Directional Dark Matter Detection, DMTPC and beyond

James Battat
Bryn Mawr College

Directional Detection

The allure

discrimination via directionality

The challenge

"directionality or event rate: pick one"

Overview for today

Motivation for directional detection

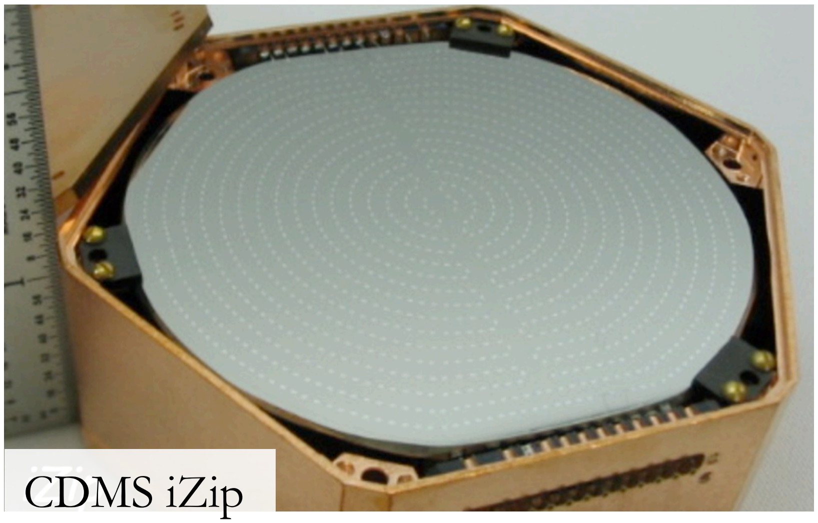
Current status of the 5 directional experiments

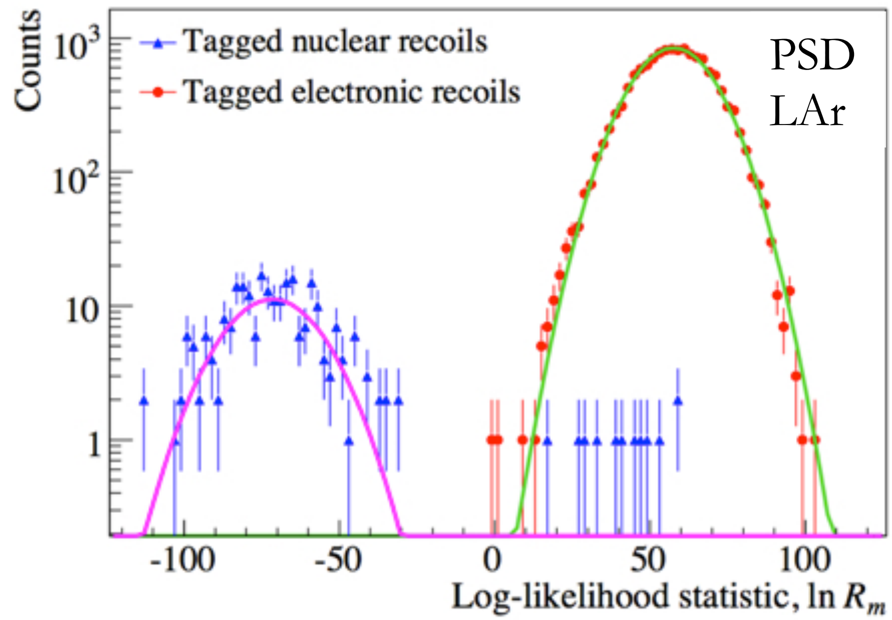
Update on the DMTPC experiment

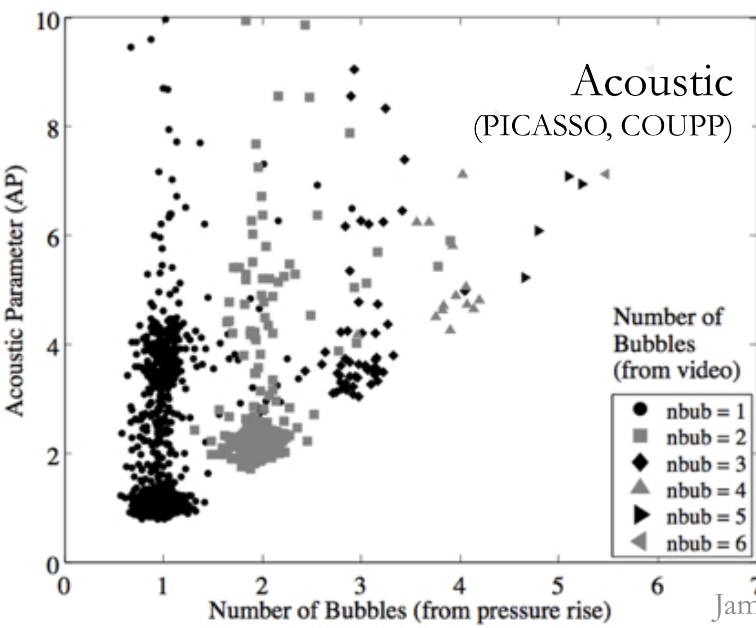
Keeping pace with non-directional experiments

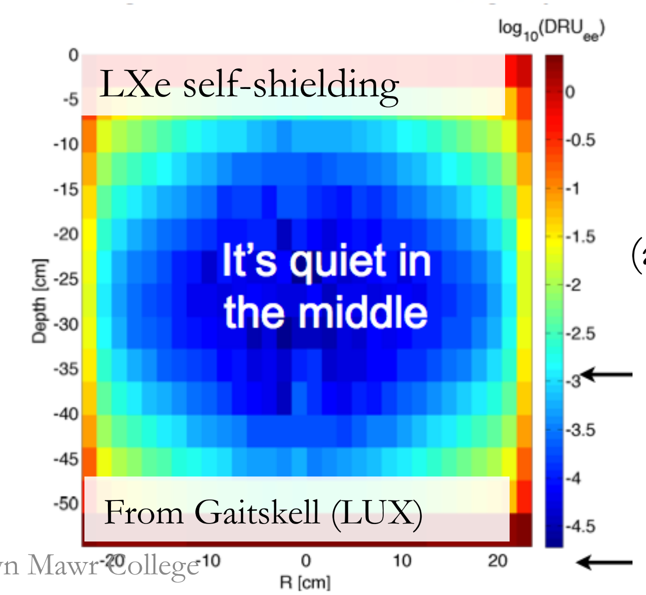
New ideas for scaling up in mass (volume)

The particle discrimination premium









(and S2/S1)

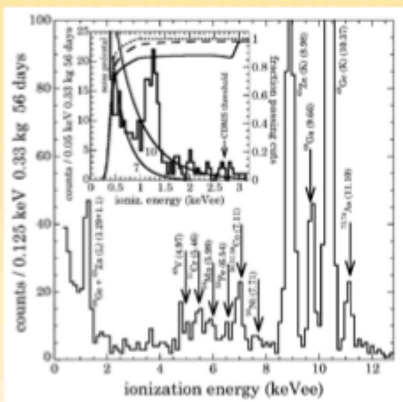
Preamble: two questions a DM direct detection experiment would like to answer:

(1) what type of particle just hit the detector?
(e.g. alpha, beta, ... neutron)

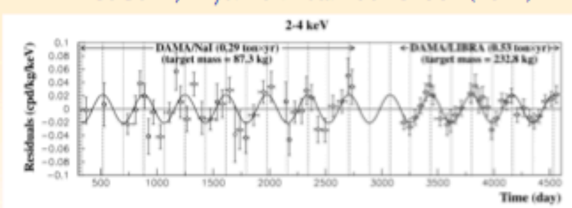
(2) what energy did it leave in the detector?

don't know (1)

do know (1)

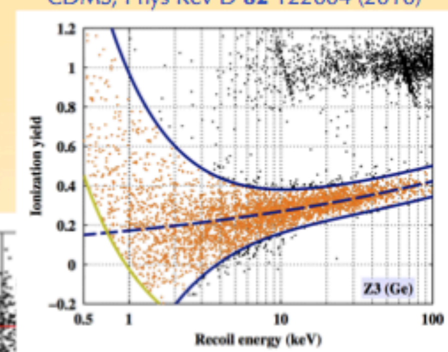


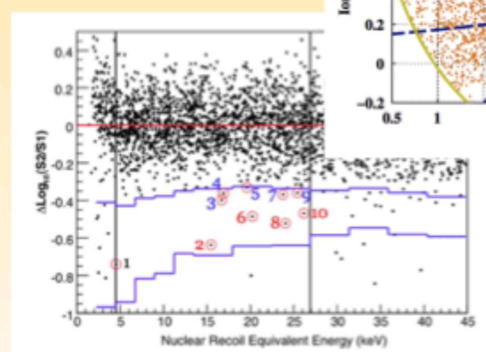
CoGeNT, Phys. Rev. Lett. 106 131301 (2011)



DAMA, Eur. Phys. J. C 56 333 (2008)

CDMS, Phys Rev D **82** 122004 (2010)





XENON10, Phys Rev. Lett **100** 021303 (2008)

Preamble: ~~two~~ three questions a DM direct detection experiment would like to answer:

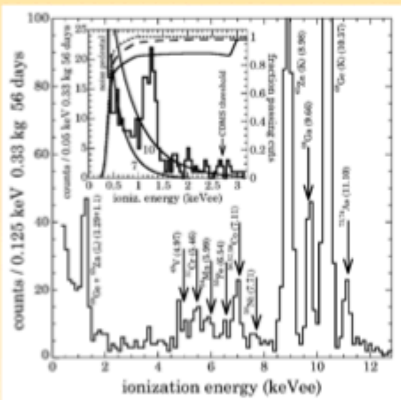
(1) what type of particle just hit the detector?
(e.g. alpha, beta, ... neutron)

(2) what energy did it leave in the detector?

(3) What direction did the particle come from?

don't know (1)

do know (1)



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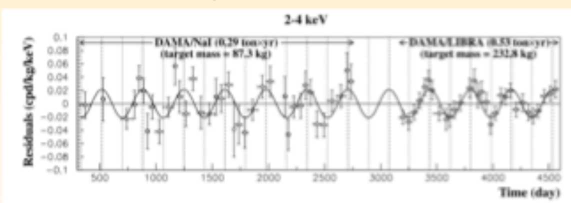

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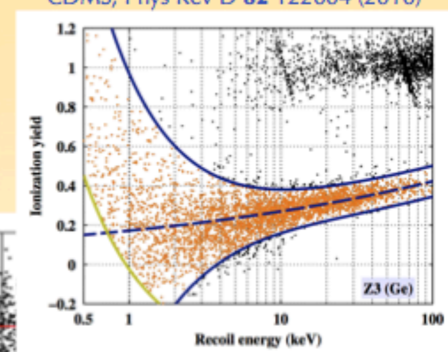
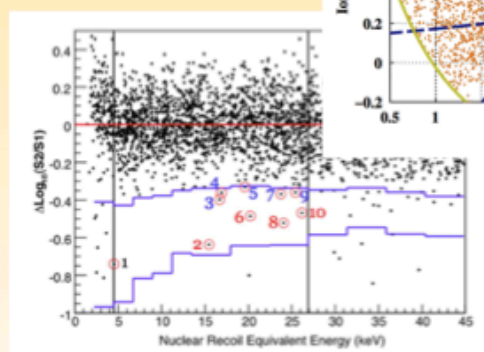
CDMS, Phys Rev D **82** 122004 (2010)





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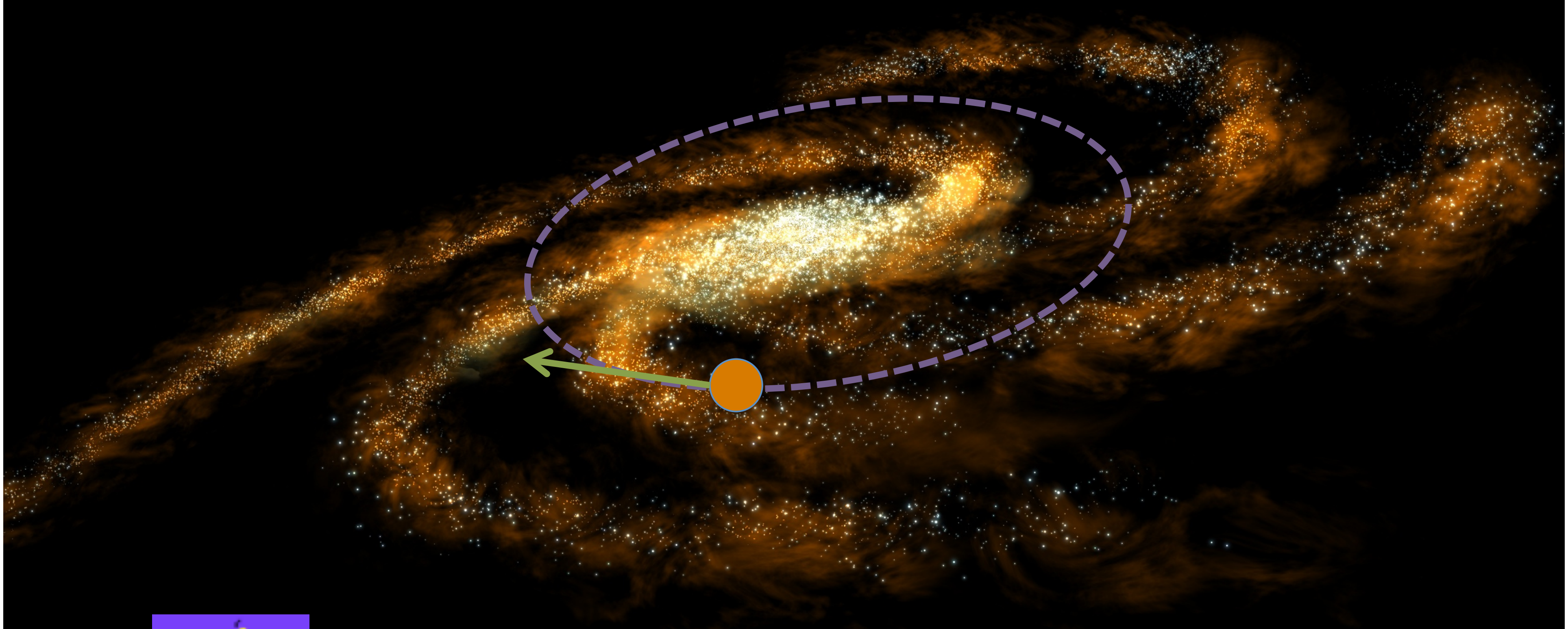
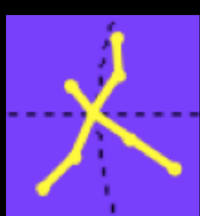




Cygnus

PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 37, NUMBER 6 15 MARCH 1988

Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.

Large directional modulation amplitude

$$\frac{d^2R}{dE_R\, d\cos\theta} \propto exp\left[\frac{-\left[(v_E + v_S)\cos\theta - v_{min}\right]^2}{v_{halo}^2}\right]$$

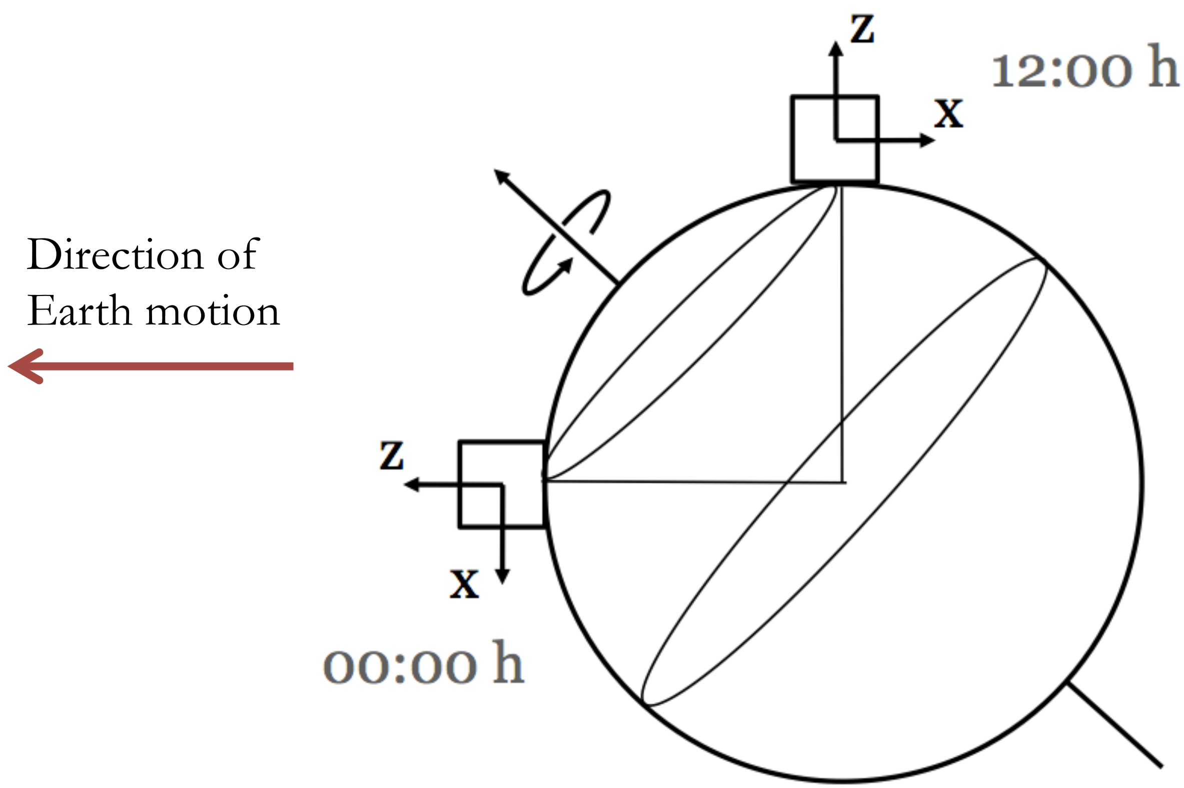
θ = Angle between recoil and a reference direction in lab

v_{th}/v_{halo}	Fraction of incident flux detected	Forward/back	July/January
0.00	1.00	4.00	1.04
0.20	0.97	4.17	1.04
0.40	0.90	4.66	1.05
0.60	0.78	5.44	1.07
0.80	0.65	6.56	1.08
1.00	0.50	8.10	1.11
1.20	0.37	10.18	1.13
1.40	0.25	12.98	1.16
1.60	0.16	16.73	1.20
1.80	0.10	21.77	1.24
2.00	0.06	28.54	1.28

Spergel PRD, 1988

Angular modulation of WIMP flux

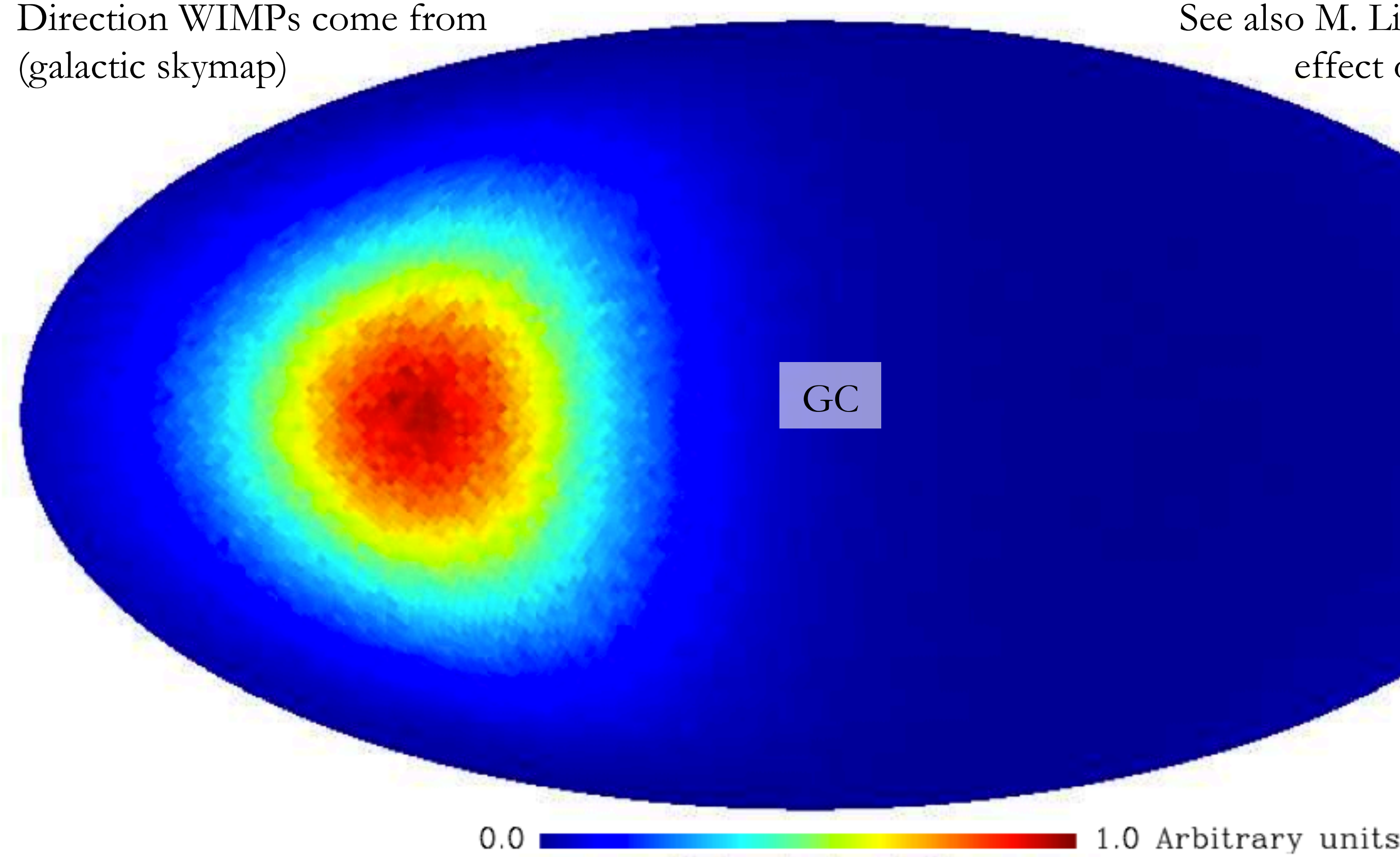
Modulation is sidereal (tied to stars) not diurnal (tied to Sun)



Forward/backward asymmetry

Direction WIMPs come from
(galactic skymap)

See also M. Lisanti's talk for
effect of debris flow

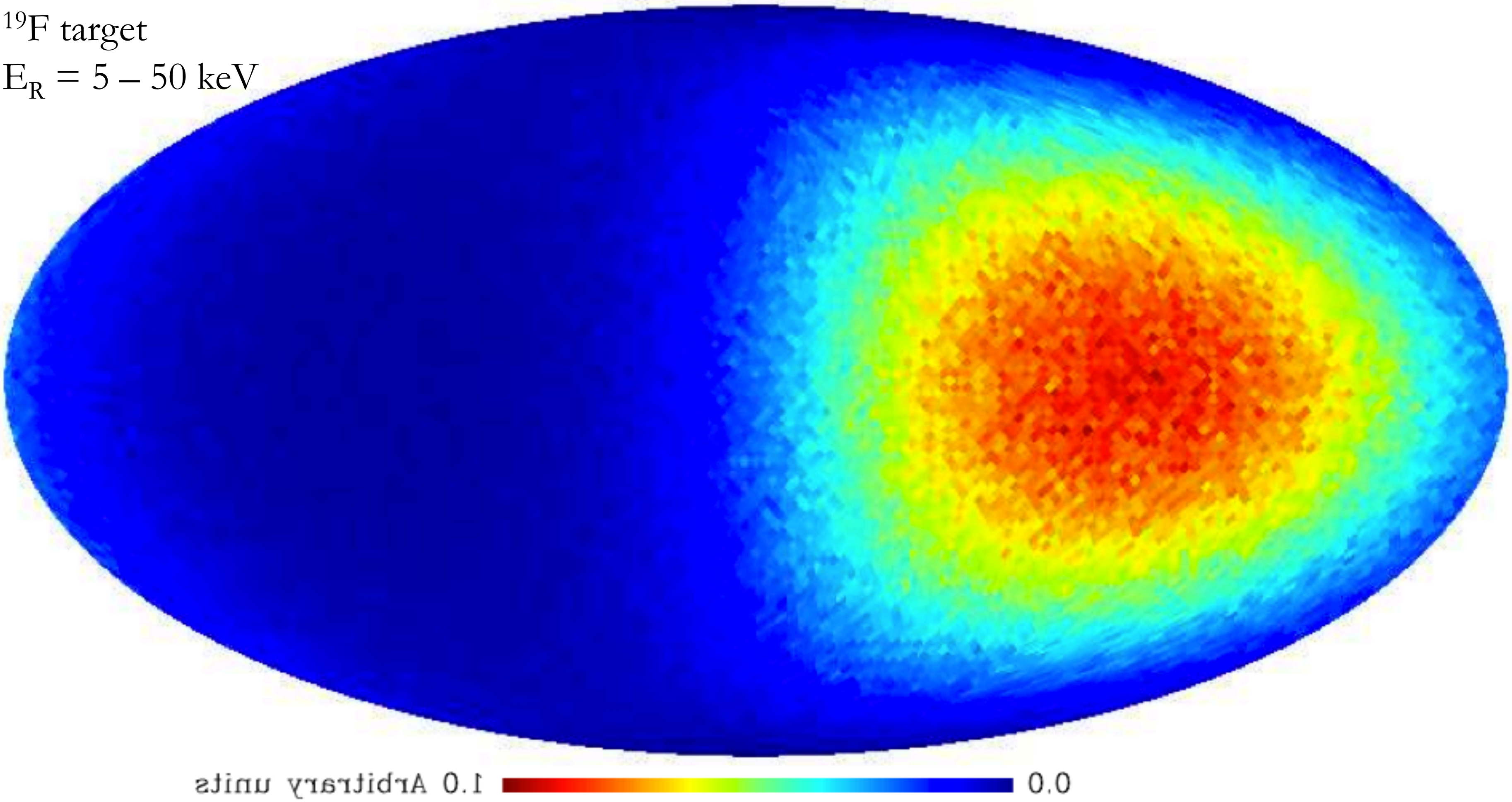


Billard et al. arXiv:0911.4086v4 PLB 691 (2010) 156-162

Recoil angular distribution

100 GeV WIMP
^{19}F target
$E_R = 5 – 50$ keV

This is the direction that recoils go

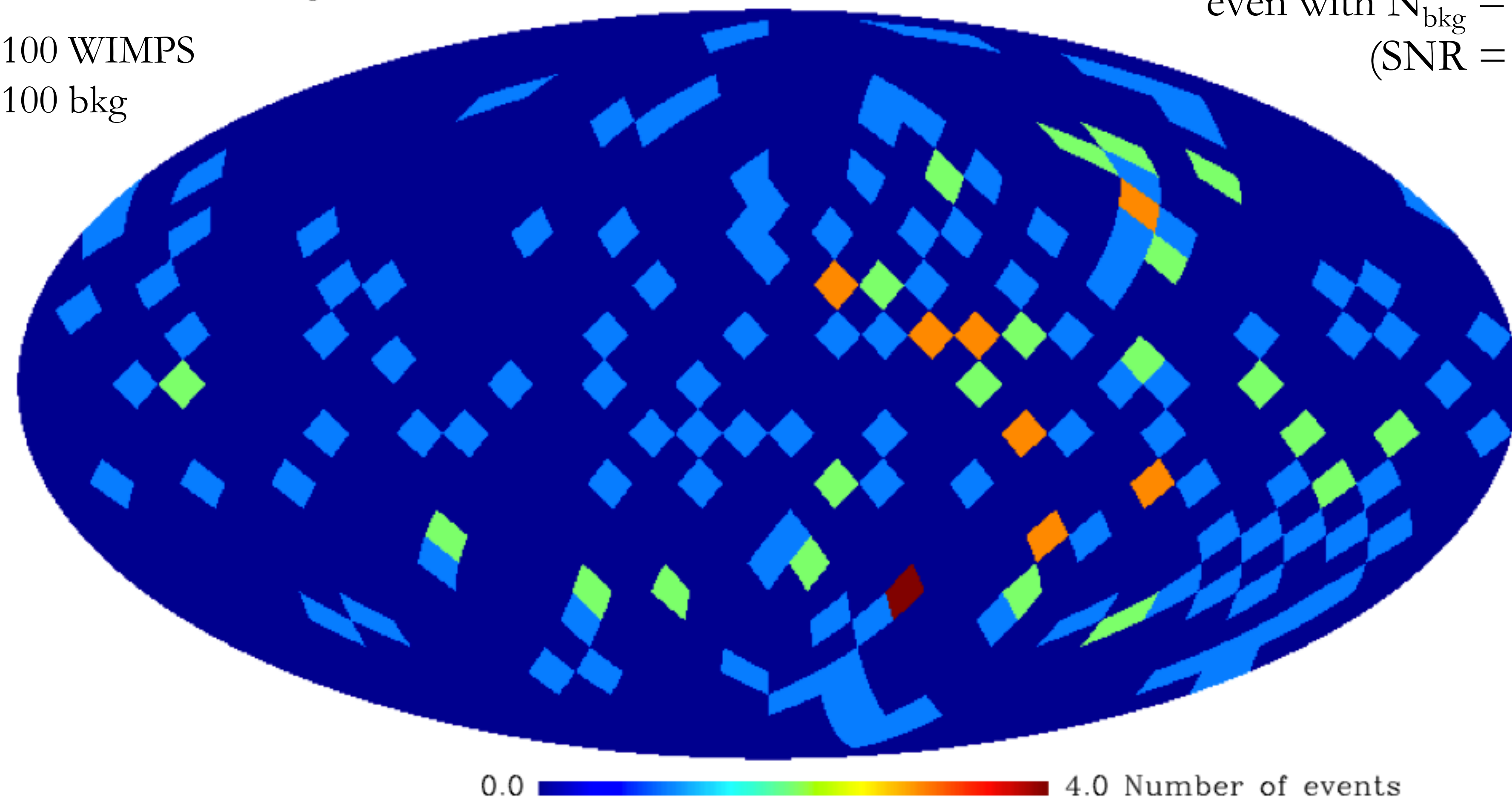


Billard et al. arXiv:0911.4086v4 PLB 691 (2010) 156-162

Finding WIMPs among backgrounds

7 sigma detection of WIMP content
even with $N_{bkg} = N_{sig}$
(SNR = 0.5)

100 WIMPS
100 bkg



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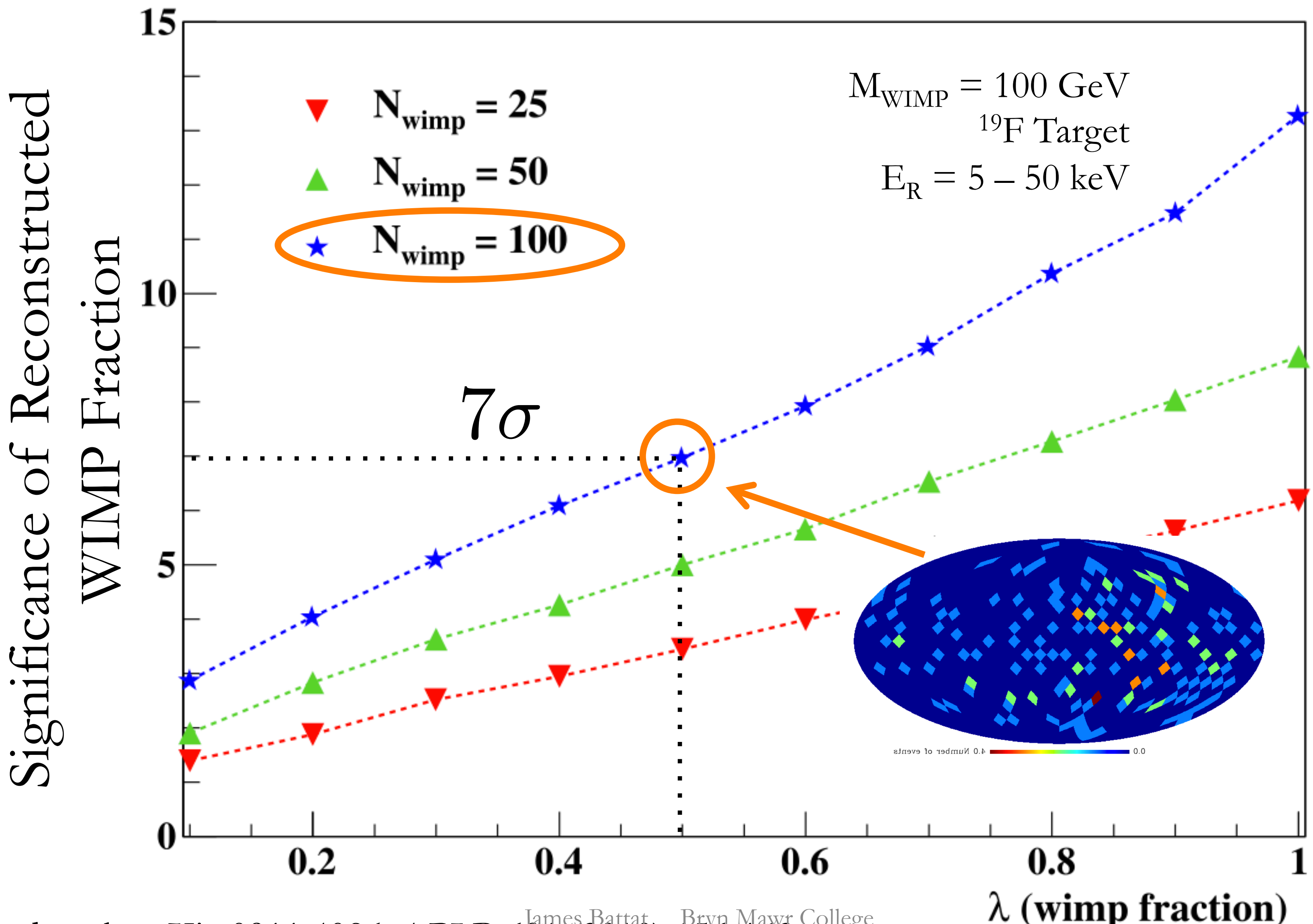

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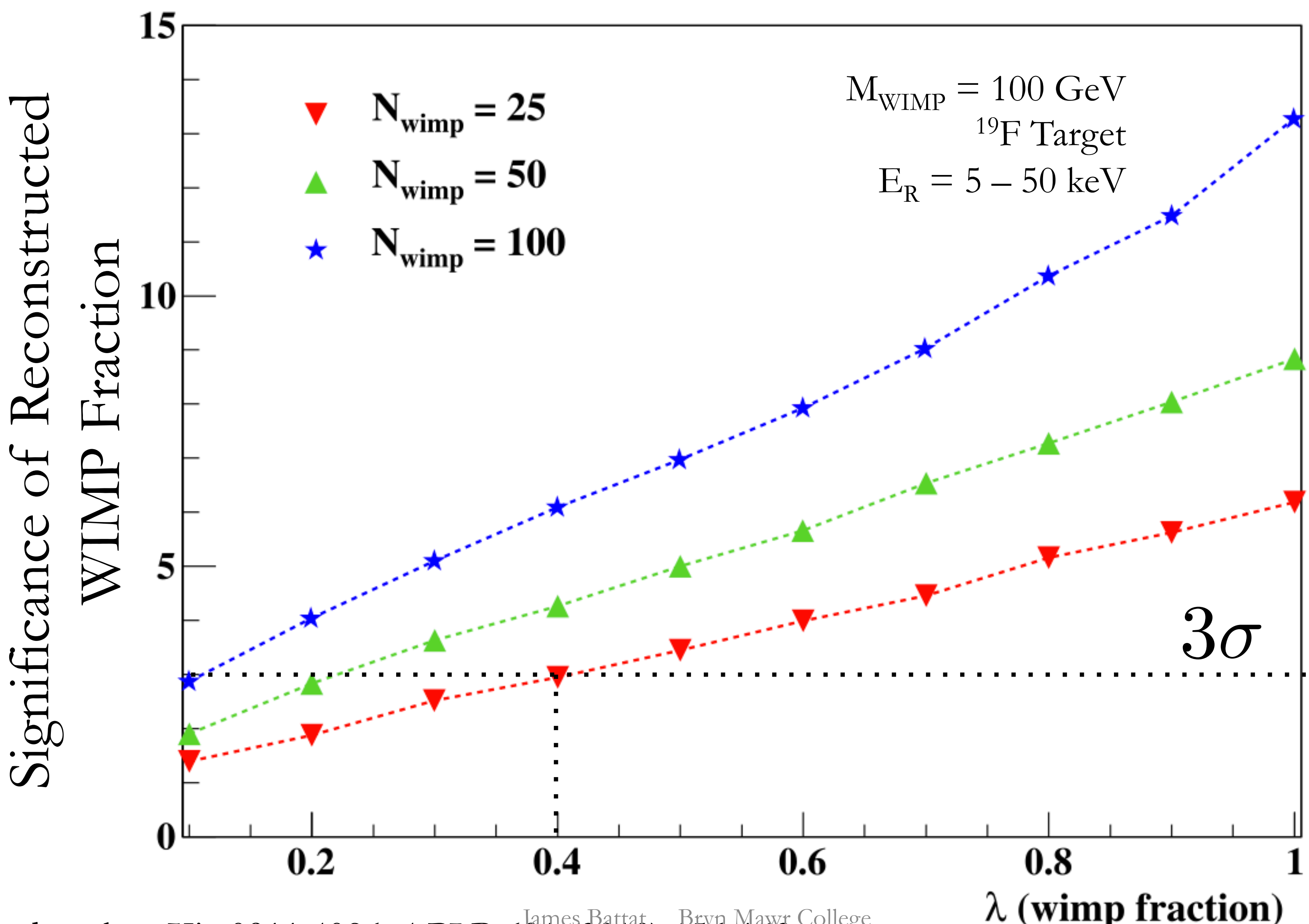

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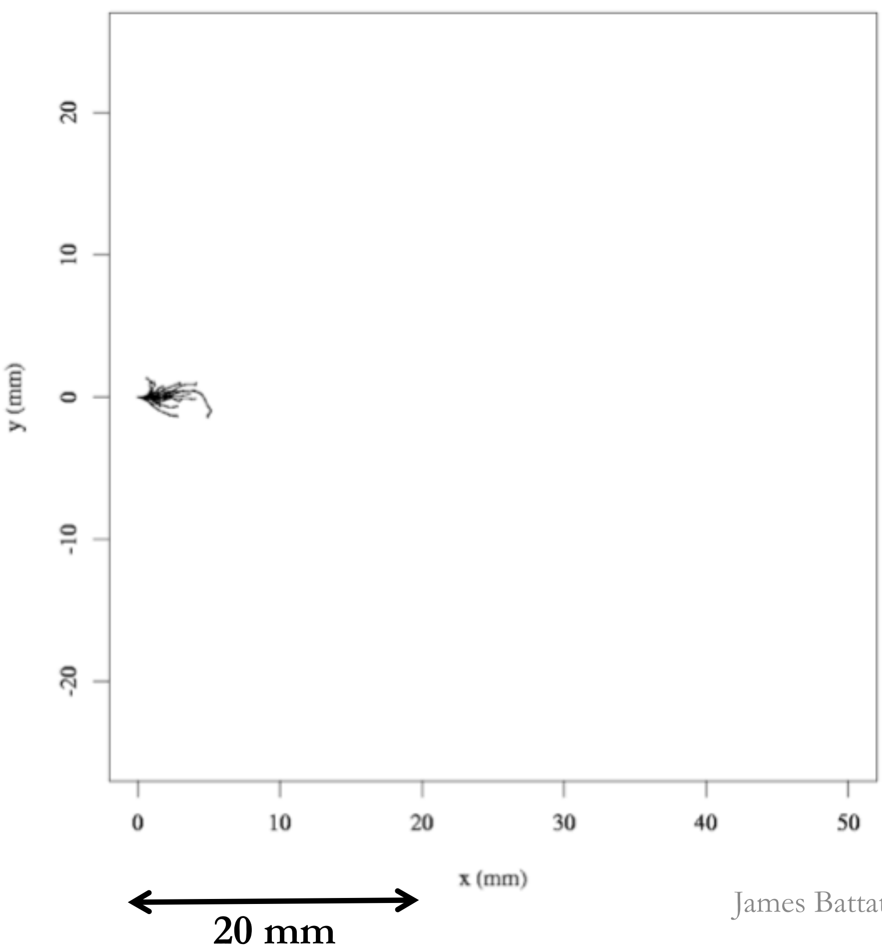
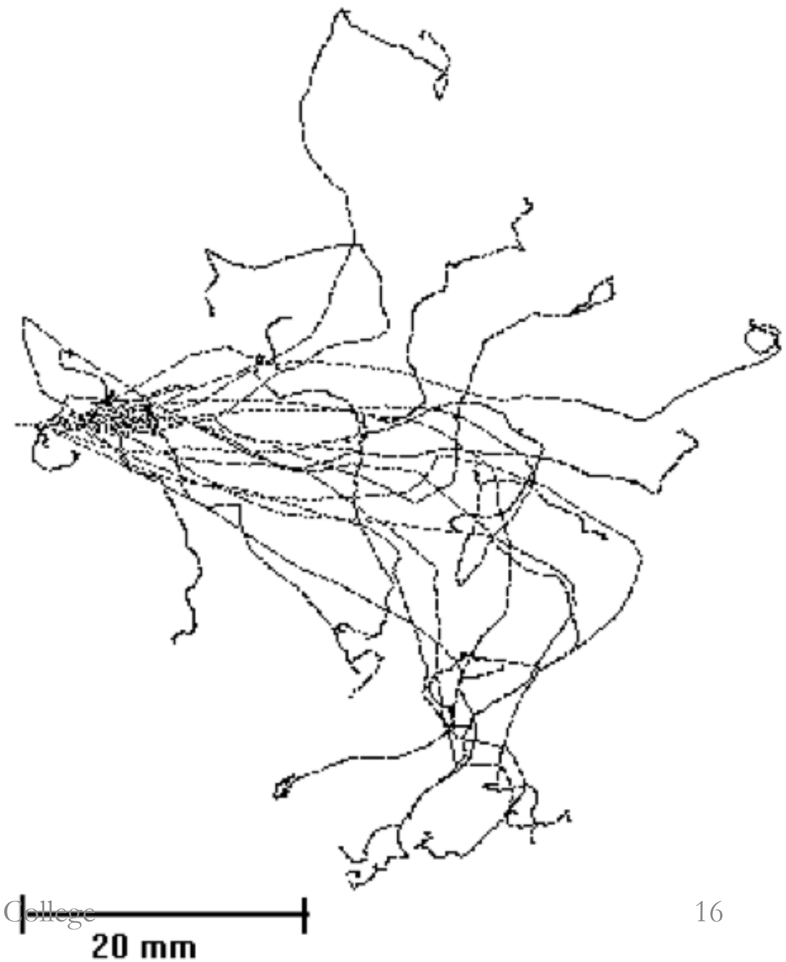
Tracking and Particle Identification

Images from Snowden-Ifft IDM 2012

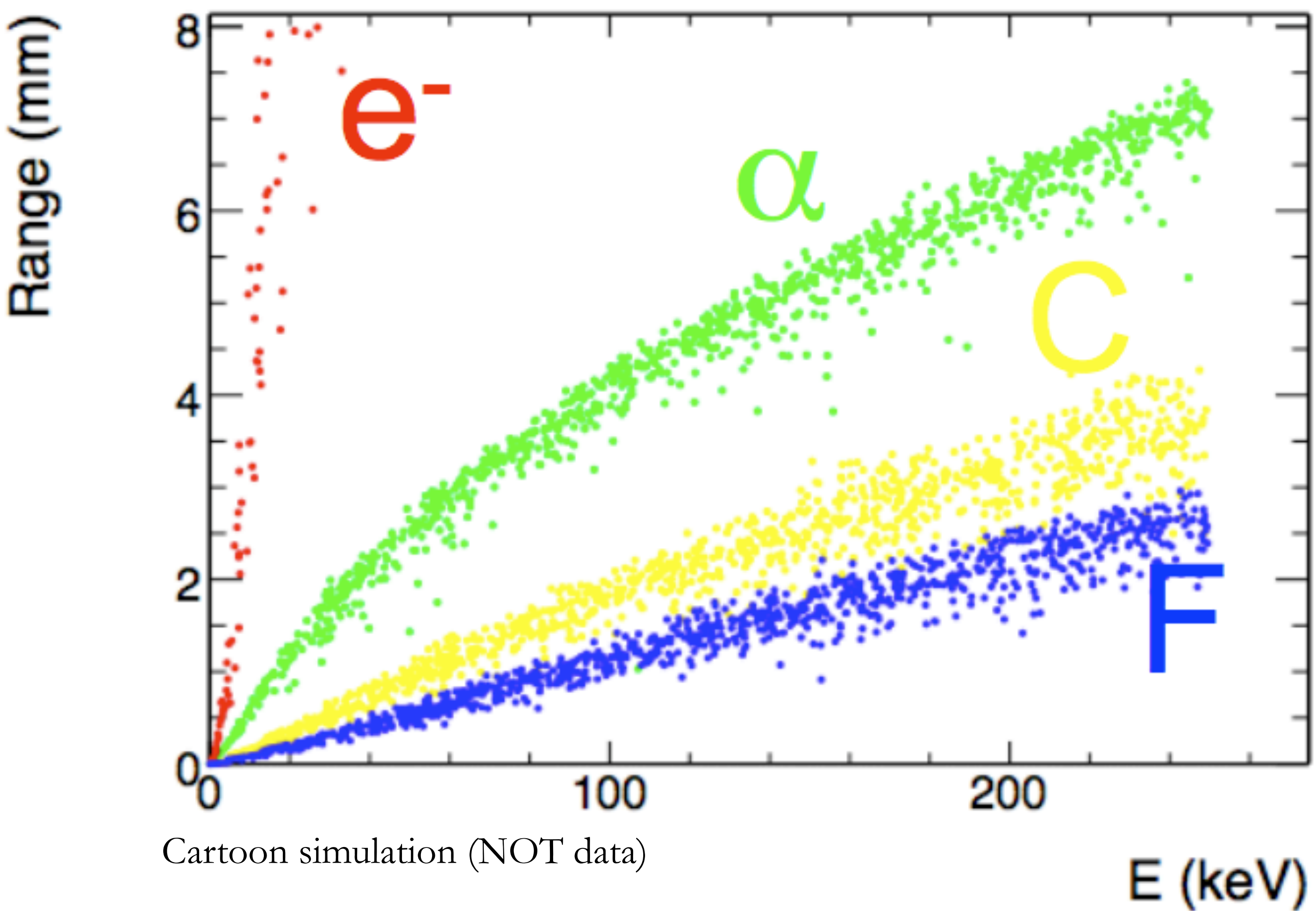
40 keV Argon in 40 Torr Argon



13 keV electron in 40 Torr Argon



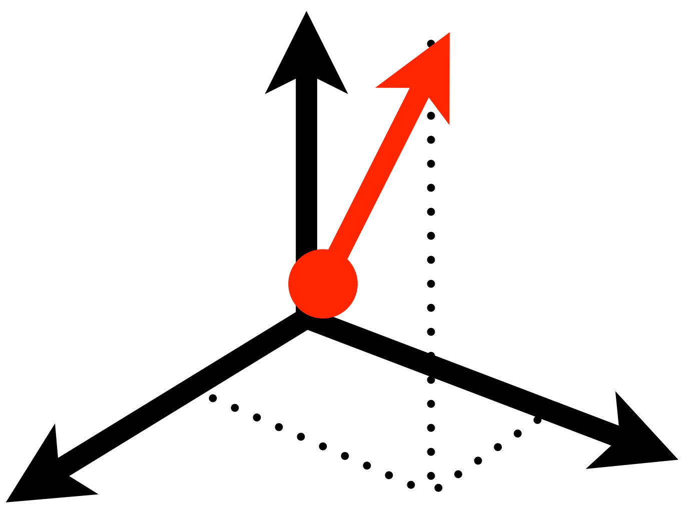
PID with Range vs. Energy

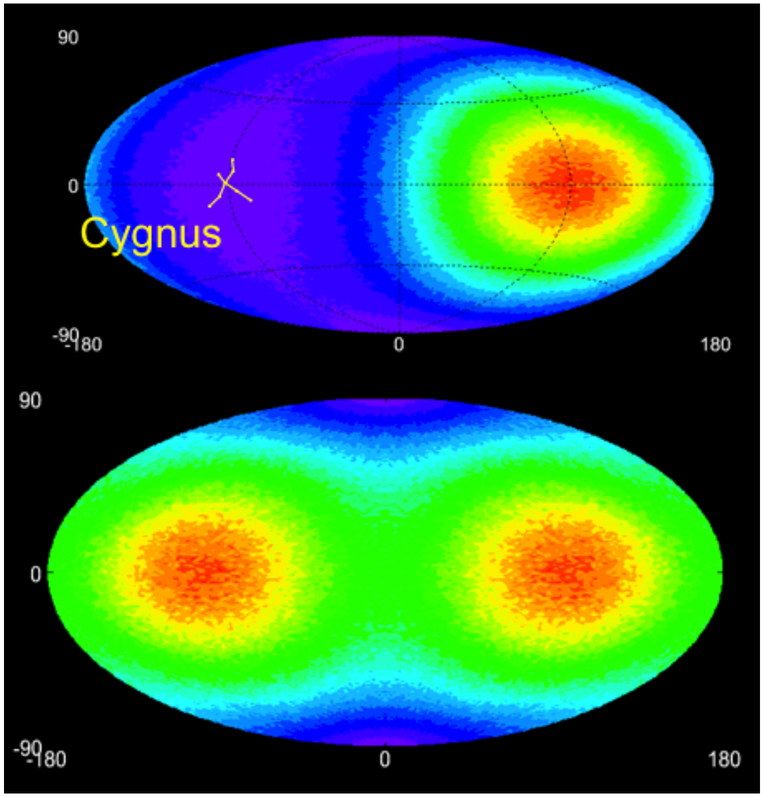


Cartoon simulation (NOT data)

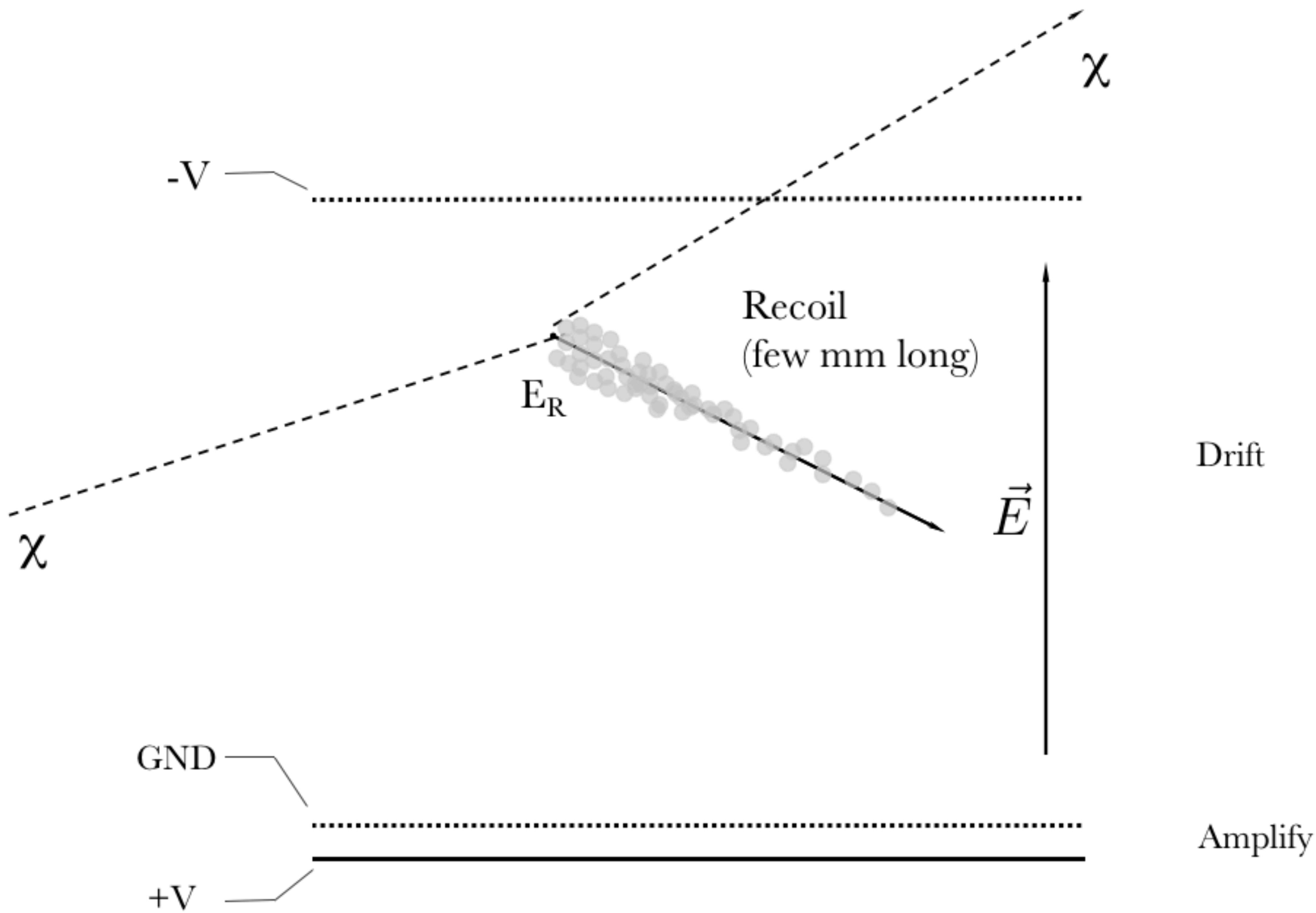
Desired features of a directional detector

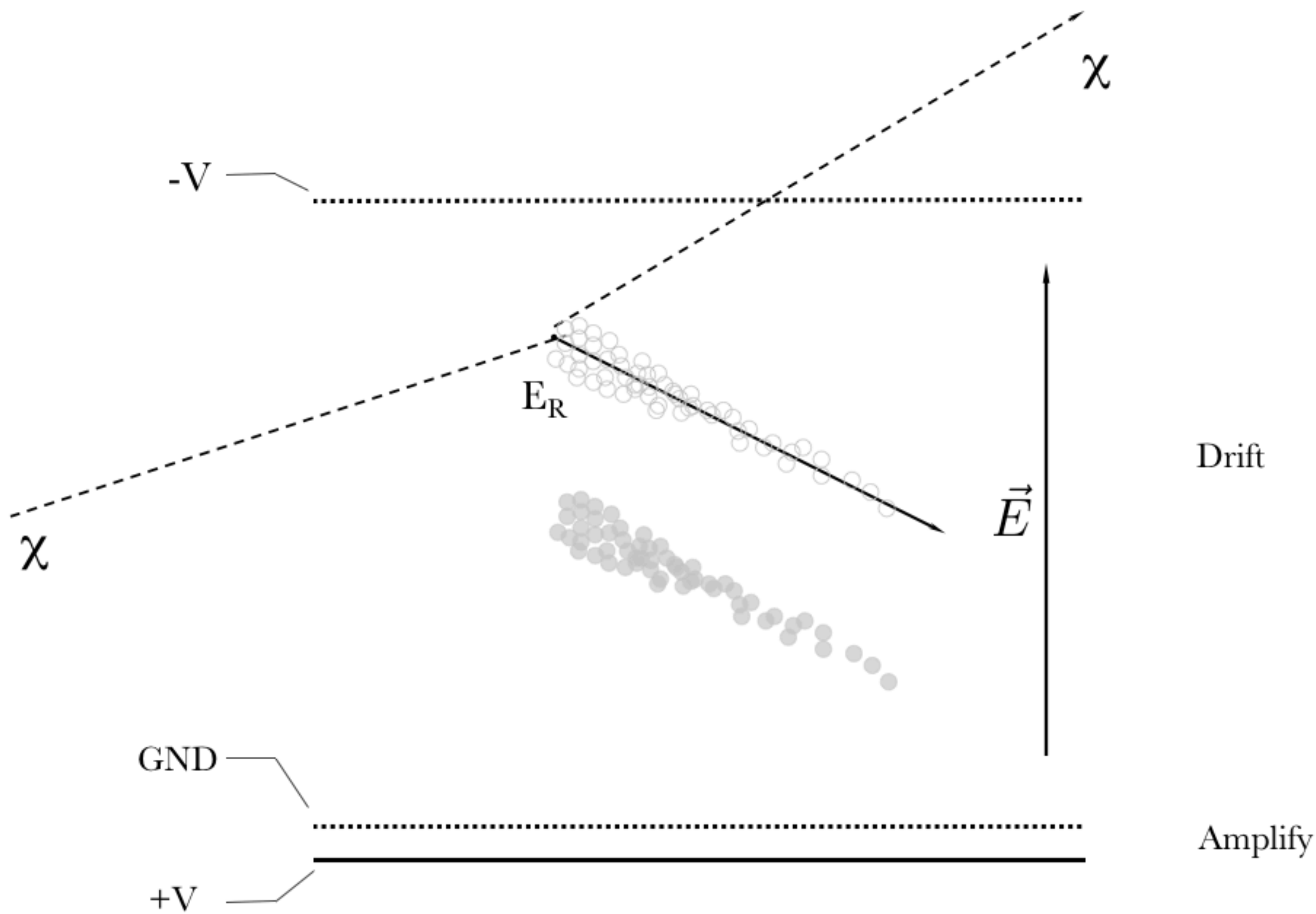
- Modest angular resolution
- Track reconstruction (*)
- Head-tail (vector direction)

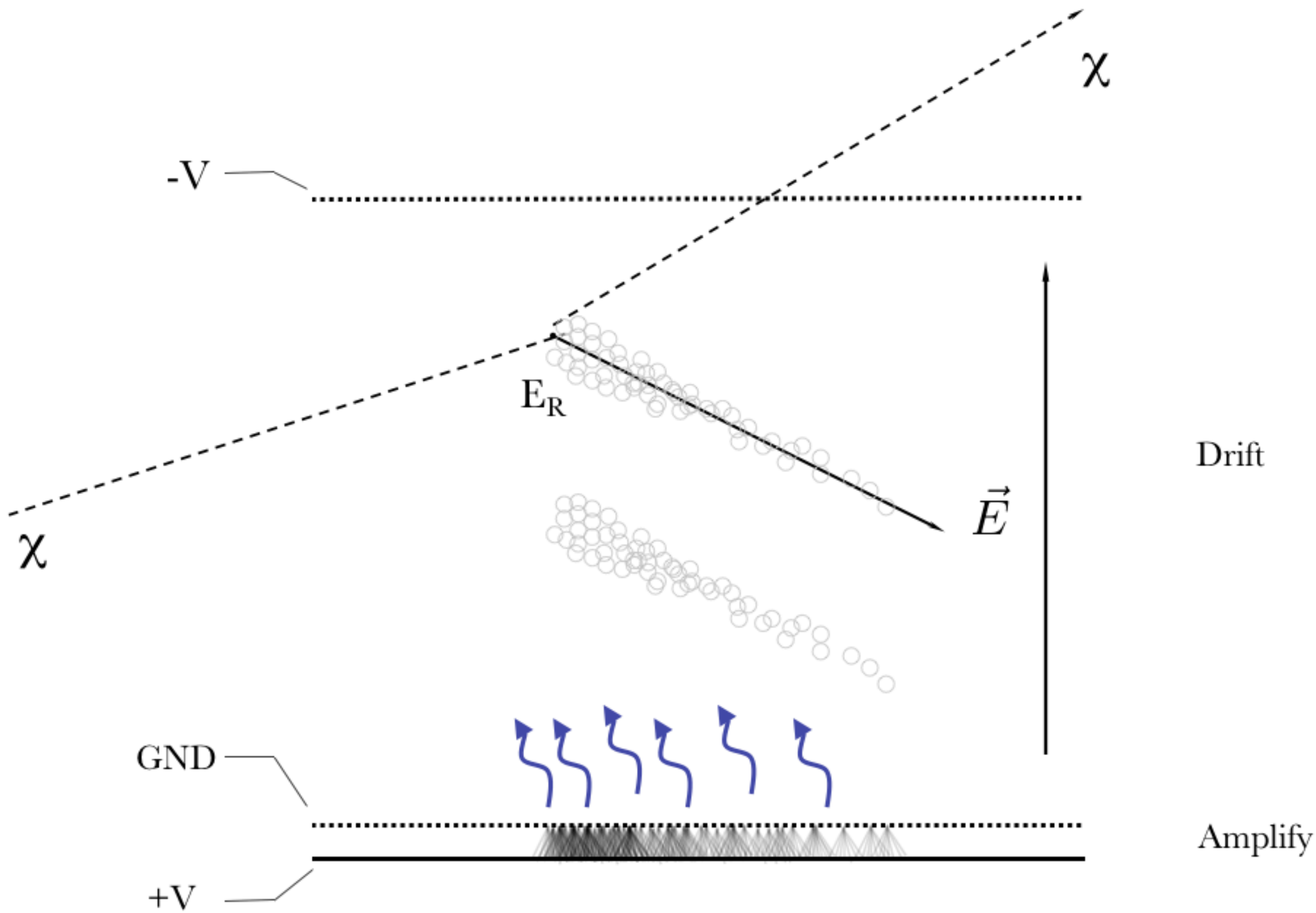




* But see Nygren Paris TPC talk, 2012


χ
-V
Recoil
(few mm long)
E_R
$\vec{E}$
Drift
χ
GND
Amplify
+V


χ
-V
χ
E_R
Drift
E
GND
Amplify
+V


χ
-V
χ
E_R
$\vec{E}$
Drift
GND
Amplify
+V

Directional experiments around the world

“The case for a directional dark matter detector and the status of current experiments”

International Journal of Modern Physics A
Vol. 25, No. 1 (2010) 1–51 arXiv:0911.0323

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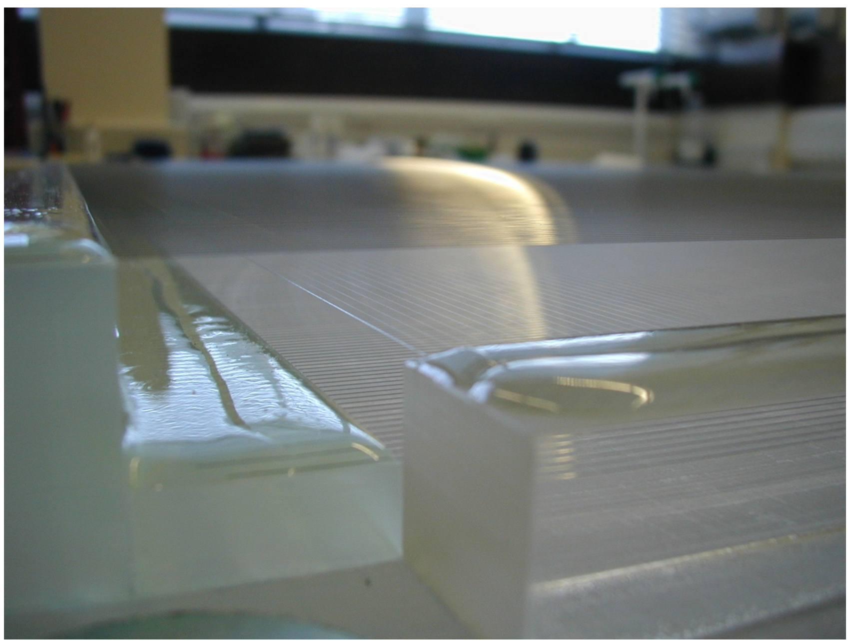
DRIFT – Directional Recoil Identification From Tracks

Started = 1998, US/UK
Underground in Boulby, England in 2001
Current operating detector = DRIFT-IId
Technology = Negative ion TPC with
MWPC wire readout

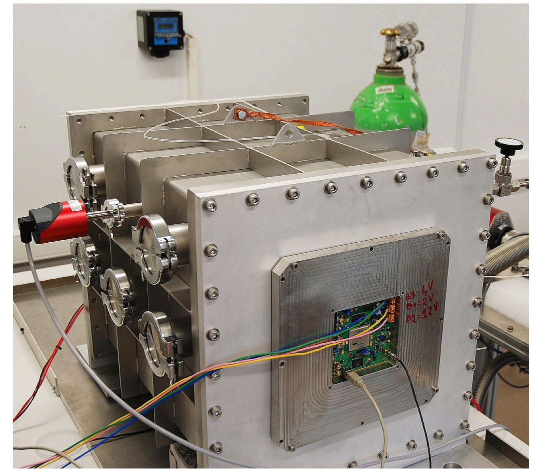


Target = 30 Torr CS_2 + 10 Torr CF_4
Fiducial volume = 800 liters
F mass = 33.3 g
Limit setting threshold = 50 keVr

MIMAC (MIcro-tpc MAtrix of Chambers)

Strategy :

- Matrix of micro-TPC (~50 mbar)
- Energy (ionization) and **3D** track)
- Multi-target (^{1}H, ^{19}F, …)
- Interaction axiale (spin-spin)
- ^{4}He, CH_4, C_4H_{10}, CF_4 has been tested !

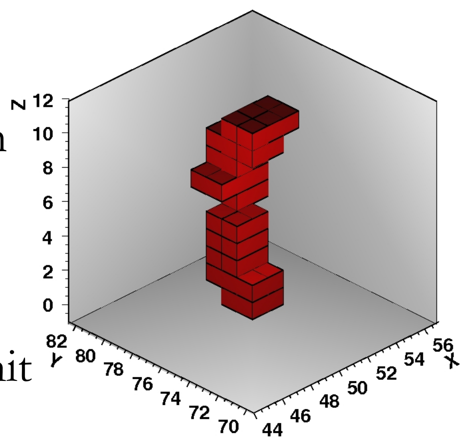


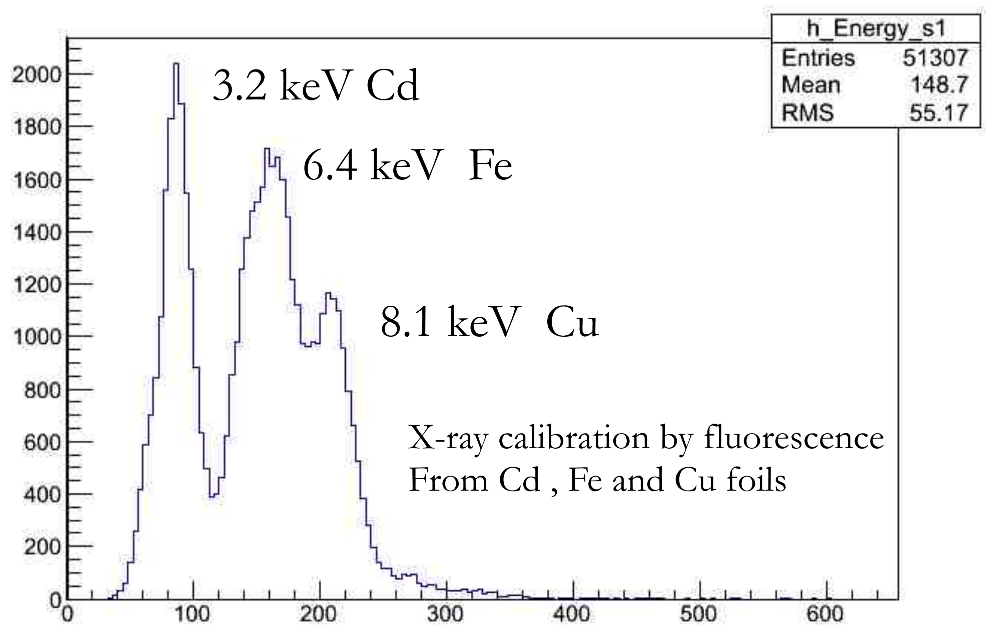
Prototype Bi-chamber (5 L) (2x (10x10x25 cm^3)
Installed at Modane –Fréjus (France) in June 2012

Recoil ^{19}F (measured)
(E ~ 40 keV_{ee})
50 mbar CF_4 + CHF_3 (30%)

Get total E from charge integral

But don't know energy of each hit



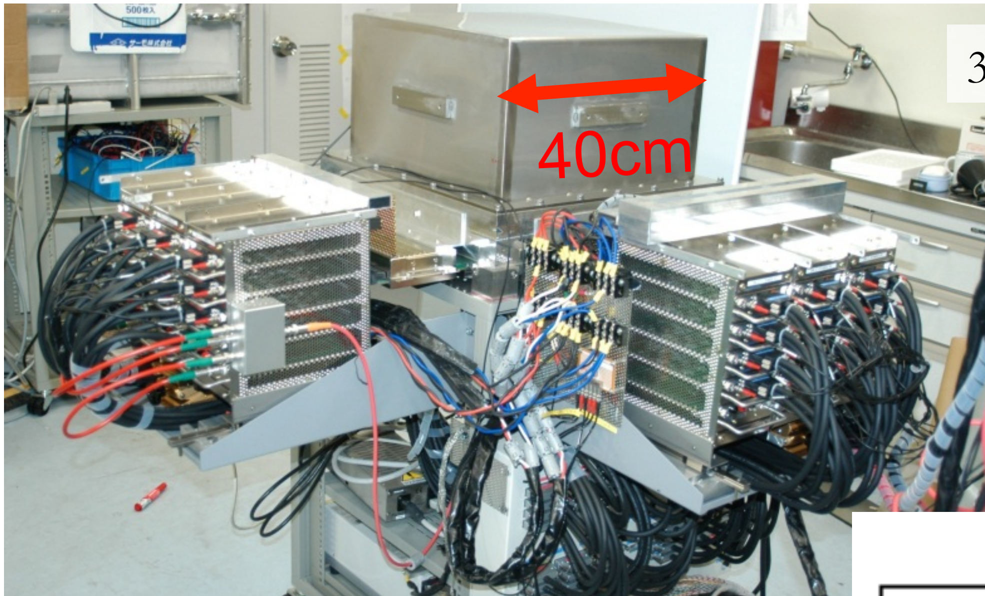


Energy (ADC units)

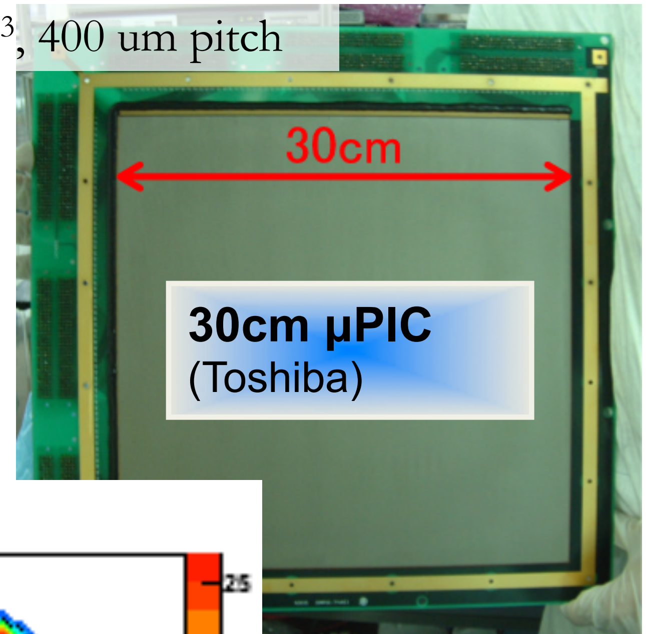
NEWAGE

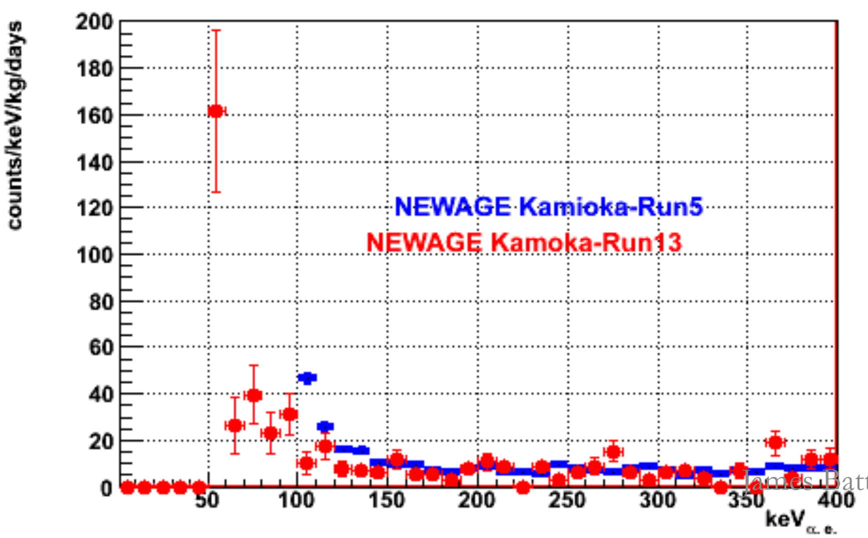
PI: Kentaro Miuchi （KOBE university）

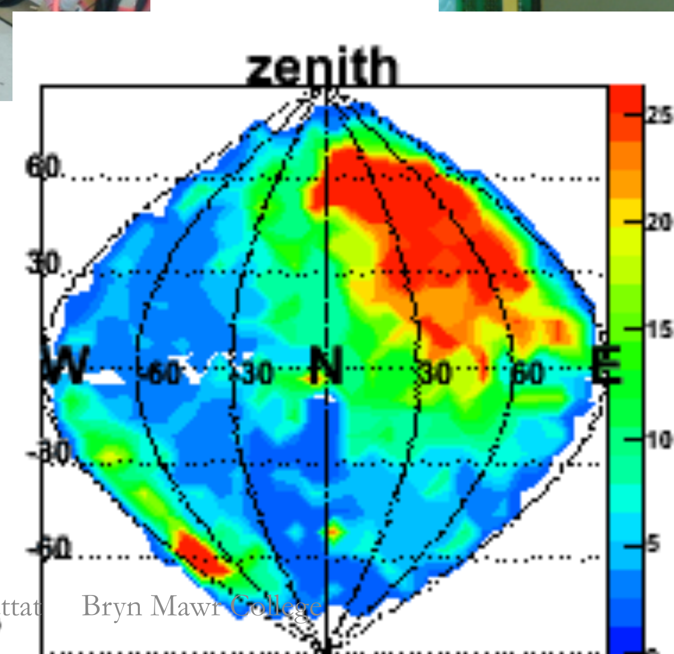
(New generation WIMP search with an advanced gaseous tracker experiment)

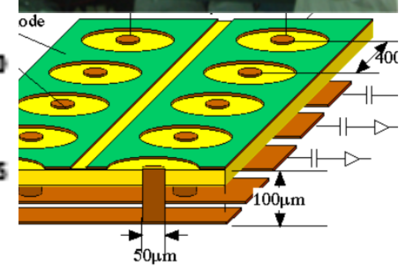


30 x 30 x 31 cm^3, 400 um pitch





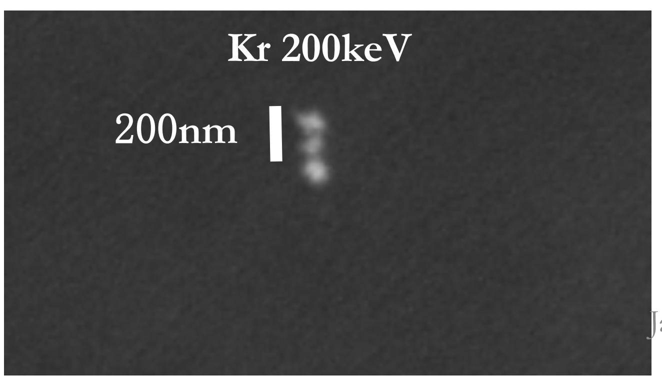


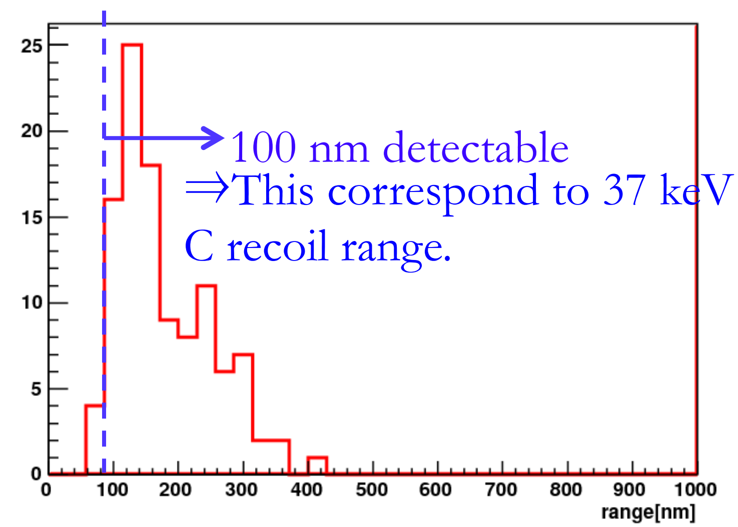


High Resolution Nuclear Emulsion Detector

Tatsuhiro Naka (Nagoya U.)

We can already produce the emulsion detector in house of ~kg detector.
(Now, we started to discuss about design of the larger scale production machine.)





Range distribution [nm]

DMTPC Collaboration

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*=PI, `postdoc`, **grad student**, *undergraduate*

DMTPC

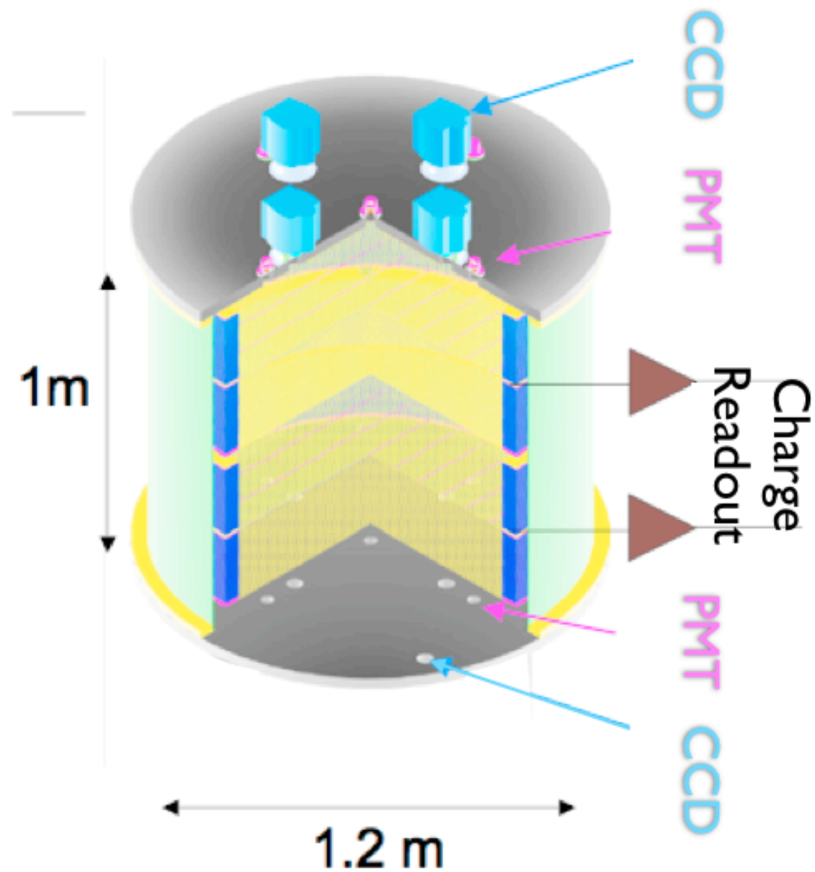
10L

Underground at WIPP

4Shooter (20L)

At MIT

DMTPCino (1 m^3)



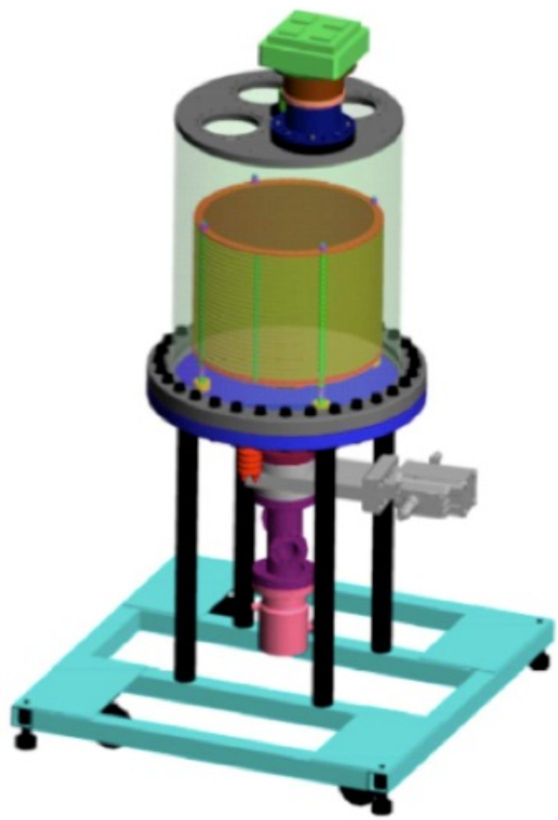
Funded by NSF+DoE

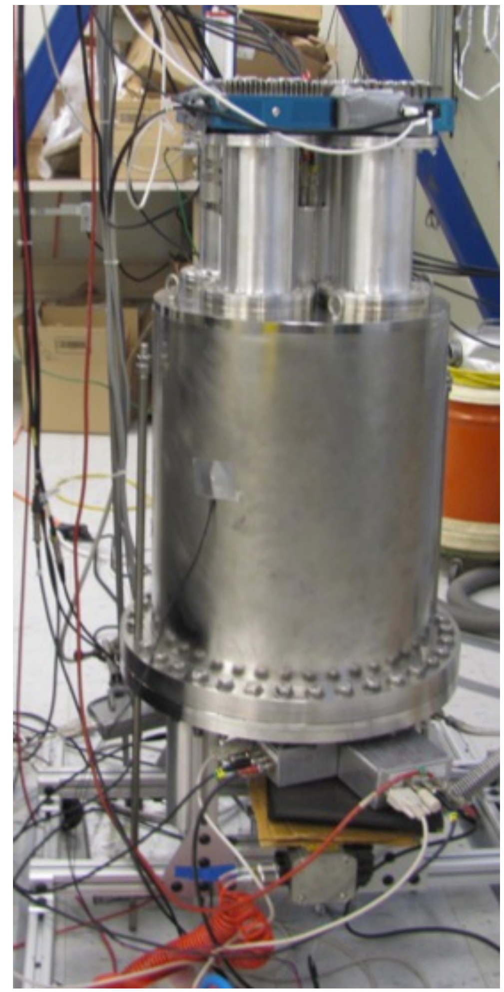
The 4shooter

- The 10L detector demonstrated the mesh amplification technique and remote-operation capability.
- Eventual goal is to build detectors with target volumes of 100+ m^3.
- As an intermediate step, 4shooter demonstrates:
  1) Reduced detector backgrounds
  2) More stable operation
  3) Multi-camera operation for large area coverage
  4) Integrated charge and light analysis (bkg rejection and 3D tracking)

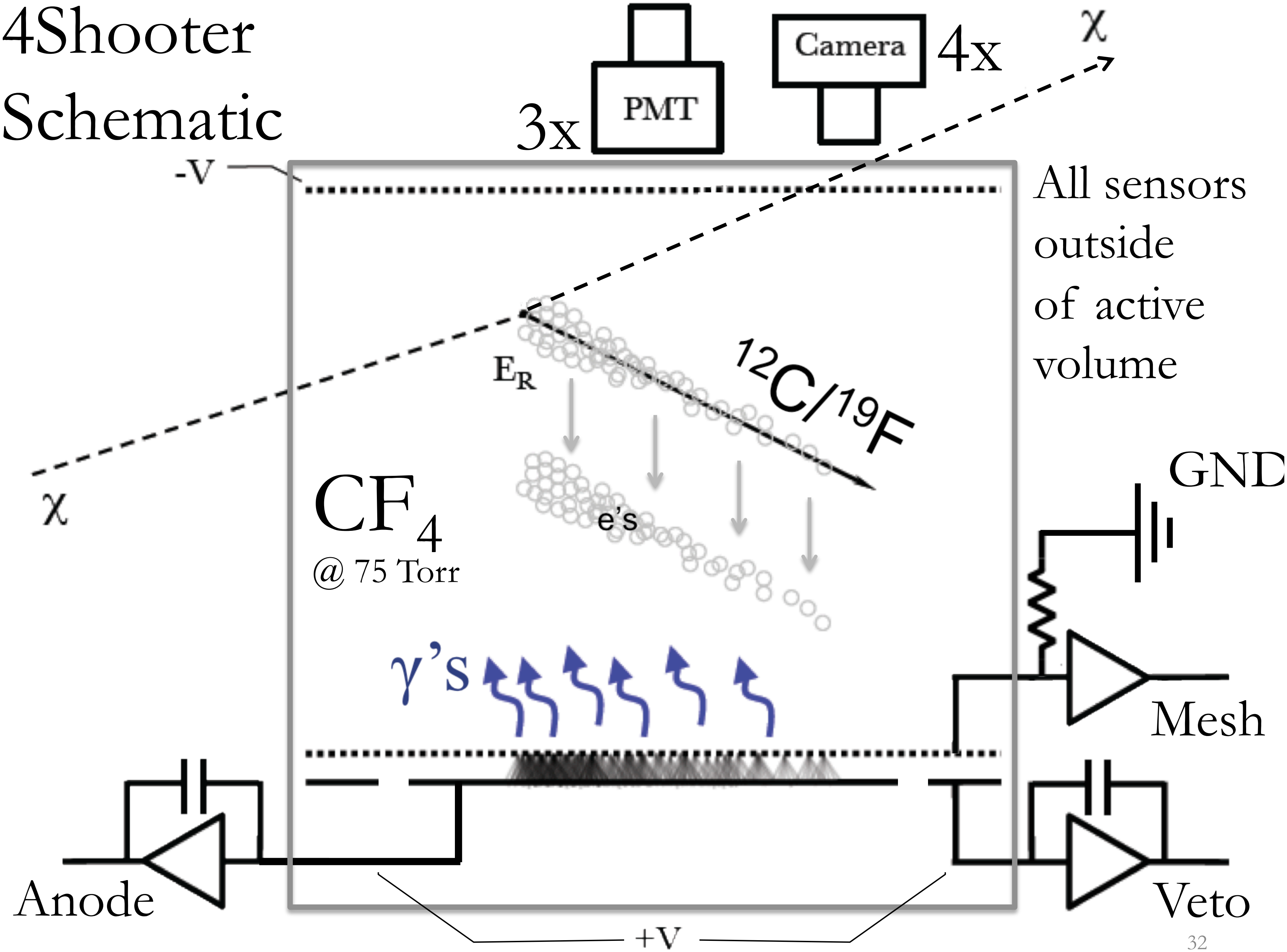
4Shooter Overview

- 20L (6.6 g CF_4)
- Higher vacuum (8e-6 Torr)
- Cleaning procedures for detector innards
- Materials selection
  OFHC copper, acetal, Stainless Steel, G-10.
  Some: epoxy (DP460EG) fused silica, kodial glass (windows), kapton, resistors (for field cage).
- 4 ccd cameras, 3 PMTs, 3 charge readout channels



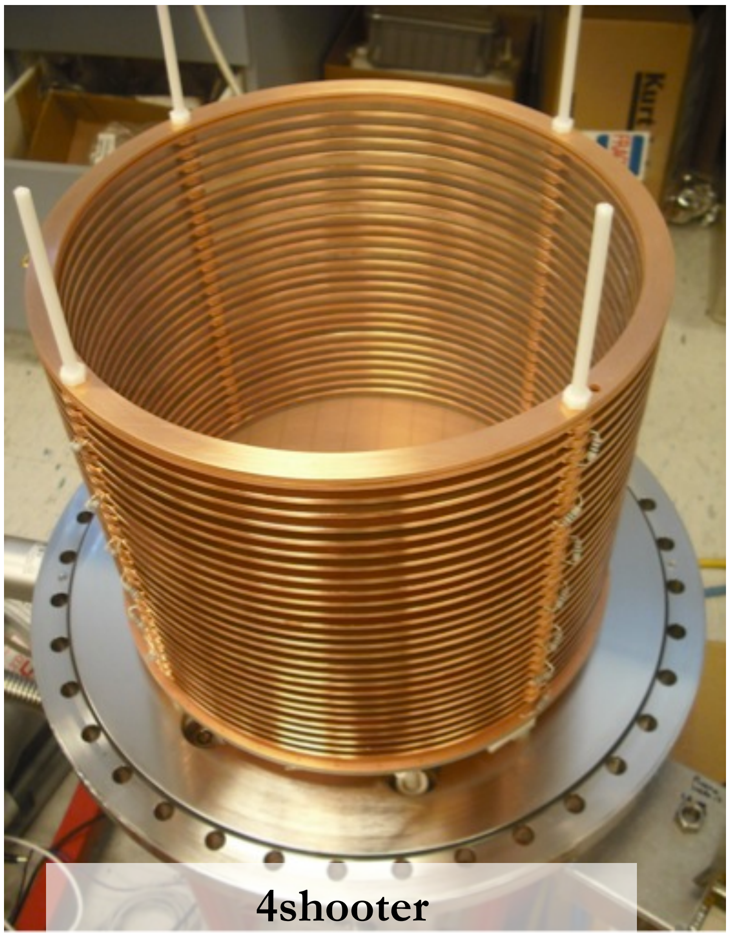


4Shooter Schematic



4Shooter Construction

Improved Field Cage (spacers), and amplification region fabrication scheme → More gain, lower spark rate. Repeatable amplification region construction technique in a clean-room environment.



vs.

Lower alpha background rate & better tagging capability

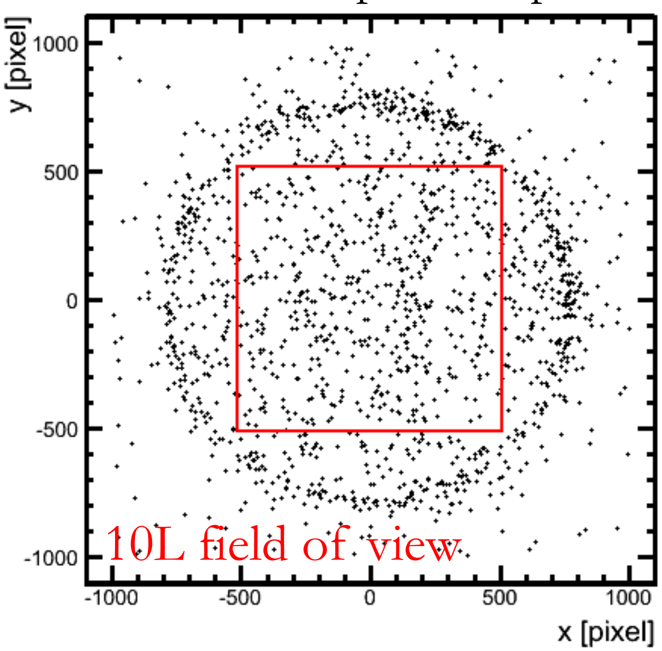
Raw α rate is 19x lower

10L 210 mHz

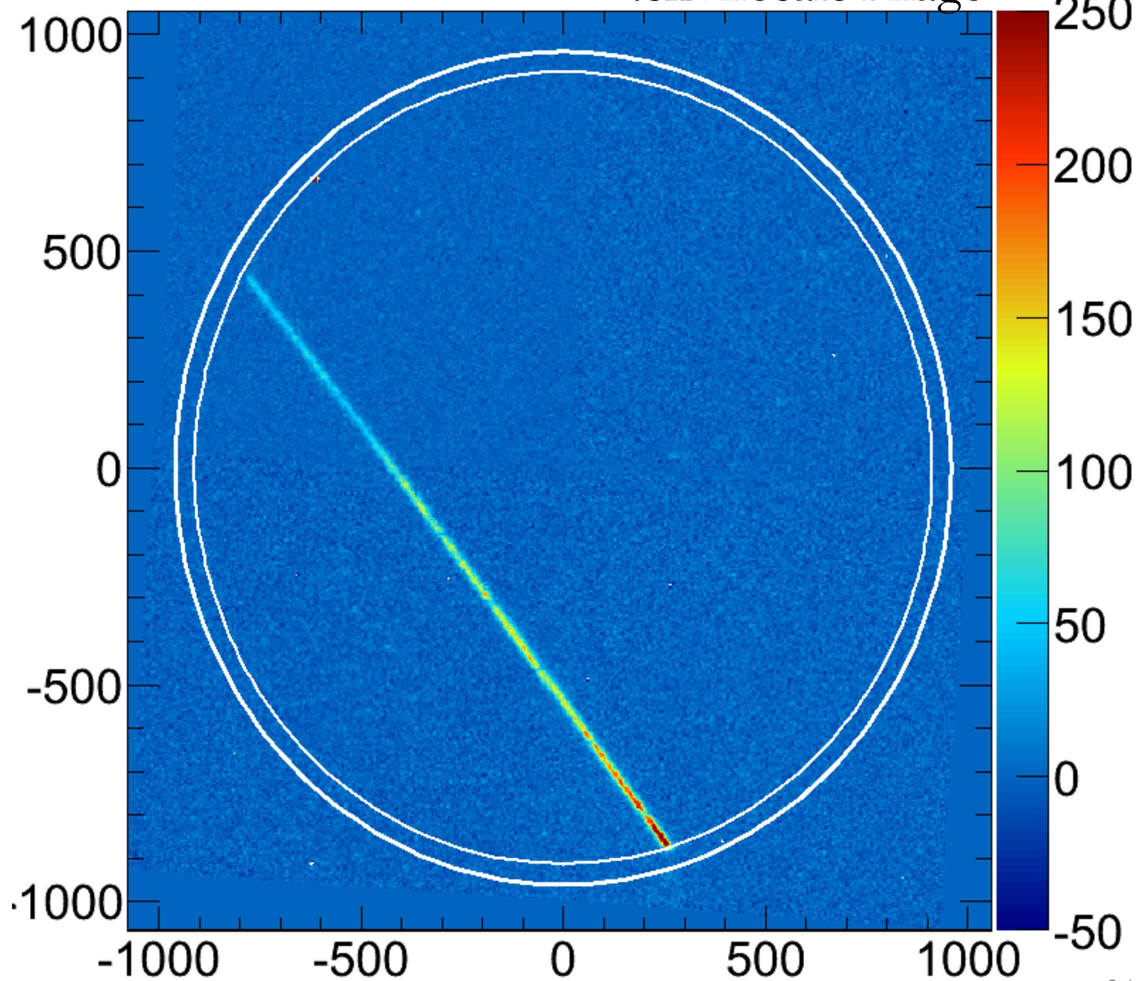
4sh 11 mHz

And 4sh field cage has 3x more internal surface area

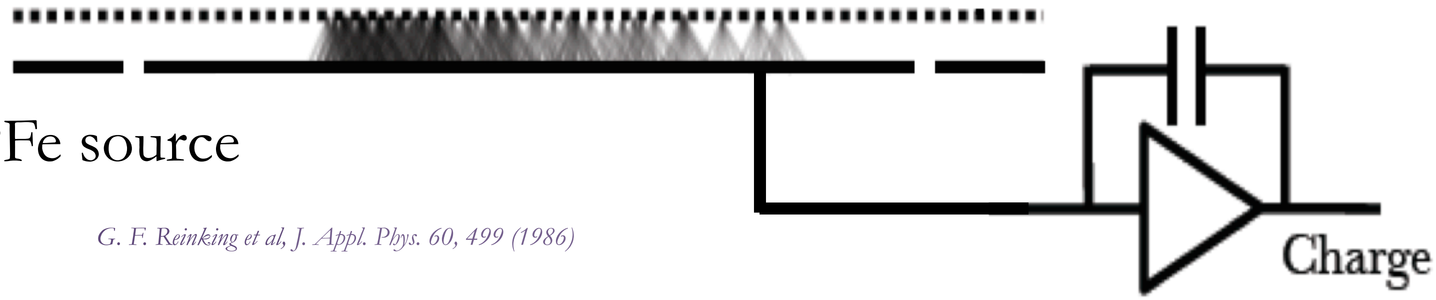
10L: inferred alpha start points



4sh mosaic image



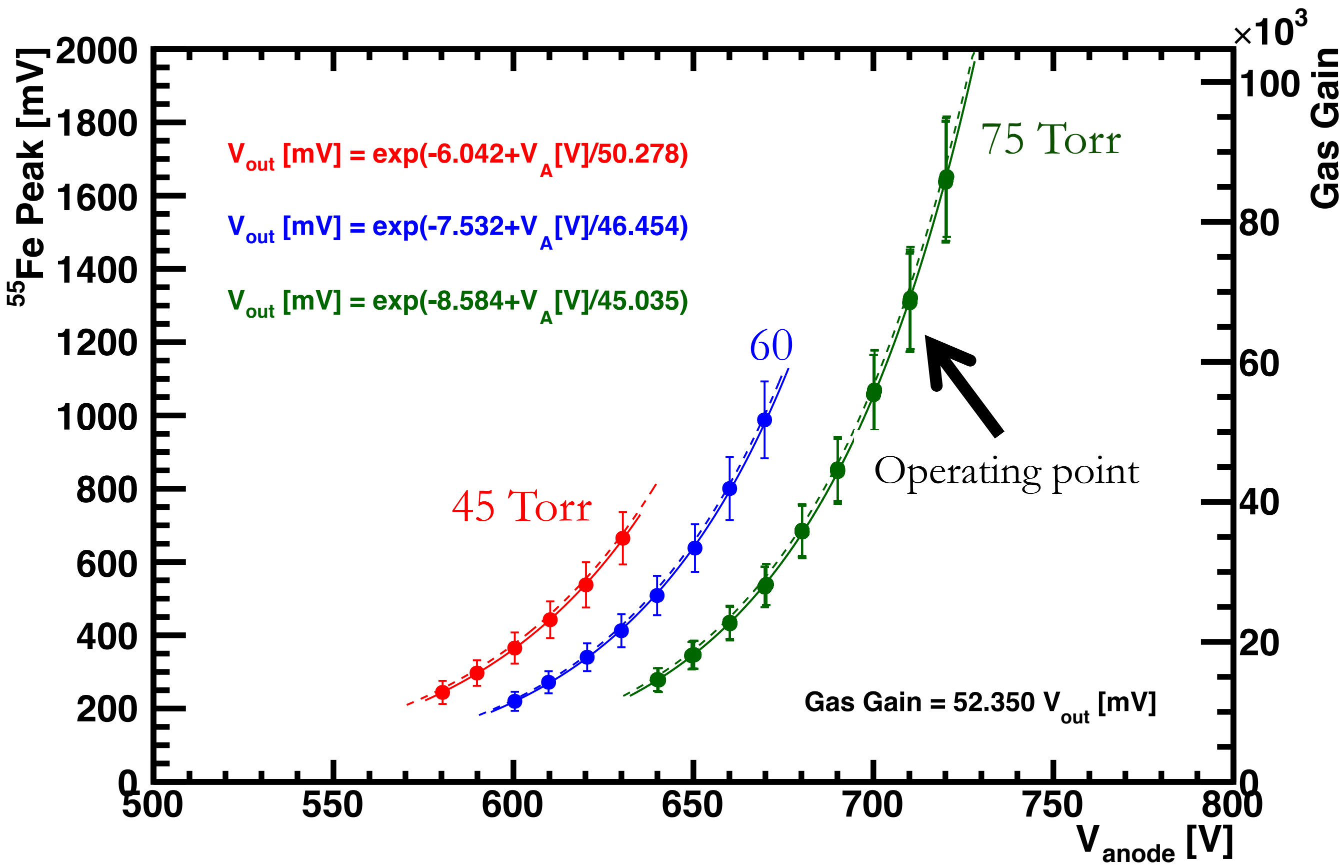
Higher gas gain & lower discharge rate



Measured with ^{55}Fe source

assumes W_{CF4}=34 eV *G. F. Reinking et al, J. Appl. Phys. 60, 499 (1986)*

W_{CF4}=54 eV also appears *A. Sharma, SLAC-JOURNAL-ICFA-16-3, 1998*



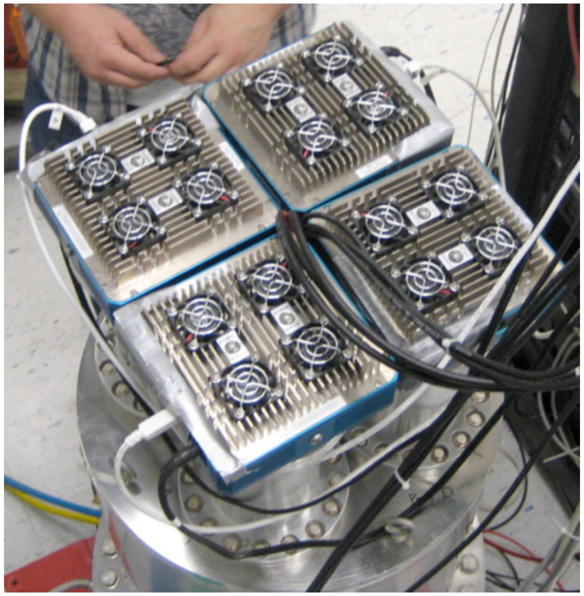
Spark Rate

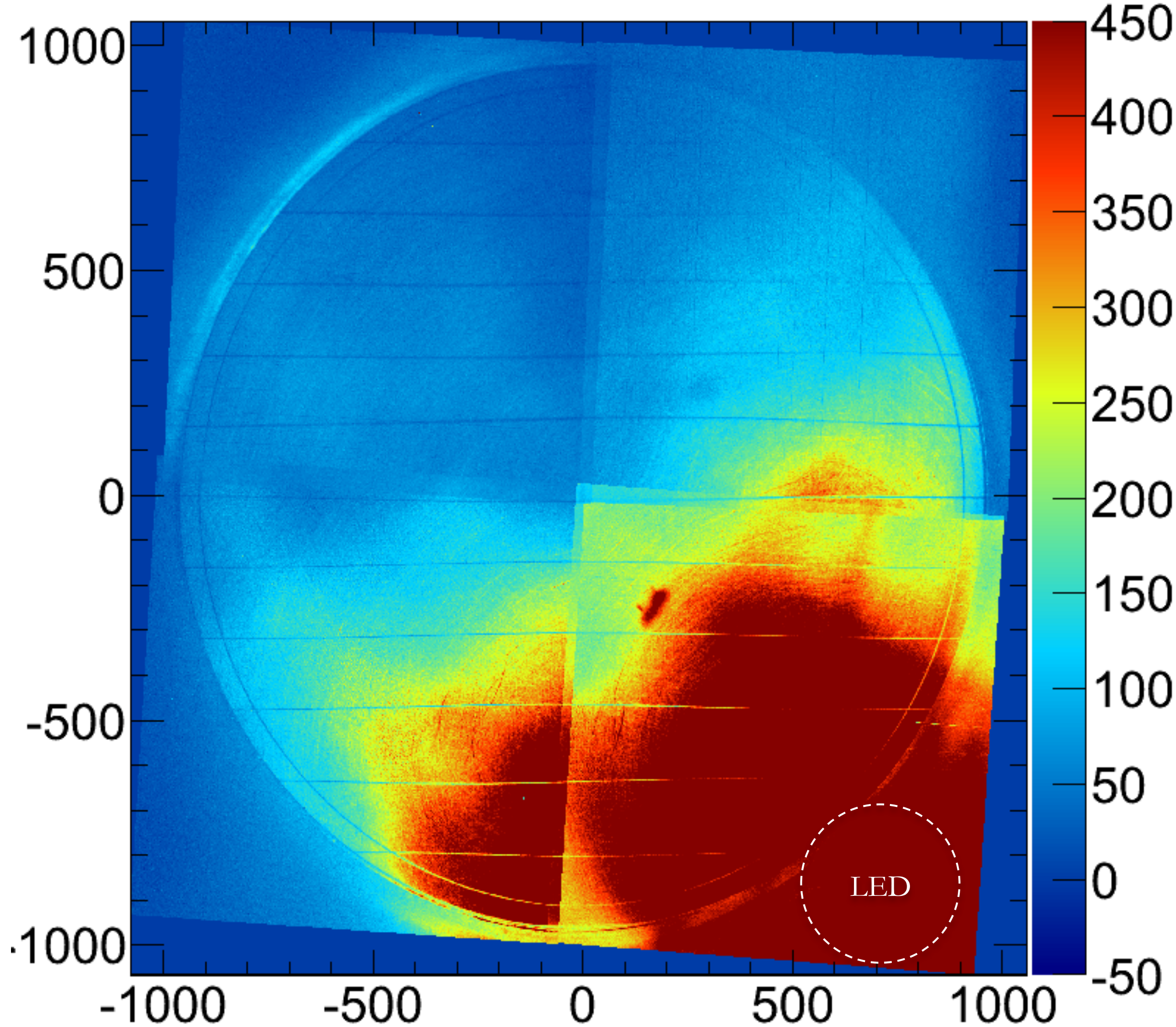
10L	125 mHz
4sh	9 mHz

Gas gain

10L	4.1×10^4
4sh	7.1×10^4

CCD readout: combining 4 cameras





Alta U6 CCDs

1024x1024, 24 μ m pixels

1”x1”, 1 Mpixel chip

Binned 4x4 in hardware

Shutter-less operation

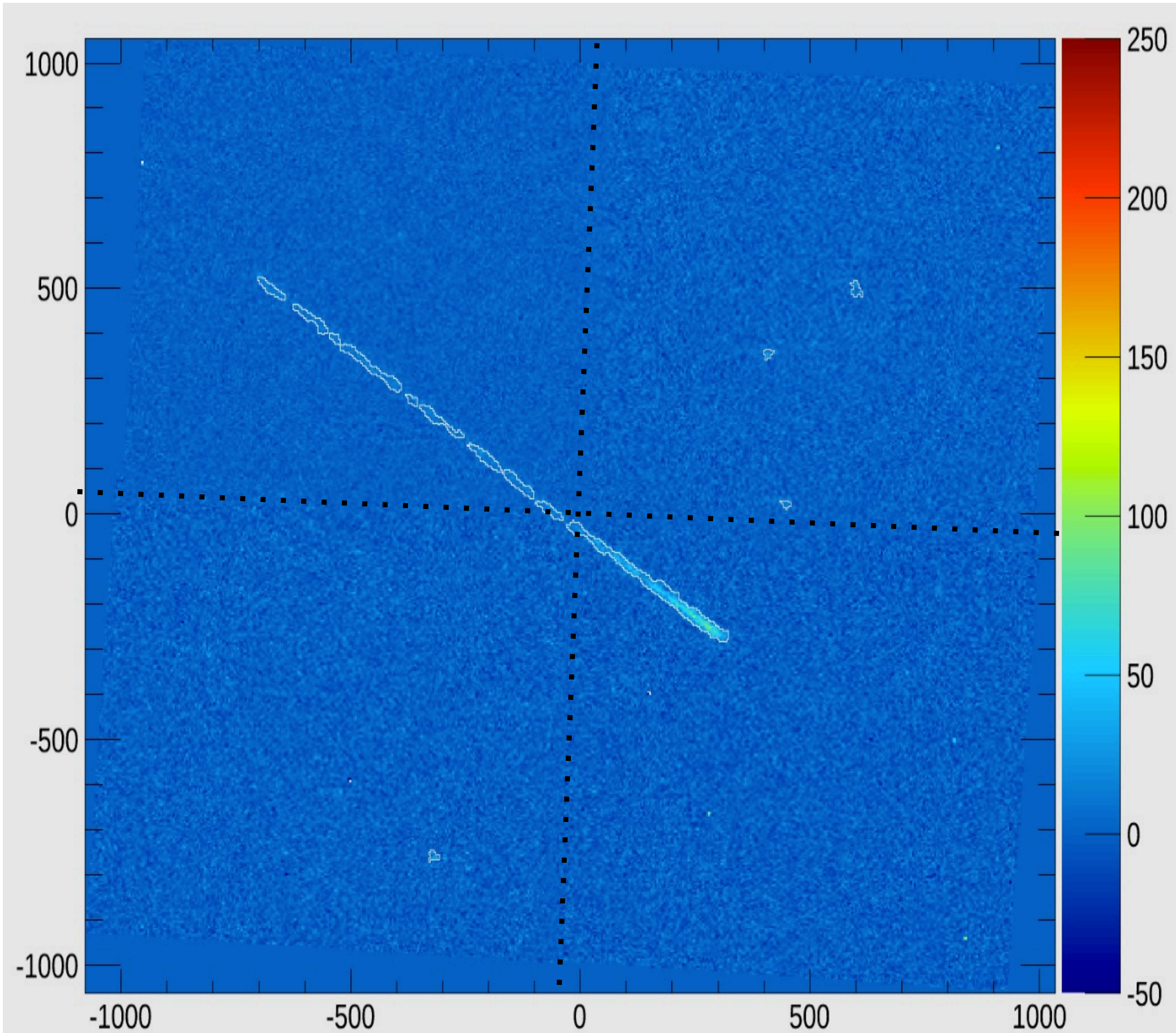
Large read-noise: 9 e^- RMS

Canon SLR lenses

FD 85mm f/1.2

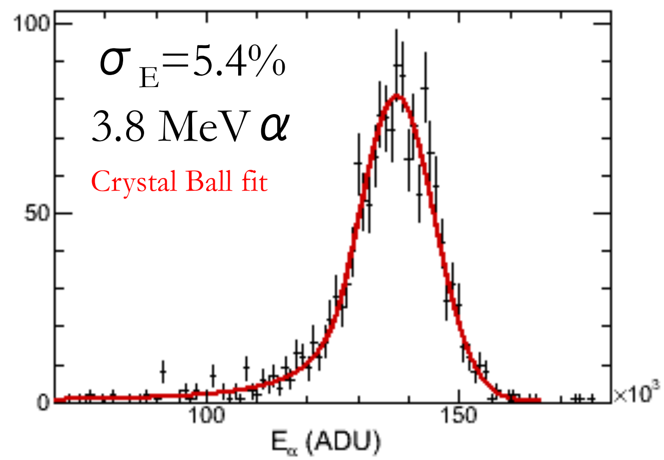
Image mosaic parameters determined from LED illumination

Track reconstruction in mosaic image

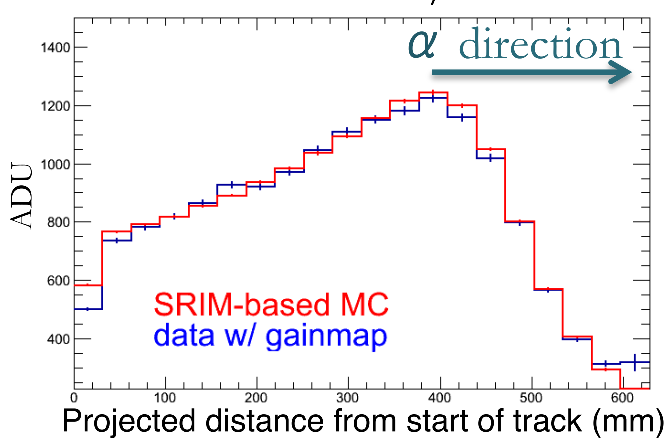


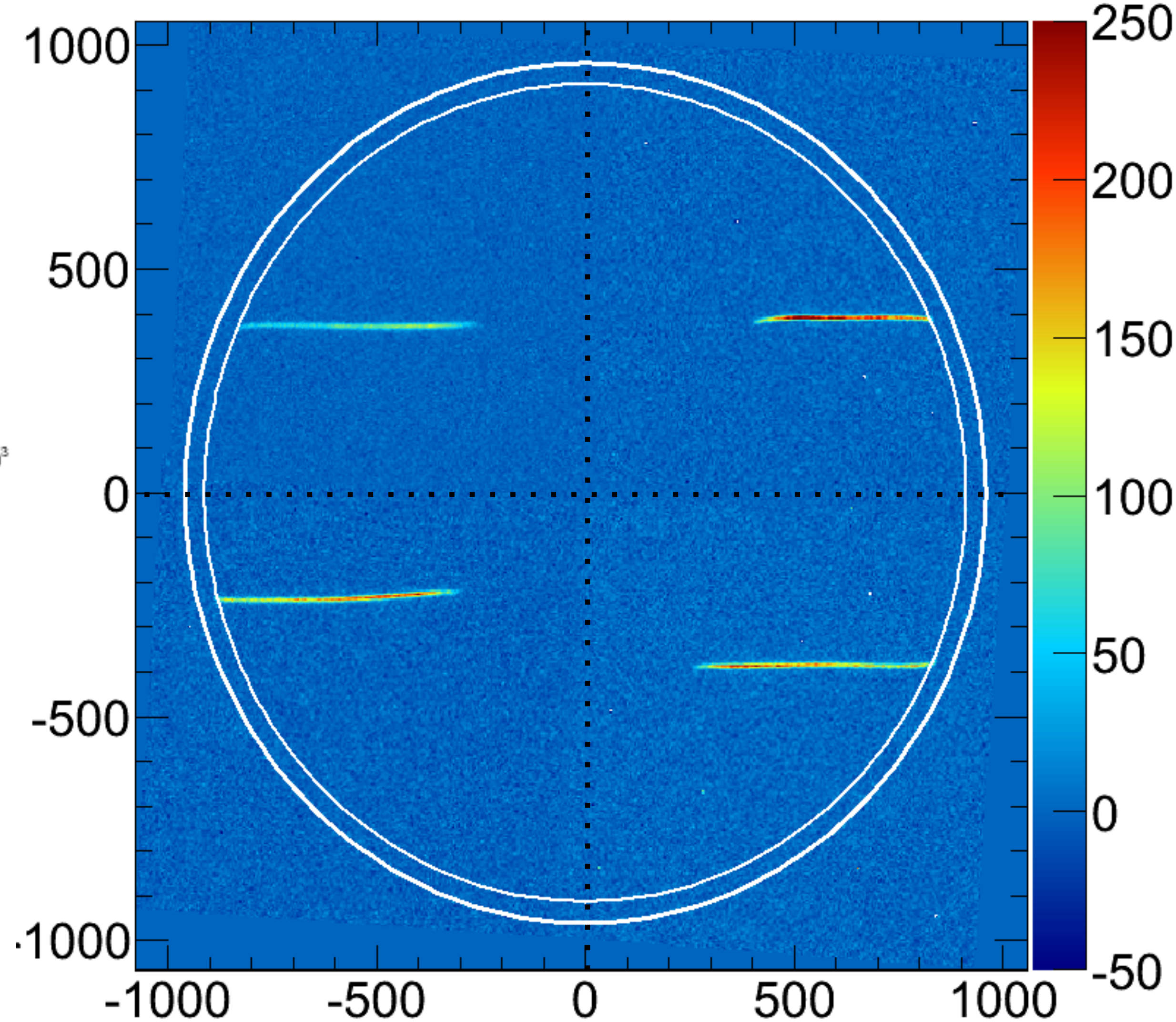
Calibrating the CCD Energy Scale

E_{CCD} Spectrum for 1 camera



^{241}Am α dE/dx



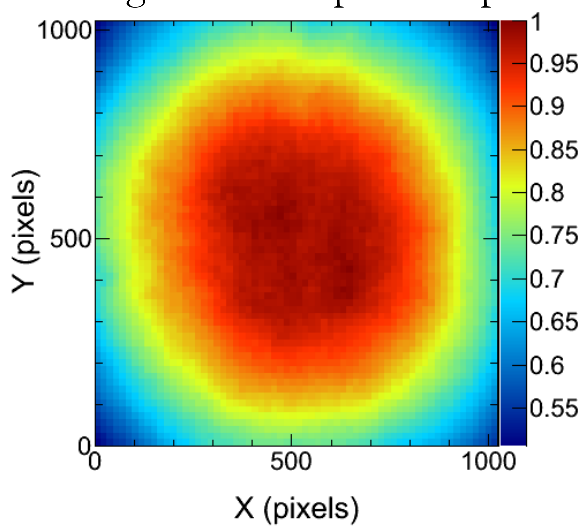


One ^{241}Am α source in each field of view

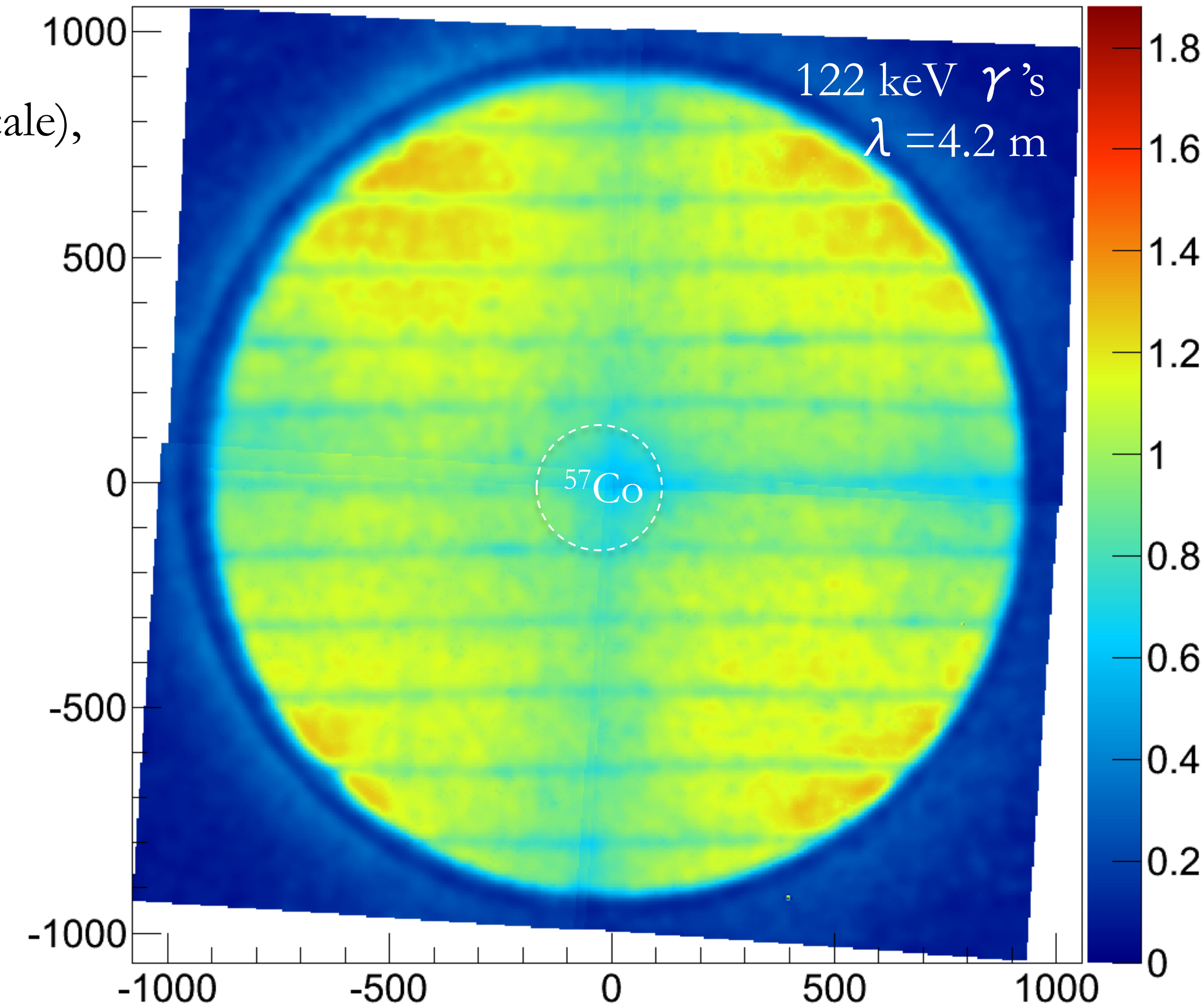
Mapping spatial gain variations

Variations in gas gain (small scale),
light blockage (spacers),
lens throughput (radial)

Single camera optical response

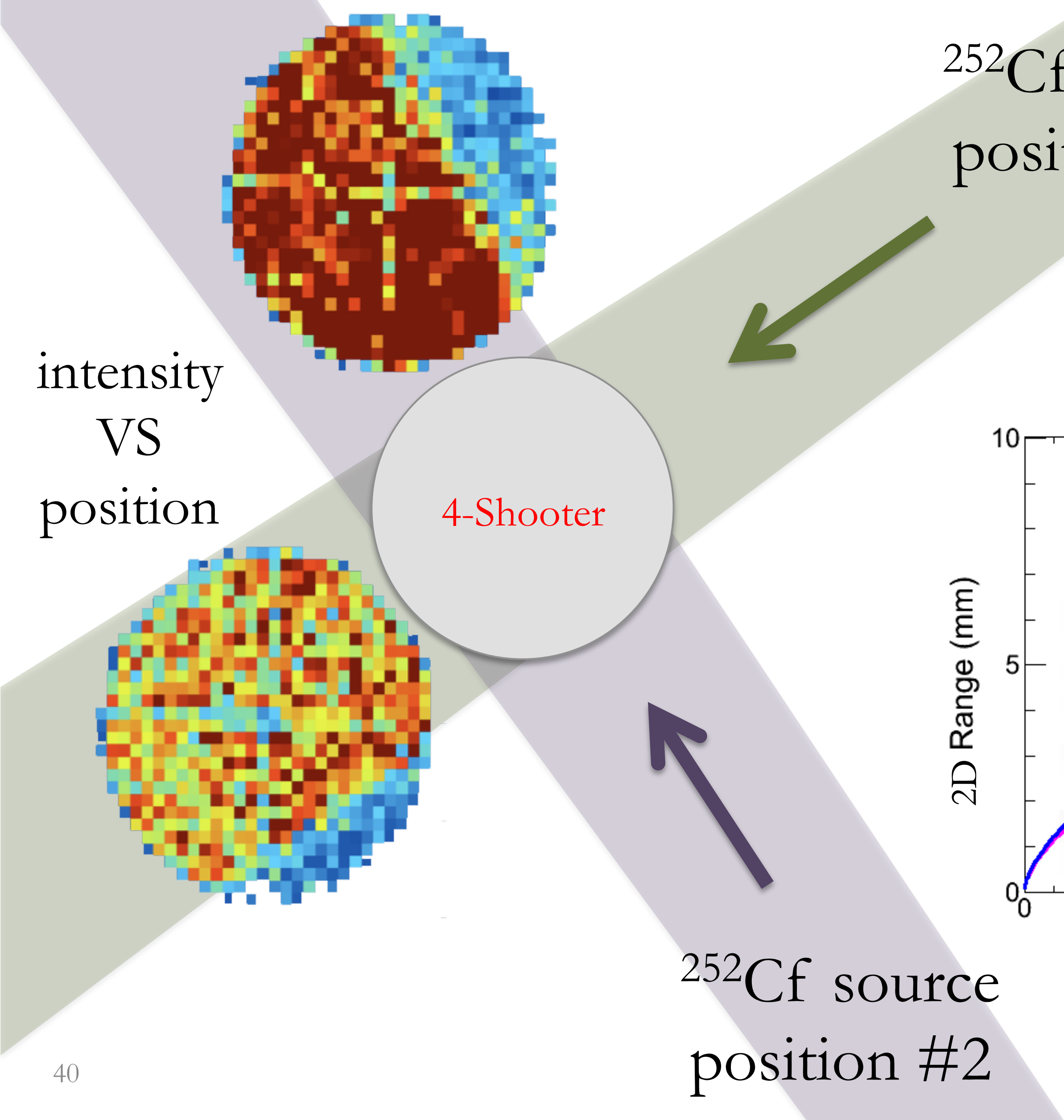


Throughput depends on angle relative to boresight

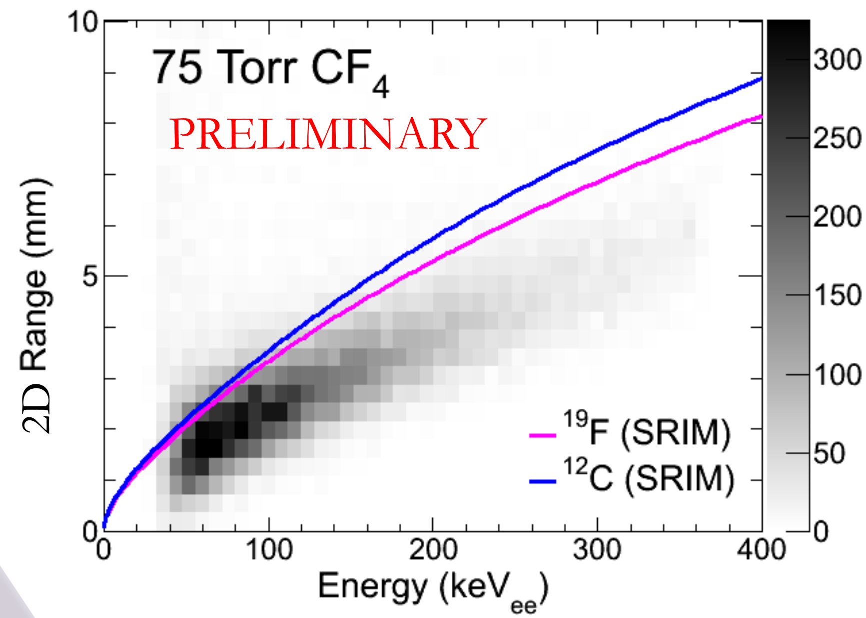


CCD gain(X,Y) measured using a ^{57}Co γ source to generate spatially uniform signal

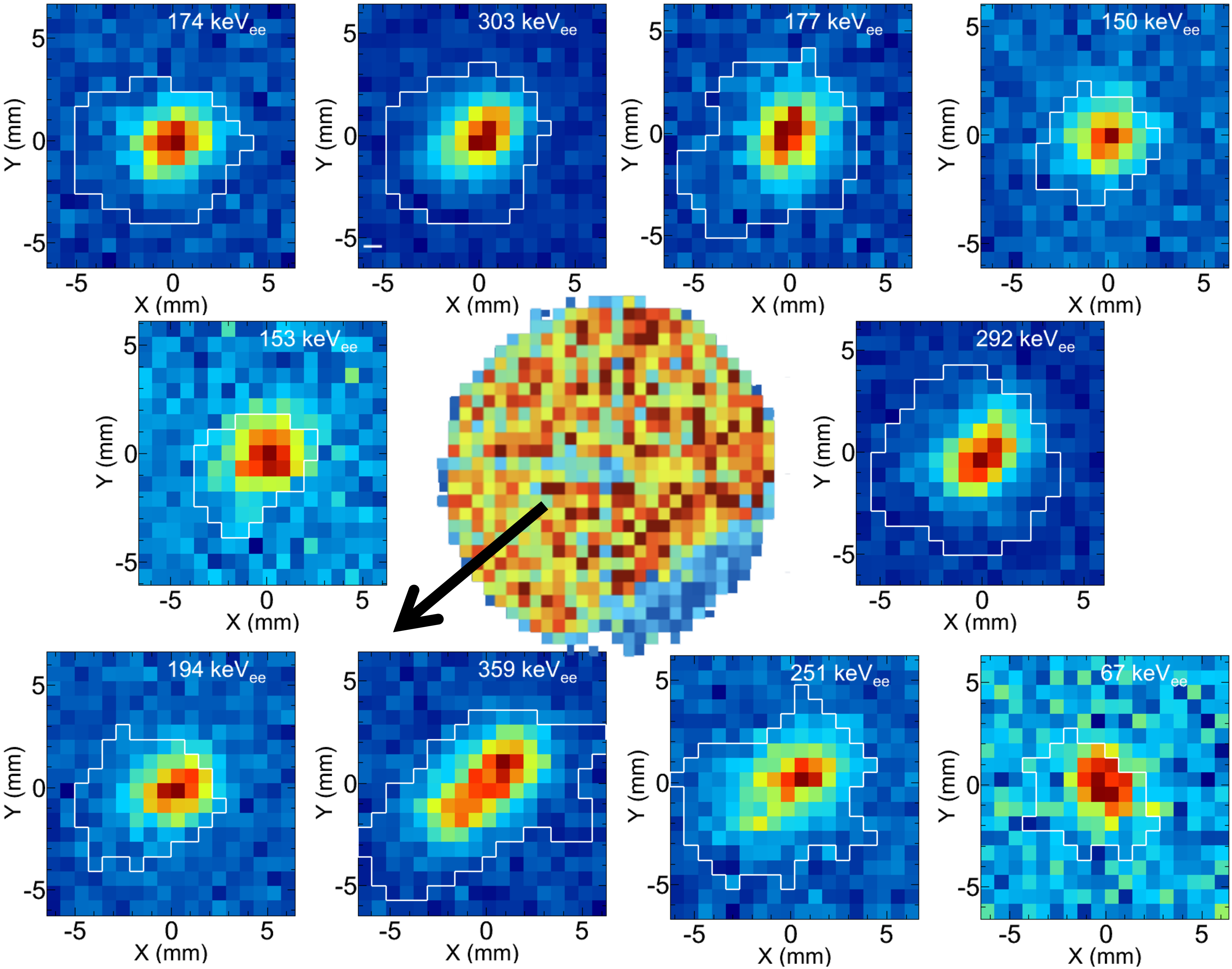
^{252}Cf calibration



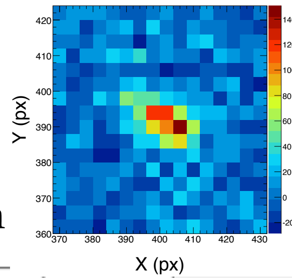
Beam profile evident in found track positions



Good range vs. energy
Agreement with SRIM

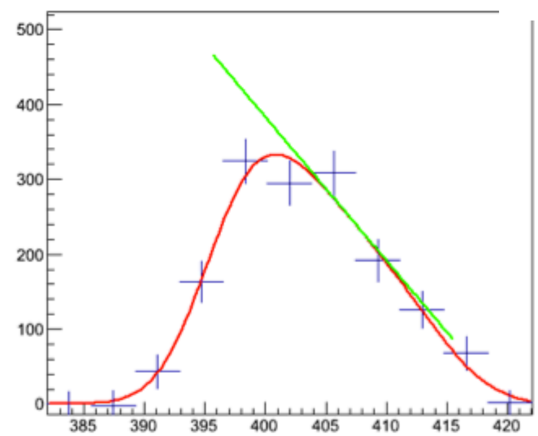

174 keVee
303 keVee
177 keVee
150 keVee
153 keVee
292 keVee
194 keVee
359 keVee
251 keVee
67 keVee
Y (mm)
X (mm)
5
0
-5

Improved Track Reconstruction



62 keVee recoil

Longitudinal Projection



χ^2/ndof : 4.352148/10 = 0.435215

x0: 395.668893 +/-0.625993 (-0.664133,0.598328)

y0: 466.210150 +/-51.341684 (-56.980963,46.037852)

y1: 85.021626 +/-103.864438 (-64.085506,99.278767)

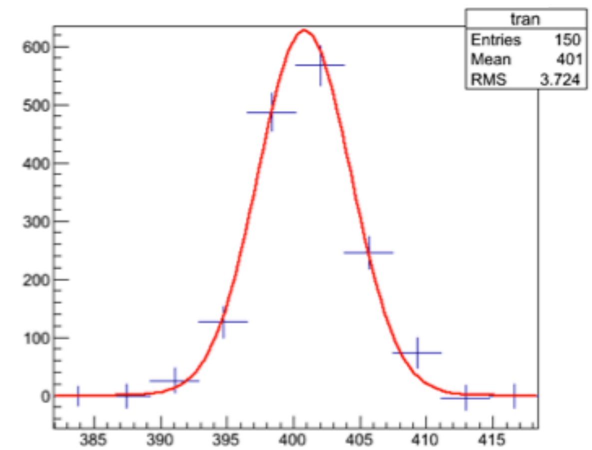
E: 1505.203272 +/- 9.356560 adu (62.716803 +/- 0.389857 keVee

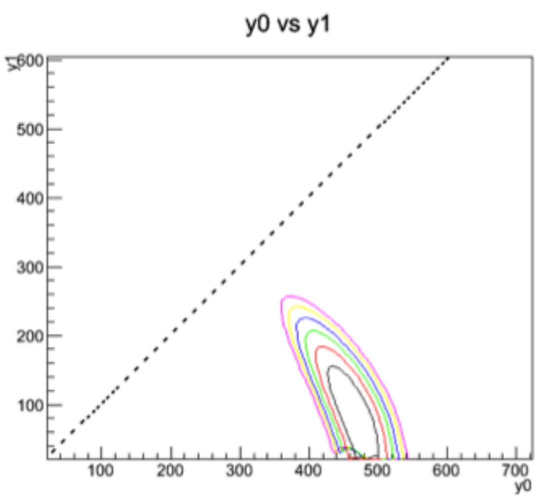
Range: 19.912867 +/- 8.374463 pixels (3.186059 +/- 1.339914 mm)

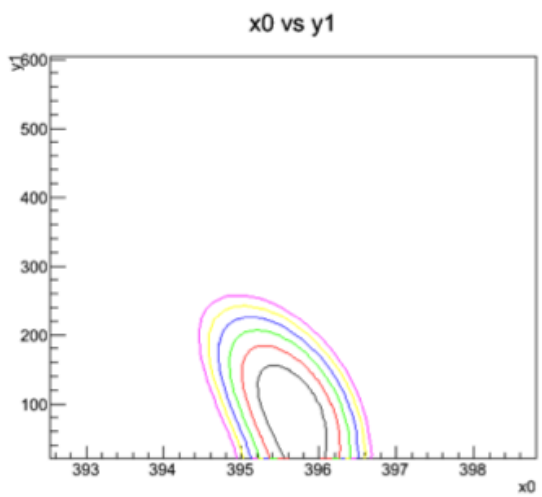
sin θ (from range): 0.888838 (from min): 1.237788

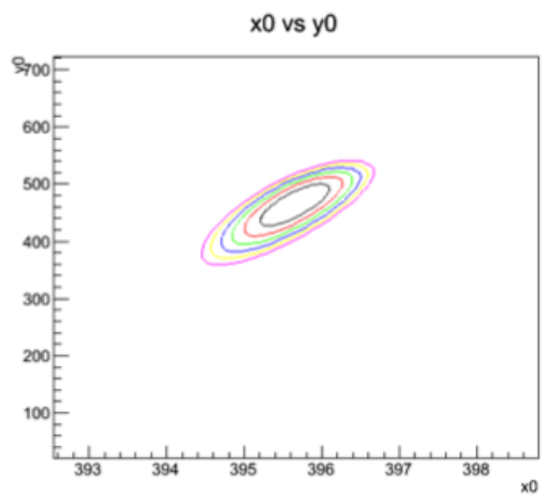
Implied Probability: 0.967850

Transverse Projection

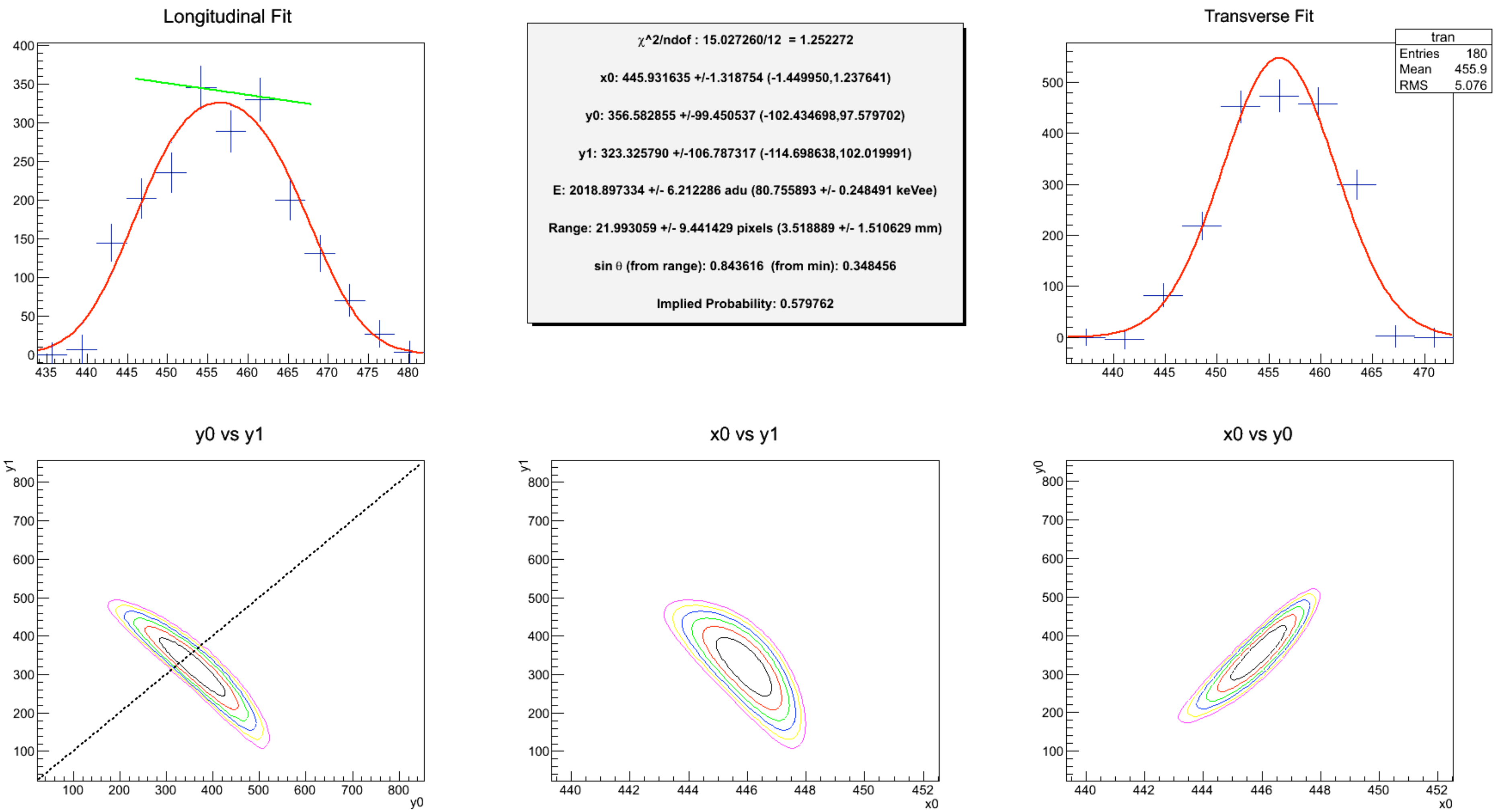




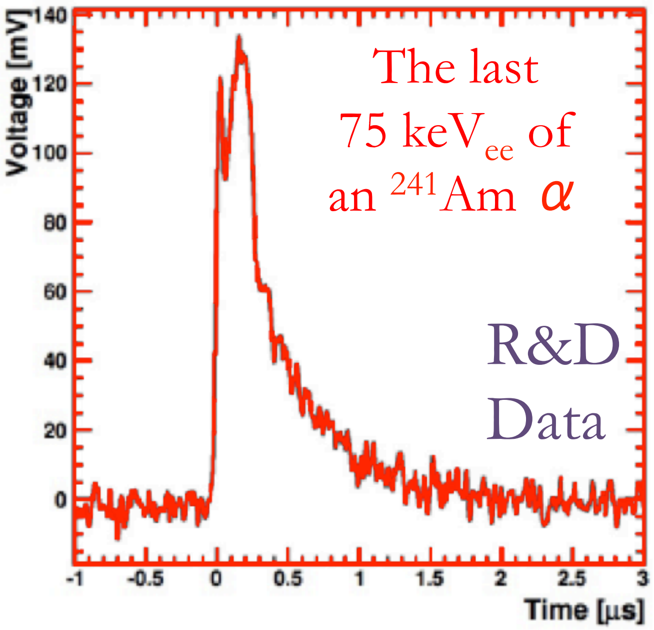


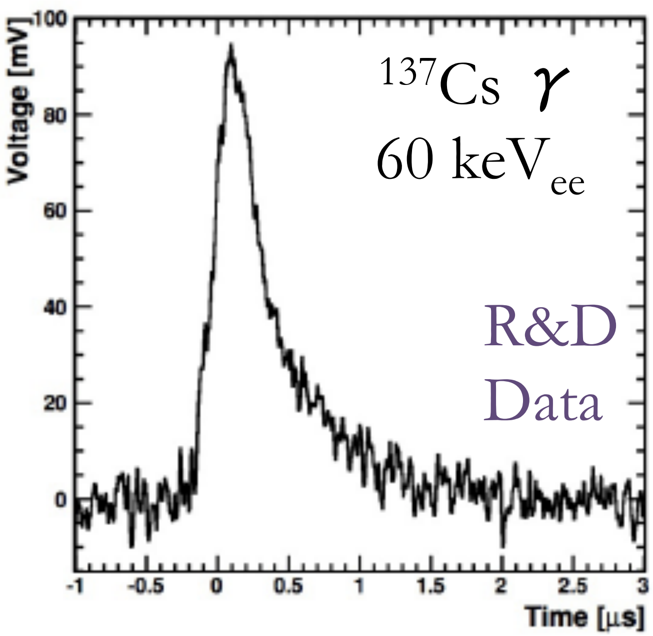


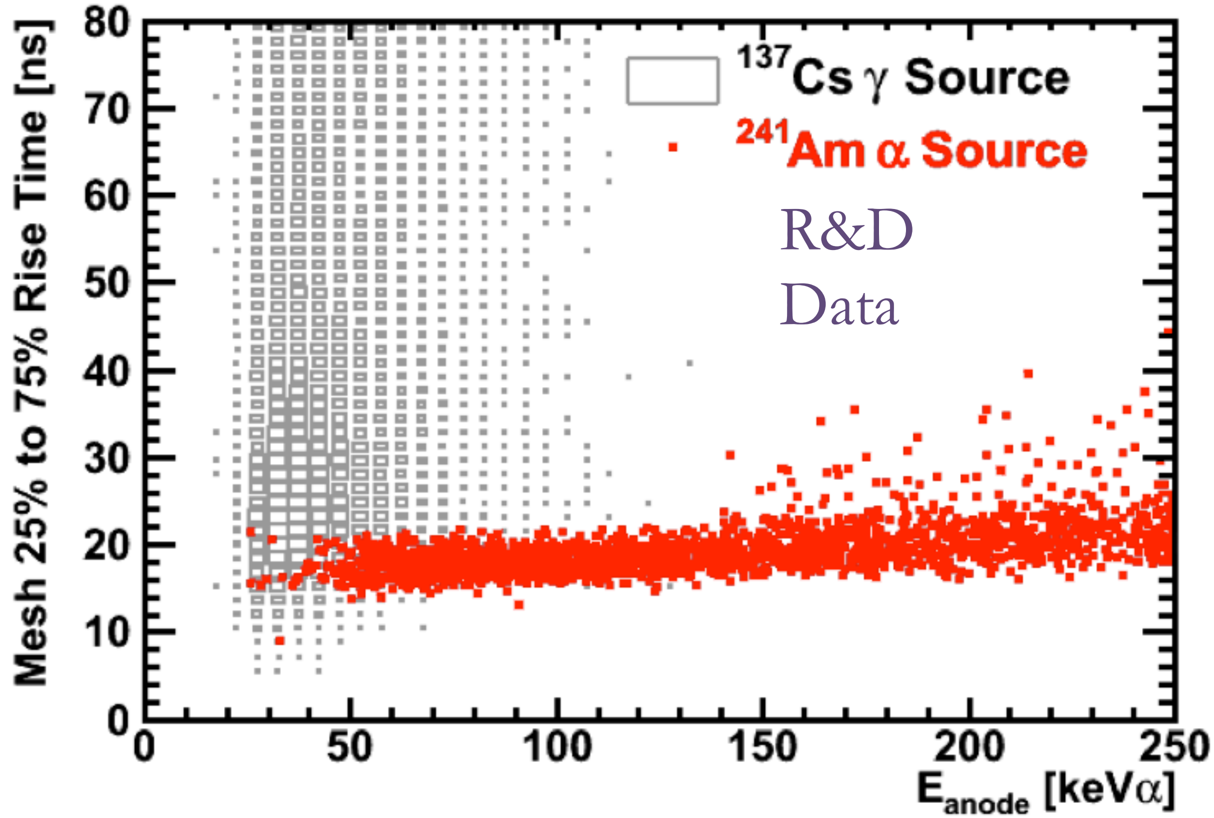
Can select recoils on Head-Tail confidence



PID with Mesh Readout





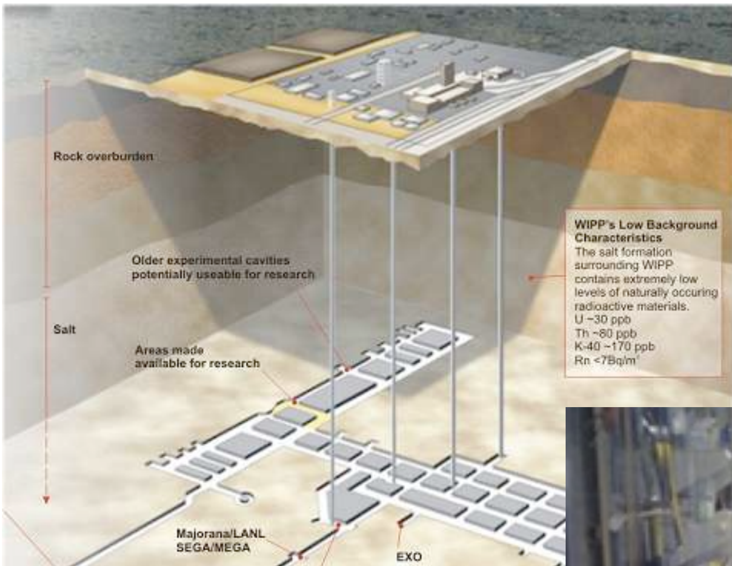


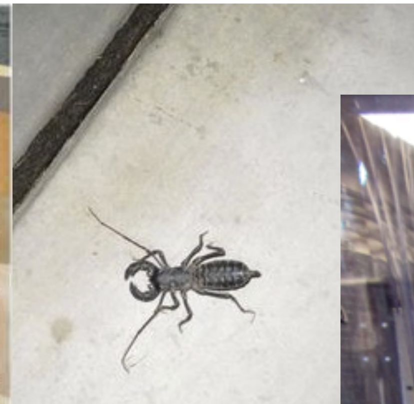
Demonstrated rejection of Cs-137 γ's between 40 keV$_{ee}$ < E < 200 keV$_{ee}$ of 10^5 (90% CL upper-limit) using CCD+veto+mesh

J. Lopez *et al.* NIMA 696, 2012

10L Detector underground at WIPP

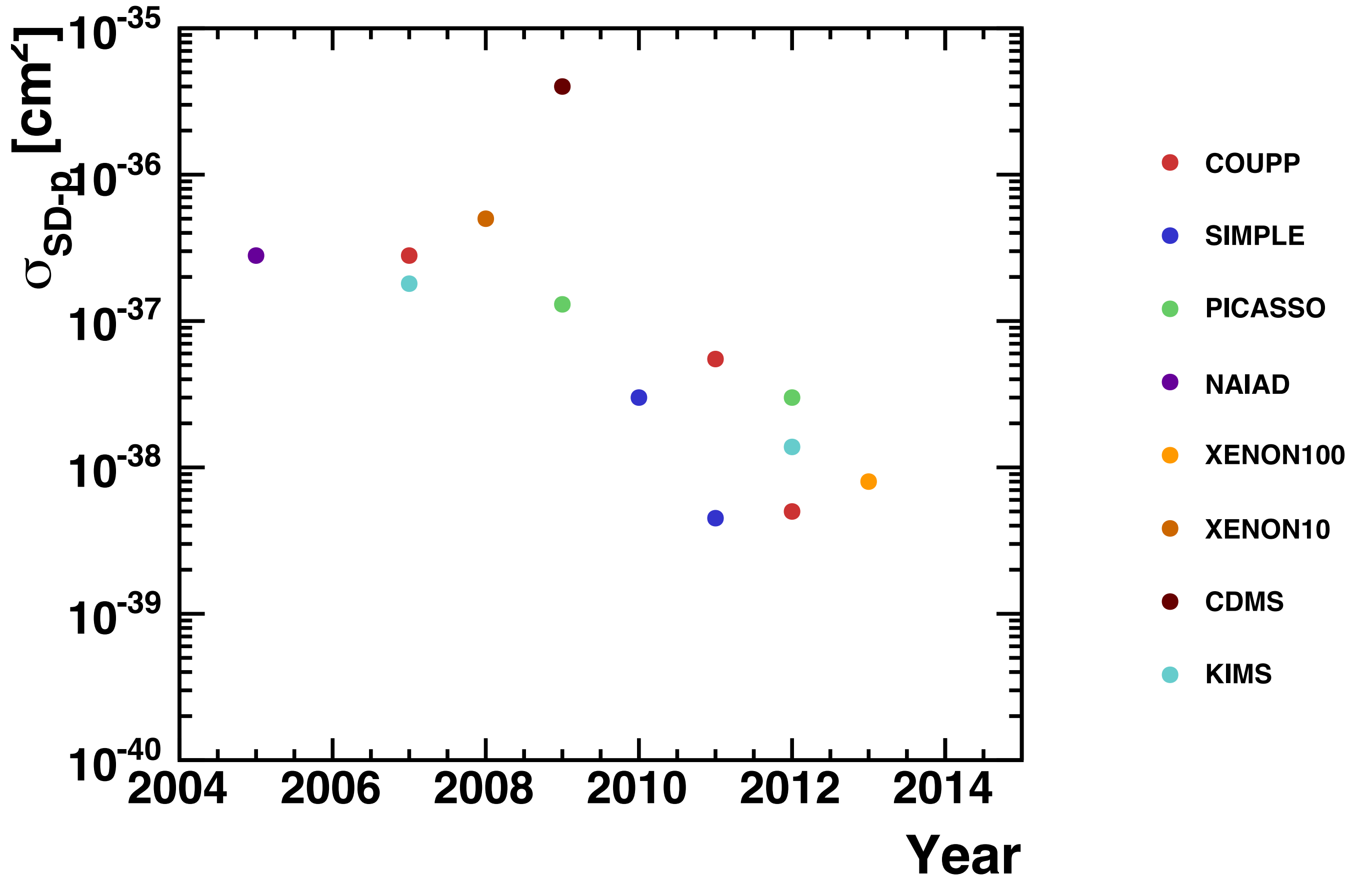
(adjacent to EXO)





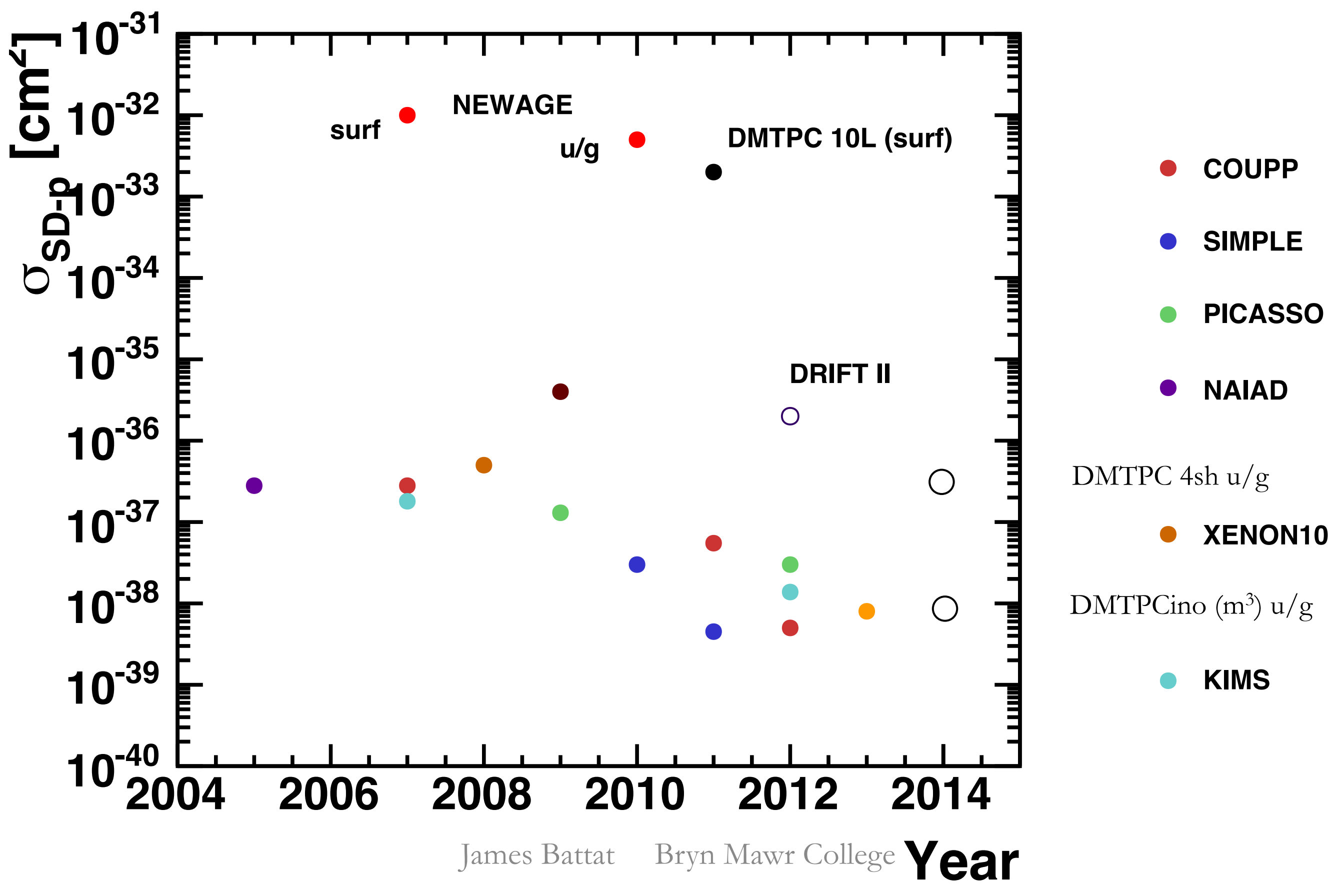
Scaling Gas Detectors

For macroscopic tracks O(mm), need low-pressure gas O(0.1 atm). Therefore large volumes.

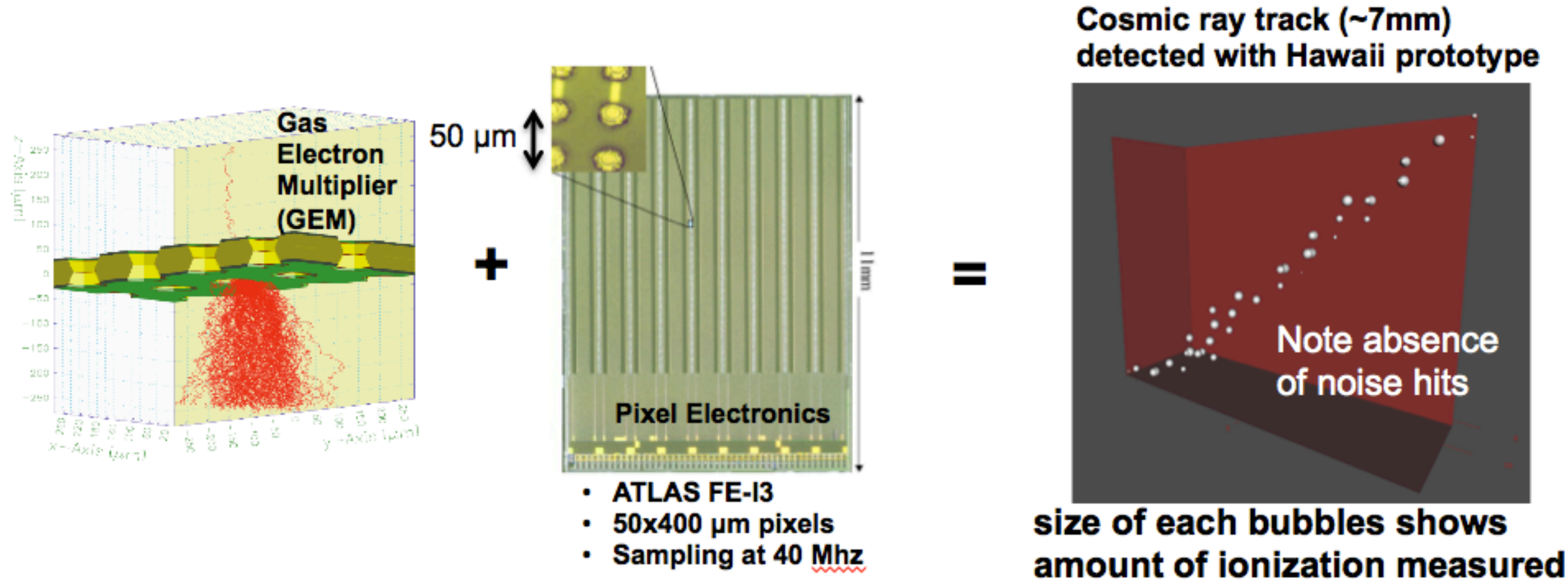


Scaling Gas Detectors

For macroscopic tracks O(mm), need low-pressure gas O(0.1 atm). Therefore large volumes.



New ideas I: Silicon Pixel Chips



- Full 3D tracking w/ ionization measurement for each spacepoint
- Pixels low noise (~100 electrons) at room temperature, self-triggering, and zero suppressed → virtually noise free → low demands on DAQ
- High-single electron efficiency → may be suitable for low-mass WIMP searches

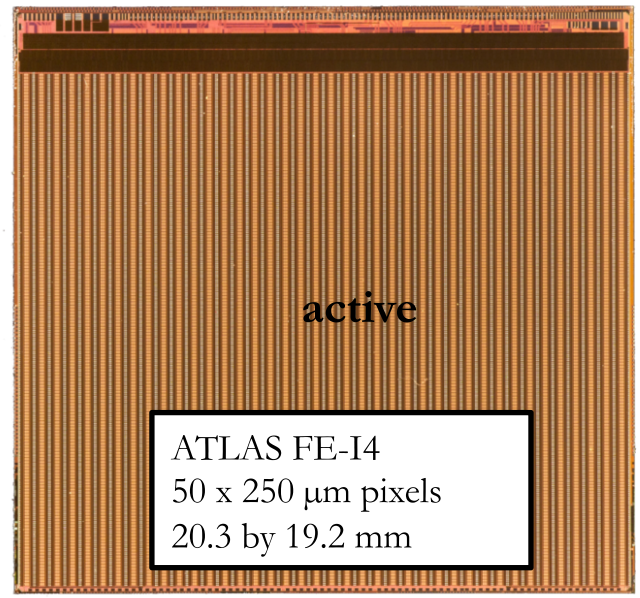
- But chips are small: 7.4 x 11 mm …..

Sven Vahsen @ U. Hawaii
John Kadyk @ LBNL
see: arXiv:1110.3401

New ideas I: Silicon Pixel Chips

Bigger chips

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



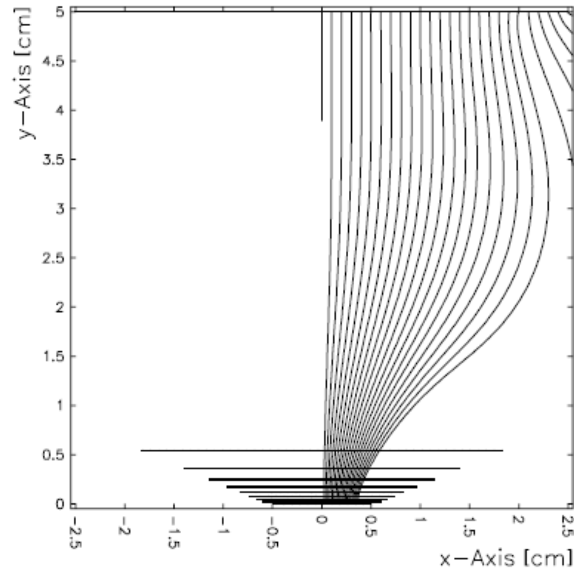
ATLAS FE-I4
50 x 250 μm pixels
20.3 by 19.2 mm

New ideas I: Silicon Pixel Chips + Charge Focusing

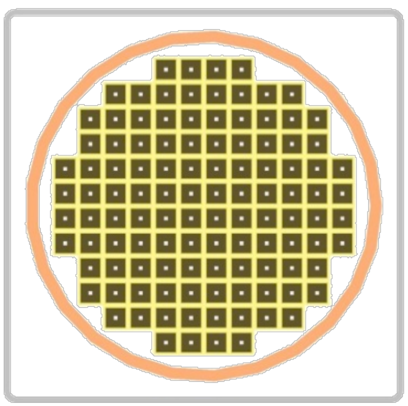
Focusing of drift charge by factor of 25 (!) in area

advantage: read out large volume with small readout plane, while retaining a key advantage of pixels: small size → low capacitance → low noise

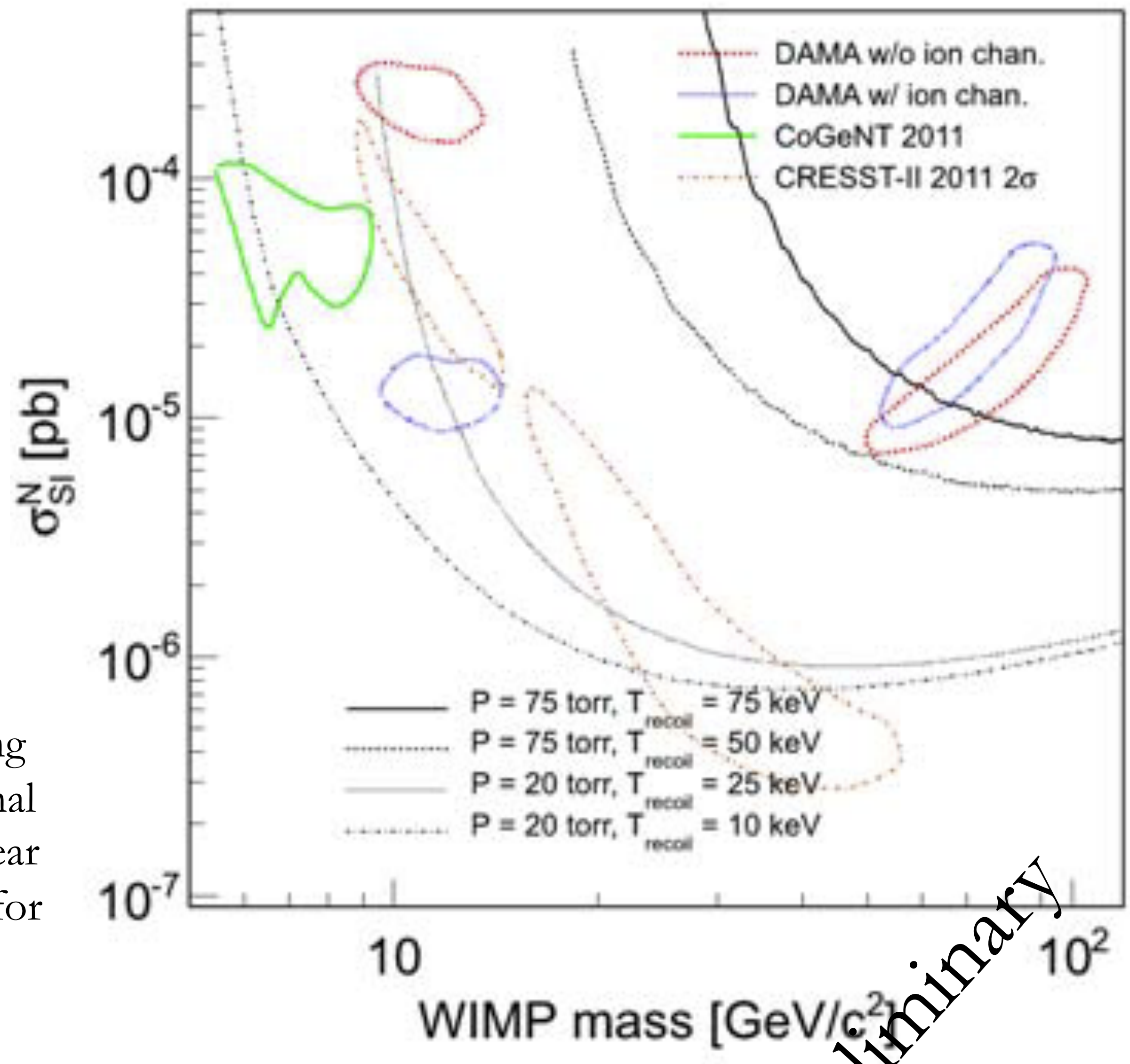
status: First experimental test promising, more detailed analysis underway



2012 IEEE Nucl. Sci. Symp
Ross, S. J. (session N31-2)



1 m3 read out with ~400 pixel chips



Estimated sensitivity to spin-independent WIMP-nucleon scattering for a pixel-chip-based 10-m^3 directional dark matter detector, running for 1 year with 33 cm drift length and CF_4 gas, for four different track reconstruction thresholds.

SD-proton reach is 10^{-3} pb

(New) Ideas II

- Anisotropic emission in scintillators

  e.g. Cappella et al. Eur. Phys. J. C 73 (2013) 2276
  N.J.C. Spooner et al., in International Workshop IDM (World Scientific, Singapore, 1997), p. 481
  Y. Shimizu, M. Minowa, H. Sekiya, Y. Inoue, Nucl. Instrum. Methods A 496, 347 (2003)

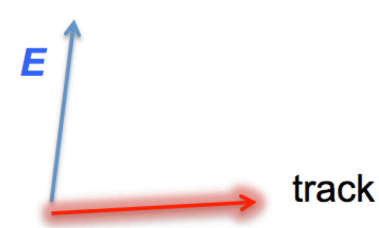
- DNA-based tracking detector

  New Dark Matter Detectors using DNA for Nanometer Tracking
  Andrzej Drukier, Katherine Freese, David Spergel, Charles Cantor, George Church, Takeshi Sano
  arXiv:1206.6809 or ask Scott Stephenson here.

- Directionality without tracking

  "Columnar recombination" in High-Pressure Xe Gas
  See: Nygren, Paris TPC 2012 Talk

Substantial CR

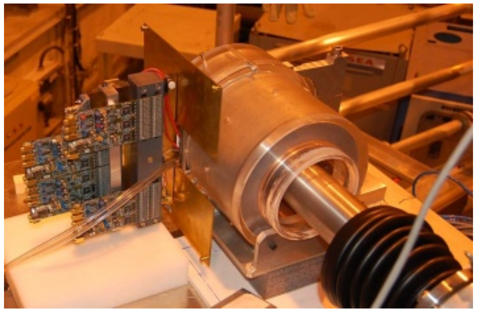


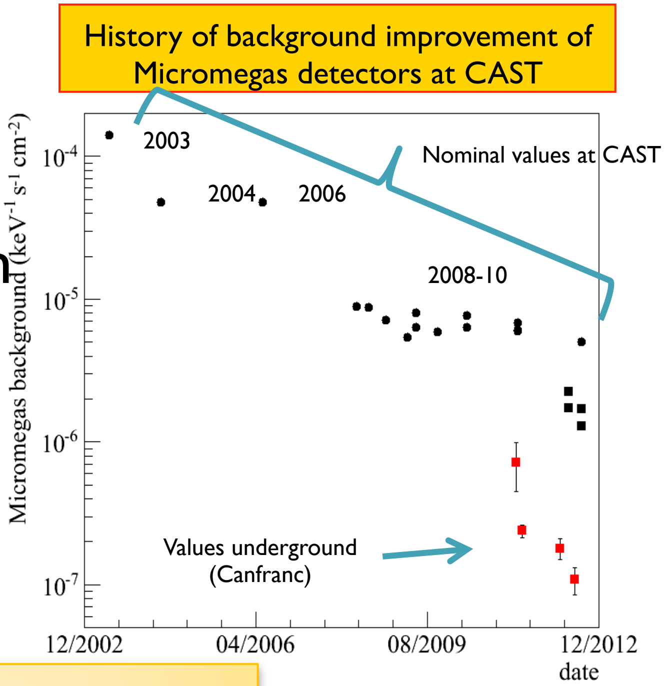
~No CR

Directionality is encoded in the ratio of recombination to ionization

Radiopurity studies for gas amplification devices

- Microbulk MM being used and improved within CAST (axion search)
  - Improvements in background level: latest achieved ~10^{-6} c/keV/cm^2/s (record in this application)
  - Due to shielding, radiopurity and offline discrimination.
- Further improvements under study in view of the future IAXO (CAST follow up)
  - Order of mag. better, ~10^{-7} c/keV/cm^2/s, already achieved in dedicated test bench underground (Canfranc).





Courtesy Igor Irastorza

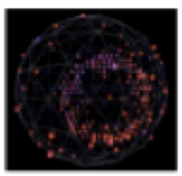
See details in Astropart. Phys. (2011) 34, 354

2007 – Boulby, England
2009 – MIT, Boston, USA
2011 – Aussois, France
2013 – Toyama, Japan

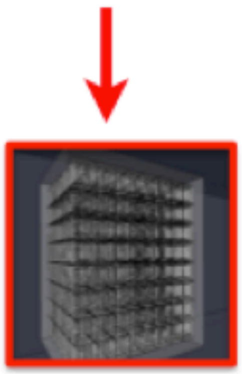
http://ppwww.phys.sci.kobe-u.ac.jp/~newage/cygnus2013/

How big is a 1 tonne directional detector?

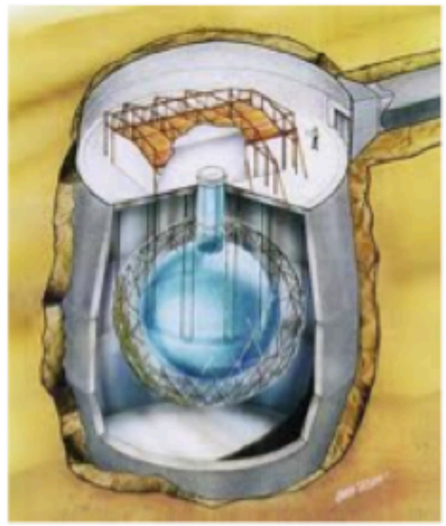
14 m x 14 m x 14 m
directional dark matter
detector



Mini-
BooNE



MINOS



SNO

Super-Kamiokande