Application of Time Projection Chambers with GEMs and Pixels to WIMP Searches and Fast Neutron Detection

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Representing the D^3 collaboration of U. Hawaii and LBNL
Material presented previously by **Sven Vansen at CYNUS 2011**

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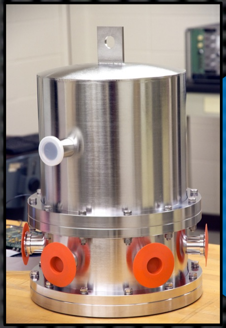
Outline

- Collaboration
- Physics Motivation
- Detection Principles/First Prototype
  - Gas Electron Multipliers
  - Pixel Chip
- Results from first Berkeley Lab (LBNL) prototype
- 2nd Generation Prototypes at LBNL and Hawaii
- Charge Focusing
- Future Plans
- Conclusions

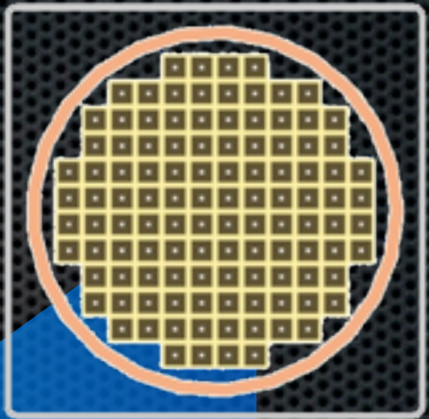
Collaboration

Physics Motivation

- **WIMPs**:
  - Expect 12 hr directional oscillation for WIMP recoils: smoking gun signature.
- **Neutrons**:
  - Interest in an He_3 replacement for Homeland Security.

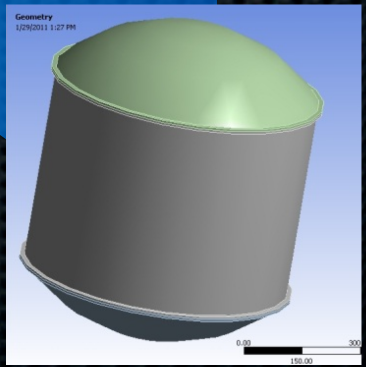


Prototype



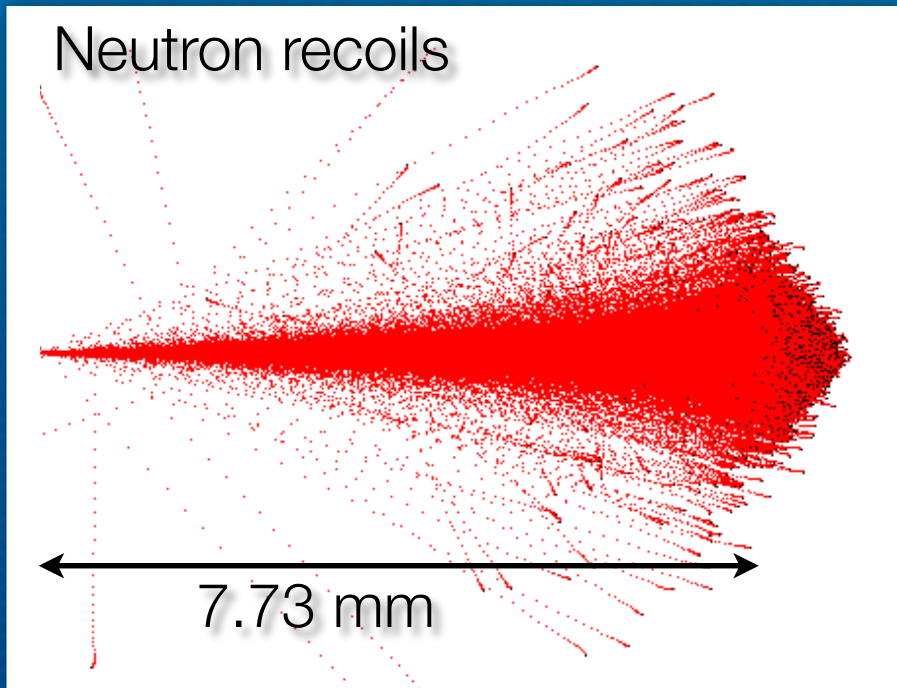
D^3: Directional Darkmatter Detector

DiNO: Directional Neutron Observer

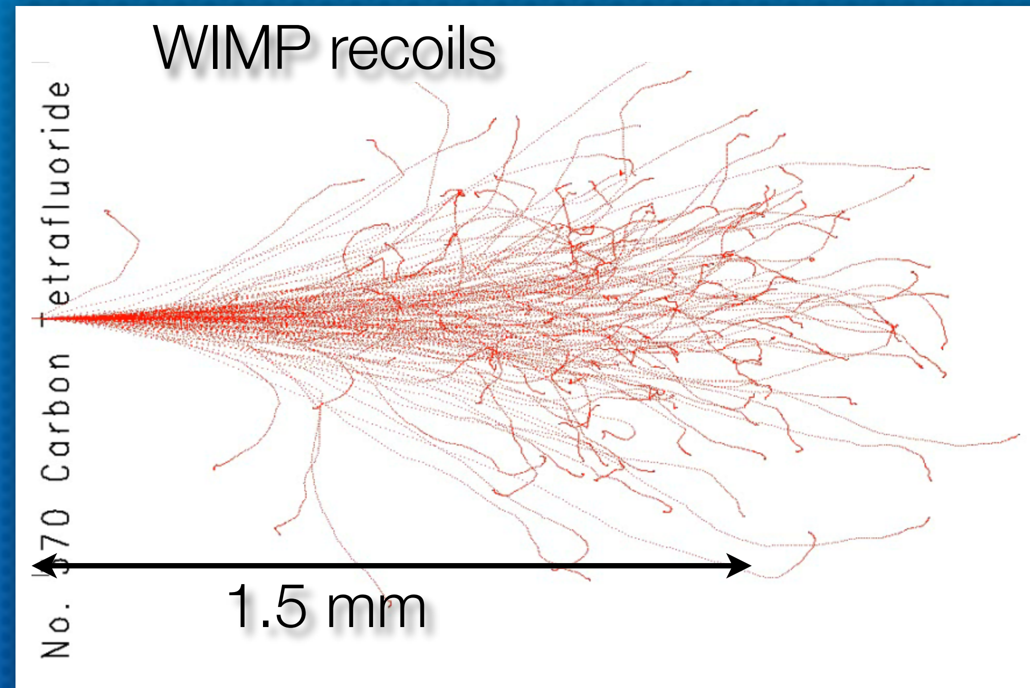


Possible beam commissioning TPCs for SuperKEKB in Japan

Neutron and WIMPs



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.

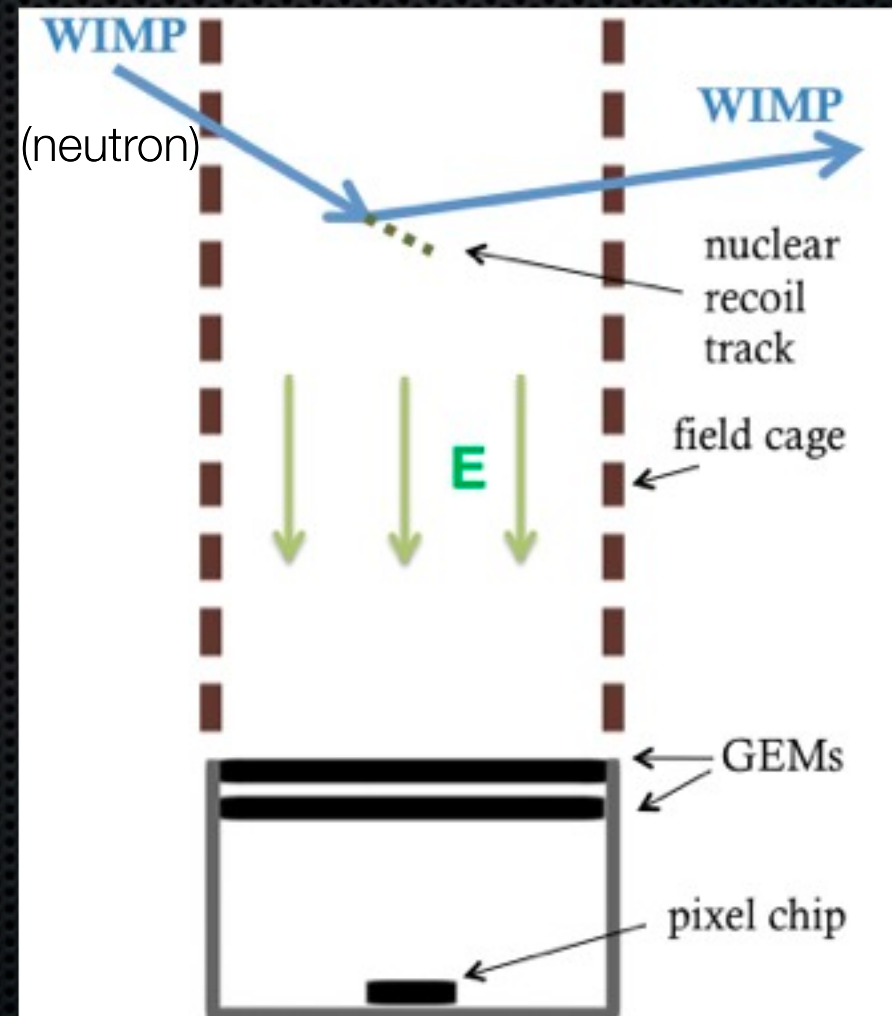


100 keV Fluorine nuclei recoiling in 75 torr of CF_4 gas.

Neutrons are easier and will be a test of applicability to WIMPs.

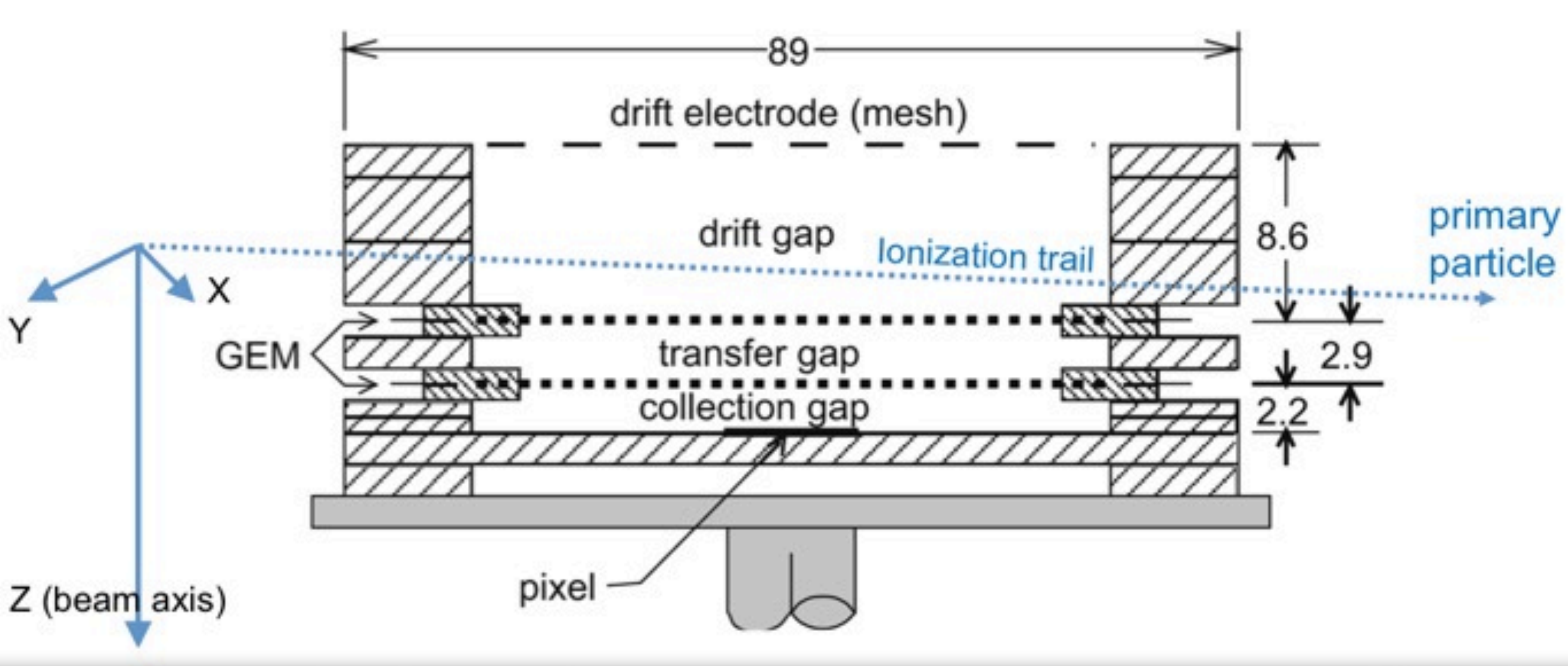
Detector Principle

- Aim: Achieve **directional sensitivity** in a Time Projection Chamber (**TPC**)
  - Gas Electron Multipliers (GEM): **High efficiency**.
  - Pixel Chip: **High precision**.
- Use to detect **WIMPs or neutrons** from nuclear recoils.



First LBNL Prototype

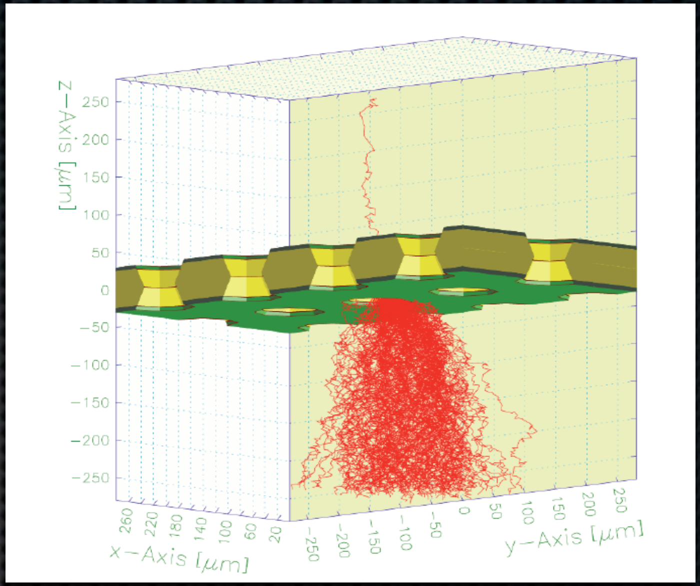
- Project led by **John Kadyk**
- Prototype small - **Dimensions in mm**!
- GEMs: 5x5 cm CERN. Pixels: ATLAS FE-I3
- **Built to investigate** charged particle tracking at future collider (**ILC**)
- Recorded large sample of cosmic rays in 2007, **published in 2008***

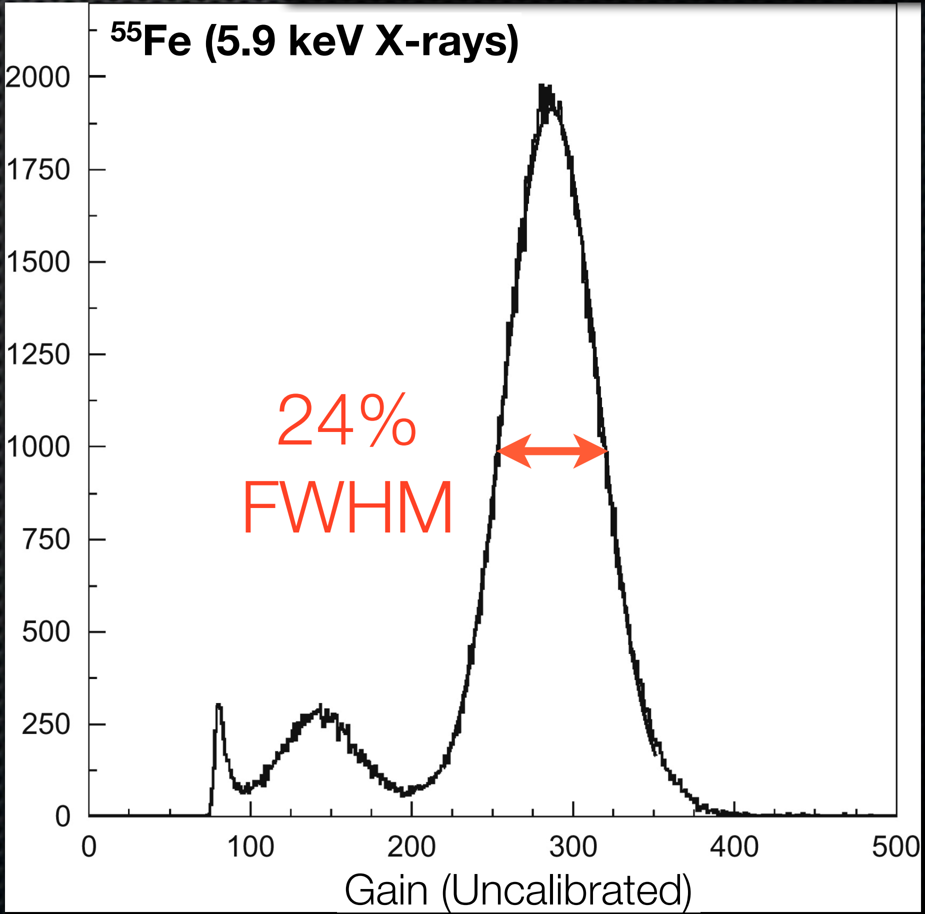


[*] Readout of TPC tracking chambers with GEMs and pixel chip. T. Kim, M. Freytsis, J. Button-Shafer, J. Kadyk, S.E. Vahsen, W.A. Wenzel (LBL, Berkeley) . 2008. 12pp. NIM (2008)

Gas Electron Multipliers (GEMs)

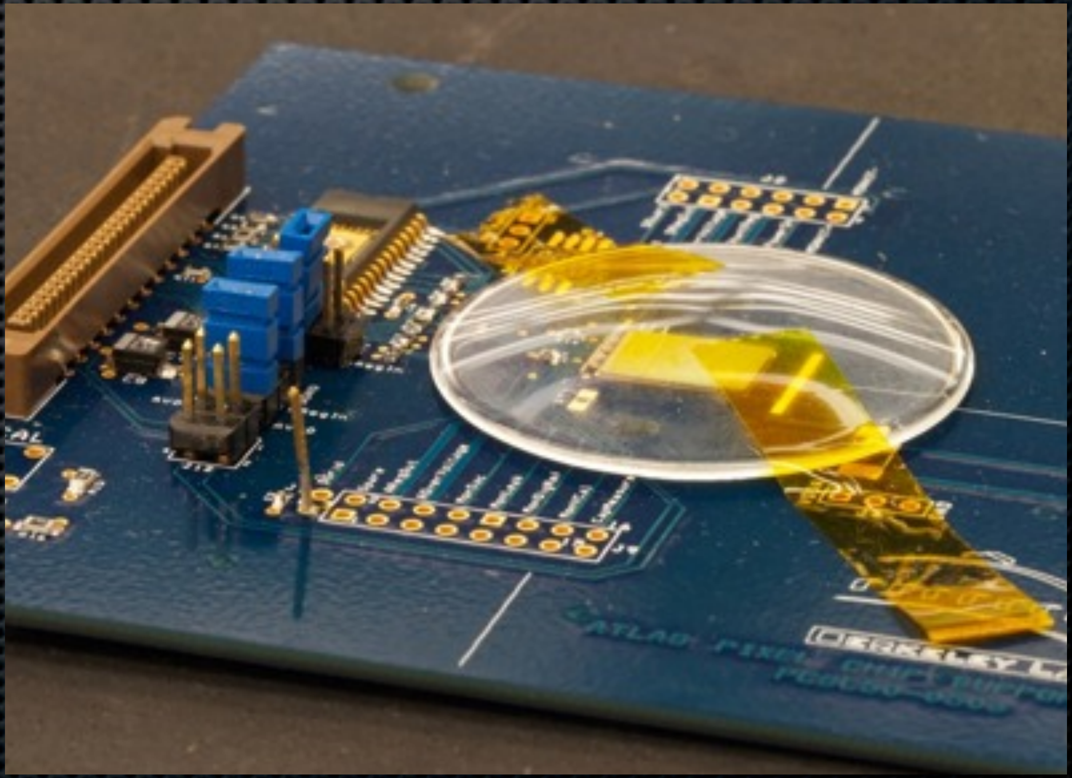
- Off the shelf GEMs from CERN
  - 5 cm x 5 cm x 60 µm
  - Hole spacing: 140 µm
- Electrons multiplied by avalanching
- ~100% area efficiency
- Reliable without sparking with **single-GEM gain up to 300** ($ArCO_2$)
- **Two GEMS in series**: higher gain with less risk of sparking: 500 V + 400 V, **gain of 40000**





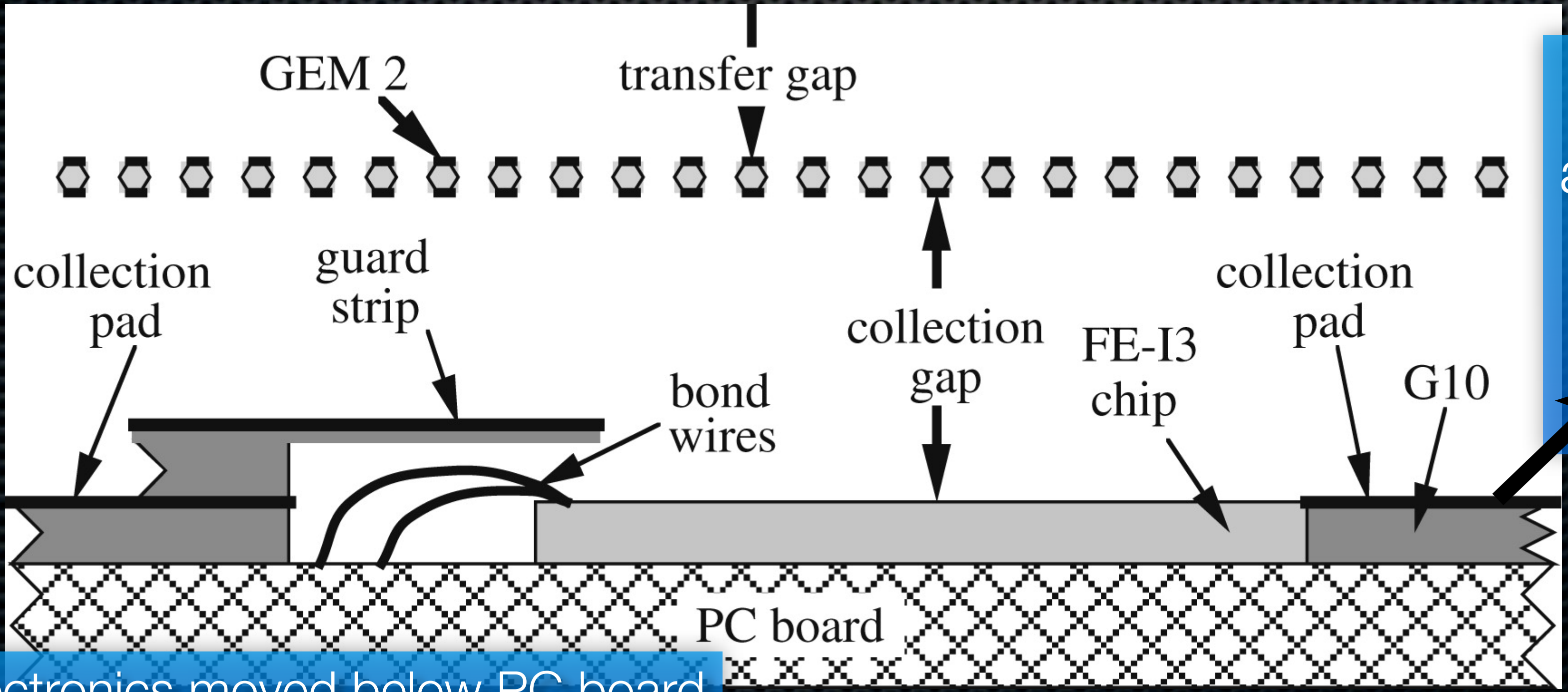
FE-I3 Pixel Chip

- **Same Front End Chip** as used in **ATLAS** Pixel Detector.
- Developed at LBNL, over ~7 years
- **2880 pixels of 50 x 400 µm**. Each pixel:
  - Is a tunable, analog amplifier w/ digital controls, digital output logic
  - measures **arrival time** and amount of **incident charge**
- **x-y** from pixel **coordinate**
- **relative z** from **drift-time** (in units of 25 ns)
- **Same DAQ** chain as during **ATLAS** pixel detector **production**
- Pixels chip in **self-trigger mode**.
- Read out 16 "bunch crossings"
  - 16 x 25 ns x 26 µm/ns = **10.4 mm** ($ArCO_2$, 1 kV/cm)
- Very **low noise**: **~120 electrons**
- **Some modifications needed for TPC running**.



Adapting FE-I3 for TPC Use

- **Pixel Chip**
  - **Pixel sites** gold or aluminum **plated**.
  - Maintain **uniform** electric **field**.
  - Prevent surface charge.
- **Mounting board**
  - Redesigned at LBNL
  - Move **readout** electrons to **back** of board.
  - Guard strip (Cu)
  - **Collection pad** (Cu)

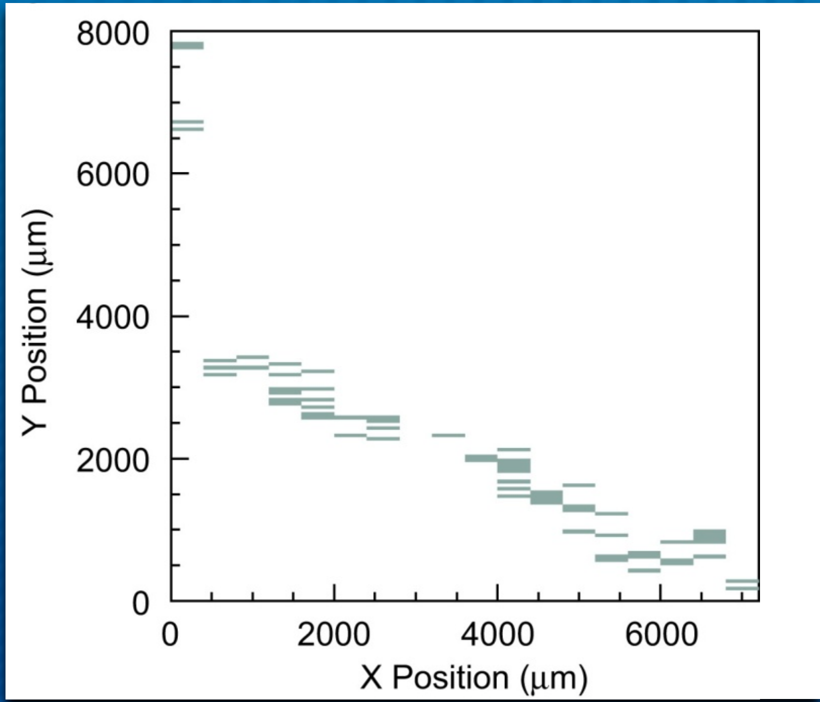


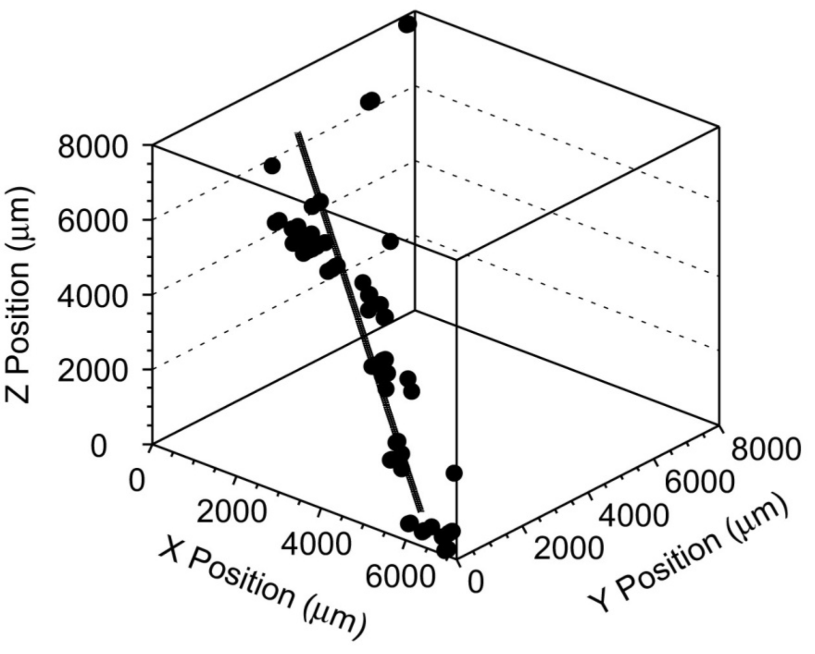
Connect pad to amplifier + pulse-height analyzer when measuring GEM gain

Electronics moved below PC board

Results from 1st LBNL Proto.

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

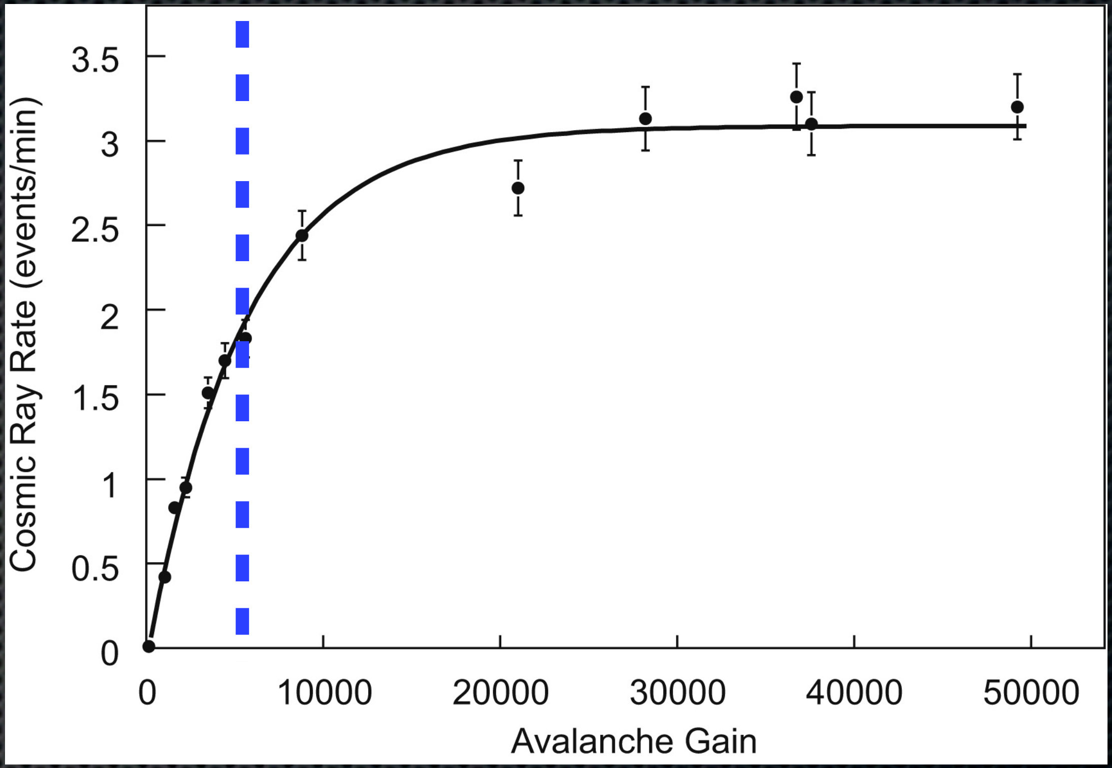




Unfolding diffusion, estimate single hit position resolution to 70 µm

High Efficiency For Single Electrons?

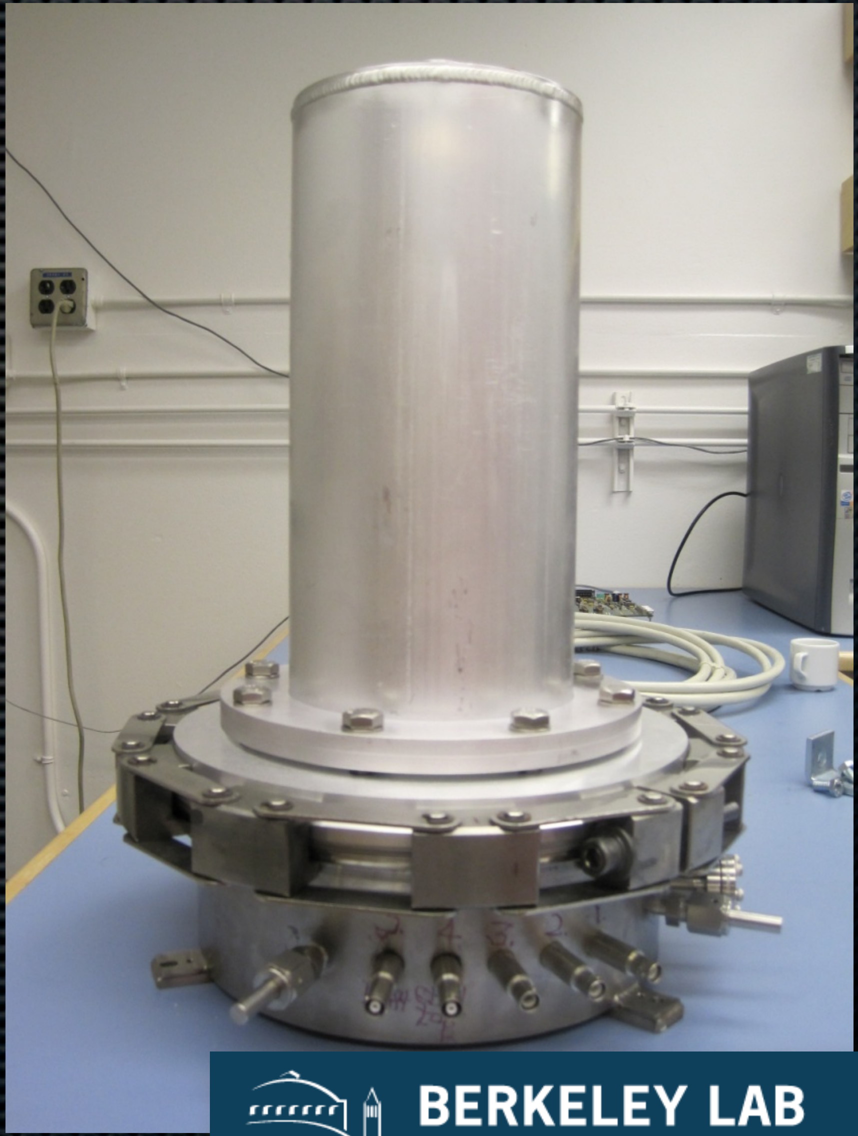
- Pixel **threshold** at **5k** electrons.
- Rate **plateaus** at gain **~20k**
- 20k electrons per primary ionization electron, **4x more than pixel threshold**
- Caveat: Did not study pixel noise versus GEM gain, more work needed



Suggest system is highly sensitive. Capable of collecting all the ionization from primary track that reaches GEM - even single electrons

2nd Generation Prototypes

- After Berkeley Setup had been disassembled, we realized that our technology might also be of interest for **WIMP Dark Matter** searches (and neutron detection).
- Started new efforts at **LBNL** and **Hawaii** targeting WIMP detection .
- **Large(r) volume detectors**.



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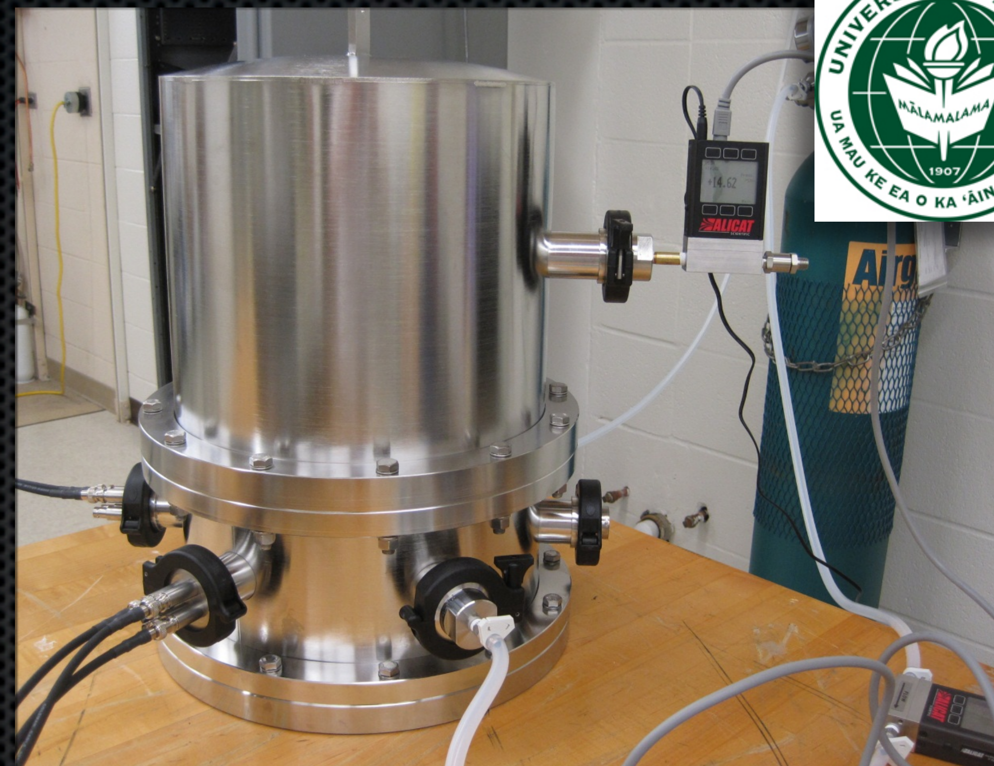
First Hawaii Prototype: D^3 micro

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

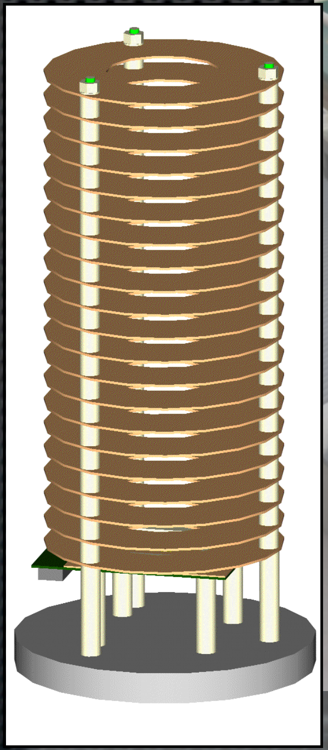


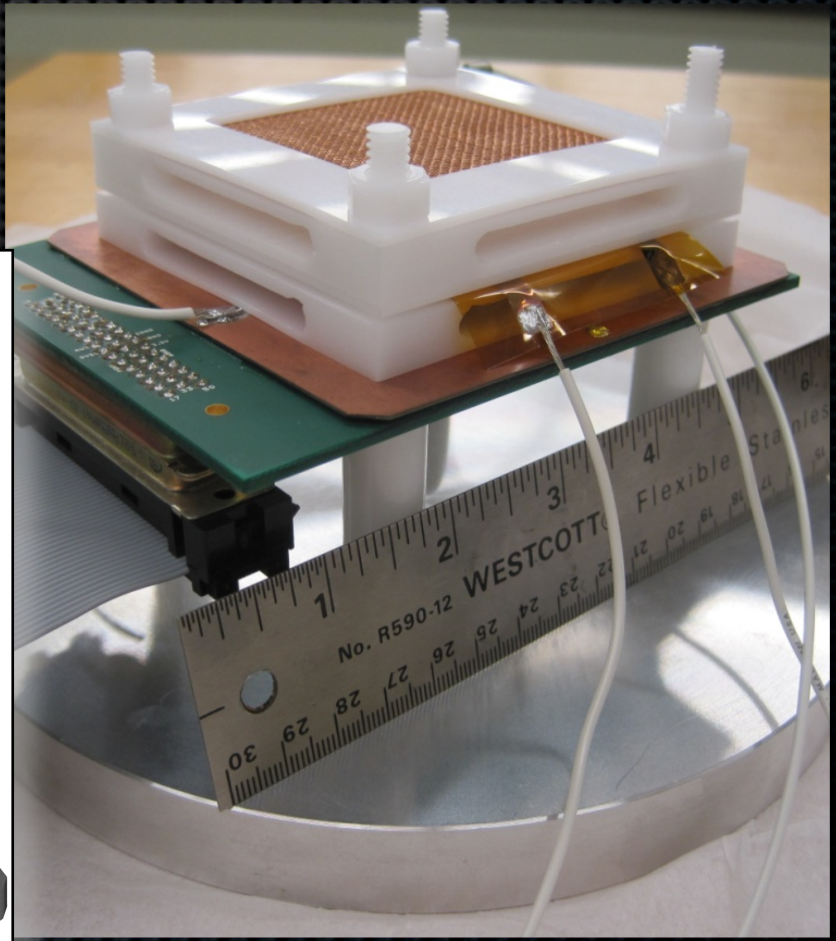
Vacuum vessel, gas supply, and gas monitoring system. The black cables feed high voltage into the vessel, while the white hoses are the gas supply and exhaust. The black boxes measure the pressure and flow of gas.

GEM + Pixel Support Structure

Mechanical support structure with Gas Electron Multiplier (orange, transparent foil) and Printed Circuit Board (green) with Pixel Chip installed.

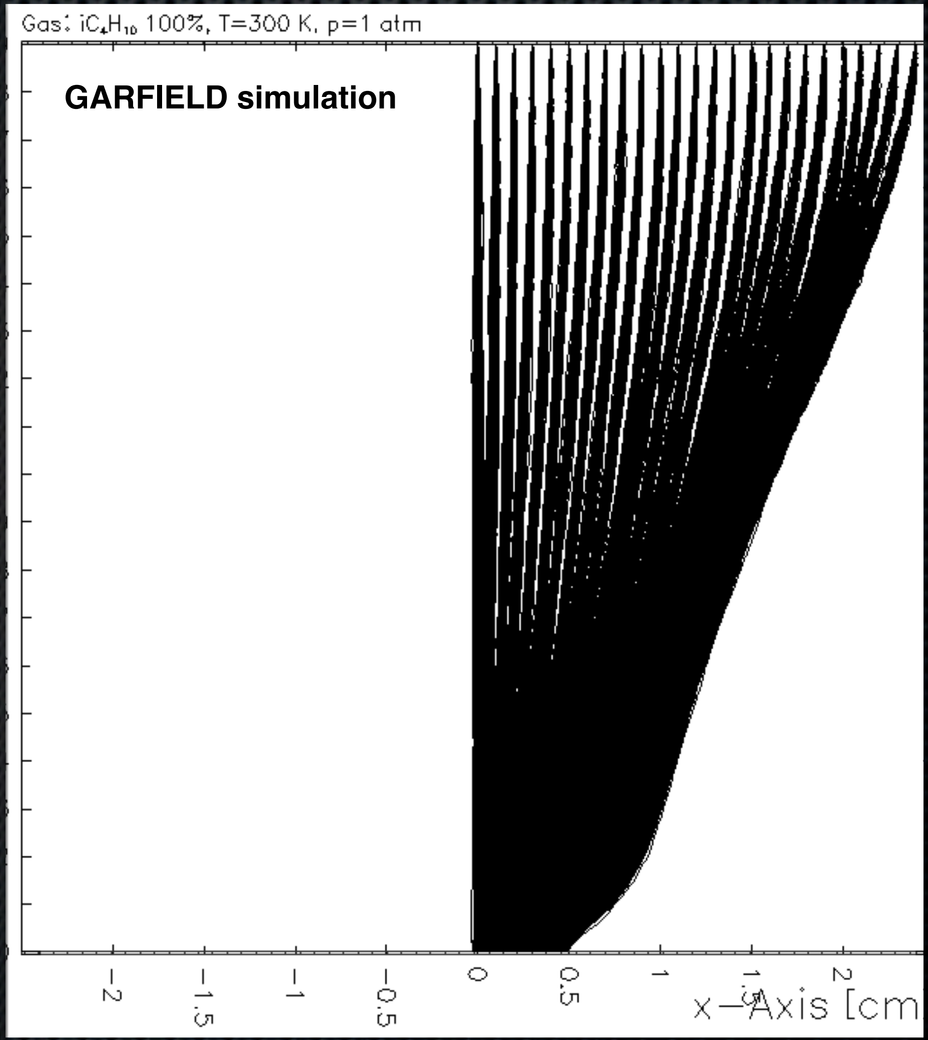
- Sensitive volume in this detector configuration is small: **8.6 mm gap**.
- Copper mesh: Held at a high voltage and provides a uniform electric field.
- Calibrate **GEM gain**.
- **Commission** the **pixel readout** with cosmic rays.
- **Extended active gas volume later with a 30 cm field cage.**





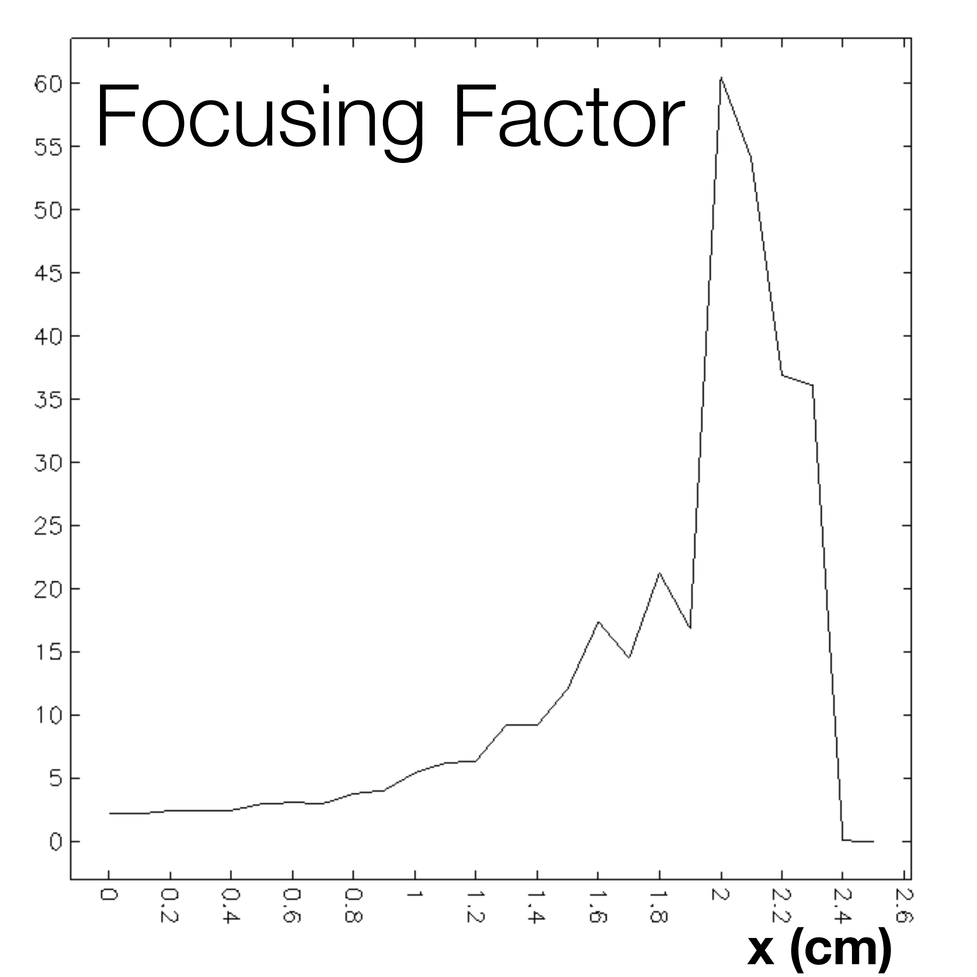
Charge Focusing

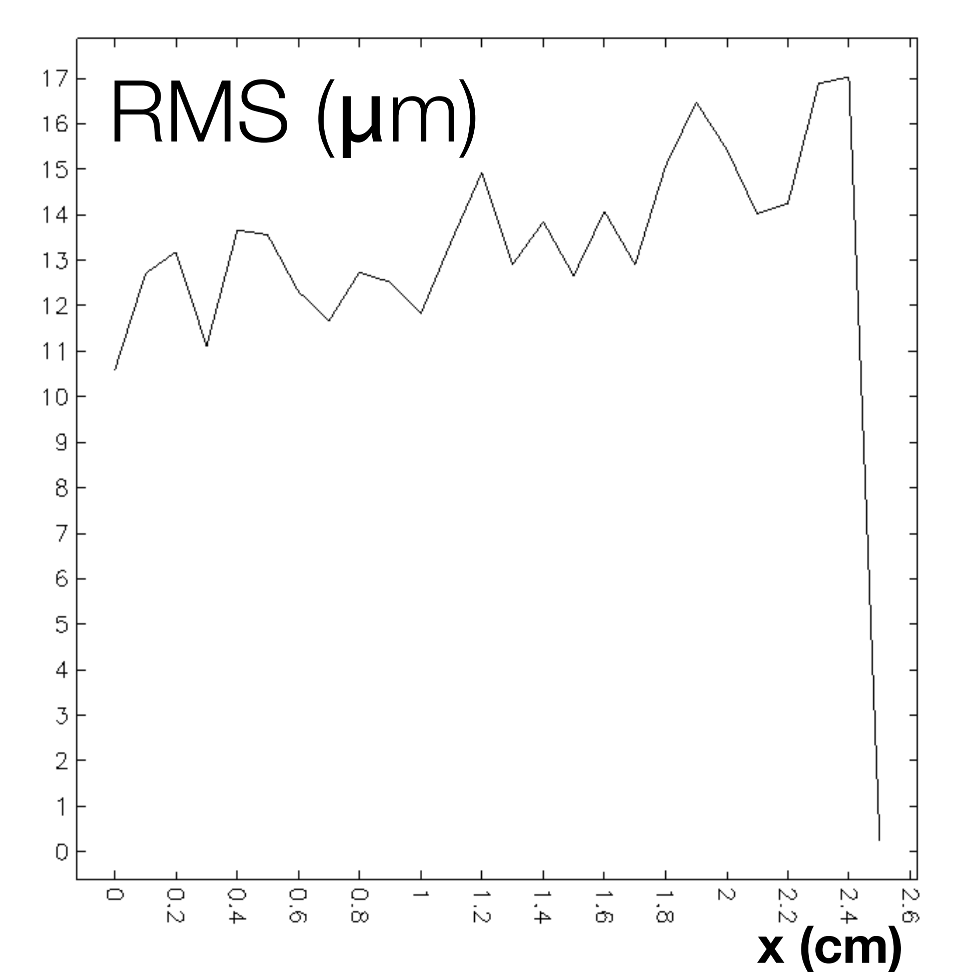
- **Pixel readout dominates detector cost (~\$18 /cm²).**
- Reduce cost by using **electrostatic focusing** of the drift electrons.
- **Reduction in readout area** and hence cost.
- Small reduction in x-y position resolution (GEM resolution worse than pixels), but still retains **low noise characteristics**.
- Enables the tiling of pixel chips, to achieve full area coverage, in high electric field (see D^3 milli slide)
- **Simulation looks promising. Experimental tests this summer.**



High priority: Up to factor 10-25 reduction in cost per sensitivity.

More on Focusing

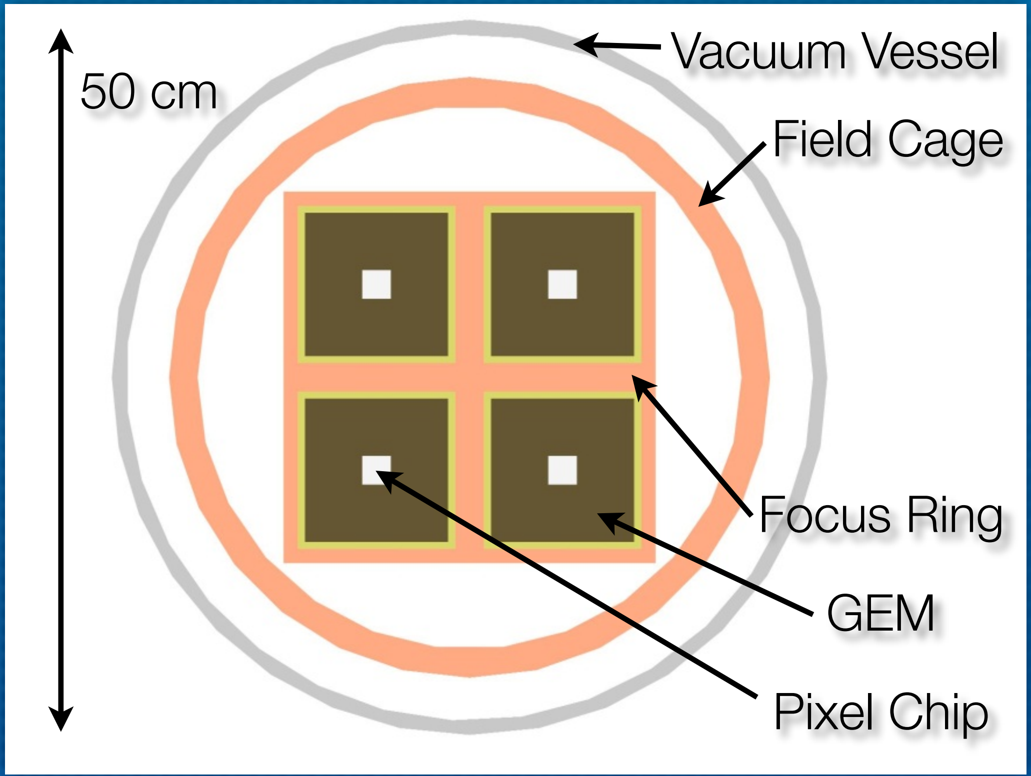




- **Focusing ~uniform**, factor of 3, but only near center of chip. Needs more work
- Diffusion added by focusing is small, compared to length of focused tracks.

Planned Prototype: D^3 milli/DiNO

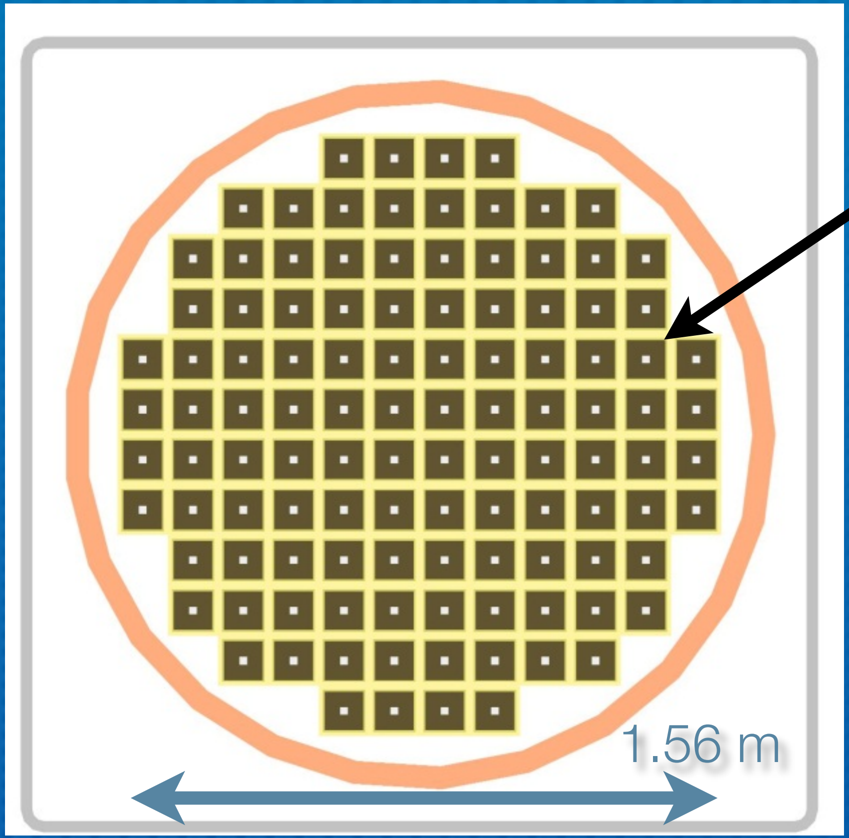
- Prototype dedicated to studying next generation pixel electronics, trigger, charge focusing.
  - **10 x 10 cm GEMs** (CERN)
  - **2 x 2 cm Pixel Chip** (ATLAS FE-I4),
  - **USBPix Readout** (Bonn University)
- Again readout board will have to adapted for TPC. Board layout SW incompatibility causing some issues.
- Differentiate for WIMP or neutron detection.



Top view of the 12-liter prototype with tiling of 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.

Planned D^3

- Similar to D^3 milli, with **stacking**.
- Expect to use **new** (v2) RCE **readout** system under development at SLAC: ~**250 chips**.
- The detector will require **radio pure materials**, **underground operation**, **and shielding**.



Cell design same as D^3 milli

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 CF4 @ 50 torr).

WIMP Sensitivity

- Due to 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**. **Can we stably operate at low pressure**?
- Gases other than CF_4 also competitive. **More work needed to fully optimize detector reach**.
- **Very preliminary** evaluation suggests we can achieve **directional sensitivity to low mass WIMPs** as reported by DAMA/LIBRA and CoGeNT.

Plot Removed

D^3 (1 m^3, three readout planes), 1 year WIMP sensitivity when optimized for **10 GeV WIMPs**. Various gases/ pressures.

Conclusions

- **First Prototype TPC with double GEMs (CERN) + Pixels (ATLAS): excellent performance.**
- Relevant to WIMP (Neutron) detection: **good spatial resolution, high single electron efficiency, very low noise**, low demand on downstream readout electronics.
- New efforts at LBNL and Hawaii targeting WIMP detection, 2nd-generation prototypes (D^3 micro) built.
- **Charge focusing could make large detectors affordable.**
- Larger detectors (D^3 milli and D^3) incorporate modified versions of **ATLAS test DAQ** systems to **reduce development cost and time**.

Back up

Focusing