The CYGNUS Galactic Directional Recoil Observatory

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On behalf of the CYGNUS proto-collaboration
Lake Louise Winter Institute 2023

UNIVERSITY of HAWAI'I®
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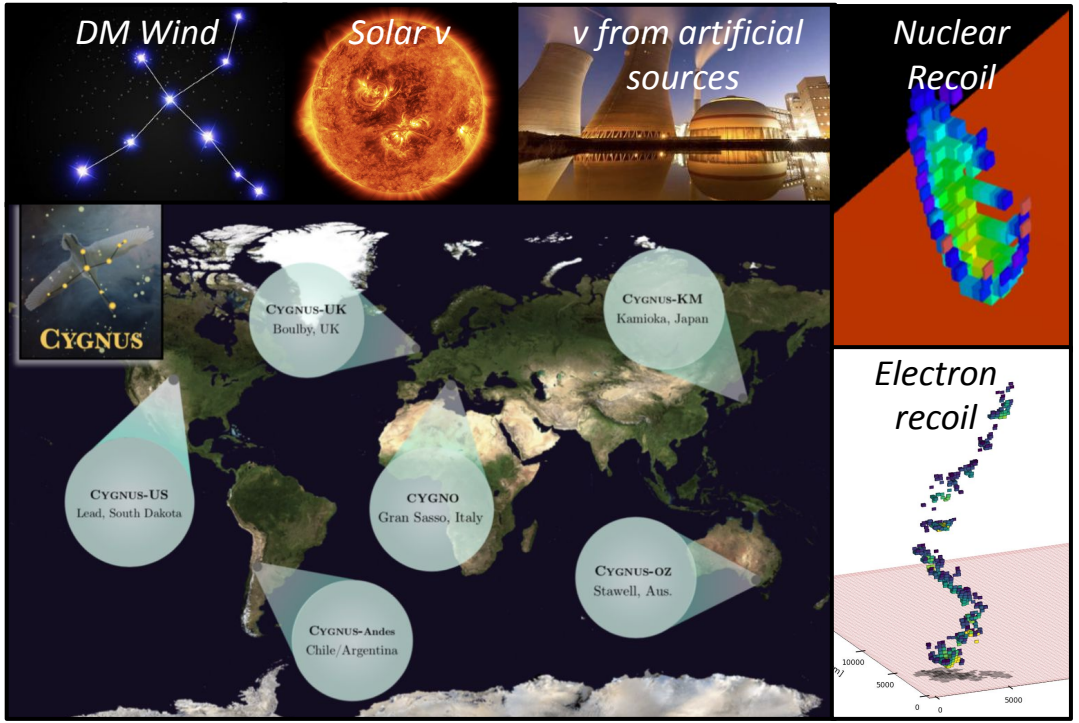
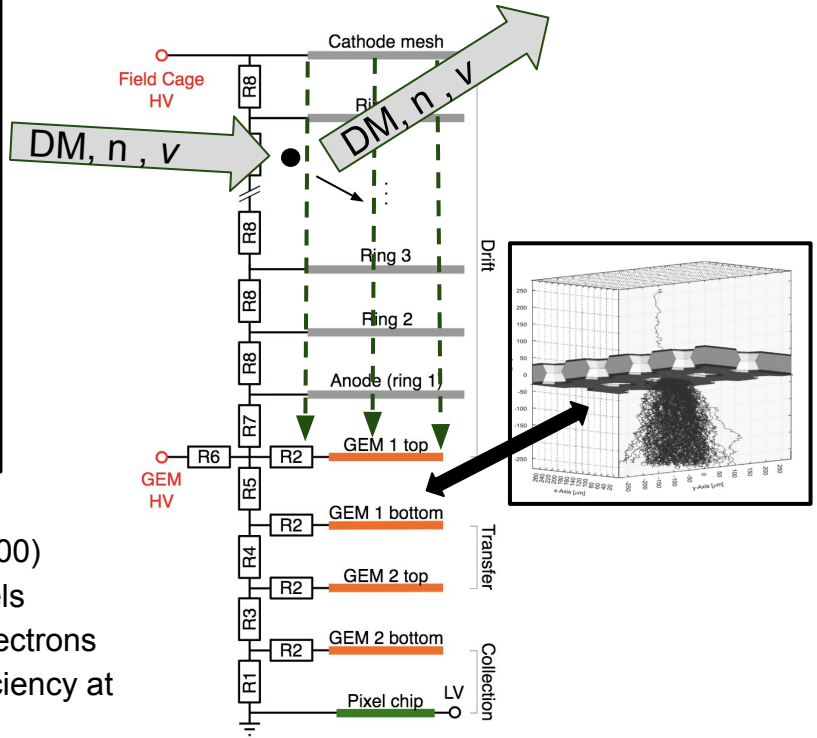
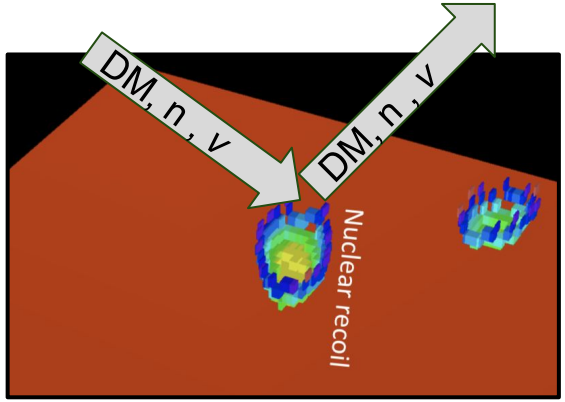
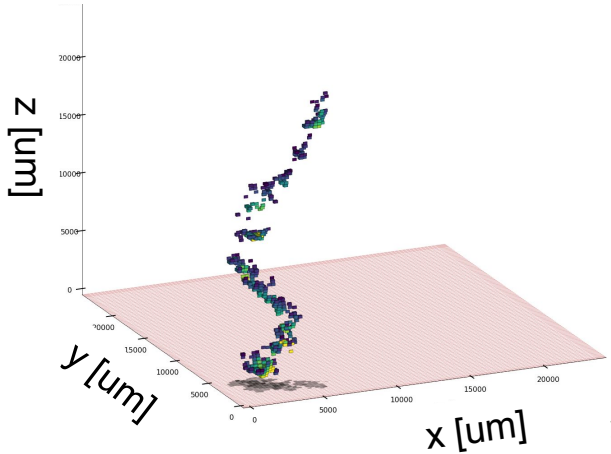


Directional Recoil Detection in Gas TPCs







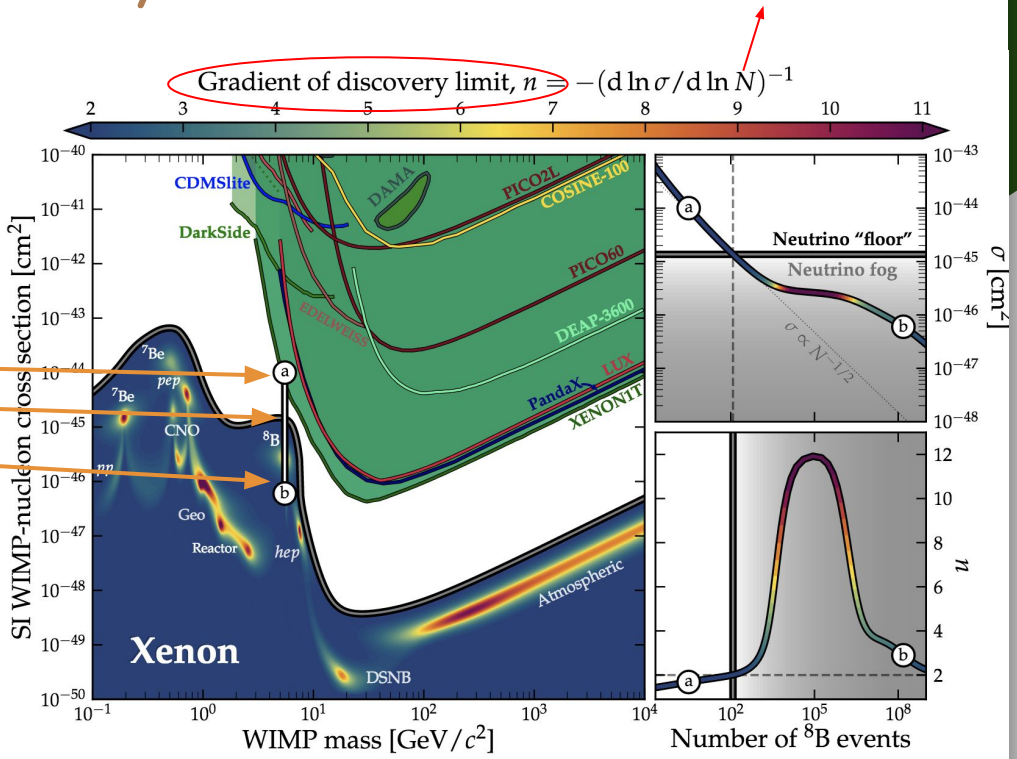
Highlights

- Gains up to O(50,000)
- (250 x 50) μm^2 pixels
- Noise floor ~100 electrons
- Single electron efficiency at ~20k gain

I. Jaegle et al., "Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging." https://doi.org/10.1016/j.nima.2019.06.037

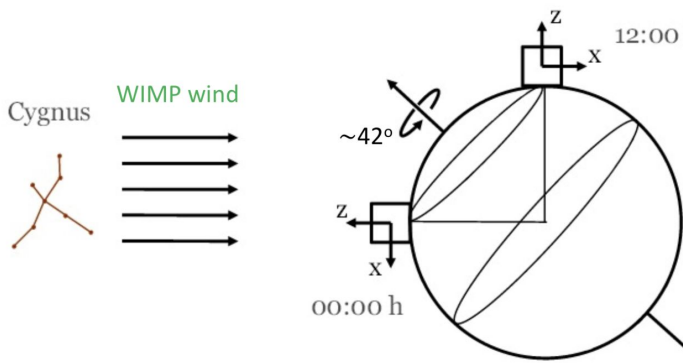
The Need for Directionality

- Direct DM searches are approaching the “neutrino fog”
  - Irreducible background from CEvNS
  - Solar neutrinos relevant first
- Quantifying neutrino fog based on how discovery limit decreases with increased exposure (Number of background events) C.A.J. O’Hare PRL 127 (2021)
  - N < 1, background free $\sigma \propto N^{-1}$
  - Poissonian bkg. Subtraction, $\sigma \propto 1/\sqrt{N}$ (n=2)
  - Saturation (signal is smaller than background uncertainties)
- Directional detectors circumvent the neutrino fog
  - Can distinguish neutrino and DM signals
  - The fog becomes a source of guaranteed signal!

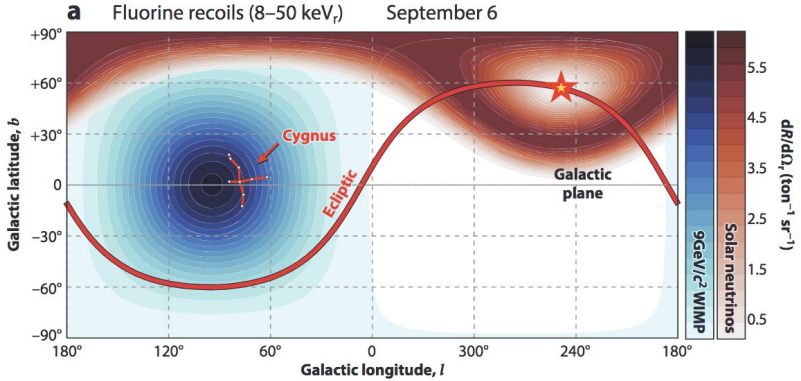


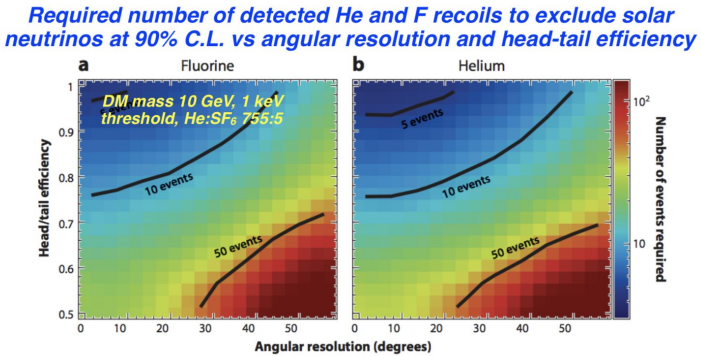
C.A.J. O’Hare, “New Definition of the Neutrino Floor for Direct Dark Matter Searches” https://doi.org/10.1103/PhysRevLett.127.251802

The Need for Directionality



- The mean recoil direction oscillates with Earth's Rotation
  - Oscillation period is in **sidereal day**, not a solar day
- This is a unique, robust signature (~10^2- 10^3 x stronger effect than annual modulation)
  - Identify galactic origin of potential DM signal with only **3-10 events**
- Distinguish DM from solar neutrinos
  - **Penetrate neutrino floor**
  - Neutrino physics



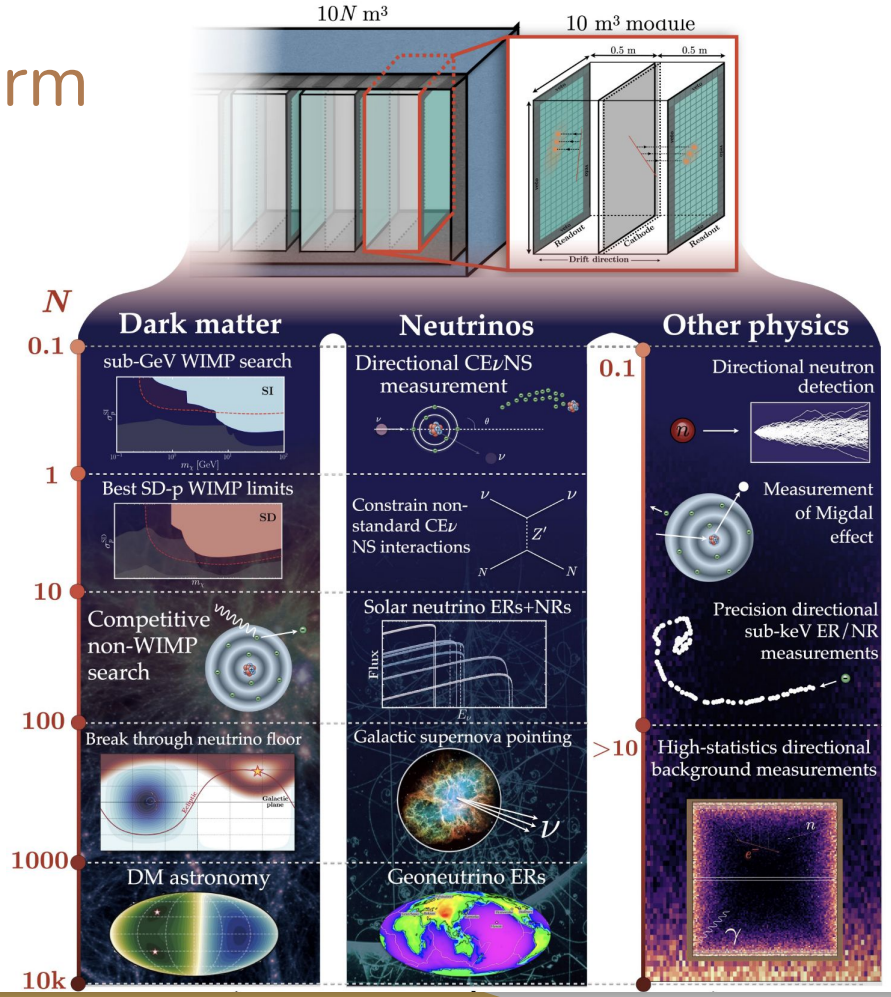


S.E. Vahsen et al., "Directional Recoil Detection" https://doi.org/10.1146/annurev-nucl-020821-035016

Opportunities for a long term physics program

Exposure, Size

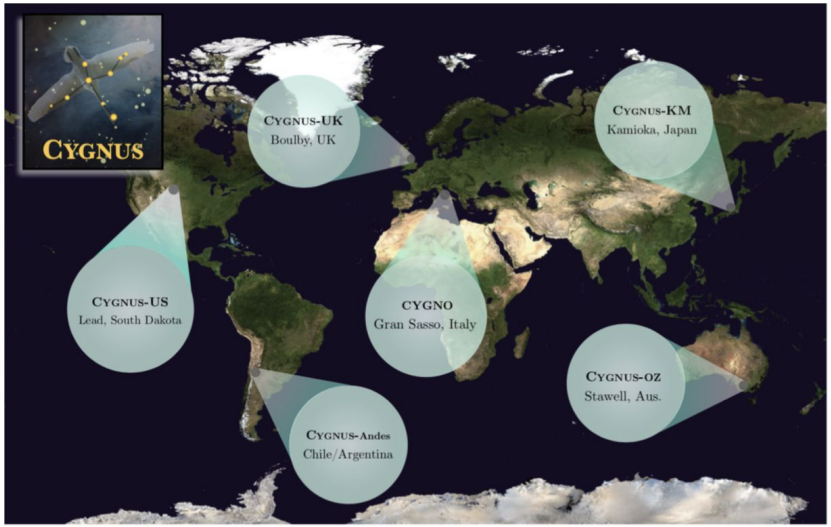
- Quenching factor and recoil physics
- Migdal Effect measurement
- CEvNS at ORNL (SNS) or Fermilab (NuMI, LBNF)
- Competitive DM limits in SI and SD
- Solar neutrinos via CEvNS and neutrino electron scattering
- Penetrating neutrino floor
- Geoneutrinos
- Measuring DM particle properties? WIMP astronomy?



S.E. Vahsen et al., "Directional Recoil Detection"
https://doi.org/10.1146/annurev-nucl-020821-035016

The CYGNUS Proto-Collaboration

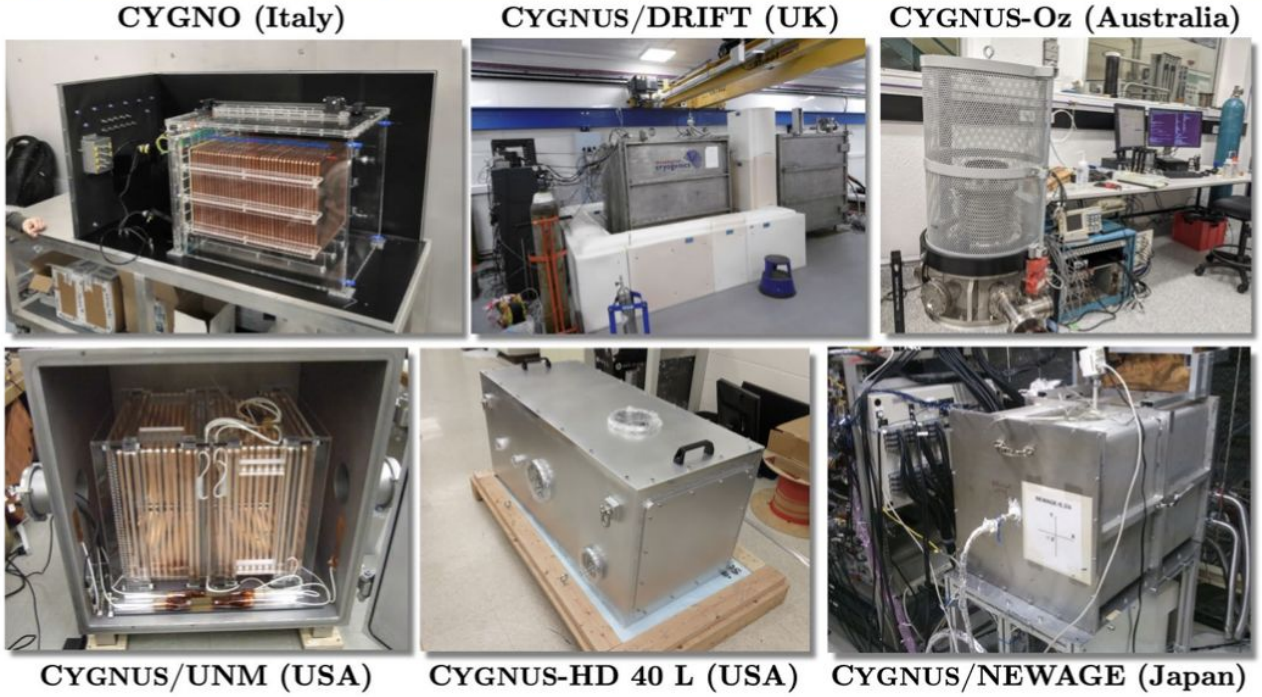
- 70 members, 6 are US faculty
- Close collaboration, regular meetings on R&D and physics studies
- Long term vision: Multi-site Galactic Recoil Observatory with directional sensitivity to WIMPS and neutrinos
- Extensive concept paper: https://arxiv.org/pdf/2008.12587.pdf
  - Technical feasibility
  - Detailed simulation of readout options
  - Background discrimination studies
  - Simulation of internal and external backgrounds
- New collaborators are welcome!



Steering group:

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

Prototypes and Experiments

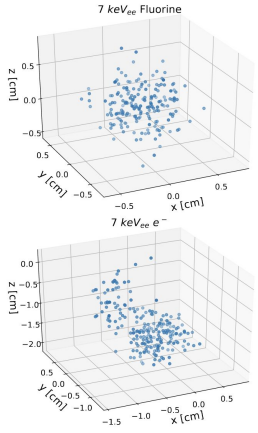


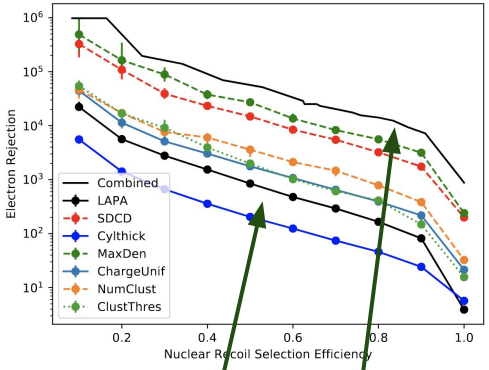
- Electron drift / negative ion drift
- Charge / optical readout
- GEM / Micromegas / PMT amplification

Latest Results: CYGNUS US

Rejection of internal electron backgrounds

- This will determine the energy threshold of a future experiment





2 order of magnitude improvement over dE/dx

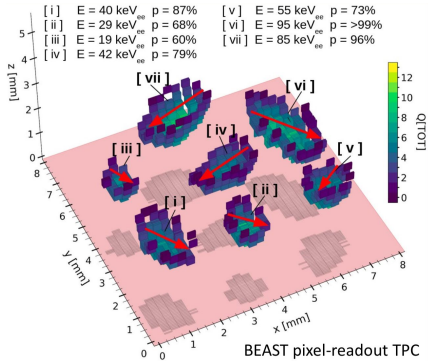
M. Ghrear et al JCAP10(2021)005

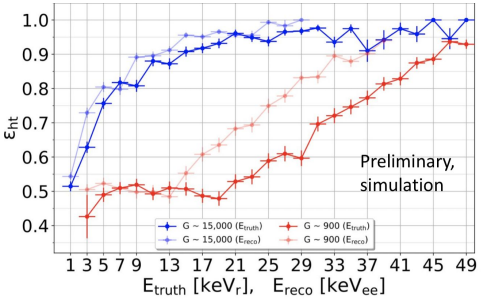
Investigating further improvements with ML

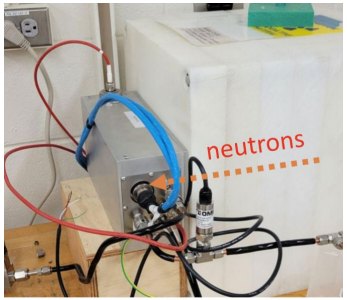
See J. Schueler et al., arXiv:2206:10822

Head/Tail Identification

- More important than angular resolution!







J. Schueler

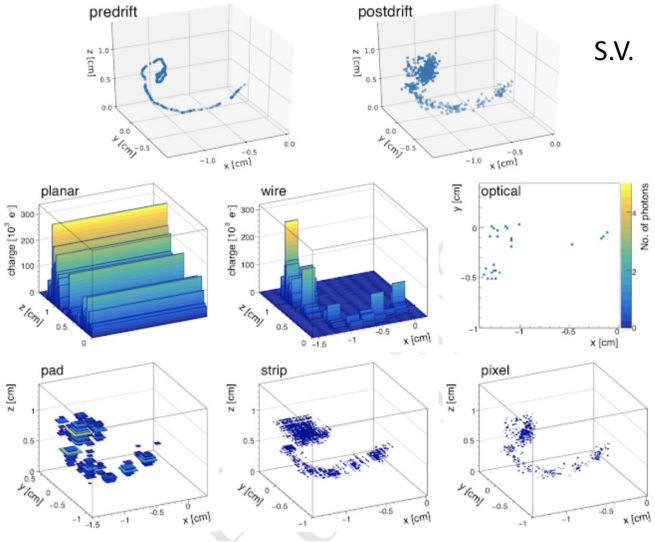
Head/Tail identification down to keV scale, experimental results coming soon!

Expect further improvements in final CYGNUS gas

Scaling up to the next generation

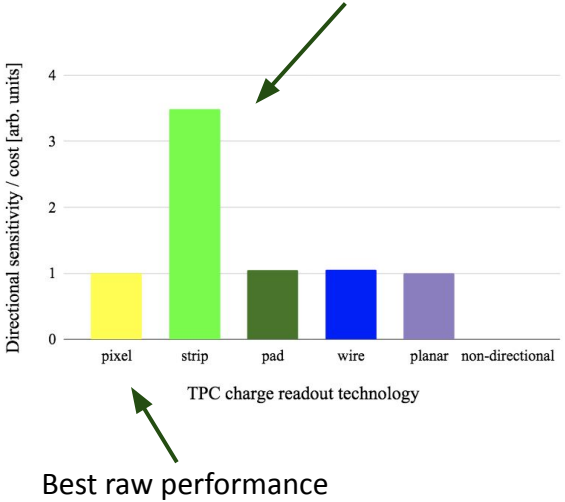
We are scaling up by an order of 10^3!

Detailed simulation of different charge readout technologies

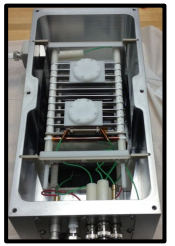


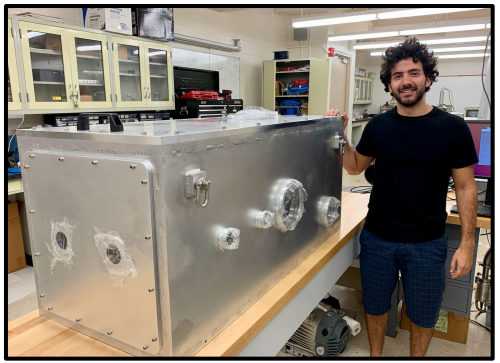
S.V.

Best directional wimp sensitivity per unit cost



Best raw performance





Construction ongoing expected Fall 2023

S.E. Vahsen et al., "CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos", https://arxiv.org/abs/2008.12587

Conclusion

- Directional Recoil detection is experimentally challenging but very beneficial
  - Neutrino fog: irreducible background => opportunity
  - Confirm galactic origin of potential DM signal
  - Enables more physics studies
- The CYGNUS proto-collaboration
  - Several groups working on directional recoil detection with close collaboration
  - Long term vision: Multi-site Galactic Recoil Observatory
  - New collaborators welcome
- Stay tuned as the next generation of CYGNUS detectors are commissioned

Thank you!
Questions?

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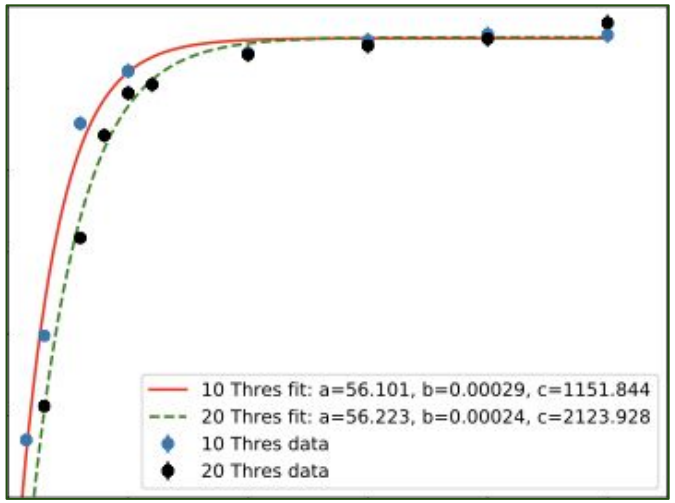
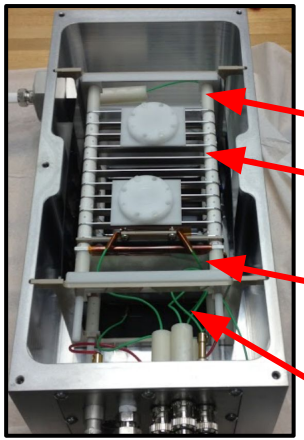
BEAST TPCs





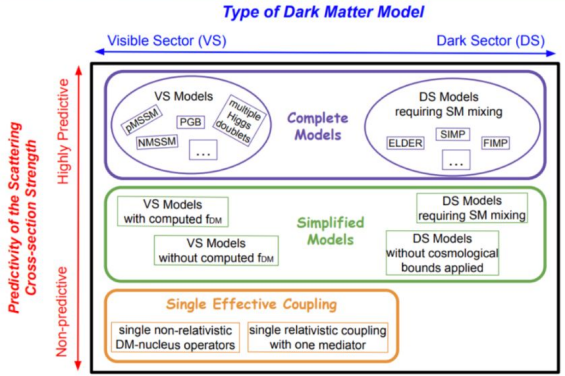
BEAST TPC

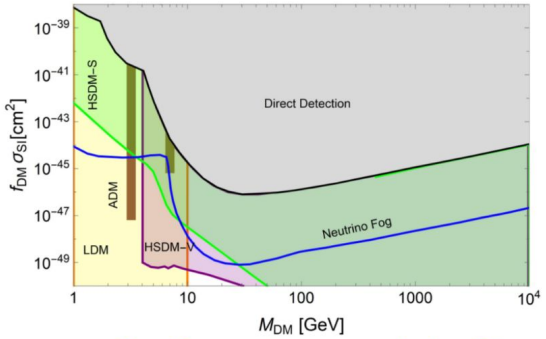
- 70:30 mixture of He:CO_2 at STP
- Cathode
- Field cage rings (~450 V/cm drift field => 220 μm / 25ns-time bin drift speed)
- Double GEM amplification capable of gains up to O(50,000)
- ATLAS FE-I4 pixel ASIC readout
- 80 x 336 grid of (250 x 50) μm^2 pixels
- 4-bit TOT charge quantization
- Noise floor ~100 electrons
- Single electron efficiency at ~20k gain

Directional Recoil Detection https://doi.org/10.1146/annurev-nucl-020821-035016
Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging https://doi.org/10.1016/j.nima.2019.06.037

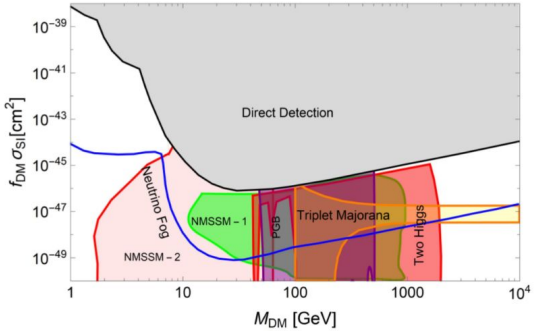
D. S. Akerib et al., 2022 Snowmass Summer Study, arXiv:2203.08084

The need to penetrate the fog

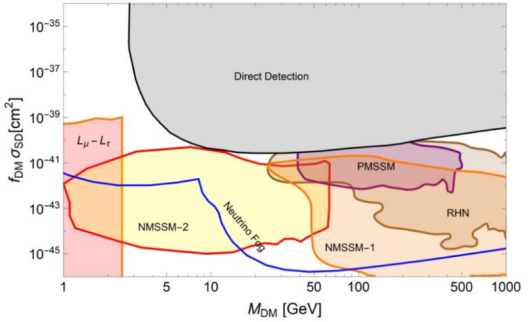




Dark sector models SI

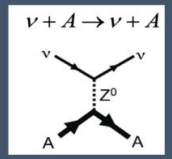


Visible sector models SI



Visible sector models SD

Directional CEvNS measurements at SNS, Oak Ridge

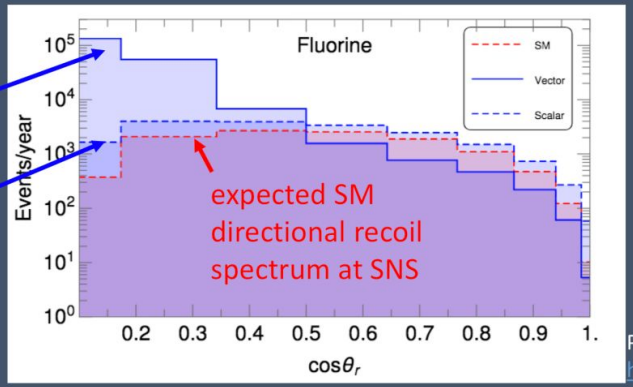


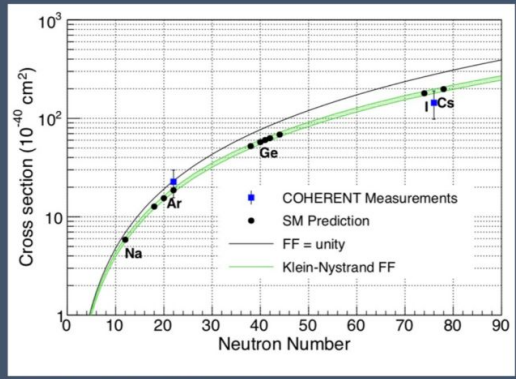
- CEvNS = Coherent elastic neutrino nucleus scattering
- This process probes the weak nuclear charge and weak mixing angle
- Precisely predicted by the SM allowing for sensitive probe of BSM physics

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

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

- 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.