8th Patras Workshop on Axions, WIMPs & WISPs

Advances in CCD Sub Electron Noise Techniques and Applications

Gustavo Cancelo, 07/18/2012

ENERGY Office of Science Fermilab Jefferson Lab URA

Goal

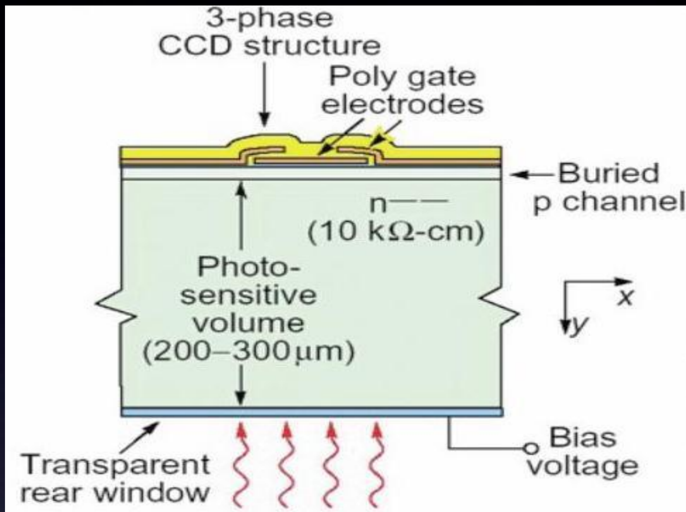
- Lower CCD readout noise using signal processing methods to be able to detect $\mathcal{O}$(eVee) energy levels.
  - These methods could be extended to other sensors.
- Applications:
  - Dark matter.
  - Dark energy.
  - Neutrino coherent scattering.
  - Spectroscopy for astronomy.

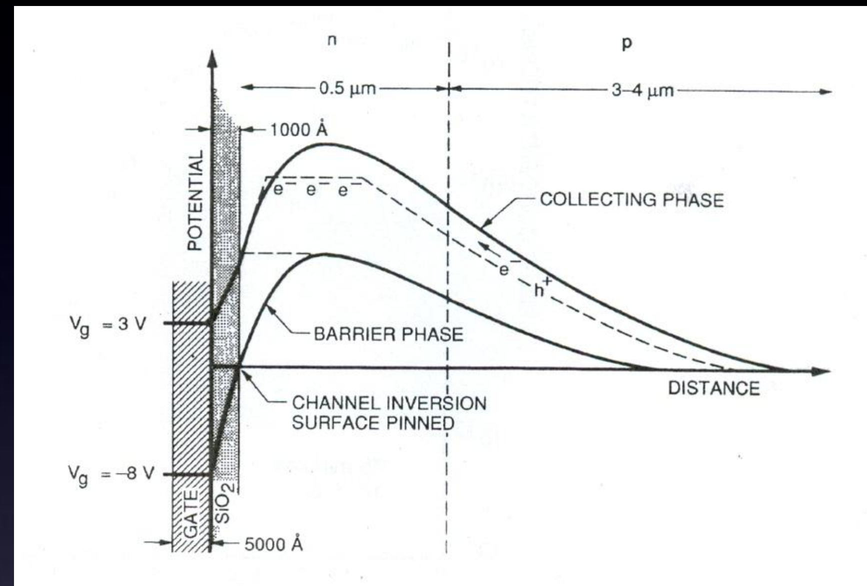
Outline

- Why CCDs?
- Sub electron noise in CCDs,.
    - Digital filtering method to reduce colored noise.
        - General method. Can be used by other detectors.
    - Skipper CCD.
    - Current applications.

Charge Coupled Devices (CCD)

Potential well

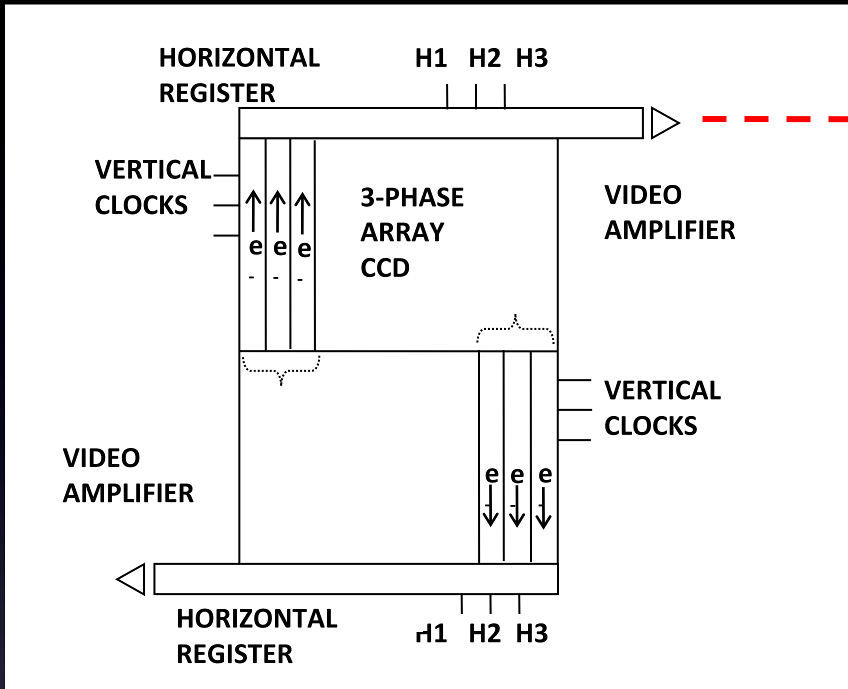


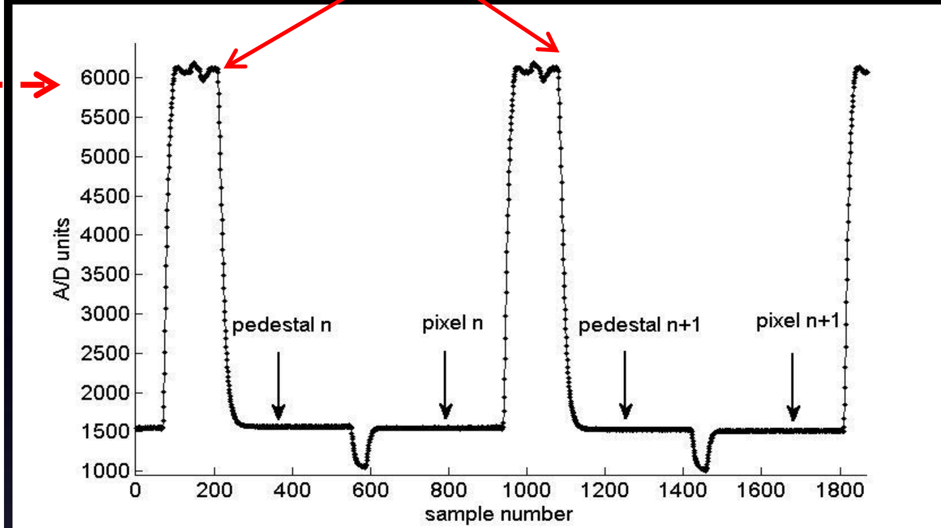


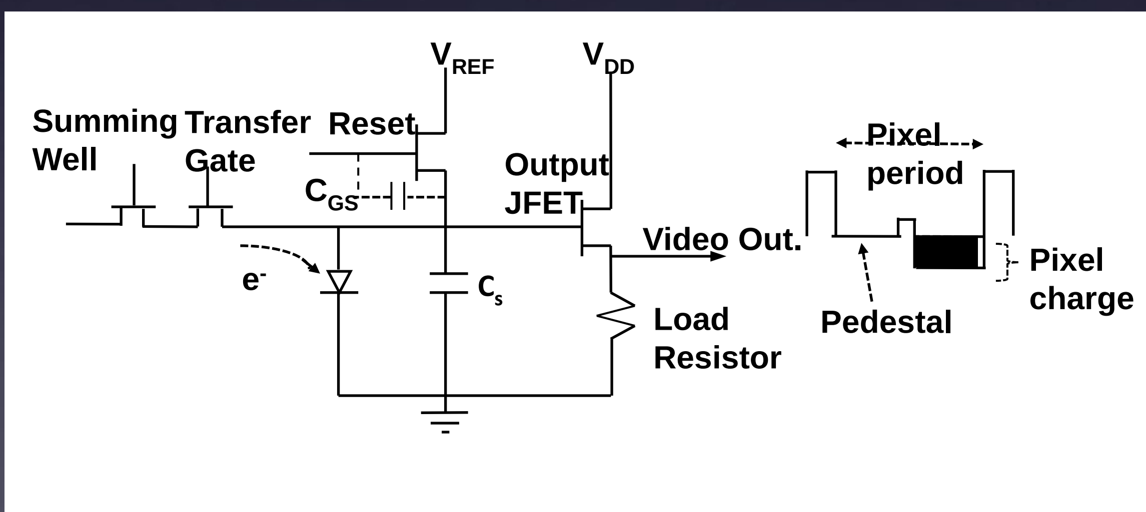
Characteristics:
Properly biased CCDs store charge in a potential well.
Very low noise detectors => high dynamic range.
1e- of noise RMS => 3.6eV ionization energy.
High spatial resolution: 15 x 15 micron pitch for DeCam CCDs.
High density: 8Mpix for DeCam CCDs.

CCD Images

Reset pulses are ~ 50,000 e^-

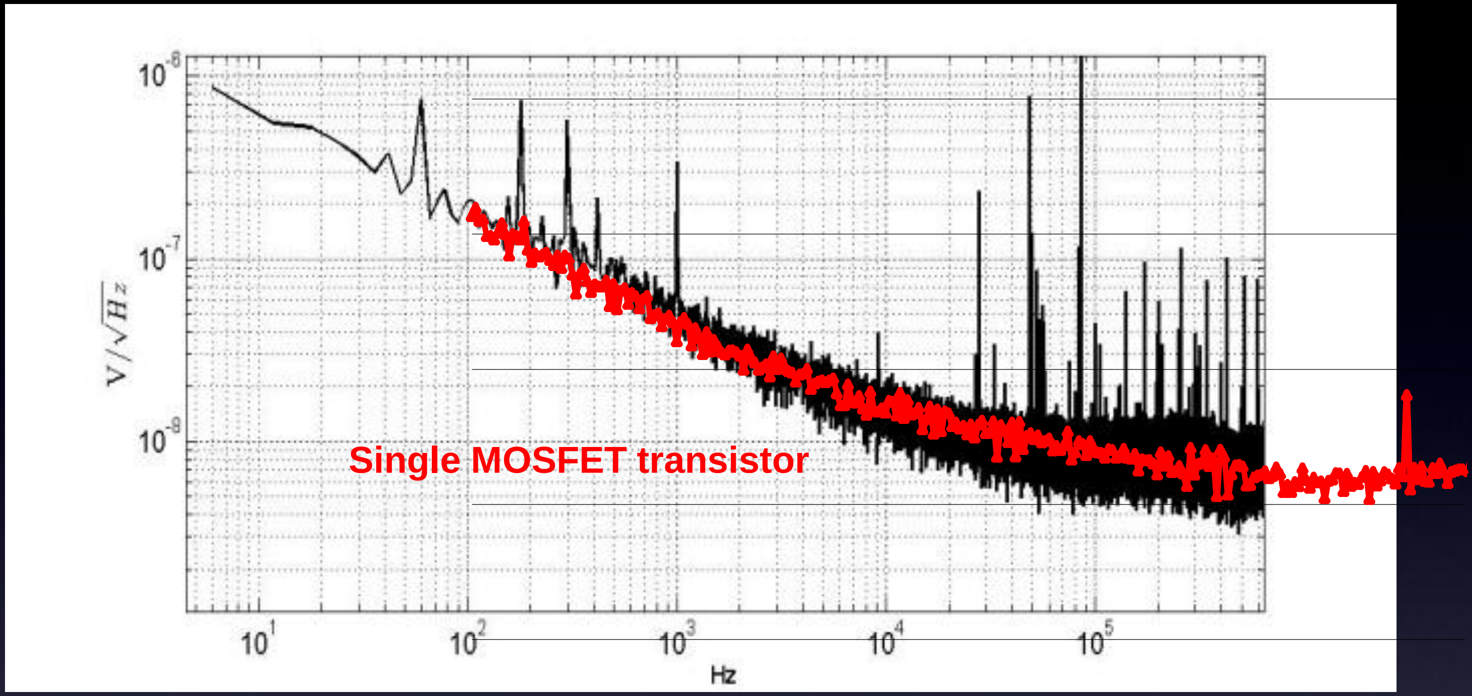






FITS image:
Each pixel is a n-bit digital representation of the pixel charge.

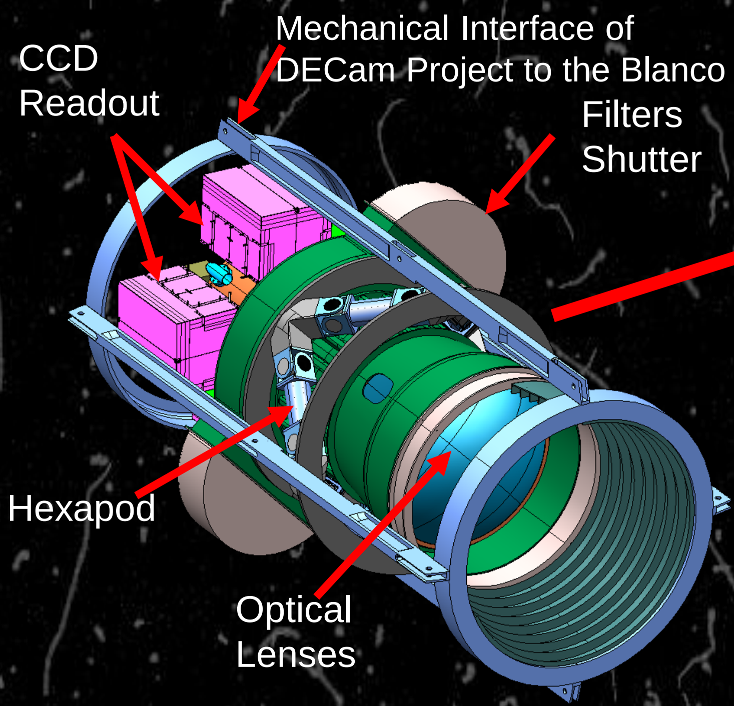
CCD noise: single video transistor and system noise



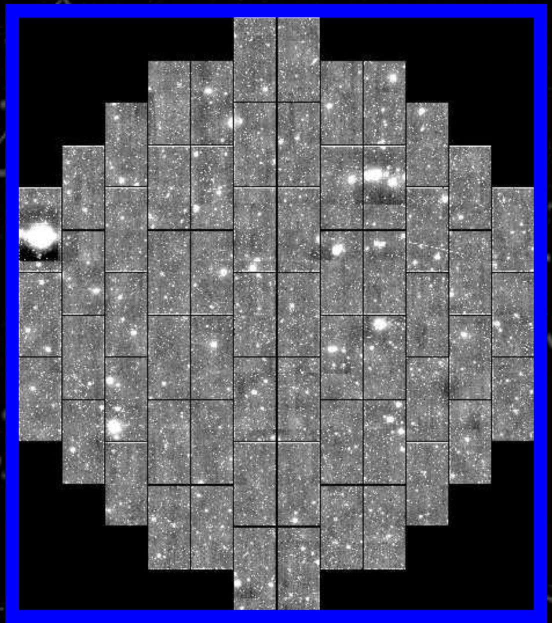
- Red trace: CCD noise measured by the LBNL designers using a test board.
  - 1/f noise larger than WGN up to 50 KHz.
  - WGN about 10nV/√Hz.
- Black trace: FNAL 24 bit ADC based system.
  - x3 lower noise than the Monsoon system used for DeCam (DES).
  - Despite power supply and EMI noise reduction the system still shows some 60Hz and high frequency resonances.

Dark Energy Camera (DECam)

New wide field imager for the Blanco telescope (largest focal plane in the southern hemisphere)
Largest CCD project at FNAL.
DECam is being built at FNAL including CCD packaging, full characterization, readout electronics.
CCD facilities at SiDet and 5+ years of experience positions FNAL as a leader for this task.

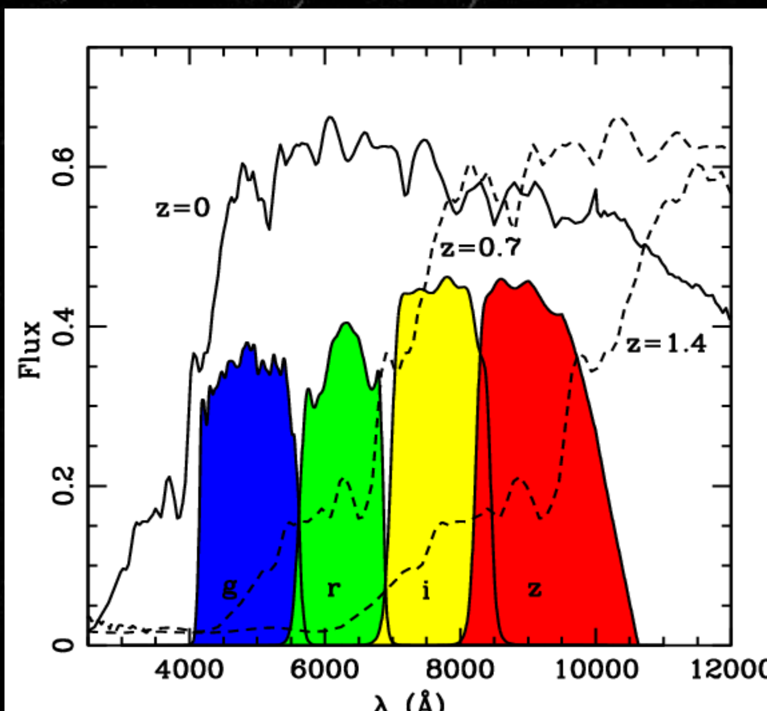


Focal plane with 74 CCDs (~600 Mpix).
All the scientific detectors in hand, packaged and characterized at FNAL.

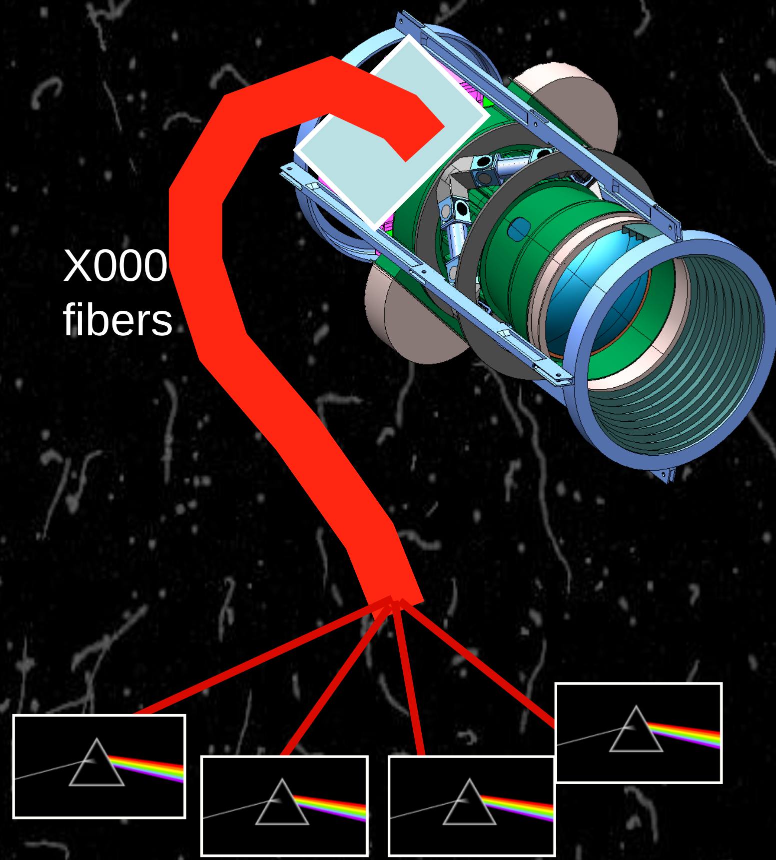


DECam estimates redshift from the colors of the objects.
DeCam used 4 filters

DeSPEC spectrograph proposal:
Lower signal to noise ratio.

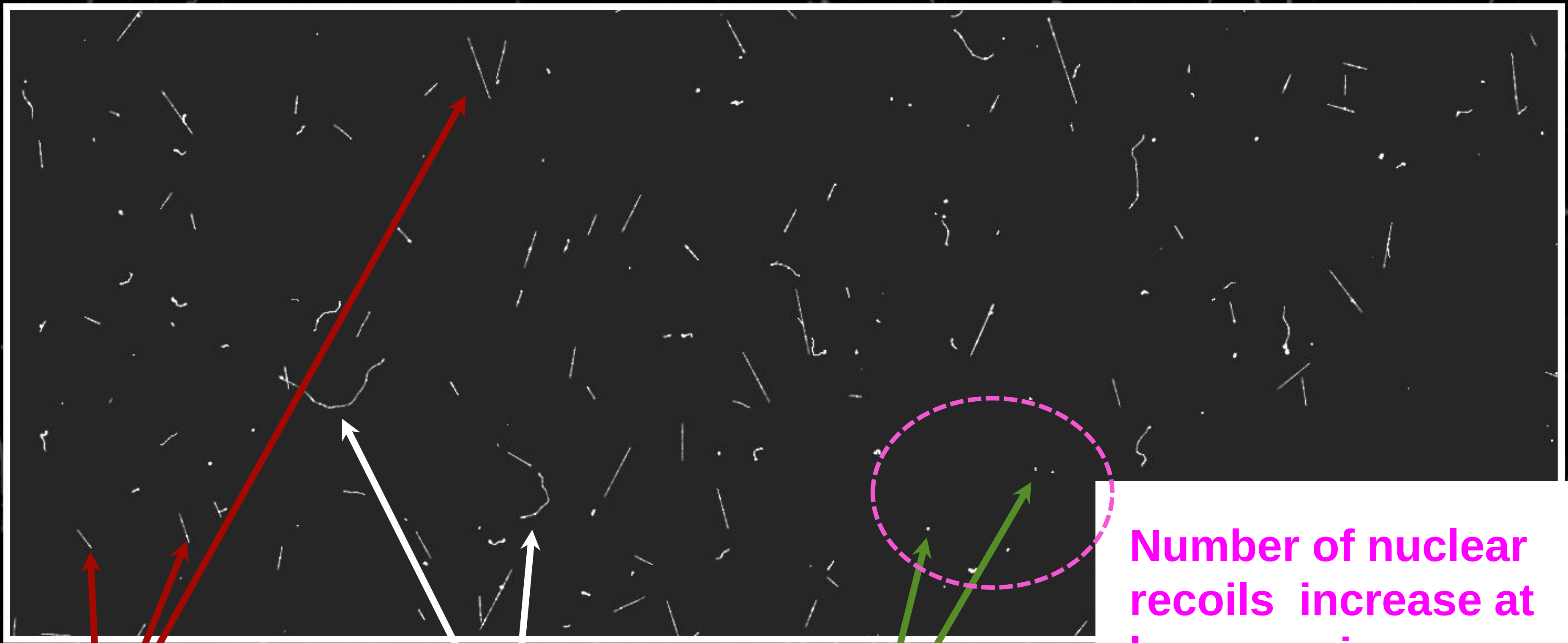


4 DES filters
colors change as galaxy moves in z

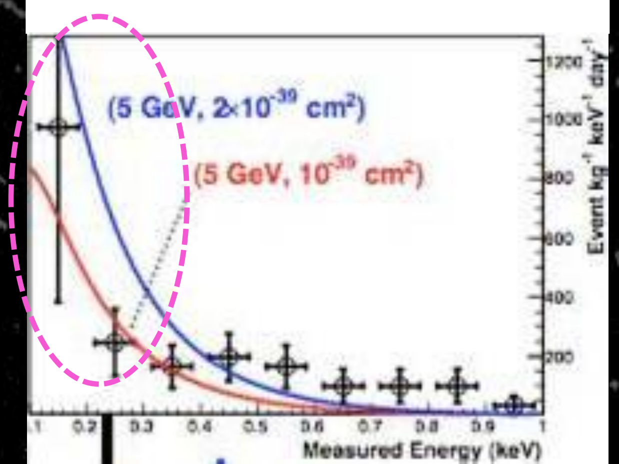


several spectrographs

Particle detection with CCDs



Number of nuclear recoils increase at low energies.



muons, electrons and diffusion limited hits.

nuclear recoils will produce diffusion limited hits

Awesome pattern recognition in a single device!!
3-D features can be inferred from CCD's 2-D images.

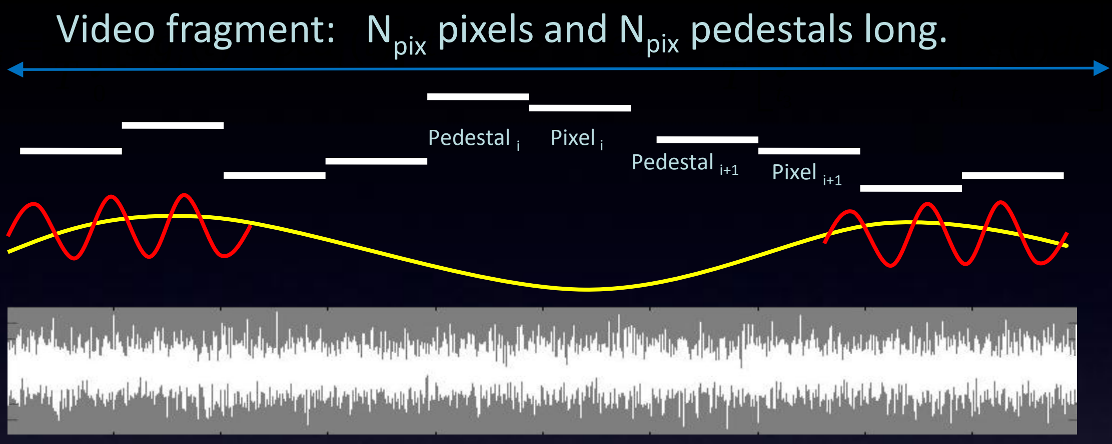
Correlated noise reduction techniques

• 1/f noise or “pink noise” is often the S/N limitation to achieve lower energy detection in cosmology and other areas of physics and engineering.

• We have developed a general technique that applies to detectors and sensors that use the Correlated Double Sampling (CDS) double ramp integration for noise reduction.

• Although the techniques have been tested it in CCDs they can be extended to other devices such as: xray, Gamma-ray, CMOS detectors, etc.

Correlated Double Sampling (CDS)



s(n) pedestals and pixels

n(n) correlated noise (LFN)

w(n) white Gaussian noise

$$x(n) = s(n) + n(n) + w(n)$$

$$cds_i = \frac{1}{T}\int_0^T \left[sig_i(t) - ped_i(t)\right]dt \quad \Rightarrow \quad cds_i = \frac{1}{T}\left[\int_{t_3}^{t_4} x_i(t)dt - \int_{t_1}^{t_2} x_i(t)dt\right]$$

$$\sigma^2_{w_{cds}} \to 0\Big|_{T\to\infty}$$

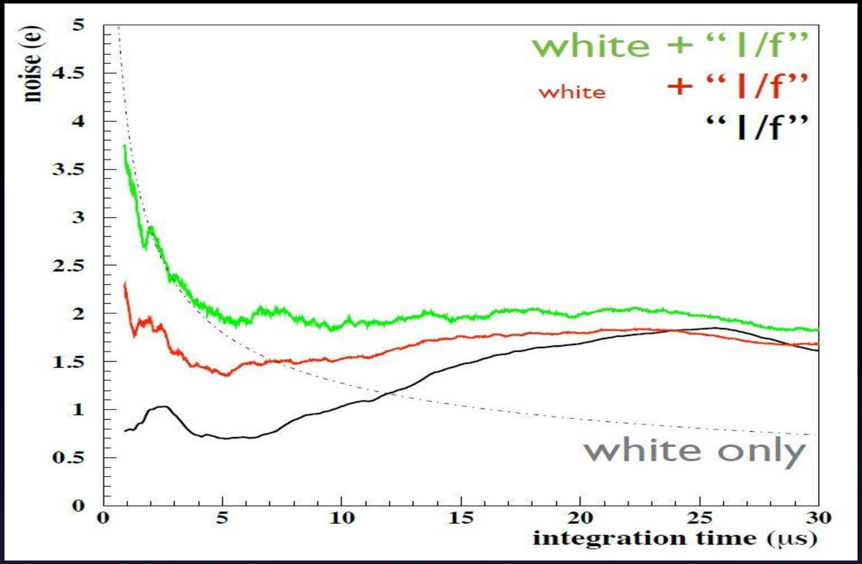
For the white and Gaussian noise w ~ N(0,σ²), the CDS is the optimum estimator.

but

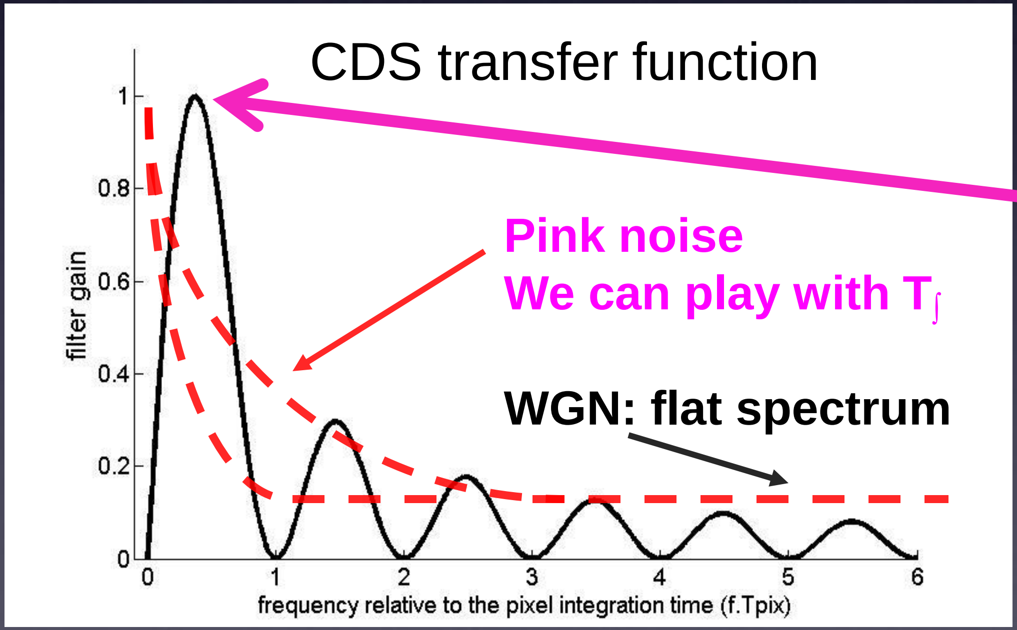
$$\sigma^2_{n_{cds}} \neq 0\Big|_{T\to\infty}$$

It actually grows for longer T because the 1/f noise grows exponentially as f->0.

CDS noise and transfer function



In CDS we can only adjust the integration time.
The noise reaches a minimum and then starts growing due to the contribution of "pink noise".



- The CDS filters very low frequency noise close to DC.
- Minimum noise rejection at $f \sim 0.4/T_{Pix}$.
- Nulls at $f=k/T_{Pix}$, where k=1,2,3,…
- Better filtering for higher frequencies.
- Transfer function maximums follow a $|\sin(x)/x|$ decay.

Estimator and digital CDS

- Digital sample the video signal.
- Estimate the correlated noise of a string of pixels.
- Subtract the correlated noise from the original video.
- Perform the digital CDS of the filtered signal.
  - χ^2 estimator, because it does not assume a particular noise model:
  - – Inversion of a large matrix. Only one time and can be done off-line.
- Goal:
  - – Implement the estimator and the digital CDS in an FPGA. Create FITS image.

We can eliminate the pedestal and pixel values s_i from the estimation problem.

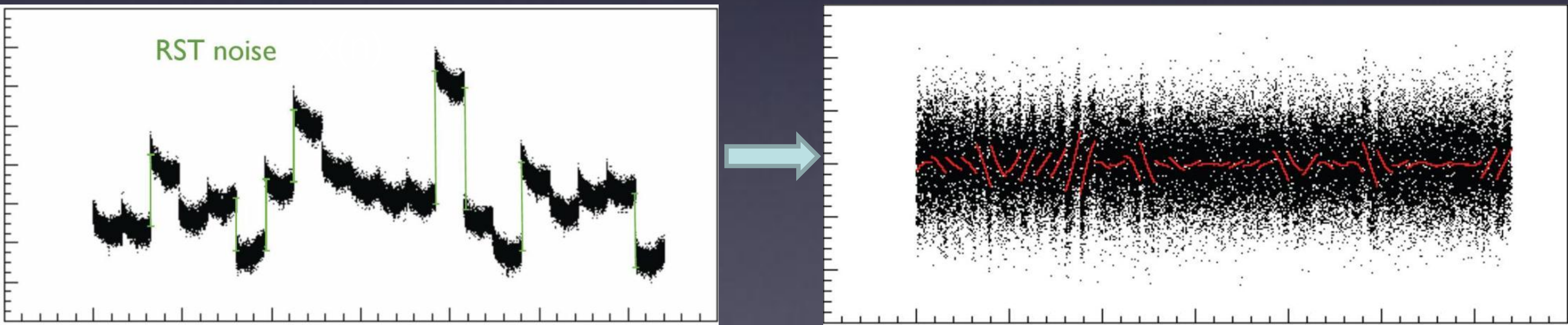
$$y(n) = x(n) - \langle x(n) \rangle$$

where <x(n)> is the average signal+noise value in each pixel (step function

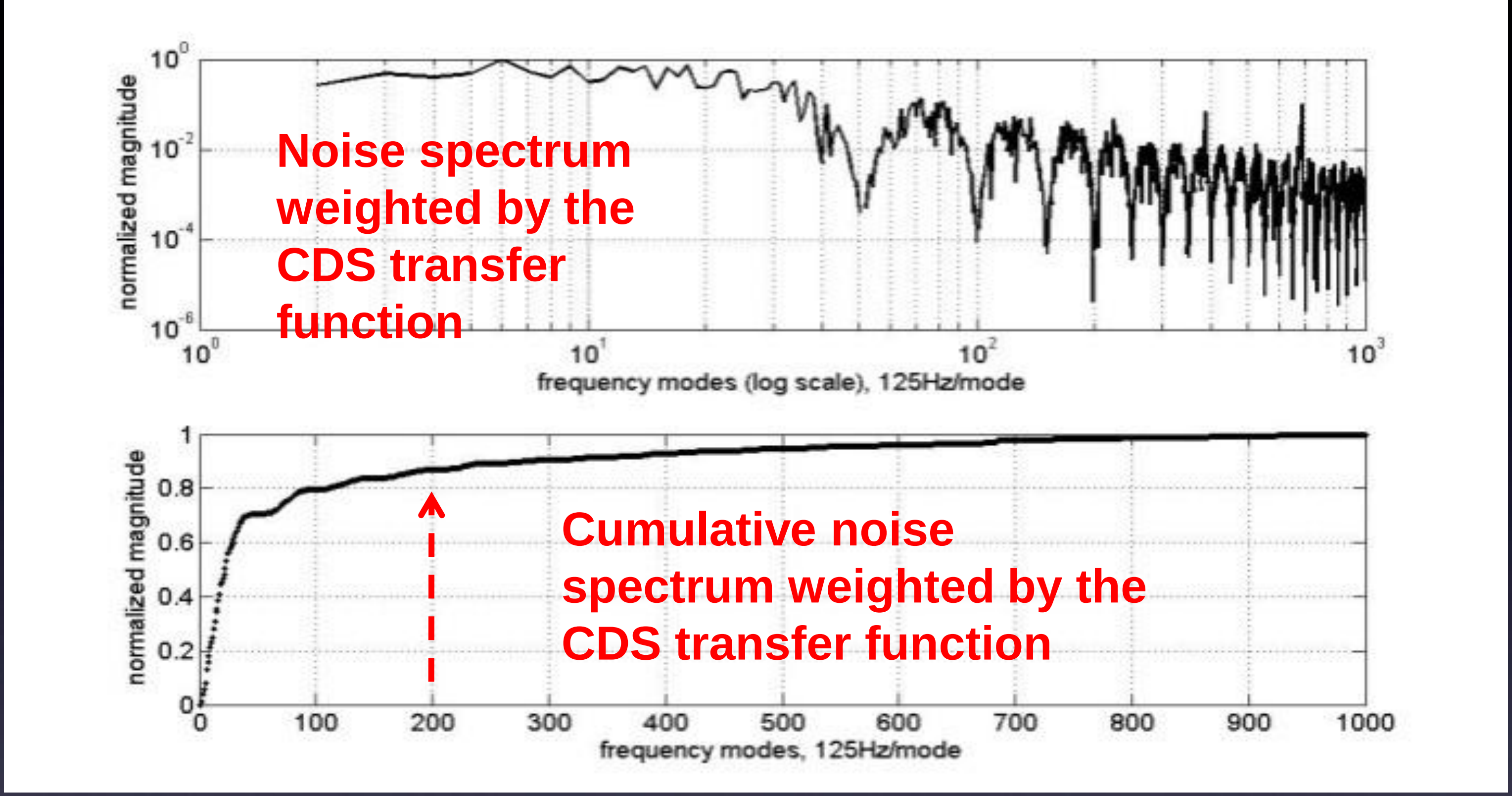
New linear model:

$$y(n) = H\theta + w(n) \Rightarrow \hat{\theta} = (H^T H)^{-1} H^T y$$

where θ is a px1 vector

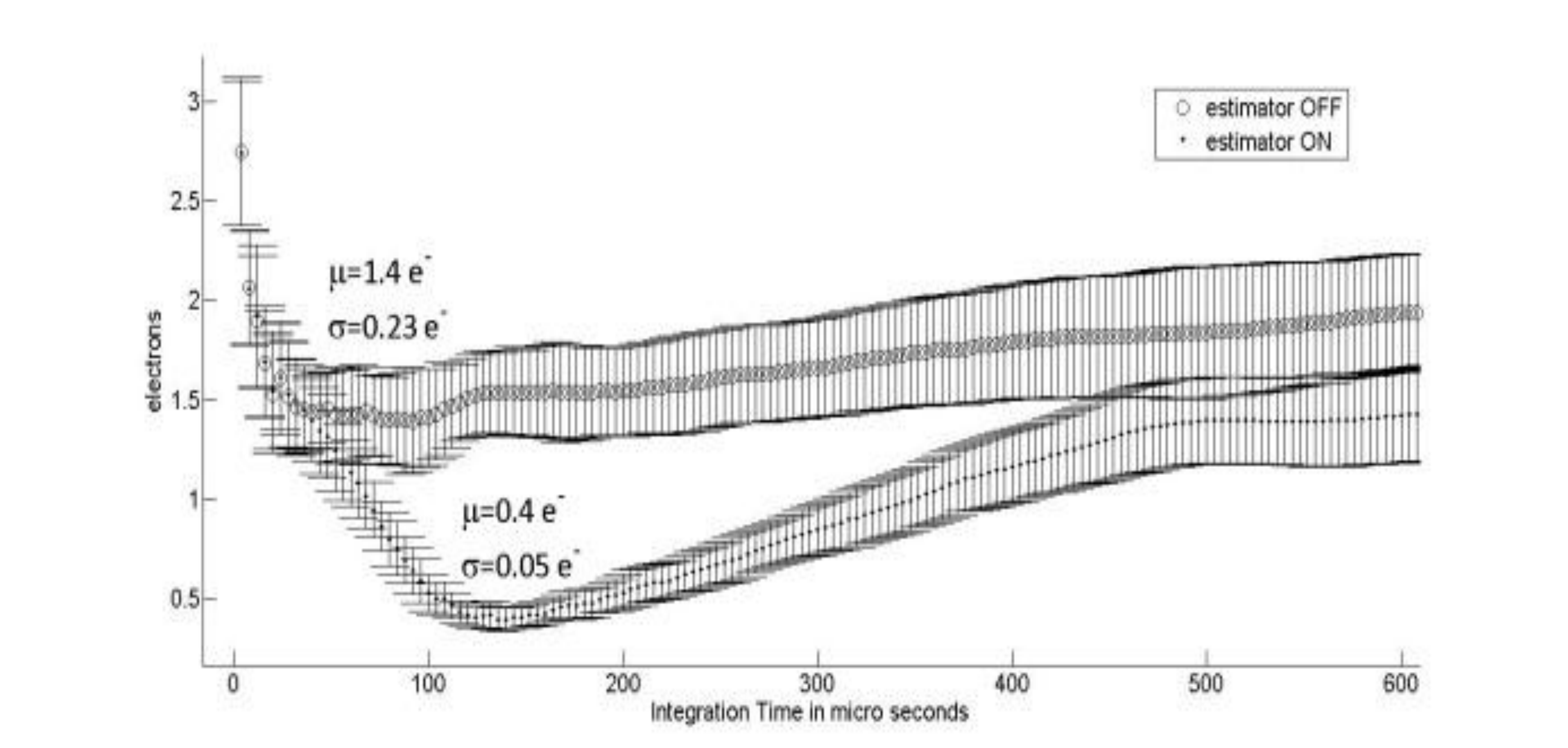


How many modes?



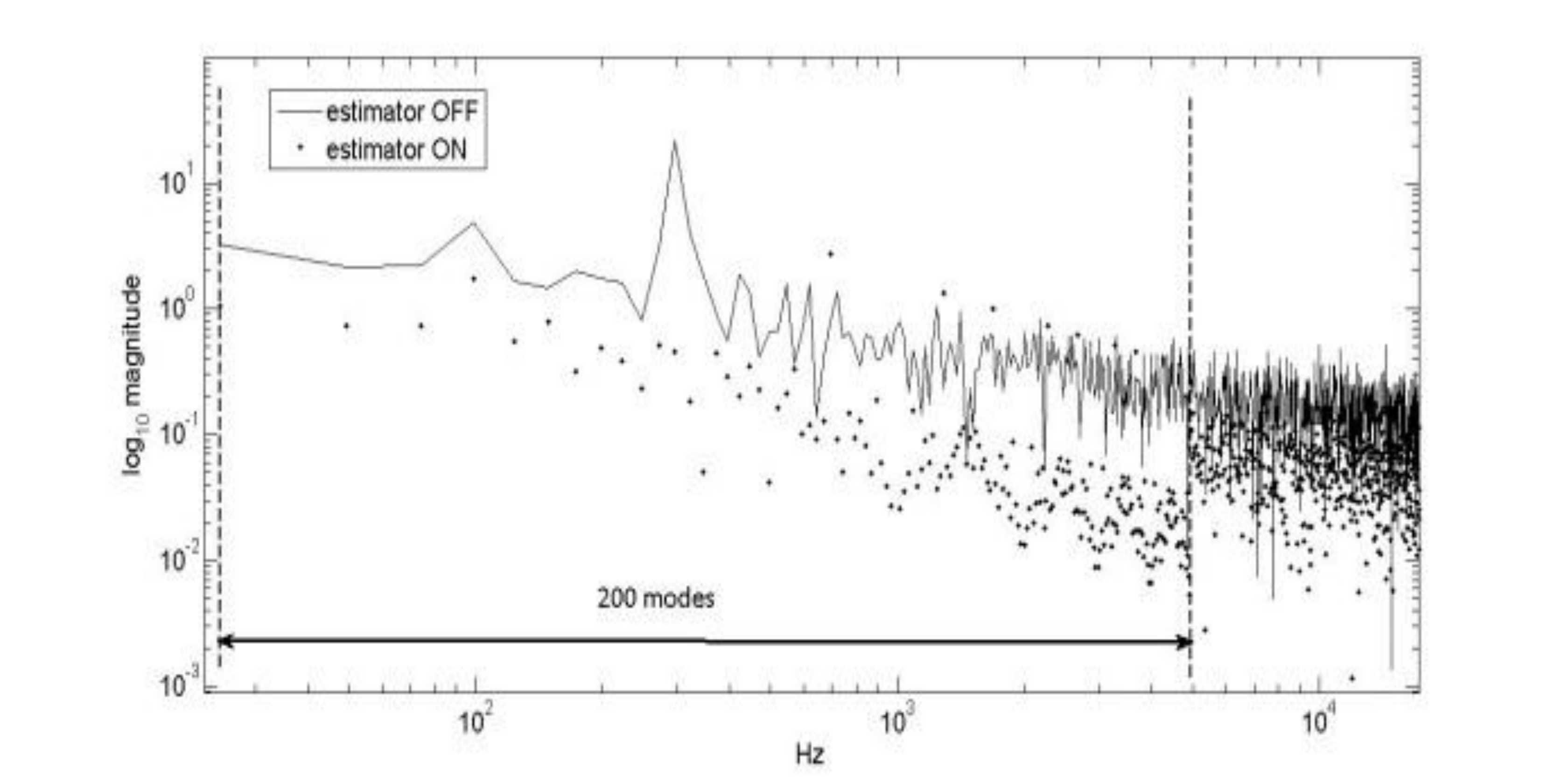
- 200 modes account for ~85% of the low frequency correlated noise.
  - Assuming that estimation could be done with zero error.

Estimator and digital CDS Results (LBNL 12 channel CCD)



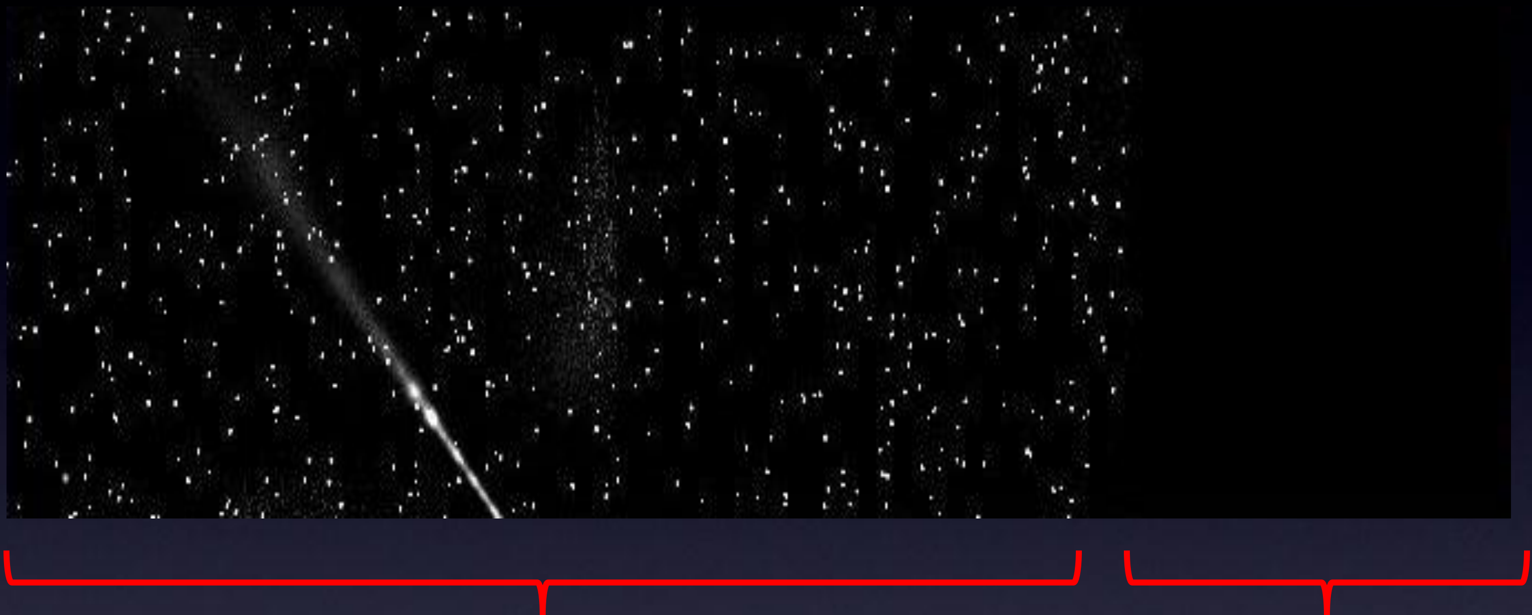
- The plot displays the average noise of 100 data sets and 1-σ error bars.
  - 0.4e- at 120 μs.
  - It is also interesting that the 1-σ error bars of the estimator processed data are 4 times smaller than the ones for the unprocessed data.

Noise spectrum comparison



- Compares the noise power spectrum of the unfiltered signal and the filtered signal after the low frequency estimation of 200 modes has been subtracted.
  - **On average, the LFC noise has been reduced by almost an order of magnitude on average.**

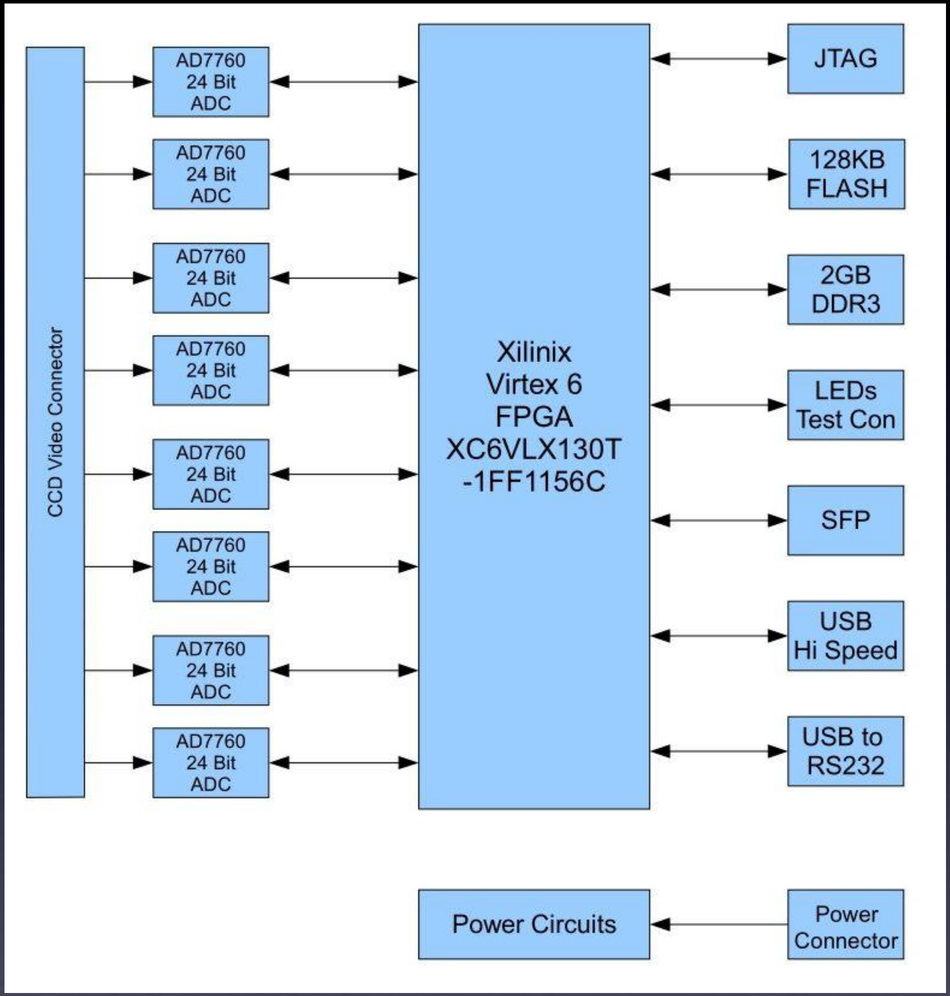
FPGA implementation of the estimator and digital CDS



X-ray image using a ^{55}FE source CCD Overscan

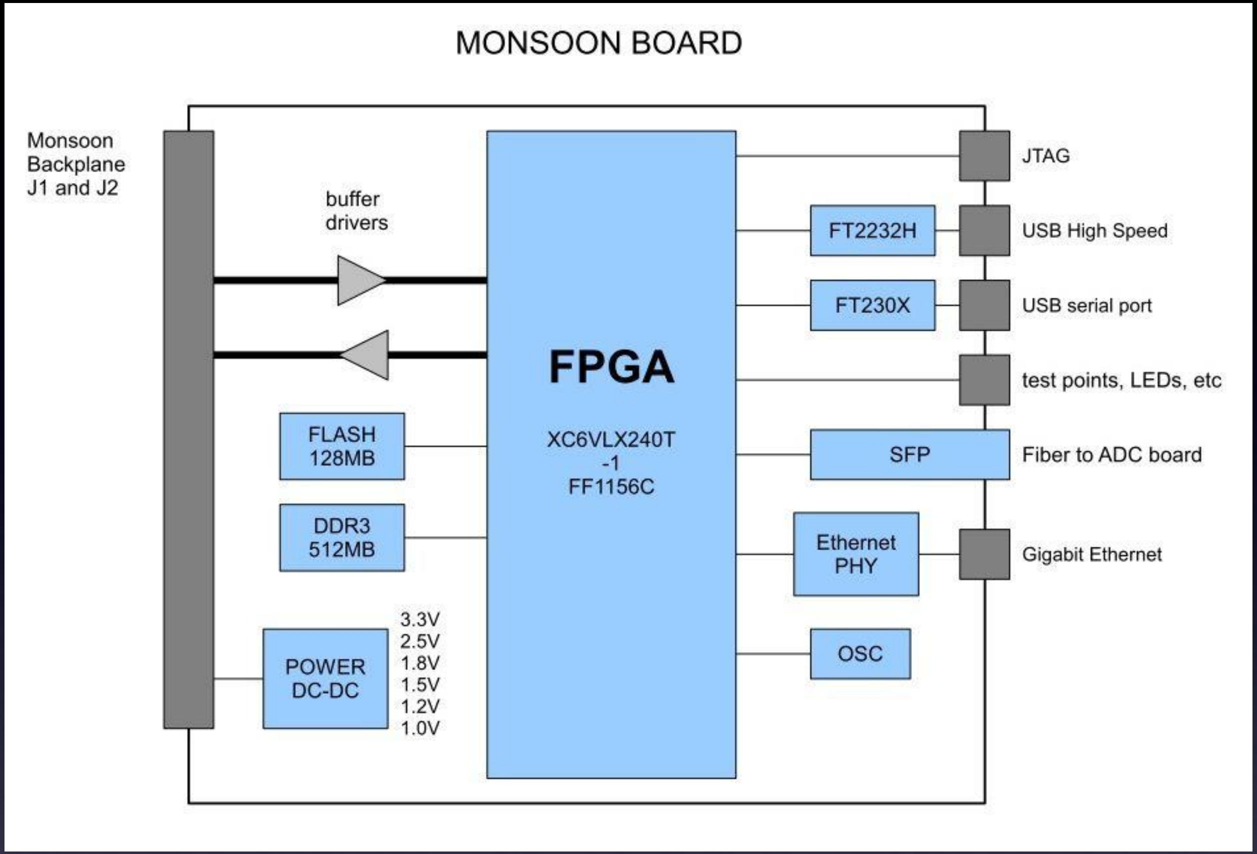
- The implementation of the estimator in the FPGA is on going.
- In this image the FPGA is performing the digital CDS with noise results very similar to the off-line results.

New electronics: front end



- Can readout up to 8 CCDs.
- The estimator and digital CDS is performed by an on board FPGA.
- It communicates with the Monsson based back end electronics.
- The front end goes mounted outside the CCD dewar.
- Status as of May 4th, 2012:
  - Schematic design complete.
  - Layout design in progress.

New electronics: back end



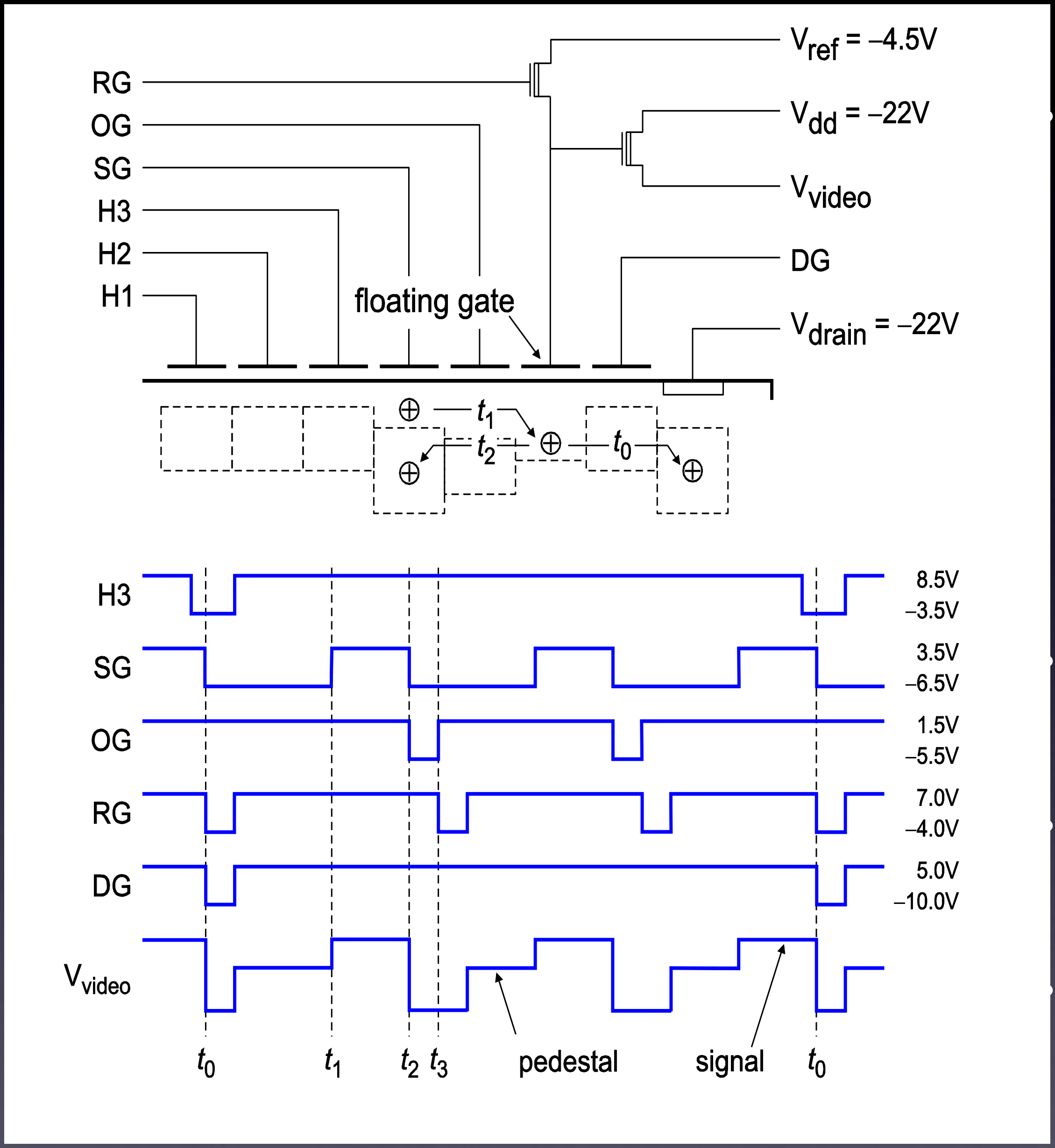
- It allow us to use the existing Monsoon framework, hardware and software.
- It can share CCD readout with standard Monsoon readout.
- Status as of May 4th, 2012:
  - Schematic design complete.
  - Layout design in progress.

R&D Plan

- Test the low noise electronics for 8 CCD channels.
- Finish the estimator and digital CDS firmware in the FPGA.
- New electronics firmware and software framework.
- Commission new electronics and test performance in a multi CCD environment.
- Publish results.

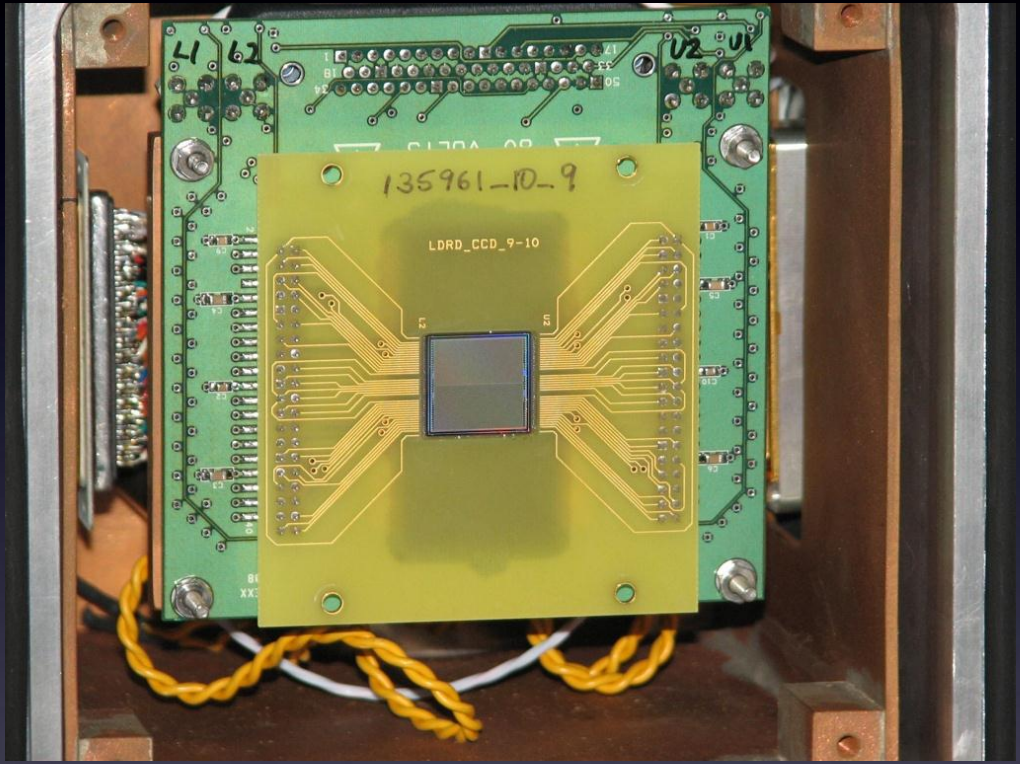
- Algorithms: Explore a further reduction of noise with a different estimator (e.g. sequential χ^2 or Kalman).
- Study the stability/robustness or the estimator.
- R&D how to scale up the electronics for a large system.

Skipper CCD



- The "skipper" allow 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.

The Skipper CCD mounted on one of our testing dewars



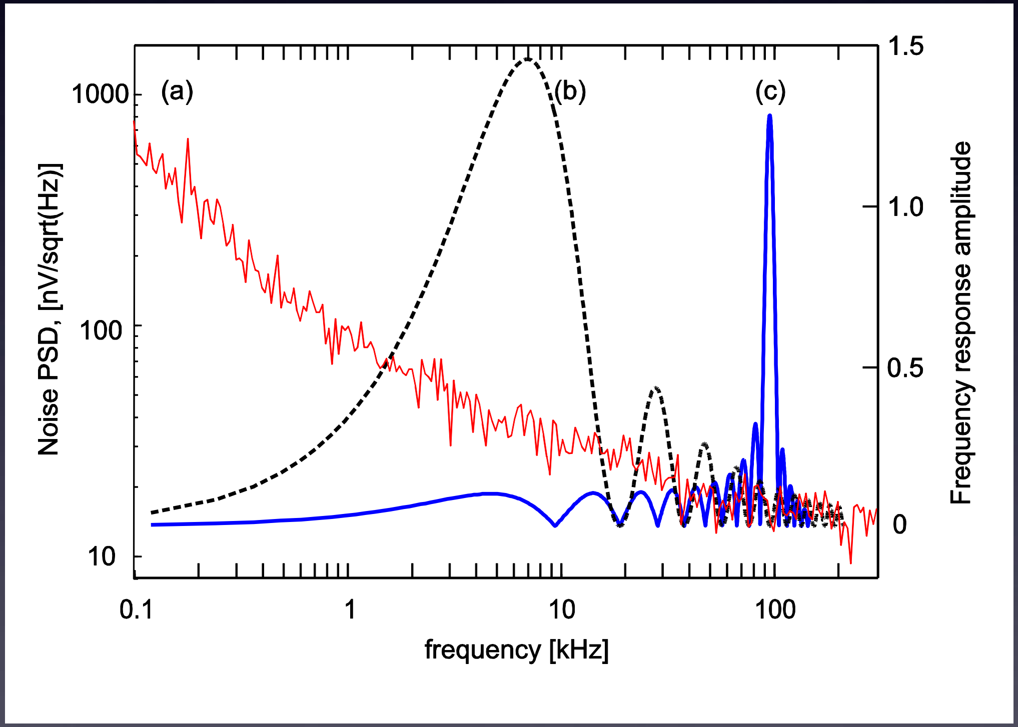
- Skipper CCD mounted on one of our testing dewars.
- The detector is 1Kx1K pixels of size 15x15µ.

Skipper CCD

The multiple sample readout averages samples for each pixel. Each pixel is the average of N CDS values,

The impulse response $h_{skp}(t)$ is the linear combination of time shifted copies of h(t)

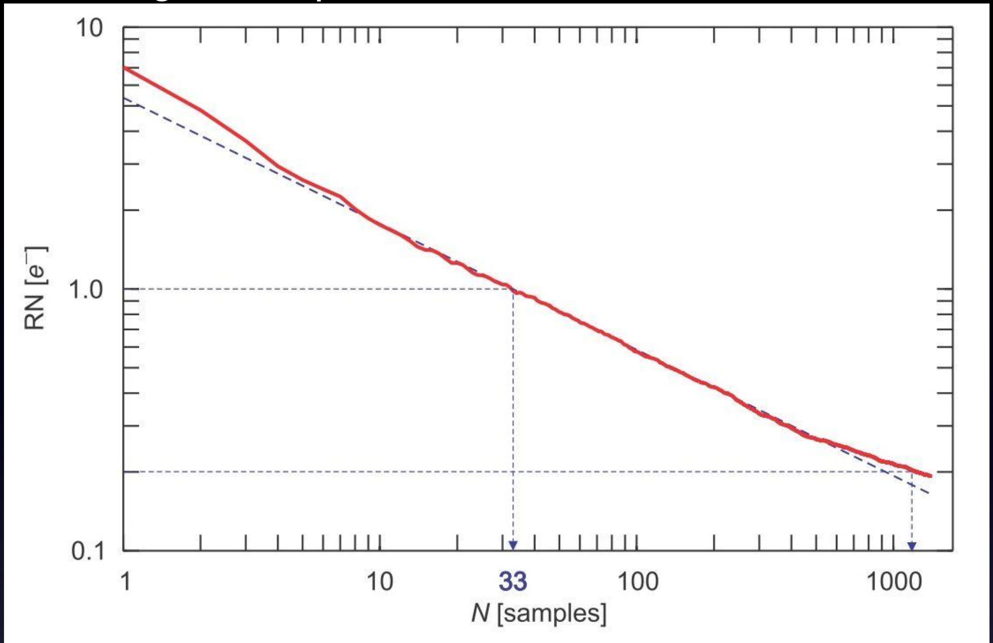
$$|H_{skp}(f)| = \frac{4A}{\pi N T_S f} \sin^2\left(\frac{\pi T_S}{2} f\right) \left| \frac{\sin(\pi N T_S f)}{\sin(\pi T_S f)} \right|$$



(a) Vertical axis: CCD noise PSD (red trace)
(b) CDS $T_\int$ = 110 μs
(c) Skipper CDS $T_\int$ = 110 μs and N = 10.

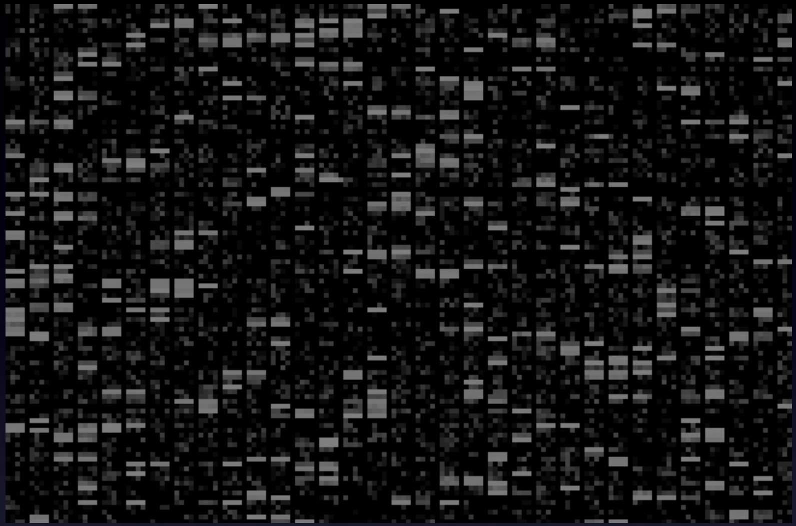
For N>1 the lobes get thinner
and the secondary lobes reduce their amplitudes so an effective reduction of
Noise is obtained for both the pink noise and WGN.

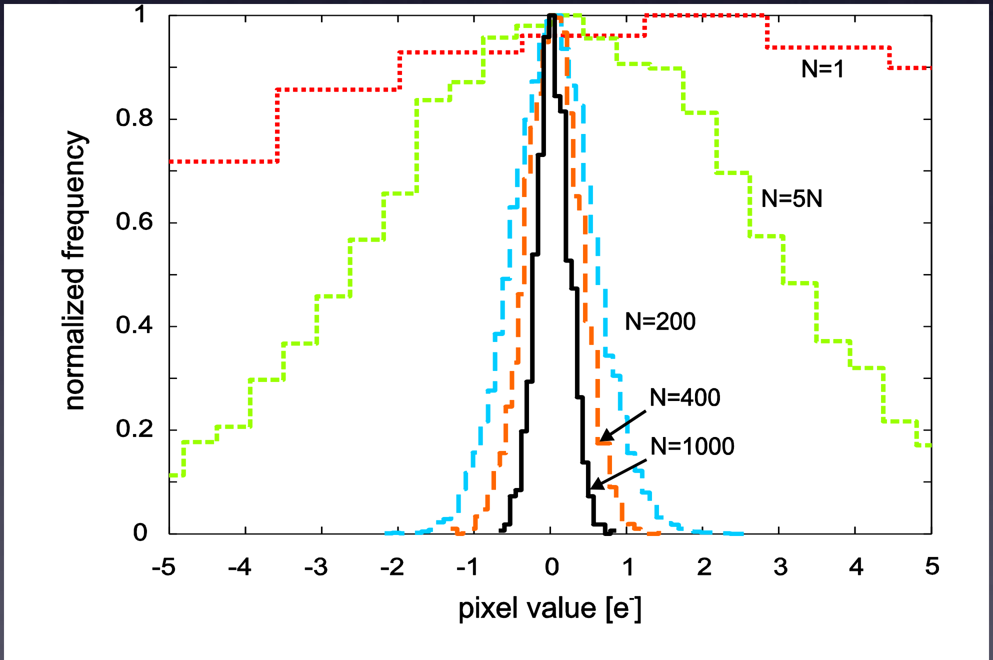
RMS noise as a function of the number of averaged samples N.



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).

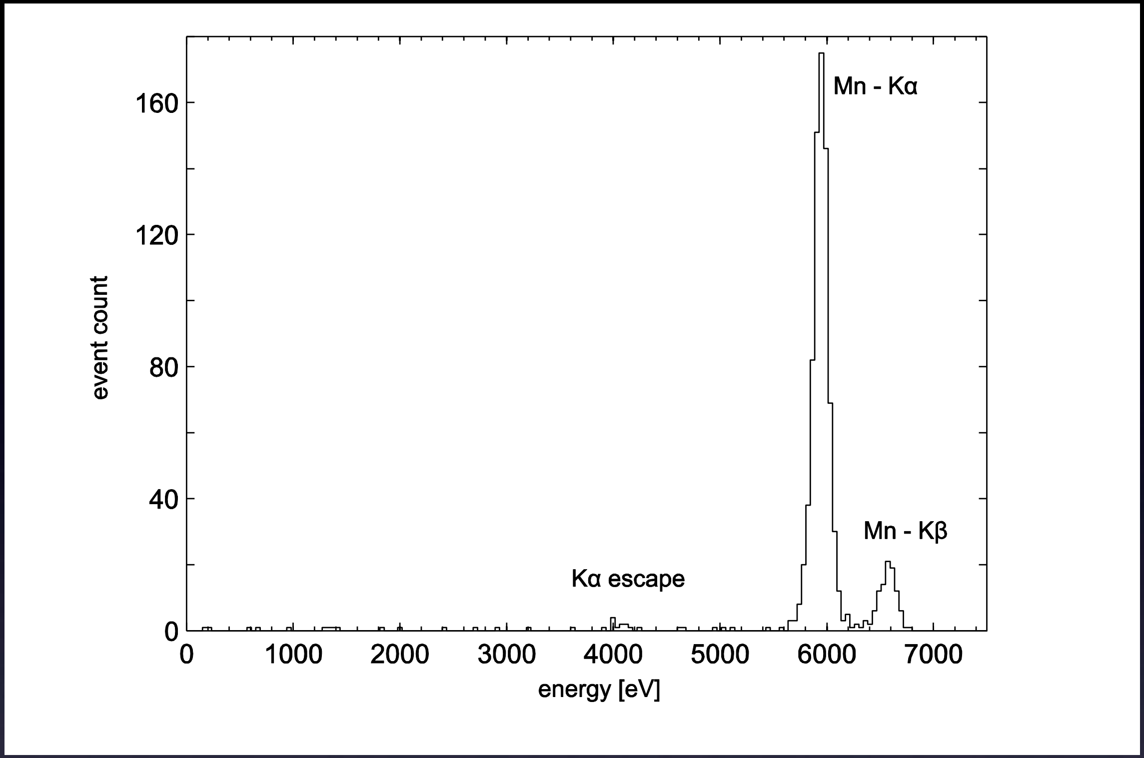
For each histogram the number of sample averages per pixel changes.

All histograms are normalized to 1.

The RMS noise is monotonically decreased as N increases.

RMS= 0.2e⁻ achieved for N=1227 (25ms/pix)

X-ray detection experiment with the Skipper CCD.



Fe55 X-ray source

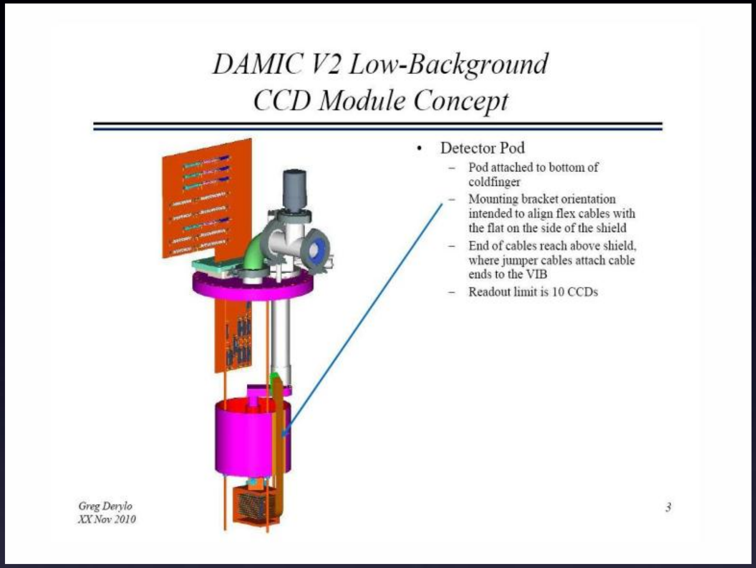
- The measured width of the 55 Fe K_α line is 151eV (FWHM) which is in a good agreement with predictions of 142 eV and 135 eV using reported measurements of CCD Fano factors.
- (The K_α peak FWHM for pixels in the single sample readout region is 199eV)
- The K_α peak in figure 14 also shows a Gaussian profile and no low energy tail, suggesting a good charge transfer at the output stage to ~1ppm.

R&D Plan

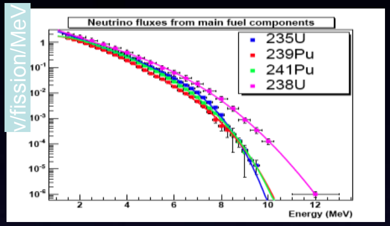
- Package and test four Skipper CCDs.
- Test Skipper CCDs with the new flex cables and Monsoon electronics.
- Characterize CCDs:
    - Study operation point stability and suitability to be used in an experiment.
    - Measure noise as a function of number of averaged number of samples.
    - Demonstrate that CCDs can achieve low energy detection and good efficiency.

Applications

Dark matter: DAMIC
(Ben Kilminster's talk)

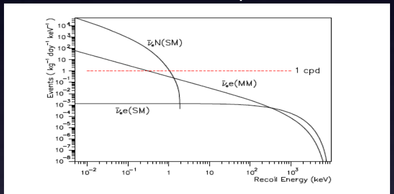


CONNIE: Coherent Neutrino scattering in Angra dos Reis (Brazil)



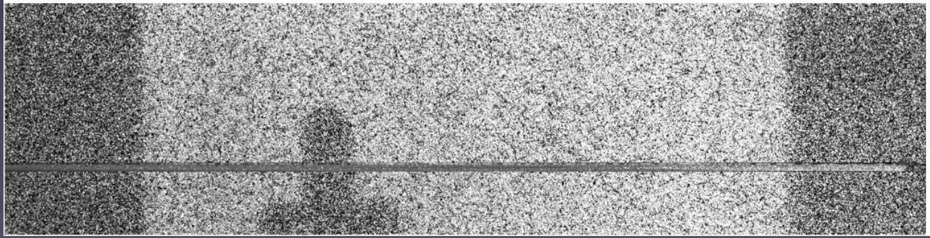
measured antineutrino spectrum at ILL

Reviewed by FNAL R&D committee in April 2012
Proposed to CNPQ in August 2011 (Helio da Motta, Martin Makler, Carla Bonifazi).
Backgrounds measured in 2012.
We hope to install a 10 gram detector in 2013



Expected recoil spectrum at 30m of 3GW reactor (Texono)

Neutron imaging with CCDs:
Goal: 1µm resolution, 1 sec readout time.



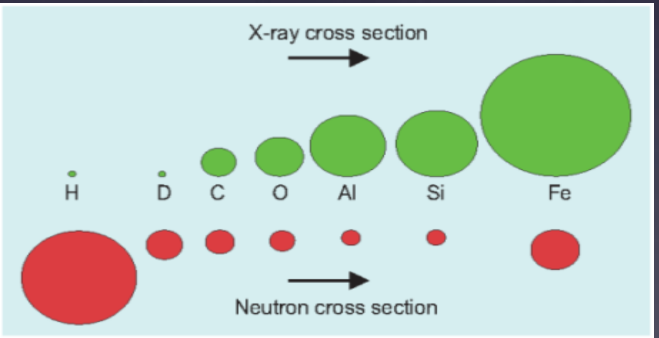


Fig. 2. Neutron and x-ray scattering cross-sections compared. Note that neutrons penetrate through Al much better than x rays do, yet are strongly scattered by hydrogen.

Recent papers

1. arXiv:1107.0925 [pdf] Title: Deep sub electron noise readout in CCD systems using digital filtering techniques
Authors: Gustavo Cancelo, Juan Estrada, Guillermo Fernandez Moroni, Ken Treptow, Ted Zmuda, Tom Diehl , Experimental Astronomy, 2012, Volume 34, Number 1, Pages 13-29

2. arXiv:1106.1839 [pdf, ps, other] Title: Achieving sub-electron readout noise in Skipper CCDs
Authors: Guillermo Fernandez Moroni, Juan Estrada, Eduardo E. Paolini, Gustavo Cancelo, Stephen E. Holland, H. Thomas Diehl , accepted for publication in Experimental Astronomy.

3. arXiv:1105.5191 [pdf, other] Title: Direct Search for Low Mass Dark Matter Particles with CCDs
Authors: J. Barreto, H. Cease, H.T. Diehl, J. Estrada, B. Flaugher, N. Harrison, J. Jones, B. Kilminster, J. Molina, J. Smith, T. Shwarz, A. Sonnenschein

4. arXiv:1105.3229 [pdf, other] Title: Plasma effect in Silicon Charge Coupled Devices (CCDs)
Authors: Juan Estrada (Fermilab, USA), Jorge Molina (FIUNA, Paraguay), J. Blostein (CAB, Argentina), G. Fernandez (UNS, Argentina), submitted to NIM.

5. arXiv:0911.2668 [pdf] Title: Direct Dark Matter Search using CCDs
Authors: Juan Estrada

In preparation:
12 channel readout results.

Full well problem in DECam CCDs results

Many conference presentations.

Collaborators

Fermilab:
J. Estrada, T. Diehl, H. Cease, D. Kubik, G. Derilo, K. Kuk, K. Schultz, A. ?, W. Struemer T. Shaw (PPD team)
G. Cancelo, T. Zmuda, K. Treptow, N. Wilcer, J. Chramowicz, (CD team)
Vic Scarpine (AD)
B. Kilminster, J. Smith, T. Schwarz, A. Sonnenschein (DAMIC)

J. Molina
Facultad de Ingeniería, Universidad Nacional de Asunción, Asunción, Paraguay

J. Blostein, Xavier Bertou
Centro Atómico Bariloche and Instituto Balseiro,
Comisión Nacional de Energía Atómica, Universidad Nacional de Cuyo, Bariloche, Argentina

G. Fernández, E. Paolini
Universidad Nacional del Sur, Bahía Blanca, Argentina.

Javier Castilla, CIEMAT, Madrid Spain.

N. Harrison: Naperville North High school, now freshman at University of Chicago
S. Wagner: Naperville North High school.

Paolo Privitera, Jacob Johansen
University of Chicago

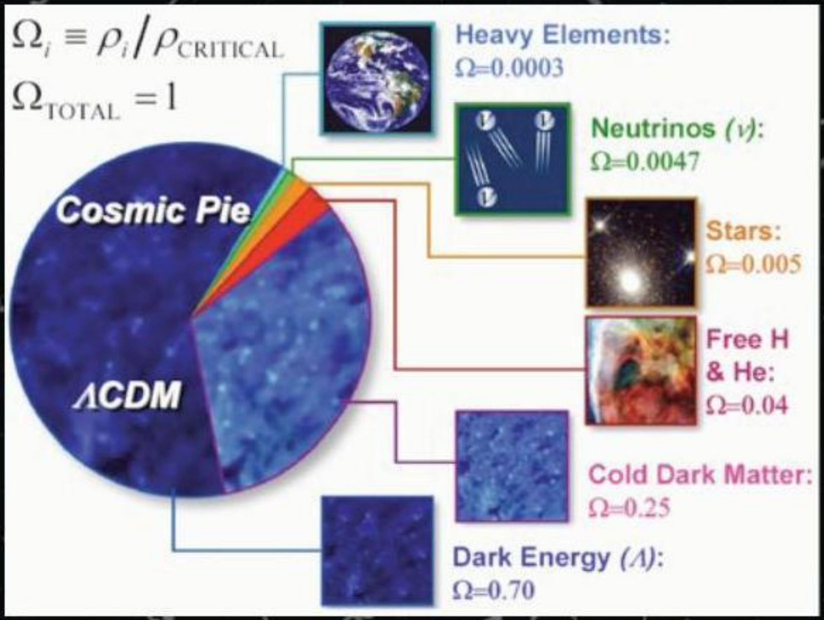
Juan Carlos D’Olivo , Alexis Aguiler (UNAM, Mexico)
Helio da Motta, Carla Bonifazi, Martin Makler (CBPF, UFRJ).

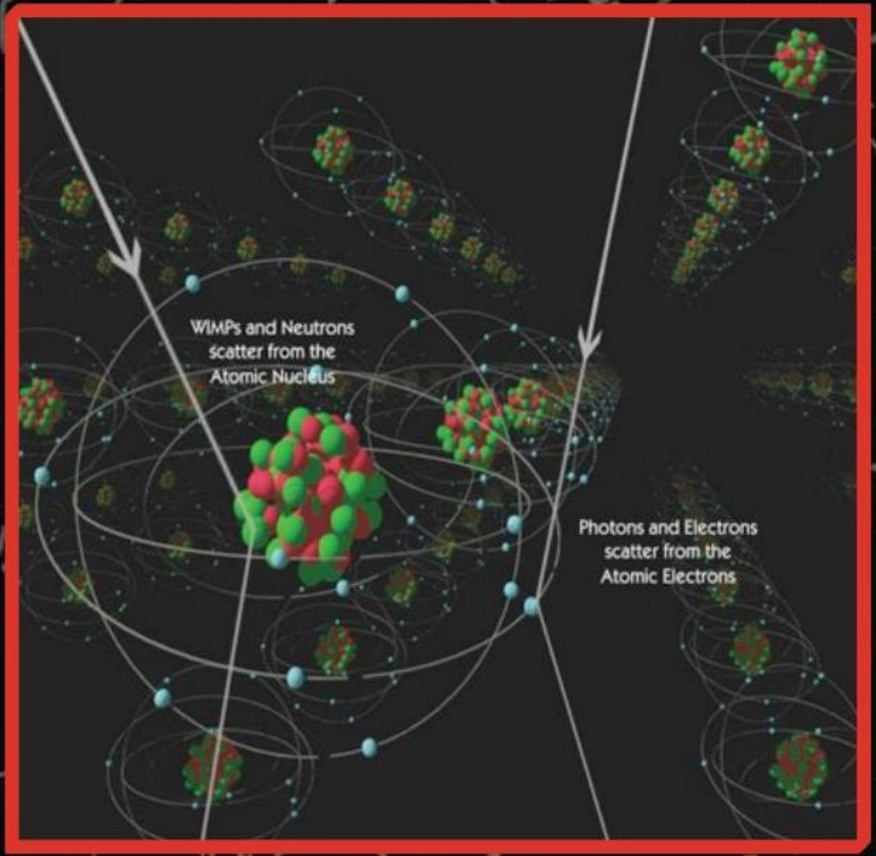
Thank you

Spare slides

DM Direct Detection Experiments

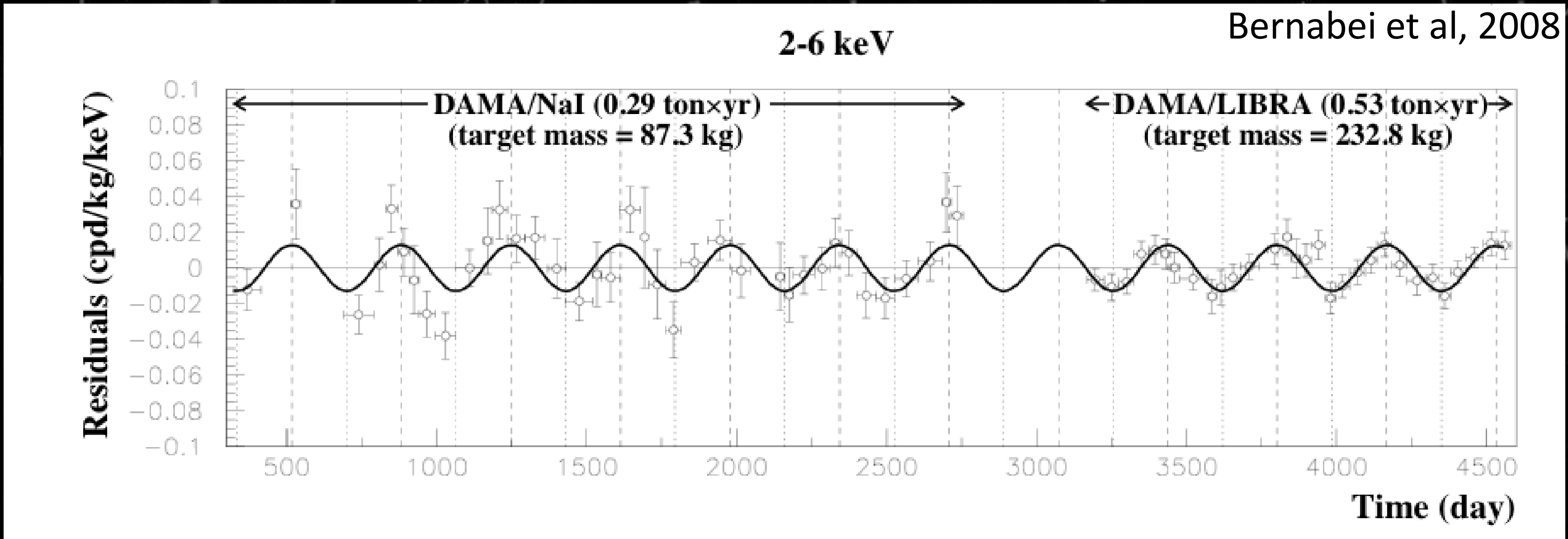
Goal: Detect the collisions of DM particles with detectors as the earth moves in the galaxy. DM particles are neutral (in most models) and would interact with the nuclei of your detector.

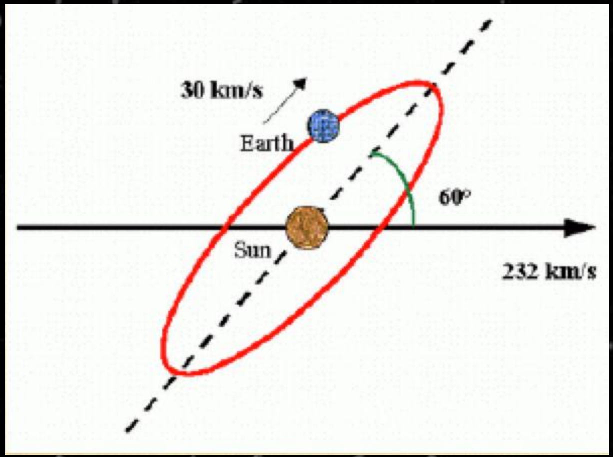




Typically people try to build detectors that will see a nuclear recoil and distinguish it from an interaction with the atomic electrons.

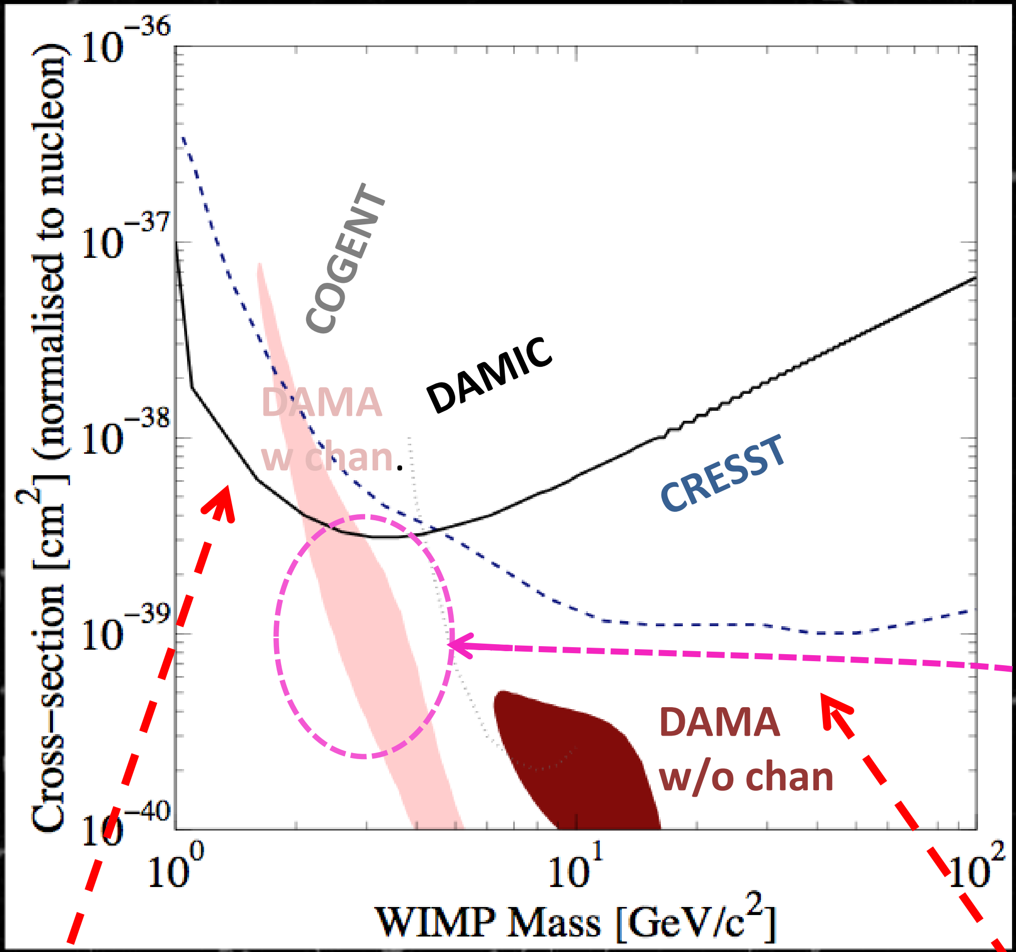
One good reason to look for low mass dark matter : The DAMA/LIBRA result



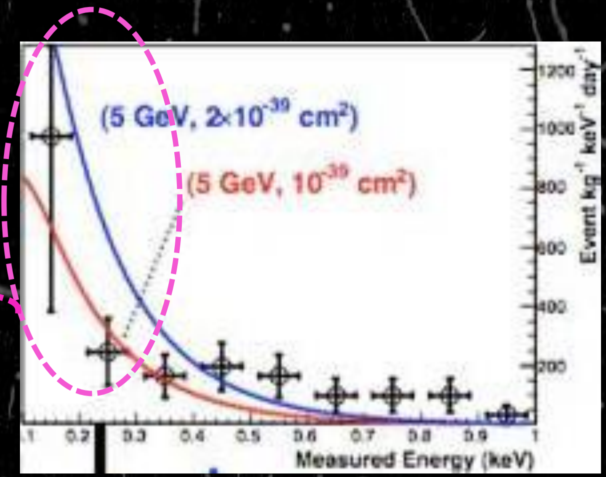


>8 σ detection of annual modulation consistent with the phase and period expected for a low mass dark matter particle (~7 GeV) consistent with recent COGENT results.

DAMIC experiment at FNAL

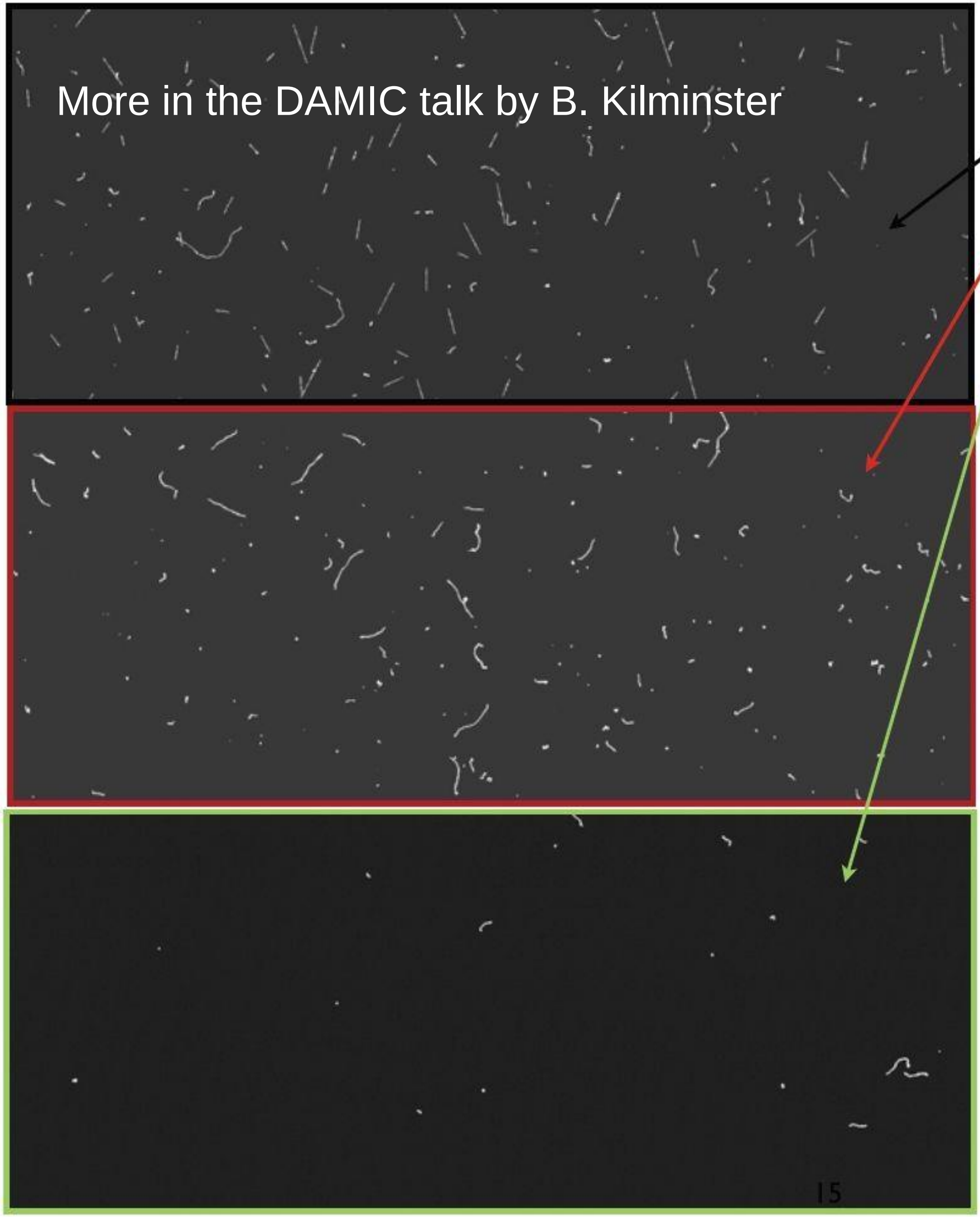


Number of recoils exponentially increase al low energies.



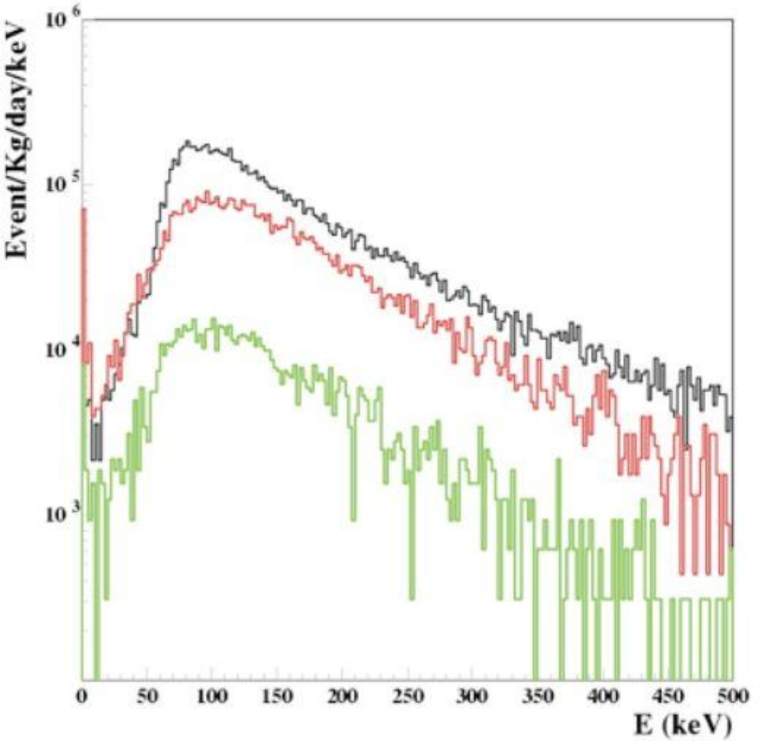
Low noise limited:
thanks to our low noise
we have the best result in the world
and we are reaching the DAMA region

Mass limited:
Need bigger detector.



I hour exposure:
- surface
- Minos (350' underg.)
- Minos + 8"lead shield

muon tracks

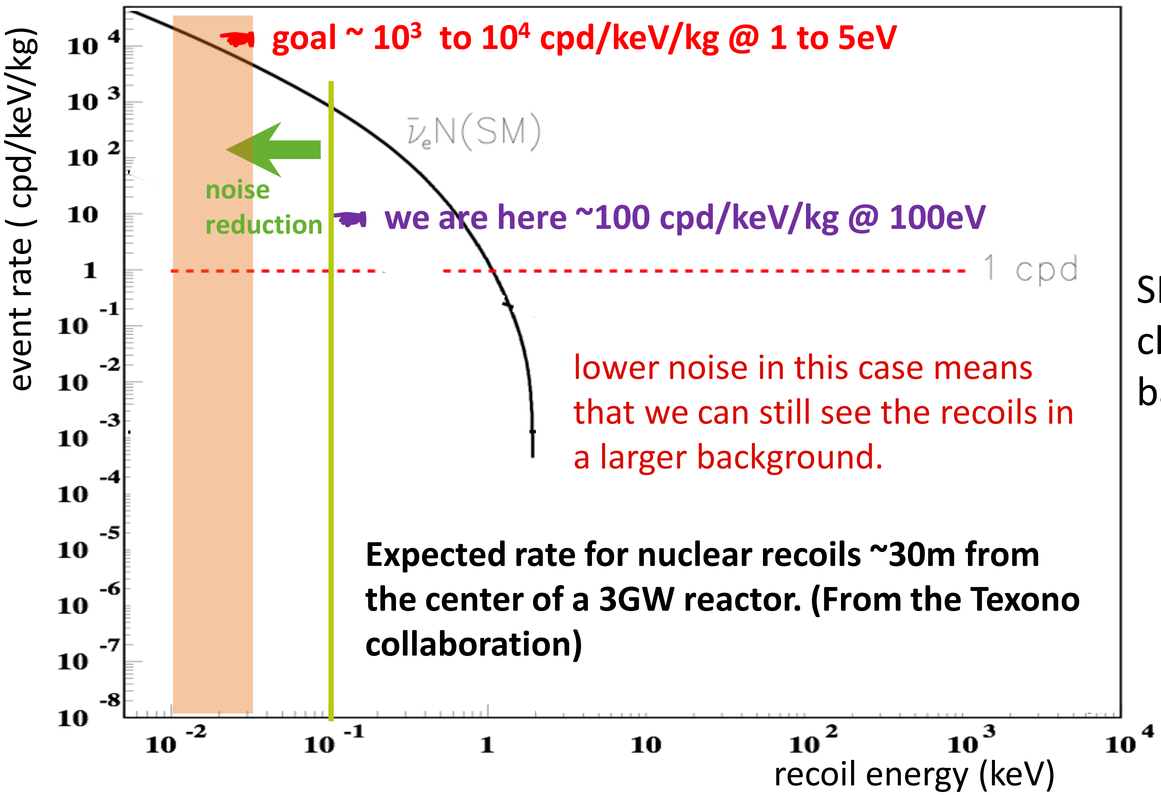


Neutrino coherent scattering

Toward Coherent Neutrino Detection Using Low-Background Micropattern Gas Detectors

P. S. Barbeau, J. I. Collar, J. Miyamoto, and I. Shipsey, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 50, NO. 5, OCTOBER 2003

Abstract: **The detection of low energy neutrinos (few tens of MeV) via coherent nuclear scattering remains a holy grail of sorts in neutrino physics. This uncontroversial mode of interaction is expected to profit from a sizeable increase in cross section proportional to neutron number squared in the target nucleus**, an advantageous feature in view of the small probability of interaction via all other channels in this energy region. A coherent neutrino detector would open the door to many new applications, ranging from the study of fundamental neutrino properties to true "neutrino technology." **Unfortunately, present-day radiation detectors of sufficiently large mass (~1 kg) are not sensitive to sub keV nuclear recoils like those expected from this channel**.

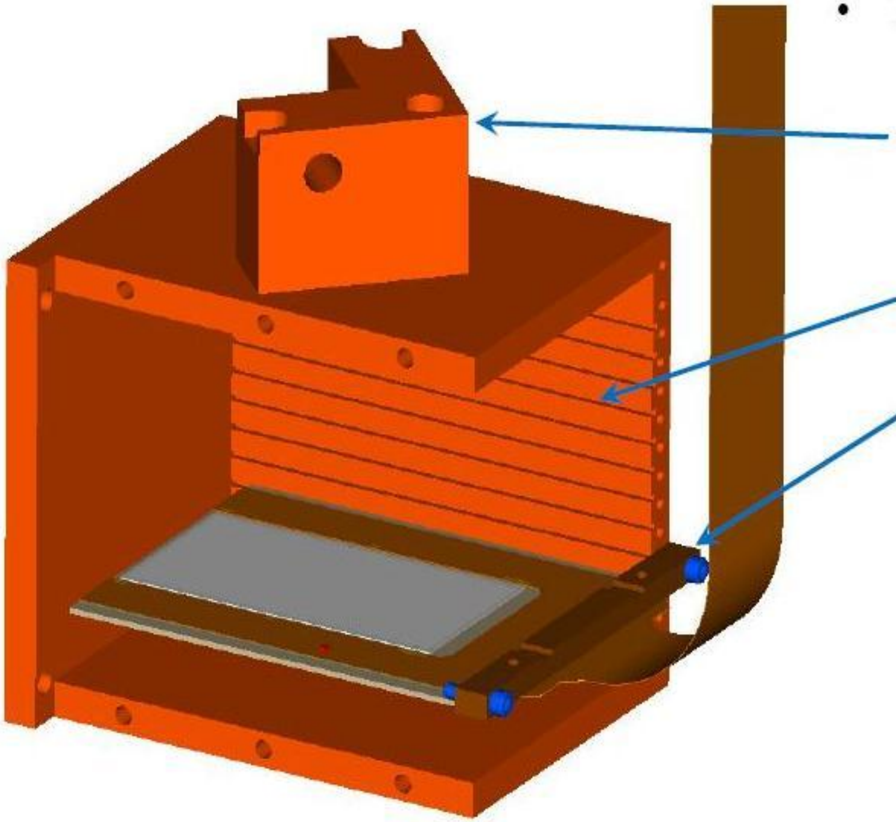


$$\nu + N \rightarrow \nu + N$$

SM cross section is relatively large, the challenges are detector sensitivity and background control.

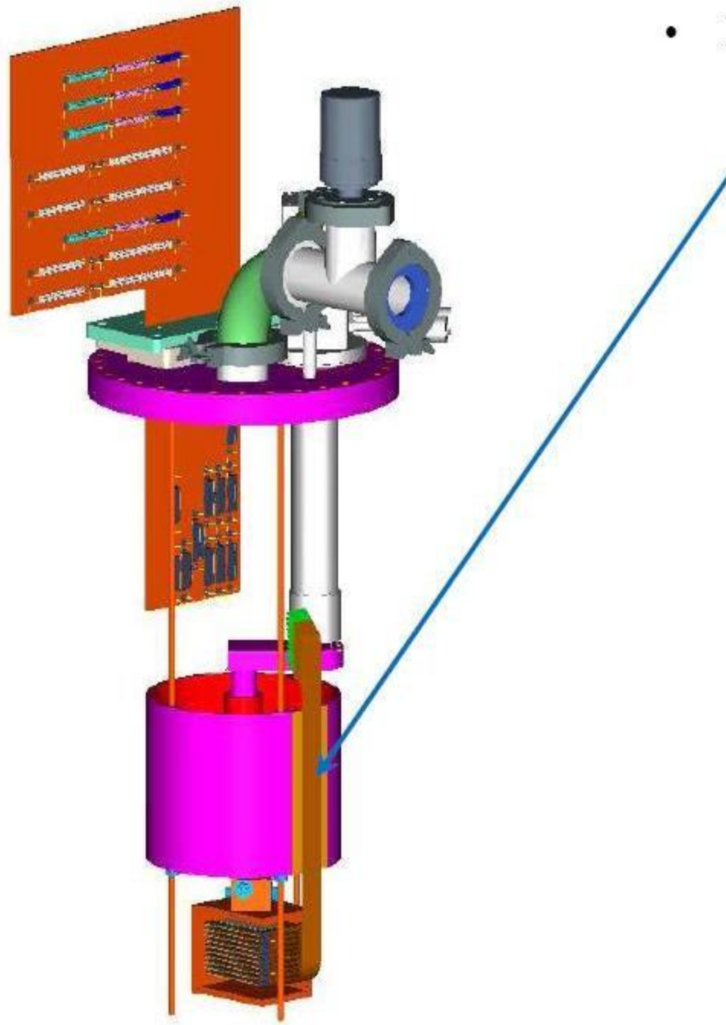
- SM and new physics.
- Help understand how to study supernovae neutrinos.
- Monitoring of nuclear reactors.

DAMIC V2 Low-Background CCD Module Concept



- Detector Pod
  - Oxygen-free copper parts with stainless steel fasteners
  - Mounting bracket attached to two faces of bottom end of coldfinger
    - Need to triple check that the orientation is OK
  - Sidewall with slots hold edges of AlN substrates
    - Only one sidewall shown
  - Copper bar on each module fastens to sidewalls using captive panel screws
  - The copper bar makes it difficult to extract a module out of the middle of the stack

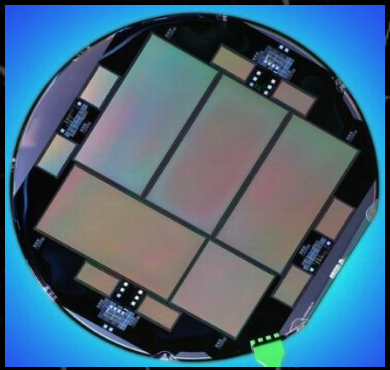
DAMIC V2 Low-Background CCD Module Concept



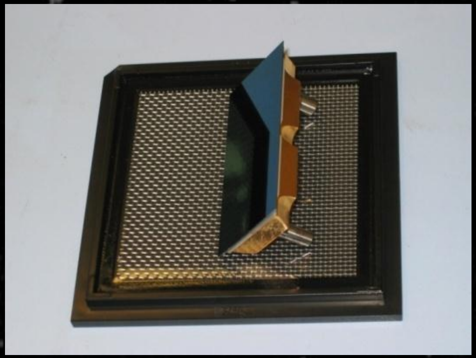
- Detector Pod
  - Pod attached to bottom of coldfinger
  - Mounting bracket orientation intended to align flex cables with the flat on the side of the shield
  - End of cables reach above shield, where jumper cables attach cable ends to the VIB
  - Readout limit is 10 CCDs

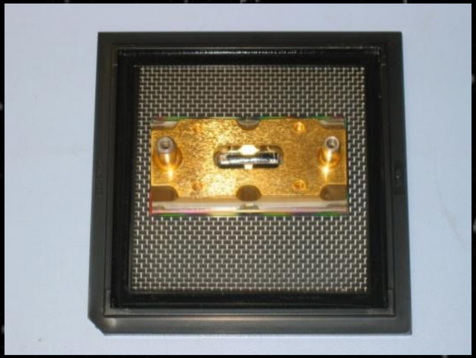
DECam has allowed us to build at FNAL a powerful CCD lab

closely monitoring production of dies for more than 2 years, giving quick feedback on performance

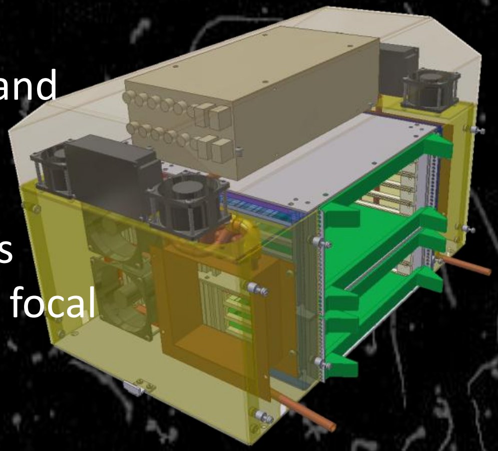


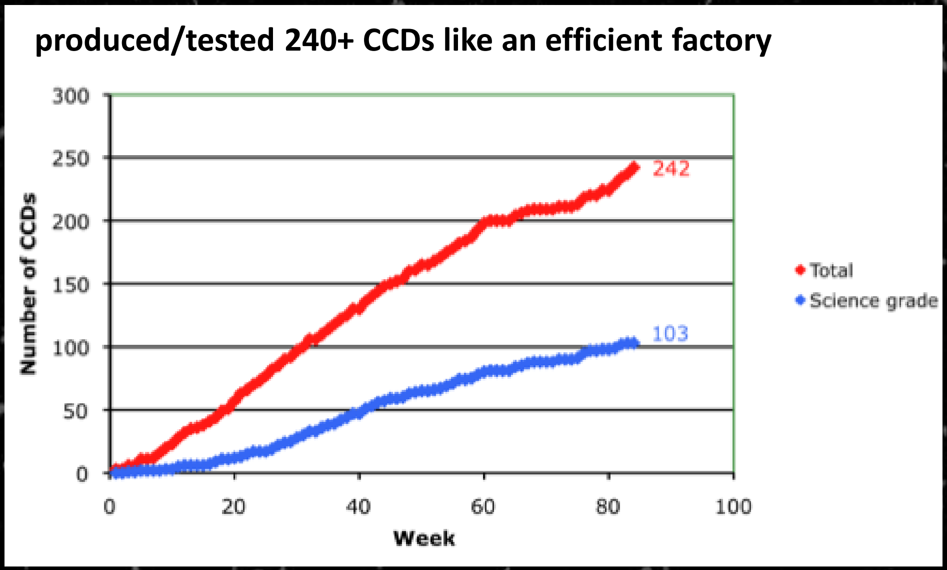
developed CCD package for focal plane that meets scientific requirements





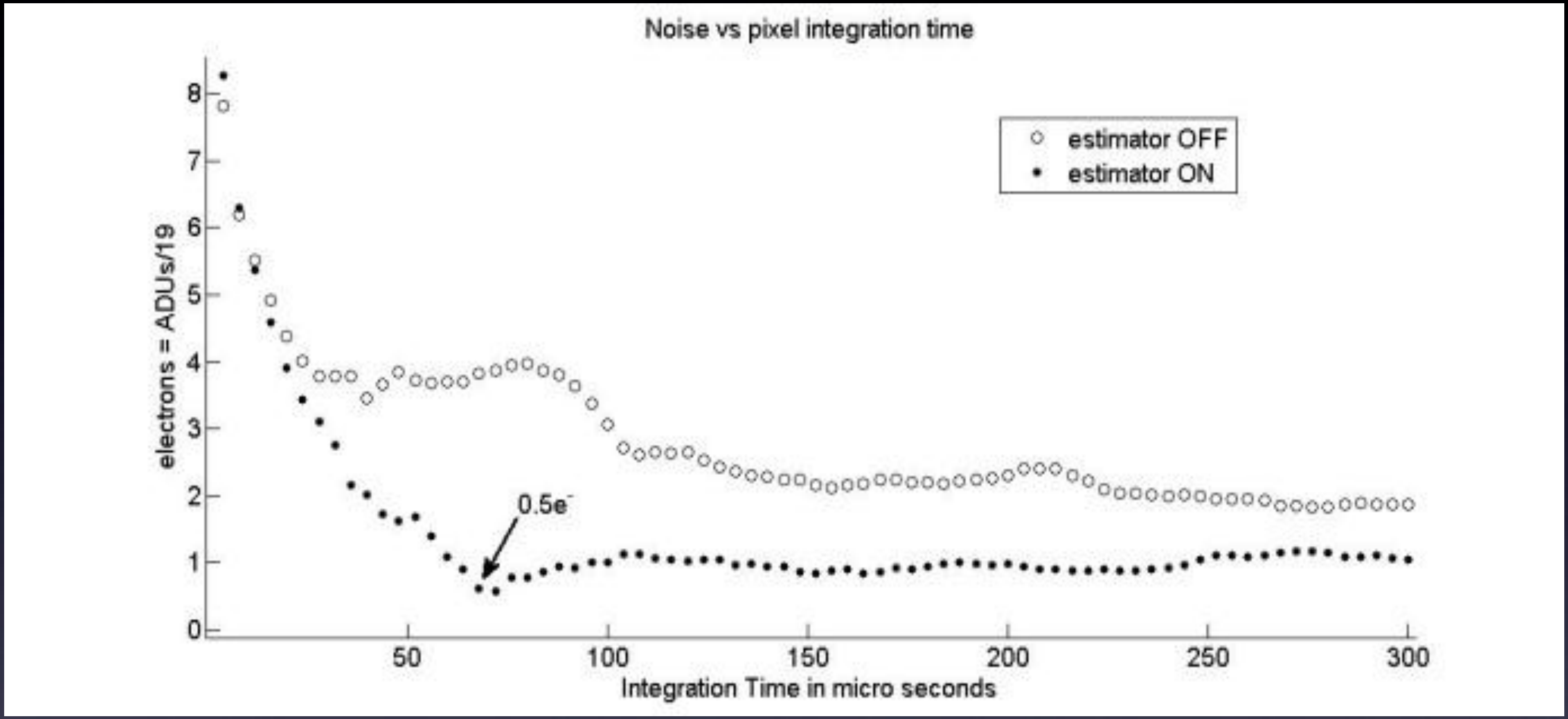
designed and build readout electronics for a large focal plane





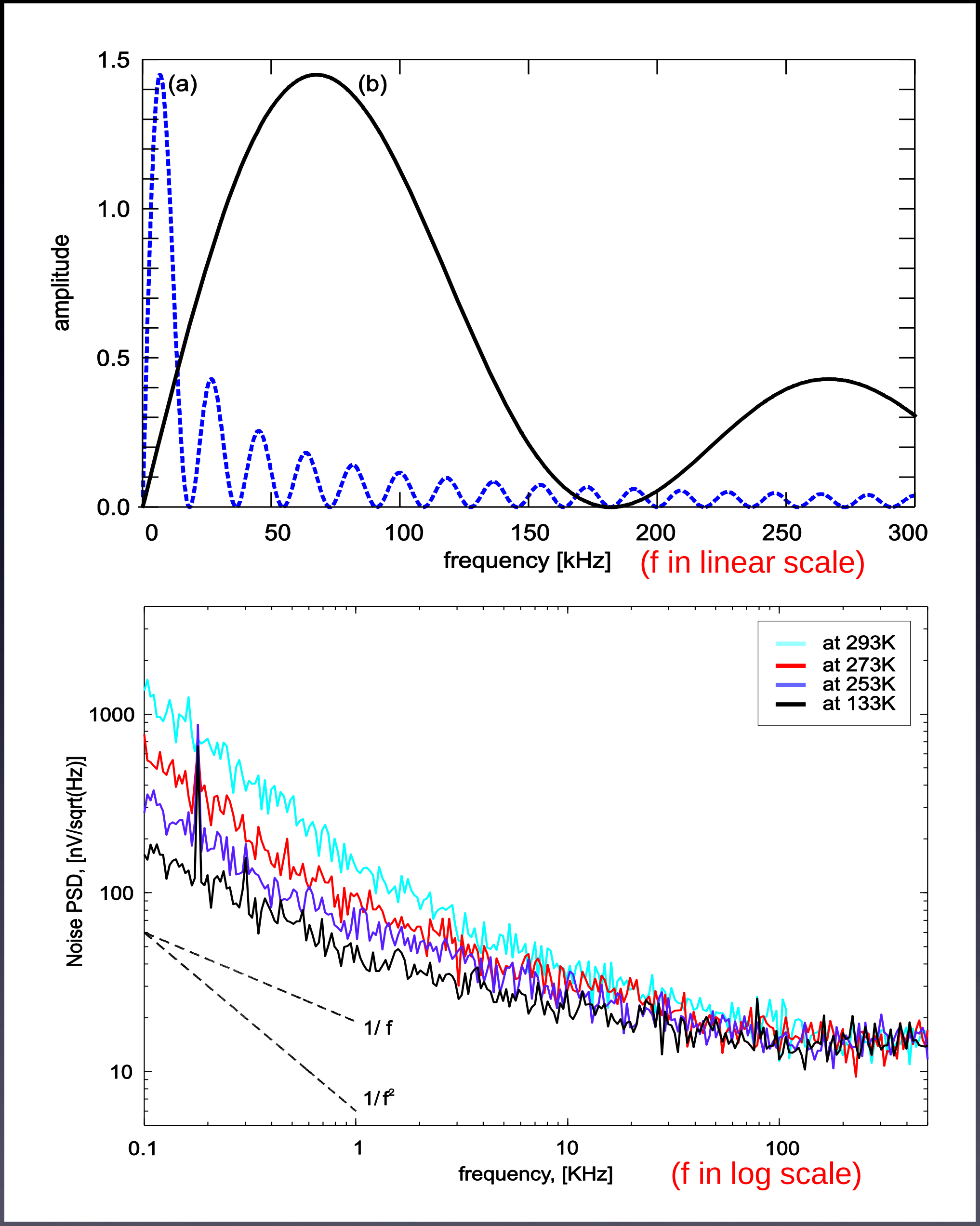
the experience building silicon trackers transferred nicely to this project. The work in this talk has been possible thanks to this CCD lab.

Estimator and digital CDS Results (DeCam CCD)



- 0.5e- of noise achieved (consistently) for T_{pix} of 70useconds.

CDS transfer function

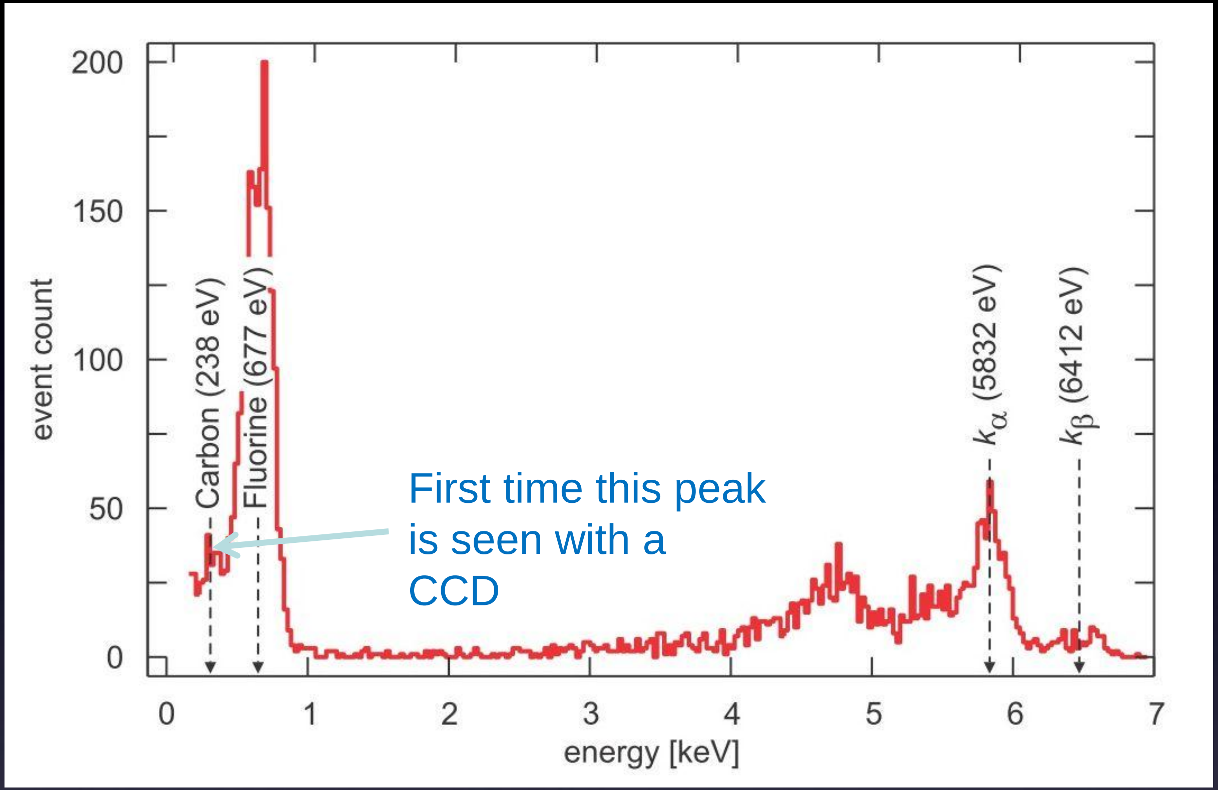


$$|H_{DSI}(f)| = \frac{4A}{\pi T_T f} \sin^2\left(\frac{\pi T_T}{2} f\right)$$

The integration time value shifts the CDS TF along the frequency axis.

For dotted plot (b) the influence of 1/f noise is negligible, but there is more noise from WGN.

Low-energy X-ray detection experiment with the Skipper CCD.

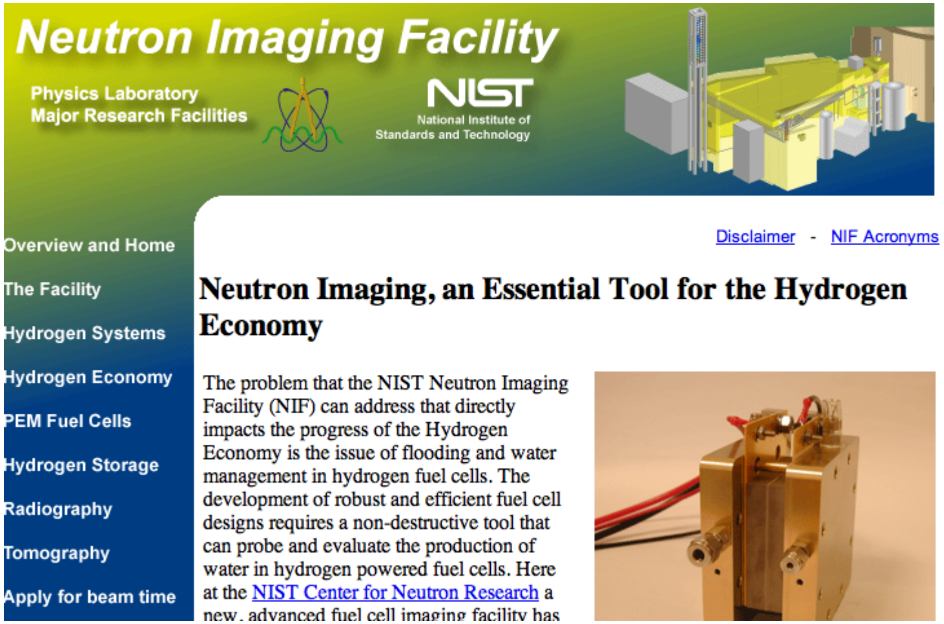


Fe55 X-ray source and a teflon target

- A shielding is placed between the source and the CCD for stopping direct X-rays.
- The Fe55 X-ray source produces two different energy rays from Mn: 5832 eV (K α) and 6412 eV (K β). Both X-rays hit the teflon with carbon and fluorine, which emits lower energy X-ray by fluorescence.
- Each atom has a precise energy pattern of emitting photons, the most probable emitted X-rays are at energies of 277 eV and 677 eV, respectively.
- These low-energy X-rays are detected by the CCD together with some high energy X-rays
- coming directly from the source that get to cross the shielding.

- Skipper paper: "Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon", has been accepted for publication in Experimental Astronomy.
- http://arxiv.org/PS_cache/arxiv/pdf/1106/1106.1839v2.pdf
- Skipper package

Neutron imager with CCDs: 1µm, 1 sec.



why neutrons?

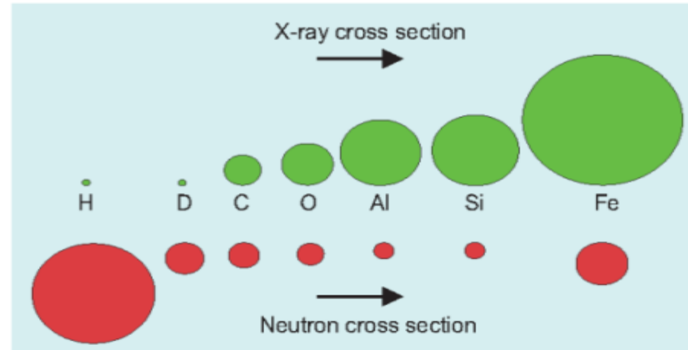
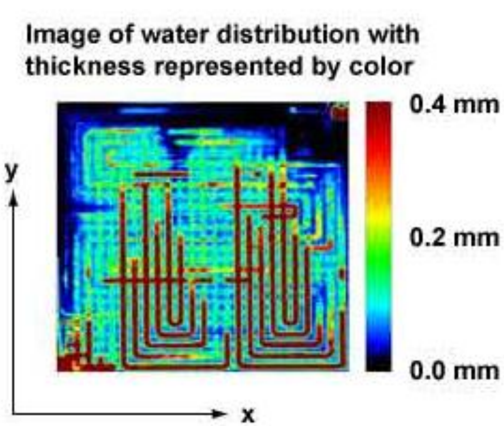
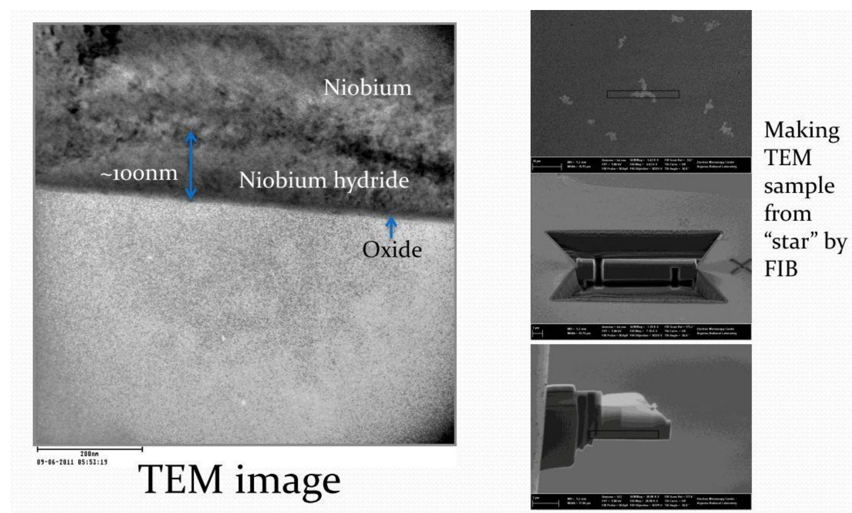


Fig. 2. Neutron and x-ray scattering cross-sections compared. Note that neutrons penetrate through Al much better than x rays do, yet are strongly scattered by hydrogen.

Potential SRF accelerator application?

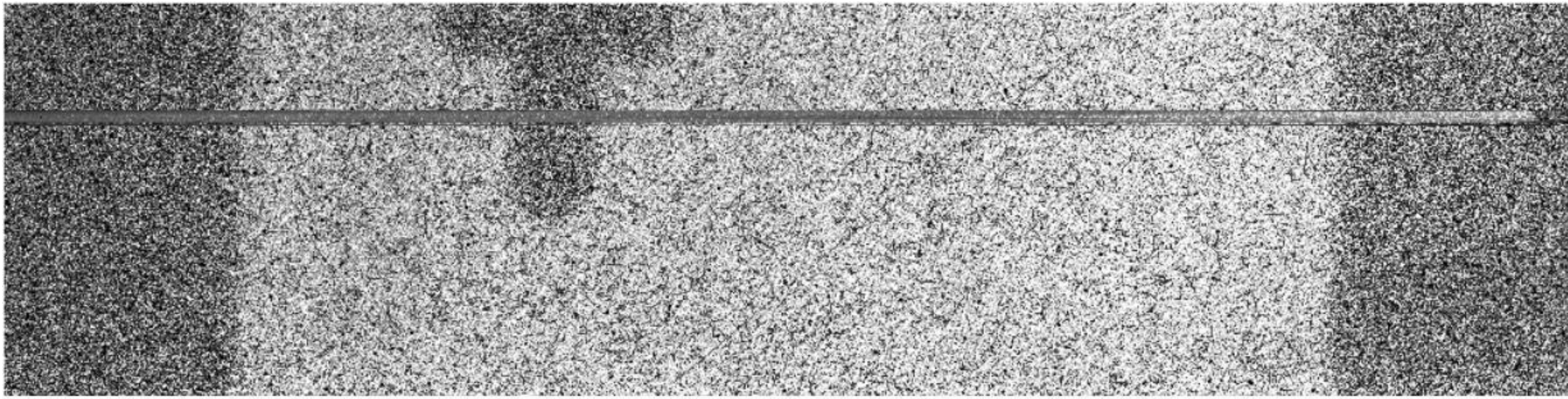
Key tool for Basic Energy Science.





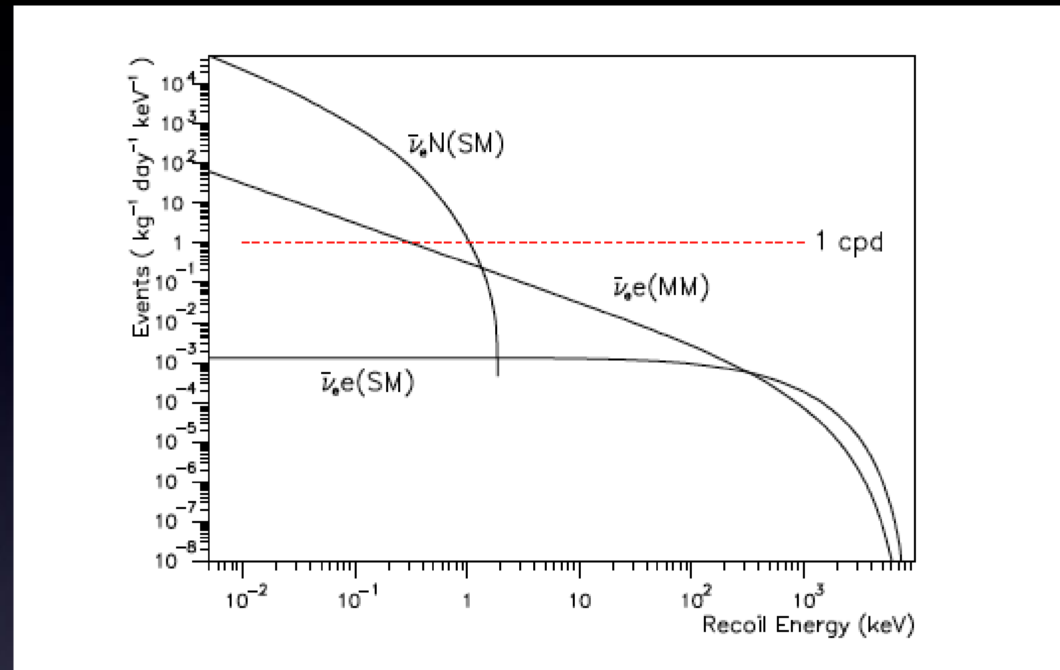
Hydrides may be a major player in Rres and Q0. (A. Romanenko, FNAL)

July 2011

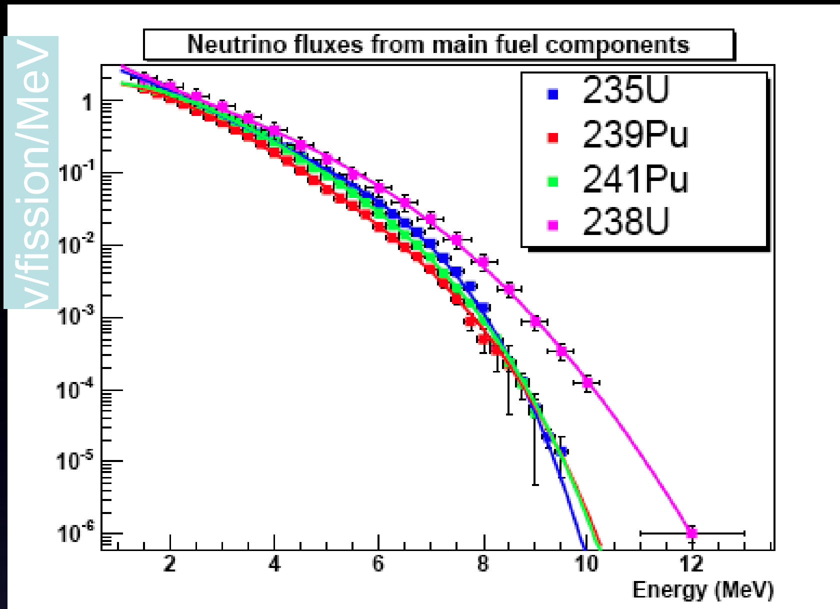


Resolution limited by neutron beam

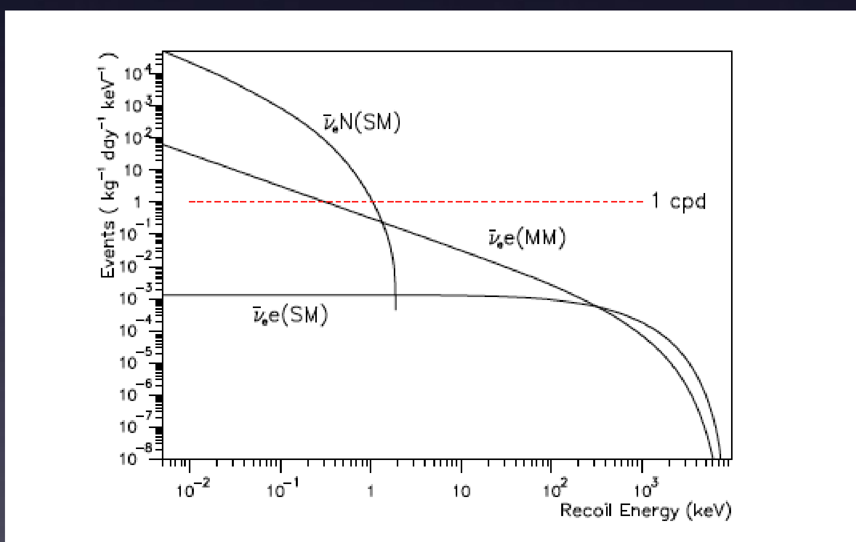
Detection of Neutrino Coherent Scattering with CCDs



CONNIE experiment at Angra dos Reis near Rio de Janeiro in Brazil
Backgrounds measured in 2012.
We hope to install a 10 gram detector in 2013.



measured antineutrino spectrum at ILL



Expected recoil spectrum at 30m of 3GW reactor (Texono)

Two groups are interested on trying this at different reactors. One group is from Mexico (UNAM) and the other Group is from Brazil(Rio).
Proposal to CNPQ in August (Helio da Motta, Martin Makler, Carla Bonifazi). The idea is to install something very similar to DAMIC with a skipper CCD.
CD is going to get the equipment (vacuum vessel, cryocooler, pump).

We hope to start measuring backgrounds in Rio this year.