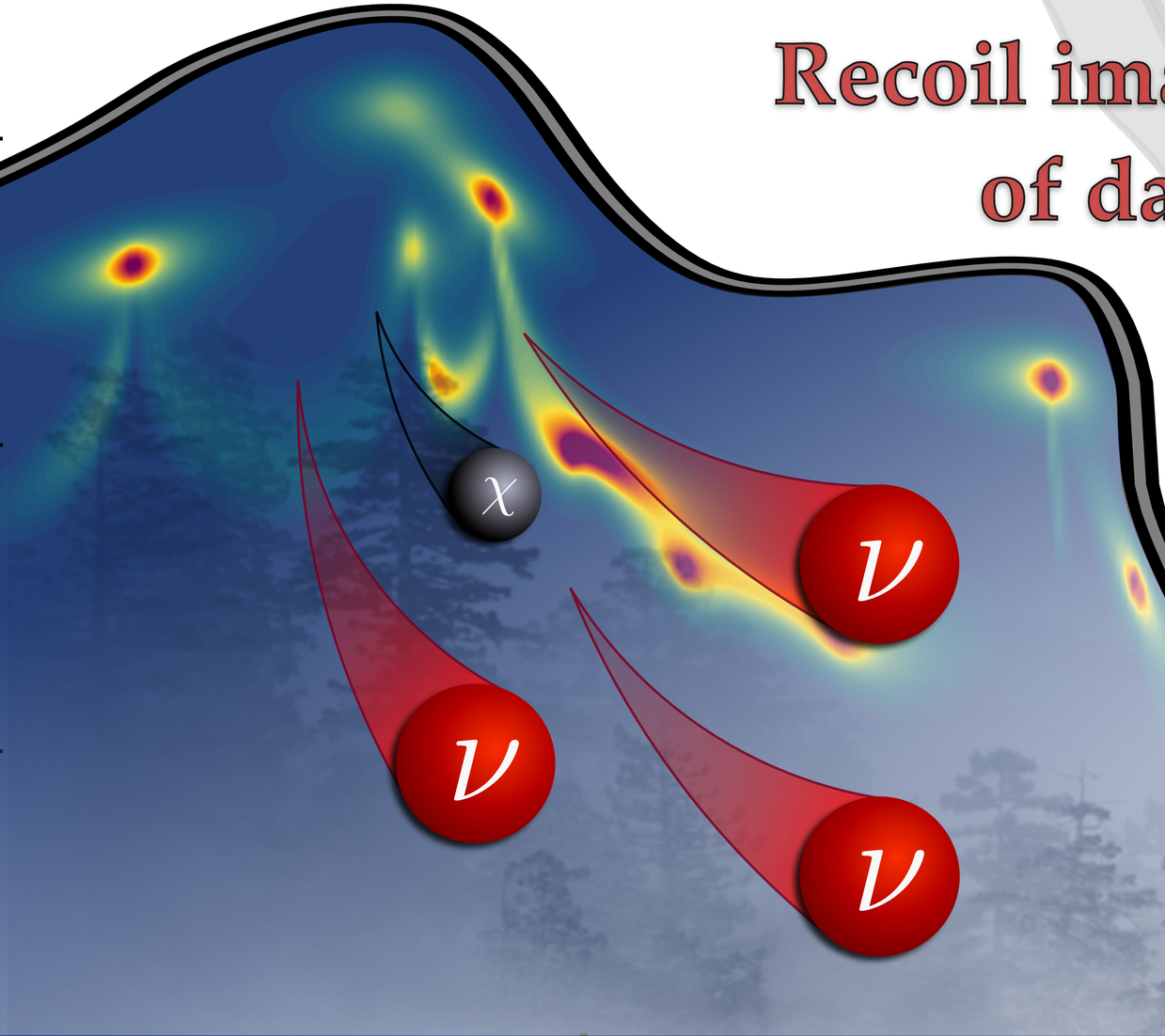
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

Recoil imaging for directional detection of dark matter, neutrinos and BSM



Ciaran O'Hare
University of Sydney

Snowmass inter-frontier white paper [2203.05914]

Strong community support: 167 signing authors, many contributing text/ideas/LOIs

Recoil imaging for dark matter, neutrinos, and physics beyond the Standard Model

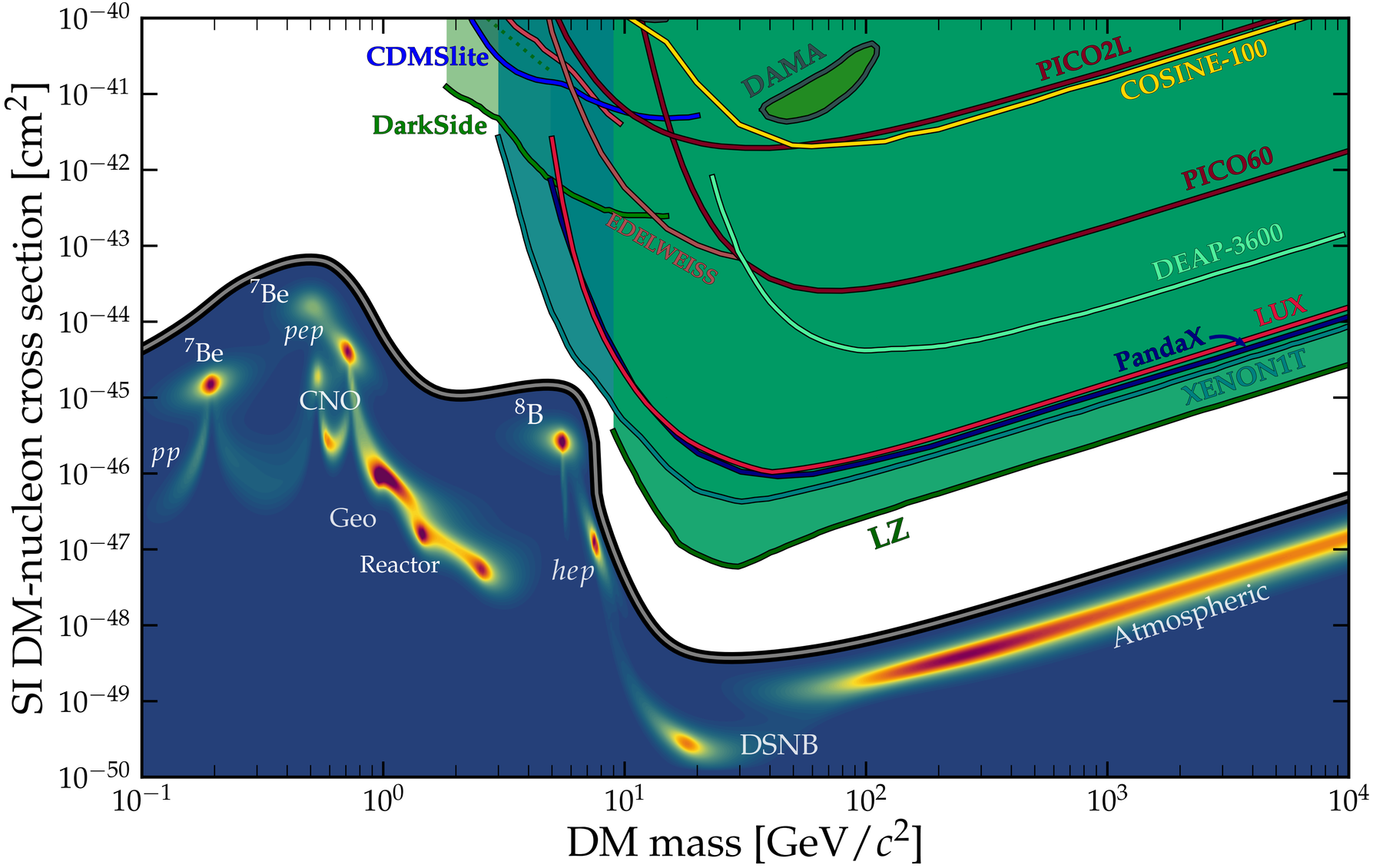
Snowmass 2021 inter-frontier white paper:
IF5: Micro-pattern gas detectors
CF1: Particle-like dark matter
NF10: Neutrino detectors

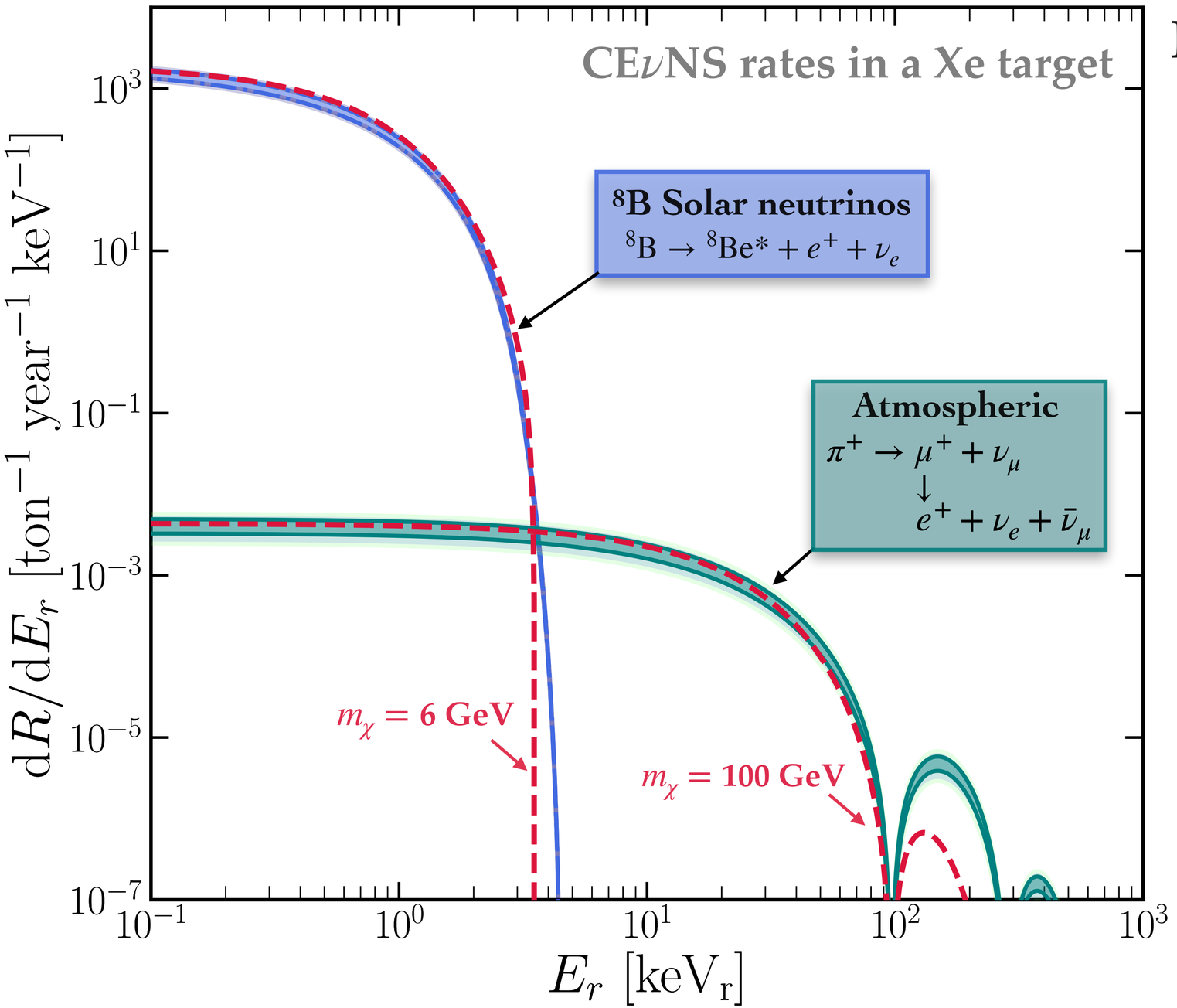
Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Abstract

C. A. J. O'Hare (Coordinator)[1,2], D. Loomba (Coordinator)[3], K. Altenmüller[4], H. Álvarez-Pol[5], F. D. Amaro[6], H. M. Araújo[7], D. Aristizabal Sierra[8,9], J. Asaadi[10], D. Attié[11], S. Aune[11], C. Awe[12,13], Y. Ayyad[5], E. Baracchini[14a,14b,14c], P. Barbeau[12,13], J. B. R. Battat[14], N. F. Bell[15], B. Biasuzzi[11], L. J. Bignell[16], C. Boehm[1,2], I. Bolognino[17], F. M. Brunbauer[18], M. Caamaño[5], C. Cabo[5], D. Caratelli[19], J. M. Carmona[4], J. F. Castel[4], S. Cebrián[4], C. Cogollos[20], D. Collison[1], E. Costa[22], T. Dafni[4], F. Dastgiri[16], C. Deaconu[23], V. De Romeri[24], K. Desch[25], G. Dho[26,27], F. Di Giambattista[26,27], D. Díez-Ibáñez[4], G. D'Imperio[15], B. Dutta[28], C. Eldridge[29], S. R. Elliott[3], A. C. Ezeribe[29], A. Fava[19], T. Felkl[30], B. Fernández-Domínguez[5], E. Ferrer Ribas[11], K. J. Flöthner[18, 66], M. Froehlich[16], J. Galán[4], J. Galindo[4], F. García[31], J. A. García Pascual[4], B. P. Gelli[32], M. Ghrear[33], Y. Giomataris[11], K. Gnanvo[34], E. Gramellini[19], G. Grilli Di Cortona[14], R. Hall-Wilton[35], J. Harton[36], S. Hedges[12], S. Higashino[37], G. Hill[17], P. C. Holanda[32], T. Ikeda[38], I. G. Irastorza[4], P. Jackson[17], D. Janssens[18, 68], B. Jones[10], J. Kaminski[39], I. Katsioulas[51], K. Kelly[19], N. Kemmerich[40], E. Kemp[32], H. B. Korandla[33], H. Kraus[41], A. Lackner[30], G. J. Lane[16], P. M. Lewis[39], M. Lisowska[18, 67], G. Luzón[4], W. A. Lynch[29], G. Maccarrone[14], K. J. Mack[42,43], P. A. Majewski[44], R. D. P. Mano[6], C. Margalejo[4], D. Markoff[45,46], T. Marley[7,44], D. J. G. Marques[26,27], R. Massarczyk[47], G. Mazzitelli[14], C. McCabe[48], L. J. McKie[16], A. G. McLean[29], P. C. McNamara[15], Y. Mei[71], A. Messina[49,15], A. F. Mills[3], H. Mirallas[4], K. Miuchi[37], C. M. B. Monteiro[6], M. R. Mosbech[1,2], H. Muller[39], K. D. Nakamura[70], H. Natal da Luz[50], A. Natochii[33], T. Neep[51], J. L. Newstead[15], K. Nikolopoulos[51], L. Obis[4], E. Oliveri[18], G. Orlandini[18, 69], A. Ortiz de Solórzano[4], J. von Oy[39], T. Papaevangelou[11], O. Pérez[4], Y. F. Perez-Gonzalez[52], D. Pfeiffer[53], N. S. Phan[47], S. Piacentini[49,15], E. Picatoste Olloqui[20], D. Pinci[15], S. Popescu[54], A. Prajapati[26,27], F. S. Queiroz[55,56,57], J. L. Raaf[19], F. Resnati[18], L. Ropelewski[18], R. C. Roque[6], E. Ruiz-Choliz[58], A. Rusu[59], J. Ruz[4], J. Samarati[35], E. M. Santos[40], J. M. F. dos Santos[6], F. Sauli[18], L. Scharenberg[18,39], T. Schiffer[39], S. Schmidt[39], K. Scholberg[12,13], M. Schott[58], J. Schueler[33], L. Segui[11], H. Sekiya[60], D. Sengupta[17], Z. Slavkovska[16], D. Snowden-Ifft[61], P. Soffitta[62], N. J. C. Spooner[29], M. van Stenis[18], L. Strigari[28], A. E. Stuchbery[16], X. Sun[72], S. Torelli[26,27], E. G. Tilly[3], A. W. Thomas[17], T. N. Thorpe[33], P. Urquijo[15], A. Utrobičić[18], S. E. Vahsen[33], R. Veenhof[18, 63], J. K. Vogel[64], A. G. Williams[17], M. H. Wood[65], and J. Zettlemoyer[19]

Current crisis in direct detection of dark matter via nuclear recoils
"The neutrino fog"



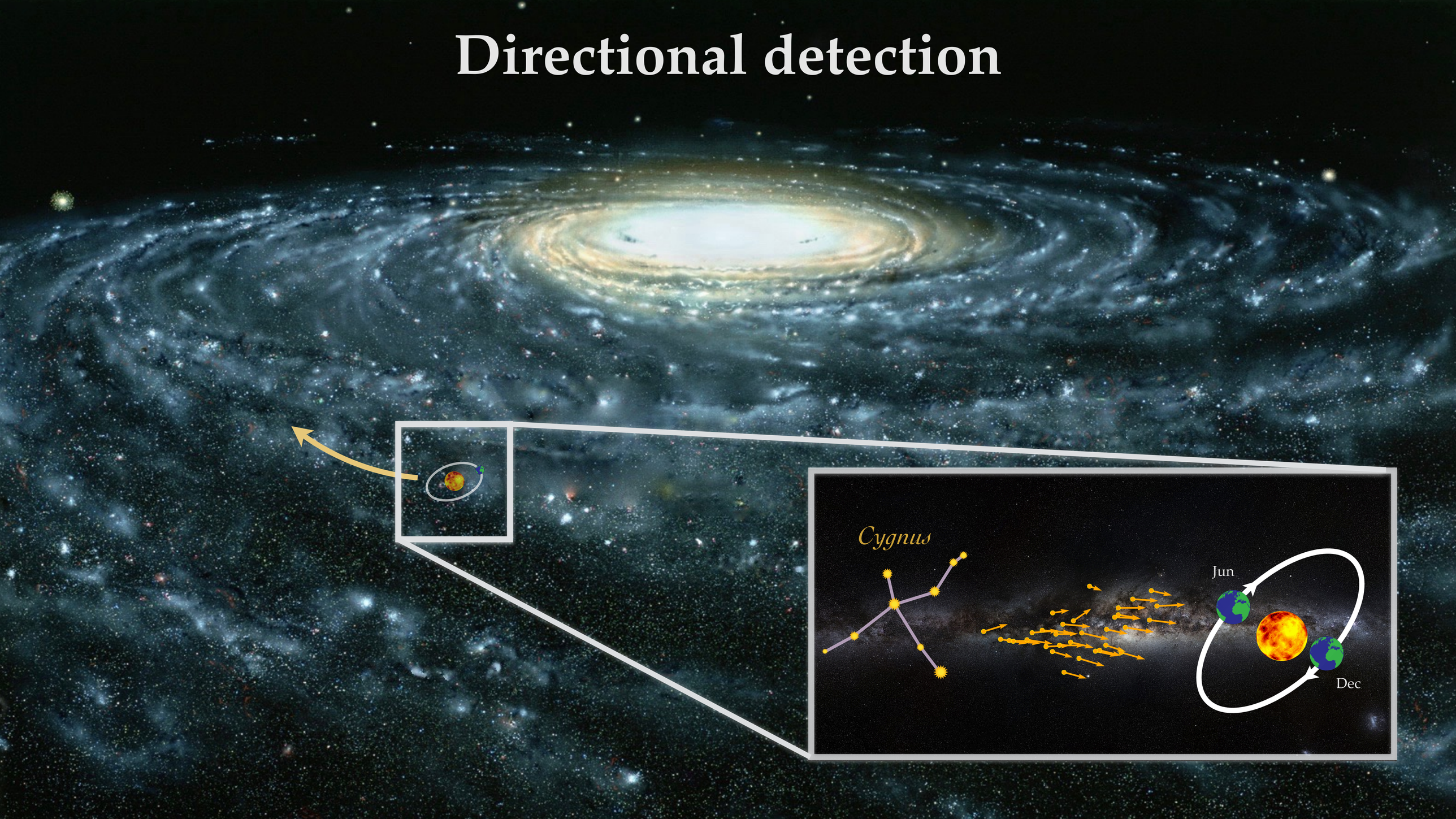


Neutrinos will be observed in LZ or XENONnT very soon

Atmospheric and ^{8}B solar neutrinos are going to be the troublemakers—their CEνNS rates look just like **6 GeV** and **100 GeV** WIMPs in Xenon

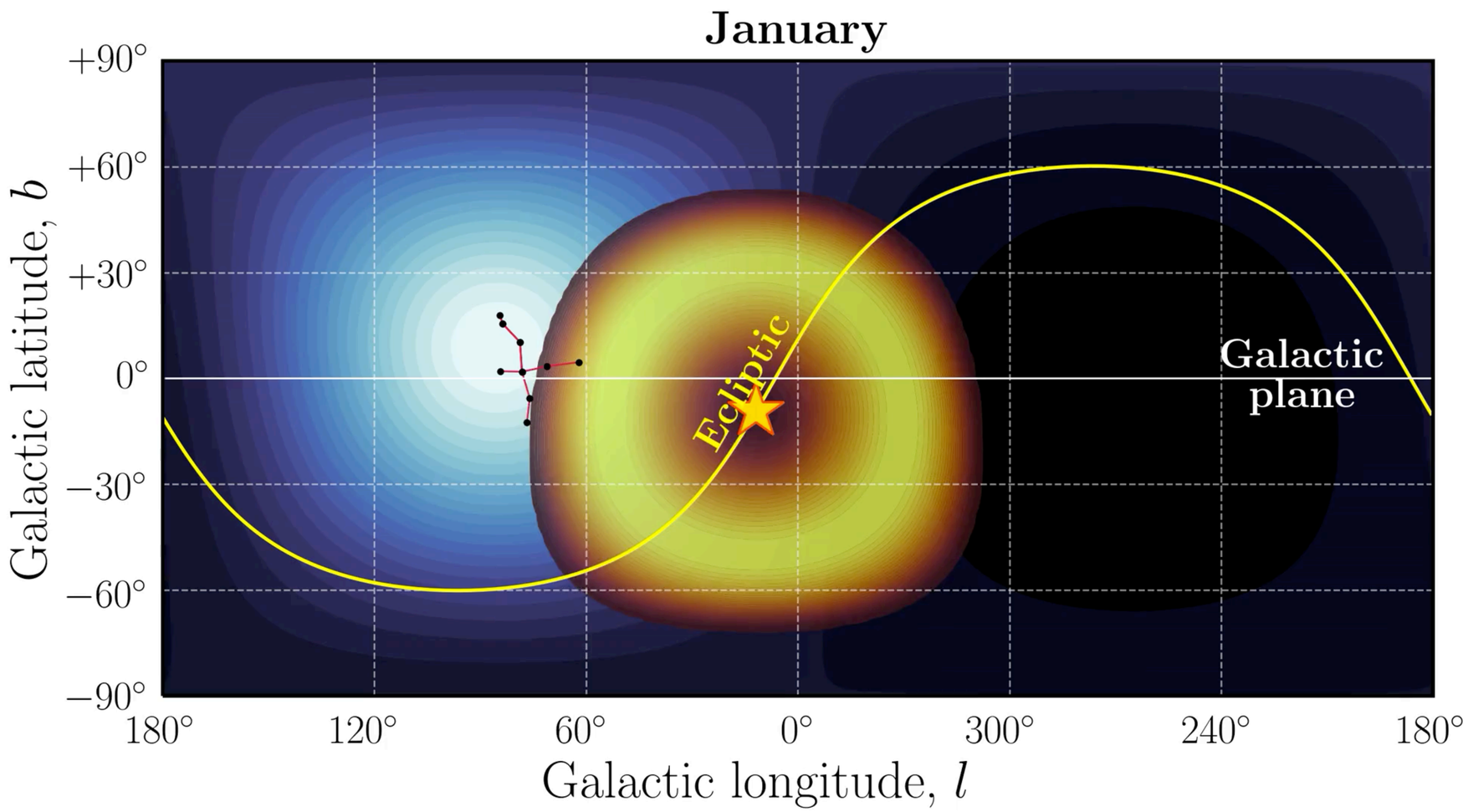
Current experiments only access observables dependent on recoil energy, this makes their signal degenerate with an unshieldable background

Directional detection



A directional detector should be able to "see through" the neutrino fog

The DM flux on Earth is highly anisotropic and should align with our galactic rotation → a highly characteristic signal that is not mimicked by any background, and is robust against particle-model and astrophysical uncertainties



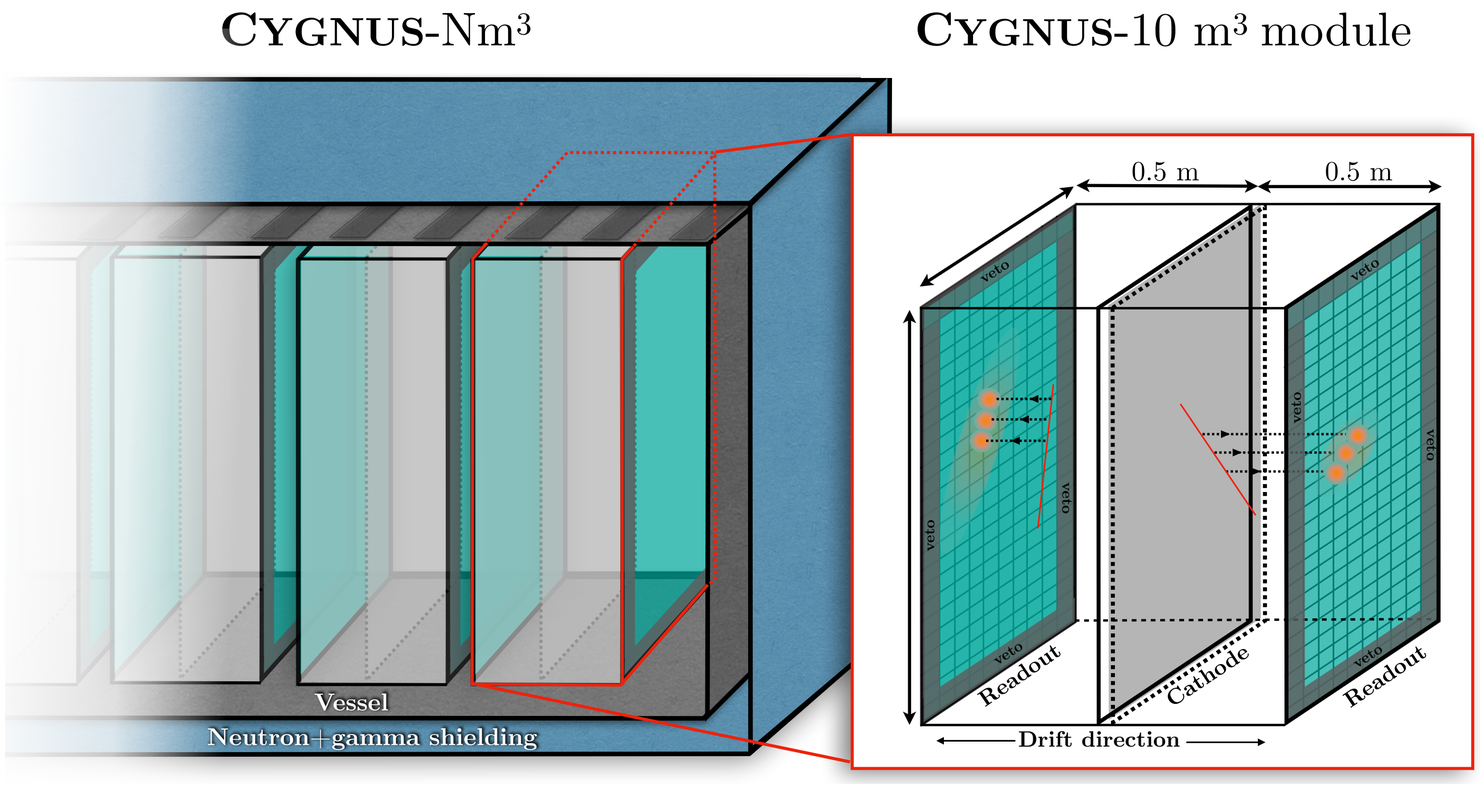
[2008.12587]

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]

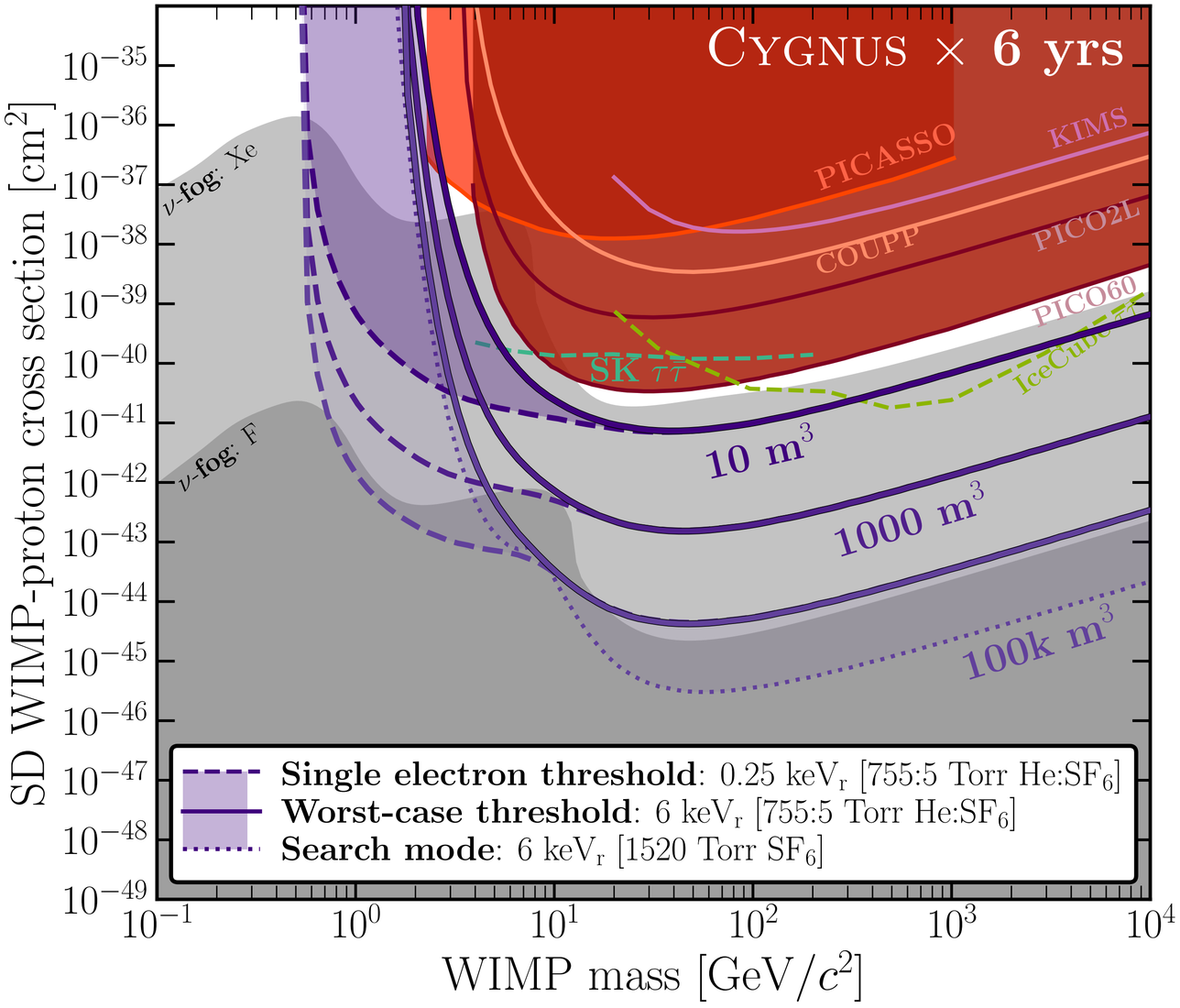
2020 CYGNUS paper discussed the feasibility of making a directional DM/neutrino observatory at the >10 m^3 scale (potentially up 1000 m^3 and beyond)

Compared the cost per physics potential of different readout technologies, keeping all other quantities (i.e gas properties) fixed.



Vahsen, CAJO+ [2008.12587]

Cygnus: projected sensitivity

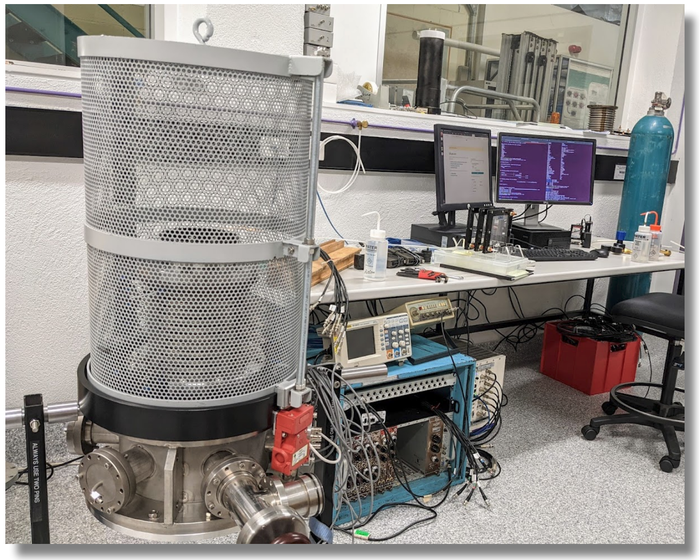


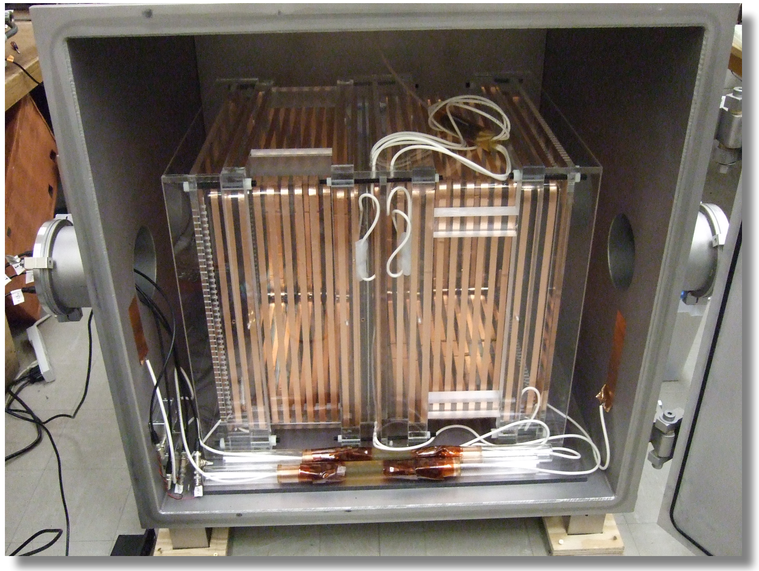
- 10 m^3: world leading DM limits (assuming using gas that contains ^{19}F)
- 1000 m^3: enter neutrino fog
- 100k m^3: competitive with late-stage xenon experiments (DARWIN)

CYGNO (Italy)

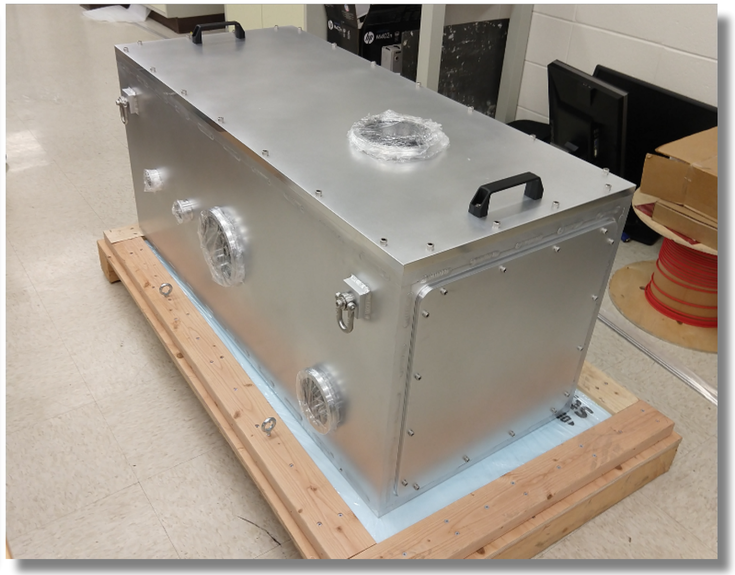
CYGNUS/DRIFT (UK)

CYGNUS-Oz (Australia)

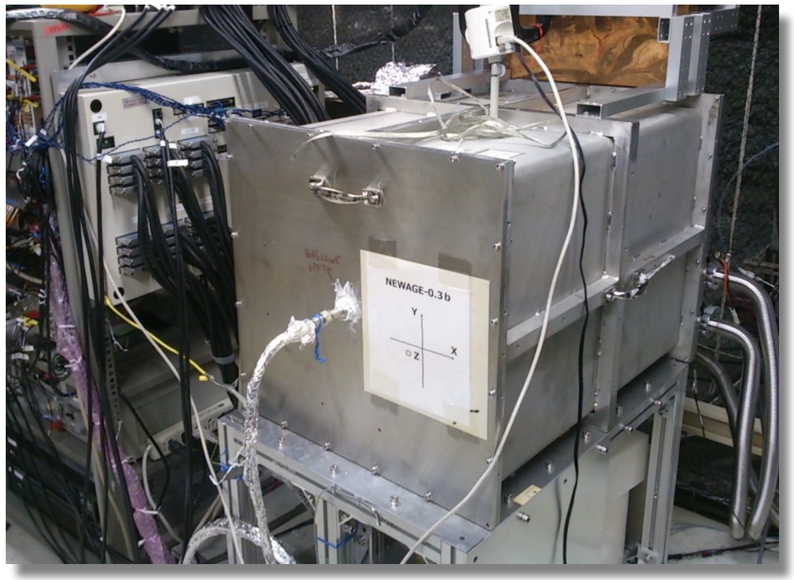




CYGNUS/UNM (USA)

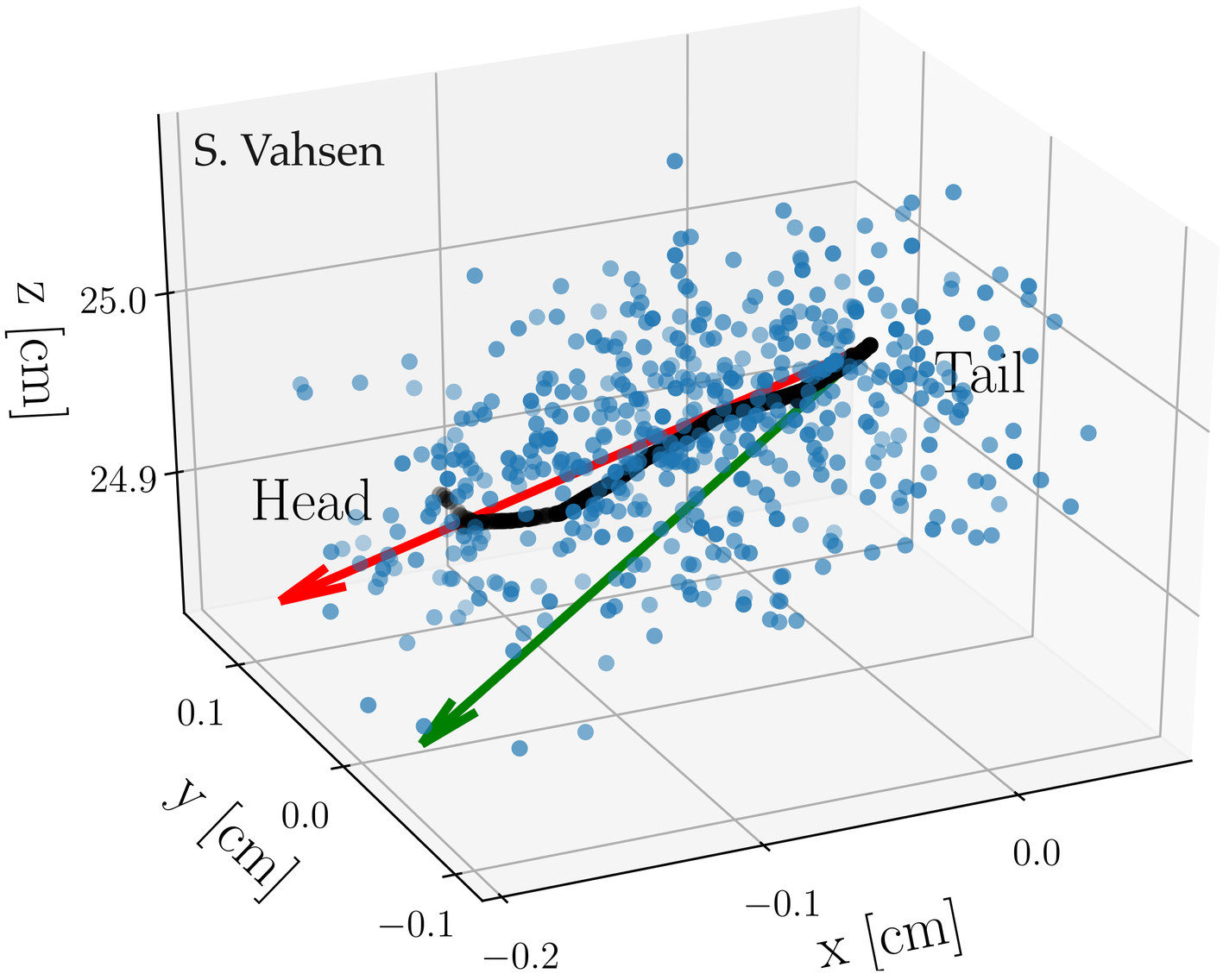


CYGNUS-HD 40 L (USA)



CYGNUS/NEWAGE (Japan)

Key issue: performance of low energy (<10 keVr) nuclear recoil track reconstruction



● **Initial track**

● **After diffusion**

↑ **True recoil dir.**

↑ **Straggled recoil dir.**

What is required to clear the neutrino fog?

(see our review [2102.04596] and Snowmass WP [2203.05914] for reasoning)

- 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

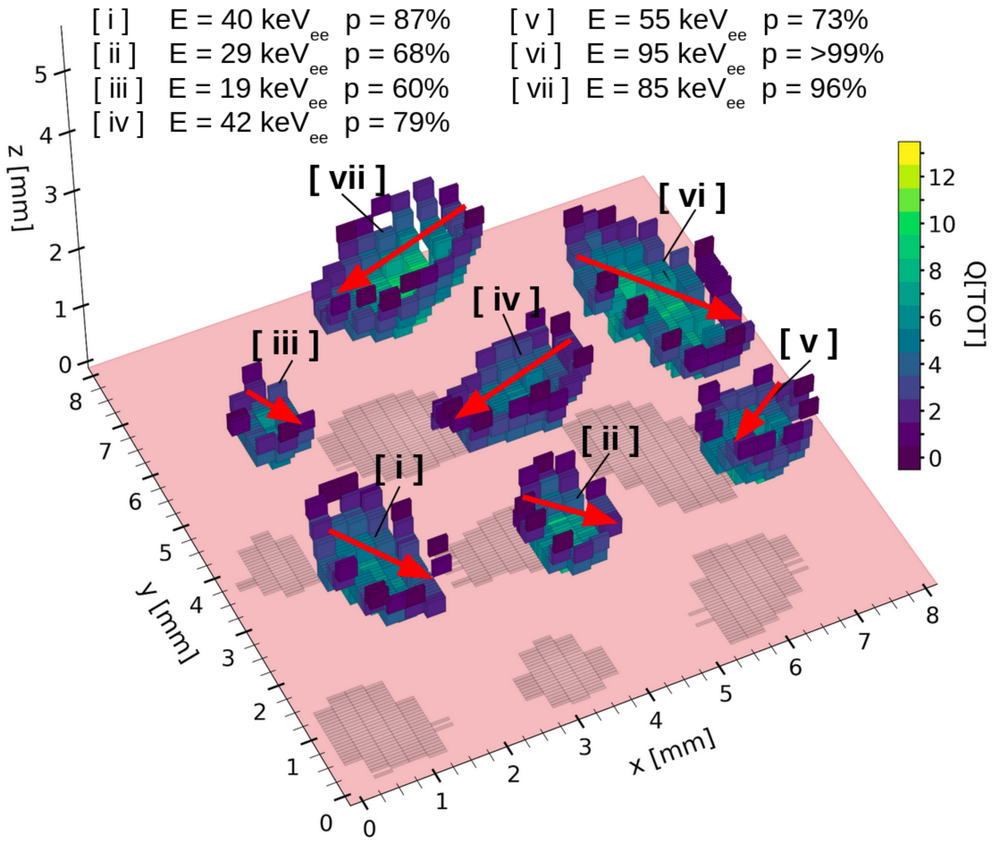
All arrows point towards:

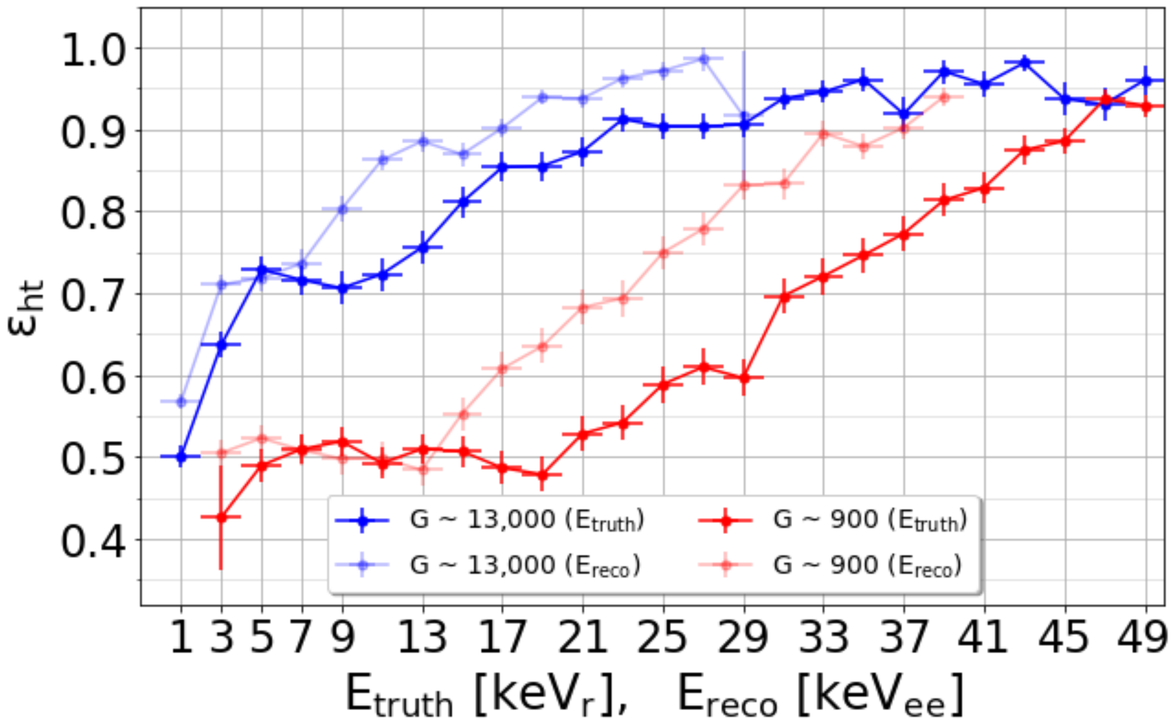
1. "Recoil imaging" Gas TPCs with MPGD readout (over other proposals in the field)

2. Specifically 3D, high-definition, electronic readout, using NID

HD TPC performance studies

Final goal for high-definition imaging of recoils in 3D, meeting low-energy performance goals may not be so far away…





CNN reconstruction of neutron-induced He recoils in BEAST TPC

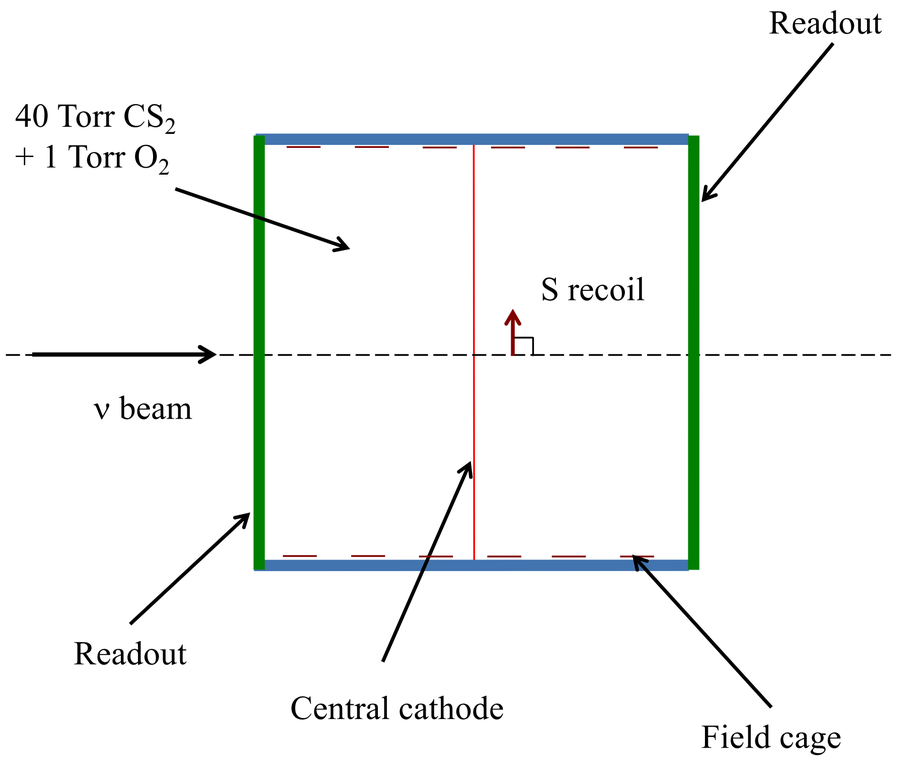
J. Schueler, S. Vahsen (U. Hawaii)

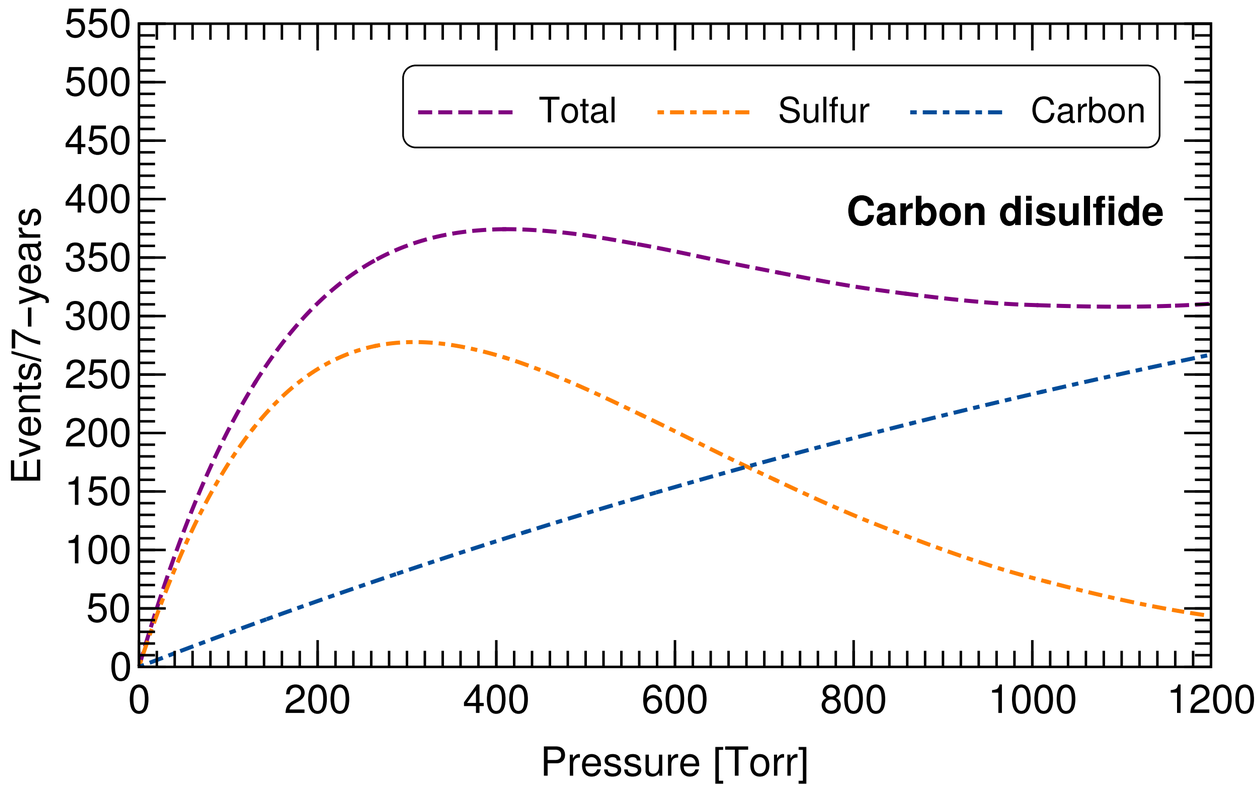
In the meantime turn a background into a signal: CEνNS physics case

→ CEνNS one of the least well-studied neutrino interactions

→ recoil imaging detector in conjunction with neutrino beam could be used to measure it.

→ Increased background rejection against non-neutrino sources, as well as for searches for BSM interactions

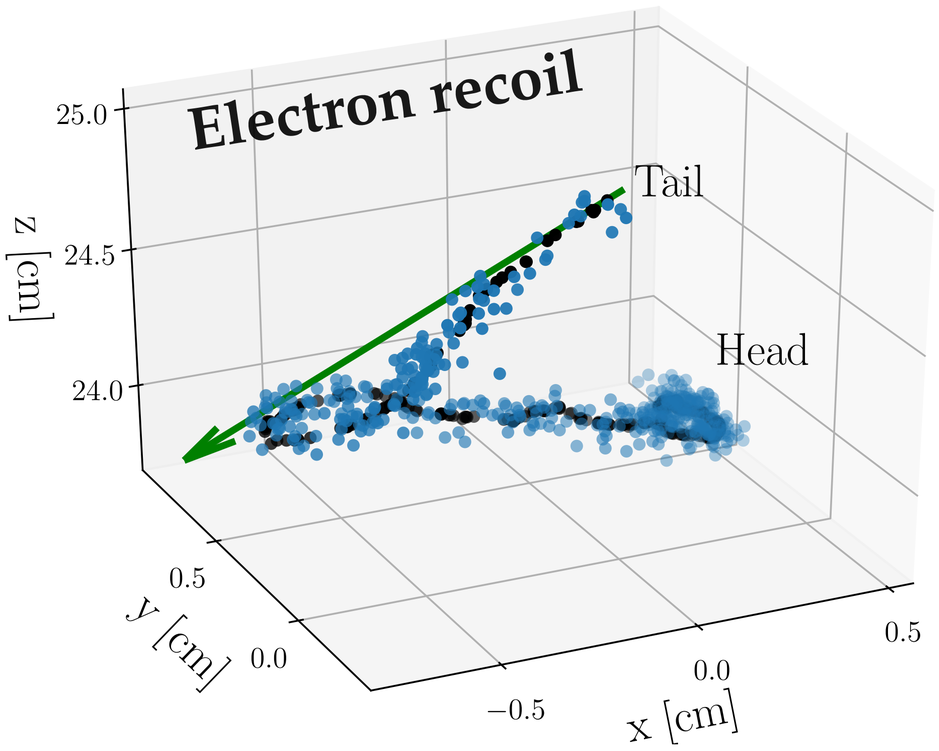


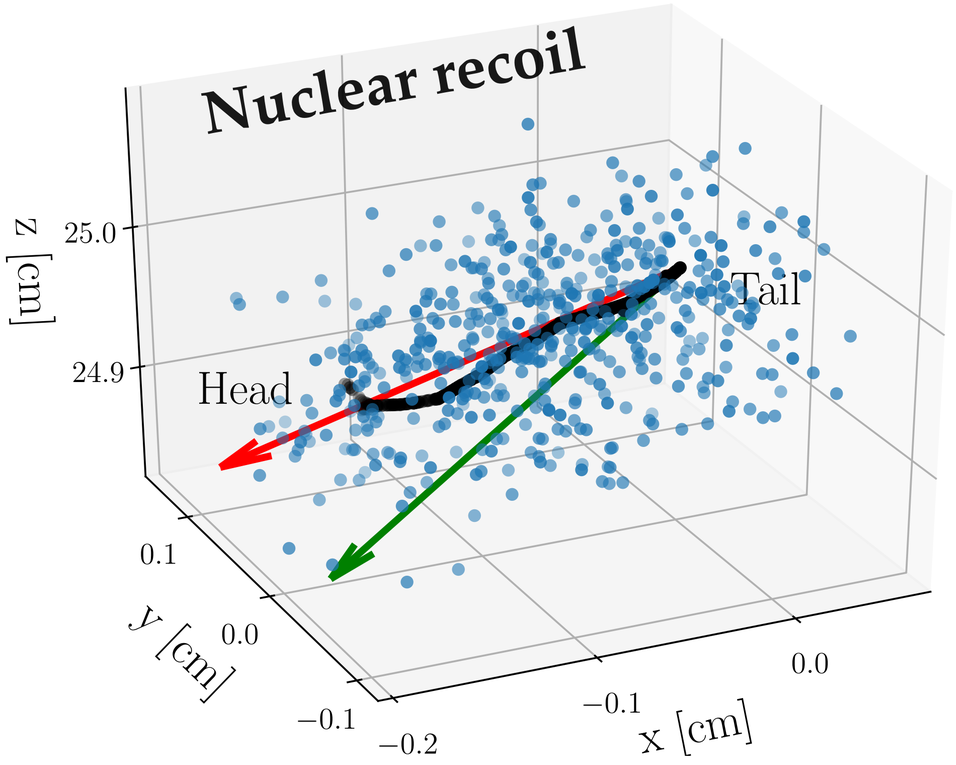


Originally pursued by νBDX-DRIFT collaboration [2103.10857] and under discussion with Oakridge to place 1 m3 TPC at SNS

Directionality in MPGDs, beyond nuclear recoils

MPGDs can measure and distinguish electrons **and** nuclear recoils.
Physics case should clearly be expanded to include electron recoils

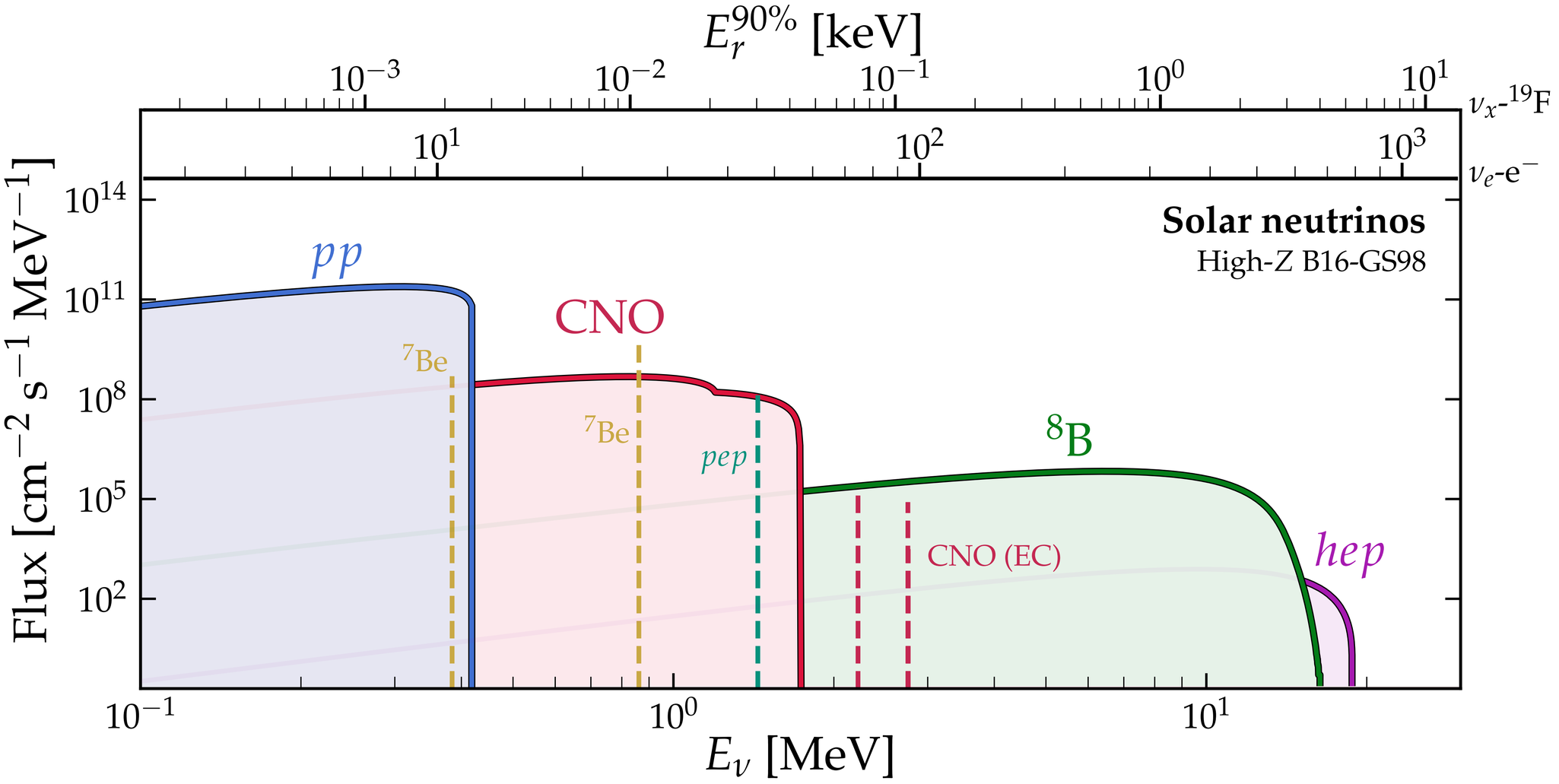




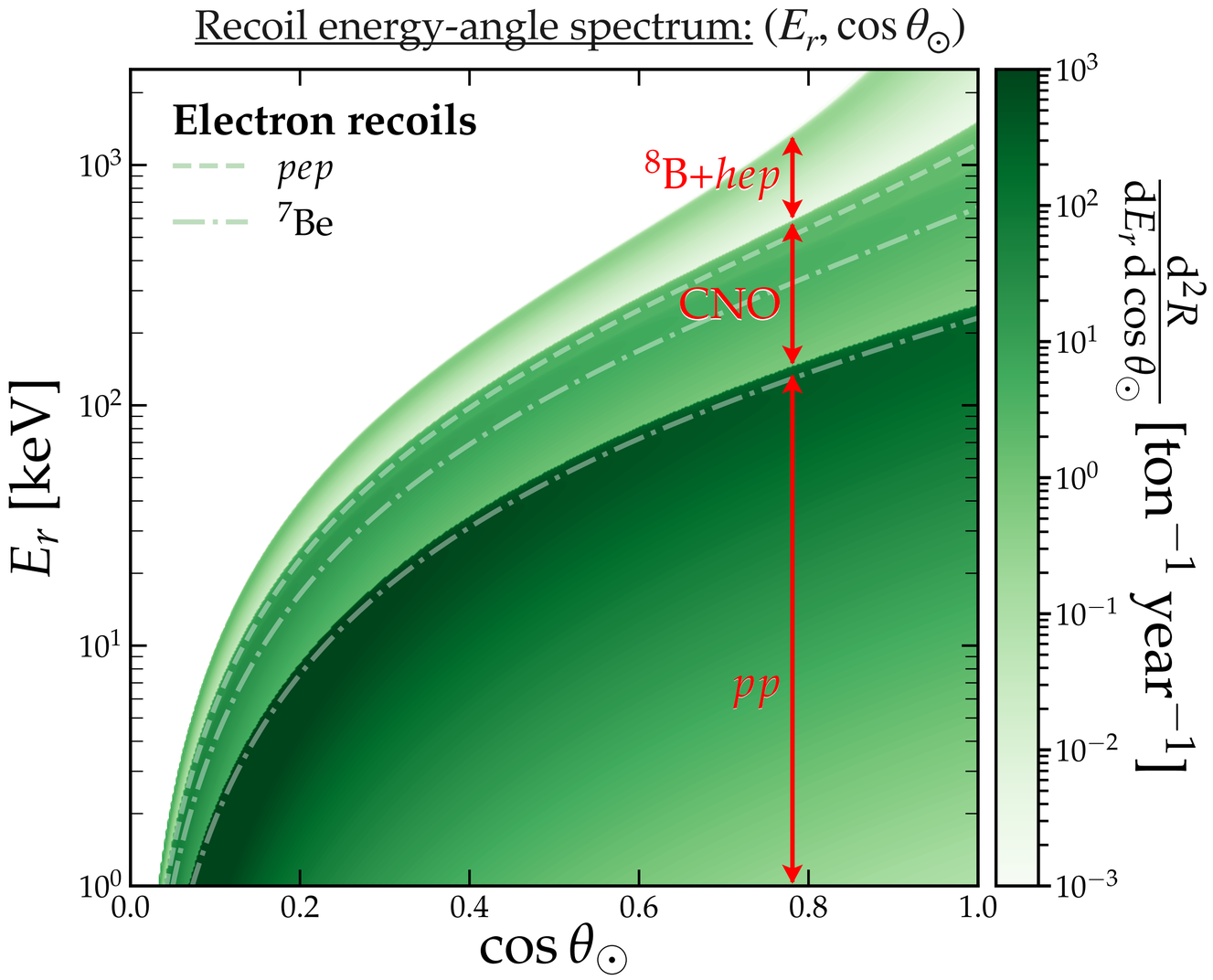
Vahsen, CAJO, Loomba [2008.12587]

Electron *and* nuclear recoils

Solar neutrinos can scatter off electrons and nuclei → gas detectors have both!



Solar neutrinos



Given known direction to the Sun, directional information allows one to reconstruct the neutrino energy spectrum event-by-event

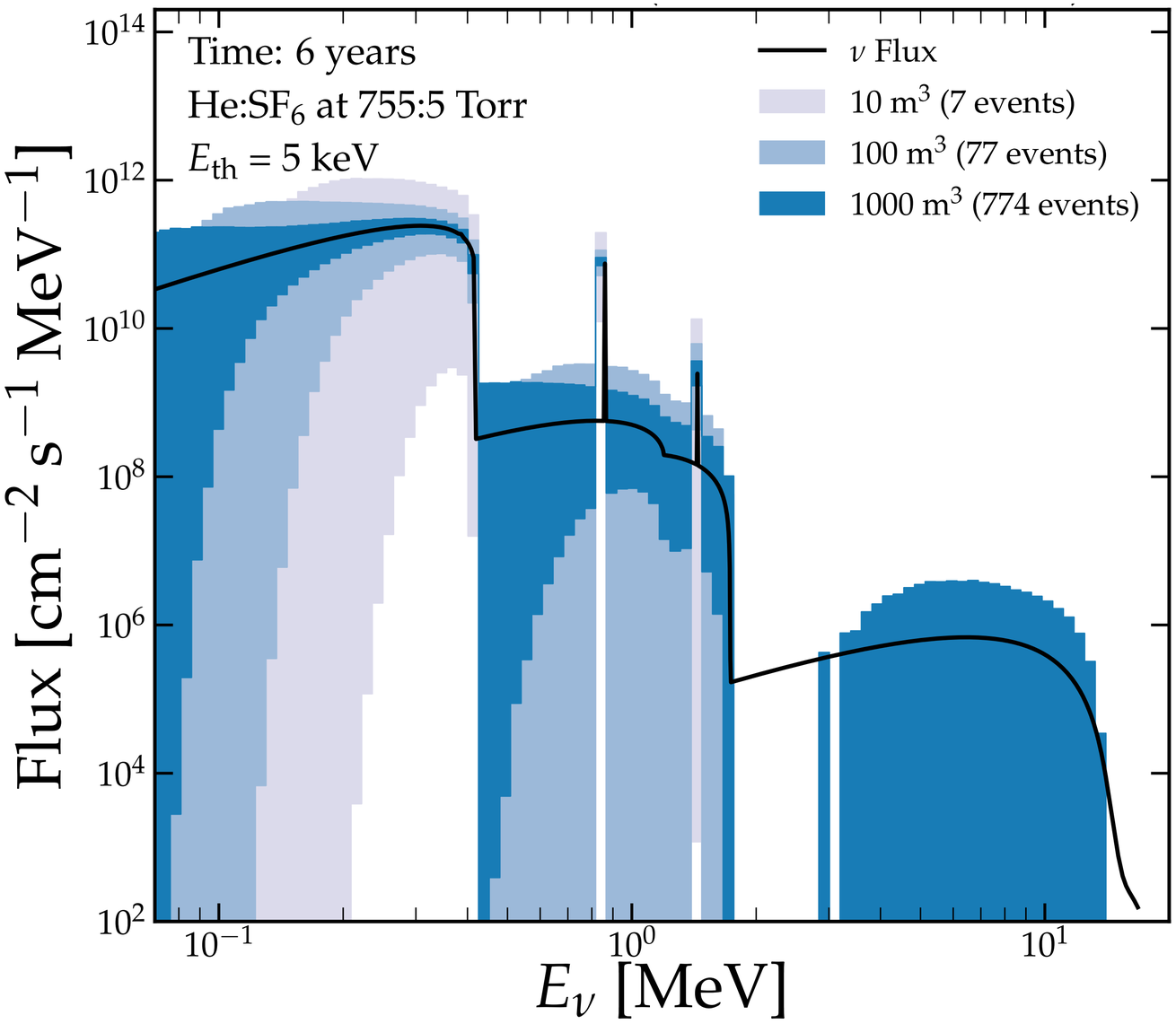
$$\cos\theta_\odot = \hat{\mathbf{q}}_r \cdot \hat{\mathbf{q}}_\odot = \frac{E_\nu + m}{E_\nu}\sqrt{\frac{E_r}{E_r + 2m}}$$

Measure recoil energies and angles

↓

Empirically measure flux, $\Phi(E_\nu)$

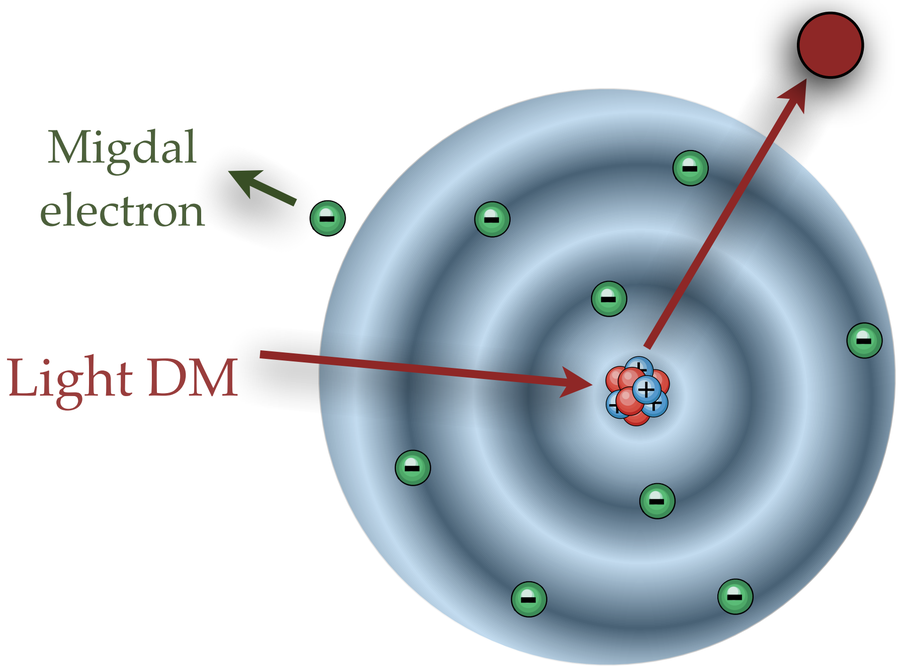
What can directional give you: Empirical flux reconstruction



- **O(10) m³ accesses only *pp***
- **O(100) m³ accesses *pp*, ^{7}Be, CNO**
- **O(1000) m³ access all fluxes except *hep***

To do this precisely need to achieve similar performance, O(10 deg.) angular resolution and O(10%) energy resolution, **on electrons.** Probably less demanding on head/tail as background can be measured in side-bands

Applied physics: The Migdal effect



Emission of a low-energy electron during an almost immeasurably low-energy nuclear recoil

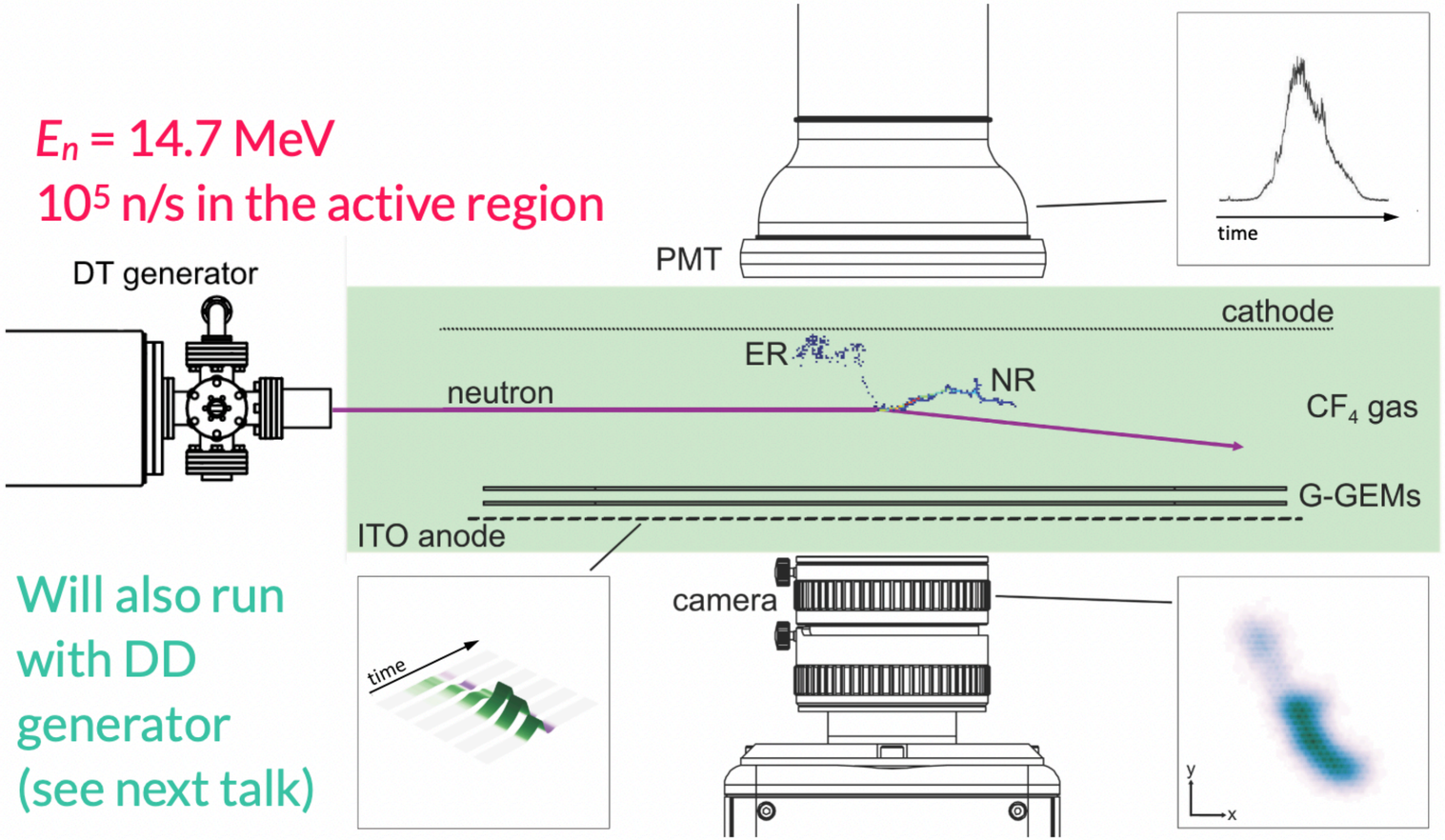
→ Dark matter experiments like XENON are using this to lower their reach to extremely small DM masses

→ But the neutral Migdal effect from NRs has never been measured

Measuring the Migdal effect using neutrons and an O-TPC

Araújo, ... ,CM, et al (MIGDAL) arXiv:2207.08284

E_n = 14.7 MeV
10^5 n/s in the active region



Will also run with DD generator (see next talk)

Neutron scattering lies in high-speed regime:

$$v/\alpha \simeq 0.5 - 2$$

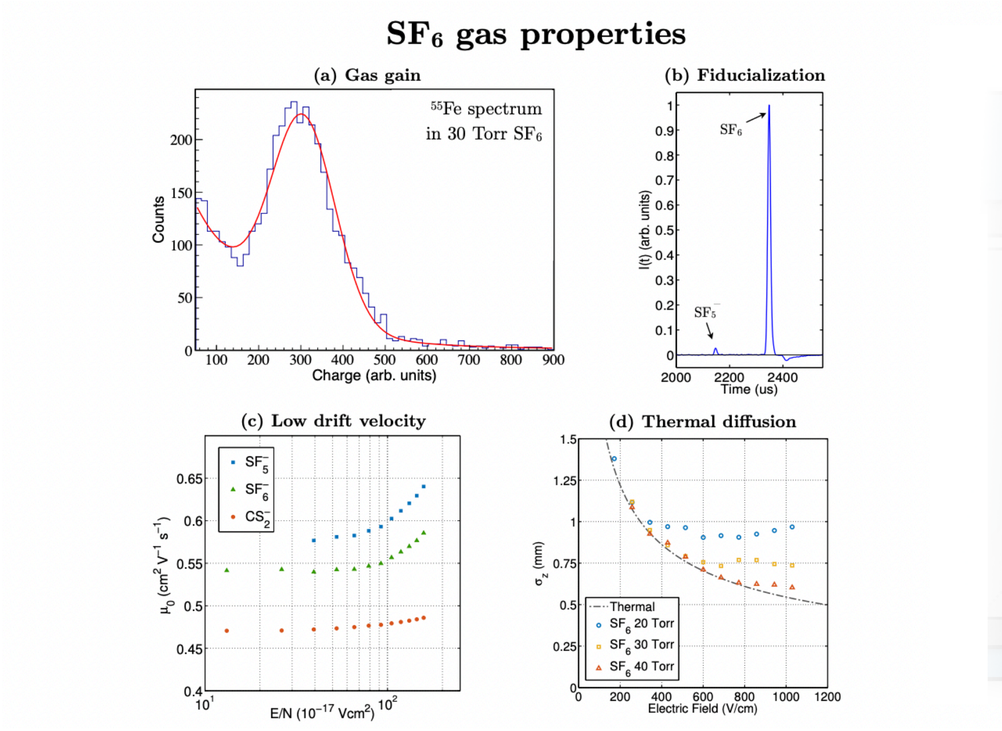
Corresponds to energy:

$$E_r \simeq 100 - 3000 \text{ keV}$$

Slide credit: Chris McCabe @ IDM

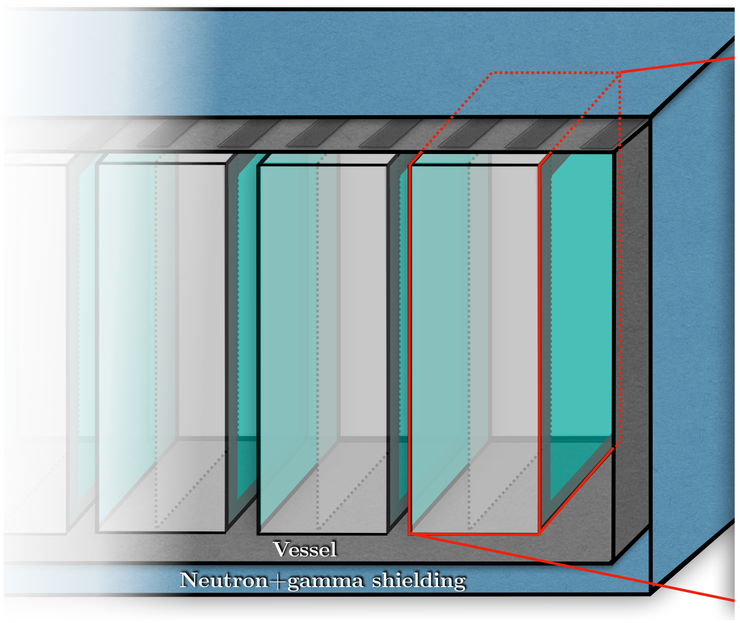
R&D directions

Use of negative ion drift in MPGDs

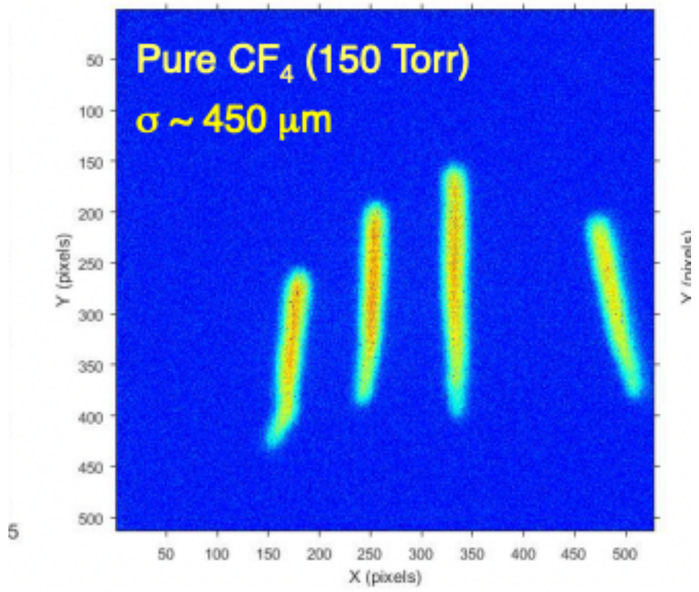


Scalable readout electronics

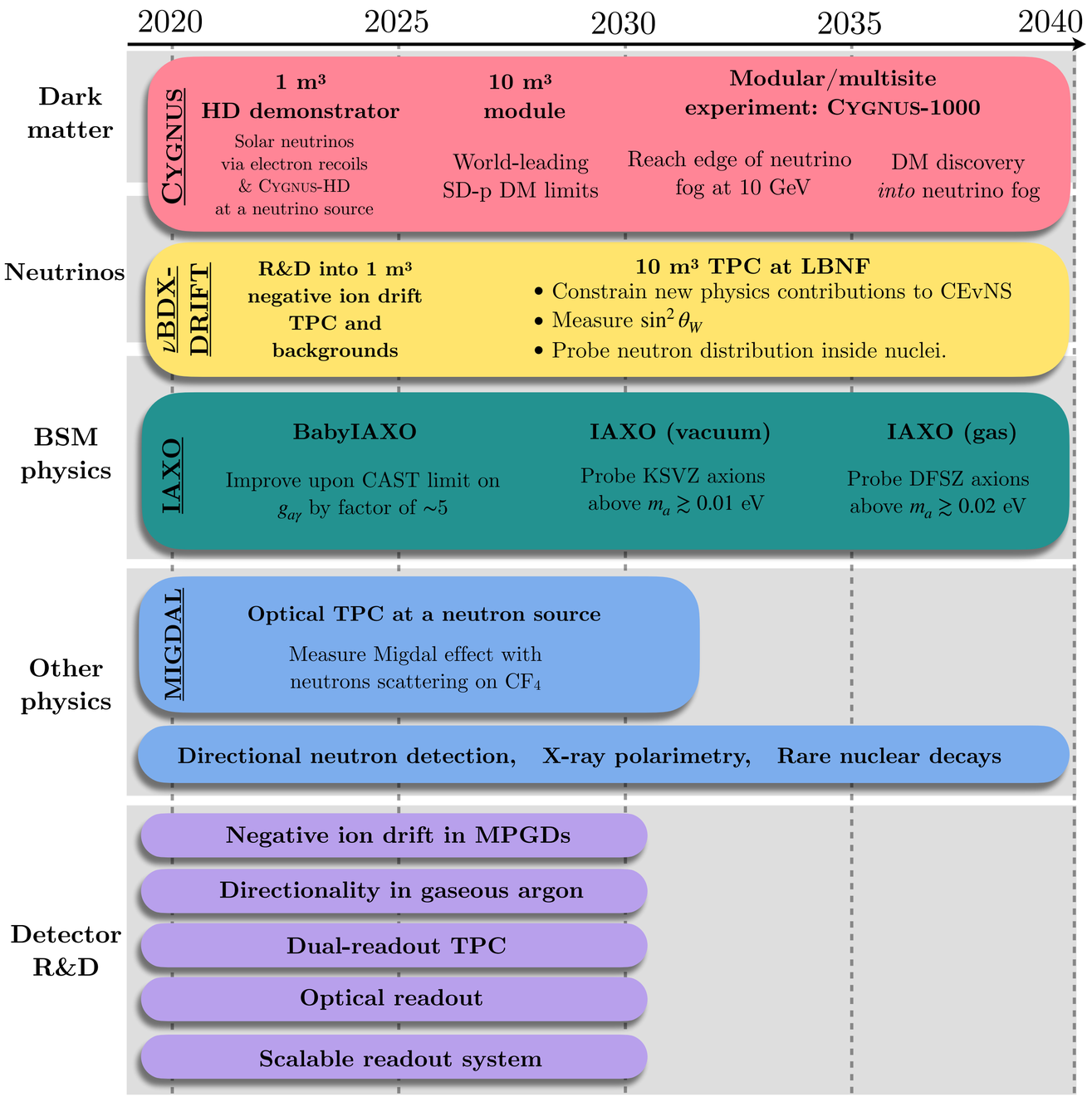
CYGNUS-Nm^3



Optical readout



A critical issue will therefore be to develop next-generation MPGDs that retain sufficient avalanche gain with negative ion drift gases, so as to count individual electrons above the noise floor while keeping cost low-enough for eventual scale-up



Rough 10—20 year timeline in place
See arXiv:[2203.05914] for more

MPGD requirements needed to achieve ambitious physics case for dark matter, neutrinos and BSM:

→ **High signal-to-noise electronic readouts with O(100 μm^3) voxel size**. Energy threshold/resolution should be driven towards ultimate theoretical limit of a single primary electron (~30 eV deposit)

→ **Reconstruction of nuclear recoil vector directions with an angular resolution better than ~30° and >75% correct head/tail recognition.** Modern machine learning techniques for track reconstruction should be investigated to achieve these at ~6 keVr energies and below.

→ **Excellent particle ID and track reconstruction on both electrons and nuclei down to O(1) keVr energies**, essential for detecting DM inside neutrino fog, and solar neutrino-physics studies

→ **Significant radio purity reduction.**

→ R&D into the use of **negative ion drift** gas mixtures in both electronic and optical readout MPGDs, as well as experimental validation of SF_6 in larger scale TPCs.

→ **Scalable readout electronics systems** suitable for the O(m^2) readout planes at a reasonable cost. Highly multiplexed DAQs utilizing programmable, topological triggers will be key for cost reduction. Ultimately mass production will be needed