DAMIC and low mass WIMP searches

Alvaro E. Chavarria,
KICP at U Chicago

Overview

- Dark matter direct detection
- Low mass WIMP controversy
- NaI results + prospects
- Ge results + prospects
- CDMS-Si results
- DAMIC

DM direct detection

- Elastic collision with atomic nuclei in ultra-low background detectors
- Energy of recoiling nucleus: few keV to tens of keV

Laura Baudis (TAUP2013)

Astrophysics

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}} d\mathbf{v} f(\mathbf{v}) v \frac{d\sigma}{dE_R}$$

Particle+nuclear physics

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$

N_N = number of target nuclei in a detector

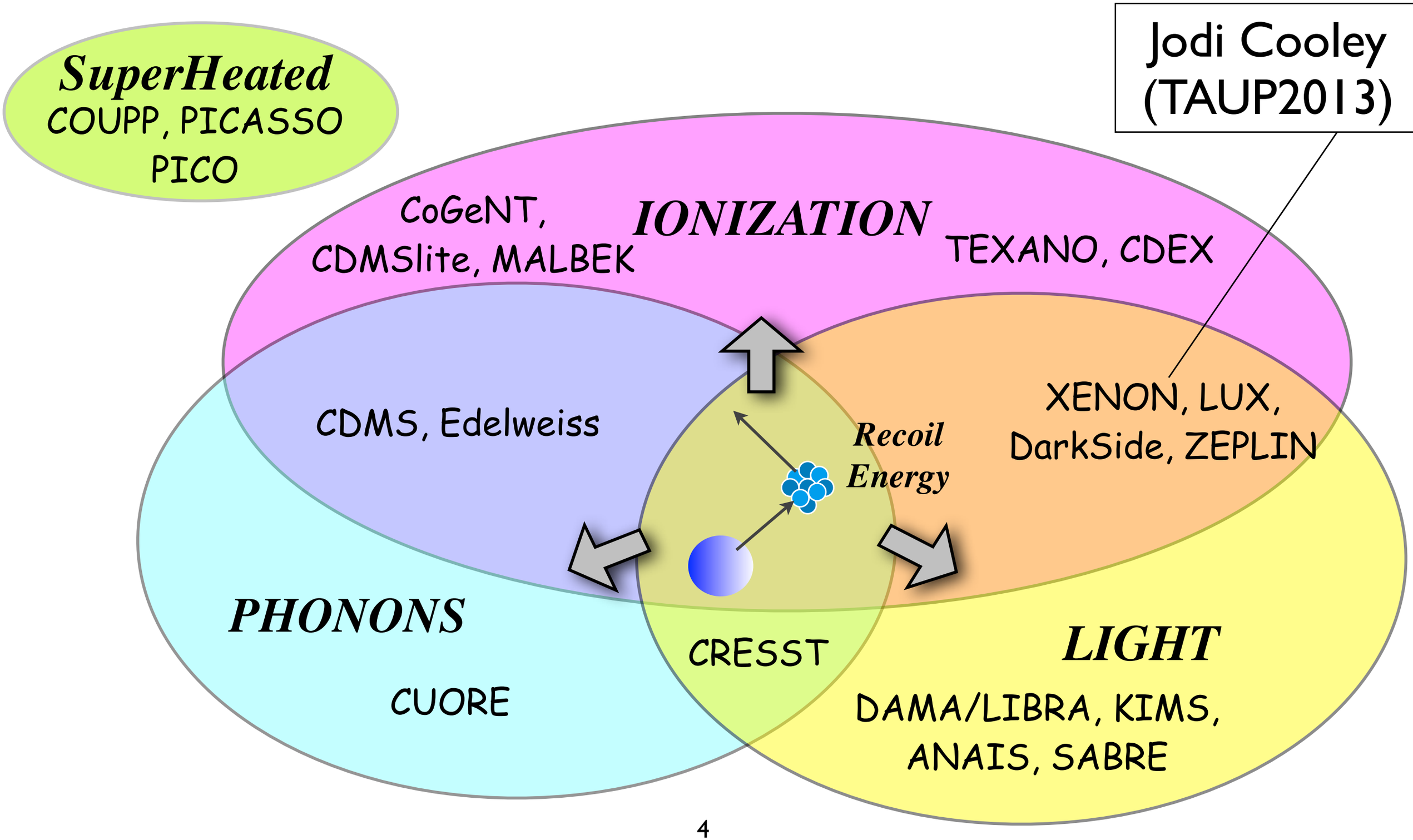
ρ_0 = local density of the dark matter in the Milky Way

$f(v)$ = WIMP velocity distribution in lab frame

m_W = WIMP-mass

σ =cross section for WIMP-nucleus elastic scattering

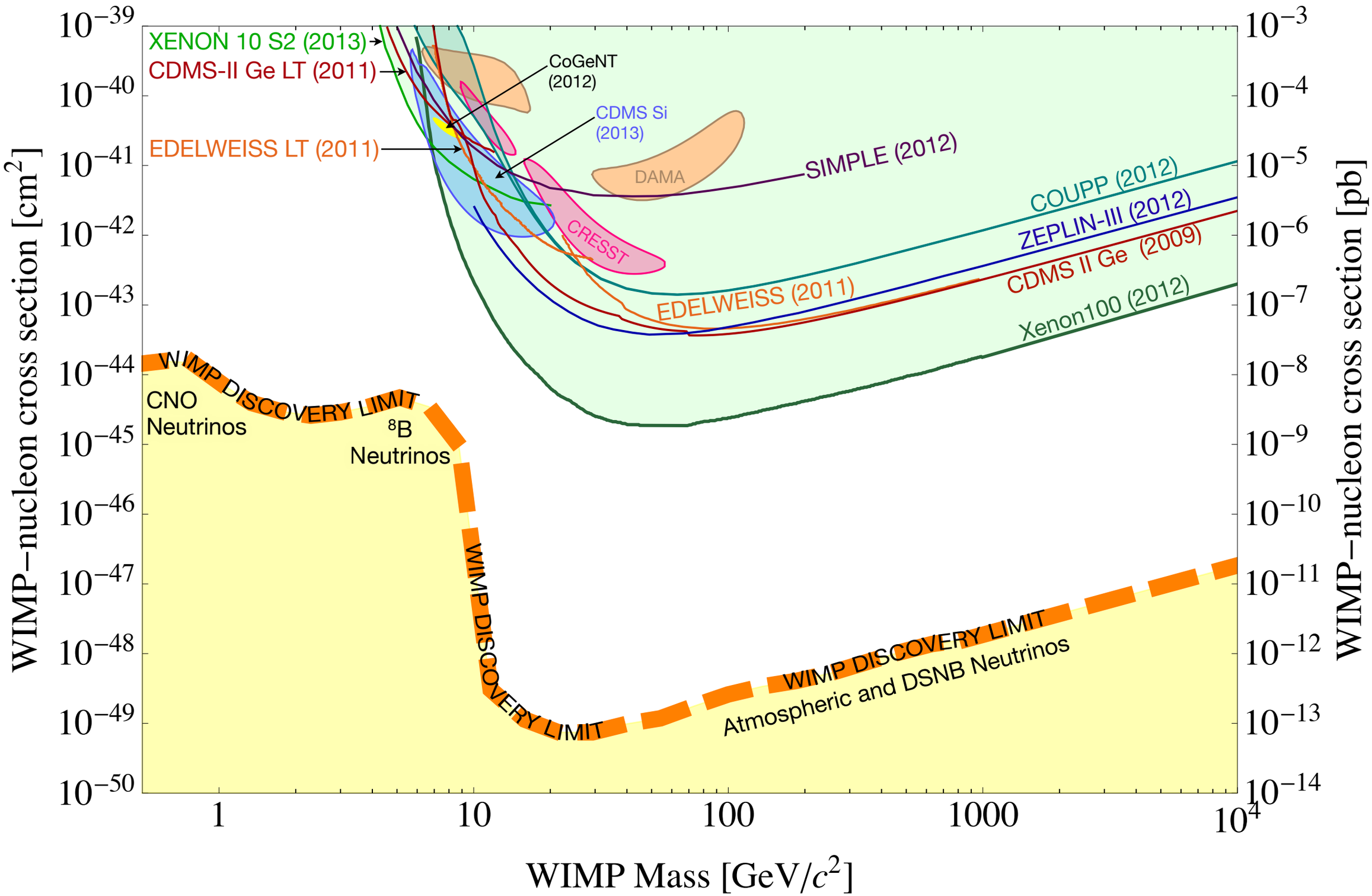
Direct Detection



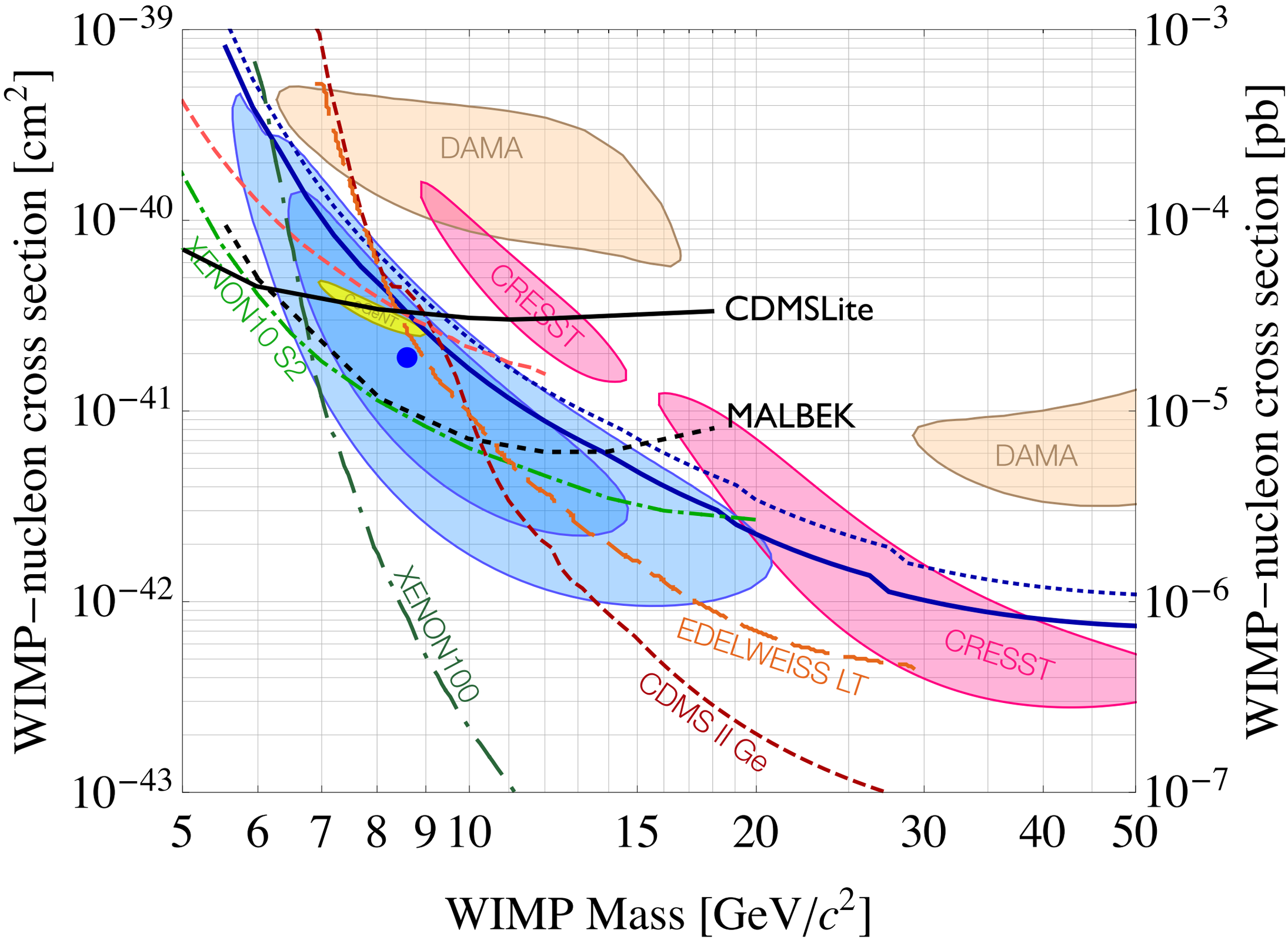
Jodi Cooley (TAUP2013)

SNOWMASS 2013

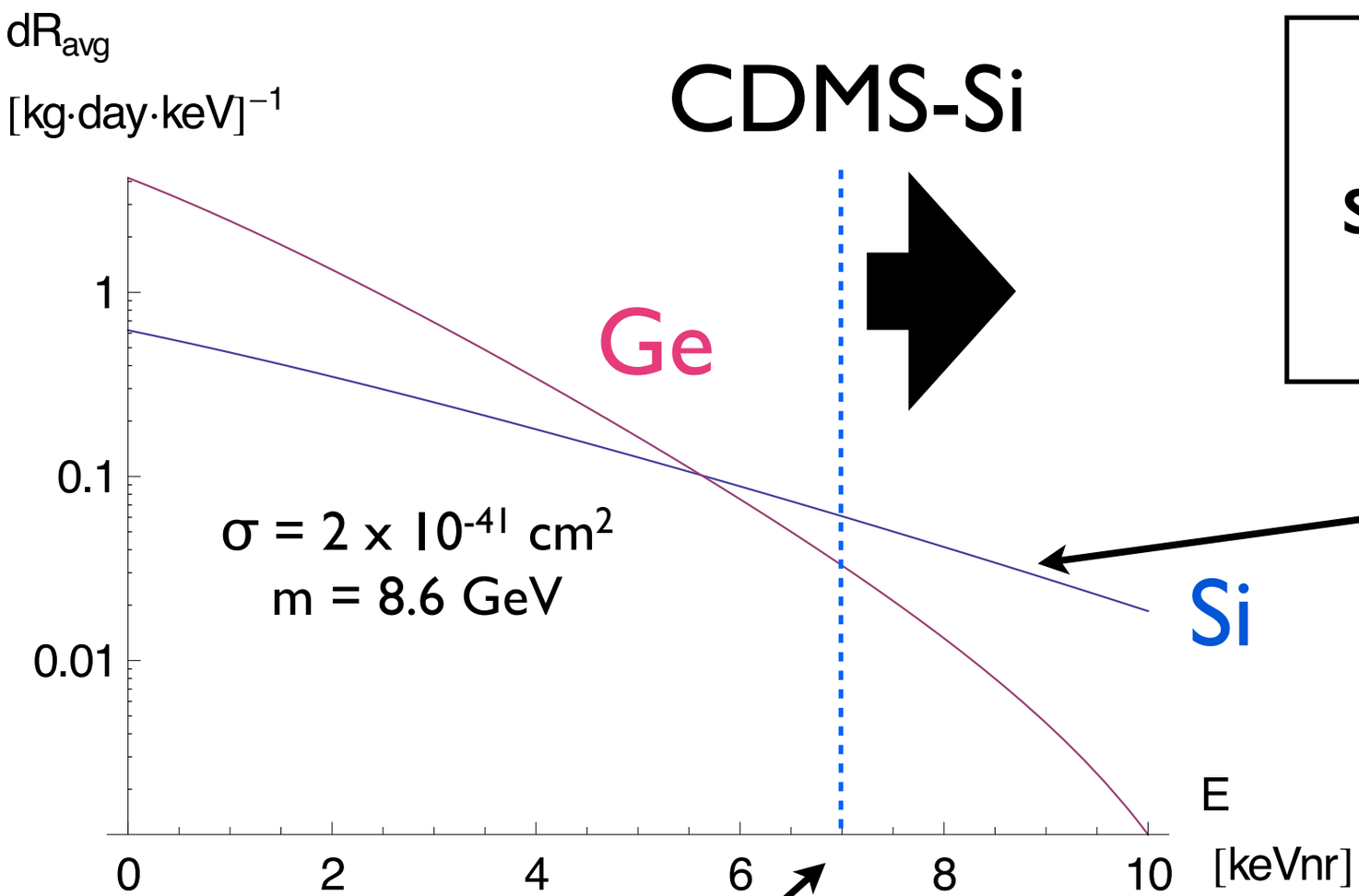
Where Are We Now?



Low mass WIMPs



Why the controversy?

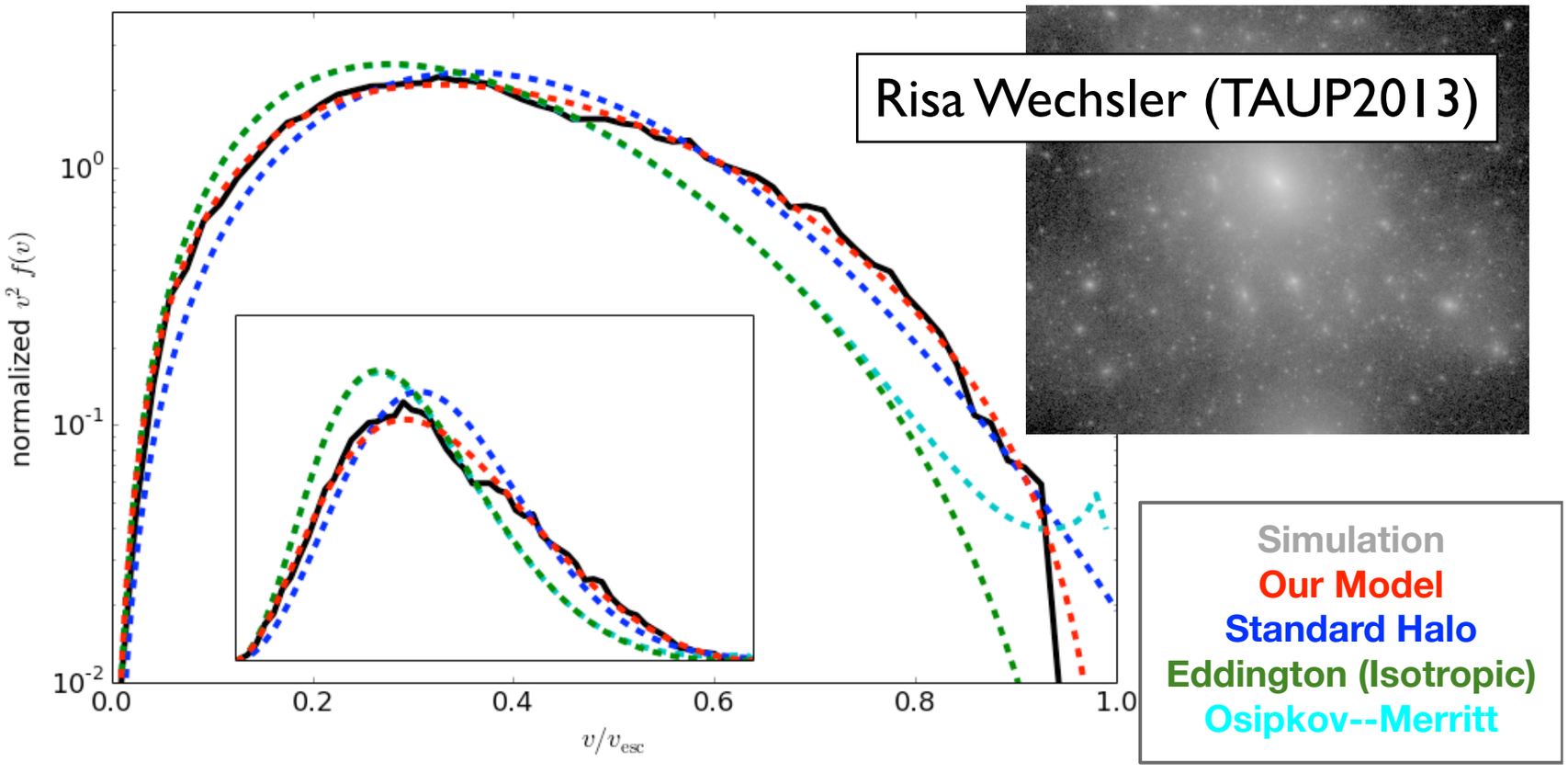


Experiments are sampling the tail of the recoil spectrum

How precisely do we know the tail of the spectral shape?

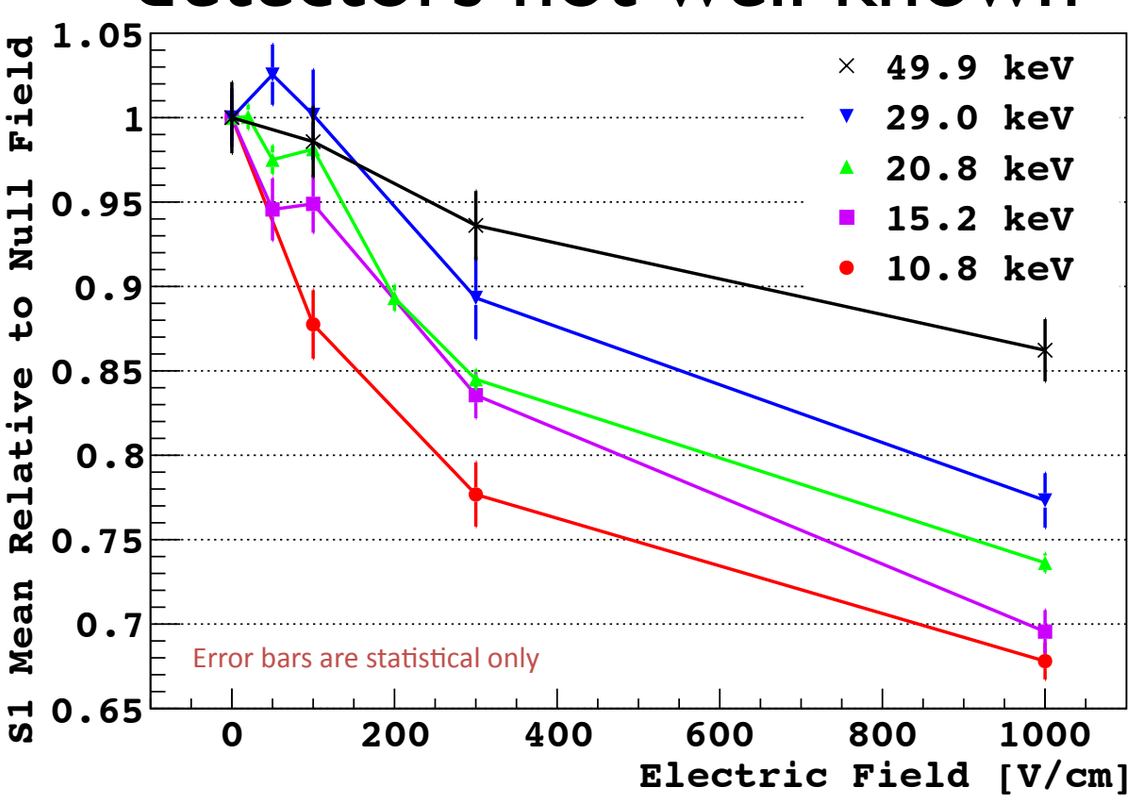
How well do we know the threshold?

Do we understand the detector backgrounds at these low rates? Especially **neutrons**

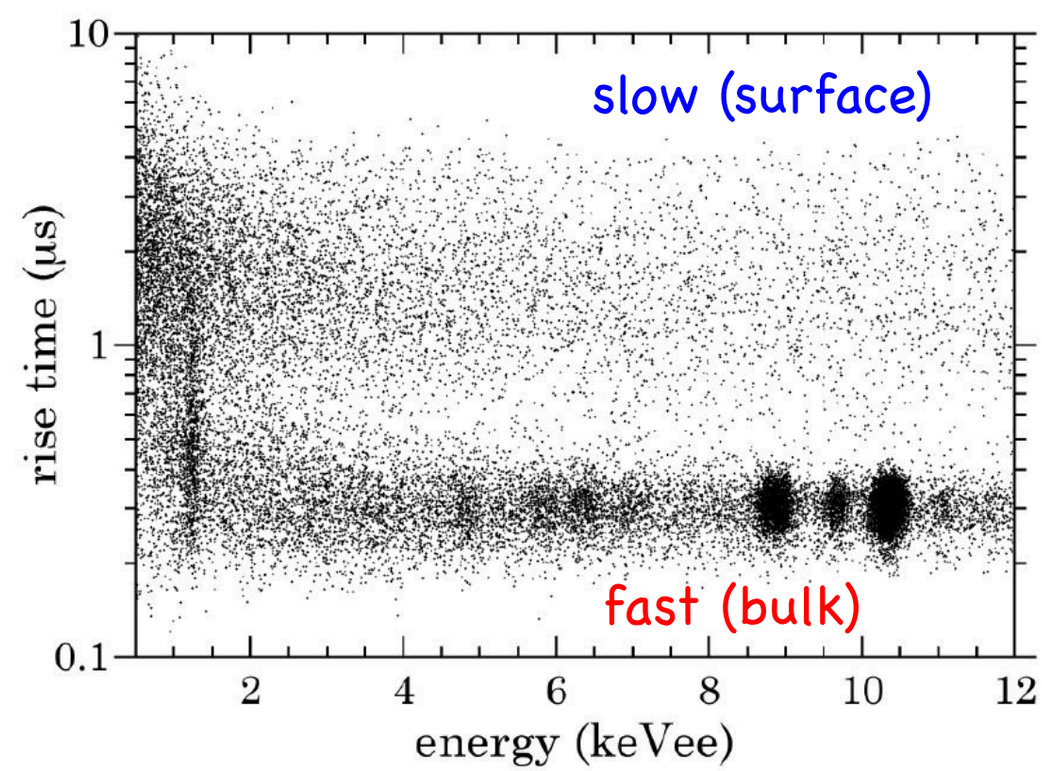


Comparisons between different targets is strongly dependent on the WIMP velocity distribution assumed

Energy response of some detectors not well known



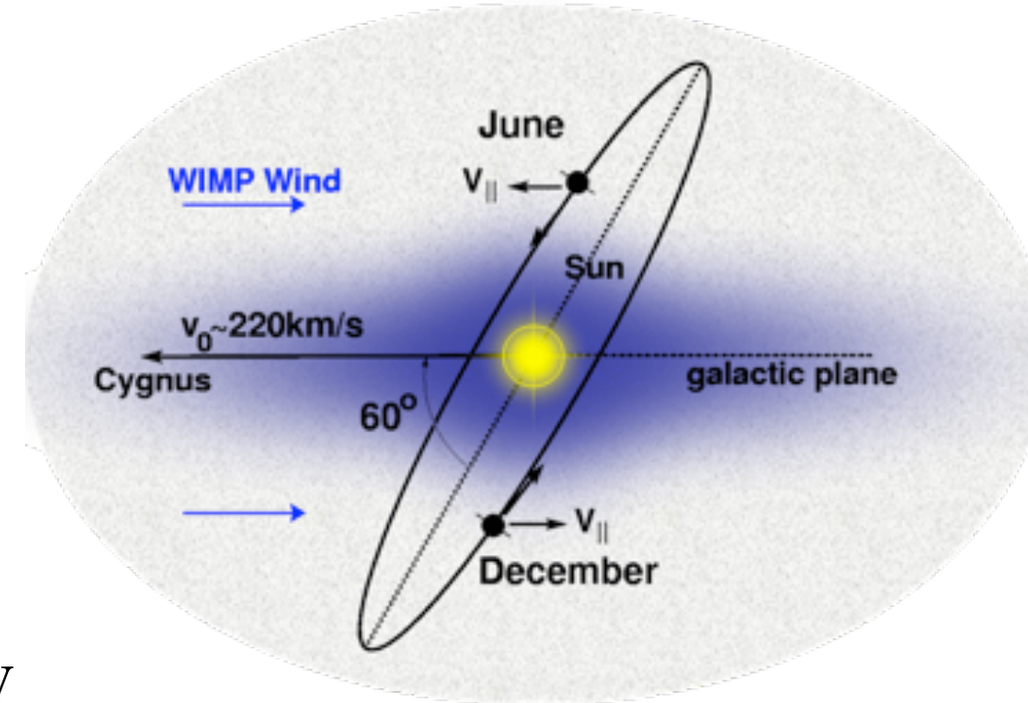
S/B separation worsens close to threshold



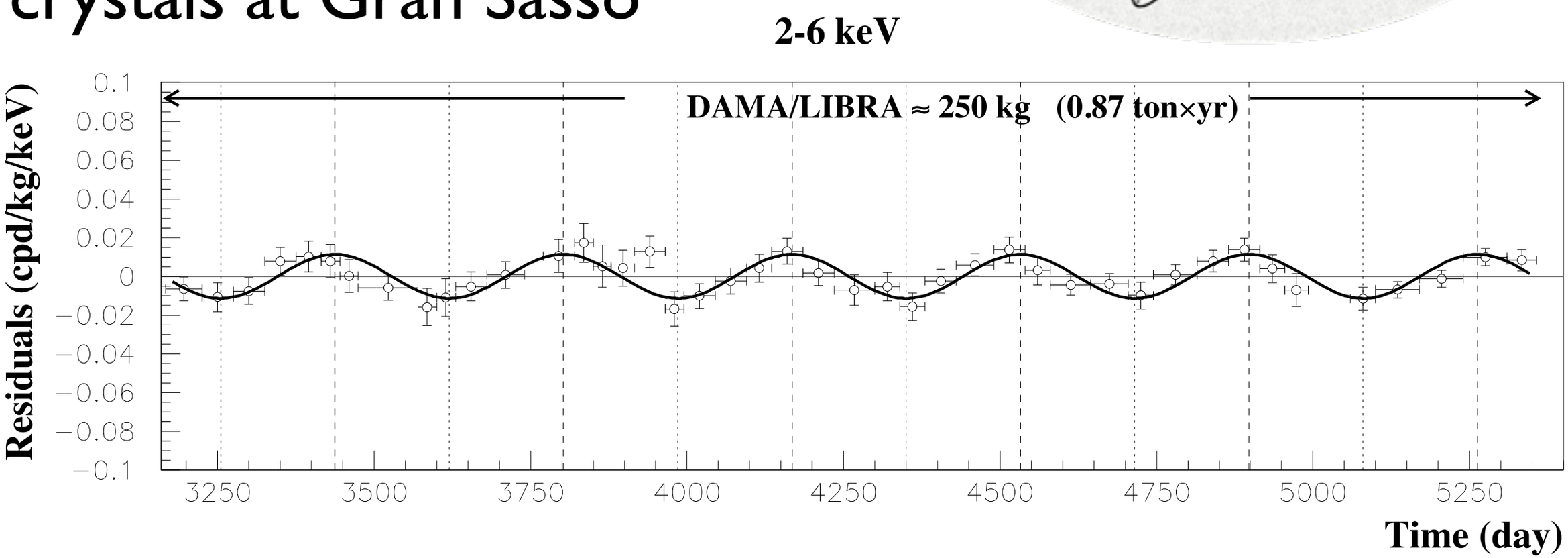
What to do?

- Astrophysical, experimental (esp. near threshold) and even nuclear uncertainties make comparisons between different targets very hard.
- Considering most recent experimental proposals, it seems that there is strong interest in performing experiments on *the same target* to check these signals.
- I will mention in some more detail the prospects for the investigation of signals in NaI, Ge and Si.

DAMA/LIBRA



Nal scintillating crystals at Gran Sasso

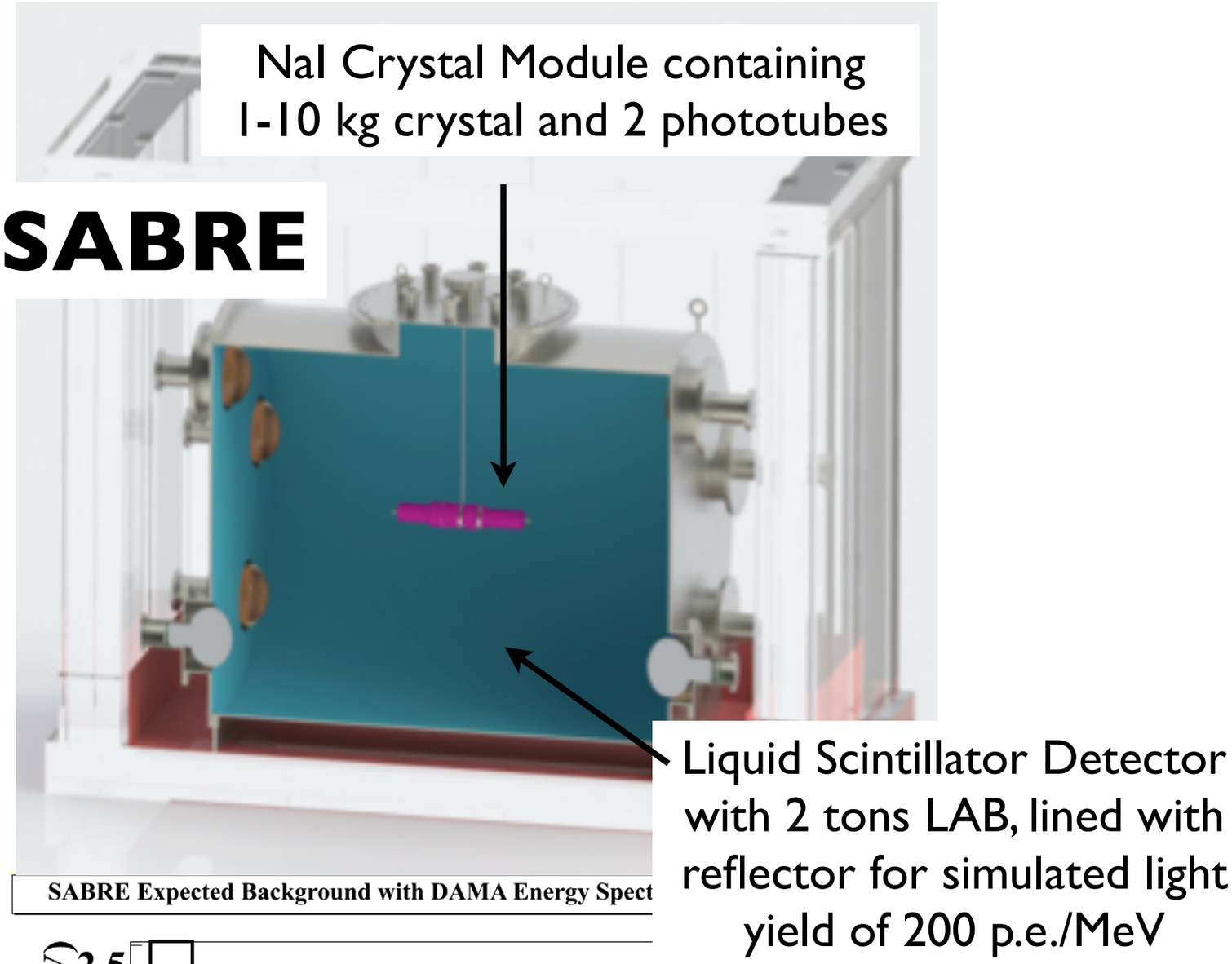


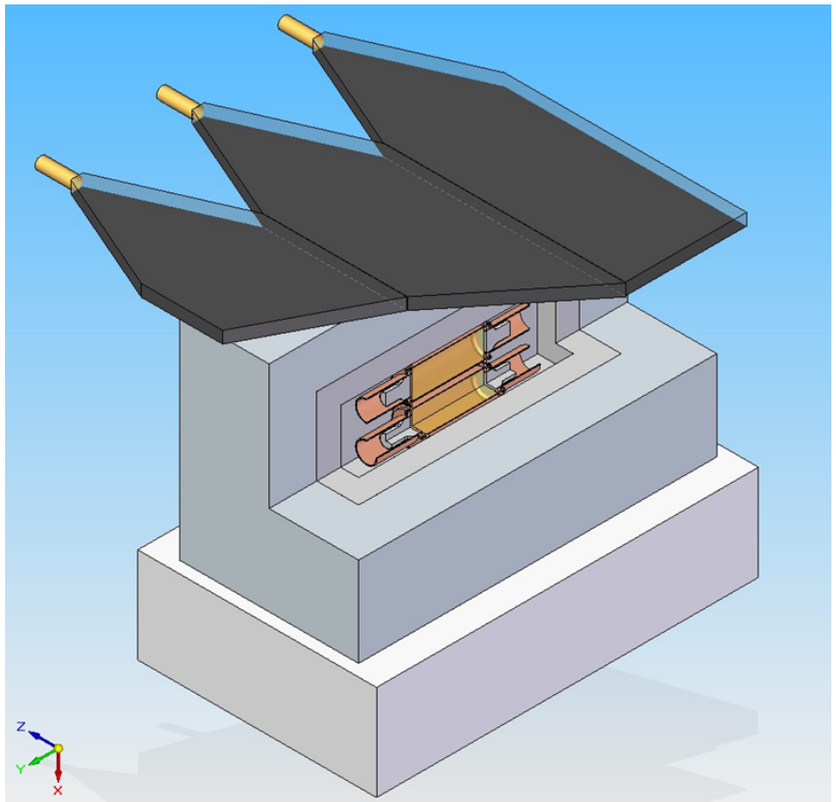
Observe a highly significant (9 σ) annual modulation, consistent with the "model independent DM signal"

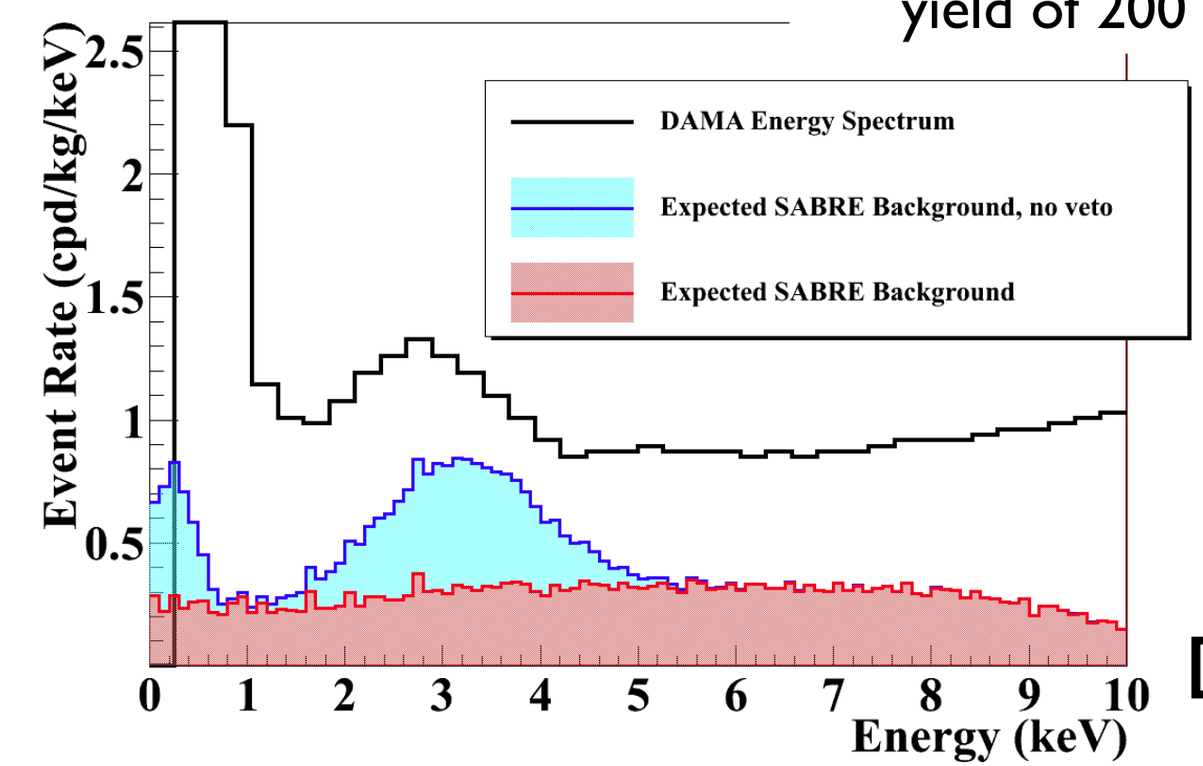
T = 0.999 ± 0.002 y and maximum ~ June 2nd ± 7 d

ANAIS-25 set-up

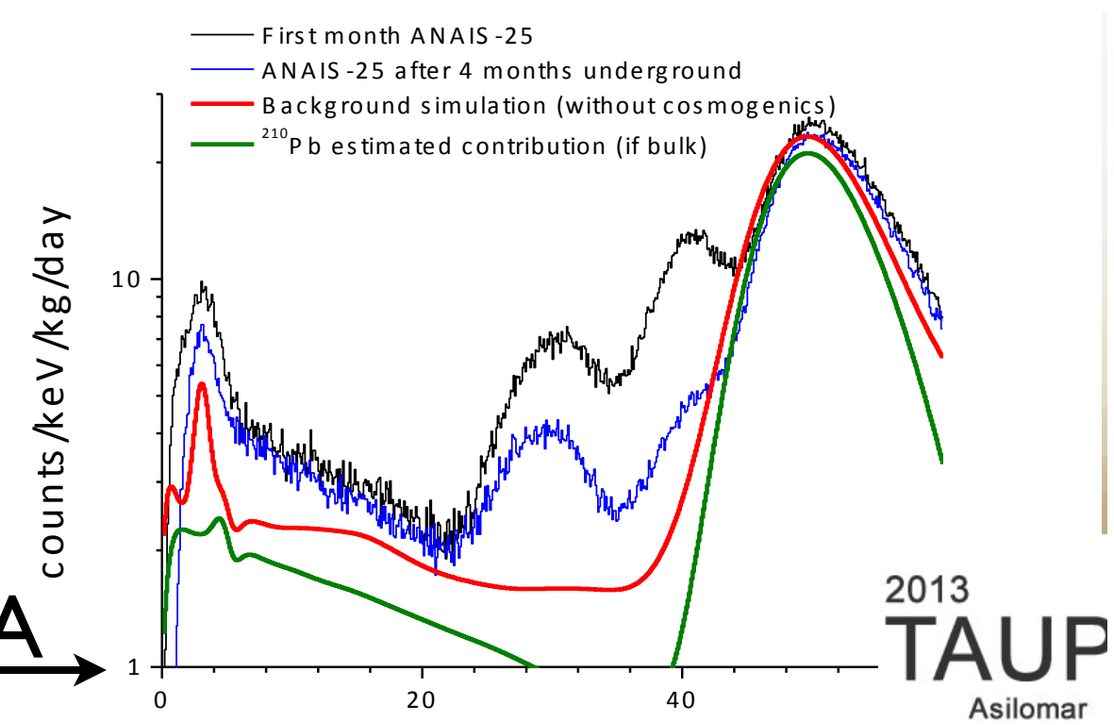
Taking data at LSC since December 2012





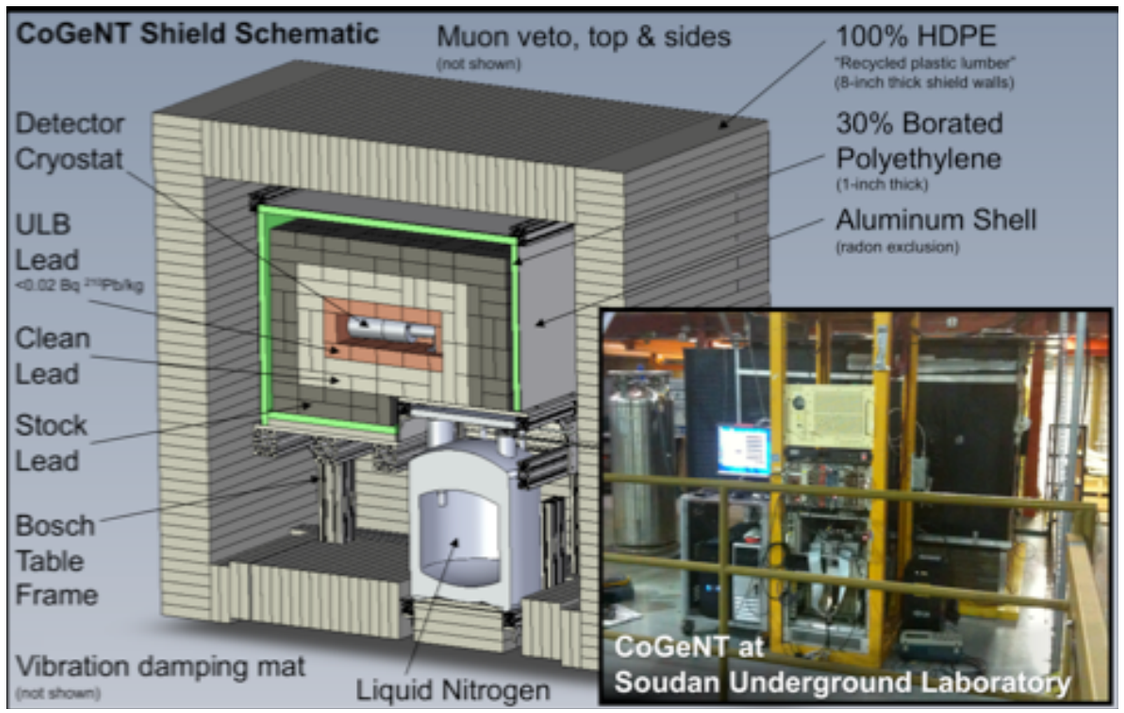


DAMA



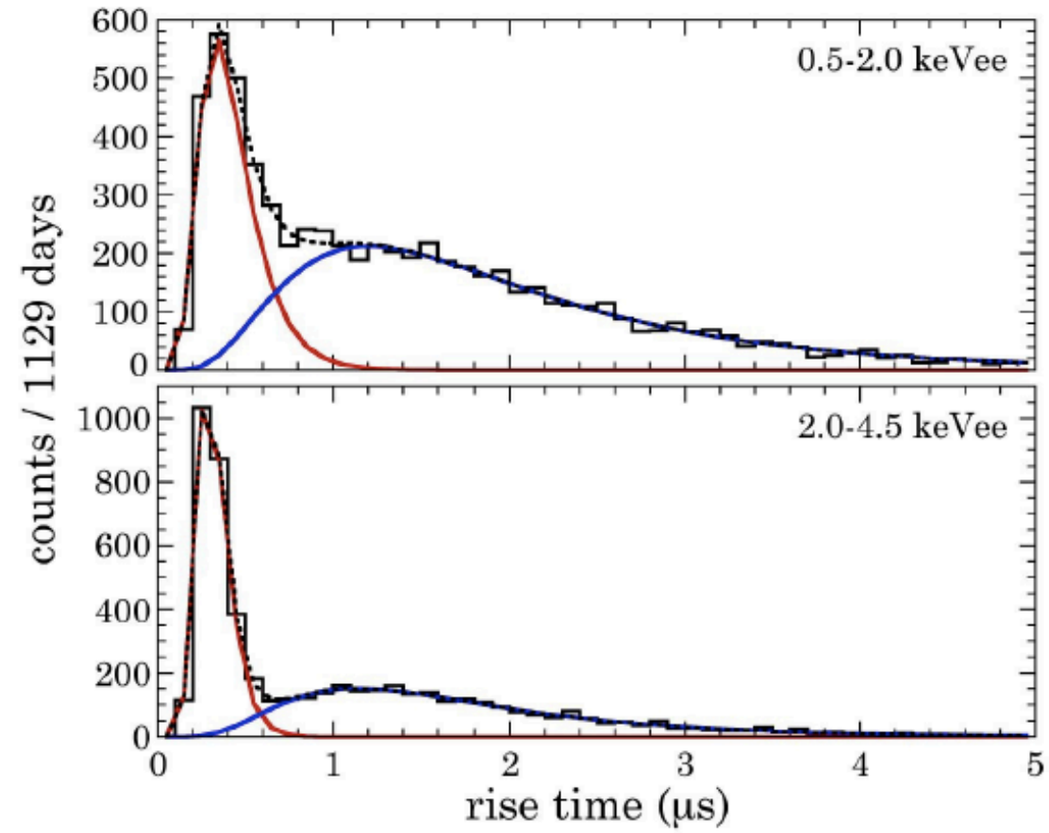
CoGeNT

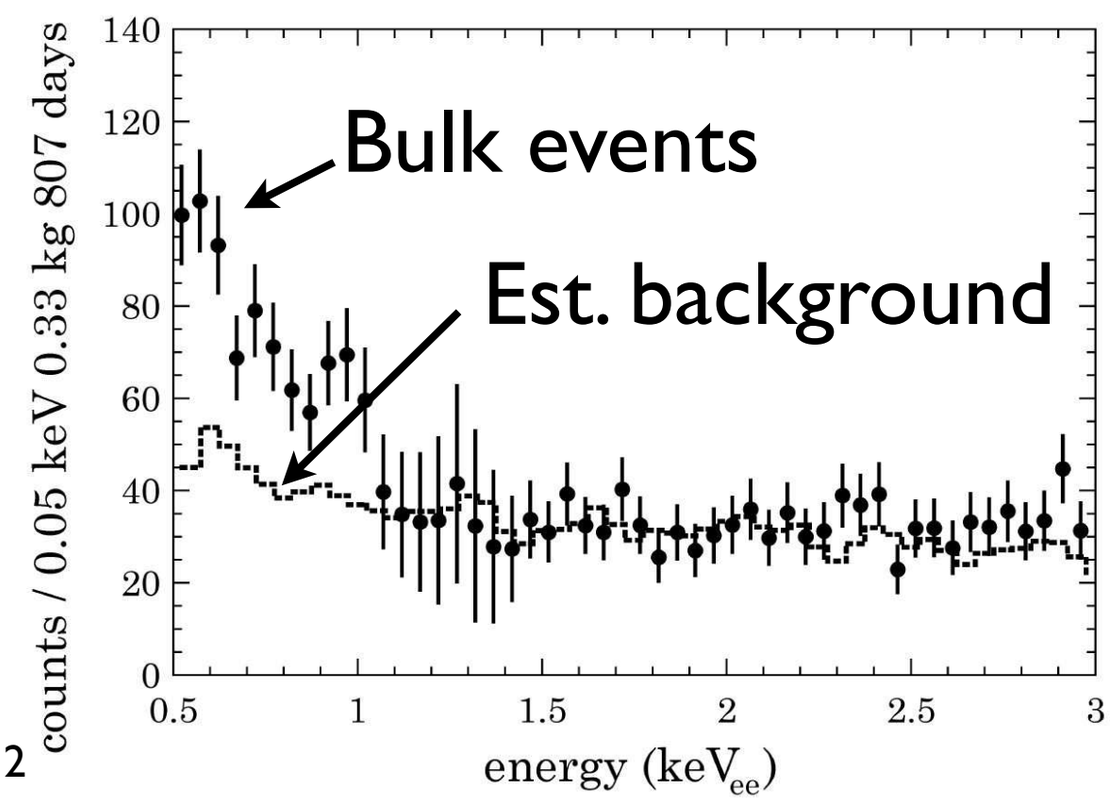
0.44 kg Ge detector with 0.5 keV_{ee} threshold



Significant excess at low energies may be interpreted as recoil events from WIMPs

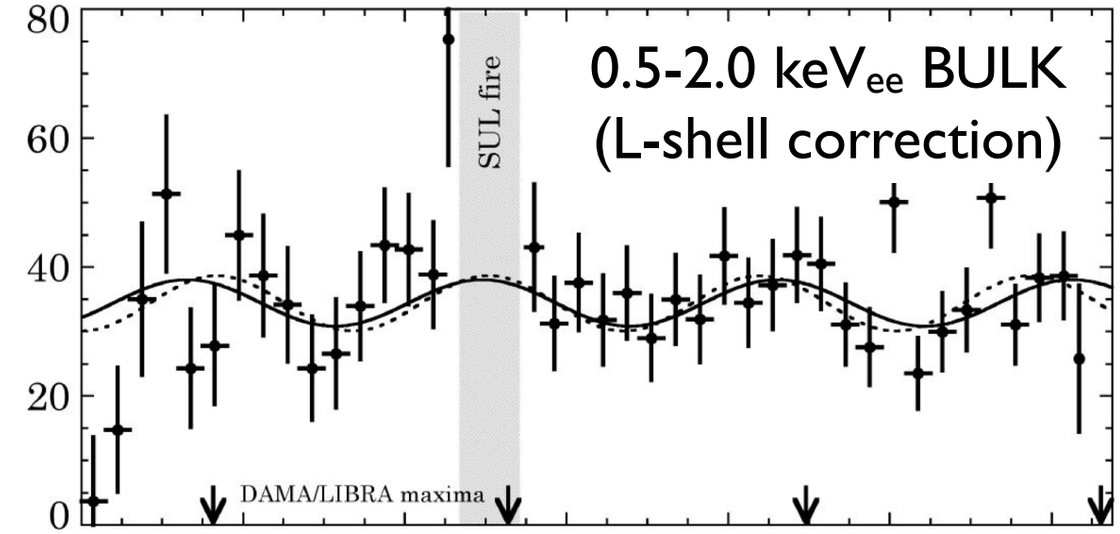
Separation between surface and bulk events by pulse right time

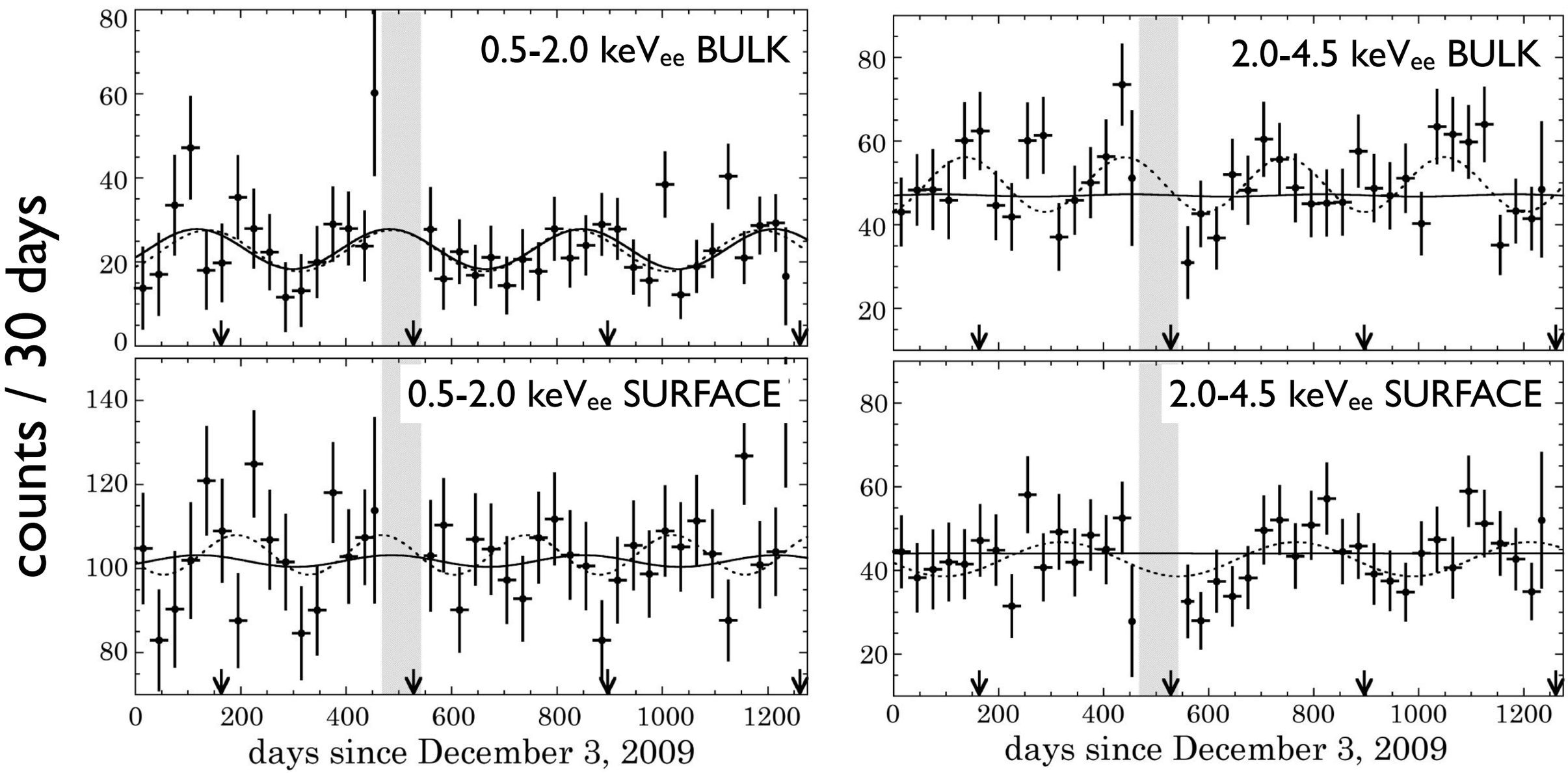




Juan Collar (TAUP2013)

"Straightforward analysis with bulk/surface separation (~90% SA for ~90% BR) from rise time"





"2.2 σ preference for modulation over null-hypothesis"

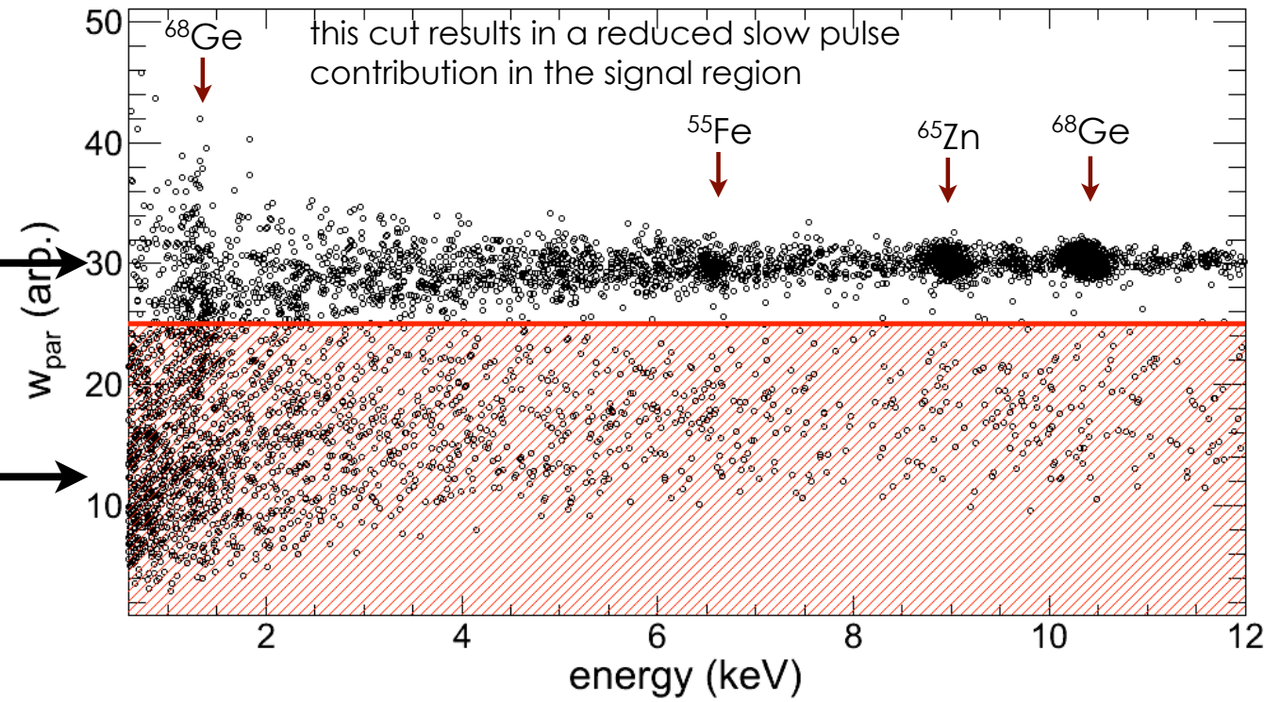
Graham Giovanetti (TAUP2013)

MALBEK

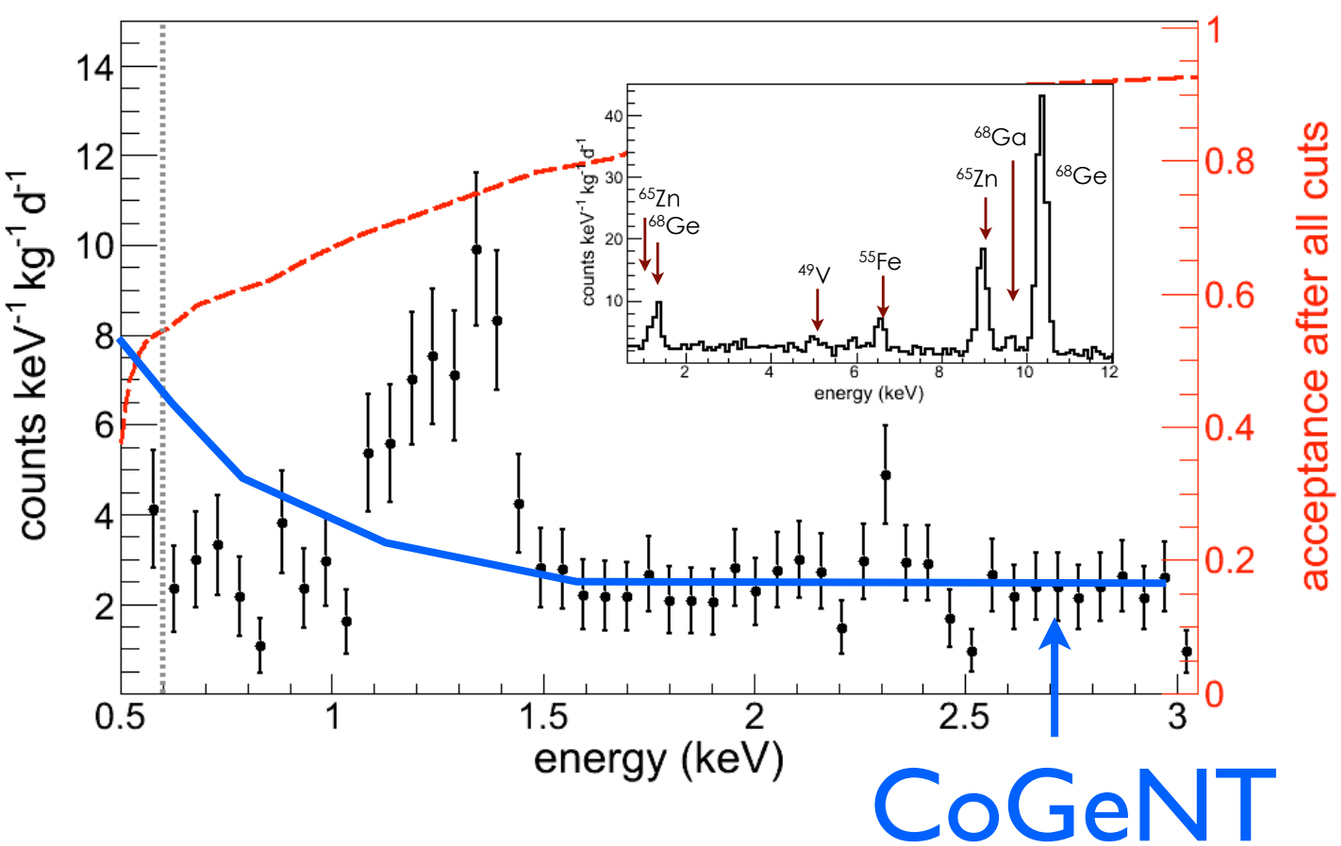
Direct test for the CoGeNT low E excess at KURF with 450 g BEGe

Bulk →

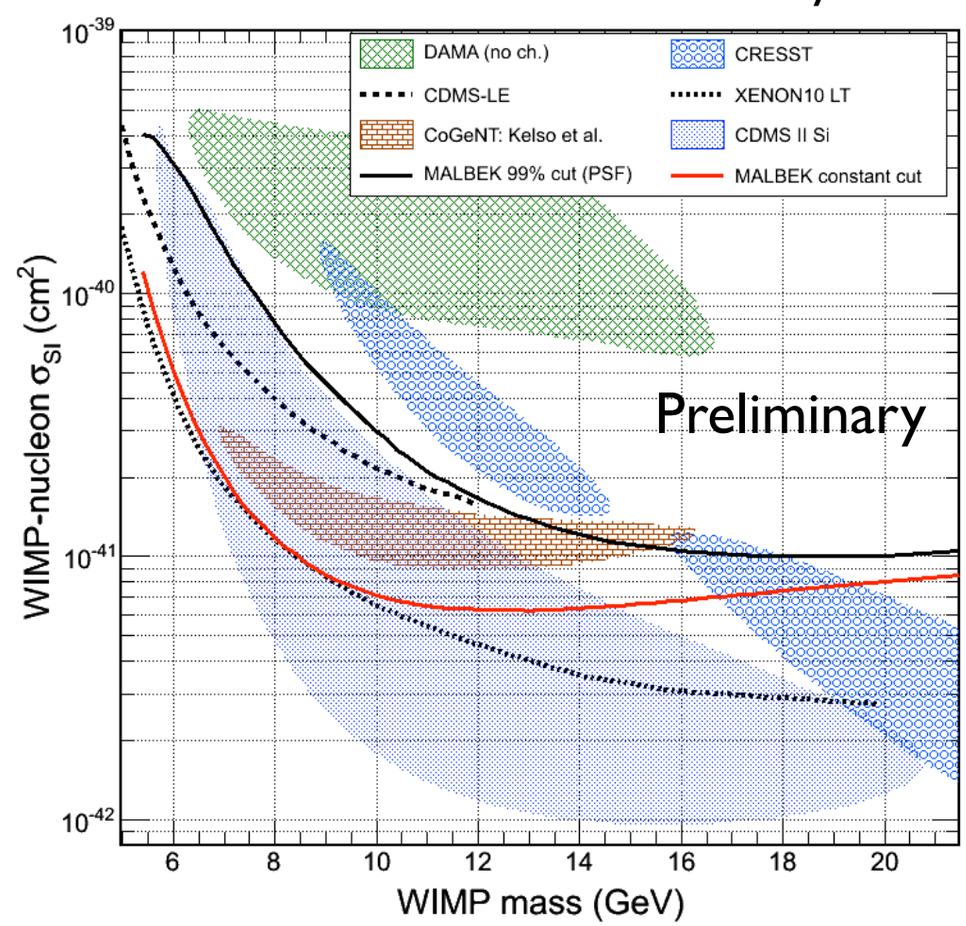
Surface →



221 day spectrum after constant w_{par} = 25 cut and efficiency correction



90% exclusions from 221 day dataset

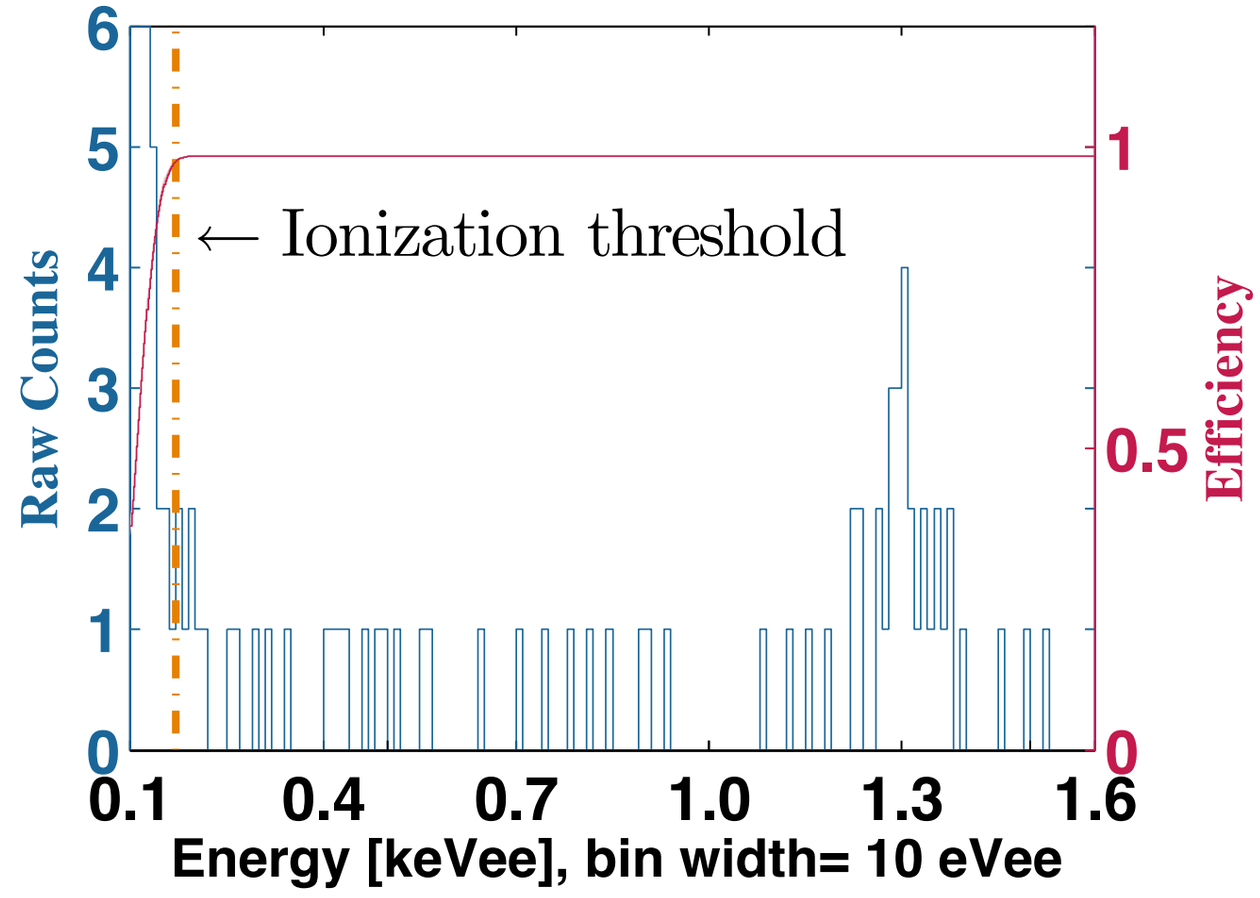


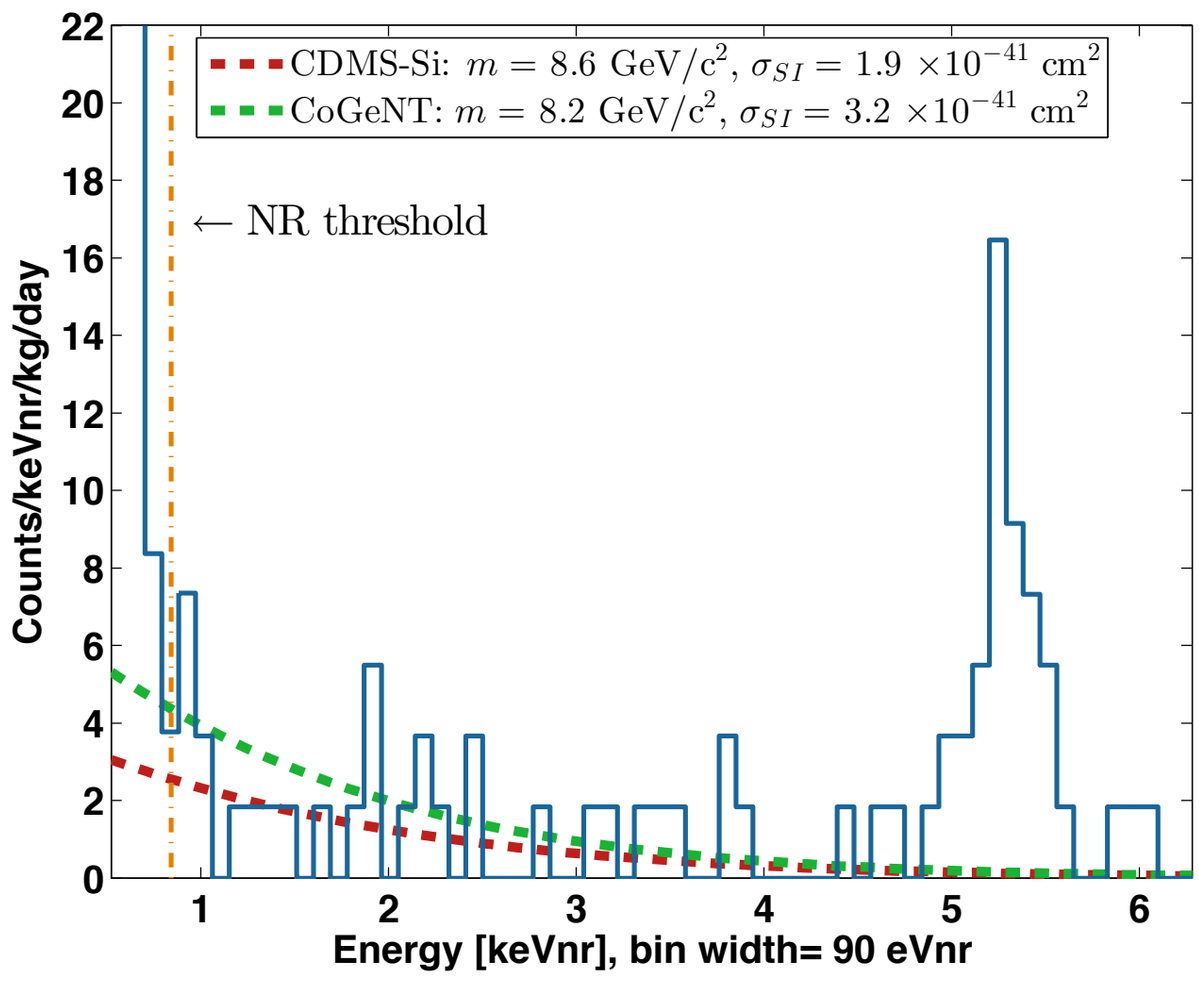
Jeter Hall (TAUP2013)

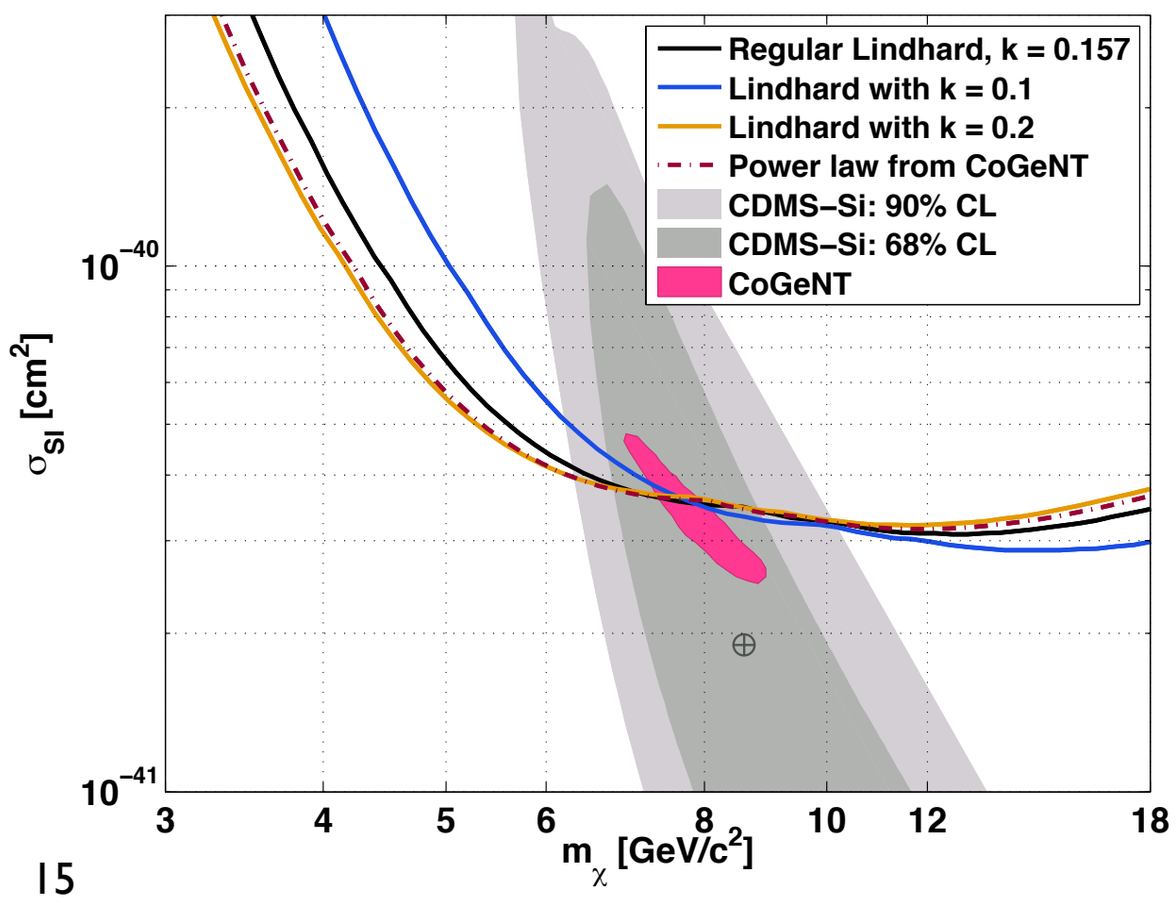
CDMSLite

Neganov-Luke amplification allows to measure ionization through phonon channel.

One detector for two weeks, 5.9 kg day final exposure.







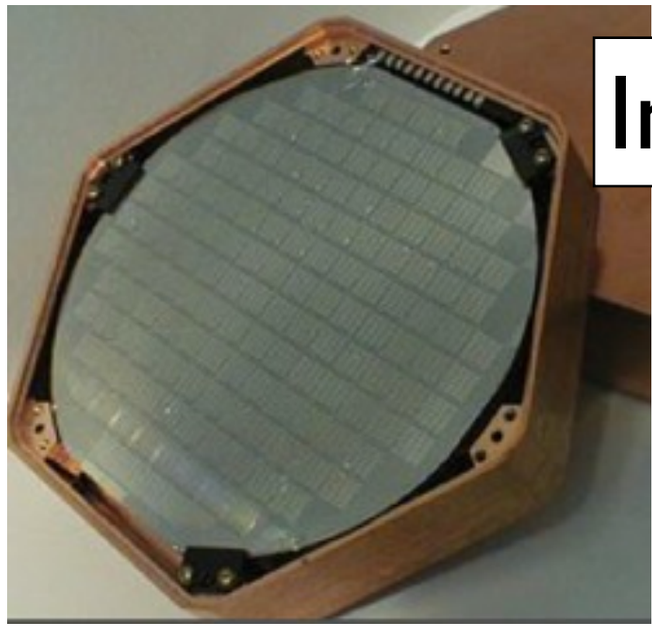
Near-future Ge results

- Ongoing analysis of 1.5 y of Super CDMS-Soudan data. May see results in the next months. e^-/NR discrimination, how much lower threshold?
- TEXONO and CDEX will continue their DM search with PPC Ge detectors at CJPL.
- We may have some more information on this soon...

CDMS-Si

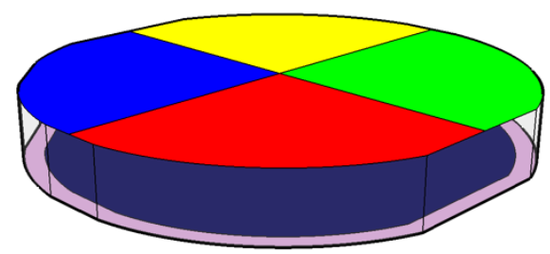
1.2 kg Si (11 x 106g)
35% NR acceptance

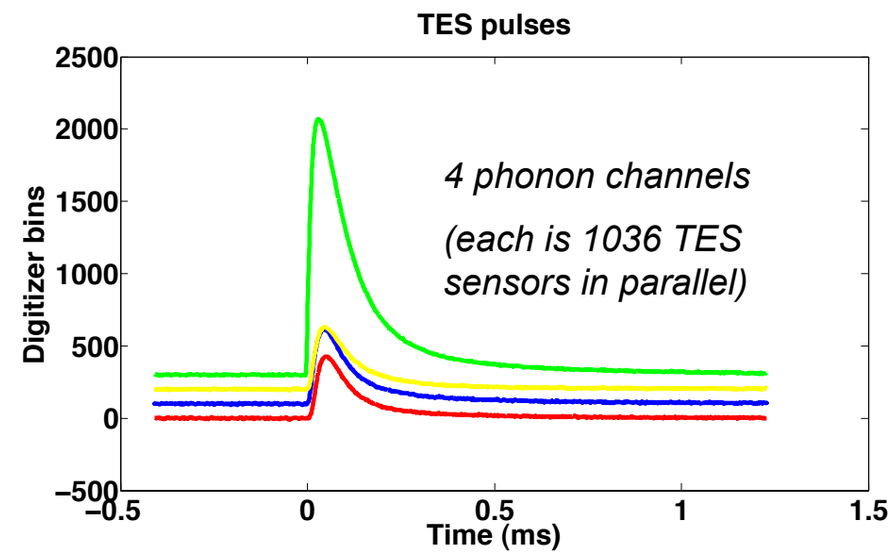
Blind analysis of 140 kg-days of Si data (8 detectors)
July 2007- September 2008

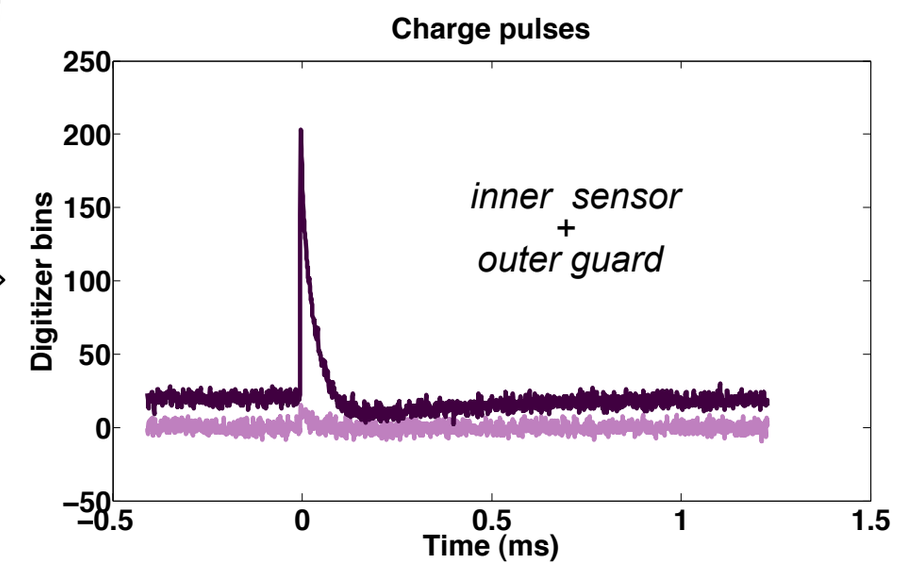


In Soudan

240 g Ge or 106 g Si crystals (1 cm thick, 7.5 cm diameter)





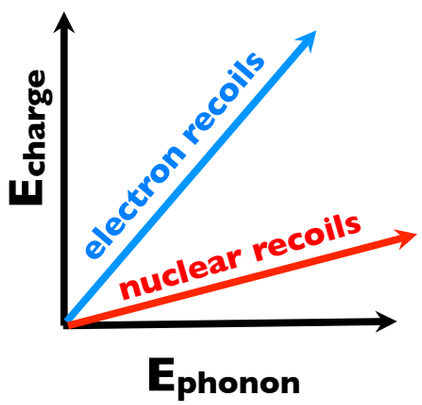


- **Z**-sensitive **I**onization and **P**honon mediated
- Measure both **charge** and **phonon** energy
- Photolithographically patterned to collect athermal phonons and ionization signals
- Direct xy-position imaging
- Surface (z) event rejection from pulse shapes and timing

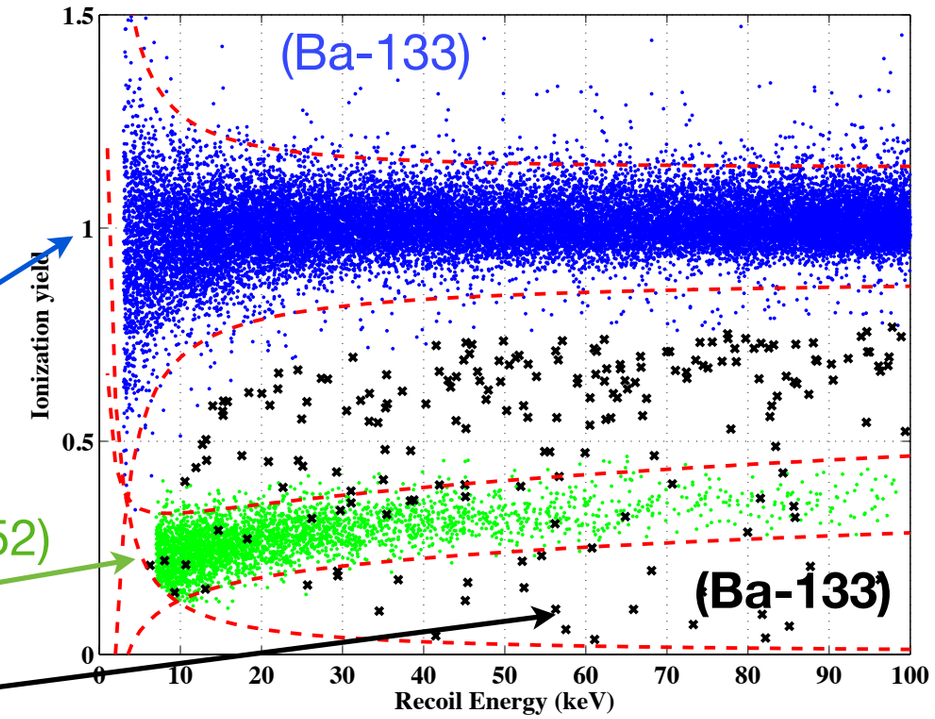
Julien Billard (TAUP2013)

CDMS strategy

Y = E_charge/E_recoil



Ionization yield (ionization energy per unit recoil energy) strongly depends on recoil type.

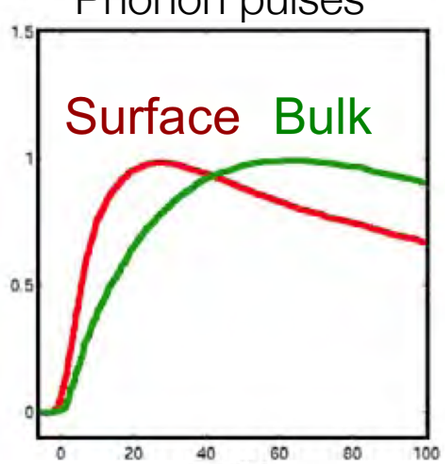


Most backgrounds produce electron recoils: Y = 1

WIMPs and neutrons produce nuclear recoils: Y ~ 0.3

Surface events: reduced ionization yield Y<1

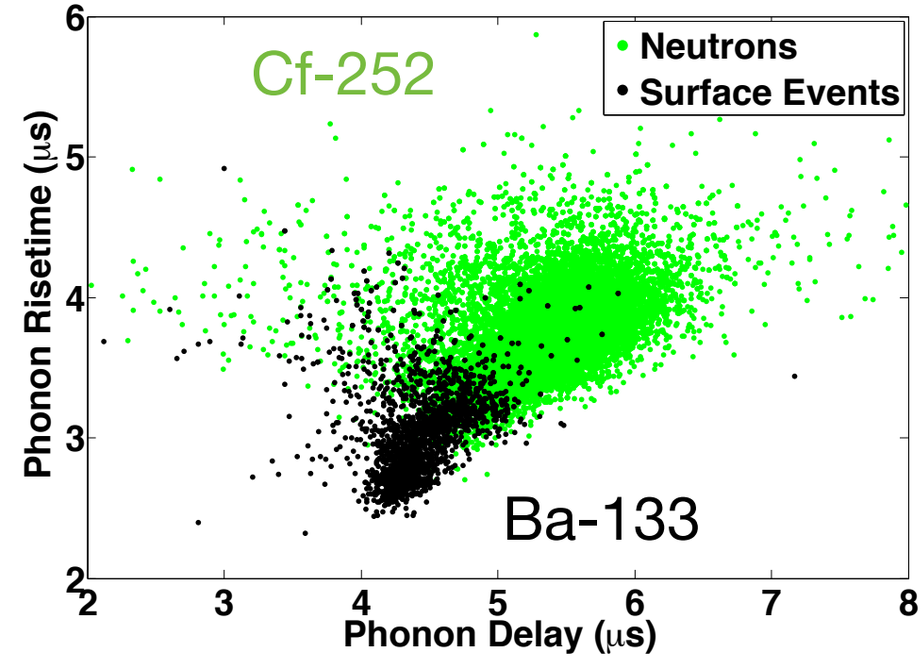
Phonon pulses



Can be rejected through a phonon timing cut

Ionization yield + timing result in <1 in 10^6 electron recoils leaking into the signal region

pre-unblinding leakage estimate of 0.47



Julien Billard (MIT) - TAUP2013

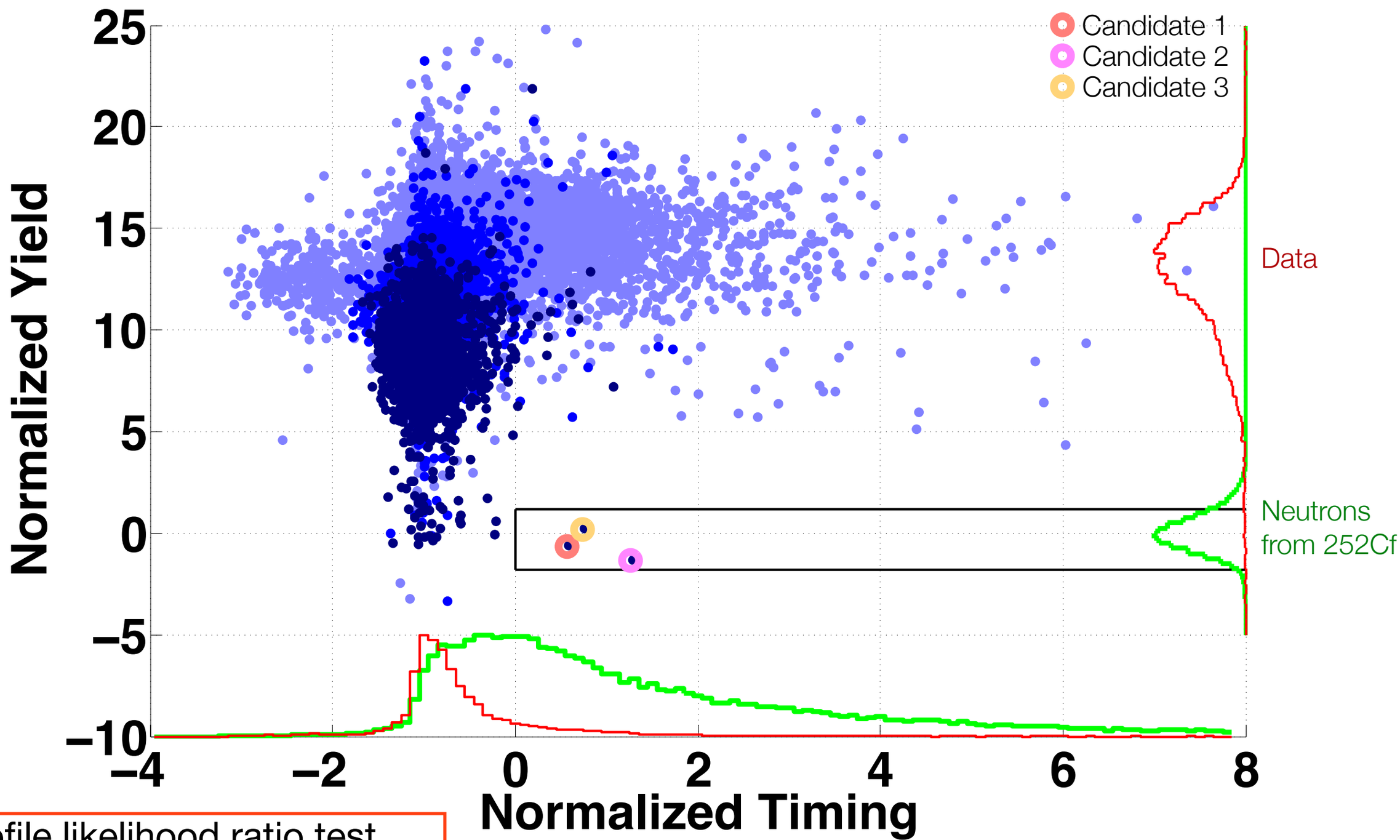
Julien Billard (TAUP2013)

Three events!

0.4 ± 0.3 expected

Julien Billard (TAUP2013)

Shades of blue indicate the three separate timing cut energy ranges.



- A profile likelihood ratio test statistic favors the WIMP +Background hypothesis over the background only at 99.81% C.L.

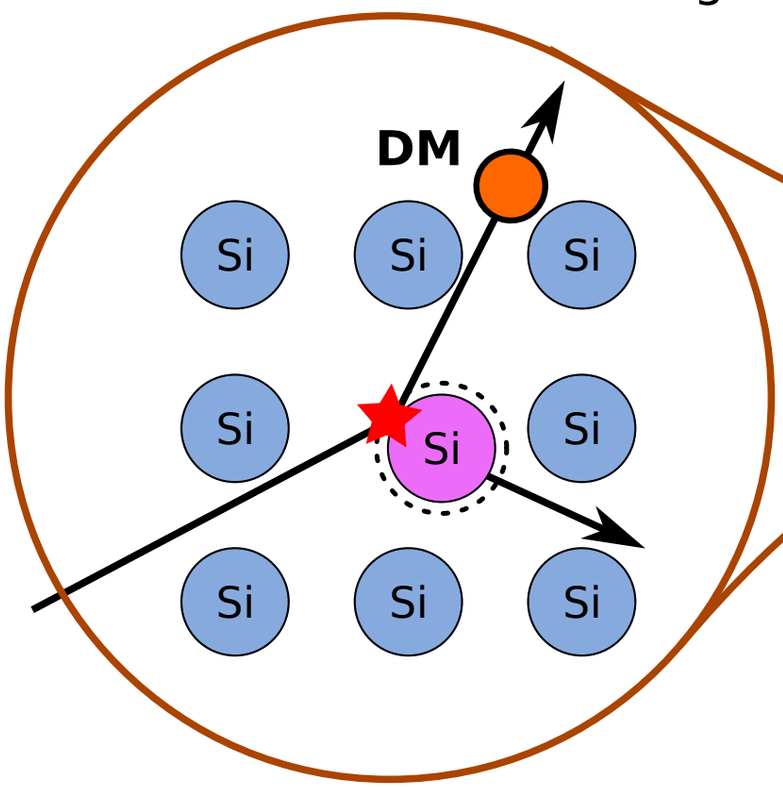
Events with 7-10 keV$_r$

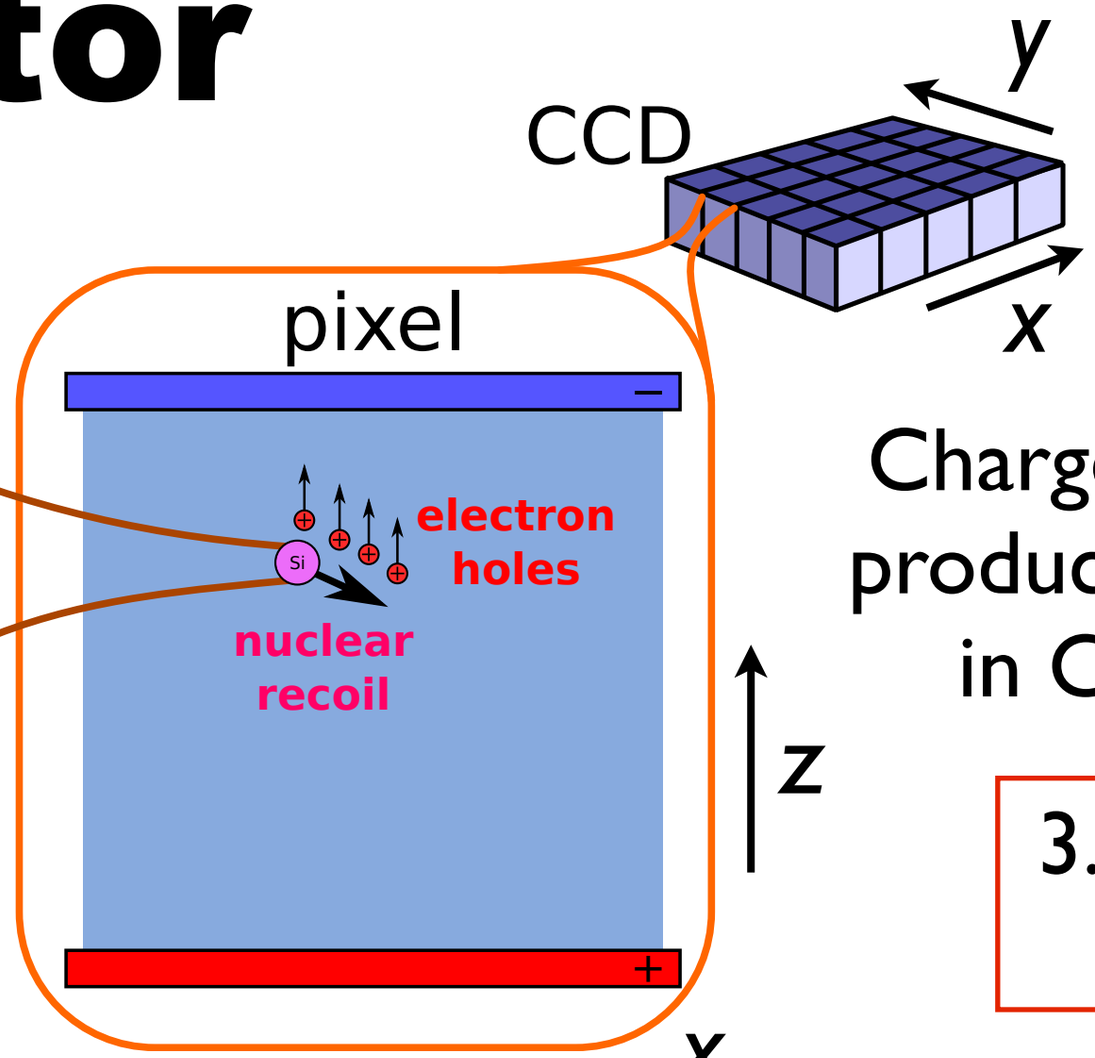
DAMIC

- Use the Si in a CCD bulk as a WIMP target.
- Very good ionization detector.
- Low electronic read out noise (~2 e^- = 7 eV 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.

Detector

coherent elastic scattering

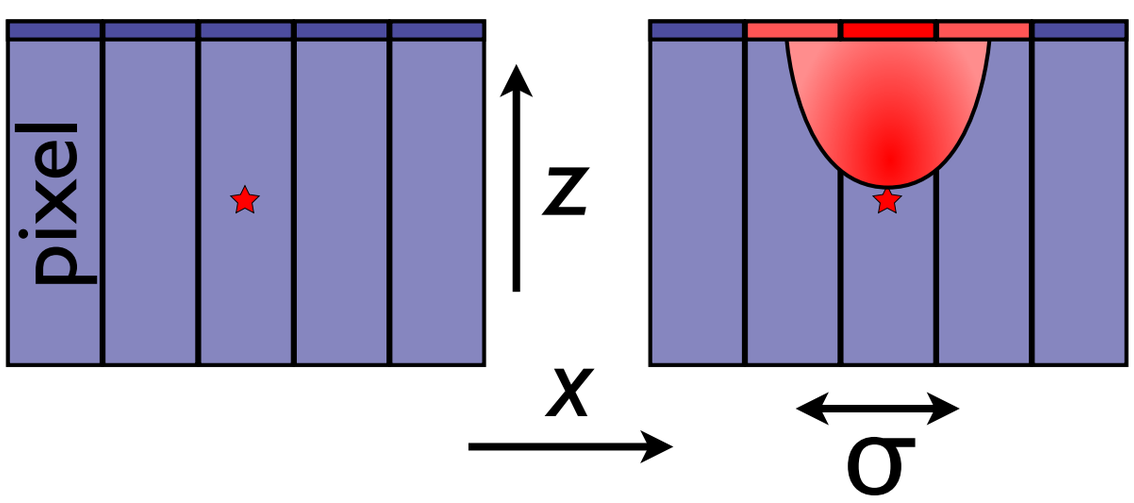


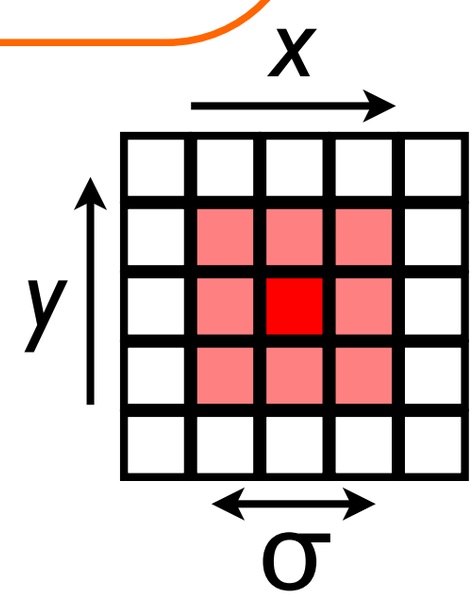


Charged particles produce ionization in CCD bulk

3.62 eV for e-h pair

Charge drifted up and held at gates

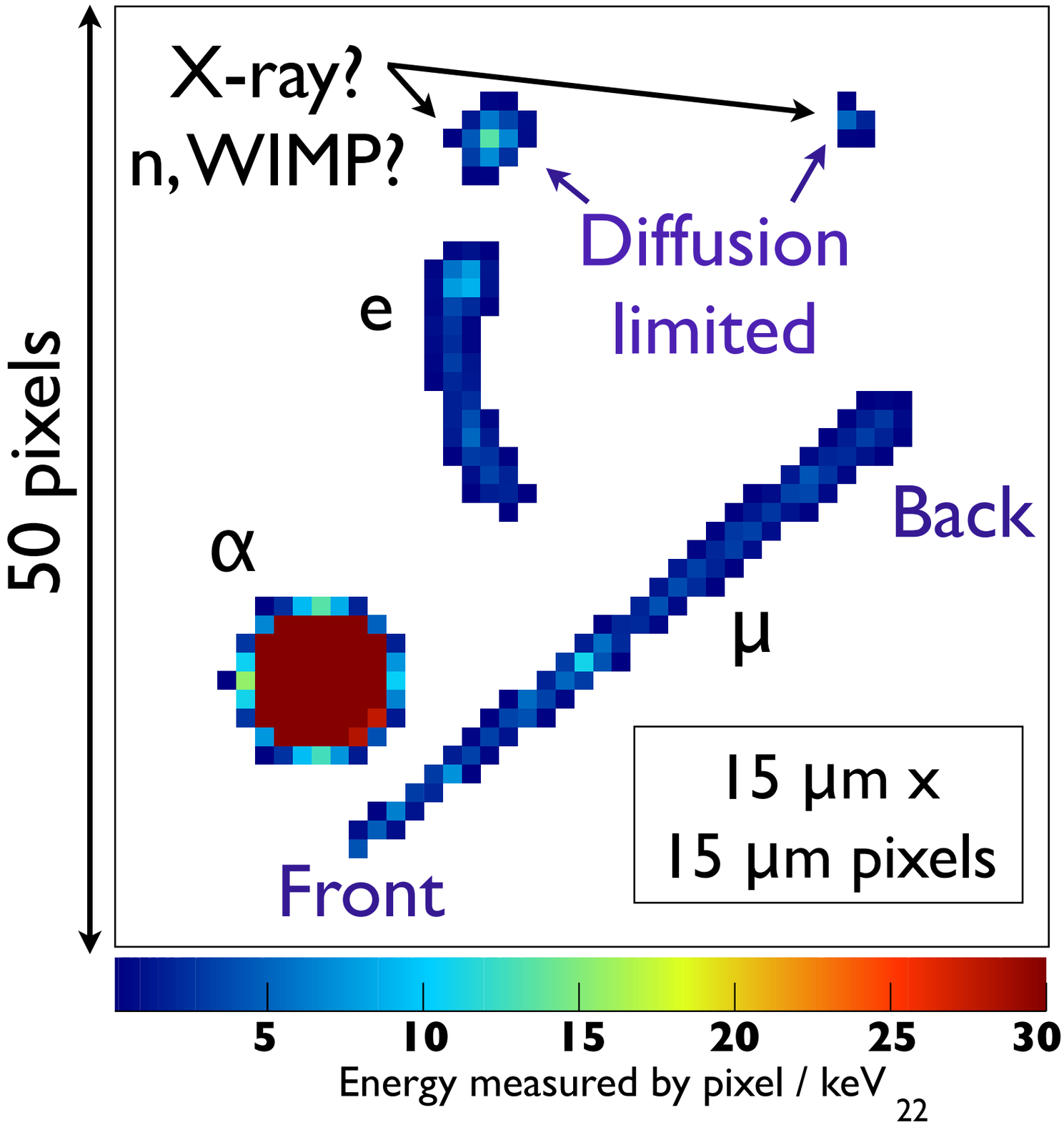




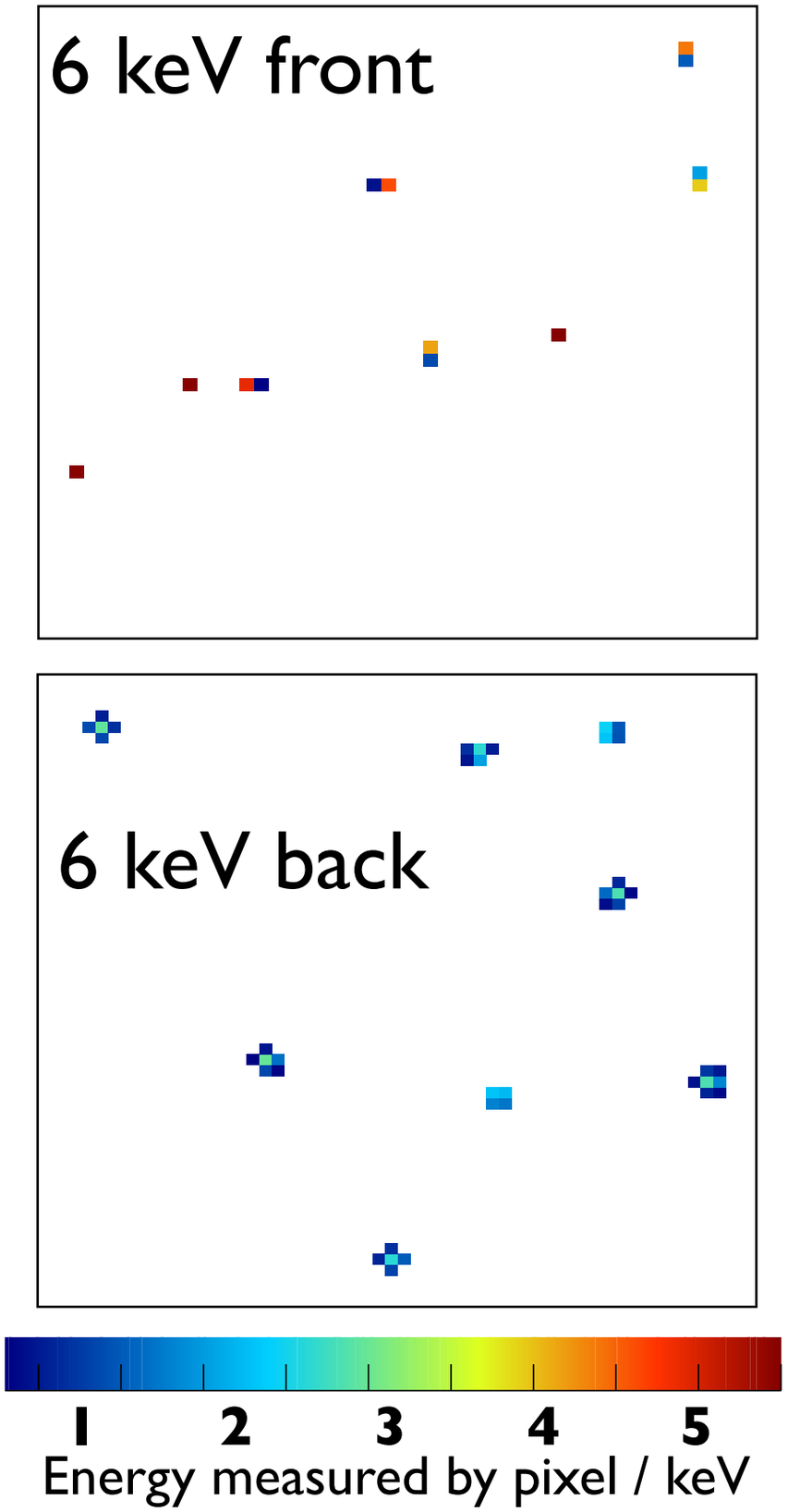
Charge collect by each pixel on CCD plane is read out

~2 e^- RMS read-out noise

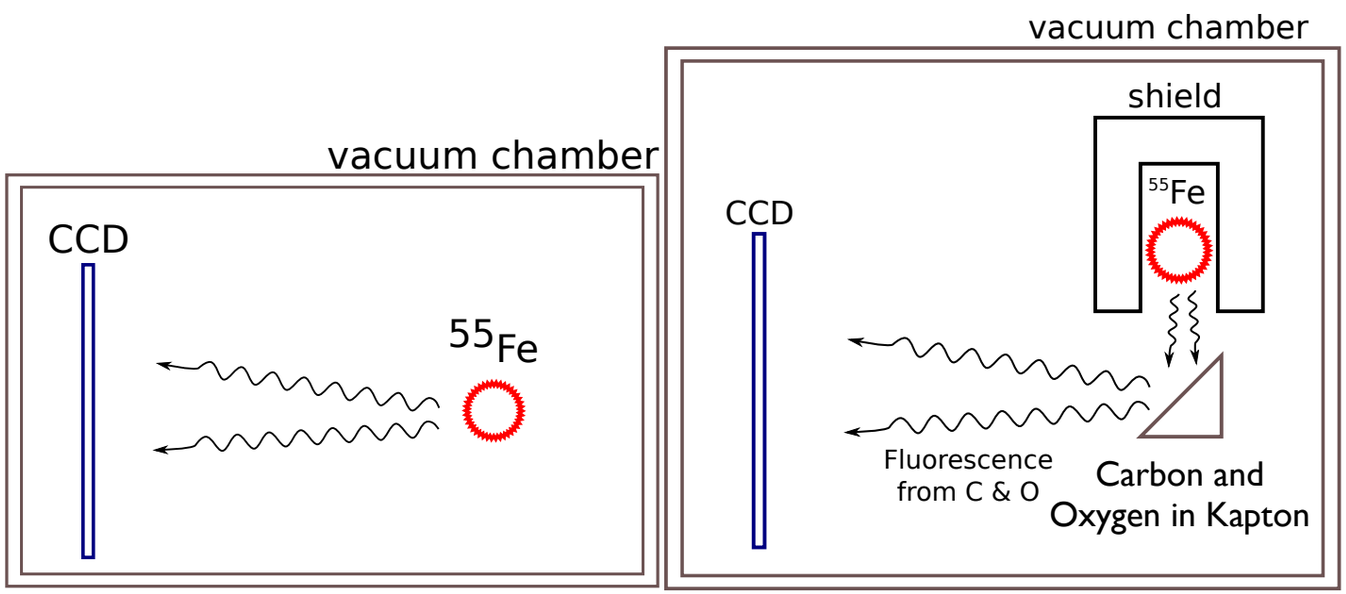
Particle tracks

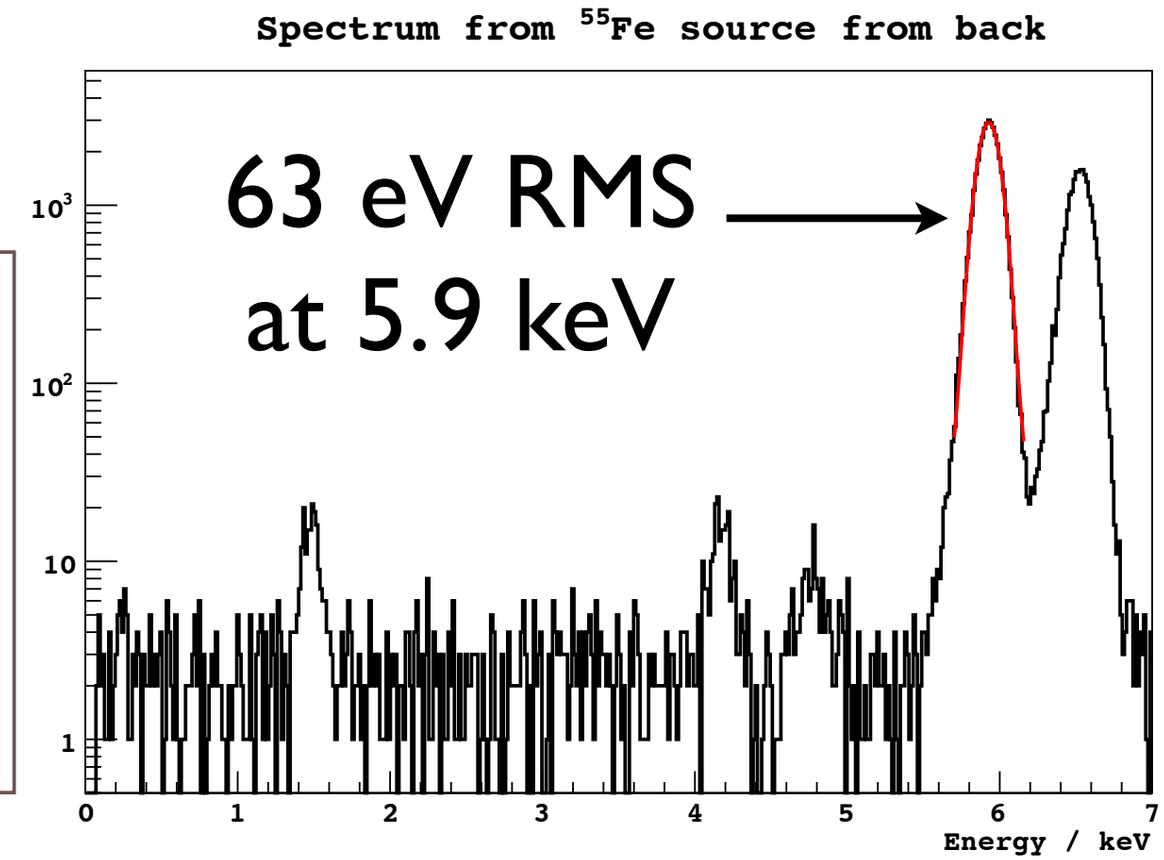


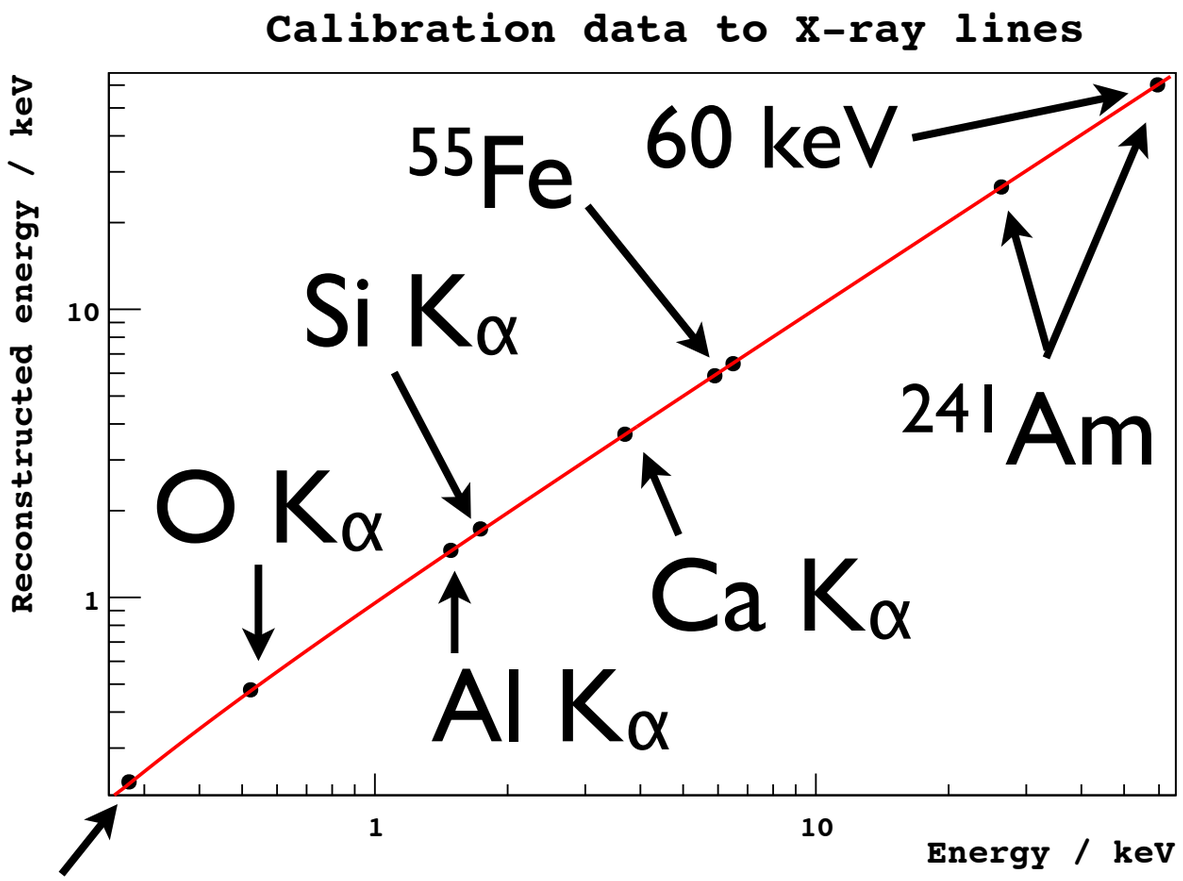
Diffusion limited

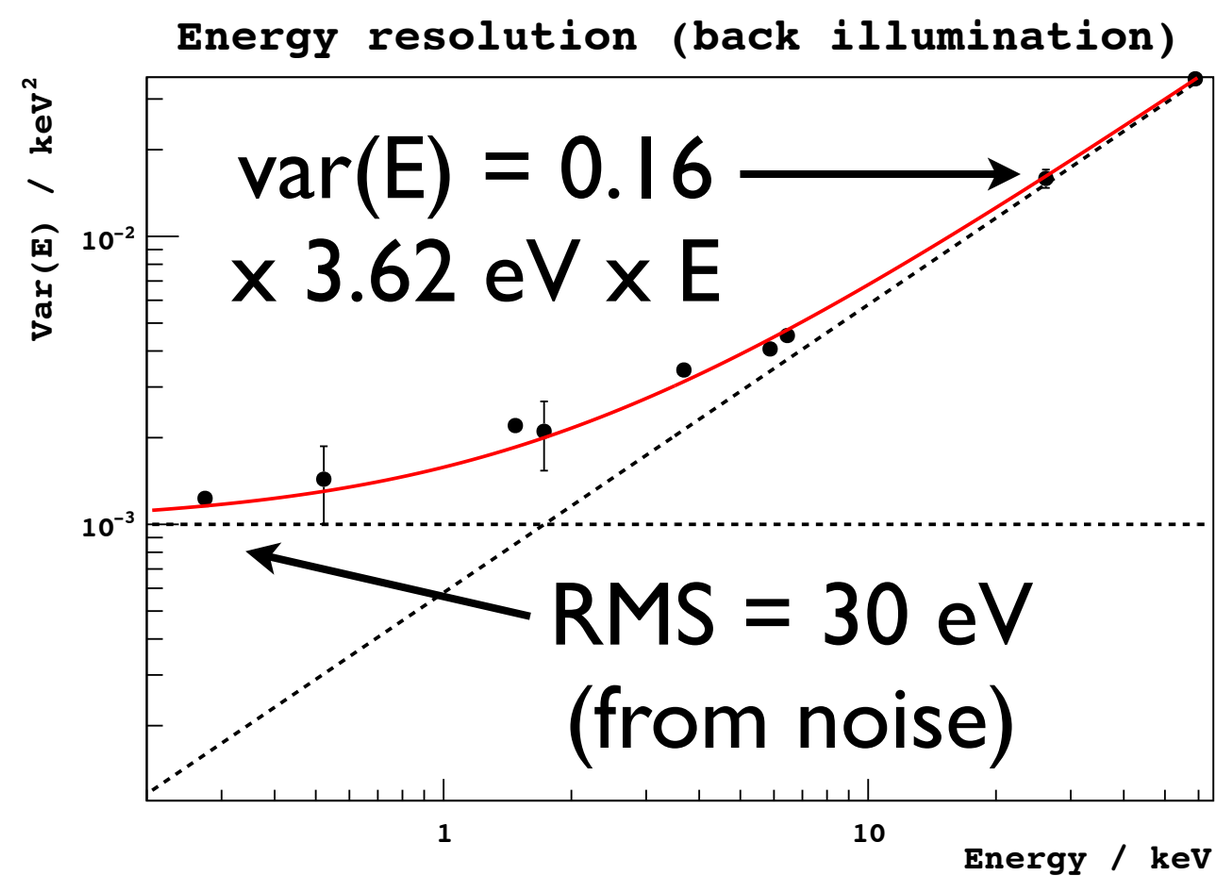


E response


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

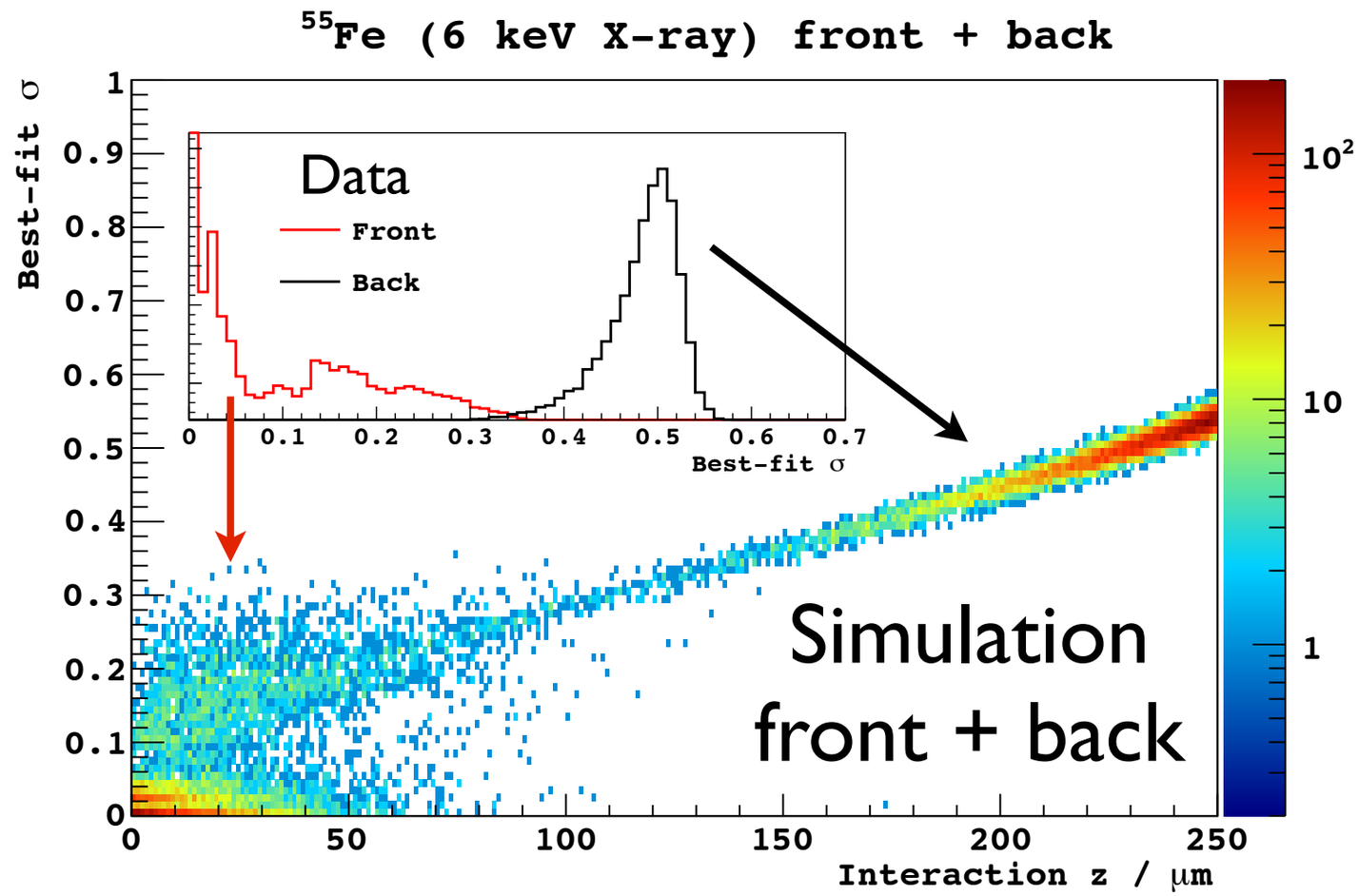

Spectrum from 55Fe source from back
63 eV RMS
at 5.9 keV
Energy / keV

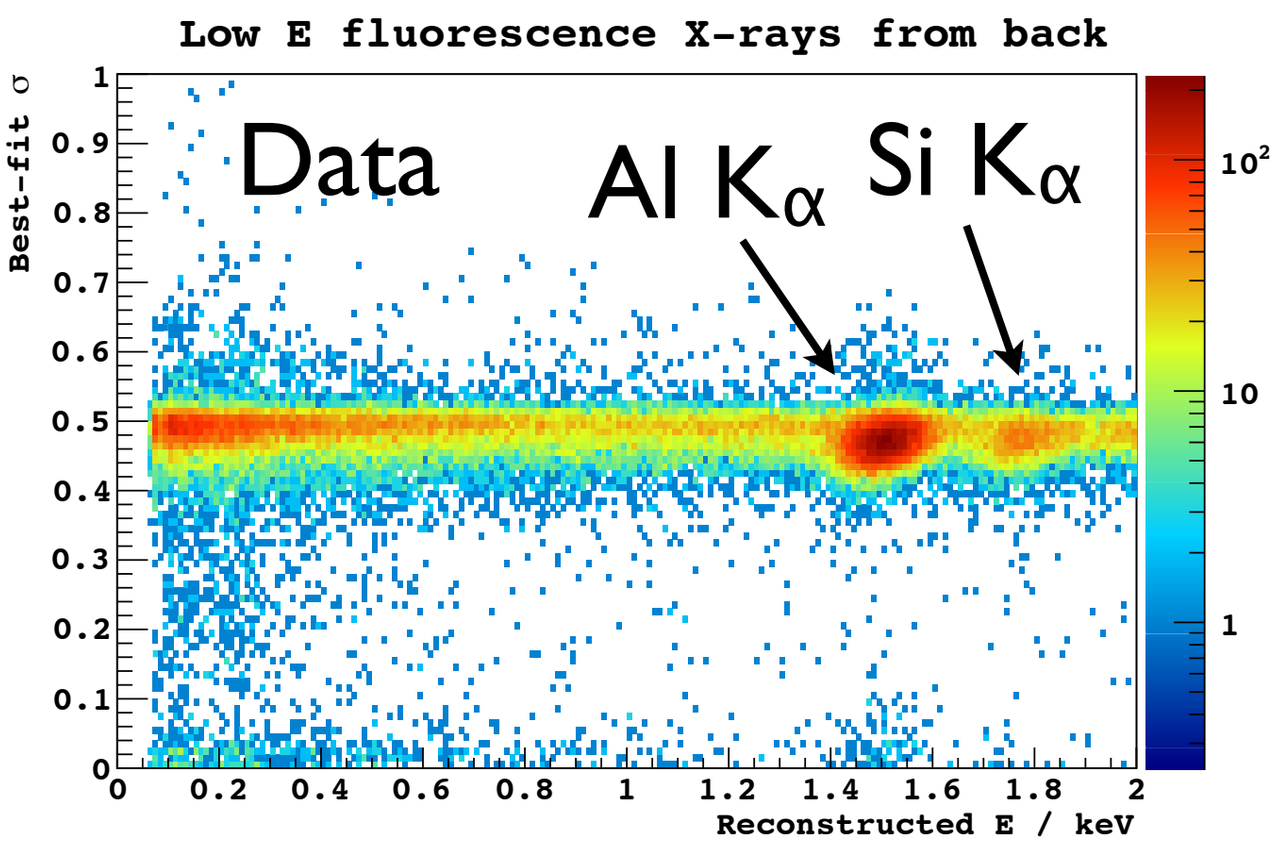

Calibration data to X-ray lines
Reconstructed energy / keV
Energy / keV
55Fe
60 keV
Si Kα
241Am
O Kα
Ca Kα
Al Kα
C Kα (0.28 keV)

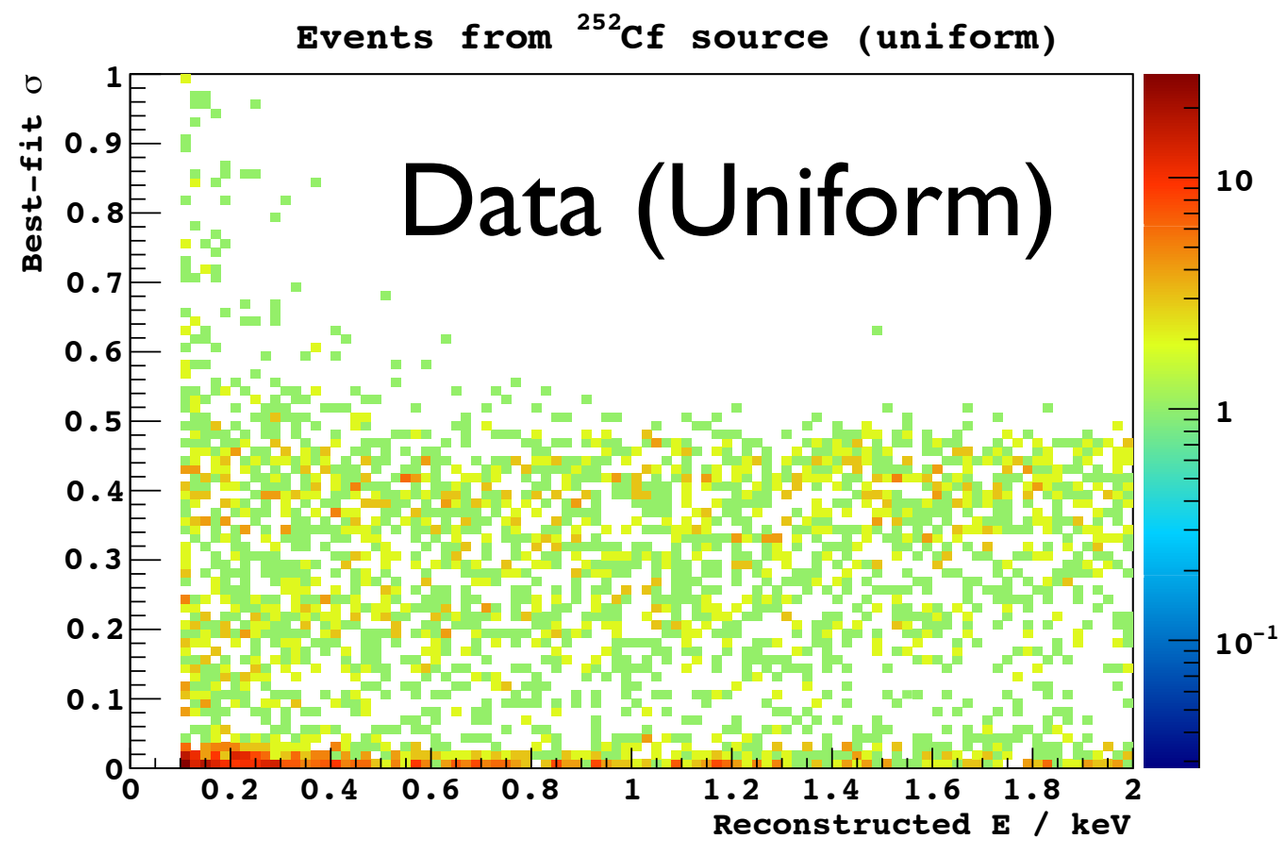

Energy resolution (back illumination)
Var(E) / keV²
Energy / keV
var(E) = 0.16
x 3.62 eV x E
RMS = 30 eV
(from noise)

Diffusion

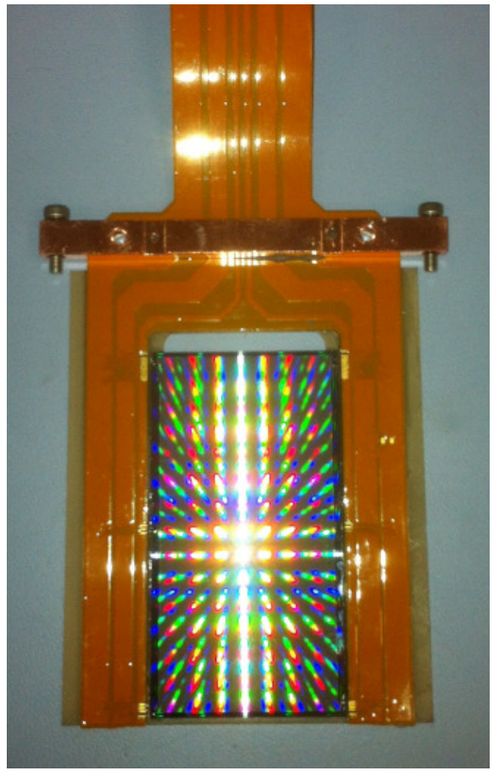
Fit to the radial spread of the cluster allows us to estimate its position in z within the CCD bulk



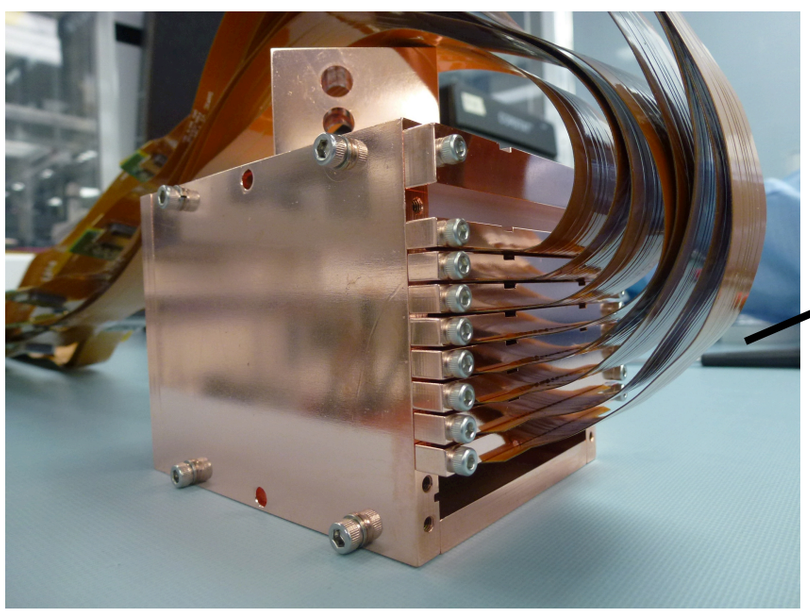




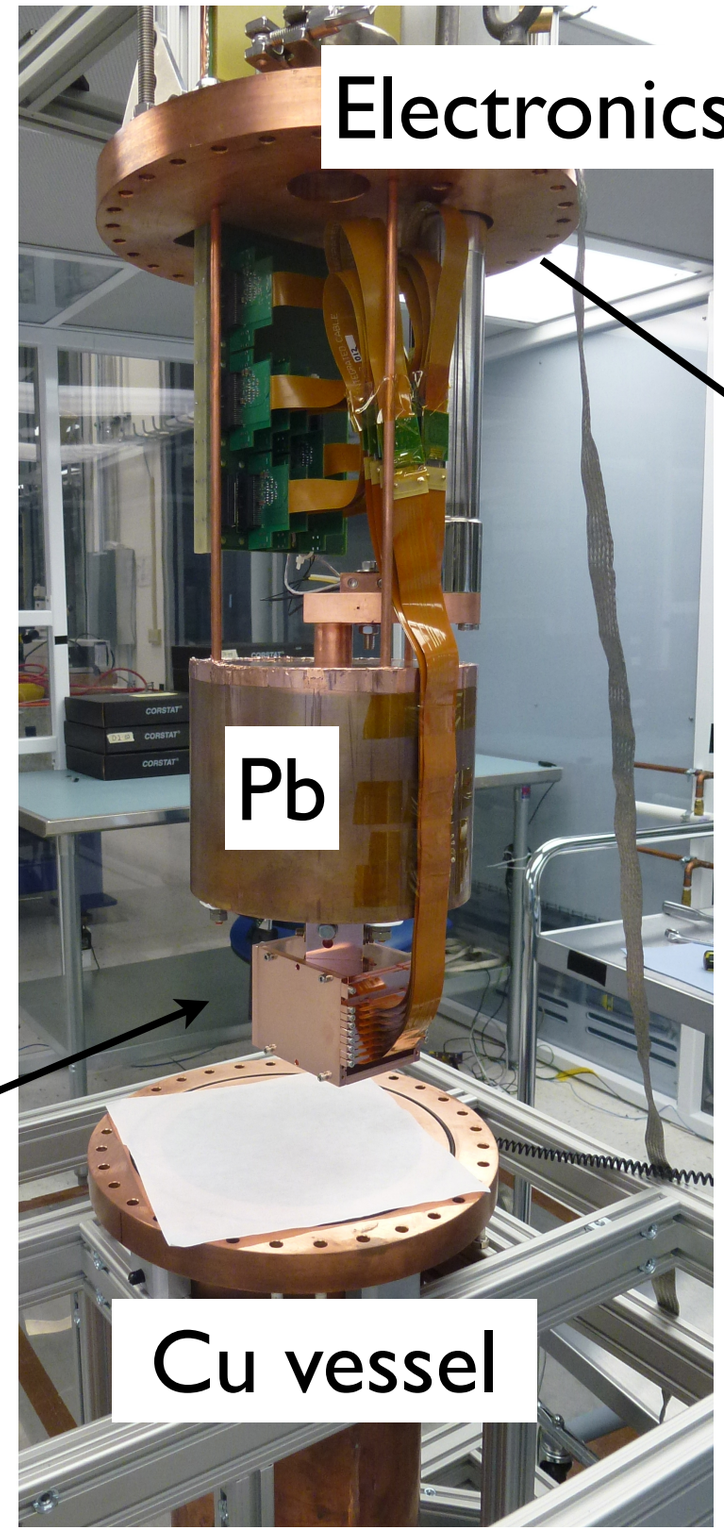
Setup at SNOLAB

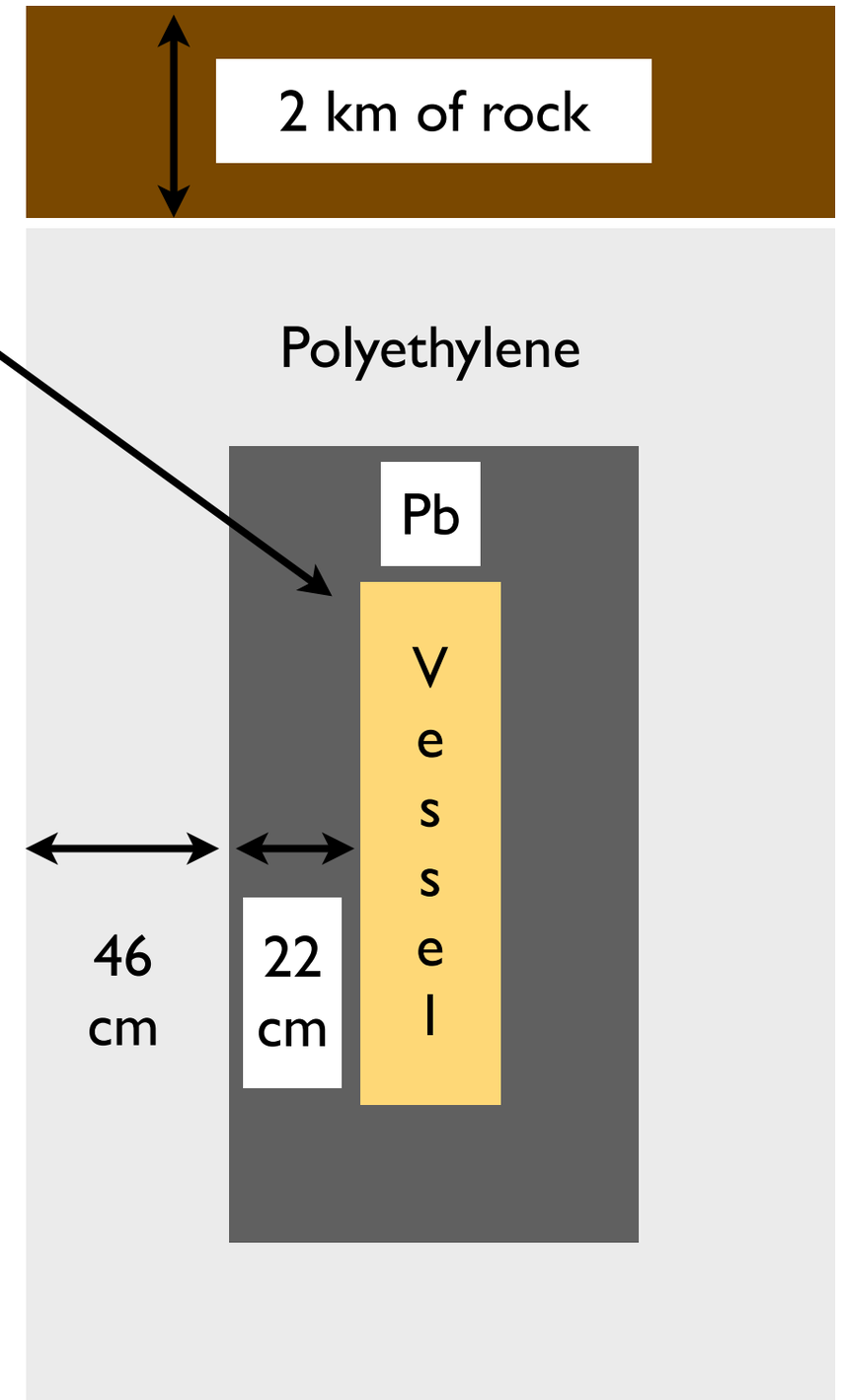


Wired CCD



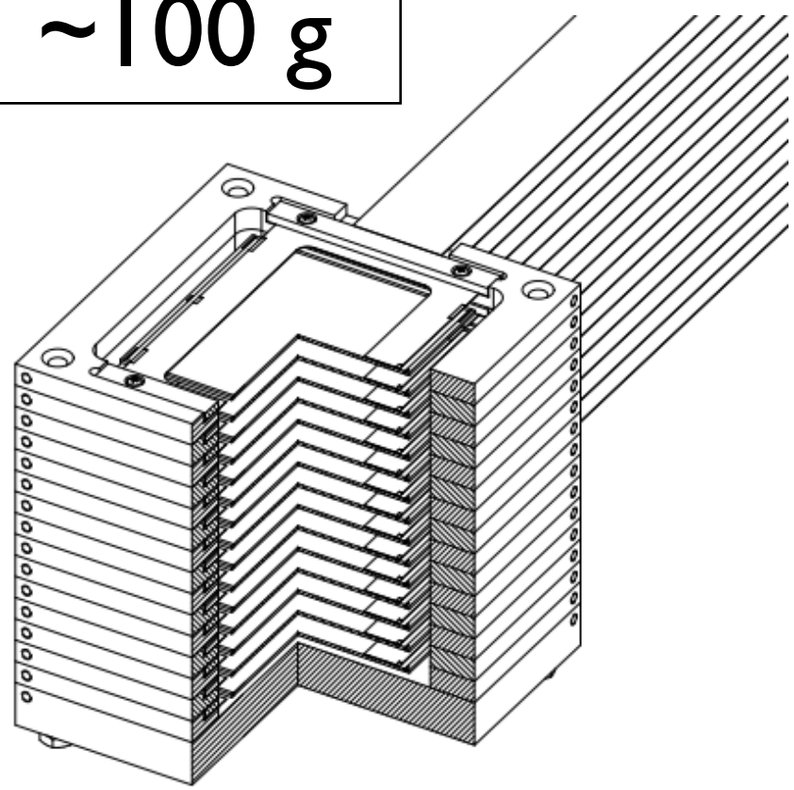
Cu box with CCDs





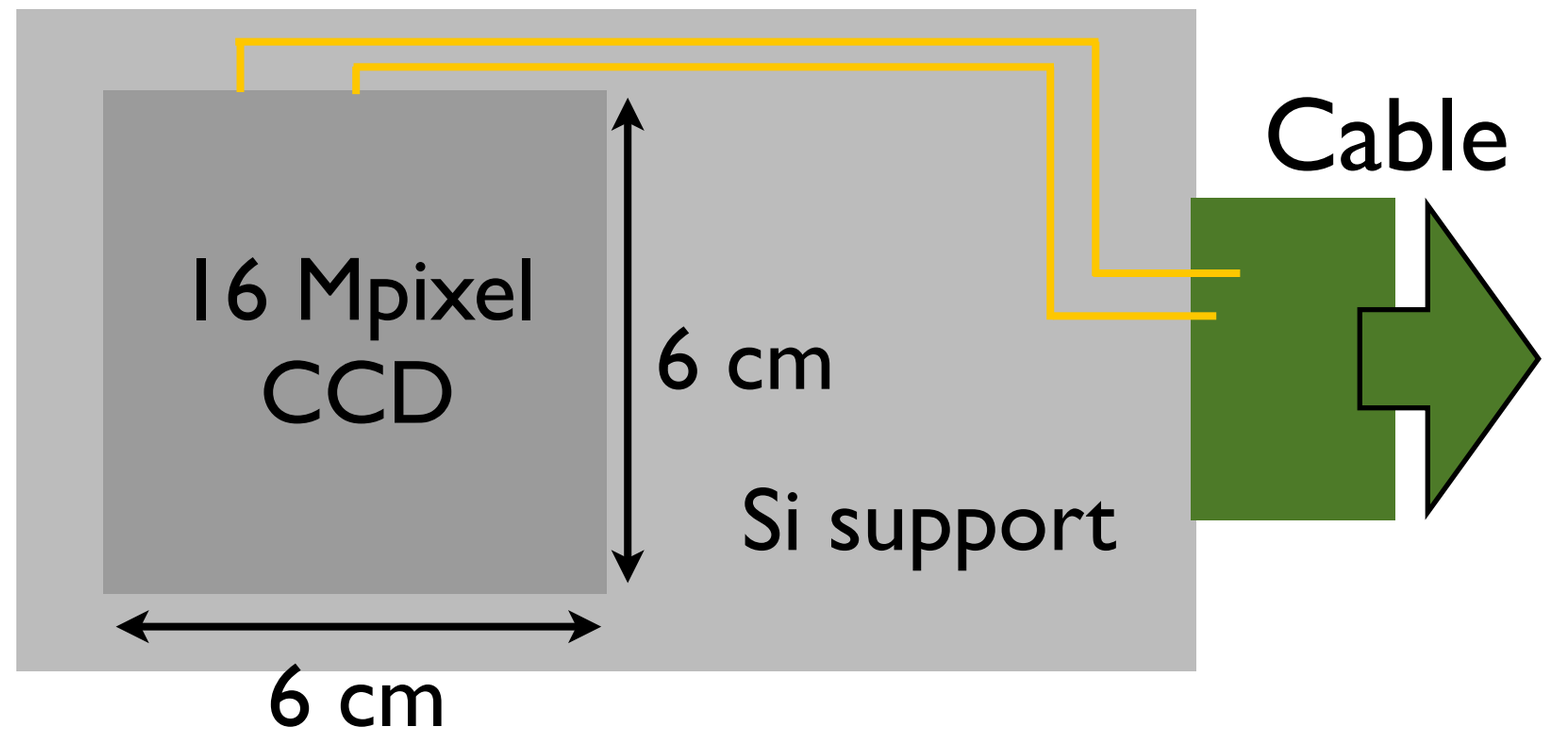
DAMIC100

15 CCDs
~100 g



650 µm thick

~20 racetracks
printed on support

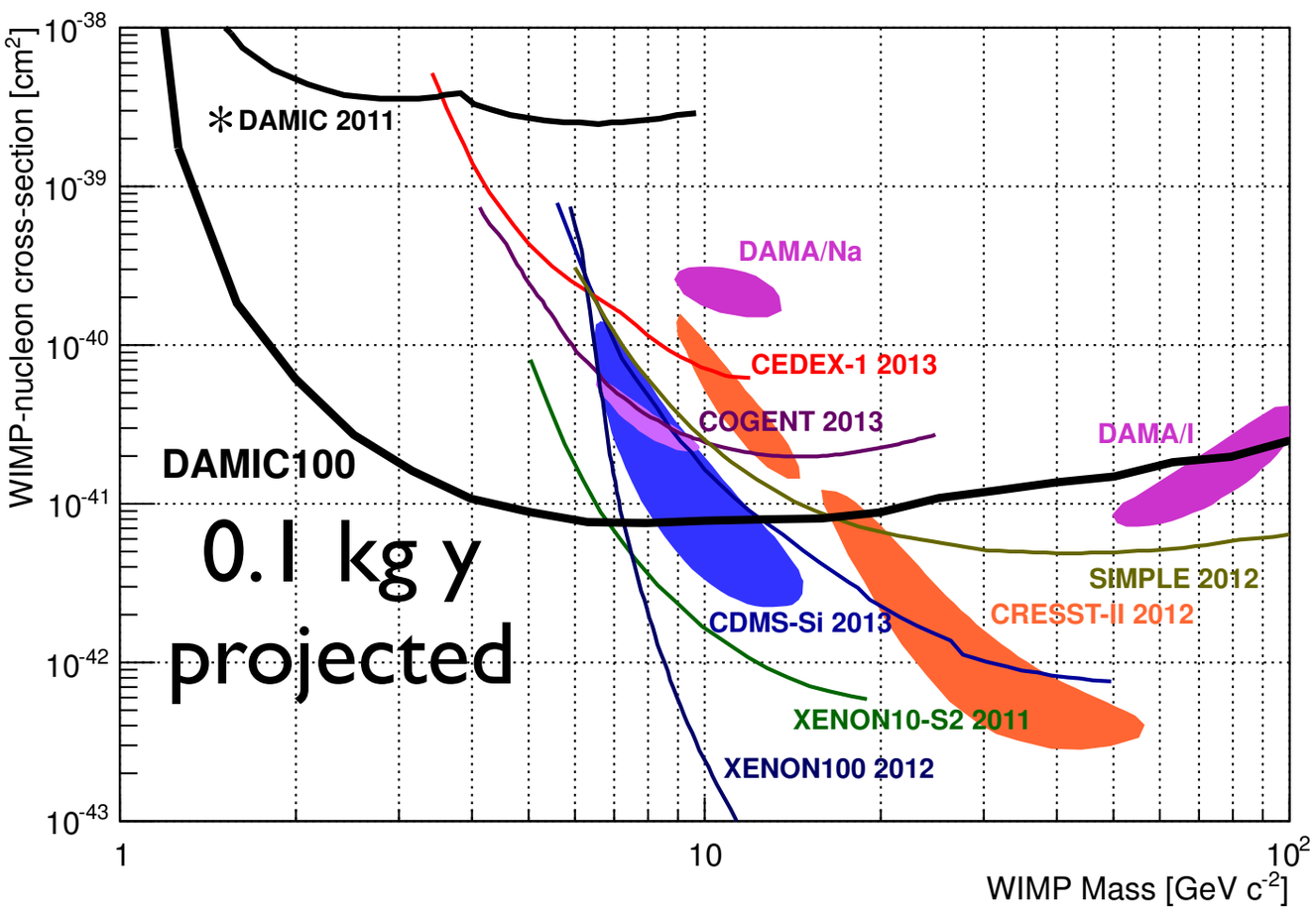


In-situ neutron background measurement with ^{10}B layer

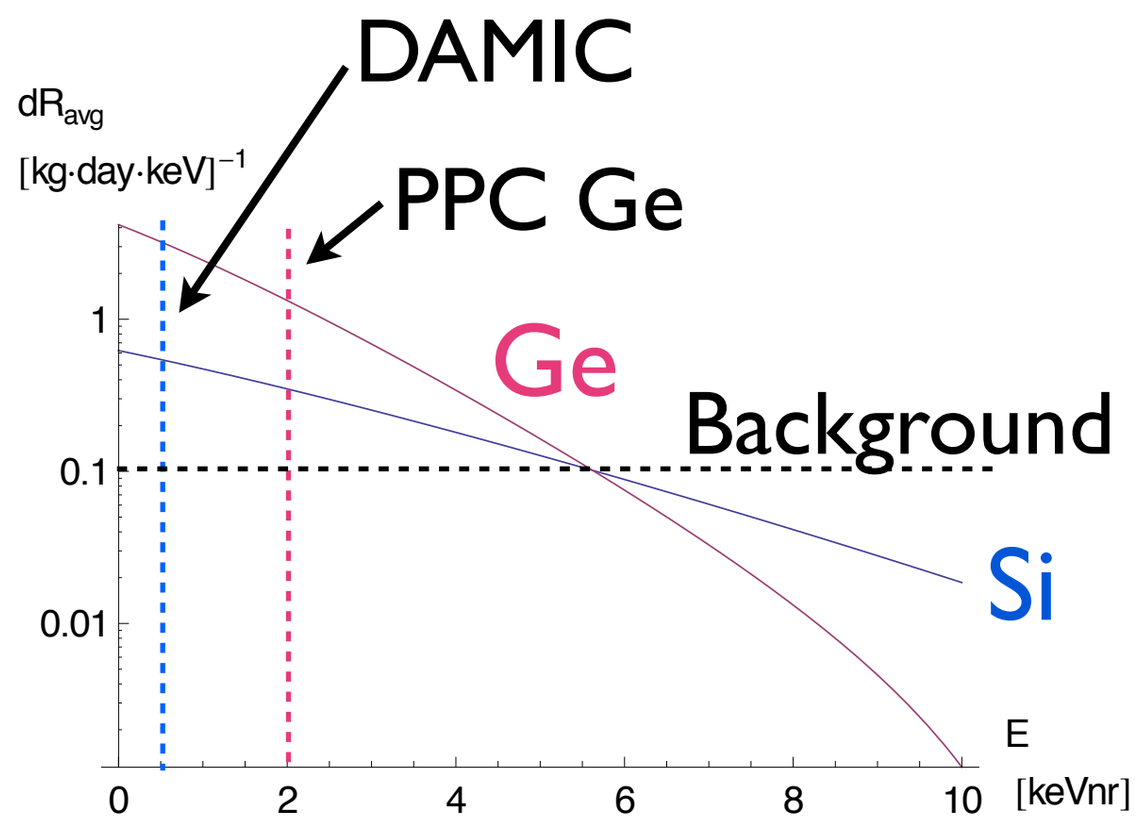
Will install 2 500 µm thick CCDs this fall in SNOLAB.
DAMIC100 to be deployed in current Cu vessel + shield in **Spring 2014**.

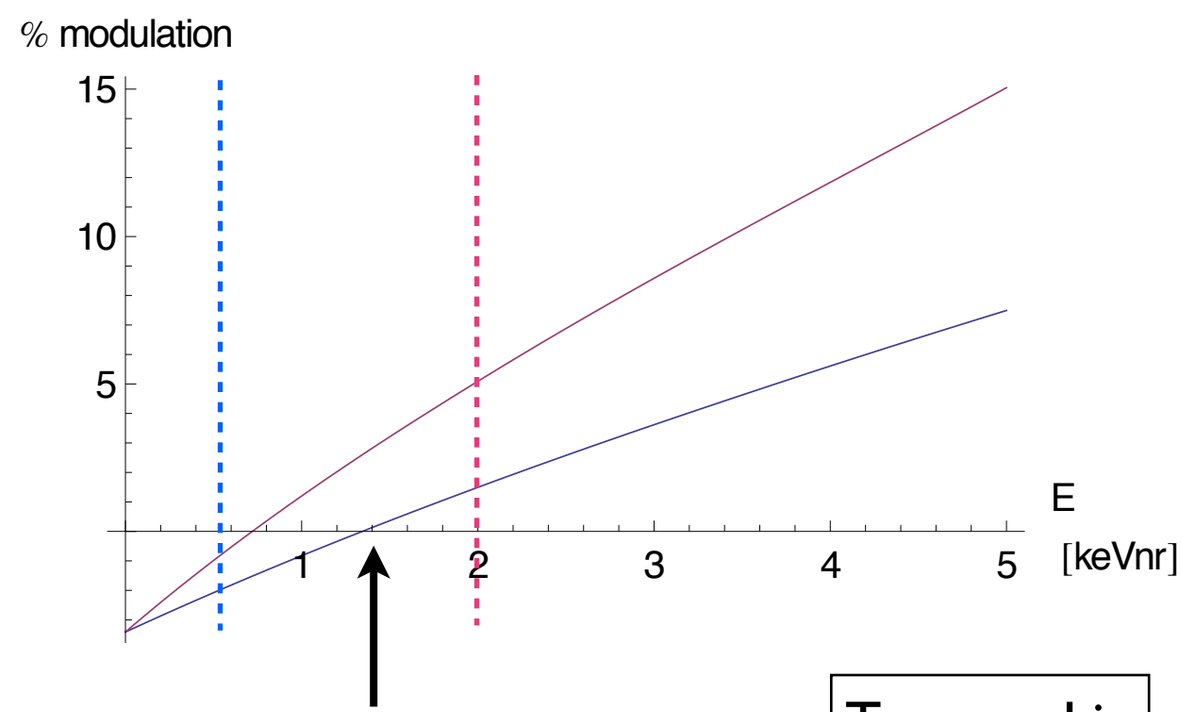
Sensitivity

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



*Physics Lett. B711 (2012) 264-269





Phase inversion

Tongyan Lin

Conclusion

- We may be able to find direct evidence for DM in underground laboratories.
- Some experiments have seen an excess of events / annual modulation that could be attribute to <10 GeV WIMPs.
- Comparison between results in different targets is hard.
- The DM experimental community has proposed several projects to check these signals.
- DAMIC will test the CDMS-Si signal.

Backup Slides

Backgrounds

CCD + support

$<10^{-4}$ Bq kg^{-1} of U + Th from counting αs. αs most likely from surface contamination ⟶ apply polymer film on CCD surface.

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

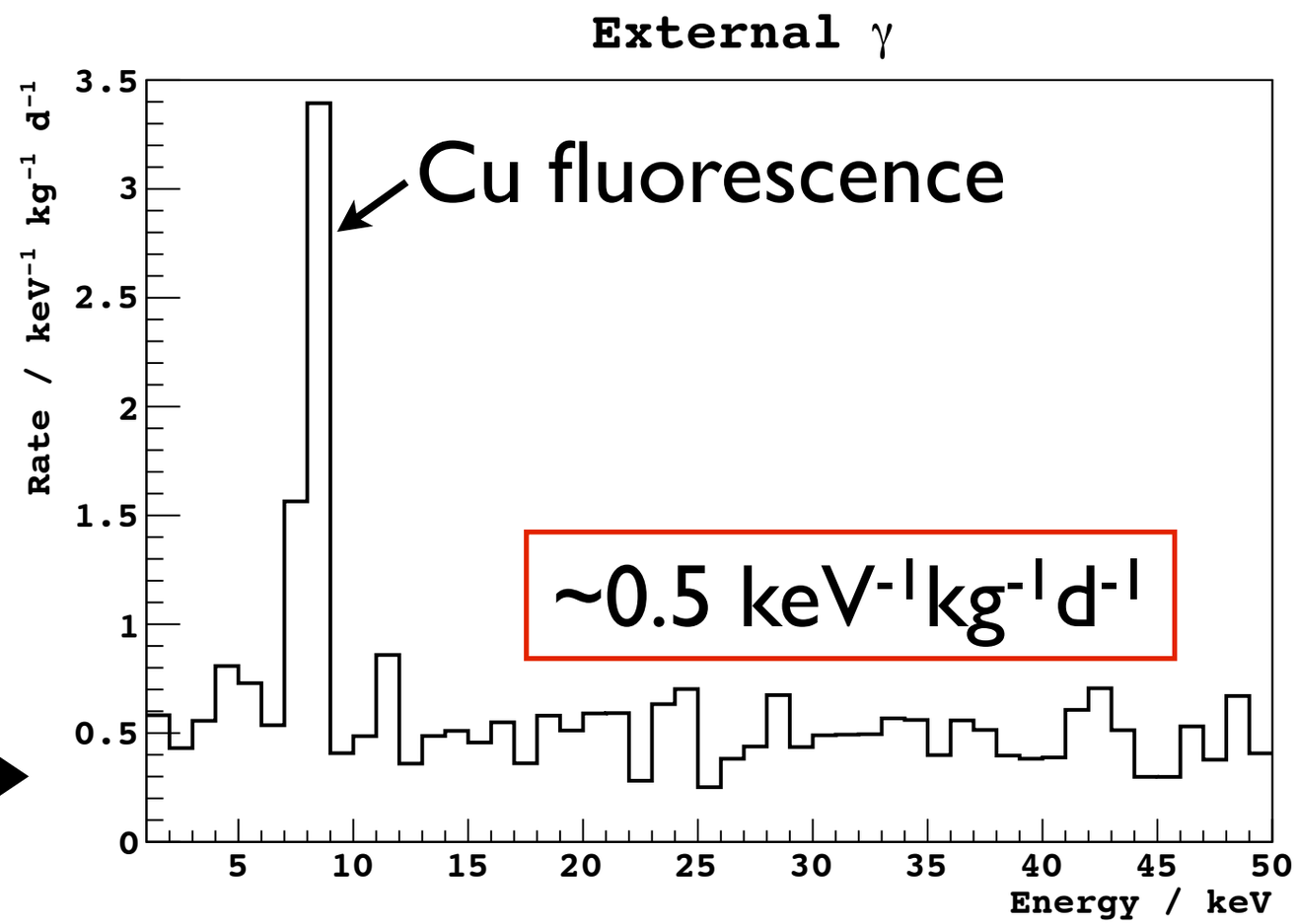
Typical analysis results of electronic-grade polysilicon (NAA and IR at RT) [4].

Element	Atoms/cm^3
Carbon	$< 2.0 \times 10^{16}$ 1)
Oxygen	$< 1.0 \times 10^{16}$ 1)

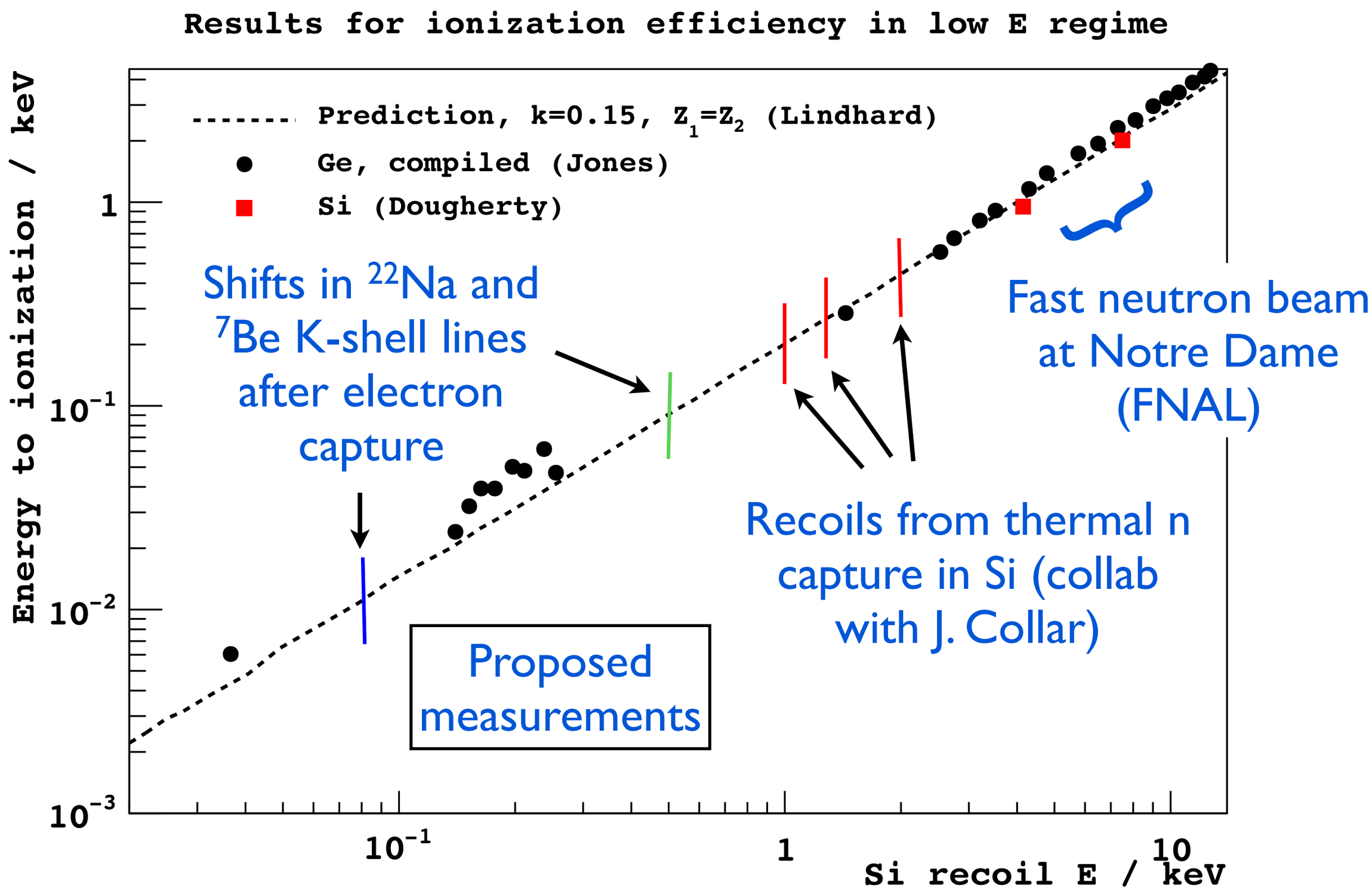
... negligible ^{14}C, etc.

Need to be careful about Epoxy

Goal: to be dominated by external γ

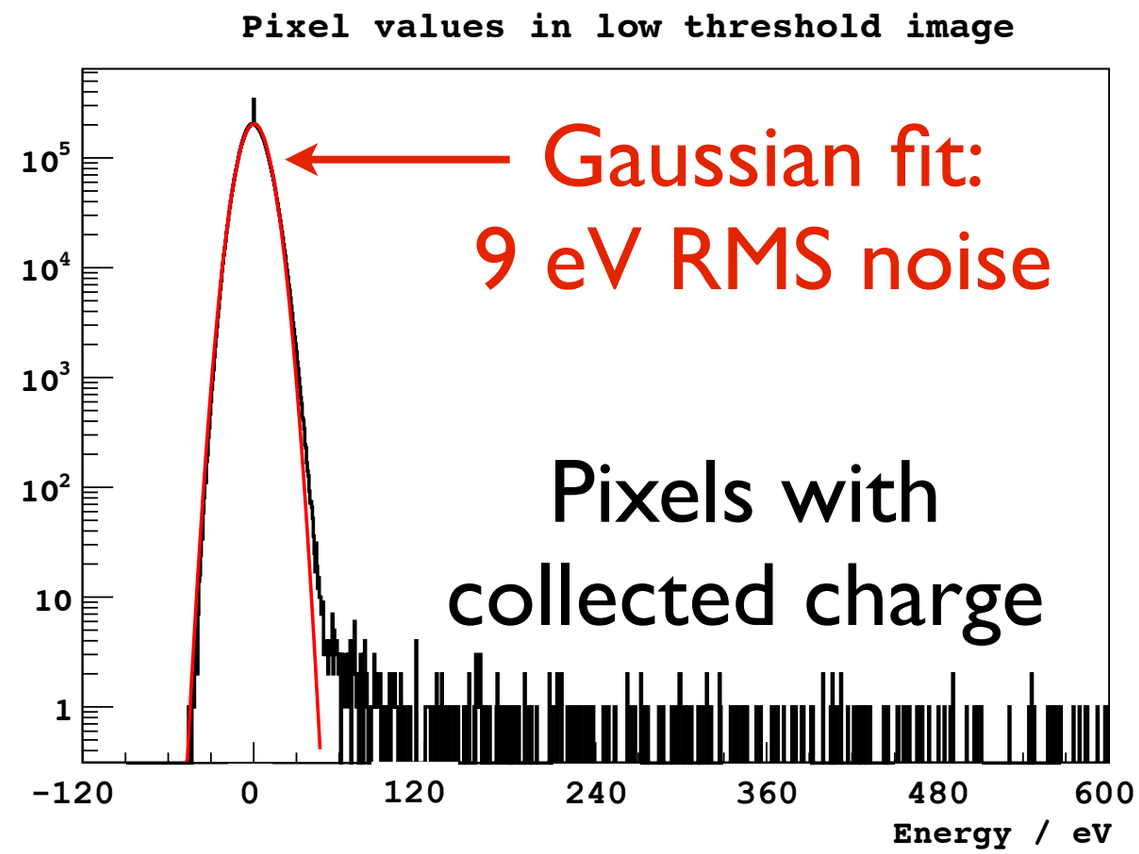


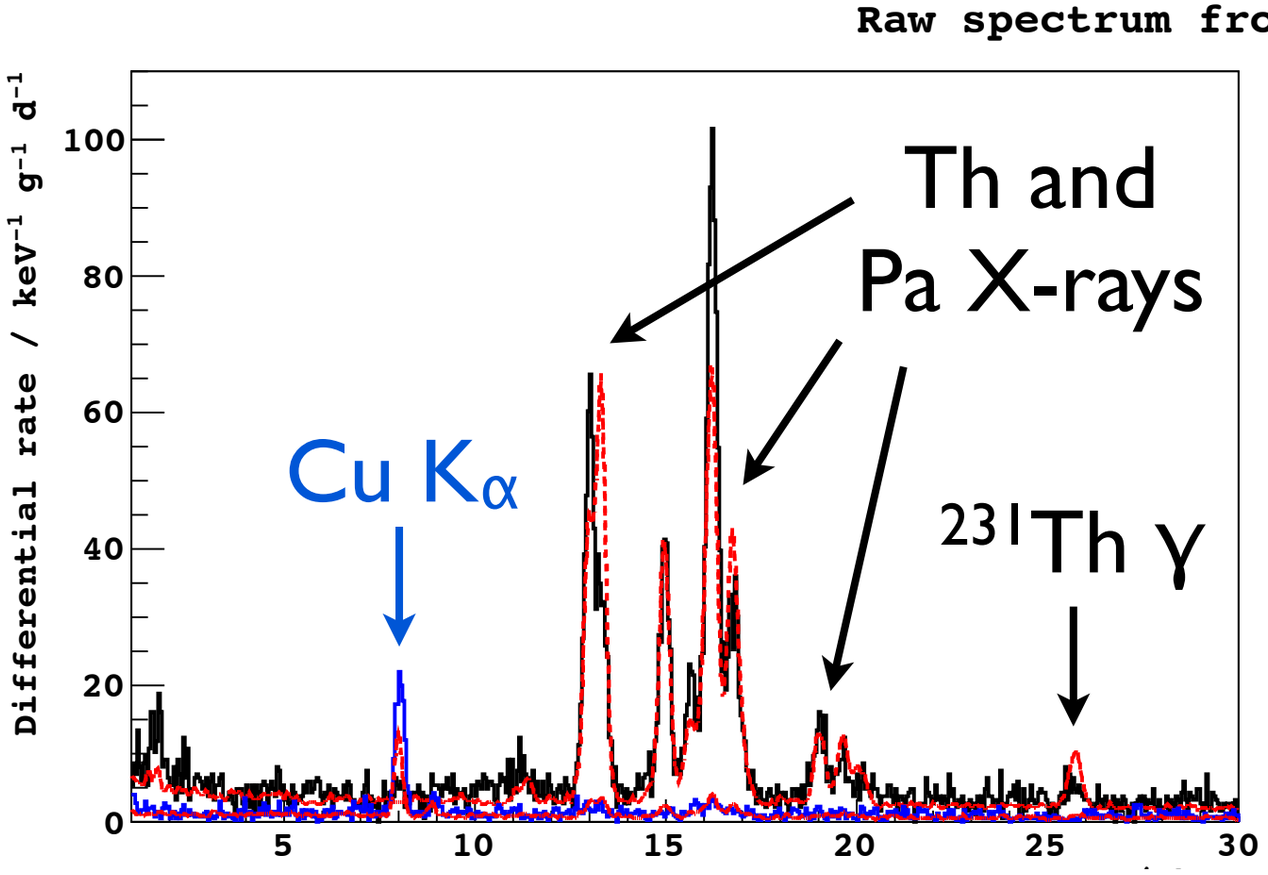
Calibration of E_r scale

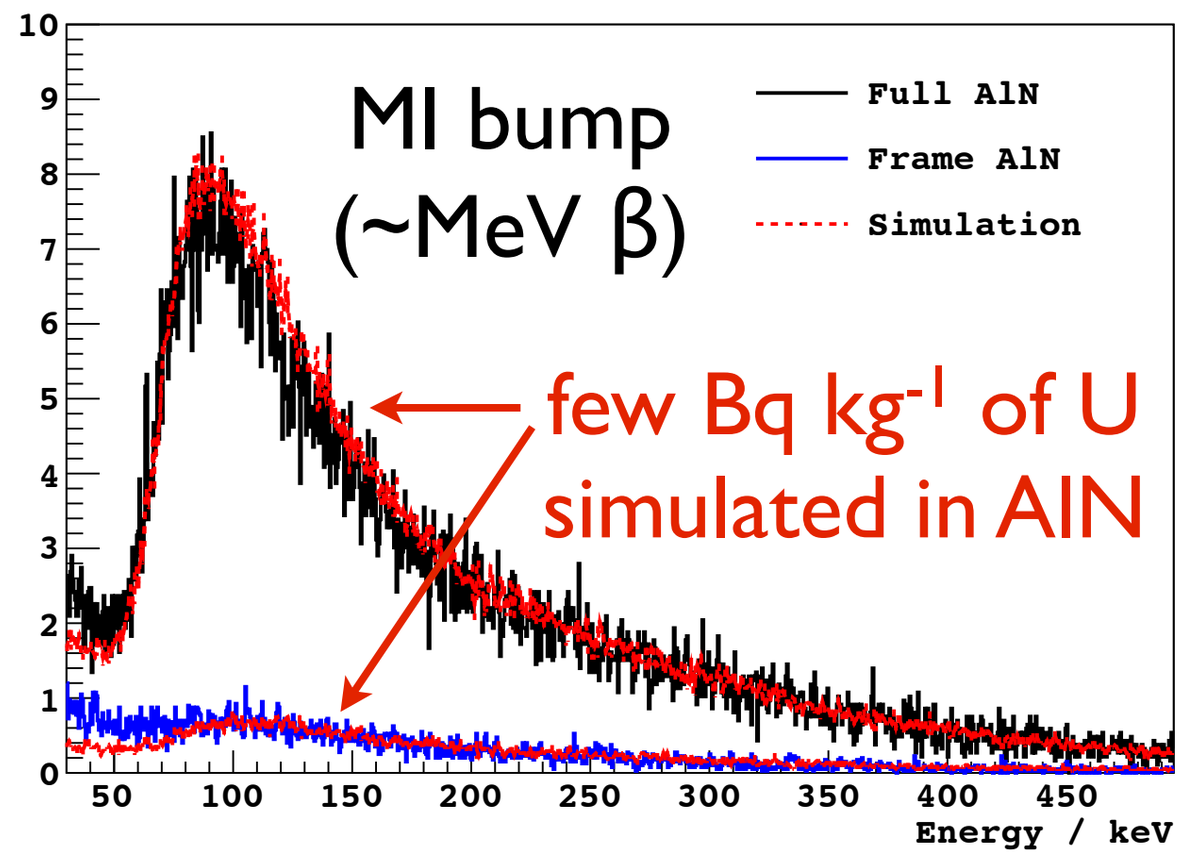


SNOLAB data

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



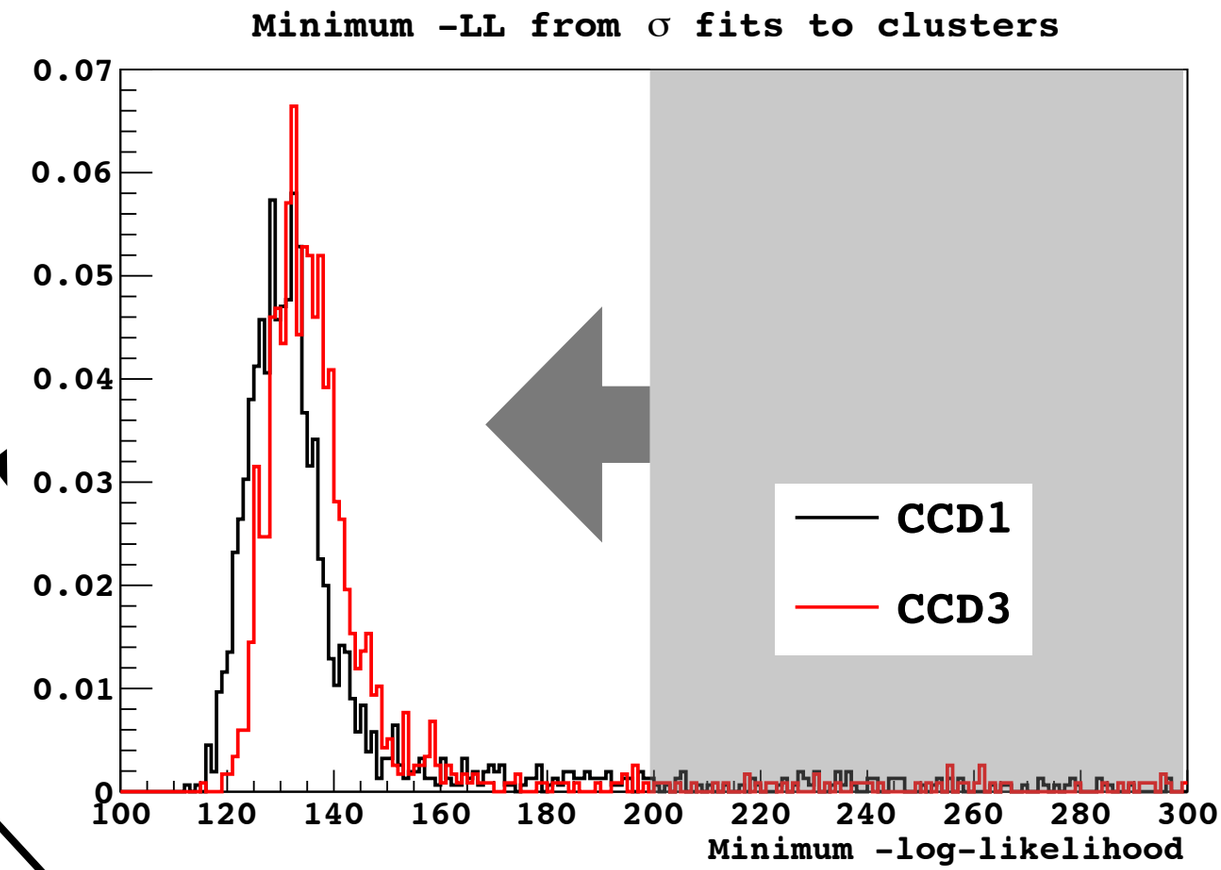


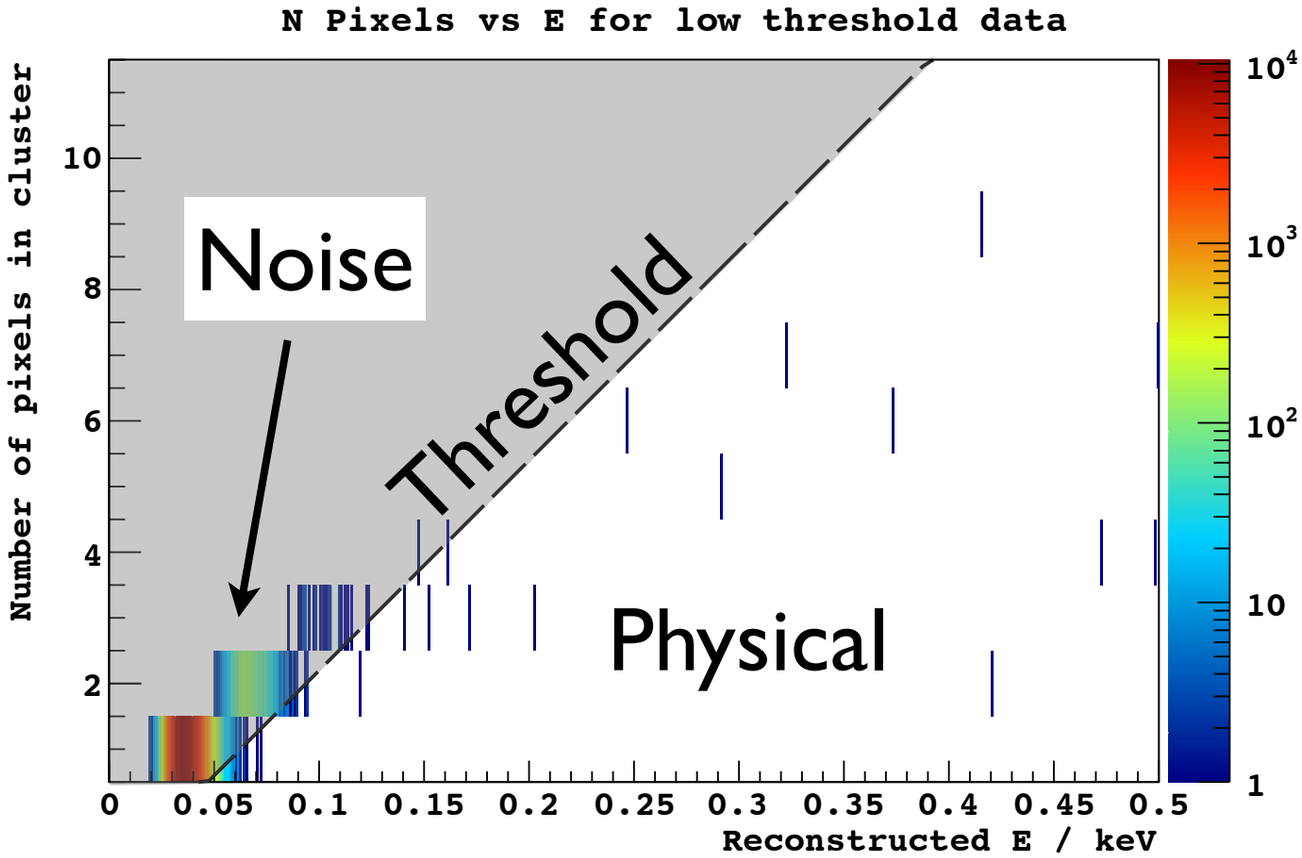


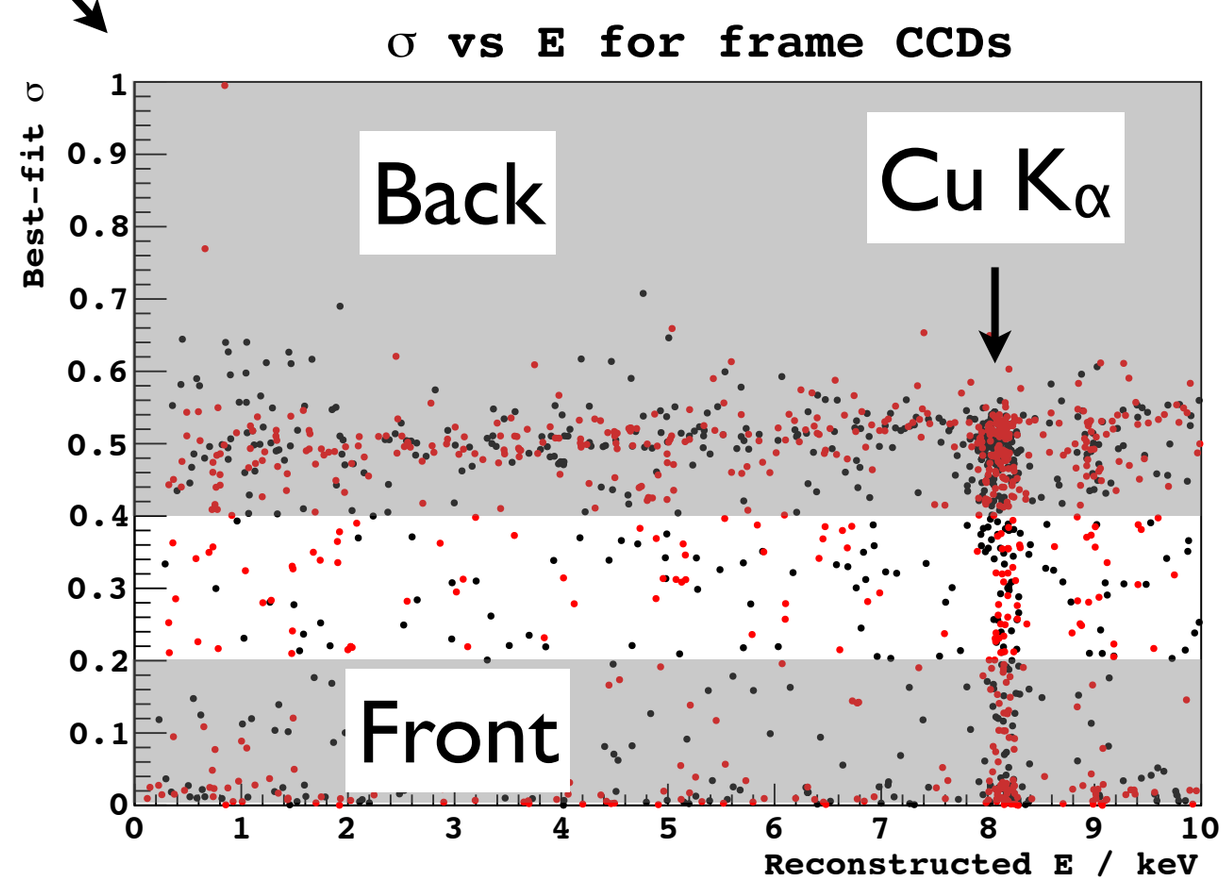
Data selection

Exclude read-out noise

Select bulk events

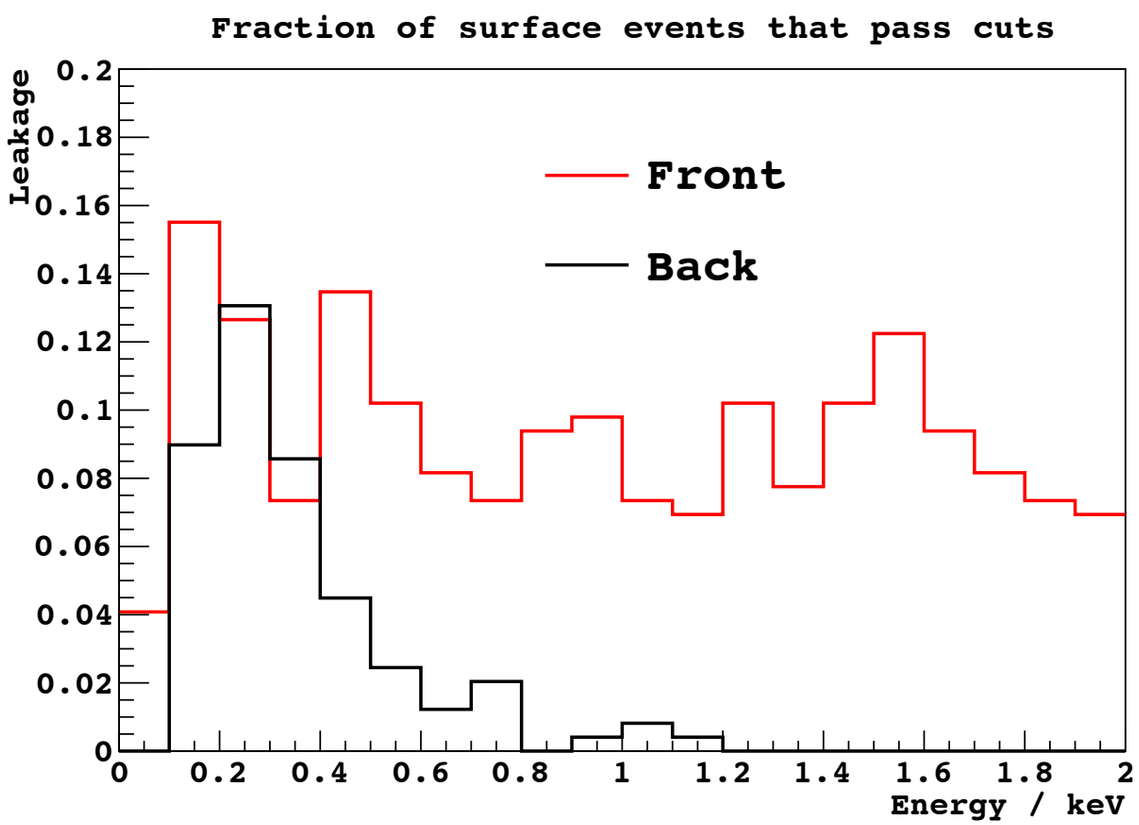


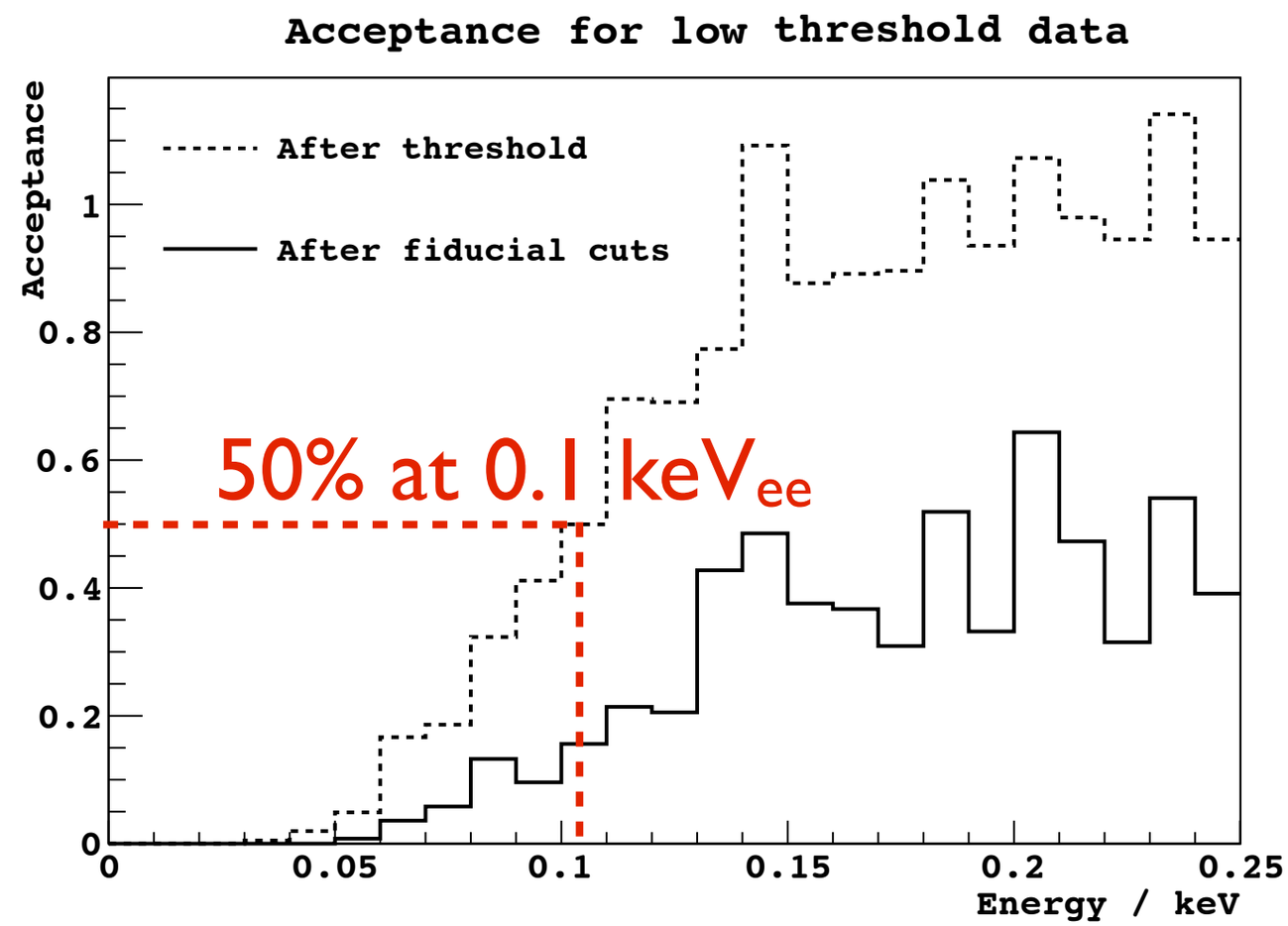




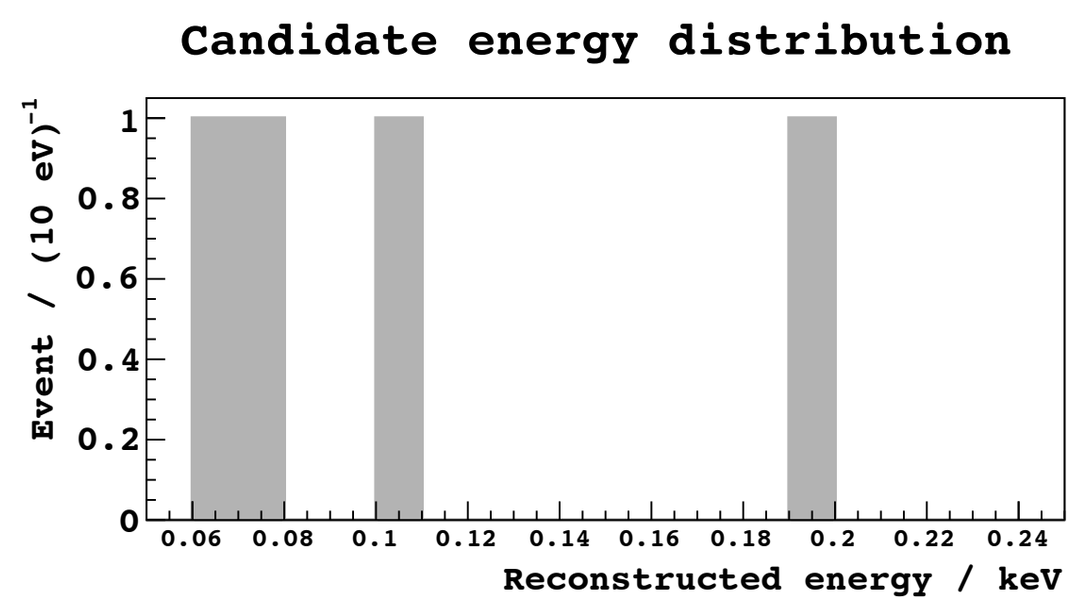
Low threshold data

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





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



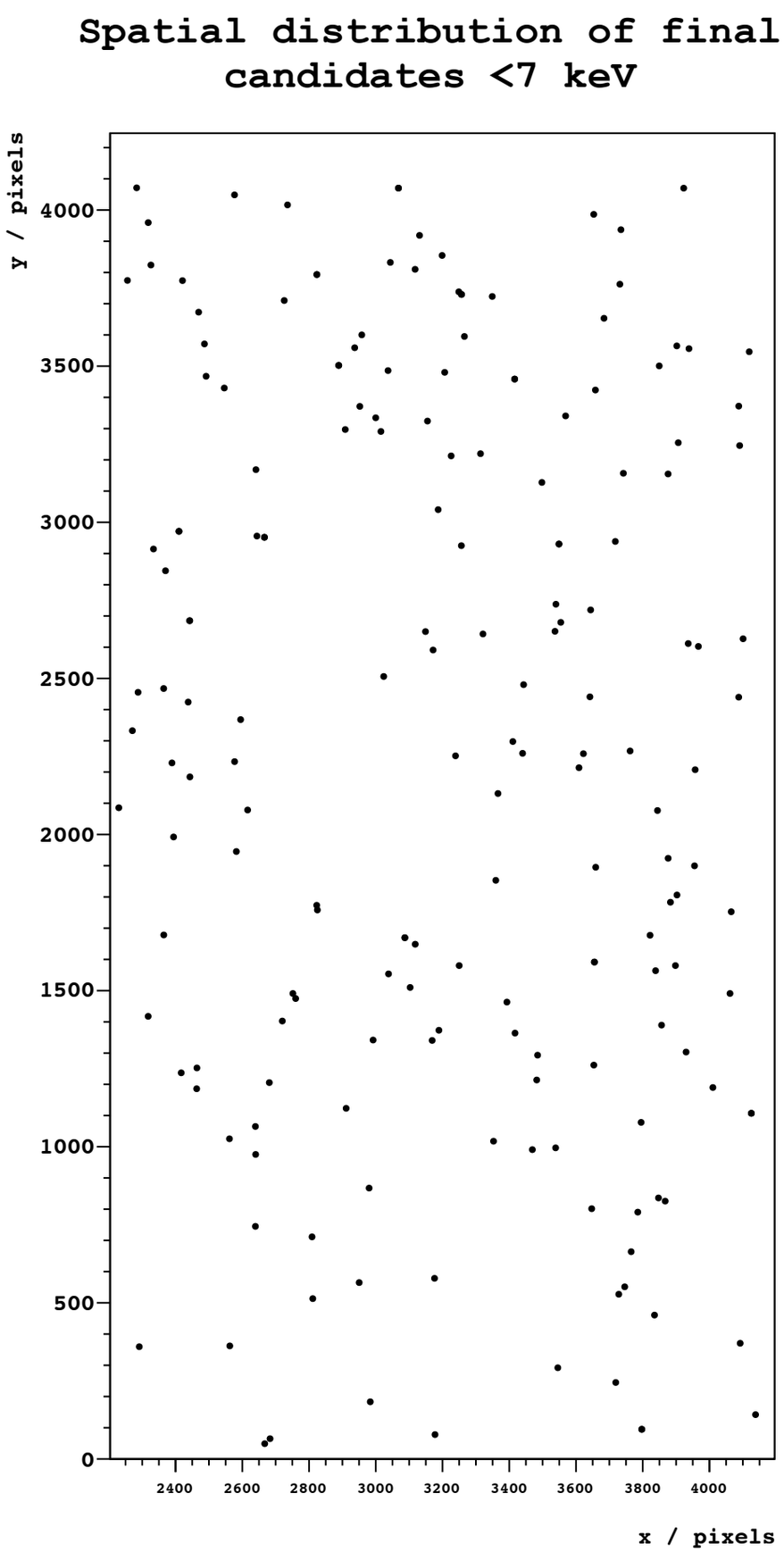
Full data

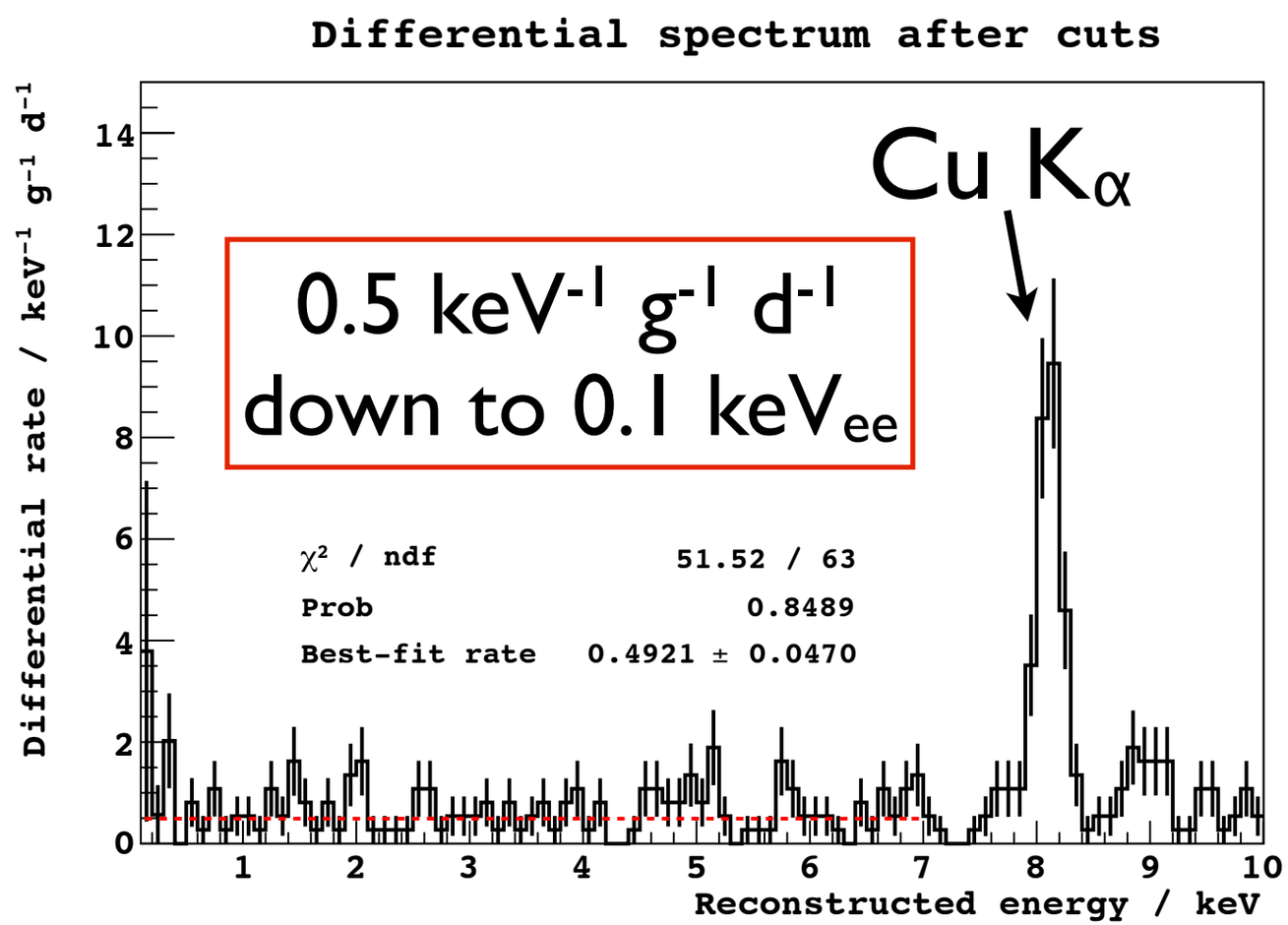
2 frame CCDs (2g)

40 days 0.3 keV threshold

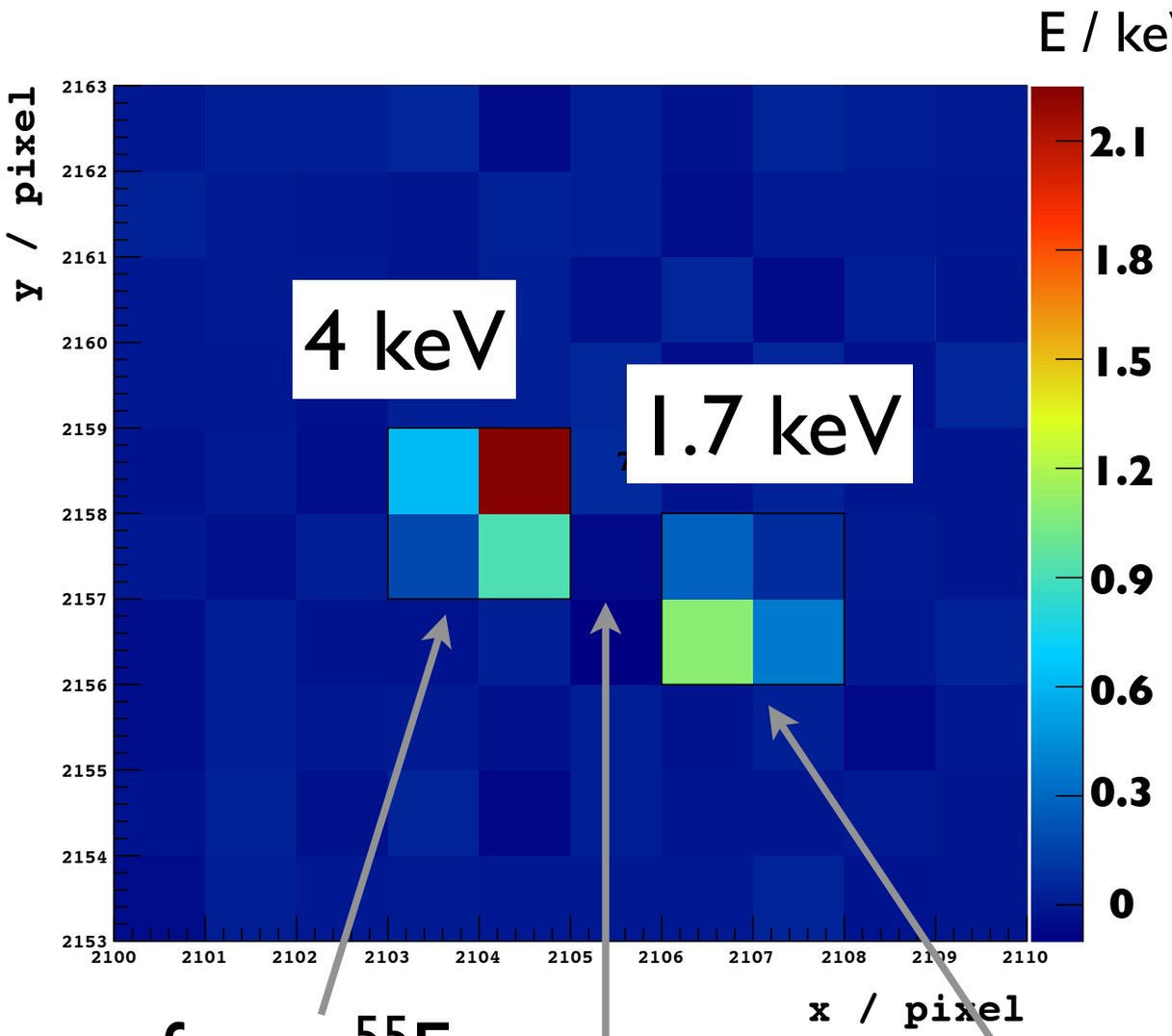
12 days 0.1 keV threshold

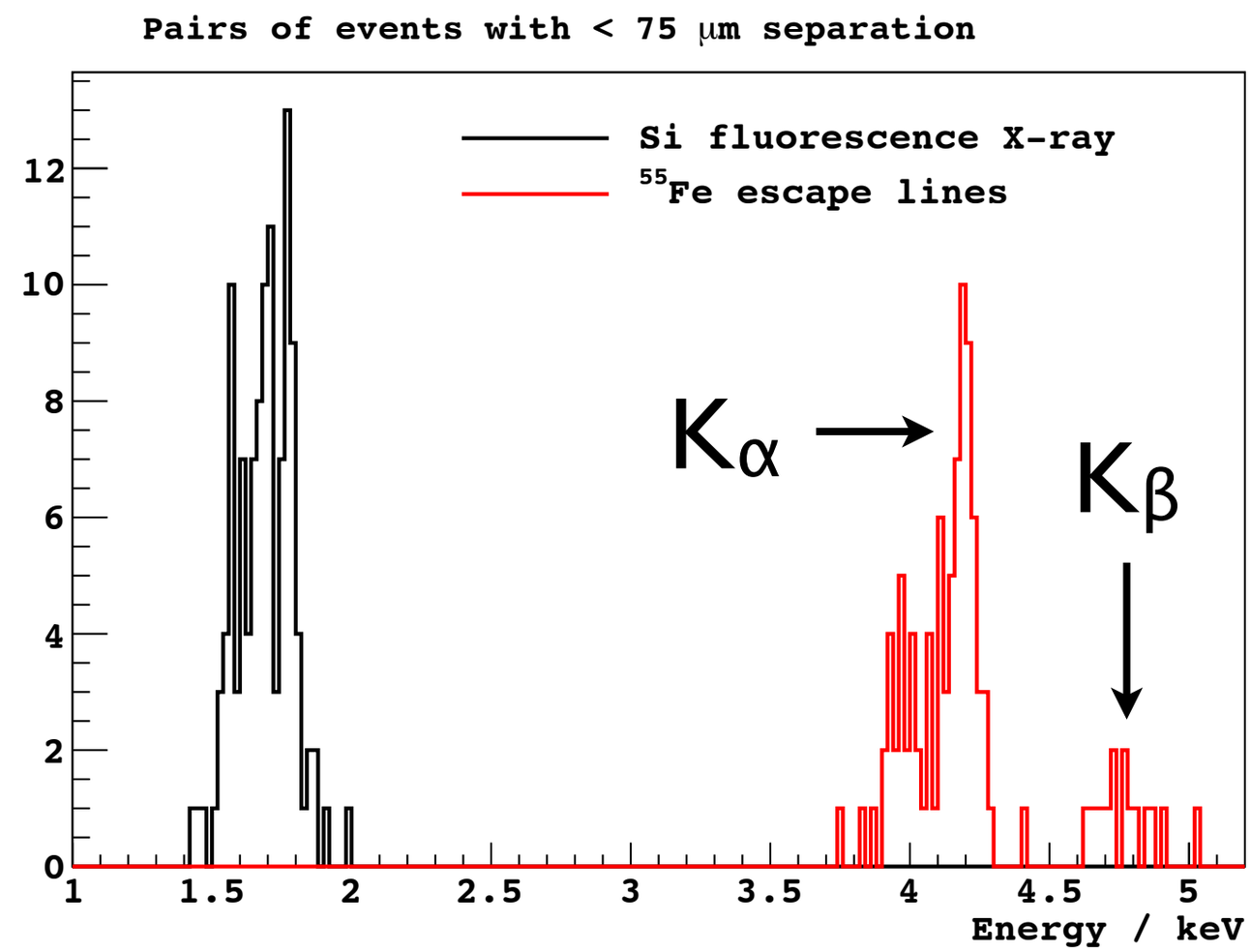
Fiducial cut (~35% acceptance)





Spatial correlation in ^{55}Fe





pe from ^{55}Fe X-ray absorption

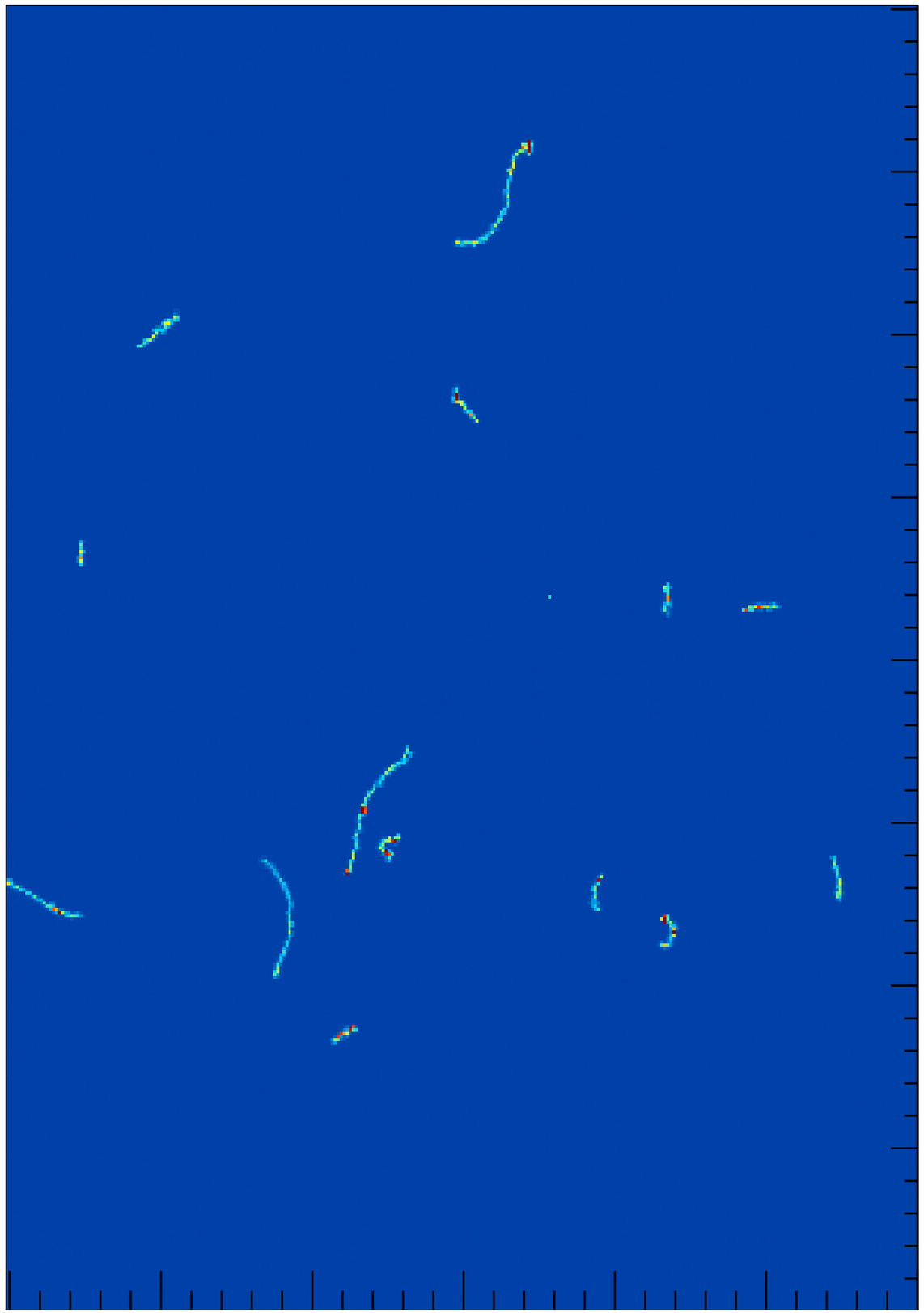
fluorescence X-ray travels tens of μm

pe from Si fluorescence X-ray absorption

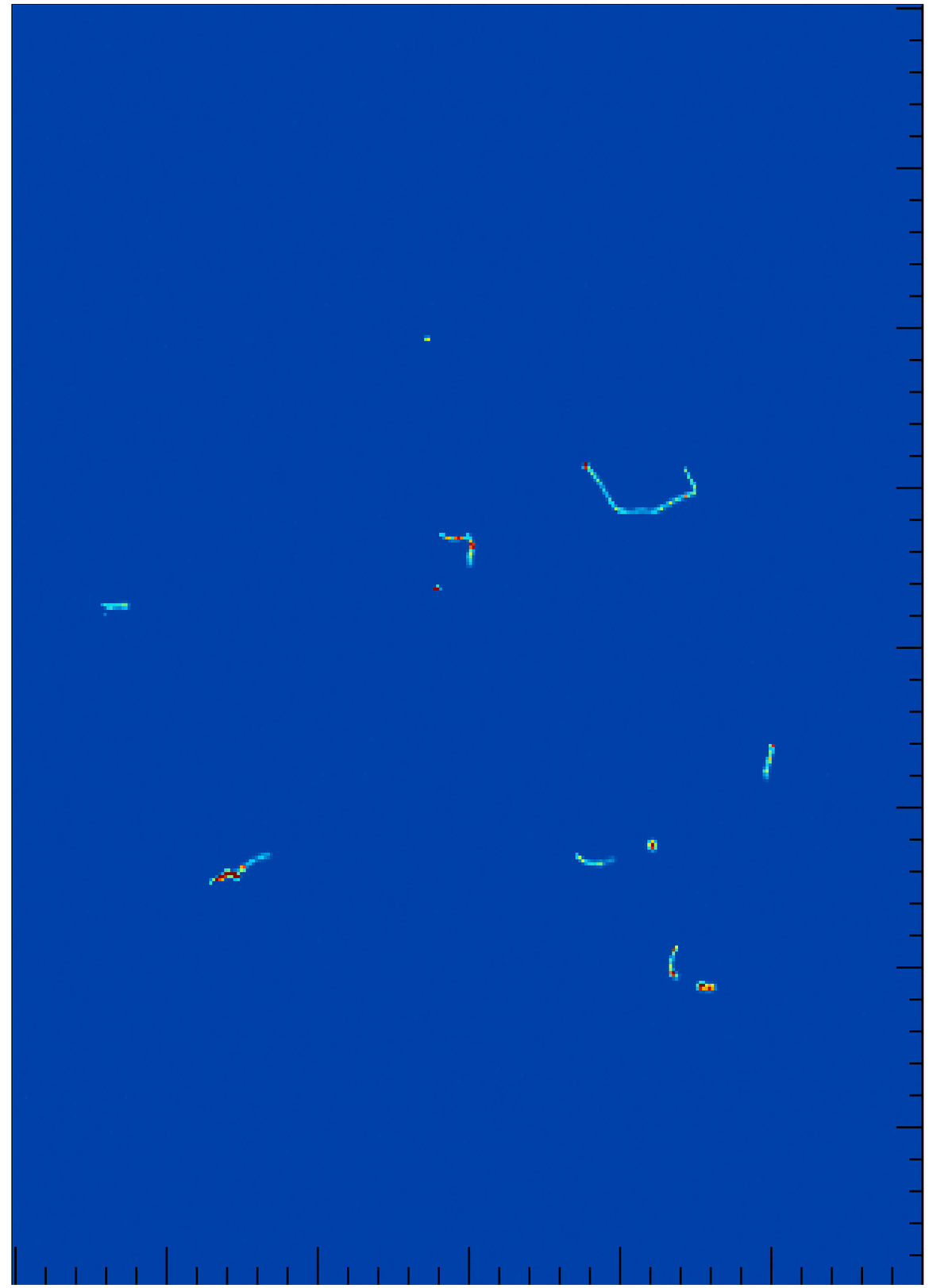
Spatial correlation between fluorescence X-rays and ^{55}Fe lines

MCNPX Simulation

- We have started a DAMIC simulation based on MCNPX.
- Given a particle source, we get energy deposits in a mesh the size of the CCD image.
- We also store the mean *x*, *y* and *z* positions of the deposits in the cell.
- We use this information with some noise + diffusion models to construct fake image.

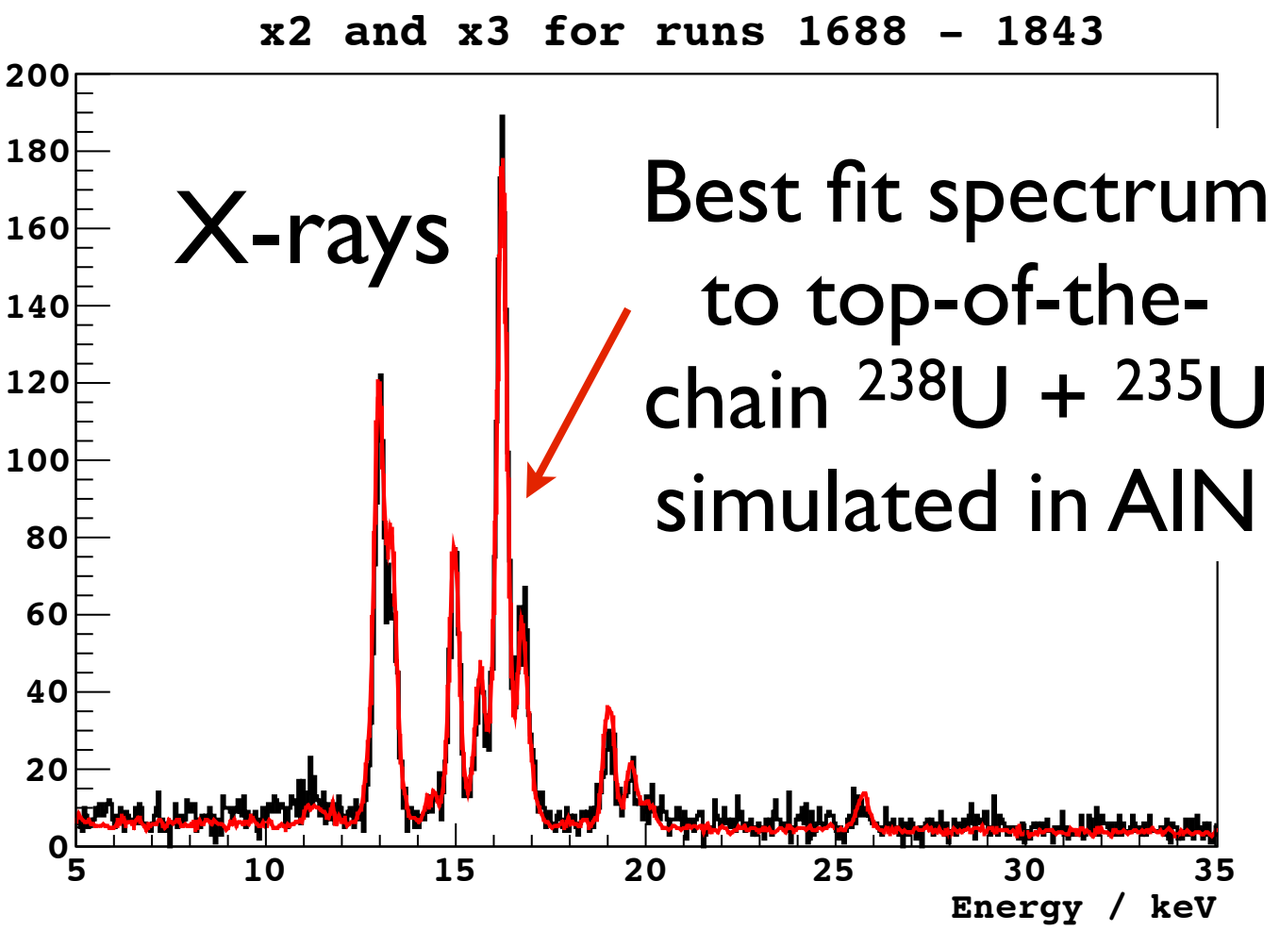


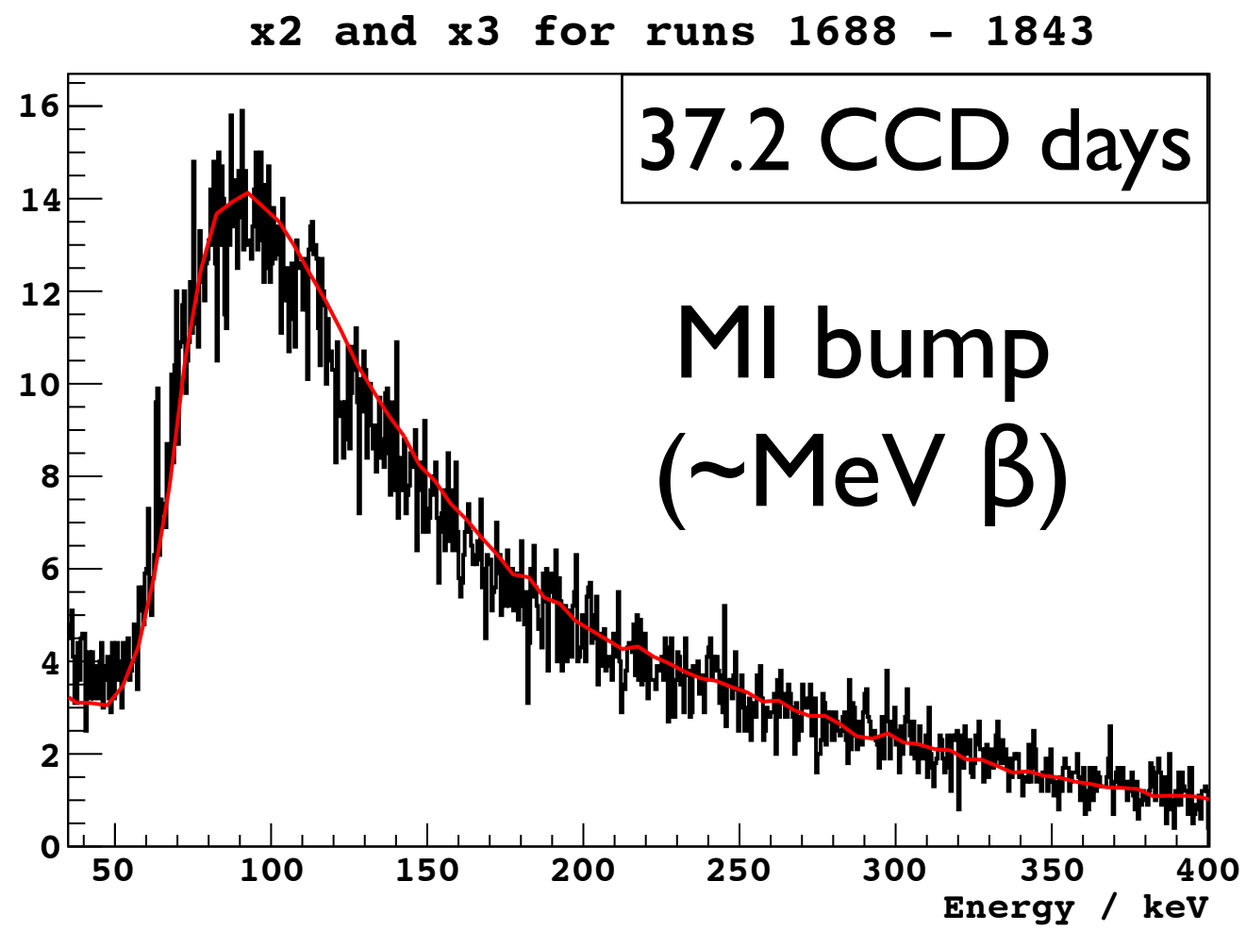
Simulated βs



Data

DAMIC full AIN spectrum





	mBq / kg
^{235}U	330 ± 30
^{238}U	4110 ± 530
^{226}Ra	42 ± 9
^{232}Th	32 ± 8

SNOLAB γ-ray measurement of AlN

} ppb levels

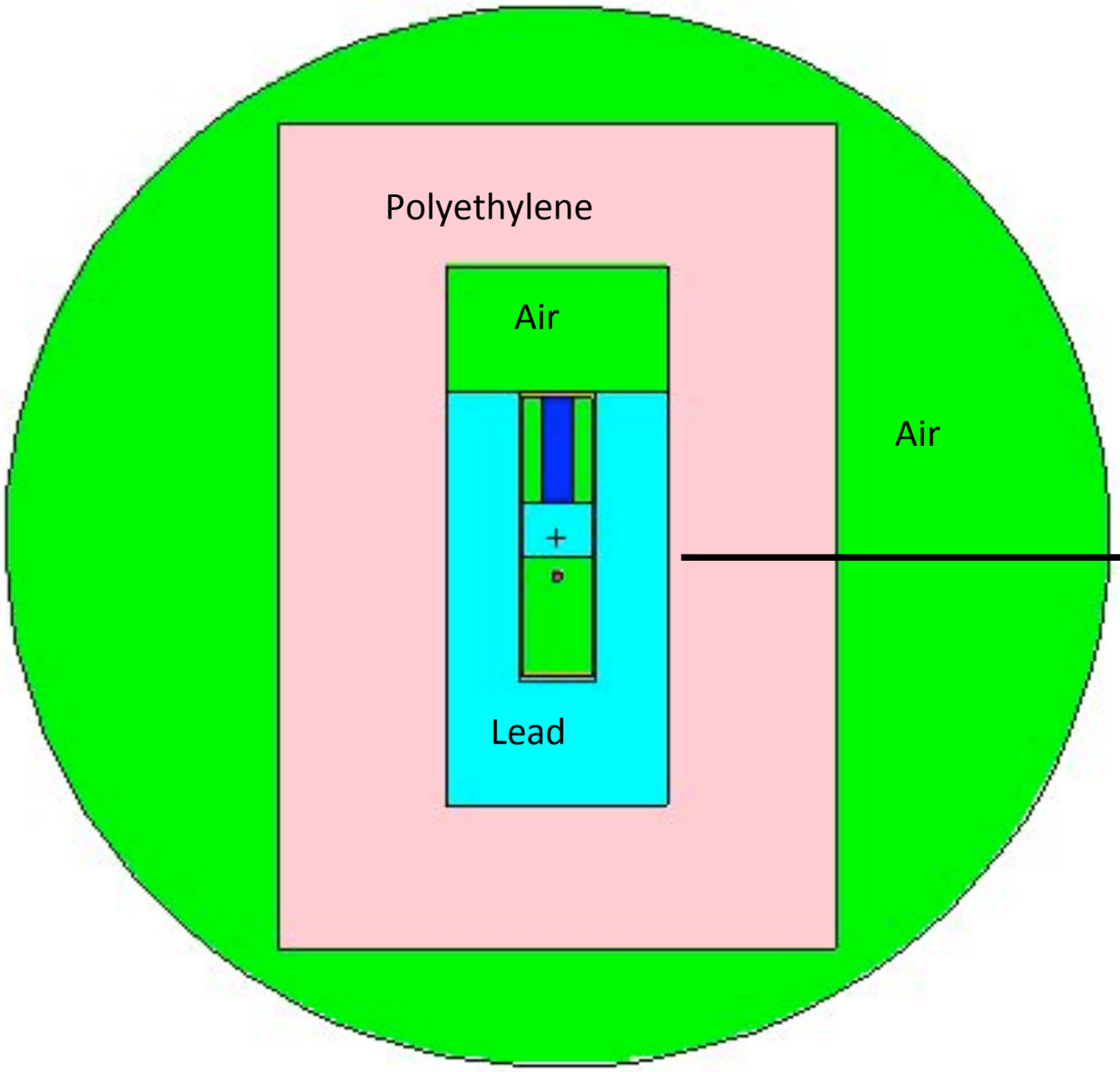
U is very dim in γ but very bright in X-rays.

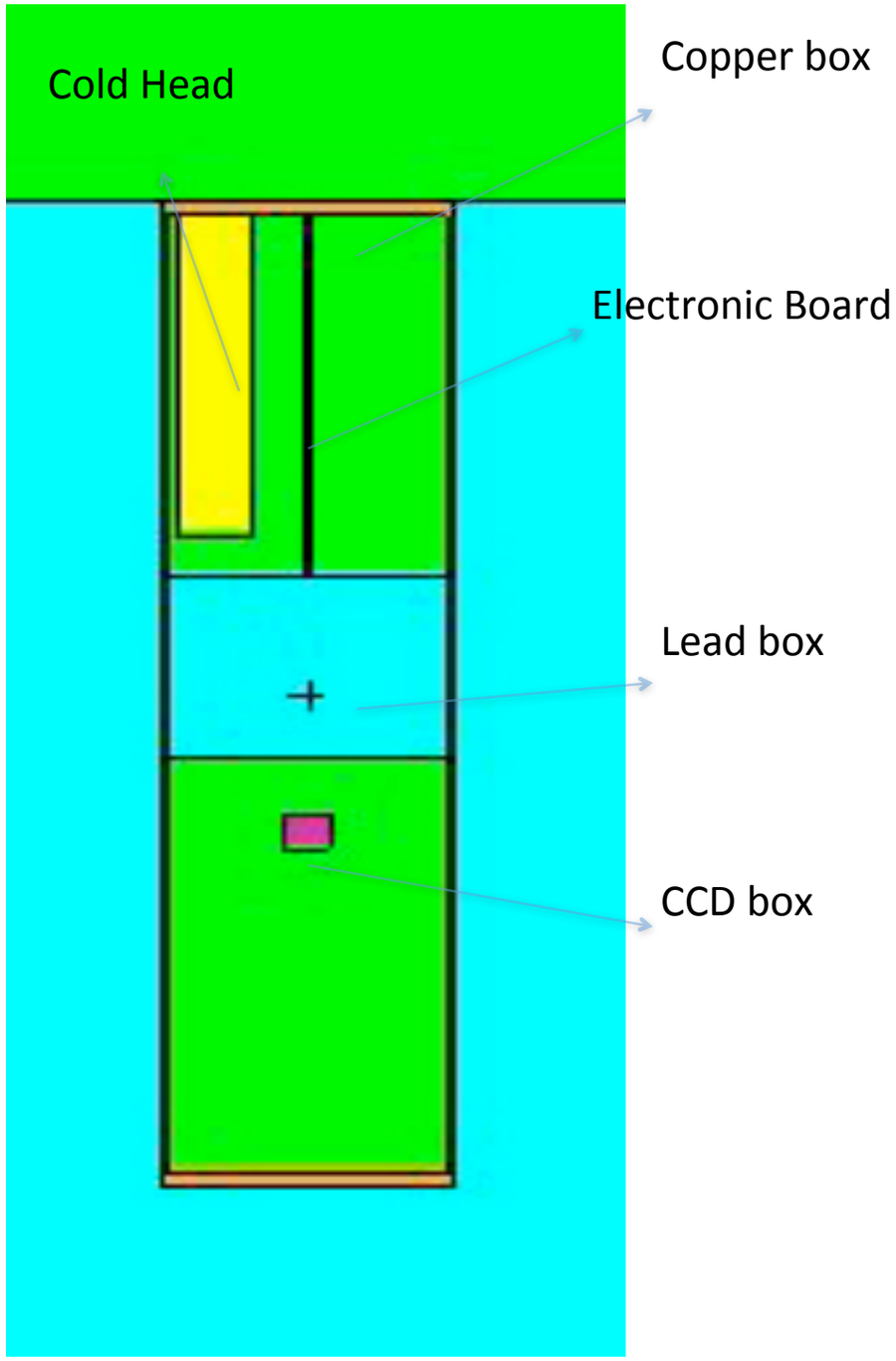
n backgrounds

Source	Collisions in 5 g x 1000 days	Ref
μ in Shield	<0.1	BX ZEPLIN
Norite rock	<0.001	COUPP
(α,n) in shield	<0.1	ZEPLIN

COUPP-4 was "dirty" (4 kg of borosilicate glass with ppm of U, piezoelectric transducers next to active volume) and it saw ~0.25 bubbles $kg^{-1}d^{-1}$.
Even that level not a problem for us.

Geometry


Polyethylene
Air
Air
Lead


Cold Head
Copper box
Electronic Board
Lead box
CCD box

Contamination

Cell	Material	Mass	^{238}U	^{232}Th	^{40}K	^{210}Pb	^{60}Co	Ref
Electronic Card	Teflon/PCB	105 g	100 mBq	3 mBq	35 mBq	-	-	GERDA PZ0
Cold head	Iron/Steel	4.5 kg	1 ppb	5 ppb	0.3 ppm	-	25 mBq / kg	ILIAS BX
Pb block above	Pb	50.7 kg	10 ppt	10 ppt	5 ppb	20 Bq/kg	-	EXO DoeRun
Copper vessel	Cu	29.5 kg	10 ppt	10 ppt	5 ppb	-	0.6 mBq / kg	EXO, DS ZEPLIN
Pb shield	Pb	4.94 ton	10 ppt	10 ppt	5 ppb	20 Bq/kg	-	EXO DoeRun
Poly shield	$(C_2H_4)_n$	4.57 ton	5 ppb	5 ppb	5 ppm	-	-	ILIAS

Black - upper limits Blue - characteristic values

Number of collisions from γs in a 5 g of Si in 1000 days

Cell	Material	Mass	^{238}U	^{232}Th	^{40}K	^{210}Pb	^{60}Co	Ref
Electronic Card	Teflon/PCB	105 g	<0.26	0.005	<0.09	-	-	GERDA PZ0
Cold head	Iron/Steel	4.5 kg	<0.14	0.078	0.11	-	<0.29	ILIAS BX
Pb block above	Pb	50.7 kg	20.3	4.44	2.65	21.2	-	EXO DoeRun
Copper vessel	Cu	29.5 kg	64.8	14.7	8.34	-	291	EXO, DS ZEPLIN
Pb shield	Pb	4.94 ton	120.6	26.16	15.84	129.8	-	EXO DoeRun
Poly shield	$(C_2H_4)_n$	4.57 ton	0.74	0.95	<0.6	-	-	ILIAS
Rock	Norite	a lot	3.6					COUPP

Shielding good enough so that the main background contribution is from the shielding itself.

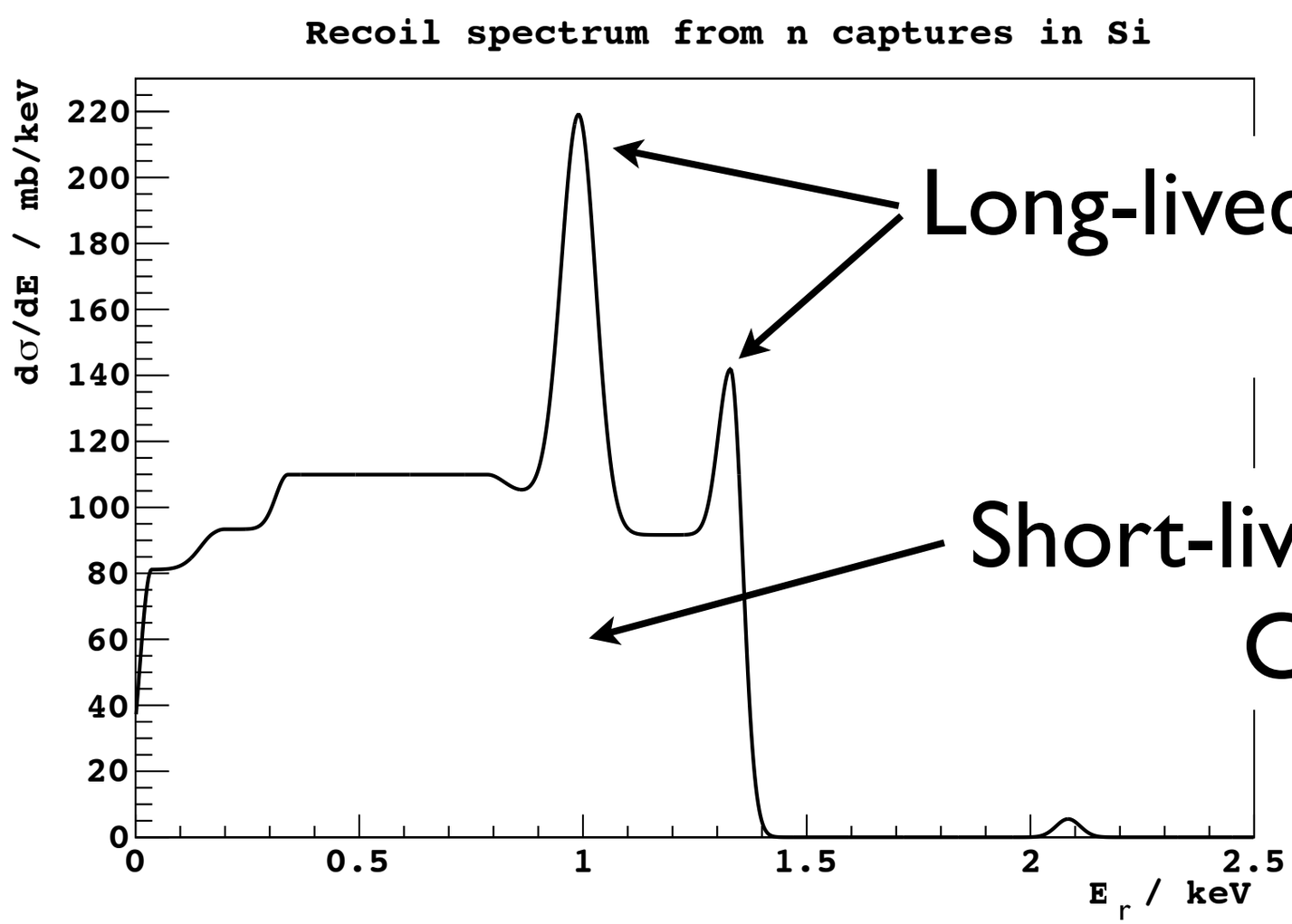
Thermal neutron capture

$^{28}Si + n \longrightarrow {}^{29}Si + \gamma$

Cascade in coincidence

~MeV

Nucleus recoils ~keV



Long-lived nuclear states
Peaks

Short-lived nuclear states
Continuum

CCD activation at a proton beam

Isotope	Half-life / days	Si(p,x) / mb	Activation / $\mathrm{Bq\,g^{-1}\,(10^{10}\ p\ cm^{-2})^{-1}}$	EC prob.	E_γ / keV	E_K / eV	σ_K / eV	E_R / eV	δ_E / eV
^{7}Be	53.12	3.2	0.103	1.000	477.6	55	7	$57+0$	10
^{22}Na	950.3	15.8	0.029	0.097	1275	870	28	$60+40$	14

Long lived EC isotopes

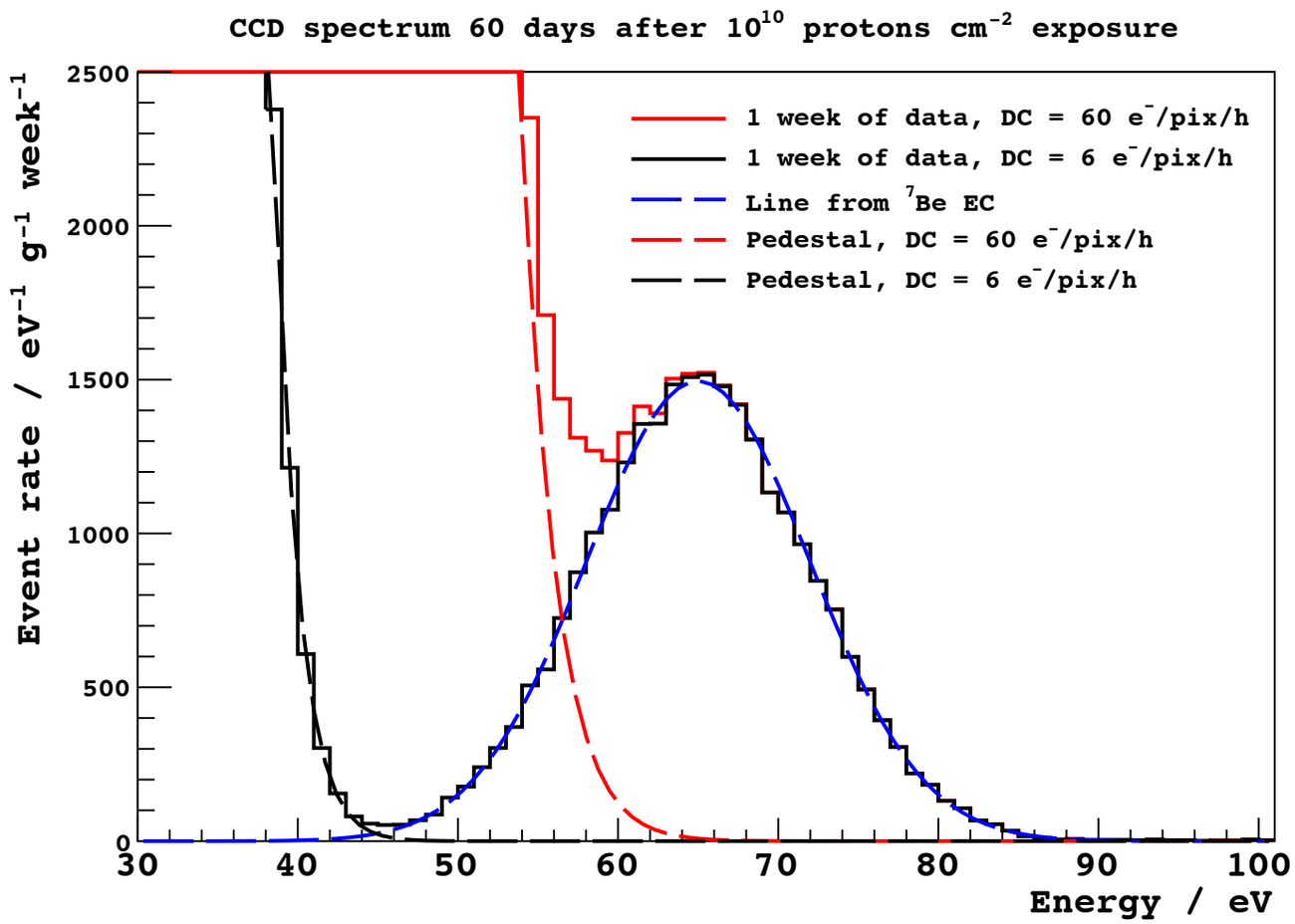
Activation of a fraction of a Bq (^{7}Be and ^{22}Na)

γ-ray may be used to precisely measure activation

K-shell line near threshold

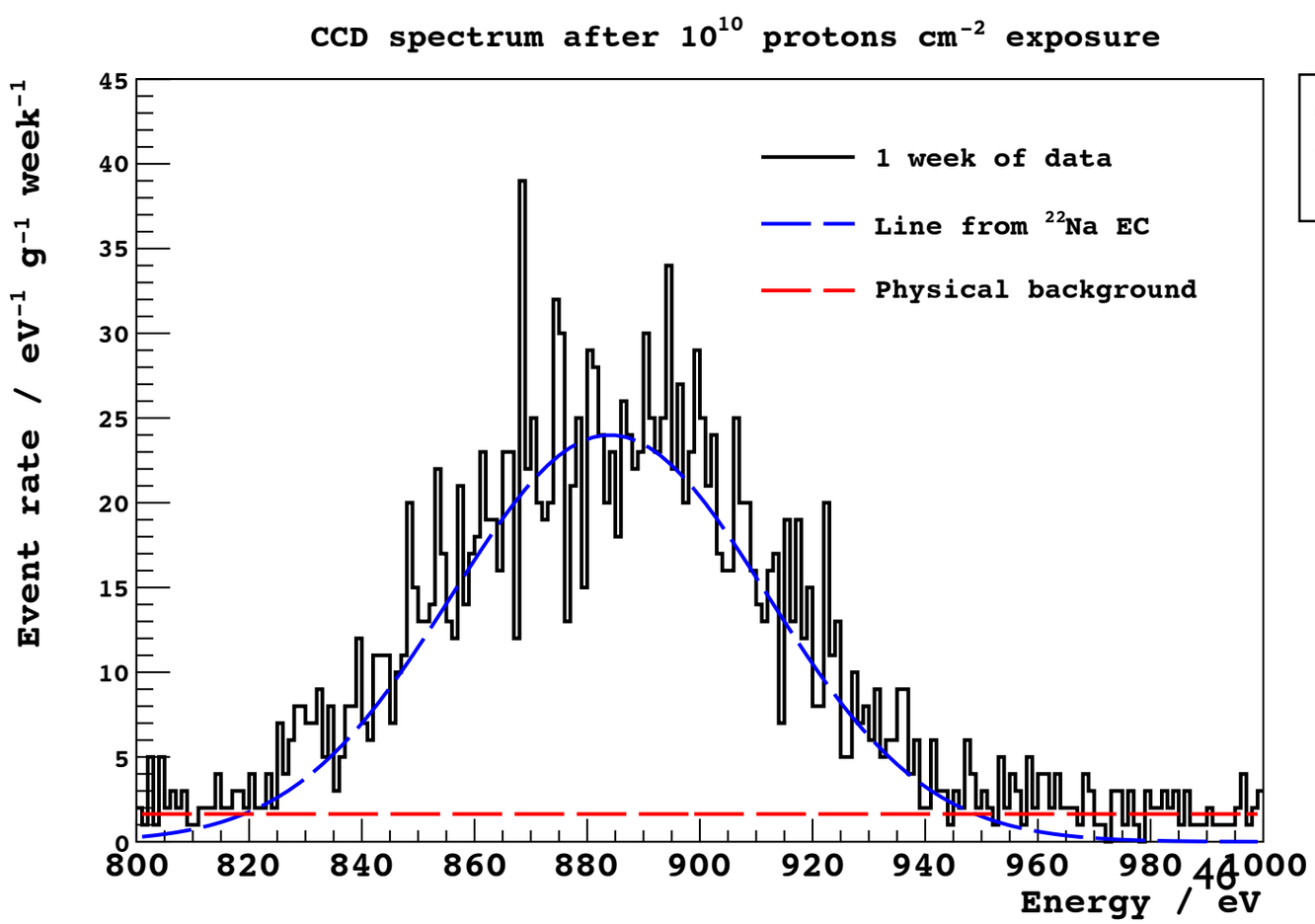
Shift in line due to A recoil

For 230 MeV *p* beam



^{7}Be EC

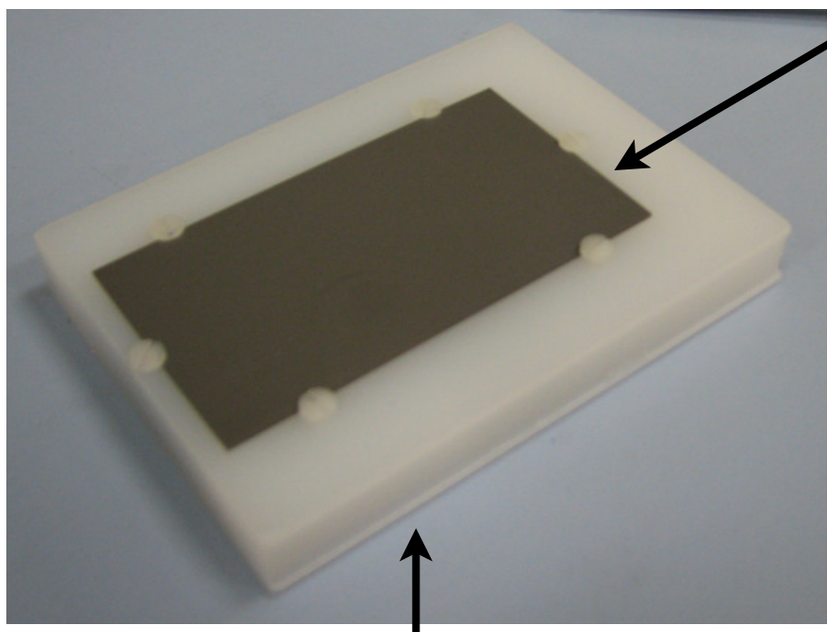
Threshold need to be as low as good CCD



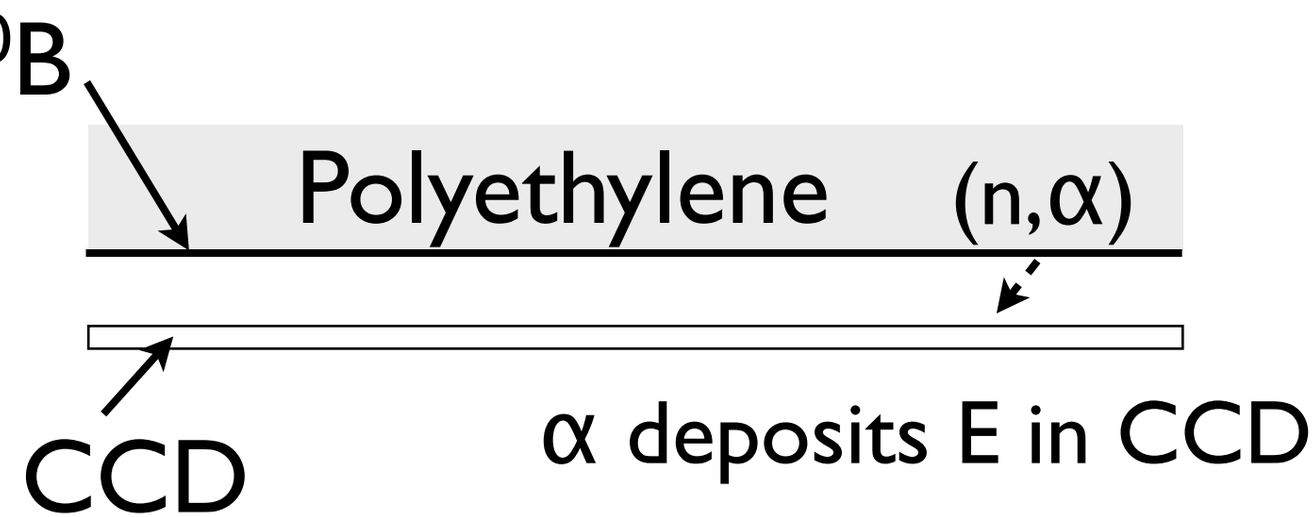
^{22}Na EC

"Easy"
Physical background from DAMIC surface run

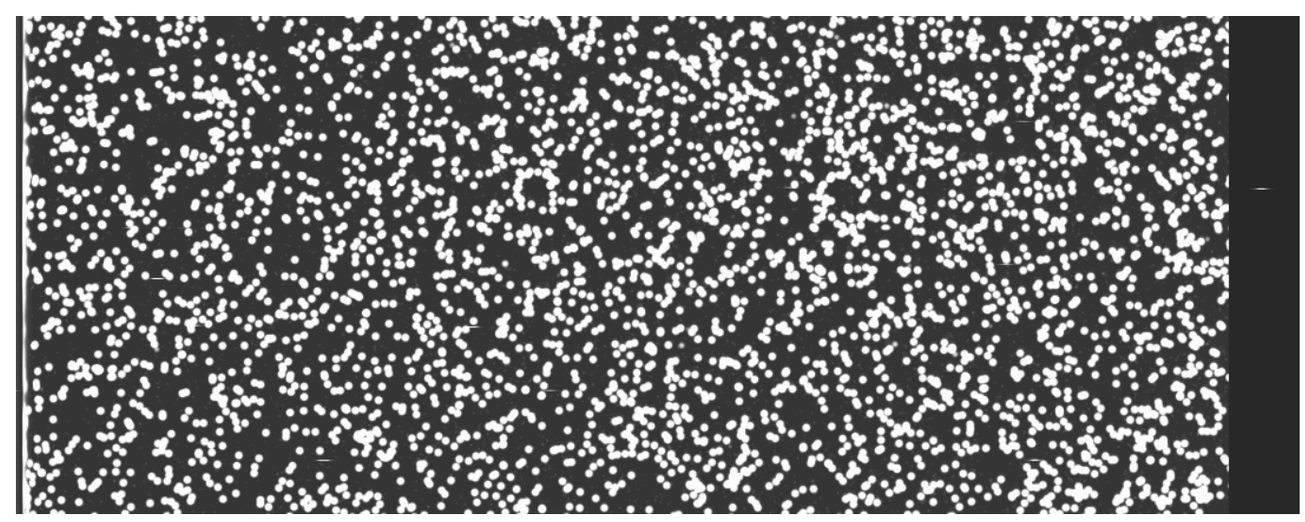
In-situ neutron background estimate



Slides into Cu box at SNOLAB



αs from ^{241}Am source

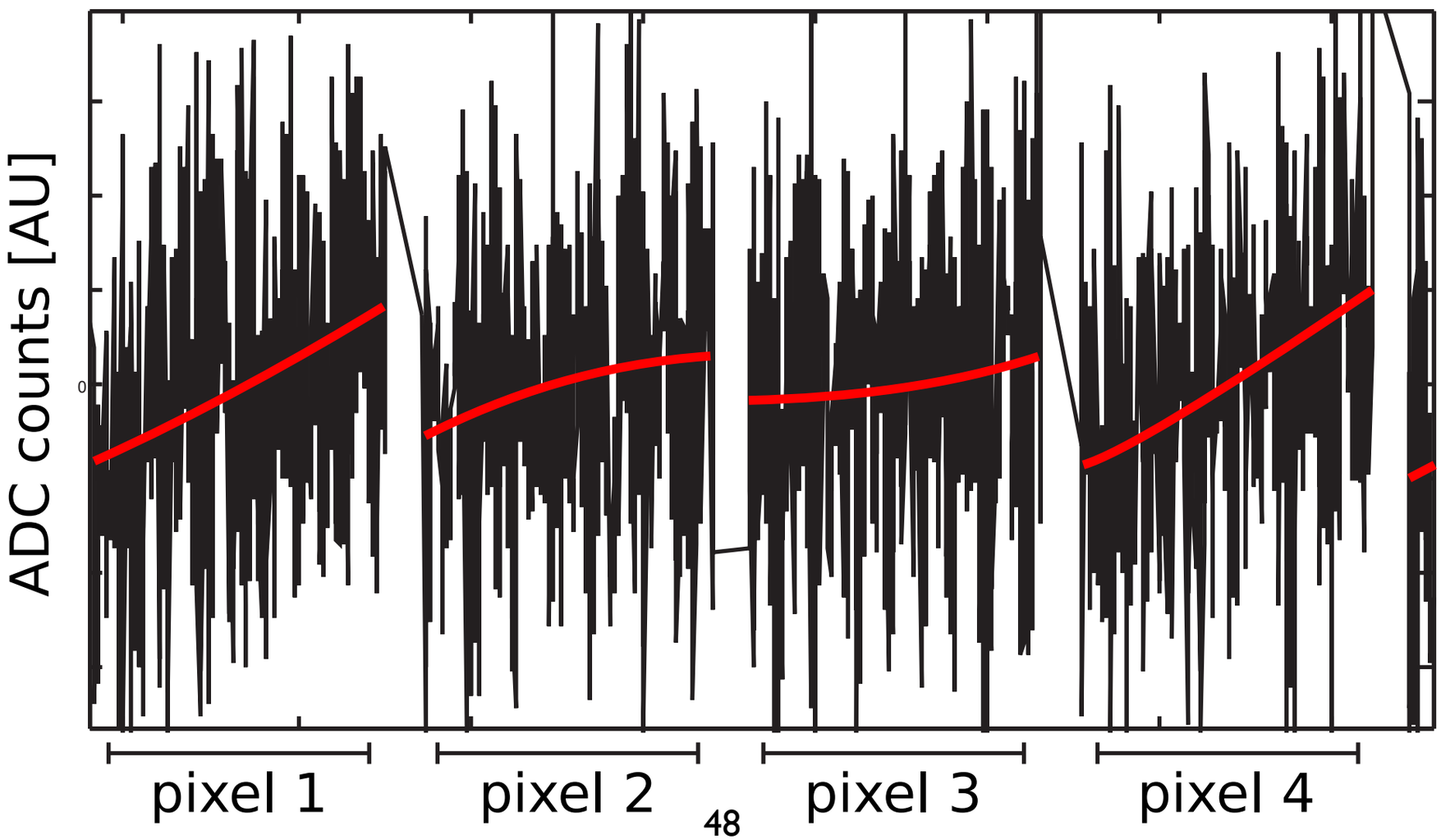


Test performed at FNAL this summer

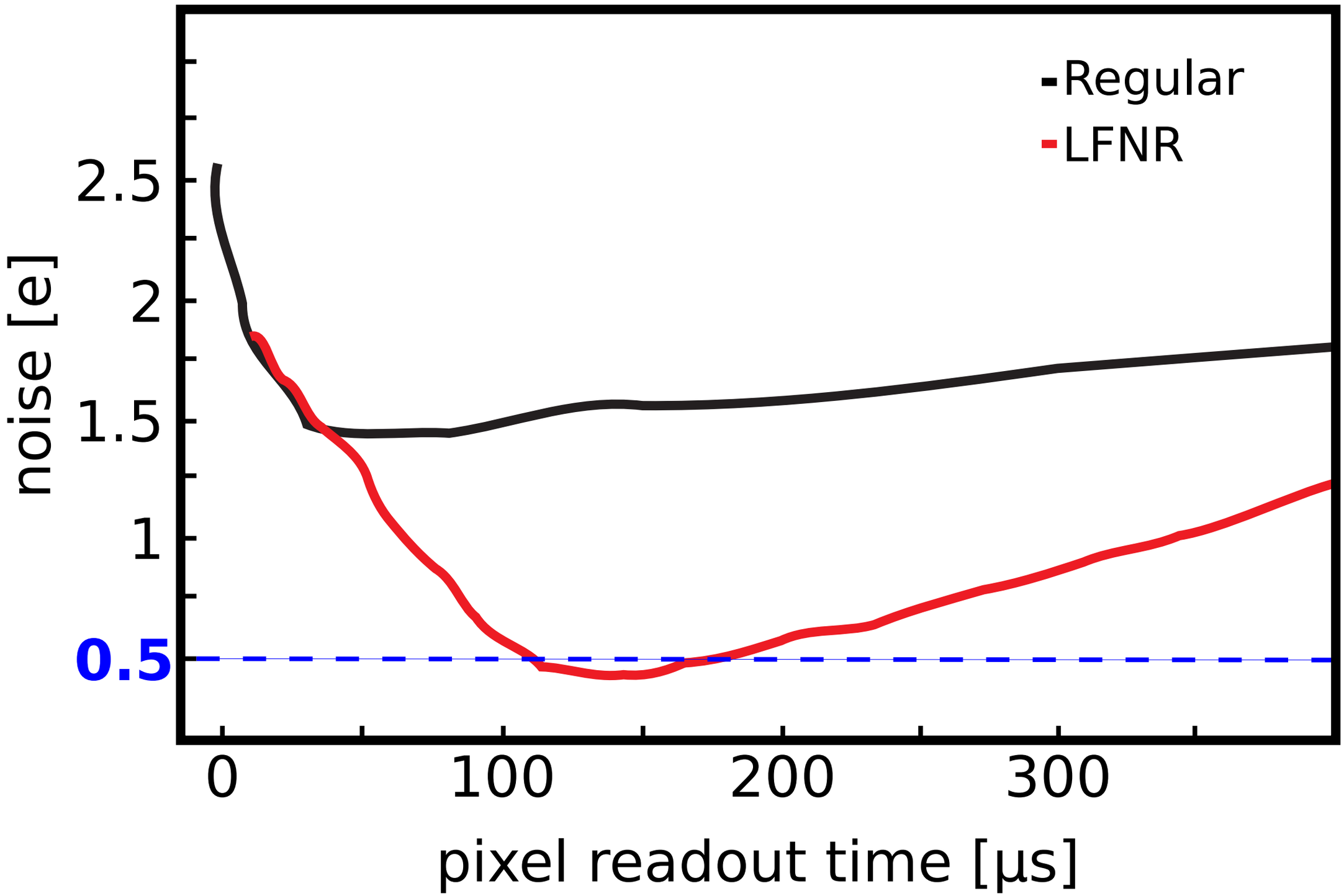
Nucl.Instrum.Meth. A665 (2011) 90-93

Lowering the noise: Low Frequency Noise Reduction

- There is some low frequency tendency that has a significant effect in the pixel error.
- This slow variation are estimated for each pixel using Least Square Fitting.



Lowering the noise: Low Frequency Noise Reduction



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
  $\textbf{Pixel value} = \frac{1}{N}\Sigma_i^N\,(\textbf{pixel sample})_i$