Recent progress on the Directional Dark matter Detector - D^3

Igal Jaegle

University of Hawai'i at Mānoa

for the D^3 Collaboration

9th PATRAS Workshop on Axions, Wimps, and WISPs
Schloss Waldthausen Mainz
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Layout

- D^3 Collaboration
- Directional Dark Matter Detection with Gas TPCs
- daily oscillation
- low-pressure operation
- low-noise and low-threshold
- preliminary reach plot
- micro-D^3 prototype setup
- track demonstration
- future plan
- conclusion

D^3 Collaboration

Youngest directional dark matter detection effort, R&D started in 2010.

- University of Hawaii at Mānoa

  Kamalu Beamer, Michael Hedges, Igal Jaegle, Marc Rosen, Steven Ross, Ilsoo Seong, Thomas Thorpe, Jared Yamaoka, Sven E. Vahsen

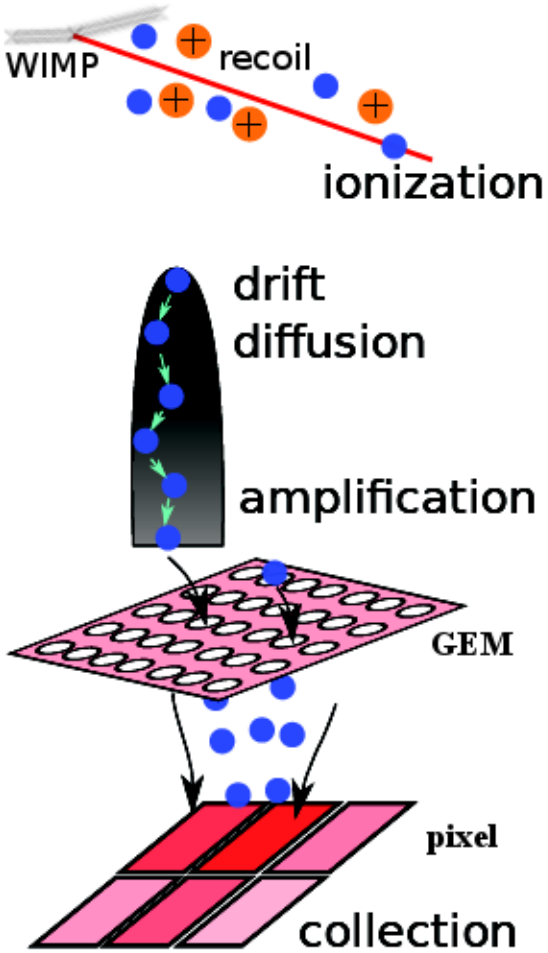
- Berkeley Lab

  John Kadyk, Maurice Garcia-Sciveres, Marya Lopez-Thibodeaux, Kelsey Oliver-Mallory

student, Post-Doc, senior engineer, Principal Investigator

Directional Dark Matter Detection with Gas TPCs

Time Projection Chamber as WIMP detector filled with gas



S.E. Vahsen et al.
http://arxiv.org/abs/1110.3401

- WIMP would not detected directly
- but through their scattering product with
- the gas-nucleus by elastic scattering: $\chi + A_{rest} \rightarrow \chi' + A_{recoil}$
- nuclear recoil ionizes gas along track
- electric field moves charges
- amplification (by 2 or 3 Gas Electron Multipliers - GEMs)
- readout (FE-I3 or FE-I4 ATLAS pixel chips)
  - 2D charge distribution
  - + timing information
  - + known drift velocity => 3D hit information

=> we reconstruct the nuclear recoil

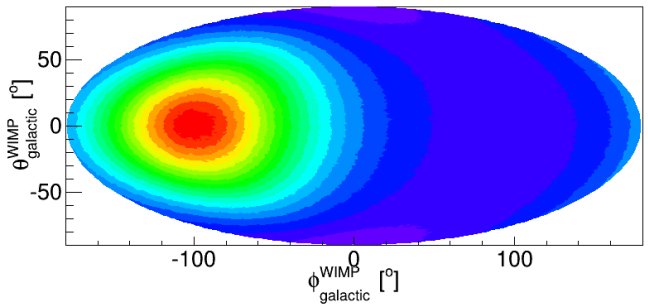
- low target mass, normally need very large gas volume
- but low track reconstruction threshold changes situation for low-mass WIMPs with only 1-10 m^3 volume
- several groups attempting directional detection with gas TPC. Advantages of our approach are:
  - 3D tracking => better DM identification & alpha BG rejection
  - single electron efficiency => expect very low track-recons. threshold
  - basically free of noise

Daily oscillation

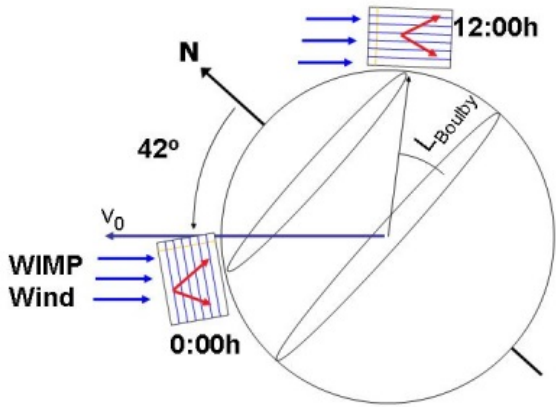
If annual modulation observed by DAMA/LIBRA is caused by WIMPs due to:

- Earth's orbit around the Sun as the Sun orbits the galactic centre
- since Earth's rotatation a daily oscillation in the mean direction of the WIMPs must be observed as well
  - passing from TPC coordinate to galactic coordinate enforce daily osciallation
  - at least 10 recoil events to measure WIMP direction
    => strong constrain, no known background with this signature

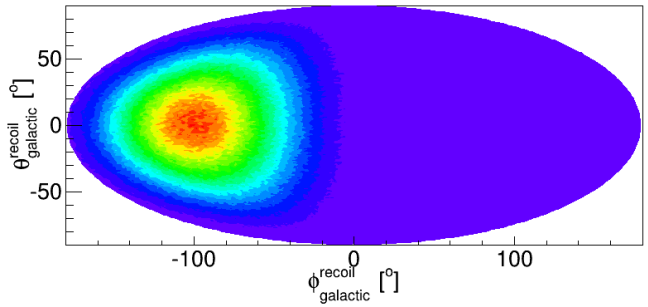
- WIMP flux in galactic coordinate



- daily oscillation scheme



- F recoil angular distribution in galactic coordinate



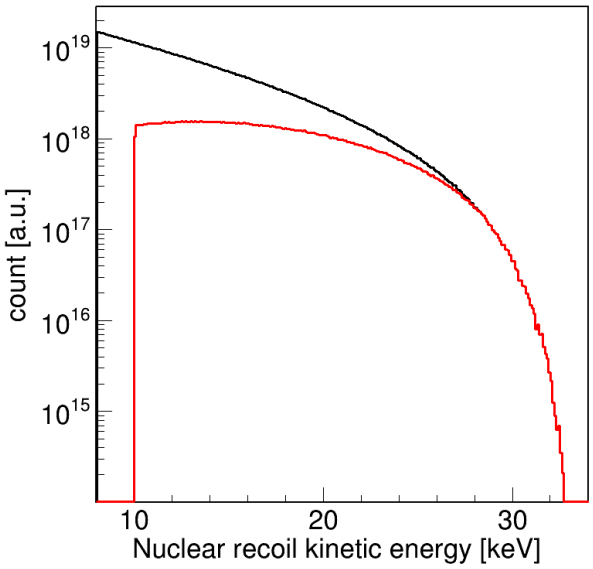
=> use daily oscillation to clean and identify the WIMP signal

Low-pressure operation

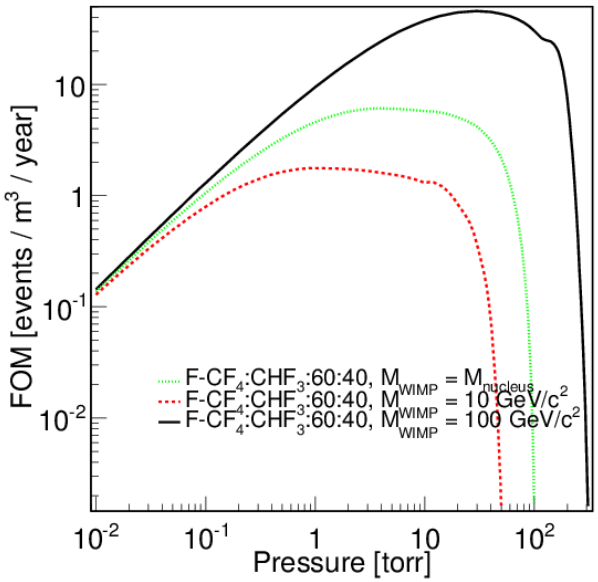
To measure low WIMP mass, eg 10 GeV/c^2:

- gas with target nucleus close to wanted WIMP mass and TPC friendly
  $\Rightarrow$ Fluorine as target and gas CF_4 or gas mixtures CF_4:CHF_3 or CF_4:CS_2
- operate at extremely low-pressure, increase track length, L(at P) = L(at P_0) x $\frac{P_0}{P}$,
  but diffusion σ(at P) = σ(at P_0) x $\sqrt{\frac{P_0}{P}}$
- find best trade off between the target mass and track length so that the directional sensitivity is maximized I. Jaegle et al. http://arxiv.org/abs/1110.3444

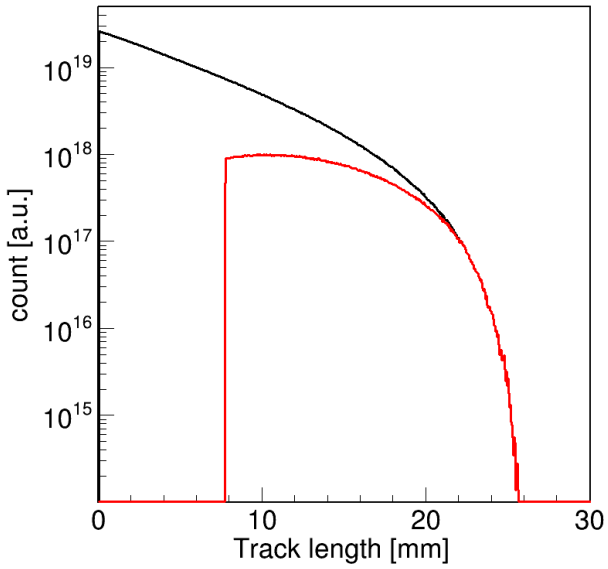
- F recoil kinetic energy
  red line: 3D-dir. and 10 keV thres.



- optimal pressure
  $\Rightarrow$ 1.5 torr for 10 GeV/c^2 WIMP



- F track length at 1.5 torr
  red line: 3D-dir. and 10 keV thres.



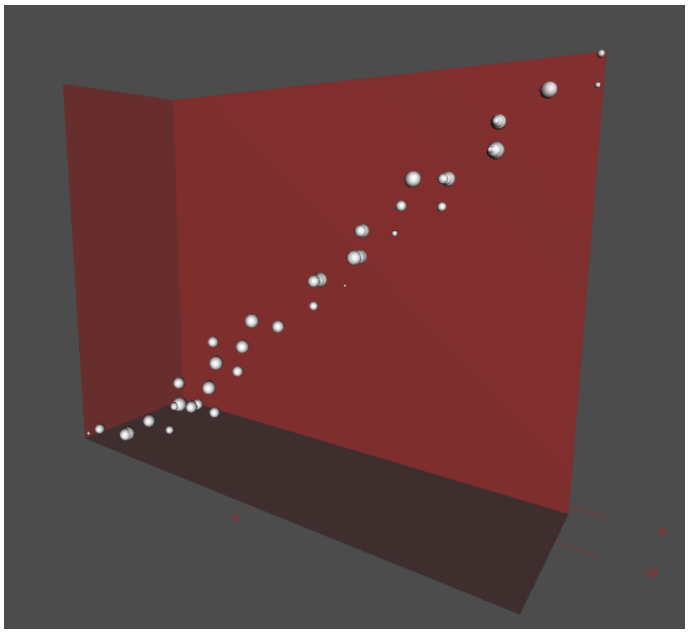
- operation at low-pressure with high gain $\sim$ 100k has been demonstrated in A.Breskin et al., NIM 217, 131 (1983), NIMA 433 476 (1999) and C.K. Shalem et al., NIMA 558 468-474 (2006)

ATLAS Pixel Chip electronics: low-noise and low-threshold

High gain + ATLAS Pixel Chip electronics allows full 3D tracking

- track range (position resolution)
- track dE/dx (topology)
- track total ionization energy (energy resolution)
- track direction (angular resolution)

- cosmic-ray trak: $\sim$ 7 mm and 2 keV measured by micro-D^3 prototype



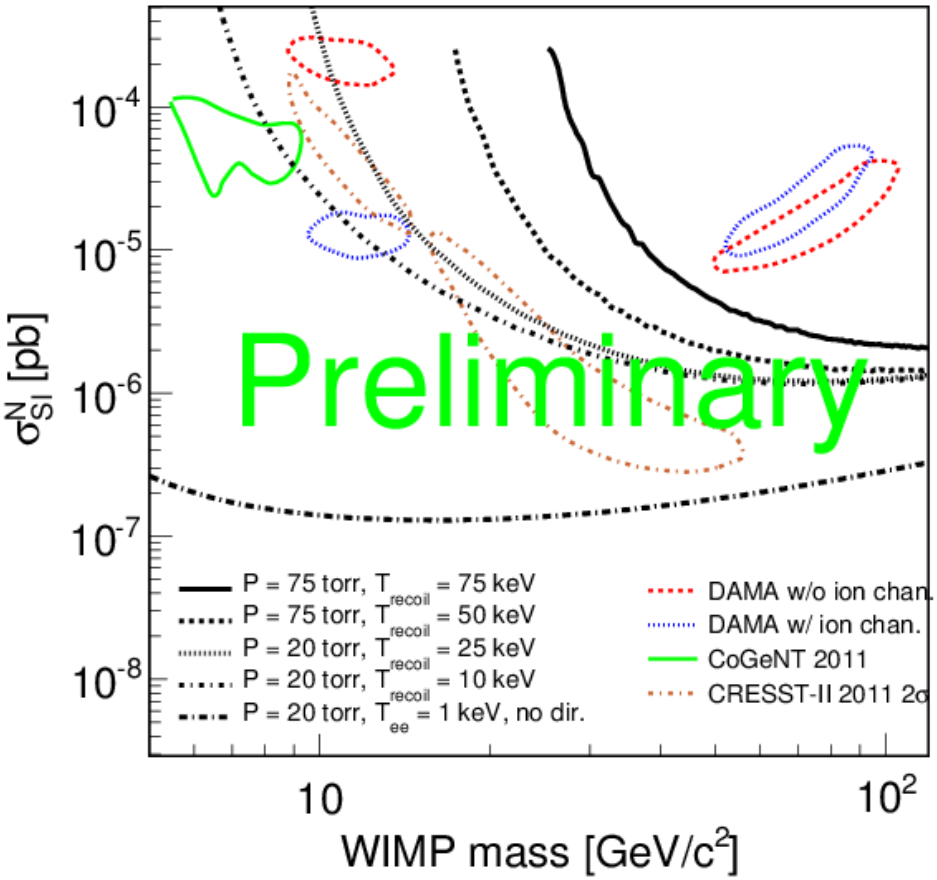
- FE-I3 in Hawaii setup
  - chip size 0.84 cm x 0.76 cm
  - pixel size 50 μm x 400 μm
  - 18 column x 160 row
  - 400 ns time range with 16 graduation
  - threshold 3000 e^-
  - 100k e^- charge range with 128 graduation
- FE-I4 in Berkeley setup
  - chip size 2 cm x 1.68 cm
  - pixel size 50 μm x 250 μm
  - 80 column x 336 row
  - 1600 ns time range with 64 graduation
  - thresold 1400 e^-
  - 100k e^- charge range with 16 graduation

- virually no noise
- high-single electron efficiency => suitable for low-mass WIMP search

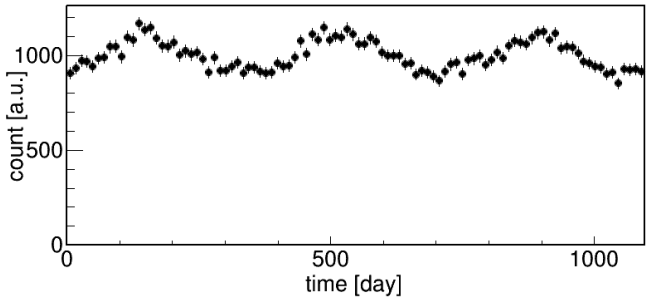
Preliminary reach plot for 3 years and 3 m^3

Preliminary reach plot shows advantages of low track energy threshold and possible golden scenario

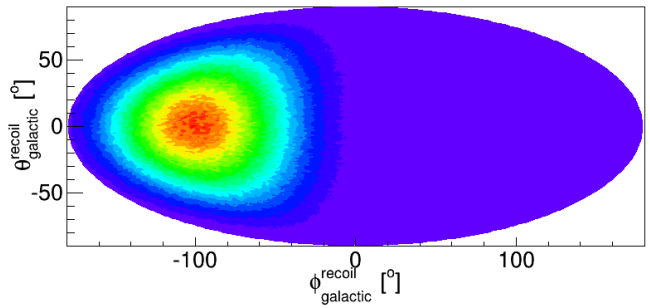
- observe annual modulation
- sub-sample of data for daily oscillation search



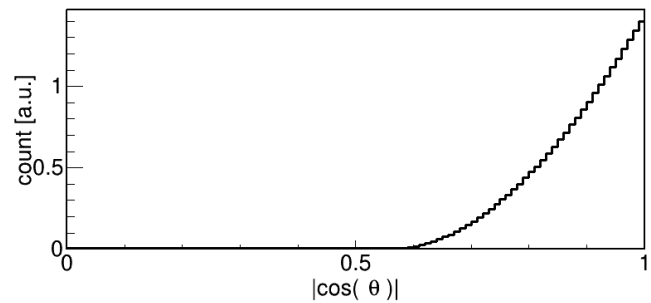
- annual modulation



- F recoil angular distribution in galactic coordinate



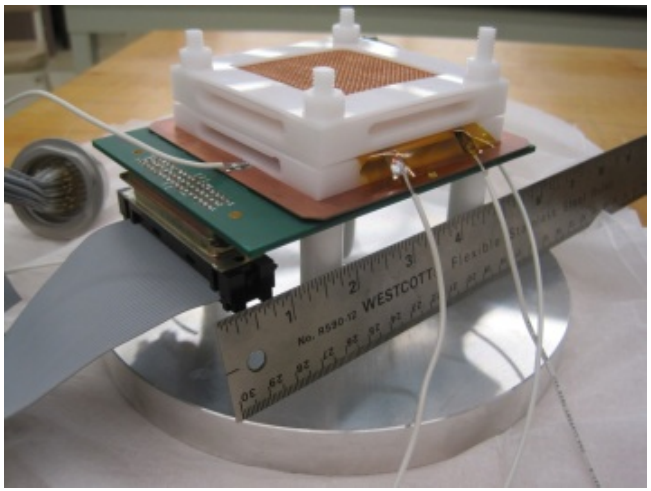
- angle between F recoil and WIMP direction



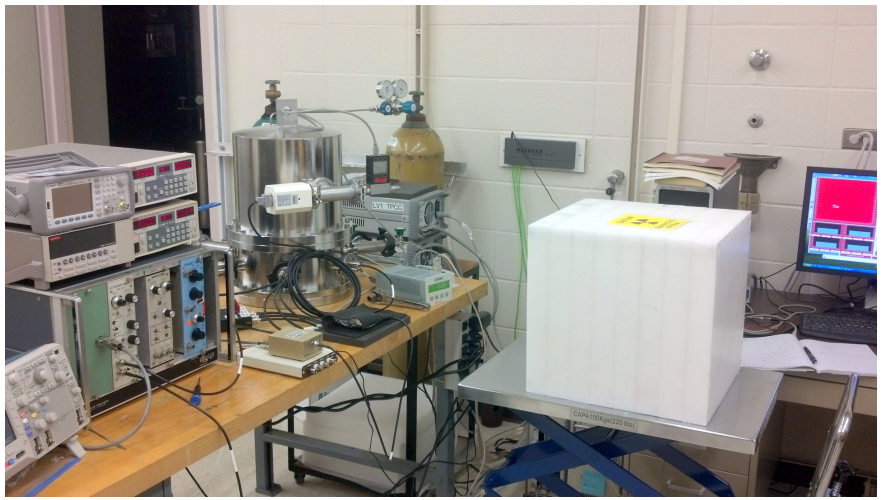
micro-D^3 setup

- volume 0.61 cm^3
- charge amplified by 2 GEMs
- detected by ATLAS Pixel Chip FE-I3

- inside vacuum vessel



- vaccum vessel + neutron source

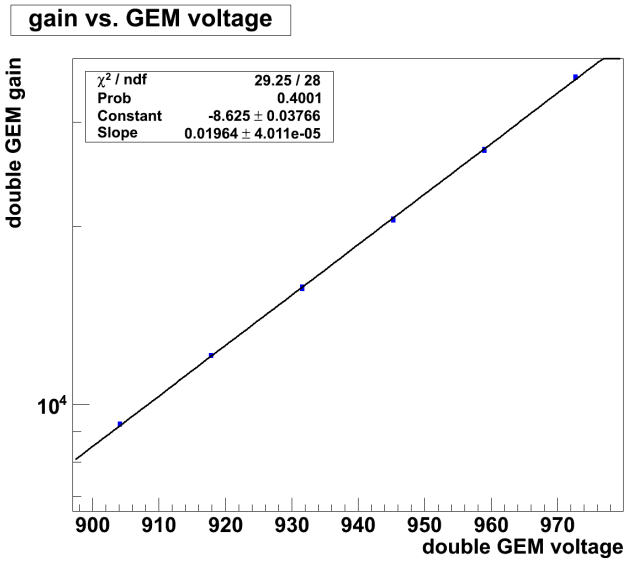


- stable operation for more than a year, large datasets recorded
  - commissioning w/ Ar:$C0_2$:70:30; muons, x-rays, alpha-particles (11,12)
  - detailed calibration & directional neutron detection w/ He:$C0_2$:70:30 (Fall 12-now)
- low-pressure operation w/ CF_4, WIMP search surface-run starting this summer

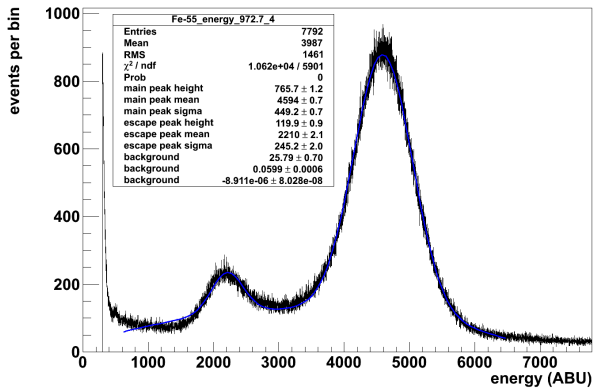
Gain resolution and stability

High gain w/o sparking for weeks, measurement w/ pulseheight analyzer

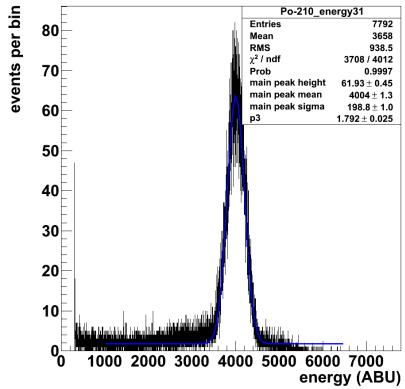
- gain vs voltage



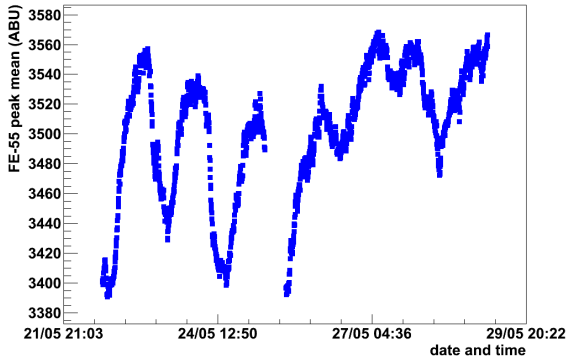
- ^{55}Fe/x-rays source
  σ_{gain} = 11 % at 3 keV
  σ_{gain} = 8 % at 5.9 keV



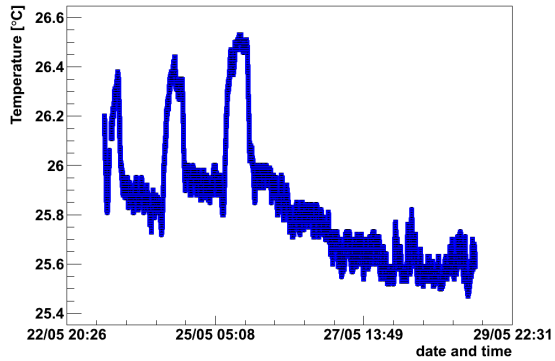
- ^{210}Po/alpha source
  σ_{gain} = 5 % at 5 MeV



- 5.9 keV x-ray peak vs. time



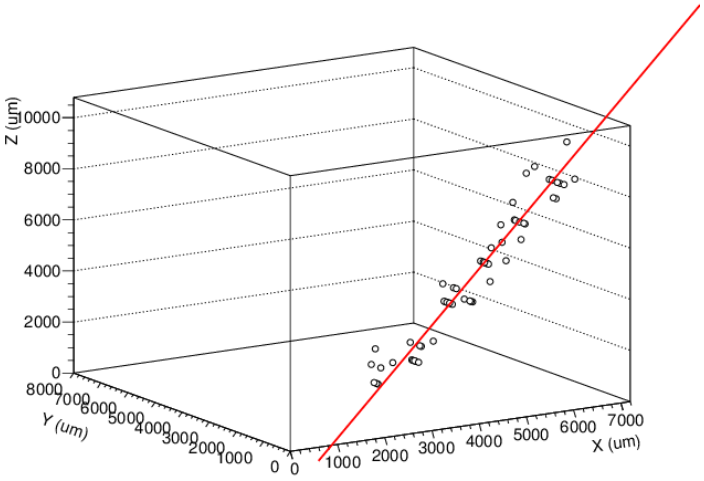
- temperature vs. time

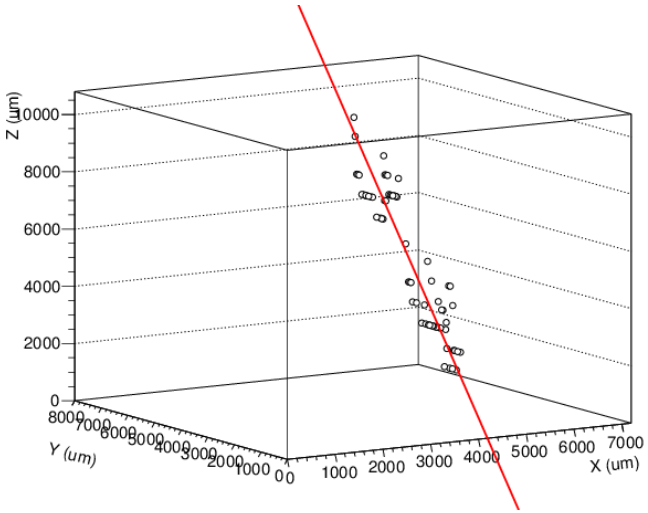


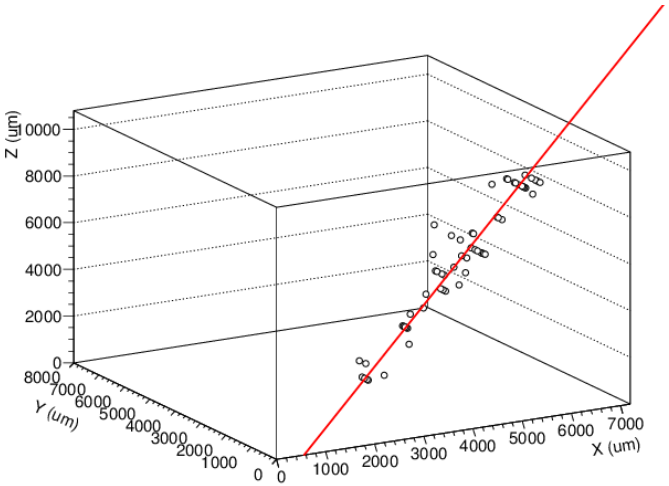
- sufficient gain to achieve single-electron sensitivity if needed
- good gain resolution for MeV-scale signals, adequate even for few-keV signals!

3D point resolution

10k events of cosmics recorded with Ar:CO_2:70:30 at 1 atm, use such events to measure detector point resolution ($< 200\ \mu$m)





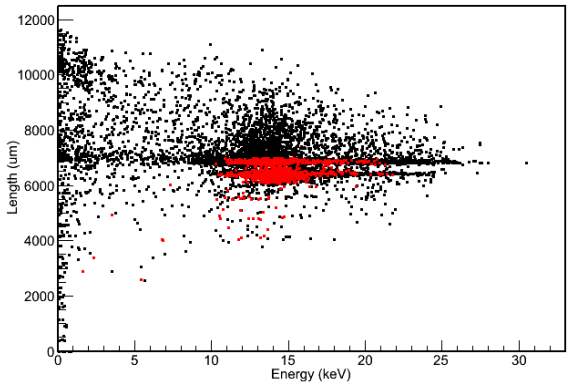


=> based on measured point resolution, expect angular resolution on nuclear recoils $\sim$ 1 degree

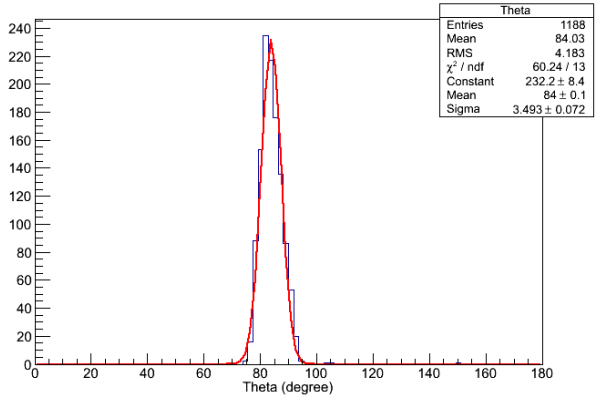
Angular resolution, nuclear recoils

^{210}Po alpha-source inside vacuum vessel, He:CO_2:70:30 at 1 atm, plots below show how well we can locate it:

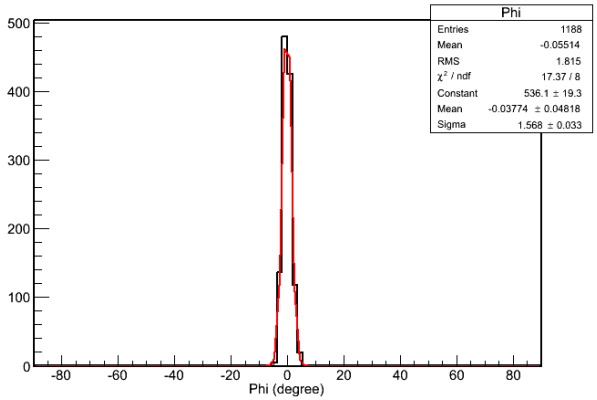
- track length vs. total ionization energy



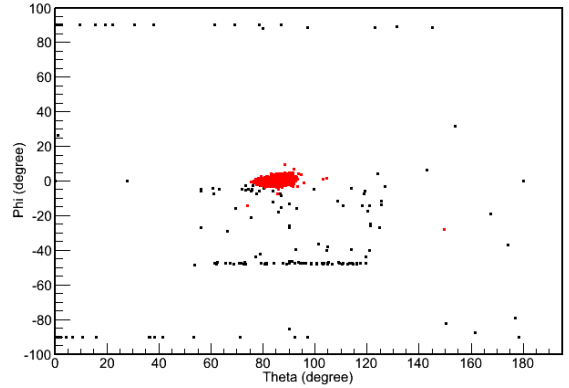
- polar angle distribution



- azimuthal angle distribution



- azimuthal vs polar angles

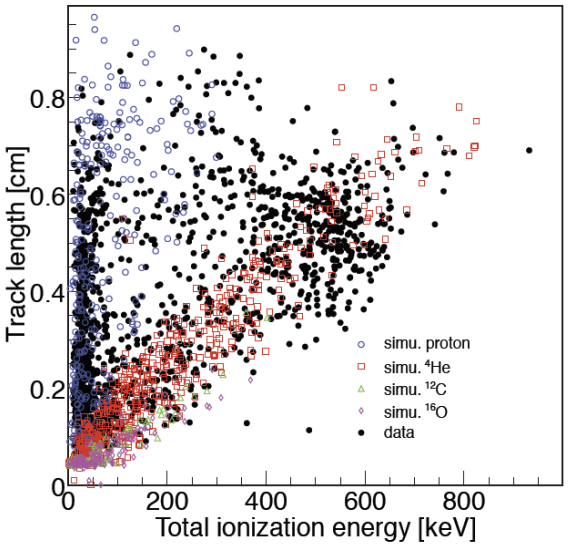


- selected events clearly point back to a single source
- No BG after good-track selection
- consistent with $\sigma(\theta,\phi)$ detector $< 1^o$

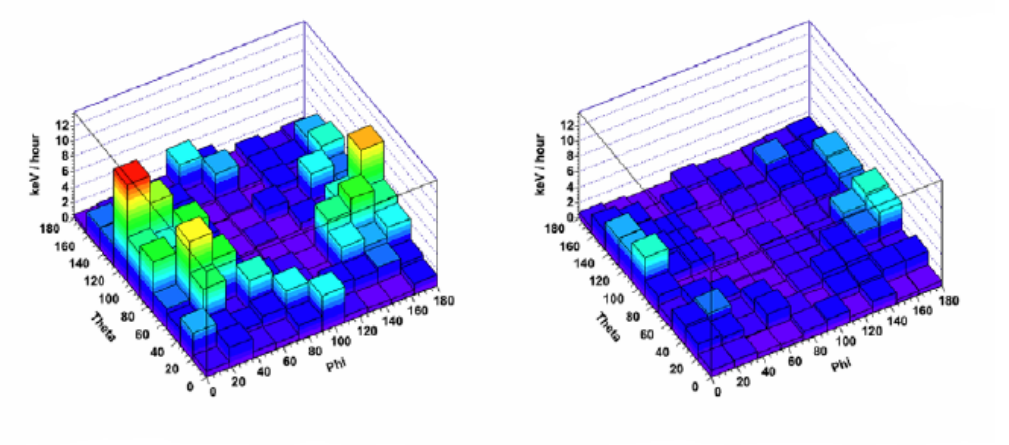
Directional neutron detection with He:CO_2:70:30 at 1 atm

- ^{252}Cf neutron source pointed at vacuum vessel. Can we locate it?
- rough agreement with simulation
- expect broad recoil-angle distribution

- dE/dx, track length vs total ionization energy



- azimuthal vs polar angles: source ON and OFF



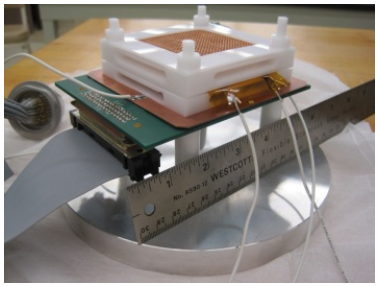
(a) Source ON (b) Source OFF

- when source present, observe increased energy-flux in expected direction (θ=90^o, ϕ=20-30^o)
- encouraging, but analysis still ongoing
- we have already recorded a number of additional datasets with source at different angles, to see if we can track it.

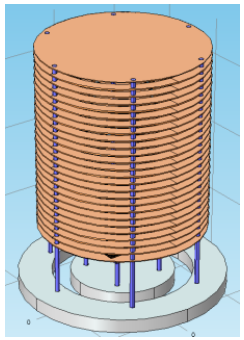
Future plan

Building this year a 10l volume detector

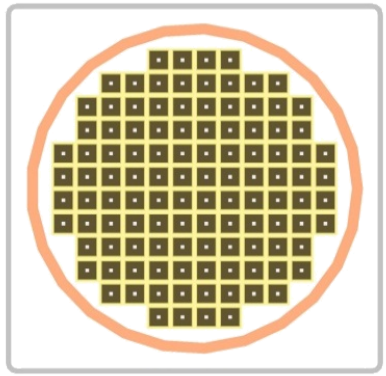
- build and run smoothly



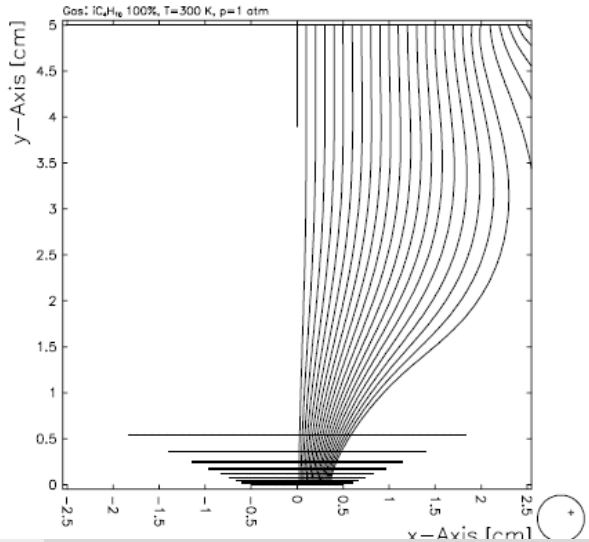
- building this year



- planned



- electrostatic focusing of drift charge
  S.Ross et al. IEEE proceedings 2012



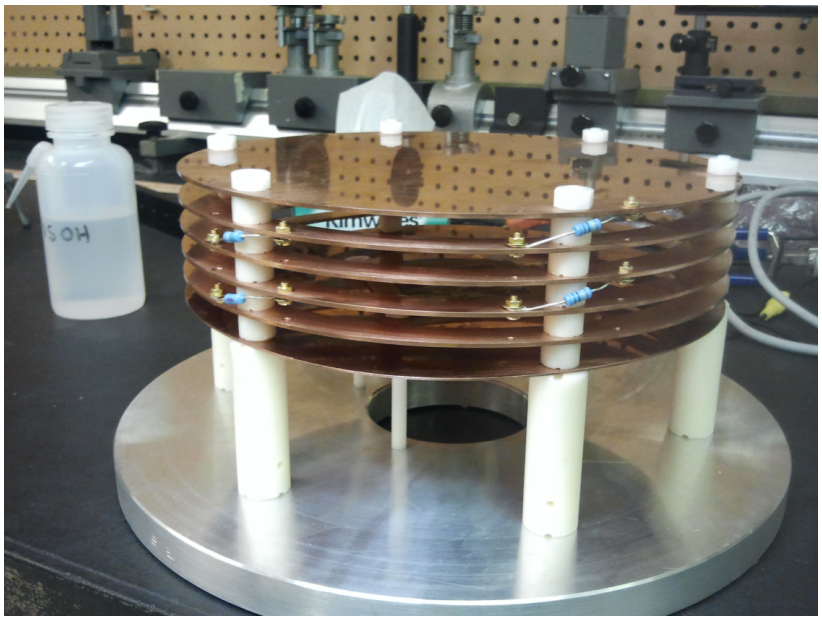
- to reduce the readout price
  - larger pixel chips
  - electrostatic focusing of drift charge
- existing ATLAS DAQ
- negative ion drift or gas w/ slow drift velocity

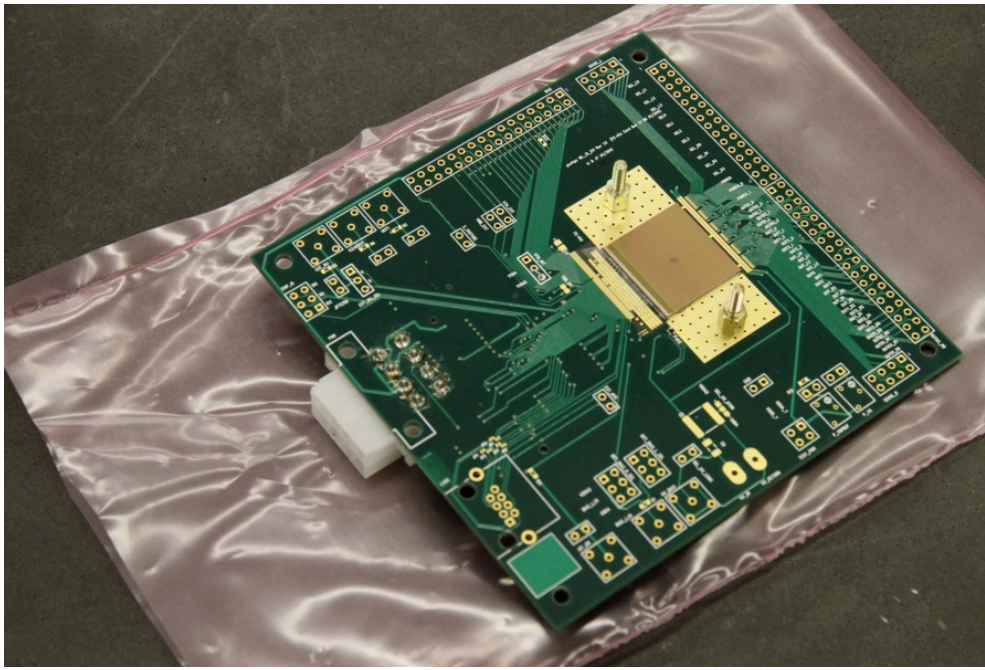
Detectors with FE-I4 Pixel Chip

- 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

- FE-I4 Pixel Chip developed in Hawaii

- detector under production



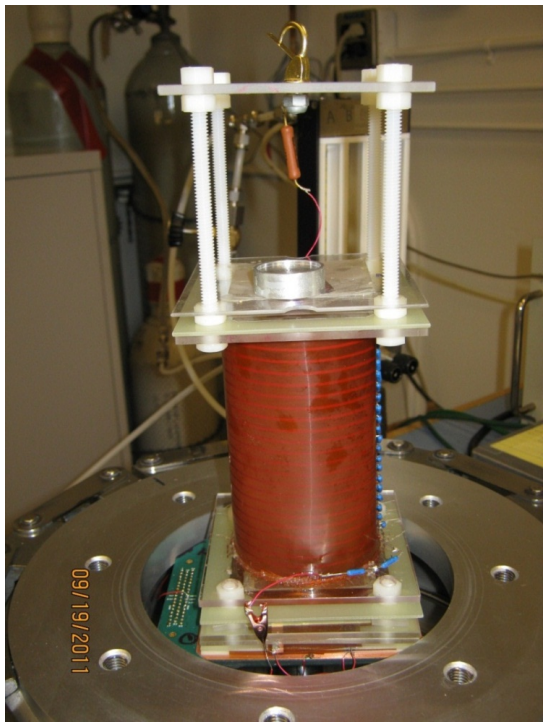


First events with larger Pixel Chip FE-I4

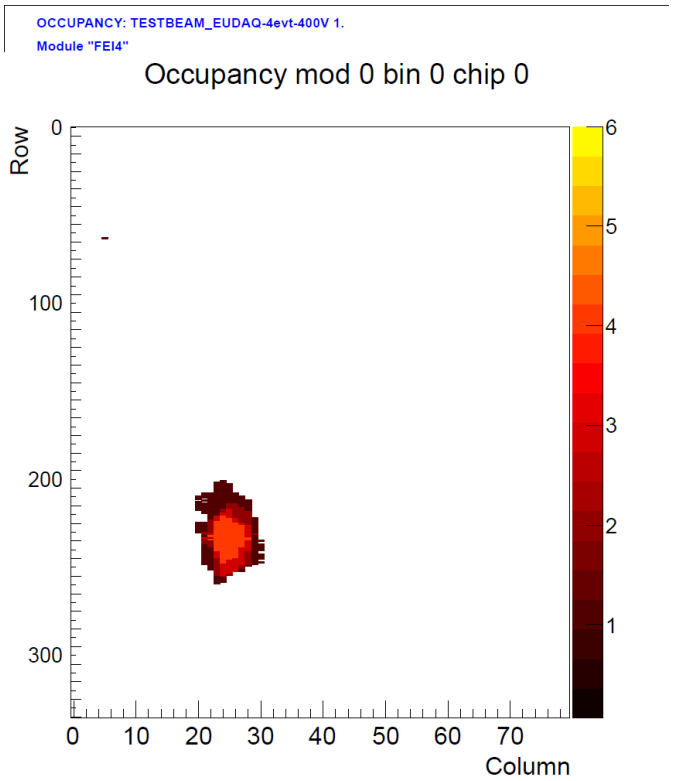
Recorded at Berkeley Lab at the beginning of this month

- Ar:CO_2:70:30 at 1 atm
- ^{55}Fe source
- high gain

- Berkeley setup, 12 cm drift distance



- first event w/ FE-I4



Conclusion

- 1-10 m^3-gas-volume with low energy threshold may be sufficient to investigate hints for low-mass WIMPs with directionality or/and possibly identified background source(s) that caused the annual modulation
  - GEM + pixel readout promising technology for this application
  - 3D tracking, single electron sensitivity
- test of 0.6-cm3 prototype micro-D^3 almost finished
  - excellent performance at 1 atm
  - moving on to low-pressure operation, larger detectors, and next generation pixel chip this year
- measured alpha recoil in micro-D^3