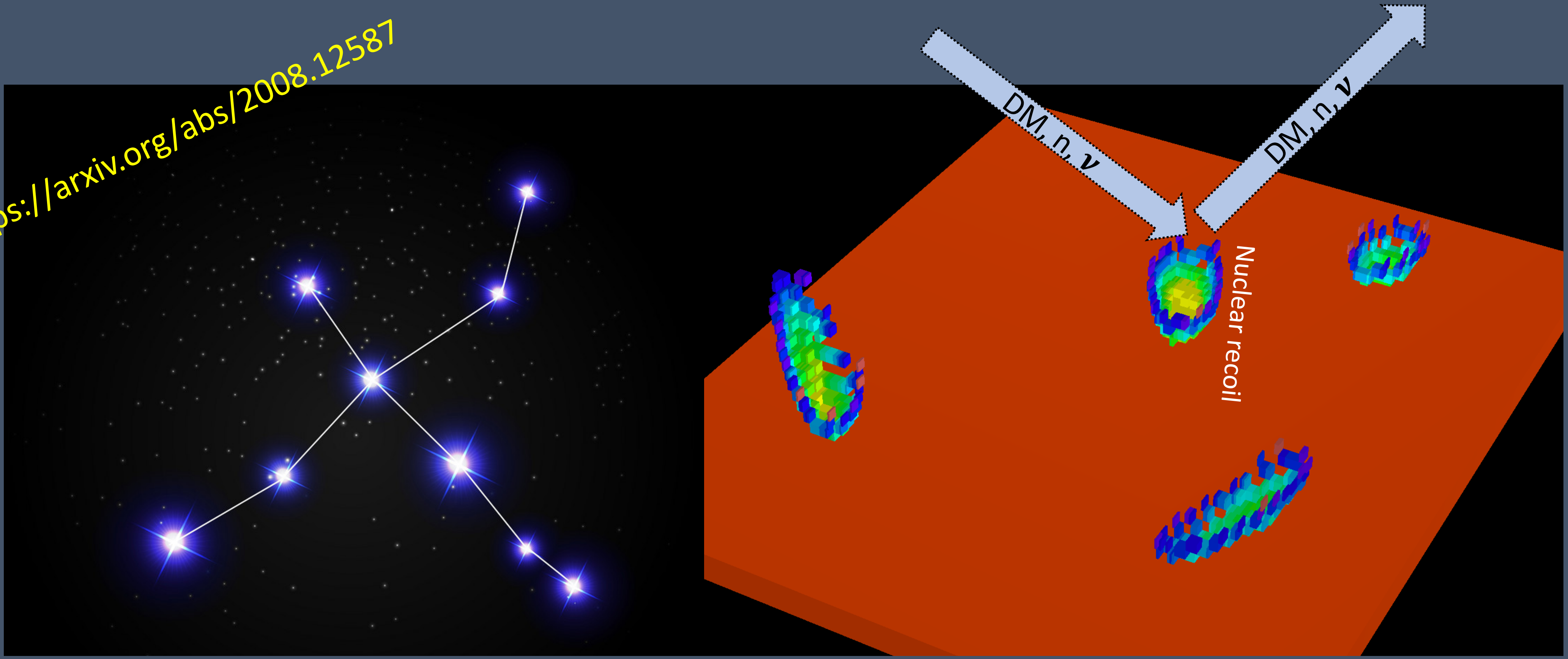
CYGNUS: a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

https://arxiv.org/abs/2008.12587



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
- Ideal case: 3D-vector-directionality, event-by-event

Many potential benefits, but experimentally challenging!

WIMP wind, approx. from CYGNUS

Neutrinos from the sun

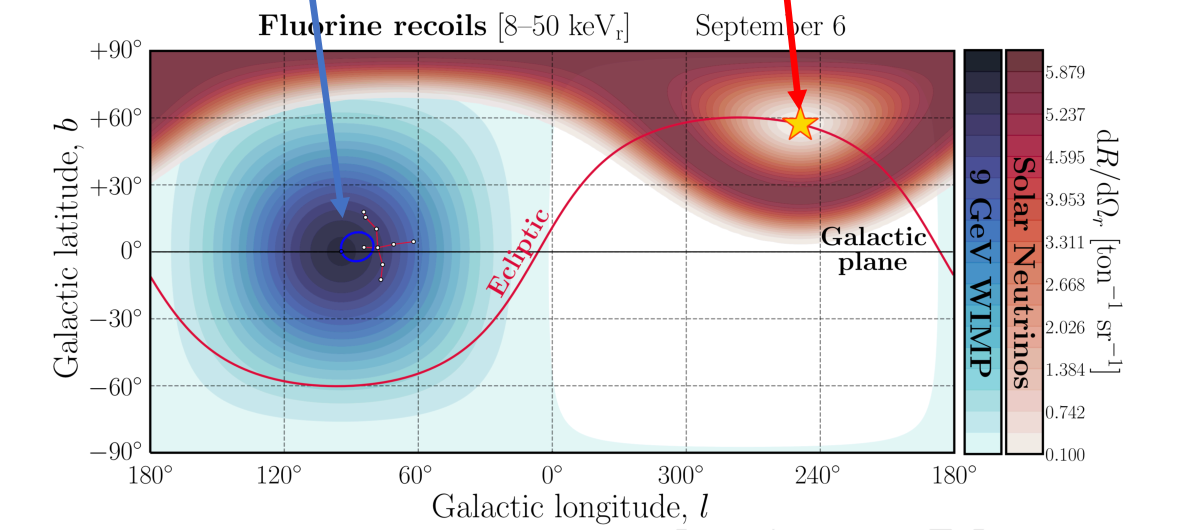
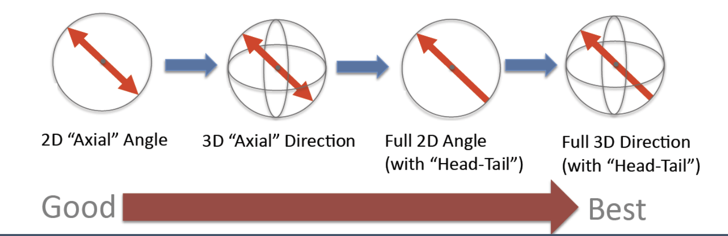
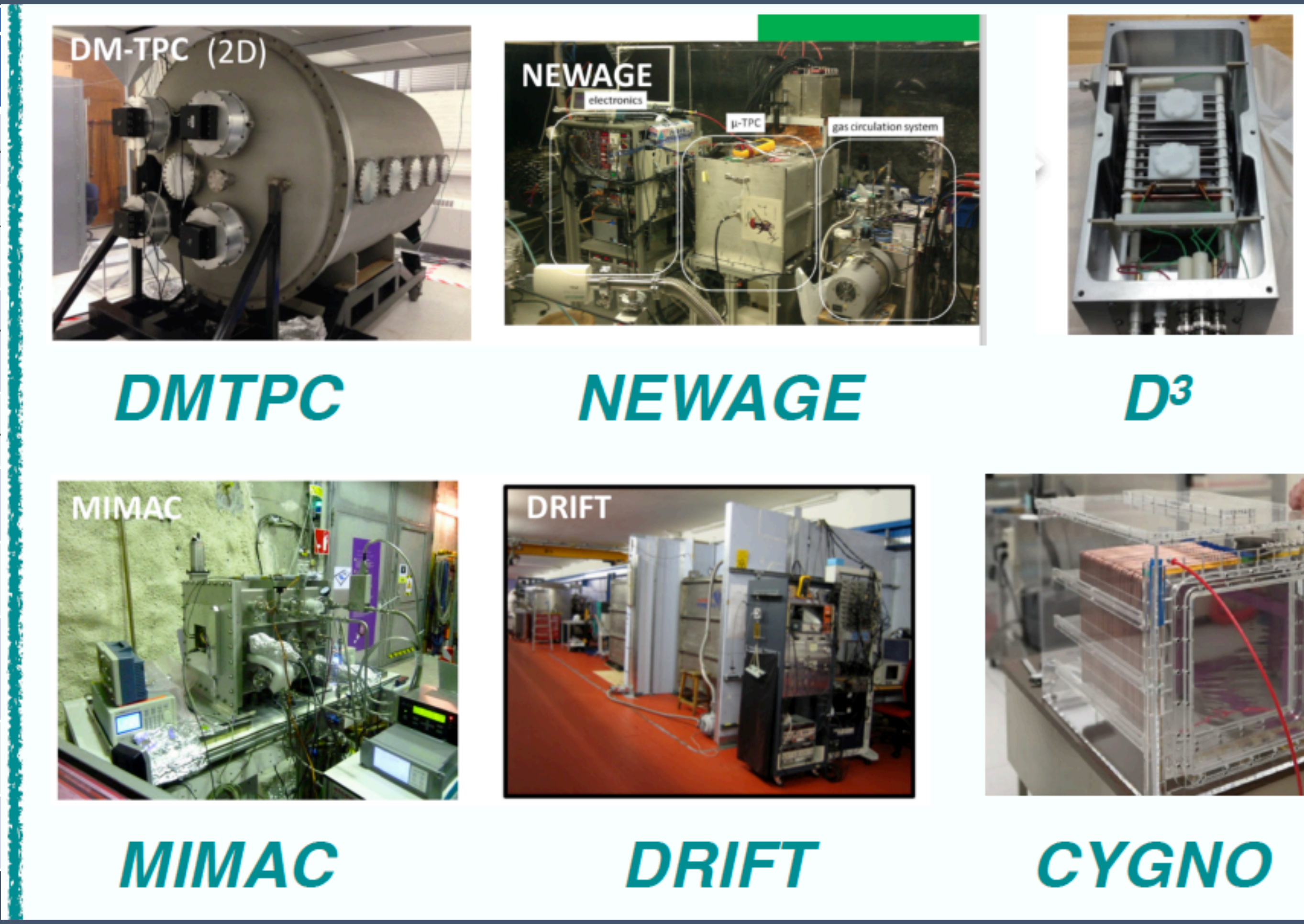


FIG. 4. Total angular distribution across the sky of WIMP-induced (blue contours) and neutrino-induced (red contours) fluorine recoils on September 6. We show the distributions in galactic coordinates (l, b) where the line for $b = 0$ corresponds to the galactic plane. Both distributions have been integrated in recoil energy between 8 and 50 keV$_r$. We choose a WIMP mass of 9 GeV c^{-2} and a SI cross section of 5×10^{-45} cm^2 so that its signal is of a similar size to that of the ^{8}B neutrinos. For reference we also show the ecliptic in red (the line along which the Sun moves over the year), the stars in the Cygnus constellation, and the path of $\hat{\mathbf{v}}_{\rm lab}$ across the sky in blue.



Prototypes and Experiments

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



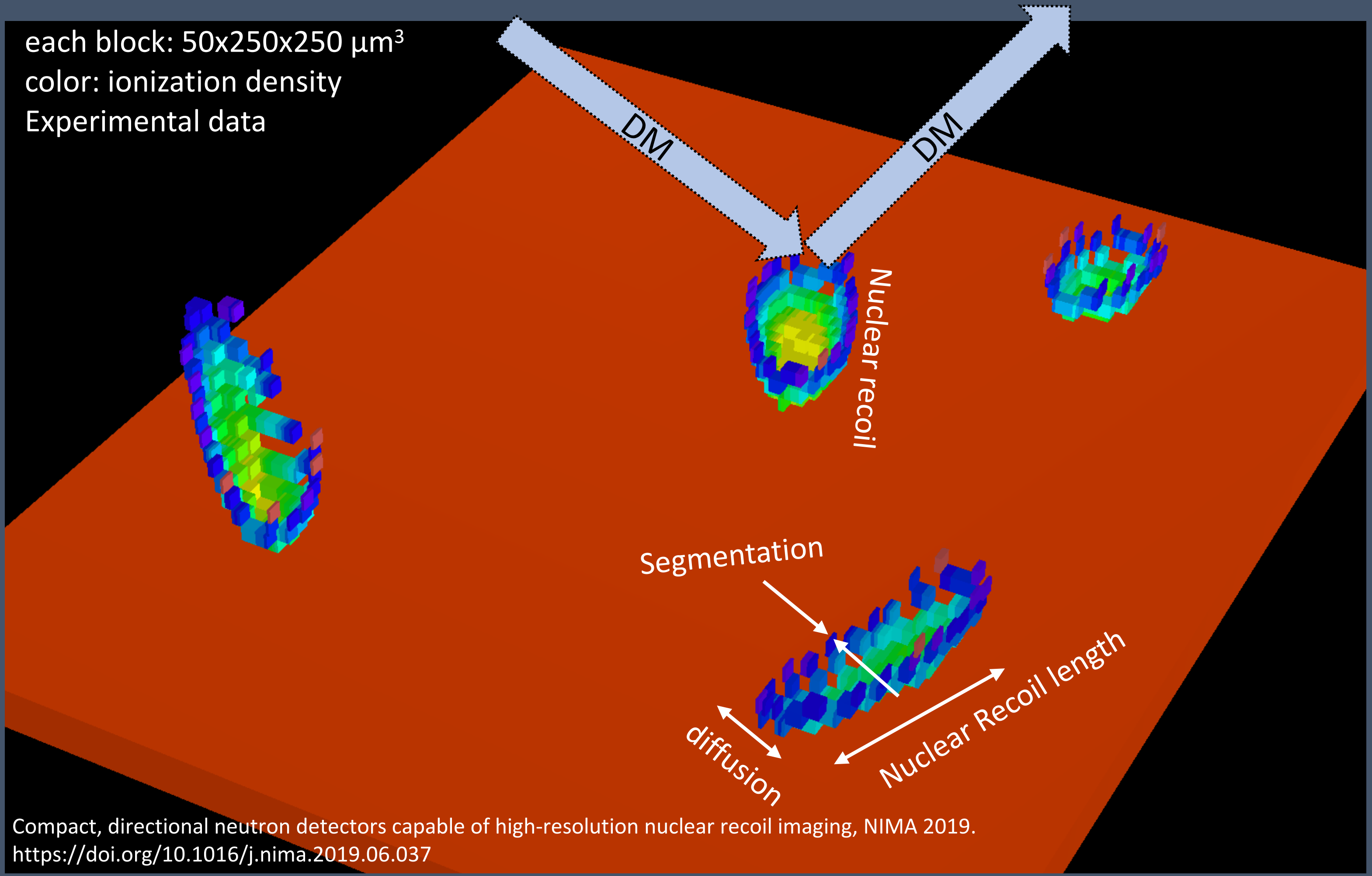
All directional experiments that have set DM limits use gas TPCs
Most TPC groups now working towards the CYGNUS project

The Power of HD gas TPCs

Capabilities resulting from HD charge readout

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

(Focus only on electron rejection today - see backup slides for other topics)



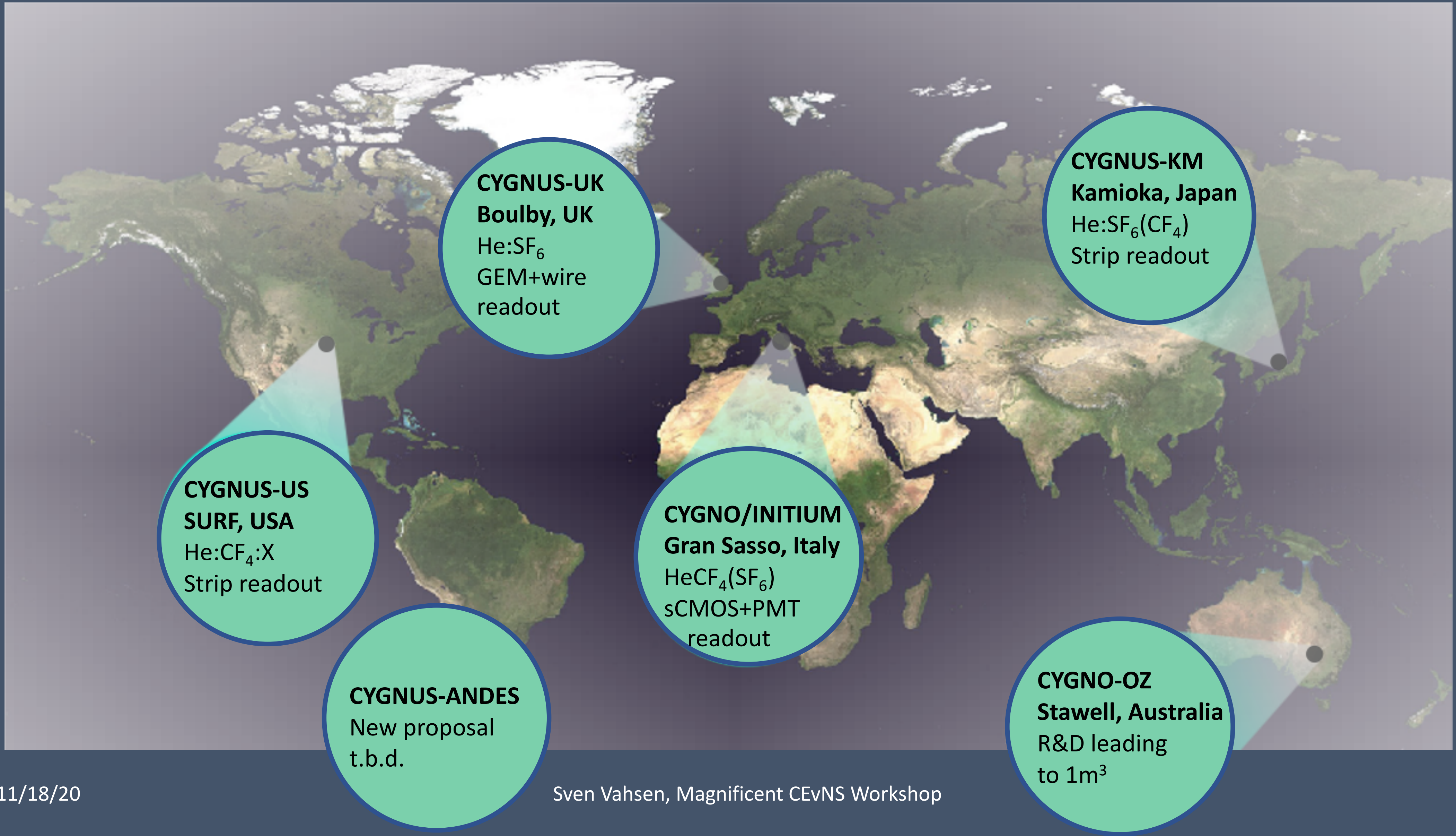
Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging, NIMA 2019. https://doi.org/10.1016/j.nima.2019.06.037

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

Event-by-event 3D vector directionality possible in gas TPC w/ highly segmented readout planes – HD TPCS

CYGNUS Vision: Multi-site Galactic Recoil Observatory

with directional sensitivity to WIMPs and neutrinos



The CYGNUS Proto-Collaboration

- 55 signed members from the US, UK, Japan, Italy, Spain, China
- Six US faculty members
- Close collaboration and regular meetings
- Interim Steering group:
  - Neil Spooner (Sheffield, UK)
  - Sven Vahsen (Hawaii, USA)
  - Kentaro Miuchi (Kobe, Japan)
  - Elisabetta Baracchini (GSSI/INFN, Italy)
  - Greg Lane (Melbourne, Australia)

Encourage new members to join!

The dark matter wind is expected to come from the constellation Cygnus.

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 (CEνNS) at either NuMI or DUNE
- Competitive DM limits in SI and SD
- CEνNS from solar neutrinos
- Efficiently penetrating the ν floor
- Observing galactic DM dipole
- Measuring DM particle properties and physics
- Geoneutrinos
- WIMP astronomy

Extensive concept paper on 1000 m³ detector on arXiv
Focused on technical feasibility and WIMP searches

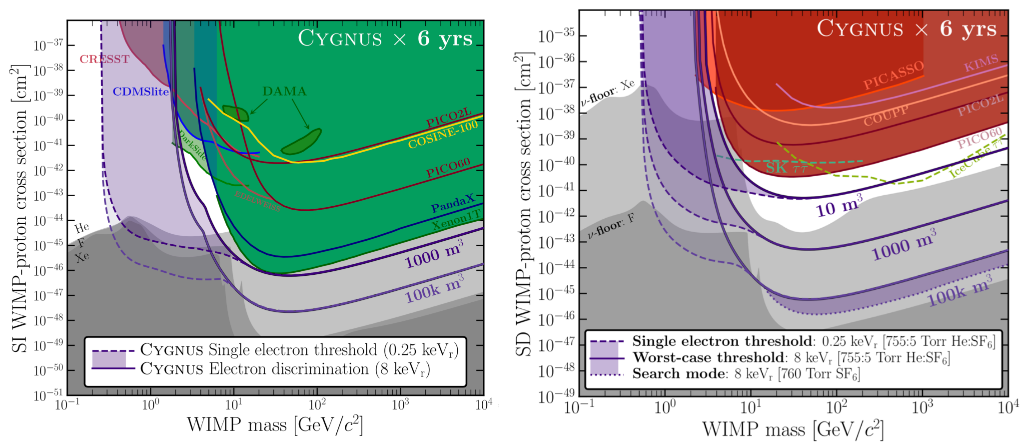


FIG. 3. Constraints on the spin-independent WIMP-nucleon (left) and spin-dependent WIMP-proton (right) cross sections. We show the existing constraints and detections from various experiments as labeled (see text for the associated references). In purple solid and dashed lines we show our projected 90% CL exclusion limits for the CYGNUS experiment operating for 6 years with 1000 m^3 and 100,000 m^3 of He:SF$_6$ gas at 755:5 Torr (corresponding to ~1 ton-year and 100 ton-year exposures respectively). For each volume we fill in between two nuclear recoil thresholds, from the electron discrimination threshold of 8 keV$_r$ to the minimum possible threshold corresponding to a single electron, 0.25 keV$_r$. In gray we shade below various neutrino floors. For the SI panel we show the neutrino floor for helium, fluorine and xenon targets (top to bottom), and for SD we show only fluorine and xenon. These correspond to cross sections giving WIMP signals that are saturated by the neutrino background in standard direct detection–the effect that CYGNUS aims to circumvent.

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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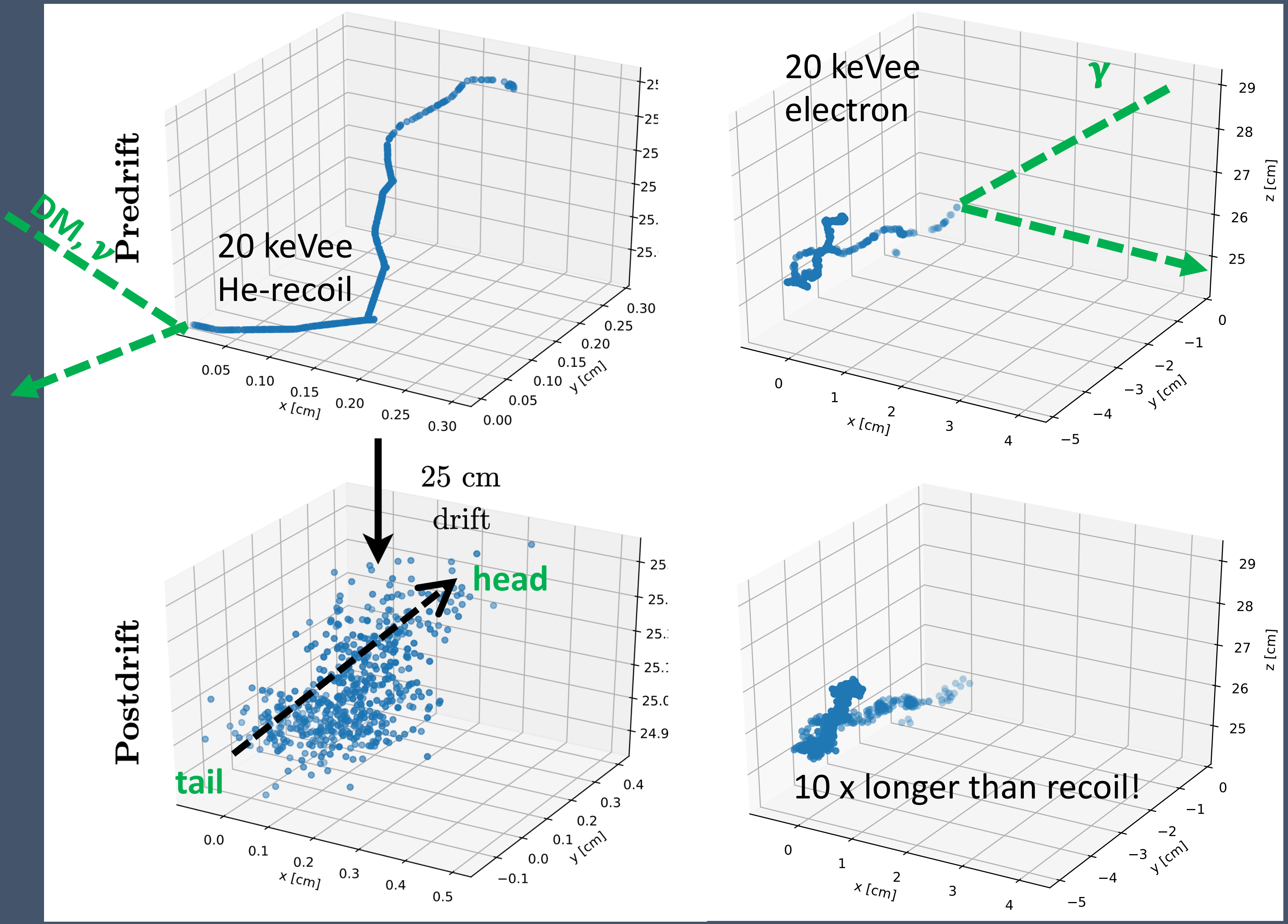
(Dated: August 20, 2020)

https://arxiv.org/abs/2008.12587

The basic idea

- DM or neutrino detection w/ Gas target TPC
- Measure 3d ionization density distribution resulting from nuclear recoils
- Expect main background from e⁻ recoils
  - reject based on 3D ionization topology
  - e.g. Length at fixed energy

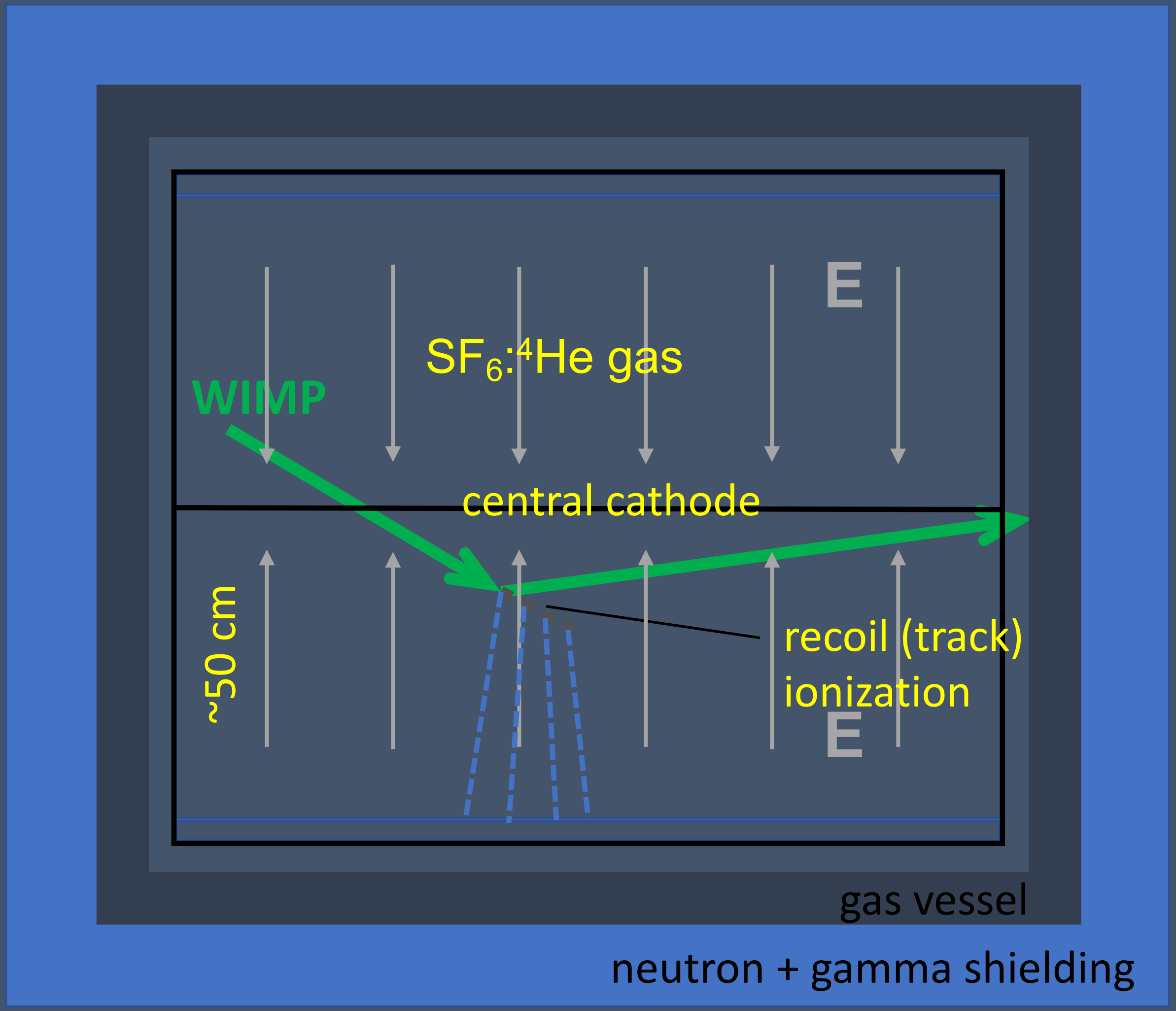
Initial ionization distribution



ionization distribution after drift in detector

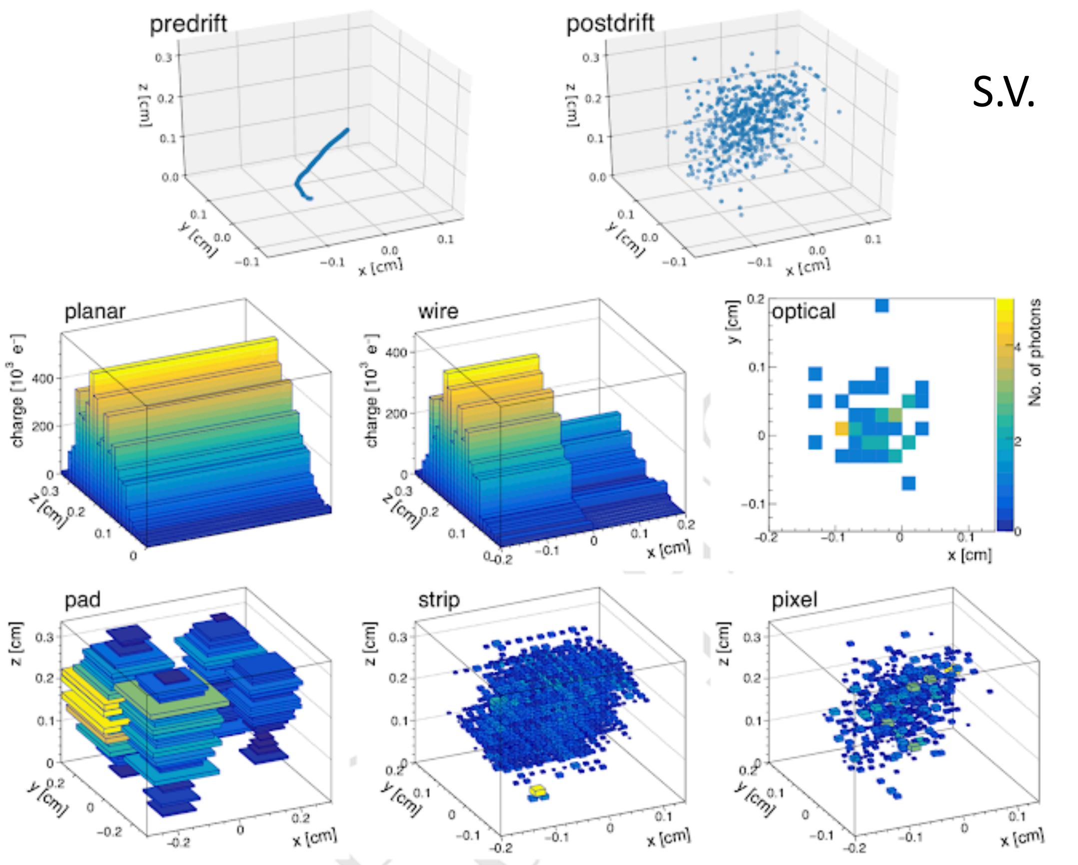
CYGNUS: Experimental Approach

- Gas Time Projection Chamber
- Order 1m^3 unit cells
- Order 1000 such cells. Flexible form factor.
- Gas mixture 1:
  - SF_6:^4He:X, p<=1 atm
  - Reduced diffusion via negative Ion drift (SF_6 gas)
- Gas mixture 2:
  - CF_4:^4He: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



But what is the optimal TPC readout technology?

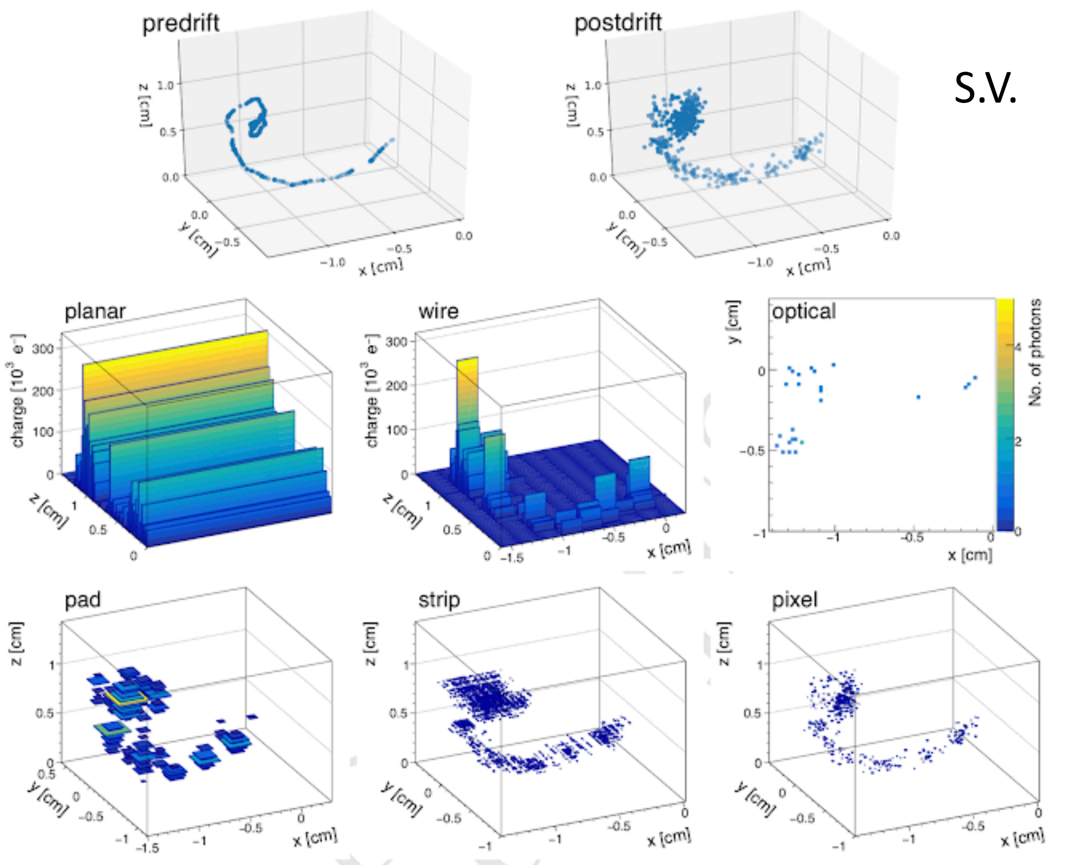
nuclear recoil



S.V.

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



S.V.

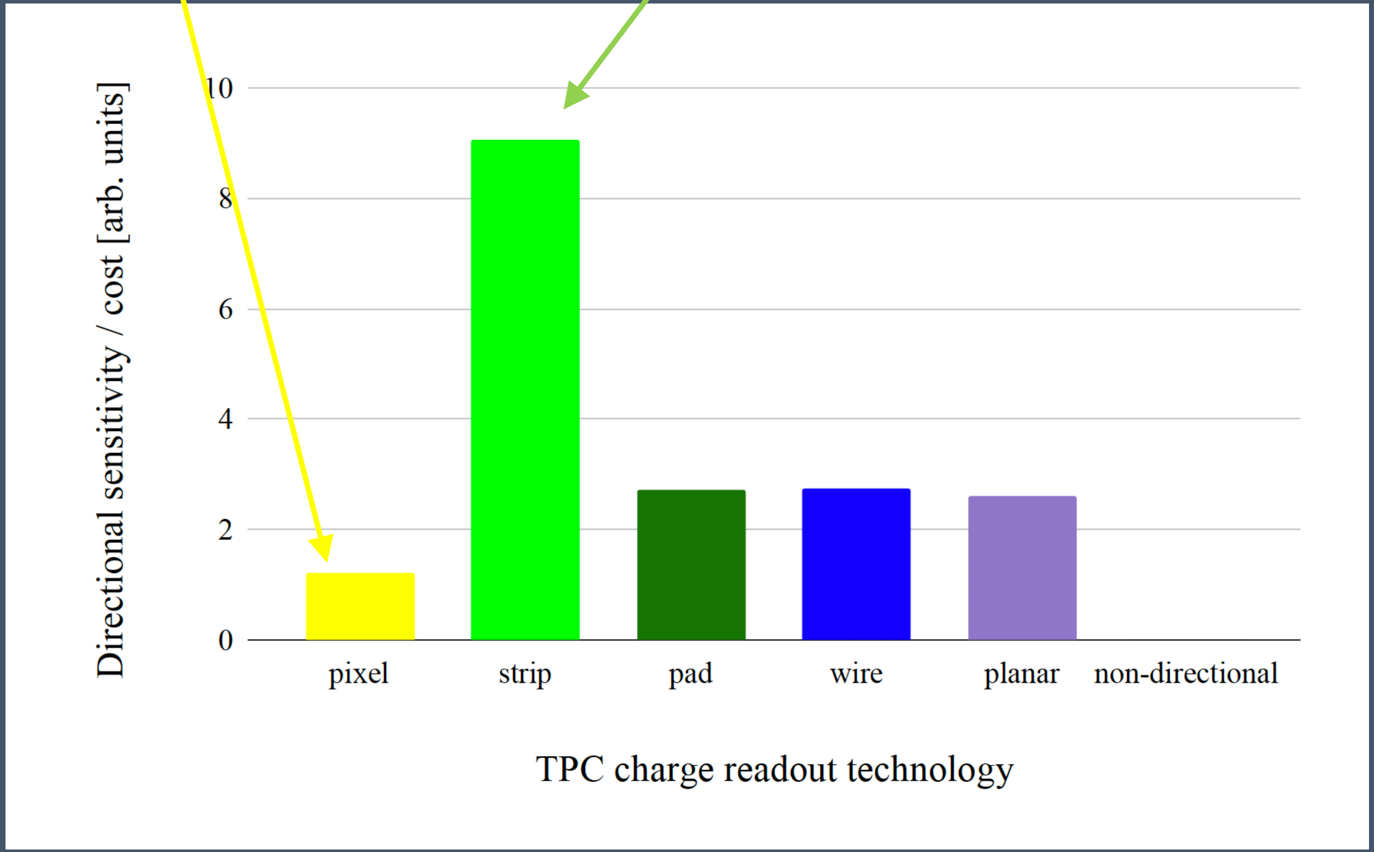
FIG. 10. Simulated 20 keV$_{ee}$ electron event in He:SF$_6$ gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

Pixel readout has best performance, with strip readout is a close 2nd …but see next page!

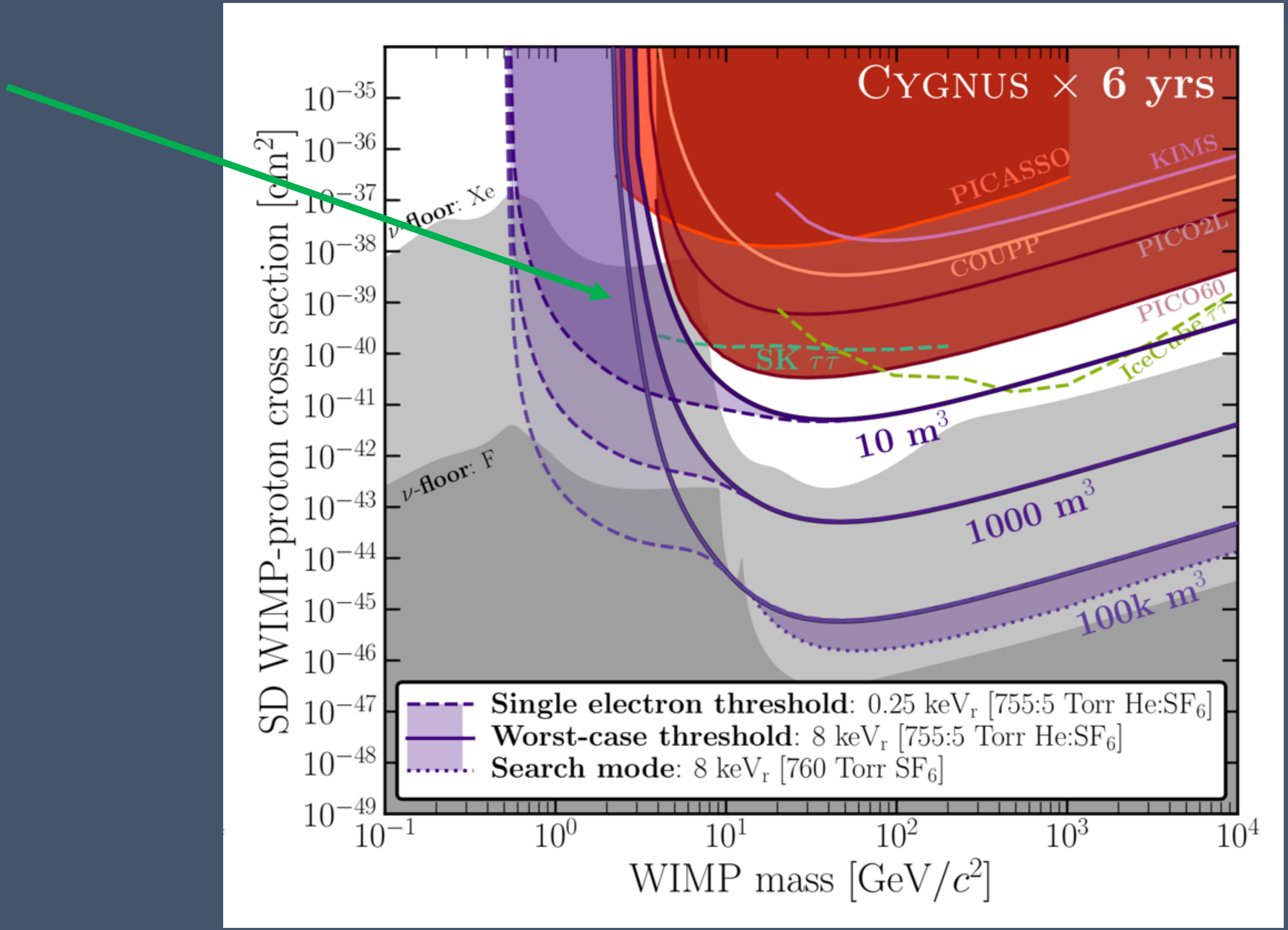
Result of cost vs performance analysis

Best raw performance – optimal for precision studies of nuclear recoils

Best directional WIMP sensitivity per unit cost – optimal for large detectors!

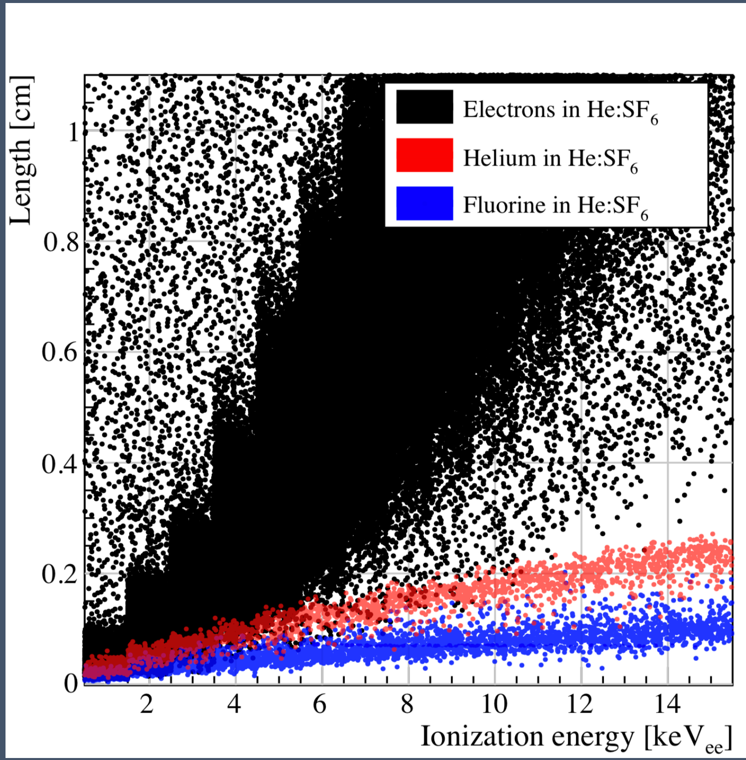


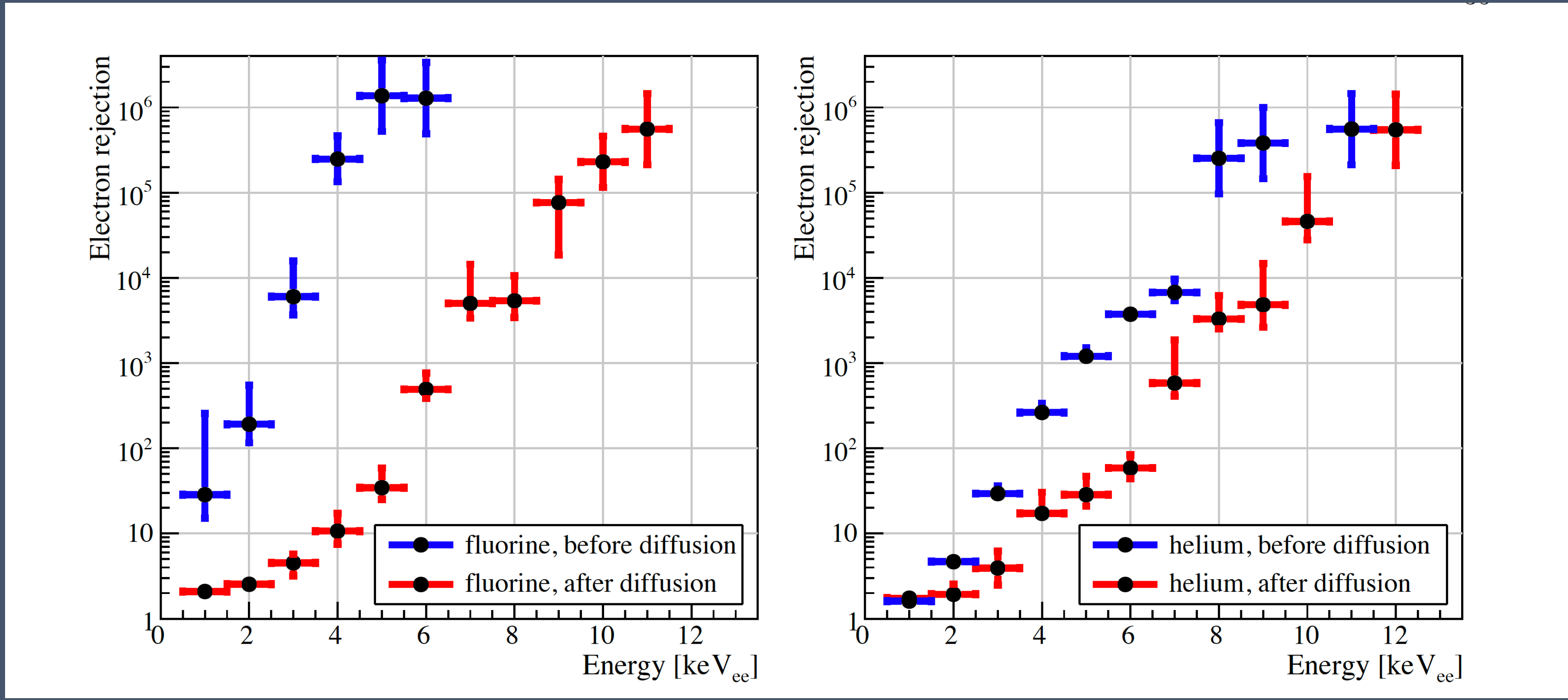
WIMP sensitivity depends on electron rejection



3D electron rejection (simulation)

20 torr SF_6 + 740 torr Helium





3d-length versus energy signature (simplest discriminant): good electron rejection down to a few keVee
Rejection rises exponentially with energy.
Will effectively determine energy threshold for background free operation.

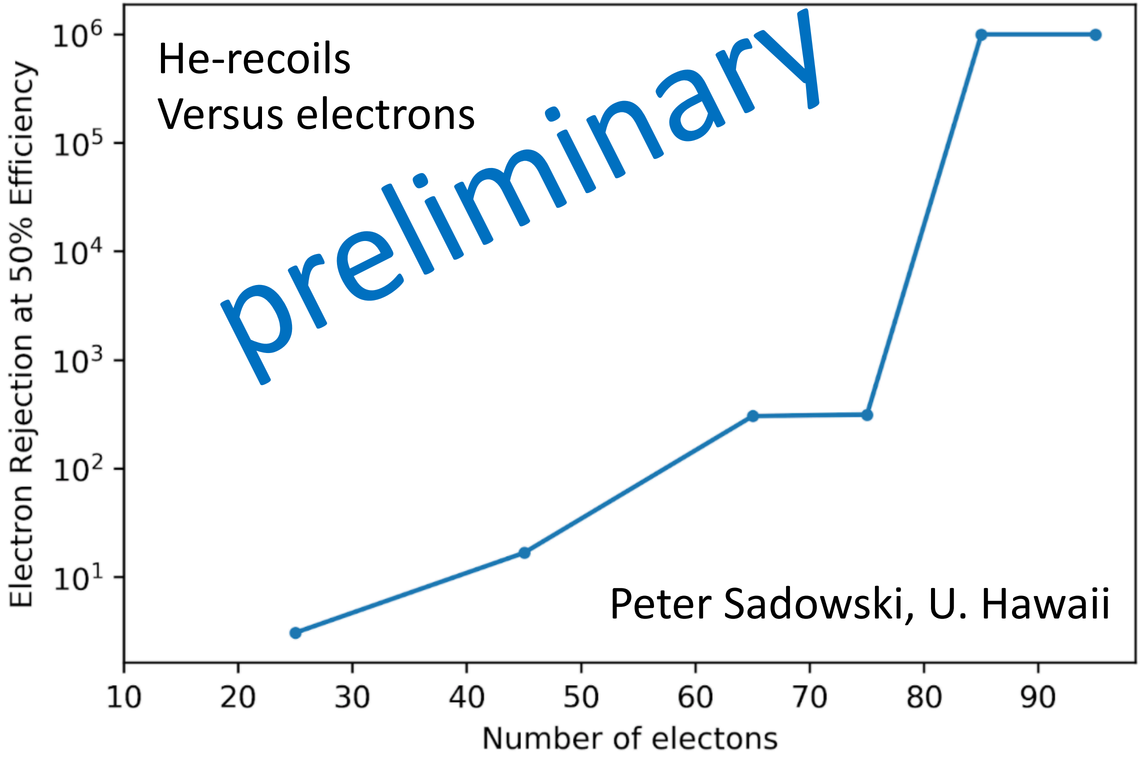
3D Electron Rejection with *Deep Learning*

Includes 100 micron diffusion + HD 3D detector.

Huge improvements appear possible!
More work needed.

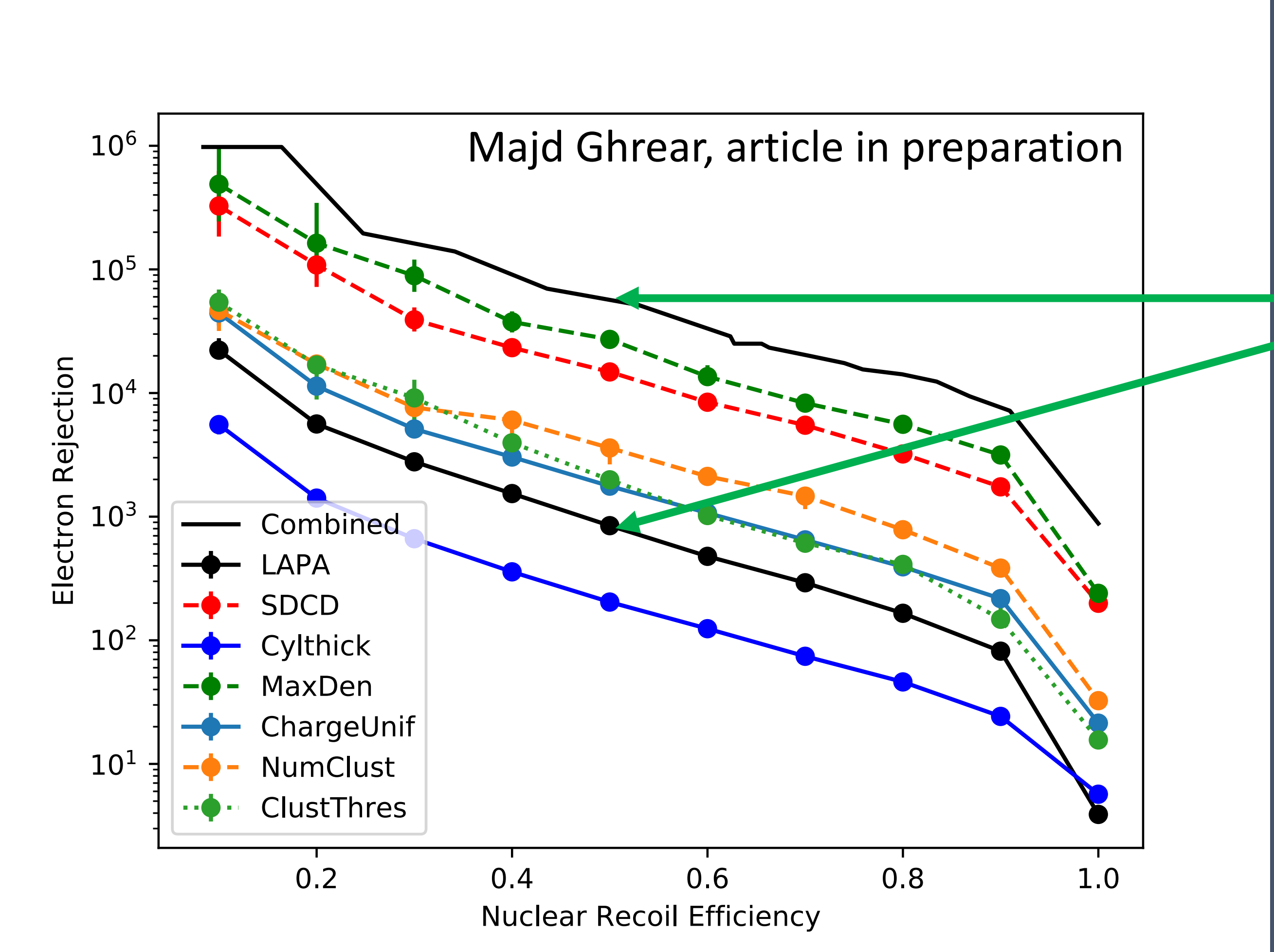
20 torr SF_6 + 740 torr Helium

Limit – all simulated electrons rejected at E ~ 3.2 keVee



- Statistically significant electron rejection down to <=1 keVee

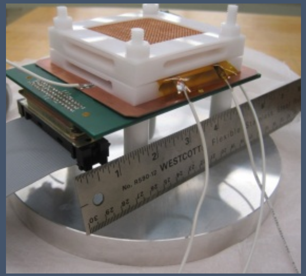
Improved, Physically motivated observables for electron rejection New



~2 orders of magnitude Improvement over length-vs-energy

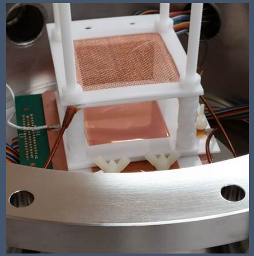
D^3 / CYGNUS U.S. (Hawaii)

2011-2013



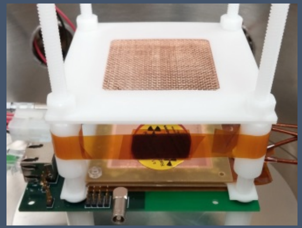
μD^3 (~1cm^3)

2013



~2.5 cm^3

2013



~ 20 cm^3

1st generation, proof of concept

2014

2 x 60 cm^3

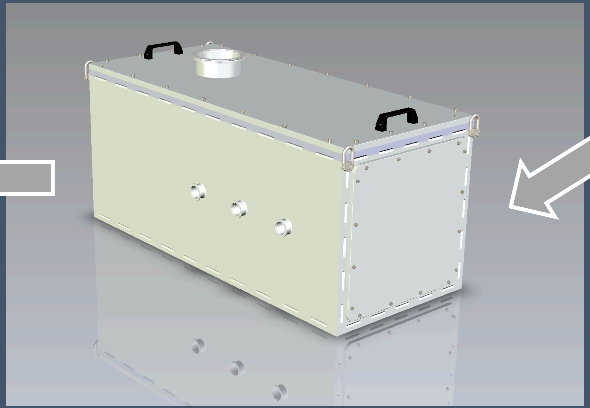
2015

8 x 40 cm^3

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

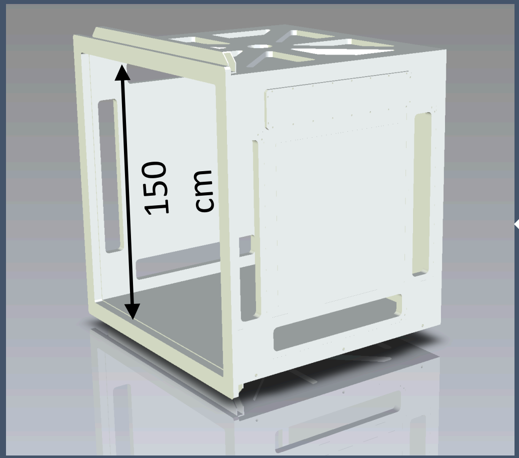
- Extensive prototyping with pixel chip readout completed
- Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for precision studies of nuclear recoil physics
- Now transitioning to 3rd generation of detectors w/ strip readout to enable relevant DM + neutrino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

2020



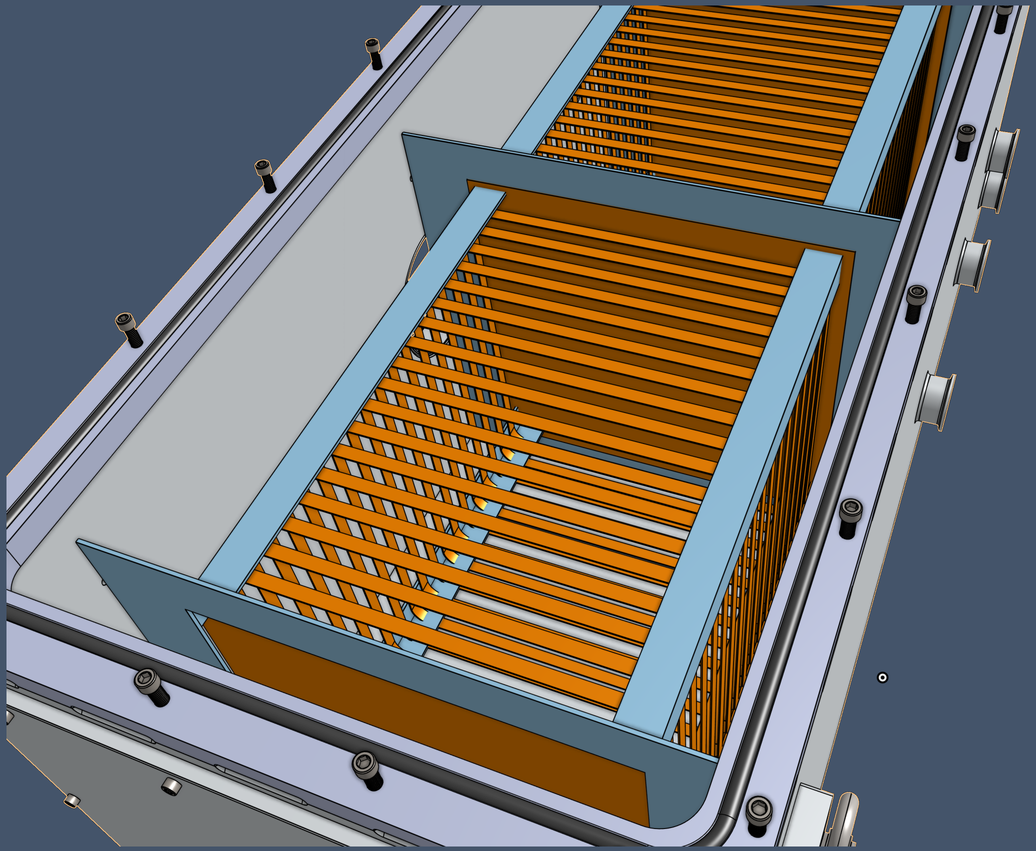
CYGNUS HD "Keiki"

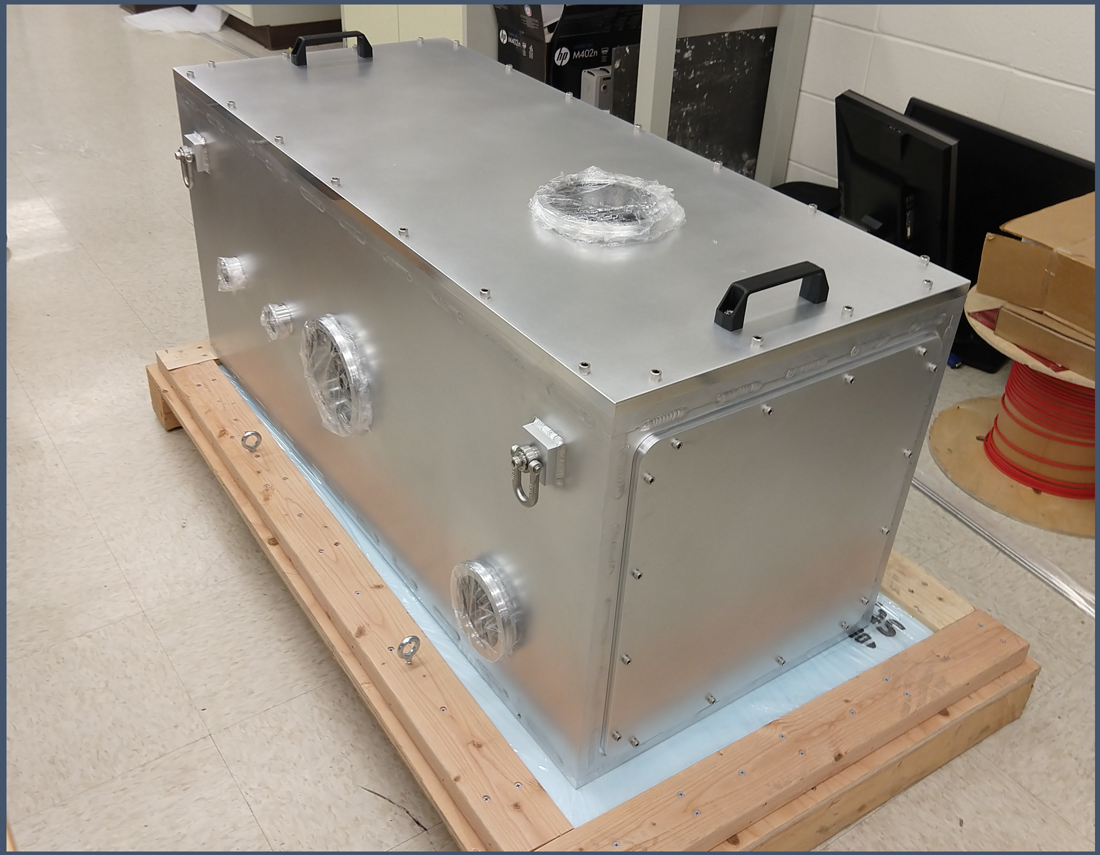
2021



3rd Generation: Optimized for dark matter

US-CYGNUS building factor 1000+25000 scaleups with strip micromegas + CERN SRS readout





CYGNUS HD “Keiki”

Yesterday's background → today's signal?

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

6

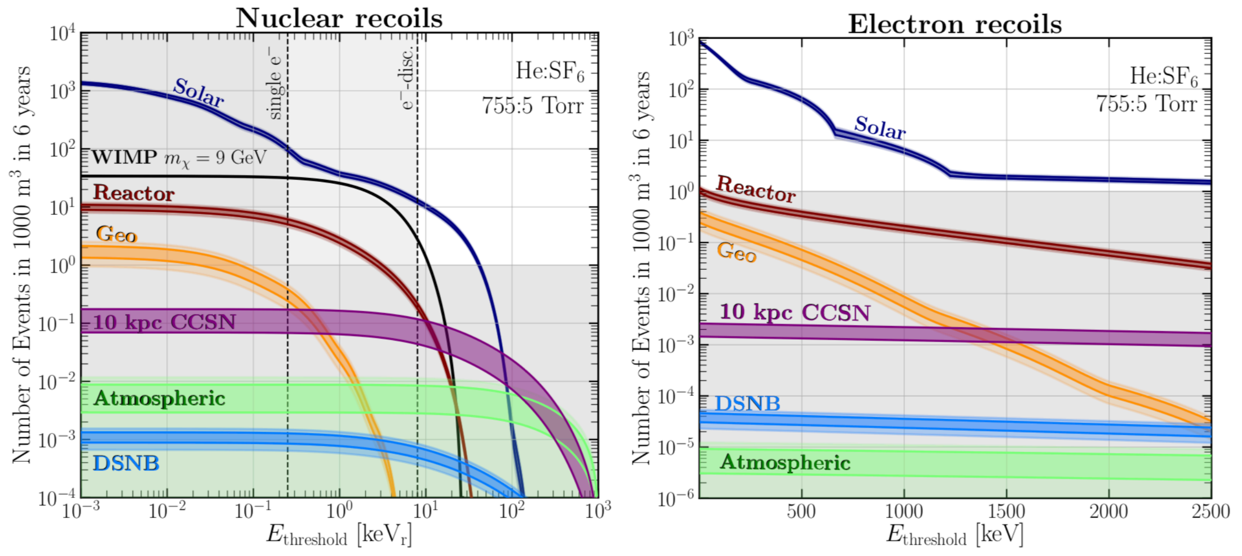
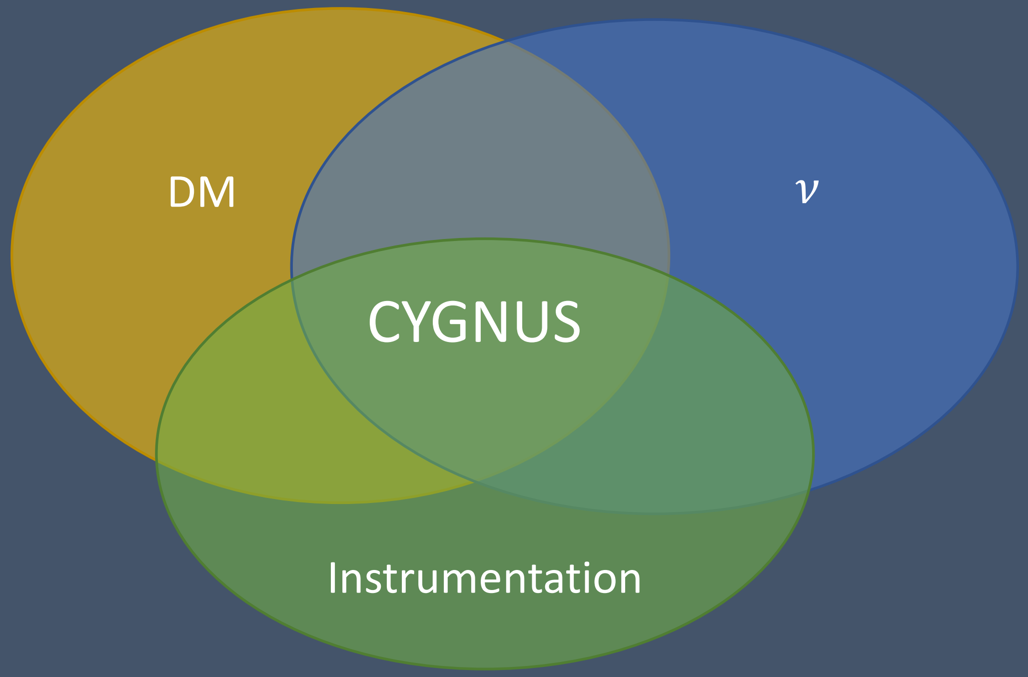


FIG. 4. Number of neutrino-nucleus (left) and neutrino-electron (right) recoil events observed in a CYGNUS-1000 m^3 detector filled with atmospheric pressure He:SF$_6$ at a 755:5 Torr ratio (the event rates are summed over each target nuclei). We calculate the expected number of observed events by integrating 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 $\sigma_p^{\rm SI} = 5\times10^{-45}$ 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$_{\rm r}$ single electron and electron discrimination thresholds respectively.

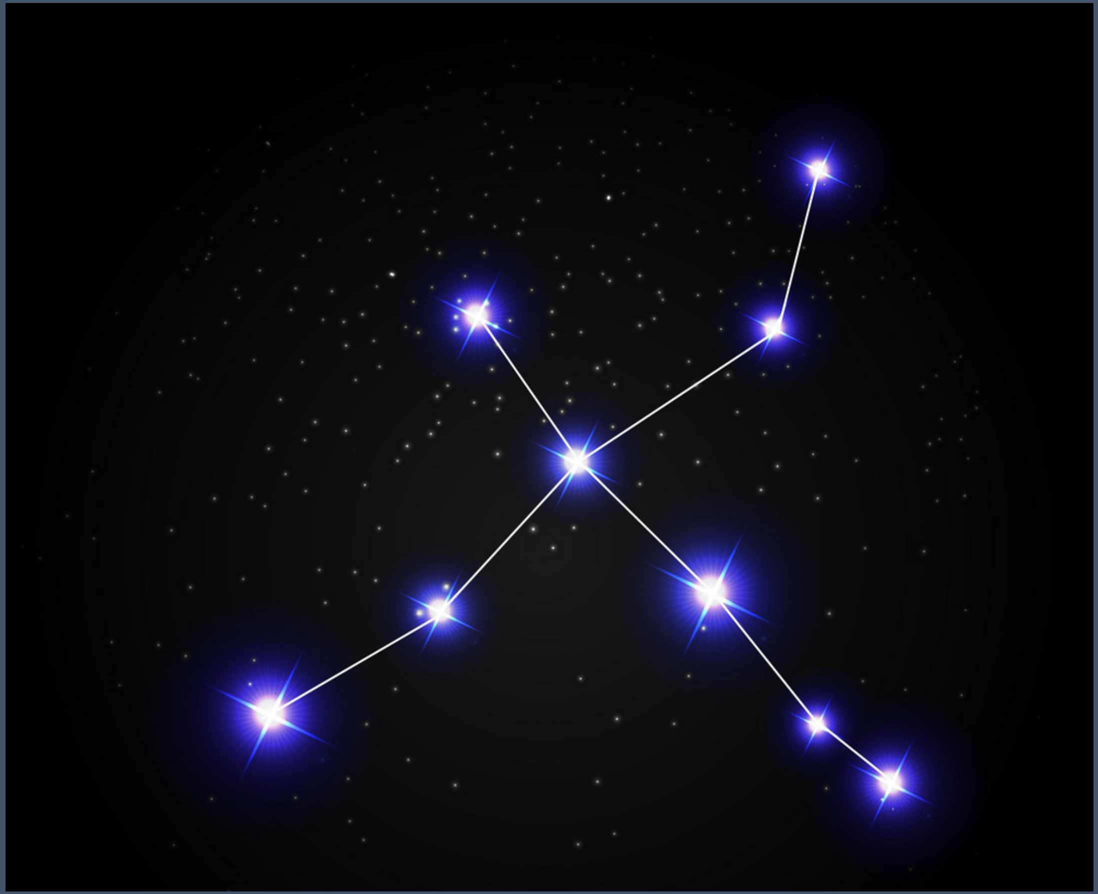
CYGNUS and the US Snowmass Process

- CYGNUS at intersection of Instrumentation, Cosmic, and Neutrino Frontiers
- We hope to engage a wider community in CYGNUS. Please join or contribute Snowmass studies on directionality!
- Planning CYGNUS Miniworkshop early 2020. (tbd)
- To result in Contributed Paper on physics case for directional recoil detection, going beyond vanilla WIMP recoils → electron recoil sensitivity to WIMPs and neutrinos.



Conclusion

- HD gas TPCs suitable for directional DM and neutrino detection
- A rich, long-term physics program is possible
- Concept paper discussing feasibility of 1000 m^3 detector on arxiv; focused on WIMPs
- US community building next generation strip detector to demonstrate scaleup
- US community also performing recoil physics measurements with small, UHD detectors
- Planning follow-up Snowmass Paper to explore complementary electron signatures
- Planning mini-workshop in early 2020 – please get in touch if interested

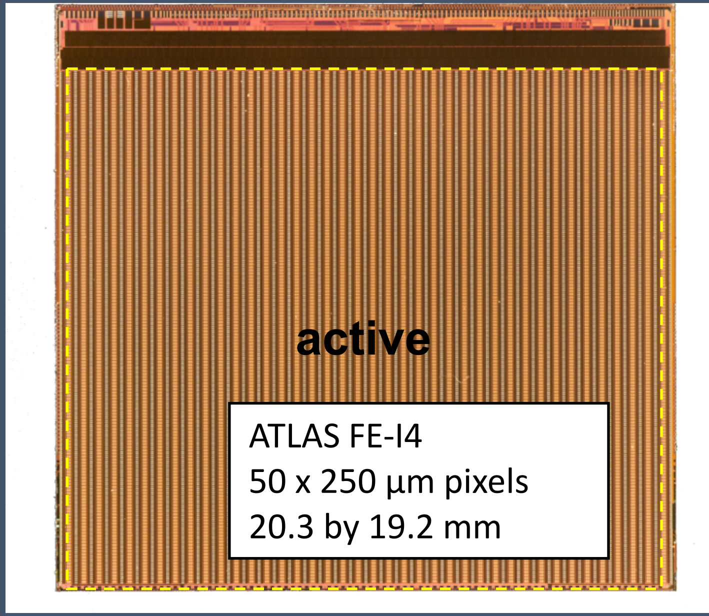


Latest operational detector: ~40 cm^3 “BEAST” TPC - eight constructed

- Compact, directional neutron detectors capable of high-resolution nuclear recoil imaging, NIMA 2019, https://doi.org/10.1016/j.nima.2019.06.037
- First measurements of beam backgrounds at SuperKEKB, NIMA 2019, https://doi.org/10.1016/j.nima.2018.05.071

in-situ, time-dependent , and z-dependent calibration of energy scale and detailed response to helium recoils

Pixel chip:

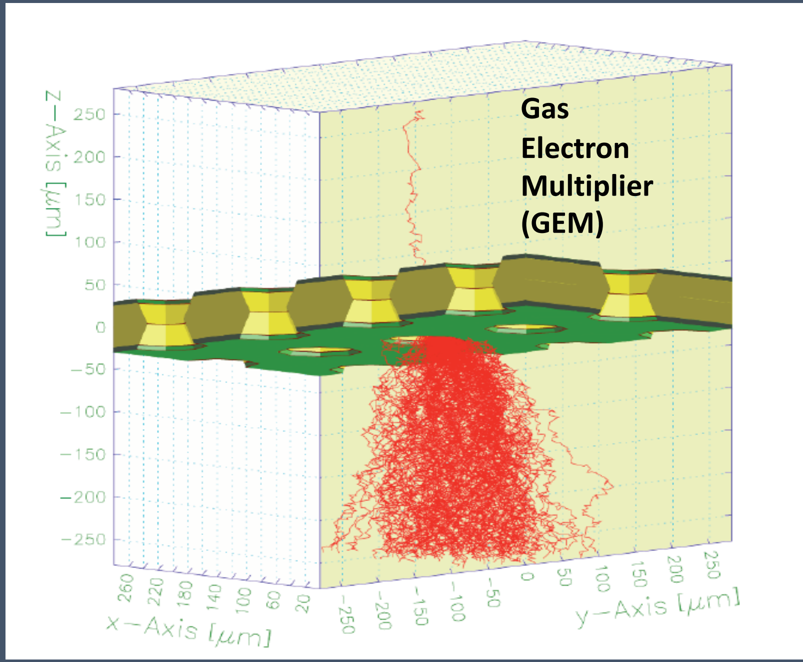


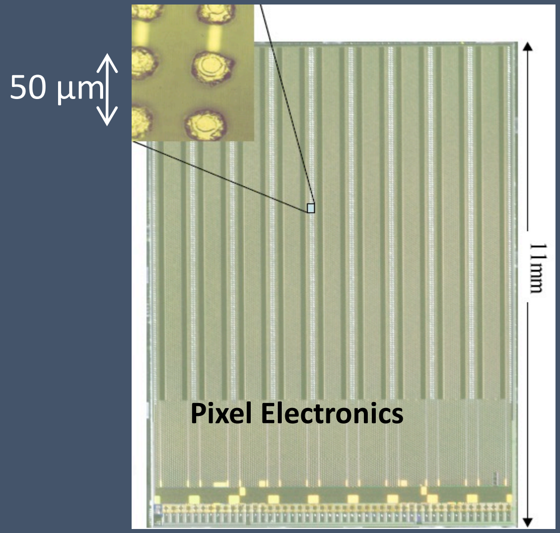
- Directional *fast neutron* detector.
- Small footprint enabled by Parylene coating on inside of pressure vessel
- Successfully measured directional neutron distribution at SuperKEKB accelerator in Japan

Typically operate at gain ~ 1000-3000
<1% gain stability *pre*-calibration - sufficient to observe annual oscillation in WIMP rate / spectrum

Charge Amplification and Detection in D^3

- Drift charge amplified with double layer of GEMs - gain ~20k at 1 atm
- Detected with pixel electronics - threshold ~2k e$^-$, noise ~ 100 e$^-$





- ATLAS FE-I3
- 50x400 μm pixels
- Sampling at 40 MHz

Advantages of this approach

- Full 3D tracking w/ ionization measurement for each space-point (head/tail sensitivity) → **improved WIMP sensitivity and rejection of electron backgrounds**
- Pixels ultra-low noise (~100 electrons), self-triggering, and zero suppressed → **virtually noise free at room temperature** → low demands on DAQ
- High single-electron efficiency (~30 eV non-directional energy threshold) → **suitable for low-mass WIMP search**

Latest operational detector: ~40 cm^3 "BEAST" TPC - eight constructed

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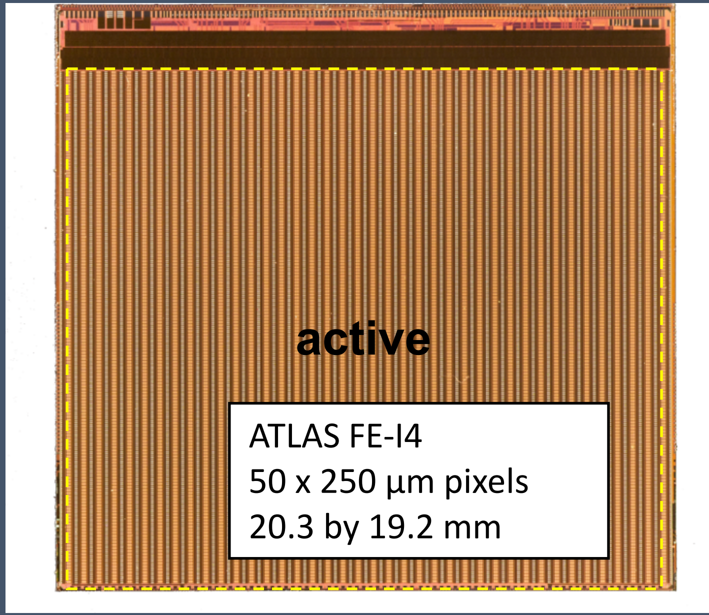

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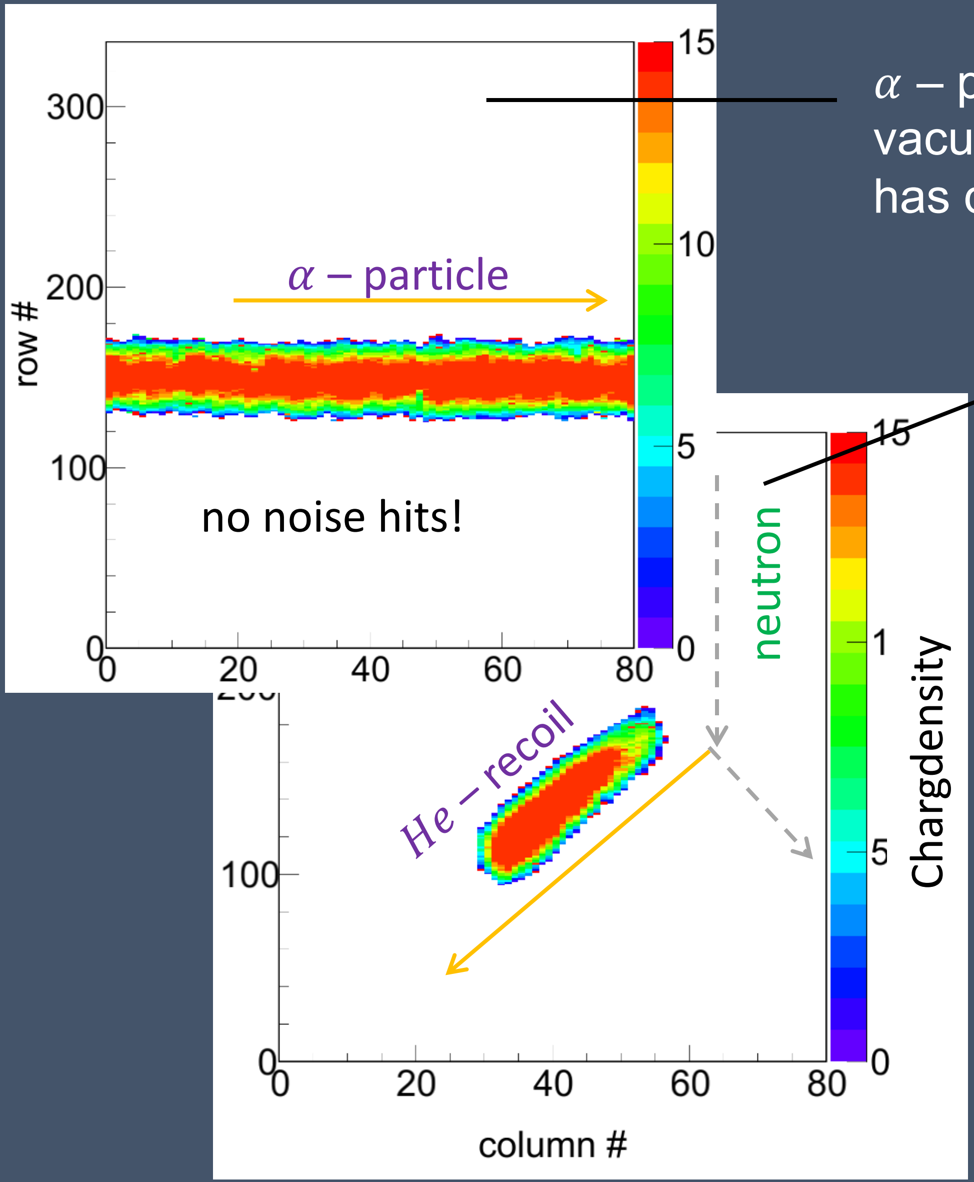
Typical Events – 2D Projections



α – particle event: Po-210 source inside vacuum vessel at z=15 cm, i.e. charge has drifted through entire detector

Neutron recoil event: Cf-252 source outside vacuum vessel, pointed at z=8 cm (middle of TPC)

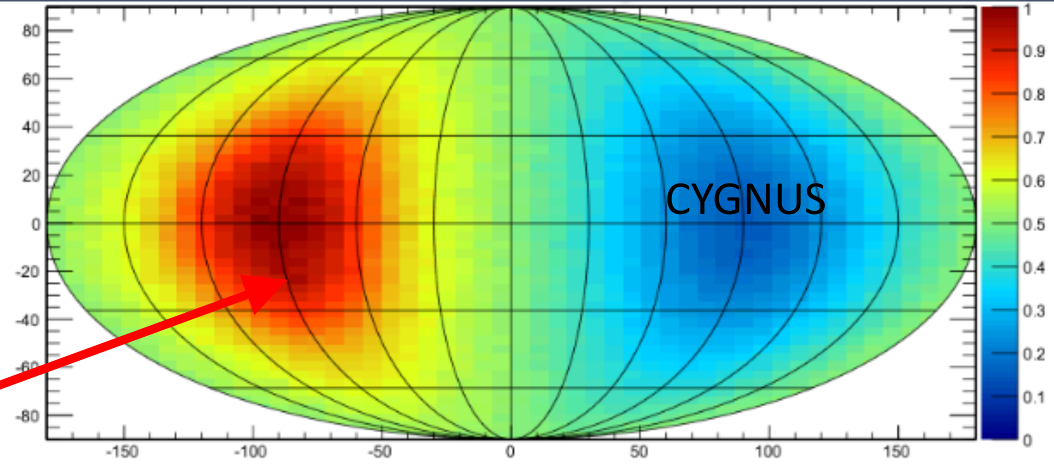
- Figures show 2-D projection of ionization density, measured w/ 2x2 cm pixel chip
- As a consequence of high gain, low threshold, and low noise, the rate of noise hits is negligible

3D vector tracking of recoils possible with this type of MPGD readout

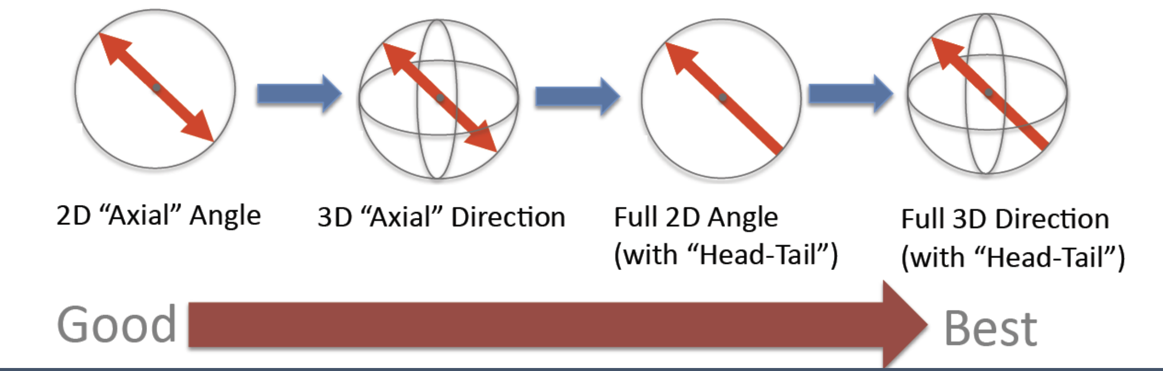
The Galactic Dipole

- The diurnal directional oscillation is equivalent to a dipole in galactic coordinates
- Recoils Point away from constellation CYGNUS

Physics Reports 627 (2016)



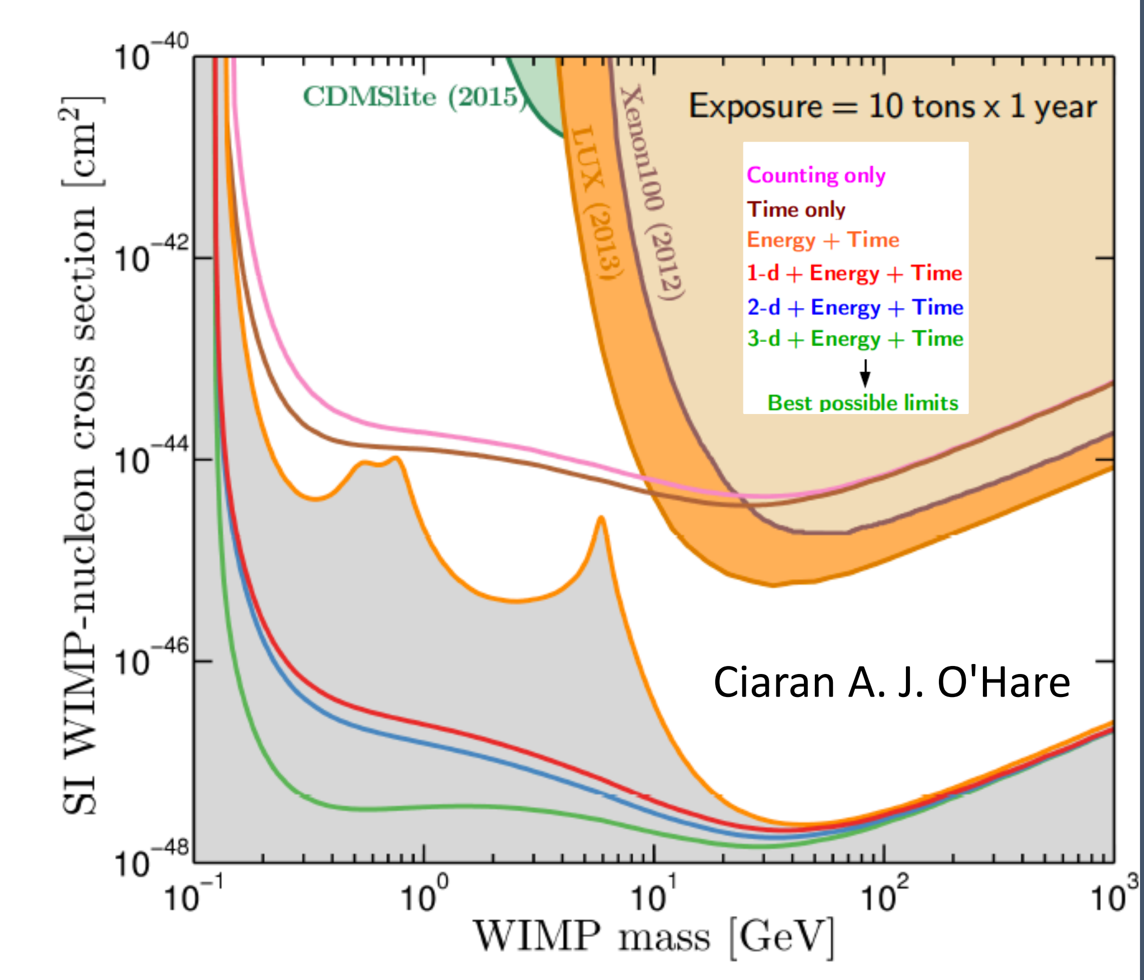
Sky map in galactic coordinates of recoils from 100 GeV WIMPs on ^{19}F, E>50 keV



Galactic dipole: - strongest predicted direct detection signature
- can unambiguously demonstrate galactic origin of signal

3D vector tracking best - need ~10 detected events to reject isotropy.

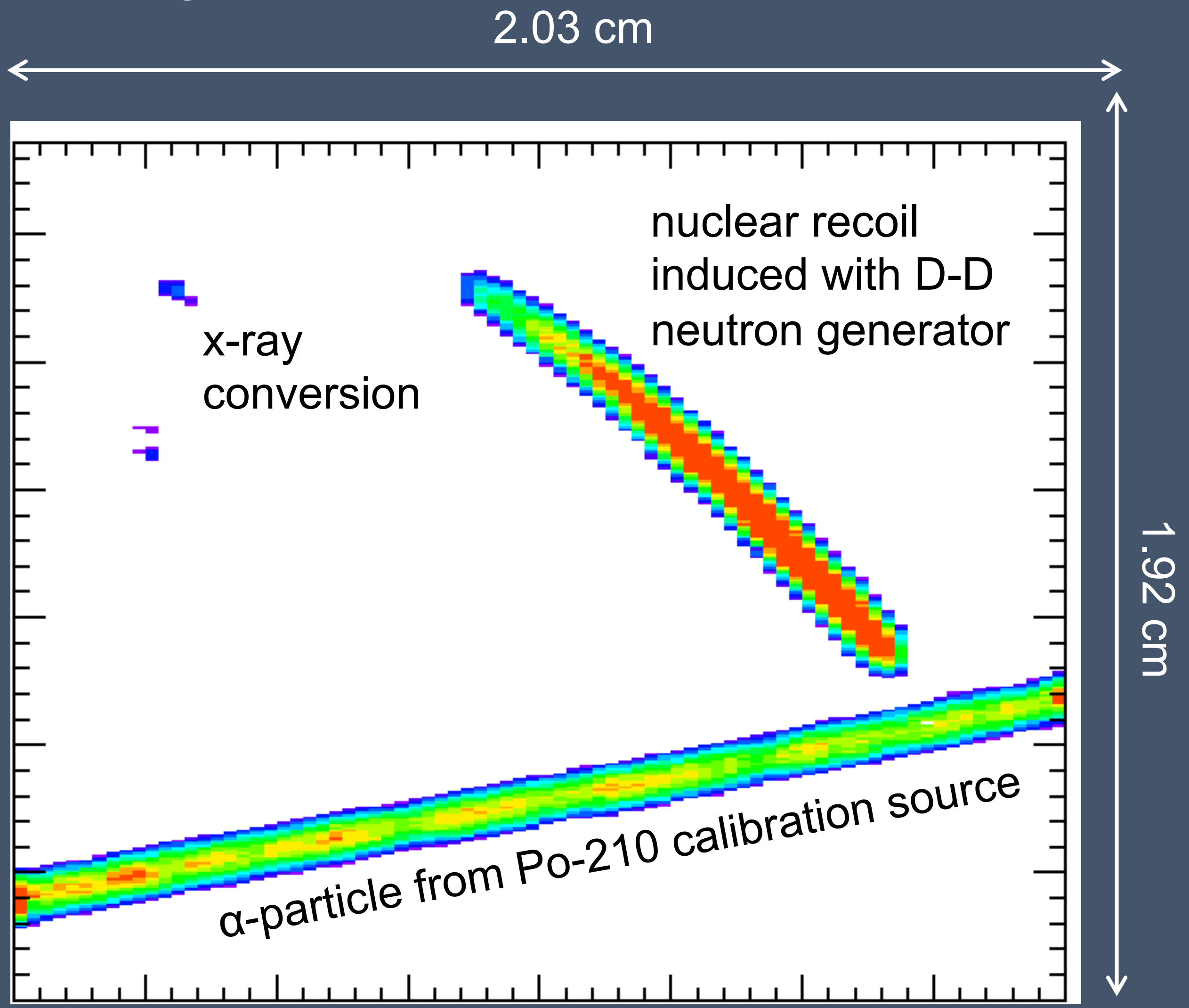
Penetrating the neutrino floor



Readout strategies for directional dark matter detection beyond the neutrino background
Ciaran A. J. O'Hare, Anne M. Green, Julien Billard, Enectali Figueroa-Feliciano, Louis E. Strigari

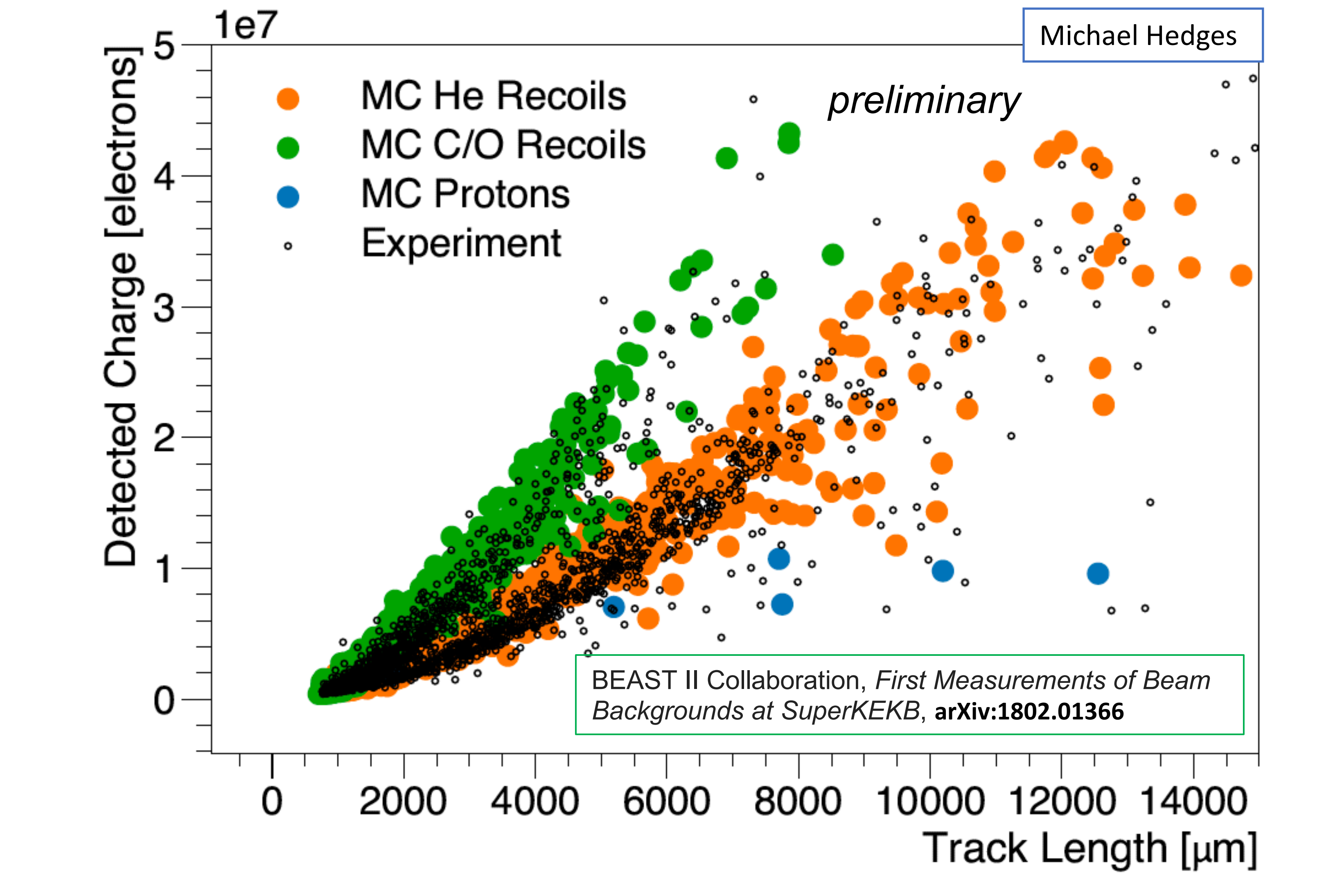
- Directionality significantly enhances the DM sensitivity below neutrino floor
  - 3D again "best"
- But note:
  - True Figure of Merit: sensitivity / unit cost
  - A realistic detector has strongly energy-dependent directionality. This was not considered in past studies.

Background rejection

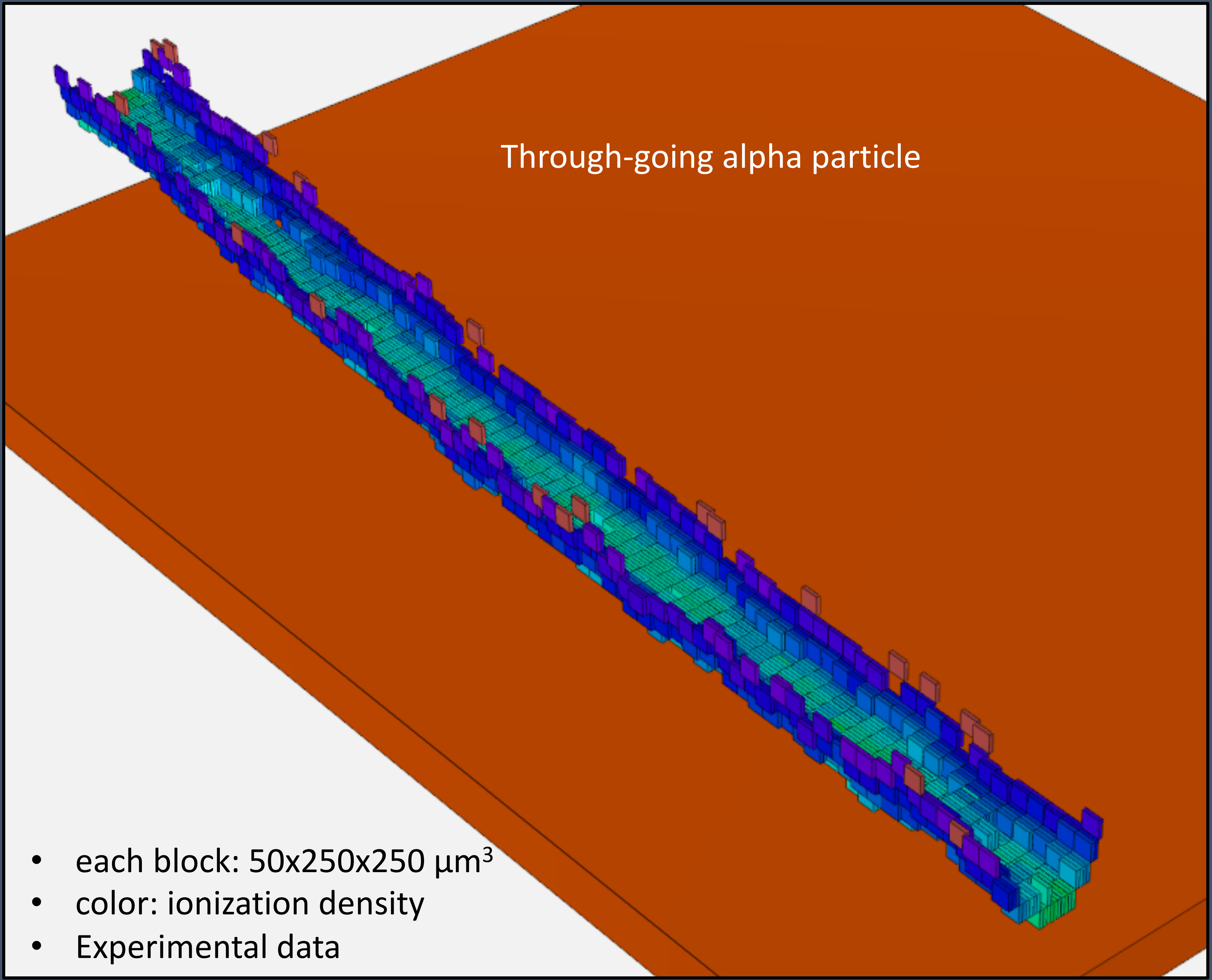


Detectors satisfying this readout requirement:
excellent electron recoil / nuclear recoil separation as a “free bonus”

Recoil Species ID – measurement vs simulation



Through-going alpha particle



- each block: 50x250x250 μm^3
- color: ionization density
- Experimental data

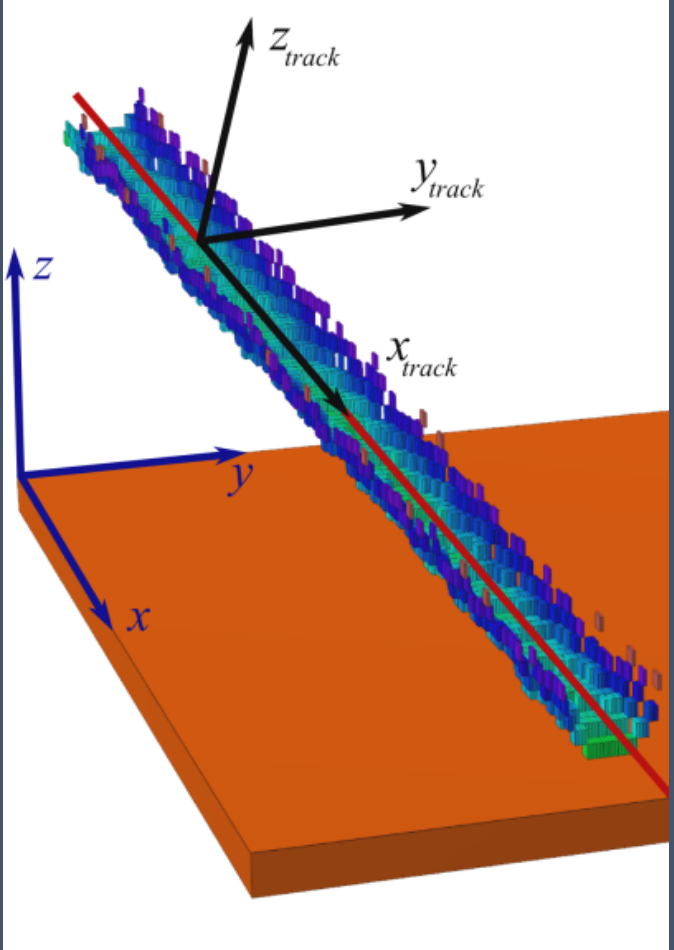
Absolute Position Measurement

P.M. Lewis, S.E. Vahsen, I.S. Seong, M.T. Hedges, I. Jaegle, T.N. Thorpe, *Absolute position measurement in a gas time projection chamber via transverse diffusion of drift charge*, Nucl. Instrum. Meth. A **789** (2015)

- Measurement of charge-profile (*not width)* of track, enables accurate measurement of transverse diffusion

→obtain absolute position in drift direction ("absolute z")

- Crucial capability for suppressing radioactive backgrounds from cathode and anode in DM detectors



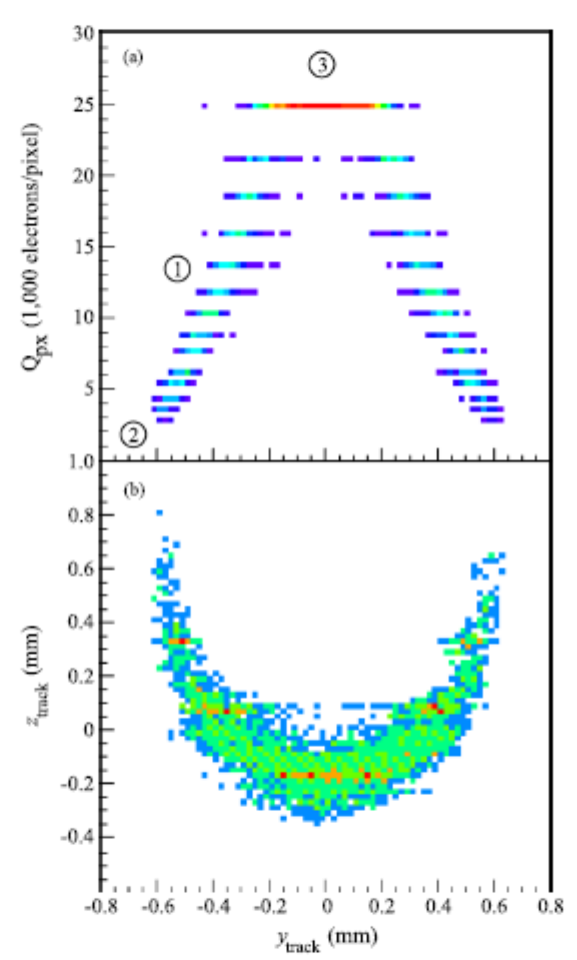


Fig. 2. Corrected pixel charge (Q_{px}) profile (a) and shell coordinates (b) for a single horizontal track from the near alpha source. Label 1 of the profile plot (a) corresponds to the Gaussian, label 2 to the threshold, and label 3 to the saturation regions of the profile. The U-shaped shell in plot (b) is very roughly the bottom half of the track in space, described in Section 2.1. These plots are two-dimensional histograms where the counts per bin are encoded by brightness: the outside points of each distribution (blue online) have the lowest count number, the center points (yellow and red online) have higher count numbers. (References to color apply to the web version of this article.)

Absolute Position Measurement

P.M. Lewis, S.E. Vahsen, I.S. Seong, M.T. Hedges, I. Jaegle, T.N. Thorpe, *Absolute position measurement in a gas time projection chamber via transverse diffusion of drift charge*, Nucl. Instrum. Meth. A **789** (2015)

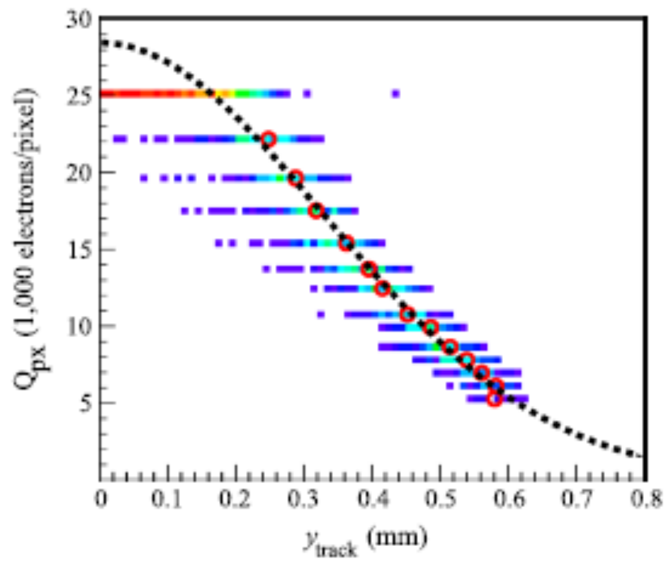
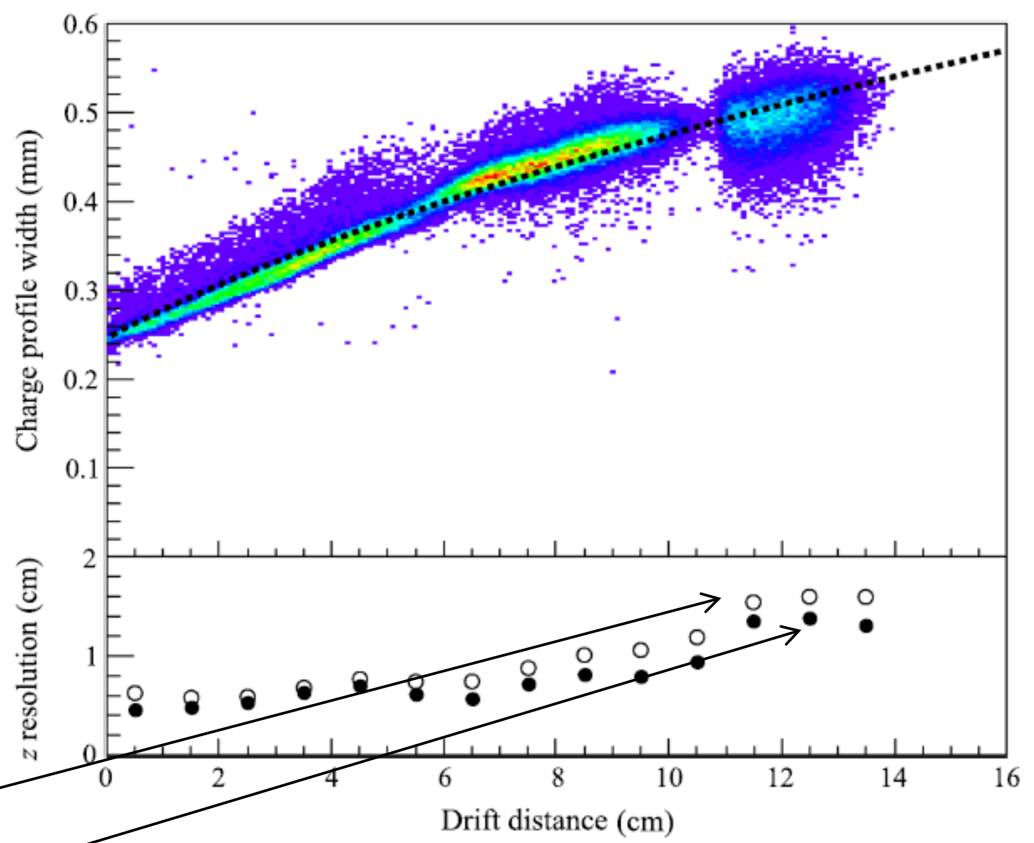


Fig. 3. Fit to the folded version of the corrected pixel charge (Q_{px}) profile shown in Fig. 2 using the profile fit method described in Section 4.3. The Gaussian function (black dotted line) is fitted to the plot points (red open circles), which are placed at the mean Q and y_{track} positions for each unsaturated TOT layer. Error bars on the points are too small to show. (References to color apply to the web version of this article.)



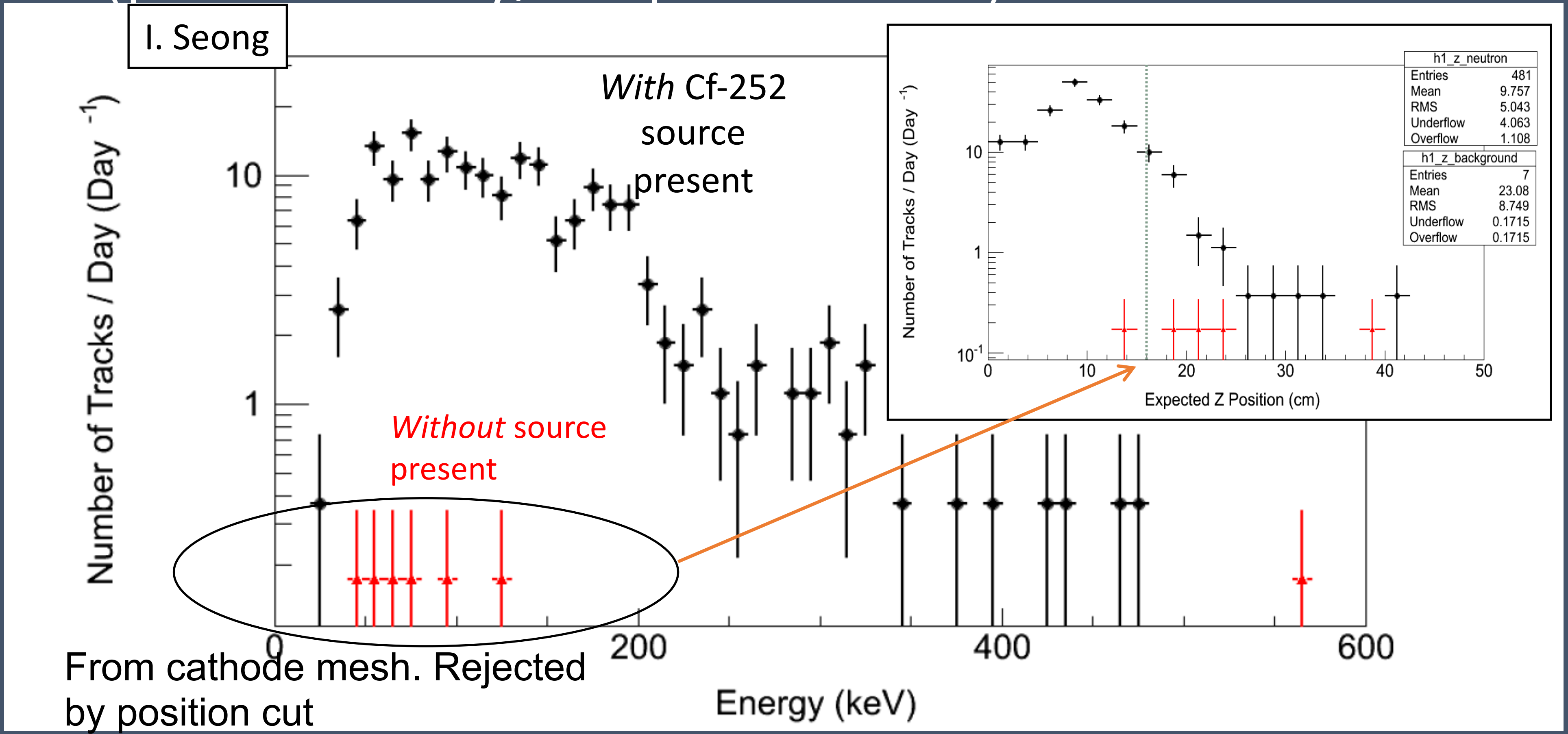
2-mm track segments.

8-mm track segments.

→ enables 3D-fiducialization, even for very short track, presumably for more or less any gas

- Charge profile analysis also enables "Energy Recovery" (unpublished)

Fast Neutron Detection & "WIMP run" (preliminary, unpublished)

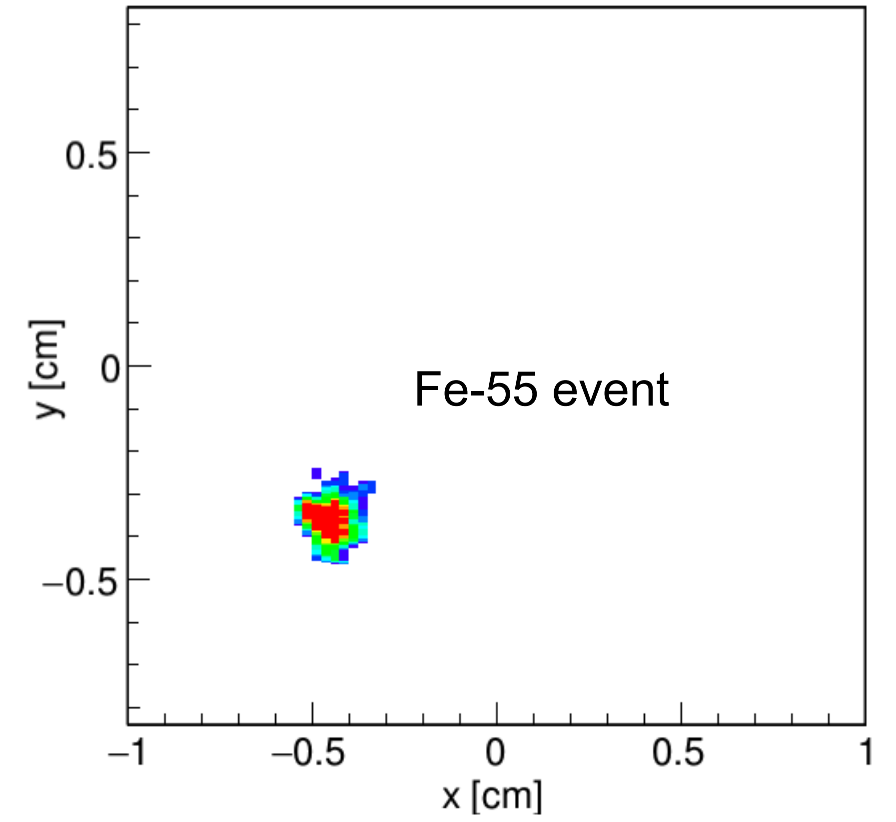


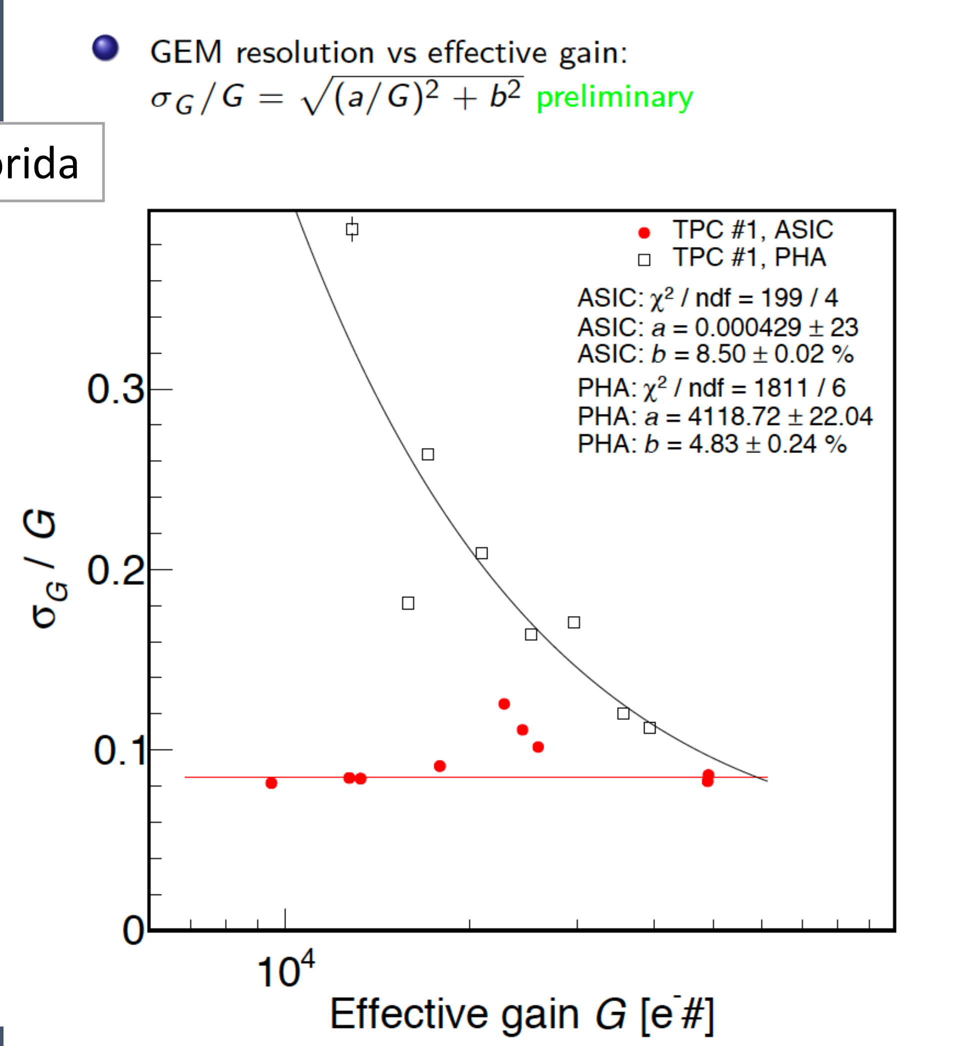
Extended absolute position measurement to neutron recoil events
Detector is essentially background free for high-energy neutron recoil events.

Improved Energy Resolution at low gain, with Pixel Chip

Jaegle et al, arXiv:1901.06657

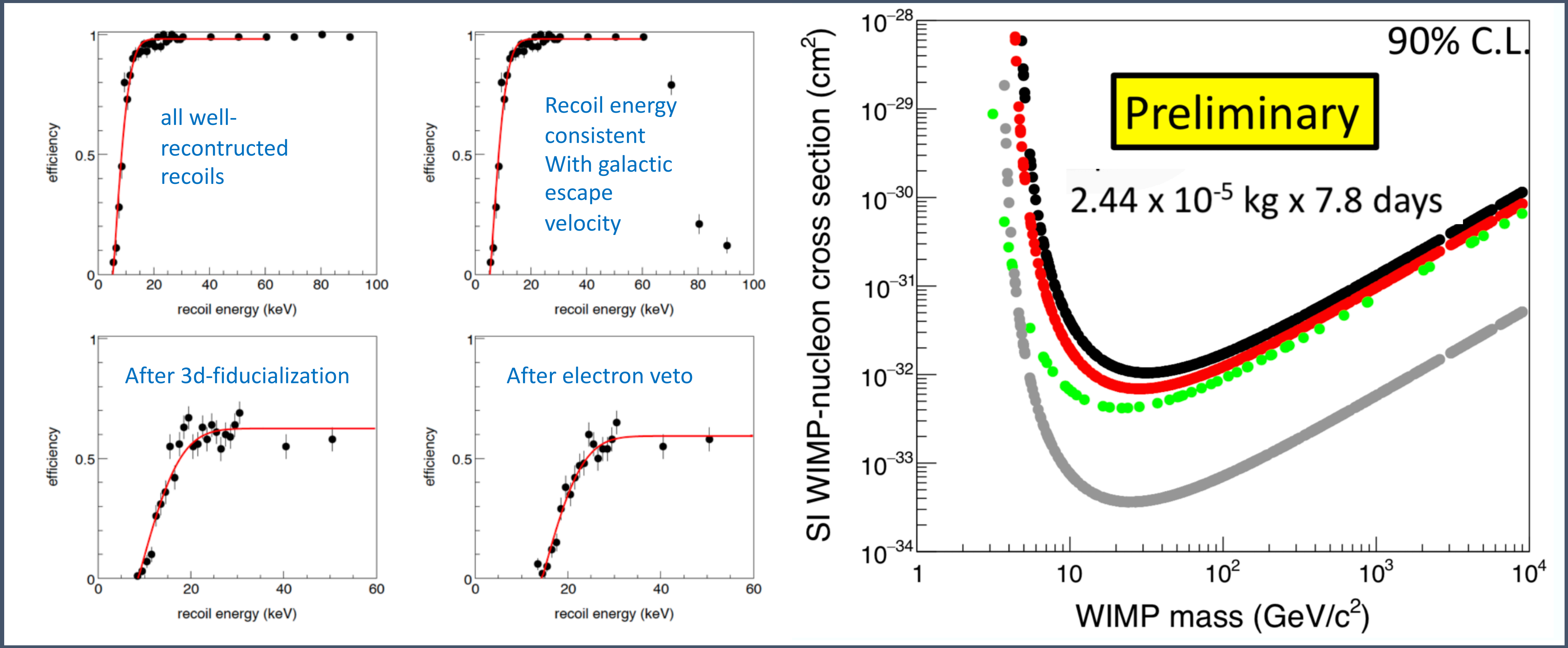
I. Jaegle, U. Florida





Demonstration: Dark Matter limit with directional neutron detector (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?

What is the cost-optimal TPC readout technology?

- Disagreement in community → I carried out a simulation study to find out
- <u>Answer: strip readout</u>!

Not yet published

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

E. Baracchini,[1,2,3] P. Barbeau,[4] J. B. R. Battat,[5] B. Crow,[6] C. Deaconu,[7] C. Eldridge,[8] A. C. Ezeribe,[8] D. Loomba,[9] W. A. Lynch,[8] K. J. Mack,[10] K. Miuchi,[11] F. M. Mouton,[8] N. S. Phan,[12] C. A. J. O'Hare,[13] K. Scholberg,[4] N. J. C. Spooner,[8] T. N. Thorpe,[6] and S. E. Vahsen[6]

Readout type	Dimensionality	Segmentation ($x \times y$)	Capacitance [pF]	σ_{noise} in 1 µs	Threshold/σ_{noise}
planar	1d (z)	10 cm × 10 cm	3000	18000	3.09
wire	2d (yz)	1 m wires, 2 mm pitch	0.25	800	4.11
pad	3d (xyz)	3 mm × 3 mm	0.25	375	4.77
optical	3d (xyz)	200 µm × 200 µm	n/a	20 photons	5.77
strip	3d (xyz)	1 m strips, 200 µm pitch	500	2800	4.61
pixel	3d (xyz)	200 µm × 200 µm	0.012 - 0.200	42	5.77

TABLE II. List of readout-specific parameters that are used in the simulation of each technology we consider here. The capacitance, which determines the noise level, is listed as that for a single detector element. For the optical readout, a loss factor of 1000 is used to account for photon yield, geometric optical acceptance, optical transparency, and quantum efficiency.

Gas mixture	SF_6	He:SF_6	He:SF_6	He:CF_4
Gas pressure [Torr]	20	740:20	755:5	740:20
W [eV/ion pair]	35.5	38.0	35.6	38.0
Trans. diffusion [µm/$\sqrt{\text{cm}}$]	116.2	78.6	78.6	213.0
Long. diffusion [µm/$\sqrt{\text{cm}}$]	116.2	78.6	78.6	148.0
Drift velocity [mm/µs]	0.140	0.140	140	24.45
Mean avalanche gain	9×10^3	9×10^3	9×10^3	10^6

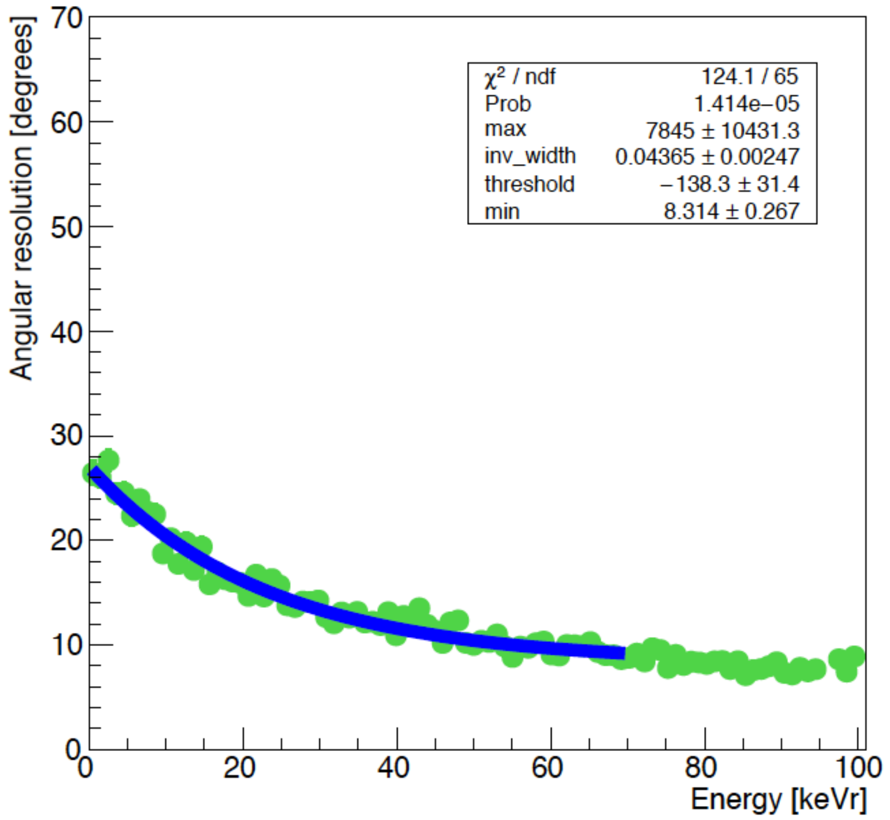
[We have previously experimentally investigated many other gases. See, e.g., Tests of gases in a mini-TPC with pixel chip readout, **S. Vahsen *et al.*, *NIMA* 738 (2014) 111-118**]

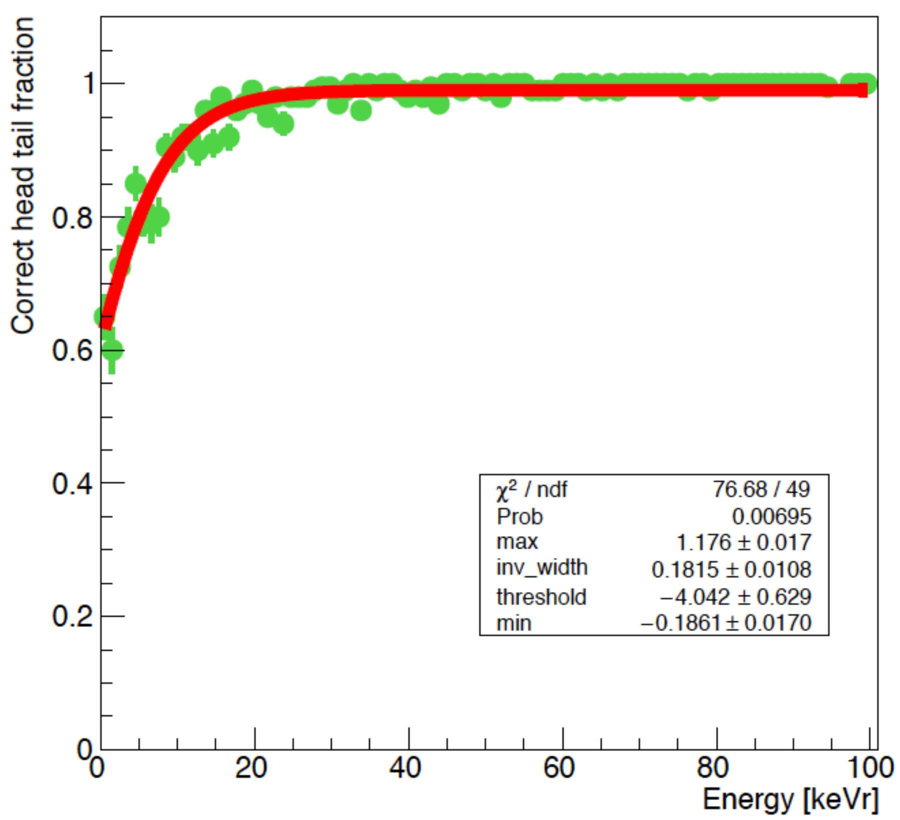
New gas mix: He+SF6 755+5. Pre-drift

straggling + reconstruction algorithm

S.V.

Helium recoil (Fluorine does <u>much</u> worse!)



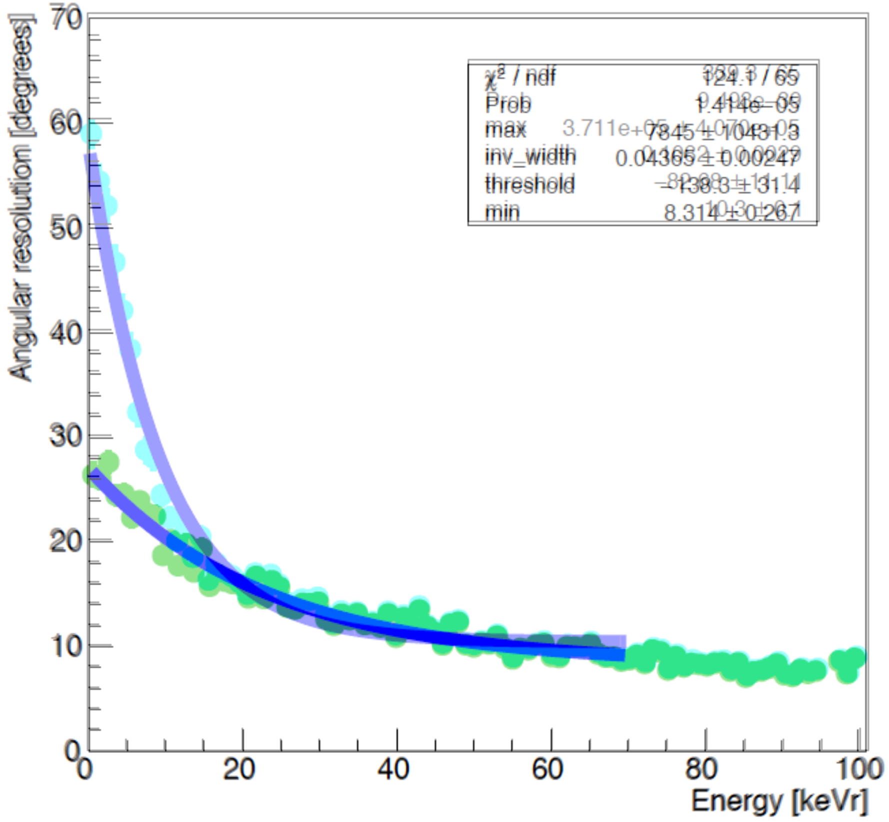


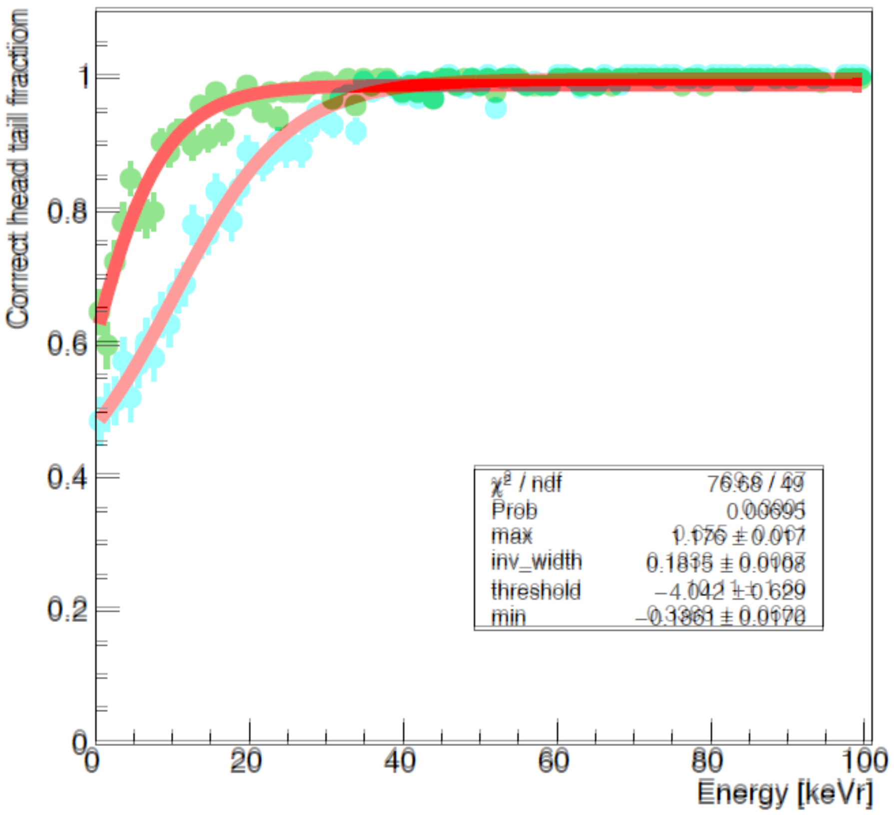
New gas mix: He+SF6 755+5. Post-drift.

straggling + reconstruction algorithm + diffusion

S.V.

Helium recoil (Fluorine does <u>much</u> worse!)



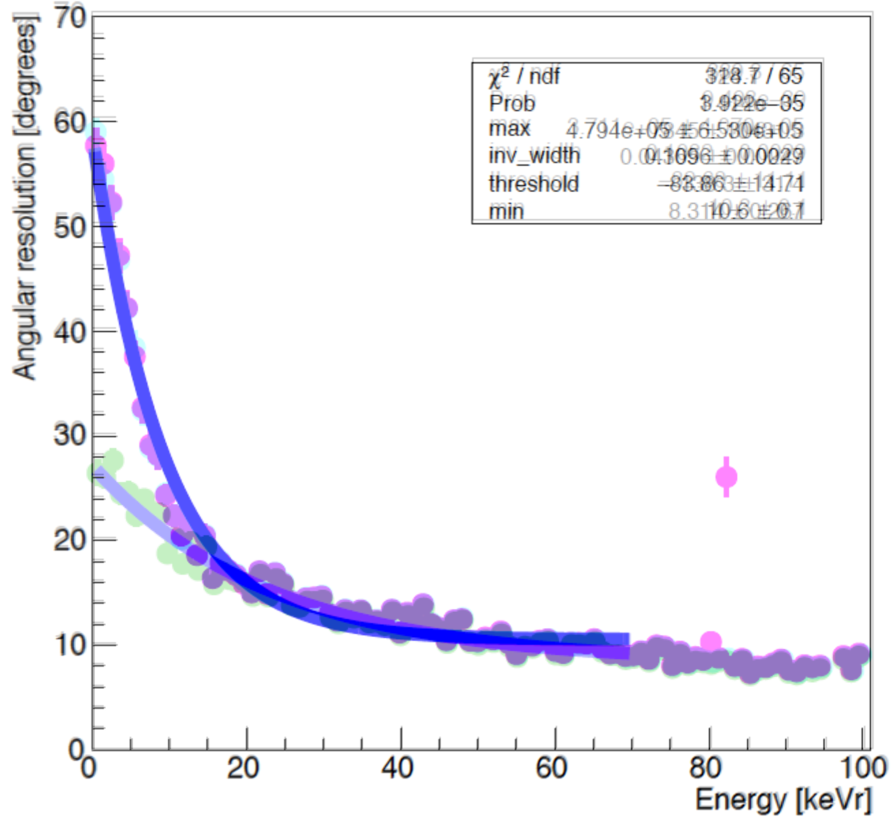


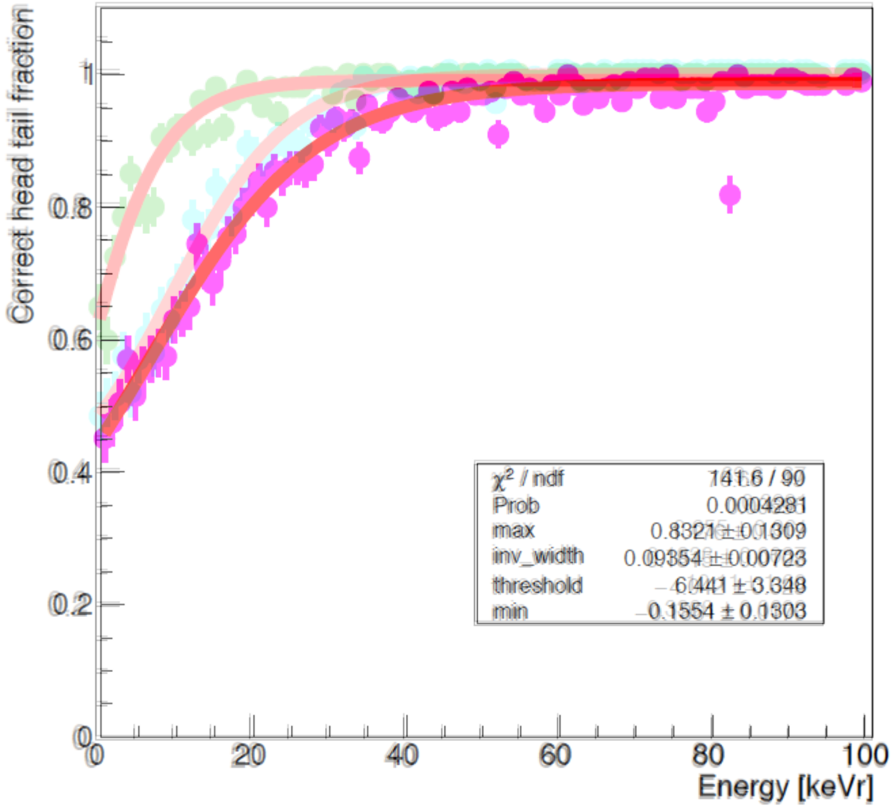
New gas mix: He+SF6 755+5. Pixel readout.

straggling + reconstruction algorithm + diffusion + readout performance

S.V.

Helium recoil (Fluorine does <u>much</u> worse!)

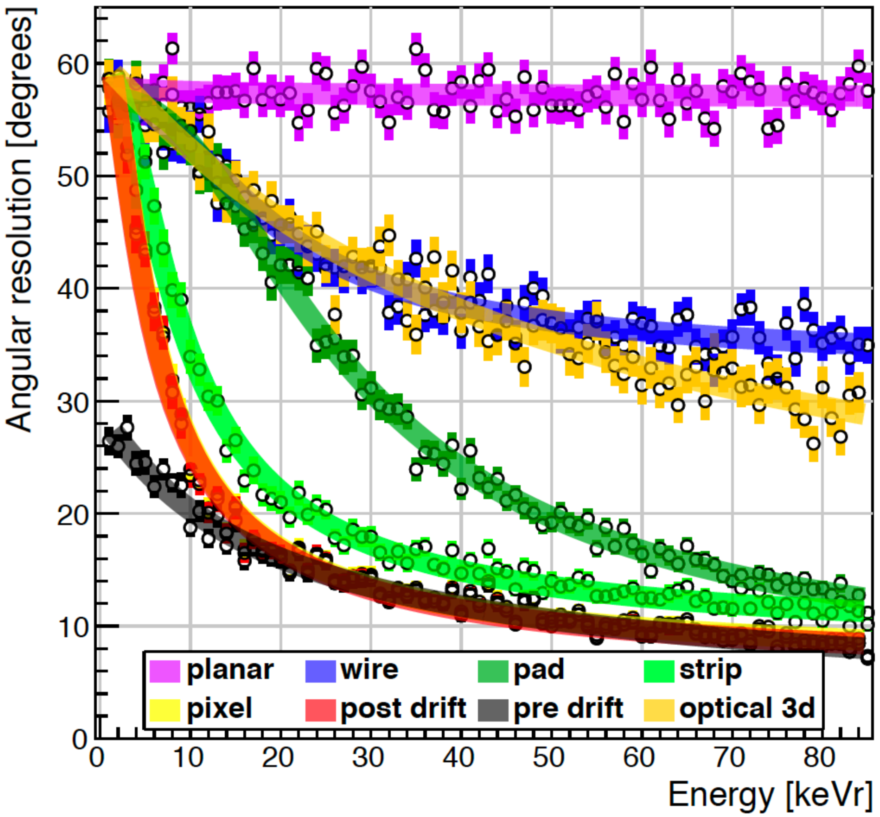


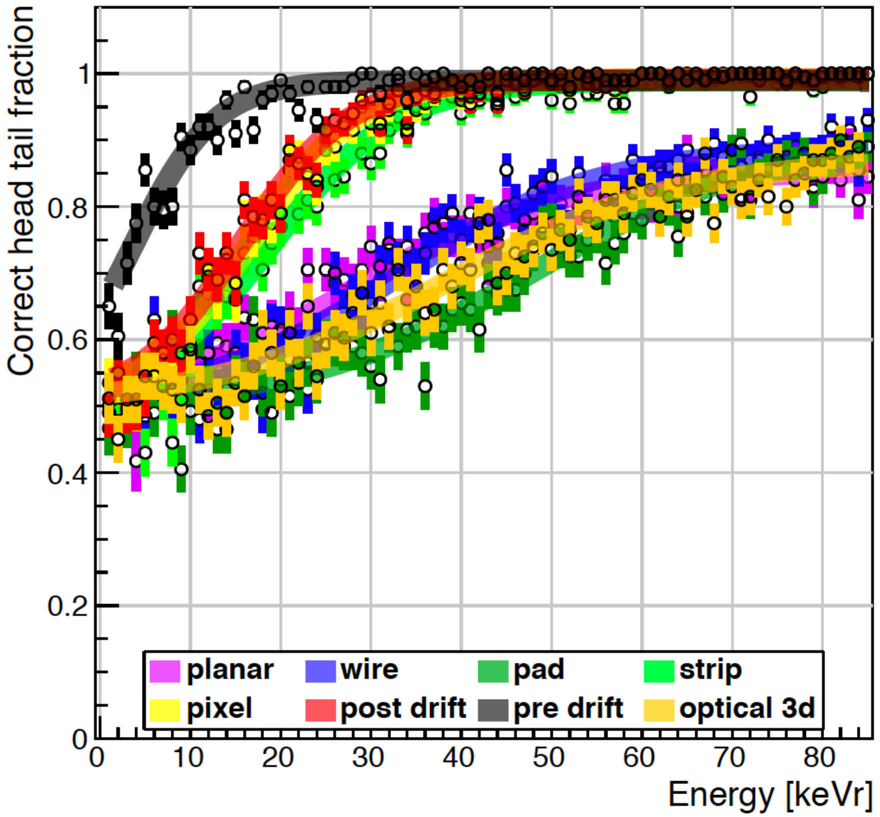


Directionality is diffusion limit. Pixel readout essentially extracts all information present after diffusion.
Possible paths to improved directionality: 1) lower diffusion 2) improved reconstruction algorithms 3) hydrogen

Comparison of readouts. He:SF_6 simulated for all readouts, except optical, where we used He:CF_4

Gas mixture	SF_6	He:SF_6	He:SF_6	He:CF_4
Gas pressure [Torr]	20	740:20	755:5	740:20





Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost