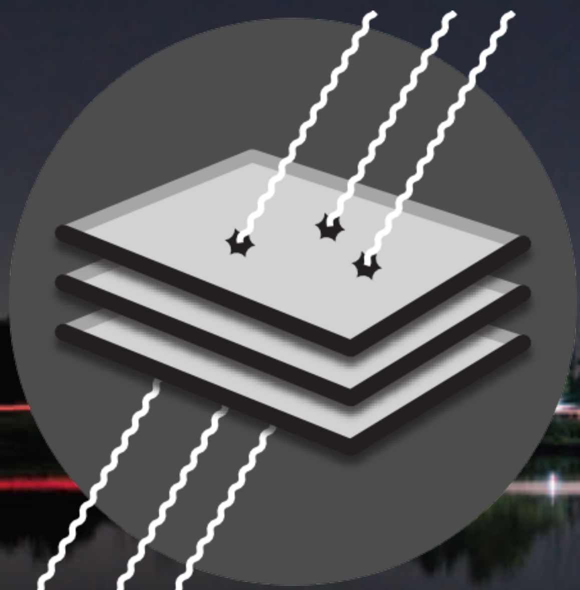
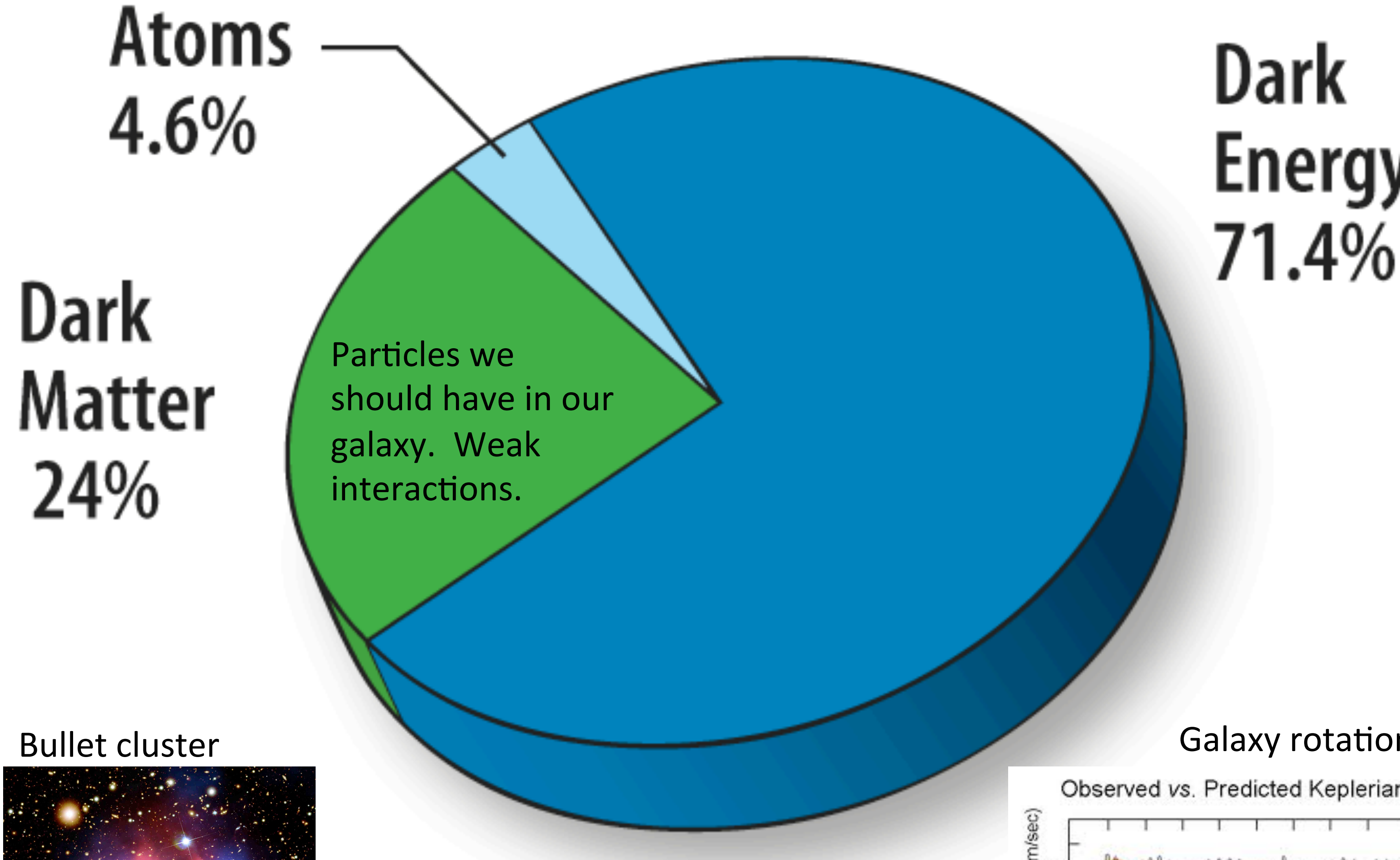
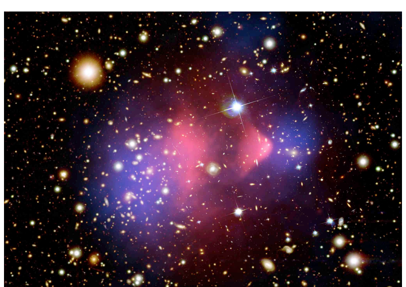
DAMIC - Direct search for low mass DM with CCDs.



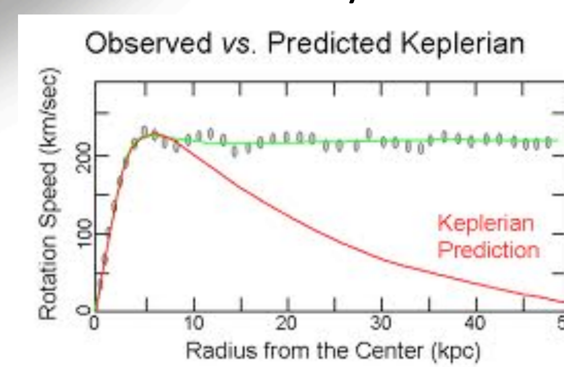
Juan Estrada
Fermilab Center for Particle Astrophysics
Feb. 12, 2015



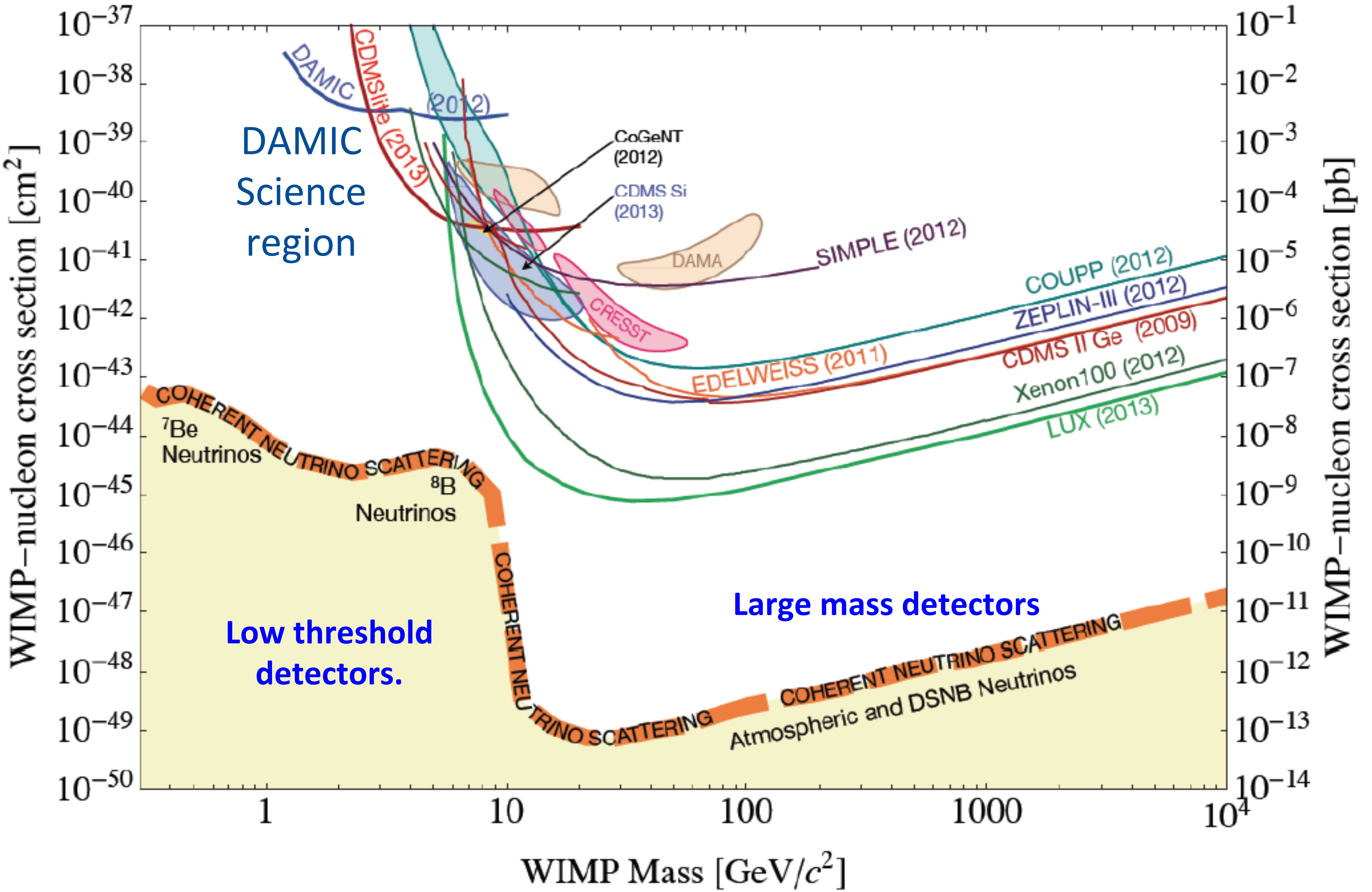
Bullet cluster



Galaxy rotations



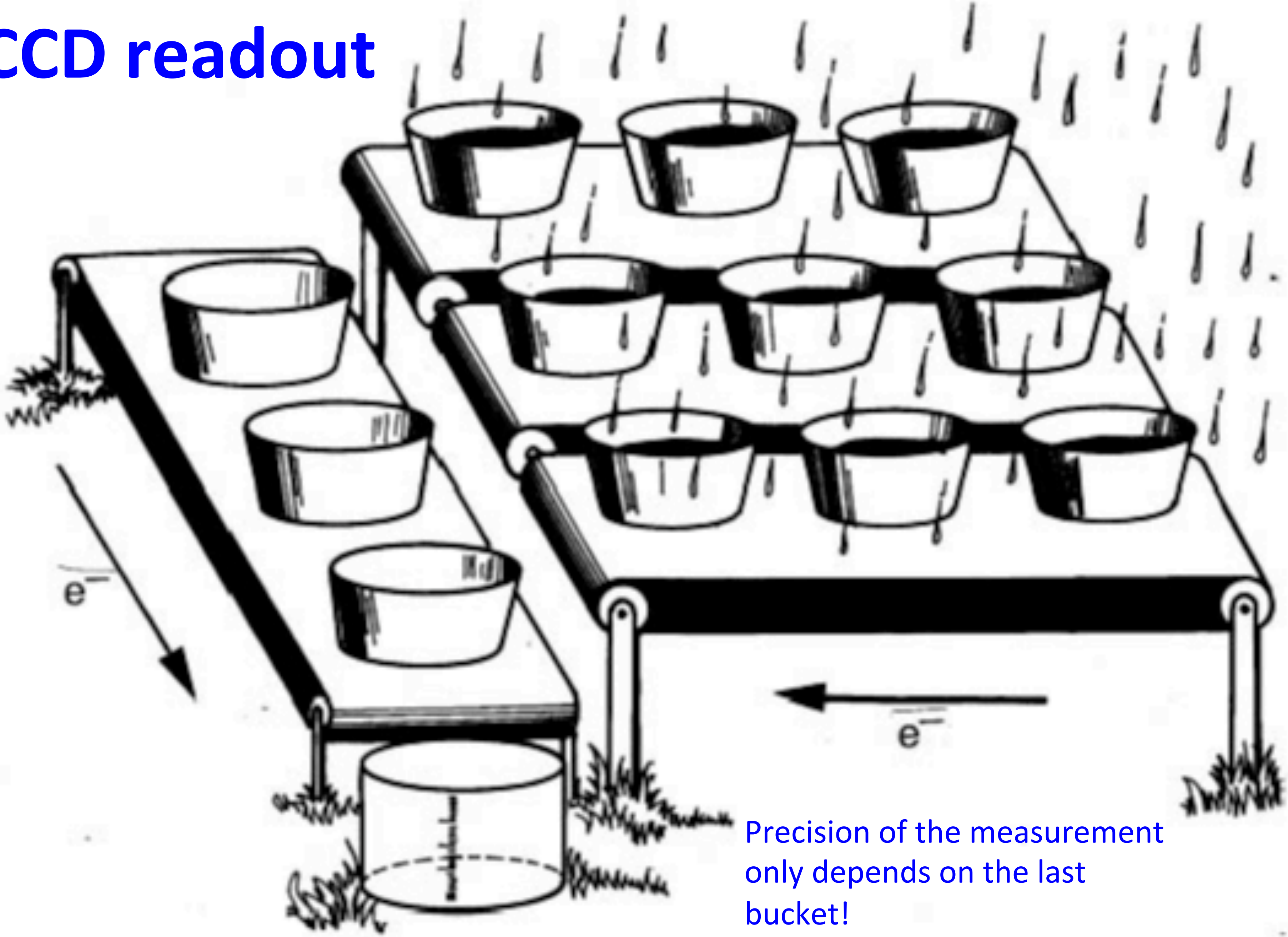
Will start from here.
If you think DM is not there, the discussion could be long.



DAMIC Science region
Low threshold detectors.
Large mass detectors
WIMP−nucleon cross section [cm^2]
WIMP−nucleon cross section [pb]
WIMP Mass [GeV/c^2]
DAMIC (2012)
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos

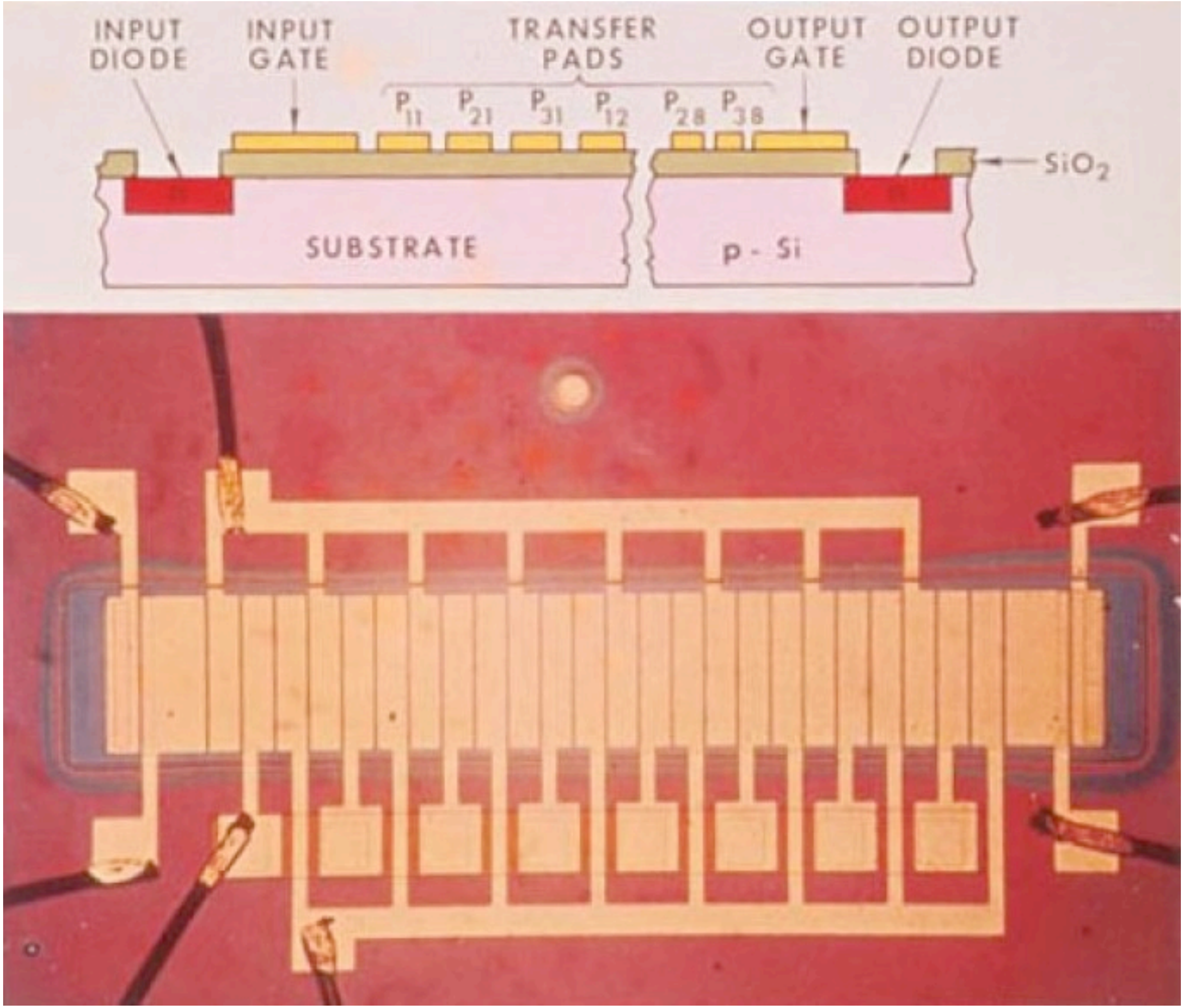
Why CCDs?

CCD readout



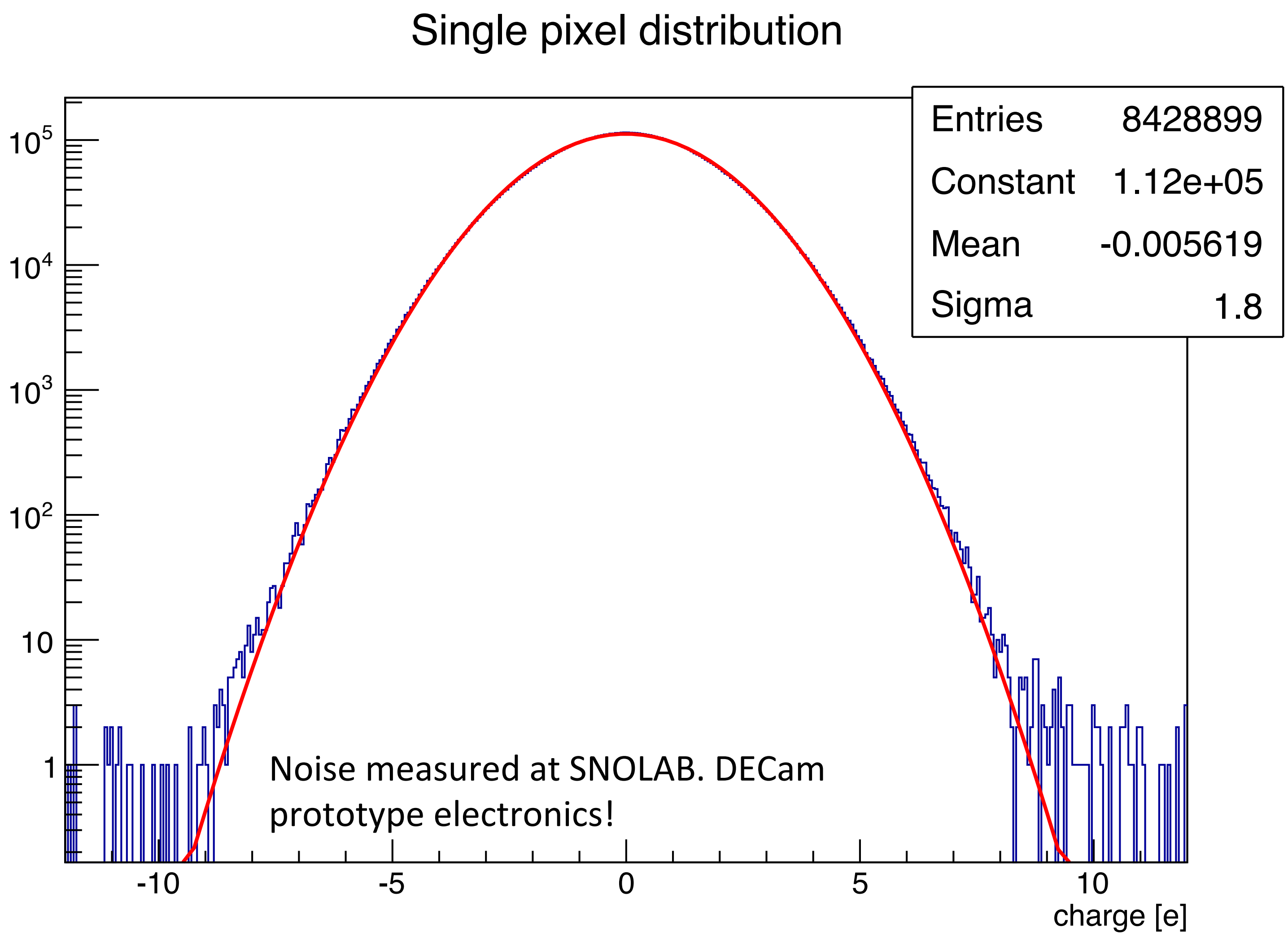
Precision of the measurement only depends on the last bucket!

Janesick



First CCD 1974 (2009 Nobel Prize)

1.8 e- RMS noise: this is what makes

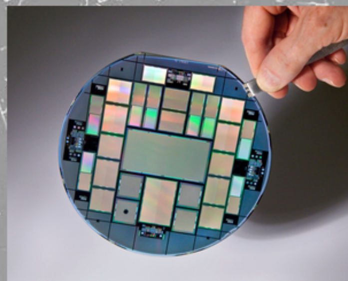


1e ≈ 3.6eV → 40eV threshold is possible (x10 lower than closer competitor)

LBNL large-format totally depleted thick CCDs

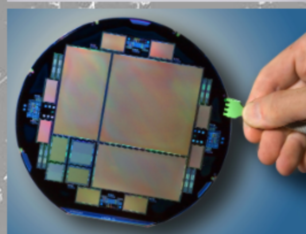
(Click on figures to get a big postscript version)

(Updating intermittently in progress. Links to papers should be OK)



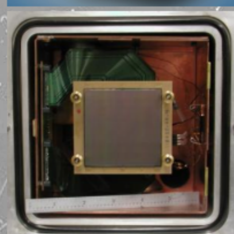
2010 LDRD wafer

Steve will supply caption.

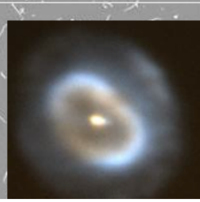


LBNL's first 4kx4k 15 um pixel CCD (Feb 2007)

150 mm wafer with a 4k x 4 k 15 um pixel CCD, two 2k x 4k 15 um pixel CCDs, and other structures.



Front-illuminated unthinned (650 um thick) picture-frame packaged 4114x4128 15 um pixel CCD in test dewar; 6 inch rule underneath for scale. CCD has 4-corner readout and high substrate voltage capability. Cosmic-ray muon tracks indidate near depletion at 80 V substrate bias. Preminary measurements show dark current (2e/px/hr) and no hot or blocked columns.



FIRST LIGHT

First light with the LBNL 200 x 200 pixel $(15\ \mathrm{um})^2$ prototype CCD. The image of NGC7662 was obtained at the Lick Observatory 1-m telescope on 1996 July 30 by Richard Stover, Mingzhi Wei, and Steve Holland. This front-illuminated CCD was 300 um thick and totally depleted.

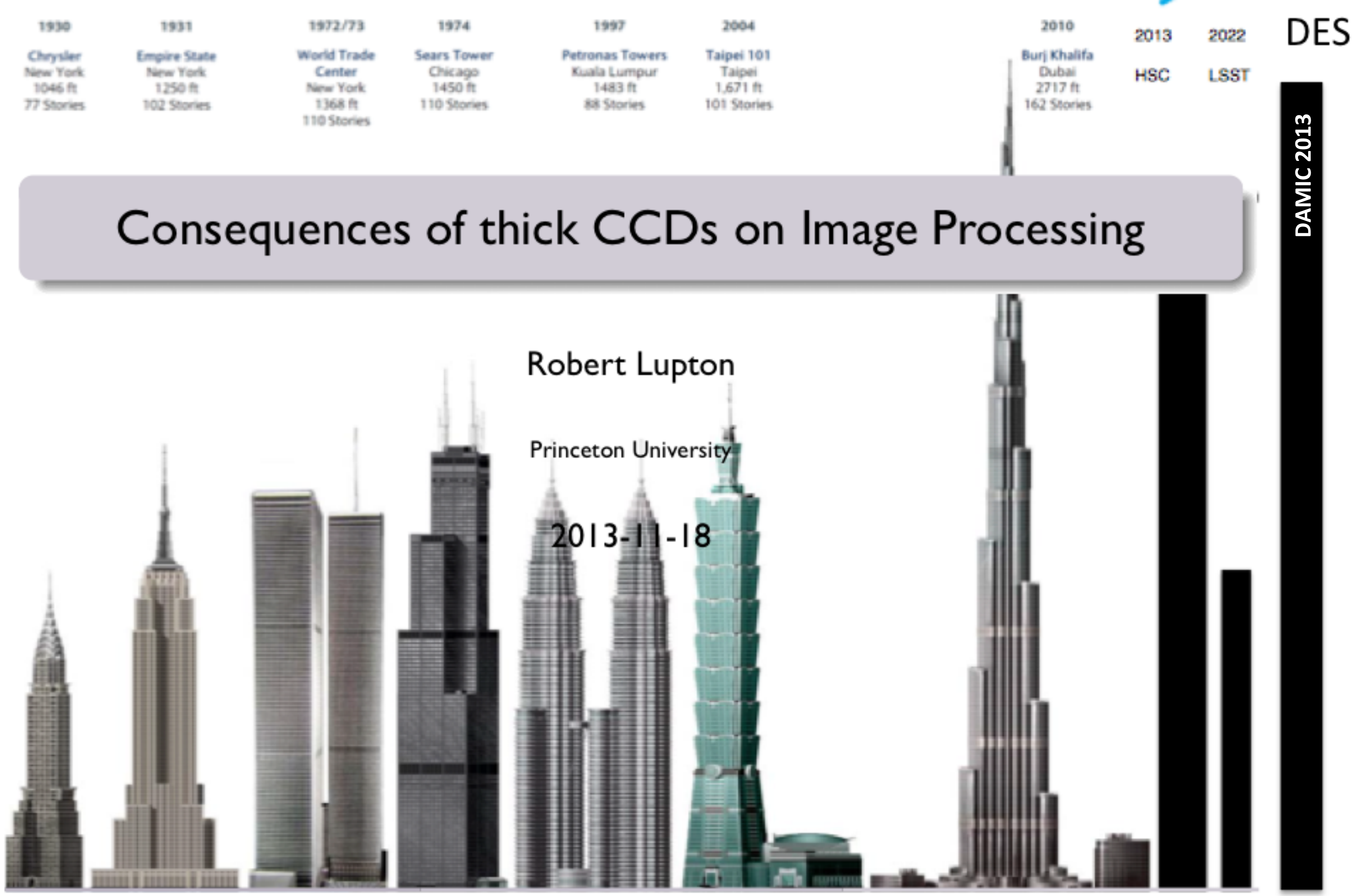
LBNL has developed thick CCDs… massive piece of silicon with 2e- readout noise!

Consequences of thick CCDs on Image Processing

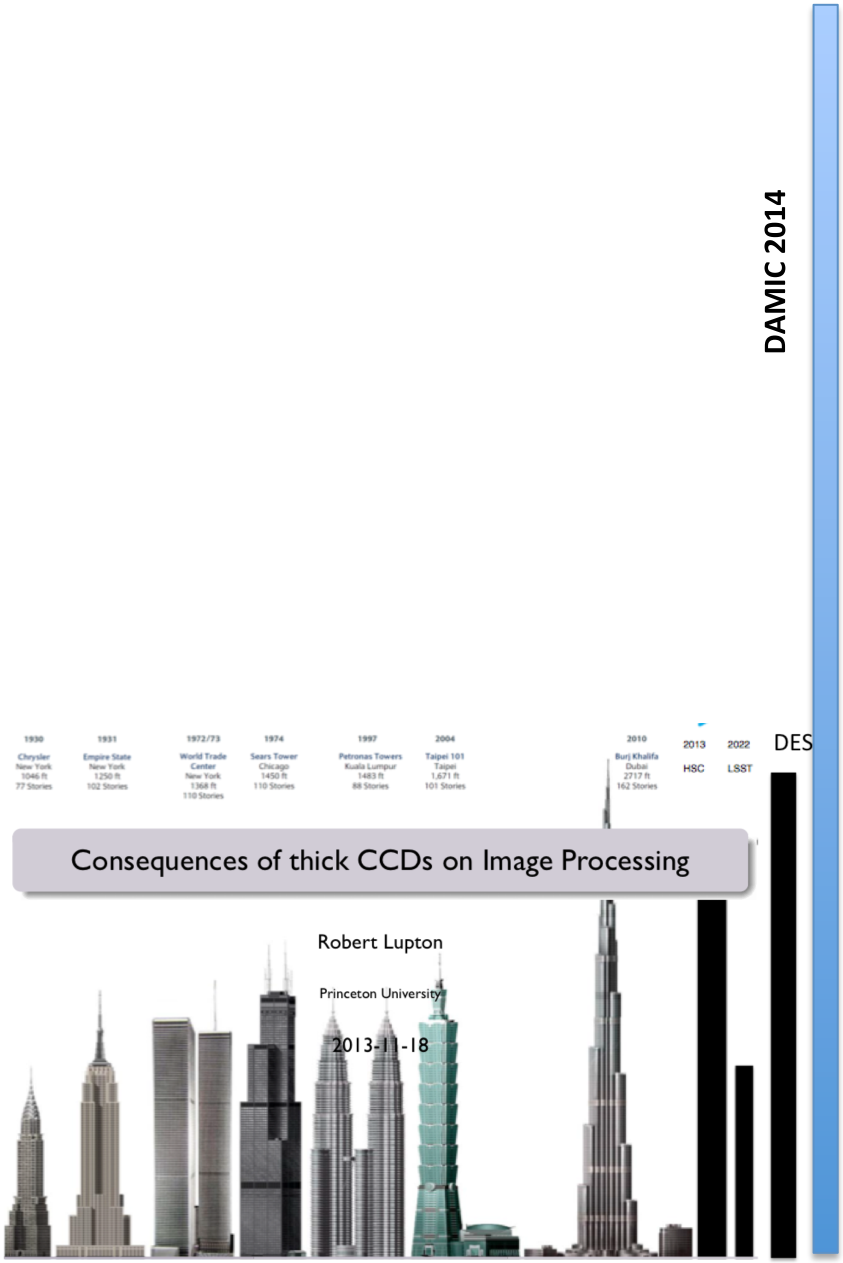
Robert Lupton

Princeton University

2013-11-18



Pixels are tall and thin. We do this in astronomy to get higher efficiency in the IR.
It is not free… optical imaging with skyscrapers is challenging.

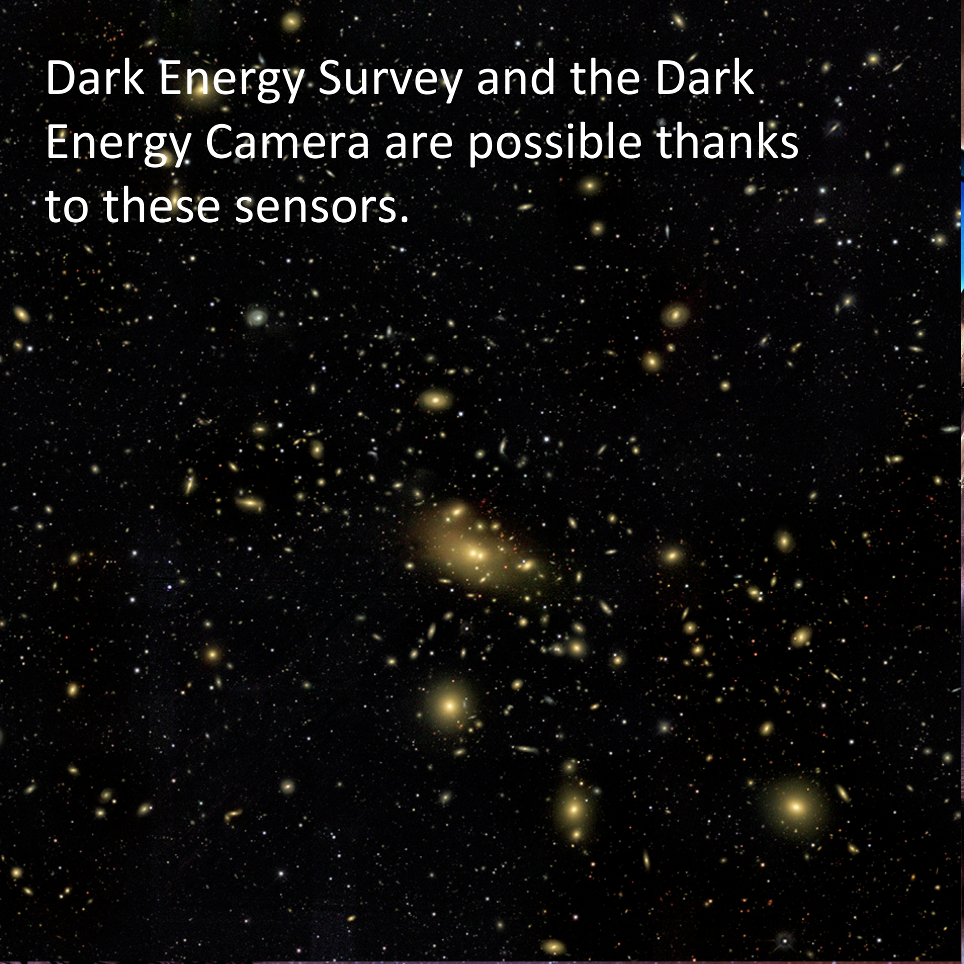


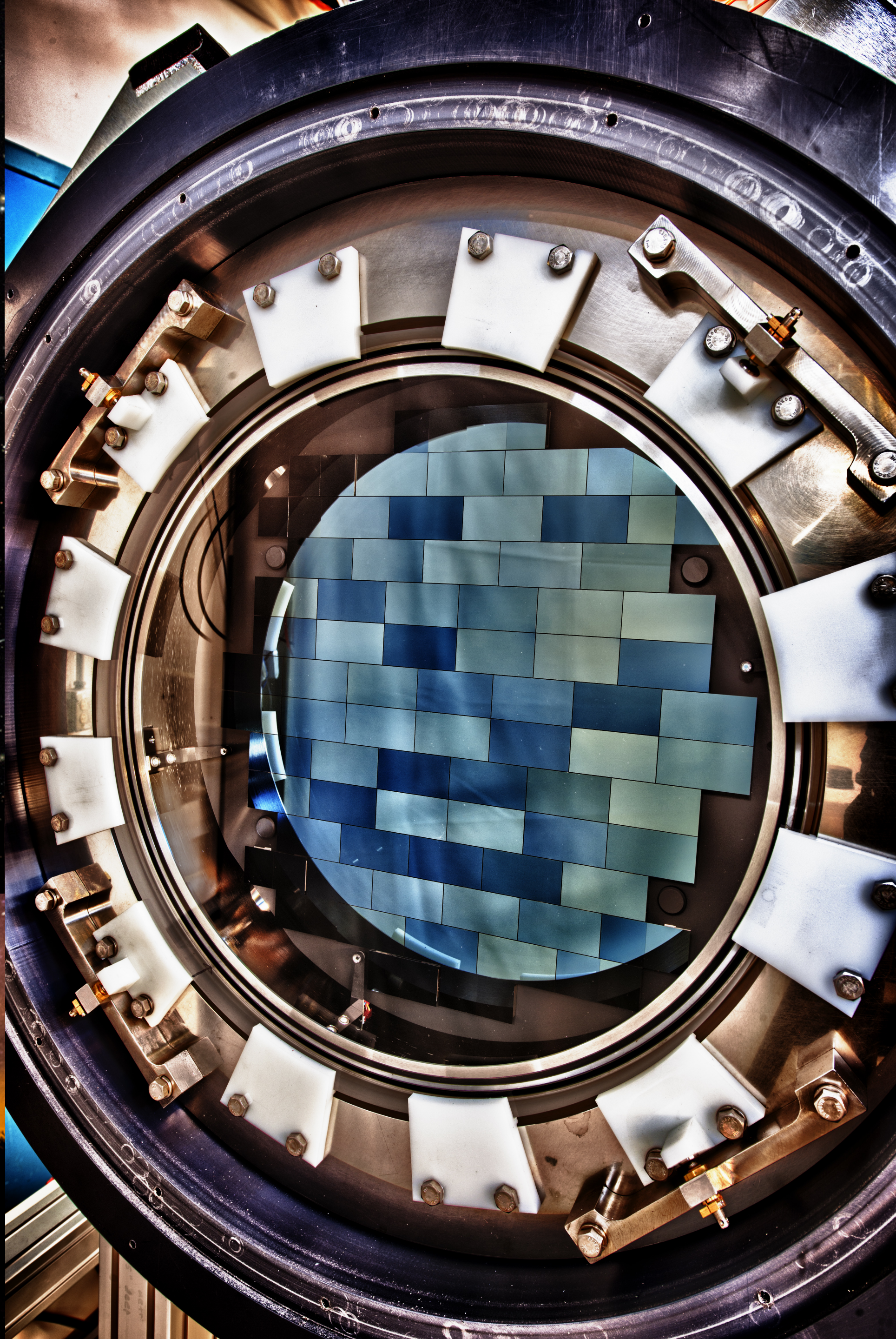
Thanks LBNL-MSL!!!!

Steve Holland

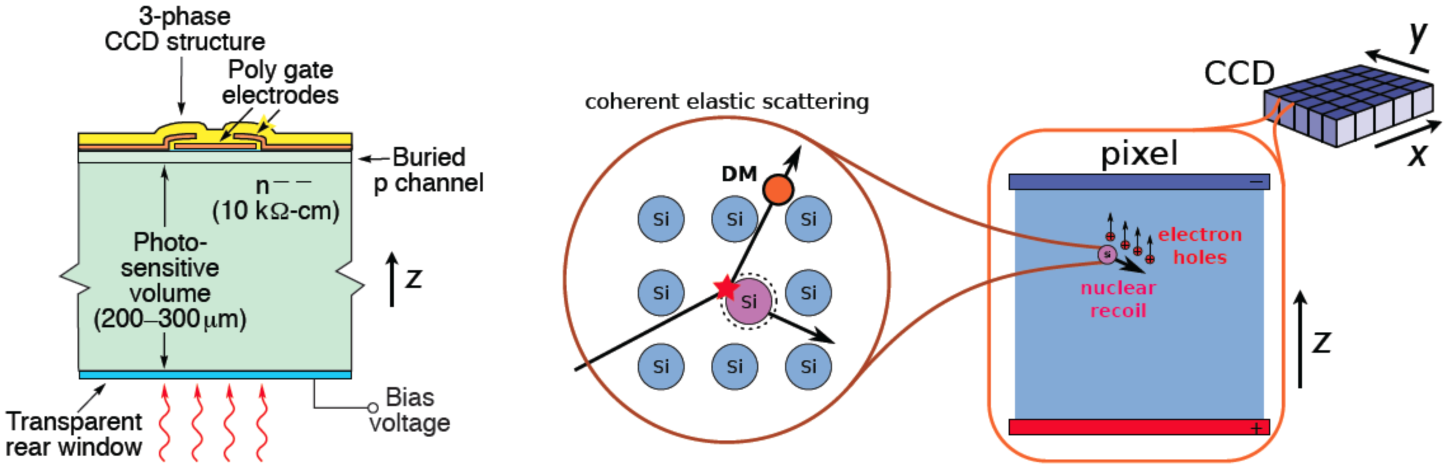
“CCD Developer Extraordinaire”

Asteroid #40981 name in his honor.

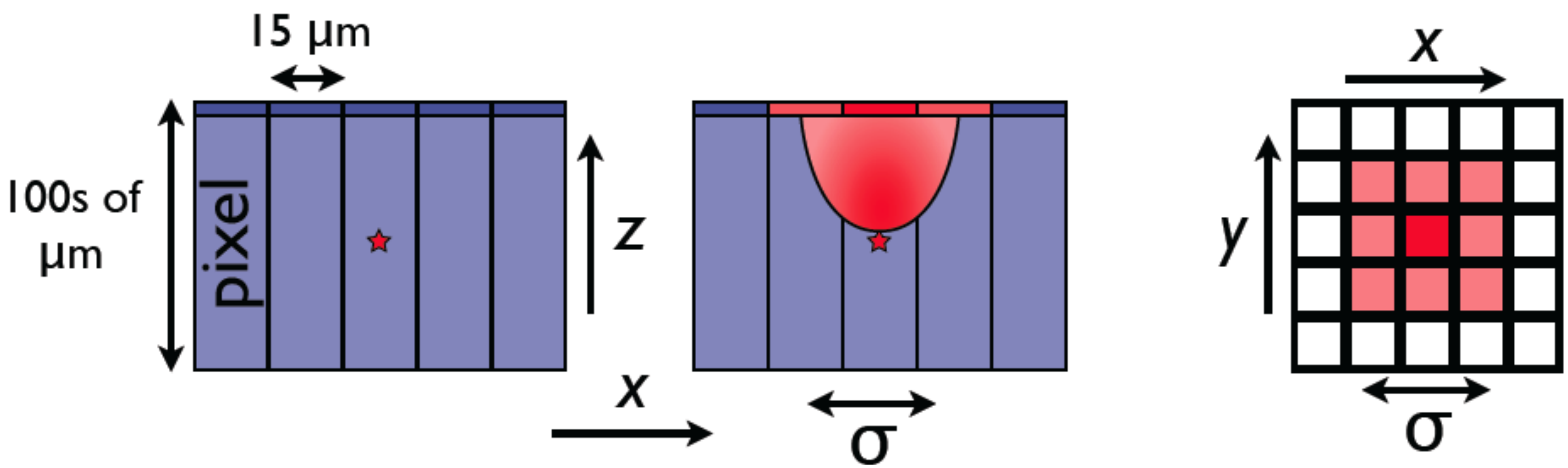

Dark Energy Survey and the Dark
Energy Camera are possible thanks
to these sensors.



Enabling Technology : thick CCD

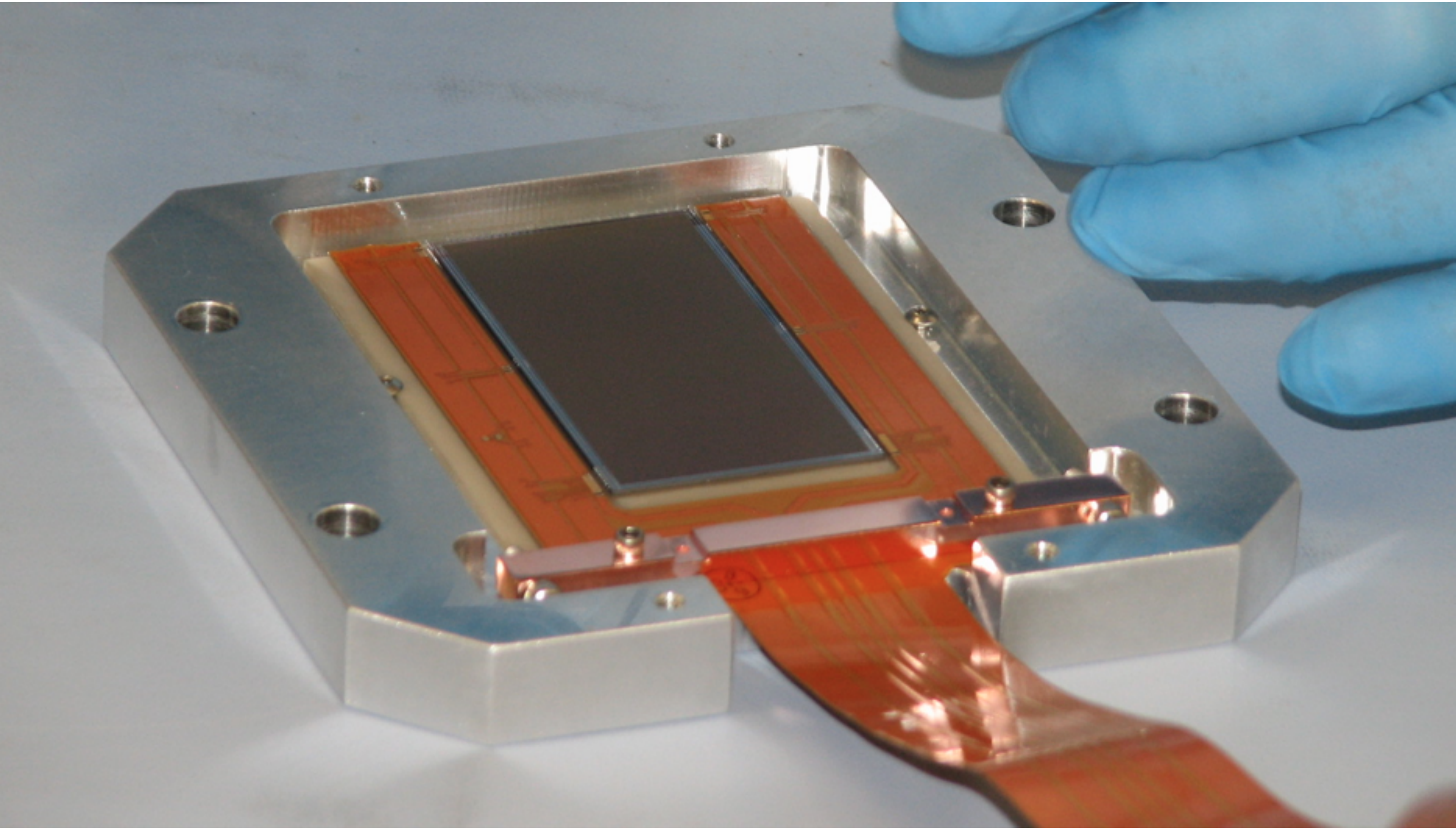


(a) A CCD pixel (b) WIMP detection principle

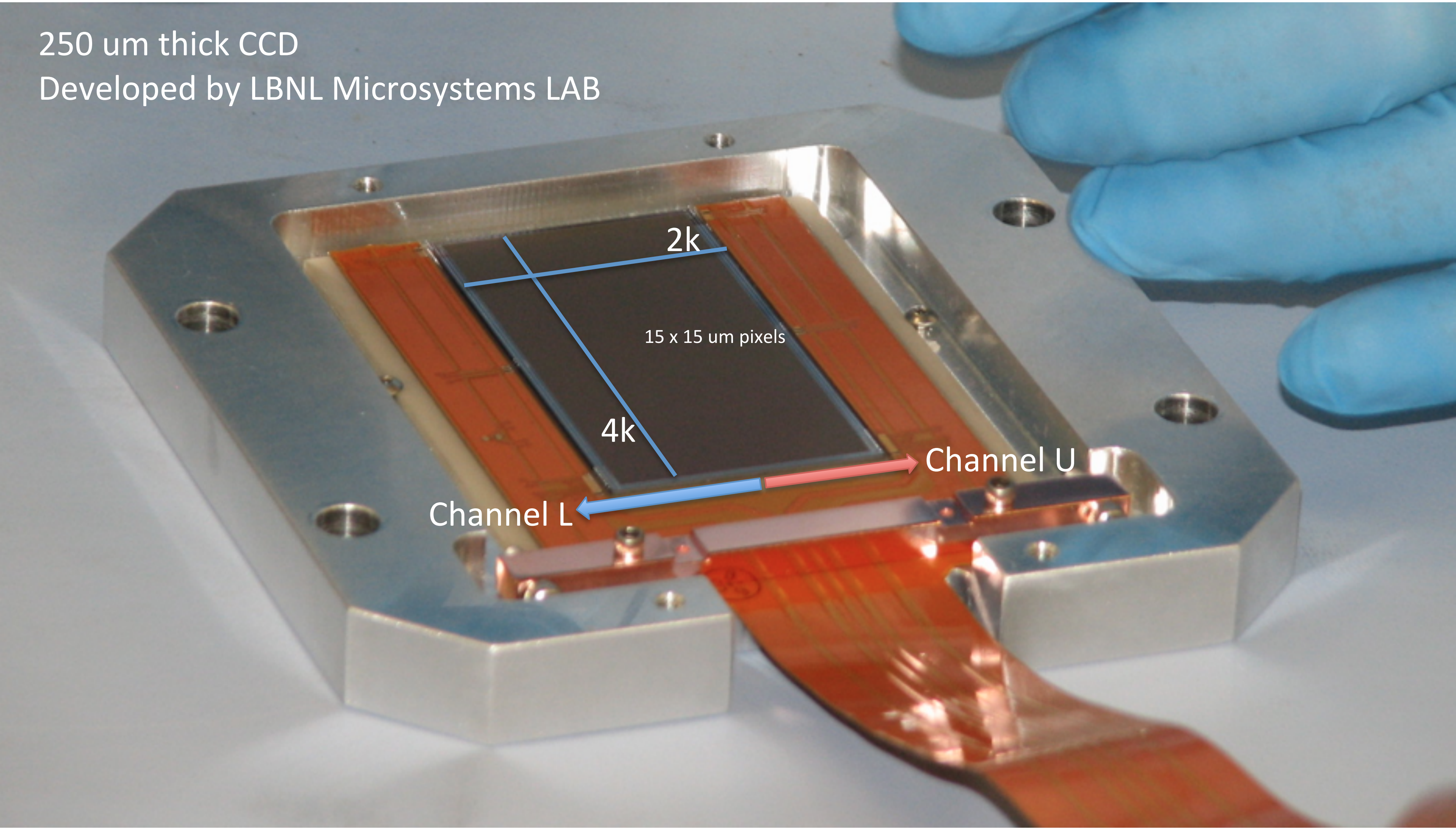


DECam detectors are 250um thick and 8 Mpix, 1g per CCD. DAMIC started with this. DAMIC-100 is now going to 675 um thick and 16 Mpix, 5.2g per CCD. In 2014 installed the first 675um detectors, provided by **LBNL** to test the concept.

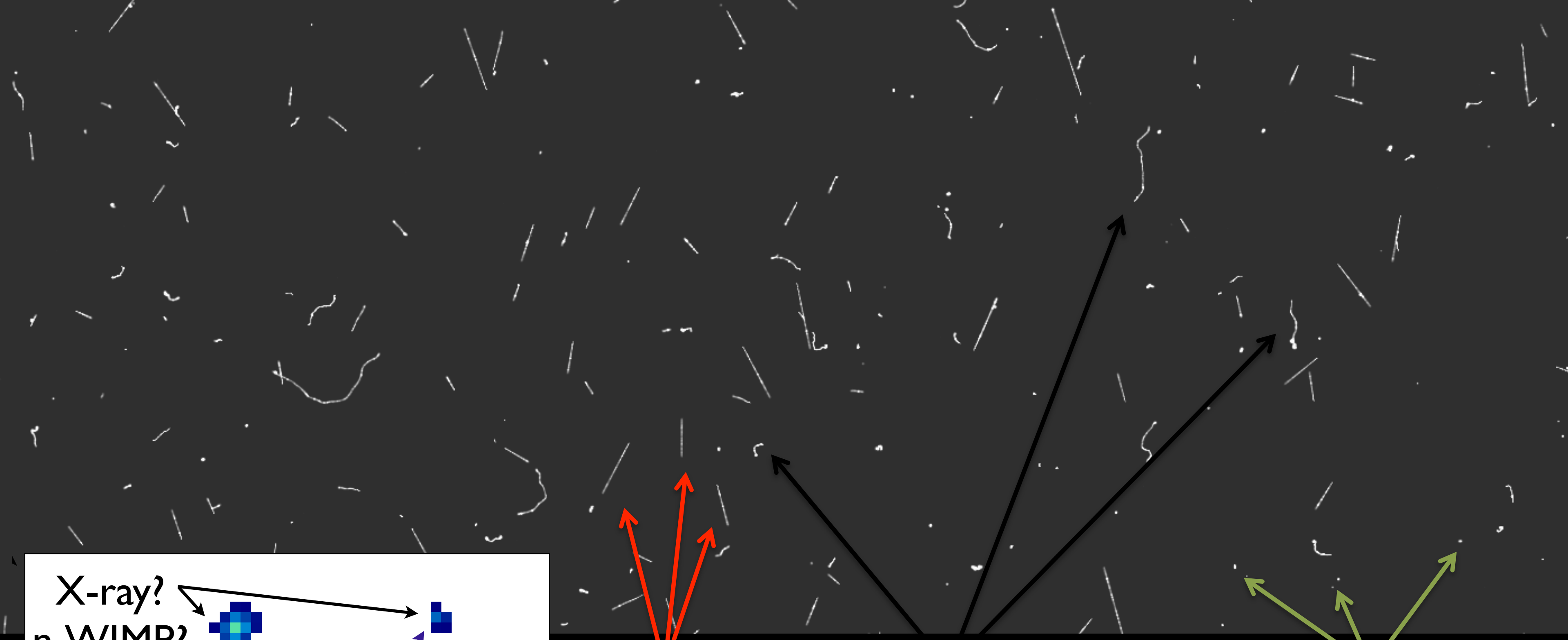
DAMIC Sensors (2013):

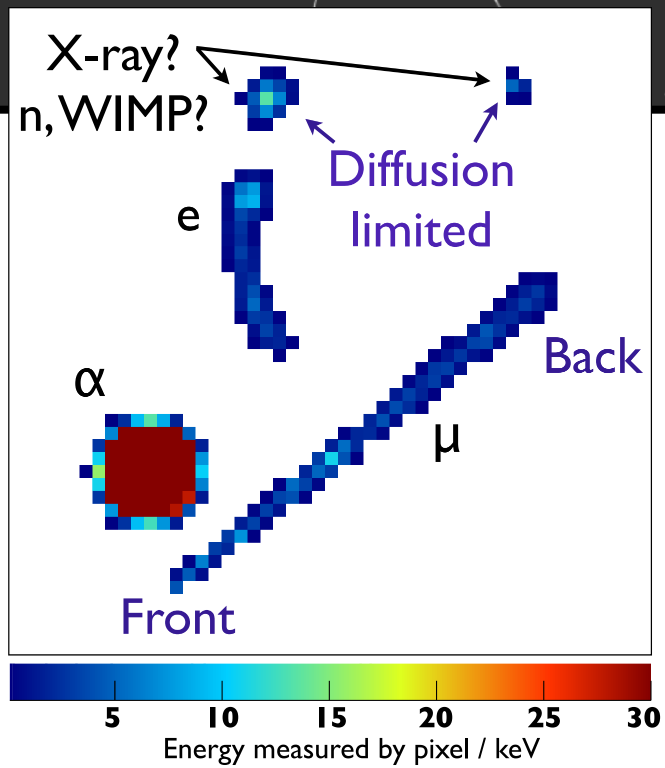


DAMIC Sensors:



The noise is determined by the capacitance of the output node.
The active pixels are decouples from the readout node!



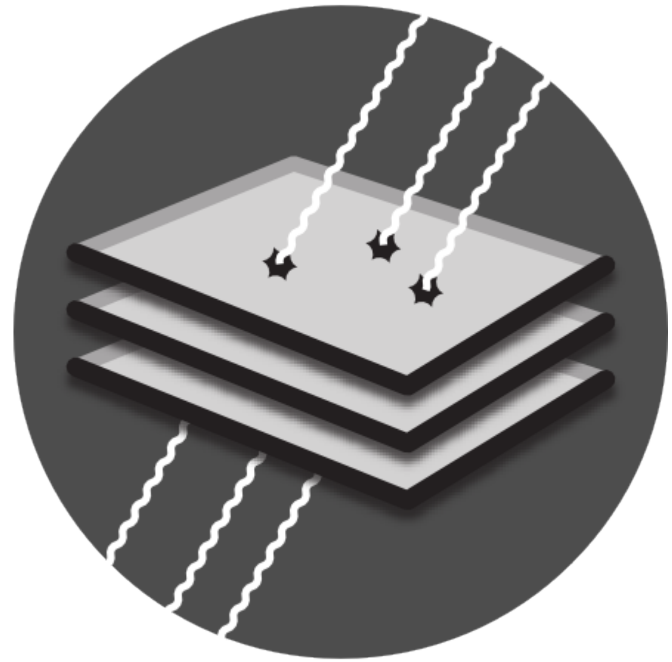


Particle ID with 15um pixels. Diffusion limited hits are dark matter candidates.

DAMIC Collaboration

Two Universities from the US, one National Laboratory and 5 institutions from abroad.

Centro Atomico Bariloche, Argentina : Xavier Bertou
Fermi National Accelerator Laboratory, USA : Gustavo Cancelo, Juan Estrada
Universidad Federal Rio Janeiro, Brazil: Joao de Mello Neto
Universidad Nacional de Asuncion, Paraguay: Jorge Molina
Universidad Nacional Autonoma de Mexico: Alexis Aguilar, Juan Carlos D'Olivo, Frederic Trillaud
University of Chicago , USA : Paolo Privitera
University of Michigan, USA : Tom Schwarz, Dante Amidei
University of Zurich, Switzerland: Ben Kilminster

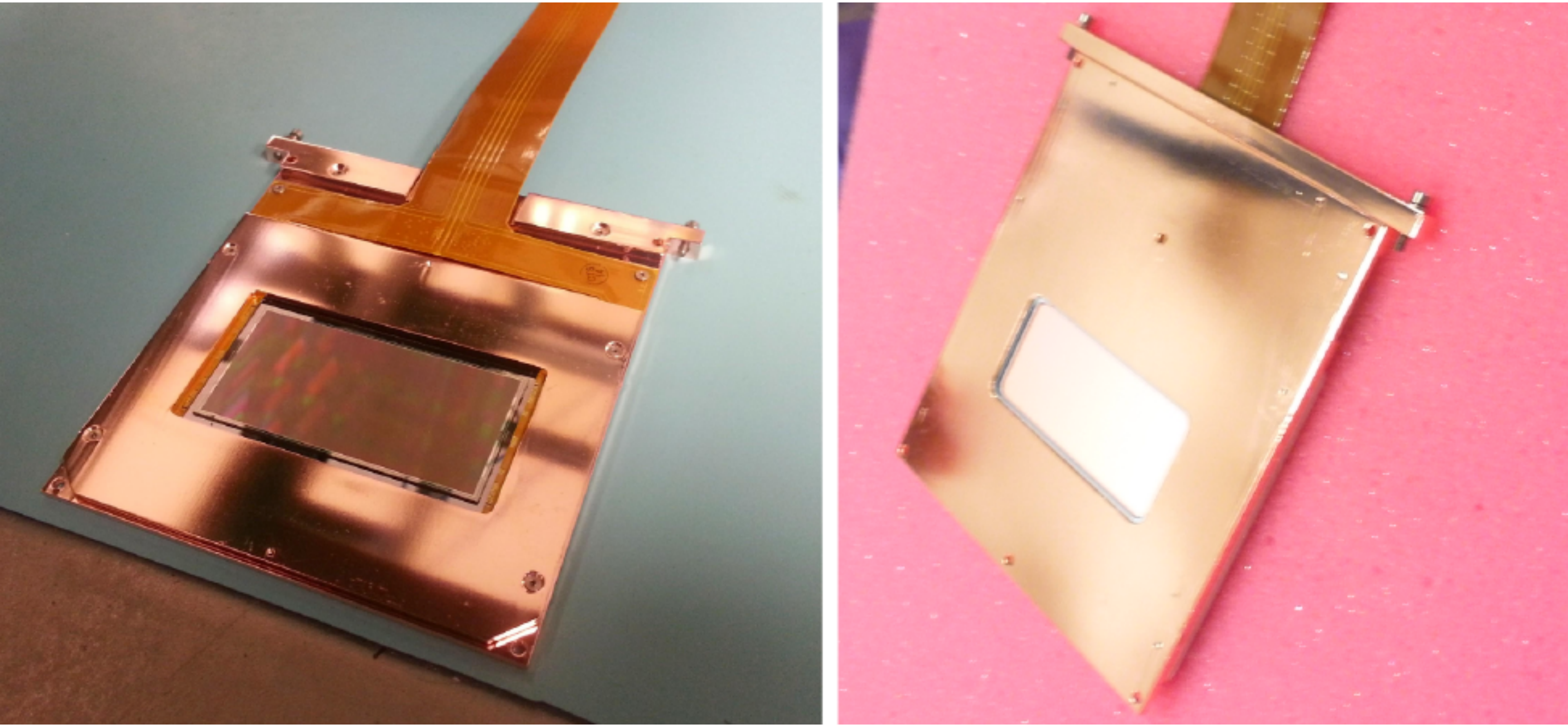


DAMIC timeline

- **2010-2011 Test at NuMI detector hall FNAL (350' underground)**
  - Single DECam engineering CCD.
  - Active mass = 0.5g
  - No neutron shield
  - **Publication showing the potential of the technology (DAMIC 2012)**
- **2012 SNOLAB (6800' underground)**
  - DECam engineering grade CCDs.
  - Active mass ~10g.
  - Limited by background in CCD package (ceramic) + lead shield.
  - **<u>Collaboration starts forming</u>**
- **2014 Upgrades at SNOLAB (DAMIC-100 R&D)**
  - Silicon only package (no ceramic)
  - Ancient lead introduced in the inner shield (U.Chicago)
  - 675 um thick CCDs (not DECam anymore)
  - Active mass ~ 10g
  - **<u>Well established international Collaboration</u>**
  - **<u>Preliminary results shown today.</u>**
- **Now**
  - Moving to 100g.
  - Unpackaged sensors in hand at FNAL.
  - Installed last week a copper box for 18 CCDs filled with 4 sensors
  - Improves Nitrogen purge.
  - Completion of 100g upgrade expected for Summer 2015.


DANGER
HOT WORK PROHIBITED IN THIS AREA
NITROGEN PURGE
Washington
Dayton
York

DAMIC sensors (2015)



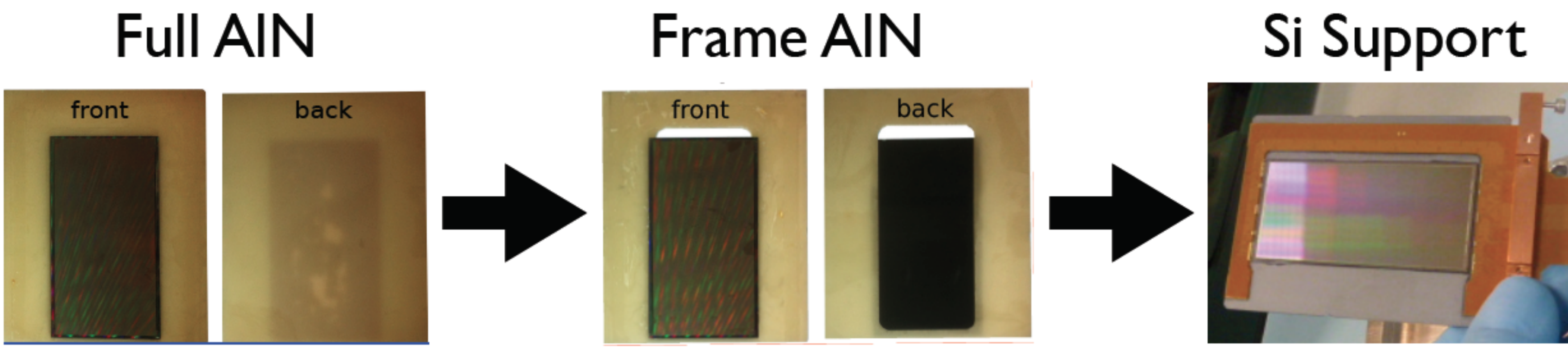
Thick CCDs

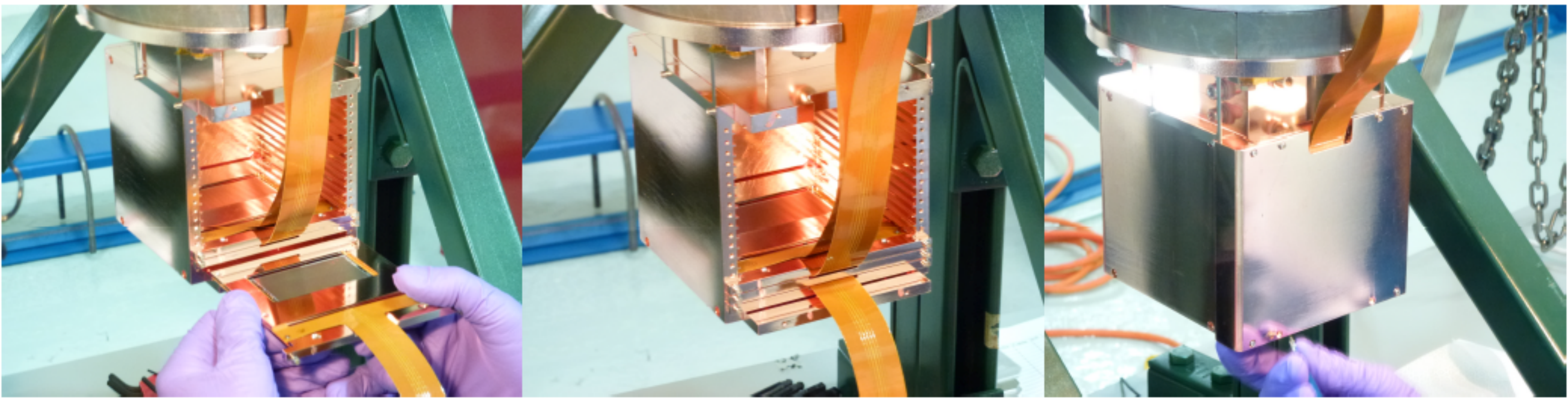
16 Mpix , 675 um thick, 5.2 g

(8 Mpix prototype shown here)

Now using CCD quality silicon for the backing structure.

AlN frame turned out to be high in active isotopes (U).
Replaced with Si support for a x10 drop in background.



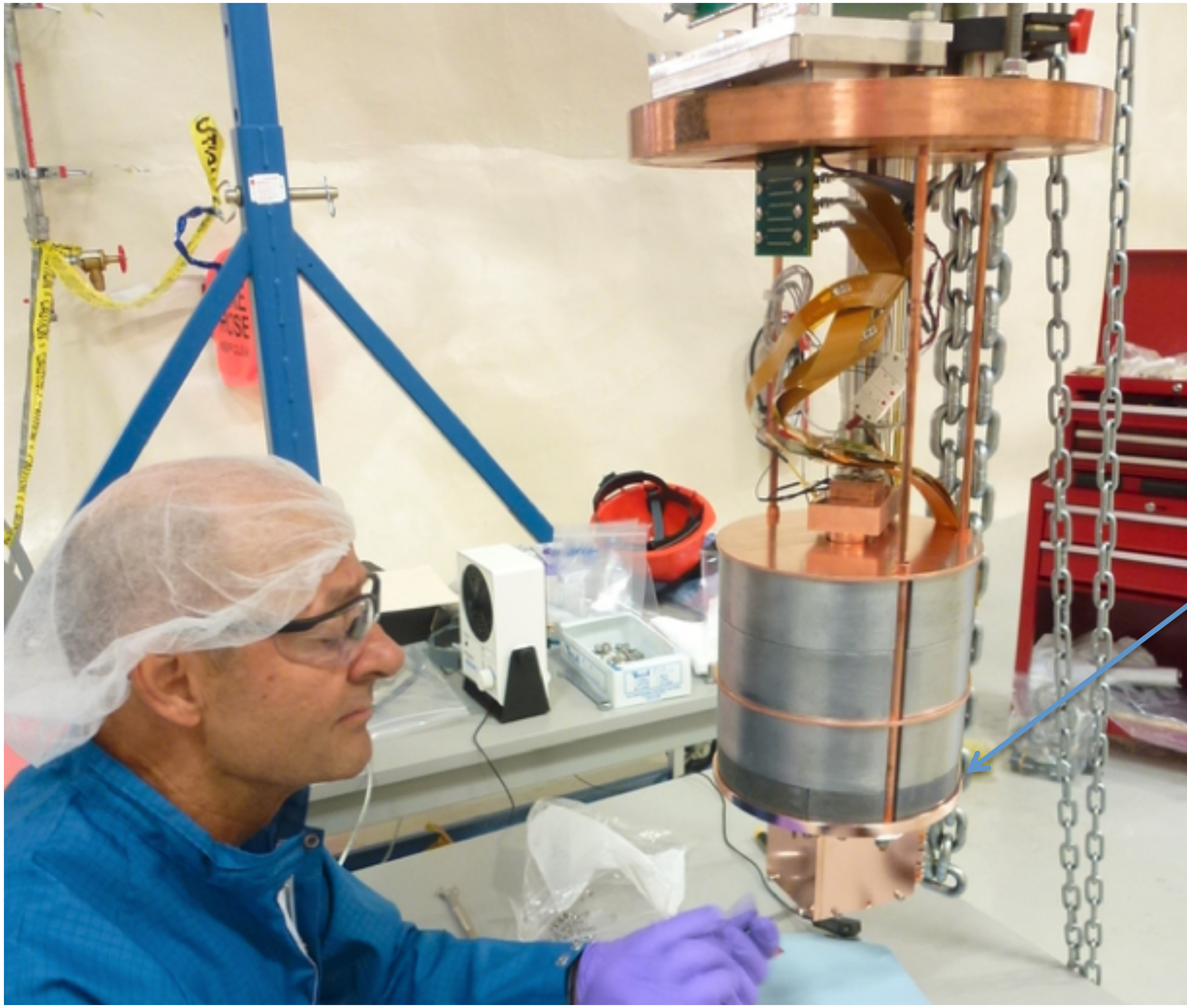


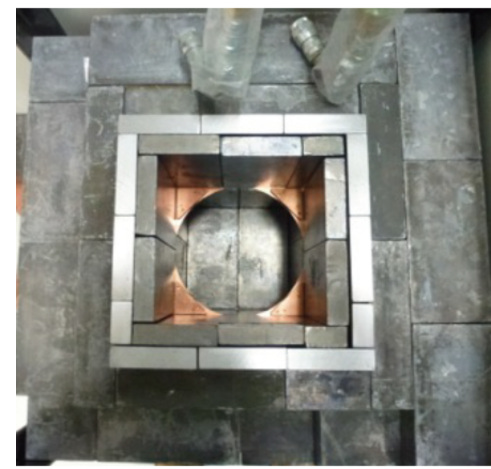
Stack of 18 CCDs for get to 100g.

Inside a copper box, cooled to -140C.

(3 prototype sensors shown here)

Lead shield





Stack mounted inside copper vessel. Inner lead shield inside vacuum. Detectors operated at -140C. Innermost inch using ancient lead (<0.02 Bq/kg ^{210}Pb) to stop 50 Bq/kg of ^{210}Pb from outer layers.

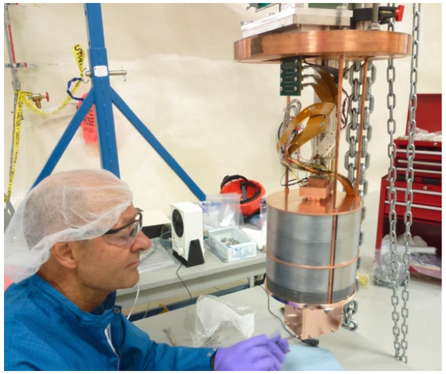
Upgrade 12/2014

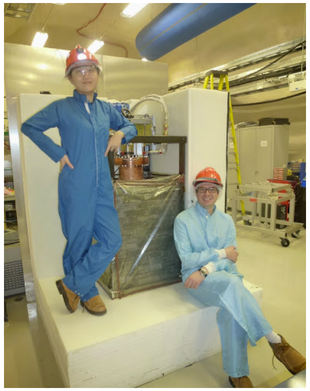
Nitrogen gas bag. 12/2014

SNOLAB is an amazing place, and a beautiful lab. Excellent support from the local personnel, reasonable level of bureaucracy and great infrastructure. All this with 0.25 muons/m2/day at 2000 mts below the surface. Thanks SNOLAB!

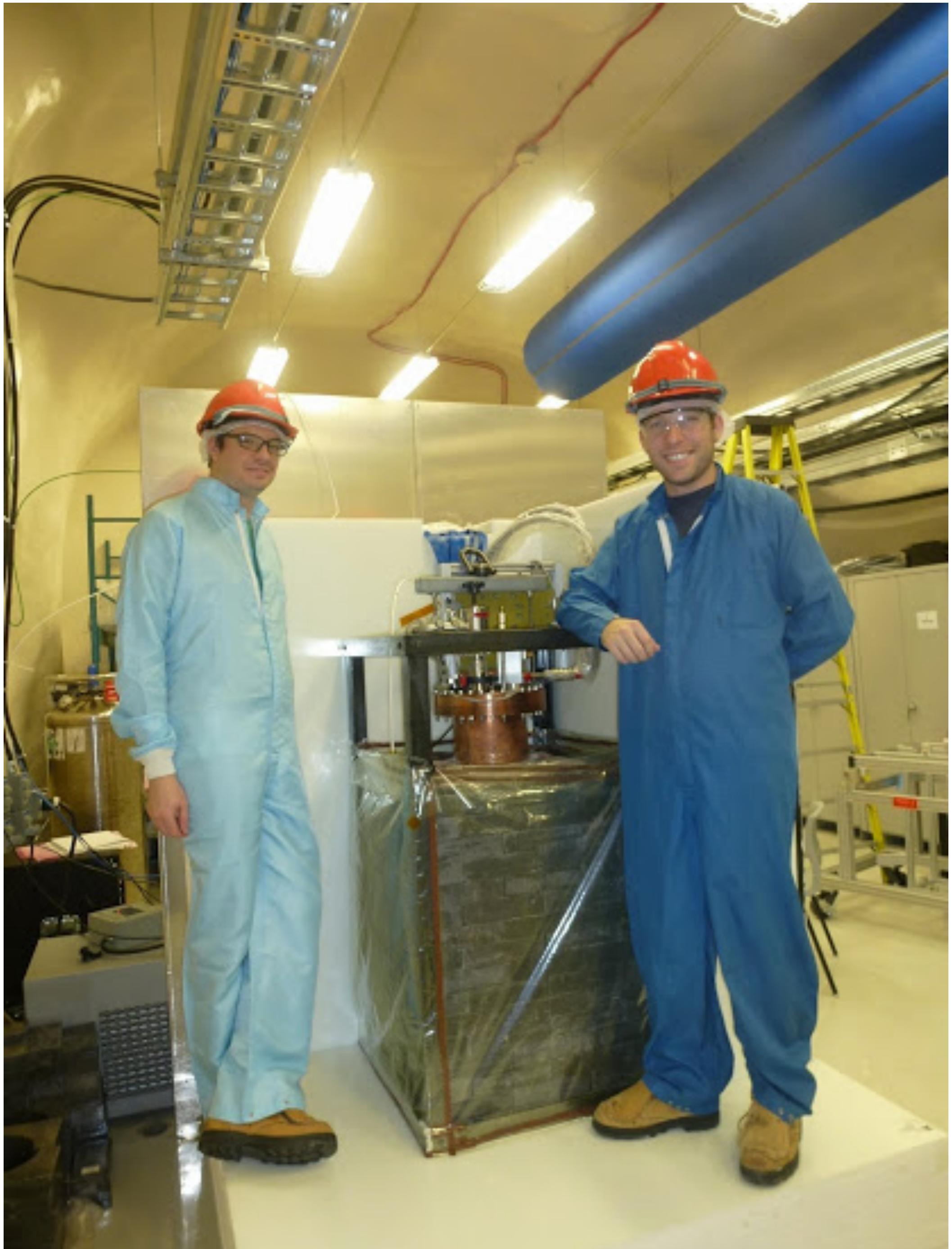
Typical DAMIC upgrade cycle (1 week)

- Weekend
  - Warmup
- Monday:
  - Early team arrives to take shield apart
- Tuesday:
  - CCD team arrives
  - vessel out of shield
  - Open vacuum vessel
- Wednesday:
  - Work inside vacuum vessel (reduced number of people)
  - Install more CCDs (for example)
- Thursday:
  - Close vessel
  - Cooldown with partial Shield
  - Check status overnight
- Friday:
  - Finish closing shield



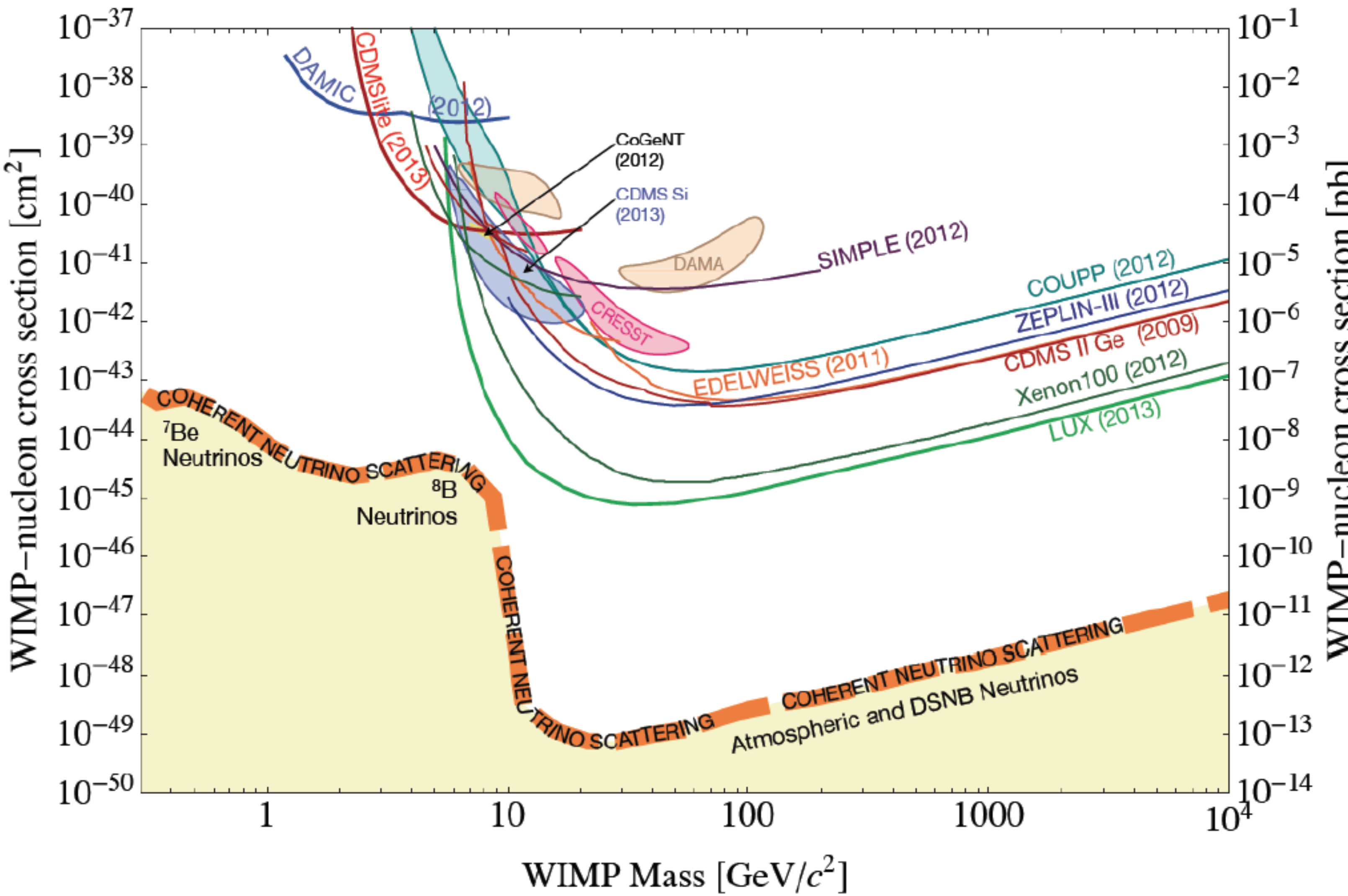


This usually involved some FNAL technical personnel, and scientific staff from FNAL and U.Chicago.

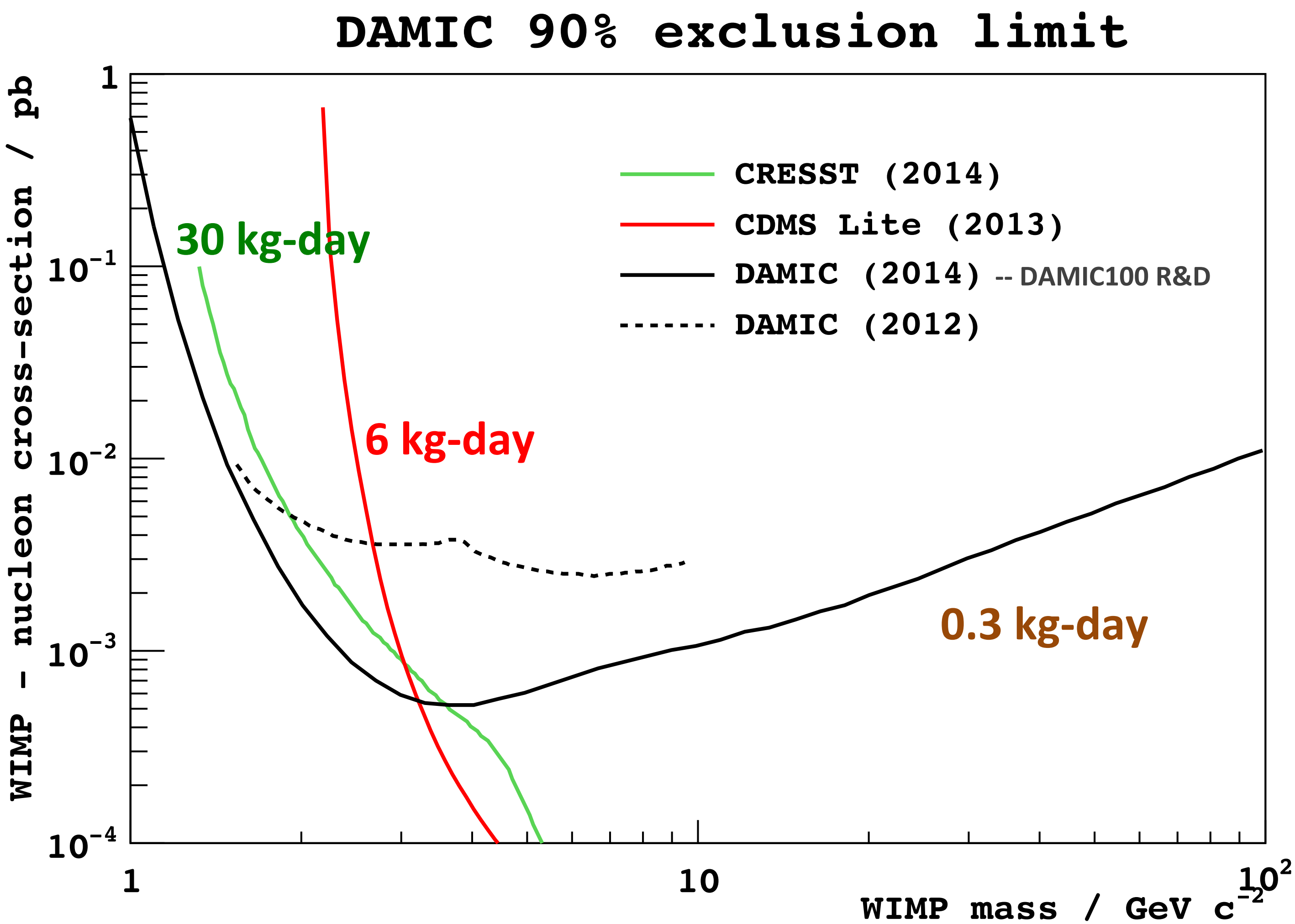


The two most critical components of DAMIC. Alvaro Chavarria, postdoc at KICP-U.Chicago. Javier Tiffenberg postdoc Fermi Center for Particle Astrophysics.

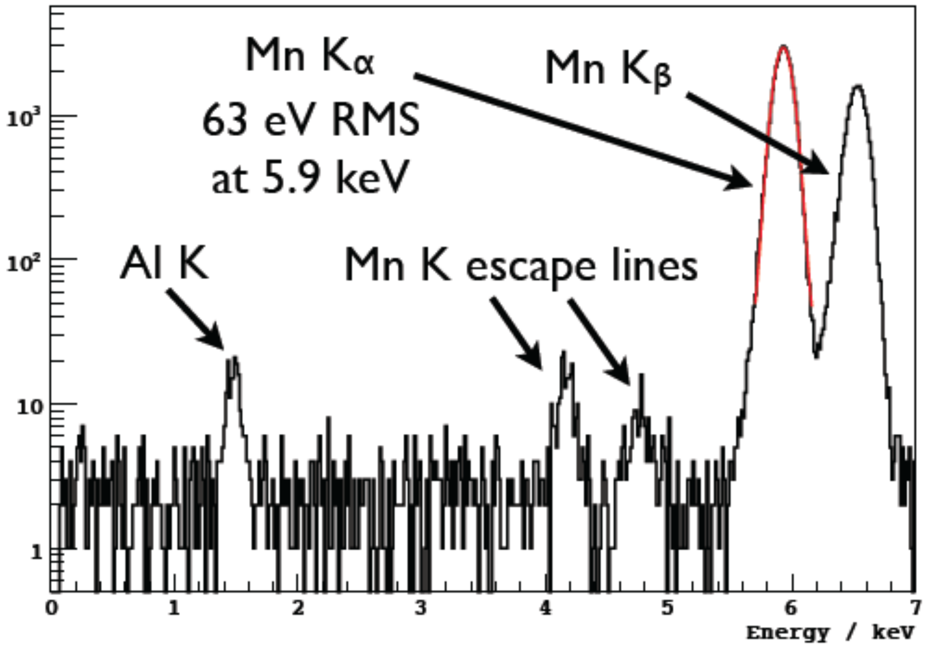
Now the result, and then the details on how we got there.

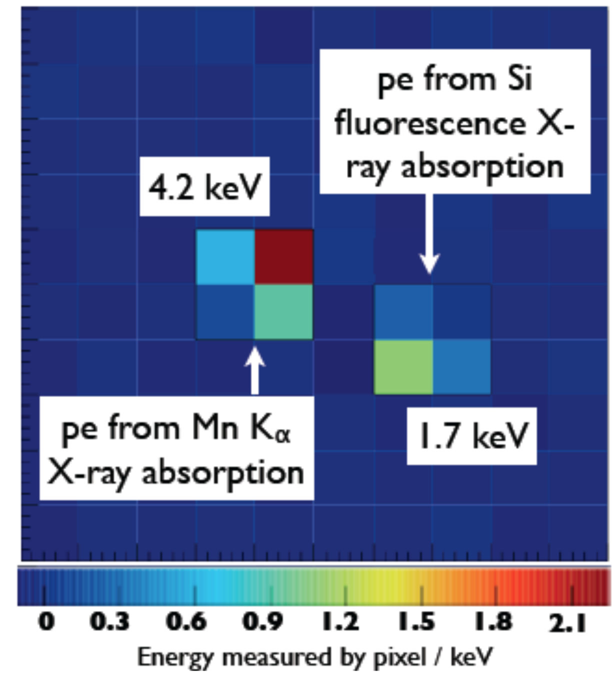


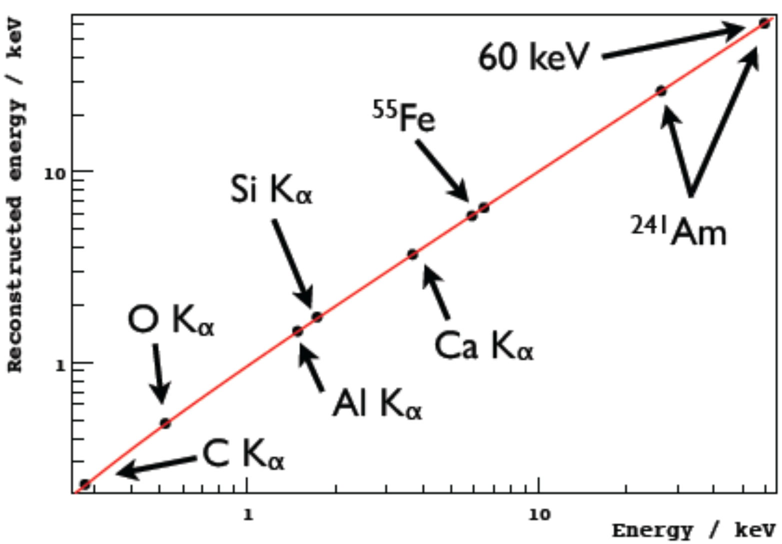
DAMIC **Preliminary** result – Best world limit @ low mass

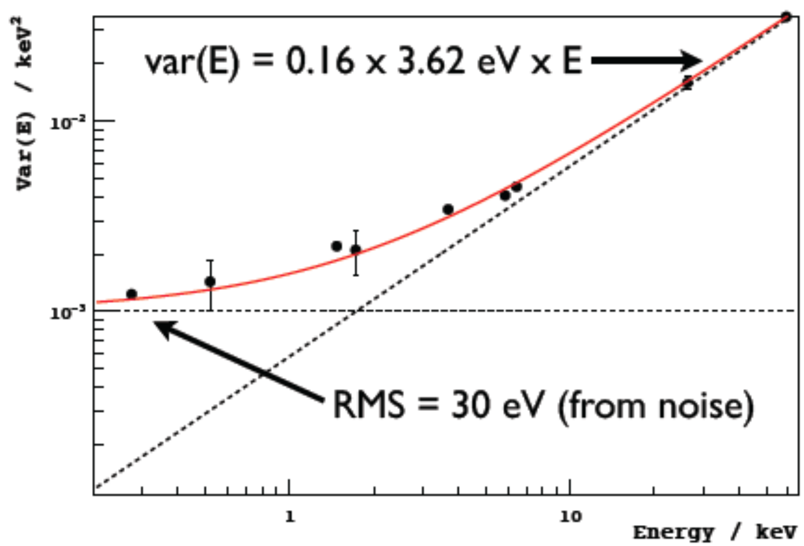


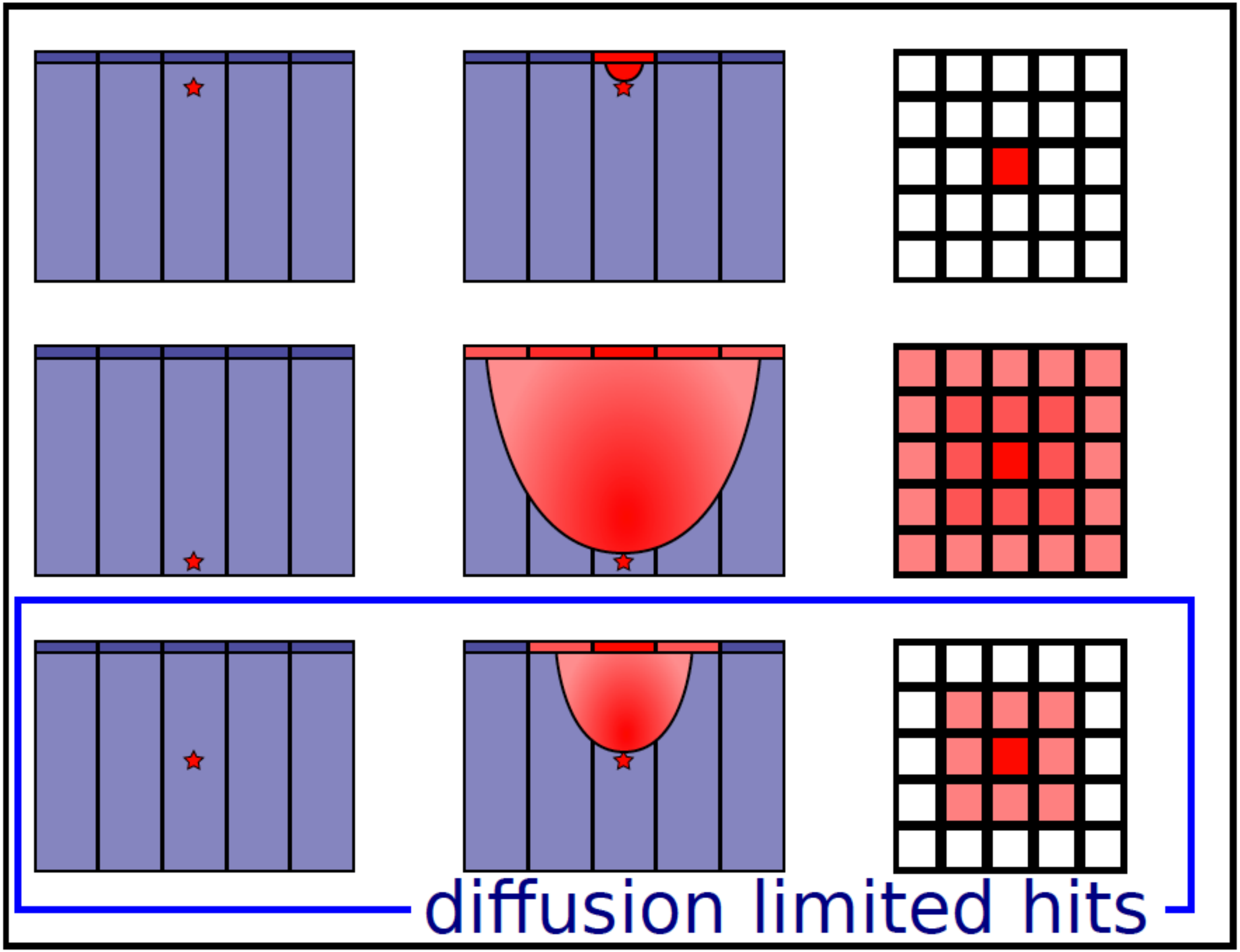
Calibration using X-rays



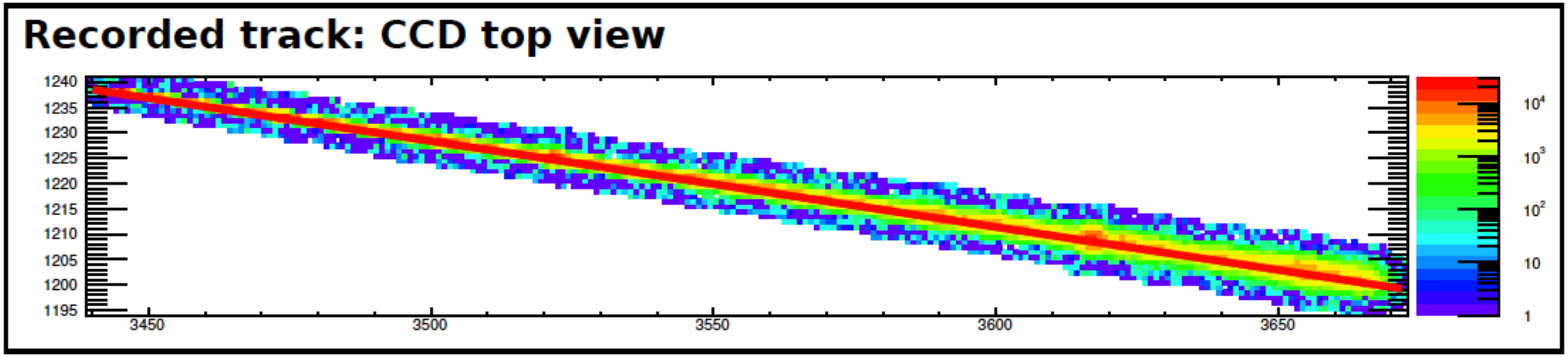


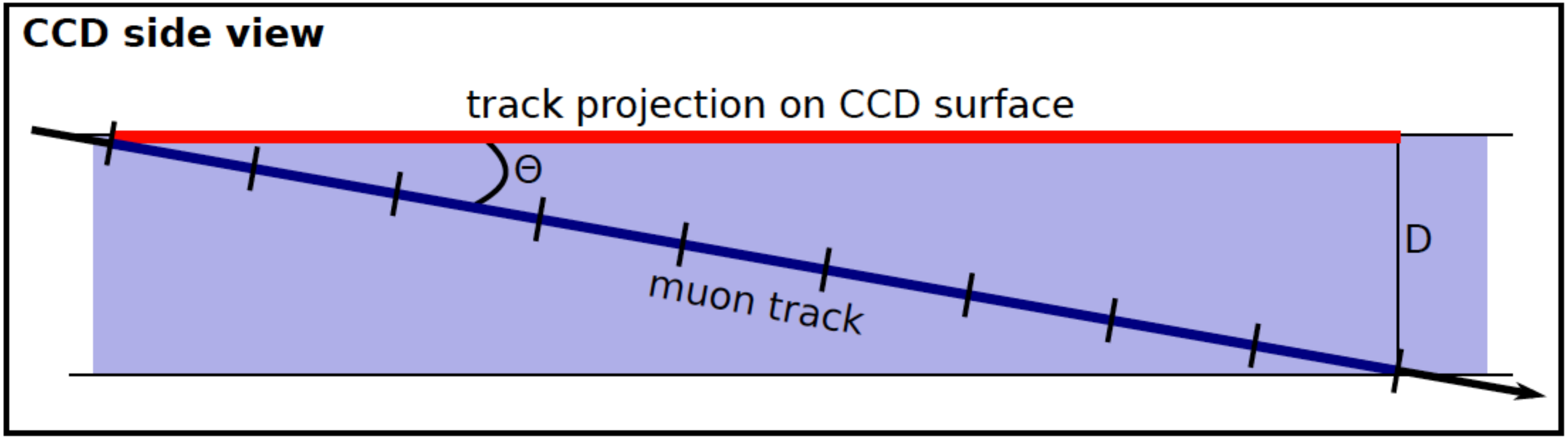




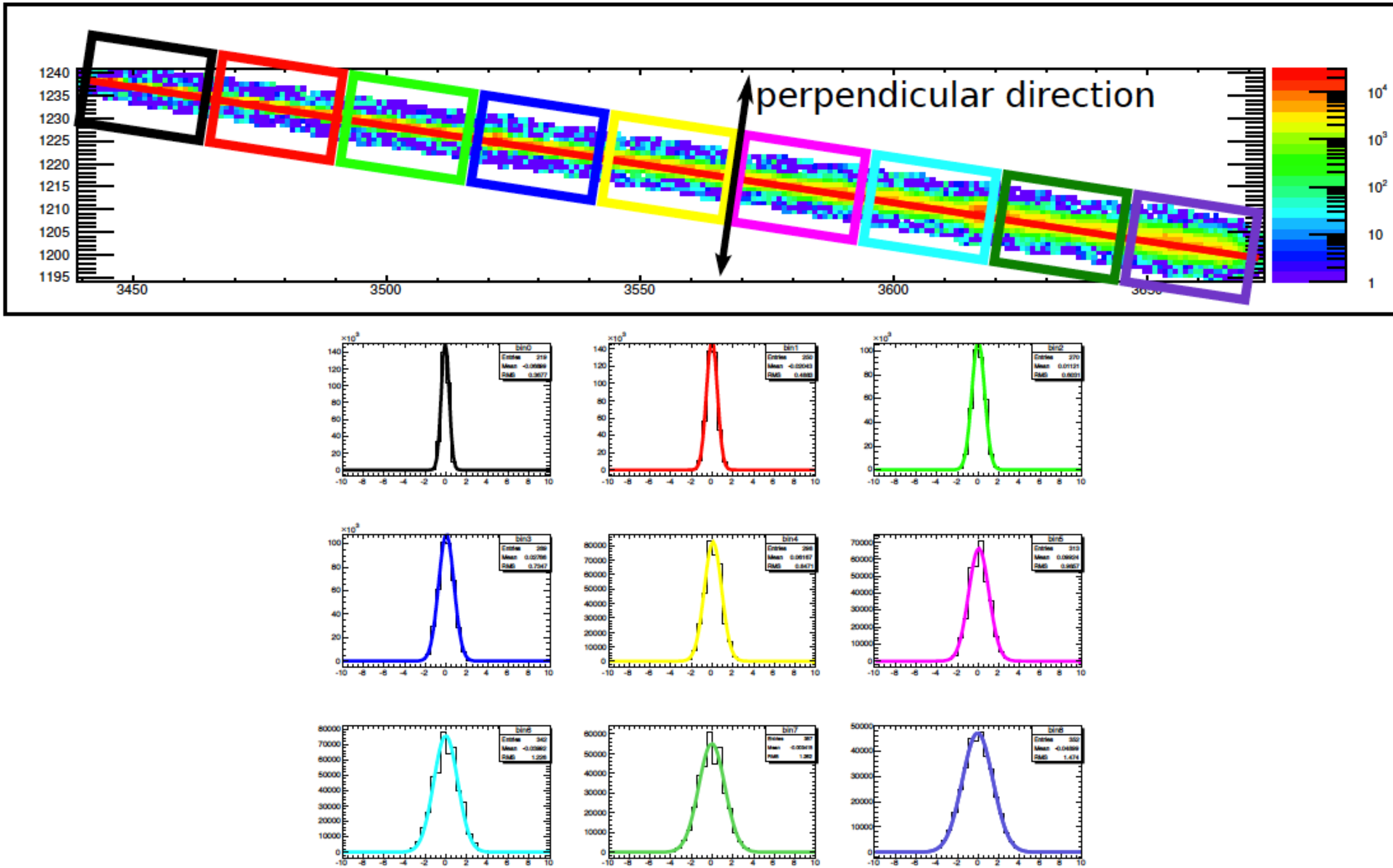

diffusion limited hits

Diffusion measurement using a muon track.

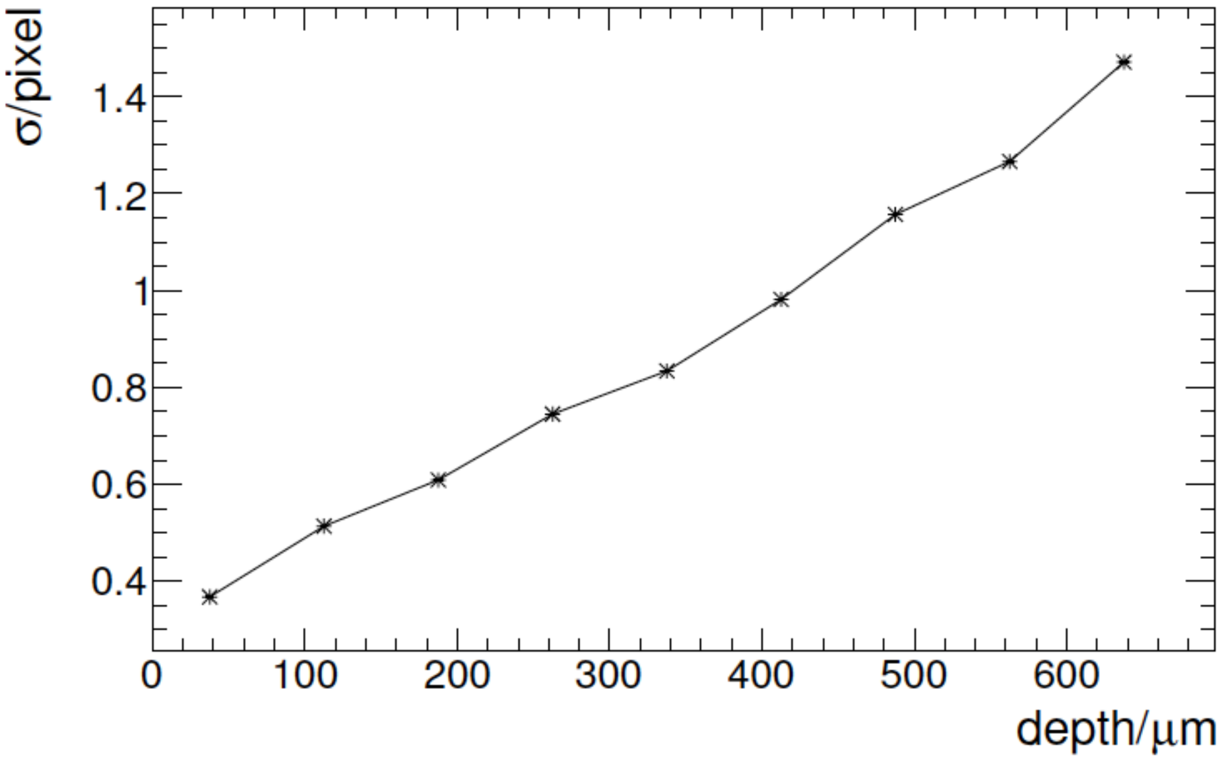




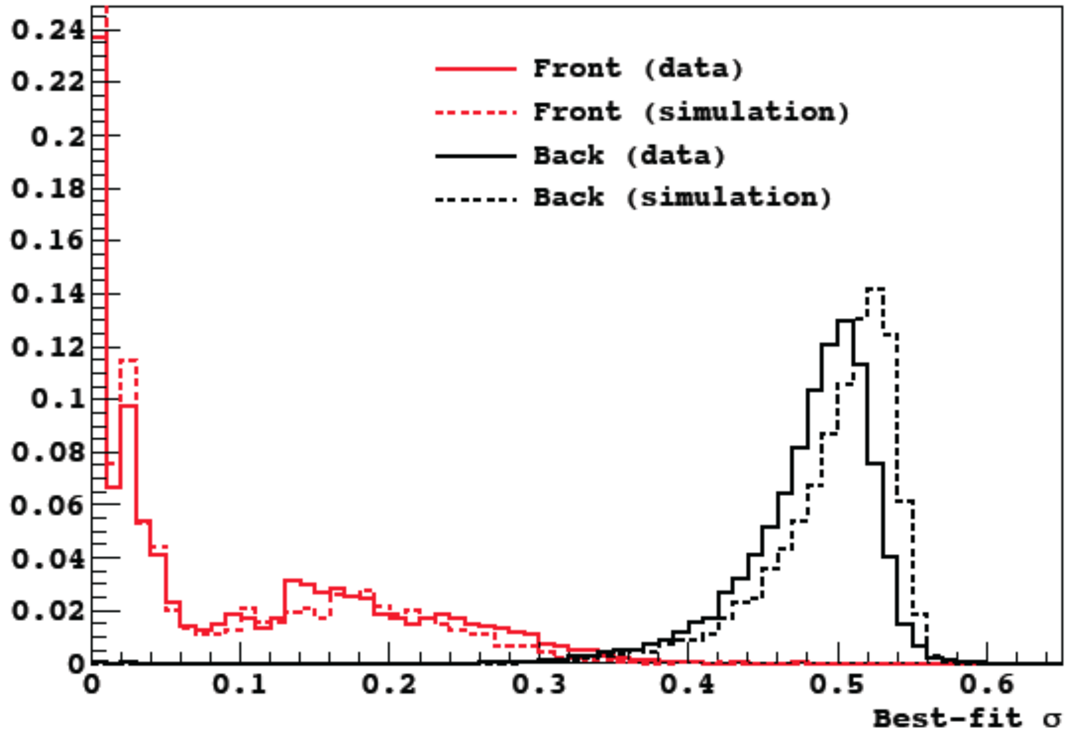
Diffusion measurement using a muon track.



Diffusion measurement using a muon track.

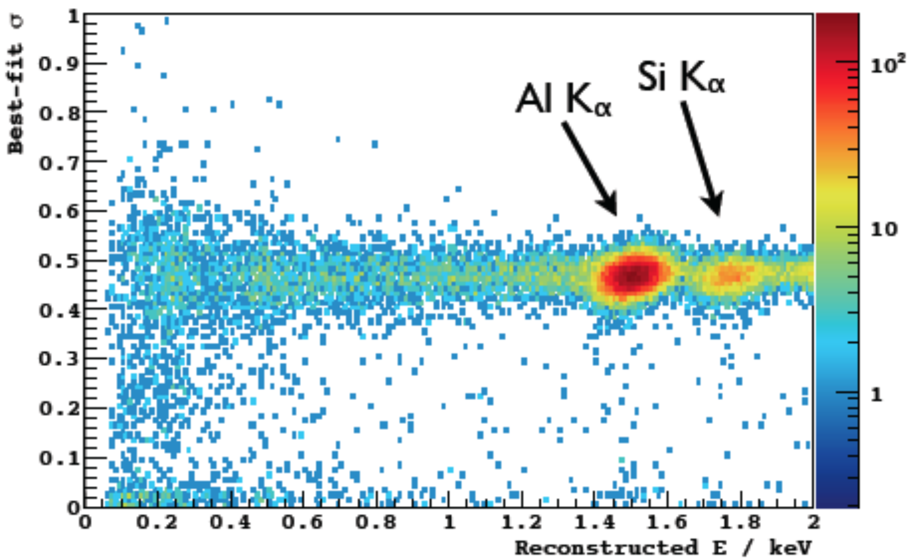


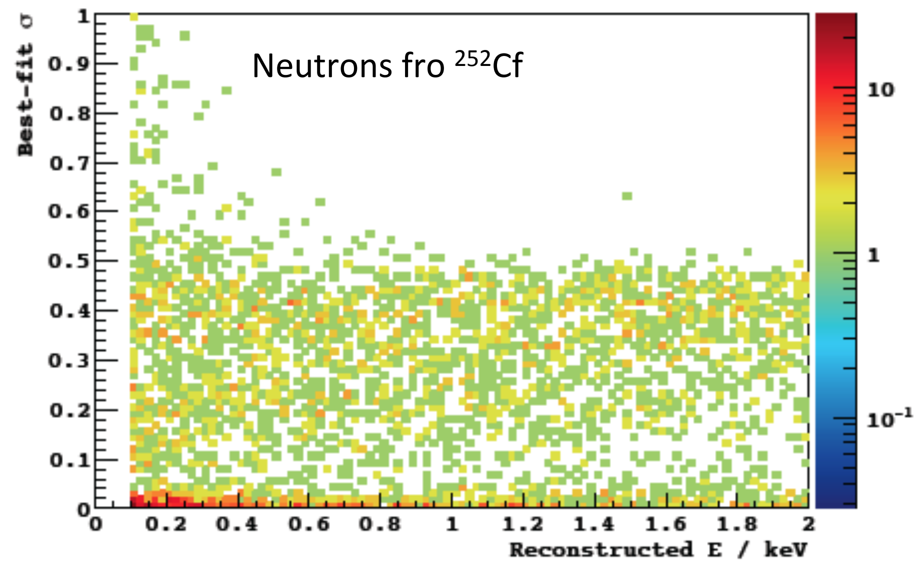
Diffusion can be measured as a function of the interaction depth.
No need to rely on models.



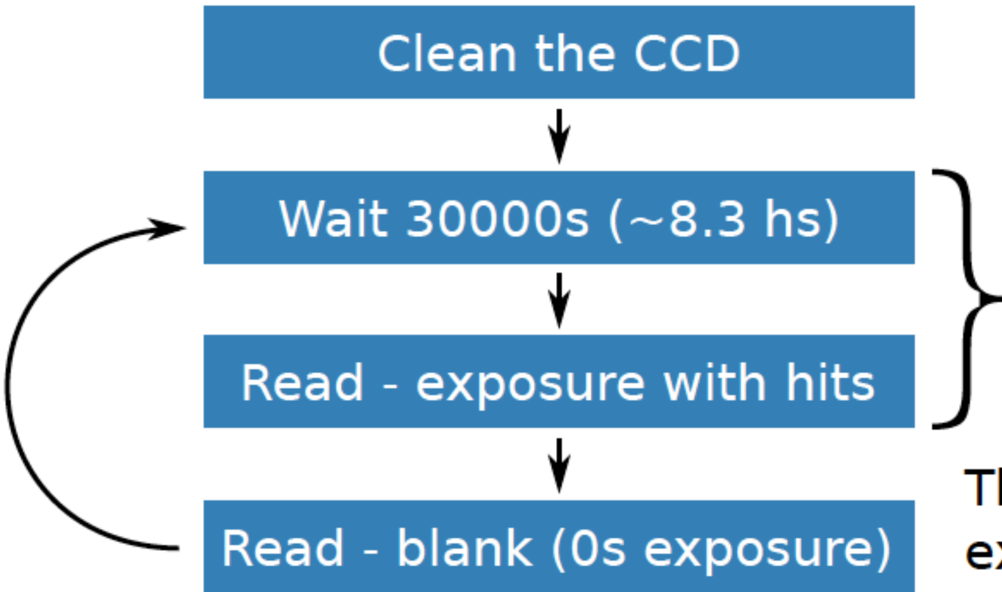
Once diffusion is measured, we can simulate X-rays and neutrons on the CCD and compare with the data.

This is important for our DM analysis.



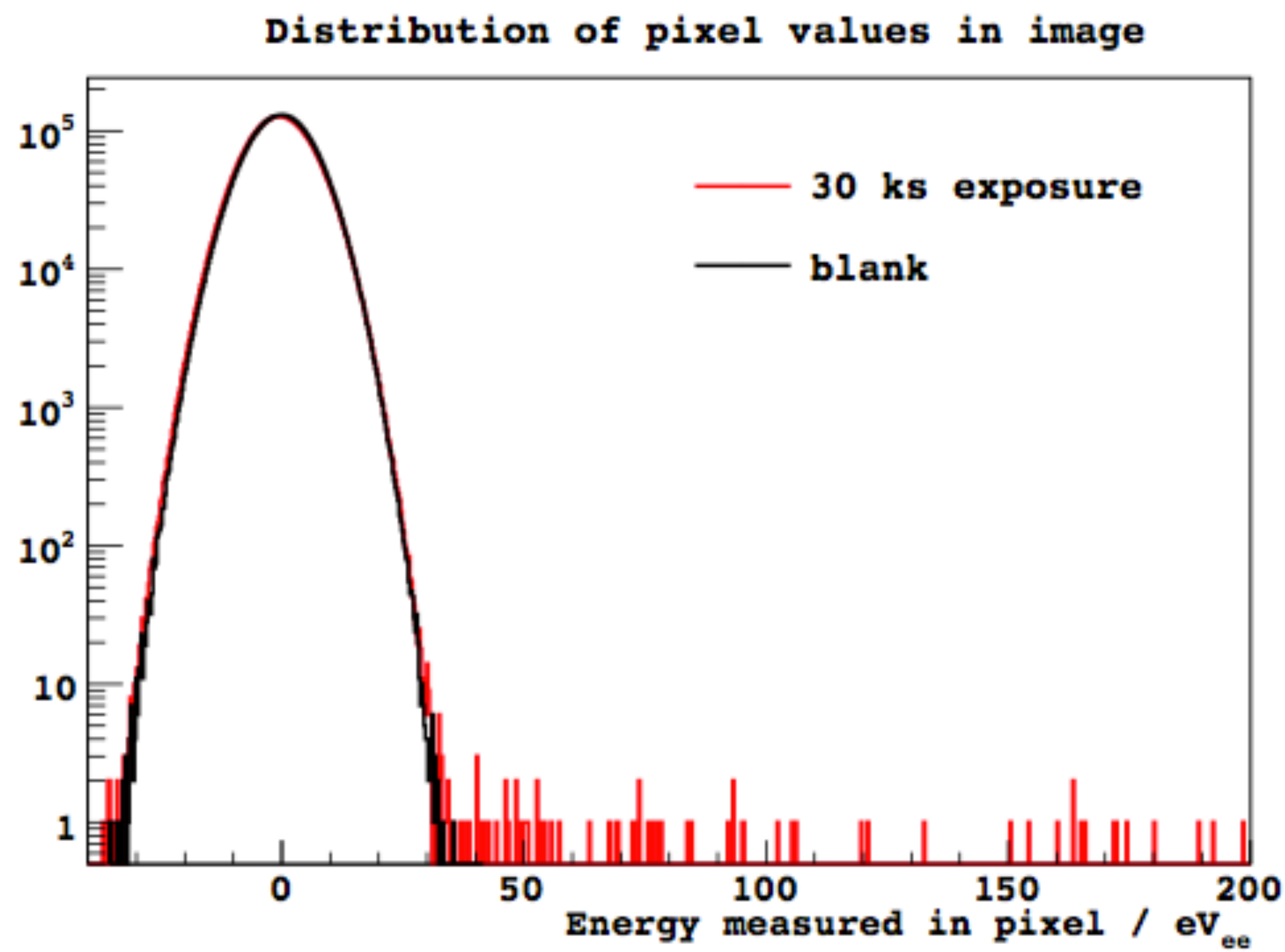


Data Collection in DAMIC.
(very long darks)

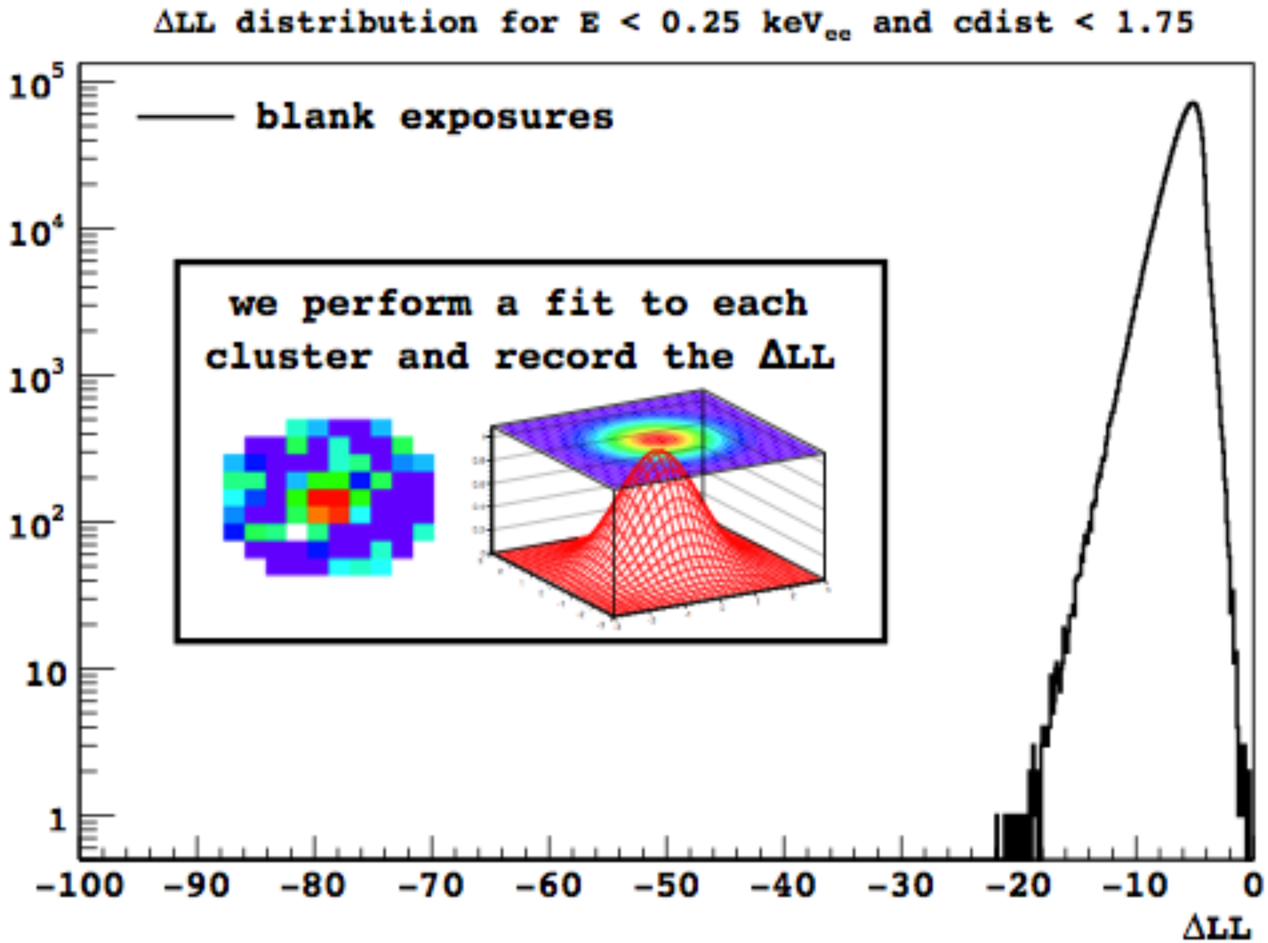


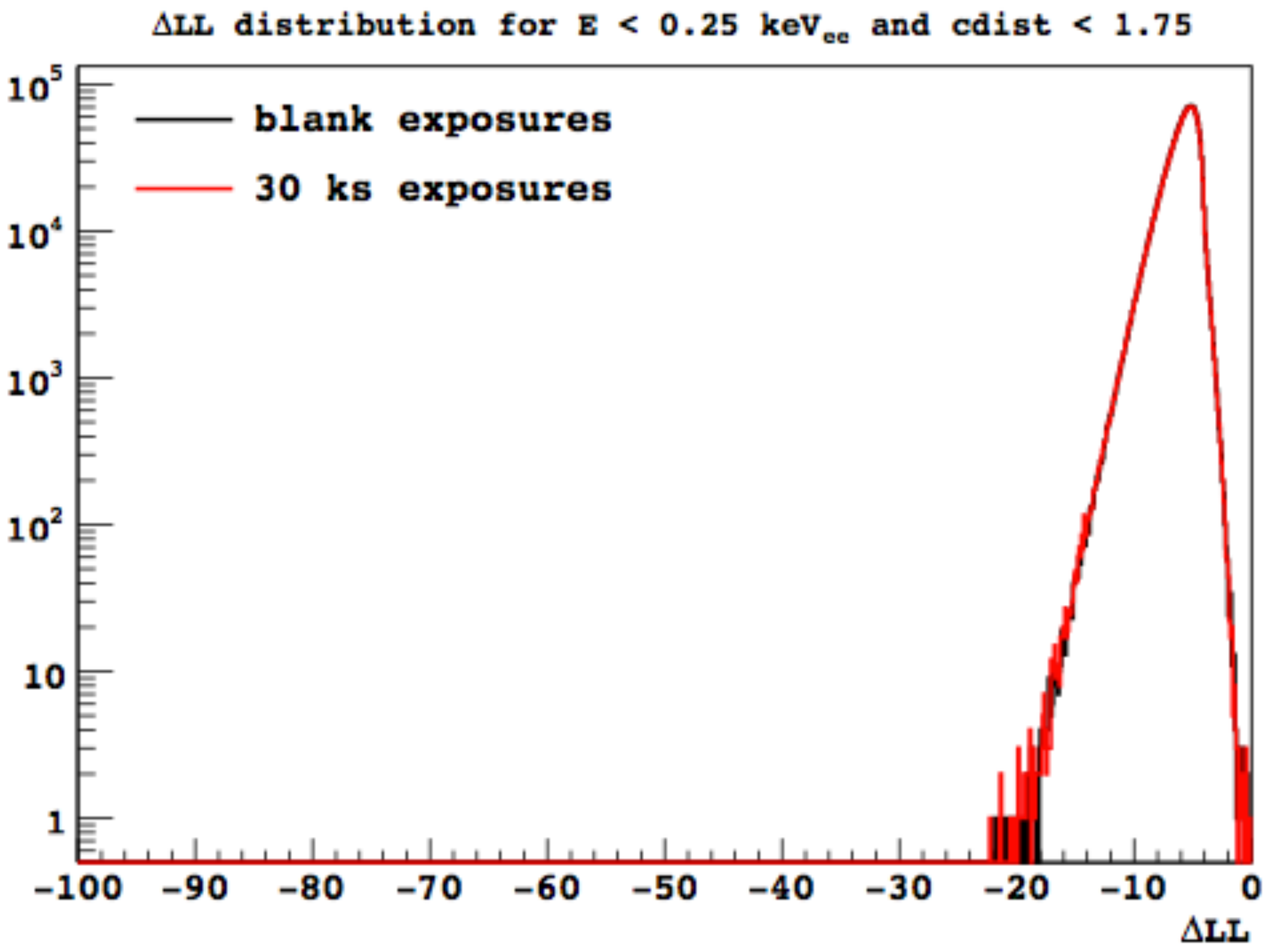
We take long exposures to minimize the number of readouts. The exposure is eventually limited by the dark current.

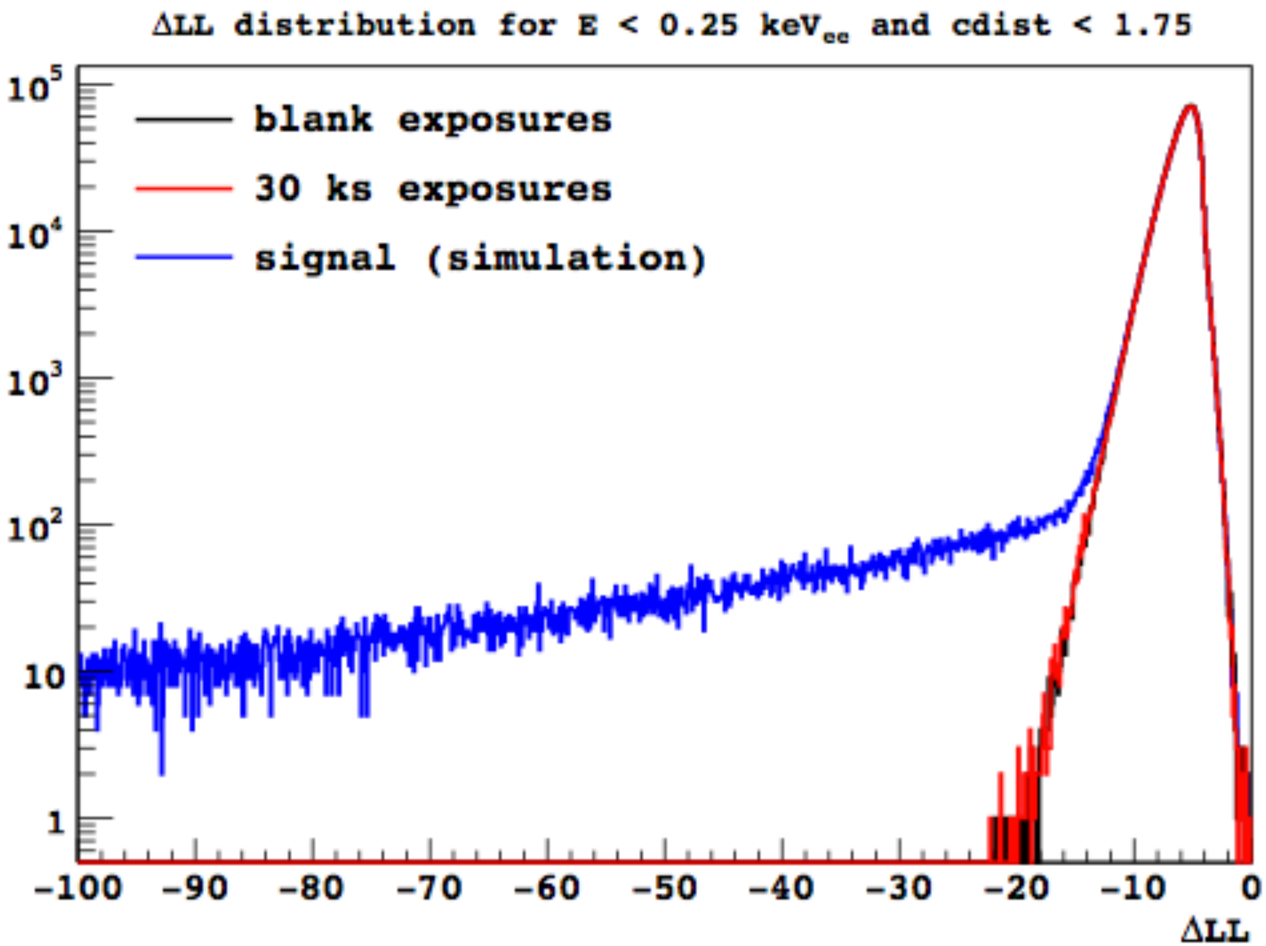
The blank images provide an excelent measurement of the background produced by readout



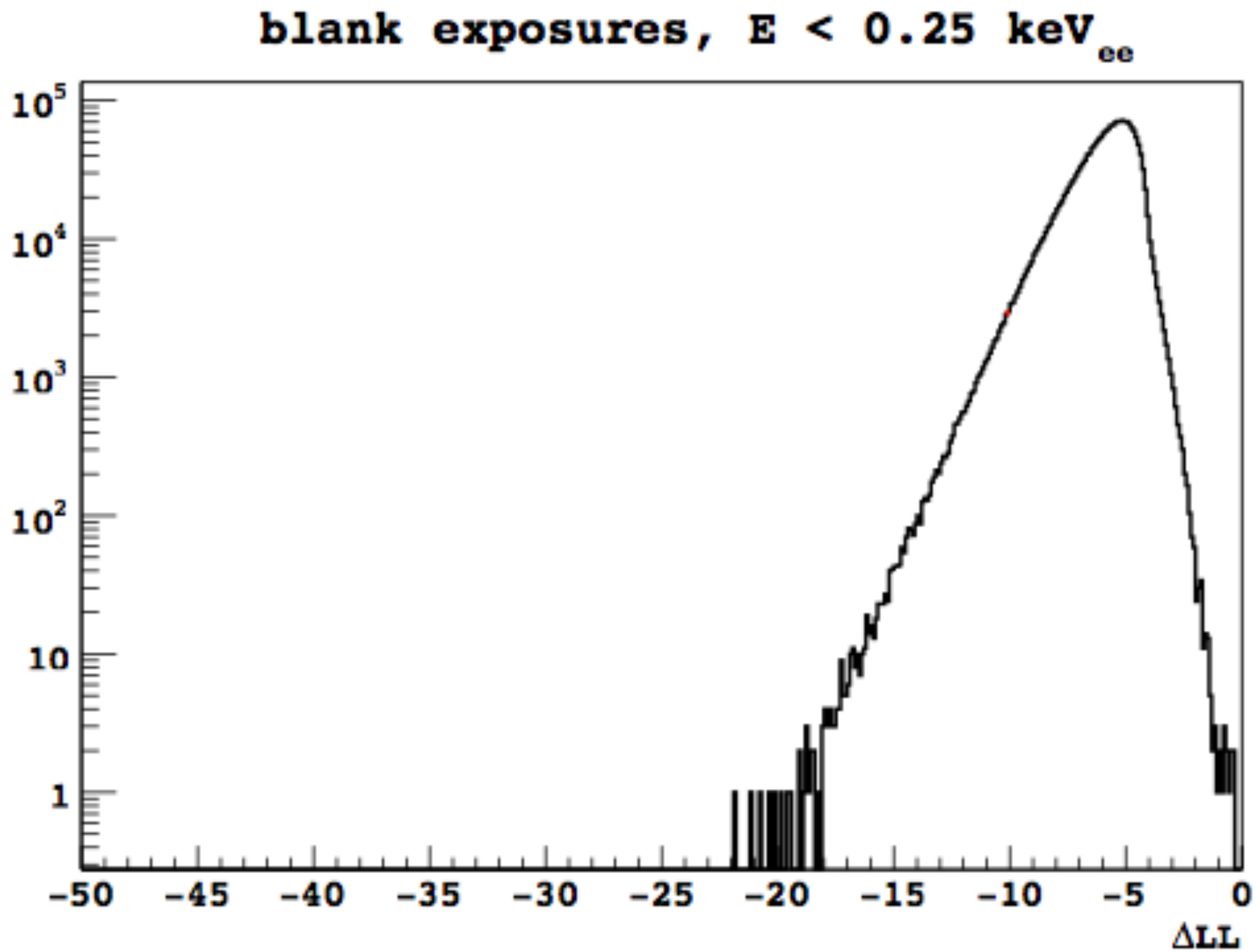
Distribution of pixel values in image
30 ks exposure
blank
10^5
10^4
10^3
10^2
10
1
0
50
100
150
200
Energy measured in pixel / eV_{ee}


ΔLL distribution for E < 0.25 keV$_{ee}$ and cdist < 1.75
blank exposures
we perform a fit to each
cluster and record the ΔLL
10^5
10^4
10^3
10^2
10
1
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
ΔLL

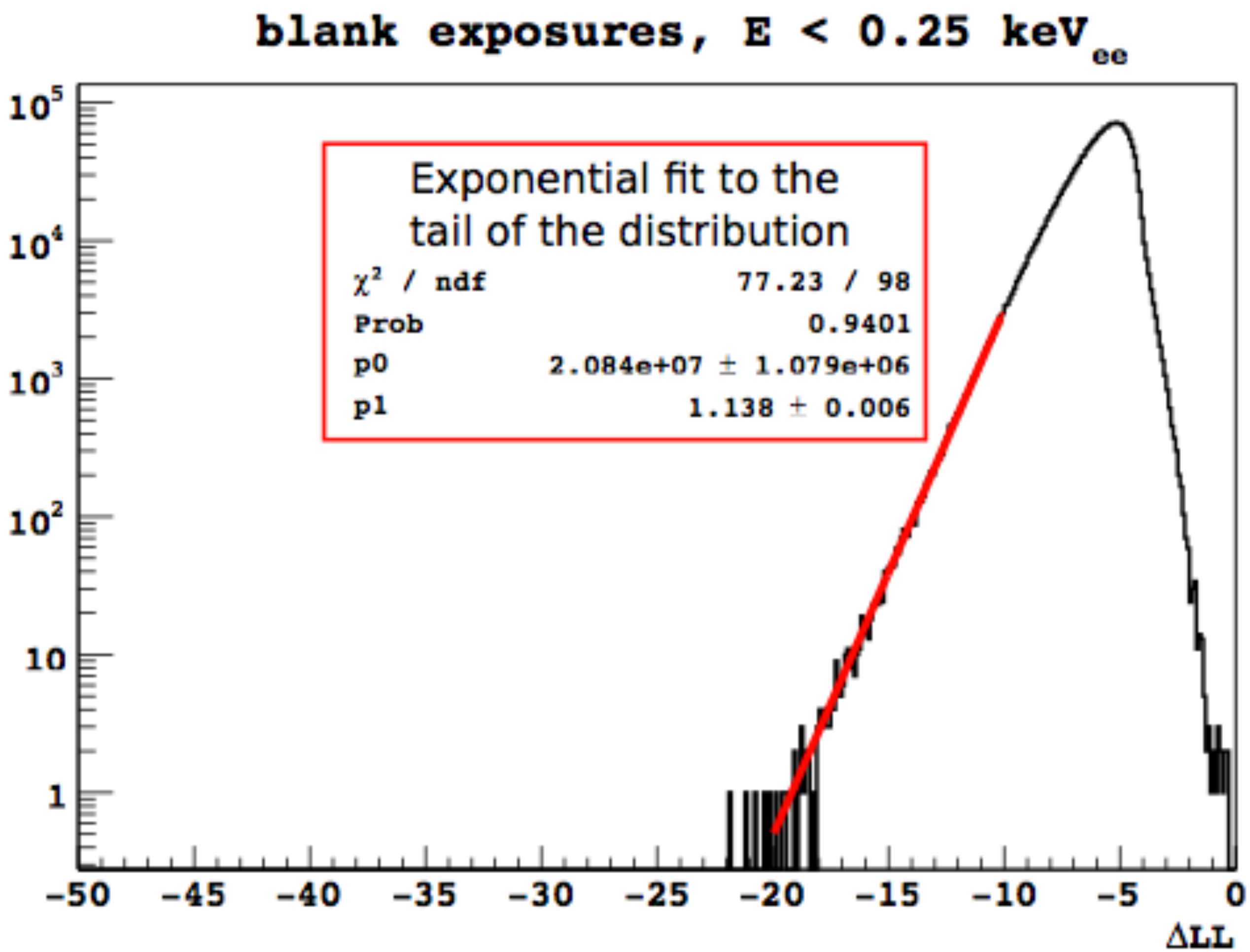

ΔLL distribution for E < 0.25 keV$_{ee}$ and cdist < 1.75
blank exposures
30 ks exposures
10^5
10^4
10^3
10^2
10
1
−100
−90
−80
−70
−60
−50
−40
−30
−20
−10
0
ΔLL



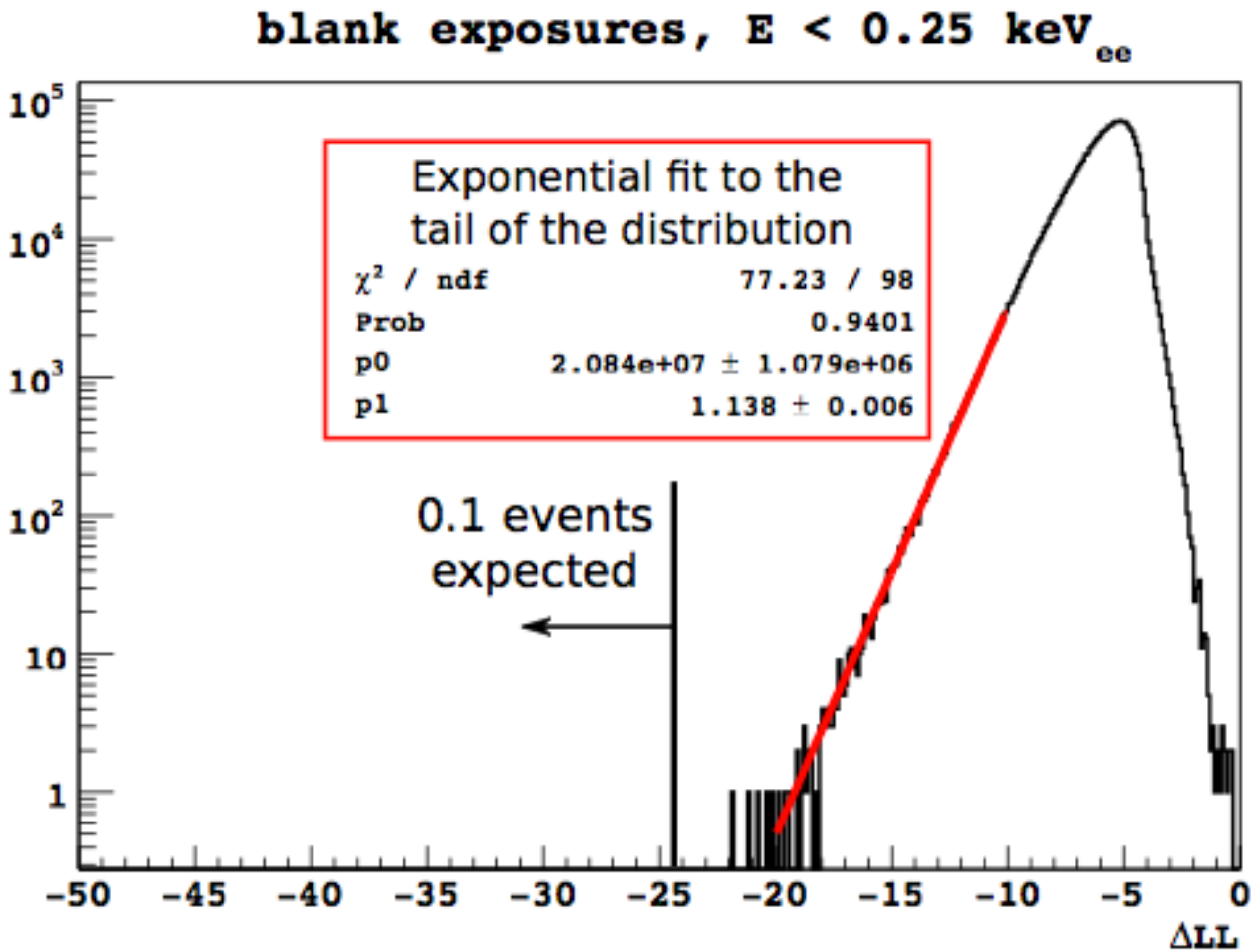
ΔLL distribution for E < 0.25 keV$_{ee}$ and cdist < 1.75
blank exposures
30 ks exposures
signal (simulation)
10^5
10^4
10^3
10^2
10
1
−100
−90
−80
−70
−60
−50
−40
−30
−20
−10
0
ΔLL



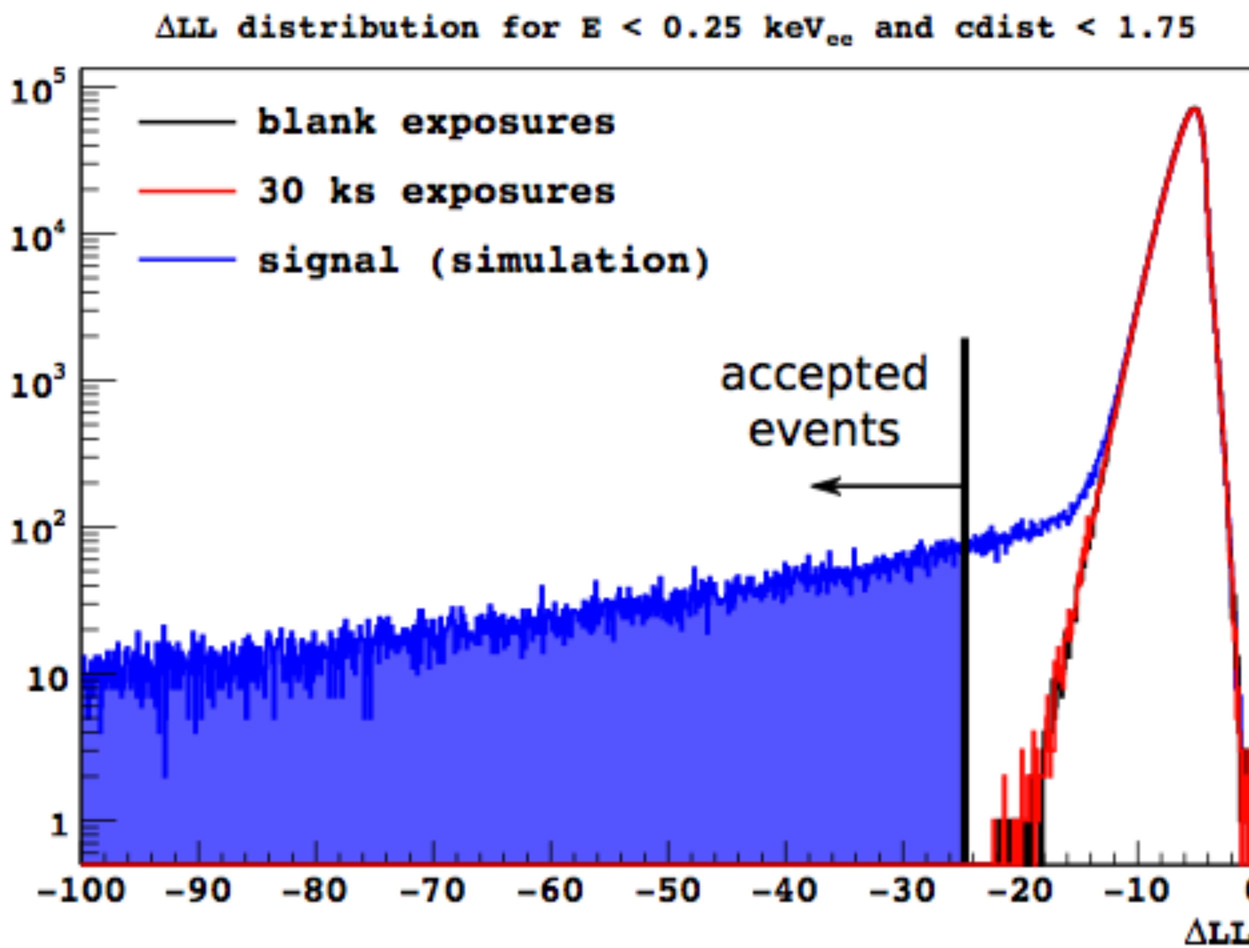
blank exposures, E < 0.25 keV$_{ee}$
10^5
10^4
10^3
10^2
10
1
−50
−45
−40
−35
−30
−25
−20
−15
−10
−5
0
ΔLL



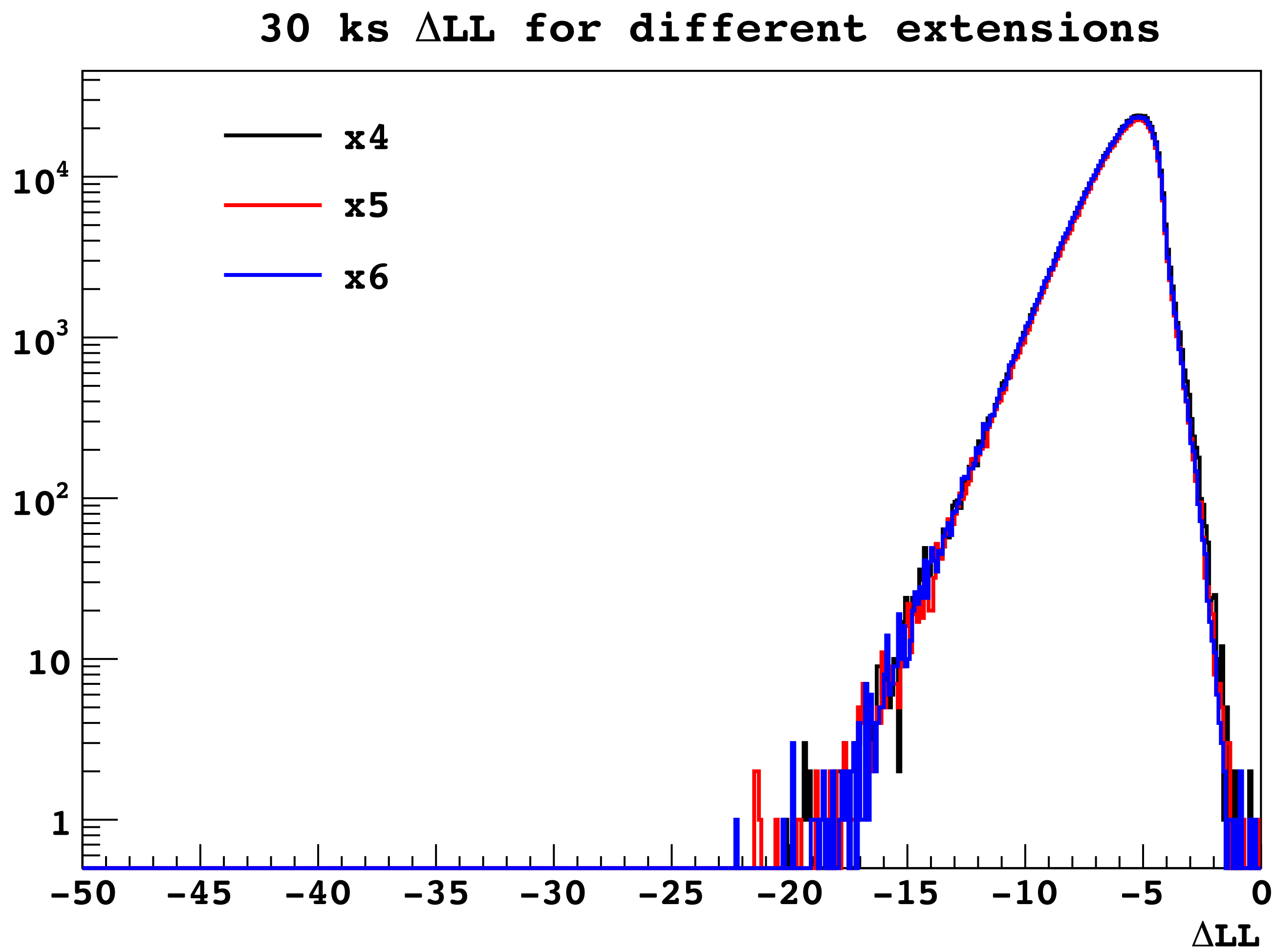
blank exposures, E < 0.25 keV$_{ee}$
Exponential fit to the tail of the distribution
χ^2 / ndf 77.23 / 98
Prob 0.9401
p0 2.084e+07 ± 1.079e+06
p1 1.138 ± 0.006
10^5
10^4
10^3
10^2
10
1
−50
−45
−40
−35
−30
−25
−20
−15
−10
−5
0
ΔLL



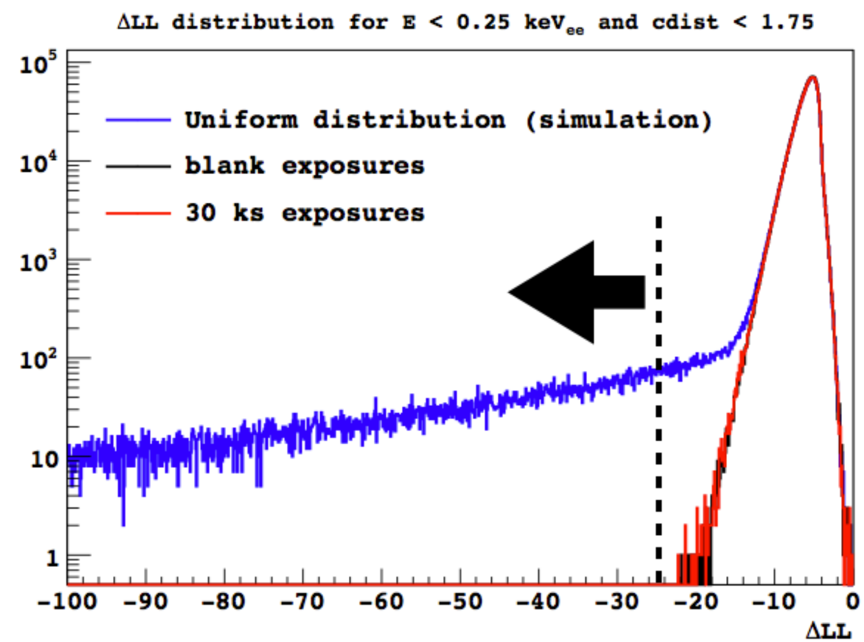
Likelihood difference between noise and 2D Gaussian hit. Blanks, with no real hits, are used to determine cuts.

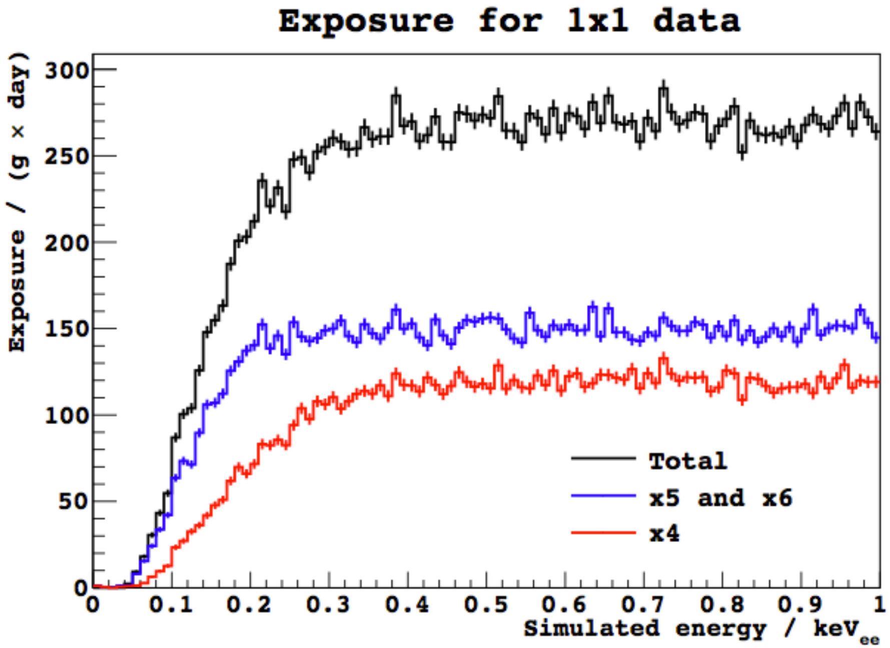


ΔLL distribution for E < 0.25 keV$_{ee}$ and cdist < 1.75
blank exposures
30 ks exposures
signal (simulation)
accepted events
10^5
10^4
10^3
10^2
10
1
−100
−90
−80
−70
−60
−50
−40
−30
−20
−10
0
ΔLL



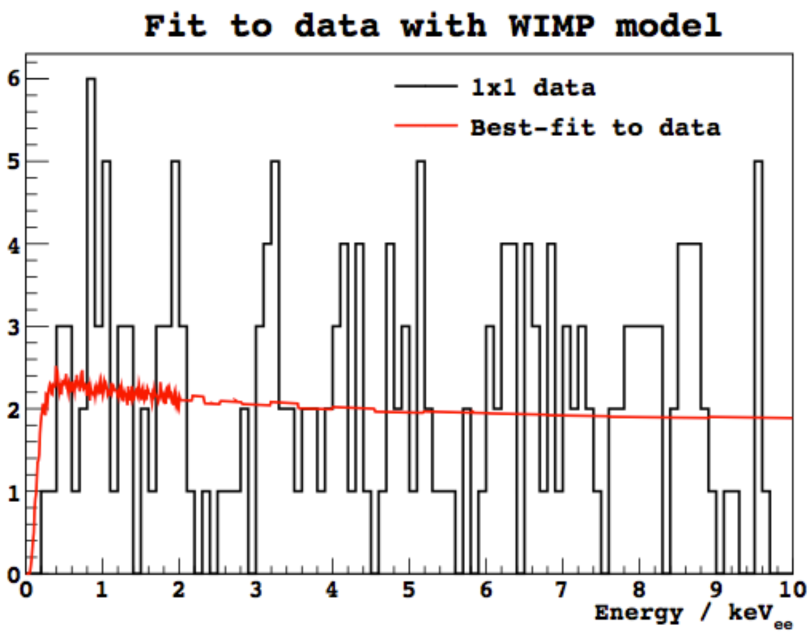
3 CCDs used for this analysis (one was not working well). Look very similar to blanks.





Simulation used to estimate the efficiency down to threshold. Based on this efficiency, an exposure is calculated.

No wimp detected



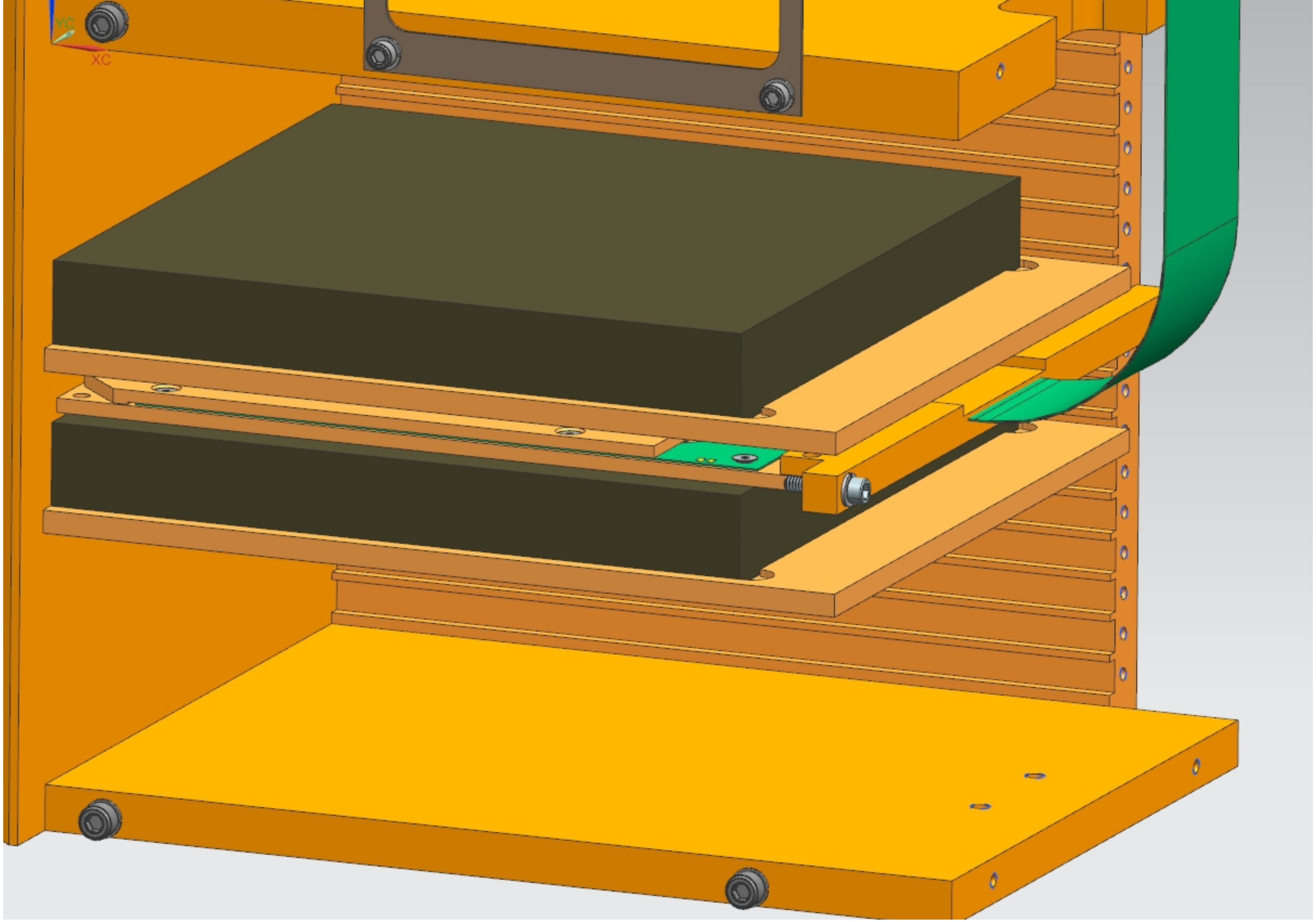
Best fit mass: 26 ± 46 GeV/c^2
Best fit xs: (7 ± 16) x 10^{-4} pb
Best fit c: 67 ± 13 dru
Minimum -ll: -396.5

Null hypothesis c: 74 ± 5 dru
Minimum -ll: -396.1

Background was still high for Dec-2014. We associated this to Randon in the volume around the lead shield.

We had nitrogen gas purge, with suspicious performance. Now things are a bit better (~1/2), but there is still something for us to understand.

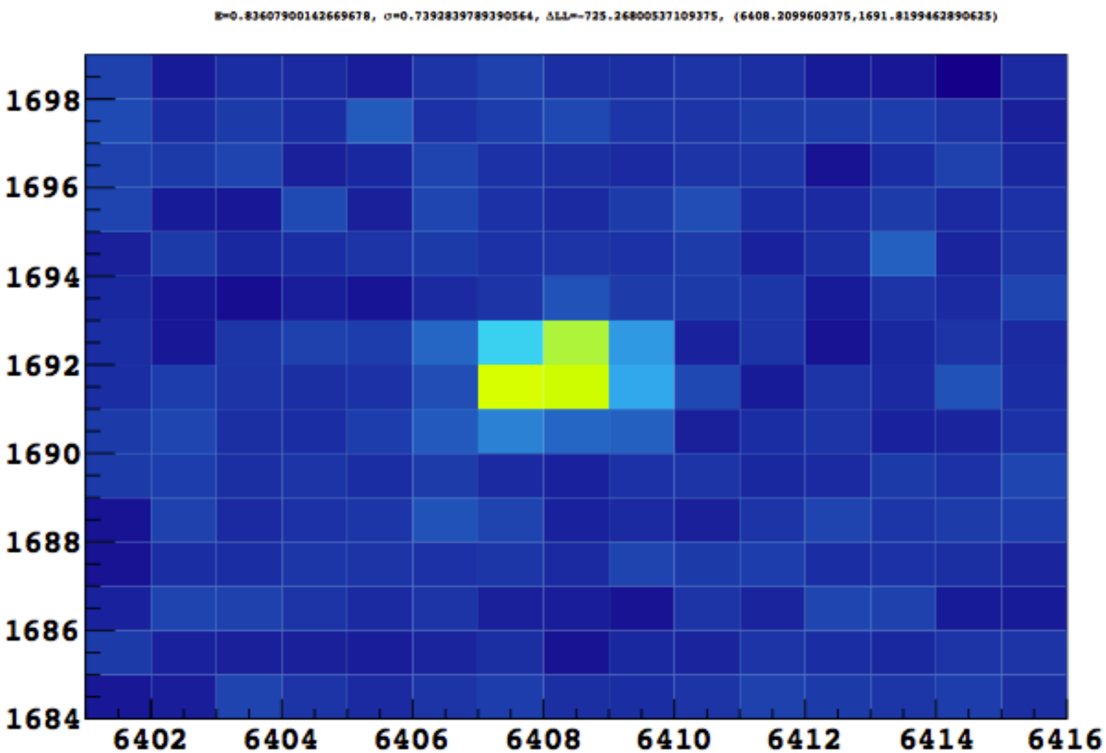
Next upgrade March



Super shielded CCD. 2.5cm of ancient lead next to the detector.

Two unique capabilities in the DAMIC detector, not used for the preliminary result yet. However, they demonstrate the flexibility of this technology.

Binning:



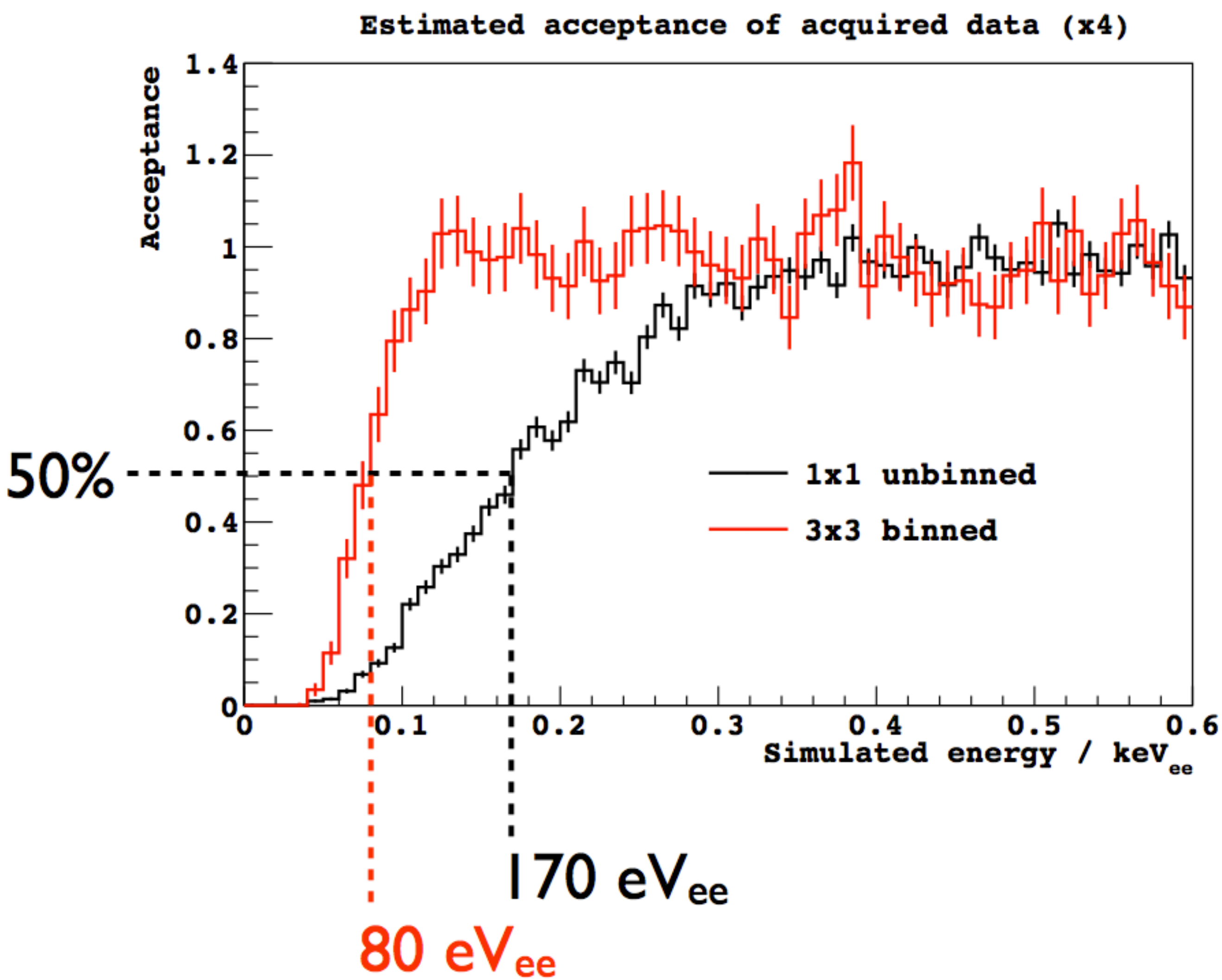
Every pixel readout has a 2e- noise. The CCD allows you to add charge in the sensor (binning) and then readout many pixels as a single one. Signal to noise.

This improves signal to noise, effectively increasing the efficiency at low energy.

$s/n = Q / N_{read}\,\sigma$

Reading the charge in less pixels is good!

DAMIC binning: the best is yet to come

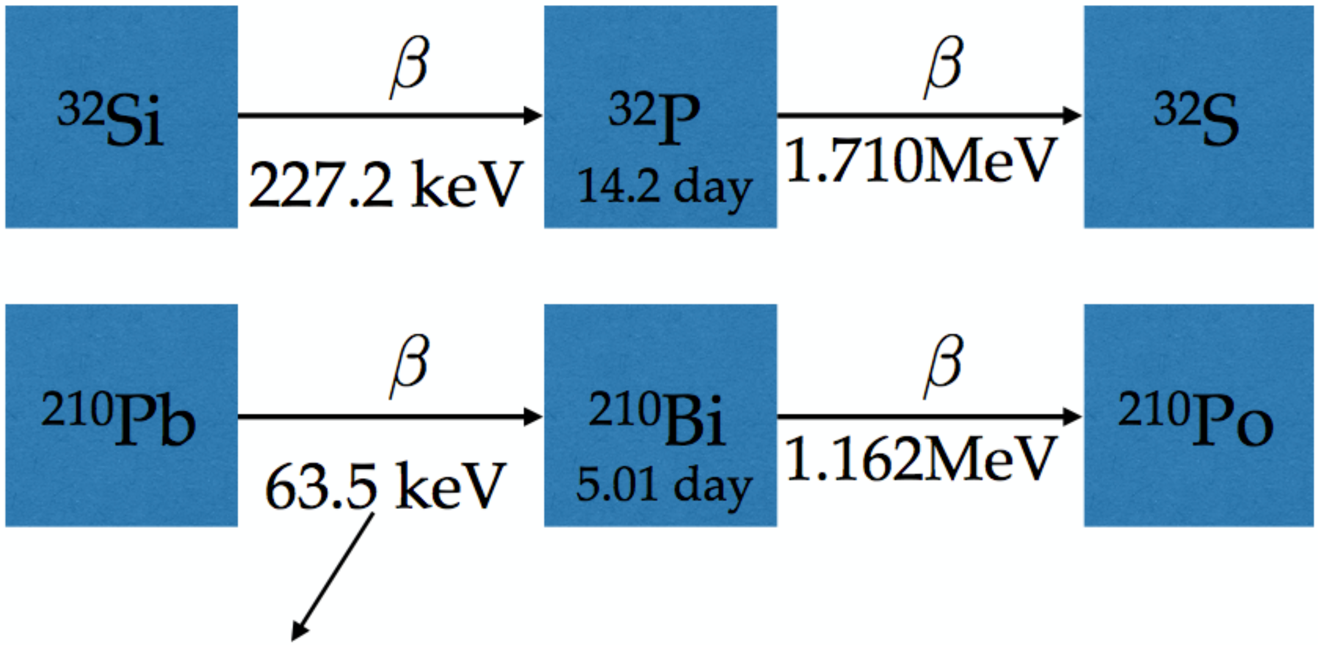


Every pixel readout has a 2e- noise. The CCD allows you to add charge in the sensor (binning) and then readout many pixels as a single one.

This improves signal to noise, effectively increasing the efficiency at low energy.

Binned data not used for preliminary result shown here.

Background from Silicon : could be a limiting

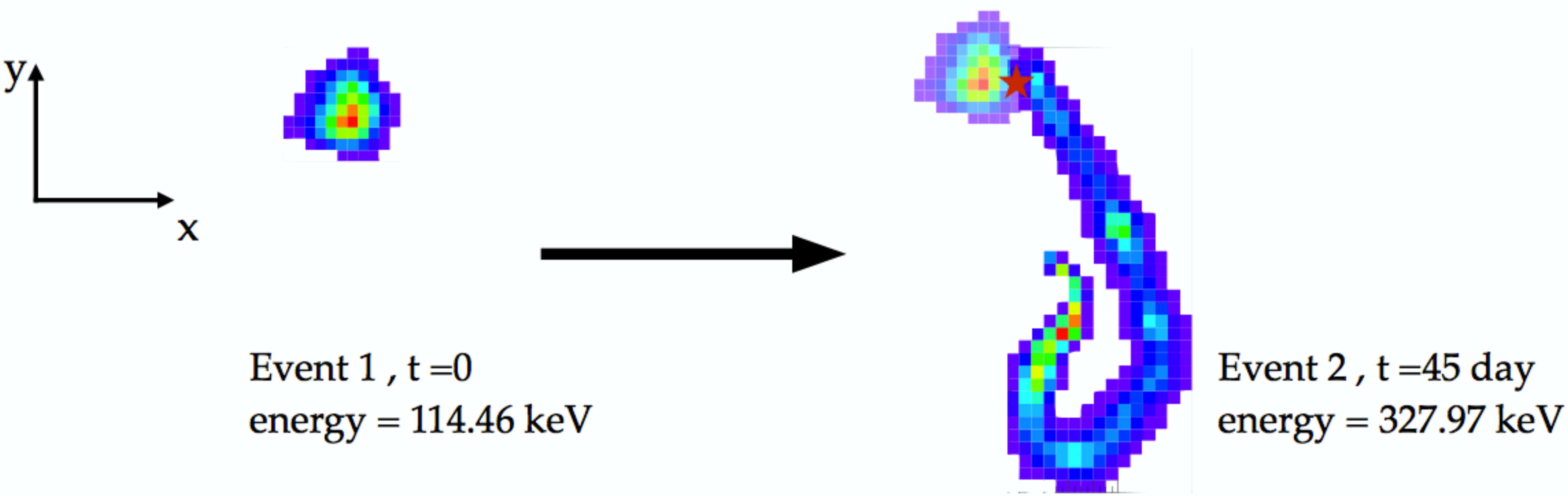


Q-value: 63.5 keV, 84% of betas with endpoint 16.5 keV, the rest energy 4% a gamma line, so, 80% would go to conversion electrons with energy around [47,63.5] keV.

Background from Silicon

The precise position reconstruction in the CCDs allows us to study spatial coincidences of those decay chains and give a limit of ^{32}Si and ^{210}Pb in the CCD.

$$^{32}\mathrm{Si} \longrightarrow ^{32}\mathrm{P} + \beta^-, \ \mathrm{Qvalue} = 227.2 \ \mathrm{keV} \quad ^{32}\mathrm{P} \longrightarrow ^{32}\mathrm{S} + \beta^- \ \mathrm{with} \ \tau = 14.2 \ \mathrm{days}, \ \mathrm{Q-value} = 1.71 \ \mathrm{MeV}$$



It is a very nice feature of the CCDs to be able to measure this rate, and also reject it. This is important for any low background experiment with Si. Our results on ^{32}Si will be published soon.

The detector Silicon seems to be low background, as seen by counting alpha particles.

From α search in 4.5 - 5 MeV energy region

^{238}**U** uncorrelated daughters ^{234}U (4.77 MeV), ^{230}Th (4.69 MeV), ^{226}Ra (4.79 MeV) place limit

$< 8\ kg^{-1}\ day^{-1} = 0.08\ mBq\ kg^{-1} = 7\ ppt\ (95\%\ C.L.)$

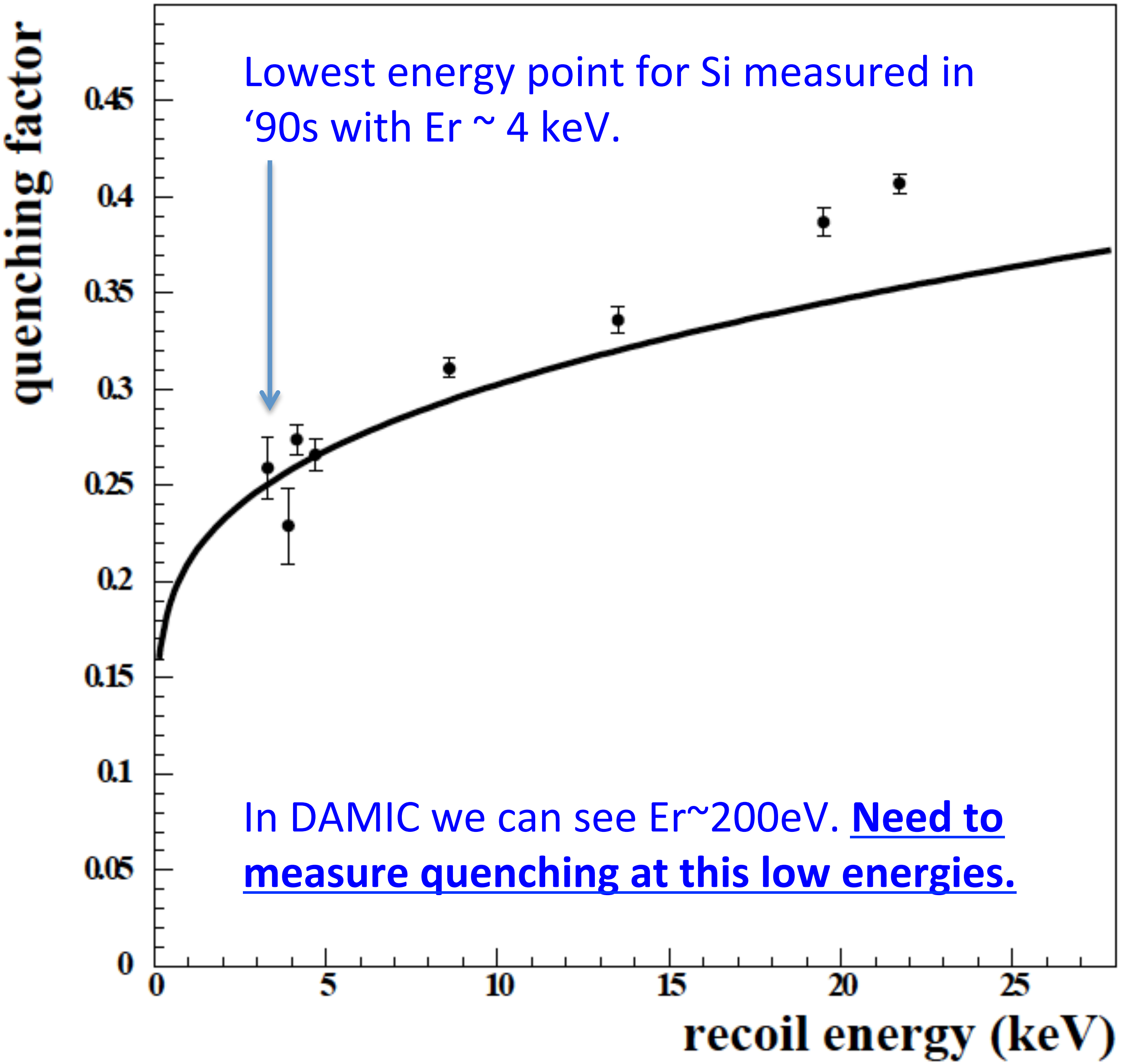
From α search of 18.8 MeV pile-up α from fast sequence

^{224}Ra (5.69 MeV) ➡ ^{220}Rn (6.29 MeV) ➡ ^{216}Po (6.78 MeV)

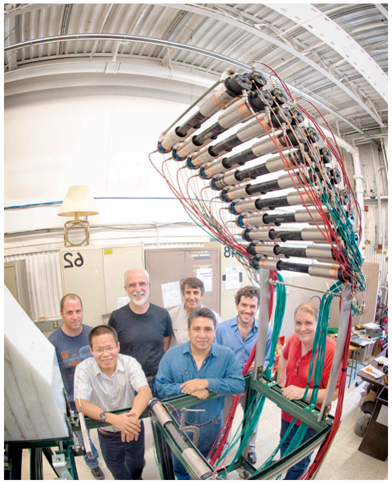
^{232}**Th:**

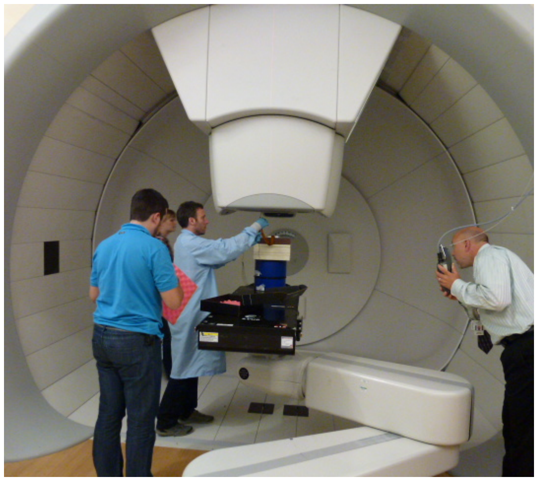
$< 15\ kg^{-1}\ d^{-1} = 0.17\ mBq\ kg^{-1} = 43\ ppt\ (95\%\ C.L.)$

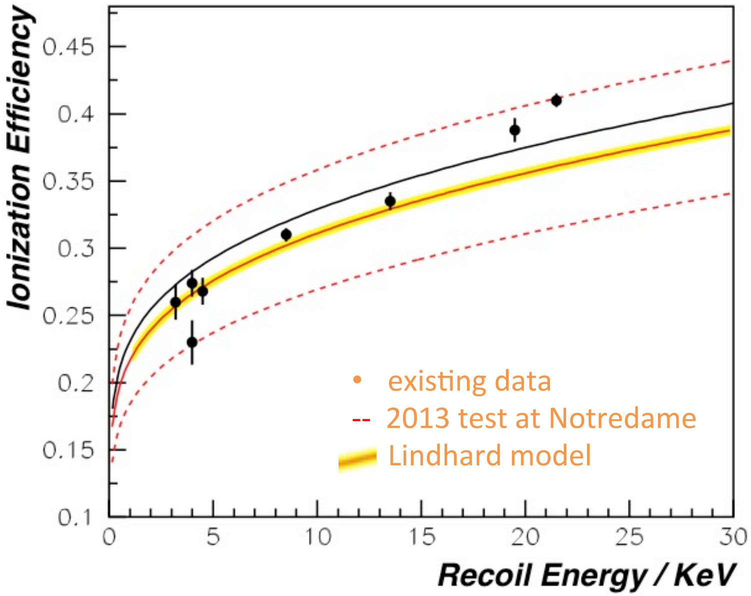
Ionization yield for a nuclear recoil, compared to an electron recoil. Critical for the dark matter search.



Lower threshold requires new calibration (5 efforts)



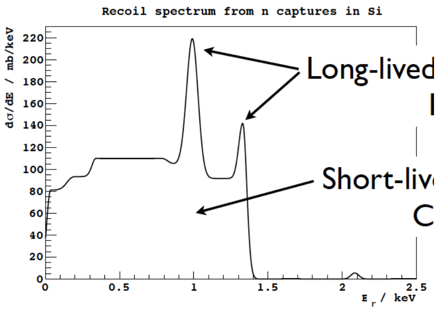


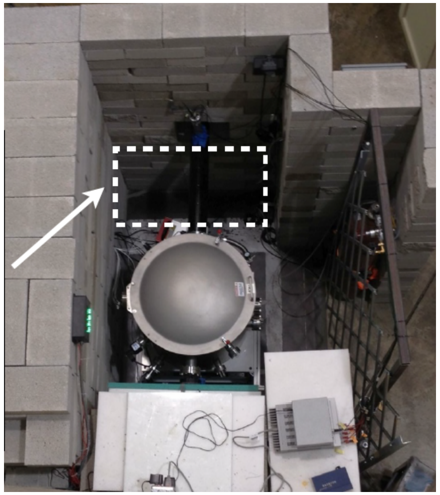


1)Neutron recoil experiment using beam at Notredame

2)Detector activation at proton therapy facility (Warrenville,IL) to produce low nuclear recoils inside CCD. (FNAL/Chicago/UNAM).

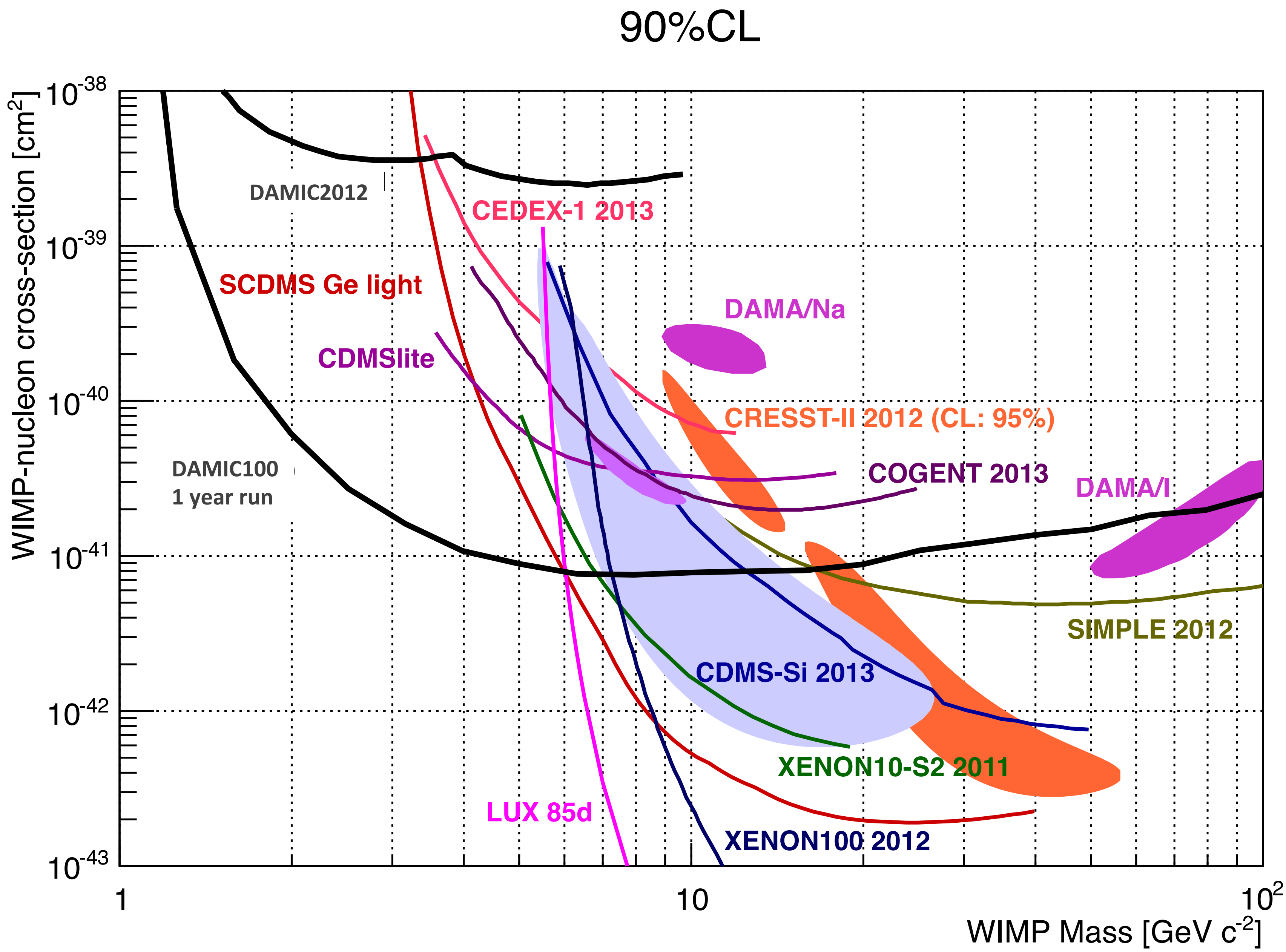
3)Thermal Neutron capture in Si at reactor (Chicago/UFRJ/CAB)





4)Monochromatic neutron source (Chicago)
5)Silicon ions on CCD (CAB)
Funded by Collaborators (non-HEP) with some scientific involvement of FNAL.

DAMIC100 sensitivity. Backg. needs to improve by ~30.



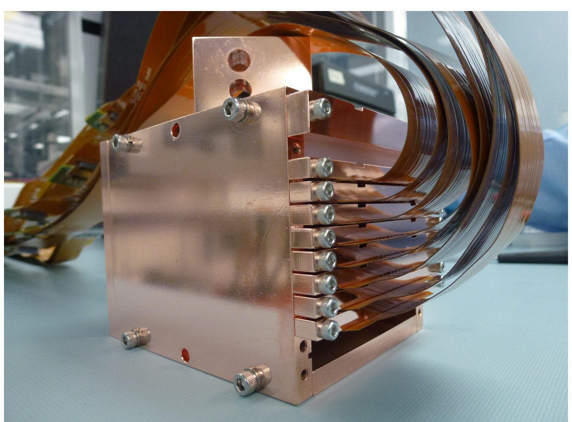
CONNIE
Coherent Neutrino-Nucleus Interaction Experiment.

Scientific goal:
First detection of neutrino-nucleus coherent scattering.

Technique:
Measure low energy nuclear recoils in silicon produced by antineutrinos generated at nuclear power plant. Scientific Charge Couple Devices (CCDs) are used for this purpose with a threshold of 40 eV.

Collaboration:
Argentina, Brazil, Mexico, Paraguay, Switzerland and USA.
(all contributing with funding)

The detector technology is the same used for a Dark Matter Search in the DAMIC experiment. This is possible thanks to the development of thick fully depleted CCDs for astrophysics at LBNL.



CCD array for CONNIE.

arXiv:1405.5761 Silicon detector at 30m of 4GWatt reactor.

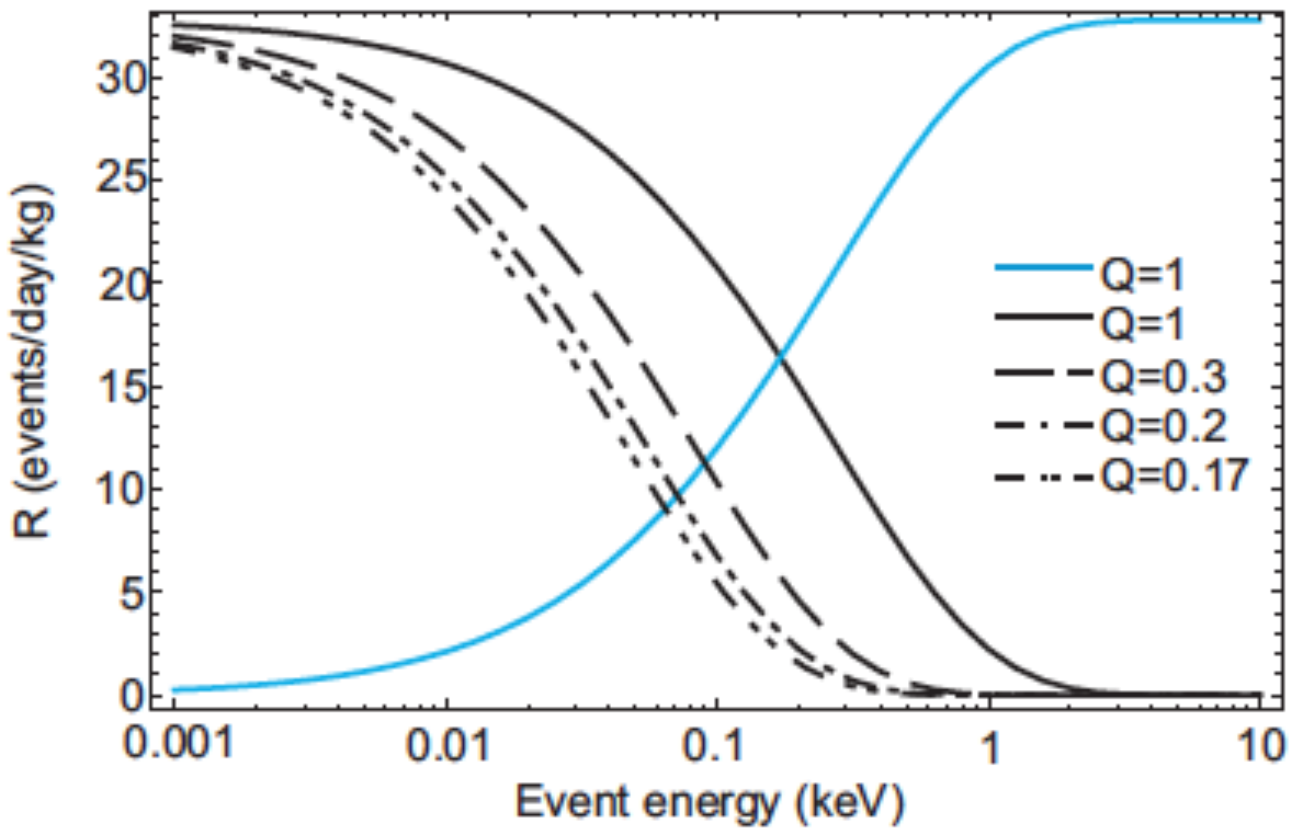


FIG. 9. Total number of events as a function of the threshold energy for different quenching factors: $Q = 1$, $Q = 0.3$, $Q = 0.2$ and $Q = 0.17$ (black curves). The light-blue curve shows the total number of events as a function of the maximum detectable recoil energy using $Q = 1$.

Angra Nuclear Power plant.

Three reactors. Two operational and one under construction.

Centro Brasileiro de Pesquisas Fisicas (Rio de Janeiro) has a agreement with the reactor to perform neutrino experiments on site.

CONNIE is one of two experiment planned.

4GW reactor at Angra do Reis, Brazil

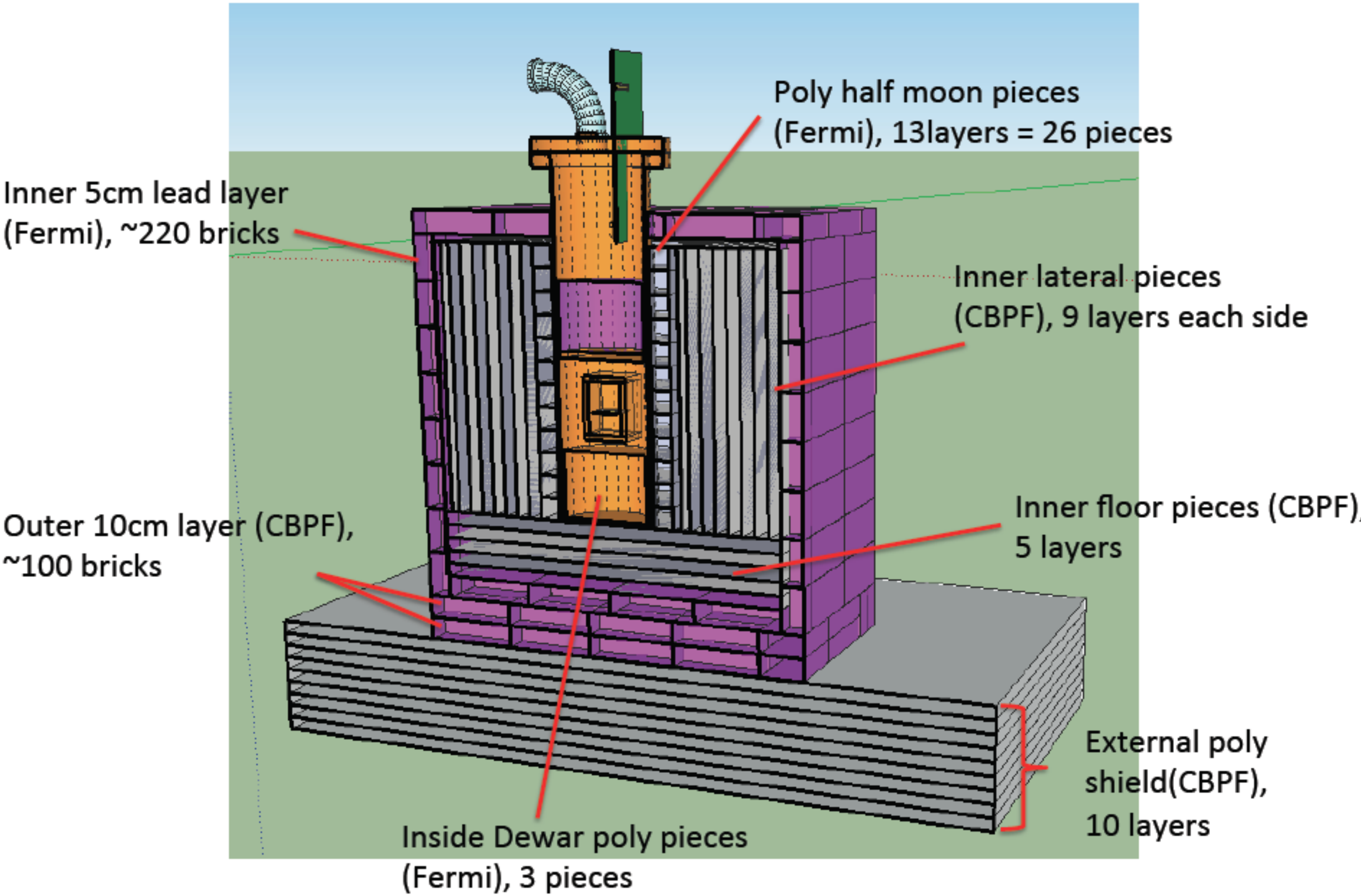
Equipment shipped from Fermilab to Angra do Reis in Sept-2014.

Shipping container conditioned for neutrino experiments, 30 meters from core.

Poly + lead shield, cryogenics, vacuum and DAQ operating on site Oct-2014.

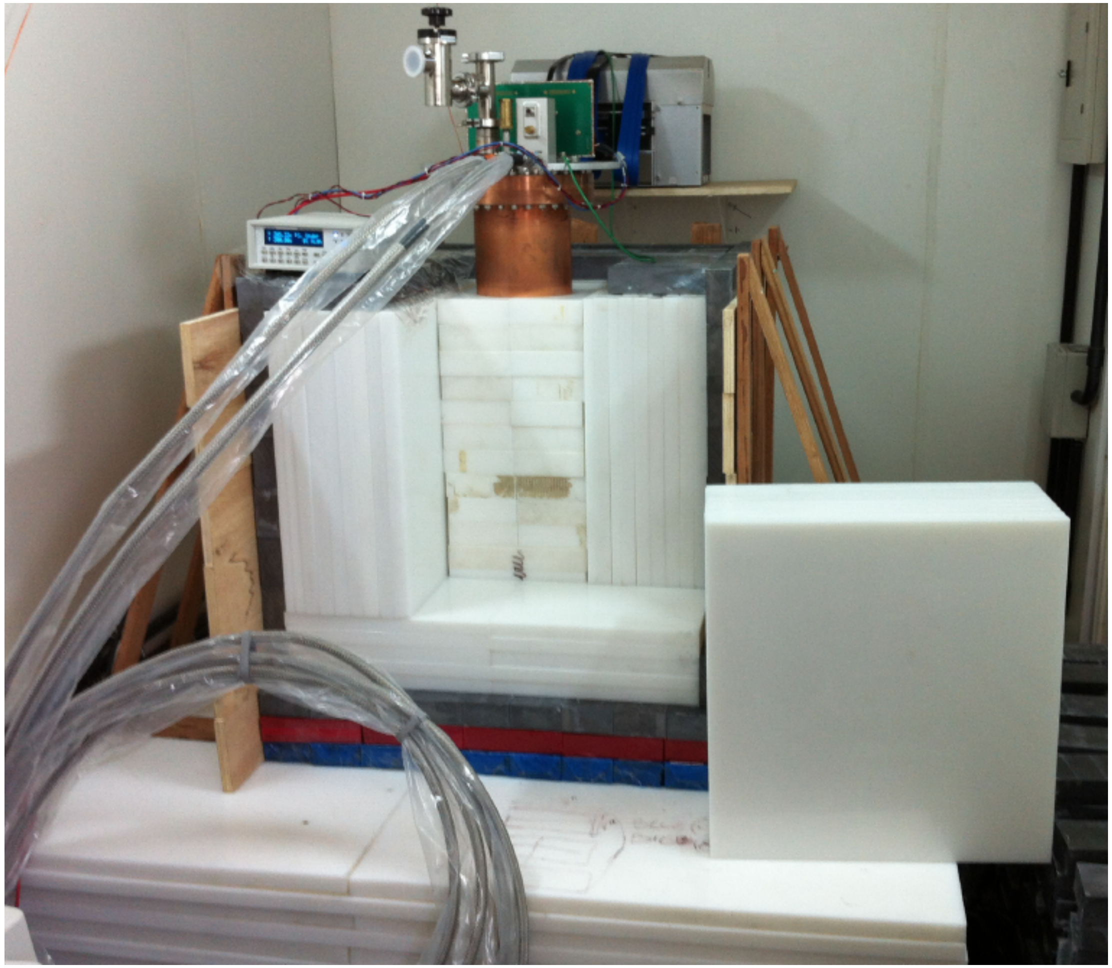
There are many reasons to visit Brazil. We did it to get this piece of plastic. Certified as workers in the nuclear plant.

Shield 1.0



Poly half moon pieces (Fermi), 13layers = 26 pieces
Inner 5cm lead layer (Fermi), ~220 bricks
Inner lateral pieces (CBPF), 9 layers each side
Inner floor pieces (CBPF), 5 layers
Outer 10cm layer (CBPF), ~100 bricks
External poly shield(CBPF), 10 layers
Inside Dewar poly pieces (Fermi), 3 pieces

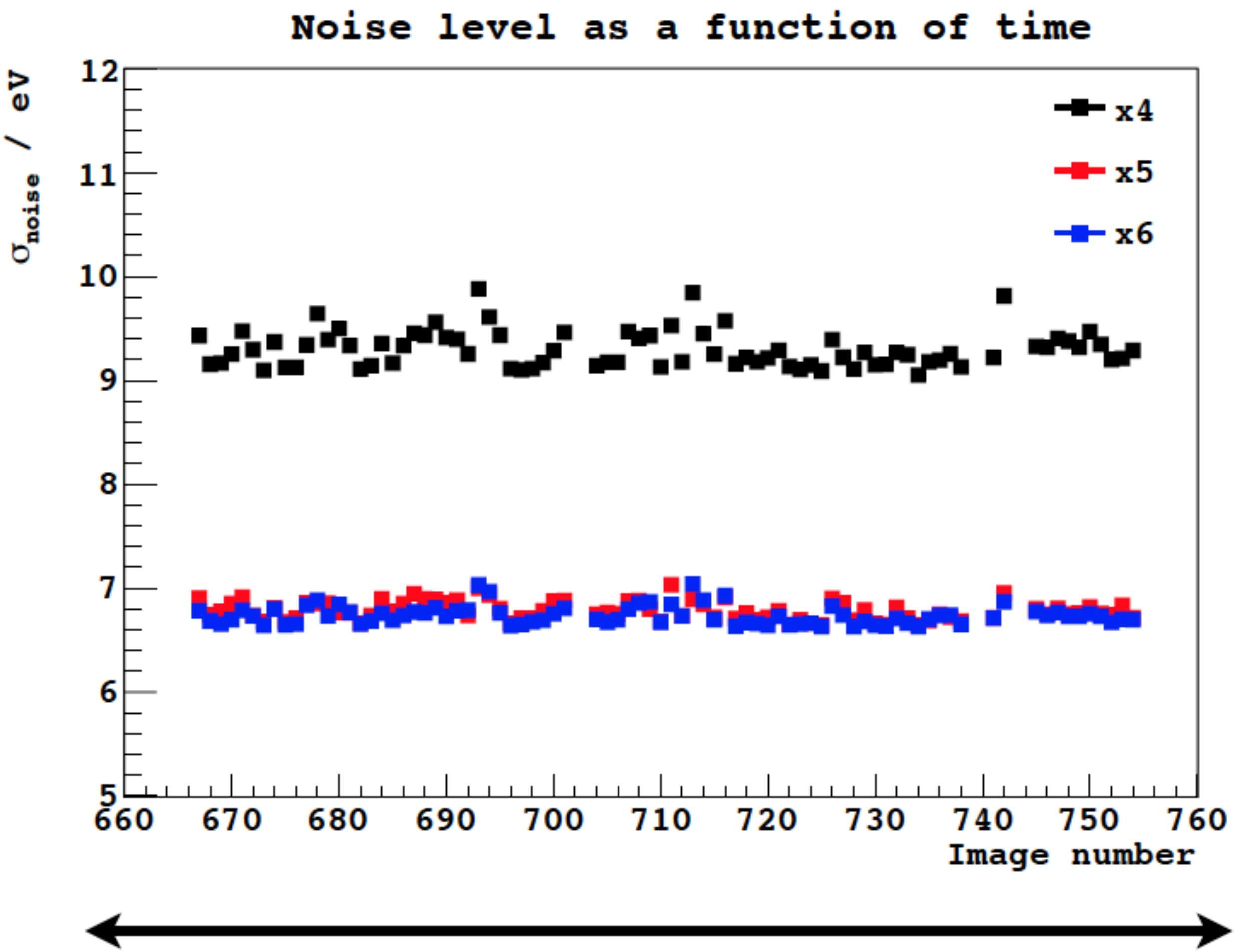
Partially instrumented shield in place. Array with a few grams running. Full shield coming soon, and proposal to increase the mass to 100g will be based on a fully measured background and running infrastructure at the reactor.



Another experiment made possible by the LBNL thick CCDs!

Conclusion

- DAMIC is running at SNOLAB and producing very competitive science. Currently the best limit below 3.5 GeV on our PRELIMINARY result. More work is needed to make this final (calibration at low energies).
- Seems like we are very far from reaching the full potential of the technology. Lower threshold are possible.
- Full Collaboration has been established, and growing.
- Thanks to LBNL-MSL group for the wonderful detectors that are allowing us to push the limits on low mass dark searches. Hopefully soon this will be more interesting than a limit.
- Stay tuned for CONNIE.

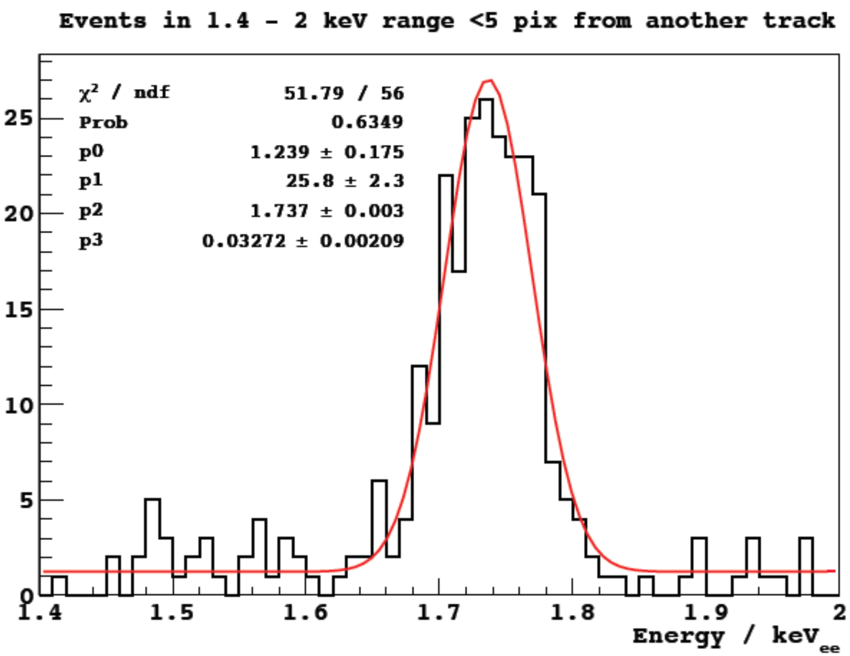


30 days of data

at SNOLAB

96% duty cycle

Si K_α in bulk



33 eV at 1.7 keV in bulk