GRAN SASSO SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES INFN

Directional Dark Matter Searches

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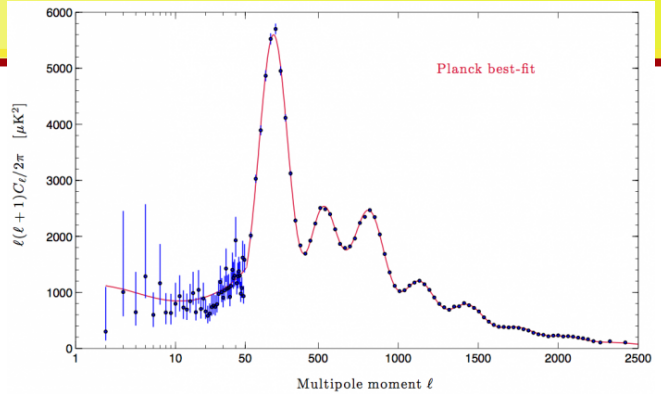
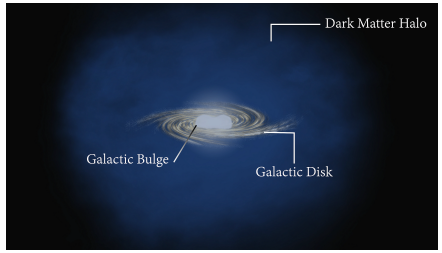
Dark Matter

- Dark Matter (DM) is considered a well established paradigm of our universe

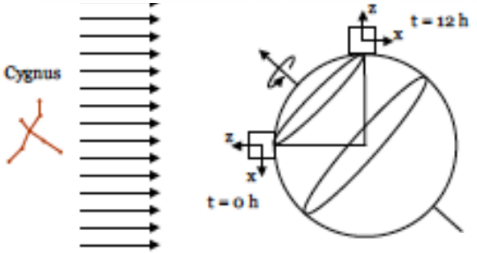


Credit: L. Jaramillo and O. Macias Virginia Tech

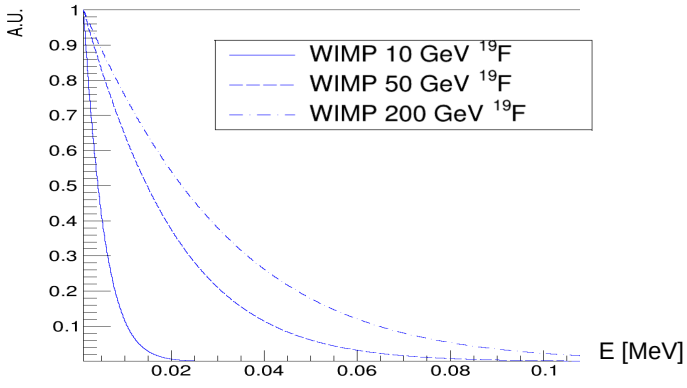


- Considerind the standard WIMP model, our Galaxy is believed to reside in a halo of WIMP–like particles.

- The motion of the Earth together with the Sun produces an apparent wind of DM particles.



- DM of about 1–10 GeV/c^2 can induce nuclear recoils of light elements of few keV.



- Direct detection experiments aim at finding those recoils

Directionality

- Nuclear recoils have also an angular distribution that could be measured → 1 more degree of freedom

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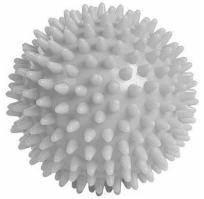
- With one more degree of freedom life changes dramatically: example of pictures

Only wave intensity



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Coloured

Adding wavelength ←

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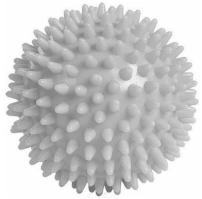

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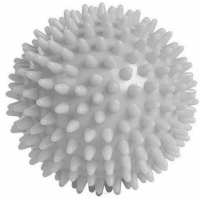
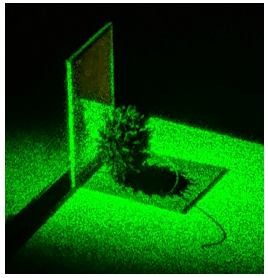


→ Adding phase

Hologram



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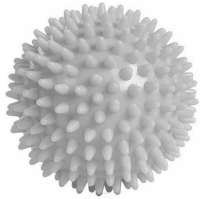

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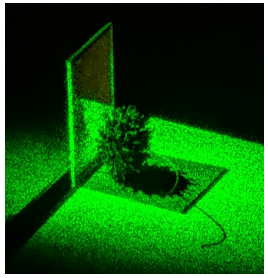
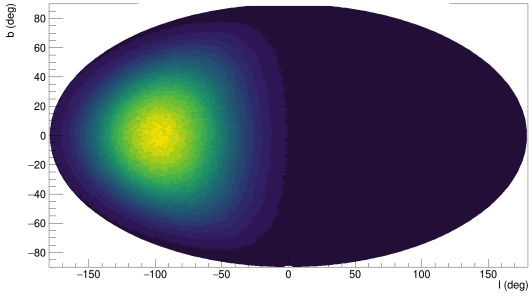
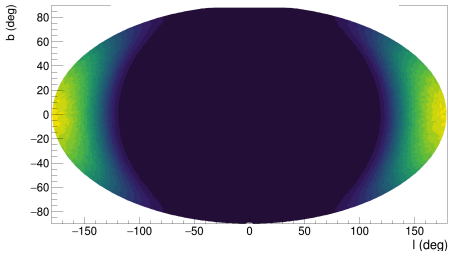


- Nuclear recoils angular distribution has a clear structure depending on the model, very different from a flat background

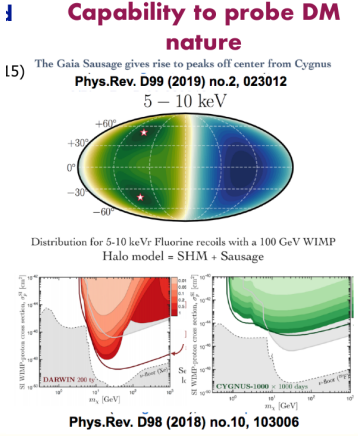
F recoil due to WIMP



F recoil due to light DM from SN



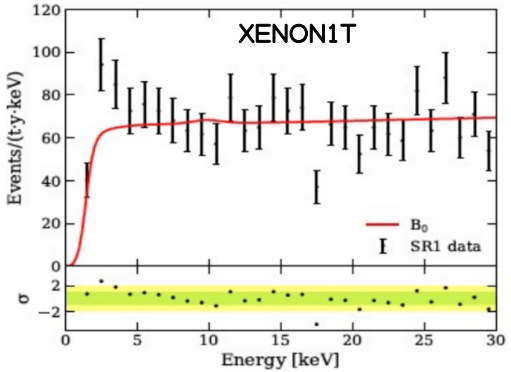
DeRocco, W., et al. Phys. Rev. D 2019, 100, 075018.



HUGE RELEVANCE FOR DM SEARCHES

Directionality: Positive Discovery

Hints of signals?



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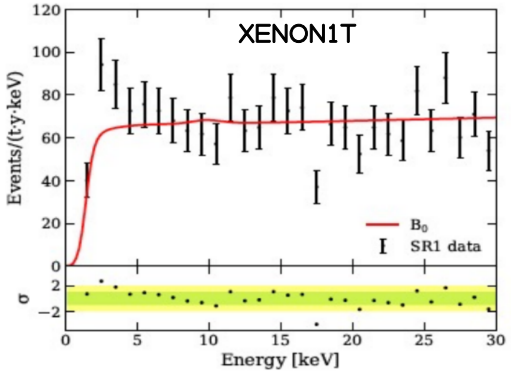

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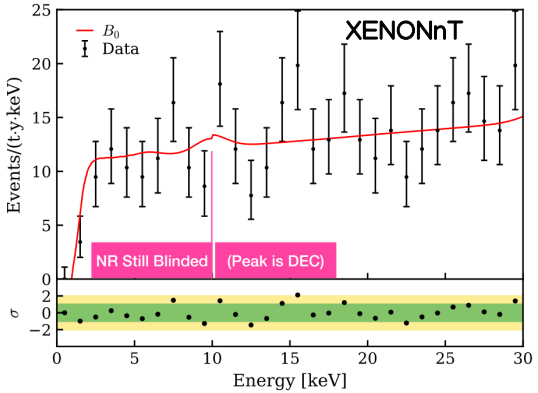

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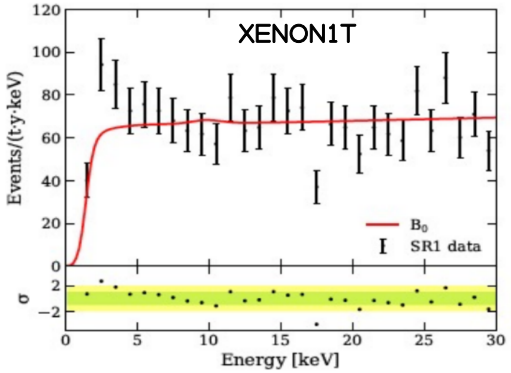

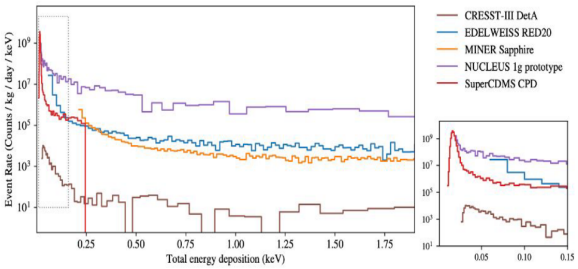

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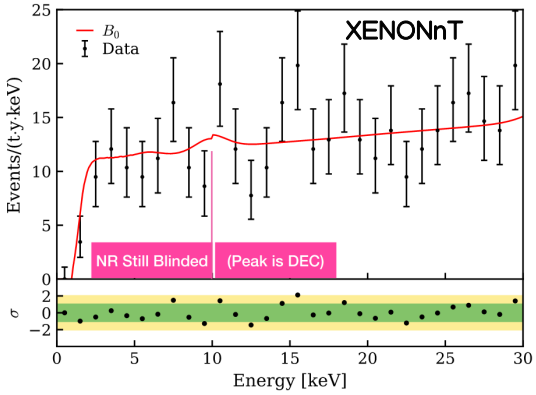

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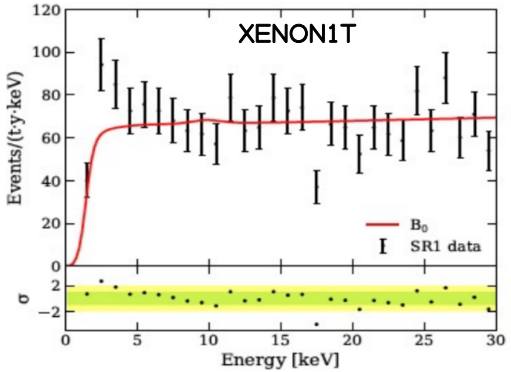

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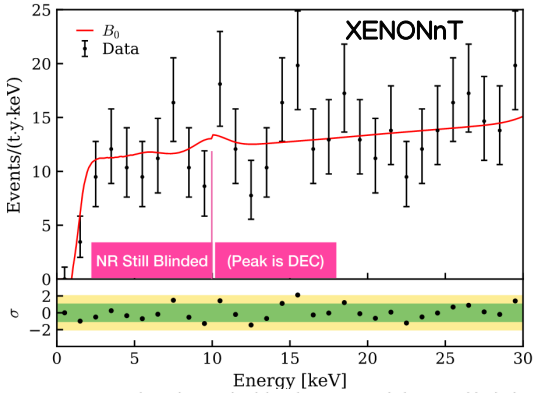
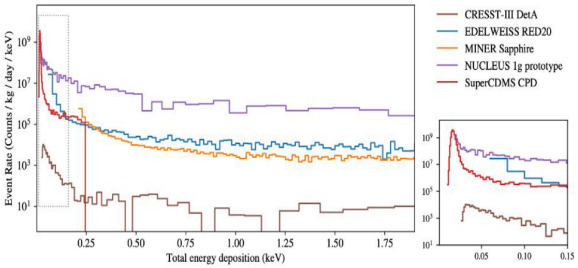
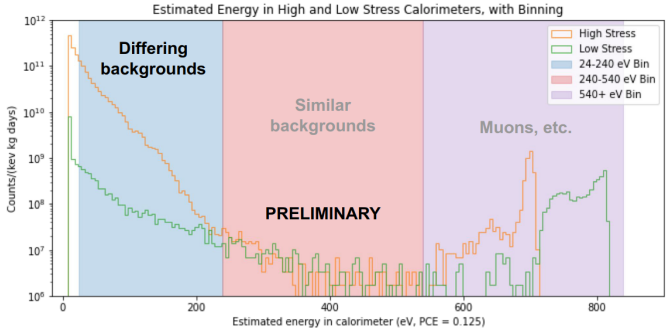




Likely mechanical stress



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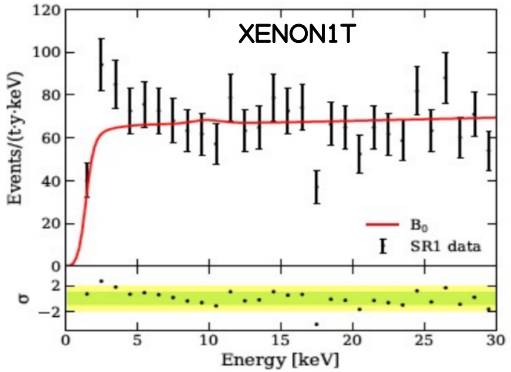

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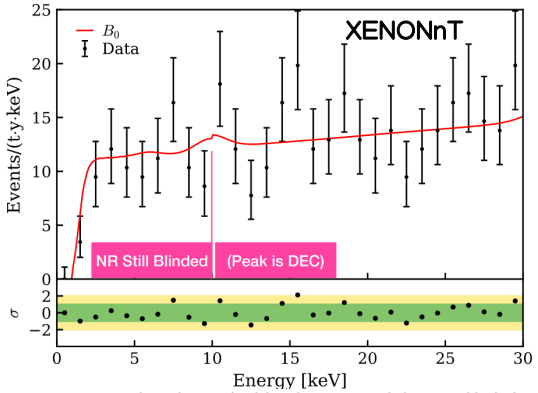

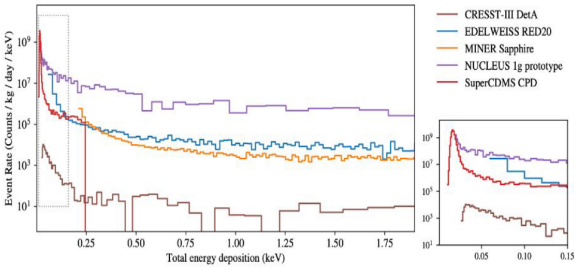

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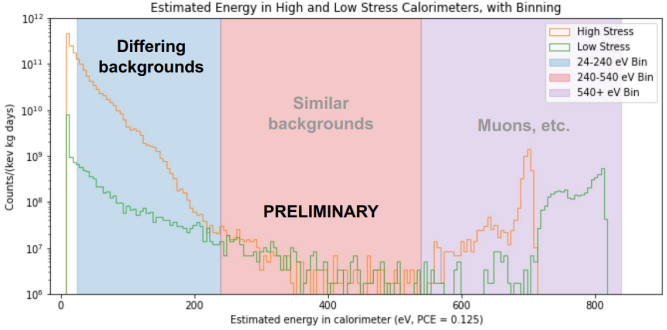

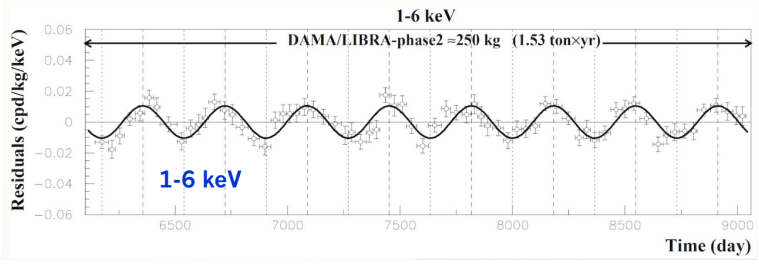

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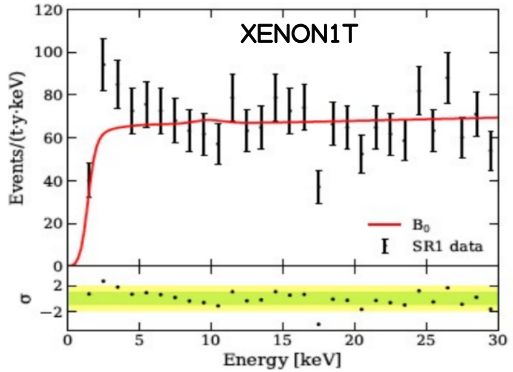

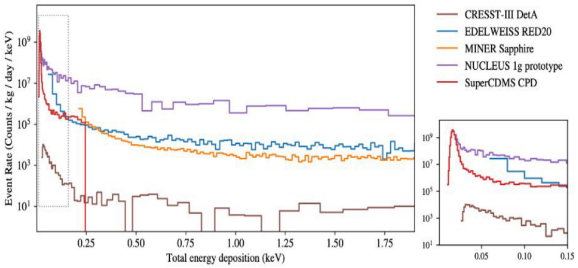

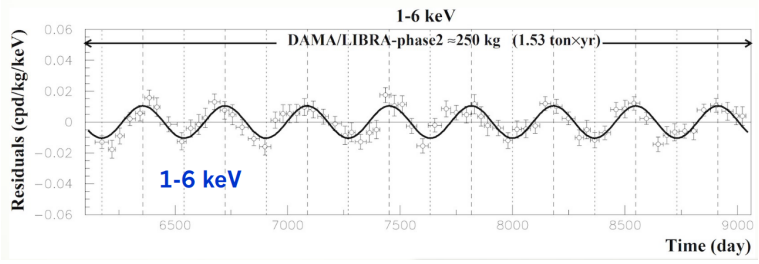

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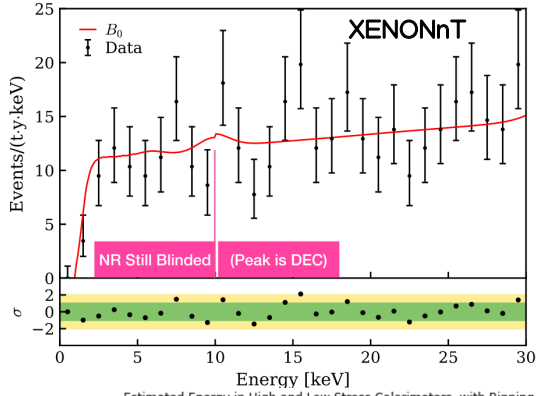

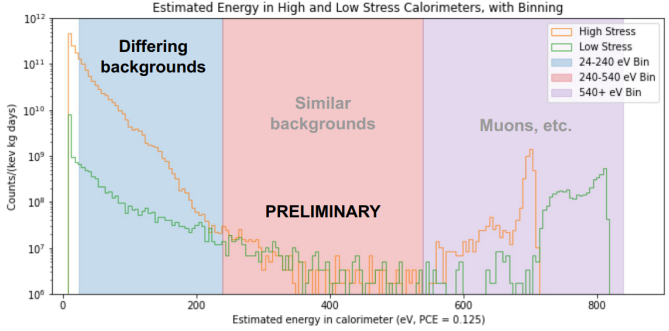

Still controversial

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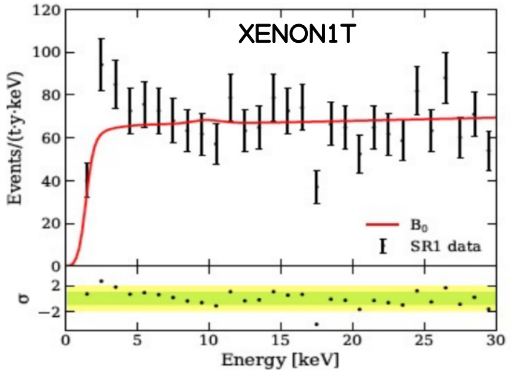

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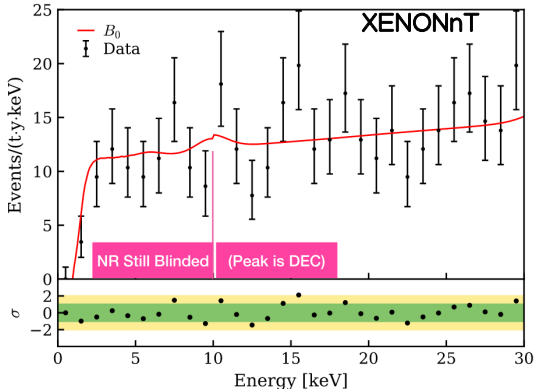

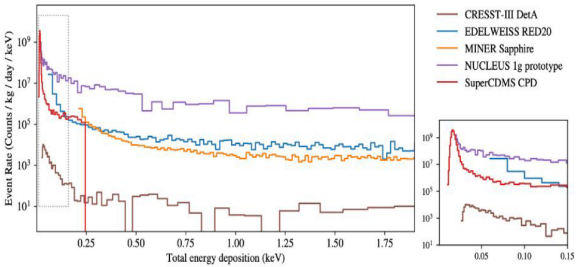

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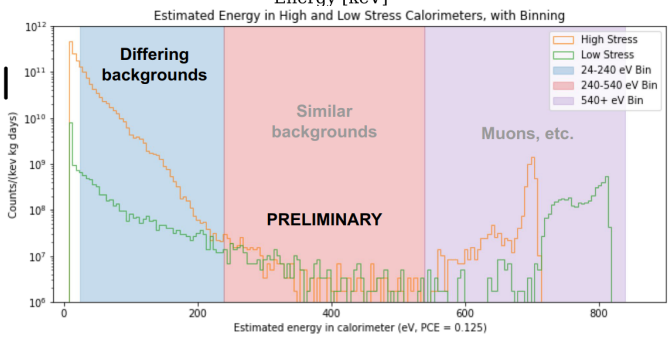
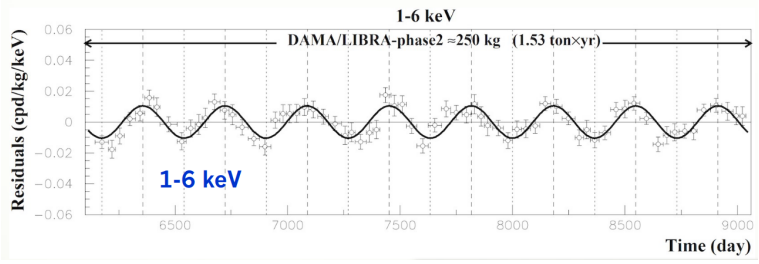
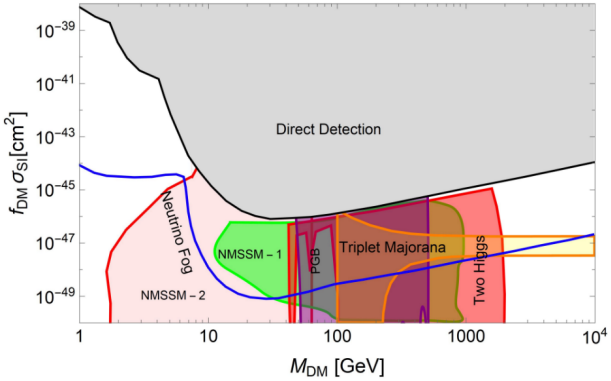




Still controversial

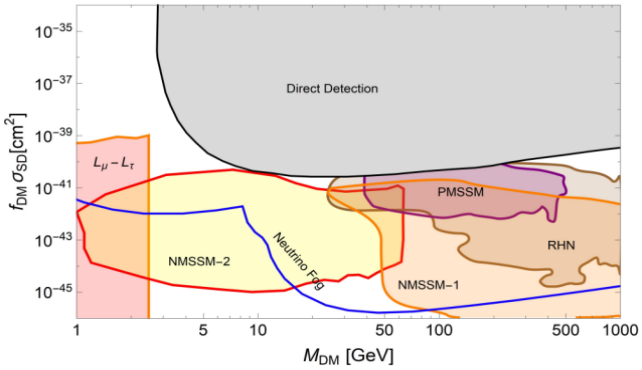
Directionality is needed for positive discovery

Directionality: Venturing the Neutrino Fog



Plenty of reasons to push further into the neutrino fog

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



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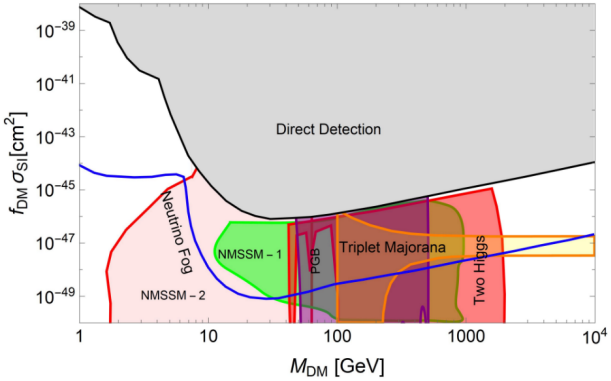

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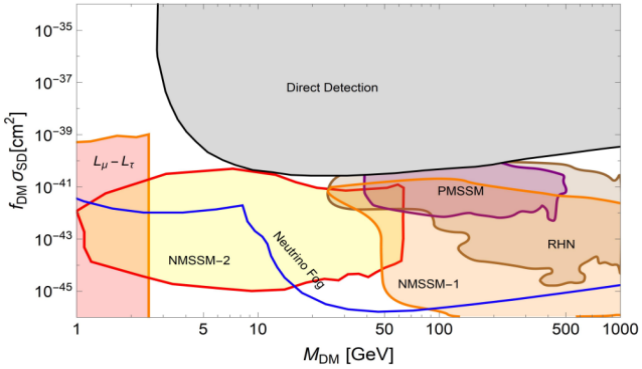

How does the discovery limit improves with exposure?

$$n = -\left(d\ln\sigma / d\ln N\right)^{-1}$$

- No background $n=1$
- Poissonian subtraction of background $n=2$
- Worse $n>2$

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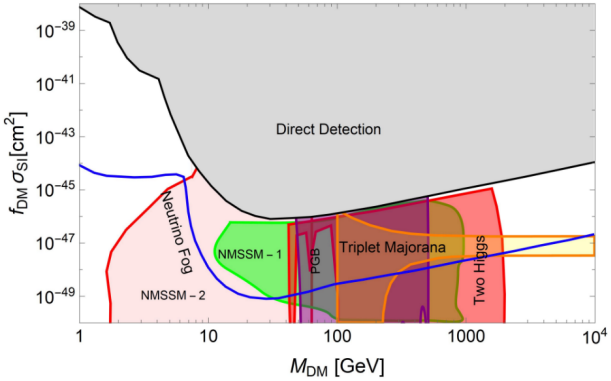

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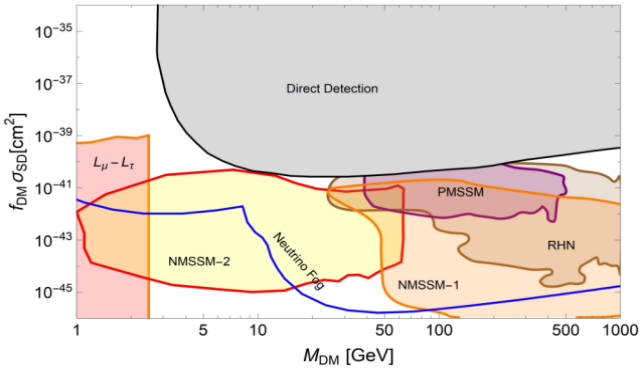

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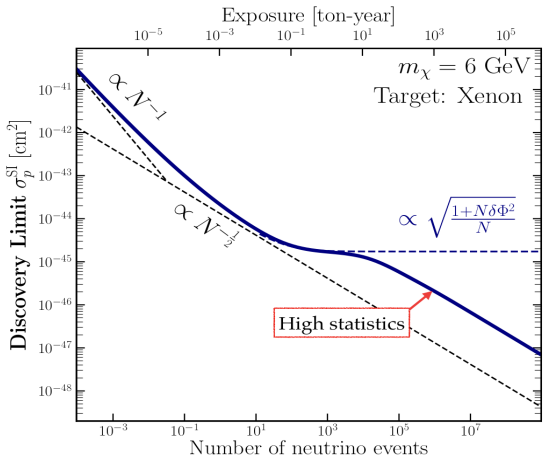
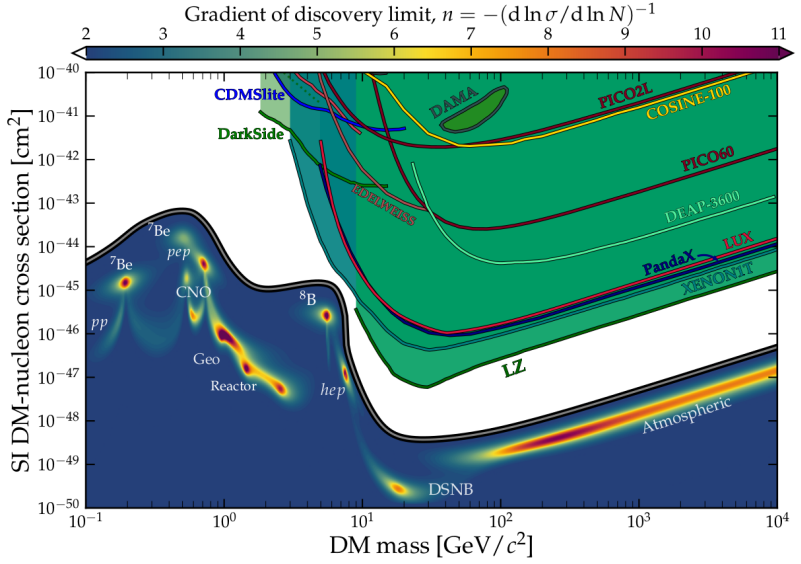
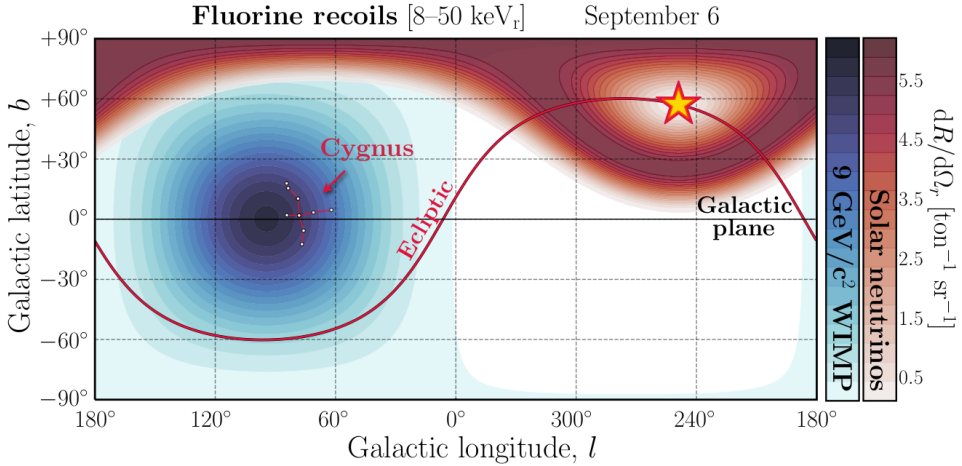




O'Hare [2109.03116]

Directionality: Seeing Through the Neutrino Fog



Directionality can easiliy prove the neutrino direction vs WIMP one

What do we need?

- 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)

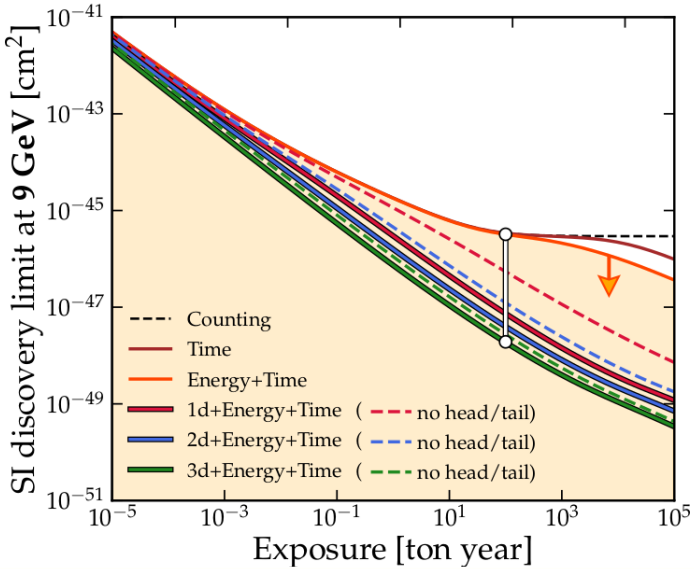
And achieved…

- 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

see [2102.04596] and Snowmass WP [2203.05914] for reasoning

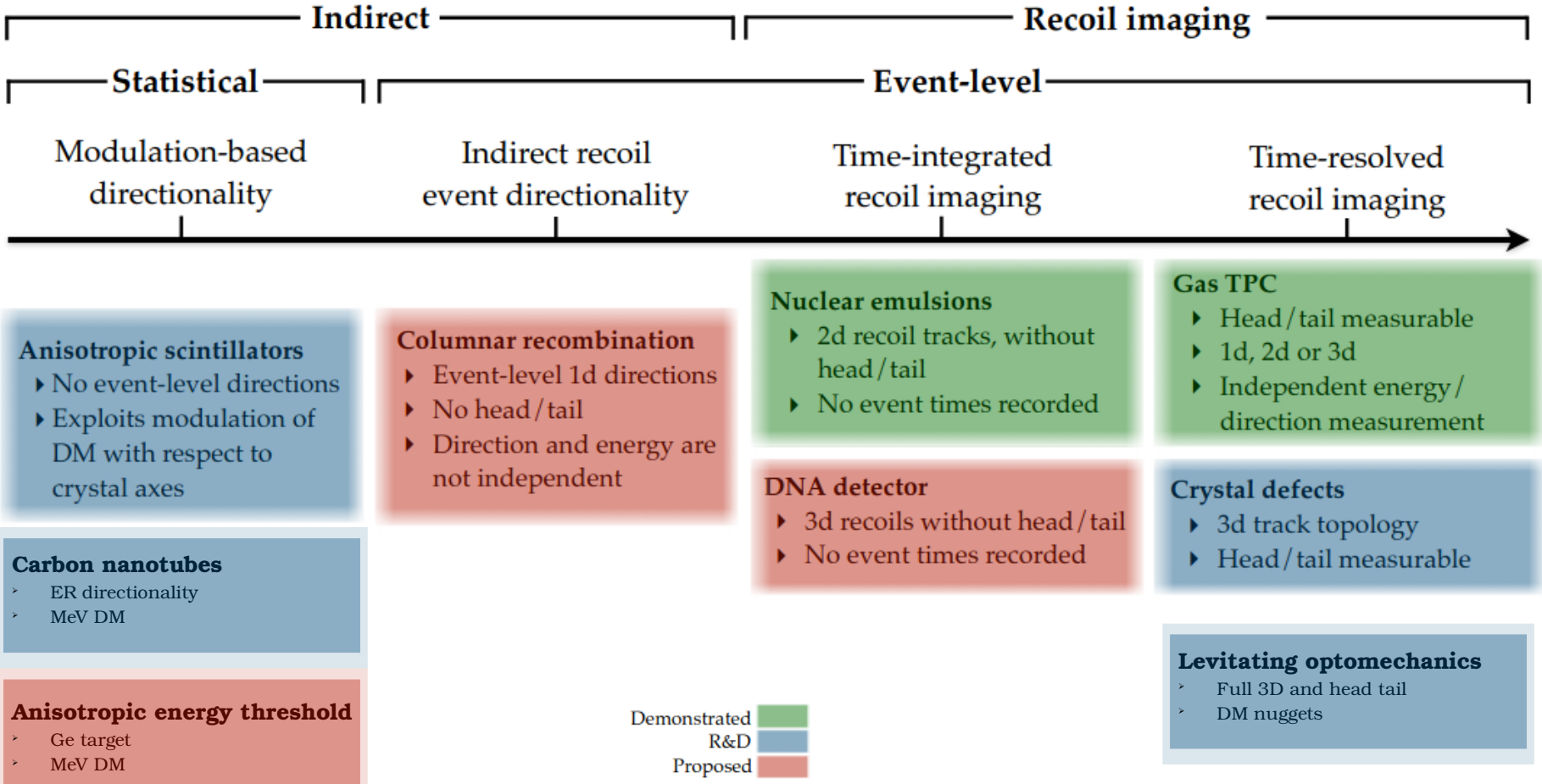
Can this be done? Maybe, but the way to go seems to be "recoil imaging"

You can go as you were background free



Directional Approaches

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



Solid Target Approaches

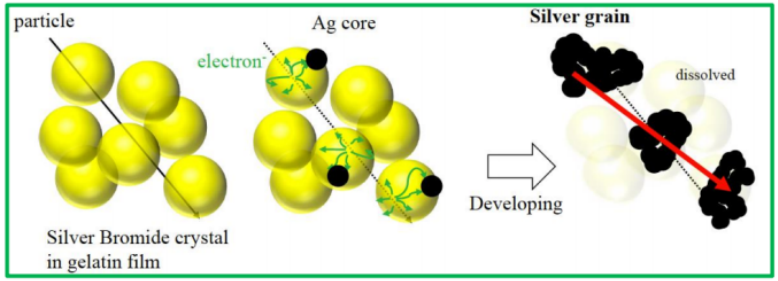
High density for big exposure

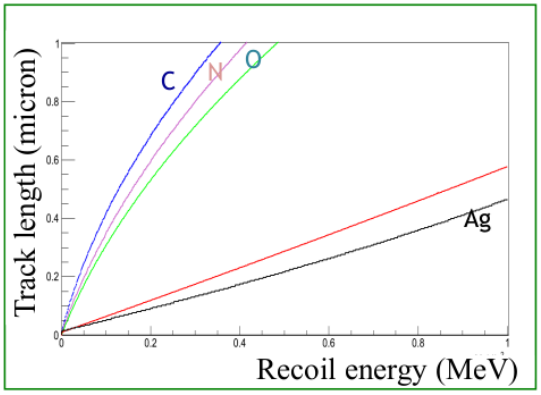
C, N, O, Ge, Si, Ag, Br, W, Zn

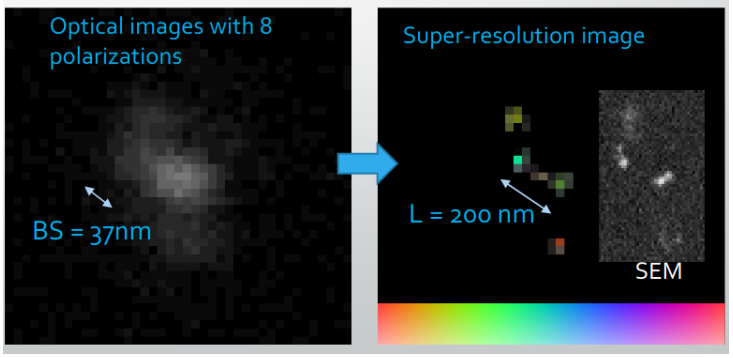
Short recoils O(nm)

- **Emulsions**
  - Time integrated 2D tracking demonstrated down to 30 keV
- **Crystals**
  - R&D with $ZnWO_4$ for anisotropic response to nuclear recoils
- **Carbon nanotubes**
  - R&D for anisotropic response to electron recoils

SOLID: EMULSIONS NEWS-DM

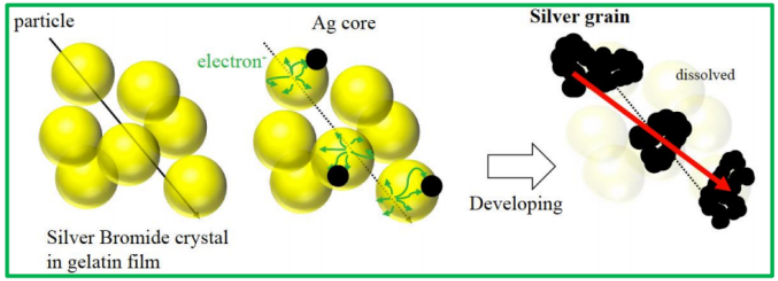


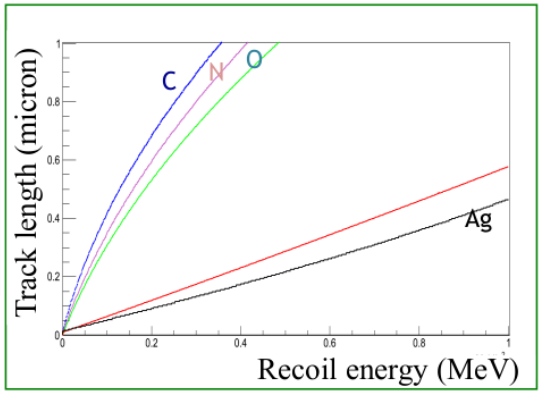


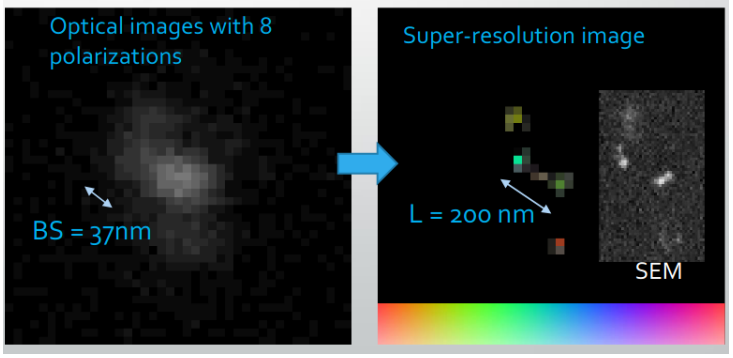


Some events

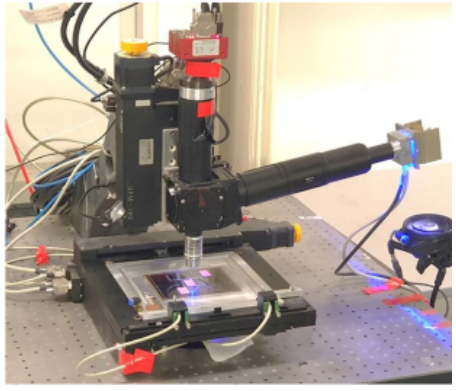
SOLID: EMULSIONS NEWS-DM

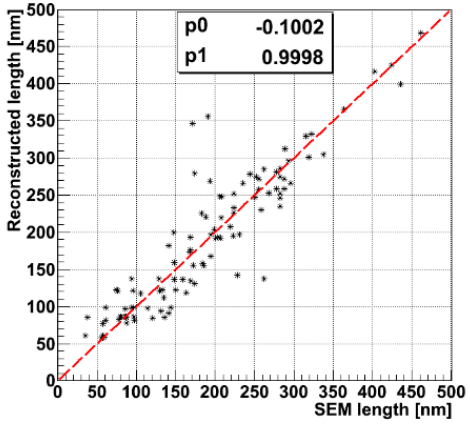




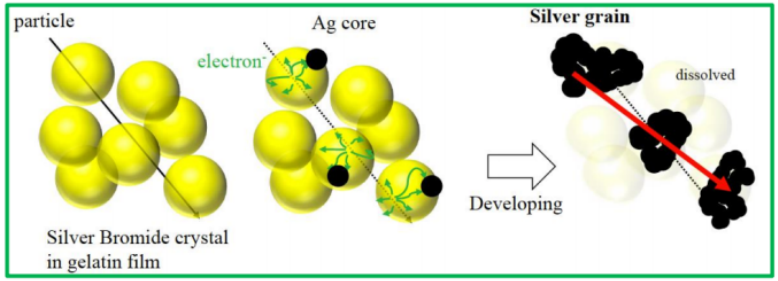


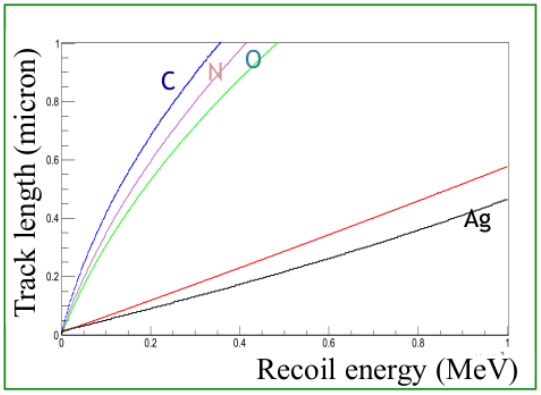
Improvements in the speed of samples analysis with plasmon resonance

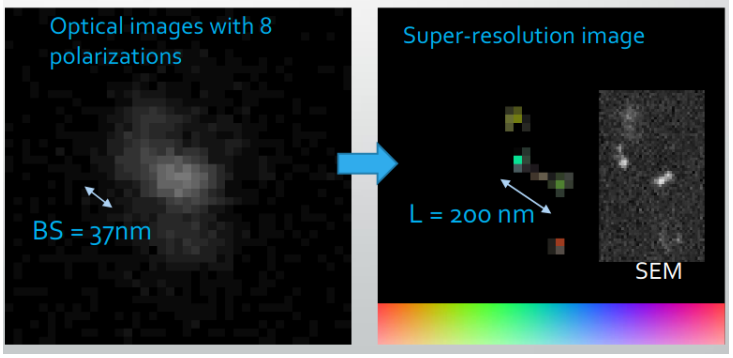




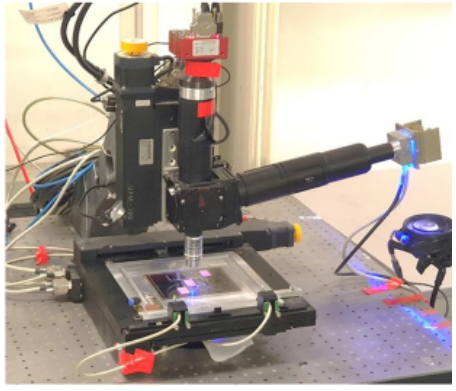
SOLID: EMULSIONS NEWS-DM

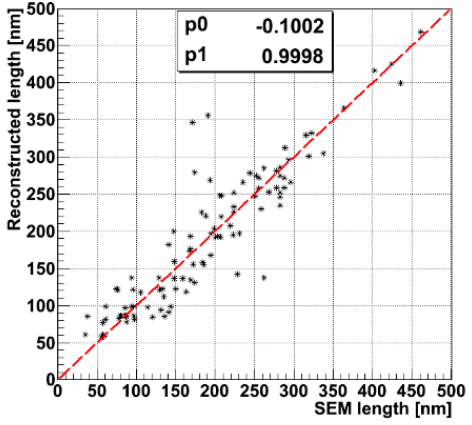




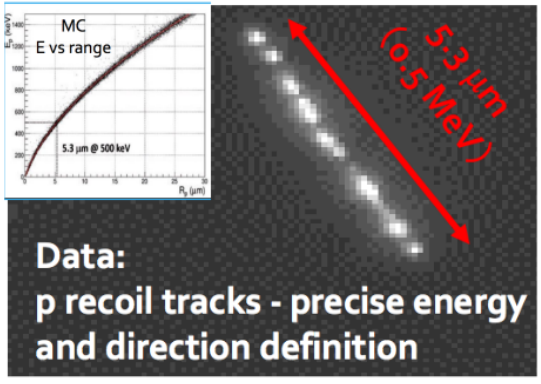


Improvements in the speed of samples analysis with plasmon resonance

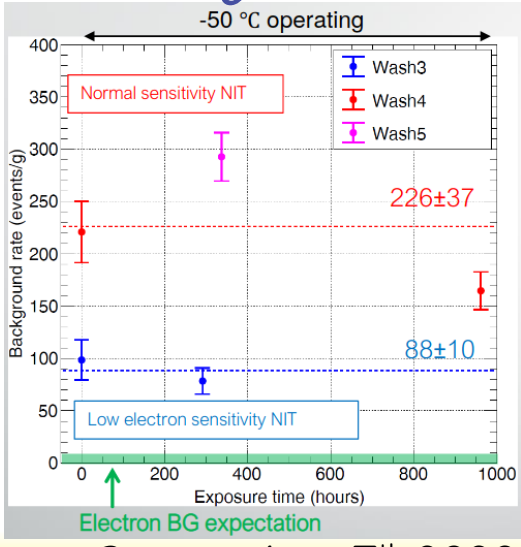




Neutron measurement and calibration

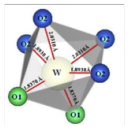


First runs underground at LNGS

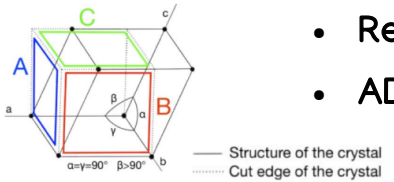


SOLID: CRYSTALS

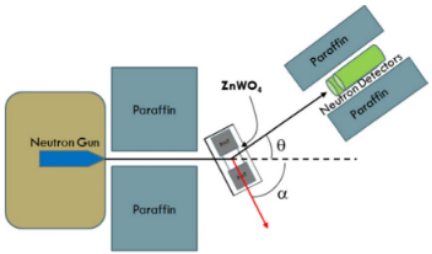
$ZnWO_4$ crystal anisotropic response

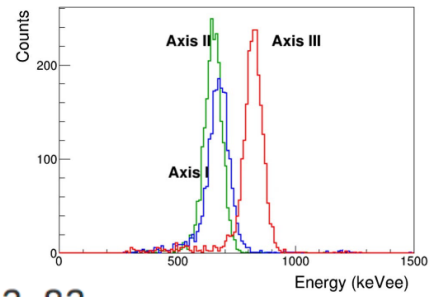


$(10 \times 10 \times 10.4)$ mm^3



- Read by PMTs
- ADAMO project





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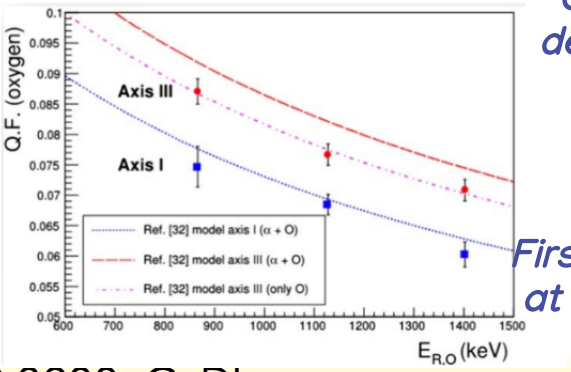
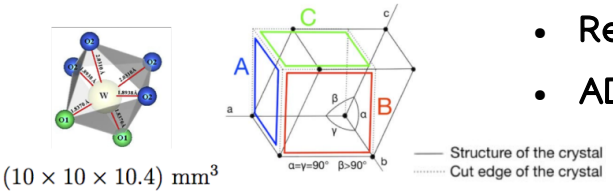
Clear difference depending on axis



First evidence at low energy

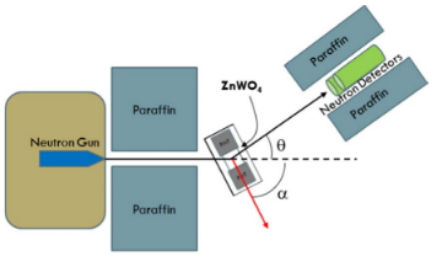
Solid: Crystals

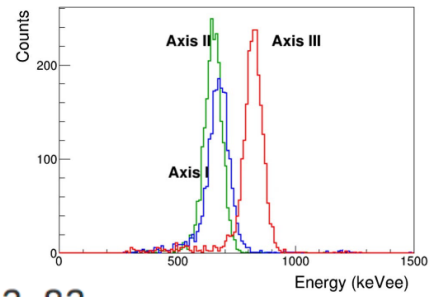
$ZnWO_4$ crystal anisotropic response



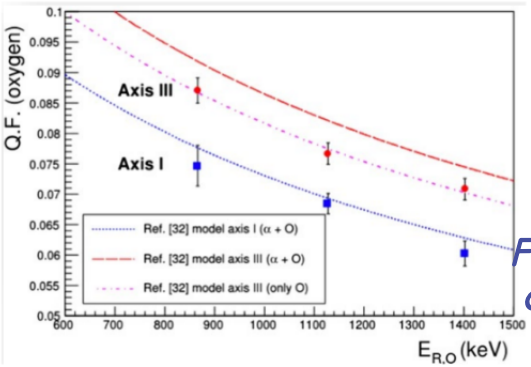
$(10 \times 10 \times 10.4)$ mm^3

- Read by PMTs
- ADAMO project





Eur.Phys.J.A 56 (2020) 3, 83

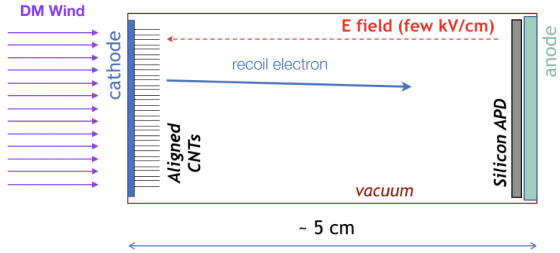


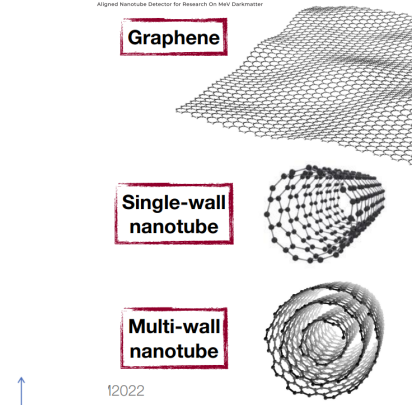
Clear difference depending on axis

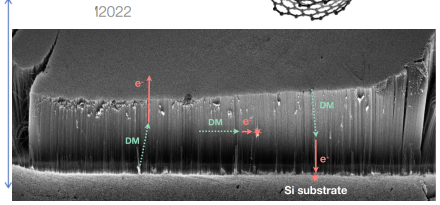
First evidence at low energy

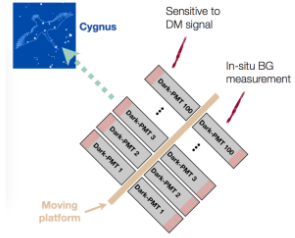
ANDROMeDa

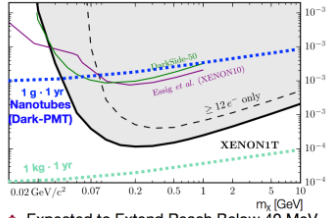
- Aim to build a Dark PMT
- Sensitive to directional electron recoils
- Currently under test the optical detector









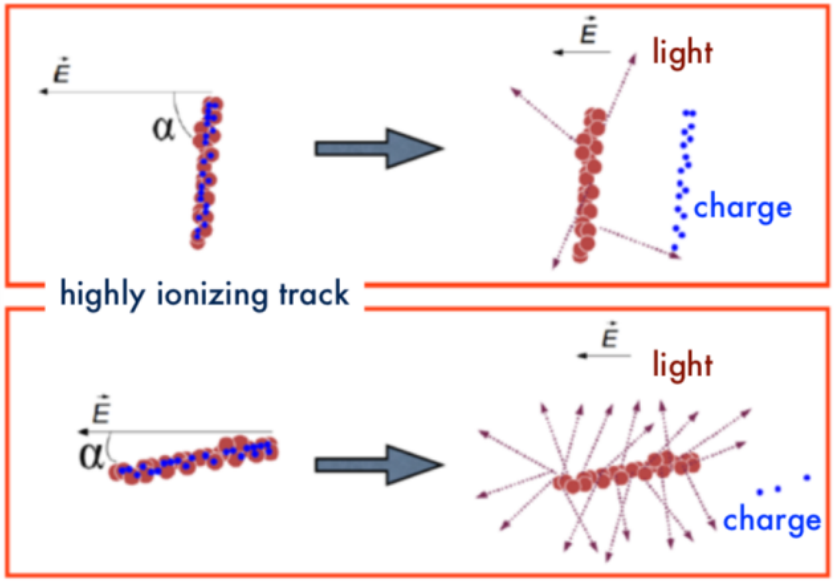


- Expected to Extend Reach Below 40 MeV
- Sensitivity down to 5 MeV

See talk of F. Virzi

Liquid Target: Columnar Recombination

- Exploitation of columnar recombination in liquid noble gases



- First proposed by Nigren in 2013 (JPCS 460 012006)
- Onsager radius vs track length is an important parameter

Liquid Target: Columnar Recombination

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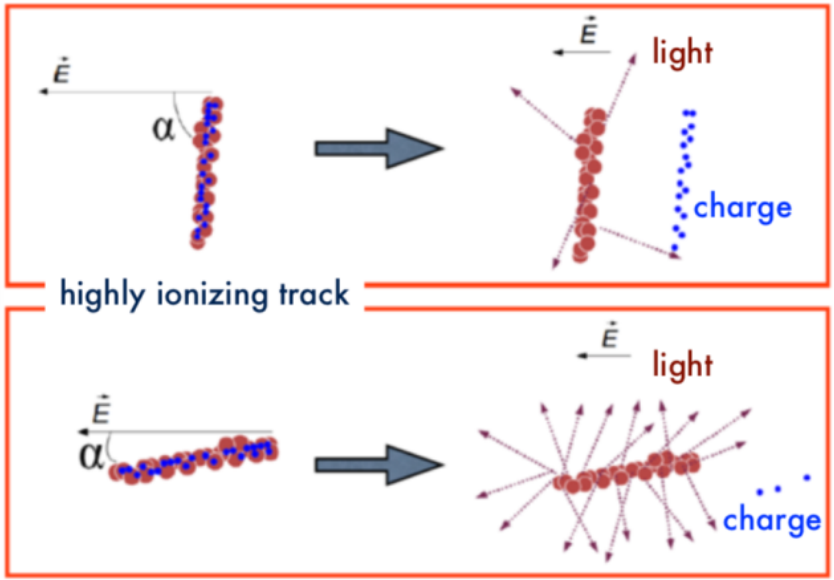

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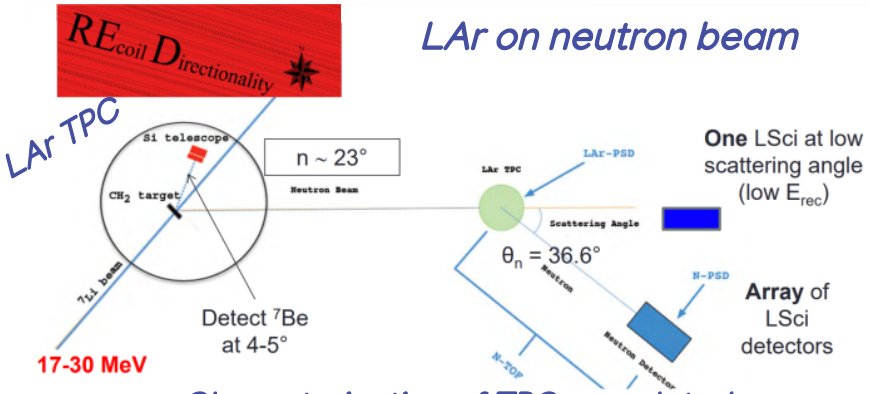
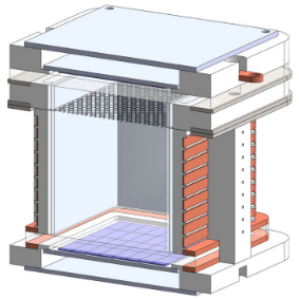
- Onsager radius vs track length is an important parameter

ReD

LAr on neutron beam



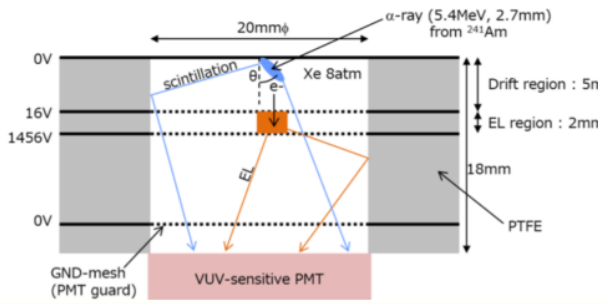


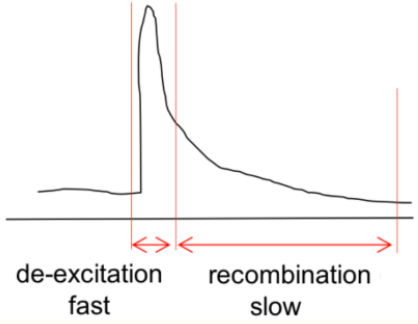
Characterization of TPC completed

See talk N. Pino

HPXe

Xe TPC analyzing waveforms component to determine recombination





Gas Target Approaches

Low density bad for exposure

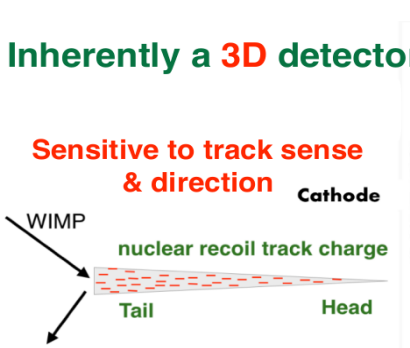
$He, CF_4, CS_2, CHF_3, C_4H_{10}, SF_6$

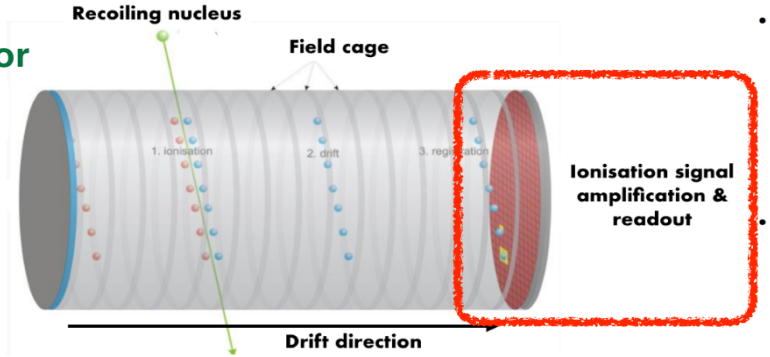
Long recoils O(mm)

TPCs at atmospheric or lower pressure for GeV WIMP mass sensitivity

Inherently a 3D detector

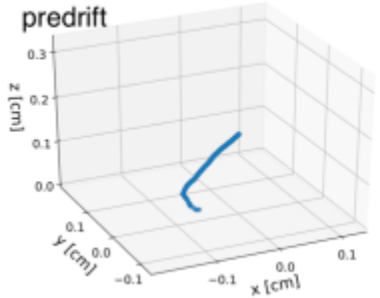
Sensitive to track sense & direction

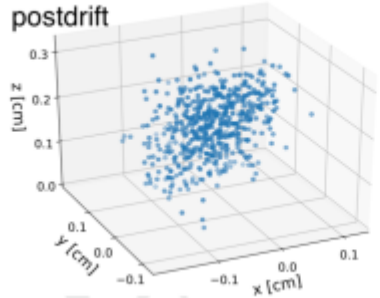




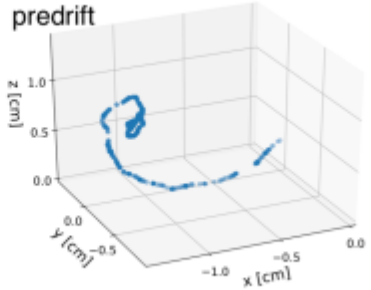
- Advantages:
  - Axial Directionality
  - **Head/tail**
  - Background rejection
  - Particle ID
  - 3D fiducialization
- Technologically challenging, but now achievable via multiple technologies

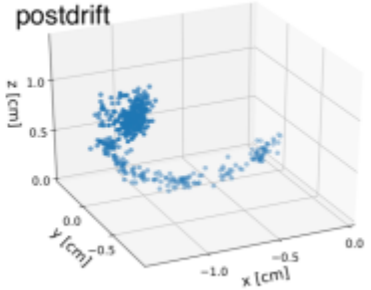
Directional reconstruction demostrated down to O(keV)





25 keV_{nr} NR in $He:SF_6$ 755:5





20 keV_{ee} NR in $He:SF_6$ 755:5

Negative Ion Operation

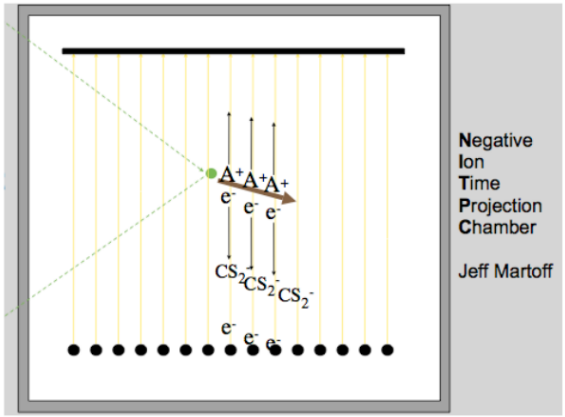
It consists in the addition of a high electronegative dopant to the gas (CS_2, SF_6)

Improved track resolution thanks to limited diffusion

- electrons get attached to the dopant close to the ionization position o(100) um
- Anions drift acting as the image carrier but with a longitudinal and transverse diffusion reduced to the thermal limit

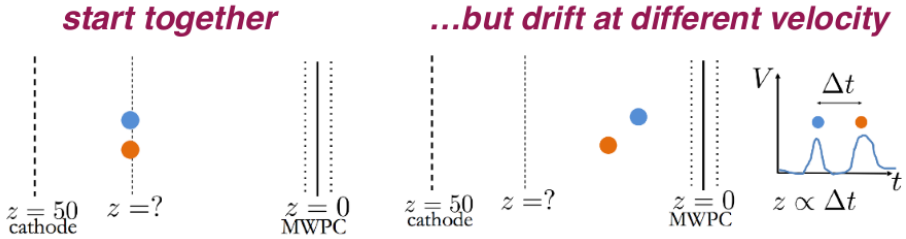
T. Ohnuki et al., J. Martoff et al., NIM A 463

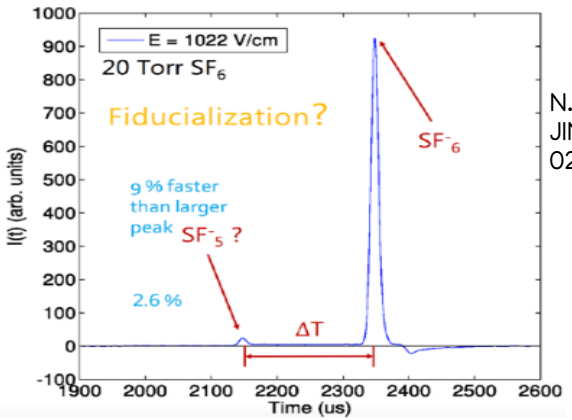
J. Martoff et al., NIM A 440 355



Full 3D fiducialization

- Thanks to multiple charge carriers, the difference in mass induces a difference in arrival time





N.S. Phan et al., JINST 12 (2017) 02, P022012

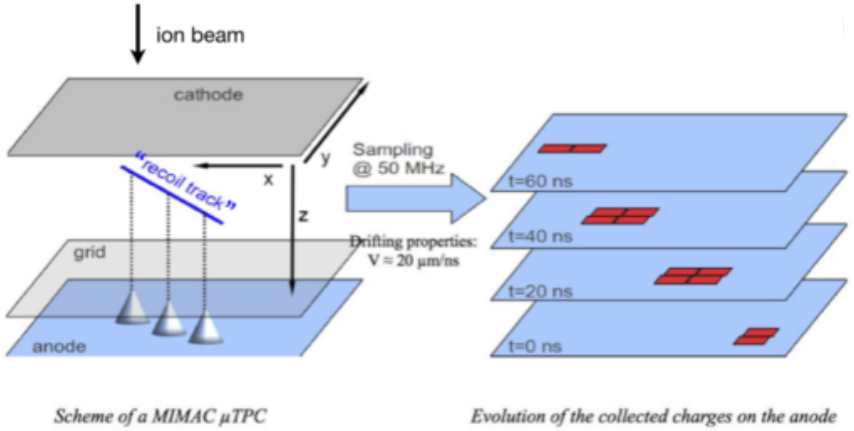
Status of the Art

	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***

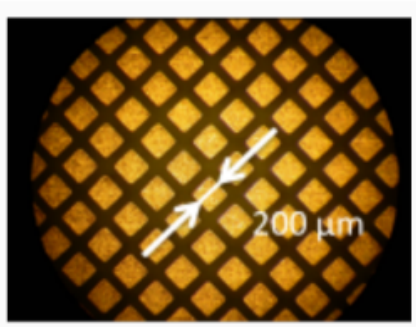
MIMAC (France)

- Micromegas +FADC
- CF_4:CHF_3: C_4H_{10} 70:28:2 at 38 torr

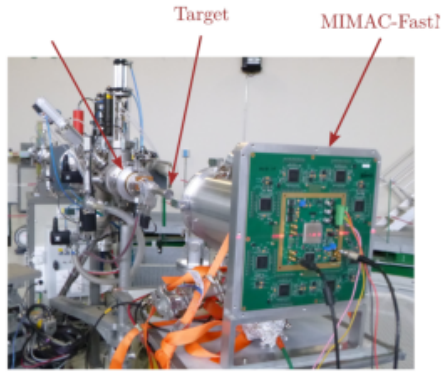


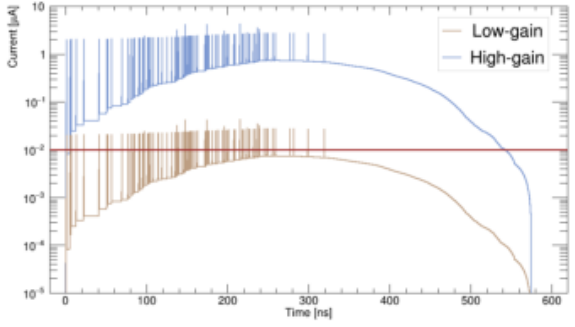
Scheme of a MIMAC µTPC *Evolution of the collected charges on the anode*

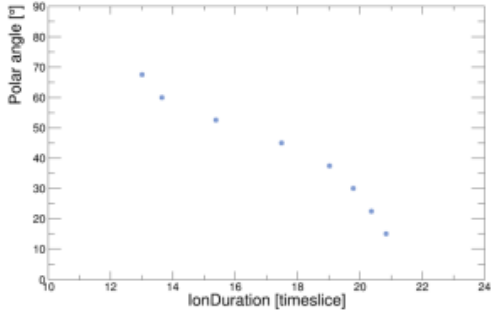
25 cm drift



Anode

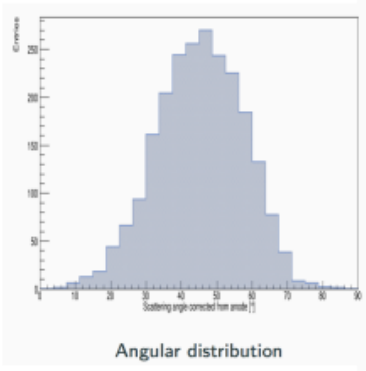




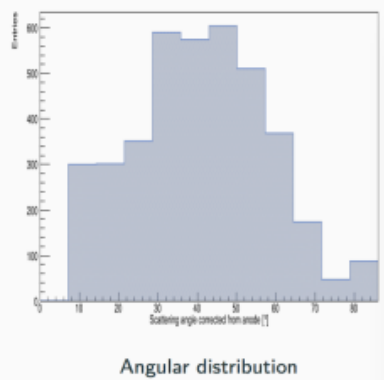


(b) The correlation between the polar angle and `IonDuration`.

Disentangling ionic signal gave possibility to measure head/tail



Angular distribution



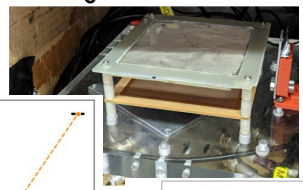
Angular distribution

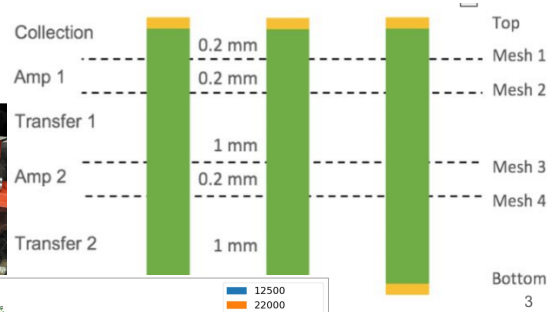
Angular resolution of 15° at 8 keV

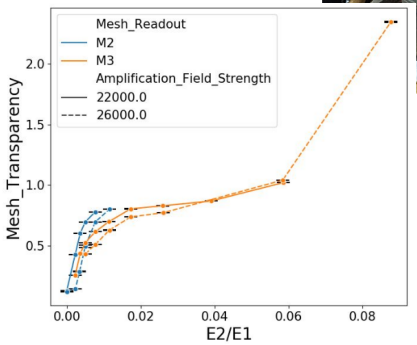
DRIFT (UK)

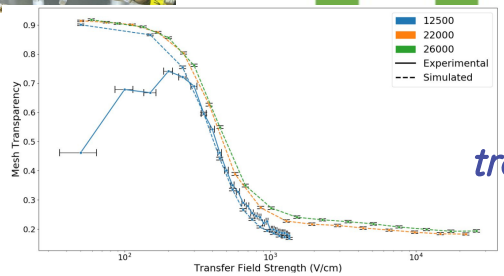
R&D on gas amplification structures

- Hybrid THGEM–Micromegas
- 40 torr of CF_4 or Sf_6



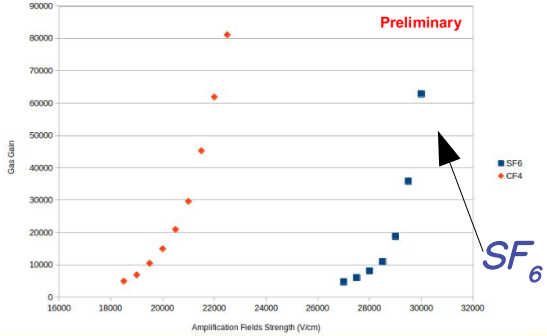






Optimizing transparency to electrons

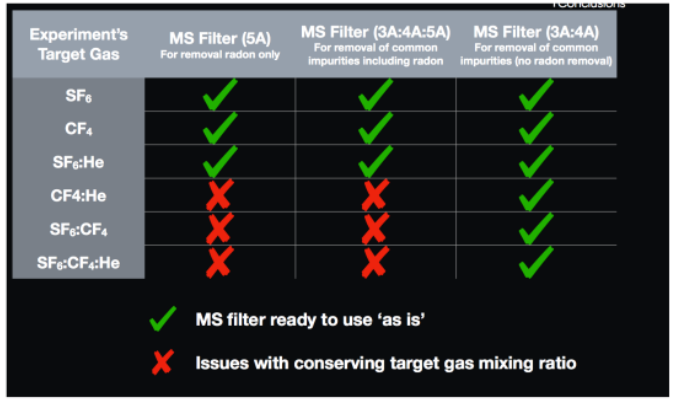
Negative ions at low pressure (40 torr)

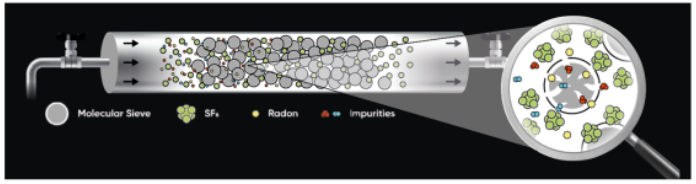


Collaborating with NEWAGE

SF_6 gain reached 10^5

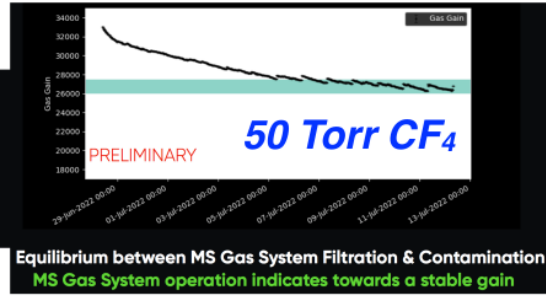
R&D on gas purification



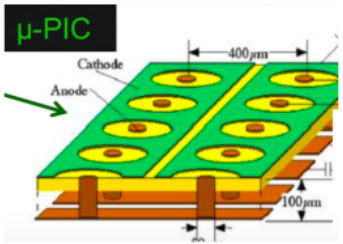


Collaborating with CYGNO

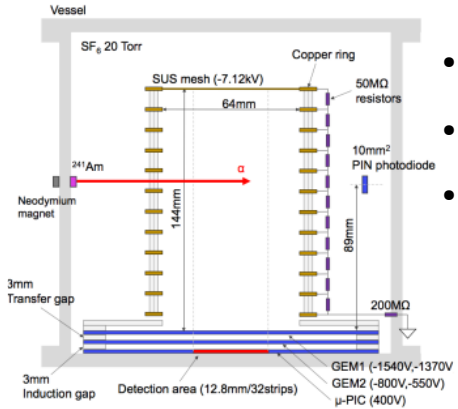
MS	Emanated per captured x10^{-3}
Sigma Aldrich (Commercial)	5.4±0.7
Nihon-Uni (V2)	<0.057



NEWAGE (Japan)



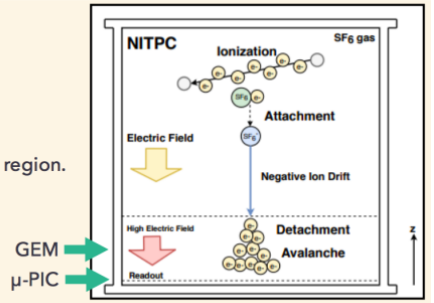
- 10x10 cm²
- Pitch 400 um
- Made in Japan



- MuPic+ GEM amplification
- 20 torr SF_6
- 14,4 cm drift

Development of Garfield –++ simulation

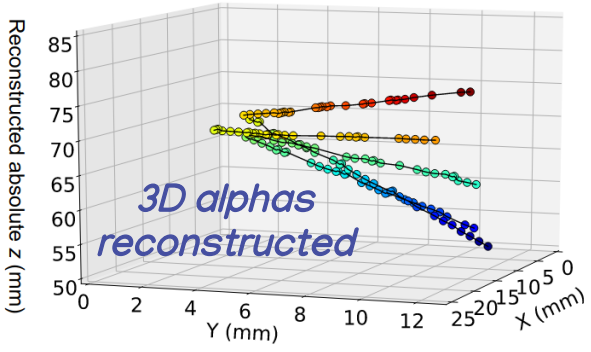
1. Ionized electrons are produced.
2. Attachment.
3. Negative ion are produced.
4. Negative ion are drifted.
5. Detachment in high electric field region.
6. Avalanche amplification.



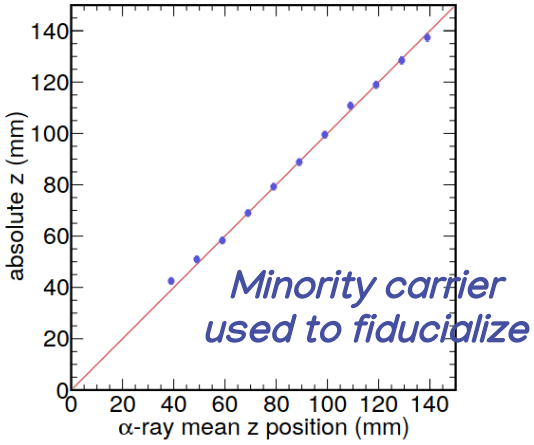
- Cross section model

Detach with probability by calculating the mean free path from energy vs cross section.

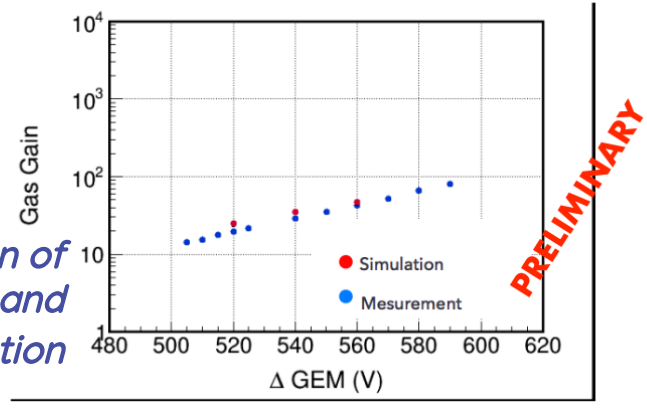
Measurements of alpha particles with 130 um resolution



JINST 15 (2020) 07, P07015

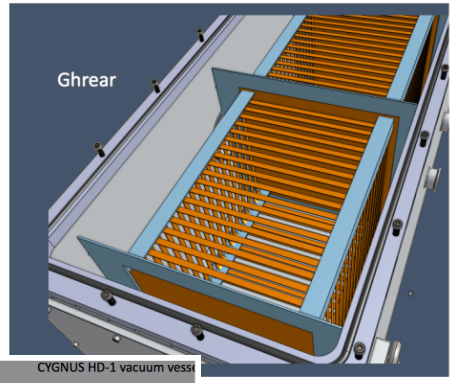


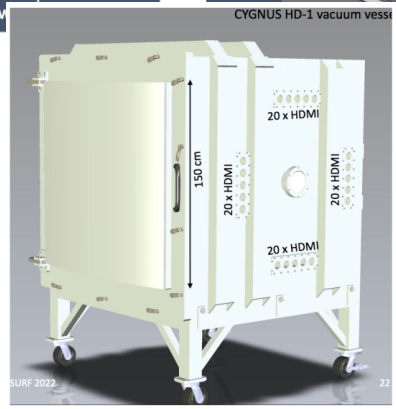
First simulation of SF_6 ion drift and amplification



D3/CYGNUS-HD (US)

- CYGNUS HD "Keiki"
- CERN strip Micromegas + SRS
- 20 x 20 cm^2 readout area
- 50 cm drift length x 2 (double sided)

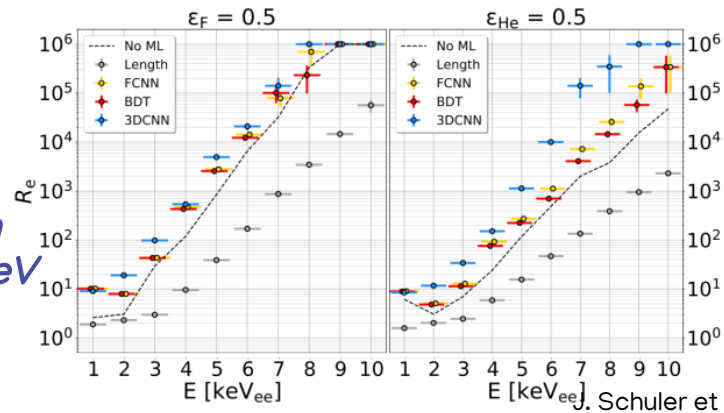




Vessel design for 1 m^3 ready!

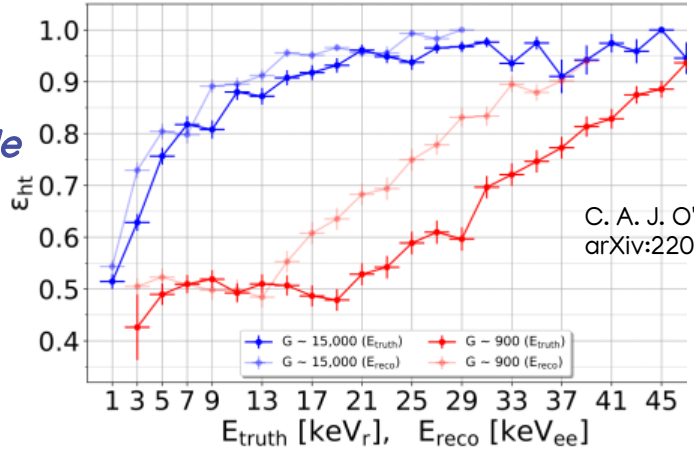
ML techniques for background discrimination and head tail

O(10^5) rejection of ER below 10 keV



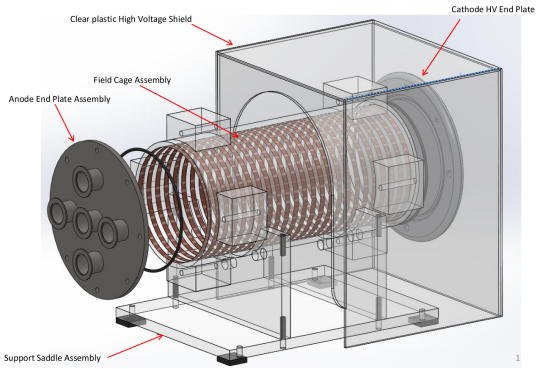
J. Schuler et al, arXiv:2206.10822

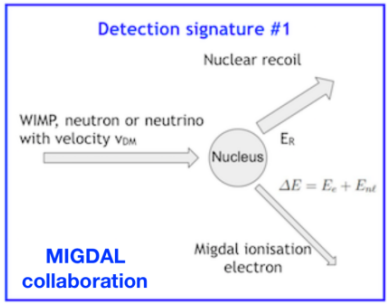
Head/tail possible down to 1 keV



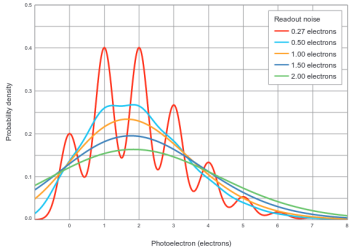
C. A. J. O'Hare et al, arXiv:2203.05914

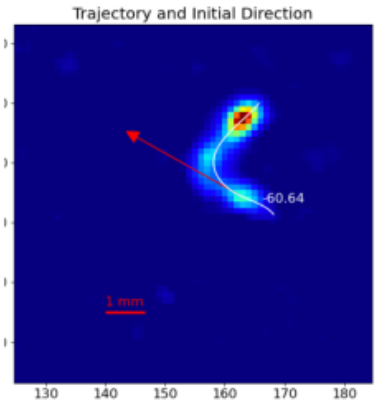
New Mexico (US)



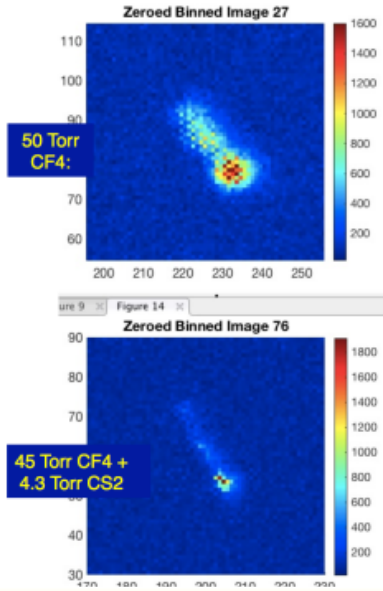


- Optical readout: CCD and Hamamatsu ORCA QUEST
- Measurement of MIGDAL effect
- 2 Glass GEM 570um thick
- Low pressure NID
- Up to 50 cm drift

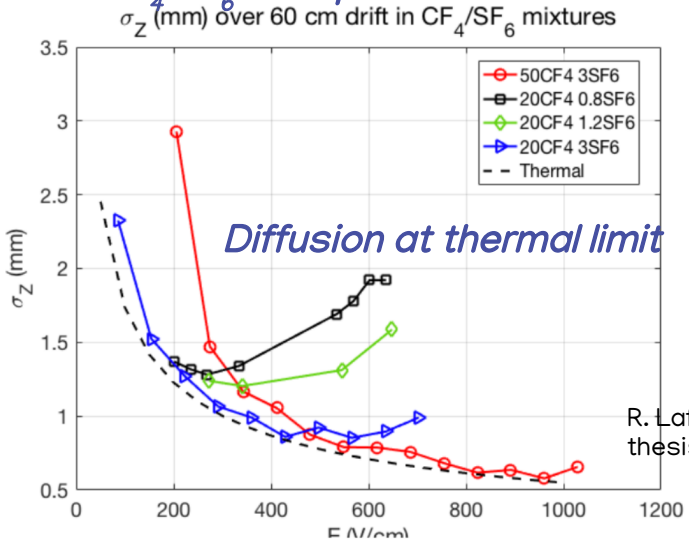




Head/tail and direction reconstruction with ^{55}Fe

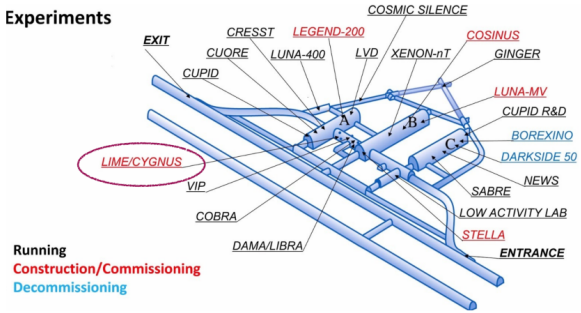


CF_4:SF_6 NID operation 20–50 torr

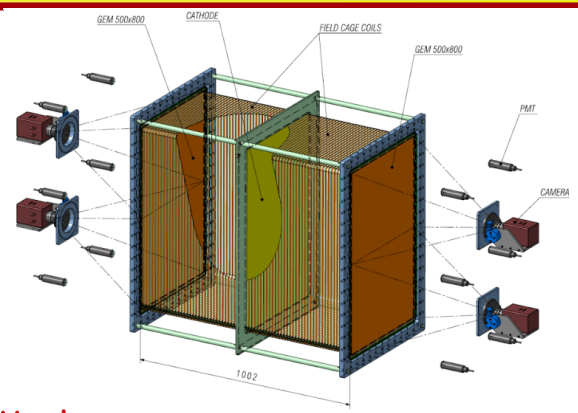


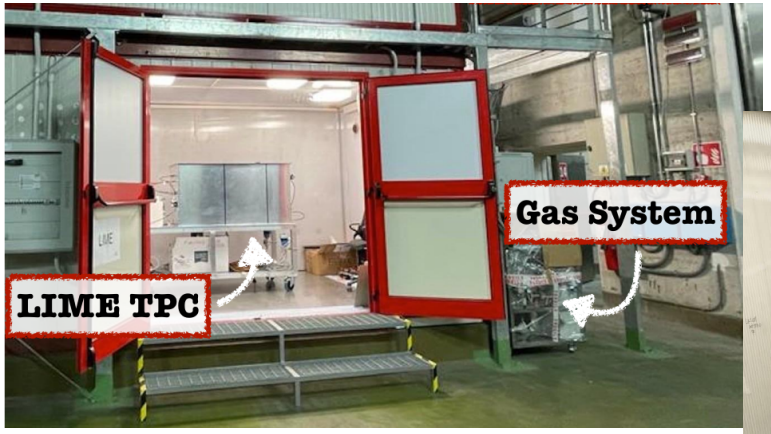
R. Lafler, PhD thesis, 2019

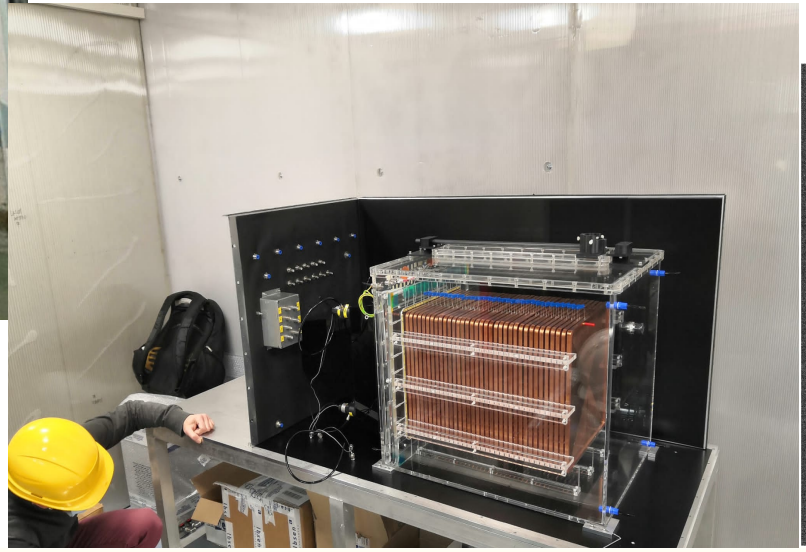
CYGNO (Italy)



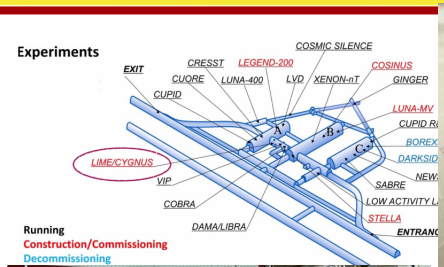
- Optical readout: sCMOS camera and PMTs
- 3 GEM 50um thick
- Atmospheric He:CF_4 60/40
- 50 cm drift
- 50 l underground @ LNGS
- 0,4 m^3 funded and TDR submitted

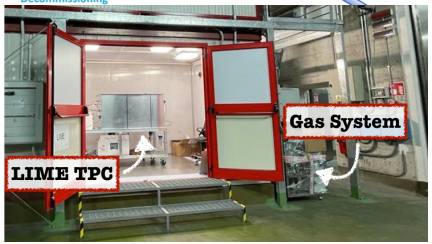


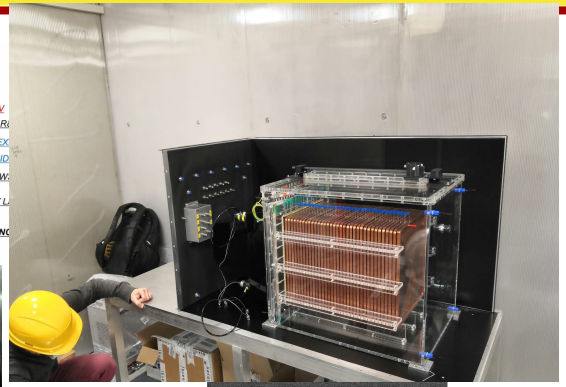




CYGNO (Italy)







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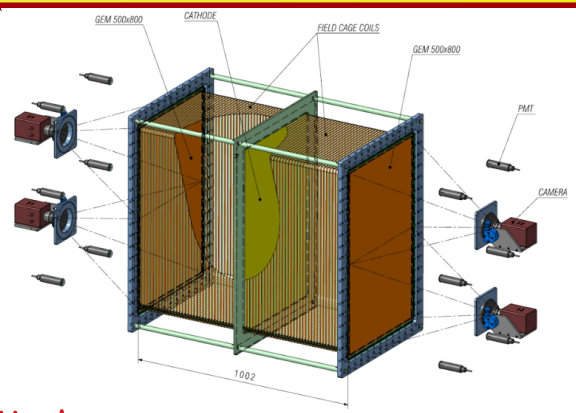
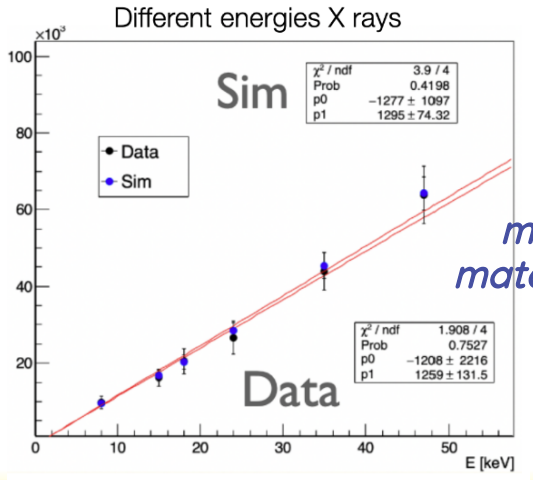
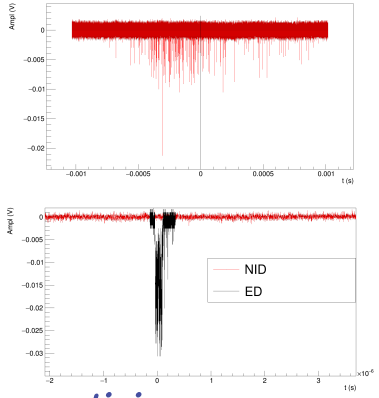
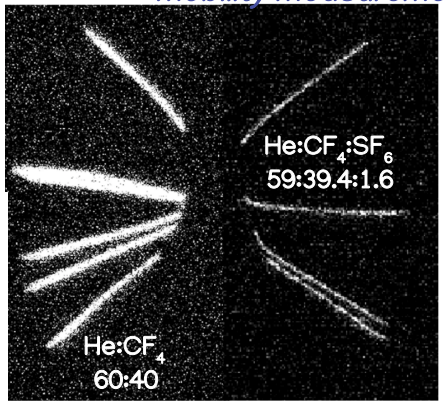


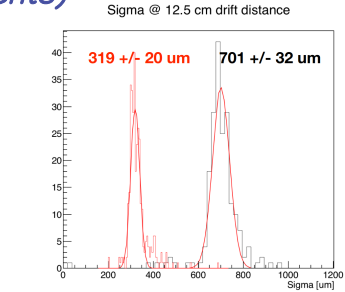
NID at high pressure demonstrated (ion mobility measurements)



Linearity measurements matched simulations







See poster of S. Piacentini

Part of this project has been funded by the European Union's Horizon 2020 research and innovation programme under the ERC Consolidator Grant Agreement No 818744

And then...

CYGNUS Proto-collaboration

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





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

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

CYGNUS Proto-collaboration

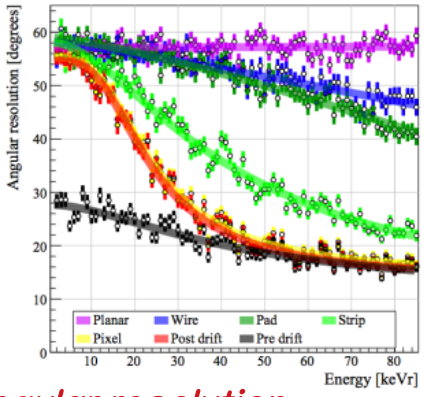
- Extensive paper on a 1000 m^3 gaseous NITPC detector for WIMP search through nuclear recoils

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

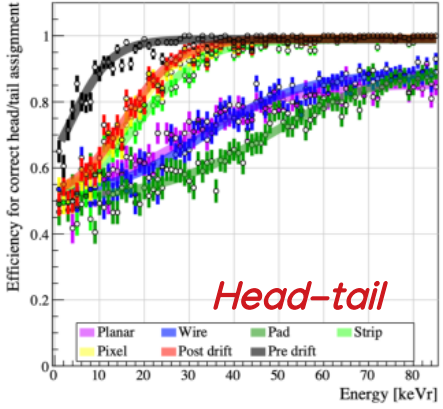
S. E. Vahsen,[1] C. A. J. O'Hare,[2] W. A. Lynch,[3] N. J. C. Spooner,[3] E. Baracchini,[4,5,6] P. Barbeau,[7] J. B. R. Battat,[8] B. Crow,[1] C. Deaconu,[9] C. Eldridge,[3] A. C. Ezeribe,[3] M. Ghrear,[1] D. Loomba,[10] K. J. Mack,[11] K. Miuchi,[12] F. M. Mouton,[3] N. S. Phan,[13] K. Scholberg,[7]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

- Detailed simulation of seven readout options with cost/benefit evaluation
- Background simulations and rejection studies and engineering of the construction

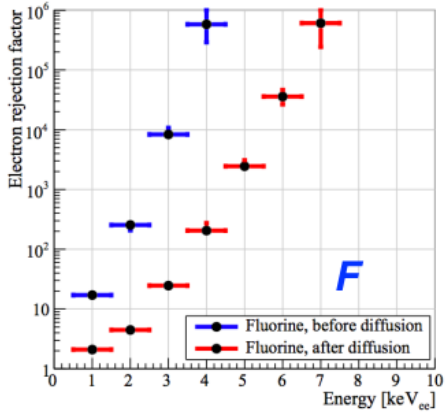
- *Pixels best at recovering the 3D track*
- *Strips almost as good but lower cost*

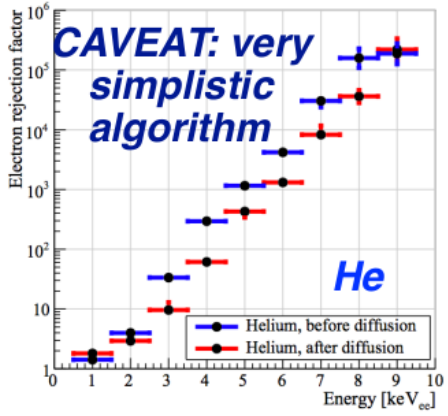


Angular resolution



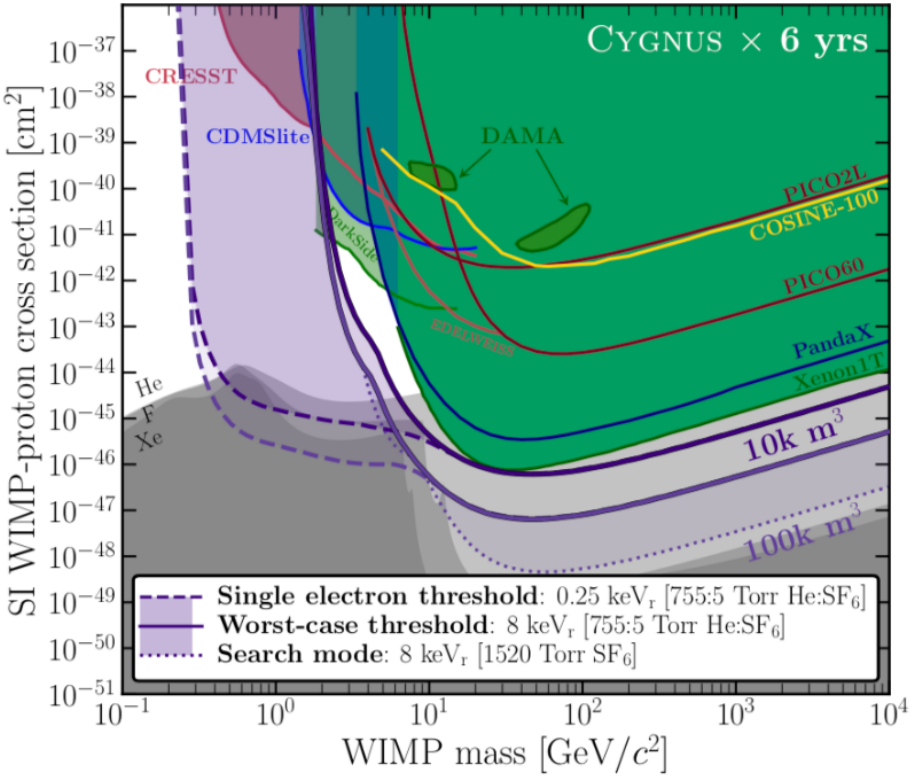
Head-tail



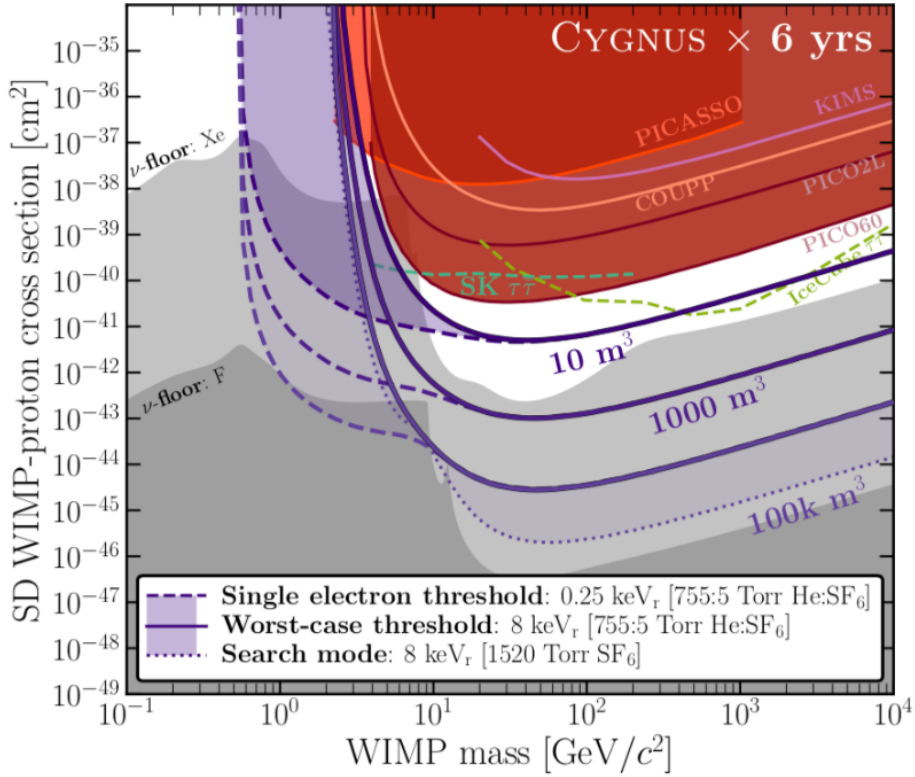


Rejection at O(keV) ER rejection possible

CYGNUS: WIMP Search and Optimization



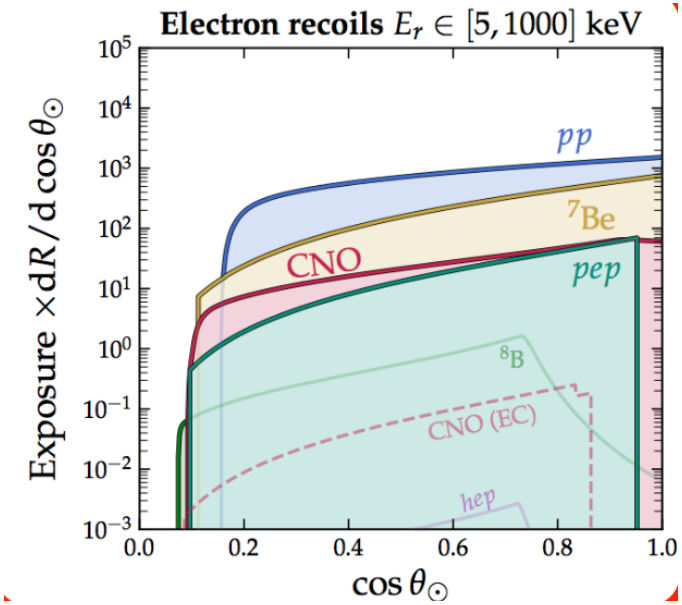
Significant contribution at low masses and expected to be measure 10–50 neutrinos

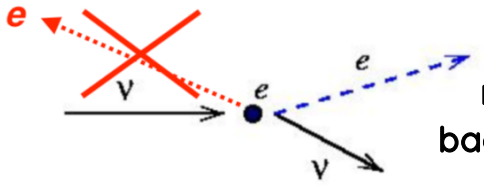


SD sensitivity with fluorine is expected to strongly improve current status

CYGNUS: Neutrino and e-recoils

Number of ER recoils induced by neutrinos vs angle away from the Sun

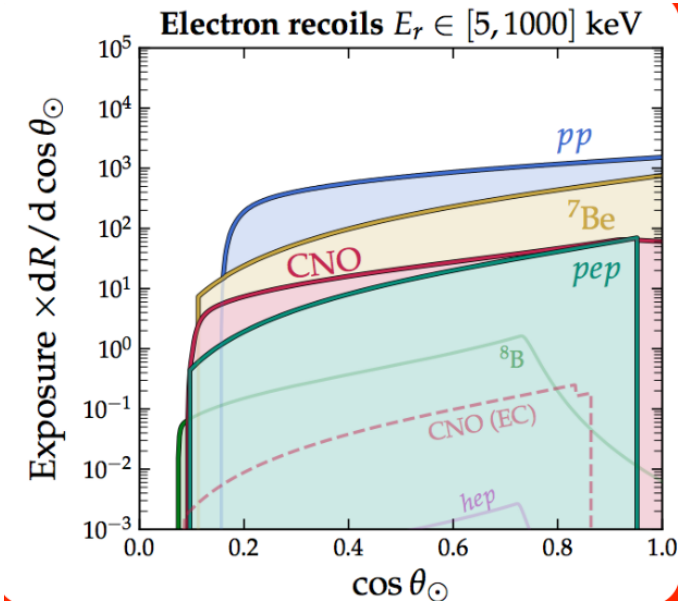


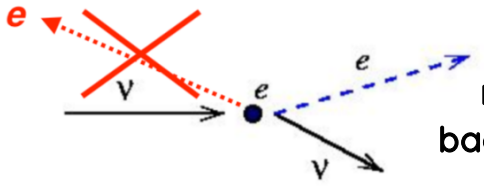


Kinematics allow to measure directly the background where recoils cannot happen

CYGNUS: Neutrino and e-recoils

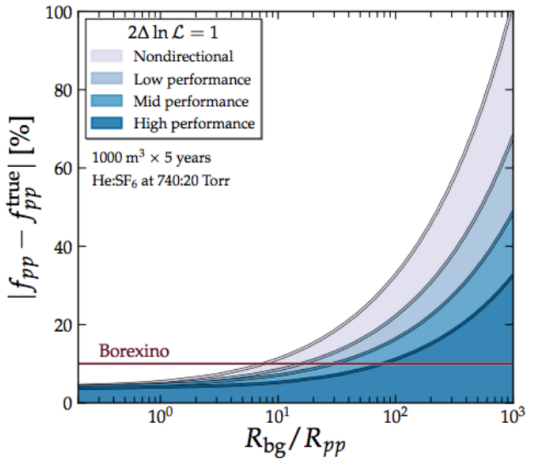
Number of ER recoils induced by neutrinos vs angle away from the Sun



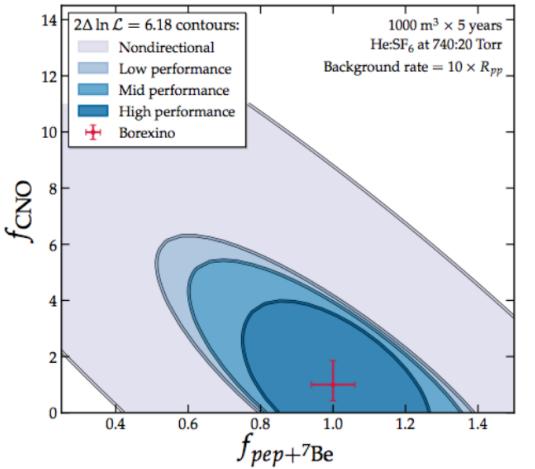


Kinematics allow to measure directly the background where recoils cannot happen

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

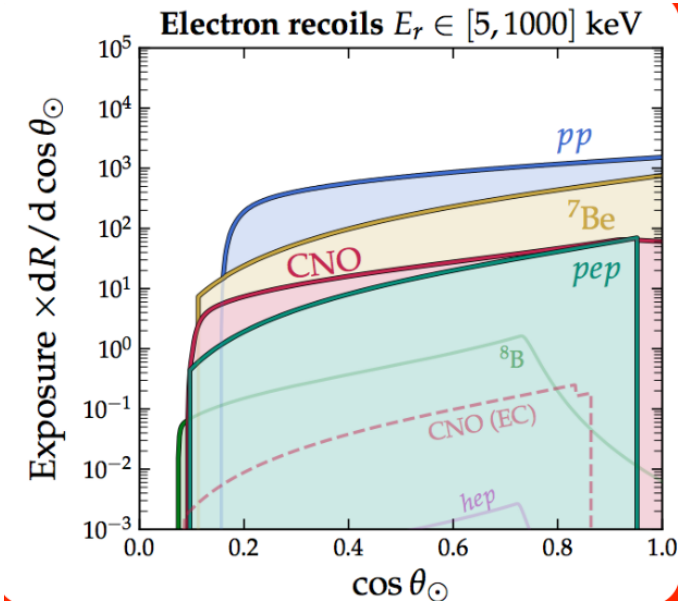


2 σ sensitivity to combined measurement of the CNO and pep + 7 Be pp fluxes, fixing the background rate to 10 times the pp electron recoil rate



CYGNUS: Neutrino and e-recoils

Number of ER recoils induced by neutrinos vs angle away from the Sun



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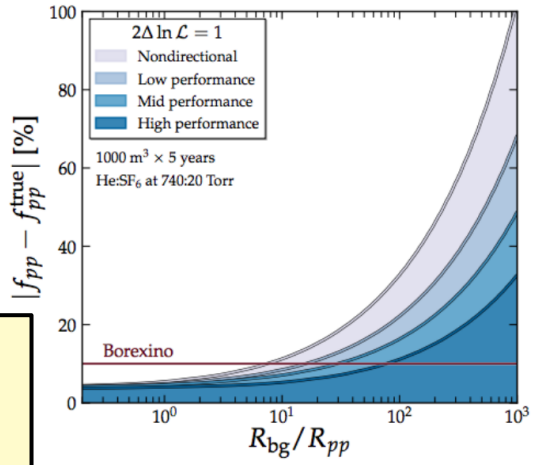
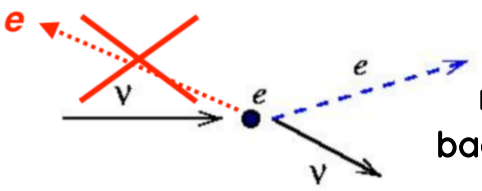
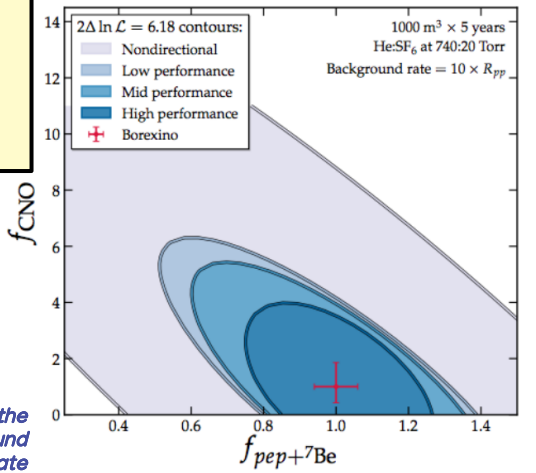


Solar neutrinos spectroscopy possible with CYGNUS:

- Borexino measurement could be extended at lower energies with O(10) m³ detector
- CYGNUS 1 ton could measure the CNO cycle



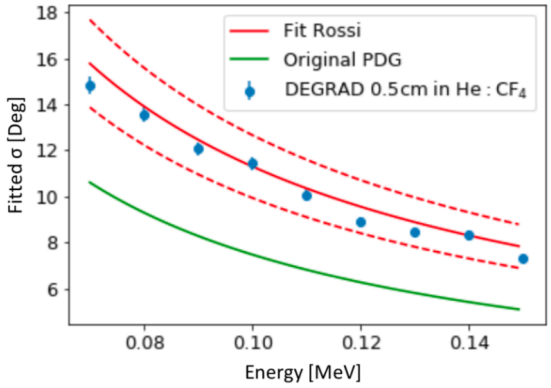
Kinematics allow to measure directly the background where recoils cannot happen



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

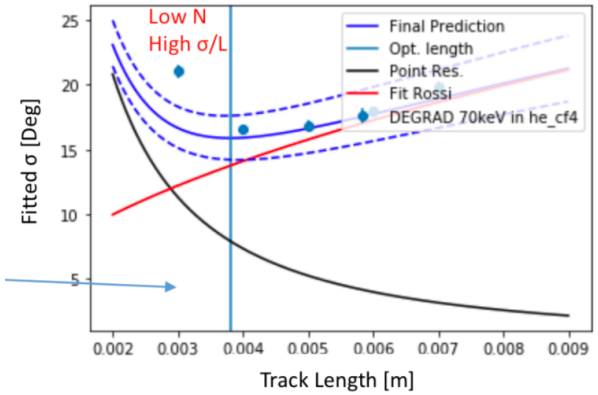
CYGNUS: Neutrino and e-recoils

- Improvements for electron recoil studies are ongoing



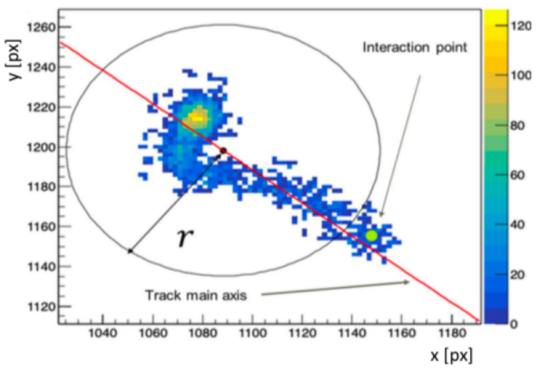
Simulating the actual multiple scattering in gases with DEGRAD

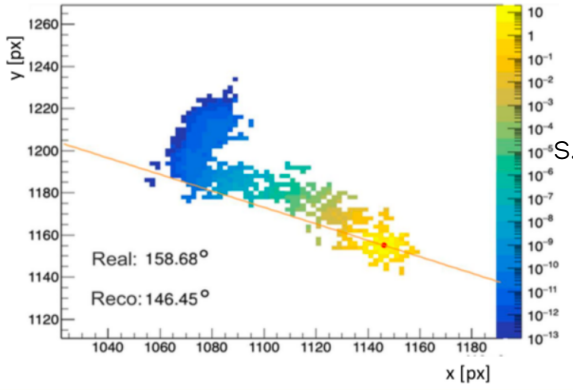
And evaluatig the expected angular resolution



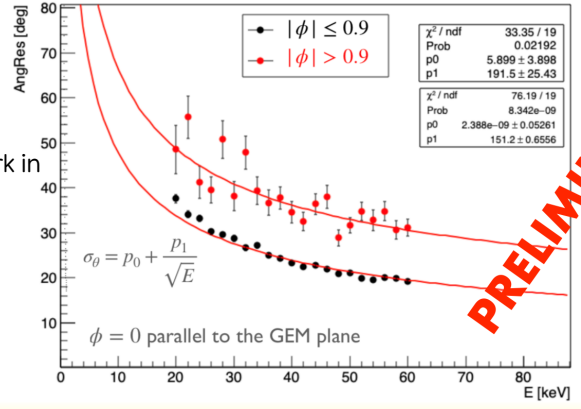
M. Ghrear & S, Vahsen, paper in preparation

Studying algorithms to retrieve the original direction of recoils





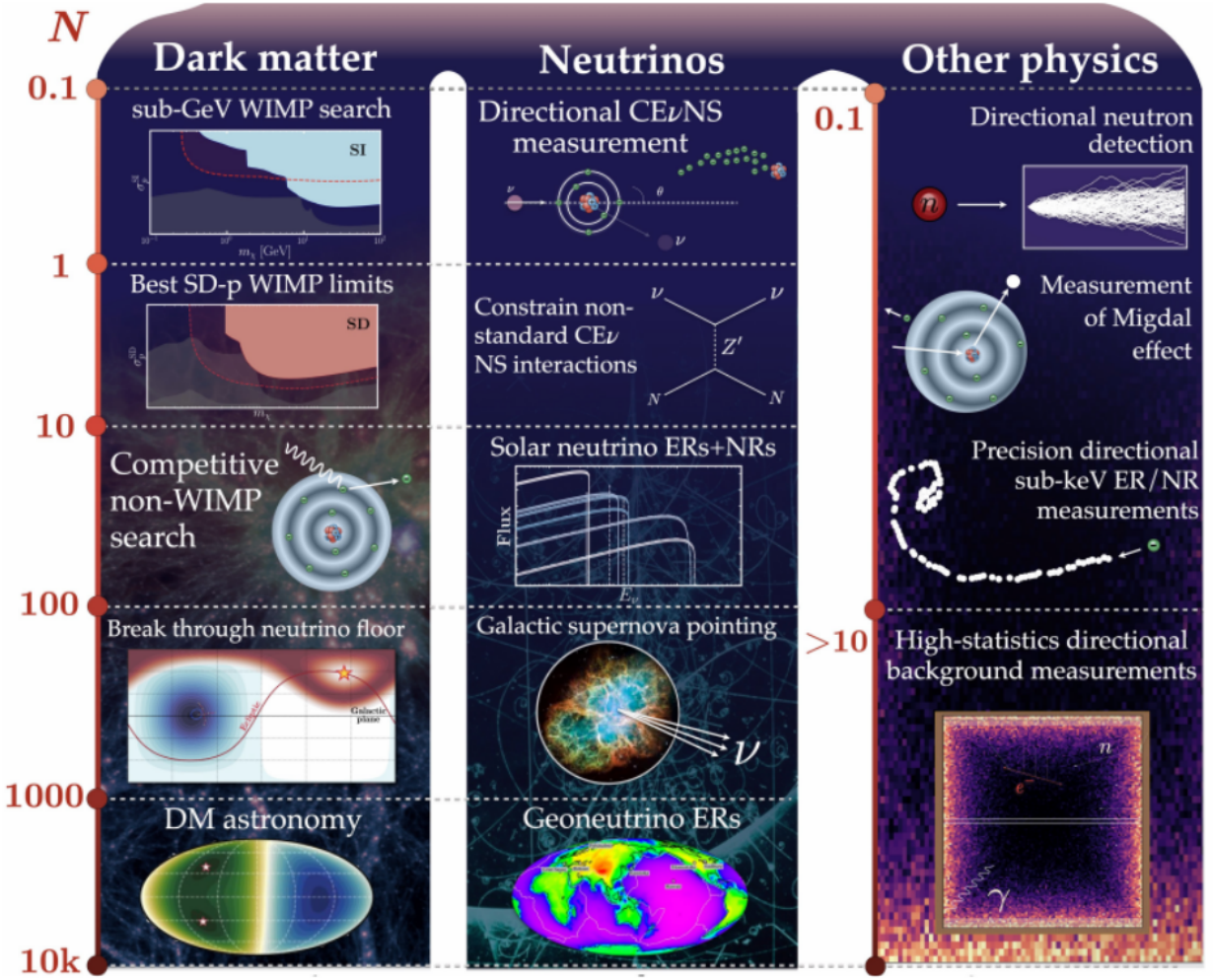
S. Torelli thesis work in CYGNO



CYGNUS: Physics Case

N = volume in m^3 and atm pressure

Many different physics studies at different scales!



Conclusions

- Today and future uncertainties (excess..) and background sources (neutrino fog..) on the Dark Matter landscape shows the necessity of exploiting extra measurable quantities.

- Directionality is the only viable option to finally positively identify and characterize DM and distinguish from other source of potential signal

- Experimentally, more and more techniques are under development or demonstrated the feasibility to measure direction of nuclear recoils induced by various DM candidates

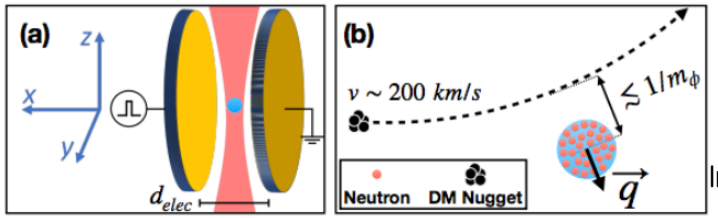
- The recoiling imaging of the recoils of the gaseous TPC is focused on the classical WIMP paradigm and is well established with good performances and already the possibility to scale at O(1) m^3 towards the realization of CYGNUS

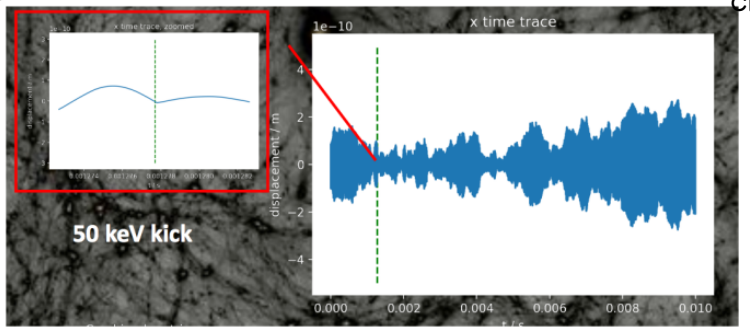
- CYGNUS projects aims at building a large scale detector for Galactic Electron and Nuclear Recoil Observatory at ton scale with time-resolving 3D imaging capabilities with the potential already expressed in an extensive conceptual and practical paper and in the Snowmass paper

BACKUP

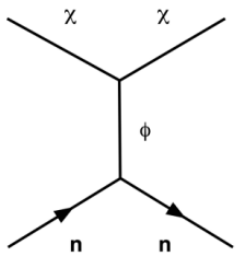
Solid: Crystals

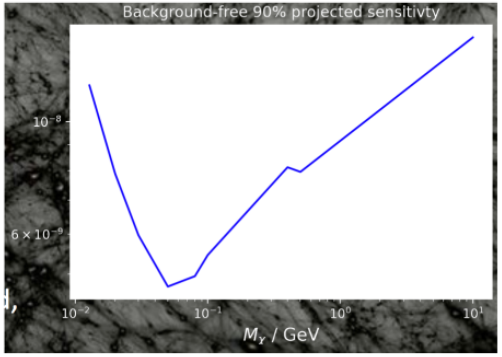
Levitating SiO_2





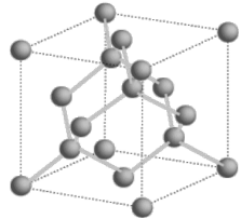
In case of DM interaction characteristic electrical signals on plates are measured in every direction

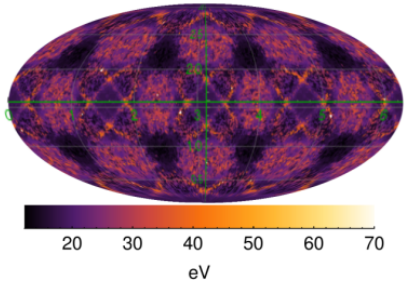




Ge crystal anisotropies

- Conjecture: The threshold for creating an electron-hole pair has a similar directional dependency.
- This idea is supported by time dependent density functional theory (TDDFT) calculations.





Promising proposal for MeV DM candidates