DMTPC:
Dark Matter Time Projection Chamber: A Directional Dark Matter Experiment

Outline

- Dark Matter and Directionality
- Detection
- Reconstruction
- Summary and Outlook

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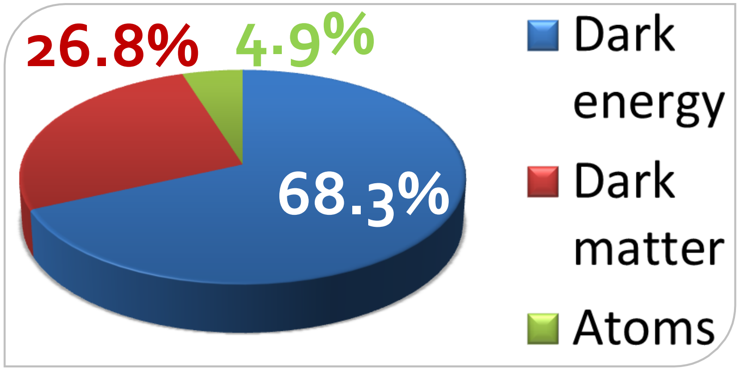
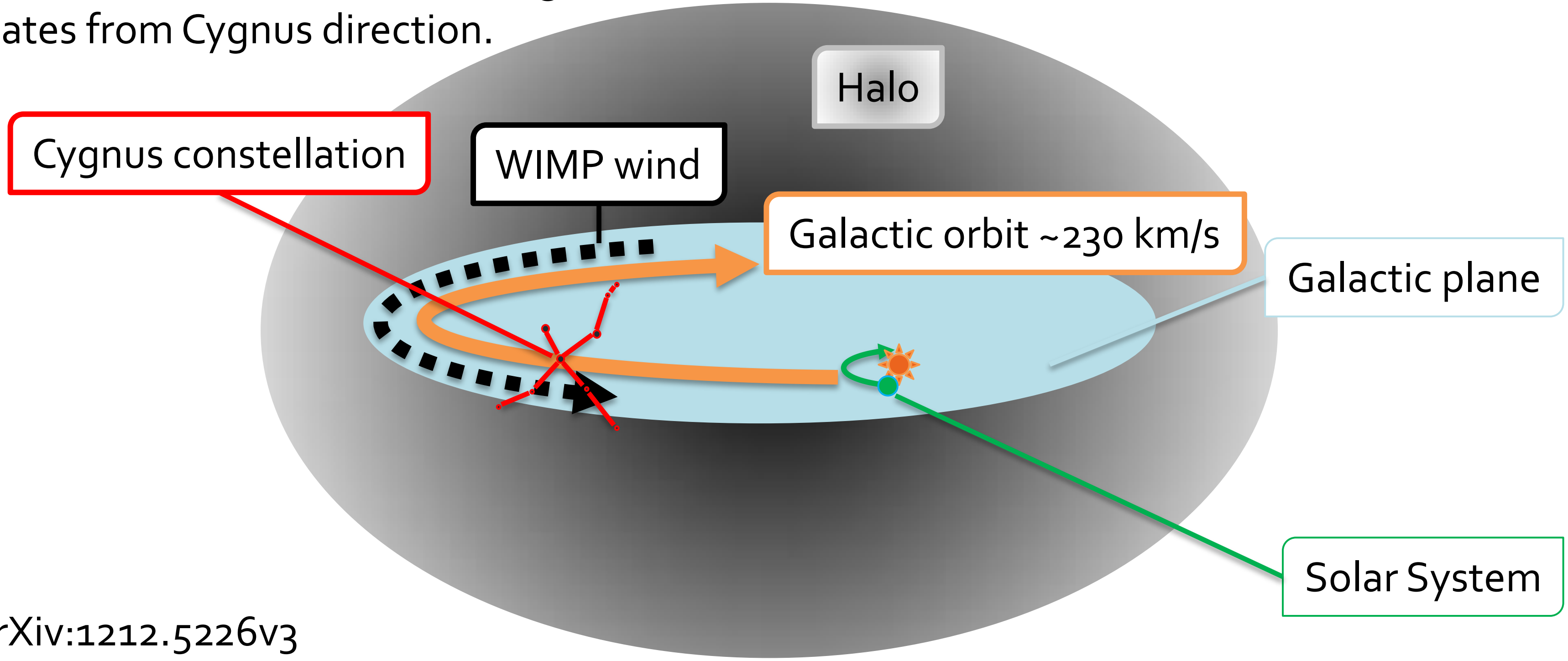
Dark Matter: Directionality

- Dark matter (DM) comprises ~27% of our Universe but is yet to be found[1].
- Popular candidate: weakly interacting massive particle (WIMP).
- Simplified distribution model – Standard Halo Model(SHM):
  - Ideal gas.
  - Isothermal sphere.
  - Maxwell Boltzmann velocity distribution.
- Apparent WIMP wind due to Earths galactic orbit, originates from Cygnus direction.

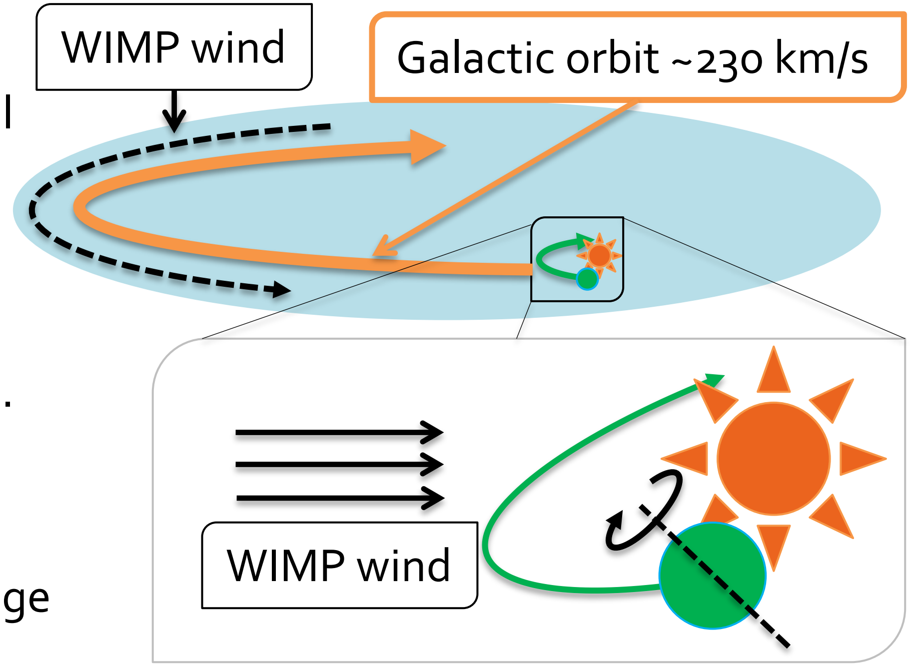


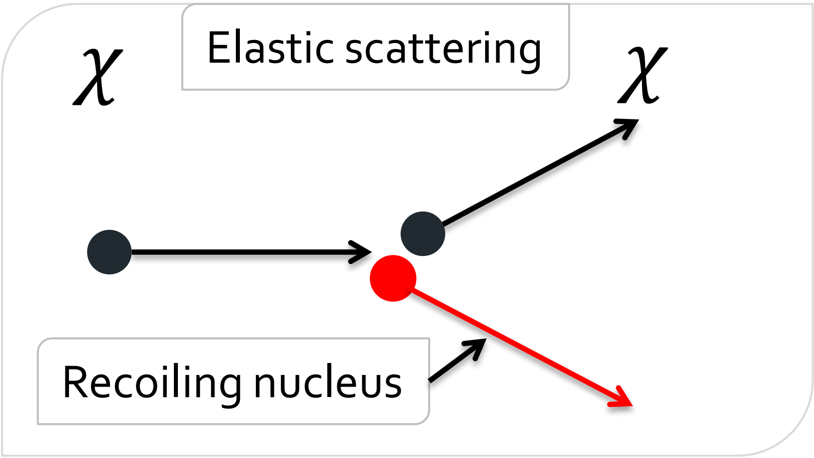


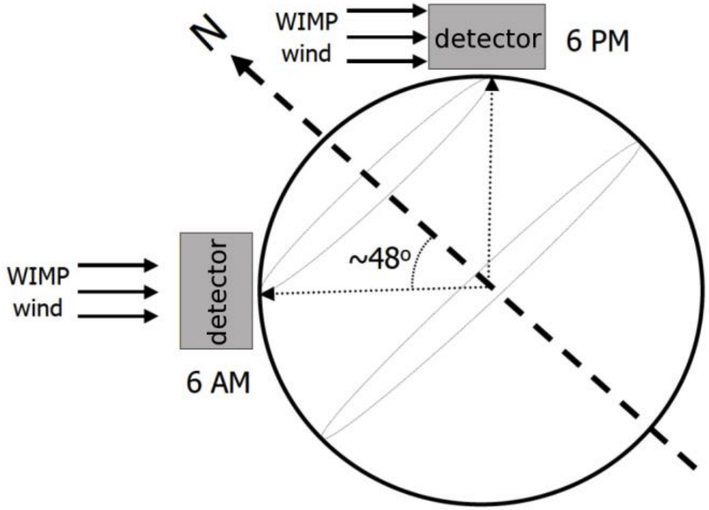
[1] arXiv:1212.5226v3

Dark Matter: Modulation

- Modulating count rate due to solar orbit.
- Apparent directional modulation over a sidereal day.
- No like signal for sidereal modulation.
- Detection via interaction with ordinary matter.
- Elastic interaction: incident direction preserved.
- Reconstructing the recoiling particle direction gives incident particle direction.
- Very low energy: $\mathcal{O}(100)$ keV meaning short range recoils, thus difficult.

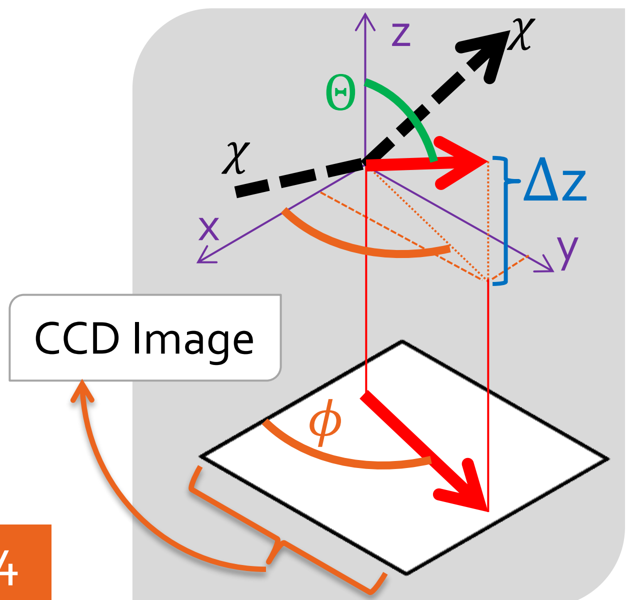


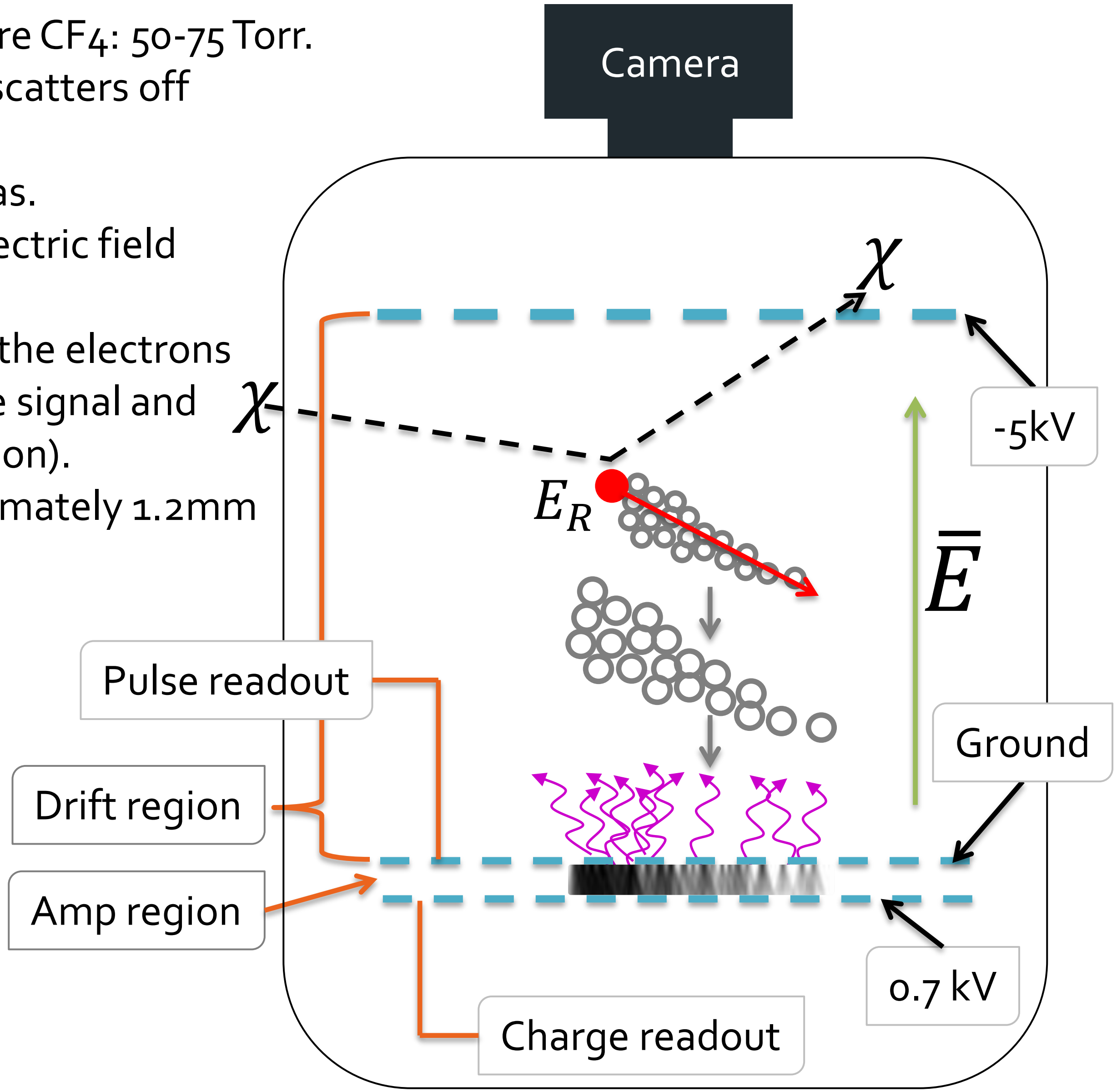




Detection Method

- Chamber filled with low pressure CF_4: 50-75 Torr.
- Incoming dark matter particle scatters off atomic nucleus.
- Recoiling nucleus ionises the gas.
- Electrons drifted by uniform electric field towards amplification region.
- Large electric field accelerates the electrons resulting in an amplified charge signal and scintillation light (track projection).
- For 50keV track expect approximately 1.2mm length track

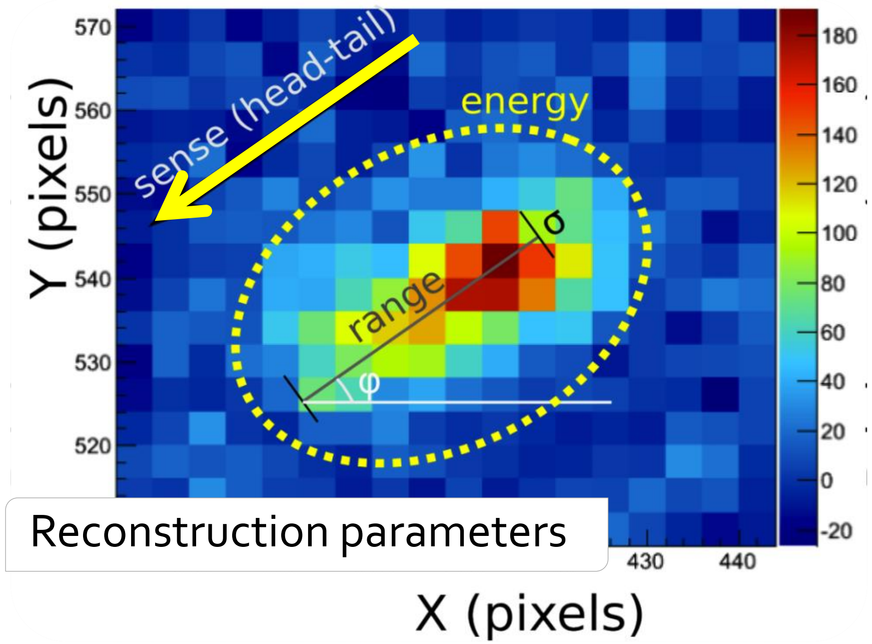




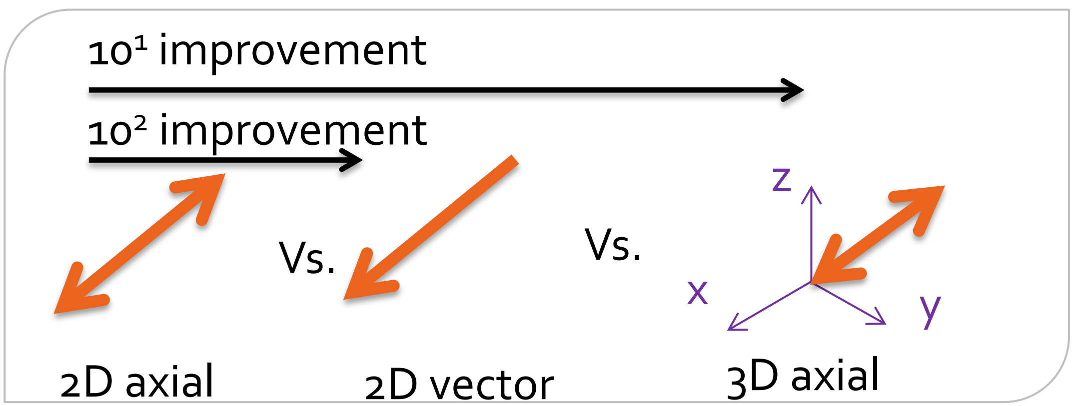
Full detector description[2]: arXiv:0810.2769v1

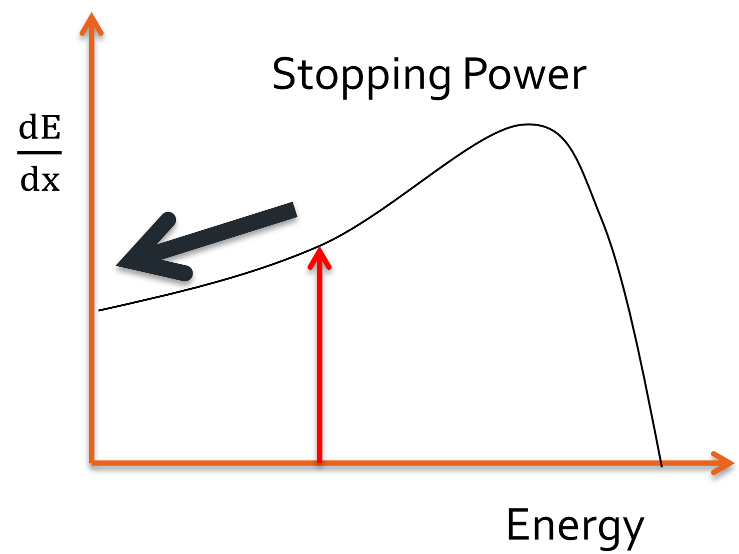
Readout Channels: CCD

- Used for energy, range and directionality.
- Energy: integral of track pixels.
- Range: maximally separated pixels.
- Sense: energy loss - most ionising at track start.
- 2D vector more important than full 3D axial reconstruction.
- Two orders of magnitude improvement over 2D axial vs. one order for 3D axial (N events required).
- 10-100 events [3] sufficient to deduce anisotropic distribution – detector dependent.



Reconstruction parameters

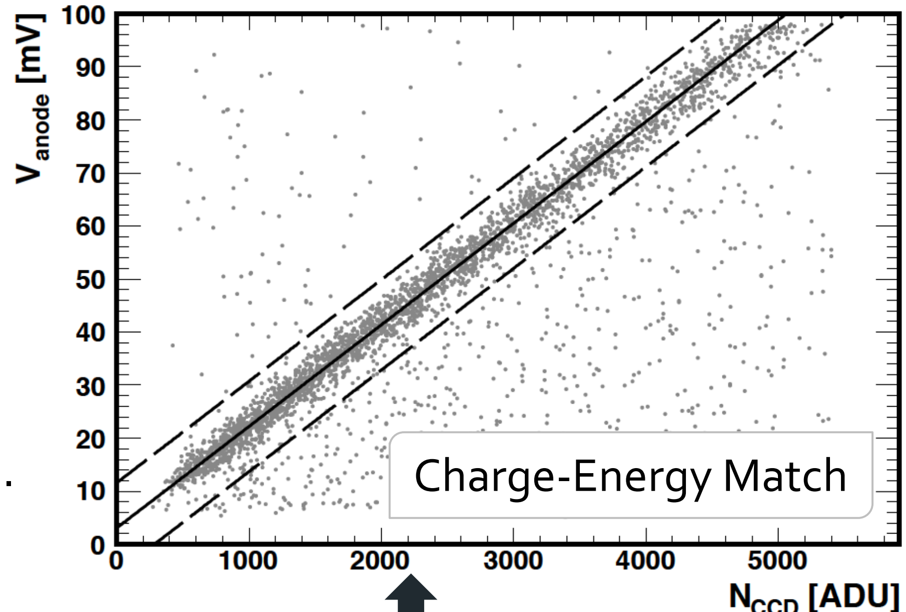


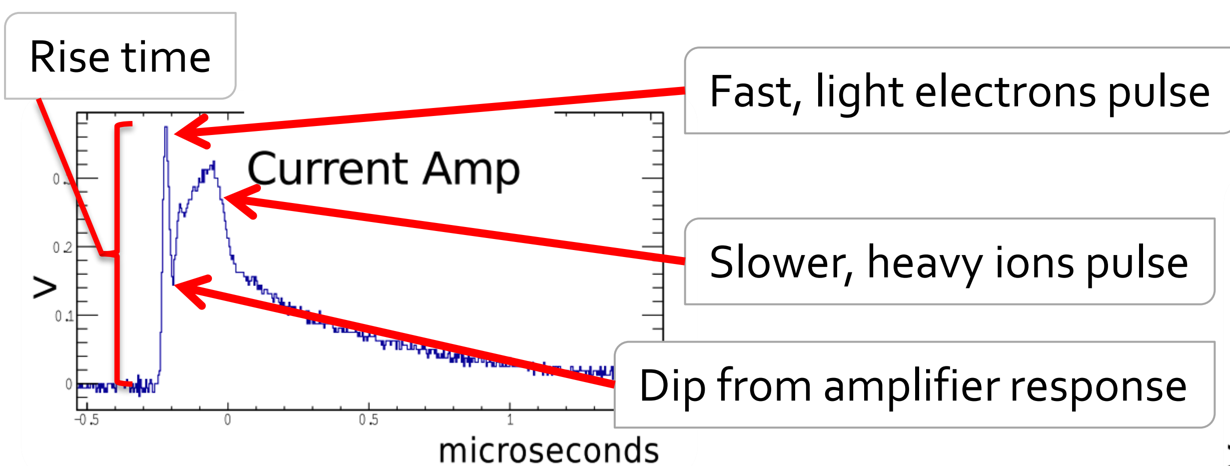


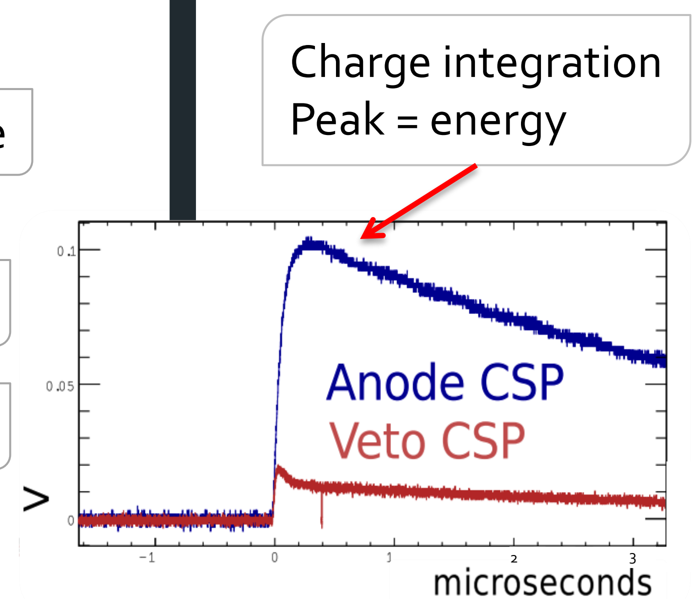
[3] arXiv:astro-ph/0508134

Readout Channels: Charge

- Two charge readouts: charge sensitive integration and current pulse.
- Used for energy measurement, background rejection.
- Nuclear recoils have distinguishable electron and positive ion peaks.
- Electron recoils have a merged peak structure.
- Electron peak rise time can give ΔZ.



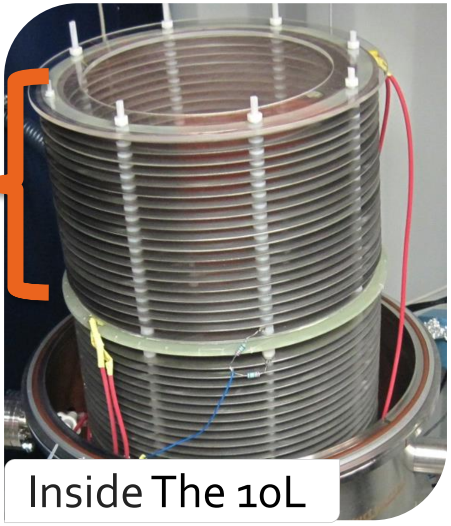




Detectors: Prototypes

- DMTPC are currently in the research and development stage.
- Two prototype detectors have been operated.
- Focus is on direction reconstruction.
- Working towards replicable $1m^3$ module.

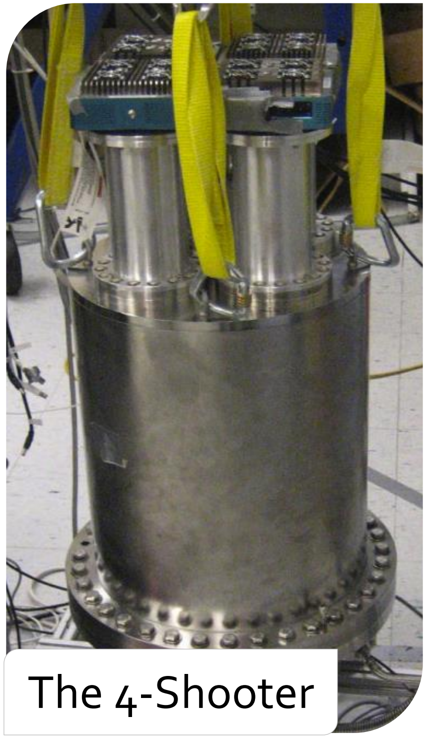
Time projection chamber (TPC)



Inside The 10L

The 10L

- Two back-to-back TPCs.
- Two cameras.
- 10L fiducial volume.
- Surface run performed and published[3].
- Is deployed underground.



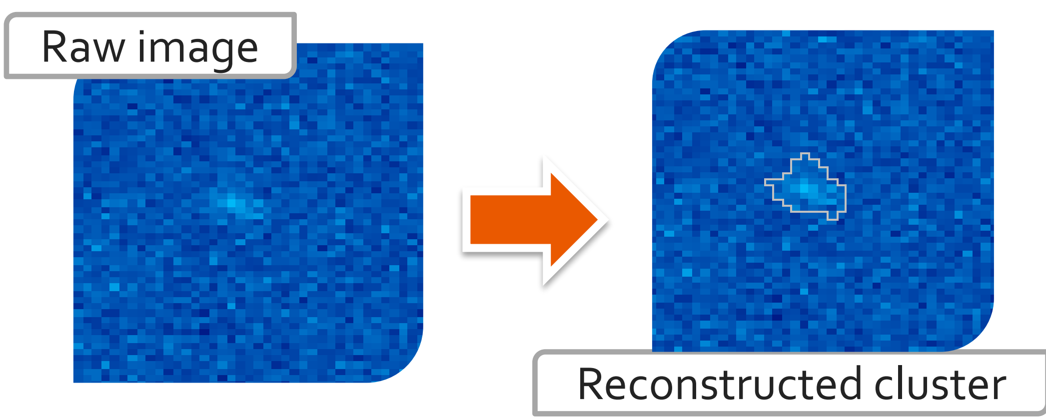
The 4-Shooter

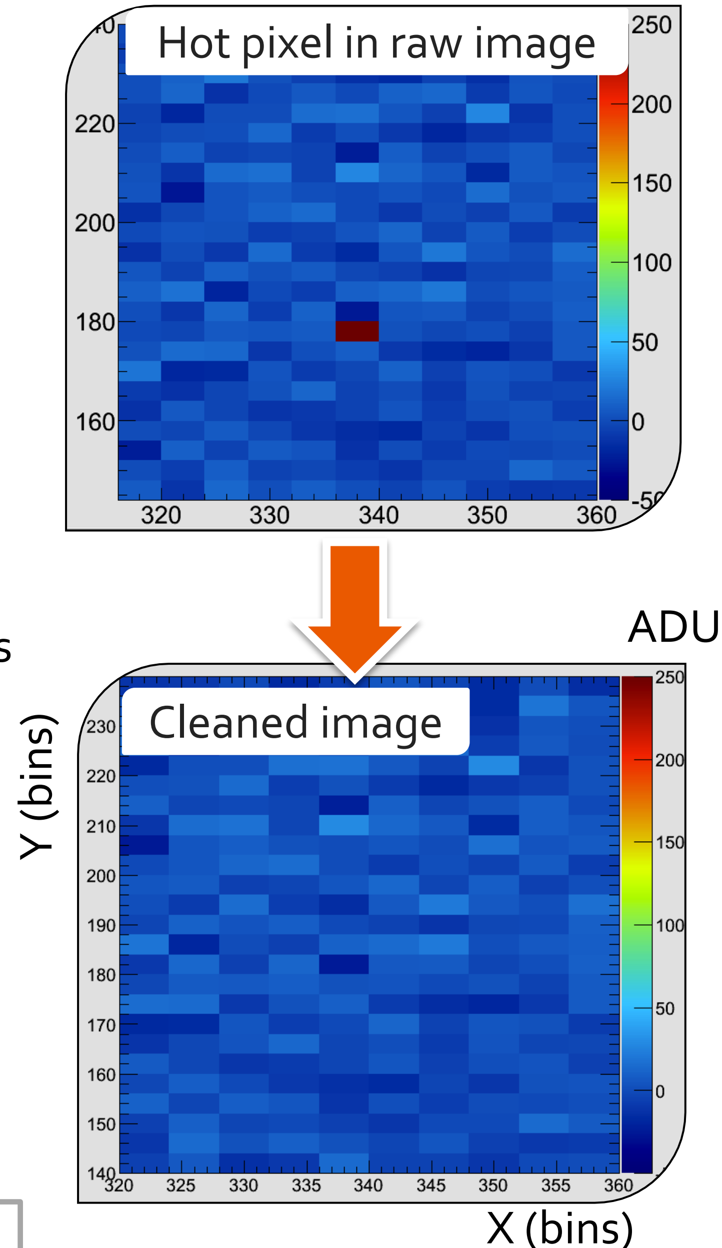
- One TPC.
- Four cameras.
- 20L fiducial volume.
- Being studied at the surface to improve readout and reconstruction capabilities.
- Angled alpha study for directional reconstruction study[4].
- Charge readout study for background rejection study[5].

[3]arXiv:1006.2928v3, [4] 4Shooter calibration preprint , [5] Nucl.Instr.Meth. A696 (2012), 121-128

Analysis Procedure

- Image processing: cleaning and cluster finding
- Calibration:
  - CCD - arbitrary digital units (ADU) to keV using source of known energy (^{241}Am: alpha ~4.5 MeV, ^{55}FE) (system gain: ~10 ADU/keV).
  - CCD - pixels to mm using amplification region spacers at known separation (1 pixel ~ 150µm).
  - 1.2mm length track equivalent to ~8 pixels
  - Charge - Volts to ADU, using source ($^{252}C_F$ - neutron).
- Cuts:
  - Configure known-background rejection methods for optimal performance.
  - Shutter-closed images (cosmic data) mixed with MC tracks to represent background.

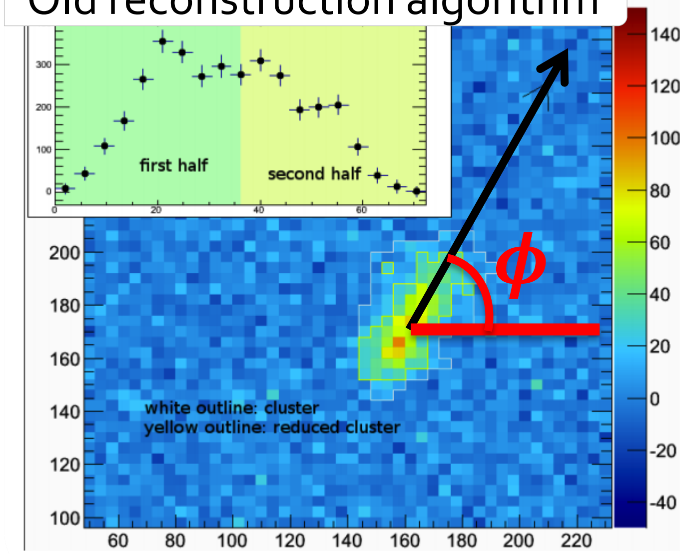




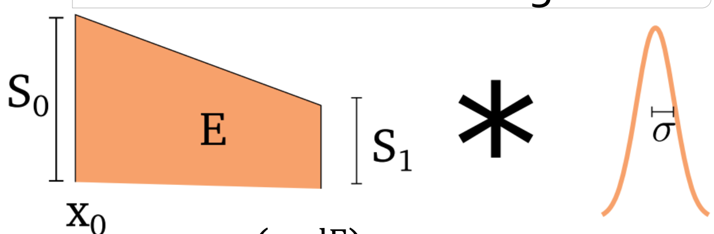
Directional Reconstruction

- Signed angle from CCD pixels using Principal Component Analysis.
- For direction (head-tail):
- Previously: moment of inertia of the track.
- Now: 2D fit to track image – convolve linear $\frac{dE}{dx}$ model with Gaussian diffusion.
- Direction given by sign of $\delta S = S_0 - S_1$ in fit.

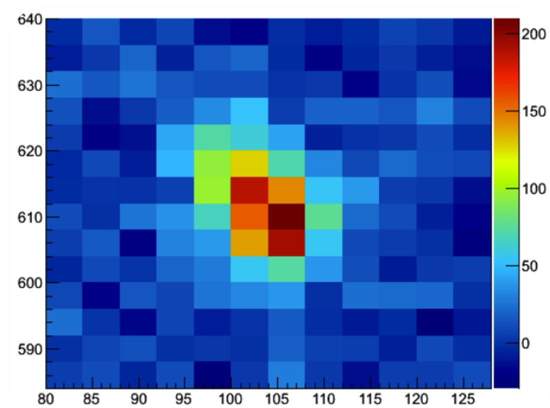
Old reconstruction algorithm

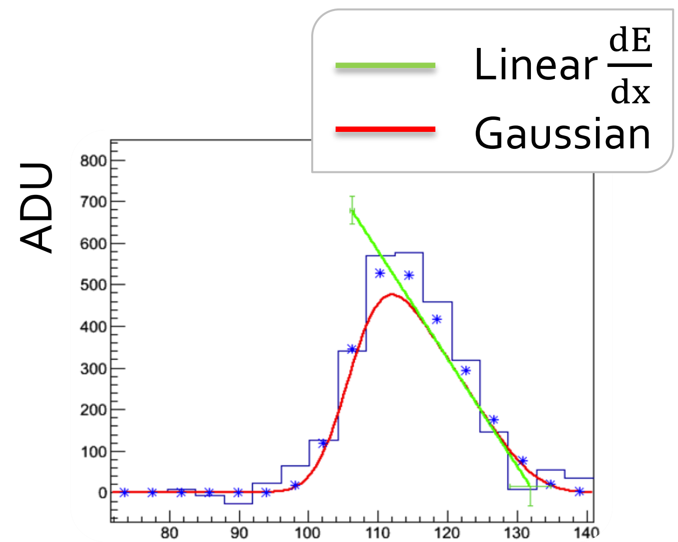


New reconstruction algorithm



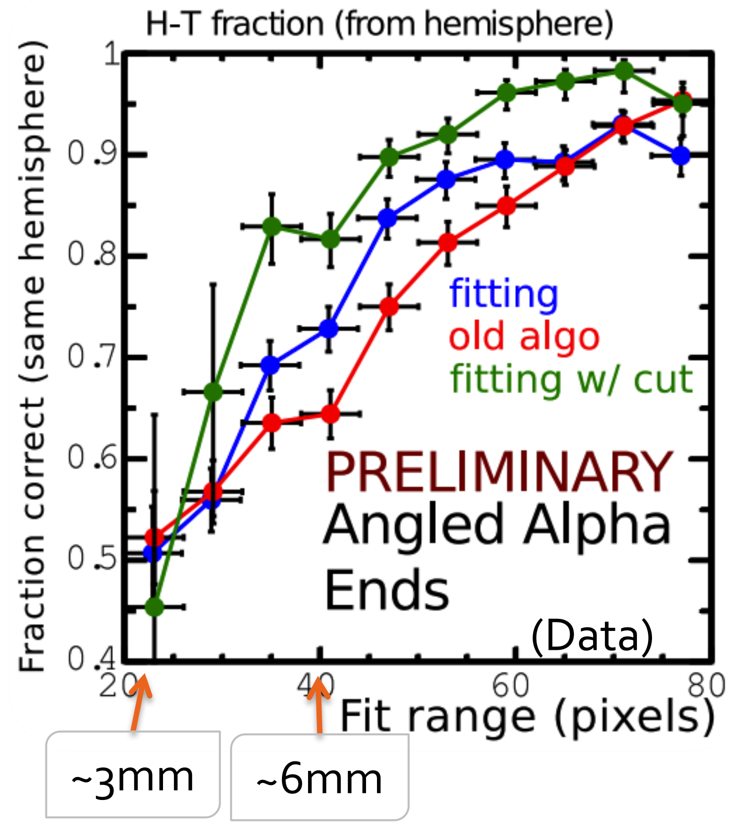
$S =$ stopping power $\left(-\frac{dE}{dx}\right)$



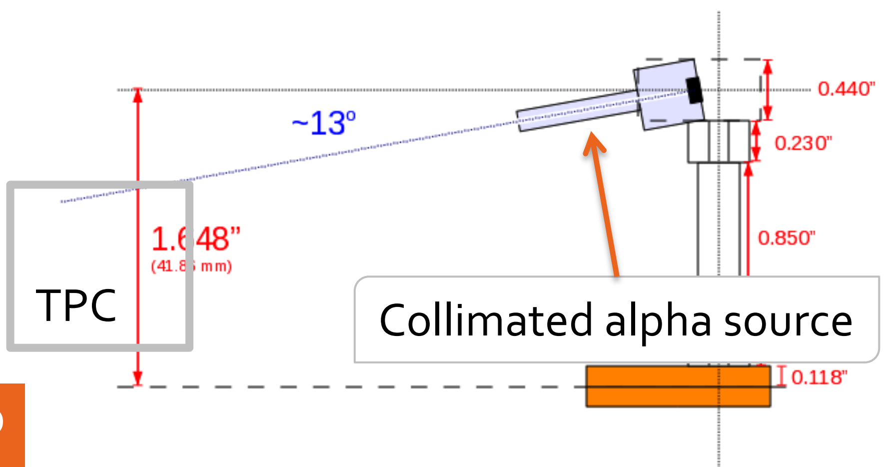


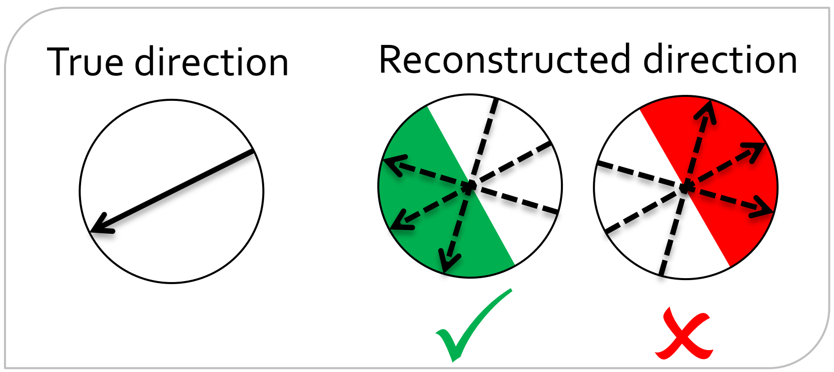
Directional Reconstruction

- Calibrate fit with end of alpha tracks.
- Mimics nuclear recoil of ~100 keV.
- True direction is known.
- Fraction correct defined by hemisphere reconstruction.
- Range drives ability to reconstruct.
- New algorithm greatly improves fraction correctly reconstructed.
- Require range/width > 3.



Energy range equivalent: ~50-200 keV

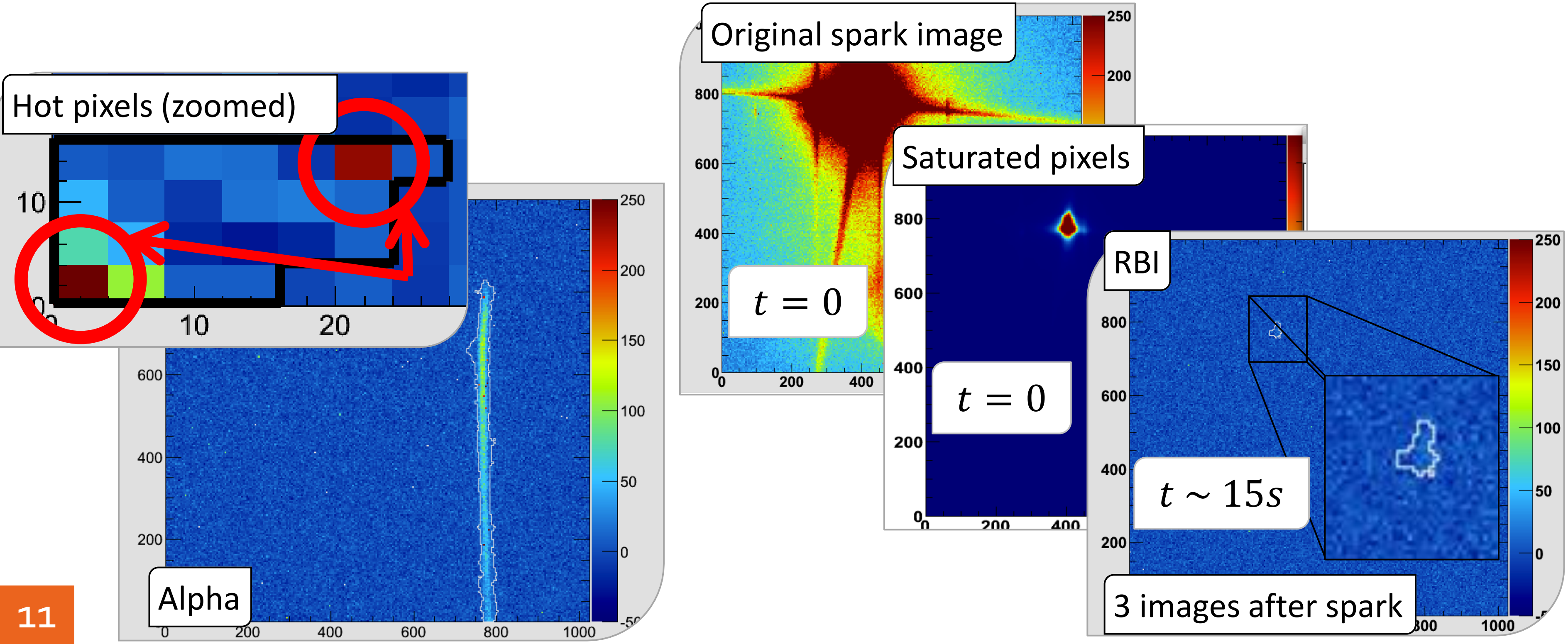




Known Backgrounds

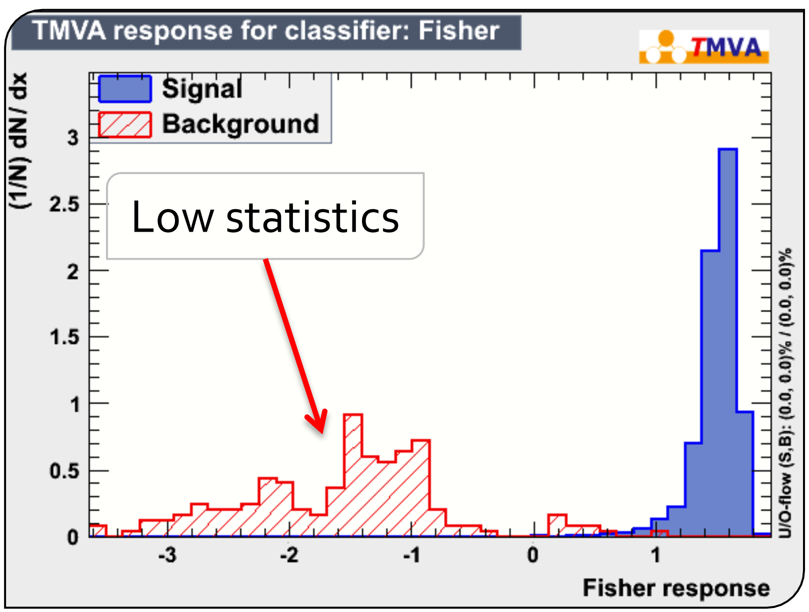
There are two main types of backgrounds that are currently observed:

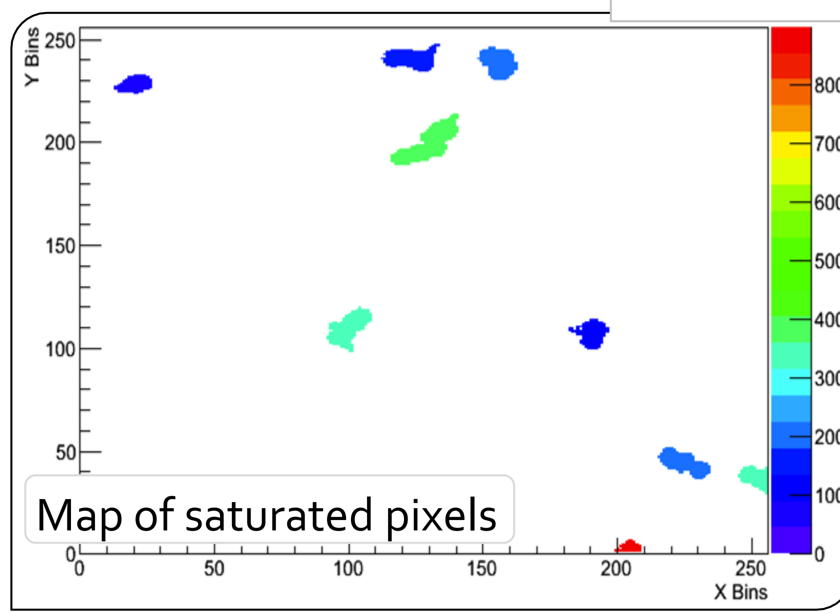
- Instrumental Noise:
  - Hot pixels, pixel noise fluctuations, cosmic ray interactions in the CCD and residual bulk images (RBIs) – caused by trapped charge in the CCD substrate. These are collectively known as 'worms'.
- Physical:
  - Neutrons, Alphas (full and mis-reconstructed tracks), Radon progeny recoils, sparks in the amplification plane (sparks are a cause of RBIs and cause a drop in gain).



Background Rejection

- Instrumental noise:
  - Charge-light energy match: ensure CCD tracks have a charge pulse with similar energy.
  - Worm cut: multivariate analysis using track parameters including range and energy. Trained using ‘cosmic’ data (background) and MC neutron recoils with expected WIMP energy spectrum (signal).
  - RBI cut: remove tracks that overlap with a spark location.
- Physical backgrounds:
  - Cut on tracks longer than 5mms to remove long alpha tracks.
  - Reject a number of images following a spark to account for drop in gain.
  - Cut tracks at image edge to remove events external to TPC





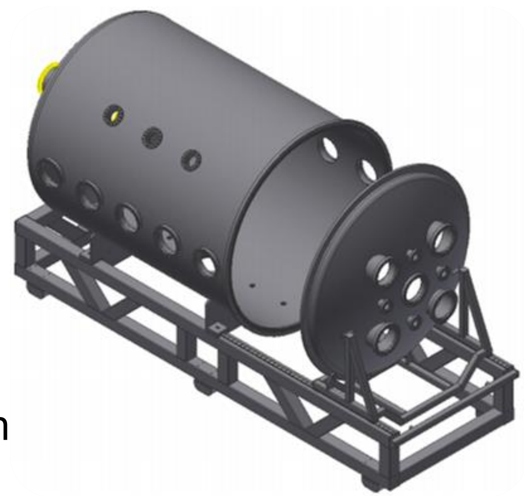
Detectors: 1m³

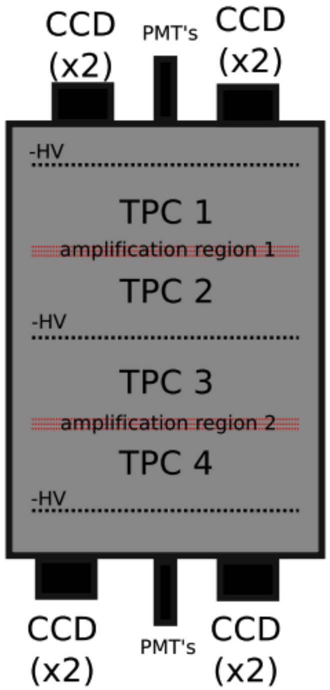
Goals:

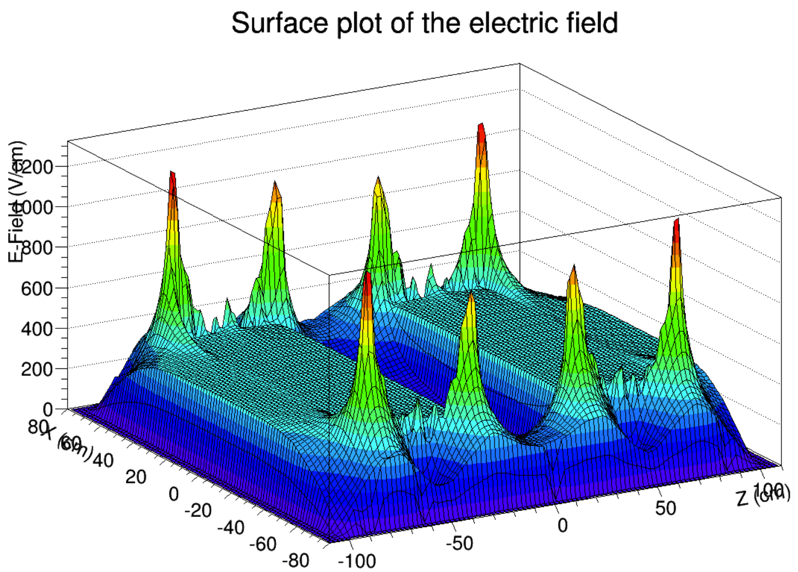
- Full 1m³ fiducial volume.
- Lower pressure operation.
- Directional reconstruction down to ~50 keV.
- Reduced background from detector materials.
- Improved rejection of remaining backgrounds.
- Combine knowledge gained from prototypes.

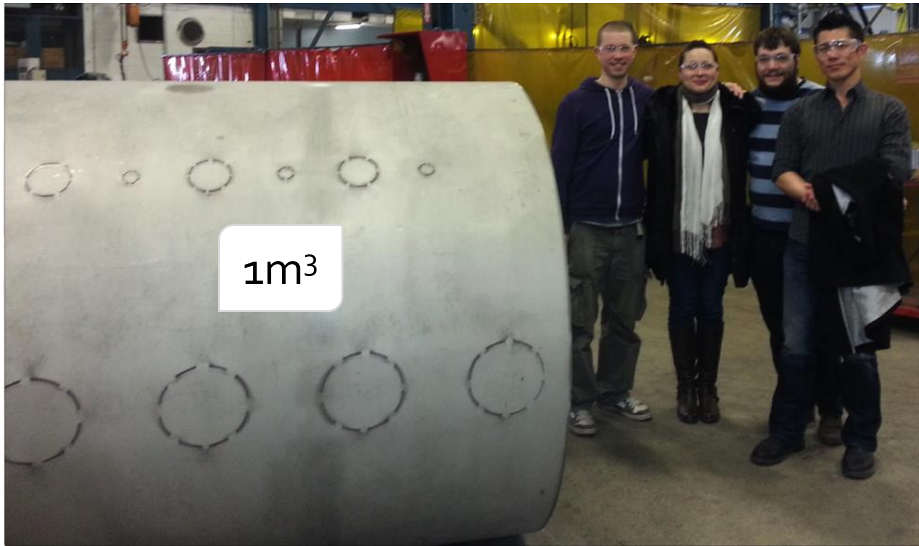
Field Cage:

- Minimise material surface area to reduce radon
- Maintain field uniformity.
- Field simulations guiding material vs. field uniformity









Summary

- DMTPC is a directional, direct-detection experiment.
- Directionality a good indicator of a dark matter signal.
- Method of detecting and reconstructing a directional signal.
- Known backgrounds and rejection methods.
- $1m^3$ progress.

The DMTPC Collaboration

Outlook

- $1m^3$ commissioning data this Summer.
- Aim to deploy $1m^3$ to WIPP, New Mexico in 2015

Underground at WIPP

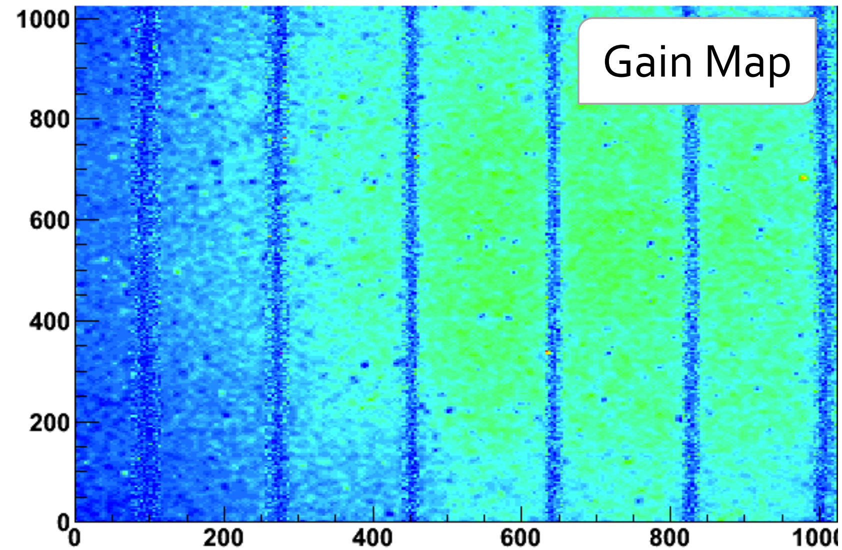
The End

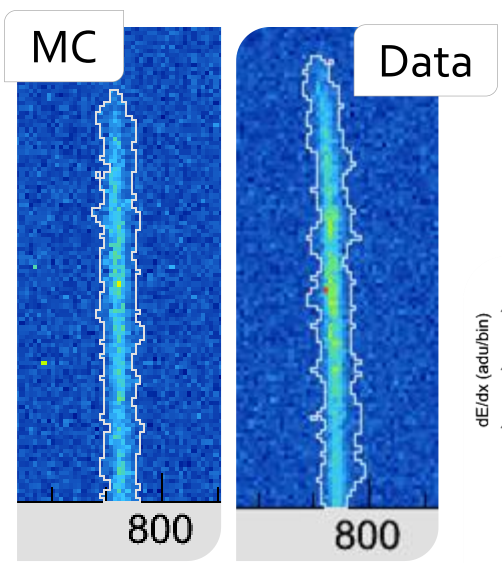
References:
[1] arXiv:1212.5226v3, [2] arXiv:0810.2769v1, [3] arXiv:astro-ph/0508134, [4]arXiv:1006.2928v3, [5] 4Shooter calibration preprint, [6] Nucl.Instr.Meth. A696 (2012), 121-128

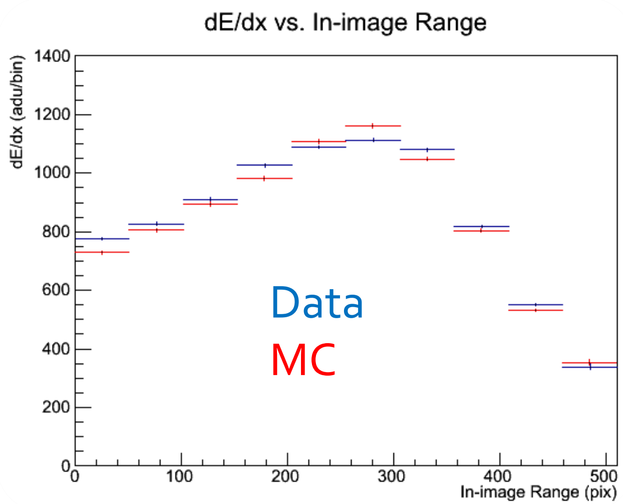
Backup Slides

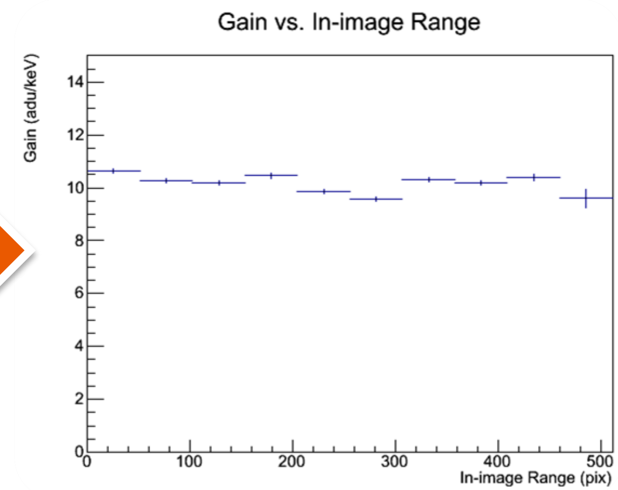
Calibration: CCD Energy

- Data is taken with an alpha source of known energy (~4.5 MeV).
- This is compared with Monte Carlo (MC) generated tracks, based on SRIM calculations.
- Plot dE/dx vs. dx for each and take the ratio.
- Multiply this by the MC gain and take average.
- Produce gain map with ^{57}Co for gain variations.



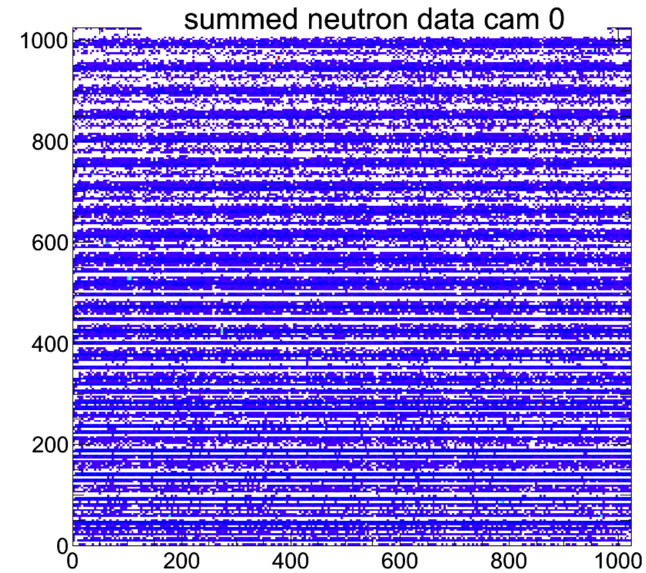




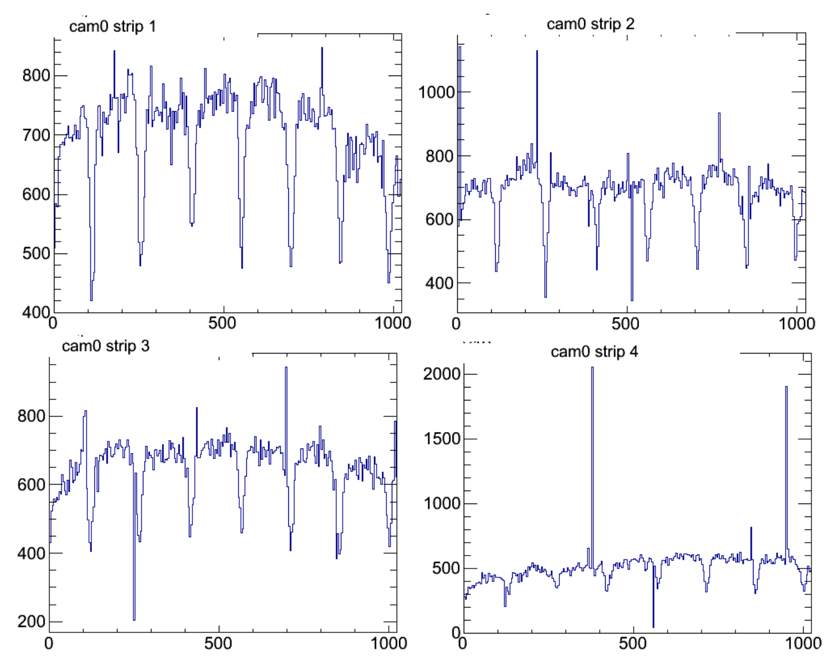


Calibration: CCD Range

- Dielectric wire is used to separate anode and ground mesh in the amplification region (spacers).
- These are at a known separation of one inch.
- Neutron ($^{252}C_F$) or gamma ($^{137}C_s$ & $^{57}C_o$) source generates isotropic distribution of events.
- Less scintillation light is detected from over-spacer regions.
- Multiple images are summed to highlight spacers.

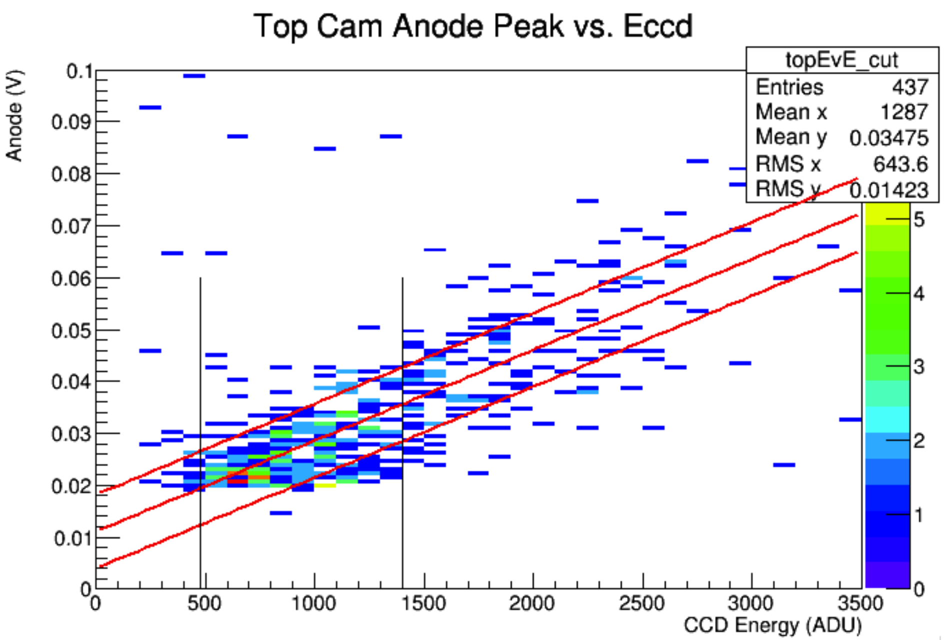


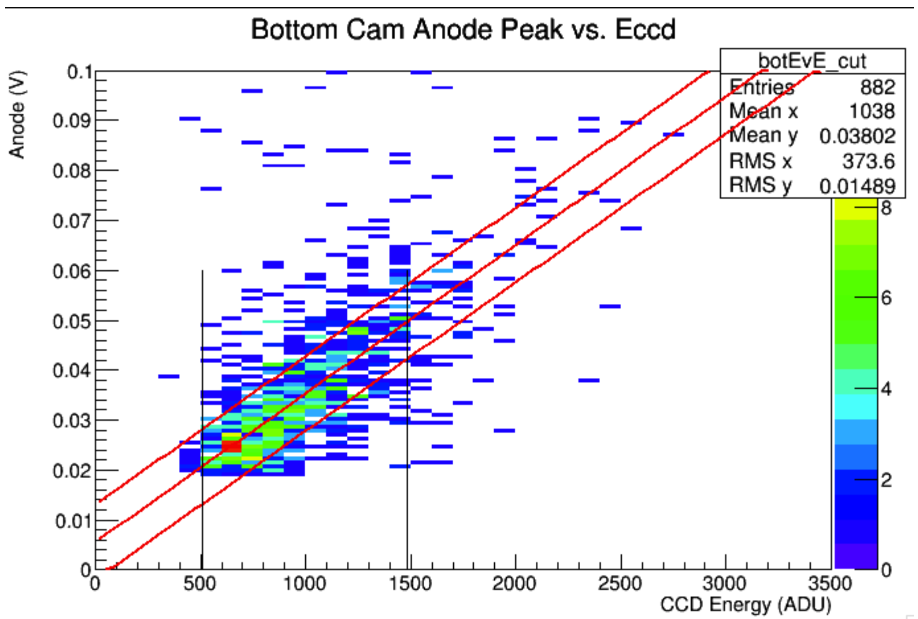
- X-projection is taken at four equidistant points.
- Low points are chosen and plotted
- A fit is applied and the parallel separation calculated.
- For 50keV track expect approximately 1.2mm length track, equivalent to ~8 pixels



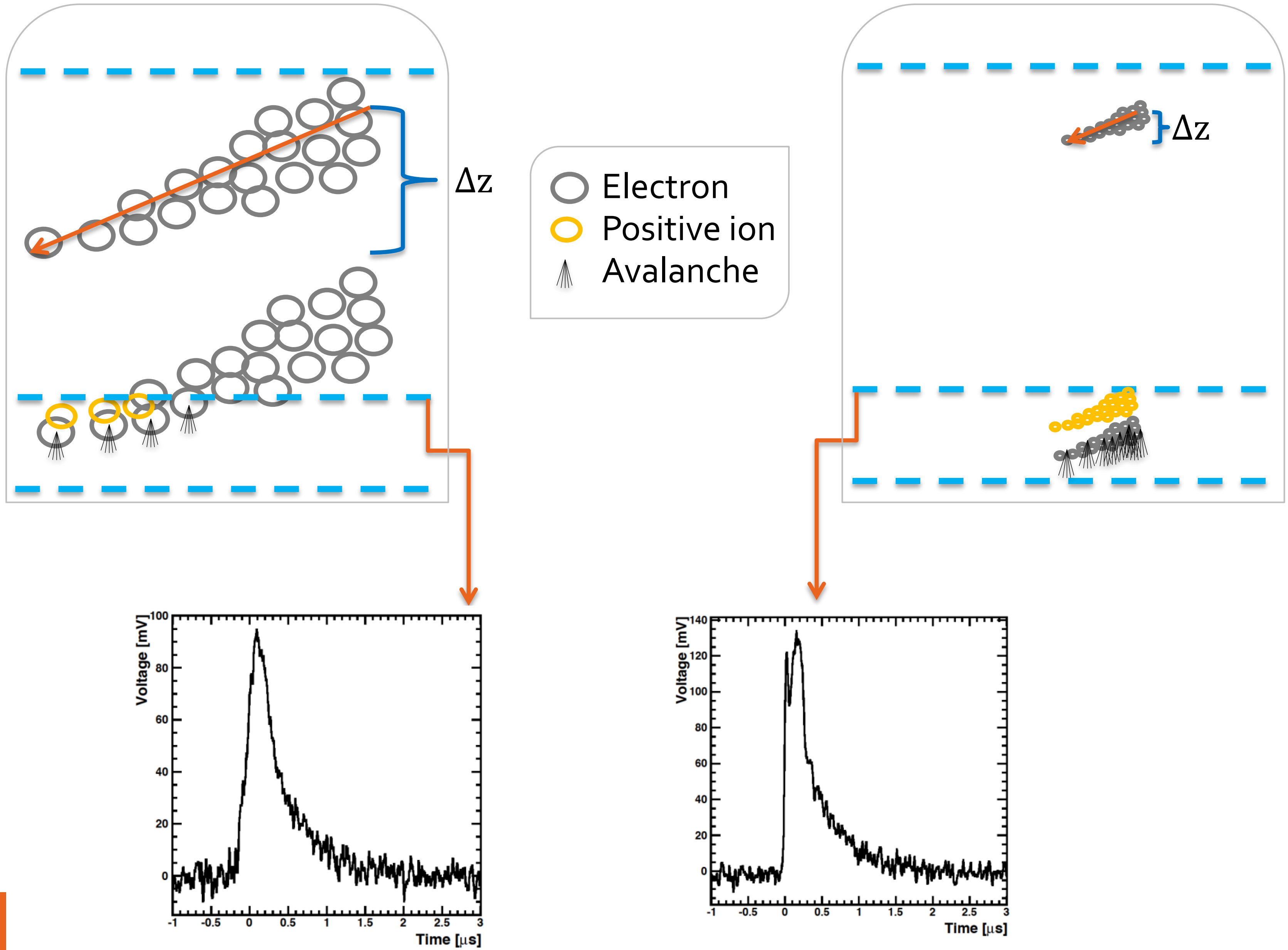
Calibration: Charge Energy

- Neutron calibration data is passed through a subset of recoil selection cuts.
- Additional cuts are applied to remove outliers from the main population, for a cleaner sample.
- A linear fit is applied.
- The one sigma bands of this fit are used to check for an energy-matching pulse.
- This corresponds to approximately ±10% of the ECCD.



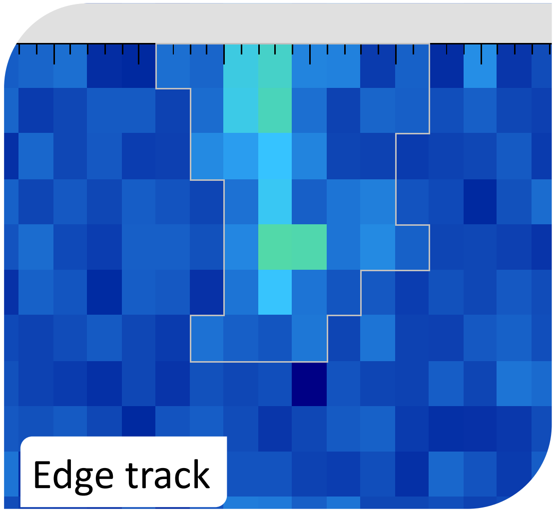


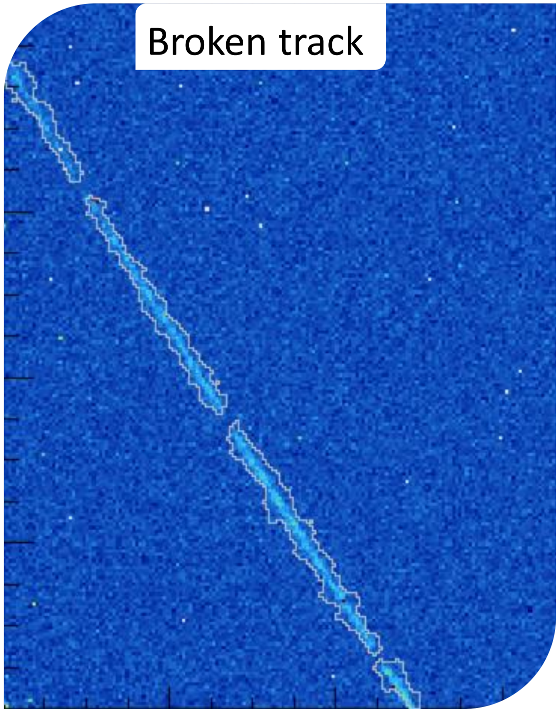
Charge Pulse Signal

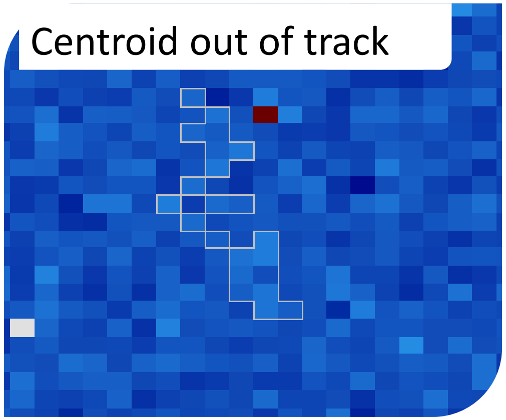


Partial Event Rejection

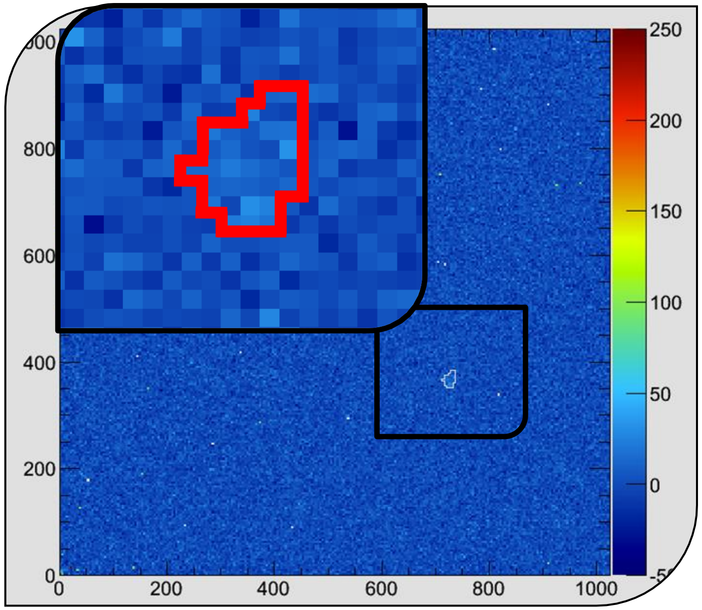
- Tracks near the edge of the image and near the spacers are rejected due to the possibility of poorly reconstructing the energy of the track.
- The spacers can cause tracks to be broken, resulting in multiple effective tracks being reconstructed. A check on the co-linear alignment of close-lying tracks is done to see if they should be considered as one.
- The centroid of the track is checked to ensure it lies within the track itself.

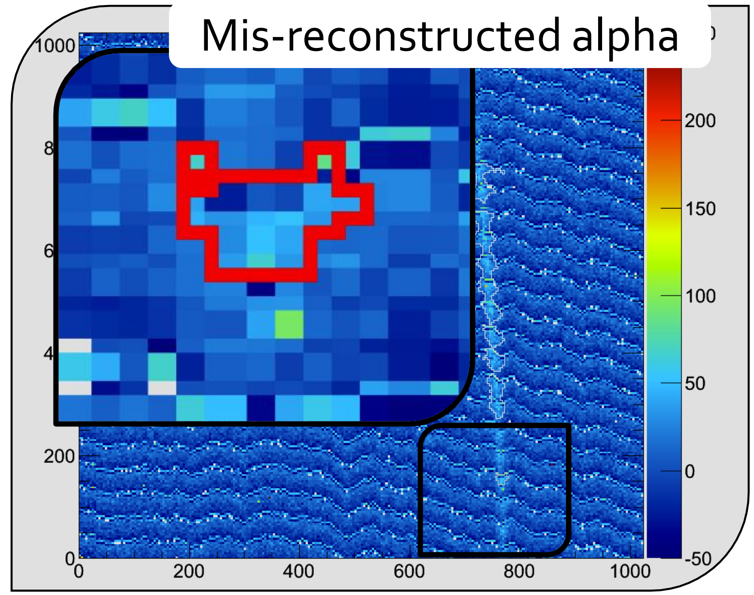


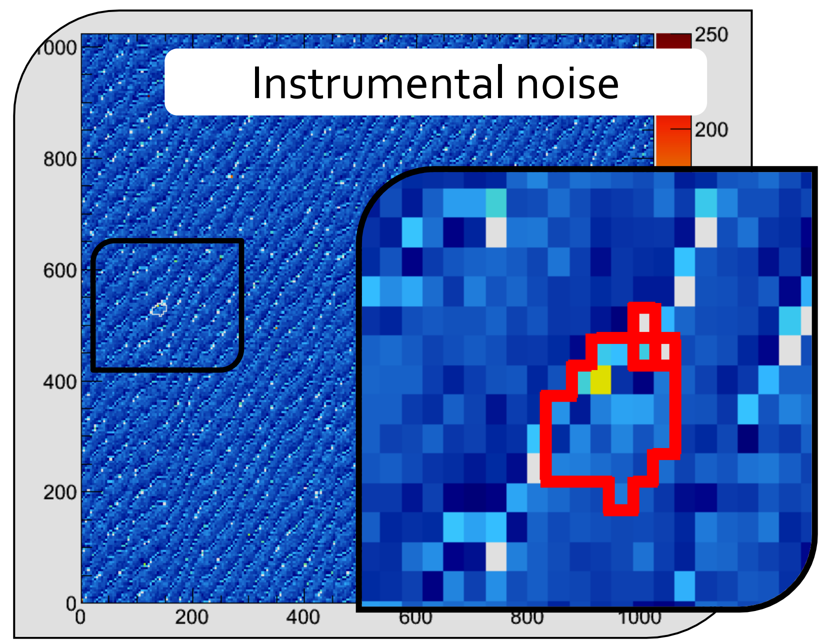




Passing Events



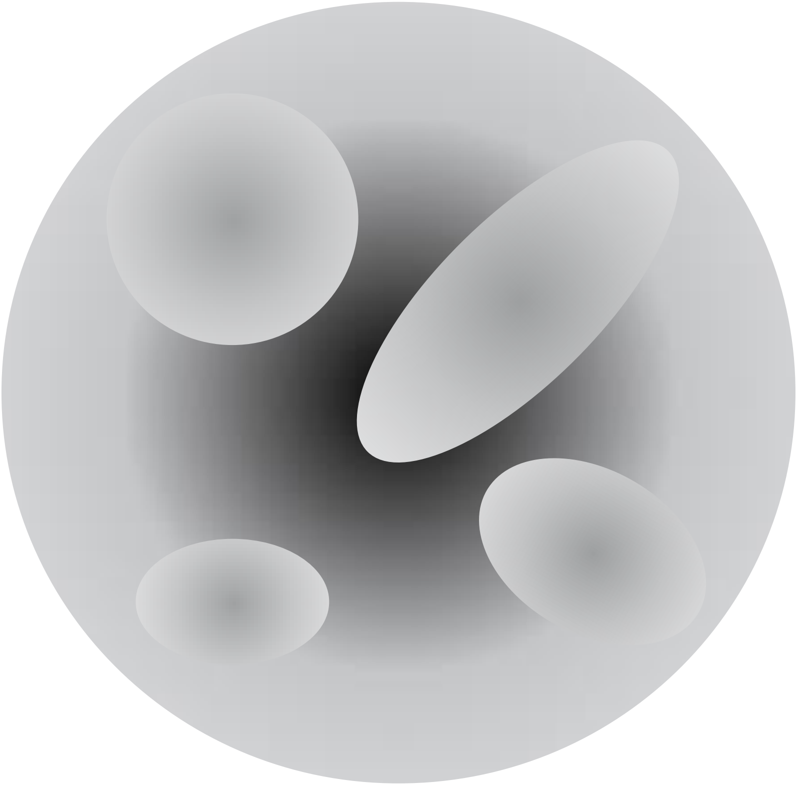


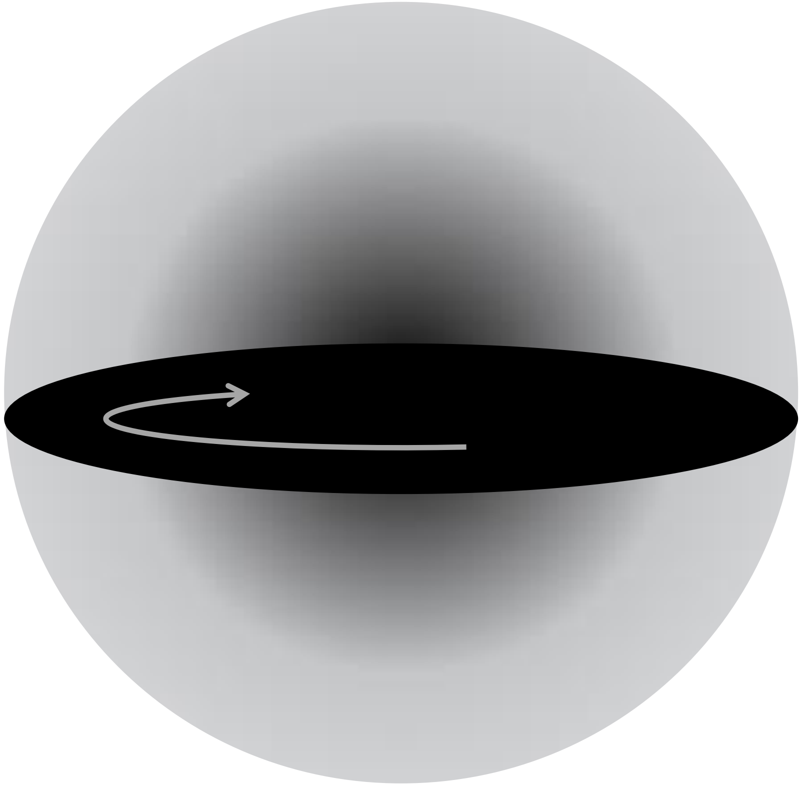


- In the passing events there are clearly some tracks that can be candidate nuclear recoils.
- There are those, however, that are clearly due to noise.
- The bottom camera developed a distinct noise pattern during the run which is the cause of several events.
- ~20% rejection can be done by eye
- These results will guide the future work on rejection algorithms.

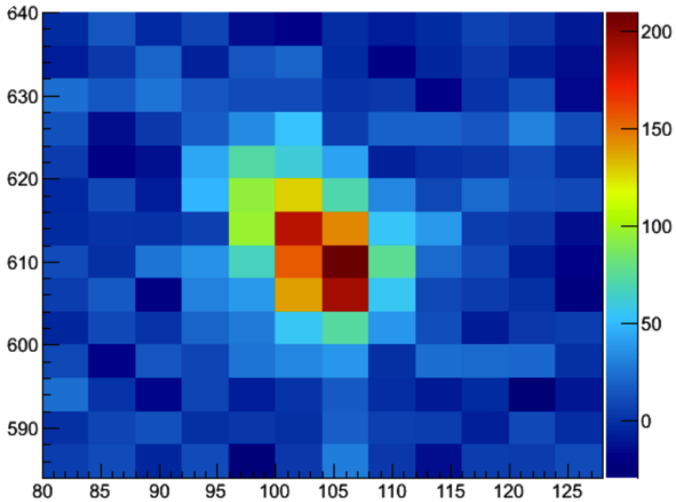
Halo Models

- The Standard Halo Model (SHM) is a simplified model of the dark matter distribution.
- Good as a first approximation but unlikely to be realistic.
- Other models include spatial and velocity non-uniformities.
- Non-uniformities can impact signal modulations.
- Dark-disk is another possibility: a co-rotating component of dark matter.



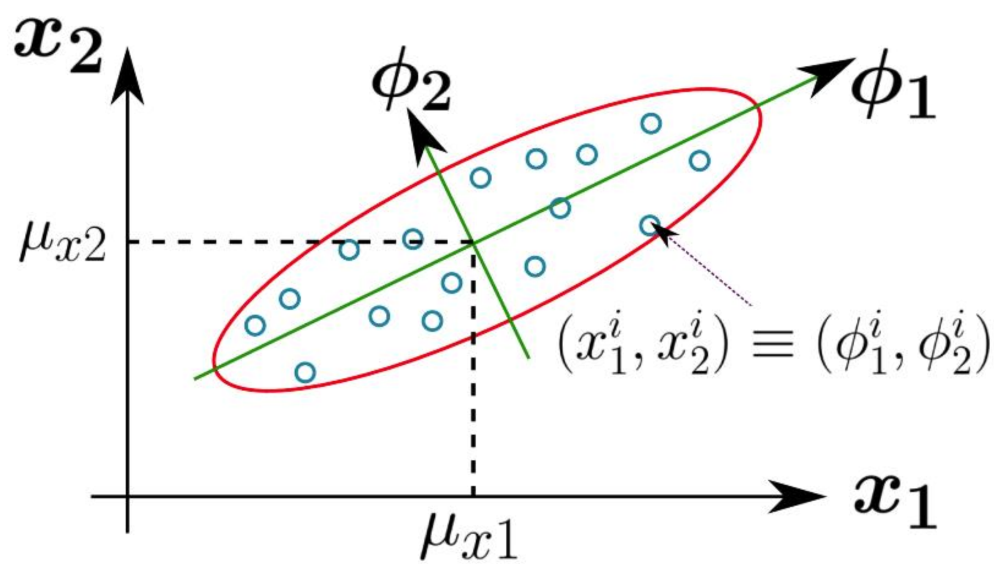


Principal Component Analysis



$$\begin{pmatrix} \text{Var}(y) & -\text{Cov}(xy) \\ -\text{Cov}(xy) & \text{Var}(x) \end{pmatrix}$$

Use eigenvectors of covariance matrix to deduce directionality.



http://www.doc.ic.ac.uk/~dfg/ProbabilisticInference/IDAPILecture15.pdf