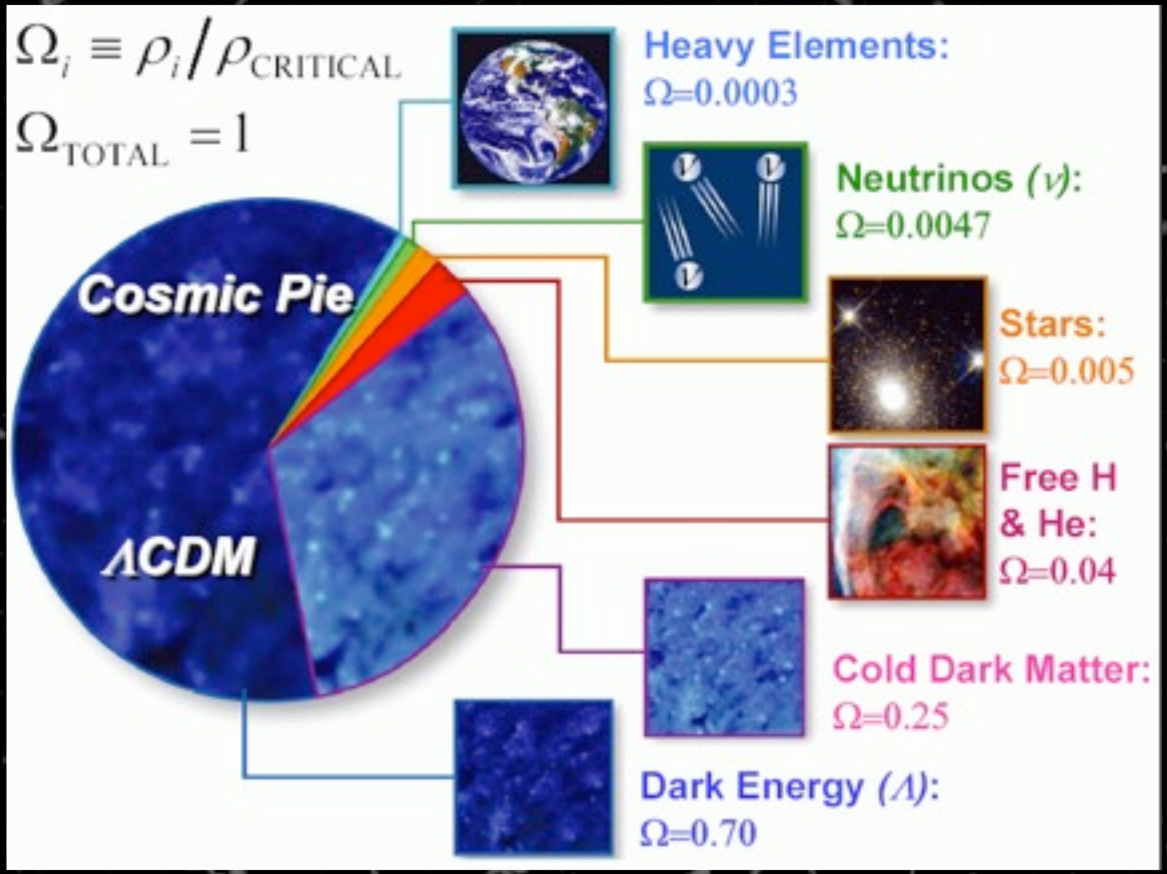
Center for Particle Astrophysics
Fermilab

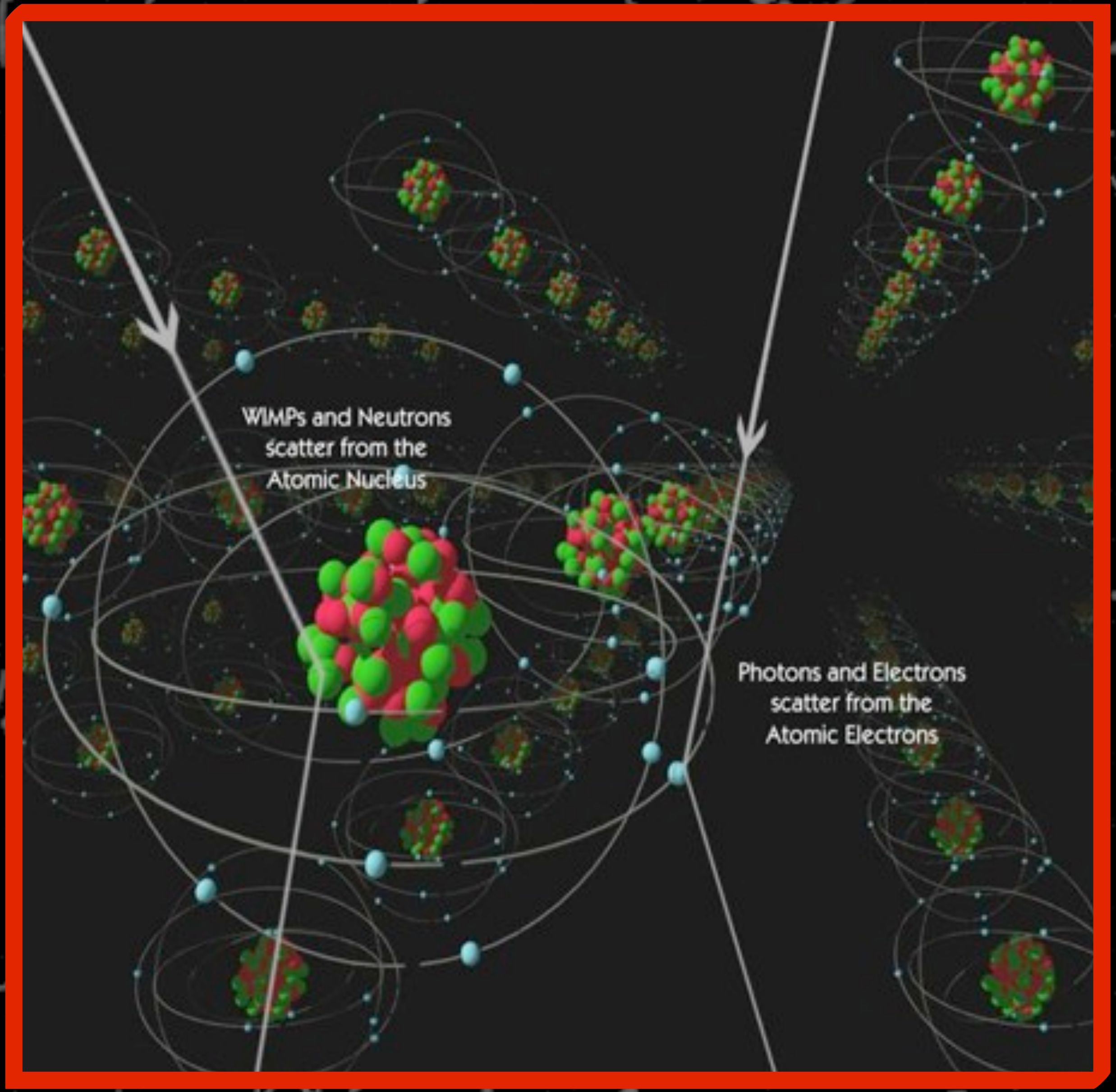
Direct search for low mass dark matter particles with CCDs

Juan Estrada - Fermilab
10/13/2009

Direct Detection Experiments

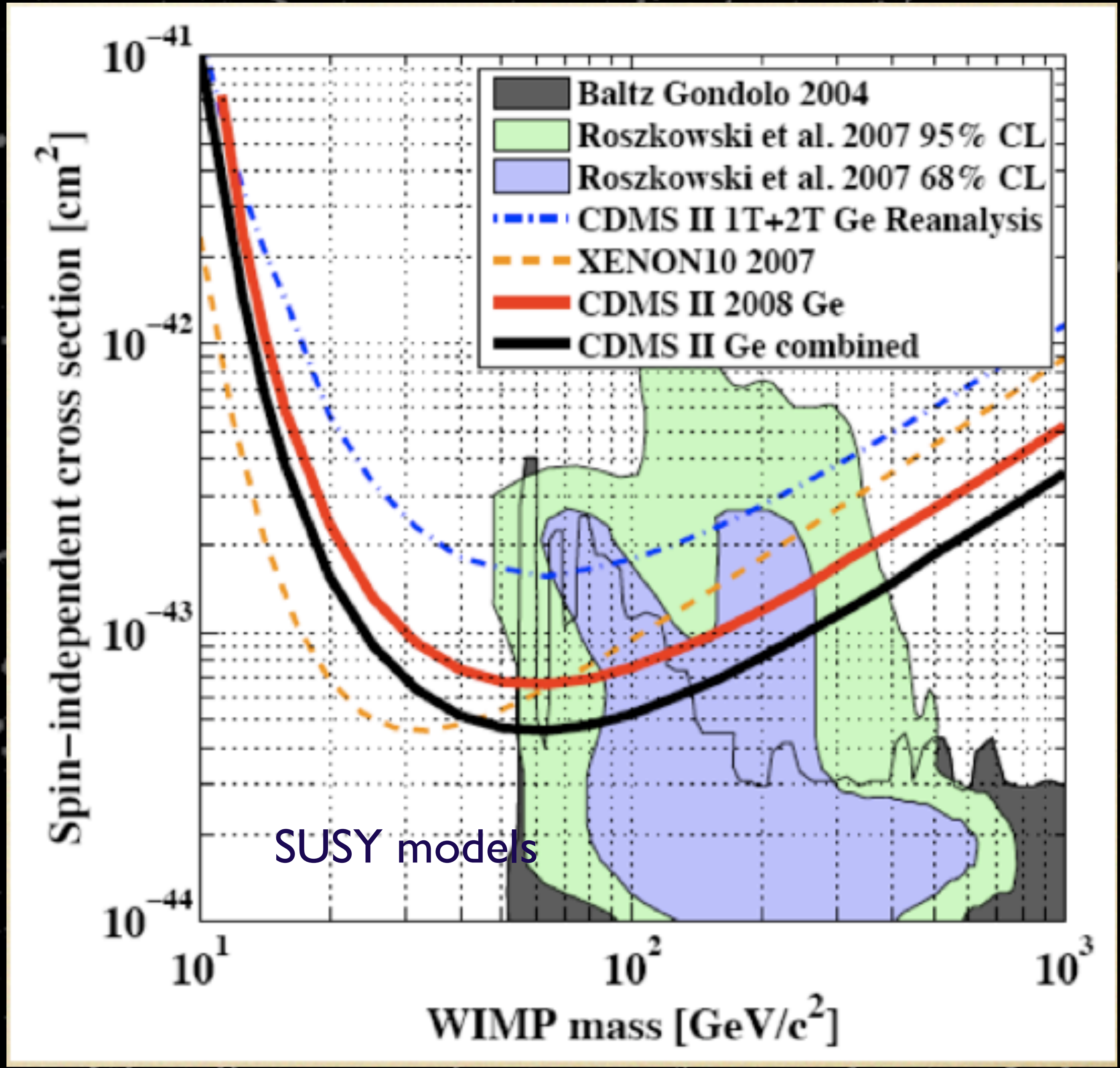
Goal: Detect the collisions of DM particles with detectors as the earth moves in the galaxy. DM particles are neutral (in most models) and would interact with the nuclei of your detector.



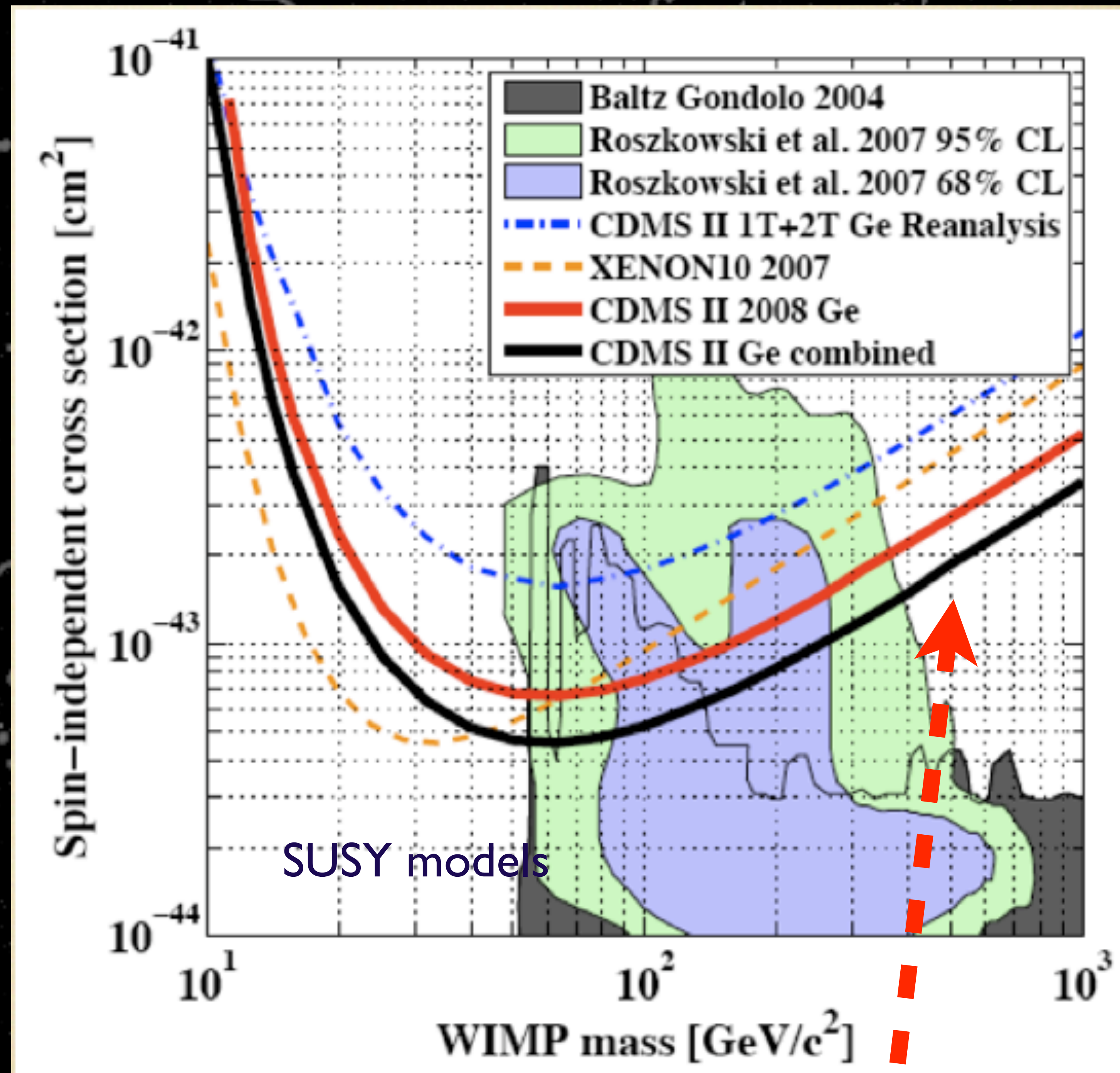


Typically people try to build detectors that will see a nuclear recoil and distinguish it from an interaction with the atomic electrons.

“Current” Results



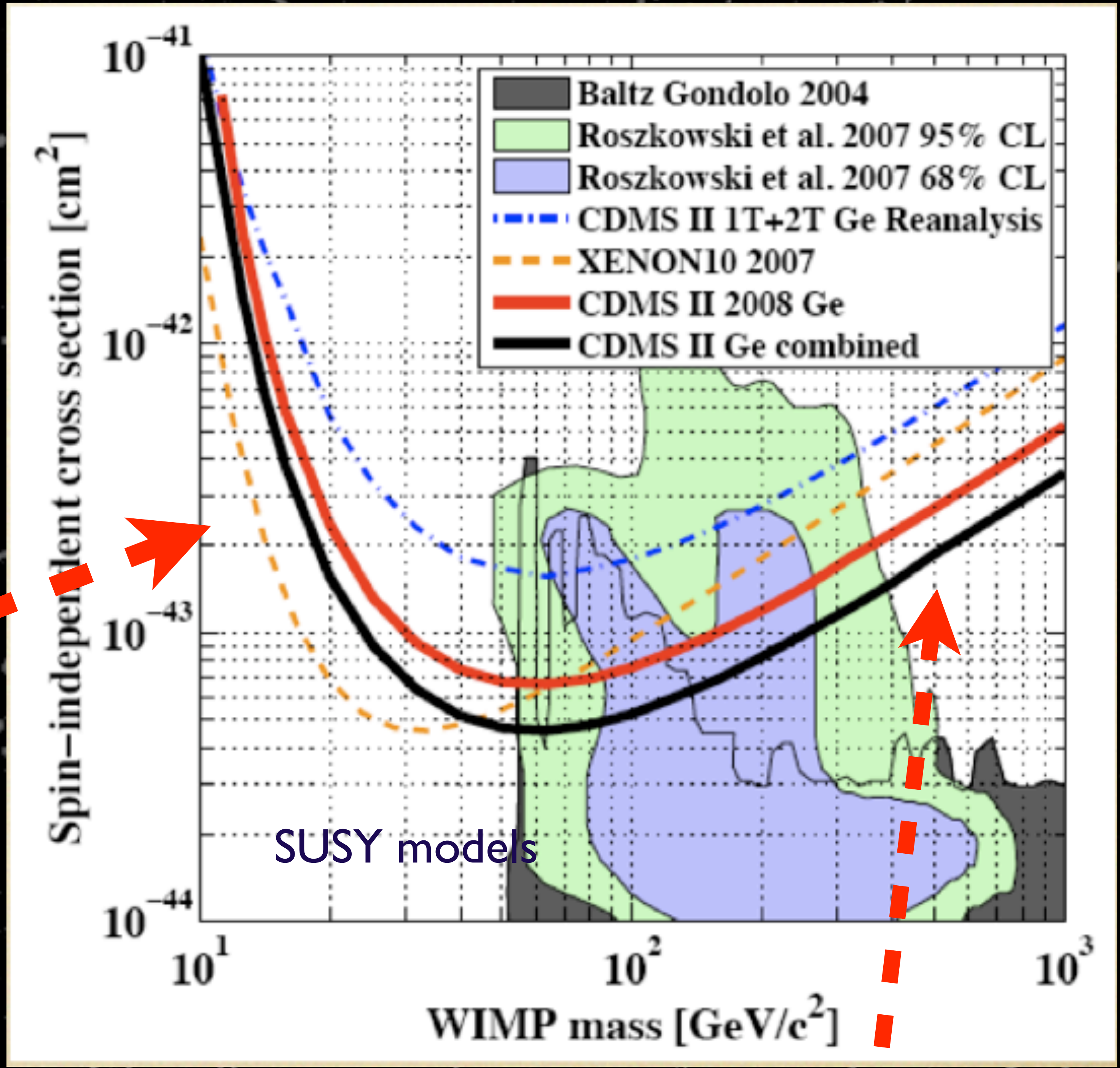
“Current” Results



limited by exposure mass
(need bigger detector)

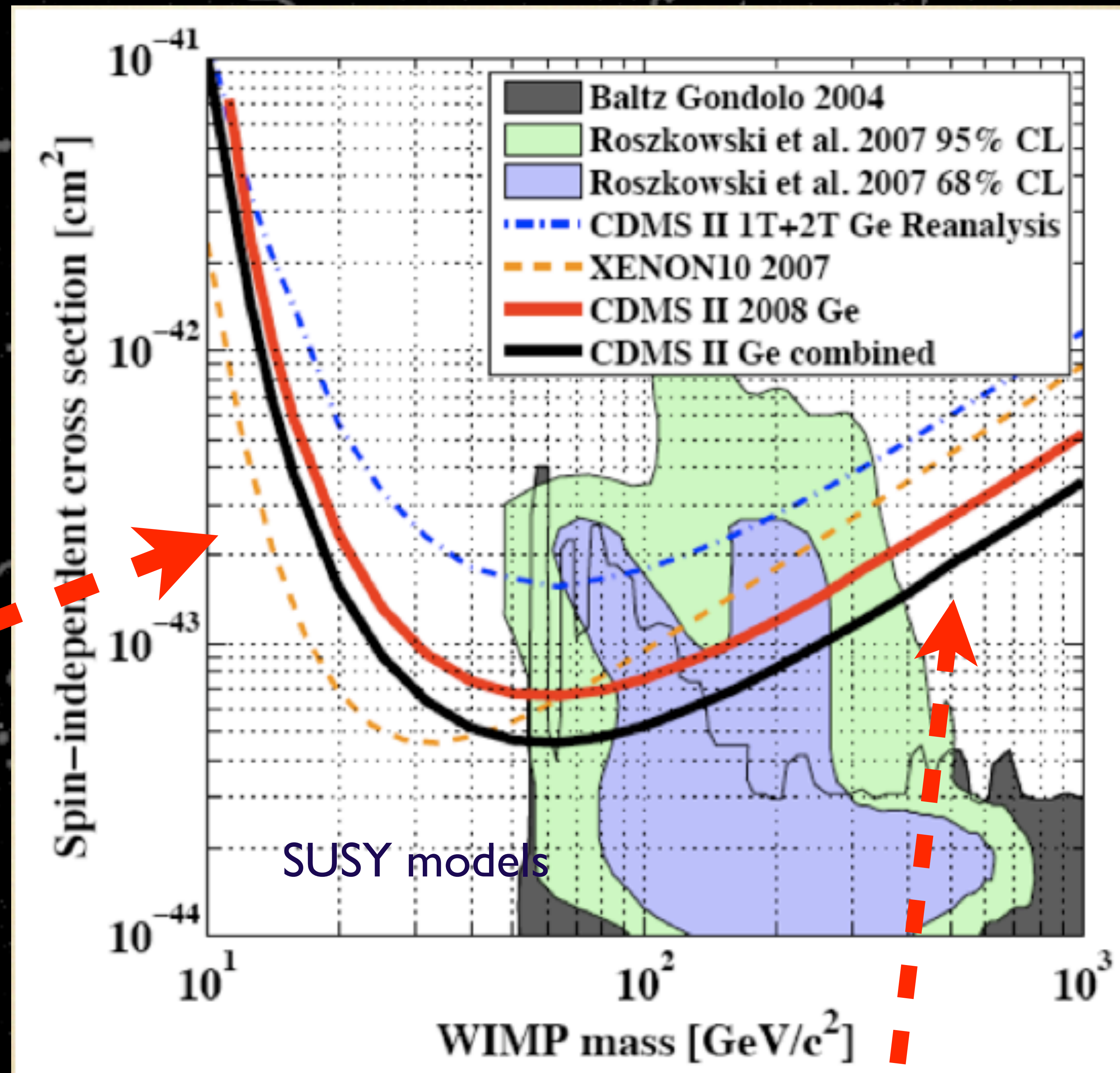
"Current" Results

Limited by detection threshold. Most experiments can not lower threshold because of the electronic readout noise in their detectors. Room for CCDs!



limited by exposure mass (need bigger detector)

“Current” Results



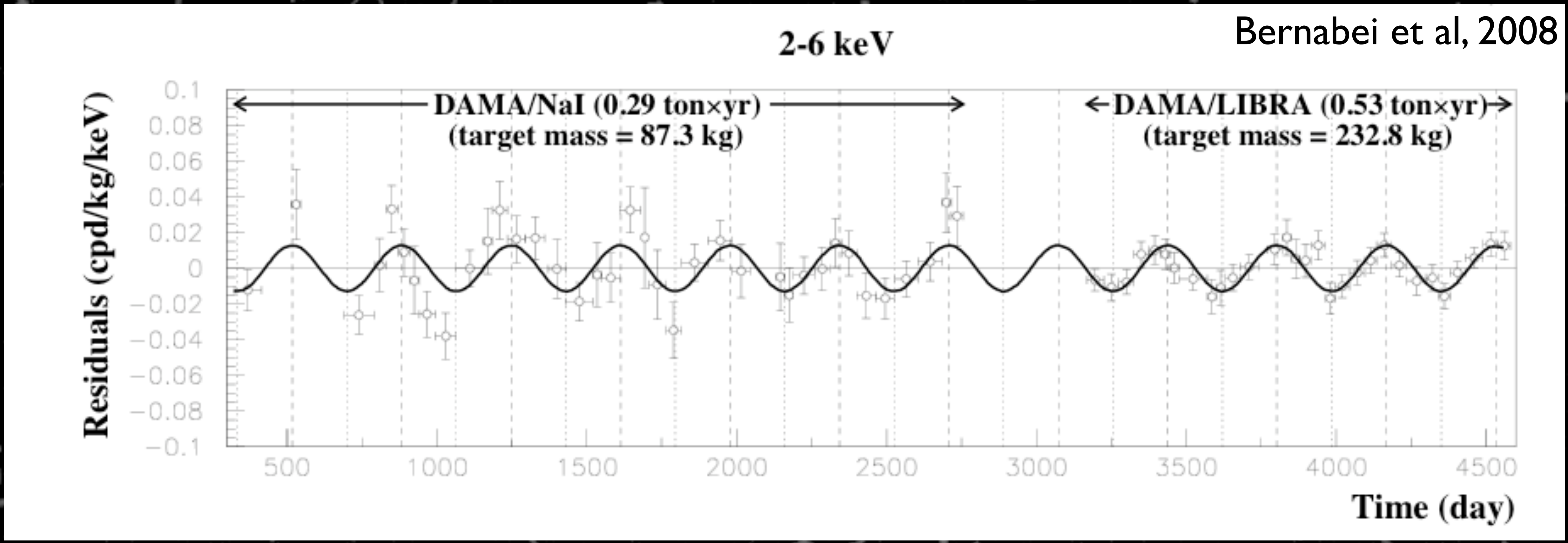
Limited by detection threshold. Most experiments can not lower threshold because of the electronic readout noise in their detectors. <u>Room for CCDs!</u>

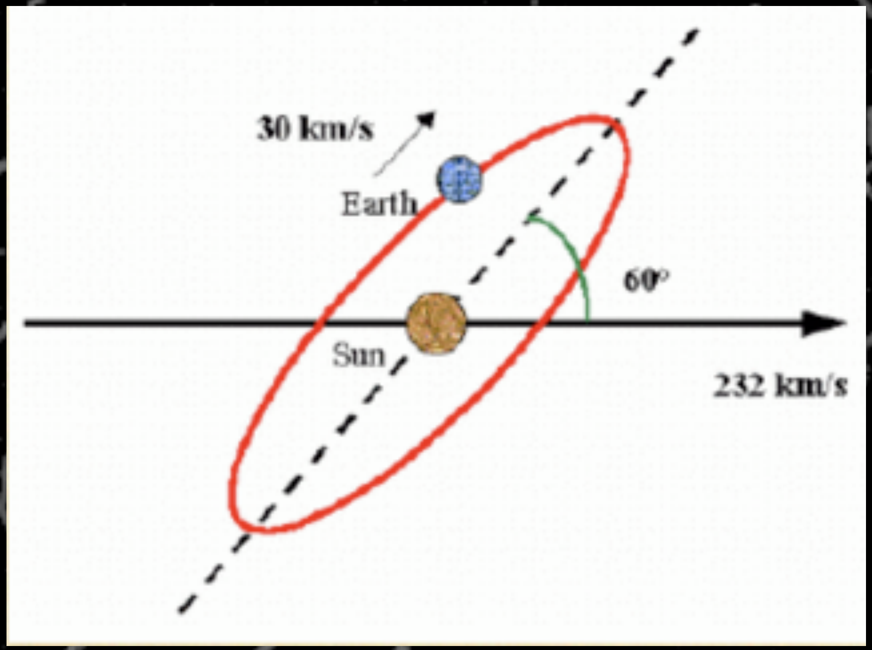
limited by exposure mass (need bigger detector)

from Petriello & Zurek 0806.3989

Experiment	Target	Exposure (kg-d)	Threshold	Ref
CDMS-SUF	Ge	65.8	5 keV	[2]
	Si	6.58	5 keV	
CDMS-II	Ge	121.3	10 keV	[3]
	Si	12.1	7 keV	[4]
XENON10	Xe	131	4.5 keV	[5]
CRESST-I	Al_2O_3	1.51	0.6 keV	[16]

One good reason to look for low mass dark matter : The DAMA/LIBRA result

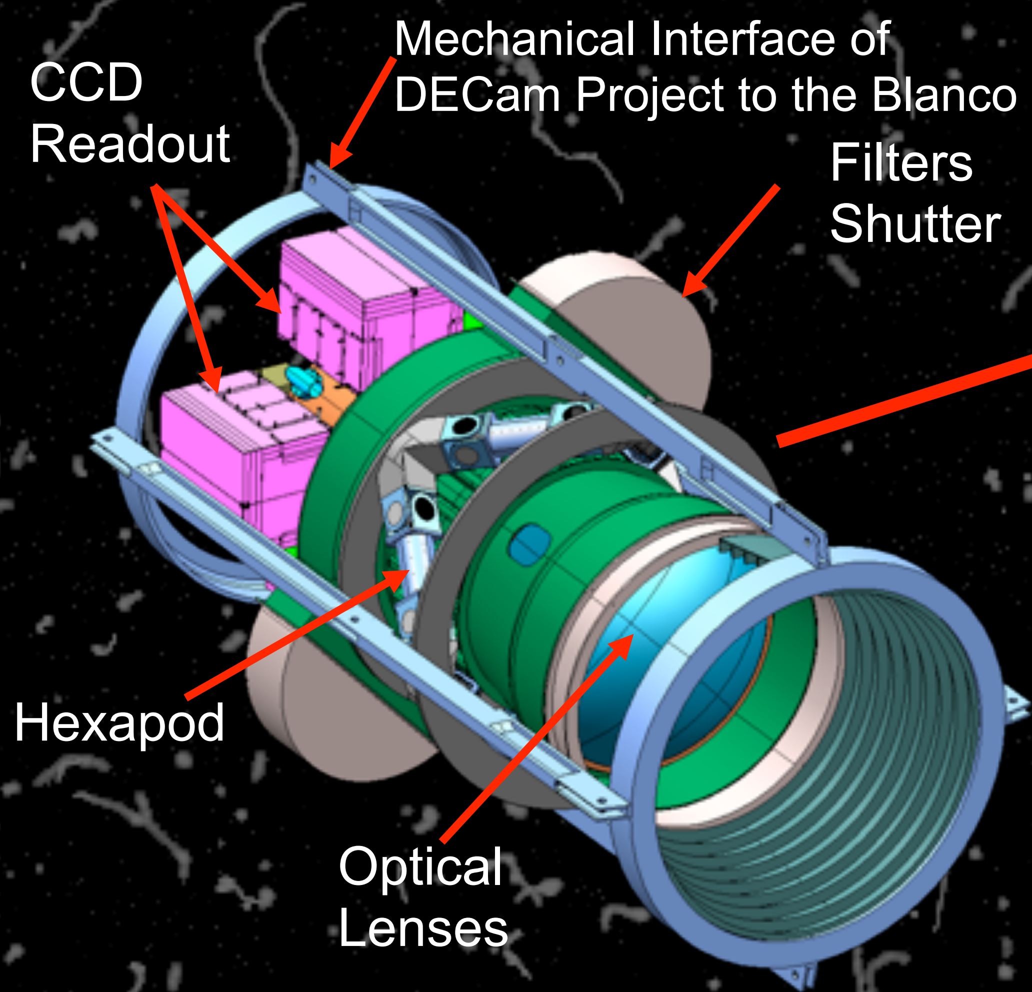


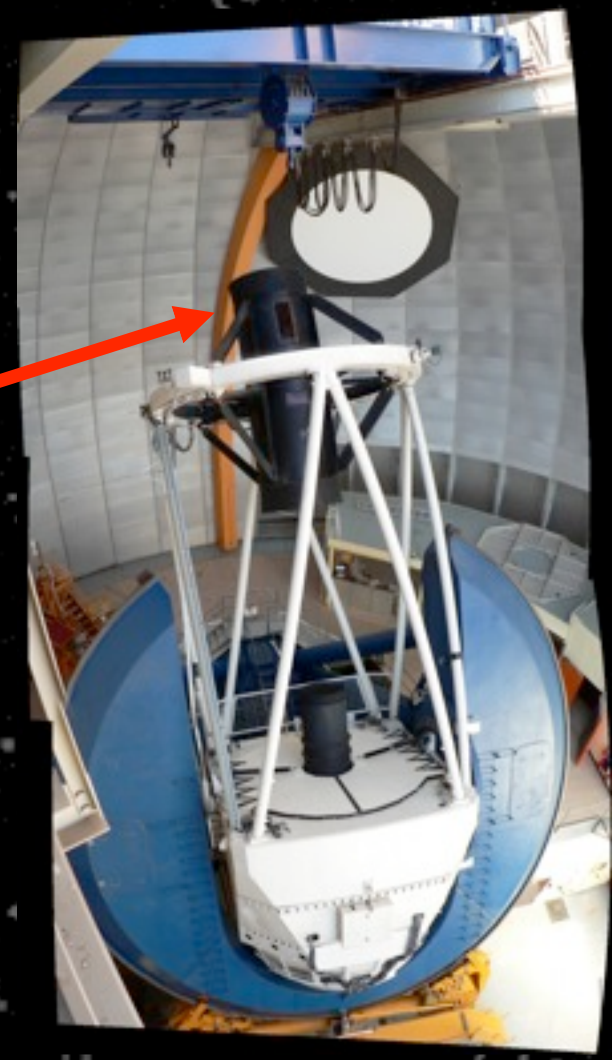


~8 σ detection of annual modulation consistent with the phase and period expected for a low mass dark matter particle (~3 GeV).

We are building the Dark Energy Camera (DECam)

New wide field imager (3 sq-deg) for the Blanco 4m telescope to be delivered in 2011 in exchange for 30% of the telescope time during 5 years.

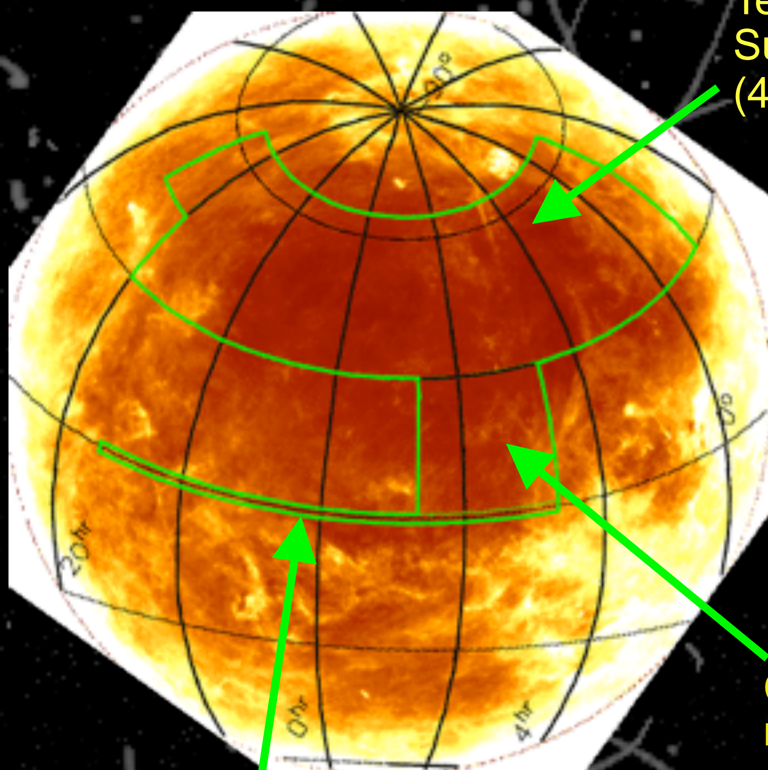




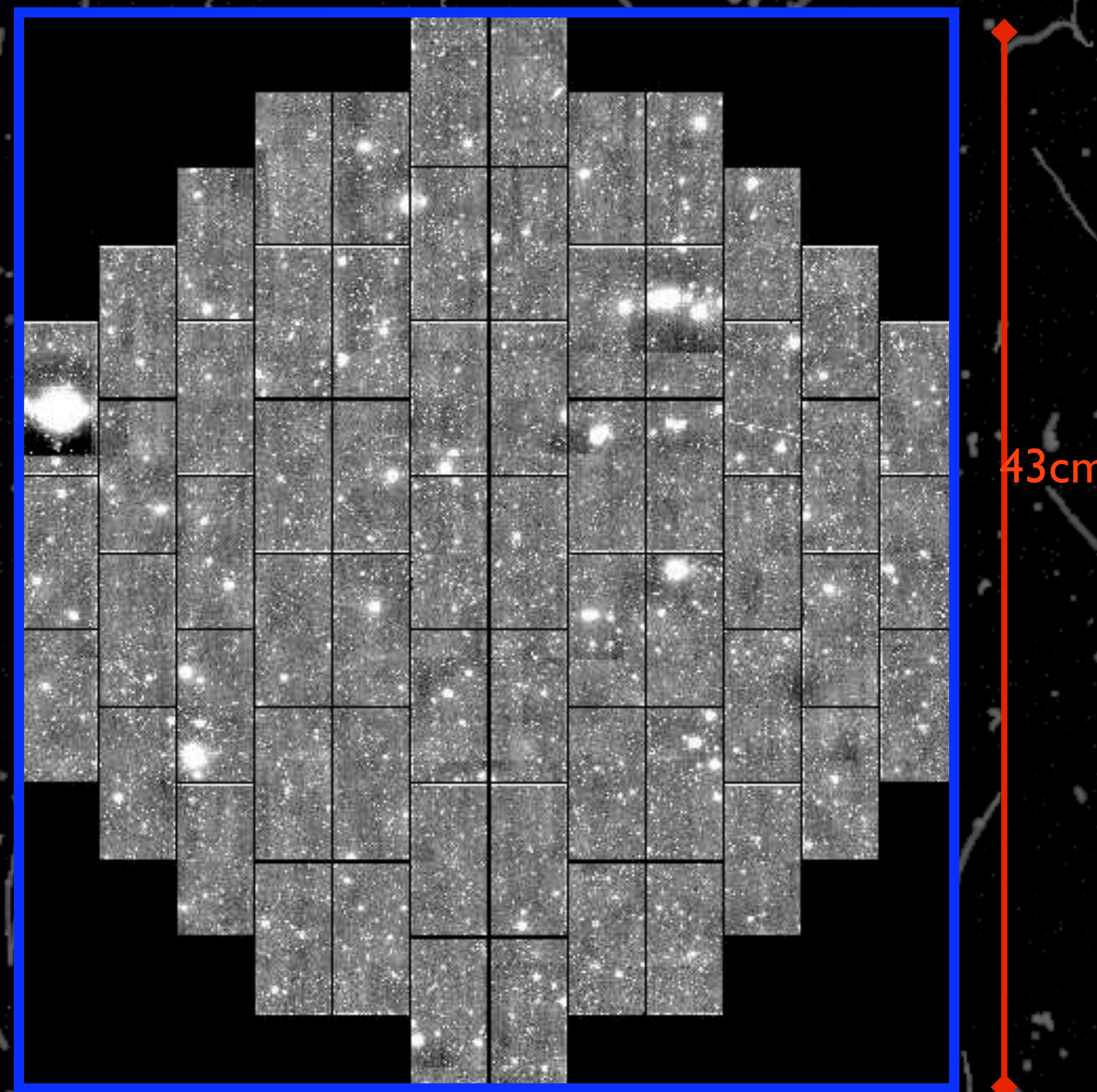
Big digital camera ~600 Mpix
talk by R. Schimidt yesterday + poster by D. Kubik on CCD testing

Dark Energy Survey

Survey Area



optimized to measure the equation of state parameter w for Dark Energy. Relation between pressure and density.



Galaxy Cluster counting
(collaboration with SPT, see next slides)
20,000 clusters to z=1 with $M > 2 \times 10^{14} M_{sun}$

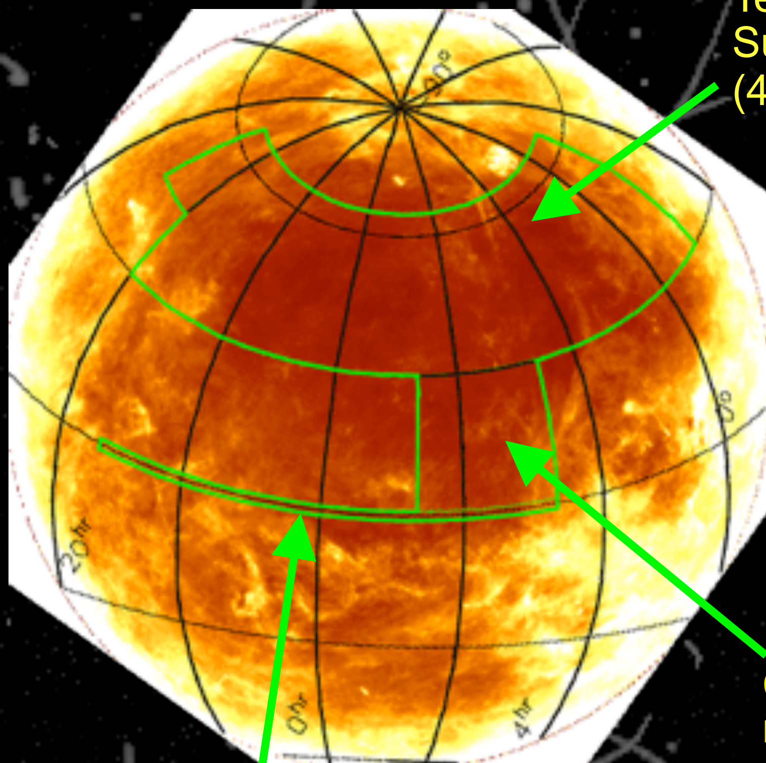
Spatial clustering of galaxies (BAO)
300 million galaxies to z ~ 1

Weak lensing
300 million galaxies with shape measurements over 5000 sq deg

Supernovae type Ia (secondary survey)
~1100 SNe Ia, to z = 1

Dark Energy Survey

Survey Area



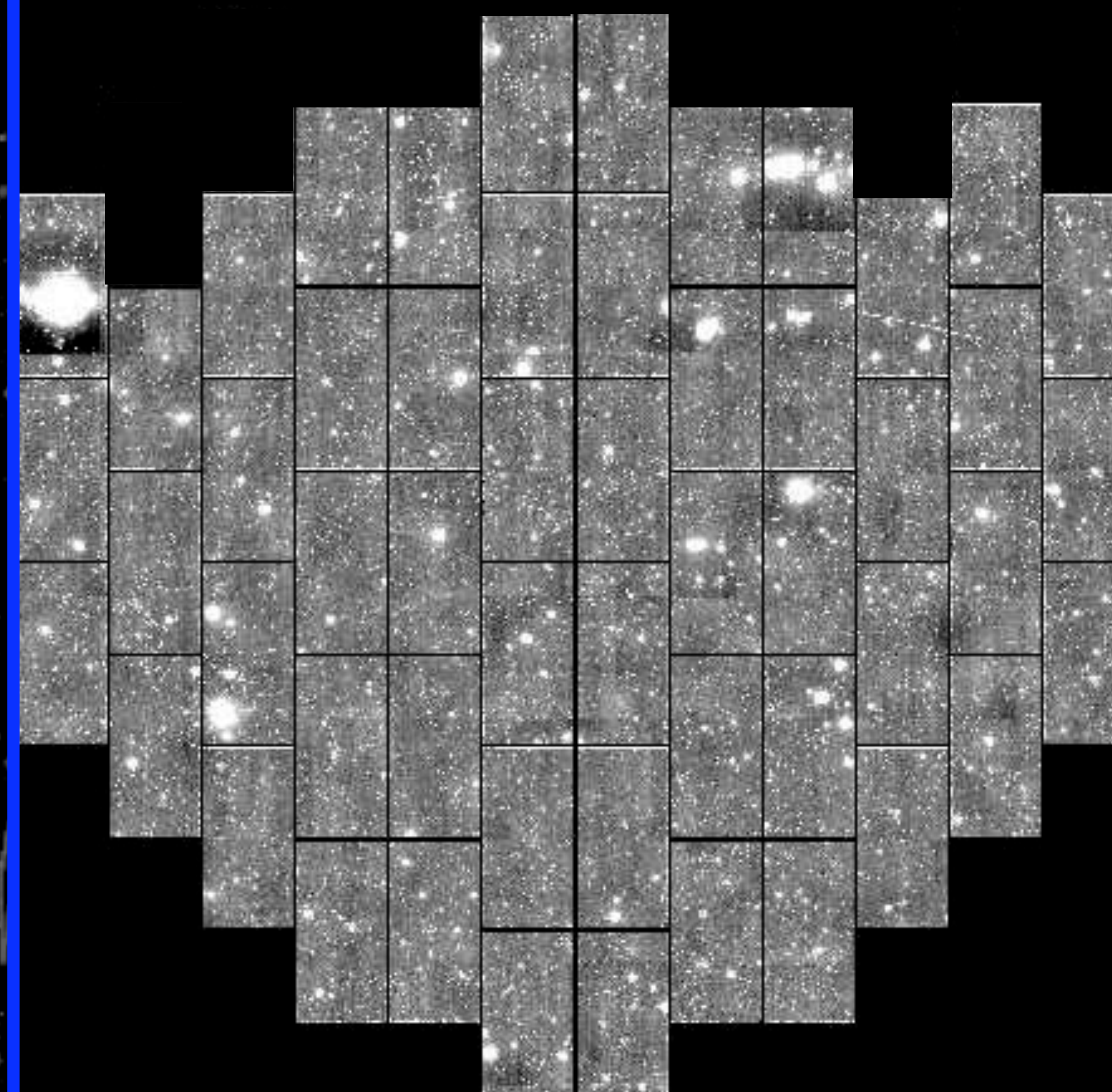
Overlap with South Pole Telescope Survey (4000 sq deg)

Connector region (800 sq deg)

Overlap with SDSS Stripe 82 for calibration (200 sq deg)

optimized to measure the equation of state parameter w for Dark Energy. Relation between pressure and density.

we have 53 ready!



43cm

Galaxy Cluster counting

(collaboration with SPT, see next slides)

20,000 clusters to $z=1$ with $M>2\times10^{14}M_{sun}$

Spatial clustering of galaxies (BAO)

300 million galaxies to $z \sim 1$

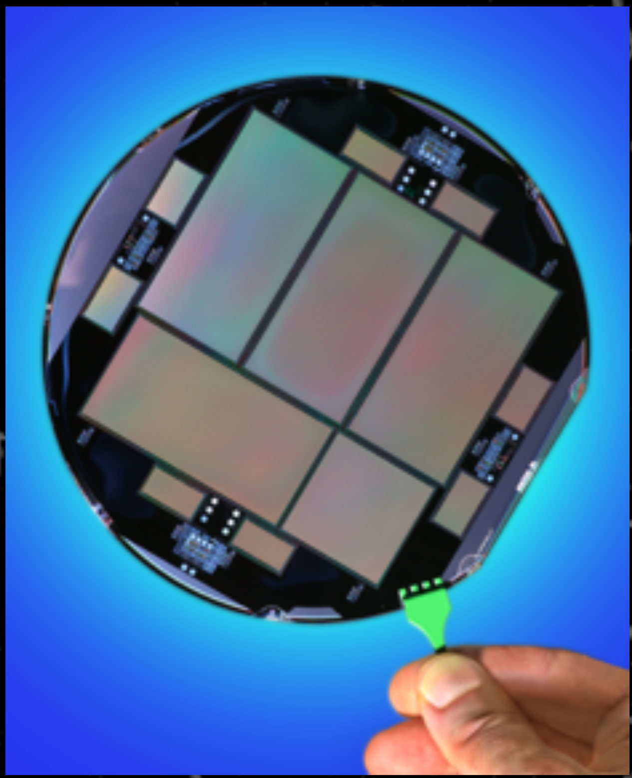
Weak lensing

300 million galaxies with shape measurements over 5000 sq deg

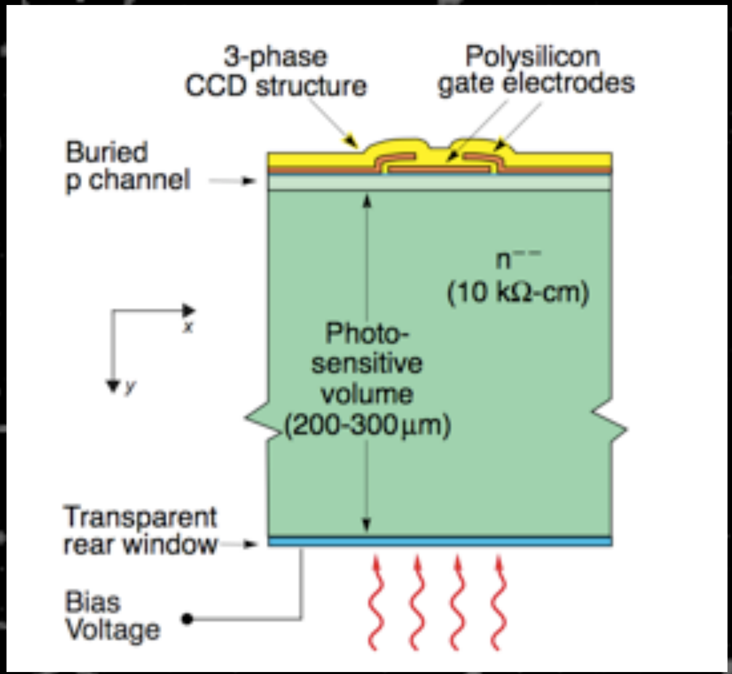
Supernovae type Ia (secondary survey)

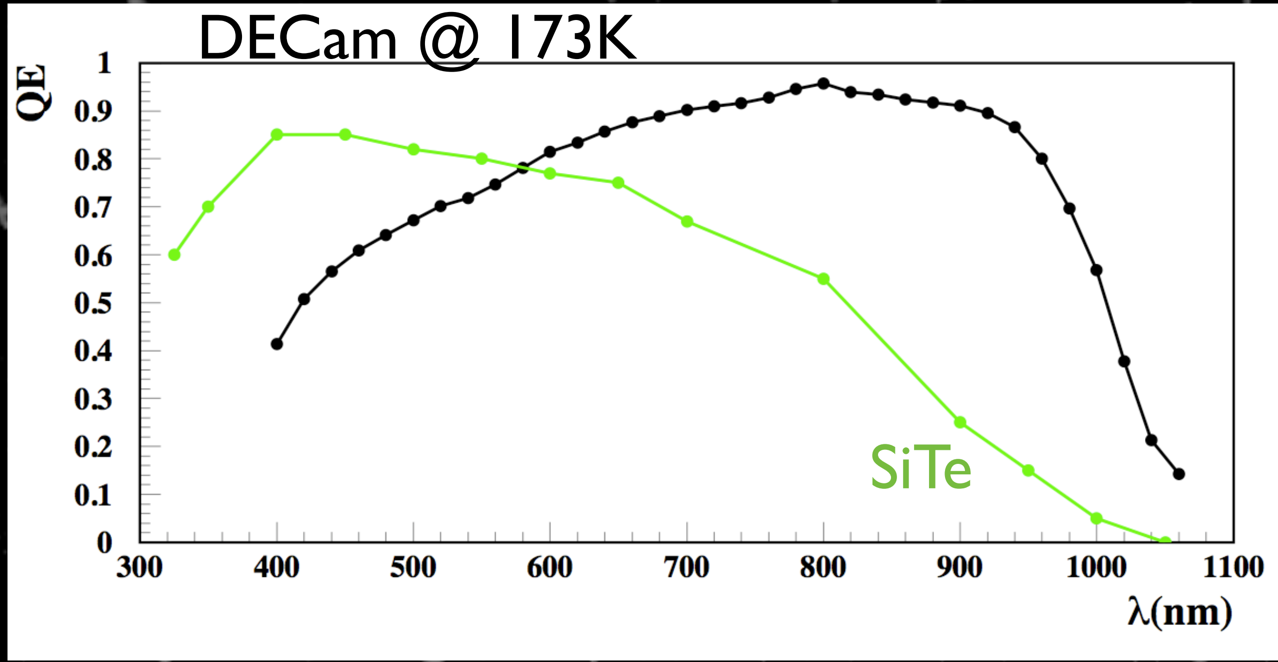
~1100 SNe Ia, to $z = 1$

DECam CCDs developed by LBNL



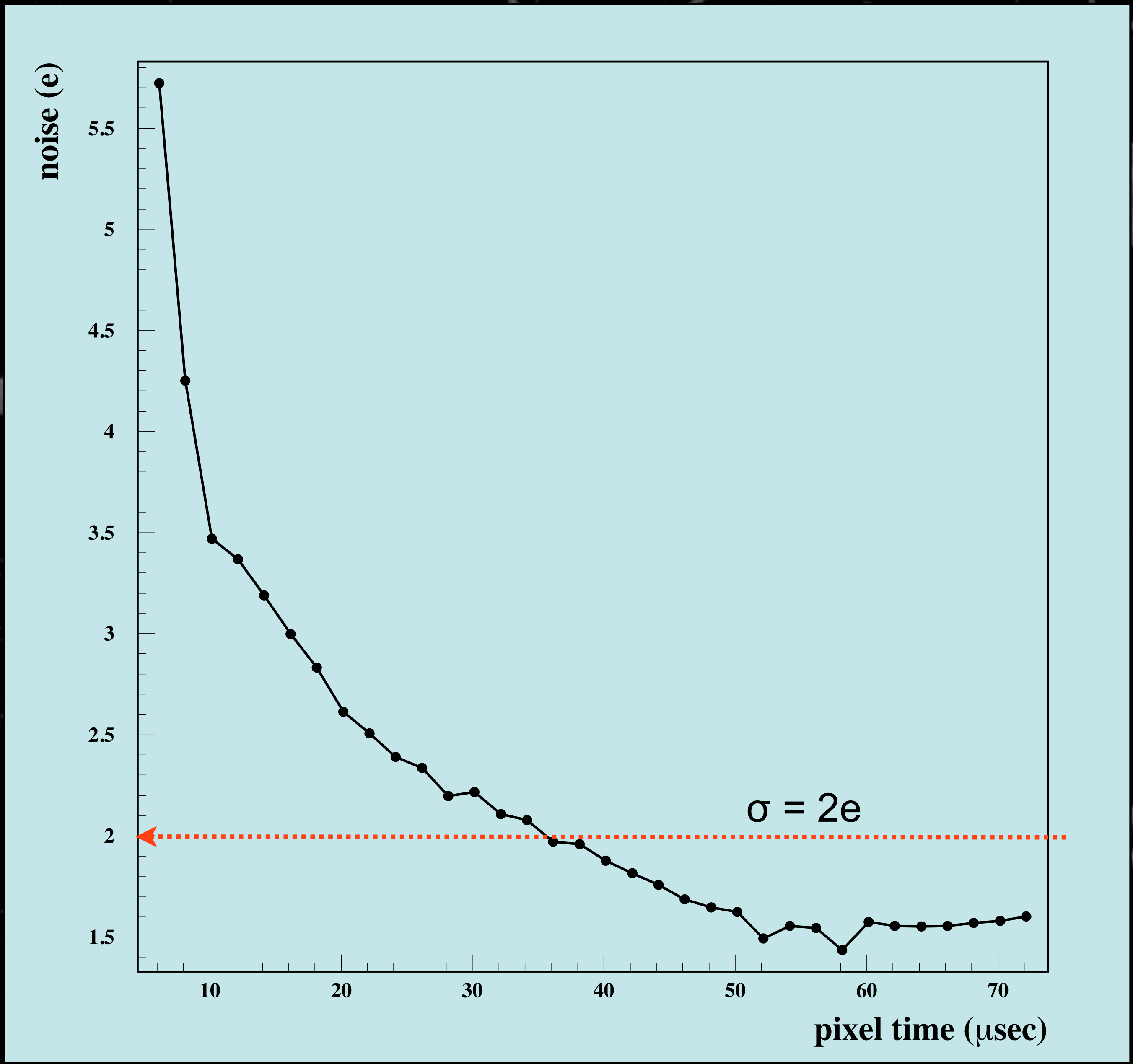
250 µm thick





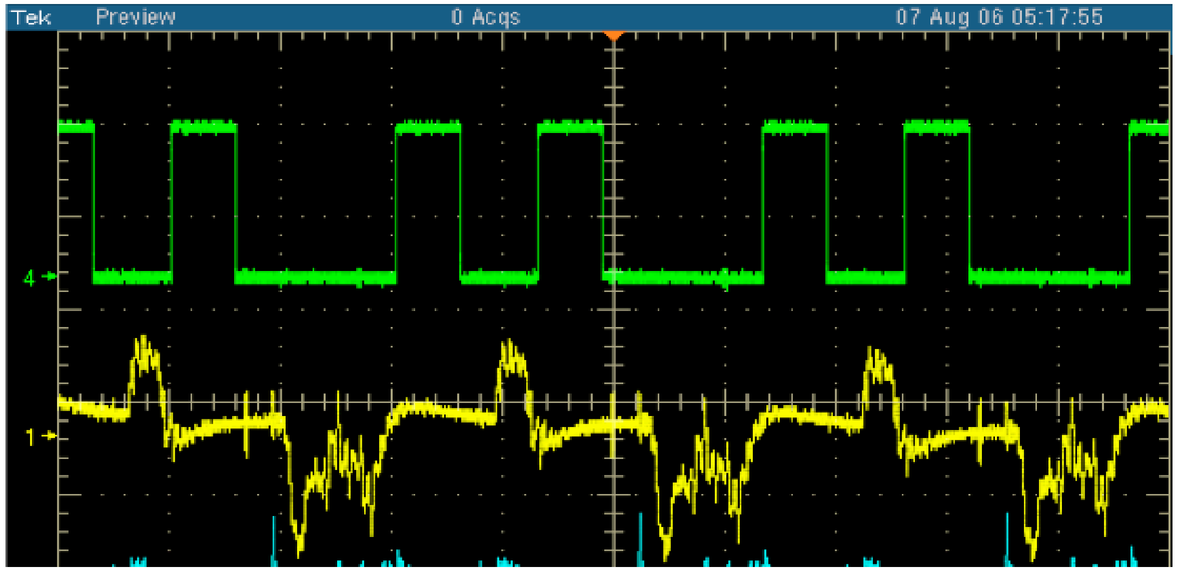
250 µm thick fully depleted
hi-resistivity p-channel technology developed by LBNL
15 µm x 15 µm pixels
operating temperature : -100 C for DES
-150C for DAMIC

Readout Noise



CCDs are readout serially. For DECam we have 17 seconds to do this (250 kpix/sec) and we get ~8e of noise. But you could go really slow and reduce the noise further.

CDS: Video is sampled with 2 integration windows.



2e- of noise corresponds to 7.2 eV for ionizing energy!!!

DECam CCDs for Dark Matter

- 7.2 eV noise ➪ low threshod (~0.036 keV)
- 250 μm thick ➪ reasonable mass (1 gram/CCD)

these two features make the detectors ideal for a low threshold dark matter search. The DAMIC experiment is testing this idea.

other experiments :

Experiment	Target	Exposure (kg-d)	Threshold	Ref
CDMS-SUF	Ge	65.8	5 keV	[2]
	Si	6.58	5 keV	
CDMS-II	Ge	121.3	10 keV	[3]
	Si	12.1	7 keV	[4]
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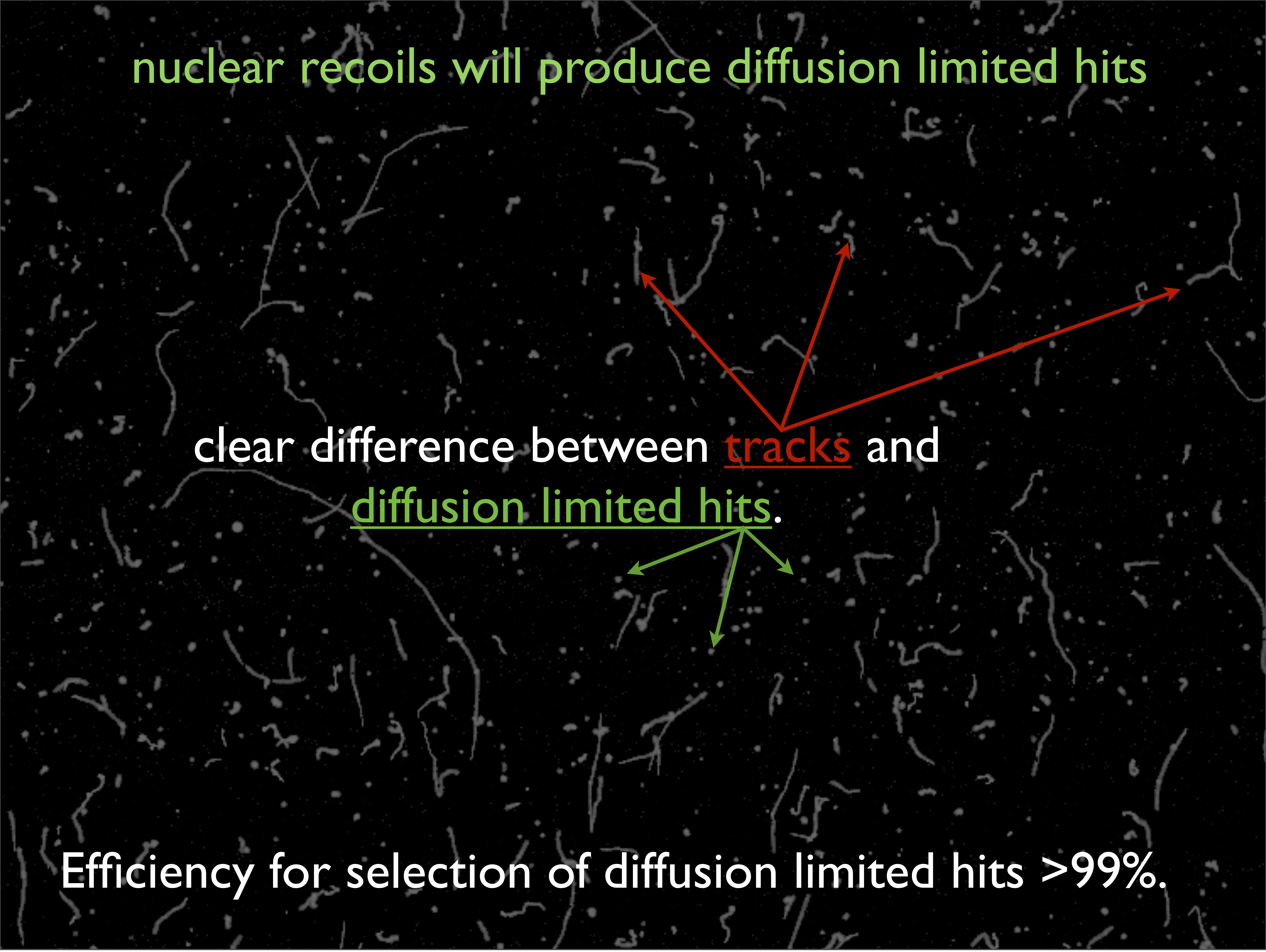
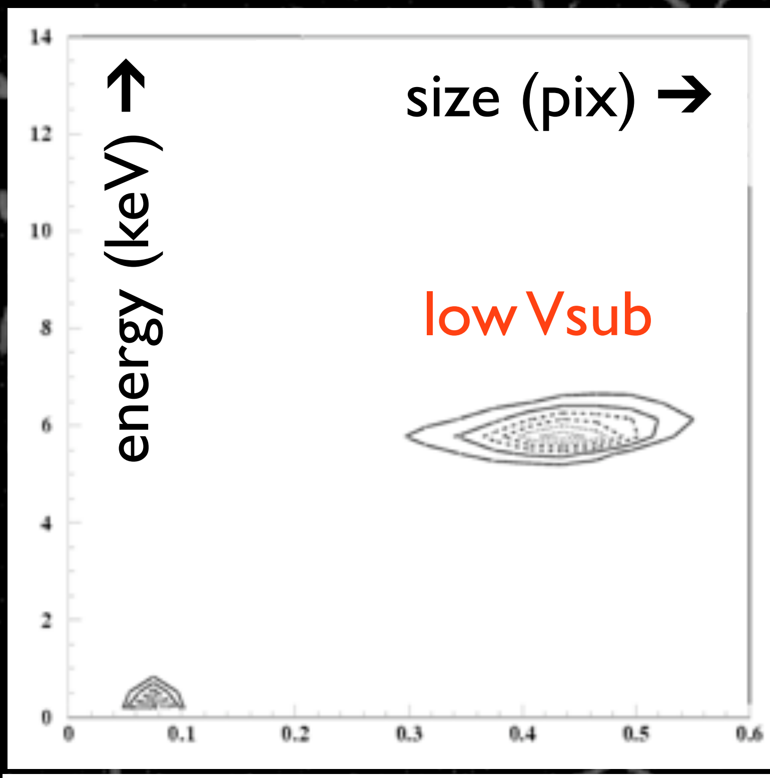
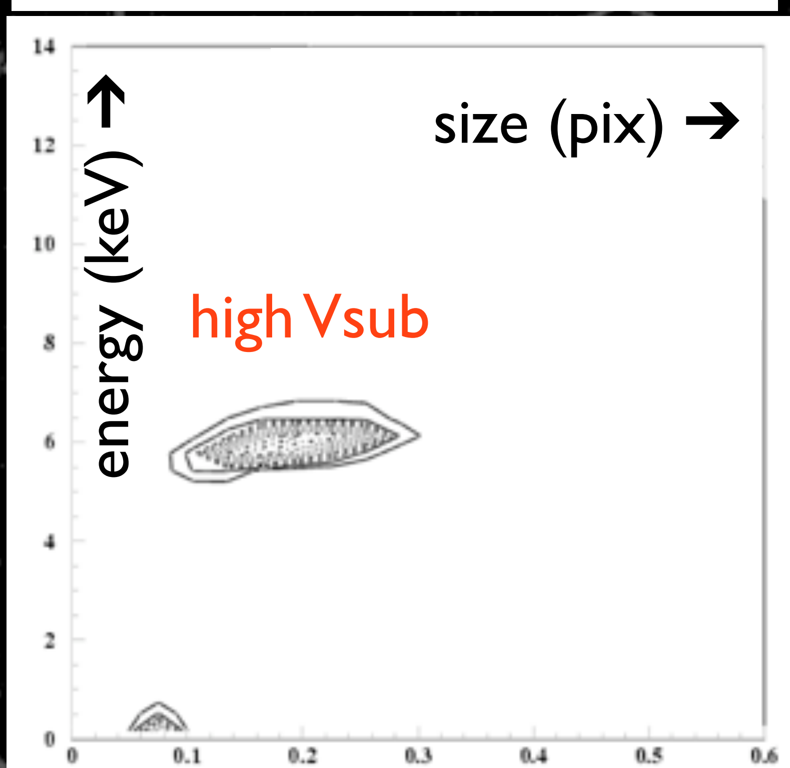
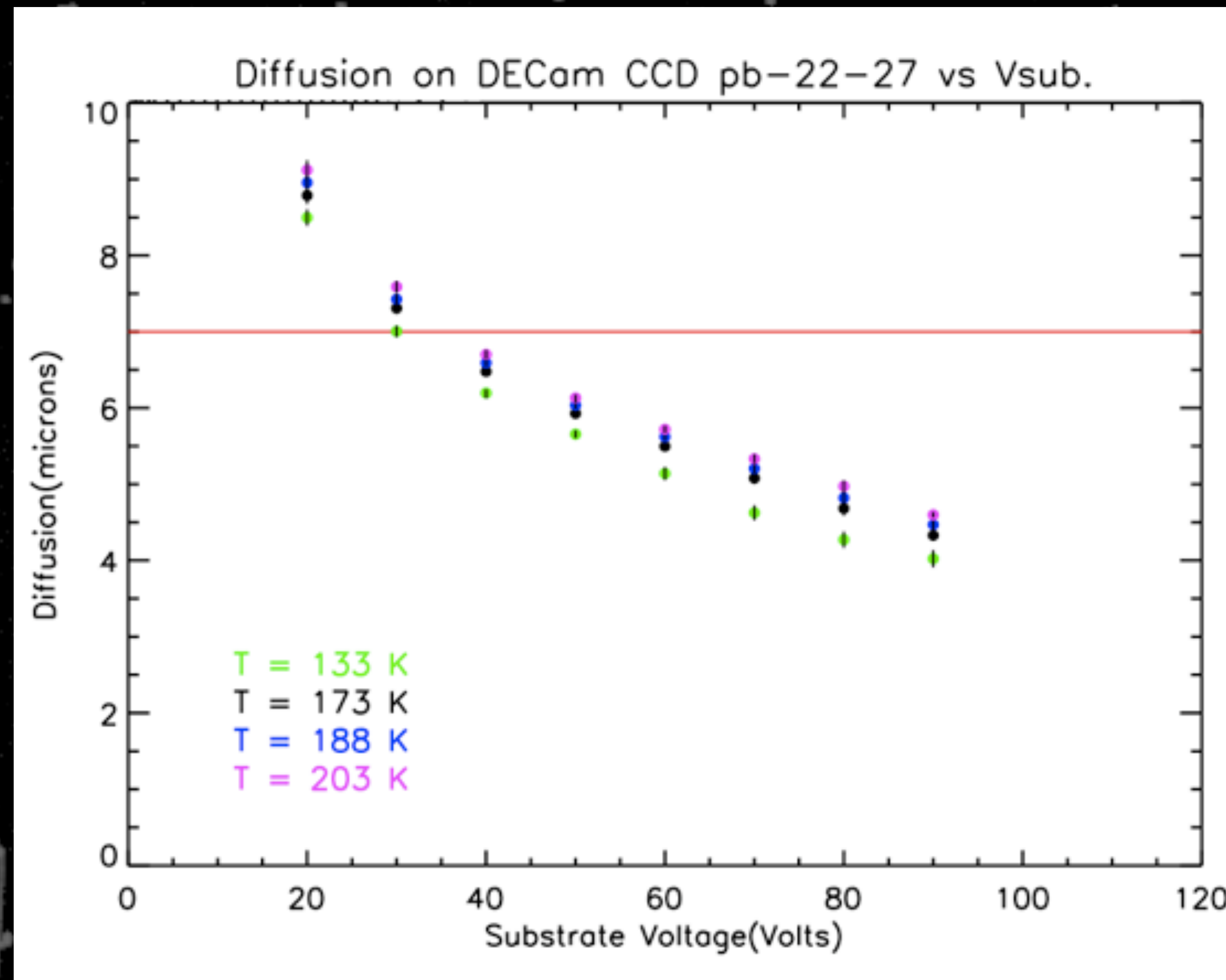
Existing efforts by a few groups going on to reduce noise on common DM detectors (Ge crystals).


nuclear recoils will produce diffusion limited hits
clear difference between tracks and
diffusion limited hits.
Efficiency for selection of diffusion limited hits >99%.

Charge diffusion with X-rays







DECam CCDs as particle detectors: X-rays

^{55}Fe

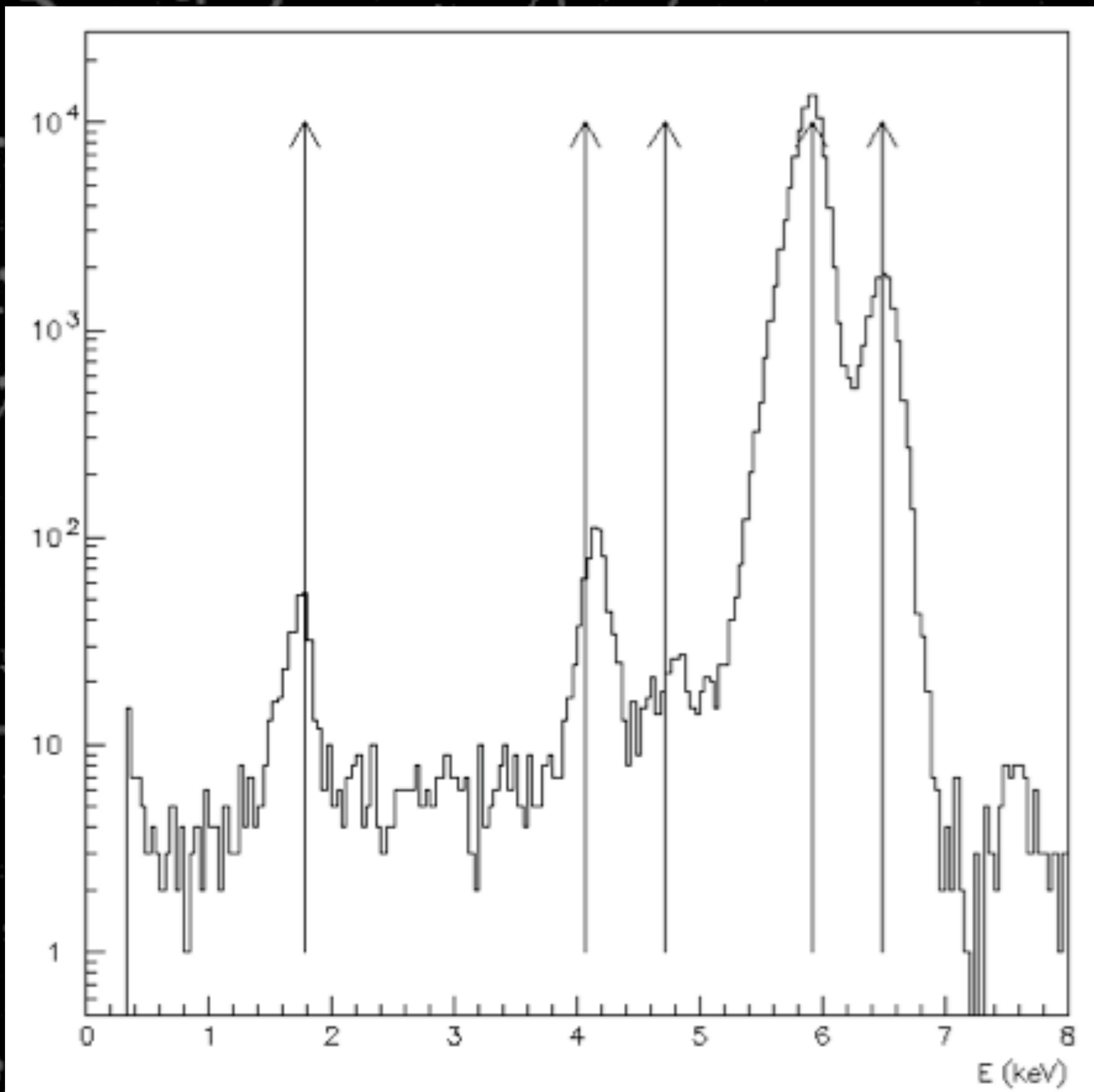
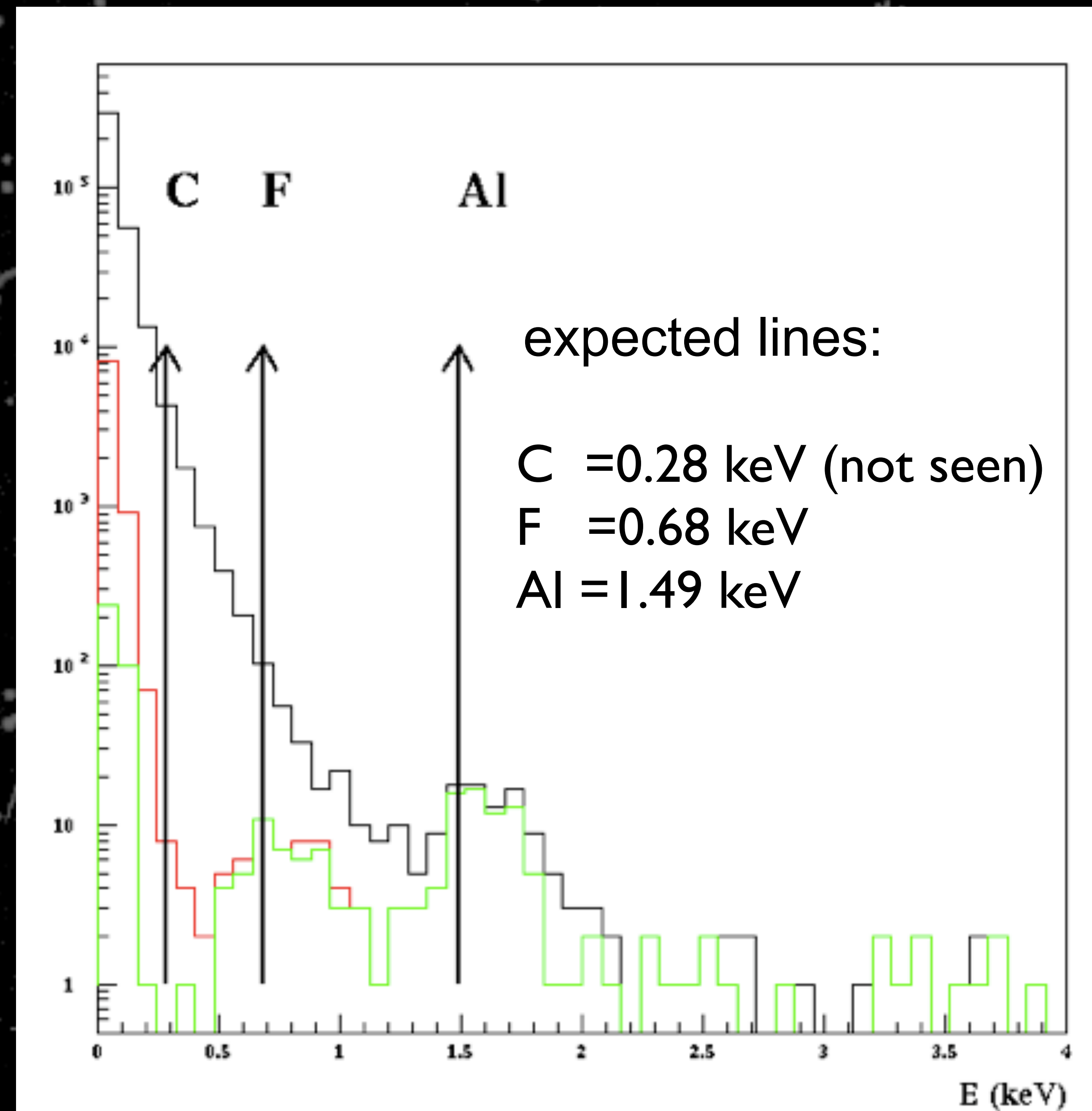


FIG. 4: Spectrum obtained for the reconstructed X-ray hits in an ^{55}Fe exposure of a DECam CCD. The arrows mark the direct X-rays from the source Kα=5.9 keV and Kα=6.5 keV, the Kα and Kβ escape lines at 4.2 and 4.8 keV, and the Si X-ray at 1.7 keV. The factor 3.64 eV/e is used to convert from charge to ionization energy.

Fluorescence

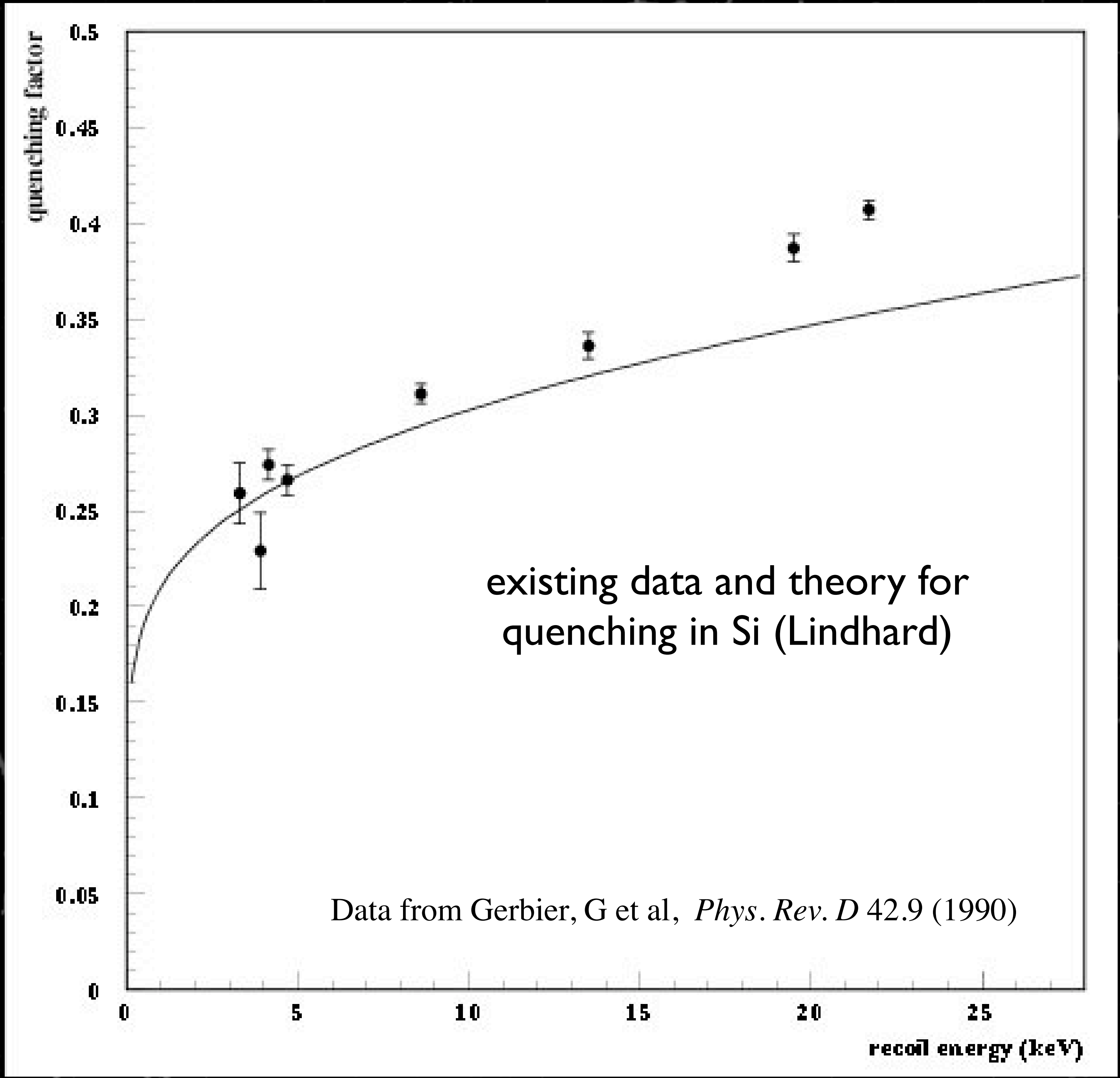


Ionization efficiency for nuclear recoils
(not 3.6 eV/e anymore)

Some fraction of the energy in nuclear recoils is converted into thermal energy with vibrations of the lattice.

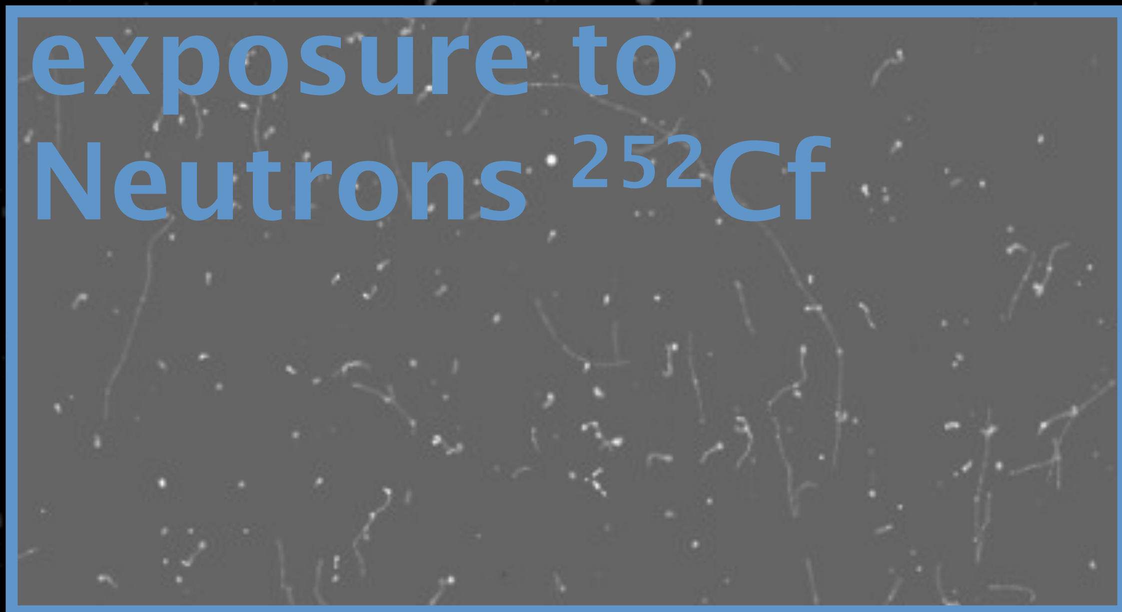
<u>New calibration required. The existing measured points do not go below 4 keV in energy.</u>

<u>Is there channeling on a CCD? Next in our list of things to investigate.</u>

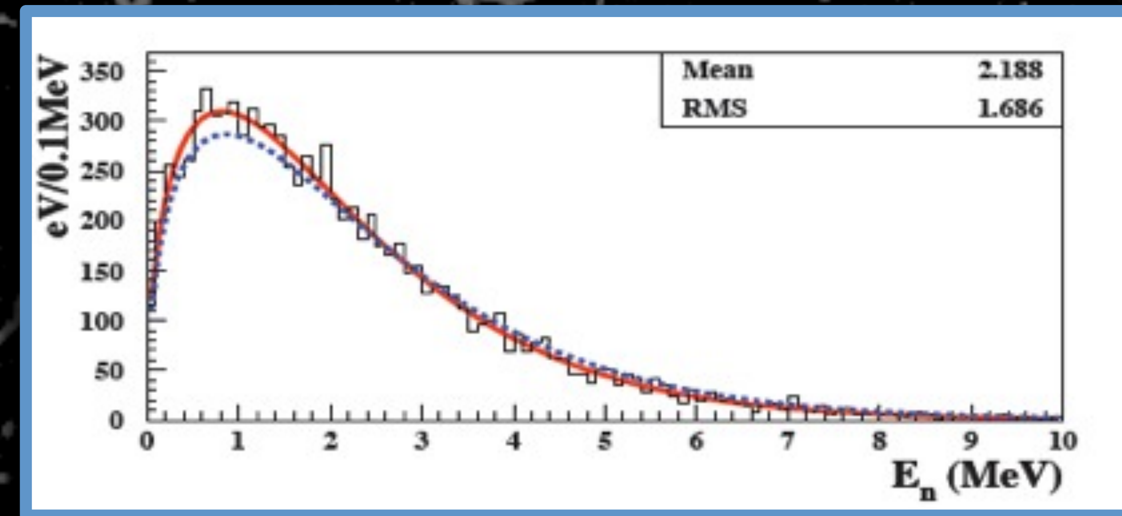


Calibration of CCDs using neutrons ^{252}Cf

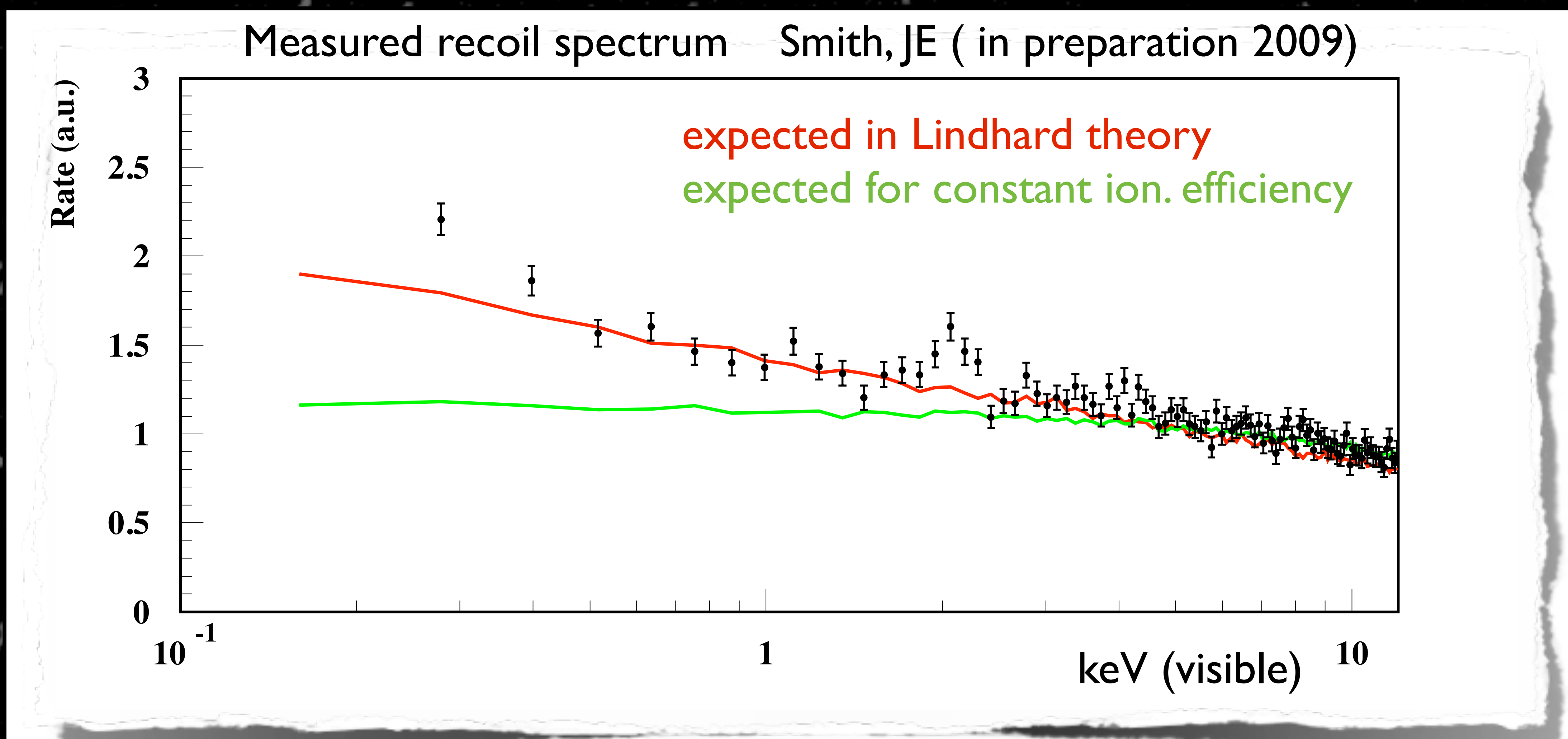
exposure to Neutrons ^{252}Cf



spectrum from source



Our first measurements below 1 keV show consistency with Lindhard theory



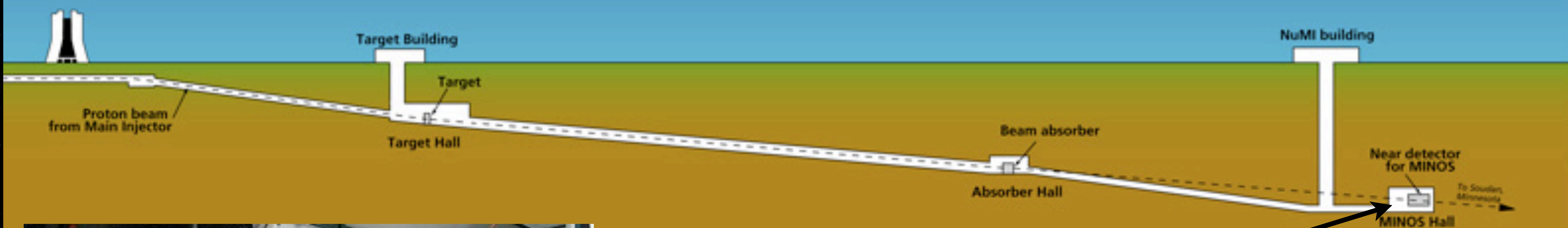
DArk Matter In CCDs
DAMIC

Located at Fermilab, Illinois, USA

Fermilab:
T. Diehl, J. Estrada, B. Flaugher, , D. Kubik, V. Scarpine, E. Ramberg, A. Sonnenschein and Ben Kilminster

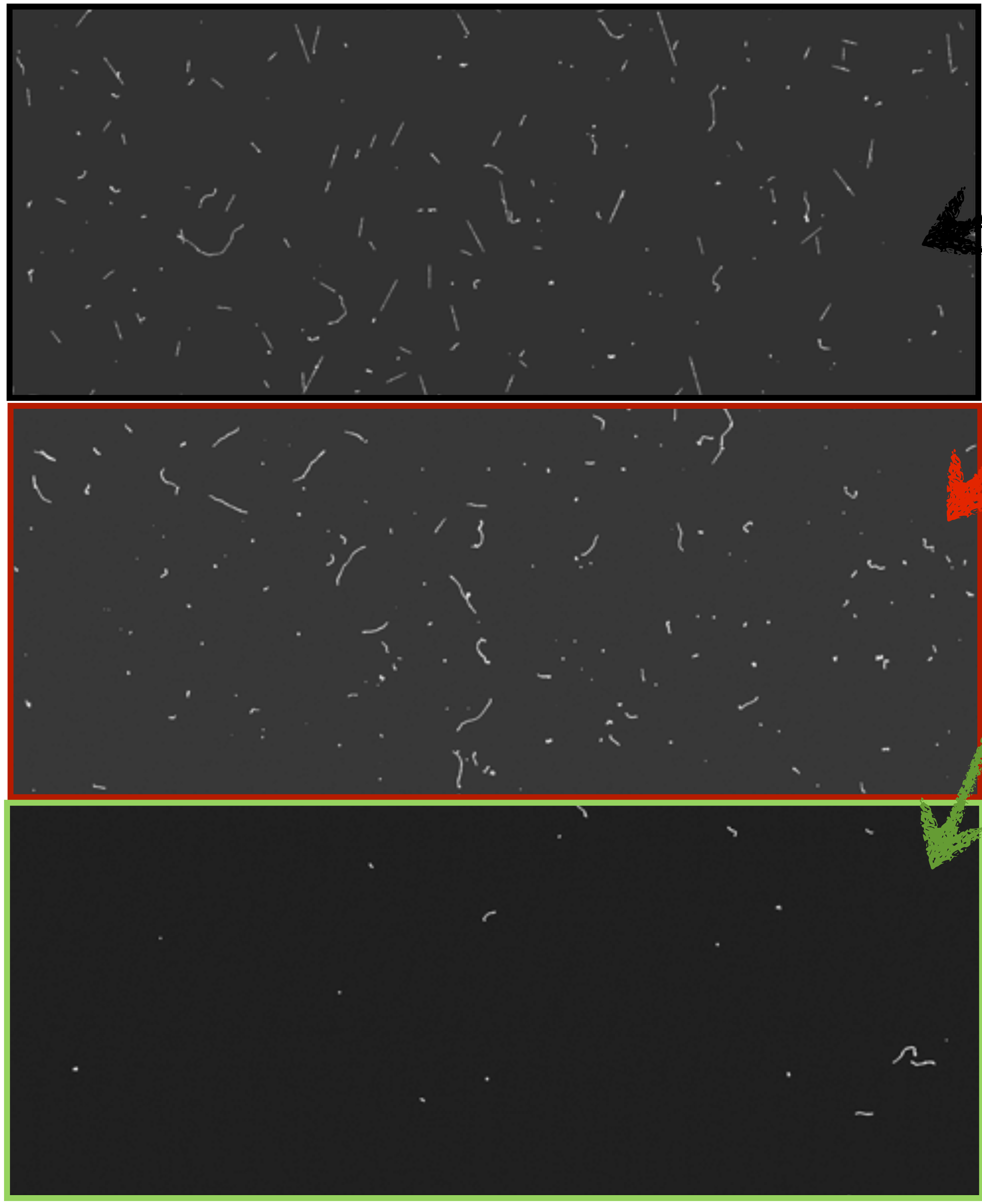
Visitors:
J. Molina (CIEMAT), J. Jones (Purdue)

Engineering: Mostly FNAL surplus parts and DECam engineering components.



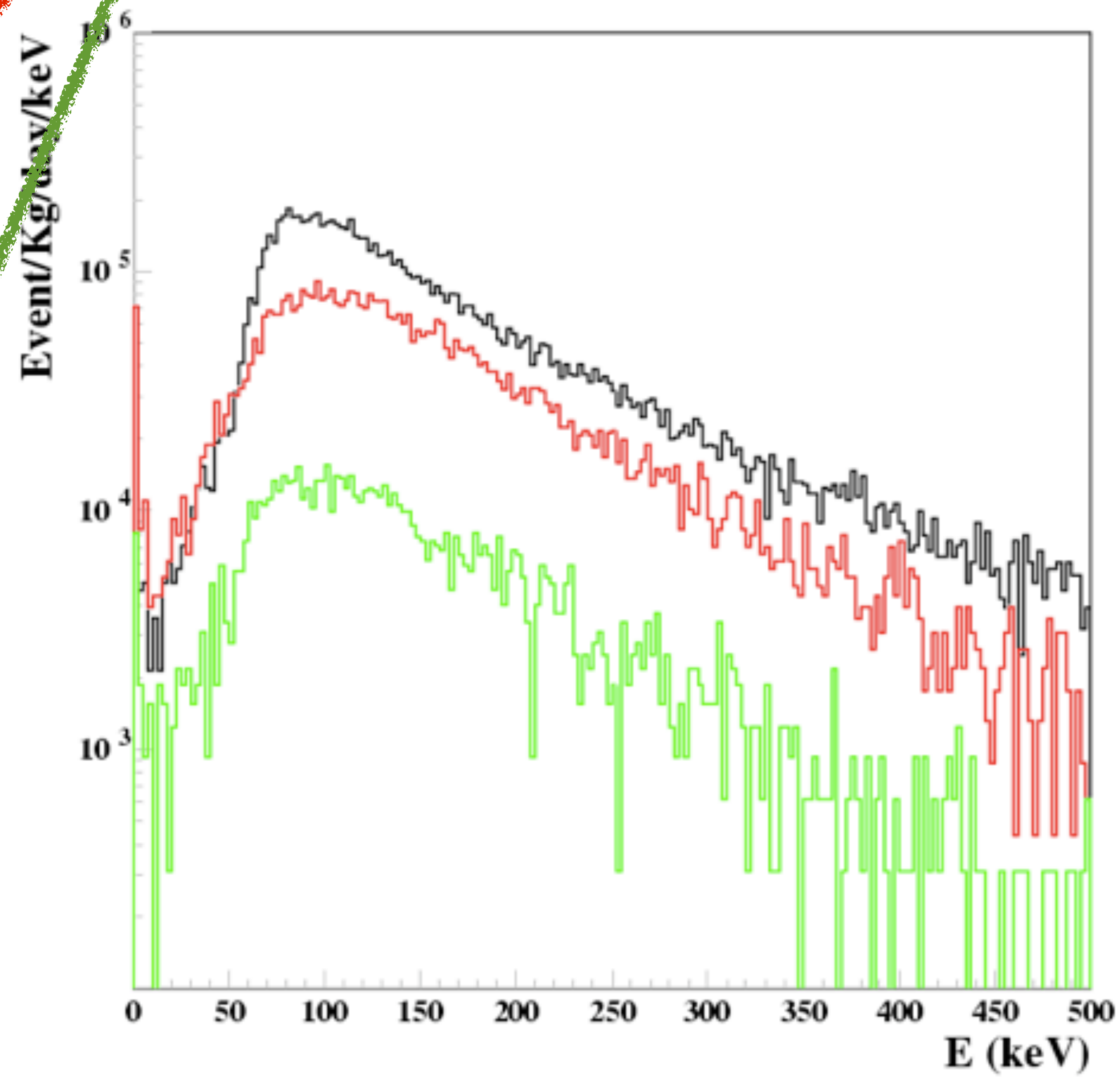
4CCD array here. ~350 foot depth

Muon Tracks:

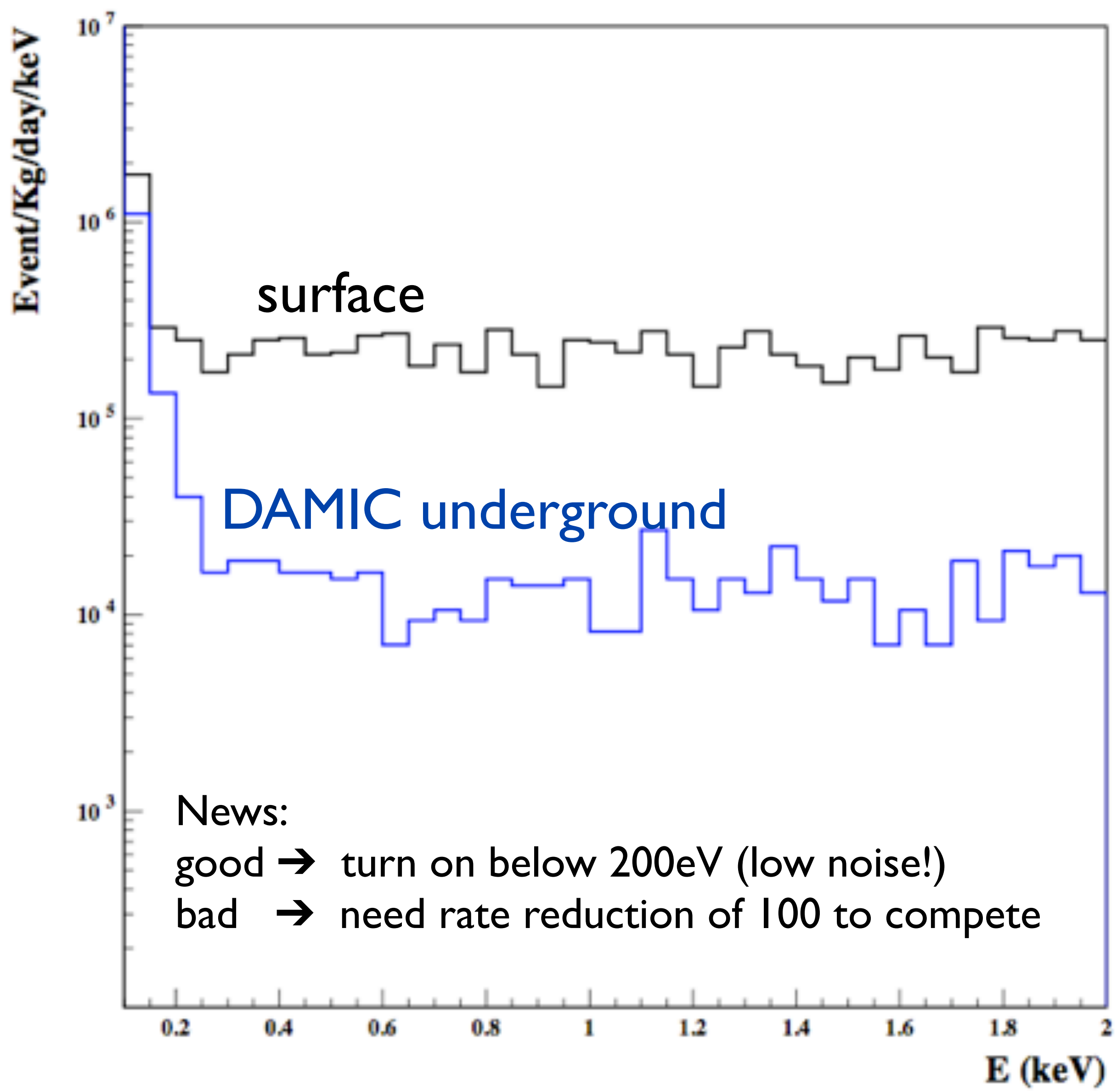


1 hour exposures:

- on the surface
- Minos (350' deep)
- Minos + lead shield



nuclear recoil candidates



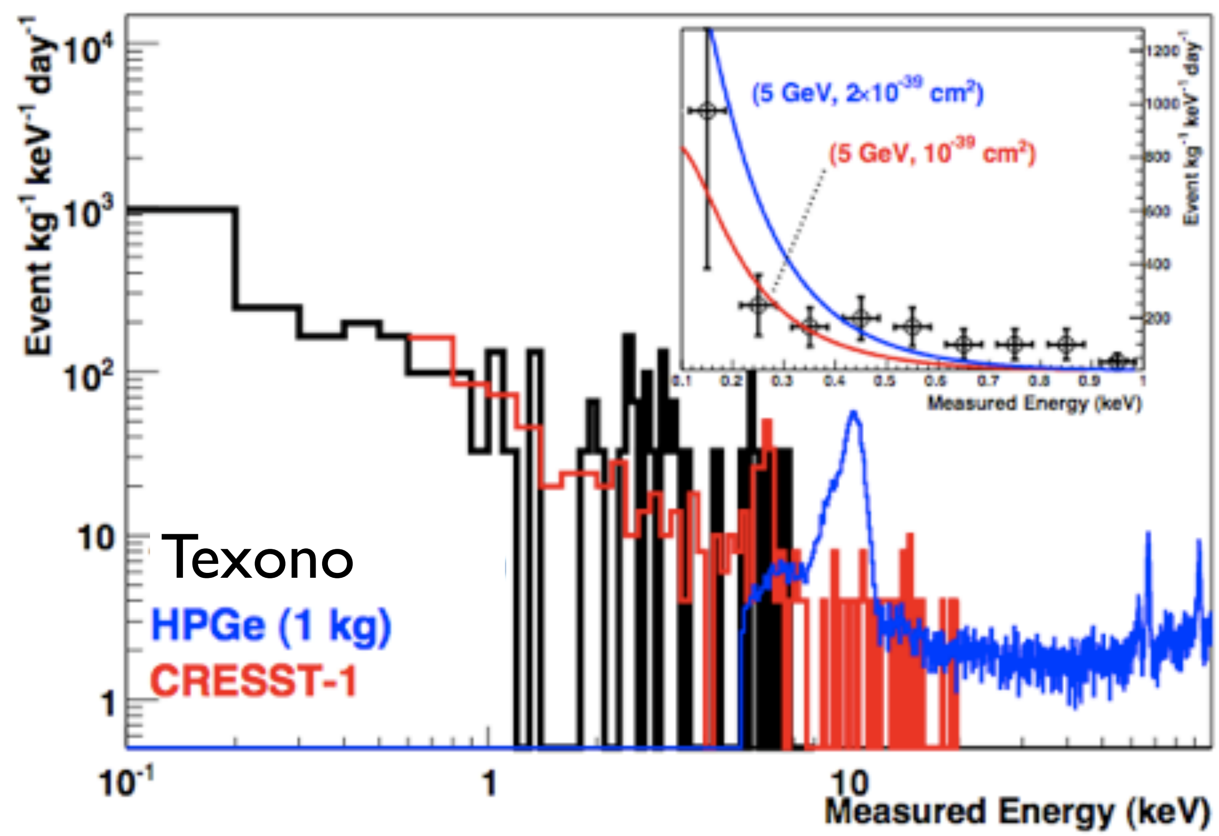


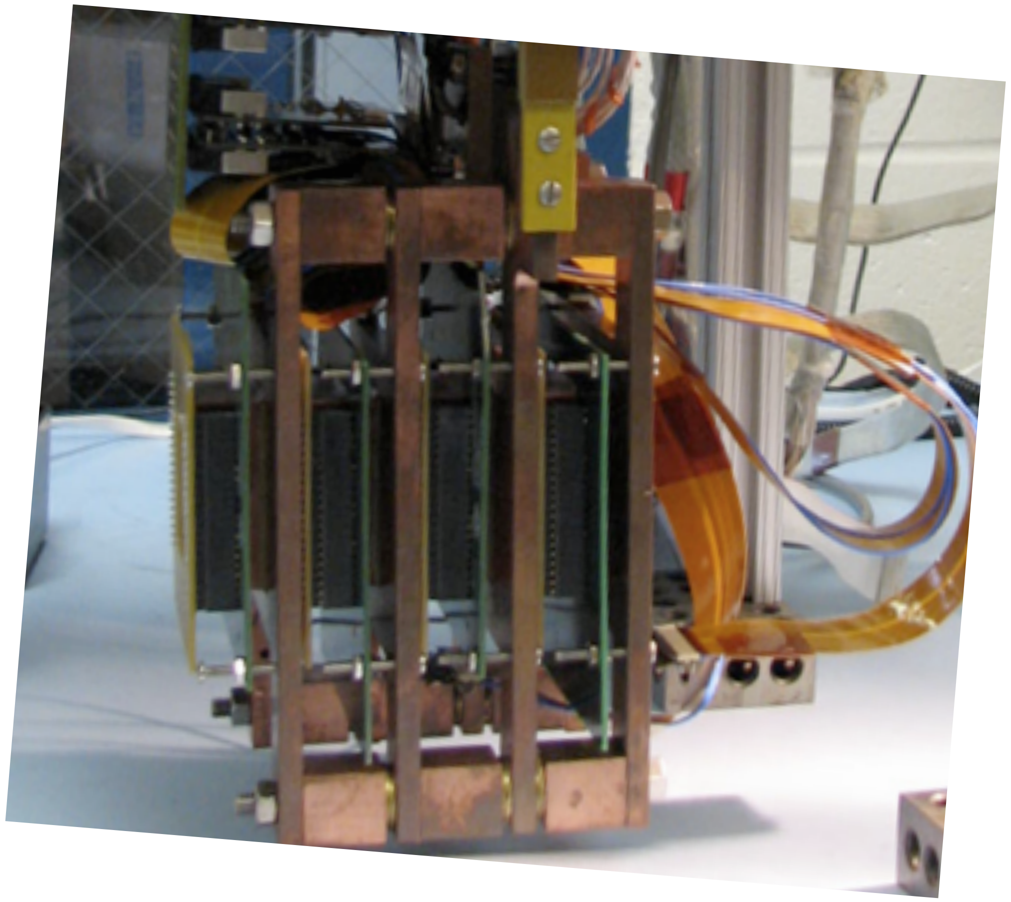
FIG. 4: The measured spectrum of ULEGe with 0.338 kg-day of data, after CRV, ACV and PSD selections. Background spectra of the CRESST-I experiment [9] and the HPGe [13] are overlaid for comparison. The expected nuclear recoil spectra for two cases of $(m_\chi, \sigma_{\chi N}^{SI})$ are superimposed onto the spectrum shown in linear scales in the inset.

...is there any intrinsic radiation on these detectors?

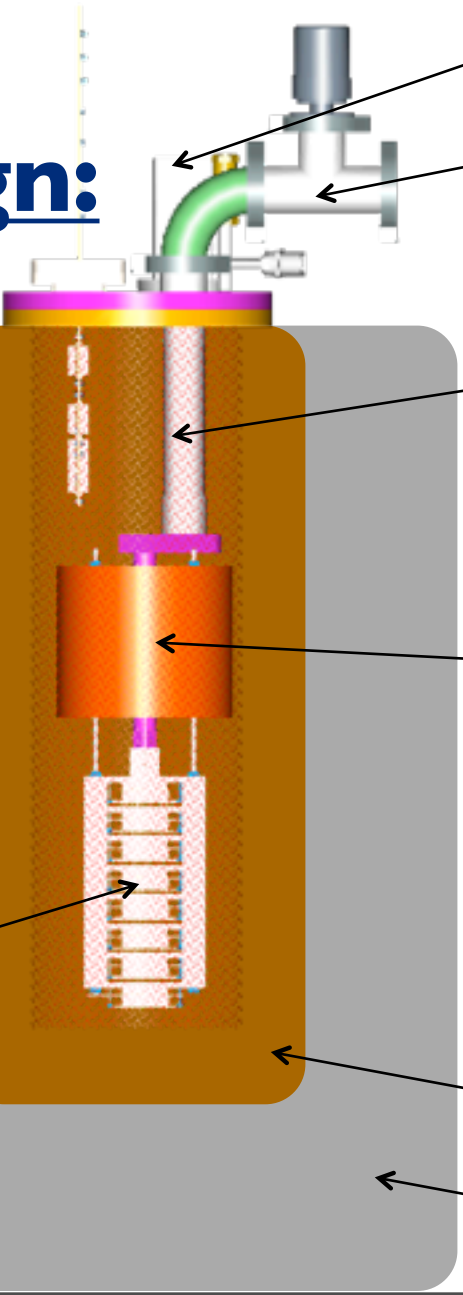
Why is the rad background so high now?

Flat level of 10^4 cpd/kg/keV:

we have measured the intrinsic **radiation of the electronic components used for readout the CCDs** (JFET next to the detector, preamp board, PC board). Their activity is enough to explain what we are seeing now. **Plan: develop low background electronics.**



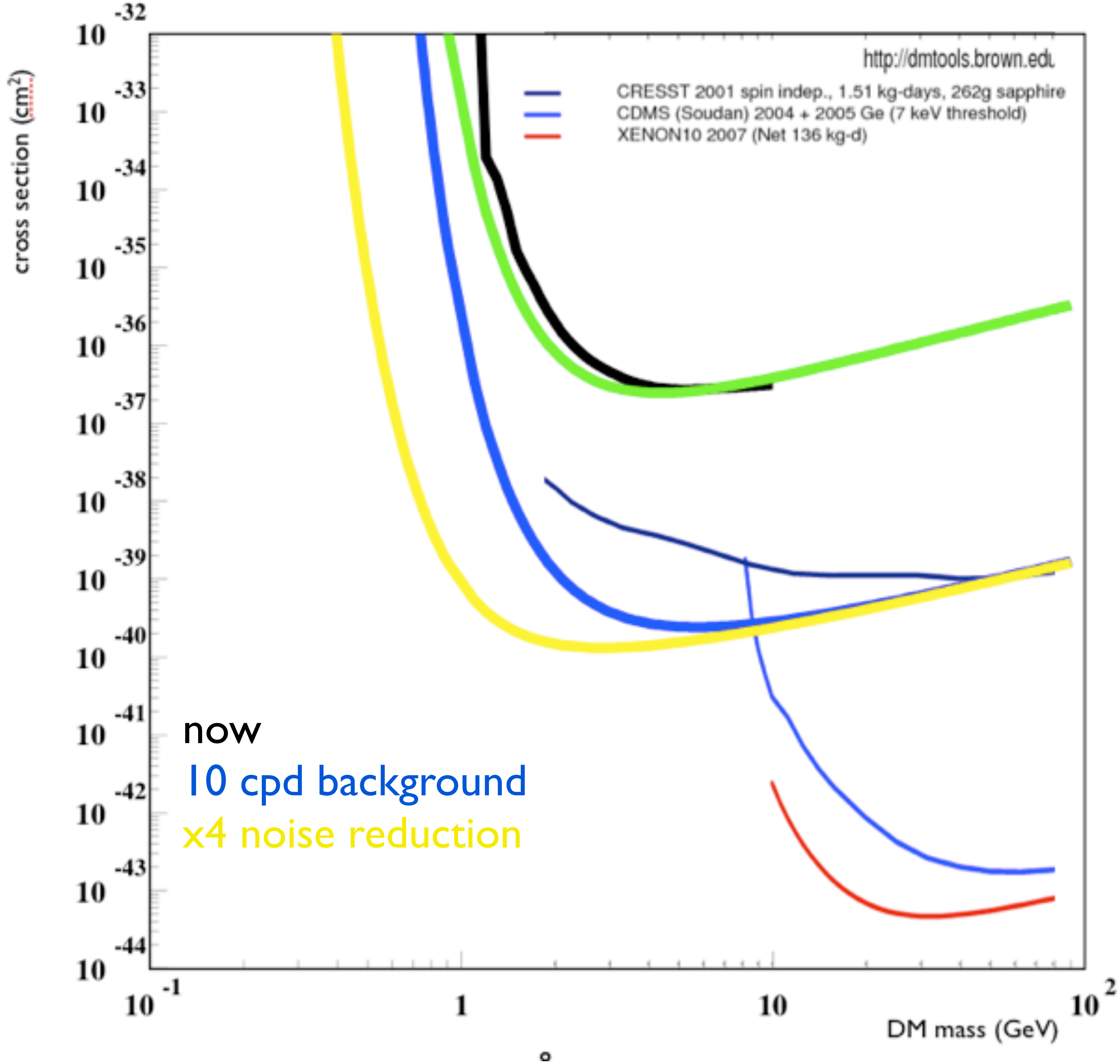
new design:



low energies:

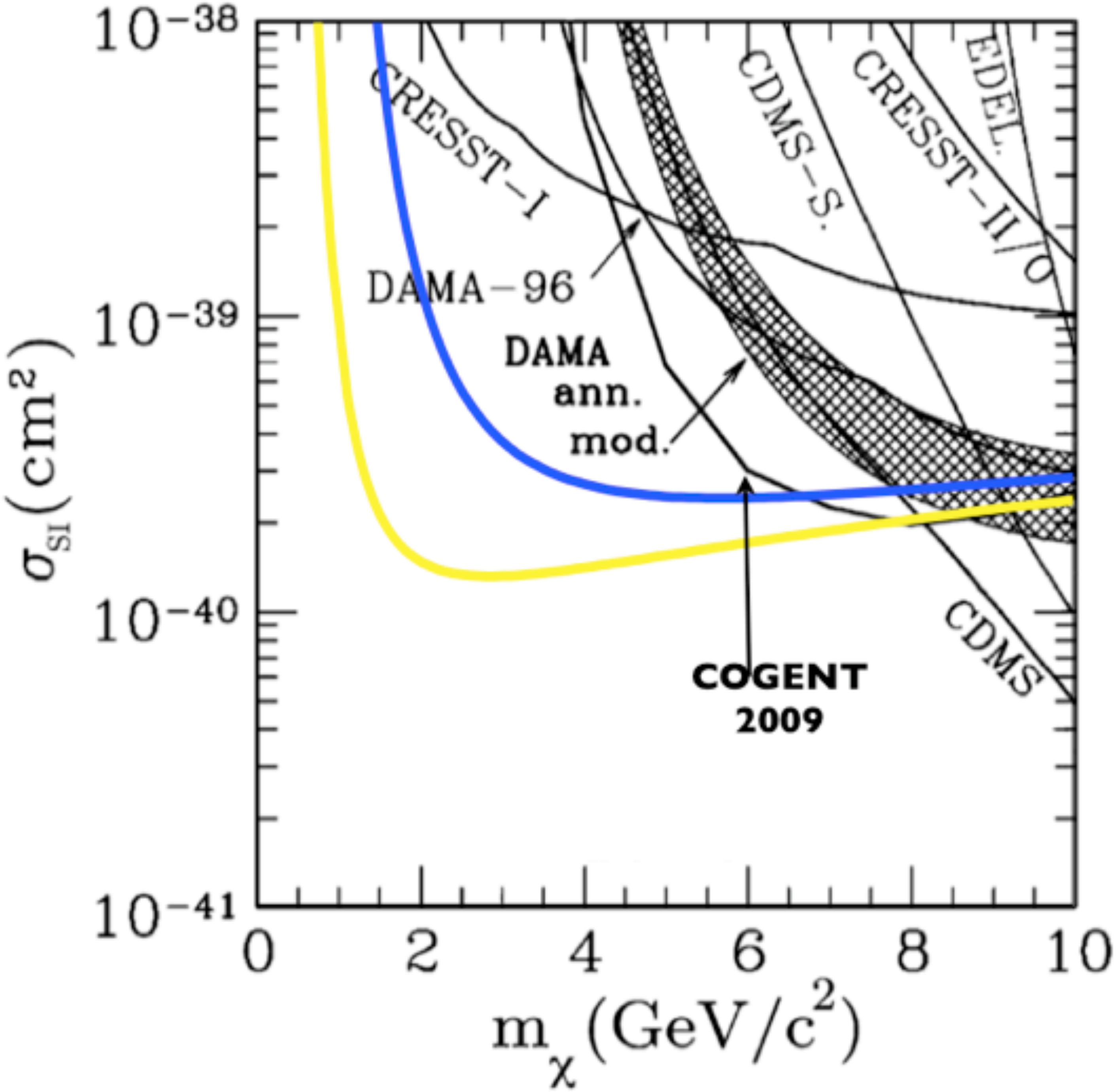
we have calculated the **IR tail from the dewar walls. Plan: cooldown the dewar wall in the net version.**

Prospects



http://dmtools.brown.edu
CRESST 2001 spin indep., 1.51 kg-days, 262g sapphire
CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
XENON10 2007 (Net 136 kg-d)
cross section (cm²)
DM mass (GeV)
now
10 cpd background
x4 noise reduction

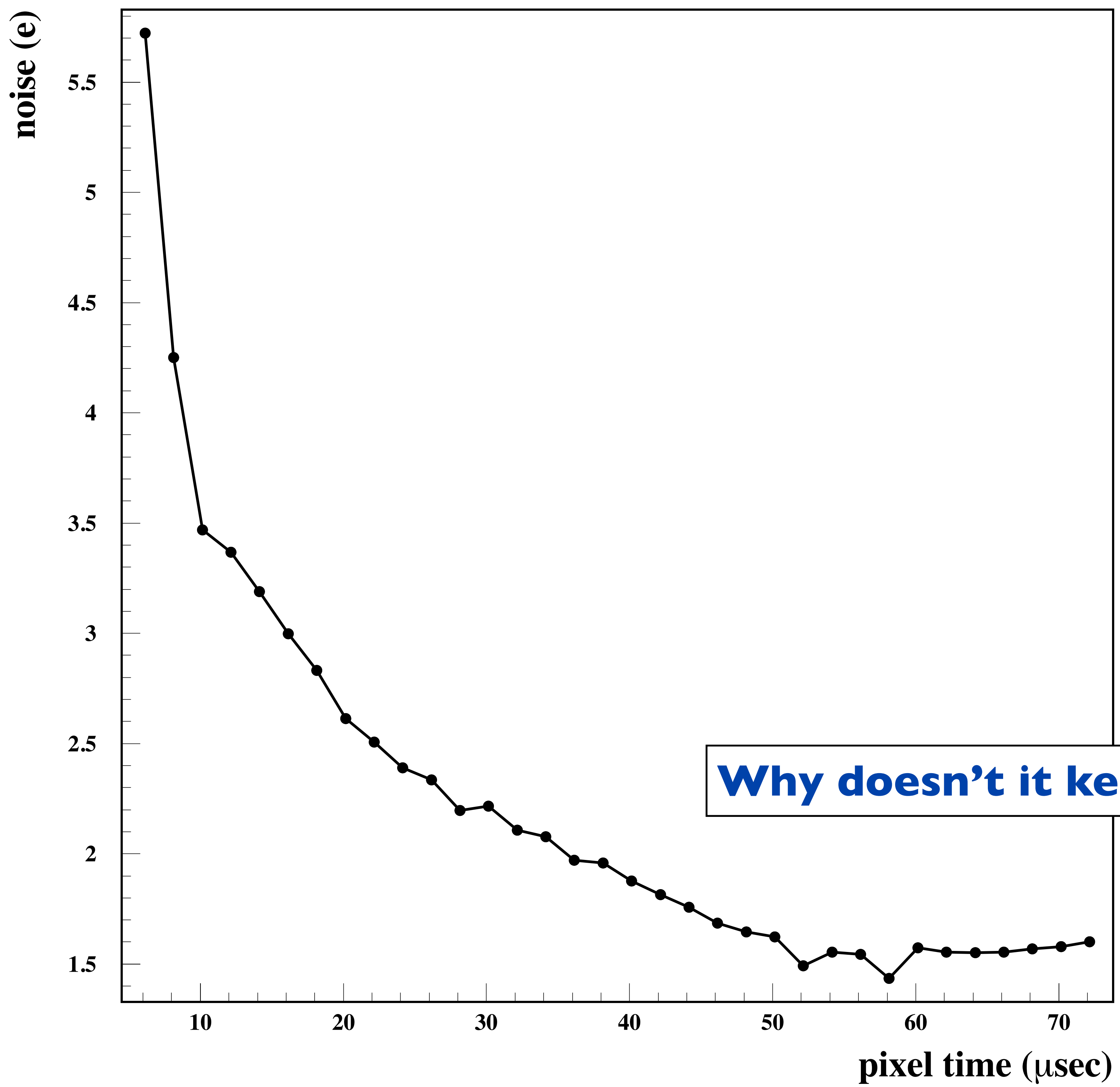
Prospects



opportunity to access a new region with CCDs!

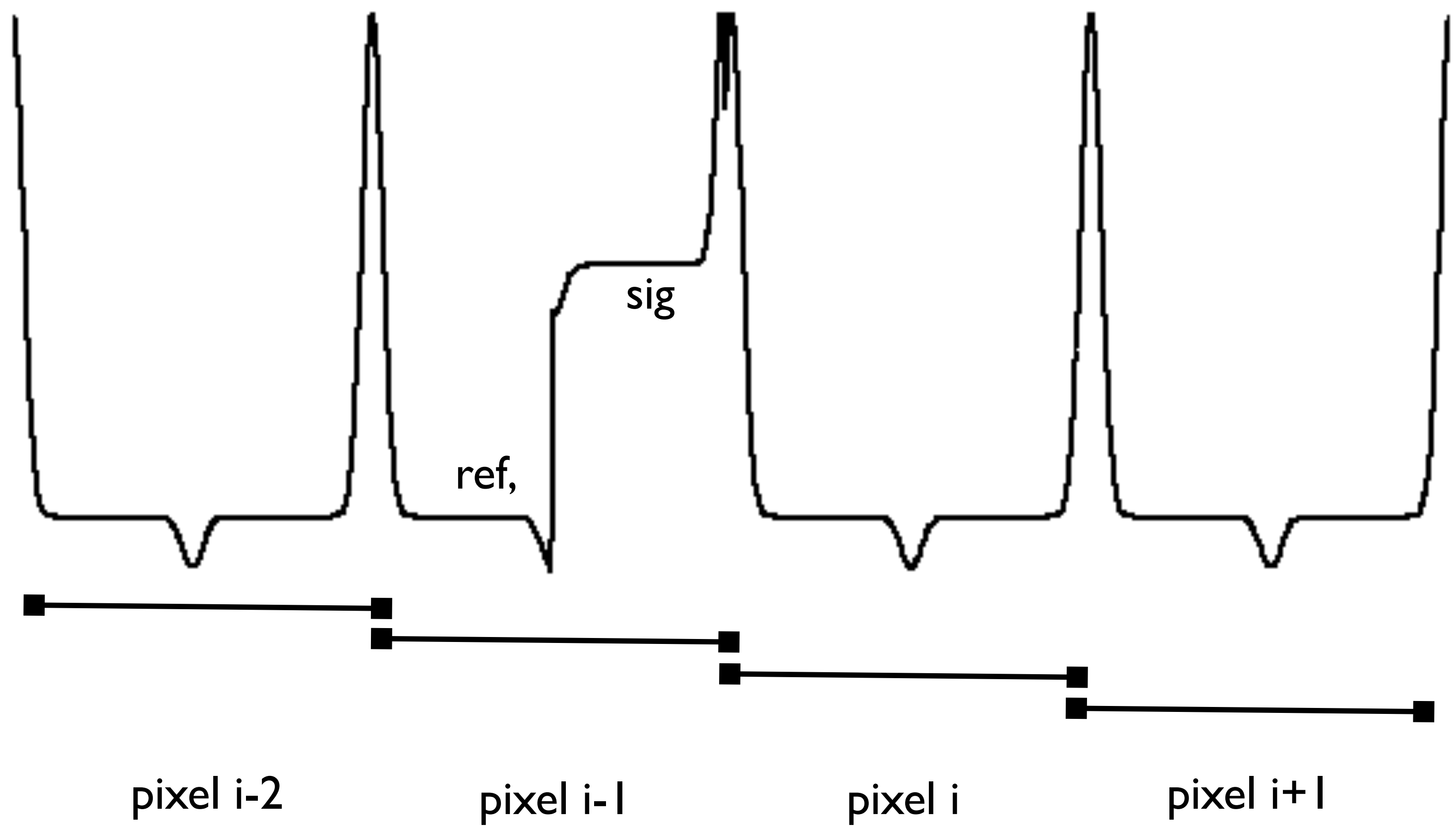
If the dark matter is light we could see it first!

Plan to reduce the readout noise



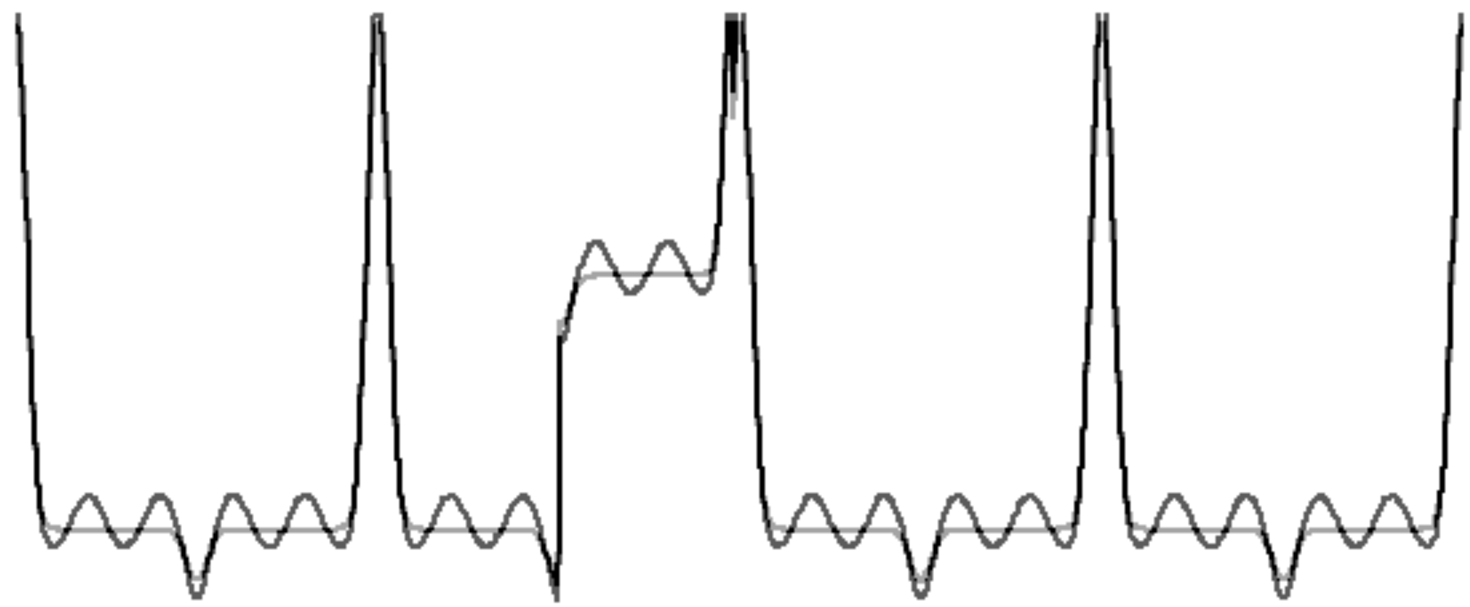
Why doesn't it keep going down?

Correlated Double Sampling readout (CDS)

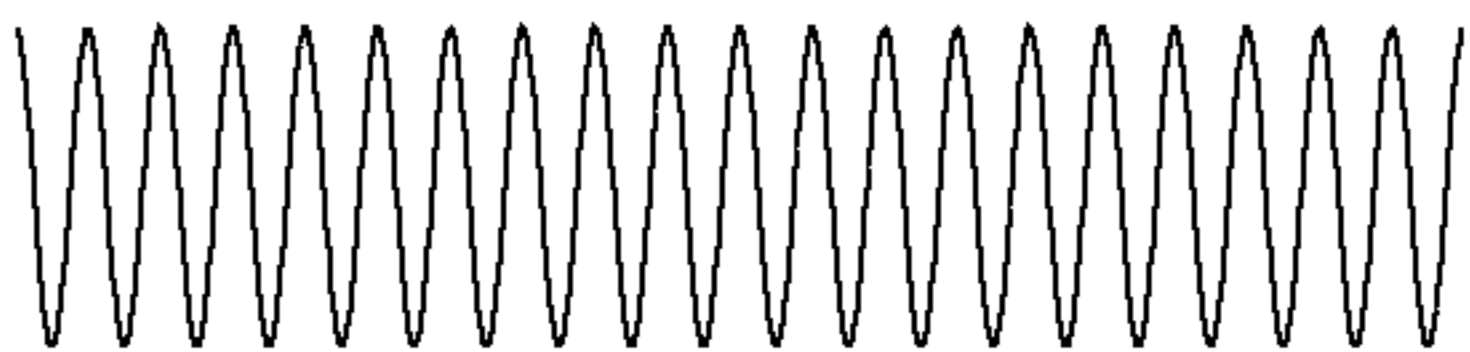


$$s_j^{cds} = \int_{t_j+\epsilon}^{t_j+\delta+\epsilon} [n(t) + \hat{s}_j]\mathrm{d}t - \int_{t_j}^{t_j+\delta} n(t)\mathrm{d}t.$$

filtering of high frequencies is responsible for reduction with integration time



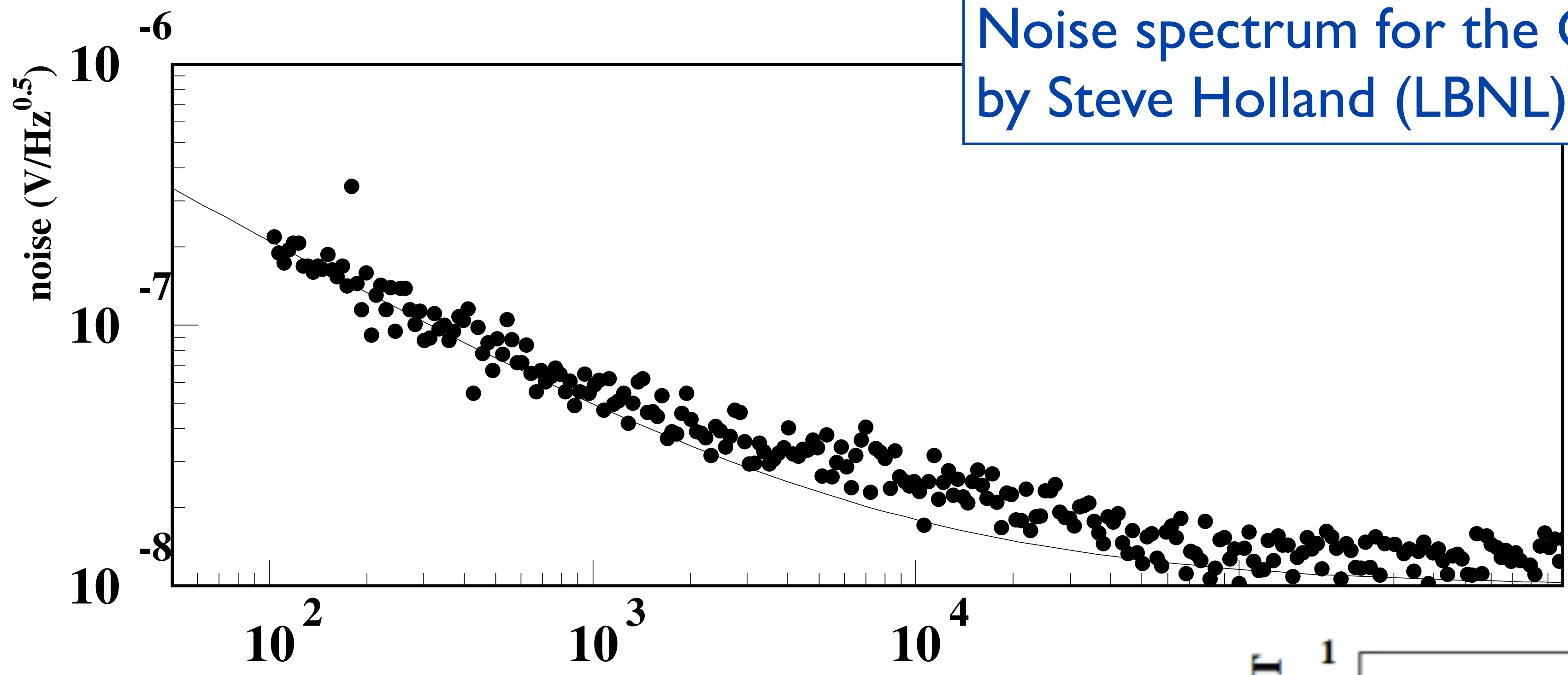
this "high frequency" noise is efficiently suppressed by the integrations for each window in the correlated double sampling.

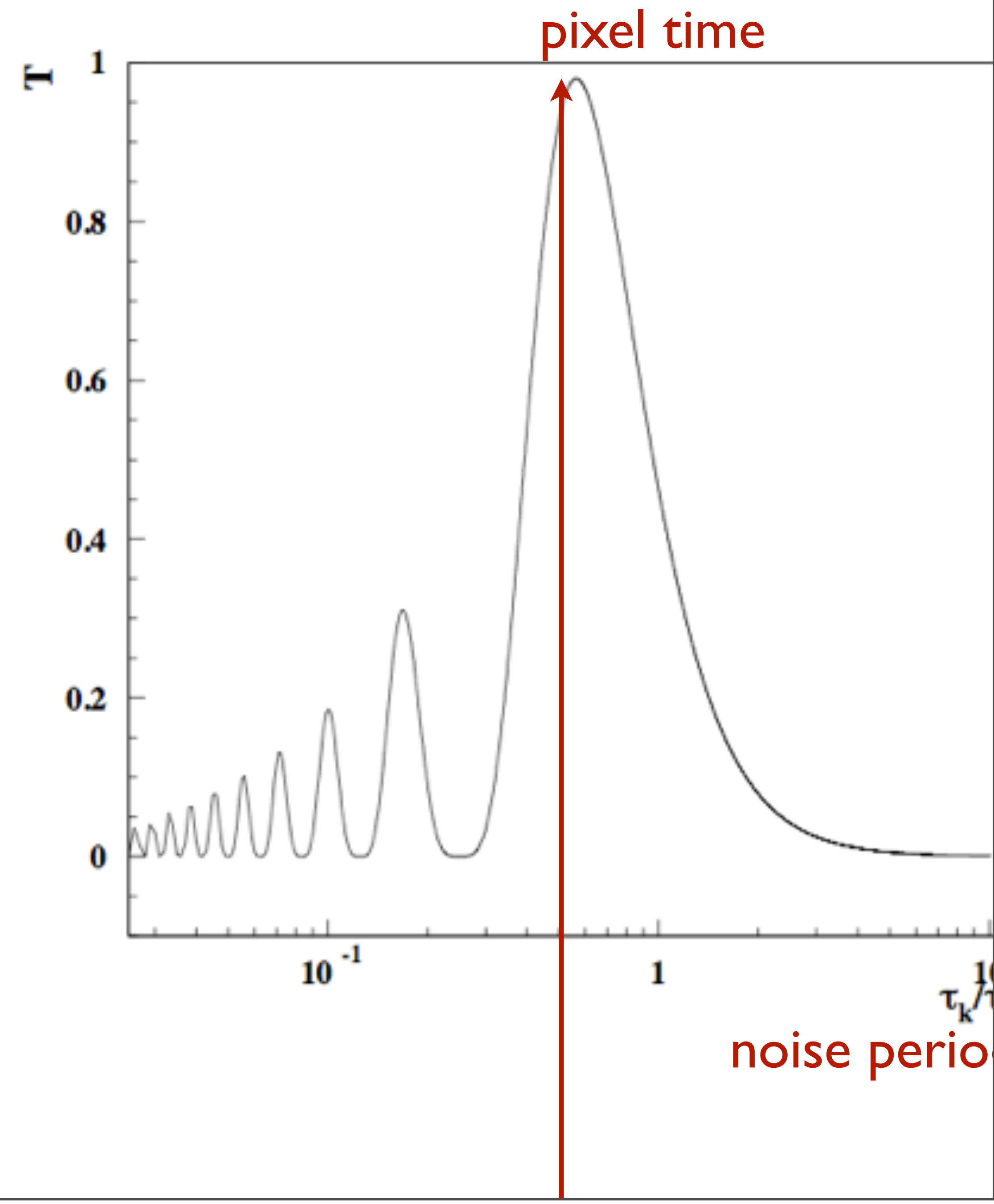


noise at pixel frequency is not suppressed by CDS

the noise with frequency of the order of the pixel is not filtered by the CDS. The only way to measure this contribution well is to look for the coherence of the noise over many pixels.

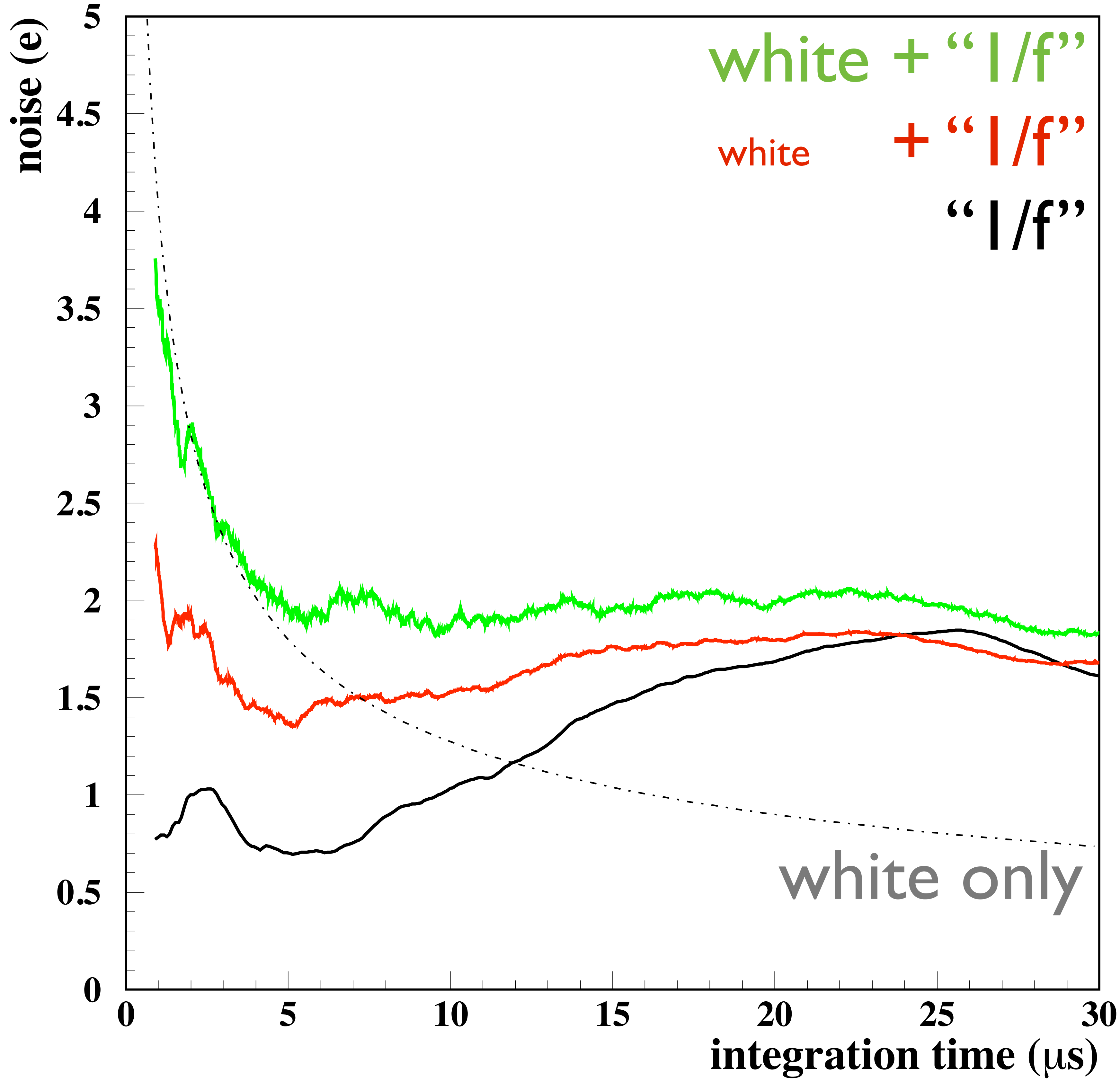
Noise spectrum for the CCD output provided by Steve Holland (LBNL).





For long pixel times, CDS becomes susceptible to lower frequencies. Since there is a "1/f" aspect of to the noise, the CDS noise goes up when you make the pixel longer.

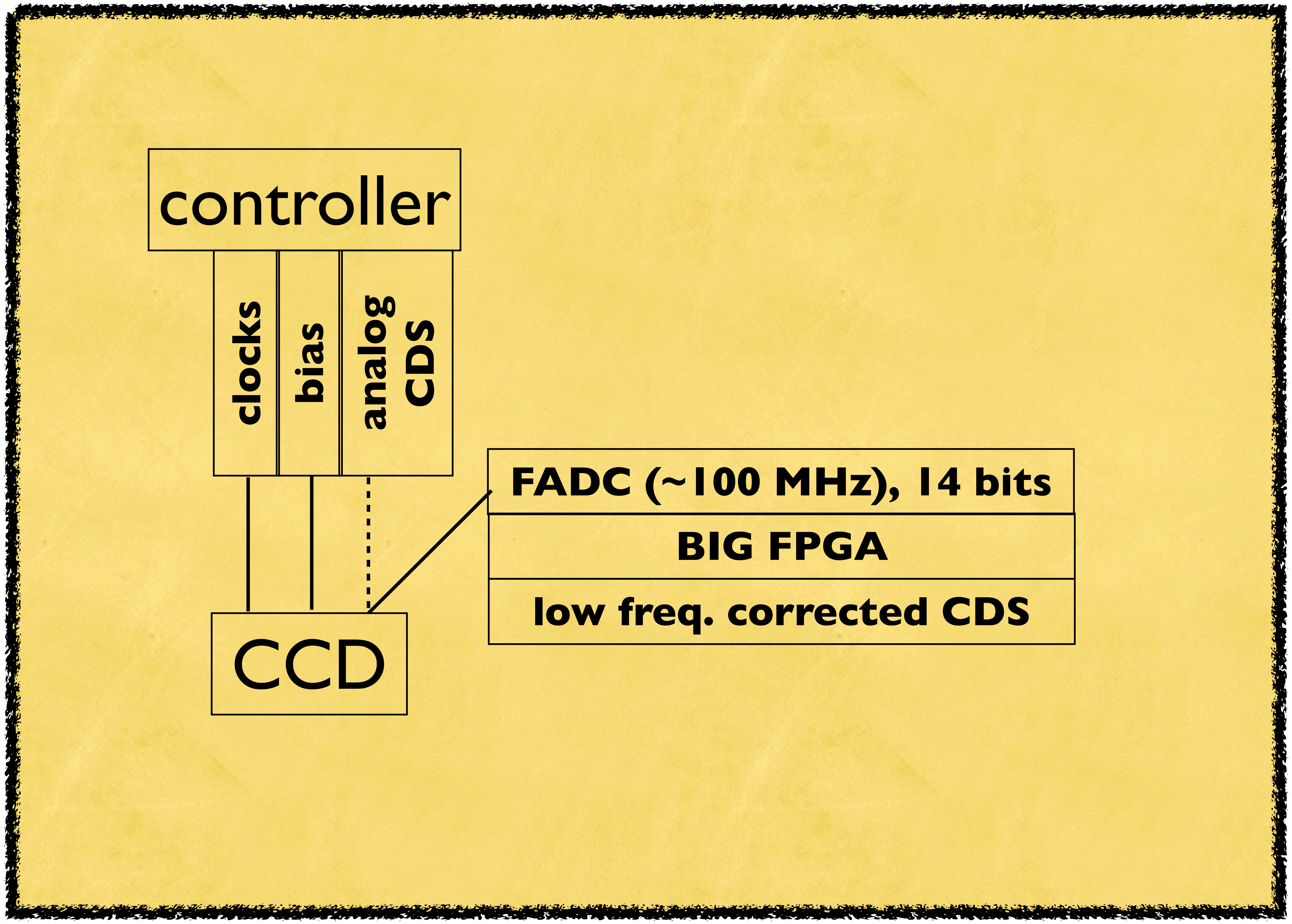
CDS noise in CCD simulation



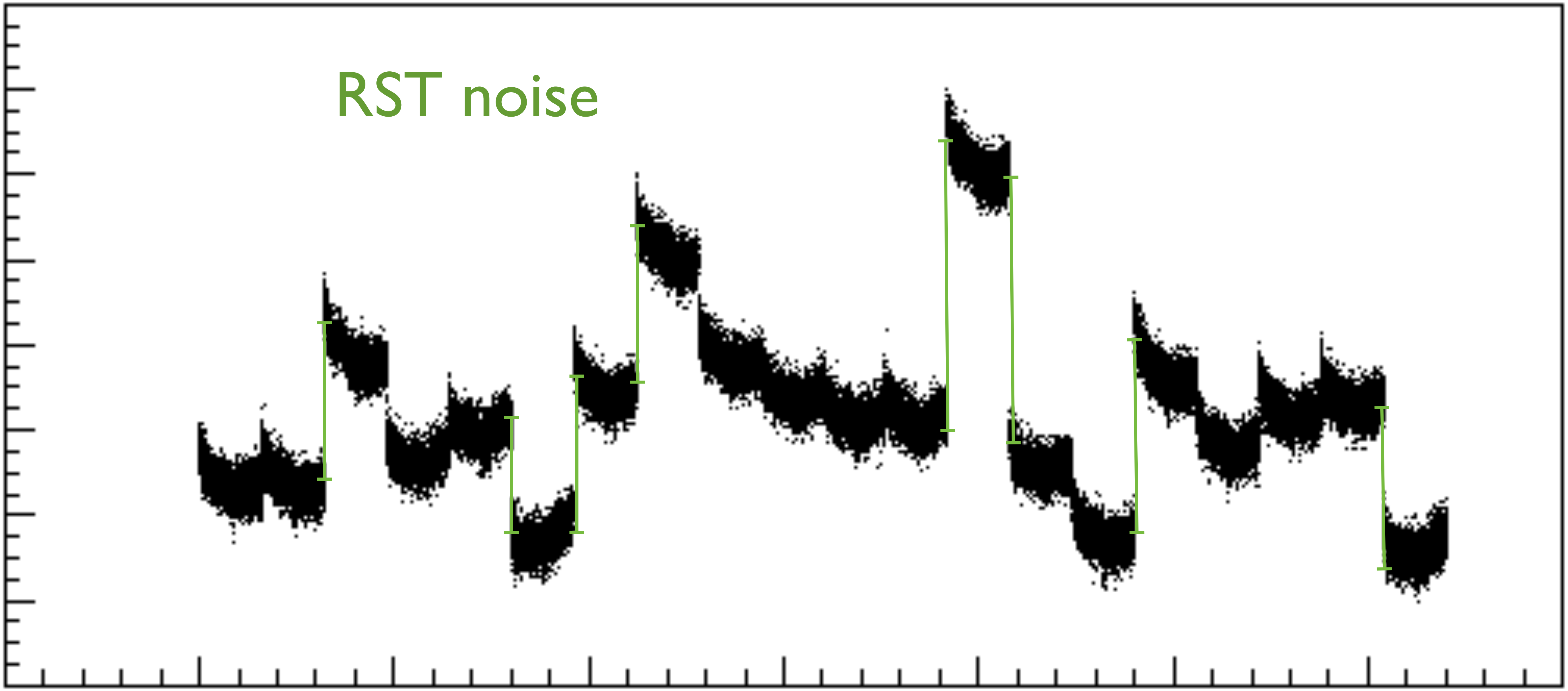
our strategy

sample the video signal of the CCD over many pixels with a fast ADC, then fit low low frequency components and subtract then before doing the CDS. This should suppress the low frequency noise contribution to CDS.

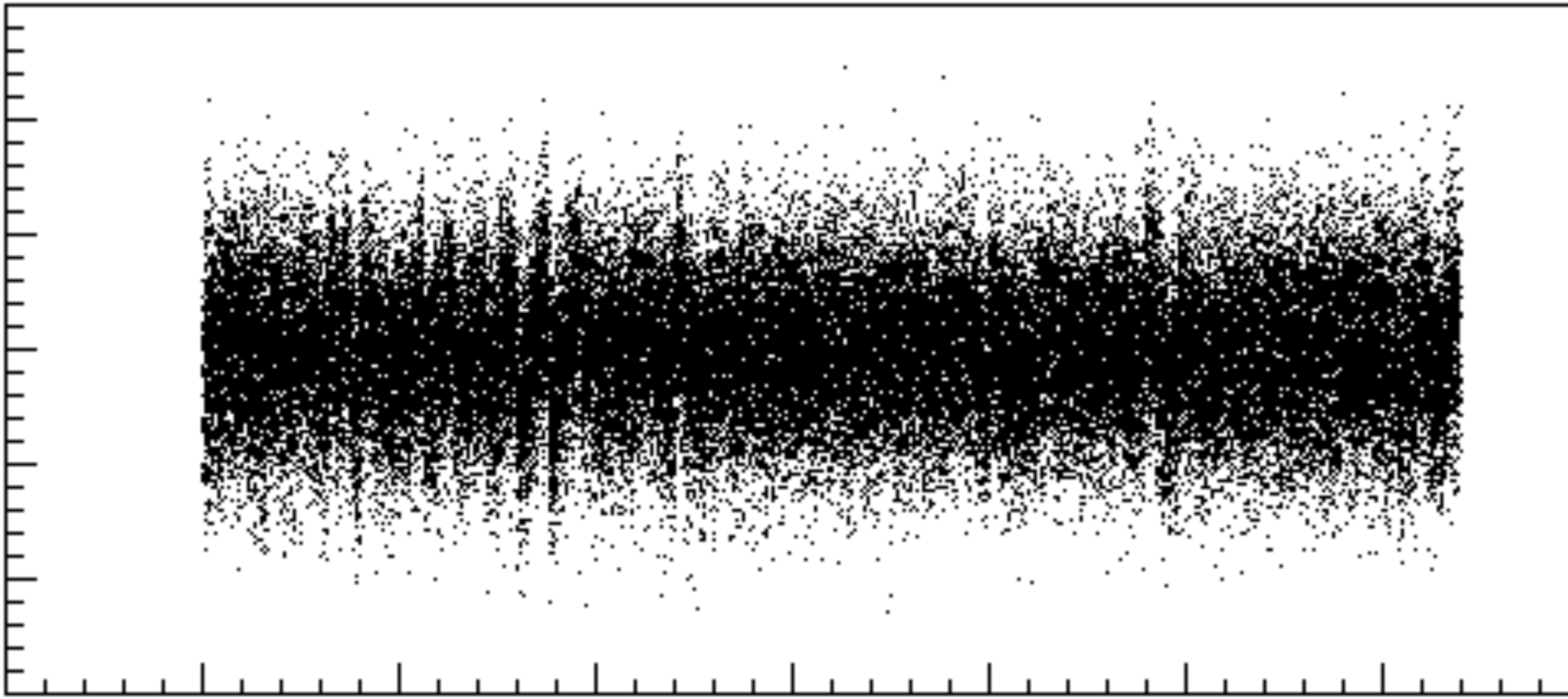
our strategy



Step 1: Digitize the signal

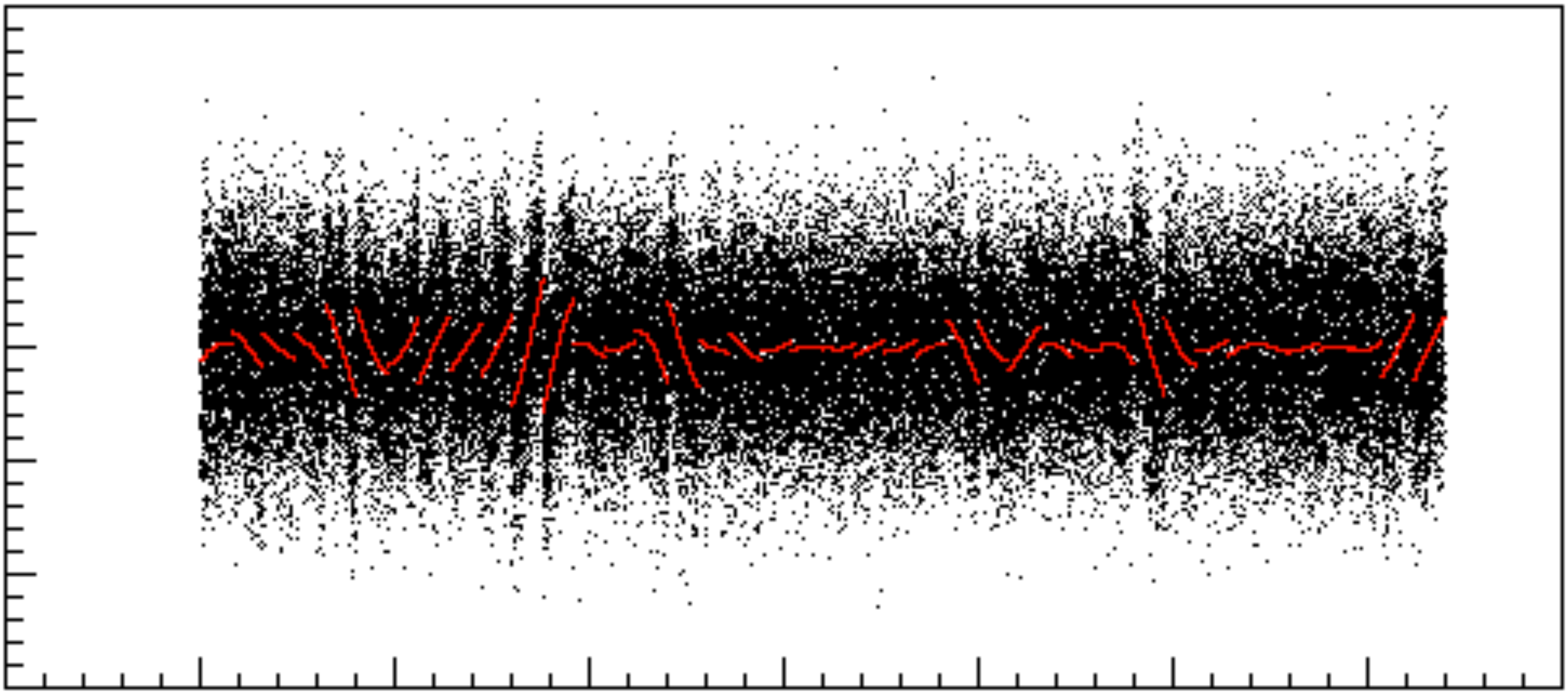


Step 2: remove features (RST noise, signal level, clocks, pixel average shape)

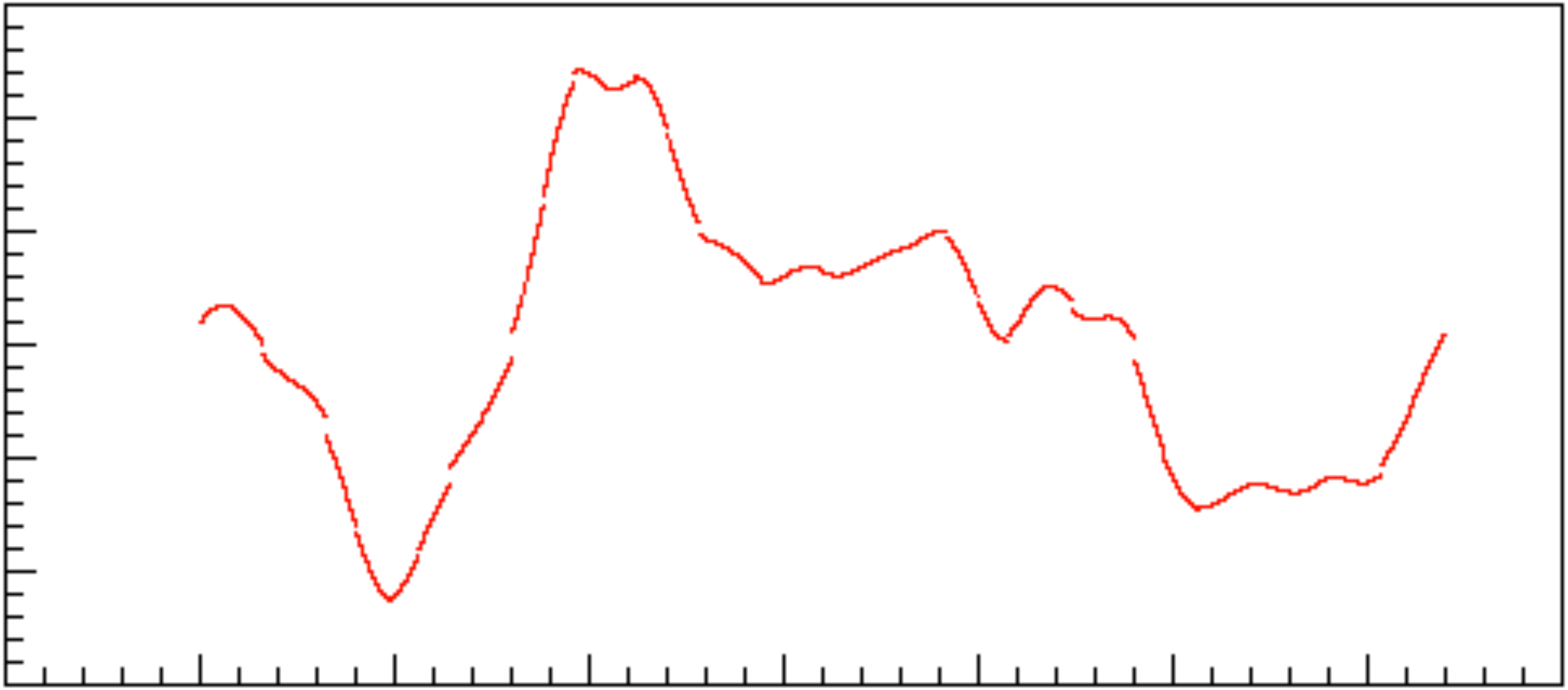


can you see the low frequency coherent components?

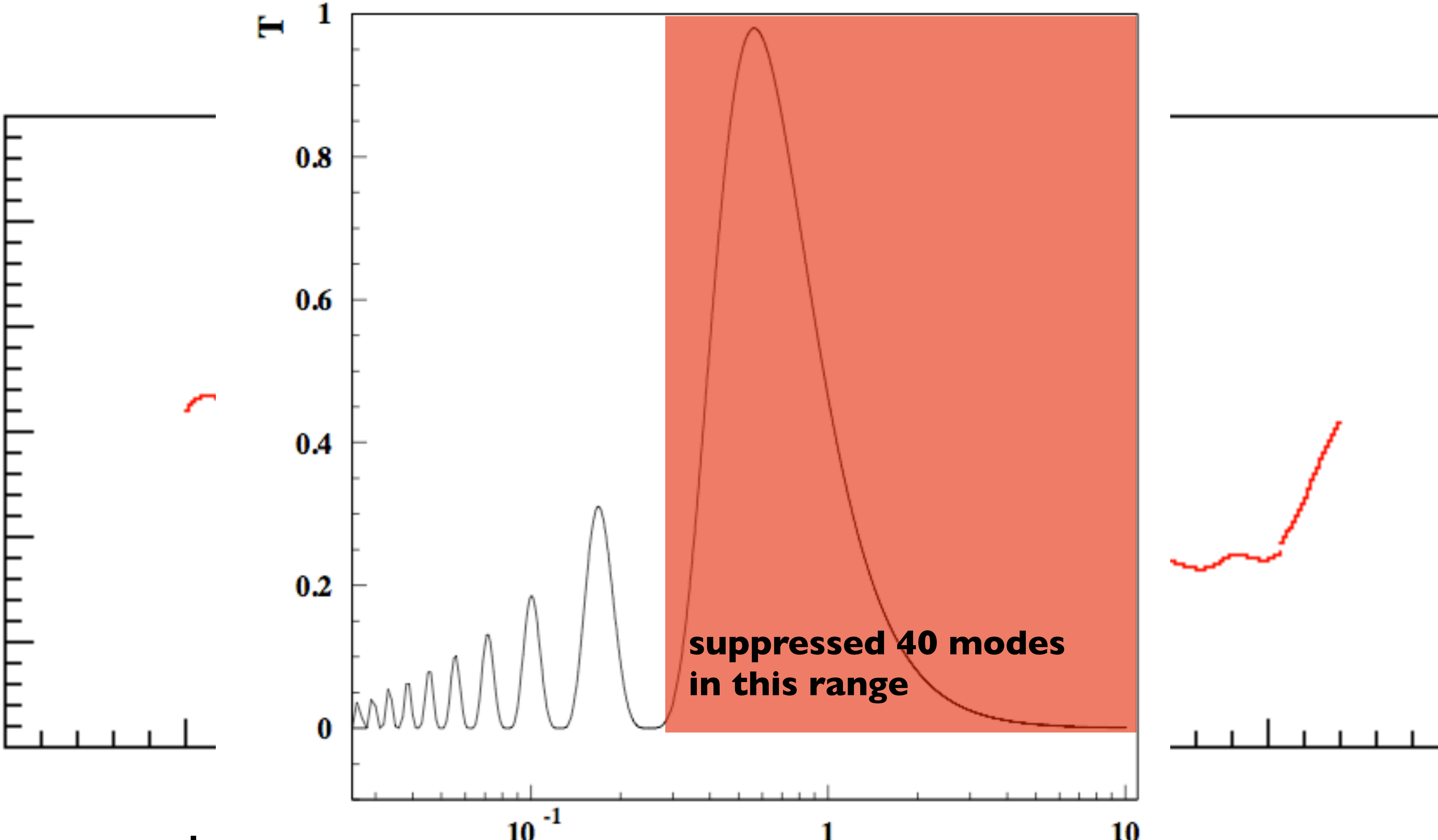
Step 3: Fit the low frequency noise (allow for jumps!)



this is the difficult part... solve a very large chi2 problem



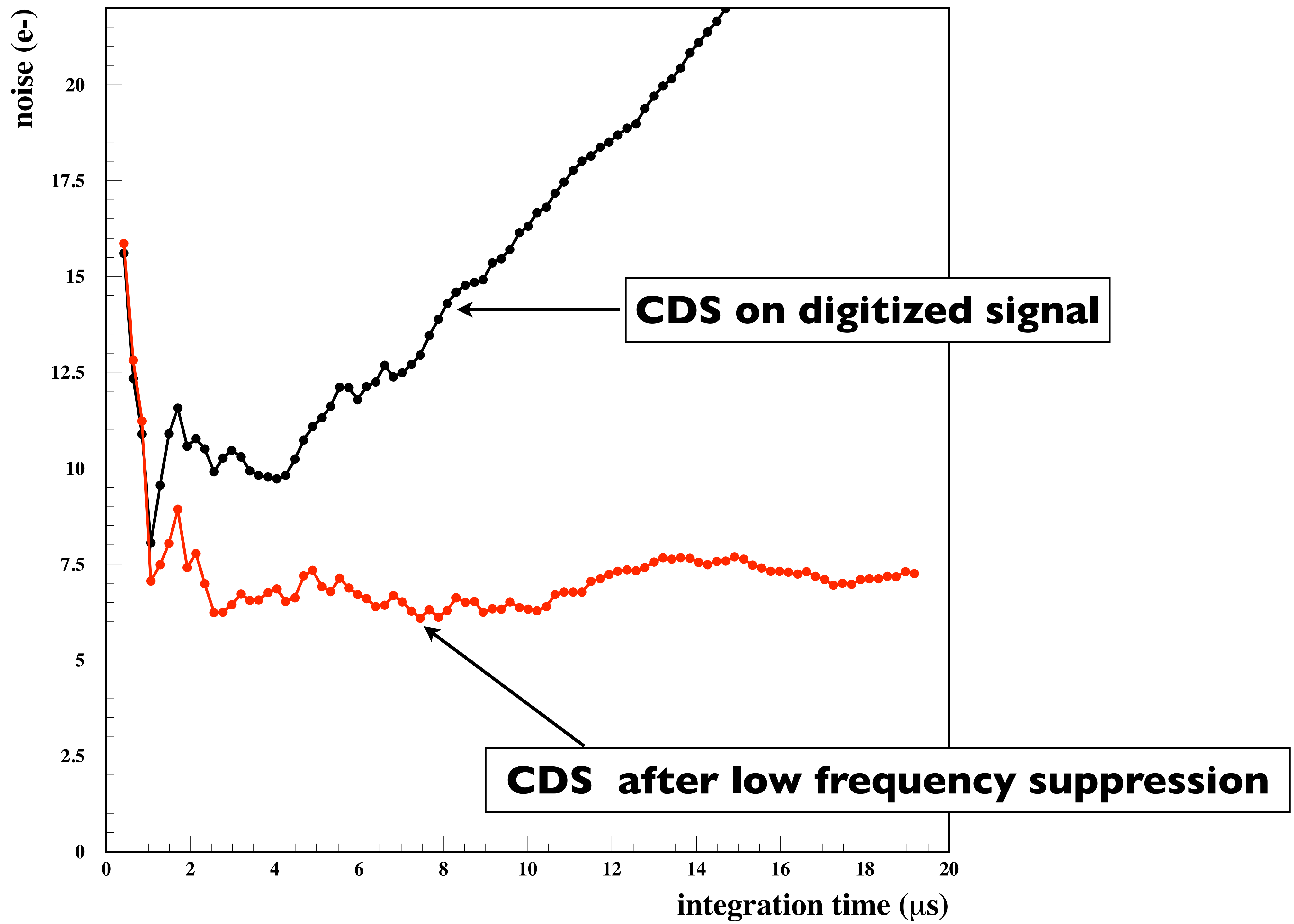
this is the low frequency stuff without jumps.


T
1
0.8
0.6
0.4
0.2
0
10 -1
1
10
τ_k/τ
suppressed 40 modes
in this range

th … mps.

Does it work?

DECam CCD driven by Leach controller.



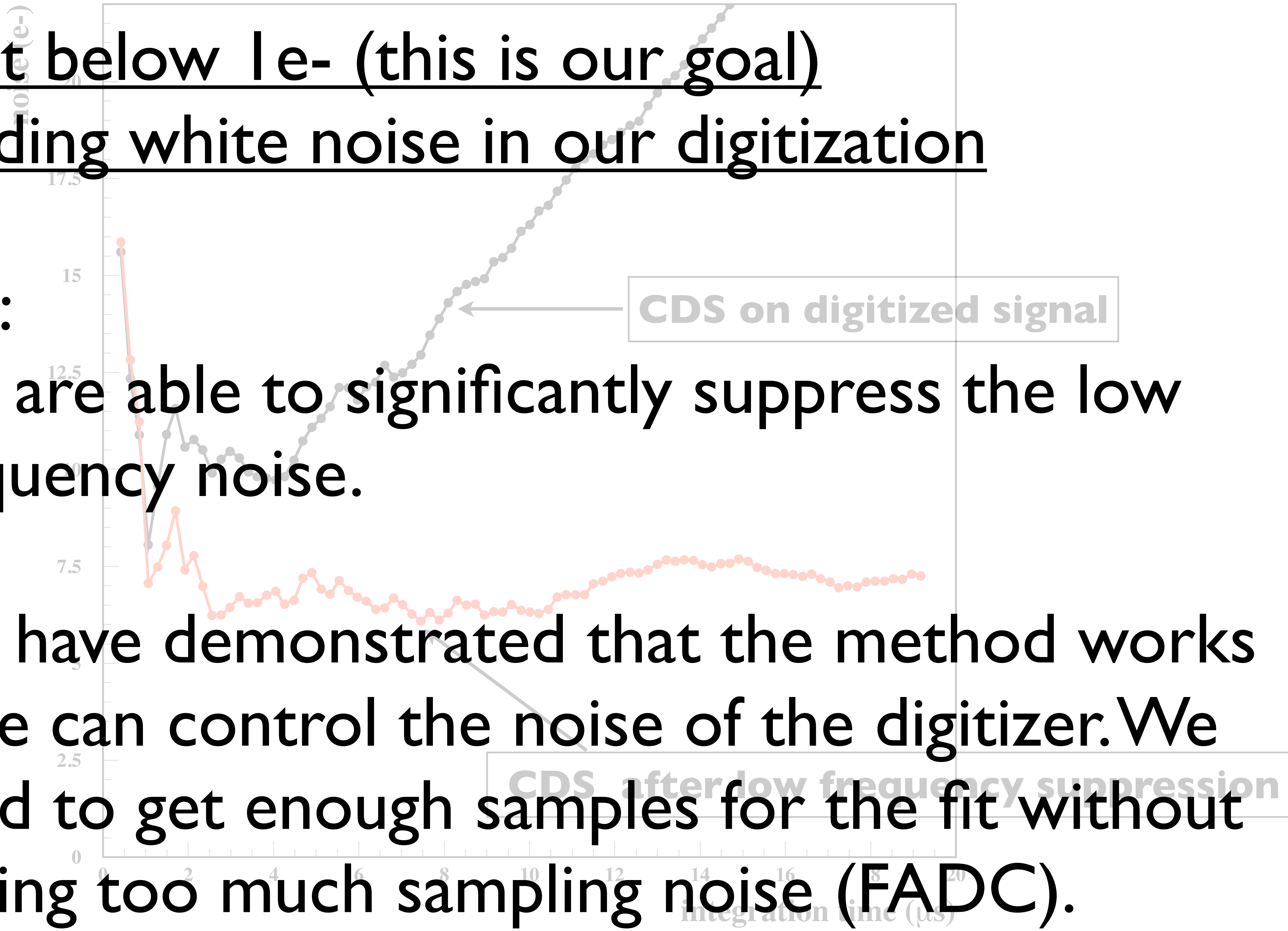
Does it work?

<u>did not get below 1e- (this is our goal)</u>
<u>we are adding white noise in our digitization</u>

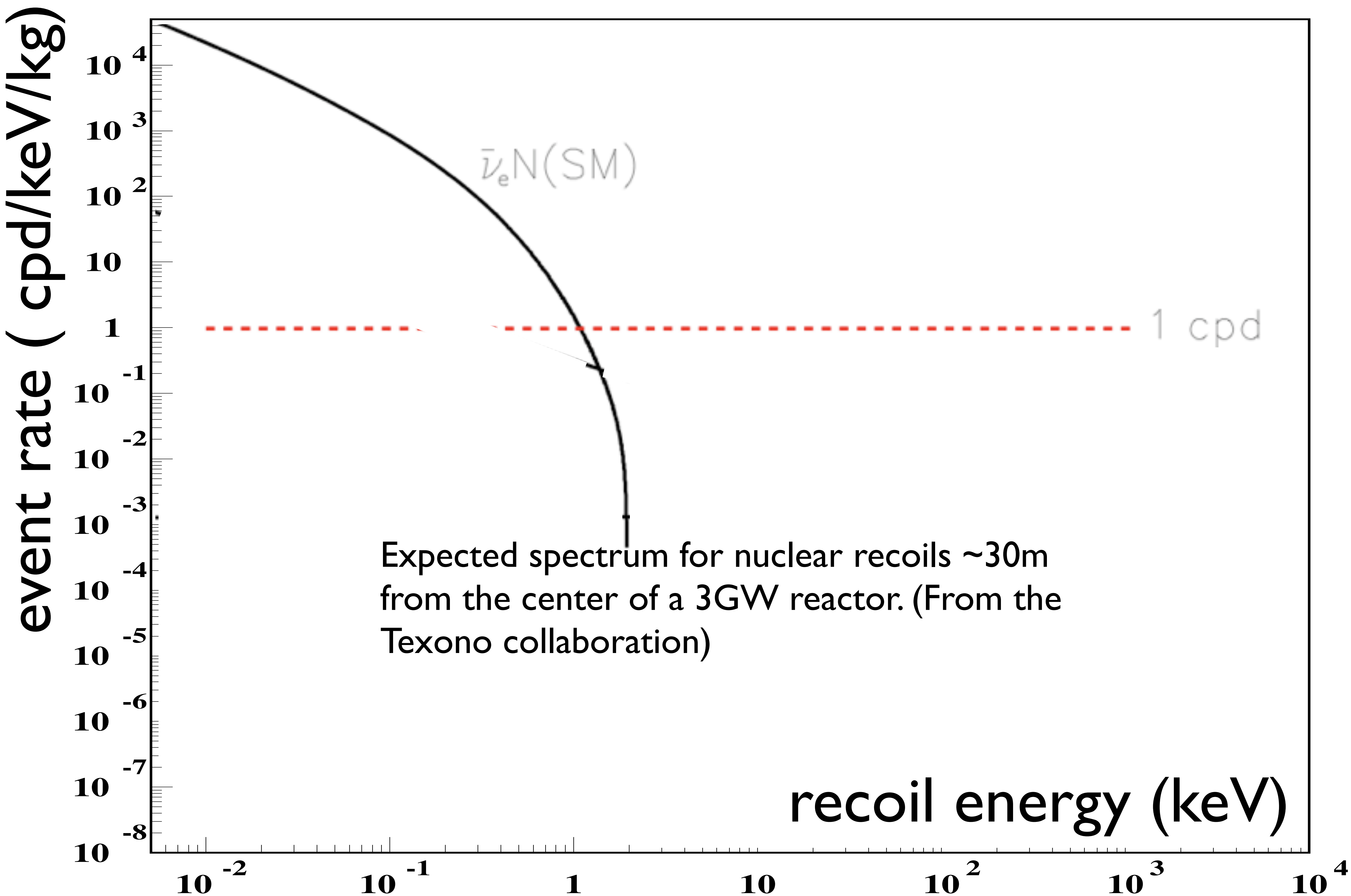
However:

We are able to significantly suppress the low frequency noise.

We have demonstrated that the method works if we can control the noise of the digitizer. We need to get enough samples for the fit without adding too much sampling noise (FADC).



Another potential application for a low background low noise CCDs **Neutrino technology** and first detection of coherent neutrino scattering.



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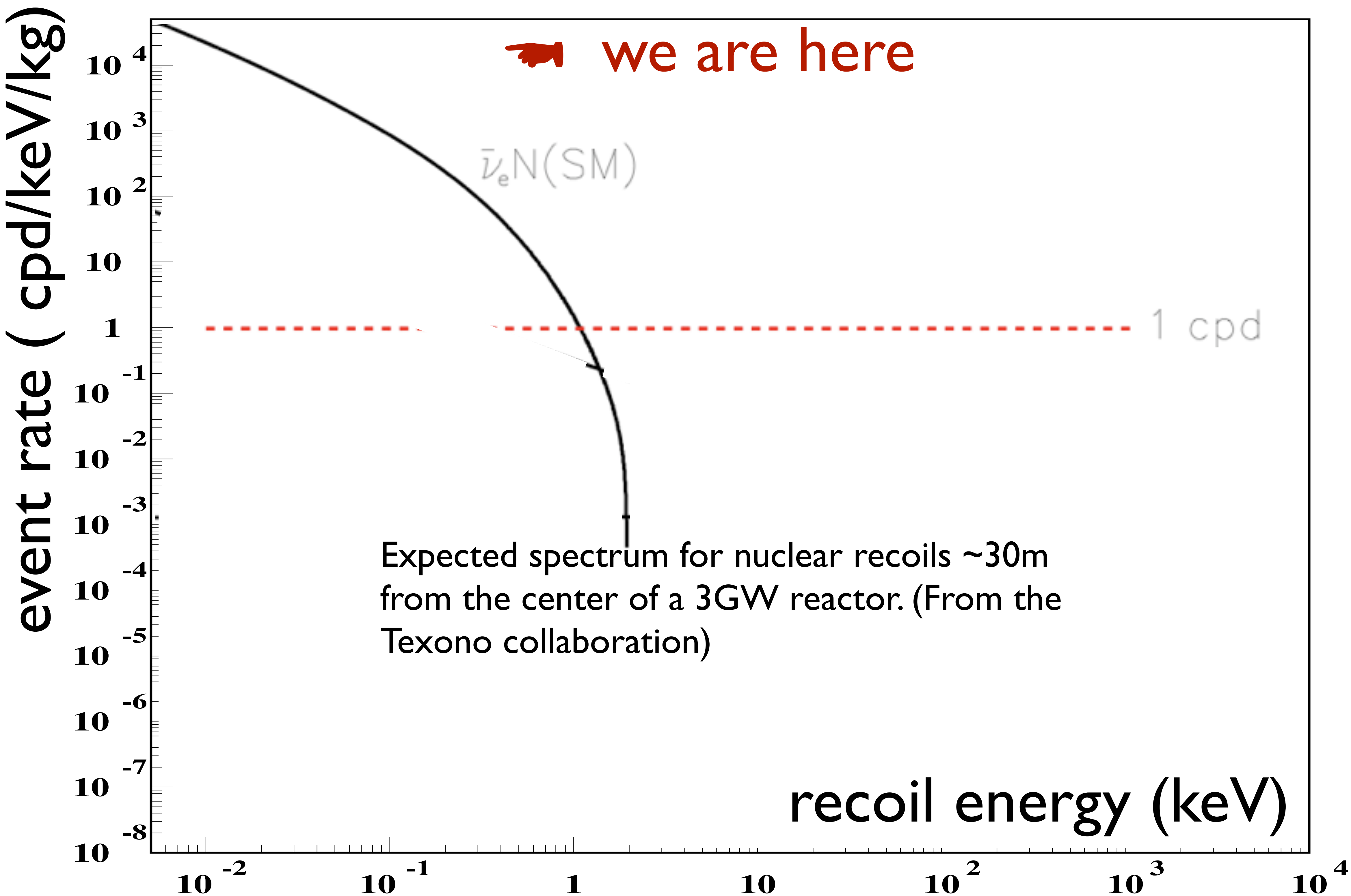
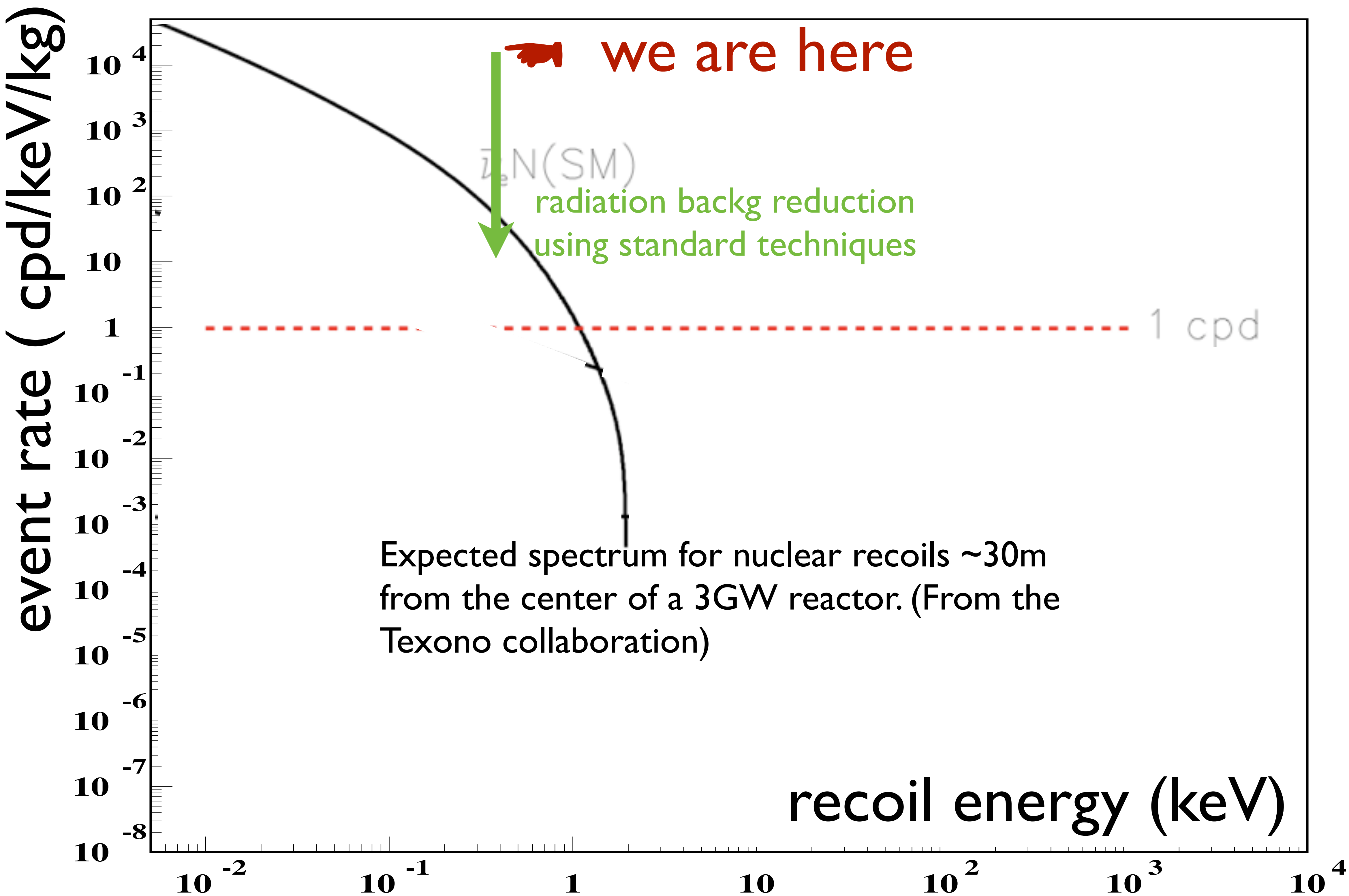


Another potential application for a low background low noise CCDs **Neutrino technology** and first detection of coherent neutrino scattering.



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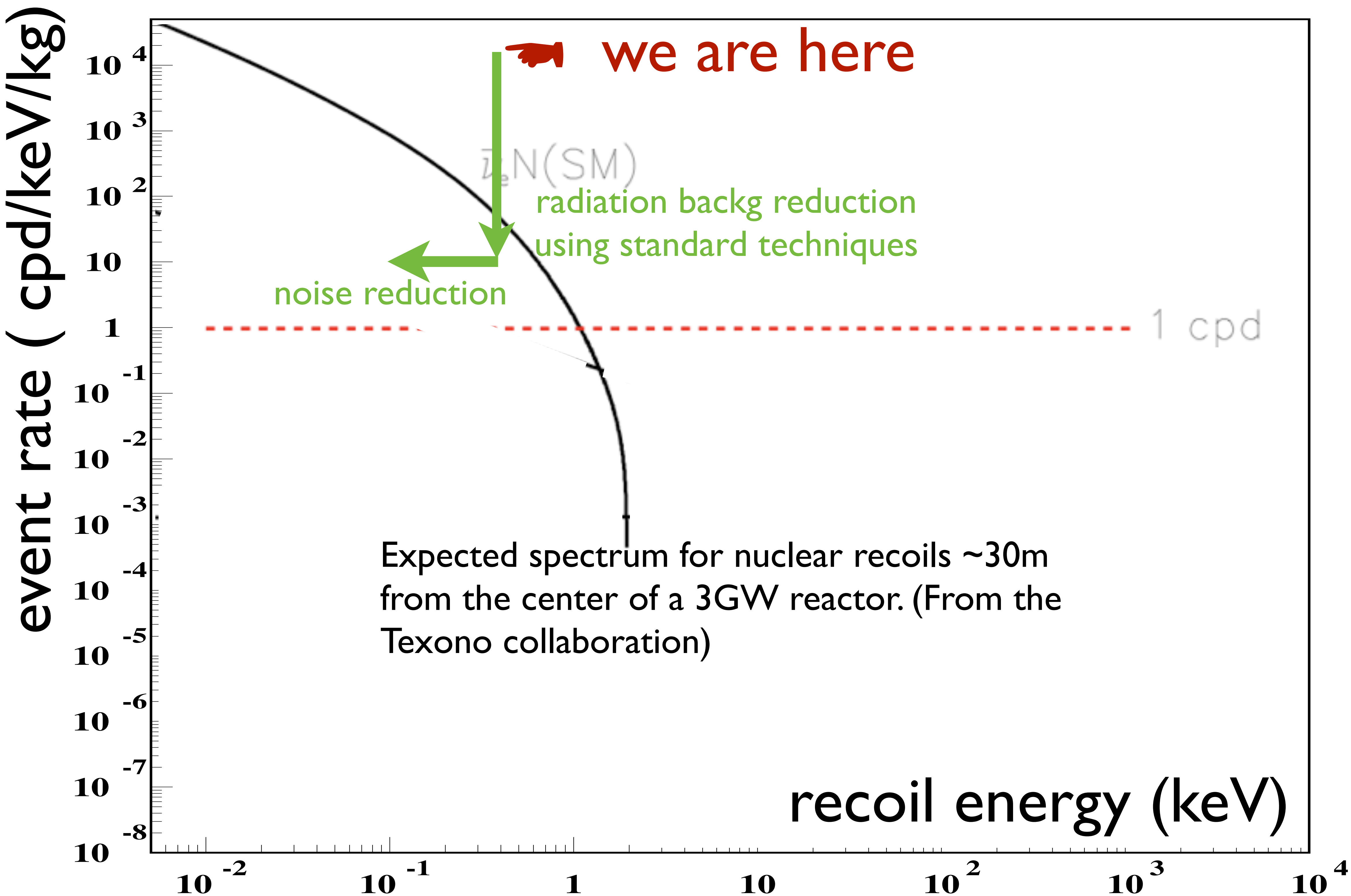

Conclusion

- We are investigating the possibility of using CCDs in low background low threshold experiments. Direct Dark Matter Search and maybe neutrino technology.
- Key question: Is there any radiation intrinsic to the detectors that would make this impossible? For the moment be believe the answer is NO.
- How low could we push the noise on these detectors?
- We need detectors with low noise (no speed requirement), thick, small pixels and with have no optical requirements (no AR coating).