Fourth International Workshop for the Design of the ANDES Underground Laboratory
Universidad Nacional Autónoma de México, Unidad de Seminarios Dr. Ignacio Chávez
30 January - 31 January 2014

The DAMIC experiment

Gustavo Cancelo (Fermilab) for the DAMIC collaboration

In search of Dark Matter

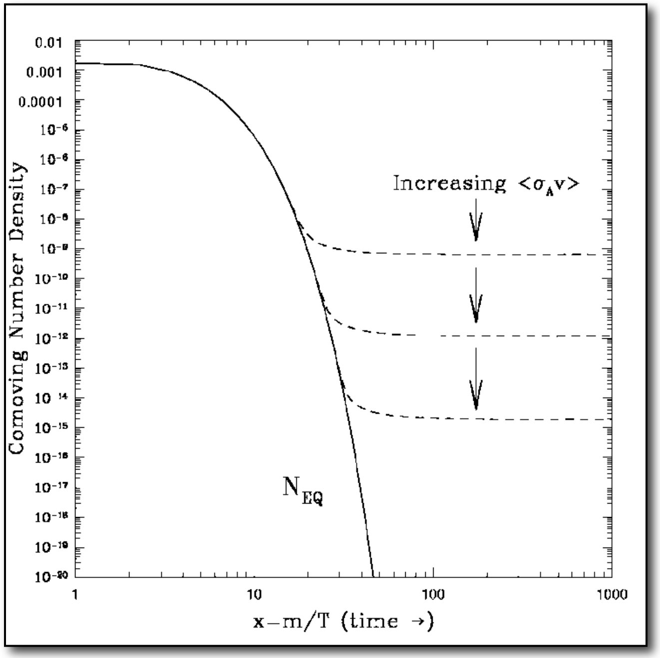
- We know only little about the nature of dark matter:
  - Cold (non-relativistic).
  - Stable.
  - Dark (no electric charge).

- No particle within the Standard Model fulfills these criteria.

- Most of the action is focused on “WIMPs” and ultra-light axions.

- Dark matter candidates in the form of weakly interacting particles with masses in the GeV-TeV range (WIMPs) stand out for their
  - Testability.
  - Theoretical motivation (solution to electroweak hierarchy problem).
  - The “WIMP Miracle”.

The WIMP miracle



A generic stable, weakly interacting particle is predicted to be produced in the early universe with an abundance similar to the observed dark matter density.
-Numerical coincidence, WIMP Miracle?

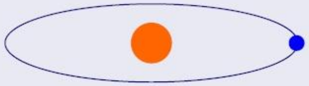
- $T \gg M_X$, WIMPs are in thermal equilibrium
- $T < M_X$, number density becomes exponentially suppressed

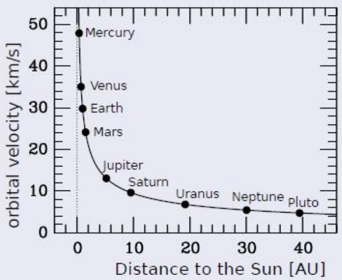
The observational evidence

Galaxy rotation velocities

Luminous matter dominated

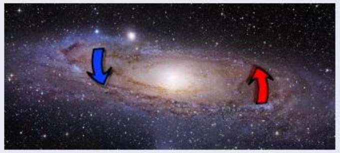
If the mass is concentrated, the orbital velocity falls just as the square of the distance.

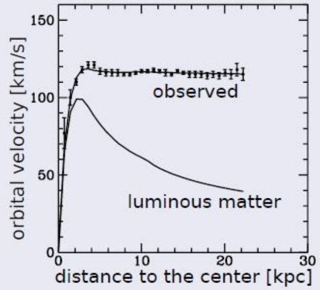




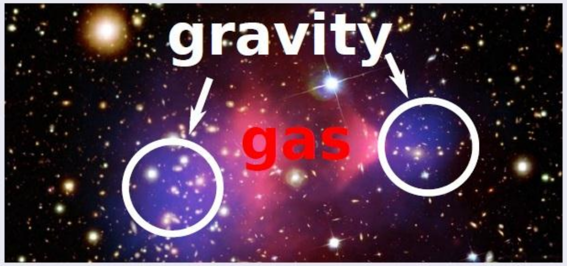
Dark Matter dominated

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

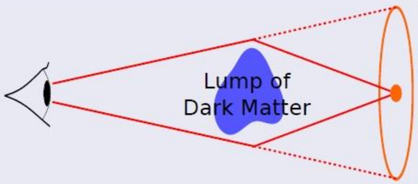


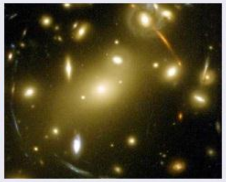


Bullet cluster

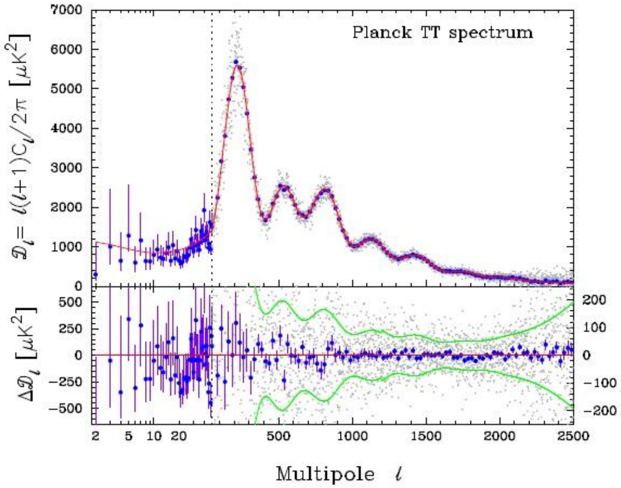


Gravitational lens



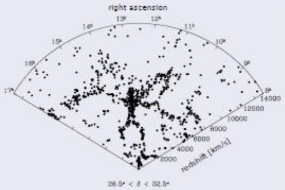


The autocorrelation seen in the background radiation



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.



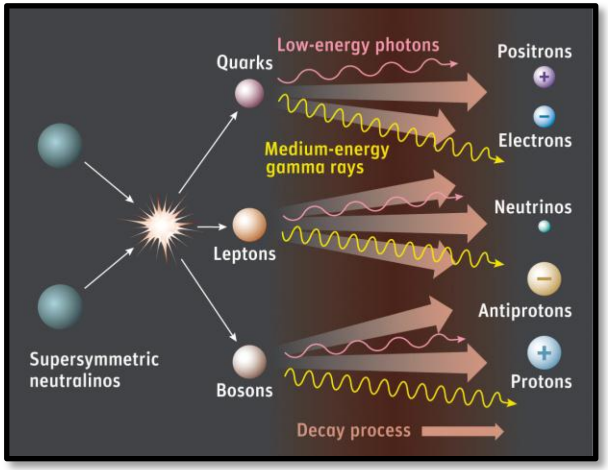
Nucleosynthesis in the Big Bang

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.

How do we search for Dark Matter?

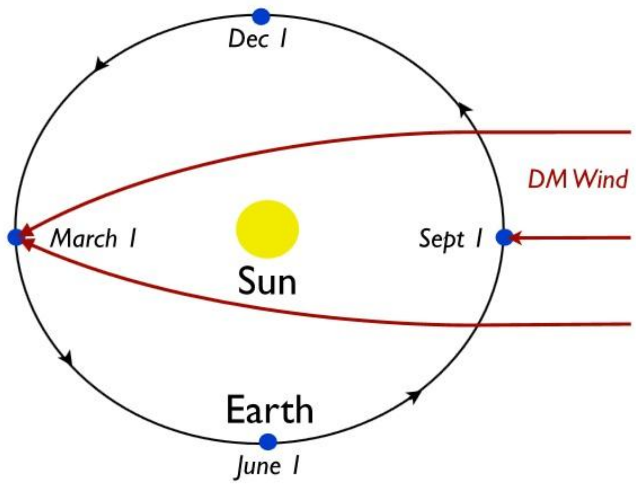
- Indirect searches test WIMP models looking for products of DM annihilation
  - E.g. FERMI LAT

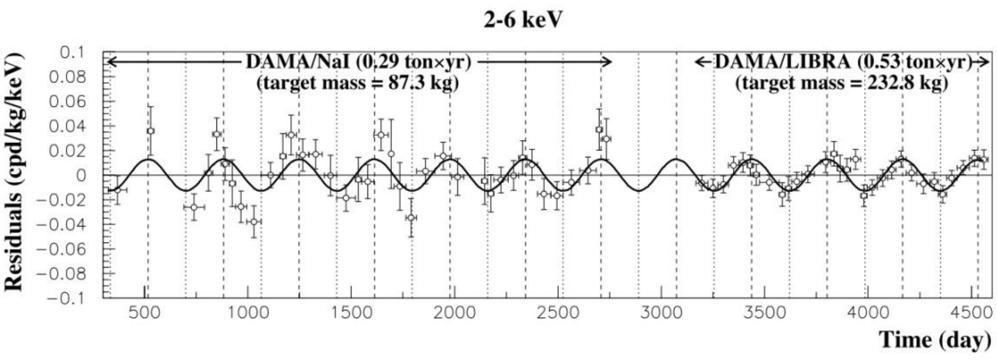


- Gamma rays from dark matter: Dwarf galaxies are bright sources with little astrophysical backgrounds.
- Ground-Based Gamma Ray Searches: WIMP models at TeV scale.
- At the Galactic Center.
- DM in anti matter: WIMP annihilations should produce equal quantities of matter and antimatter. A large flux of antimatter in the cosmic ray spectrum could be indicative of a contribution from dark matter (e.g. PAMELA).
- DM with radio telescopes: (e.g. WMAP, PLANK)
- Accelerators (e.g. LHC): could produce and detect DM.
- ETC.

Direct Detection

- A GeV-TeV particle moving at typical halo velocities (~300 km/s) striking a nucleus imparts a recoil of ~1-100 keV
- Numerous technologies have been developed and deployed in an effort to observe these collisions – scintillation, ionization, phonons.
- Most state-of-the-art experiments make use of large detector masses (10-1000) kg of heavy nuclei targets (e.g. Ge, Xe), and located deep underground to minimize backgrounds.





DAMA/LIBRA claim with sig. > 8 σ

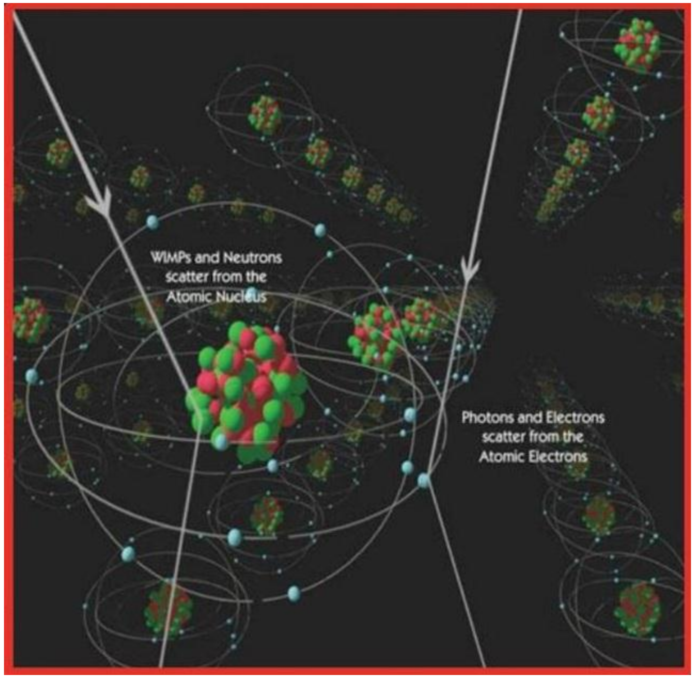


Table 4. Characteristics of selected dark matter experiments,[81] including fiducial mass M and whether scintillation light (γ), phonons (ϕ), ionization (q), or another form of energy is detected, and whether the experiment's primary mission is neutrinoless double-beta decay ($\beta\beta$).

Experiment	Location	Readout (γ, ϕ, q)	T (K)	M (kg)	Target	Search Dates
NAIAD	Boulby	γ	300	50	NaI	2001–2005
DAMA/NaI	Gran Sasso	γ	300	87	NaI	1995–2002
DAMA/LIBRA	Gran Sasso	γ	300	233	NaI	2003–
ANAIS	Canfranc	γ	300	11	NaI	2000–2005
ANAIS	Canfranc	γ	300	100	NaI	2011–
KIMS	Yangyang	γ	300	35	CsI	2006–2007
KIMS	Yangyang	γ	300	104	CsI	2008–
CDMS II	Soudan	ϕ, q	< 1	1	Si	2001–2008
				3	Ge	2001–2008
SuperCDMS	Soudan	ϕ, q	< 1	12	Ge	2010–2012
SuperCDMS	SNOLAB	ϕ, q	< 1	120	Ge	2013–2016
GEODM	DUSEL	ϕ, q	< 1	1200	Ge	2017–
EDELWEISS I	Modane	ϕ, q	< 1	1	Ge	2000–2004
EDELWEISS II	Modane	ϕ, q	< 1	4	Ge	2005–
CRESST II	Gran Sasso	ϕ, γ	< 1	1	$CaWO_4$	2000–
EURECA	Modane	ϕ, q	< 1	50	Ge	2012–2017
		ϕ, γ	< 1	50	$CaWO_4$	2012–2017
SIMPLE	Rustrel	Threshold	300	0.2	Freon	1999–
PICASSO	Sudbury	Threshold	300	2	Freon	2001–
COUPP	Fermilab	Threshold	300	2	Freon	2004–2009
COUPP	Fermilab	Threshold	300	60	Freon	2010–
TEXONO	Kuo-Sheng	q, $\beta\beta$	77	0.02	Ge	2006–
CoGeNT	Chicago	q, $\beta\beta$	77	0.3	Ge	2005–
	Soudan	q, $\beta\beta$	77	0.3	Ge	2008–
MAJORANA	Sanford	q, $\beta\beta$	77	60	Ge	2011–
ZEPLIN III	Boulby	γ, q	150	7	LXe	2004–
LUX	Sanford	γ, q	150	100	LXe	2010–
XMASS	Kamioke	γ, q	150	3	LXe	2002–2004
XMASS	Kamioke	γ, q	150	100	LXe	2010–
XENON10	Gran Sasso	γ, q	150	5	LXe	2005–2007
XENON100	Gran Sasso	γ, q	150	50	LXe	2009–
WArP	Gran Sasso	γ, q	86	3	LAr	2005–2007
WArP	Gran Sasso	γ, q	86	140	LAr	2010–
ArDM	CERN	γ, q	86	850	LAr	2009–
DEAP-1	SNOLAB	γ	86	7	LAr	2008–
MiniCLEAN	SNOLAB	γ	86	150	LAr	2012–
DEAP-3600	SNOLAB	γ	86	1000	LAr	2013–
DRIFT-I	Boulby	Direction	300	0.17	CS_2	2002–2005
DRIFT-2	Boulby	Direction	300	0.34	CS_2	2005–
NEWAGE	Kamioka	Direction	300	0.01	CF_4	2008–
MIMAC	Saclay	Direction	300	0.01	many	2006–
DMTPC	MIT	Direction	300	0.01	CF_4	2007–

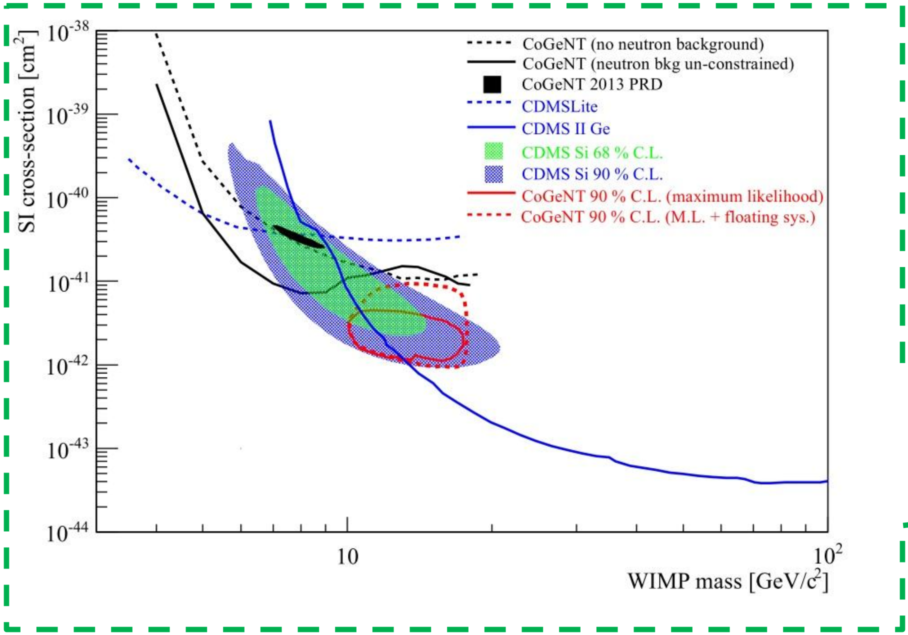
DM direct search Table of experiments by 2011
R. W. Schnee (Syracuse University)
(arXiv:1101.5205)

DAMIC is not shown in 2011

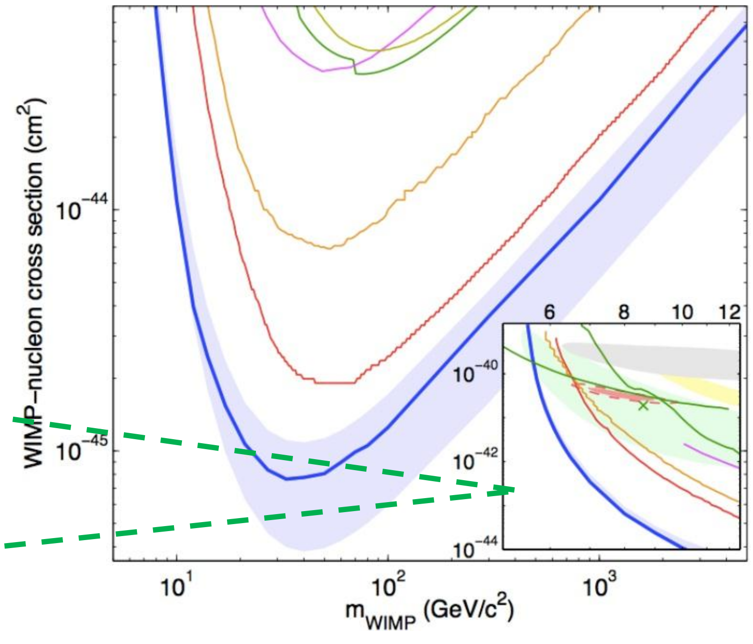
What can we say about DDM searches and results until today?

- Exciting field
- Creative experiments.
- Controverted results.

CoGeNT result, Jan 2014 (arXiv 401.3295v1)



LUX result, Oct. 2013 (arXiv 1310.8214v1)



DAMIC (DArk Matter In Ccds)

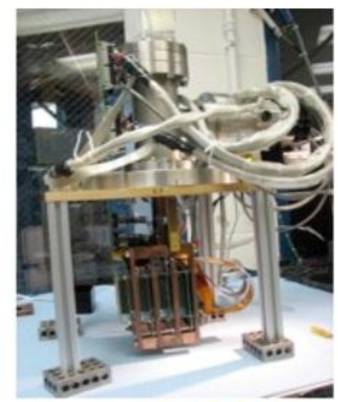
- Before 2008: CCD tests and background measurements at SiDet (Silicon Detector Facility at Fermilab).
- 2008: J. Estrada, MEMORANDUM OF UNDERSTANDING (Fermilab Test Beam Program T987)

At NuMI near detector hall (300mwe) in January 2009:

tent

8” lead shield

vacuum vessel

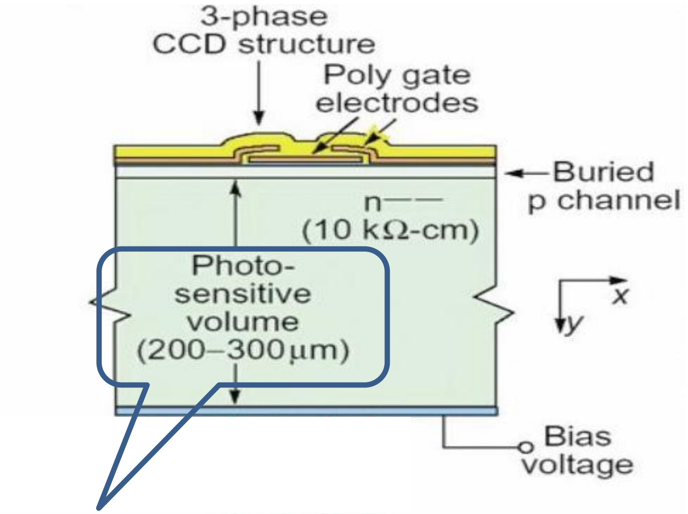


4 CCDs (up to 10 grams)

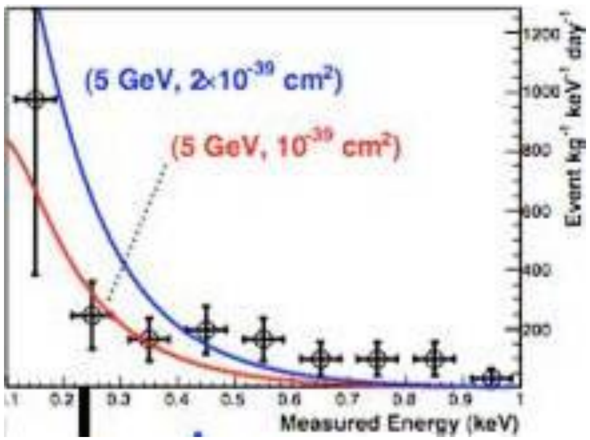
- A two year run at NuMI proved the feasibility of a larger scale experiment and aiming for:
  - Lower backgrounds.
  - Larger detector mass.

CCDs as DM detector

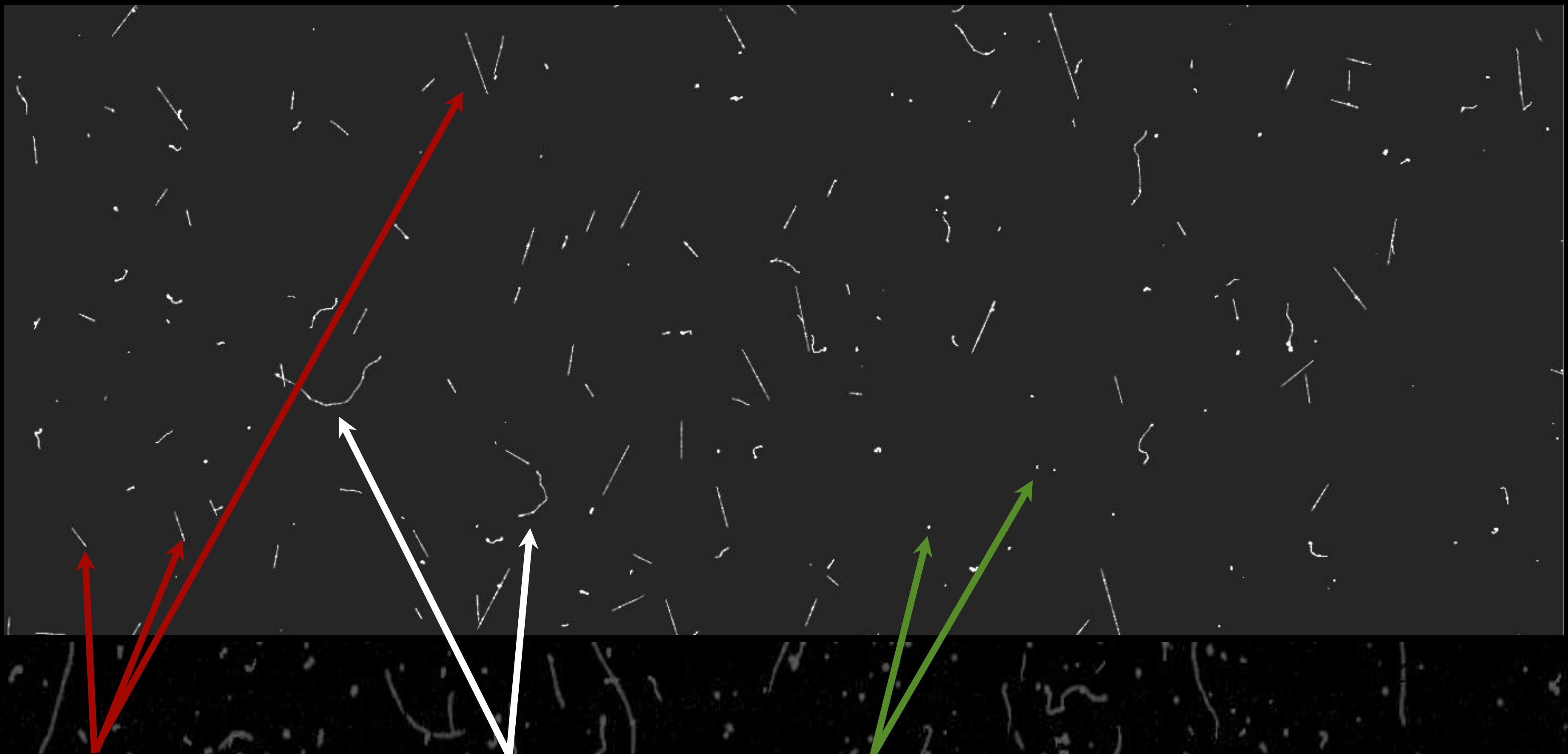
- Our CCDs are thick compared to most CCDs.
  - CCDs at SNOLAB have 1 gram of mass each.
  - New CCDs for DAMIC100 are larger and thicker: up to 5.7 grams each.
  - Effective threshold levels of ~30 eVee.
  - Lower thresholds are possible (R&D).
- Compared to other DDM experiments:
  - DAMIC low threshold allows the exploration of a WIMP mass area that has been forbidden to most DDM experiments so far.
  - The number of recoils exponentially increases at lower energies.



New CCDs 500 to 650 um



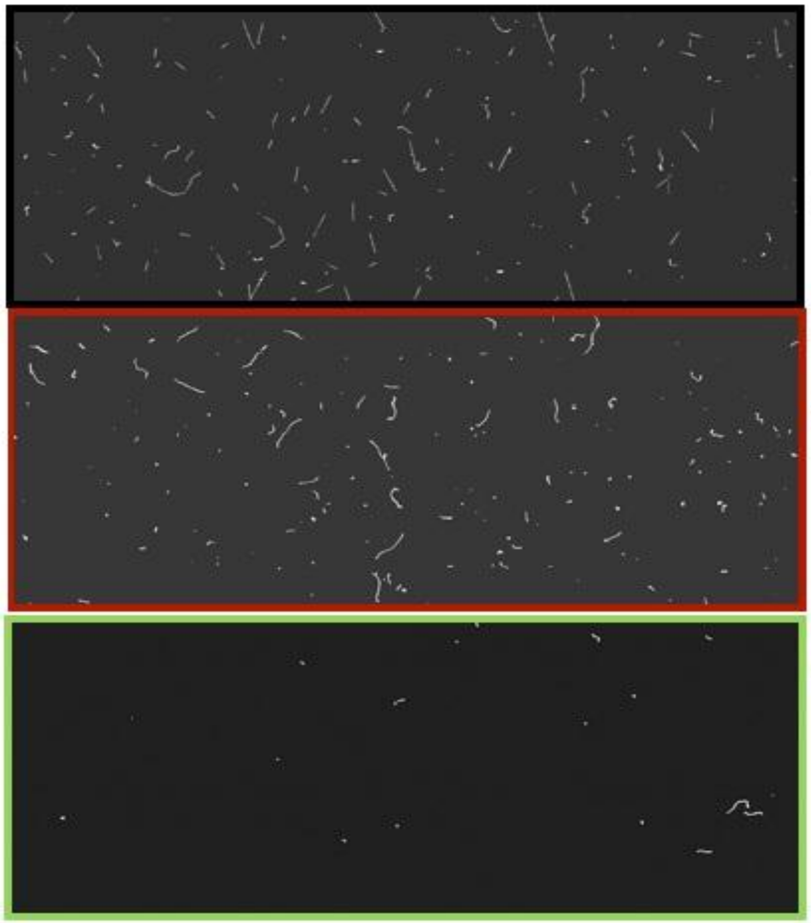
Particle detection with CCDs



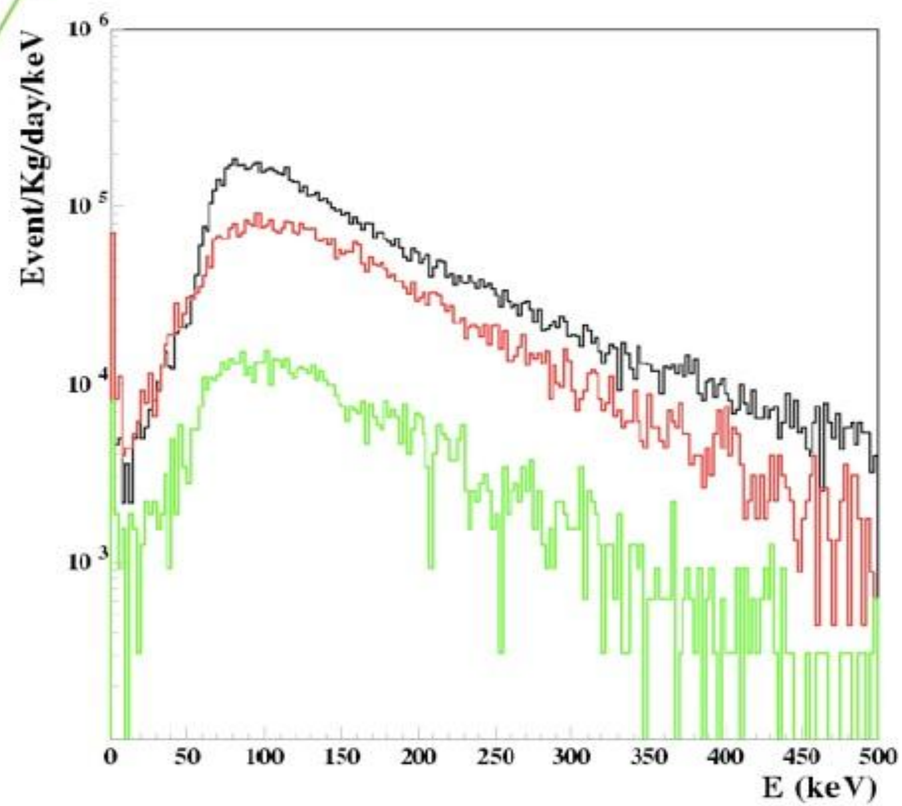
muons, electrons and diffusion limited hits.

nuclear recoils will produce diffusion limited hits

Early background measurements at different depth levels

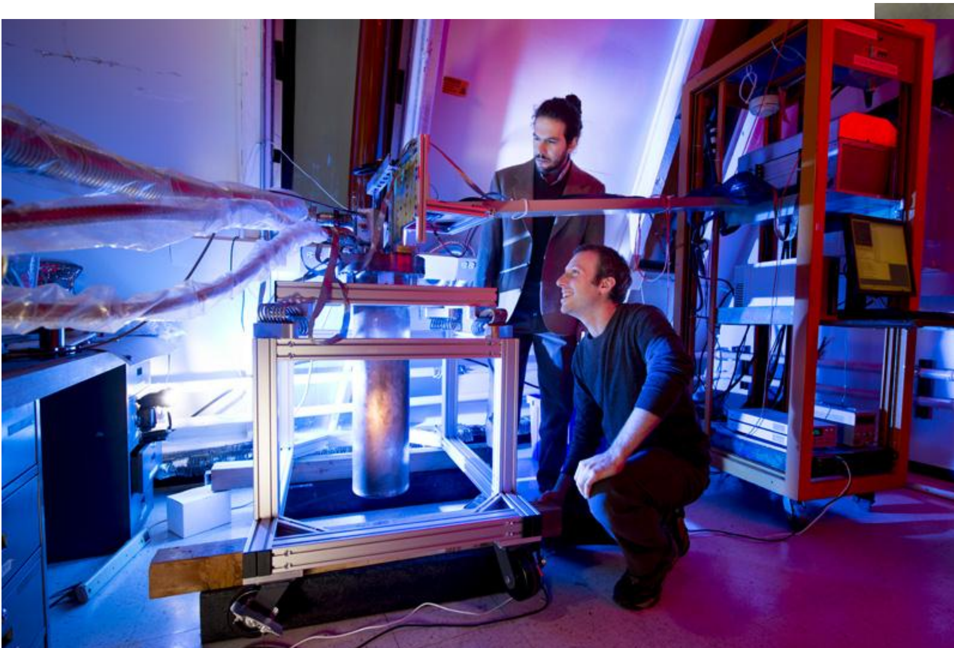


tracks:
- surface
- Minos (350’ underg.)
- Minos + 8”lead shield



2012 DAMIC goes to SNOLAB

- The DAMIC collaboration grows:
  - Fermilab, U Chicago, U Zurich (Switzerland), Michigan, UNAM (Mexico), FIUNA (Paraguay), CAB (Argentina)



DAMIC ready at Fermilab

DAMIC installed at SNOLAB

DAMIC Collaboration

First Collaboration meeting in Mexico, May 2013

Centro Atomico Bariloche, Fermi National Accelerator Laboratory, Universidad Autonoma Nacional de Mexico, Universidad Nacional de Asuncion, University of Chicago, University of Michigan, University of Zurich

10 faculty, 2 postdocs, 5 graduate students, undergraduate students

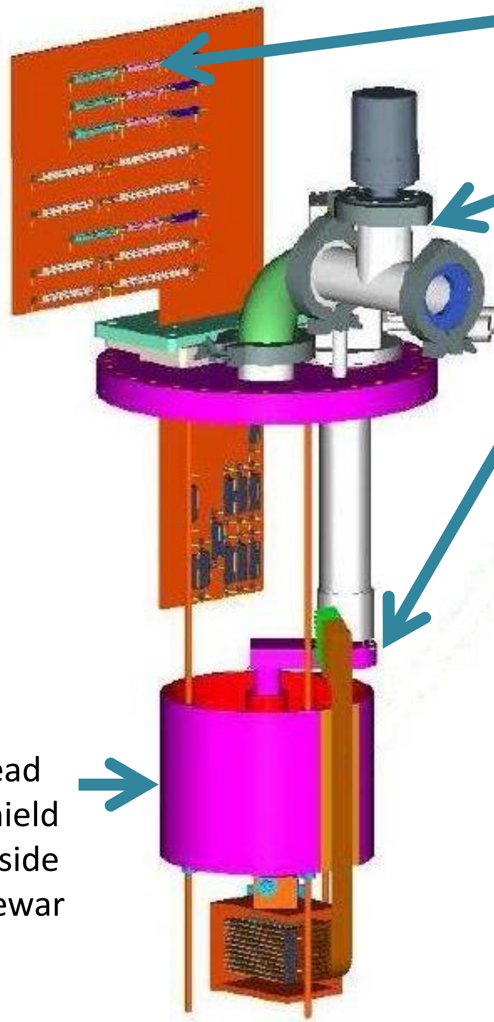
DAMIC at SNOLAB in Canada

- SNOLAB: 10 grams of mass, installed and commissioned in Dic 2012.
- Not all the detectors worked.
  - The detectors were free leftovers from DES-DECam and some were defective.

Vacuum feed trough for electronics

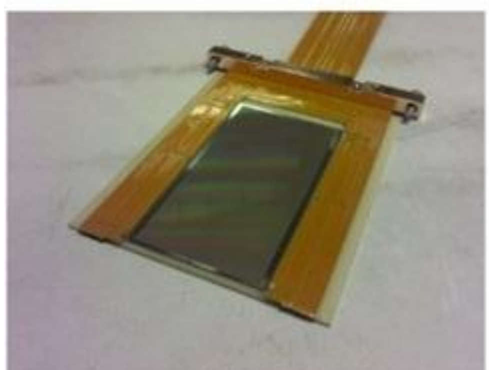
Vacuum pipe and gauge

Cold finger

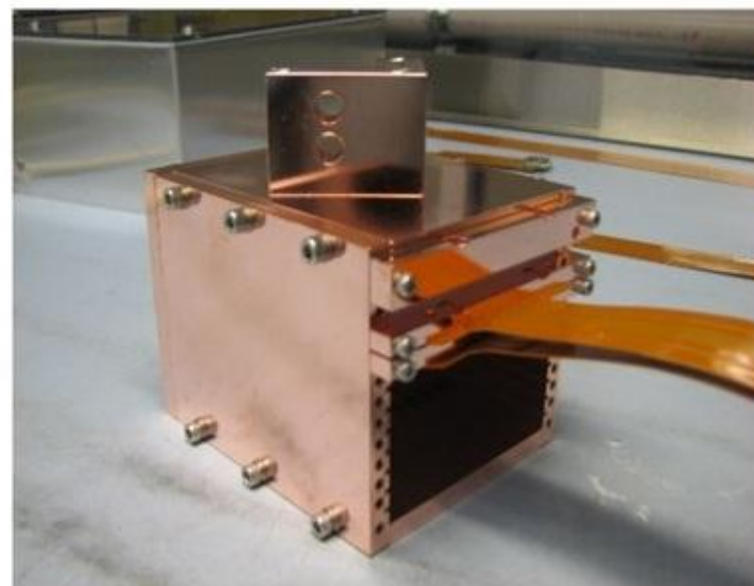


Lead shield inside dewar

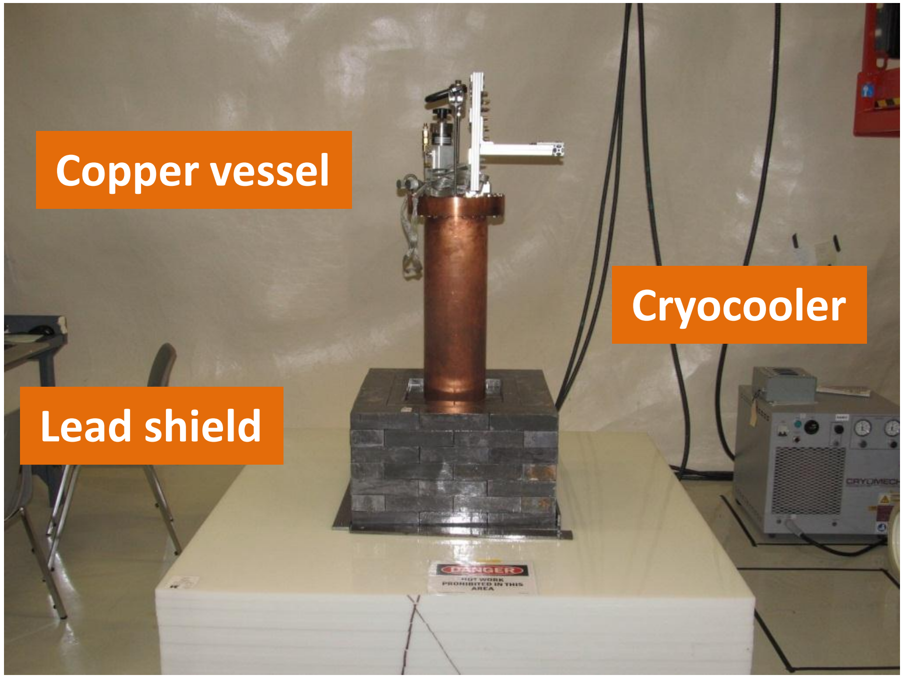
Packaged CCD showing substrate and flex circuit for electrical signals

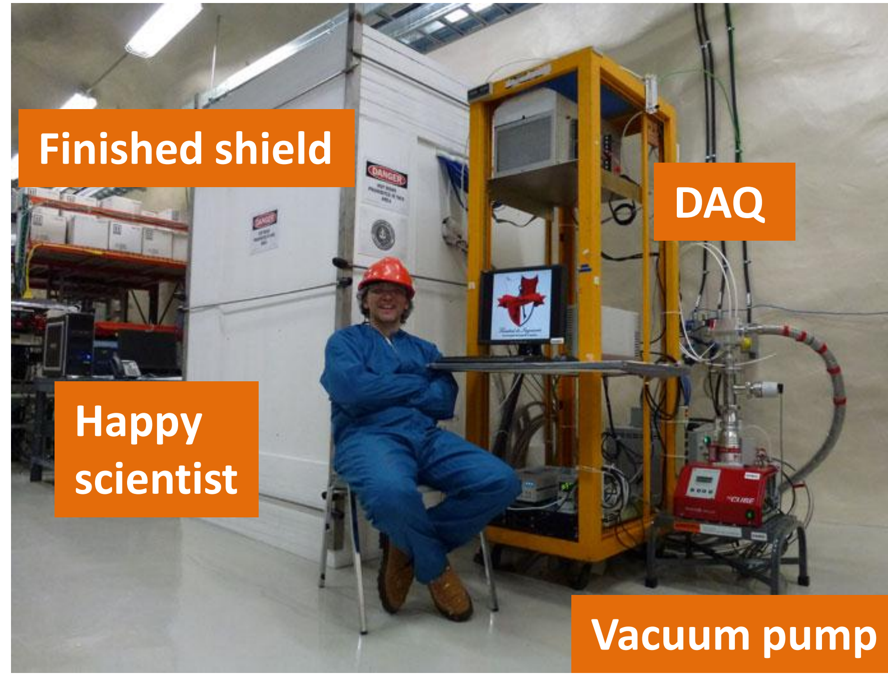


Copper box can host up to 10 CCDs
And keeps them cold



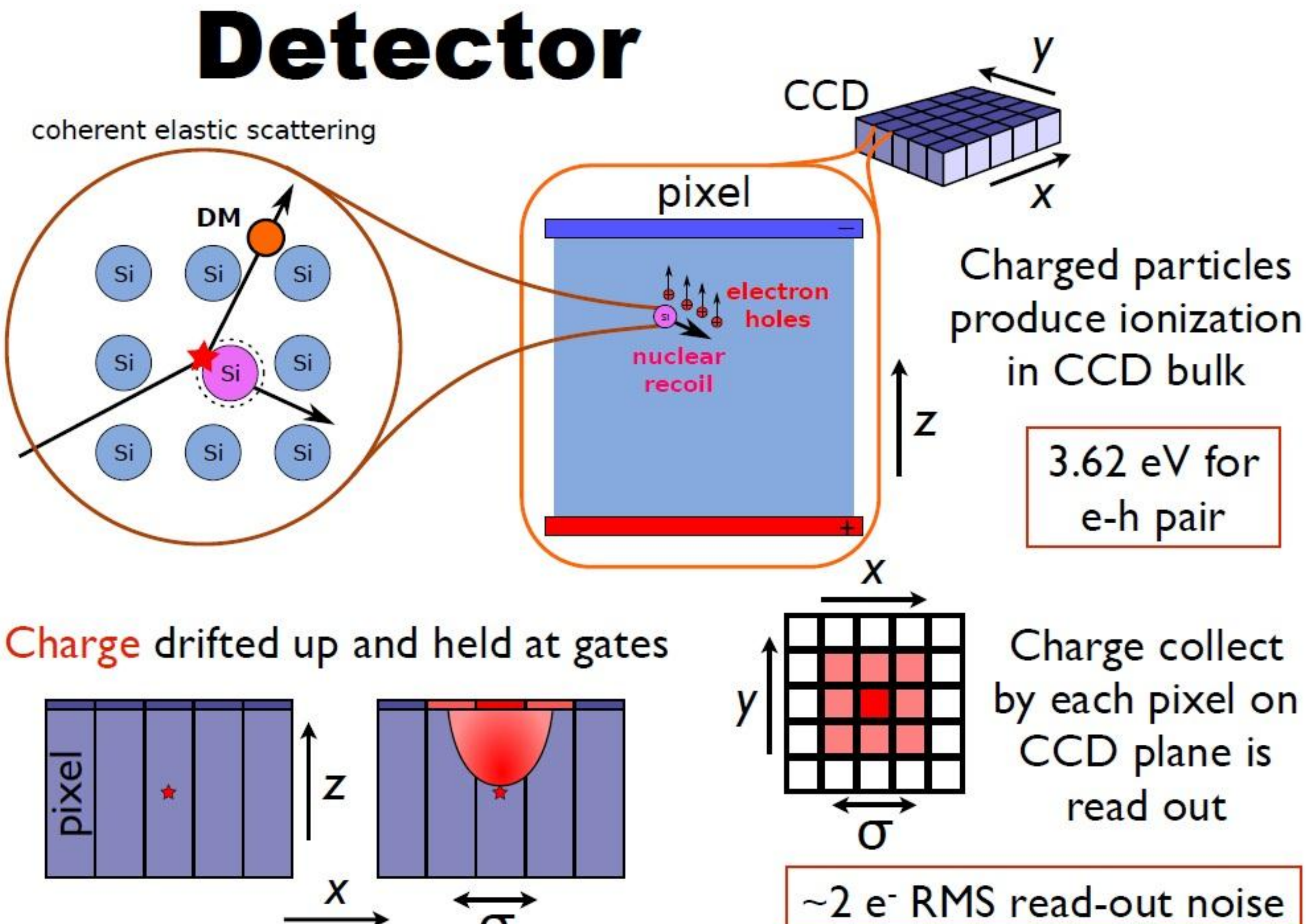
DAMIC at Snolab



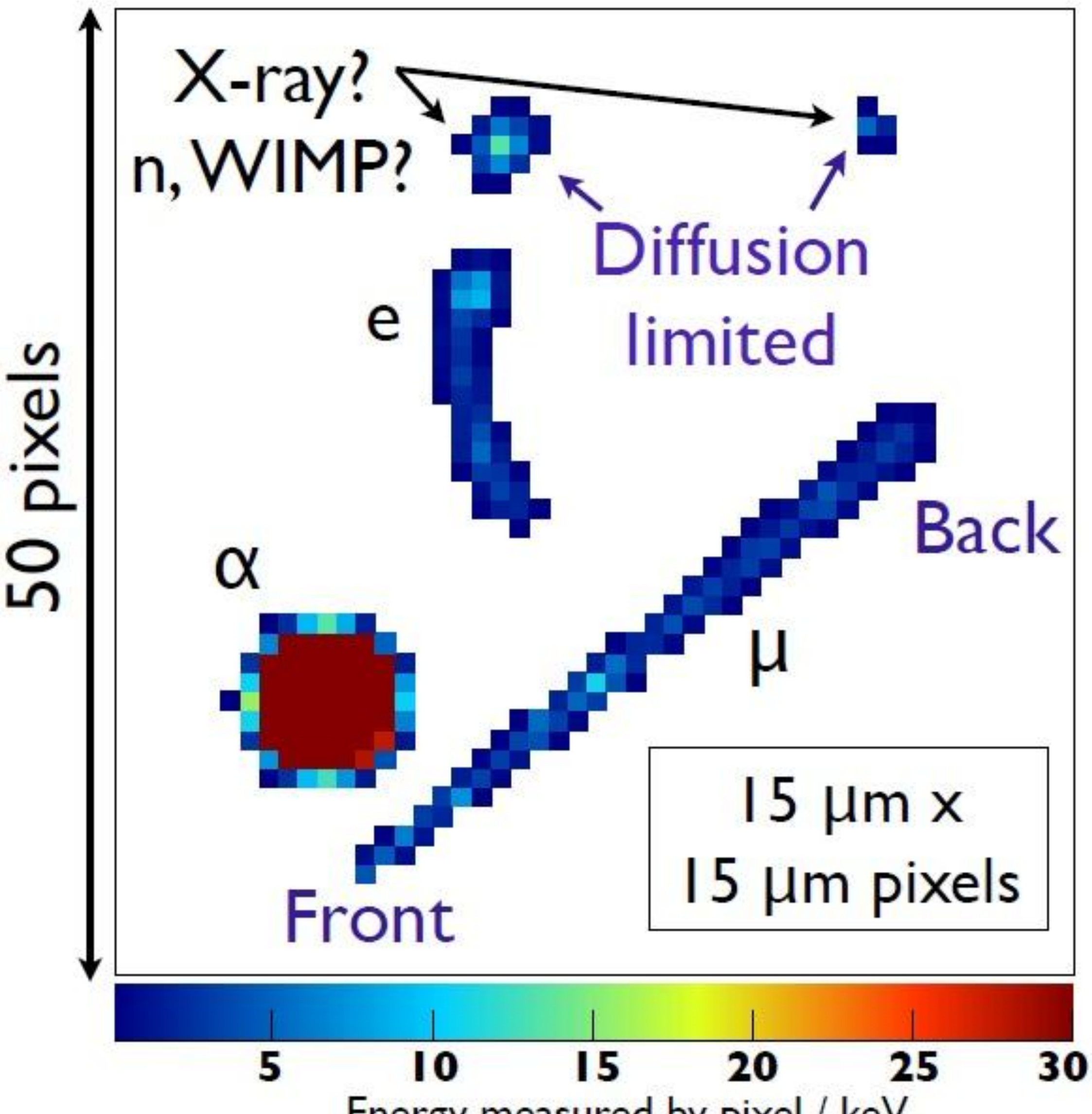


- DAMIC occupies a small footprint
- No short term maintenance required for vacuum, cryo or electronics.
- Operated remotely (currently from Fermilab).

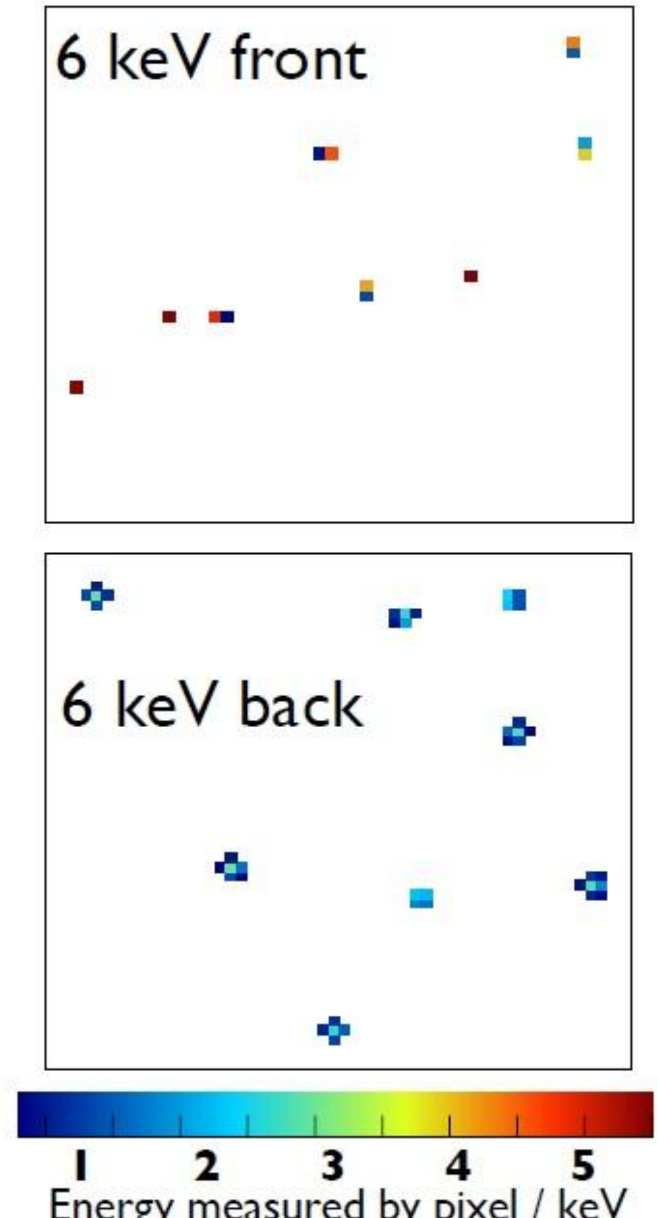
2D images with 3D pattern recognition capabilities



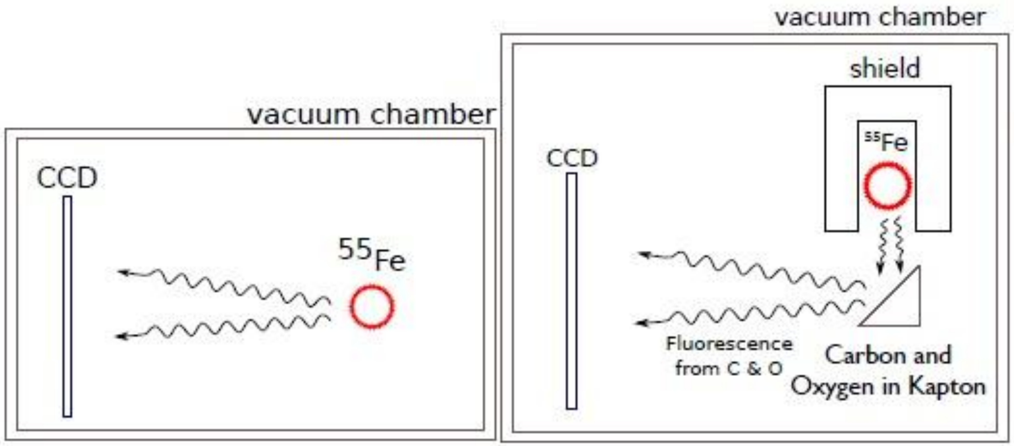
Particle tracks

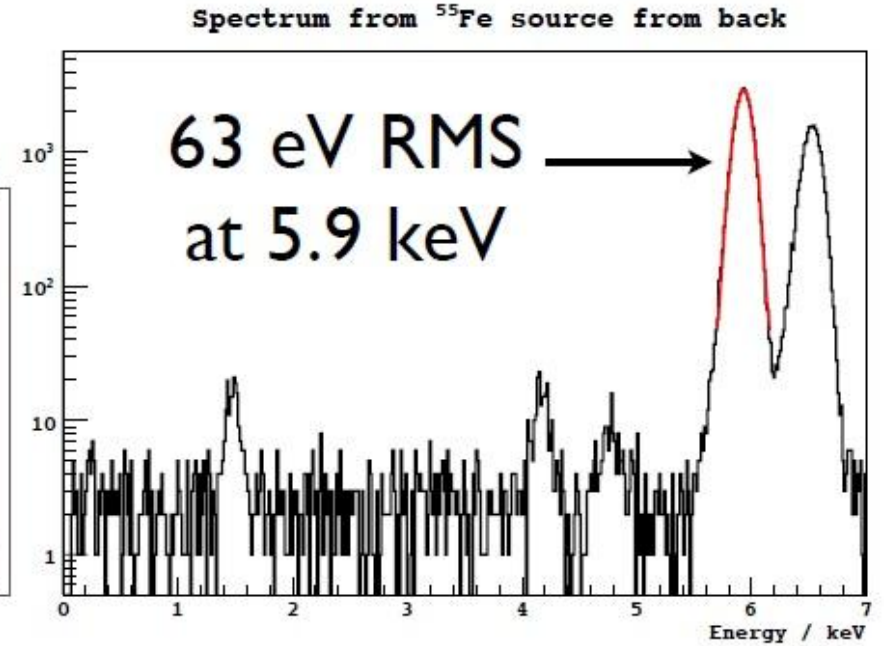


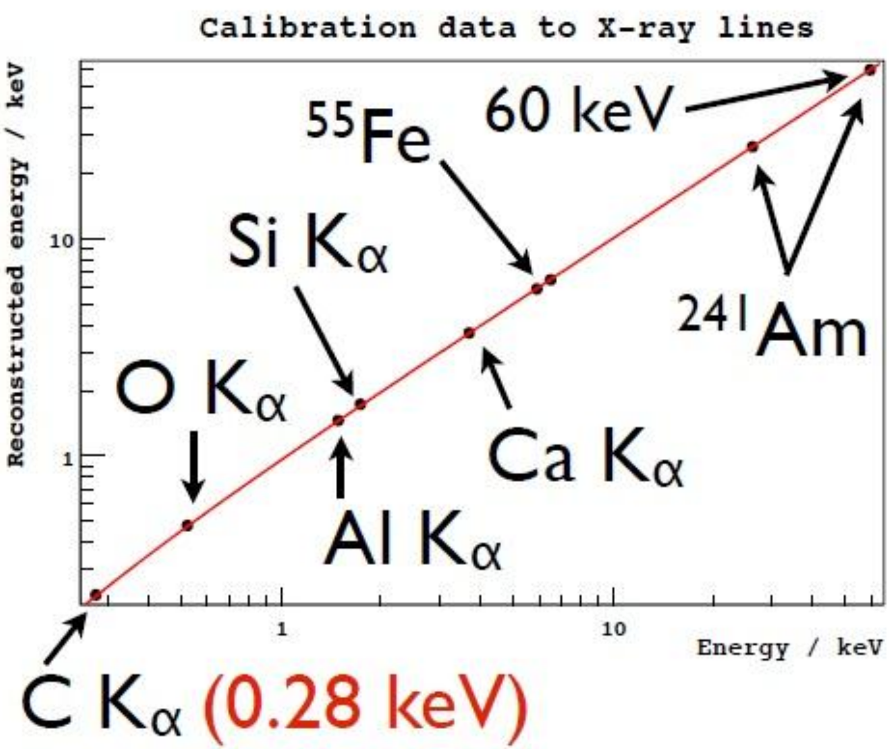
Diffusion limited

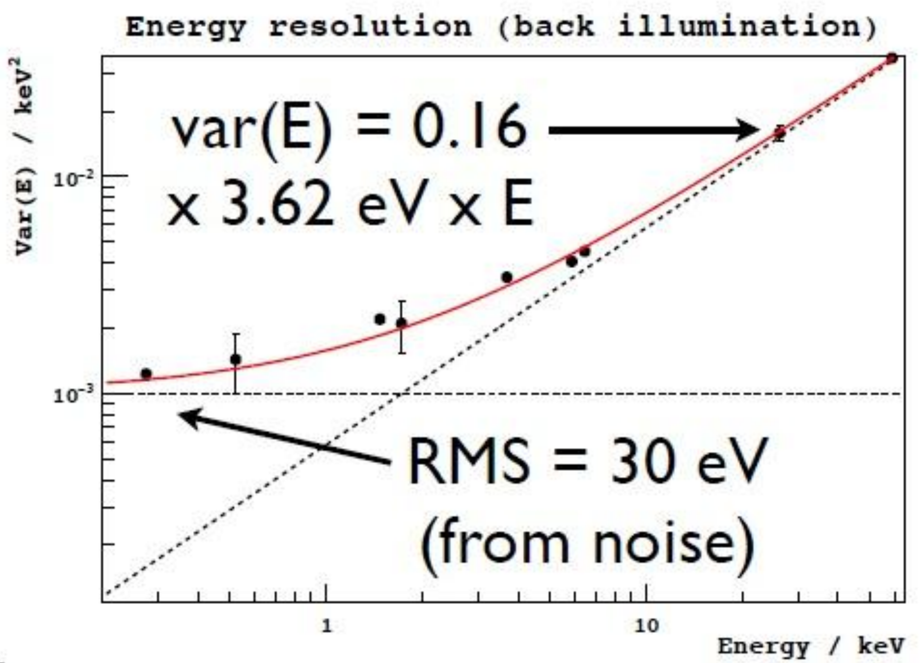


E response


vacuum chamber
CCD
55Fe
vacuum chamber
shield
55Fe
CCD
Fluorescence from C & O
Carbon and Oxygen in Kapton


Spectrum from 55Fe source from back
63 eV RMS
at 5.9 keV
Energy / keV

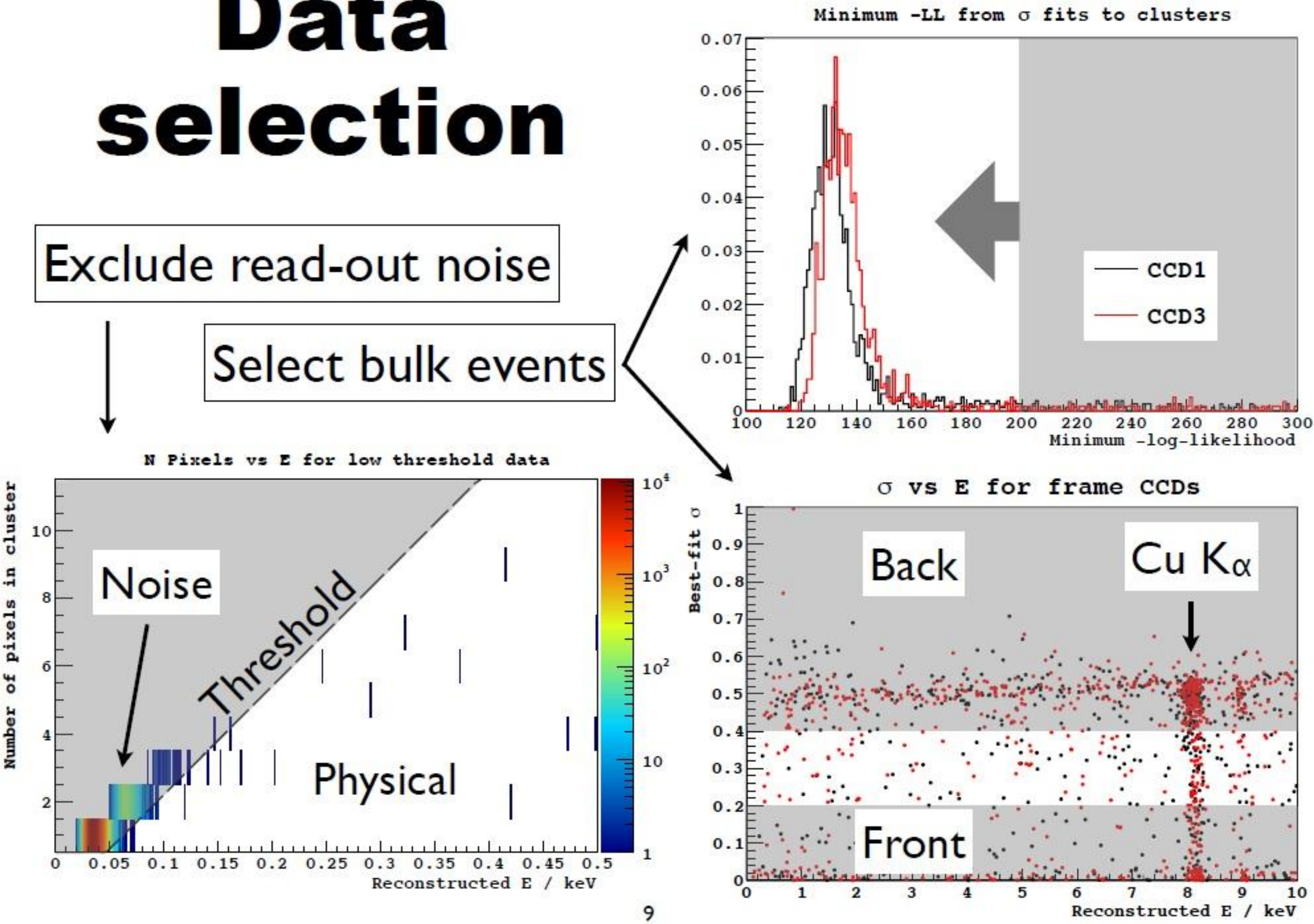

Calibration data to X-ray lines
Reconstructed energy / keV
Energy / keV
55Fe
60 keV
Si Kα
241Am
O Kα
Ca Kα
Al Kα
C Kα (0.28 keV)


Energy resolution (back illumination)
Var(E) / keV2
var(E) = 0.16
x 3.62 eV x E
RMS = 30 eV
(from noise)
Energy / keV

Data selection

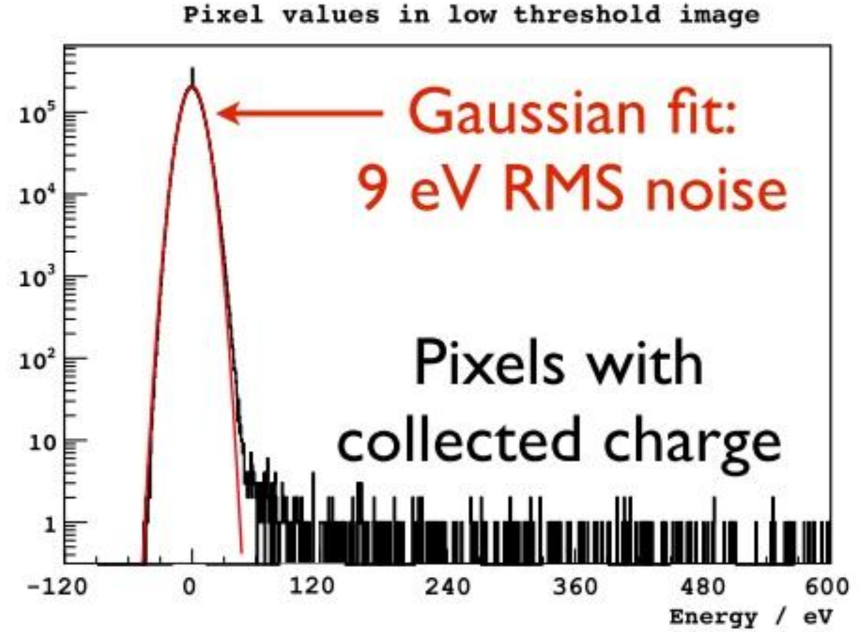
Exclude read-out noise

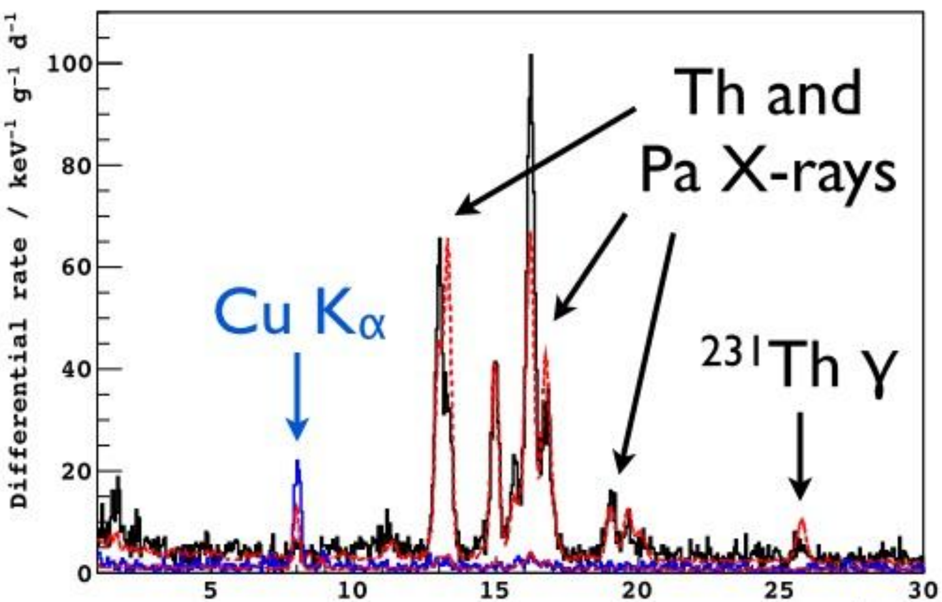
Select bulk events

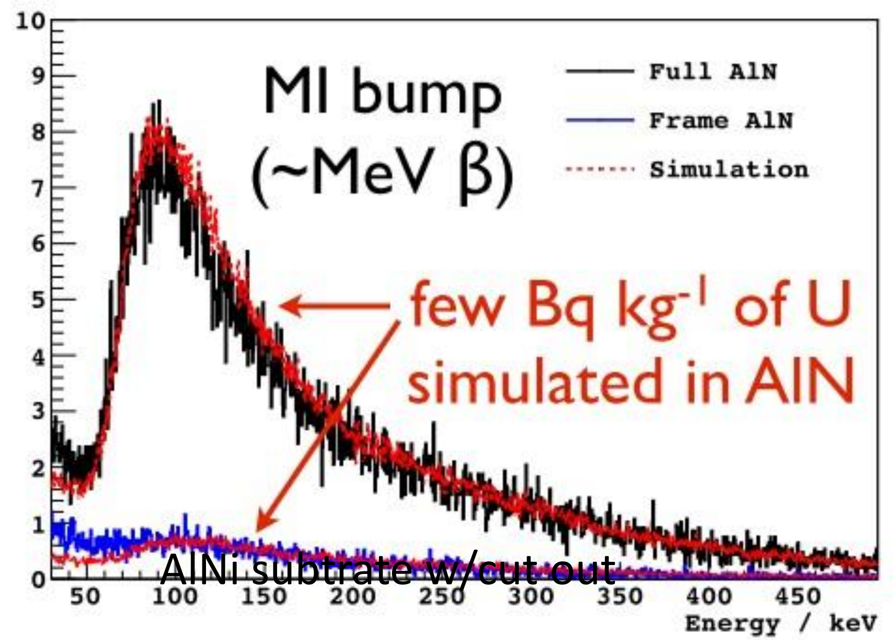


SNOLAB data

1g, 8 Mpixel CCDs
6 cm x 3 cm x 250 μm
~50 days of data
2 CCDs with full AlN
and 2 with frame AlN

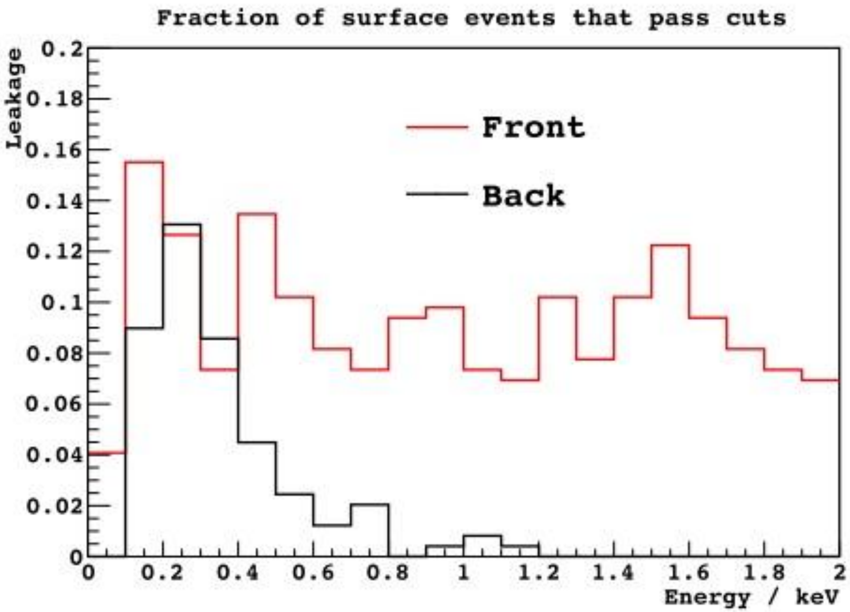




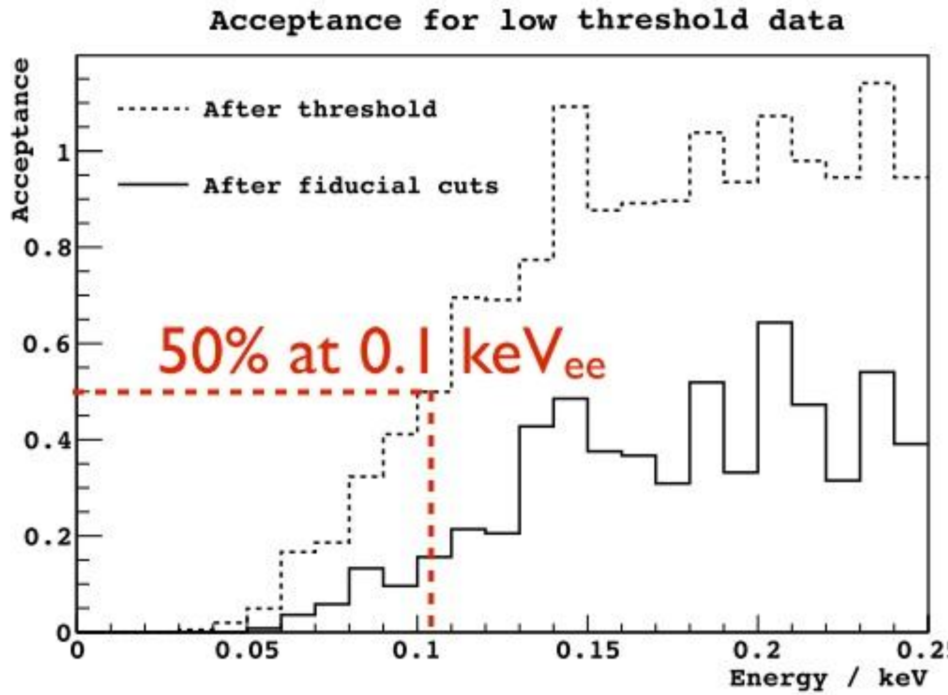


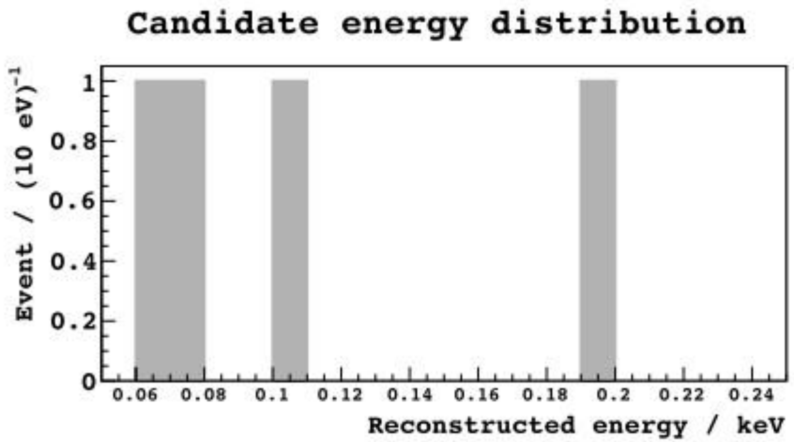
Low threshold data

From simulation on SNOLAB blanks and data from ^{252}Cf source



200 read-outs
(every 2.8 h)
24 g d exposure





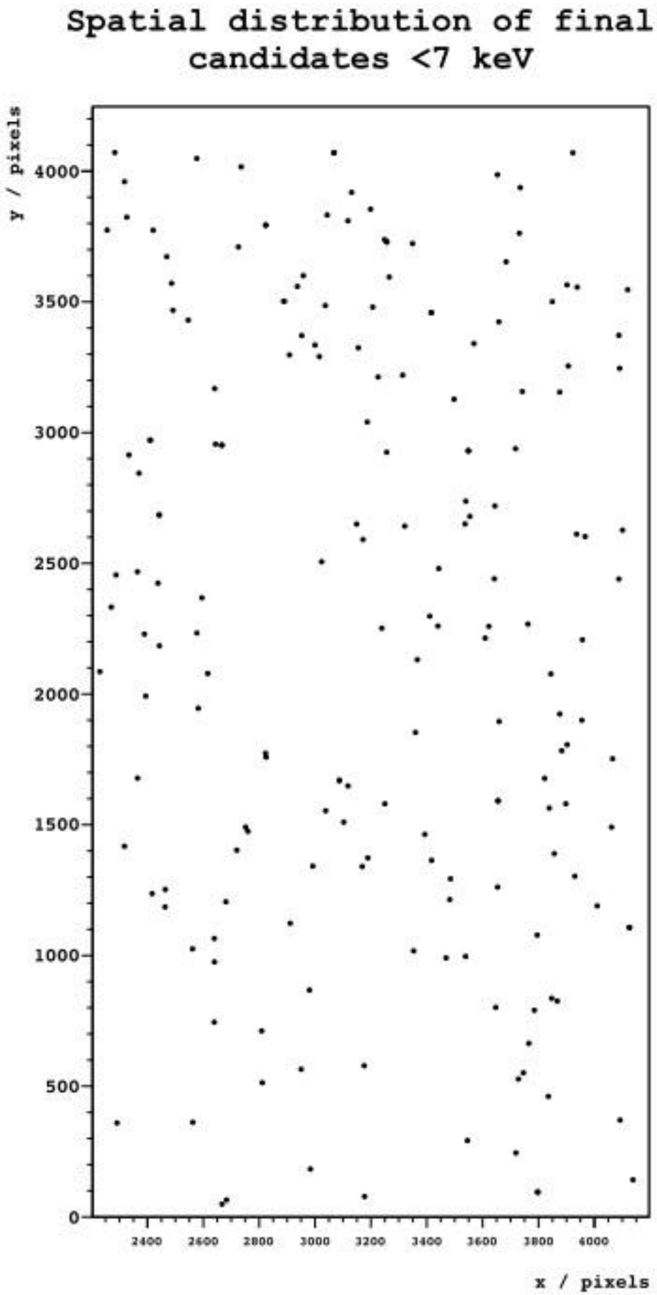
Full data

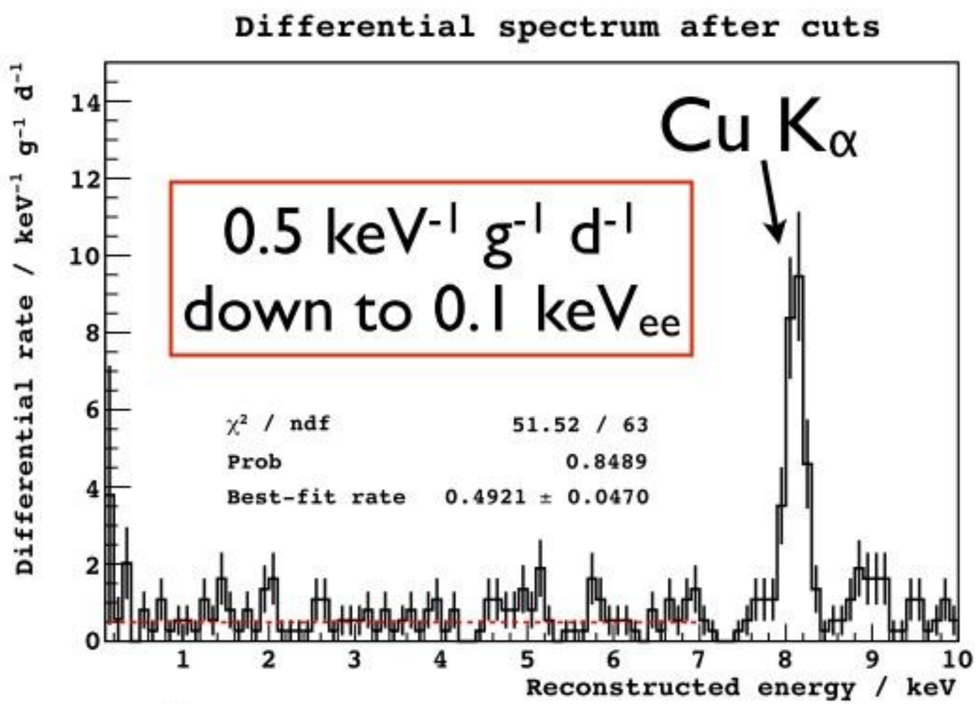
2 frame CCDs (2g)

40 days 0.3 keV threshold

12 days 0.1 keV threshold

Fiducial cut (~35% acceptance)





Backgrounds

CCD + support:

<10 -4 Bq kg -1 of U + Th from counting α s. α s most likely from surface contamination.

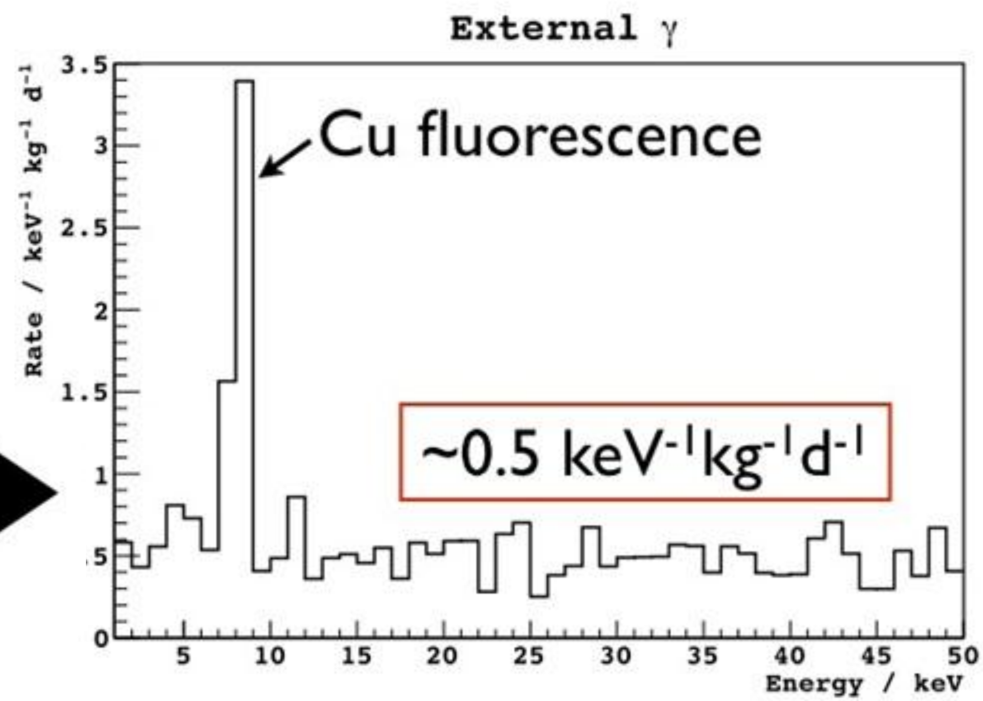
^{32}Si at 300 day^{-1} kg^{-1} can be vetoed by the ^{32}Si → ^{32}P → ^{32}S decay sequence with <1% loss of exposure. Similar Veto works for 210 Pb.

Typical analysis results of electronic-grade polysilicon (NAA and IR at RT) [4].

Element	Atoms/cm^3
Carbon	$< 2.0\times10^{16}$ [1)]
Oxygen	$< 1.0\times10^{16}$ [1)]

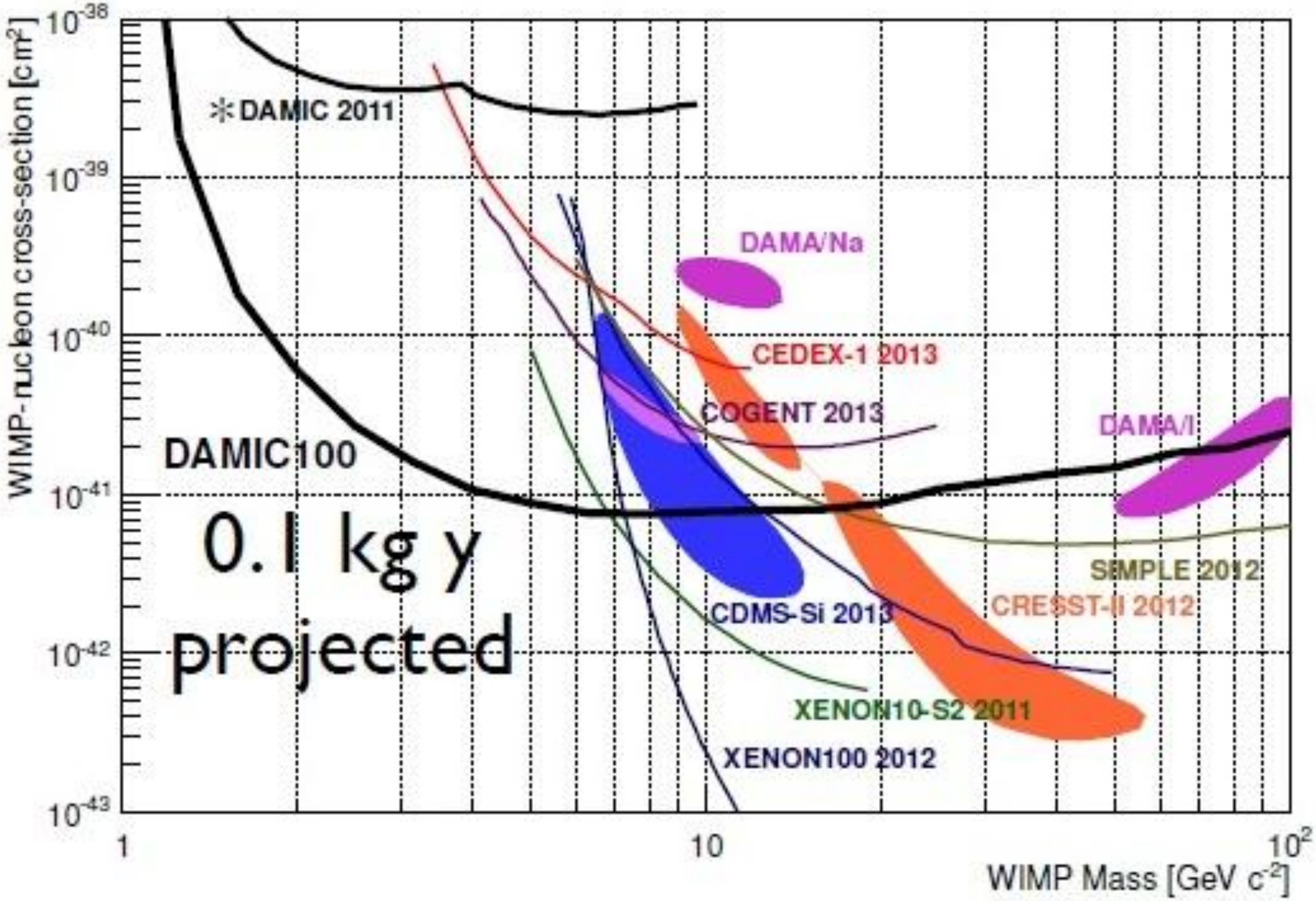
... negligible ^{14}C, etc.

Goal: to be dominated by external γ



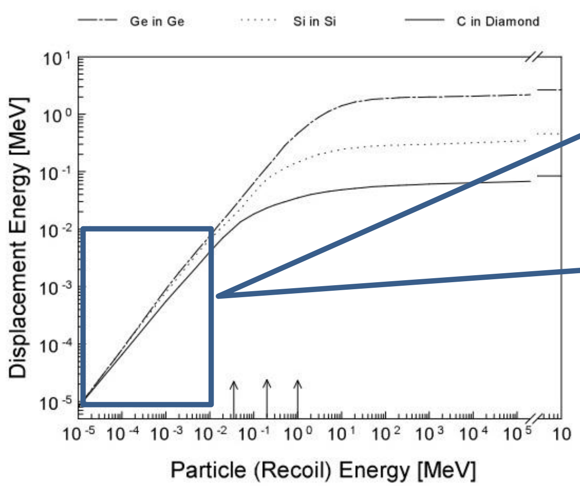
Calculated sensitivity of DAMIC100 at SNOLAB

To be explored by DAMIC100 starting in 2014



Limit: 100grams/year, 1 year of exposure, background of 1/kev/kg/day

Calibration of the quenching factor in Si at low energies is crucial

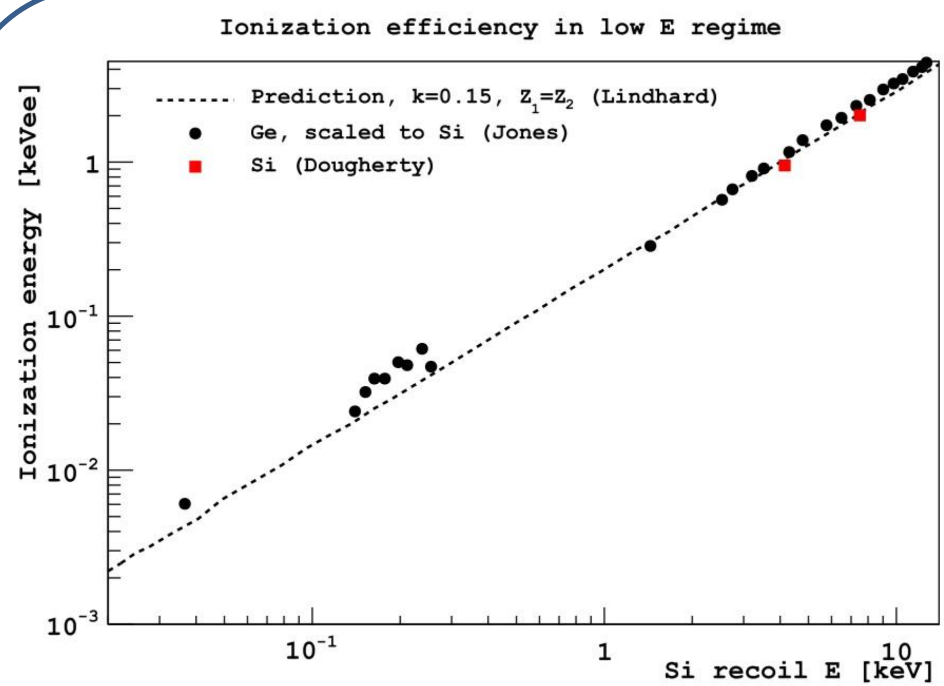


S.Lazanu[a] and I.Lazanu[b]

[a]*National Institute for Materials Physics, POBox MG-7, Bucharest-Magurele, Romania, e-mail:lazanu@alpha1.infim.ro*

[b]*University of Bucharest, POBox MG-11, Bucharest-Magurele, Romania, e-mail: ilaz@scut.fizica.unibuc.ro*

Quenching factor



Measuring Q and detection efficiency: ongoing efforts

Fermilab

Scattering experiment at a neutron beam.

University of Chicago & Fermilab

CCD activation at a neutron beam:

measure nuclear recoils after EC of ^{7}Be ^{22}Na.

University of Chicago

Neutron capture: $^{28}\text{Si}+\text{n} \rightarrow {}^{29}\text{Si}+\gamma$

Using a LAAPD + NaI detector in coincidence.

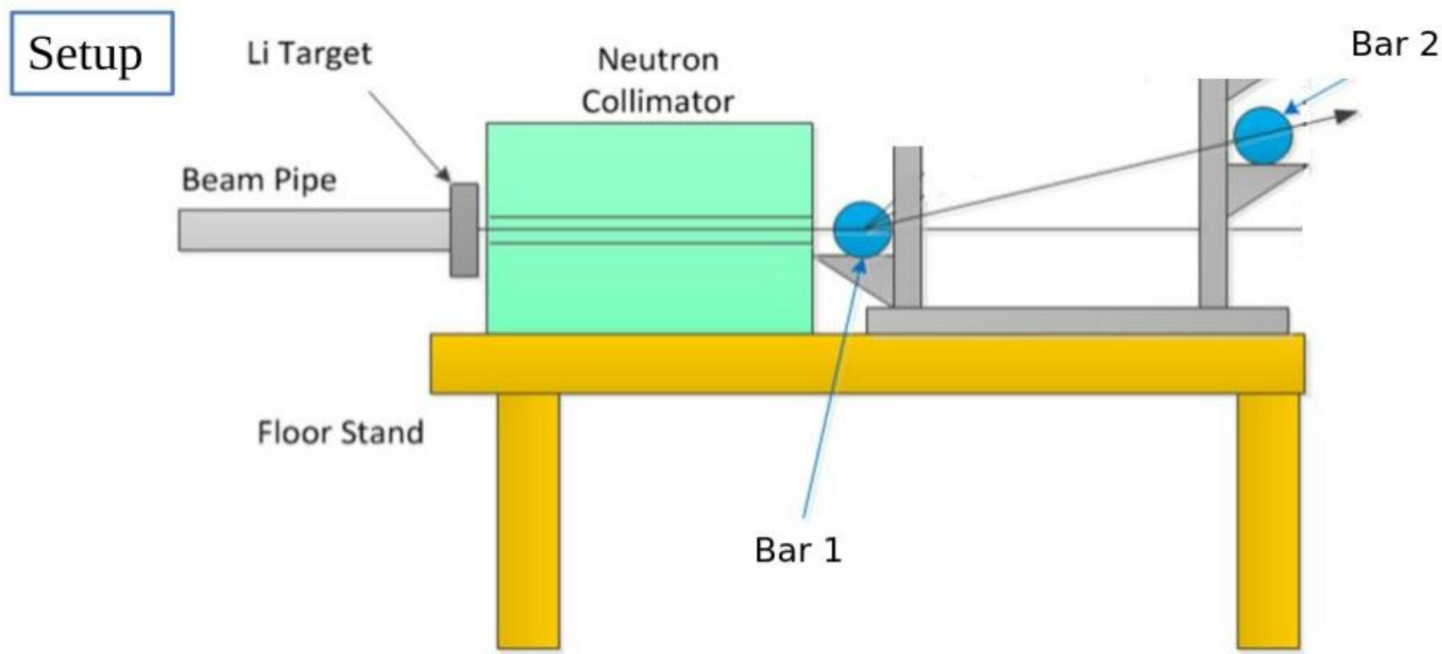
Balseiro Institute

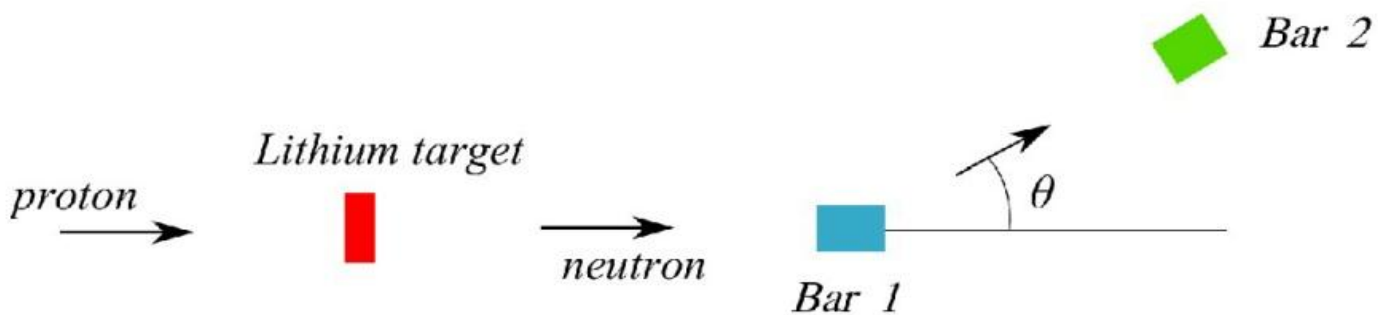
Neutron capture: $^{28}\text{Si}+\text{n} \rightarrow {}^{29}\text{Si}+\gamma$

Using a CCD at a nuclear reactor.

DAMIC calibration with fast neutrons: Test experiment, end of 2013

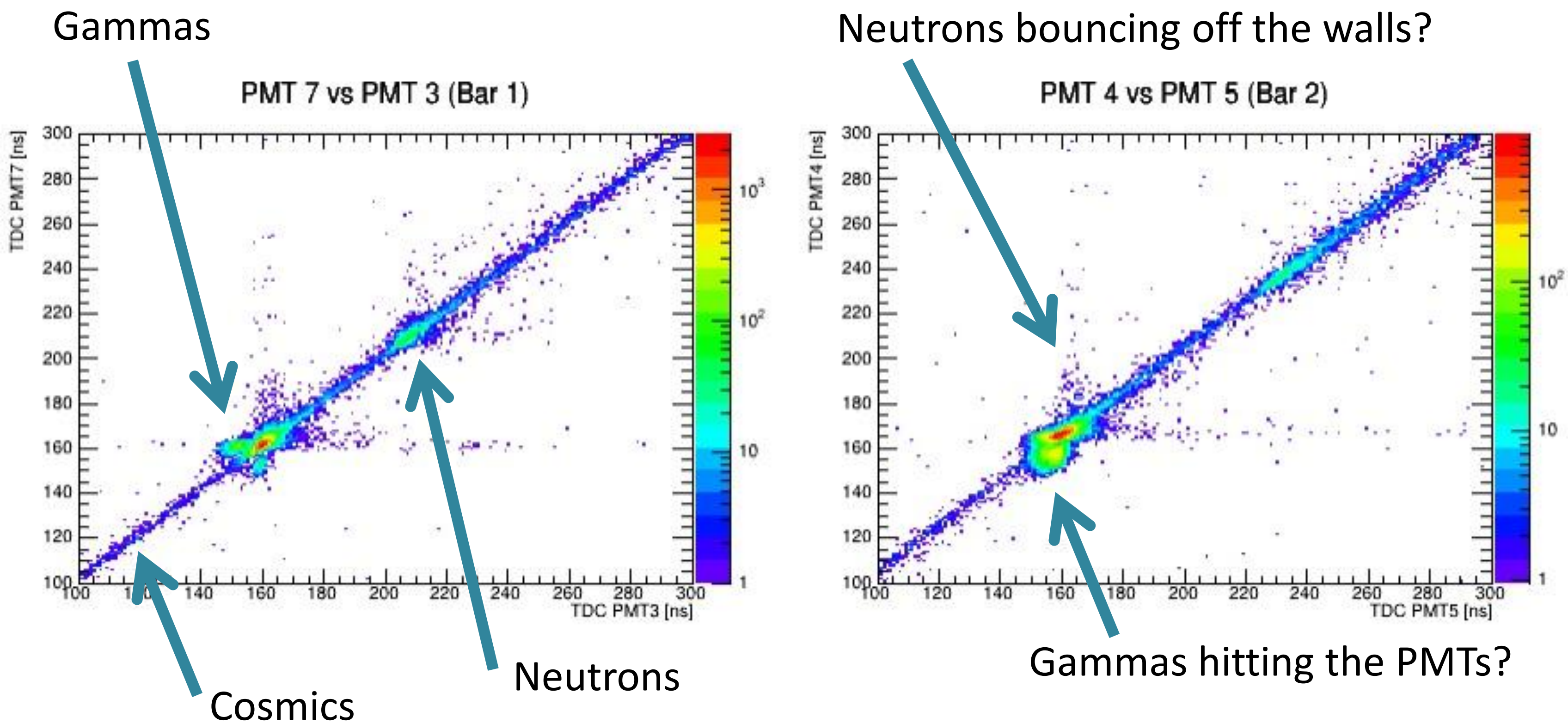
Analysis of the 2-days beam run at the University of Notre Dame



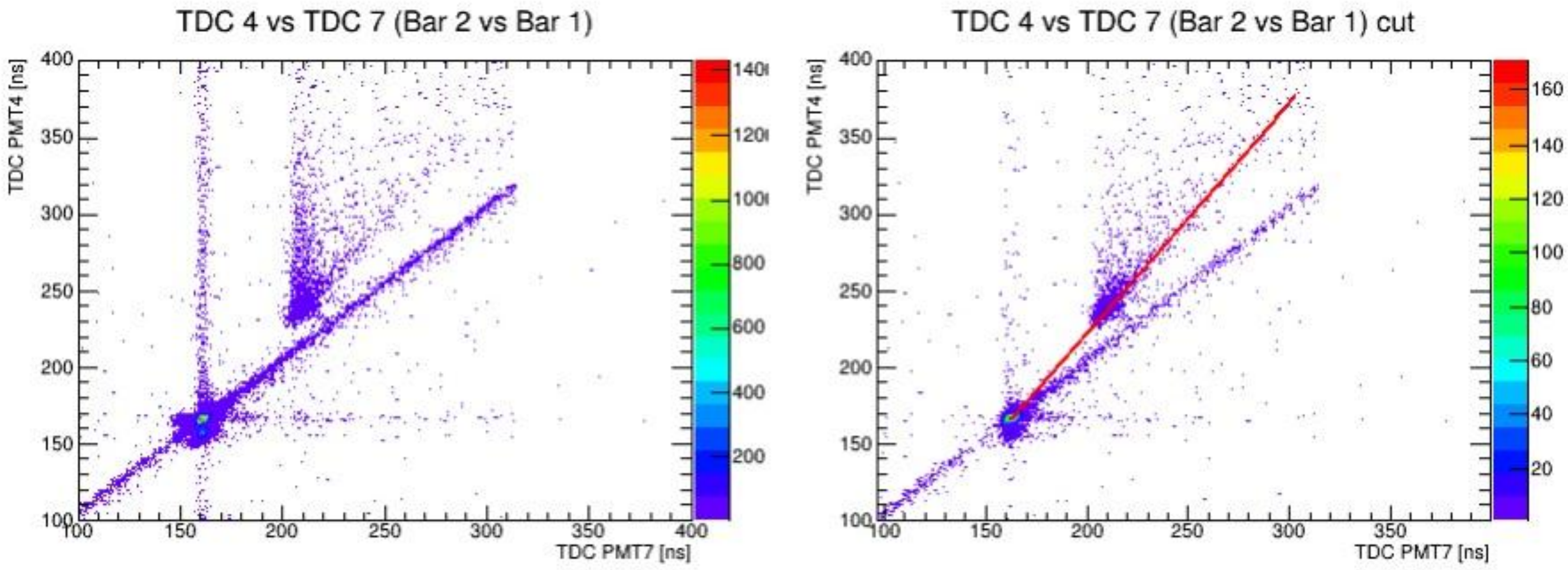


Time calibration

Two scintillator bars with PMTs at each end.
Bar1 is on beam axis. Bar2 is off axis.
Trigger: coincidence on Bar1.



Neutron elastic scattering on scintillator



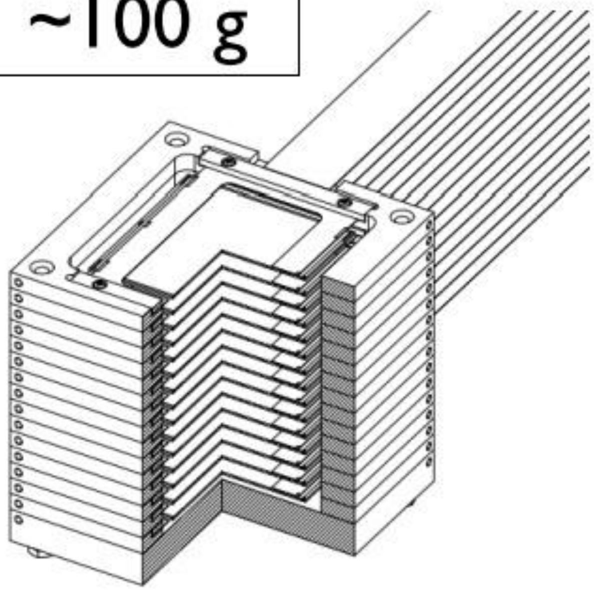
Cut on ADC value of Bar 1

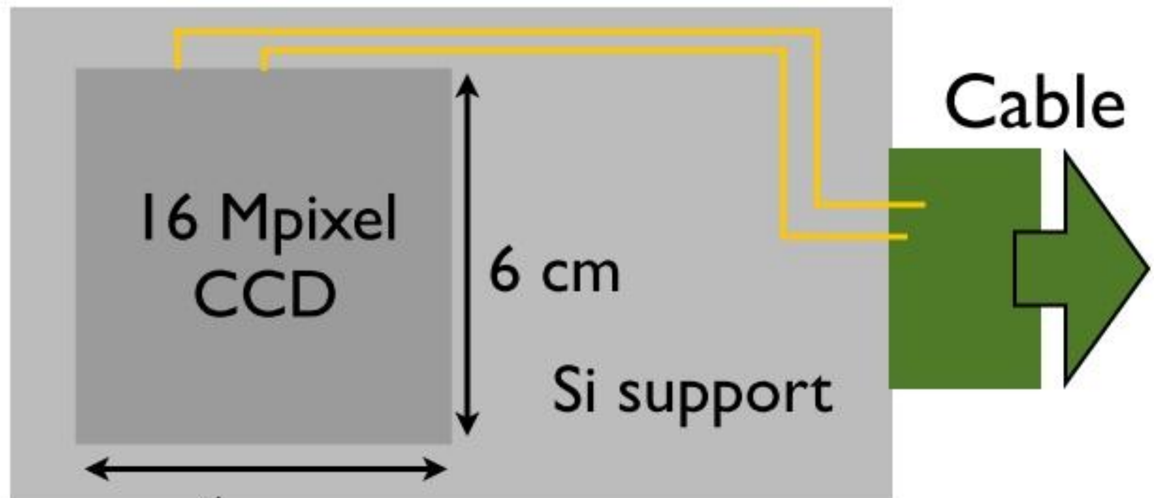
The drift time of neutrons between Bar1 and Bar2 should follow the red line.
The red line angle with respect to 45° is given by the off axis angle of Bar2.

Study of recoils in the silicon detector is being done now.

DAMIC100

15 CCDs
~100 g



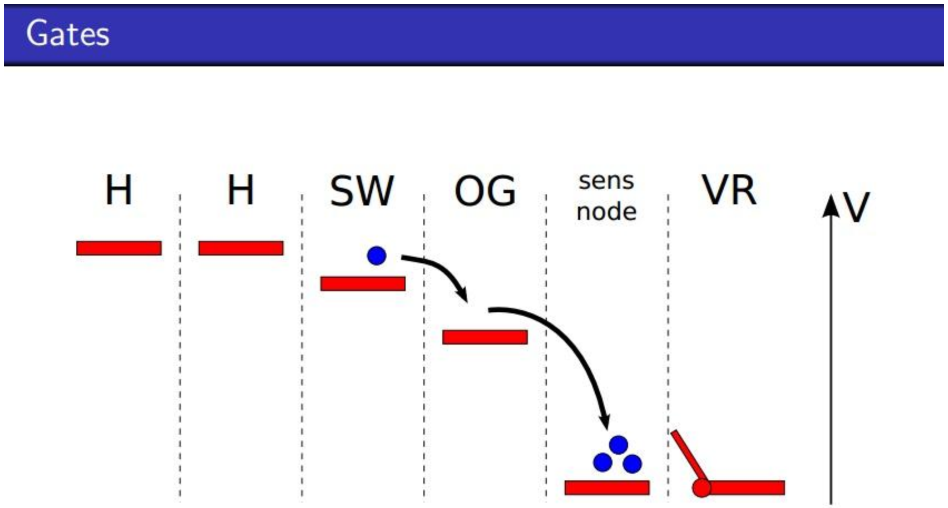


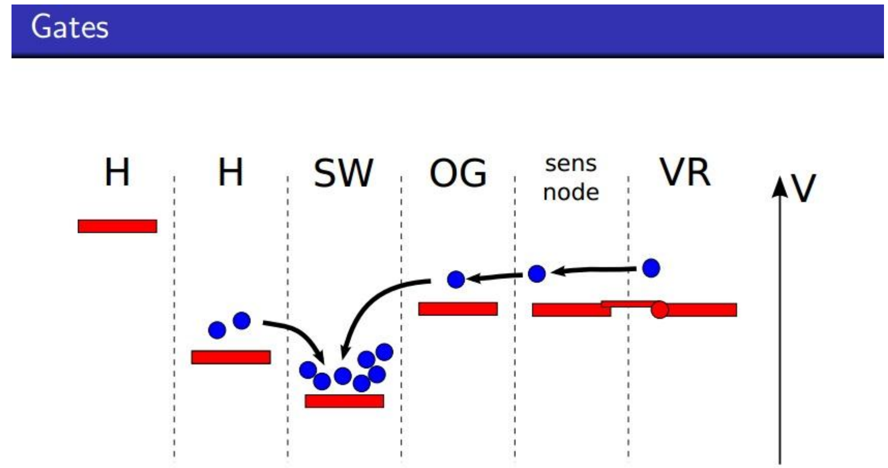
In-situ neutron background measurement with ^{10}B layer

Will install 2 500 µm thick CCDs this fall in SNOLAB. DAMIC100 to be deployed in current Cu vessel + shield in **Spring 2014**.

Testing of new 2Kx4K 500µm and 650µm CCDs

Last pixel in the horizontal register closest to the summing well, sense node and video amplifier

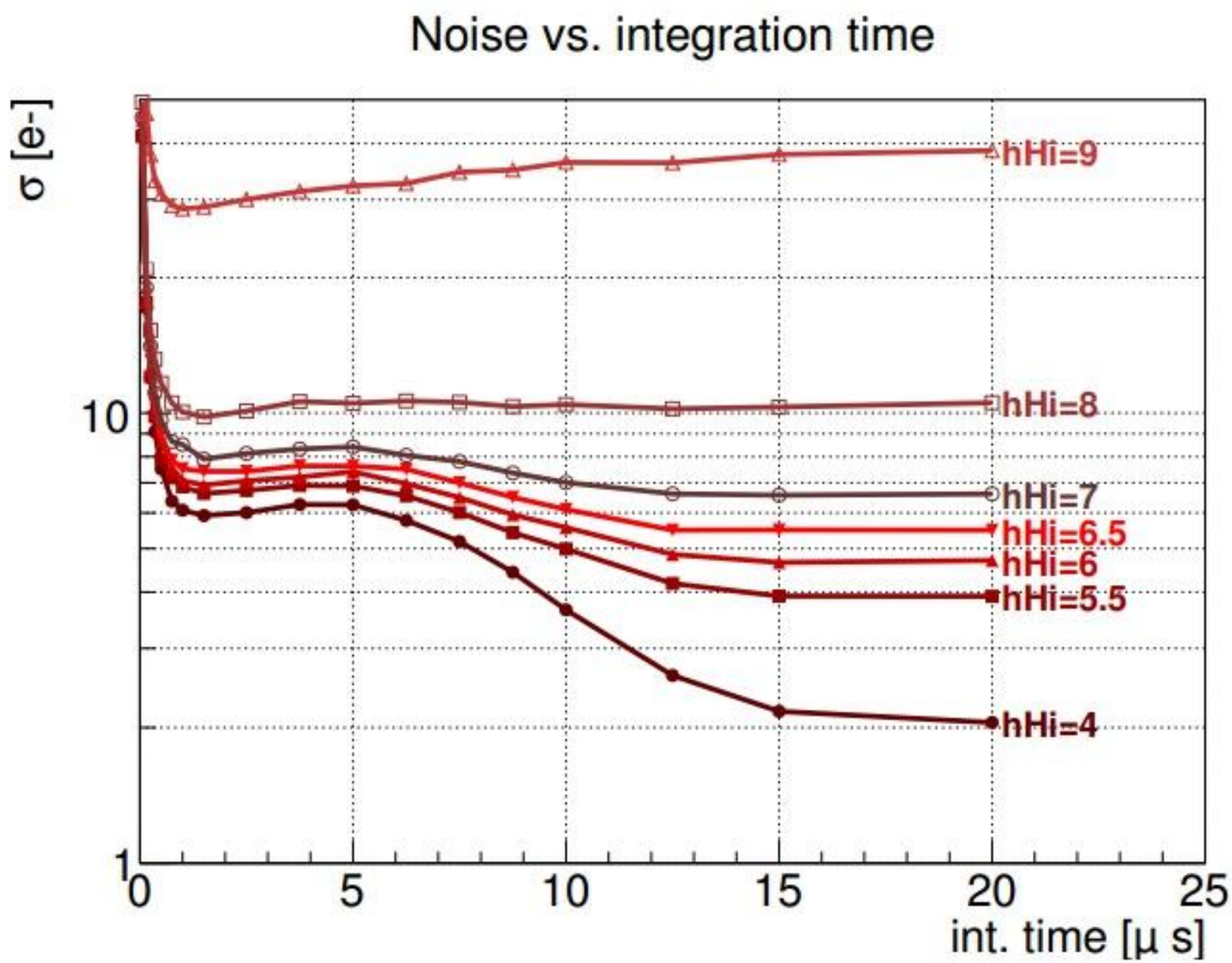




Depending on the voltages the charge could flow either way.
In a normal readout the charge flows from the pixel array to the summing well, to the sense node and out to the video amplifier.
There are several voltages that change state during this process. Including the reset of the sense node before every pixel charge readout.
The voltages have an impact on the charge transfer.
If voltages are not tuned up correctly there are chances for the charge to move in the wrong way and show up as increased “noise”.
The voltage configuration used with the DES CCDs do not seem to be the optimal.

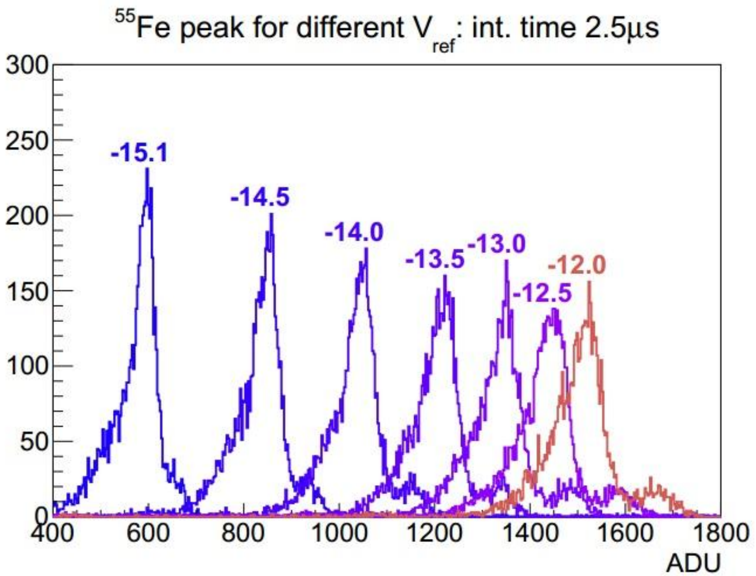
650 µm CCD

The noise depends on the high value of the h. clocks

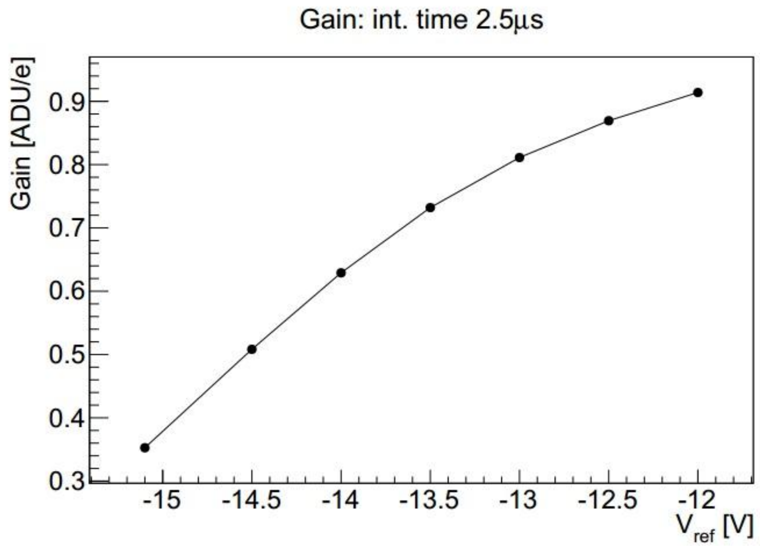


The gain issue

The gain changes with V_{ref}

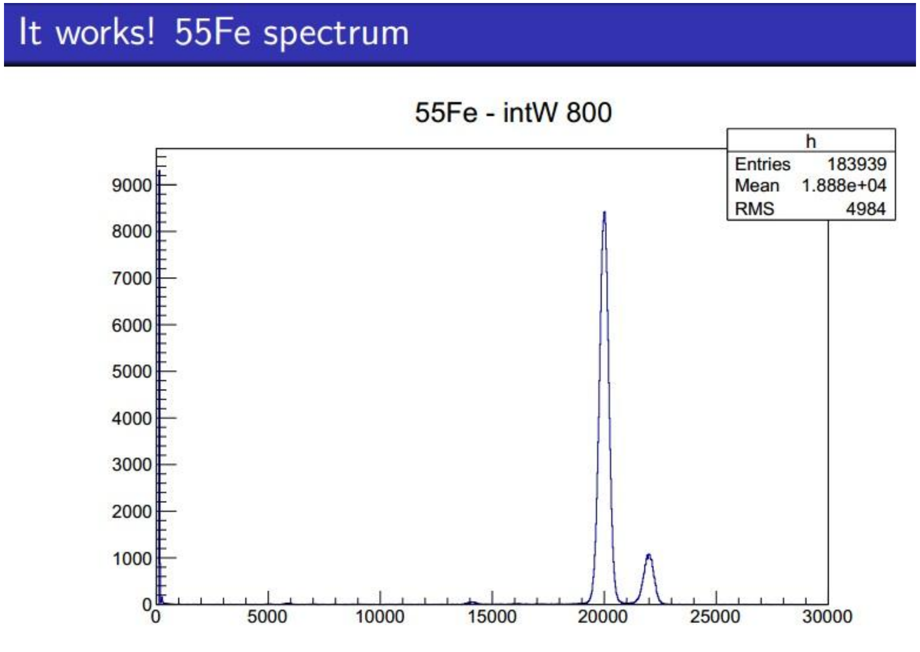


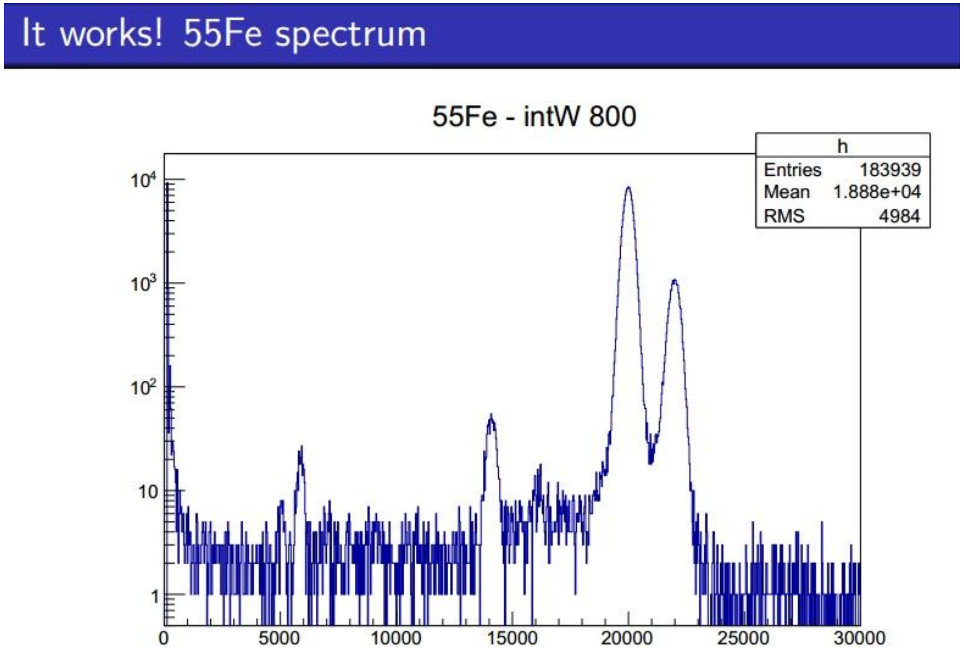
The gain changes with V_{ref}



The CCD gain is defined by the last stage of the readout circuit: Reset circuit and video amplifier .
The gain of the new CCD changes a factor of ~3 with a voltage that bias the video amplifier.
The DES CCD has a 30% gain dependence for the same voltage range.
We need input from the CCD designer to understand that.

Testing of new 2Kx4K 500μm and 650μm CCDs

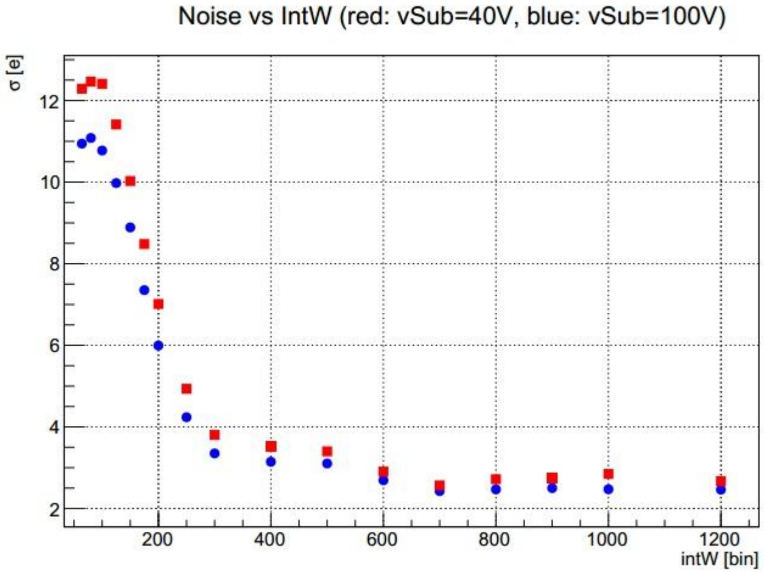




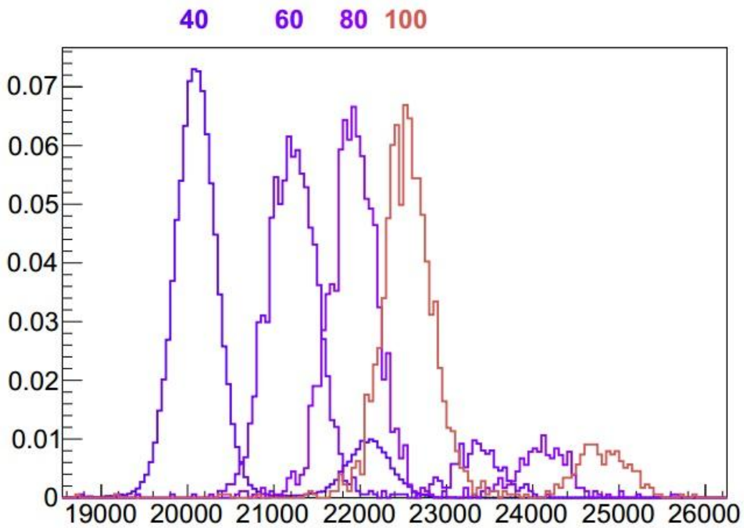
- We generated a set of voltages that produce acceptable results.
  - Still need to understand this detectors better.
- We are testing a 500 um detector, the voltages seem to work fine.

Noise measurements and V_{sub} dependency

Noise



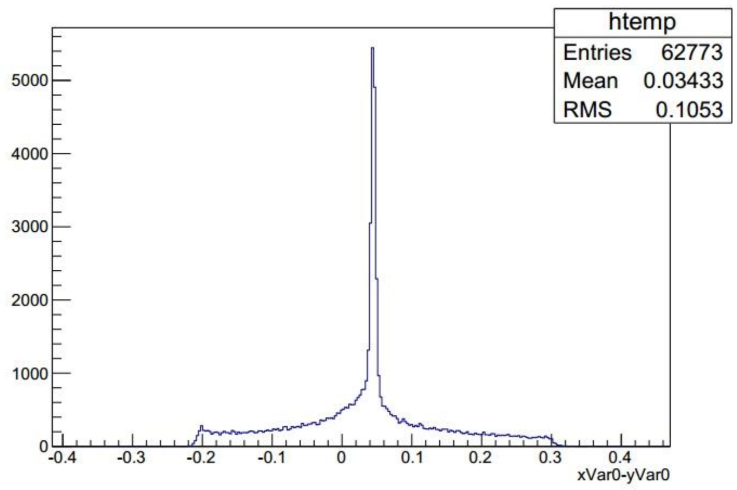
Gain for different bias voltages



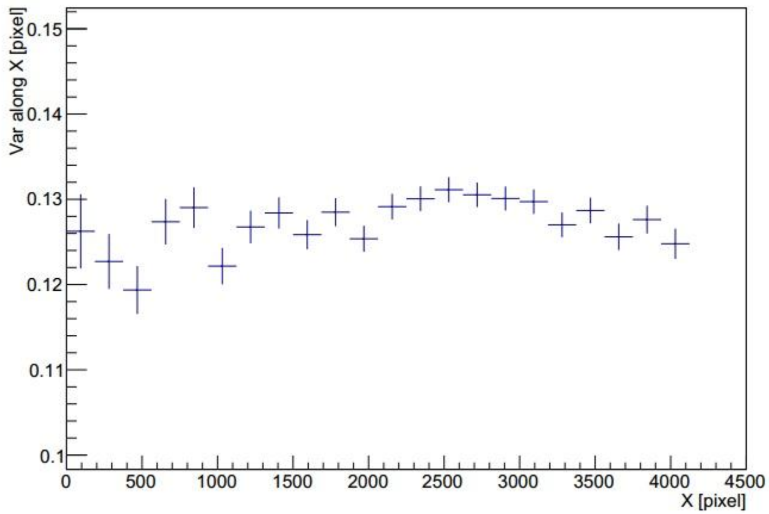
- This is a good result because the noise is almost 2e- and does not depend critically on a high Vsub value.
- The gain increases ~30% as we increase Vsub from 40V to 100V. This is not a surprise.

More characterization needed

Some charge transfer problems



But not that bad..



Is fair to say that the prototype detector are approved for prototype DAMIC100 and that we do not foresee problems moving ahead with the production of the CCDs for DAMIC100.

DAMIC100 prototype schedule

- The installation of 4 sensors is happening now though February 11th.
- We also hope to improve some ground loops in the system to further lower the noise.

DAMIC100 schedule

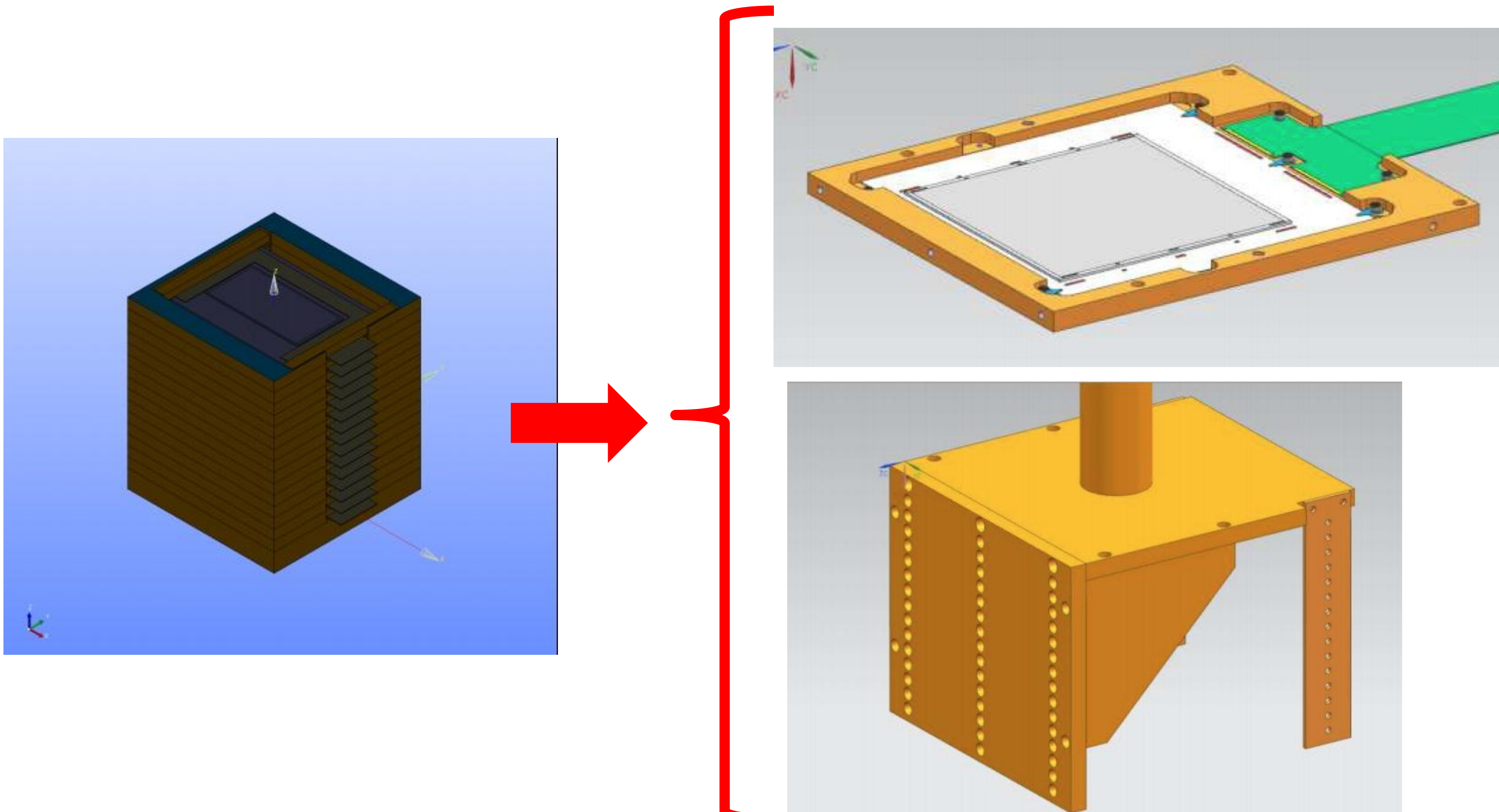
- High resistivity wafers are in hand at Dalsa.
- Order between LBNL and Dalsa is in the process of being signed .
- Once order is signed Dalsa will start fabrication (soon).
- Fabrication will take 2/3 months (due to their queue).
- **Detectors are expected show up at FNAL in mid April.**

- To make use of DAMIC/100 sensors in Mid/April:
  - Flex circuit to fabrication by 3/24/2014.
  - Silicon substrate order by 3/15/2014.

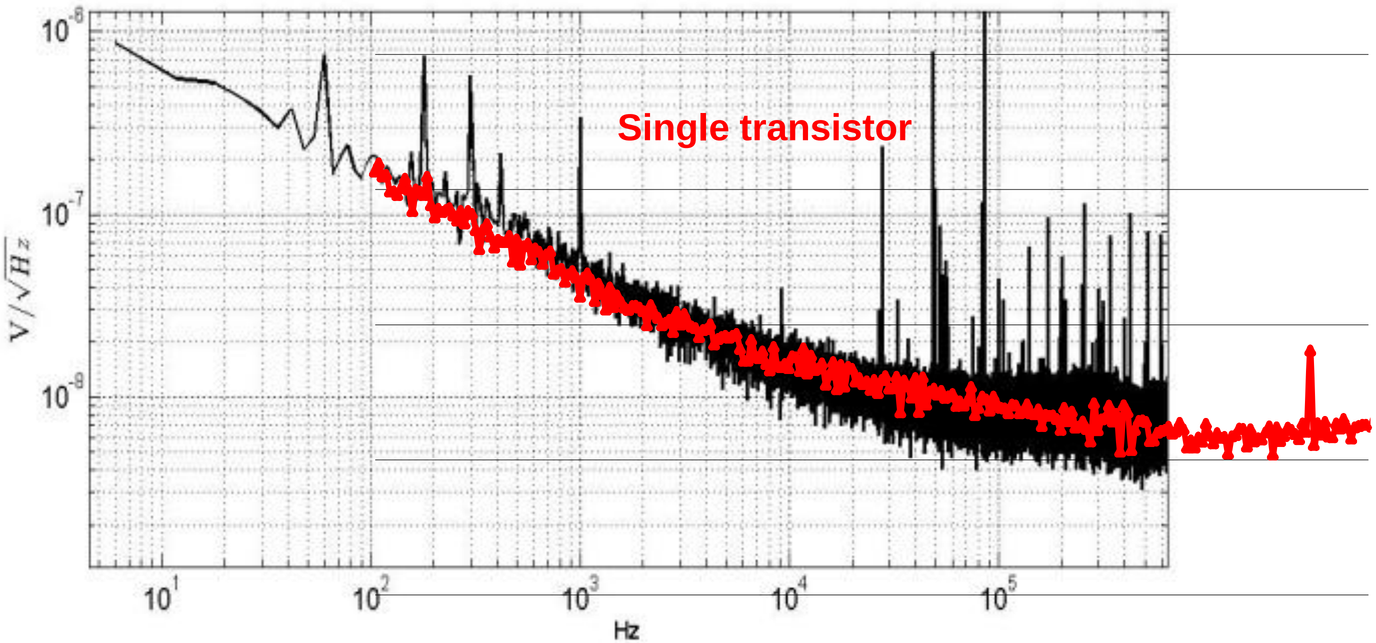
- For signal routing on silicon substrate option:
  - Need a design in February.
  - Important to get results on the prototype soon.

DAMIC100 thermal design

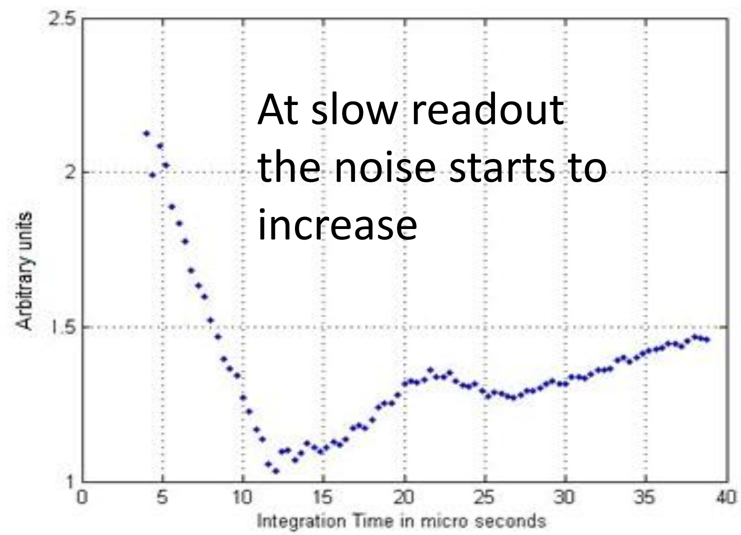
Frederic Trillaud(UNAM) simulated the stack of sensors with some reasonable assumptions for the package.
He sees a large temperature gradient between the detectors. This is something that we need to understand and fix before we start packaging damic/100.
Greg Derylo (FNAL) will be also involved.



Low noise R&D

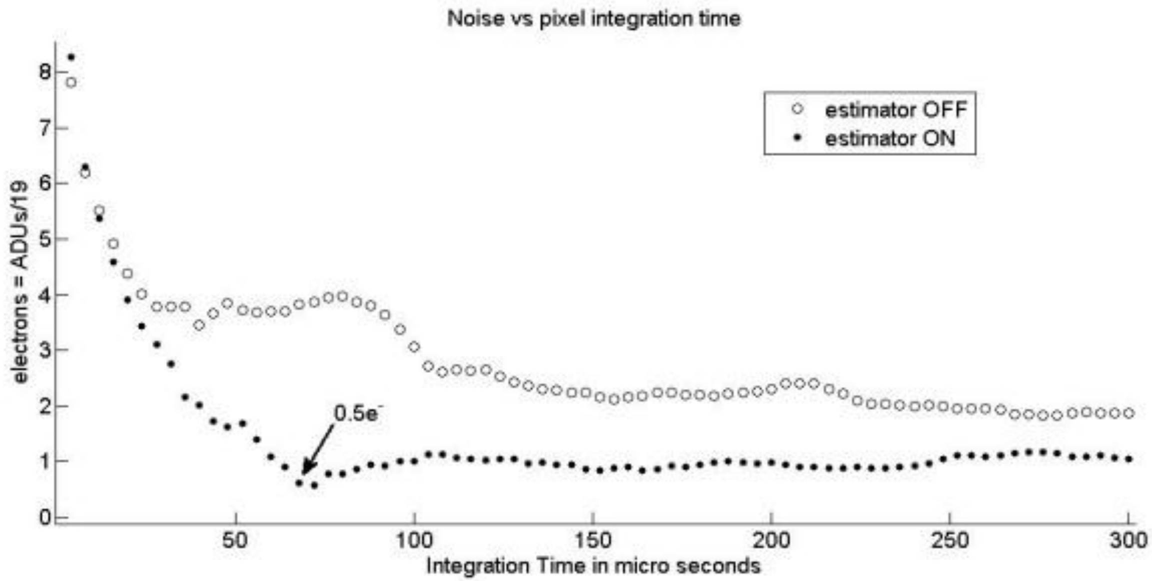


At low frequencies the CCD noise is 1/f.
At high frequencies the noise spectrum is flat (white and Gaussian).



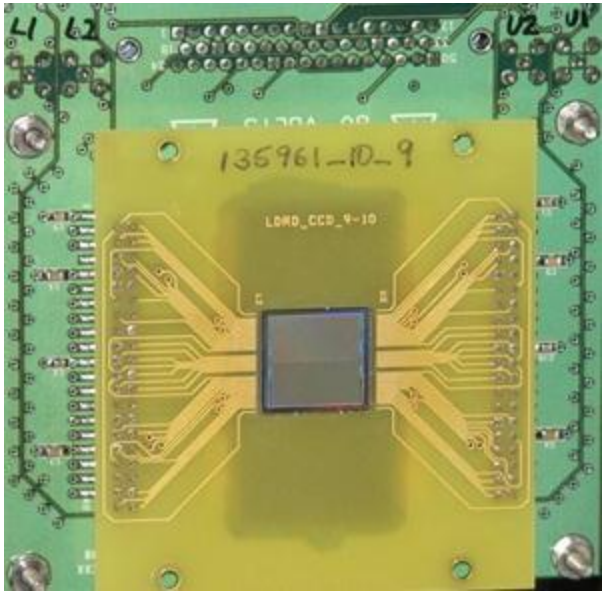
Two approaches to limit the 1/f noise

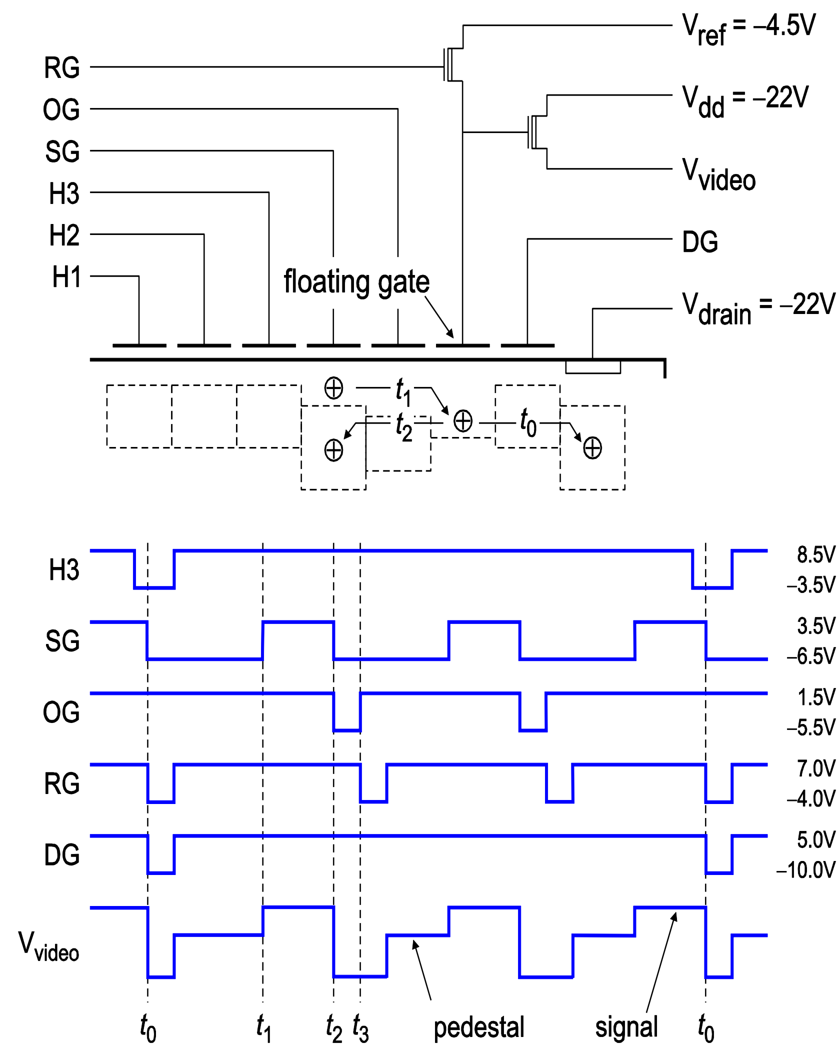
- Estimate the amount of 1/f noise and subtract it.
  - The estimation is done modeling the 1/f noise as a discrete time series of low frequency modes.
  - The modes must be estimated in amplitude and phase.
  - The accuracy of the estimation depends on the Gaussian noise.



Problems: We have not been able to achieve this result consistently and for an entire image.
Most problems are with having two pieces of hardware and probably grounding issues.
Gaussian noise spectrum not consistent over time.
Limited manpower to make progress.

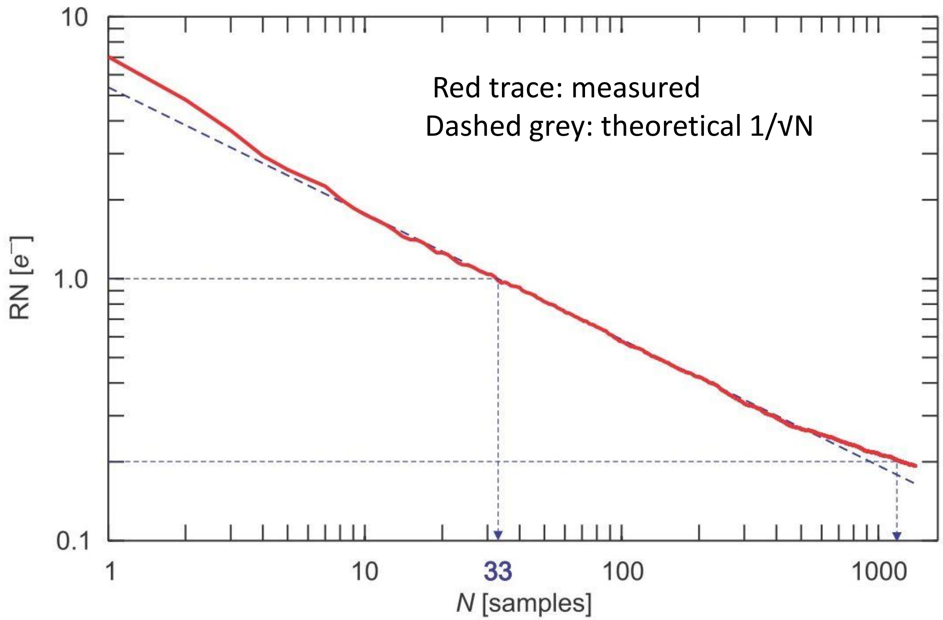
The skipper CCD





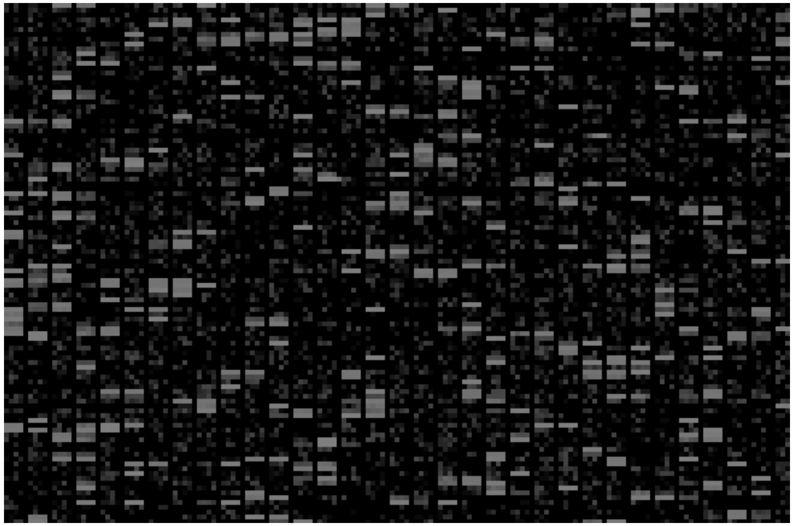
- The "skipper" allows multiple readouts of the charge in each pixel.
  - Floating gate output instead of floating diffusion output used in regular CCDs.
  - The charge can be moved back and forth between
- Each readout integration time is kept short to make 1/f noise negligible.
- A noise reduction of 1/sqrt(N) is achieved for N reads.
- The total readout time per pixel increases linearly with N.

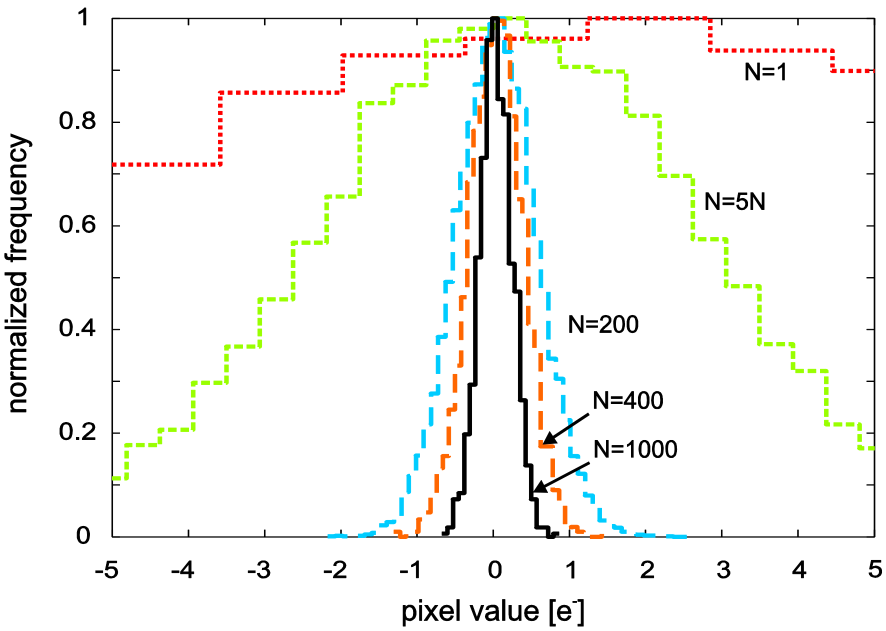
RMS noise as a function of the number of averaged samples N.



x-ray exposure

x-ray hits look like small horizontal bars in the image because the same pixel is readout several times.



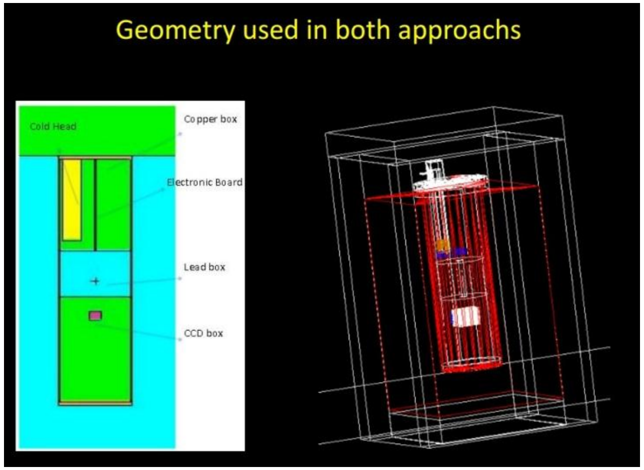


Histogram of only noise (dark image).
For each histogram the number of sample averages per pixel changes.
All histograms are normalized to 1.
The RMS noise is monotonically decreased as N increases.
RMS= 0.2e^- achieved for N=1227 (25ms/pix)

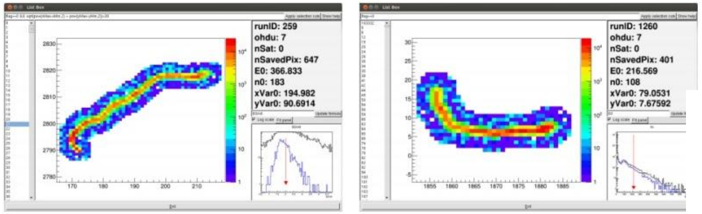
More DAMIC work (not enough time to mention in detail) please look for these documents in our docDB

- Simulations in Geant4 by Jorge Molina (FIUNA, Paraguay) and MCNP (Chavarria, Zhou, UChicago).
- Simulations by Youssef Mobarak (UNAM, Mexico)
- Data analysis: UC, Zurich, FNAL, etc

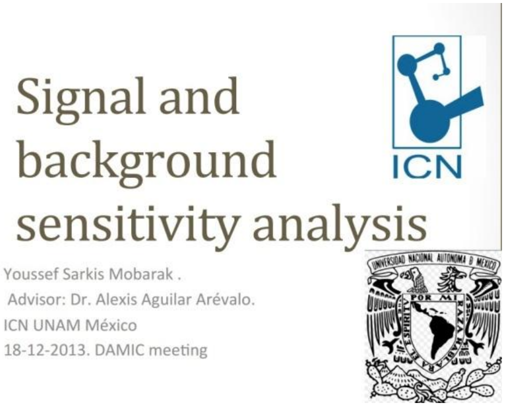
- Analysis tools: Javier Tiffenberg (Fermilab)



Extracted hits viewer



* It reads the root files produced by the extract software.
* Currently only a limited set of track parameters are available, more to be included soon.



DAMIC collaboration meeting at Fermilab

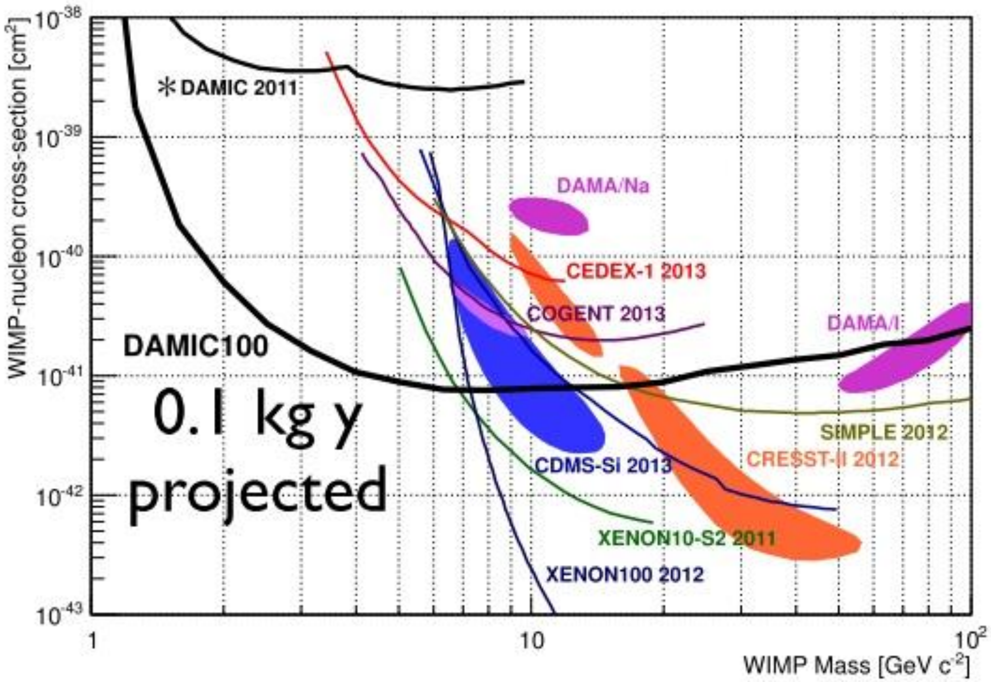
March 20-21, 2014


That's all Folks!

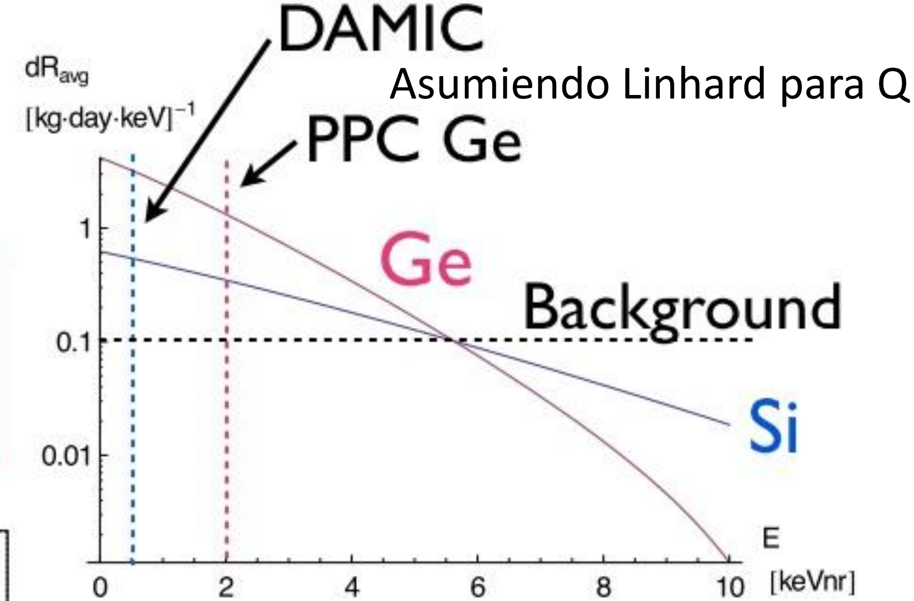
Spare slides

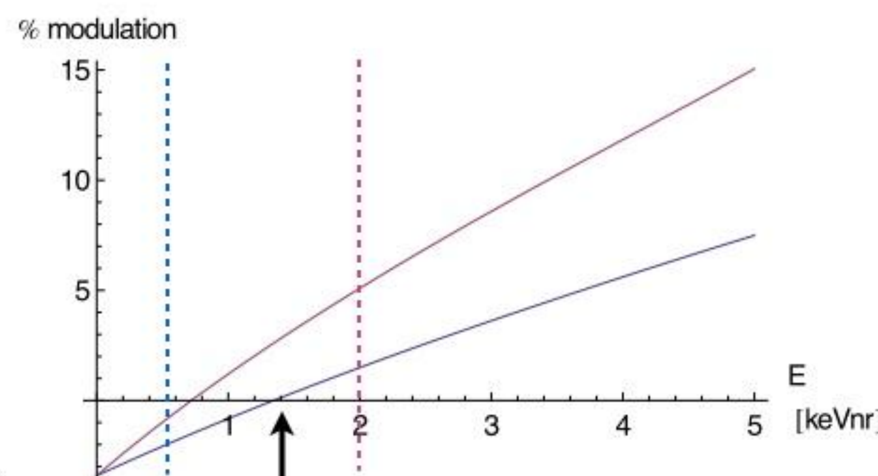
Sensitivity

DAMIC100 is well-suited to explore the CDMS-Si result



*Physics Lett. B711 (2012) 264-269





Tongyan Lin

Status of DAMIC at SNOLAB

- The charge was being injected/produced in the SW when the voltage difference between the high value of the last horizontal clock was large.
- Some theories but we dont have a solid explanation for this.
  - defects in the lattice.
  - injection from a rail, problem with the isolation of the well.
- We optimized the voltages under this assumption and we where able to find a set of voltages that work much better.

- We generated a set of voltages that produce acceptable results.
  - Need to understand why this detectors deeper.
- We are testing a 500 um detector, the voltages seem to work fine.

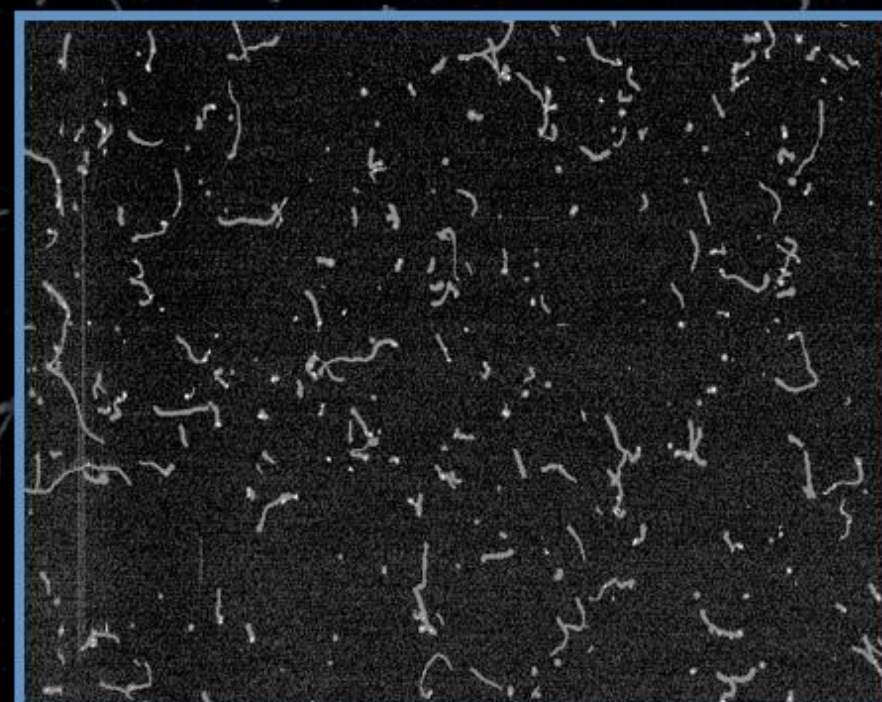
DAMIC overview

- Use the Si in a CCD bulk as a WIMP target.
- Very good ionization detector.
- Low electronic read out noise (~2 e- RMS) allows for a low energy threshold.
- Position reconstruction.
- Good characterization and estimation of backgrounds.
- Aim to build a detector large enough to explore CDMS-Si
- result (~0.1 kg) in a ~1 year timescale.
- Fermilab, U Chicago, U Zurich, Michigan, UNAM, FIUNA,CAB.

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.