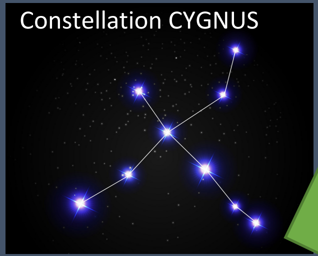
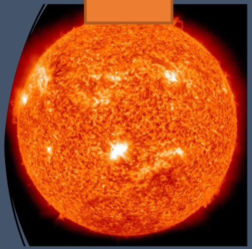
CYGNUS: Directional Neutrino and Dark Matter Detection



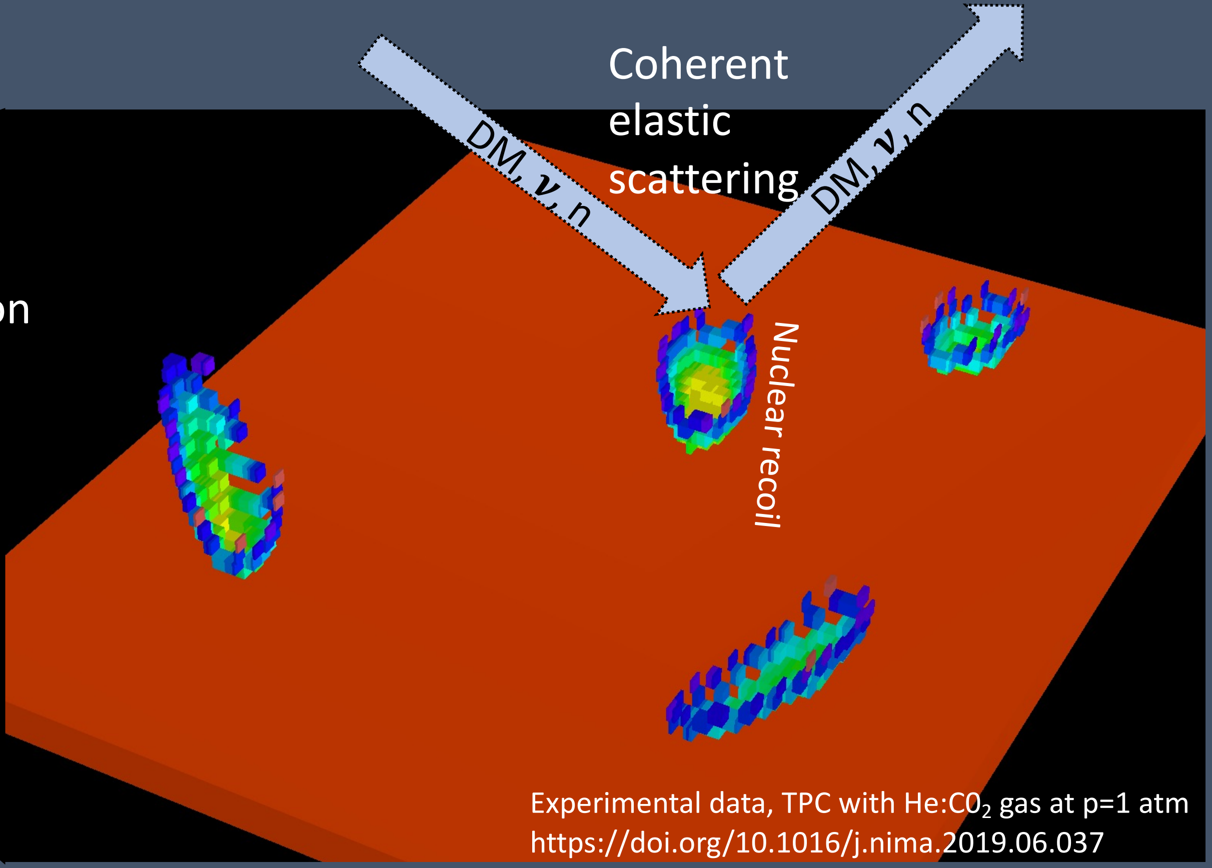
Dark Matter Wind

Neutrinos from artificial sources



Astrophysical neutrinos

via imaging of ionization topology in gas TPC (“recoil imaging”)



Experimental data, TPC with He:CO_2 gas at p=1 atm
https://doi.org/10.1016/j.nima.2019.06.037

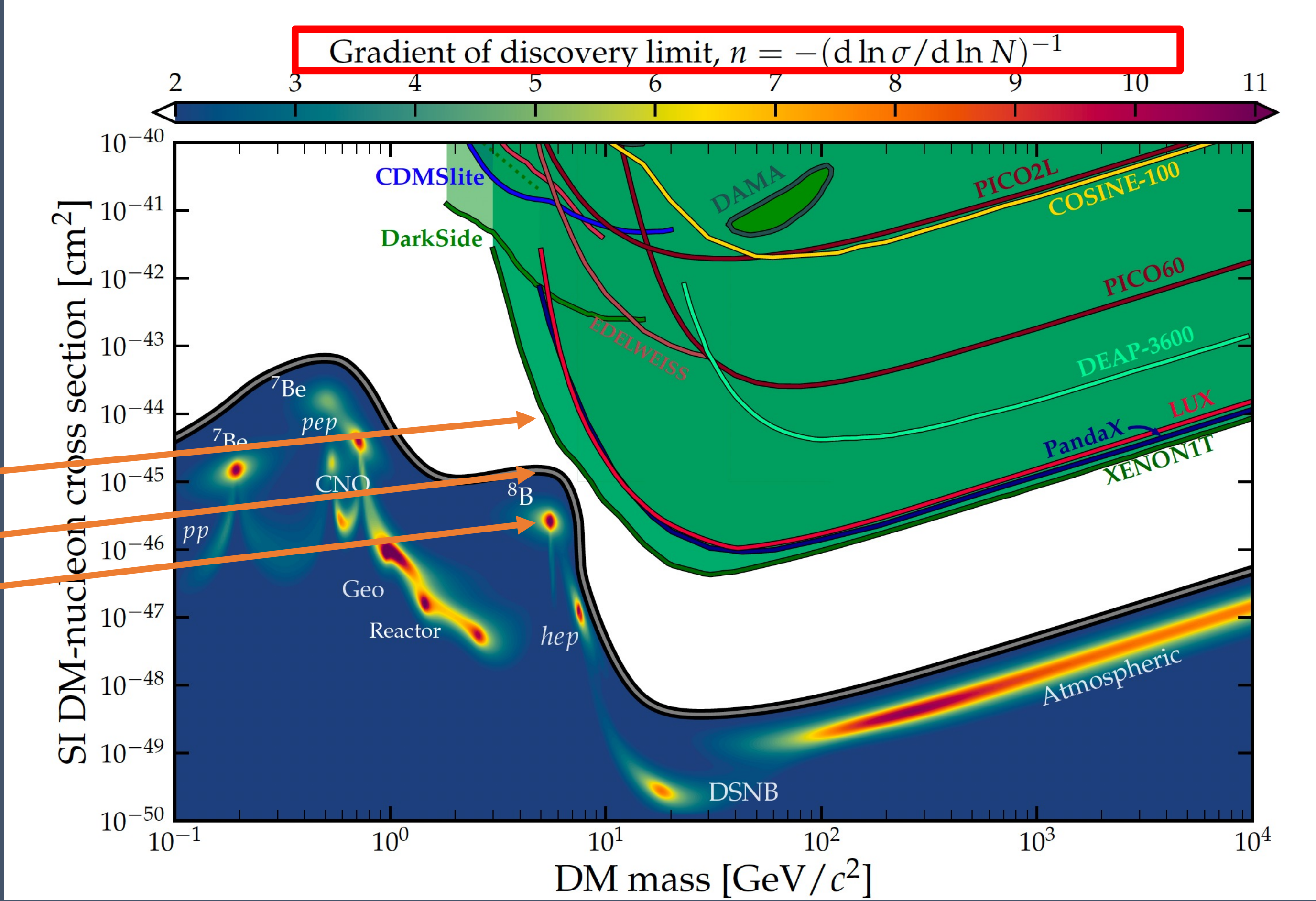
Community Summer Study SNOWMASS July 17-26 2022, Seattle

Sven Vahsen (University of Hawaii)

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

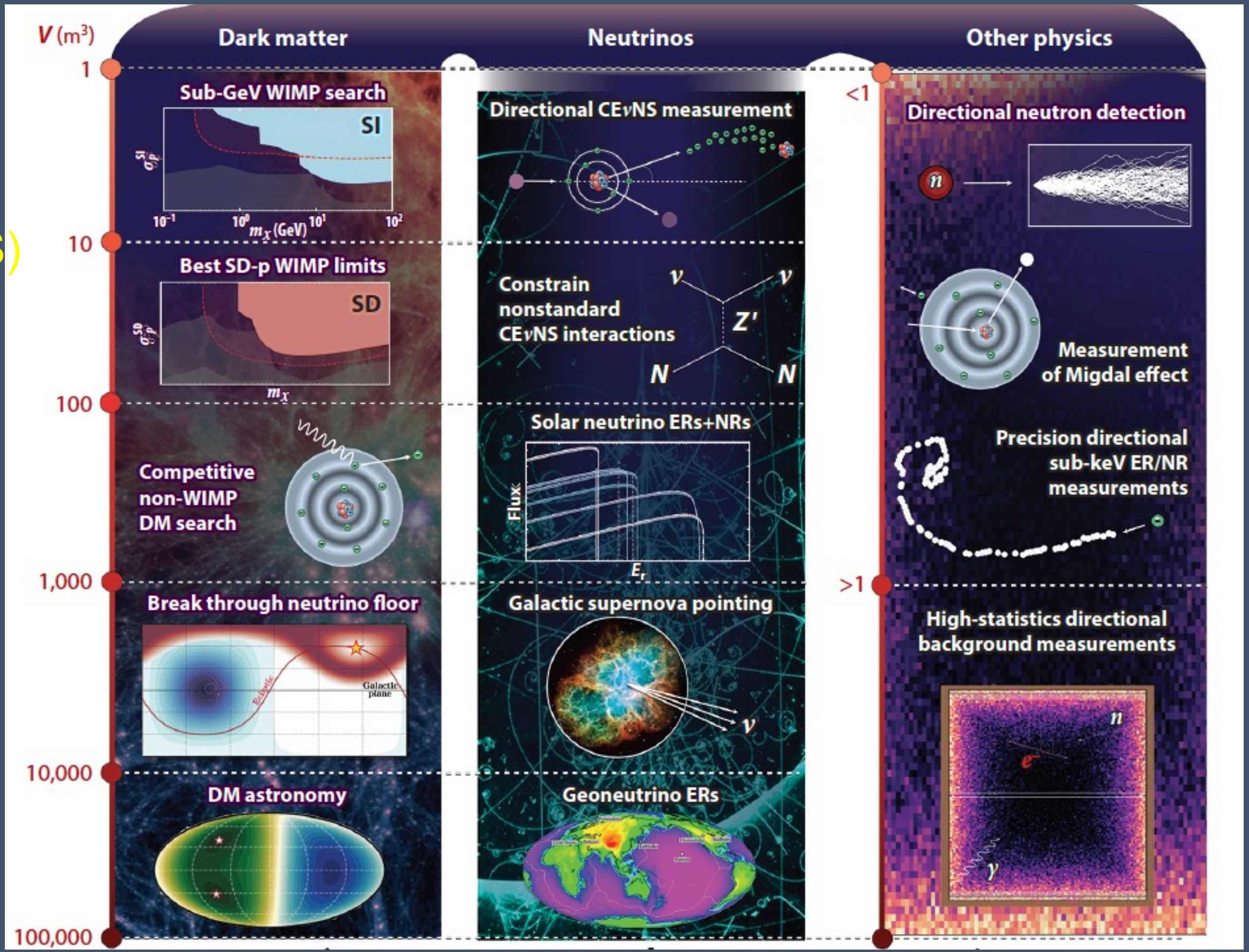
Opportunities for a long-term physics program

New physics opportunities for each factor 10 increase in exposure (yellow = measurement/observation)

Exposure, size

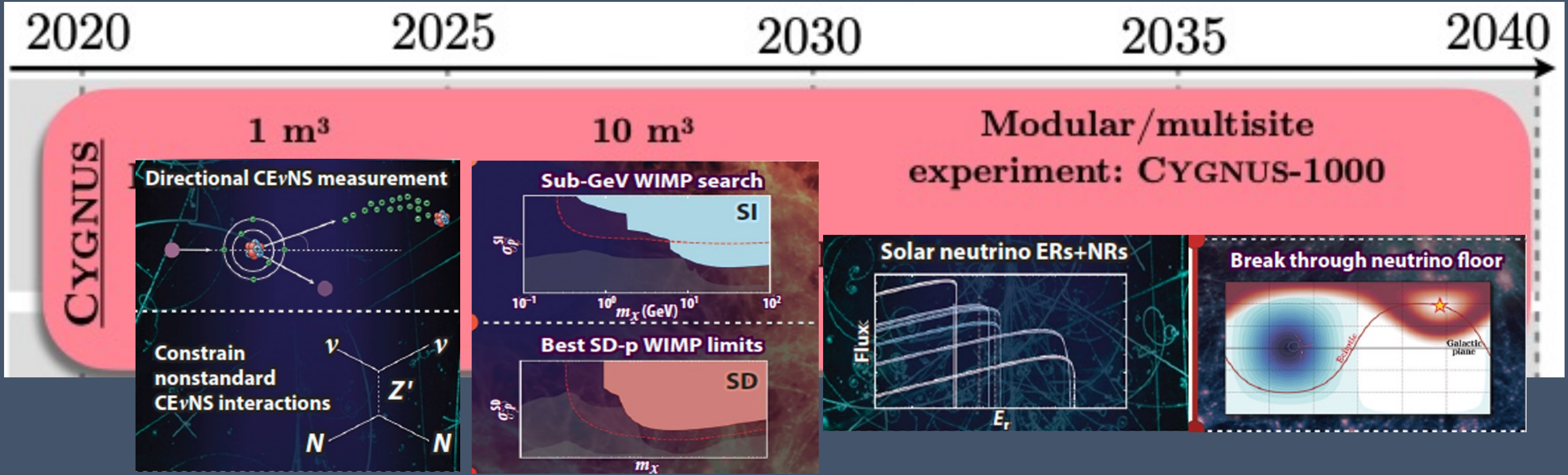
- Quenching factor and recoil physics (TUNL)
- Migdal Effect measurement
- Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) at ORNL (SNS) or Fermilab (NuMI and later LBNF)
- Competitive DM limits in SI and SD
- CEνNS and e-recoils from solar neutrinos
- Efficiently penetrating the LDM ν floor
- Observing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

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



https://arxiv.org/abs/2102.04596

CYGNUS: US Program Vision



U.S. Site	SNS, Oak Ridge, TN	SURF, Lead, SD	International, multi-site (Utilize DUNE cavern?)
Approx. Detector Cost	~$0.5M+	~$5M	~$50 M, for 1000m^3 in U.S.

https://arxiv.org/abs/2008.12587

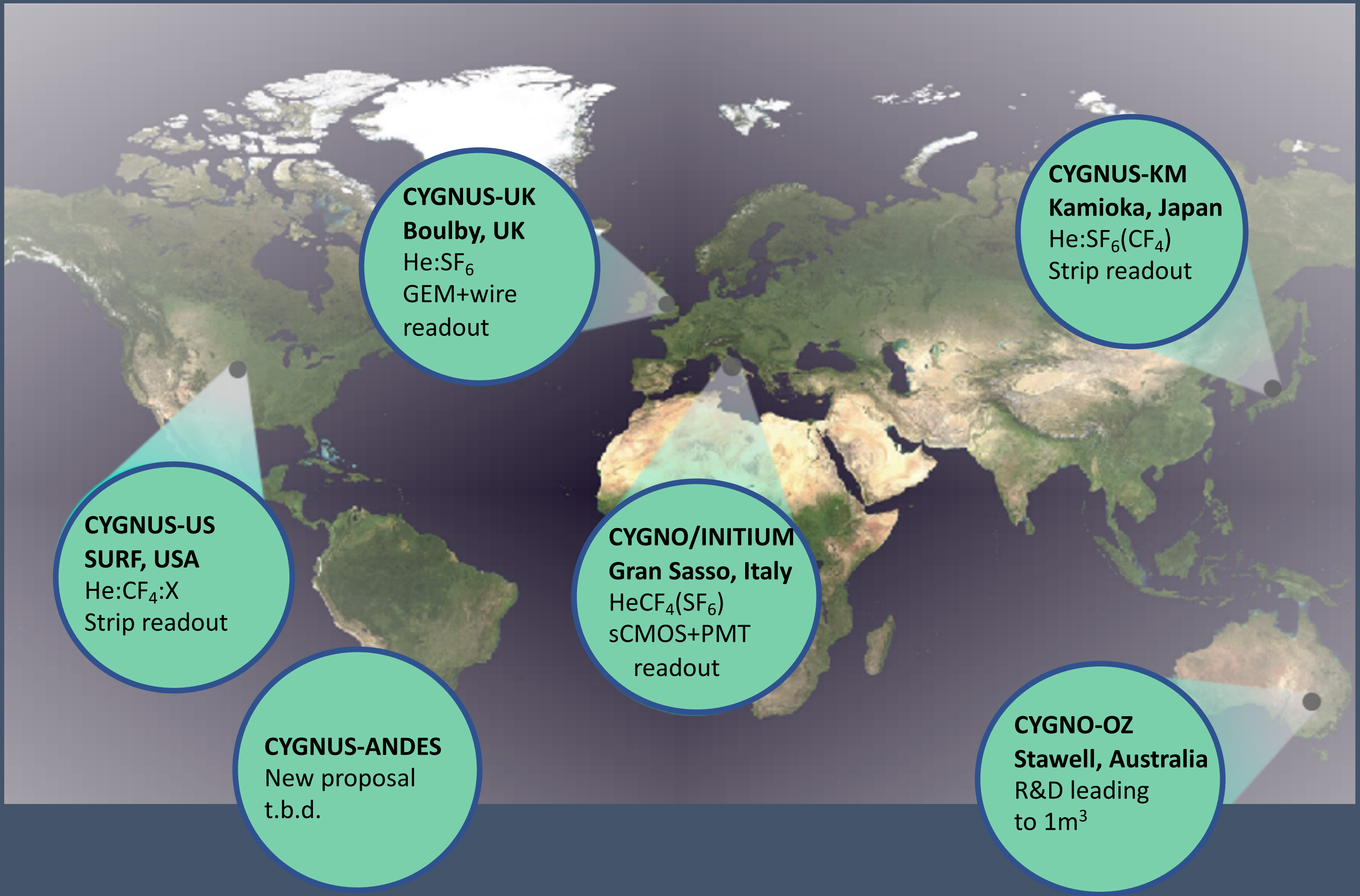
Long term CYGNUS Vision: Multi-site Galactic Recoil Observatory
with directional sensitivity to WIMPs and neutrinos

https://arxiv.org/abs/2008.12587

Proto Collaboration formed:

- 55+ signed members from the US, UK, Japan, Italy, Spain, China
- Six US faculty members
- Close collaboration and regular meetings on detector R&D and physics studies

New collaborators welcome!



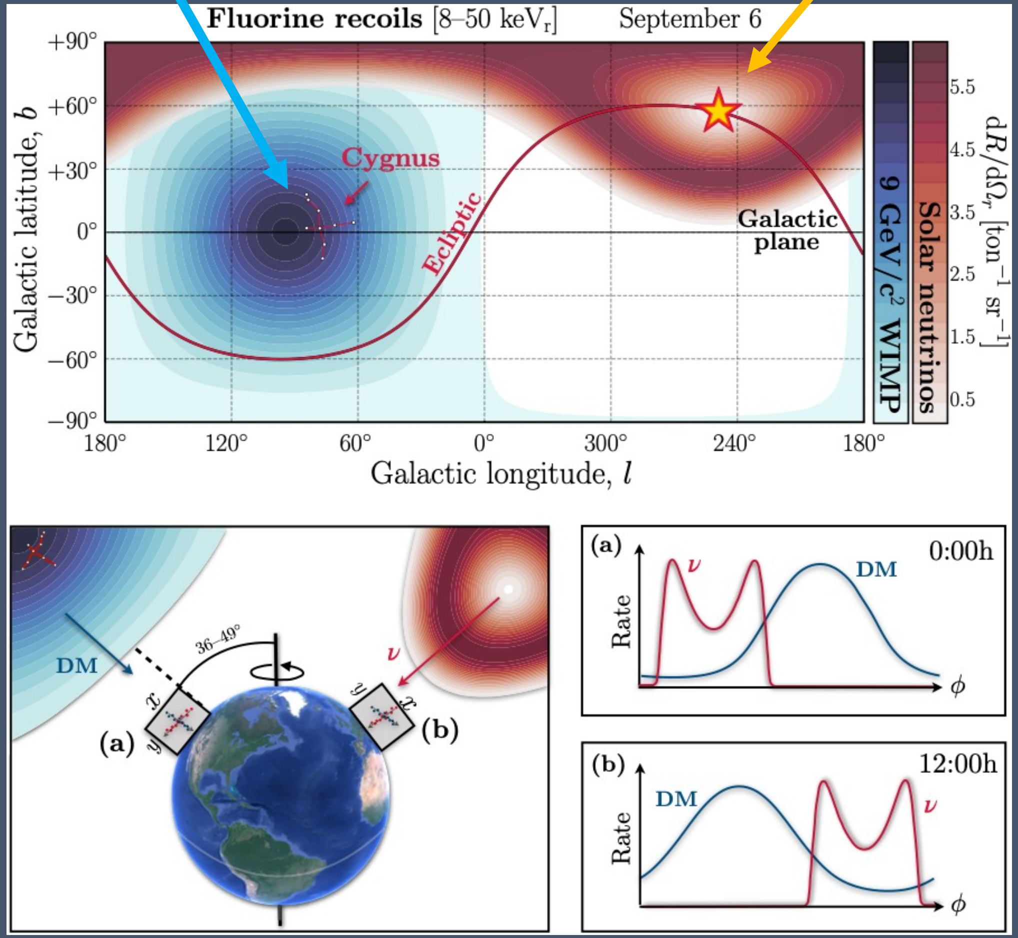
The Power of Directionality

arxiv:2102.04596

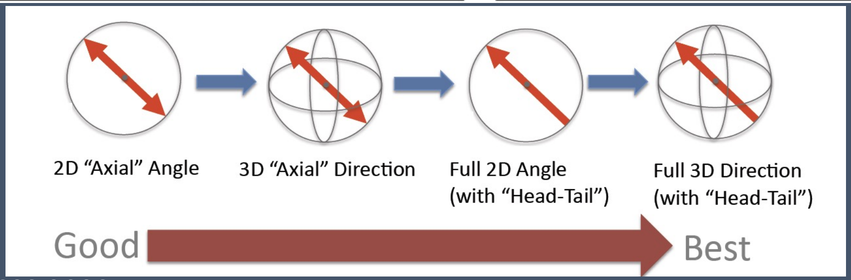
Neutrinos from the sun

WIMP wind, approx. from CYGNUS

- 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
  - Enabled Neutrino spectroscopy



Directionality: highly beneficial…
…but experimentally challenging!

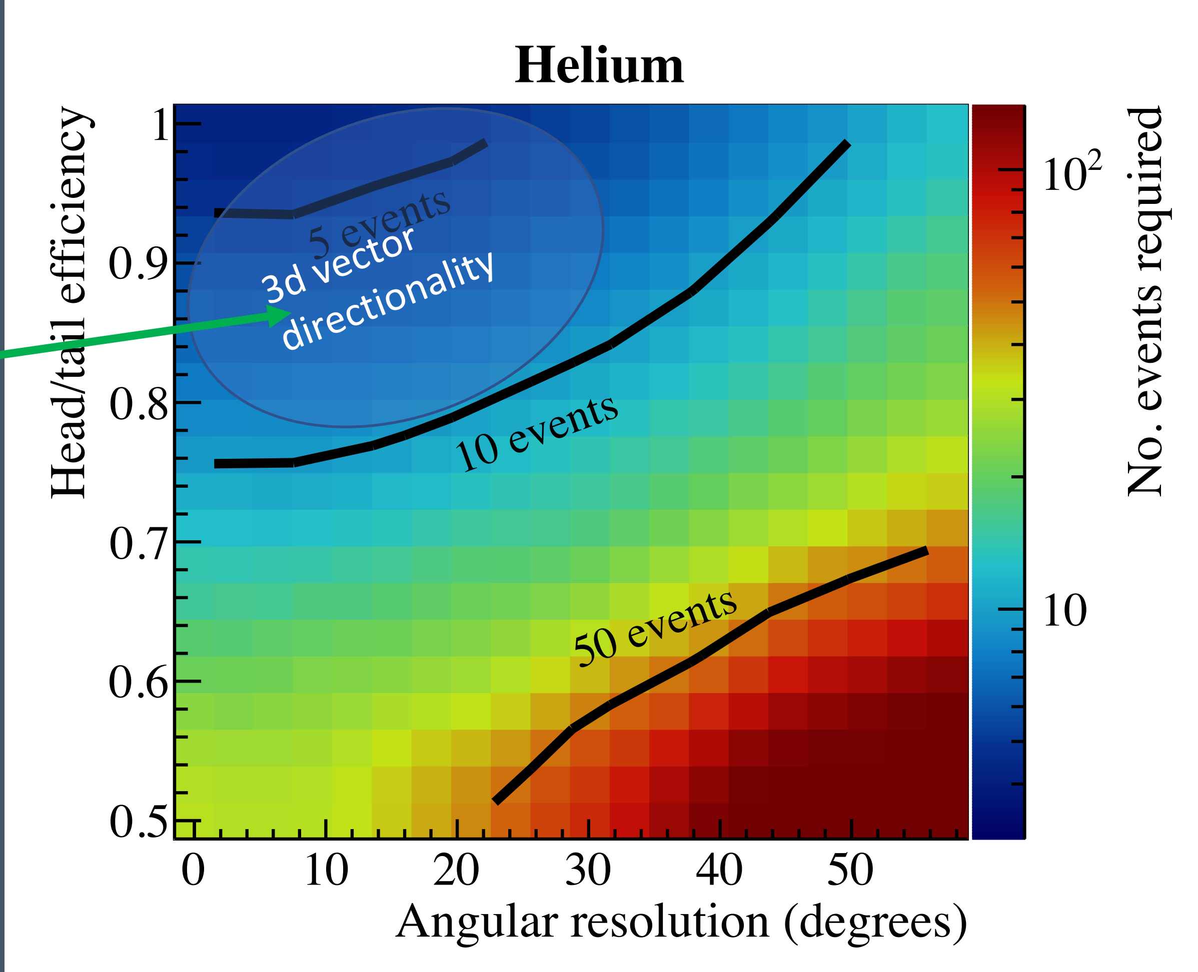


Detector Performance Requirements

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

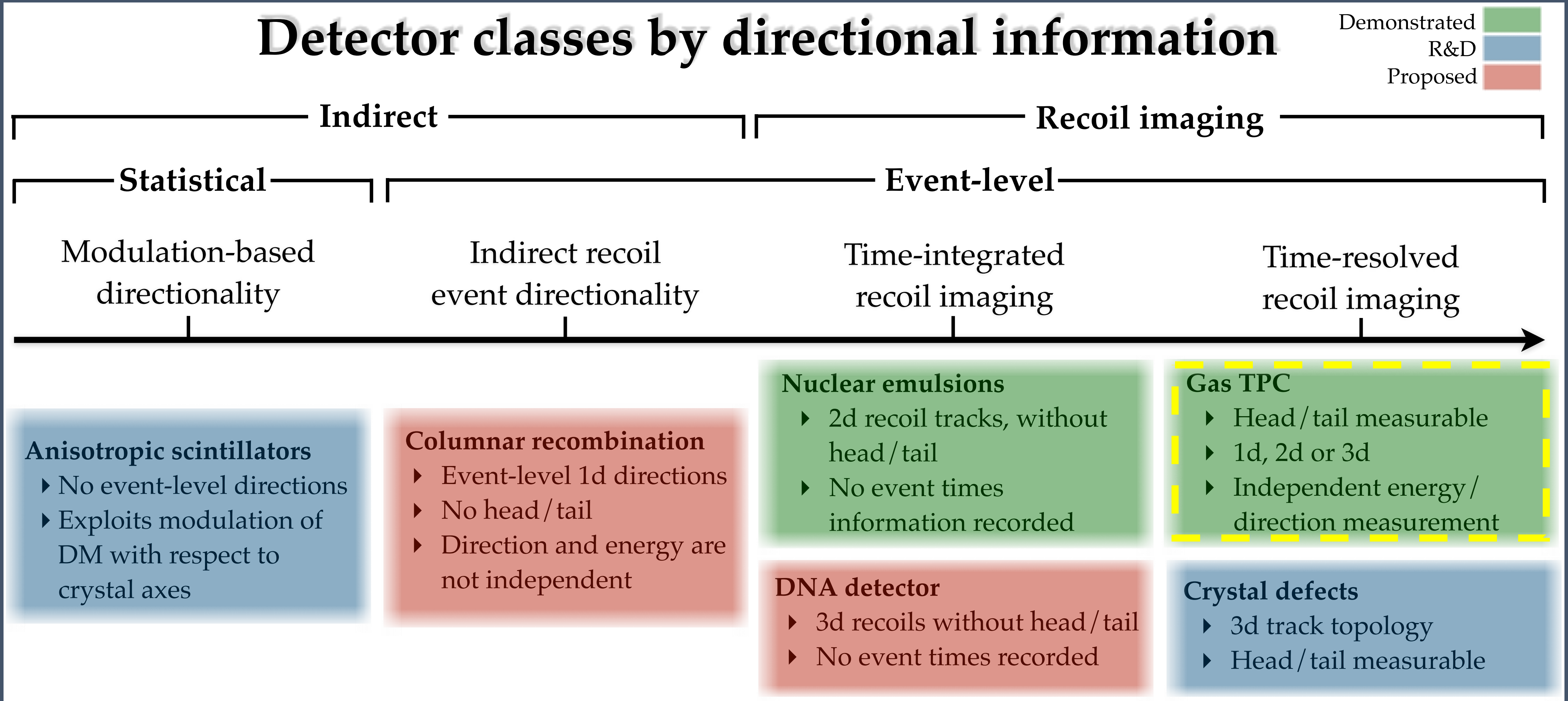


detected WIMP events required to exclude **ν**-hypothesis at 90% CL

Assumptions: mχ = 10 GeV, He:SF_6 gas

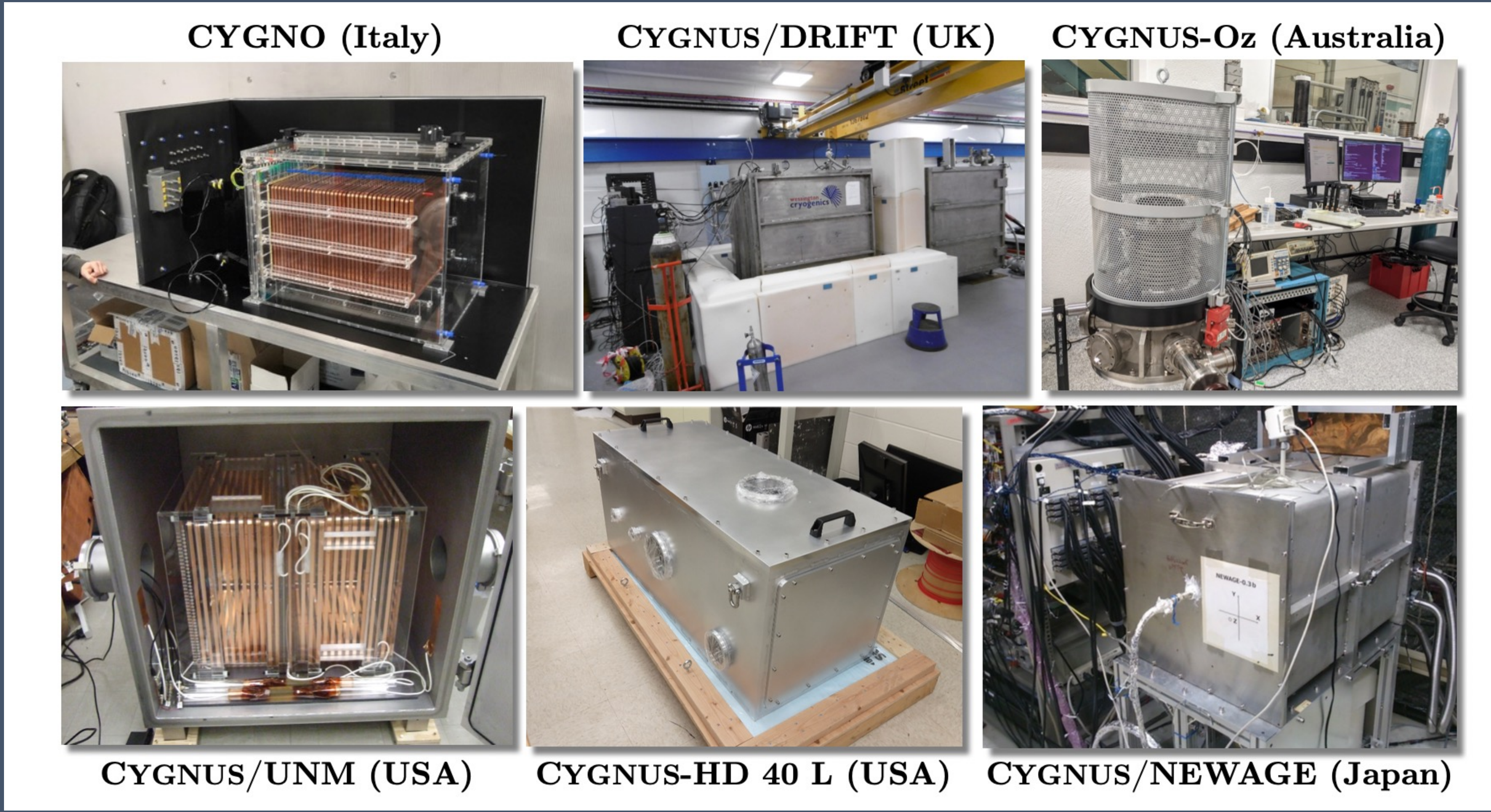
Gas Detectors Required for "best directionality"

https://arxiv.org/abs/2102.04596



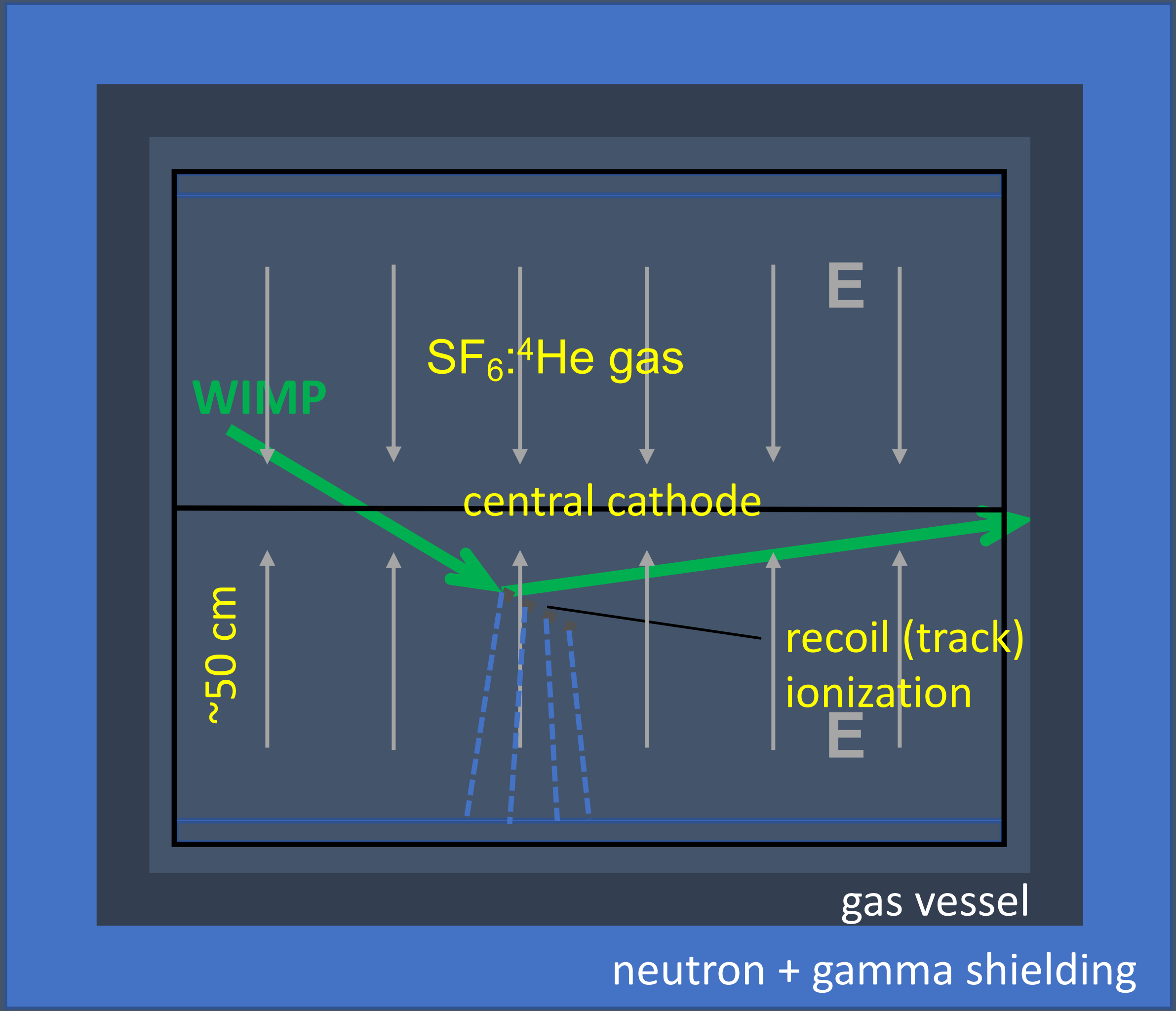
Gas TPCs provide the most event information, enabling a physics program beyond DM searches

Prototypes and Experiments



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: CYGNUS HD and CYGNO

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

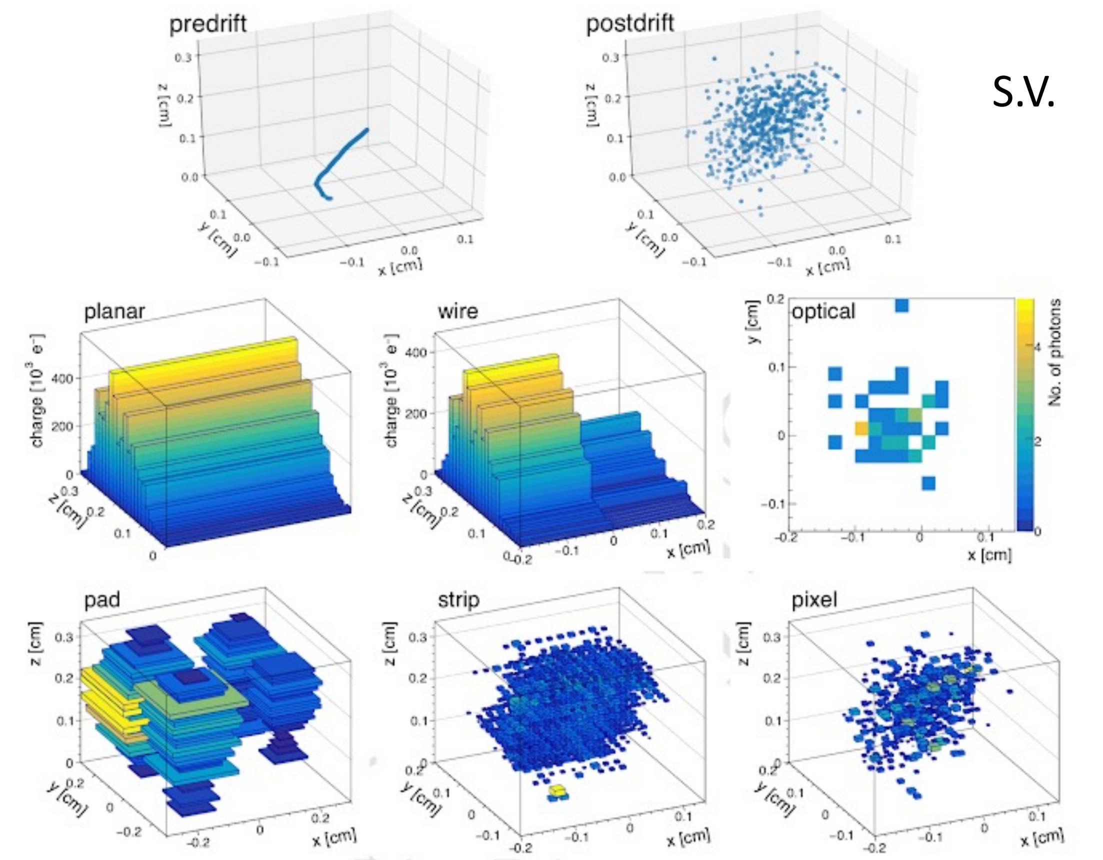


FIG. 9. Simulated 25 keV$_r$ helium recoil event in $He:SF_6$ gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

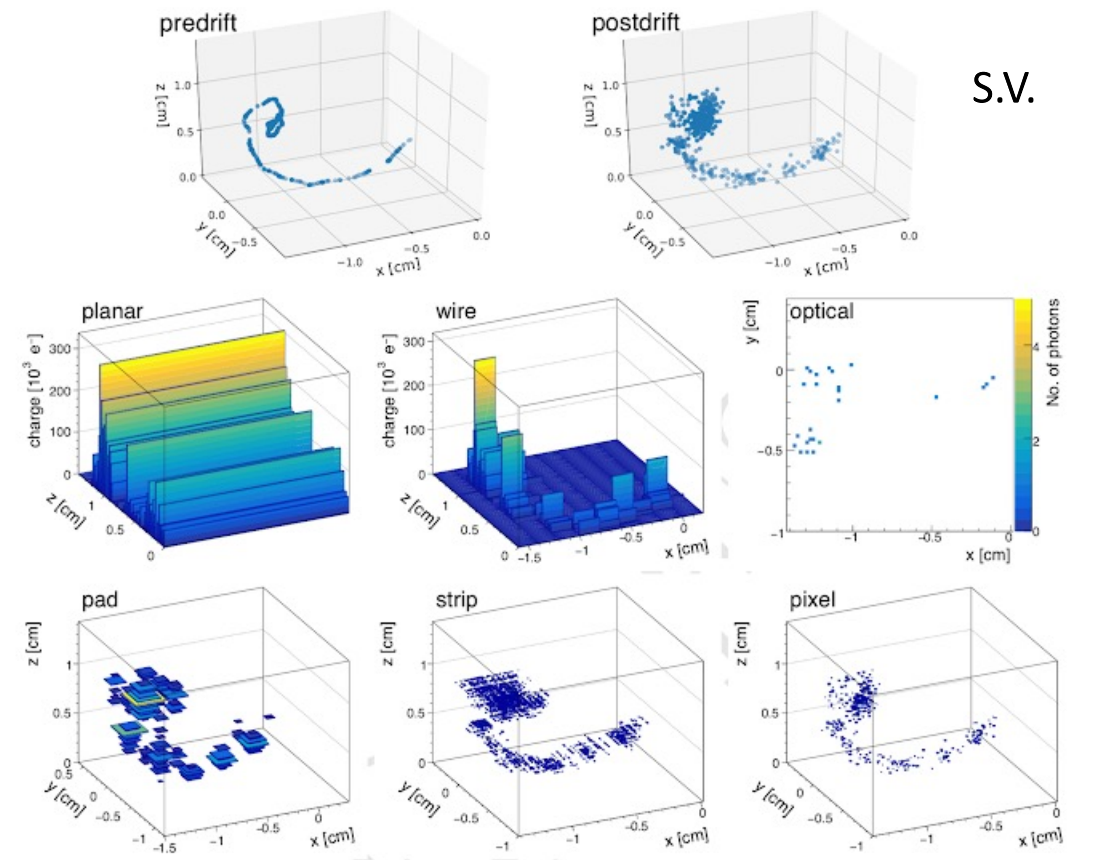
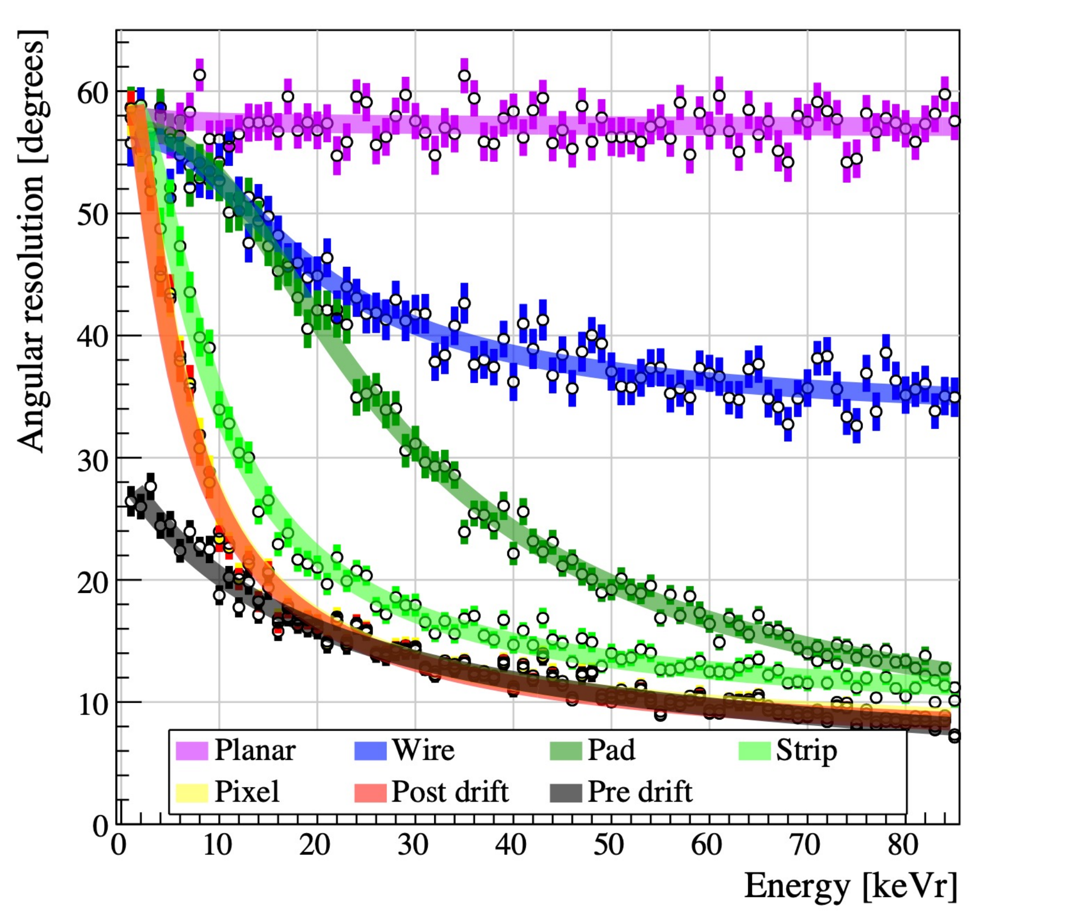


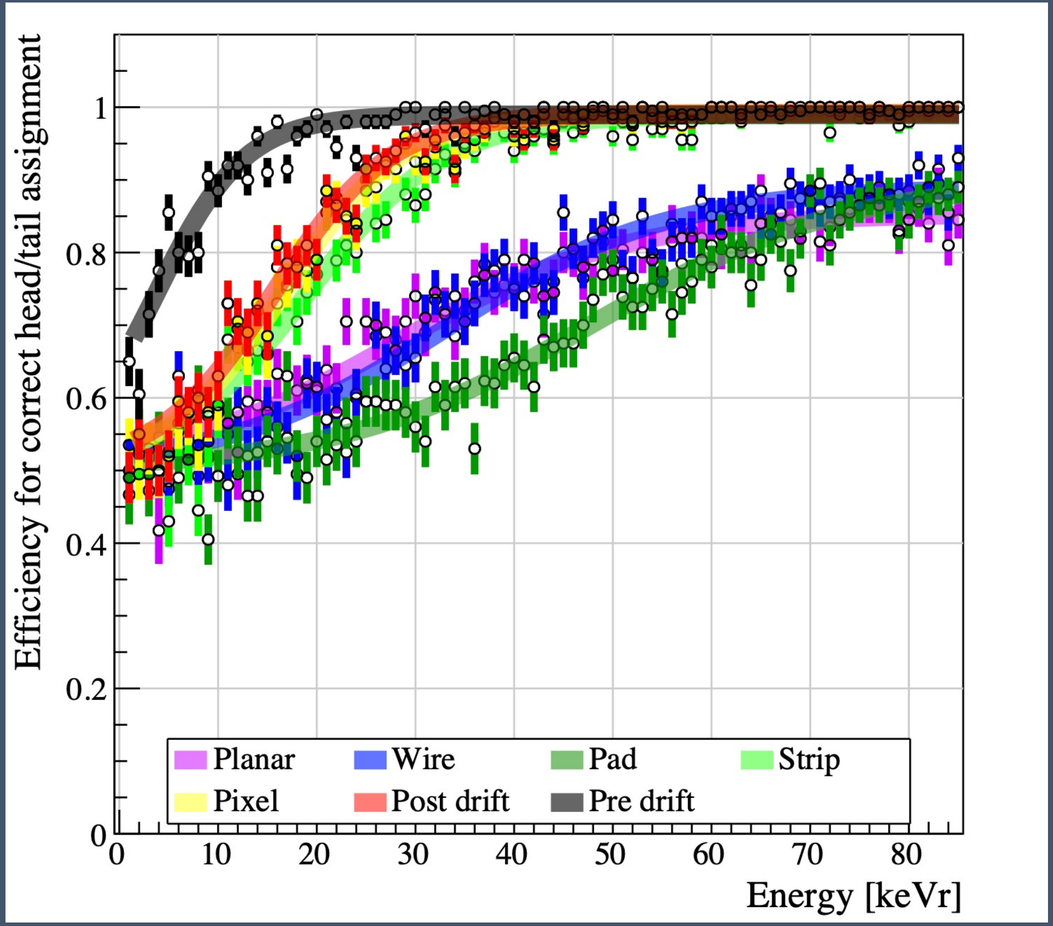
FIG. 10. Simulated 20 keV$_{ee}$ electron event in $He:SF_6$ gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

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

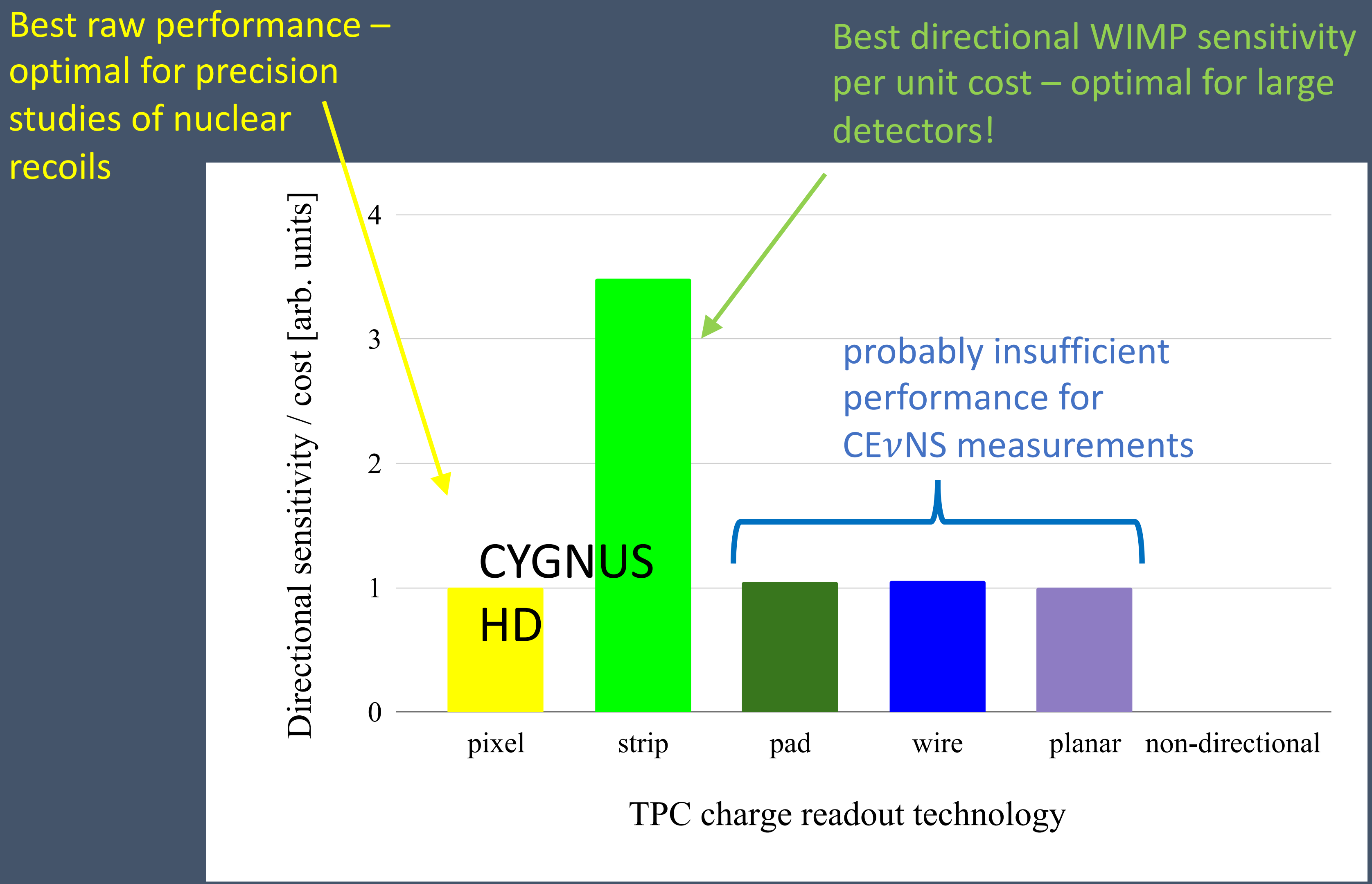




Pixel readout extracts the entire directional information left after diffusion (red and yellow curves overlap fully)
Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost

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

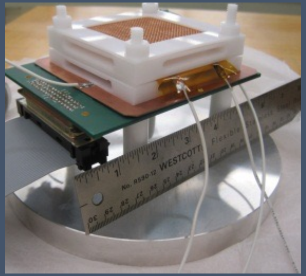
Result of cost vs performance analysis



https://arxiv.org/abs/2008.12587

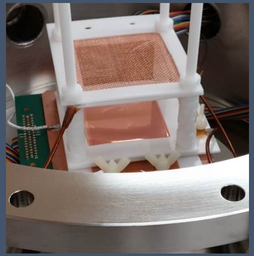
CYGNUS HD: MPGD gas TPCs for nuclear recoil imaging

2011-2013



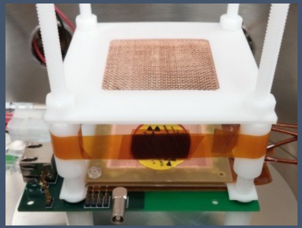
μD^3 (~1cm^3)

2013



~2.5 cm^3

2013



~ 20 cm^3

1st generation, proof of concept

2014

2 x 60 cm^3

2015

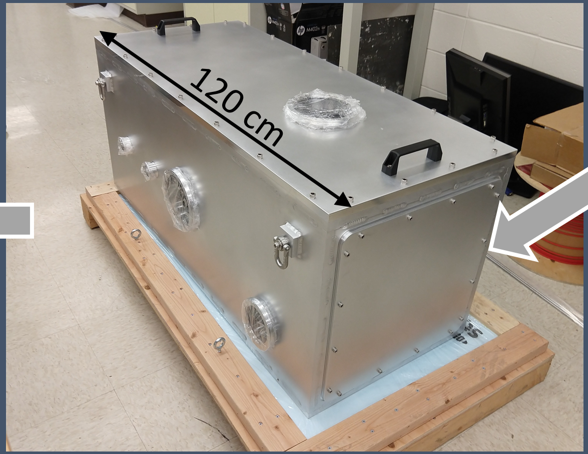
BEAST TPCs

8 x 40 cm^3

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

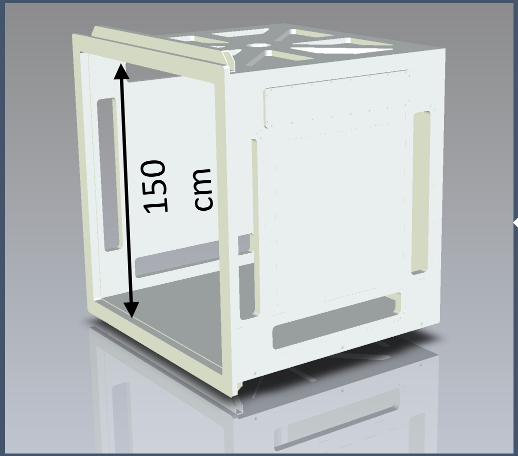
- Extensive prototyping with pixel chip readout completed
- Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for precision studies of nuclear recoil physics
- Now constructing 3rd generation detectors w/ CERN strip micromegas readout to achieve DM + solar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

2020



CYGNUS HD “Keiki” (40 liters)

2022



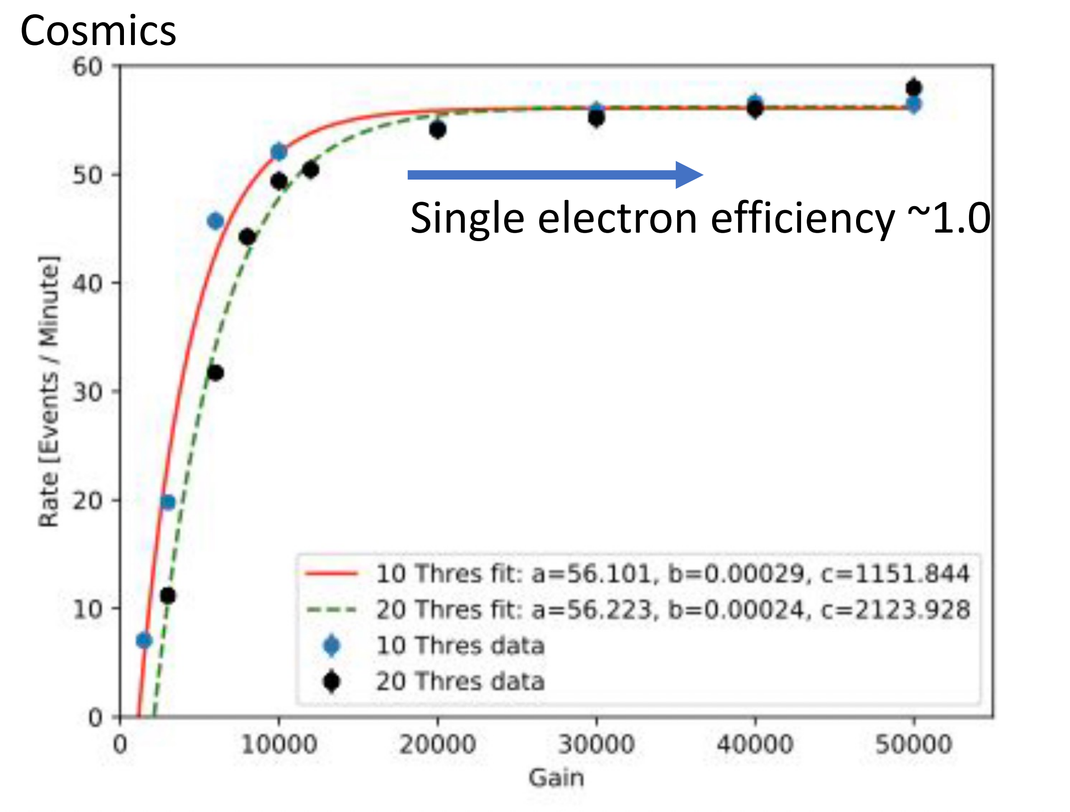
CYGNUS HD 1 Demonstrator (1 m^3)

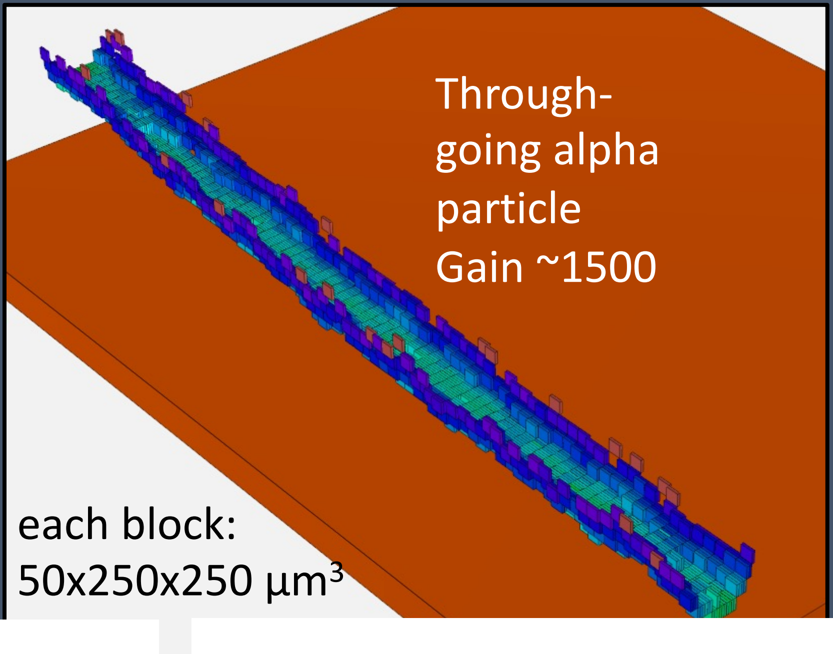
3rd Generation: Optimized for dark matter

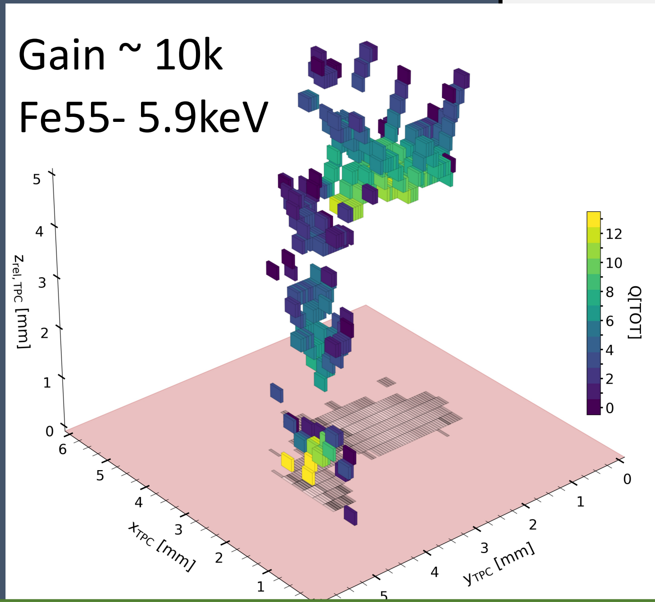
Noiseless Single Electron Detection

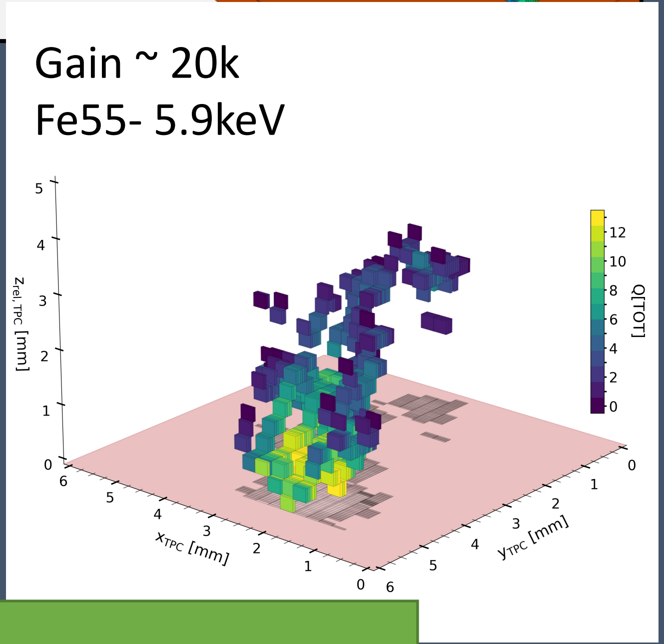
Majd Ghrear
Jeff Schueler

Cosmic ray rate









- In high-gain mode, even single electrons of ionization easily detected
- Energy threshold is ~30 keVee, w/ virtually zero noise-occupancy
- Physics performance will instead be limited by *directionality and PID thresholds*

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

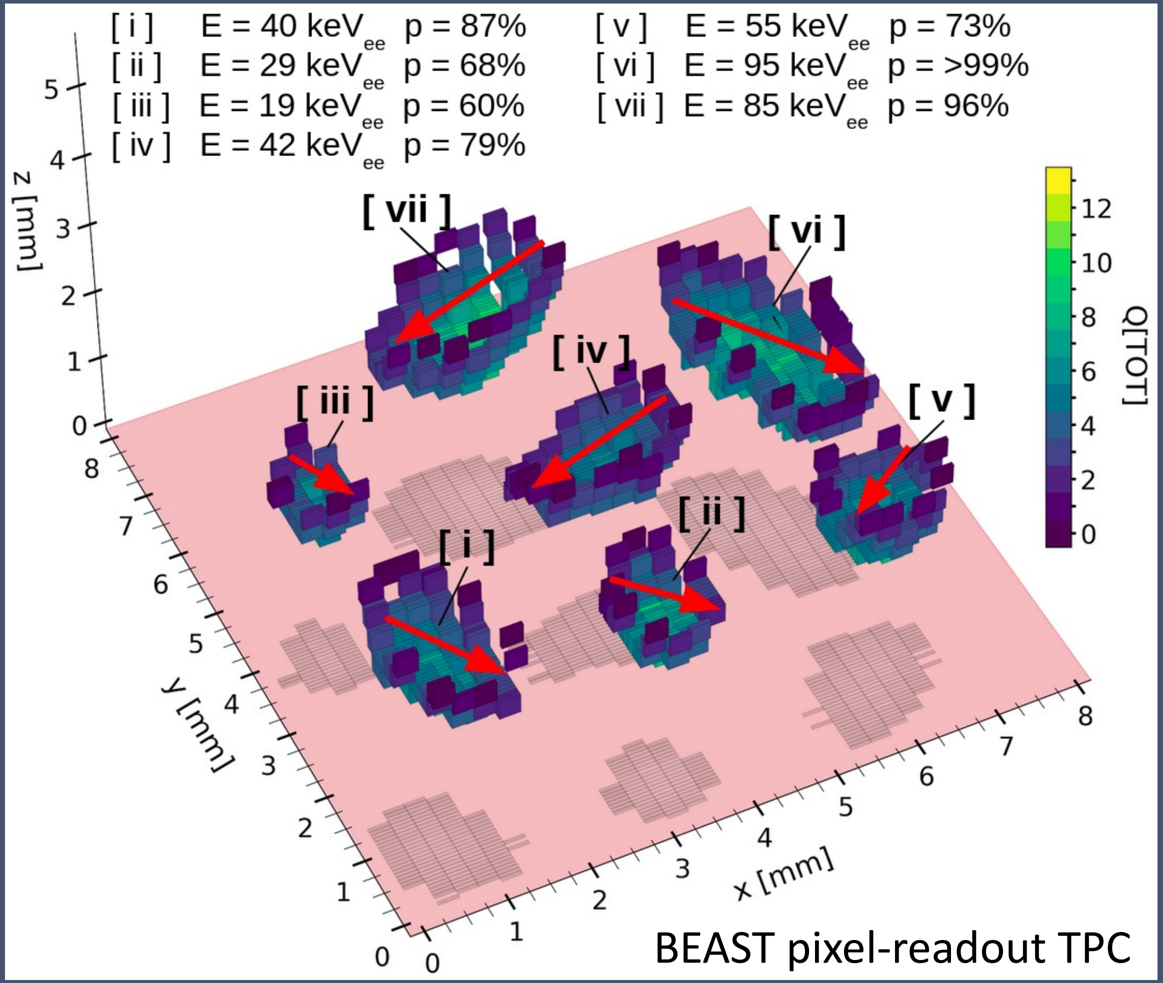
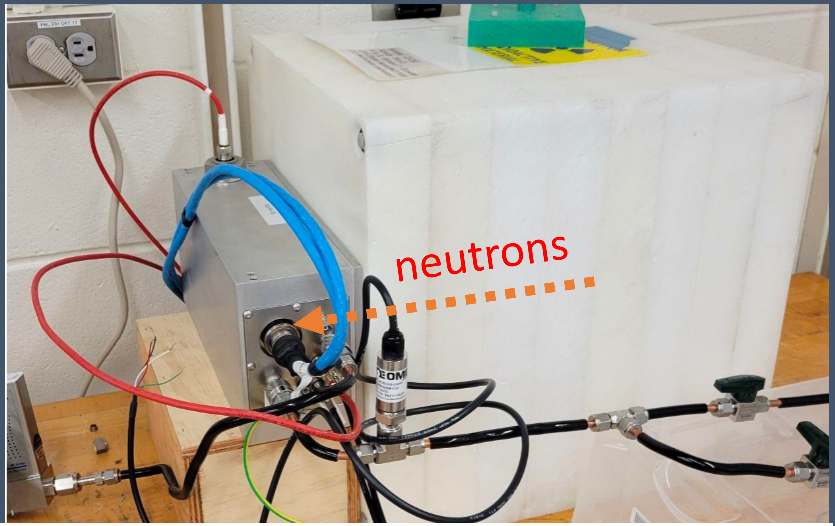
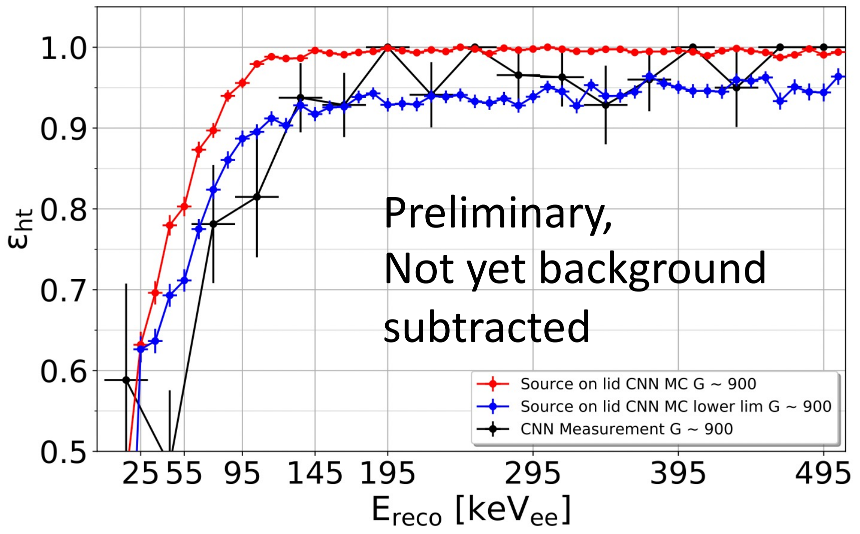


Figure1: Left: Helium recoil tracks detected in a pixel-readout time projection chamber at low gain (900). Color of voxels indicates ionization density.

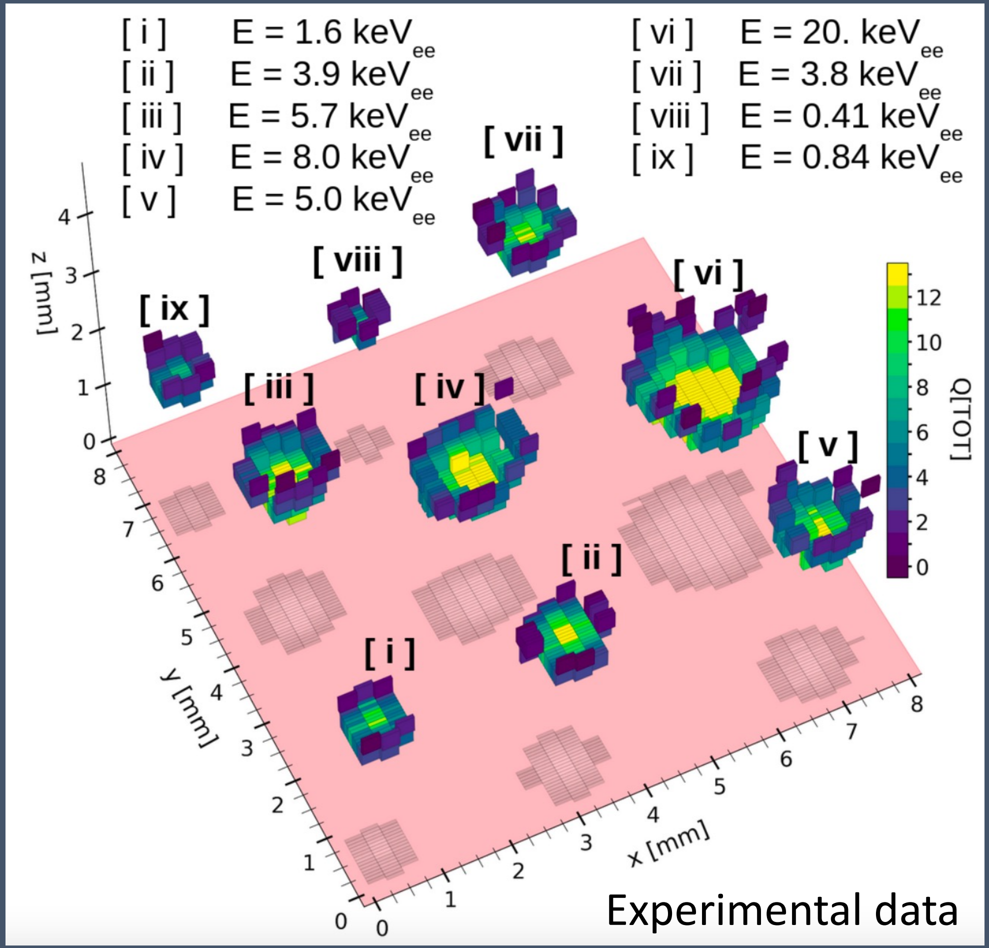


Jeff Schueler

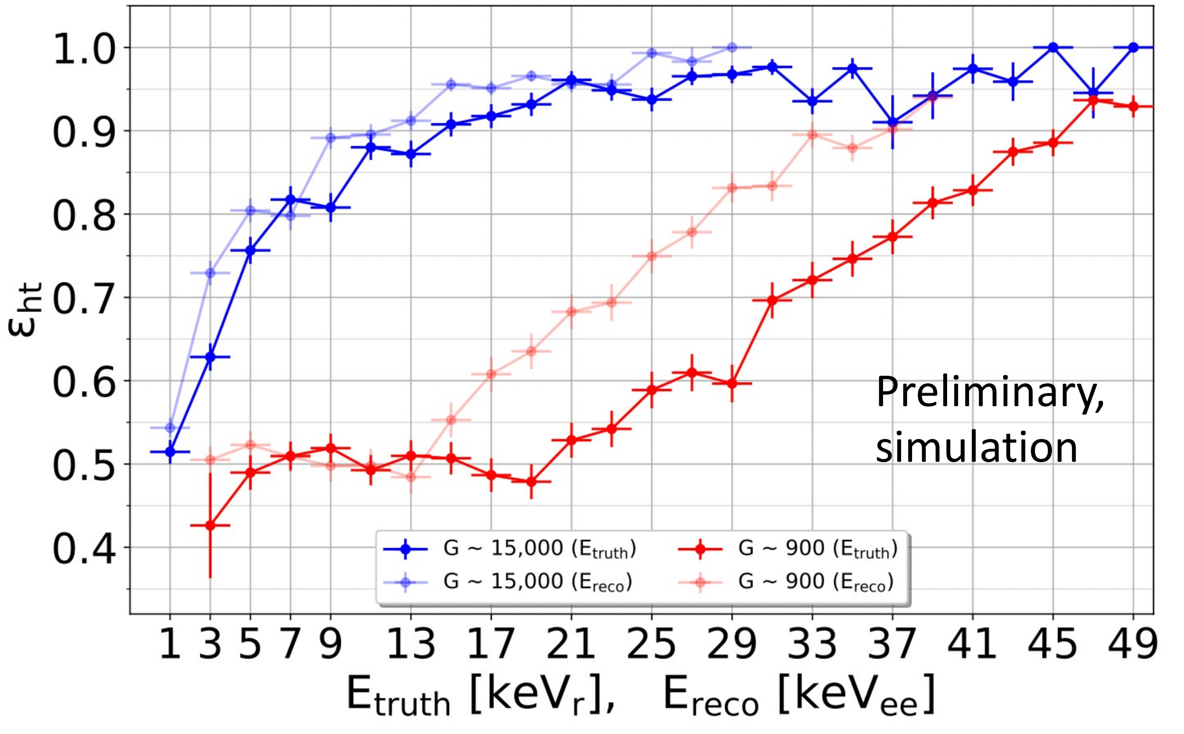


At low TPC gain (900), event-level head/tail sensitivity down to 25 keV at atmospheric pressure!
Measurement is a lower limit – not yet background subtracted.

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



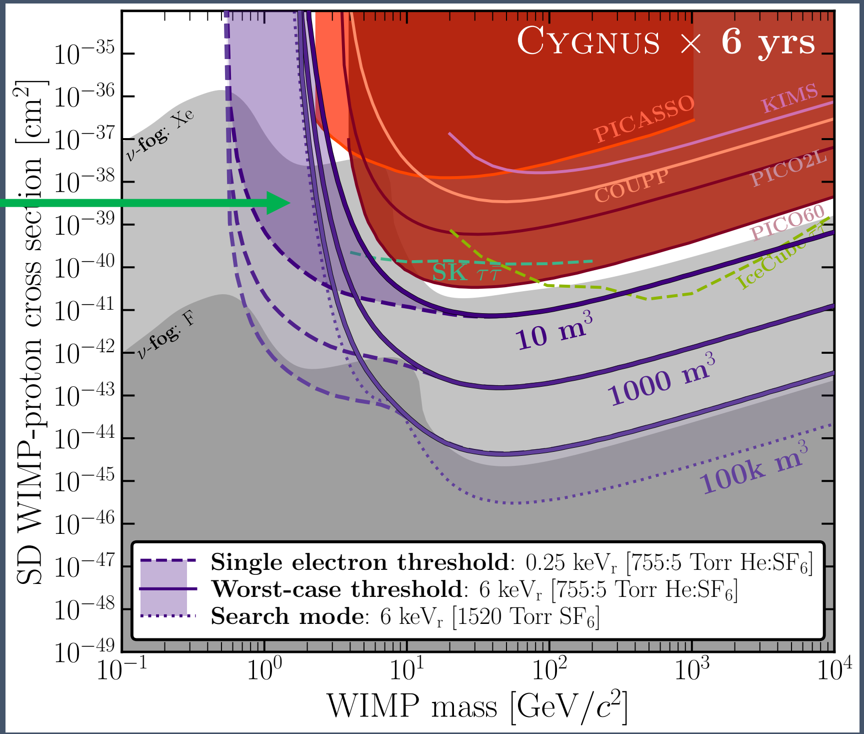
Jeff Schueler



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!

WIMP sensitivity: depends on electron rejection

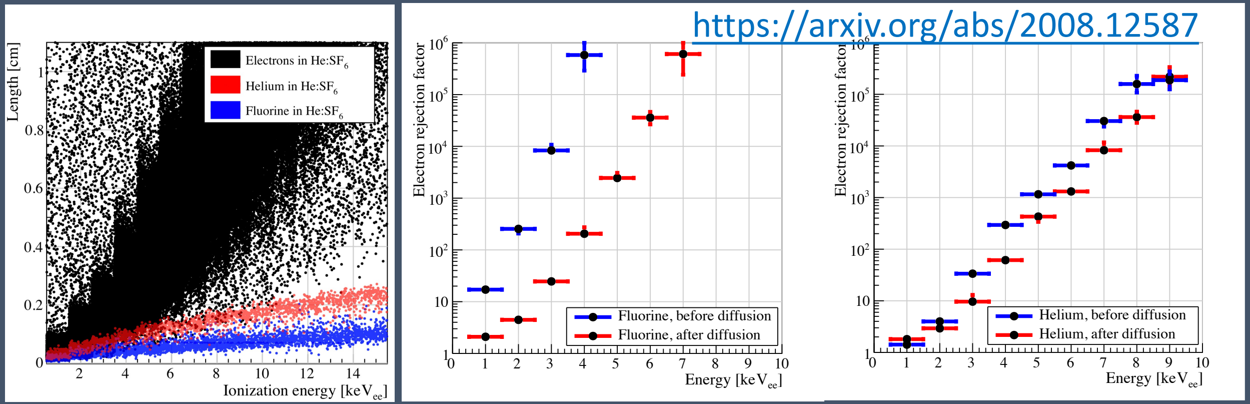


https://arxiv.org/abs/2008.12587

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

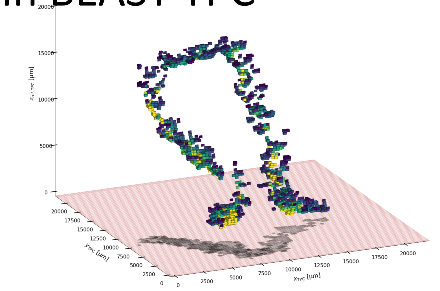
3D electron rejection (simulation) via dE/dx   5 torr SF_6 + 755 torr Helium

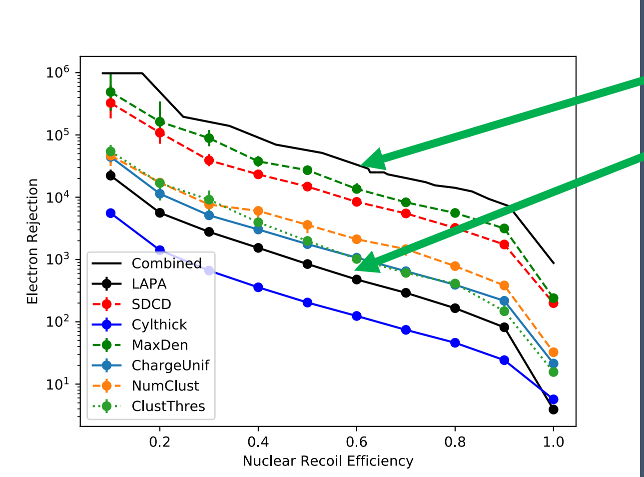
https://arxiv.org/abs/2008.12587



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

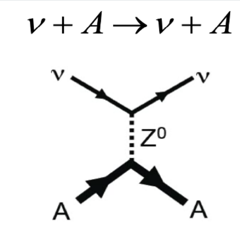




~2 orders of magnitude improvement over dE/dx !

Majd Ghrear et al., arxiv.:2012.13649

Directional CEvNS measurements at SNS, Oak Ridge

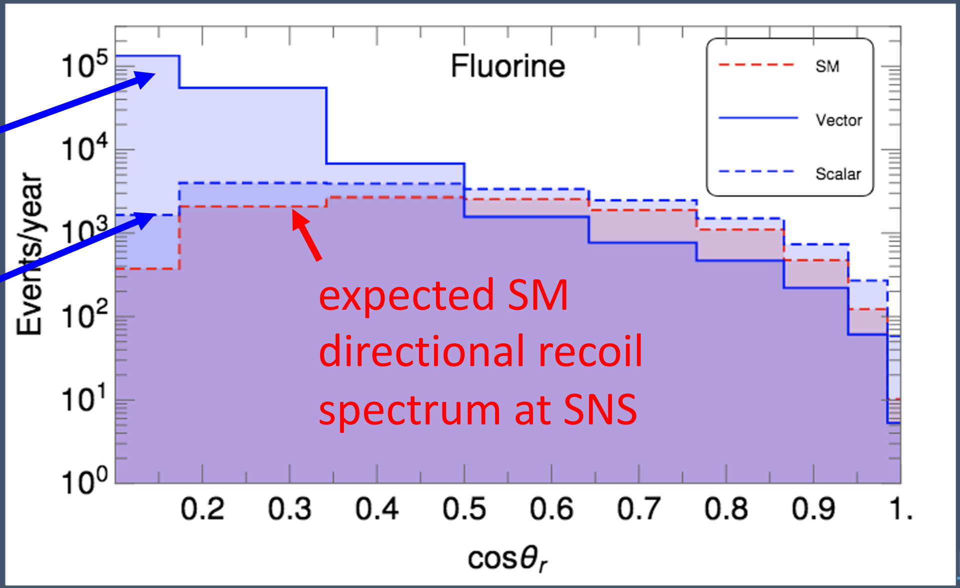


- CEvNS = Coherent elastic neutrino nucleus scattering
- This process probes the weak nuclear charge and weak mixing angle
- Precisely predicted by the SM allowing for sensitive probe of BSM physics

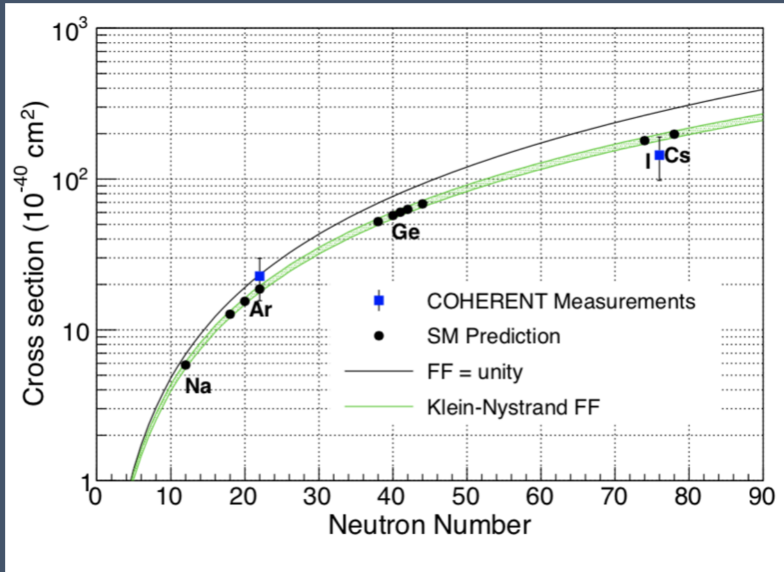
- COHERENT detected CEvNS in CsI[Na] (2017), and later in liquid argon (2021)
- Directional detectors sensitive to new physics in CEvNS via recoil-angle distribution

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.

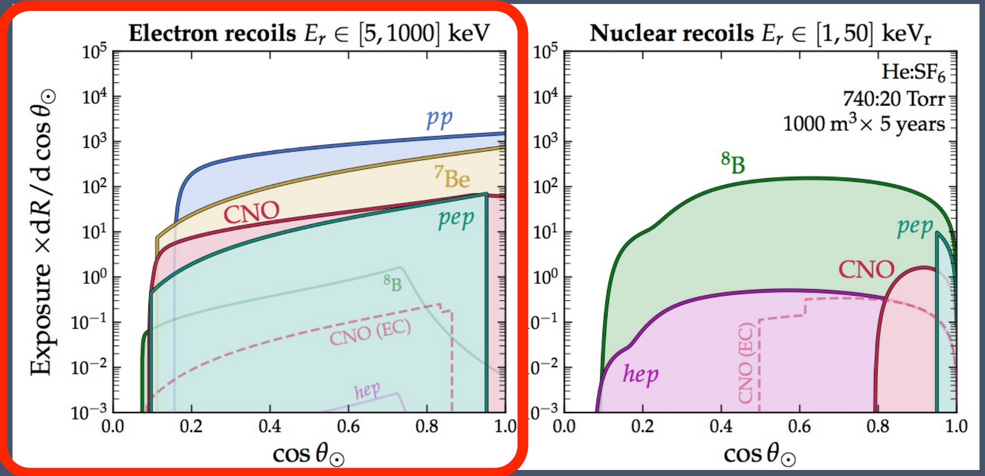
Solar Neutrinos in CYGNUS: promoting background to signal

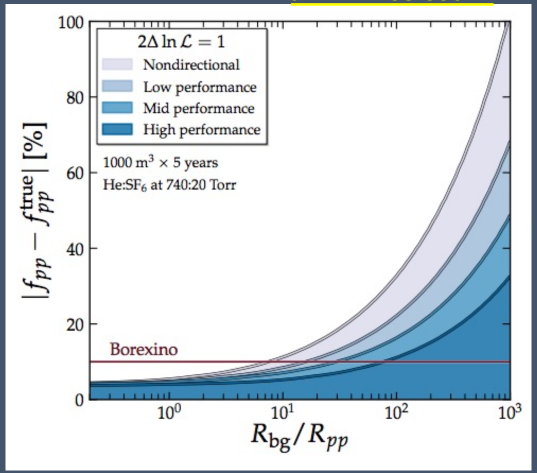
CYGNUS 1000

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

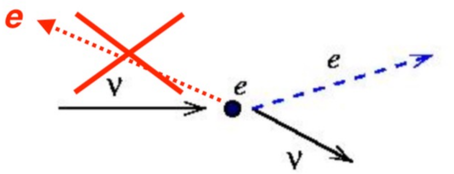
Electron recoils





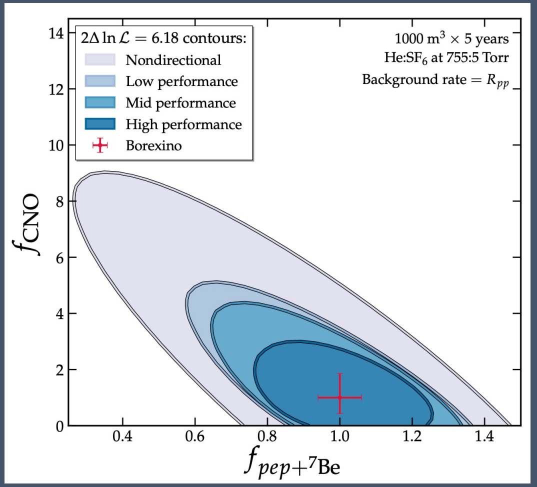
1 σ sensitivity to pp flux as a function of the total non-neutrino ER background

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.

Also need to revisit multiple scattering! Ongoing.

ER multiple scattering **revisited** & optimal track length for directionality

GSSI | INFN

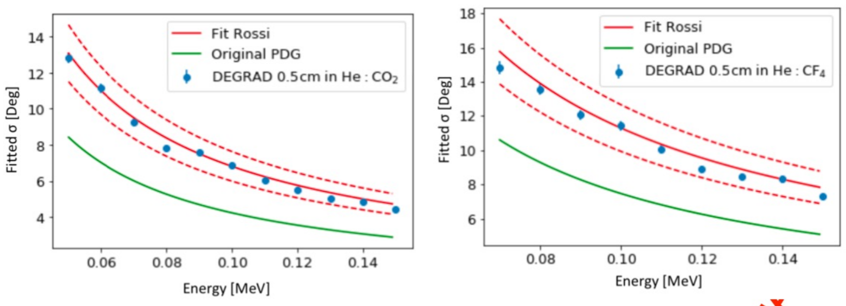
Found to be inadequate to describe MS for ER: we fit these two parameters to DEGRAD simulation of gas mixtures

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

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

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:

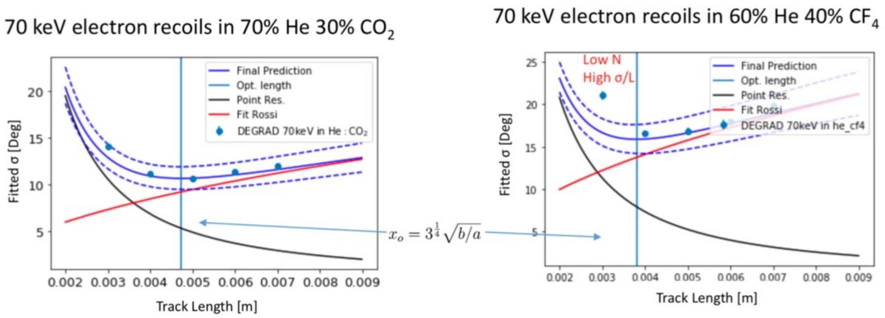
$$\sigma_\phi^{\text{plane}} = \frac{\sqrt{12}\sigma_{x/y/z}}{L\sqrt{N}}$$

PRELIMINA

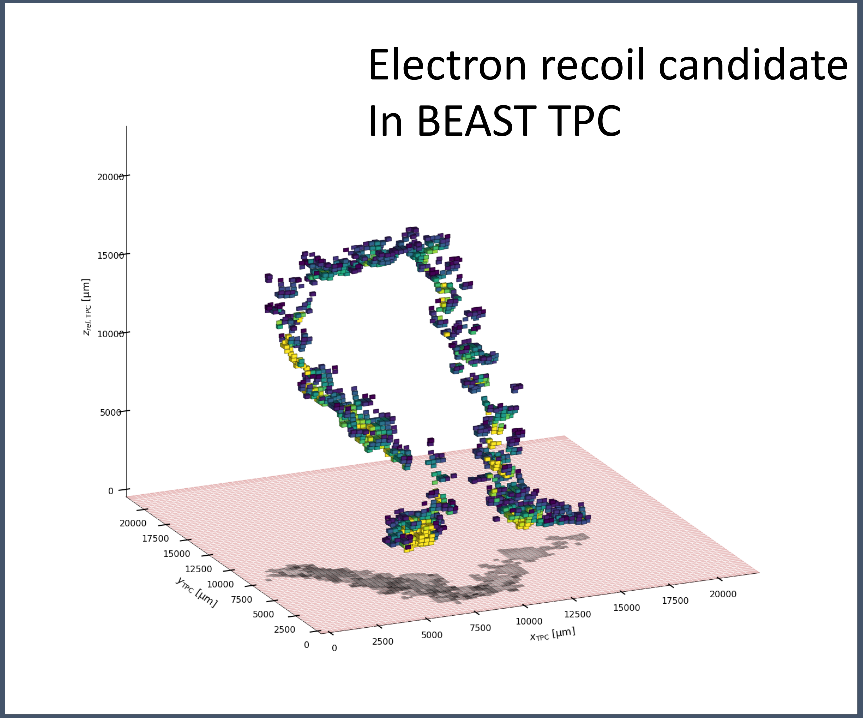
$$\sigma_\Psi^{\text{plane}}(x) = \sqrt{a^2 x + b^2 x^{-3}}$$

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

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)



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



Conclusion

- Excellent recent progress made both on detector R&D and physics case for recoil-imaging in CYGNUS-style gas TPCs in the last few years
  - C. A. J. O'Hare et al., 2022 Snowmass Summer Study arXiv:2203.05914
- New direction: directionality with electron recoils
- Ideal next step: Demonstrate fully optimized, 1m^3-scale module at SNS
- Could be start of a 30-year program, and would put us an excellent position by next Snowmass
  - Demonstration of directional neutrino measurement
  - Limits on BSM neutrino interactions
  - Solar neutrino measurements
  - DM discovery possible (esp. SD)
  - Ready to follow up WIMP discovery by any other experiment, or to do a deep dive into neutrino floor later