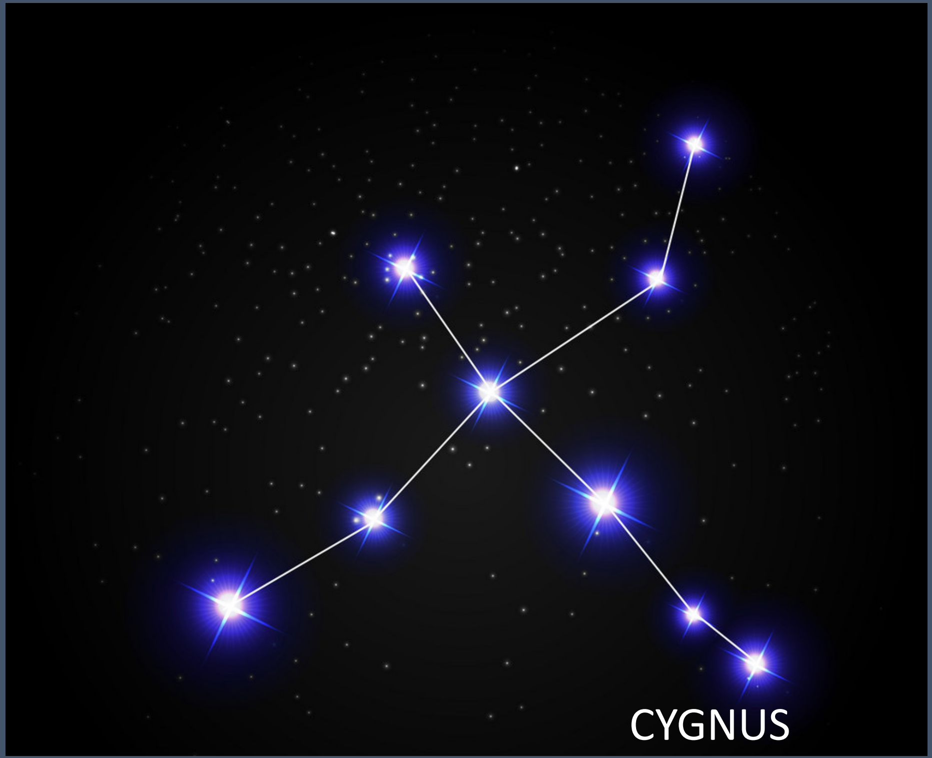
Dynamic range in MPGD-based directional neutron and dark matter detection

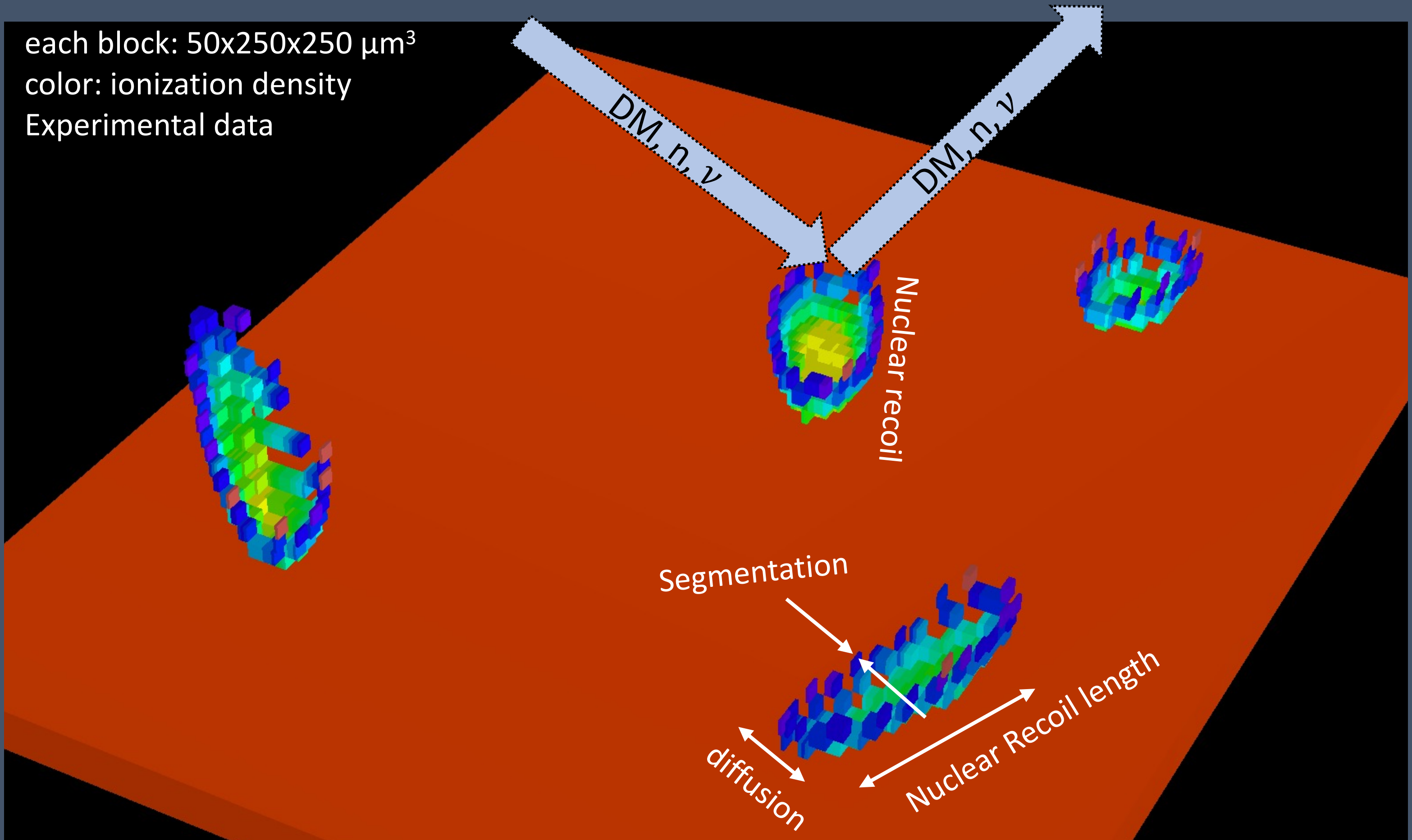


Sven Vahsen (University of Hawaii)

The Power of MPGD gas TPCs

Capabilities resulting from HD charge readout

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



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)

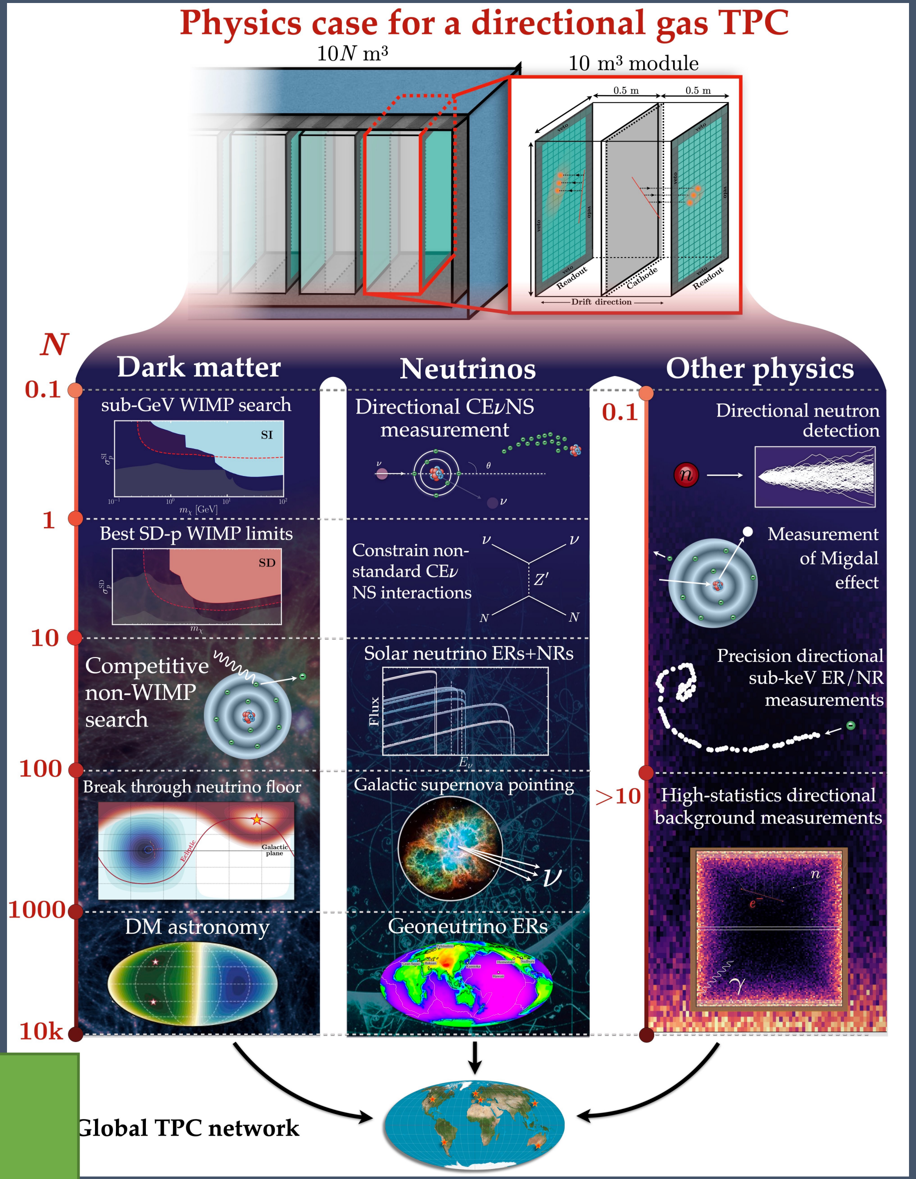
Event-by-event 3D vector directionality w/ event timing possible in gas TPC w/ highly segmented MGPD readout planes
Unique – not available with any other technology!

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

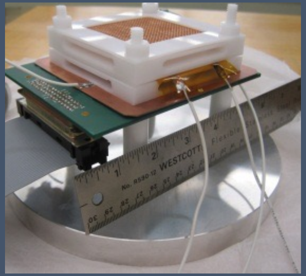


https://arxiv.org/abs/2102.04596

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

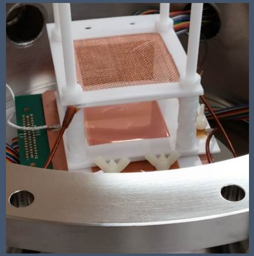
Detectors in development at U. Hawaii

2011-2013



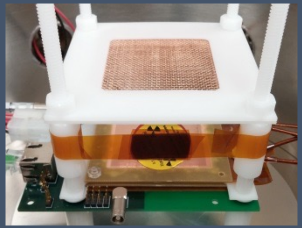
μD^3 (~1cm^3)

2013



~2.5 cm^3

2013



~ 20 cm^3

1st generation, proof of concept

2014

2 x 60 cm^3

2015

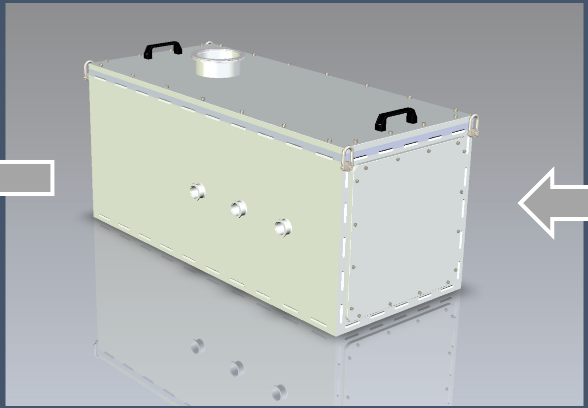
8 x 40 cm^3

BEAST TPCs (still operating at SuperKEKB)

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

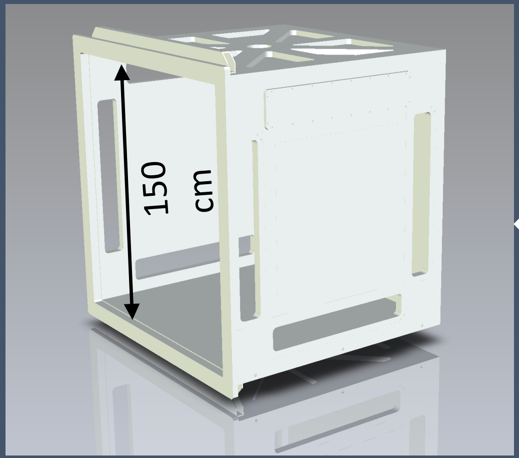
- Extensive prototyping with pixel chip readout completed, leading to "BEAST TPCS"
- Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for precision studies of nuclear recoil physics
- Now transitioning to 3rd generation of detectors w/ strip readout to enable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

2020



CYGNUS HD "Keiki"

2021



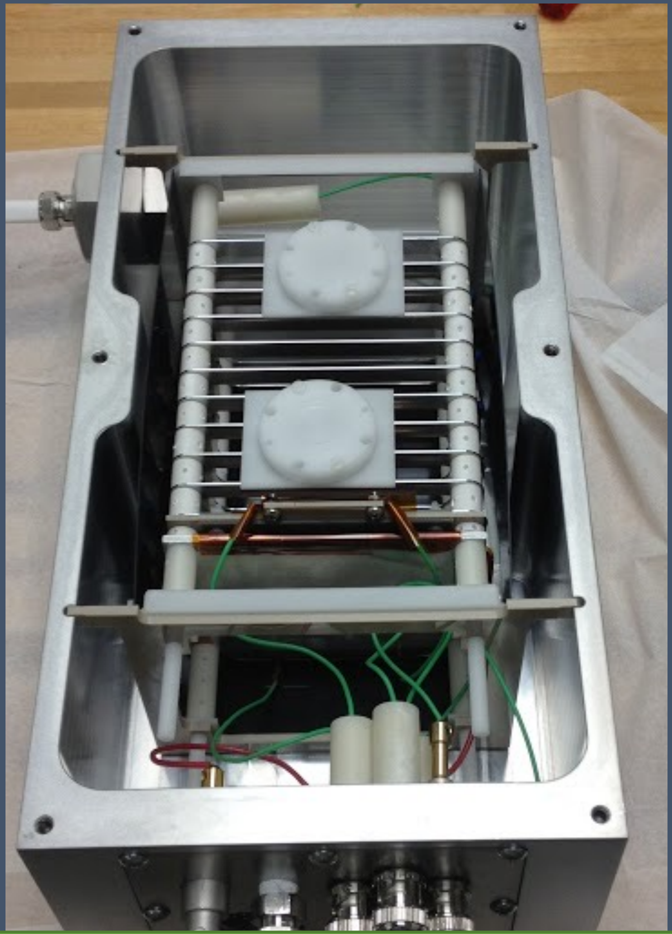
CYGNUS HD1 Demonstrator

3rd Generation: Optimized for dark matter

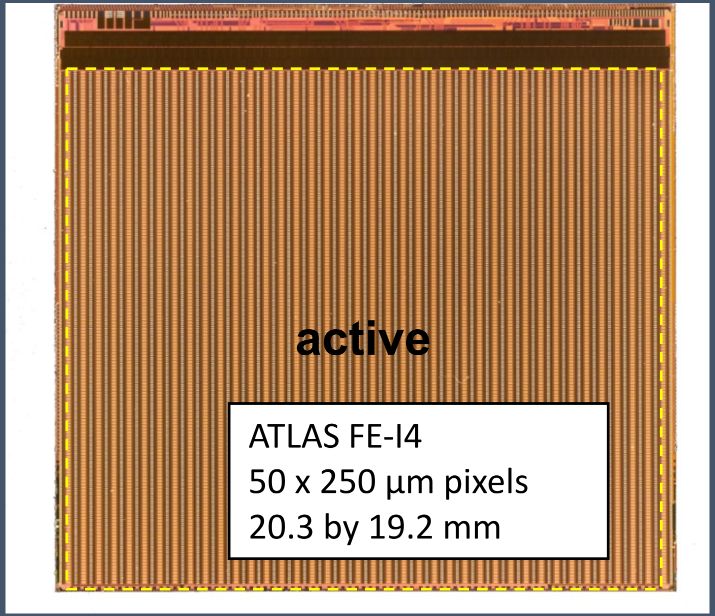
Latest operational detector: ~40 cm^3 "BEAST" TPC - eight constructed

- 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:

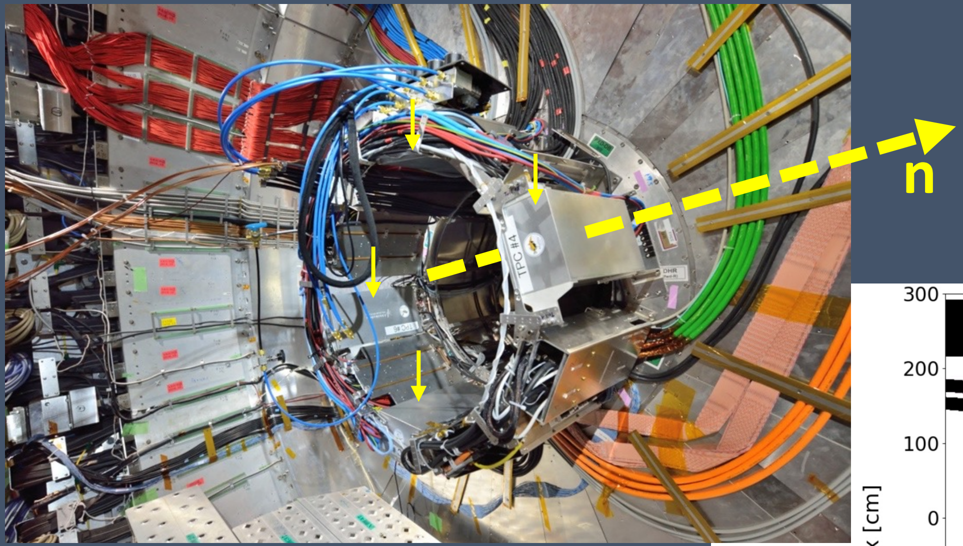


- Directional *fast neutron* detector.
- Small footprint enabled by Parylene coating on inside of pressure vessel
- Successfully measured directional neutron distribution at SuperKEKB

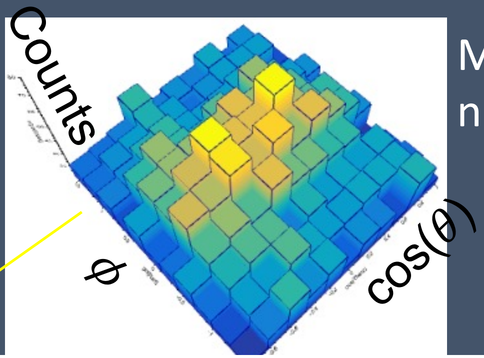
Double GEM amplification for gain up to ~50k. But, typically operate at gain ~1k. He:$C0_2$ gas (70:30).
Pixel ASIC readout (noise ~100 electrons). Threshold ~2k. 4bit ToT. 40MHz.
At gain > ~10k, detect even single electrons. Essentially noise-less. Only see events when there is ionization in detector.
Can use novel charge-density-trigger veto to only trigger on *nuclear* recoils

SuperKEKB Neutron Background Measurements

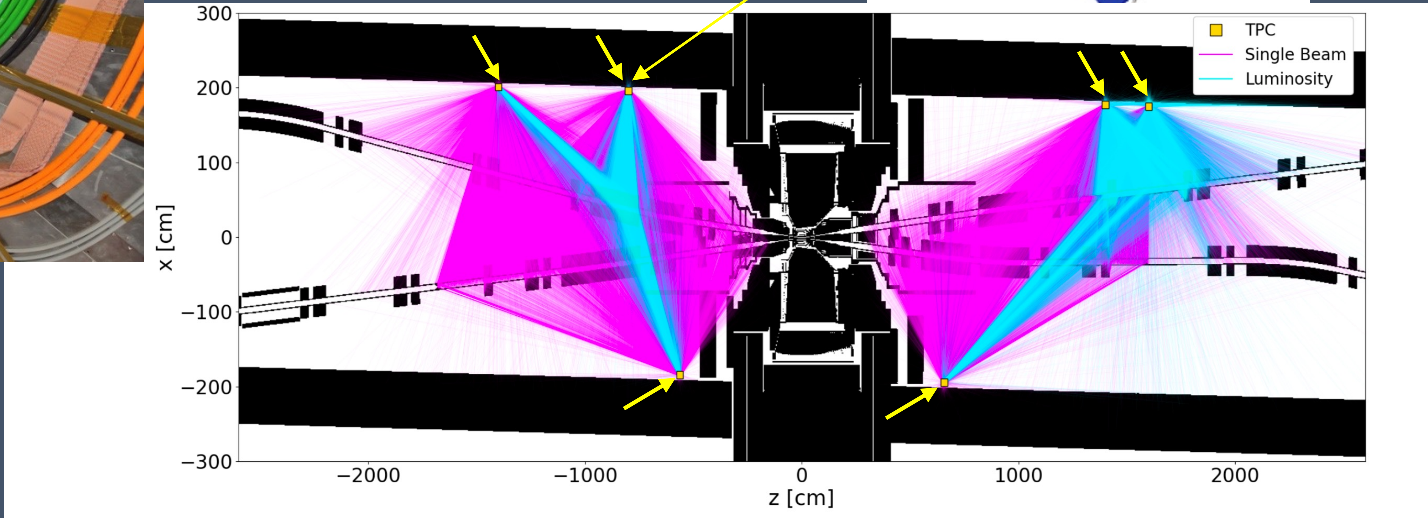
Phase 2



Phase 3



Measured directional neutron flux at TPC



- BEAST TPCs used at SuperKEKB electron-positron collider (world's highest luminosity machine)
- TPCs are semi-portable and have been moved around for different measurements
- Currently Phase 3: six BEAST TPCs to measure neutrons in the SuperKEKB accelerator tunnel
- Observed neutron hotspots – due to gamma rays from Radiative Bhabba scattering.
- See J. Schueler et al., http://arxiv.org/abs/2111.03841

Dynamic range optimization for nuclear recoils: choose low-gain

Table 2

Summary of formal TPC acceptance criteria and achieved performance. All performance threshold values are satisfied for all TPCs. For most parameters, the measured performance exceeds the specification and significantly exceeds the objective. For the gain, however, we found that a lower gain, near 1500, was in fact optimal, and hence only tested the first few detectors at higher gains.

Quantity	Threshold	Objective	Specification	Achieved
Angular resolution (1-cm tracks)	n/a	15°	5°	2.5°
Gain	1,000	10,000	20,000	50,000
Gain stability, one week	n/a	20%	5%	1%
Energy resolution at 5.9 keV	n/a	20%	12%	10%

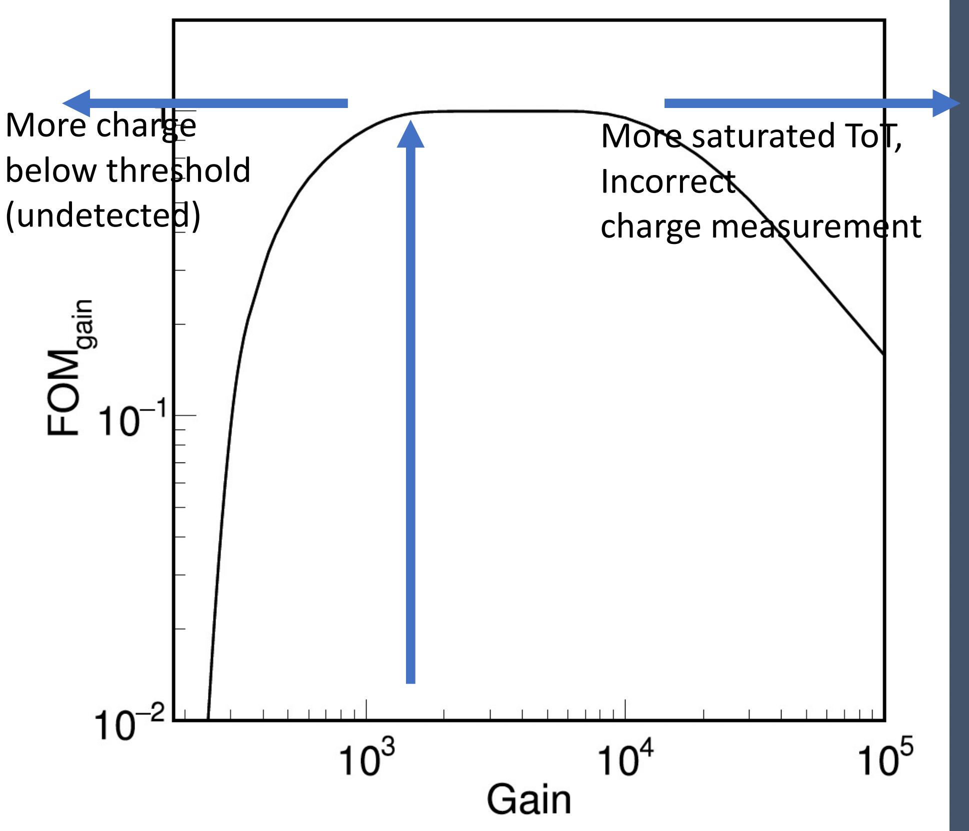
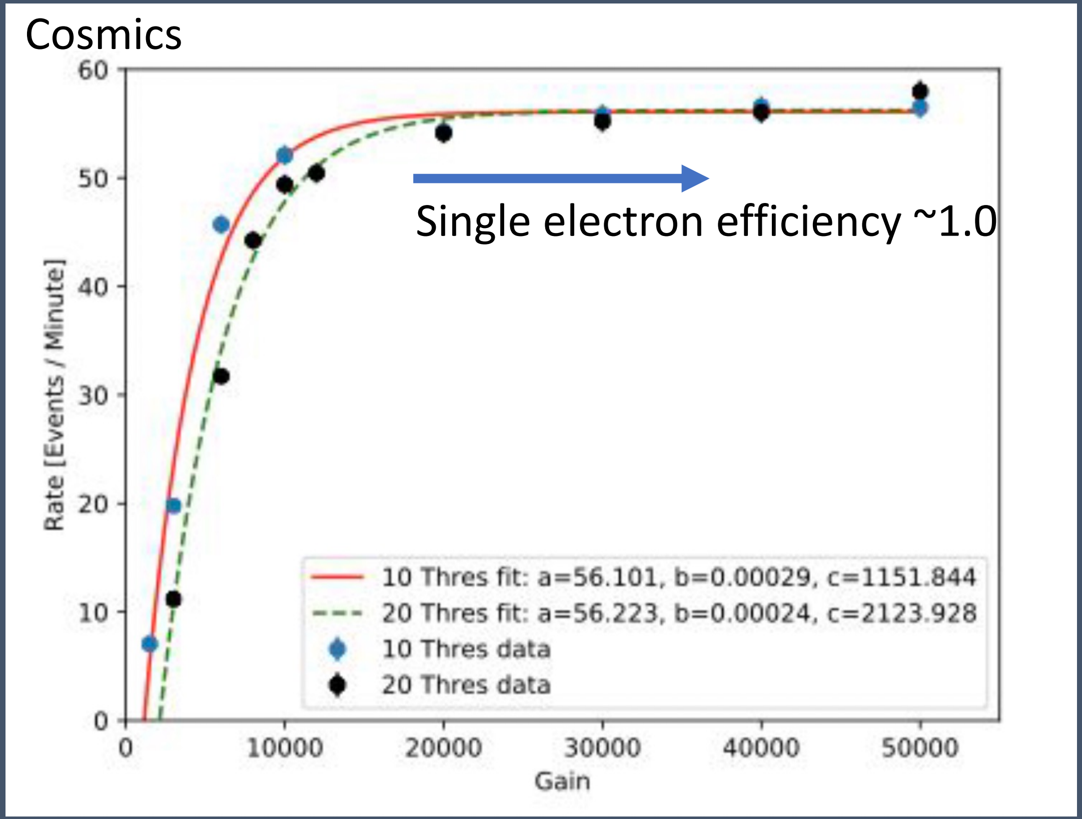


Fig. 4. Gain figure of merit (FOM_{gain}) value for the ionization charge from a 300 keV ^{4}He recoil after drifting 8 cm.

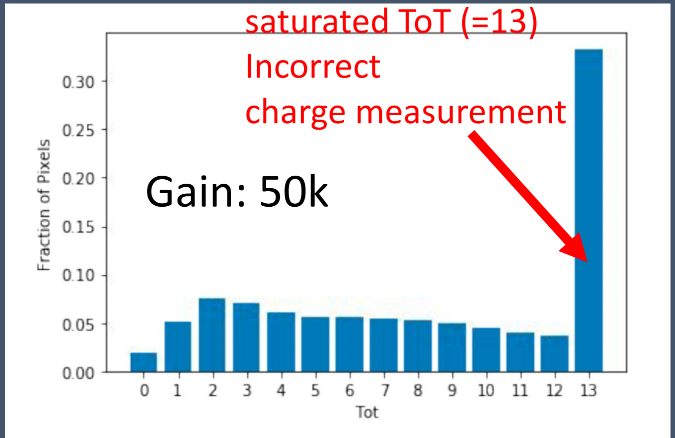
- Due to finite dynamic range of charge measurement, highest gain (50k) is not optimal
- Due to high radiation dose at SuperKEKB, also concerned about
  - Gas detector aging
  - Sparking from GEMs → accidental discharges killing pixel ASICs
- Decided to operate at lowest optimal gain; ~1500
- Successful running for four years – not a single ASIC has been damaged!

Dynamic range optimization w/ cosmics and FE-55 (5.9 keV electron recoils): Gain ~ 20k optimal

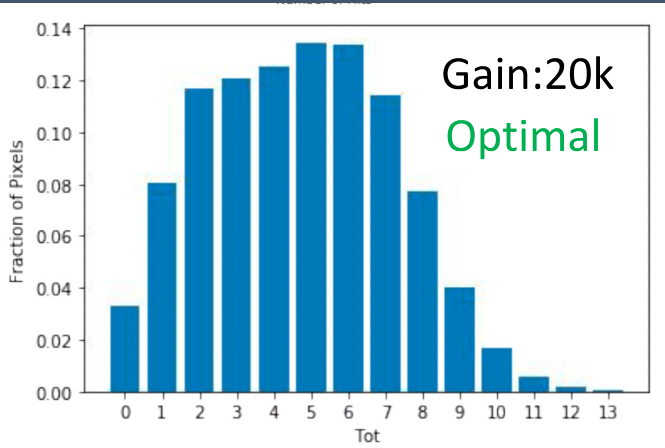
Cosmic ray rate



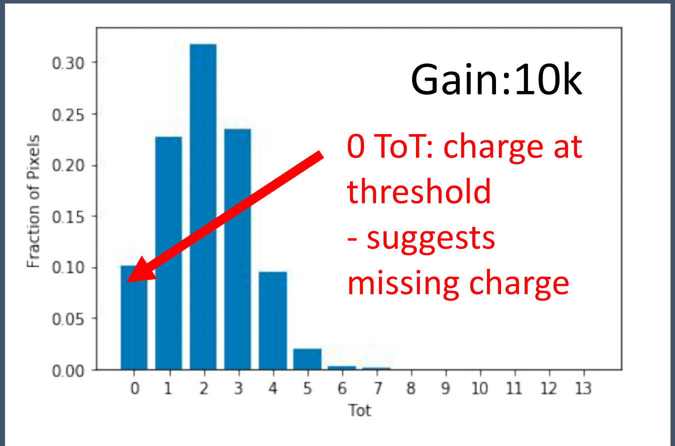
Fe-55



Fe-55

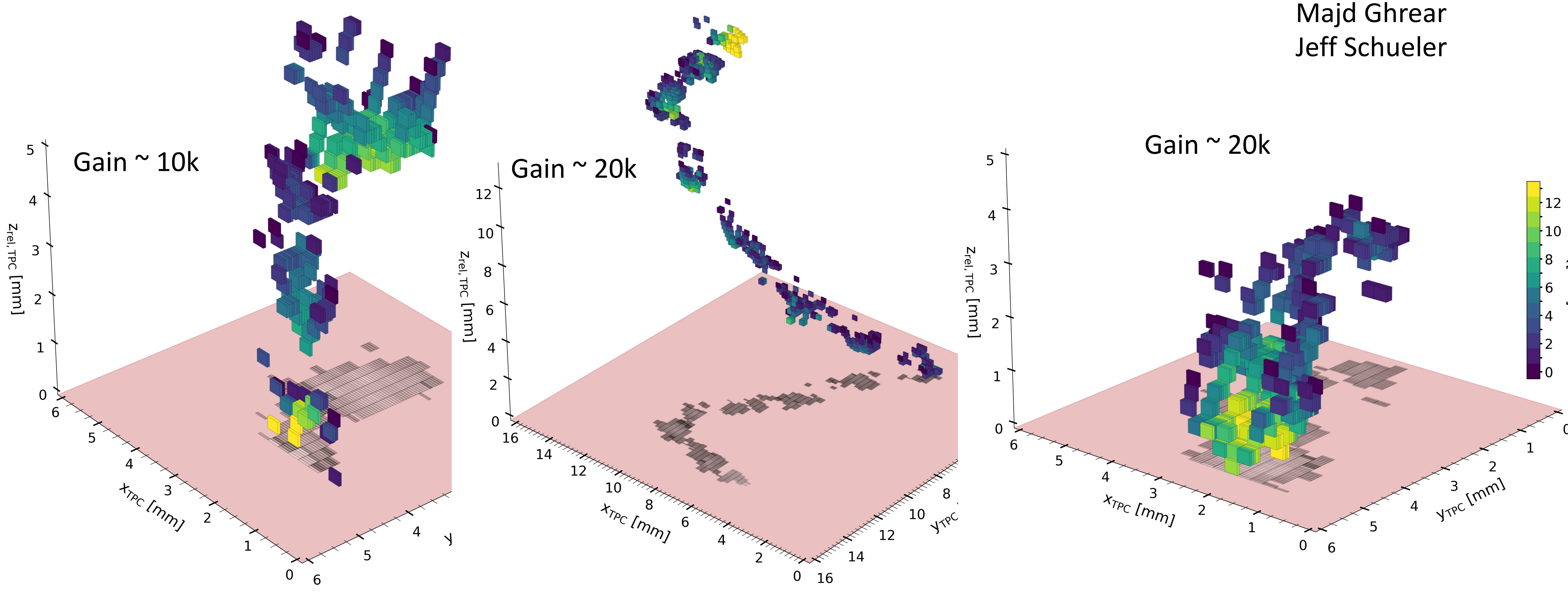


Fe-55

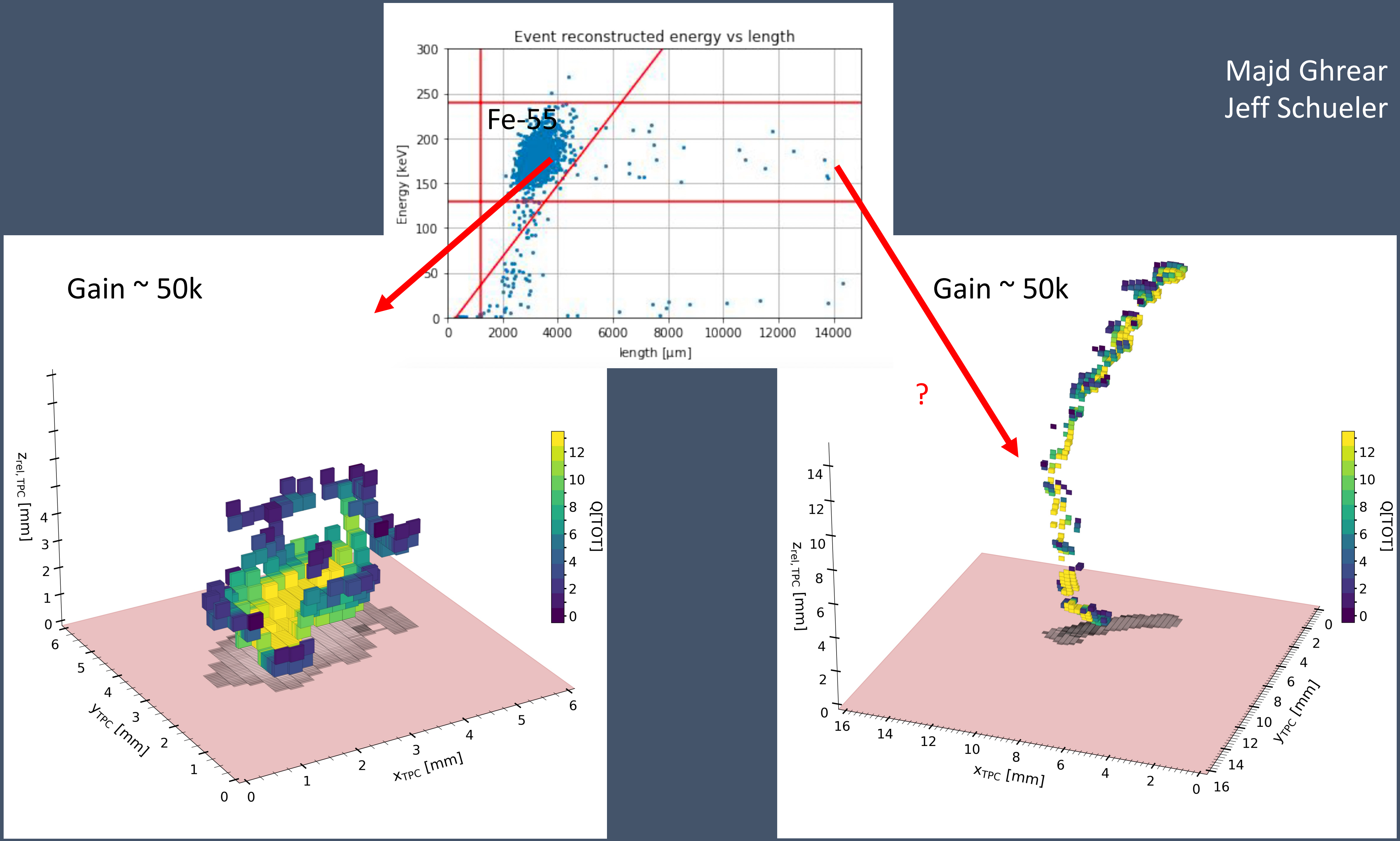


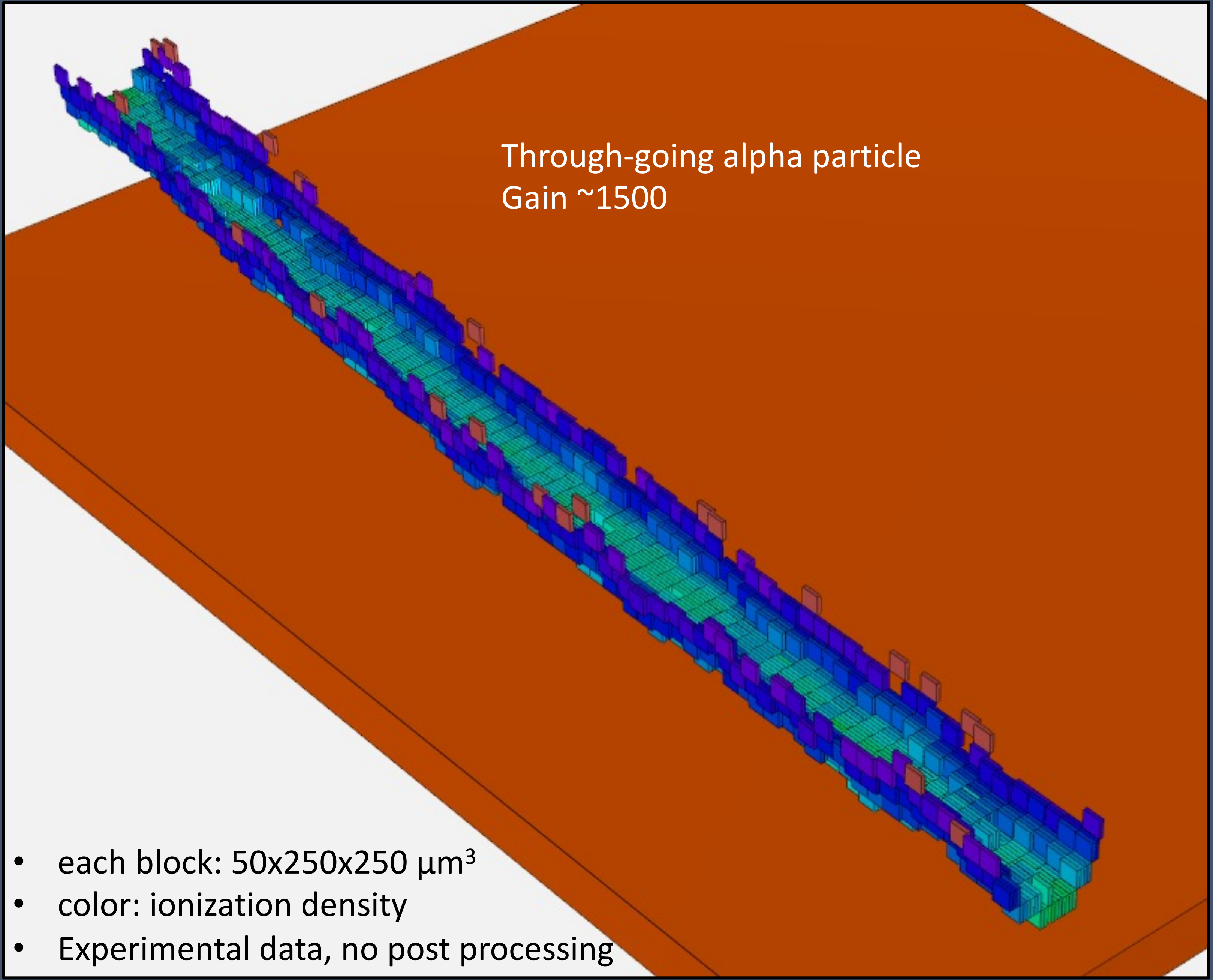
Fe-55 data set (5.9 keV) new – unpublished!

Majd Ghrear
Jeff Schueler



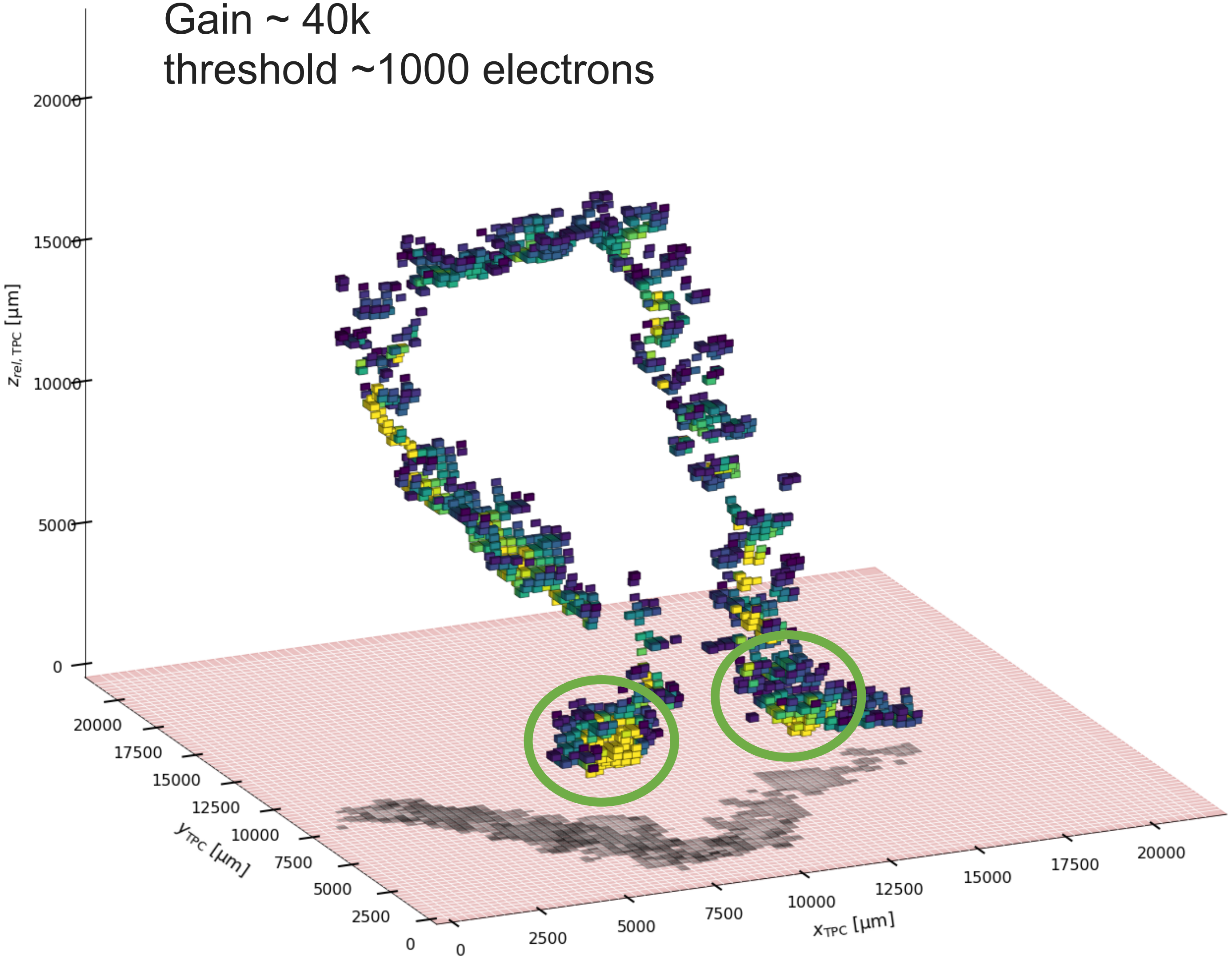
Majd Ghrear
Jeff Schueler





- each block: 50x250x250 μm^3
- color: ionization density
- Experimental data, no post processing

Electron recoil candidate event (not FE-55, higher energy)
Gain ~ 40k
threshold ~1000 electrons



RAW experimental data, no post processing

Dynamic range issues w/ BEAST TPCs

Gain ~1500

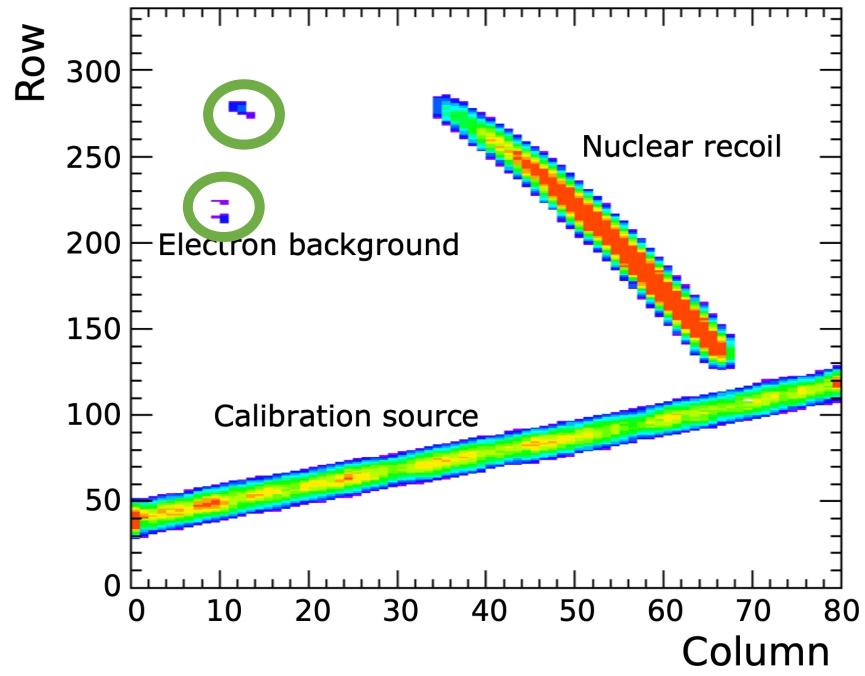
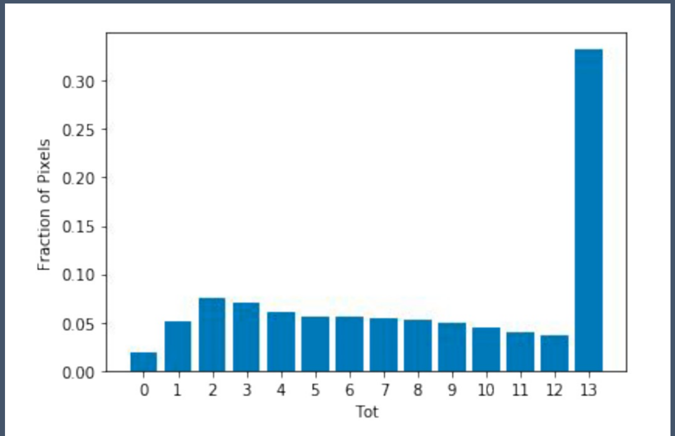


Figure 6: Adapted from Ref. [1]. Three separate events, illustrating the typical signatures of electron recoils, alpha particles from the internal calibration sources, and the nuclear recoil signal. The horizontal and vertical axes show the row and column number, respectively, of the pixels on the FE-I4B pixel chip. The color illustrates the amount of charge detected in each pixel.

- Huge energy density variation between particle species
- Cannot optimally detect both electron and nuclear recoils
  - Nuclear recoil is saturated
  - Electron background shown is likely a single recoil event as on previous page, but now with most of the charge below threshold
- OK for high-energy applications
- But, detecting the whole recoil track *required* for particle ID at lowest energies, relevant for DM searches

Offline correction for finite dynamic range – take 1



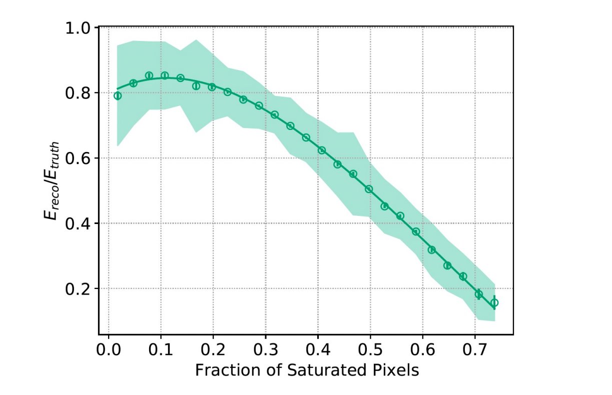


Figure 2: Ratio of reconstructed to true energy versus fraction of saturated pixels per event in all simulated recoils fit to a fourth-order polynomial. The shaded area represents one standard deviation of the data in each bin.

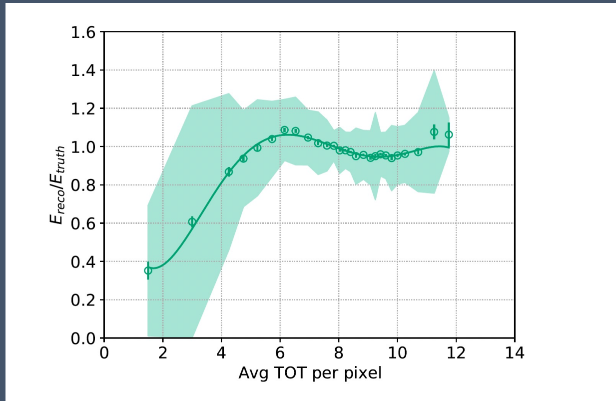
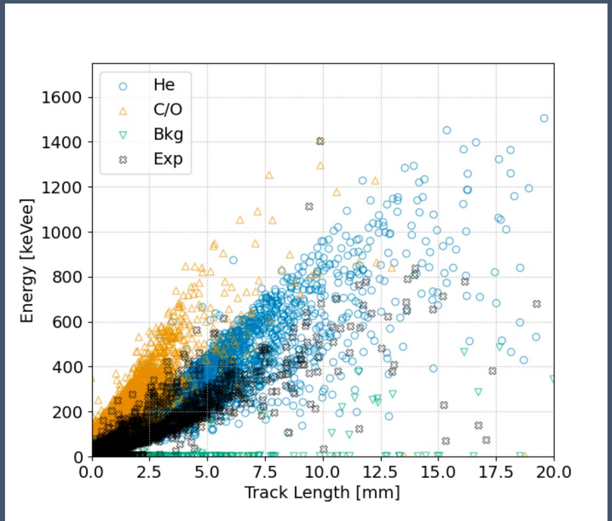


Figure 3: Ratio of reconstructed to true energy versus the average TOT in a single pixel per event fit to a fifth order polynomial. The shaded area represents one standard deviation of the data in each bin.

before corrections



after corrections

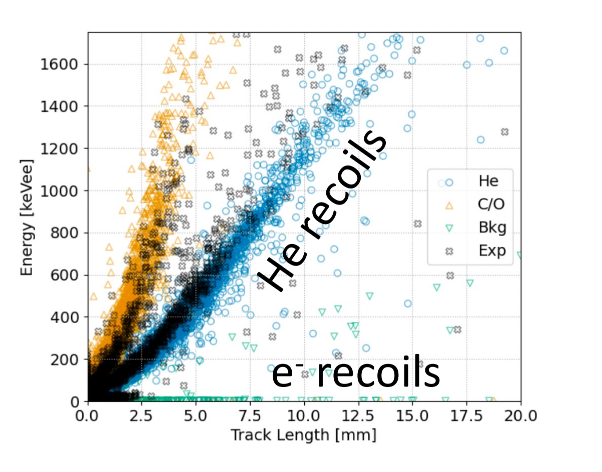


Figure 8: Reconstructed energy versus reconstructed length in simulated and experimental data in both TPCs before charge-loss corrections (top), after

Use measured ToT distribution of each event to correct measured energy for saturation and charge below threshold

→ Improved energy resolution, particle ID, and improved matching with simulation

Electron events suppressed in experimental data due to charge-density trigger veto

Data quality after corrections

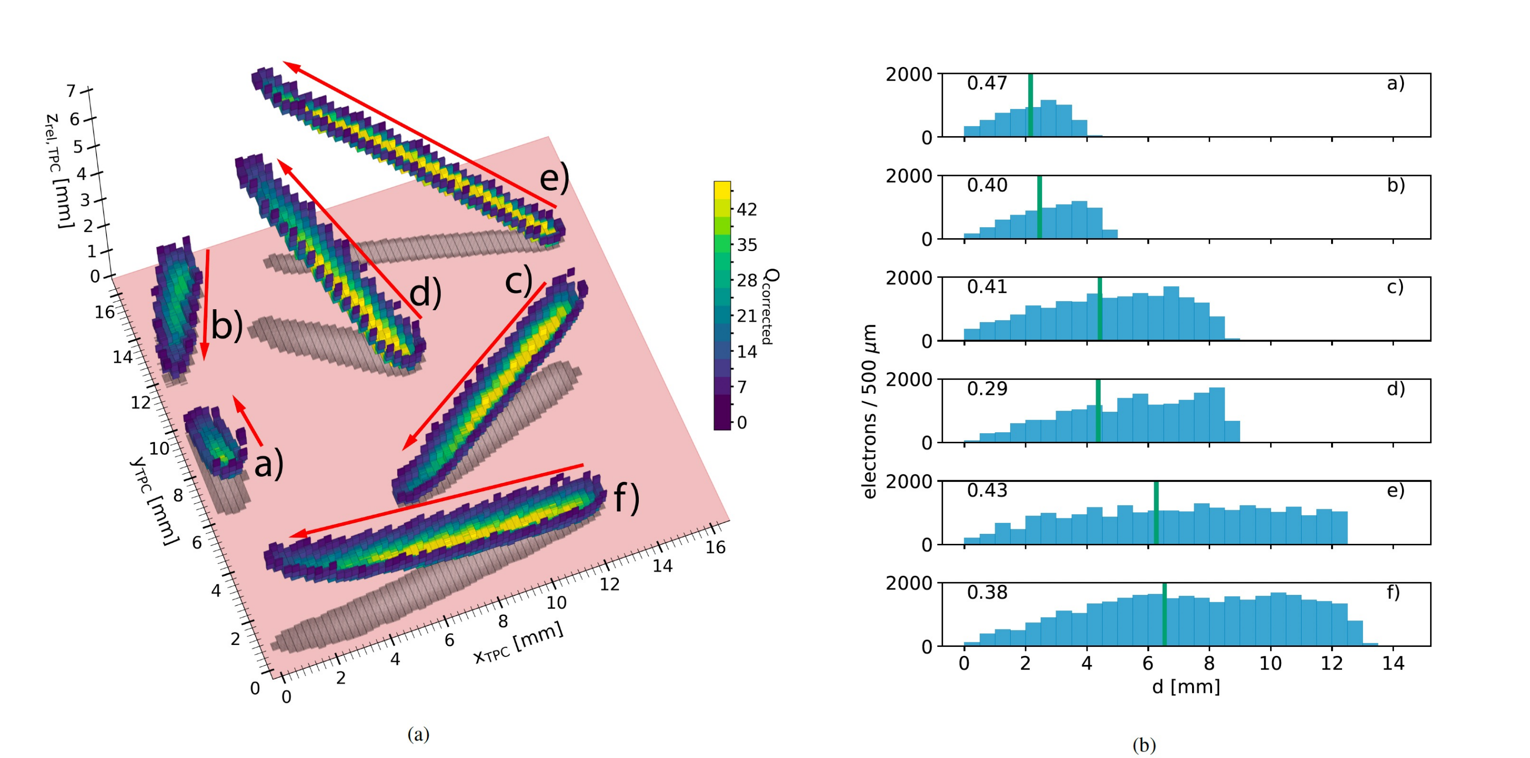


Figure 16: Six tracks visualized in 3D (a) alongside their charge distributions versus distance from the track head (b). The head-direction of the tracks is shown with red arrows, and is determined by designating the half with less charge as the head, as shown by the color scale. On the right, the geometric midpoint of each track is shown as a vertical green bar. The number in the upper left displays the head charge-fraction of the track.

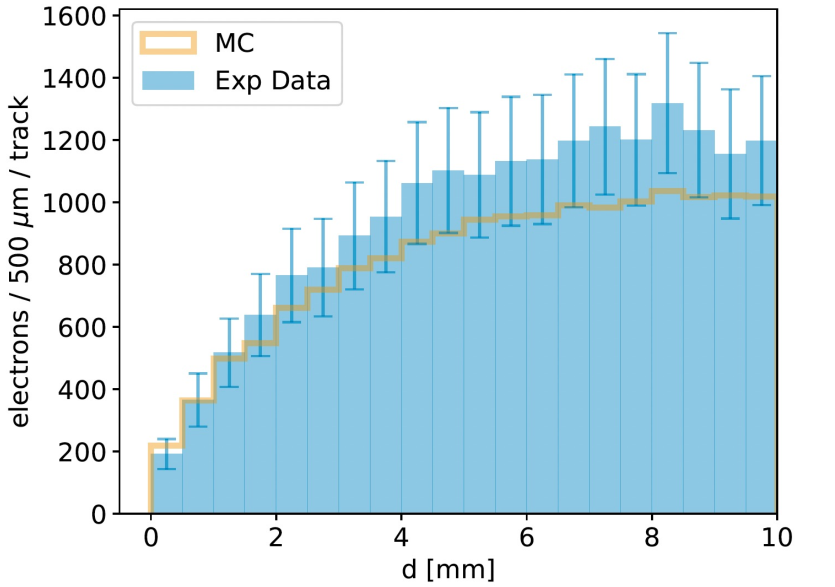


Figure 15: Detected charge versus distance from the track head in selected helium recoils. The orange line corresponds to a digitization of SRIM-based events in simulated data and the blue histogram corresponds to the equivalent measurement in data. The error bars show the statistical variation in the charge density in the experimental track sample analyzed.

- Angular resolution < 20 degrees for recoil tracks longer than 1.7 mm, corresponding to an average ionization energy of approximately 100 keVee.
- Full 3D vector direction of helium recoils by utilizing charge profile measurements along the recoil axis, with a correct head/tail assignment efficiency of approximately 80%.

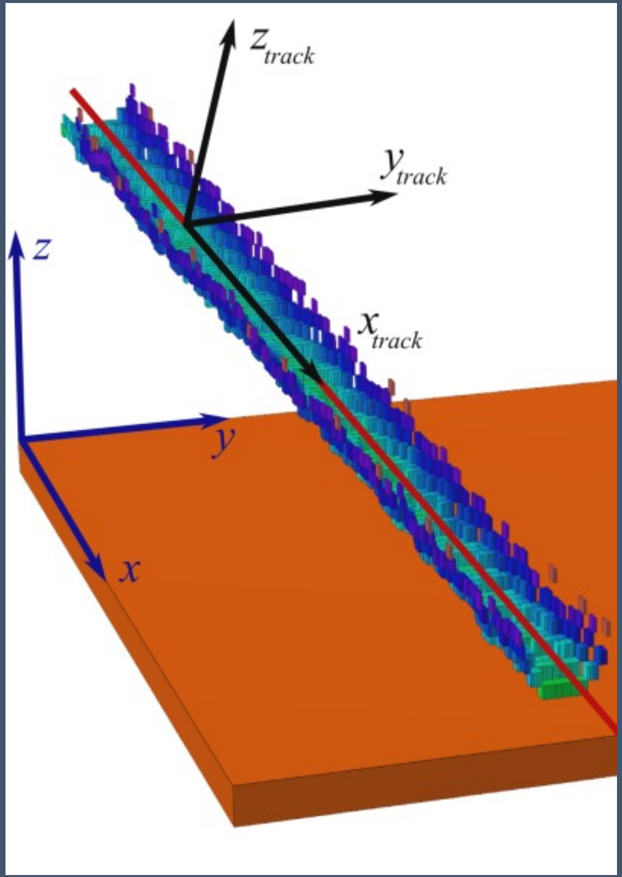
Improved offline correction– take 2

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



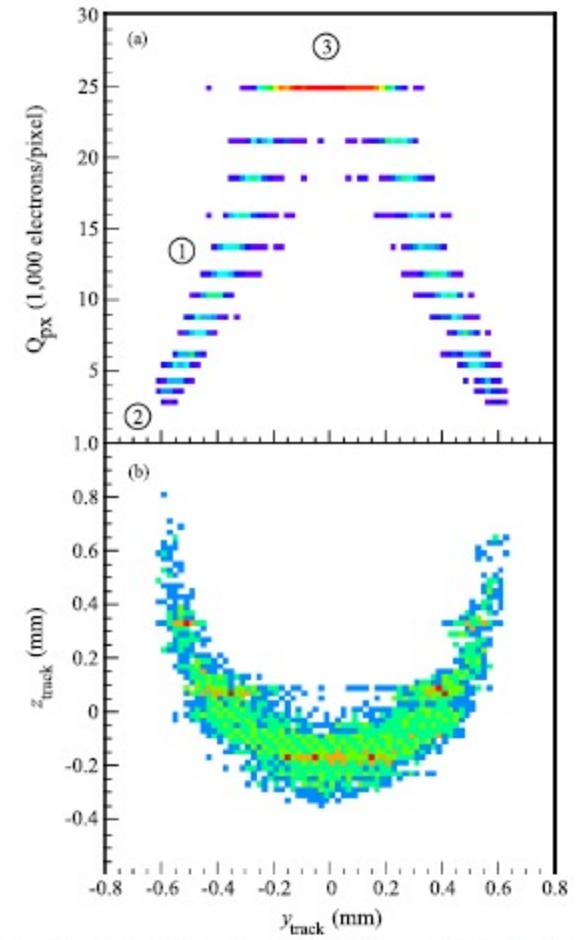


Fig. 2. Corrected pixel charge (Q_{px}) profile (a) and shell coordinates (b) for a single horizontal track from the near alpha source. Label 1 of the profile plot (a) corresponds to the Gaussian, label 2 to the threshold, and label 3 to the saturation regions of the profile. The U-shaped shell in plot (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.)

charge above ToT scale saturation limit

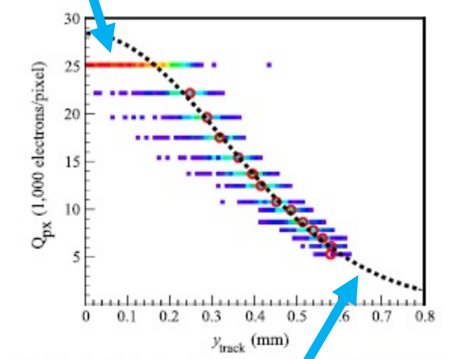
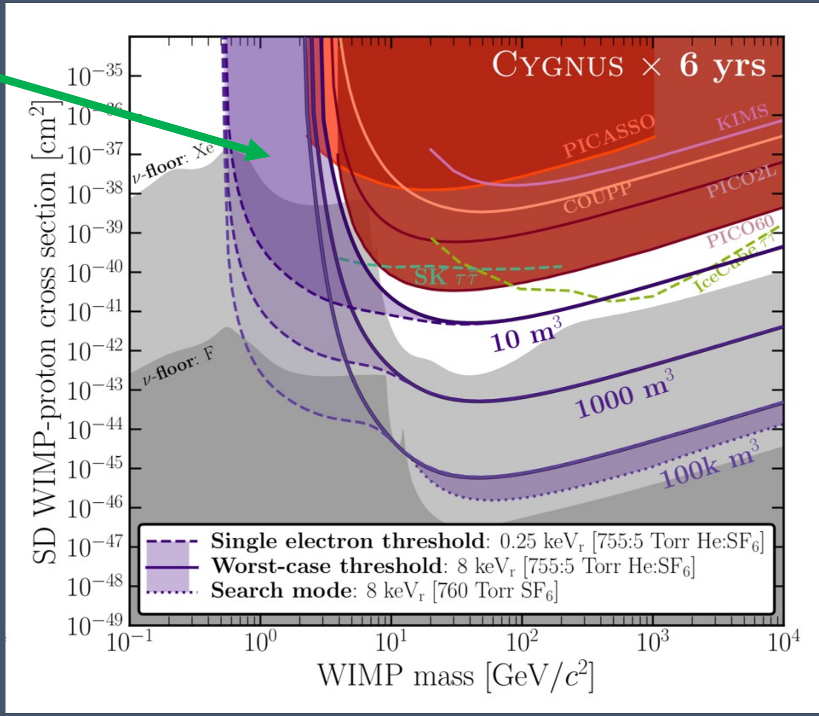


Fig. 3. Fit to the folded version of the corrected pixel charge (Q_{px}) profile shown in Fig. 2 using the profile fit method described in Section 4.3. The Gaussian function (black dotted line) is fitted to the plot points (red open circles), which are placed at the mean Q and y_{track} positions for 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.)

charge below pixel threshold

Charge-profile analysis can correct for saturation, charge below threshold, and measured absolute position in drift direction!
Recently: P. Lewis improved technique further to recover 3d primary ionization distribution: https://arxiv.org/abs/2106.15829

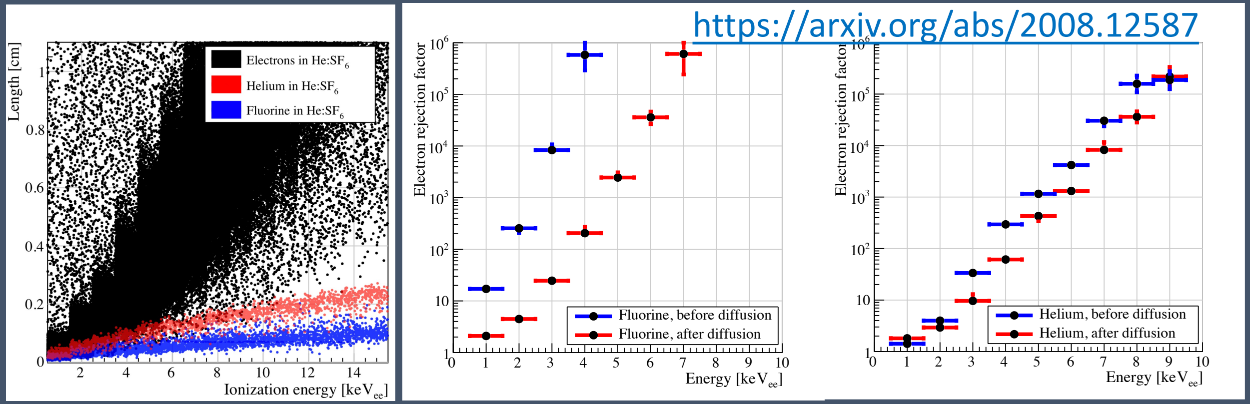
Key issue: WIMP sensitivity depends on electron rejection



https://arxiv.org/abs/2008.12587

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

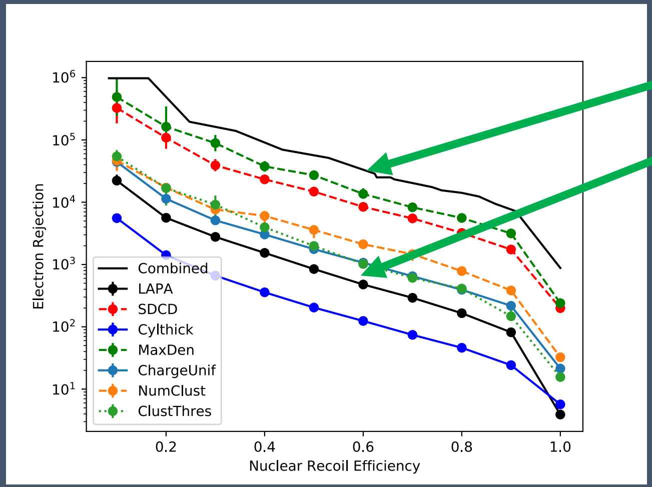
https://arxiv.org/abs/2008.12587



Electron rejection rises exponentially with ionization energy. When combined with flat bkg spectrum, will determine CYGNUS energy threshold for background free operation.

Majd Ghrear et al., arxiv.:2012.13649

Improved, physically motivated observables for electron rejection. Requires HD readout.

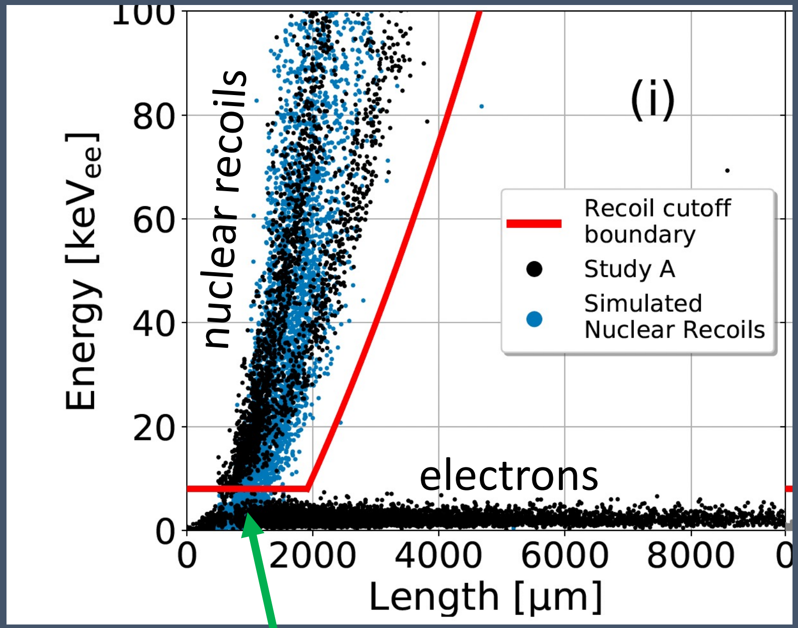


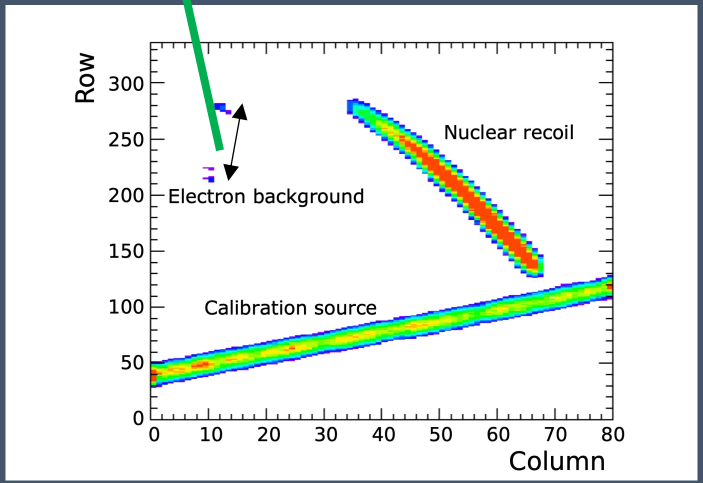
~2 orders of magnitude improvement over dE/dx !

But electron rejection is limited by dynamic range!

- At SuperKEKB, in the tunnel of an operating accelerator, all electrons down to 6-8 keVee rejected in low gain mode (gain ~ 1k)
- We're already well within the regime relevant for DM detection
- Limited by dynamic range, because at low gain, e^- only partially reconstructed, presumably grossly under-estimating recoil length *L*

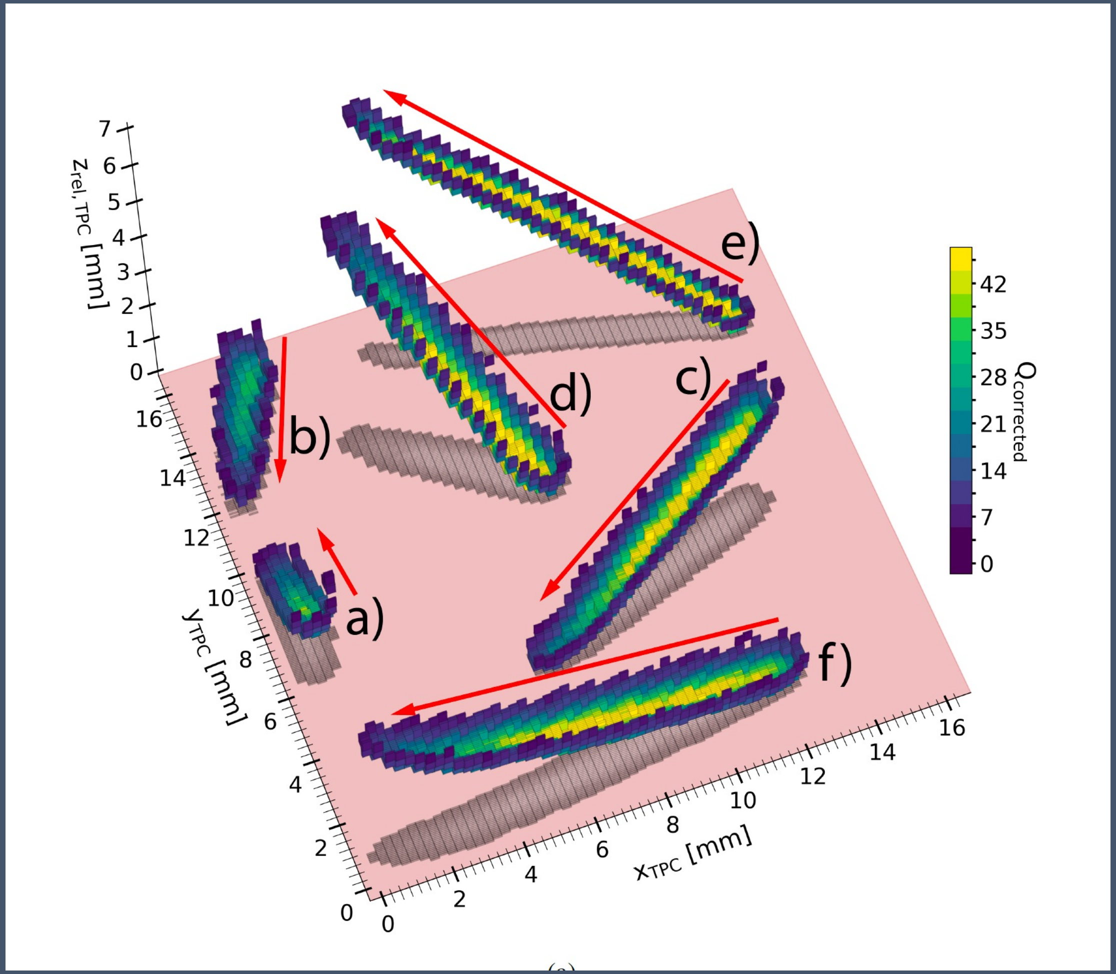
http://arxiv.org/abs/2111.03841





Next steps

- Currently evaluating high-gain particle ID performance of BEAST TPCs
- Main drawbacks of BEAST TPC (=pixel chip readout) approach for low background experiments
    - Internal radioactivity
    - Charge integration time --> events are "2.5D"
    - Finite charge scale
    - Cost and labor intensive to instrument large readout areas



http://arxiv.org/abs/2111.03841

Next Steps II

- Two strip-based detectors being constructed
- Initially: electron drift gases.
- Ideal scenario: single-electron-counting with negative ion drift and strips. Numerous benefits if it works!
    - Greatly extended dynamic range
    - Improved energy resolution
    - Reduced diffusion
- Modified components may be required
    - MPGD gas avalanche devices capable of high gain at low gas densities. THGEM-like with smaller hole spacing (200 micron), to bring single electrons above noise floor of long strips
    - Integrated amplification and charge readout (as in GridPix, to avoid re-attachment in collection gaps)
    - Electronics with appropriate shaping time
    - Trigger-multiplexed DAQ to reduce cost
- We will need your help!
- Plan to estimate requirements via simulation, for US Snowmass process.

CERN strip micromegas,
VMM3a hybrids, SRS readout

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

Summary

- Modern MPGD gas detectors can image 3D charge density with high resolution
- BEAST TPCs have demonstrated this for nuclear recoils and electrons – but not both with same settings, due to limited dynamic range
  - Important consequence: deterioration of particle ID at lowest energies
- So far, focused on low-gain operation, detection of fast-neutron-recoils
  - A number of novel reconstruction techniques have been developed to correct for missing dynamic range and charge integration effects
  - Particle ID at trigger level via firmware was a critical ingredient
- A properly optimized strip-based detectors using negative ion drift could be the way forward, and may resolve the dynamic range issue via single-electron counting

BACKUP

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

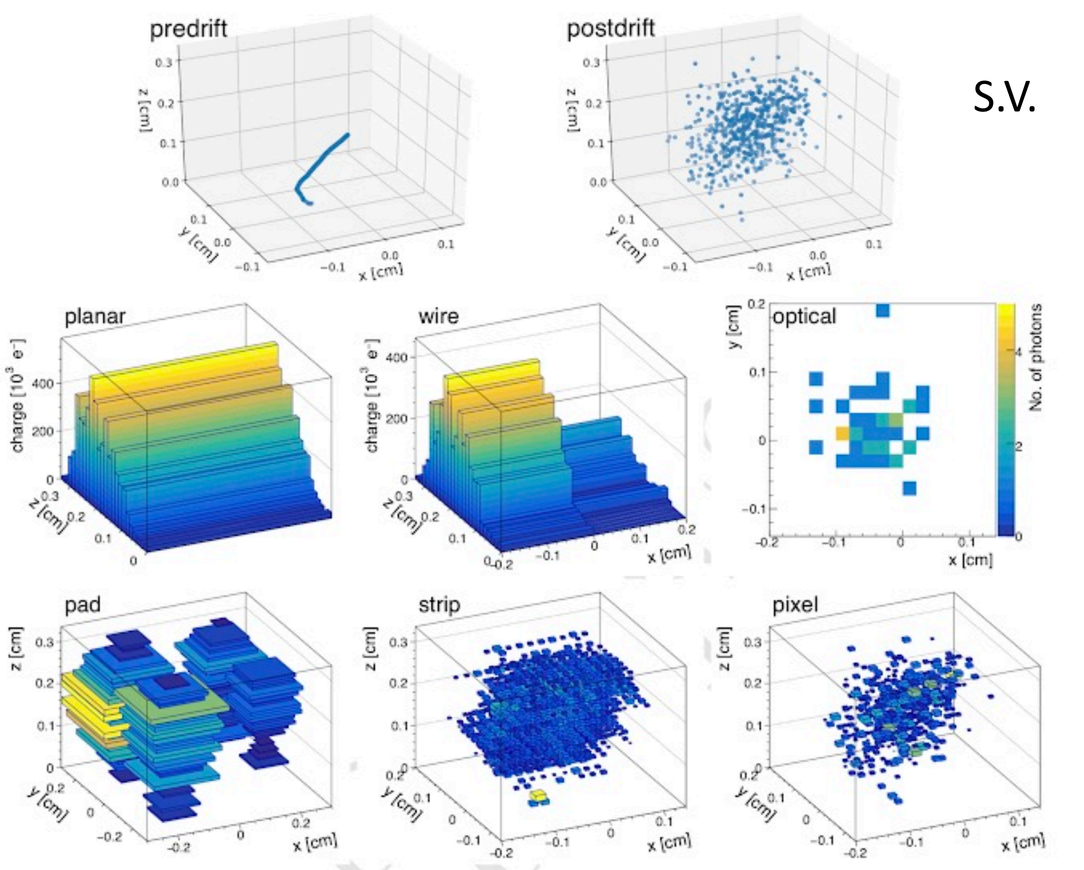


FIG. 9. Simulated 25 keV$_r$ helium recoil event in He:SF_6 gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

electron recoil

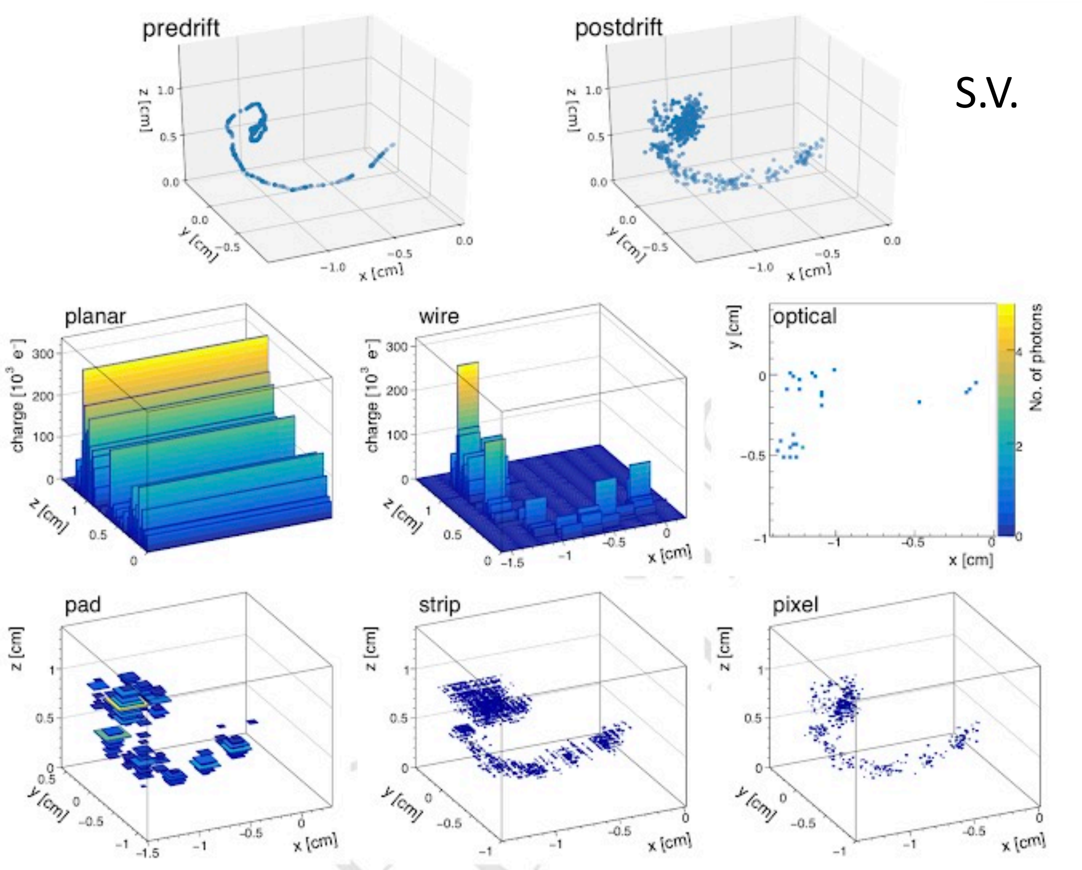


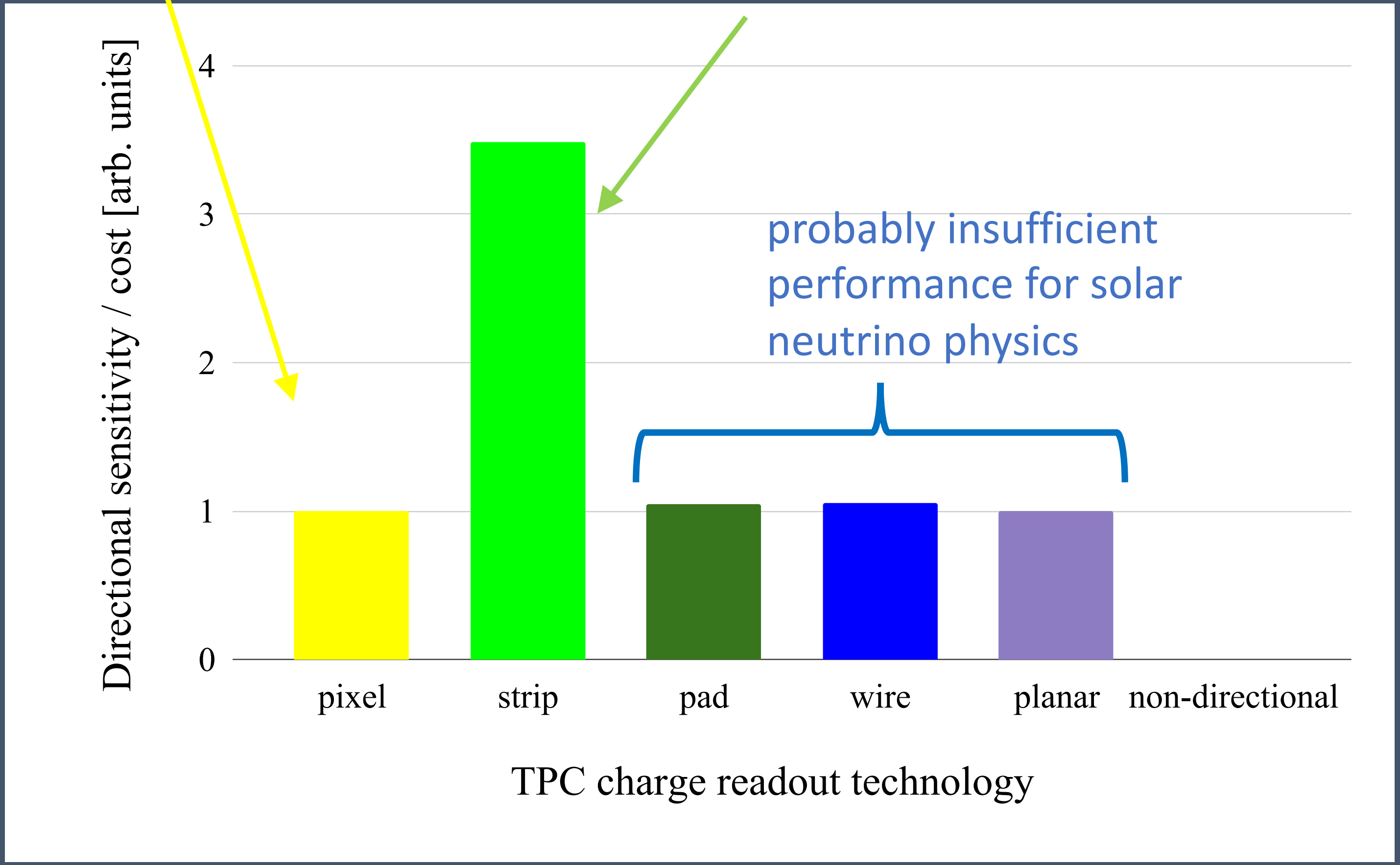
FIG. 10. Simulated 20 keV$_{ee}$ electron event in He:SF_6 gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

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

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!



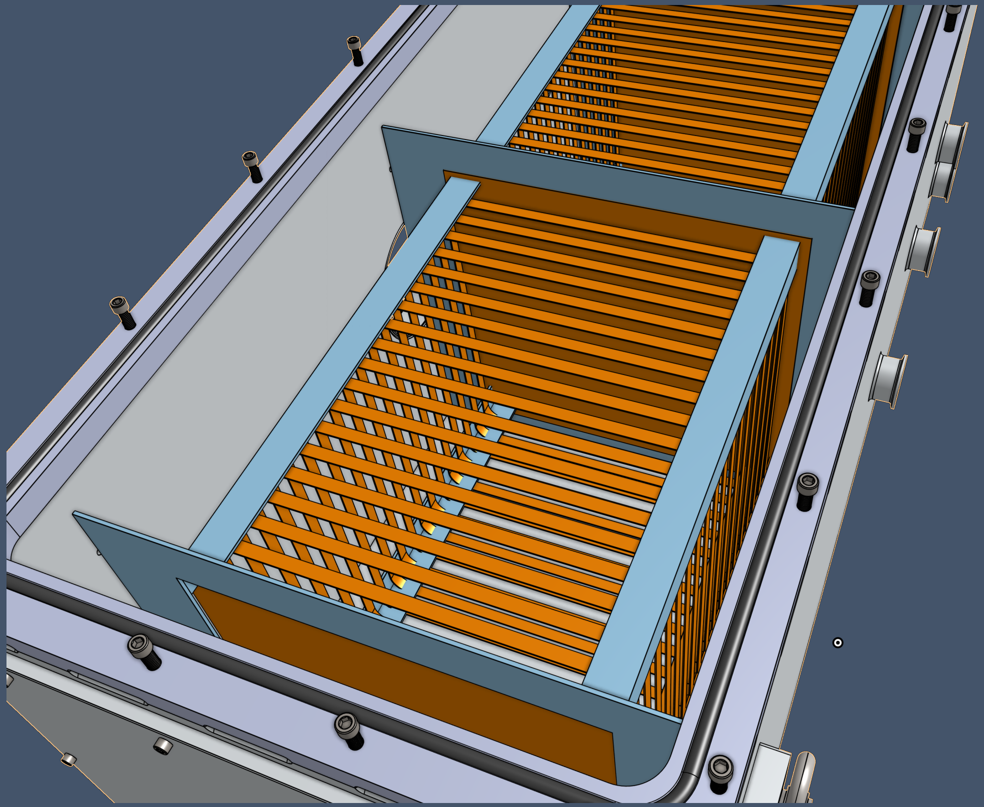
probably insufficient performance for solar neutrino physics

https://arxiv.org/abs/2008.12587

New US effort: CYGNUS HD – two detectors

Cost-effective scale up via existing collider technologies

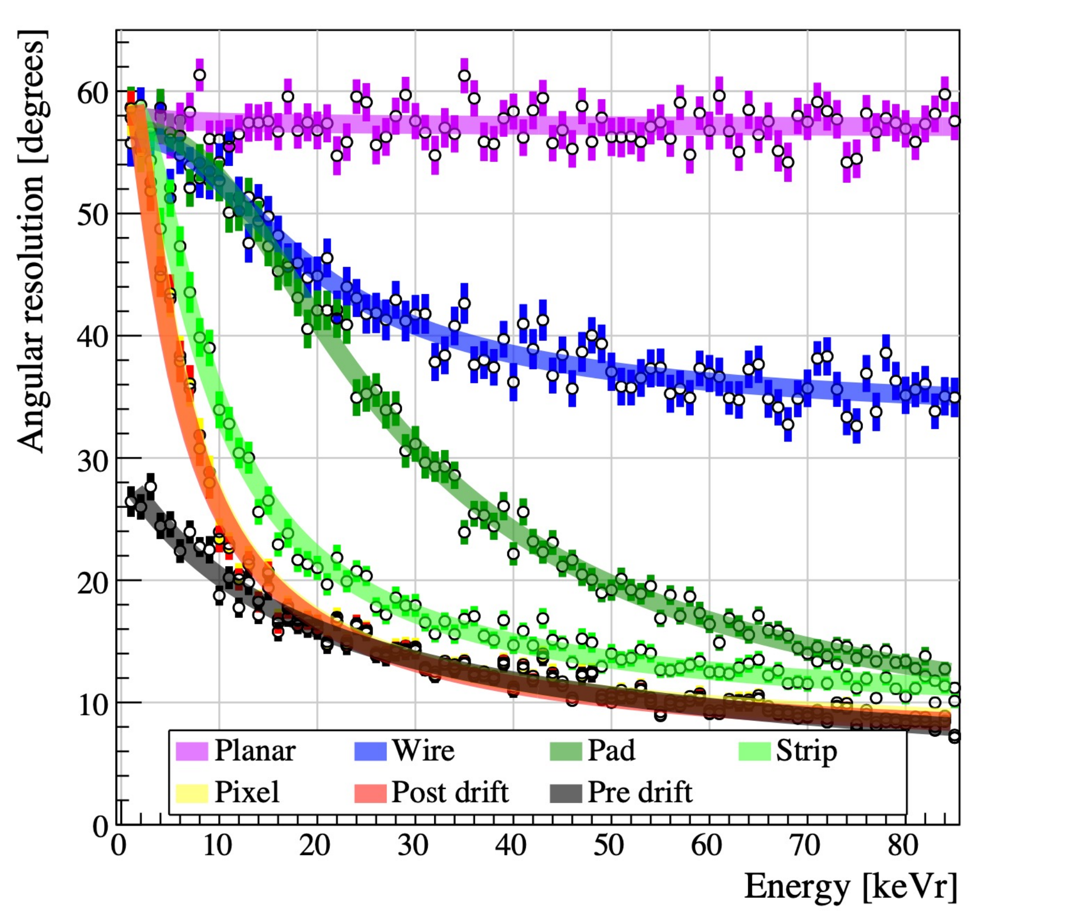
CERN strip micromegas, CERN VMM3a hybrids, CERN SRS readout

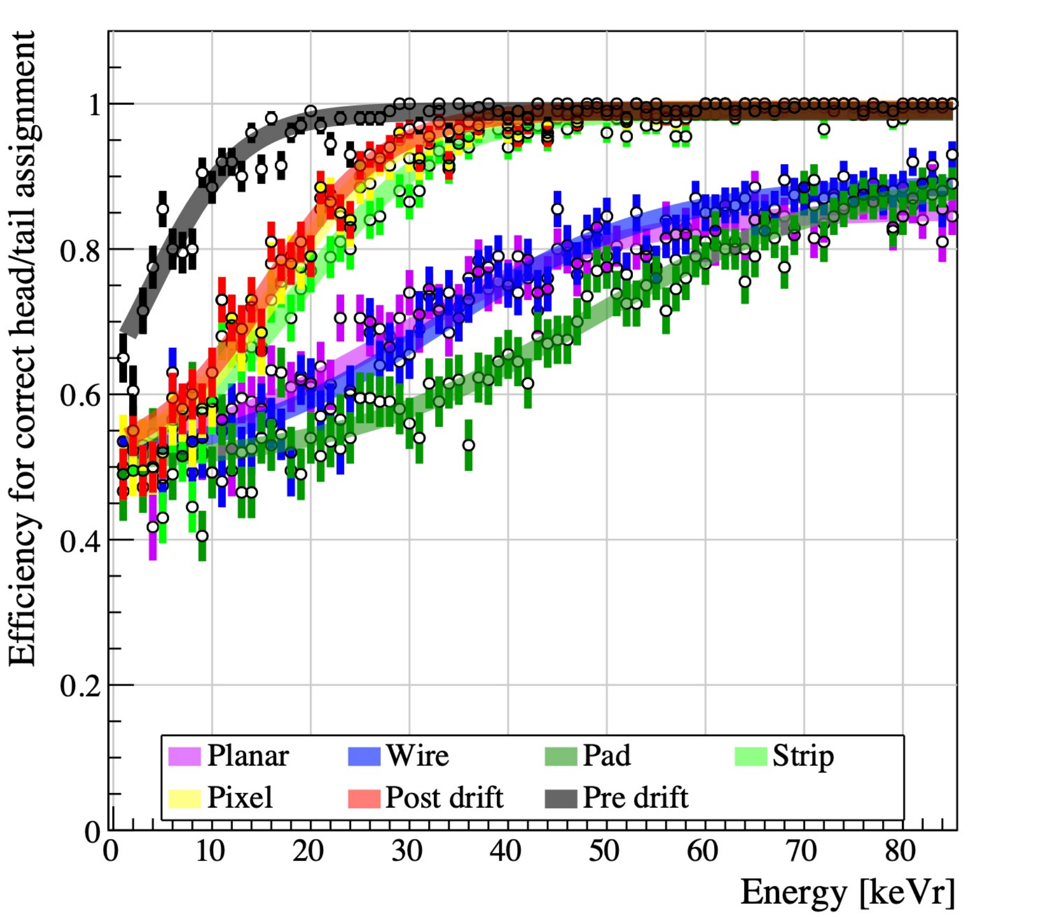


CYGNUS HD “Keiki” - factor 1000 scaleup of BEAST TPC
Evaluation of components for follow-on 1m^3 detector

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

Both nuclear and electron recoils are of interest

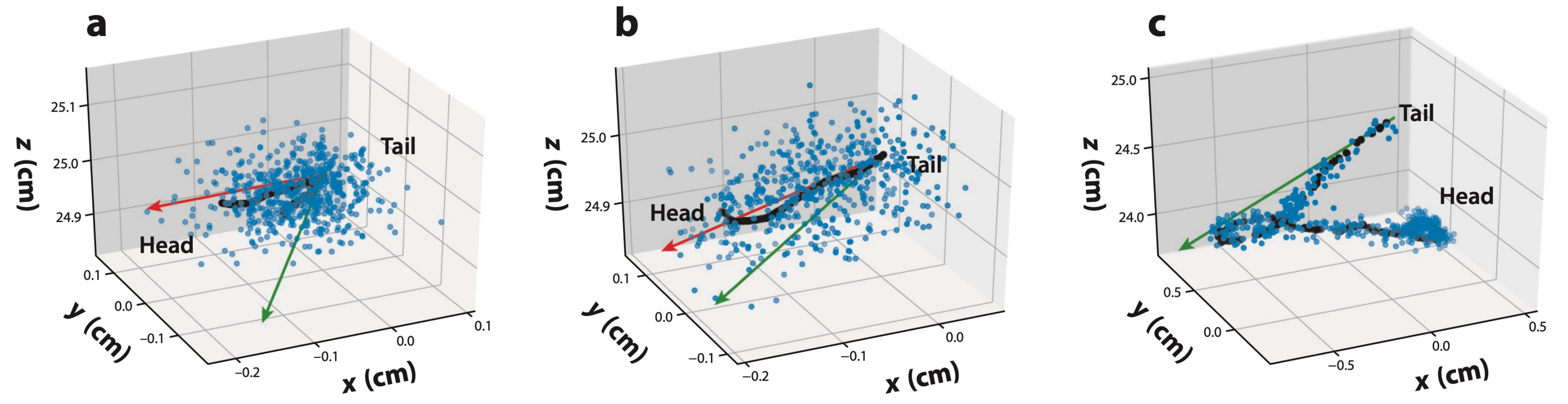


Figure 4

Simulation illustrating true and reconstructed recoil directions. The black points represent ionized electrons created by (*a*) a 41-keV$_r$ fluorine recoil, (*b*) a 25-keV$_r$ helium recoil, and (*c*) a 20-keV electron recoil in atmospheric-pressure He:SF_6 gas. Note that the electron recoil is approximately one order of magnitude longer than the two nuclear recoils. Due to ionization quenching, the ionization is nearly the same in these three events, despite the different recoil energies. The blue points represent the same ionized electrons after a diffusion of $\sigma_{x,y,z} = 393$ μm, typical for a gas time projection chamber. The reconstructed nuclear recoil direction (*red arrows*) clearly differs from the true recoil direction (*green arrows*); the angle between the red and green arrows represents the angular resolution. Both the curved recoil trajectory and the diffuse nature of the charge cloud contribute to this measurement error. In the case of fluorine (*a*), the short recoil length and secondary recoils make the direction measurement particularly hard. For electron recoils (*c*), a straight-line track fit is clearly not applicable—a dedicated curled-track fitter would be required.

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)

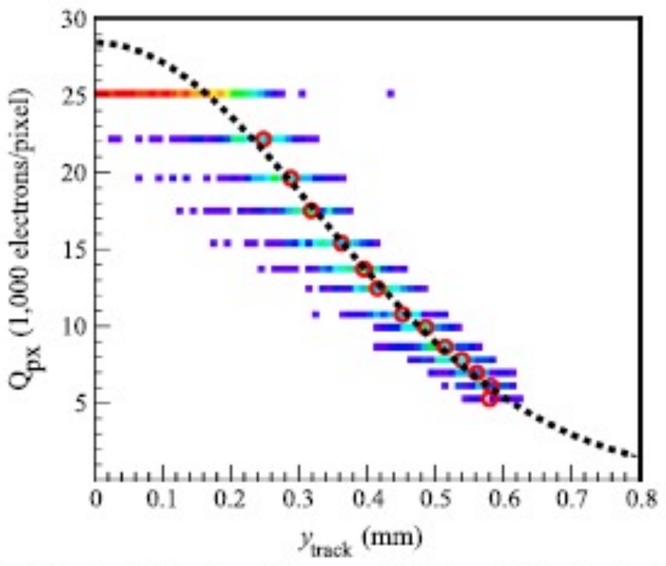
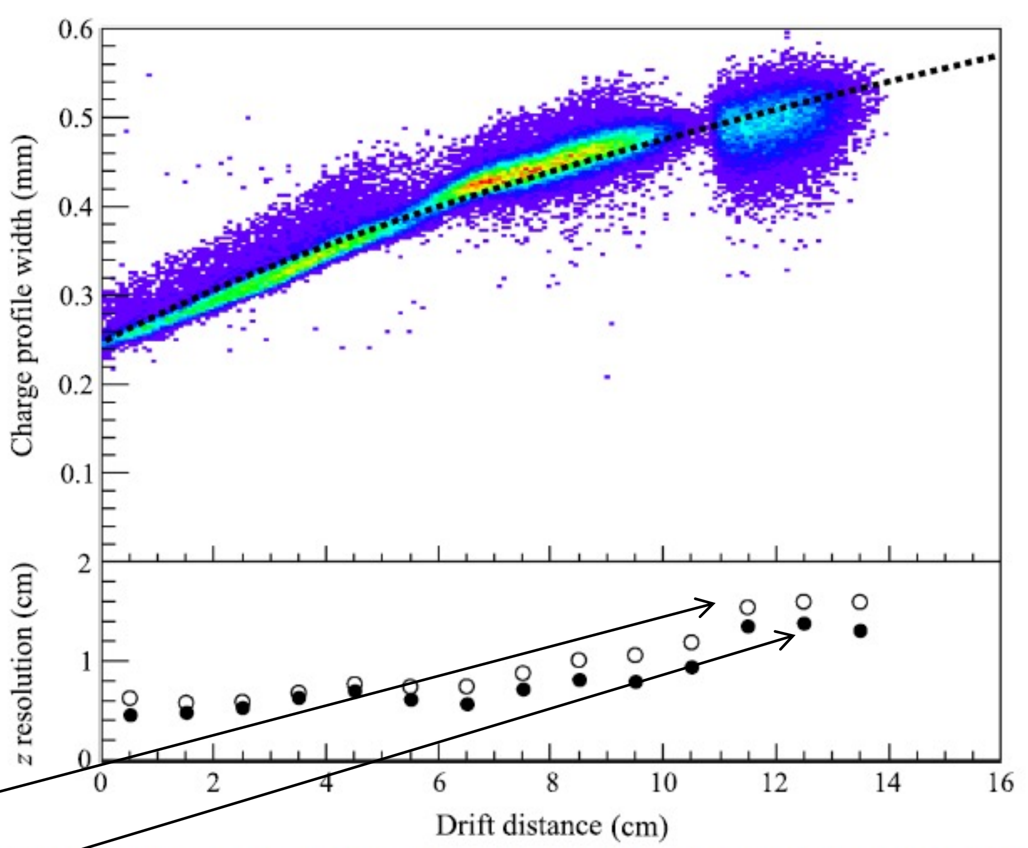


Fig. 3. Fit to the folded version of the corrected pixel charge (Q_{px}) profile shown in Fig. 2 using the profile fit method described in Section 4.3. The Gaussian function (black dotted line) is fitted to the plot points (red open circles), which are placed at the mean Q and y_{track} positions for 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

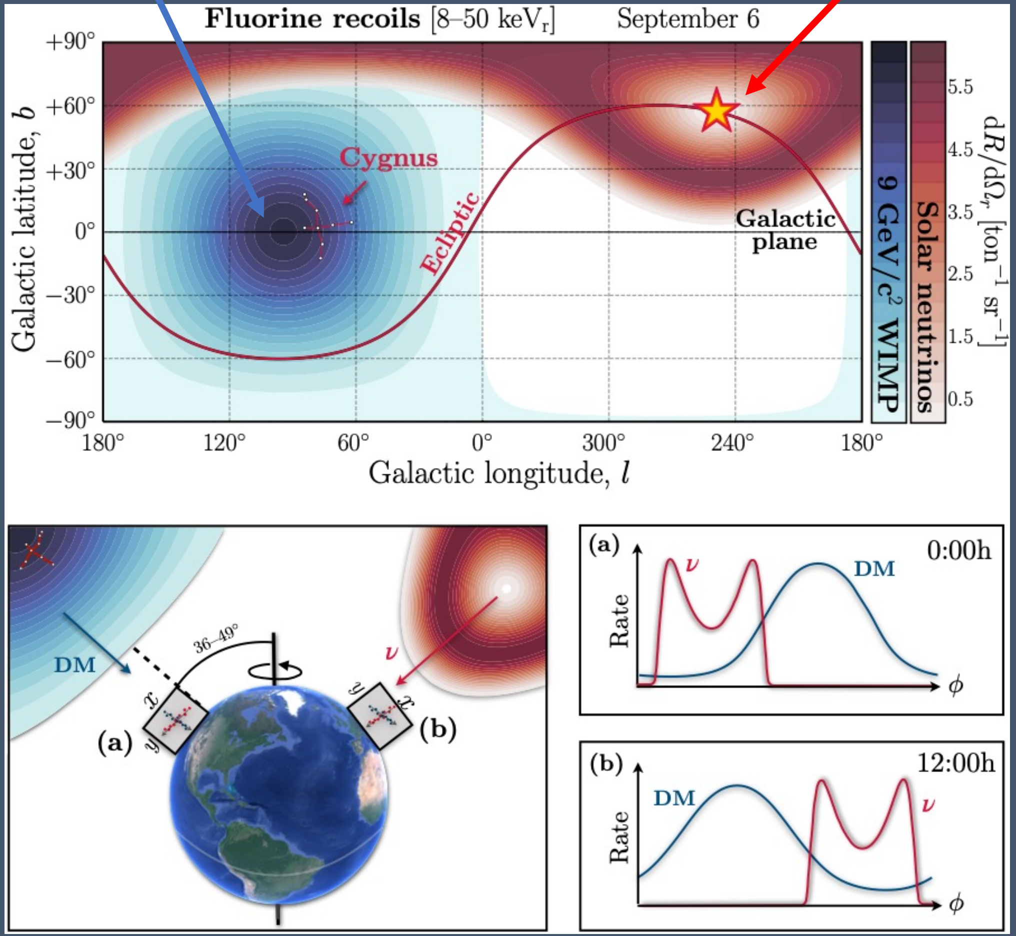
- Charge profile analysis also enables “Energy Recovery” (unpublished)

The Power of Directionality

Neutrinos from the sun

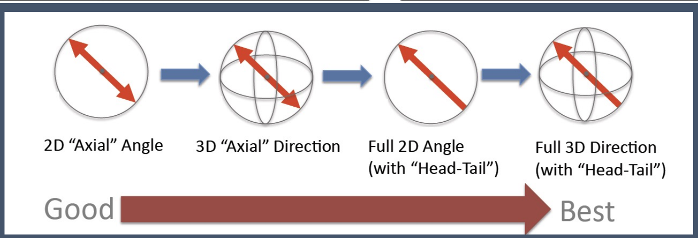
WIMP wind, approx. from CYGNUS

arxiv:2102.04596



- 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 ($\sim 10^3$ 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

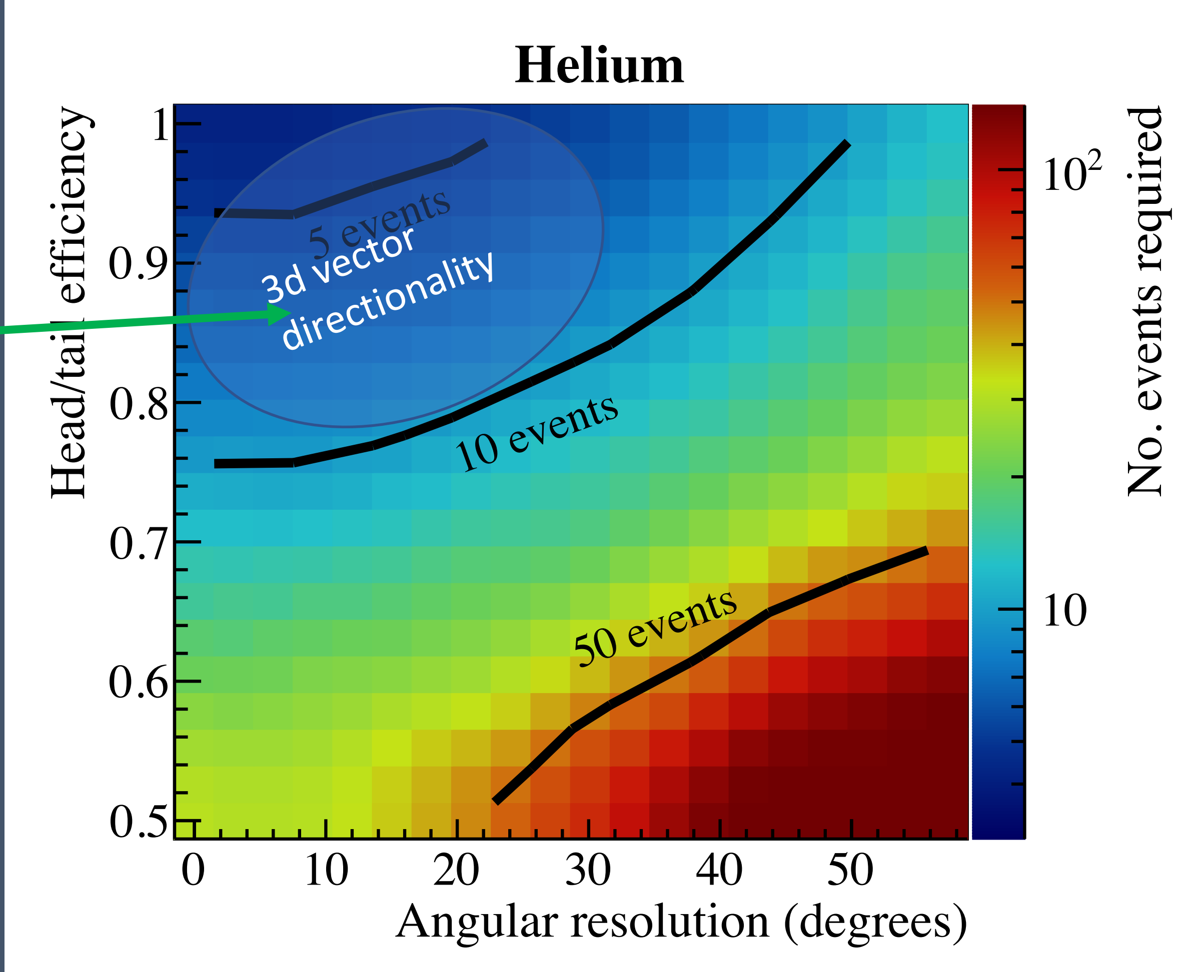


Detector Performance Requirements

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



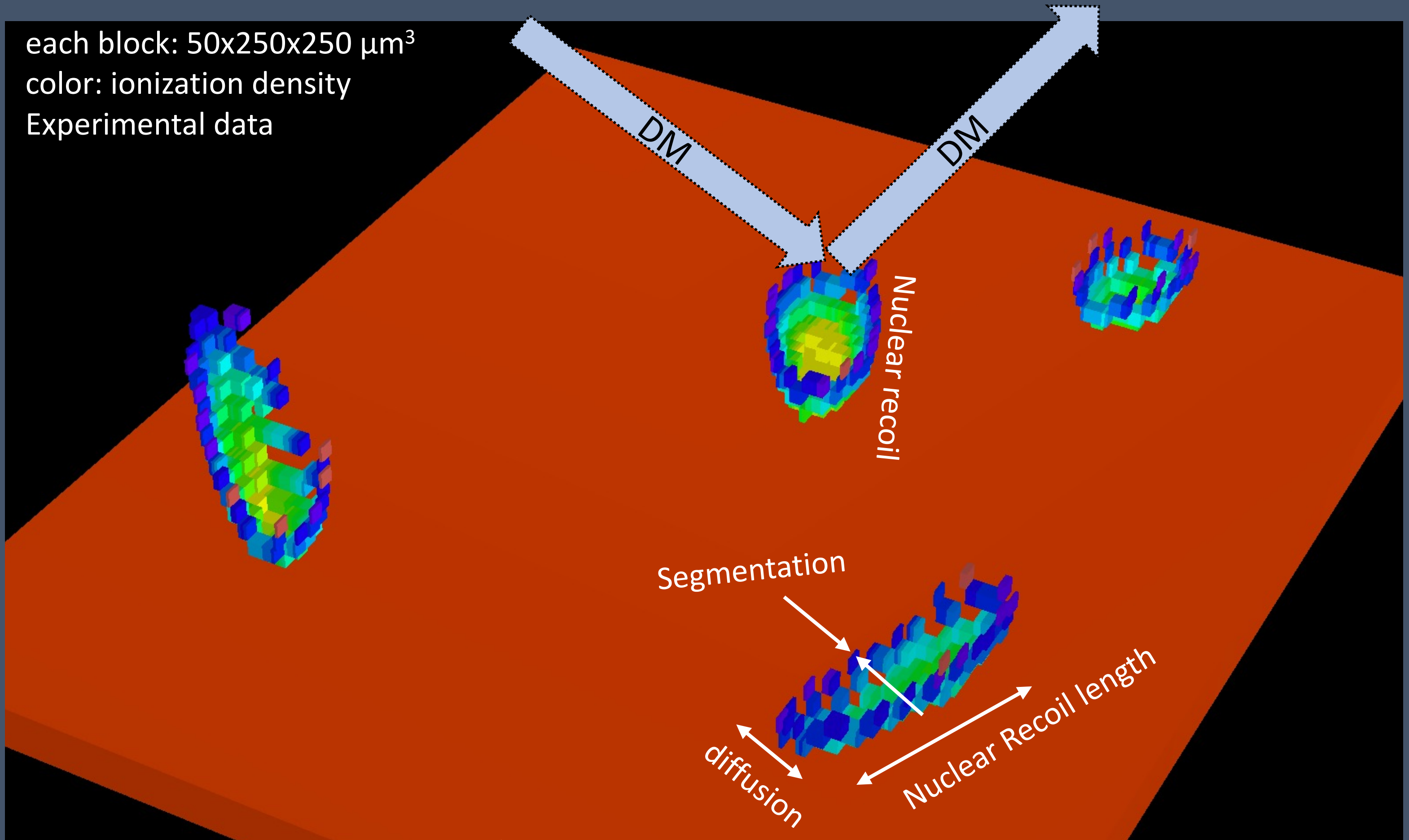
detected WIMP events required to exclude **ν**-hypothesis at 90% CL

Assumptions: mχ = 10 GeV, He:SF_6 gas

Definition (HD) gas TPCs

Capabilities resulting from HD charge readout

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



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)

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

Requires large, highly granular MPGDs, ideally at lower cost than currently available