Searching for low mass dark matter with DAMIC

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8th Patras Workshop on Axions, WIMPs, WISPs
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Results in Phys. Lett. B 711, 264-269 (2012)
arXiv:1105.5191 [astro-ph.IM]

Fermilab
Center for Particle Astrophysics

Naturalness of Dark Matter Mass scale

1. "Wimp miracle" scale :
   - Why do SUSY cross-sections provide correct relic DM density ?

     M_{DM} ~ 100 GeV

Naturalness of Dark Matter Mass scale

1. "Wimp miracle" scale :
   - Why do SUSY cross-sections provide correct relic DM density ?

     $M_{DM} \sim 100$ GeV

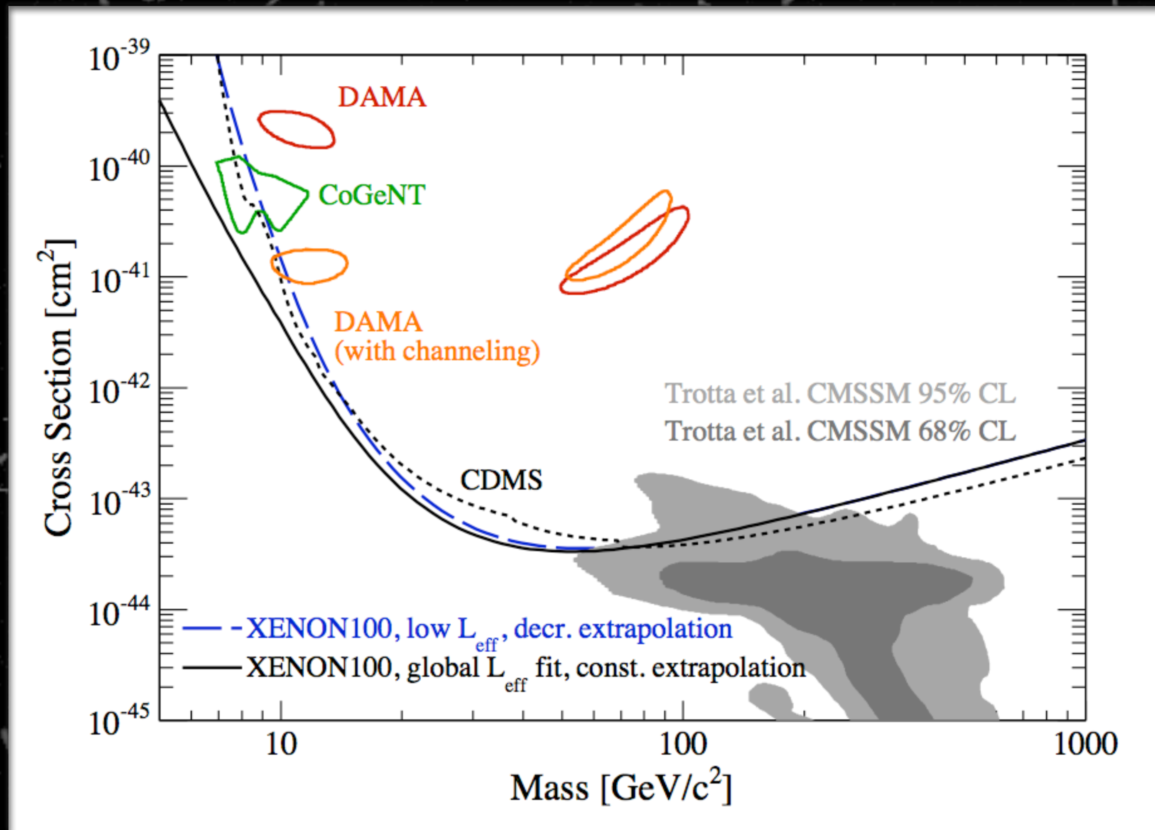
2. "Baryon-DM coincidence" scale :
   - Why is the DM abundance so close to matter ?

     $\rho_{DM} \sim 5 \cdot \rho_M$
   - What if dark matter is more baryon-like ?
   - Assume $N_{DM} \sim N_{baryon}$ in early universe

     $M_{DM} \sim 5$ GeV

Asymmetric DM hep-ph/1111.0293

Status of DM searches



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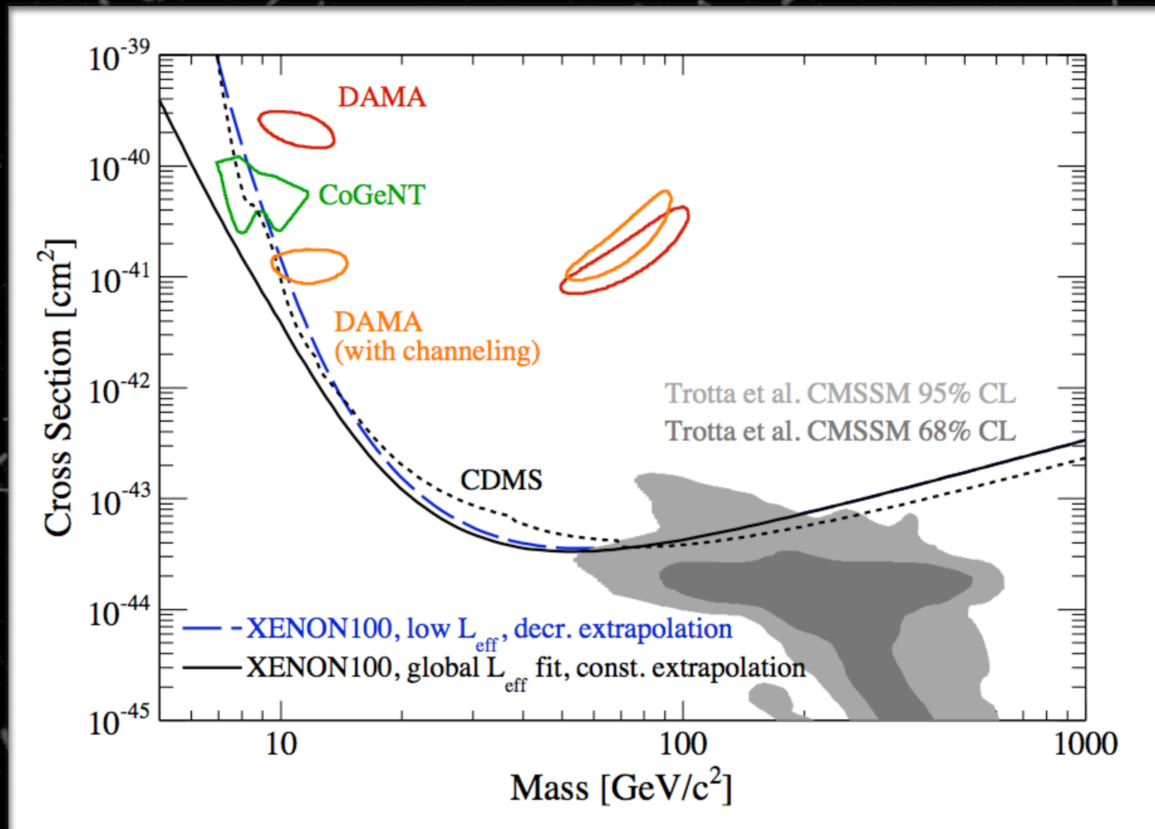
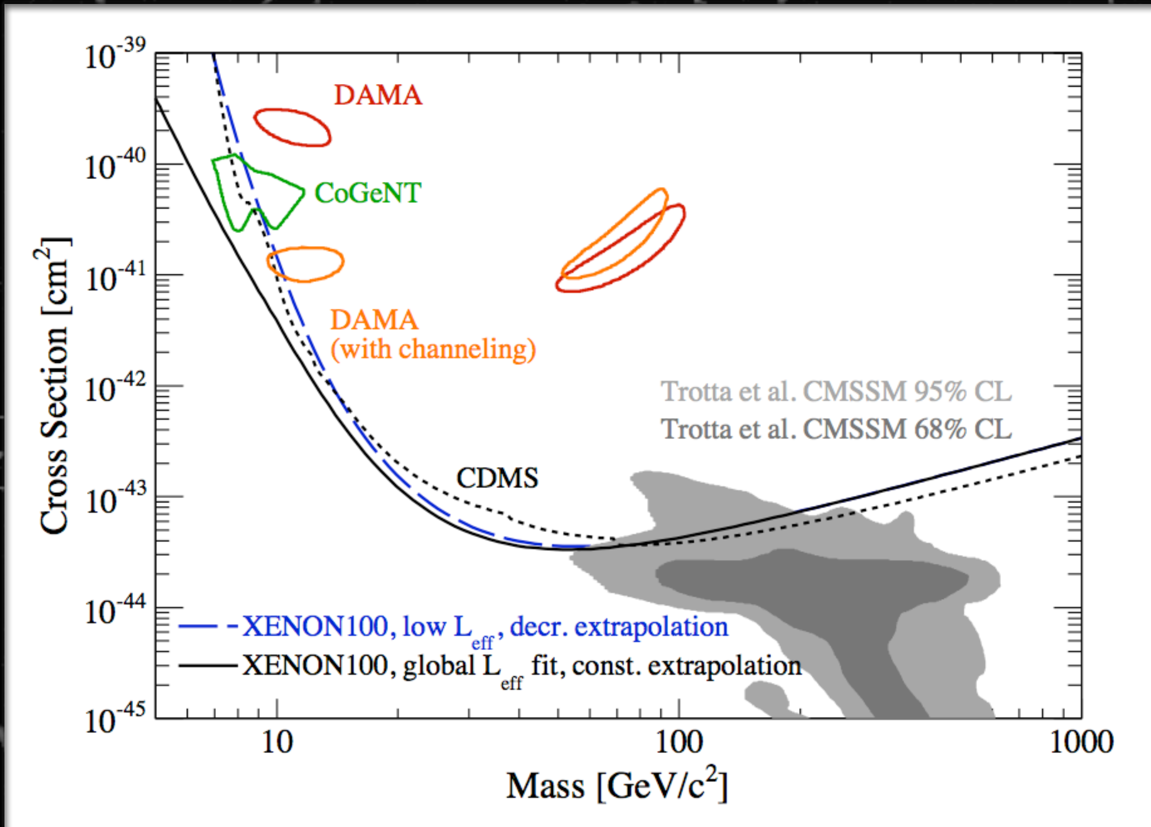


CMSSM prefers heavy WIMPs ~200 GeV
But ... increasingly ruled out by LHC

Status of DM searches

Hints of signal at lower masses



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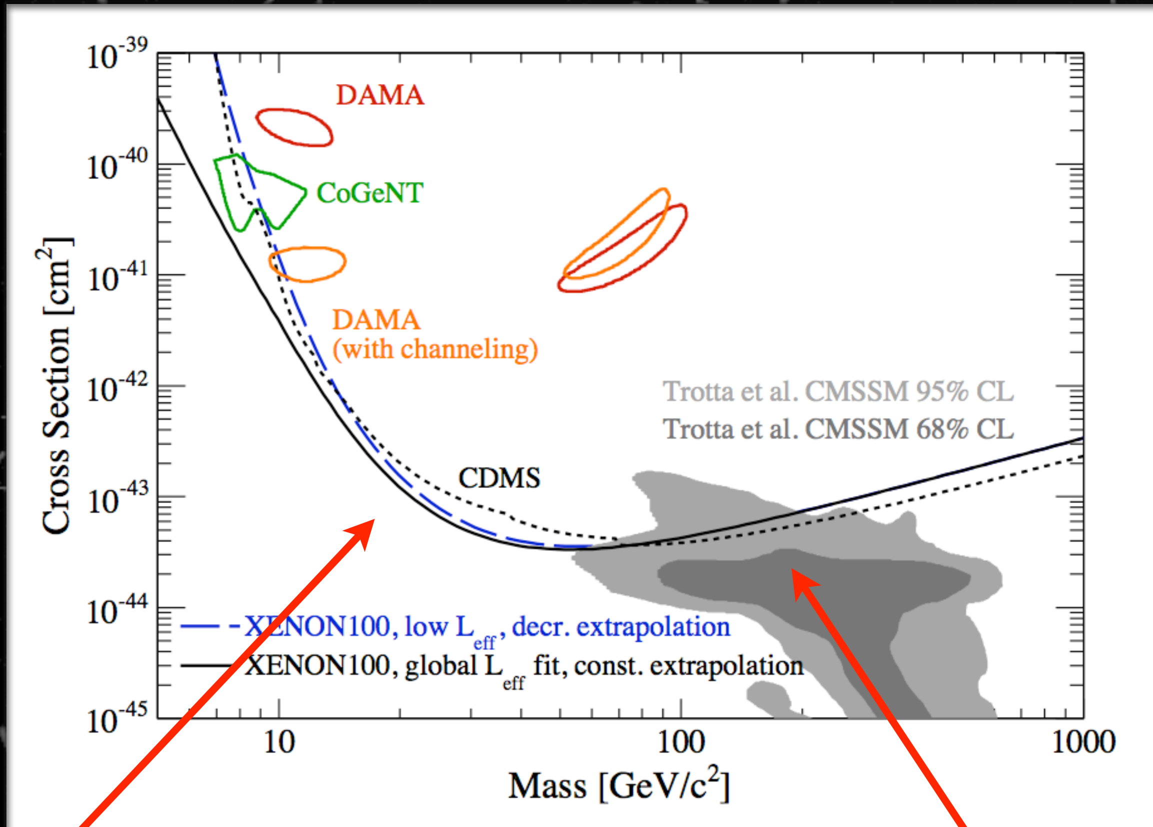


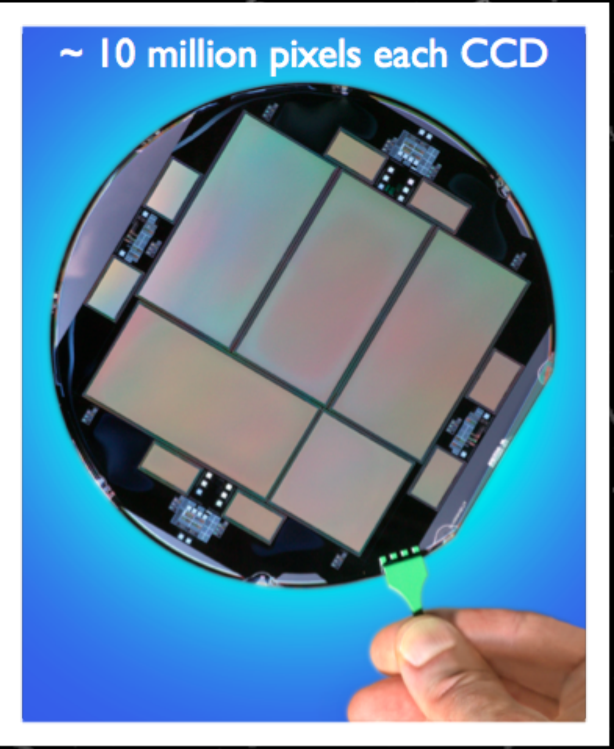
CMSSM prefers heavy WIMPs ~200 GeV
But ... increasingly ruled out by LHC

Limited by threshold, typically a few keV
(need lower energy detection)

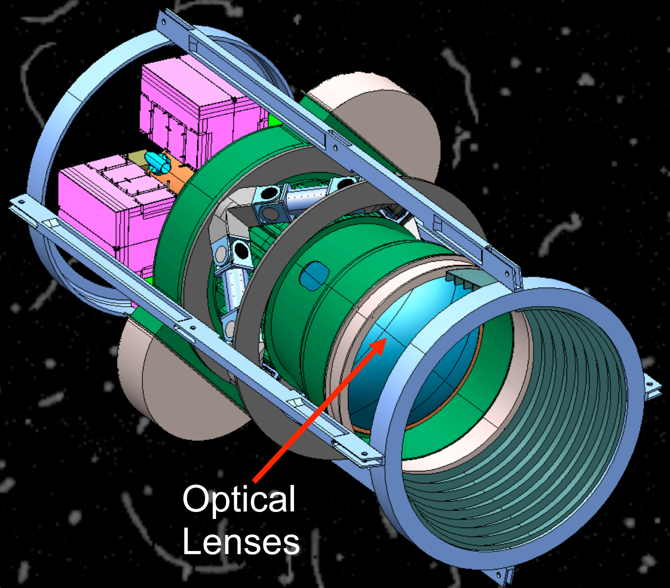
Limited by exposure mass
(need bigger detector)
multi-kg-sized detectors

DArk Matter In CCDs (DAMIC)

- Fermilab experiment - T987 DAMIC
- DM collides with nuclei in silicon pixel detectors of CCDs
- Goal is to extend sensitivity for low mass dark matter, $M_{DM} < 5$ GeV (< 1 GeV, < 100 MeV ?)
  - Focus on low noise, low threshold nuclear recoil detection



The Dark Energy Camera (DECam) for Dark Energy Survey (DES)



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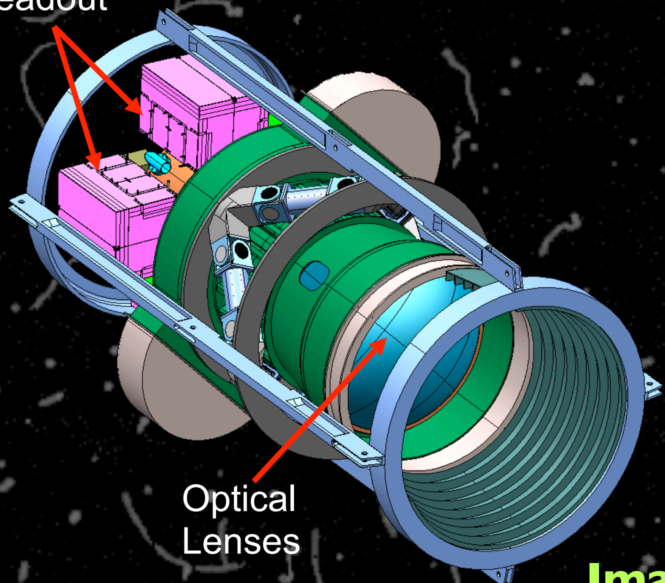
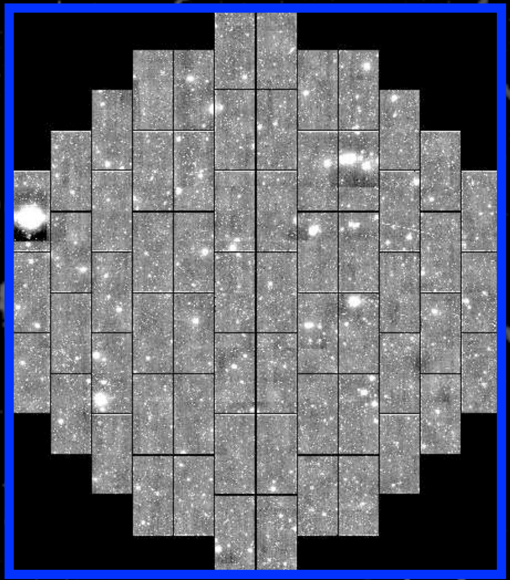
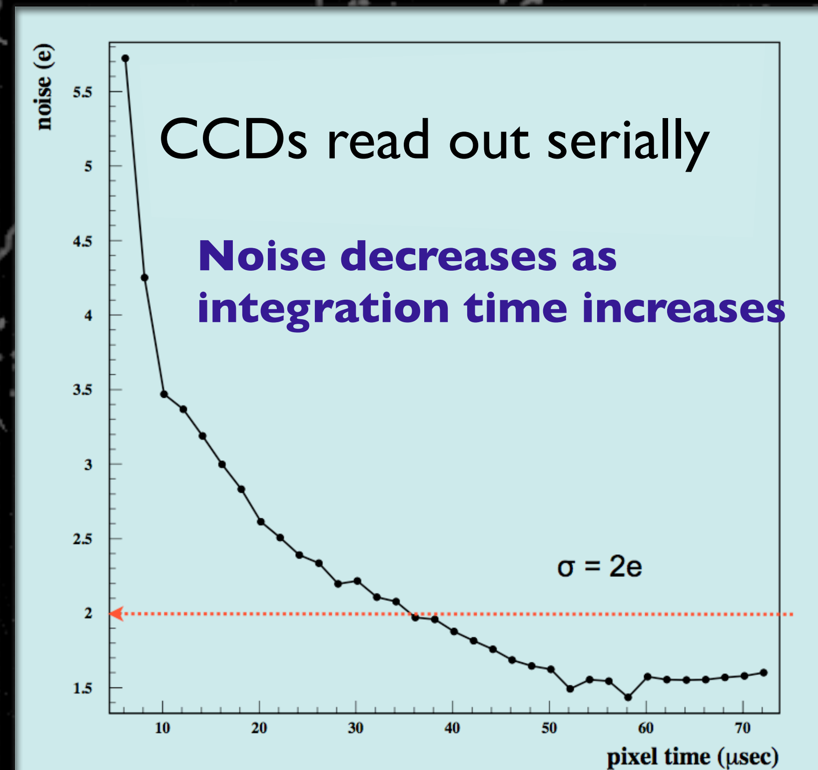


Images collected on ~60 CCDs ~600 Mpix Developed by LBNL



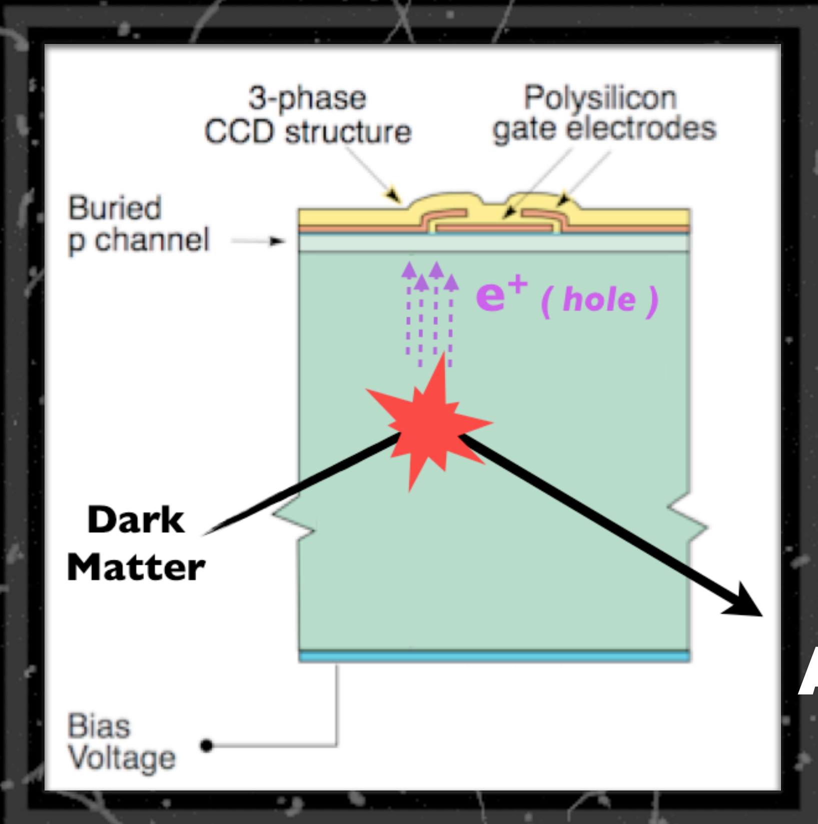
Energy threshold for DM search

- CCDs cooled to -150 C to reduce noise
- 50 µs / pixel
    - RMS of 2 e-
        - 7.2 eV equivalent ionizing in Silicon
  - Threshold of 40 eVee
    - Lowest of current DM experiments
- We are pushing energy threshold even further
  - See G. Cancelo's talk before this



Experiment	Threshold
DAMIC	0.04 eV_{ee}
COGENT	0.5 keV_{ee}
CDMS II	3 keV_{ee}
Xenon 100	8.4 keV_{nr}

DECam CCDs for DM



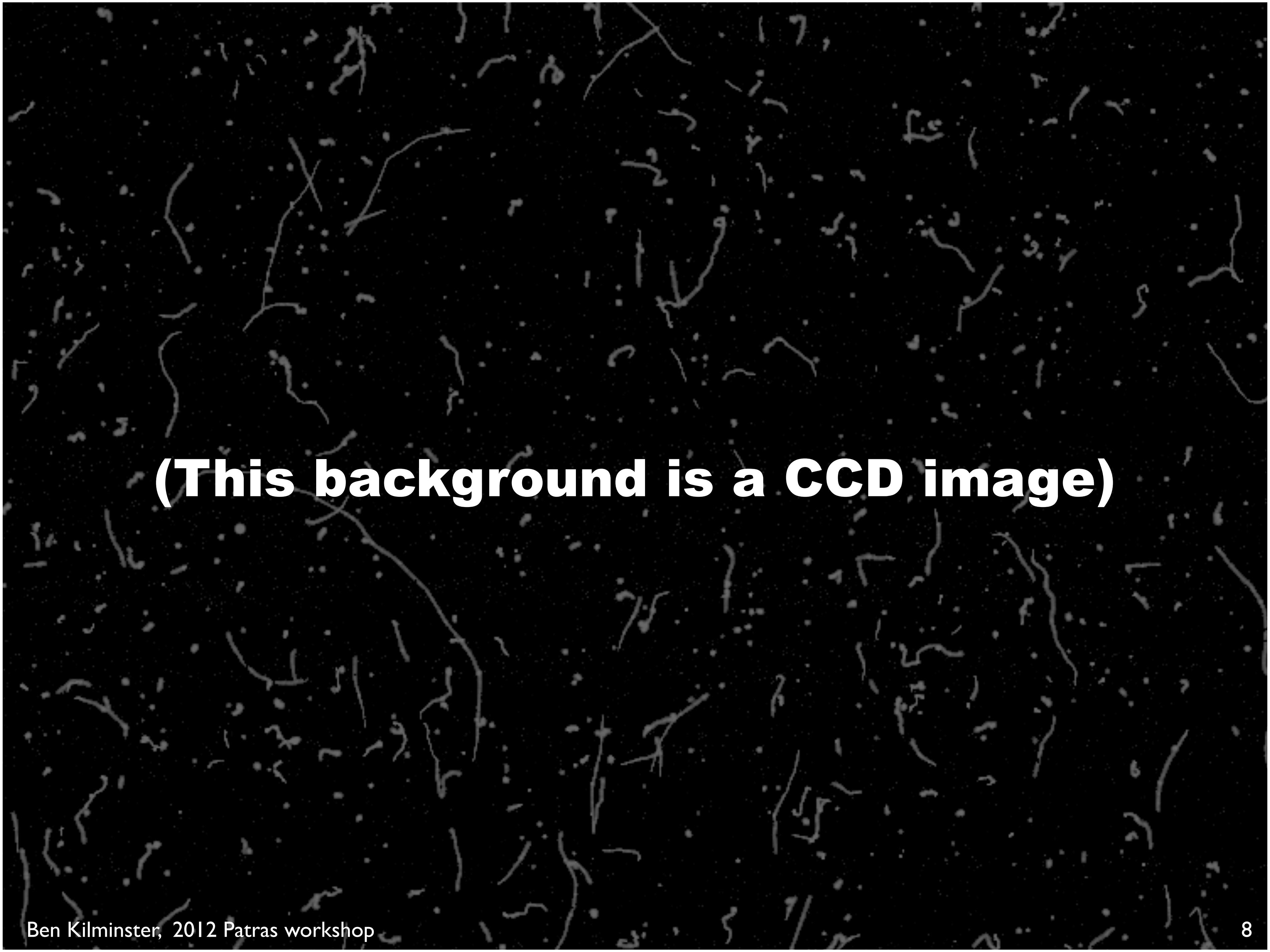
Instead of exposing CCD to light on its back surface, we shield it, and look for nuclear recoils in silicon volume

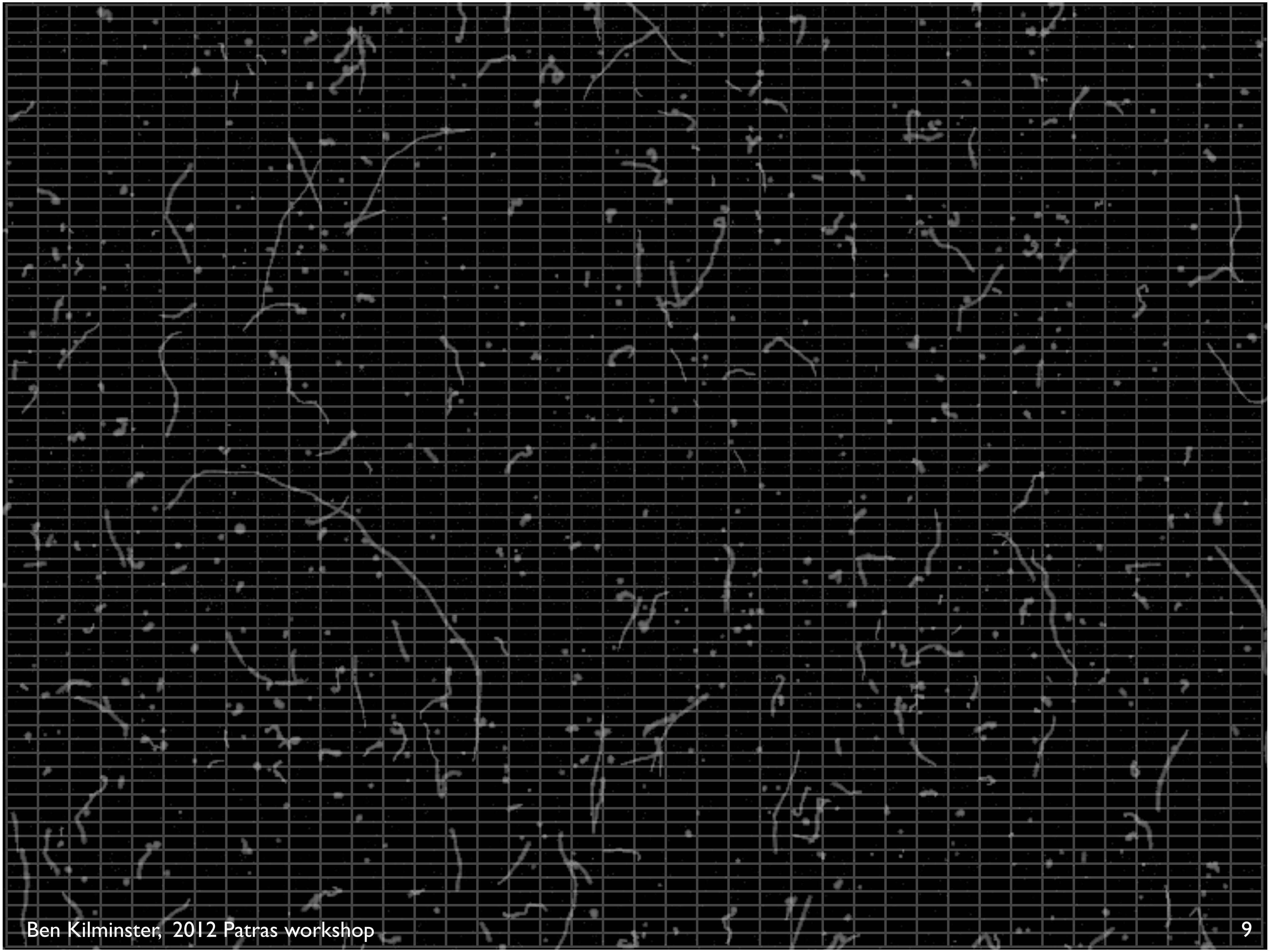
Advantages of DECam CCDs

10x thicker than most CCDs (250 μm)

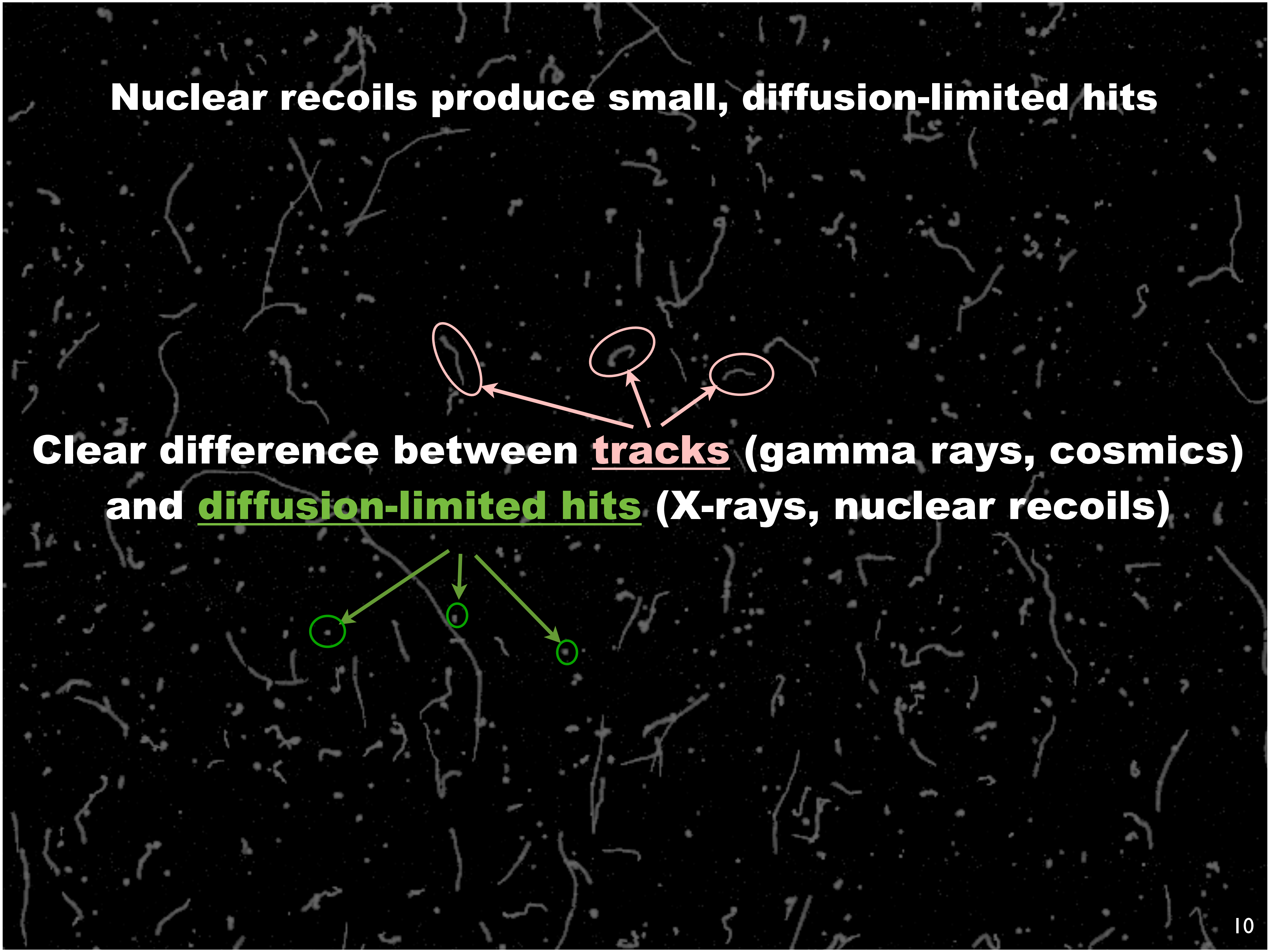
- **Relatively massive ~ 1g / CCD**

- **High resistivity silicon, allows high bias voltage**
  - ➡ **Limits diffusion**


(This background is a CCD image)



Nuclear recoils produce small, diffusion-limited hits

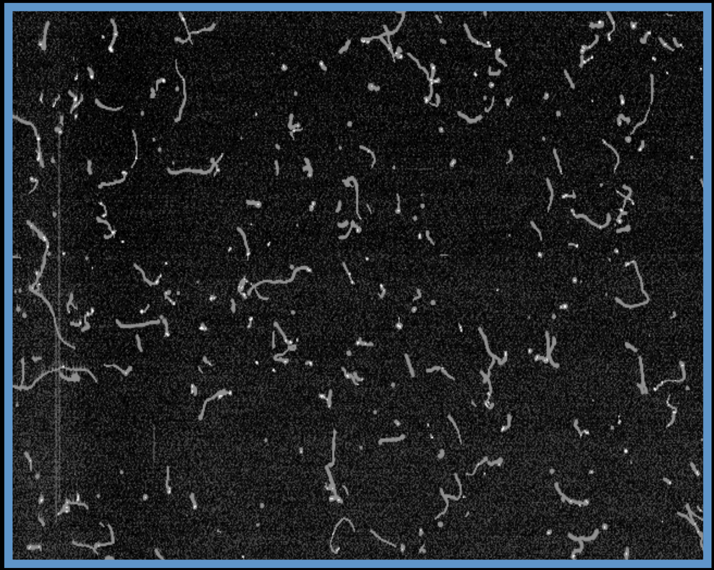


Clear difference between tracks (gamma rays, cosmics) and diffusion-limited hits (X-rays, nuclear recoils)

X-ray ^{55}Fe (5.9 keV)

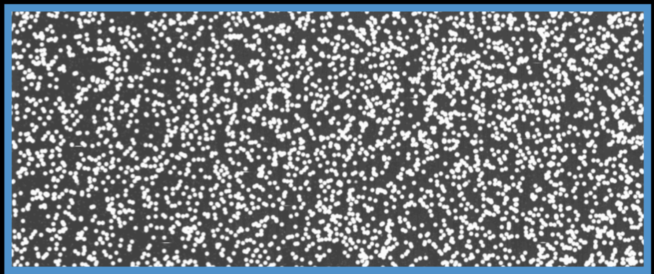
Point like hits (diffusion limited)

Gammas ^{60}Co (1.33 & 1.77 MeV)



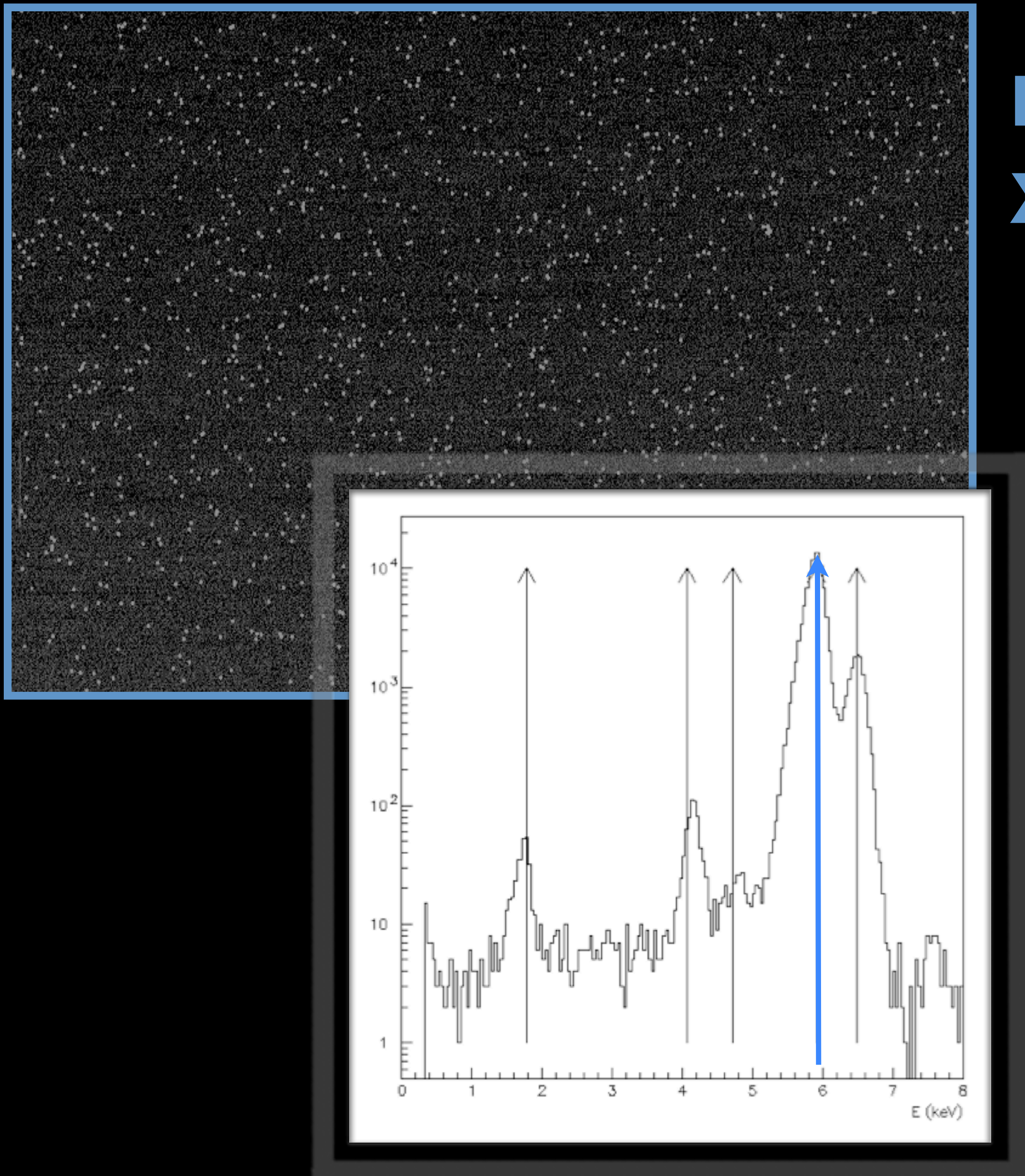
Compton electrons (worms) and point like hits.

Alphas



plasma effect creates large hits

Calibration - X-rays



Expose CCD to X-ray ^{55}Fe

5.9 KeV X-ray line yields 1620 e^-

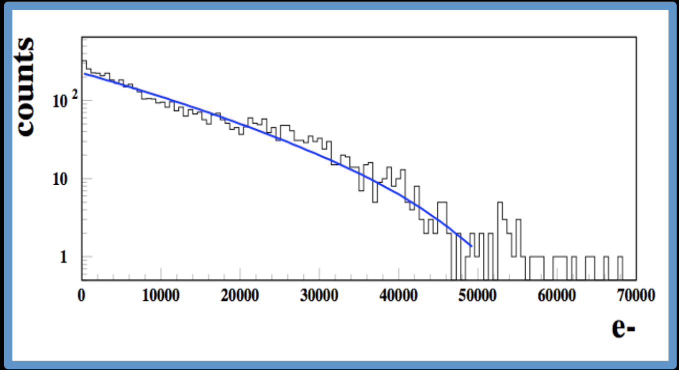
So : 3.64 eV / e^- converts charge to ionization energy

We can select diffusion-limited hits from tracks with 99.9% efficiency

“Calibration” of quenching factor with Neutrons

Q = signal from X-rays / signal from neutrons

What we measure with CCDs



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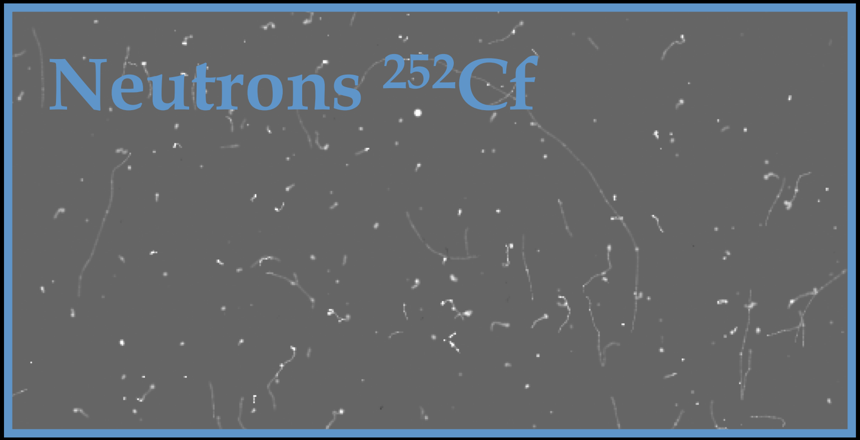
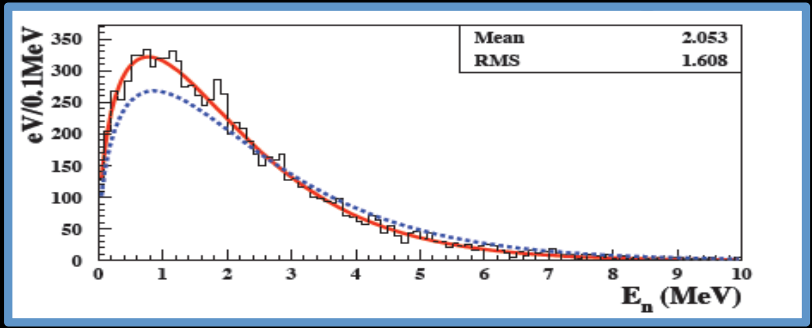


Neutron energy spectrum
with GEANT-simulated detector effects



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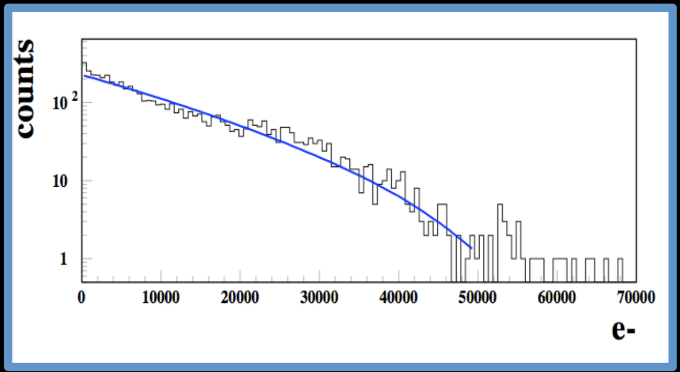

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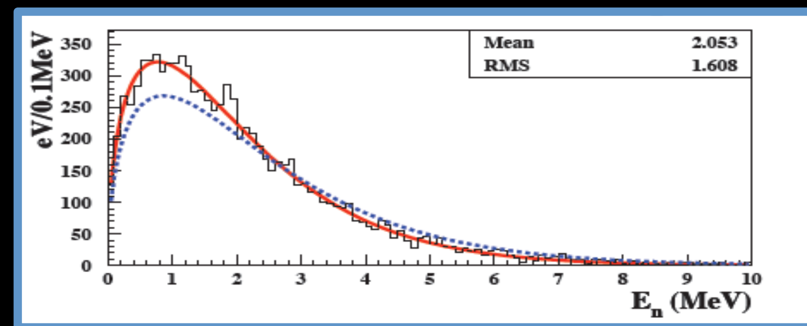

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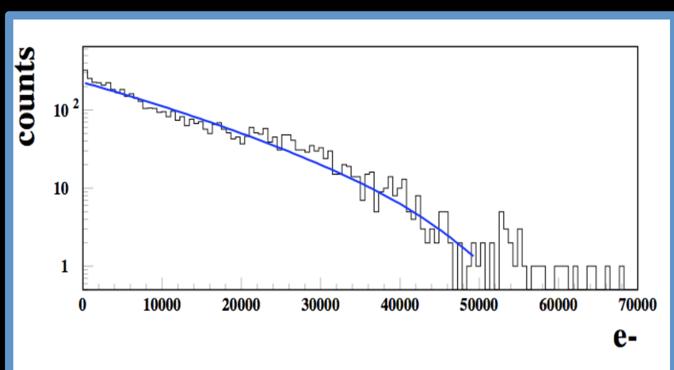
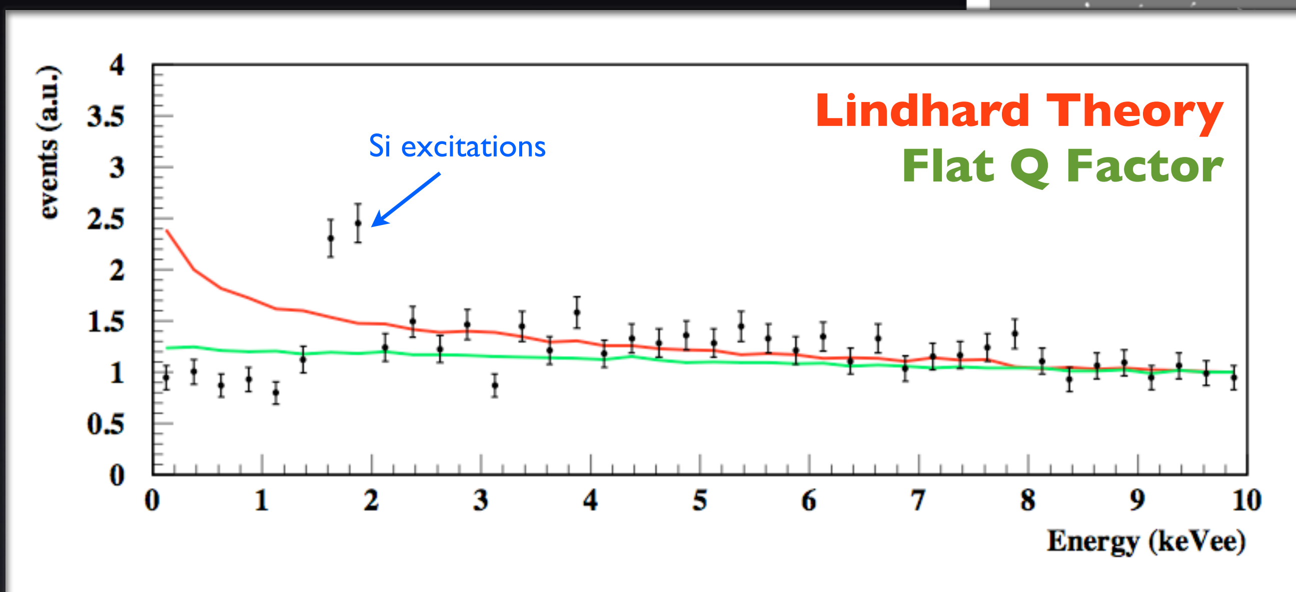


Can’t fit energy dependence since neutrons have energy distribution

Unfold these distributions to determine ionization yield from nuclear recoils of 13.9 ev/e$^-$

Quenching Factor

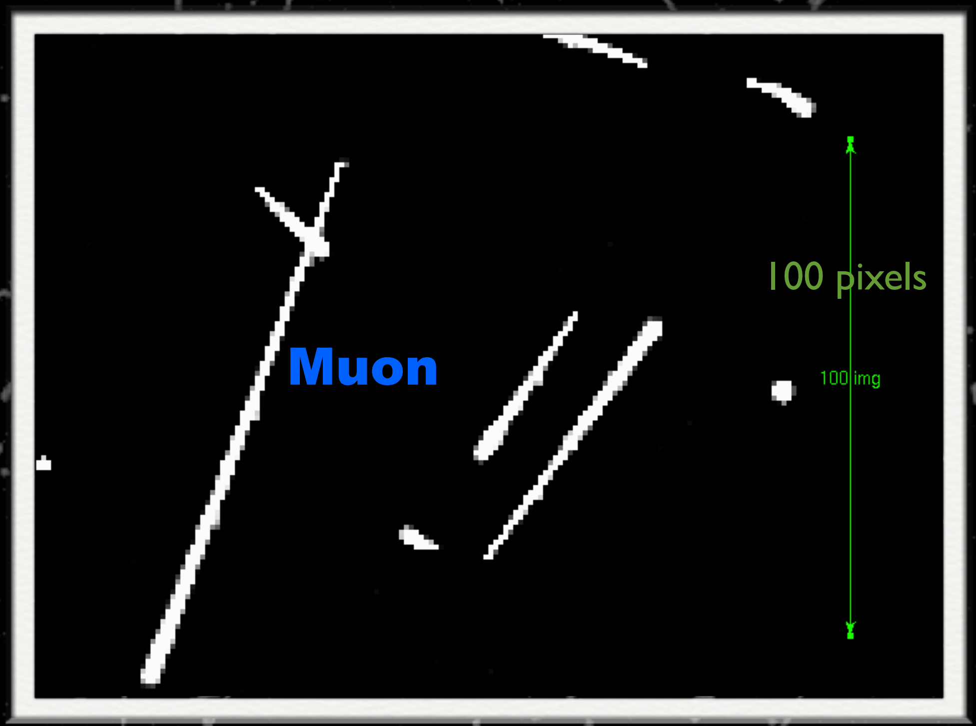
- Comparison to Lindhard theory assuming constant detection efficiency
-



Lindhard used to produce more conservative limits
-
we are following up with a dedicated low energy neutron calibration this year

Nuclear recoil selection

- **Diffusion varies as a function of depth**

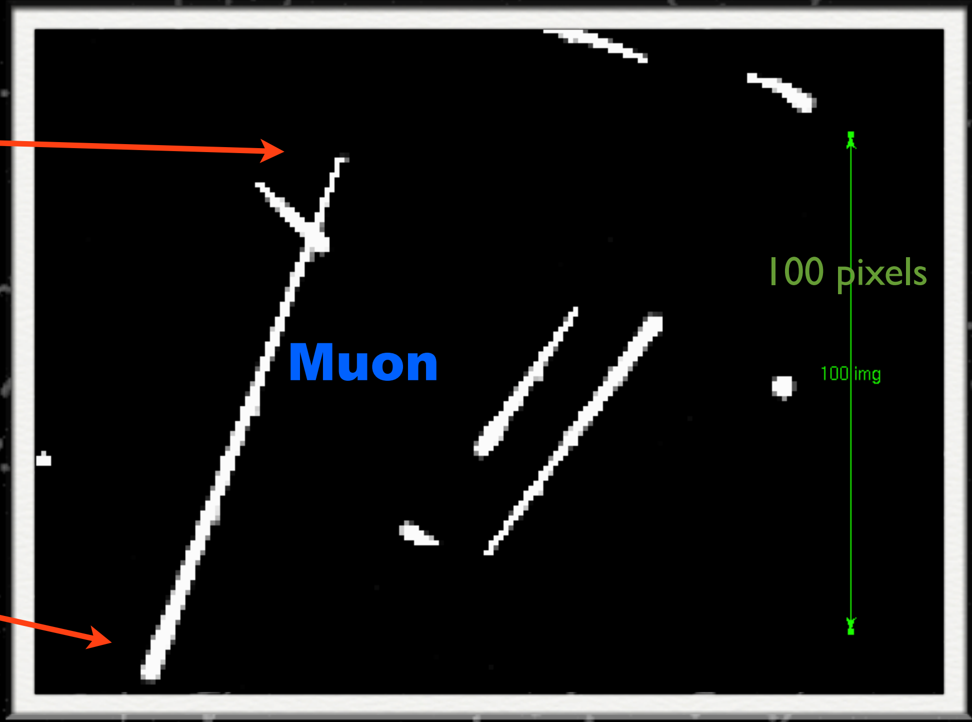


Nuclear recoil selection

- **Diffusion varies as a function of depth**

Narrower end - front of CCD - minimal diffusion

Thicker end - back of CCD - maximal diffusion



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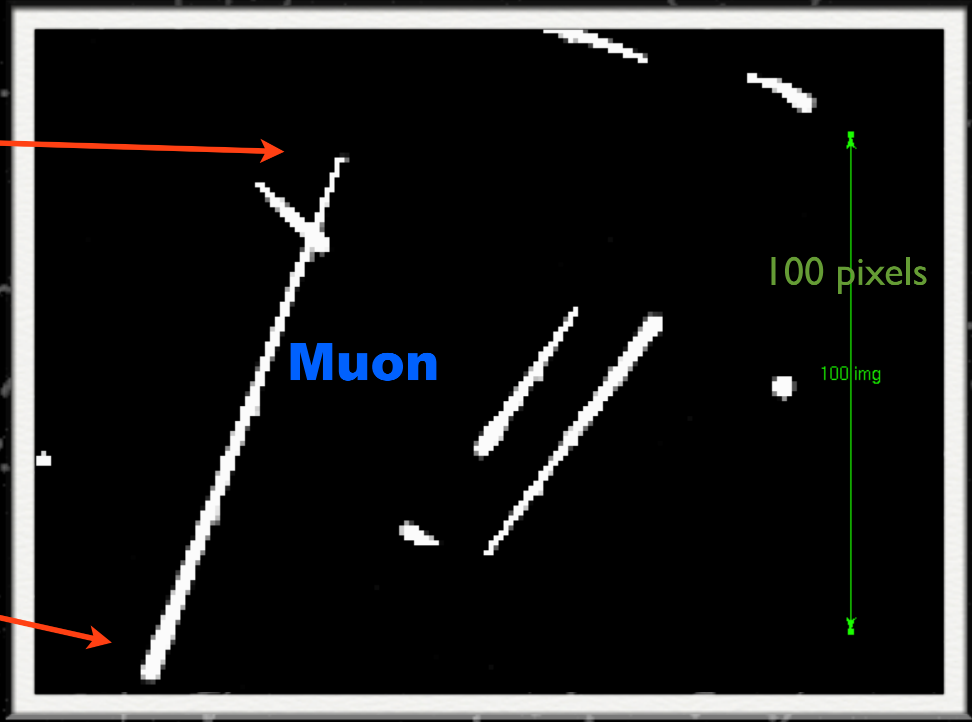


- **Can apply fiducial cuts based on hit size to select recoils consistent with bulk**

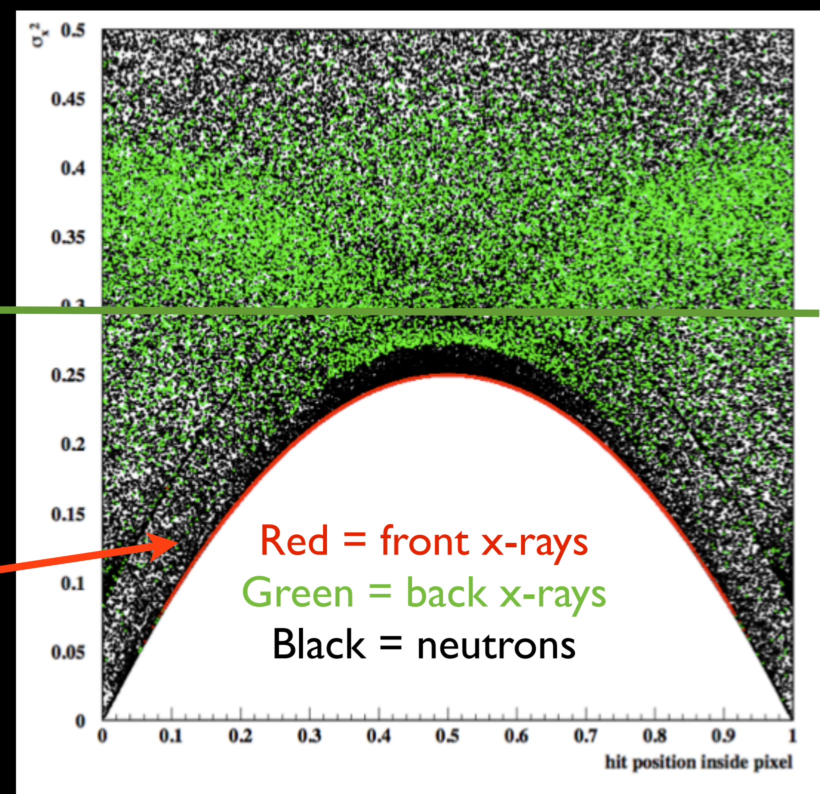
Selection

- **Energy threshold 0.04 keVee to suppress readout noise**
- **Fiducial cuts based on RMS of hits to suppress X-rays**

σ^2_x

Flat cut to reject large diffusion hits

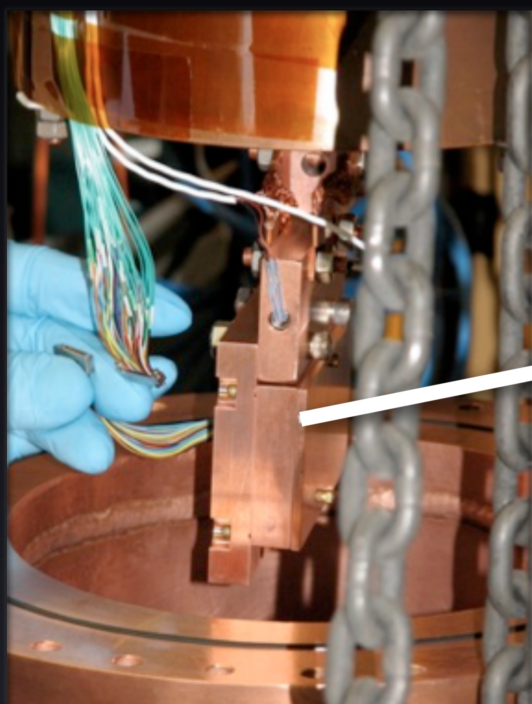
Parabolic cut to reject small diffusion hits based on RMS as a function of hit position



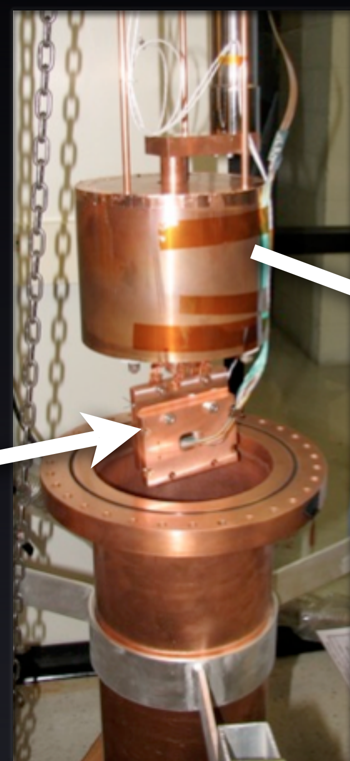
$\hat{x}$

DAMIC

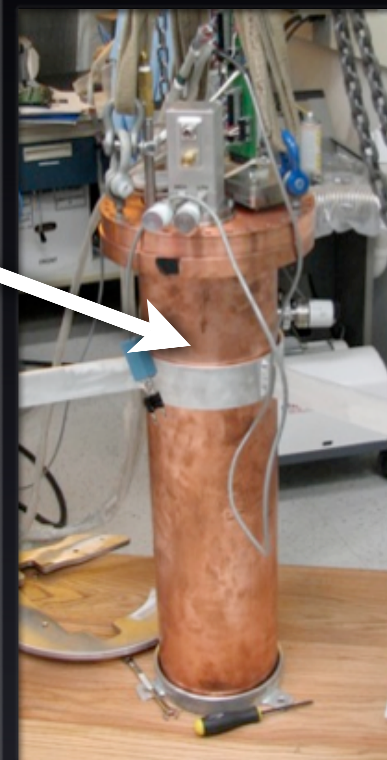
CCD Inside a cold Cu box



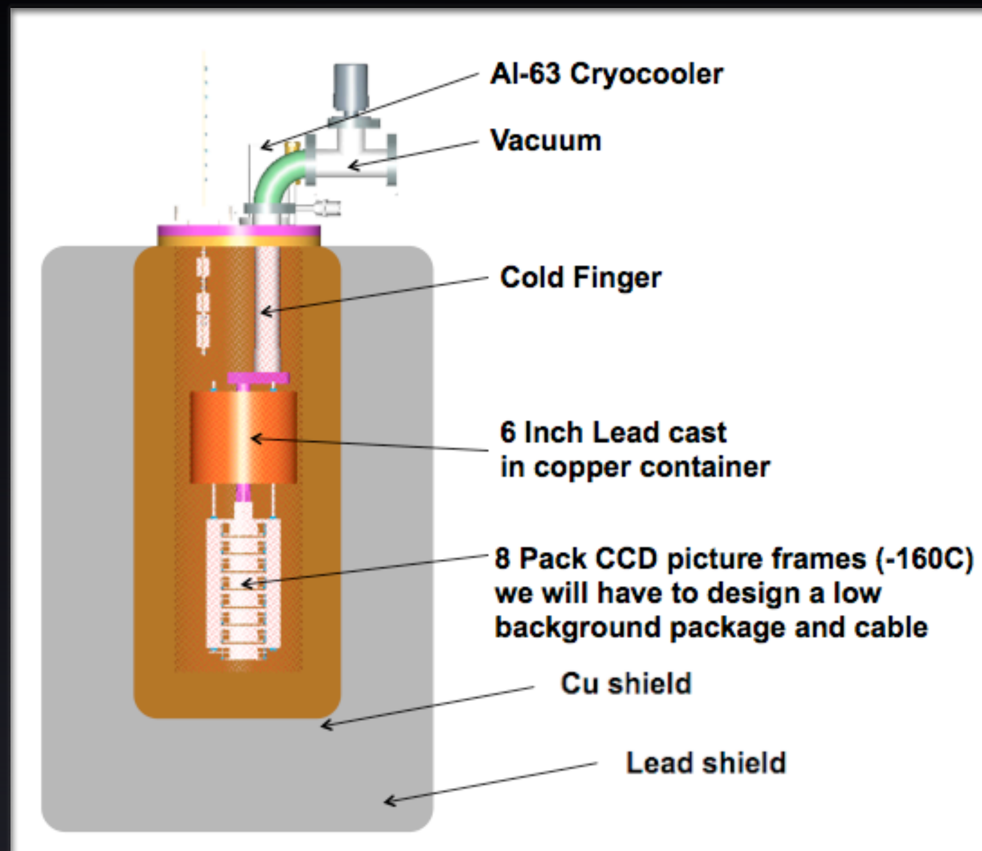
Lead Bucket



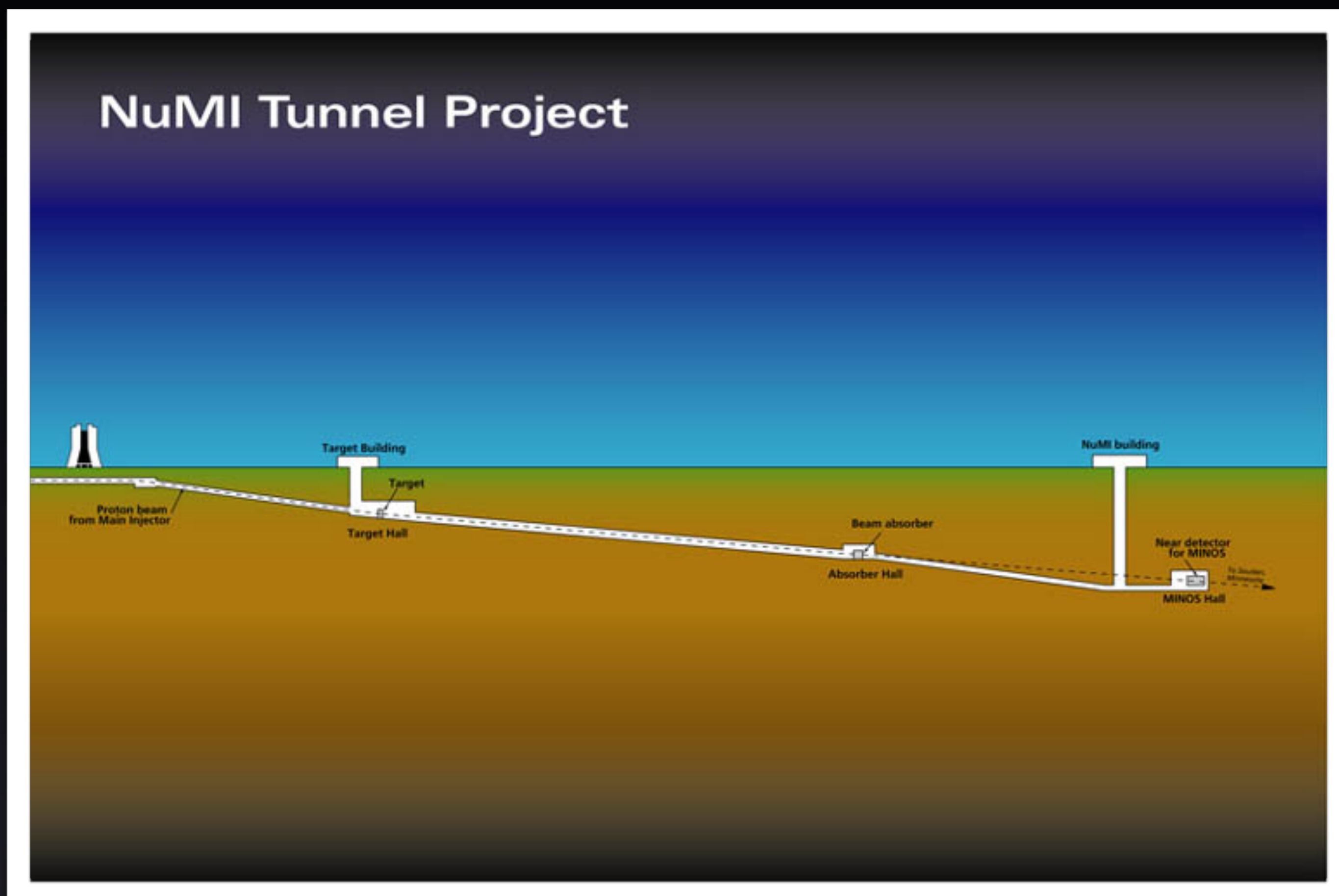
Cylindrical Cu Dewar



DAMIC

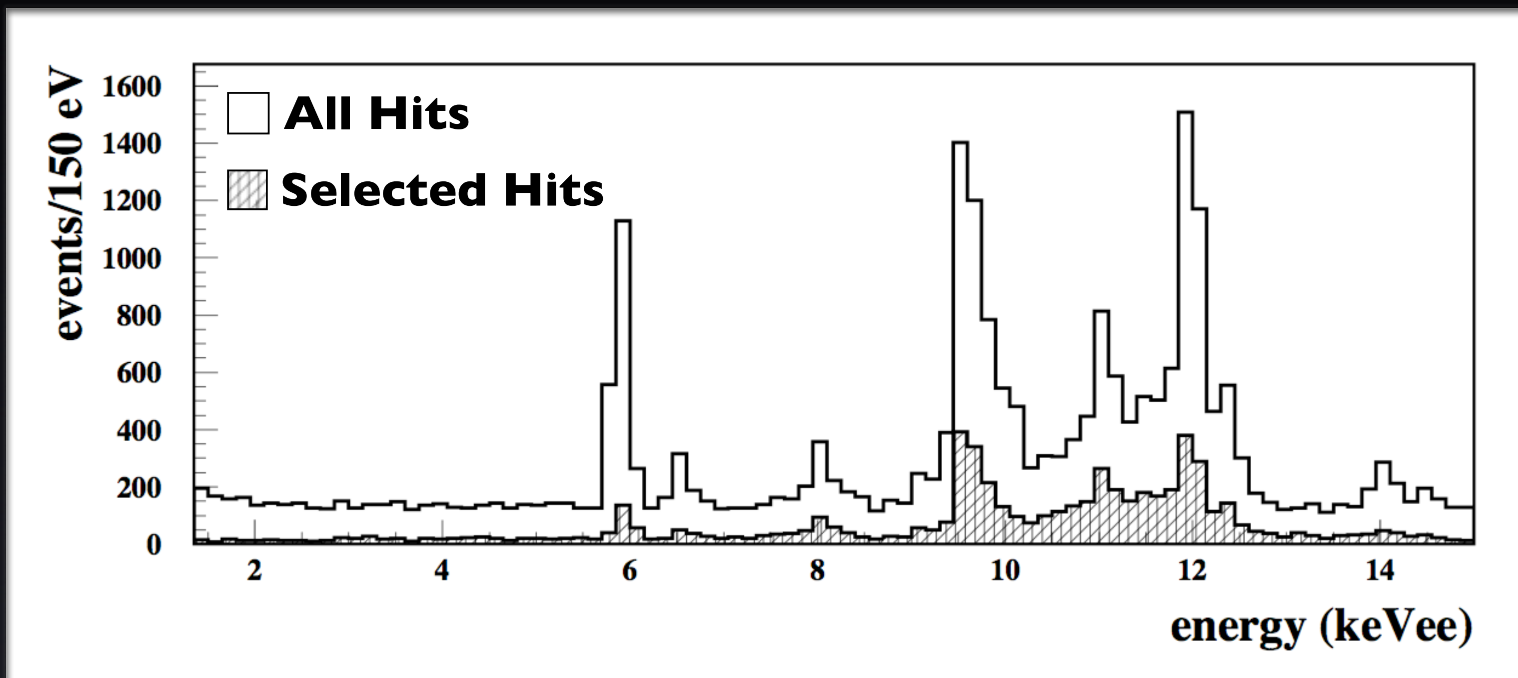

Al-63 Cryocooler
Vacuum
Cold Finger
6 Inch Lead cast
in copper container
8 Pack CCD picture frames (-160C)
we will have to design a low
background package and cable
Cu shield
Lead shield

DAMIC

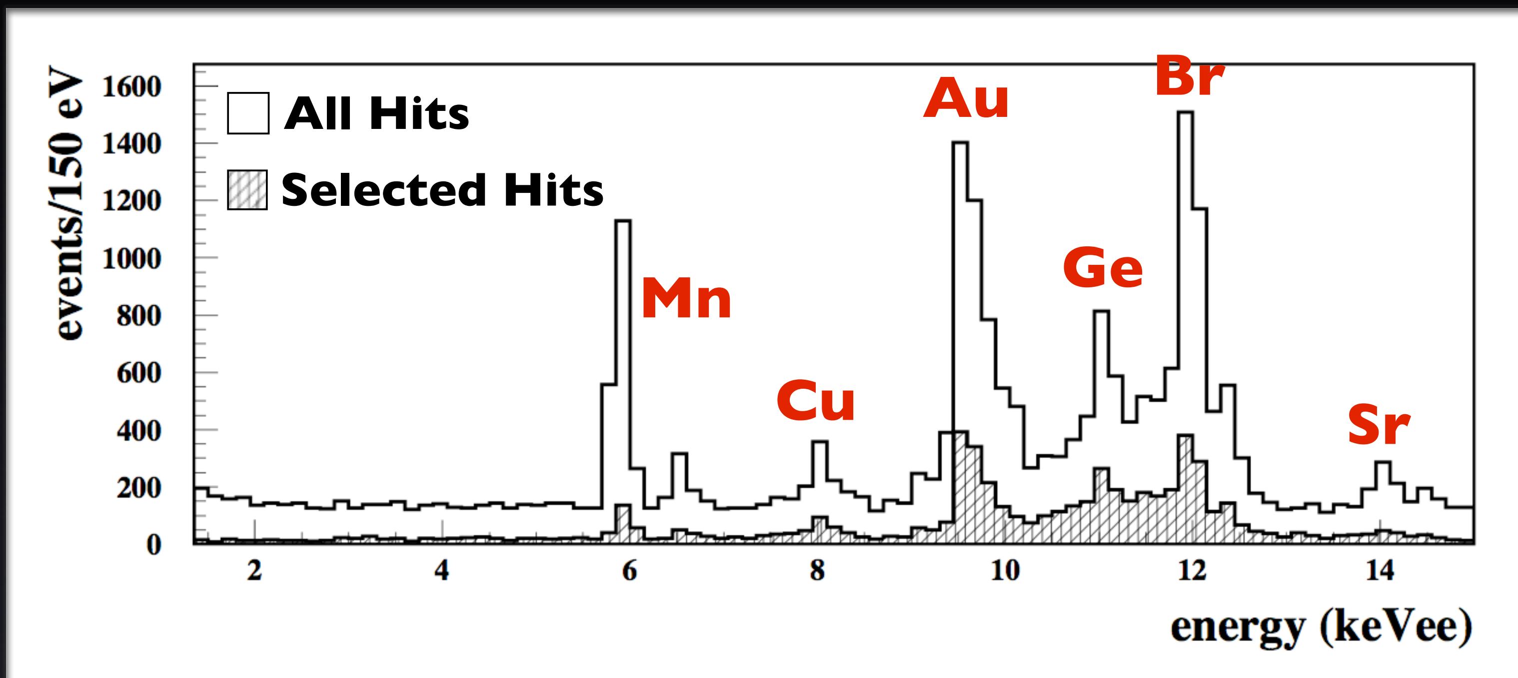

NuMI Tunnel Project
Target Building
Target
Proton beam
from Main Injector
Target Hall
Beam absorber
Absorber Hall
NuMI building
Near detector
for MINOS
MINOS Hall

DAMIC

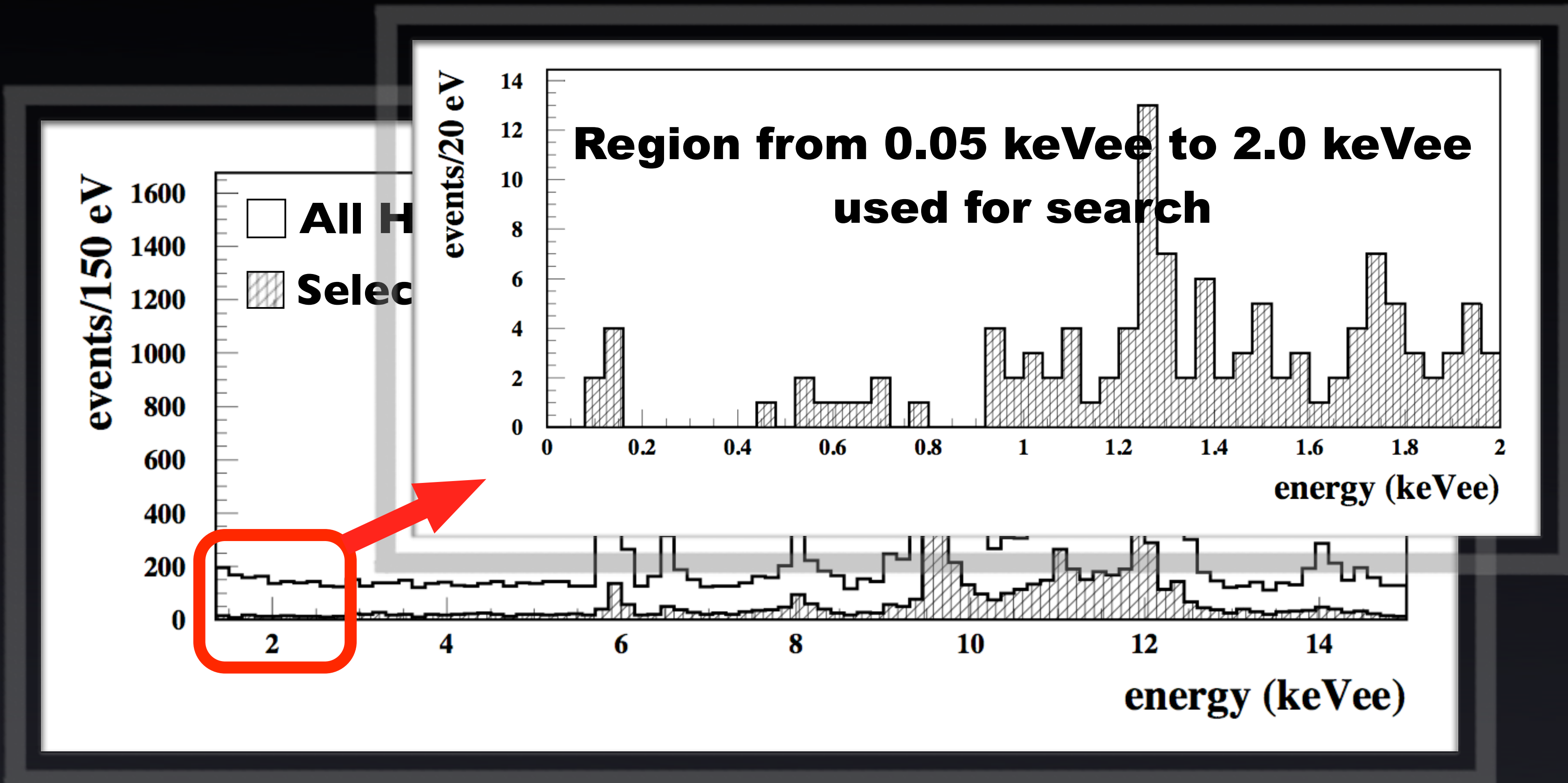
Energy Spectrum



X-Ray Contamination



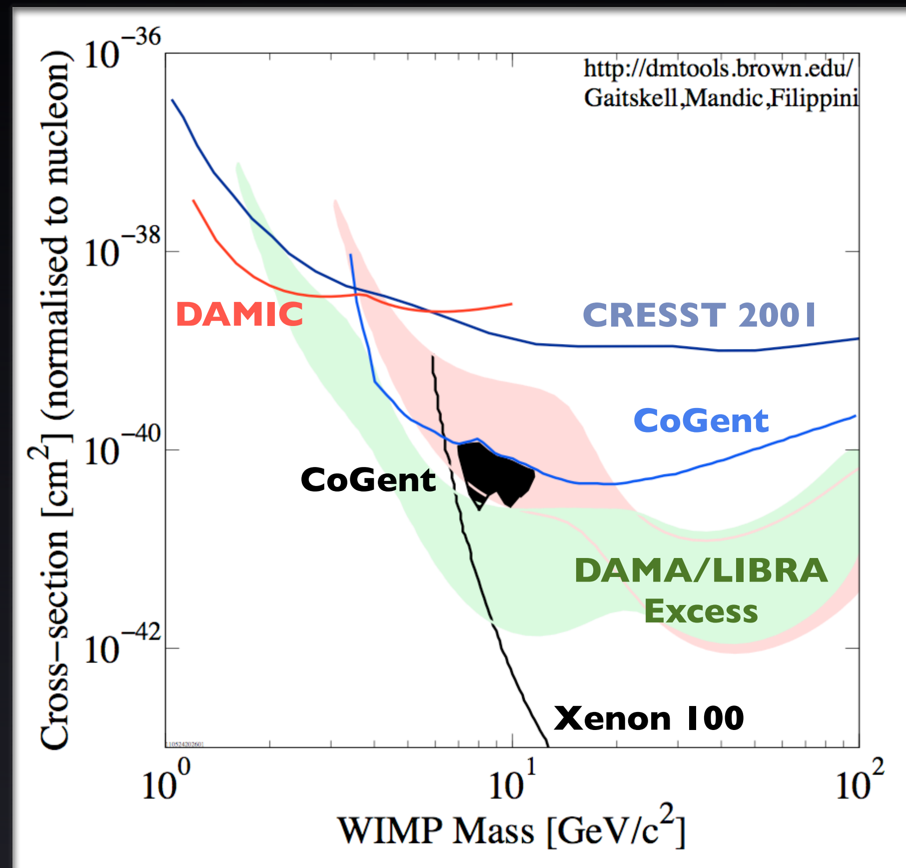
Energy Spectrum



Results from First Run

- **Wimp density → 0.3 GeV/cm**
- **V_{earth} = 244 km/s**
- **V_{escape} = 650 km/s**

Assumes Lindhard quenching factor for conservative limits



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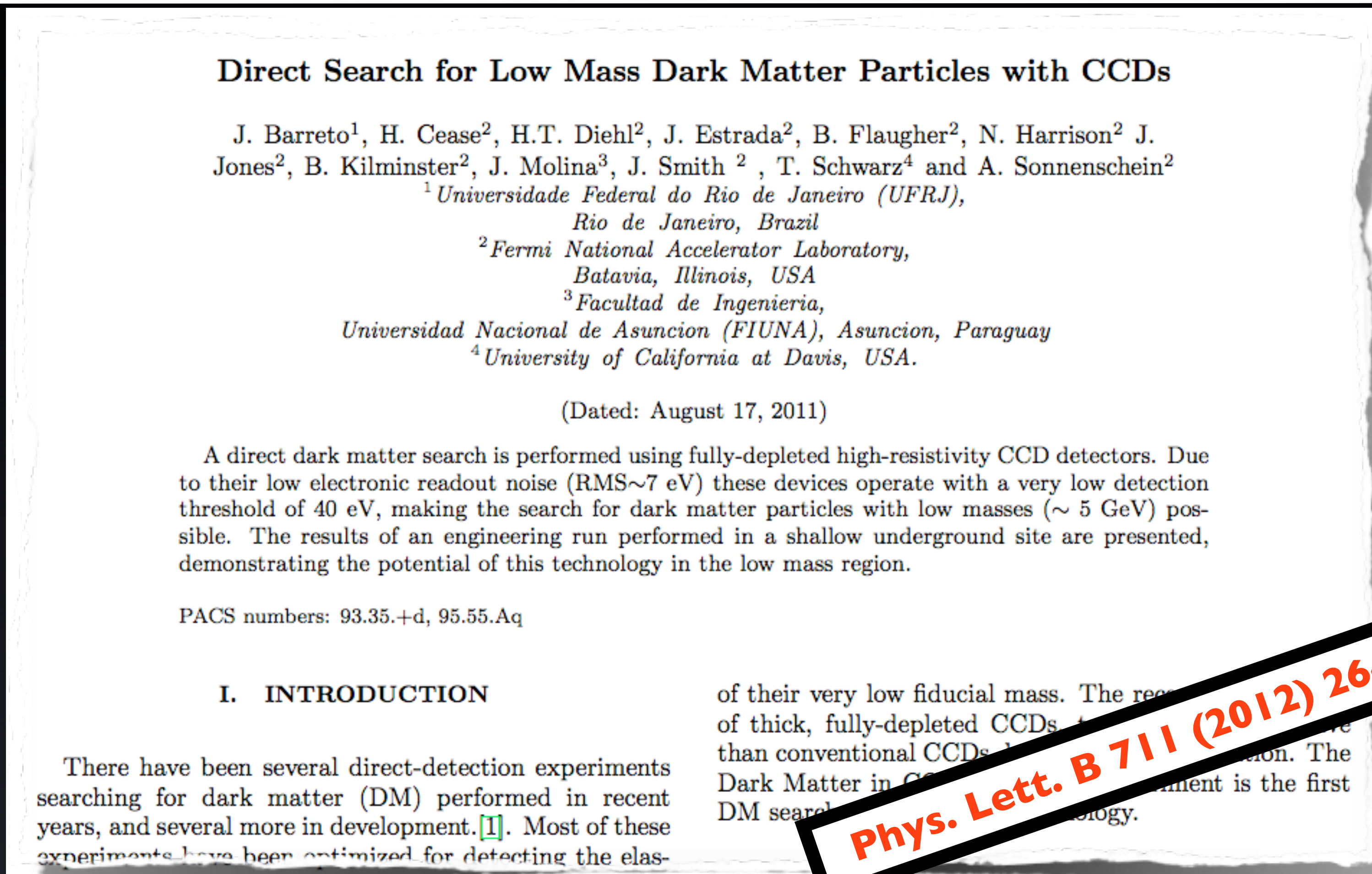


Direct Search for Low Mass Dark Matter Particles with CCDs

J. Barreto[1], H. Cease[2], H.T. Diehl[2], J. Estrada[2], B. Flaugher[2], N. Harrison[2] J. Jones[2], B. Kilminster[2], J. Molina[3], J. Smith [2] , T. Schwarz[4] and A. Sonnenschein[2]

[1] *Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*

[2] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*

[3] *Facultad de Ingenieria, Universidad Nacional de Asuncion (FIUNA), Asuncion, Paraguay*

[4] *University of California at Davis, USA.*

(Dated: August 17, 2011)

A direct dark matter search is performed using fully-depleted high-resistivity CCD detectors. Due to their low electronic readout noise (RMS∼7 eV) these devices operate with a very low detection threshold of 40 eV, making the search for dark matter particles with low masses (∼ 5 GeV) possible. The results of an engineering run performed in a shallow underground site are presented, demonstrating the potential of this technology in the low mass region.

PACS numbers: 93.35.+d, 95.55.Aq

I. INTRODUCTION

There have been several direct-detection experiments searching for dark matter (DM) performed in recent years, and several more in development.[1]. Most of these experiments have been optimized for detecting the elas-

of their very low fiducial mass. The re of thick, fully-depleted CCDs, than conventional CCDs ion. The Dark Matter in C ment is the first DM sear ology.

Phys. Lett. B 711 (2012) 264-269

Ramping Up!

Adding Mass and Going Deeper

- **Adding 10x more mass by adding CCD's (8 CCD's/10g)**
- **Moving to SNOLAB within months (2km deep)**
- **1 year, 3.5 kg-day @ 40 eV threshold**

Ramping Up!

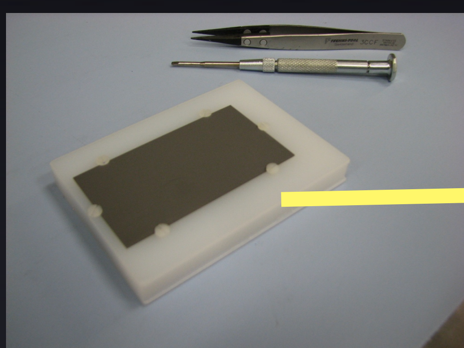
Better Shielding, Better Materials

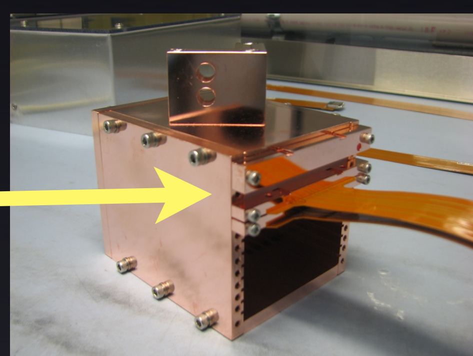
- **Re-using 6500 lbs of lead shielding**
- **Adding 9800 lbs of polyethylene shielding**
- **Removed connectors and colored cables with some unknown materials**

Ramping Up!

Better Background Predictions

- **In-situ measurement of neutron contamination**
- **Layer of Boron-10 on polyethylene**
- **Poly slows down neutrons - B10 produces alpha radiation (2 protons & 2 neutrons) from the interacting neutrons**
- **Alphas have a distinct signature in DAMIC CCD's**





Ramping Up!

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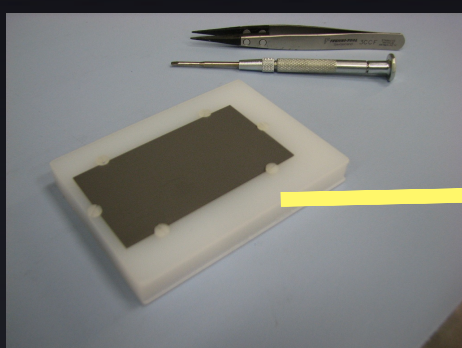
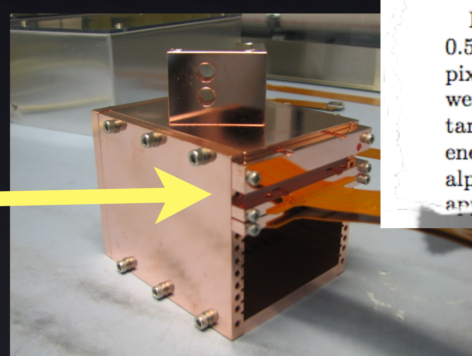
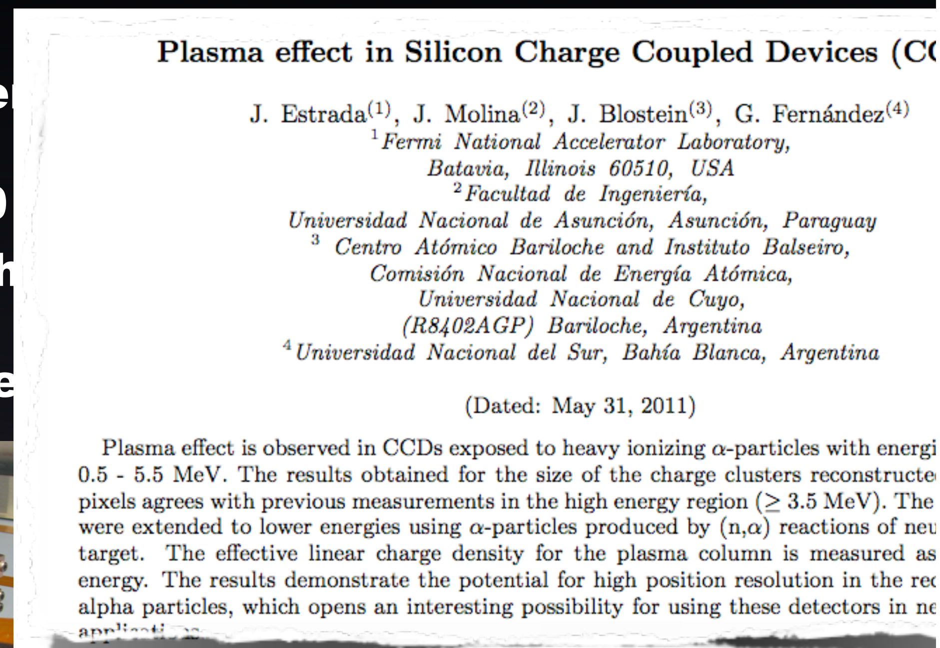


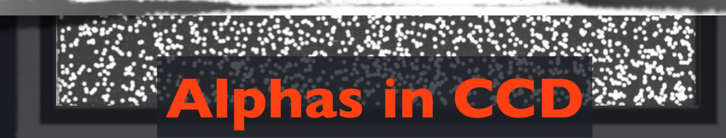



Plasma effect in Silicon Charge Coupled Devices (CC

J. Estrada[(1)], J. Molina[(2)], J. Blostein[(3)], G. Fernández[(4)]
[1] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[2] *Facultad de Ingeniería, Universidad Nacional de Asunción, Asunción, Paraguay*
[3] *Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica, Universidad Nacional de Cuyo, (R8402AGP) Bariloche, Argentina*
[4] *Universidad Nacional del Sur, Bahía Blanca, Argentina*

(Dated: May 31, 2011)

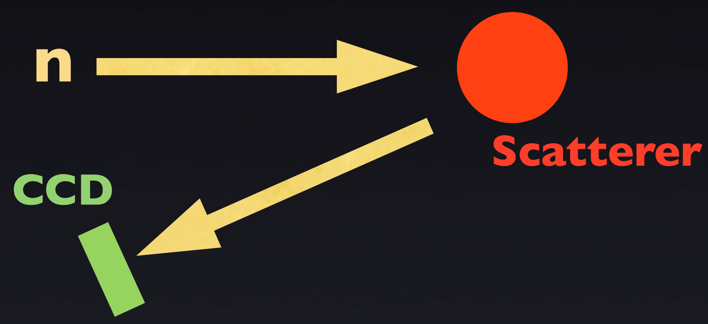
Plasma effect is observed in CCDs exposed to heavy ionizing α-particles with energi
0.5 - 5.5 MeV. The results obtained for the size of the charge clusters reconstructe
pixels agrees with previous measurements in the high energy region ($\geq$ 3.5 MeV). The
were extended to lower energies using α-particles produced by (n,α) reactions of neu
target. The effective linear charge density for the plasma column is measured as
energy. The results demonstrate the potential for high position resolution in the re
alpha particles, which opens an interesting possibility for using these detectors in ne

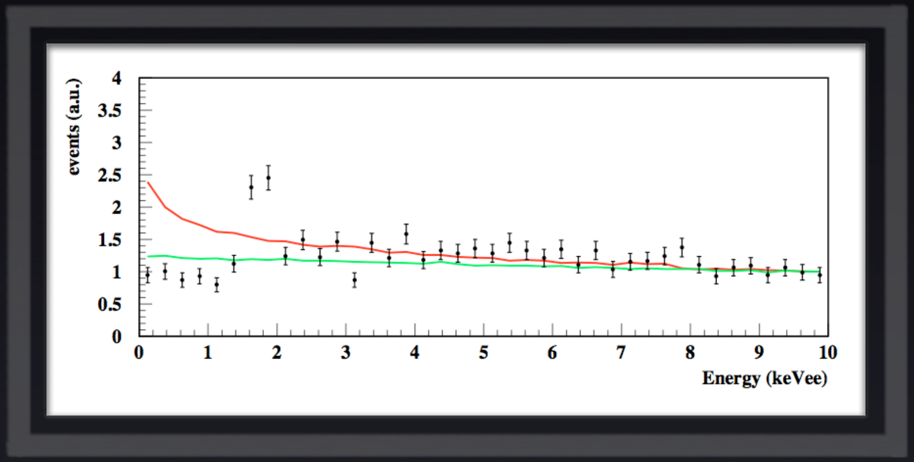


Ramping Up!

Calibrating to Lower Energy

- **Using a mono-energetic beam of neutrons to calibrate quenching factor to very low energies**



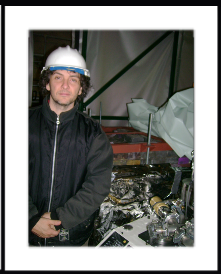


Ramping Up!

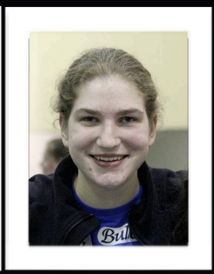
Adding People Mass

J.Estrada
FNAL
Project Lead

B.Kilminster
FNAL



J.Molina
UNA



K.Chinetti
IMSA

G.Cancelo
FNAL

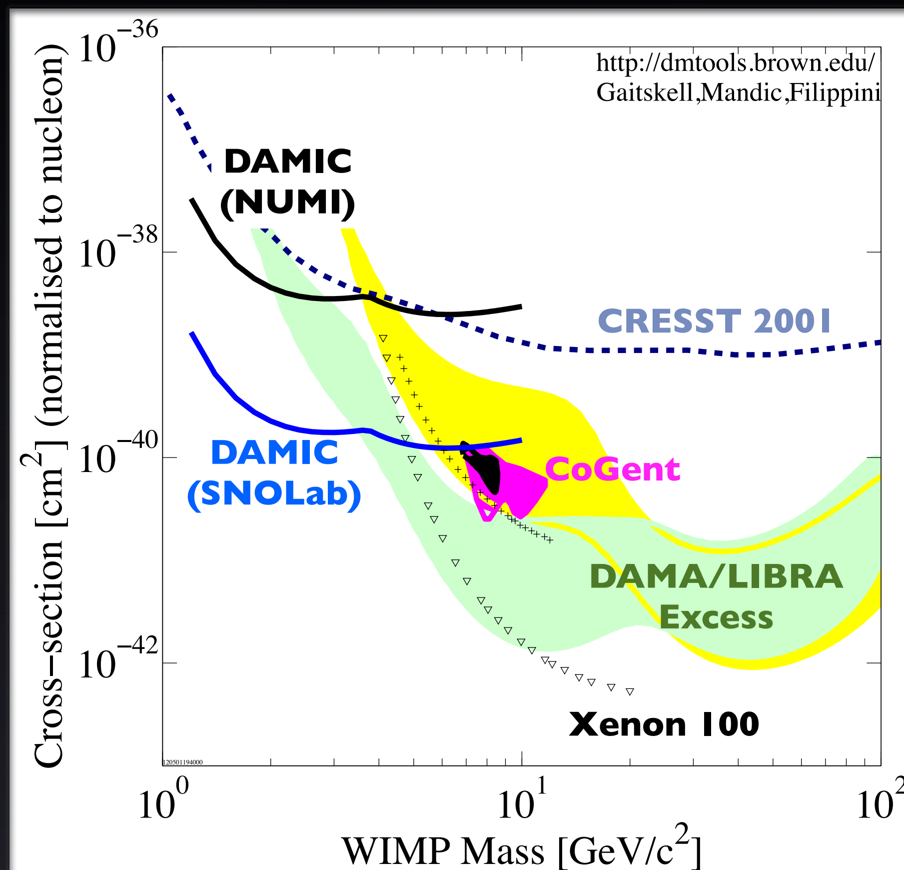
T.Schwarz
Univ. Michigan

P.Privitera
U.Chicago

Adding Students

Projecting Sensitivity for Next Run

- **Expected sensitivity from**
  - **Adding mass**
    8 CCD's (x10 more mass)
  - **Going deeper and better shielding**
    SNOLab ~ 2km
    Polyethylene
    Better Materials
  - **Increase sensitivity**
    Better calibration
    Bkg Predictions



Long Term Goal

- 100g of CCD @ SNOLab ~ $50K per 10g
- Lower energy thresholds
  - Skipper CCD & Digital Filters
- DAMIC-SOUTH UNAM (Mexico) CNEA (Argentina) UTFSM (Chile)
  - Will construct and install a DAMIC over the next 3 years in ANGRA
  - Cancel systematic effects when combined with DAMIC-NORTH

Conclusions

- DAMIC @ NuMI 2011-12 data (Fermilab tunnel)
  - Demonstrated sensitivity to low mass DM
    - 107 g-days set best limits below 4 GeV

- DAMIC @ Snolab
  - Will significantly reduce cosmogenic neutron backgrounds
  - Some other improvements planned
  - Improve limits by ~50

- DAMIC in the future
  - Will focus on pushing lower energy thresholds
    - Requires better neutron calibrations
  - Larger mass when bkgs are under control