CCDs as particle detectors for low energy threshold experiments

Javier Tiffenberg[†]

† Fermi National Laboratory

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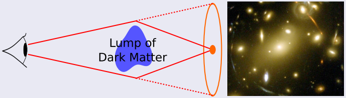
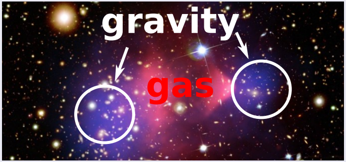
Observational evidence of Dark Matter (DM)

Lots of Observational evidence

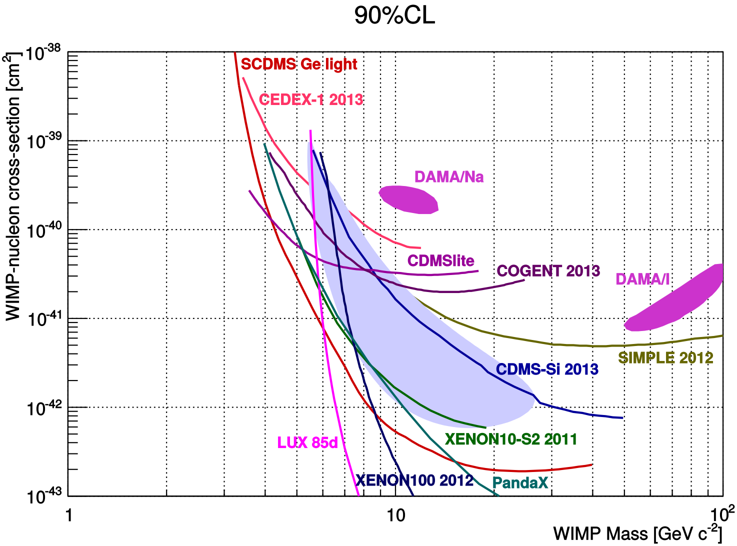
- Galactic Rotation Curves
- Galaxy Clusters Dynamics
- Strong Gravitational Lensing
- The Bullet Cluster
- Large-Scale Structure Formation
- Big Bang Nucleosynthesis





DM may not exist, but if it doesn't we have a lot to explain..

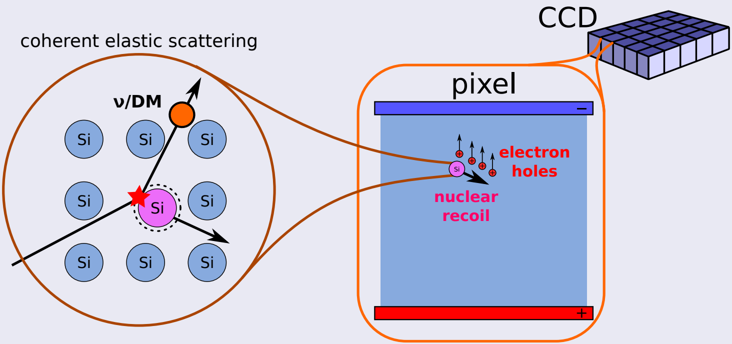
Motivation


90%CL
WIMP-nucleon cross-section [cm^2]
WIMP Mass [GeV c^-2]
10^-38
10^-39
10^-40
10^-41
10^-42
10^-43
1
10
10^2
SCDMS Ge light
CEDEX-1 2013
DAMA/Na
CDMSlite
COGENT 2013
DAMA/I
SIMPLE 2012
CDMS-Si 2013
XENON10-S2 2011
LUX 85d
XENON100 2012
PandaX

Goal: lower the energy threshold in Si detectors

Detect coherent DM/ν-nucleus interactions by measuring the ionization produced by the nuclear recoils

Idea: use CCDs as target and record the ionization produced



Goal: lower the energy threshold in Si detectors

Detect DM/ν-e interactions by measuring the ionization produced by the electron recoils.

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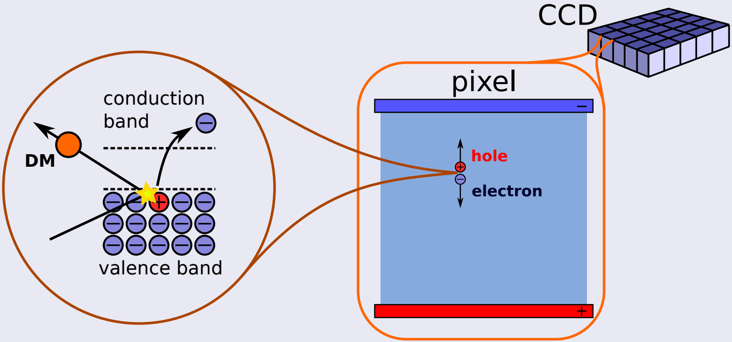
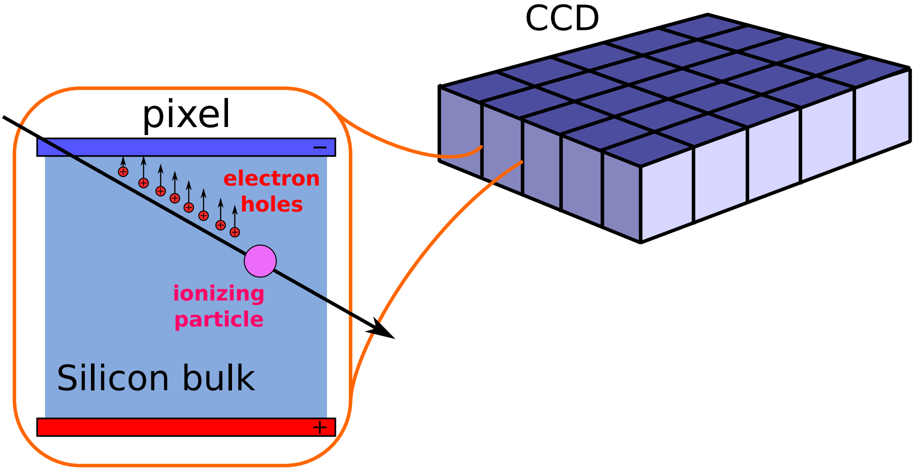
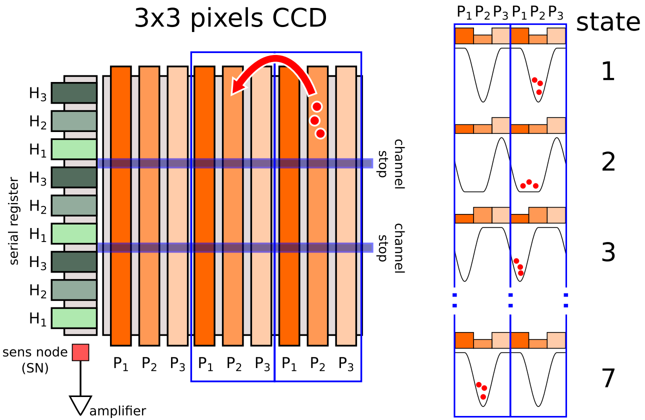


CCD: charge generation

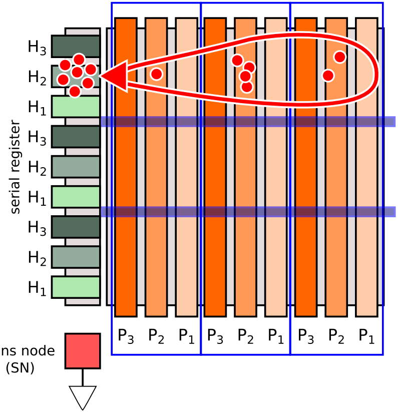


CCD: readout



capacitance of the system is set by the Sens Node: C=0.05pF→ 3μV/e

Hardware Binning

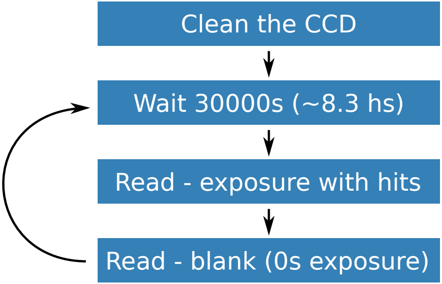


- Every readout introduces a $2e^-$ noise
- The CCD allows you to add charge in the sensor (binning) and then readout many pixels as a single one
- This improves signal to noise, effectively increasing the efficiency at low energy

$$\mathbf{S/Noise} = \frac{\mathbf{Q}}{\mathbf{N_{reads}}}\sigma$$

Reading the charge in less pixels is good!

CCD: readout - typical operation for DM searches



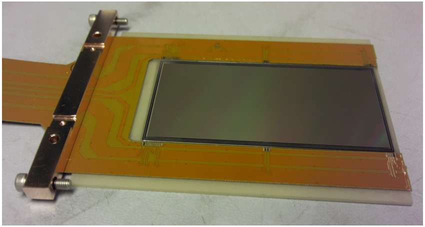
We take long exposures to minimize the number of readouts. The exposure is eventually limited by the dark current.

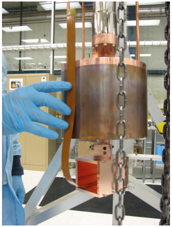
The blank images provide an excelent measurement of the background produced by readout

Detectors:

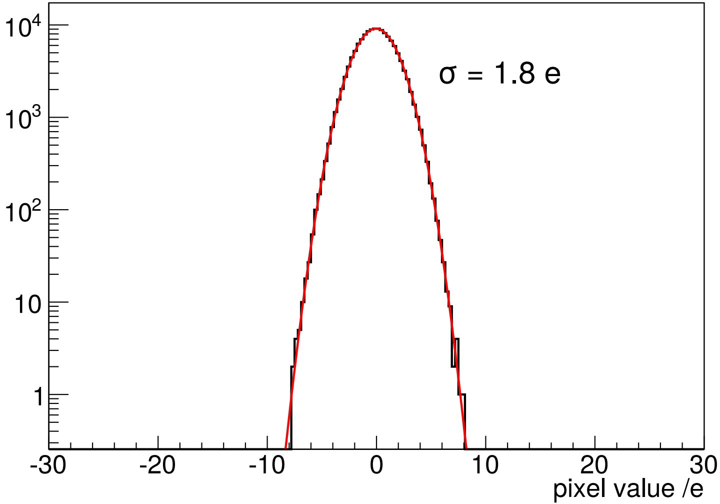
We use scientific CCDs developed by LBNL microdectors group

- pixel size of 15 μm
- 10x/27x thicker than most CCDs (250/675 μm)
  - up to 5.5 gr per CCD
  - diffusion $\rightarrow$ 3D rec $\rightarrow$ rejection of surface events
- CCDs cooled to 150 K to achieve readout noise RMS $\sim$ 2 e^-
- Energy threshold of $\sim$0.05 keVee

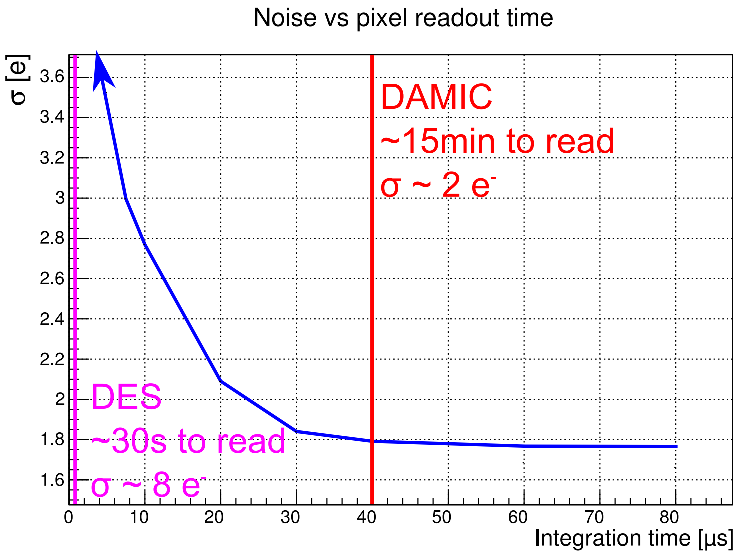




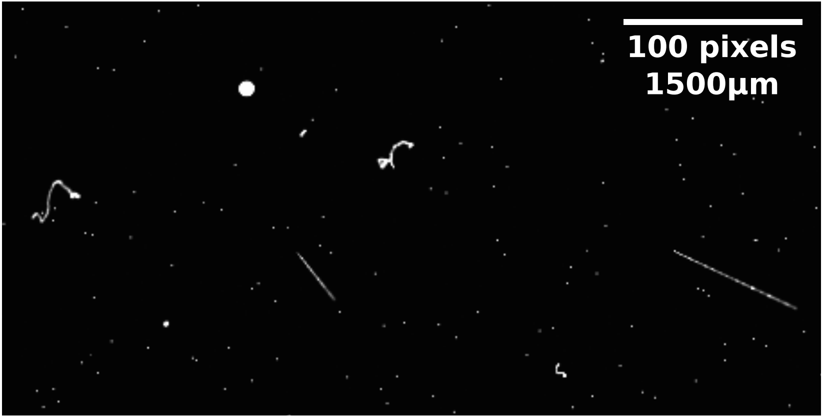
Readout Noise: empty pixels distribution



Readout Noise:

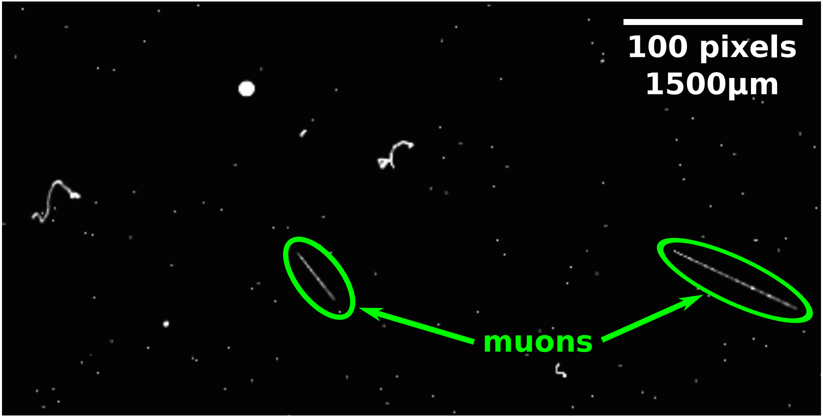


Particle ID



Data taken at Fermilab (sea level, no radiation shielding, expo ∼1min)

Particle ID



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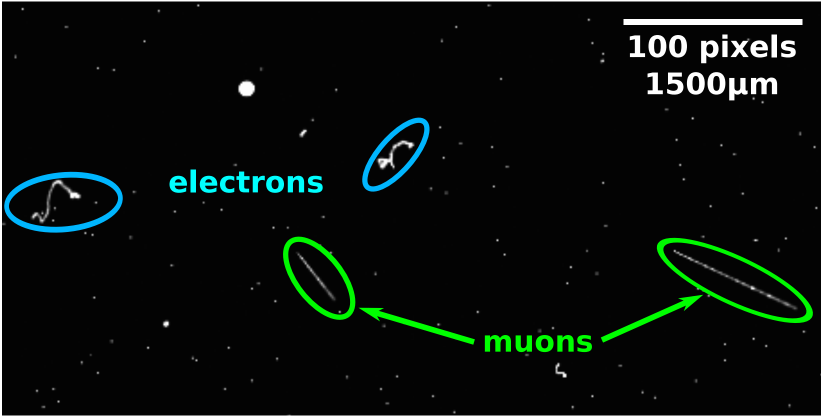

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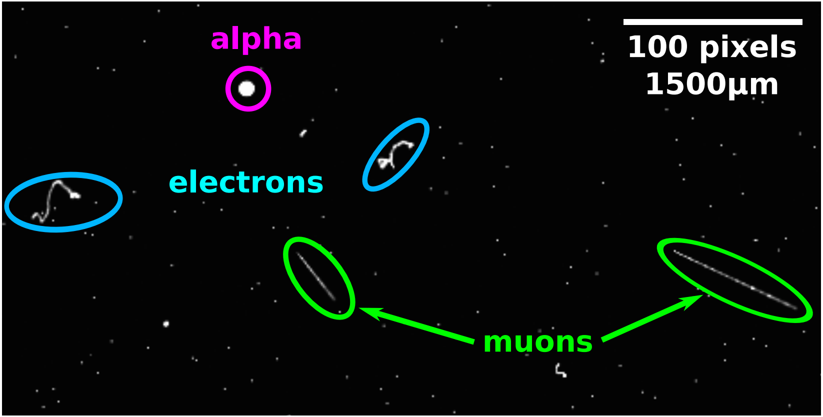

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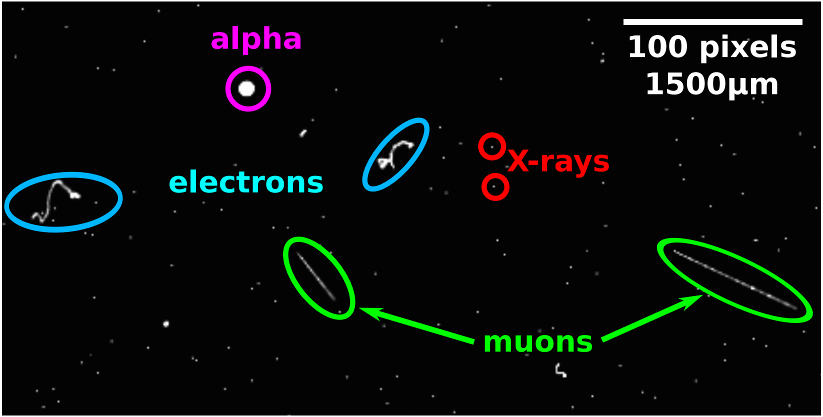
Particle ID



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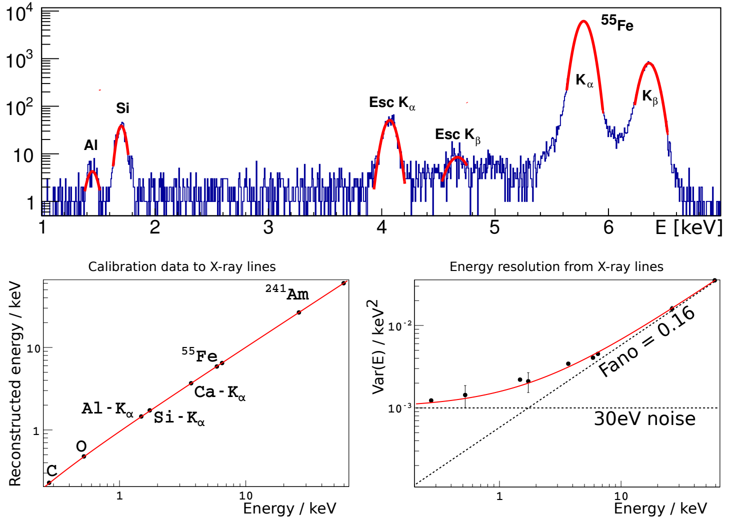
Energy calibration using X-rays



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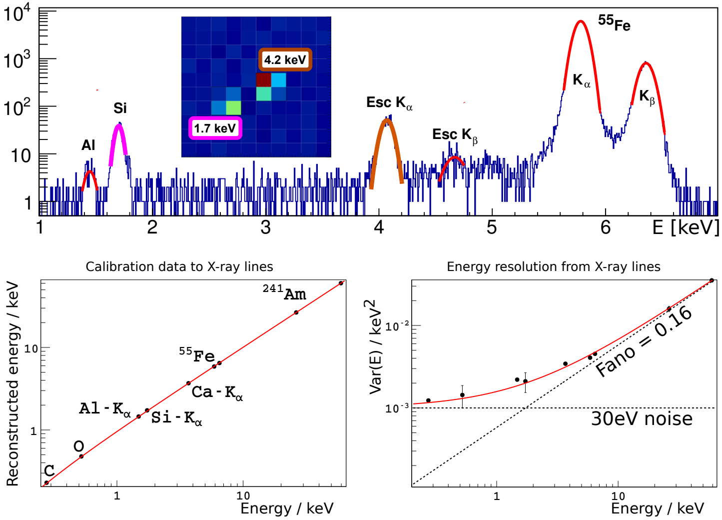
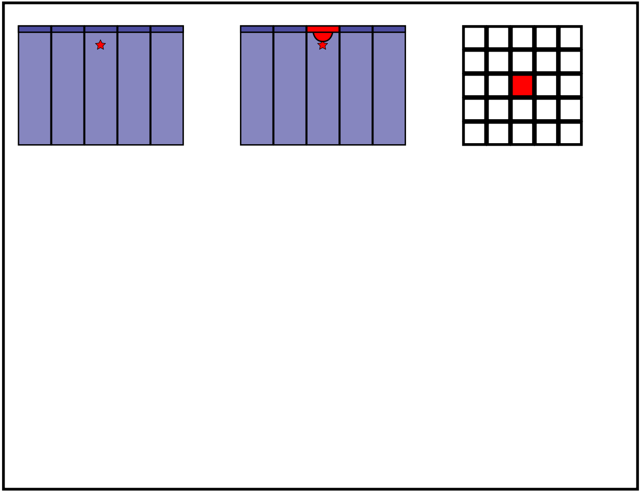
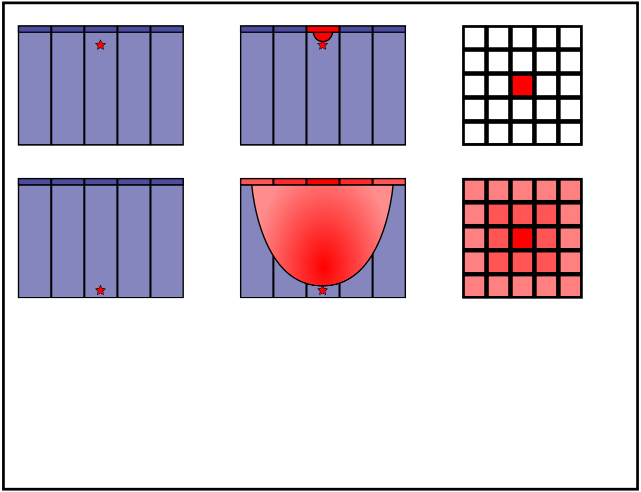


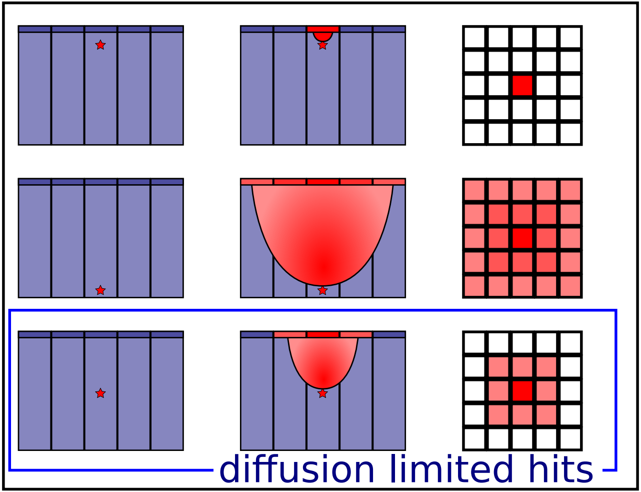
Diffusion



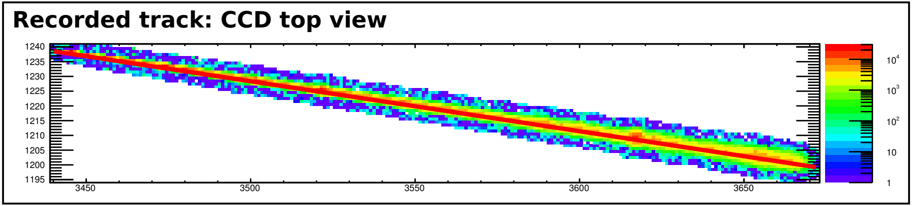
Diffusion

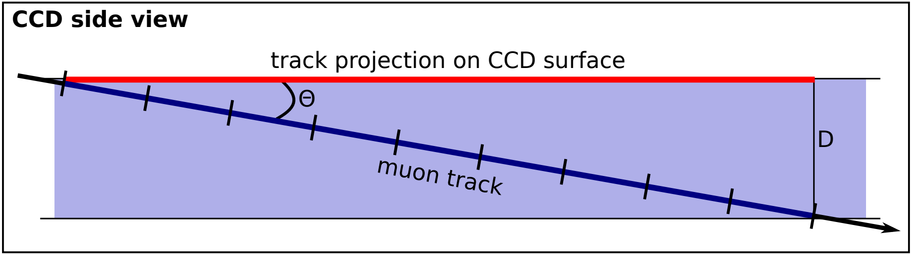


Diffusion

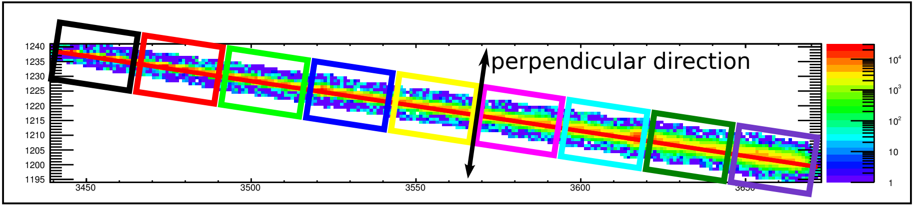


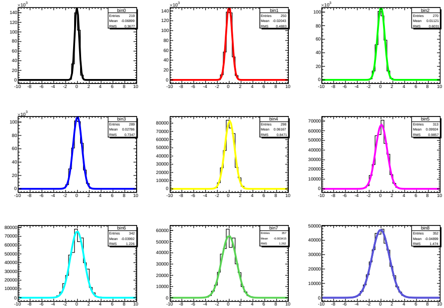
Measuring diffusion



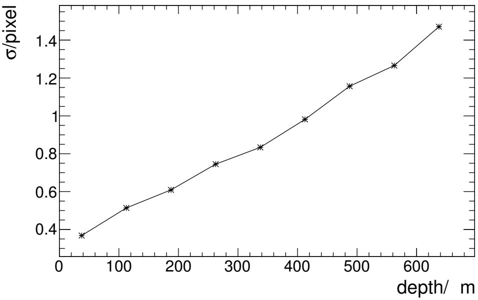


Measuring diffusion





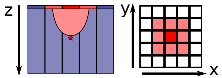
Measuring diffusion

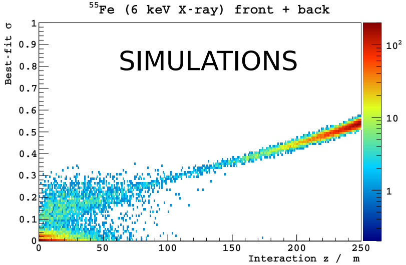


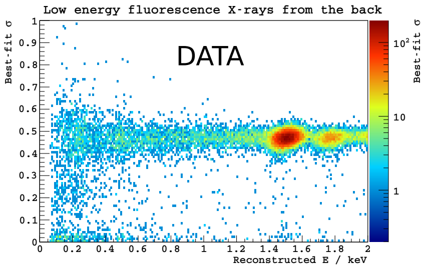
Diffusion can be measured as a function of the interaction depth.
No need to rely on models.

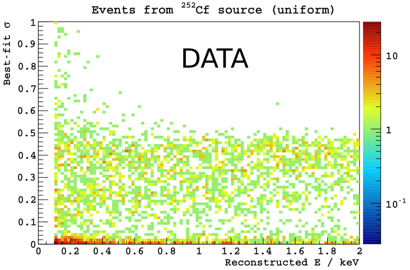
3D reconstruction of low energy (point like) like events

We fit to the radial spread of the cluster to estimate its position in z within the CCD bulk

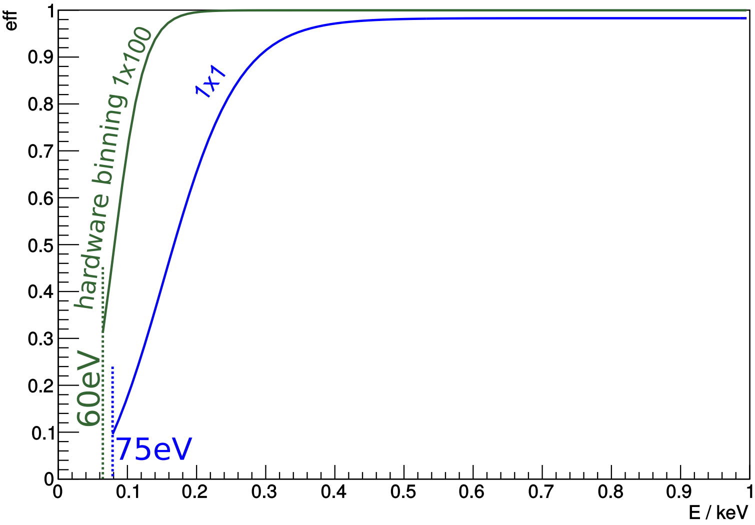






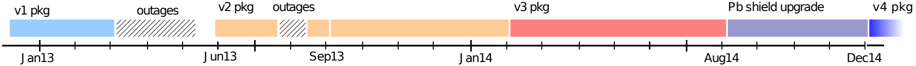


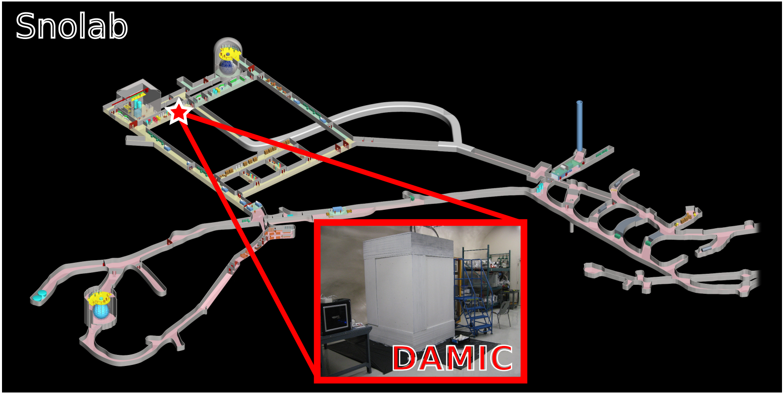
Efficiency



eff
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
E / keV
hardware binning 1x100
1x1
60eV
75eV

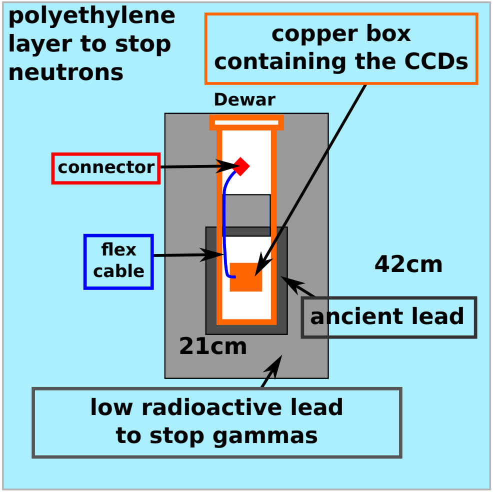
DAMIC @Snolab (installed Dec12)

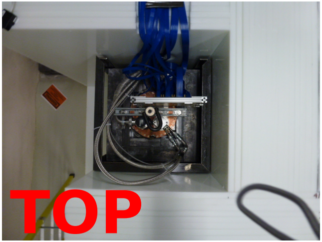




Installed at Snolab: 2km of norite overburden → 6000m water equivalent

DAMIC detector: shielding

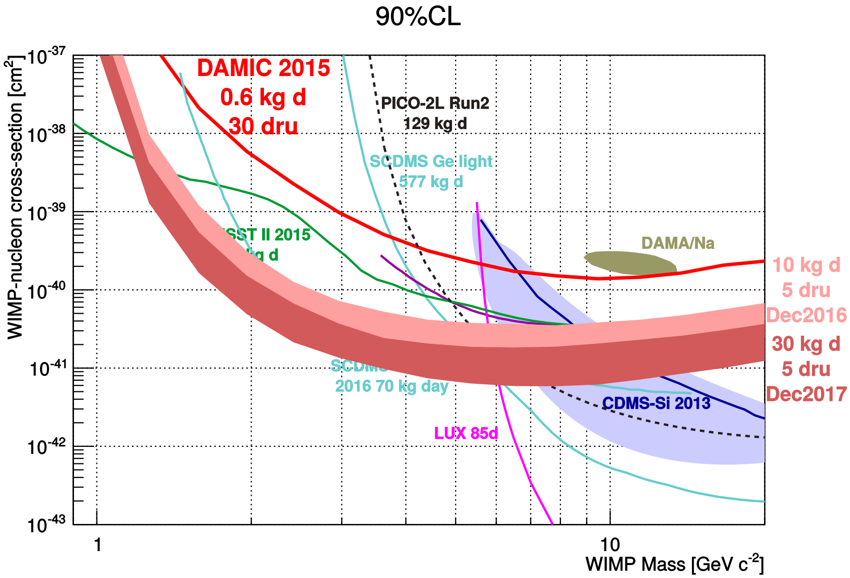




WIMP search

Although during 2015 we dedicated most of the time to identify the backgrounds and screen materials we where a able to acquire a small sample of WIMP search data to test and develop our analysis framework

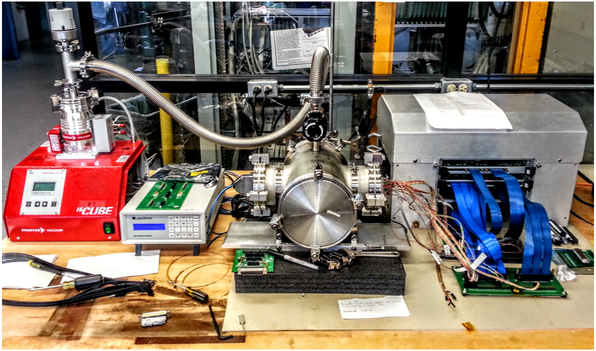
DAMIC100 reach



LDRD: Devt of an ultra low-energy threshold particle detector

Awarded proposal, ongoing project

Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) and a readout noise of 0.1 electrons using a new generation skipper CCD developed by the LBNL MicroSystems Lab



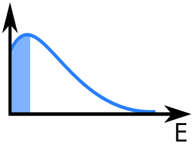
Fermilab

BACK UP SLIDES

Background from Silicon: could be a limiting factor

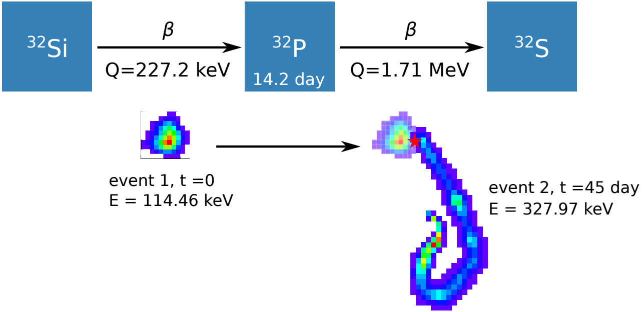
There is a long lived radiactive silicon isotope that is cosmogenically produced in to the interaction of cosmic rays with atmospheric argon and other elements

Low energy electrons from β decays could be a significant background in silicon



Background from Silicon: candidate ^{32}Si event

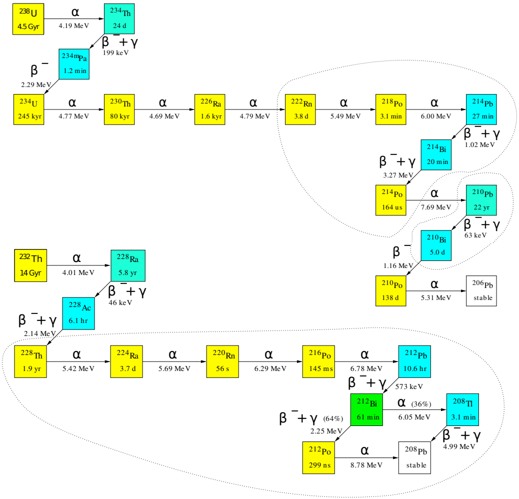
The precise position reconstruction in the CCD allows the study of spatial coincidences to measure and veto ^{32}Si events in the CCD

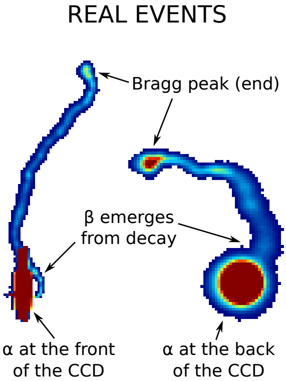


The pixelation of the DAMIC detector allows us to reject this background.
This is a unique capability of the DAMIC sensors.

Measured ^{32}Si dacay rate: 80^{+110}_{-65} (95% CI) (arxiv:1506.02562)

U/Th decay chains

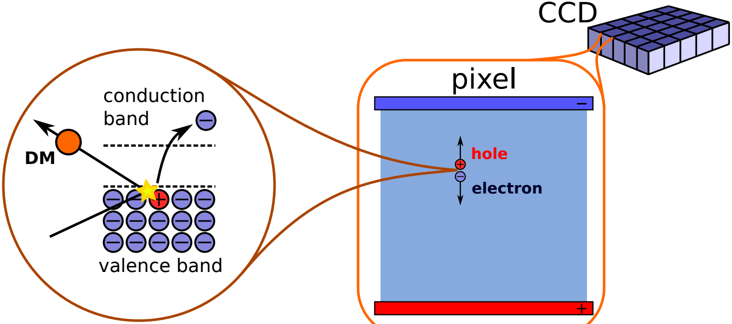




Radioctive elements can be identified and (spacialy located) by looking at $\alpha - \alpha$ and $\alpha - \beta$ coincidences.

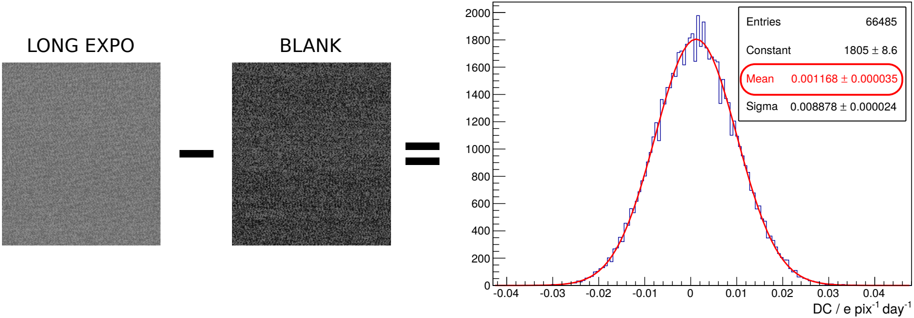
Fermilab

Electron recoil



Electron recoil

We can measure the Dark Current by looking at the "empty" pixels distribution after an extremely long exposure O(days)

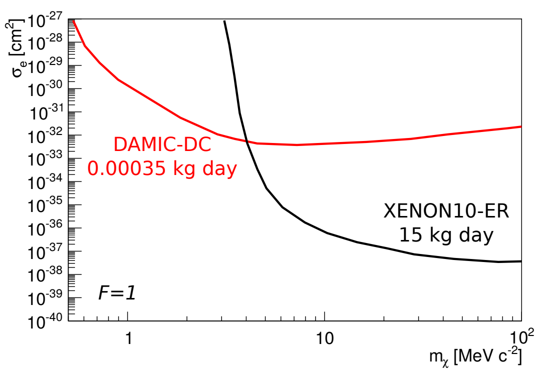


Measured Dark Current 0.001 e pix^{-1} day^{-1} (x10^6 smaller than DES)
We can use this information to compute a limit on DM-e^- xsec.

Electron recoil

Looking for extremely low mass DM: world best limit

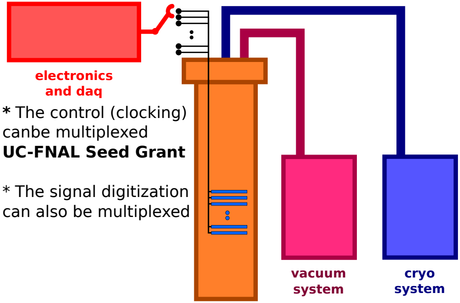
We can use the measured DC to compute a limit on DM-e^- xsec



In collaboration with Jeremy Mardon (Stanford), Rouven Essig, Tien-Tien Yu (Stony Brook) and Tomer Volansky (Tel Aviv)

DAMIC-1kg: readout electronics scaling

- we read the CCDs only a few times per day (or even less)
- we don't need to read all of them at the same time
  $\rightarrow$ **the readout and CCD clocking can be multiplexed**

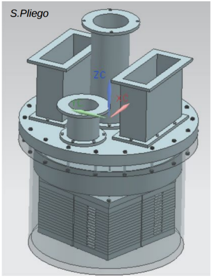


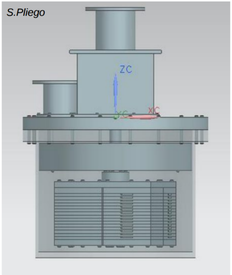
currently developing the technology

- Fermilab and Paris

DAMIC-1kg: mechanical design

- Cryogenics: CCDs operate at 100K. Commercial solutions available
- Shielding: need to minimize materials close to the CCDs
  - electronic connections could be a challenge

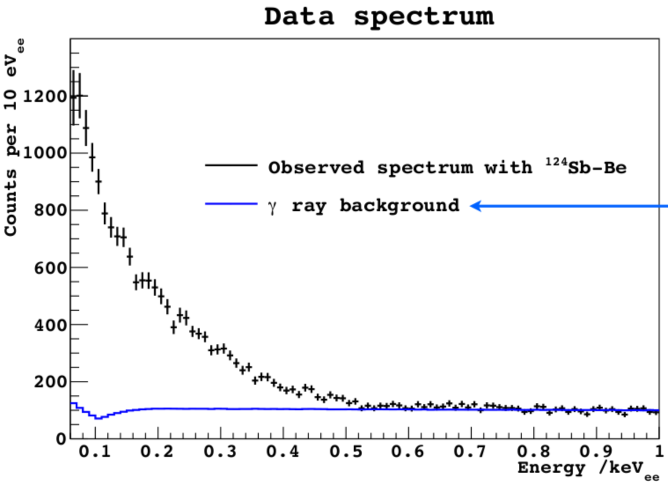




currently developing the technology

- UNAM: working on design concepts for the vessel

Nuclear recoil calibration



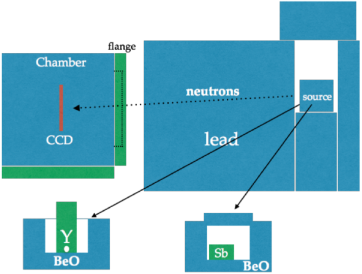
Normalized to count rate 2-5 keV$_{ee}$.

Uncertainty propagated in analysis.

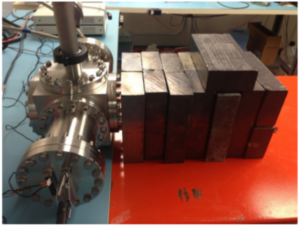
Quenching factor

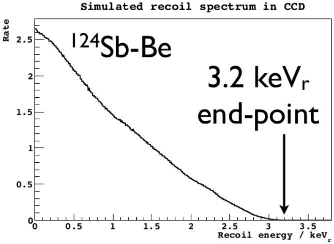
Neutrons

Fast neutrons from
$^9Be(\gamma,n)$ reaction

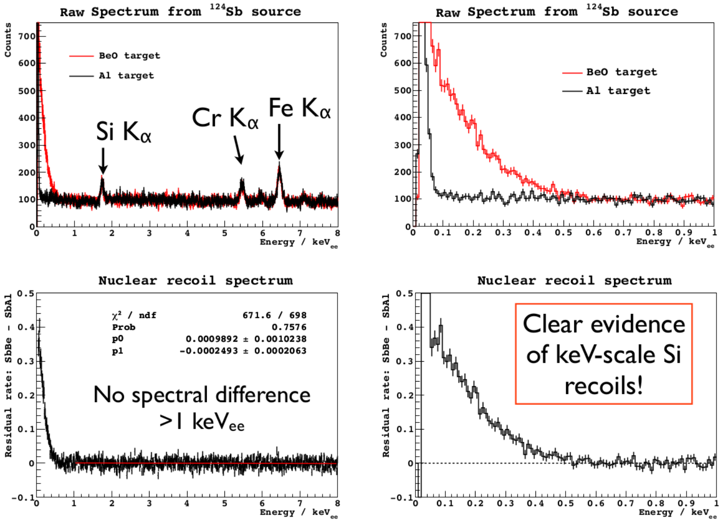


Neutrons from
^{124}Sb-Be source: **24 keV**





Quenching factor

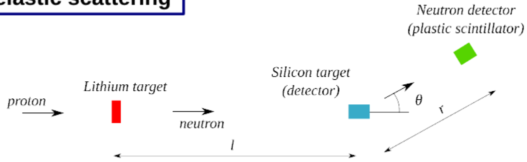


Quenching factor

Fast neutrons elastic scattering

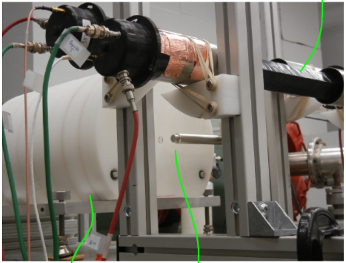
E_p = 2.3 MeV

E_n in [100,600] keV



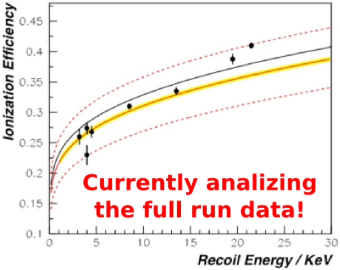
University of Notre Dame
(Indiana, USA)

Scintillator Bar



Collimator

Silicon Detector

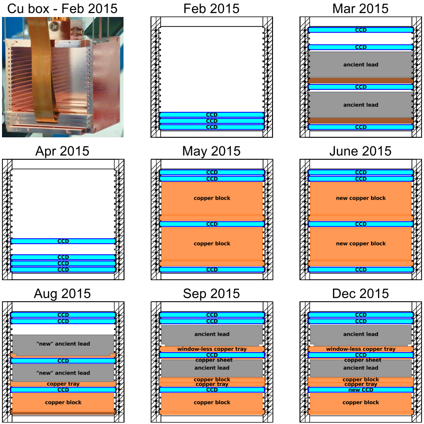


Intrinsic contamination of the CCDs

Analysis method	Isotope(s)	Tracer for	Bulk rate kg^{-1} d^{-1}
α spectroscopy	^{210}Po	^{210}Pb	<37
	^{234}U + ^{230}Th + ^{226}Ra	^{238}U	<5 (4 ppt)
	^{224}Ra–^{220}Ra–^{216}Po	^{232}Th	<15 (43 ppt)
β spatial coincidence	^{32}Si–^{32}P	^{32}Si	110^{+150}_{-90}
	^{210}Pb–^{210}Bi	^{210}Pb	<46

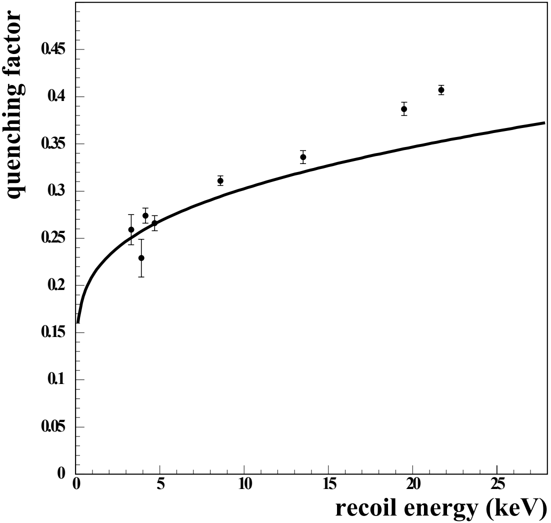
Fermilab

2015 campaign: tracking backgrounds

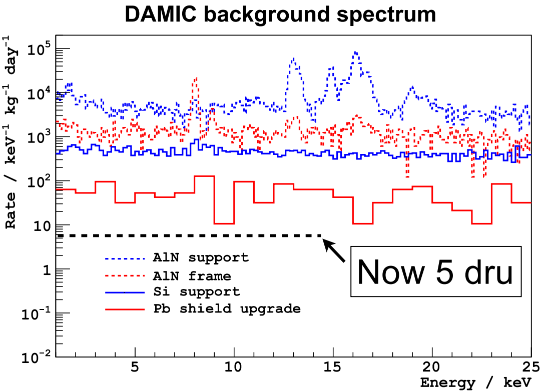


$\sim$80% of the time in low gain mode (high dynamic range) to identify backgrounds. Little time dedicated to science runs.

Quenching factor.



2015 campaign: tracking backgrounds



In production mode

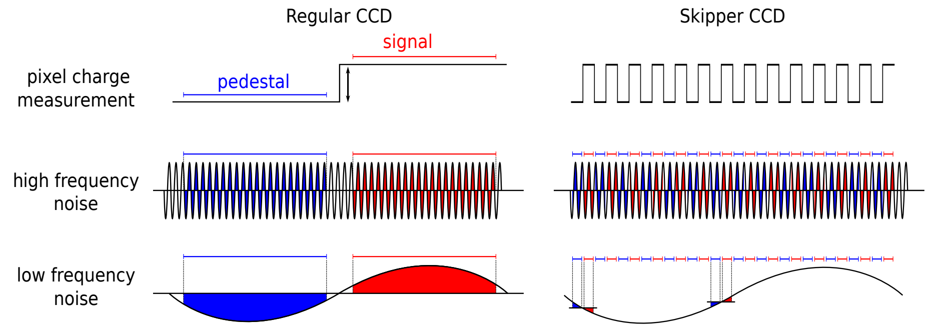
Converged on package design and materials

10/18 detectors tested and ready for deployment

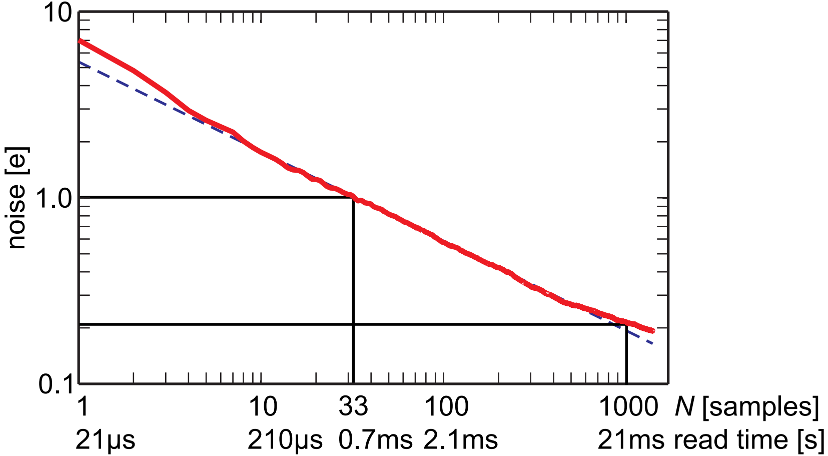
Will commission during April 2016

Lowering the noise: Skipper CCD

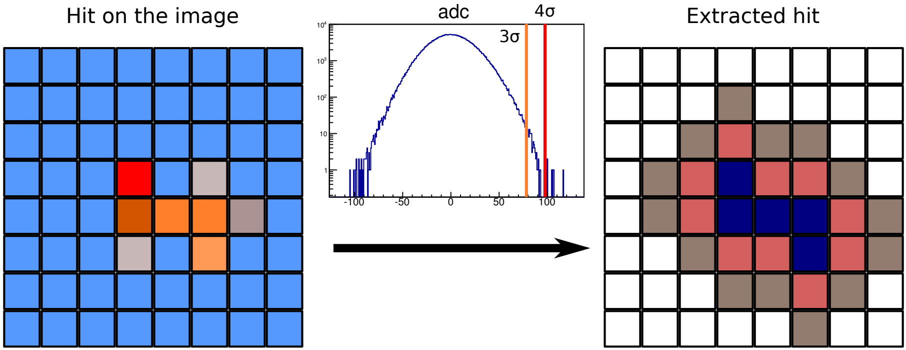
- Main difference: the CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  $\mathbf{Pixel\,value} = \frac{1}{N}\Sigma_i^N\,\mathbf{(pixel\,sample)}_i$



Lowering the noise: Skipper CCD



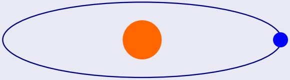
hit extraction

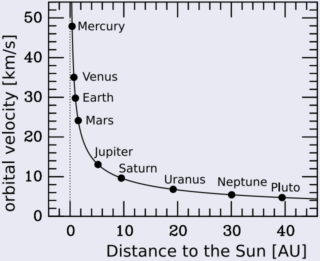


Observational evidence of Dark Matter (DM)

Luminous matter dominated

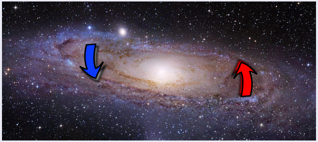
If the mass is concentrated, the orbital velocity falls as 1 over the square root of the distance.

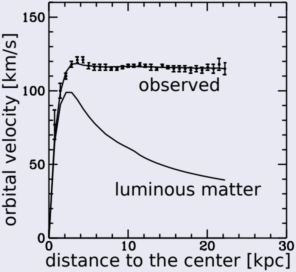




Dark Matter dominated

Measuring the shift in the spectrum one can calculate the speed of rotation

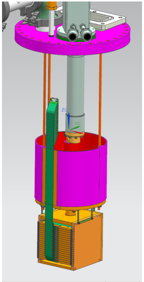


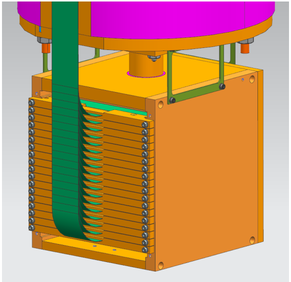


DAMIC100 @Snolab

Currently deploying 100 g of active mass. 2 (out of 18) already installed.

- 10/18 detectors ready to be deployed. **Commisioning on April-2016**
- So far we focused on understanding the activity of the inner materials to get full advantage of the mass increase.
- We still managed to collect a small sample of WIMP search data..

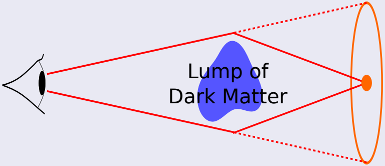




Observational evidence of Dark Matter (DM)

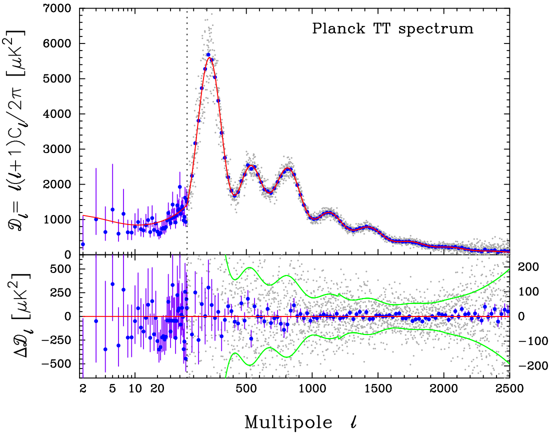
Bullet cluster

Gravitational lens



Observational evidence of Dark Matter (DM)

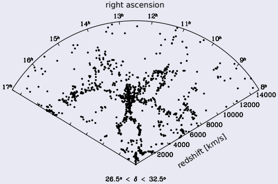
The autocorrelation seen in the background radiation is explained if one assumes that the amount of dark matter present is $\simeq 5.5$ times that of ordinary baryonic matter



Observational evidence of Dark Matter (DM)

Large-scale structure of the universe

The observed large-scale structure of the universe requires the presence of DM to form. DM is also necessary to understand the large-scale dynamics of galaxy clusters.



Nucleosynthesis in the Big Bang

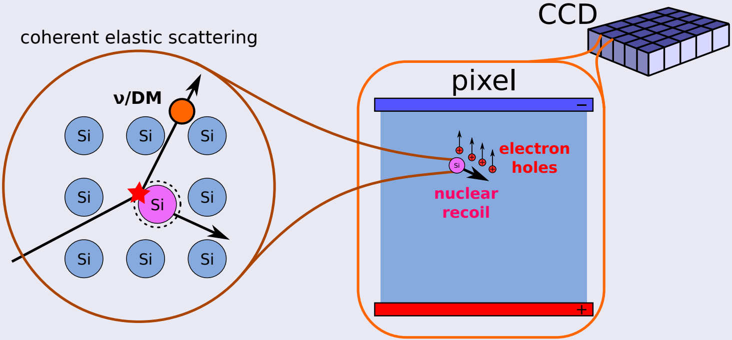
The relative amounts of elements generated in the primordial nucleosynthesis depends on the density of the universe and the relationship between the amount of baryonic matter and photons.

The current explanation for the relative amount of ^{3}He and ^{7}Li observed requires the existence of dark matter.

Nuclear recoil ionization efficiency

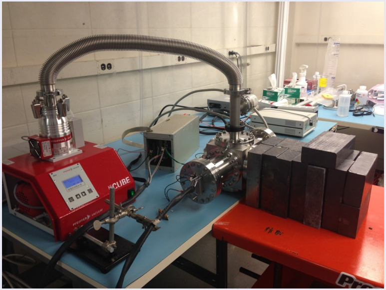
Quenching factor / nuclear recoil ionization efficiency

It's critical to know/measure the fraction of the nuclear recoil kinetic energy that goes into ionization (which is the only thing that we can see)



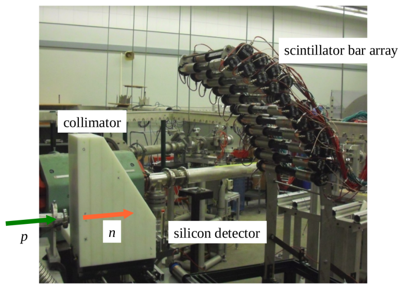
Nuclear recoil calibration program

Sb/Be source



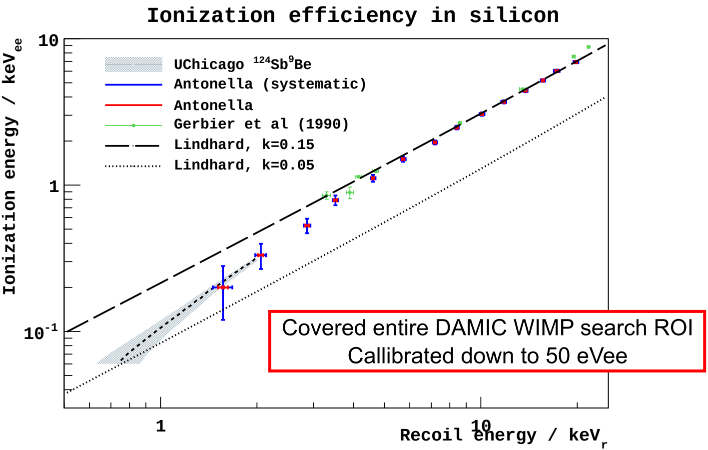
- Photo-neutron source at U. of Chicago
- 0.7 - 2 keV NR

Antonella (Fermilab)



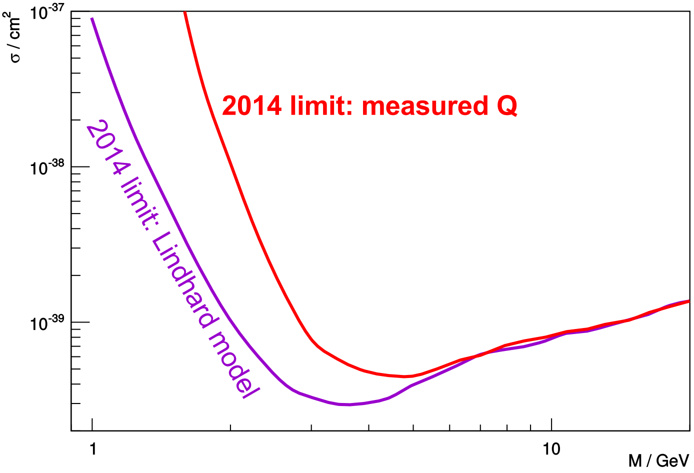
- Neutron beam at U. of Notre Dame
- 2 - 20 keV NR

Nuclear recoil calibration



Discrepancy with Lindhard model below 5 keVee

2014 run (DAMIC-2014): limit reanalysis



The quenching model has a huge impact on the sensitivity at low masses