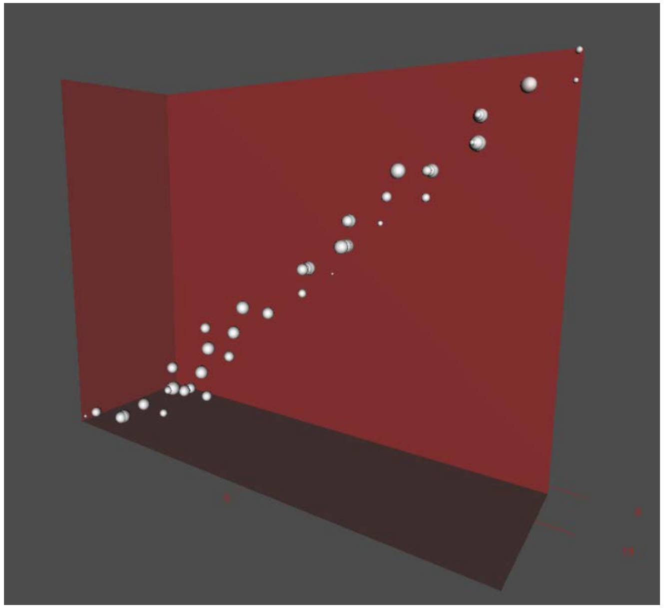
D^3 - The Directional Dark Matter Detector



Sven E. Vahsen, University of Hawaii

Contents

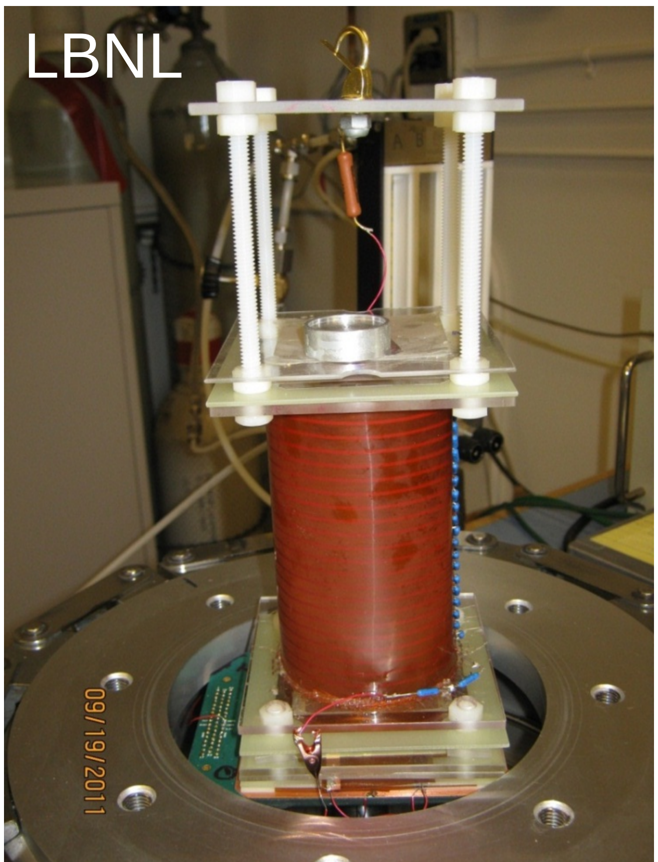
- Intro to D^3
  - technology & unique capabilities (w.r.t. other gas-target TPCs)
  - estimated DM sensitivity
  - experimental status, plans, challenges

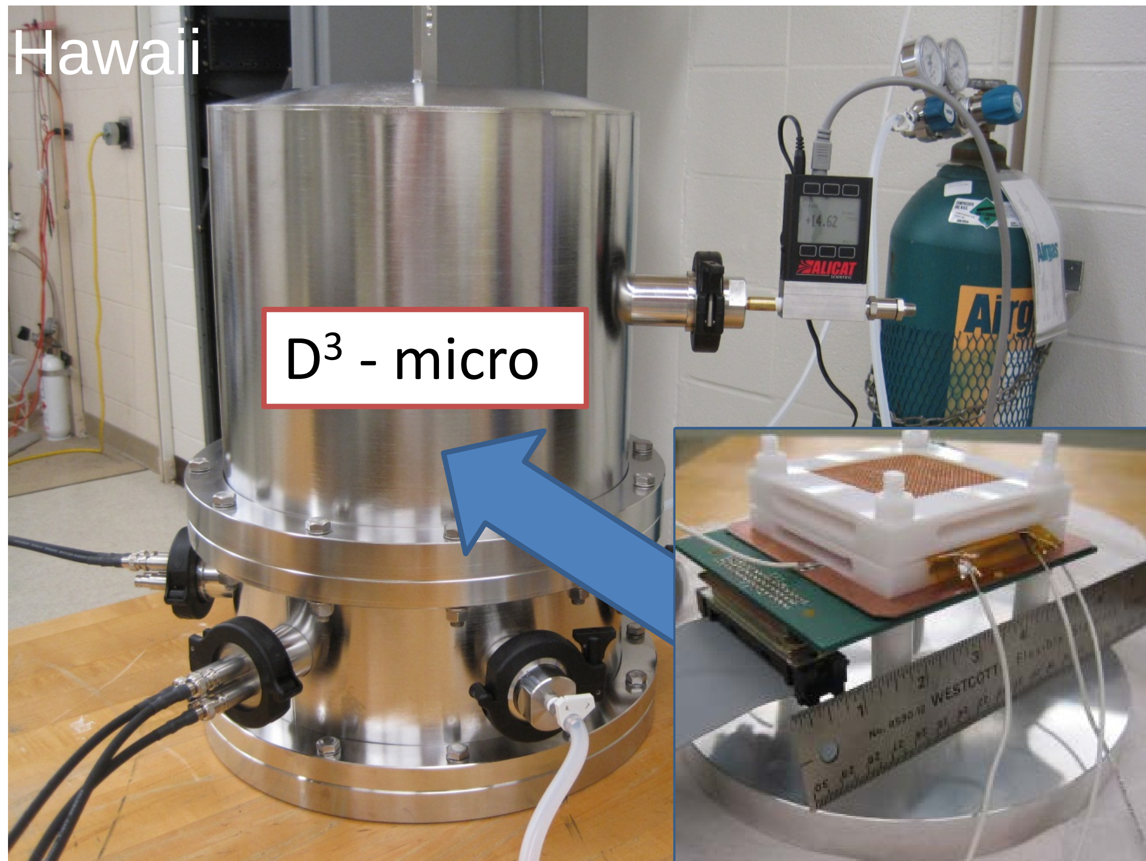
- Preliminary attempt at directly answering your questions…

- Disclaimer: Won't discuss general benefits of directionality
  - directional oscillation as smoking gun for DM
  - robust sensitivity to DM in presence of BG
  - identification of recoiling nucleus
  - measurements of WIMP velocity distribution.

D^3 - Directional Dark Matter Detector

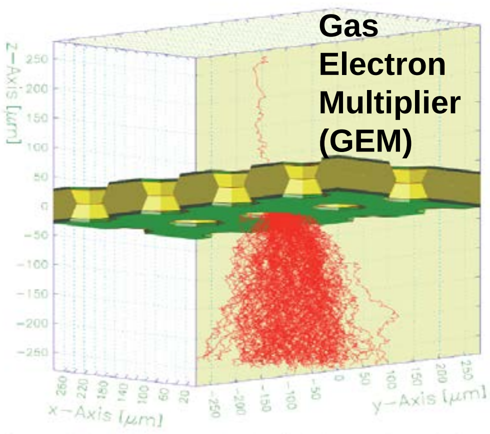
- Hawaii / LBNL collaboration (S. Vahsen / J. Kadyk, M. Garcia-Sciveres)
- Gas TPCs - drift charge read out w/ GEMs & ATLAS pixel electronics
- Small (1-10 cm^3) prototypes built to investigate feasibility of direction-sensitive DM search with this type of detector.
- Ongoing since ~Fall 2010 – youngest gas-target DM TPC effort





D^3 Operating Principle

- Drift charge amplified with double layer of GEMS, detected with pixel electronics
- Gain ~20k, threshold ~2k e^-, noise ~ 100 e^-



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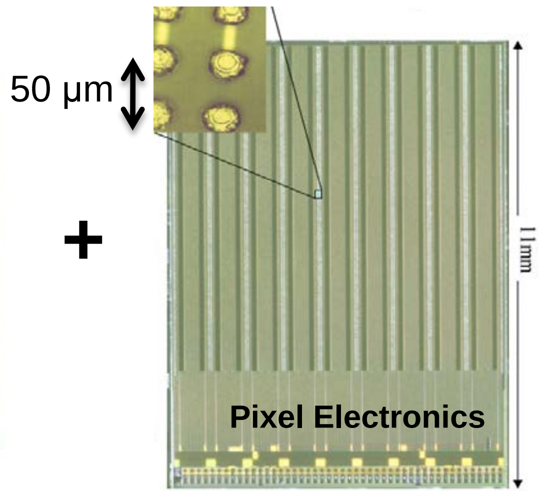
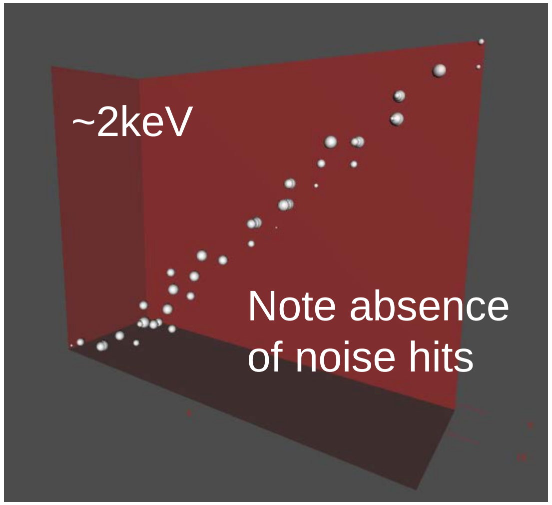


- ATLAS FE-I3
- 50x400 µm pixels
- Sampling at 40 Mhz

=

Cosmic ray track (~7mm) detected with Hawaii prototype



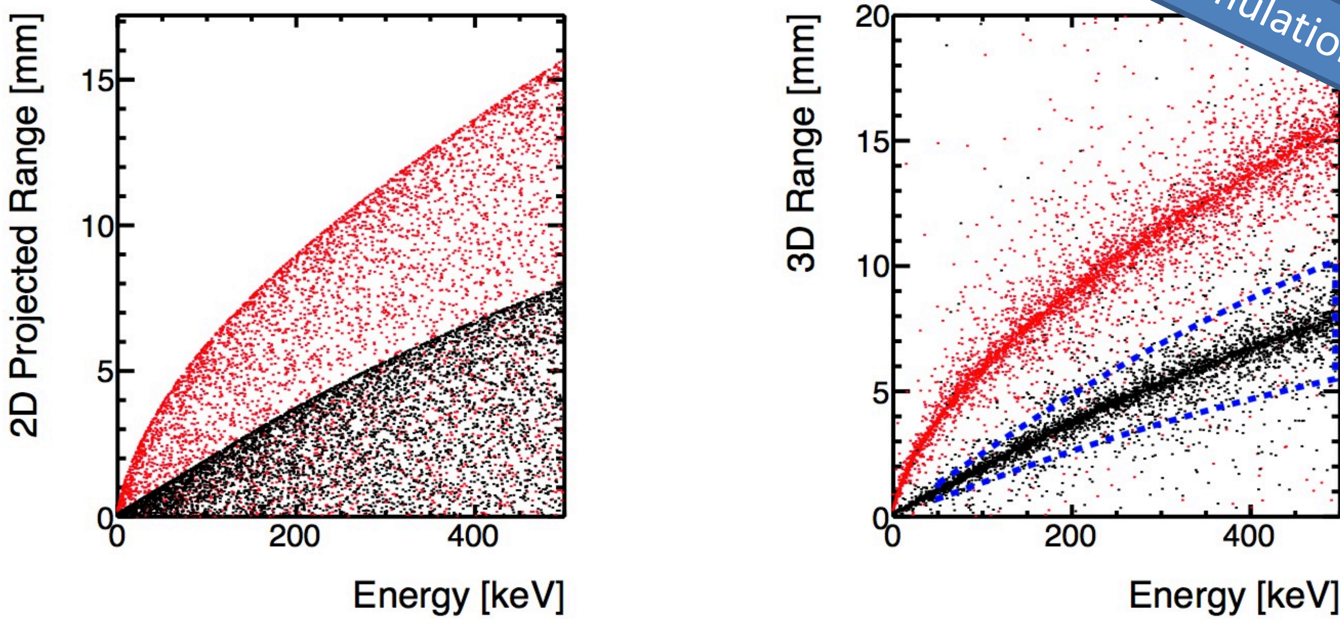
size of each bubble shows amount of ionization measured

Advantages of this approach

- Full 3D tracking w/ ionization measurement for each spacepoint
  → **improved directional sensitivity and rejection of alpha particle 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 → may be **suitable for (ultra?) low-mass** WIMP searches

Advantage of 3D Tracking

(simulation by James Battatt)

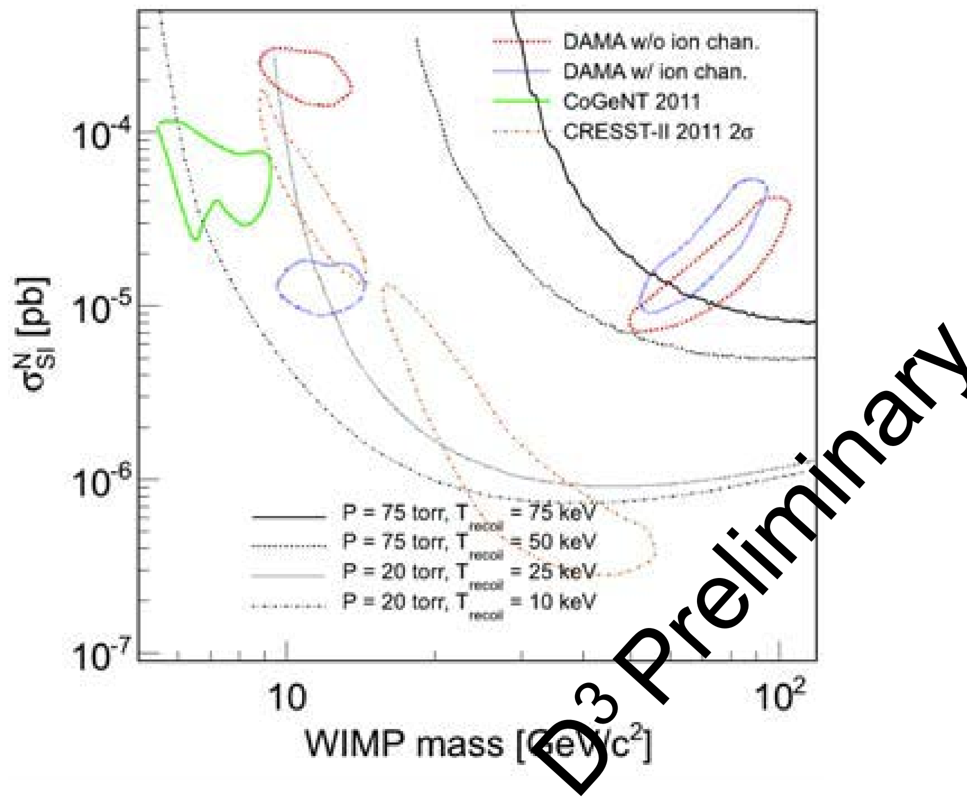


Simulation of the range vs. energy profiles for alpha particles (red) and fluorine recoils (black) in 75 Torr CF_4. *Left*: With only 2D range reconstruction, a degeneracy exists between steep-angle alphas and nuclear recoils of the same energy. *Right*: With 3D tracking, the alpha and fluorine recoil bands separate. In this simulation, the angular resolution was 5°. The blue dashed lines represent a cut above 50 keV that achieves a 10^2 alpha rejection with an 86% fluorine recoil acceptance.

Directional Sensitivity vs Track Energy Threshold

- Due to combination of high single-electron efficiency and low noise, expect low threshold operation, and good sensitivity to low-mass WIMPs
- Preliminary evaluation: relatively small detector could achieve *directional sensitivity* to ~7 GeV WIMPS as (controversially) suggested by DAMA/LIBRA, CoGeNT, and CRESST-II
- Non-directional sensitivity would be much better! (not shown in figure)
- Preliminary, needs further experimental input.

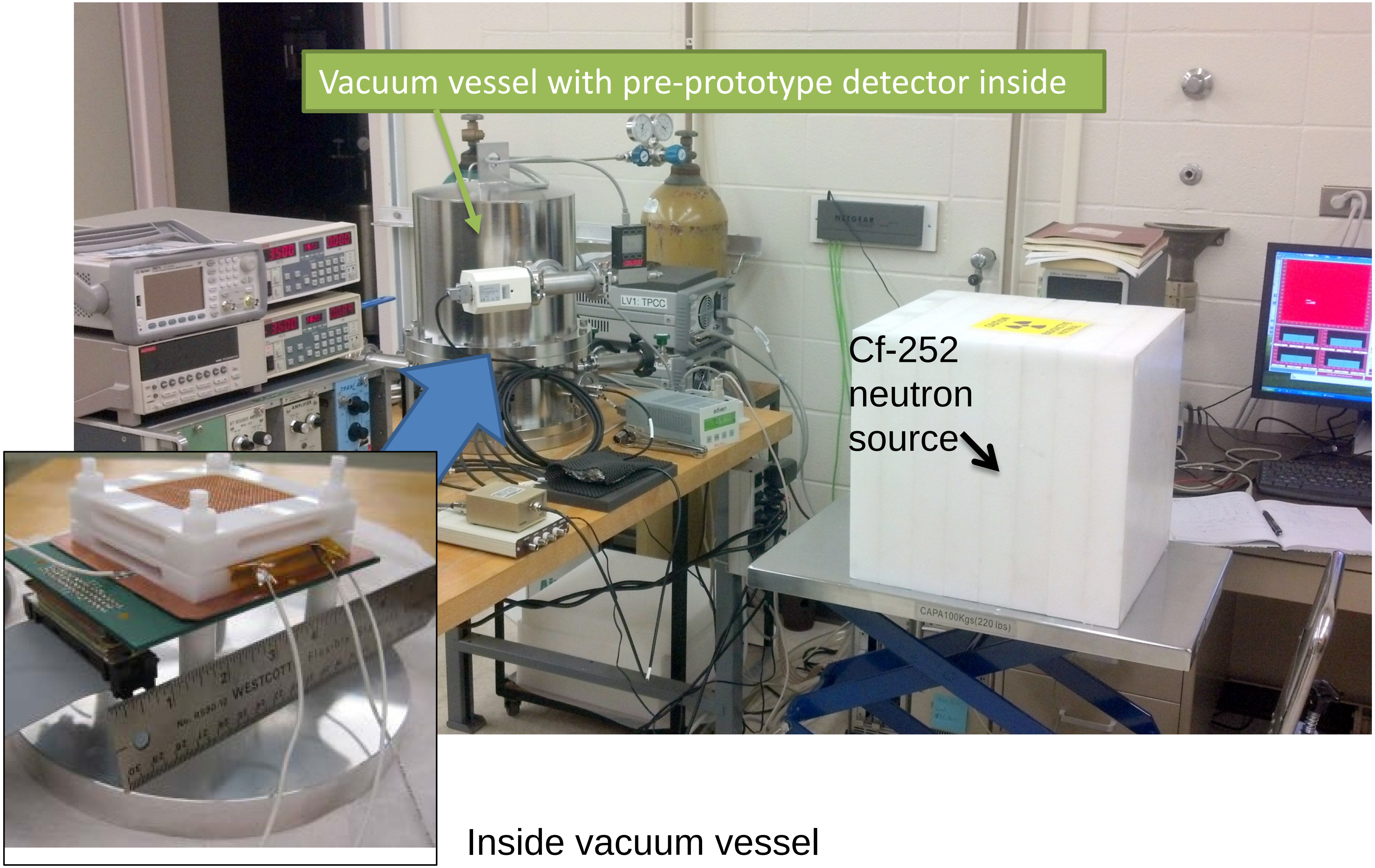
http://arxiv.org/abs/1110.3401



Estimated directional sensitivity to spin-independent WIMP-nucleon scattering for a 3-m^3 directional dark matter detector, running for 3 years with 33 cm drift length and CF_4 gas, for four different track reconstruction thresholds.

Current Prototype – D^3-milli

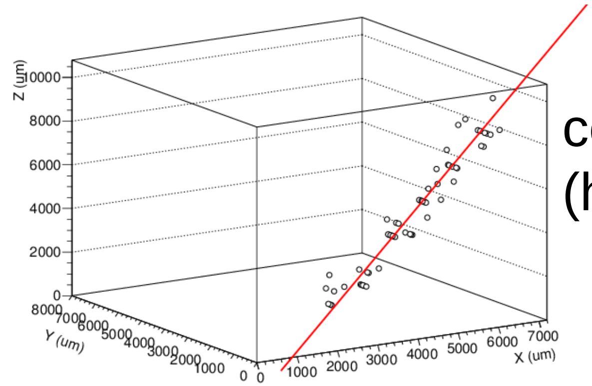
Tiny! - 1 cm^3



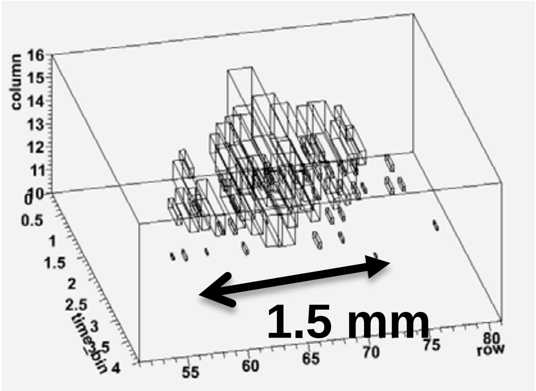
Inside vacuum vessel

Current Prototype Performance

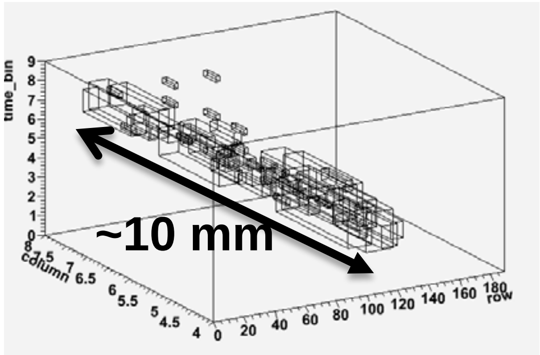
- Mostly excellent
  - Point resolution ~200 µm
  - Angular resolution ~ 1 degree for 5-10 mm tracks
  - Gain resolution ~5-10%
  - Gain stability <2%
- Problem: lower gain in some regions of detector, degrading energy resolution → under study, suspect due to pixel chip metal deposition



cosmic muon
(high gain mode)



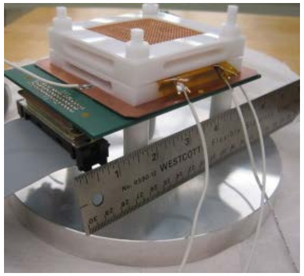
He-recoil
candidate
(low gain)



RPR event?
(low gain)

Critical Issues: How to Scale Up

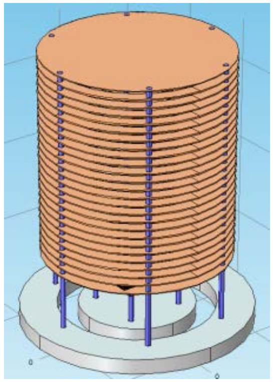
Built, stable operation for > 1 year



μD³ (1cm³)

1 pixel chip

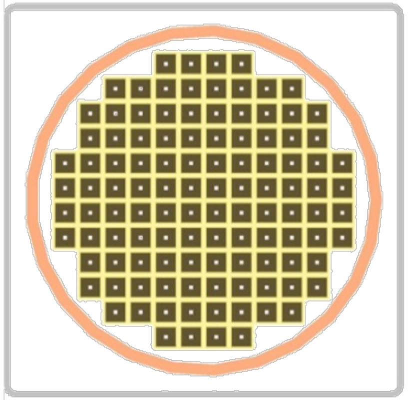
building this year



mD³ (~10 liters)

4 pixel chips

planned



D³ (~1m³)

~400 pixel chips

http://arxiv.org/abs/1110.3401

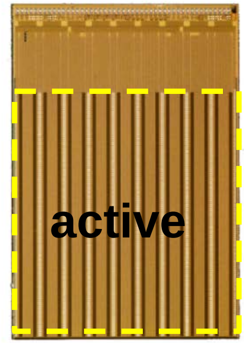
1. larger pixel chips → fewer chips required
2. electrostatic focusing of drift charge → fewer pixel chips still
3. existing ATLAS DAQ → greatly reduced development cost & time
4. negative ion drift → reduced diffusion → fewer readout planes required

effort has focused on 1 through 3 up to now – perhaps sufficient for m³–scale detectors w/ interesting physics reach at reasonable cost.

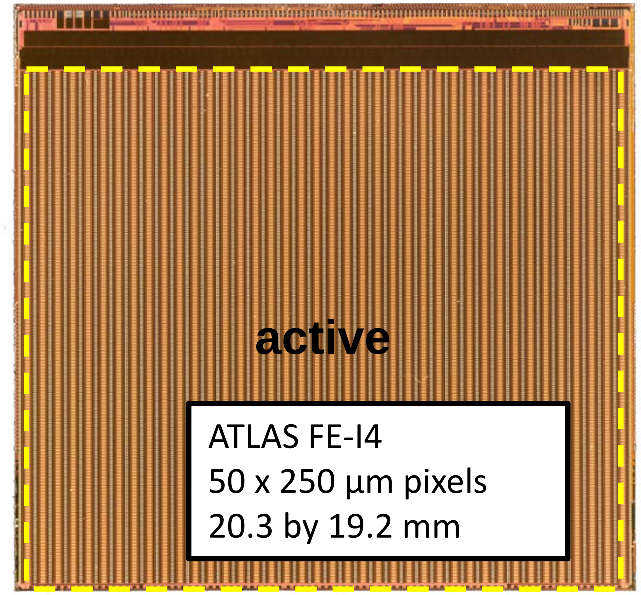
Two possible ways to reduce # chips

Larger pixel chips

- ATLAS FE-I4: 10 x more pixels per dollar
- Modified DAQ electronics fabricated and tested OK
- First detector operation w/ FE-I4 this month?

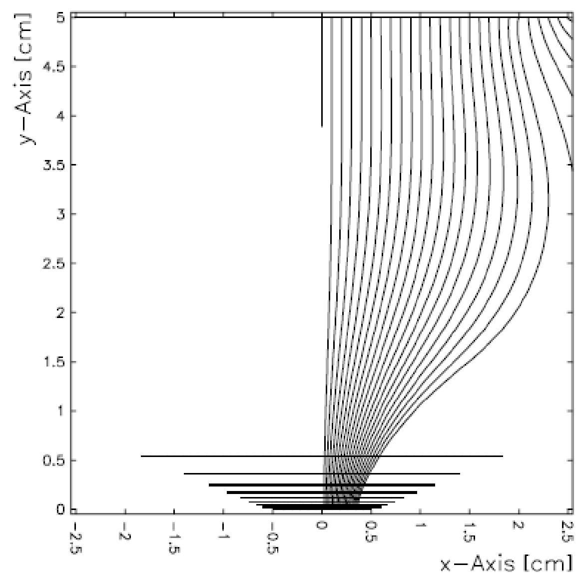


ATLAS FE-I3
50 x 400 µm pixels
7.4 by 11.0 mm



Focusing of drift charge

- advantage: read out large volume with small readout plane, while retaining a key advantage of pixels: small size → low capacitance → low noise
- status: First experimental test promising, but more detailed analysis needed



S. Ross et al., "Charge-Focusing Readout of Time Projection Chambers", proceedings of IEEE NSS 2012

Conclusion / Punch Line

- Biggest drawback of directional detection via gas TPCs is low target mass
- By achieving lowest possible track-reconstruction threshold, we hope to perform directional search for low-mass WIMPs, where current limits are less strong
- Opportunity: Use m^3-scale D^3 to investigate DAMA/CoGeNT/CRESST-II hints. If DM candidates observed in D^3, can check if WIMPs or backgrounds by looking for evidence of 24-h directional oscillation
- More generally, due to high single-electron efficiency, expect good sensitivity to any WIMP models that predict very small ionization deposits in detector (e.g. ultra-low mass WIMPS, electron scattering). Need to evaluate reach in specific models.

Answers to the Questions

Disclaimer: *These answers need much more work. Also our detector is still an early prototype – and much of the information asked for has not yet been measured. So please take with a grain of salt, and I will update throughout the year as we approach Snowmass.*

1. Is your experiment currently operating, and with what total target mass?
   - 2011 Prototype (D3-micro): ~1 mg
- If not, when do you expect to operate, and with what total target mass?
   - 2013: D^3-milli: ~10g
   - 2014? D^3: ~ 1kg
- What total target mass do you expect to have operating 10 years from now?
   - Too early to say

2. Fiducial target mass . What is your current ratio of fiducial target mass to total target mass?
   80%

   How do you expect that ratio to scale in the future? Describe briefly the basis for this scaling.

   Too early to say for sure… but expect the ratio will go up quickly: We are using outer detector edge for self-vetoing charged-particle events. The thickness of this veto region may not need to increase much for larger detectors, i.e. does not scale with R.

3. Backgrounds after passive and active Shielding

- No passive shielding, and no effort at choosing radiopure materials yet, so backgrounds are *very* large!
- In D^3-micro we see ~3 events/hr/mg for $10<\text{keV}<E_{ee}<100\text{keV}$. Disclaimer: energy scale uncalibrated, could be off.
- Backgrounds seem to be dominated by radio-impurities in internal support structure and electric field cage materials. Will mitigate by selecting radio-pure materials from EXO list for larger detector.
- We can self-veto 90% of the abovementioned BG events, and then dominant surviving BG (rate: 0.3/hr/mg/100keV) appears to be due to cosmogenic neutrons.

4. Detector Discrimination

- Not yet measured.

5. Energy Threshold

- Not yet measured. Goal is *directional* threshold of 10keV or lower. Non-directional threshold can be of order a few times 100 eV.

6. Sensitivity versus WIMP mass

- See p7.

Do you expect to develop sensitivity to WIMPS with masses < 5 GeV and, if so, how?

- Yes, it's one of our main goals. We should have non-directional sensitivity to lower masses, and *directional* sensitivity down towards 5 GeV.

7. Experimental Challenges , R&D needed

- To scale up at low cost, need two out of three: 1) larger pixel chips 2) charge focusing 3) Negative Ion drift. See pages 10,11. More work needed to assess how deep underground we need to be.

8. Annual Modulation

- Should be possible. Detector gain has been measured stable to <2% level, with variation being correlated with temperature. <0.5% level stability should be possible with temperature stabilization or gain correction.

9. Unique Capabilities

Do you have unique capabilities to identify whether a signal is due to WIMPs, aside from the standard event by event discrimination and multiple scattering?

Yes, 24-hour directional oscillation. Also full reconstruction of nuclear recoils - distribution of charge in 3D for each event.

Does your technology allow different targets in the same experiment? If so, what changes are required to make use of these? Does your experiment have sensitivity to dark matter interactions other than spin-independent
or spin-dependent?

Yes, just fill in new gas. Detector has high single-electron efficiency, and should be sensitive to ultra-low mass and electron-interaction models. Still need to study specific models. Can also mix gases and identify/distinguish species of recoiling nuclei via ionization profile.

10. Determining WIMP properties and astrophysical parameters

If a signal is detected, what information does your experiment provide about WIMP properties (especially WIMP mass), and about dark matter distribution in
the galaxy?

Yes; directional detectors should be particularly powerful. at constraining the WIMP properties – see e.g. MIMAC presentation for study of this. Also the WIMP velocity distribution is a tranform of the distribution of recoil directions, which such detector can measure.

BACKUP SLIDES

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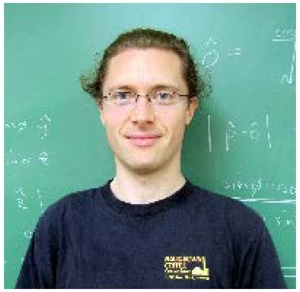
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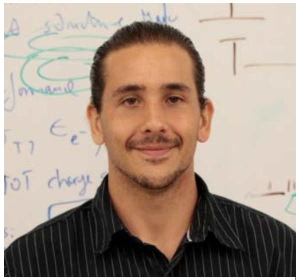
Kamaluoawaiku Beamer
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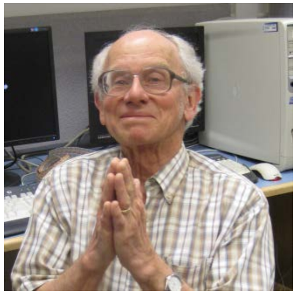
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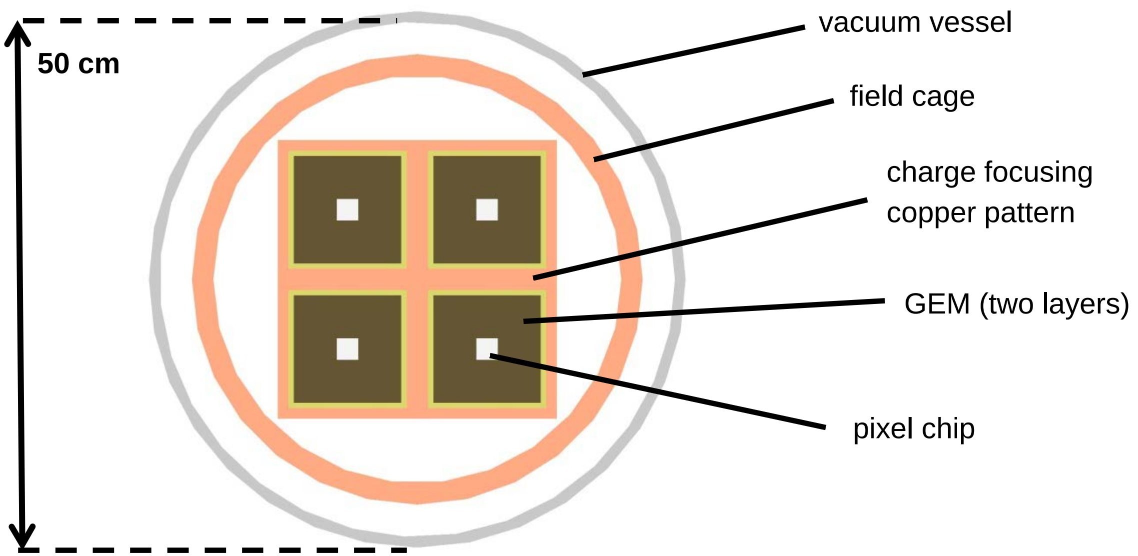
LAWRENCE BERKELEY NATIONAL LABORATORY

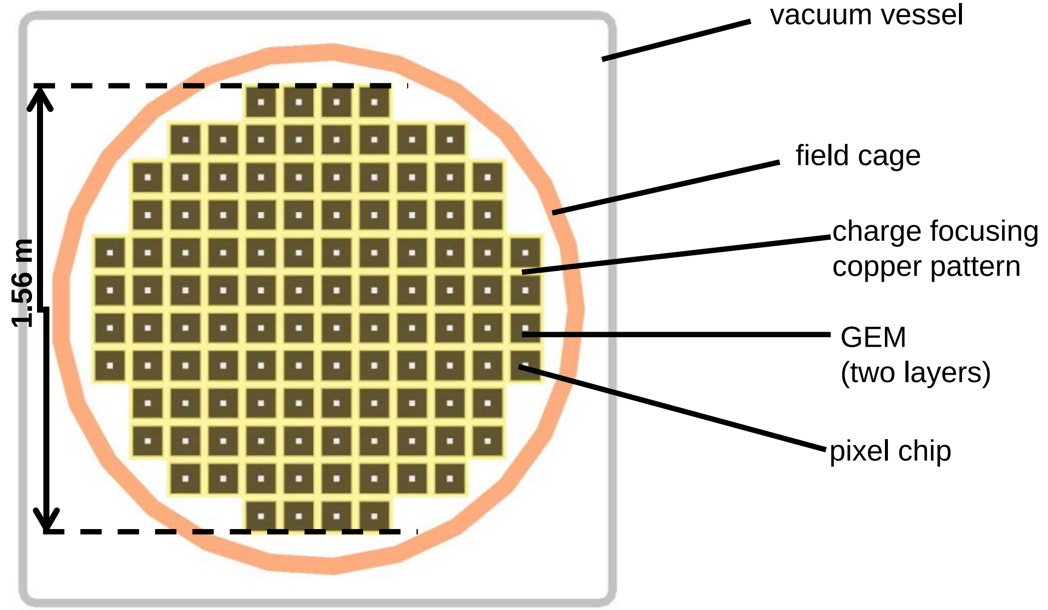
Next Prototype, 2013: D^3-*milli*

- Prototype dedicated to studying next generation pixel electronics, trigger, charge focusing
- 10x10 cm GEMs (CERN), 2x2cm Pixel Chip (ATLAS-FEI4), SEABAS DAQ System from KEK



Top-view of the 12-liter prototype, which implements four unit cells inside a common field cage. The shown geometry assumes a charge focusing factor of 1.2 before the GEMs, and a charge focusing factor of 5.0 between the GEMs and pixel chips.

Concept drawing of D^3



- D^3 top view: Each 30-cm drift layer contains 112 double GEMS, each imaged by a single pixel chip. Between two and eight drift layers can be stacked, for a total target mass between 0.36 and 1.44 kg (for CF_4 @ 50 torr). The detector will require radiopure materials, underground operation, and shielding (not shown).
- Design based on 10x10 cm CERN GEMs, ATLAS FE-I4 pixels
- Expect to use new (v2) RCE readout system under development at SLAC

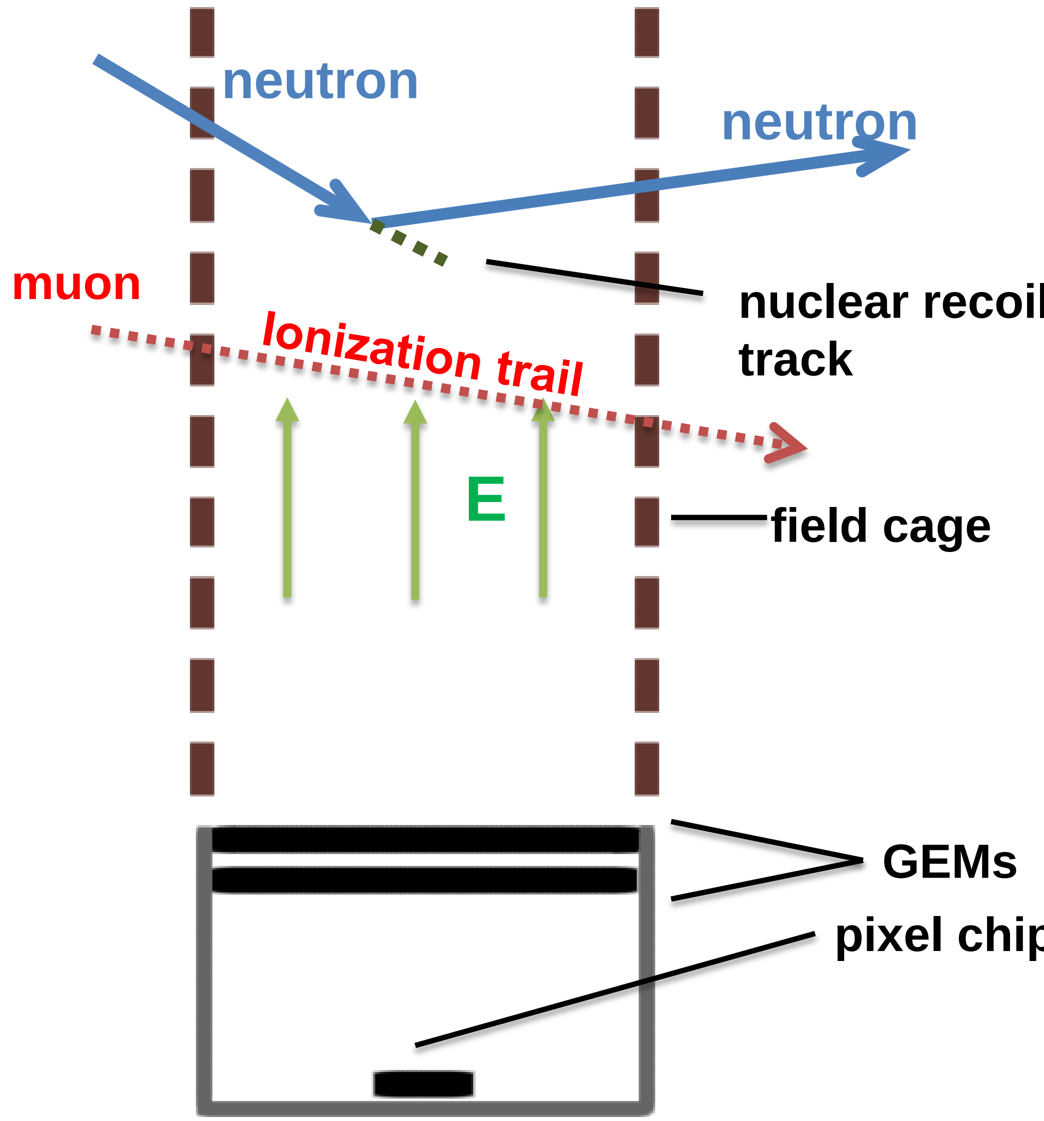
Reminder: How TPC Works

<u>In high-gain (~20k) mode:</u>

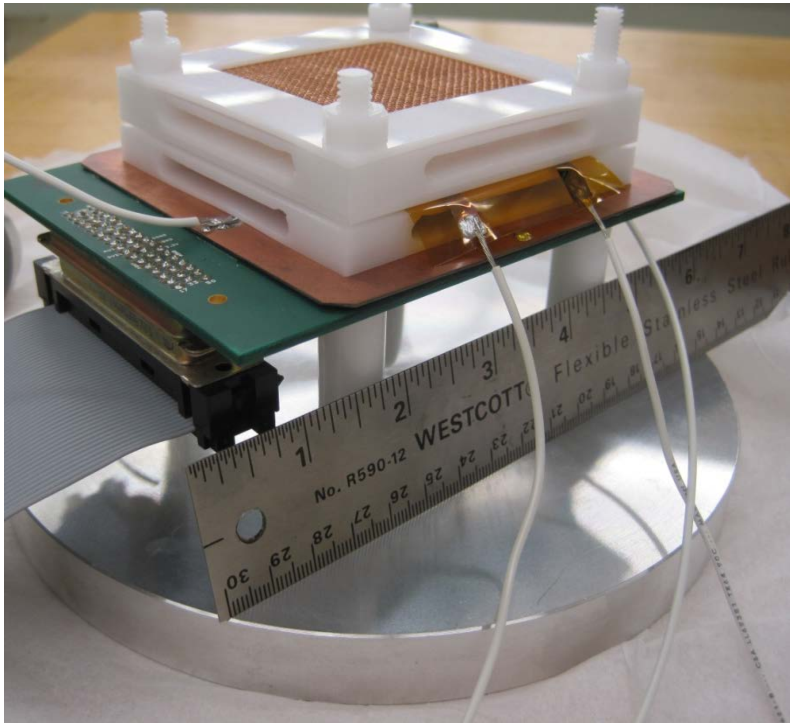
- Detect MIPS and other charged particles

<u>In low-gain (~200) mode</u>

- blind to MIPs
- sensitive to slow-moving nuclei w/ higher dE/dX
- including those resulting from elastic scattering of fast neutrons
- Typical recoils are short (mm)
- Reconstruct both energy and 3D-trajectory of individual recoils
- Locate (point) sources of fast neutrons and measure their energy spectra?

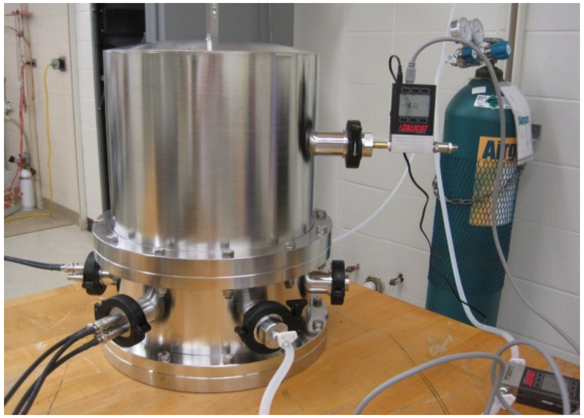


Pre-prototype



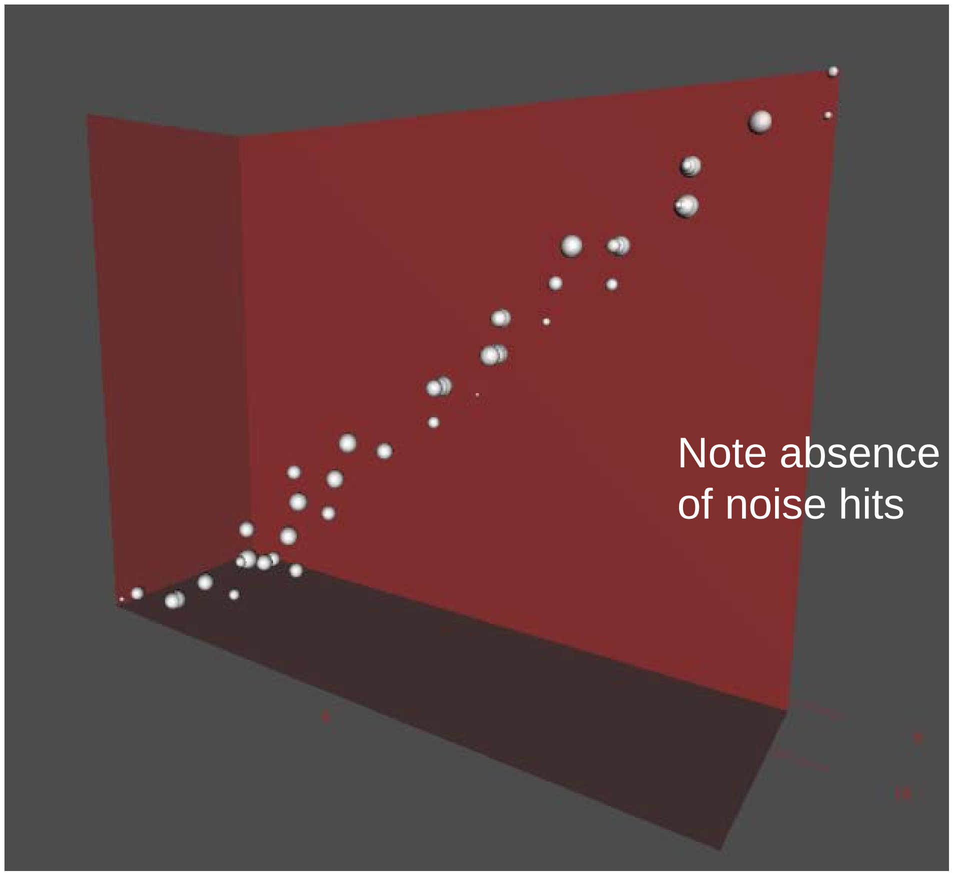
- Tiny TPC prototype, sensitive volume ~ $1 cm^3$
- Based closely on previous LBNL design
- Sits inside much larger vacuum vessel

TPC support structure with Gas Electron Multipliers (orange, transparent foil) and Printed Circuit Board (green) with Pixel Chip installed. The sensitive volume in this detector configuration is small – an 8.6-mm gap between the GEMs and a copper mesh, which is held at a high voltage and provides a uniform electric field.



Stable operation w/ $ArC0_2$ gas at 1 am for many months. Recorded large dataset for calibration

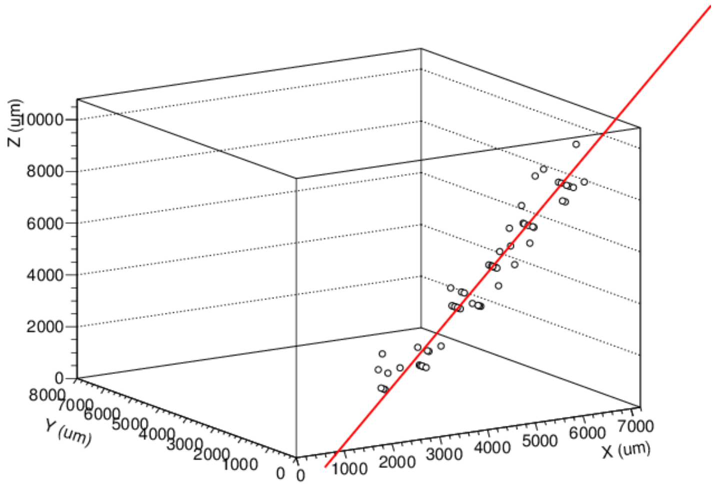
Example of cosmic event in high gain mode

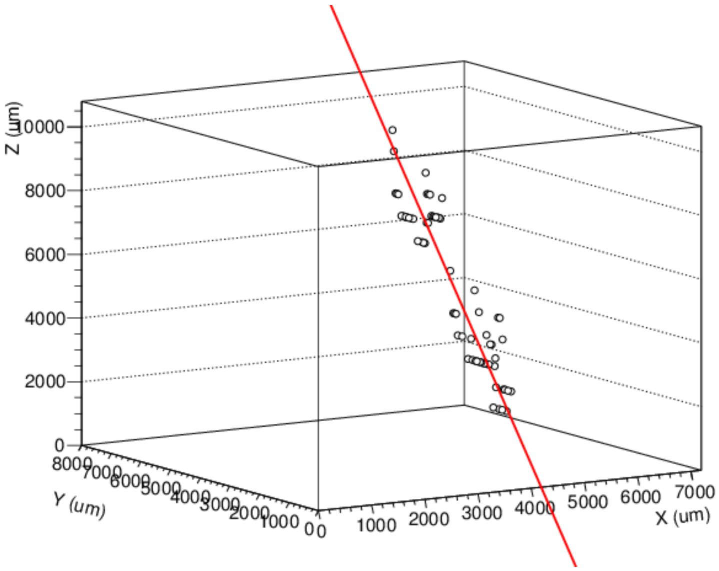


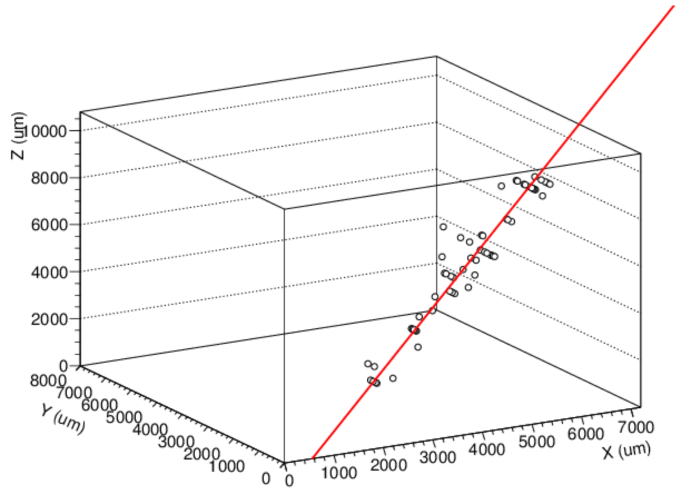
Cosmic ray track (~7mm) detected with Hawaii pre-prototype

**size of each bubble shows
amount of ionization measured at each point**

3D Tracking of Cosmic Muons





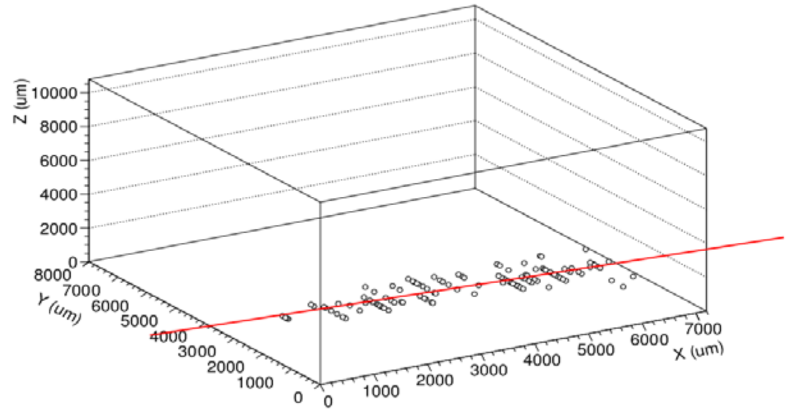


- > 10k cosmic events recorded.
- Use such events to measure detector point resolution (=~200 μm)

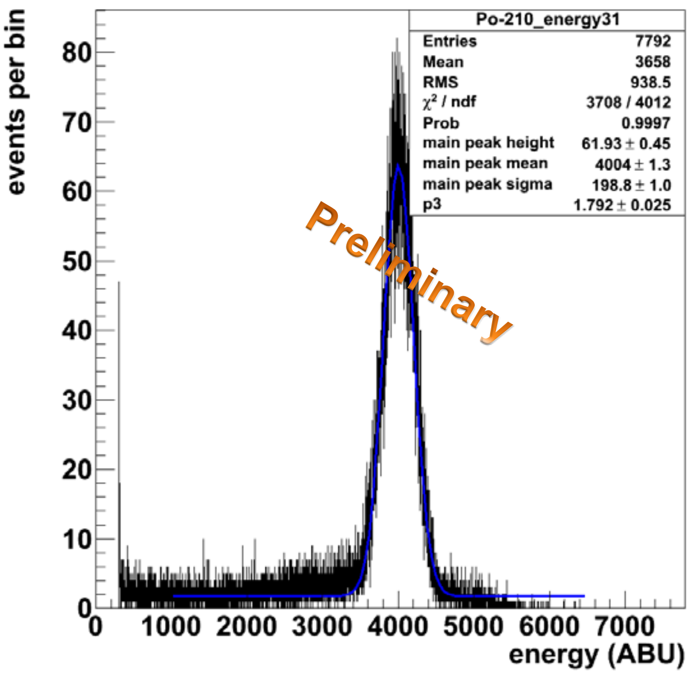
Based on measured point resolution, expect angular resolution on nuclear recoils ~1 degree

3D Tracking of Alpha-particles

- Po-210 alpha's (5.3 MeV)

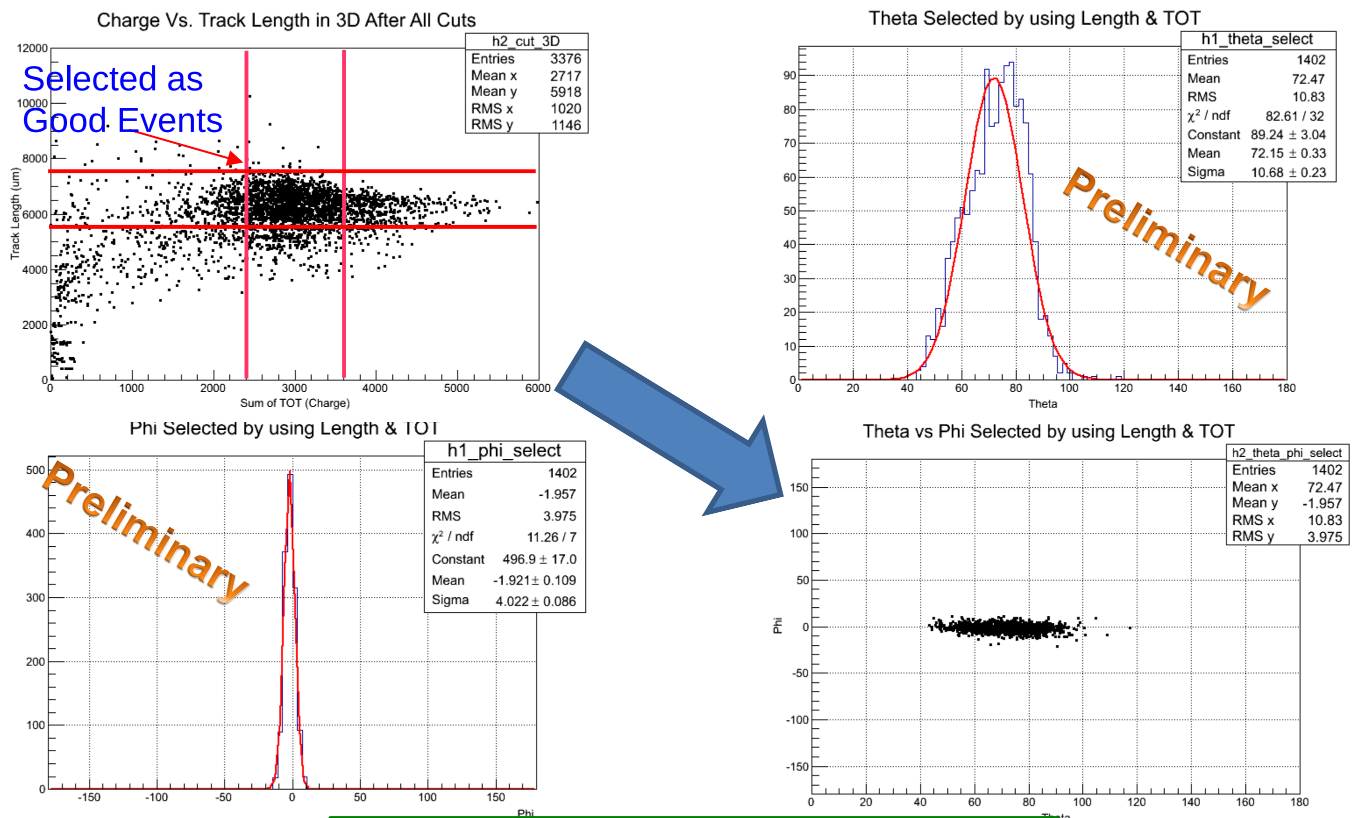


Gain resolution ~ 5%



Preliminary conclusion: performance mostly *better* than expected.

Locating a Po-210 Alpha Source

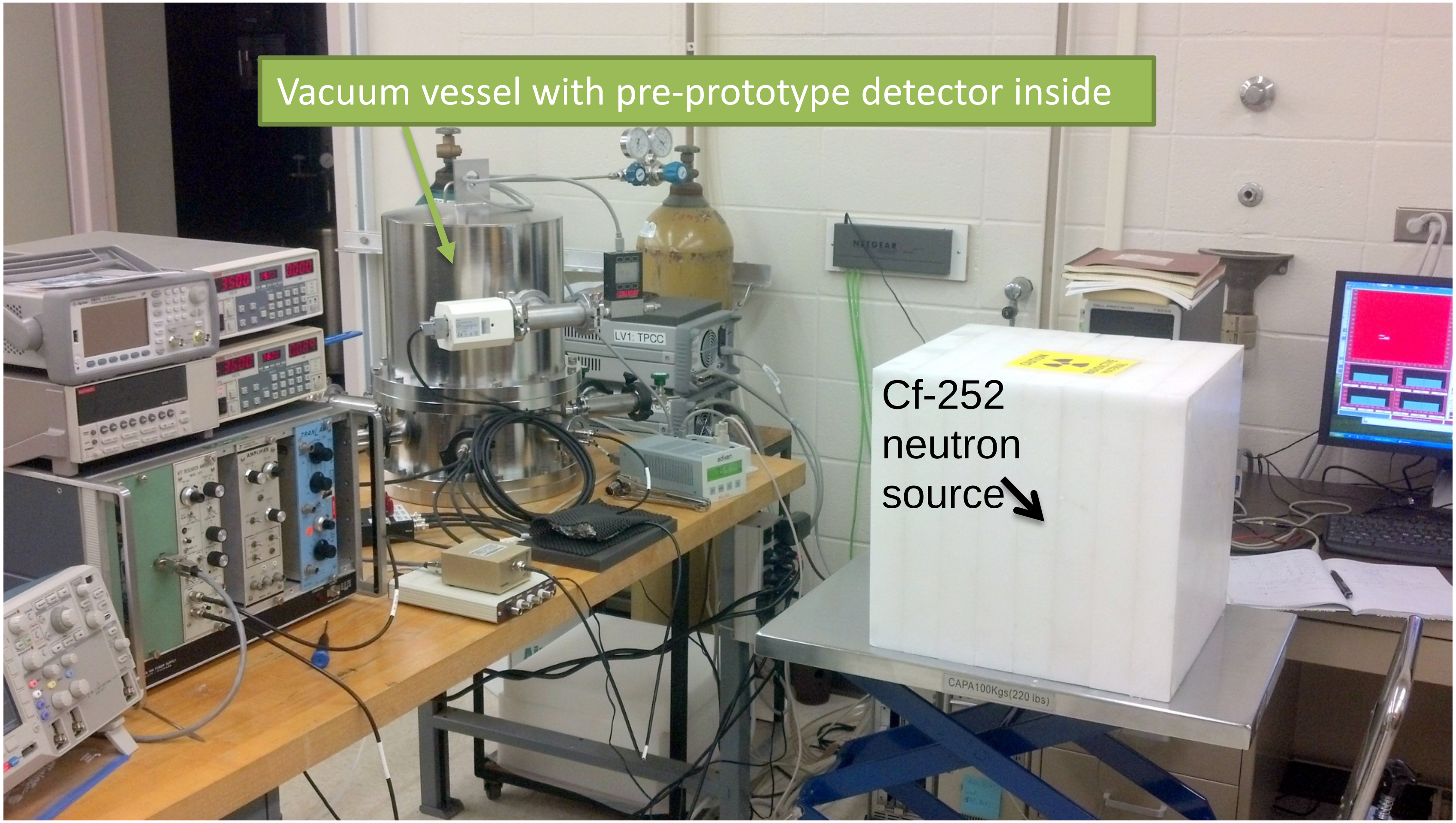


$$\text{upper limits: } \sigma_\theta = 10.68^\circ, \sigma_\phi = 4.022^\circ$$

$$\sigma_{angle} = \sqrt{\sigma^2_{detector} + \sigma^2_{straggling} + \sigma^2_{source\ cone} + \sigma^2_{source\ size}}$$

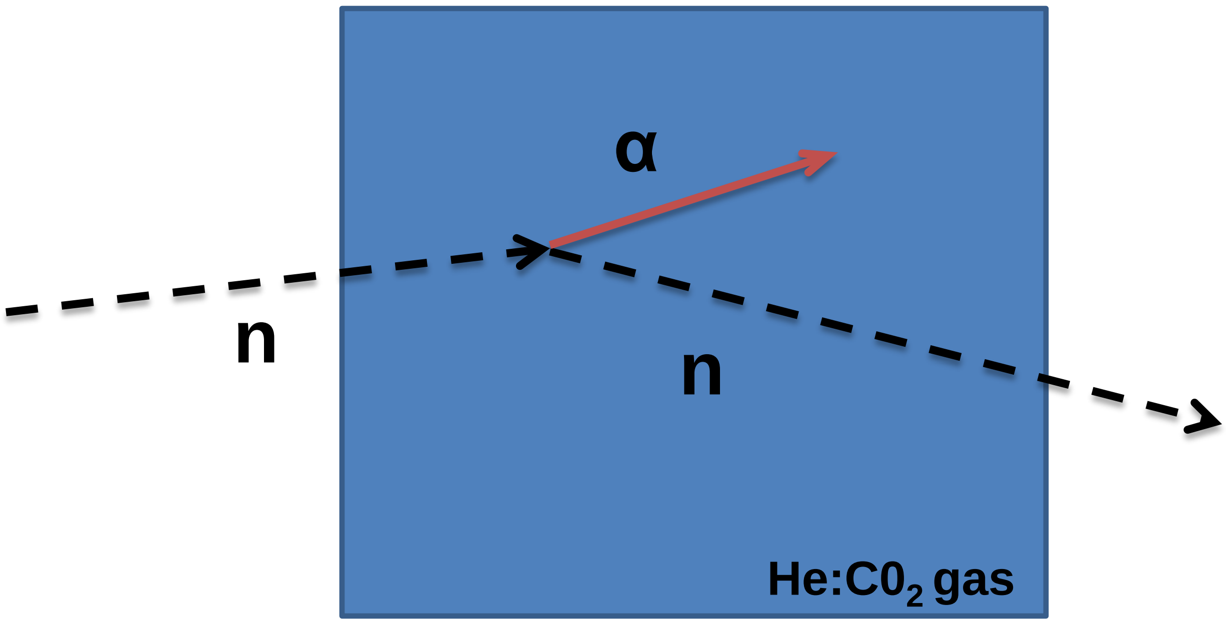
- Selected events clearly point back to a single source
- Analysis still ongoing, but expect to obtain $\sigma_{\phi\ detector}$ ~1°
- σ_θ too large - reduce TPC drift velocity

Neutron Detection



Recorded large datasets with $HeC0_2$ gas. With/without source, two source locations

Expected Signal for Neutron Scattering

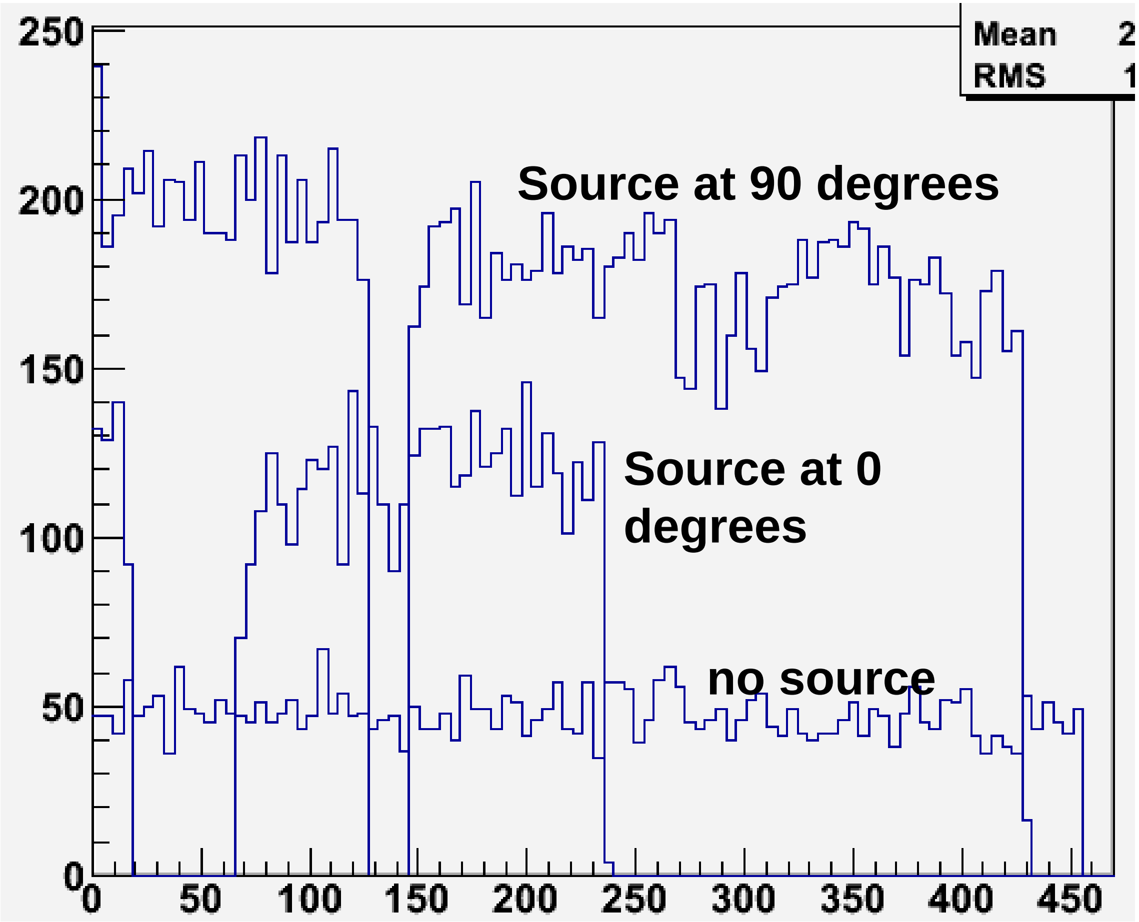


- **He-recoils (= α – particles)**
- **Fully contained in detector volume**

Can we detect the source?

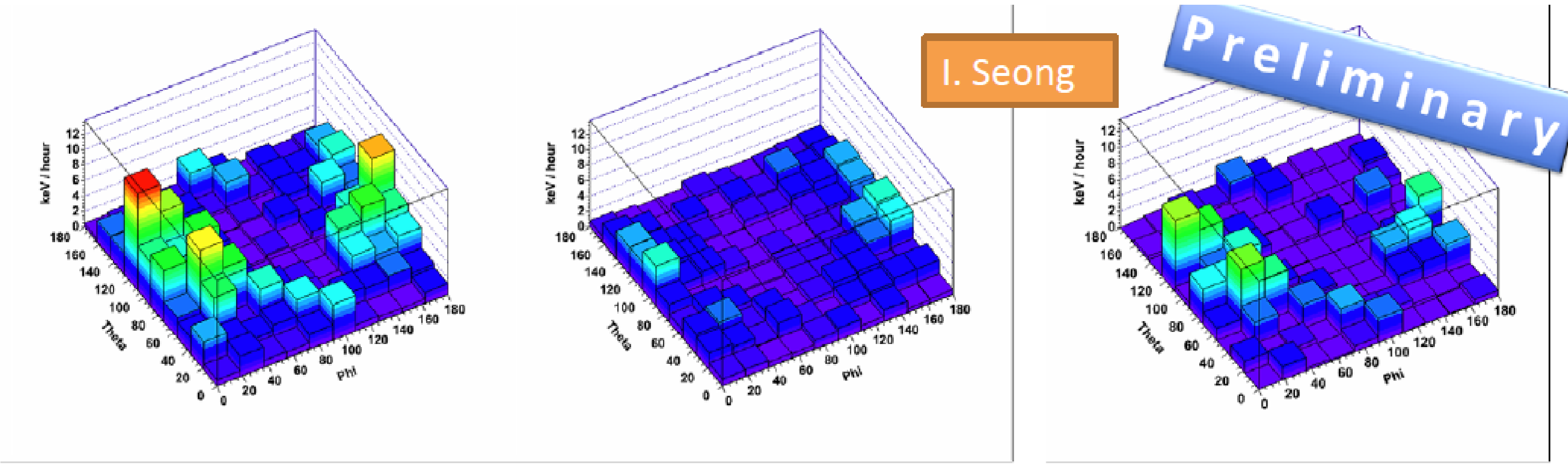
- Yes!
- Note: Strictly speaking, this does *not* yet prove that we are detecting *neutrons*

includes all detected events with >1 hit on pixel chip (rejects noise hits)



Can we locate the source?

- Maybe… needs more work. Preliminary result shown below.
- Event selection:
  - Nhit > 1
  - Ltrack > 565 microns
  - Tracks not allowed to cross edge of pixel chip

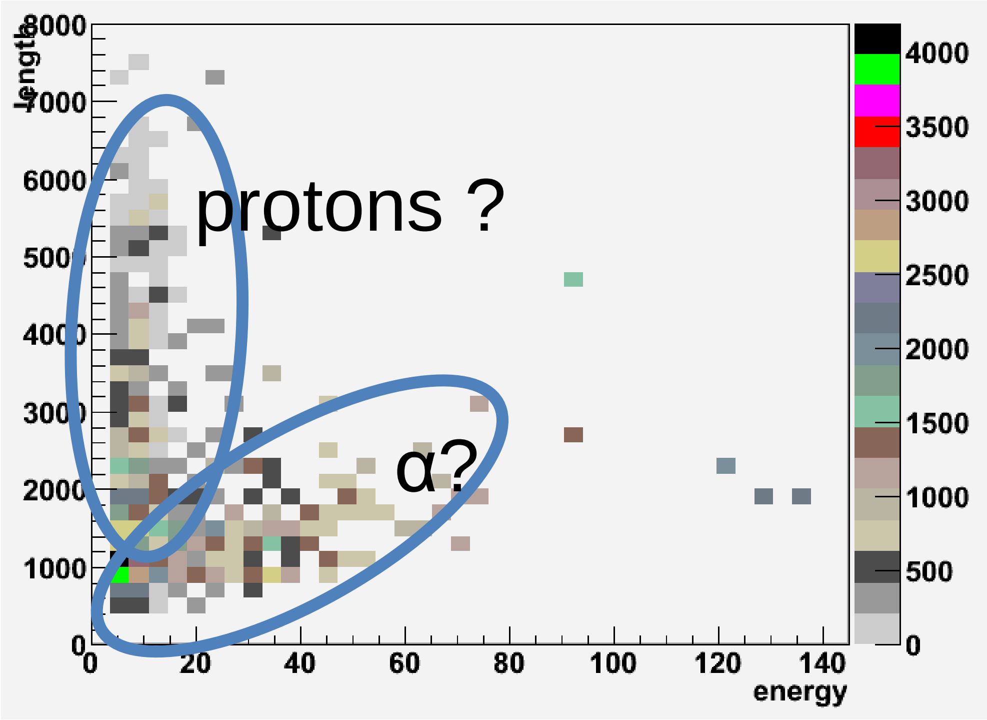


(a) Source ON (b) Source OFF (c) After Background Subtraction

- source location: theta=90, phi=20-30 degrees
- Very encouraging, but not totally convincing
- We have already moved the source by 90 degrees, to see if we can track it.

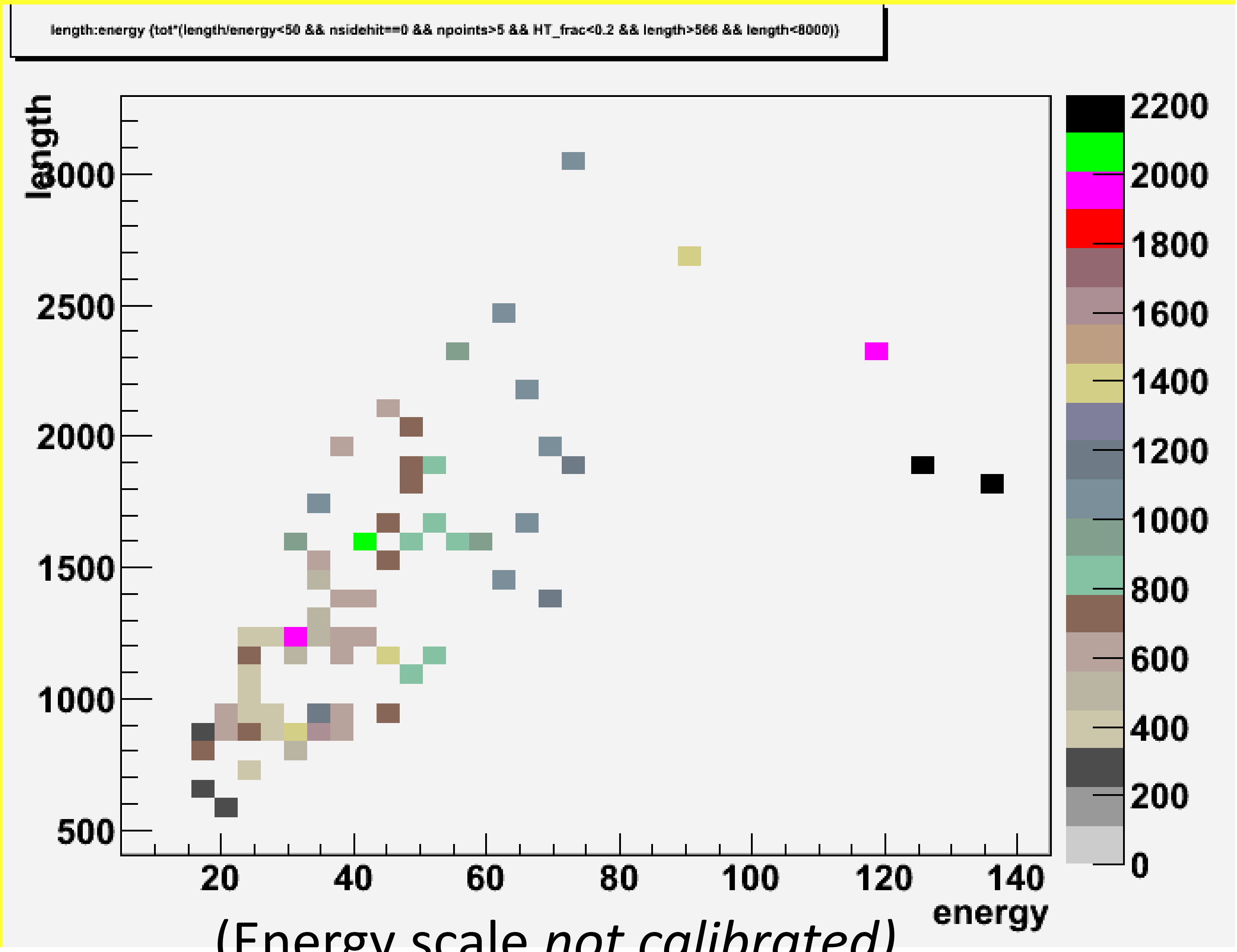
Particle ID via dE/dX

- Once energy scale is calibrated, can utilize L vs E (~similar to dE/dX) for improved BG rejection
- Work on this just started



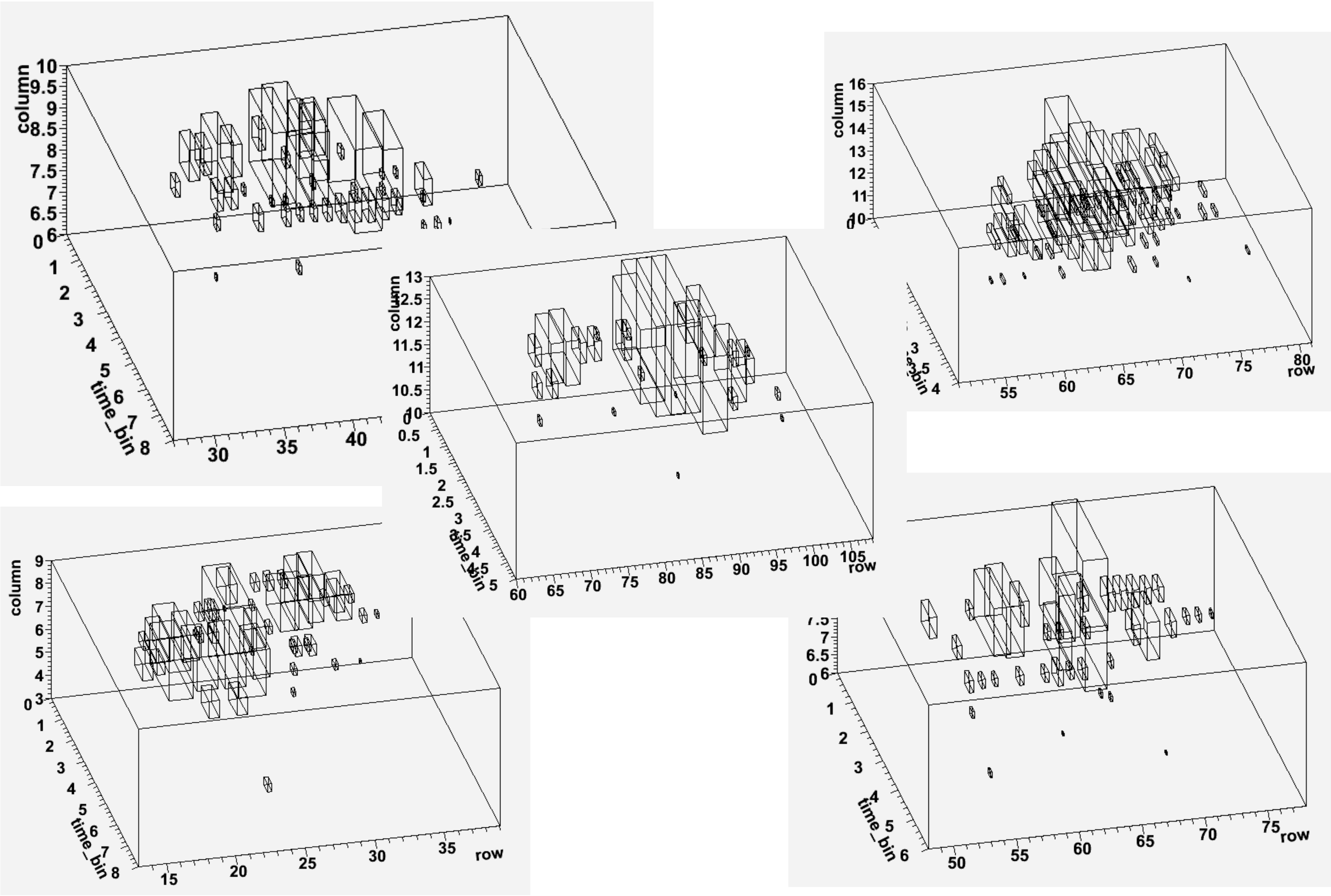
(Energy scale *not calibrated)*

After dE/dX cut



(Energy scale *not calibrated)*

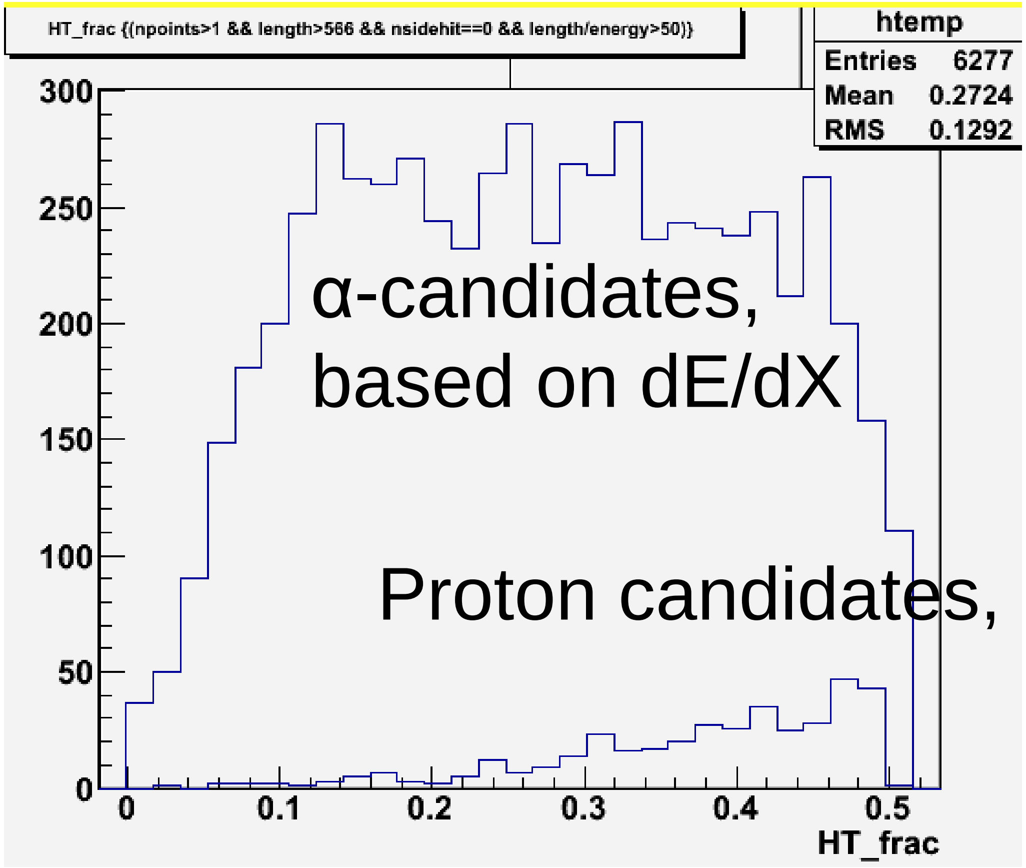
Examples of Events in alpha-band



Head/Tail determination via dE/dX

- Can also use detailed charge distribution along track to
  - distinguish nuclear recoils from faster particles
  - identify “head” and “tail” of nuclear recoils

(also work in progress)



asymmetric dE/dX ⟷ **symmetric dE/dX**