The Directional Dark Matter Detector (D^3)

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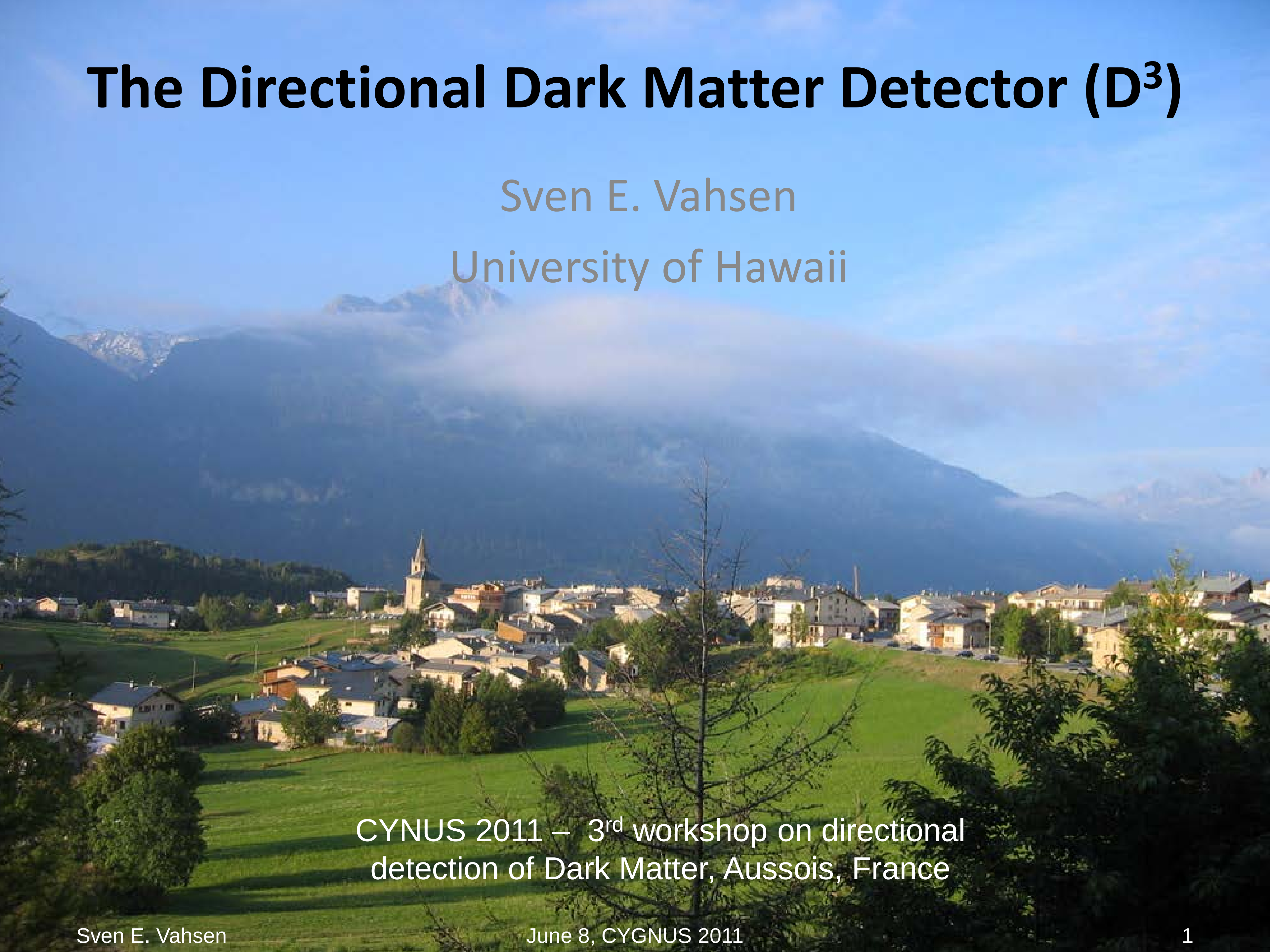

CYNUS 2011 – 3rd workshop on directional detection of Dark Matter, Aussois, France

Presentation Contents

- Will discuss past, present and future of the D^3 project. We're currently at the 2^{nd} prototype stage ("D^3 micro").
  - Team
  - Detection Principle
  - Results from first prototype at LBNL
  - 2^{nd} generation prototypes at LBNL and UH
  - A New idea: Charge Focusing → Lower Cost
  - Plans for future detectors
  - Expected WIMP sensitivity
  - Other applications of Pixel TPCs
  - Conclusion

D^3 Directional Dark Matter Detector

Team at U. Hawaii and Berkeley Lab

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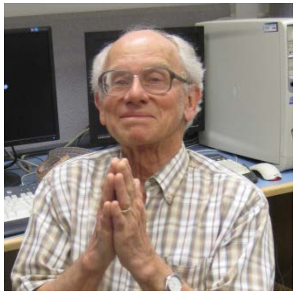
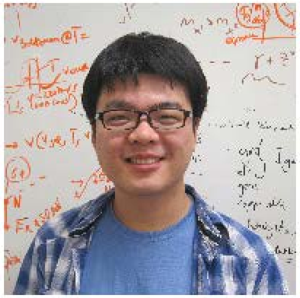


John Kadyk

Maurice Garcia-Sciveres



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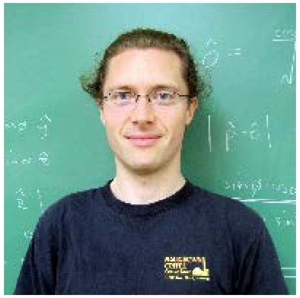


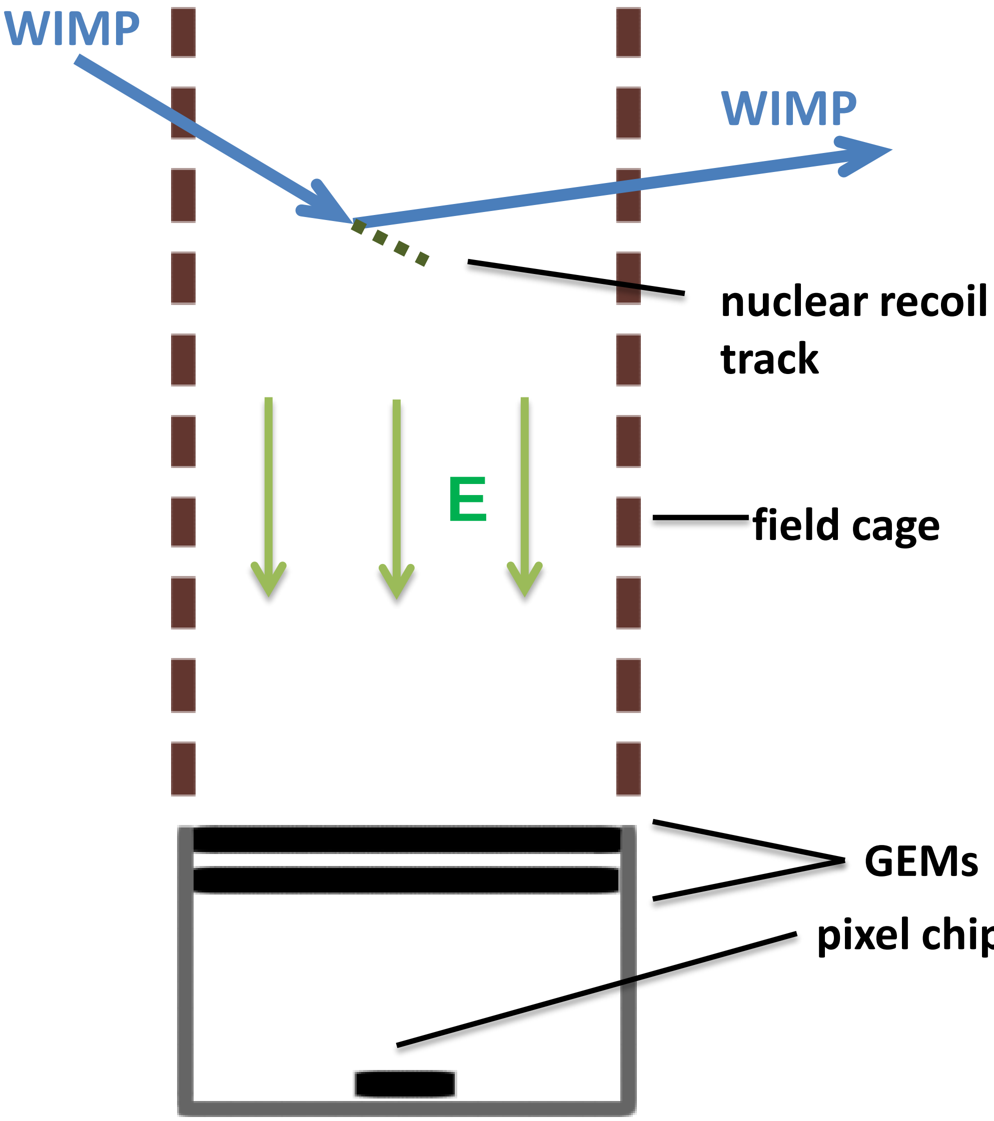
Thomas Thorpe
Unclassified Graduate Student

Sven E. Vahsen

Young Nguyen
(UC Berkeley Student)

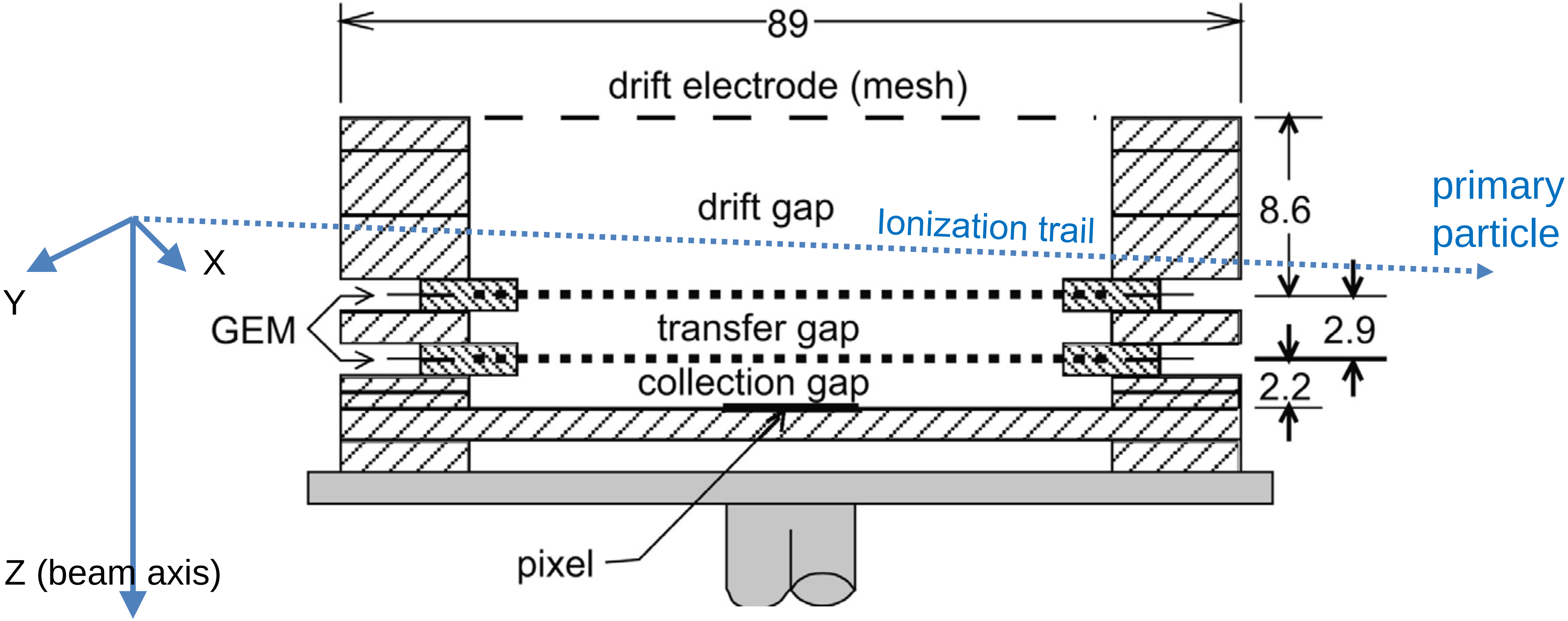
Detection Principle

- Goal: achieve directional sensitivity to WIMPs in low-pressure gas Time Projection Chamber (TPC) by measuring nuclear recoils in 3D
- For WIMP induced recoils, expect 12h directional oscillation → smoking gun signature
- Detector measures ionization; 3D direction of track & distribution of charge along track
  - Charge amplified with Gas Electron Multipliers (GEMs)
  - Charge detected with pixels
- New idea: charge focusing; potential for significant cost reduction of large detectors. First simulations promising.



First Prototype at Berkeley Lab

- Project led by John Kadyk
- Prototype small - dimensions in *mm!*
- *GEMS: 5x5 cm CERN. Pixels: ATLAS FE-I3*
- Built to investigate charged particle tracking at future collider (ILC)
- Recorded large sample of cosmic rays in 2007, published in 2008

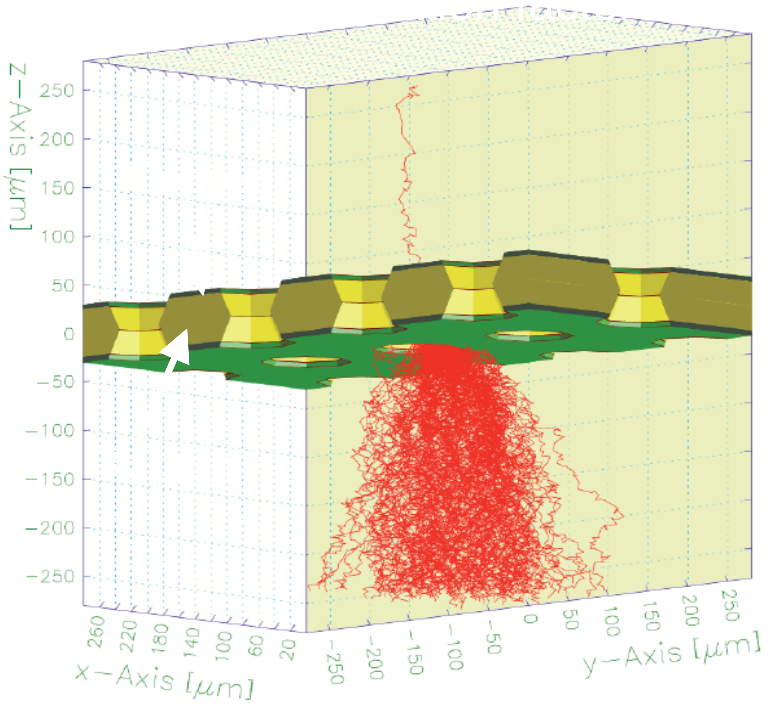


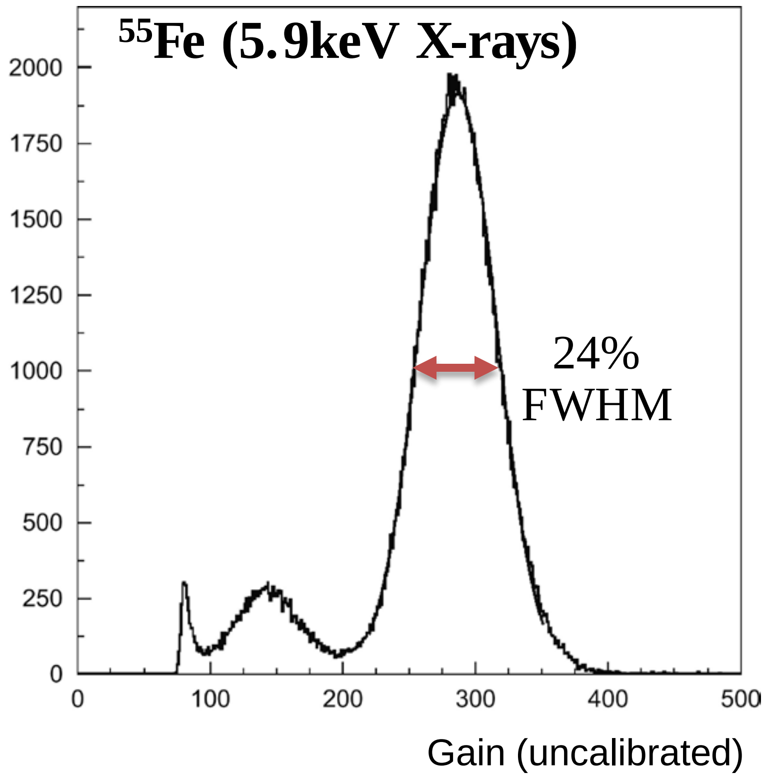
Readout of TPC tracking chambers with GEMs and pixel chip. T. Kim, M. Freytsis, J. Button-Shafer, J. Kadyk, S.E. Vahsen, W.A. Wenzel (LBL, Berkeley) . 2008. 12pp. NIM (2008)

Amplification: Gas Electron Multipliers (GEMs)

- Off-the shelf GEMs from CERN
  - 5cm x 5cm x 60 µm
  - Hole spacing: 140 µm
- Electrons multiplied by avalanching
- ~100% area efficiency

- Reliable without sparking with single-GEM gain up to 300 (Ar/CO_2)
- Two GEMS in series: higher gain with less risk of sparking:
  500V + 400V → gain = 40000



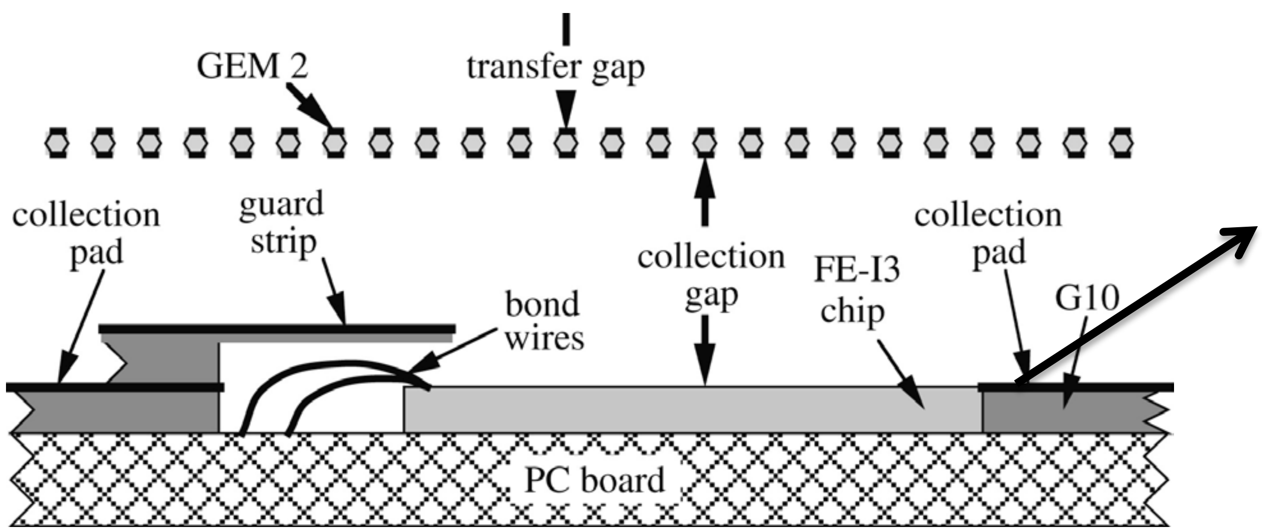


High gain, good resolution, stable, simulated and measured gain consistent

Charge Collection: FE-I3 Pixel Chip

- Same Front End Chip as used in ATLAS Pixel Detector, but Gold/Aluminum plated
- Developed at LBNL, over ~7 years
- 2880 pixels of 50x400 µm. Each pixel
  - tunable, analog amplifier w/ digital controls, digital output logic
  - measures position, arrival time and amount of incident charge
- x/y from pixel coordinate
- Relative z from drift-time (in units of 25ns)

- Same DAQ chain as during ATLAS pixel detector production
- Pixel chip in self-trigger mode
- Read out 16 time bins after trigger
  - 16x 25ns*26 µm/ns = 10.4 mm (Ar/CO_2, 1kV/cm)
- **Very low noise: ~120 electrons**
- **2-3 pixels out of 2880 masked → < 0.5 noise hits / hour / cm^2**



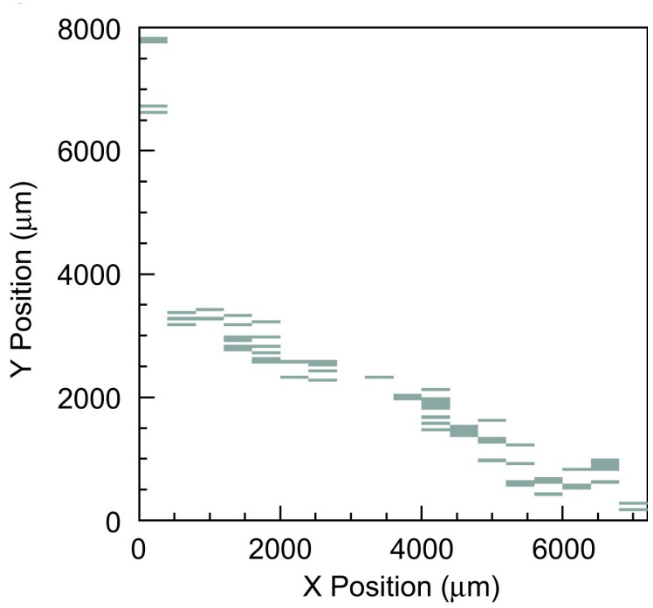
(connect pad to amplifier + pulse-height analyzer when measuring GEM gain)

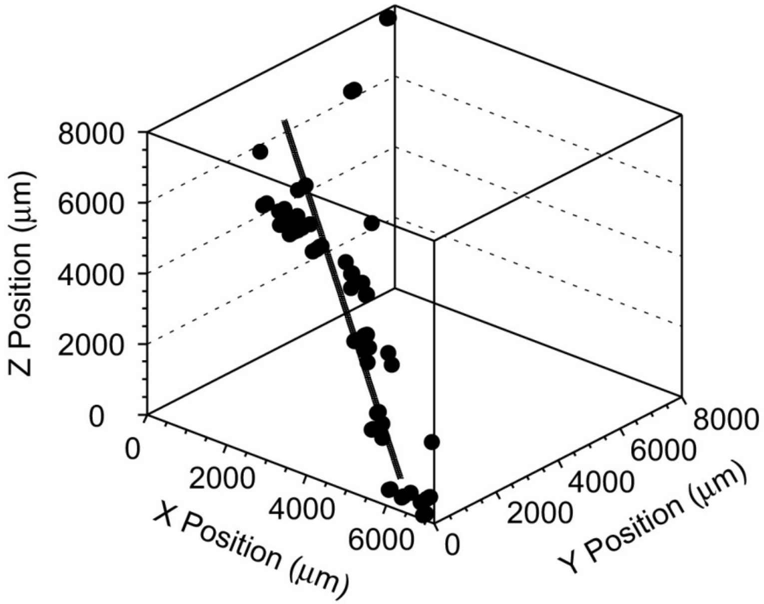
low noise level, compared to expected single-electron signal
low demand on downstream DAQ electronics when used for DM detection

Position Resolution with Cosmic Rays

- Large sample of cosmic rays
- Require >10 pixel hits
- 3D track at least 4.5mm long
- GEM Gain=9000, pixel threshold=1800e-

	track fit residual	Diffusion	$\sigma_{GEM+Pixel}$
σ_X (μm)	170	110	130
σ_Y (μm)	130	110	70
σ_Z (μm)	240	190	150

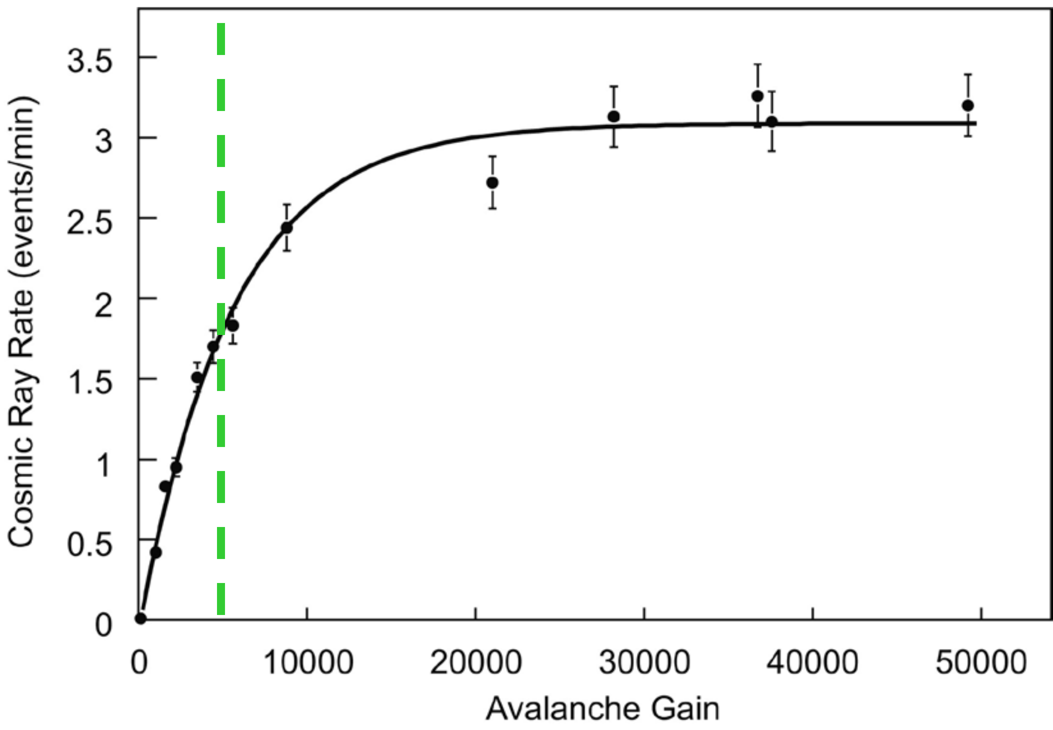




Unfolding diffusion, estimate single hit position resolution to 70 μm
(At collider detectors, would use magnet to keep diffusion < 100 μm.)

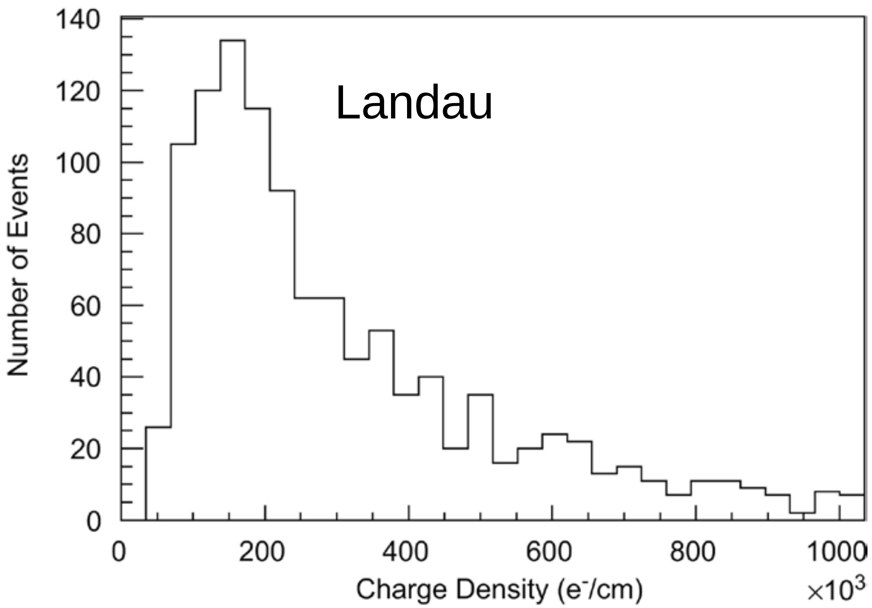
High Efficiency For Single Electrons?

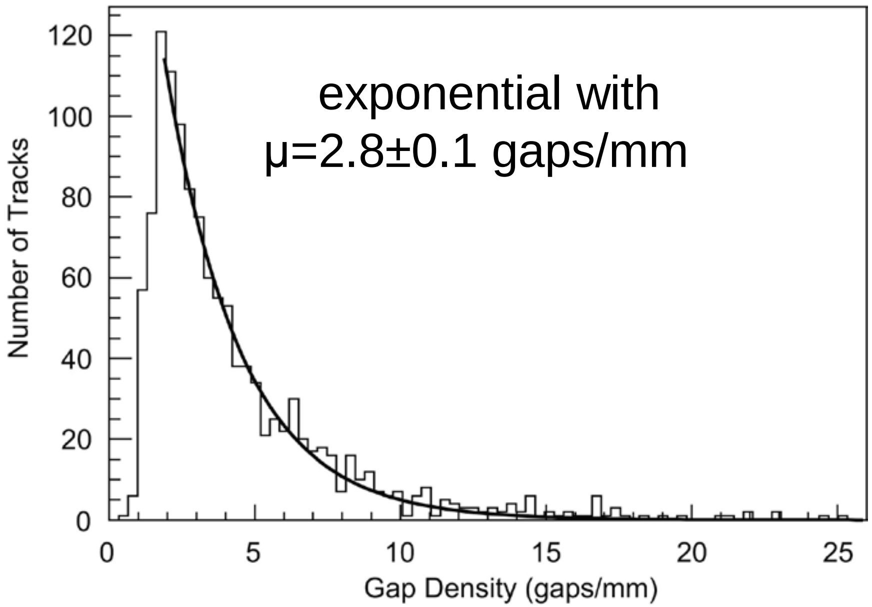
- Pixel threshold at 5k electrons
- Rate plateaus at gain ~20k
- 20k electrons per primary ionization electron, 4x more than pixel threshold
- *Suggest system is highly sensitive: capable of collecting all the ionization from primary track that reaches GEM - even single electrons!*
- *Caveat: Did not study pixel noise versus GEM gain – more work needed*



Ionization/Energy Measurement

- Measurement of specific ionization for particle ID
- Demonstrated two methods
  1. Charge / unit track length from Pixel TOT
  2. Track gap density distribution

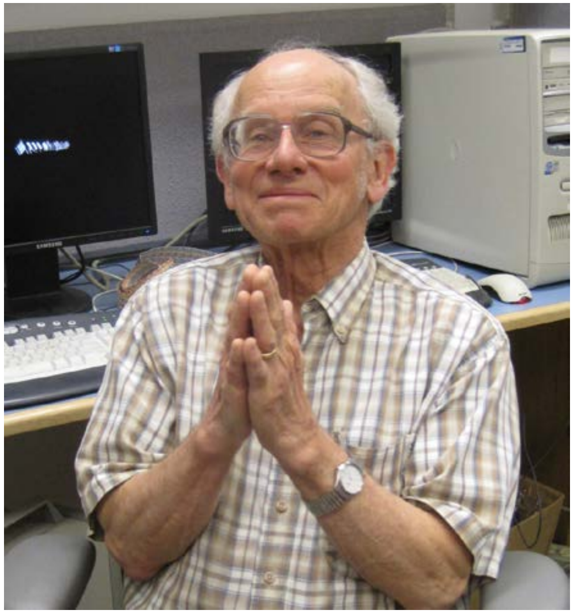


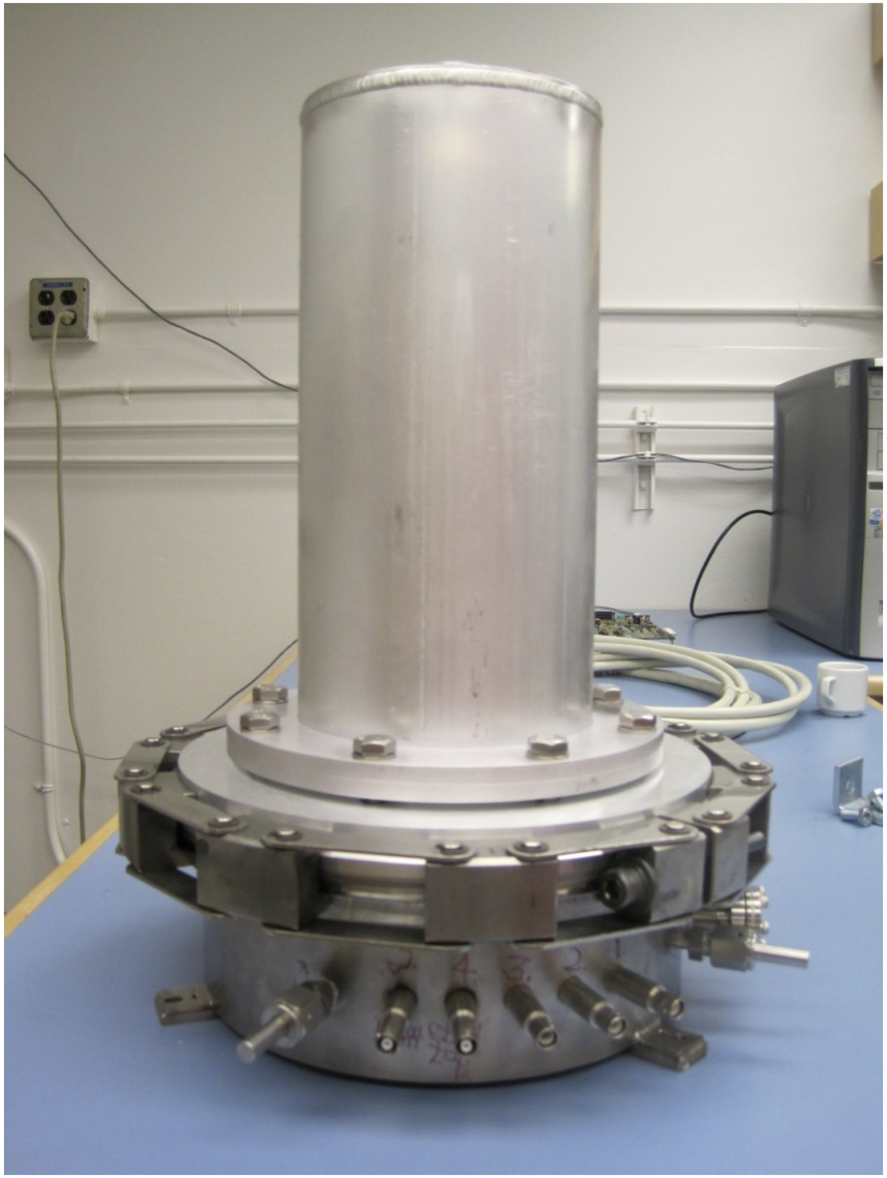


Looks promising!

2nd Generation Prototypes

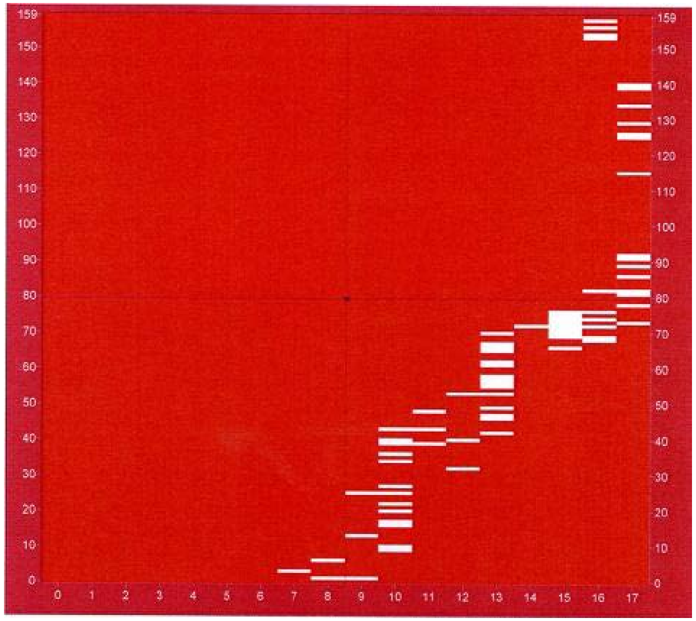
- *After* Berkeley Setup had been disassembled, we realized that our technology might also be of interest for WIMP Dark Matter searches.
- Started new efforts at LBNL and Hawaii targeting WIMP detection.
- Kadyk led effort to upgrade LBNL prototype.

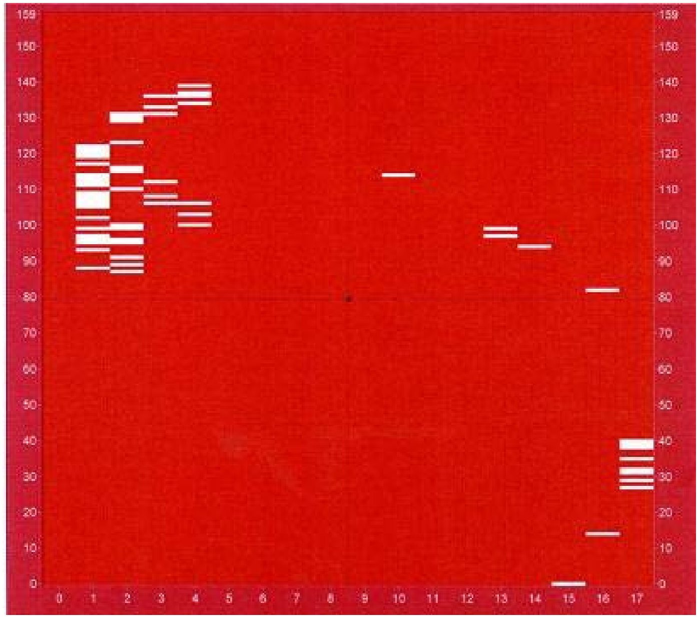




Upgraded LBNL prototype: First Data

- Drift gap increased to 15 mm (field cage exists, but not installed)
- Ar/CO_2 (70/30%) at 1 atmosphere
- Performed gain calibration, recorded cosmic rays during last two months
- Two interesting, cosmic-induced, events:

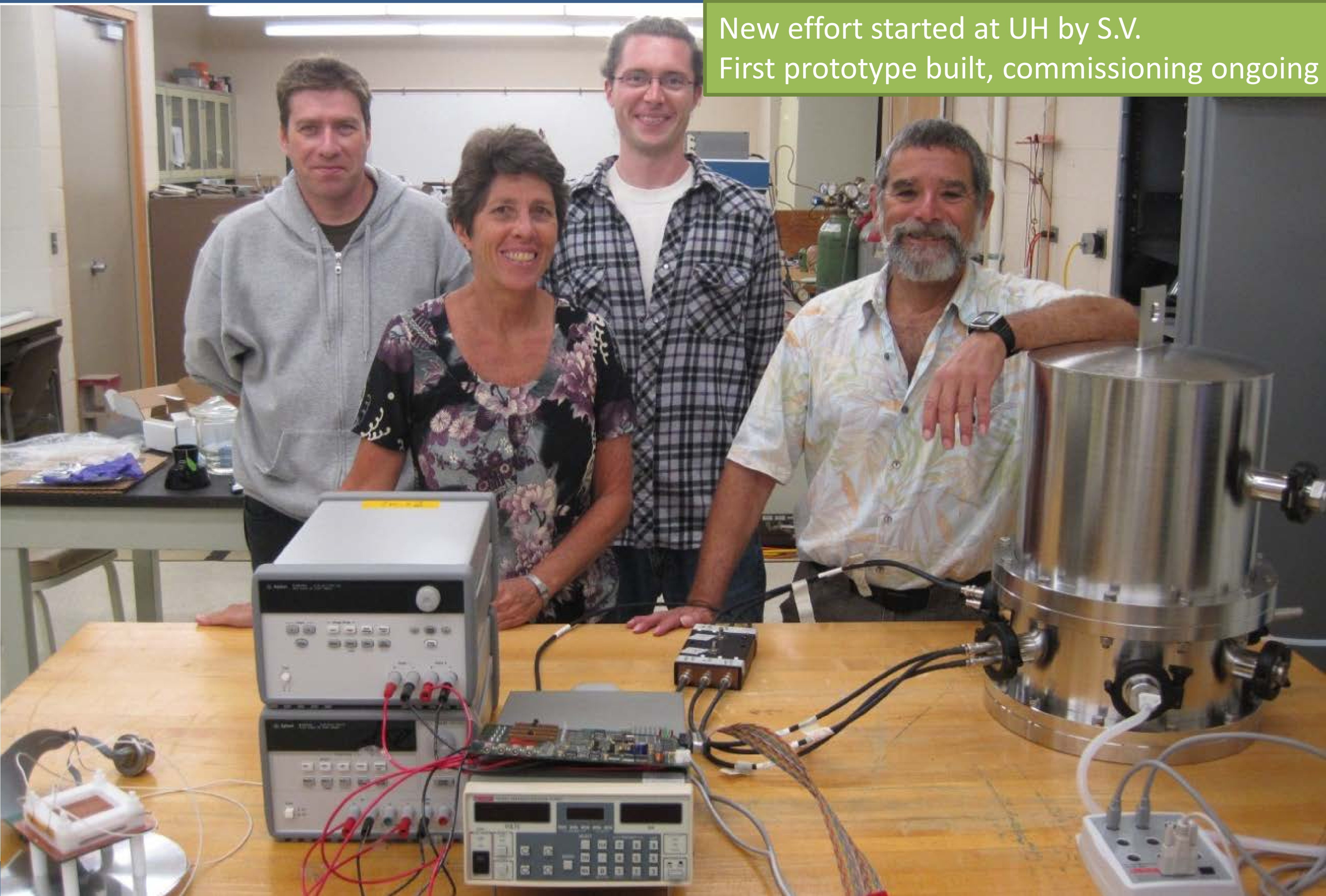




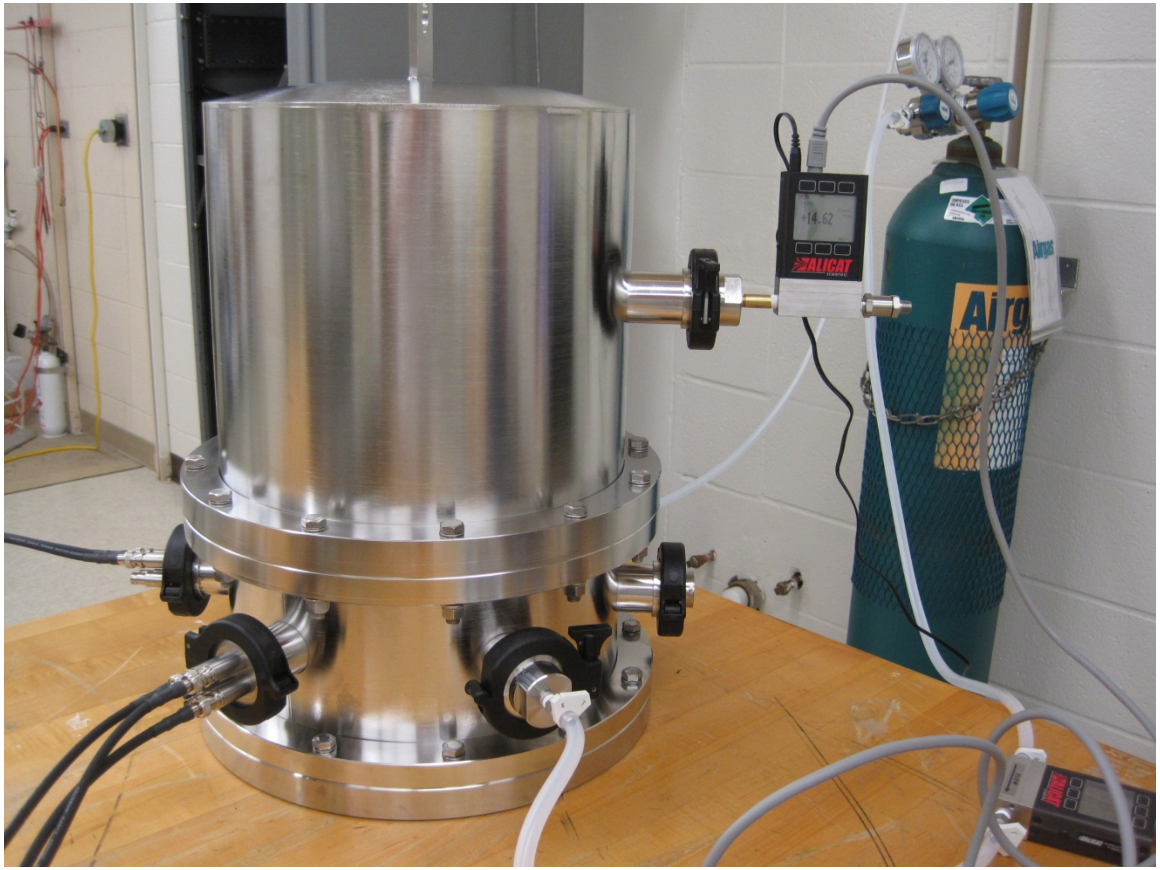
- System operating well overall
- Gain resolution as good or better than past, but gain lower
- Planning to attempt low-pressure operation next

First Hawaii Prototype: D^3 micro

New effort started at UH by S.V.
First prototype built, commissioning ongoing



First Hawaii Prototype: D^3-micro



Vacuum vessel, gas supply, and gas monitoring system. The black cables feed high voltage into the vessel, while the white hoses are the gas supply and exhaust. The black boxes measure the pressure and flow of gas.

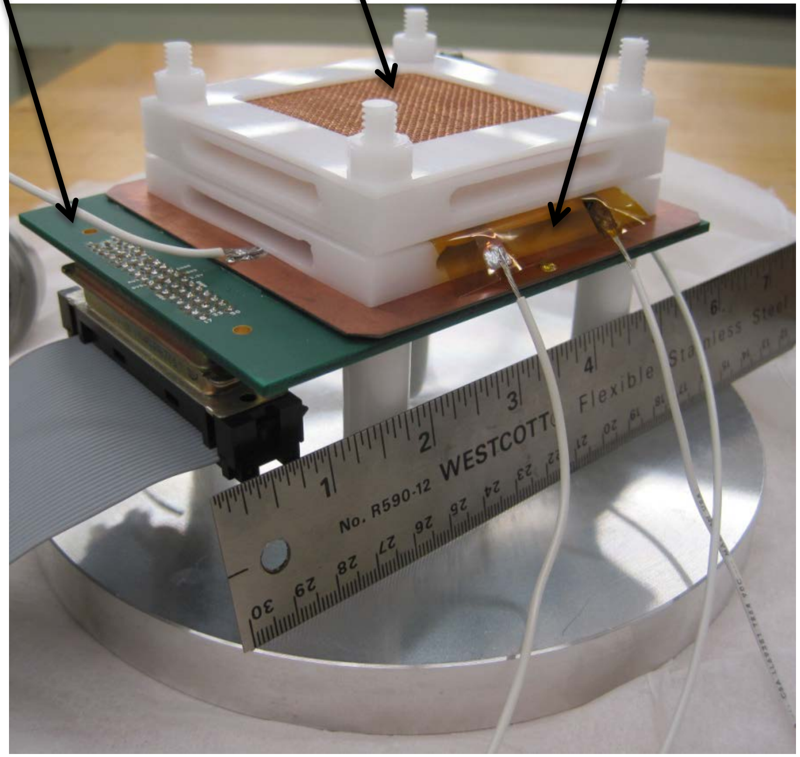
- Similar to Berkeley Prototypes
  - Drift length ~30cm
  - Room for radioactive sources inside vessel
- To be used for
  - Gain calibration
  - Detailed measurements with cosmic rays and radioactive sources
  - → Validation of full detector simulation
  - First experimental tests of "charge focusing" (see later slide)

Mechical Support Structure

PCB with Pixel Chip

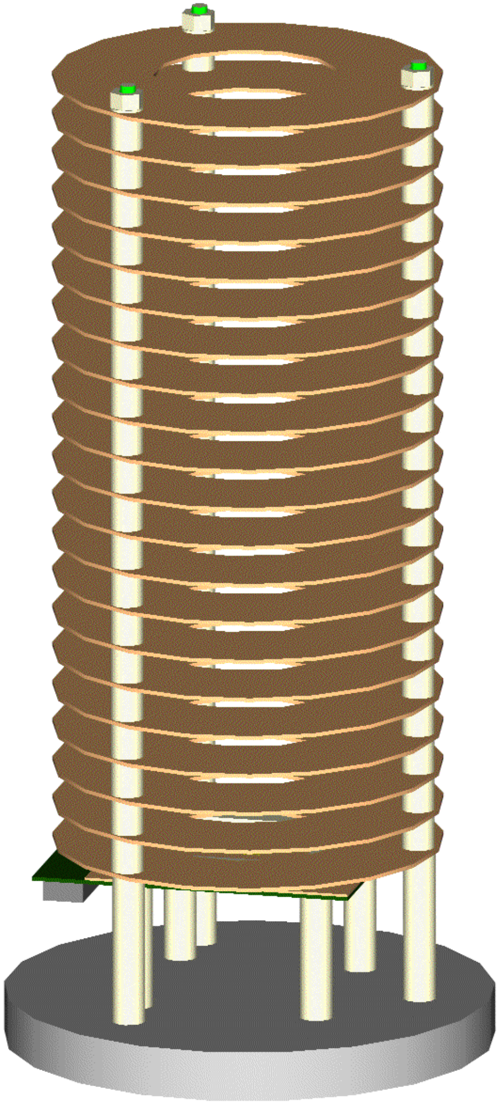
Copper mesh

Gas Electron Multipliers



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. The small volume is sufficient for gain calibration & commissioning with cosmic rays, but will be extended later with a 30-cm field cage.

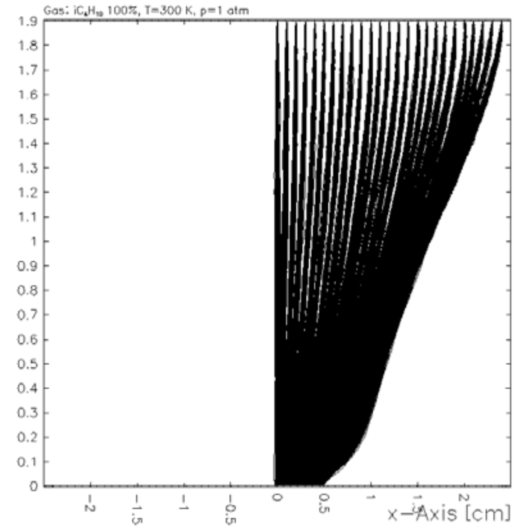
CAD Model of Field Cage



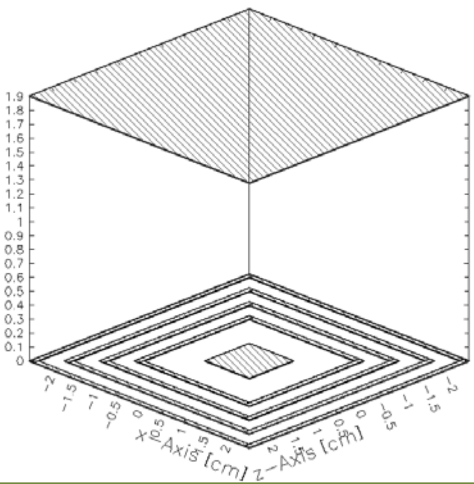
CAD model of mechanical support structure with electric field cage added. We expect to machine the rings this summer, and will add the field cage to the setup after commissioning the current system. This will extend the vertical size of the sensitive volume to 30 cm.

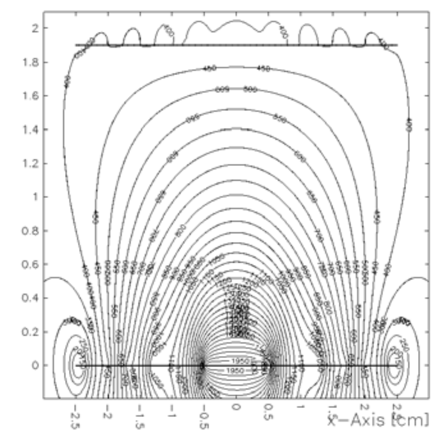
A New Idea: Charge Focusing

- Pixel readout dominates detector cost (~$18 /cm^2)
- Can reduce cost by electrostatically focusing the drift charge between GEMs and pixels
- Not the same as using larger pixels
  - Reduction in needed readout area and hence cost
  - Small reduction in position resolution (diffusion + GEM resolution worse than pixel resolution)
  - Expect to retain excellent noise level and high speed (due to small pixel feature size / capacitance)
  - Also solves the problem of tiling pixel chips (to achieve full area coverage) in high electric field
- Simulation looks promising → experimental tests this summer



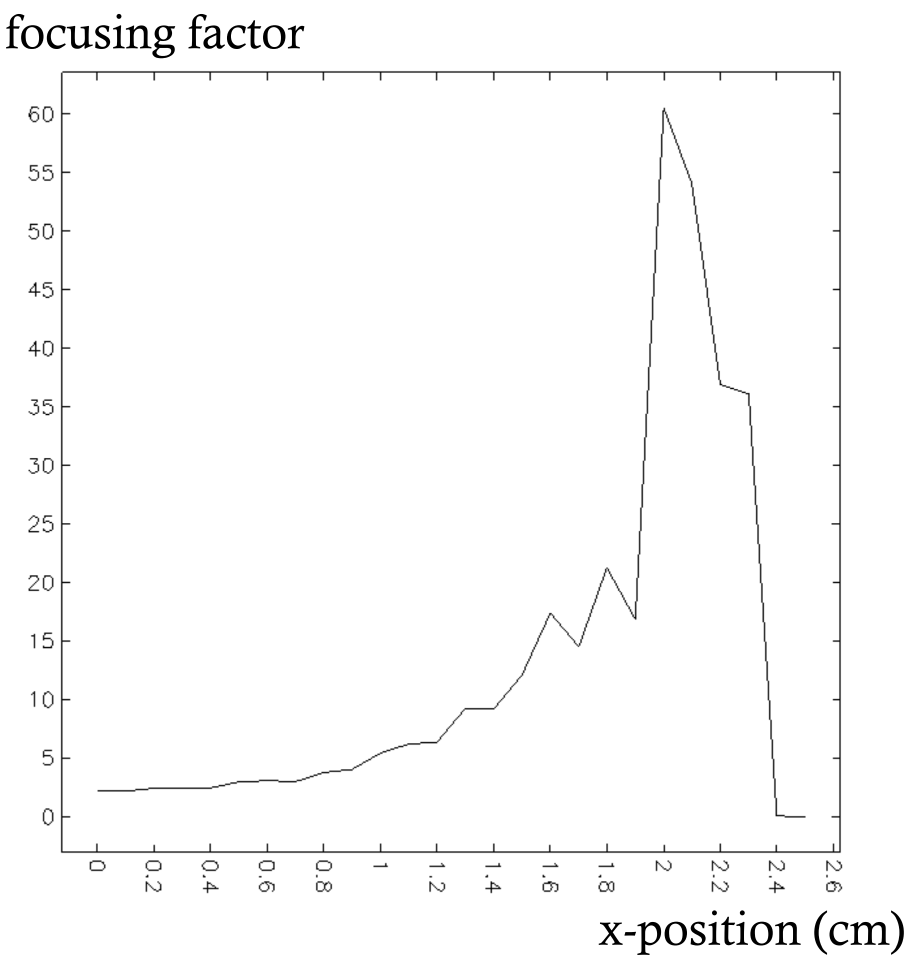
GARFIELD simulation

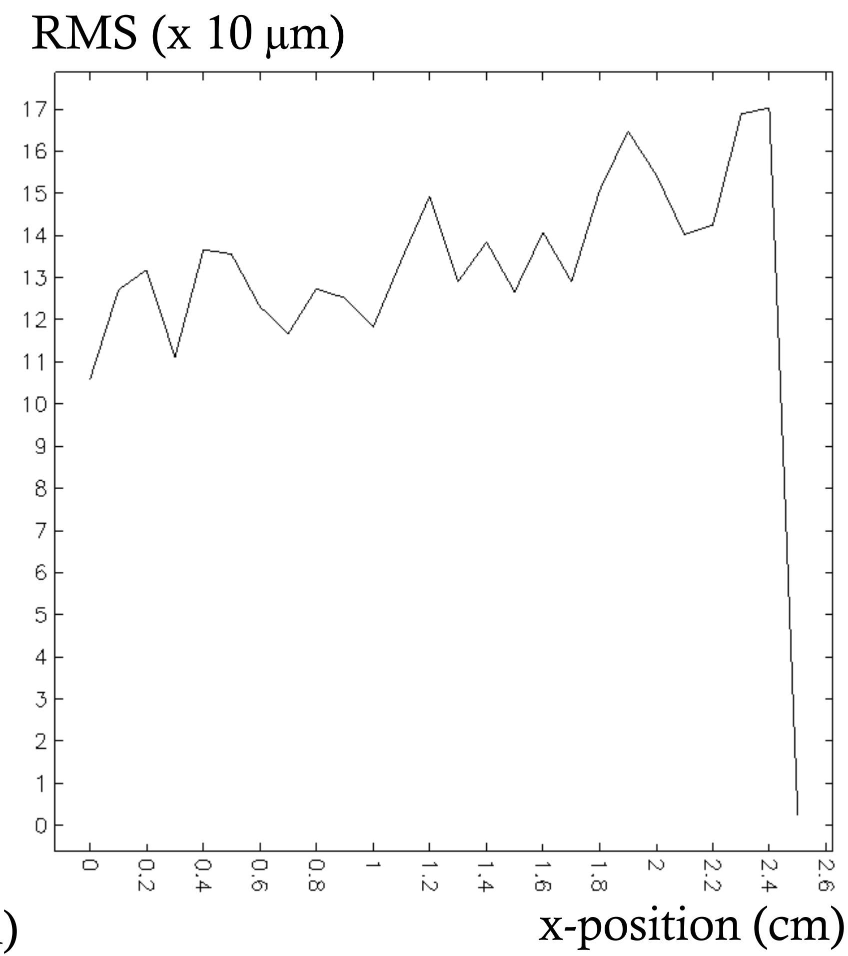




→ High priority since reward in case of success is large (up to factor 10-25 reduction in cost per sensitivity)

More on Charge Focusing

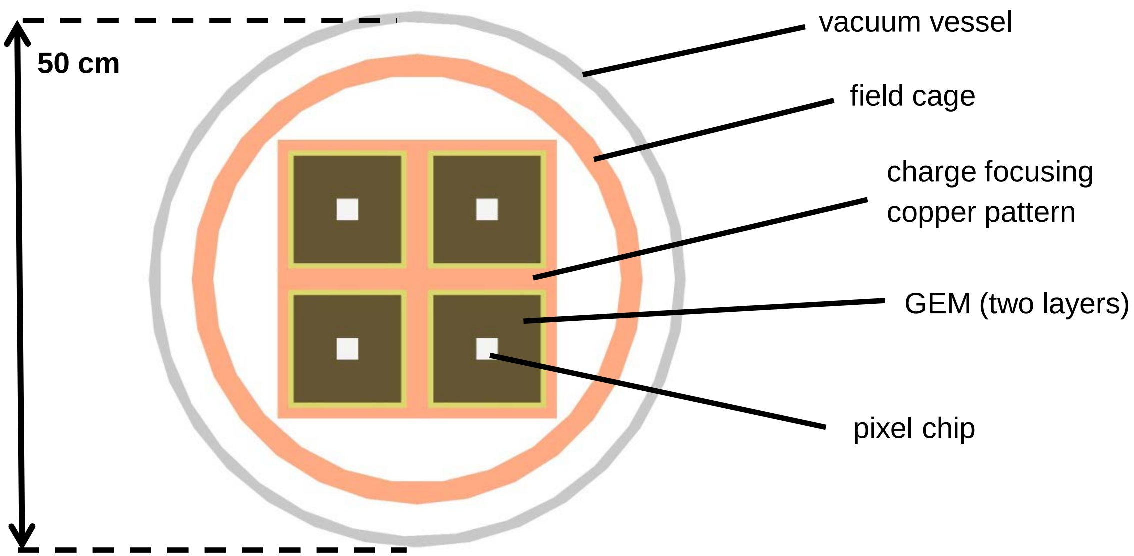




- Focusing factor >=3, but uniform only around center of chip → needs more work
- Diffusion added by focusing is small, compared to length of focused tracks → good

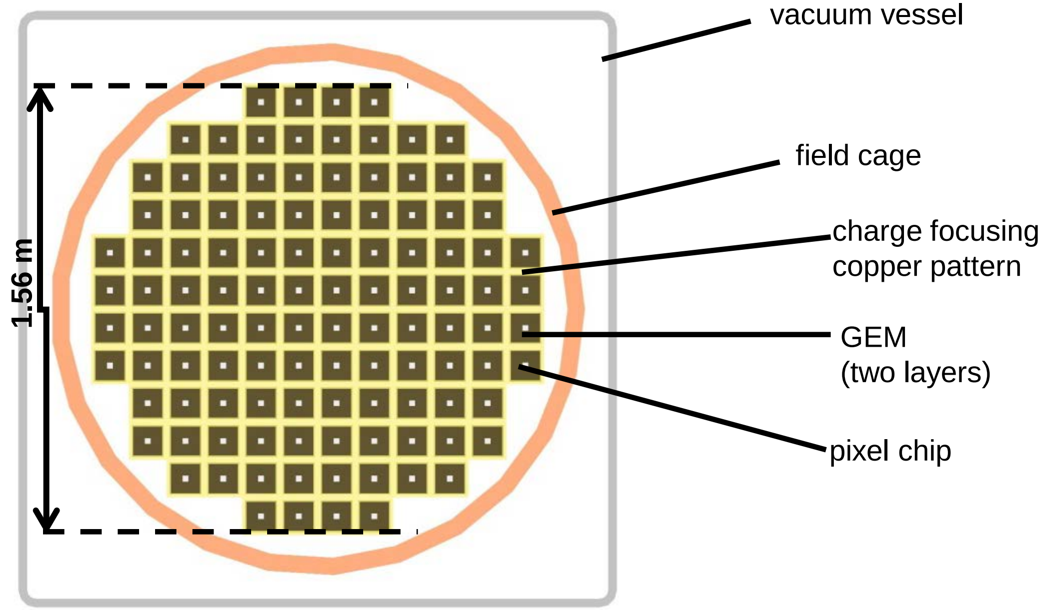
Next Prototype: D^3-*milli*

- Prototype dedicated to studying next generation pixel electronics, trigger, charge focusing
- 10x10 cm GEMs (CERN), 2x2cm Pixel Chip (ATLAS-FEI4), USBPix Readout (Bonn University)



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.

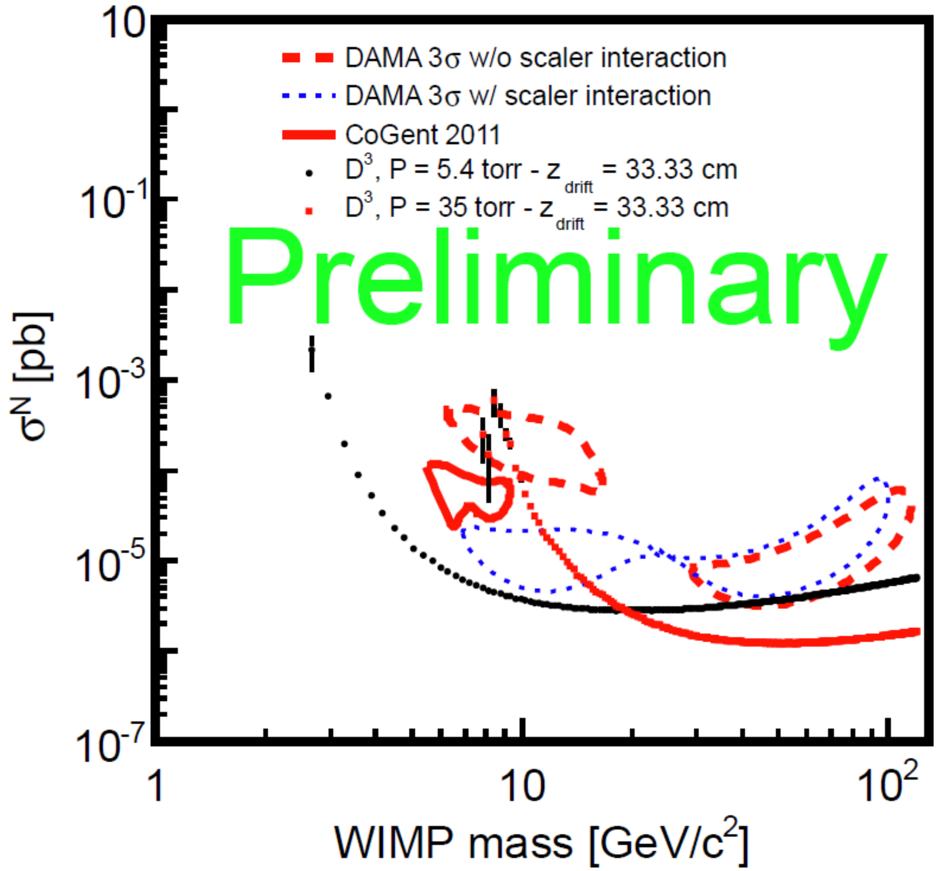
Concept drawing of D^3



- 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

D^3 WIMP sensitivity

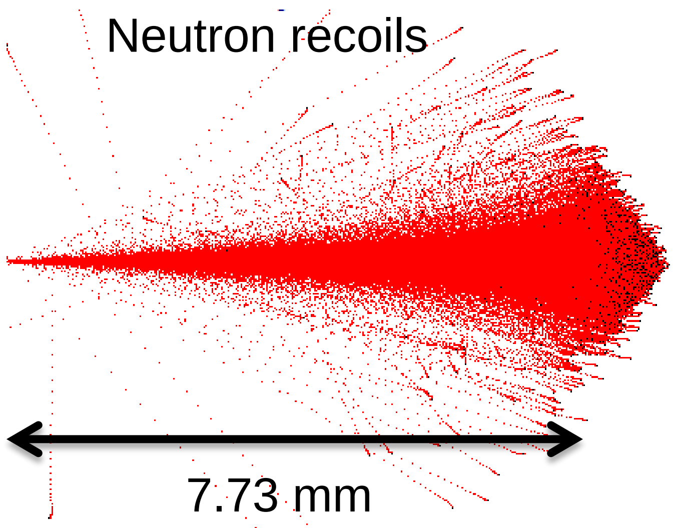
- Due combination of high single-electron efficiency and low noise, expect very low threshold operation, and good sensitivity to low-mass WIMPs possible. Needs experimental input.
- Preliminary evaluation suggests we can achieve *directional sensitivity* to ~7 GeV WIMPS as (controversially) suggested by DAMA/LIBRA and CoGeNT.
- Gases other than CF_4 also competitive. More work needed to fully optimize detector reach → See talk by Igal Jaegle tomorrow.



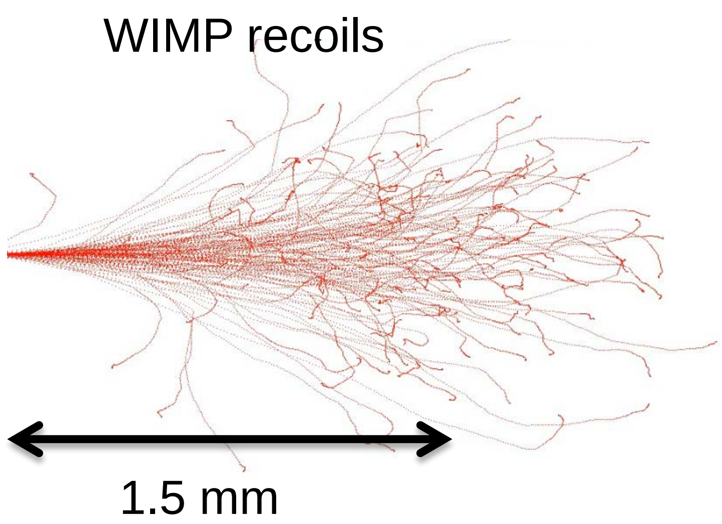
D^3 ($1m^3$ CF_4, three readout planes), 1-year WIMP sensitivity when optimized for 100 GeV WIMPs (→ 35 torr pressure) and 10 GeV WIMPs (5.4 torr)

Other Applications of Pixel TPC

- More generally, we're studying a new approach to 3D tracking in large volumes → many potential applications
- Also investigating
  - Fast neutron detection (**DiNO**: Directional Neutron Observer)
  - **Beam commissioning TPCs** for SuperKEKB in Japan



1-MeV Hydrogen nuclei recoiling in 1 atmosphere of C_4H_{10} gas. 10^5 recoils with identical start position and velocity have been superimposed



100keV Fluorine nuclei recoling in 75 torr of CF_4 gas.

Conclusion

- First Prototype TPC with double GEMs (CERN) + Pixels (ATLAS): excellent performance. Particularly relevant to WIMP detection: good spatial resolution, high single electron efficiency, very low noise, low demand on downstream readout electronics
- Started new efforts at LBNL and Hawaii targeting WIMP detection, 2^{nd}-generation prototypes (D^3-micro) built
- Charge focusing could make large detectors affordable
- Larger detectors (D^3-milli and D^3) , incorporating charge focusing, in planning stage. Use modified versions of ATLAS test DAQ systems to reduce development cost and time
- D^3 may have *directional sensitivity* to (controversial) 7-GeV WIMPs
- Progress on simulation side & first estimates of WIMP discovery reach: talk by Igal Jaegle tomorrow

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