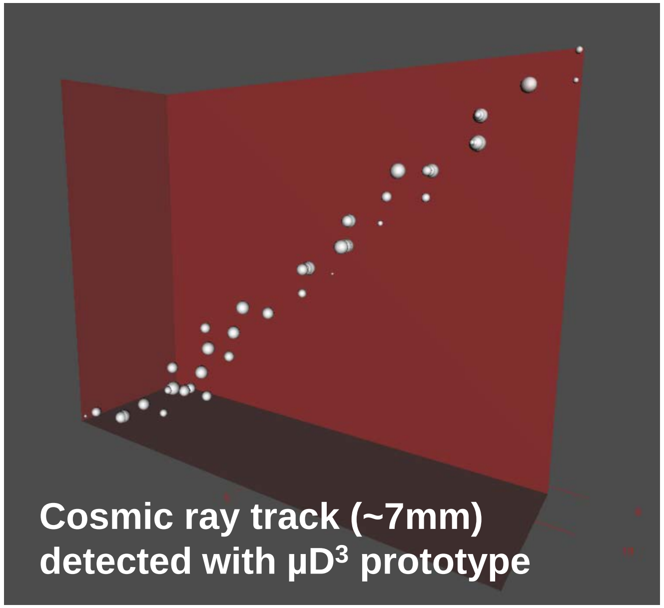
Recent Progress on D^3 - The Directional Dark Matter Detector

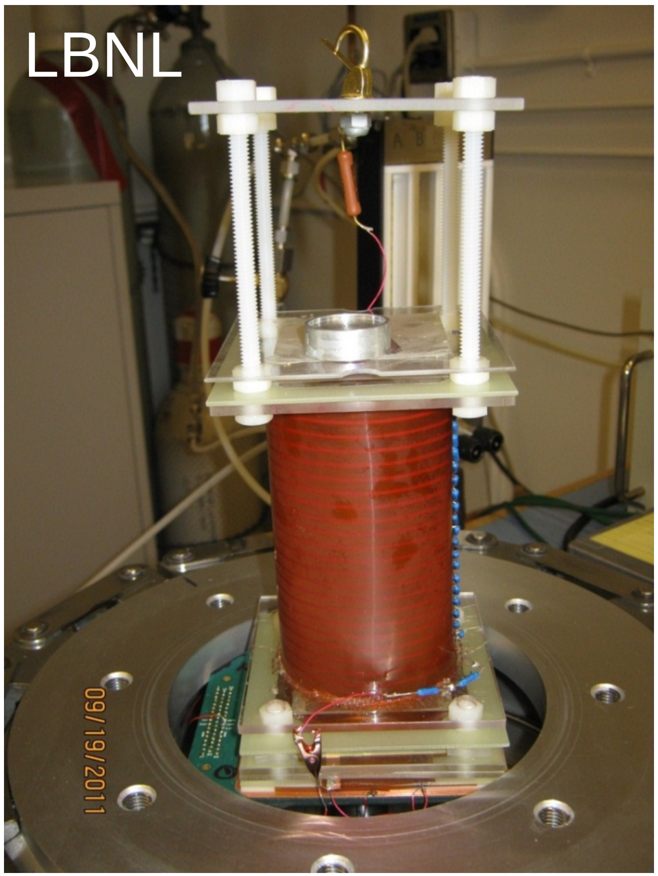


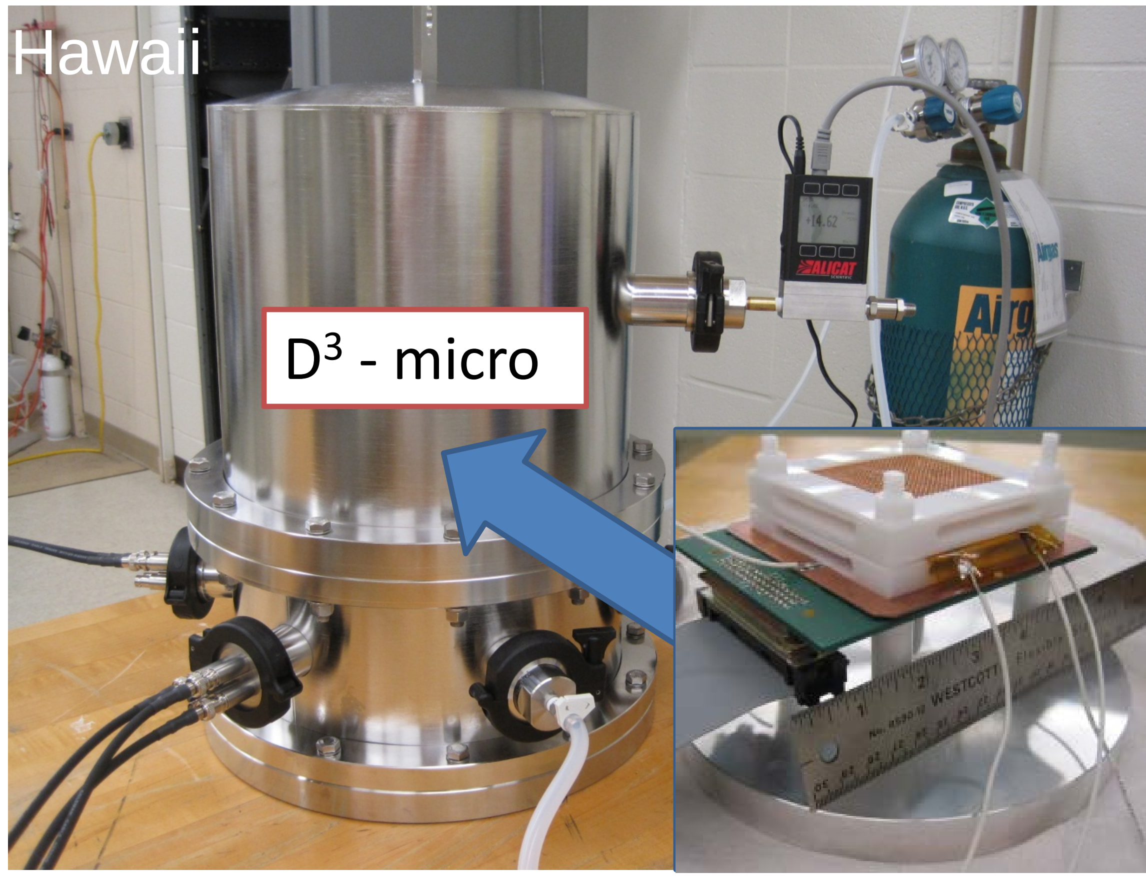
- Motivation
- Detection Principle
- Performance of prototypes
- Plans for future
- Related activities

Sven E. Vahsen, University of Hawaii

D^3 - Directional Dark Matter Detector

- Investigating feasibility of directional DM search w/ micro-pattern gas detectors
- Technology also of interest for detecting neutrons and charged particles
- Small (1-10 cm^3) prototypes built at LBNL and U. Hawaii
- Ongoing since ~Fall 2010





Team at U. Hawaii and Berkeley Lab

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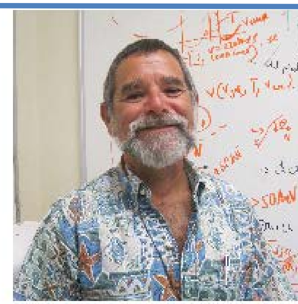

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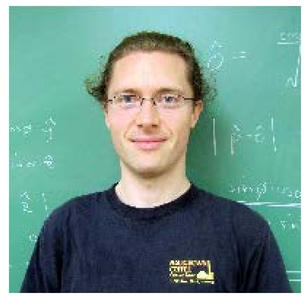

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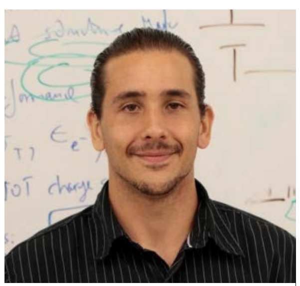

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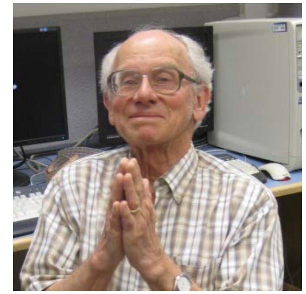

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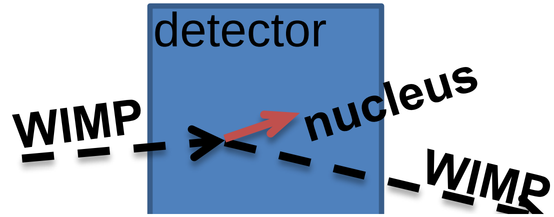
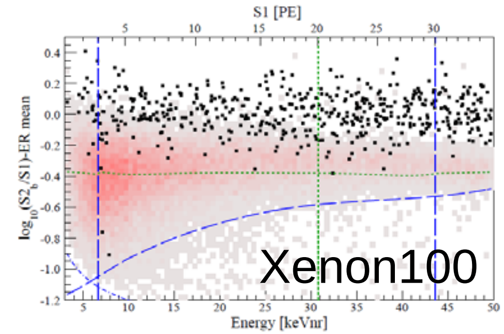
LAWRENCE BERKELEY NATIONAL LABORATORY

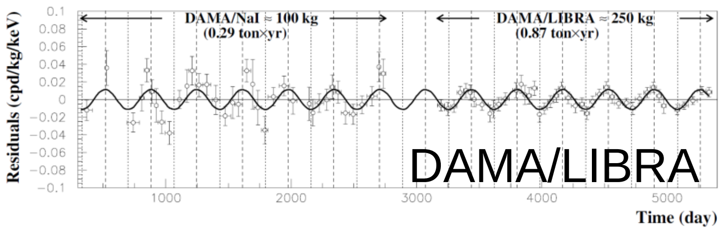
Motivation for Directional WIMP Search

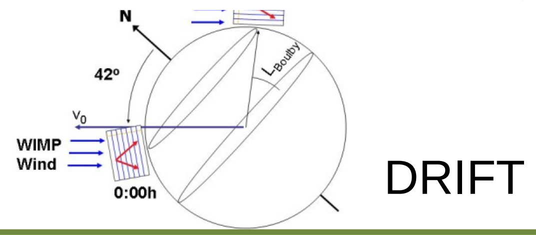


<u>Three possible signatures of direct DM detection:</u>



1. **Excess count rate over predicted BG**
   - Requires ultra-clean detectors & precise understanding of remaining backgrounds
   - neutrons produce identical events
2. **Annual modulation of count rate**
   - ***due to motion of earth around sun***
   - expect %-level effect → requires thousands of signal events & < %-level control of BGs
3. **Daily oscillation in mean recoil direction**
   - ***due to rotation of earth***
   - expect large effect, only ~10 events required
   - no known background with this signature

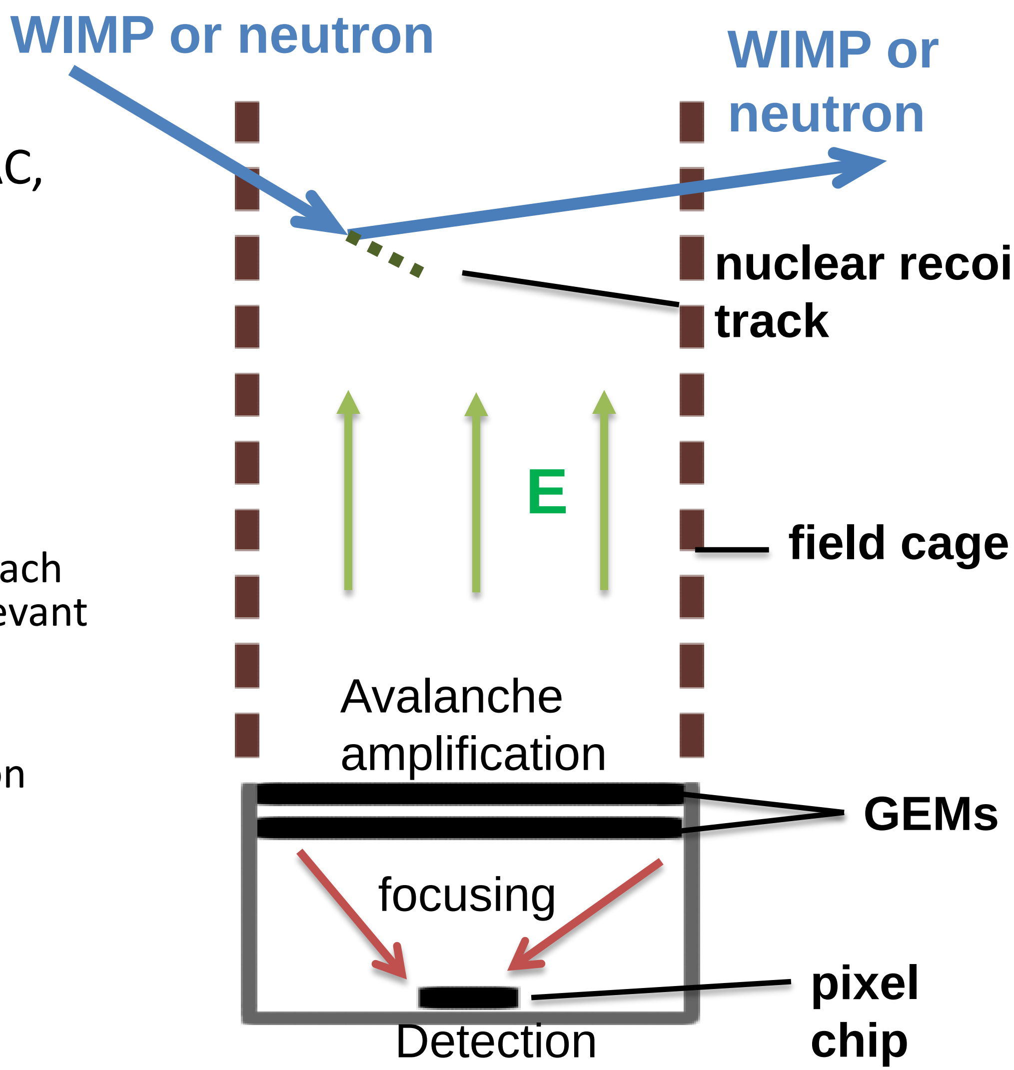




- Detector with directional sensitivity could provide unambiguous evidence for WIMPs
- Post-WIMP-discovery, a (huge) directional detector could perform WIMP astronomy
- A *small*, m^3-scale, directional detector with *low energy* threshold would be relevant *today*
  - could investigate the recent hints for low-mass (~10-GeV) WIMPS

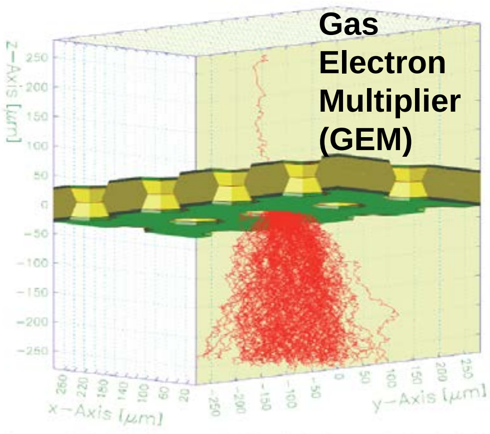
Directional Recoil Detection in Gas TPCs

- Several efforts based on low-pressure gas time projection chambers: DRIFT, DMTPC, MIMAC, NEWAGE, D^3
- Benefits
  - Directional sensitivity
  - Can ID recoiling particle
  - Easy to change target nucleus
- Drawback
  - low target density → harder to reach large target mass required for relevant sensitivity
- D^3
  - Charge amplified with Gas Electron Multipliers (GEMs)
  - Charge detected with pixel chip
  - Charge focusing - potential for significant cost reduction of large detectors



Charge Amplification and Detection in D^3

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



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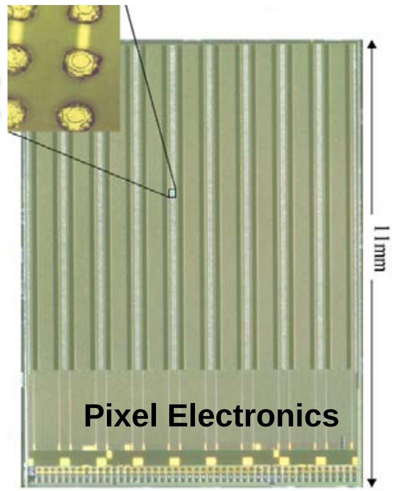
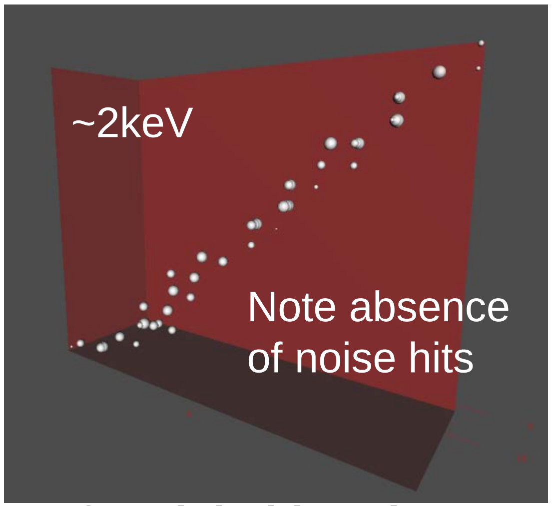


- ATLAS FE-I3
- 50x400 µm pixels
- Sampling at 40 MHz

=

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



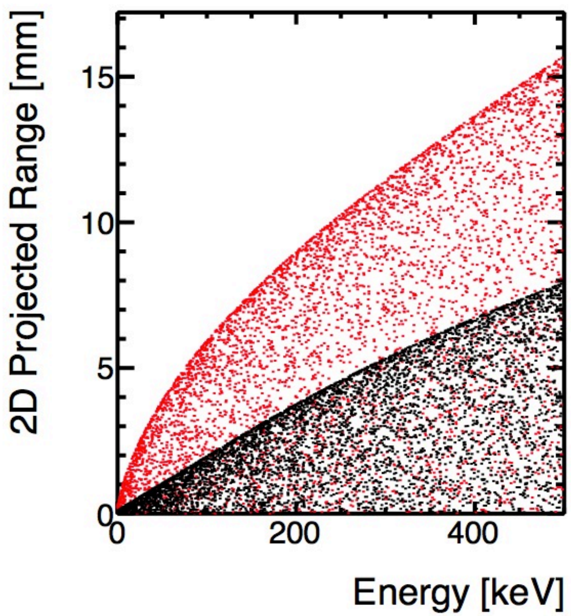
size of each bubble shows amount of ionization measured

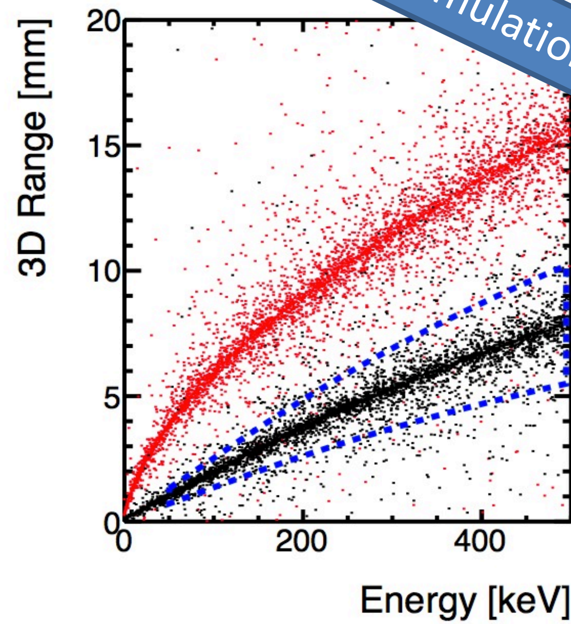
Advantages of this approach

- Full 3D tracking w/ ionization measurement for each space-point (head/tail sensitivity)
  → **improved WIMP 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 → **suitable for low-mass WIMP search**

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.

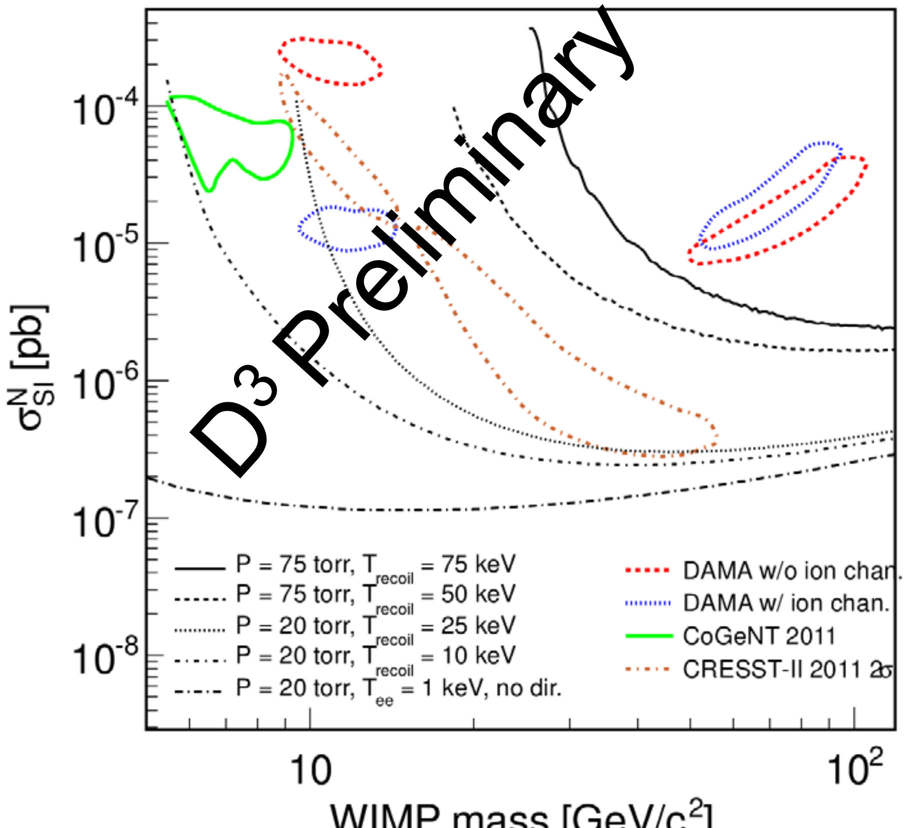
Right: With 3D tracking, the alpha and fluorine recoil bands separate. In this simulation, the angular resolution was 5°. The blue dashed lines represent a cut above 50 keV that achieves a 10^2 alpha rejection with an 86% fluorine recoil acceptance.

3D tracking: much improved rejection of alpha-particle backgrounds

Advantage of Low Track Energy Threshold

- Preliminary evaluation: 3-m^3 detector could achieve *directional sensitivity* to (controversial) ~10 GeV WIMPS
- Golden scenario - if DAMA/LIBRA were due to WIMPs:
  - observe ~1000s of non-directional events (can observe yearly oscillation)
  - use subset (~100) of these to search for daily directional oscillation, to determine if BG or WIMPs

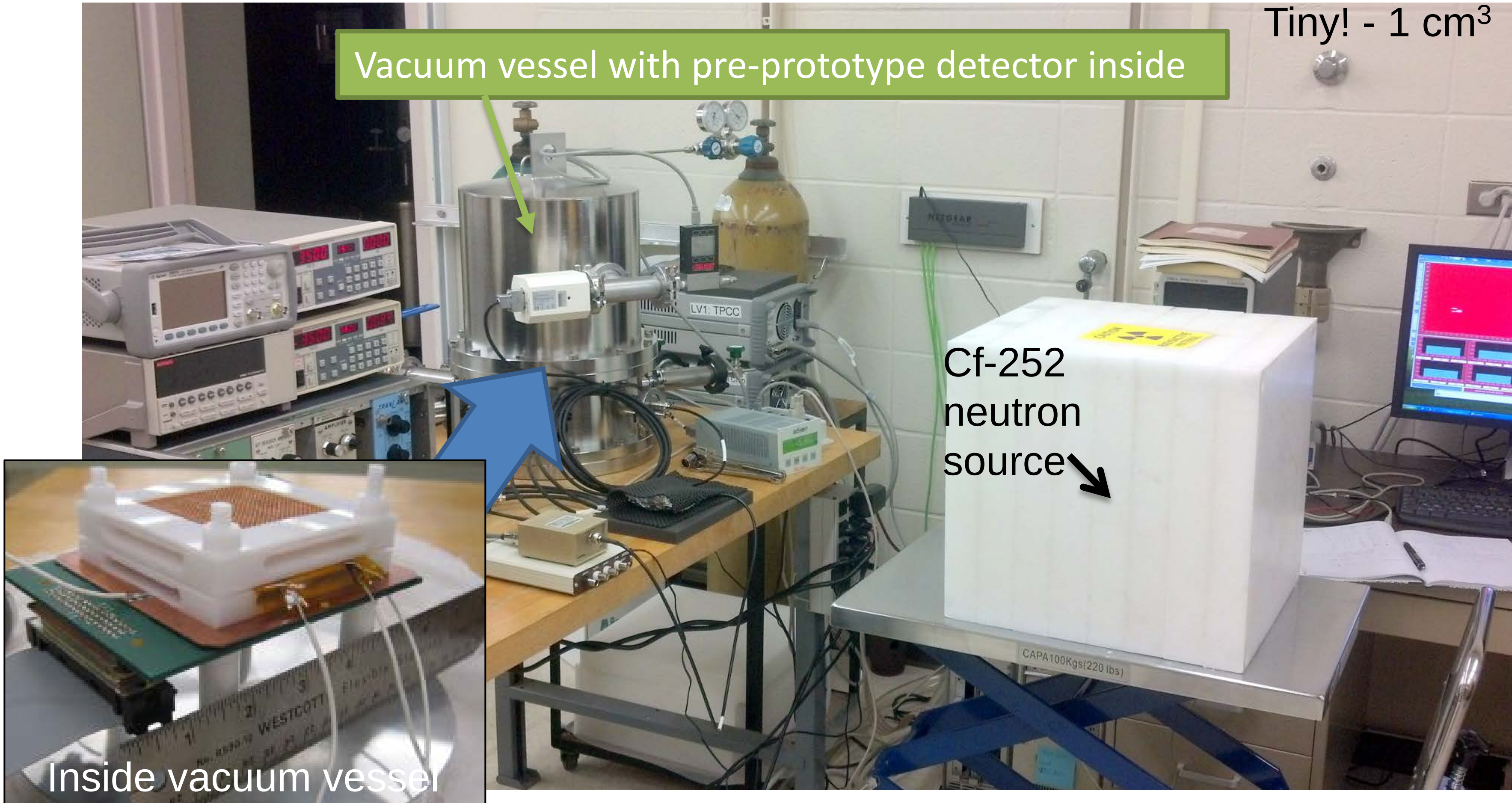
http://arxiv.org/abs/1110.3401



Estimated sensitivity to spin-independent WIMP-nucleon scattering, 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 and for non-directional analysis.

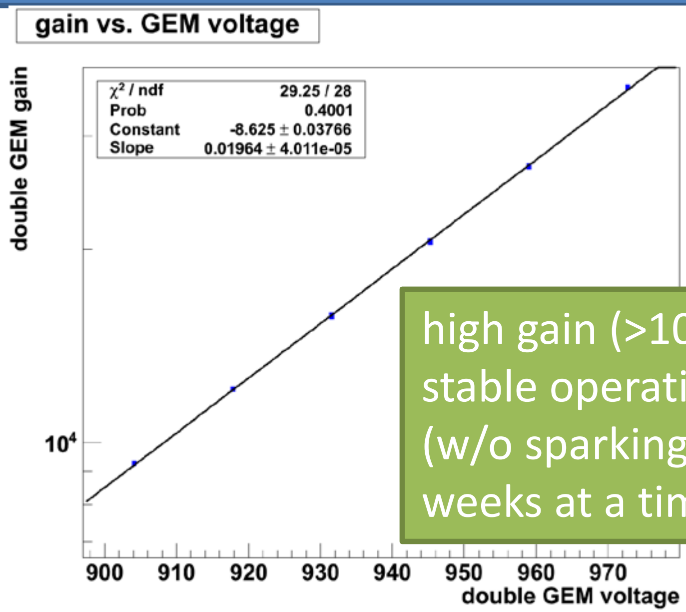
Track energy treshold as low as 10 keV crucial for detecting 10 GeV WIMPS!

Characterization of Current Prototype - $D^3\mu$



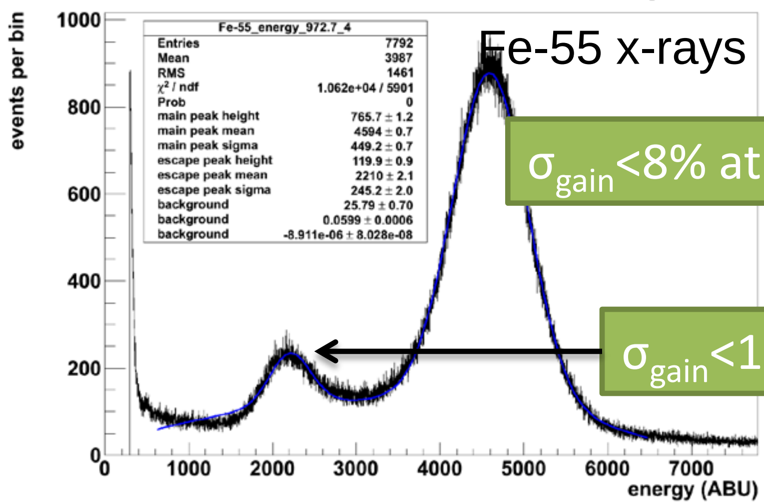
- Stable operation for >1 year, large datasets recorded
  1. commissioning w/ $ArC0_2$; muons, x-rays, α-particles ('11,'12)
  2. detailed calibration & directional neutron detection w/ $HeC0_2$ (Fall '12-now)
- Low-pressure operation w/ CF_4, WIMP search surface-run starting this summer

Gain and Gain Resolution of Double GEM



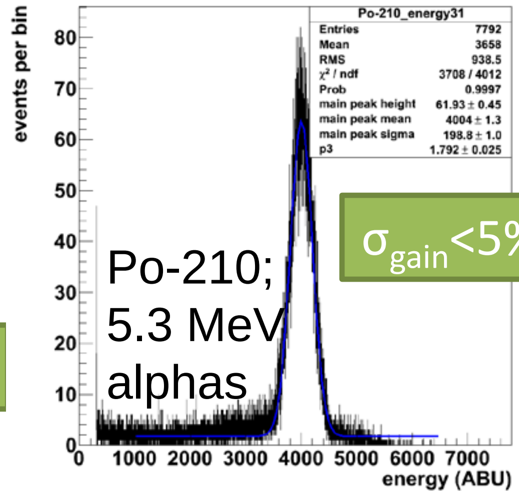
high gain (>10^4), stable operation (w/o sparking) for weeks at a time

- $ArCO_2$ at p=1atm
- ($HeCO_2$ results, not shown, are slight *better*)



σ_{gain}<8% at 5.9 keV

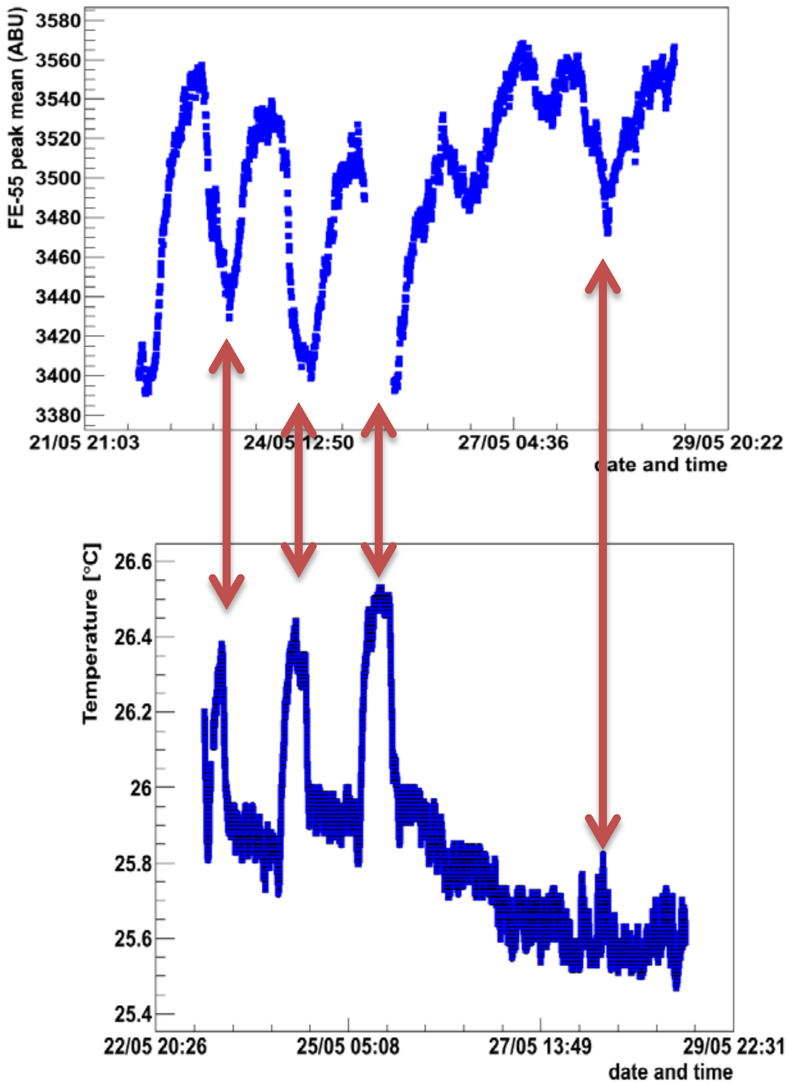
σ_{gain}<11% at 3 keV



σ_{gain}<5% at ~ 5 MeV

- Sufficient gain to achieve single-electron sensitivity if needed
- Good gain resolution for MeV-scale signals, adequate even for few-keV signals!

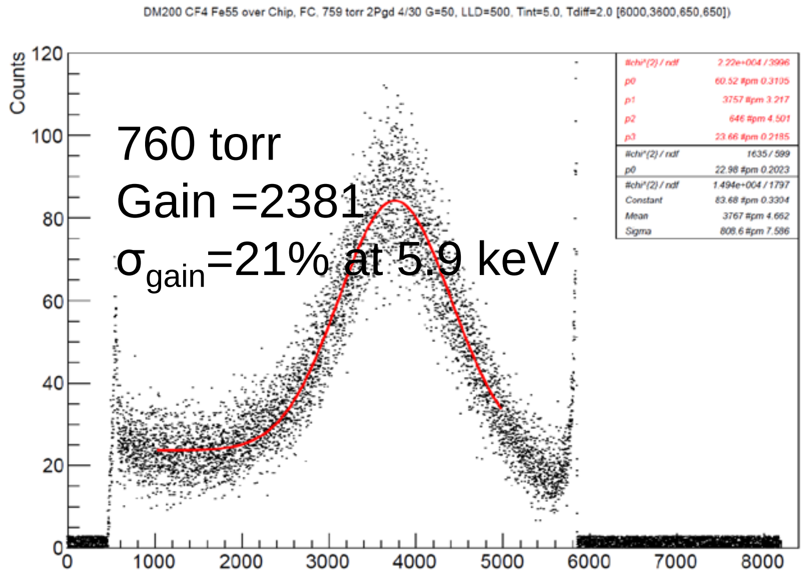
Gain Stability

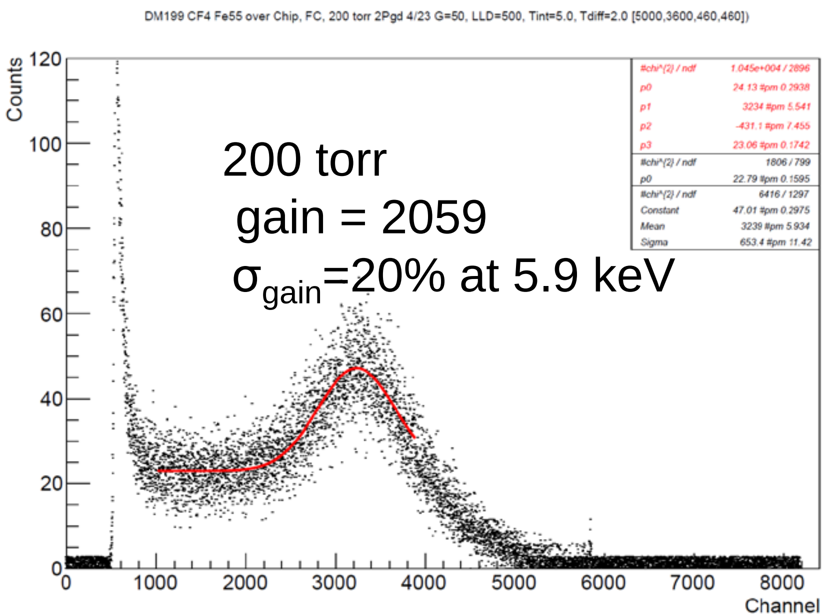


- Measured gain continuously for 5 days, to test for possible gain degradation due to decreasing gas purity
- Not observed (=good!)
- Instead observed +/- 2% gain variation tightly correlated with lab temperature; guessing this is due to NIM electronics

Excellent gain stability without flowing gas

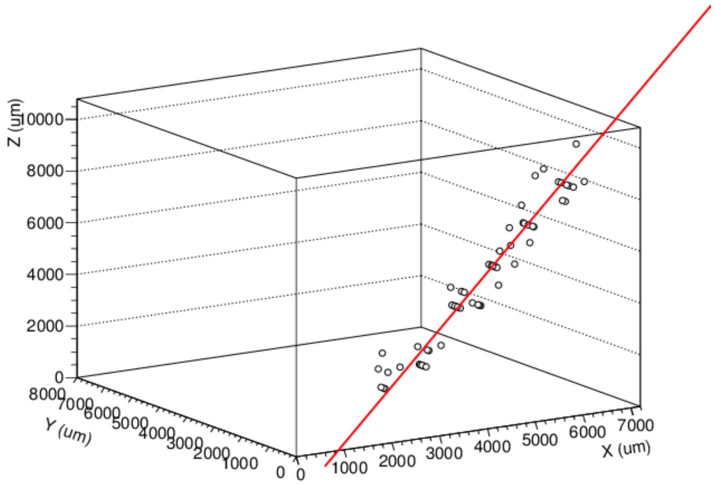
Gain Resolution w/ CF_4 @ Berkeley Lab

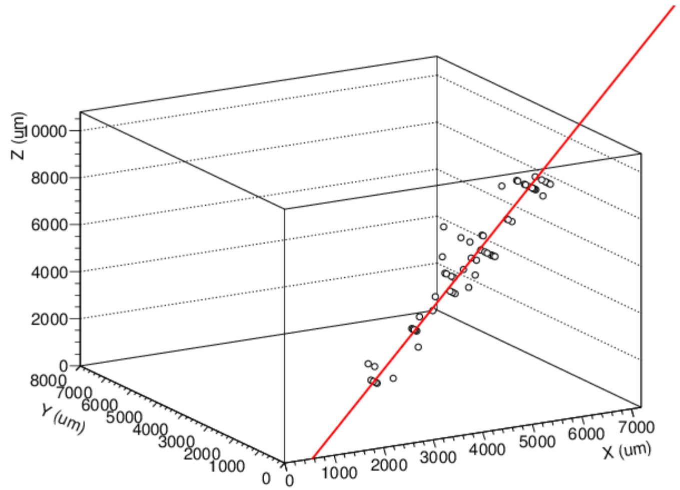




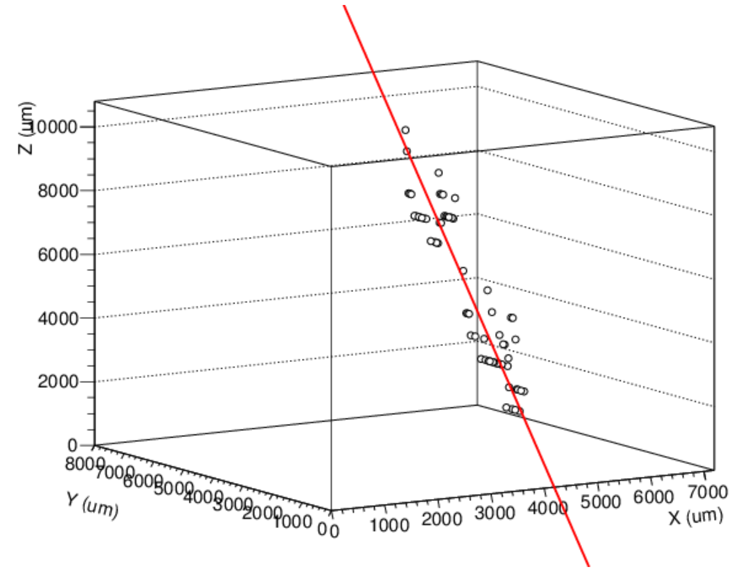
- Detectors work well with CF_4
- May need 3rd GEM to get gain > 1000 at low pressure
- Figures
  - Fe-55 x-rays
  - 12 cm drift in field cage
  - Pulseheight analyzer

3D Point resolution





$ArCO_2$ at p=1atm

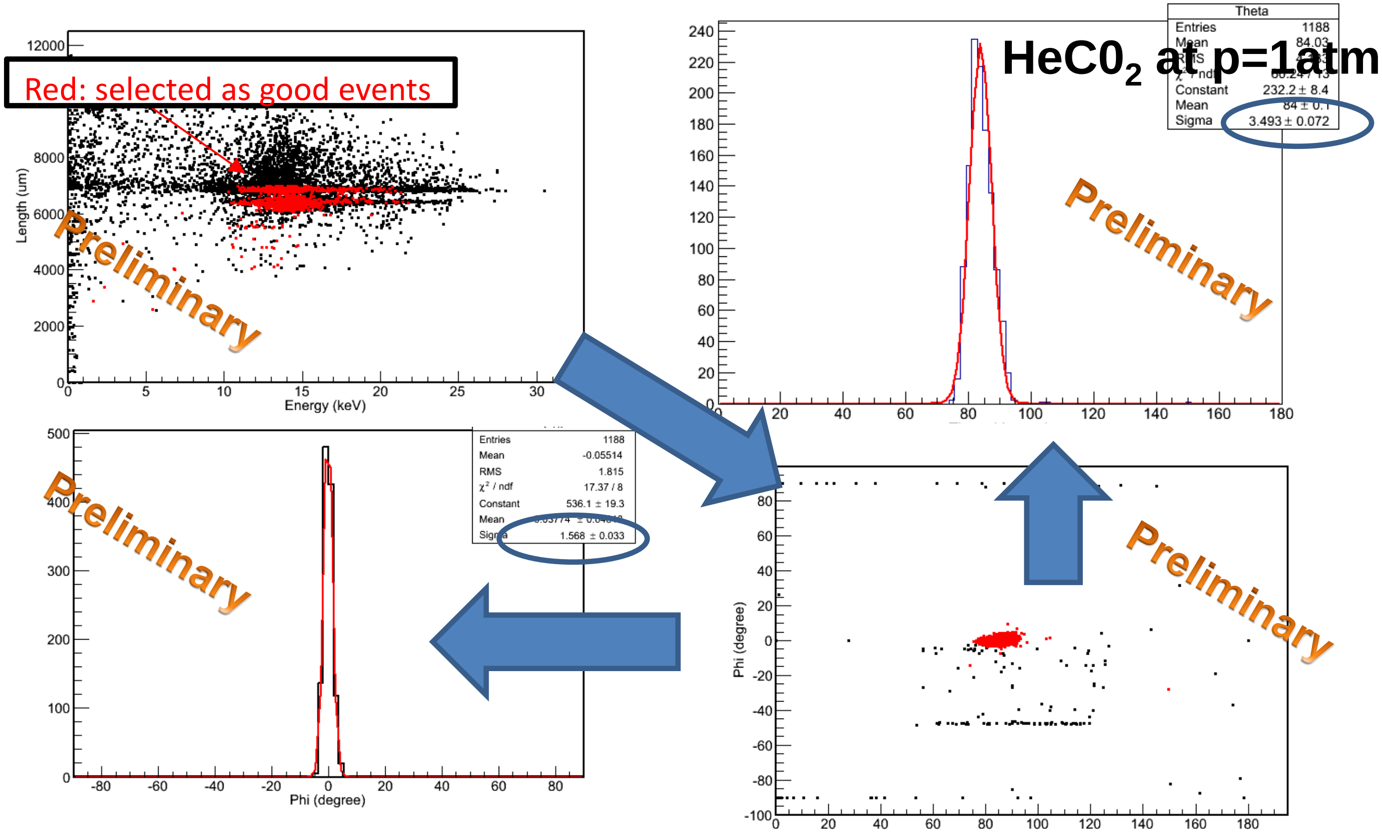


- > 10k cosmic events recorded.
- Use such events to measure detector point resolution (<=200 μm)

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

Angular and Energy Resolution, nuclear recoils

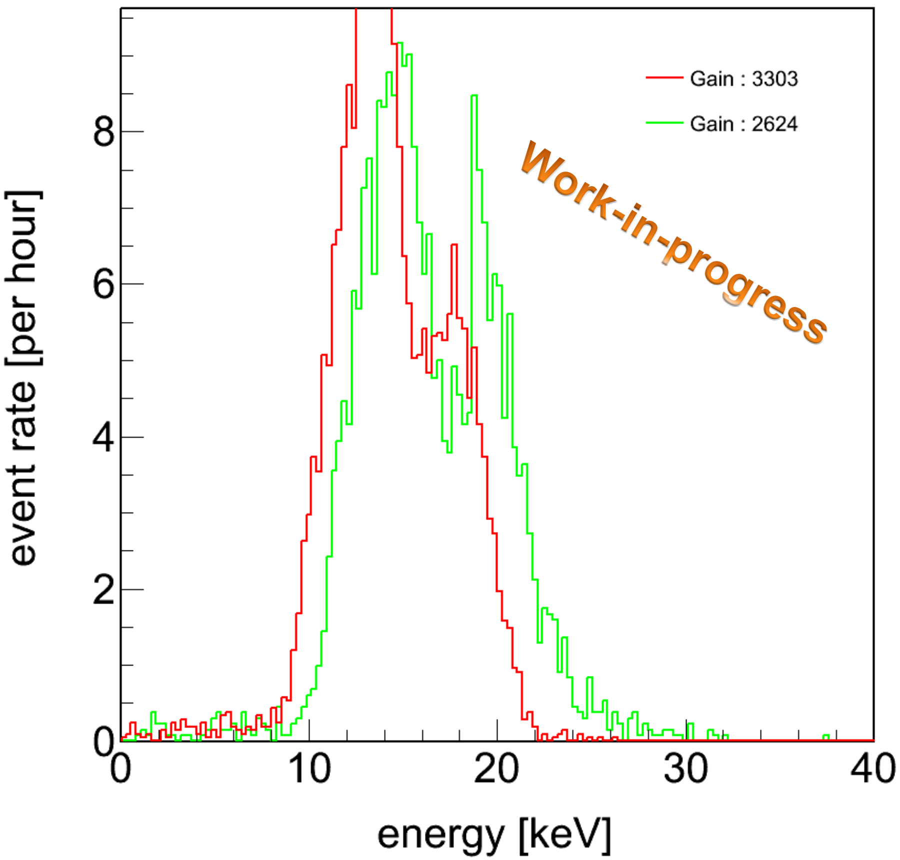
Po-210 α-source inside vaccum vessel. How well can we locate it?



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

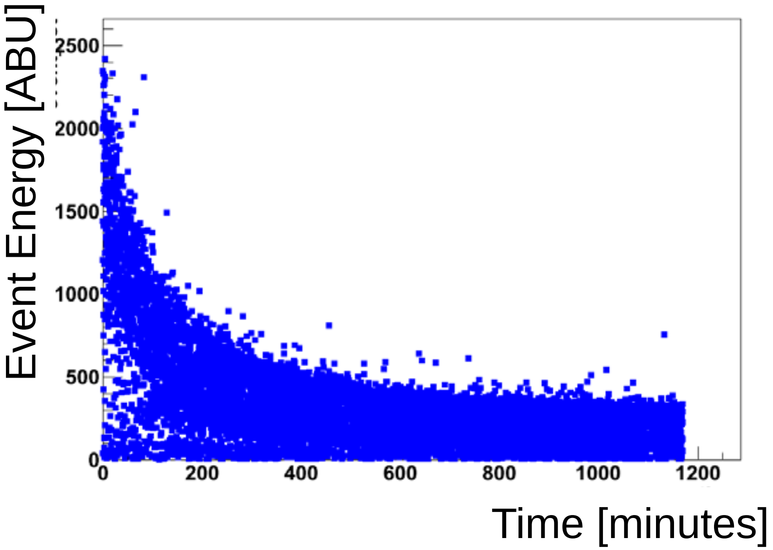
- Selected events clearly point back to a single source
- No BG after good-track selection
- consistent with $\sigma_{\phi,\theta\ \mathrm{detector}} <= 1^{\circ}$

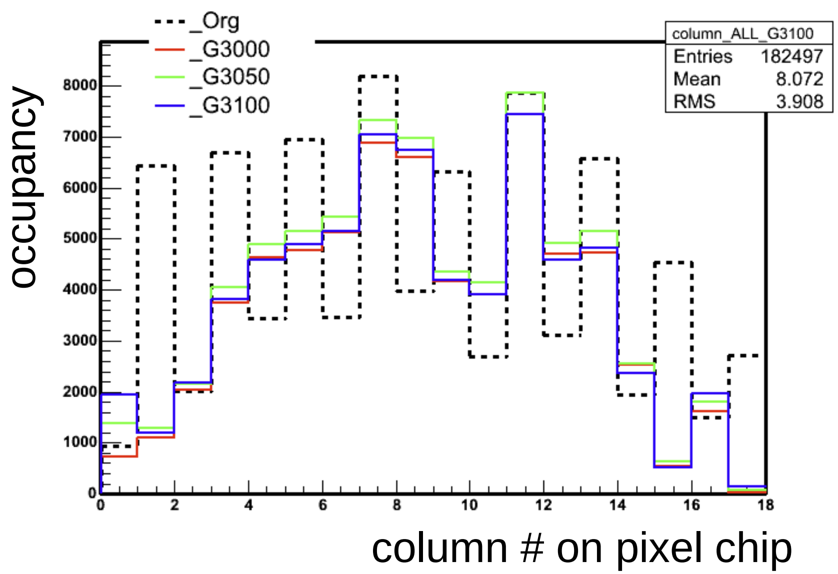
Energy Resolution - Surprises



- Energy resolution significantly worse than gain resolution when measured over entire pixel chip area
- Surprising, as both GEM gain and pixel chip calibration measured independently to be uniform (<5%) and stable in time (<2%)
- If we restrict only to small region of chip, energy resolution approaches ~10% as expected (not shown)

Energy VS Time and Position





- …More detailed investigation revealed: even though GEM gain and pixel calibration are stable & uniform, effective gain is time and position dependent
- Hypothesis: charge-up of pixel chip surface distorting E-fields and affecting ***charge collection efficiency***
- *Supporting evidence:*
  - *Higher gain → faster gain reduction*
  - *Gain recovers when E-field turned off*

Studying Time /Position Dependence I

rectangular aluminum pads deposited on top of chip, grounded during operation

ATLAS FE-I3

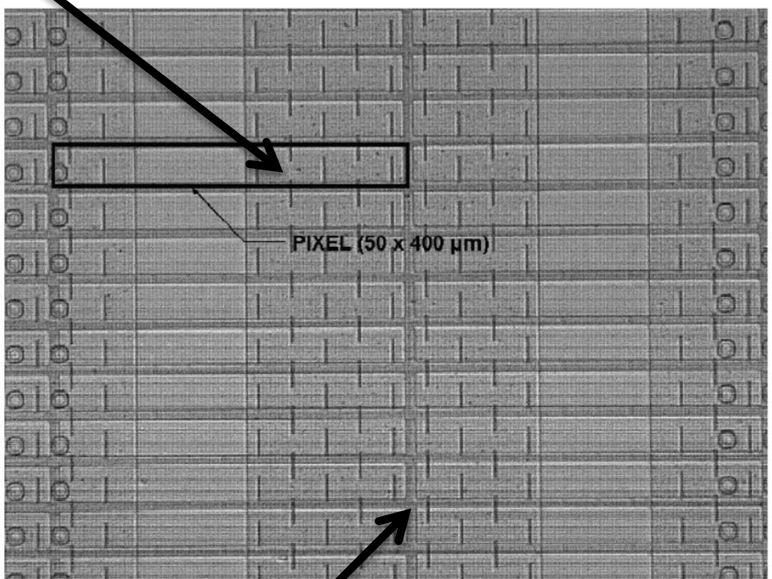
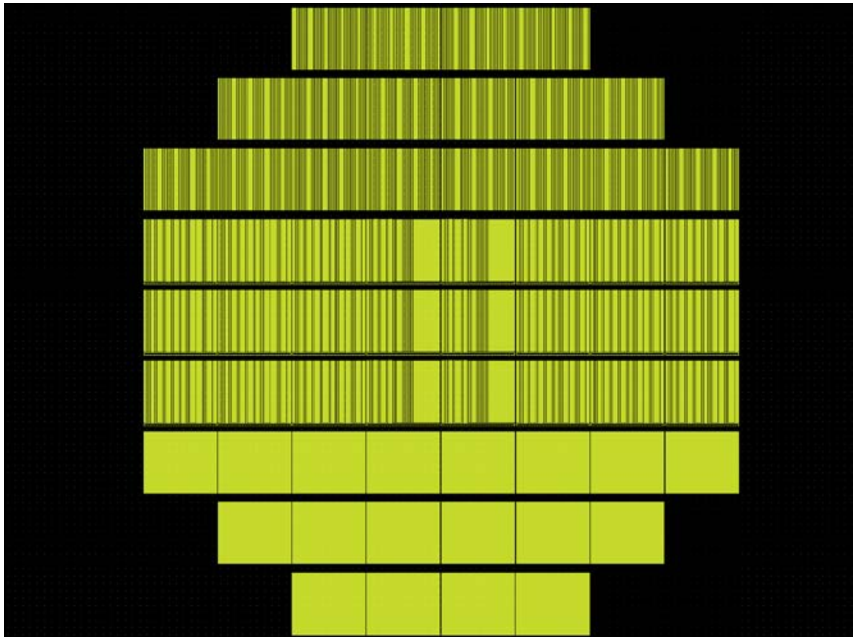


Fig. 6. Microphotograph of the surface of the ATLAS FEI3 chip after deposition of gold. One of the 50 x 400-micron cells is outlined. The entire chip, containing 2880 pixel cells, is 7.2 mm by 10.8 mm in surface dimensions and is 700 microns in thickness.

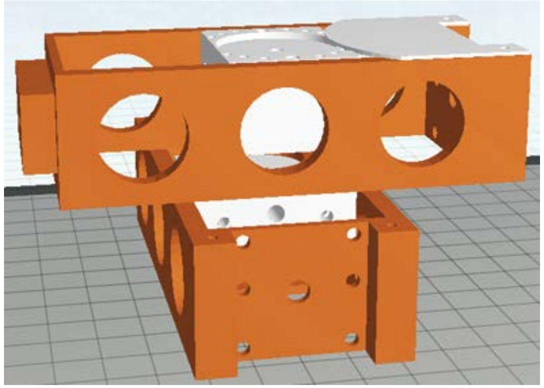
FE-I4: depositing a variety of metal pad shapes to study effect on effective gain (see backup slides)

ATLAS FE-I4 Wafer

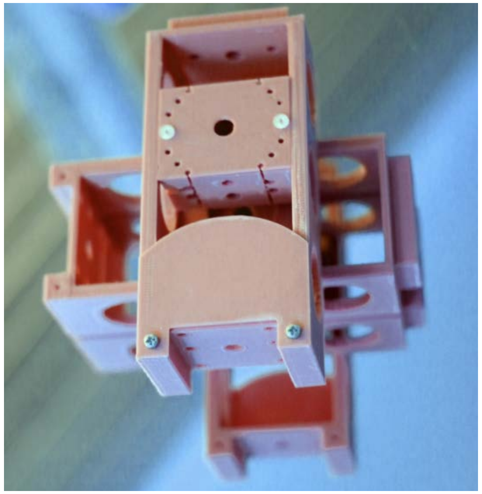


SiOxide between pad is insulating. Charging up at high gains & rates?
→ may explain both position and time-dependence

Studying Time /Position Dependence II

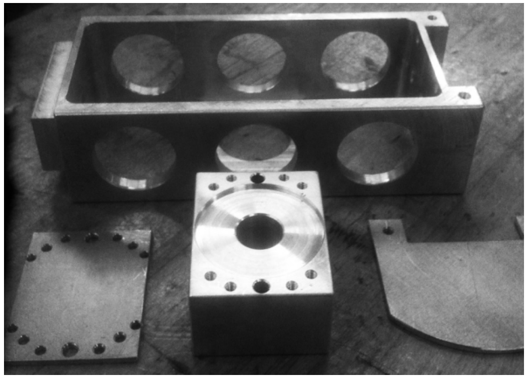


CAD design



3D-printed model

- Undergrad student designed 2D-motion stage for scanning collimated Fe-55 calibration source across chip
- Will allow us to measure position and time dependence of energy scale versus metal pad shape

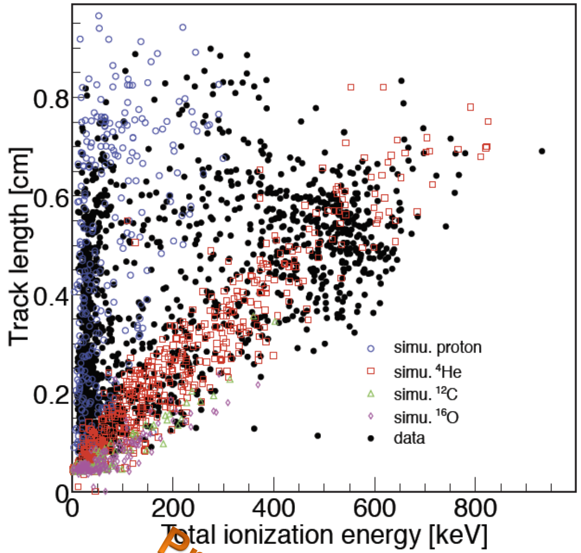


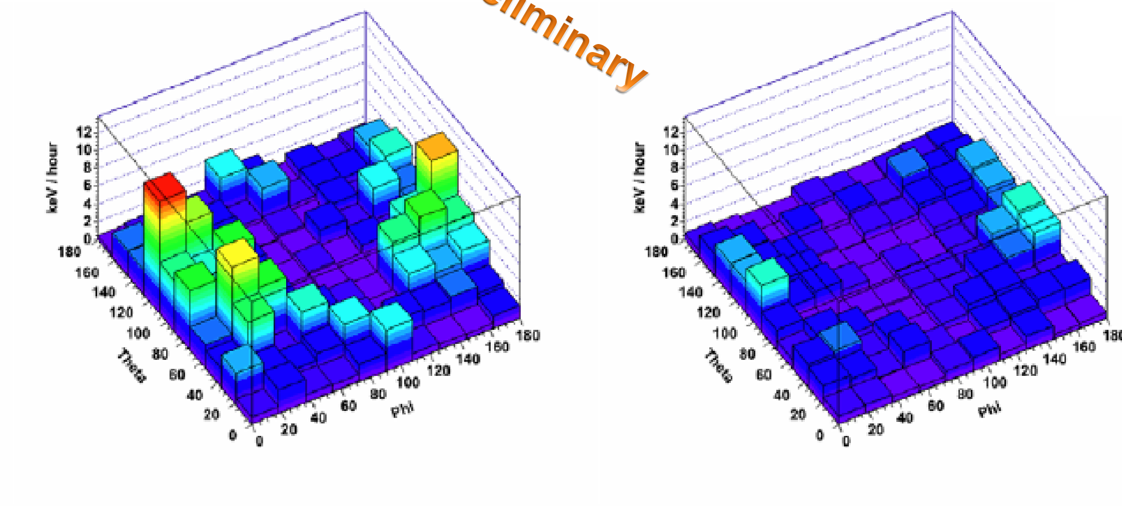
machined, final aluminum parts

Directional Neutron Detection

$HeCO_2$ at p=1atm

- **Cf-252 neutron source pointed at vacuum vessel. Can we locate it?**
- Rough agreement with simulation
- Expect broad recoil-angle distribution
- When source present, observe increased energy-flux in expected direction (Θ=90, ϕ=20-30 degrees)
- Encouraging, but analysis still ongoing
- We have already recorded a number of additional datasets with source at different angles, see if we can track it.

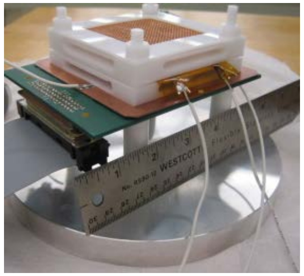




(a) Source ON (b) Source OFF

Next Generation Detectors

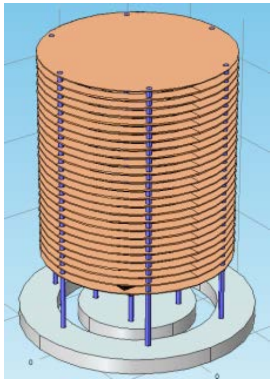
Built, stable operation for > 1 year



μD^3 ($1 cm^3$)

1 pixel chip

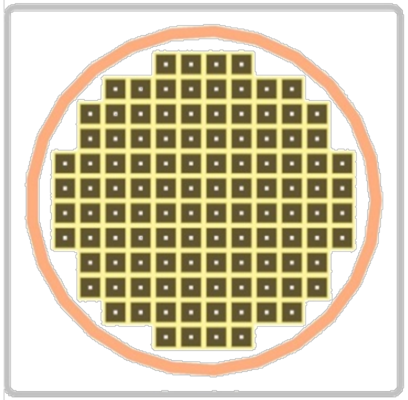
building this year



mD^3 (~10 liters)

4 pixel chips

planned



D^3 (~$1 m^3$)

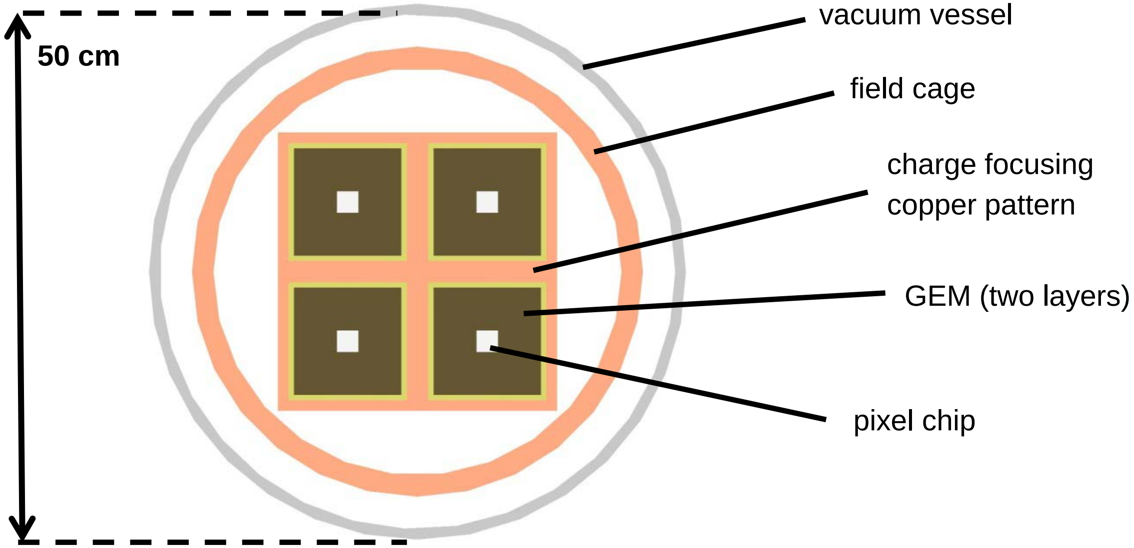
~400 pixel chips

Ingredient

1. larger pixel chips
2. electrostatic focusing of drift charge
3. existing ATLAS DAQ
4. negative ion drift

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.

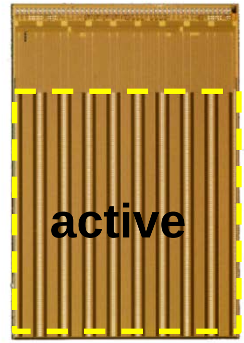
Two possible ways to reduce # chips

Larger pixel chips

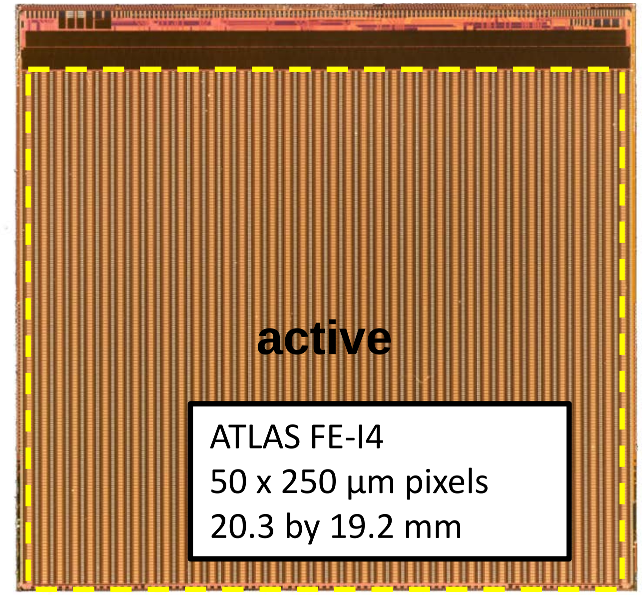
- ATLAS FE-I4: 10 x more pixels per dollar

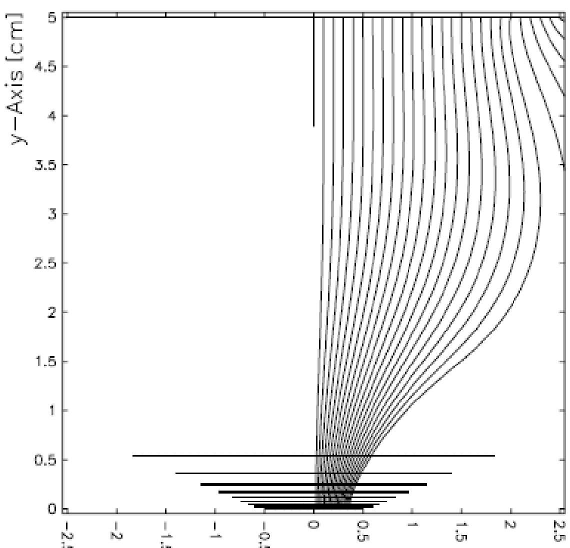
Focusing of drift charge

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



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



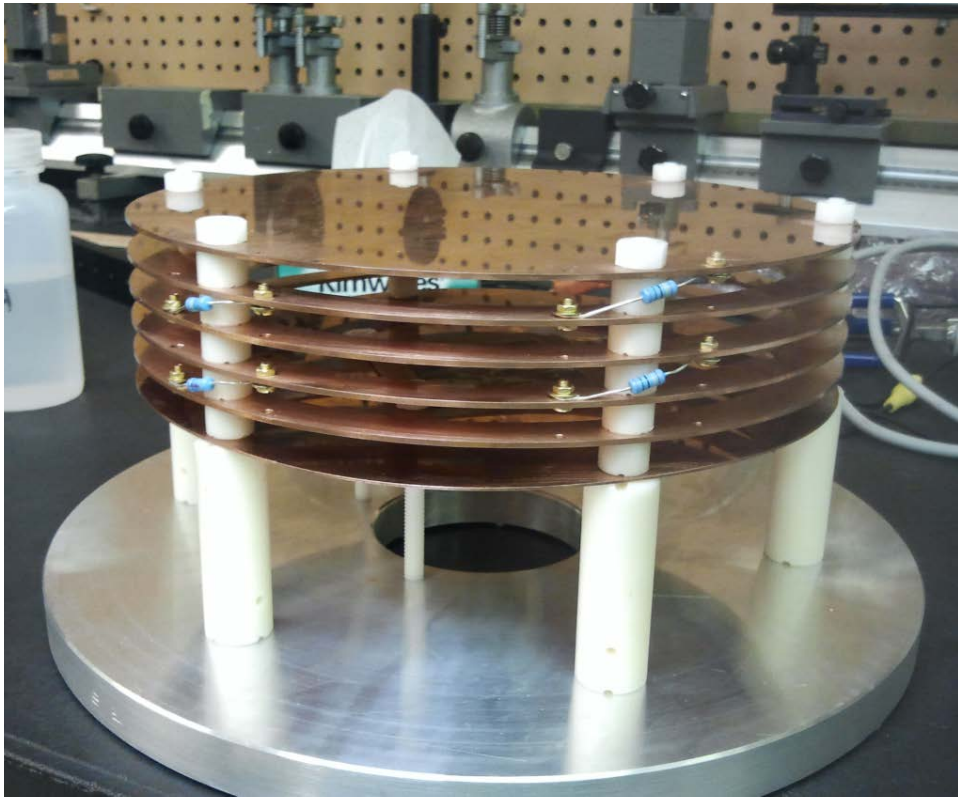


S. Ross et al., "Charge-Focusing Readout of Time Projection Chambers", proceedings of IEEE NSS 2012

Detectors with FE-I4 Pixel Chip

- FE-I4 single chip TPC card developed at Hawaii
- LBNL currently attempting first operation with this chip in their TPC
- Hawaii to operate larger mD^3 detector this fall – components under production

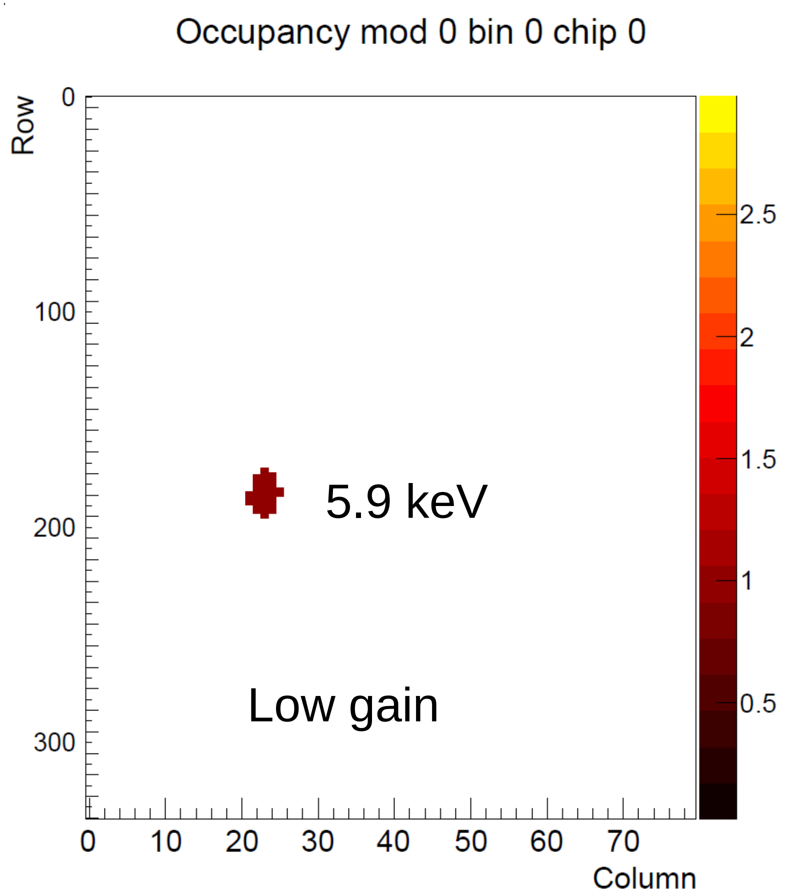
- Field cage

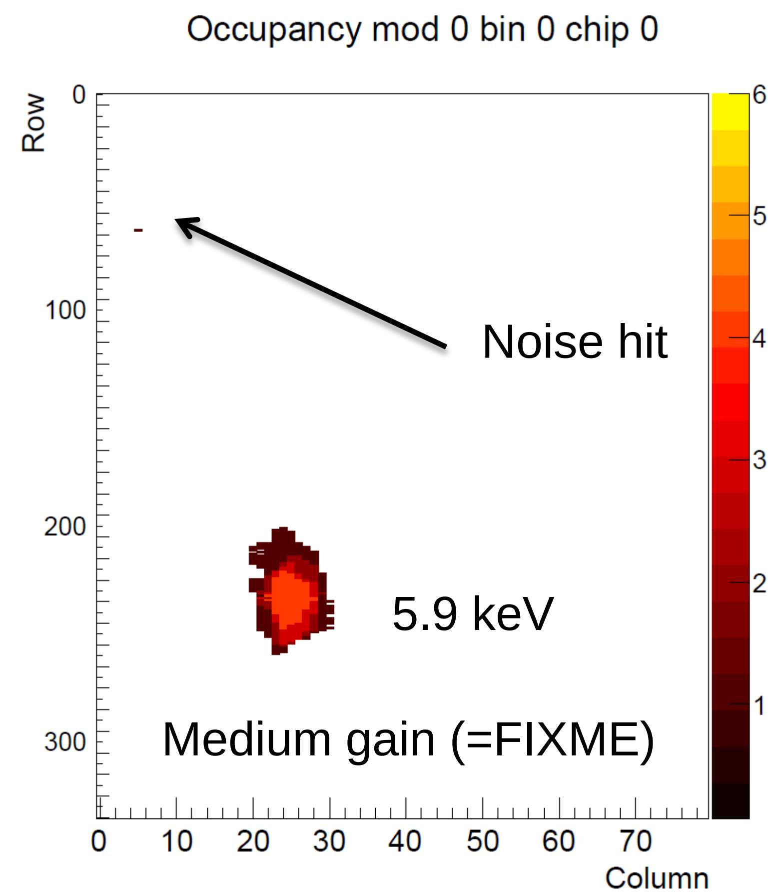


- FE-I4 TPC card

First events with larger pixel chip; FE-I4

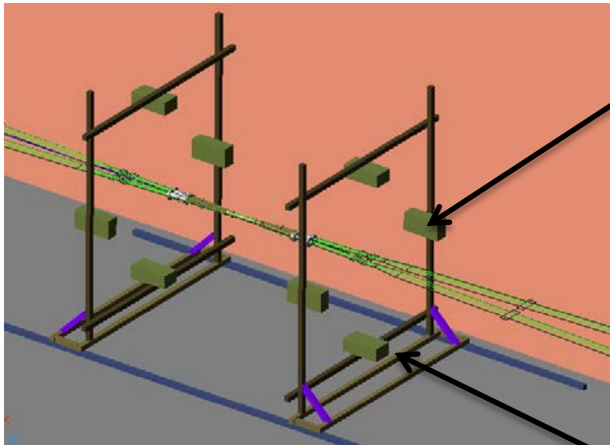
- Recorded at Berkeley Lab just last Friday - 6/7/2013
- Theses are self-triggered raw data – no noise suppression!
- Looks better than FE-I3 – no column dependence





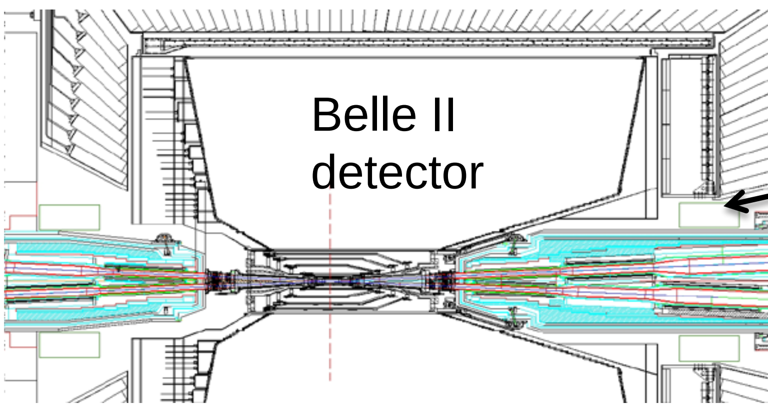
Broader Impacts: Neutrons at SuperKEKB

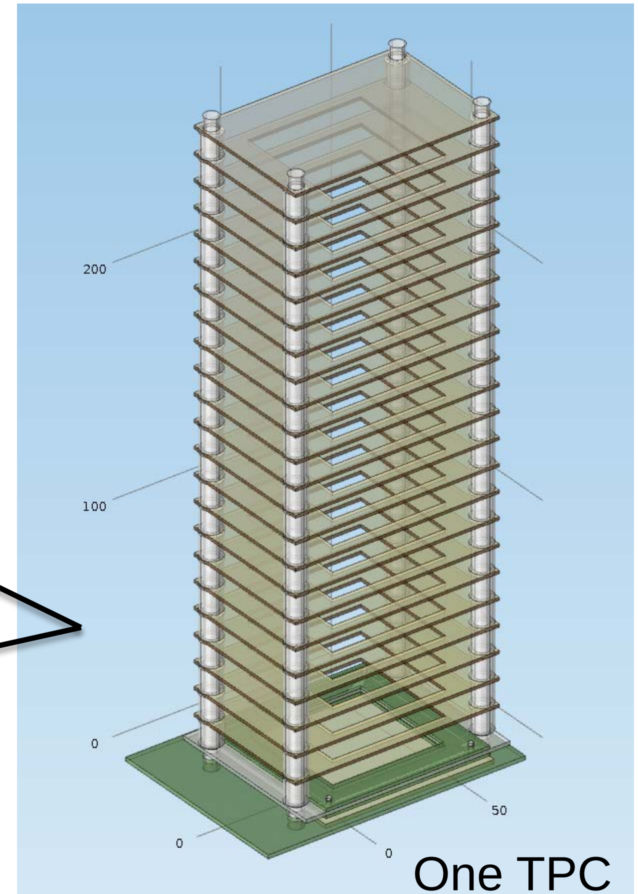
Commissioning Phase I – Jan 2015



SuperKEKB beam lines

Commissioning Phase II – Summer 2015





Fast neutrons are important beam background component at SuperKEKB e^+e^- collider
→ Will measure with eight neutron-TPCs; 25 cm drift lengths, 4 pixel chips each

Conclusion

- m^3-scale gas TPC w/ low energy threshold may be sufficient to investigate hints for low-mass WIMPs w/ directionality
  - GEM + pixel readout promising technology for this application
  - 3D tracking, single electron sensitivity
- Characterization of 1-cm^3 prototype "D^3-micro" nearly complete
  - Excellent performance at 1 atm
  - Some mysteries related to energy scale still under investigation
- Moving on to low-pressure operation, larger detectors, and next generation pixel chip this year