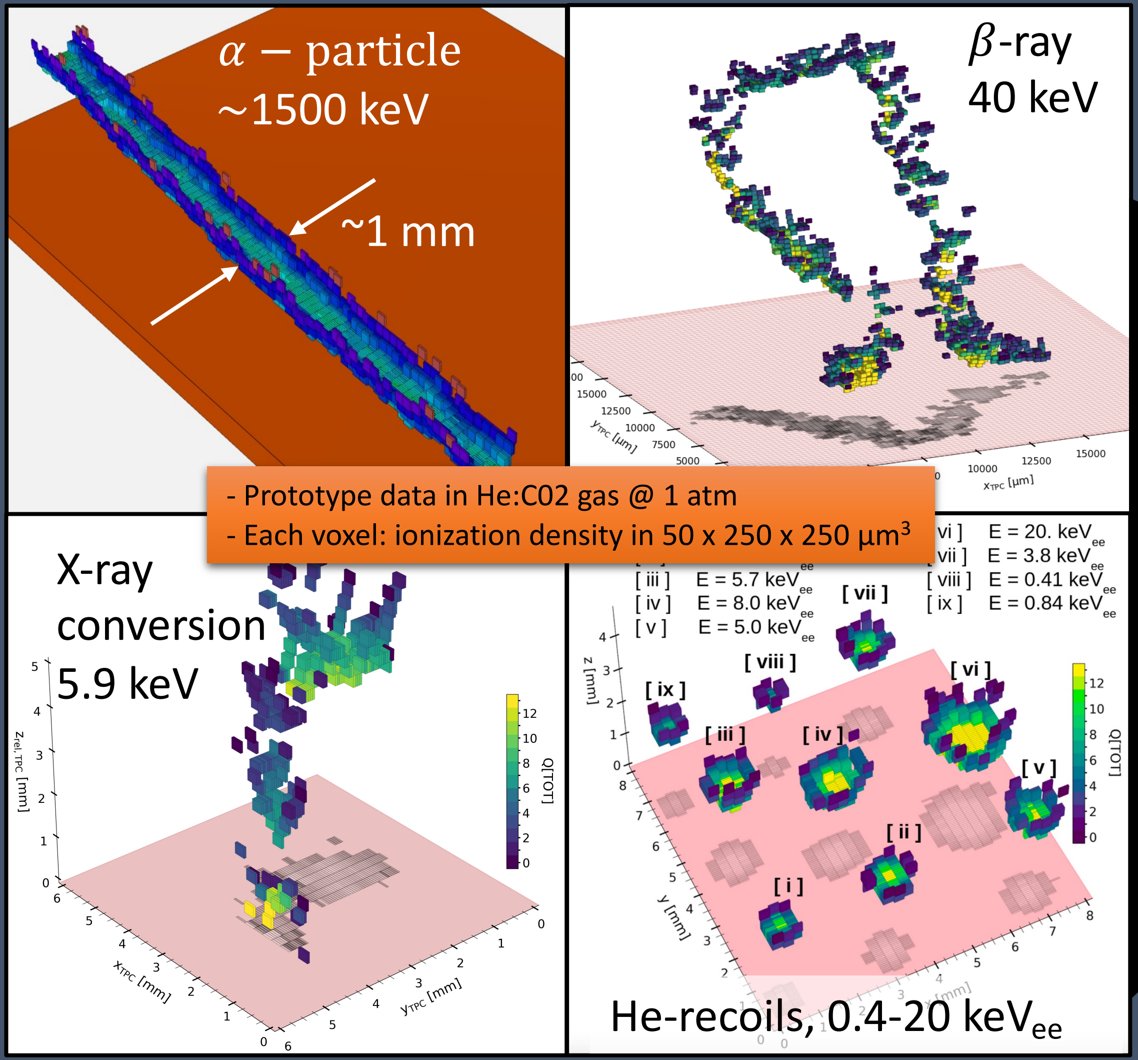
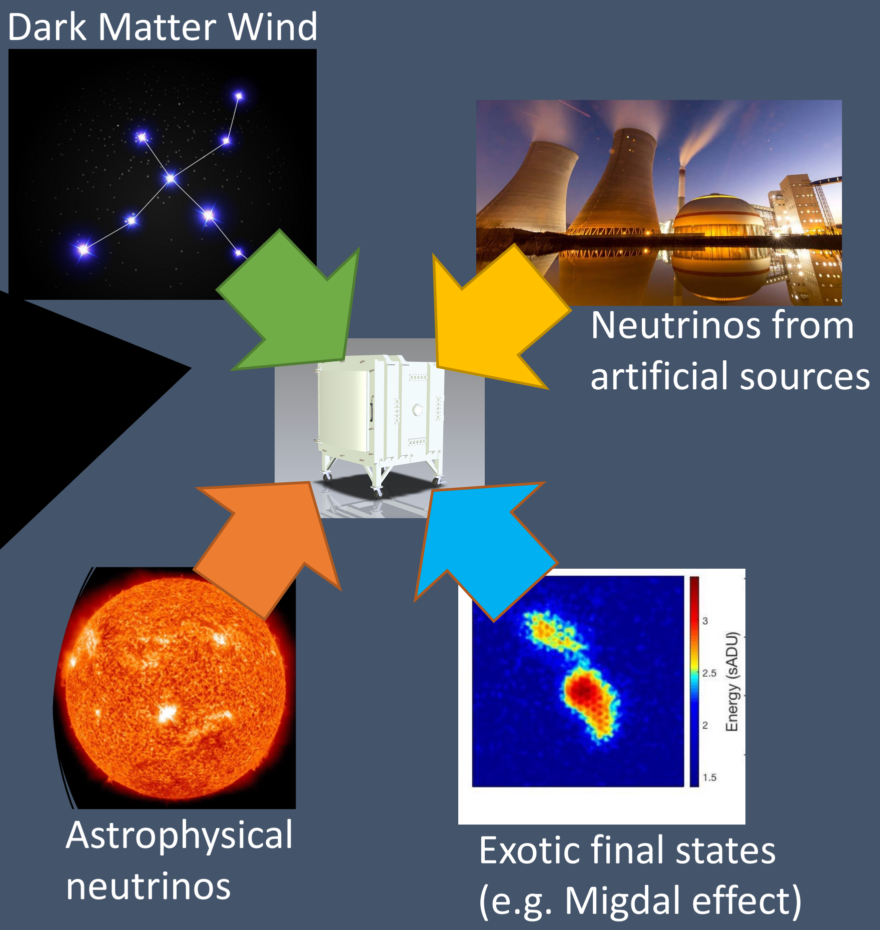
Directional Dark Matter Detection

Sven Vahsen (Univ. of Hawaii)



"recoil imaging": detection of detailed ionization topology in gas TPCs



- A Snowmass working group of 167 physicists considered the case for "recoil imaging" (arXiv:2203.05914)
- Topological and directional reconstruction of low-energy nuclear and electronic recoils enables new experiments

https://indico.cern.ch/event/1258644/

- Please join us in Australia in December!
- Workshop will have broad scope, to grow the Snowmass effort and community further

8th CYGNUS Workshop on Directional Recoil Detection

Dec 11 – 15, 2023
Sydney Nanoscience Hub (SNH)
Australia/Sydney timezone

Enter your search term

- Overview
- Scientific Program
- Venue and transportation
- Call for Abstracts
- Timetable
- Contribution List
- Book of Abstracts
- Registration
- Participant List
- Visa information

We invite you to join us in Sydney, Australia for the 8th edition of the international *CYGNUS Workshop on Directional Recoil Detection.*

Location: School of Physics, University of Sydney, NSW, Australia

When: 11th - 15th December 2023

Conference fee: Free!

Topics covered include:

- Directional detection of dark matter
- Directional neutrino detection
- Directional neutron detection
- Gas TPCs and MPGDs
- Novel directional detection technologies
- Recoil simulation tools
- Detection of rare nuclear decays

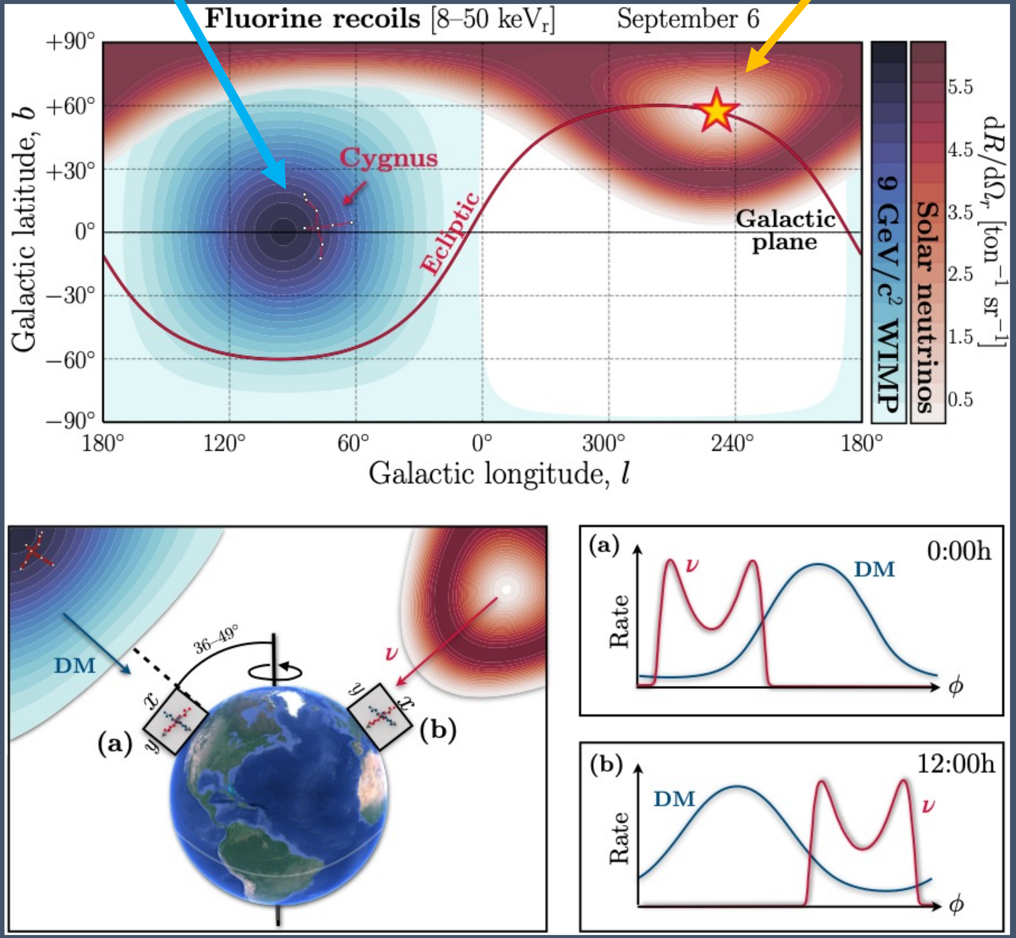
The Power of Directionality

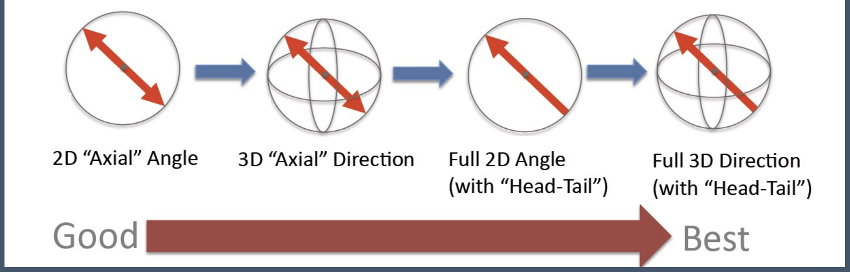
- Positively identify galactic origin of a potential dark matter signal
  - w/ only 3-10 recoil events
  - 10^2 -10^3 x stronger effect than annual oscillation)
- Distinguish dark matter and solar neutrinos
- Want 3D-vector-directionality at event-level
  - 3d recoil axis
  - head/tail
  - Ionization energy
- *Recoil imaging* provides this!

→ Fewest events for DM discovery

→ Enables Neutrino spectroscopy

arxiv:2102.04596

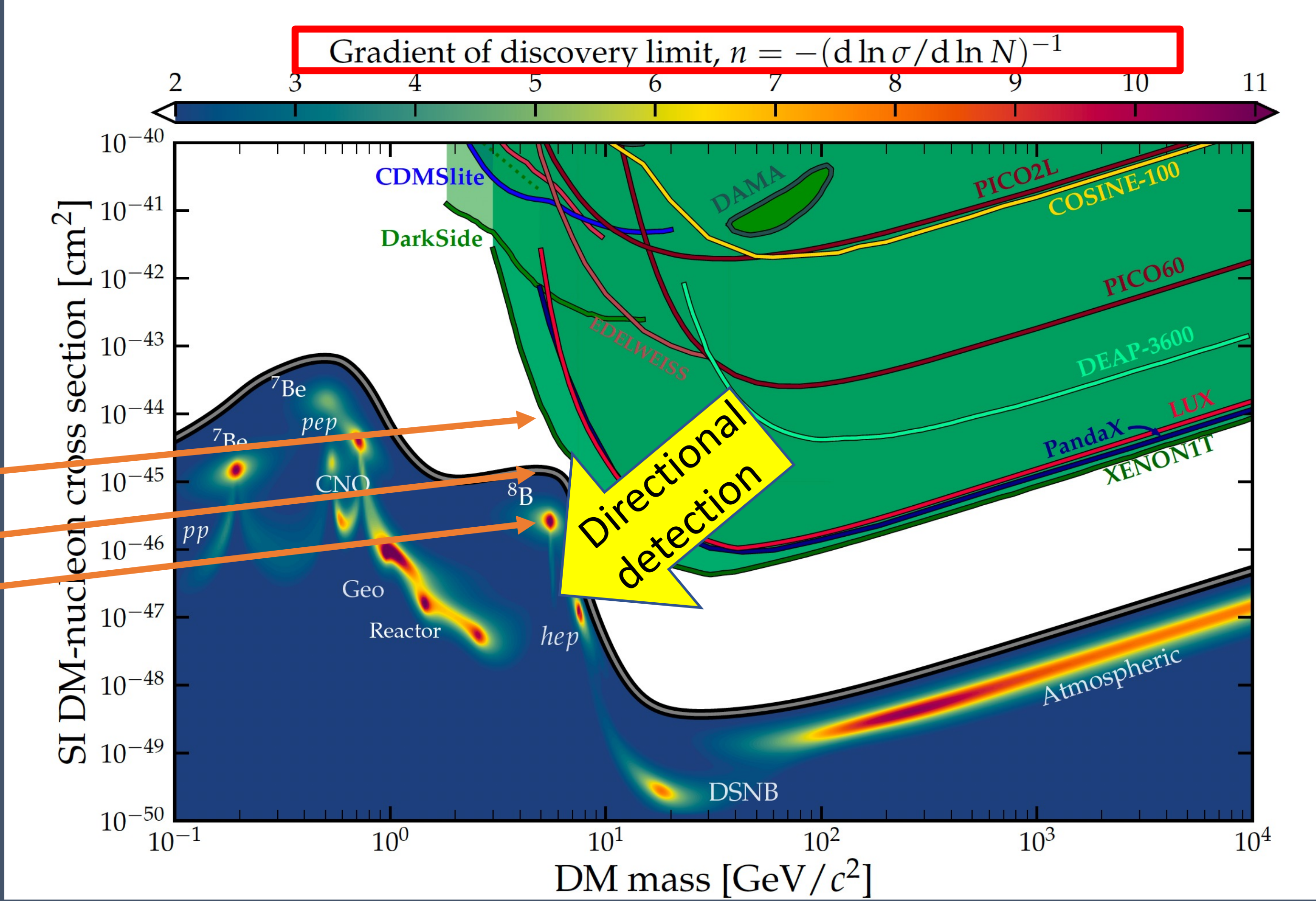




Turning the Neutrino Fog into an Opportunity

O'Hare, PRL 127 (2021) and
C. A. J. O'Hare et al., Snowmass White Paper on recoil imaging

- Dark matter direct detection experiments approaching 'neutrino fog'
  - Irreducible backgrounds from coherent elastic neutrino-nucleon scattering, a.k.a. CEυNS
  - Solar neutrinos relevant first
- Neutrinos reduces DM sensitivity of detectors
  - index *n, which* quantifies sensitivity reduction
  - To reduce σ sensitivity by factor 10, need 10^n larger exposure
- Directional detectors
  - can separate neutrino and DM signals!
  - n remains <2 even in the neutrino fog
  - fog becomes a positive: A source of guaranteed signal in DM experiment!



Directional detectors can separate neutrino and WIMP signals, hence are more motivated now than ever before

Opportunities for a 30+ year physics program

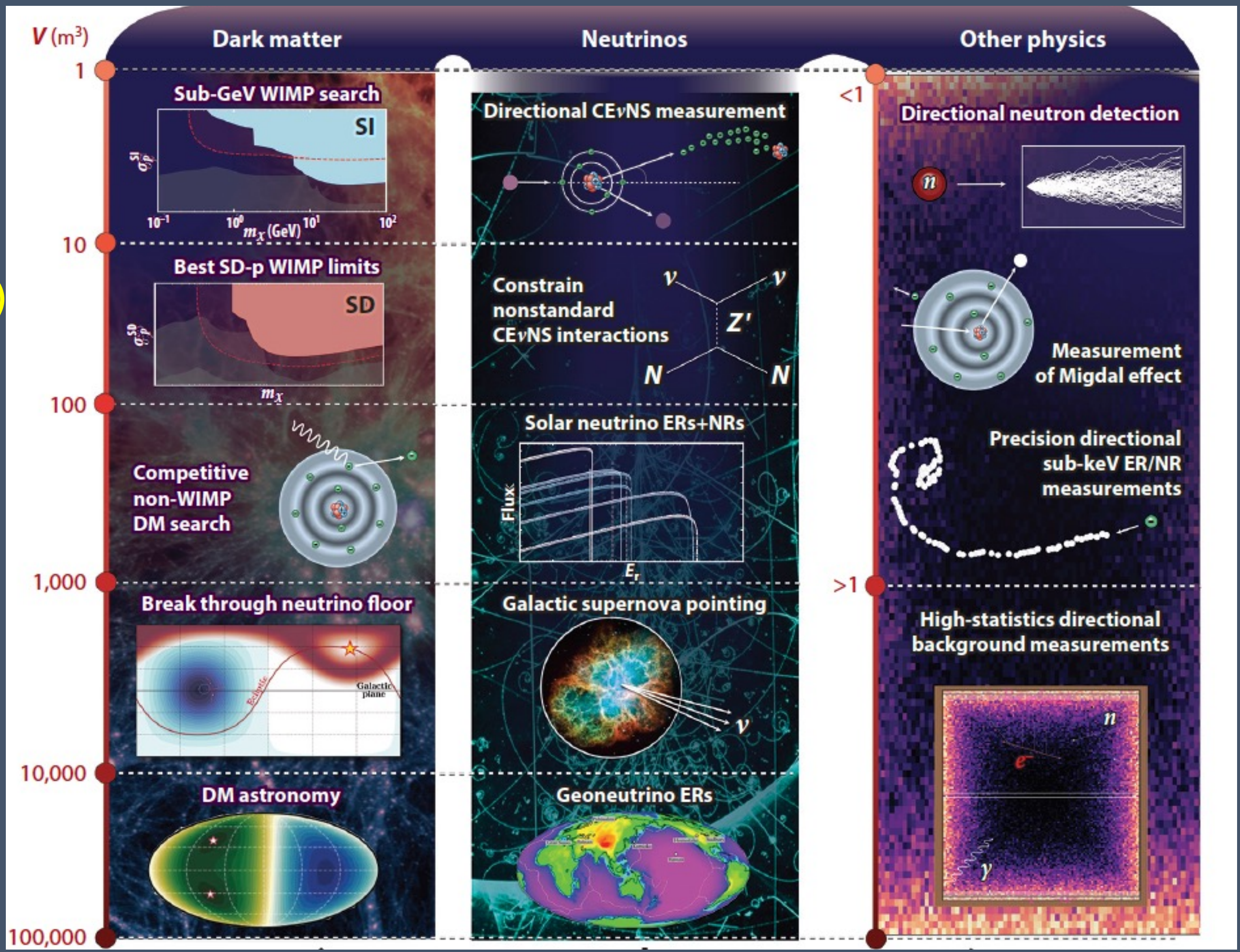
arxiv:2102.04596

Approx. volume of gas TPC required.
Expect 10 m^3 modules eventually

With *recoil imaging* directional detectors,
a smorgasbord of opportunities

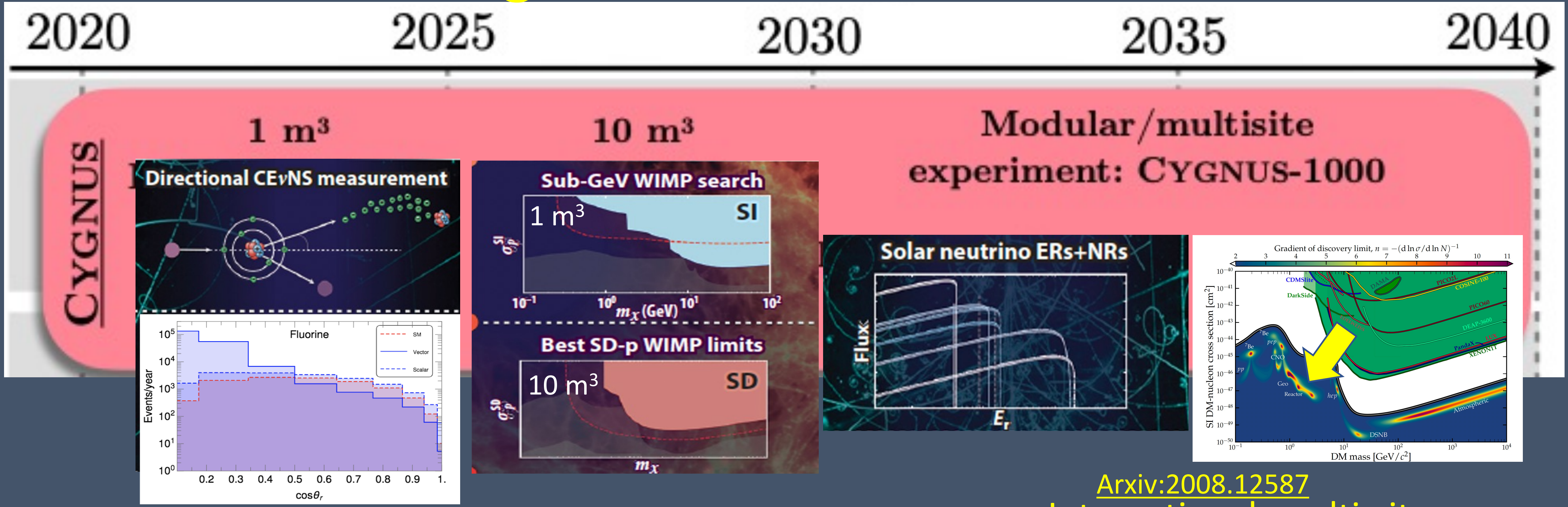
Exposure, size

- Quenching factor and recoil physics (TUNL)
- Migdal Effect measurement
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) at ORNL (SNS) or Fermilab (NuMI and later LBNF)
- Competitive DM limits in SI and SD
- CEvNS and e-recoils from solar neutrinos
- Efficiently penetrating the LDM ν floor
- Observing galactic DM dipole
- Measuring DM particle properties and physics
- Geoneutrinos
- WIMP astronomy



- New physics opportunities for each factor of 10 increase in exposure
- Both guaranteed measurements (yellow text) and novel, exciting searches --- across frontiers!

CYGNUS: US Program Vision & P5 Ask



Arxiv:2008.12587

SNS, Oak Ridge, TN
Directional BSM-search in CEvNS

SURF, Lead, SD
World-leading DM limits

International, multi-site
$10-50M, for 1000m³ in the U.S.
DM search in the neutrino fog!

- 3 years of R&D to establish electron counting & 1-keV recoil directionality
- Directional BSM search in 1 m³ ν-scattering experiment, aboveground
- Radio-pure 10 m³ experiment, underground (DM)
- MIE for large-scale, underground observatory (solar neutrinos + DM below neutrino floor) $10-50M (hardware only)

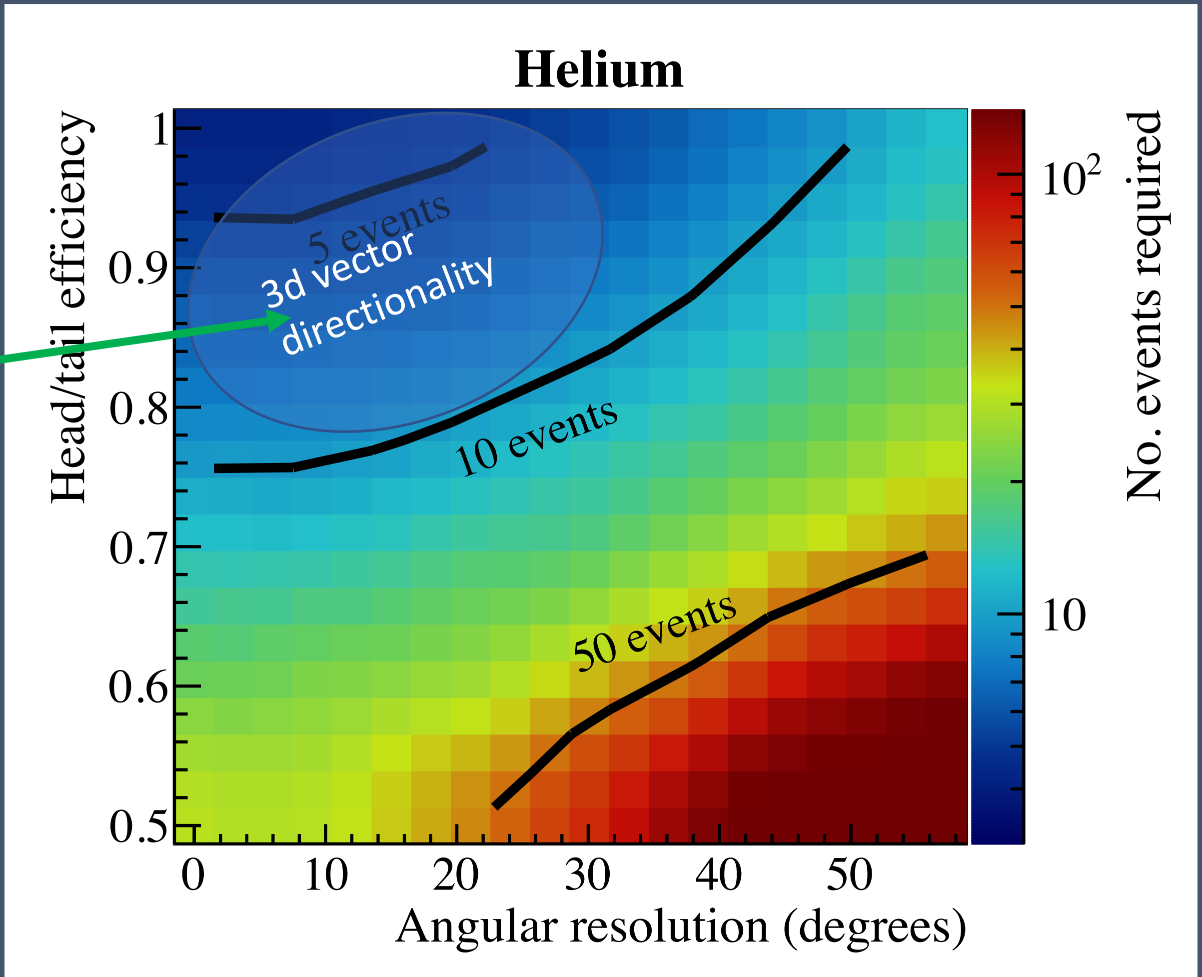
Detector Performance Requirements

(if targeting solar neutrinos and
m= ~10 GeV Dark Matter)

- Event-level recoil directionality
  - angular resolution ≤ 30 degrees
  - excellent head/tail sensitivity
- Rejection of internal electron backgrounds
  - by factor >= 10^5 for 1000 m^3 detector
- All of above down to E_{recoil} ~ 5 keV
- Energy resolution ~ 10% at 5.9 keV
- Timing resolution ~ 0.5 h

Head/tail recognition is critical!

https://arxiv.org/abs/2102.04596

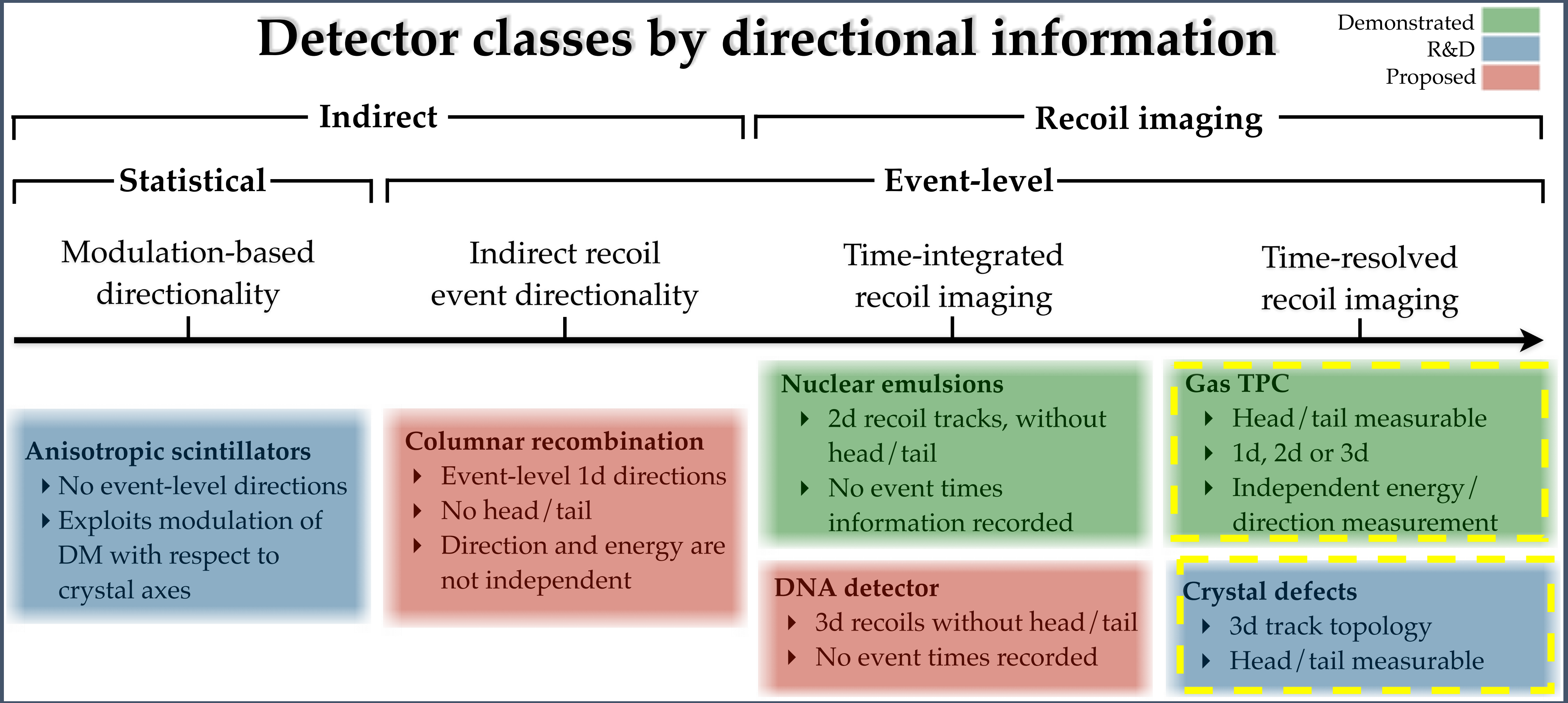


detected WIMP events required to exclude **ν**-hypothesis at 90% CL

Assumptions: m_χ = 10 GeV, He:SF_6 gas

Gas Detectors Required for "best directionality"

https://arxiv.org/abs/2102.04596



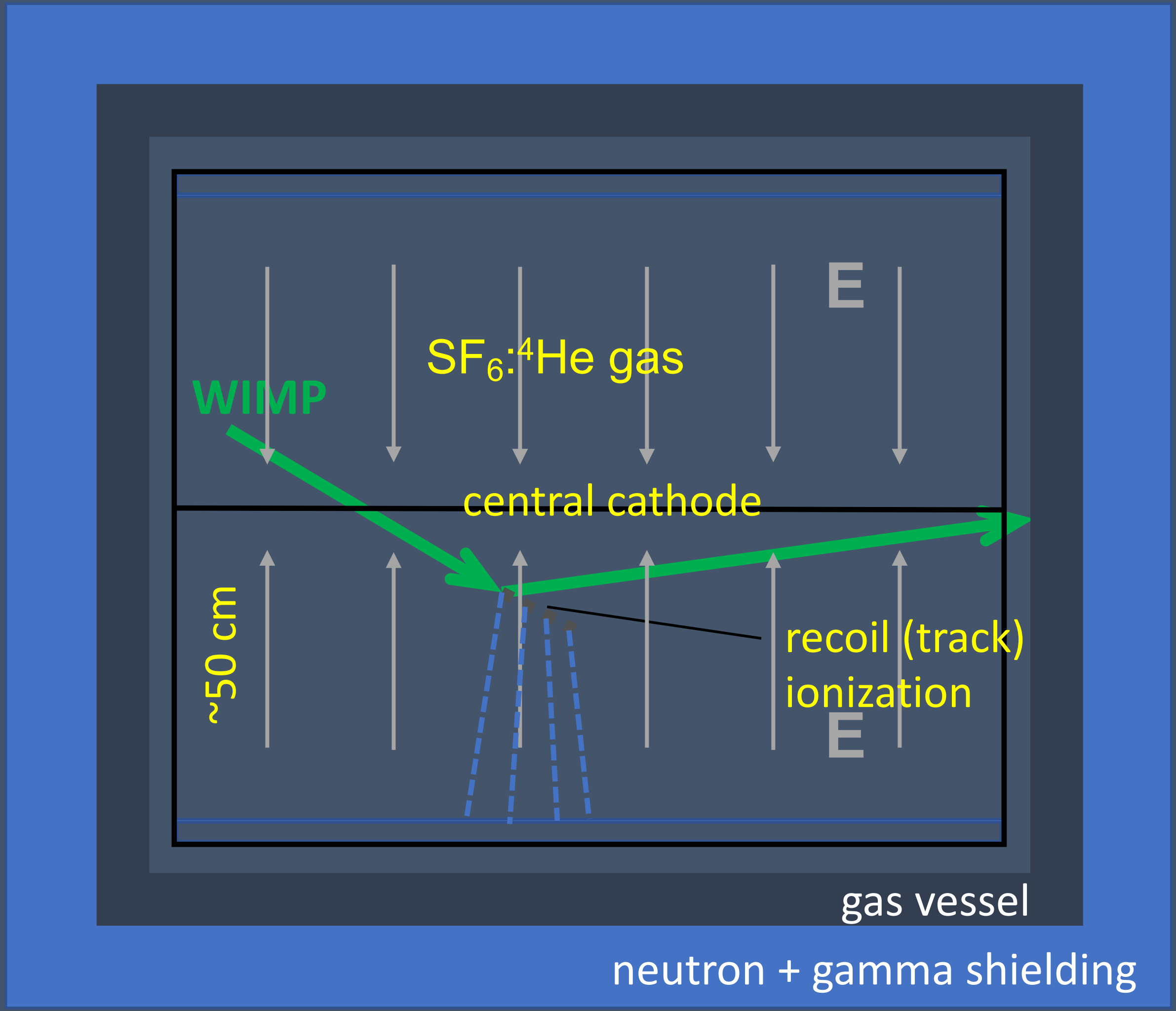
This talk

Next talk

Gas TPCs: provide time-resolved recoil imaging, enabling broad physics program beyond DM
cost-effective: non-cryogenic and easily scaleable to large volumes

Gas TPCs / CYGNUS: Experimental Approach

- Gas Time Projection Chamber
  - ~ 1-10 m^3 unit cells
  - ~ 100-1000 such cells. Flexible form factor.
- Gas mixture 1:
  - SF_6:^4He:X, p<=1 atm
  - Reduced diffusion via negative Ion drift (SF_6 gas)
- Gas mixture 2:
  - CF_4:^4He:X, p<=1 atm
  - Trades diffusion for higher gain
- Fluorine: SD WIMP sensitivity
- Helium target
  - SI, low mass WIMP sensitivity
  - Longer recoil tracks, extending directionality to lower energies
- 3D fiducialization techniques
  - SF_6 minority carriers
  - charge cloud profile



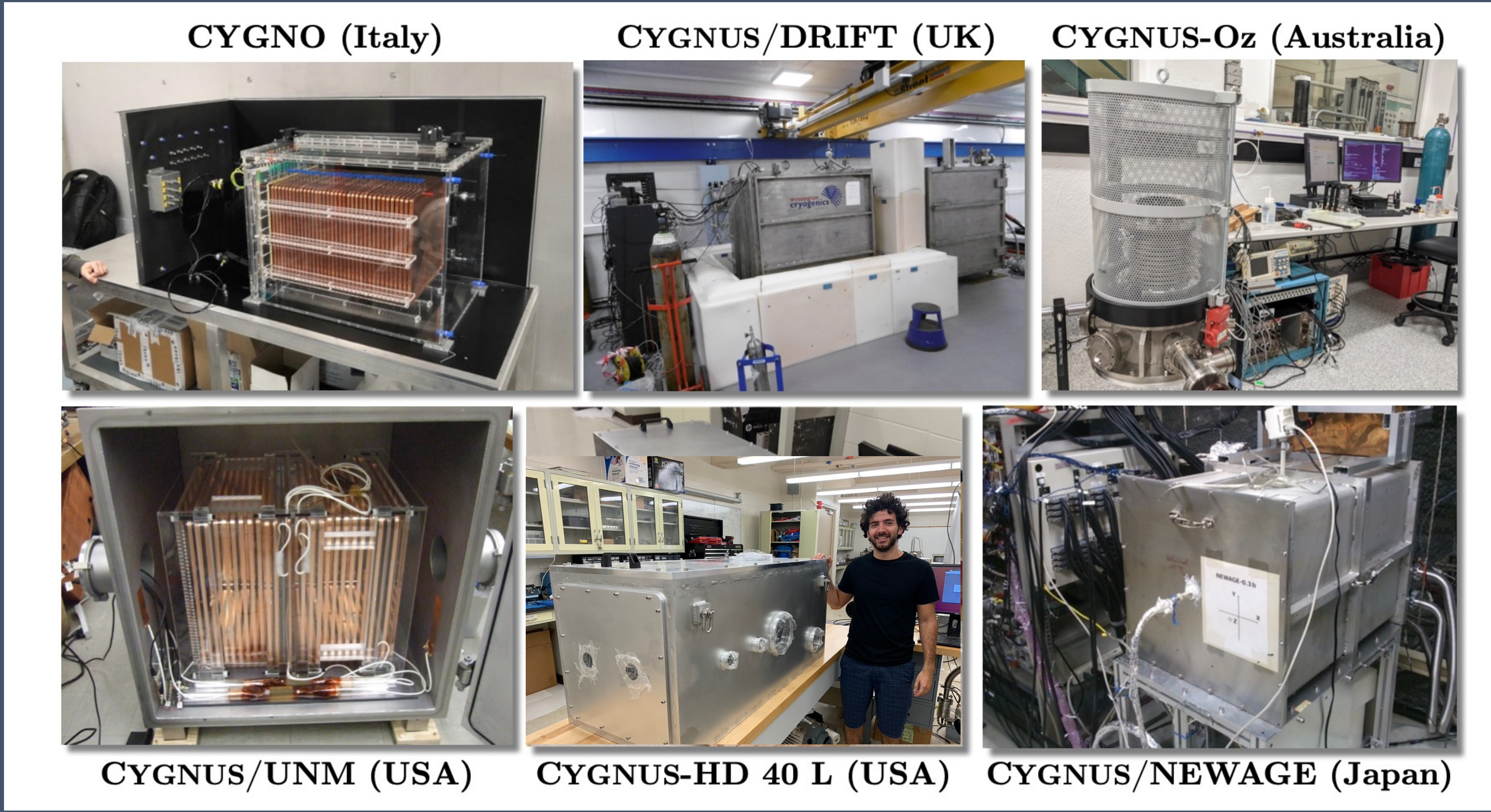
Both electronic and optical charge readout being investigated

Prototypes and Experiments

Name	Detector, [TPC readout]	Directionality	Status
NEWAGE	**Gas TPC**, GEM + μPIC, **NID**	3d	Running underground (Kamioka), scaling up to $1m^3$
DRIFT	**Gas TPC**, MWPC, **NID**	1.5d	Ran $1m^3$ underground (Boulby). MPGD R&D at Sheffield.
MIMAC	**Gas TPC**, Micromegas + Strips	3d	Ran underground (Modane), scaling up
DMTPC	**Gas TPC**, Optical readout	2d	Ran underground (WIPP), scaled up, stopped
D^3 / BEAST / CYGNUS HD	**Gas TPC**, 2xGEM + CMOS pixel, **NID**	3d	Prototypes evaluated, ran above-ground, scaling up
New Mexico readout R&D / CYGNUS HD	**Gas TPC**, Optical readout, **NID**	2d	Prototypes evaluated
CYGNO	**Gas TPC**, 3xGEM + CMOS optical + PMT	3d / 2d+1d	Prototypes evaluated, funded to scale up
CYGNUS-Oz	**Gas TPC**, Optical and electronic	?	Prototyping, then scale up
NEWSdm	Nuclear Emulsions	2d	Prototyping / going underground

Most efforts focused on gas Time Projection Chambers (TPCs)

Prototypes and Experiments: CYGNUS

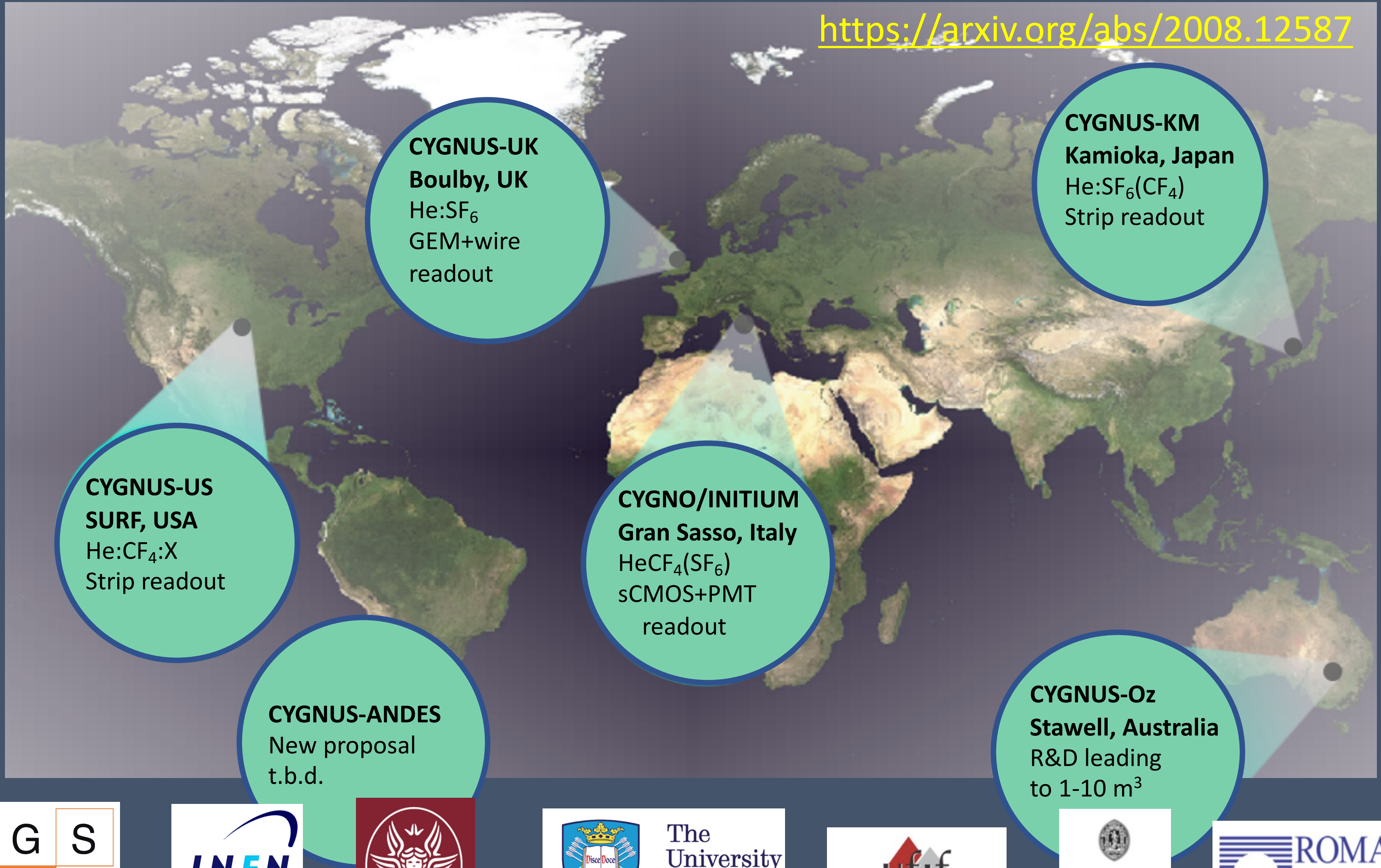


Most gas TPC efforts now collaborating closely as CYGNUS

Long term CYGNUS Vision: Multi-site Galactic Recoil Observatory

with directional sensitivity to WIMPs and neutrinos

https://arxiv.org/abs/2008.12587

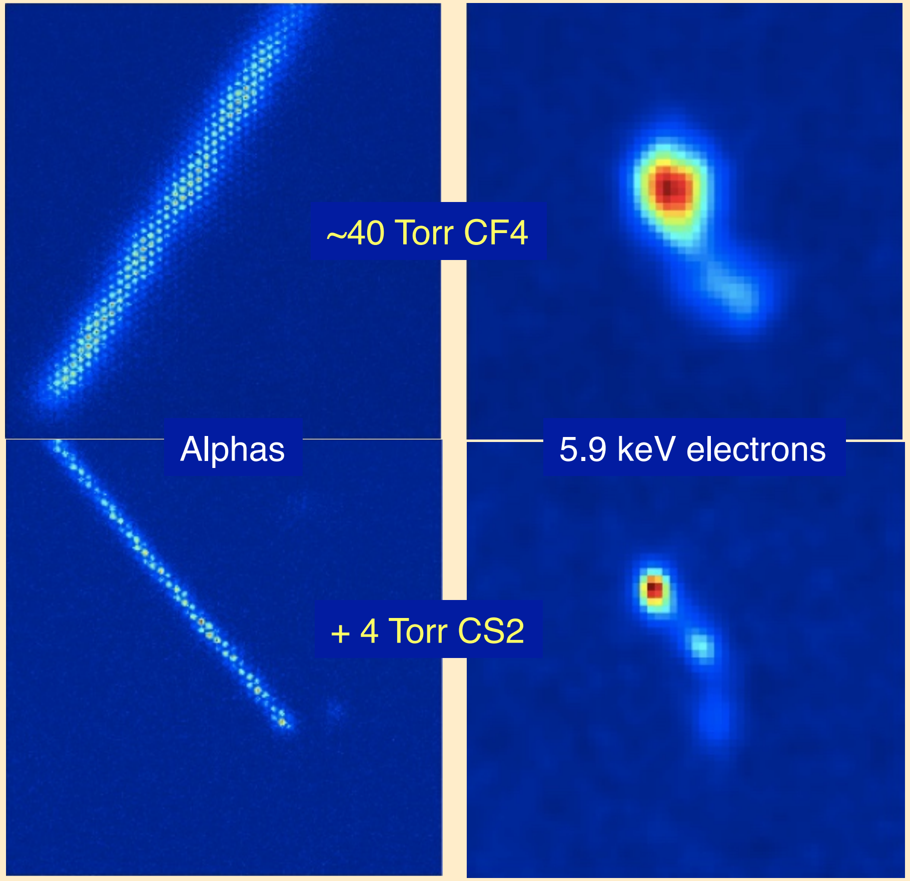


The University of New Mexico
University of Hawai'i Mānoa
Wellesley
Perimeter Institute
Berkeley Lab
Oak Ridge National Laboratory
Duke University
Los Alamos National Laboratory
Occidental College Los Angeles
University of Sheffield
Kobe University
Boulby Underground Laboratory
Australian National University
The University of Adelaide
The University of Melbourne
The University of Sydney
GSSI
INFN
Sapienza
The University Of Sheffield.
Universidade Federal de Juiz de Fora
Universidade de Coimbra
Roma Tre Università degli Studi
ENEA
CBPF
UNICAMP

2D Optical Readout and Negative Ion Drift R&D at UNM

- NID-gas doping key to cost-effective scaleup
  - Lower diffusion → longer driftlength
  - 3D Fiducialization → background reduction
- UNM pioneered use of SF_6
  - Safe
  - Spin-dependent target
- Key challenge with NID is reduced gain
  - Solved here with glass-GEMs

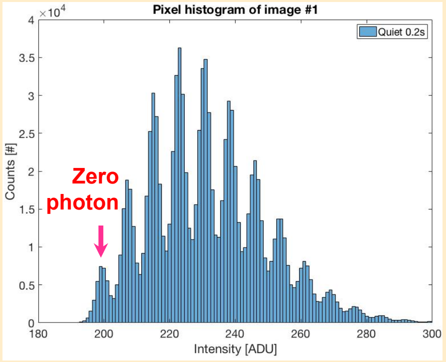
Negative-ion OTPC



D. Loomba, UNM

Hamamatsu ORCA-Quest

- Photon Resolving Power:

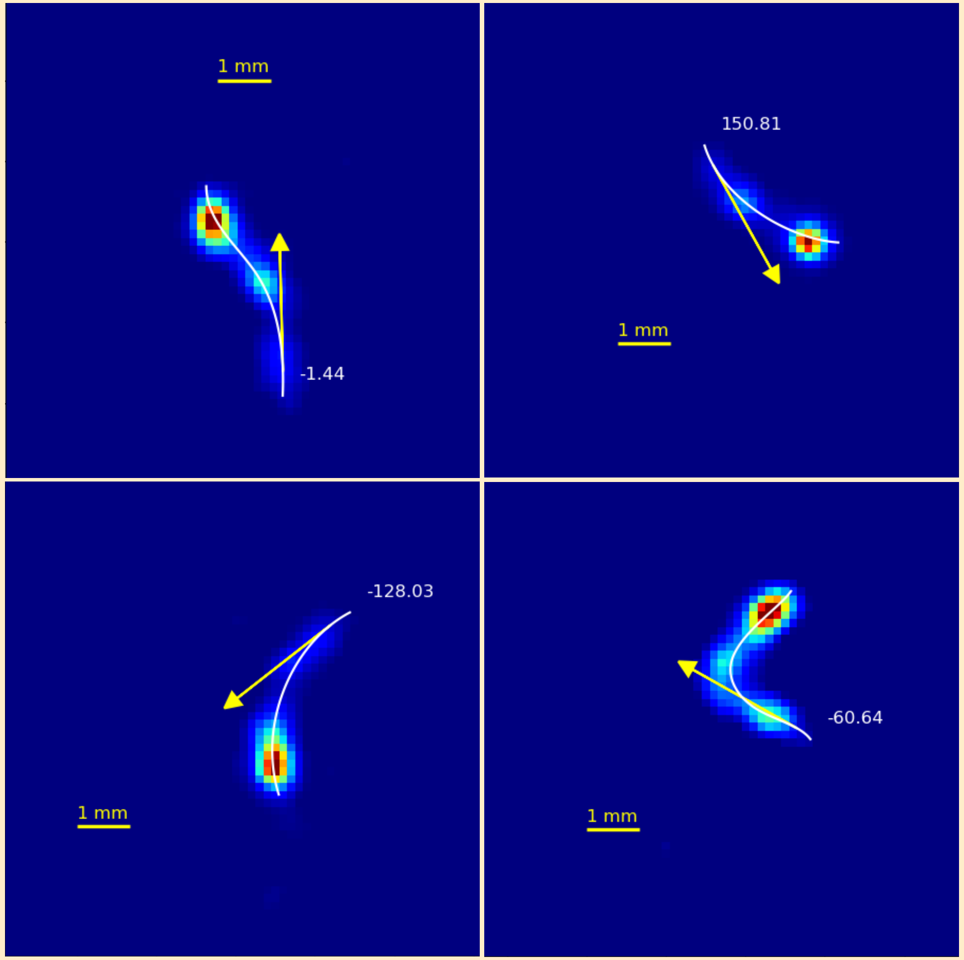


Radiment Glass-GEMs

- 270 micron pitch

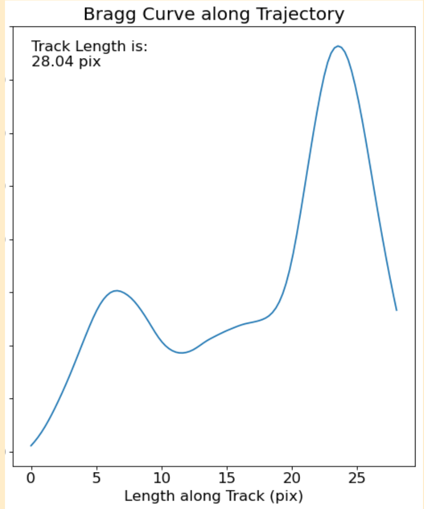
~45 Torr CF_4 + x Torr CS_2

CS_2 (Torr)	σ(μm)
0	~500
4	~150-200



Low diffusion, high spatial resolution enables detailed reconstruction of particle's trajectory:

- **Head/tail** of track
- **Initial direction**
- **Range**
- **dE/dx** (Bragg curve):

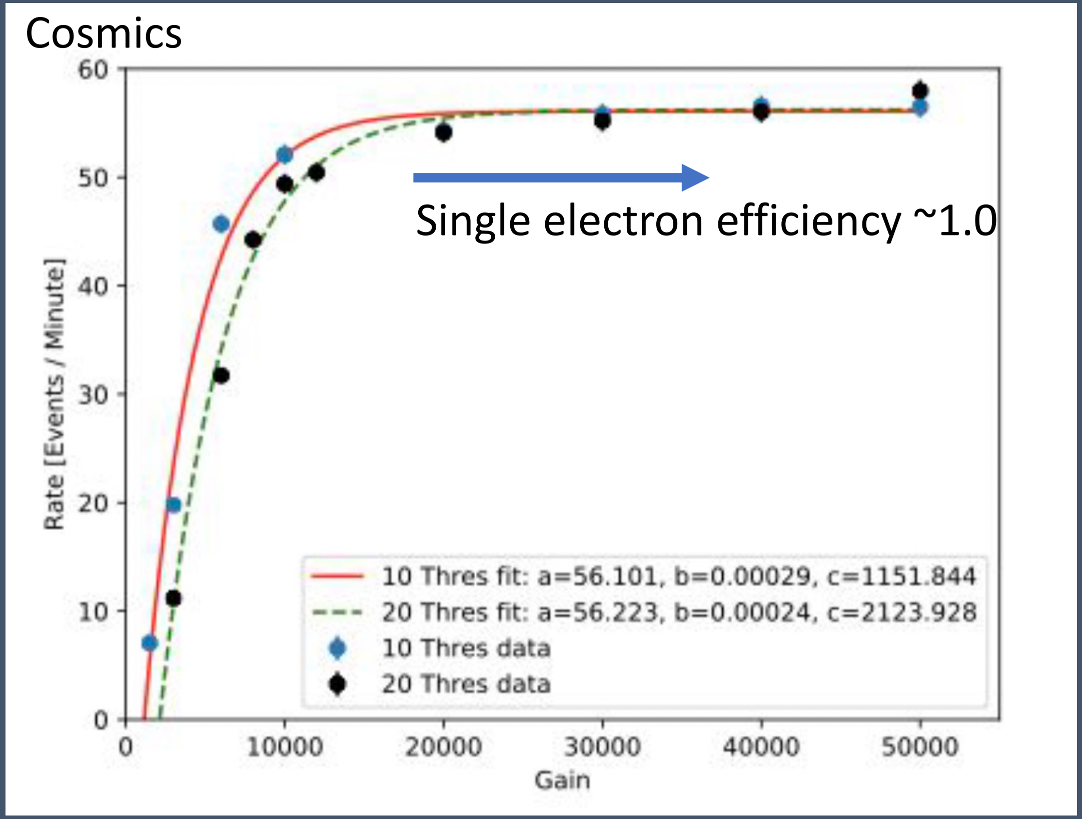


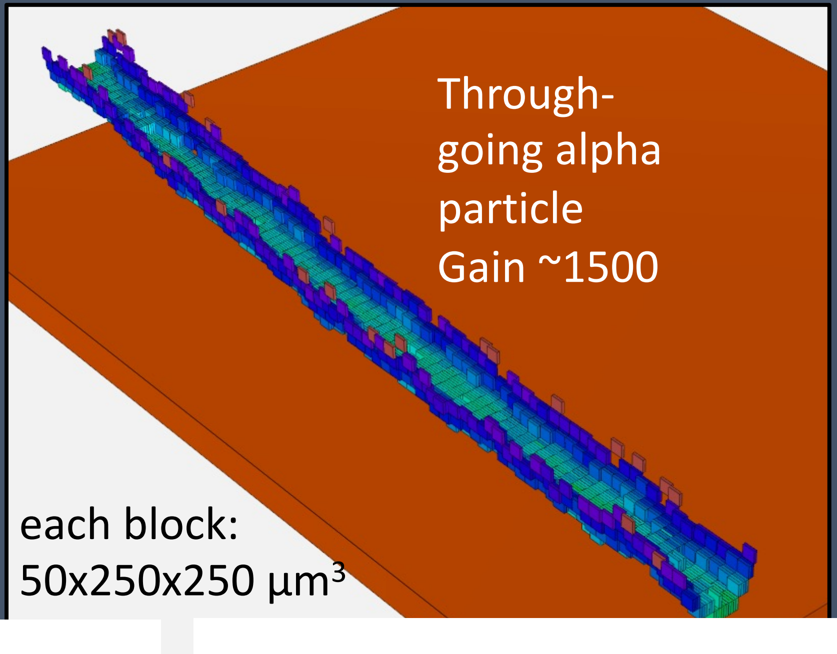
D. Loomba, UNM

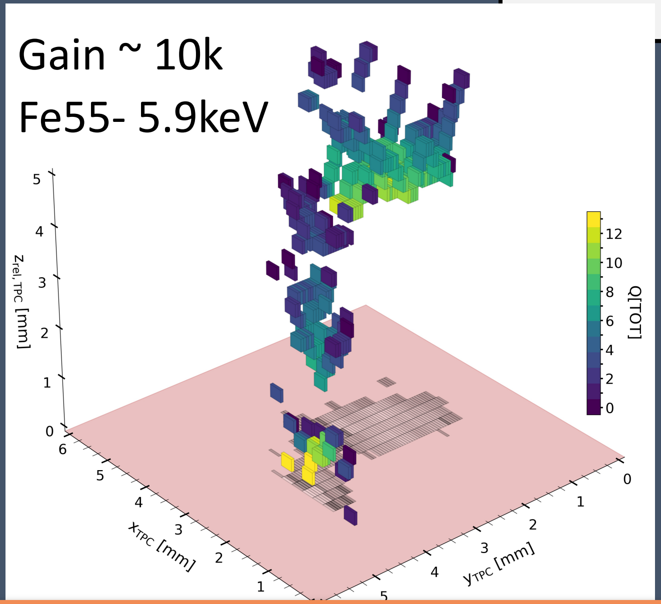
Directional detection of 5.9 keV electron recoils!

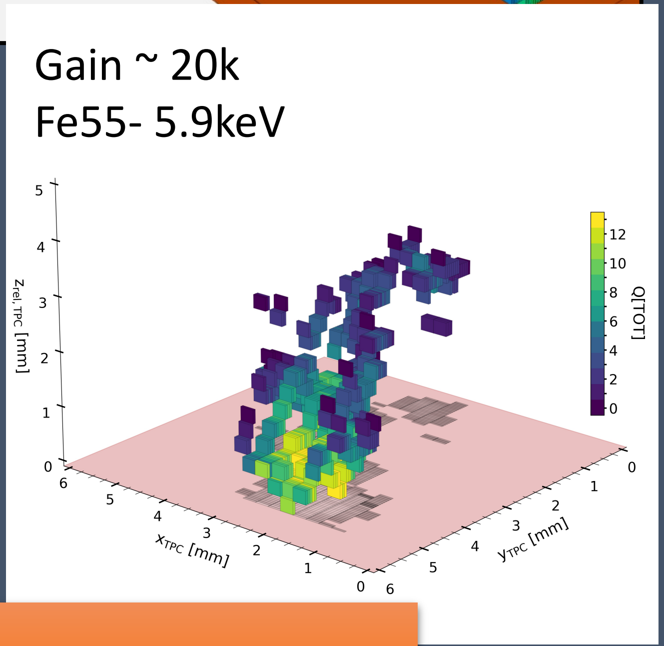
3D single-electron sensitivity: Charge Readout via GEMs and CMOS pixel ASICs

Cosmic ray rate



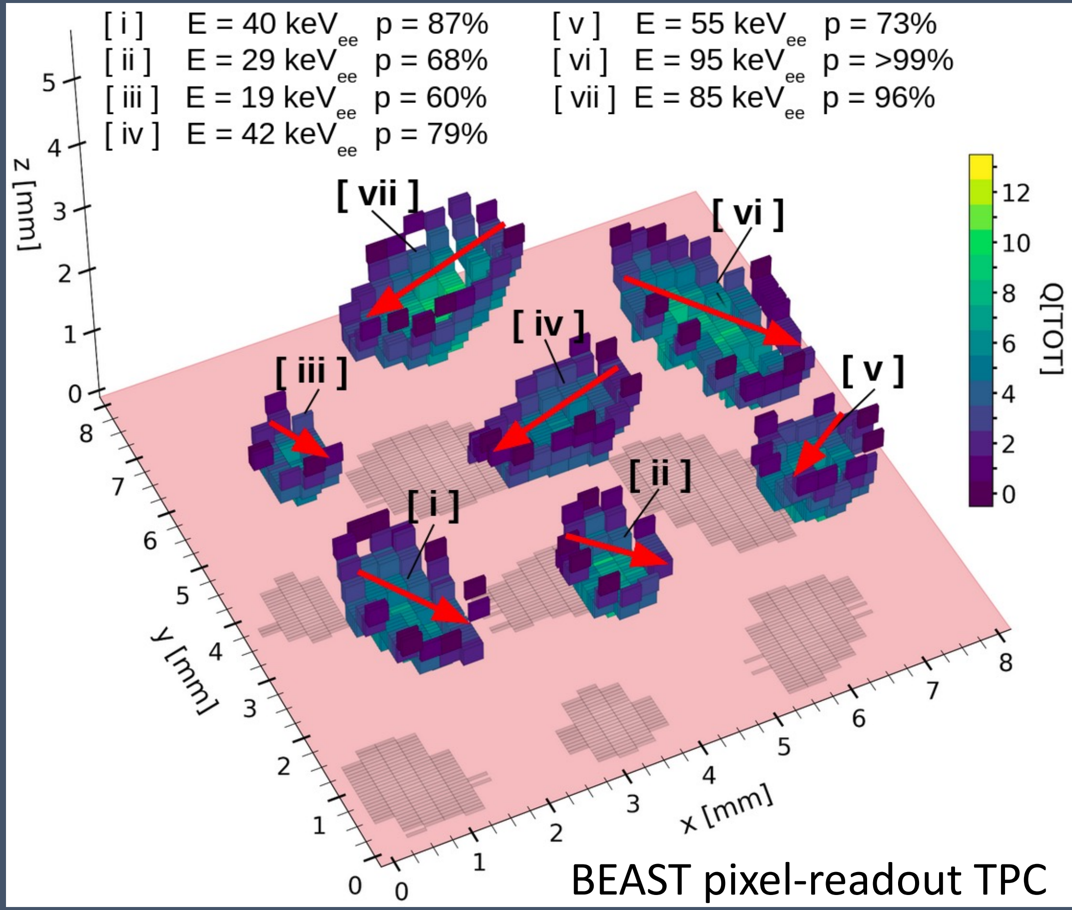




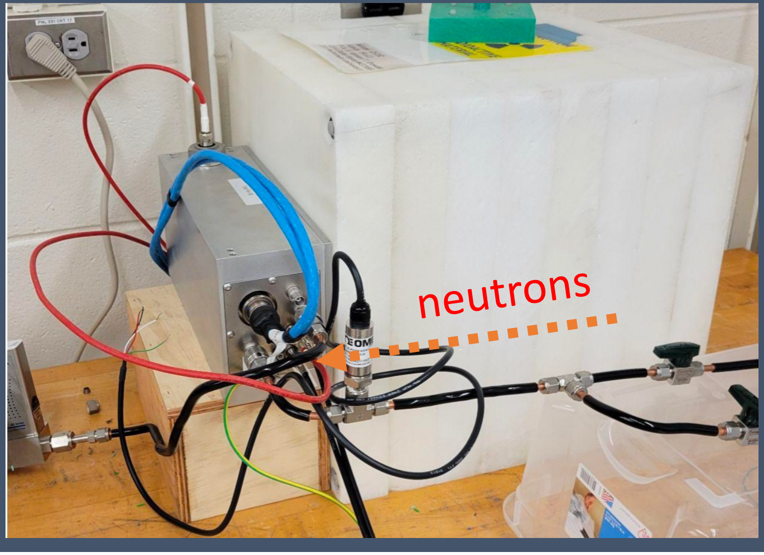


- In high-gain mode, even single electrons of ionization easily detected
- Energy threshold is ~30 eVee, w/ virtually zero noise-occupancy

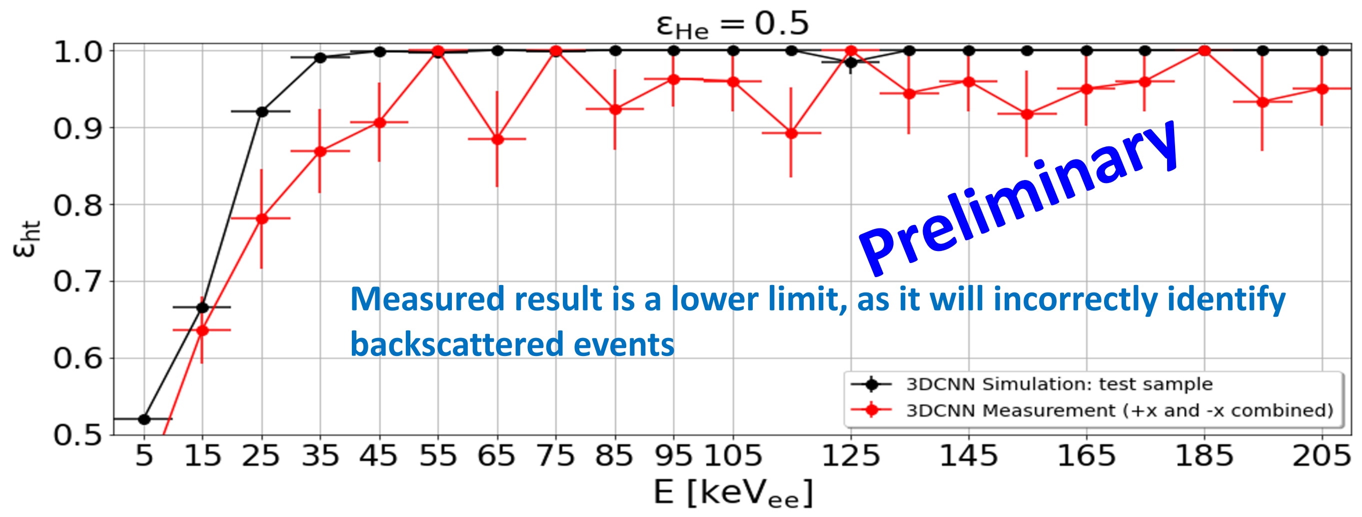
Event-level head/tail via Machine Vision: low gain



Helium recoil tracks detected in a pixel-readout time projection chamber at low gain (900). Color of voxels indicates ionization density.



Jeff Schueler



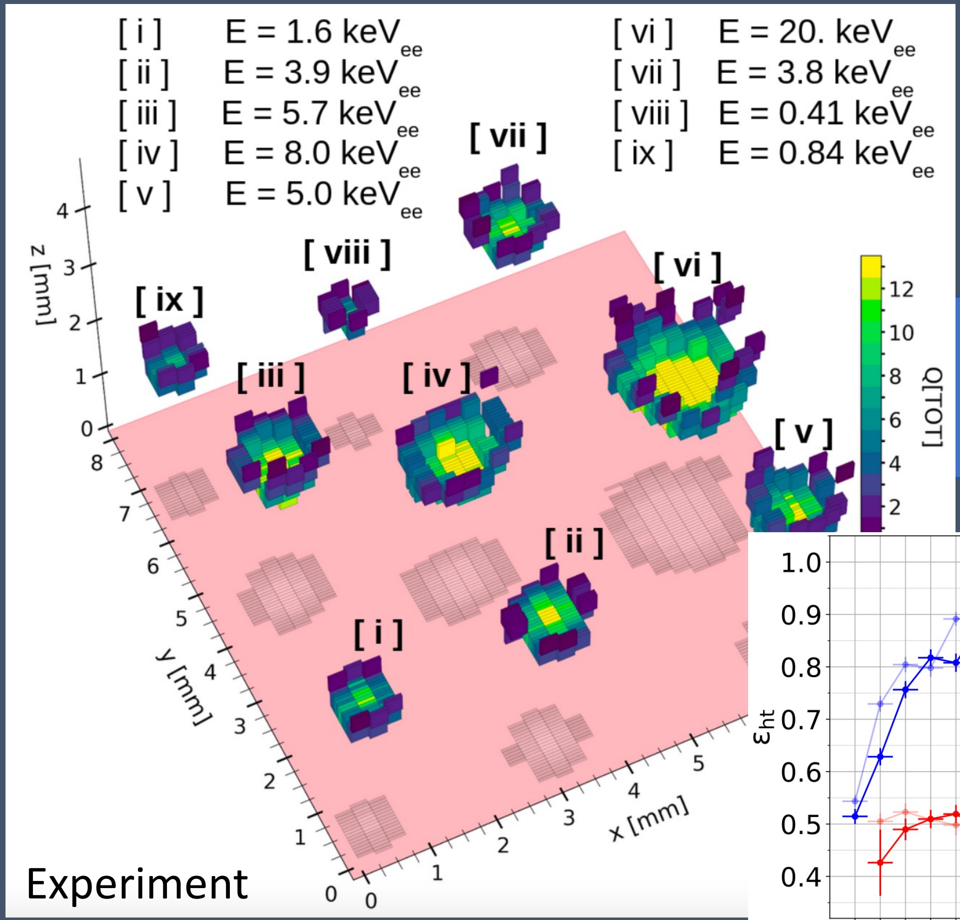
ε_{ht} = 63.6 +/- 4.3% for 10-20 keV$_{ee}$ recoils → first demonstration of significant *event-level* head/tail sensitivity below 20 keV$_{ee}$ in measurement. (still at *low* detector gain!)

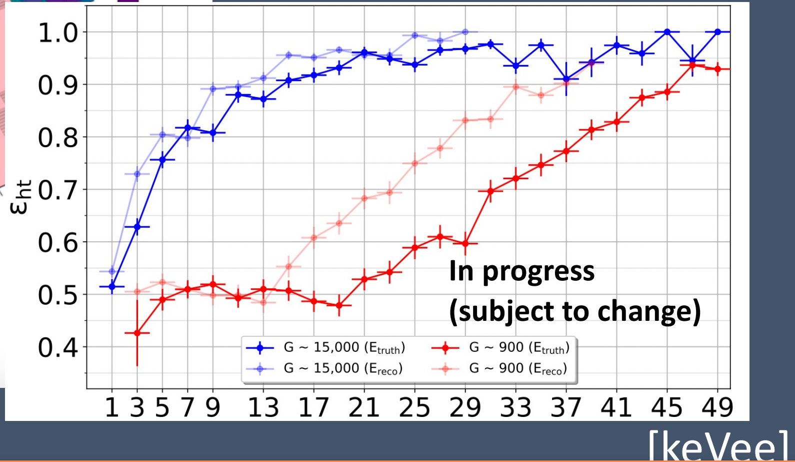
High gain operation: keV scale directionality

In progress and highly preliminary!

Have:

3D single electron efficiency ~1.0

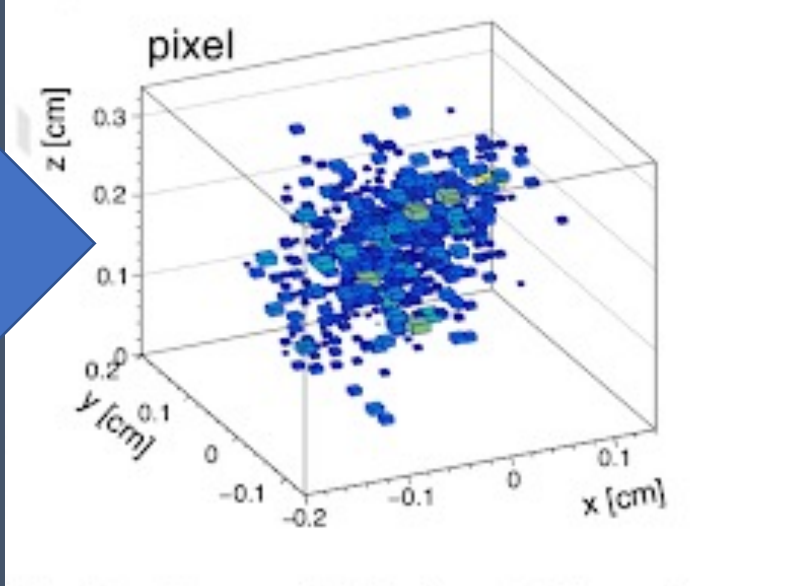




Without saturation,
With negative ion drift +
optimized gas (e.g. He:SF_6)

Want:

3D single electron *counting*



Directionality at 1keV scale

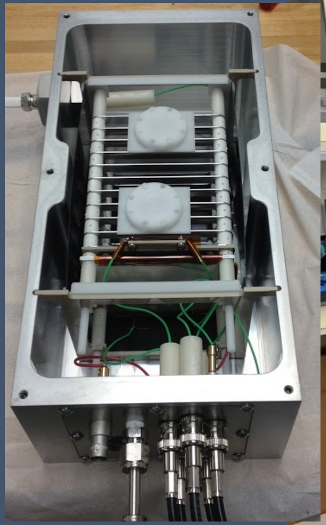
At high gain, directionality at 3 keVee for p=1 atm sems achievable in current detectors. Planning three improvements, aiming for 1keV recoil directionality.

CYGNUS HD Scaleup

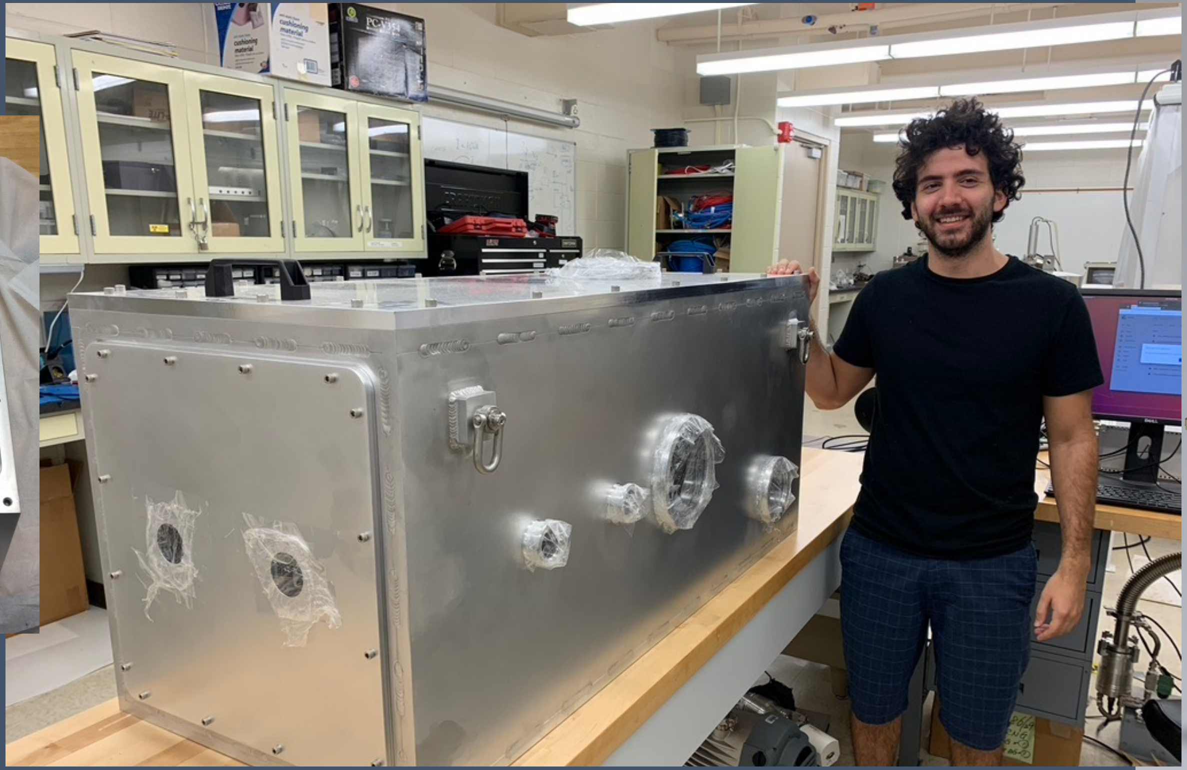
Vessel delivery expected April 2023!

x1000

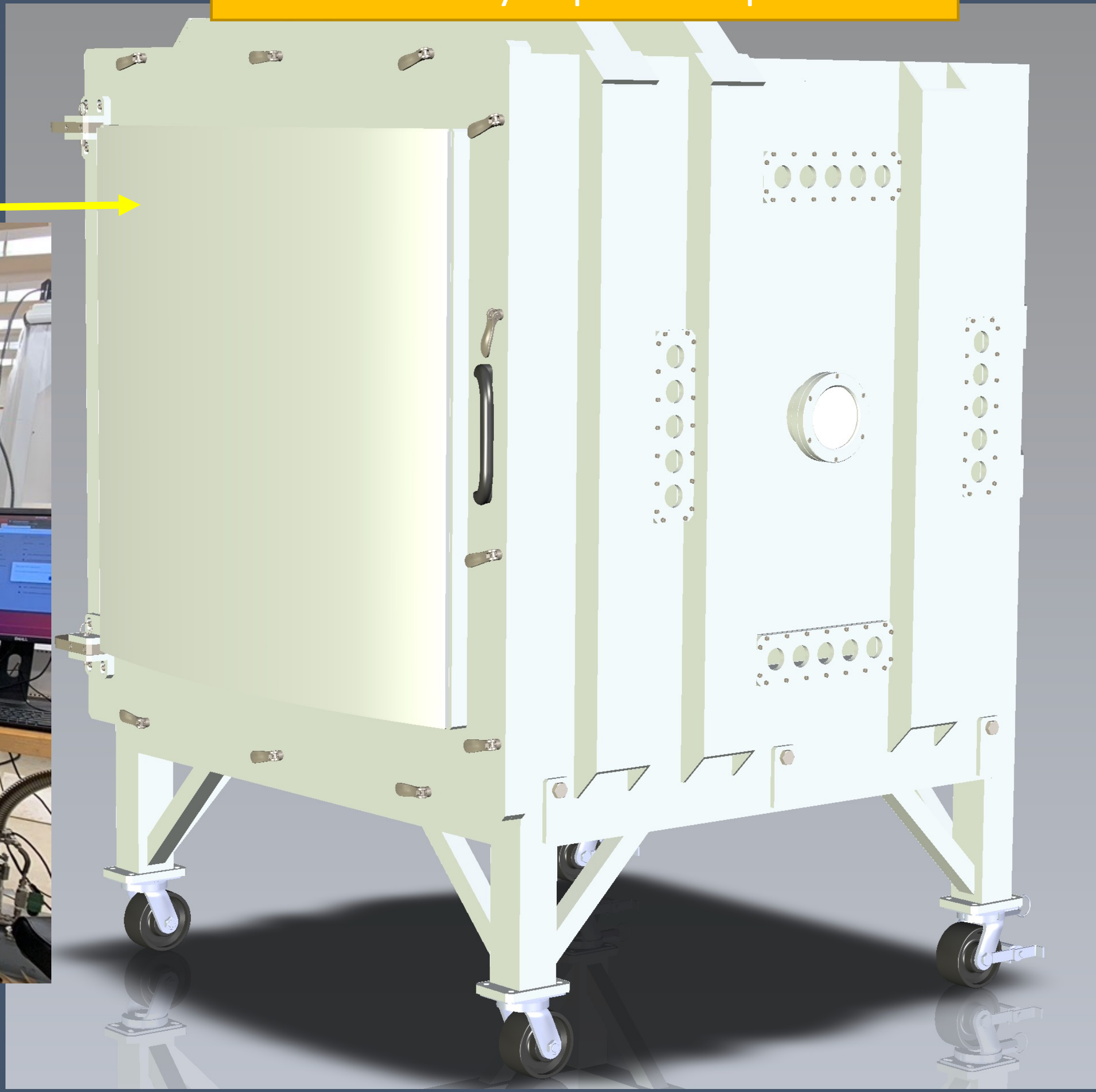
x25



BEAST TPC
Neutron
detector



BEAST TPC x 1000 (40 l fiducial)
Neutrino / Dark Matter Detector Prototype
for technology down-select



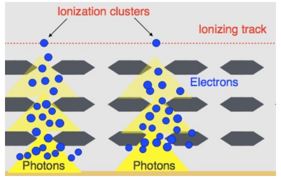
CYGNUS HD-1 Demonstrator (1 m^3 fiducial)
Unit-cell technology demonstrator for
future, large CYGNUS neutrino/DM observatory

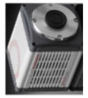
The CYGNO project : 3D optical readout

Lime (50l) running underground!

CYGNO-04 funded & TDR submitted!

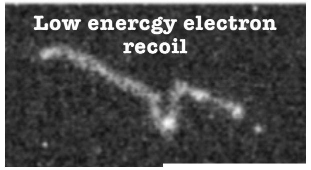
He:CF_4 @ 1 atm

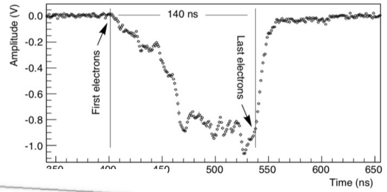


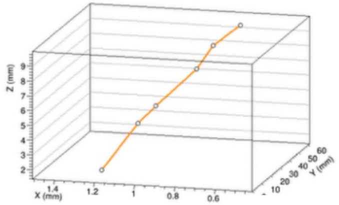


sCMOS:
high granularity
X-Y + energy measurements

PMT:
integrated
Z + energy measurement





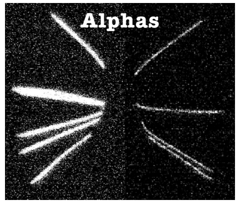


3D track reconstruction

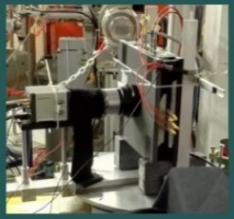
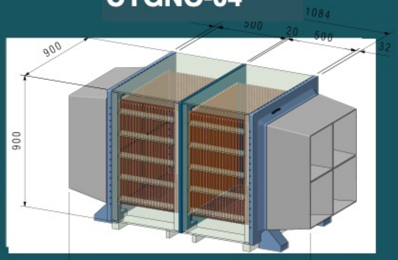
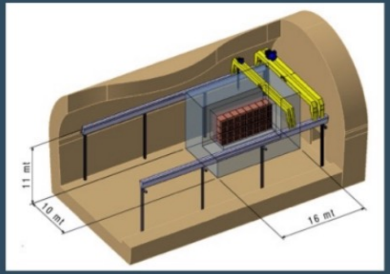
+ SF_6 for negative ion drift

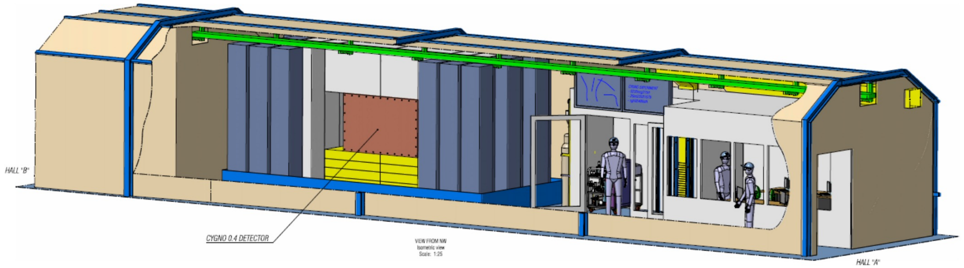
European Research Council

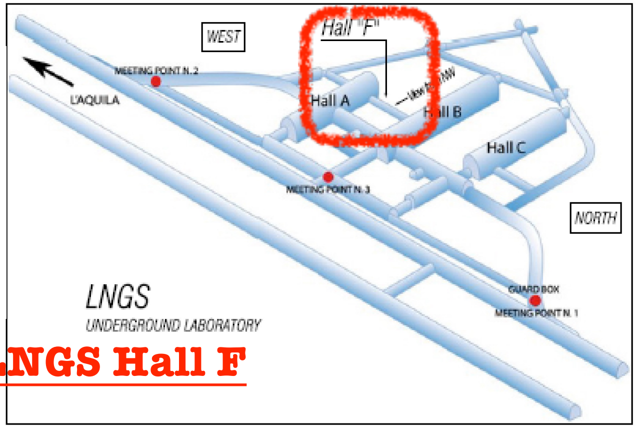
INITIUM



E. Baracchini, MPGD 2022 talk

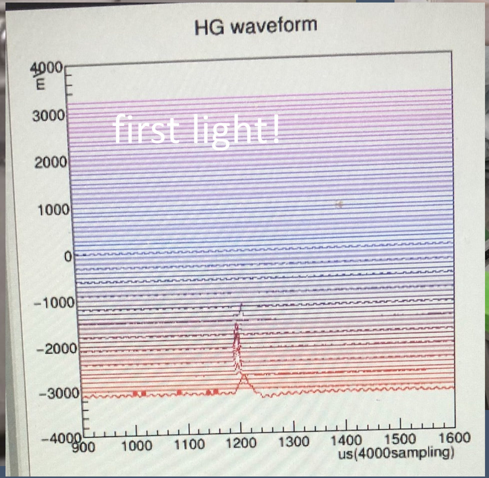
PHASE 0: R&D and prototypes			PHASE 1: O(1) m³ Demonstrator	PHASE 2: 30 m³ Experiment
2015/16 ROMA1	2017/18 LNF	2019/22 LNF/LNGS	2023/26 LNF/LNGS	2026.. LNGS
ORANGE	LEMON	LIME	CYGNO-04	CYGNO_30
				
- 1 cm drift	- 3D printing - 20 cm drift	- 50 cm drift - underground tests - MC validation	- background - materials test, gas purification - scalability	- Physics research
0.0001 m³	0.01 m³	0.05 m³	0.4 m³	30 m³ ?



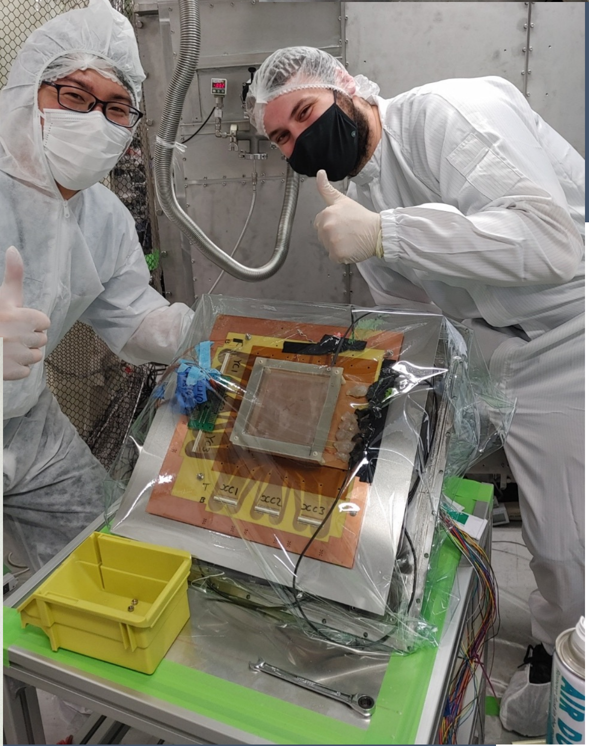


CYGNO-04 To be installed in LNGS Hall F

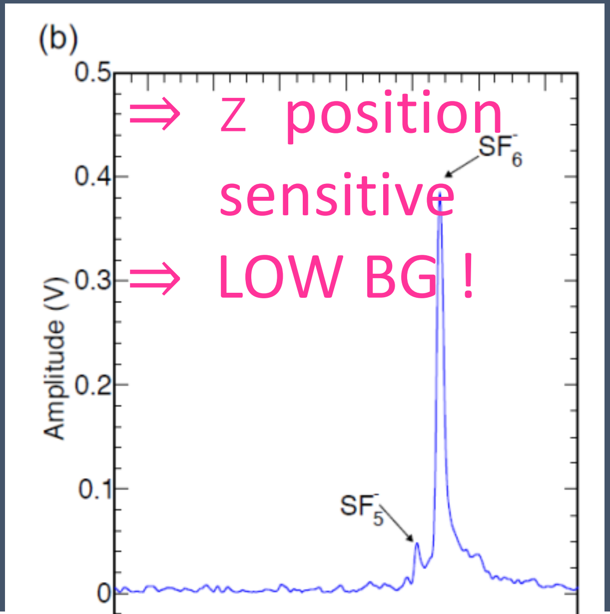
- NEWAGE running underground @ Komioka
- Larger, CYGNUS/NEWAGE-1.0 m^3 chamber being commissioned @ Kobe U.

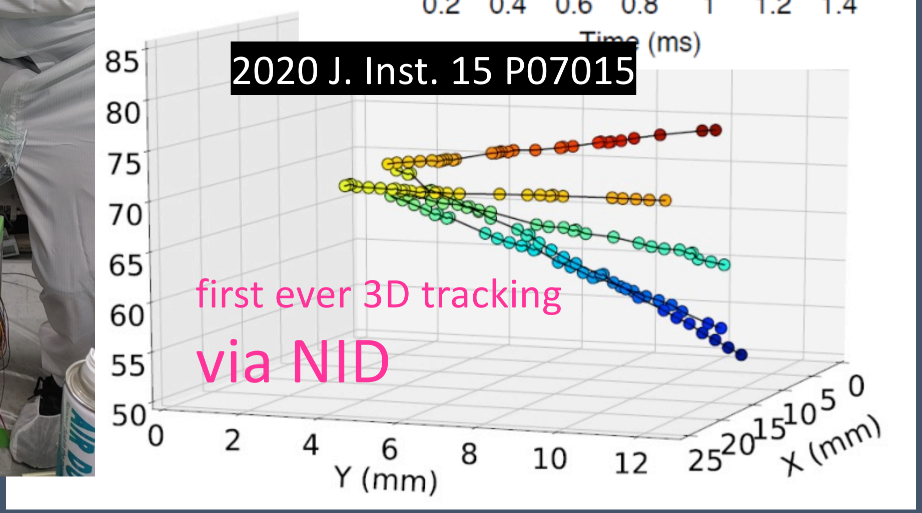


test module installation



Investigating switch to negative ions





SF_6 R&D at The University of Sheffield

- Focusing on charge amplification and readout in the NID gas SF_6 and SF_6 mixtures at low pressure (~40 Torr)
- A small scale (10 x 10 cm) R&D TPC consists of a novel MMThGEM device coupled to a micromegas
- Gas gains of order 5 x 10^4 (comparable to CF_4) achieved with NID - not possible with previously tested MPGD designs!
- Pitch of the holes in the MMThGEM is currently limiting positional resolution in the Micromegas readout.

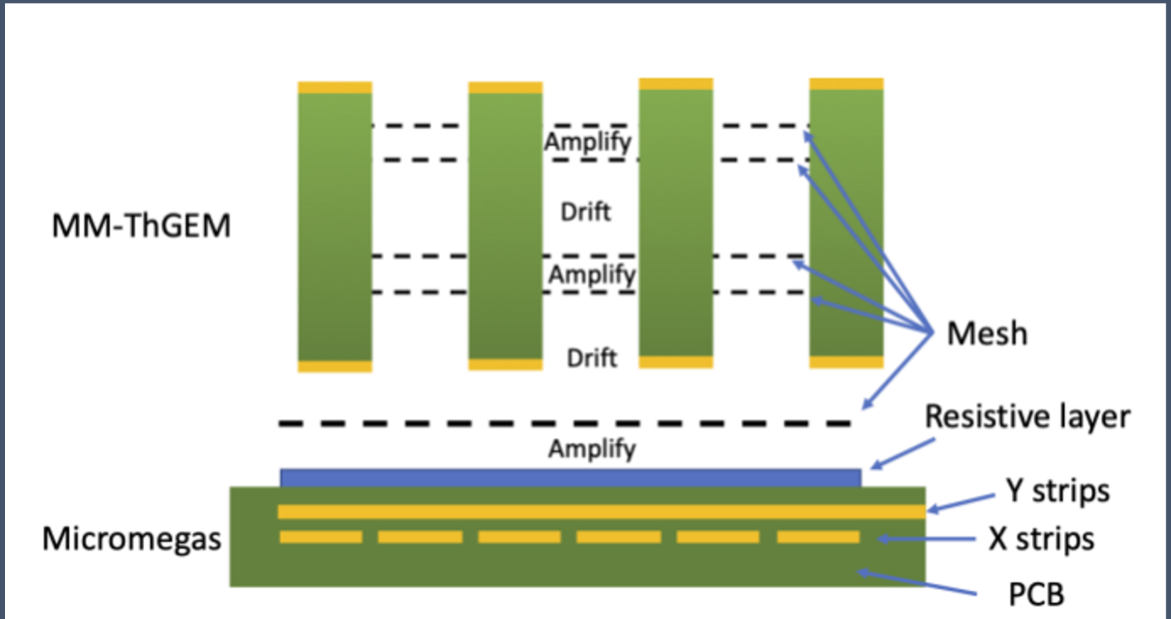


Figure 1: Diagram of the R&D amplification and readout stages.

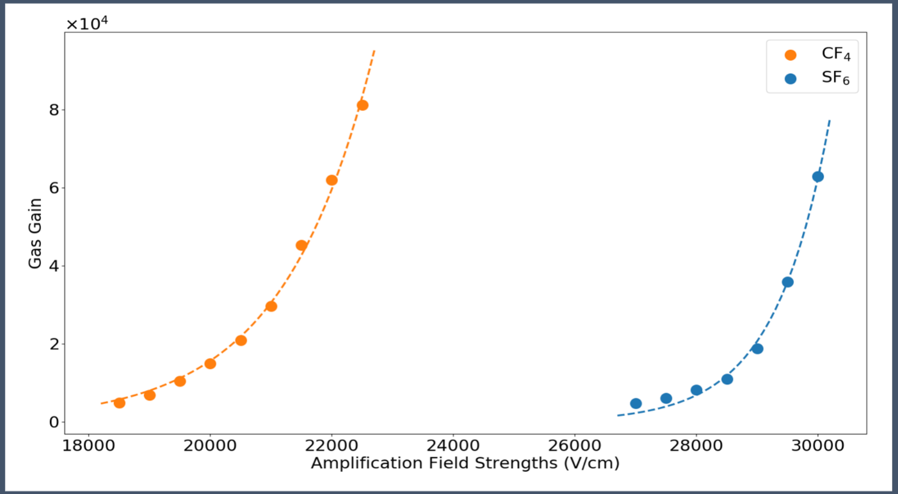
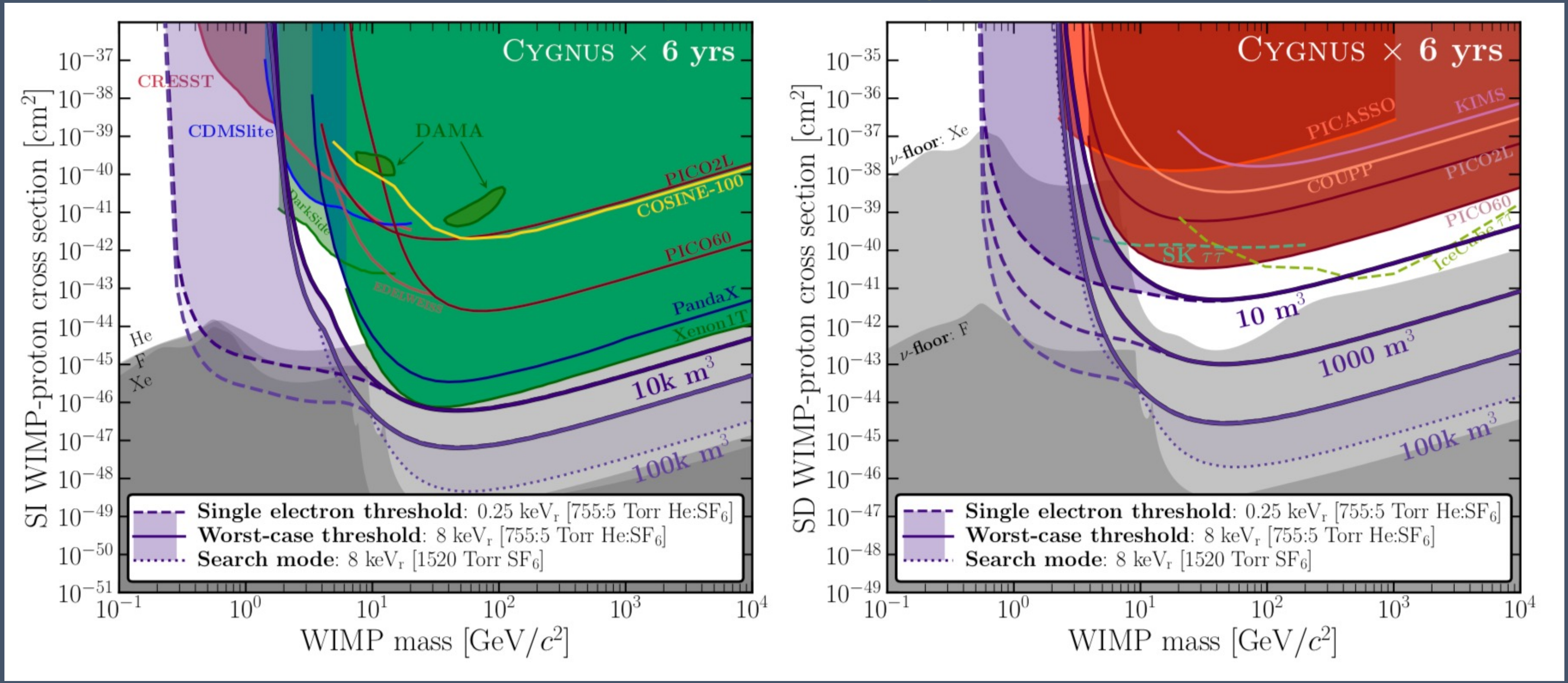


Figure 3: Demonstration of the gas gains achievable with the MMThGEM in both CF_4 (orange) and SF_6 (blue) as a function of amplification field strengths.

CYGNUS 1 ton WIMP search expected sensitivity

Large volume uncertainty as final gas not chosen.
Here assume He:SF_6 755:5, where 1000 m^3 x 6 year ~1 tonne-year
Limits do not yet include the large improvements from machine vision techniques

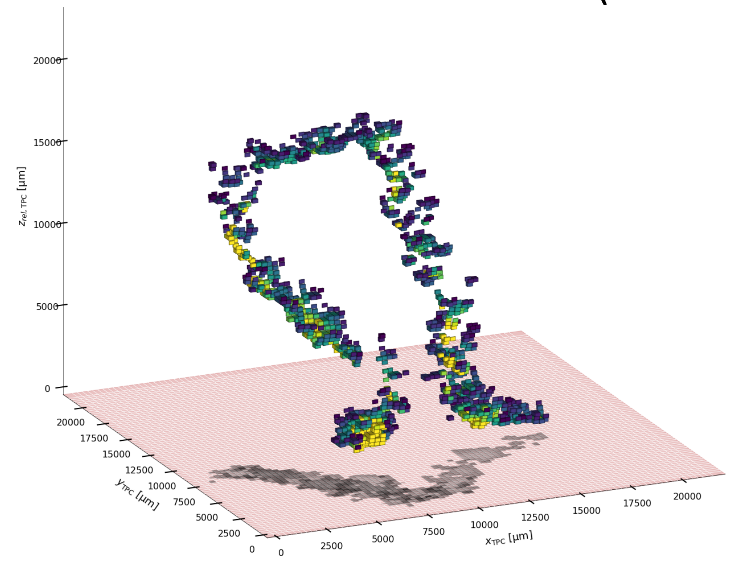


Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

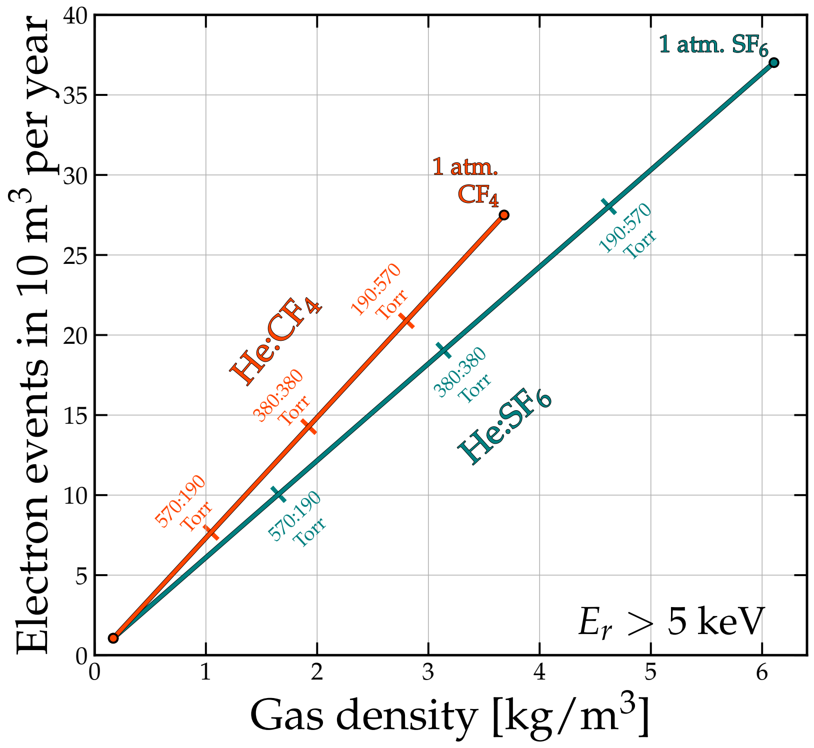
Significant improvement in SD reach over existing experiments for all WIMP masses, a 10 m^3 detector can already breach the Xe neutrino floor

A new signature: Electron Recoils

40 keV
BEAST TPC (Hawaii)

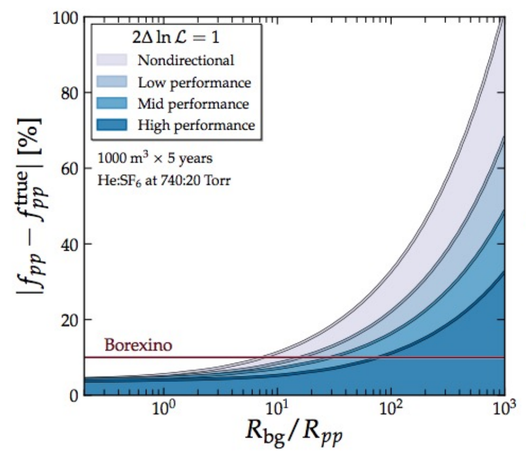


CYGNUS 10

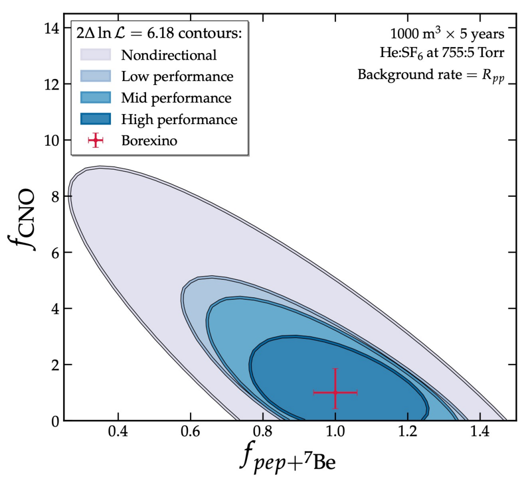


C.O'Hare

CYGNUS 1000



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

- ***Electron recoil directionality in CYGNUS enables solar neutrino spectroscopy through neutrino-electron elastic scattering on an event-by-event basis***
  - **An O(10) m^3 ER directional detector could extend Borexino pp measurement to lower energy**
  - **CYGNUS 1000 could measure the CNO cycle by breaking the degeneracy with pep + ^{7}Be fluxes through directionality**
- **PDG formula does not describe angular resolution properly. M. Grehr & S. Vahsen extending to low-E electrons, including TPC detector contribution**

Conclusion

- Significant recent advancements in directional detection capabilities
  - Detect single electrons of ionization
  - AI/ML techniques important
  - Demonstrated event-level directionality <20 keV (recoils) and <6 keV (electrons)
- Aiming for 1-keV directionality via electron *counting*
- Starting gradual scale-up towards >=1000 m^3
- Recoil imaging capabilities greatly expand physics reach of detectors
- Dark matter, neutrinos, and precision measurements

- Join us for workshop on directional detection in Sydney in December --- hoping for broad participation!

BACKUP

CYGNUS–Oz

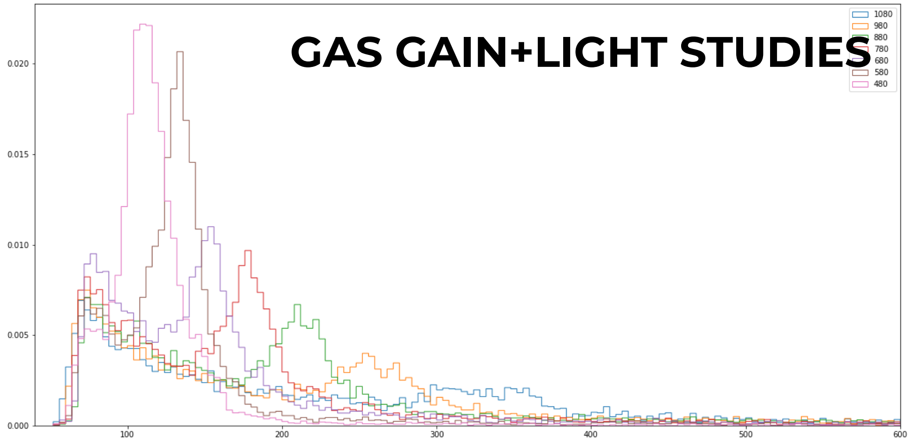
Australian National University

THE UNIVERSITY of ADELAIDE

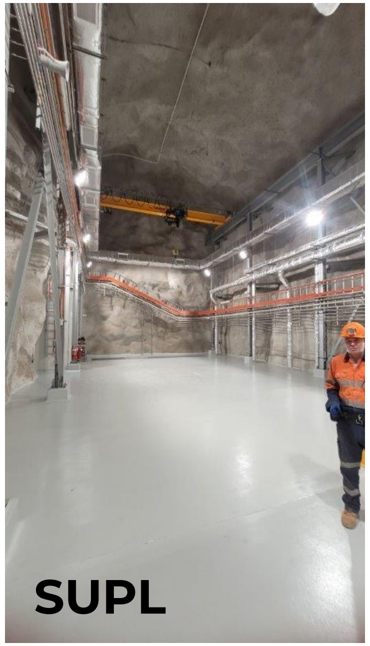
THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY OF SYDNEY

- *“development of the underlying science... operation of detectors in Australia... participation in international CYGNUS detectors and coordinated analysis.”* ***(CYGNUS-Oz collaboration agreement, Sep 2022)***
- R&D scale detectors being designed/built at ANU
- Theory/analysis at Sydney, Melbourne, Adelaide
- 1m³ demonstrator in 2-3 years
- ~10m³ at Stawell Underground Physics Lab in 5+ years

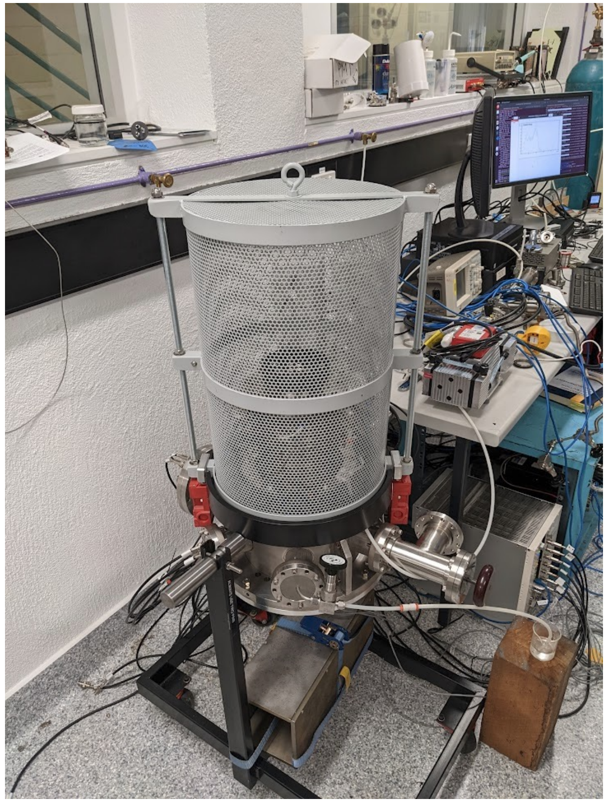


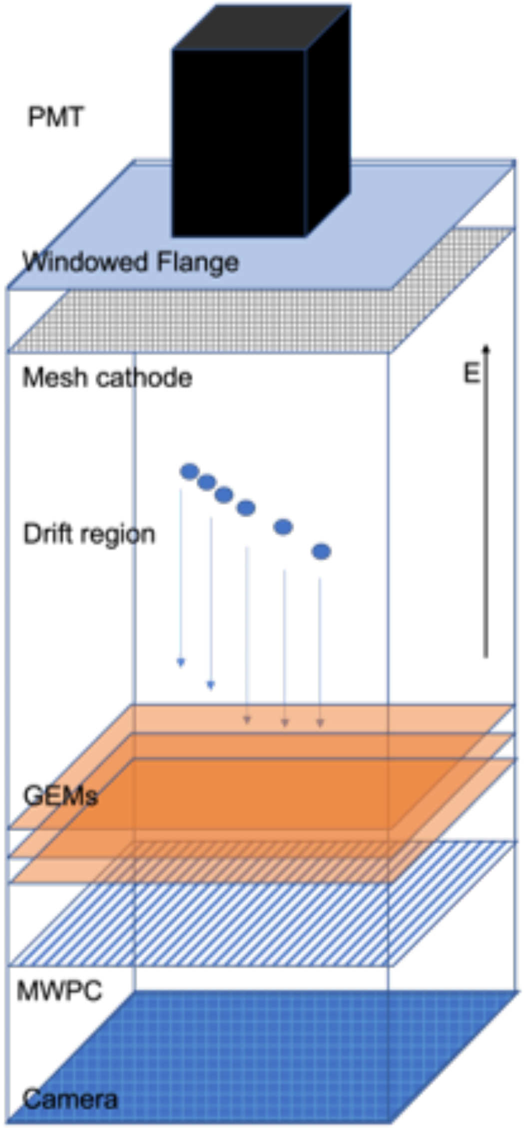
GAS GAIN+LIGHT STUDIES



SUPL

CYGNUS-1





GAS/GEM LIGHT+ CHARGE – FULL CHARACTERISATION

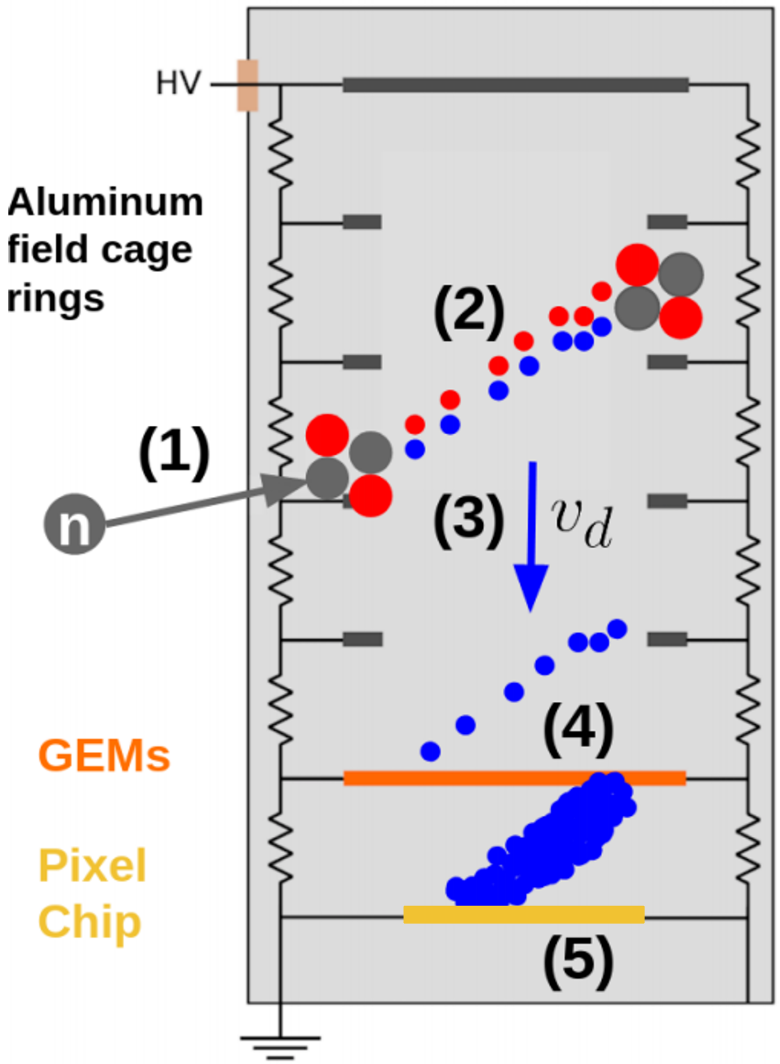
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Status of MIMAC

- Bi-chamber module running at LSM (Modane) with C4H10 + 50% CHF3 gas at high gain (threshold 500 eV) (H and F targets)
- New bi-chamber module with detectors 35 cm side, 1792 channels each foreseen by September 2023
- Recent achievement : 3D-Directionality in the keV range demonstrated by 8 keV neutron spectroscopy published EJPC (2022)

- arXiv:2112.12469 [pdf, other]
- Directionality and head-tail recognition in the keV-range with the MIMAC detector by deconvolution of the ionic signal

BEAST TPC operation at a glance

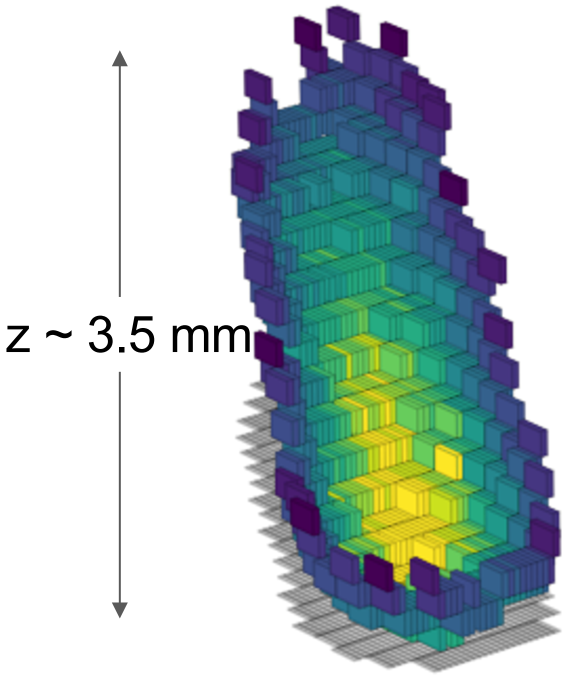


- Filled with a 70:30 mixture of He:CO_2 at STP

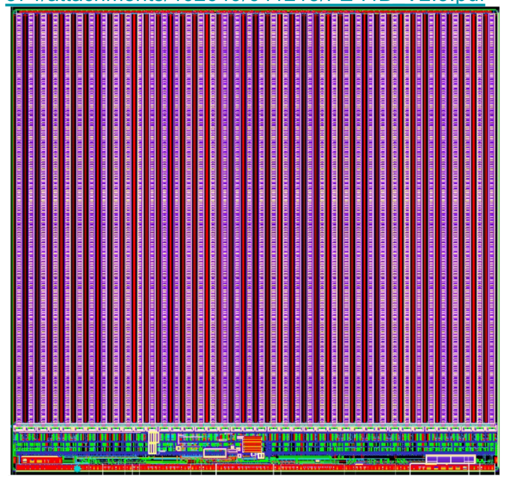
- Drift field of ~450 V/cm corresponding to drift speeds of about 220 μm / 25-ns time bin

- Double GEM amplification capable of gains up to O(50,000), single e^- efficiency at gain ~ 20k

~300 keV_{ee} He recoil at a gain of O(1,000)



https://indico.cern.ch/event/261840/contributions/1594374/attachments/462649/641213/FE-I4B_V2.3.pdf



ATLAS FE-I4 pixel ASIC readout

- 80 x 336 grid of (250 x 50) μm^2 pixels
- (2 x 1.68) cm^2 readout area
- 4-bit TOT charge quantization
- Custom firmware → up to 256 consecutive 25-ns time bins

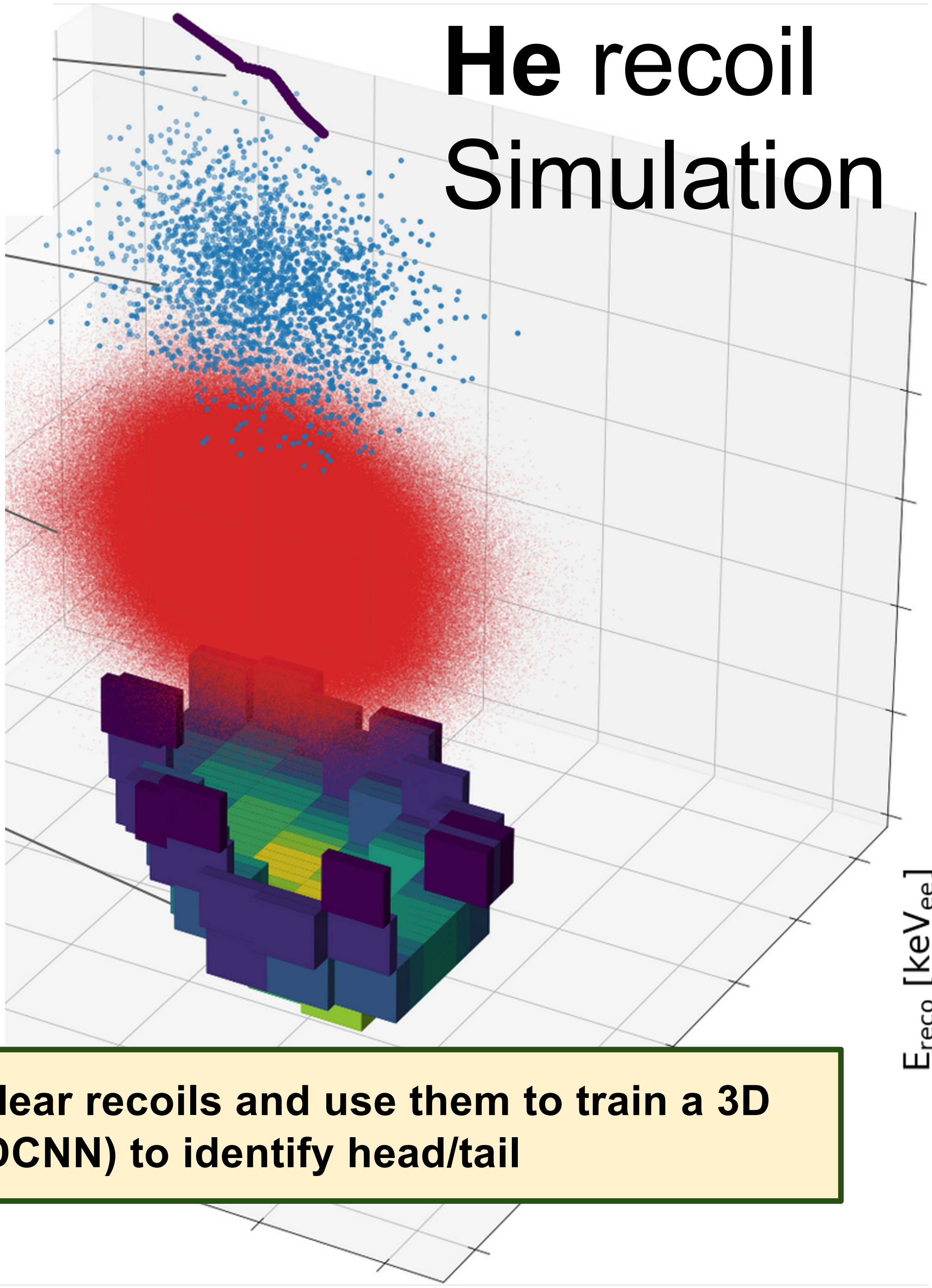
He recoil Simulation

Primary track: recoil trajectories simulated with SRIM* (isotropic angular distribution)

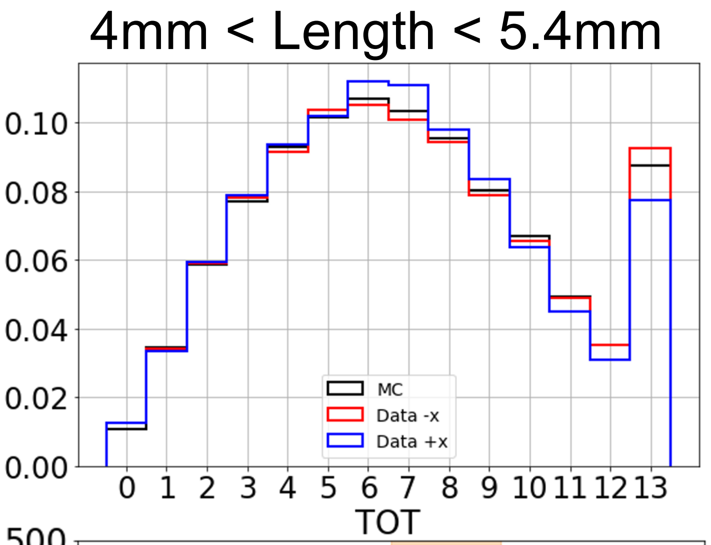
Drift tracks and apply diffusion:
Drift length = 4cm
σ_T = 133.1 μm/cm$^{1/2}$
σ_L = 122.9 μm/cm$^{1/2}$

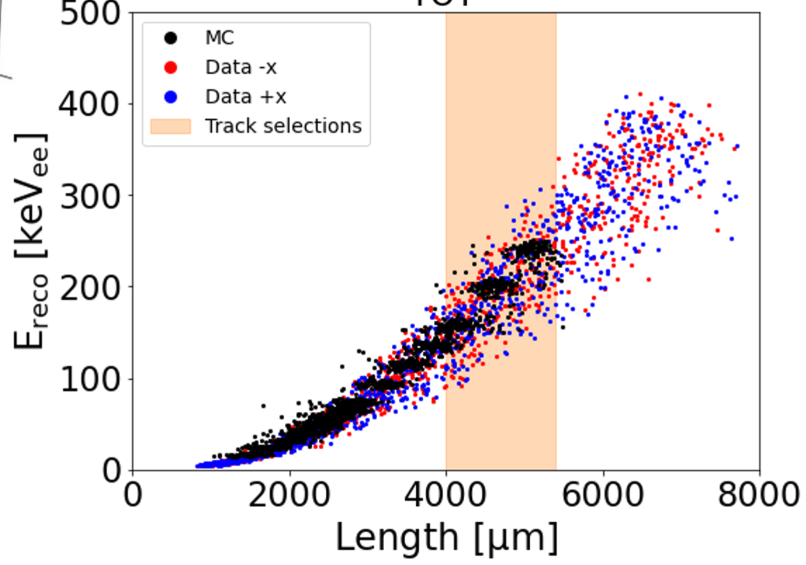
Amplify charge with a double GEM gain of 1,320 using a random exponential distribution

Digitize using the binning of the ATLAS pixel chip. For each bin above threshold, record the z position where the cumulative charge first passes above threshold as the time bin.



Data vs. MC agreement is crucial for models trained on simulation to generalize to measurement!





We simulate around 200,000 nuclear recoils and use them to train a 3D convolutional neural network (3DCNN) to identify head/tail

*Also used retrim

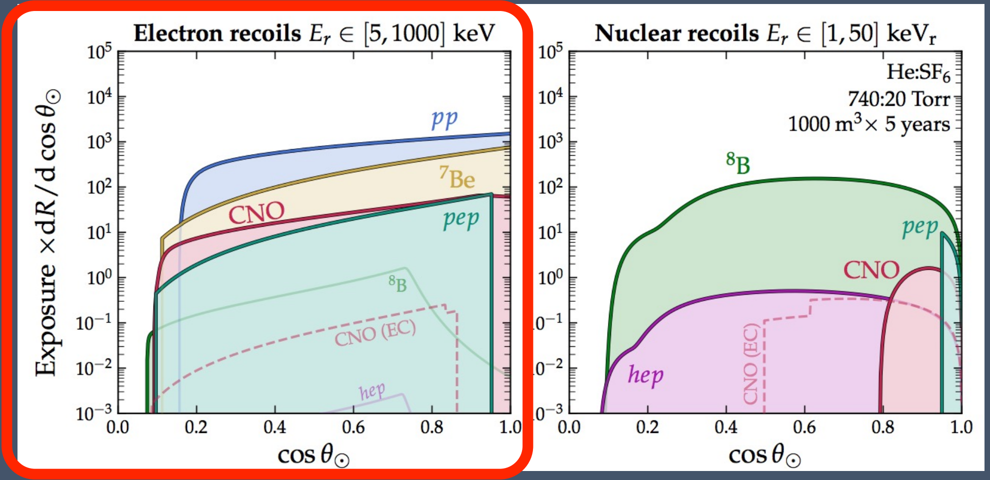
Solar Neutrinos in CYGNUS: promoting background to signal

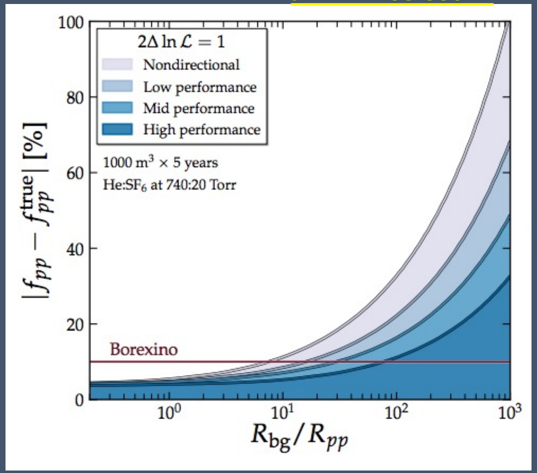
CYGNUS 1000

C. A. J. O'Hare et al., 2022 Snowmass Summer Study, arXiv:2203.05914

Expected number of ER and NR events as a function vs cosine of angle w.r.t. the Sun

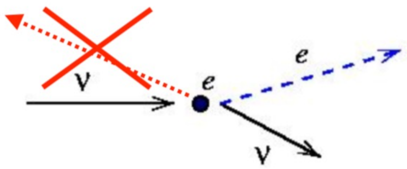
Electron recoils





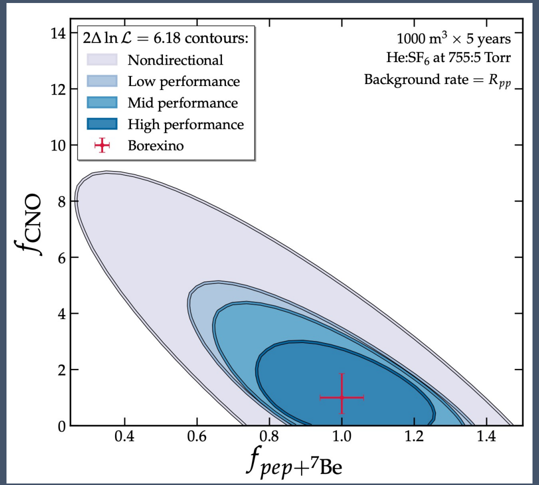
1 σ sensitivity to pp flux as a function of the total non-neutrino ER background

Given the Sun position, recoils in opposite direction are kinematically forbidden



Differently from WIMPs, background can be measured on sidebands data

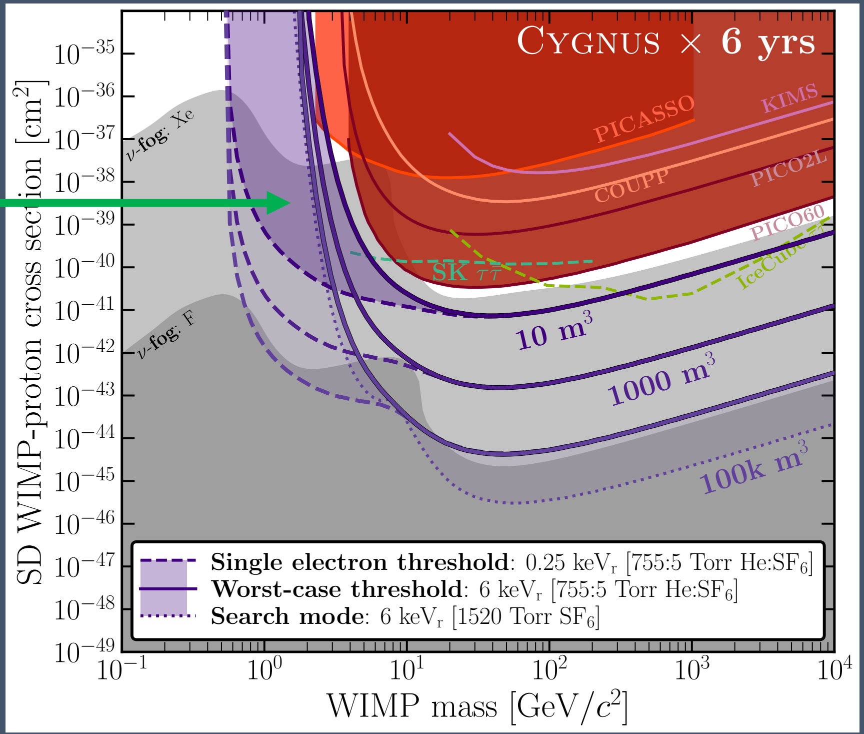
- ***Electron recoil directionality in CYGNUS enables solar neutrino spectroscopy through neutrino-electron elastic scattering on an event-by-event basis***
  - **An O(10) m^3 ER directional detector could extend Borexino pp measurement to lower energy**
  - **CYGNUS 1000 could measure the CNO cycle by breaking the degeneracy with pep + ^{7}Be fluxes through directionality**



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

Preliminary study shows potential. Increasing directional performance alone can lead to a massive jump in the physics potential in terms of measuring these fluxes, without any increase in event rate. Next: optimize gas for electron recoil signature.

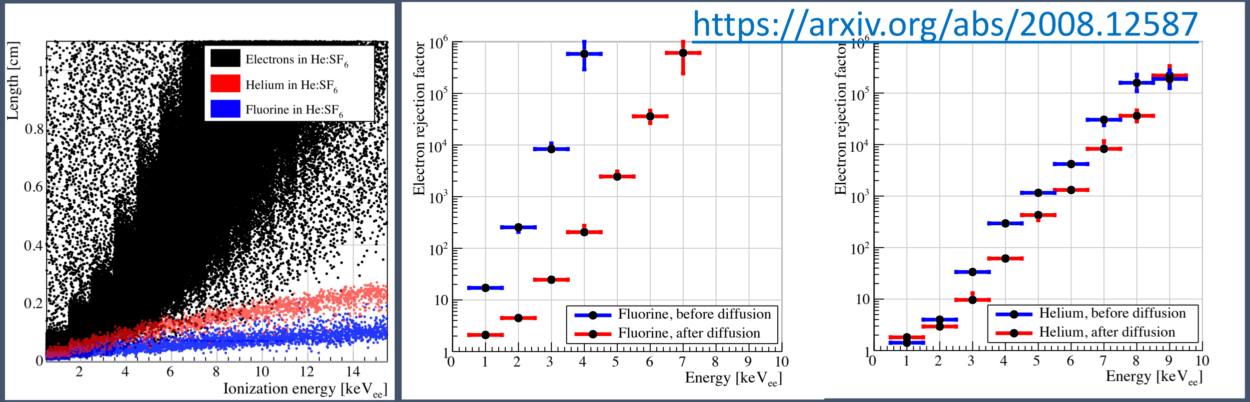
WIMP sensitivity: depends on electron rejection



https://arxiv.org/abs/2008.12587

- Improved, physically motivated observables for electron rejection. Requires HD readout.
- Improved even further with 3DCNN, publication forthcoming.
- Demonstration measurement next.

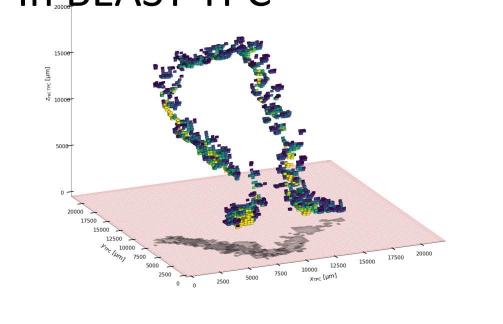
3D electron rejection (simulation) via dE/dx 5 torr SF_6 + 755 torr Helium

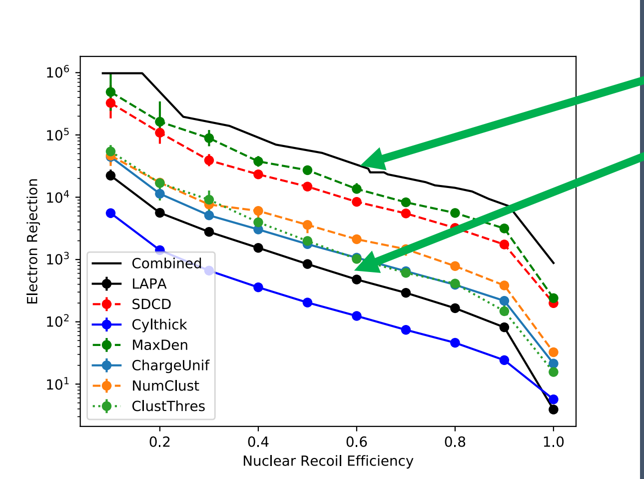


https://arxiv.org/abs/2008.12587

Electron rejection rises exponentially with ionization energy. When combined with flat bkg spectrum, will determine CYGNUS energy threshold for background free operation.

Electron recoil candidate In BEAST TPC



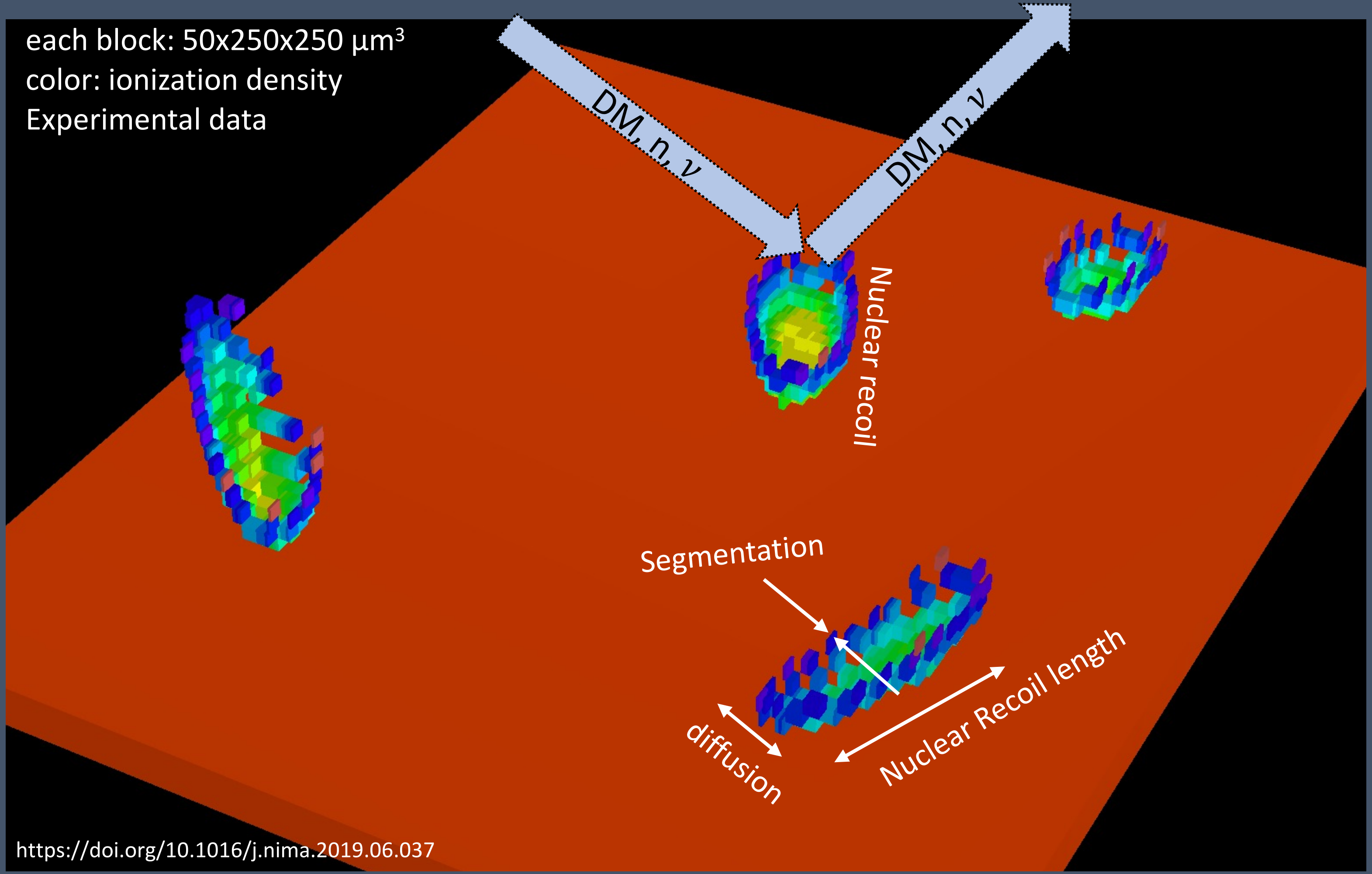


~2 orders of magnitude improvement over dE/dx !

Majd Ghrear et al., arxiv.:2012.13649

3D Charge Readout via double GEMs and pixel ASIC

- 3D axial directionality
- Head/tail detection
- Particle ID
  - Electron rejection
  - Nuclear Recoil ID
- 3D fiducialization
- Event timing

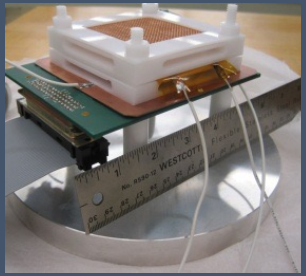


Want: segmentation (here: 50 x 250 µm) < diffusion (~200-500 µm) < recoil length (~mm)

Unique capabilities – not available with any other technology!

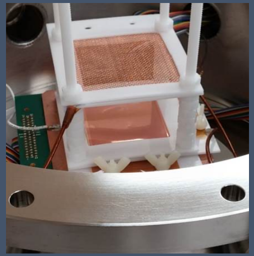
CYGNUS HD: MPGD gas TPCs for nuclear recoil imaging

2011-2013



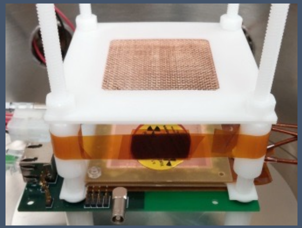
μD³ (~1cm³)

2013



~2.5 cm³

2013



~ 20 cm³

1st generation, proof of concept

2014

2 x 60 cm³

2015

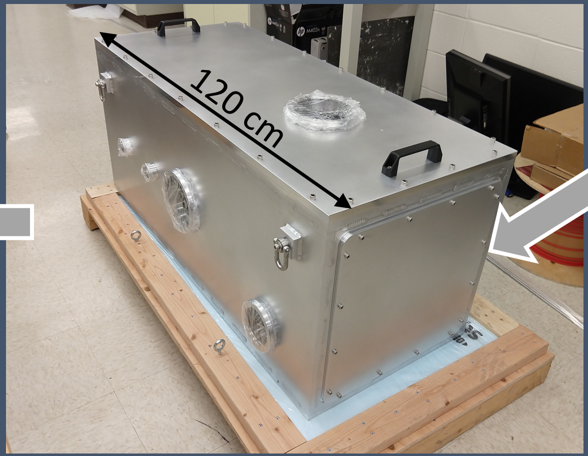
BEAST TPCs

8 x 40 cm³

2nd Generation: compact directional neutron detectors. *currently operating* @ KEK, Japan.

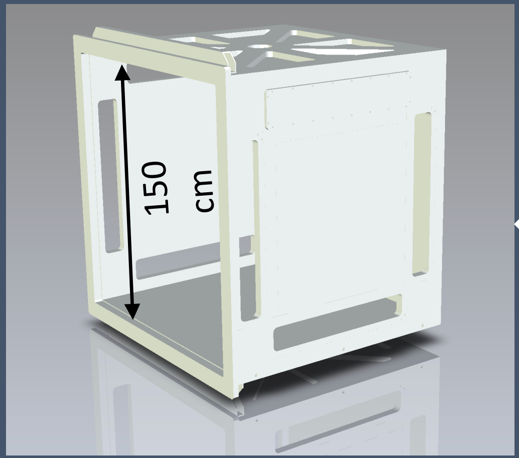
- Extensive prototyping with pixel chip readout completed
- Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for precision studies of nuclear recoil physics
- Now constructing 3rd generation detectors w/ CERN strip micromegas readout to achieve DM + solar neutrino sensitivity at reduced cost

2020



CYGNUS HD "Keiki" (40 liters)

2022



CYGNUS HD 1 Demonstrator (1 m³)

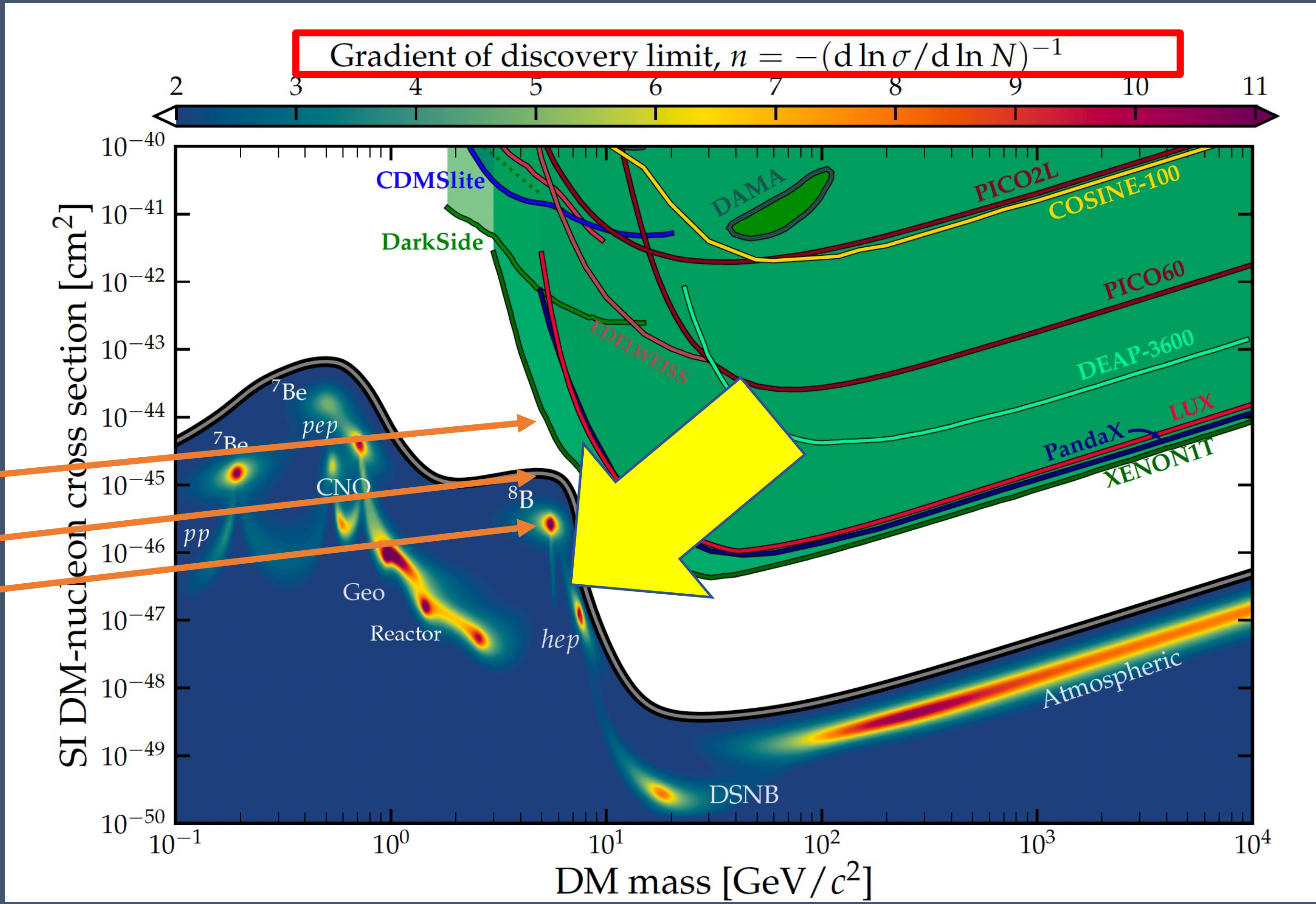
3rd Generation: Optimized for dark matter

Neutrino Fog as Opportunity

- Dark matter direct detection experiments approaching ‘neutrino fog’
  - Irreducible backgrounds from coherent elastic neutrino-nucleon scattering, a.k.a. CEυNS
  - Solar neutrinos relevant first
- Neutrinos reduces DM sensitivity of detectors

  O’Hare, PRL 127 (2021) introduced:
  - index *n, which* quantifies sensitivity reduction
  - To reduce σ sensitivity by factor 10, need 10^n larger expusre
    - above the fog: n=1, (background free), $\sigma \sim \frac{1}{Mt}$
    - neutrino floor: n=2, Poissonion subtraction, $\sigma \sim \frac{1}{\sqrt{Mt}}$
    - neutrino fog: n>2, σ saturates
- Directional detectors
  - can separate neutrino and DM signals!
  - n remains <2 even in the neutrino fog
  - fog becomes a positive: A source of guaranteed signal in DM experiment!

C. A. J. O'Hare et al., Snowmass White Paper on recoil imaging



Directional detectors can separate neutrino and WIMP signals, hence are more motivated now than ever before

The CYGNO project: 3D optical readout

CYGNO Experiment

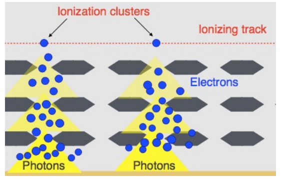
GSSI · INFN · Sapienza (Studium Urbis) · The University Of Sheffield. · UFJF Universidade Federal de Juiz de Fora · Universidade de Coimbra · Roma Tre Università degli Studi · ENEA · CBPF · UNICAMP

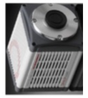
Instruments 6 (2022) 1, 6
JINST 15 (2020) 12, T12003
JINST 15 (2020) P08018
Measur.Sci.Tech. 32 (2021) 2, 025902

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

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

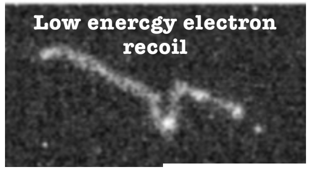
He:CF_4
@ 1 atm

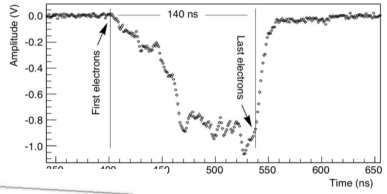


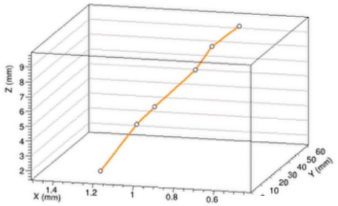


sCMOS:
high granularity
X-Y + energy measurements

PMT:
integrated
Z + energy measurement



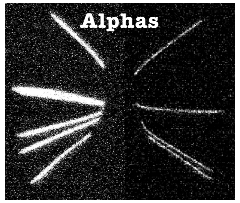




3D track reconstruction

+ SF_6 for negative ion drift

erc European Research Council
INITIUM



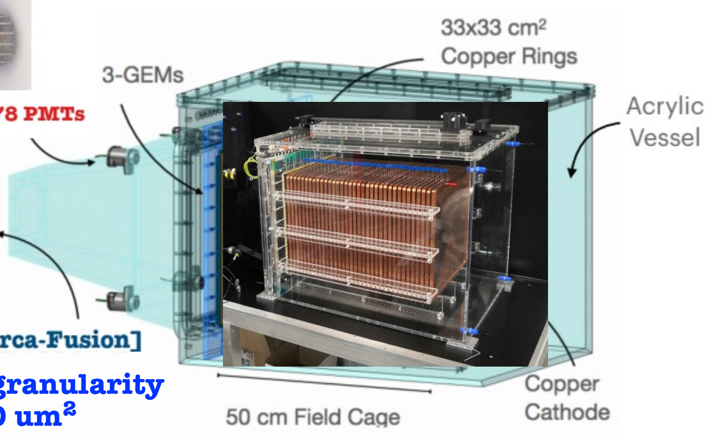
E. Baracchini, MPGD 2022 talk

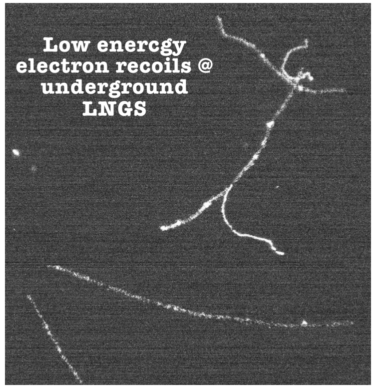
LIME: 50 L volume, 1 CMOS + 4 PMT

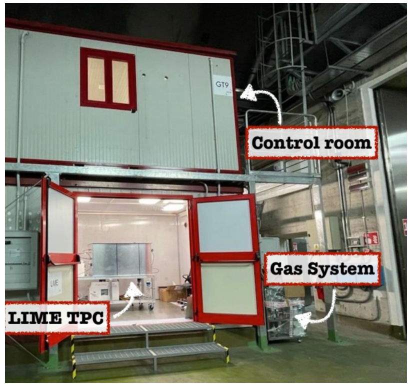
4 Hamamatsu R7378 PMTs

[Hamamatsu Orca-Fusion]

effective pixel granularity 160 x 160 um²





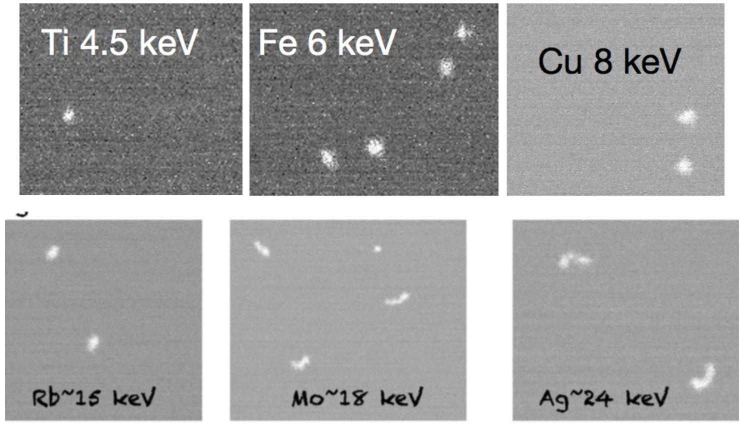


Now taking data underground LNGS

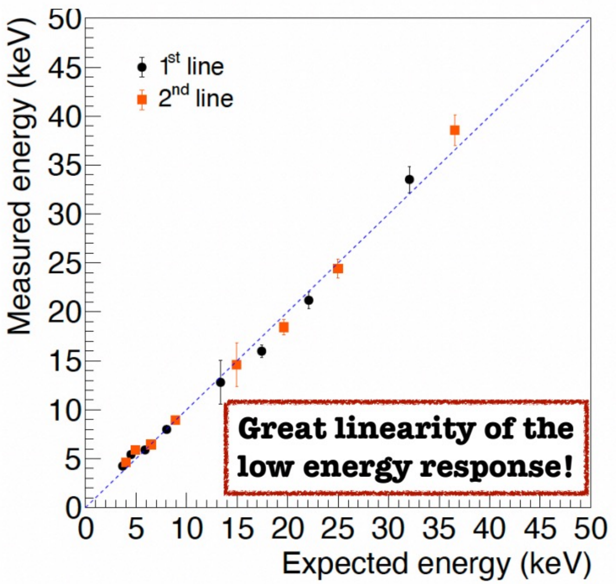
LIME overground commissioning and underground data campain

ER calibration @ LNF

LIME response to low energy ERs



Measured energy



LNGS data campaing

expected event rate from Geant4 simulation

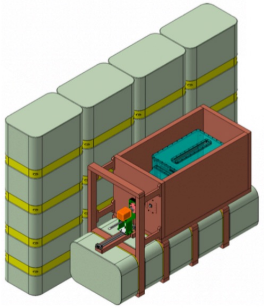
Run	Shielding	Internal [ev/yr] (1-20 keV)	External* [ev/yr] (1-20 keV)
1	No shield	1.5344(7)×10^6	4.061(8)×10^8
2	5cm copper	1.5344(7)×10^6	1.90(2)×10^7
3	10cm copper	1.5344(7)×10^6	1.024(2)×10^6
4	40cm water + 10cm copper	1.5344(7)×10^6	2.46(1)×10^5

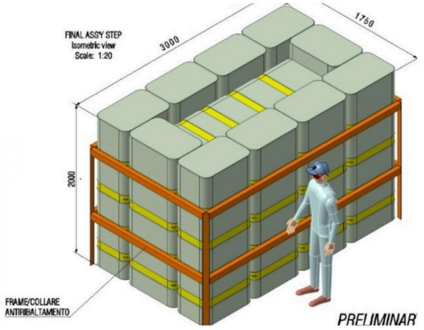
Run 1 & 2 data under analysis

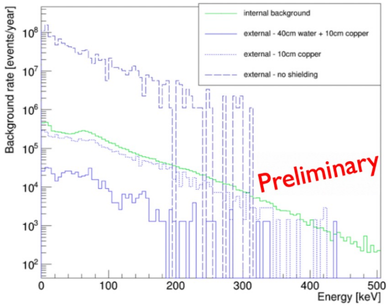
Now setting up LIME for Run 3

Goals

- Validate detector MC simulation
- Measure the neutron flux (expected 300 NRs from neutrons in 6 months) **@ the 10 Cu shielding stage**



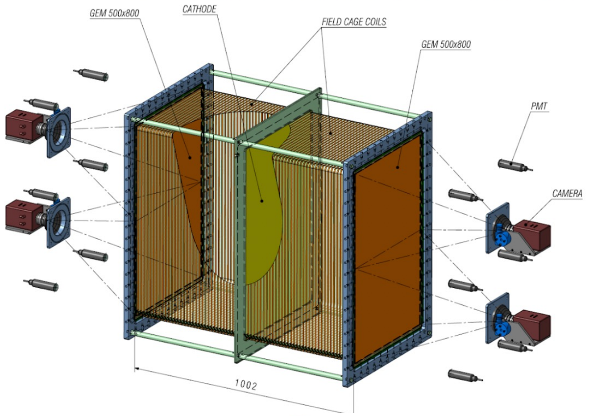


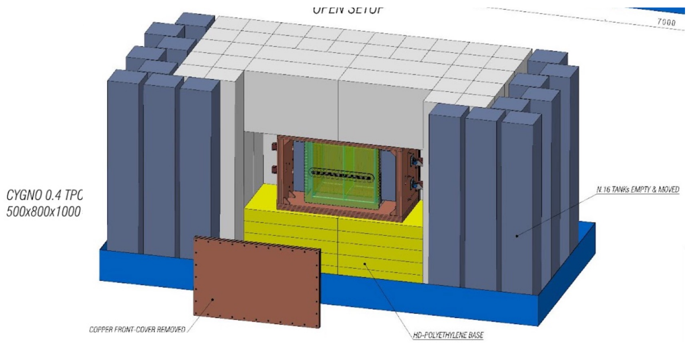


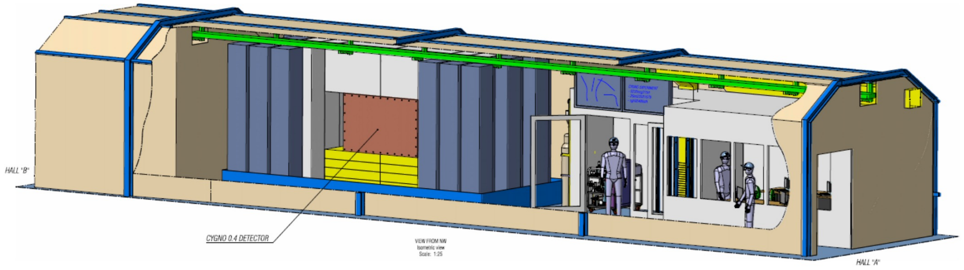
CYGNO project demonstrator: CYGNO-04

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

Designed at LNF and to be installed at LNGS

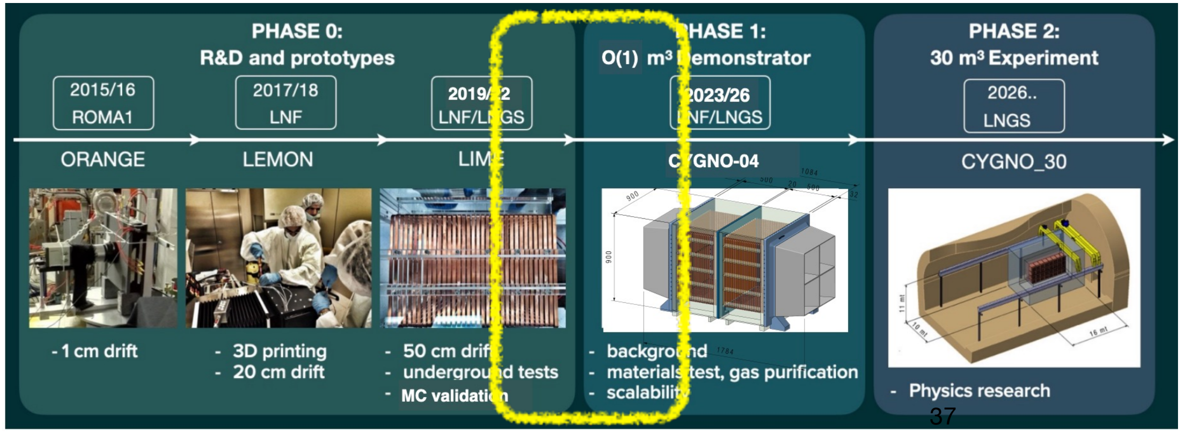


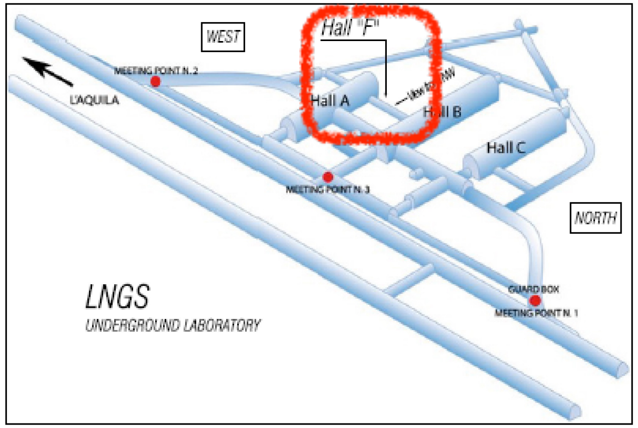




CYGNO-04 funded & TDR submitted

To be installed in LNGS Hall F

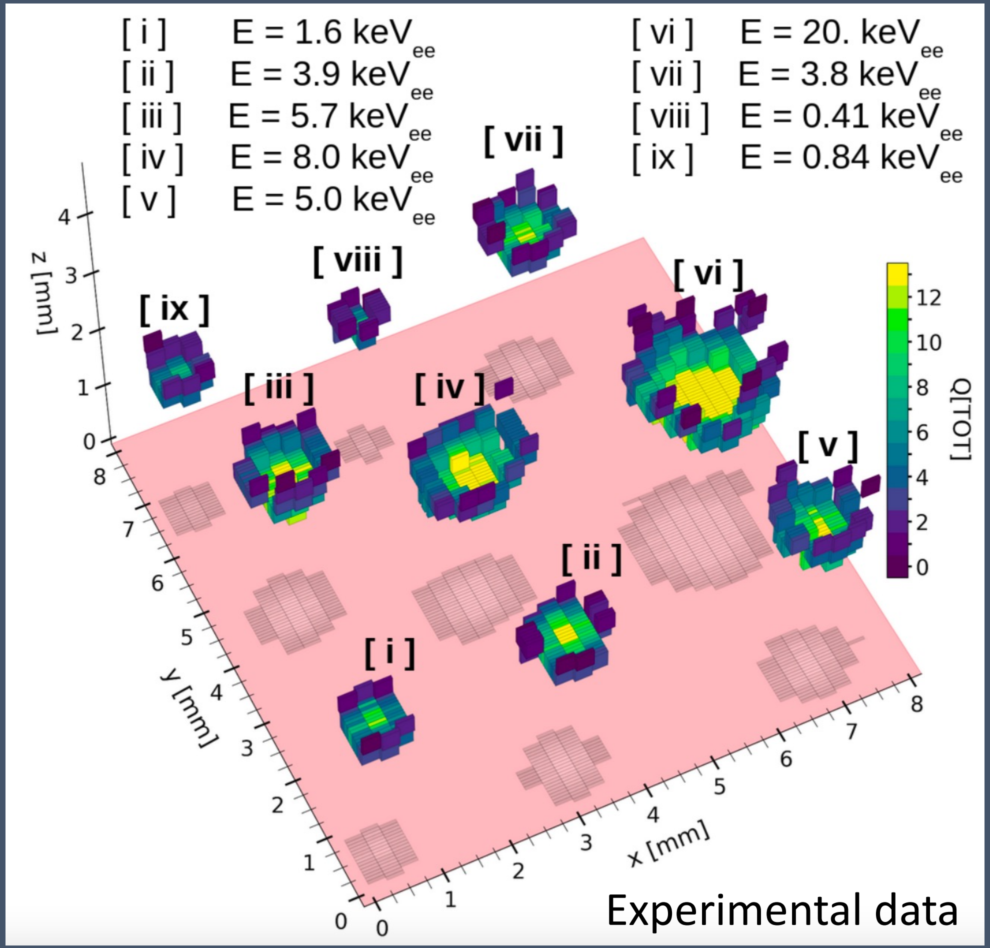


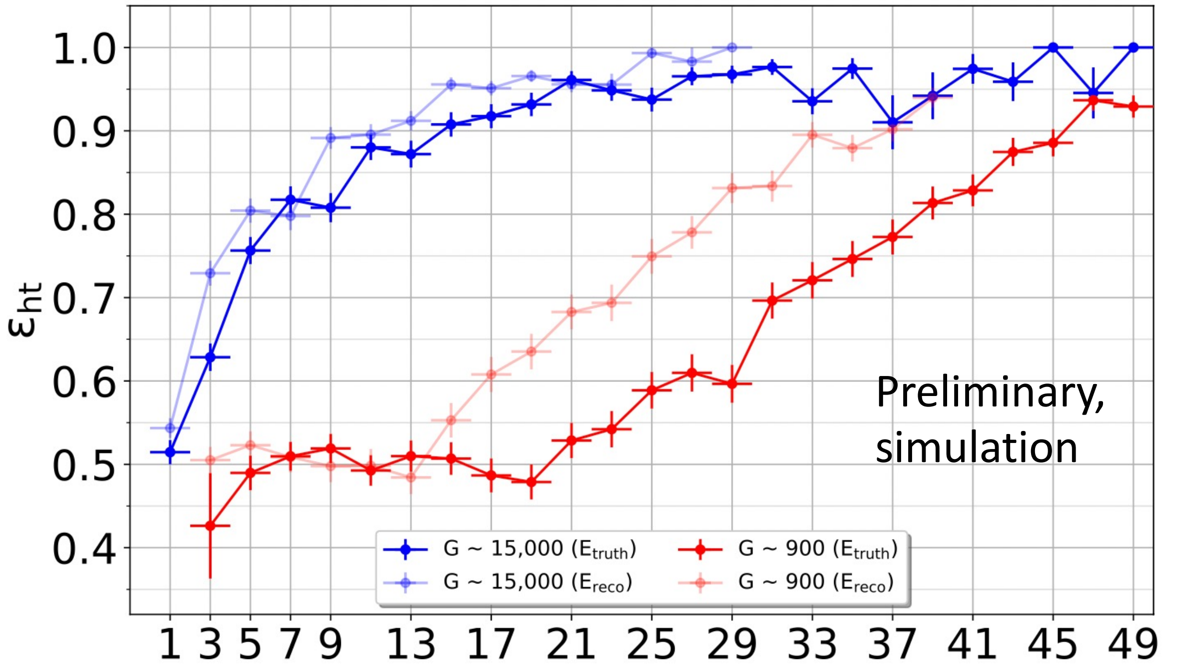


0.0001 m³ **0.01 m³** **0.05 m³** **0.4 m³** **30 m³ ?**

Event-level head/tail via ML: high gain mode

Jeff Schueler





Ionization energy [keVee]

High gain: Excellent head/tail down to 3keV, at p=1 atm, T=300K !
Experimental verification ongoing. (Difficult!)

Expect significant further improvement with final CYGNUS gas!

https://arxiv.org/abs/2008.12587

But what is the optimal TPC charge readout technology?

Helium recoils in 755:5 He:SF_6

nuclear recoil

electron recoil

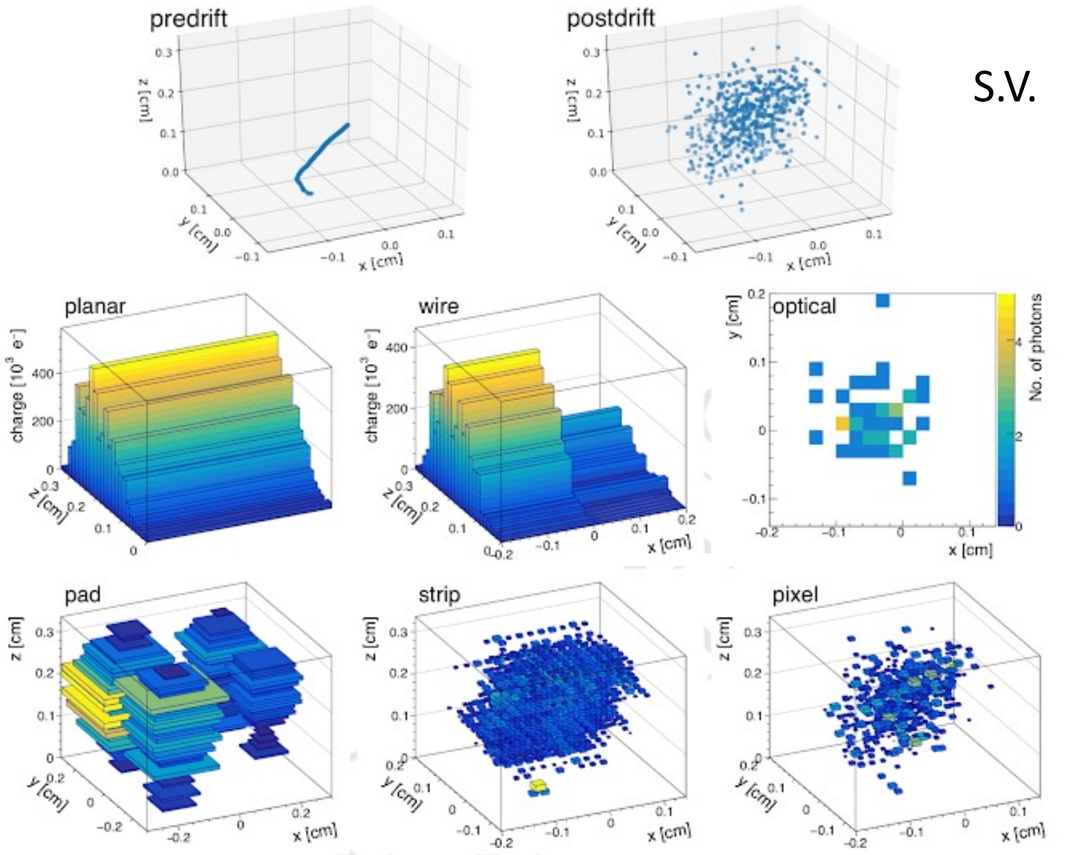


FIG. 9. Simulated 25 keV$_r$ helium recoil event in He:SF_6 gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

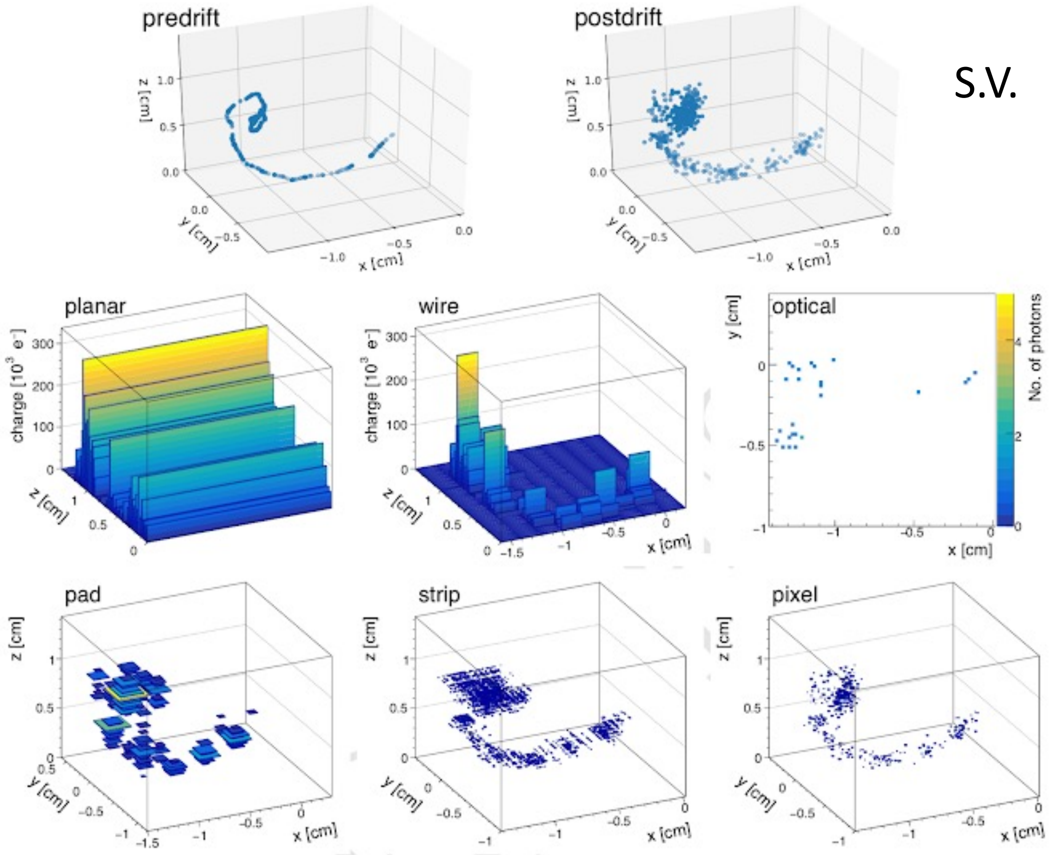
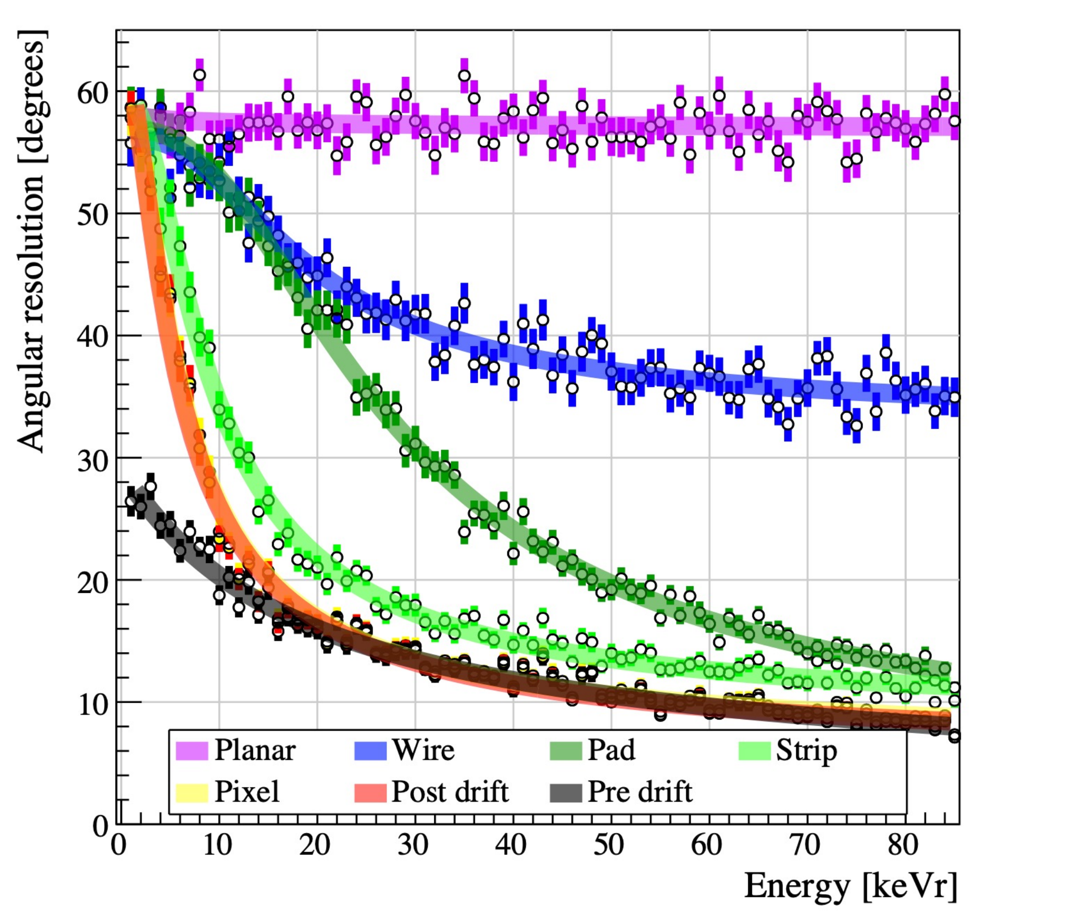


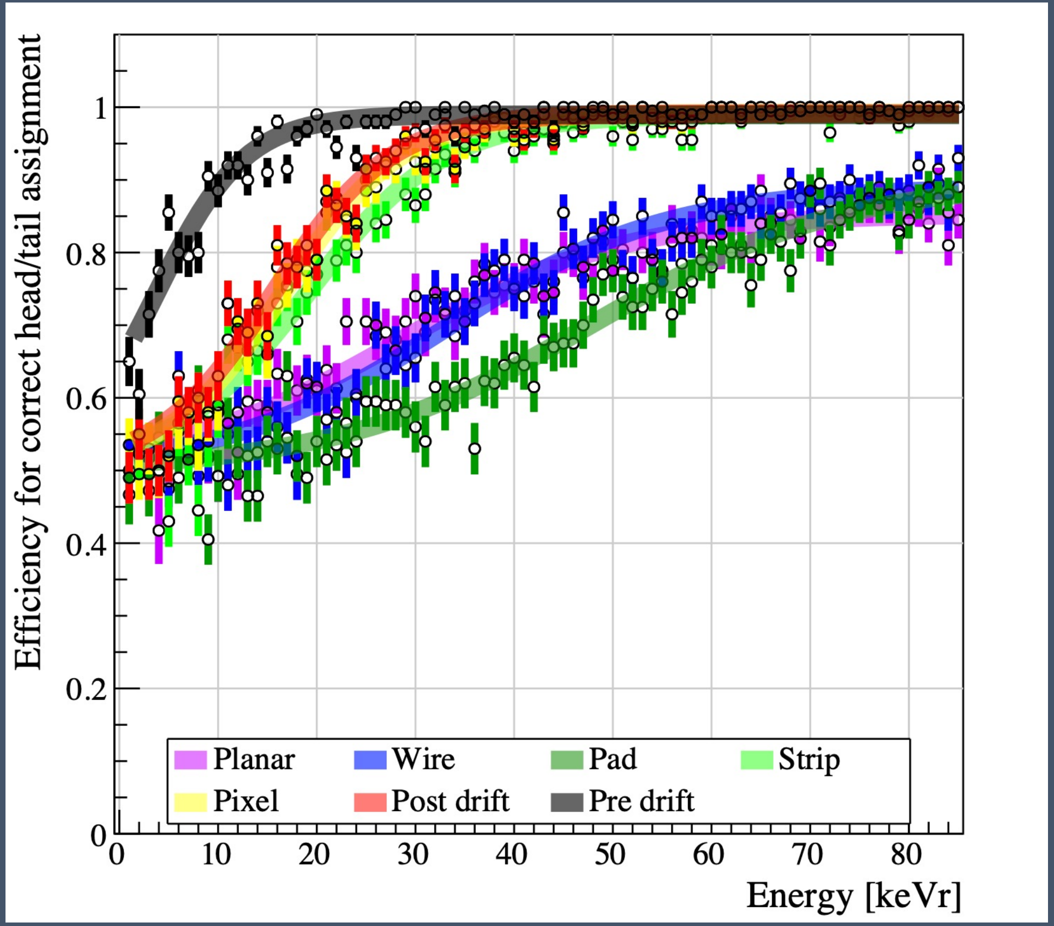
FIG. 10. Simulated 20 keV$_{ee}$ electron event in He:SF_6 gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost

Comparison of TPC charge readout technologies

Helium recoils in 755:5 He:SF_6 https://arxiv.org/abs/2008.12587





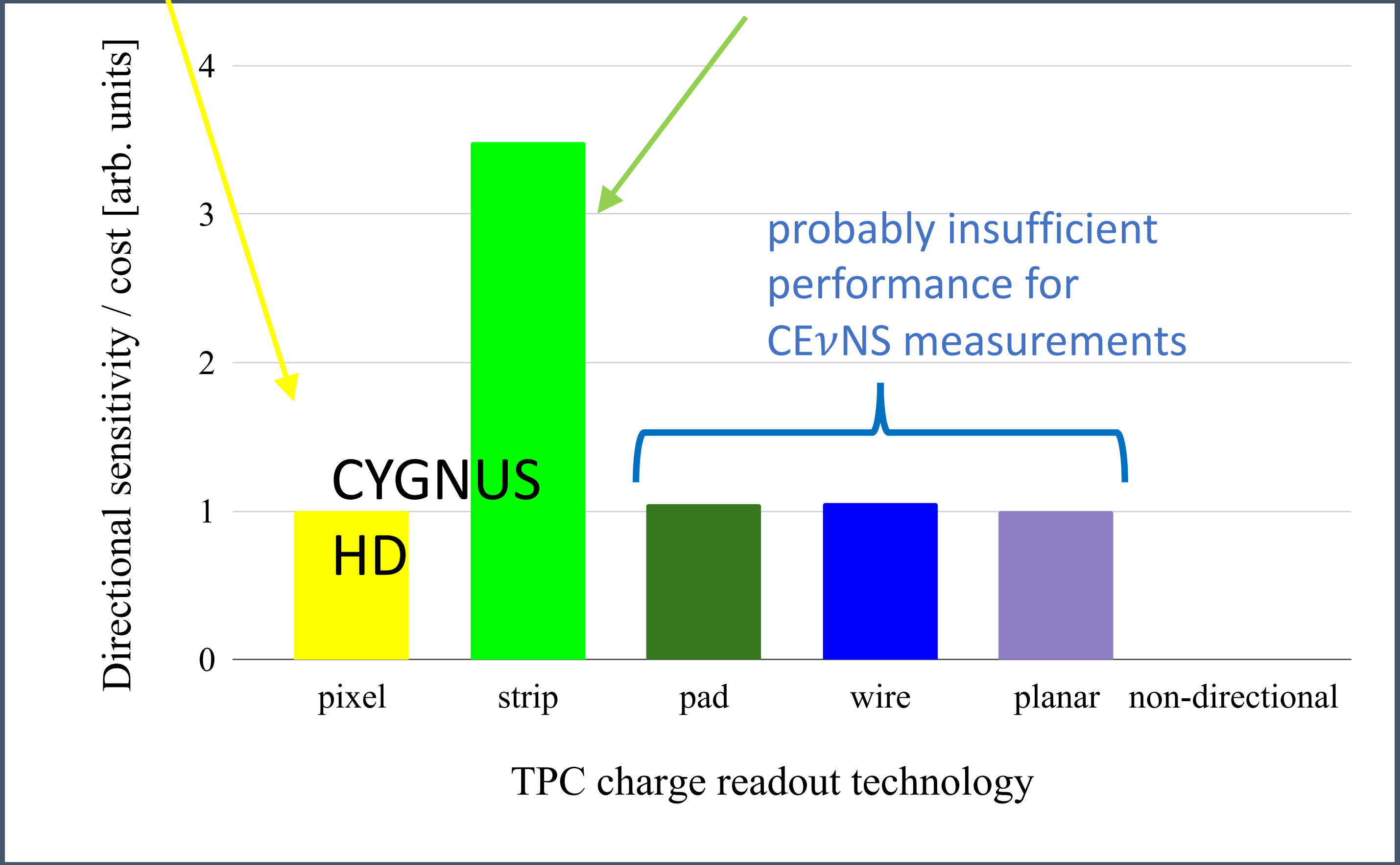
Pixel readout extracts the entire directional information left after diffusion (red and yellow curves overlap fully)
Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost

Caveats: Quantitative performance depends strongly on gas pressure (density) and analysis algorithm

Result of cost vs performance analysis

Best raw performance – optimal for precision studies of nuclear recoils

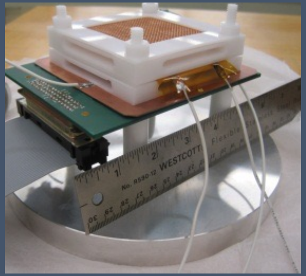
Best directional WIMP sensitivity per unit cost – optimal for large detectors!



https://arxiv.org/abs/2008.12587

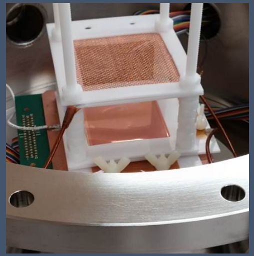
CYGNUS HD: MPGD gas TPCs for nuclear recoil imaging

2011-2013



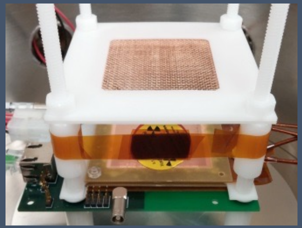
μD^3 (~1cm^3)

2013



~2.5 cm^3

2013



~ 20 cm^3

1st generation, proof of concept

2014

2 x 60 cm^3

2015

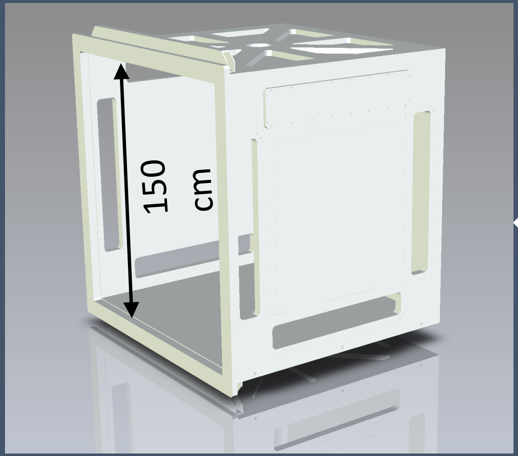
BEAST TPCs

8 x 40 cm^3

2nd Generation: compact directional neutron detectors. *currently operating* @ KEK, Japan.

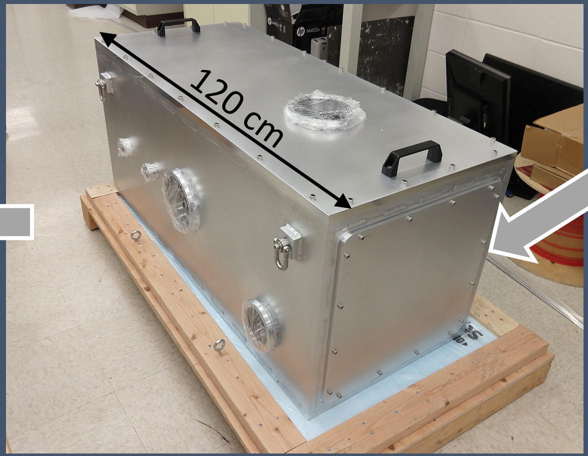
- Extensive prototyping with pixel chip readout completed
- Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for precision studies of nuclear recoil physics
- Now constructing 3rd generation detectors w/ CERN strip micromegas readout to achieve DM + solar neutrino sensitivity at reduced cost

2022



CYGNUS HD 1 Demonstrator (1 m^3)

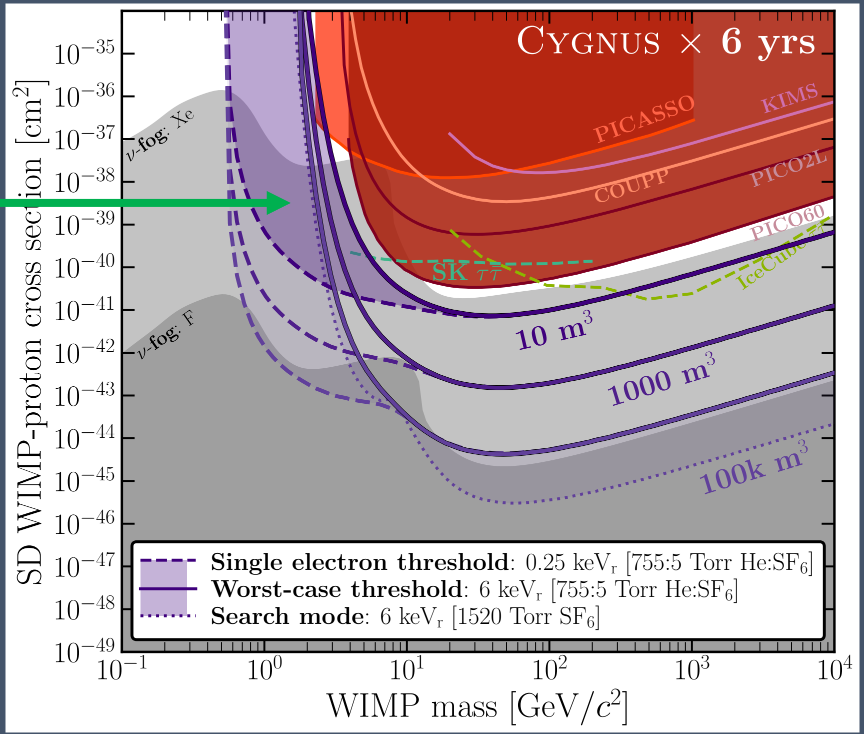
2020



CYGNUS HD “Keiki” (40 liters)

3rd Generation: Optimized for dark matter

WIMP sensitivity: depends on electron rejection

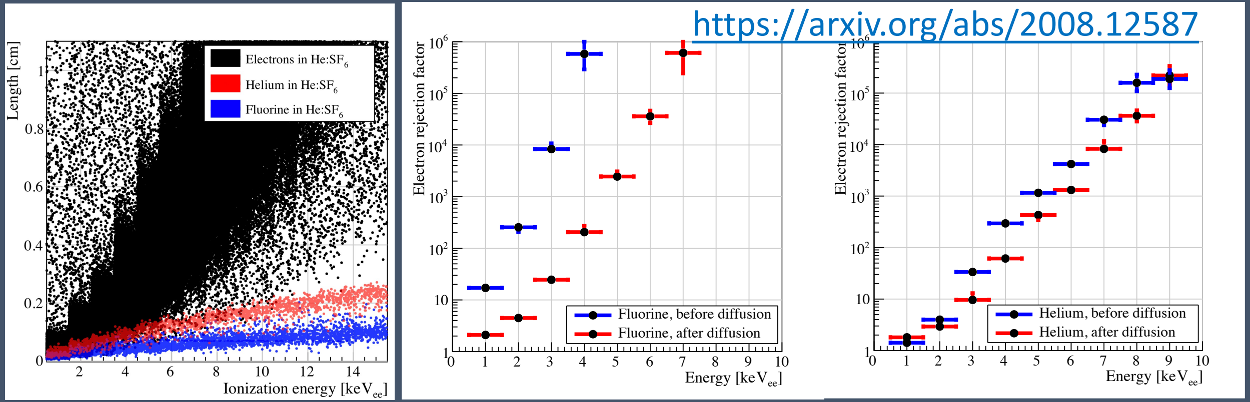


https://arxiv.org/abs/2008.12587

- Improved, physically motivated observables for electron rejection. Requires HD readout.
- Improved even further with 3DCNN, publication forthcoming.
- Demonstration measurement next.

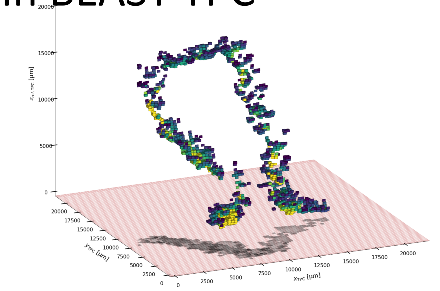
3D electron rejection (simulation) via dE/dx   5 torr SF_6 + 755 torr Helium

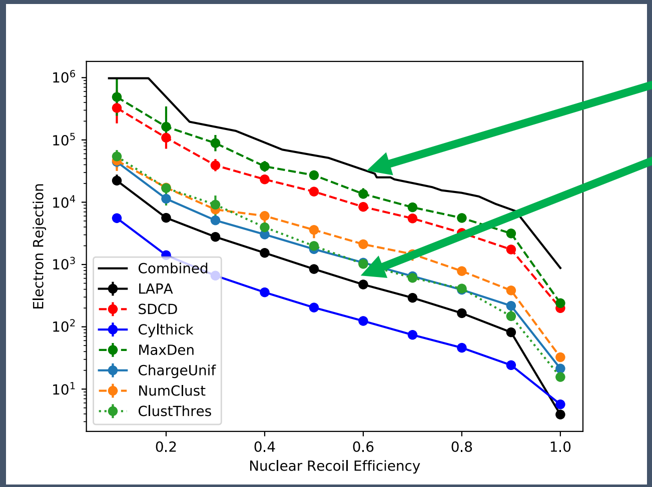
https://arxiv.org/abs/2008.12587



Electron rejection rises exponentially with ionization energy. When combined with flat bkg spectrum, will determine CYGNUS energy threshold for background free operation.

Electron recoil candidate
In BEAST TPC

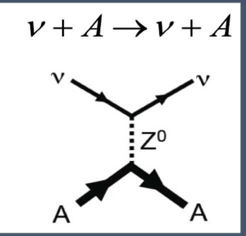




~2 orders of magnitude improvement over dE/dx !

Majd Ghrear et al., arxiv.:2012.13649

Directional CEvNS measurements at SNS, Oak Ridge

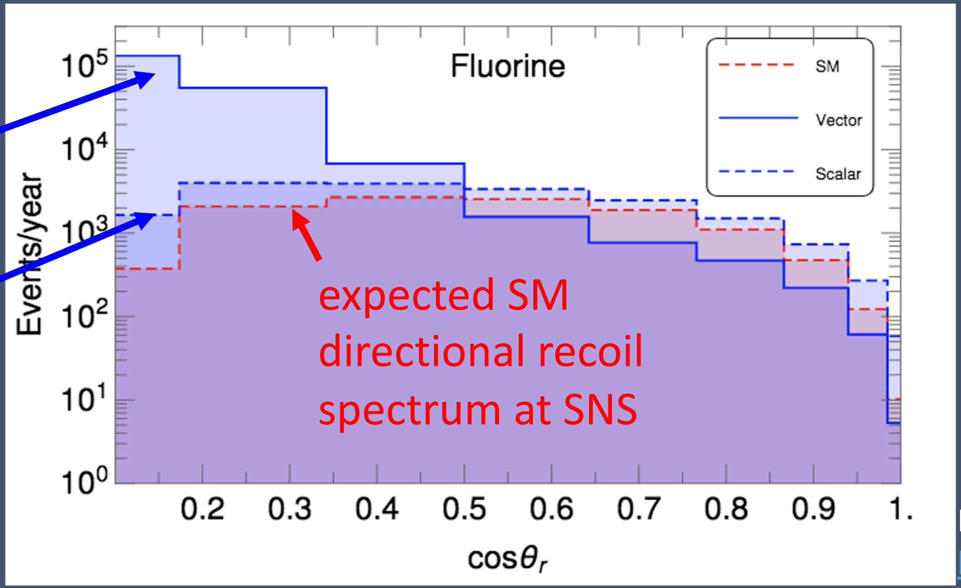


- CEvNS = Coherent elastic neutrino nucleus scattering
- This process probes the weak nuclear charge and weak mixing angle
- Precisely predicted by the SM allowing for sensitive probe of BSM physics

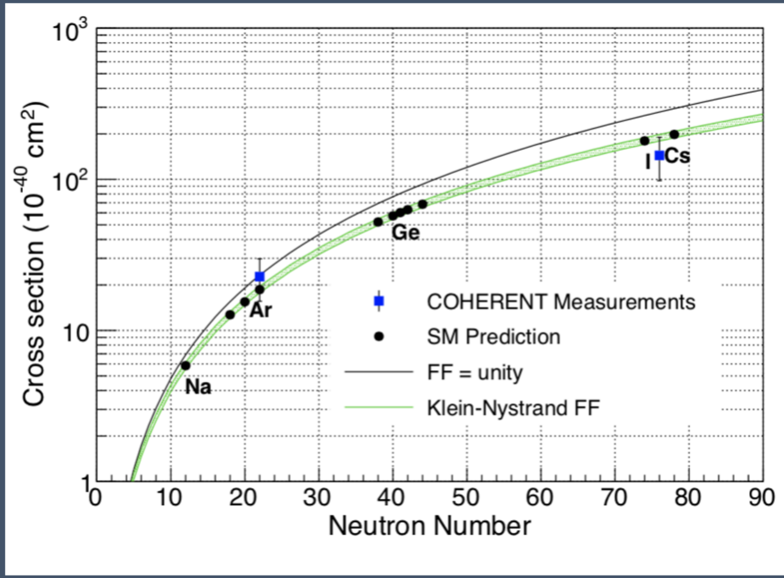
- COHERENT detected CEvNS in CsI[Na] (2017), and later in liquid argon (2021)
- Directional detectors sensitive to new physics in CEvNS via recoil-angle distribution

BSM light vector mediator

BSM light scalar mediators



Phys. Rev. D 102, 015009
https://doi.org/10.1103/PhysRevD.102.015009



Phys. Rev. Lett. 126, 012002
https://doi.org/10.1103/PhysRevLett.126.012002

- Potential for competitive measurement. 3-30 SM recoil events/year, w/ 1-10 m^3 gaseous TPC, E>1keVr (depends on gas)
- We can *detect* sub-keV events, and based on most recent simulations expect some directionality above E~1keV
- Would benefit from higher flux / moving closer to source. Under discussion. Need more careful evaluation.

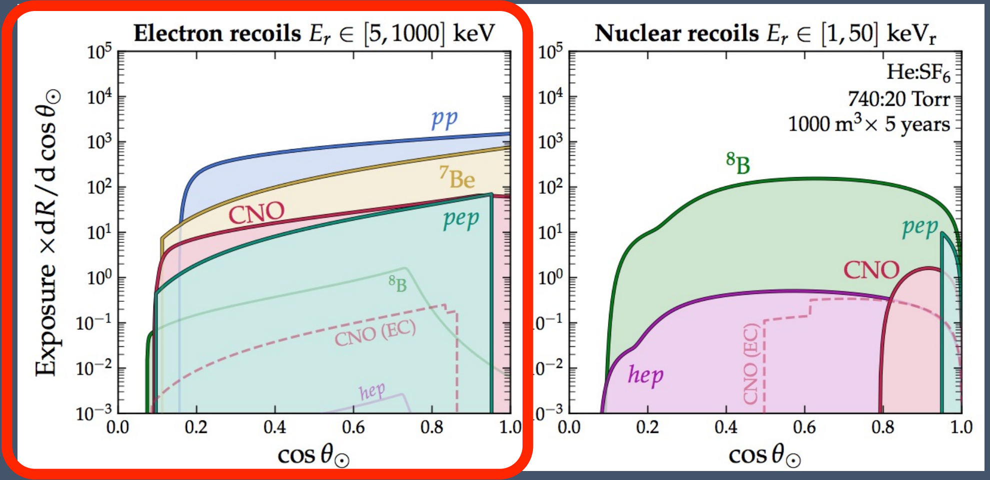
Solar Neutrinos in CYGNUS: promoting background to signal

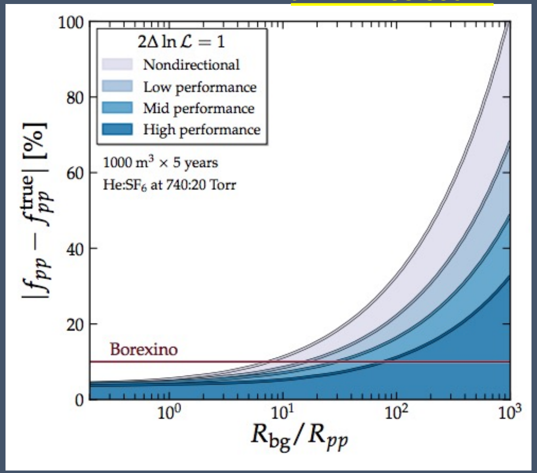
CYGNUS 1000

Expected number of ER and NR events as a function vs cosine of angle w.r.t. the Sun

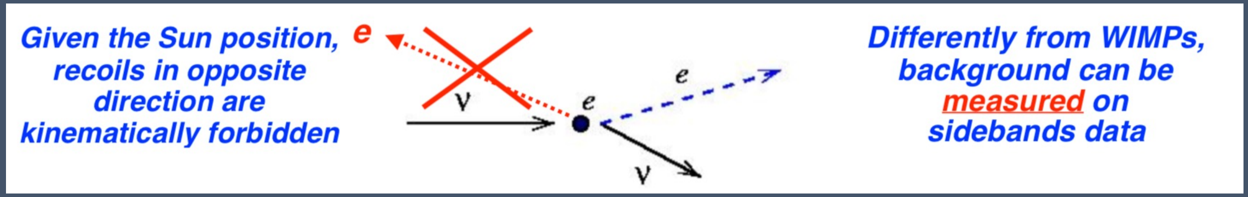
C. A. J. O'Hare et al., 2022 Snowmass Summer Study, arXiv:2203.05914

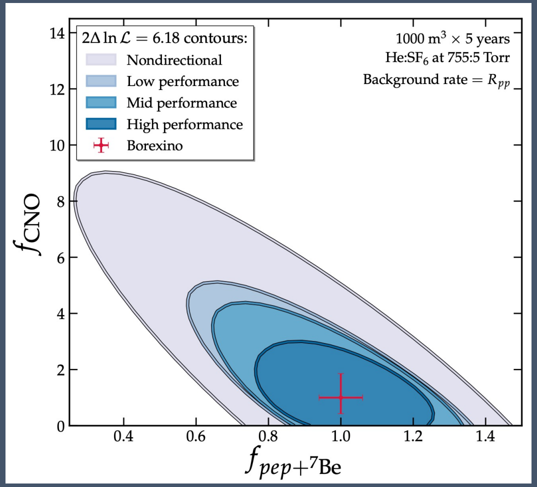
Electron recoils





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

- ***Electron recoil directionality in CYGNUS enables solar neutrino spectroscopy through neutrino-electron elastic scattering on an event-by-event basis***
  - **An O(10) m^3 ER directional detector could extend Borexino pp measurement to lower energy**
  - **CYGNUS 1000 could measure the CNO cycle by breaking the degeneracy with pep + ^{7}Be fluxes through directionality**

Preliminary study shows potential. Increasing directional performance alone can lead to a massive jump in the physics potential in terms of measuring these fluxes, without any increase in event rate. Next: optimize gas for electron recoil signature.

Also need to revisit multiple scattering! Ongoing.

ER multiple scattering revisited & optimal track length for directionality

GSSI — INFN

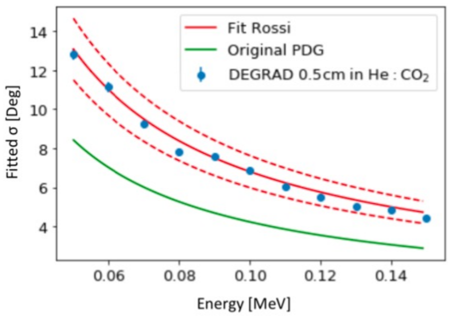
Found to be inadequate to describe MS for ER: we fit these two parameters to DEGRAD simulation of gas mixtures

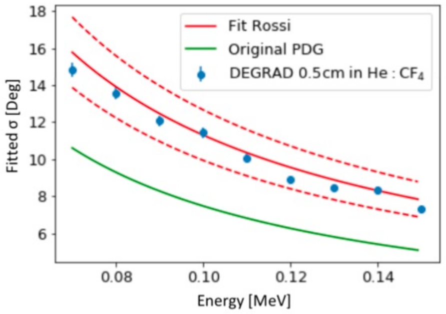
Gas Mixture	Pressure	Rad. Length
60% He 40% CF_4	760 torr	220 m
70% He 30% CO_2	760 torr	606 m

M. Ghrear & S. Vahsen, paper in preparation

$$\sigma_{\Psi_{\rm plane}} = \frac{1}{\sqrt{3}}\frac{13.6\mathrm{MeV}}{\beta c p}\sqrt{\frac{x}{X_o}}\left[1+0.038\ln\frac{x}{X_o\beta^2}\right]$$

Lynch and Dahl obtain these parameters by fitting to RMS values for nuclear recoils distributions with Geant. They fit to different values of x and Z (X_o), for **singly charged (z=1) heavy particles with beta = 1**.





By combining the fitted multiple scattering with the point resolution as from S. E. Vahsen et al. NIM A 788 (2015) 95-105:

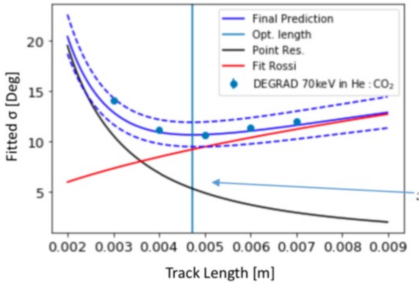
$$\sigma_\phi^{\rm plane} = \frac{\sqrt{12}\sigma_{x/y/z}}{L\sqrt{N}}$$

$$\sigma_\Psi^{\rm plane}(x) = \sqrt{a^2x + b^2x^{-3}}$$

$$a \equiv \frac{1}{\sqrt{3}}\frac{13.1\mathrm{MeV}}{\beta c p\sqrt{X_o}} \qquad b \equiv \sigma_{x/y/z}\sqrt{\frac{12W}{dE/dx}}$$

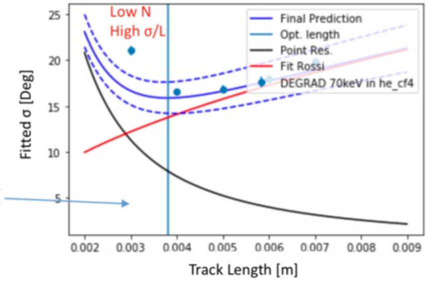
we can estimate the expected ER angular resolution from gas mixture properties and predict the optimal track length for angle evaluation (with simple SVD algorithm)

70 keV electron recoils in 70% He 30% CO_2



$x_o = 3^{\frac{1}{4}}\sqrt{b/a}$

70 keV electron recoils in 60% He 40% CF_4



E. Baracchini - The CYGNUS Galactic Recoil Observatory - ICHEP 2022, Bologna, 9th July 2022 — 19

Table 1 Approximate expected numbers of neutrino-induced nuclear and electron recoils[a]

Nuclear recoils	SF_6			CF_4			He		
Threshold (keV_r)	1	5	10	1	5	10	1	5	10
Solar (mainly ^8B)	73	15	2	54	16	3	3	2	1
3-kpc supernova	25	18	12	18	13	10	0.6	0.5	0.5
Electron recoils	**SF_6**			**CF_4**			**He**		
Threshold (keV)	5	500	1,000	5	500	1,000	1	500	1,000
Solar (total)	537	42	4	438	34	3	102	8	0.8
Solar (CNO)	15	5	0.6	12	4	0.5	3	0.9	0.1
Geoneutrinos	0.2	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1

[a]Assuming a target volume of 1,000 m^3, 1 atmosphere pressure, and an exposure time of 1 year.