Directional Recoil Detection

Sven Vahsen
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8th CYGNUS Workshop on Directional Recoil Detection, University of Sydney, Australia

THE UNIVERSITY OF SYDNEY

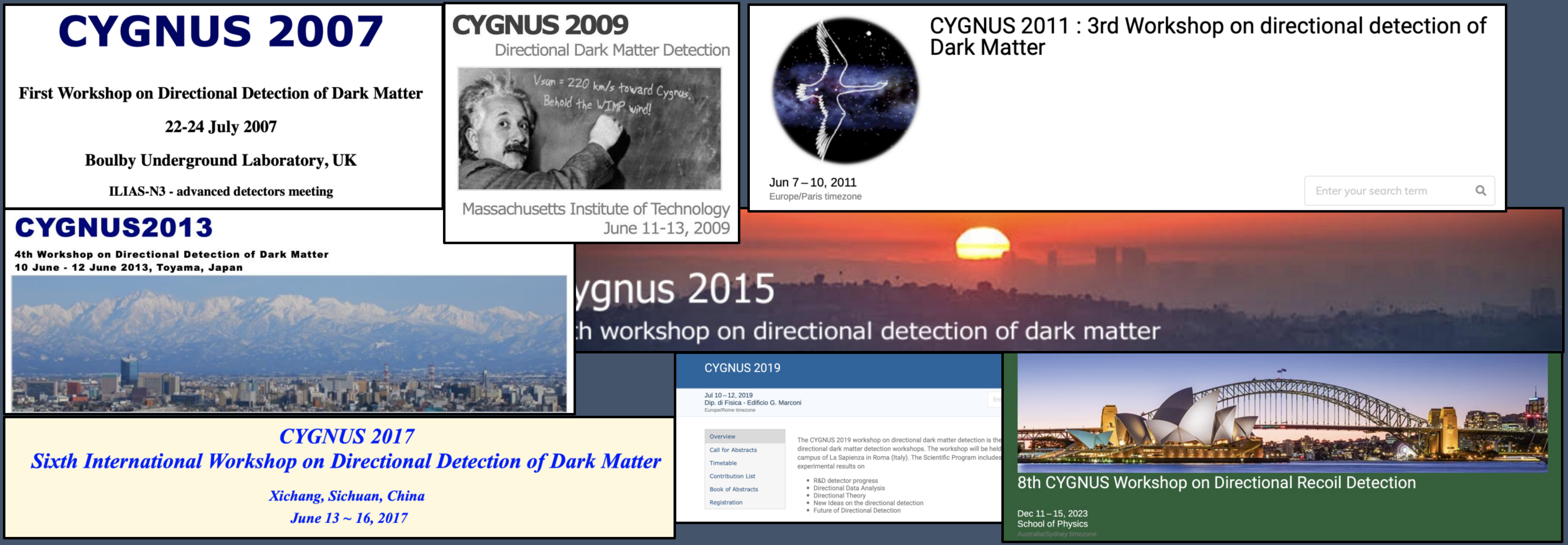
UNIVERSITY of HAWAI'I MĀNOA

Outline

- Physics Motivation / Applications
- Directional Recoil Detection
- A Combined Directional Dark Matter & Neutrino Observatory
- Personal Outlook

← Directional Recoil Detection

Which of the following doesn't belong in the group?



CYGNUS 2023: the 8th CYGNUS workshop

But first one on Directional *Recoil* Detection

The scope has broadened!

From the organizers

- The aim of CYGNUS 2023 is to bring together experimentalists and theorists interested in developing detectors with the capability of detecting the directions of recoiling particles, especially for low-energy applications.
- The scientific scope of the workshop is broad and will cover applications from across particle physics, astroparticle physics, and nuclear physics.

Dark Matter via Nuclear Recoils (<2019)

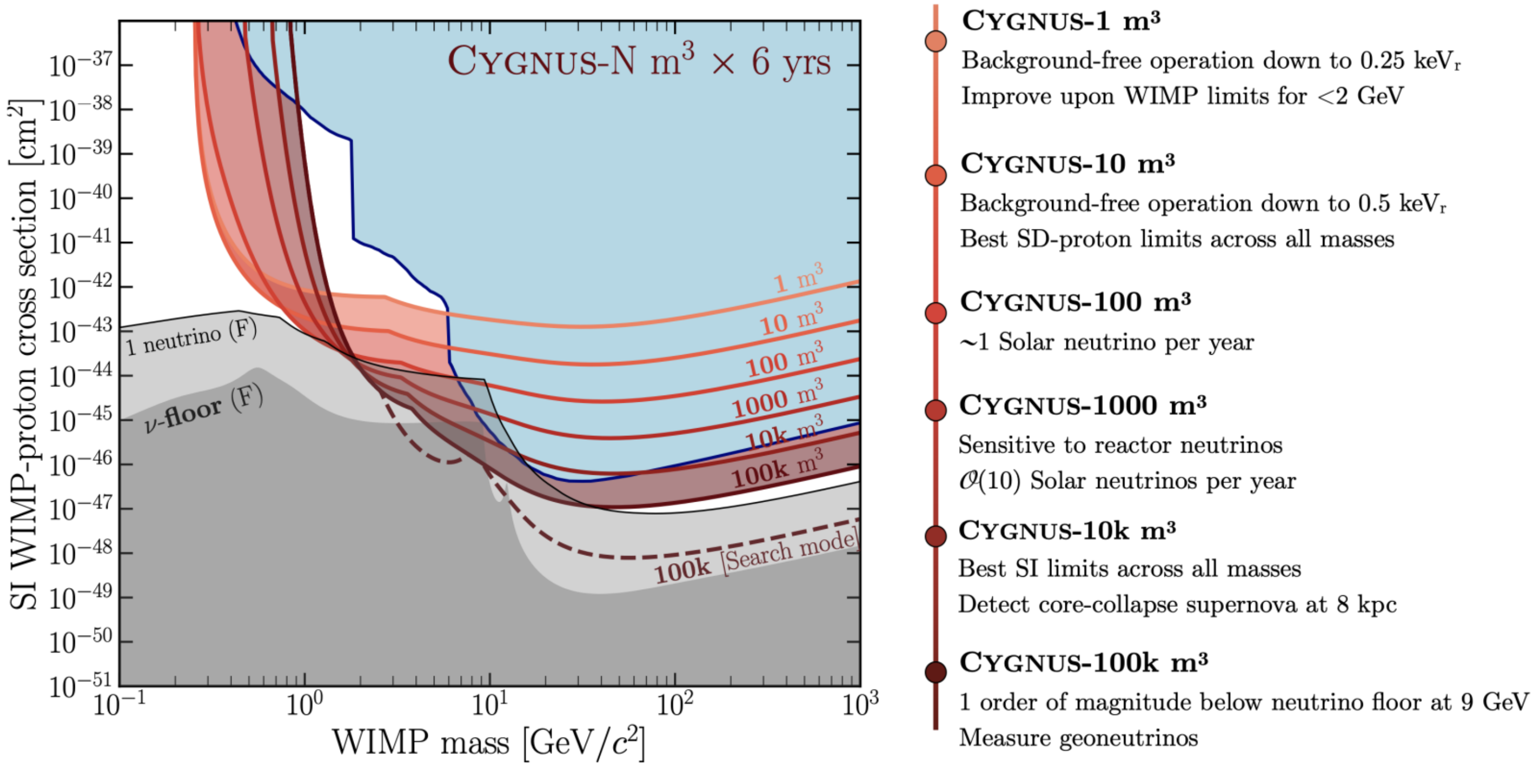


FIG. 34. Summary of the projected SI WIMP 90% CL exclusion limits as a function of the total fiducial volume of the network of detectors comprising the CYGNUS experiment. All experimental exposures are multiplied by a running time of 6 years such that the listed benchmarks are all approximately multiples of 1 ton year (1 ton year corresponds to 1000 m^3). We shade in blue the currently excluded limits on the SI WIMP-nucleon cross section as of 2020. The thresholds are increased evenly between 0.25 and 8 keV_r and for each increasing volume to illustrate the range of possible thresholds envisaged for the final experiment. Below the final volume we also extend the reach by including the possibility of a "search mode" experiment which would have 1520 Torr of SF_6 (as opposed to 5 Torr), but would have no directional sensitivity.

https://arxiv.org/abs/2008.12587 (2020)

2021

ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

Directional Recoil Detection

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"Directional Recoil Detection": Expanded physics program for directional detectors (link)

2022

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

Recoil imaging entails the detection of spatially resolved ionization tracks generated by particle interactions. This is a highly sought-after capability in many classes of detector, with broad applications across particle and astroparticle physics. However, at low energies, where ionization signatures are small in size, recoil imaging only seems to be a practical goal for micro-pattern gas detectors. This white paper outlines the physics case for recoil imaging, and puts forward a decadal plan to advance towards the directional detection of low-energy recoils with sensitivity and resolution close to fundamental performance limits. The science case covered includes: the discovery of dark matter into the neutrino fog, directional detection of sub-MeV solar neutrinos, the precision study of coherent-elastic neutrino-nucleus scattering, the detection of solar axions, the measurement of the Migdal effect, X-ray polarimetry, and several other applied physics goals. We also outline the R&D programs necessary to test concepts that are crucial to advance detector performance towards their fundamental limit: single primary electron sensitivity with full 3D spatial resolution at the ~100 micron-scale. These advancements include: the use of negative ion drift, electron counting with high-definition electronic readout, time projection chambers with optical readout, and the possibility for nuclear recoil tracking in high-density gases such as argon. We also discuss the readout and electronics systems needed to scale-up detectors to the ton-scale and beyond.

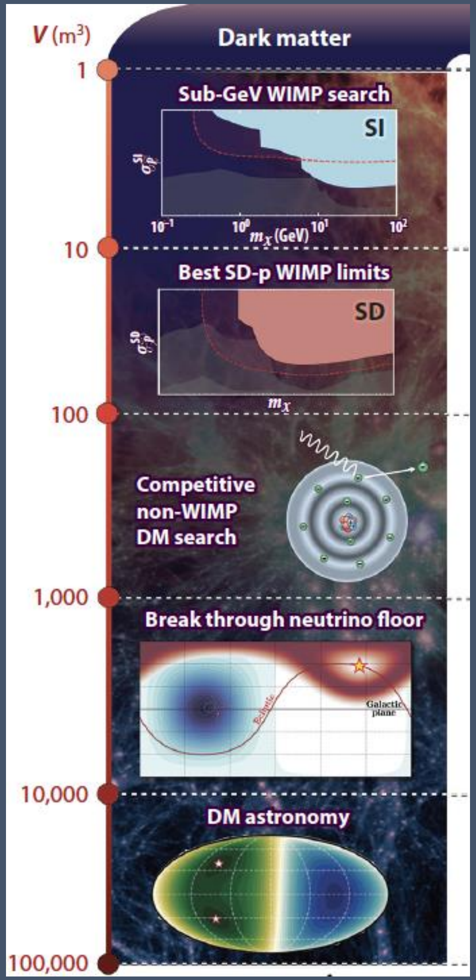
C. A. J. O'Hare (Coordinator)[1,2], D. Loomba (Coordinator)[3], K. Altenmüller[4], H. Álvarez-Pol[5], F. D. Amaro[6], H. M. Araújo[7], D. Aristizabal Sierra[8,9], J. Asaadi[10], D. Attié[11], S. Aune[11], C. Awe[12,13], Y. Ayyad[5], E. Baracchini[14a,14b,14c], P. Barbeau[12,13], J. B. R. Battat[14], 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]

arXiv:2203.05914

"Recoil imaging": Also expanded community (167 physicists)

Dark Matter via Nuclear Recoils

Exposure, size

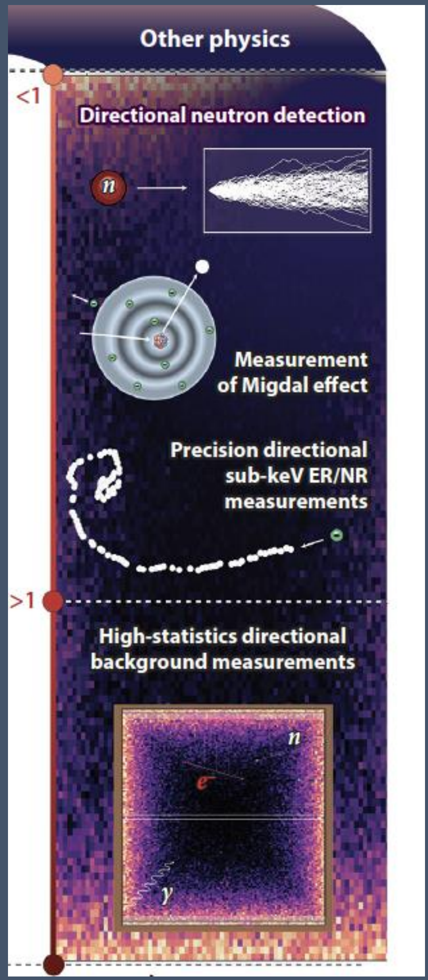


Neutrinos via nuclear and electronic recoils

Exposure, size

Other applications

Exposure, size



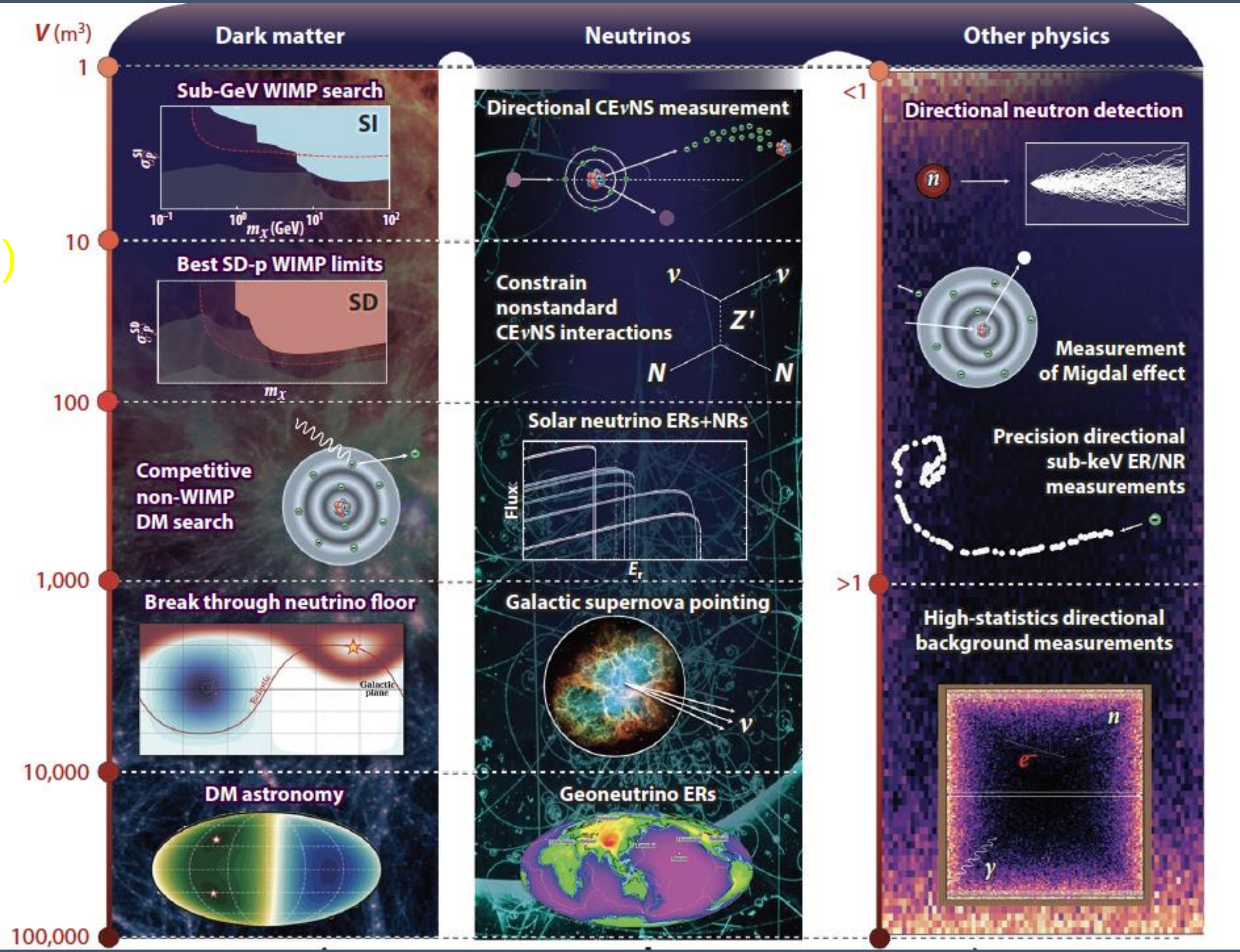
Opportunities for a 30+ year physics program

arxiv:2102.04596

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

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



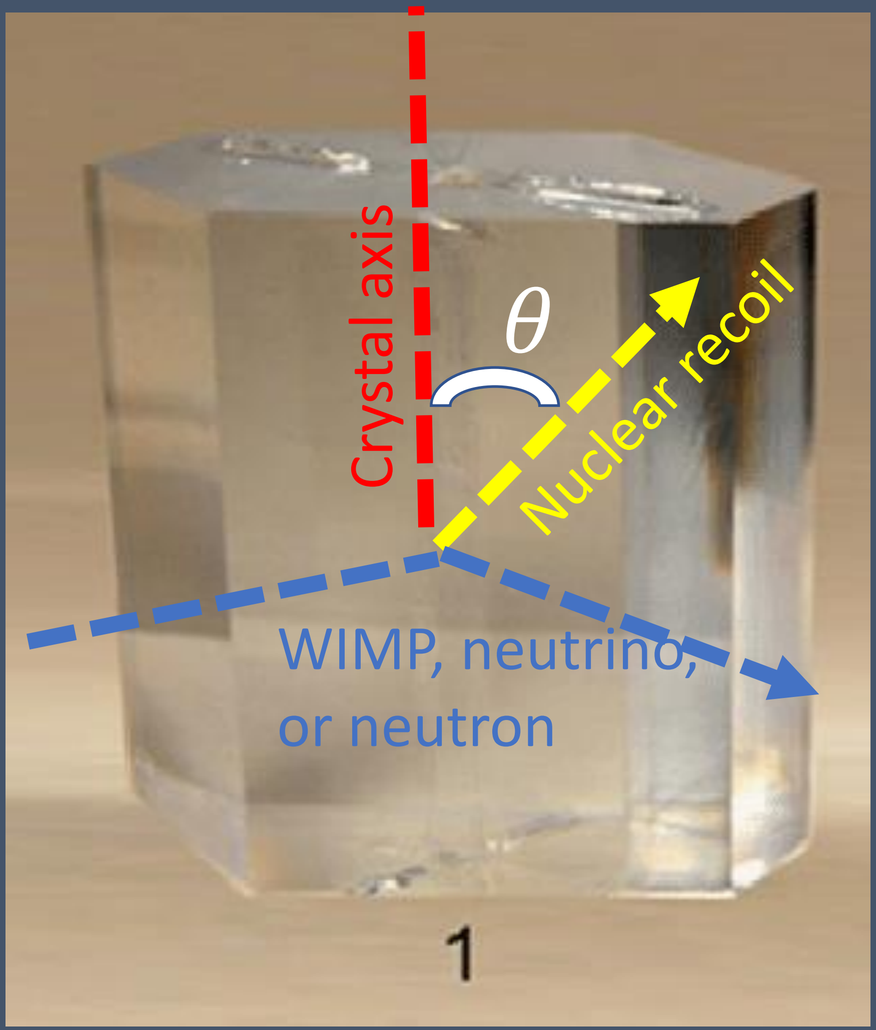
- New physics opportunities for each factor of 10 increase in exposure
- Both guaranteed measurements (yellow text) and novel, exciting searches --- across frontiers!

Types of directionality

Has to match physics requirements

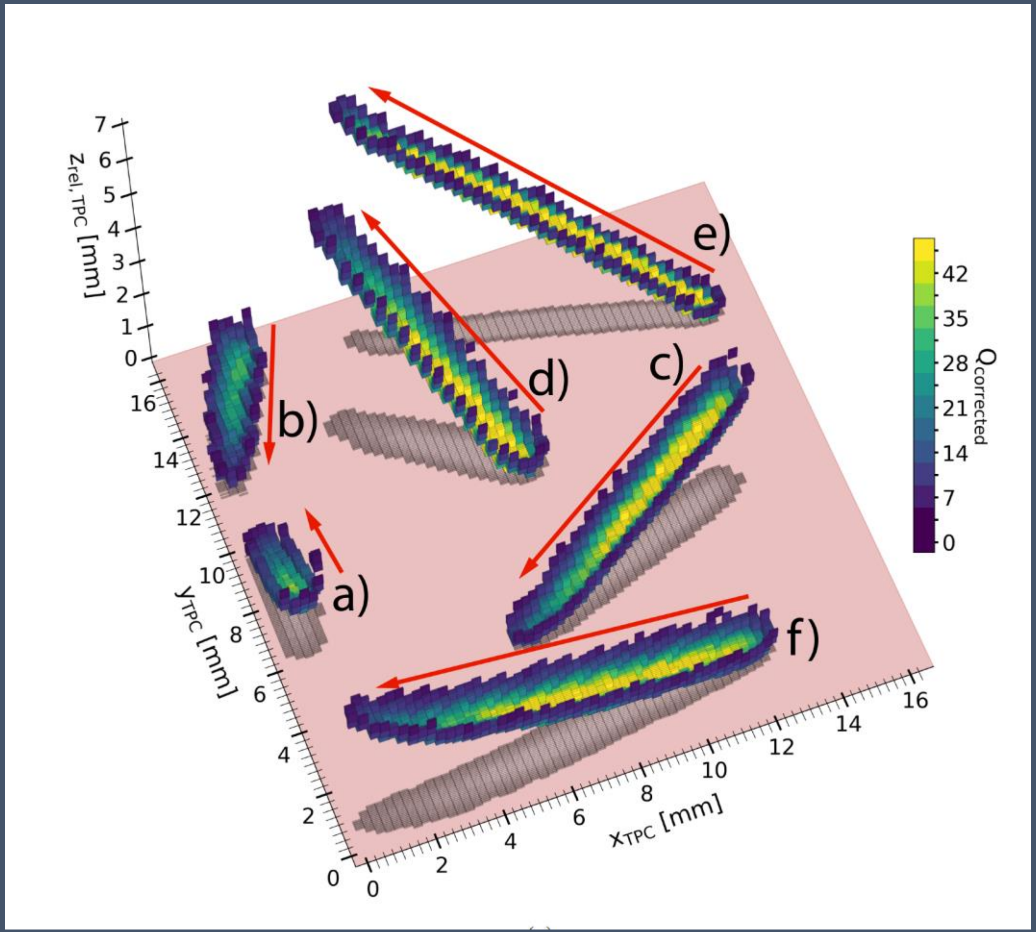
Statistical directionality

- Example
  - Light yield from recoil depends on recoil angle w.r.t. crystal axis
  - Assume only integrated light yield is measured, event-by-event
- One pro
  - Condensed medium → high target mass (event rate)
- One con
  - Recoil energy and direction measurements not independent
- Directional Performance metric
  - % variation in light yield versus angle and energy



Event level directionality

- Example: measure recoil ionization track
- Pro:
  - Independent energy and direction info
- Con:
  - Better directionality typically requires lower target density



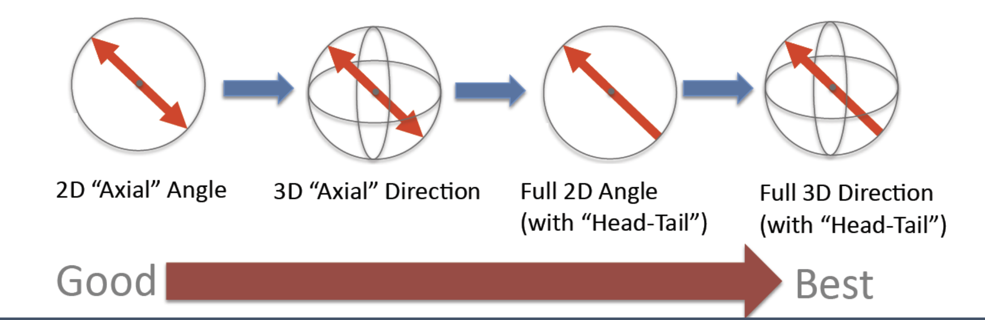
He recoils in $HeC0_2$ gas, E>~200keV

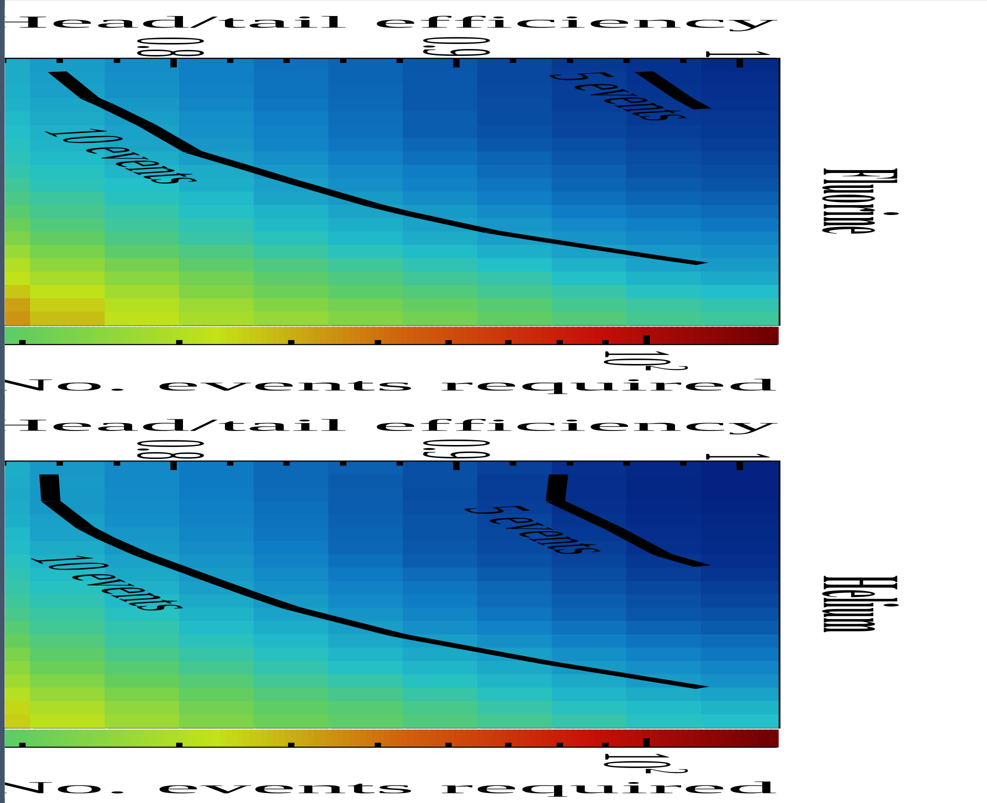
Event level directionality

- Directional Performance metrics:

1. Head tail efficiency
2. Average recoil-angle (axial) error

[both versus recoil energy]





https://arxiv.org/abs/2102.04596

Detector classes by directional information

Demonstrated
R&D
Proposed

Indirect — **Recoil imaging**

Statistical — **Event-level**

Modulation-based directionality → Indirect recoil event directionality → Time-integrated recoil imaging → Time-resolved recoil imaging

Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes

Columnar recombination
- Event-level 1d directions
- No head/ tail
- Direction and energy are not independent

Nuclear emulsions
- 2d recoil tracks, without head/ tail
- No event times information recorded

DNA detector
- 3d recoils without head/ tail
- No event times recorded

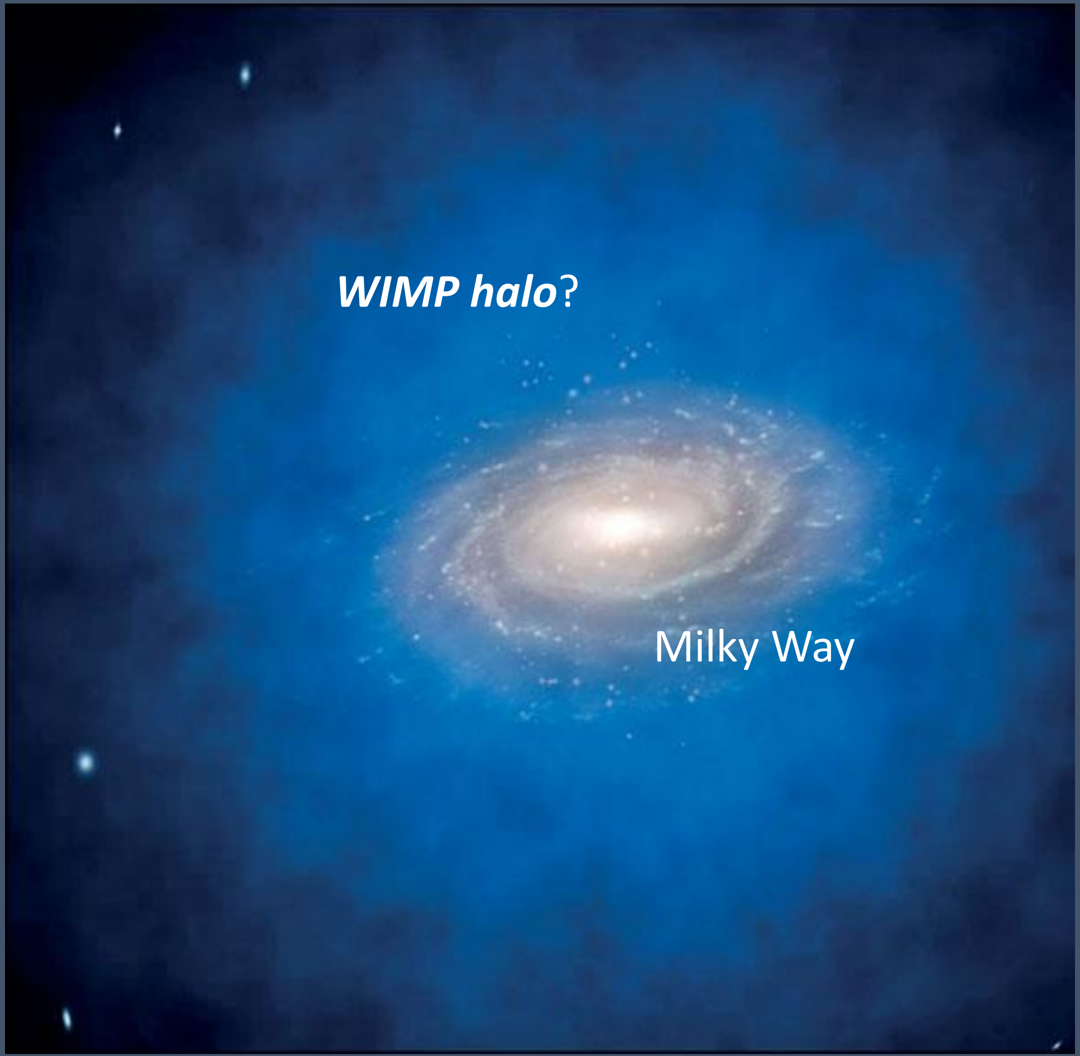
Gas TPC
- Head/ tail measurable
- 1d, 2d or 3d
- Independent energy/ direction measurement

Crystal defects
- 3d track topology
- Head/ tail measurable

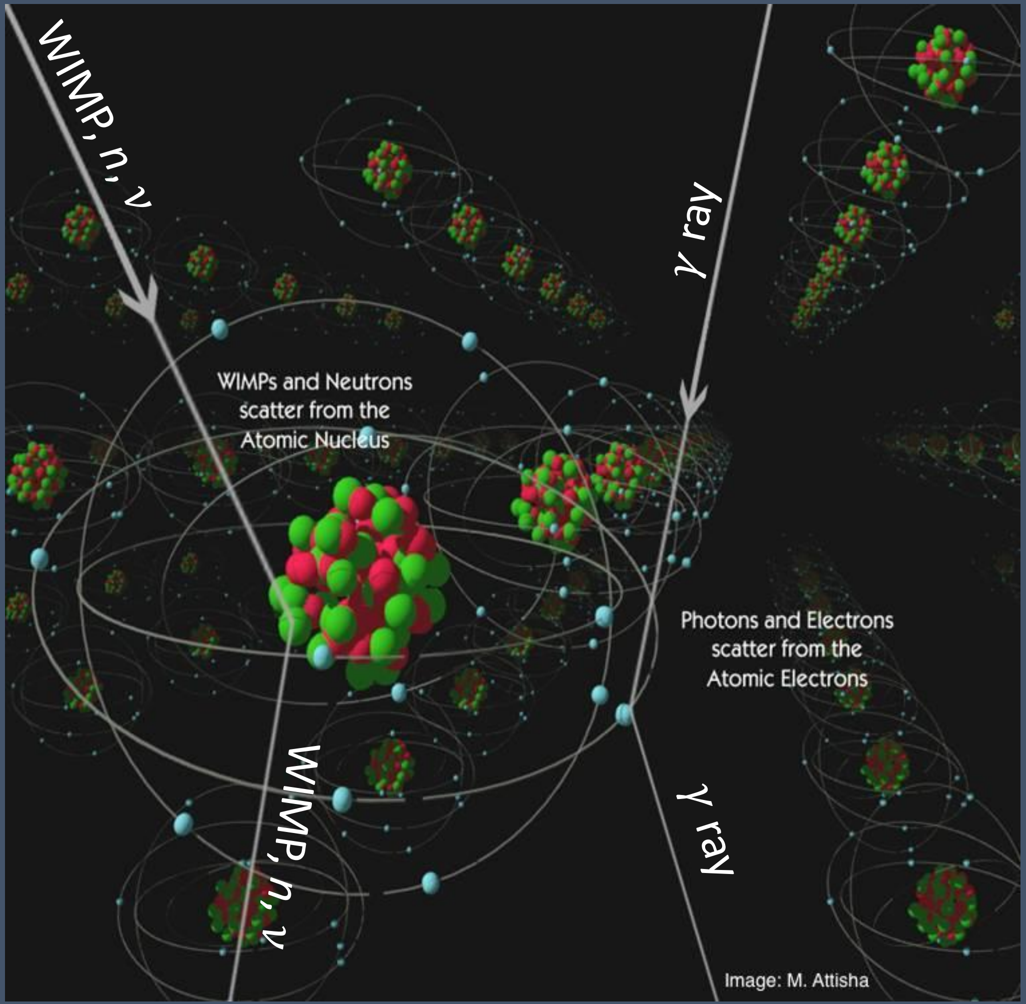
A Combined Dark Matter & Neutrino Observatory

Do we live in a *WIMP halo*?

- Dark Matter exists
  - Overwhelming evidence at distance scales from Milky Way to visible universe
  - All gravitational
- WIMPs are one hypothesis
- Direct DM Detection seeks to answer
  - Does the local Milky Way DM halo contain WIMP-like particles?
  - What are their properties?
  - What is their local density and velocity distribution ?



Challenges in Direct DM Detection



- Huge detectors
- Stringent requirements on
  - Shielding
  - Radiopurity
  - Background rejection

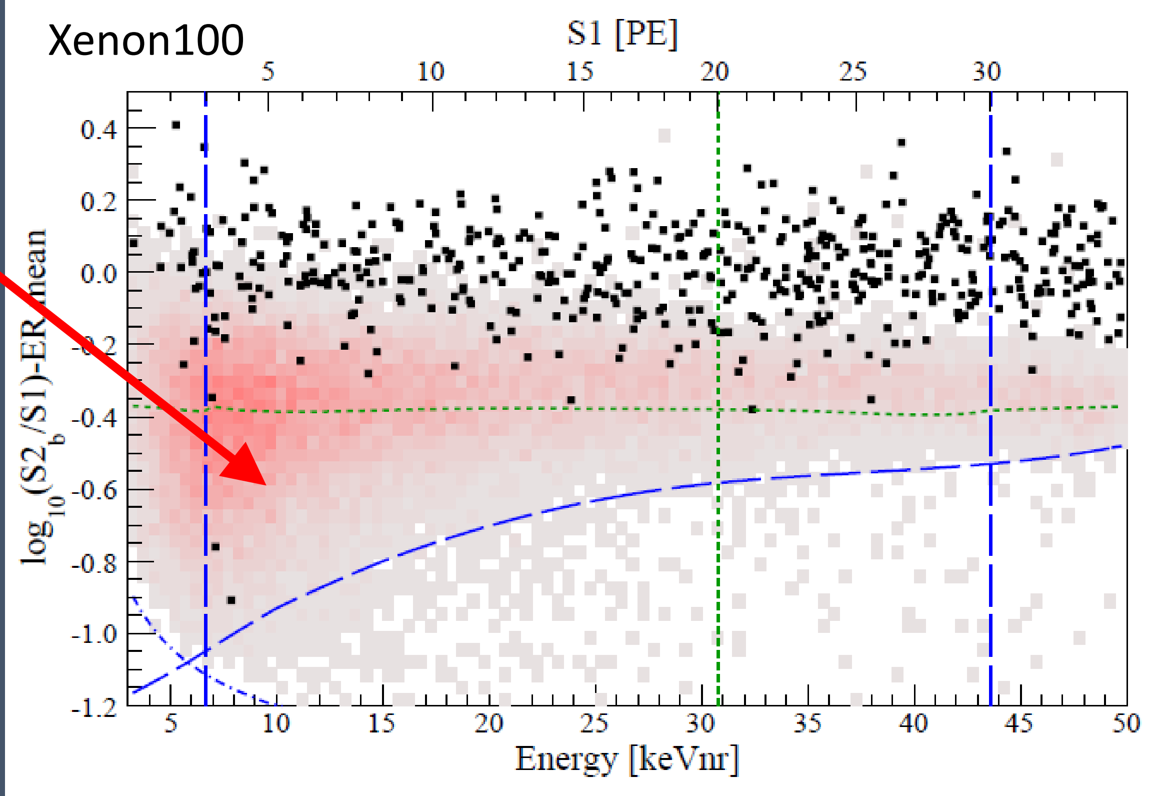
Challenges in Direct Detection

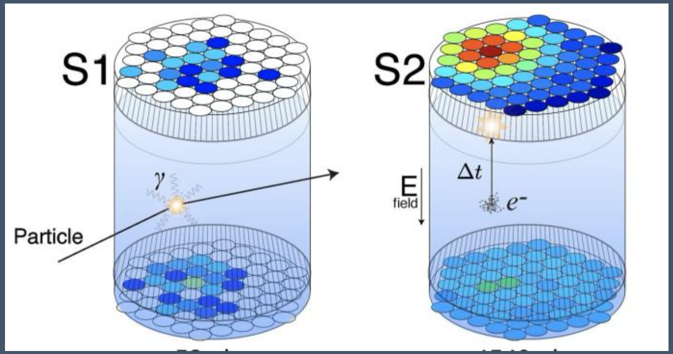
- G2 experiments will probe cross-sections within factor 10-100 of the neutrino floor for m > 1 GeV/c^2
- Challenges to further progress in this mass range
  - Irreducible neutrino background
  - Lack of particle ID in ionization-only experiments for E ~< 10 keV
  - Calibrations at lowest recoil energies
  - Ever stricter requirements on radio purity and background rejection
  - Lingering controversial signals from DAMA
  - Lack of clear discovery signal / way to demonstrate DM signal is galactic

- Directional Recoil Detection can help address most these challenges!

Non-directional WIMP search

- Observable: excess count rate over predicted BG in signal region
- Requires ultra-clean detectors & precise understanding of remaining backgrounds
- Single-scattering neutrons produce identical events to WIMPs





The WIMP Wind

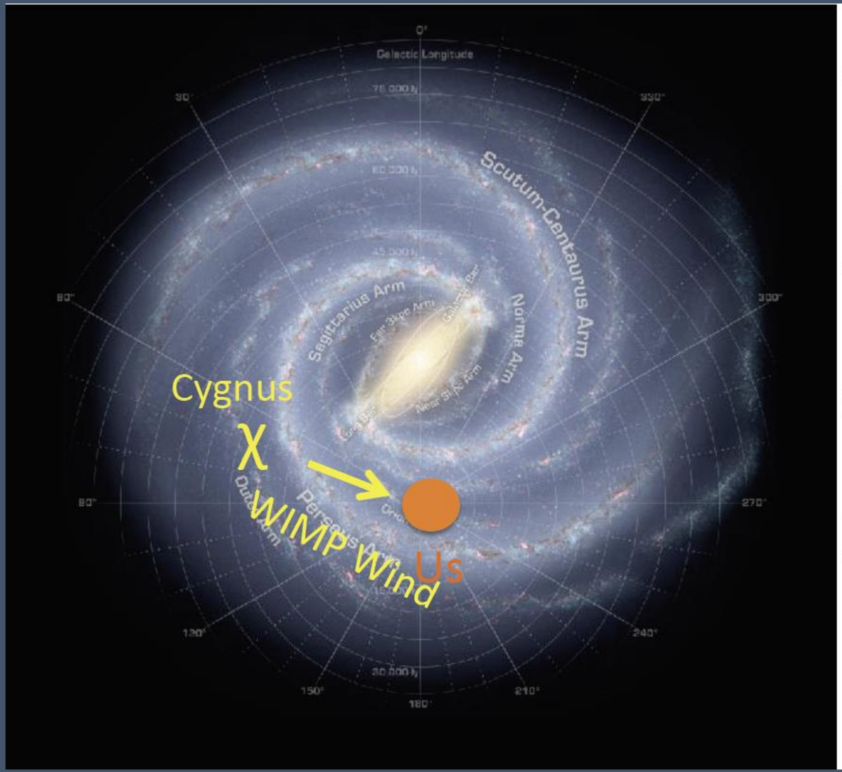
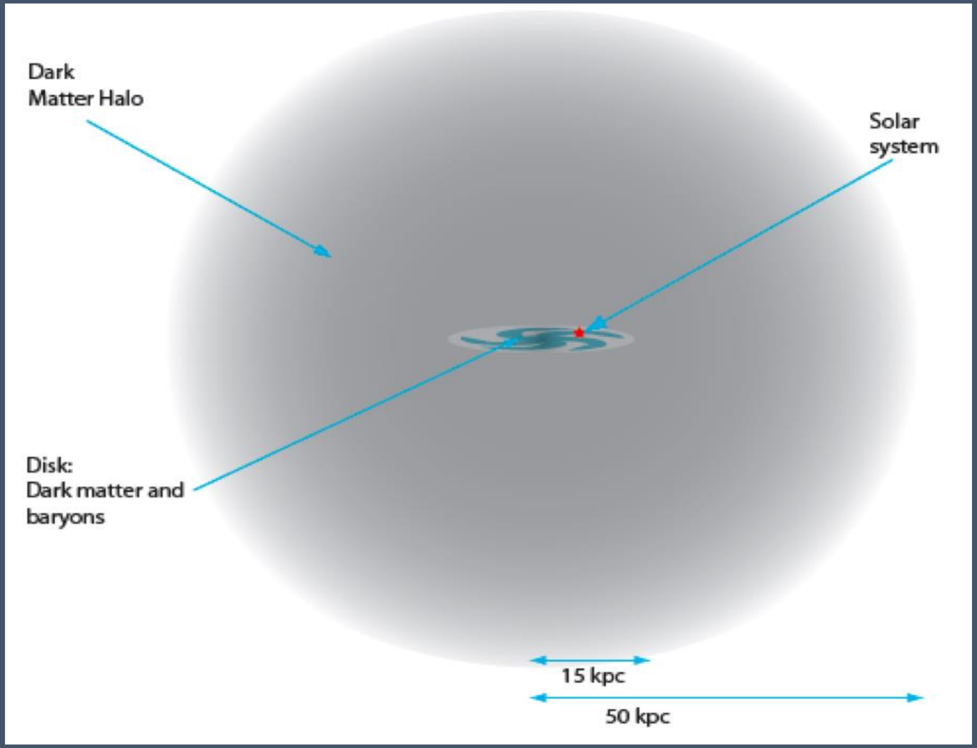
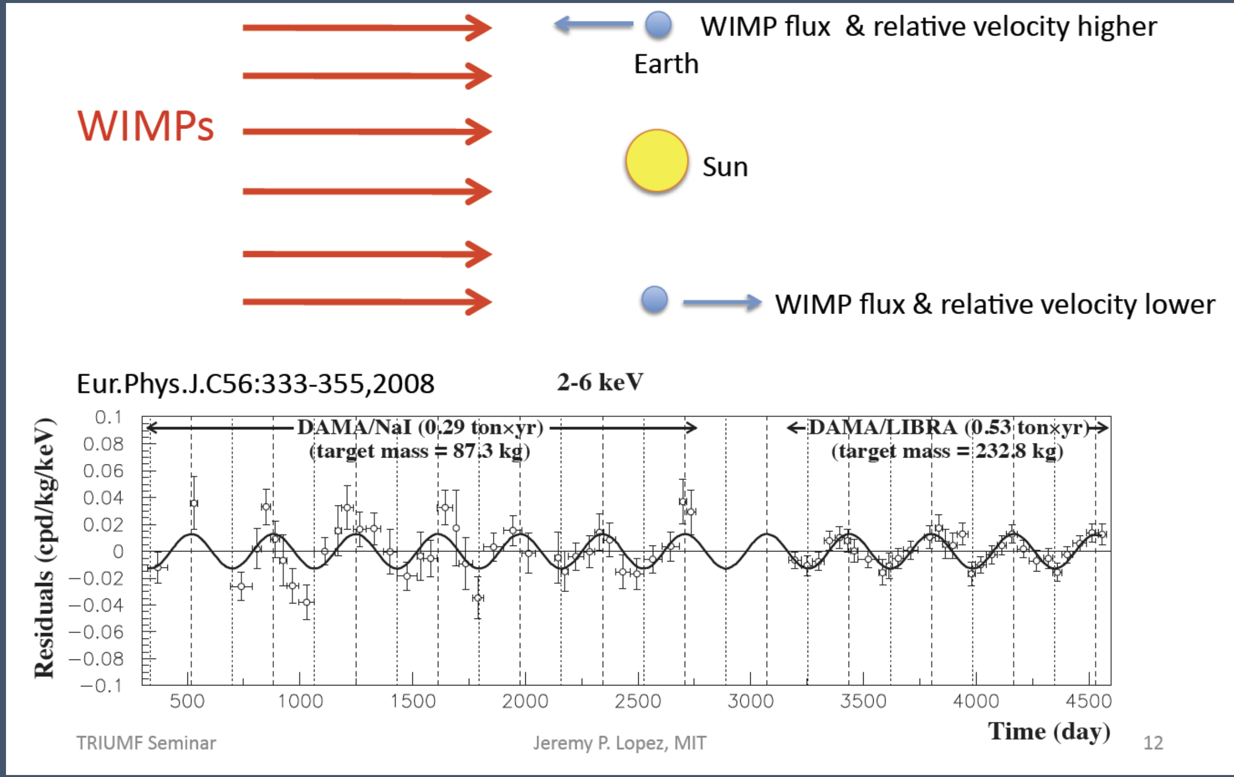


Image: NASA/Adler/U. Chicago/Wesleyan/JPL-Caltech



- ~220 km / s
- blows from CYGNUS
- provides two additional WIMP signatures…

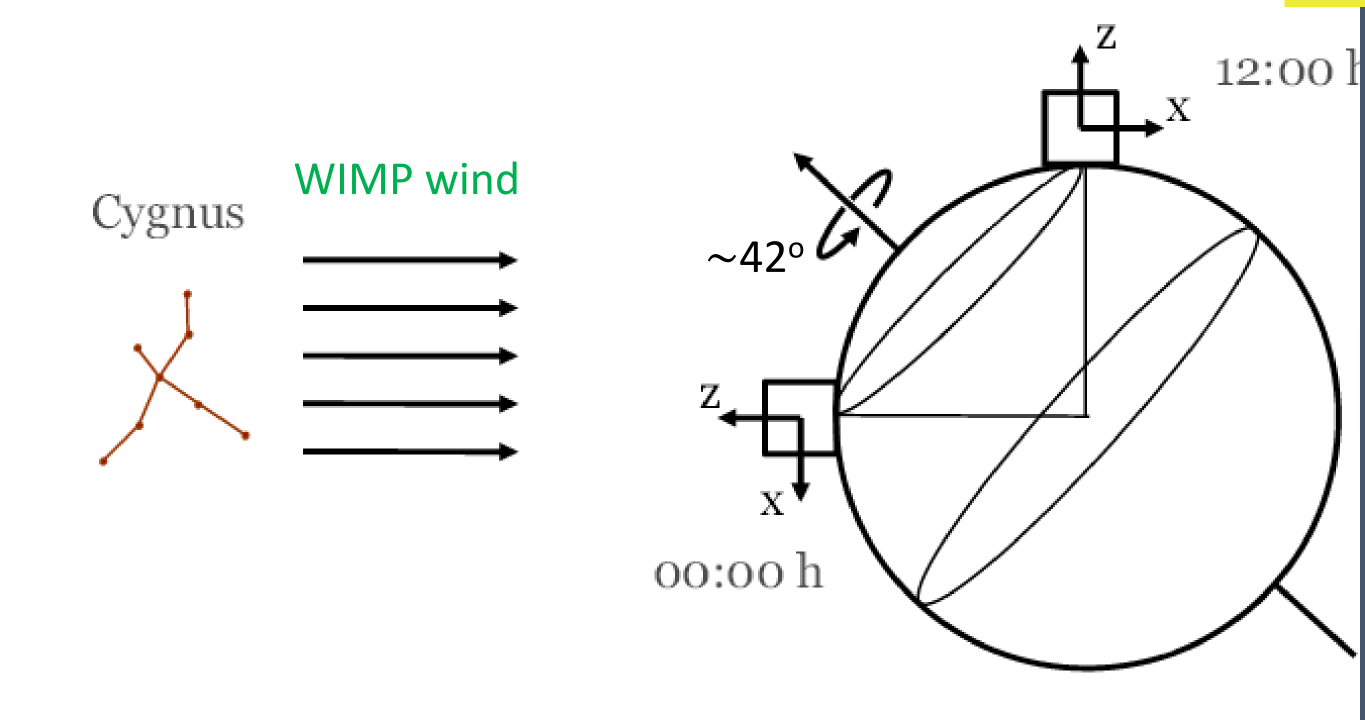
Annual Rate Modulation



- ***due to motion of earth around sun***
- ***%-level effect***
- requires thousands of signal events, and %-level control of BGs and gain

Diurnal (Daily) Directional Oscillation

Spergel PRD 37,1353 (1988)



- oscillation of the mean recoil direction, due to rotation of earth
- order 1 effect
- oscillation period = sidereal day ≠ solar day
- no known background with this signature

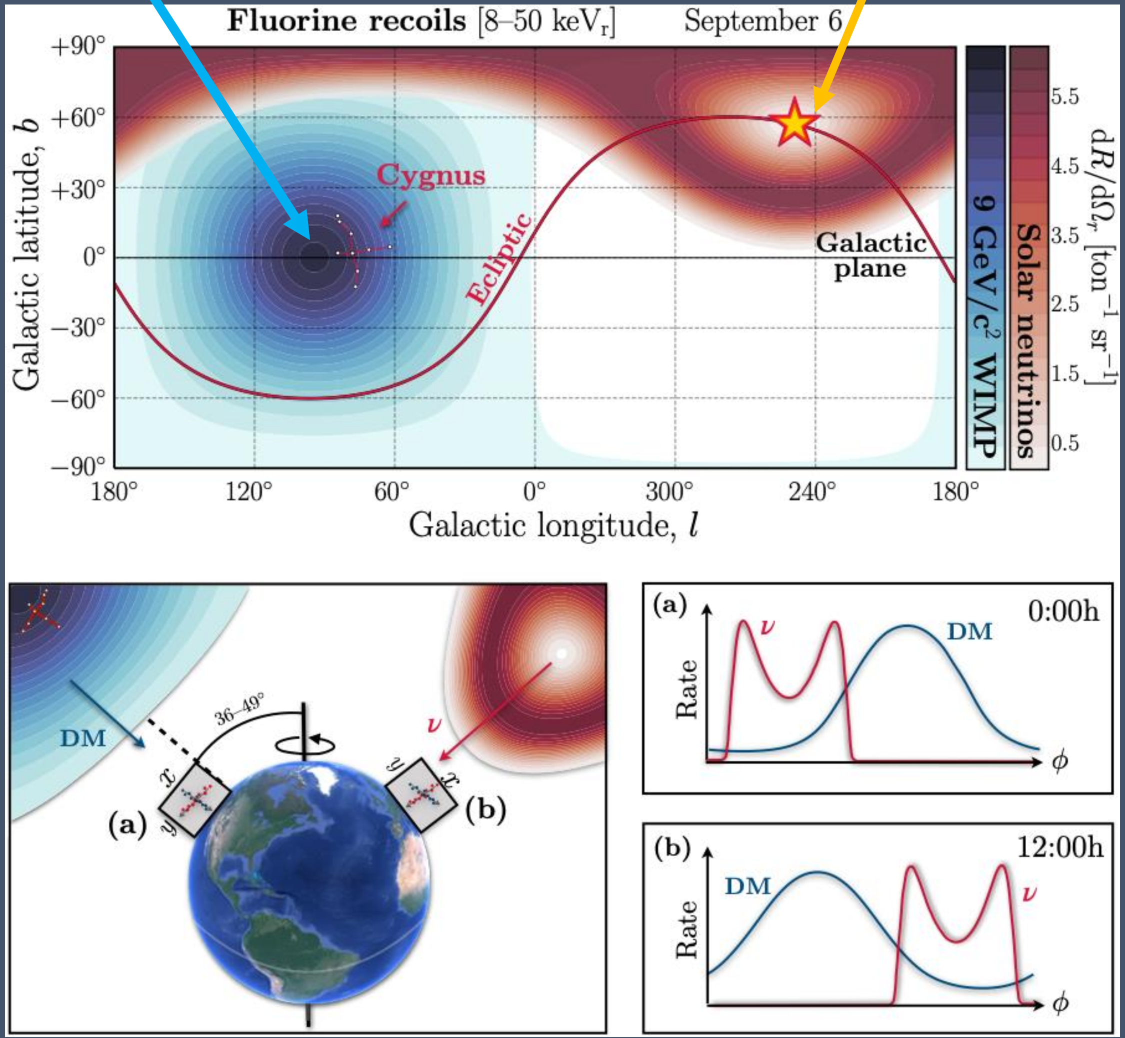
The Power of Directionality

arxiv:2102.04596

WIMP wind, approx. from CYGNUS

Neutrinos from the sun

- Diurnal directional oscillation
  ⬄ dipole in galactic coordinates
- Can 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 → penetrate neutrino floor
- Neutrino physics
- Ideal case: 3D-vector-direction + energy measured for each event
  - Fewest events for DM discovery
  - Enables Neutrino spectroscopy

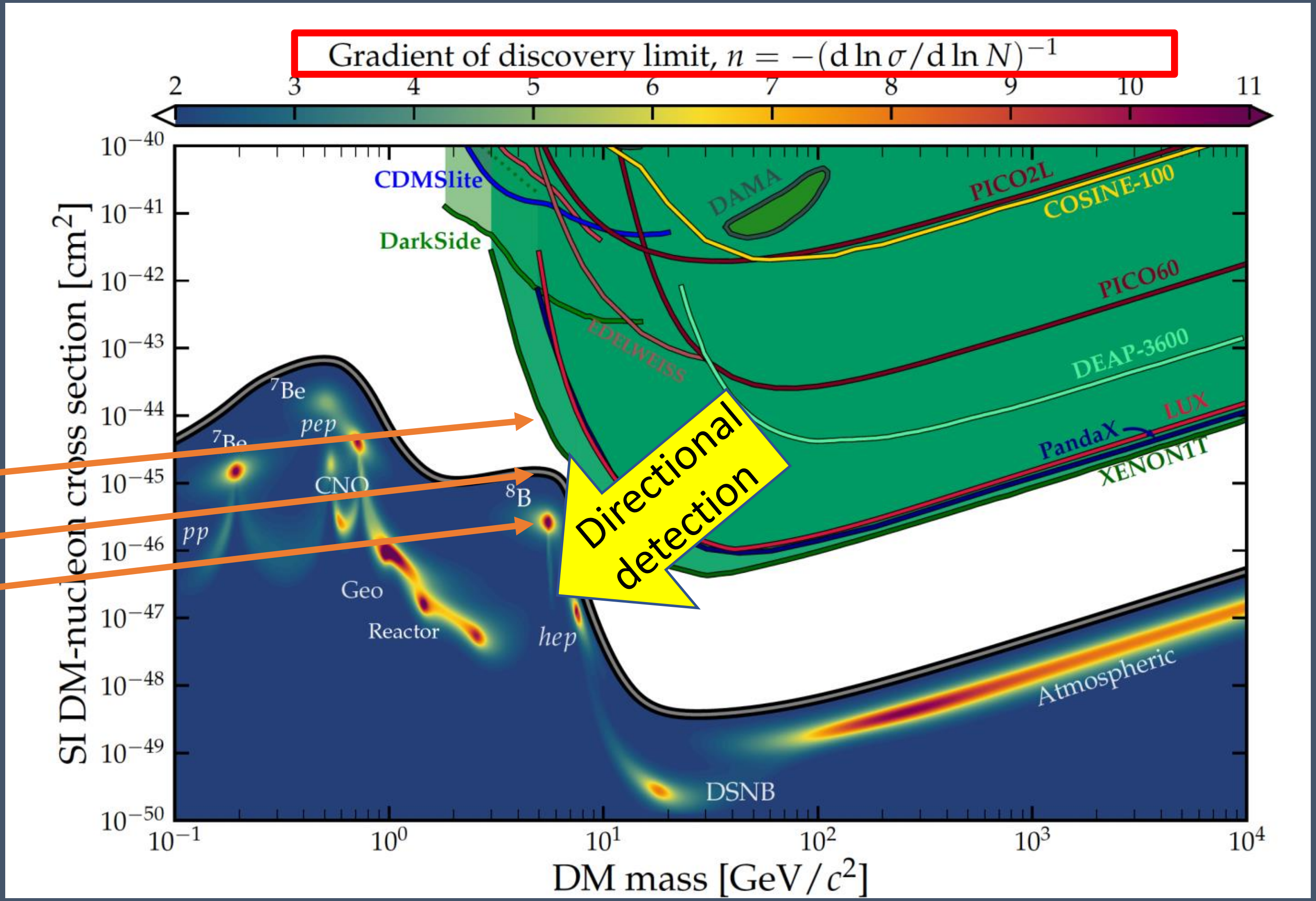


Directionality: highly beneficial…
…but experimentally challenging!

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

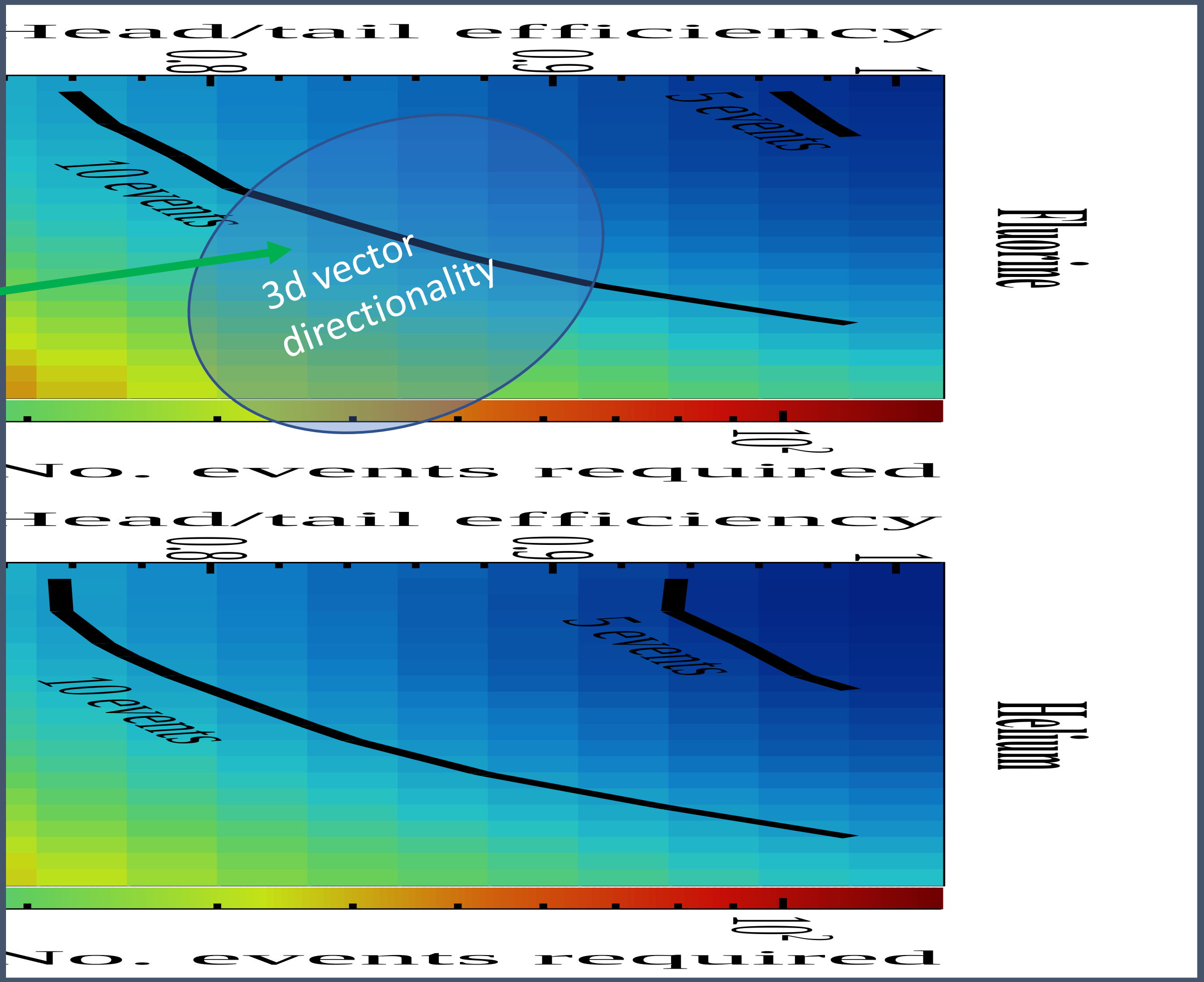
Detector Performance Requirements

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

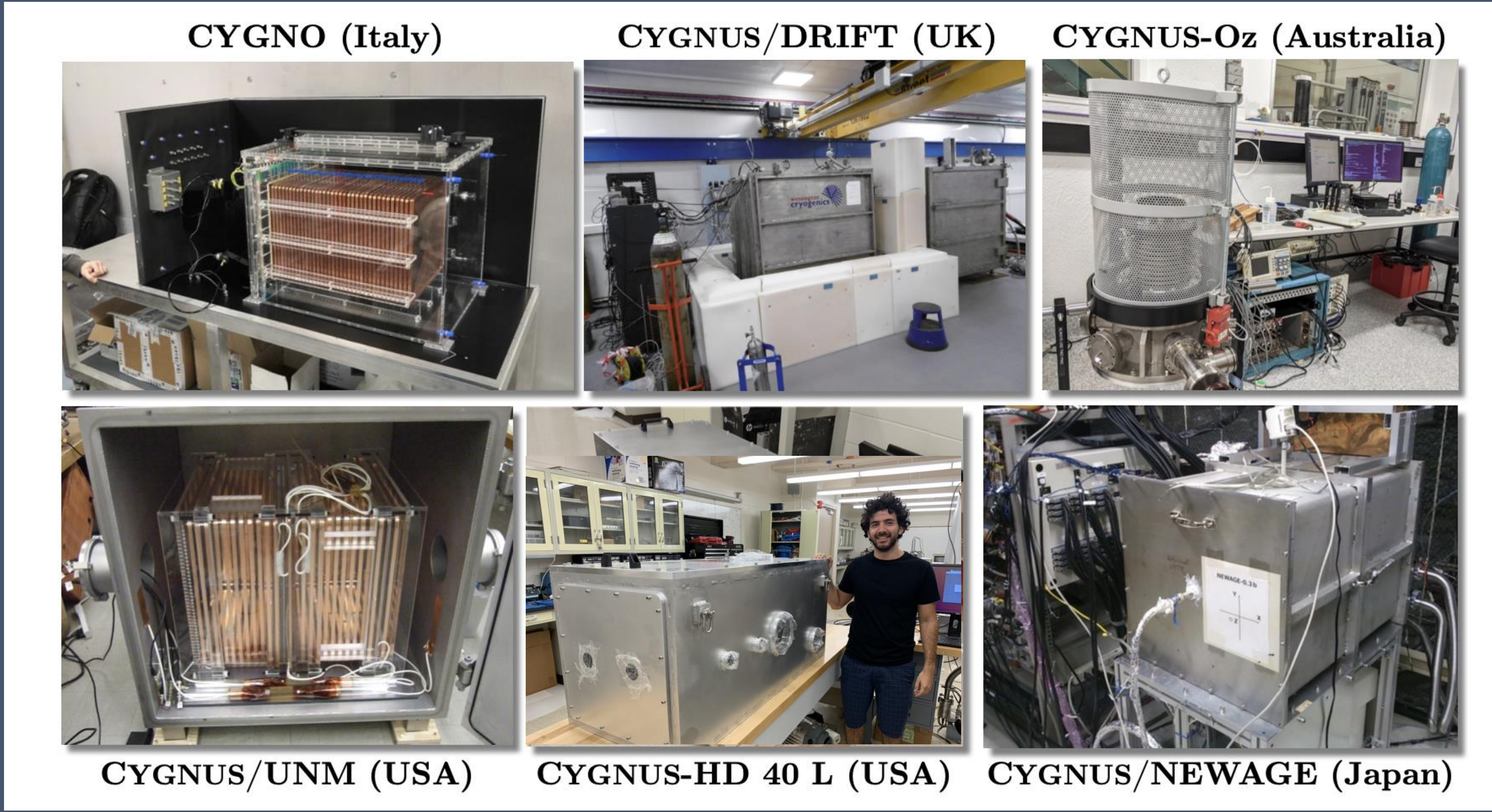
Recoil imaging in gas TPCs has performance approaching this, hence a main experimental approach being pursued



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

Assumptions: m_χ = 10 GeV, He:SF_6 gas

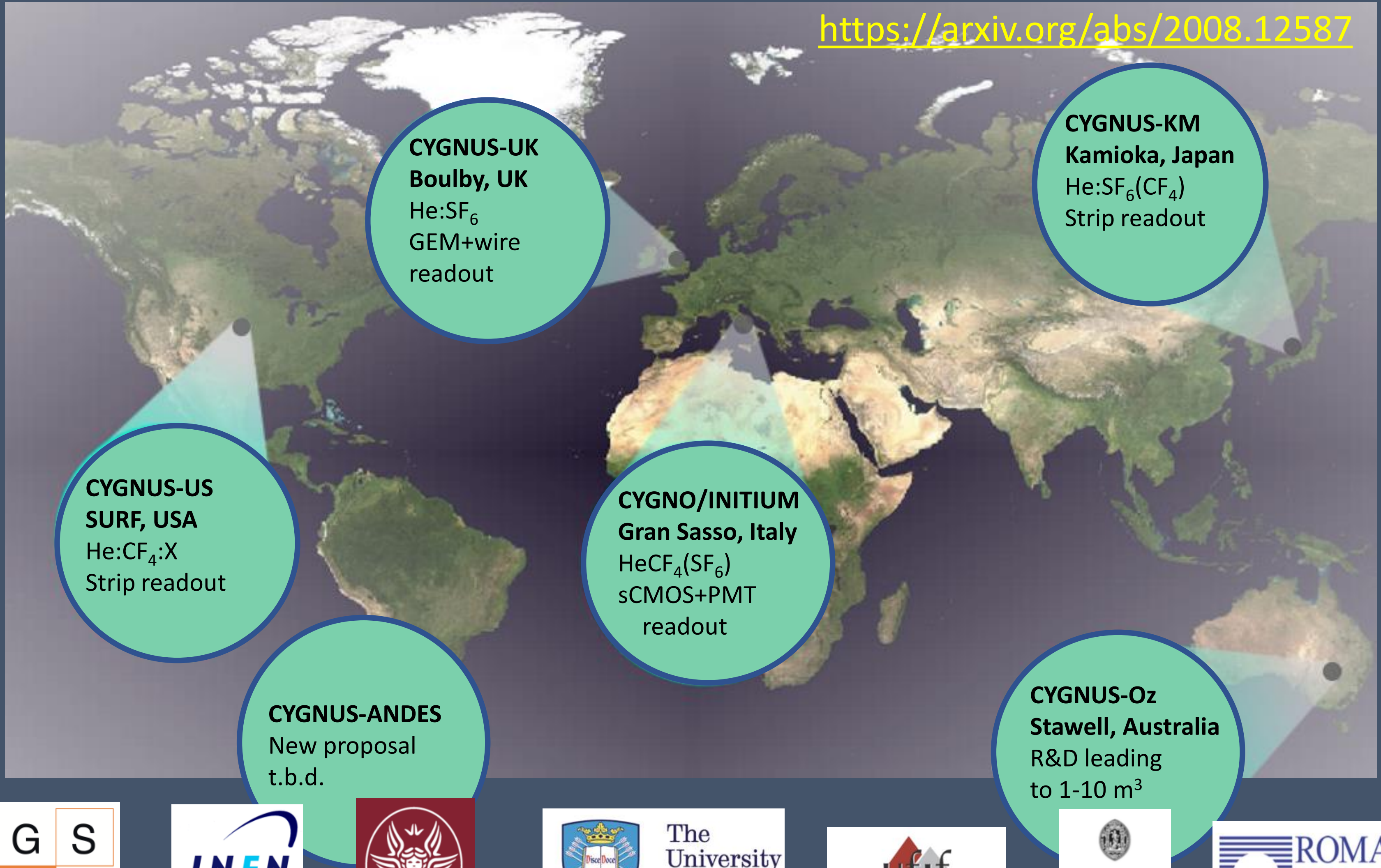
Prototypes and Experiments: CYGNUS



Most gas TPC efforts now collaborating closely as CYGNUS (not all efforts shown here)

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
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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
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The University of Sydney
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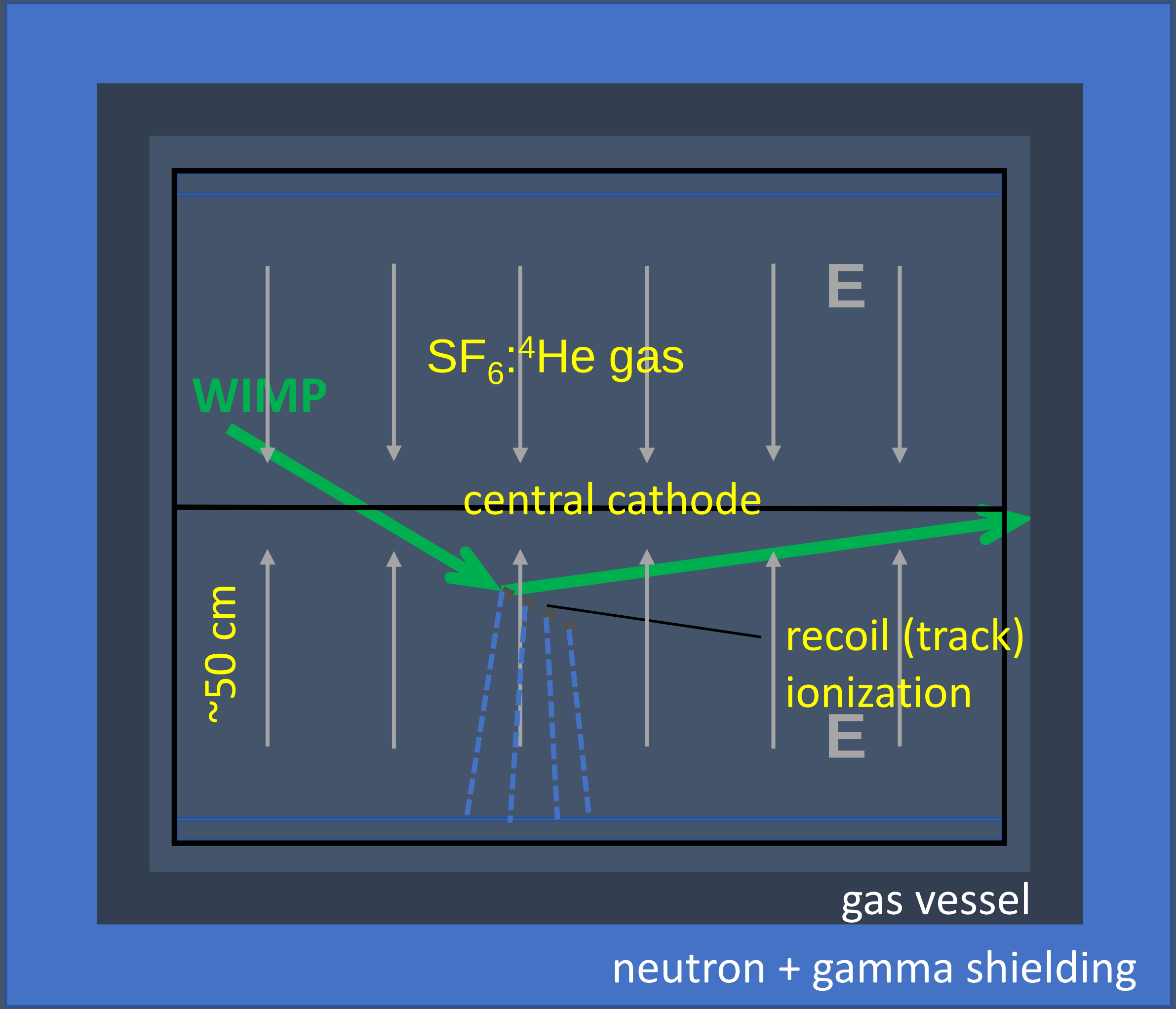
The University Of Sheffield.
ufjf Universidade Federal de Juiz de Fora
Universidade de Coimbra
Roma Tre Università degli Studi
ENEA
CBPF
UNICAMP

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:^{4}He:X, p<=1 atm
  - Reduced diffusion via negative Ion drift (SF_6 gas)
- Gas mixture 2:
  - CF_4:^{4}He: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

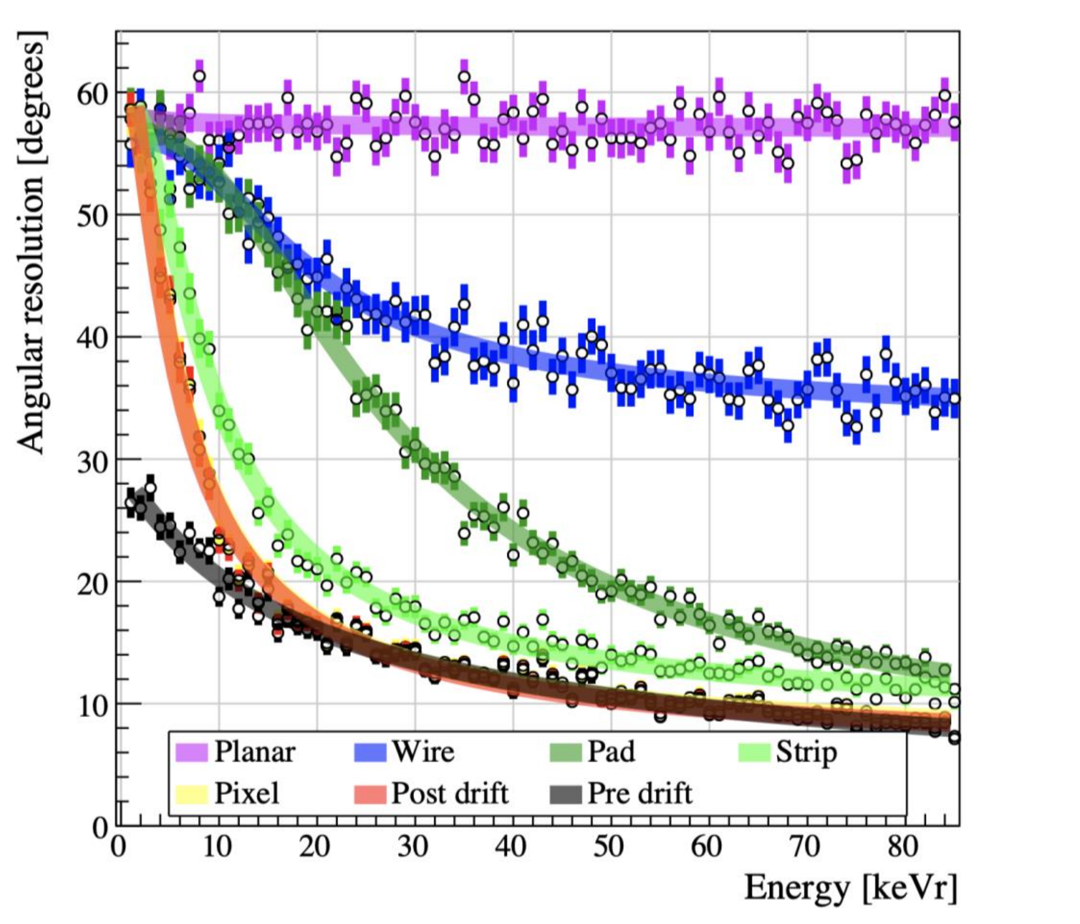


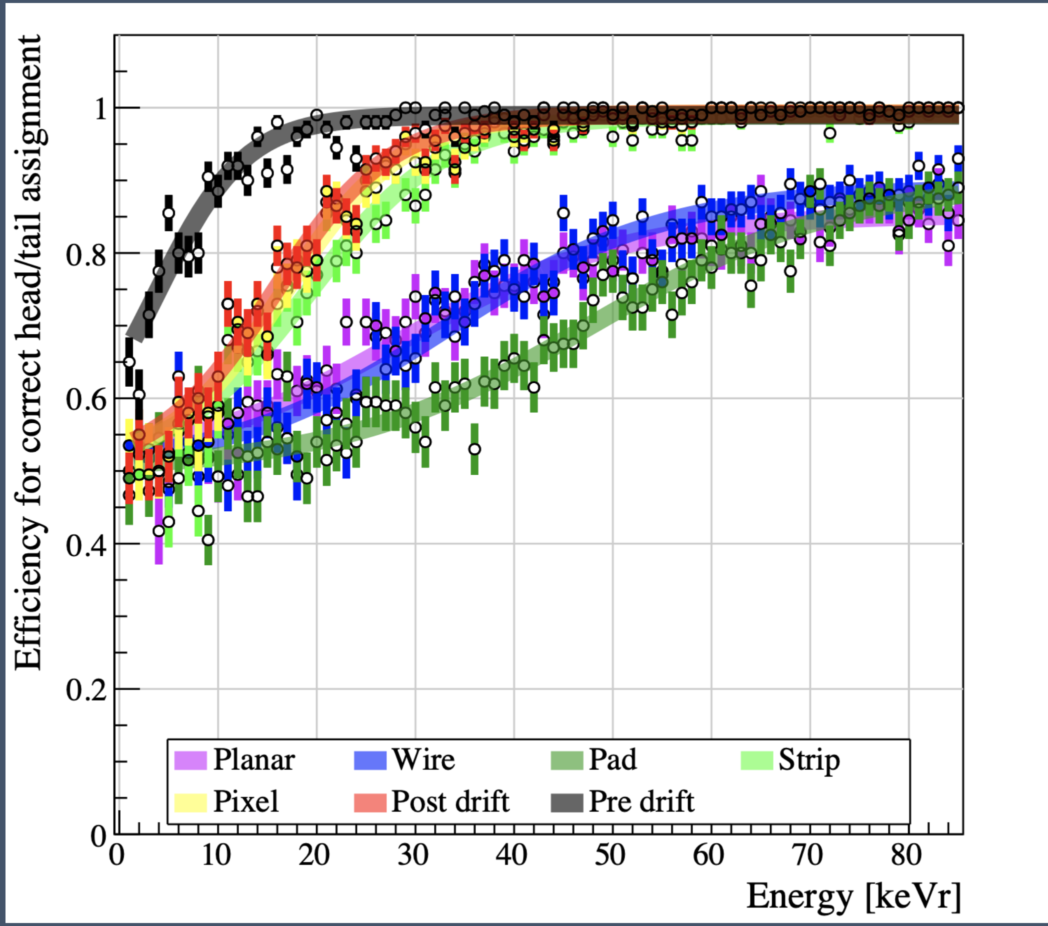
Both electronic and optical charge readout being investigated.

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

Comparison of TPC charge readout technologies

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





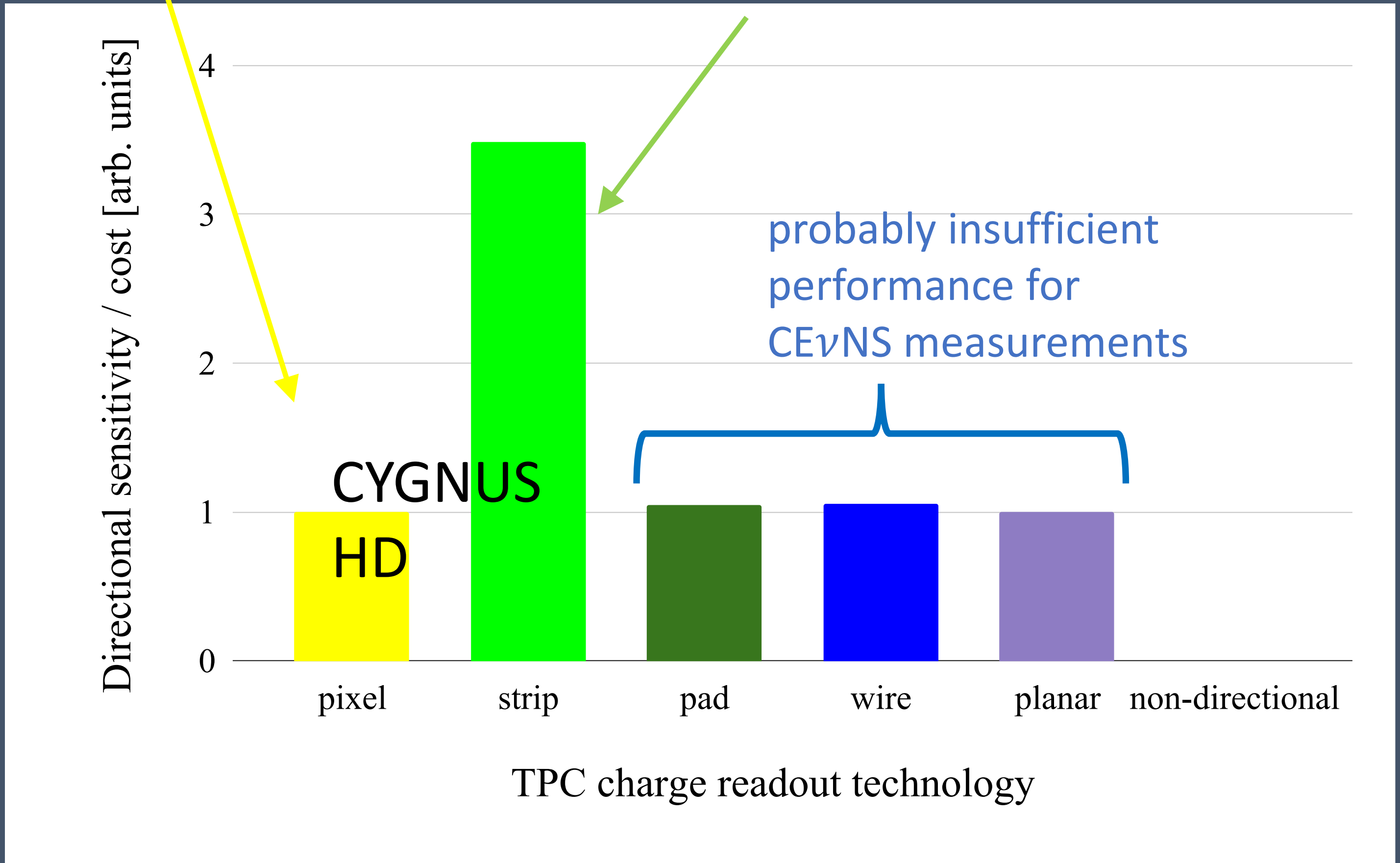
Pixel readout extracts the entire directional information left after diffusion (red and yellow curves overlap fully)
Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost

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!

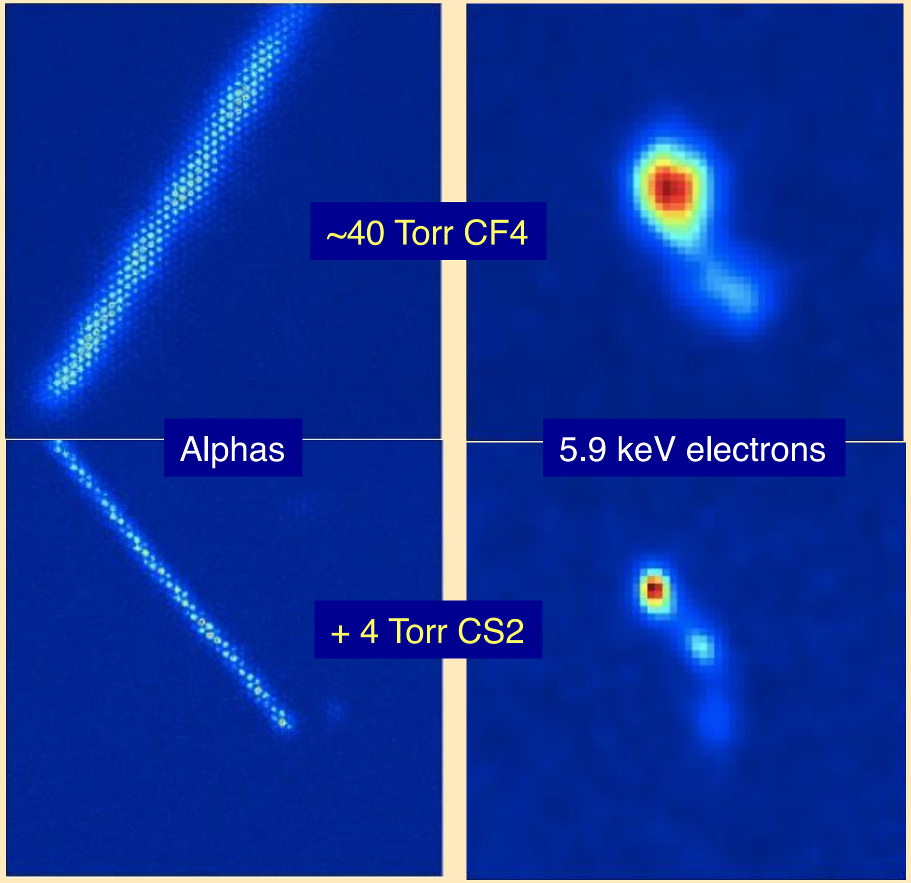


https://arxiv.org/abs/2008.12587

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

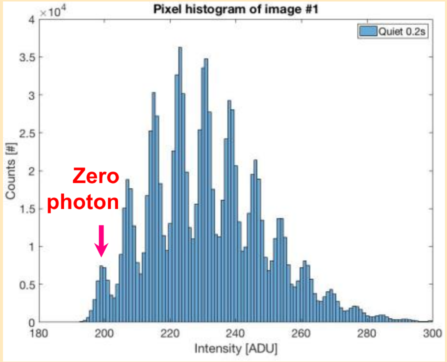
Negative-ion OTPC



D. Loomba, UNM

Hamamatsu ORCA-Quest

- Photon Resolving Power:

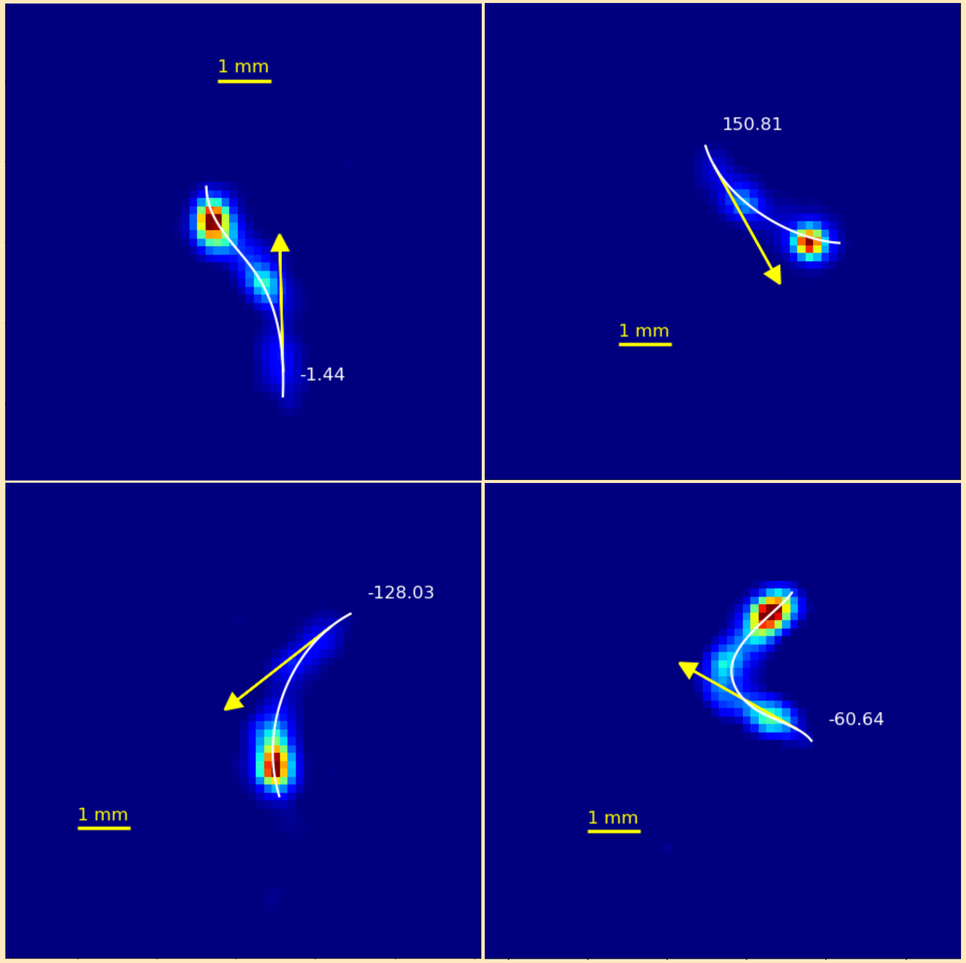


Radiment Glass-GEMs

- 270 micron pitch

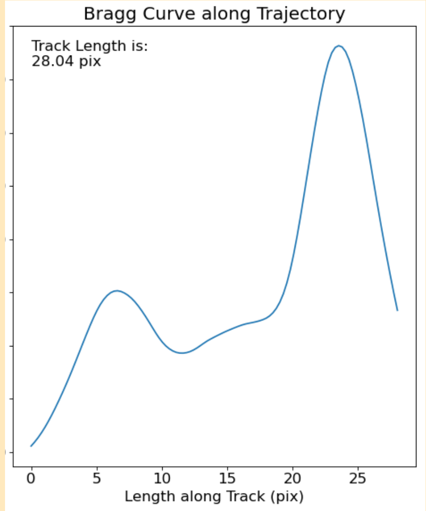
~45 Torr CF_4 + x Torr CS_2

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):



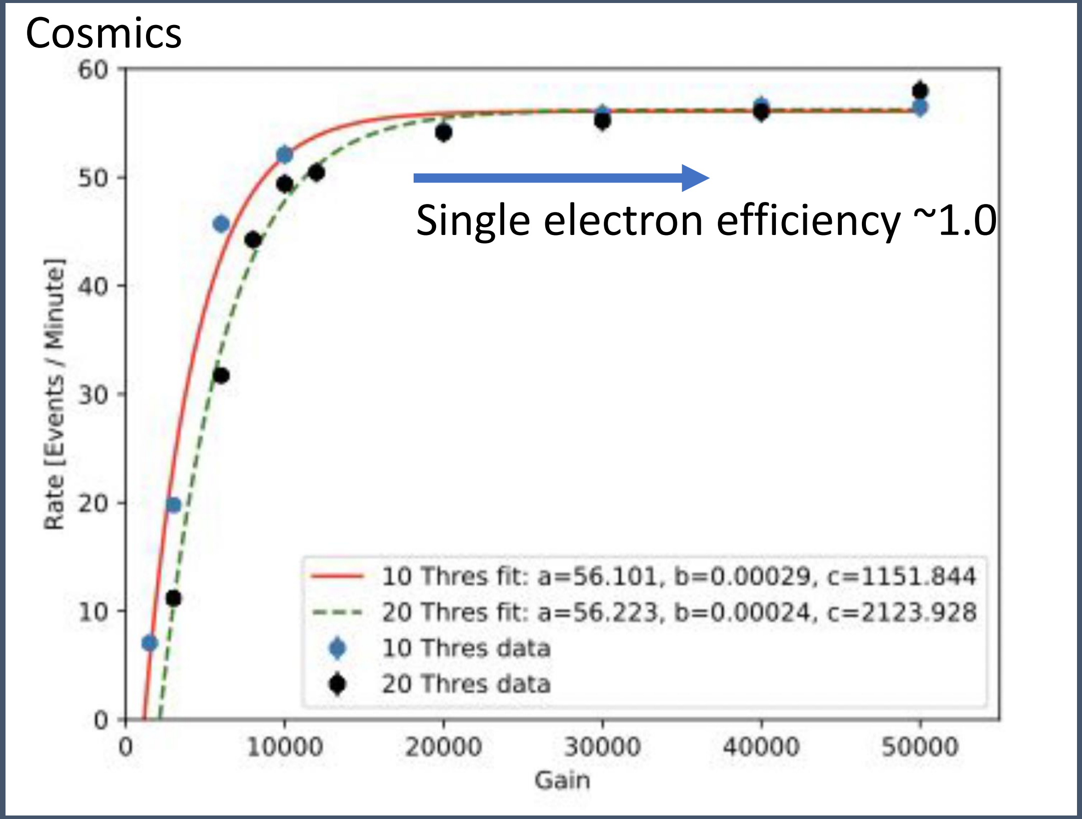
D. Loomba, UNM

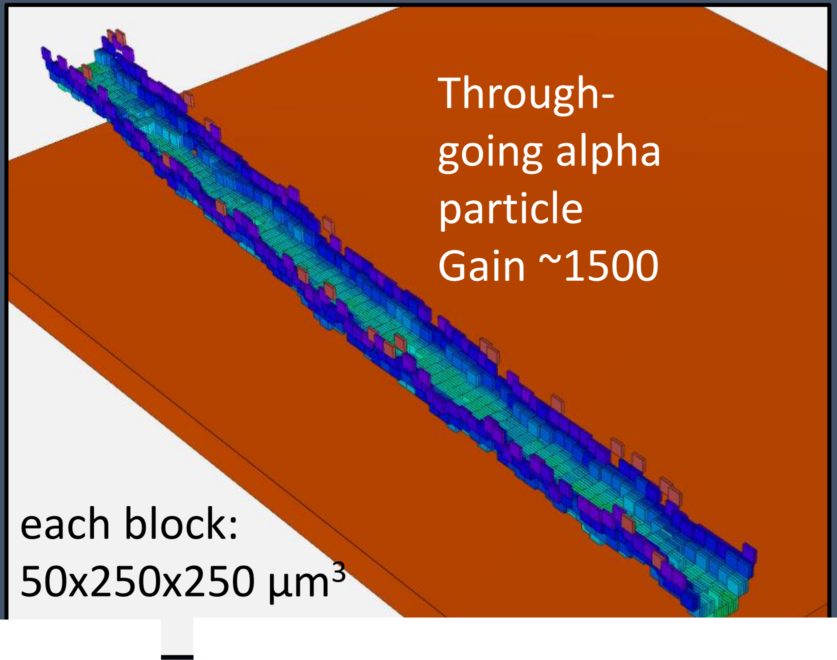
Directional detection of 5.9 keV electron recoils!

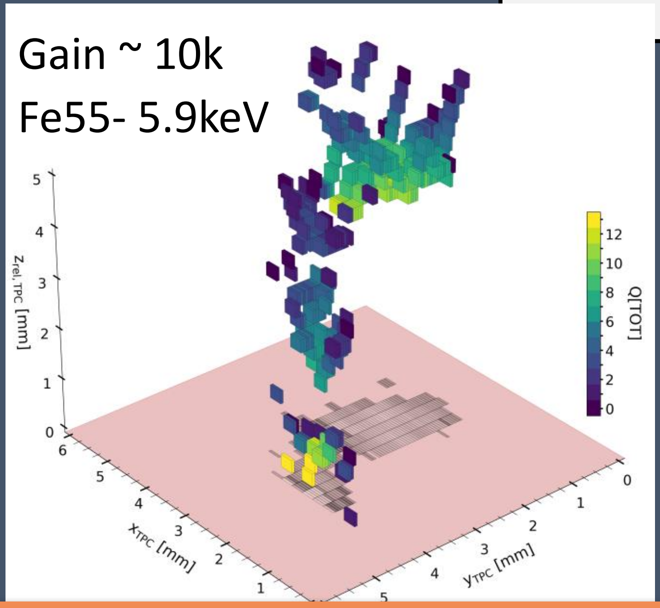
3D single-electron sensitivity: Charge Readout via GEMs and CMOS pixel ASICs

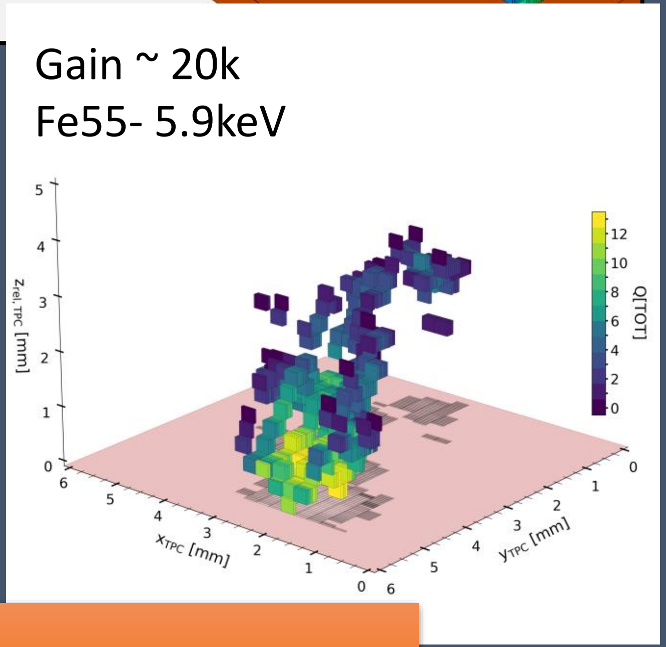
University of Hawai'i Mānoa

Cosmic ray rate



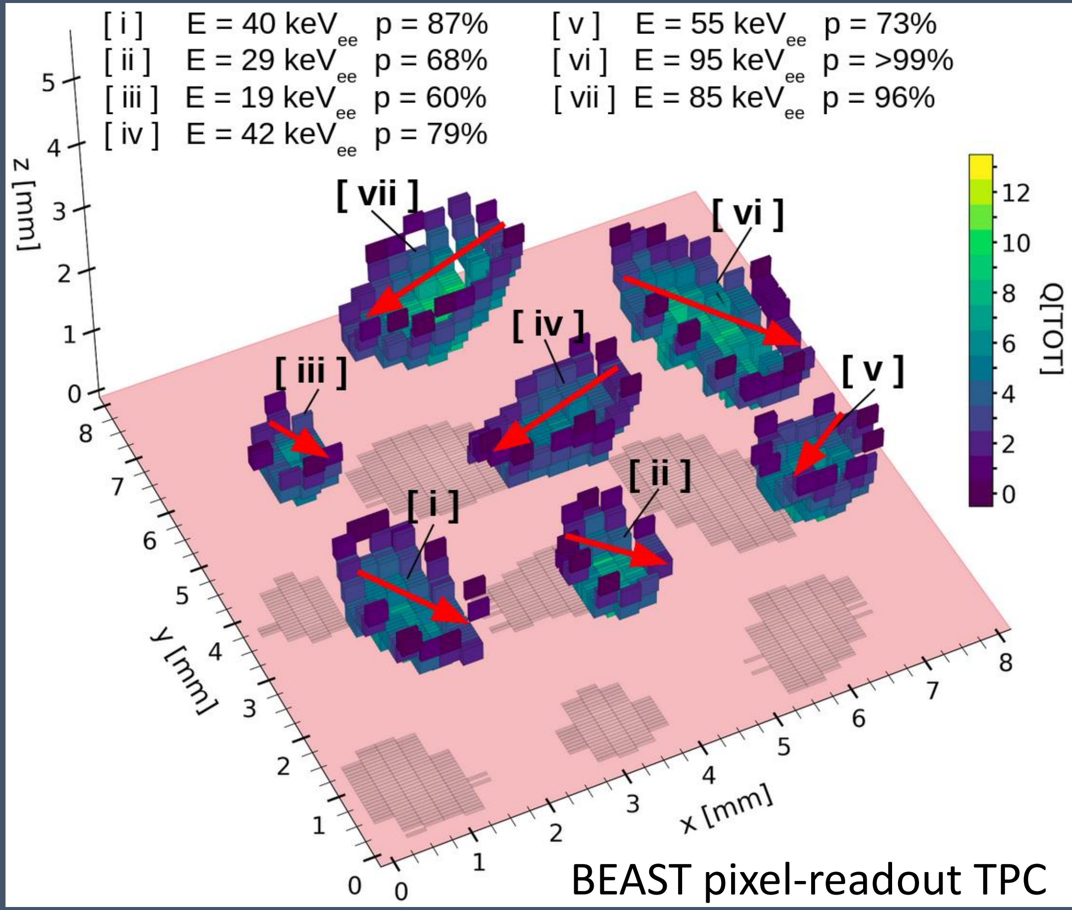




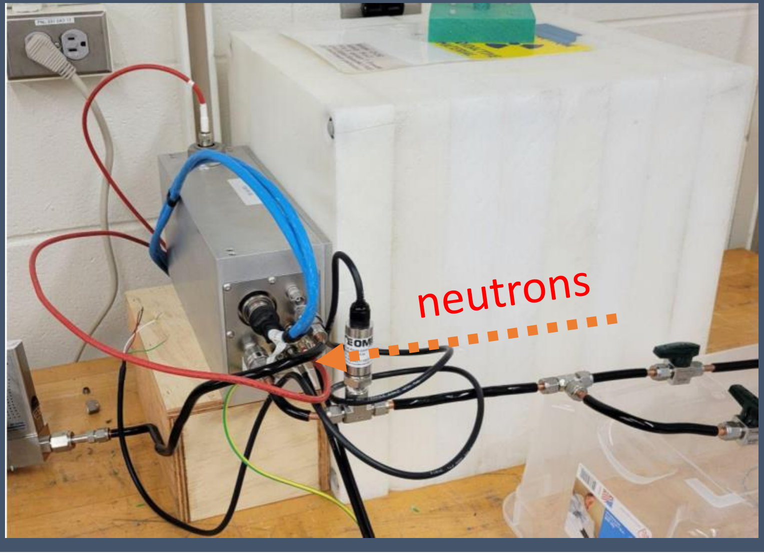


- In high-gain mode, even single electrons of ionization easily detected
- Energy threshold is ~30 eVee, w/ virtually zero noise-occupancy

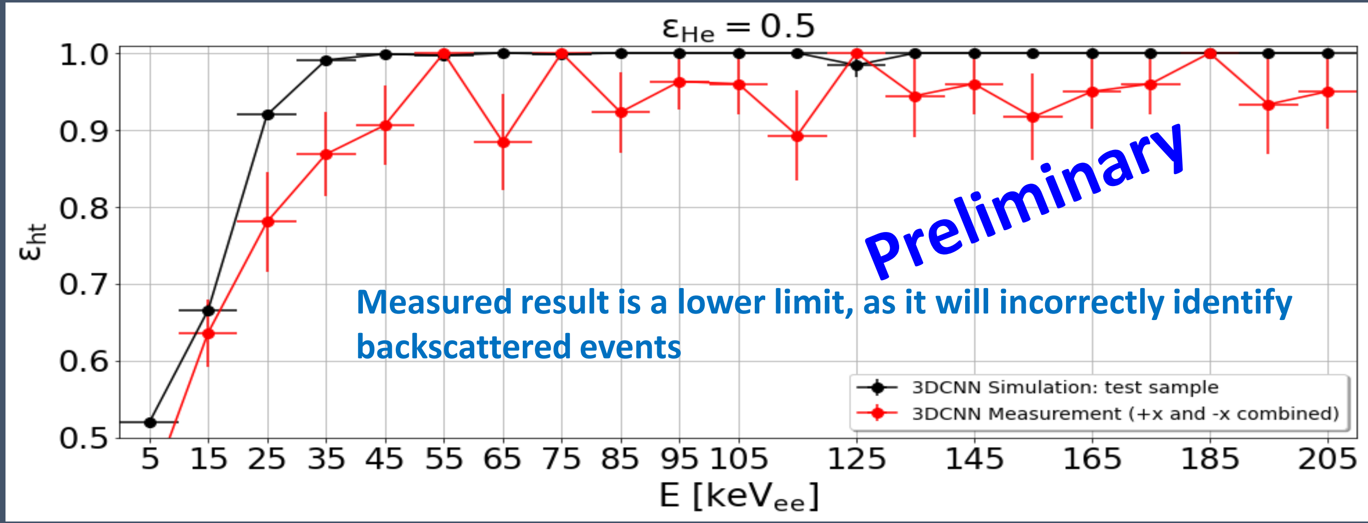
Event-level head/tail via Machine Vision: low gain



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



Jeff Schueler



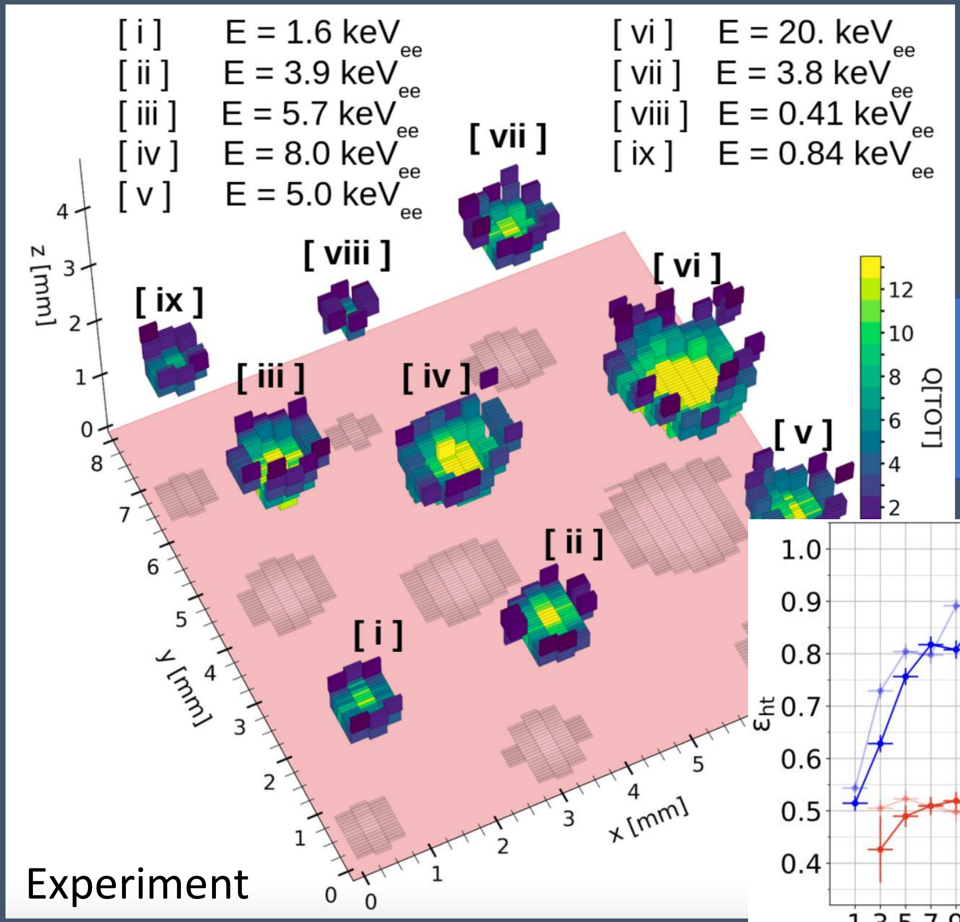
First experimental demonstration of significant *event-level* head/tail sensitivity below 20 keV (still at *low* detector gain!) See talk today by Jeff Schueler.

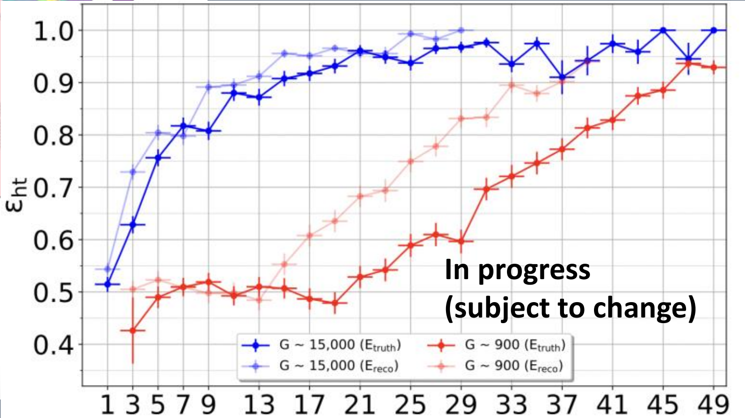
High gain operation: keV scale directionality

In progress and highly preliminary!

Have:

3D single electron efficiency ~1.0



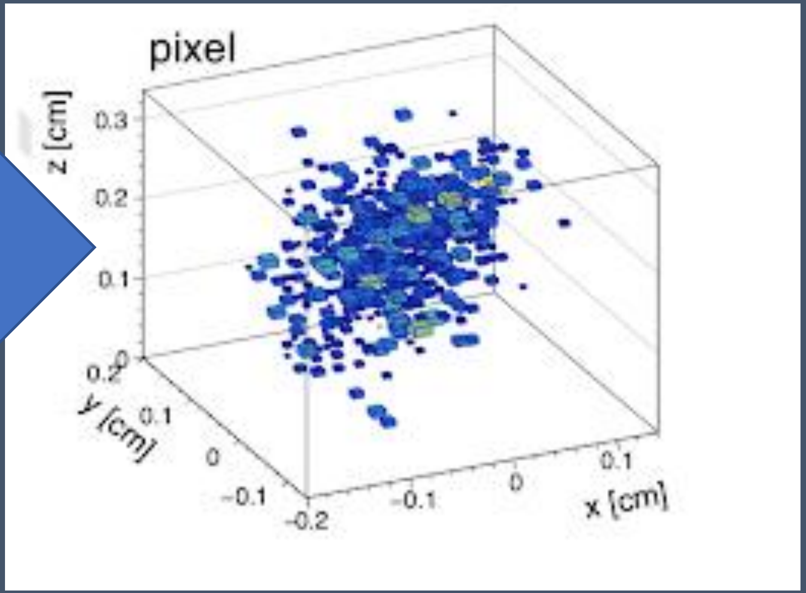


[keVee]

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

Want:

3D single electron *counting*



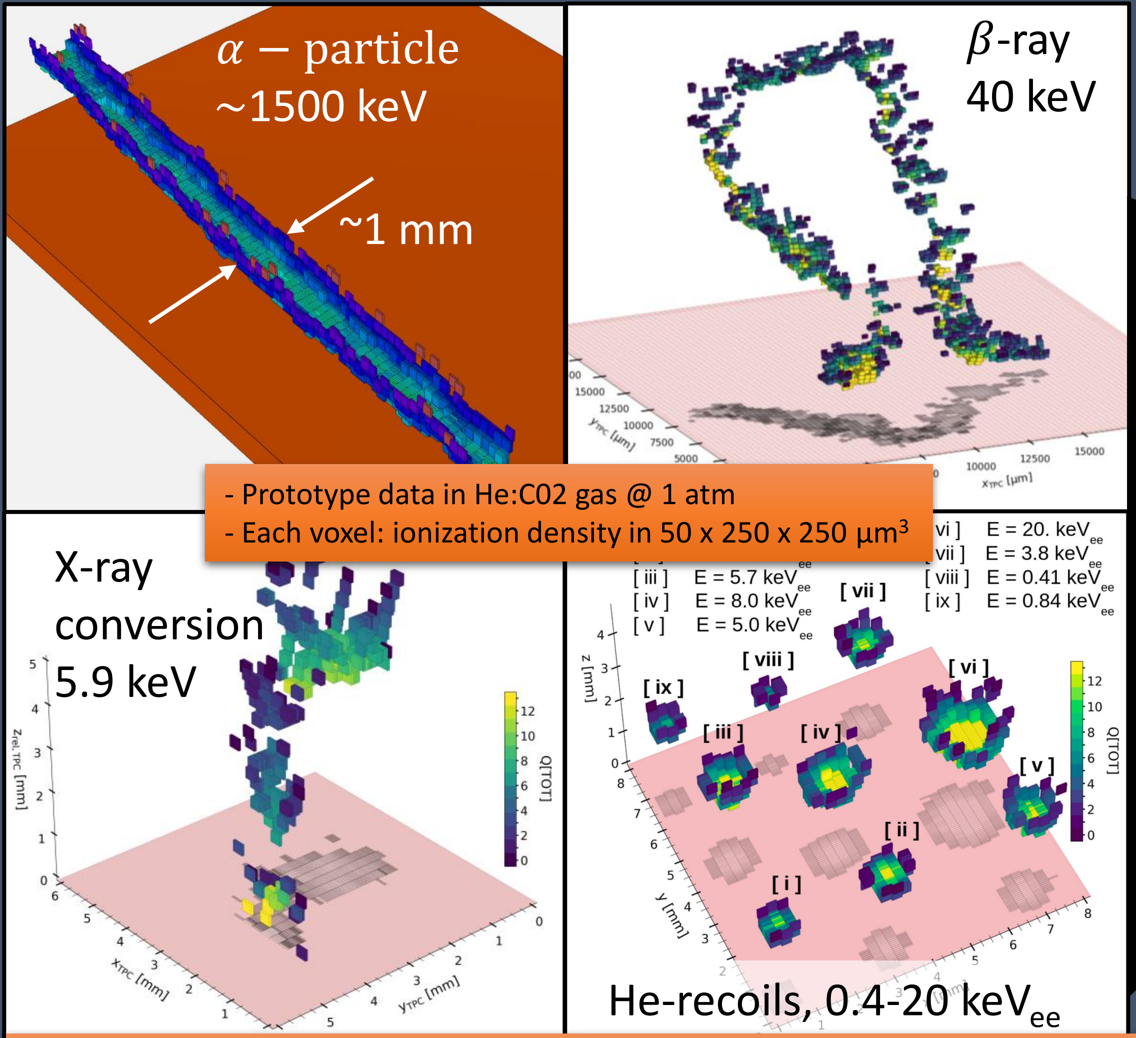
Directionality at 1keV scale

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.

Personal Outlook

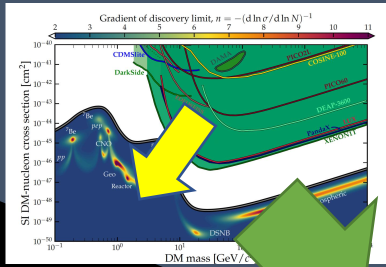
Vision or madness? DUNE-scale gas TPC w/ 30 eV threshold

Sven Vahsen (Univ. of Hawaii) for CYGNUS

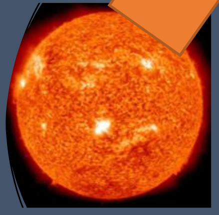


Topological & directional reconstruction of low-energy nuclear and electronic recoils in gas enables new experiments

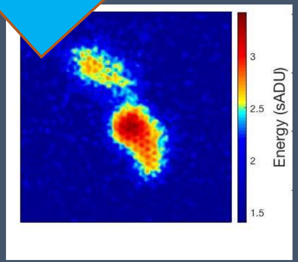
Distinguish dark matter wind from solar-υ → probe υ fog



Search for BSM neutral currents at υ sources



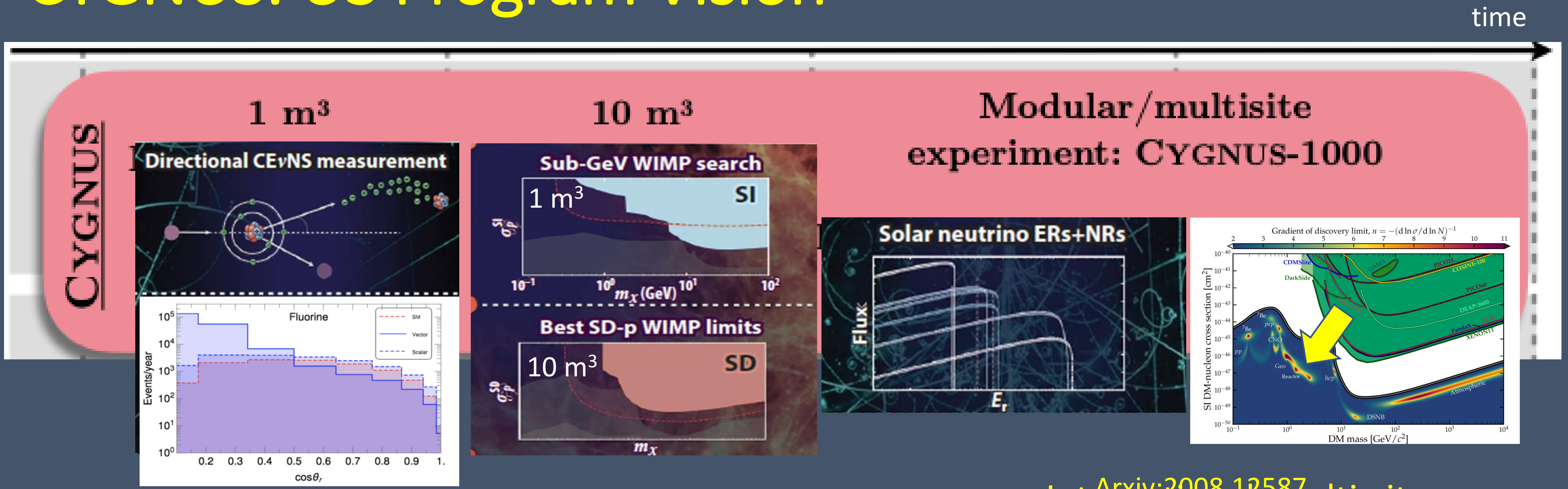
Spectroscopy of Astrophysical neutrinos



Detect Exotic final states (e.g. Migdal effect)

- Already near the fundamental performance limit – single electron counting in 3d – w/ 100 μm spatial resolution
  - in small detectors using MPGD amplification and pixel ASIC readout
- A DUNE scale experiment with 30 eV energy threshold would be game changing
  - multi-mesh strip micromegas, negative ion drift, and extreme trigger multiplexed readout schemes for cost reduction

CYGNUS: US Program Vision



SNS, Oak Ridge, TN

Directional BSM-search in CEvNS

SURF, Lead, SD

World-leading DM limits

Arxiv:2008.12587

International, multi-site

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)
- Large-scale, underground observatory (solar neutrinos + DM below neutrino floor)

Final remarks

- CYGNUS workshop has much widened scope this year
  - I only scratched the surface on what can be done with directional reccoil detection
  - I look forward to hearing your latest developments and new, exciting ideas
- We should get more organized
  - R&D collaborations: DRDs (Europe), RDCs (US) now forming. May be an opportunity for more blue sky R&D funding for our field
  - Even so, it may help us formalize the CYGNUS collaboration further
- To make the case for scale-up
  - We need to report clear, practical performance metrics
  - The ultimate performance metric is cost/unit-sensitivity
- Shoot for the stars!
  - Demonstrate 3d electron counting
  - Develop detailed plans for scaling up to DUNE scale: starting with >= 10 m^3 designs

BACKUP