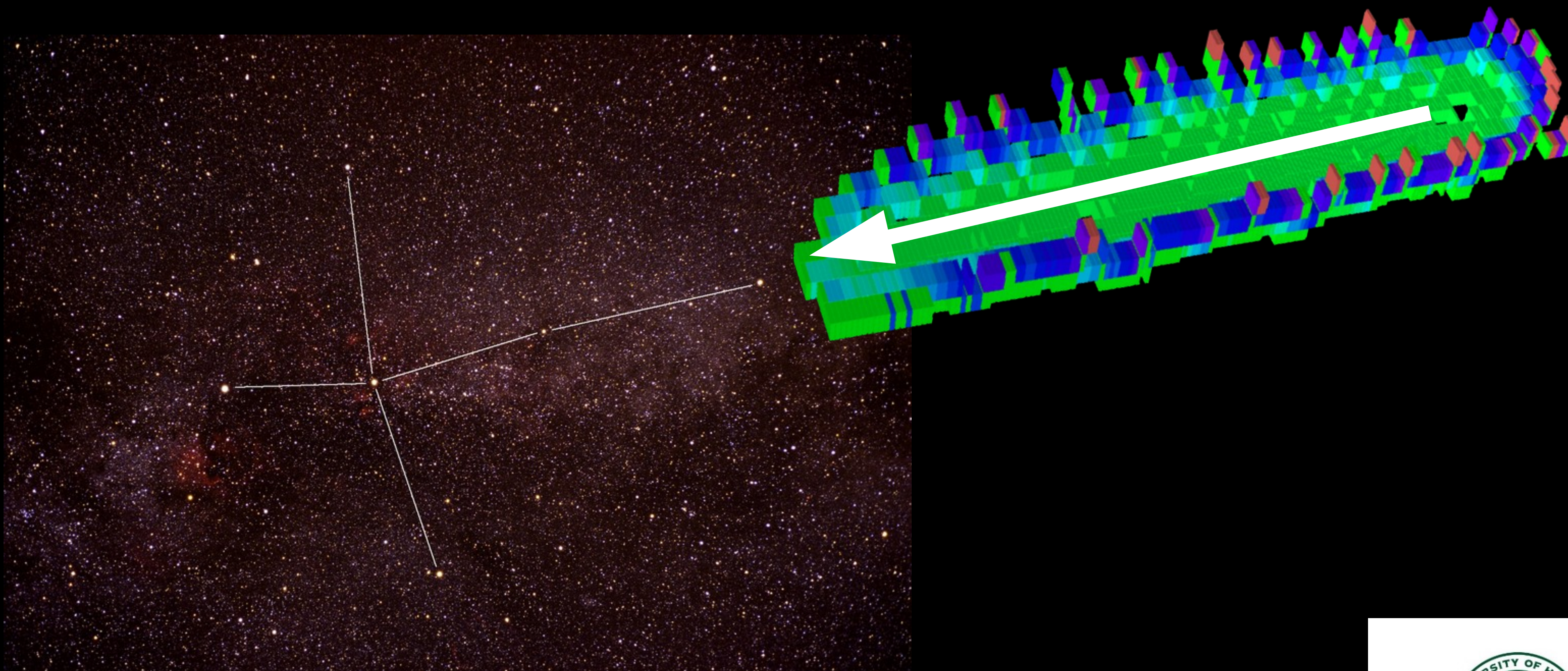
Progress on D^3 - Milli, a prototype Directional Dark matter Detector

http://www.cambridgeblog.org/wp-content/uploads/2013/07/cygnus-lines-for-web.jpg



Tom Thorpe – D^3 collaboration

CAASTRO/CoEPP workshop – Melbourne U.

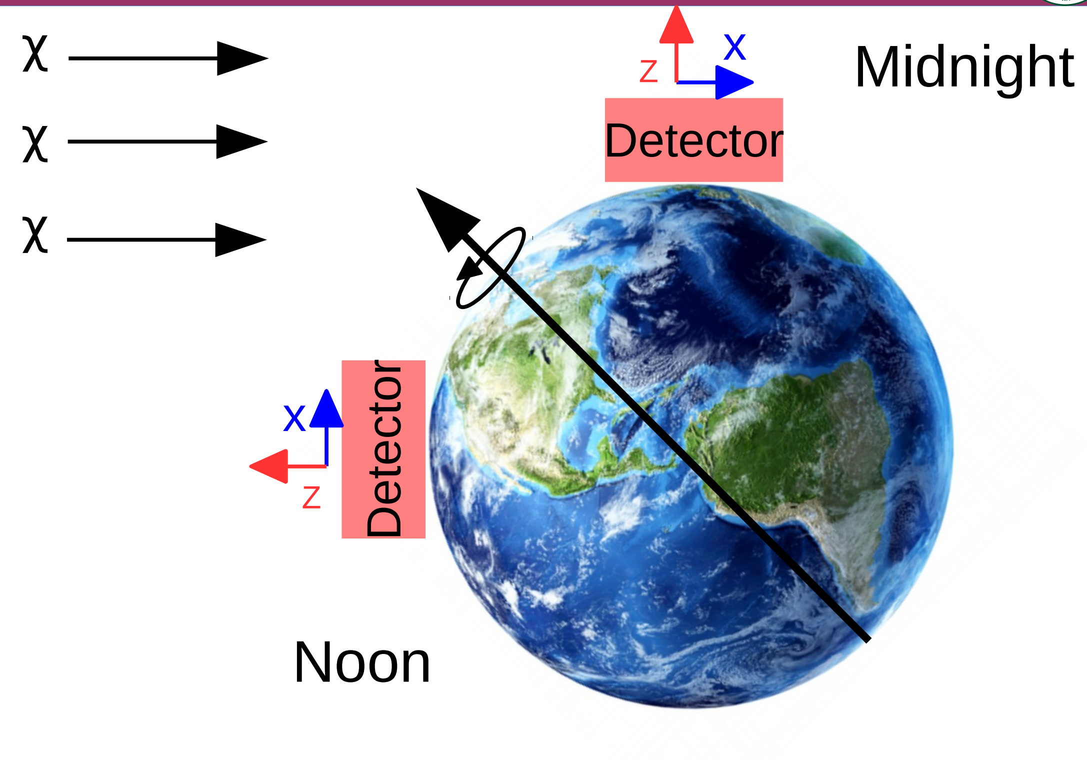
January, 31 2017

UNIVERSITY of HAWAI'I® MĀNOA

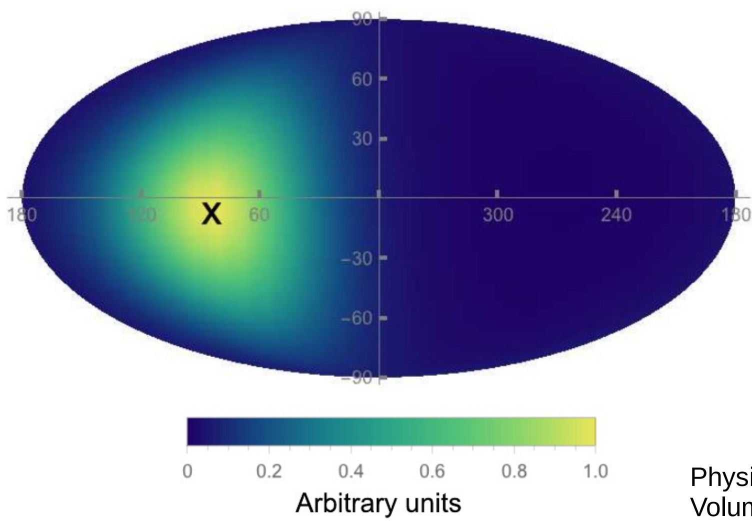
Outline

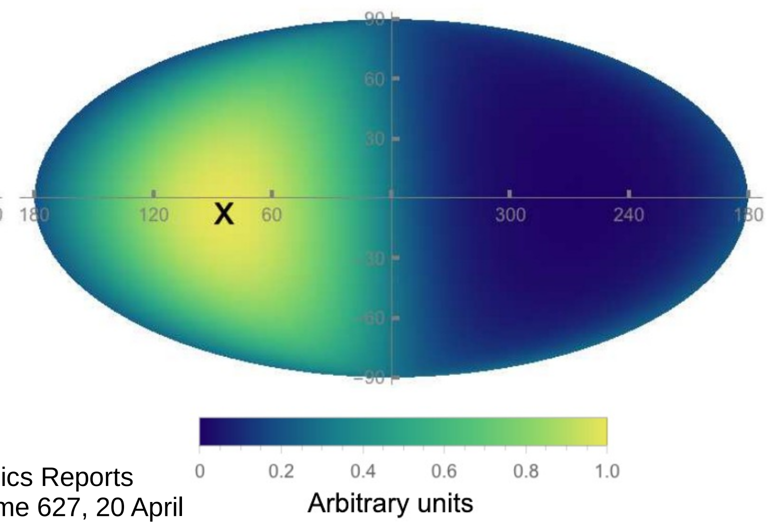
- Directional detection
- TPCs with GEMs and pixel chips
  - Energy and angular measurements
  - Absolute position measurement
  - Directional neutron detection
- Moving to directional dark matter detection
  - What is different?
  - Impacts on detector requirements
- D^3 - Milli design & status
- Summary

- Earth's rotation causes **daily oscillation of mean direction** of WIMP wind in lab coordinates
- Reconstruction of recoils gives a preferred direction in galactic coordinates; towards Cygnus
- No known background should produce such a signal



WIMP wind

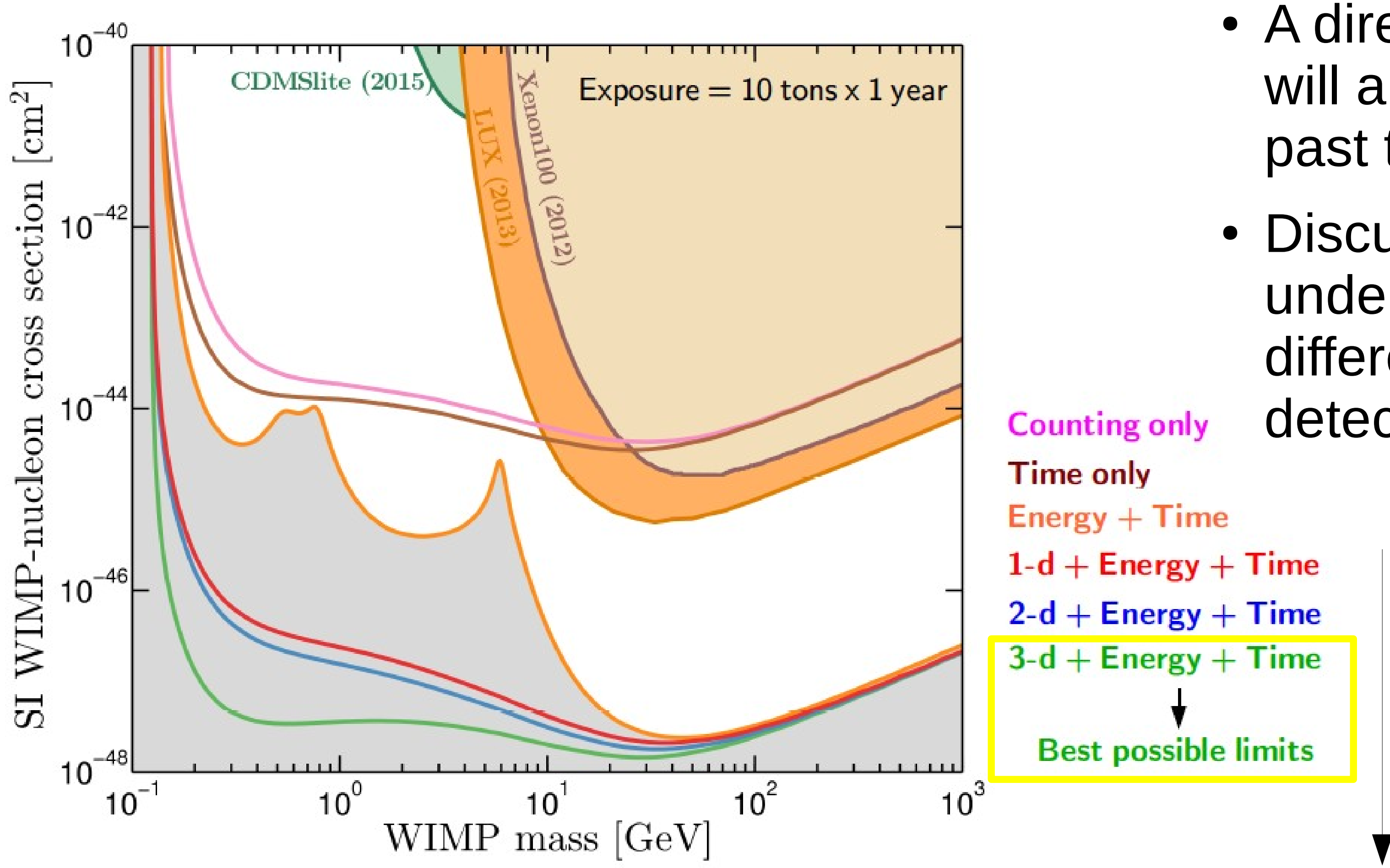




Reconstructed nuclear recoils

Physics Reports Volume 627, 20 April 2016, Pages 1–49

Comparing readout strategies

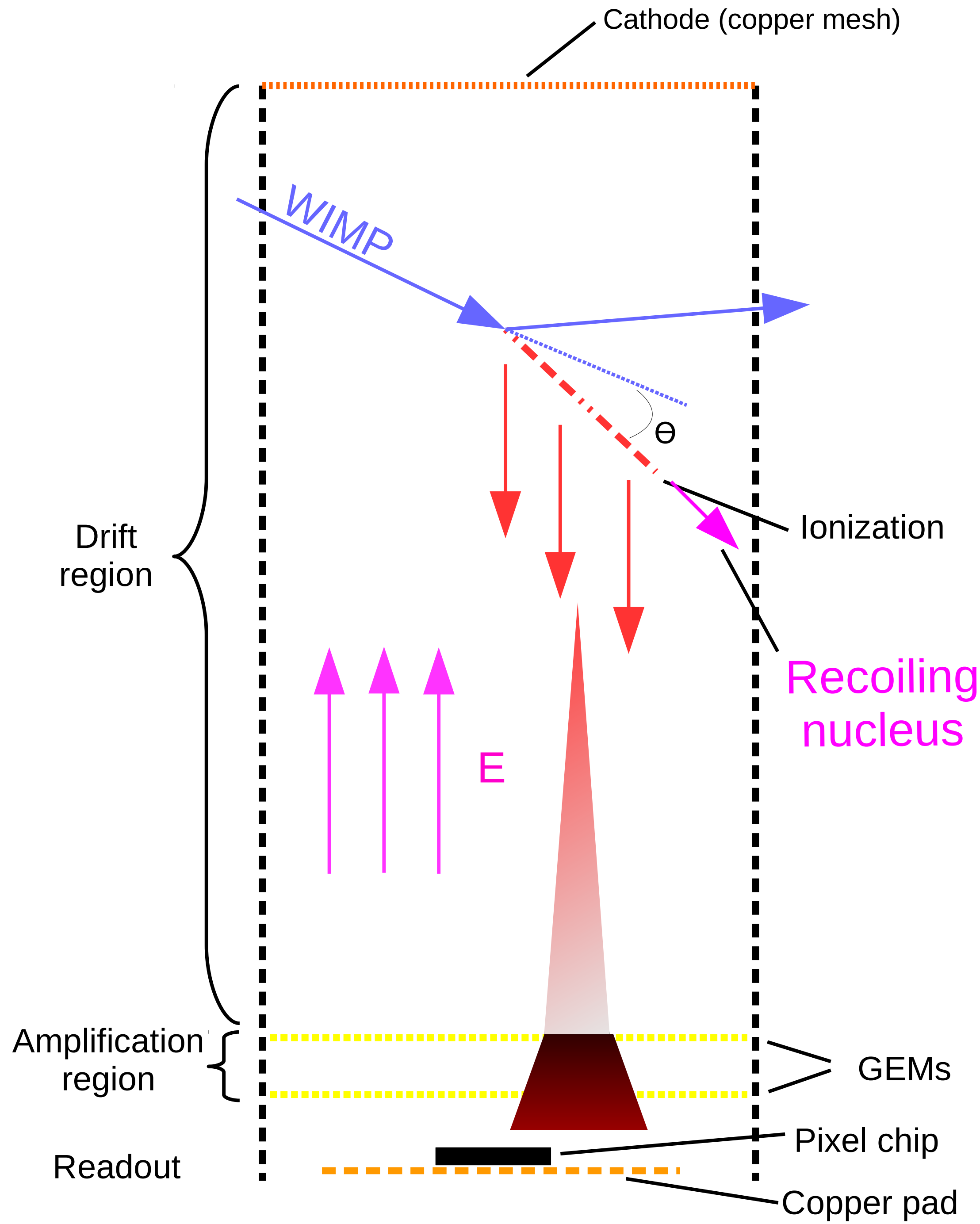


Difficulty & Cost

From Ciaran O'Hare's iDM talk

- Coherent neutrino scattering will start to swamp energy-only detectors
- A directional detector will allow us to “see” past this
- Discussion is now underway about different directional detection strategies

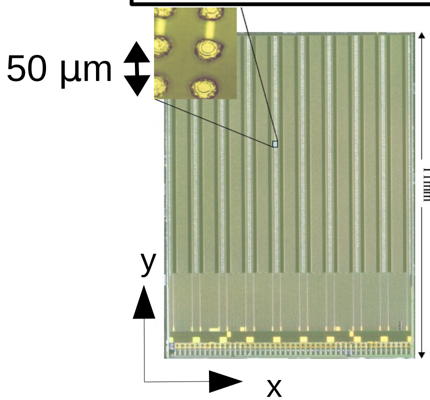
- Particle enters detector interacting with target
- Ionization is drifted to amplification region and read out
- Idea is to build a low pressure Negative Ion (NI) TPC with GEM amplification and pixel chip readout as a unit cell
- This could then be used for scaling up to a large directional detector

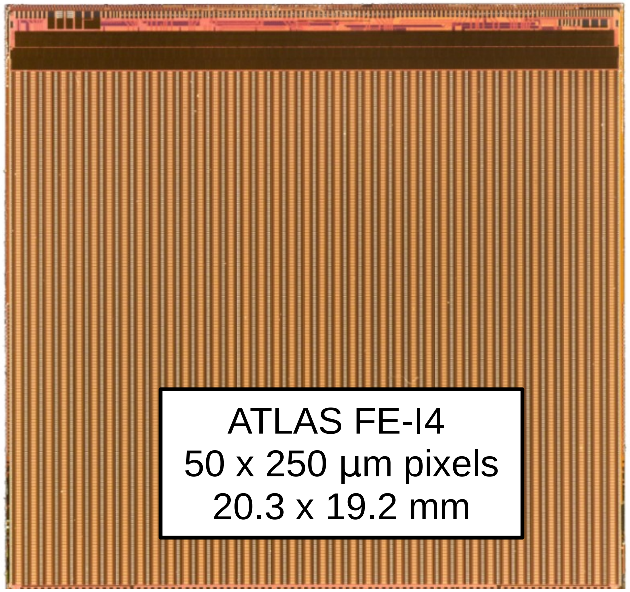


GEMs and Pixel Chips

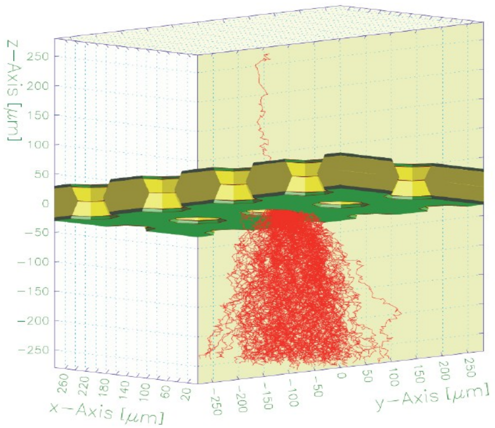
- Gas Electron Multiplier (GEM)
  - Two layers of copper sandwiching a thin (50µm) layer of Kapton (insulator)
  - Acid-etched holes w/ 70µm pitch
  - Single GEM turns 1 electron into 100s - "Avalanching"

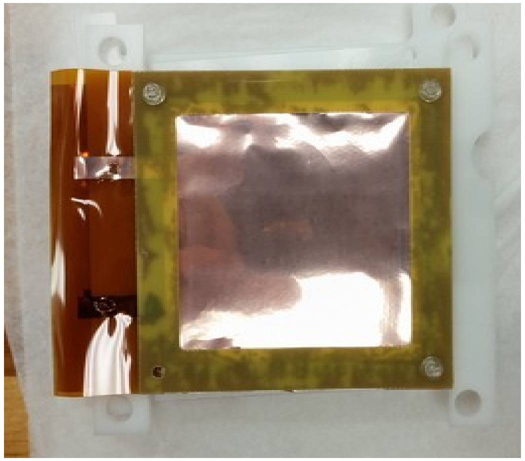
ATLAS FE-I3
50 x 400 µm pixels
7.4 x 11.0 mm





ATLAS FE-I4
50 x 250 µm pixels
20.3 x 19.2 mm





- ATLAS pixel chips
  - Each pixel is a charge integrating amplifier which measures the ionization energy
  - Low noise ~100 e-
  - Adjustable threshold
  - Self-triggering
  - 40Mhz clock

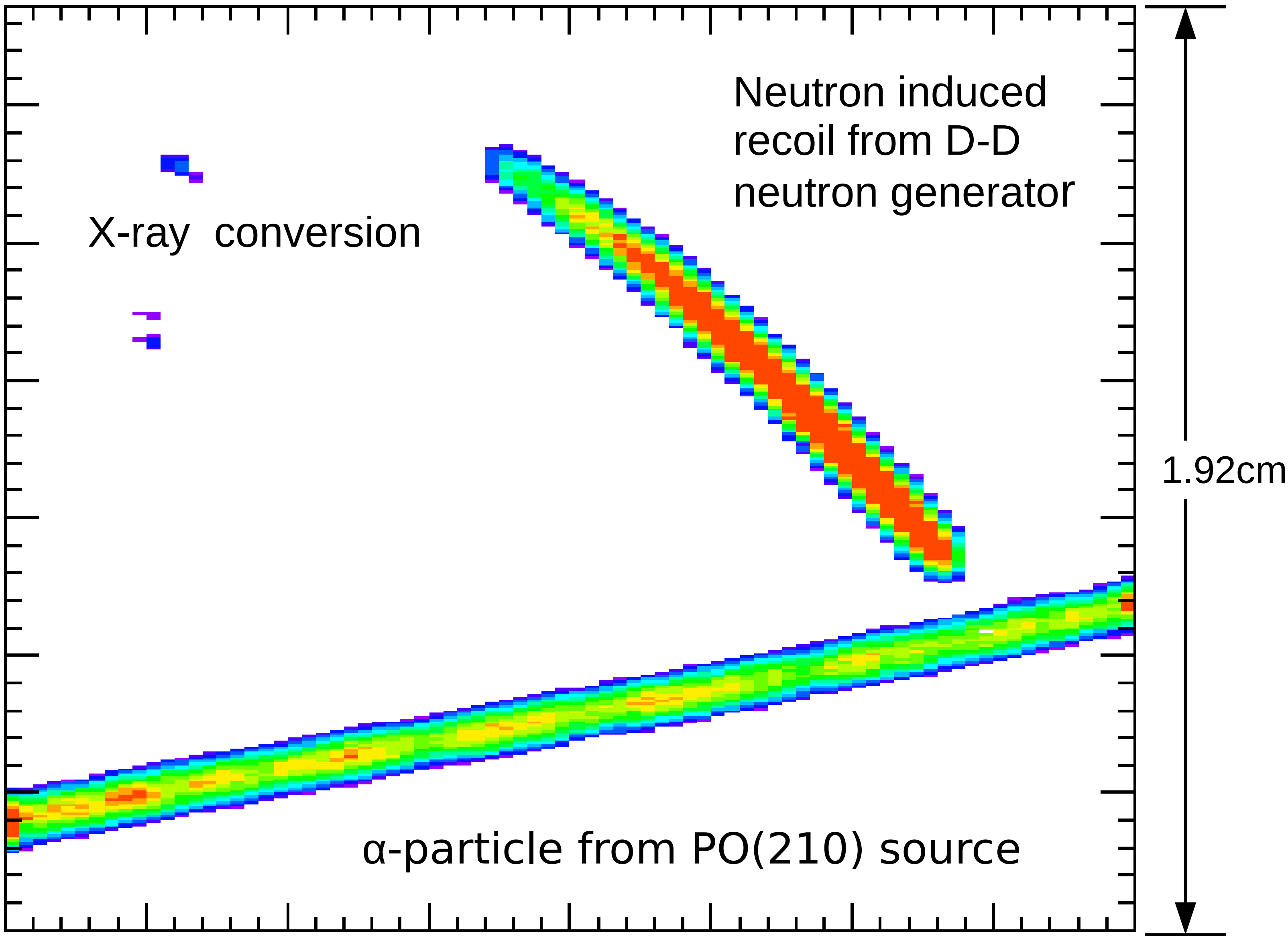
Advantages

- Full 3D track reconstruction
- High single electron efficiency which is needed for low-mass WIMP searches

HeCO$_2$ (70/30) @ 1atm

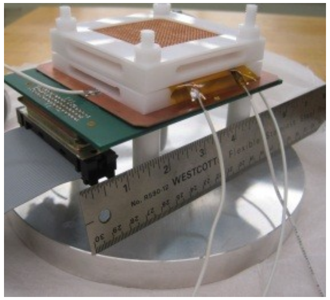
3 Superimposed events

- High gain and low noise yields detailed 3D images of ionization
  - 2D projections shown
- Powerful background rejection; event separation
- Virtually noise free
- Head/tail information
  - Particle coming from +z or -z



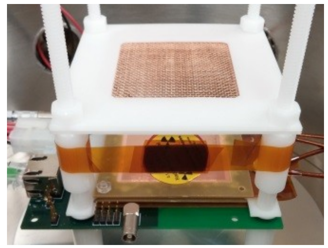
D^3 Timeline

2011 - 2013



D^3 - Micro (~1cm^3)
1 pixel chip

2013



~ 20 cm^3

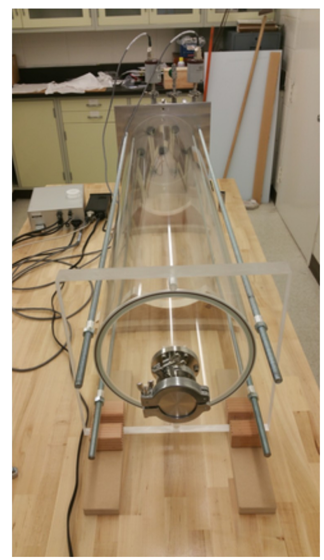
2014

2 x 60 cm^3

2015

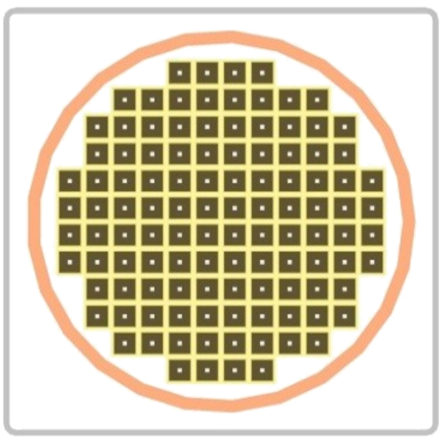
8 x 40 cm^3

Under construction!



D^3 - Milli (~10 liters)
4 - 16 pixel chips **(NID w/ SF_6)**

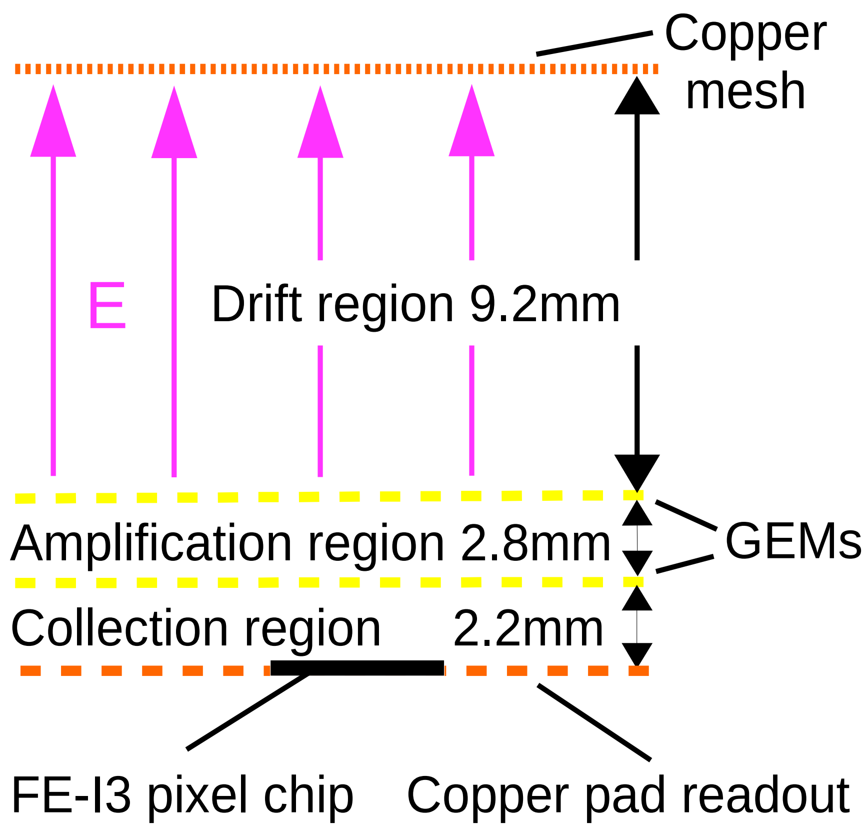
(planned, still unfunded
- unit cell of CYGNUS)

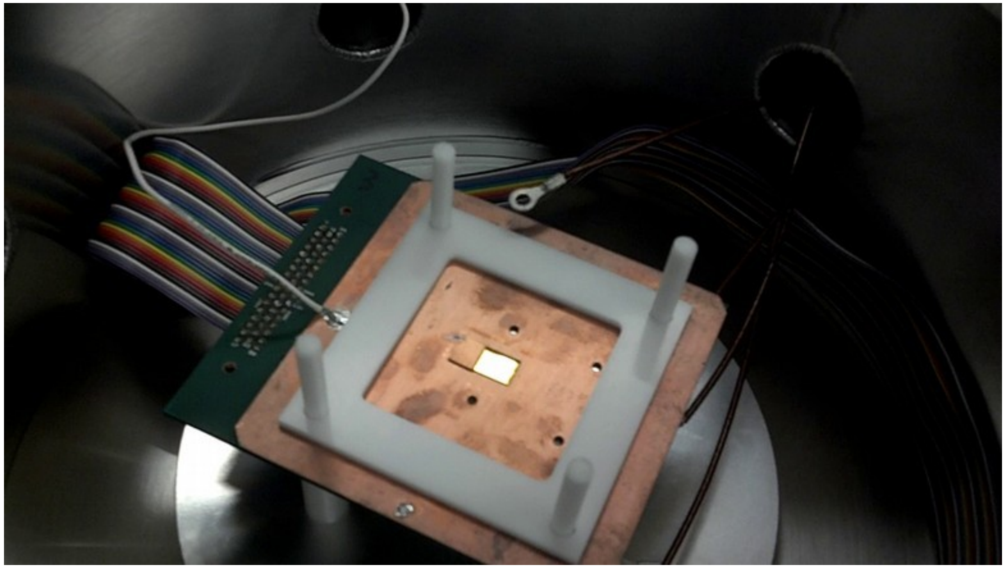


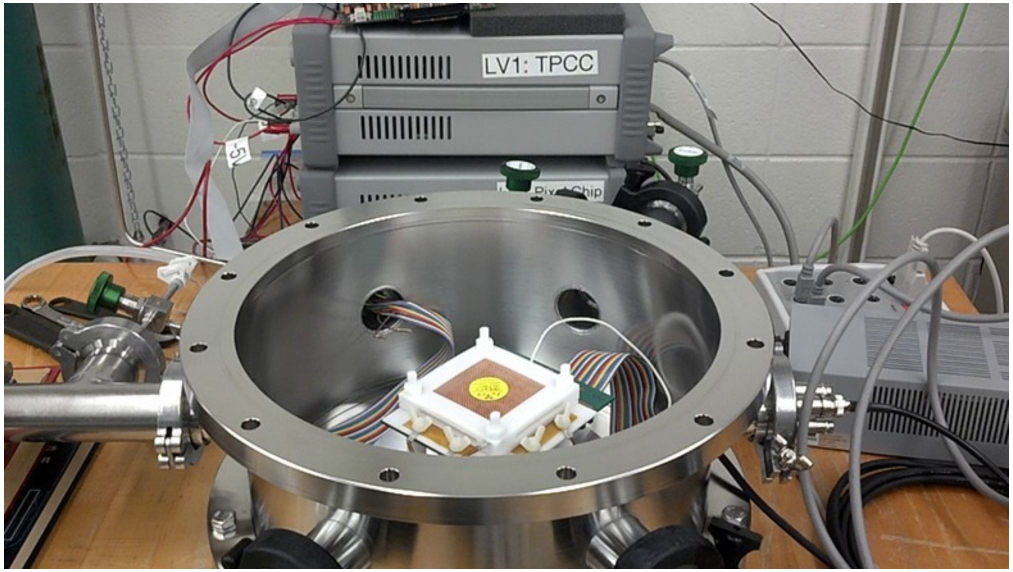
D^3 (~1m^3)
~400 pixel chips

D³ - Micro (2011-2013)

- First prototype at U. Hawaii
  - ~ 1 cm³ detector volume
  - Used for performance testing
  - Double GEM amplification
  - Readout
    - **Copper pad – for initial gain calibration**
    - ATLAS FE-I3 pixel chip
- Very stable - > 1 year operation







Performance Studies – Gain/Energy

- Ionization collected by copper pad and sent through analog electronics chain
- Gain stable to a few % for weeks
- Need to repeat this study with SF_6

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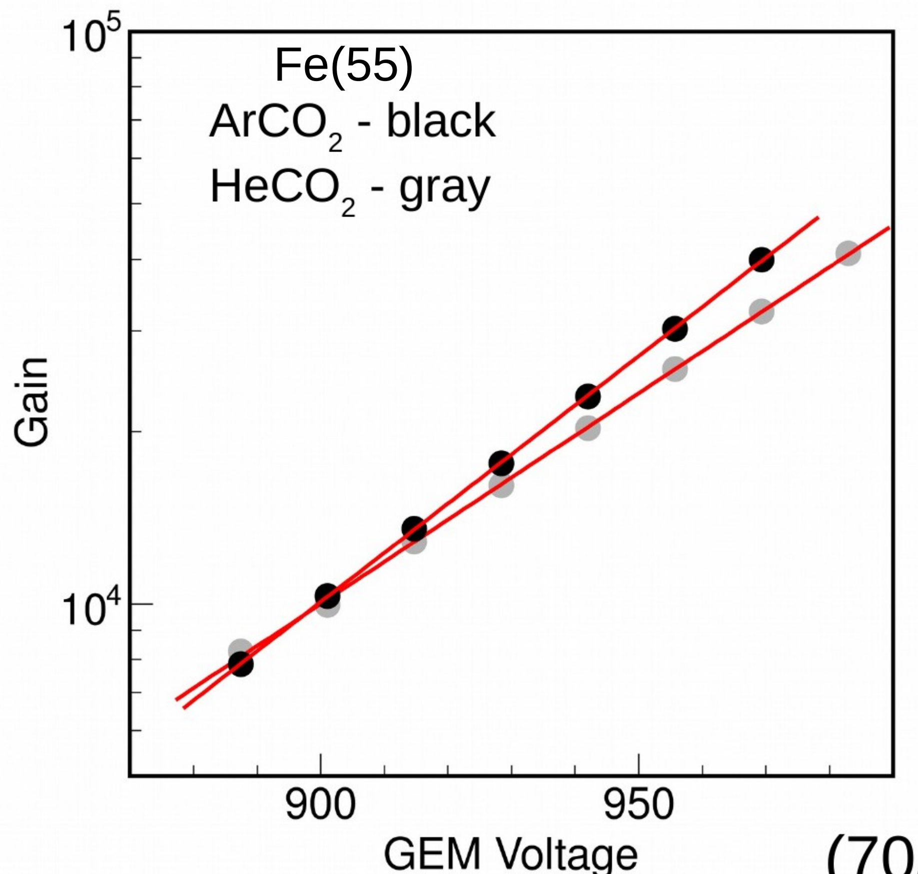
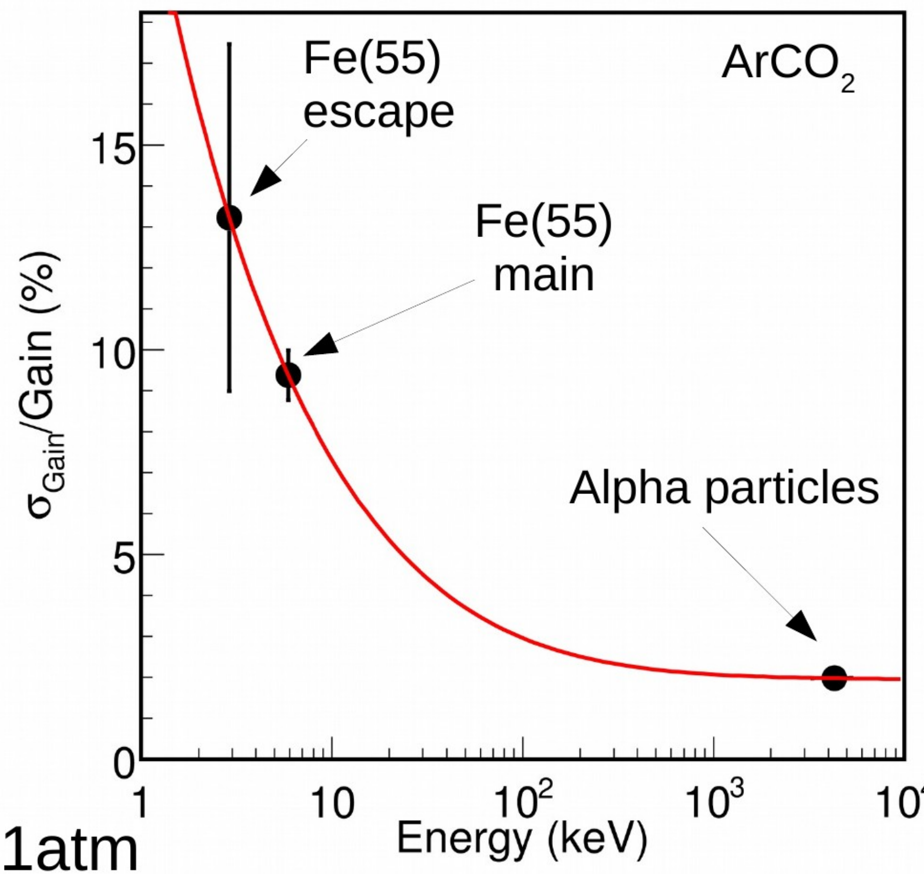
S.E. Vahsen, M.T. Hedges, I. Jaegle, S.J. Ross, I.S. Seong, **T.N. Thorpe**, J. Yamaoka, J.A. Kadyk, M. Garcia-Sciveres

- Asymptotic gain resolution values plotted vs. ionization energy
- Gives ultimate energy resolution
  - Pixel chip can't do better

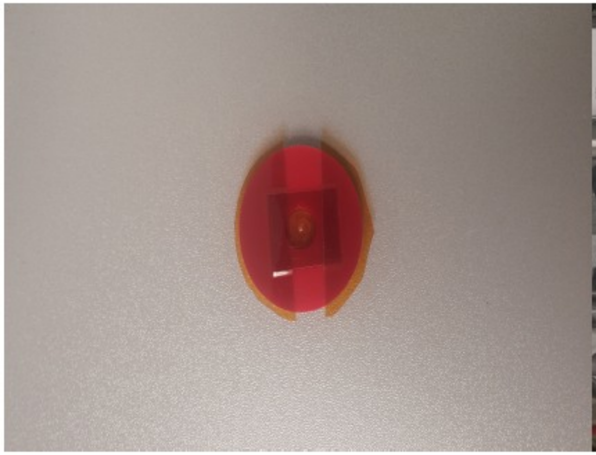


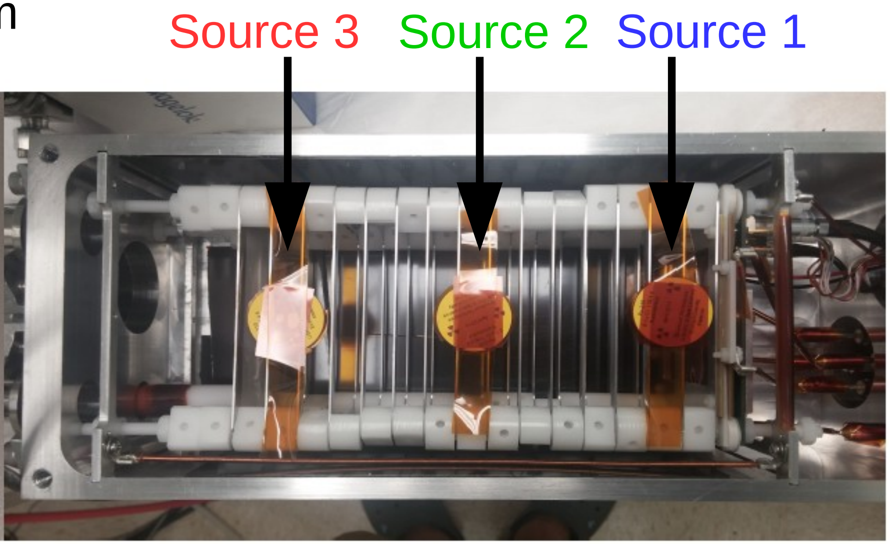
(70/30) @ 1atm



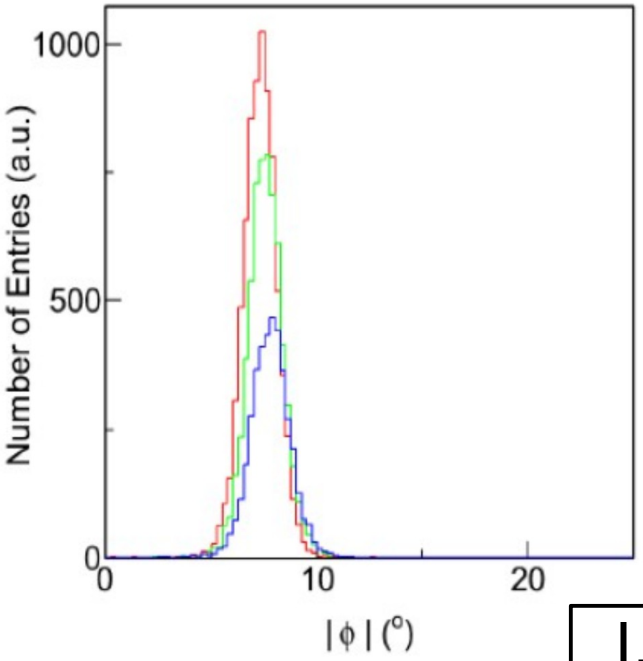
- Three PO(210) alpha particle sources
  - Different z positions gives z dependent calibration
  - Used for monitoring gain stability
- Done with 2cm alpha tracks segments

$HeCO_2$ (70/30) @ 1atm

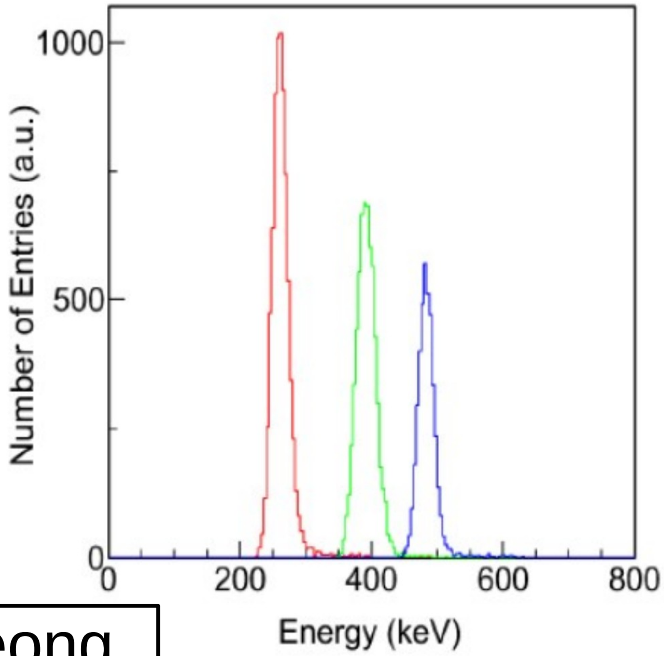




- Less than 1-degree angular resolution w/ 15 cm drift
- Energy resolution consistent with gain resolution measurements



Sigma Phi : 0.78, 0.82, 0.89 degree

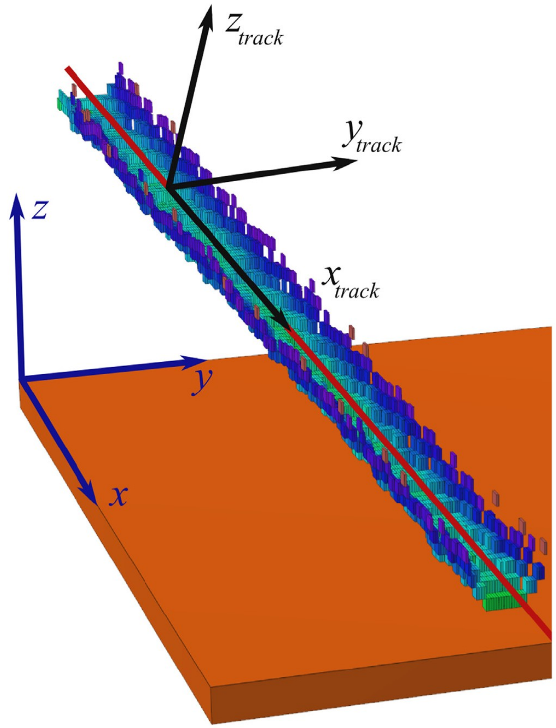


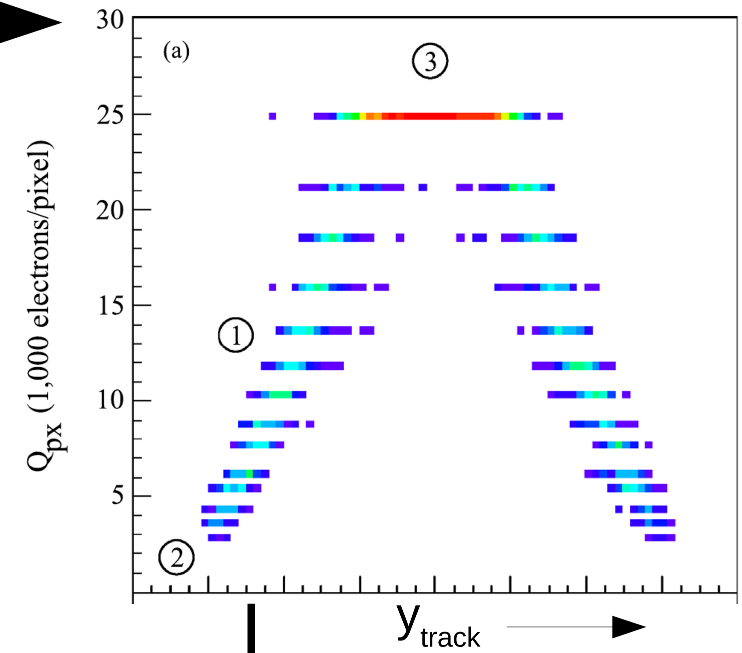
Resolution : 4.45, 3.60, 2.41 %

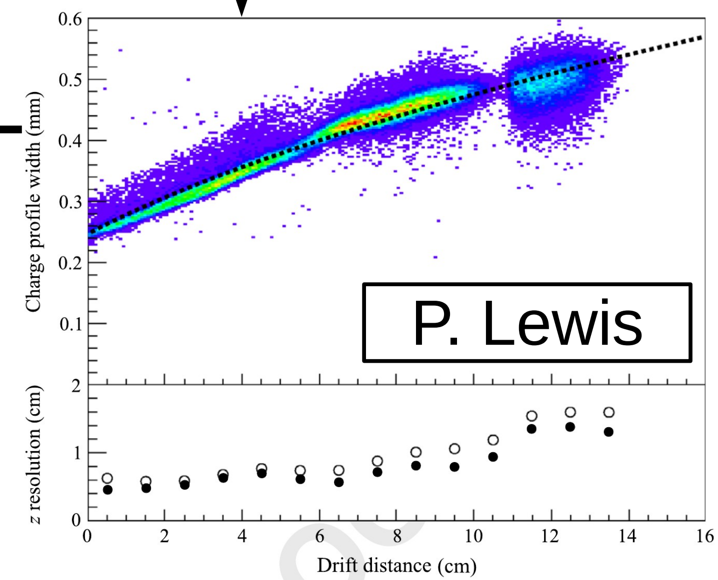
I. Seong

Absolute Position Measurement

- Plot charge profile, Q_{px}, vs. distance from center of track; fit with Gaussian
- Take width of Gaussian and plot vs known z based on 3 known source positions
  - This gives a one-to-one relationship between z and charge profile width
- Allows for absolute z within ~1cm; even for short, 2mm, tracks







● 8mm tracks
○ 2mm tracks

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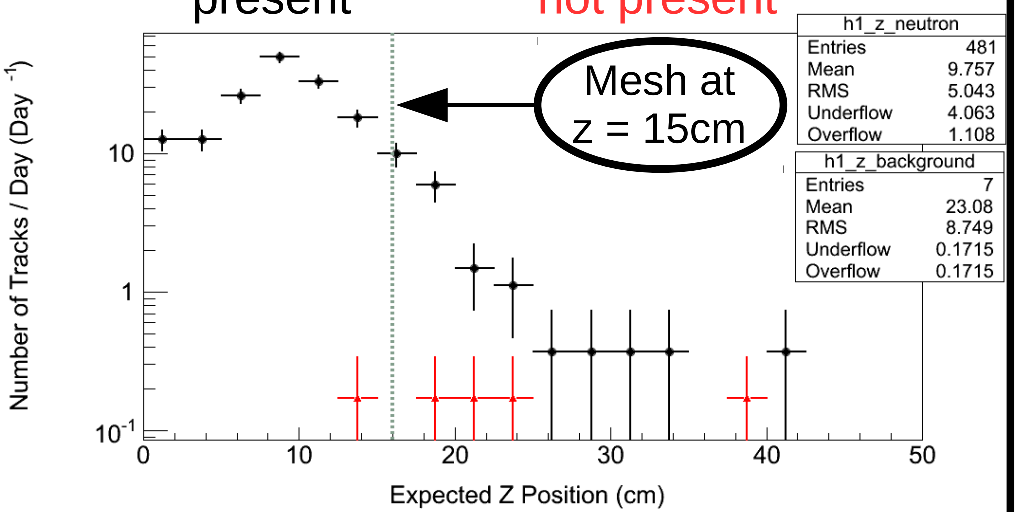
3D – fiducialization allows for background free running

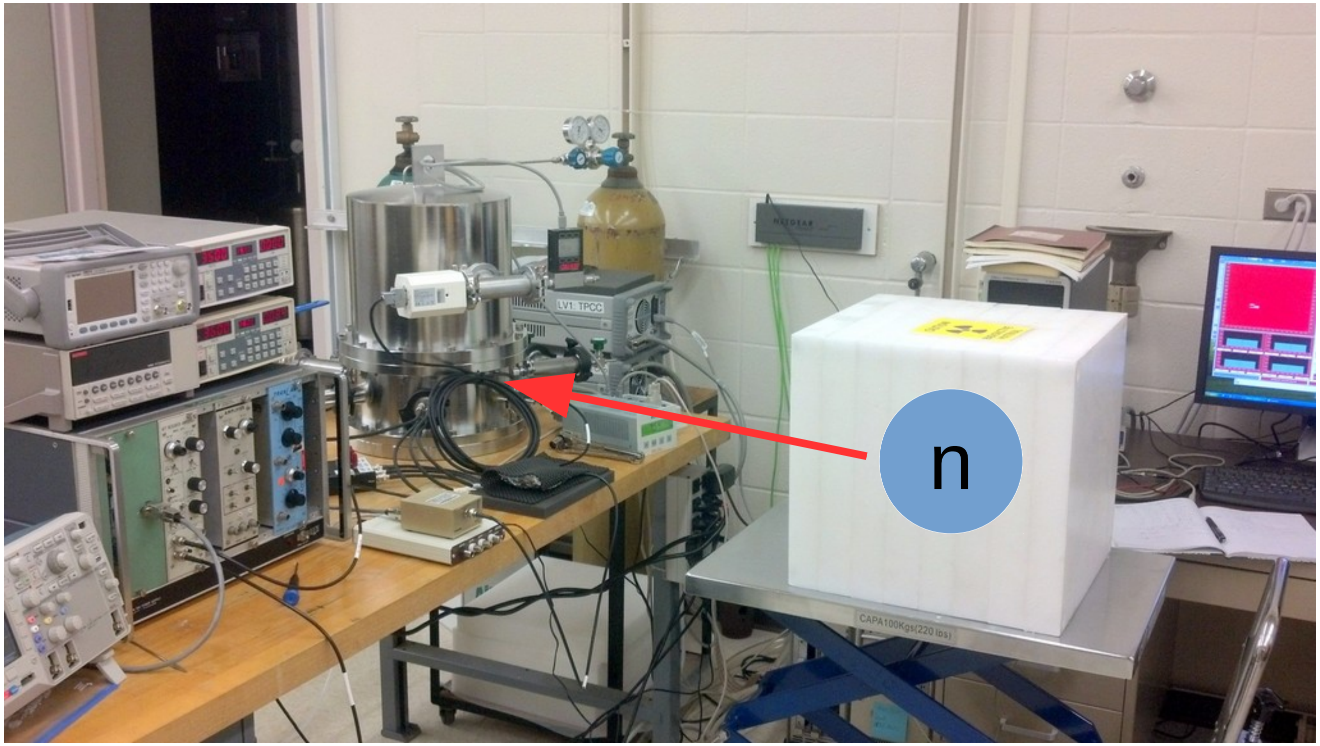
Neutron source present

Neutron source not present

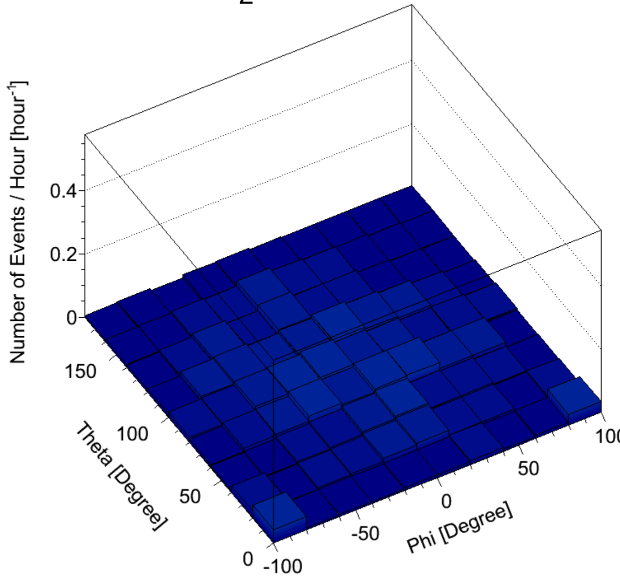


Directional Neutron Detection

- Energy and angular resolution allow reconstruction of "neutron wind" in lab... just like the "WIMP wind"
- Cf(252) source - ~MeV neutrons give ~100s keV He recoils
  - Result is a few mm track length @ 1atm

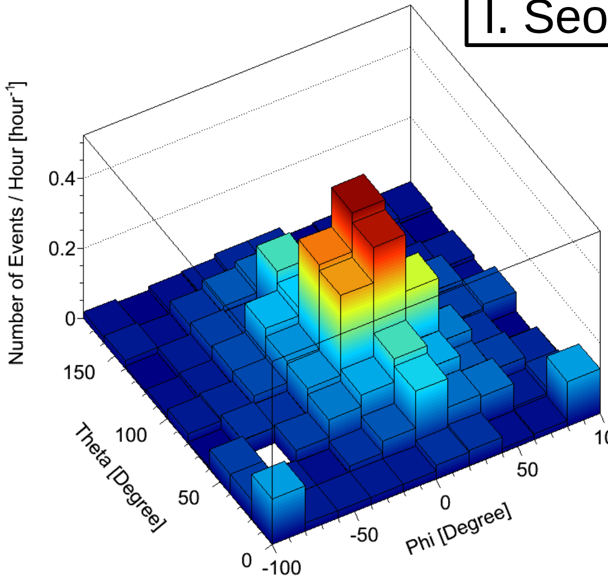


$HeCO_2$ (70/30) @ 1atm



Background Run

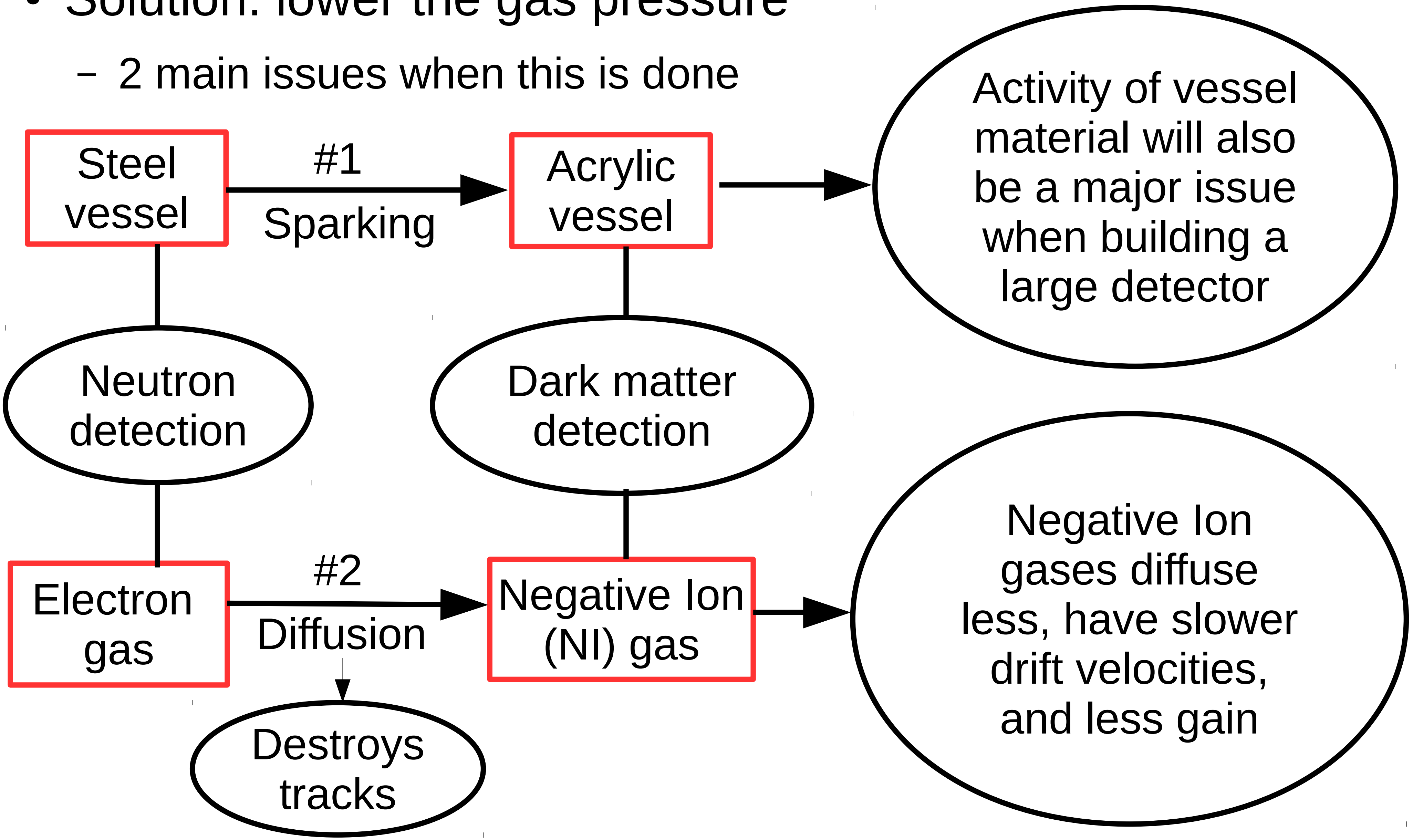
I. Seong



Source Run

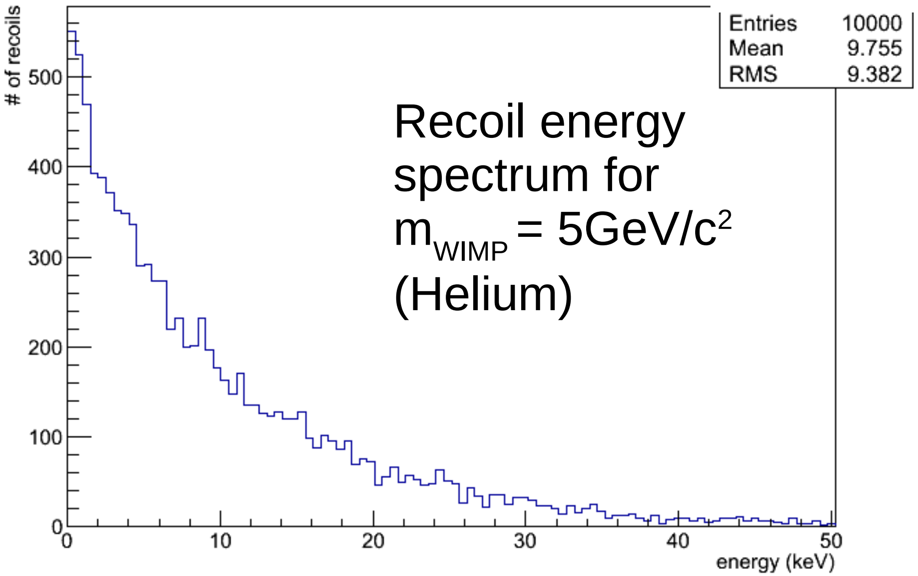
What's Different About Detecting Dark Matter?

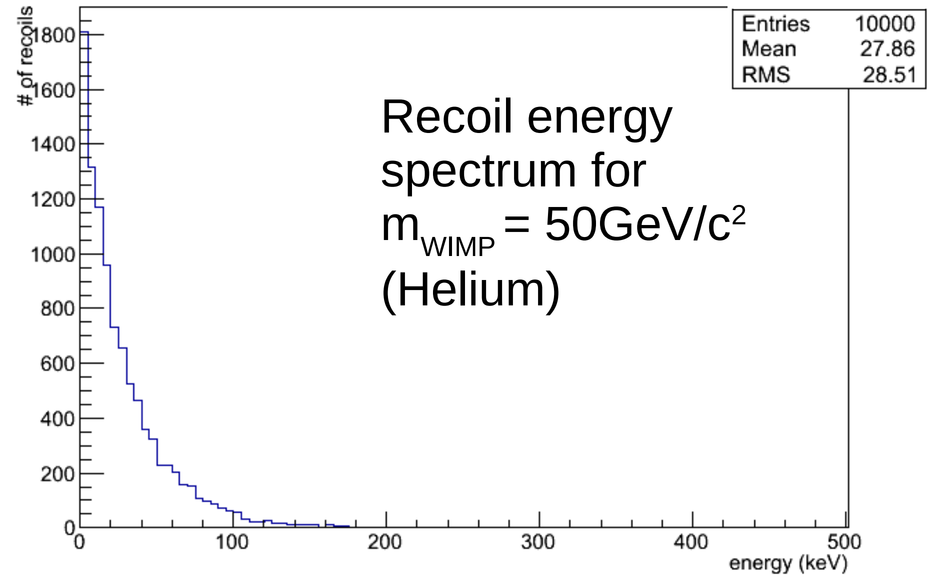
- WIMPs give less energy to targets → Shorter recoil tracks
- Solution: lower the gas pressure
  - 2 main issues when this is done

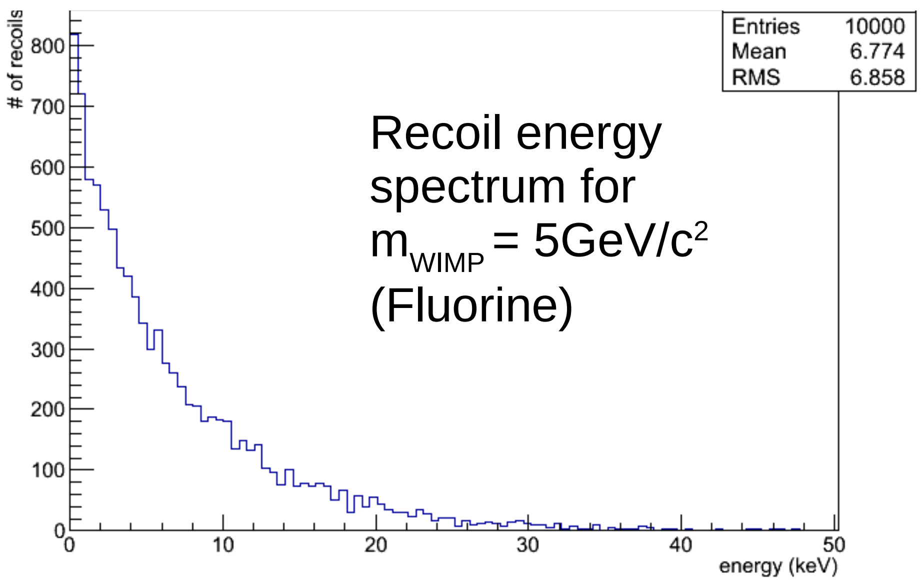


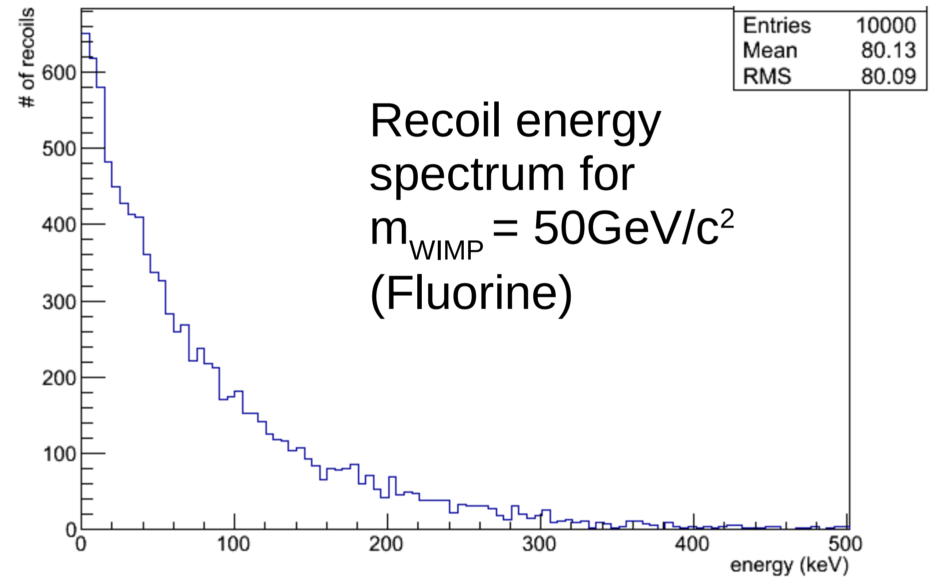
WIMP Recoil Energy Spectra

- Good rule of thumb is for a WIMP of mass x GeV the detector threshold should be x keV or less; around the mean of the recoil distribution
- Energy transfer is maximized when the target mass equals WIMP mass

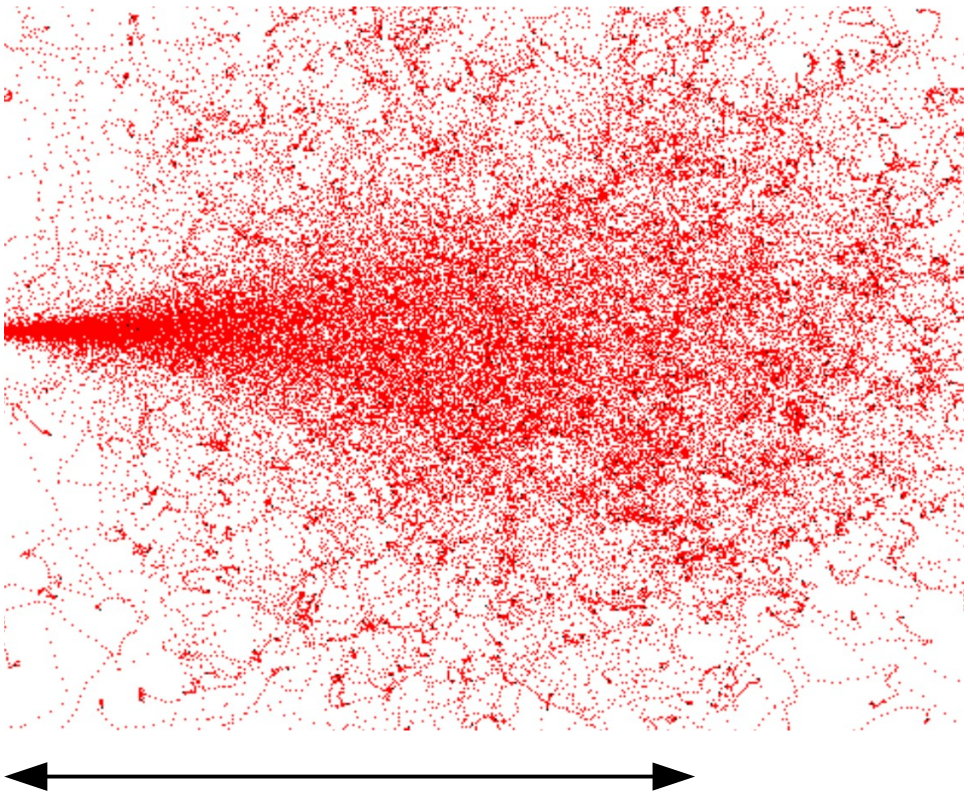






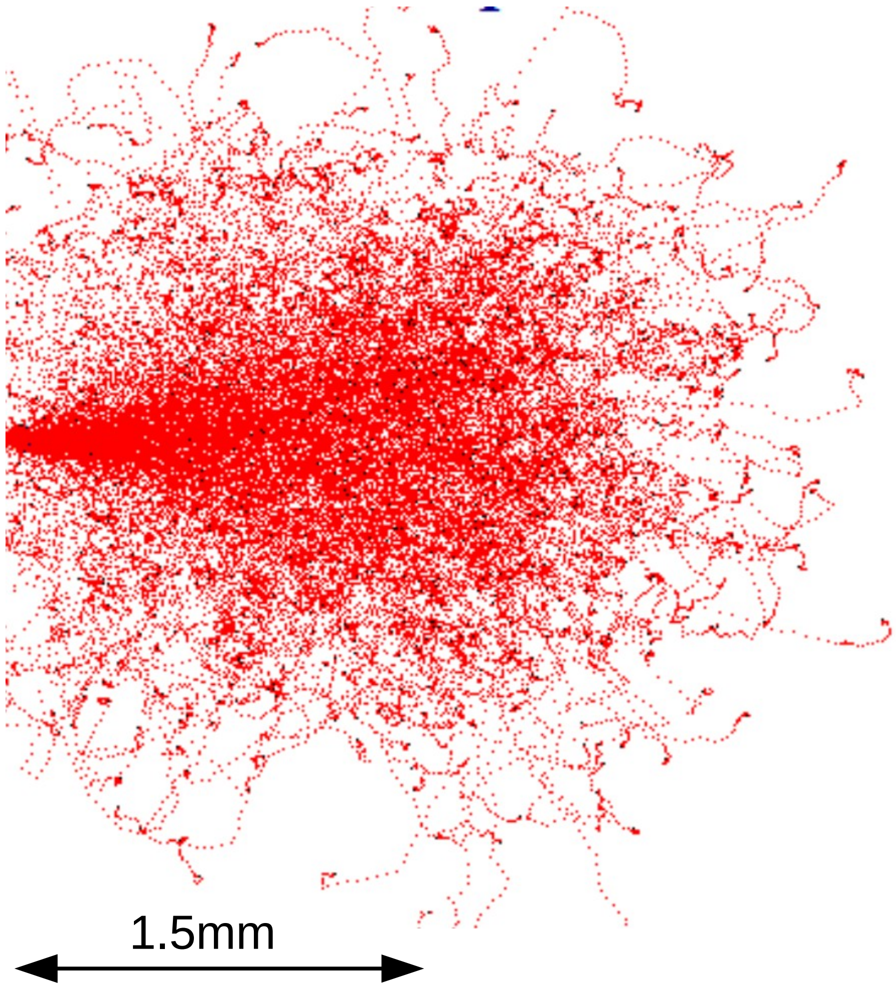


20keV He in 10 torr SF_6 + 50 torr He



2.9mm

5keV He in 10 torr SF_6 + 50 torr He

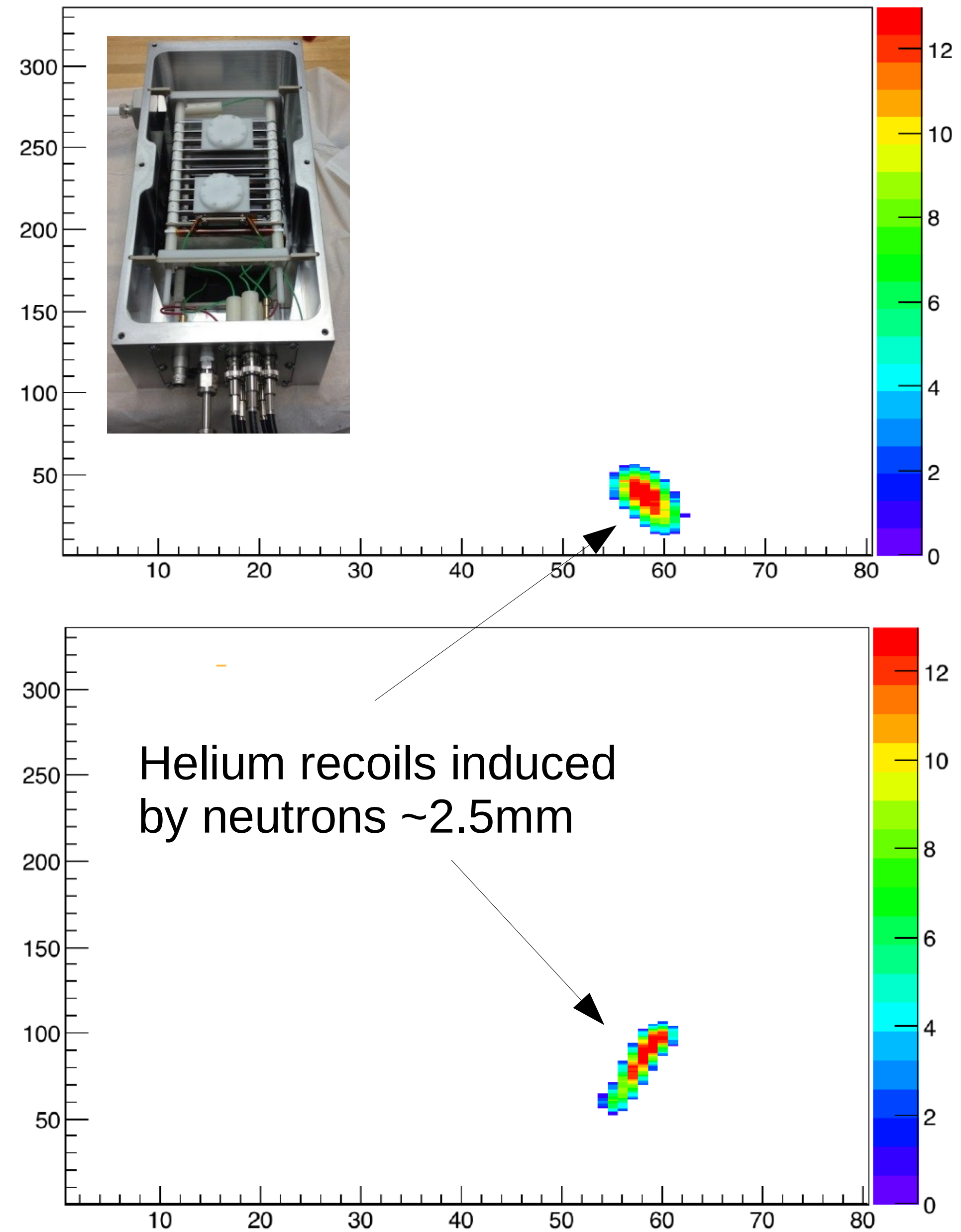


1.5mm

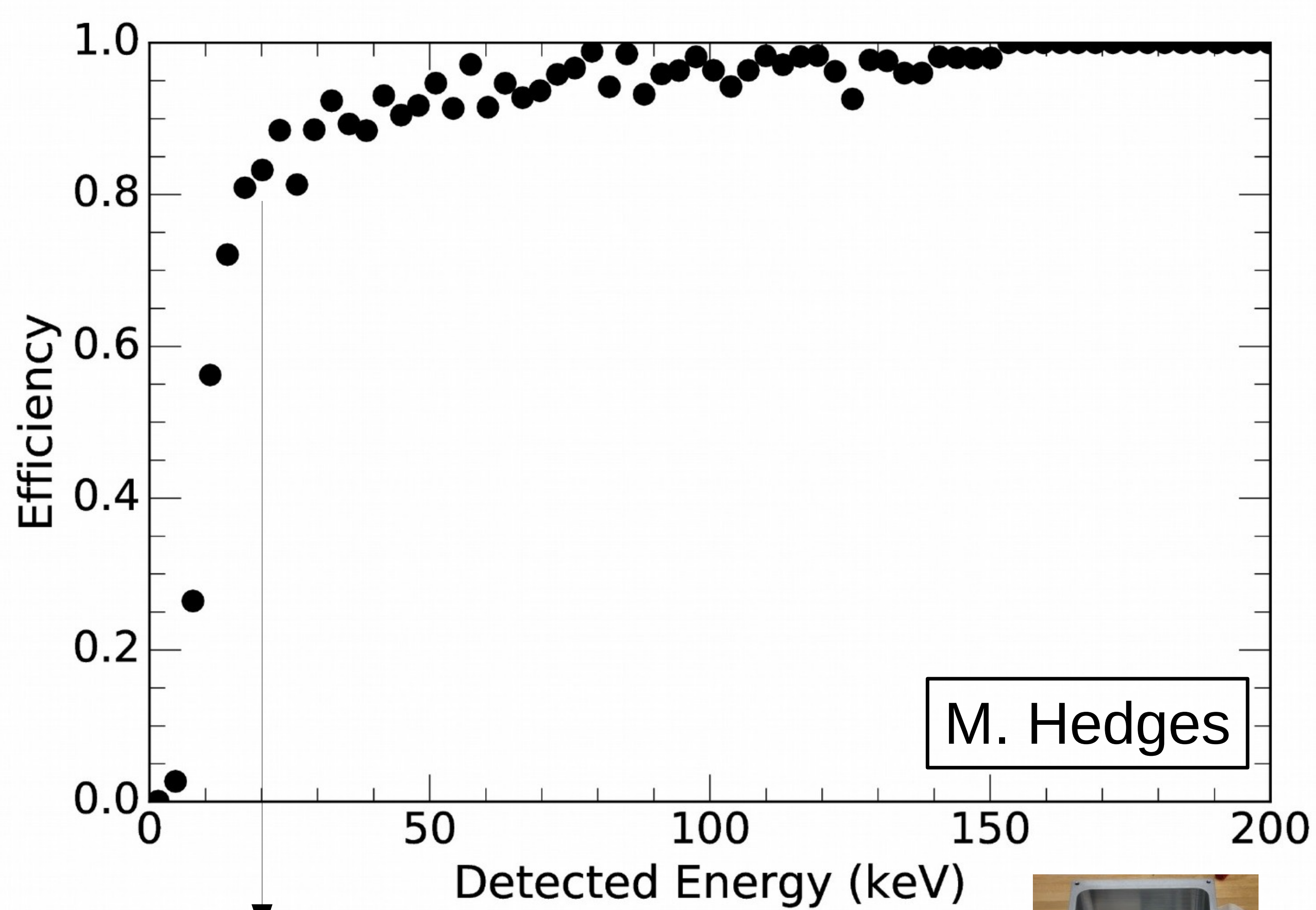
- For low mass WIMPs helium may be a good target
- Is directionality at 5keV possible?

HeCO$_2$ (70/30) @ 1atm

- What do ~20keV 2-3 mm tracks look like?
- Can see asymmetry in the energy deposition
- Need to study even lower energy recoils than this
- Goal being to have directionality for the lowest energy recoils possible
- Also must quantify background discrimination at low energies



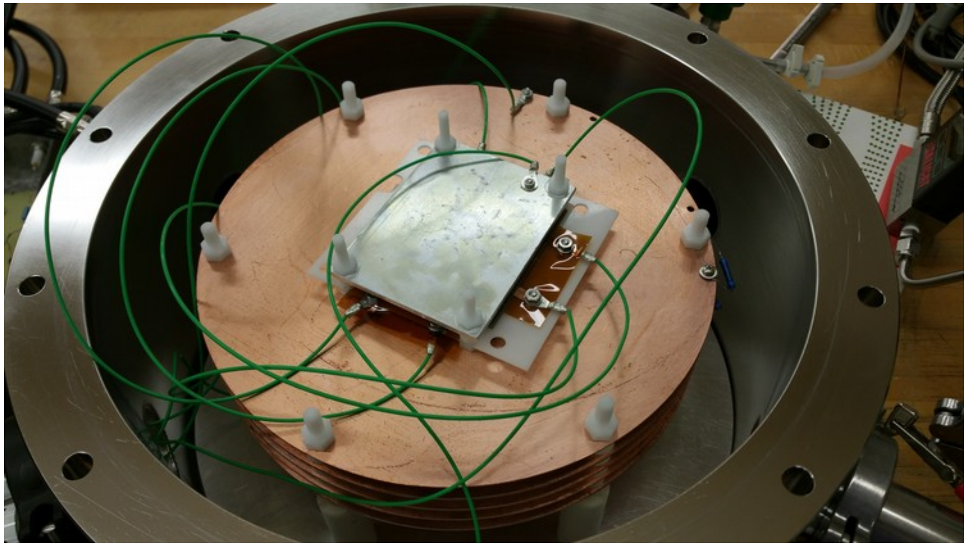
- Data from directional neutron detector deployed at SuperKEK e^+e^- collider
- With tight event selection that rejects all of the large x-ray background, 50% efficiency for nuclear recoils is at 15 keV
  - This will likely be much better in a low background detector

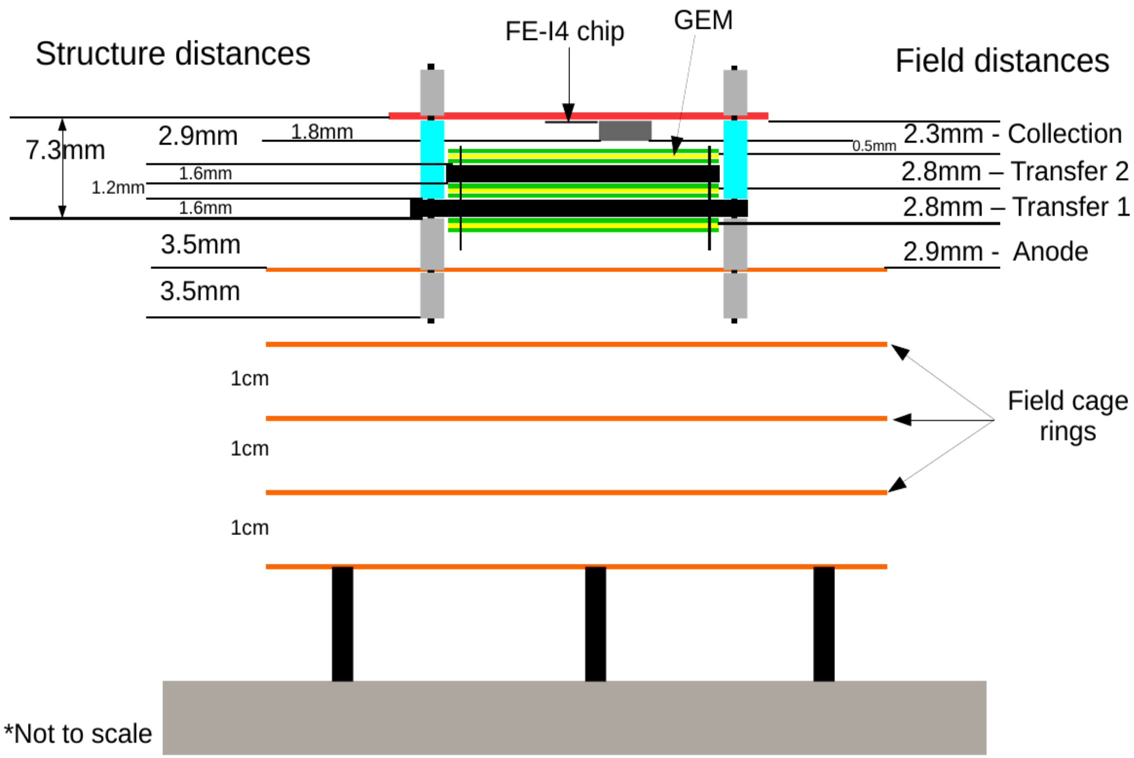


20keV recoil tracks that are 2-3 mm long should give a strong directional signal for WIMPs as well

R&D setup for SF_6

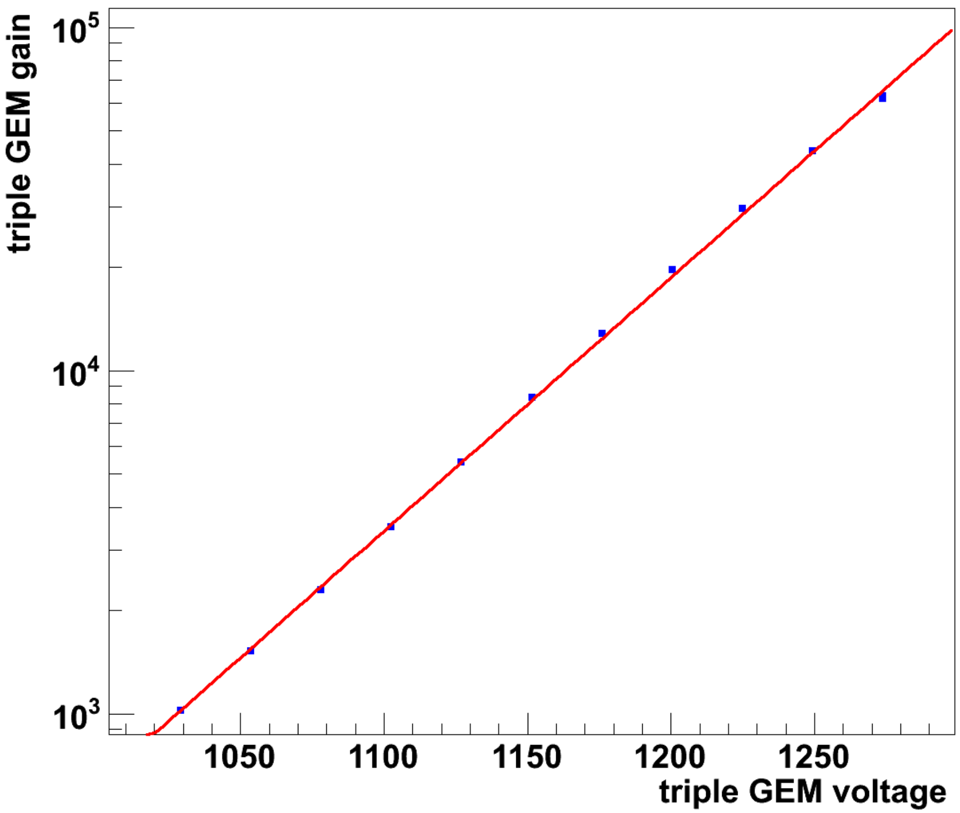
- 4cm drift w/ triple GEM gain stage
- Working well in electron gases
- SF_6 studies in progress
  - Noise has been a major factor
  - Sparking
  - SF_6 contamination when moving back to electron gases
- Currently modifying so source can be turned on/off



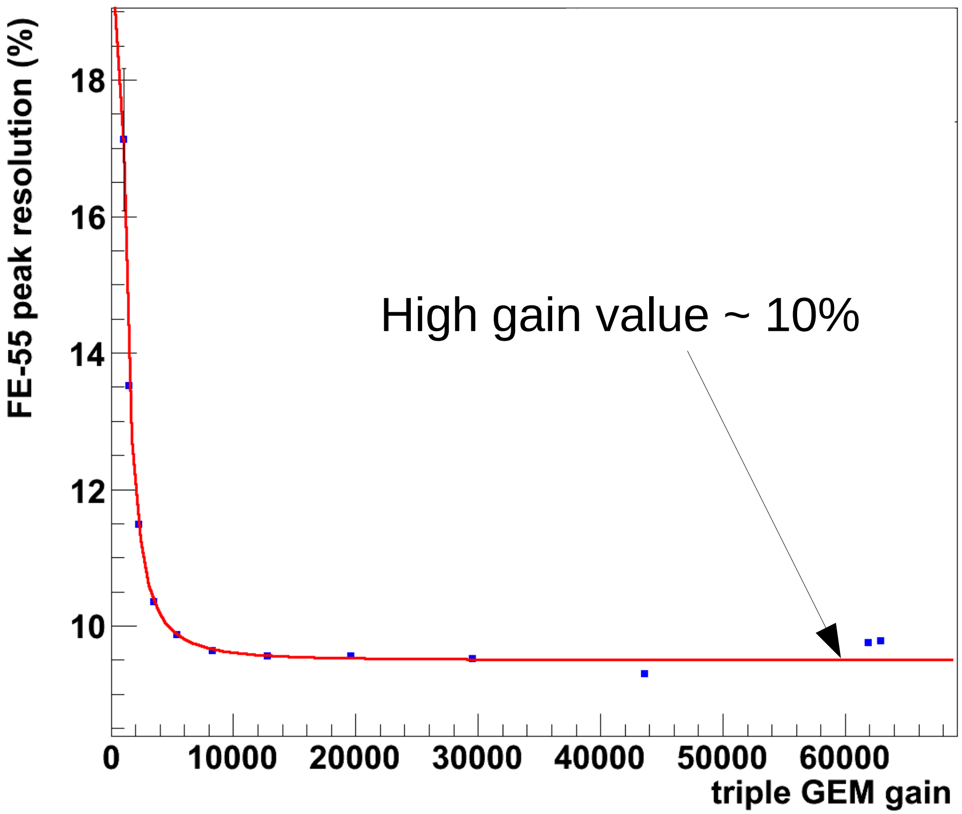


- FE(55) source – 5.9keV ; $HeCO_2$ (70/30) @ 1atm
- Triple GEM resolution is nearly the same as double GEM @ high gain

Gain vs. GEM voltage

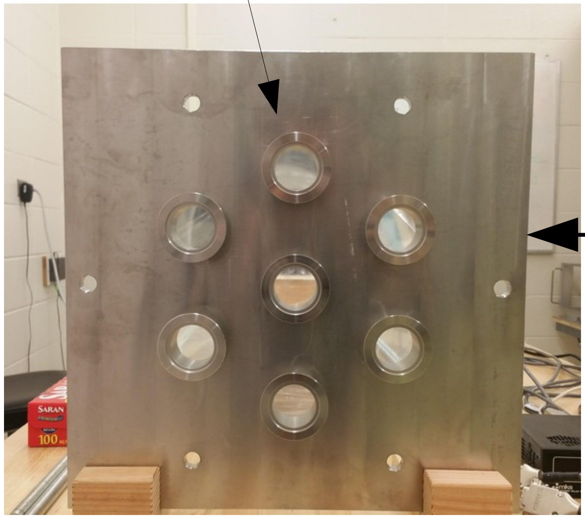


Gain resolution vs. Gain

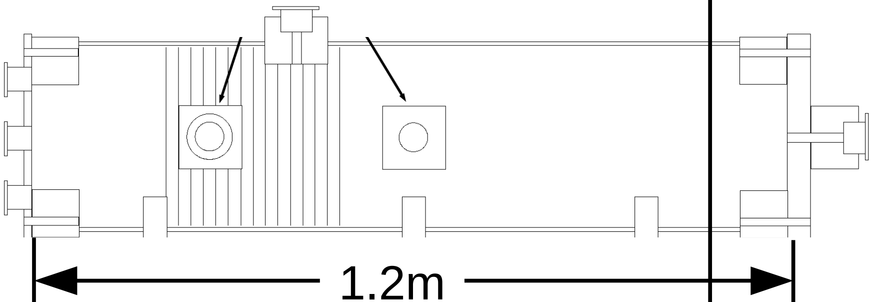


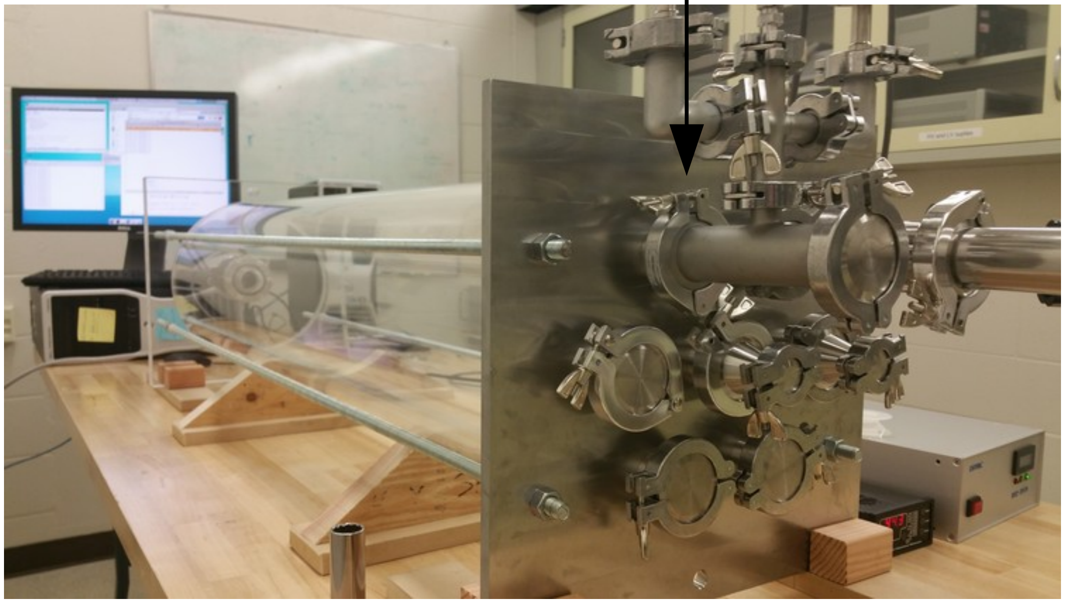
D^3 – Milli Acrylic Vacuum Vessel

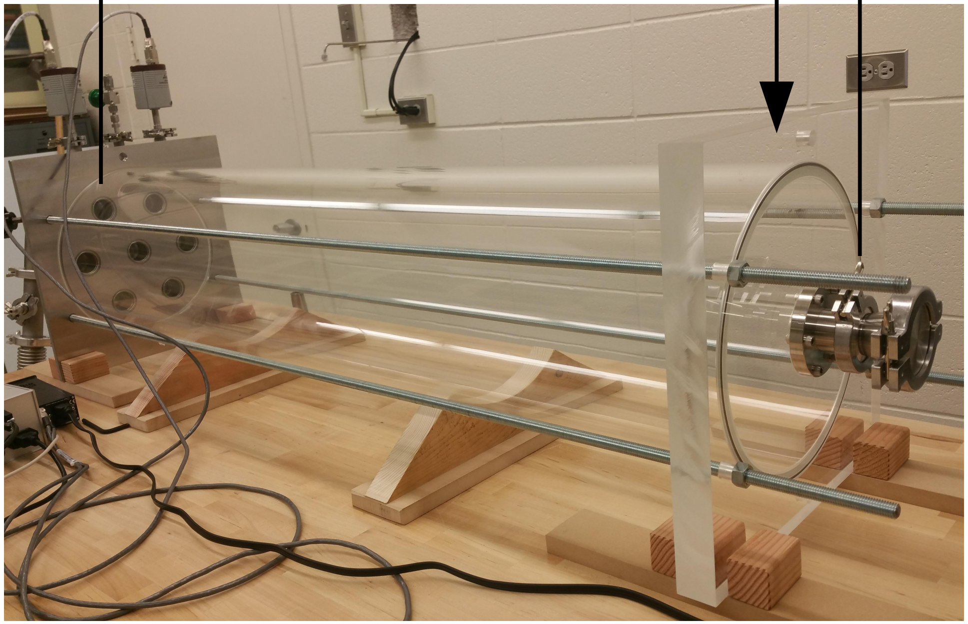
KF-40 x 7



- Wooden stands were made to line endplates up with vessel
  - Field cage slides in; make connections
  - Push endplates against vessel
  - Insert rods and tighten nuts
- SHV/LV endplate
  - GEM power
  - Gas in/out
  - Readout electronics
- 30kV endplate
  - Field cage power

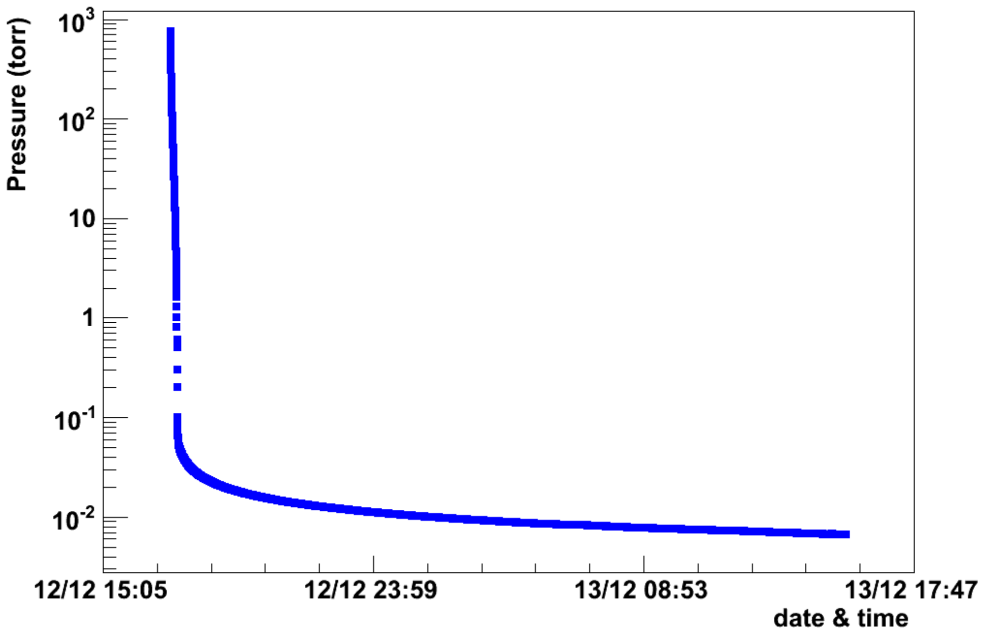






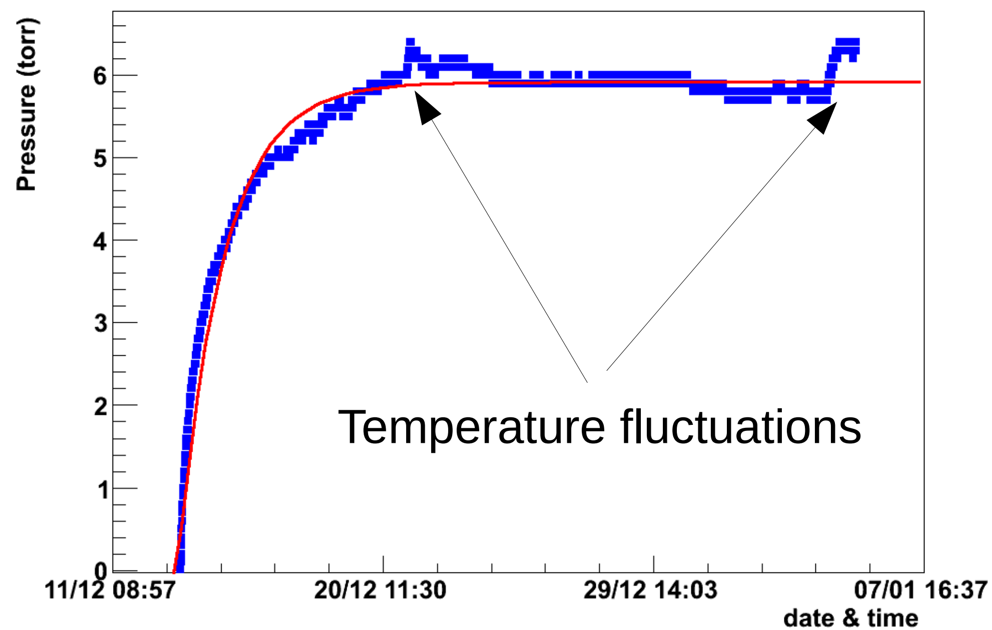
- Acrylic vessel > 3 orders of magnitude higher outgassing than stainless R&D vessel
- May have to flow gas for low pressure measurements
  - Others have shown gain in low pressure SF_6 in acrylic

Pumpdown curve



~ 1 day

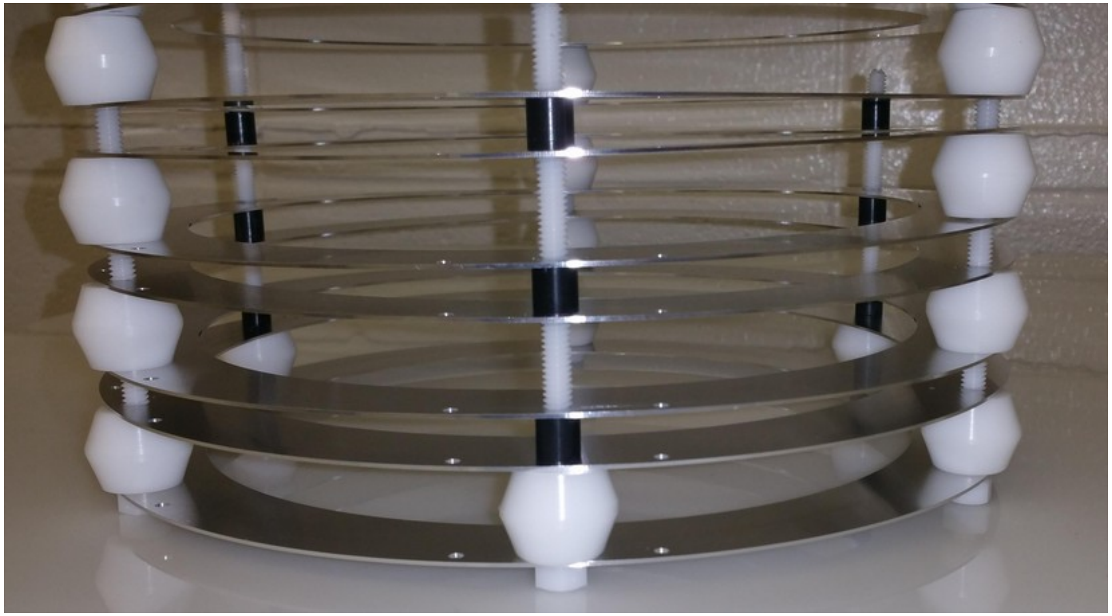
Outgassing curve

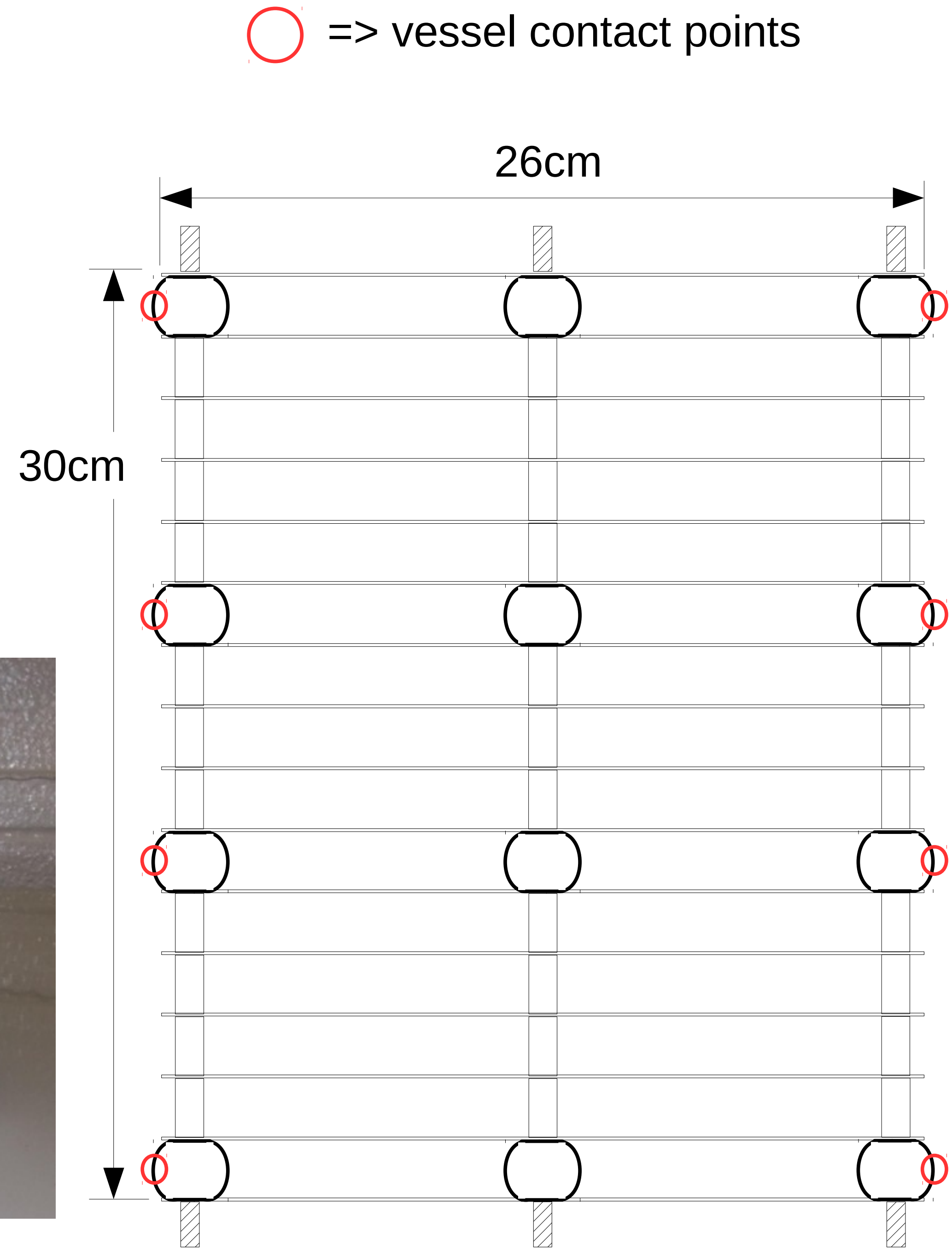


~ 3 weeks

D^3 – Milli Field Cage

- Aluminum rings w/ 2cm delrin spacers
- 30cm w/ 30 kV power supply to start but idea is to maximize the drift length
- Self supporting
  - Will assemble in clean room and place in chamber completed
- Will have 12 contact points with acrylic tube; should slide easily
- Interfacing with GEM stage is being designed
  - Idea is to mount GEM stage and pixel chip circuit board to field cage

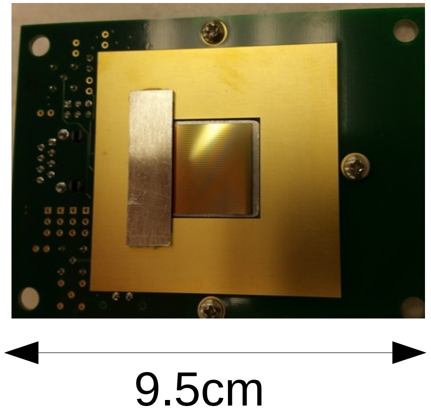


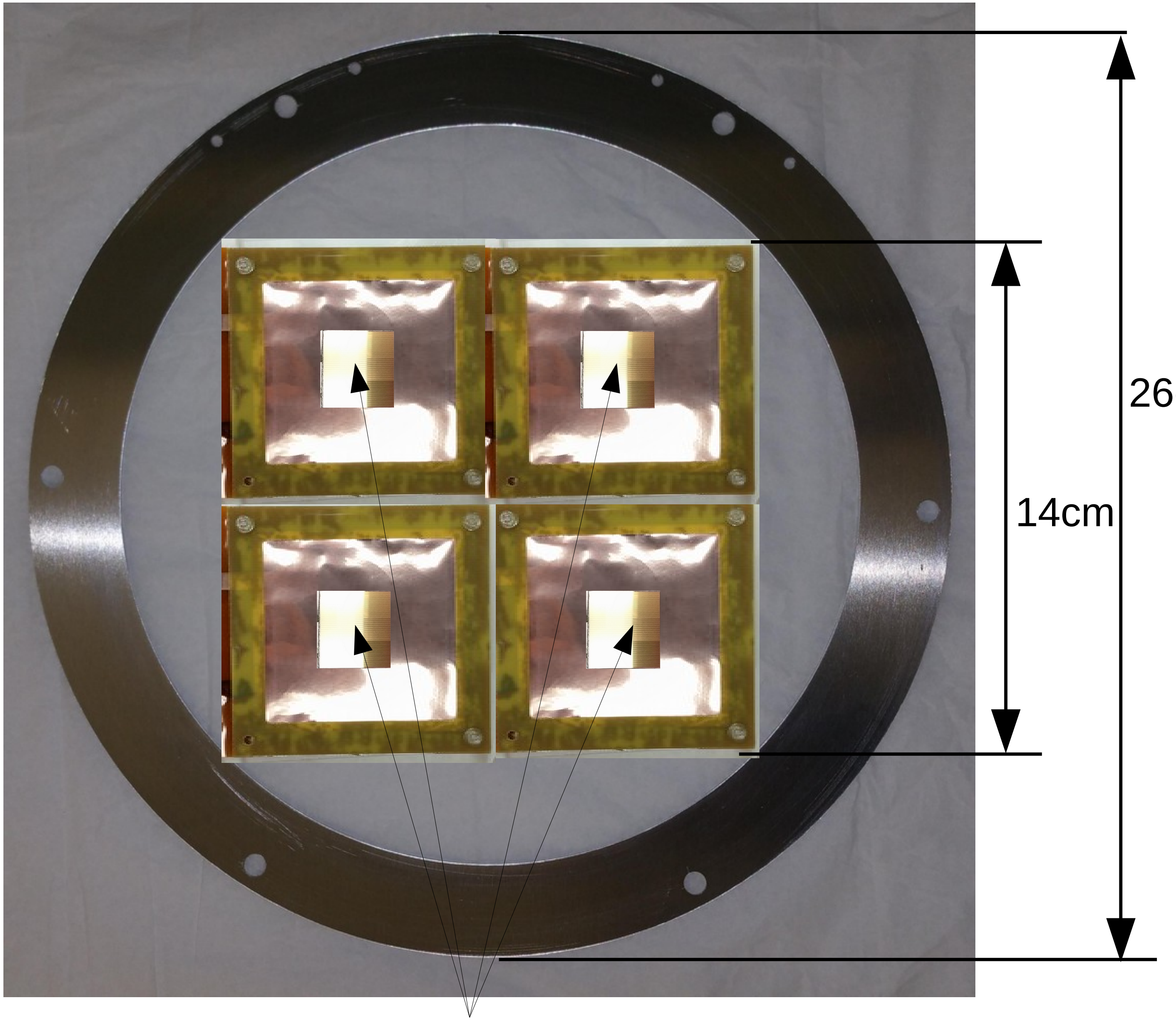


D^3 – Milli Unit Cell

- Will start with 1 GEM/chip cell
- Move to 4
  - Have DAQ to do this; USBPIX 3
- Ultimate goal is to instrument entire readout area with 16 chips, or 4 chips with “charge focusing”
  - https://arxiv.org/abs/1304.0507

FE-I4 circuit board

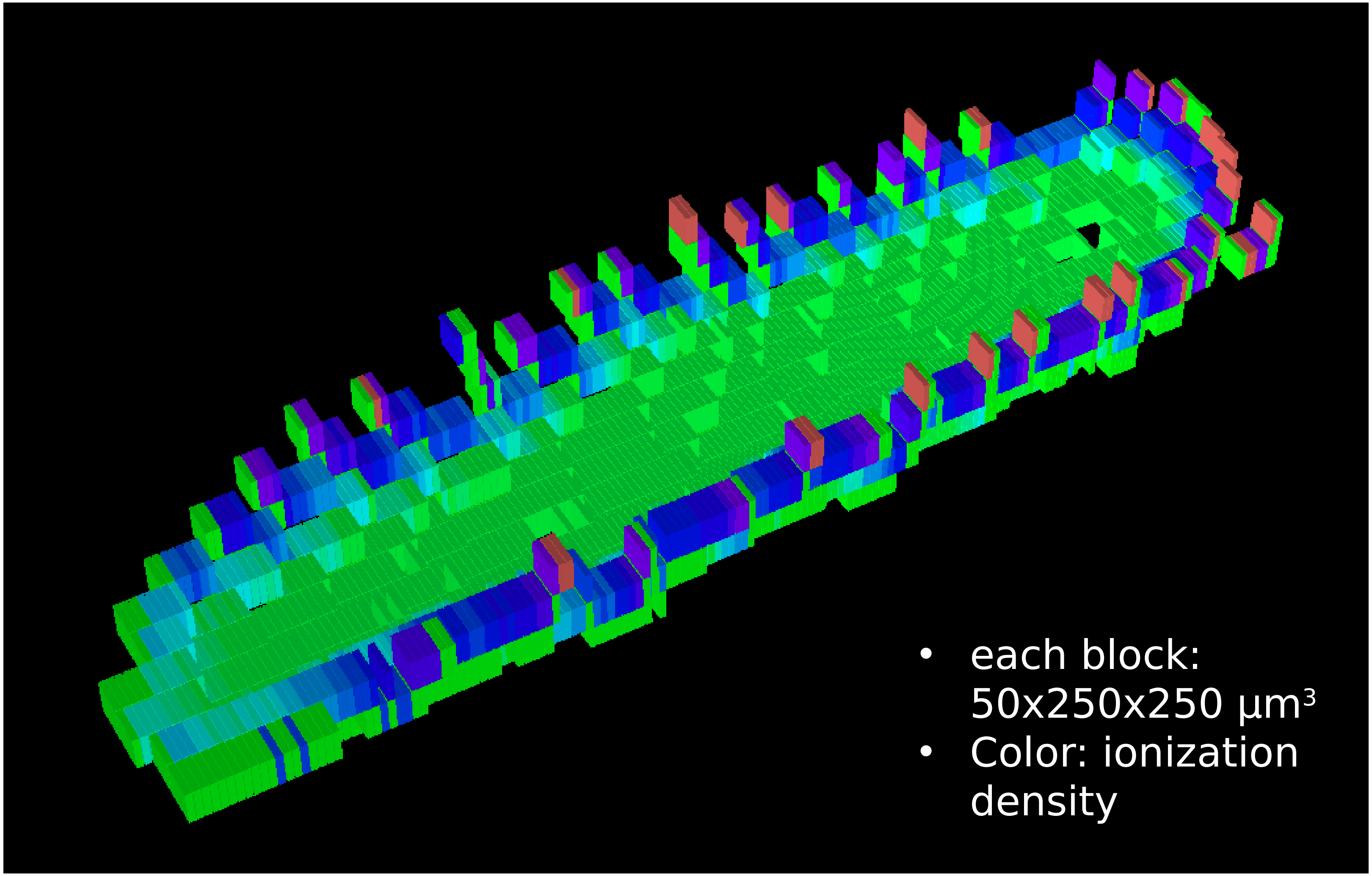




Summary

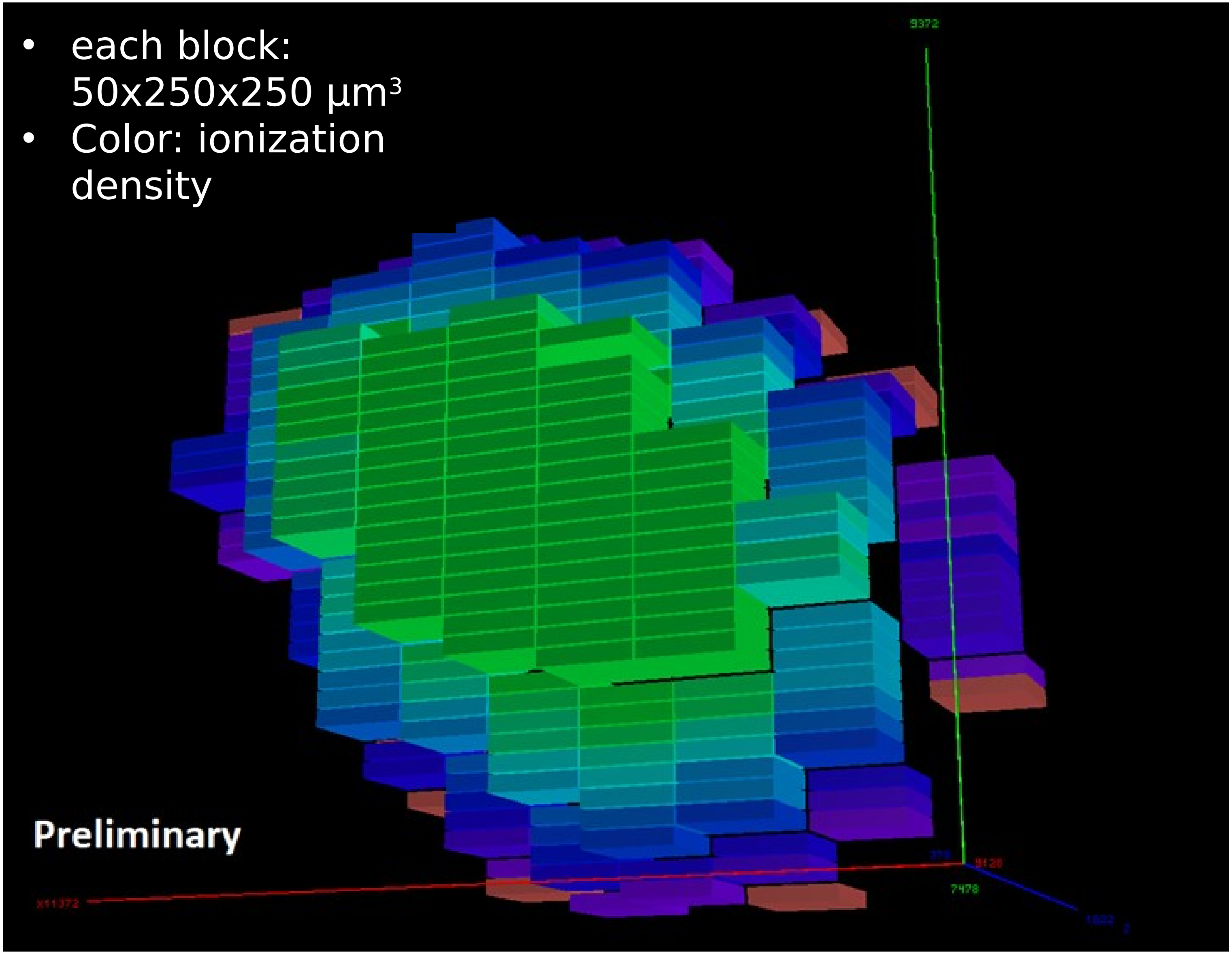
- TPCs with GEMs and pixel chips are capable of reconstructing nuclear recoils in 3D with high-resolution
- Have demonstrated 3D directional neutron detection with multiple detectors
- Discussed how directional neutron detection is related to directional dark matter detection
  - And what makes it more challenging
- Working on getting gain with R&D setup using SF_6 (Negative Ion gas)
- Now constructing our first dedicated directional dark matter prototype, D^3 - Milli, as a possible unit cell for a larger directional dark matter detector

Backup



Ionization cloud from 1MeV recoiling Helium nucleus

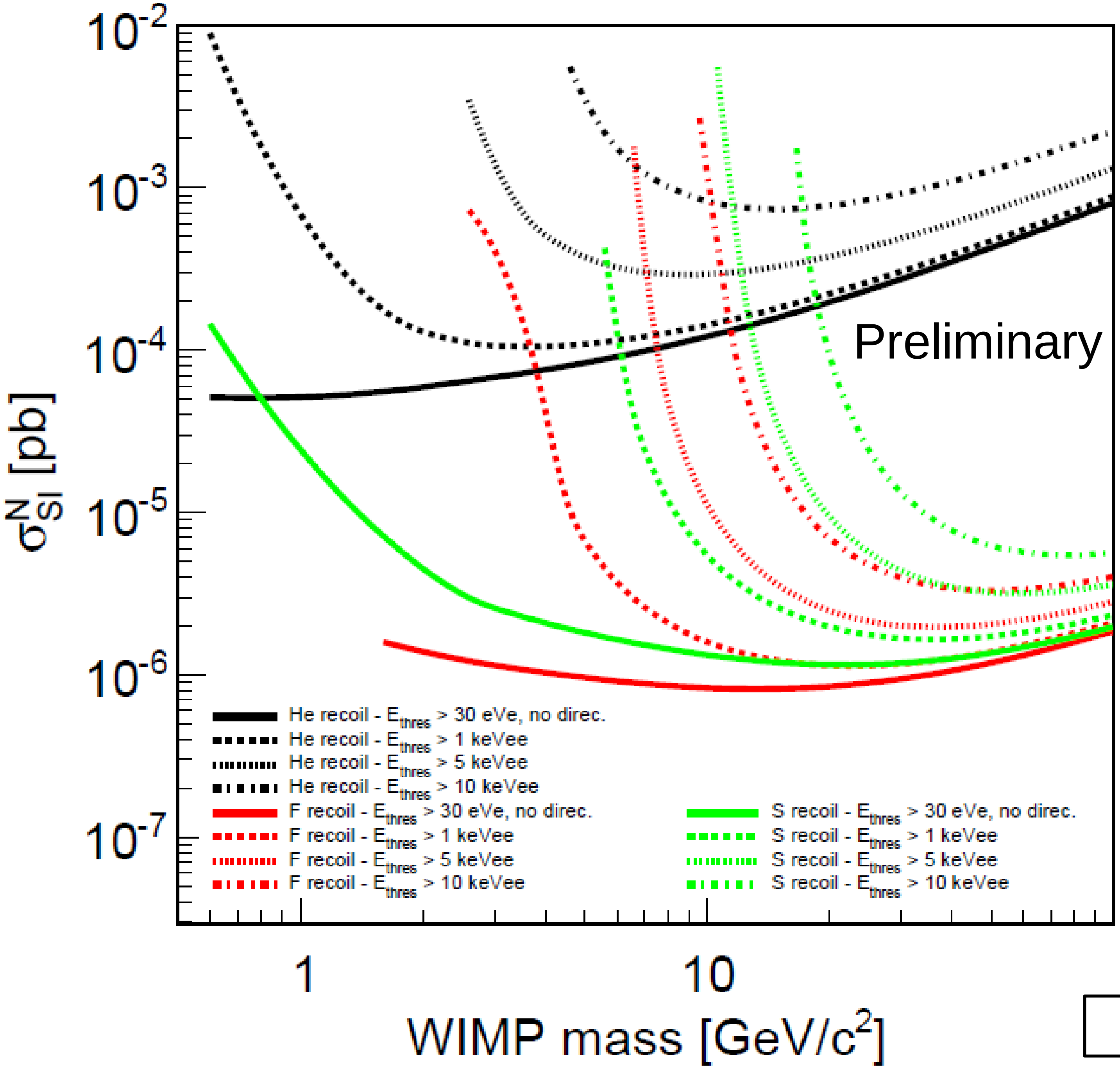
Medium Energy 3D Nuclear Recoil



Ionization cloud from E_{ee} ~25keV recoiling Helium nucleus

WIMP-Target Limits (SI)

3-m³ for
3 years



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