TIPP 2011

9-14 June 2011

Technology and Instrumentation in Particle Physics 2011

Low noise readout techniques for Charge Coupled Devices (CCD)

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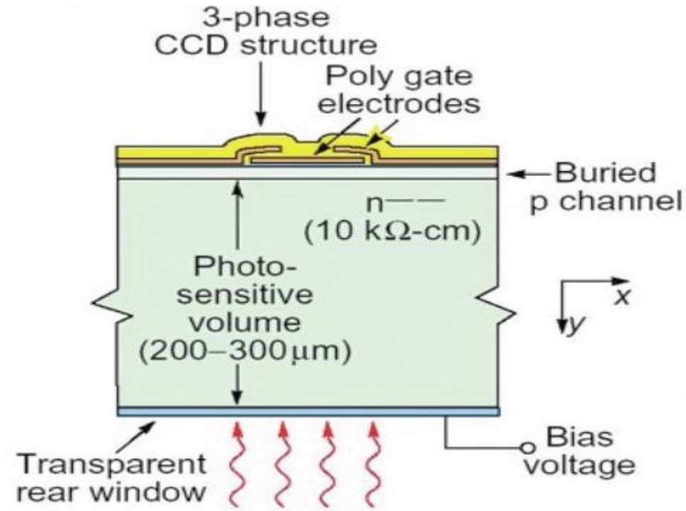
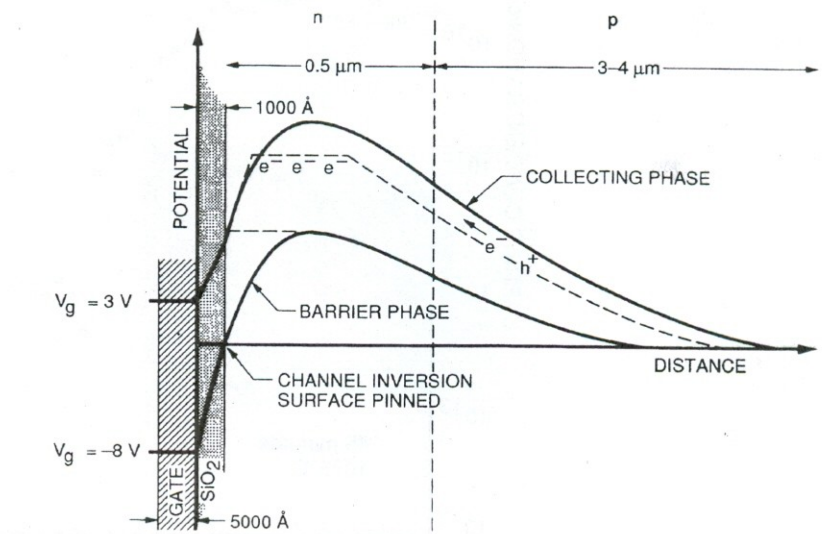
Charge Coupled Devices (CCD)



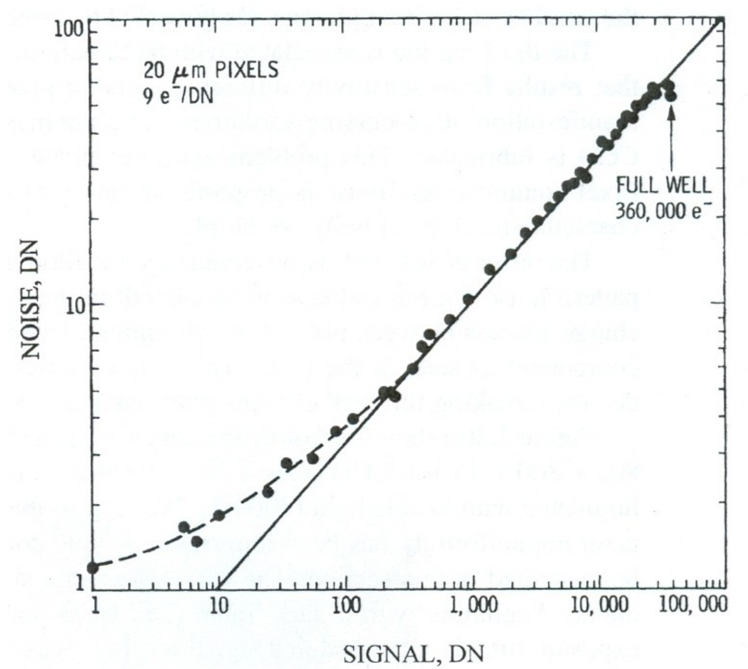
Potential well



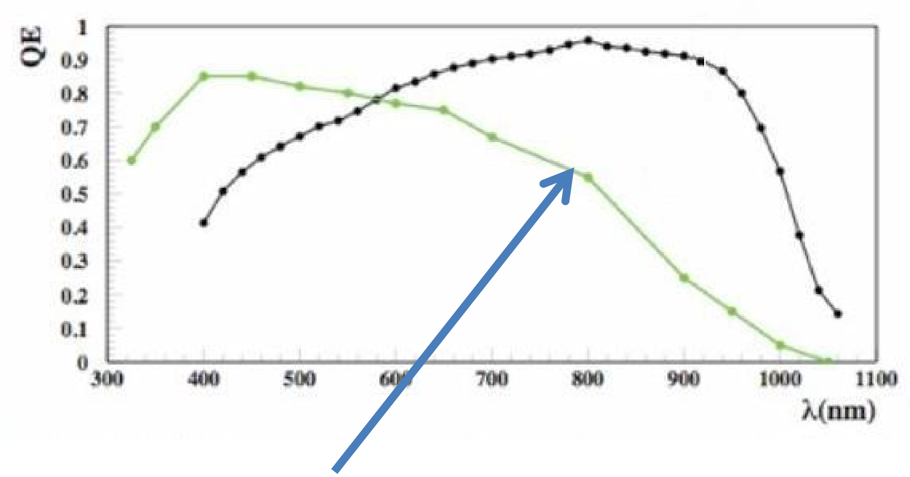
- Characteristics:
  - Properly biased CCDs store charge in a potential well.
  - Very low noise detectors => high dynamic range.
    - 1e- of noise RMS => 3.6eV ionization energy.
  - High spatial resolution: 15 x 15 micron pitch for DeCam CCDs.
  - High density: 8Mpix for DeCam CCDs.

Optical characteristics of LBNL CCDs used for DES DECam: High resistivity, 250μ thick. Fully depleted!

Photon Transfer Curve (PTC)



High QE in near infrared. Z>1
1g of mass, good for direct DM search.
p-channel, better than n-channel for space telescopes



- Photon Transfer Curve:
  - Full well
  - Readout gain
  - Pixel and dark current non uniformity
  - more...

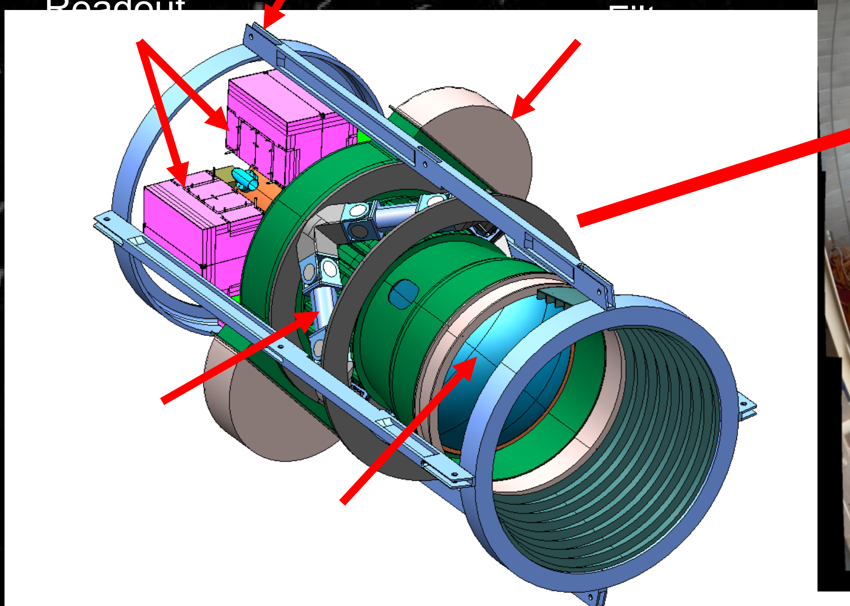
Low resistivity CCDs

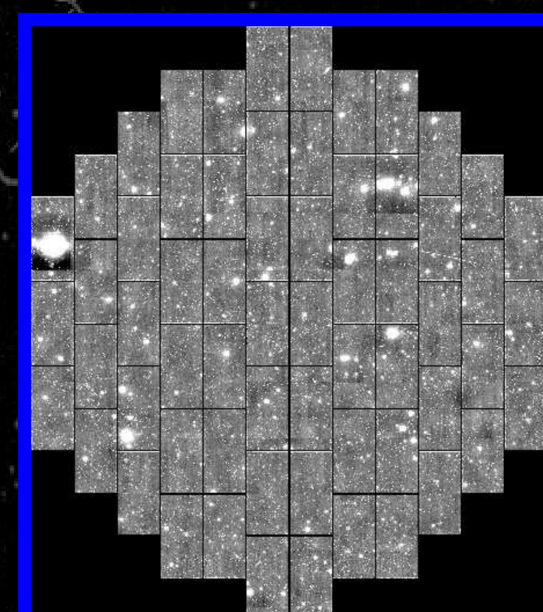
Dark Energy Camera (DECam)

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.

CCD

Mechanical Interface of DECam Project to the Blanco

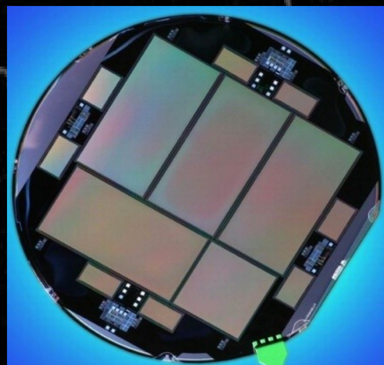




Focal plane with 74 CCDs (~600 Mpix).
All the scientific detectors in hand, packaged and characterized at FNAL.

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

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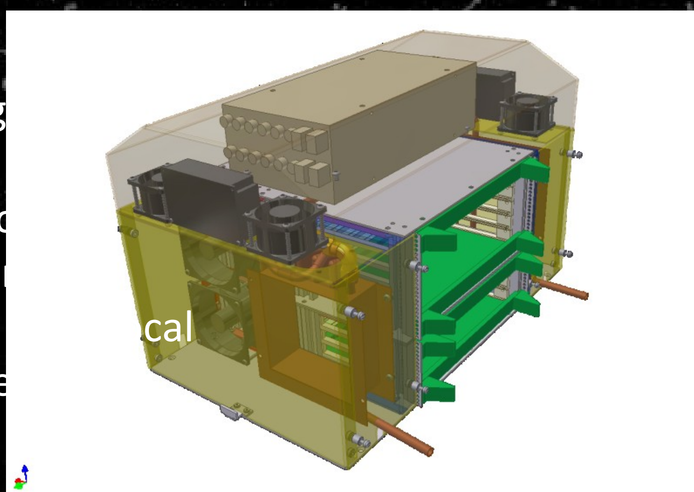
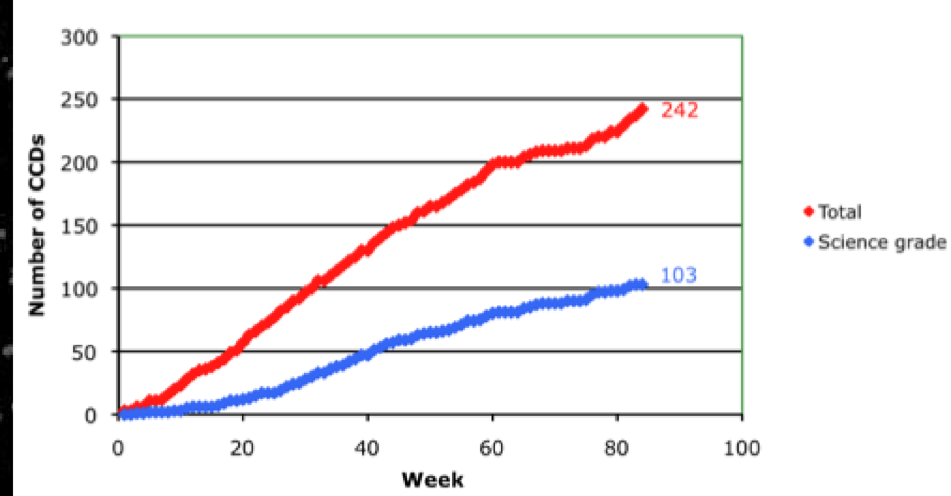
build
reado
electr
for a cal
plane



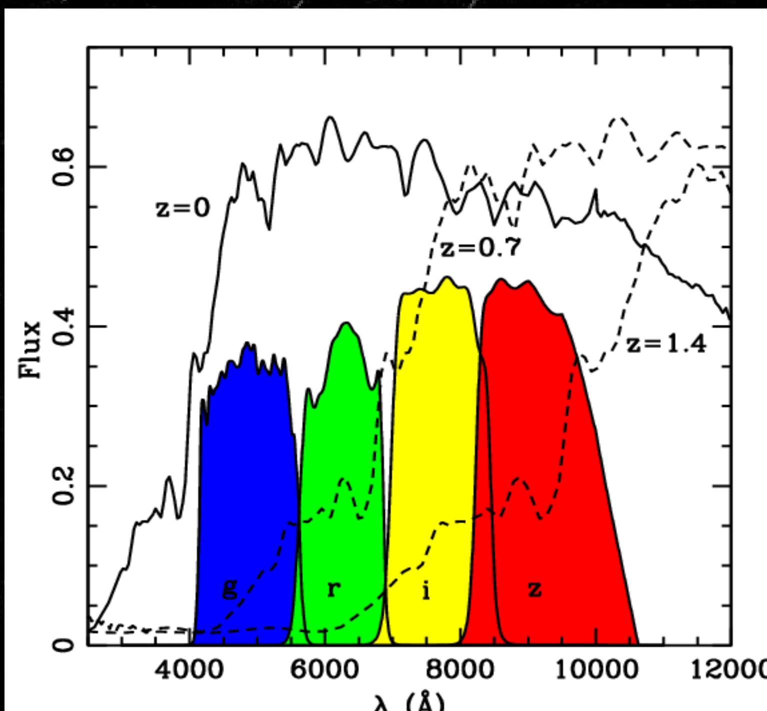
produced/tested 240+ CCDs like an efficient factory



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

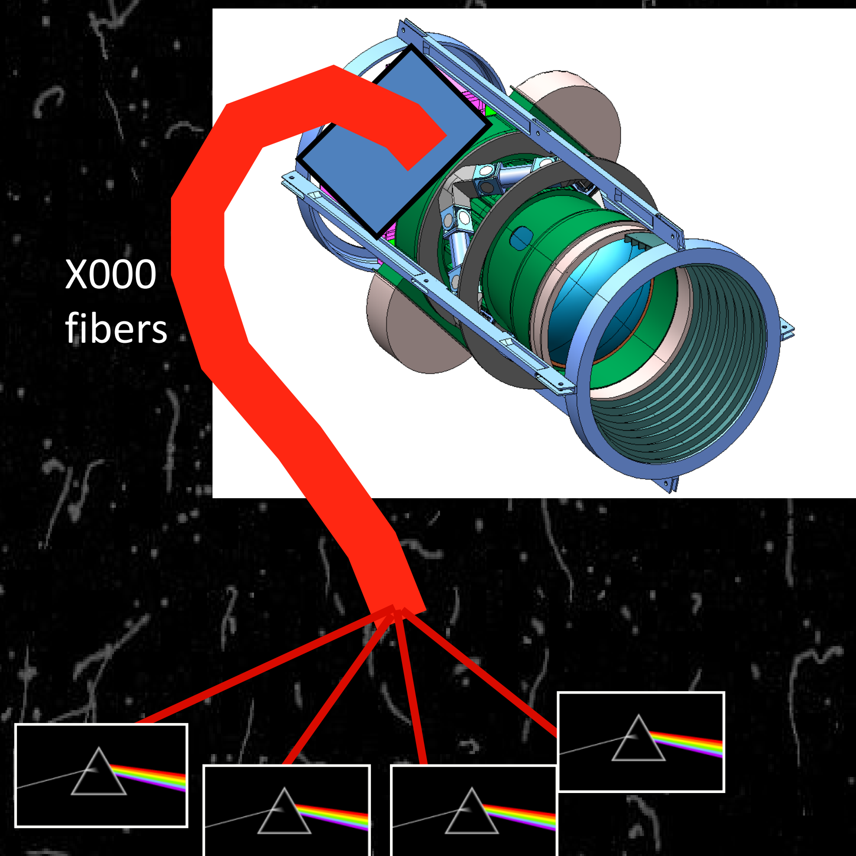
Low noise is critical in spectroscopy

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



4 DES filters
colors change as galaxy moves in z

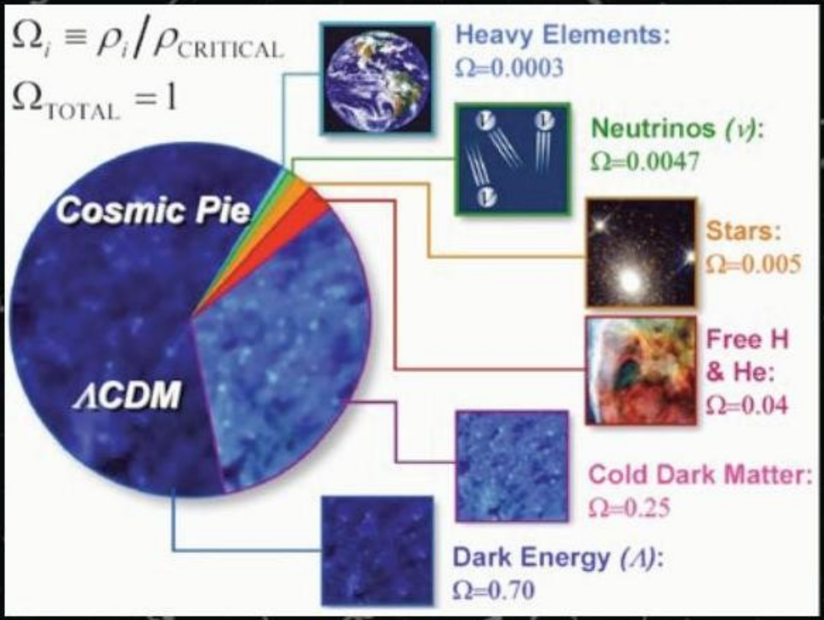
DeSPEC spectrograph proposal:
Lower signal to noise ratio.

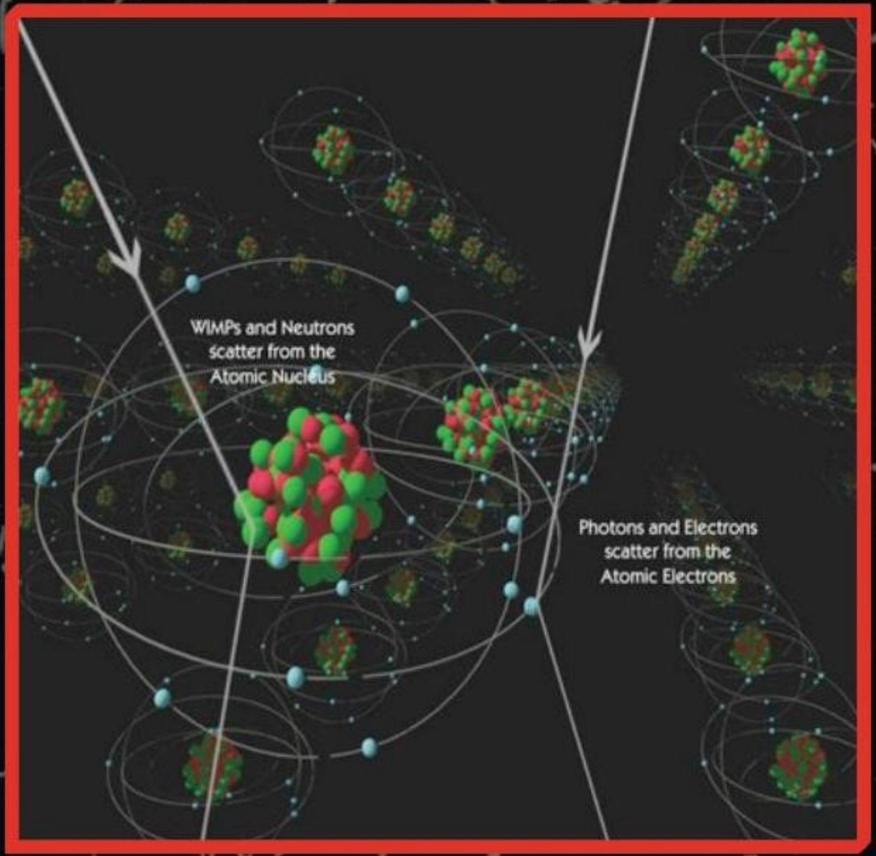


several spectrographs

DM Direct Detection Experiments

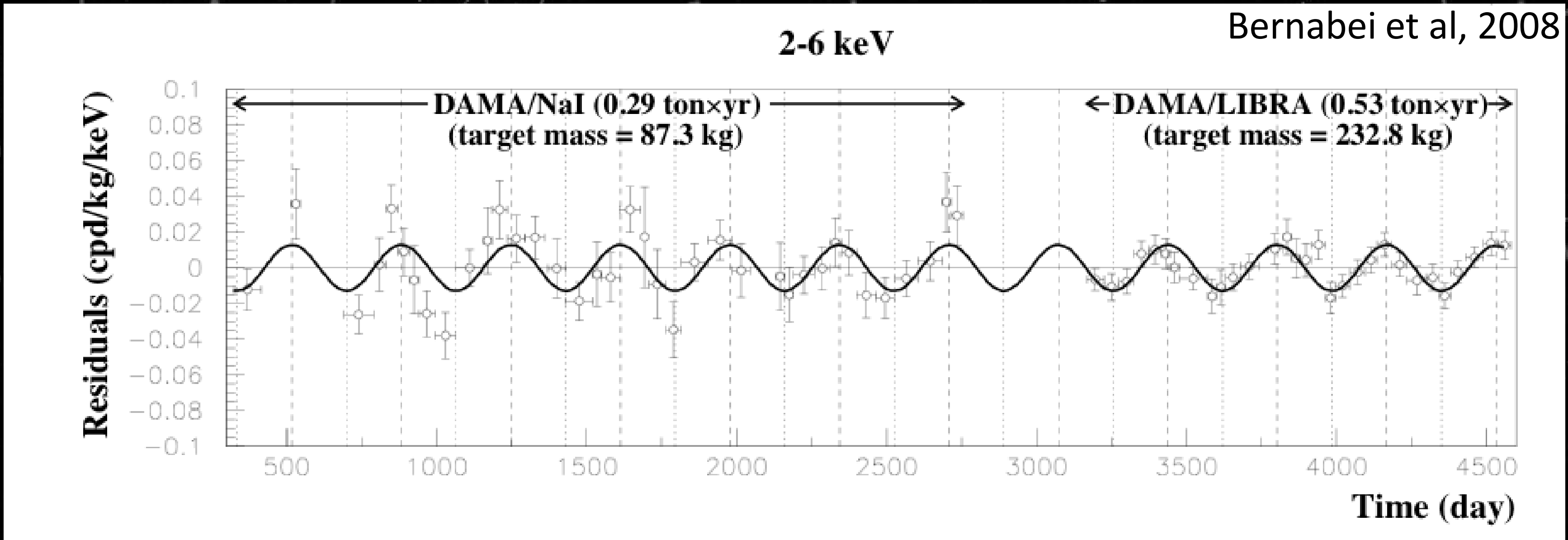
Goal: Detect the collisions of DM particles with detectors as the earth moves in the galaxy. DM particles are neutral (in most models) and would interact with the nuclei of your detector.

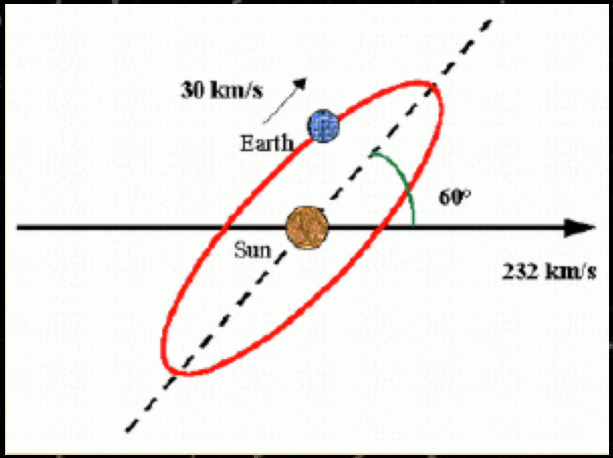




Typically people try to build detectors that will see a nuclear recoil and distinguish it from an interaction with the atomic electrons.

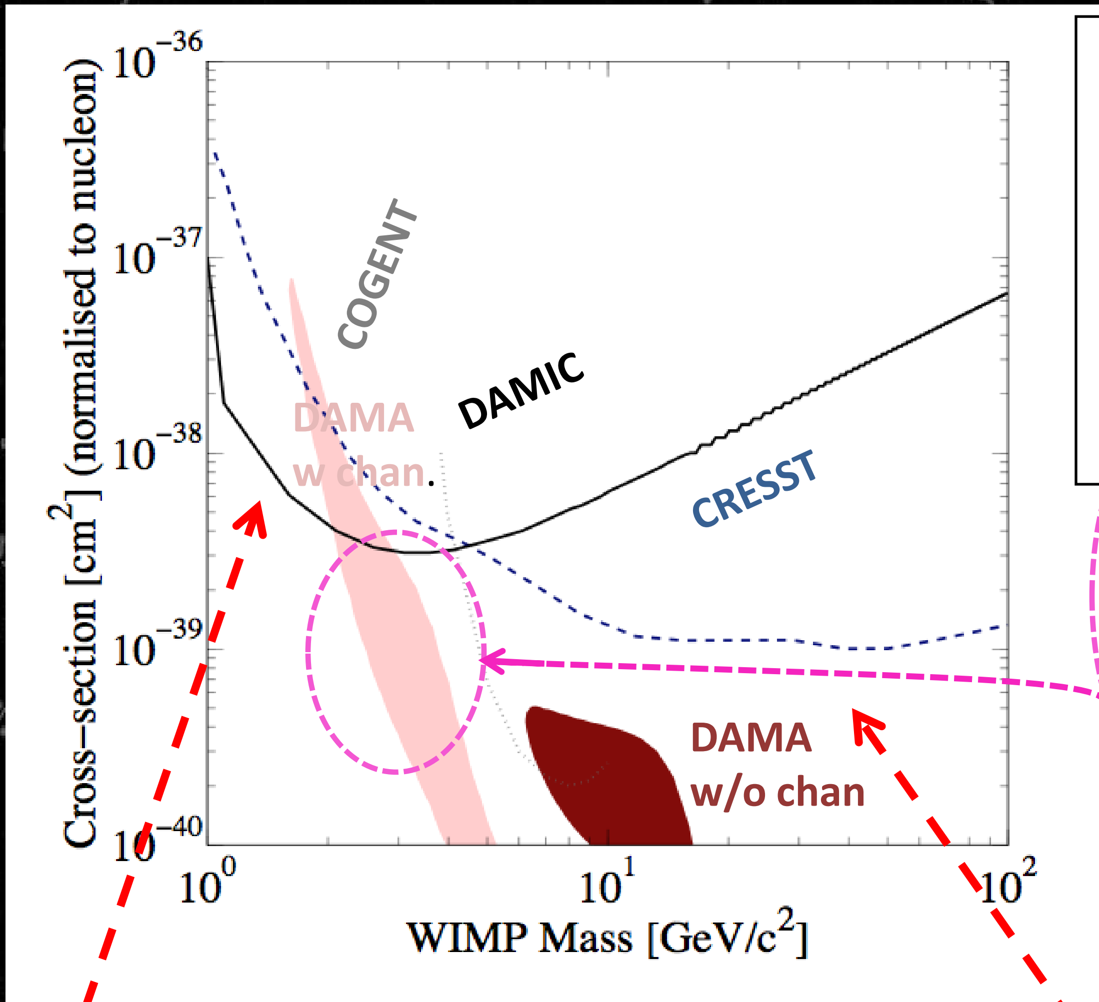
One good reason to look for low mass dark matter : The DAMA/LIBRA result



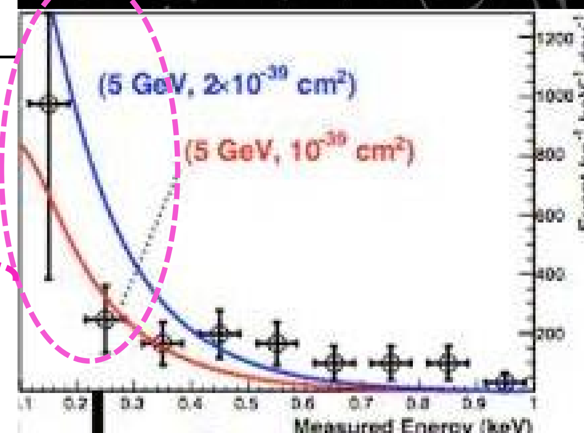


>8 σ detection of annual modulation consistent with the phase and period expected for a low mass dark matter particle (~7 GeV) consistent with recent COGENT results.

DAMIC experiment at FNAL



umber of recoils
xponentially increase
l low energies.



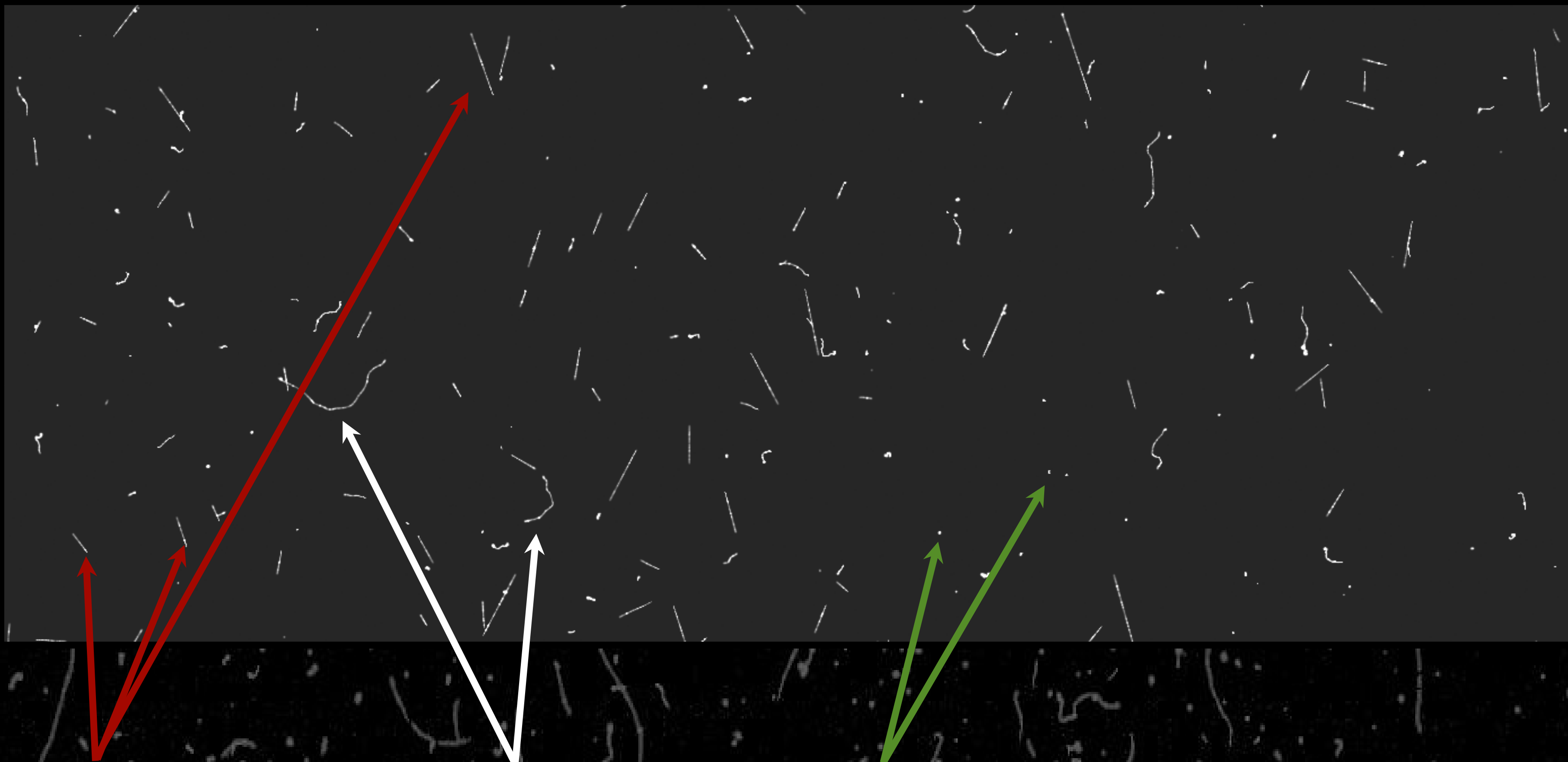
Low noise limited:

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.

Particle detection with CCDs



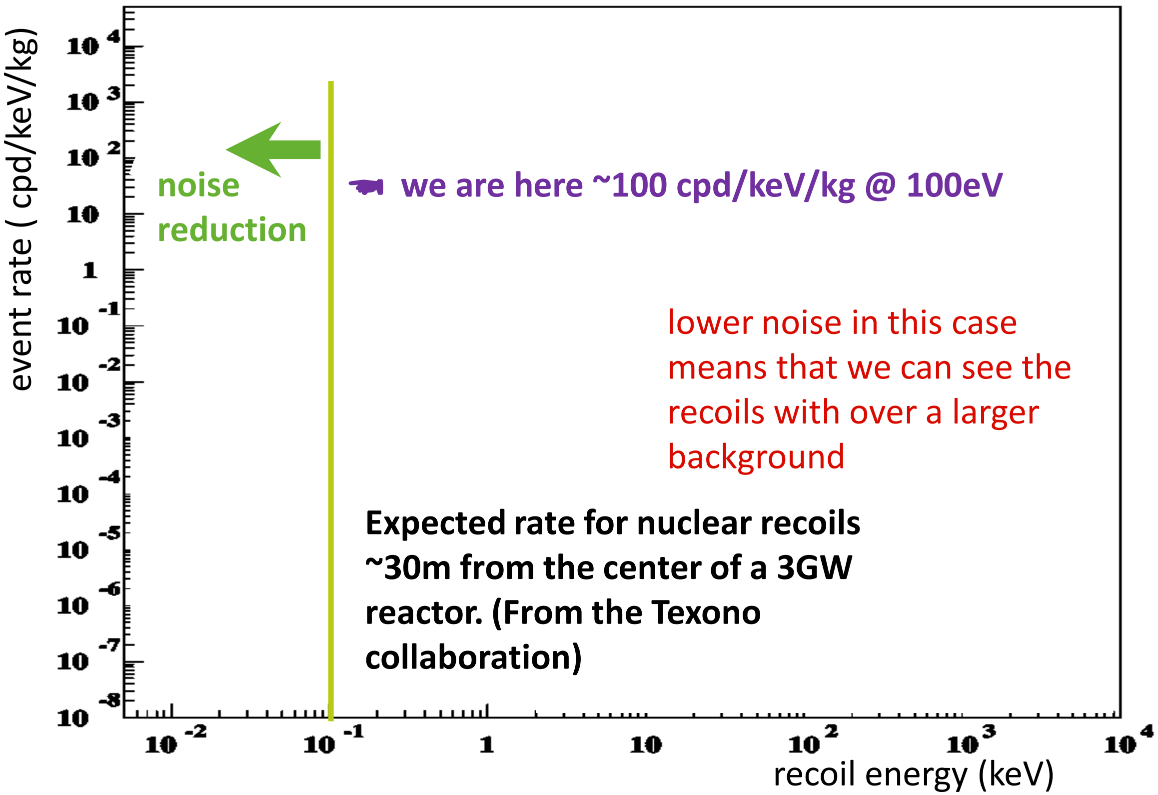
muons, electrons and diffusion limited hits.

nuclear recoils will produce diffusion limited hits

Neutrino coherent scattering:

- **CCD threshold <100 eV (goal ~10 to 15eV)**

$$\nu + \mathrm{N} \rightarrow \nu + \mathrm{N}$$



oss section is relatively large,
iallenges are detector
:ivity and background control.

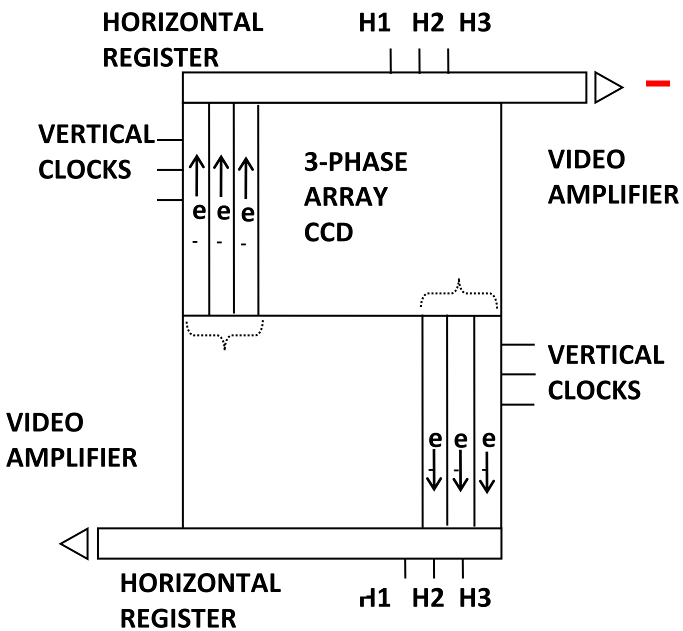
SM and new physics.
Help understand how to study
;upernovae neutrinos.
Monitoring of nuclear
eactors.

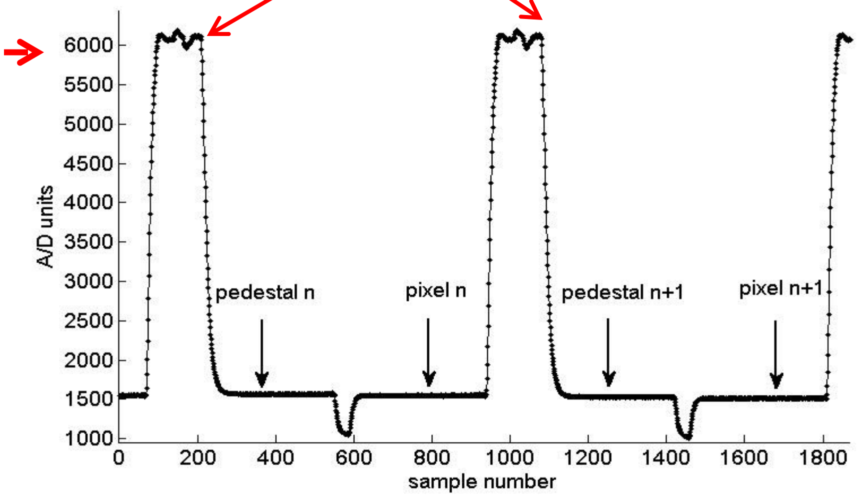
Low noise CCD readout

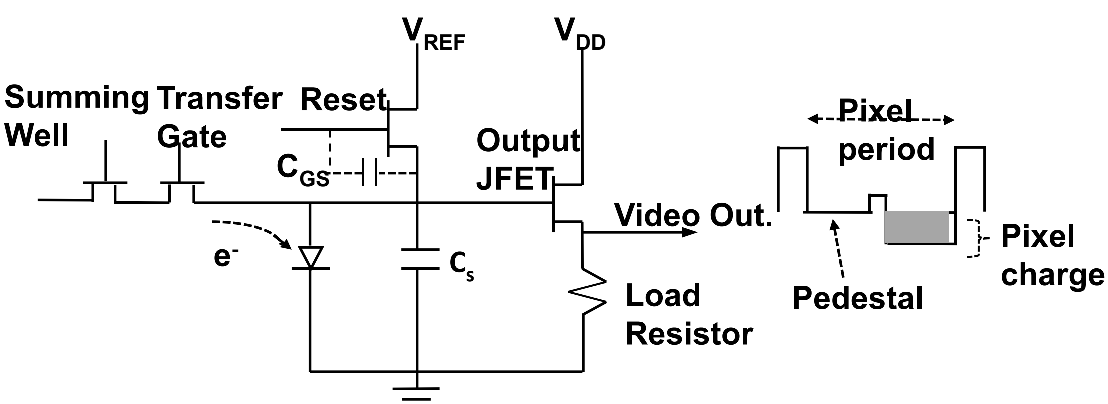
- A low noise CCD based readout system will greatly benefit projects such as:
  - Direct search for Dark Matter
  - Neutrino coherent scattering.
  - Spectroscopy.
- Two Low noise reduction techniques:
  - Reduction of Pixel to pixel correlated noise using fast sampling, precision A/D conversion and digital filtering.
  - Skipper CCDs (see poster at this conference and recent paper in …)

CCD Images

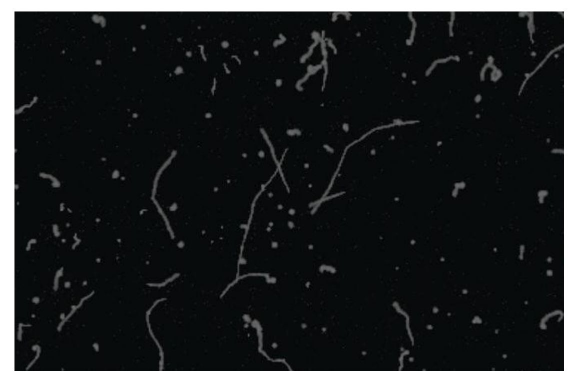
Reset pulses are ~ 50,000 e^-



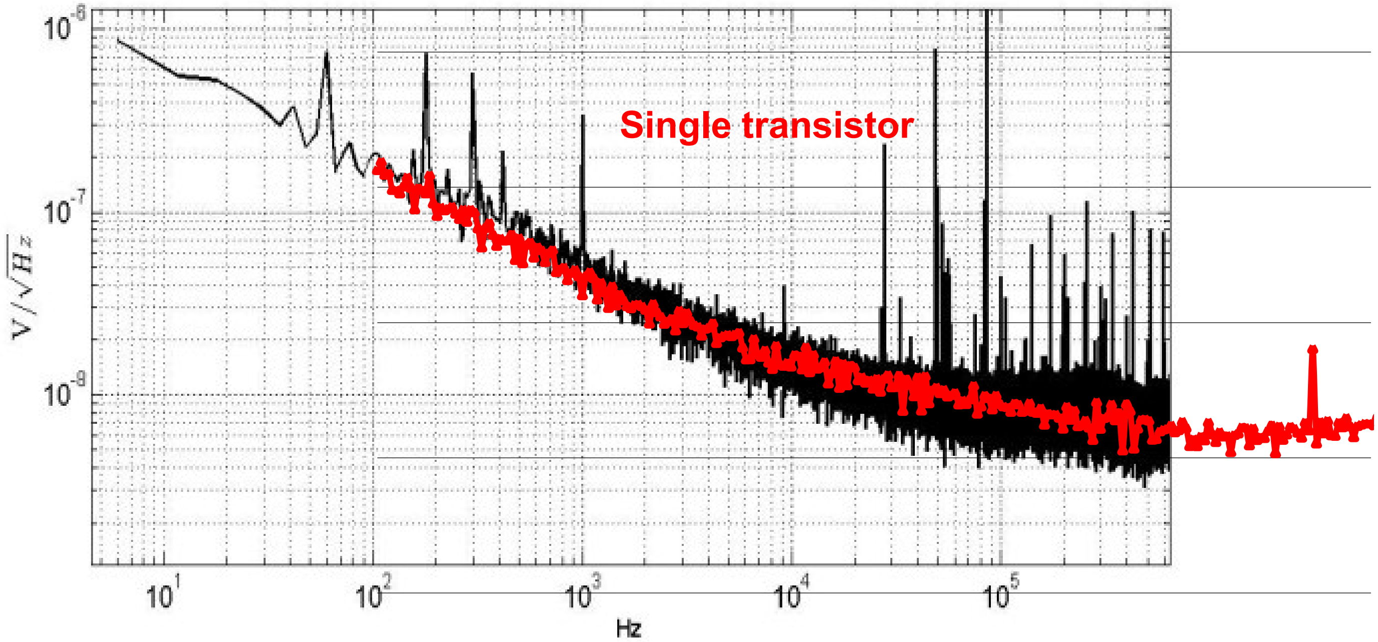




FITS image:
Each pixel is a n-bit digital representation of the pixel charge.



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.

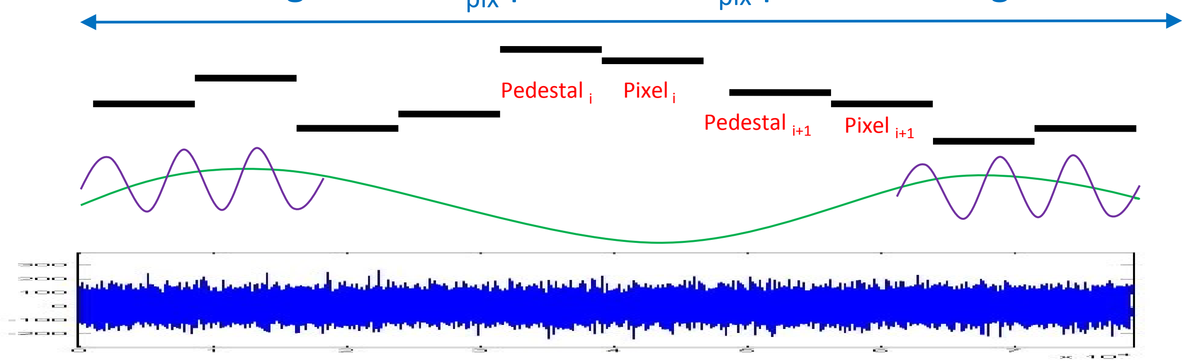
Correlated Double Sampling (CDS)

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

Integration intervals: $t_4 - t_3 = t_2 - t_1 = T$

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

Video fragment: N_{pix} pixels and N_{pix} pedestals long.



s(n) pedestals and pixels

n(n) correlated noise (LFN)

w(n) white Gaussian noise

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

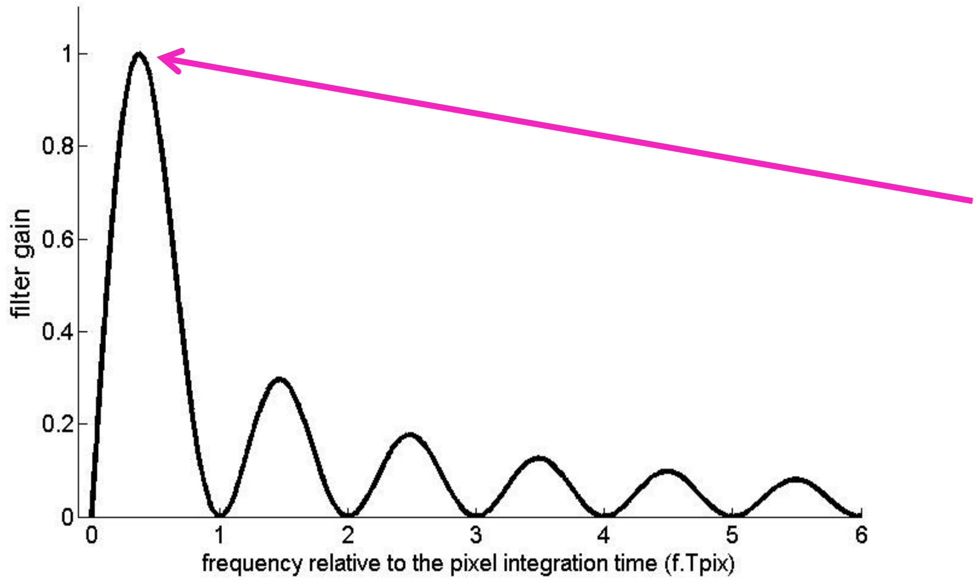
For the white and Gaussian noise w ~ N(0,σ²), the CDS is the optimum estimator.

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 transfer function



- The CDS filters very low frequency noise close to DC.
- Minimum noise rejection at f~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.

T_{pix} is a "free" parameter.
In the analog CDS we adjust T_{pix} for the minimum noise where the 1/f contribution is small.
But short T_{pix} limit WGN reduction.

So far analog CDS techniques achieve ~2e- of noise at T_{pix} of ~20useconds.

Estimator and digital CDS

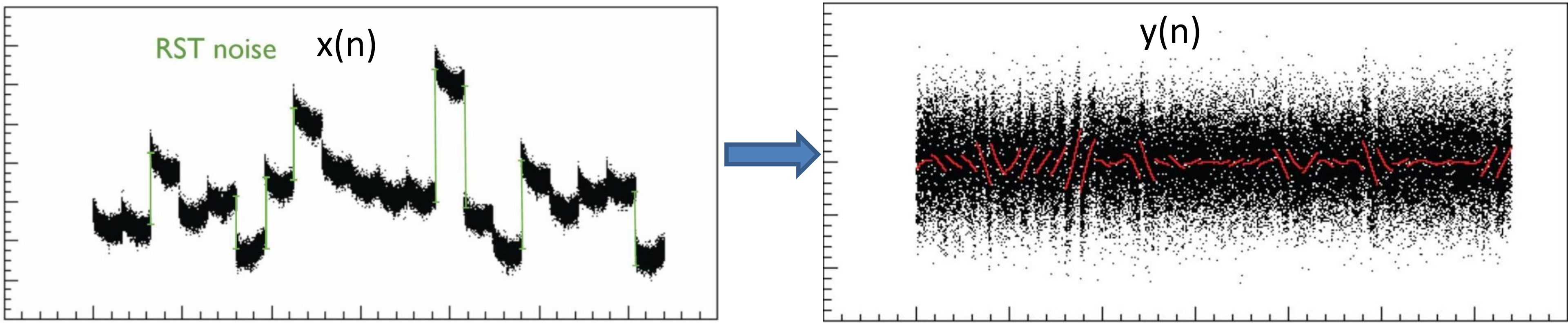
- Digital sample the video signal.
- Estimate the correlated noise of a string of pixels.
- Subtract the correlated noise from the original video.
- Perform the digital CDS of the filtered signal.
  - χ^2 estimator, because it does not assume a particular noise model:
  - Inversion of a large matrix. Only one time and can be done off-line.
  - Linear model is not orthogonal. Ill-posed problem.
- 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.

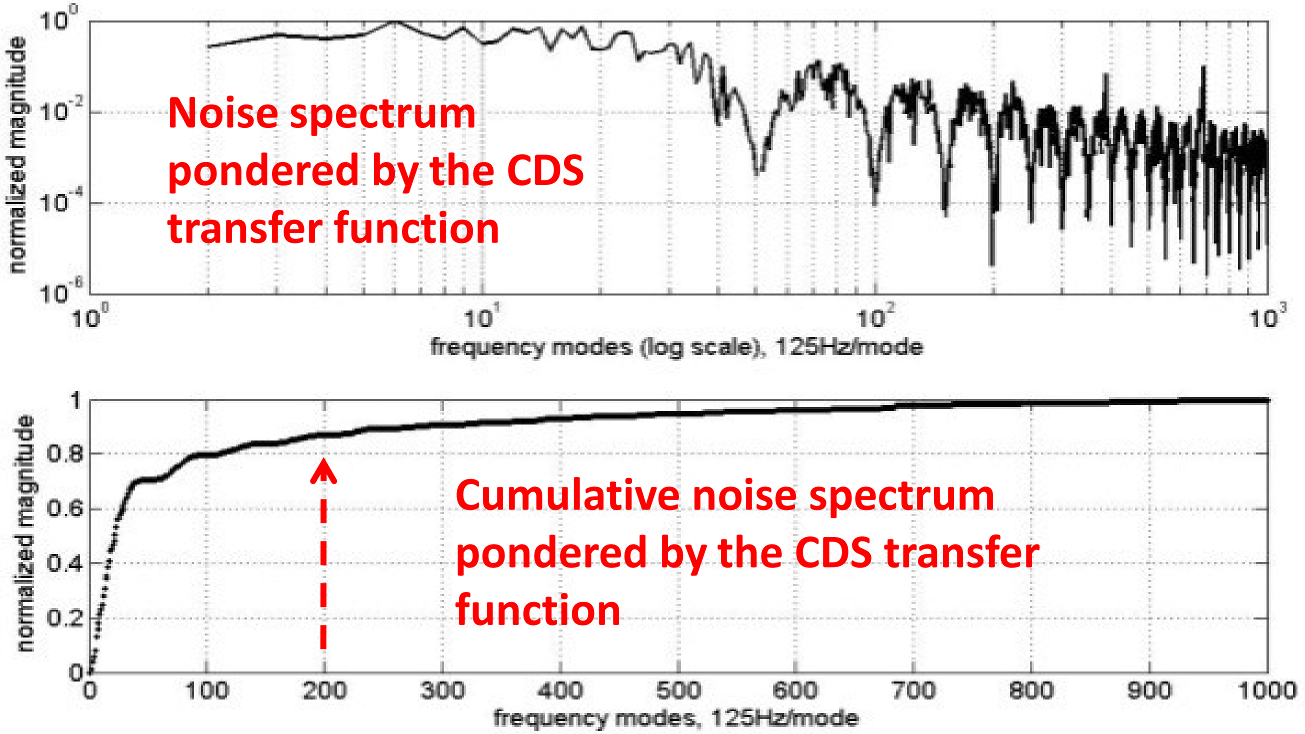
$$y(n) = x(n) - \langle x(n) \rangle$$

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

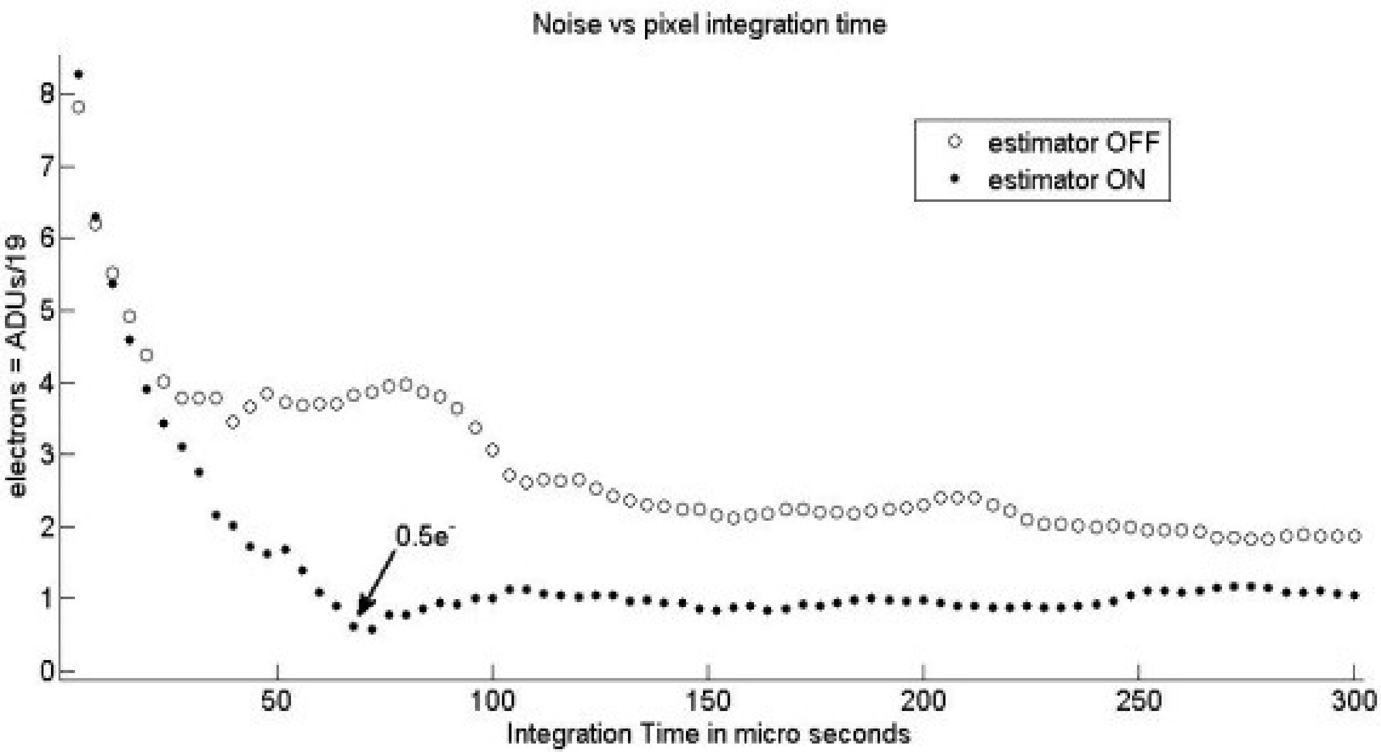


How many modes?



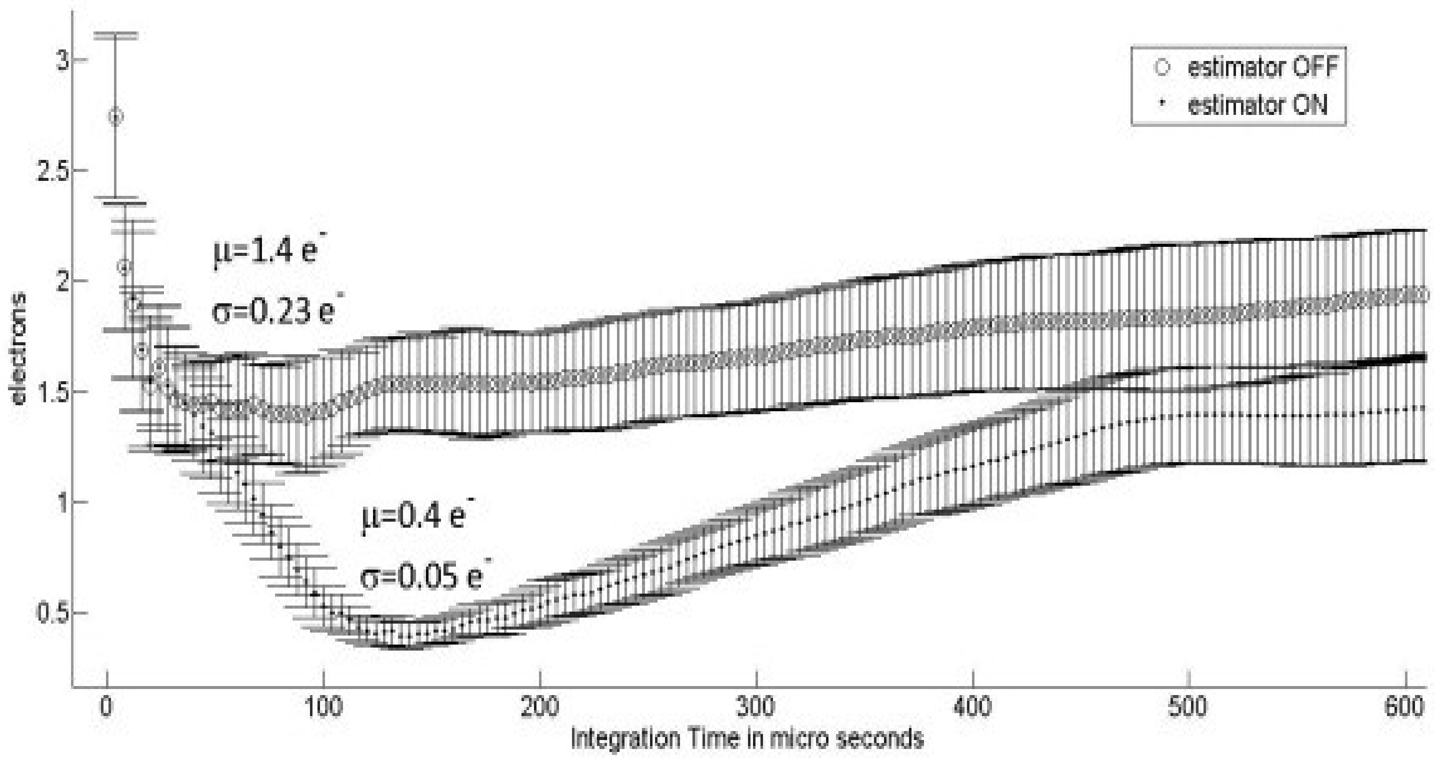
- 200 modes account for ~85% of the low frequency correlated noise.
- If parameter estimation could be done with zero error.

Estimator and digital CDS Results (DeCam CCD)



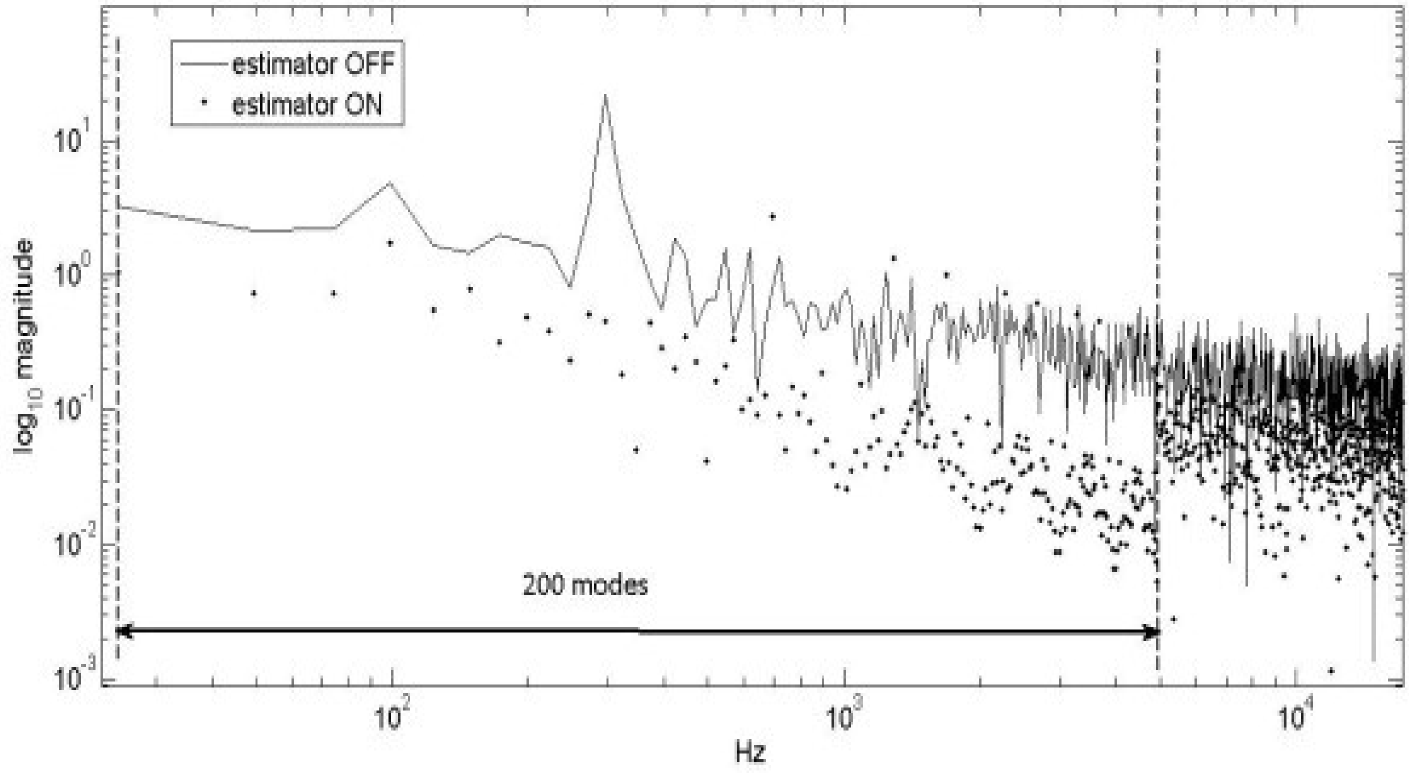
- 0.5e- of noise achieved (consistently) for T_{pix} of 70useconds.

Estimator and digital CDS Results (LBNL 12 channel CCD)



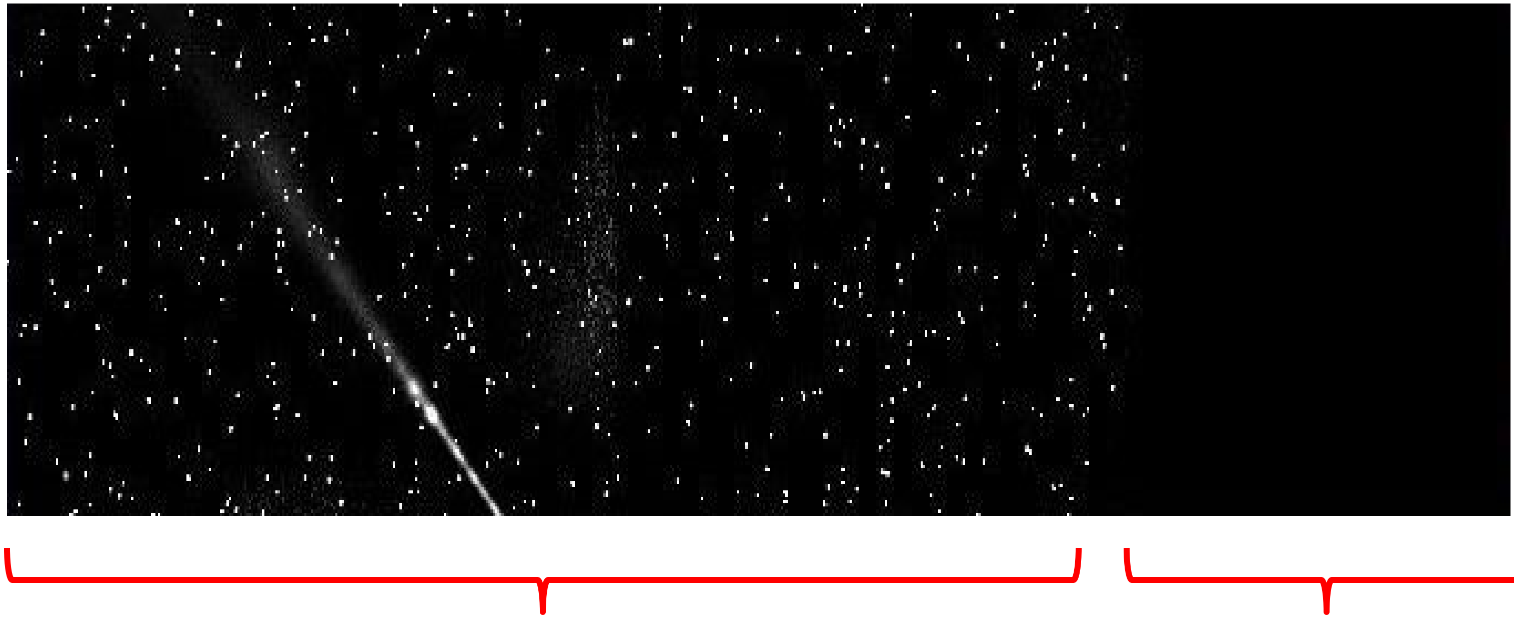
- The plot displays the average noise of 100 data sets and 1-σ error bars.
  - 0.4e- at 120 μs.
  - It is also interesting that the 1-σ error bars of the estimator processed data are 4 times smaller than the ones for the unprocessed data.

Noise spectrum comparison



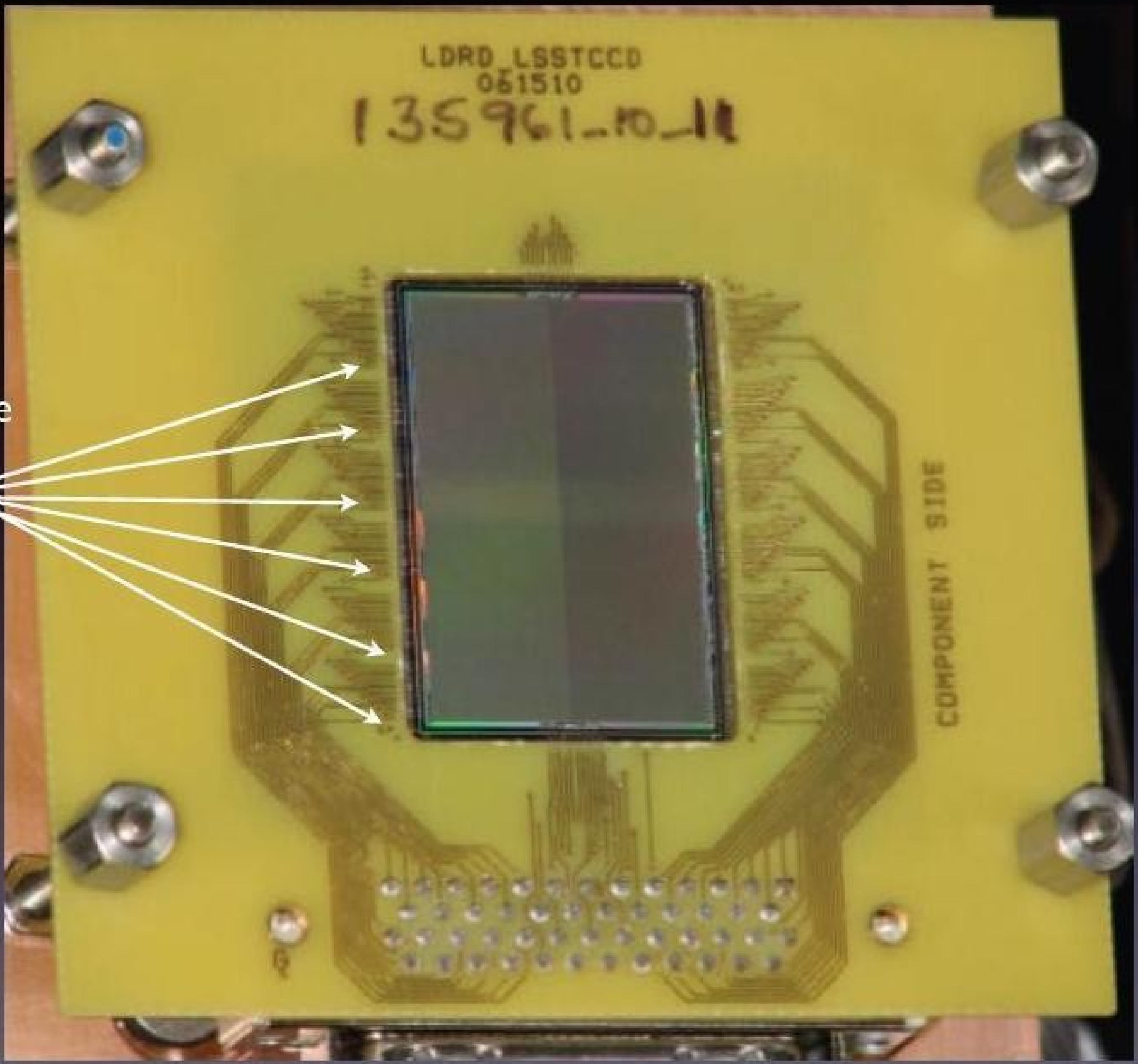
- Compares the noise power spectrum of the unfiltered signal and the filtered signal after the low frequency estimation of 200 modes has been subtracted.
  - **On average, the LFC noise has been reduced by almost an order of magnitude on average.**

FPGA implementation of the estimator and digital CDS



- 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.

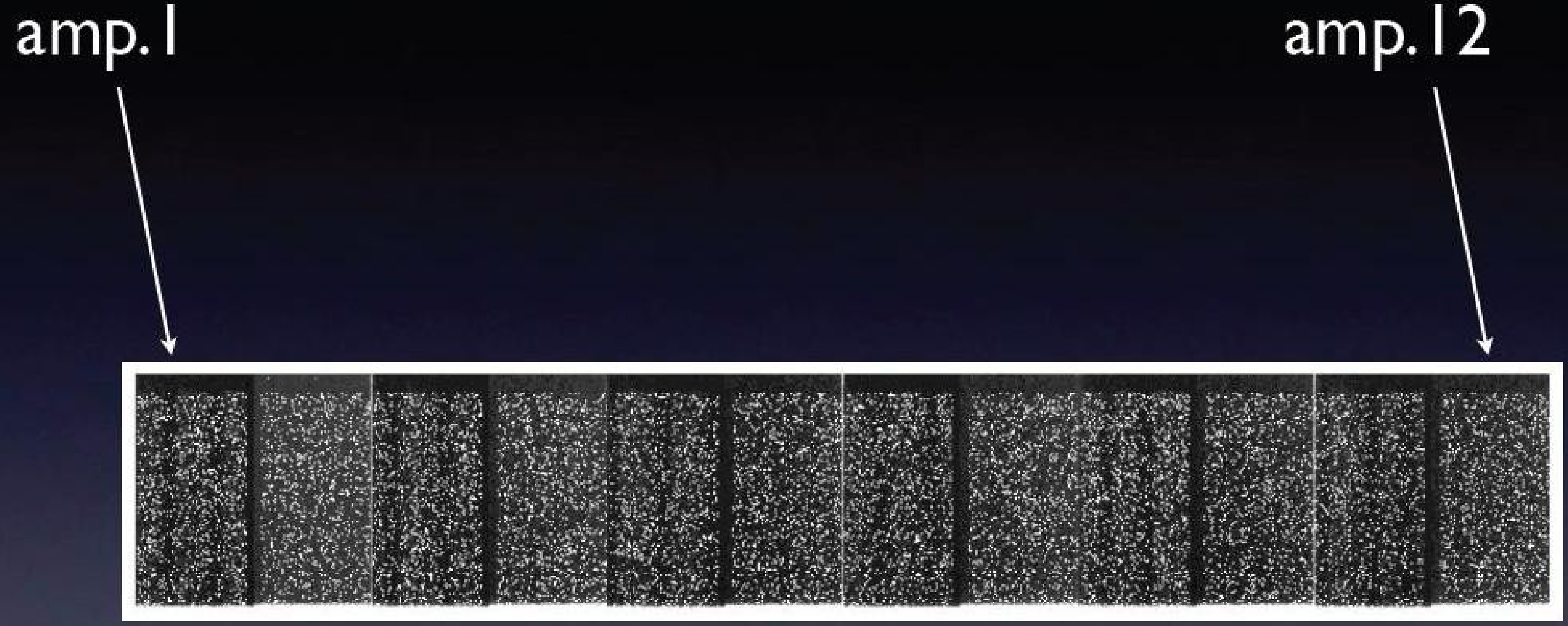
12 channel LBNL CCD



6 amplifiers per side each side
0.5 Mpix per amp

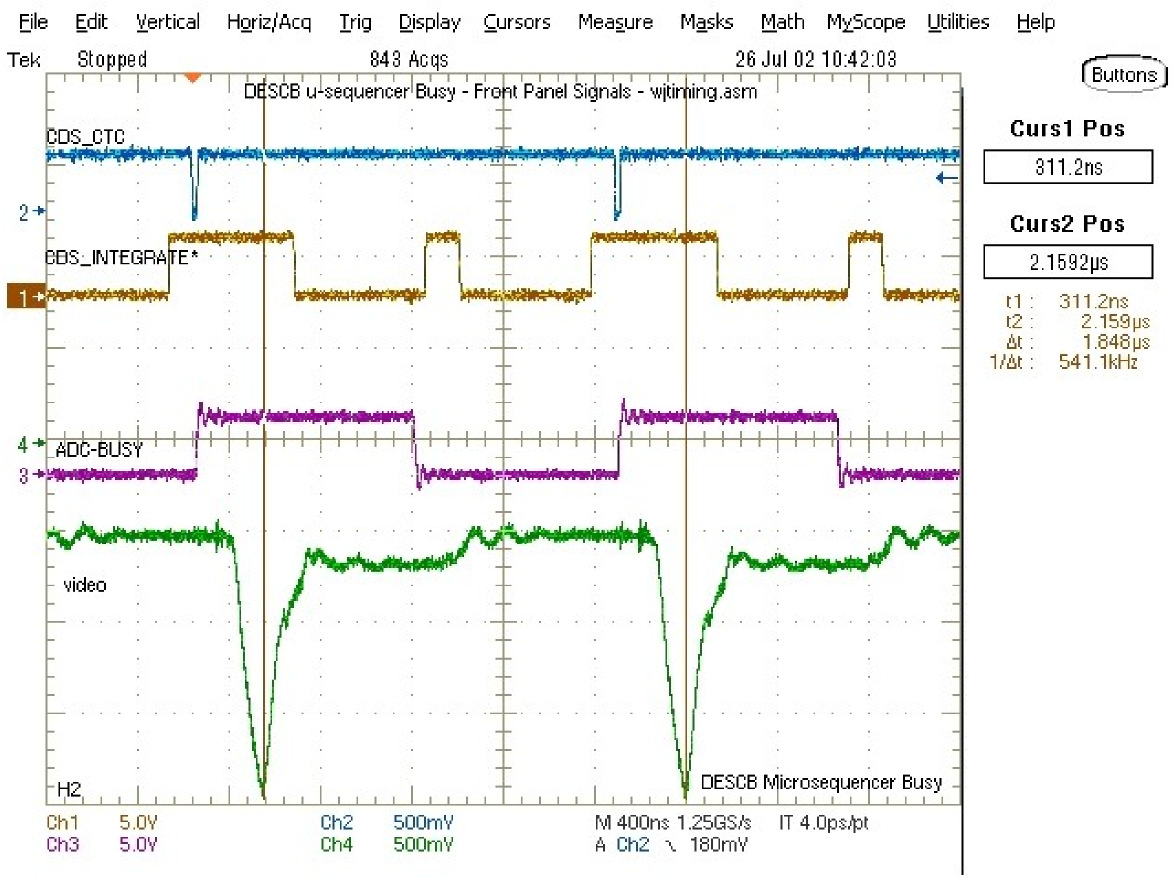
- **This CCD would be a good candidate for telescopes that require high pixel bandwidth such as LSST.**

Images taken with a 12 channel Monsoon system



all the amplifiers work.

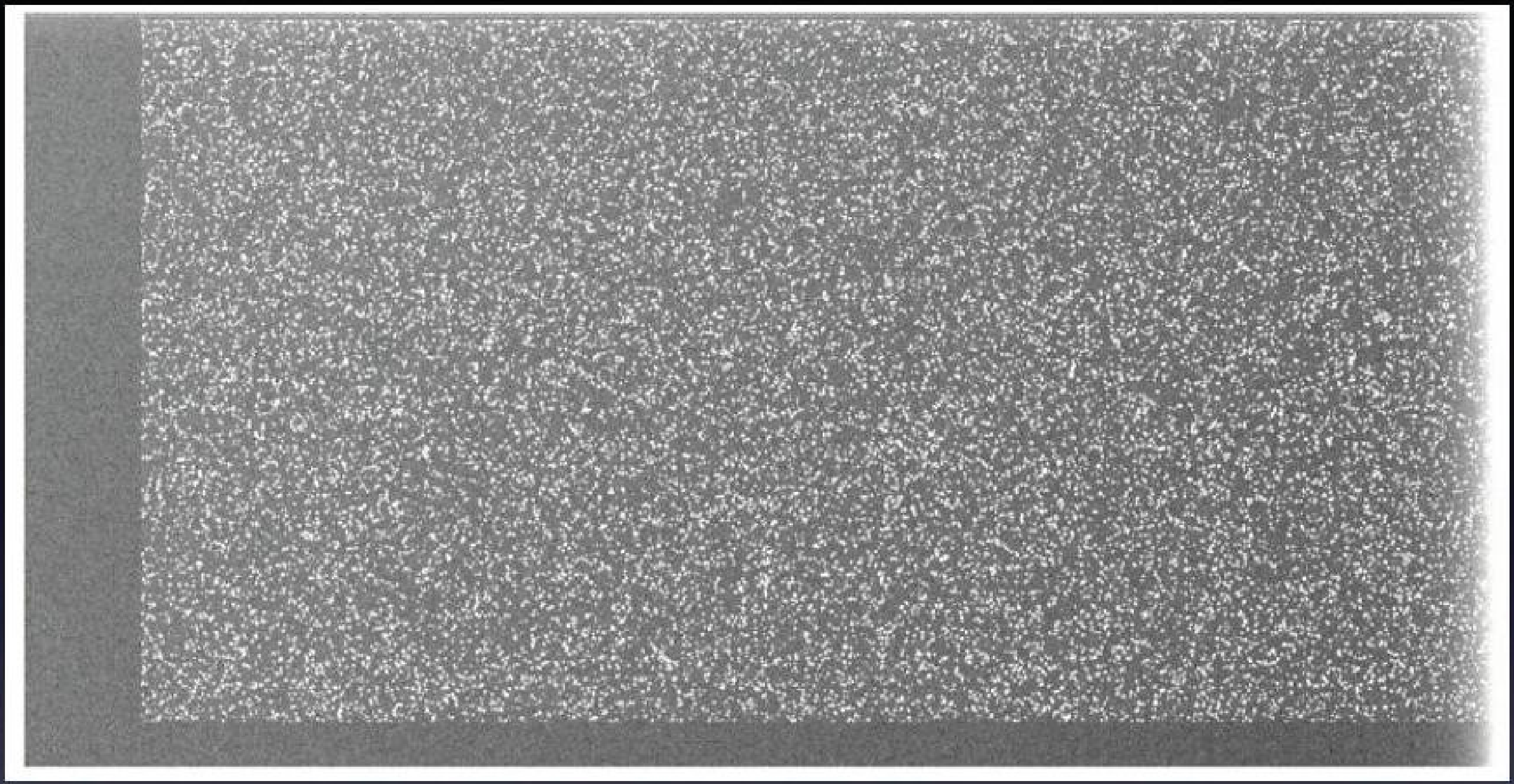
12-channel :Pixel cycle time 1.85us



Pixel cycle: 1.848 us

INTEG_WIDTH = 2*500 ns

Noise : 10.7 e-



this is X-ray image
no trials... good transfer efficiency
running at 500 kpix/sec!
noise 8e- RMS!

At slow readout the noise performance is comparable with DeCam CCDs

Summary

- The estimator and digital CDS reduce the CCD noise deep into the sub-electron region.
- New avenues for HEP experiments and telescopes are open:
  - The price to pay for lower noise is a more sophisticated readout system.
  - The estimator and digital CDS is being implemented in an FPGA with good success.

- 12 video channel p-channel high resistivity CCDs from LBNL have been tested at 500Kpix/s with 8e- of noise

Thank you!