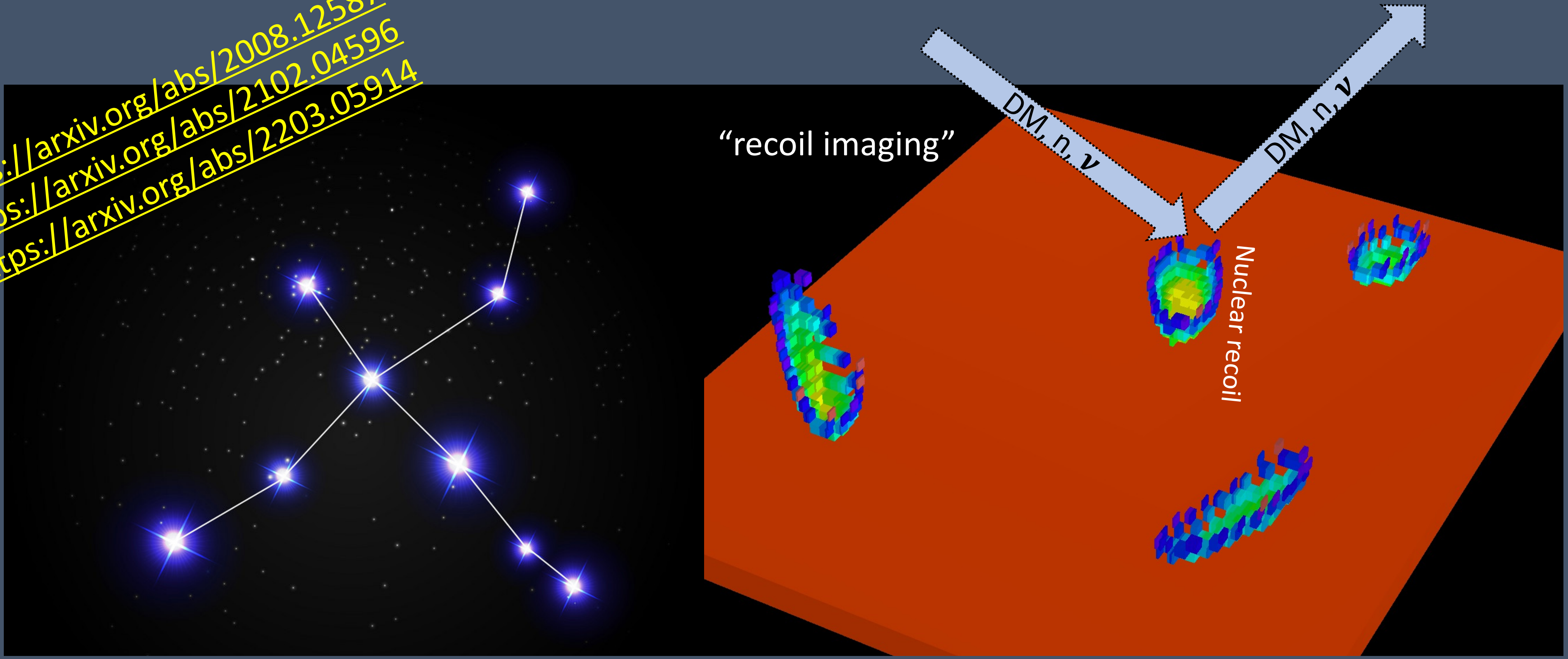
The CYGNUS Directional Recoil Observatory

https://arxiv.org/abs/2008.12587
https://arxiv.org/abs/2102.04596
https://arxiv.org/abs/2203.05914



CONFERENCE ON SCIENCE AT THE SANFORD UNDERGROUND RESEARCH FACILITY
South Dakota Mines campus, May 11-13, 2022

Sven Vahsen (University of Hawaii) @ CoSSURF 2022

CYGNUS Vision: Multi-site Galactic Recoil Observatory

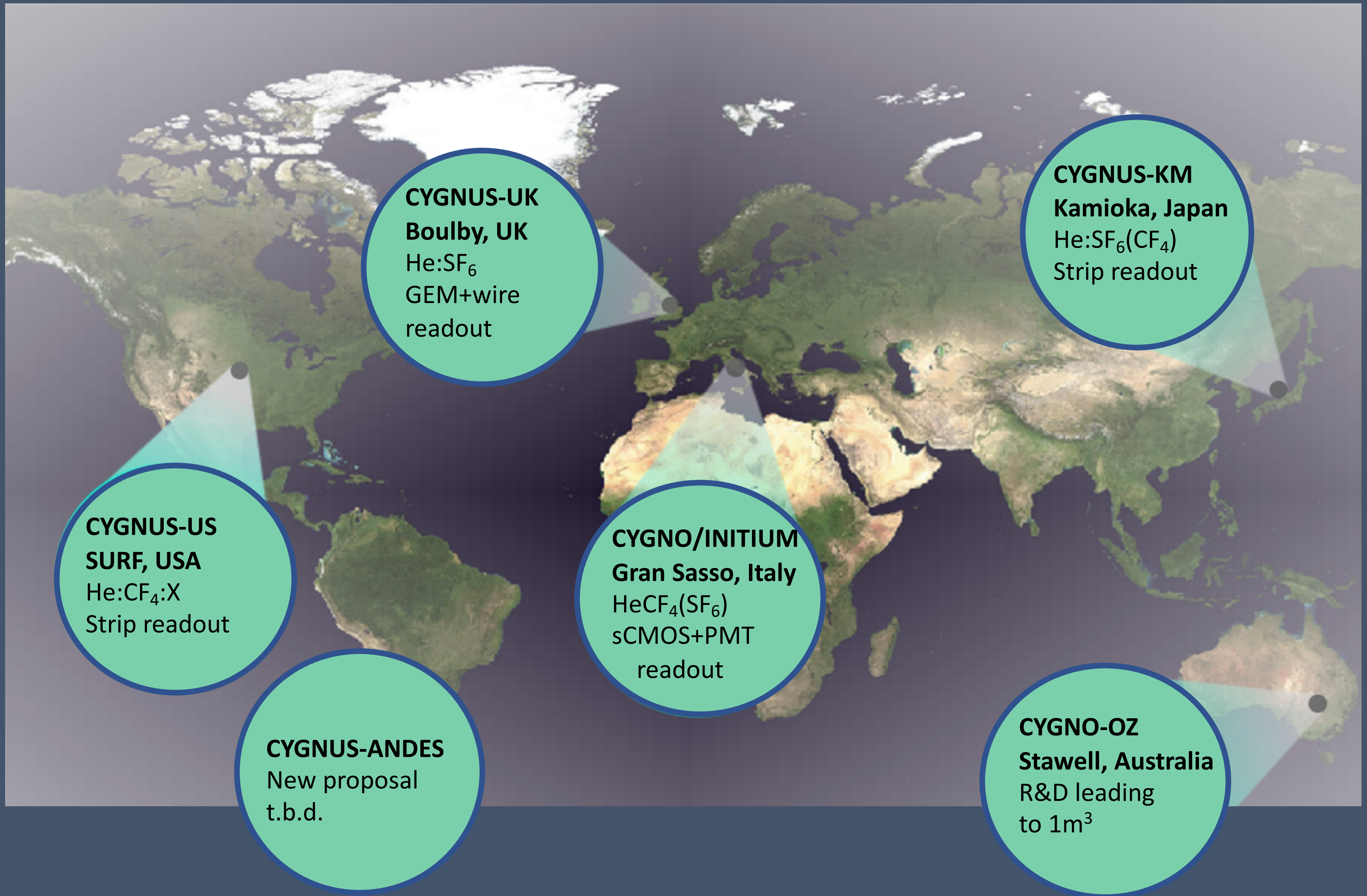
with directional sensitivity to WIMPs and neutrinos

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!



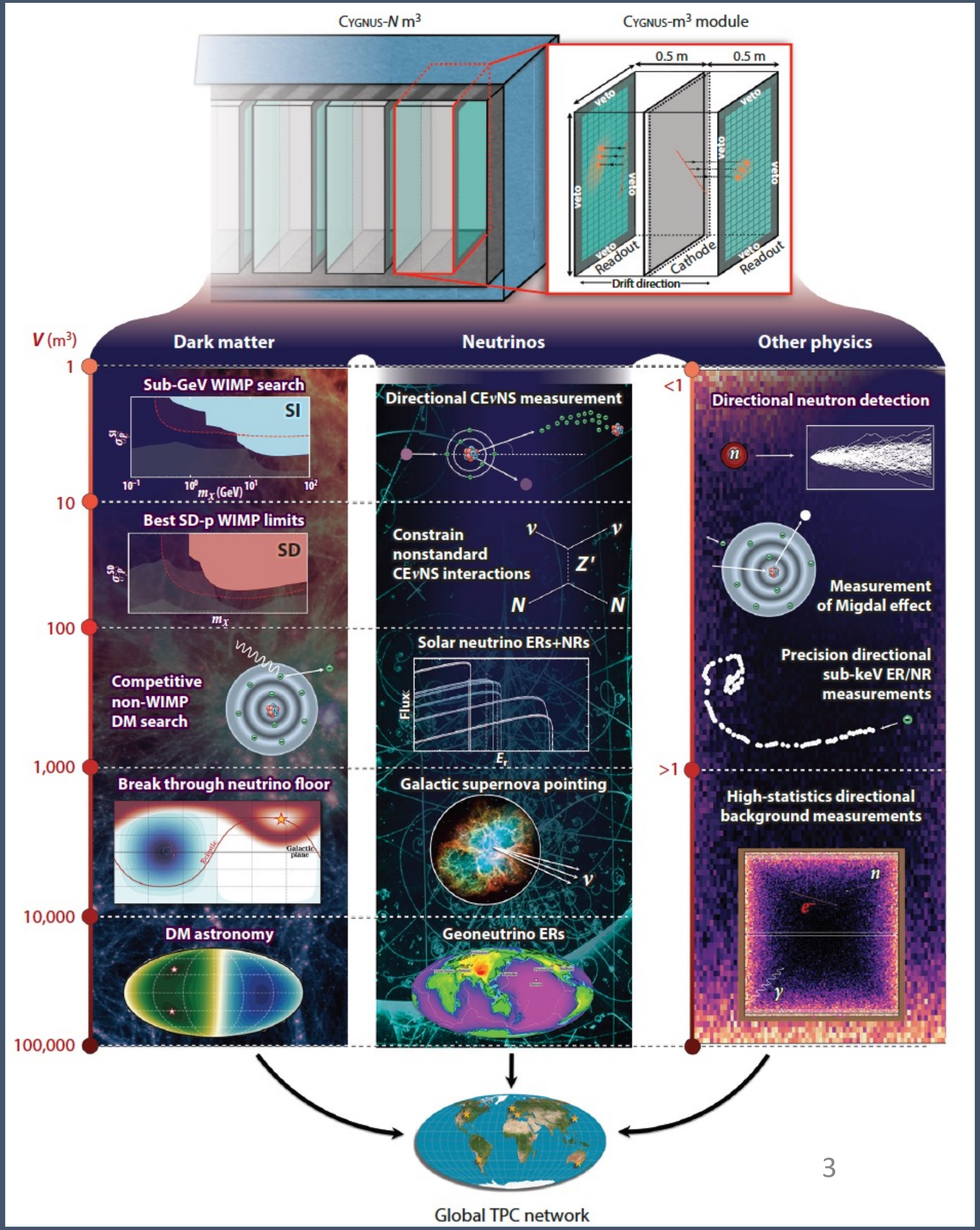
Opportunities for a long-term physics program

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 (CEvNS) at ORNL (Neutrino Alley), Fermilab (NuMI and later LBNF)
- Competitive DM limits in SI and SD
- CEvNS and e-recoils from solar neutrinos
- Efficiently penetrating the LDM ν floor
- Observing galactic DM dipole
- Measuring DM particle properties and physics
- Geoneutrinos
- WIMP astronomy

https://arxiv.org/abs/2102.04596



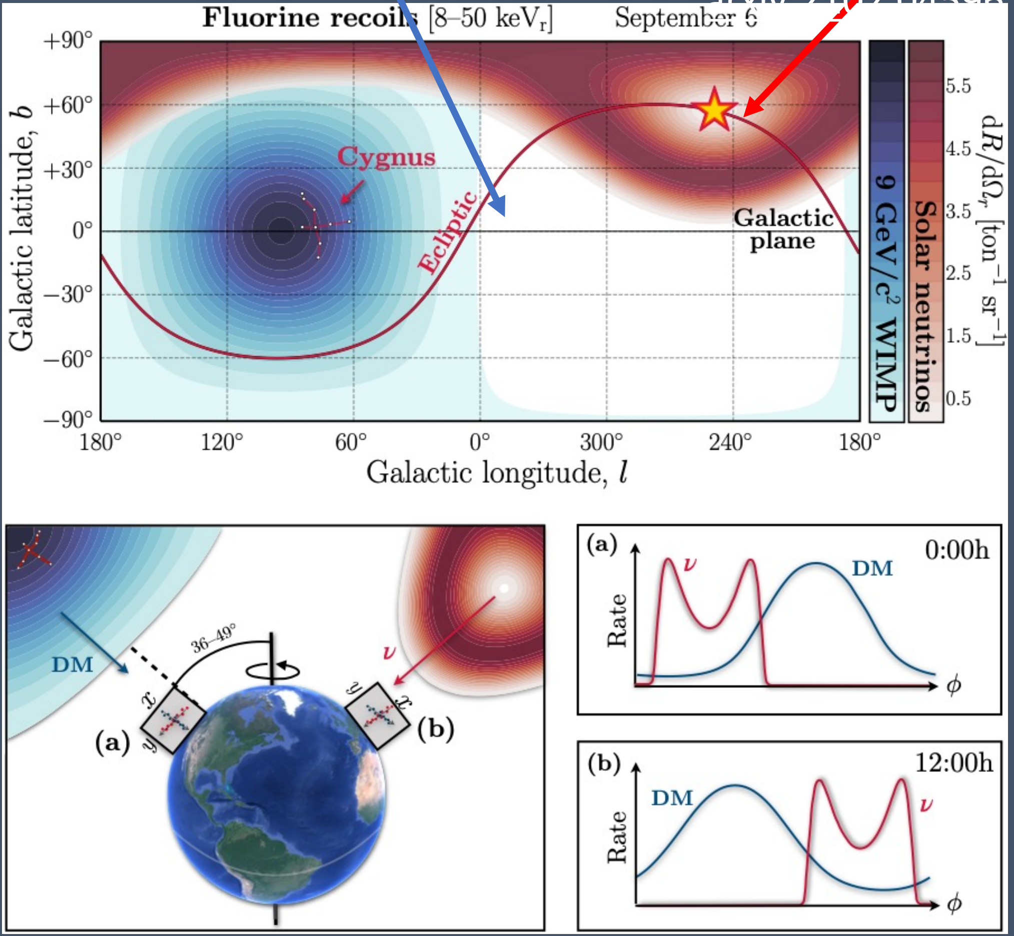
The Power of Directionality

- 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-directionality, event-by-event

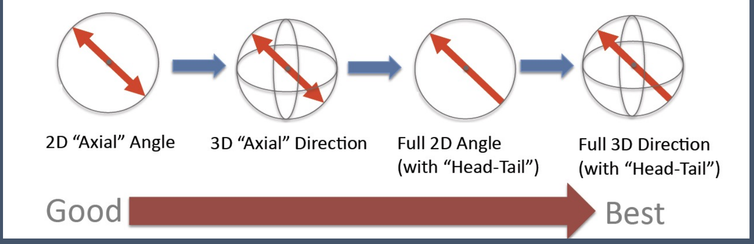
Neutrinos from the sun

WIMP wind, approx. from CYGNUS

arXiv:2102.04596



Many potential benefits, but experimentally challenging!

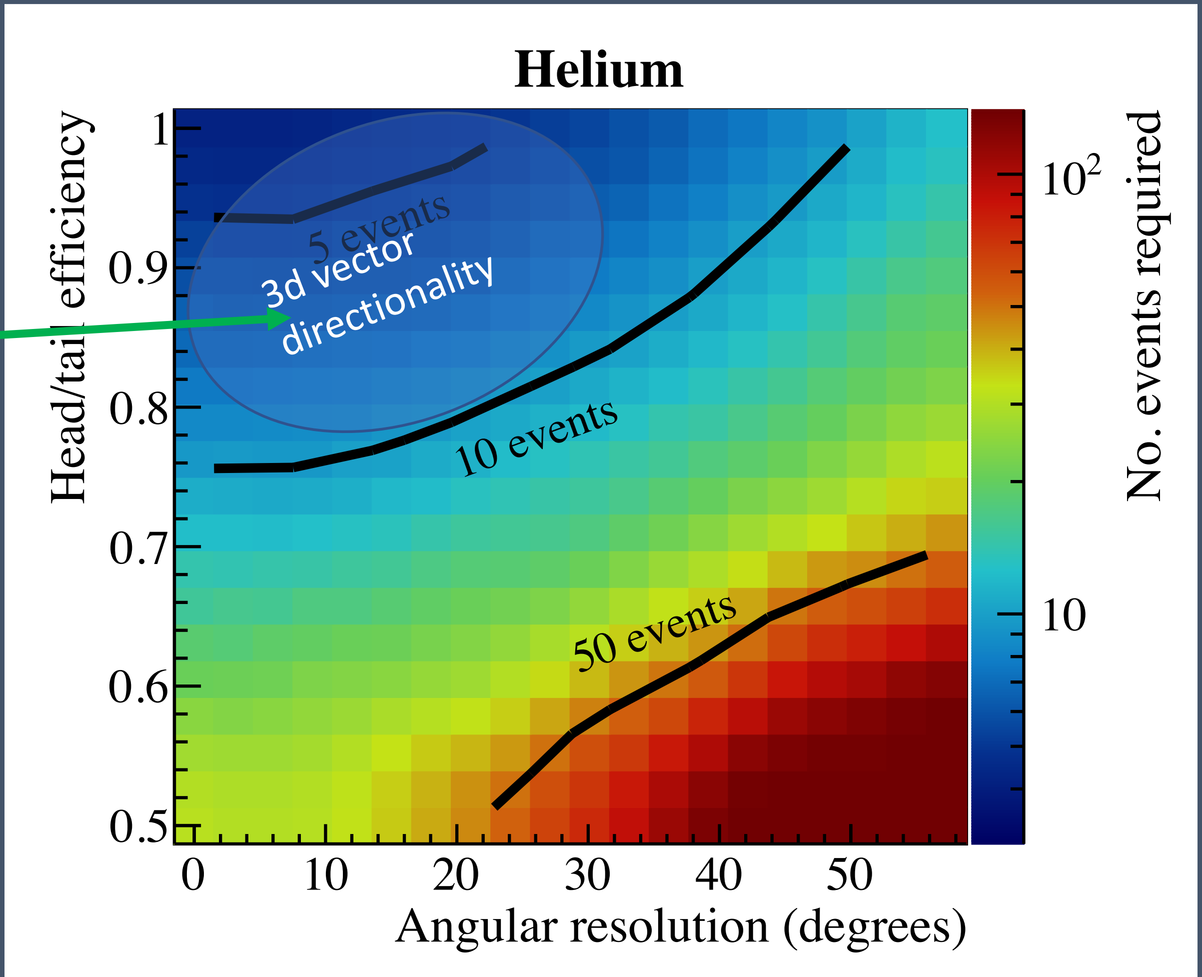


Detector Performance Requirements

https://arxiv.org/abs/2102.04596

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

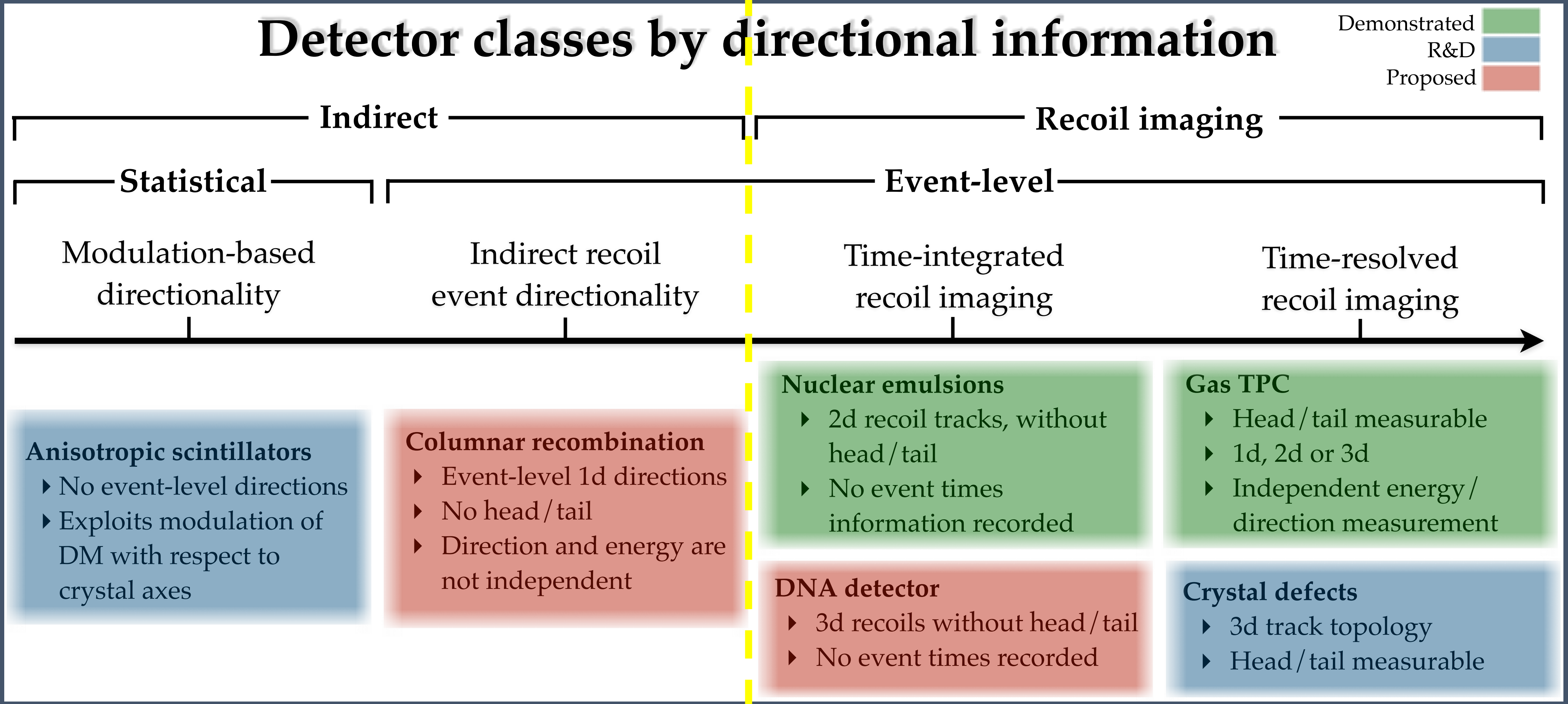
- Event-level recoil directionality
  - angular resolution ≤ 30 degrees
  - excellent head/tail sensitivity
- Rejection of internal electron backgrounds
  - by factor >= 10^5 for 1000 m^3 detector
- All of above down to E_{recoil} ~ 5 keV
- Energy resolution ~ 10% at 5.9 keV
- Timing resolution ~ 0.5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



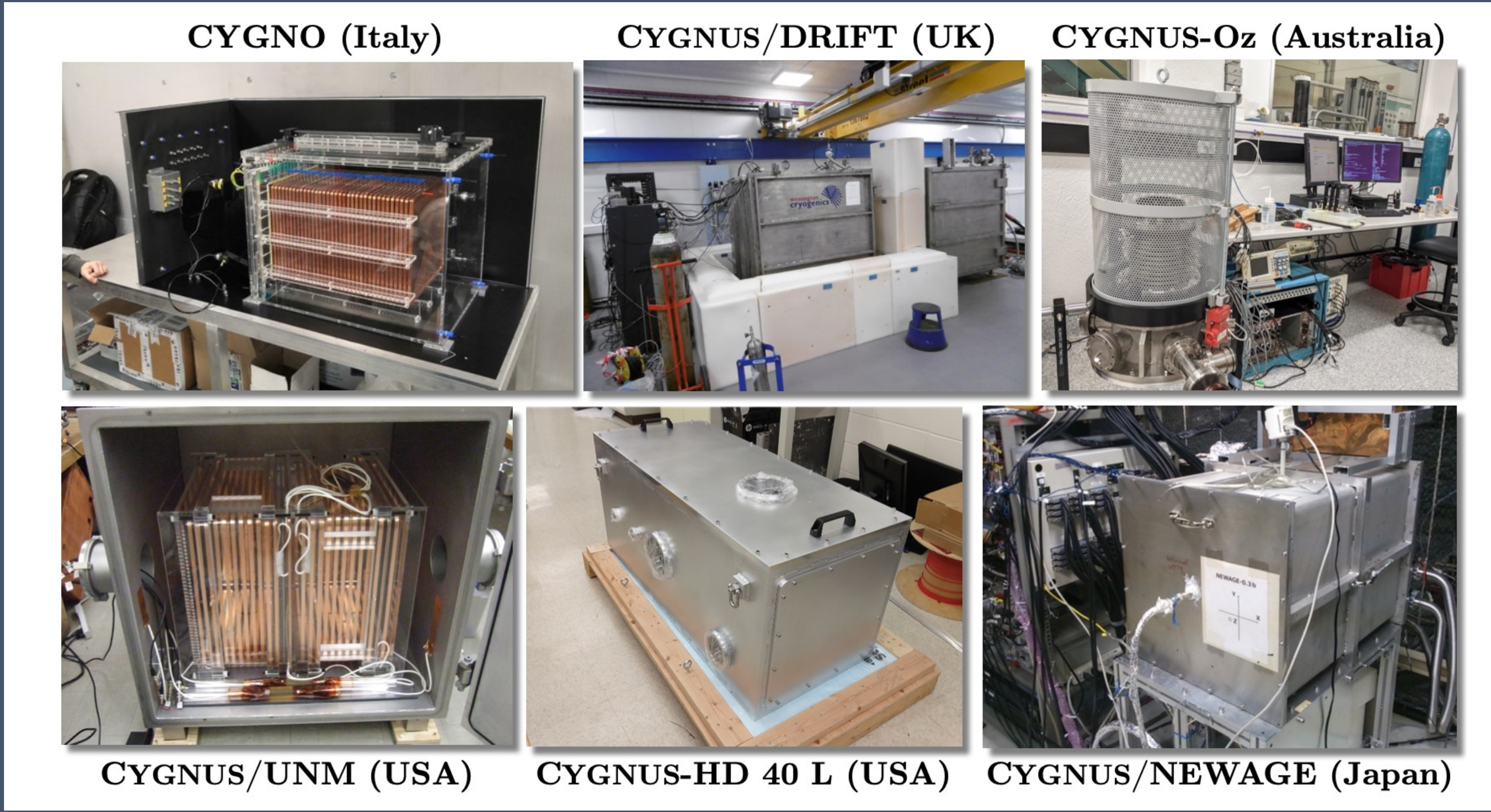
detected WIMP events required to exclude **ν**-hypothesis at 90% CL

Assumptions: mχ = 10 GeV, He:SF_6 gas

https://arxiv.org/abs/2102.04596



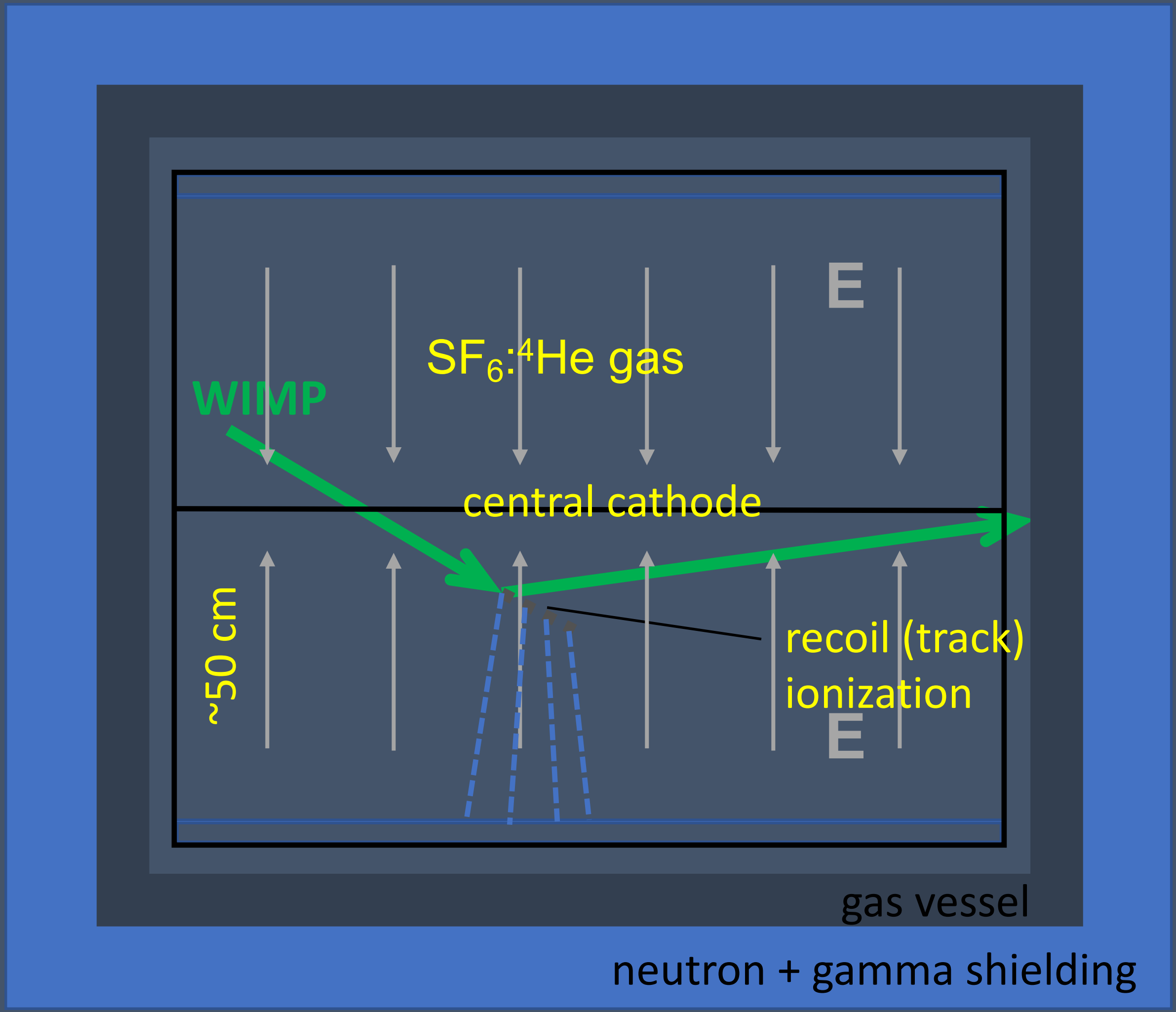
Prototypes and Experiments



All directional experiments that have set DM limits use gas TPCs – currently at <=1 m^3 scale
Most TPC groups now working towards the CYGNUS project

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

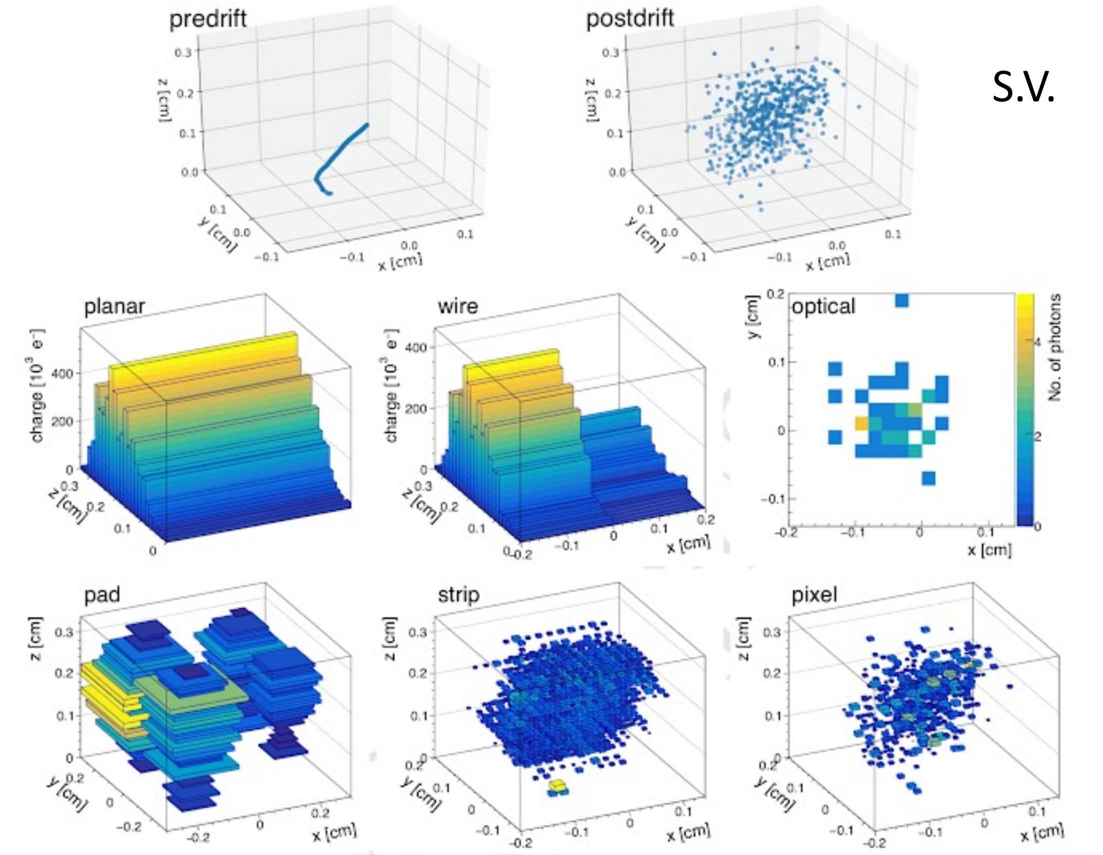
https://arxiv.org/abs/2008.12587

But what is the optimal TPC charge readout technology?

Helium recoils in 755:5 He:SF_6

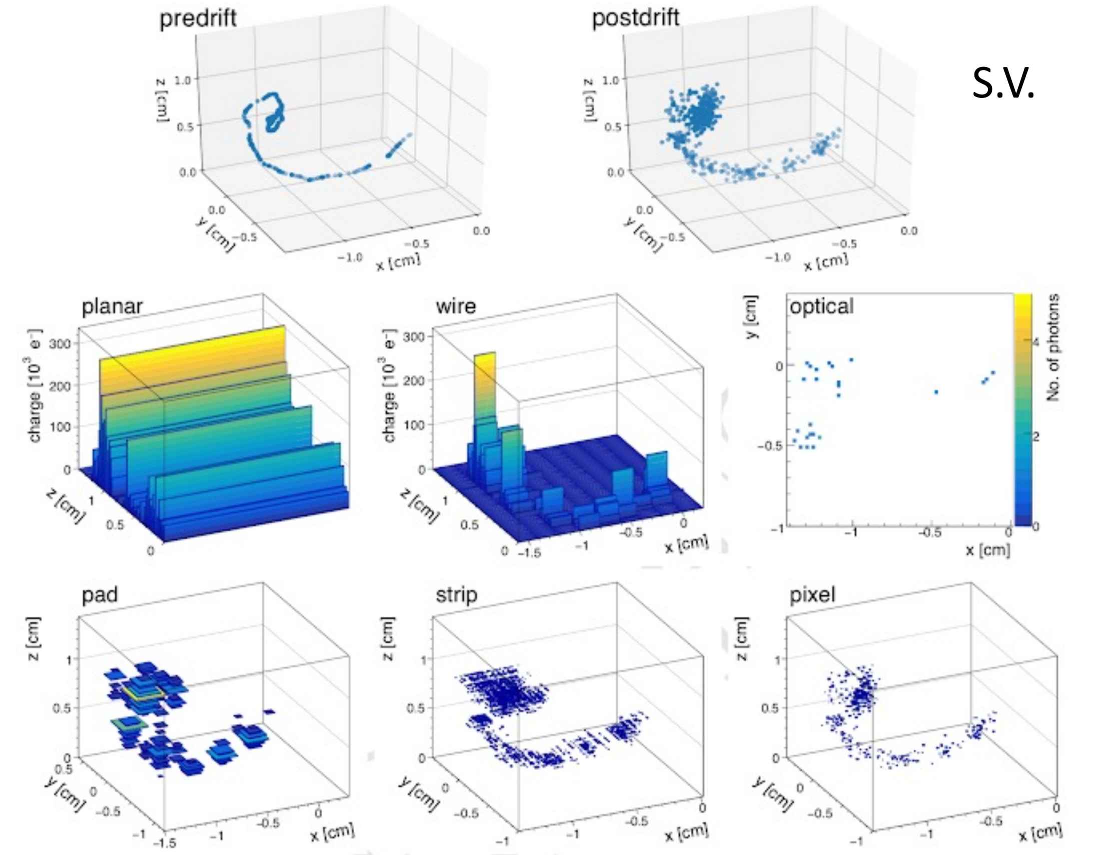
nuclear recoil

electron recoil



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.



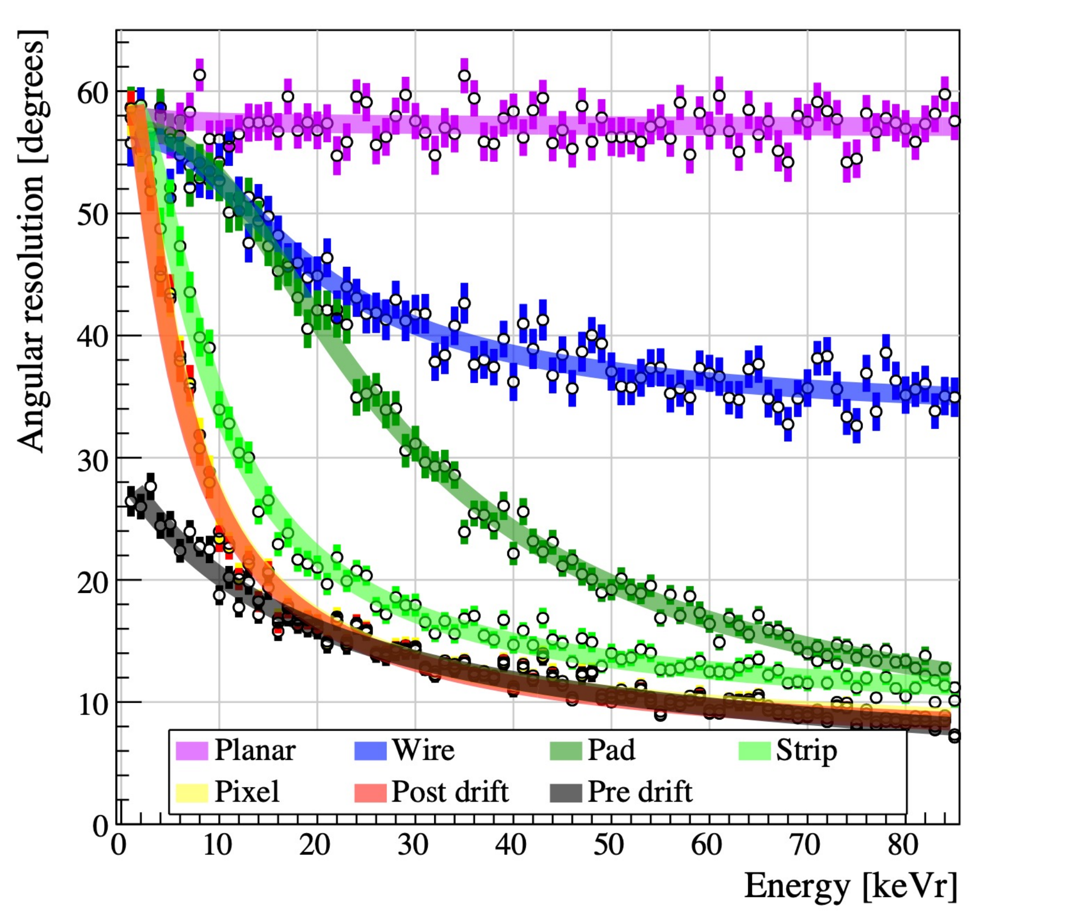
S.V.

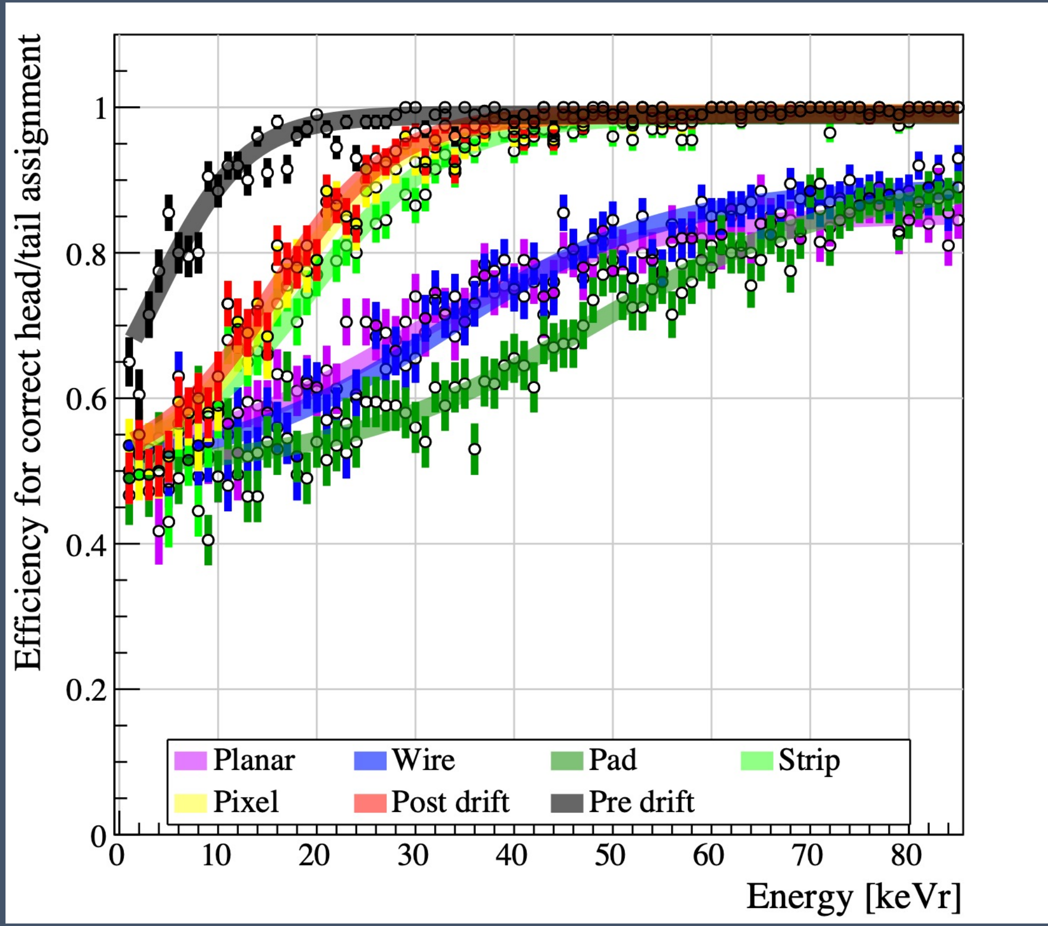
FIG. 10. Simulated 20 keV$_{ee}$ electron event in He:SF_6 gas before drift (top left), after 25 cm of drift (top right), and as measured by six readout technologies (remaining plots as labelled). Readout noise and threshold effects have been disabled.

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



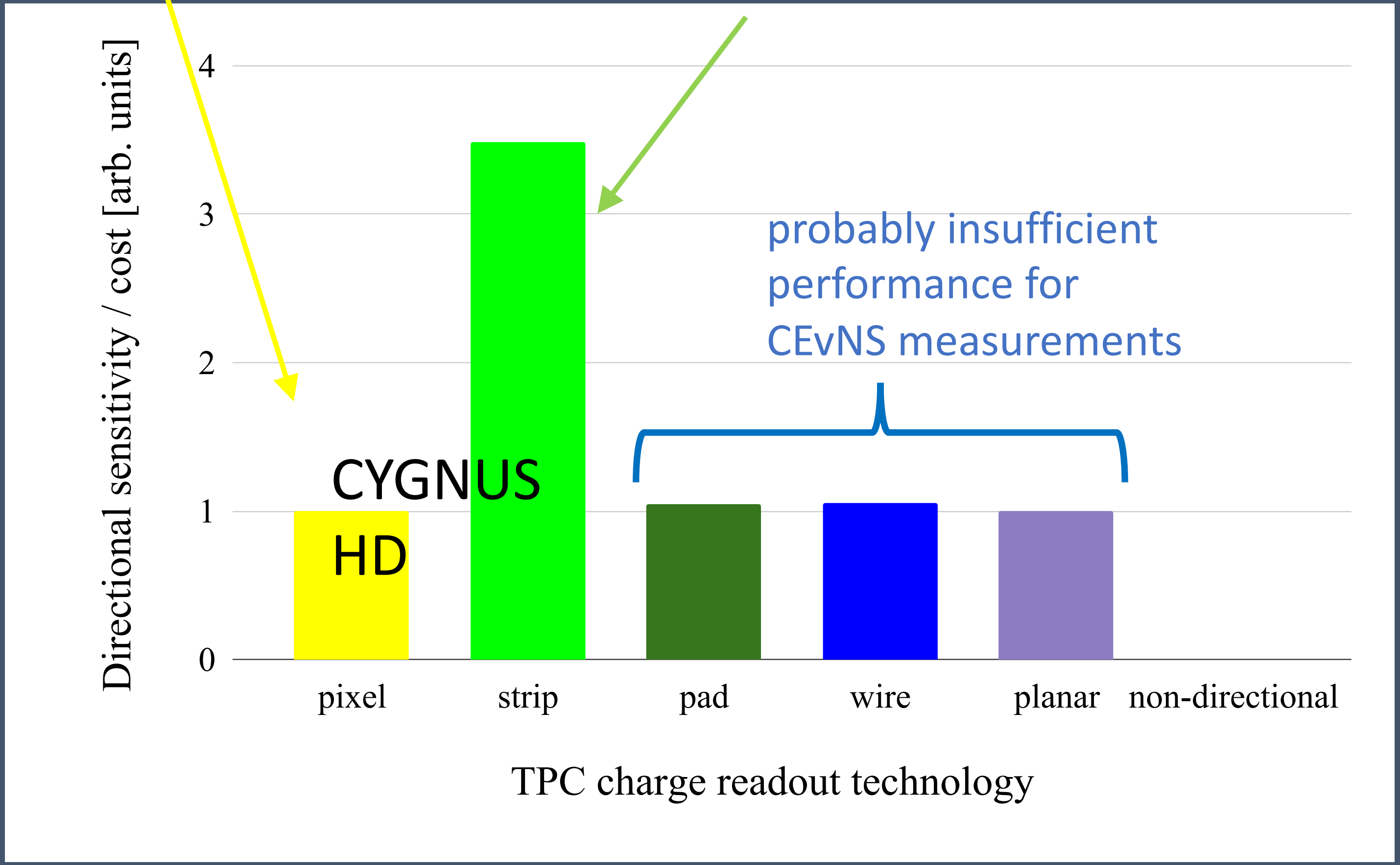


Pixel readout extracts the entire directional information left after diffusion (red and yellow curves overlap fully)
Strip readout has almost same performance as pixel readout, but at approx. one order of magnitude lower cost
Caveats: Quantitative performance depends strongly on gas pressure (density) and analysis algorithm

Result of cost vs performance analysis

Best raw performance – optimal for precision studies of nuclear recoils

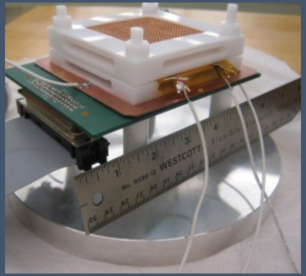
Best directional WIMP sensitivity per unit cost – optimal for large detectors!



https://arxiv.org/abs/2008.12587

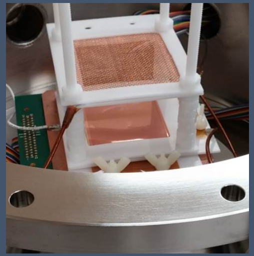
CYGNUS HD: MPGD gas TPCs for nuclear recoil imaging

2011-2013



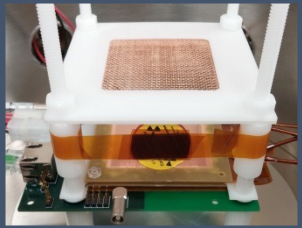
μD^3 (~1cm^3)

2013



~2.5 cm^3

2013



~ 20 cm^3

1[st] generation, proof of concept

2014

2 x 60 cm^3

2015

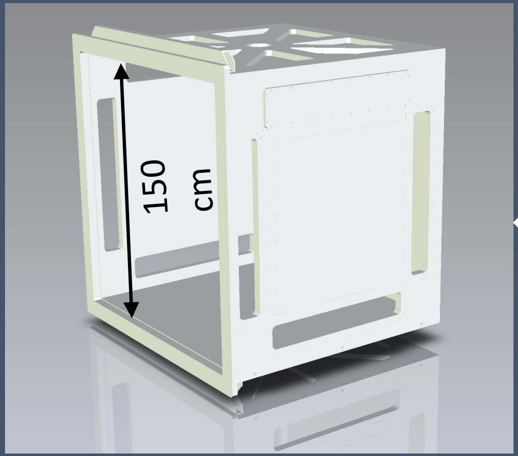
BEAST TPCs

8 x 40 cm^3

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

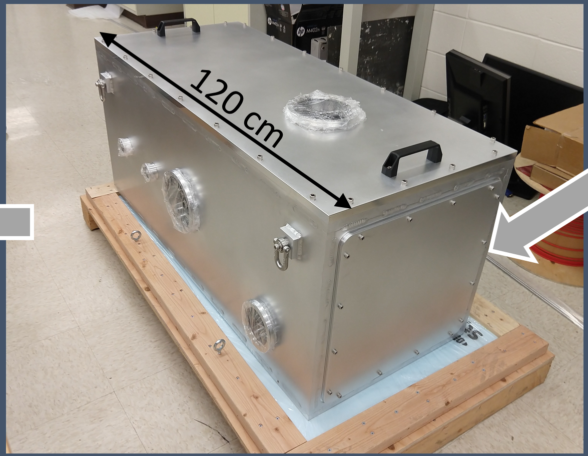
- Extensive prototyping with pixel chip readout completed
- Due to high spatial resolution and single-electron sensitivity, these prototypes remain in use for precision studies of nuclear recoil physics
- Now constructing 3[rd] generation detectors w/ CERN strip micromegas readout to achieve DM + solar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

2022



CYGNUS HD 1 Demonstrator (1 m^3)

2020



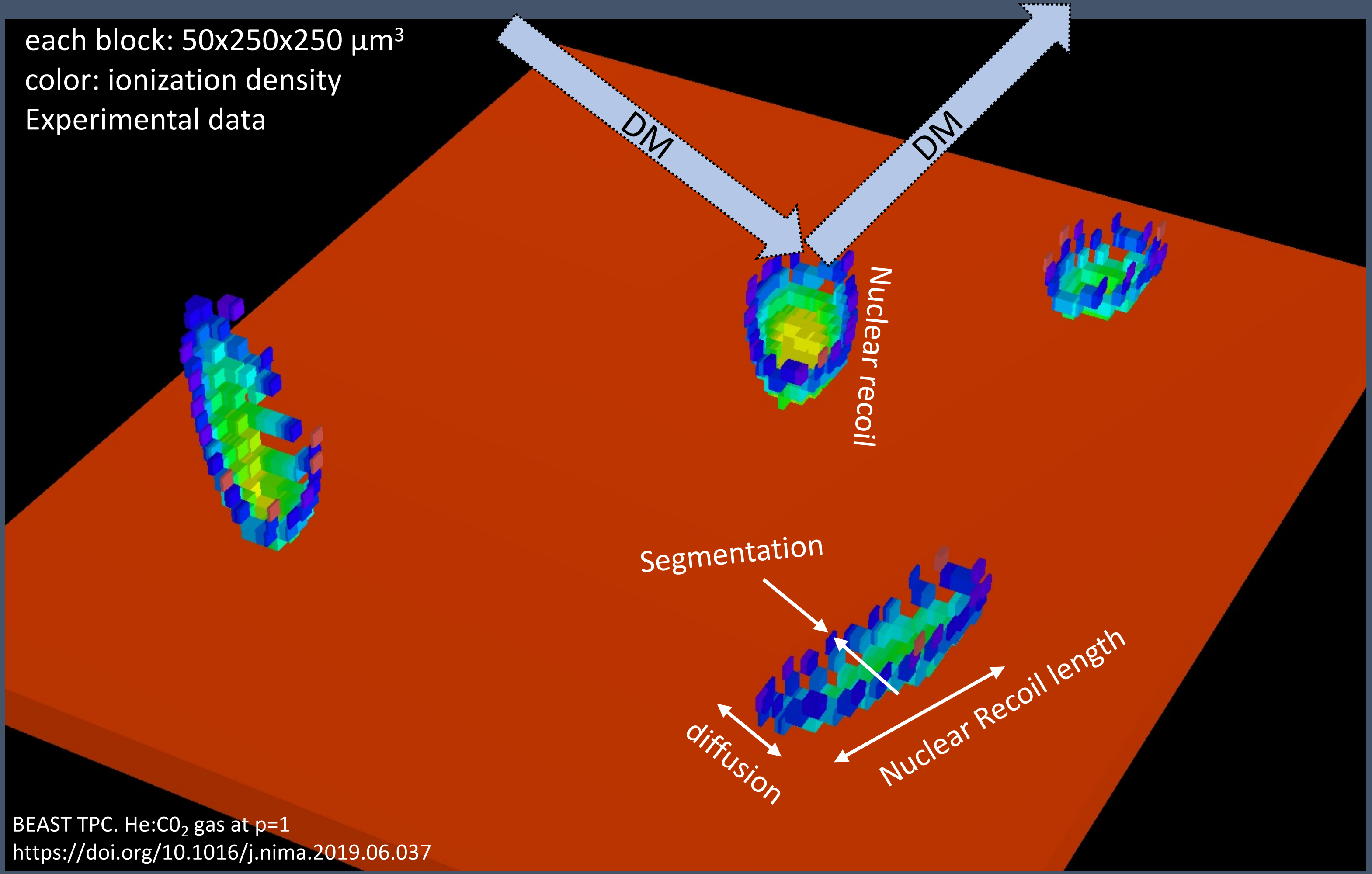
CYGNUS HD “Keiki” (40 liters)

3[rd] Generation: Optimized for dark matter

The Power of HD gas TPCs

Capabilities resulting from HD charge readout

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

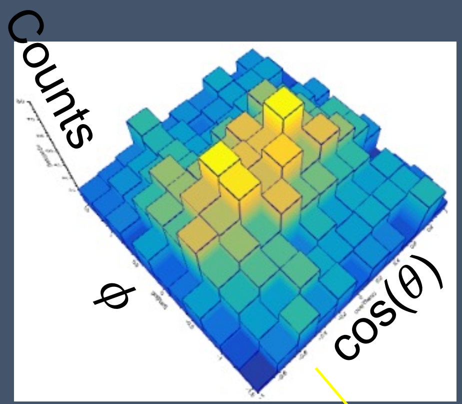


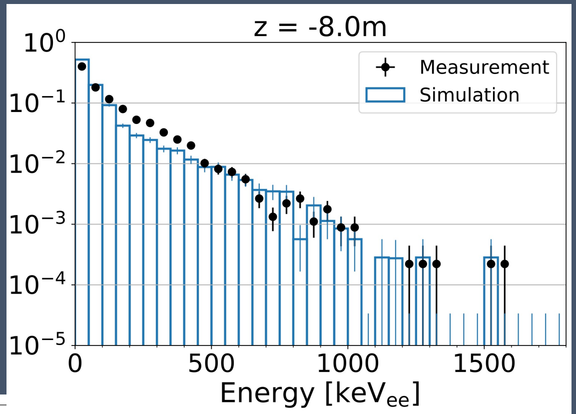
Want: segmentation (here: 50 x 250 µm) < diffusion (~200-500 µm) < recoil length (~mm)

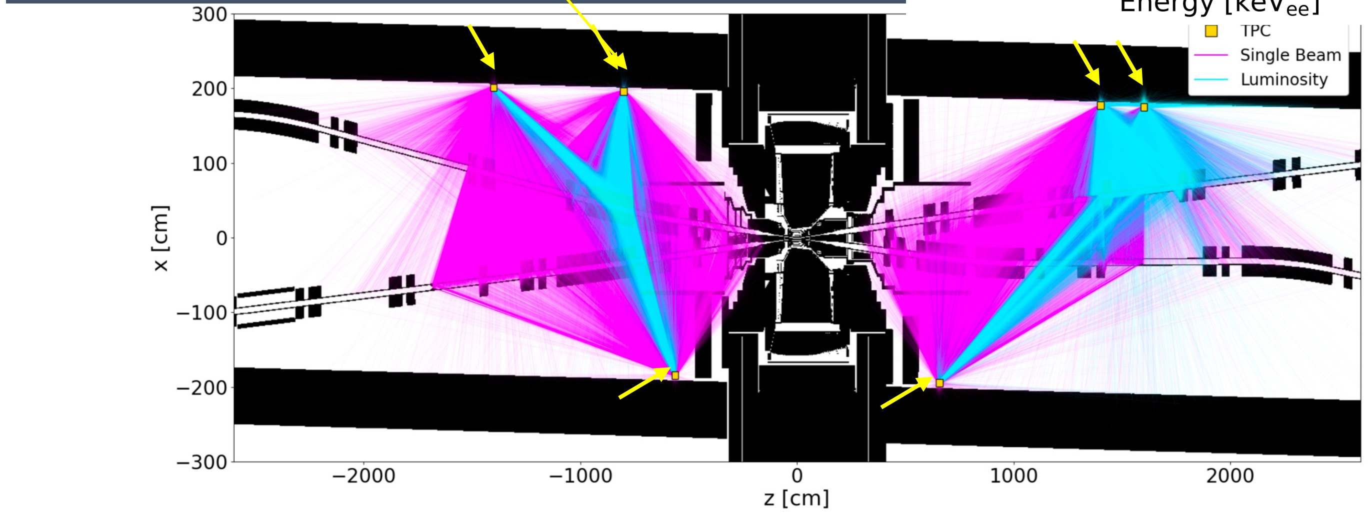
- Event-by-event 3D vector directionality possible in gas TPC w/ highly segmented readout planes – HD TPCS
- In BEAST TPCs, event and data rate is negligeable, due to zero-suppression on chip.

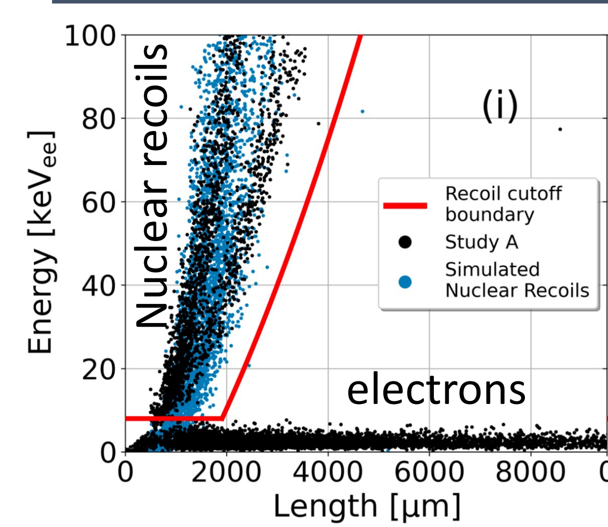
Directional Neutron Background Monitoring

J. Schueler et al., http://arxiv.org/abs/2111.03841







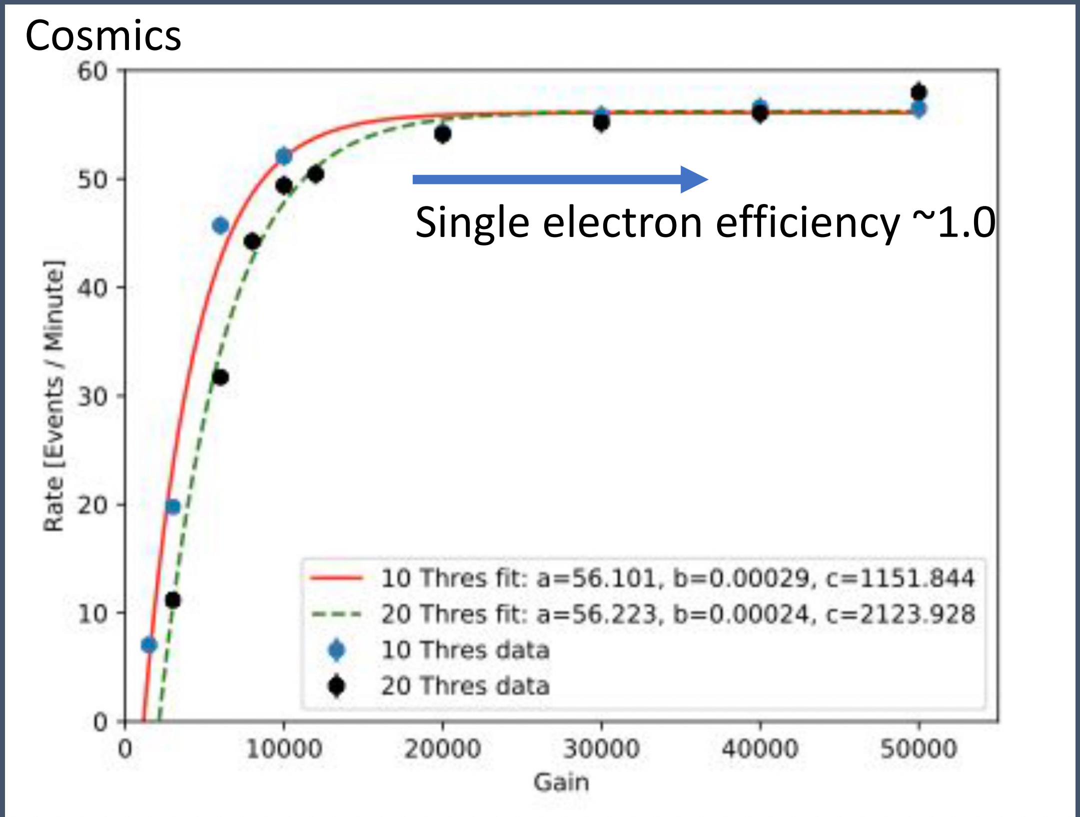


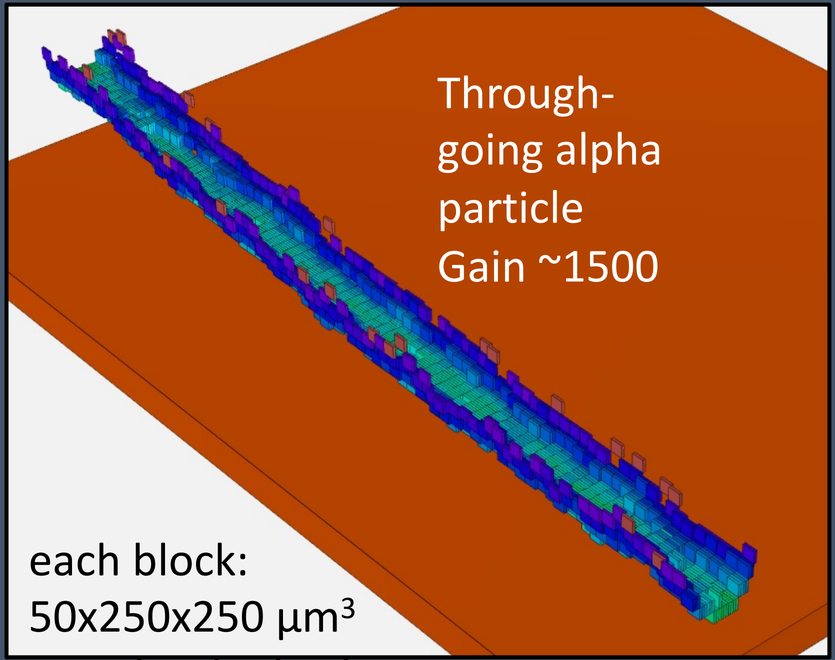
- BEAST TPCs used at SuperKEKB electron-positron collider (world's highest luminosity machine)
- TPCs are semi-portable and have been moved around for different measurements
- Used in *low-gain mode* to reduce x-ray background. Operating ~bkg free > 8 keVee

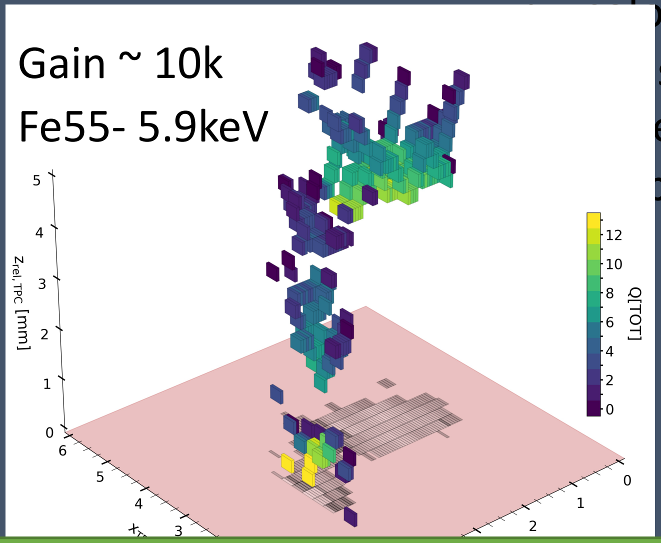
Noiseless Single Electron Detection

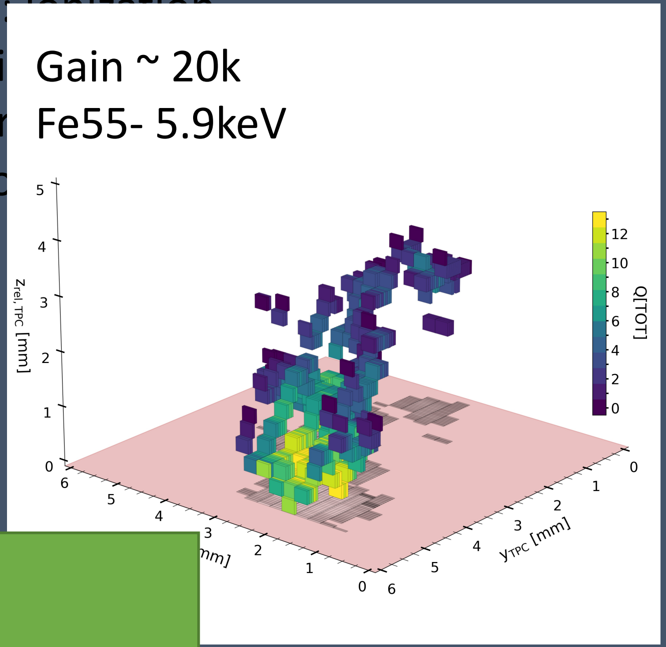
Majd Ghrear
Jeff Schueler

Cosmic ray rate



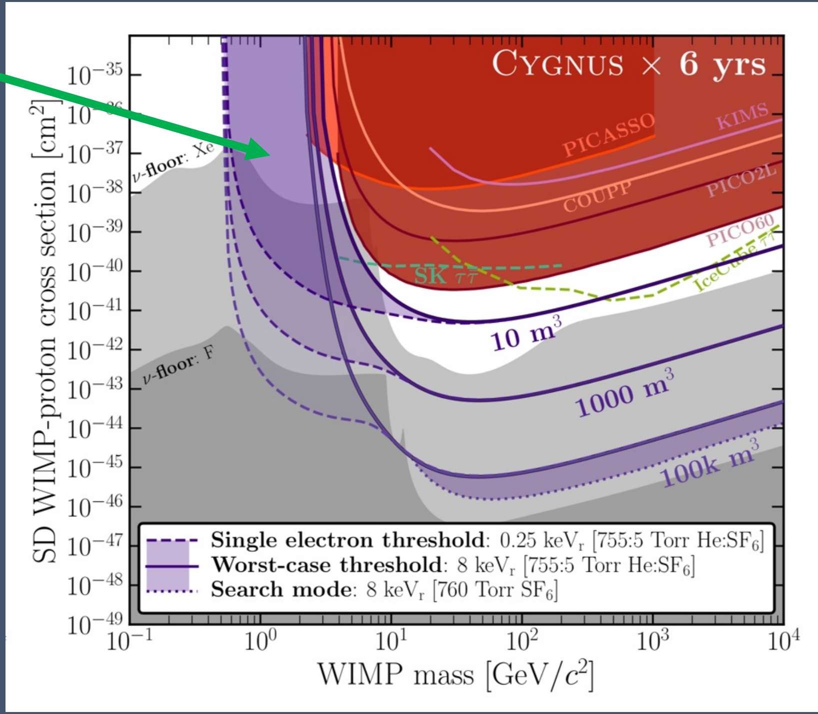






- In high-gain mode, even single electrons of ionization easily detected
- Energy threshold is ~30 keVee, w/ virtually zero noise-occupancy
- Physics performance will instead be limited by *directionality and PID thresholds*

Key issue: WIMP sensitivity depends on electron rejection

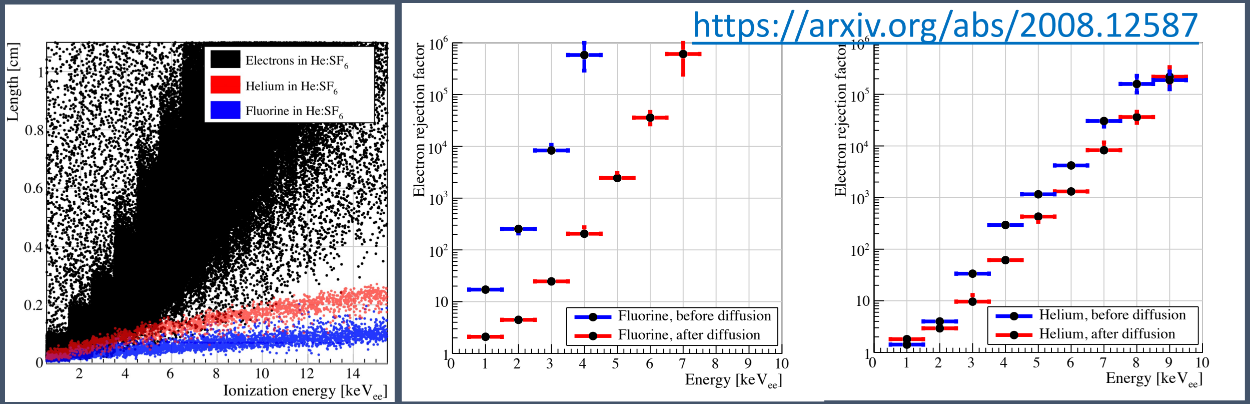


https://arxiv.org/abs/2008.12587

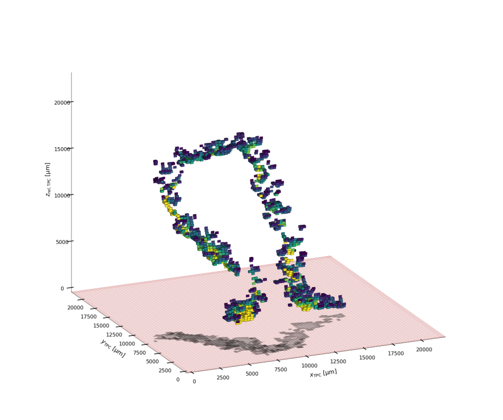
- Improved, physically motivated observables for electron rejection. Requires HD readout.
- Improved even further with 3DCNN, publication forthcoming.
- Demonstration measurement next.

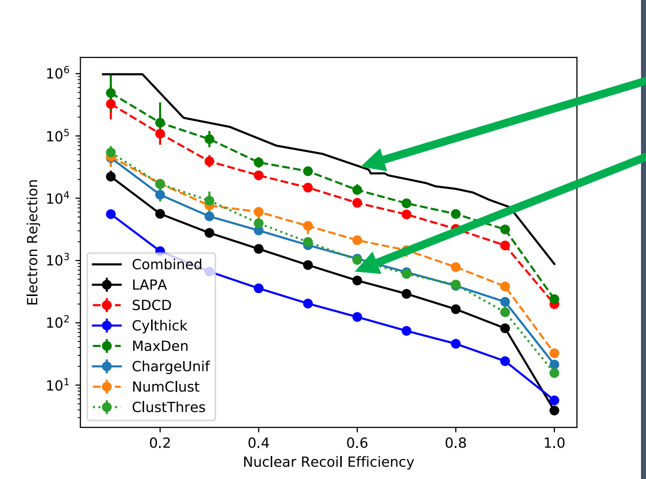
3D electron rejection (simulation) via dE/dx   5 torr SF_6 + 755 torr Helium

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.





~2 orders of magnitude improvement over dE/dx !

Majd Ghrear et al., arxiv.:2012.13649

Event-level head/tail via 3DCNN: low gain mode

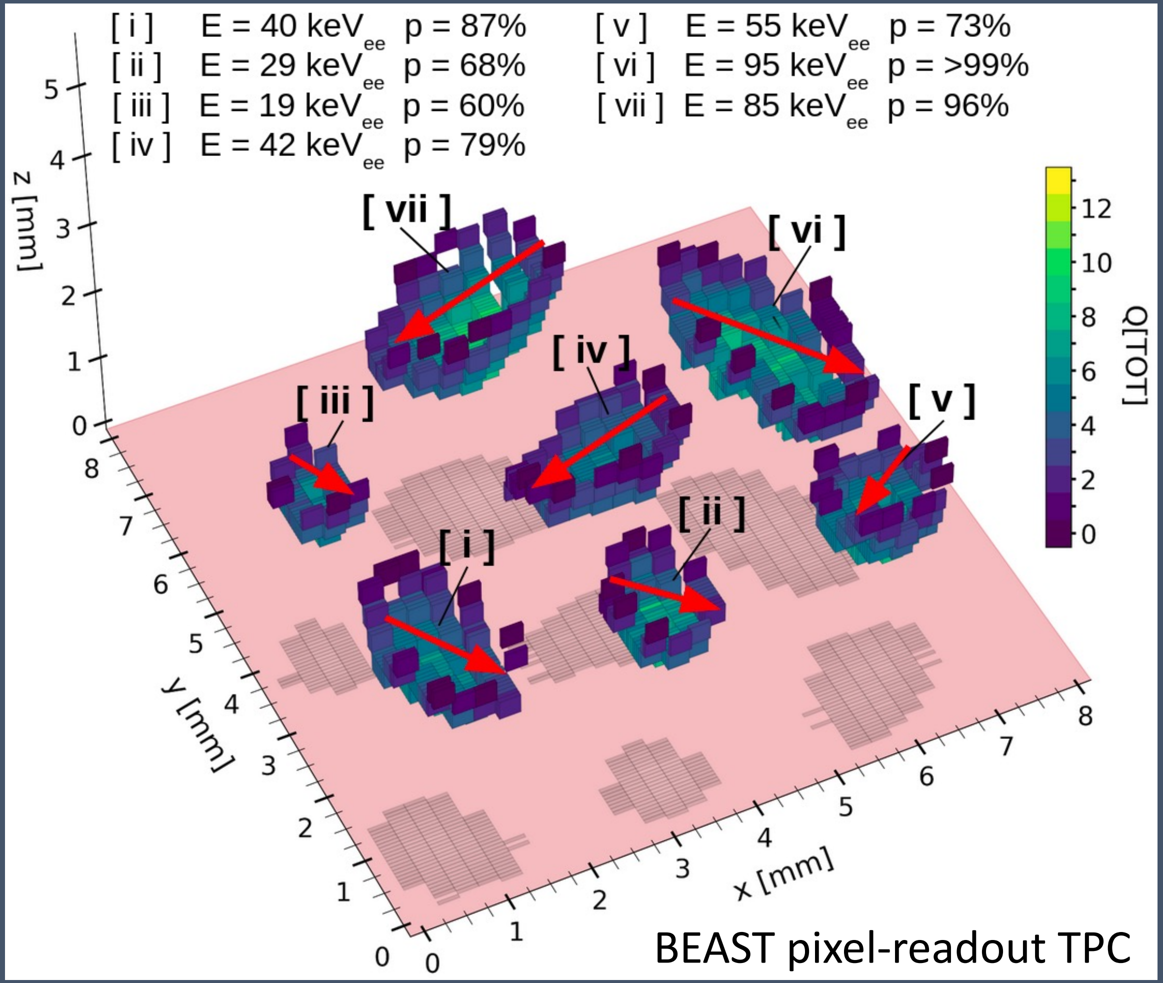
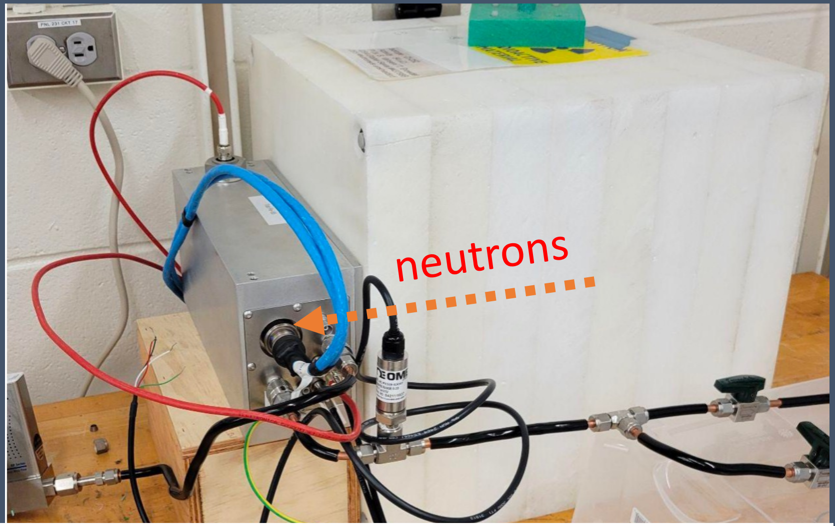


Figure1: Left: Helium recoil tracks detected in a pixel-readout time projection chamber at low gain (900). Color of voxels indicates ionization density.



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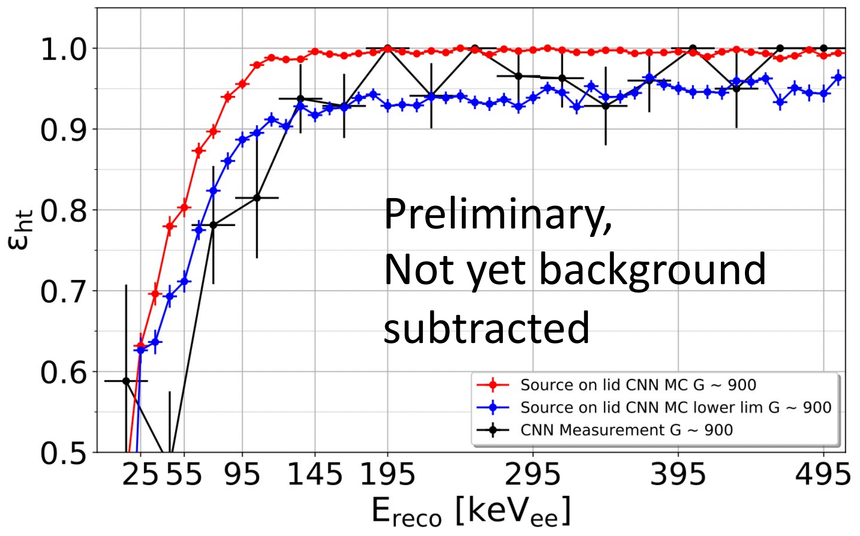
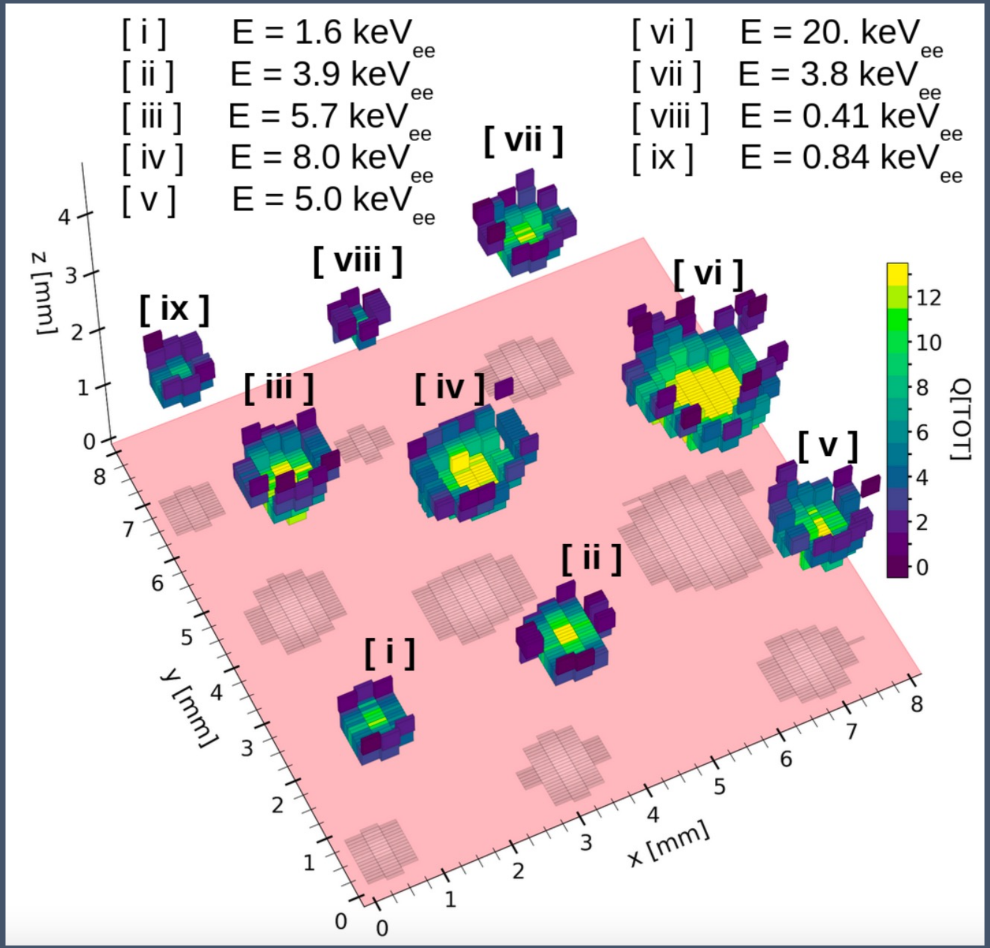
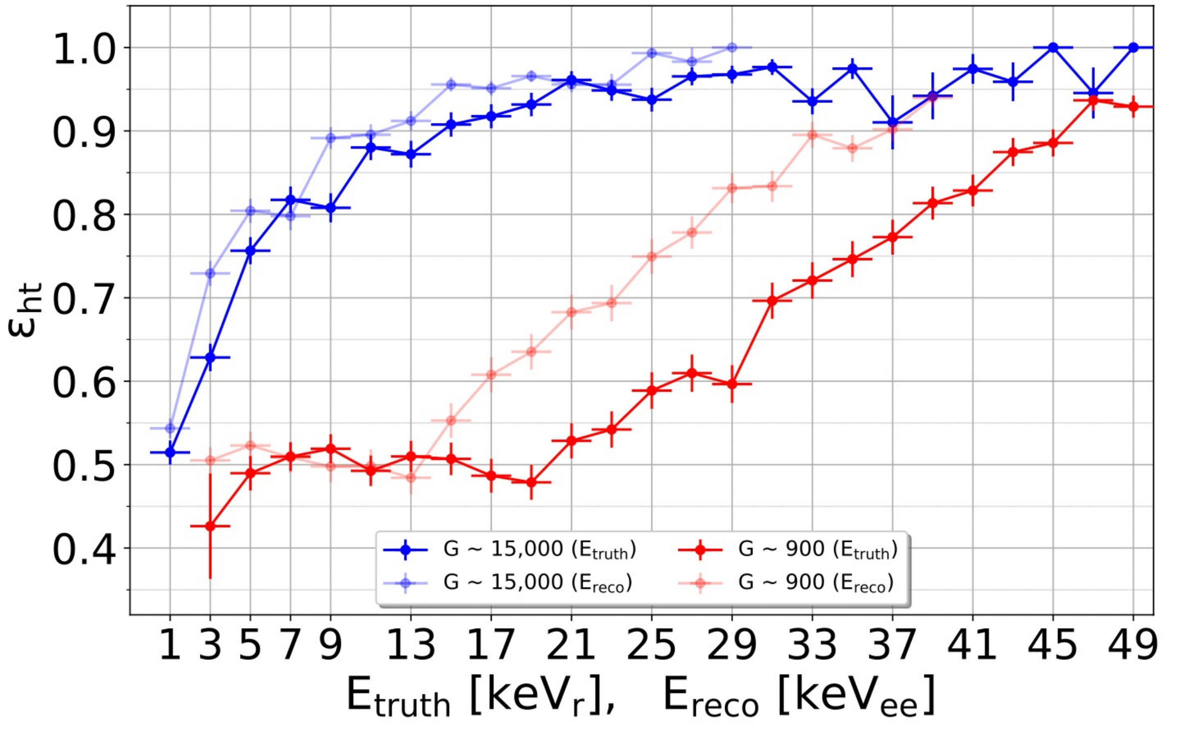


At low TPC gain (900), event-level head/tail sensitivity down to 25 keV at atmospheric pressure!
Measurement is a lower limit – not yet background subtracted.

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

Jeff Schueler



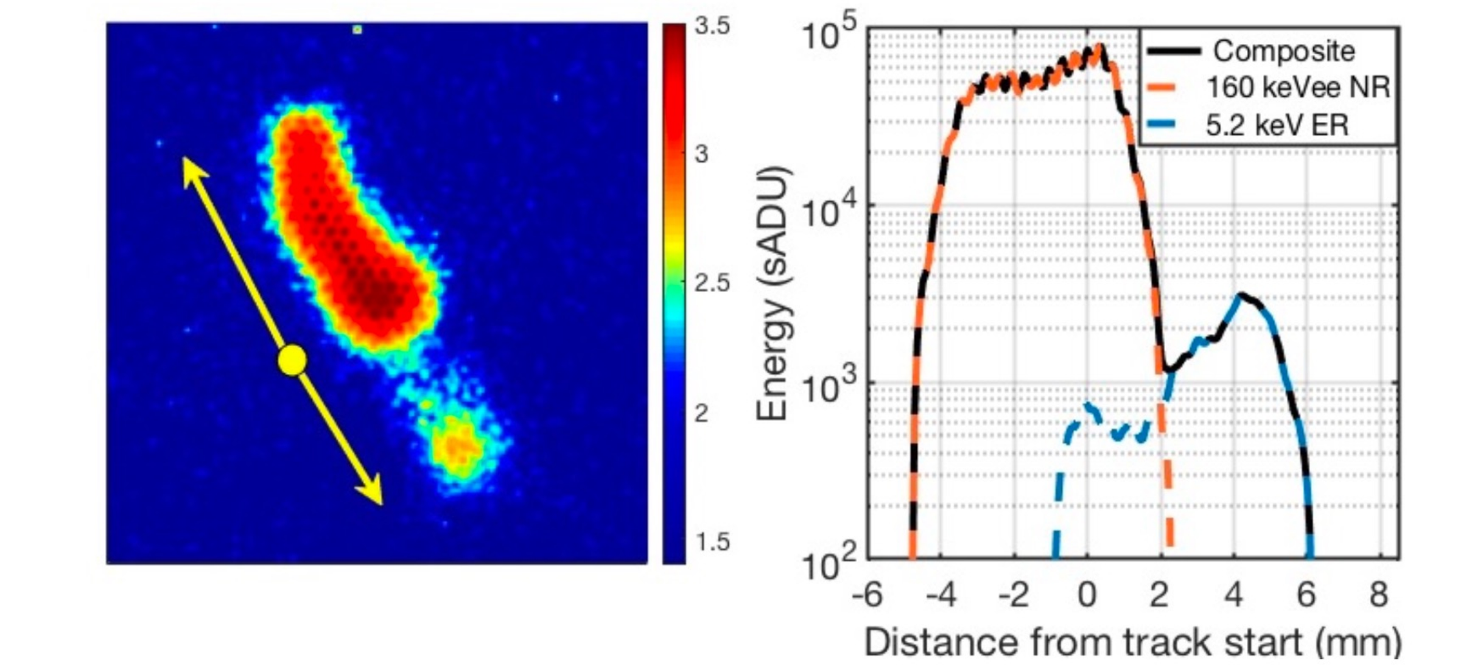


High gain: Excellent head/tail down to 3keV, at p=1 atm, T=300K !
Experimental verification ongoing. (Difficult!)

Migdal / BSM

- HD gas TPCs ideal for identifying non-standard or unexpected final states
  - Migdal Effect
  - Non-standard WIMP models
- Other types of detectors cannot resolve such final states
- Dedicated MIGDAL experiment / collaboration planning measurement this year

N. Phan, E. Lee and D. Loomba, Imaging 55Fe electron tracks in a GEM-based TPC using a CCD readout, JINST 15 (2020) P05012 [1703.09883].



~30 Torr of CF_4, double-THGEM gas amplification device and a CCD-based optical readout.

Yesterday's background → tomorrow's signal?

- HD gas TPC *excellent* at identifying electron-recoil events
- So far, treated as background
- CYGNUS should see large rate of electron recoils from solar neutrinos
- CNO neutrino measurements look feasible, due to low energy threshold combined with good angular resolution
- CYGNUS study still ongoing, see Poster, this conference, by Majd Grehr

C. O'Hare

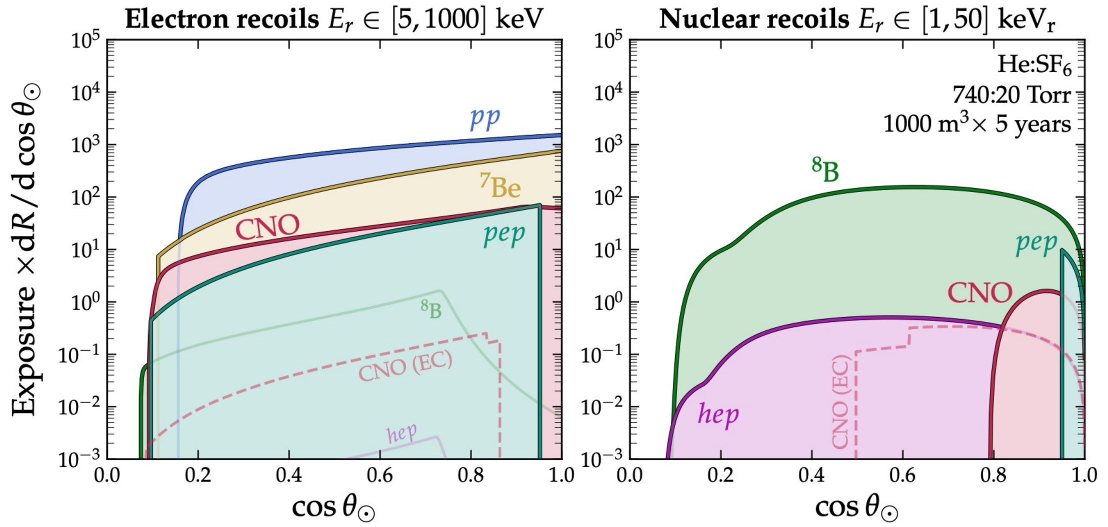


Figure 7: Expected number of nuclear (left) and electron (right) recoil events as a function of the cosine of the angle away from the Sun. The calculated rates assume a 740:20 He:SF_6 gas mixture at 1 atmosphere, and a volume of 1000 m^3 run for five years.

Table 1 Approximate expected numbers of neutrino-induced nuclear and electron recoils[a]

Nuclear recoils	SF_6			CF_4			He		
Threshold (keV$_r$)	1	5	10	1	5	10	1	5	10
Solar (mainly ^{8}B)	73	15	2	54	16	3	3	2	1
3-kpc supernova	25	18	12	18	13	10	0.6	0.5	0.5
Electron recoils	SF_6			CF_4			He		
Threshold (keV)	5	500	1,000	5	500	1,000	1	500	1,000
Solar (total)	537	42	4	438	34	3	102	8	0.8
Solar (CNO)	15	5	0.6	12	4	0.5	3	0.9	0.1
Geoneutrinos	0.2	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1

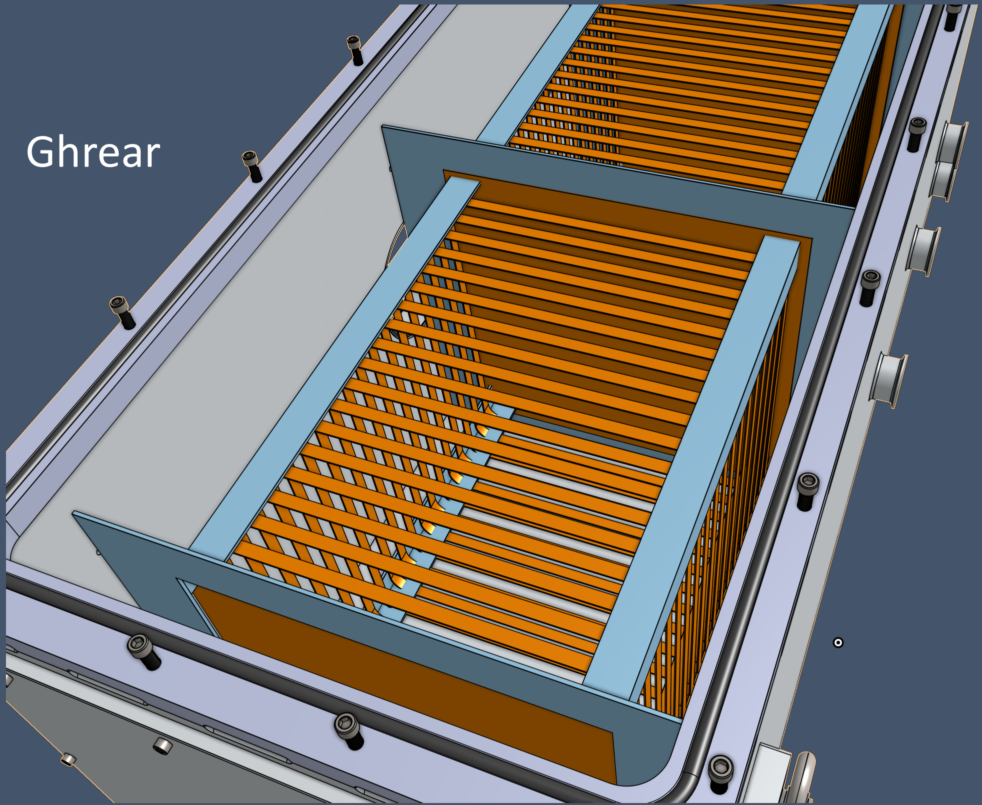
[a]Assuming a target volume of 1,000 m^3, 1 atmosphere pressure, and an exposure time of 1 year.

CYGNUS HD “Keiki”

Cost-effective scale up via existing collider technologies

CERN strip micromegas, CERN VMM3a hybrids, CERN SRS readout

Ghrear



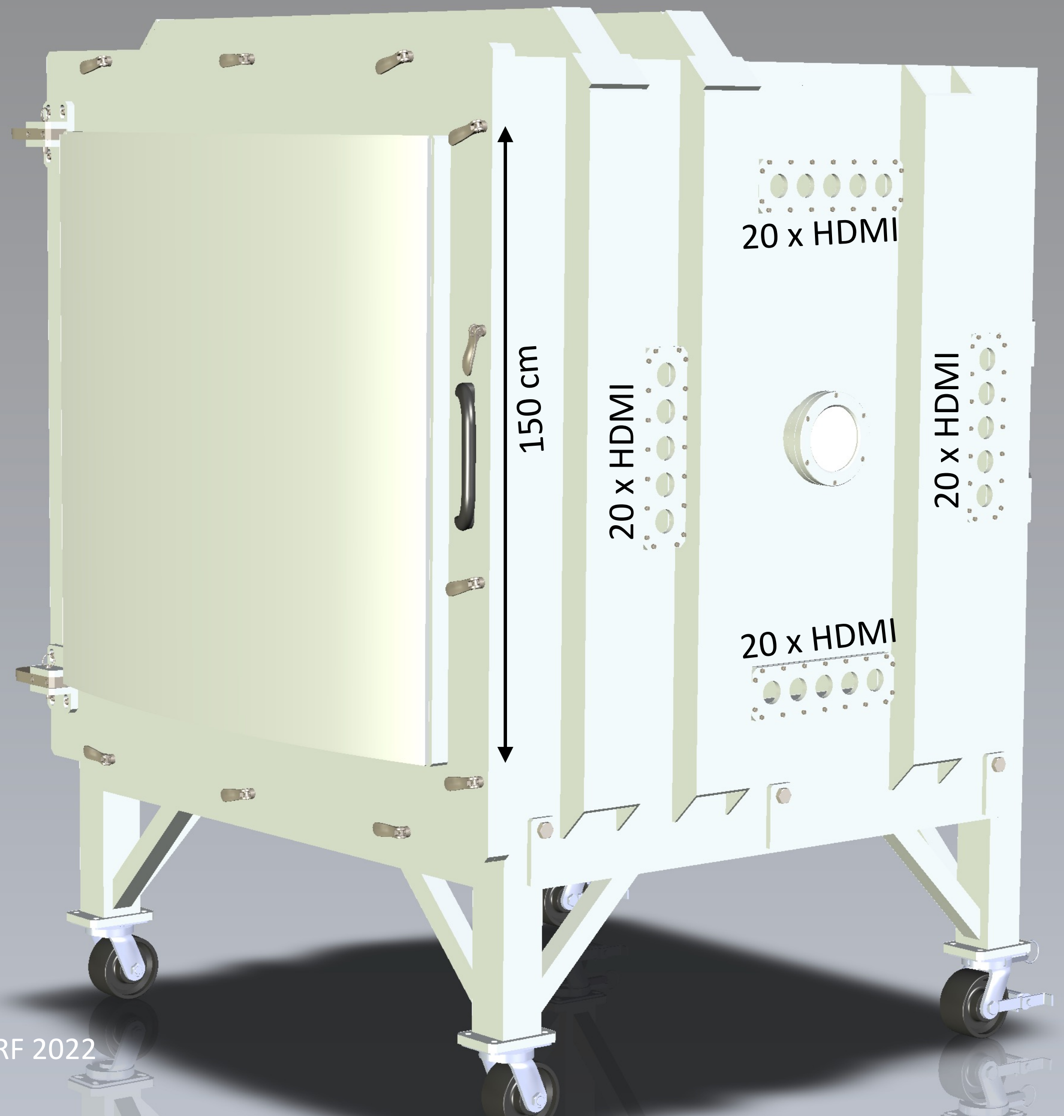
CYGNUS HD “Keiki” - factor 1000 scaleup of BEAST TPC
Evaluation of components for follow-on $1m^3$ detector

CYGNUS HD-1 Demonstrator

- Six orders of magnitude larger than our first prototype
- 1000 l sensitive volume
- CERN eSRS readout for topical rejection of non-recoil events at trigger level
- Unit-cell technology demonstrator for future, large CYGNUS neutrino/DM observatory

Vessel design ongoing at vendor
Delivery this year!

CYGNUS HD-1 vacuum vessel



https://arxiv.org/abs/2203.05914

Final Thoughts

- HD gas TPCs (T=300K, p~1 atm) enable precision measurements of the ionization topology of nuclear and electronic recoils at the lowest energies
- Potential for a rich, long-term physics program based on incremental scale-ups
- Will eventually require mass-production of low-background MPGD readout planes
- Observation: SURF would be optimal location for CYGNUS HD. A small prototype, even if not radiopure, could characterize neutron backgrounds, and serve to kick-start a program…
- Dream: single-electron-counting recoil observatory

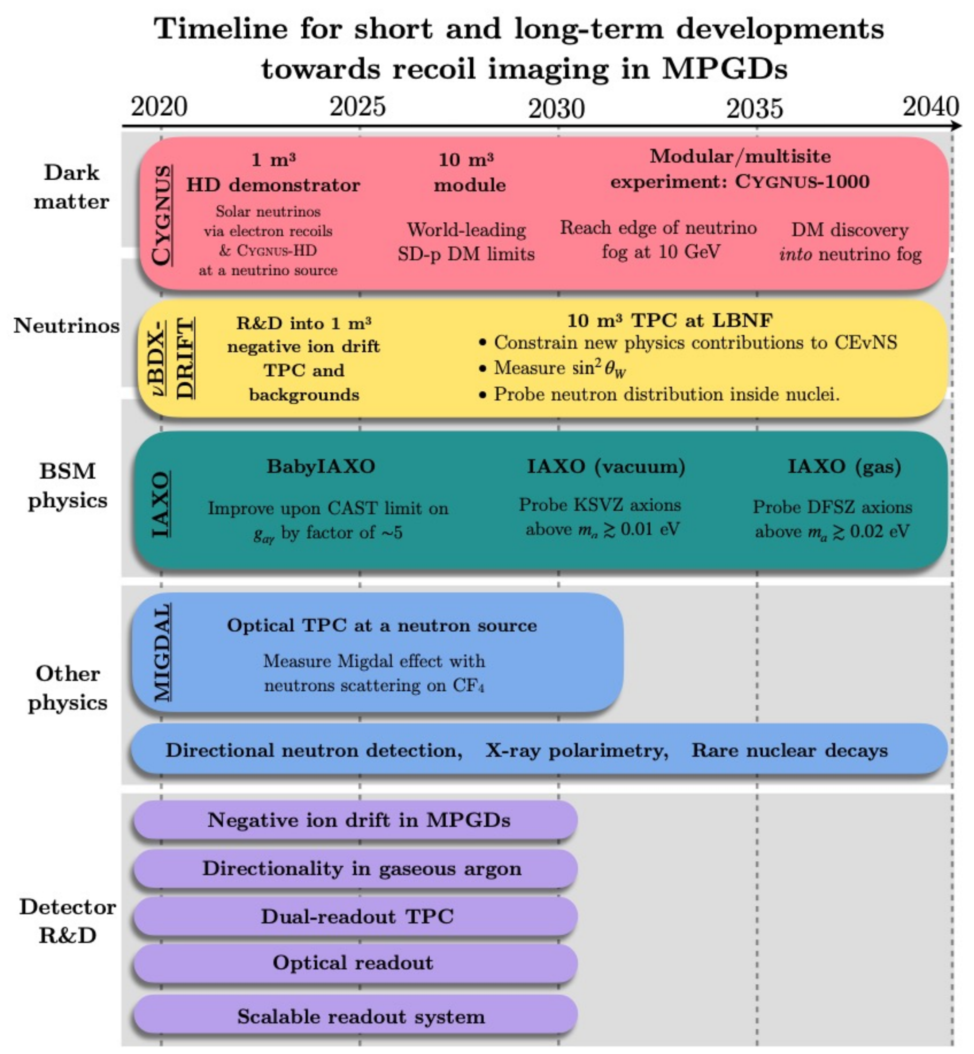


Figure 1: The plan for developments towards recoil imaging over the next decade and beyond. We have divided the physics undertaken in terms of DM, neutrinos, beyond-the-Standard-Model (BSM) physics, other physics, and detector R&D. The latter component is not anticipated to span two decades, instead the knowledge gained during those R&D programs will gradually be incorporated into the large-scale projects such as CYGNUS, and νBDX-DRIFT.

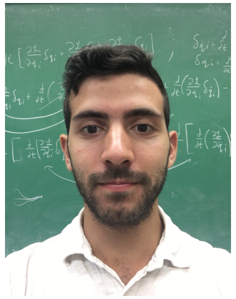
Current and Former Hawaii / LBNL Contributors


Igal Jaegle
Postdoc


Jared Yamaoka
Postdoc


Marc Rosen
Mechanical Engineer

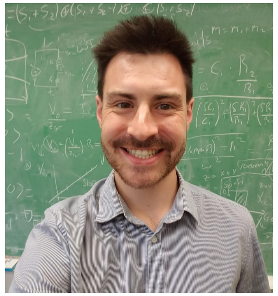

Peter Lewis
Postdoc


Majd Ghrear
Graduate Student


Michael Hedges
Graduate Student

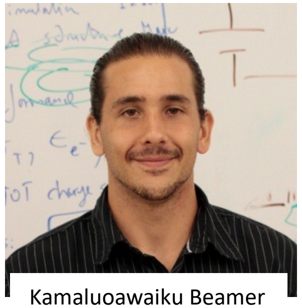

Josh Murillo
Graduate Student


Thomas Thorpe
Graduate Student


Jeffrey Schueler
Graduate Student


Hima Korandla,
Graduate student

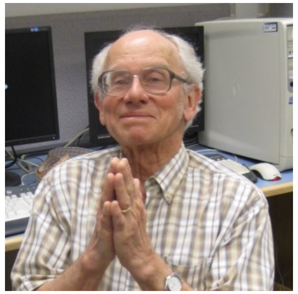

Ilsoo Seong
Graduate Student


Kamaluoawaiku Beamer
Undergraduate Student
(+rotating group)


Zachary Liptak
Postdoc


Andrii Natochii
Postdoc


Sven E. Vahsen


John Kadyk


Maurice Garcia-Sciveres


Mayra Lopez-Thibodeaux
(UC Berkeley Student)

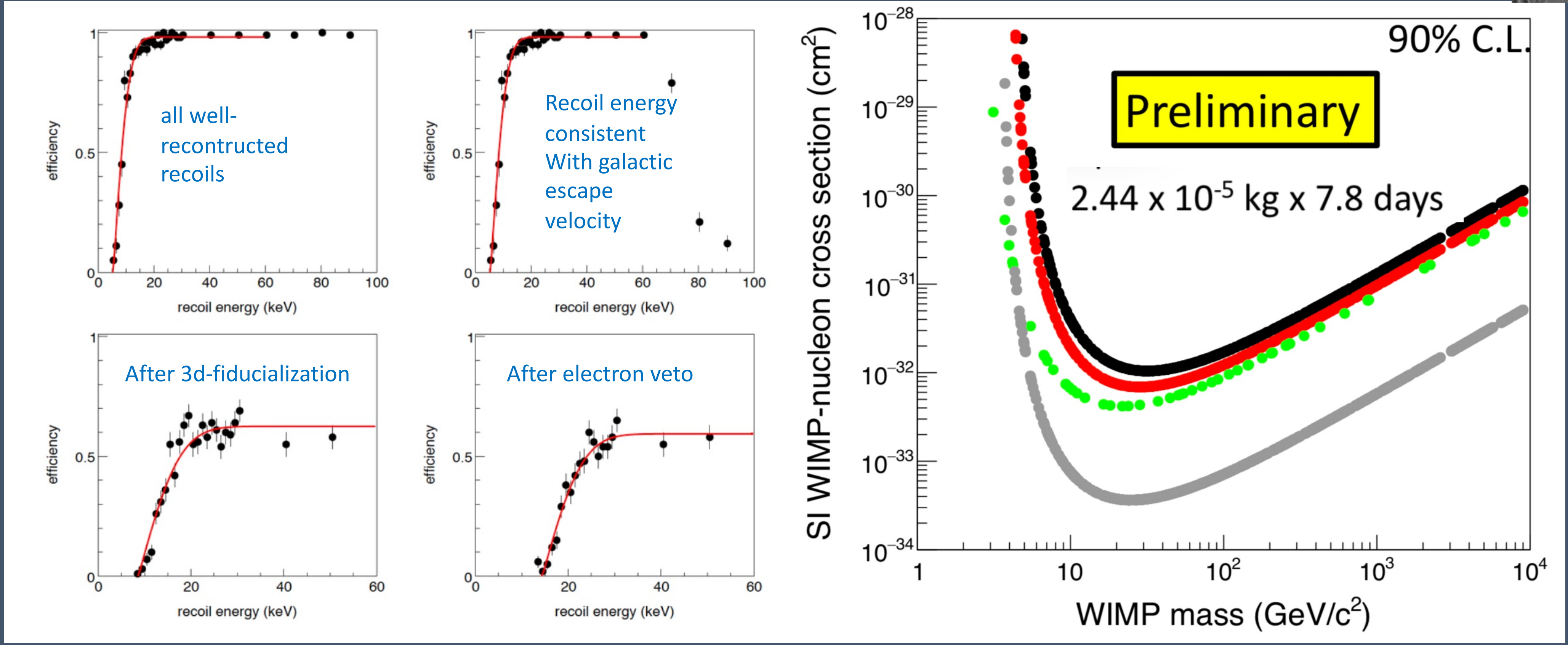

Kelsey Oliver-Mallory
(UC Berkeley Student)

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

UNIVERSITY of HAWAI'I
MĀNOA

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

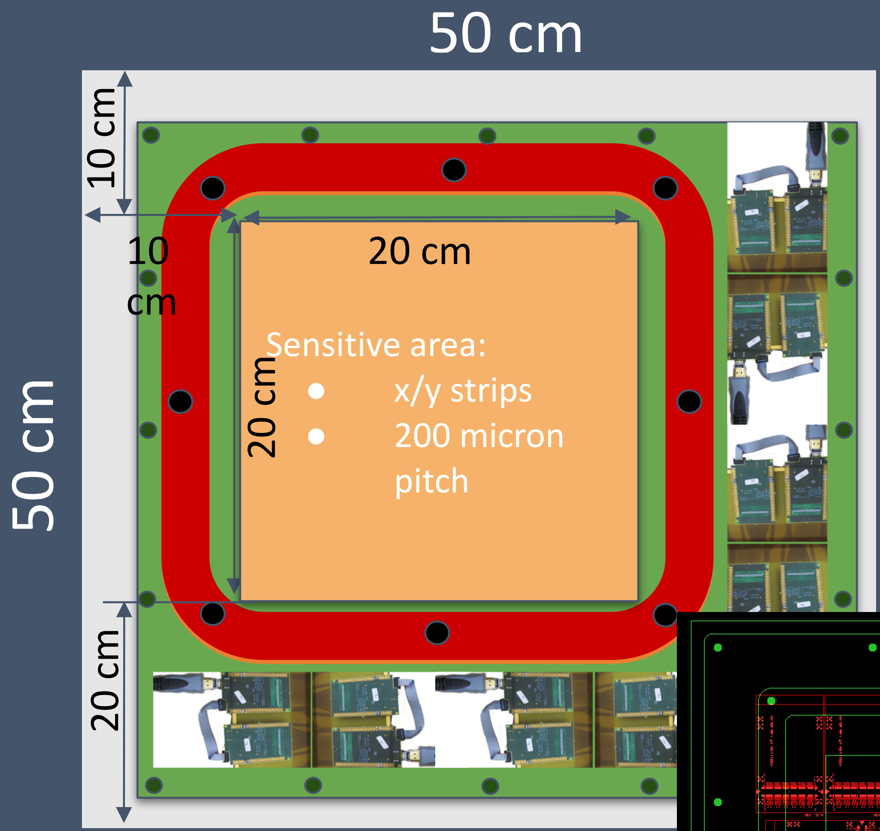
Tom Thorpe



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?

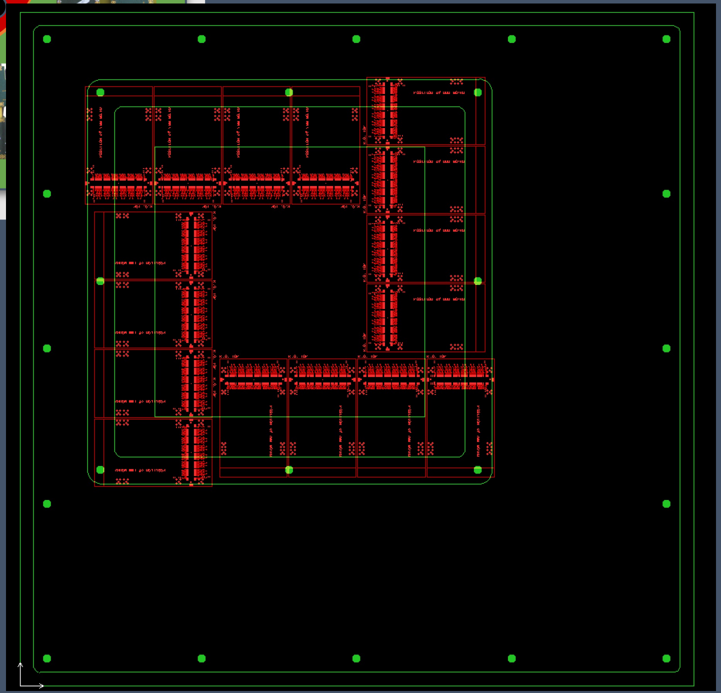
CYGNUS HD Keiki readout plane

- 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

Past & 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

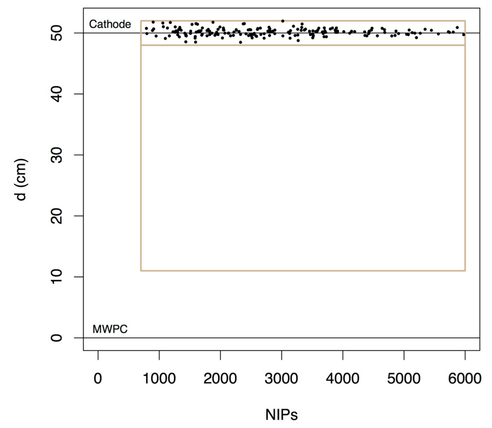
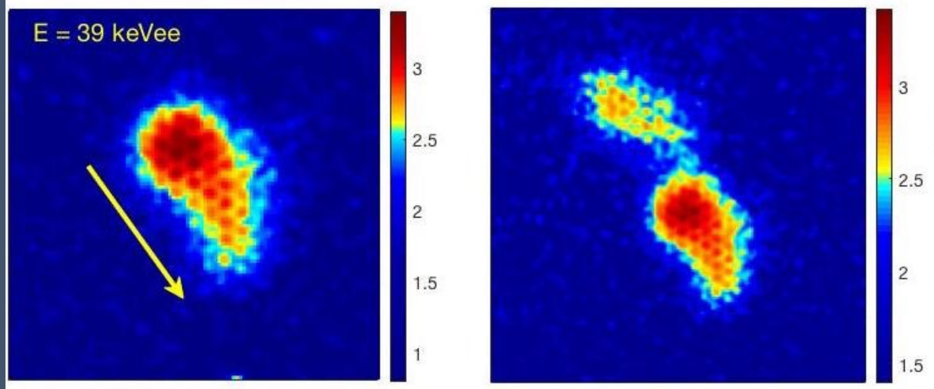
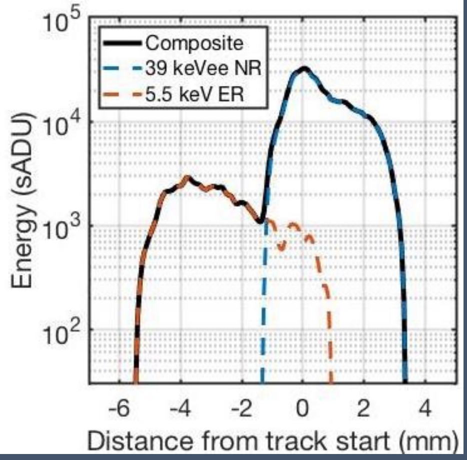


Fig. 7 – *d* vs. *NIPs* data for 54.7 live-days of shielded background data. All of the events passing the analysis cuts cluster around the central cathode consistent with the expectation of RPRs events there. In the fiducial window, large tan rectangle, no events were observed. This background-free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



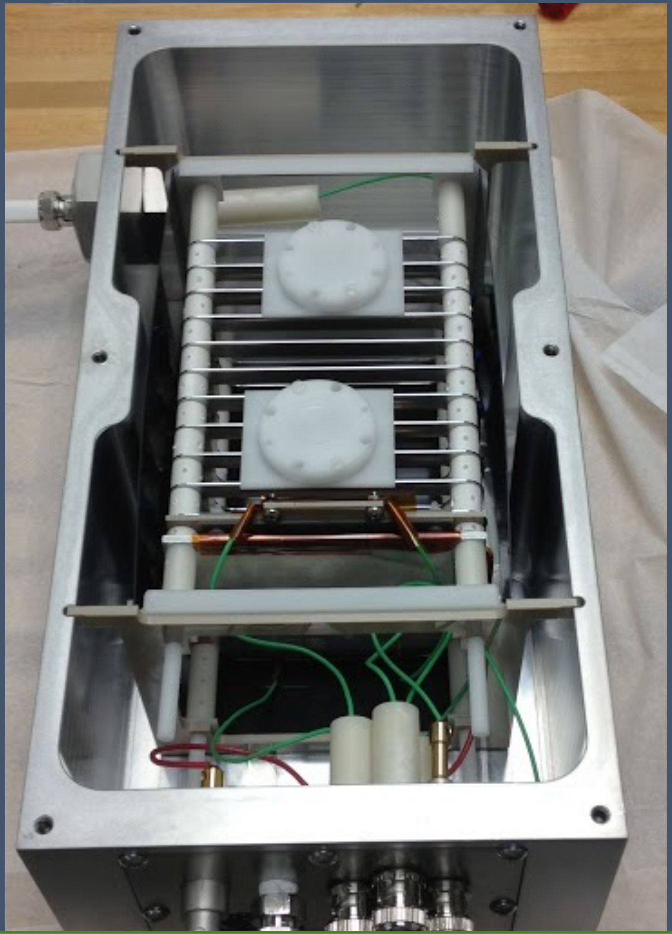


U. New Mexico. Double THGEM + EMCCD

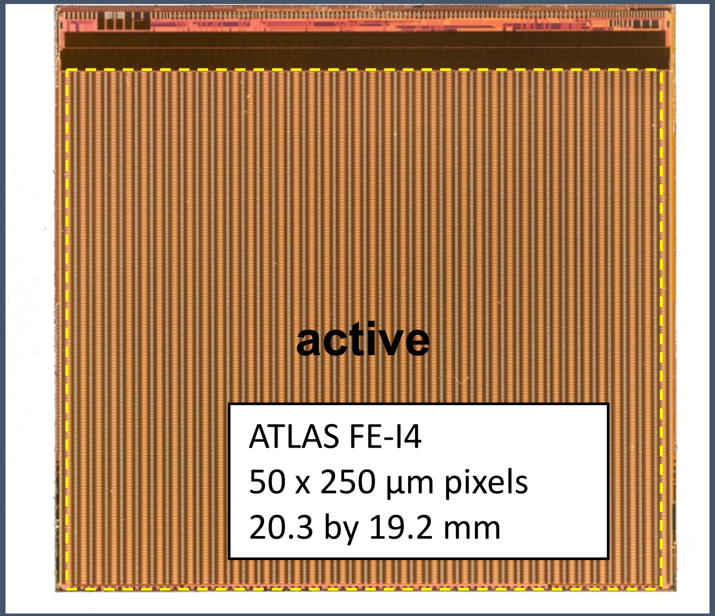
Latest operational detector: ~40 cm^3 "BEAST" TPC - eight constructed

- 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

Data quality after corrections

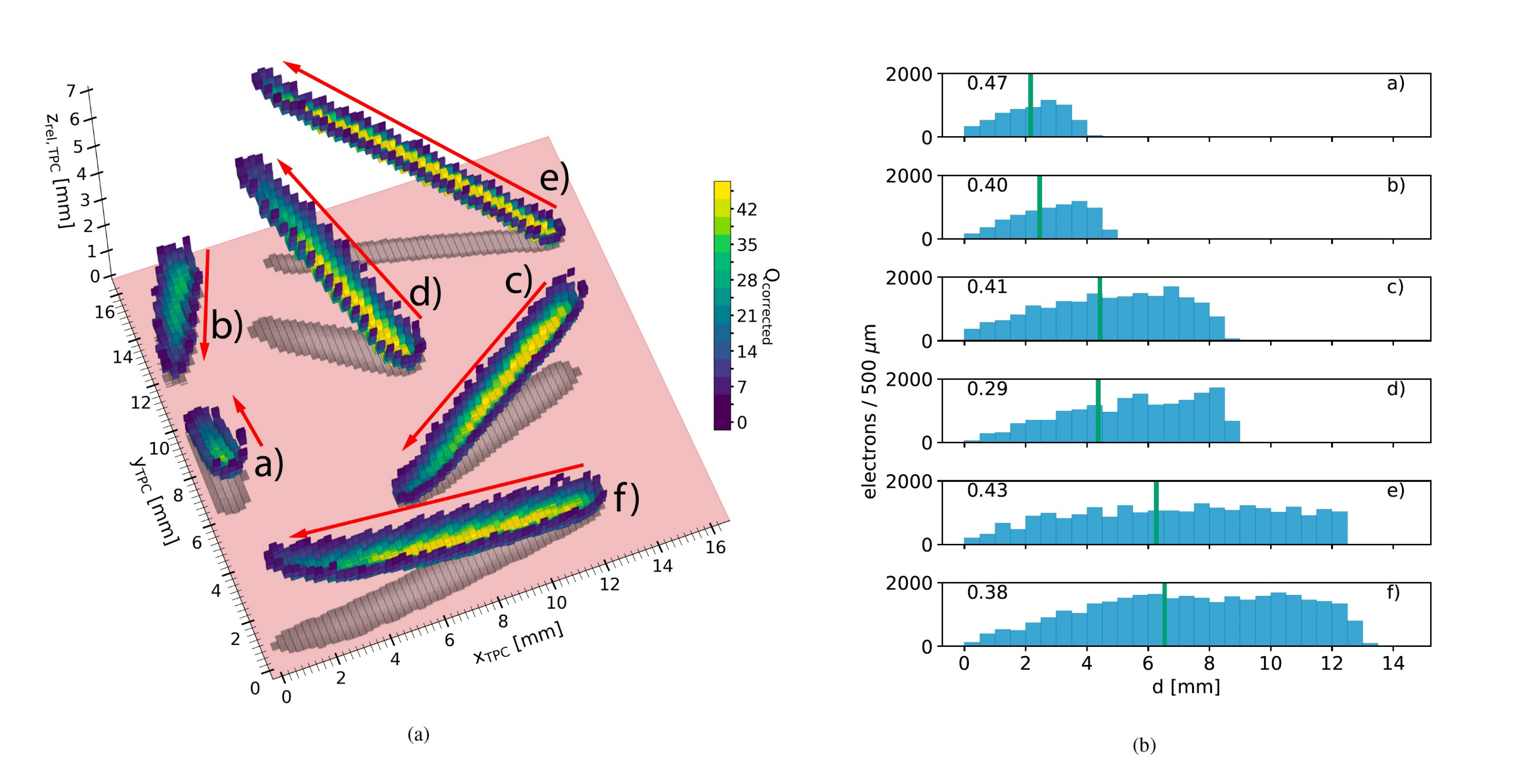


Figure 16: Six tracks visualized in 3D (a) alongside their charge distributions versus distance from the track head (b). The head-direction of the tracks is shown with red arrows, and is determined by designating the half with less charge as the head, as shown by the color scale. On the right, the geometric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

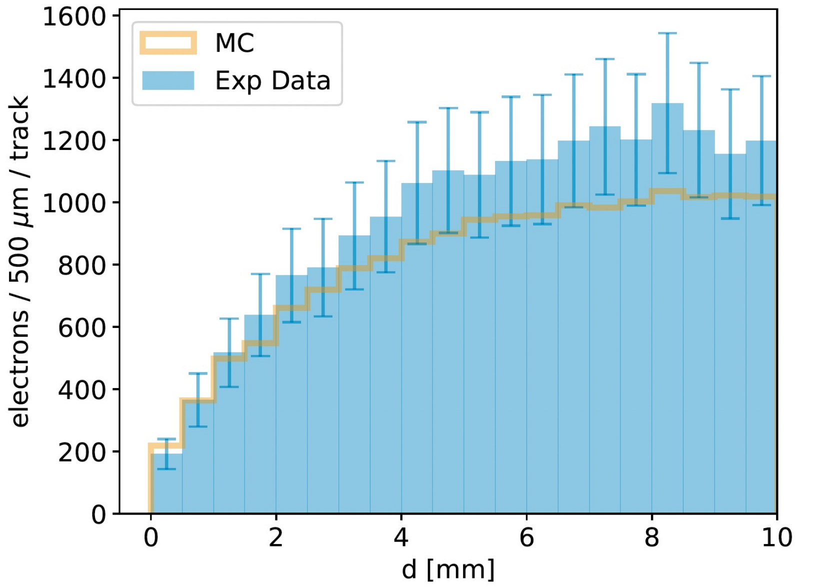


Figure 15: Detected charge versus distance from the track head in selected helium recoils. The orange line corresponds to a digitization of SRIM-based events in simulated data and the blue histogram corresponds to the equivalent measurement in data. The error bars show the statistical variation in the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