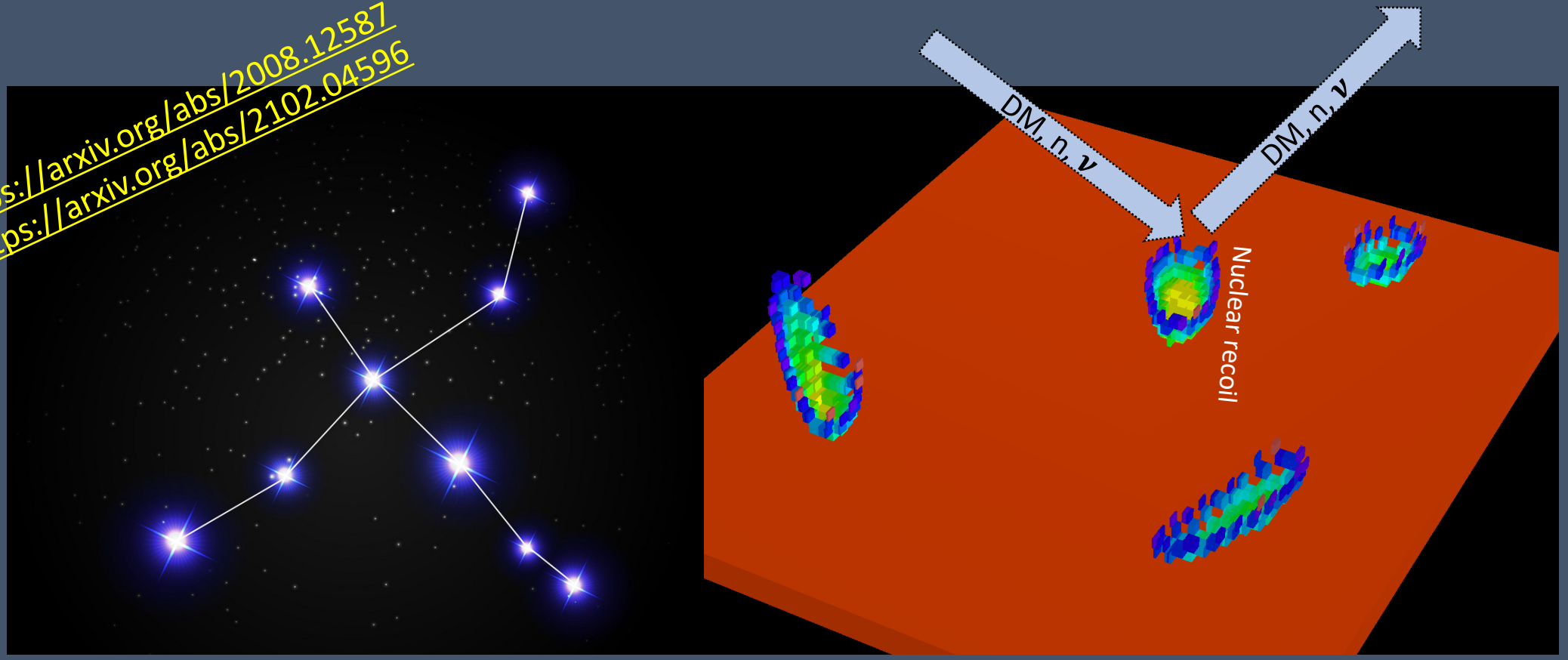
CYGNUS: Imaging of low-energy nuclear recoils in gas TPCs

for directional dark matter searches, neutrino detection, and more

https://arxiv.org/abs/2008.12587
https://arxiv.org/abs/2102.04596



Sven Vahsen (University of Hawaii)

The Power of Directionality

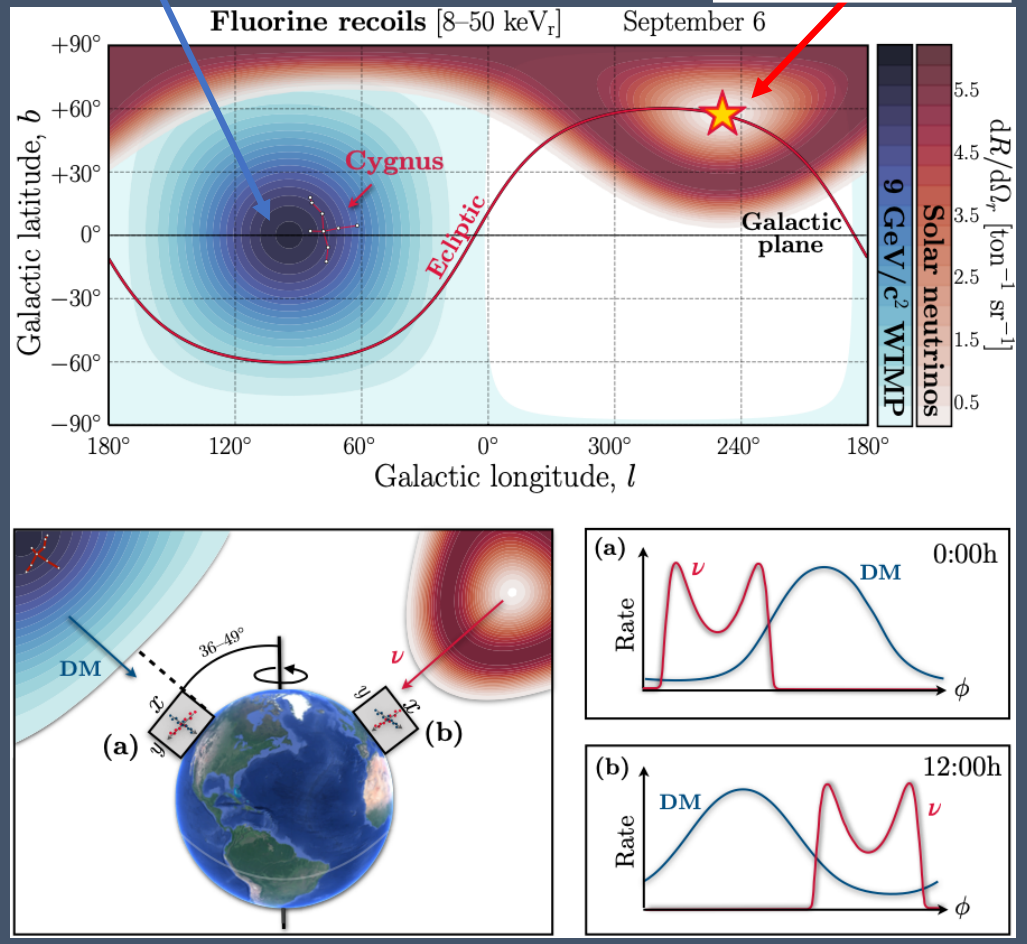
- An experiment that can measure the direction of nuclear recoils...
- Can positively identify galactic origin of a potential dark matter signal w/ only 3-10 recoil events (~10^3 x stronger effect than annual oscillation)
- Can Distinguish dark matter and solar neutrinos → penetrate neutrino floor
- Can do neutrino physics

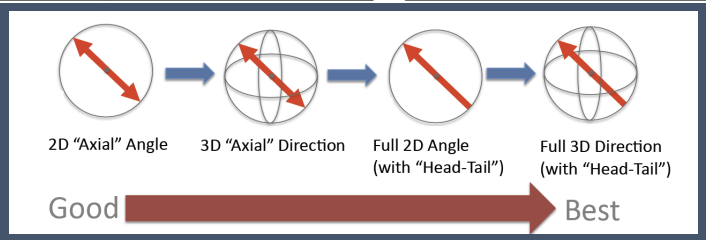
Many potential benefits, but experimentally challenging!
Ideal experiment: 3D-vector-directionality

Neutrinos from the sun

WIMP wind, approx. from CYGNUS

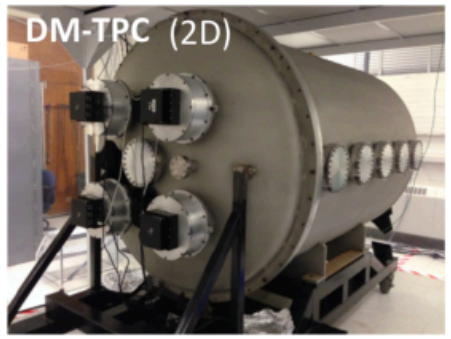
arxiv:2102.04596



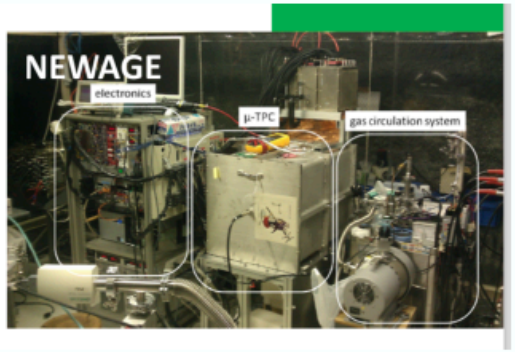


Prototypes and Experiments

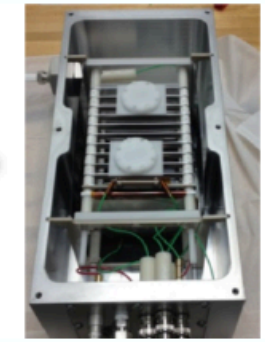
Name	Detector, [TPC readout]	Directionality
NEWAGE	**Gas TPC**, GEM + μPIC	3d
DRIFT	**Gas TPC**, MWPC, **NID**	1.5d
MIMAC	**Gas TPC**, Micromegas + Strips	3d
DMTPC	**Gas TPC**, Optical readout	2d
D^3	**Gas TPC**, 2xGEM + CMOS pixel	3d
New Mexico readout R&D	**Gas TPC**, Optical readout, **NID**	2d
CYGNO	**Gas TPC**, 3xGEM + CMOS optical + PMT	3d / 2d+1d
NEWSdm	Nuclear Emulsions	2d
PTOLEMY	Graphene	2d



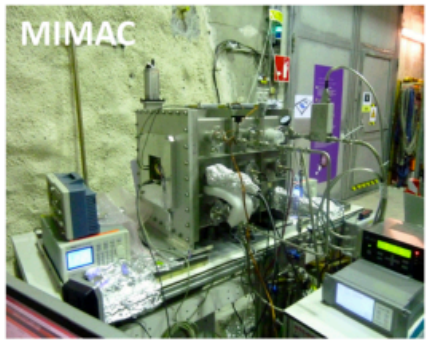
DMTPC



NEWAGE

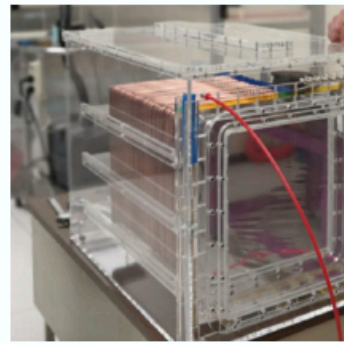


D^3



MIMAC

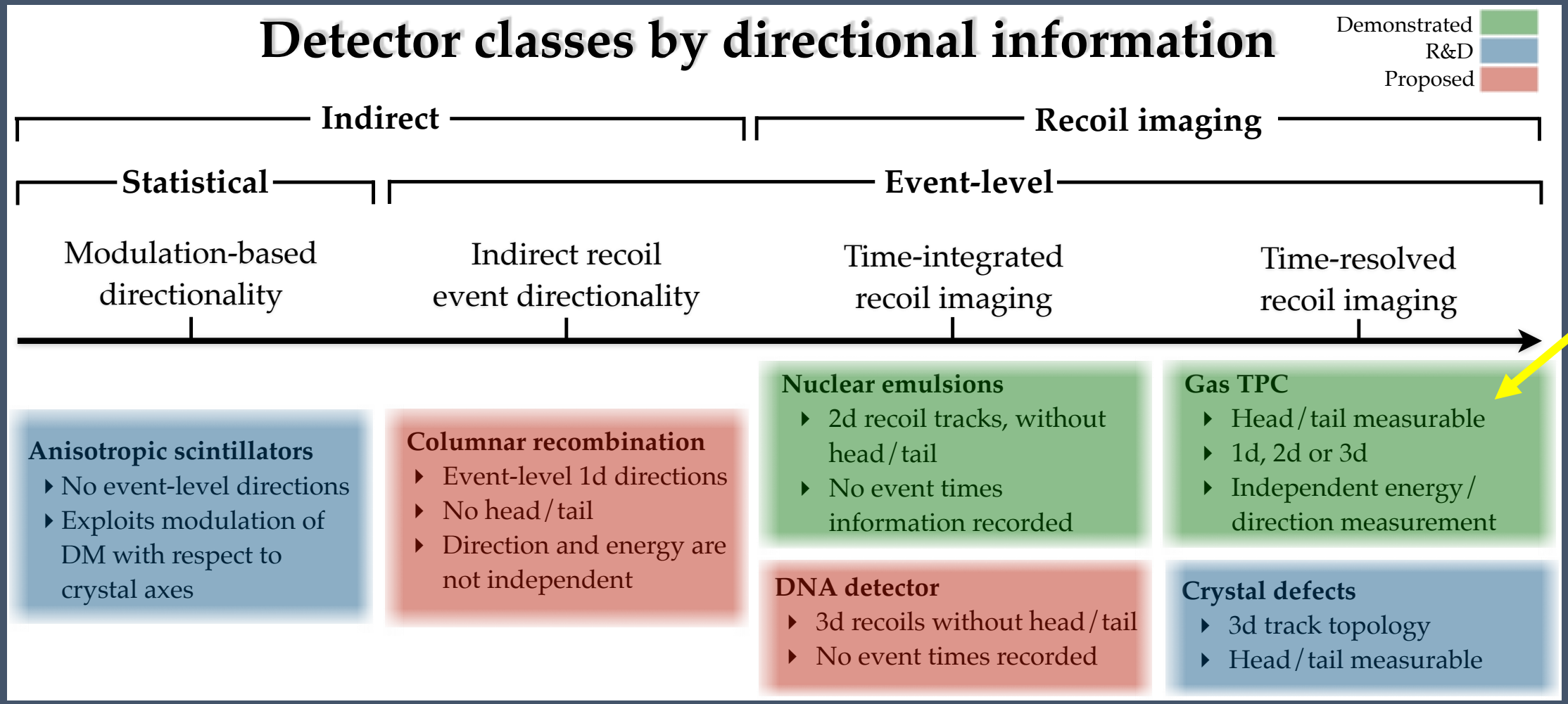
DRIFT



CYGNO

All directional experiments that have set DM limits use gas TPCs
Most TPC groups now working towards the CYGNUS project

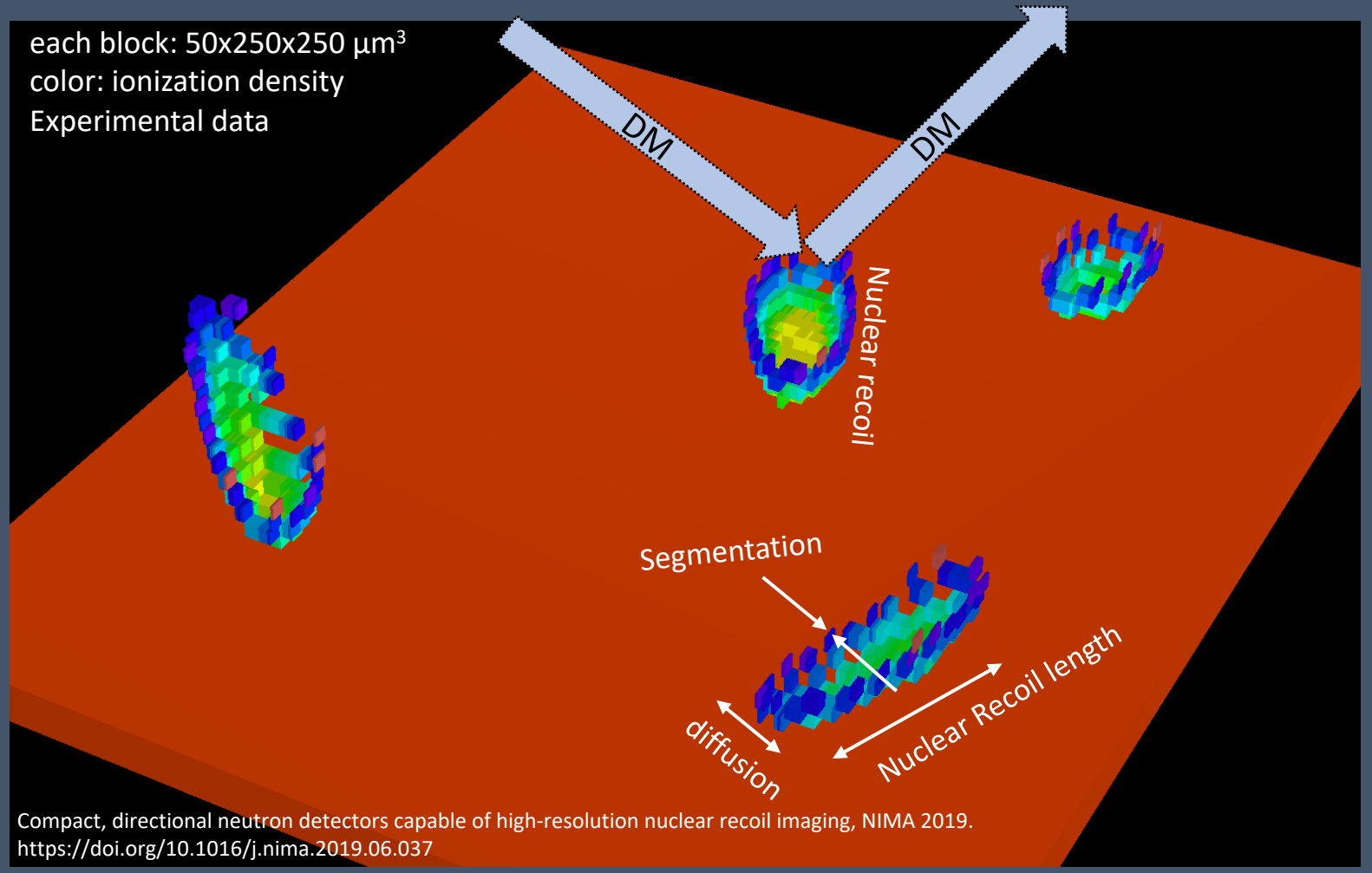
https://arxiv.org/abs/2102.04596



The Power of High Definition (HD) gas TPCs

Capabilities resulting from HD charge readout

- 3D directionality
- Head/tail
- Electron rejection
- Nuclear Recoil ID
- 3D fiducialization



Want: segmentation (here: 50 x 250 µm) < diffusion (~200-500 µm) < recoil length (~mm)

3D vector directionality possible in gas TPC w/ highly segmented readout planes – HD TPCS
See talks by P. Lewis, Pinchi, and Monteiro today, Giambattista Monday

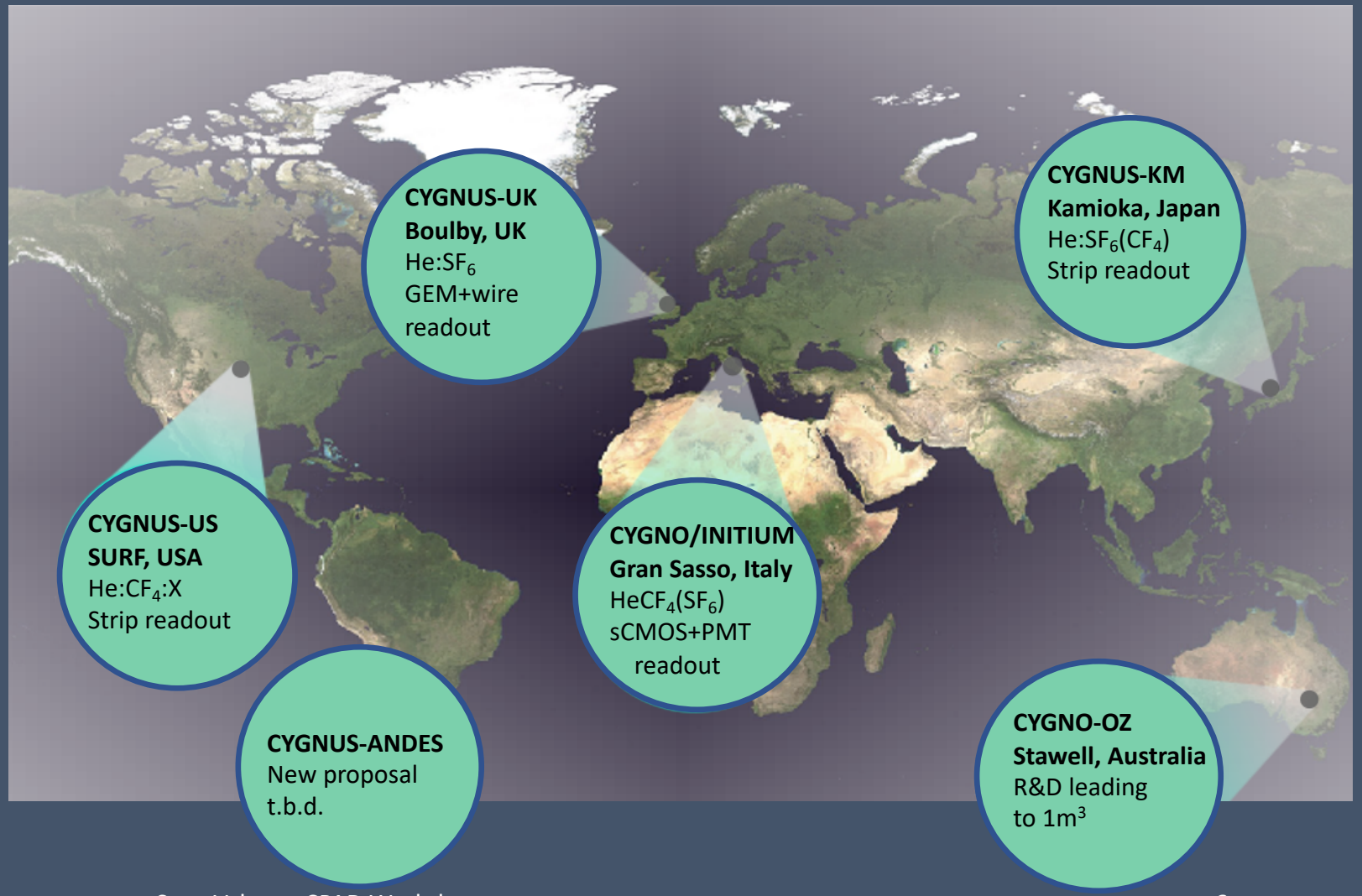
CYGNUS Vision: Multi-site Galactic Recoil Observatory

with directional sensitivity to WIMPs and neutrinos

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!

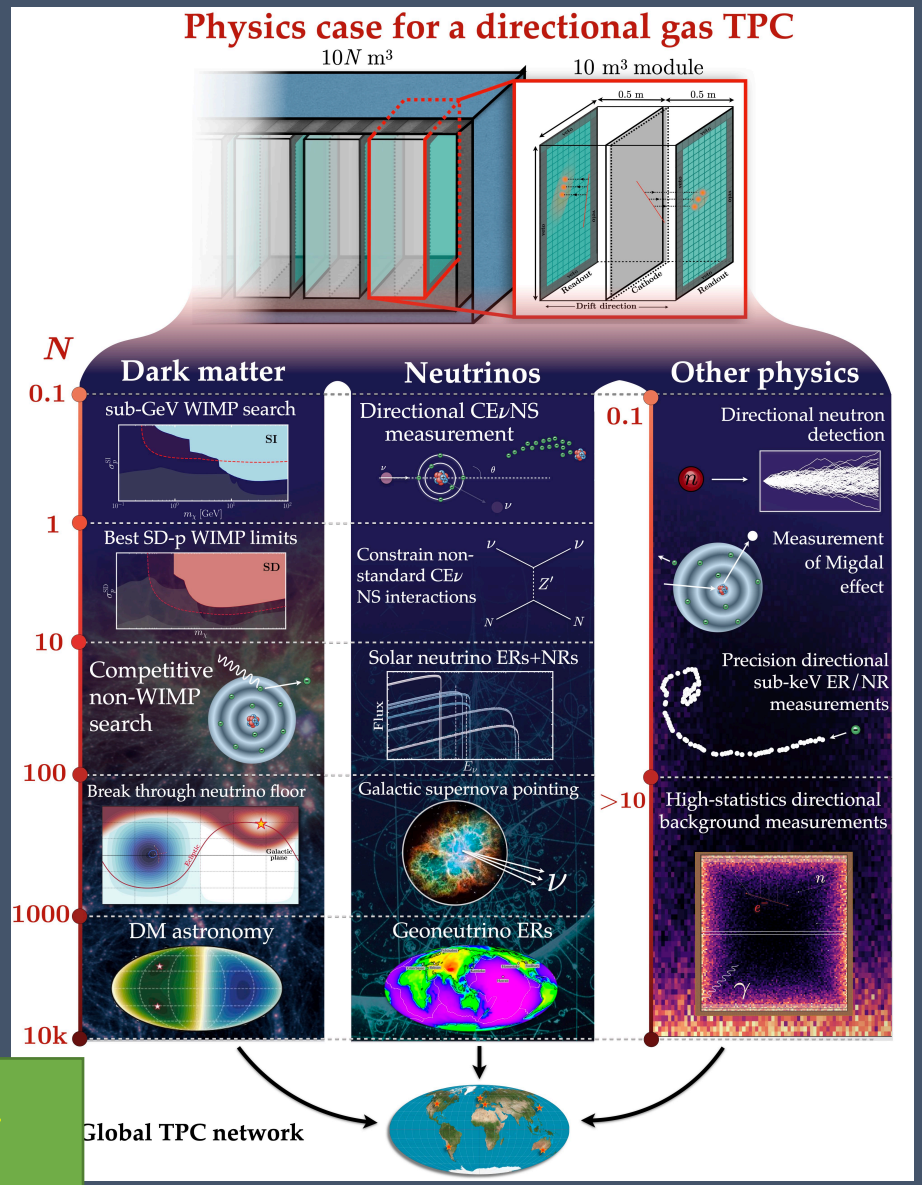


Opportunities for a long-term physics program

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

Exposure, size

- Migdal Effect measurement
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) at either NuMI or DUNE
- Competitive DM limits in SI and SD
- CEvNS from solar neutrinos
- Efficiently penetrating the LDM ν floor
- Observing galactic DM dipole
- Measuring DM particle properties and physics
- Geoneutrinos
- WIMP astronomy



https://arxiv.org/abs/2102.04596

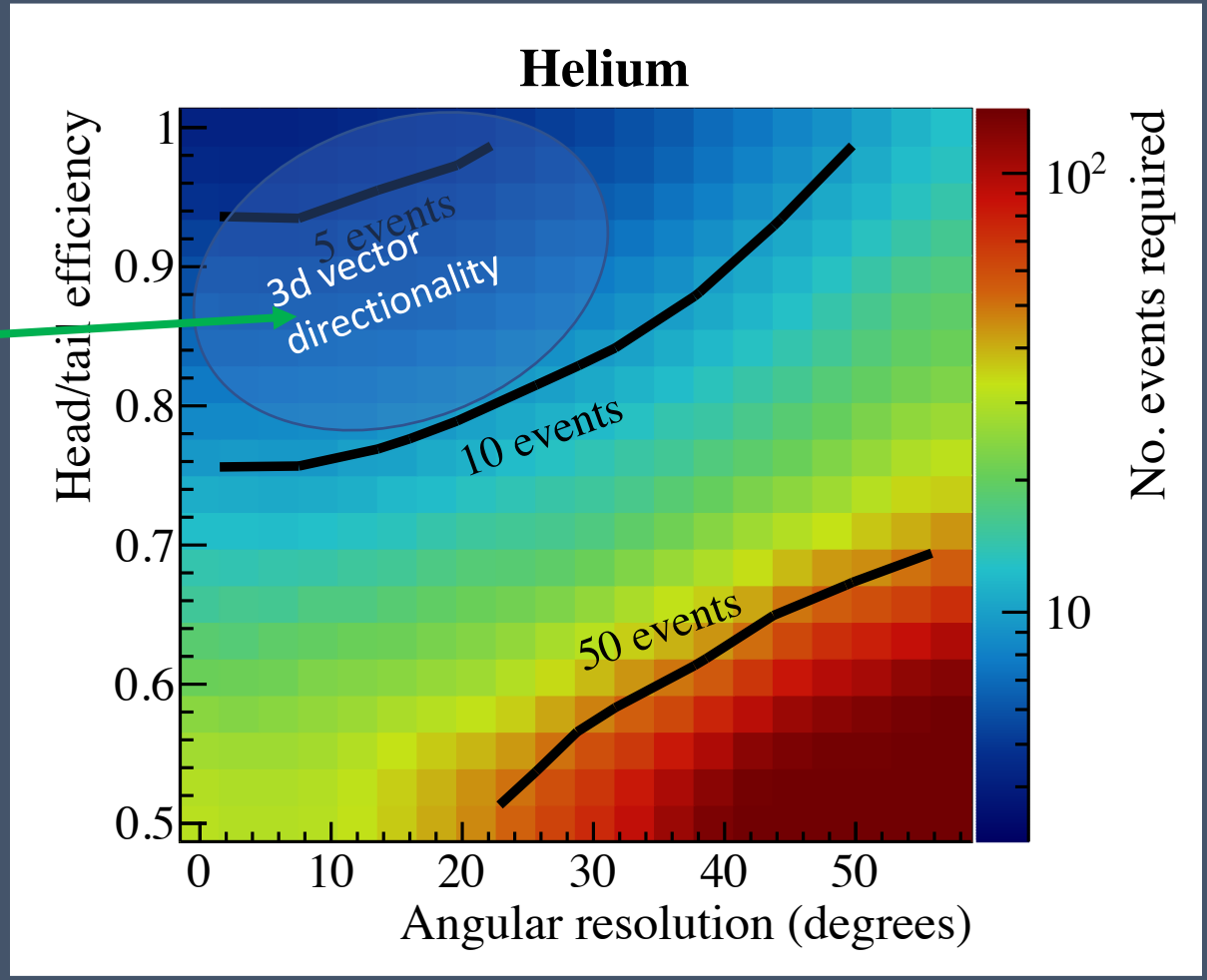
Extensive concept paper on 1000 m³ detector: https://arxiv.org/abs/2008.12587
Focused on technical feasibility and WIMP searches
Wider physics potential being explored as part of US Snowmass process

Detector Performance Requirements

https://arxiv.org/abs/2102.04596

(if targeting solar neutrinos and m= ~10 GeV Dark Matter)

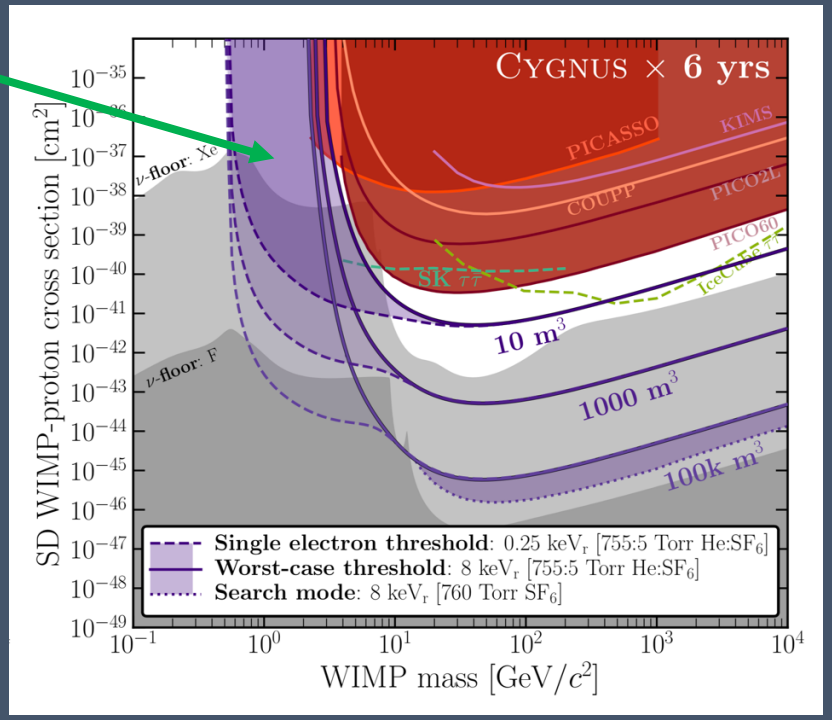
- Event-level recoil directionality
  - angular resolution ≤ 30 degrees
  - excellent head/tail sensitivity
- Rejection of internal electron backgrounds
  - by factor >= 10^5 for 1000 m^3 detector
- All of above down to E_{recoil} ~ 5 keV
- Energy resolution ~ 10% at 5.9 keV
- Timing resolution ~ 0.5 h



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

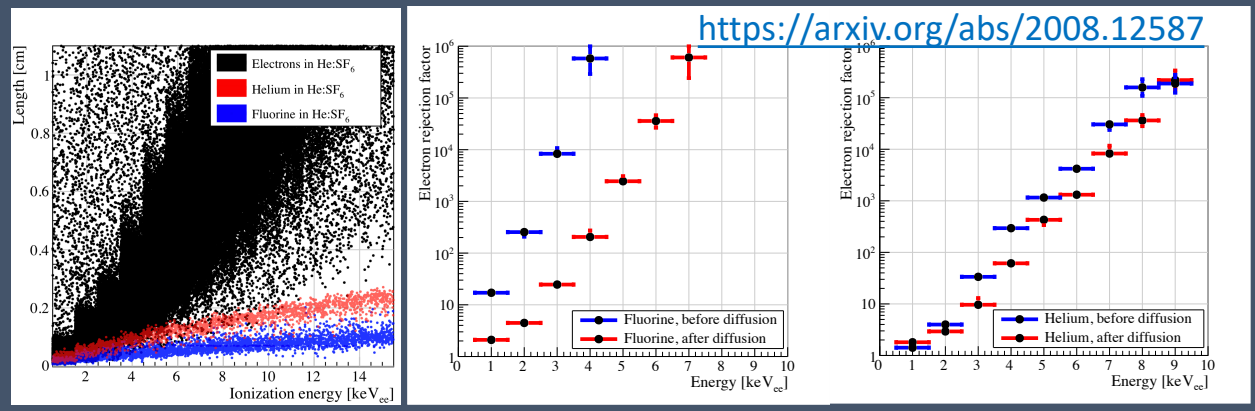
Assumptions: mχ = 10 GeV, He:SF_6 gas

Key issue: WIMP sensitivity depends on electron rejection

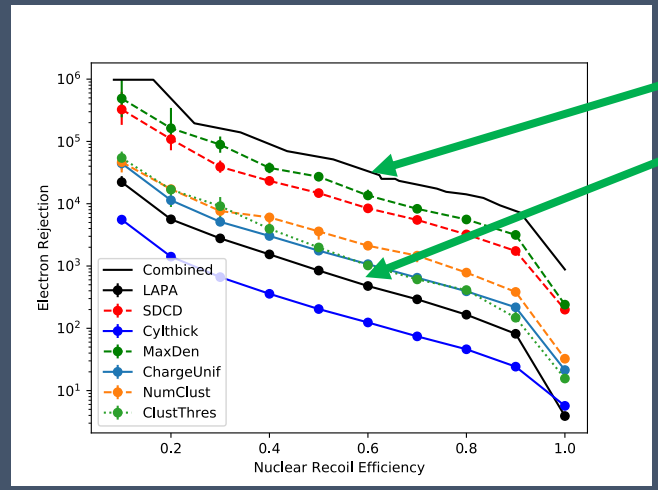


3D electron rejection (simulation) via dE/dx 5 torr SF_6 + 755 torr Helium

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.

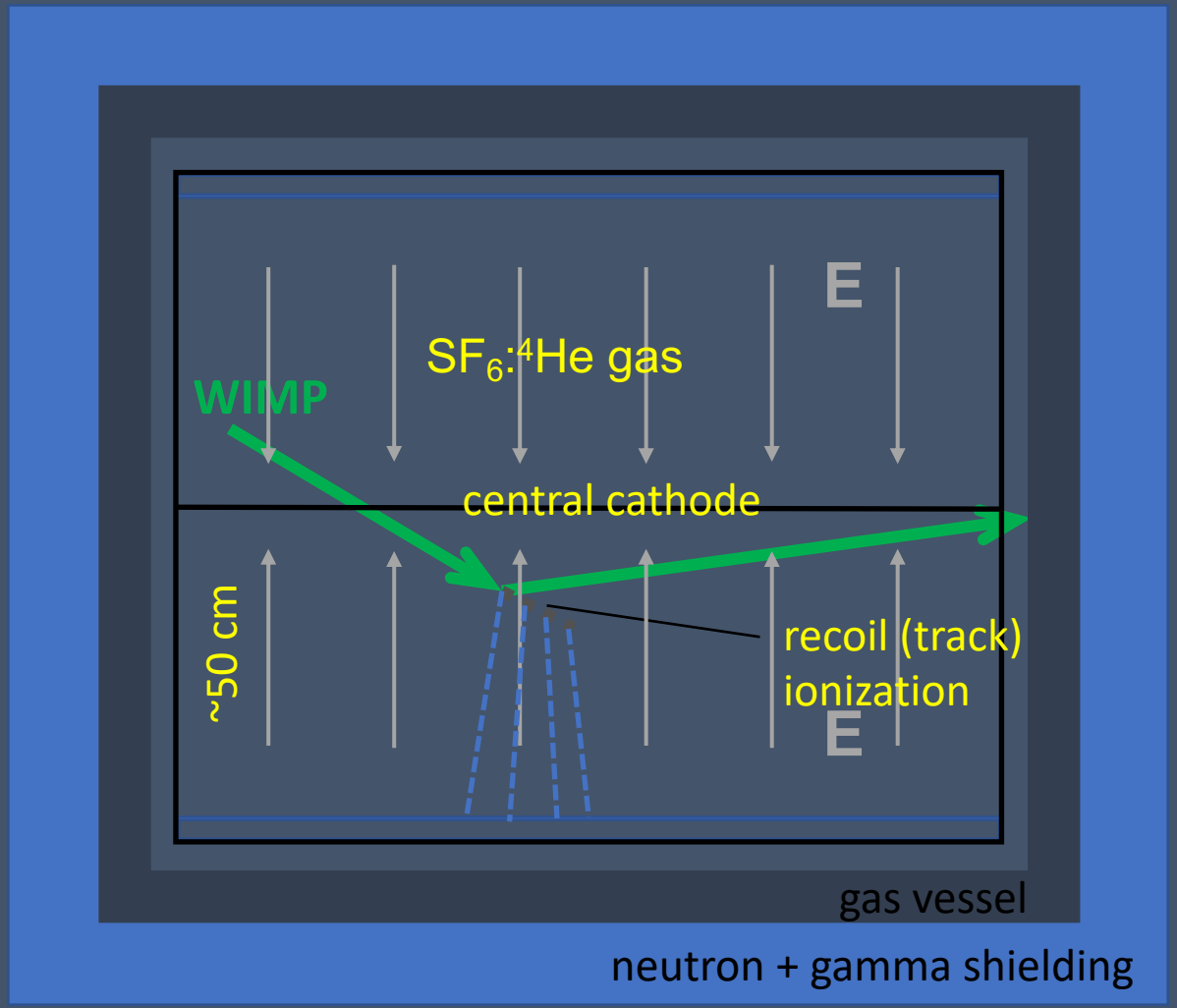


~2 orders of magnitude improvement over dE/dx !

Majd Ghrear et al., arxiv.:2012.13649
Improved, physically motivated observables for electron rejection. Requires HD readout.

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

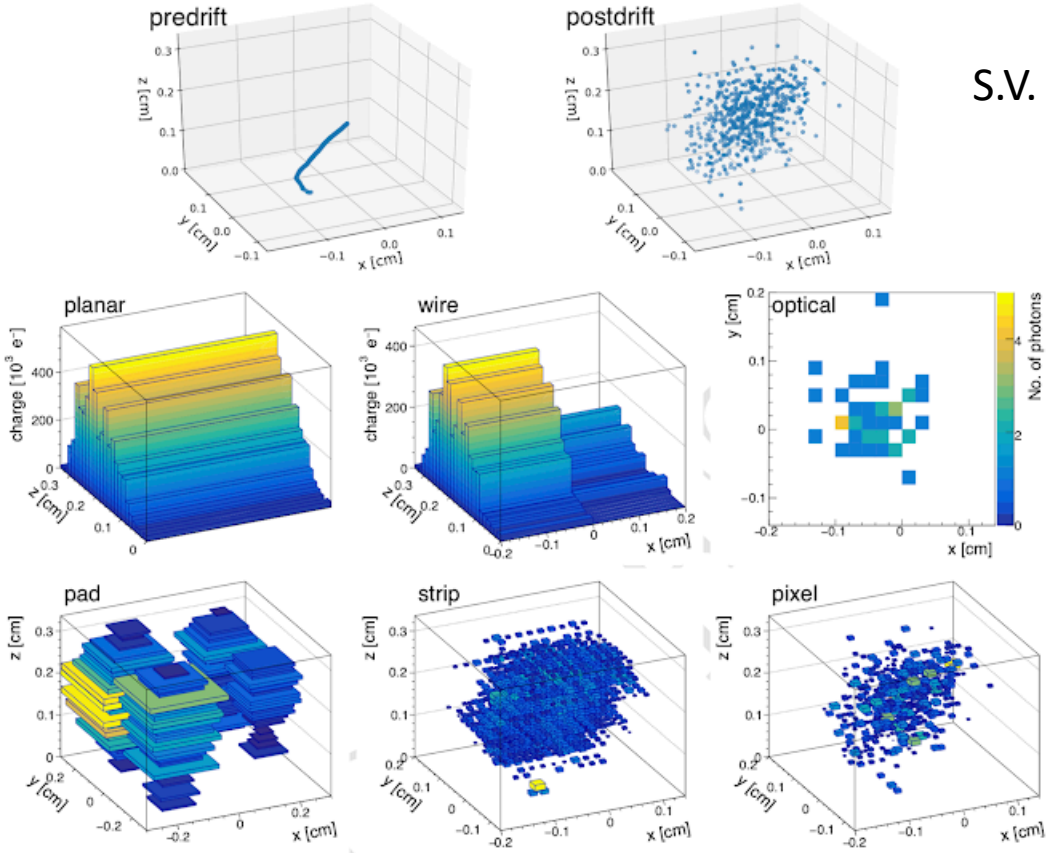


FIG. 9. Simulated 25 keV_r helium recoil event in He:SF_6 gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

electron recoil

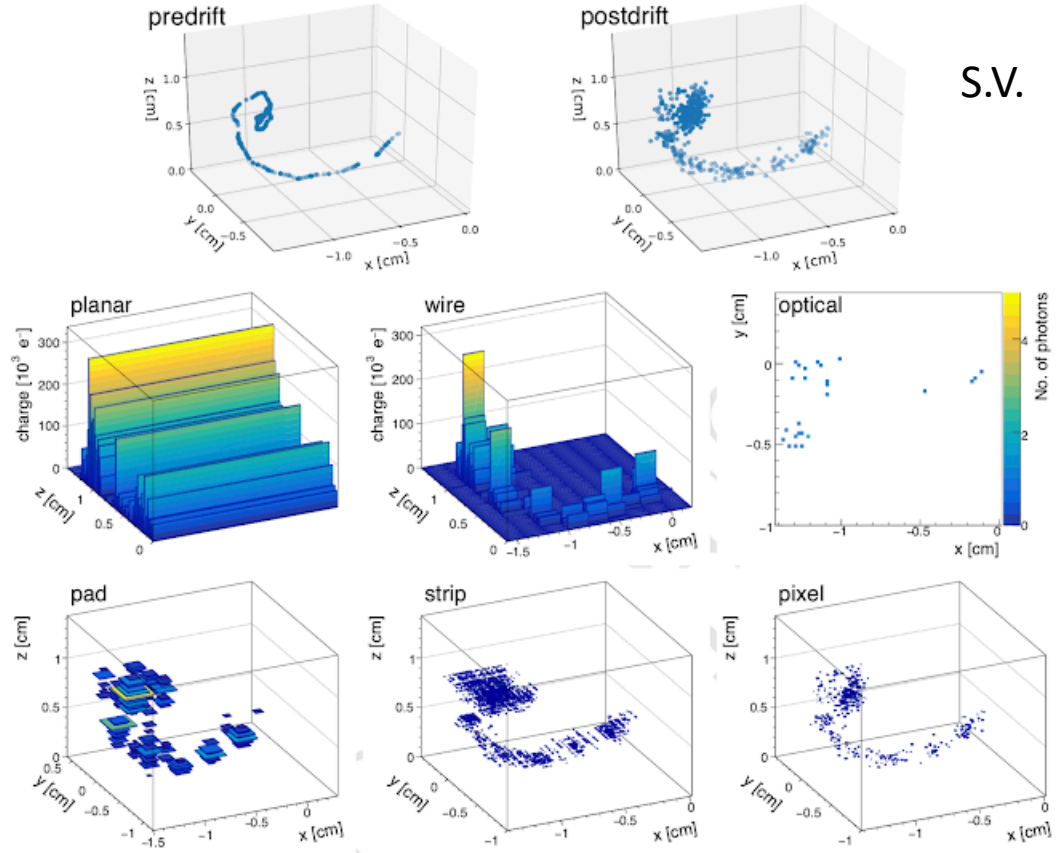
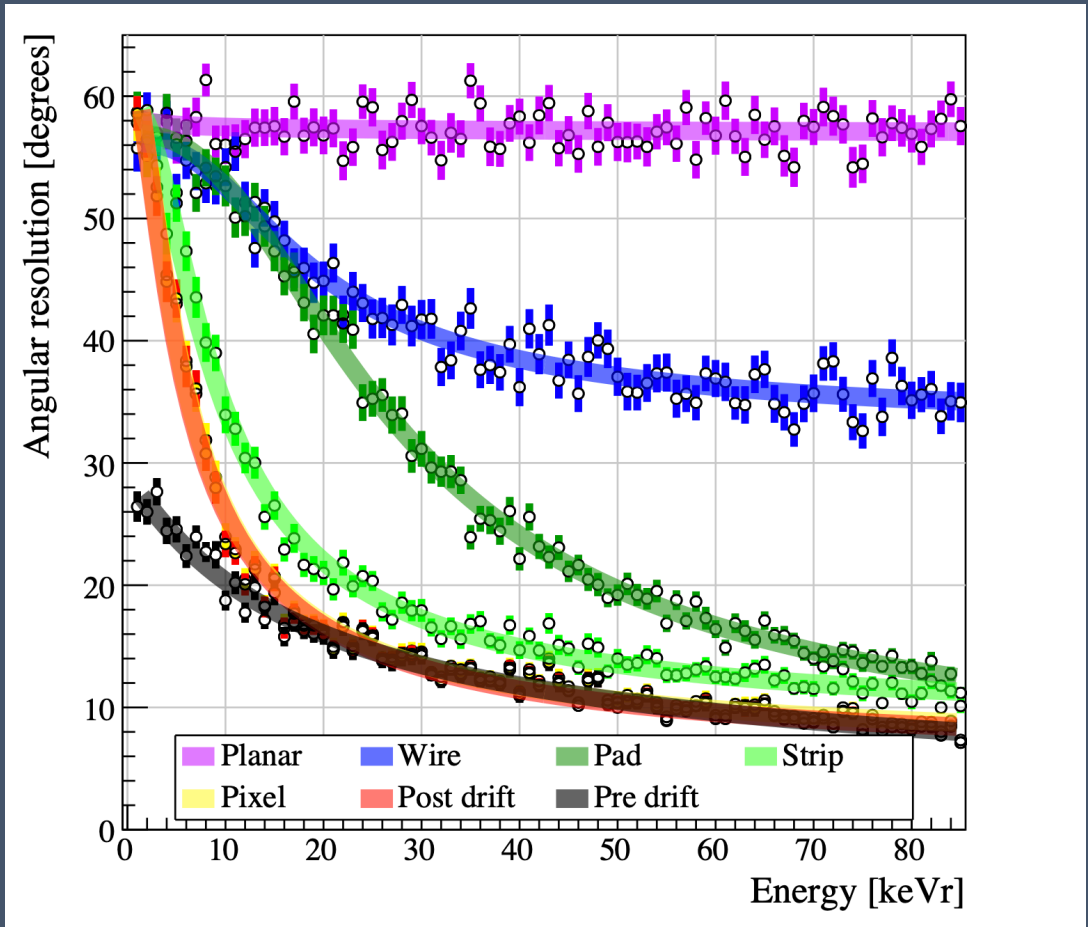


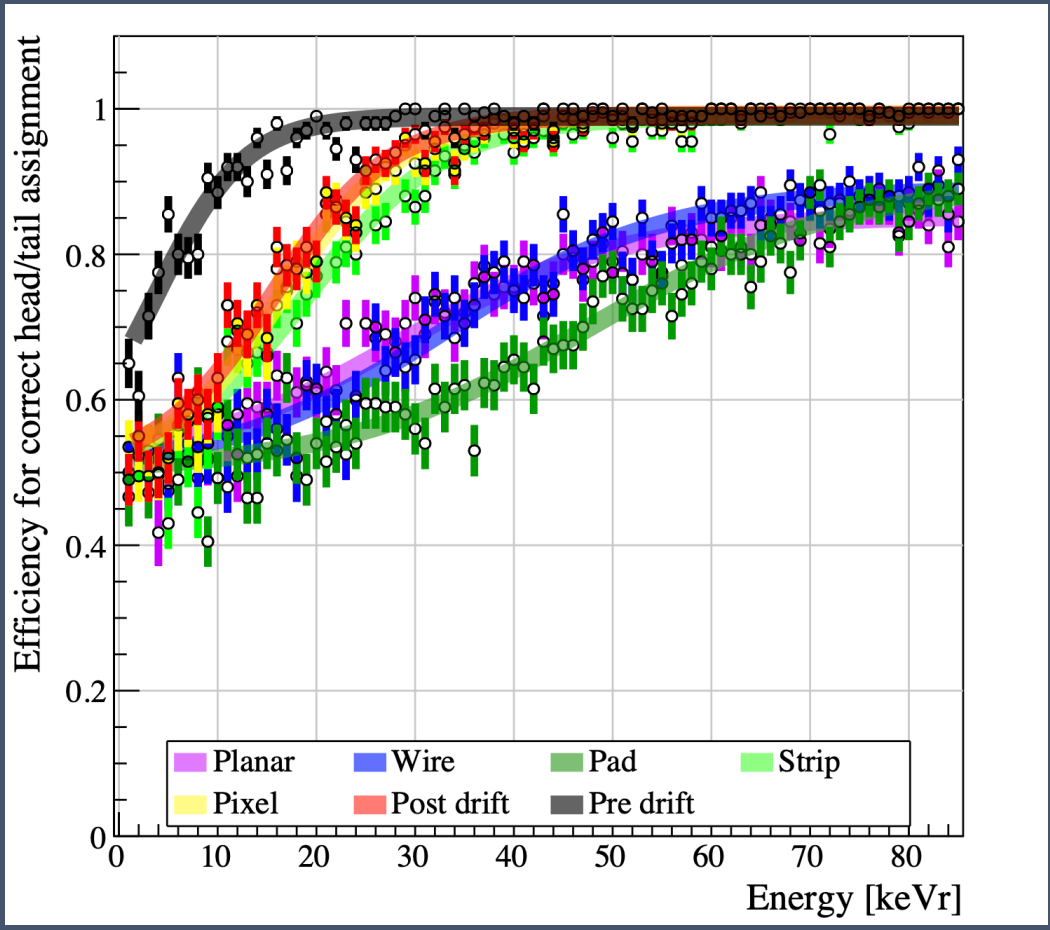
FIG. 10. Simulated 20 keV_{ee} electron event in He:SF_6 gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

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



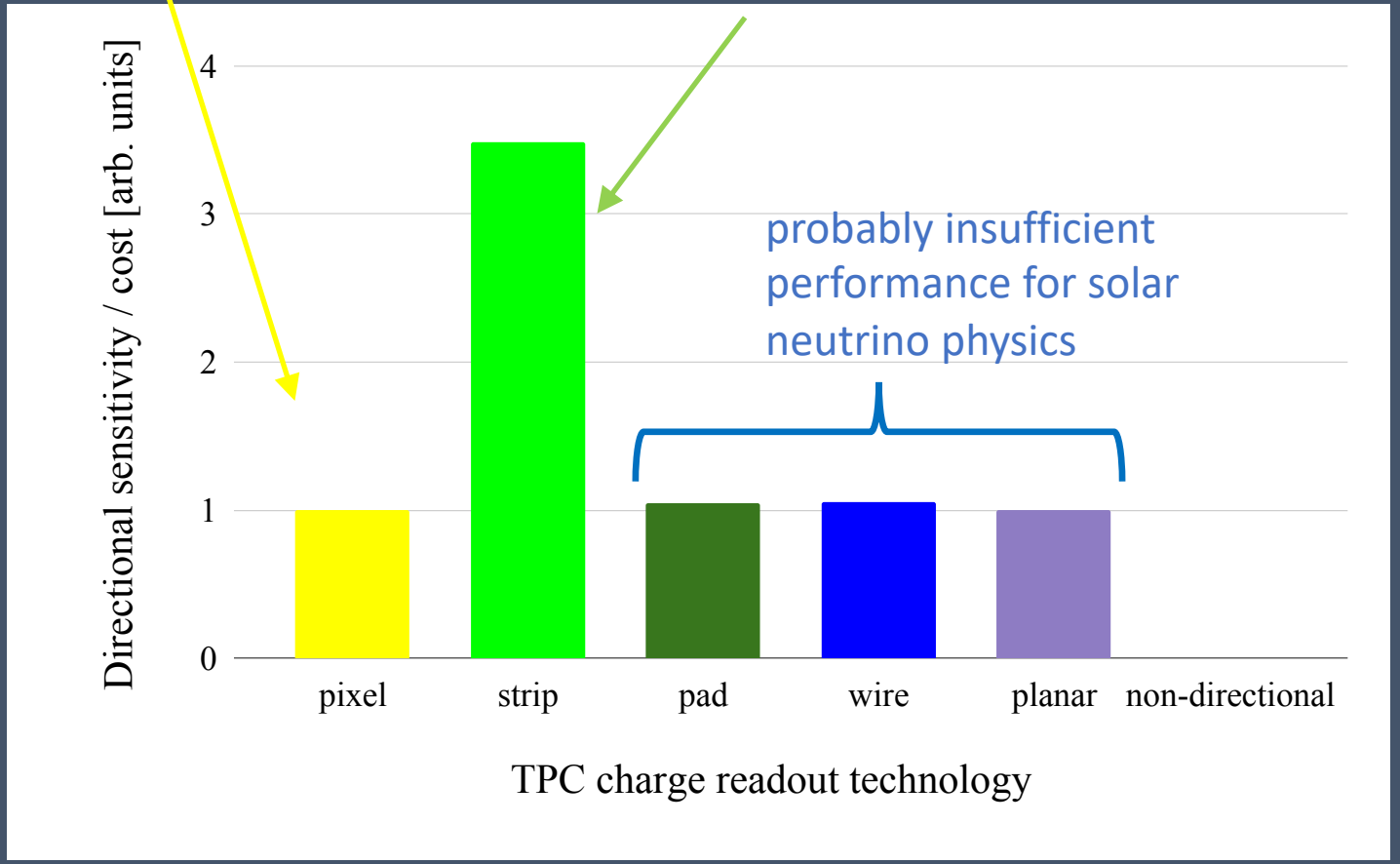


Pixel readout extracts the entire directional information left after diffusion (red and yellow curves overlap fully)
Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost

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

Current U.S. efforts

- DRIFT experiment
  - Pioneering directional TPC
  - MWPC charge readout
  - First to demonstrate negative ion drift, fiducialization via minority carriers → background free
- Readout R&D on HD TPCs
  - U. New Mexico
  - Wellesley
  - U. Hawaii
- Quenching factor measurements
  - Duke/ TUNL

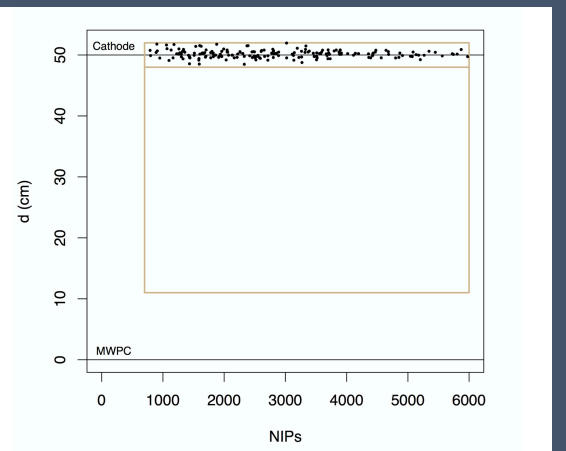
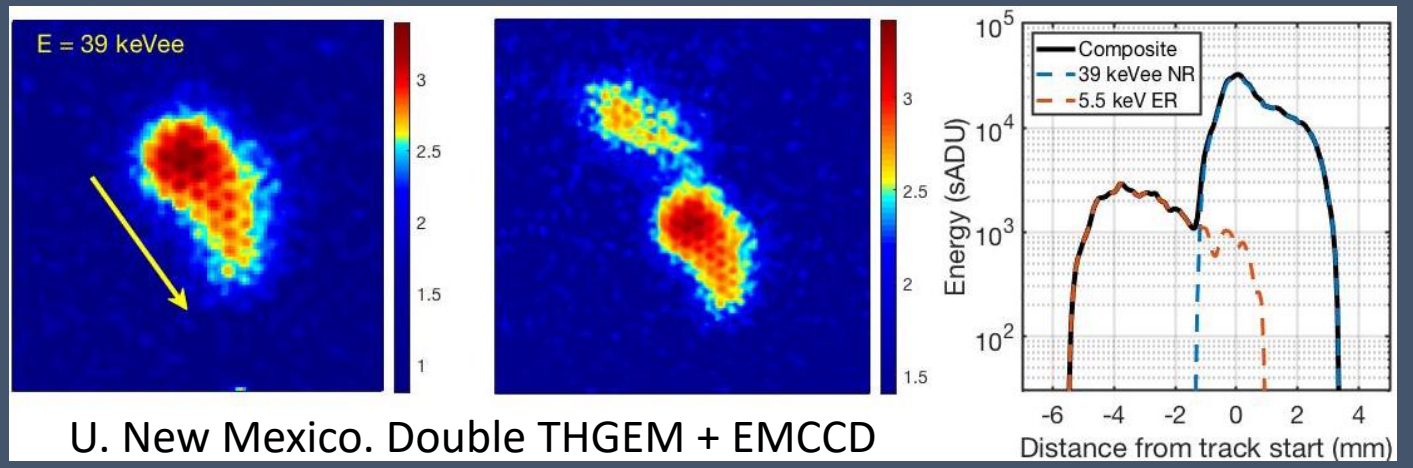


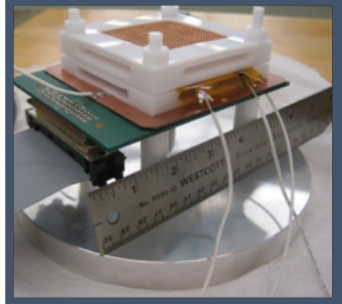
Fig. 7 – *d* vs. *NIPs* data for 54.7 live-days of shielded background data. All of the events passing the analysis cuts cluster around the central cathode consistent with the expectation of RPRs events there. In the fiducial window, large tan rectangle, no events were observed. This background-free result provides us with a limit on WIMP dark matter.



U. New Mexico. Double THGEM + EMCCD

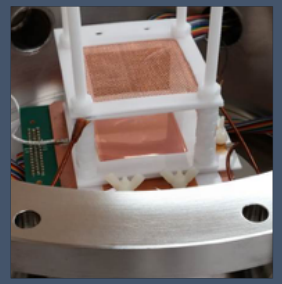
CYGNUS HD: Double GEM + Pixel readout activities

2011-2013



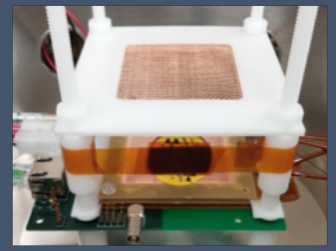
μD^3 (~1cm^3)

2013



~2.5 cm^3

2013



~ 20 cm^3

1st generation, proof of concept

2014

2 x 60 cm^3

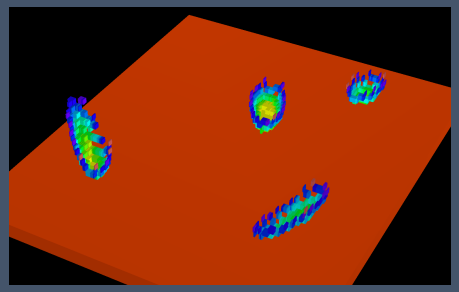
2015

8 x 40 cm^3

BEAST TPCs

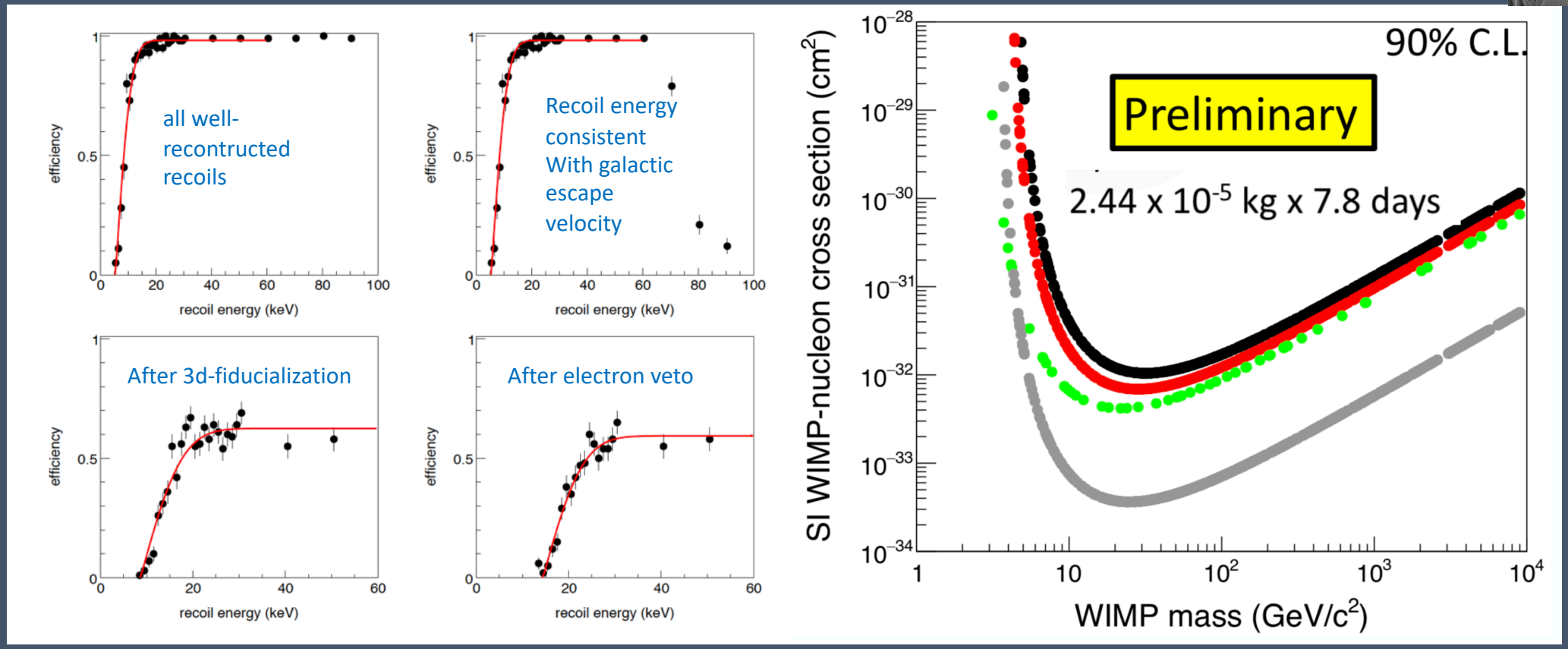
2nd Generation: compact directional neutron detectors. *currently operating* @ KEK, Japan.

- Extensive prototyping with HD pixel readout completed @ U. Hawaii, culminating in BEAST TPCs
- Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for quenching factor measurements and precision studies of nuclear recoil physics
- Planning to evaluate GridPix charge readout ~Summer 2021 (see next talk)



Demonstration: Dark Matter limit with BEAST TPC directional neutron detectors (low gain)

Tom Thorpe

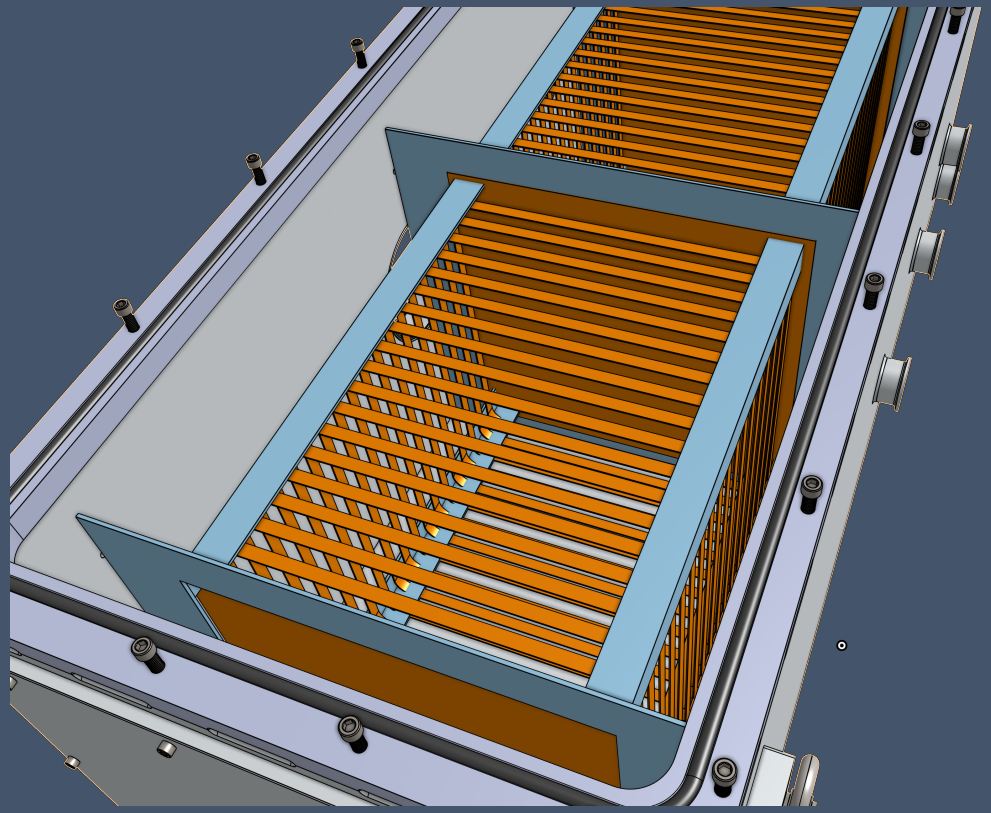


Double GEM + pixel readout, *even at gain ~1500*, already has outstanding performance. At gain >20k, can detect single electrons. But is this level of performance worth the cost?

New US effort: CYGNUS HD – two detectors

Cost-effective scale up via existing collider technologies

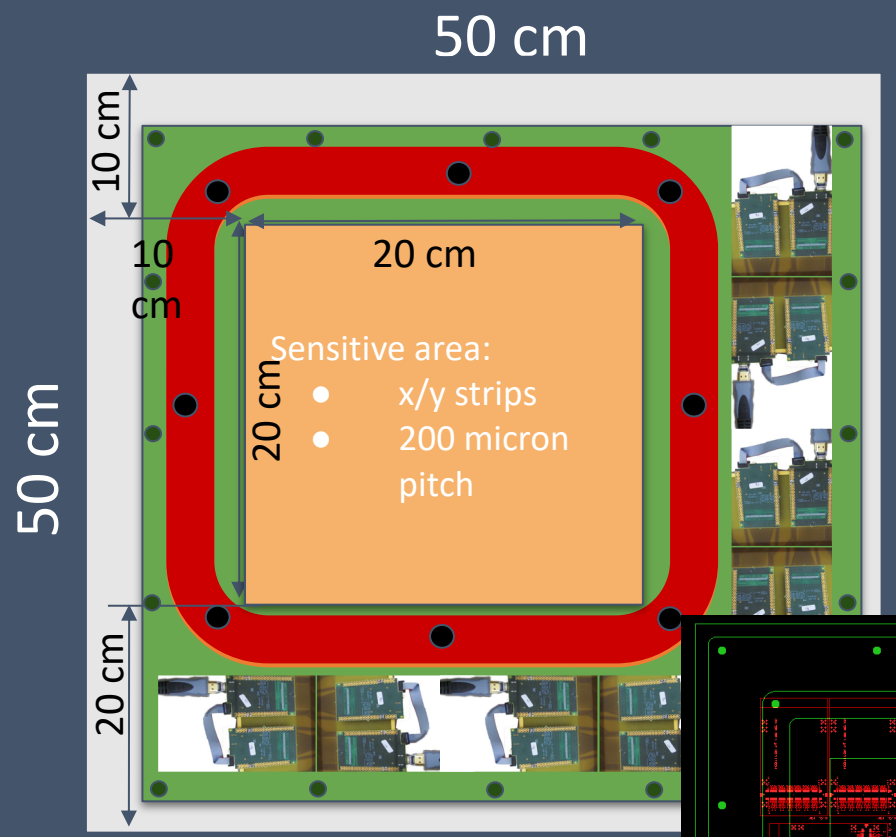
CERN strip micromegas, CERN VMM3a hybrids, CERN SRS readout



CYGNUS HD “Keiki” - factor 1000 scaleup of BEAST TPC
Evaluation of components for follow-on 1m^3 detector

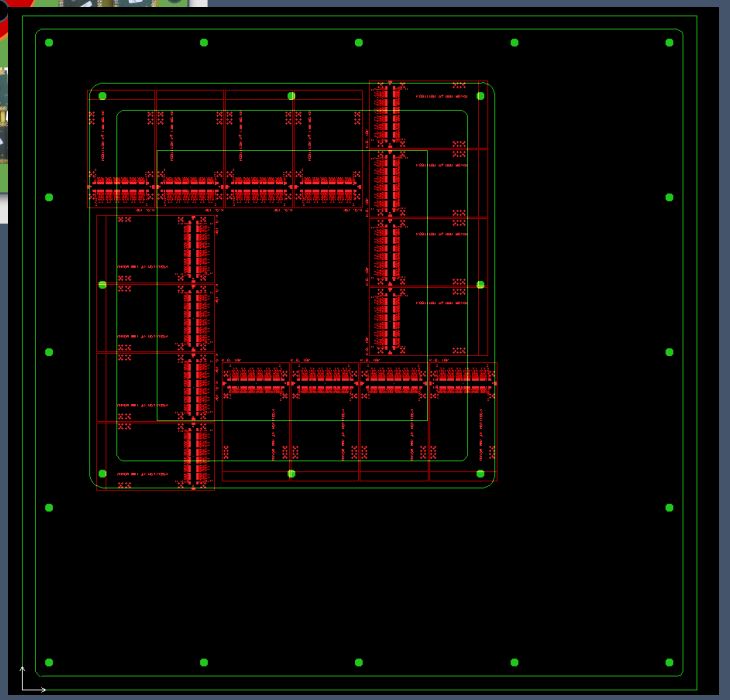
CYGNUS HD Keiki readout plane

- Vacuum vessel interior: 50 x 50 cm
- Strip micromegas sensitive area: 20x20cm
- 200 micron pitch
- 1000 x-strips, 1000 y-strips
- 16 Front end-cards
  - 8 on x-side
  - 8 on y-side
- 8 HDMI connectors
  - 4 on x-side
  - 4 on y-side
- Hybrids on back of readout plane, to allow tighter packing in large detector
- Iterating readout plane design with CERN
- Plan to evaluate 1) resistive, diamond like carbon x/y strips and 2) x/y strips w/ dielectric protection



Conceptual drawing

Preliminary design

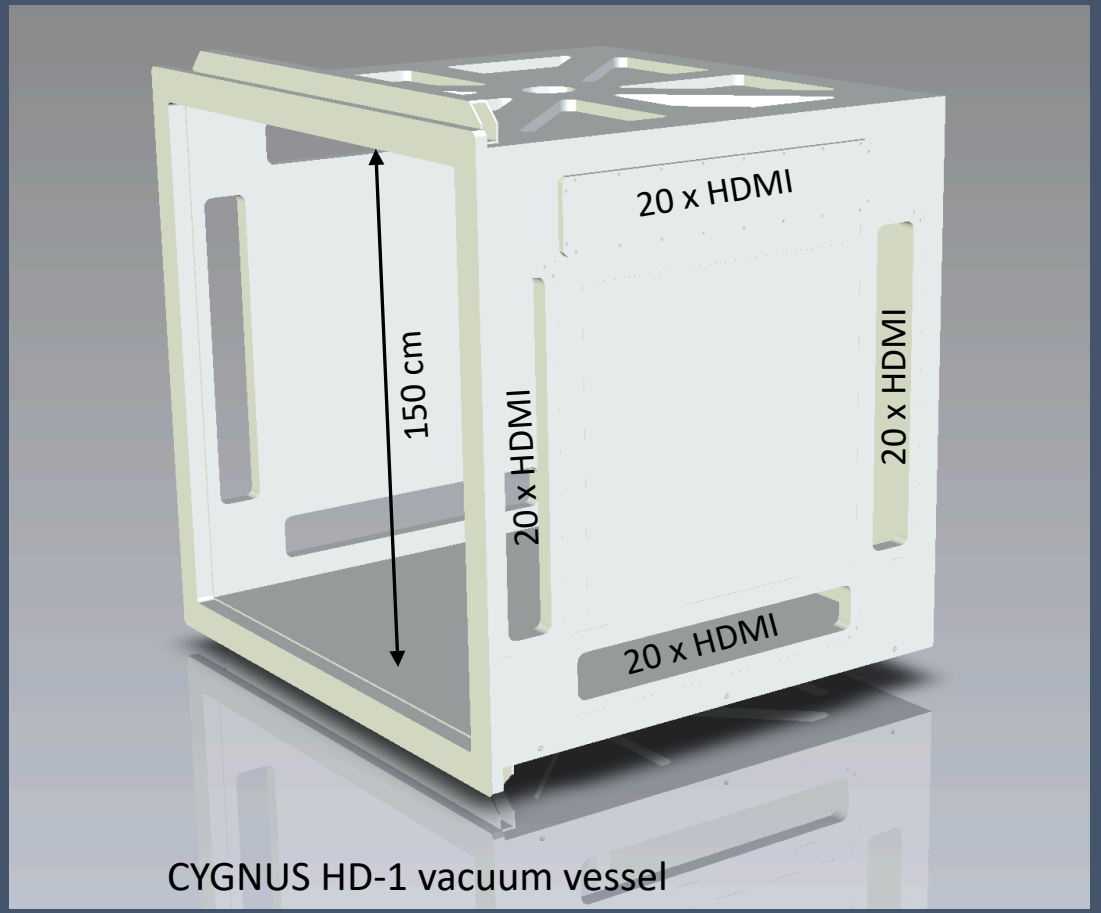


Digitize inside vessel, custom HDMI feedthroughs

CYGNUS HD-1 Demonstrator

- 1000 liter sensitive volume
- 2 x 50 cm drift
- Unit-cell technology demonstrator for future, large CYGNUS neutrino/DM observatory
- 1.5 x 1.5 x 1.5 m internal volume.
- May go underground
- CERN strip micromegas readout, 2 x 1m^2
- Custom feedthroughs with ~20 HDMI connectors

Vacuum vessel design ongoing at vendor



CYGNUS HD-1 vacuum vessel

Yesterday's background → today's signal?

- HD gas TPC *excellent* at identifying electron-recoil events
- So far, treated as background
- But they could be an important new signal
- A *vector-directional* signal
- CYGNUS study ongoing!

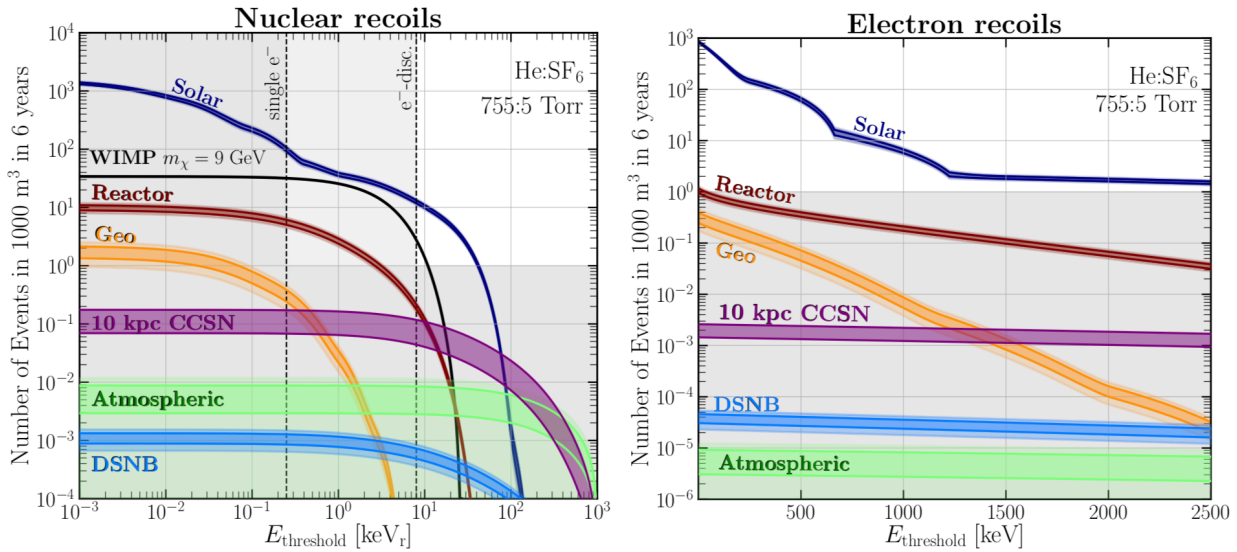
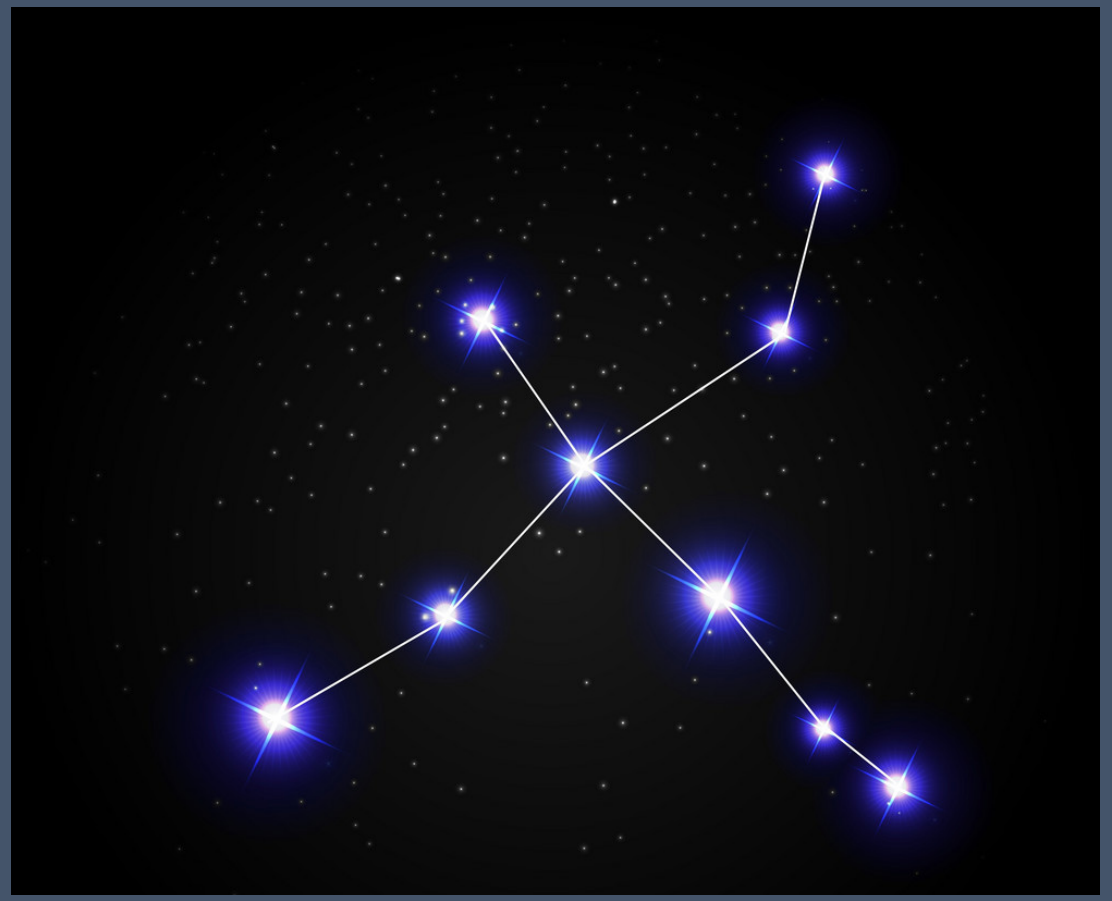


FIG. 4. Number of neutrino-nucleus (left) and neutrino-electron (right) recoil events observed in a CYGNUS-1000 m^3 detector filled with atmospheric pressure He:SF_6 at a 755:5 Torr ratio (the event rates are summed over each target nuclei). We calculate the expected number of observed events by integrating the event rate for each background component above a lower energy threshold $E_{\rm threshold}$. The background components are shown as darker and lighter shaded regions indicating the 1 and 2σ uncertainties from the predicted flux. For comparison we also show the nuclear recoil event rate expected from a $m_\chi = 9\,{\rm GeV}\,c^{-2}$ WIMP with a SI WIMP-proton cross section of $\sigma_p^{\rm SI} = 5 \times 10^{-45}$ cm^2 as a black line. For the reactor and geoneutrinos we assume the entire 1000 m^3 is located at Boulby, UK. The purple region indicates the range of expected numbers of events from the neutrino bursts from 11–27 $M_\odot$ core-collapse supernovae located 8 kpc away from Earth. To add further clarity we shade in gray parts of the plot which give fewer than one event in this exposure. In the left panel we also show as dashed lines the 0.25 and 8 keV_r single electron and electron discrimination thresholds respectively.

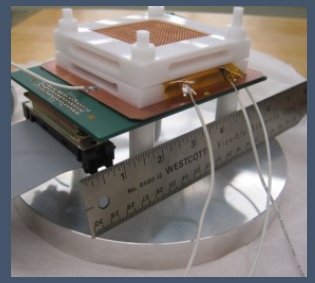
Conclusion

- HD gas TPCs suitable for directional DM, neutrino detection, and precision measurement
- Potential for a rich, long-term physics program based on incremental scale-ups
- CYGNUS concept paper and new review of directional detection:
  https://arxiv.org/abs/2008.12587
  https://arxiv.org/abs/2102.04596
- CYGNUS US
  - performing recoil physics measurements with small, UHD detectors
  - building next generation strip detectors to demonstrate scaleup
- CYGNUS now exploring complementary electron recoil signatures
- Planning Snowmass mini-workshop on directional detection in Fall 2021



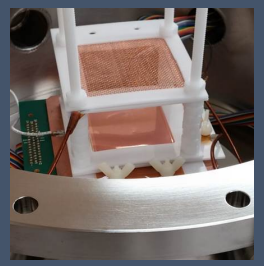
CYGNUS HD: MPGD gas TPCs for nuclear recoil imaging

2011-2013



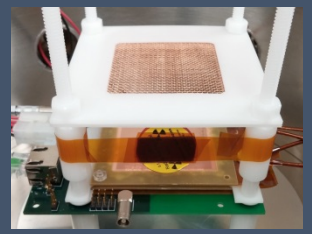
μD³ (~1cm³)

2013



~2.5 cm³

2013



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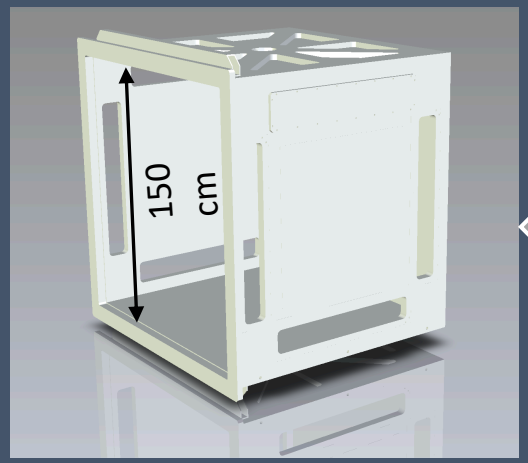
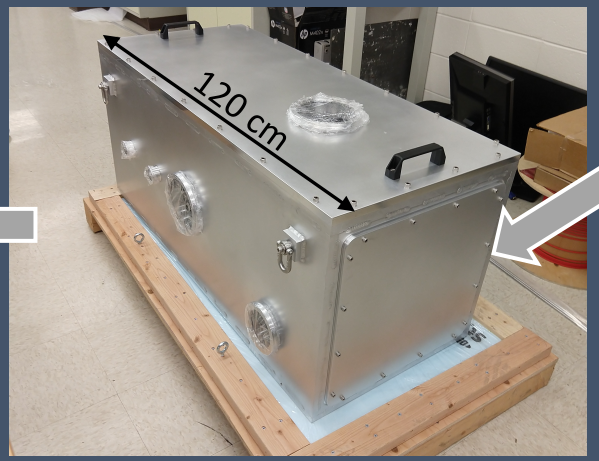
2nd Generation: compact directional neutron detectors. *currently operating* @ KEK, Japan.

2021



CYGNUS HD 1 Demonstrator (1 m³)

2020



CYGNUS HD "Keiki" (40 liters)

3rd Generation: Optimized for dark matter

- 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