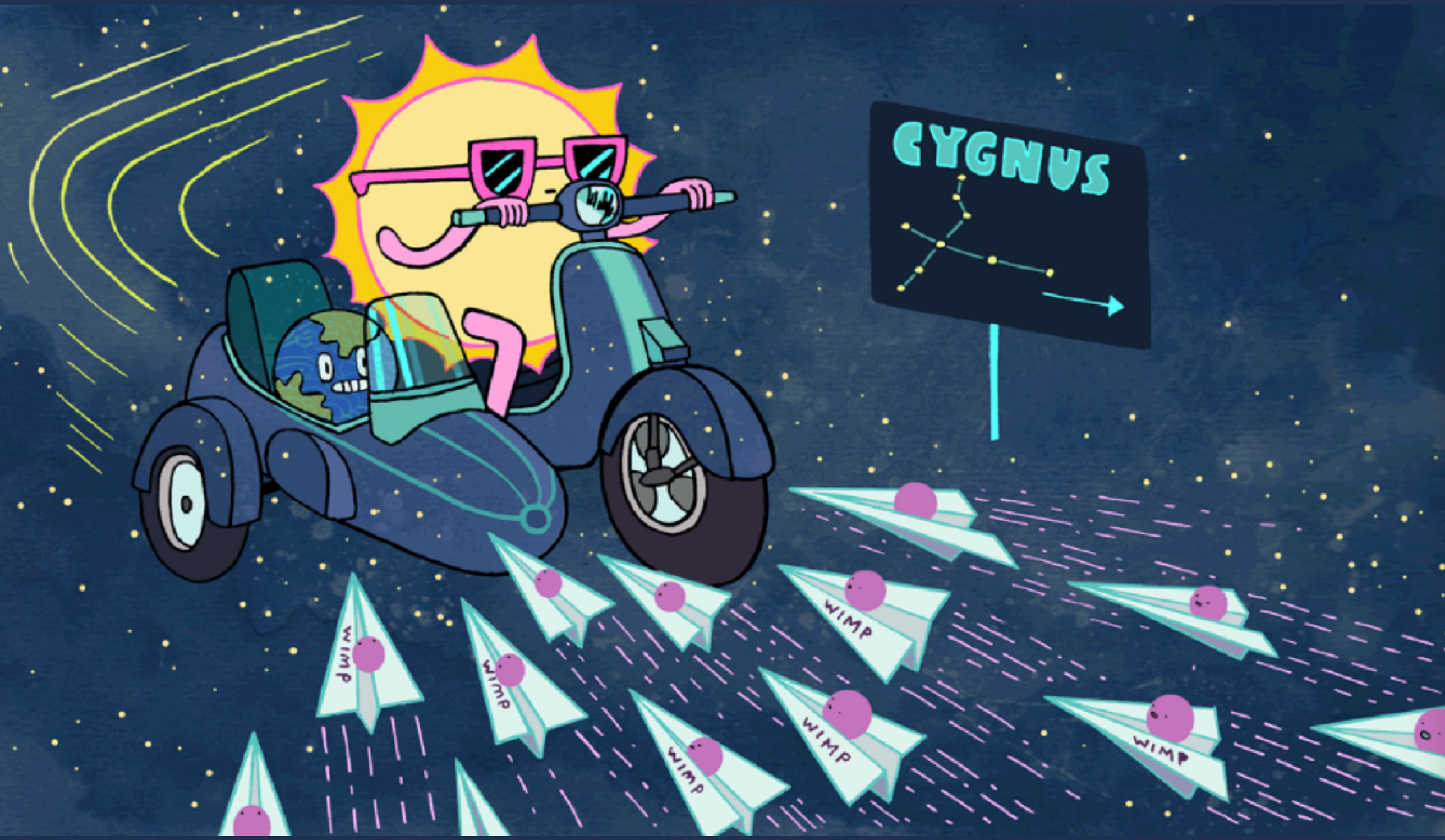




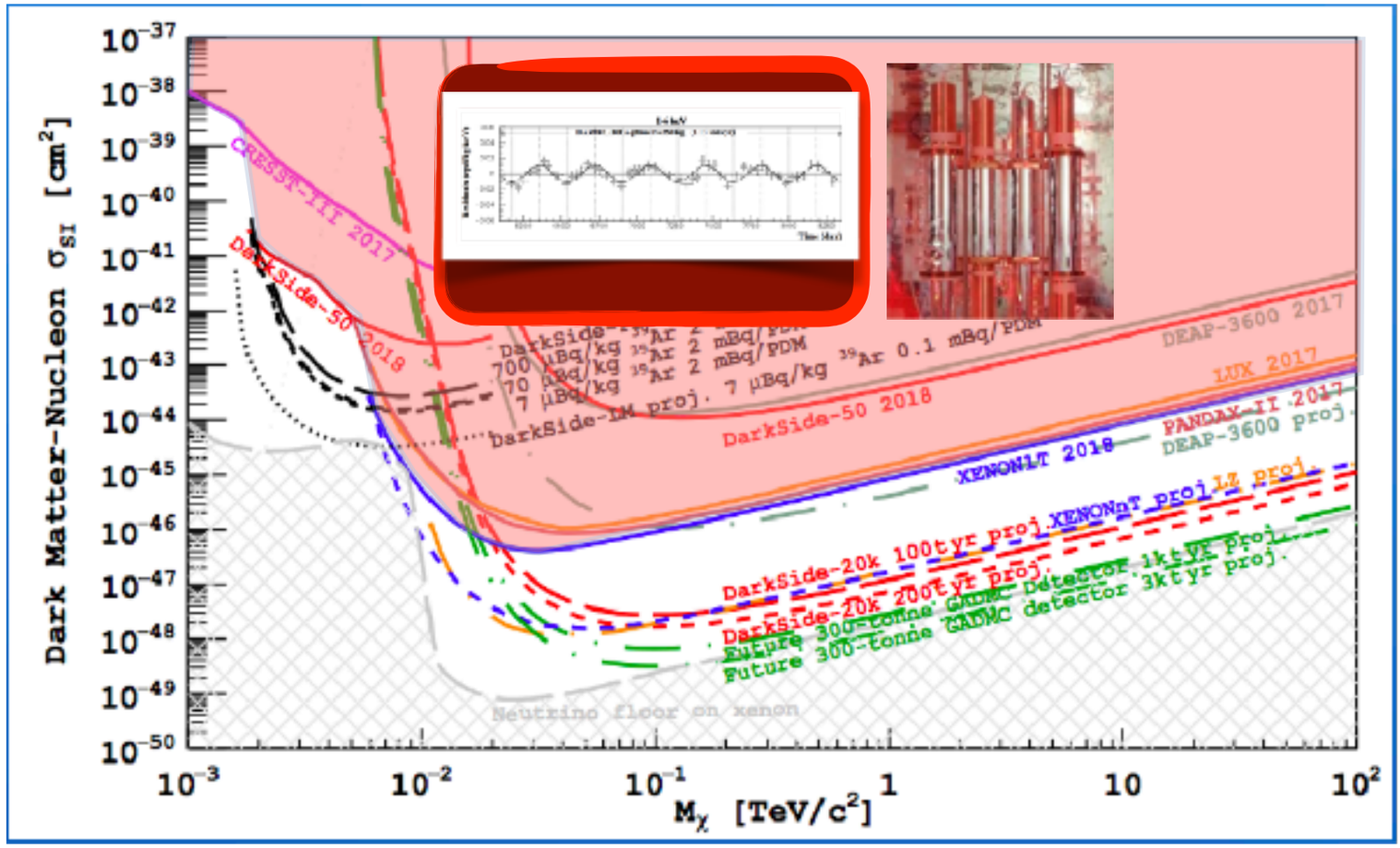


(nuclear or electron) recoil

Driving to Cygnus, with a DM wind blowing in your hair…



Direct DM searches overview & context



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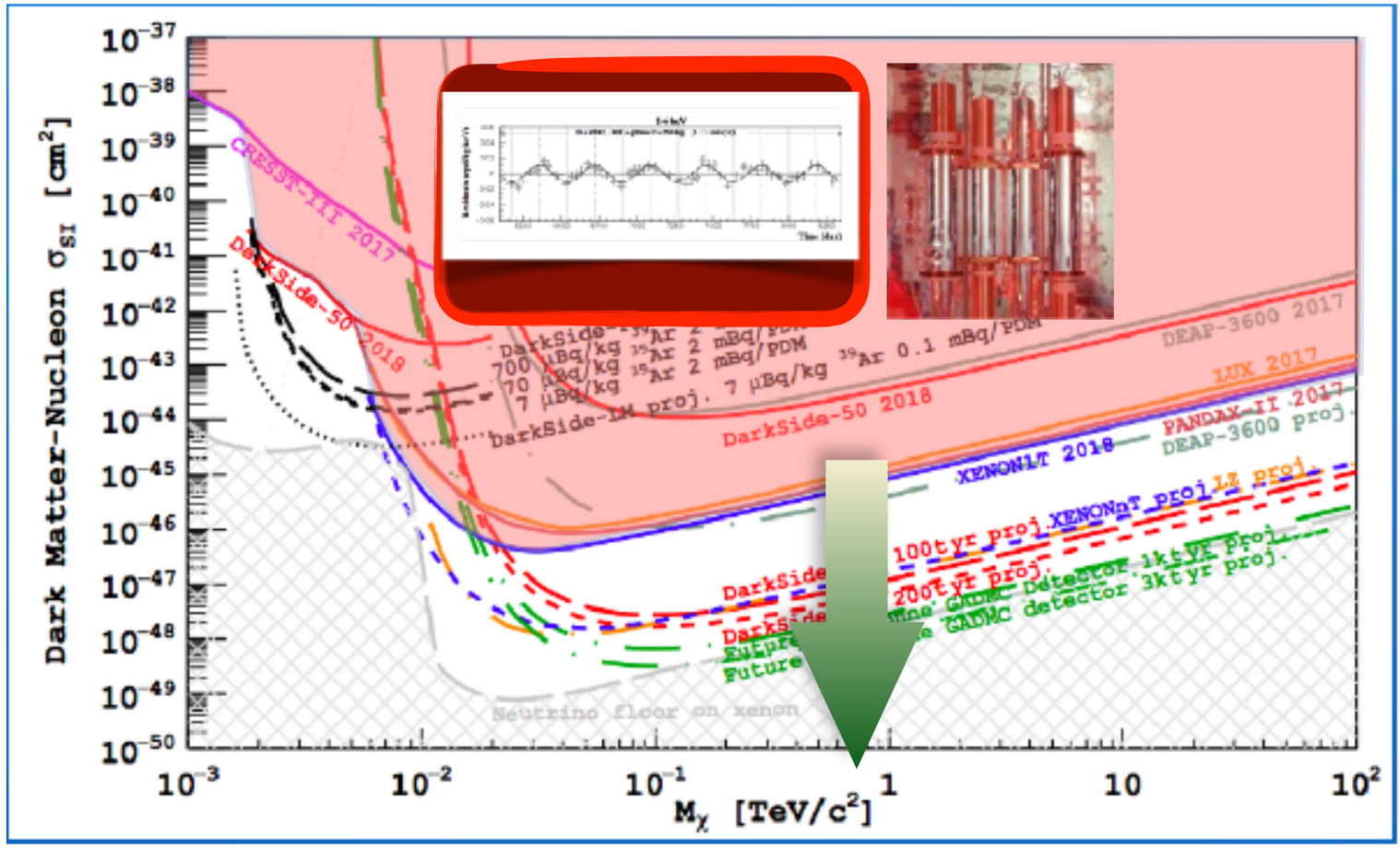
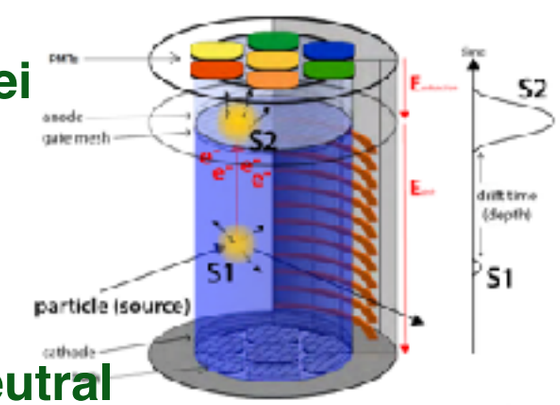


- Ton scale detector with heavy nuclei
- Can go to M_{WIMP} <10 GeV only completely giving up background discrimination (S_2 only analyses)
- Eventually, will be dominated by neutral background also at high masses



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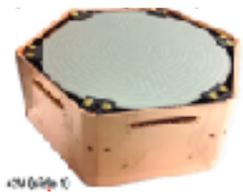
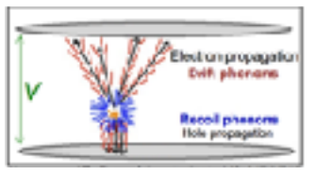
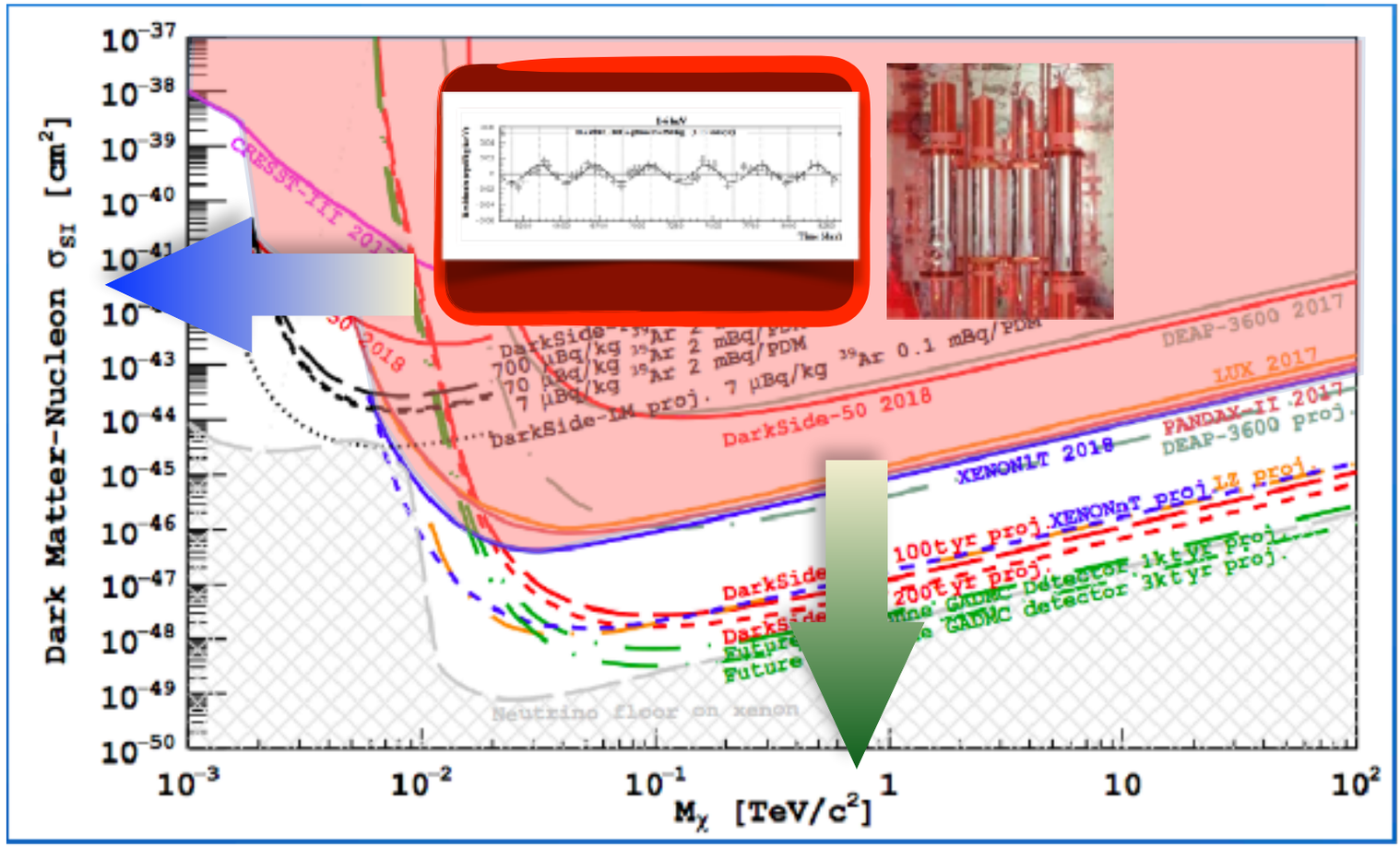




- Small mass detectors with light nuclei
- 0.1-1 kg enough to explore uncharted territories
- Trend to reduce module mass & background discrimination to reach lower threshold



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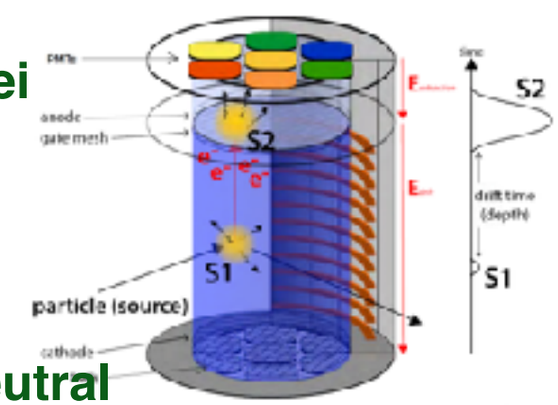

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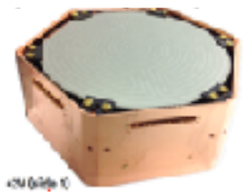

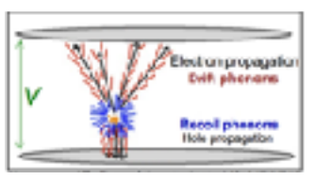

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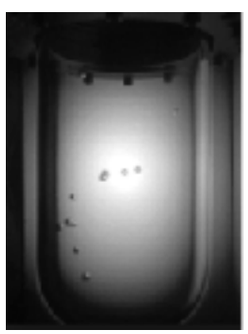
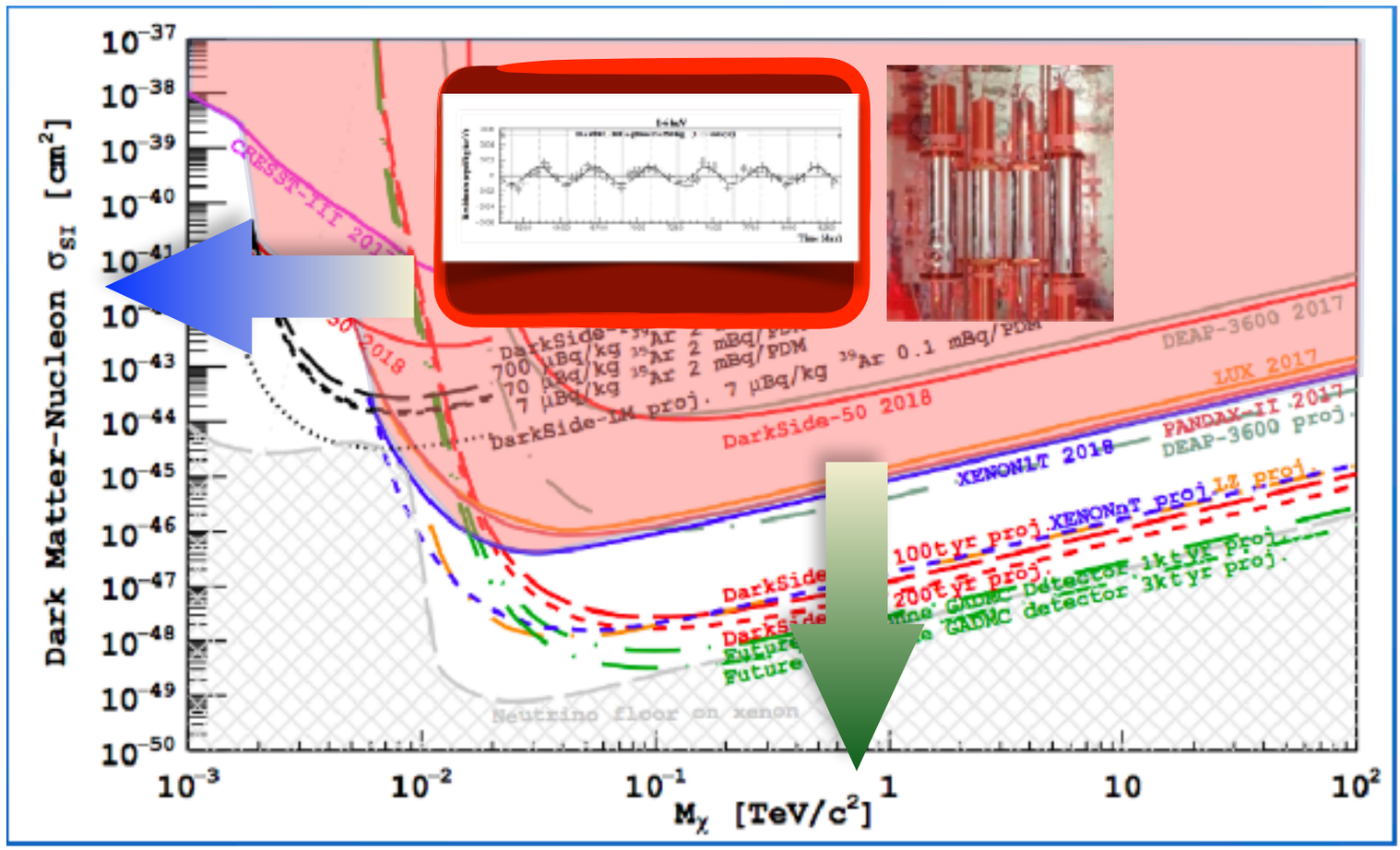


- PICO dominating SD searches
- Insensitive to e/γ by construction (10^{10} rejection @ 3 keV)



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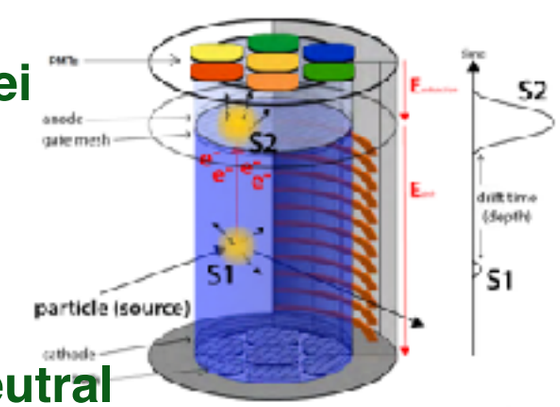

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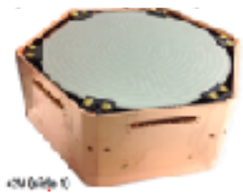

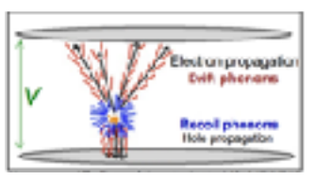

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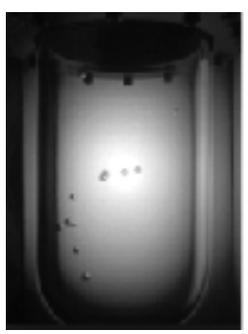

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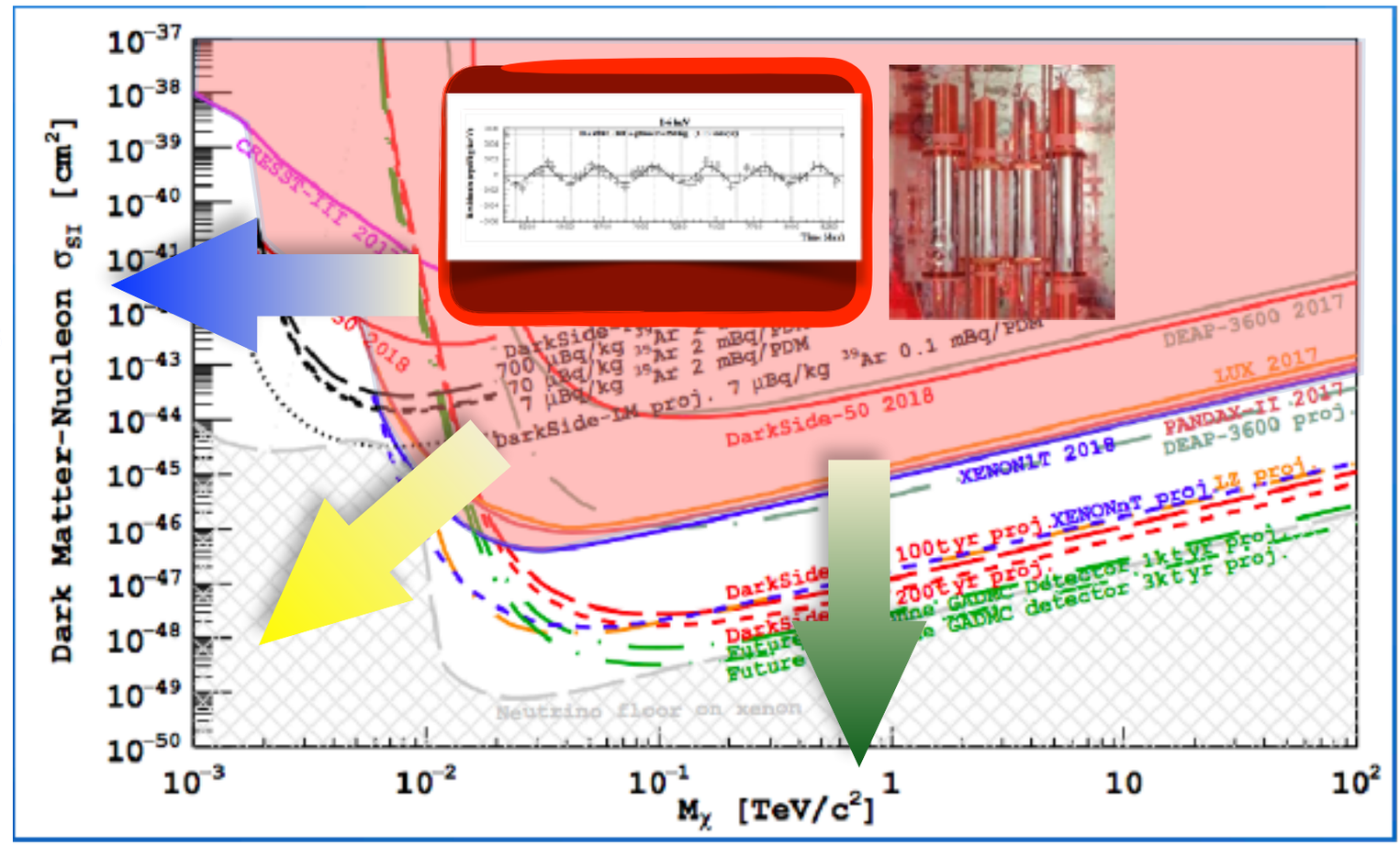
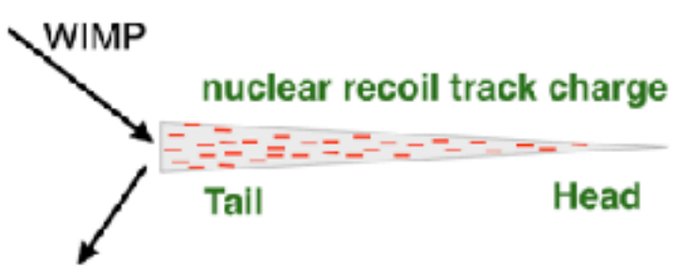


The "third way": directional tracking detectors for both SI and SD



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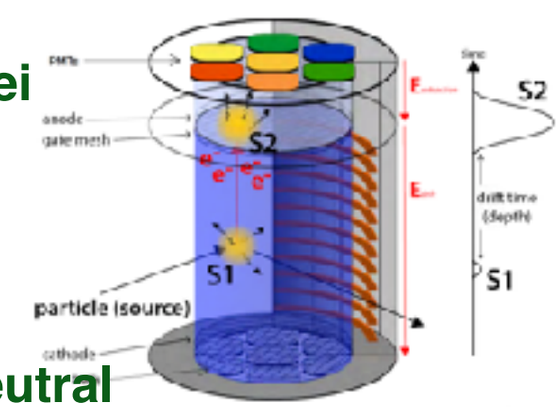
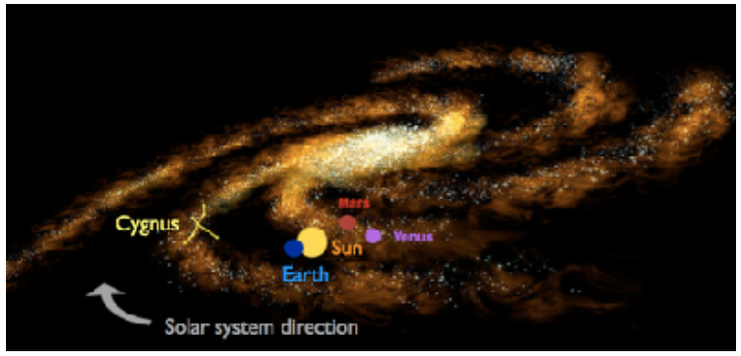
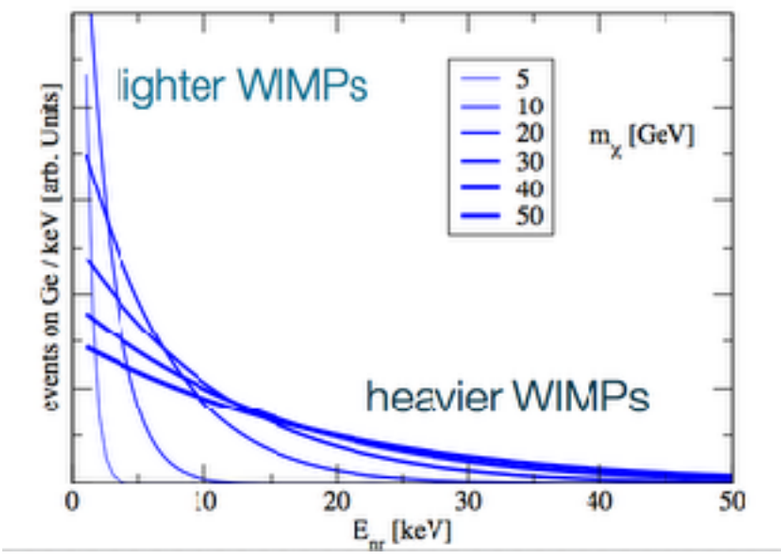


Directionality as key for unambiguous identification of DM

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





Energy dependence:
a falling exponential with
no peculiar features

Directionality as key for unambiguous identification of DM

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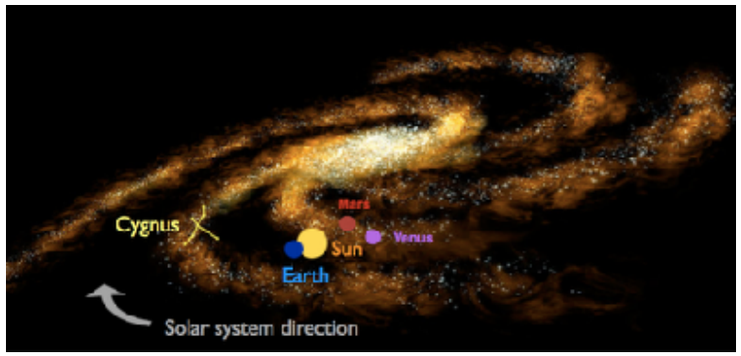
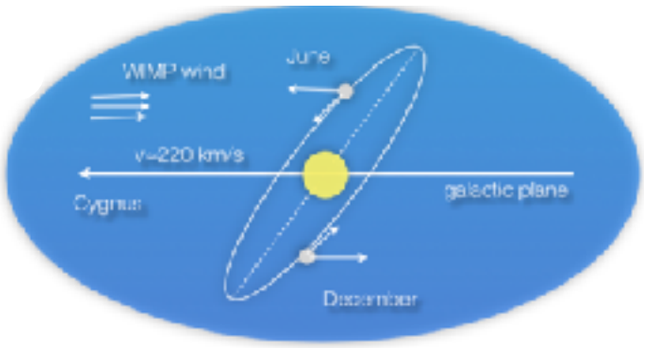
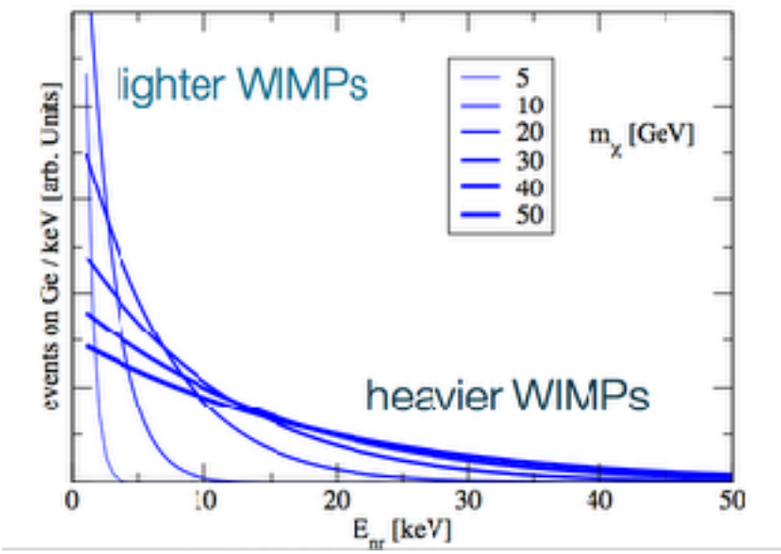
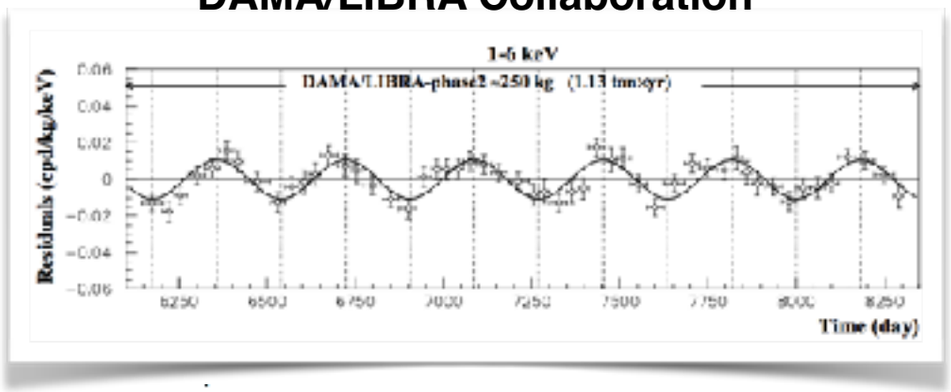






DAMA/LIBRA Collaboration



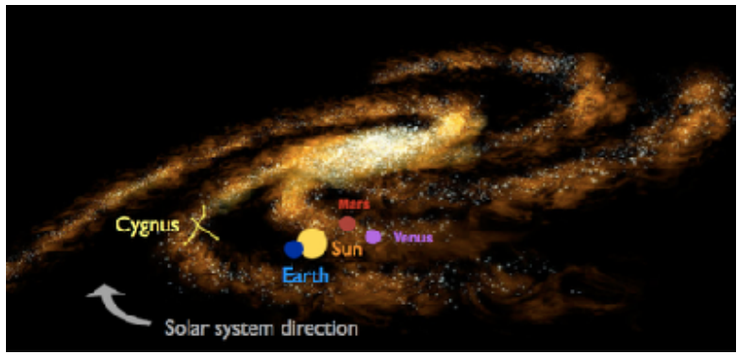
Universe 4 (2018) no.11, 116

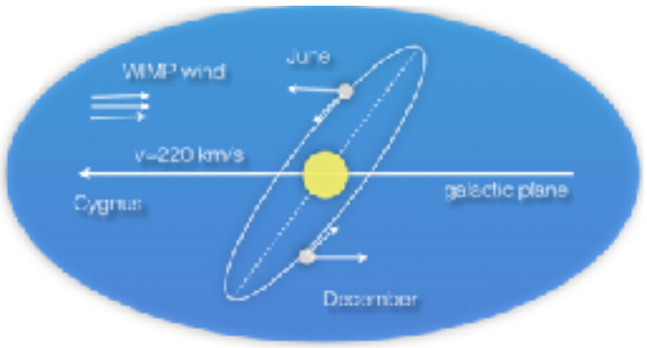
Energy dependence:
a falling exponential with
<u>no peculiar features</u>

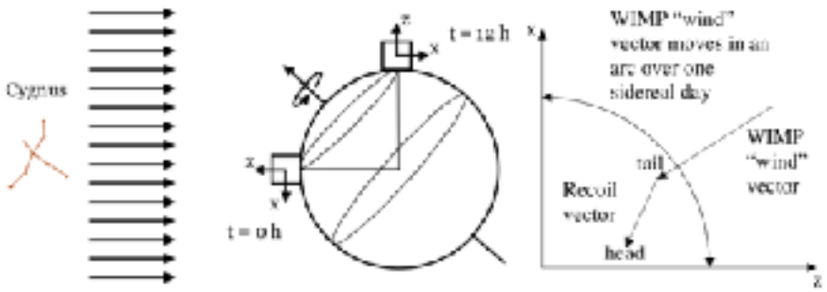
Temporal dependence:
<u>a few %</u> annual
modulation

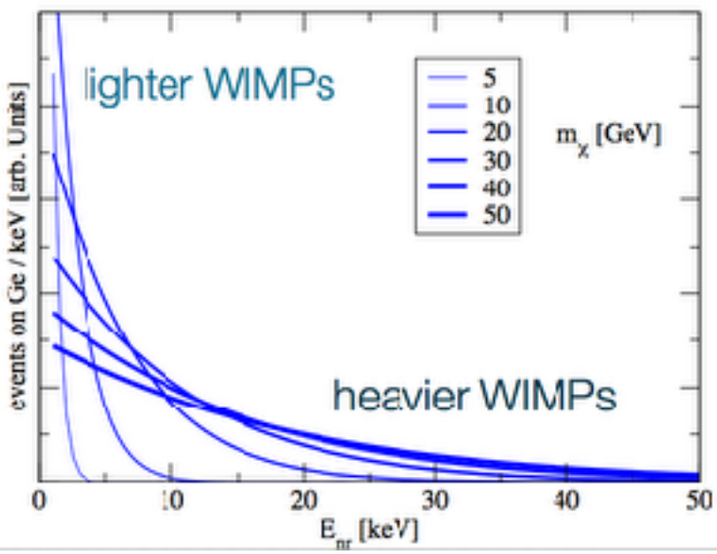
Directionality as key for unambiguous identification of DM

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









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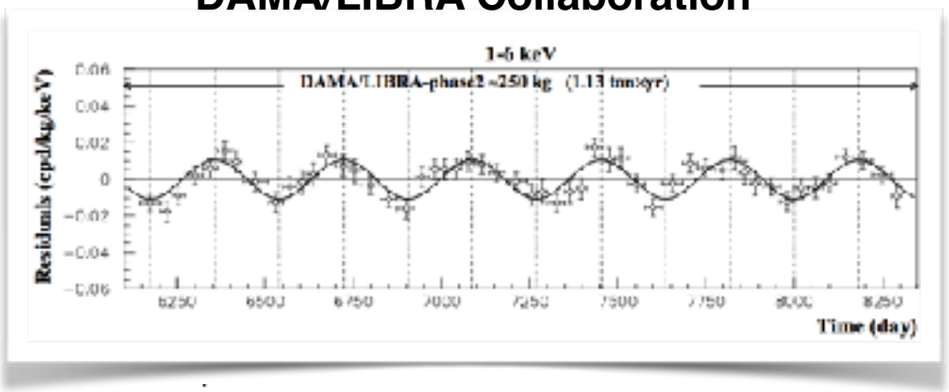

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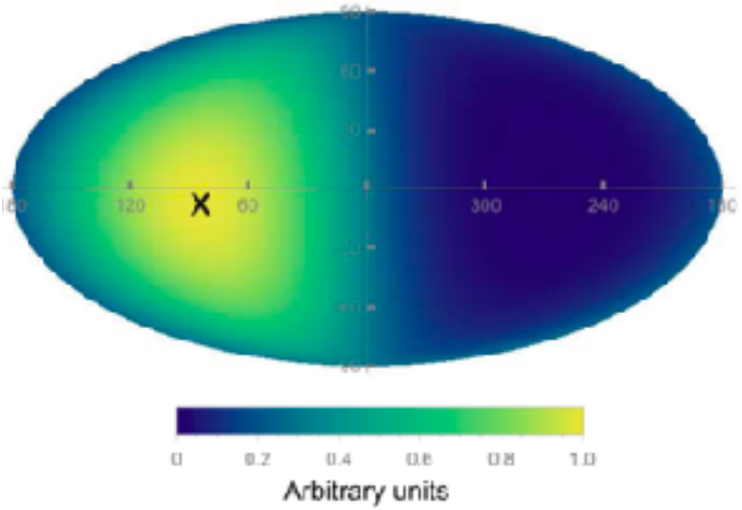


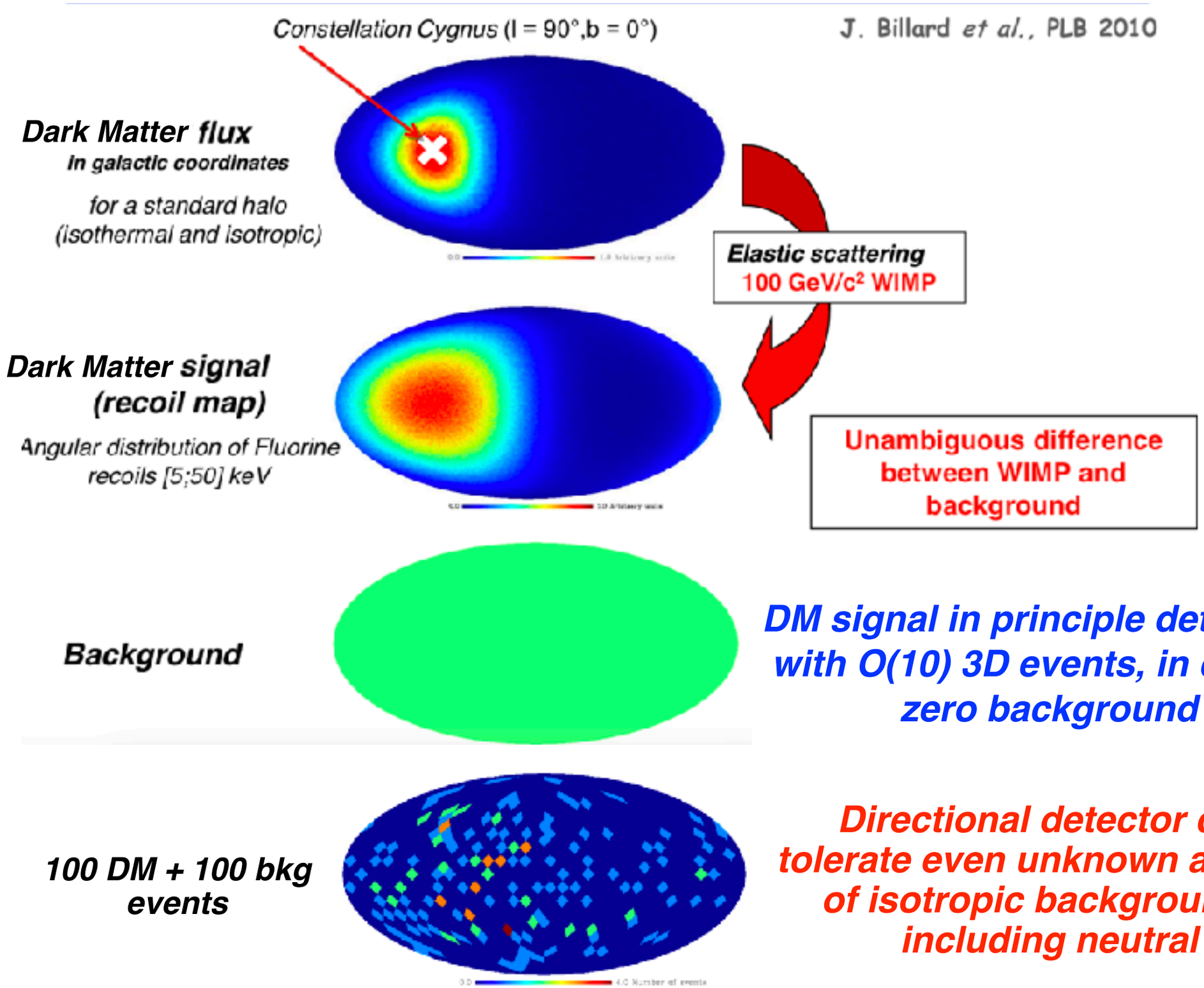
Energy dependence: a falling exponential with no peculiar features

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 weapon for background rejection

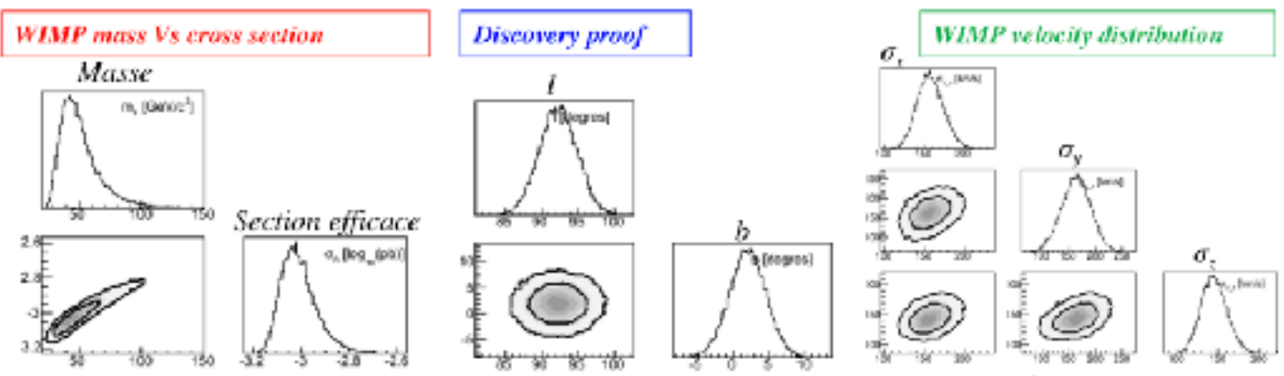


DM signal in principle detectable with O(10) 3D events, in case of zero background

Directional detector can tolerate even unknown amount of isotropic backgrounds, including neutral

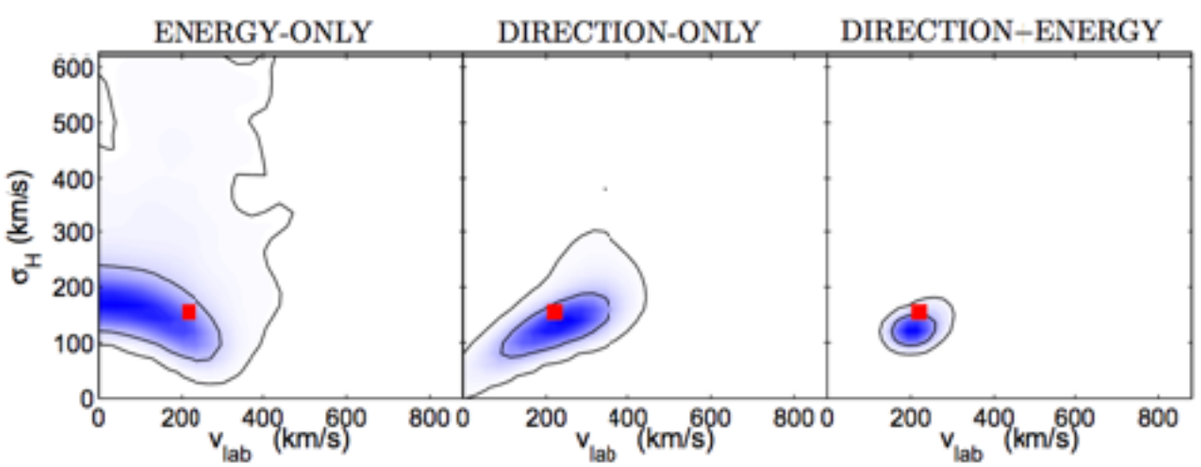
Directionality as an instrument to probe DM nature and perform DM astronomy

J. Billard *et al.*, PRD 2011



	m_χ (GeV/c^2)	$\log_{10}(\sigma_n$ (pb))	$\ell_\odot$ (°)	$b_\odot$ (°)	σ_x (km.s^{-1})	σ_y (km.s^{-1})	σ_z (km.s^{-1})	β	R_b (kg^{-1}year^{-1})
Input	50	-3	90	0	155	155	155	0	10
Output	$51.8^{+5.6}_{-19.4}$	$-3.01^{+0.05}_{-0.08}$	$92.2^{+2.5}_{-2.5}$	$2.0^{+2.5}_{-2.5}$	158^{+15}_{-17}	164^{+27}_{-26}	145^{+14}_{-17}	$-0.073^{+0.29}_{-0.18}$	10.97 ± 1.2

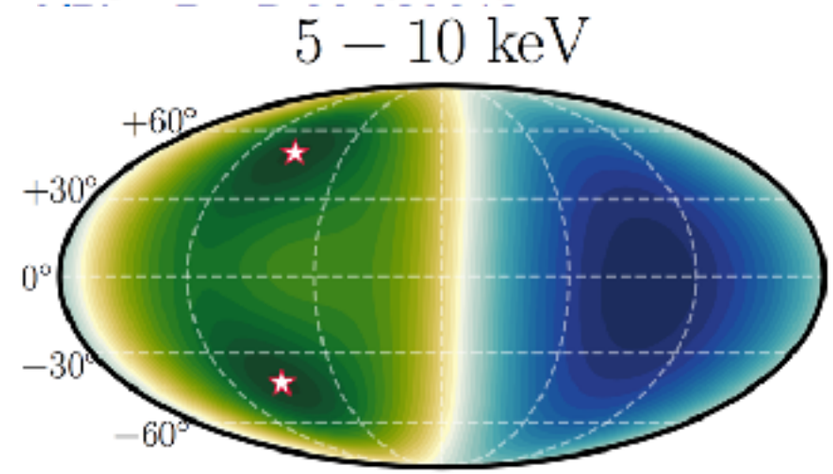
F. Mayet et al., Phys. Rept 627 (2016)



WIMP & halo properties unbiased constrained with a single measurement

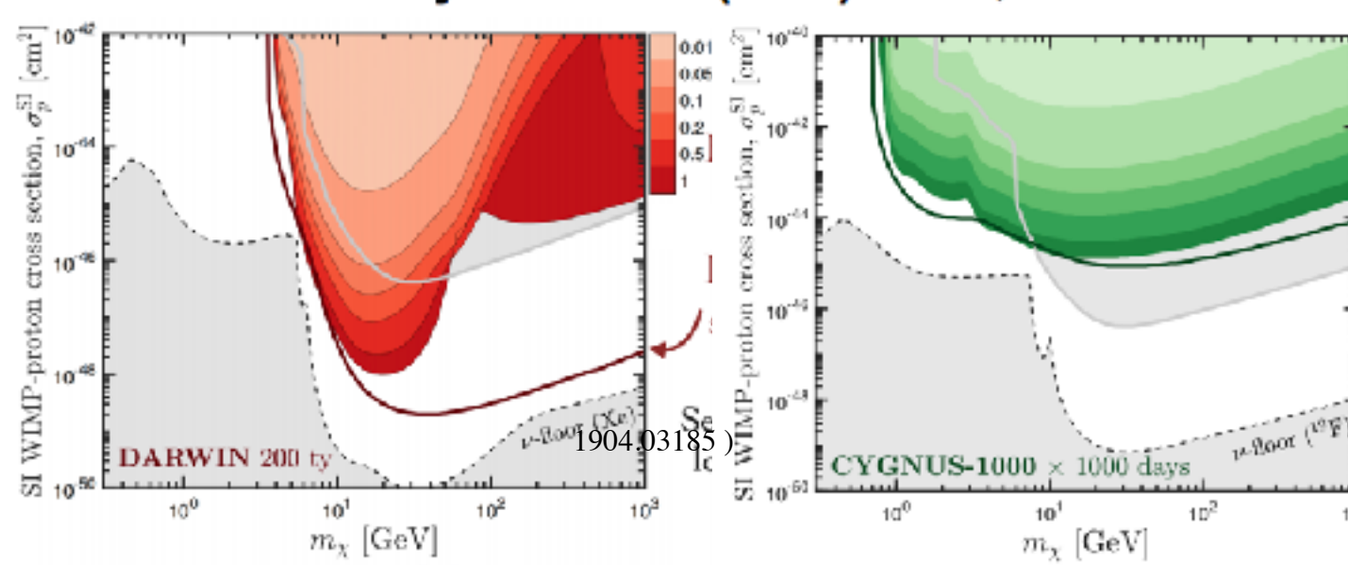
The Gaia Sausage gives rise to peaks off center from Cygnus

Phys.Rev. D99 (2019) no.2, 023012



Distribution for 5-10 keVr Fluorine recoils with a 100 GeV WIMP
Halo model = SHM + Sausage

Phys.Rev. D98 (2018) no.10, 103006



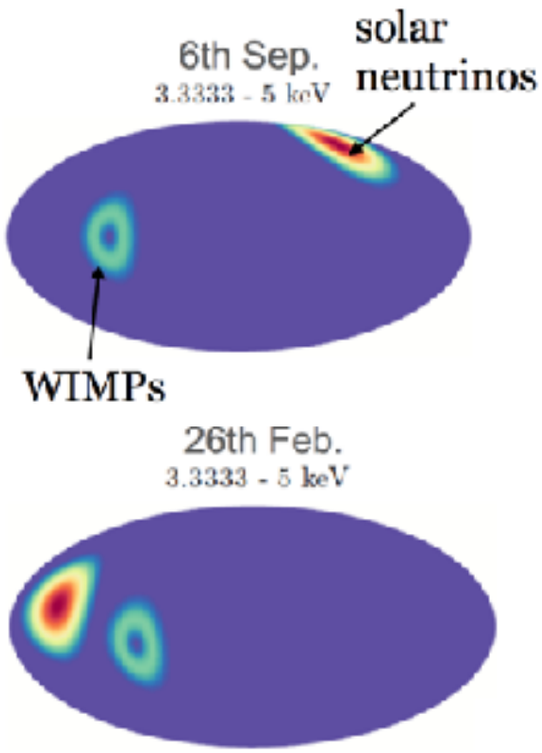
1904.03185)

Full capability to probe halo substructures, such as Gaia Sausage and S1 hurricane

Directionality as a new window on neutrino physics

Neutrinos: an opportunity for directional DM detectors, rather than an inconvenience

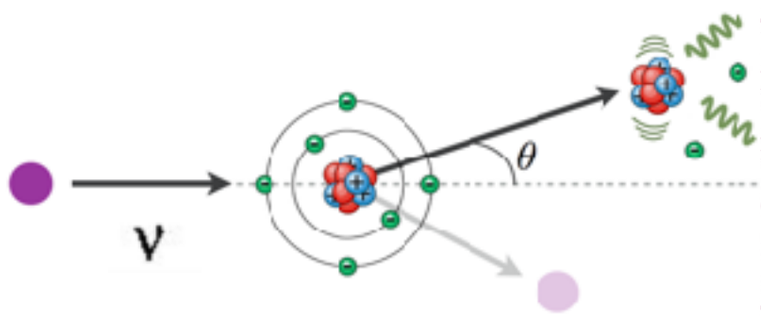
C. O'Hare et al, Phys. Rev. D 92 063518 (2015)



Directionality as a new window on neutrino physics

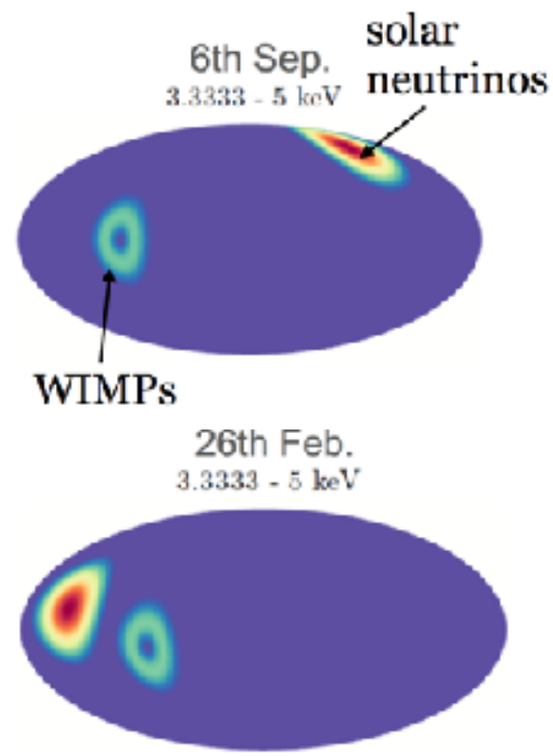
Neutrinos: an opportunity for directional DM detectors, rather than an inconvenience

Coherent Neutrino-Nucleus scattering



NOTE: only a directional DM detector can distinguish from WIMP signal

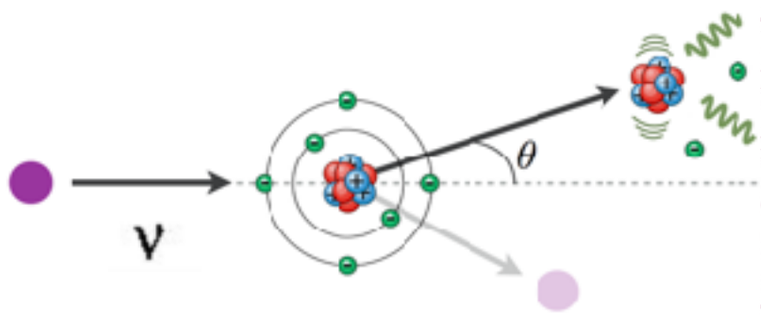
C. O'Hare et al, Phys. Rev. D 92 063518 (2015)



Directionality as a new window on neutrino physics

Neutrinos: an opportunity for directional DM detectors, rather than an inconvenience

Coherent Neutrino-Nucleus scattering



NOTE: only a directional DM detector can distinguish from WIMP signal

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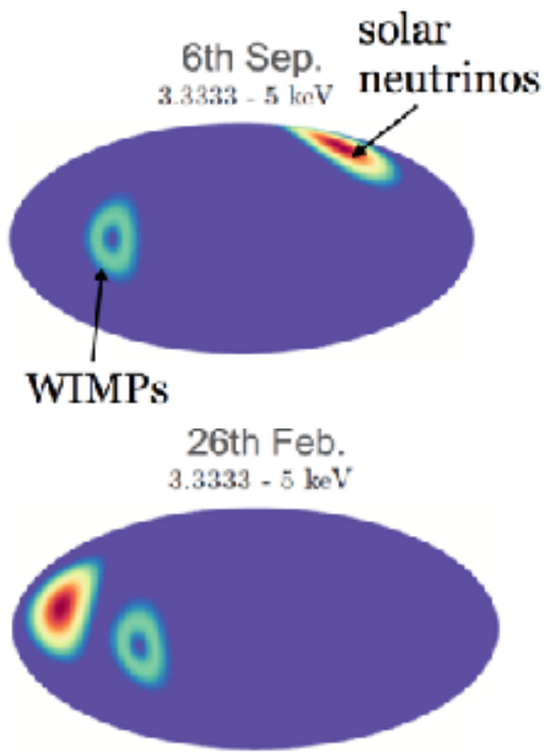
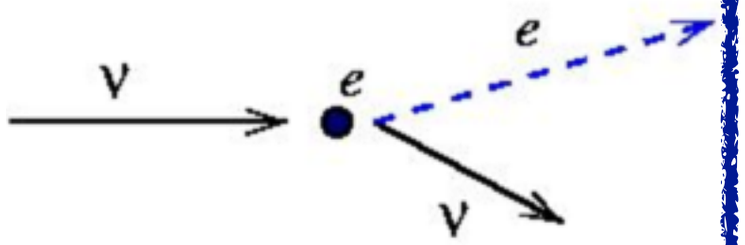


NEW! Physics reach under study

Elastic Neutrino-Electron scattering

with event by event precise neutrino energy measurement



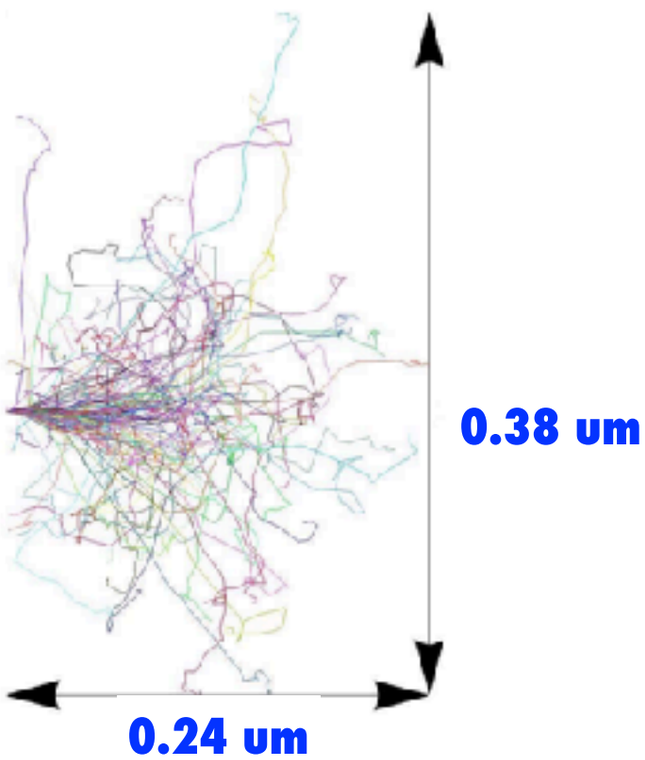
NOTE: only a directional DM detector can distinguish from ER background

A directional DM detector is also a Sun and Supernovae neutrino observatory

Directionality: how well preserved in nuclear recoils? Choose your target material & resolution

- Emulsion layers
- Crystals scintillators
- Low pressure TPCs *

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

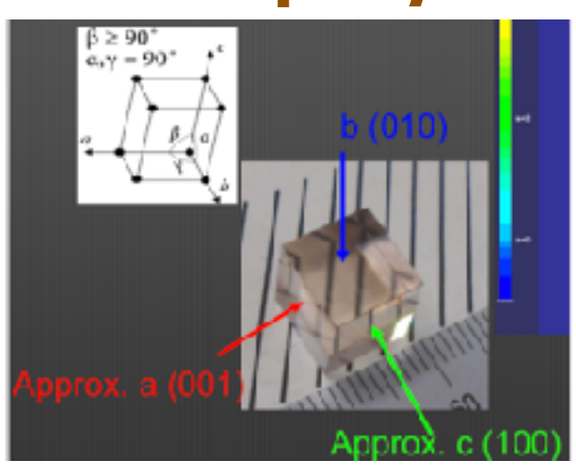


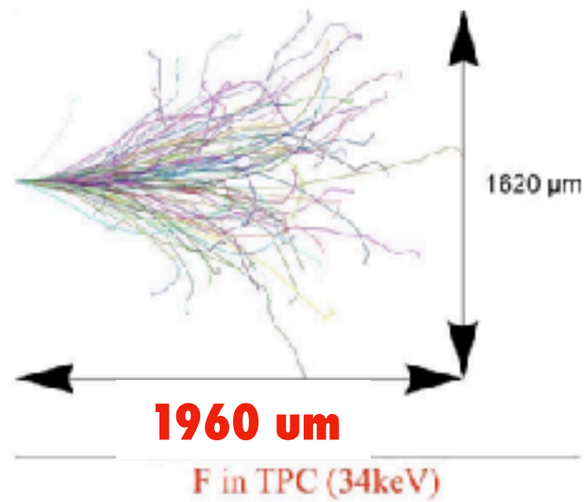
C in Emulsion (22keV)

NEWS-DM (emulsions)

O in Crystal (29keV)

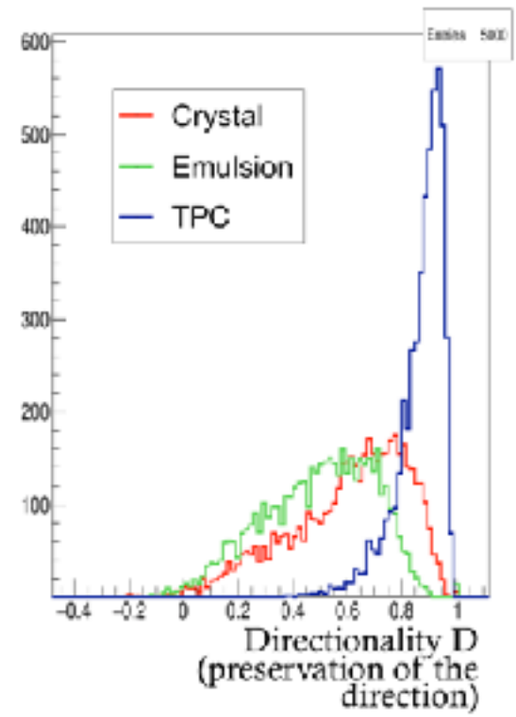
Anisotropic crystals





F in TPC (34keV)

From SRIM software simulation

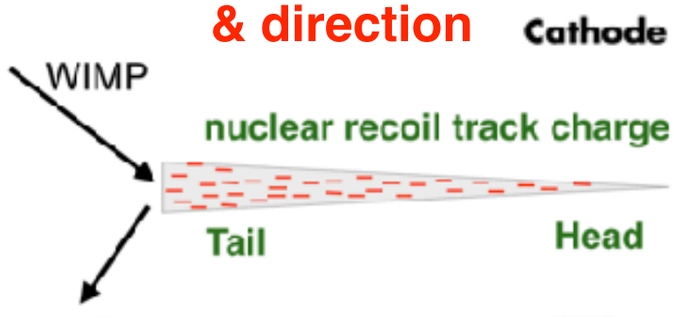


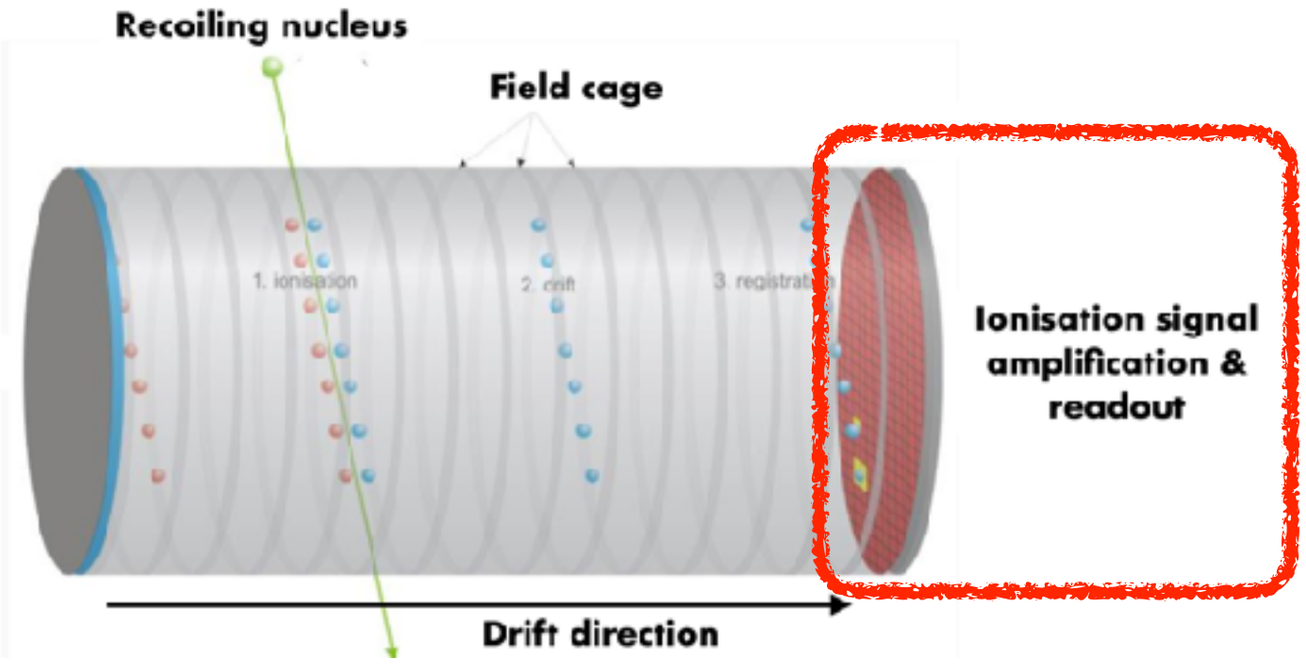
JCAP 1701 (2017) no.01, 027

Gaseous TPC facts & figures

Gaseous Time Projection Chamber, inherently a 3D detector

Sensitive to track sense & direction

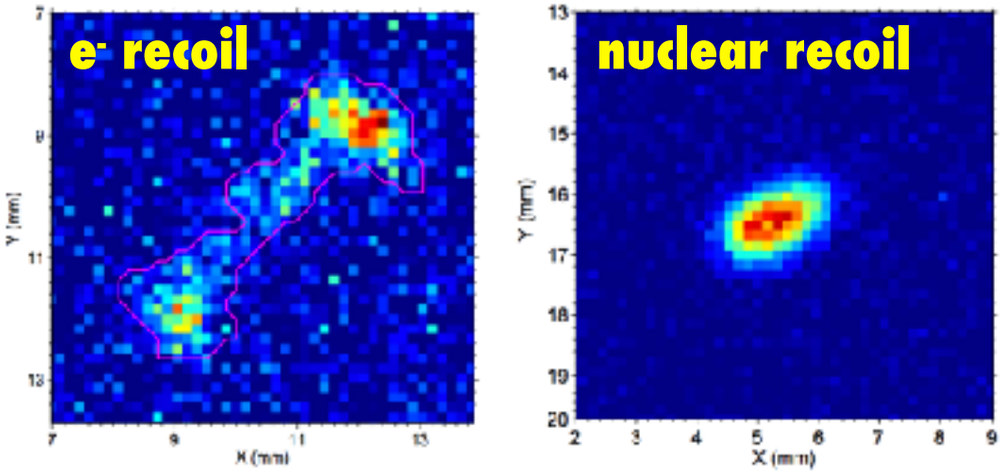




How much 3D? It all depends on your readout & gas mixture (cost/benefit?)

- 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



CYGNUS proto-collaboration vision

Since fall 2016

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





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*

The CYGNUS Galactic Directional Recoil Observatory
Proto-Collaboration Agreement

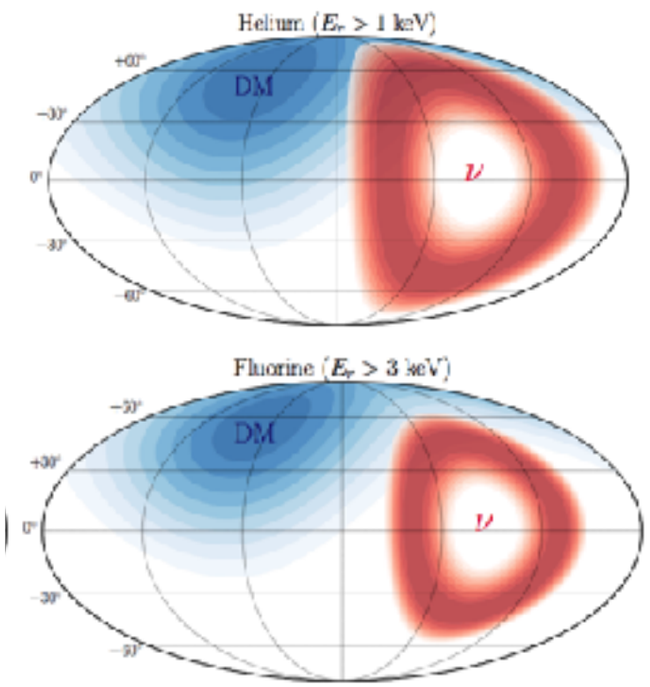
Now that conventional WIMP dark matter searches are approaching the neutrino floor, there has been a resurgence of interest in the possibility of introducing recoil direction sensitivity into the field. Such directional sensitivity would offer the powerful prospect of reaching below this floor, introducing both the possibility of identifying a clear signature for dark matter particles in the galaxy below this level but also of exploiting observation of coherent neutrino scattering from the Sun and other sources with directional sensitivity. There has also been significant progress recently in development of technology able to record the directional information from nuclear recoils at low energy (sub-100 keV) necessary for these goals. This includes progress on improving the sensitivity of low pressure gas time projection chamber technology but also on novel ideas with higher density targets, such as ultra-fine grain emulsions, scintillation materials, columnar recombination with noble gas targets and concepts

- **Helium/Fluorine-based gaseous TPC for sensitivity to O(GeV) WIMP region for both SI and SD couplings**
- **Goal of zero background operation after electron/gamma rejection and fiducialization at O(keV)**
- **Directional threshold at O(keV)**

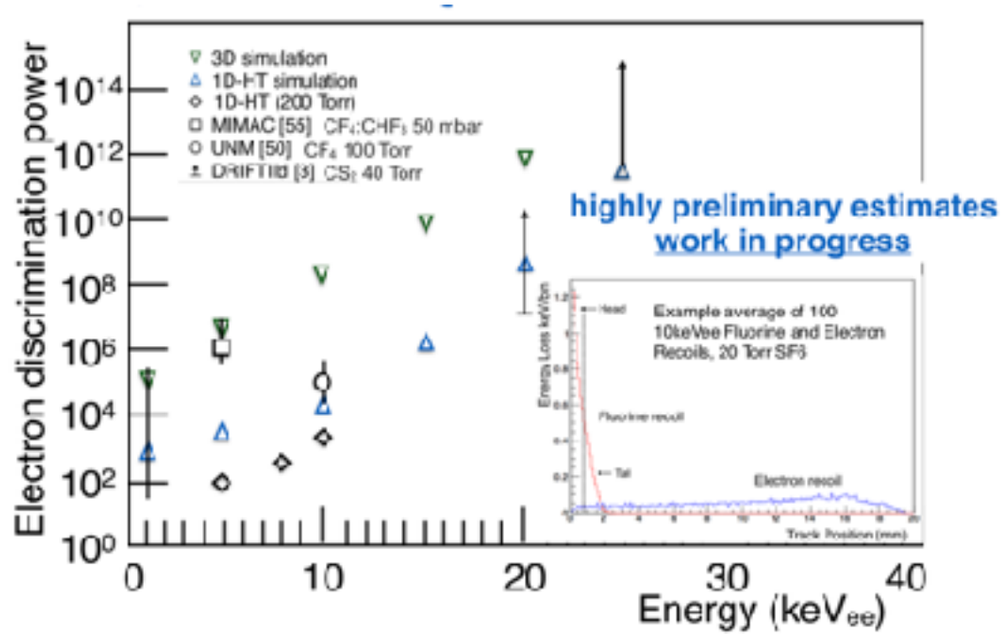
What you will find in the Whitepaper

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

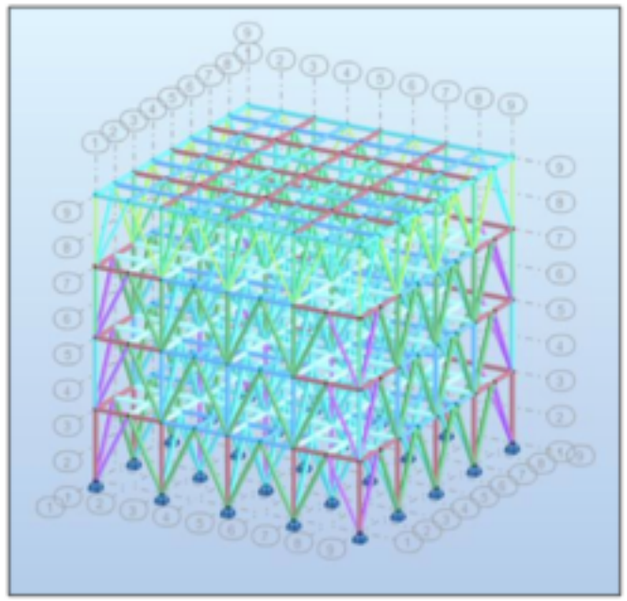
The physics case for DM and neutrinos measurements



Background discrimination @ 10^5 (for 3D readout) down to 1 keV, with simulation and supported by measurements

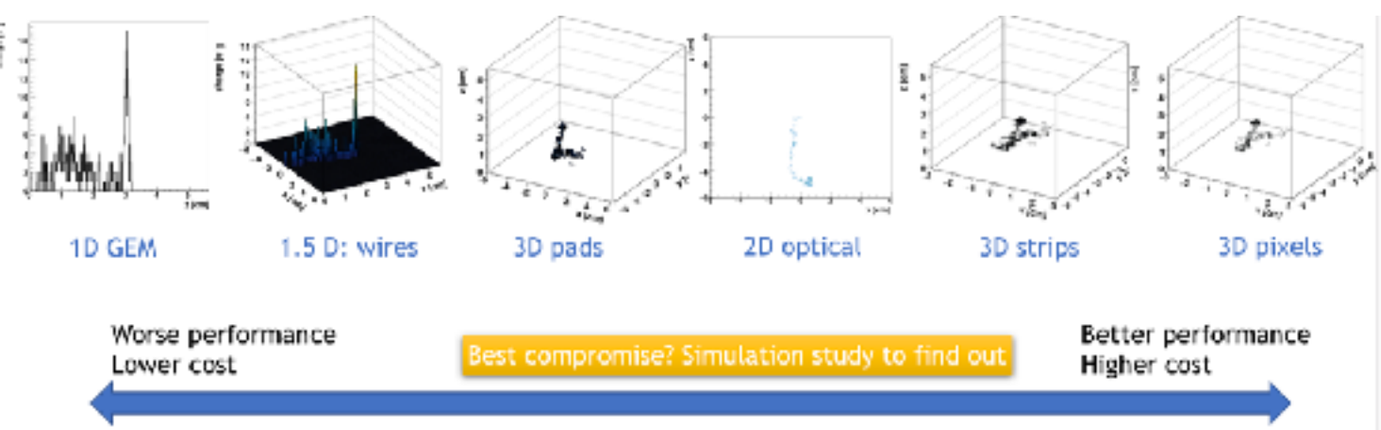


Engineering studies for 1000 m³ detector



PRELIMINARY

Detailed simulation of six readout options, with both negative ion and electron drift, with a cost/benefit FOM



A detailed simulation & studies of all the internal and external backgrounds

Readout	Material	Thickness (mm)	Total mass (tons)
THGEM	Acrylic	1.0	2.36
THGEM	Copper	0.1	3.6
μ-PIC	Polyimide	1.0	2.84
GEM	Kapton	(0.05)	0.0142
Wires	Steel	0.05	1.94×10^{-3}
Wires (frame)	Acrylic	10	0.236
Pixel Chip	Silicon	0.400	1.86
Pixel Chip	Copper	3.9×10^{-3}	0.07
Pixel Chip	Aluminium	4.5×10^{3}	0.024

What I can show you now

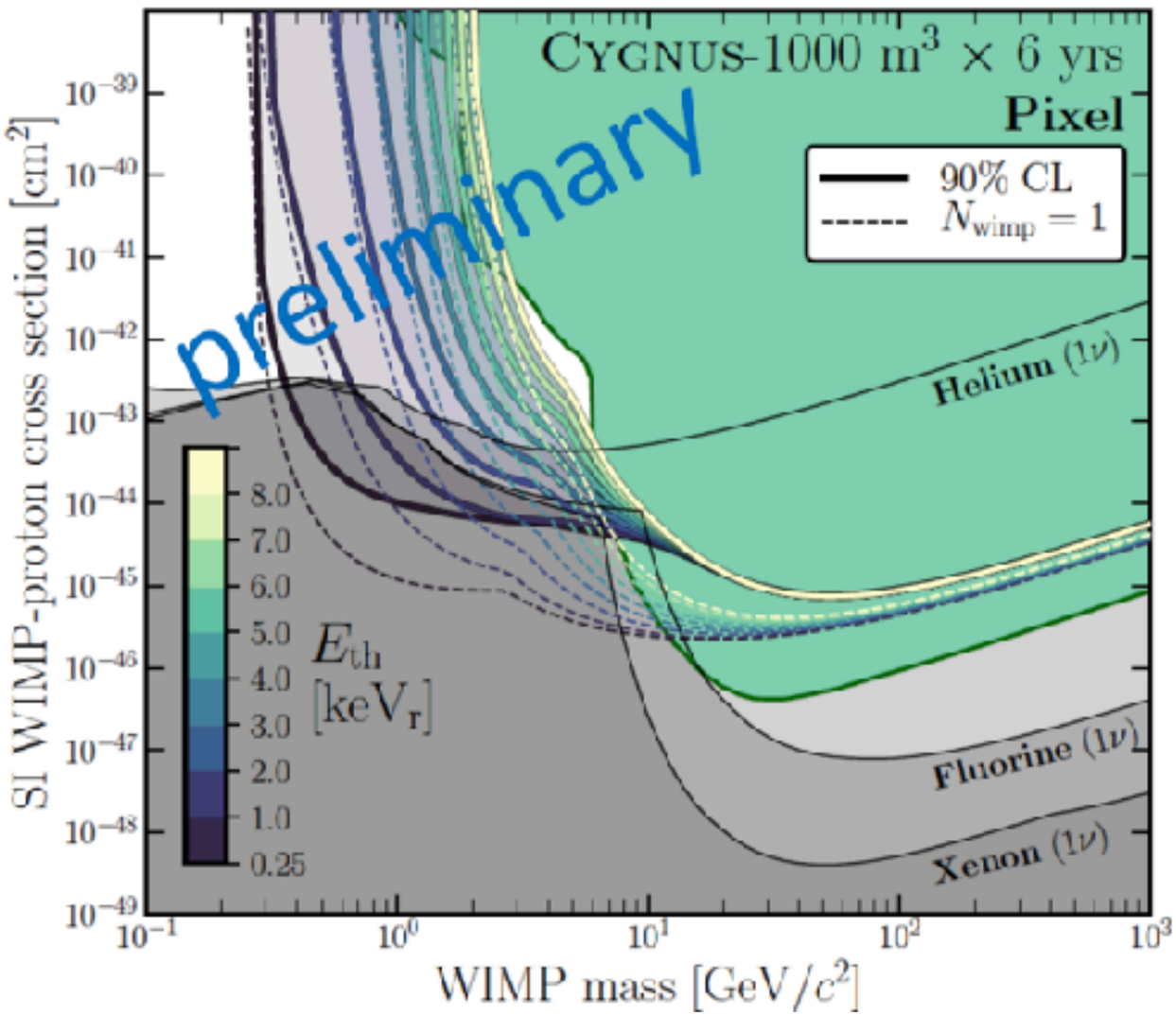
PRELIMINARY

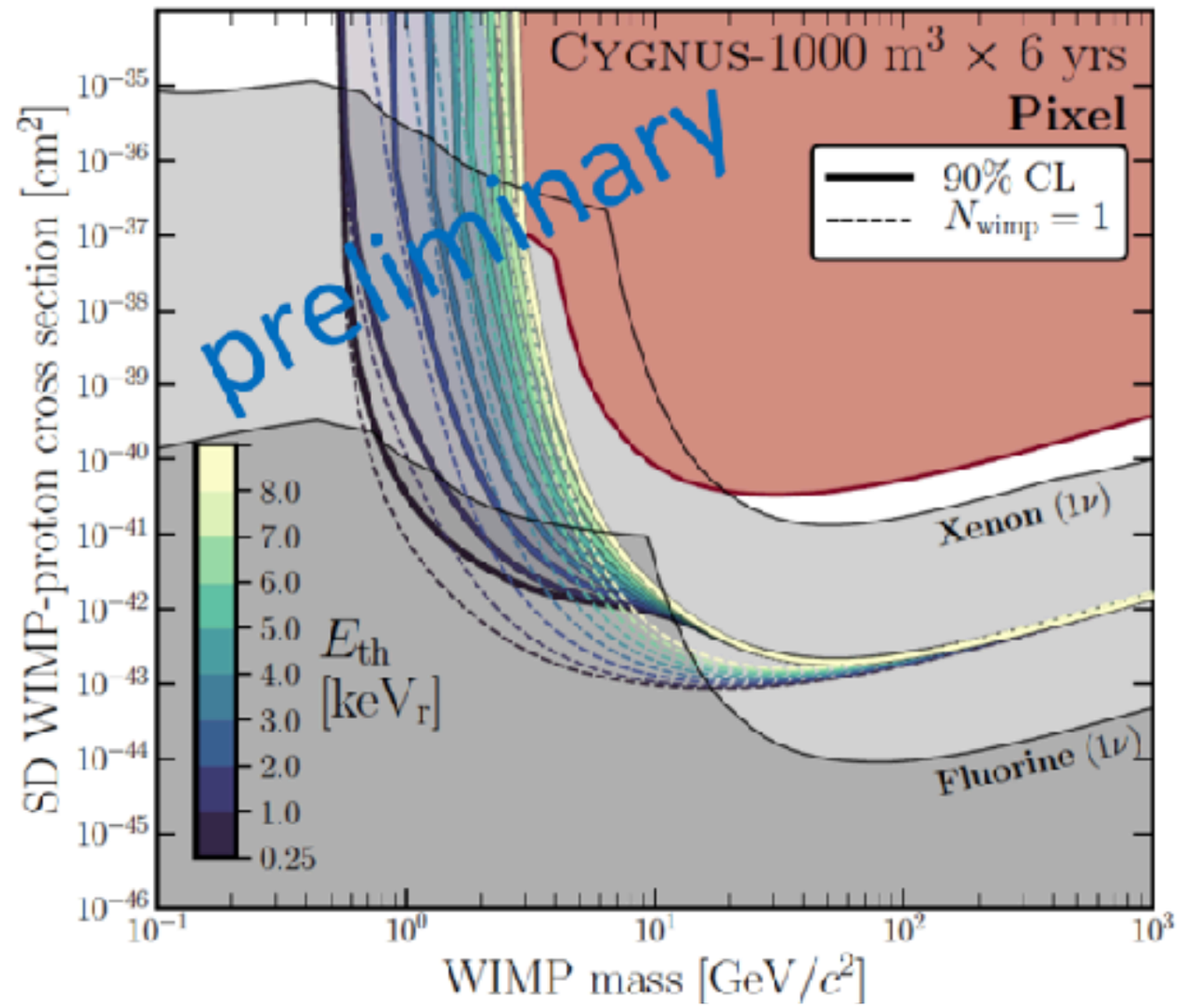
CYGNUS SI & SD sensitivity

CYGNUS 1000: 10m x 10m x 10m

$He+SF_6$ 755+5

Ciaran O'Hare





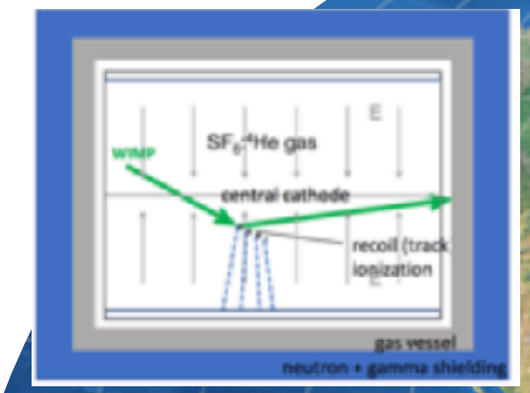
Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

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

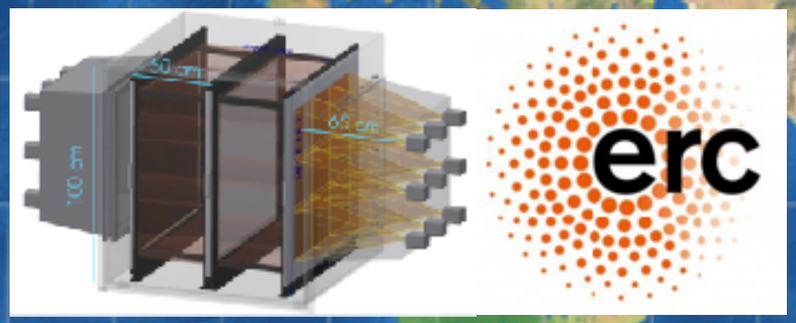
Low energy reach strongly dependent on electron rejection

CYGNUS projects in the world

CYGNUS-10
10 m³, GEMs + wires
He:SF_6
Boulby, UK



CYGNUS-HD10
GEMs + 2D strips
He:CF_4:C_4H_{10}
SURF, USA



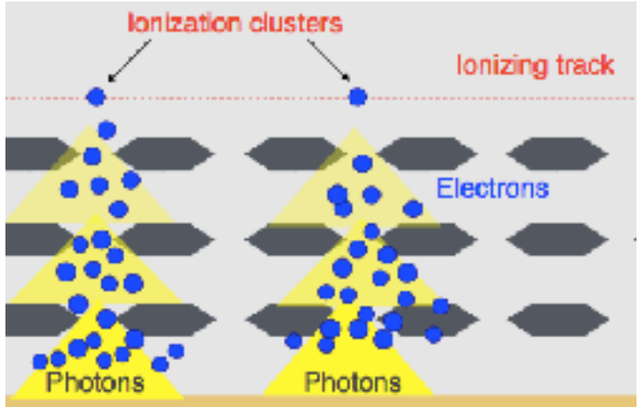
CYGNO/INITIUM
GEMs + sCMOS + PMT
He:CF_4 (:SF_6)
LNGS, Italy
1 m³ demonstrator
funded towards 30 m³
detector

CYGNUS-KM
1 m³, GEMs + 2D strips
SF_6/CF_4
Kamioka, Japan

CYGNUS-OZ
Stawell, Australia
GEMs + CCDs

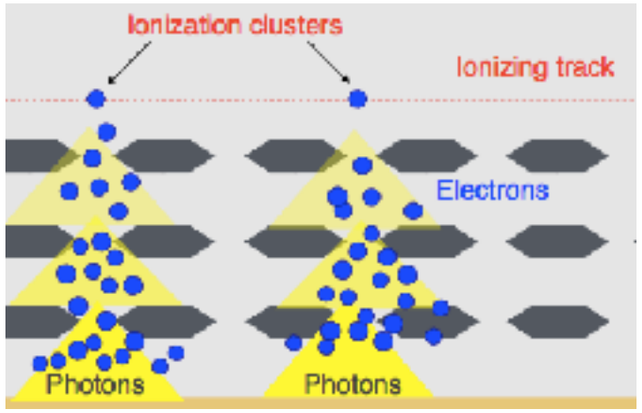
3D optical readout

CYGNO: GEMs + sCMOS + PMT



3D optical readout

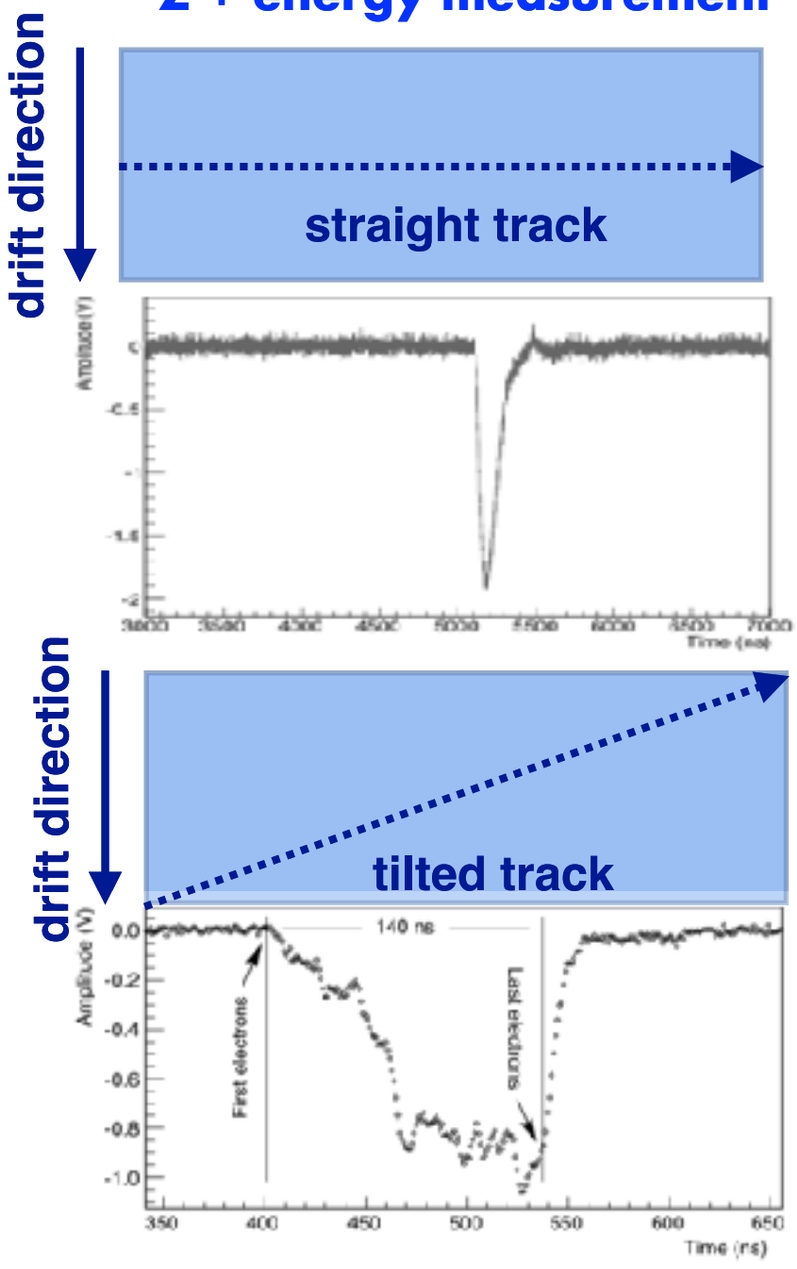
CYGNO: GEMs + sCMOS + PMT



PMT:

integrated

Z + energy measurement



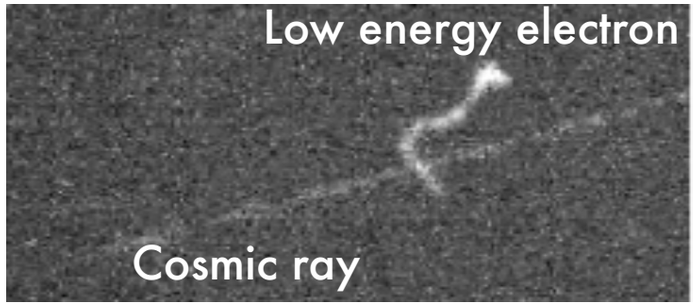
3D optical readout

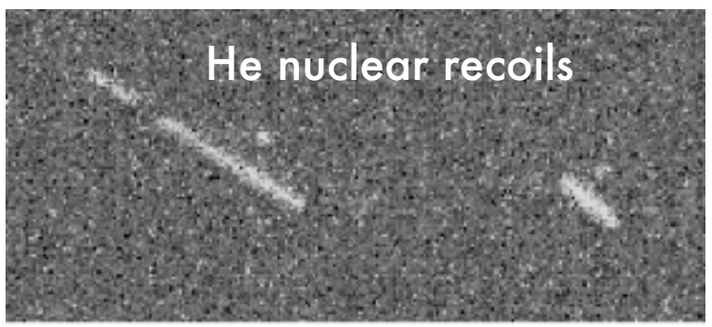
CYGNO: GEMs + sCMOS + PMT

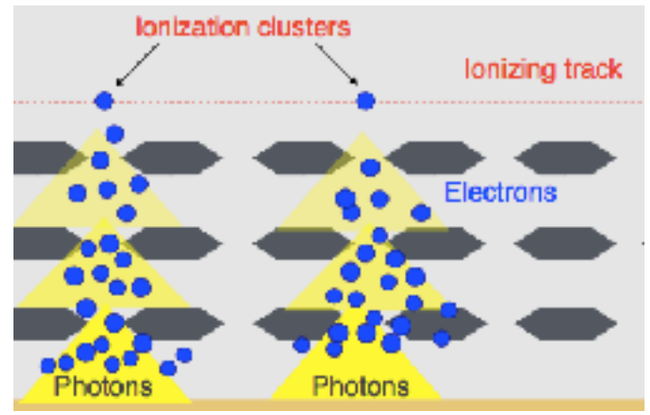
sCMOS:

high granularity

X-Y + energy measurements



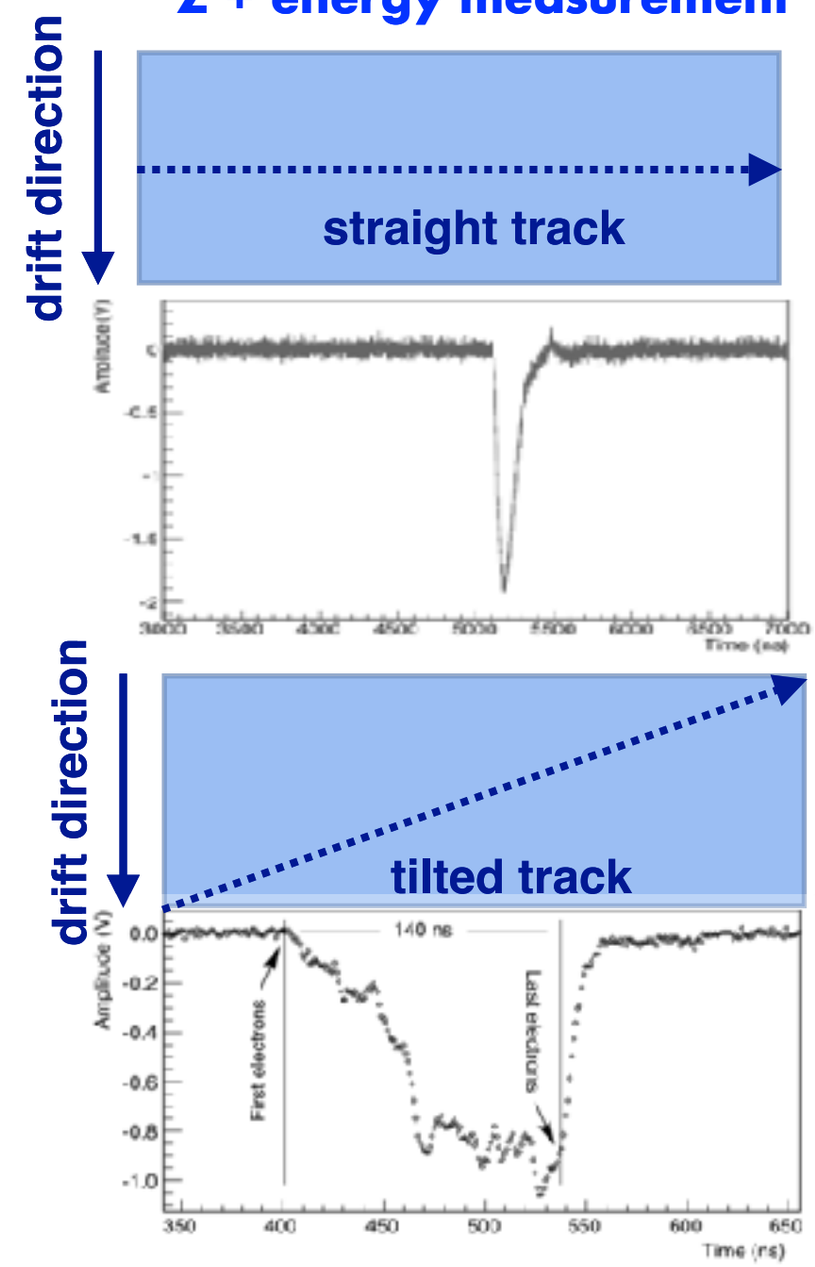




PMT:

integrated

Z + energy measurement



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

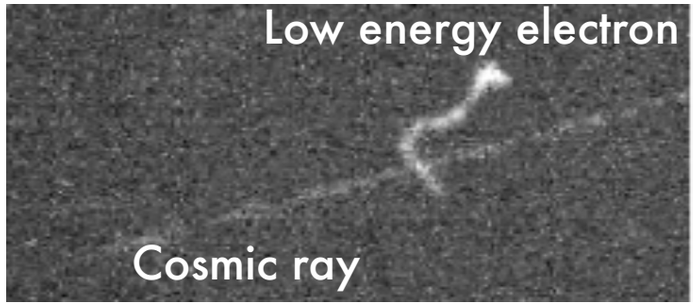
3D optical readout

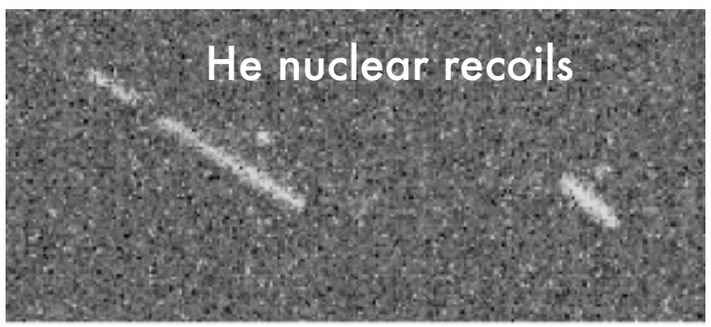
CYGNO: GEMs + sCMOS + PMT

sCMOS:

high granularity

X-Y + energy measurements





- **1/3 noise w.r.t. CCDs**
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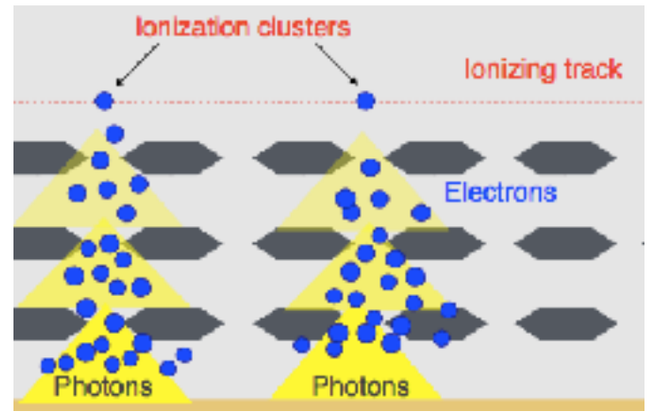
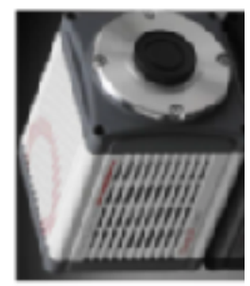
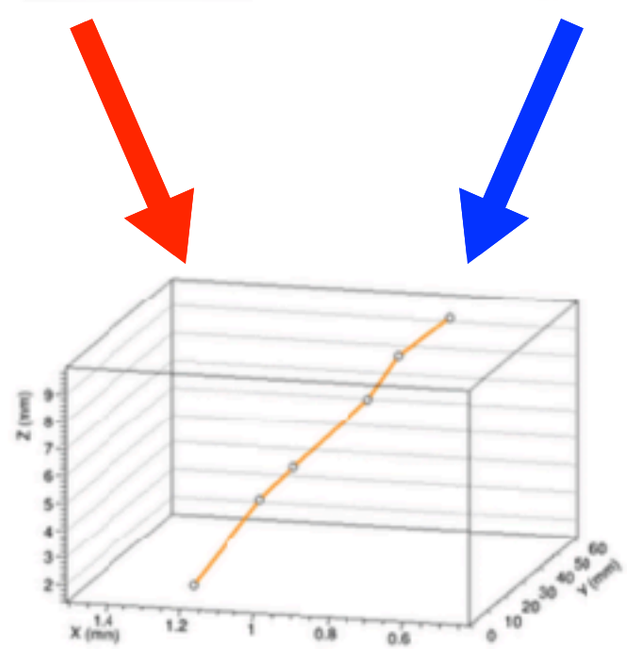
JINST 13 (2018) no.05, P05001



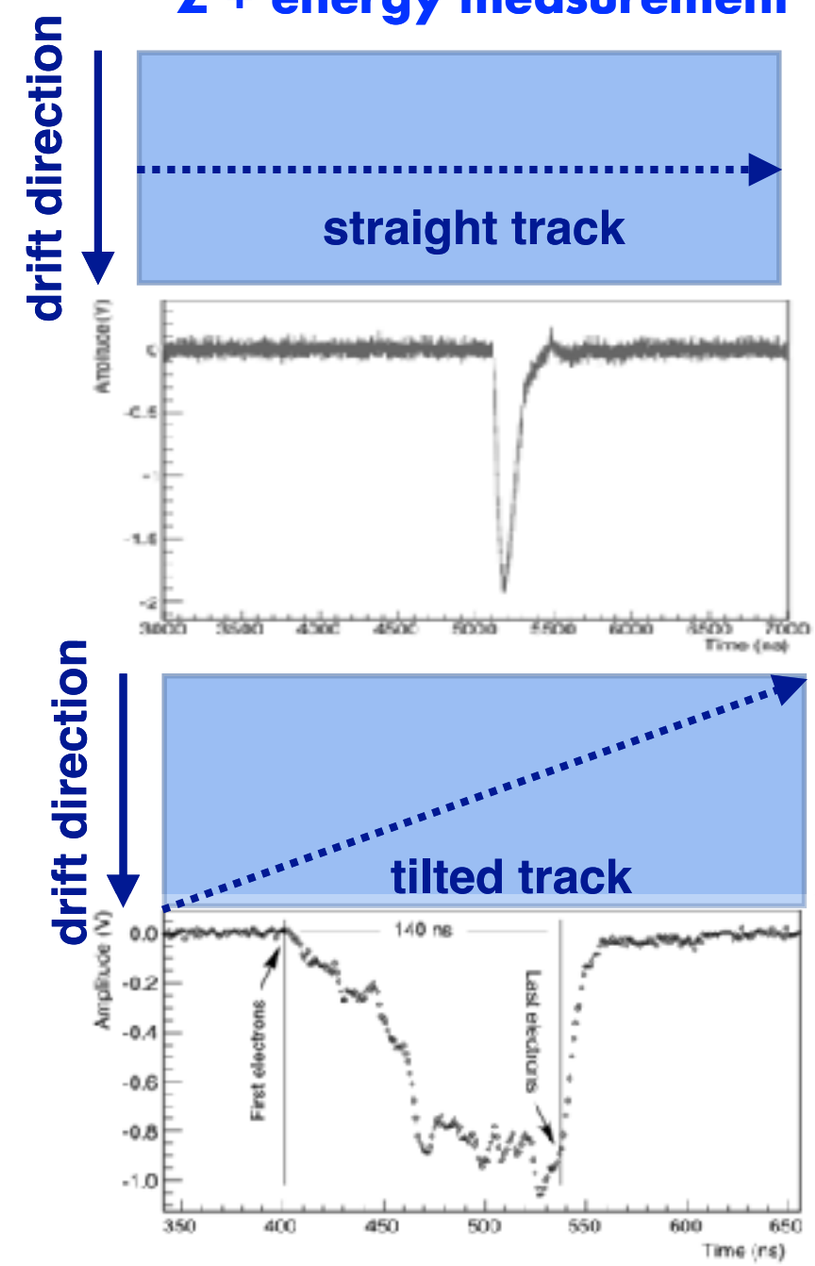




PMT:

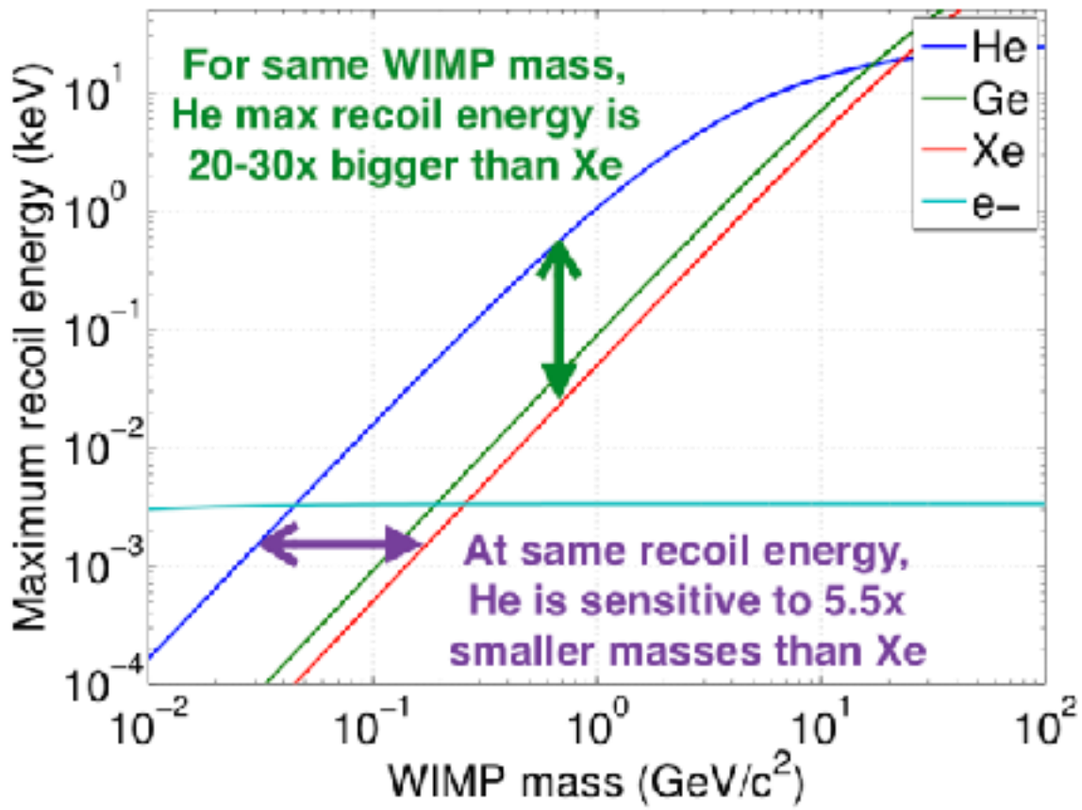
integrated

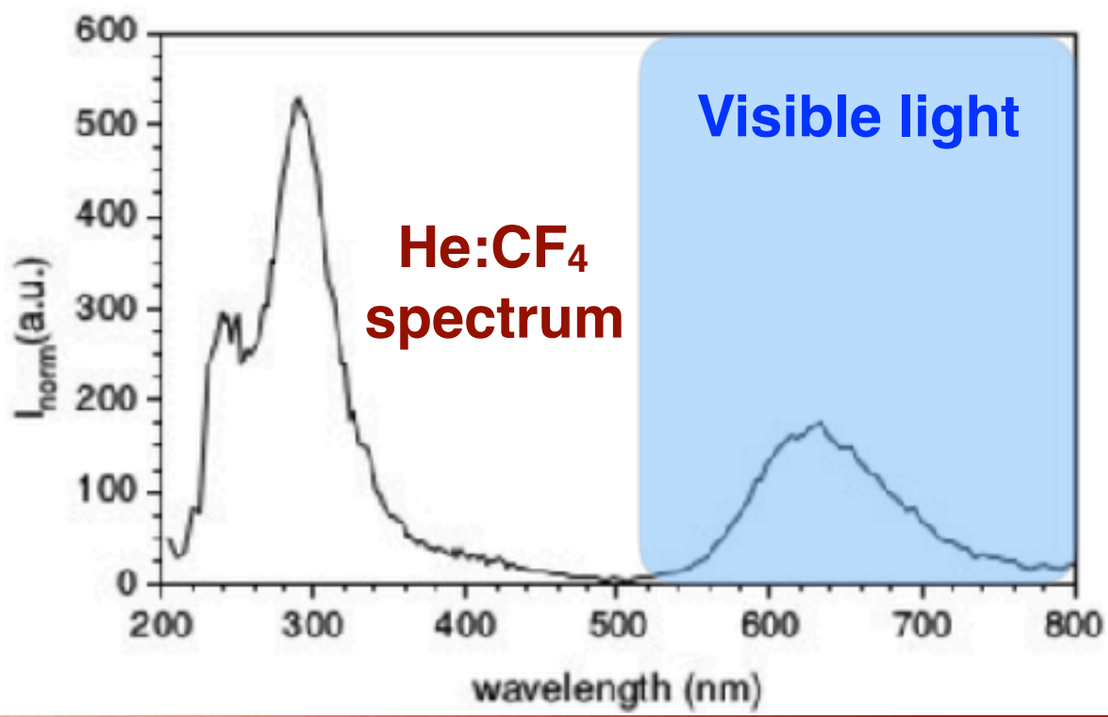
Z + energy measurement



O(100) um 3D tracking with high quality particle identification (PID)

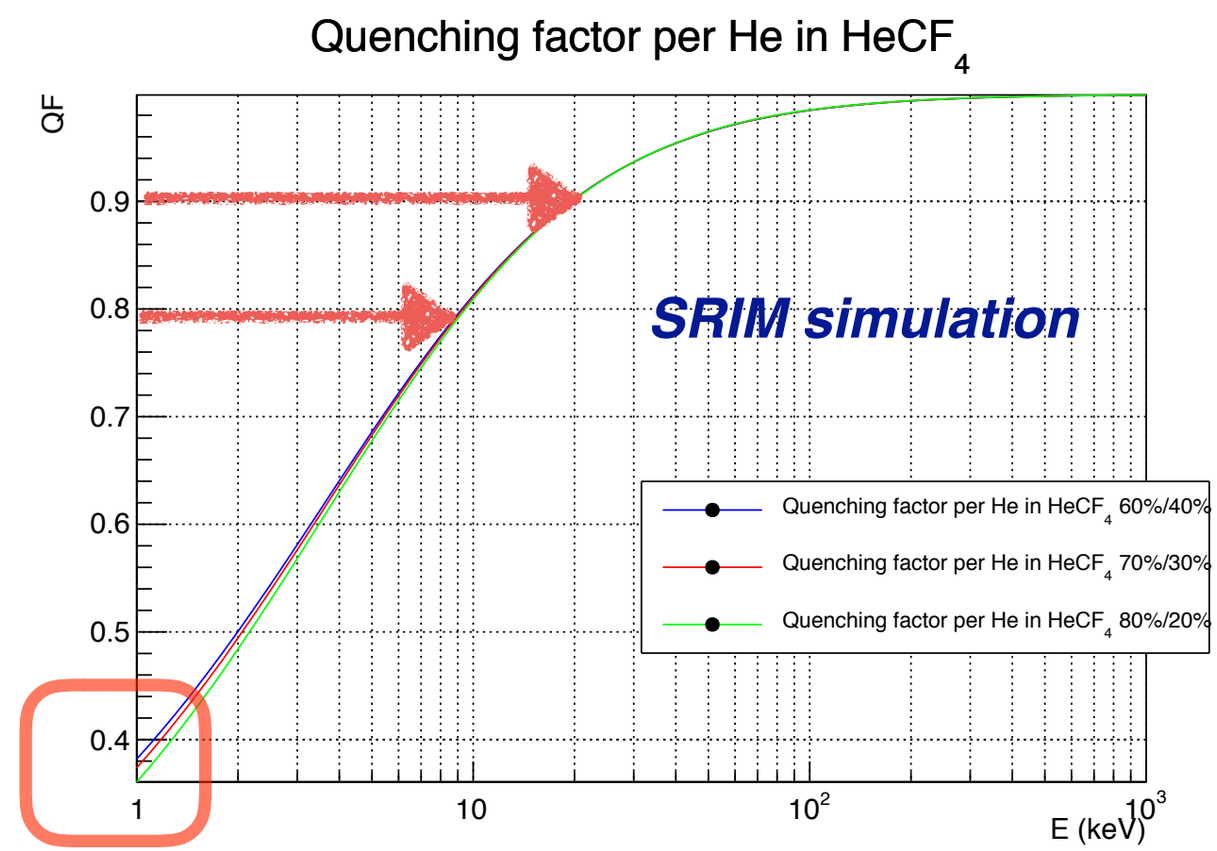
He & CF_4: choose the content of your gas target wisely



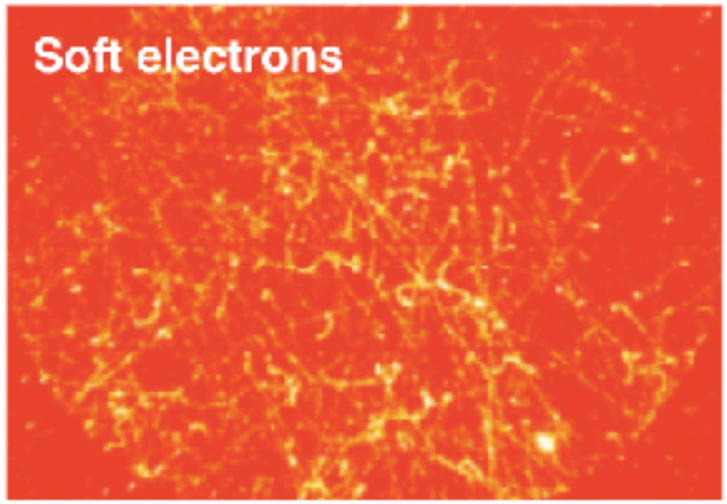


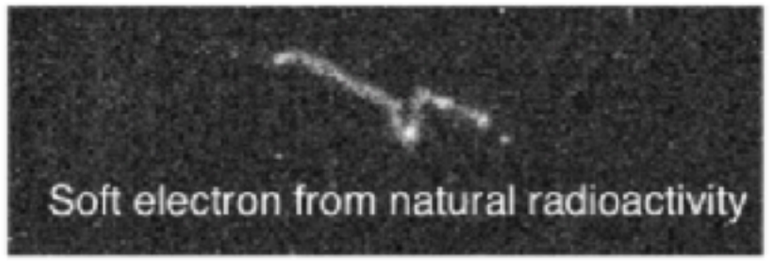
He:CF_4 gas mixture at ATMOSPHERIC PRESSURE

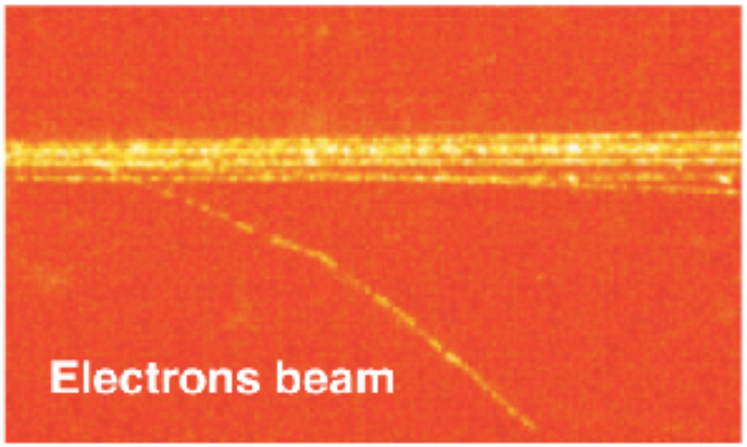
Sensitive to both SI & SD interactions

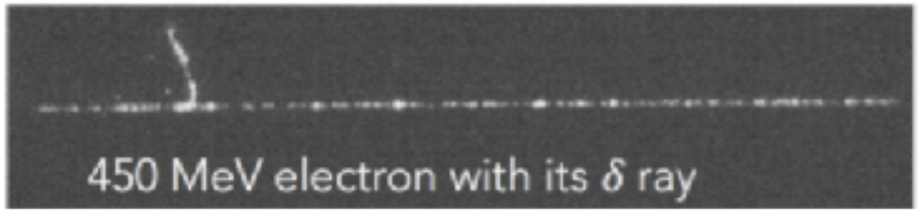


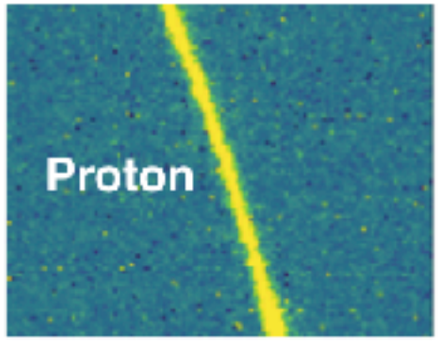
CYGNO: photographing tracks

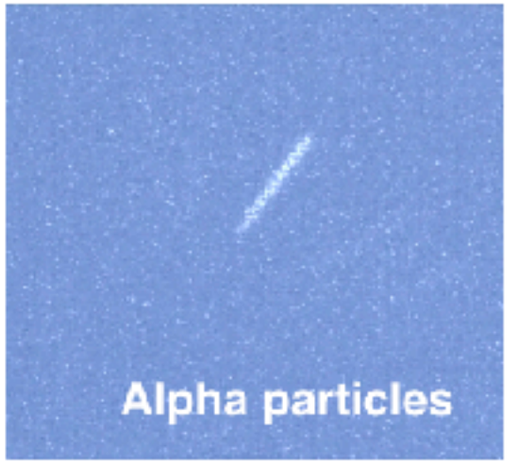


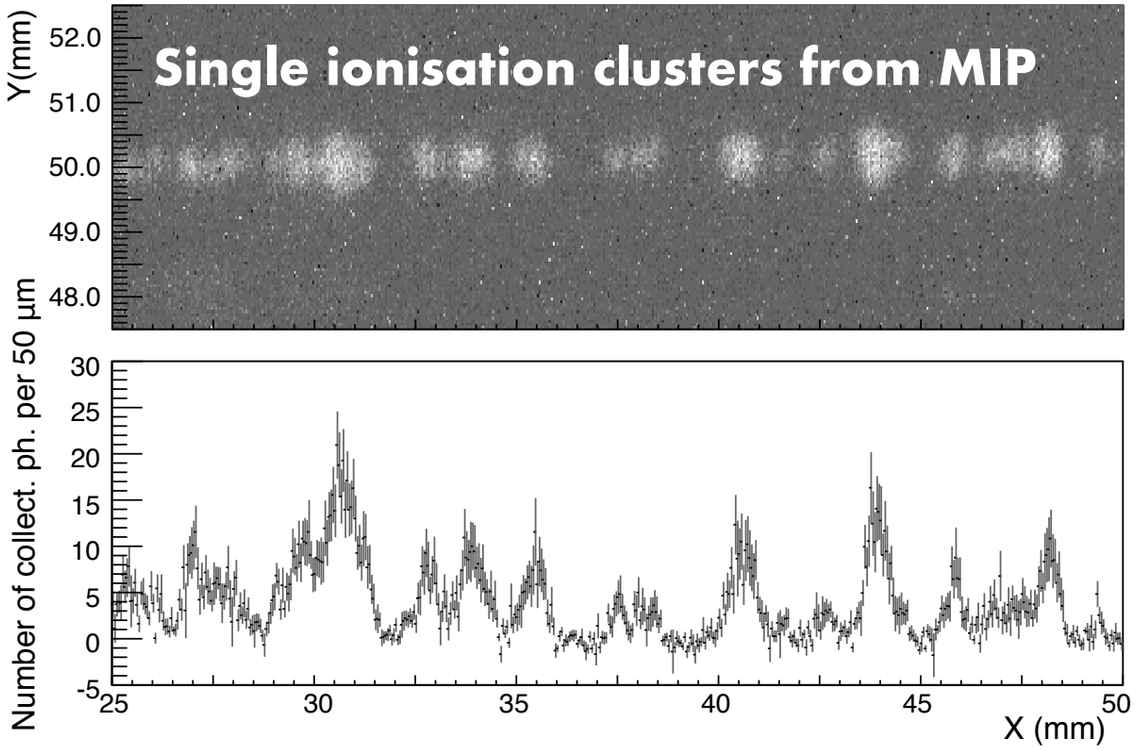


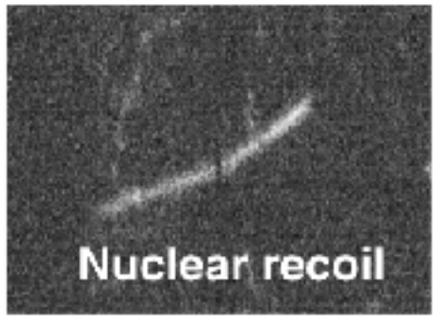


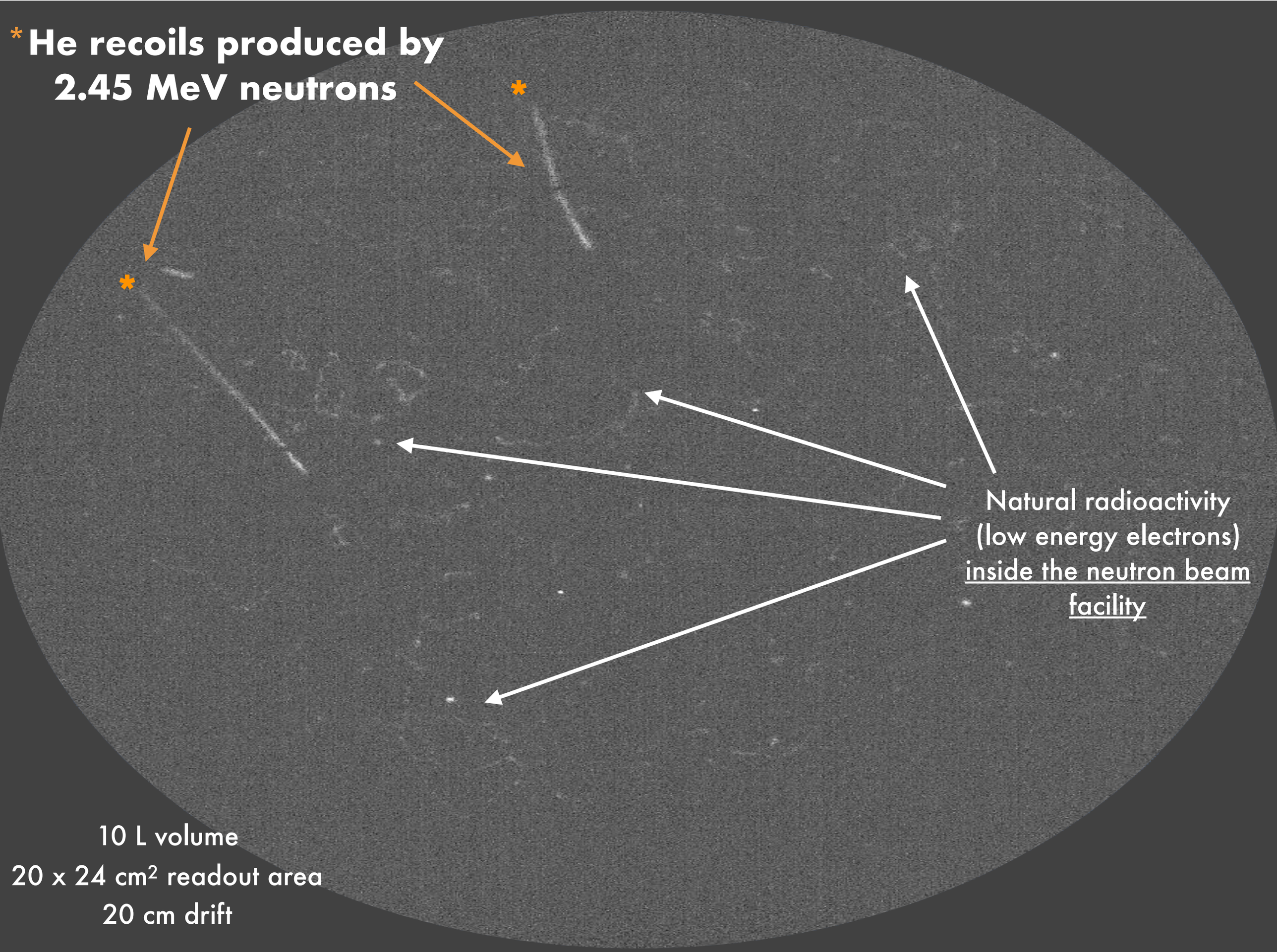











*He recoils produced by
2.45 MeV neutrons
*
*
Natural radioactivity
(low energy electrons)
inside the neutron beam
facility
10 L volume
20 x 24 cm² readout area
20 cm drift

CYGNO: photographing ourselves

#socialdetector #infn

https://web.infn.it/cygnus

3D optical readout
CYGNO roadmap

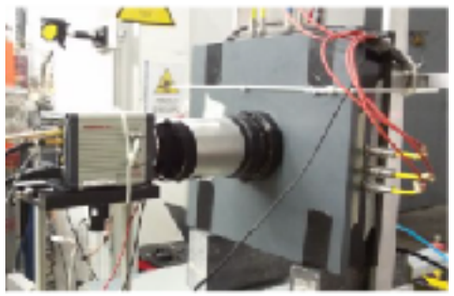
CYGNUS_RD | PHASE_0 | PHASE_1 | PHASE_2

2015 | 201 | 2018 | 2019 | 2020 | 2021 | 2022 | …

Electron drift

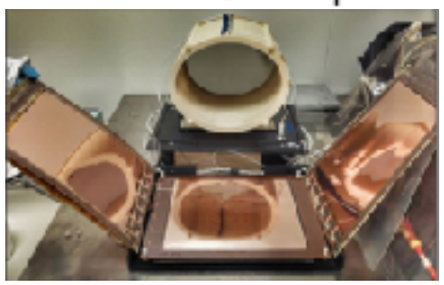
He:CF$_4$
1 atm

100 cm³ — ORANGE



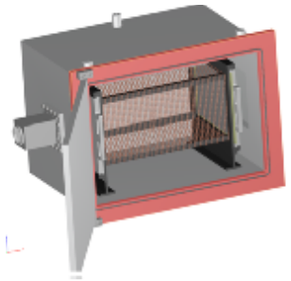
1 sCMOS
10 x 10 cm² area

@ RO… — 0.01 m³ — LEMON



1 sCMOS
20 x 24 cm² area

@ LNF — 0.05 m³ — LIME



1 sCMOS
33 x 33 cm² area

@ LNF — Construction & test

@ LNGS — Installation & data taking

PHASE_0 funded by INFN

He:CF$_4$:SF$_6$
0.8-1 atm

Negative ion drift

4 Timepix chips
3 x 3 cm² area

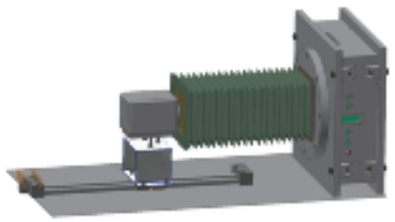
NITEC

50 cm³

2015 | 2016 | 2017 | 2018

1 sCMOS
10 x 10 cm² area

MANGO

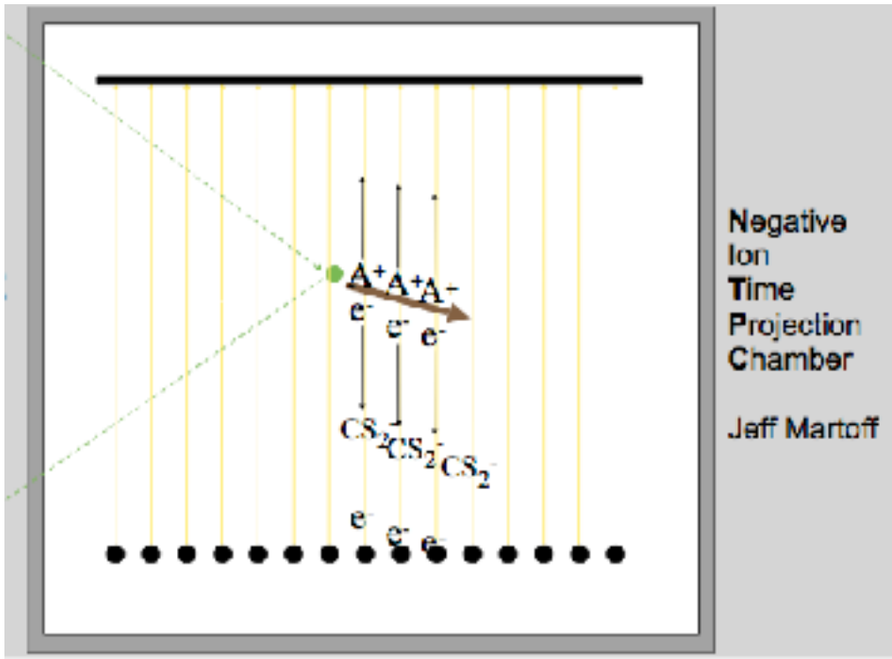


500 cm³ — @ LN…

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

Negative ion drift operation

Reduced diffusion = improved tracking



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

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

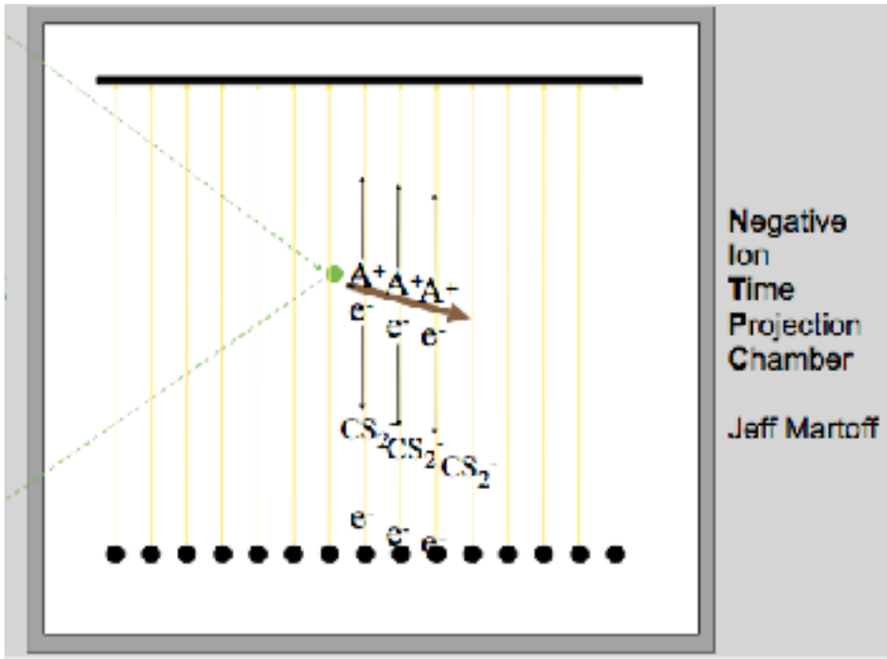
low diffusion increases active volume per readout area

T. Ohnuki et al., NIM A 463

J. Martoff et al., NIM A 440 355

Negative ion drift operation

Reduced diffusion = improved tracking



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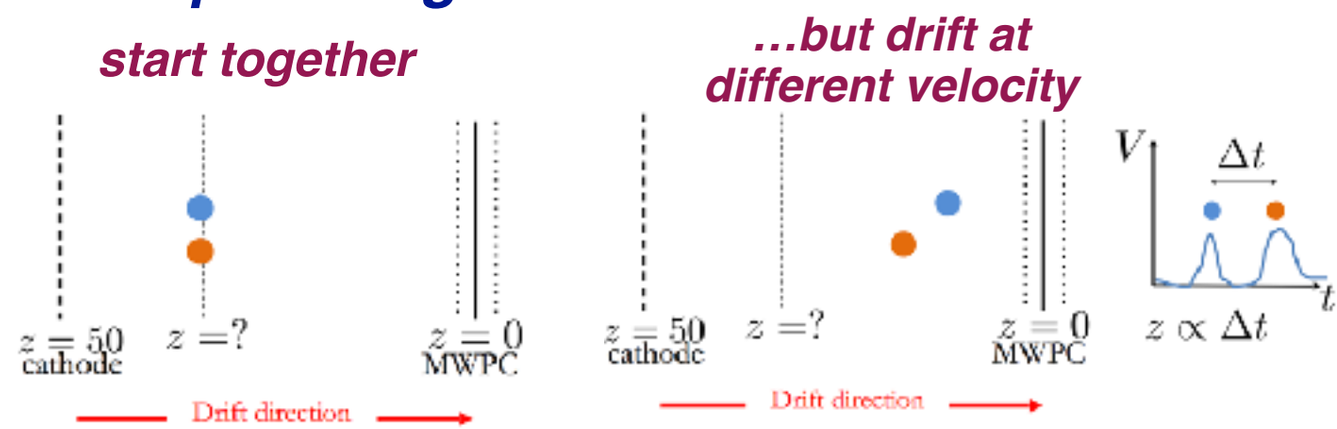
low diffusion increases active volume per readout area

T. Ohnuki et al., NIM A 463

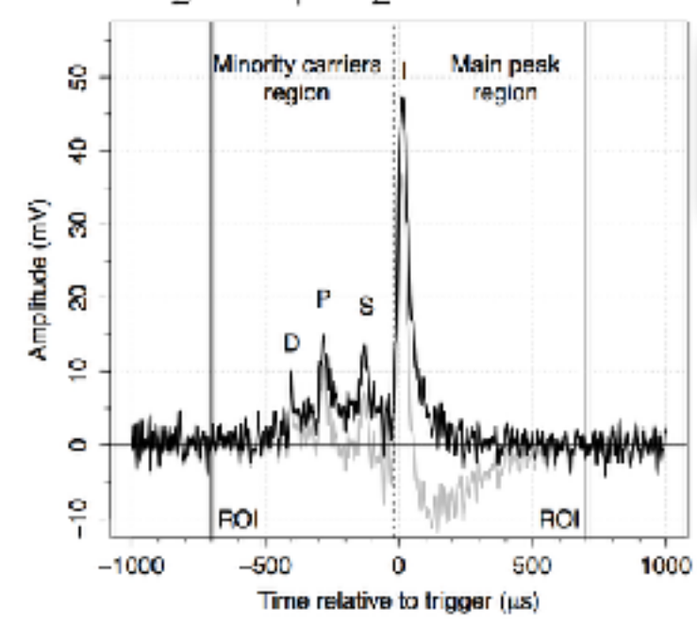
J. Martoff et al., NIM A 440 355

Multiple charge carriers = fiducialization!!



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

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



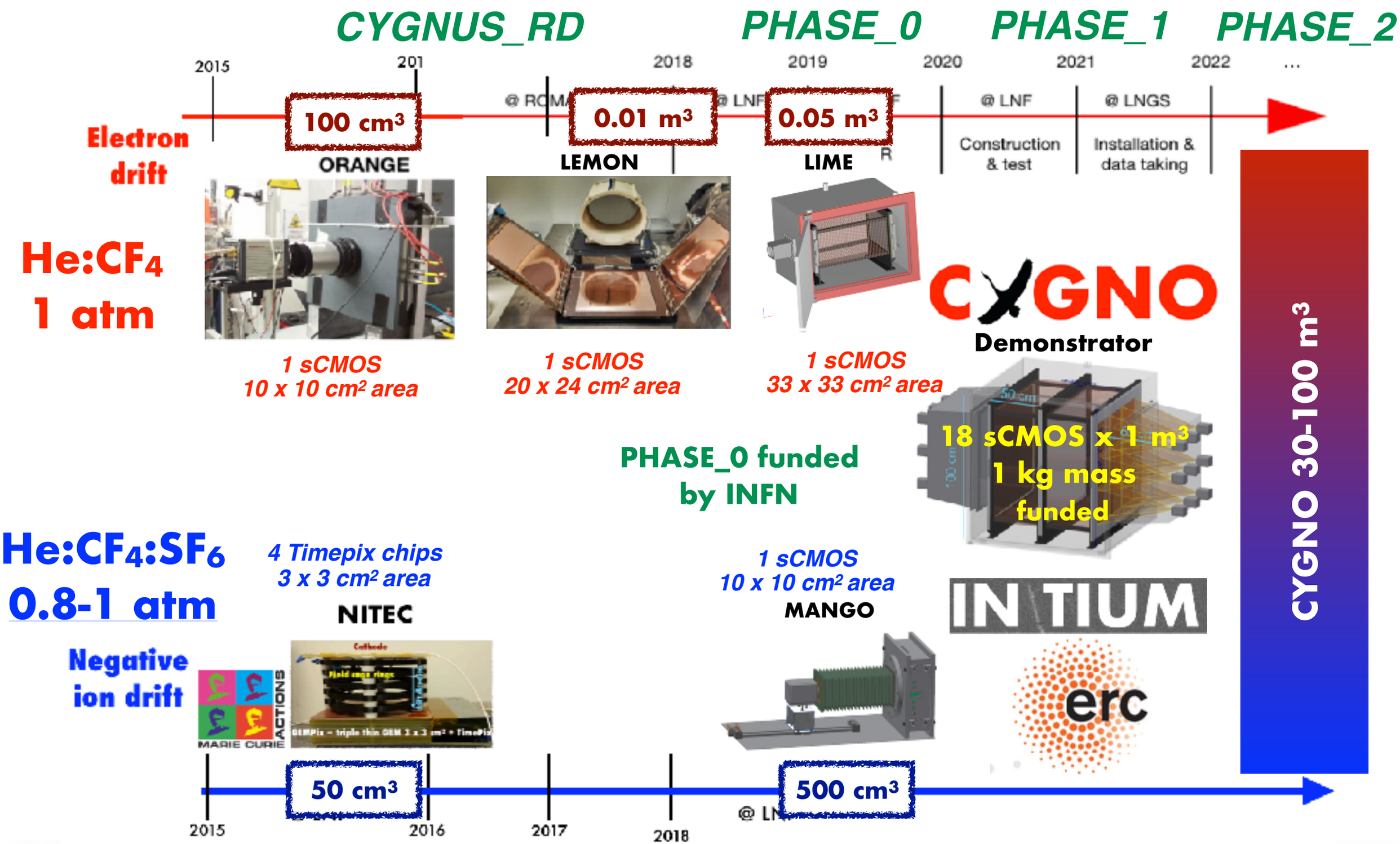
D. Snowden-Ifft, Rev. Sci. Instrum. 85 (2014) 013303

DRIFT

From 2015 available also with non-toxic, easy to handle, good DM target as SF_6

3D optical readout with negative ion drift

CYGNO roadmap & synergy with INTIUM



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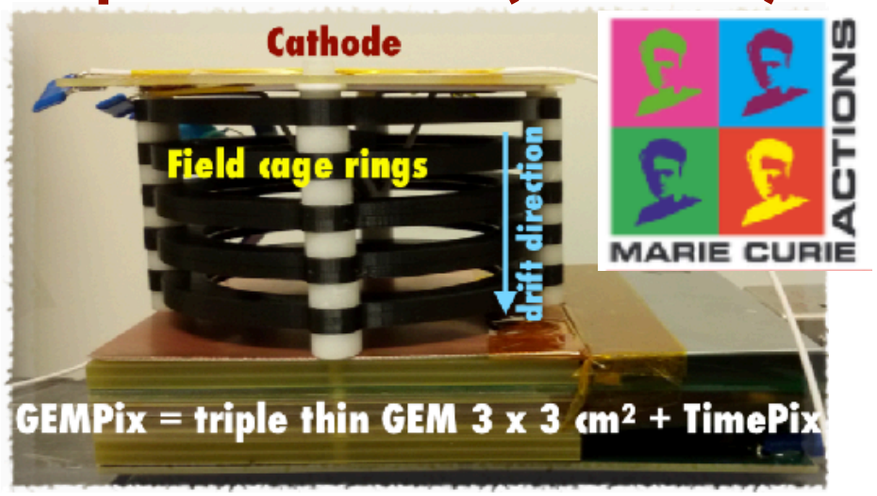
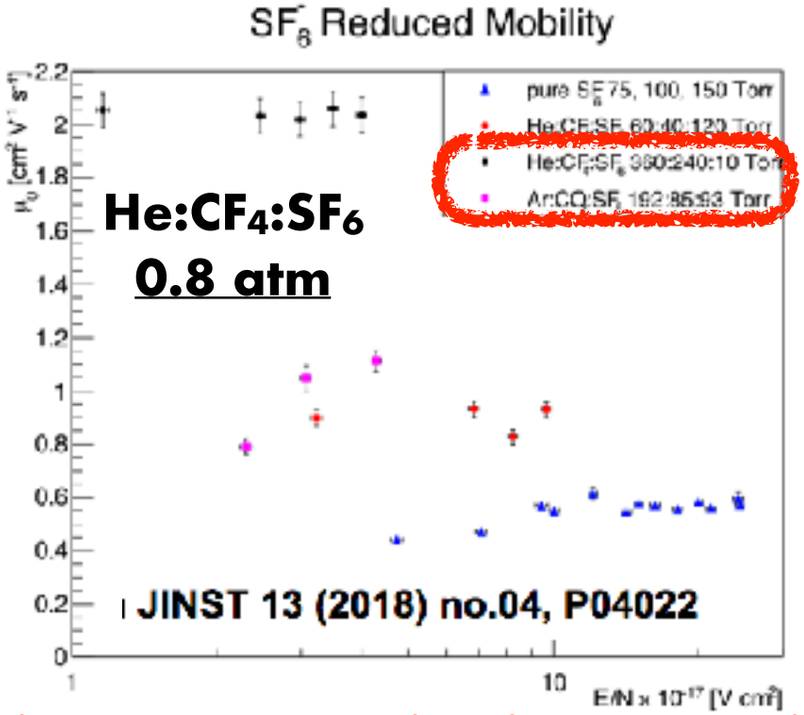
NITEC: a Negative Ion Time Expansion Chamber (2015-2016)





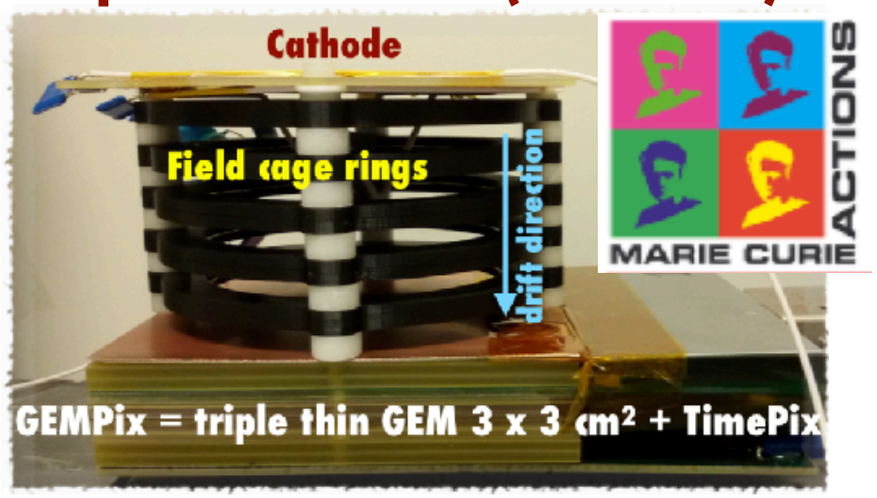
Opened the doors for a realistic development of NITPC at 1 bar with SF_6

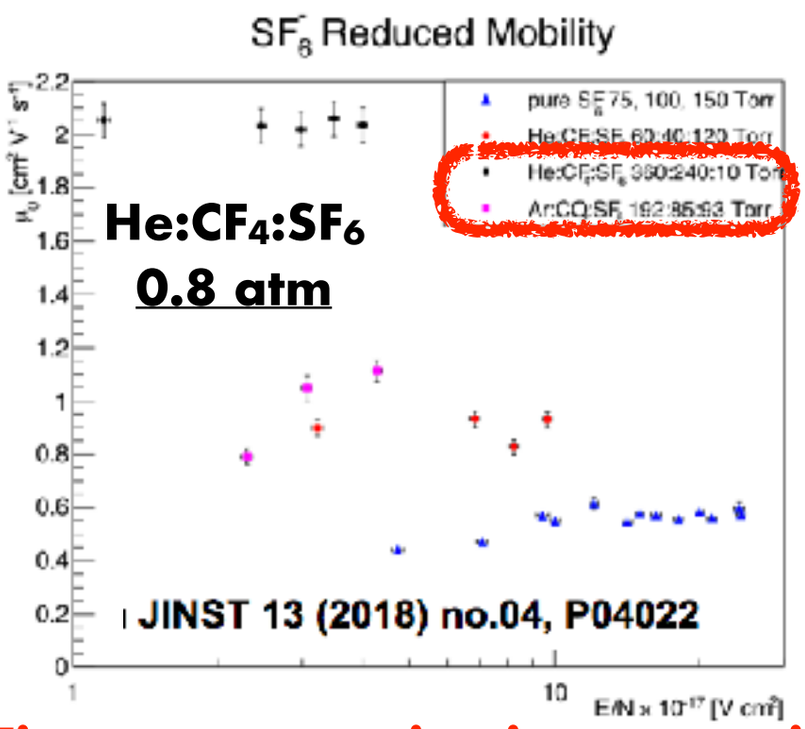
First ever negative ion operation at nearly atmospheric pressure with SF_6

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

CYGNO IN TIUM synergy

NITEC: a Negative Ion Time Expansion Chamber (2015-2016)





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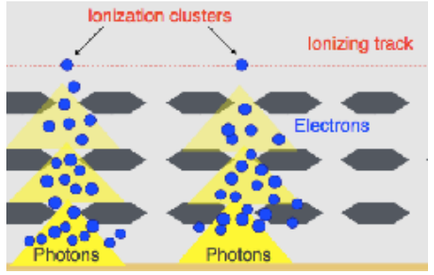
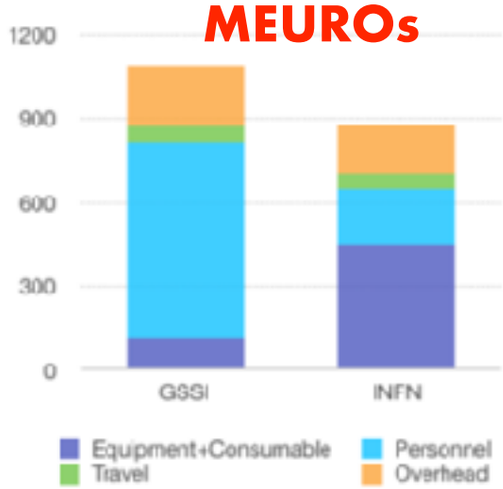


3D optical readout with negative ion drift demonstrator towards the development of 100-1000 m³ directional DM detector (i.e. CYGNO PHASE_2)

±80% He ±19% CF_4 ±1% SF_6

Funded with 2 MEUROs



European Research Council

Supporting top researchers from anywhere in the world

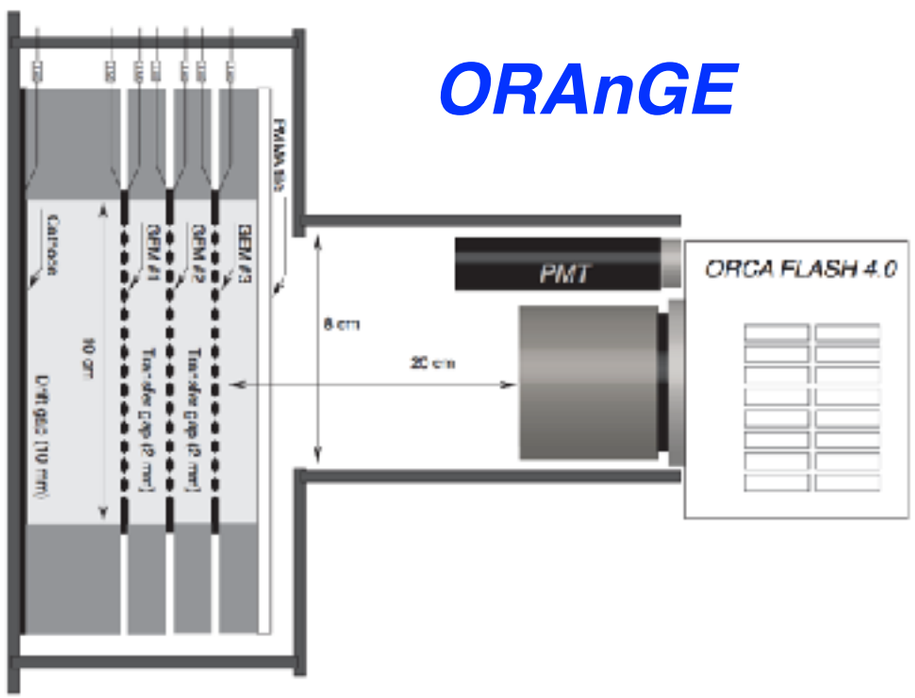
This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the Marie Sklodowska-Curie grant agreement No 657751 and from the European Research Council (ERC) grant agreement No 818744

CYGNUS-RD project (2016-2018)

JINST 13 (2018) no.05, P05001

10 x 10 x 1 cm^3
0.1 Liters
Triple thin GEMs
CMOS & PMT on same side

ORAnGE



ORANGE: small prototype

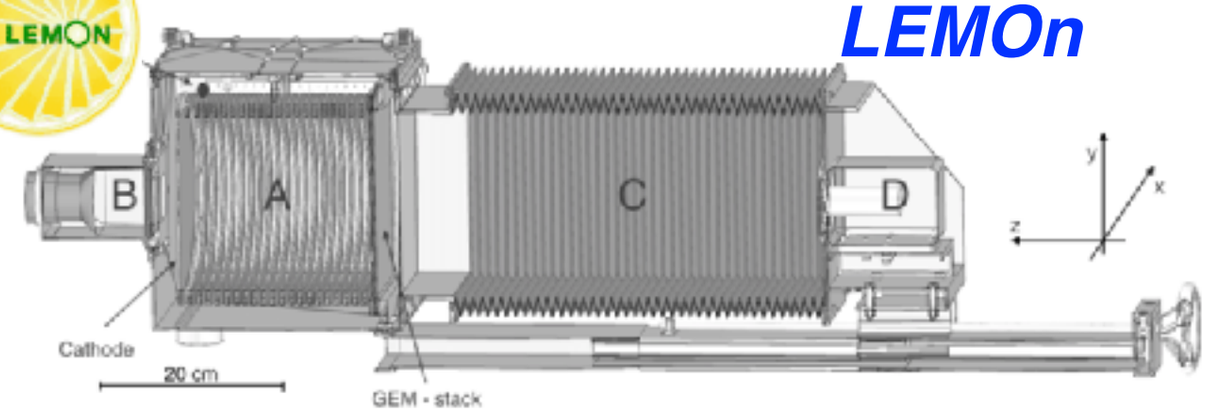
Optically ReAdout GEms

Camera distance ± 18 cm

PoS EPS-HEP2017 (2017) 077

24 x 20 x 20 cm^3
9.6 Liters
Triple thin GEMs
CMOS & PMT on opposite sides

LEMOn



- 3D printed gas box
- 3D printed field cage with metallic rings
- semi-transparent cathode (wire mesh)

(A) Field Cage
(B) PMT
(C) Adaptable bellow
(D) CMOS camera

LEMOn: large prototype

Large Elliptical Module Optically readout

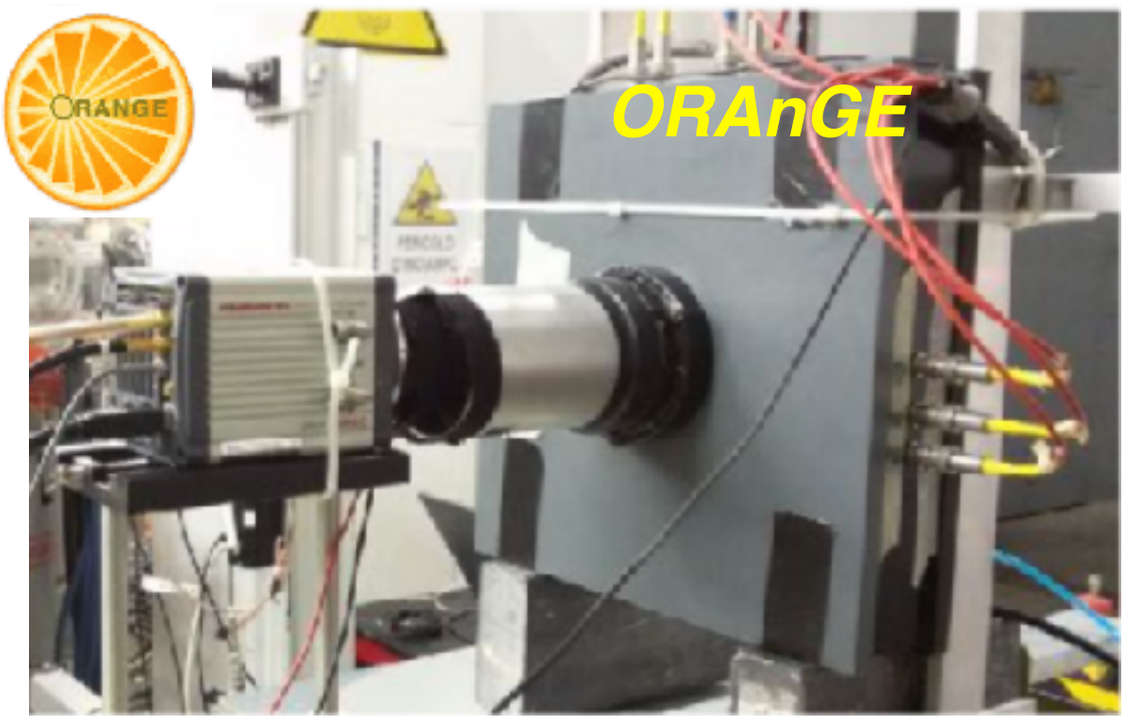
Camera distance ± 53 cm

Equipped with a suitable large aperture (f/0.95) and a short focal length (25 mm) lens

CYGNUS-RD project (2016-2018)

JINST 13 (2018) no.05, P05001

10 x 10 x 1 cm^3
0.1 Liters
Triple thin GEMs
CMOS & PMT on same side



PoS EPS-HEP2017 (2017) 077

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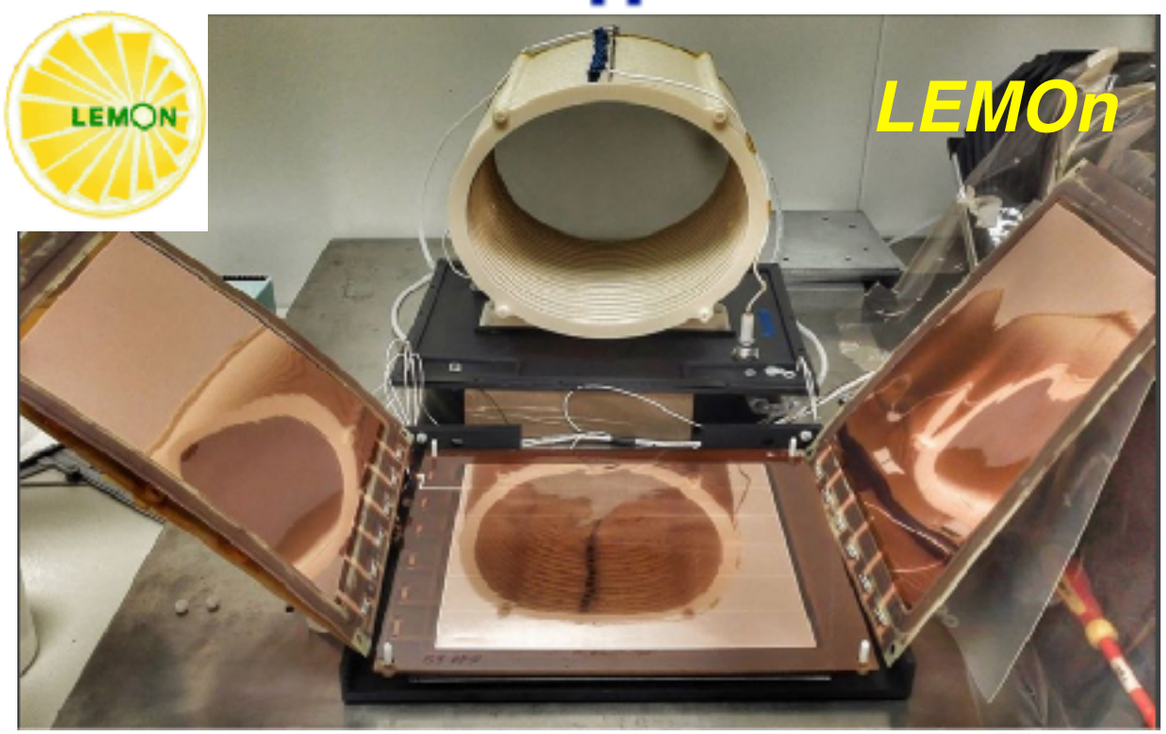
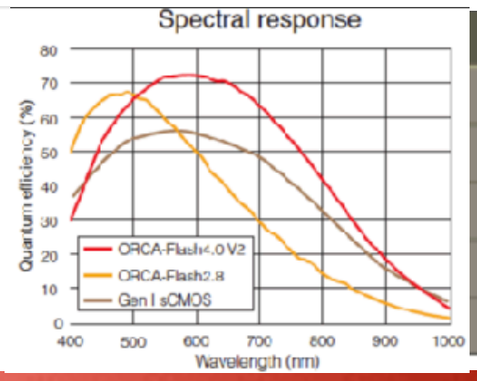


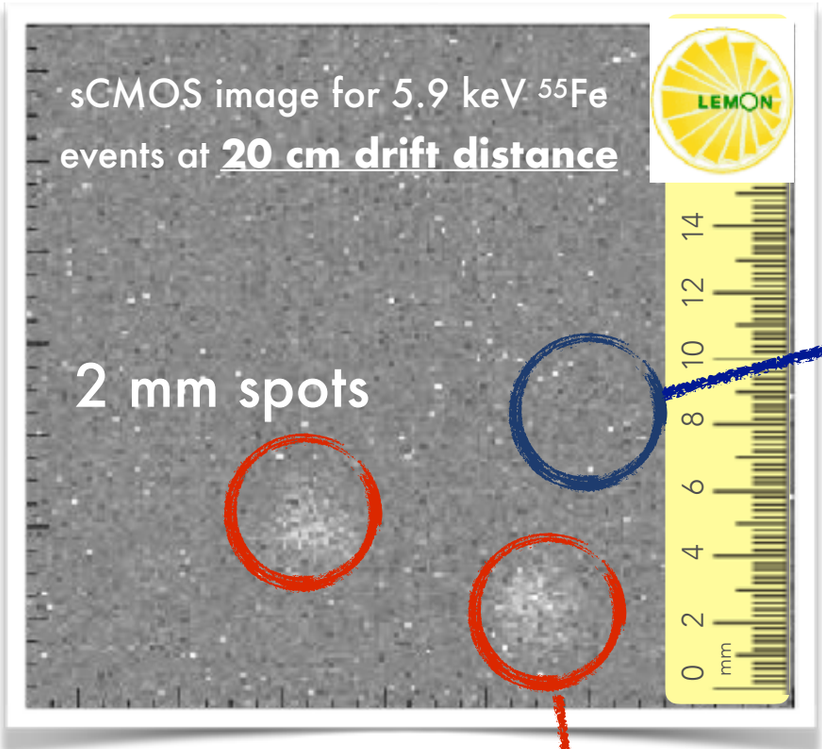


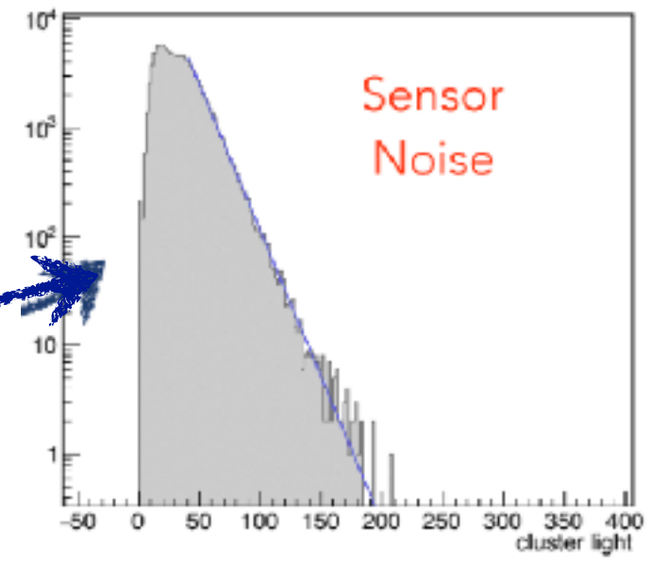
Hamamatsu Orca Flash V.3	
Pixels	2048 x 2048
Pixel size	6.5 μm
Eff. area	13.312 x 13.312 mm^2
Readout noise	1.4e RMS (slow scan mode, < 30 frame/s)
Resolution	16 bit

f/0.95 aperture, 25 mm focal length optics —> 160 μm pixel size at the object plane (GEM) @ 60 cm object distance

CYGNUS-RD developments toward CYGNO

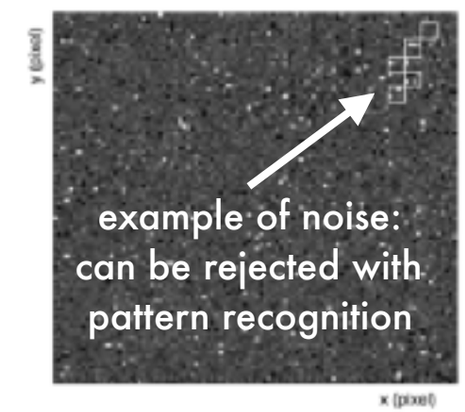
Deetction energy threshold @ 2 keV (conservative)





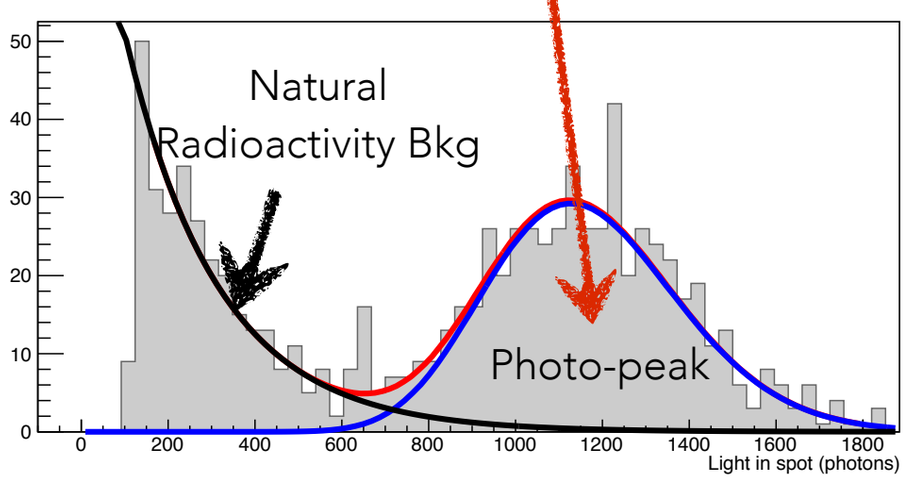
Exponential distribution for noise (slope ~ 16 photons).

With 400 ph. threshold (2 keV) : *fake rate 10 events/year per sCMOS sensor*

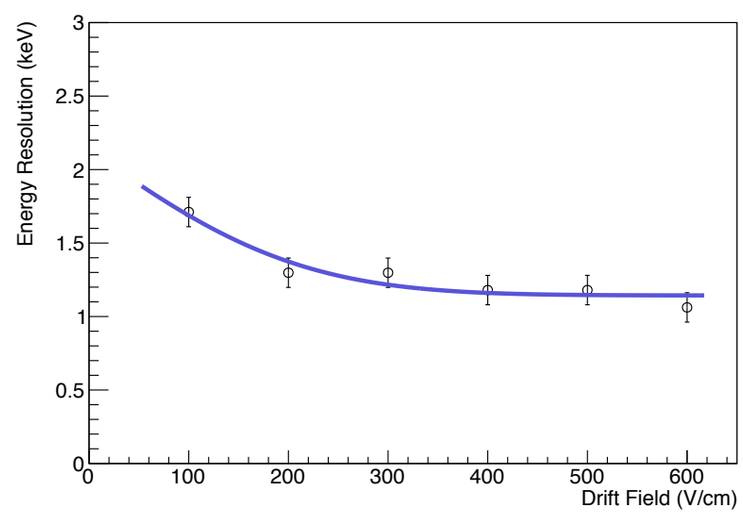


LEMON: 20 x 24 cm² readout area, with 20 cm drift

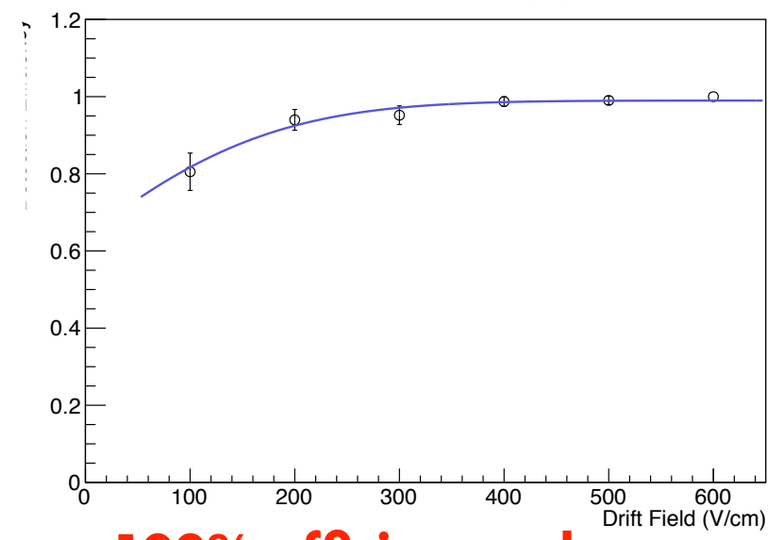
JINST 14 (2019) P07011



1 photon detected every 5 eV



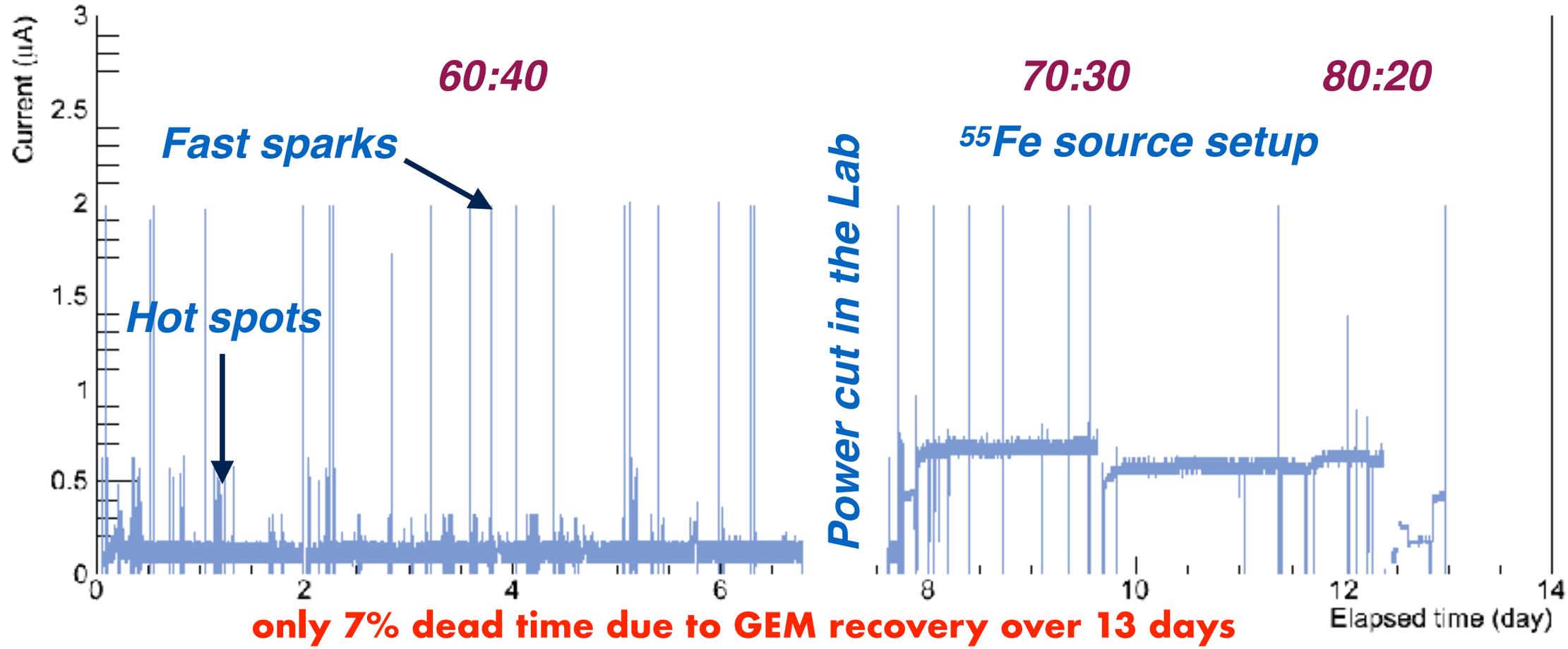
18% energy resolution @ 5.9 keV



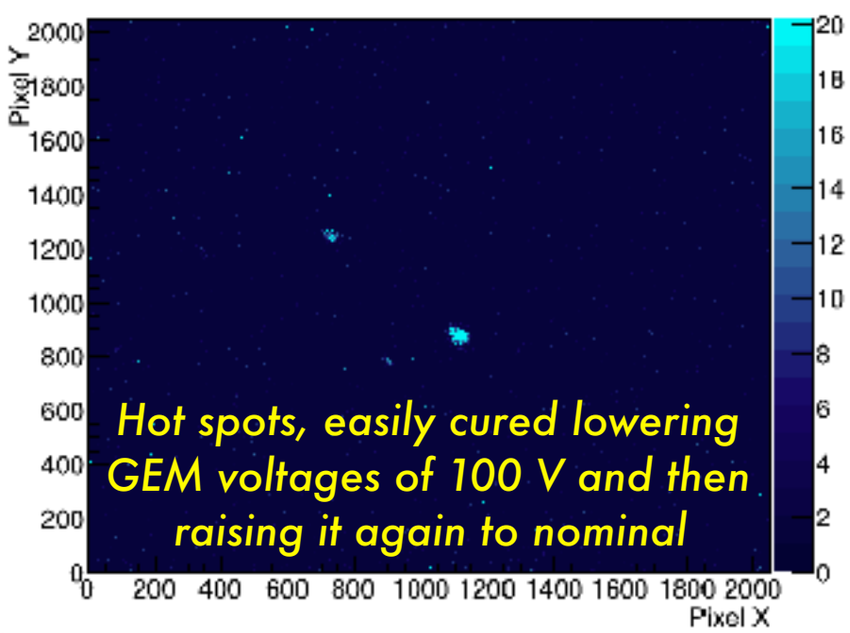
100% efficiency above 300 V/cm drift field

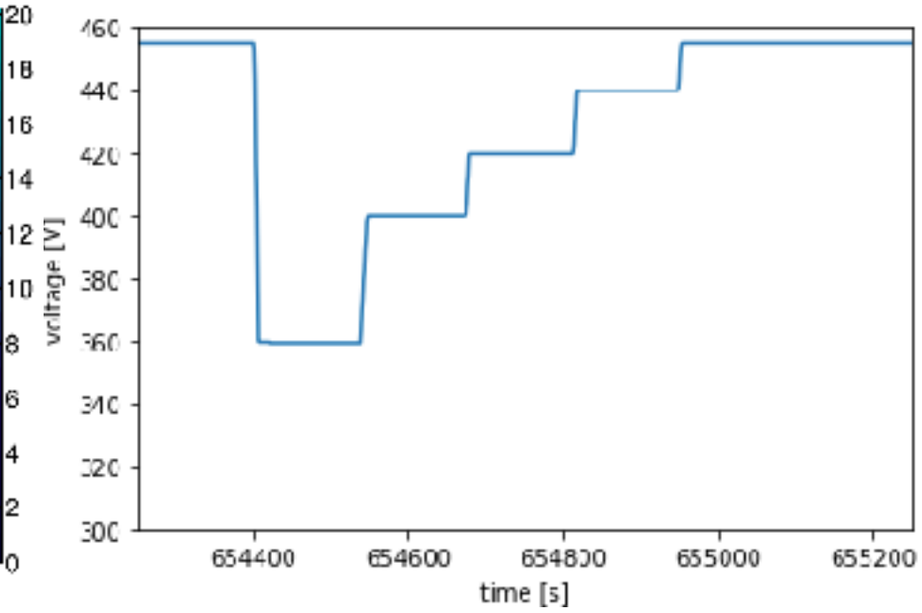
Large prototype stability test

1 atm
He:CF_4



only 7% dead time due to GEM recovery over 13 days



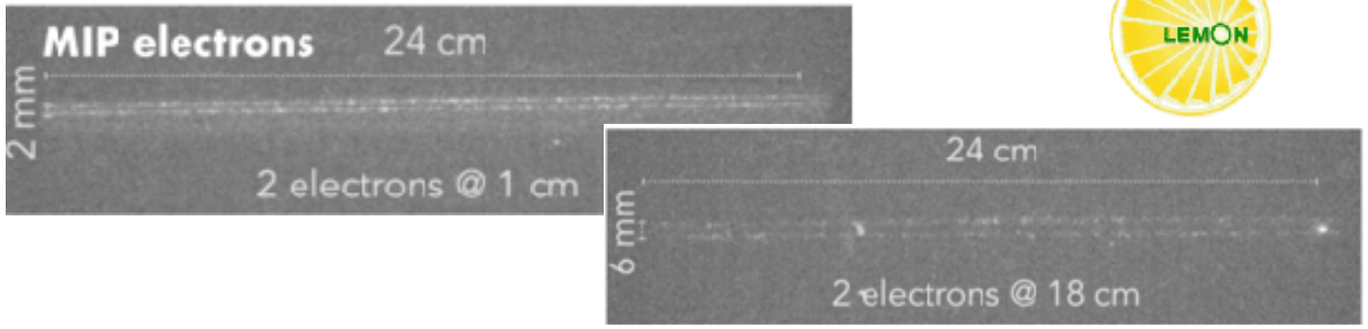


LEMOn (20 x 20 x 24 cm³) successfully operated for 13 consecutive days, with automatic GEM hot spots + trips recovery

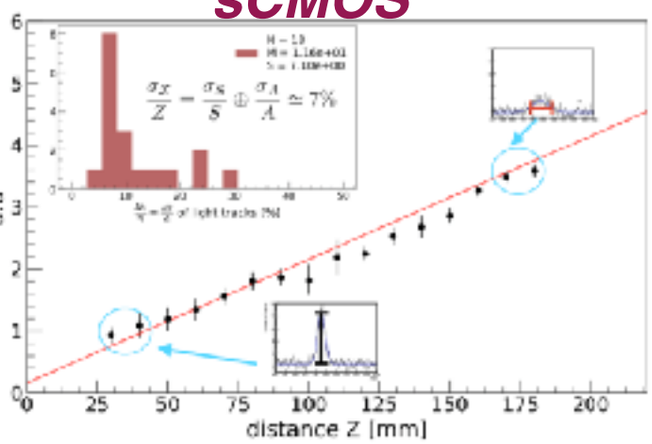
He:CF_4 1 atm

CYGNUS-RD developments toward CYGNO

absolute position measurement = background reduction through fiducialization with electron drift!!!

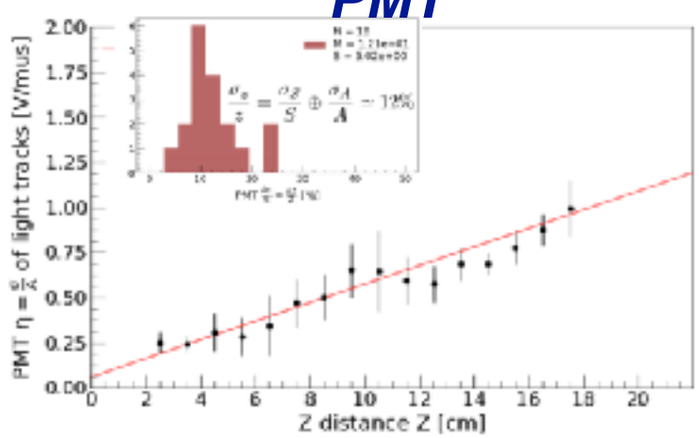


sCMOS



±2 cm resolution over 20 cm drift

PMT



±2 cm resolution over 20 cm drift

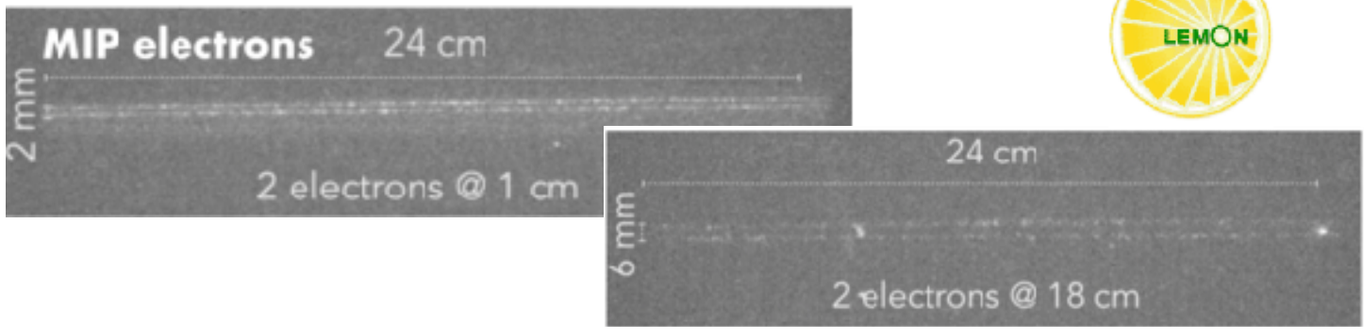
Light transverse profile of both sCMOS images and PMT waveforms sensitive to absolute Z position via fit to diffusion

NIM A 936 (2019) 453-455

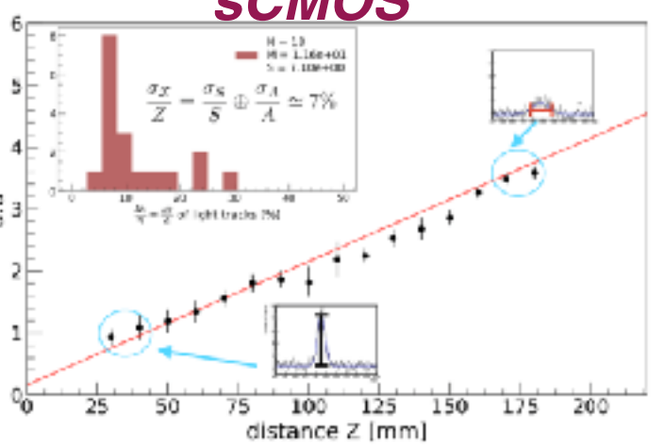
He:CF_4 1 atm

CYGNUS-RD developments toward CYGNO

absolute position measurement = background reduction through fiducialization with electron drift!!!

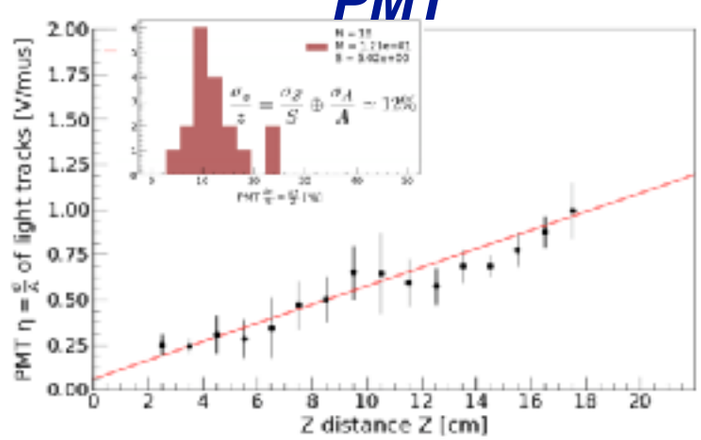


sCMOS



±2 cm resolution over 20 cm drift

PMT

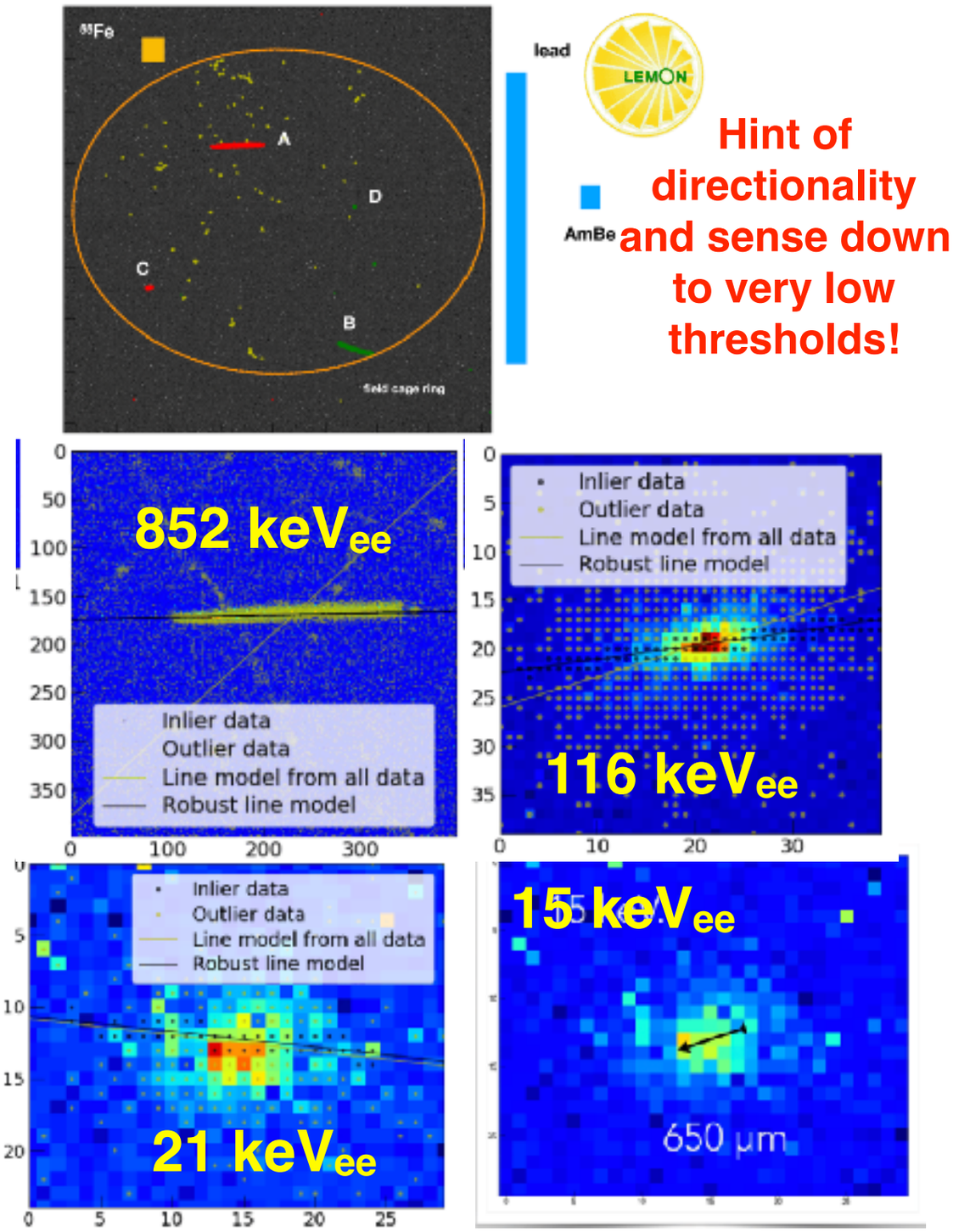


±2 cm resolution over 20 cm drift

Light transverse profile of both sCMOS images and PMT waveforms sensitive to absolute Z position via fit to diffusion

NIM A 936 (2019) 453-455

PRELIMINARY



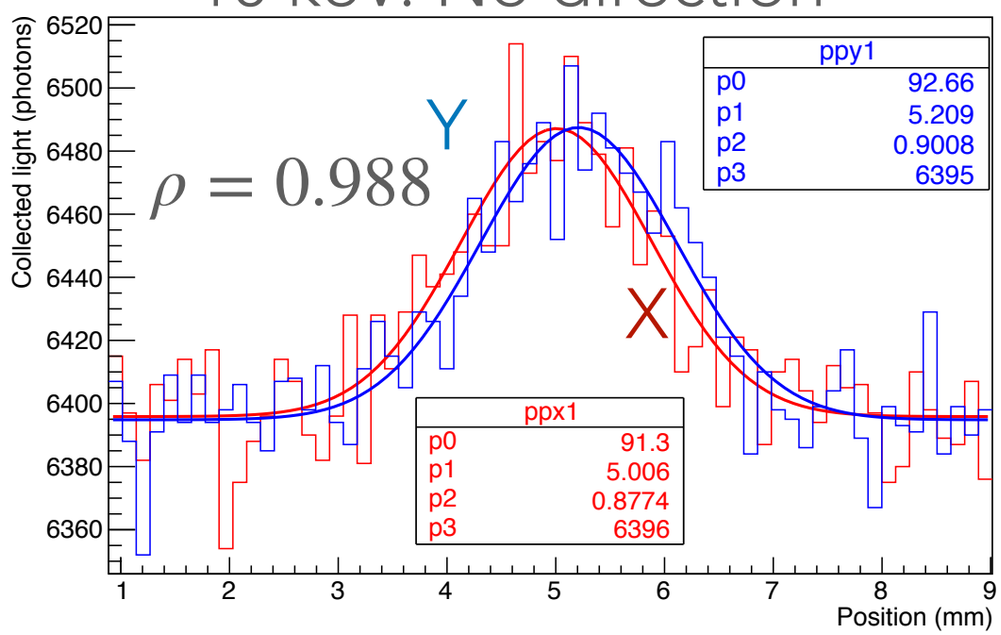
Hint of directionality and sense down to very low thresholds!

Directionality: simulations

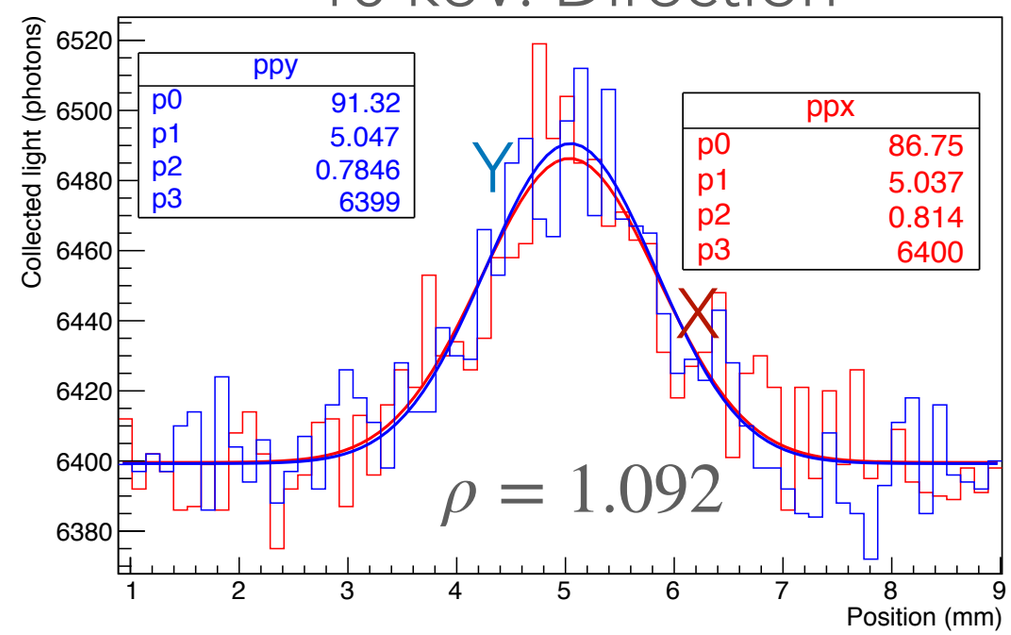
We developed a preliminary 2D simulation starting from ion recoils produced by SRIM, taking into account quenching factor, gas ionisation, diffusion during drift, gas gain and light yield, and sCMOS sensor noise, to study our directionality capability

Eccentricity evaluated from the double ratio ρ between amplitude A and sigma σ : $\rho = \frac{(A/\sigma)_y}{(A/\sigma)_x}$

10 keV: No direction



10 keV: Direction



For 10 keV$_{nr}$ tracks with 50 cm drift we obtain an eccentricity of:

10 keV: Direction

ρ =1.10 ± 0.03

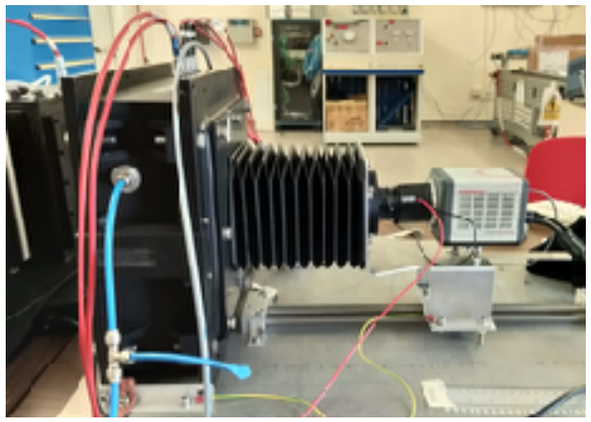
10 keV: No direction

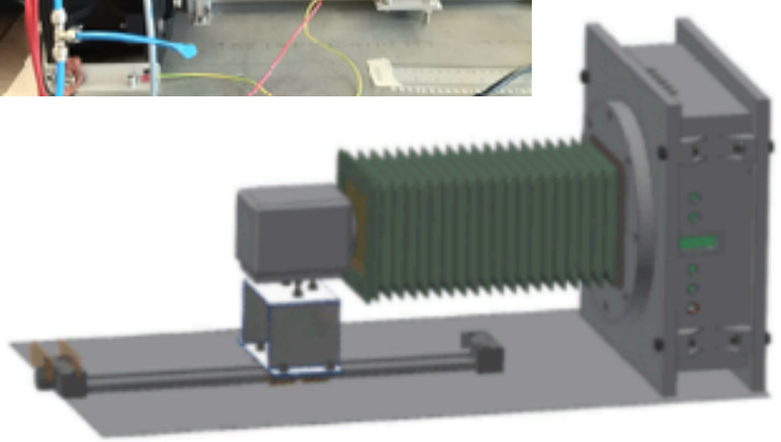
ρ =0.98 ± 0.01

PRELIMINARY

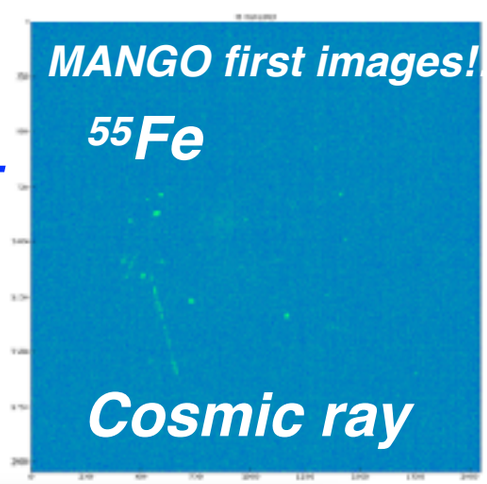
PHASE_0: Mango & Lime

MANGO: a Multipurpose Apparatus for Negative ion studies with GEM Optically readout



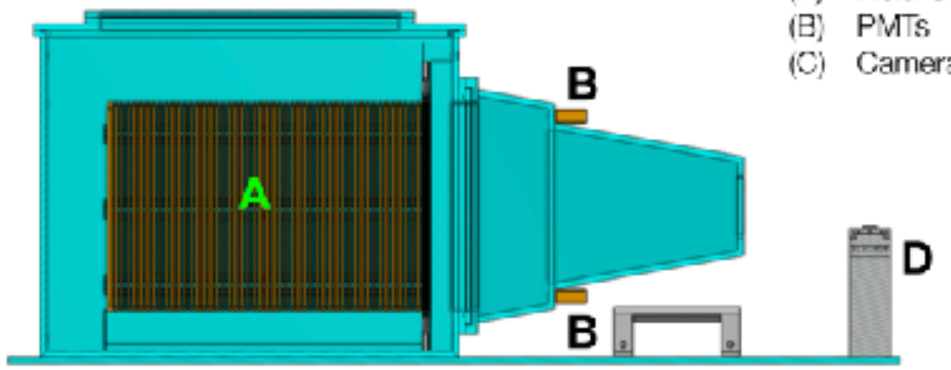


1 sCMOS + 1 PMT
10 x 10 cm² area
1-5 cm drift



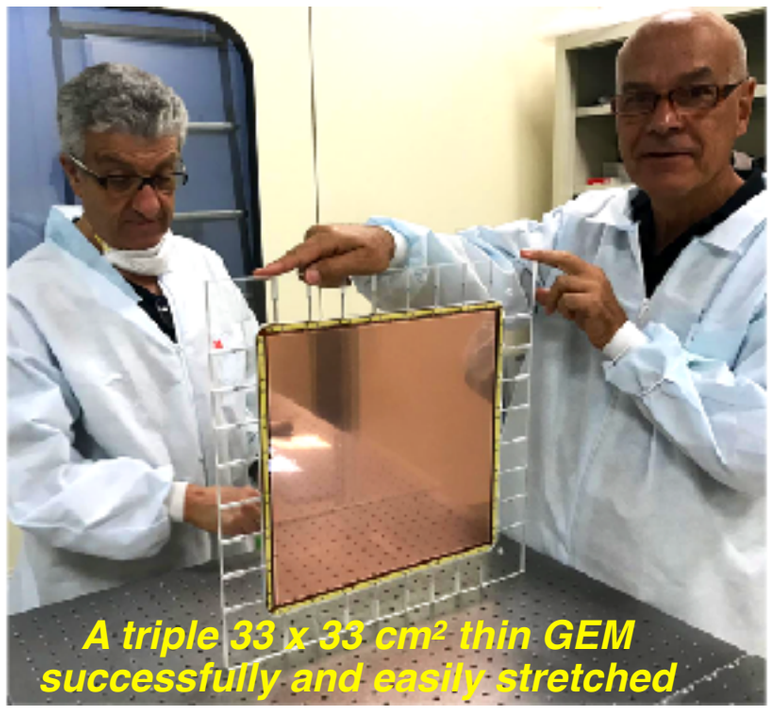
LIME: Long Imaging ModulE

50 L volume under manufacturing

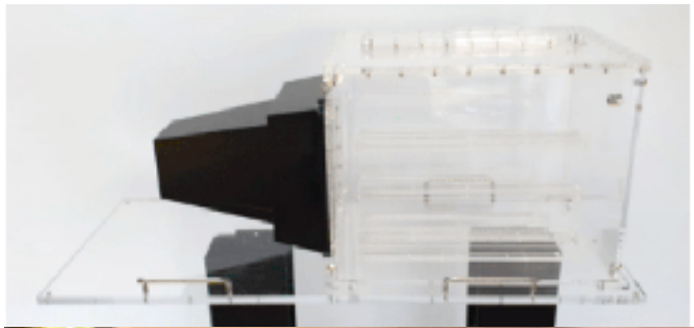


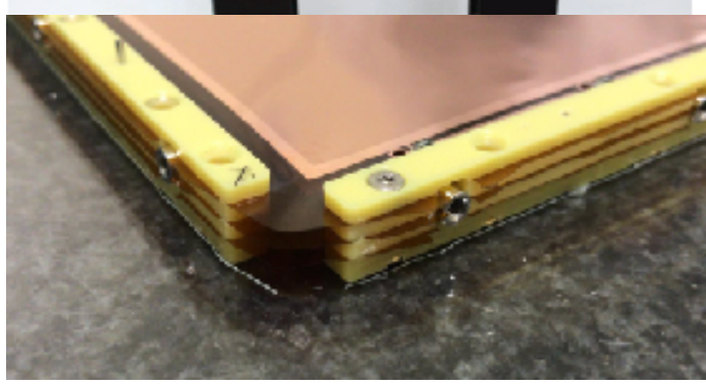
- PMMA gas box + copper sheet for EM shielding/gamma shielding/darkening
- Field cage made of copper rings on PMMA supports
  - possibility of testing also DRIFT-like field cage (Kapton foil with copper strips) and **resistive foil**
- 4 PMT for positioning sensitivity with fast readout (center-of-gravity)

1 sCMOS + 4 PMT
33 x 33 cm² area
50 cm drift
1/18 of CYGNO



A triple 33 x 33 cm² thin GEM successfully and easily stretched

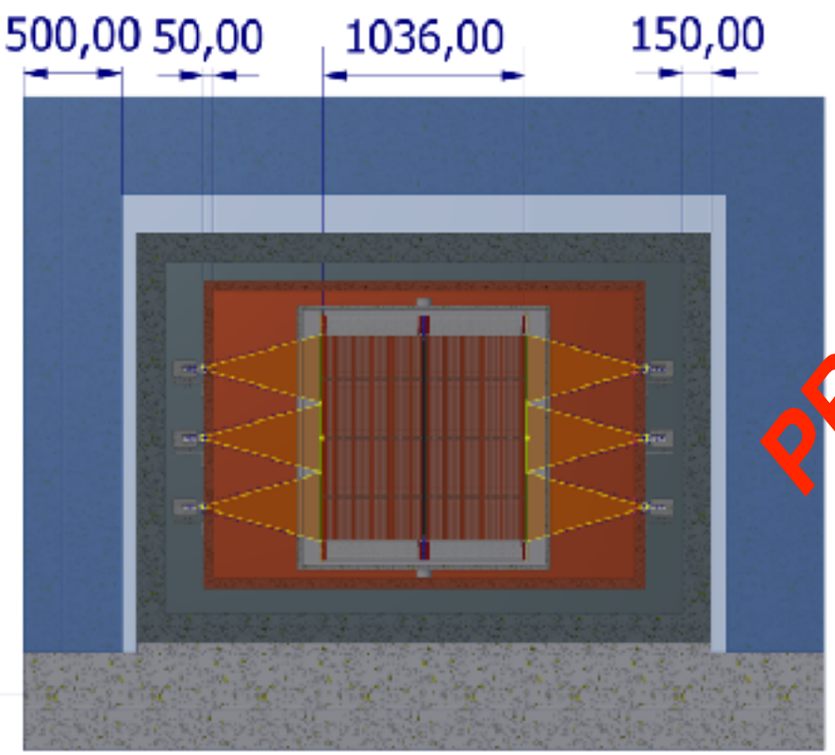




PHASE_1: detector preliminary design

He:CF_4(:SF_6) 1 kg mass, 1 m^3 volume

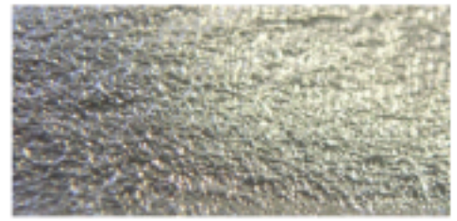
18 cameras monitoring
330*330 mm each
with **160 μm** resolution



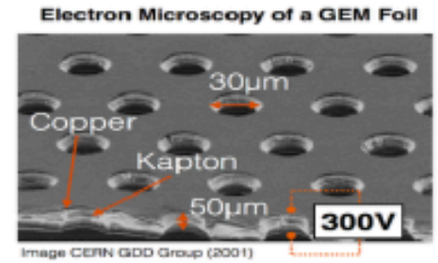
9 cameras/m^2

A total of 72 10^6 readout
165 x 165 μm^2 pixels

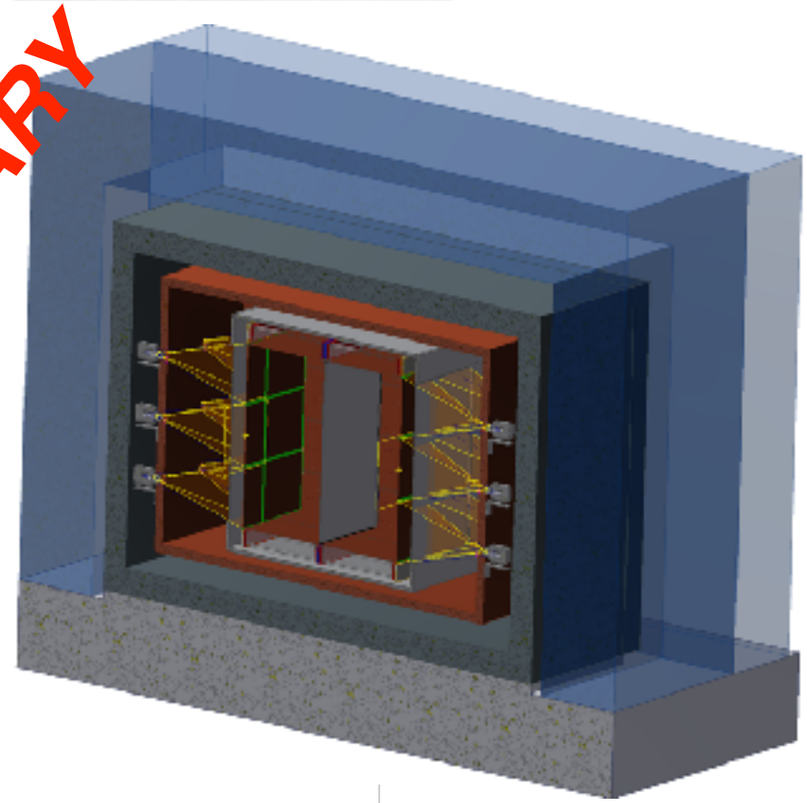
Transparent texturised mylar cathode a'la DRIFT

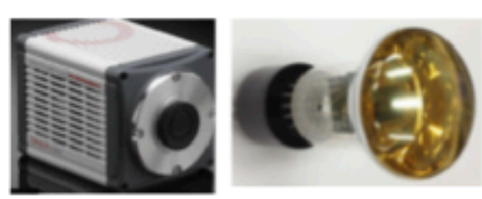


Gas Electron Multipliers (GEMs) amplification



PRELIMINARY

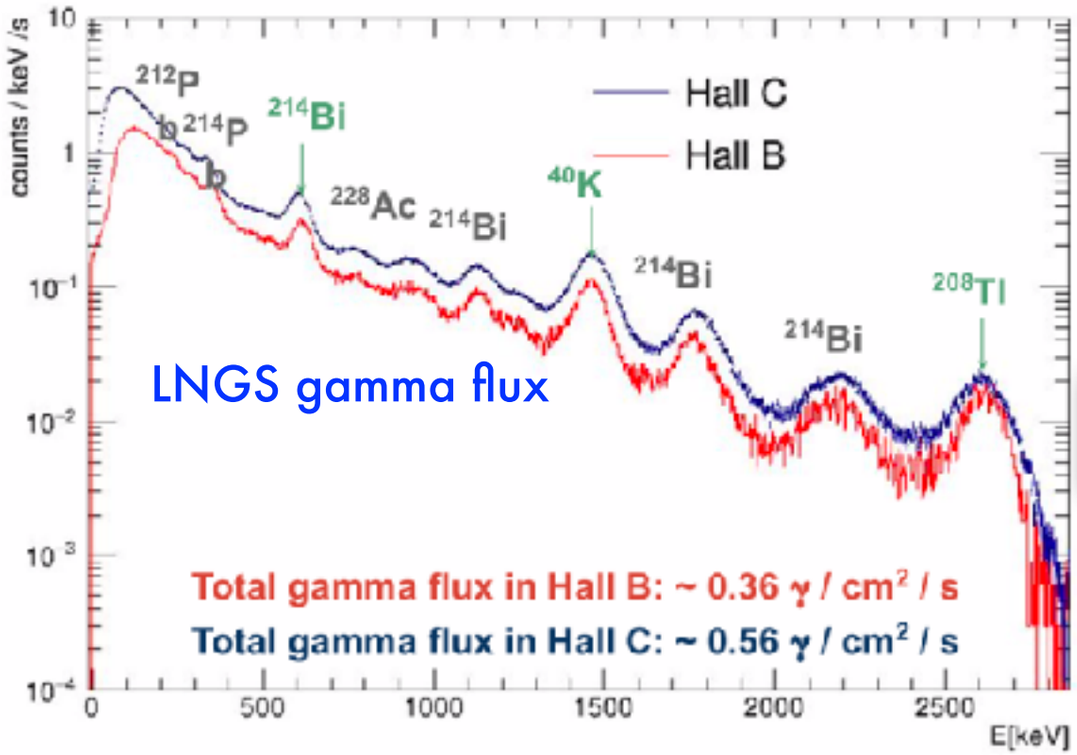


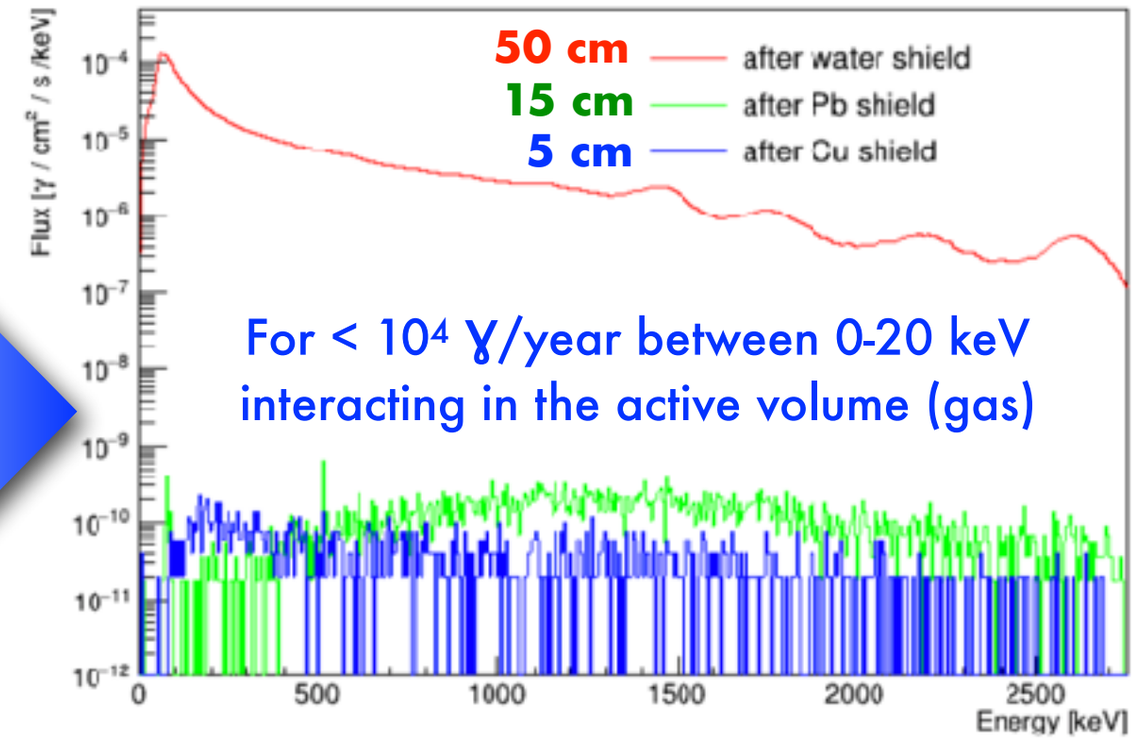


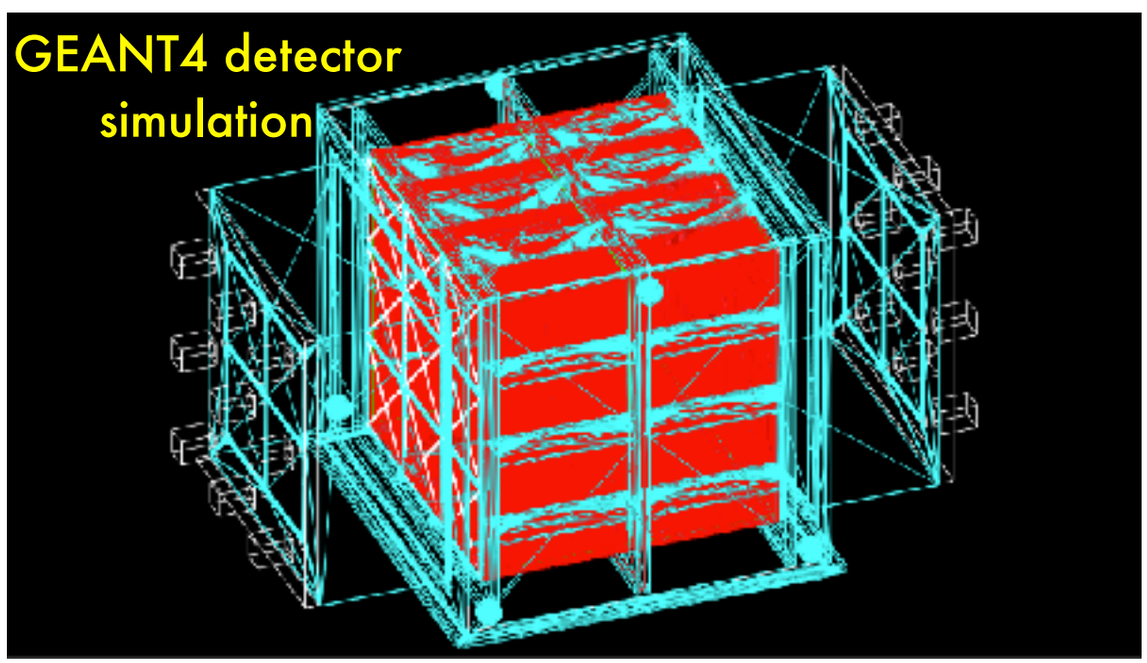
PMT + sCMOS optical readout decoupled from target volume

Atmospheric pressure & room temperature: minimal infrastructure

PHASE_1: preliminary backgrounds & shielding

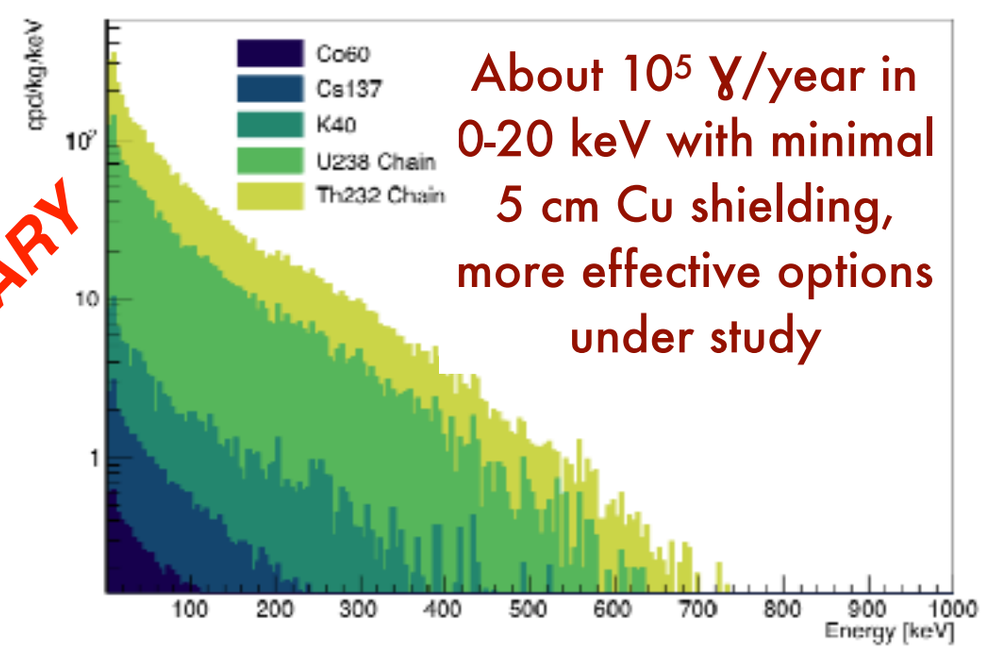






Largest internal background from sCMOS cameras

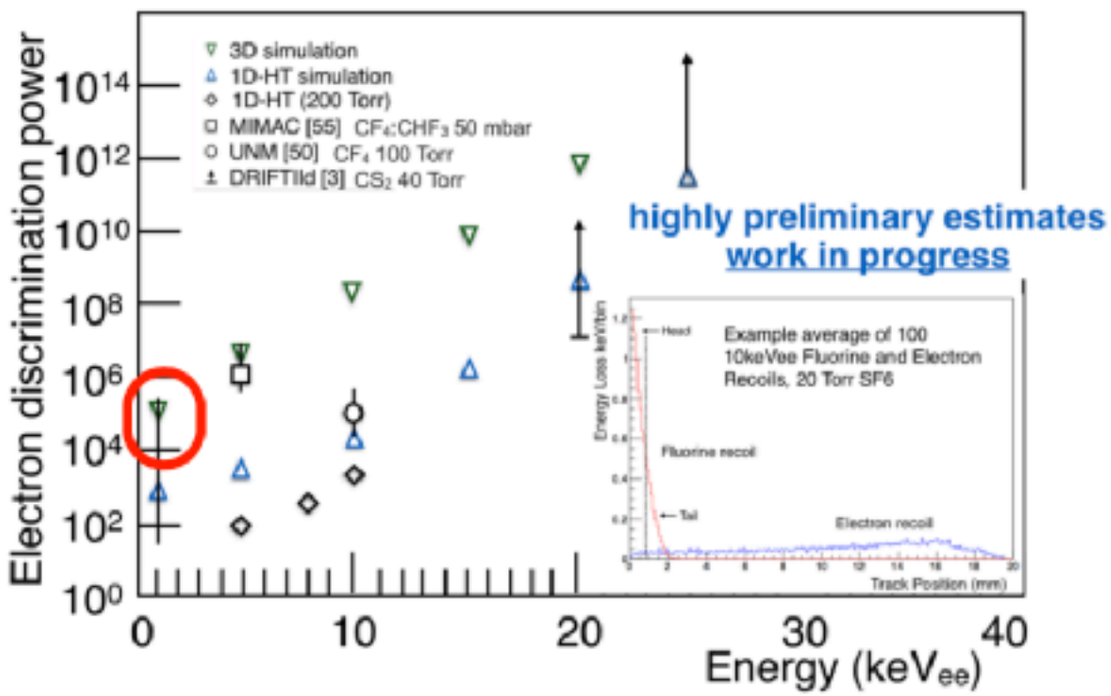
PRELIMINARY



Feasibility of 10^4-10^5 e^-/γ rejection @ 1 keV

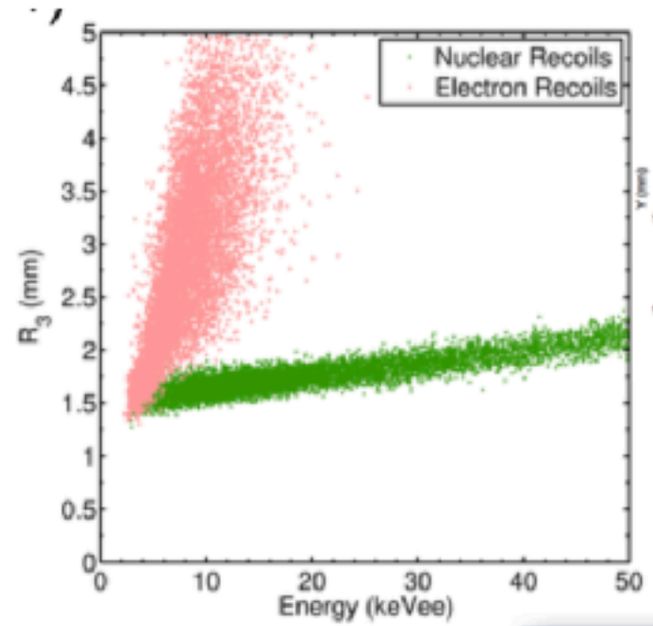
From simulation within CYGNUS collaboration (paper in preparation)

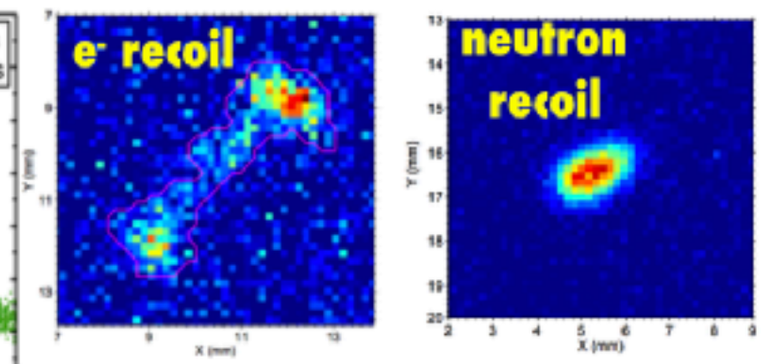
- Simulations (Hawaii, Sheffield) CASINO, SRIM (mod), DEGRAD, GEANT4 all being used



CYGNO is a 3D detector

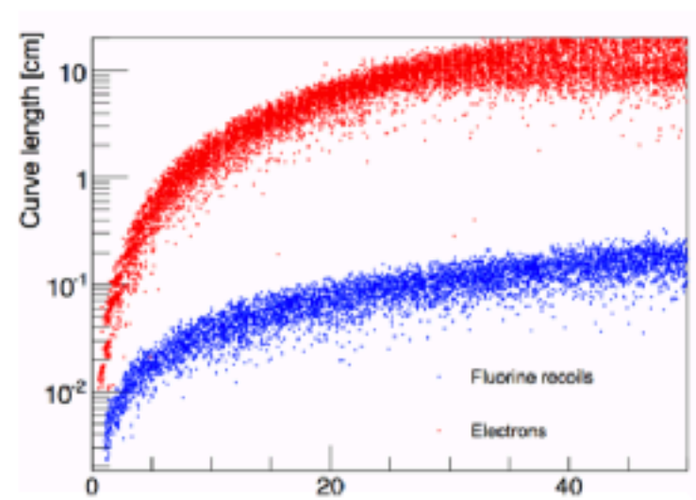
From measurements





100 Torr CF_4, GEM + CCD
10^5 rejection @ 10 keVee

N.S. Phan et al, Phys.Rev. D90 no.5, 055018

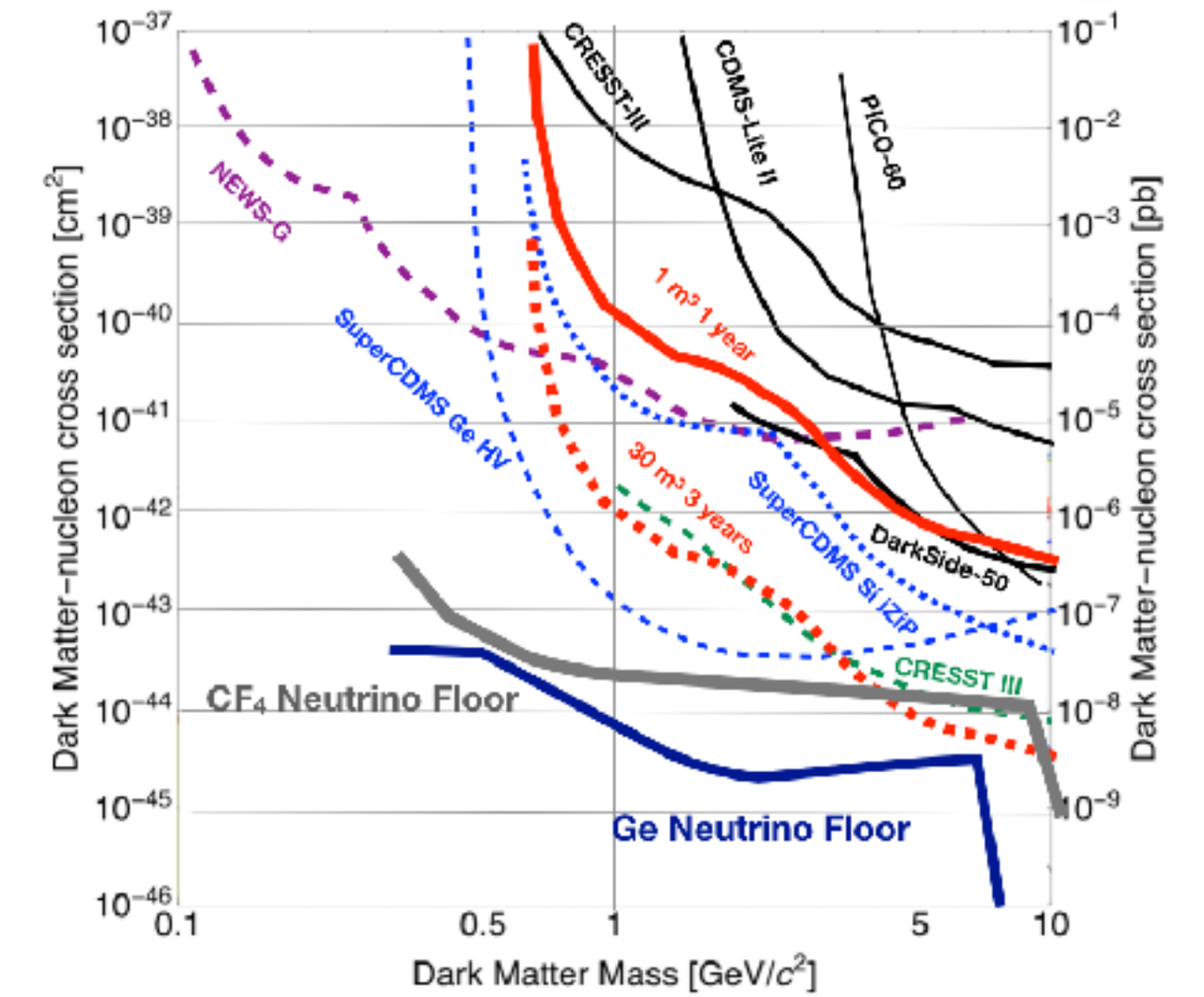


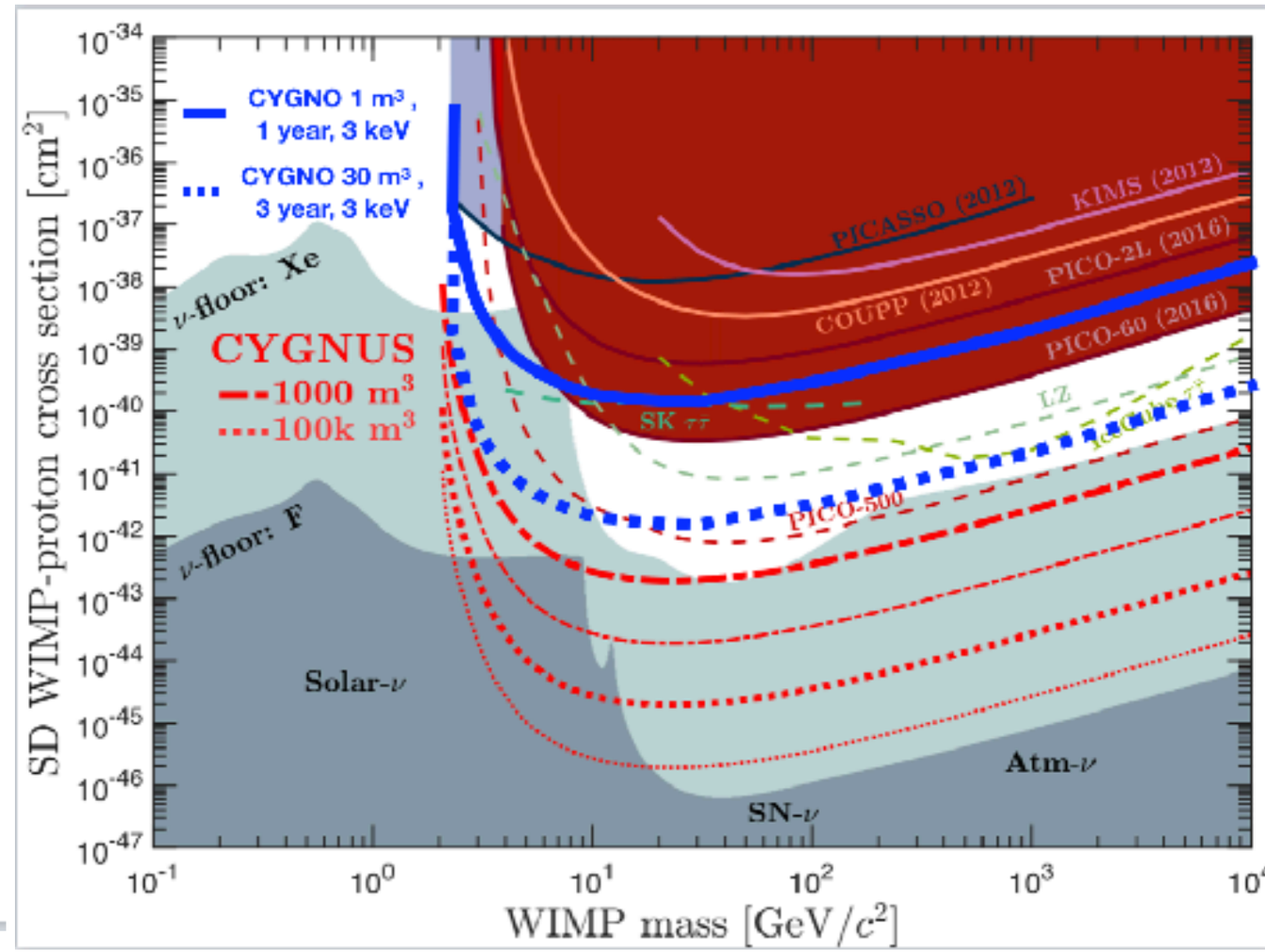
70% CF_4 + 30% CHF_3 @ 50 mbar, Micromegas
10^5 rejection @ 2 keVee
(with multivariate analysis)

J. Billard et al., JCAP 1207 (2012) 020

CYGNO prospects sensitivity at low WIMP masses

PRELIMINARY





Zero background assumed

1 keV threshold on He recoils (2 keV on C, 3 keV on F)

Stay tuned for (a flock of) CYGNUS birth

2018	2019	2020	2021	2022	...
@ ROMA1/LNF	@ LNF	@ LNF	@ LNF	@ LNGS	
ORANGE		TDR	Construction & test	Installation & data taking	CYGNUS

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

Backup slides

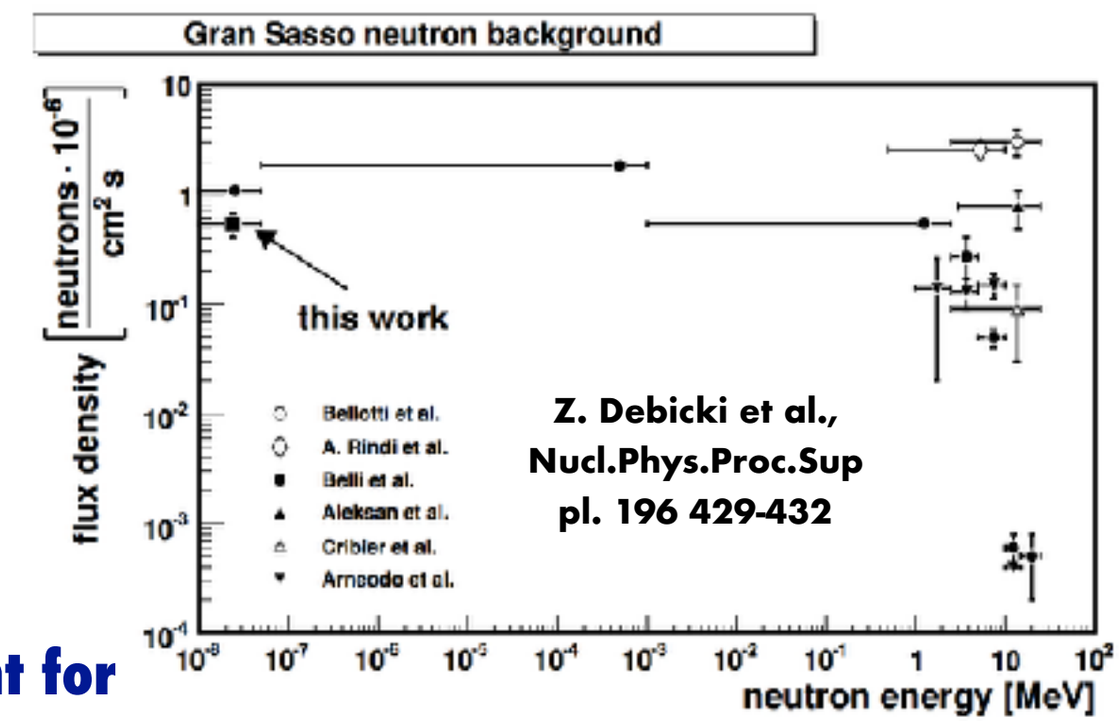
CYGNO neutron flux measurement @ LNGS

Environmental neutrons in underground halls are background to all current & future experiments: their precise knowledge is fundamental

- **Simultaneous sensitivity to thermal and fast neutron flux with $^3He:He:CF_4:SF_6$ at atmospheric pressure**
  - Fast neutron through nuclear recoil
  - Thermal neutron through capture on ^3He (0.5% is enough thanks to the large capture cross section).
- **O(10 keV) or lower threshold on fast neutrons**
- **Precise spectral measurement**
- **Directional measurement**
- **Seasonal measurement**
- **Background free measurement**
- **Hall B measurement**
- **Possibility to optimize pressure and gases content for higher yield or lower directional threshold**
- **Demonstrator for DM searches**

Proton 573 keV **Tritium 191 keV**

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



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