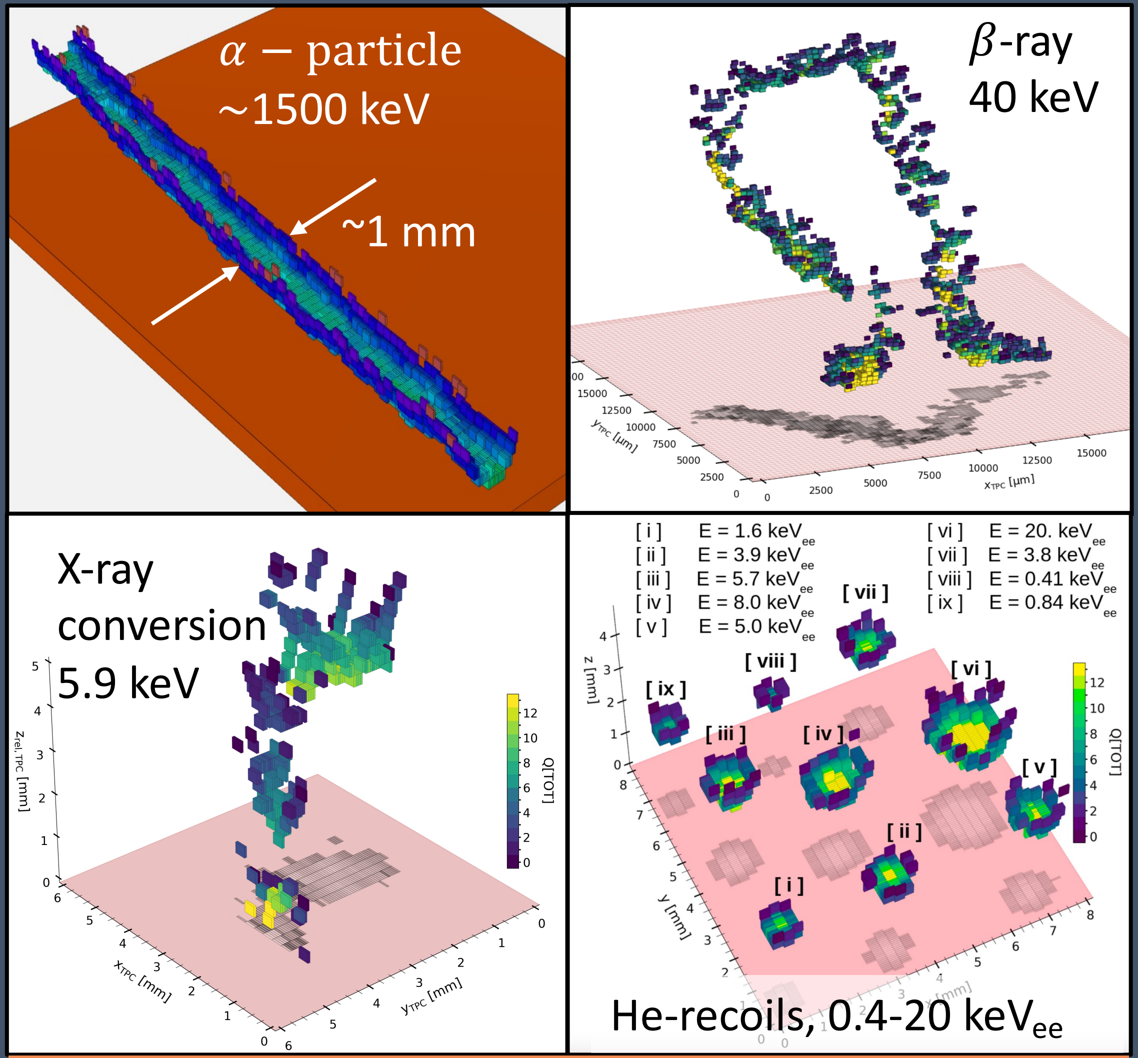
Gaseous Detector R&D Aimed at Recoil Imaging



- Experimental data from BEAST TPC directional neutron detectors
- He:C02 gas @ 1 atm
- Each colored voxel: ionization density in 50 x 250 x 250 μm^3

- "Recoil imaging": Topological and directional reconstruction of low-energy nuclear and electronic recoils
- A Snowmass working group of 167 physicists considered the case for this technique (arXiv:2203.05914)
  - Conclusion: enables new experiments!
- Blue sky R&D challenge: can we advance this technique to the fundamental limit?
  - Detect every single electron in 3d
  - In volumes up to DUNE scales
  - At HEP-feasible cost

Opportunities for a 30+ year physics program

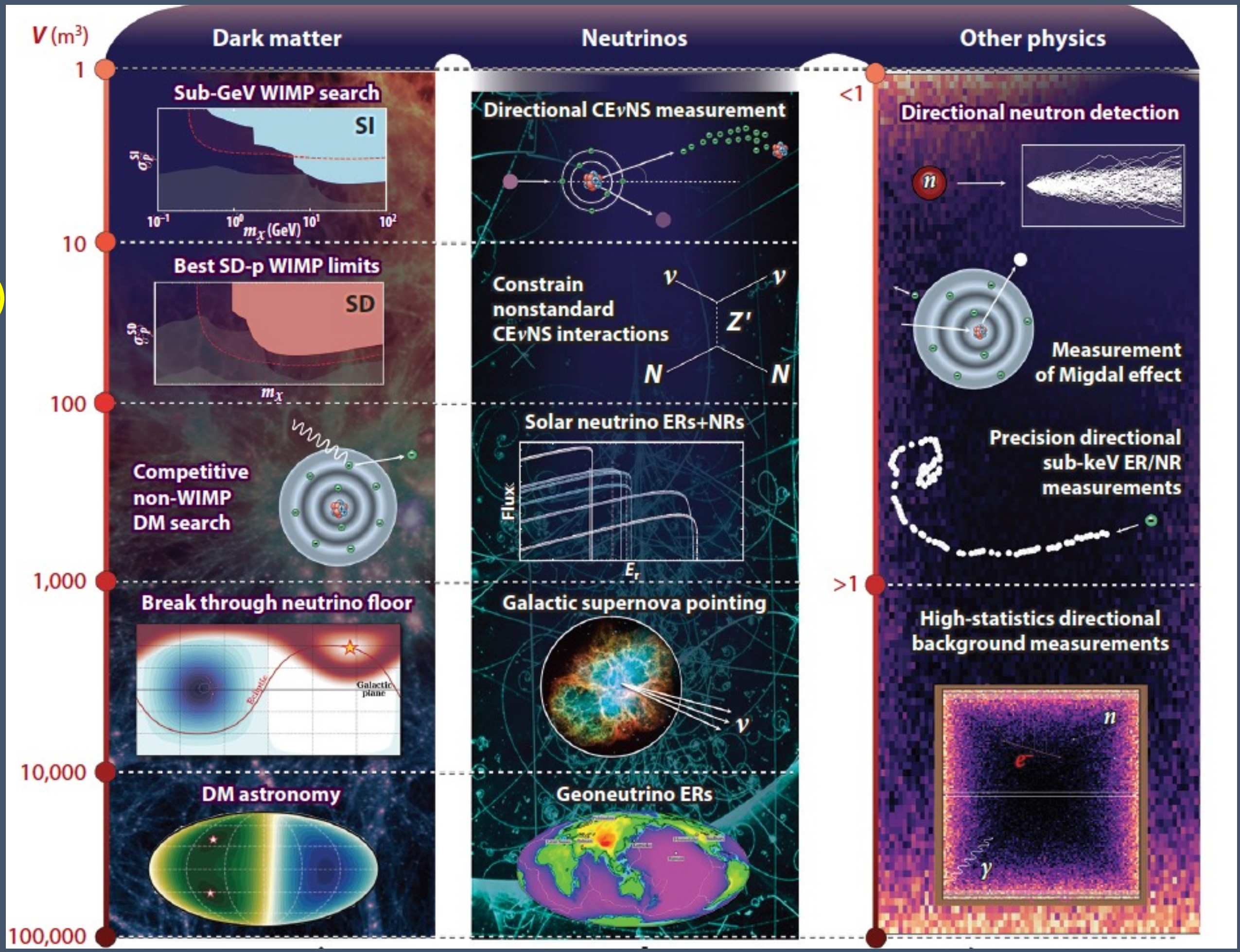
arxiv:2102.04596

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

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

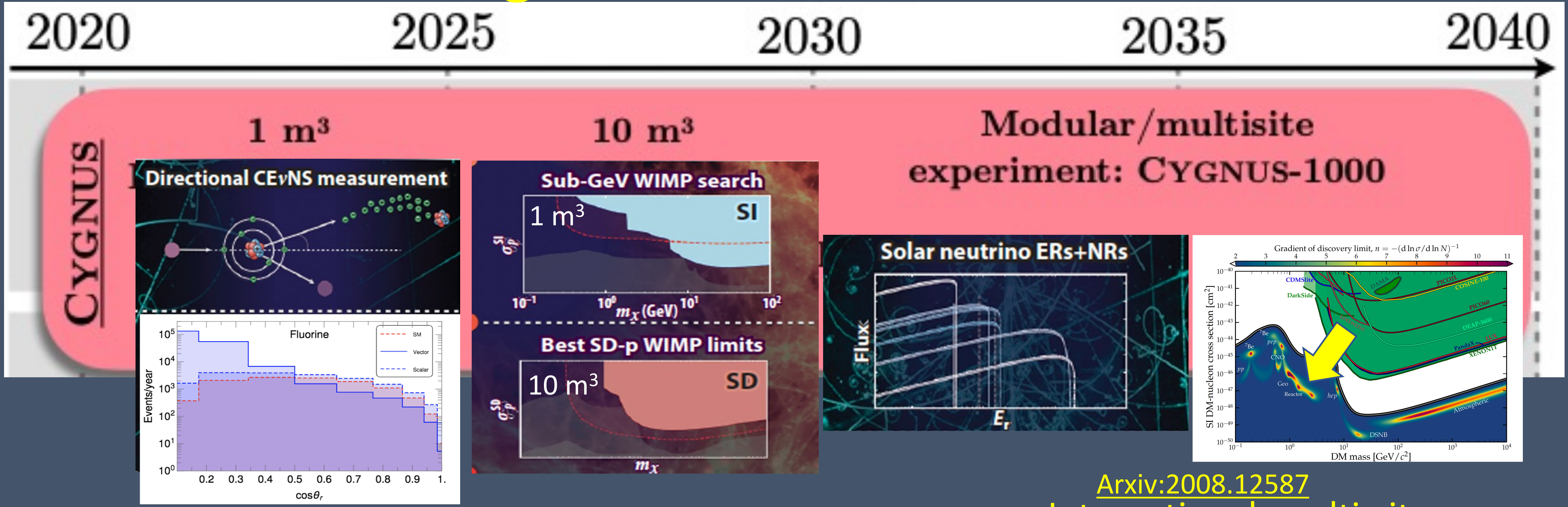
Exposure, size

- 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



SNS, Oak Ridge, TN

Directional BSM-search in CEvNS

SURF, Lead, SD

World-leading DM limits

Arxiv:2008.12587

International, multi-site

$10-50M, for 1000m^3 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 m^3 ν-scattering experiment, aboveground
- Radio-pure 10 m^3 experiment, underground (DM)
- MIE for large-scale, underground observatory (solar neutrinos + DM below neutrino floor) $10-50M (hardware only)

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!

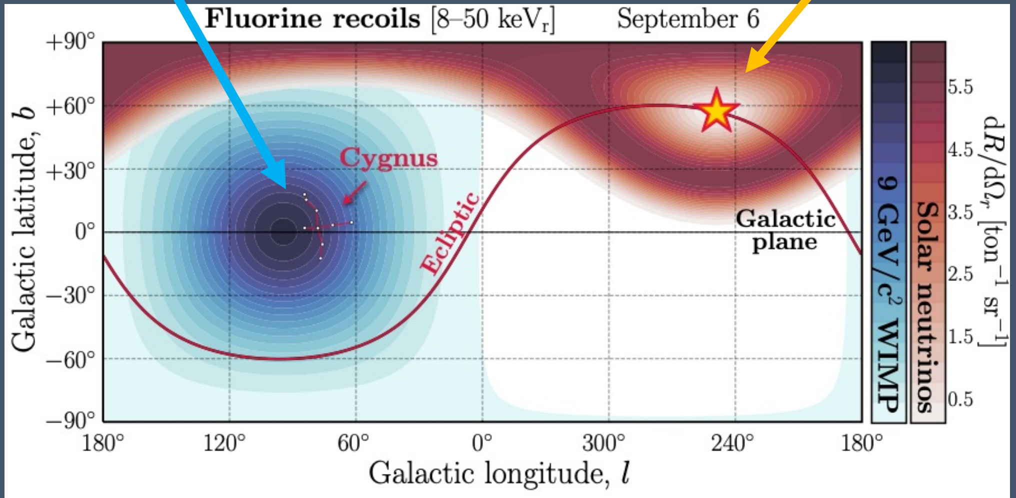
→ Fewest events for DM discovery

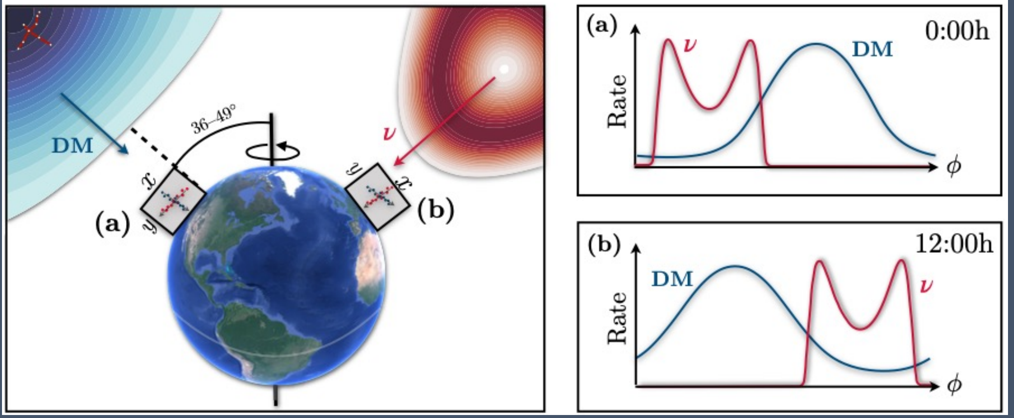
→ Enables Neutrino spectroscopy

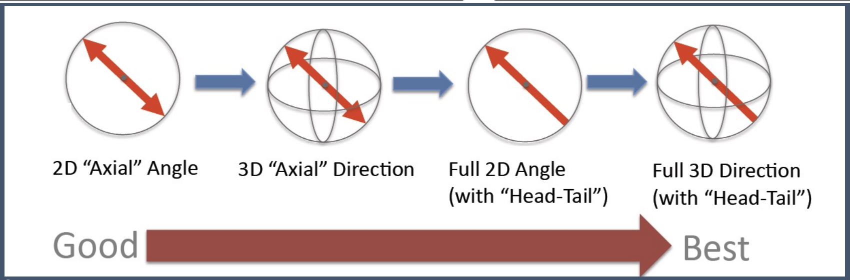
arxiv:2102.04596

Neutrinos from the sun

WIMP wind, approx. from CYGNUS



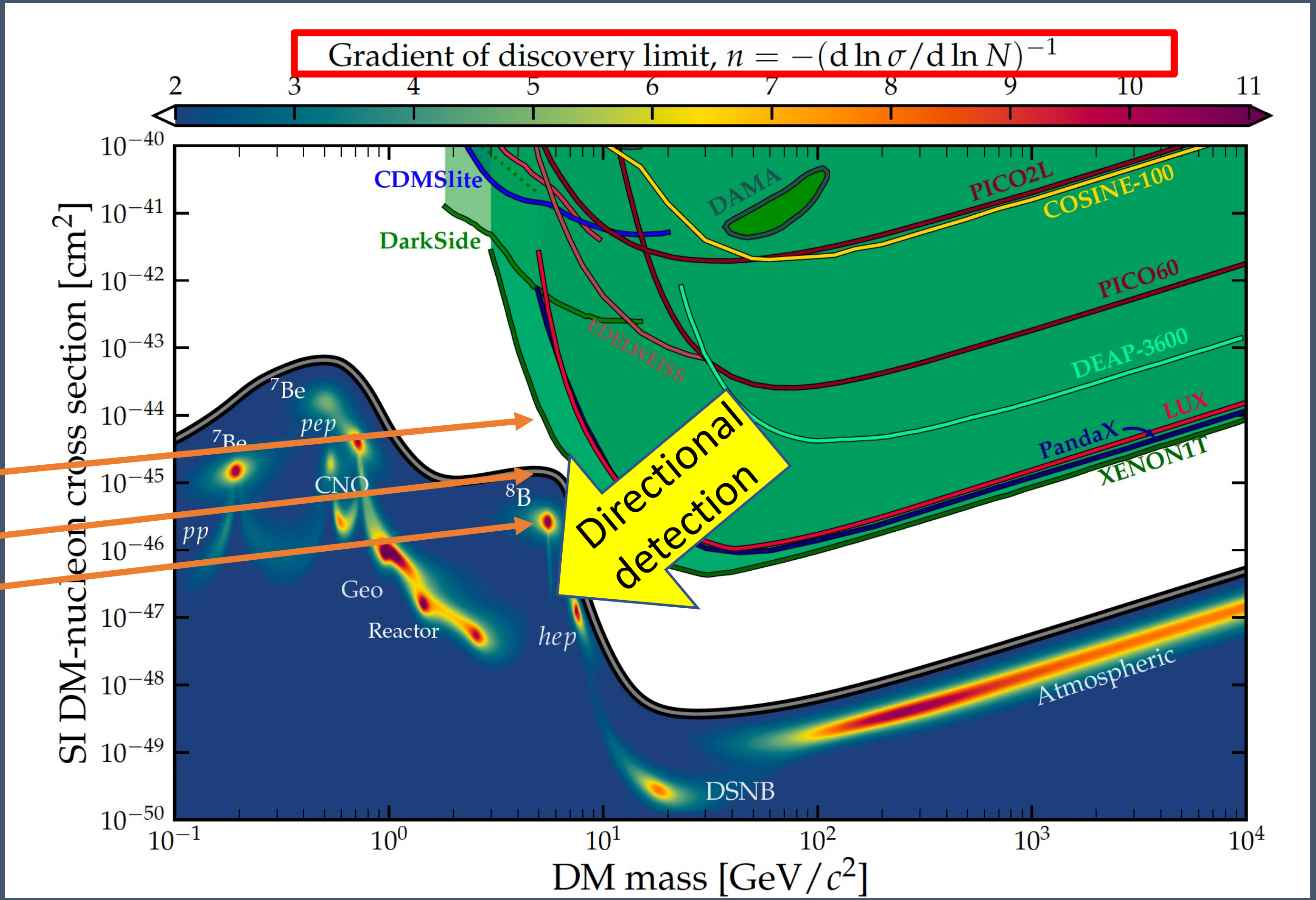




Turning the Neutrino Fog into an Opportunity

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 reduce 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

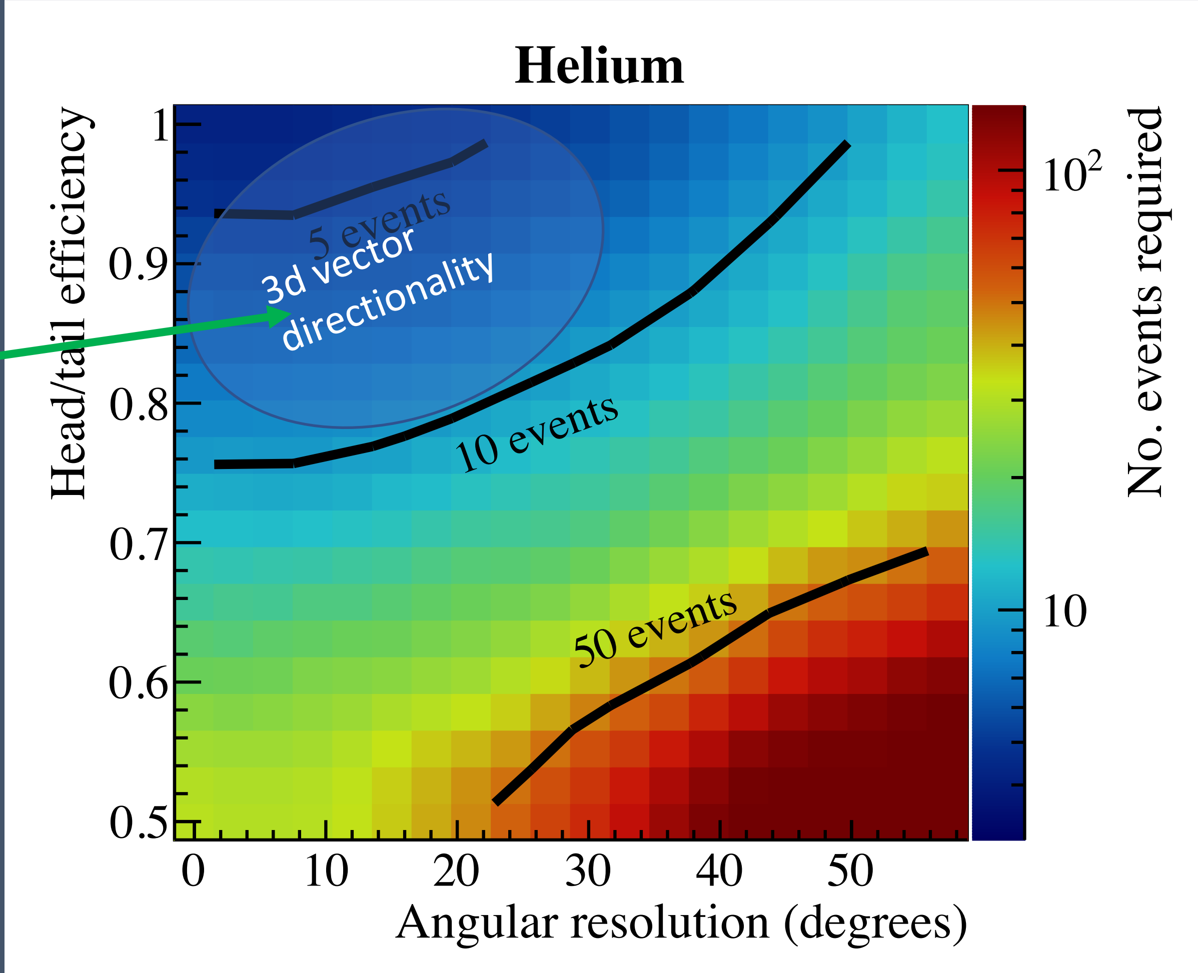
Detector Performance Requirements

https://arxiv.org/abs/2102.04596

(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!

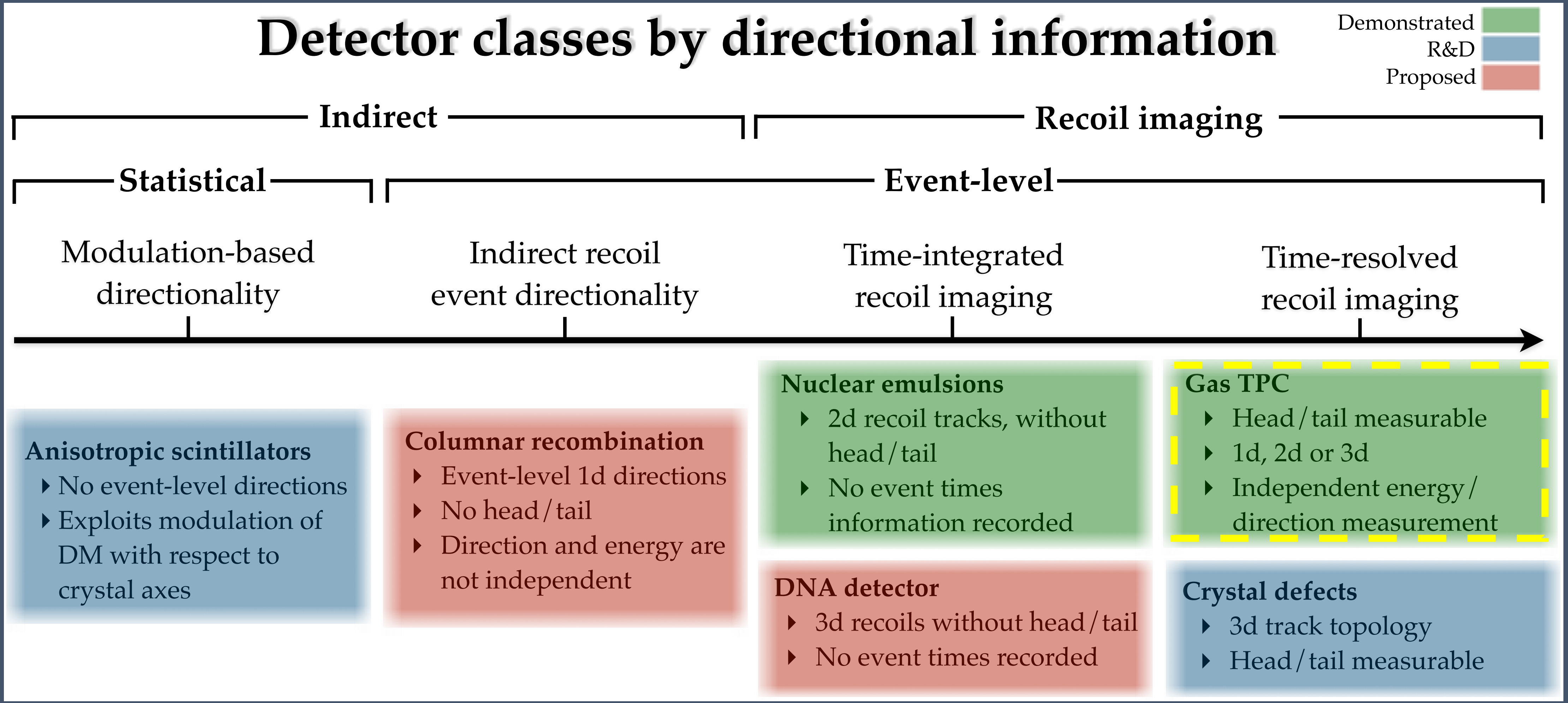


detected WIMP events required to exclude ν-hypothesis at 90% CL

Assumptions: m_χ = 10 GeV, He:SF_6 gas

Gas Detectors Required for “best directionality”

https://arxiv.org/abs/2102.04596

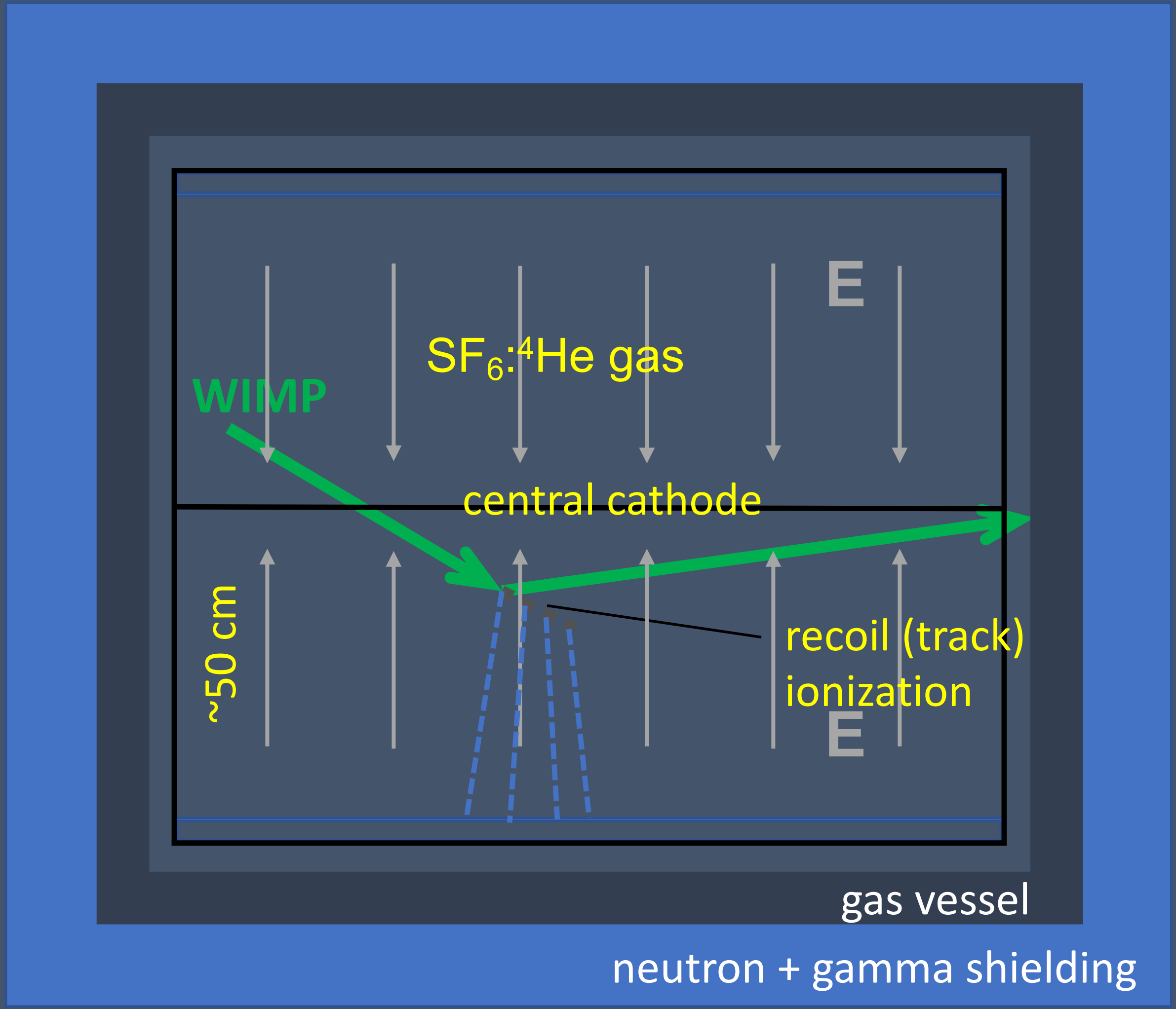


This talk

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.

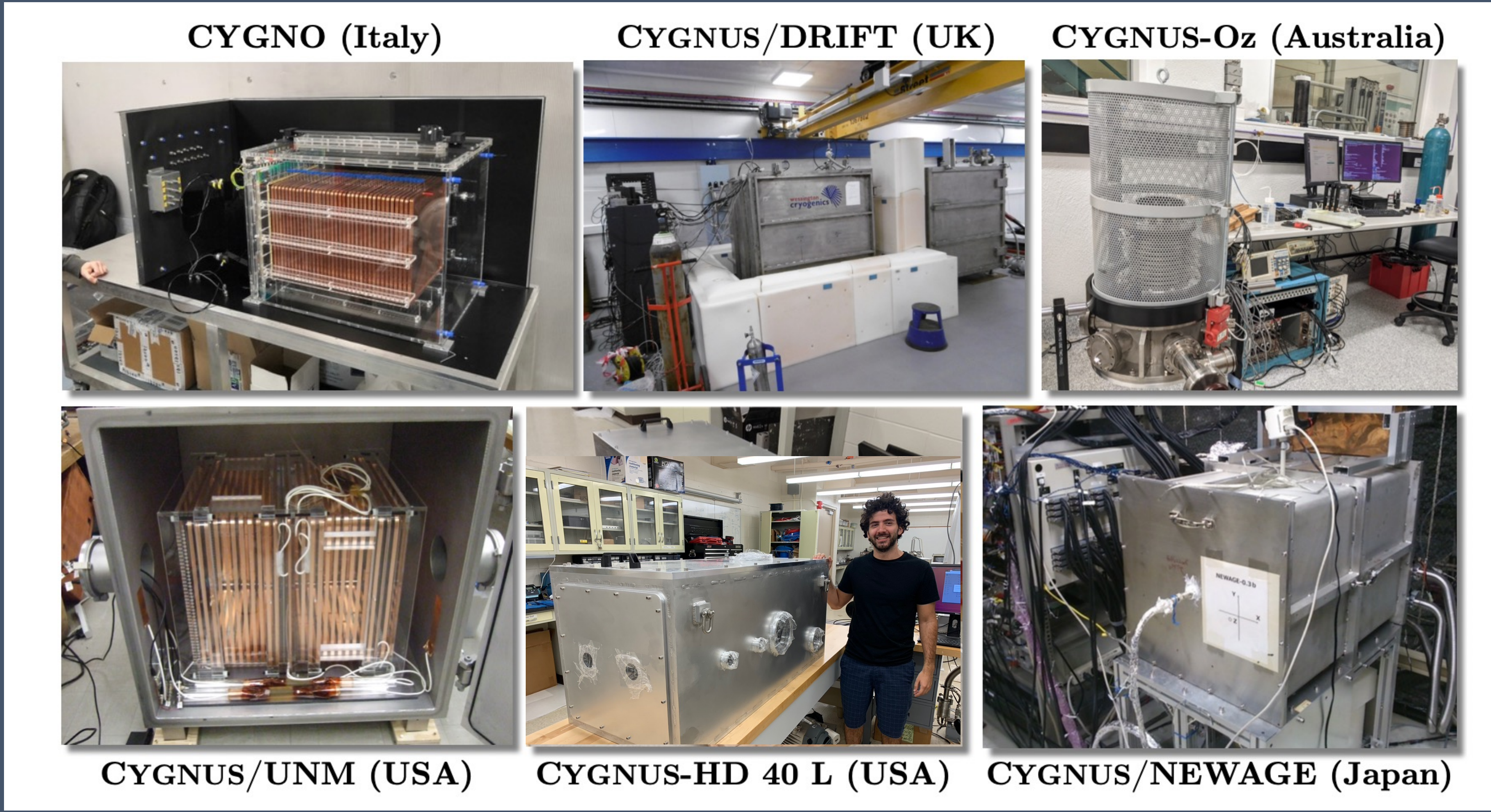
Larger detector would consist of ~1m^3 unit-cell TPCs inside a single, large, gas vessel.

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

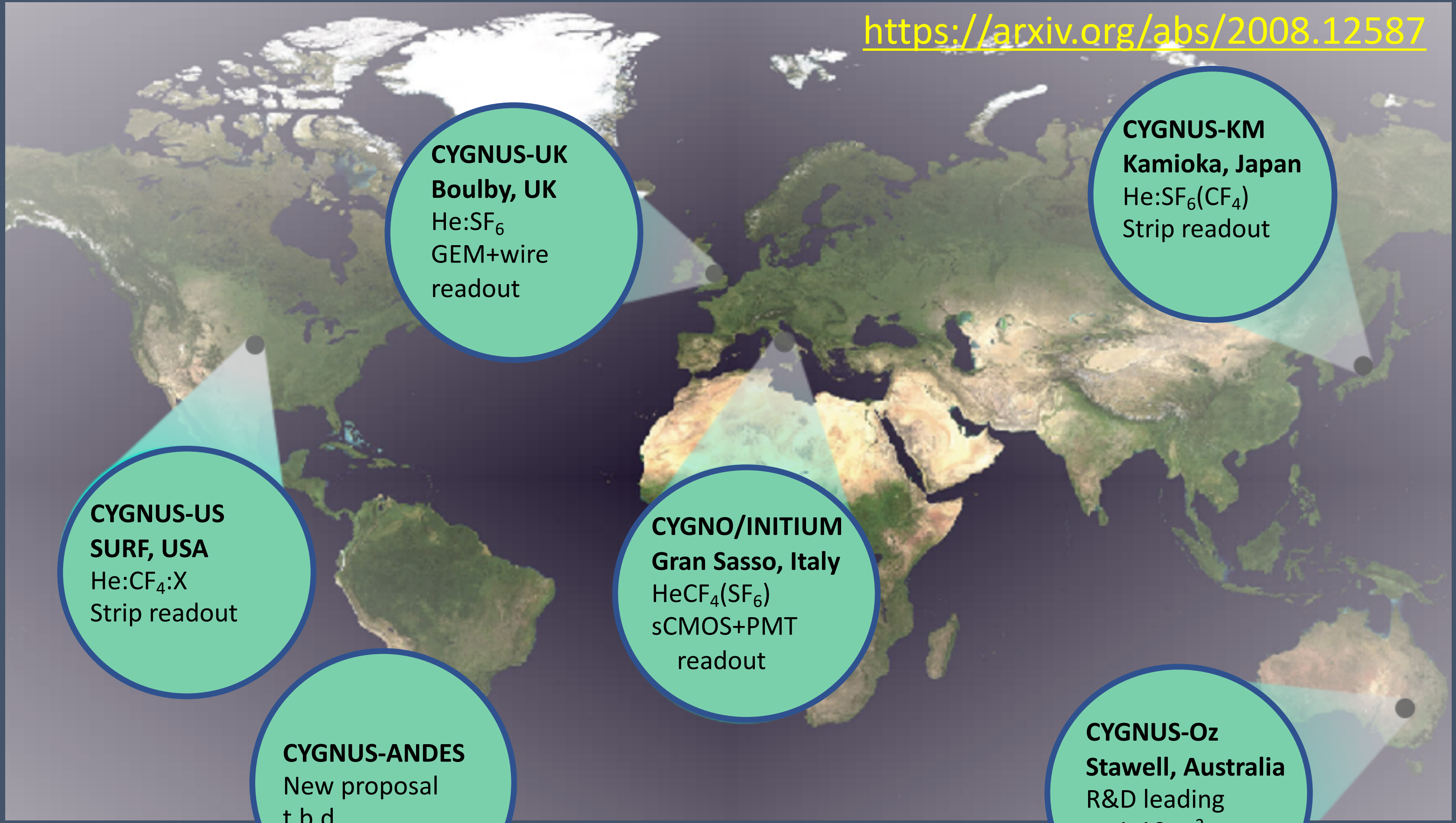


Most gas TPC efforts now collaborating closely as CYGNUS

Long term CYGNUS Vision: Multi-site Galactic Recoil Observatory

with directional sensitivity to WIMPs and neutrinos

https://arxiv.org/abs/2008.12587



CYGNUS-UK
Boulby, UK
He:SF_6
GEM+wire readout

CYGNUS-KM
Kamioka, Japan
He:SF_6(CF_4)
Strip readout

CYGNUS-US
SURF, USA
He:CF_4:X
Strip readout

CYGNO/INITIUM
Gran Sasso, Italy
HeCF_4(SF_6)
sCMOS+PMT readout

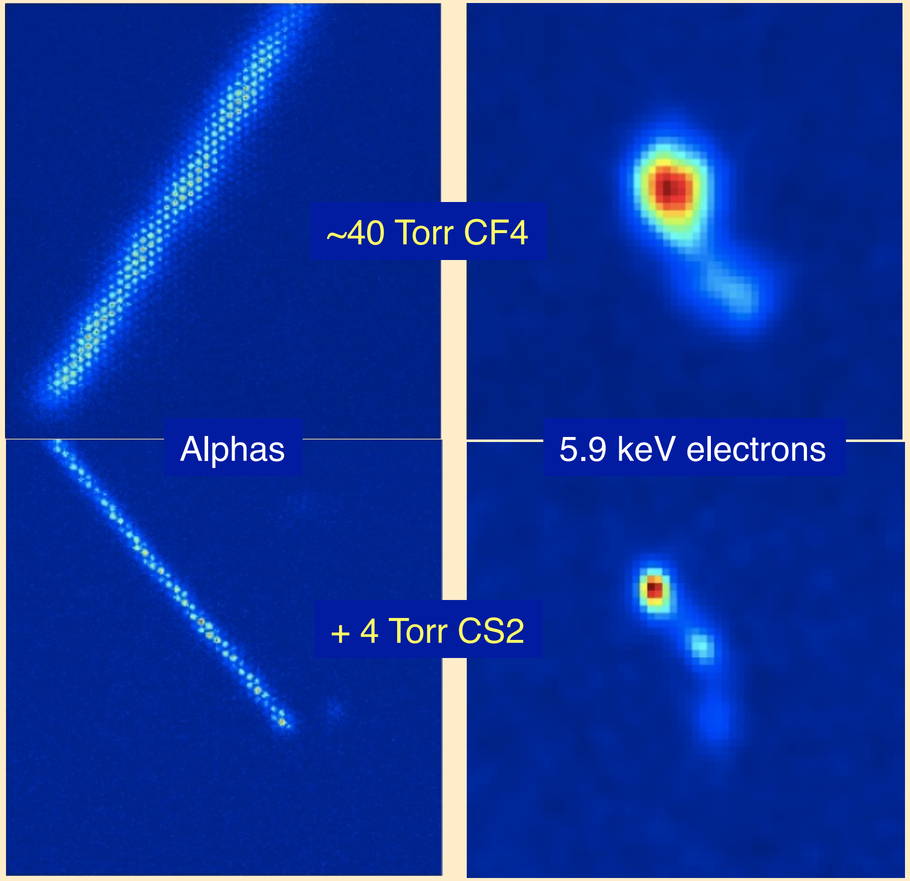
CYGNUS-ANDES
New proposal
t.b.d.

CYGNUS-Oz
Stawell, Australia
R&D leading to 1-10 m^3

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

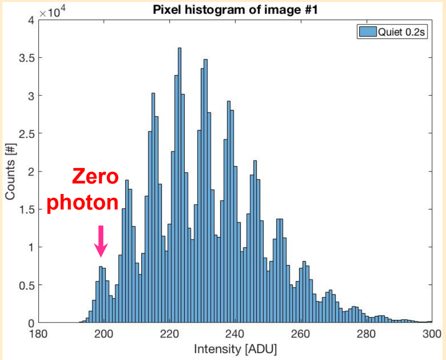
Negative-ion OTPC



D. Loomba, UNM

Hamamatsu ORCA-Quest

- Photon Resolving Power:

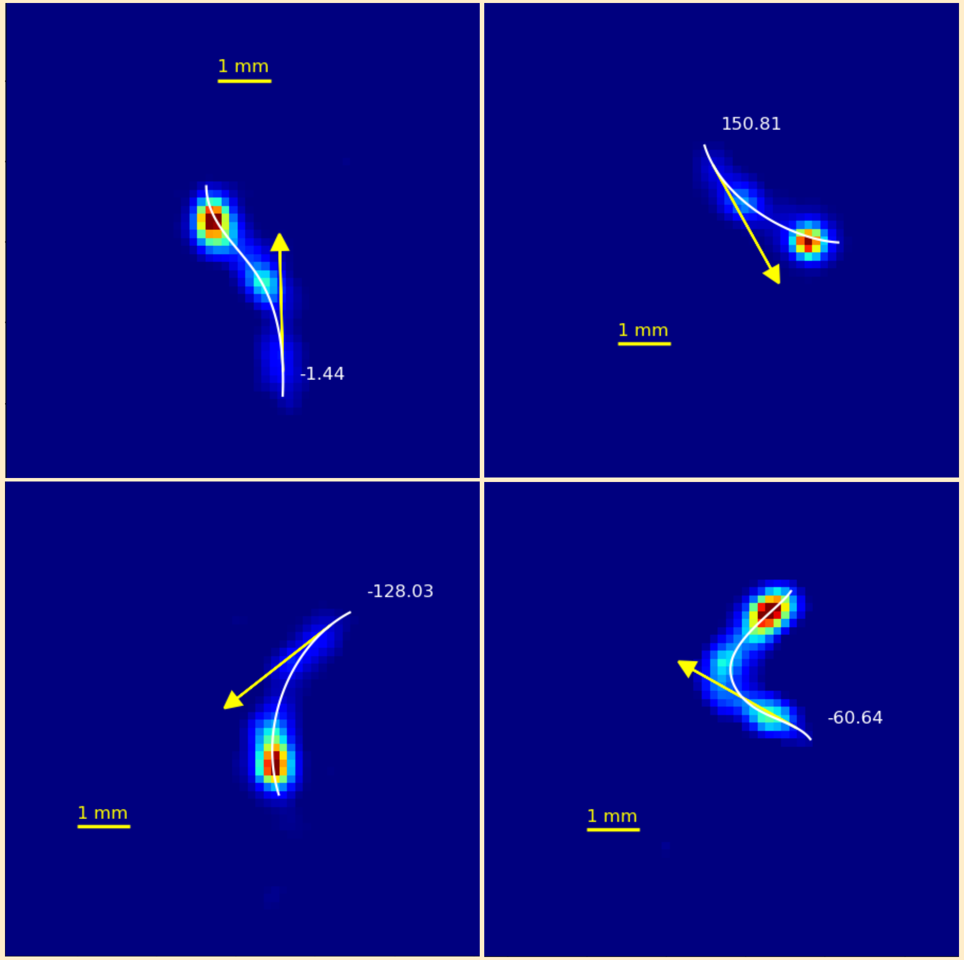


Radiment Glass-GEMs

- 270 micron pitch

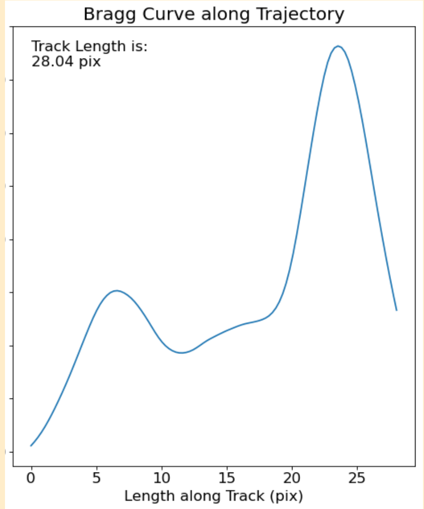
~45 Torr CF_4 + x Torr CS_2

CS_2 (Torr)	σ(μm)
0	~500
4	~150-200



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

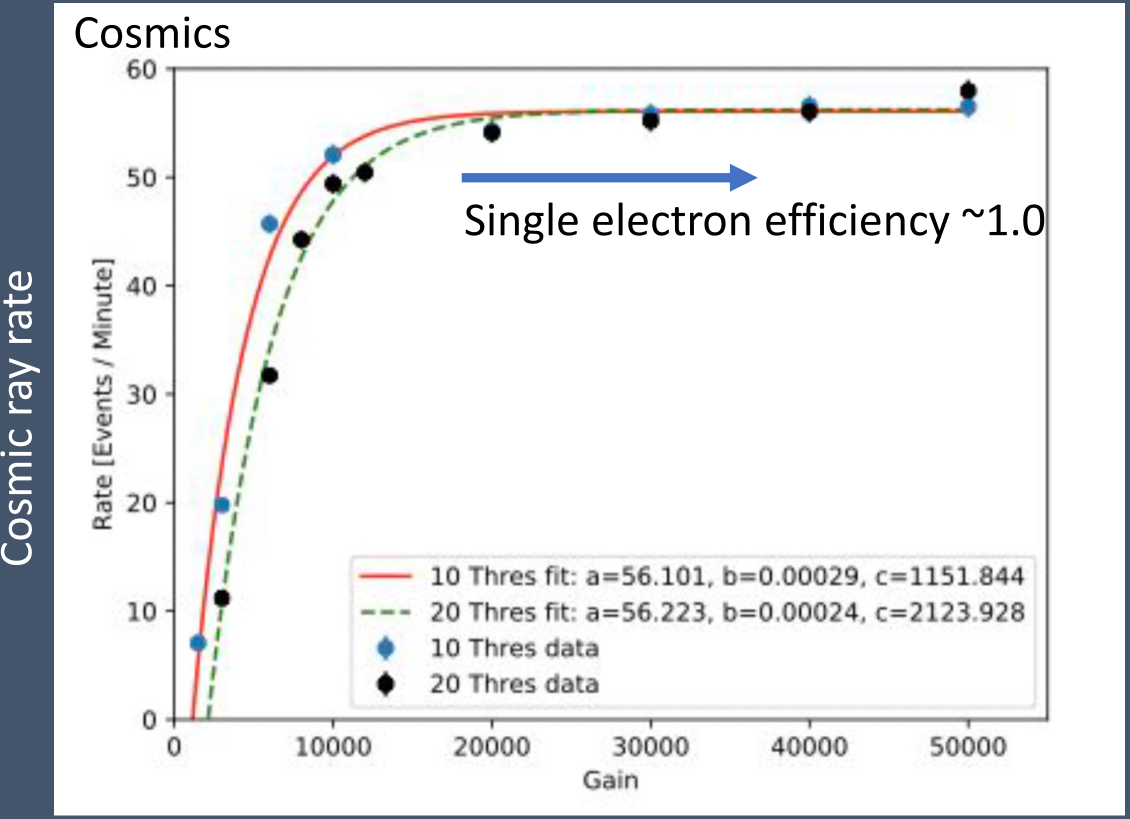
- **Head/tail** of track
- **Initial direction**
- **Range**
- **dE/dx** (Bragg curve):

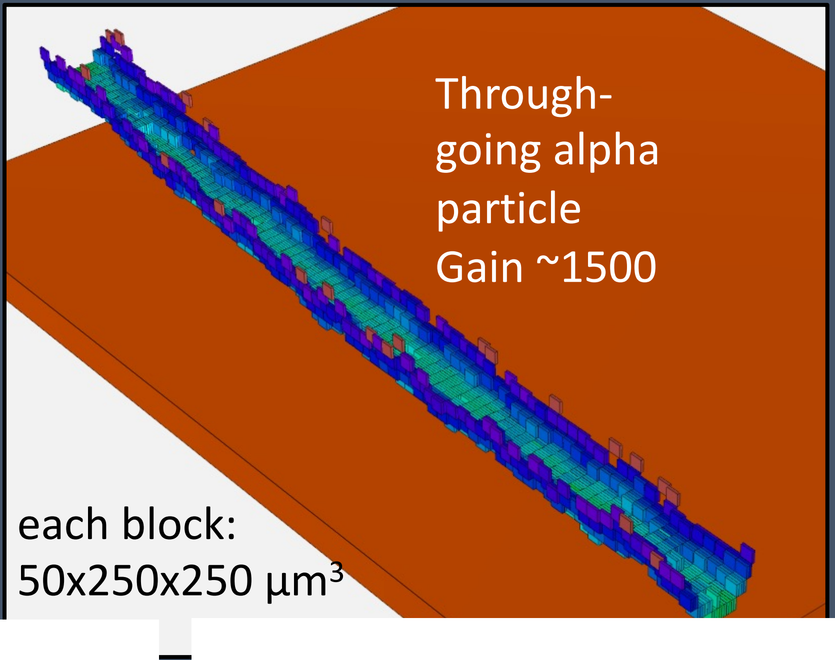


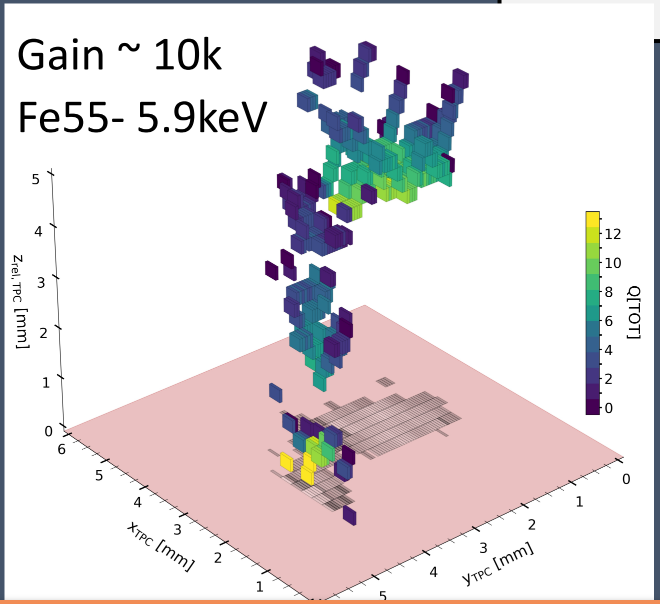
D. Loomba, UNM

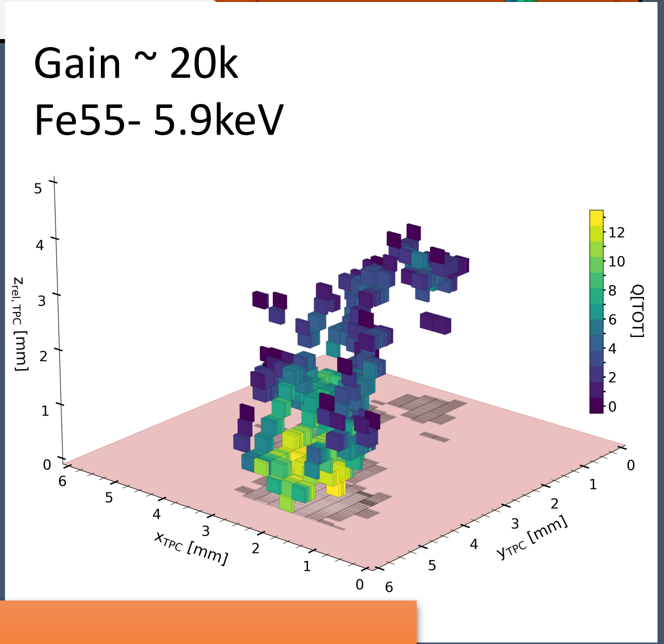
Directional detection of 5.9 keV electron recoils!

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



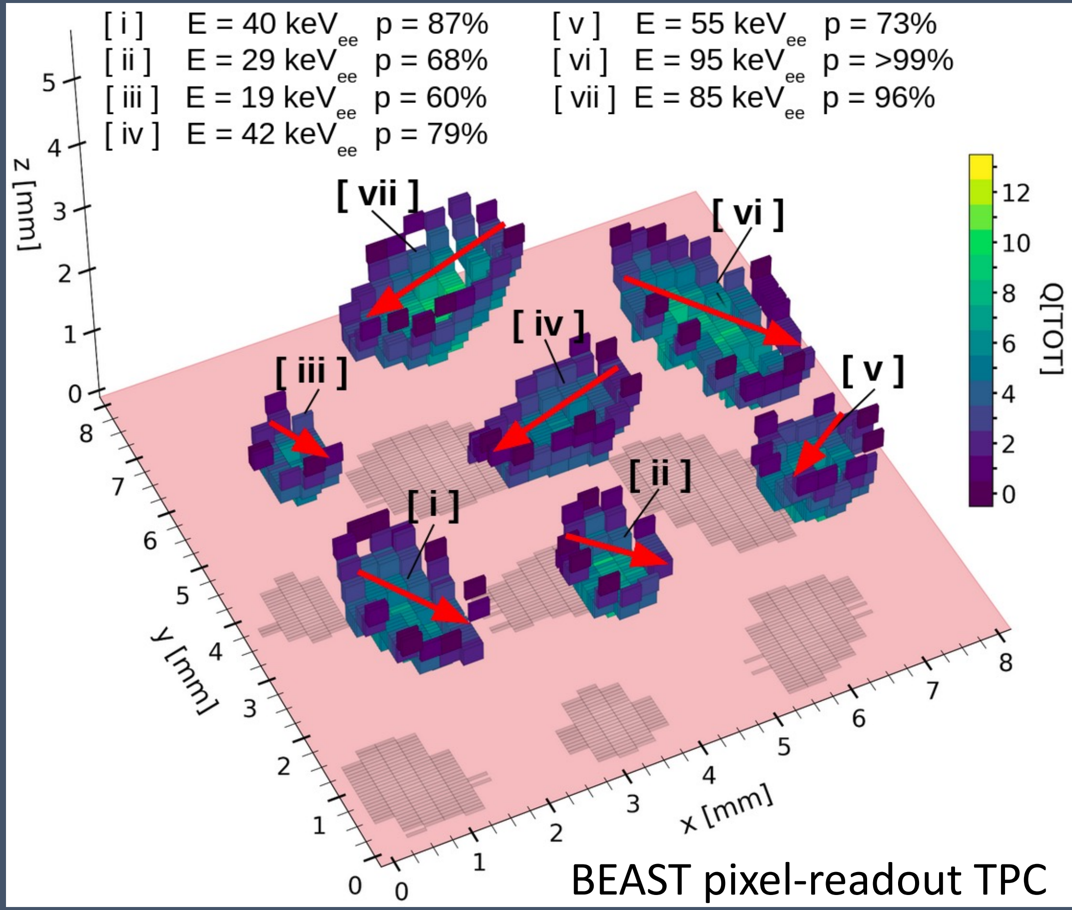




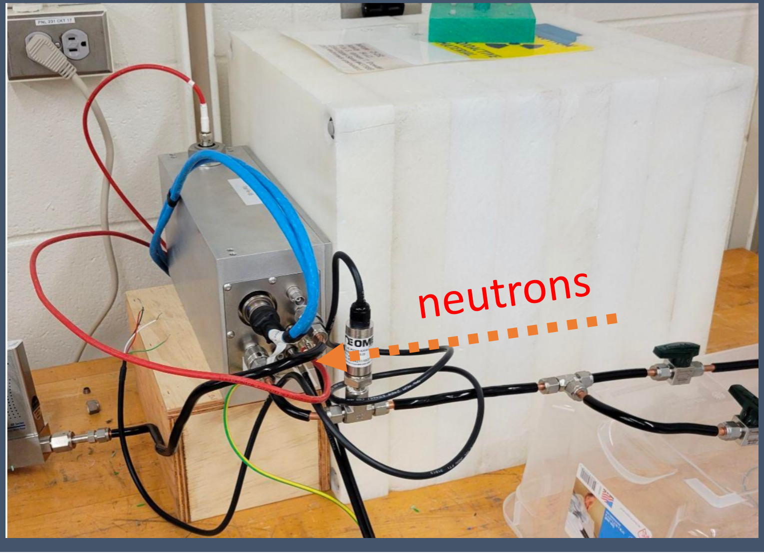


- In high-gain mode, even single electrons of ionization easily detected
- Energy threshold is ~30 eVee, w/ virtually zero noise-occupancy

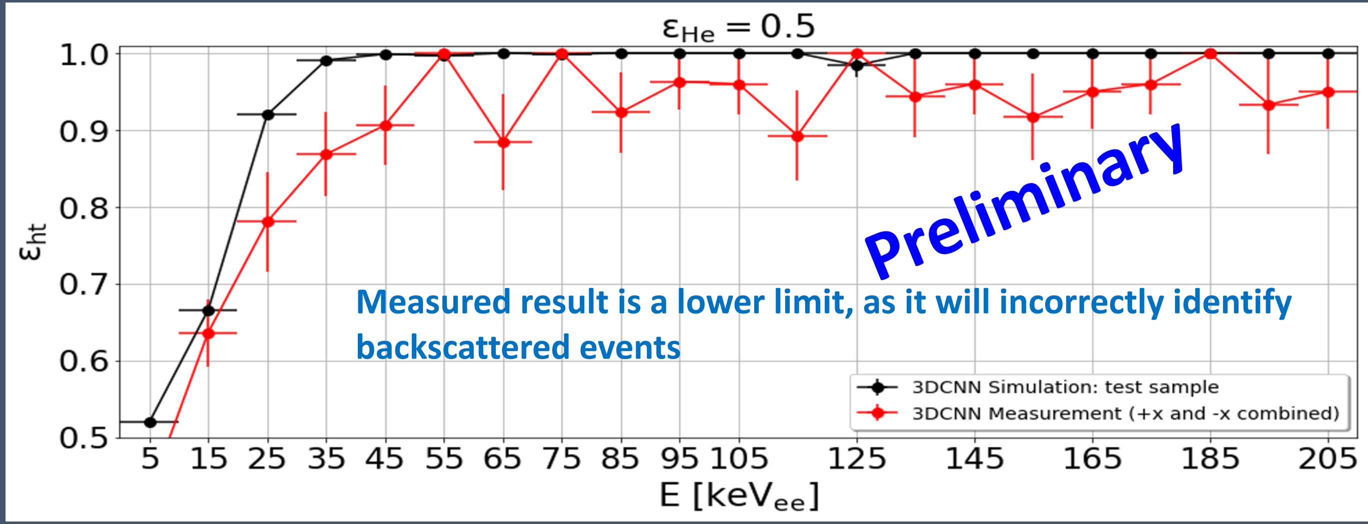
Event-level head/tail via Machine Vision: low gain



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



Jeff Schueler



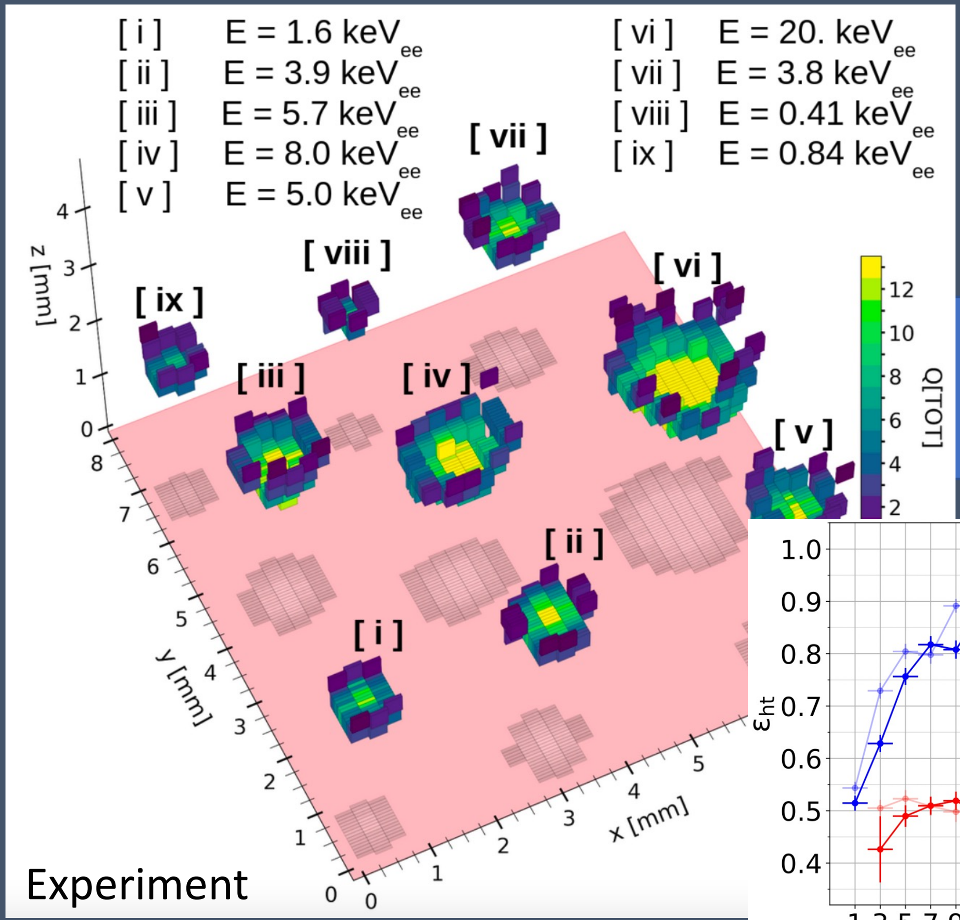
First experimental demonstration of significant *event-level* head/tail sensitivity below 20 keV (still at *low* detector gain!) See talk today by Jeff Schueler.

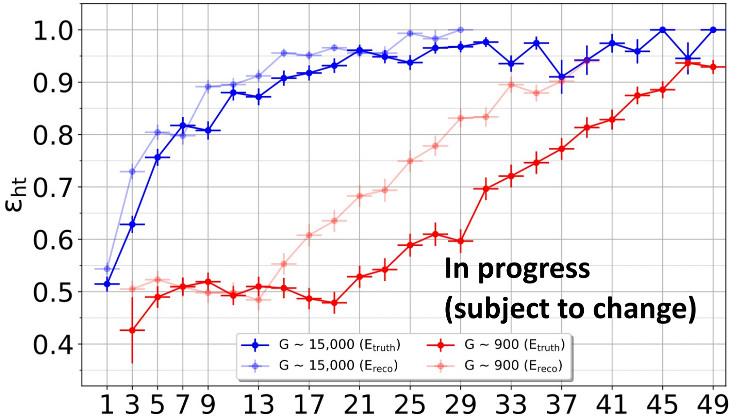
High gain operation: keV scale directionality

In progress and highly preliminary!

Have:

3D single electron efficiency ~1.0



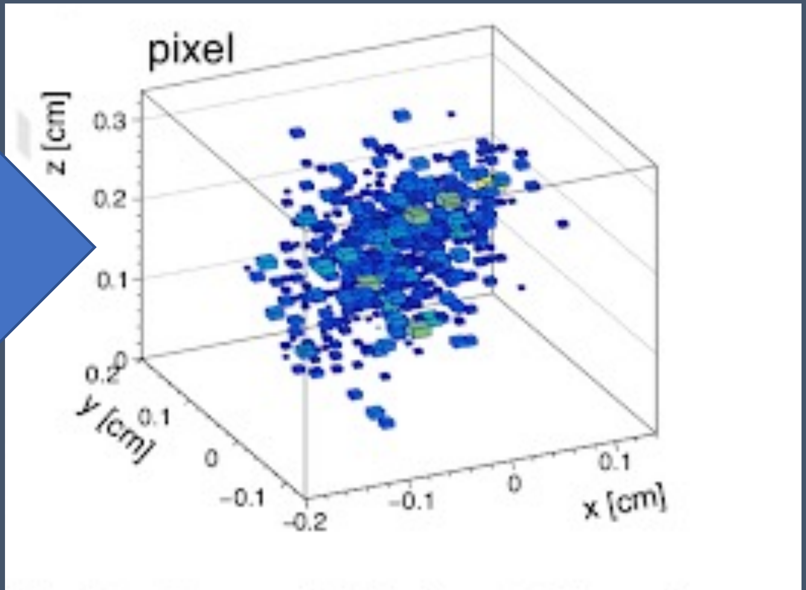


[keVee]

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

Want:

3D single electron *counting*



Directionality at 1keV scale

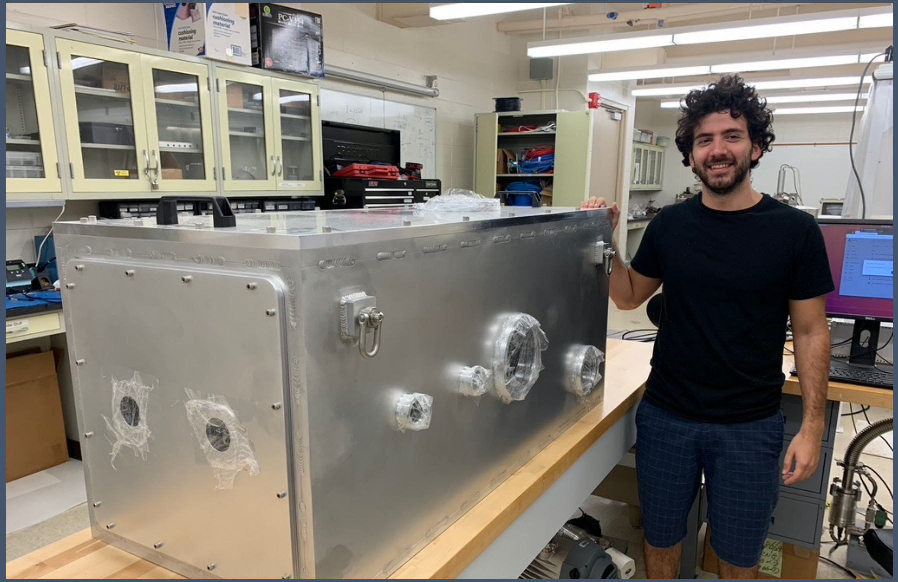
Directionality at 3 keVee for p=1 atm might be achievable in current detectors at higher gain.
In future detectors, planning three improvements, aiming for 1keV recoil directionality.

CYGNUS HD Scaleup

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

Summary and final thoughts

- Recoil imaging capabilities greatly expand physics reach of detectors
  - Dark matter, neutrinos, and precision measurements
- Aiming to reach the fundamental performance limit of ionization detection
  - 3d single-electron-counting, at DUNE-scales, at feasible cost
- Expected detector charge readout requirements
  - Order 200-micron-feature size MPGDs for amplification and detection
  - Gain/noise ratio sufficiently high for single electron counting
  - Ideally even with negative ion drift (to slow drift and reduce diffusion)
  - Eventually radio-pure
  - Matching front end electronics with suitable dynamic range
  - Highly (trigger-)multiplexed digital readout for cost-effective scaling
  - AI/ML techniques, including at trigger level
  - Cost < $ 10k / m^2
- Micromegas + pixel ASIC readout (e.g. GridPix) currently closest to achieving these
- R&D needs overlap with those for future trackers (see talks by Garg and Lewis)

→ Good opportunity for an RDC6 work-package and consortium

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

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

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

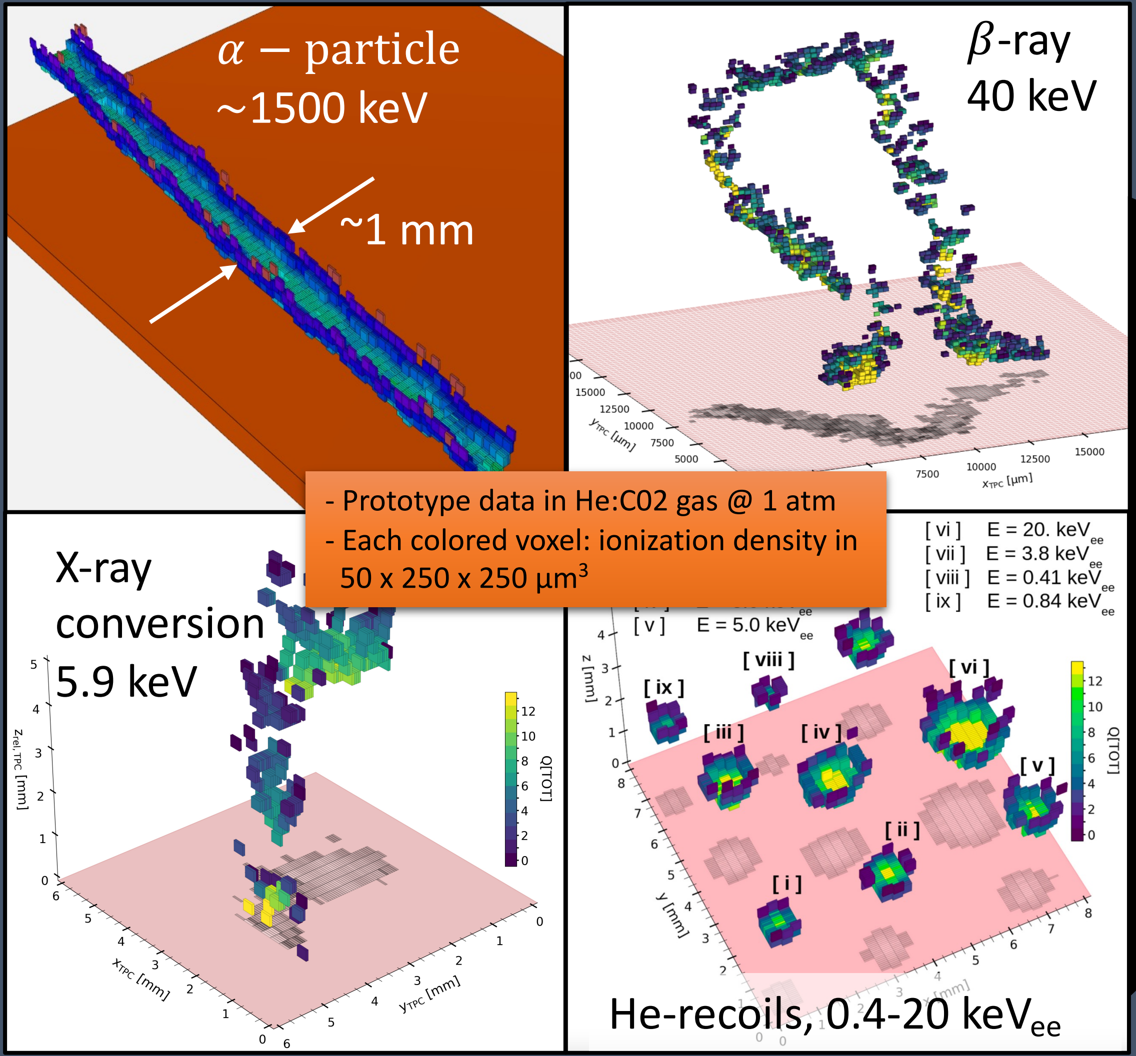
When: 11th - 15th December 2023

Conference fee: Free!

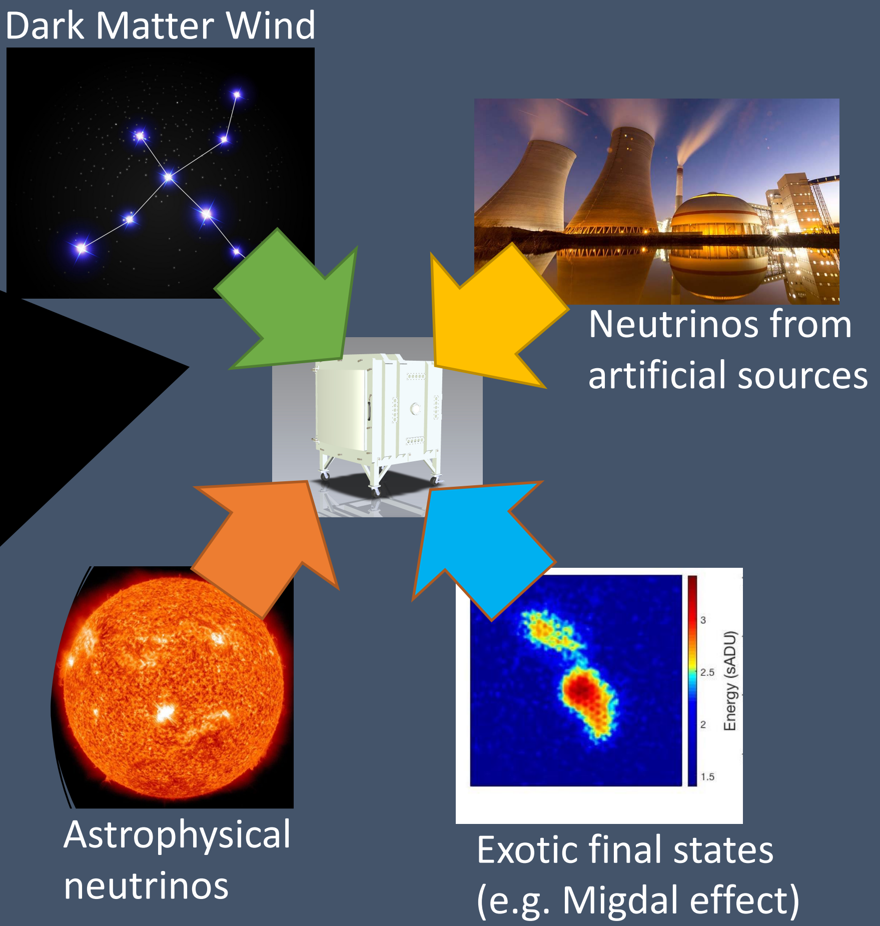
Topics covered include:

- 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

Gaseous Detector R&D Aimed at Recoil Imaging



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



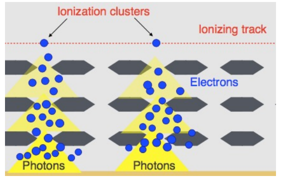
- A Snowmass working group of 167 physicists considered the case for "recoil imaging" (arXiv:2203.05914)
- Topological and directional reconstruction of low-energy nuclear and electronic recoils enables new experiments

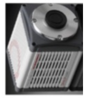
The CYGNO project : 3D optical readout

Lime (50l) running underground!

CYGNO-04 funded & TDR submitted!

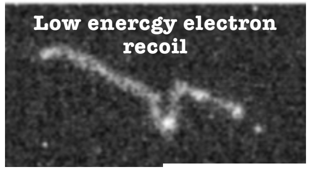
He:CF_4 @ 1 atm

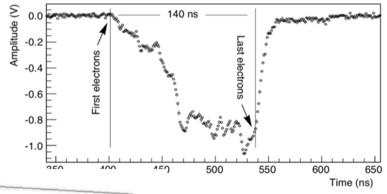


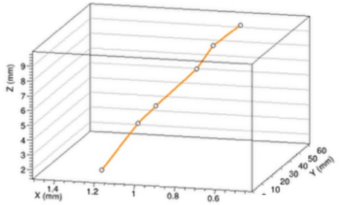


sCMOS: high granularity X-Y + energy measurements

PMT: integrated Z + energy measurement





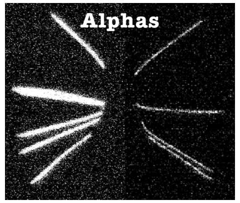


3D track reconstruction

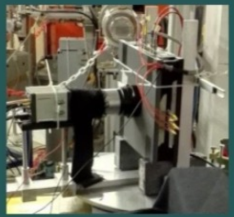
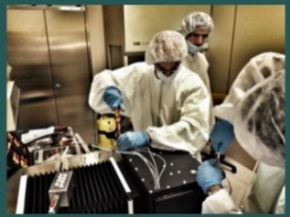
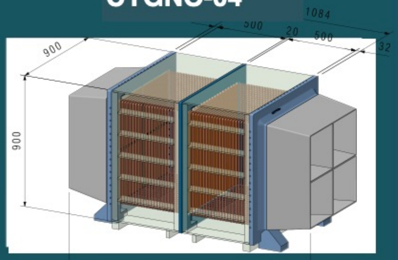
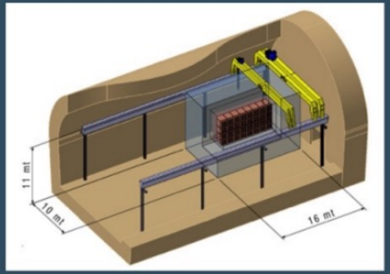
+ SF_6 for negative ion drift

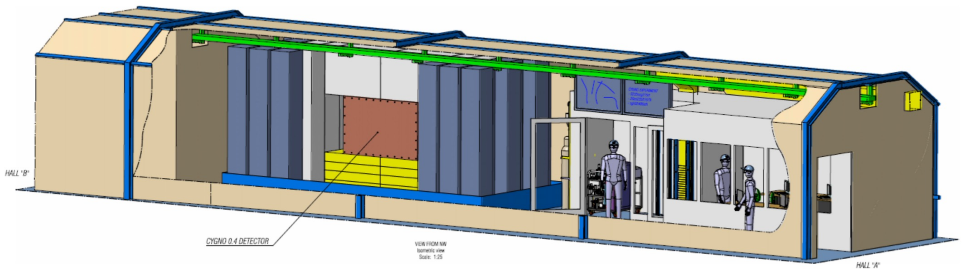
European Research Council

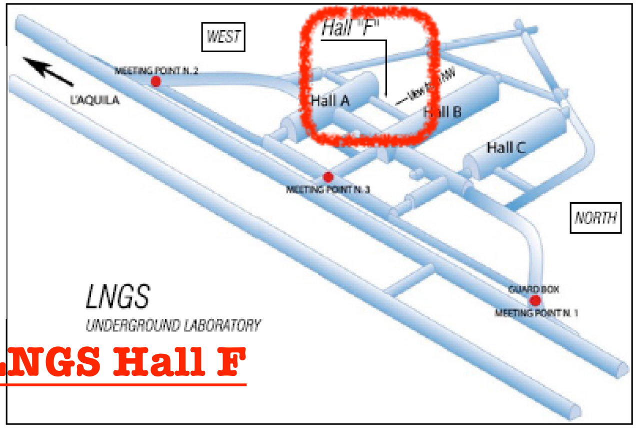
INITIUM



E. Baracchini, MPGD 2022 talk

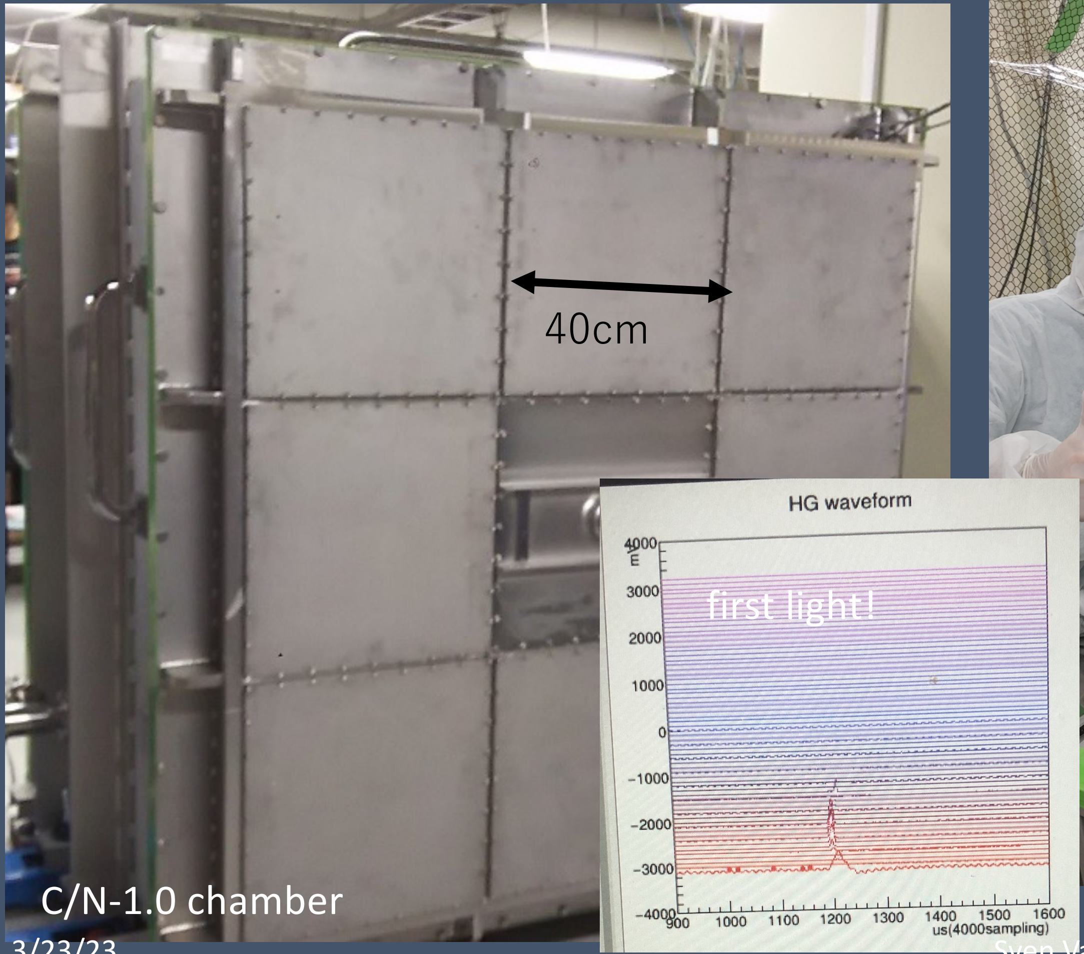
PHASE 0: R&D and prototypes			PHASE 1: O(1) m³ Demonstrator	PHASE 2: 30 m³ Experiment
2015/16 ROMA1	2017/18 LNF	2019/22 LNF/LNGS	2023/26 LNF/LNGS	2026.. LNGS
ORANGE	LEMON	LIME	CYGNO-04	CYGNO_30
				
- 1 cm drift	- 3D printing - 20 cm drift	- 50 cm drift - underground tests - MC validation	- background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



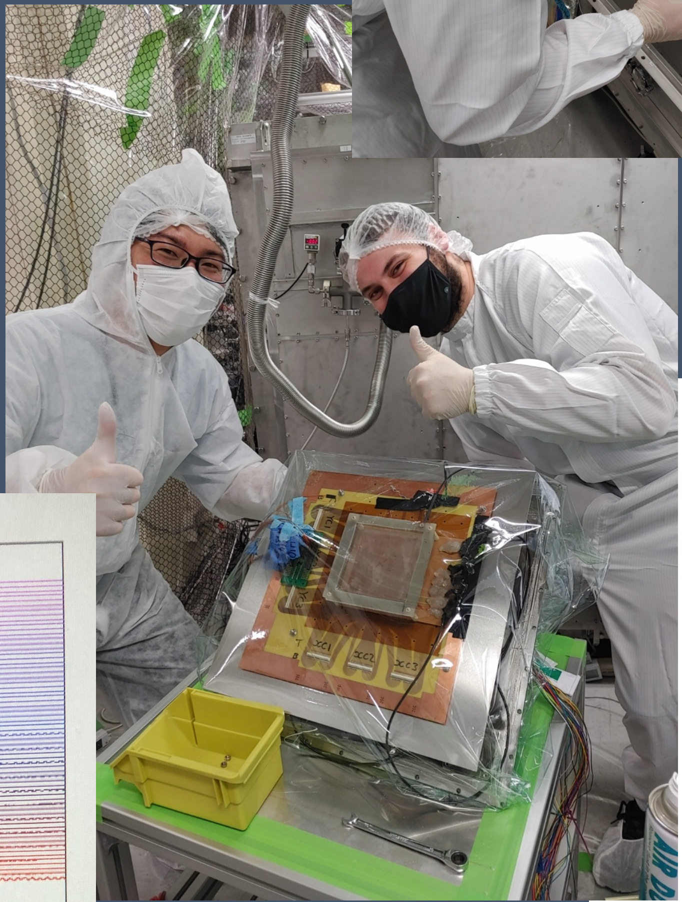


CYGNO-04 To be installed in LNGS Hall F

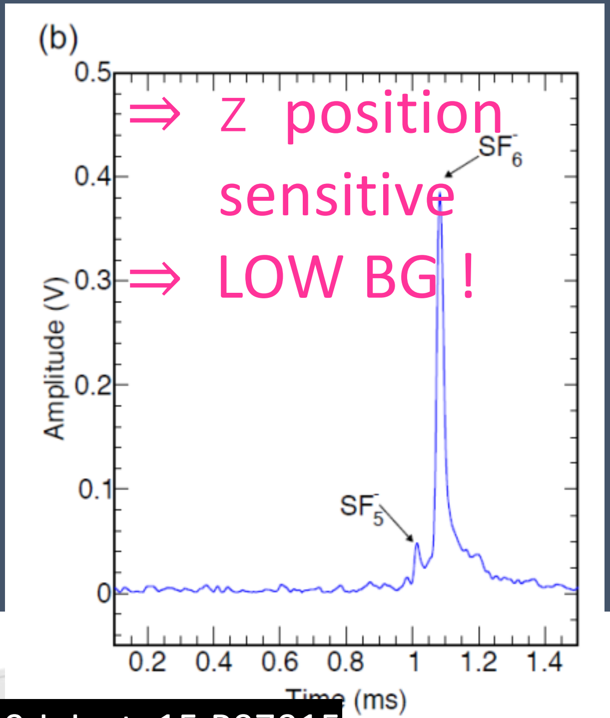
- NEWAGE running underground @ Komioka
- Larger, CYGNUS/NEWAGE-1.0 m^3 chamber being commissioned @ Kobe U.

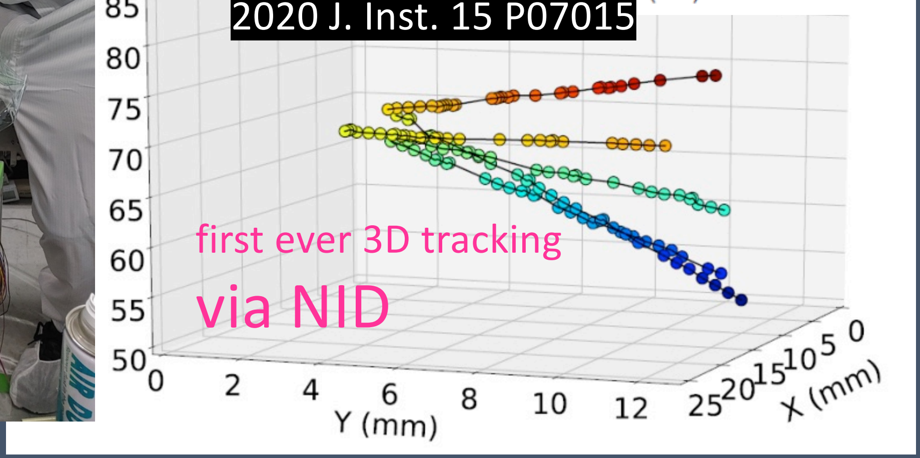


test module installation



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.

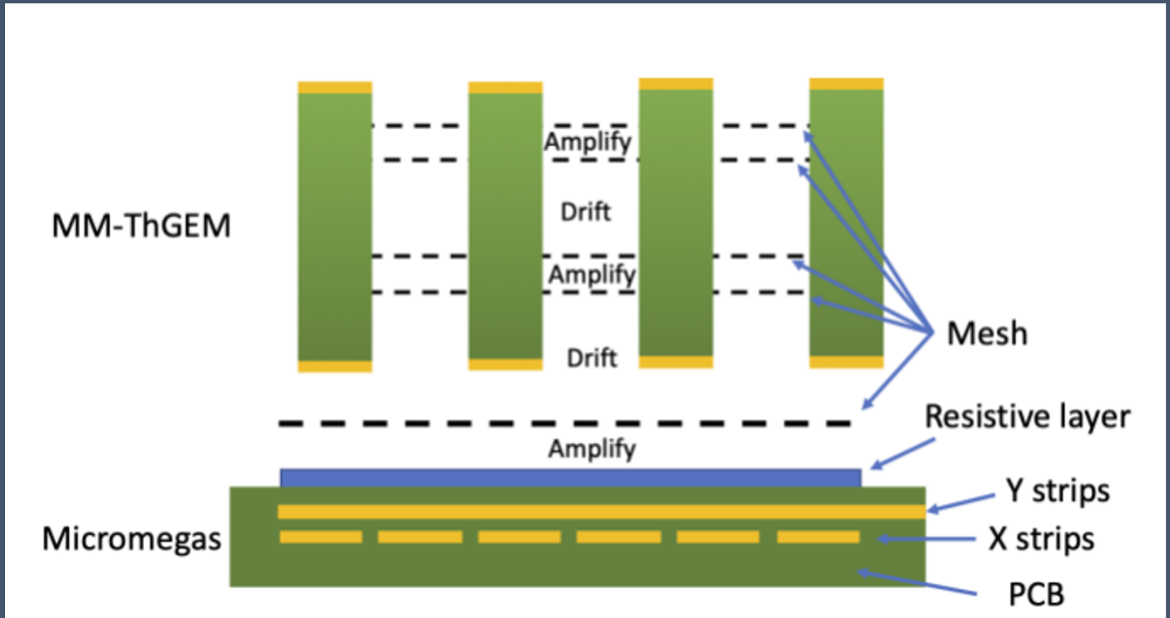


Figure 1: Diagram of the R&D amplification and readout stages.

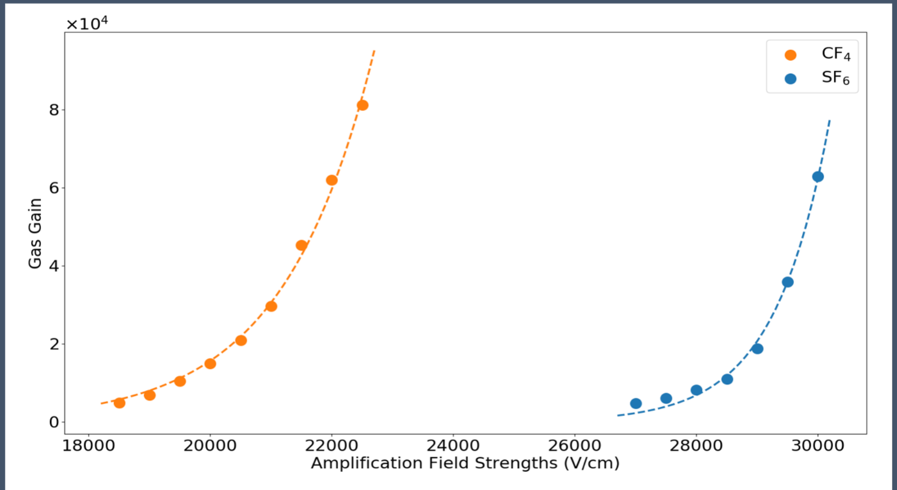
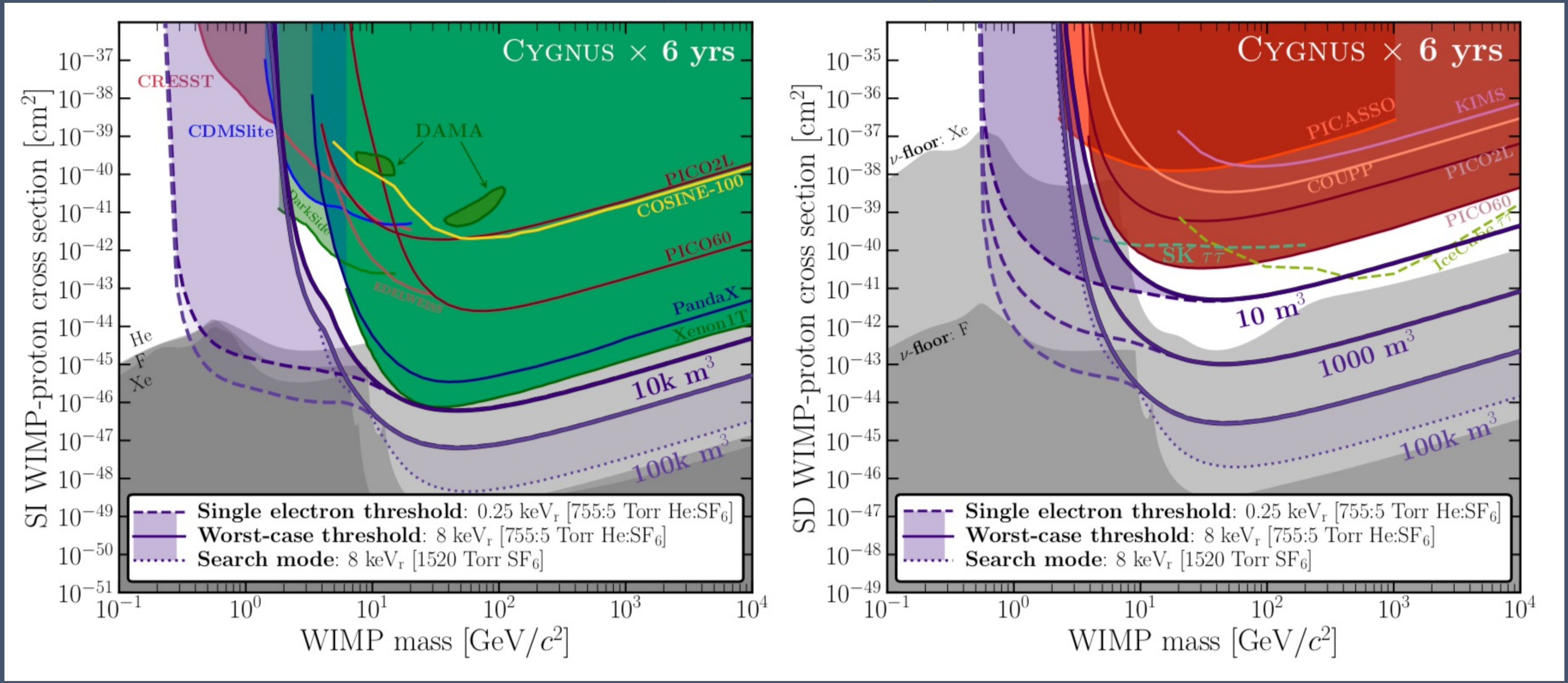


Figure 3: Demonstration of the gas gains achievable with the MMThGEM in both CF_4 (orange) and SF_6 (blue) as a function of amplification field strengths.

CYGNUS 1 ton WIMP search expected sensitivity

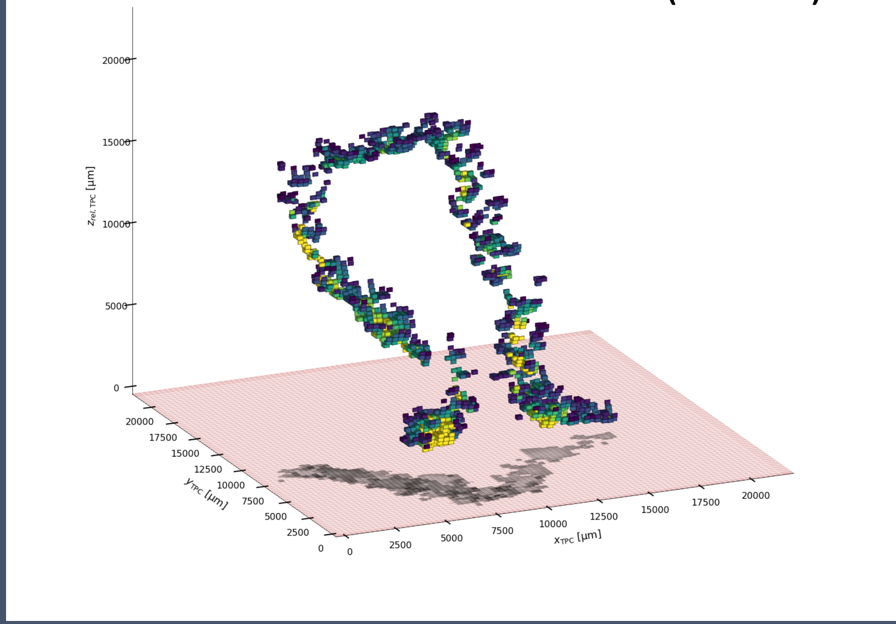
Large volume uncertainty as final gas not chosen.
Here assume He:SF_6 755:5, where 1000 m^3 x 6 year ~1 tonne-year
Limits do not yet include the large improvements from machine vision techniques



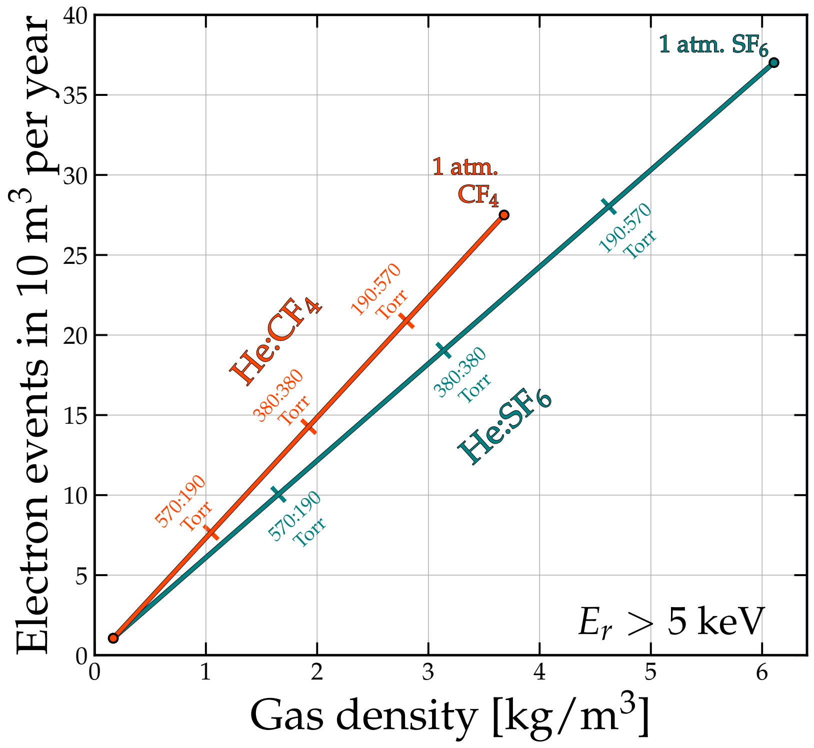
Significant improvement in SI in the low WIMP mass region, expect 10-50 IDENTIFIED neutrino nuclear recoil events

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

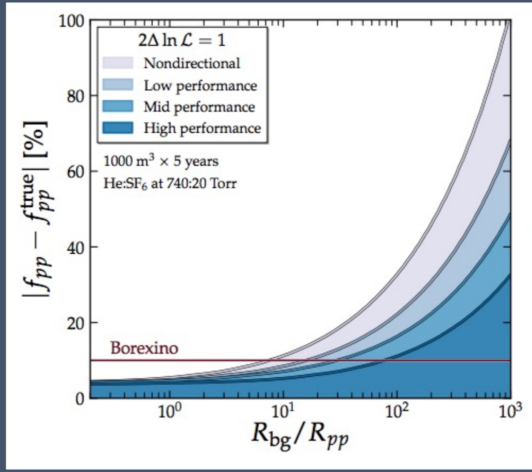


CYGNUS 10

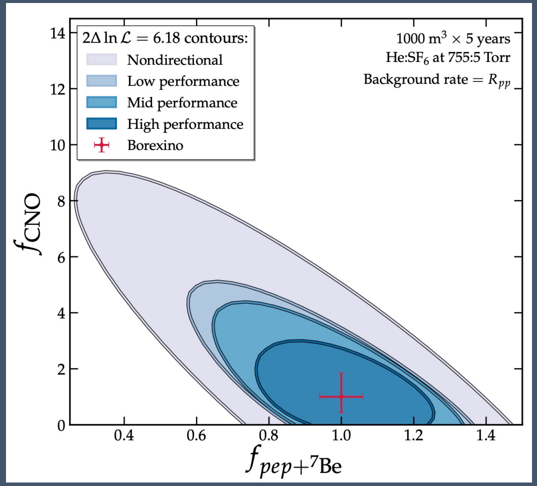


C.O'Hare

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**