Charge Coupled Devices (CCDs) for the Dark Energy Camera (DECam)

Juan Estrada
11/12/2010

Outline

- CCDs:
  - light into the detector ➙ digital image
- DECam :
  - general
  - focal plane detectors requirements
- Details of DECam CCDs
  - Quantum Efficiency
  - diffusion
  - edge distortions
  - noise
  - full well
- Next : LSST

2009 Nobel Prize in Physics awarded to the inventors of the CCD

In 1969, Willard S. Boyle and George E. Smith invented the first successful imaging technology using a digital sensor, a CCD (charge-coupled device). The two researchers came up with the idea in just an hour of brainstorming.

Bell Labs researchers Willard Boyle (left) and George Smith (right) with the charge-coupled device.
Photo taken in 1974. Photo credit: Alcatel-Lucent/Bell Labs.

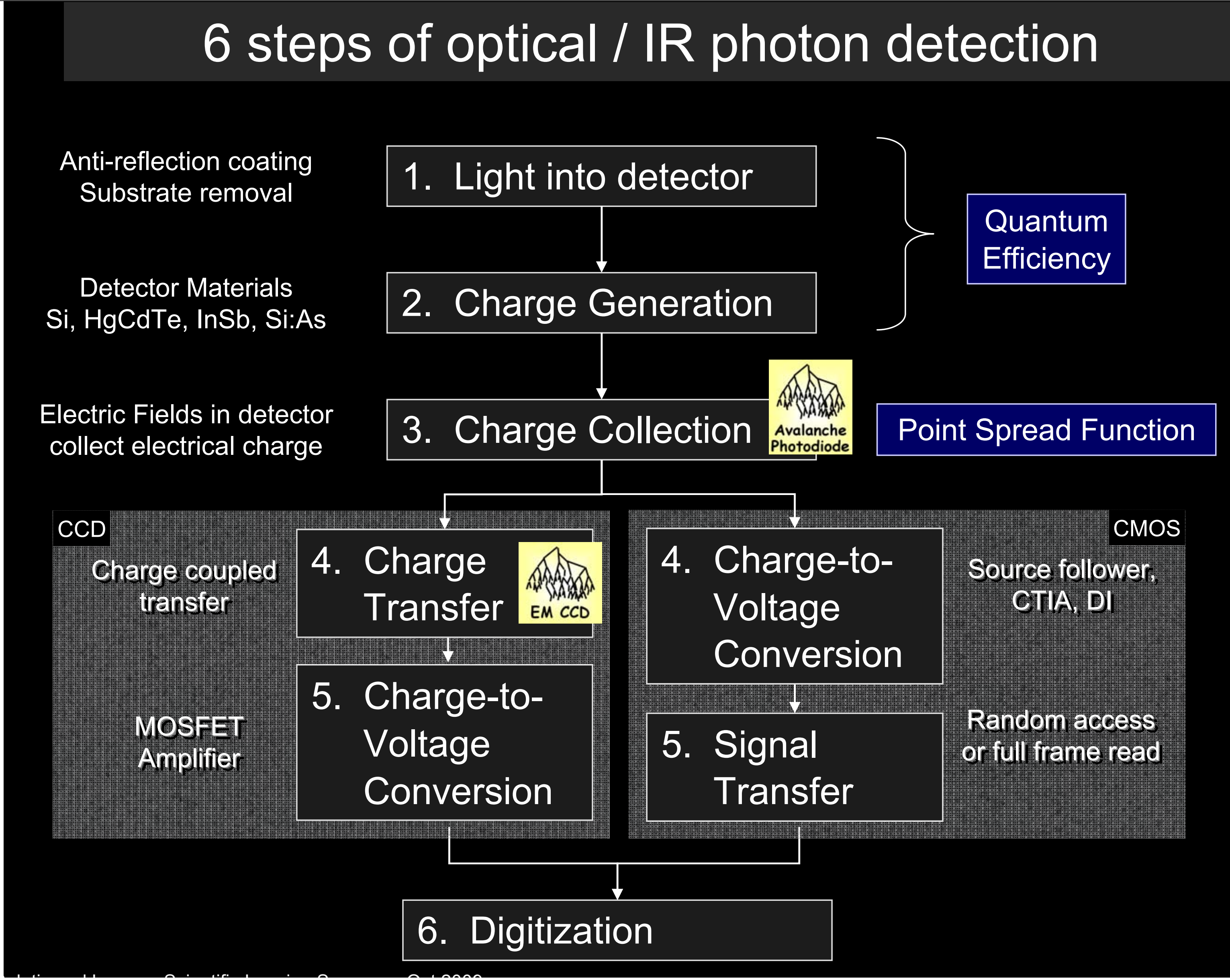
The Nobel Prize in Physics 2009

"for the invention of an imaging semiconductor circuit – the CCD sensor"

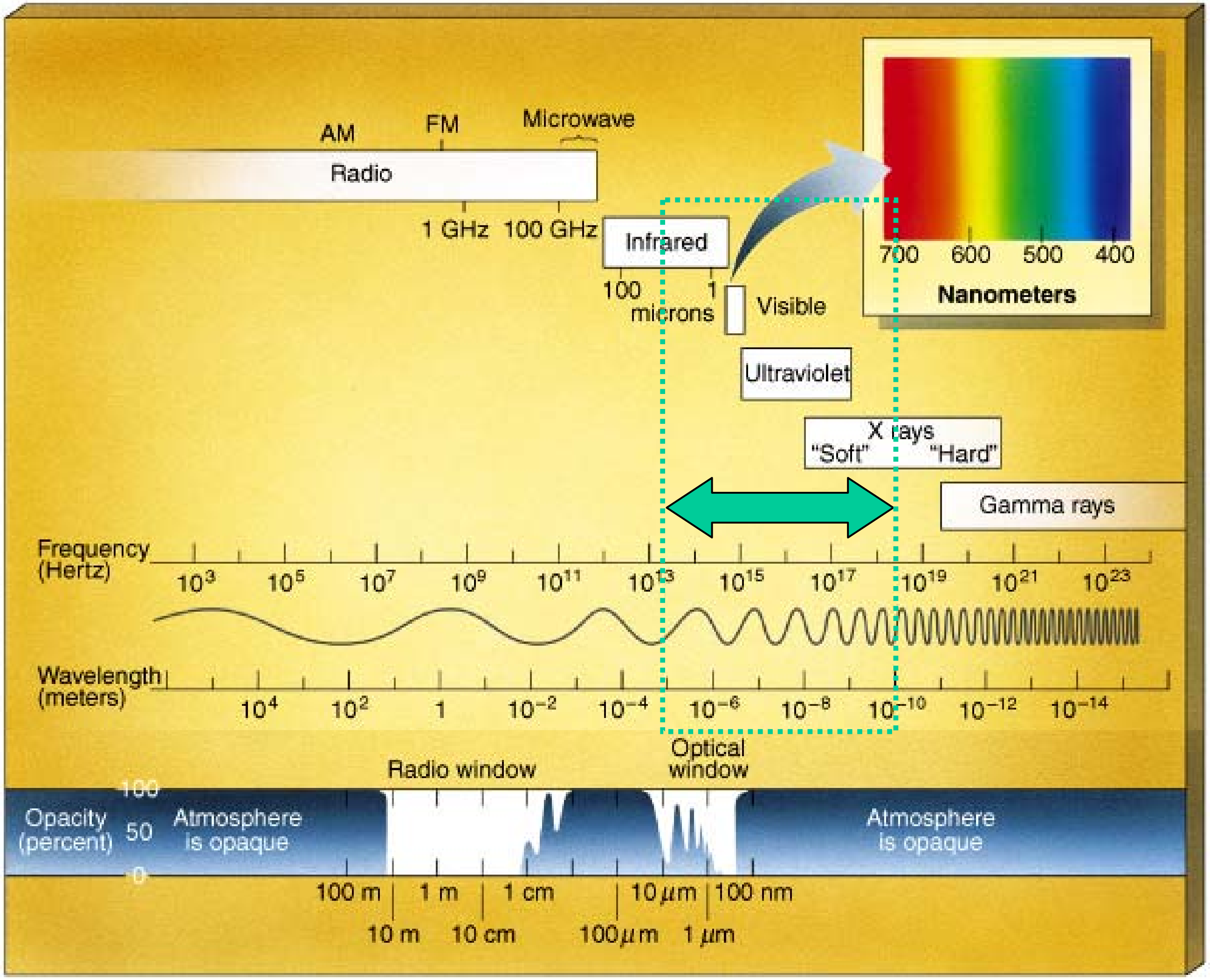
Willard S. Boyle

George E. Smith

@U.Chicago two weeks ago



a few slides from J. Beletic



AM
FM
Microwave
Radio
1 GHz
100 GHz
Infrared
100 microns
1
Visible
Ultraviolet
X rays
"Soft"
"Hard"
Gamma rays
700
600
500
400
Nanometers
Frequency (Hertz)
10^3 10^5 10^7 10^9 10^11 10^13 10^15 10^17 10^19 10^21 10^23
Wavelength (meters)
10^4 10^2 1 10^-2 10^-4 10^-6 10^-8 10^-10 10^-12 10^-14
Radio window
Optical window
Opacity (percent)
100
50
0
Atmosphere is opaque
Atmosphere is opaque
100 m
1 m
1 cm
10 µm
100 nm
10 m
10 cm
100 µm
1 µm

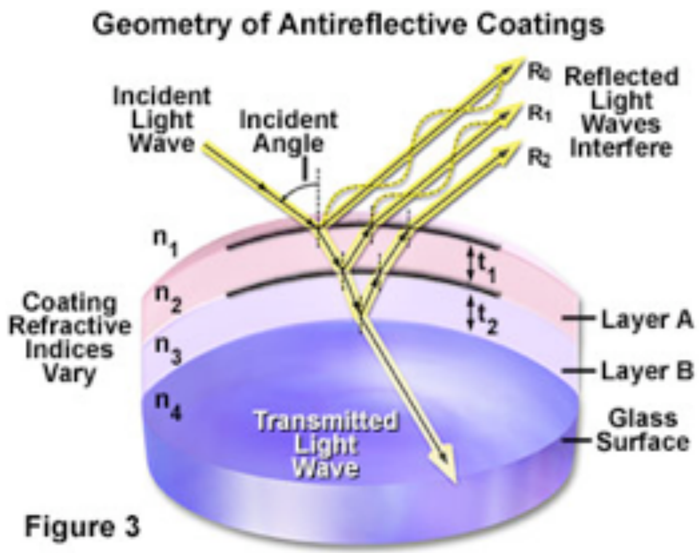
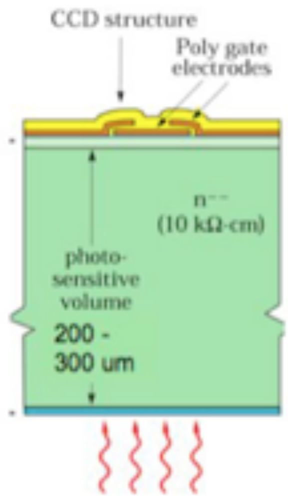
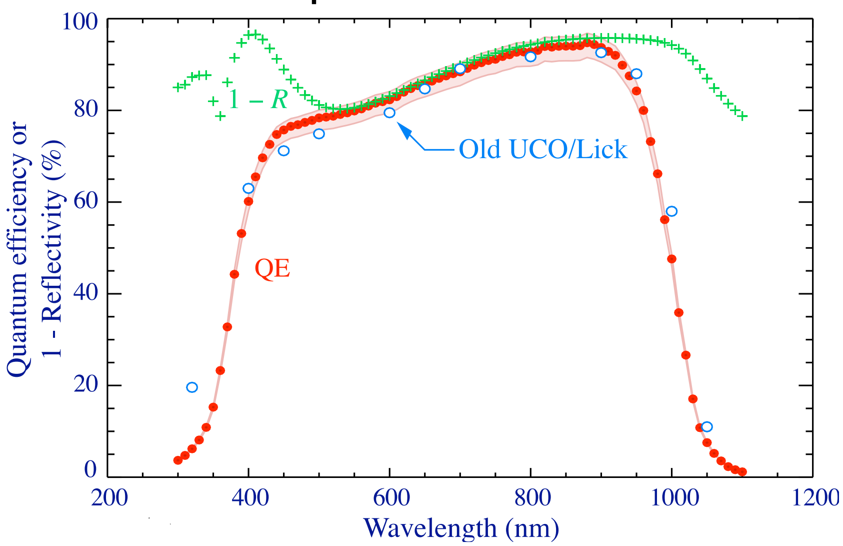


Figure 3

Light into the detector

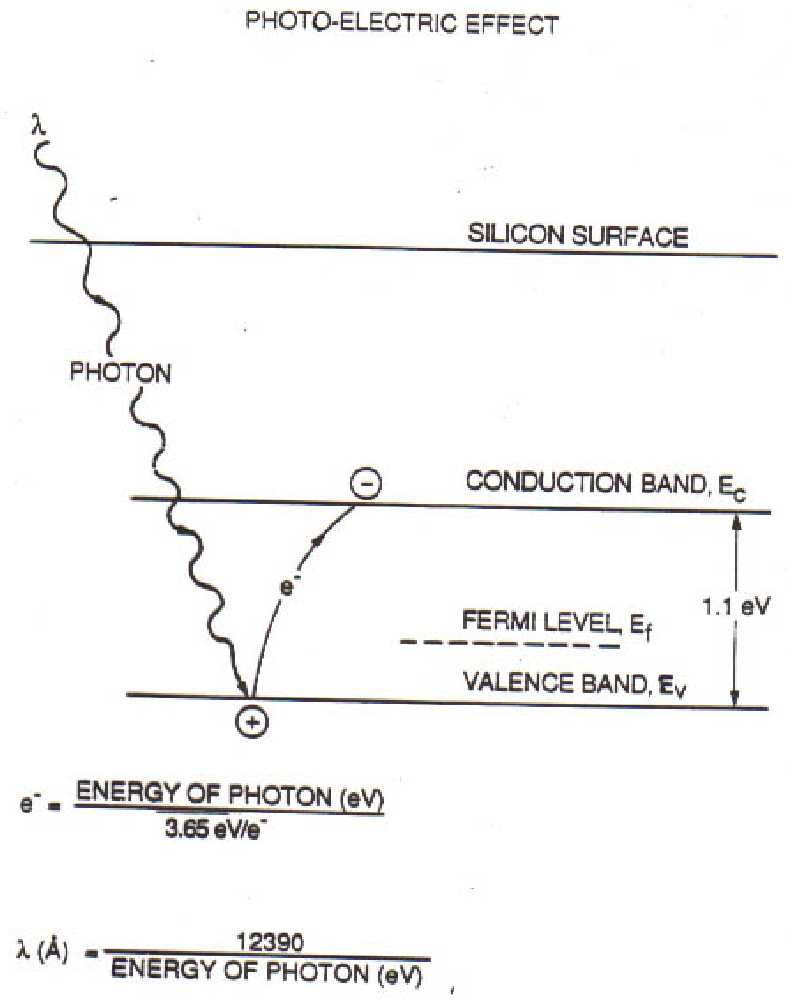


example for DECam CCD



light has to get inside the CCD for detection. This means that destructive interference has to be accommodated for reflections.

Charge Generation



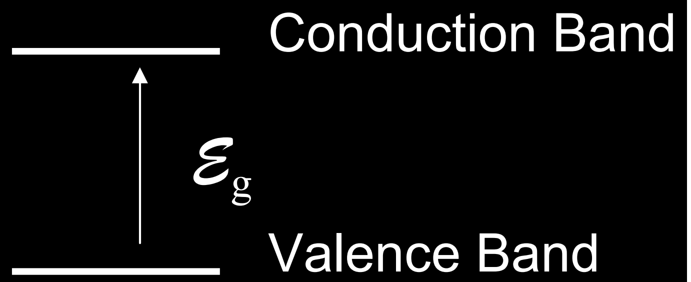
Silicon CCD

Similar physics for IR materials

For an electron to be excited from the conduction band to the valence band

$$h\nu > \mathcal{E}_g$$

h = Planck constant (6.6310^{-34} Joule•sec)
ν = frequency of light (cycles/sec) = λ/c
$\mathcal{E}_g$ = energy gap of material (electron-volts)

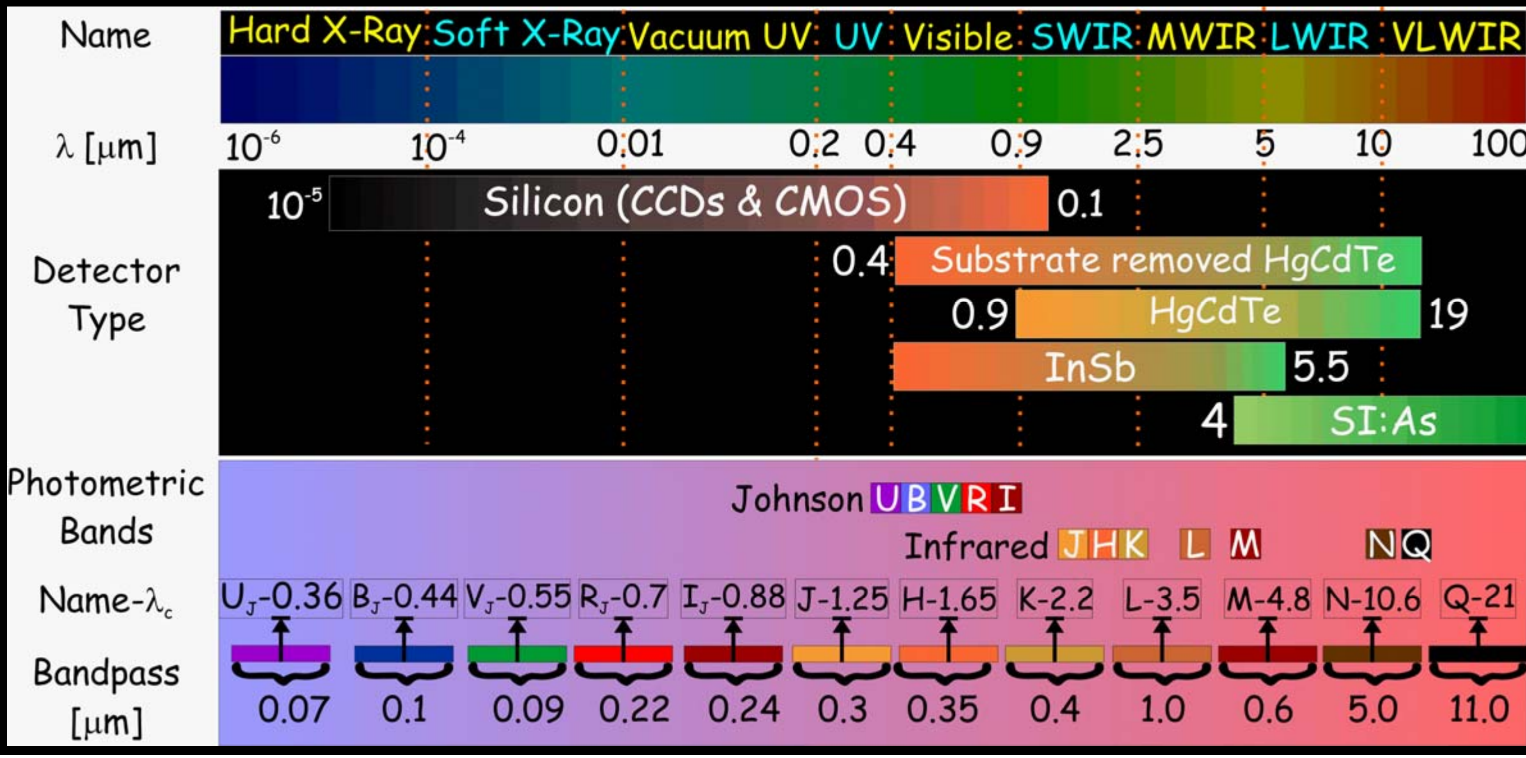


$$\lambda_c = 1.238 / \mathcal{E}_g \text{ (eV)}$$

Material Name	Symbol	$\mathcal{E}_g$ (eV)	λ_c (μm)
Silicon	Si	1.12	1.1
Indium-Gallium-Arsenide	InGaAs	0.73 – 0.48	1.68* – 2.6
Mer-Cad-Tel	HgCdTe	1.00 – 0.07	1.24 – 18
Indium Antimonide	InSb	0.23	5.5
Arsenic doped Silicon	Si:As	0.05	25

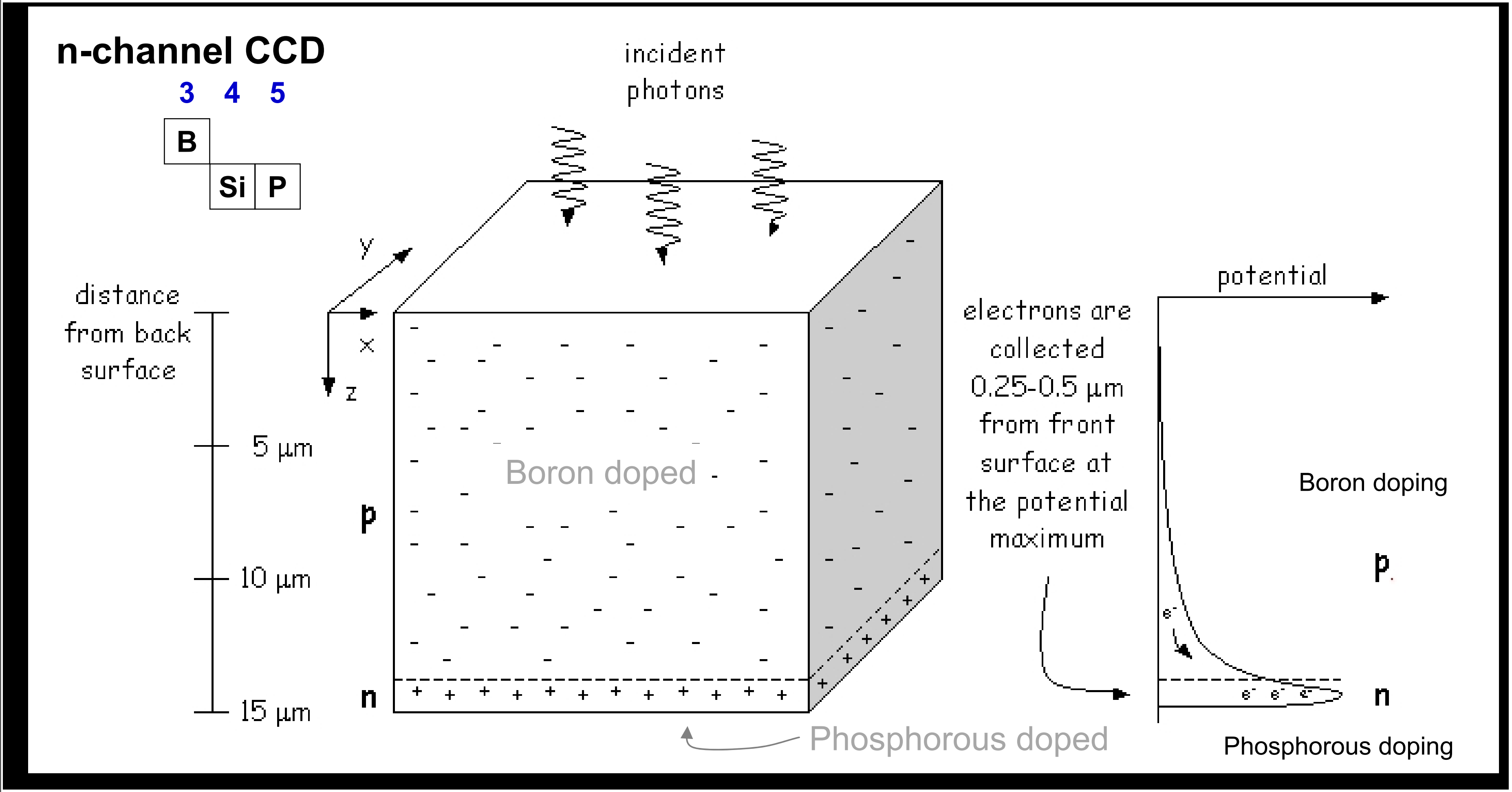
IR detectors ($$) . Si is easy...

Detector Zoology

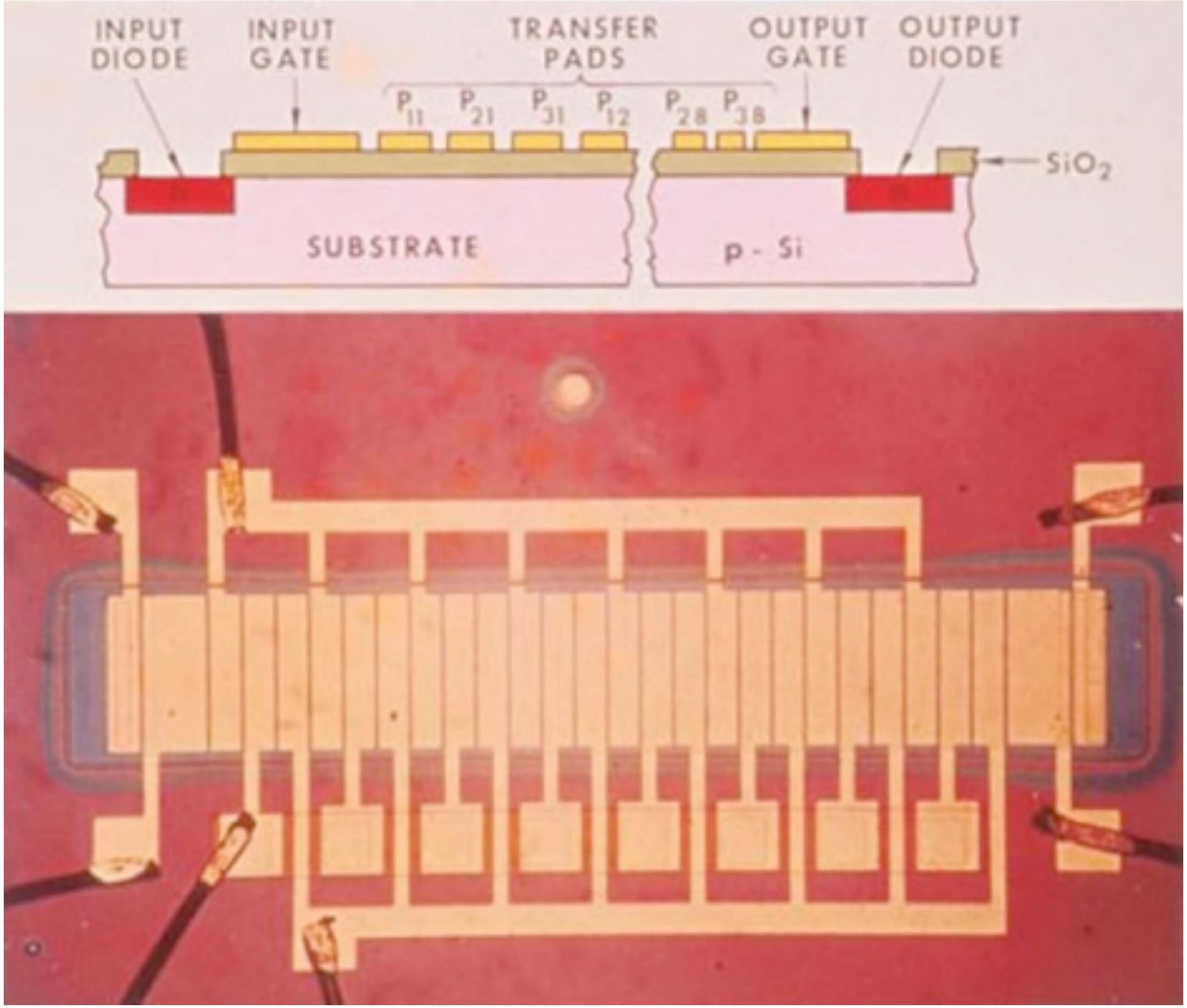


Friday, November 12, 2010

Charge Collection

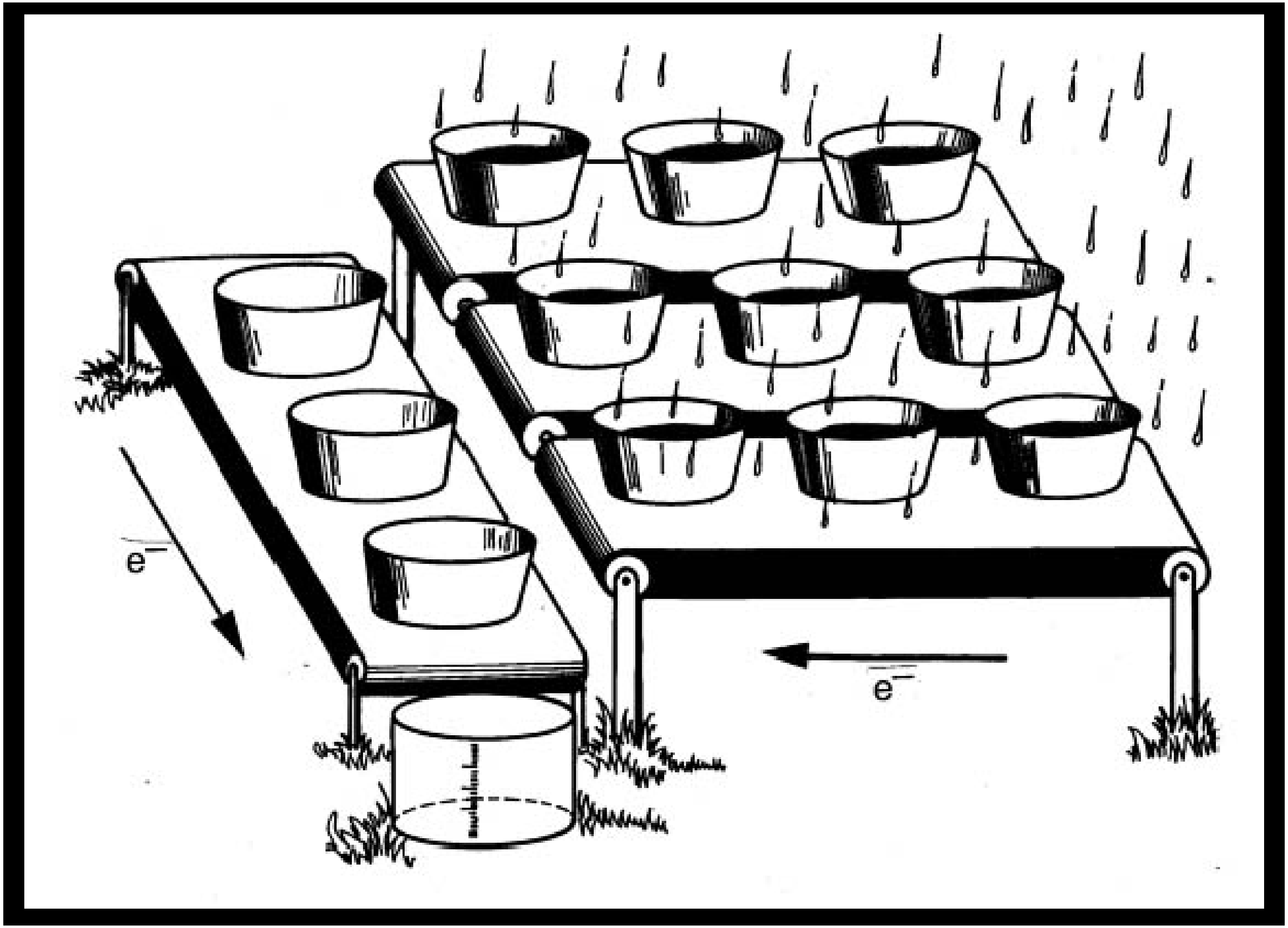


Charge Transfer

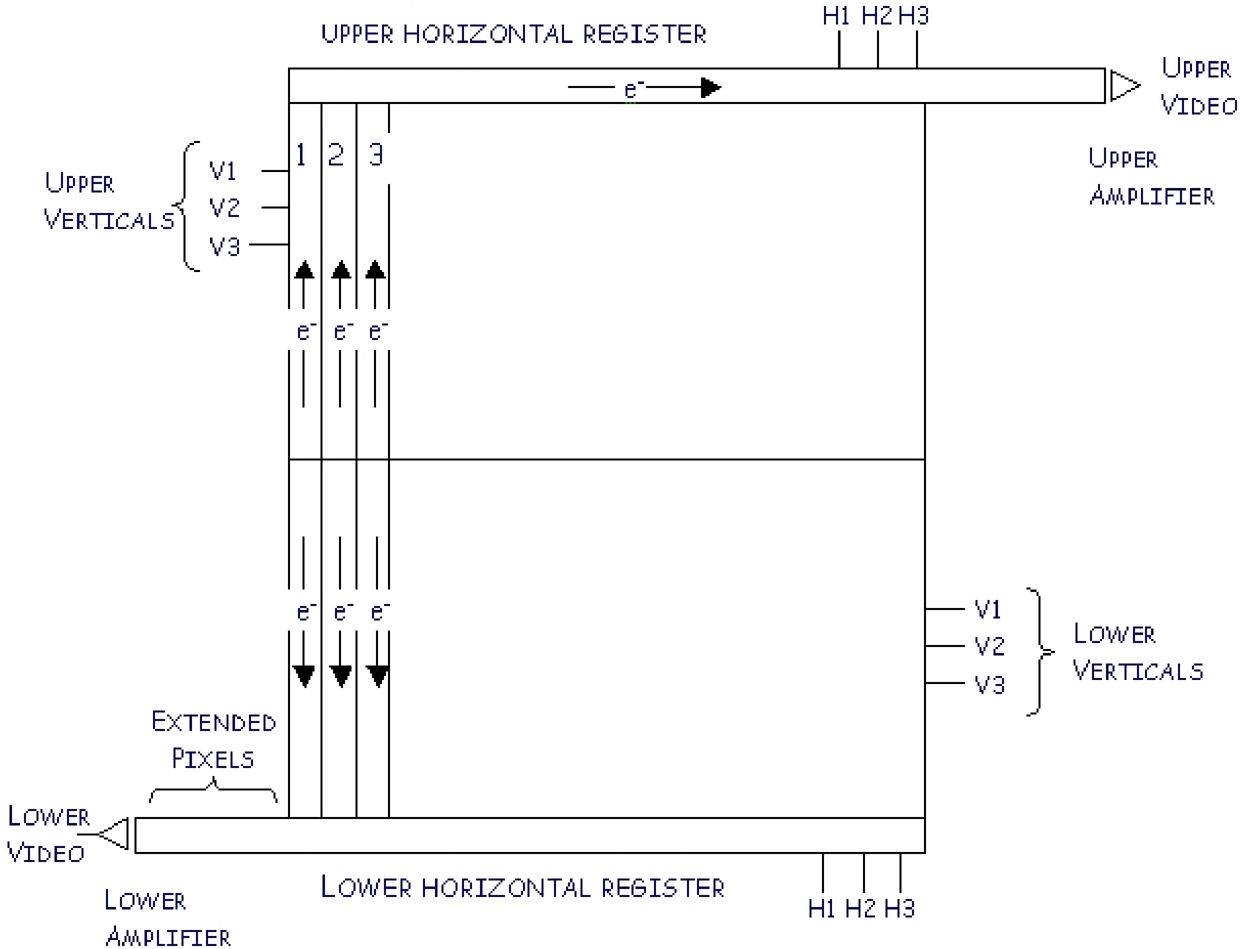


First CCD

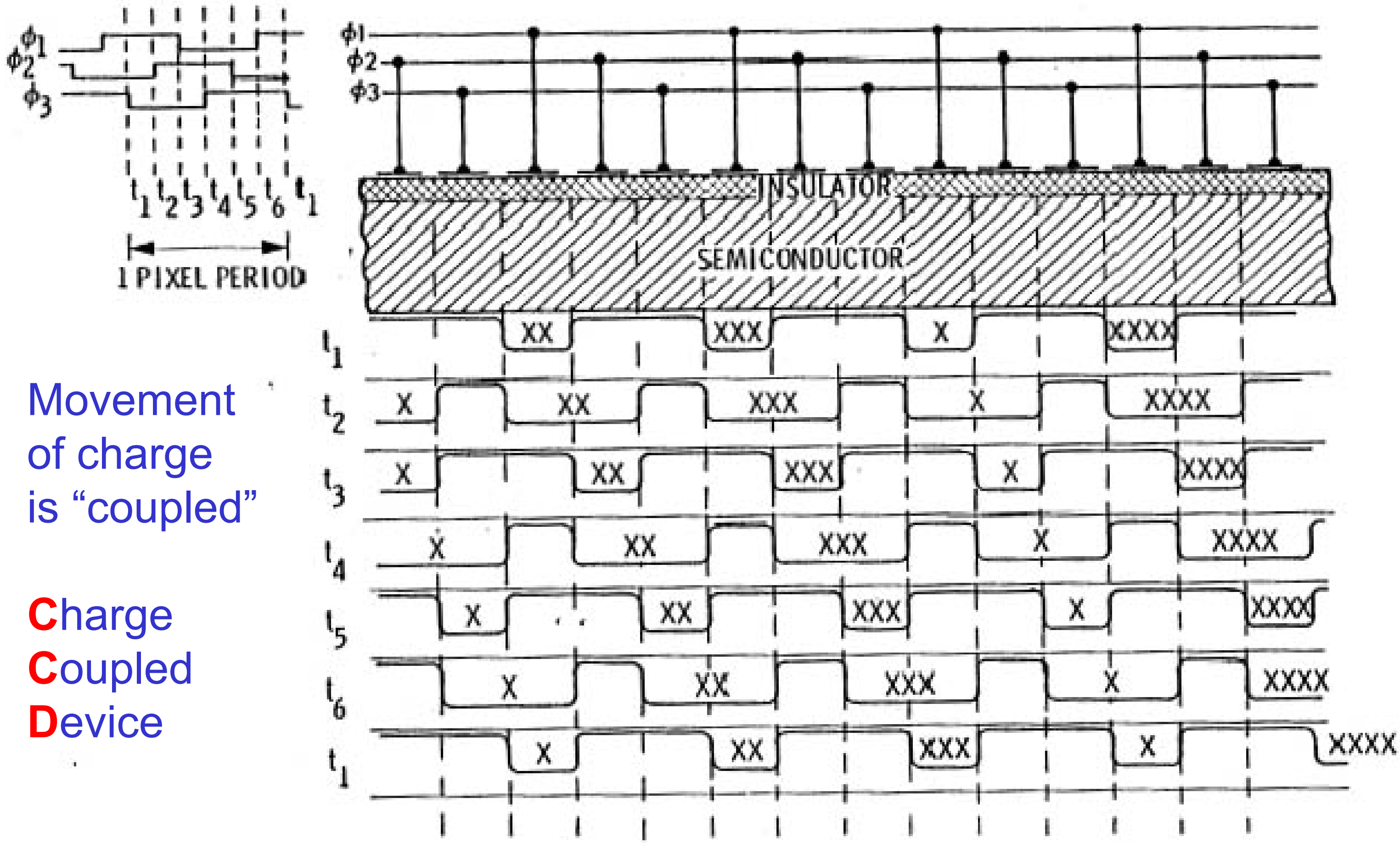
Charge Transfer



Charge Transfer: CCD architecture



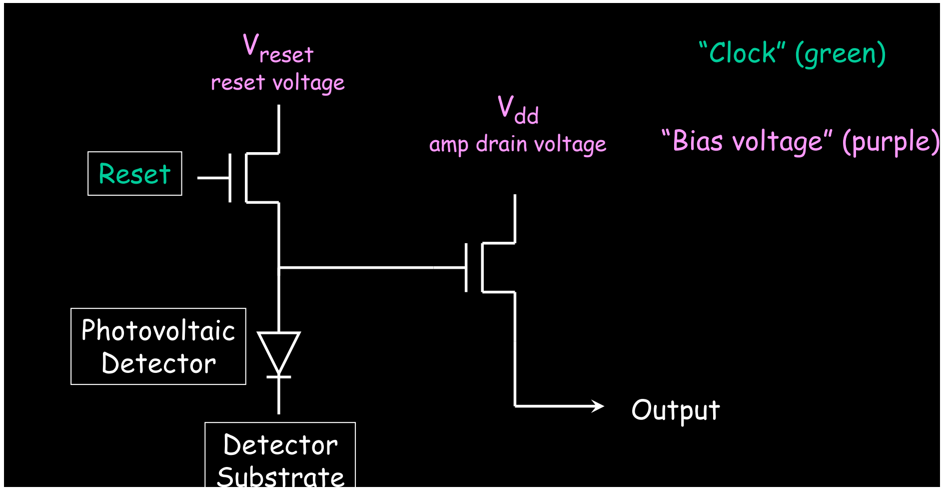
CCD Timing

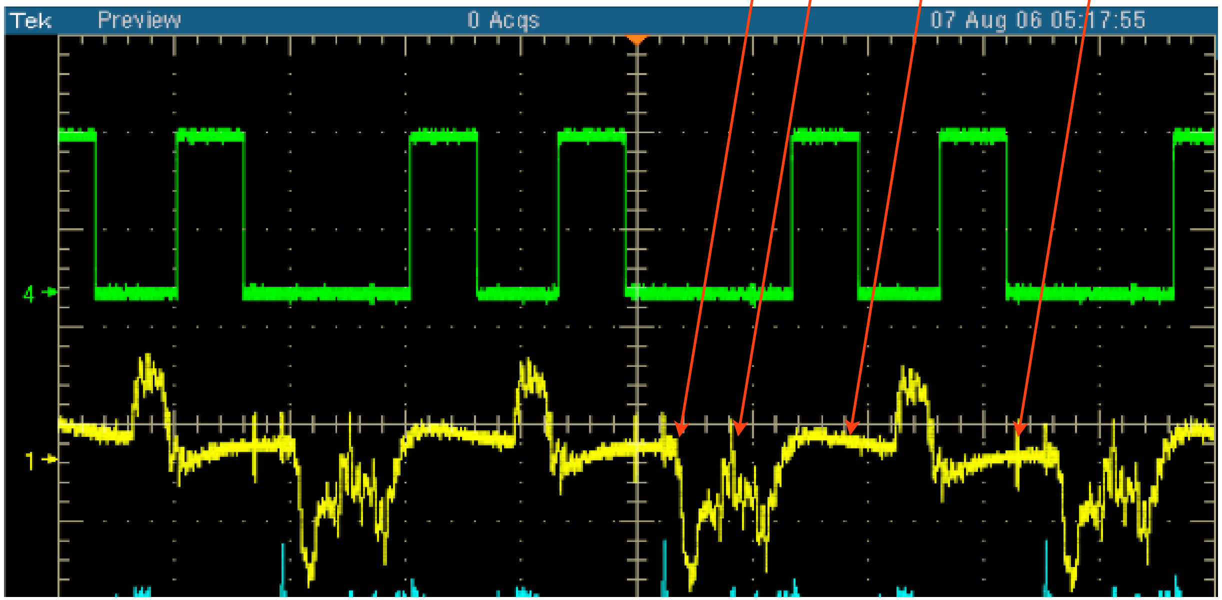


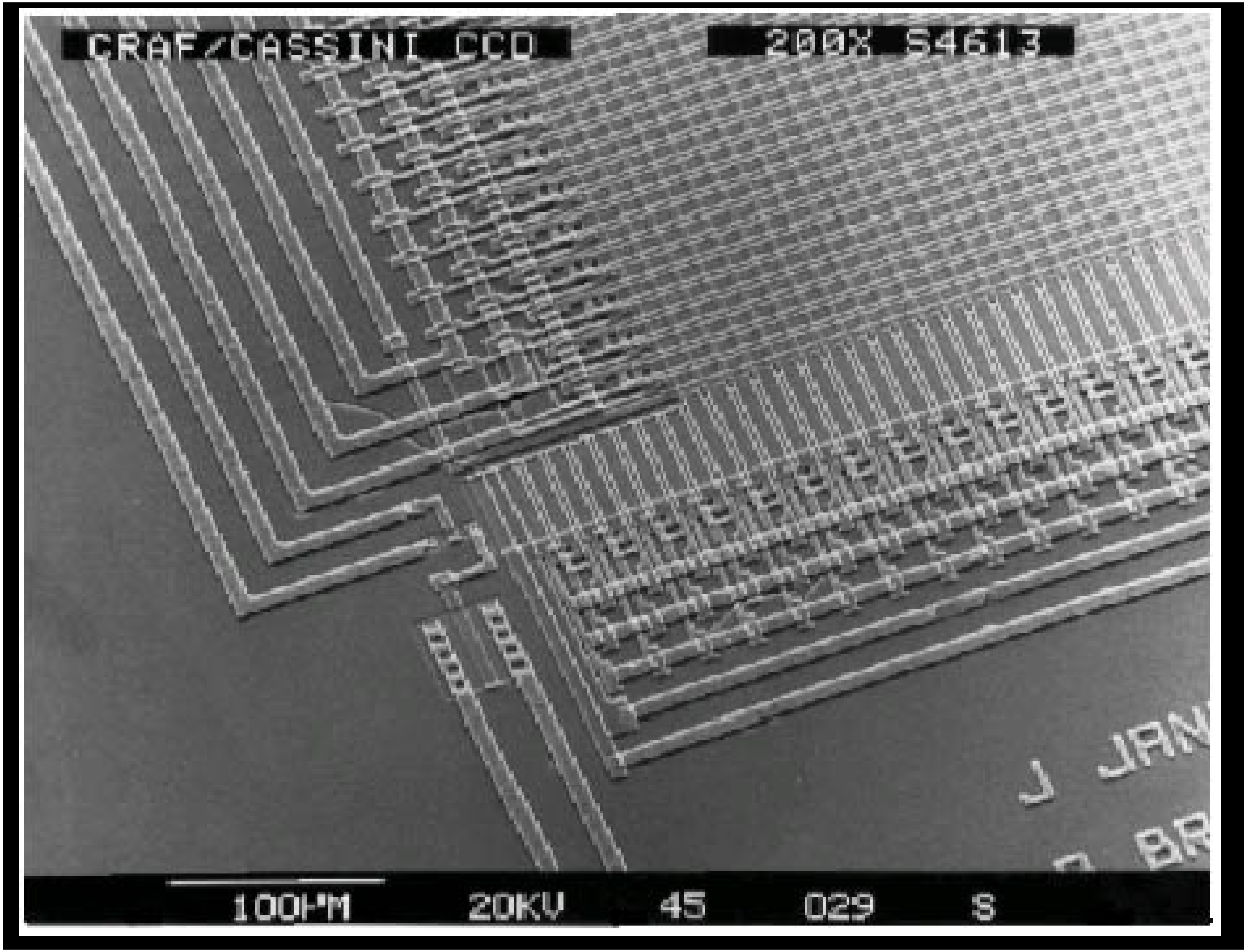
Movement of charge is “coupled”

Charge
Coupled
Device

Conversion to Voltage

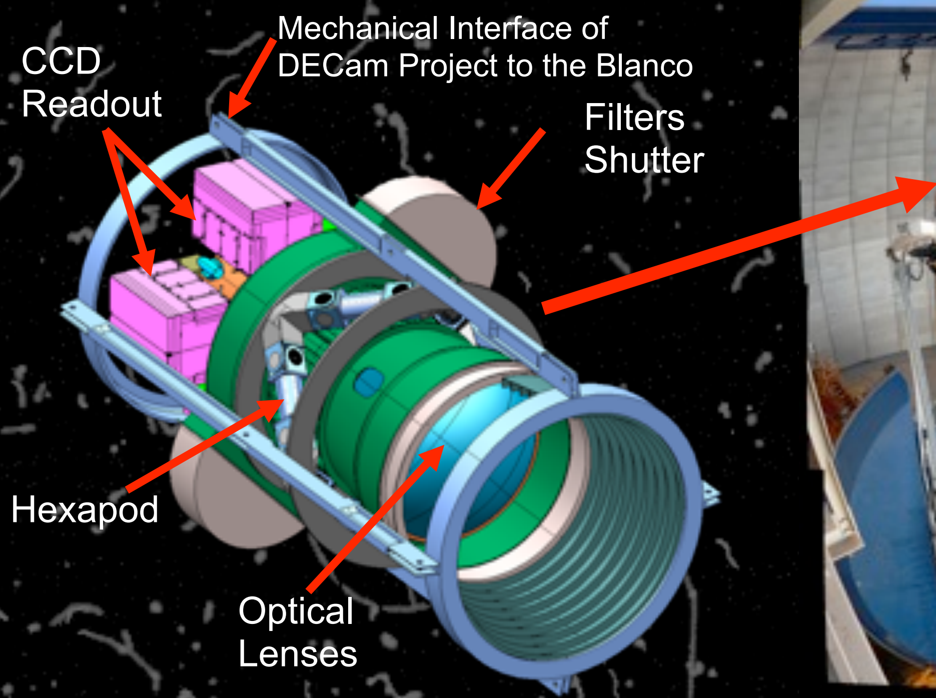





CRAF/CASSINI CCD
200X S4613
100UM 20KV 45 029 S

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. Being built at FNAL by a large collaboration.

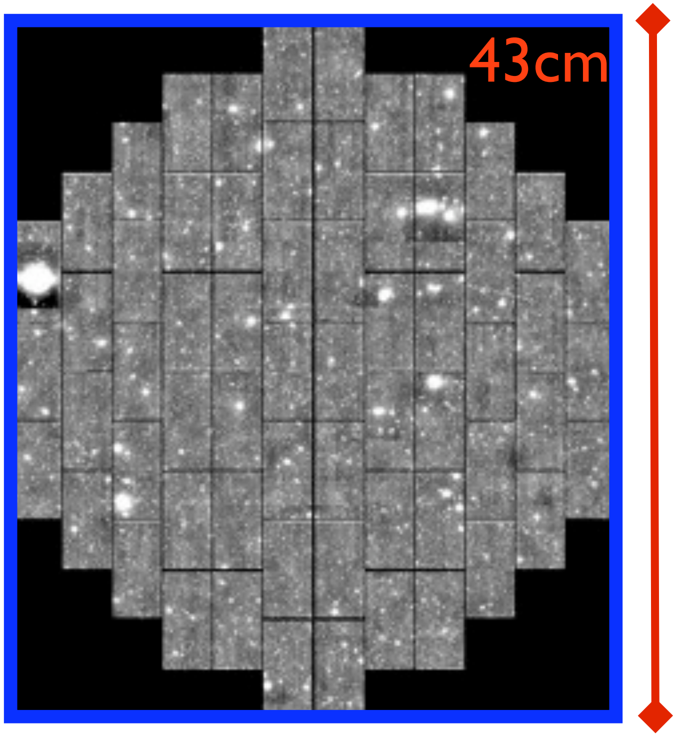


One night at the Blanco 4m telescope in Chile (R. Smith)

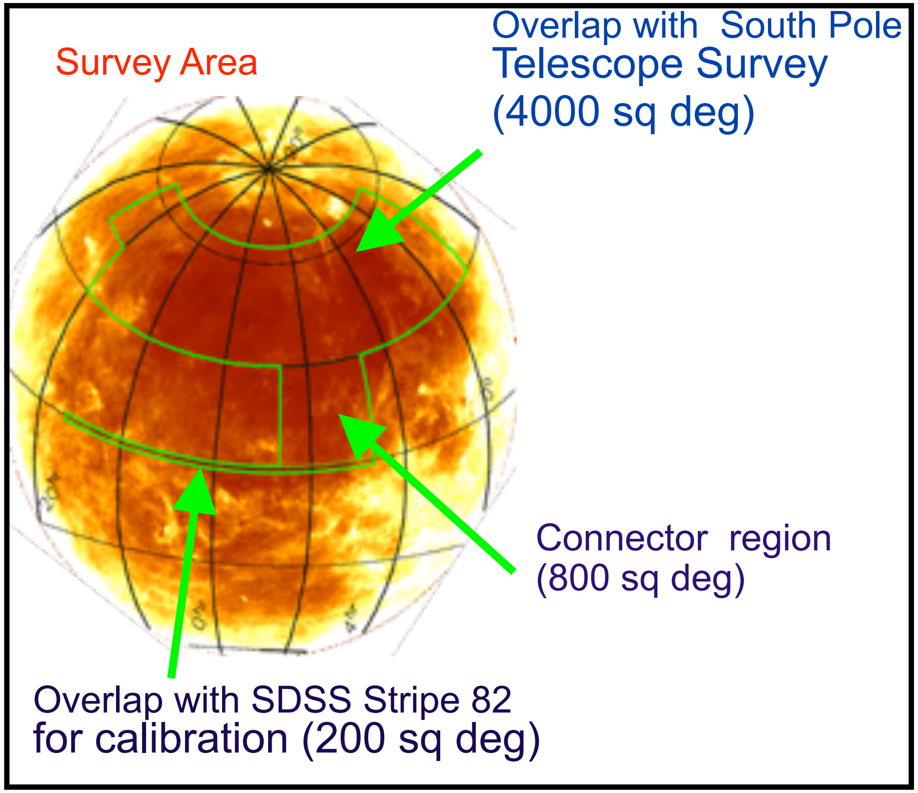
One night at the Blanco 4m telescope in Chile (R. Smith)

replace this (mosaicII)

with this (DECam)



...and do this (DES)



<u>Science goals (Dark Energy, z~1):</u>

Galaxy Cluster counting
Spatial clustering of galaxies (BAO)
Weak lensing
Supernovae type Ia (secondary survey)

→ to do this from the ground we need detectors with high efficiency in the near-IR

DECAM hardware

CCD focal plane is housed in a vacuum vessel

LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to **-100 C**

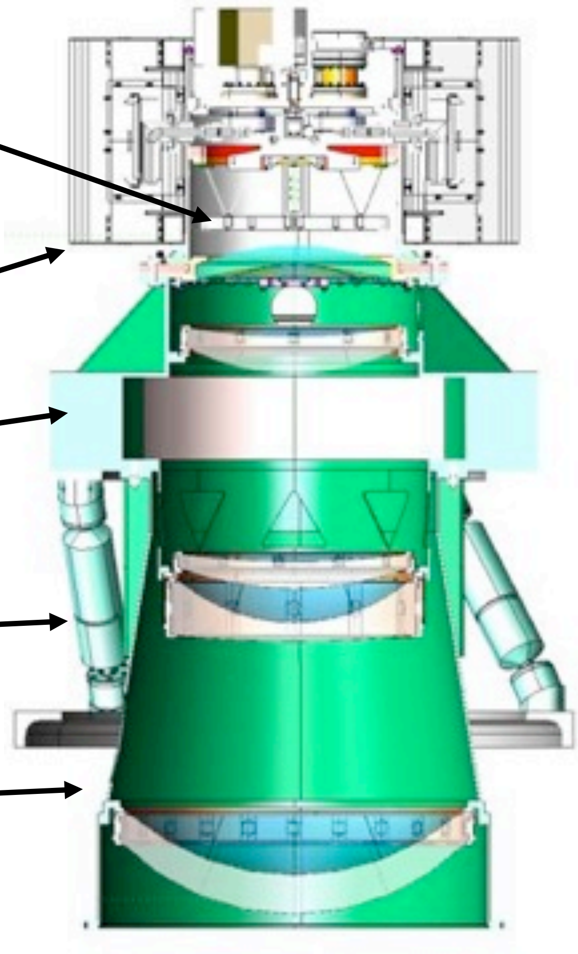
CCD readout electronic crates are mounted to the outside of the Imager and are actively cooled (UIUC).

Filter changer (8 filter capacity) and shutter form one mechanical unit (UMichigan).

Hexapod provides focus and lateral alignment capability for the corrector-imager system

Barrel supports **5 lenses** and imager

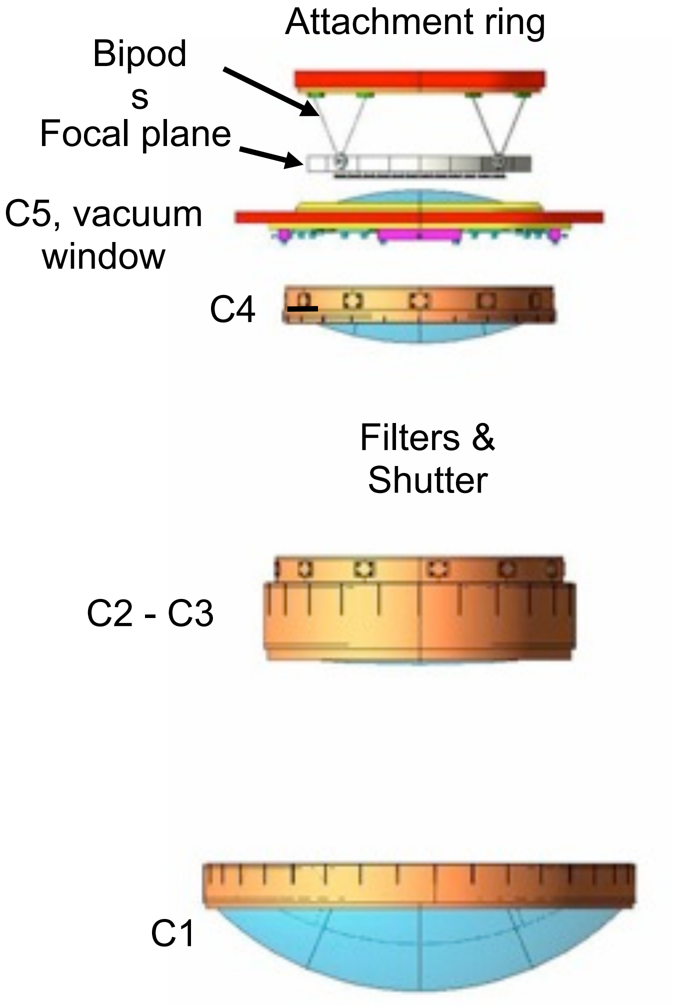
DECam weighs about **4 tons**



optics being fabricated

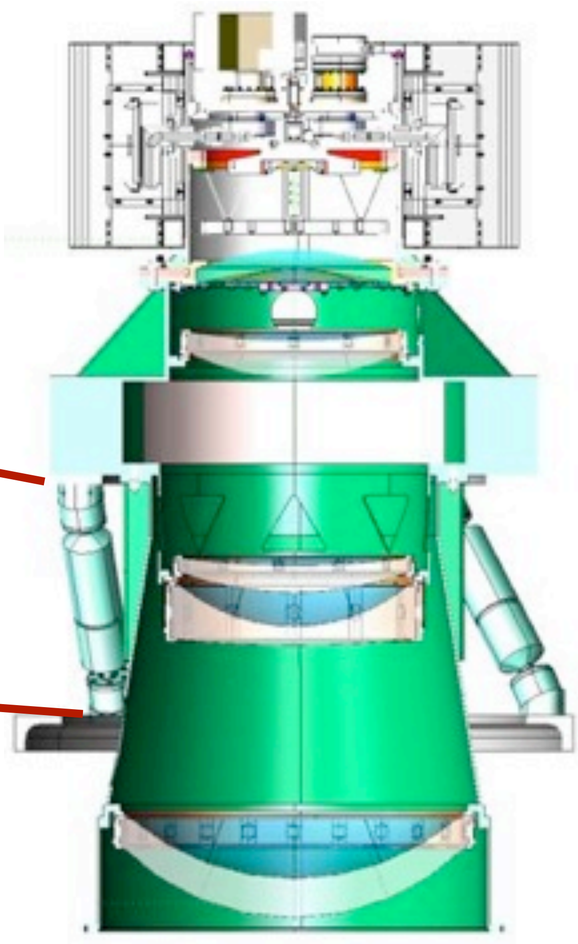
Larger field of view requires a new corrector.

- Field of view: 2.2° diameter
  - C1 is the largest: 980mm diameter
  - C5 is 0.5m diameter
- Pixel (15 μm) scale: 0.26”/pixel
- Image quality Design FWHM: 0.27”



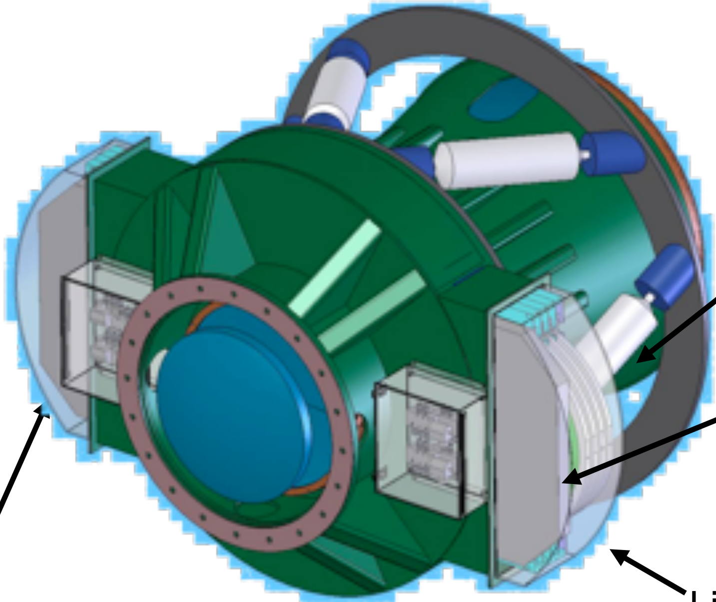
hexapod for focusing

ADS International



DARK ENERGY SURVEY

filters and shutter



Filter cassettes

Shutter (Bonn)
Bolts to base plate of the filter changer

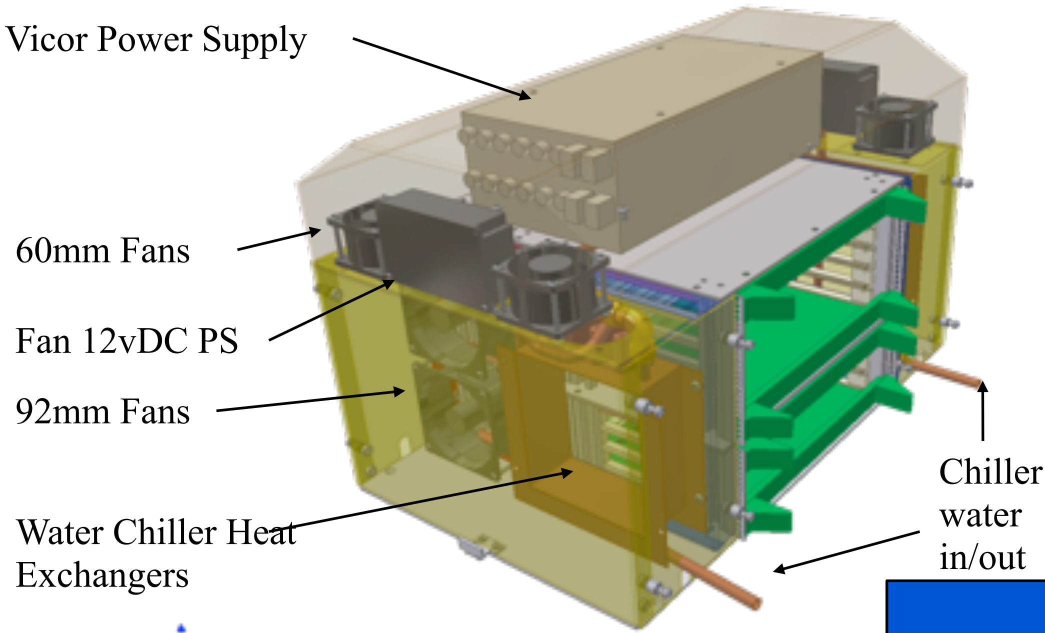
Light-tight, dust-tight covers

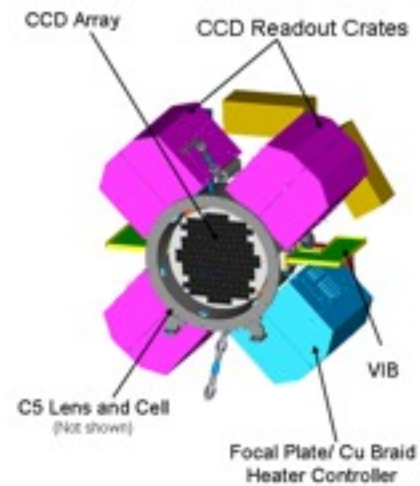
Filter changer control enclosures

custom-made electronics

final testing these days, production to start around May.

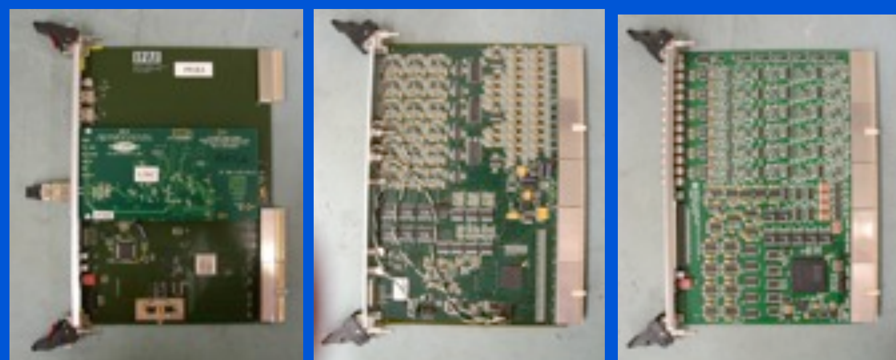
144 readout channels. Three crates mounted on the imager.





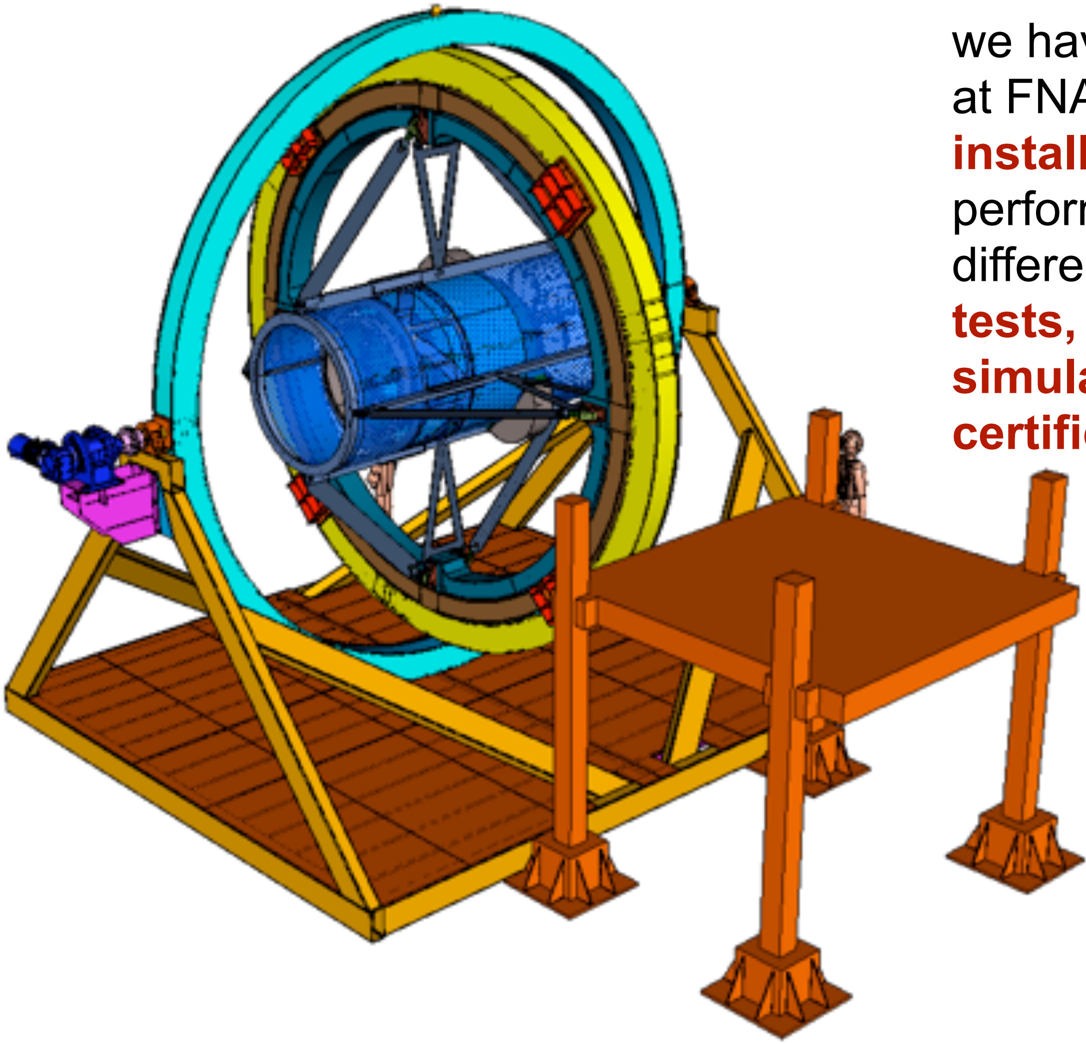
cold components

three boards to control CCDs



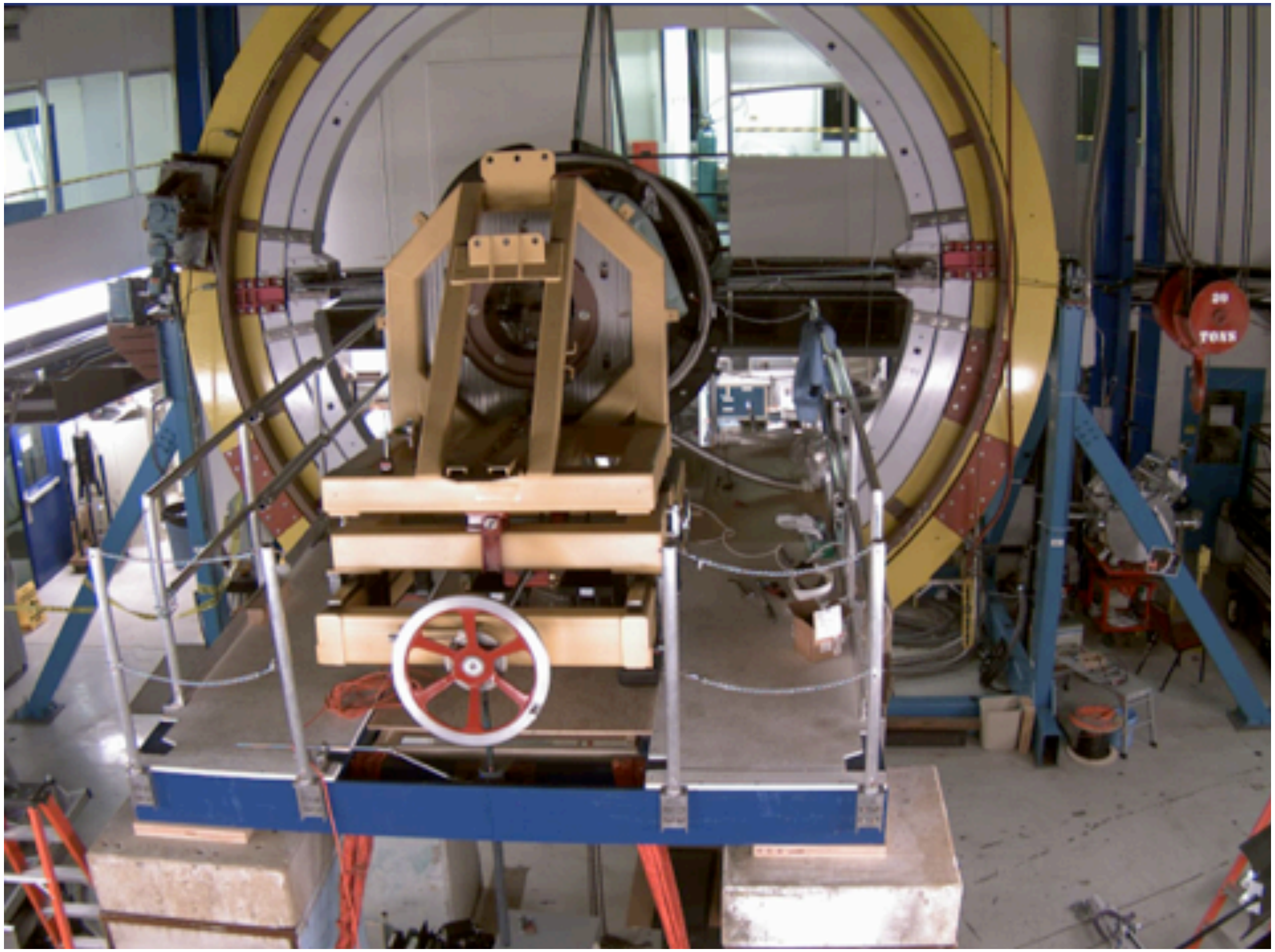
Goal: Fast readout with 10e of noise.

DECam integration at FNAL



we have built the top of the telescope at FNAL to understand the **installation of DECam** and also the performance of the camera in different orientations. **Full integration tests, including "observing" simulation for software certification.**

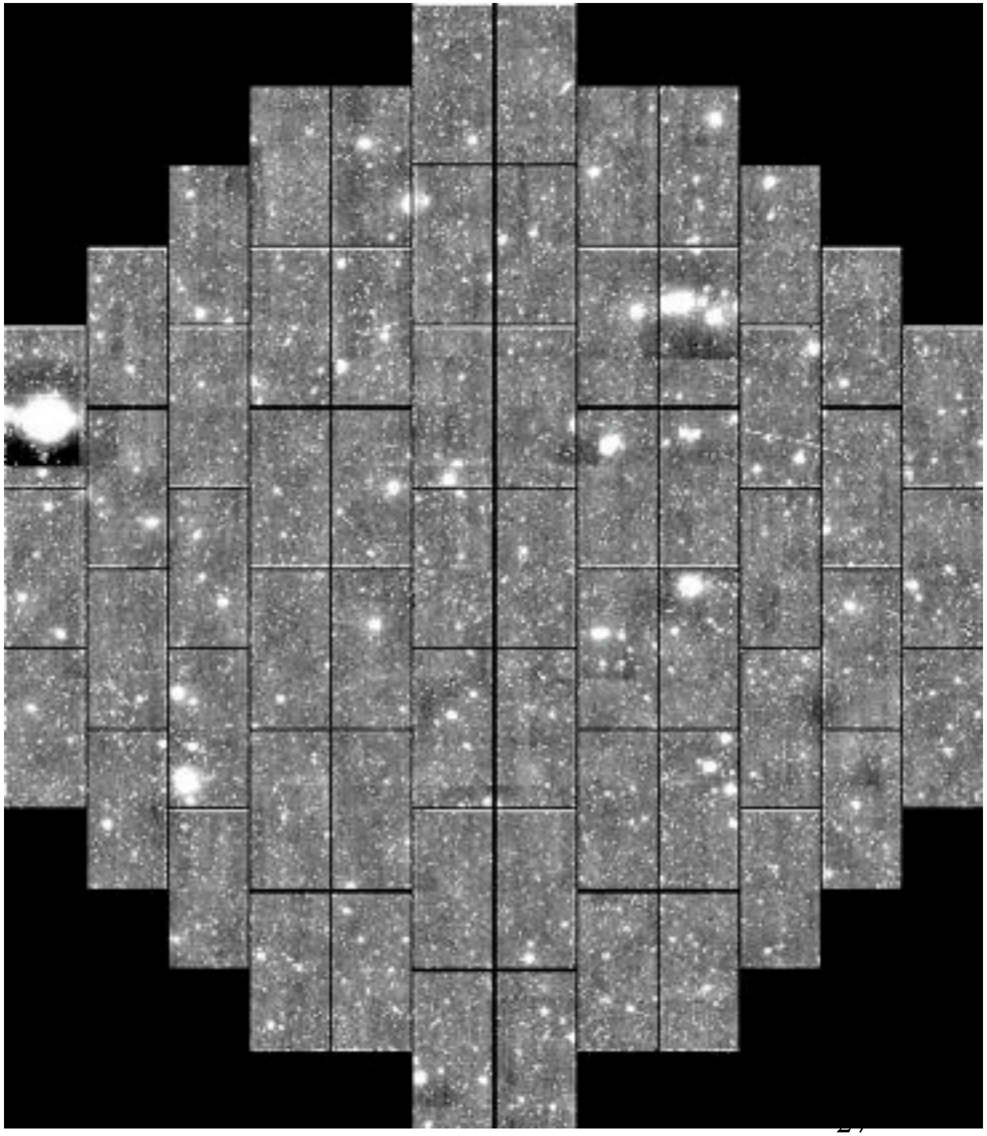
Yesterday



it is always nice to get away from the lab... thanks Josh!

DECam Focal Plane

DES Image simulation



3 sq-deg imager:

62 2kx4k Image CCDs: 520 MPix
8 2kx2k focus, alignment CCDs
4 2kx2k guide CCDs
0.27"/pixel (15x15 μm)

Imager to start taking data on September 2011. In exchange we get 30% of telescope time for DES during 5 years.

Facility instrument available the rest of the time.

Requirements for DECam CCDs

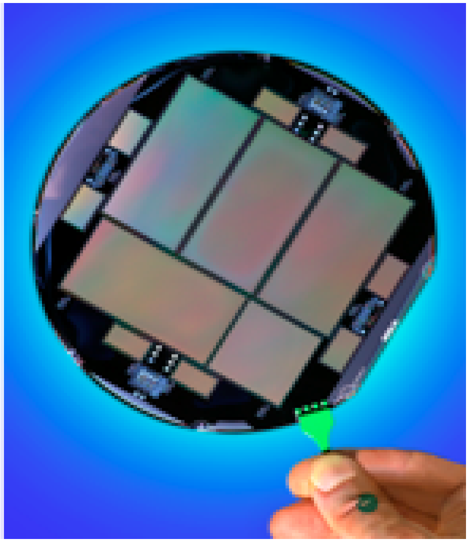
#	description specification
1	nonlinearity <1%
2	full well: >130,000 e^-
3	no residual image
4	readout time < 17 sec
5	dark current <35 e^-/pix/hour
6	QE [g, r, i, z]: [60%, 75%, 75%, 65%]
7	QE < 0.5 % per degree K
8	read noise <15 electrons
9	Charge diffusion σ <7.5μm
10	Cosmetic defects < 0.5 %
11	Crosstalk for two amps. on CCD < 0.001%

These requirements come from the science goals for DES. Get to z~1.

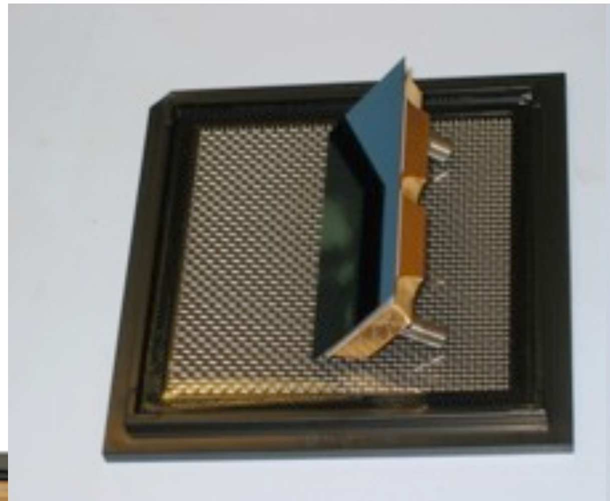
For this we need detectors that get higher QE in the red and near-IR. Without degrading the rest of the performance.

Detectors : CCD

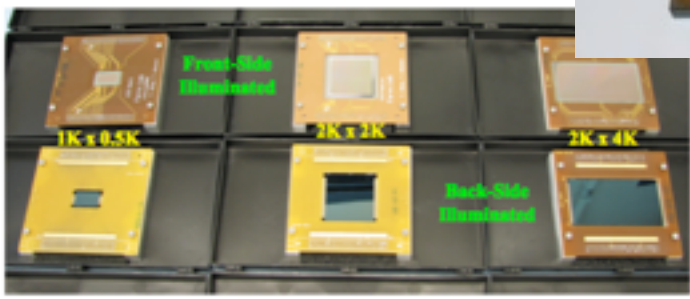
DECam wafer



DECam wafer developed from SNAP R&D effort.
We now all science packages ready for installation.



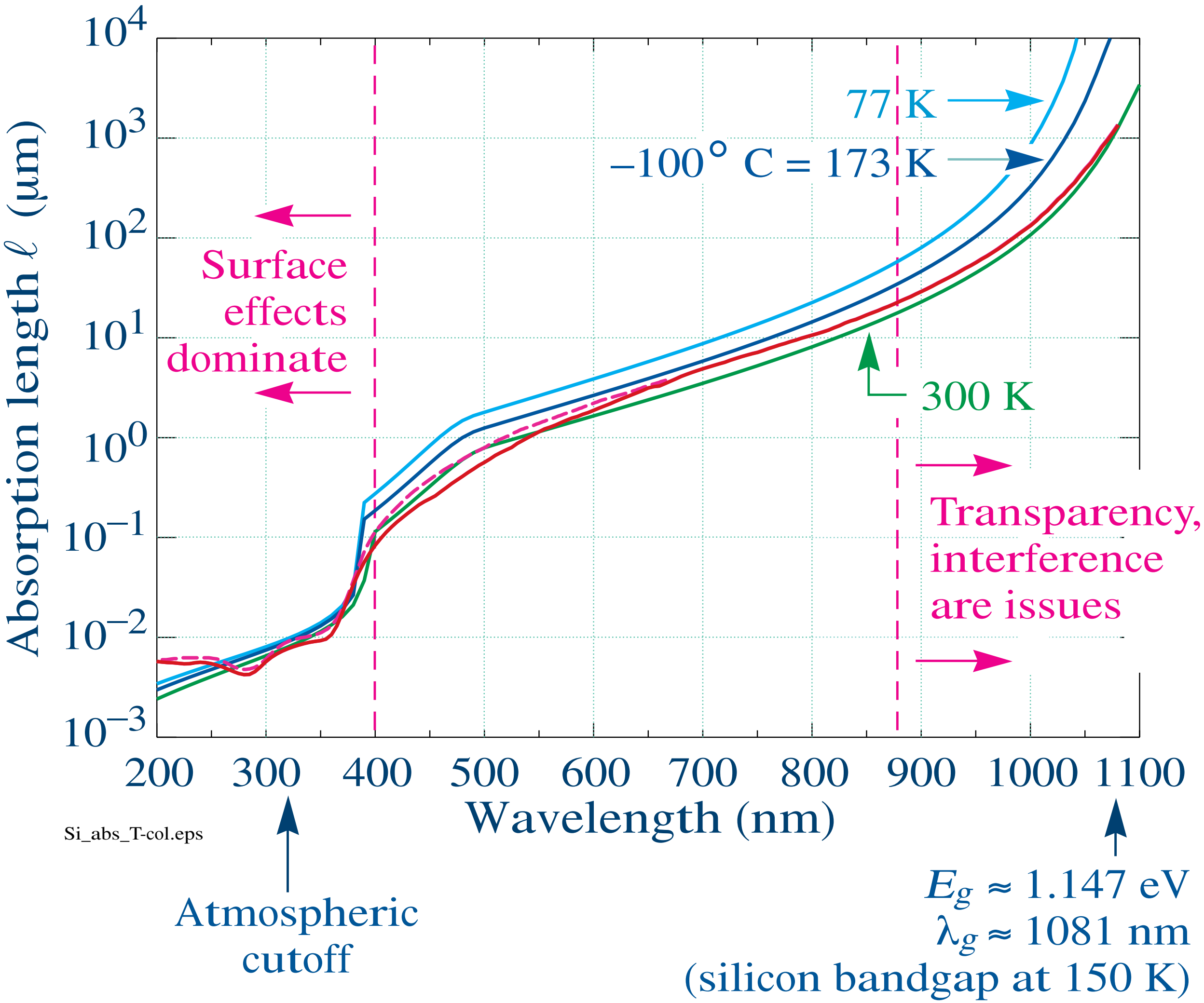
Engineering CCDs



+100 built and tested during our R&D stage

Fermilab's expertise in building silicon trackers has transfered nicely to the design and fabrication of these CCDs (strict mechanical requirements).

How to get high QE in the red with Si?



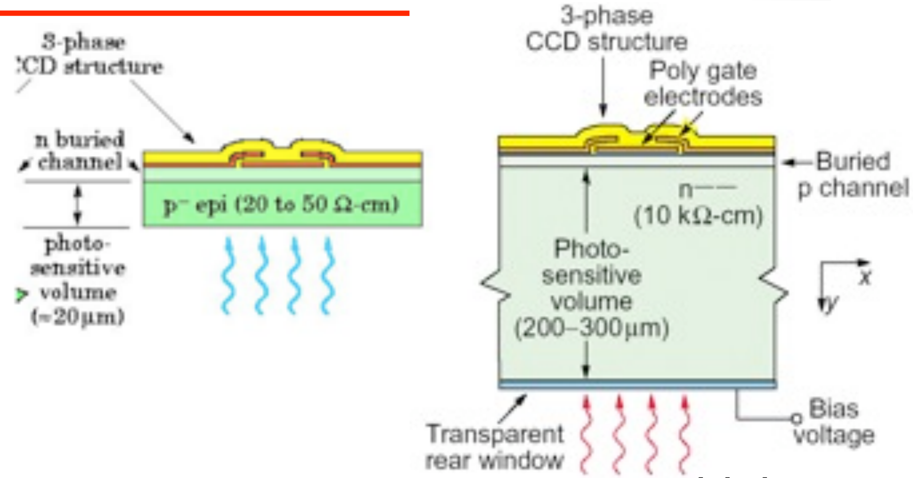
Focal Plane Detectors

Science goal for DES: z~1

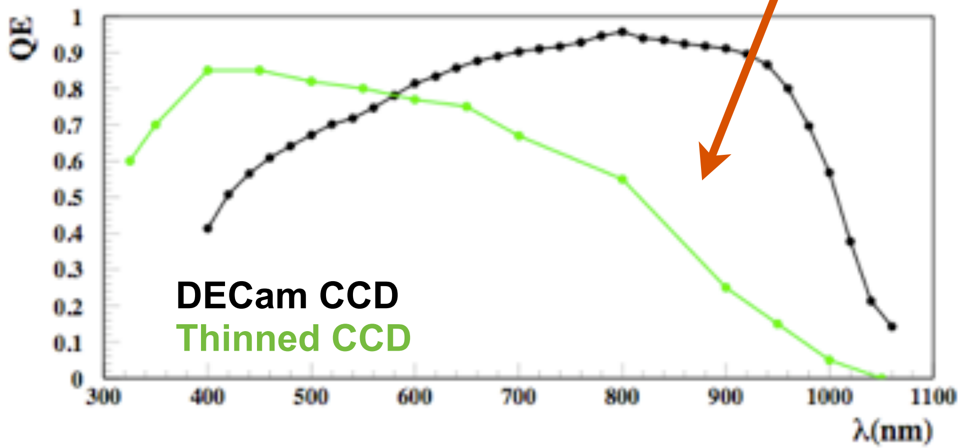
~50% of time in z-filter
825-1100nm

LBNL full depletion CCD

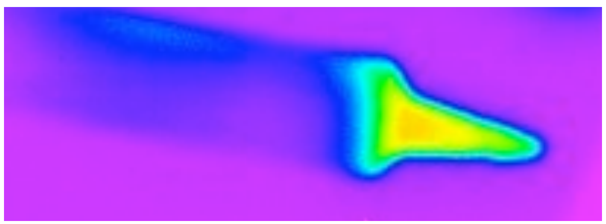
–250 microns thick (instead of 20 microns)
–high resistivity silicon
–QE> 50% at 1000 nm



high-z objects

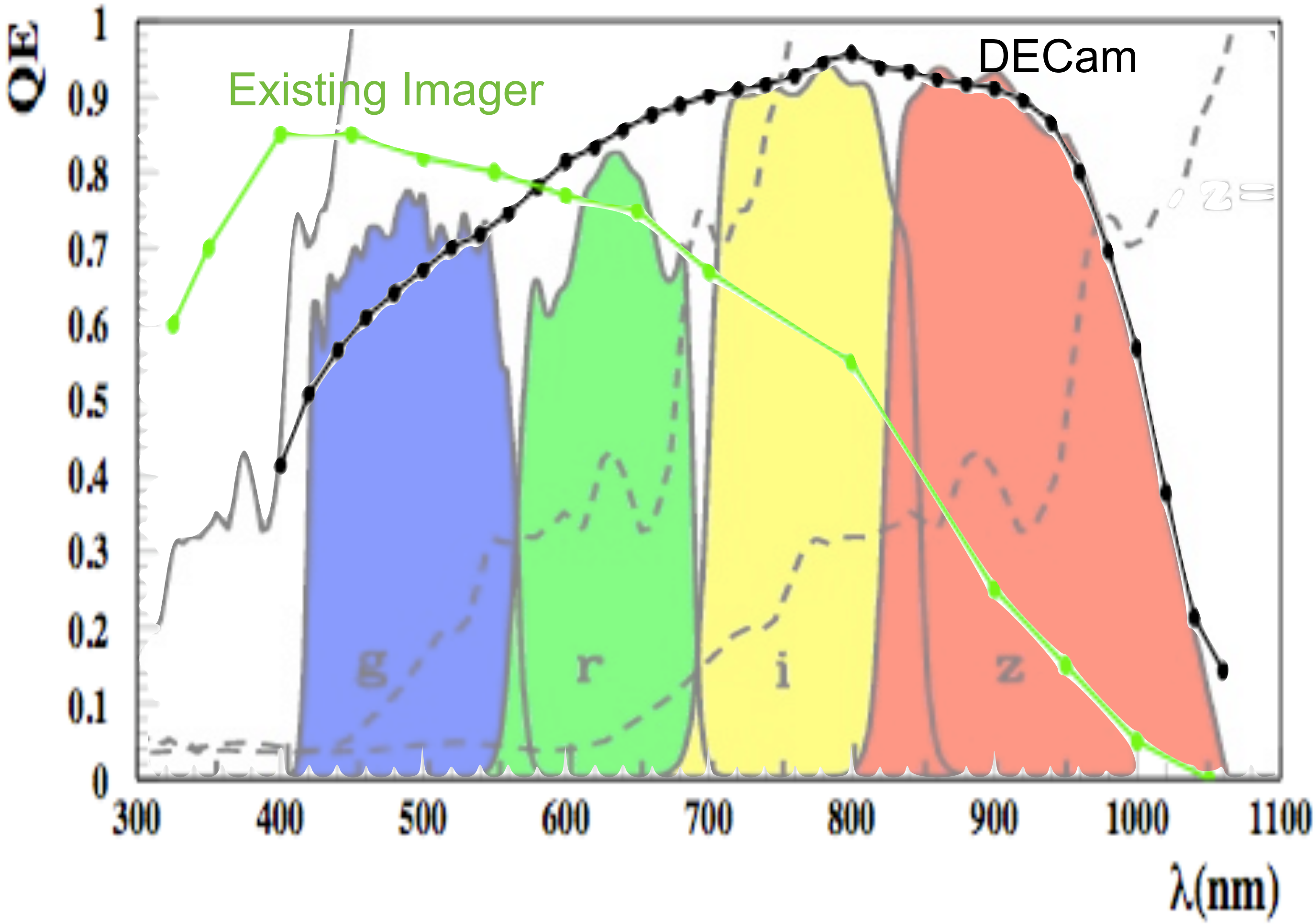


IR image of soldering iron with DECam CCDs

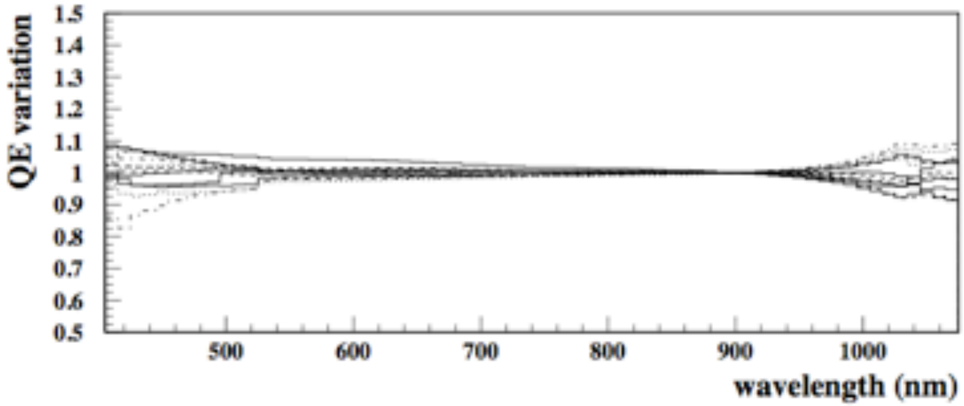


QE in the DES filters

DARK ENERGY SURVEY

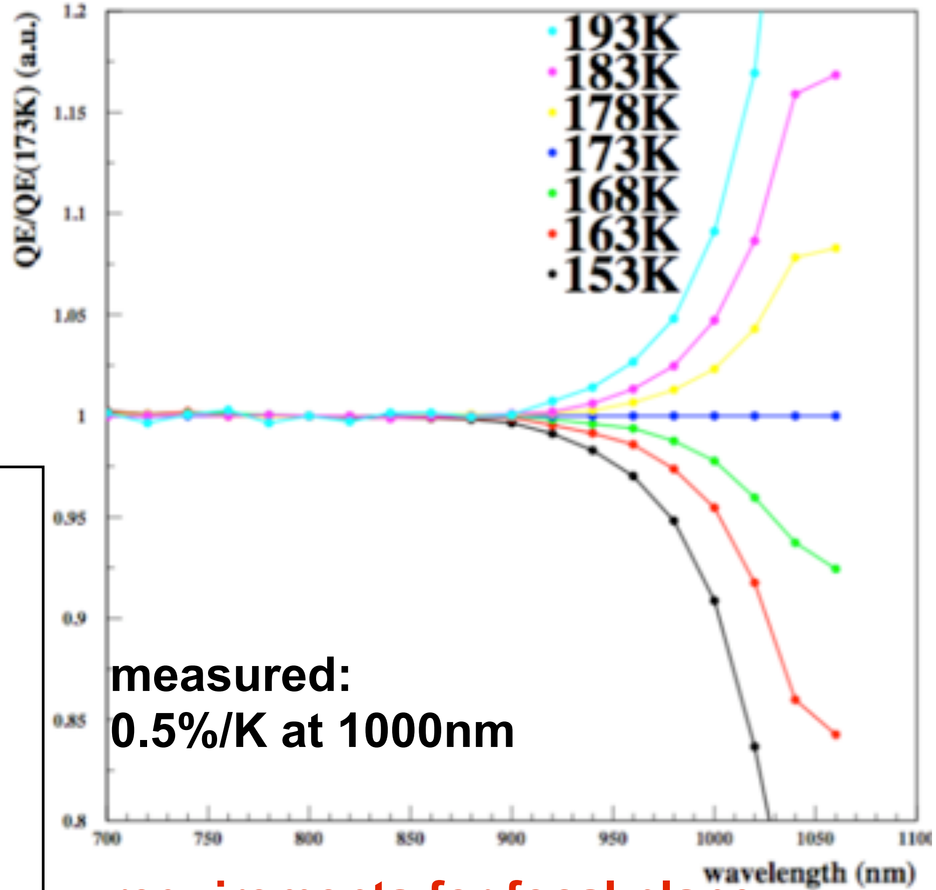


Stability/Uniformity in QE



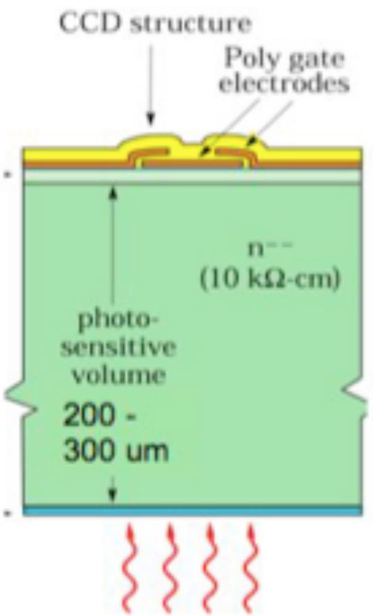
The DECam detectors show very uniform QE. DES requires better 10% QE uniformity from CCD to CCD.

We also check the dependence with temperature to establish the requirement for temperature stability and uniformity on our focal plane.



requirements for focal plane:
> 0.25K stability
> 10K uniformity
(achieved in prototype)

Charge diffusion



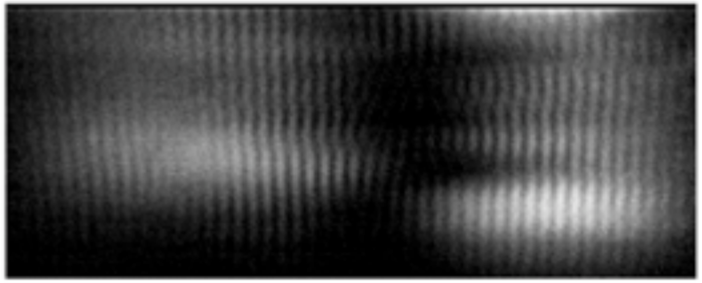
Holes produced in the back surface have to travel to the collection area. **Thicker means more opportunity for diffusion**. (fully depleted). Higher QE could get compensated by lower image quality. **<u>That is why other detectors are thinner.</u>**

The 40V applied to the substrate (Vsub) to control diffusion

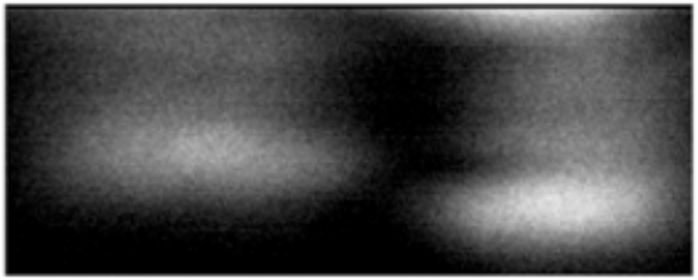
Imaging a diffraction pattern

Diffusion is measured from the analysis of these images

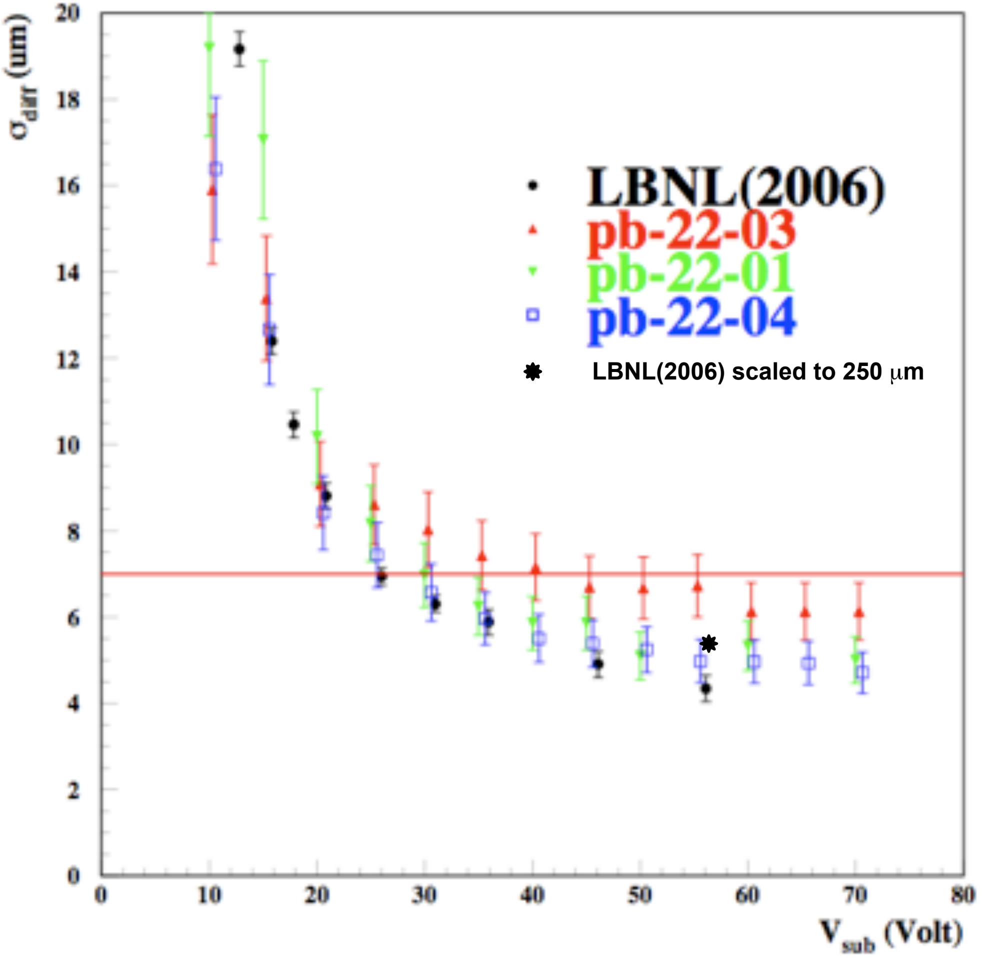
high Vsub



low Vsub



Diffusion results

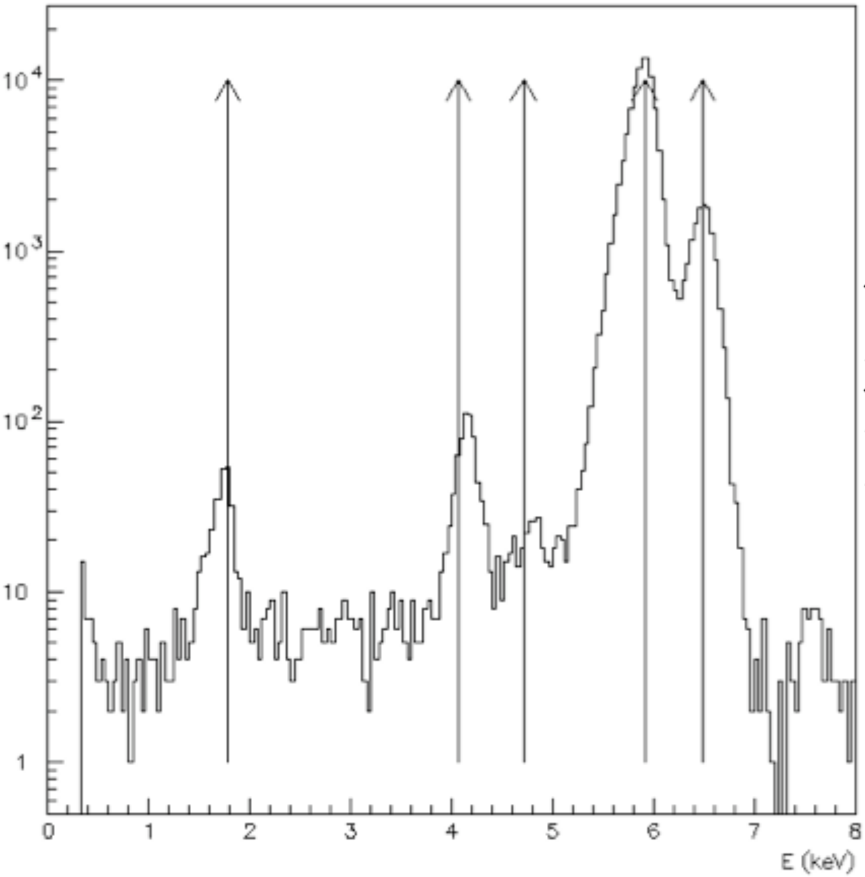


substrate voltage

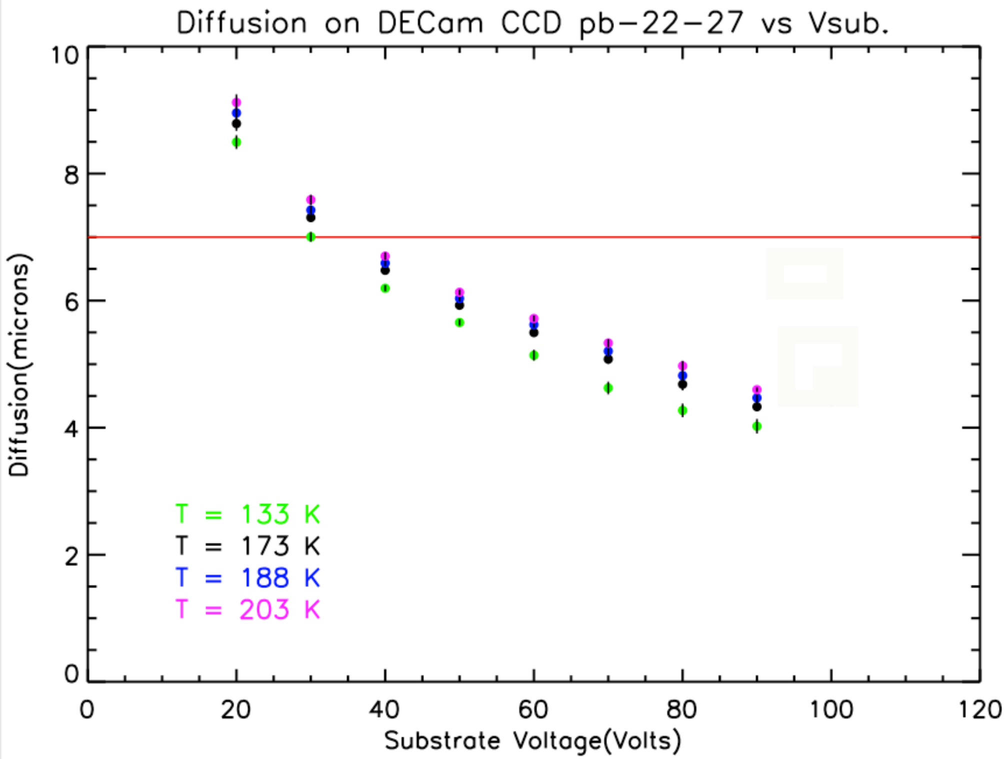
Results of the DES devices (blue,red and green) are compared with measurements done at LBNL for a 200 μm SNAP CCD (black). These results also show that the devices are fully depleted well before 40 V.

Diffusion is also measured using X-rays from an Fe55 source.

X-rays



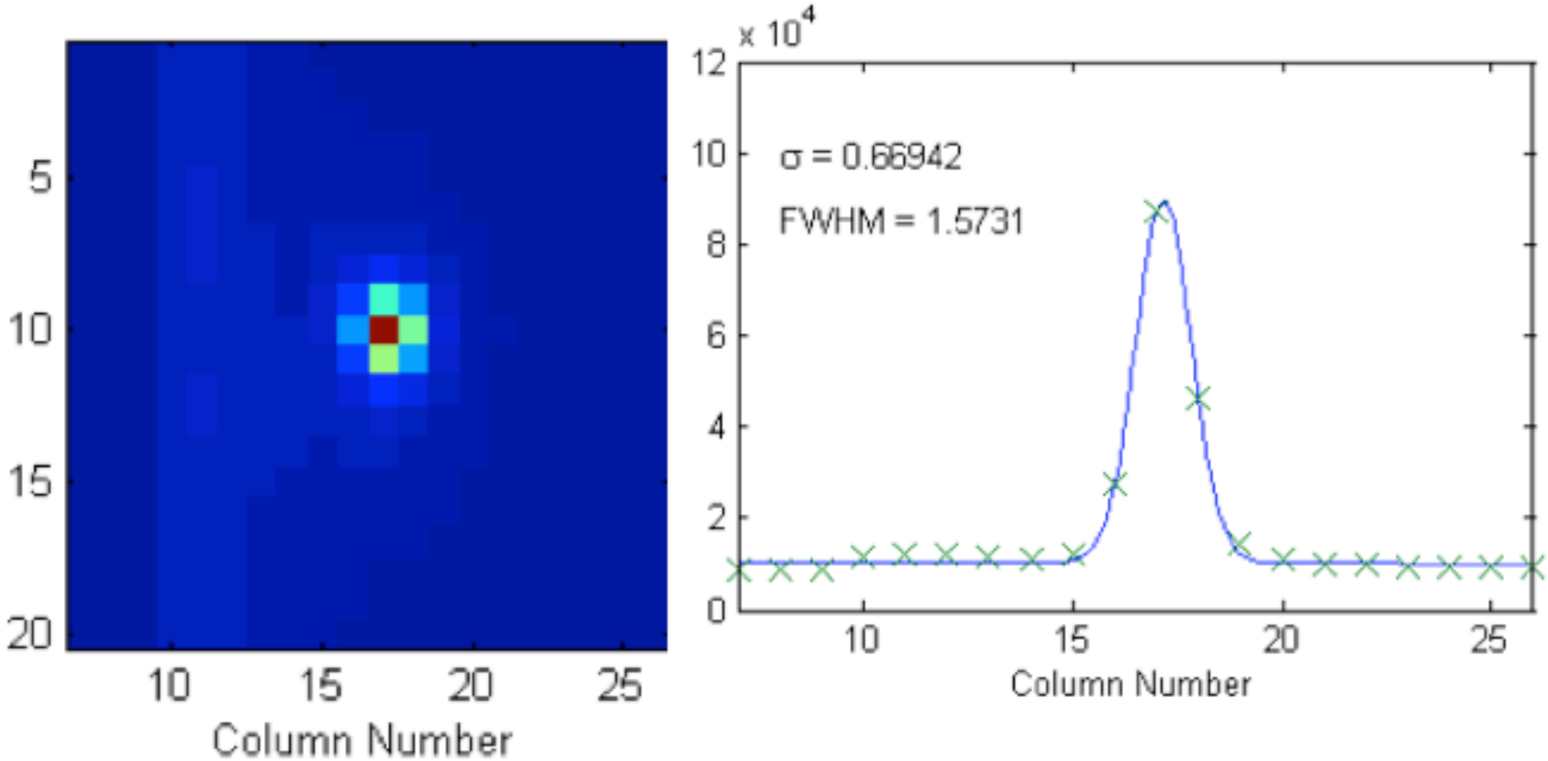
10^4
10^3
10^2
10
1
0
1
2
3
4
5
6
7
8
E (keV)



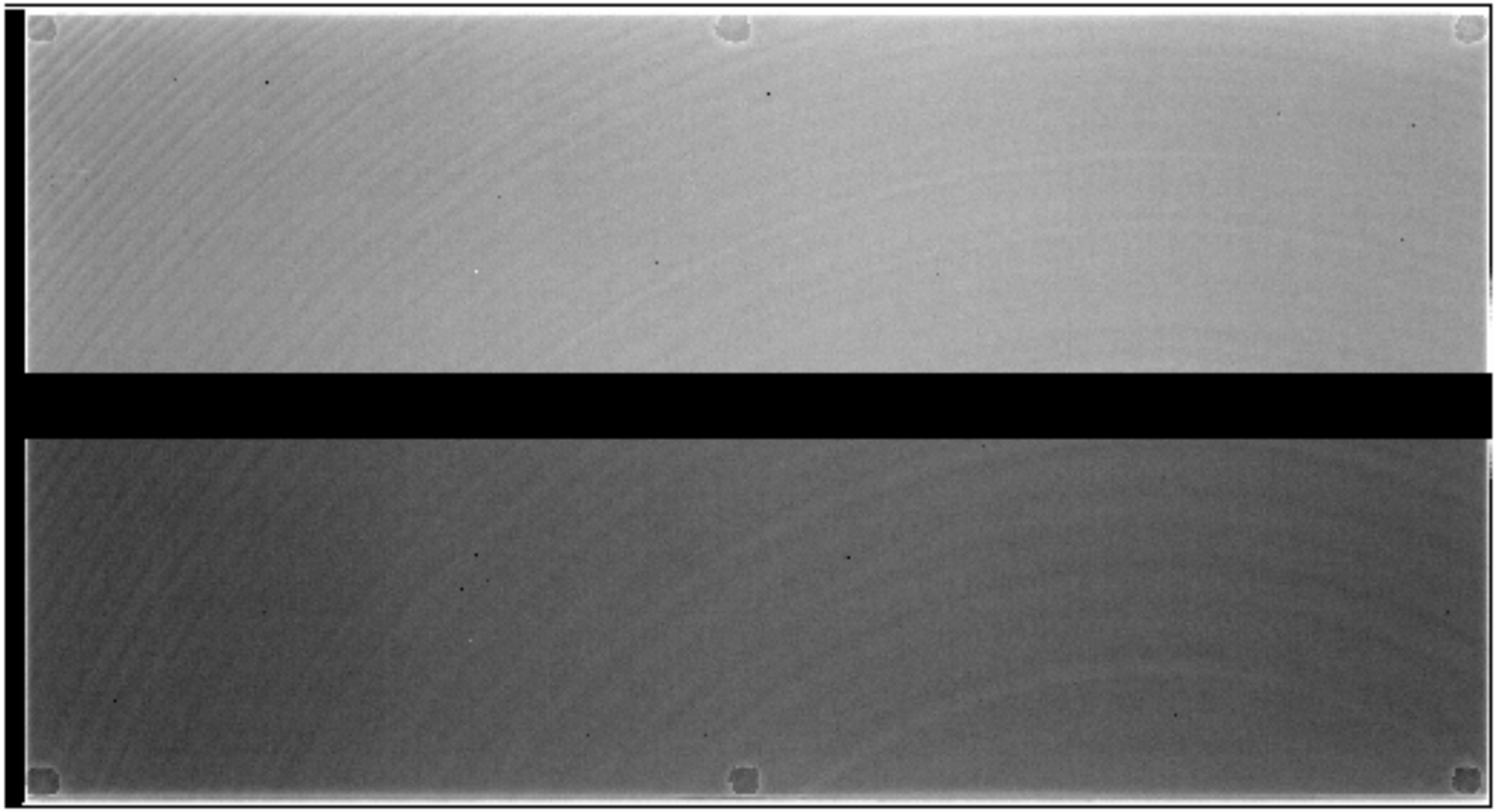
Diffusion on DECam CCD pb-22-27 vs Vsub.
Diffusion(microns)
Substrate Voltage(Volts)
T = 133 K
T = 173 K
T = 188 K
T = 203 K
0
2
4
6
8
10
0
20
40
60
80
100
120

Simulated stars

As an additional check we projected “stars” on our detectors. We were able to got what would correspond to a PSF=0.43” FWHM for DECam (0.27’’/pixel). This is a, demonstration of good image quality with these CCDs. **The CCDs diffusion will NOT be a limiting factor in DECam.**

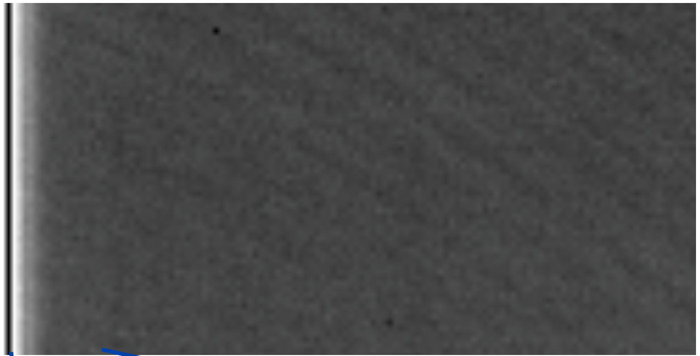


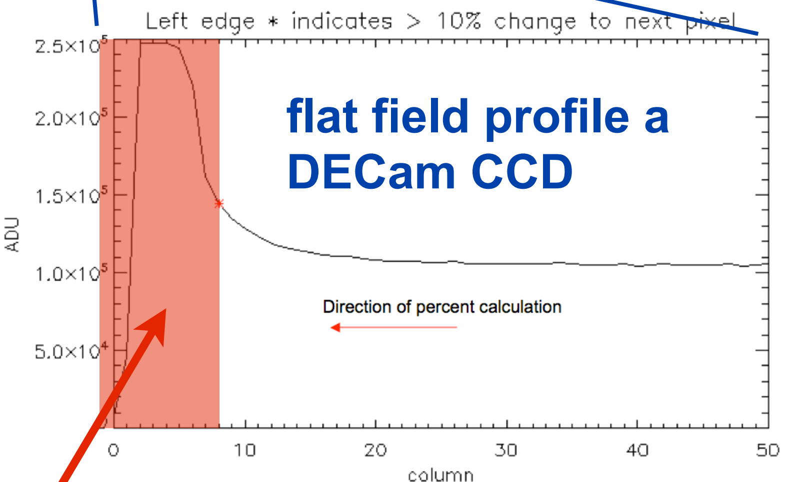
Glowing edge



Edge effects on DECam CCDs

DARK ENERGY SURVEY

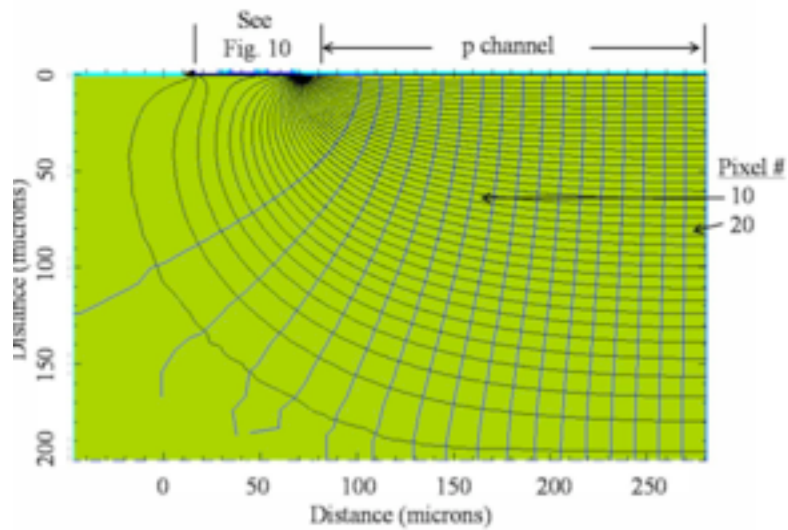




region not used for DES imaging.

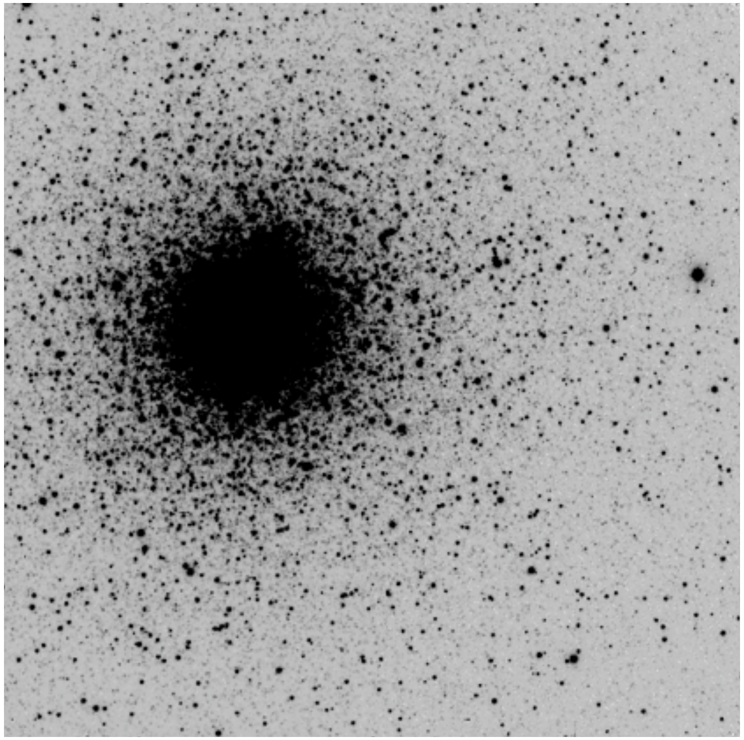
Flat field shows **additional light collected on the edge pixels.** This light comes from the edge of the CCD, from outside the pixel grid.

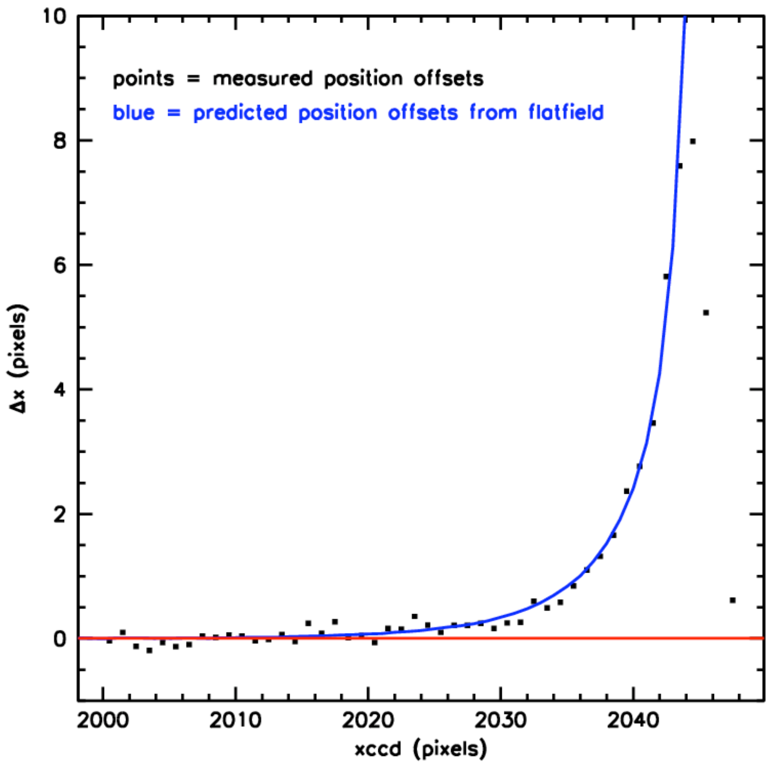
equipotential and electric field lines



S. Holland et al 2009 (for a similar CCD)

Edge effects studies on the sky

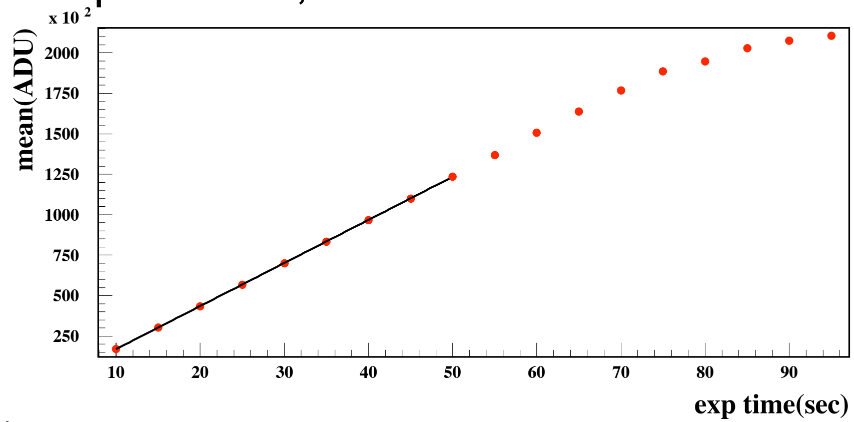


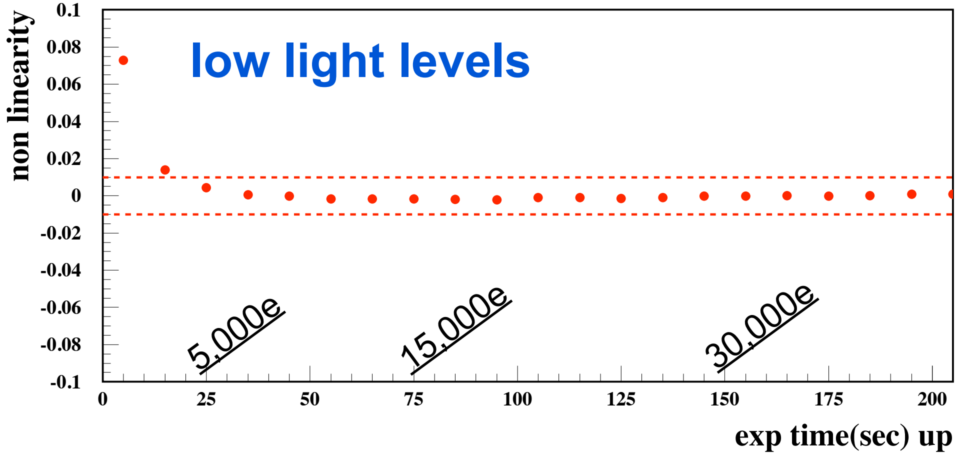


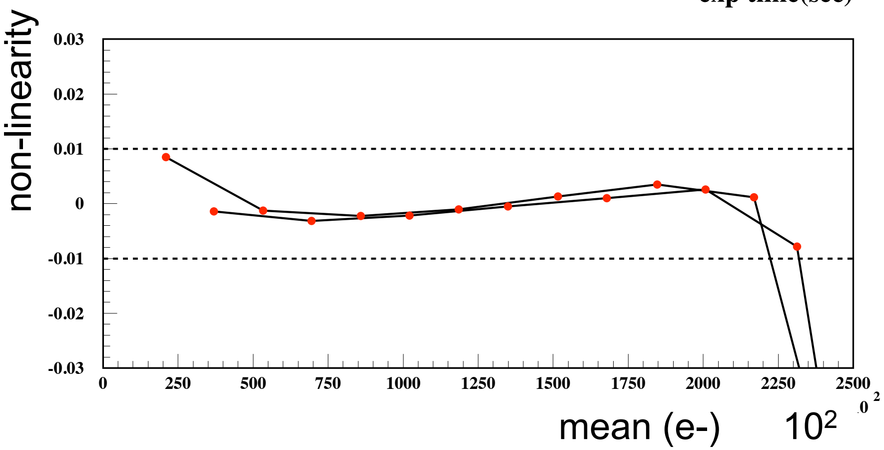
by **imaging a globular cluster** on different locations of the CCD we measured the **distortion due to this effect**. Results **agree with flat field studies**. We understand the issue.

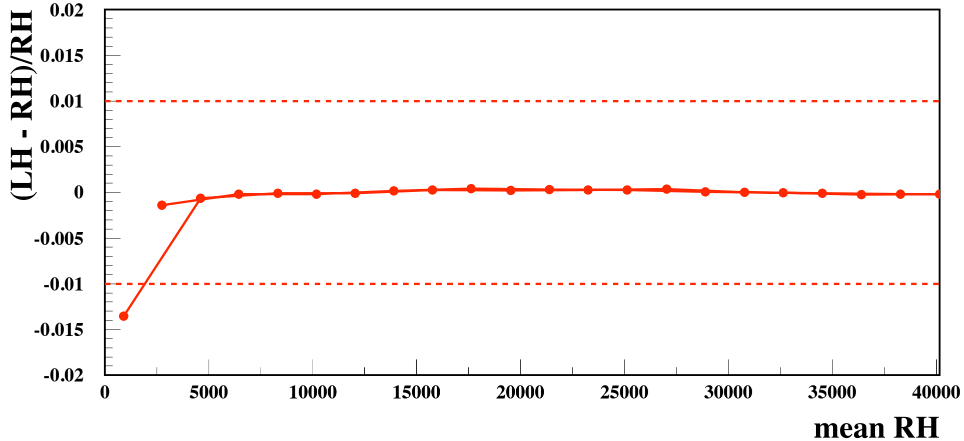
Linearity

The CCDs show good linearity up to ~200,000e.





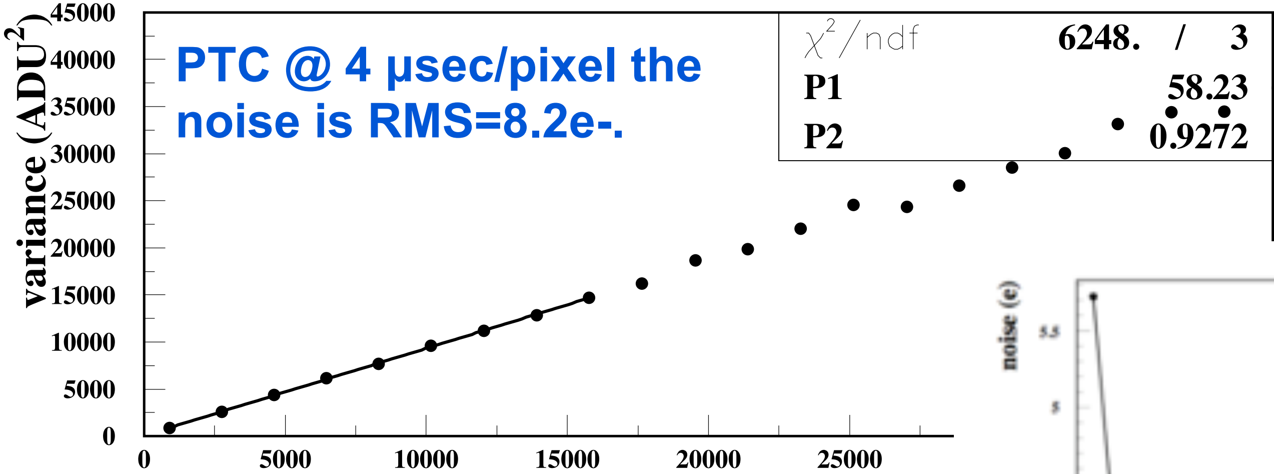




left amp vs rigth amp to eliminate lamp fluctuations or shutter problems. (note the scale!)

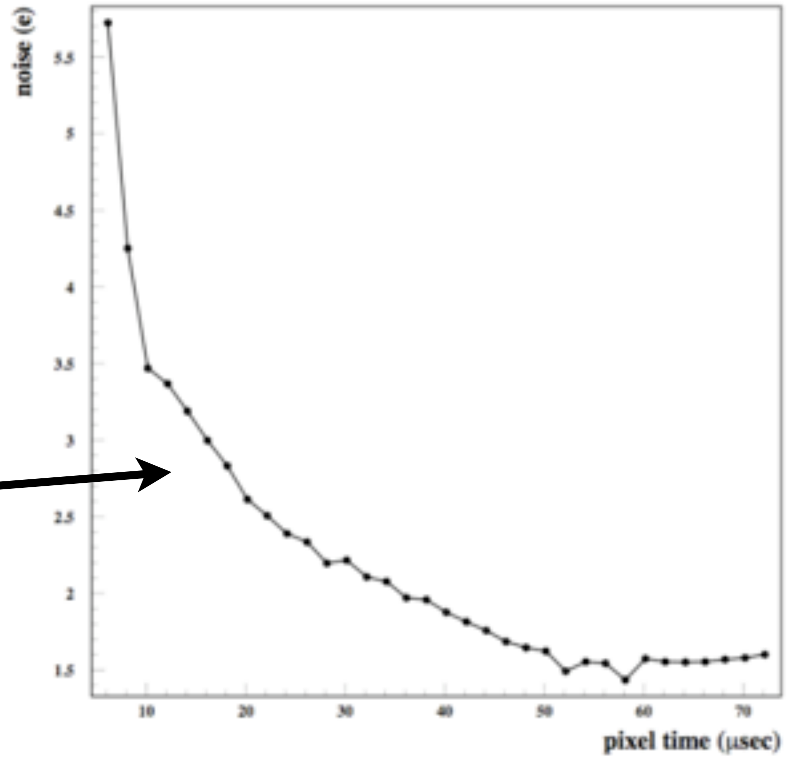
Noise

PTC @ 4 µsec/pixel the noise is RMS=8.2e-.

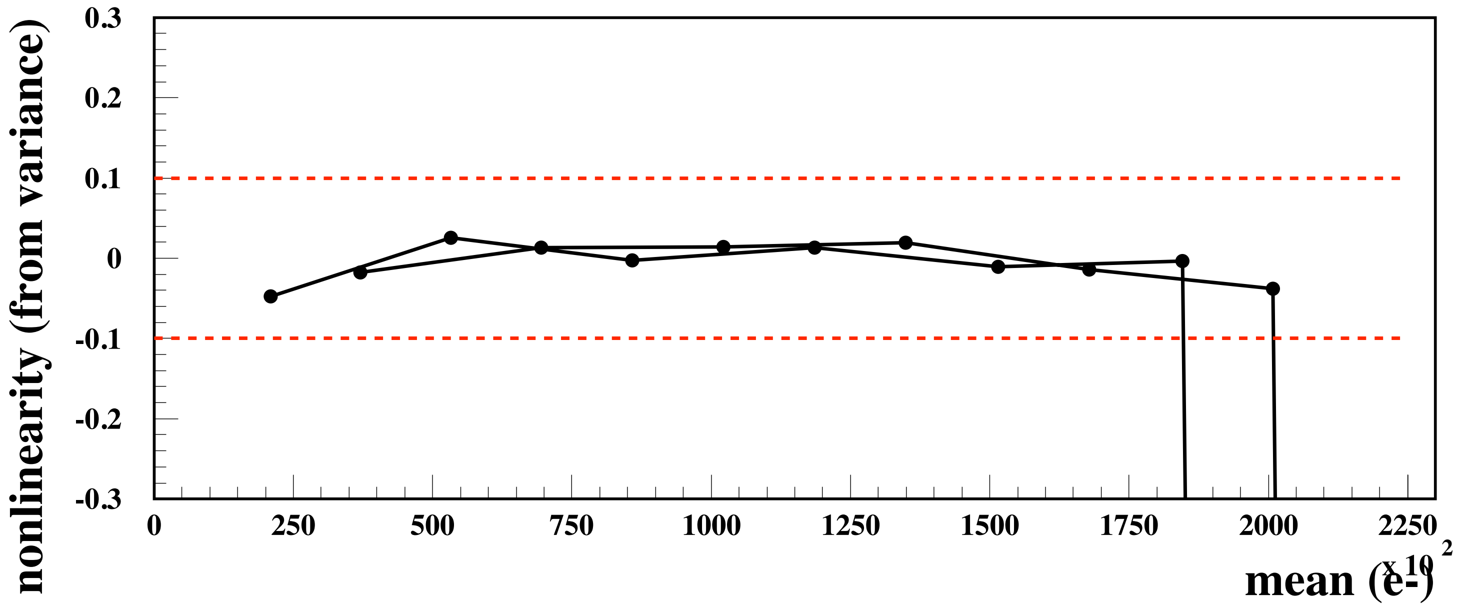


Our spec is 15e- at this speed. <u>No problem!</u>

The noise for these detectors could be reduced down to 2e- RMS for ~30usec/pixel time (33kpix/sec).



Pixel full well capacity



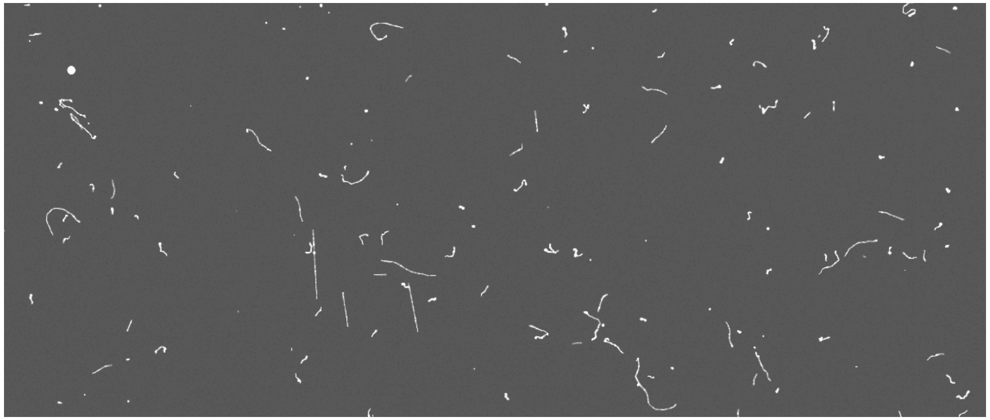
There is a **10% non-linearity on the variance at 180,000e-** (from the photon transfer curve). **This determined our pixel capacity. DES requires this to be above 130,000e-. No problem!**

System testing

DECam CCDs + DECAm electronics tested in a **single CCD camera in the 1m telescope at CTIO**. ~ 5 observing runs. Astronomers involved early with the reduction of data from these CCDs. Requirements met on site.

(1)

Long term reliability tested by running 4 DECam CCDs continuously for 13 months. Detectors perform in a stable way and no characterization showed no performance change after the long operation.



1 hour dark produced during long term reliability tests.

(2)

DARK ENERGY SURVEY

System testing: prototype focal plane

(3)

Full size prototype built very early in the project (more than 2 years ago). It a allowed us to optimize and certify:

- mechanical aspects
- cooling system
- electronics integration
- control software development

great thing to do early! Operated large (28CCD) focal plane meeting all the DECam specs.

Demonstrated robustness to power cycles, thermal cycles, board swaps. In general standard operation and maintenance cycles.

All system testing done with non-science grade CCDs. If you plan to built a big focal plane get lots of crappy detectors for your system tests.

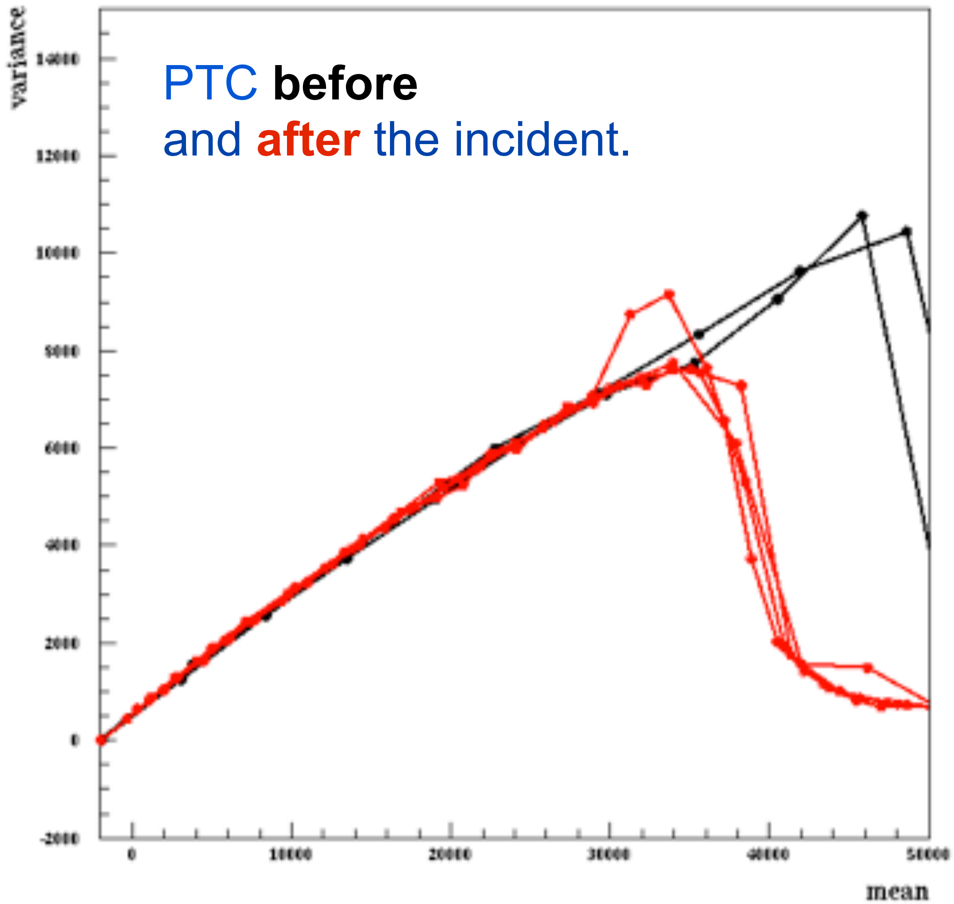
(4)

Now extensive testing with final imager with engineering grade CCDs, before installing science grade

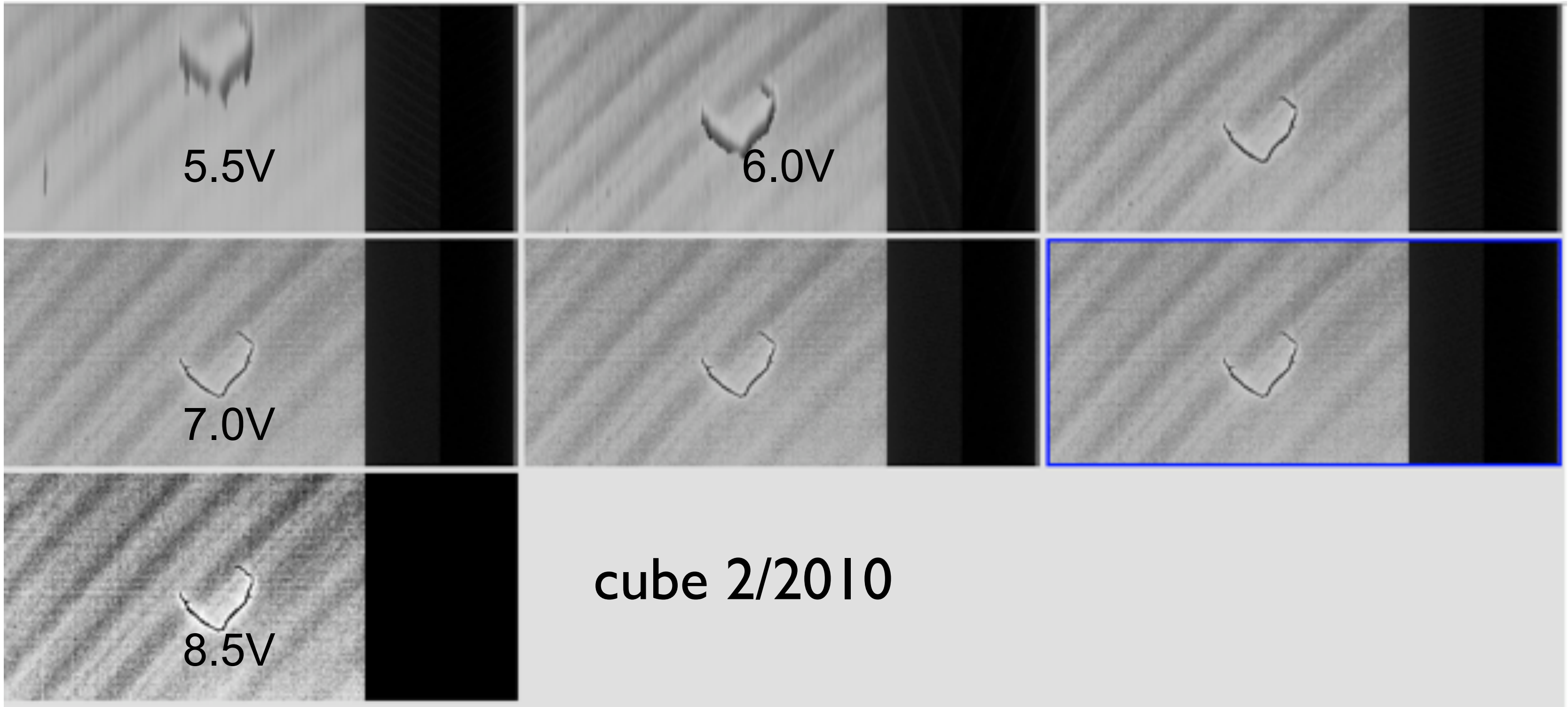
System testing: prototype focal plane

DARK ENERGY SURVEY

We also learned that we CAN get in trouble. Three different events produced an abrupt full-well reduction of some of the detectors on the focal plane.



... the CCDs have changed!

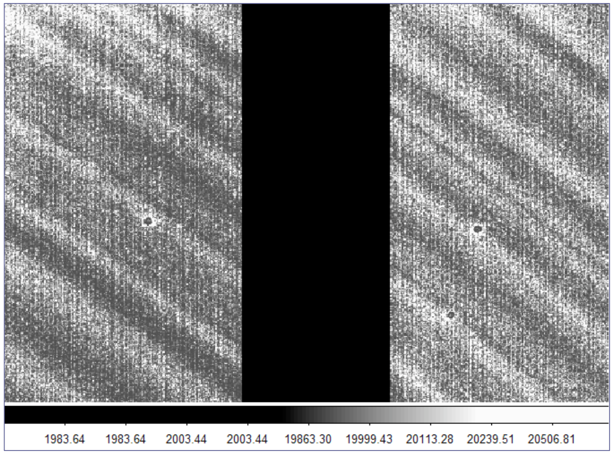


could get it back to specs by increasing the V+ clock.

s3-126

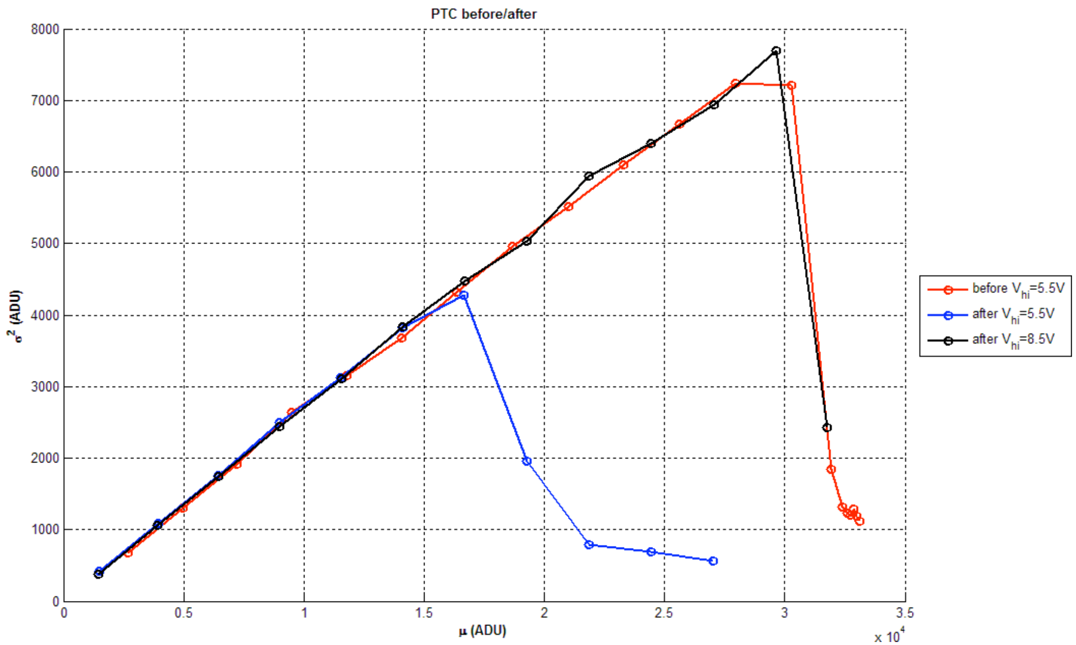
DARK ENERGY SURVEY

exercise in the lab

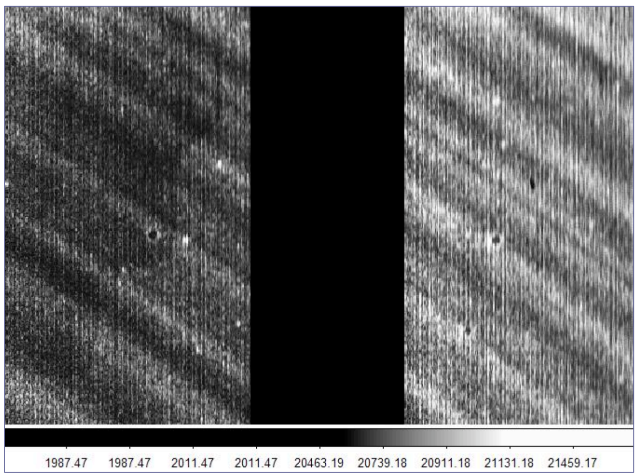


Before the damage

V+ = 5.5 V (default)



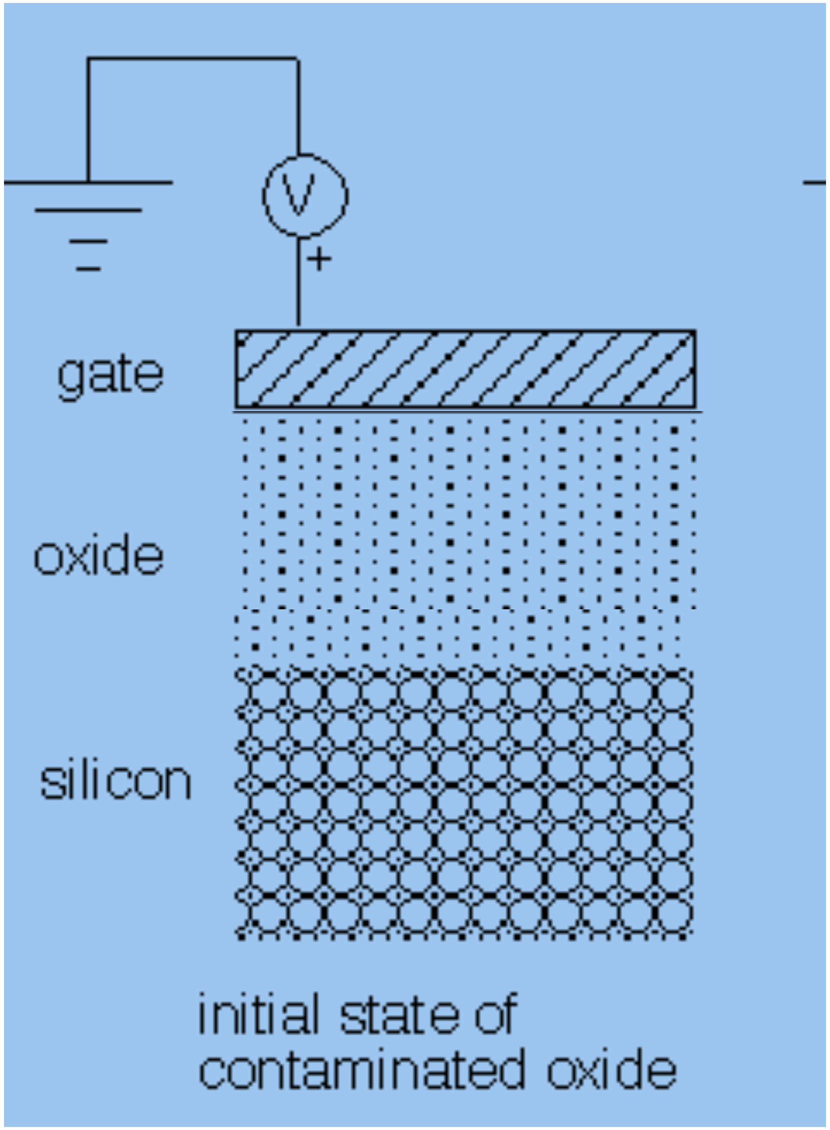
after gate set to 60V



After the damage

V+ = 5.5 V (default)

what is going on.

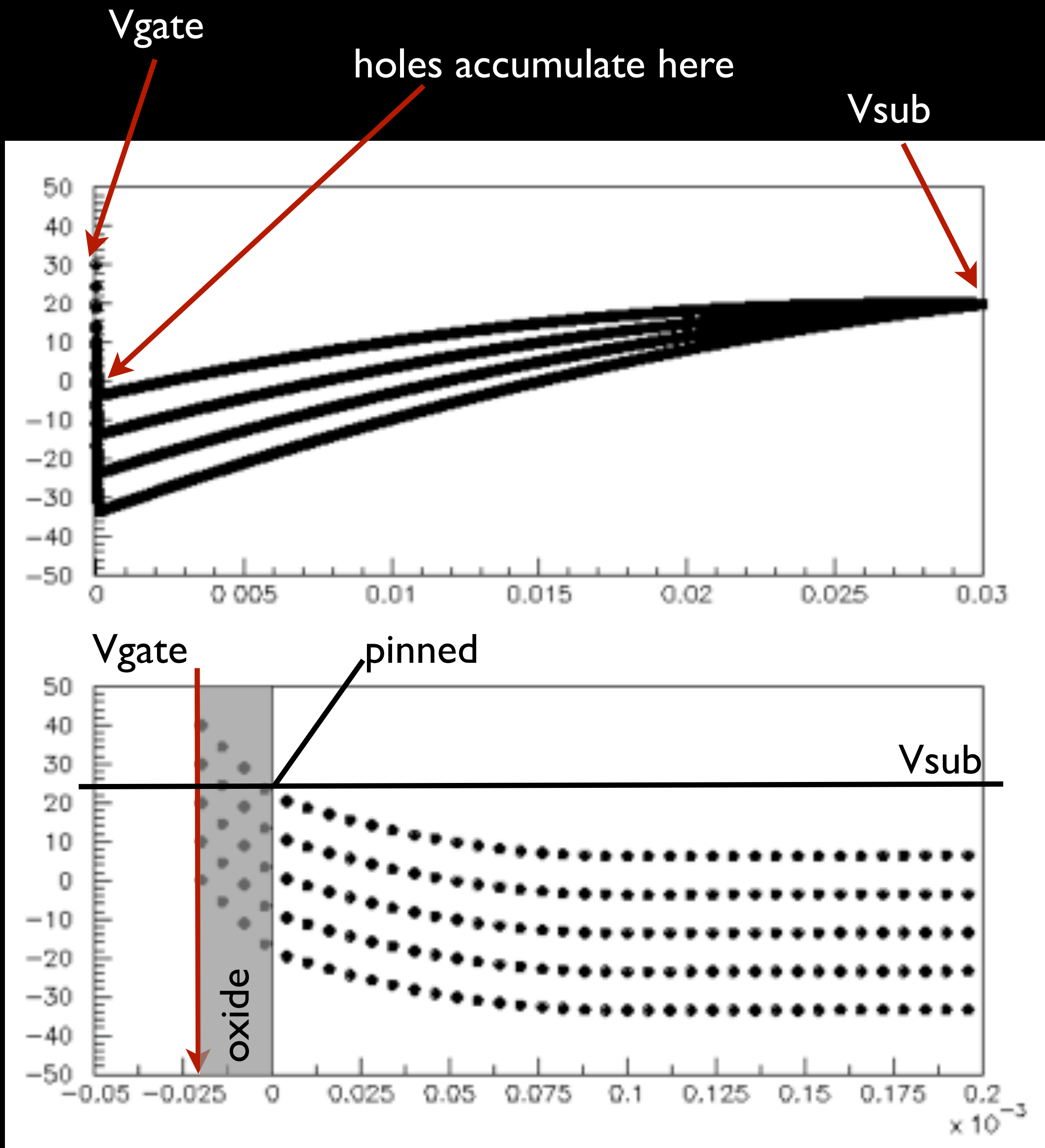


If the voltage on the gate is high enough you could move charge into the oxide, and this charge will then shield the silicon from the gate.

By using a higher V+ you recover the performance, compensate for the shielding.

This is how the old memories use to work. So now we are trying to ERASE it with UV...

potential inside CCD



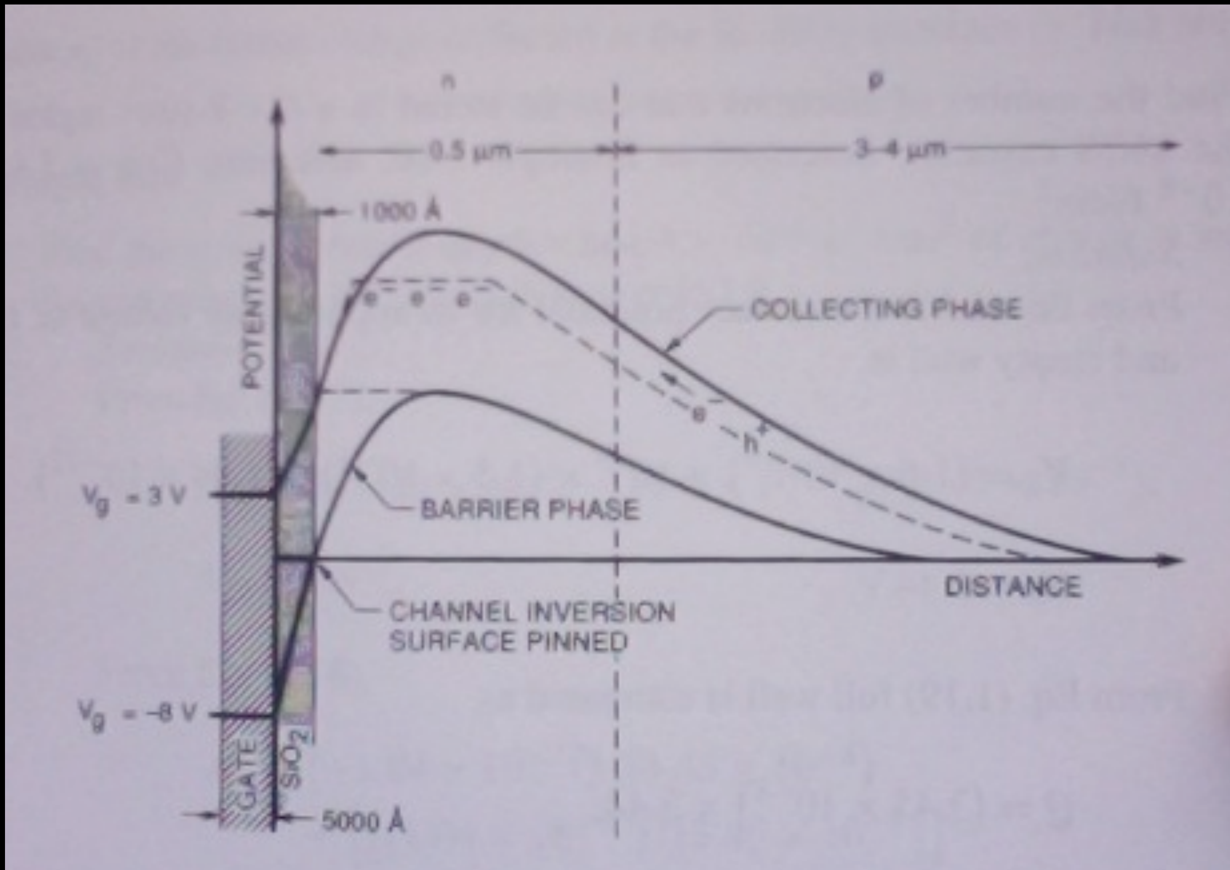
in normal operating conditions the voltage drop in the gate (E*d) does not change much with Vgate .

If Vgate is too large compared with Vsub. Detector goes into "inversion", and all the extra voltage drops across the gate. The voltage at the interface gets pinned.

We put the detectors in inversion all the time to ERASE them. For this we set Vsub=0 and Vgate=8V.

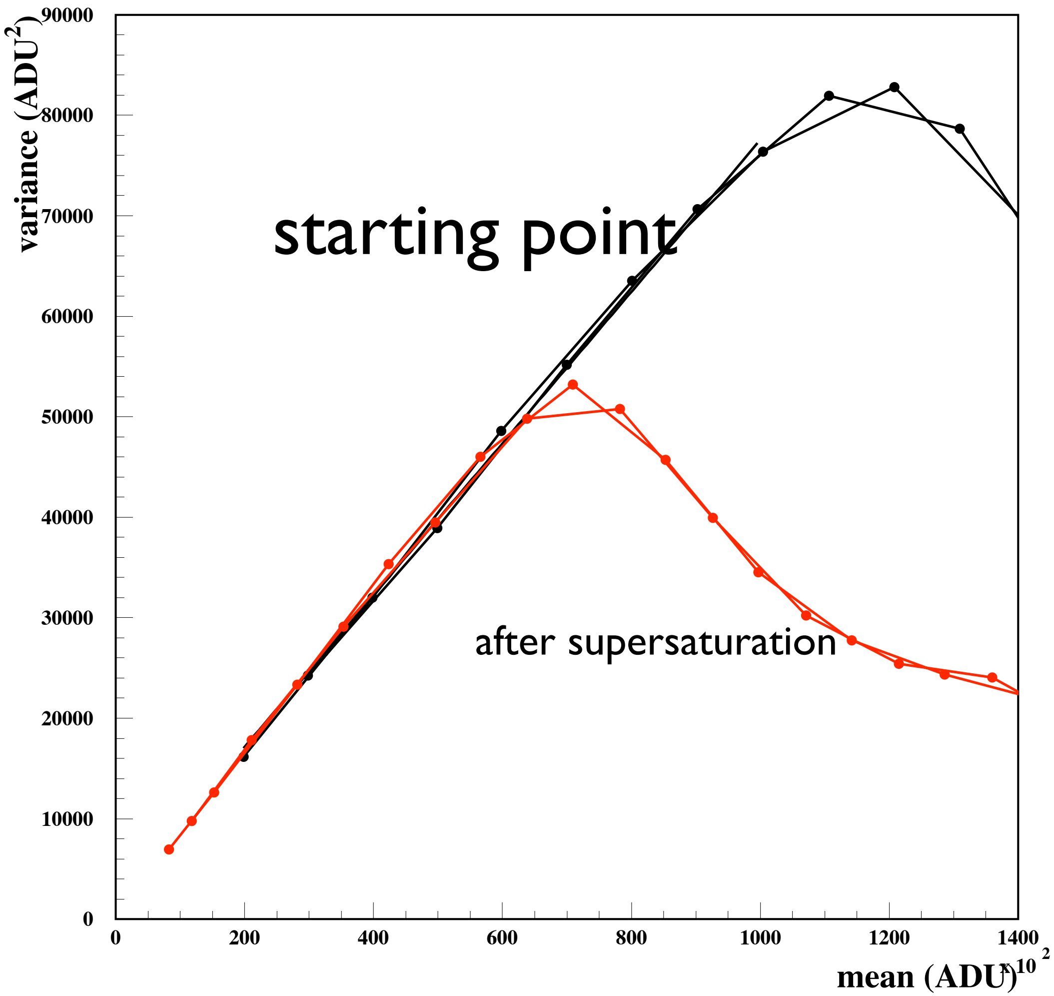
We damaged the detector in our test by going 50V beyond inversion.

Unfortunately does not recover with inverted voltage.



this happens for all the detectors, here is a plot in Janesick for one normal CCD with opposite polarity.

more in the lab



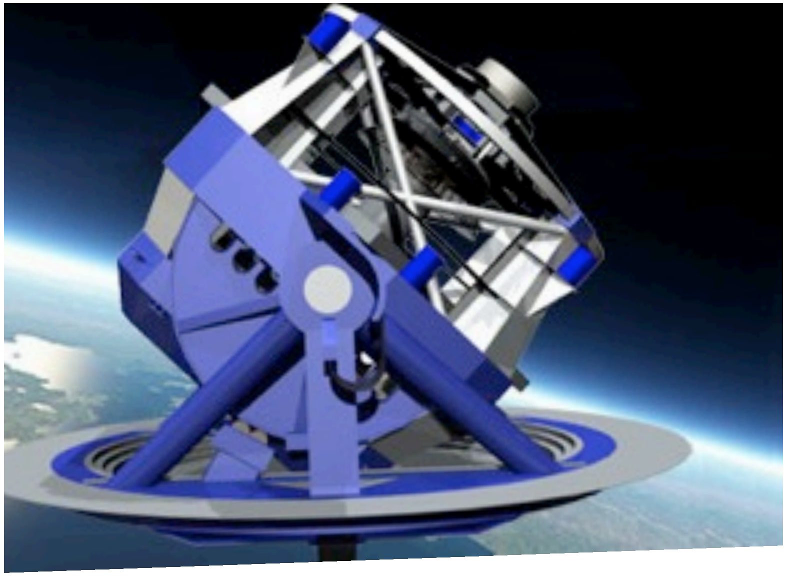
Similar levels of high field in the silicon could also be achieved by accumulating too much charge in the CCD.

We now believe that this is what happened to our detectors in the imager. During our operations we were not concerned about excessive illumination and this has produced charge migration into the oxide layer.

Now we are trying to understand the threshold for this effect.

Why are our detectors specially sensitive to this issue.

LSST : things are harder for the future



the next big survey project presents a new challenge for the CCDs. The most important things to work on are:

> focal plane flatness

about x5 flatter than DECam!

> readout speed and noise

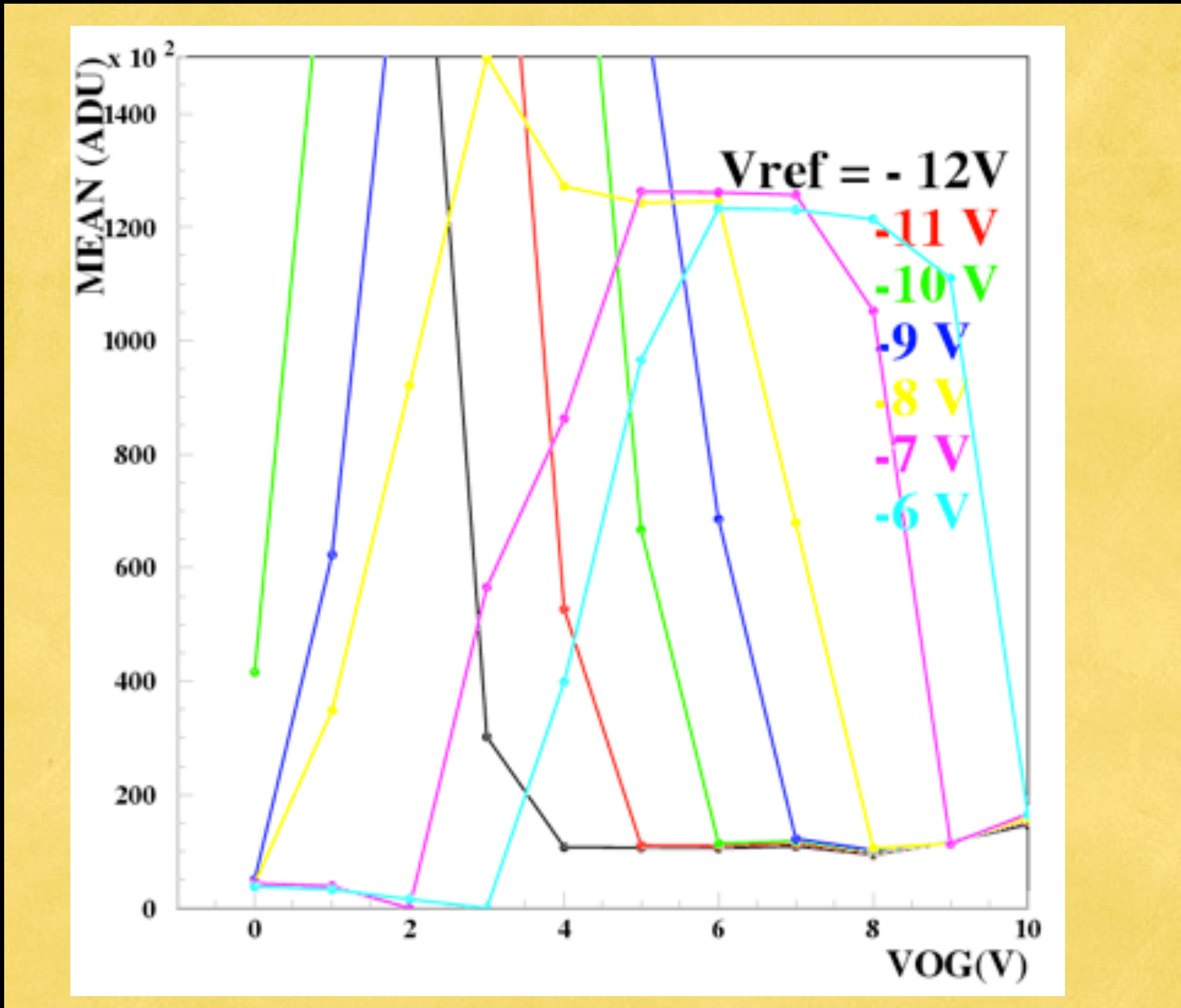
twice as fast with 1/2 the noise!

> CCD production

a lot more CCDs

Thanks!

measurement of charge injection in s3-126 (now 9/2010)



charge injection is produced when the voltage under the Vog gate is below Vref.

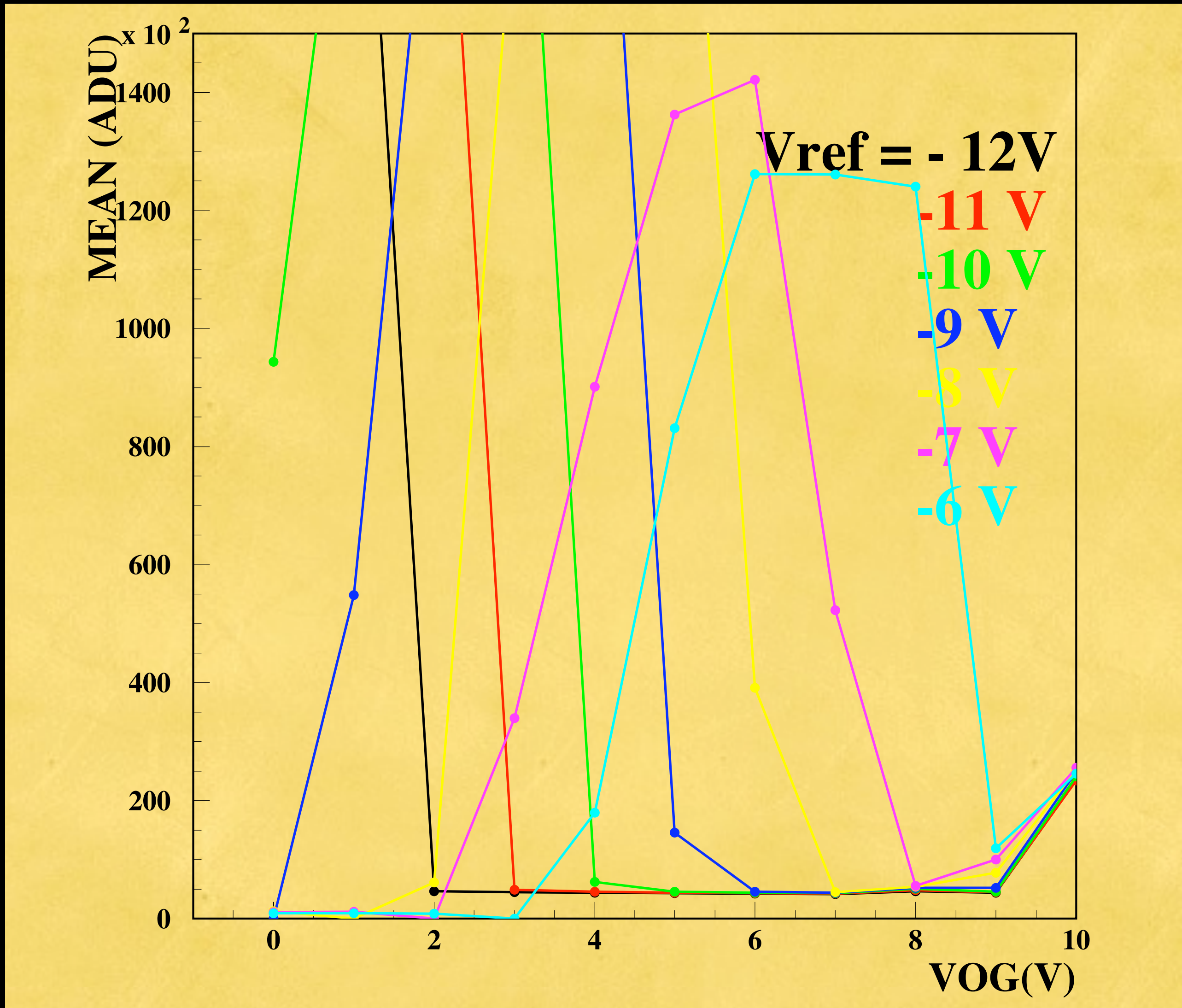
Vref = Vog - Voffset

In this case -12 = 4 -16
Voffset=-16

it moved by 2V.

This effect is similar to what we see on the Vertical clocks! Similar voltage shift everywhere.

measurement of charge injection in s3-126 (CCD testing RH, 9/2009)



charge injection is produced when the voltage under the Vog gate is below Vref.

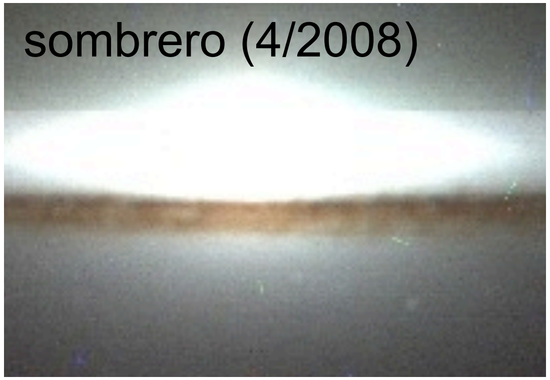
Vref = Vog - Voffset

In this case -12 = 2 -14
Voffset=-14

Observing with DECam CCDs

Detectors have **not been use extensively in astronomy**. We are also **studying them also on the sky**. These are also **tests of the readout electronics** developed for DECam.

(10/2008)



sombrero (4/2008)

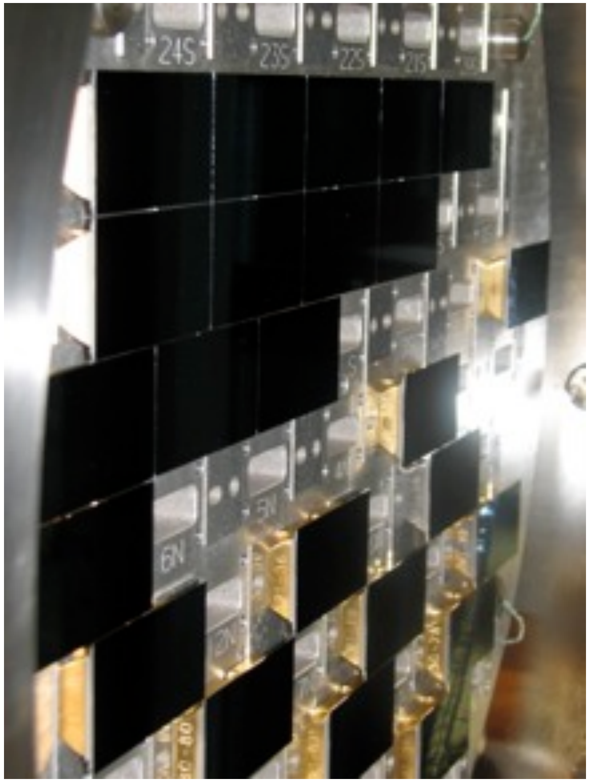
1m telescope at CTIO

M42 (11/2009)

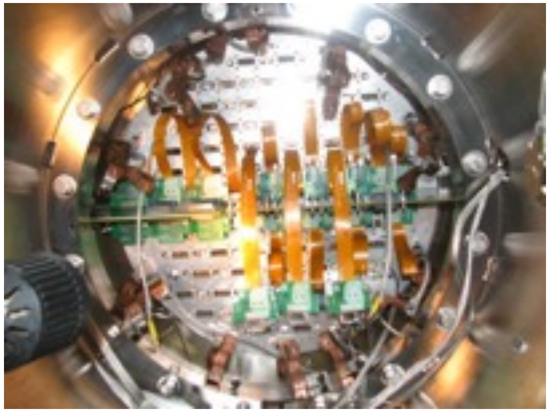
last month completed a new engineering run to understand grounding and filtering at CTIO. **Demonstrated that the DECam production electronics meets requirements when used on the mountain.**

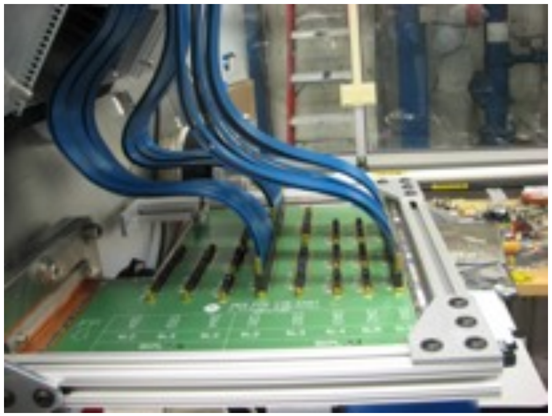
This is also useful for our technical staff to get familiar with CTIO (people, equipment, environment).

operations with prototype mosaic



produced a flat focal plane. Tested cooling system design.



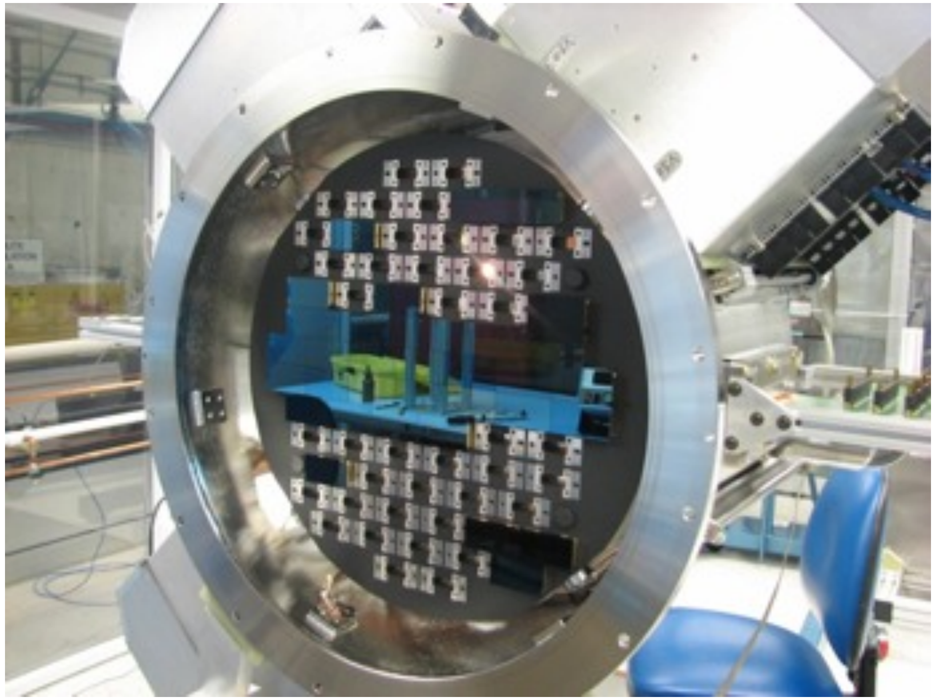


mechanical details as this support also benefited from prototyping cycles.

cold electronics (cables/ connectors) + front end crates used in prototype

+ lots of extremely valuable experience operating a mosaic like this.

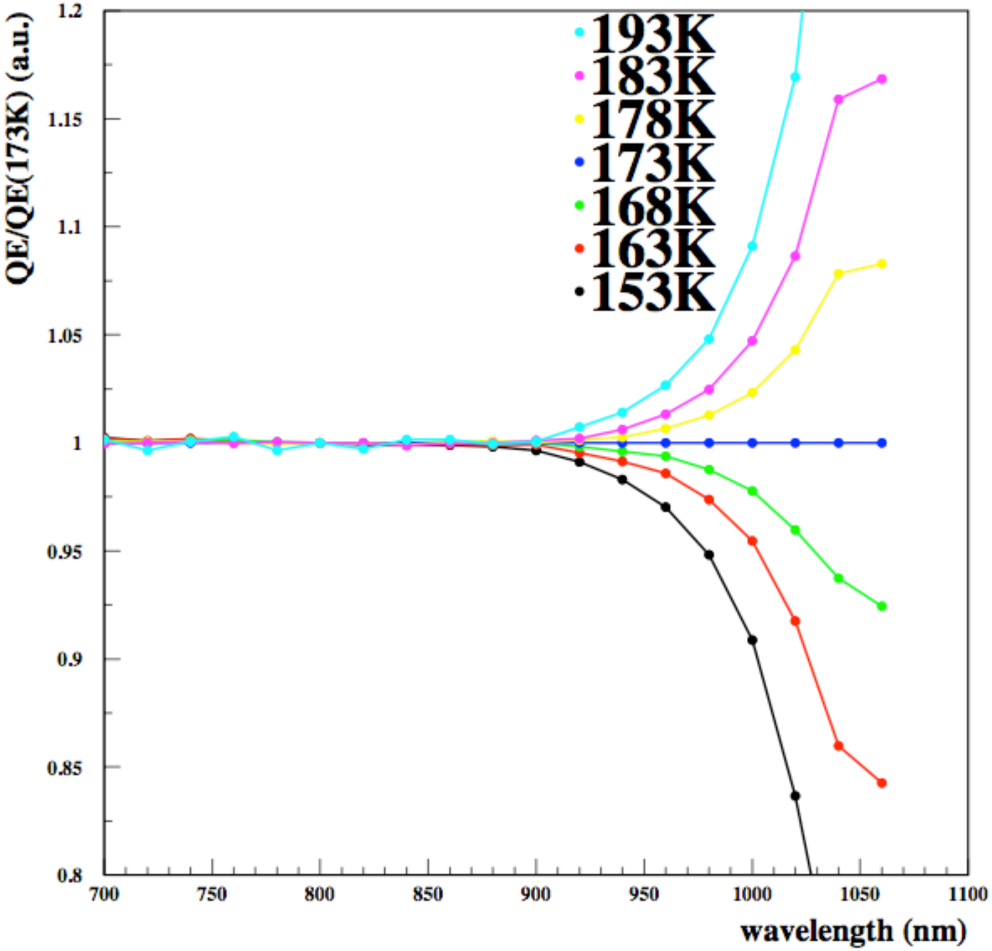
DECam Imager

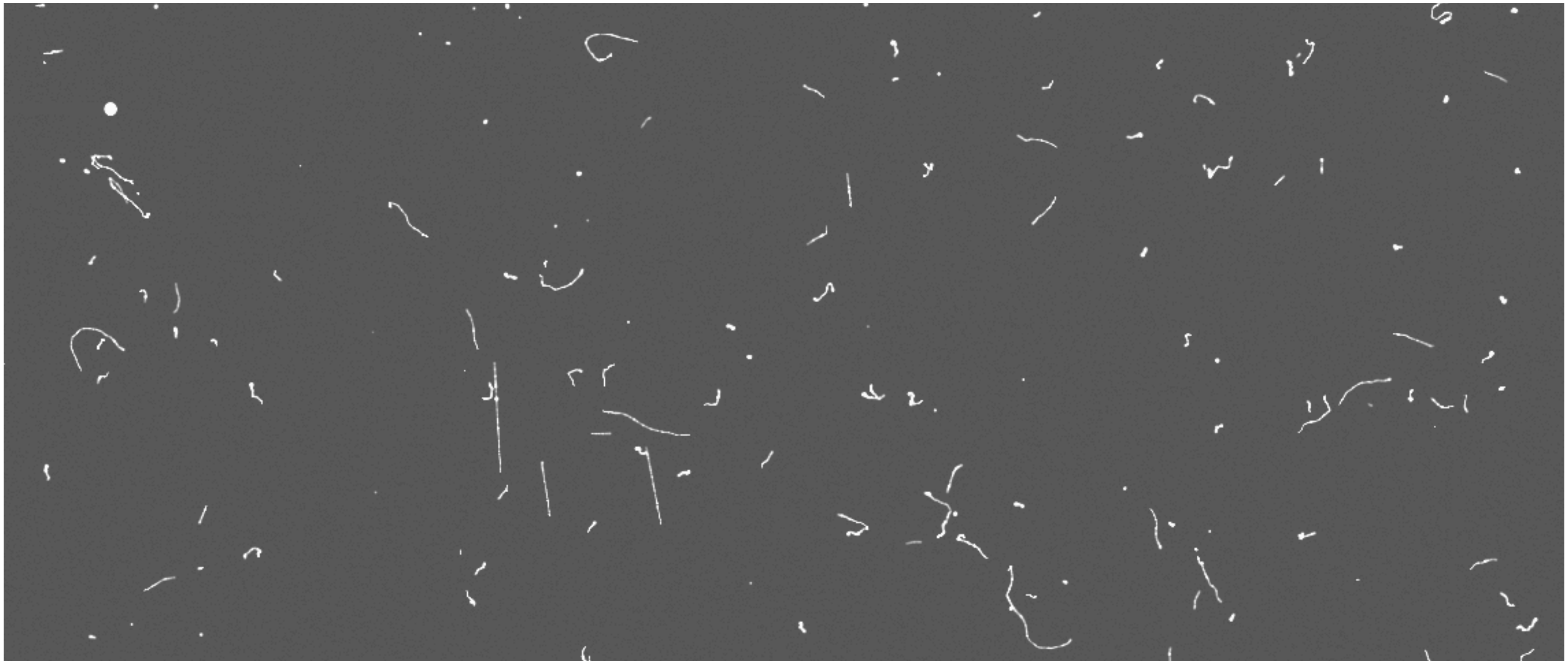


Prototype imager operated with ~50% of detectors instrumented operated for ~3 years

real imager instrumented this summer

QE stability

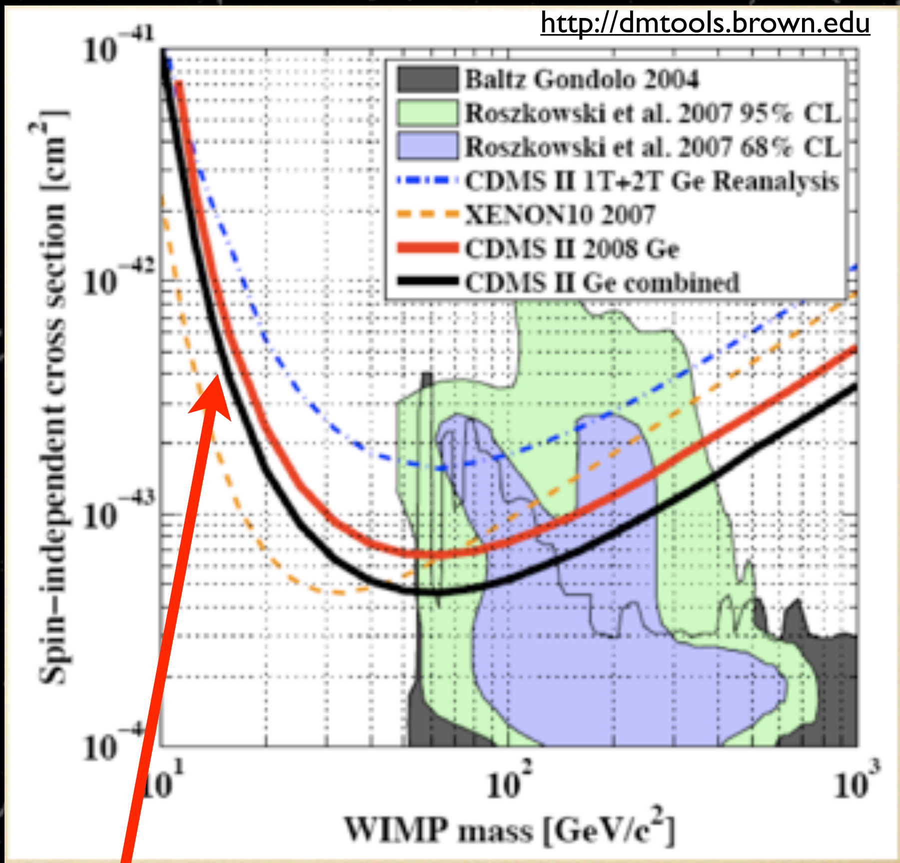




Detour from DES:

... these are cool detectors and is hard to avoid thinking about other applications.

"Current" DM search results



limited by detector threshold, typically a few keV. This limitation comes in part from the readout noise.

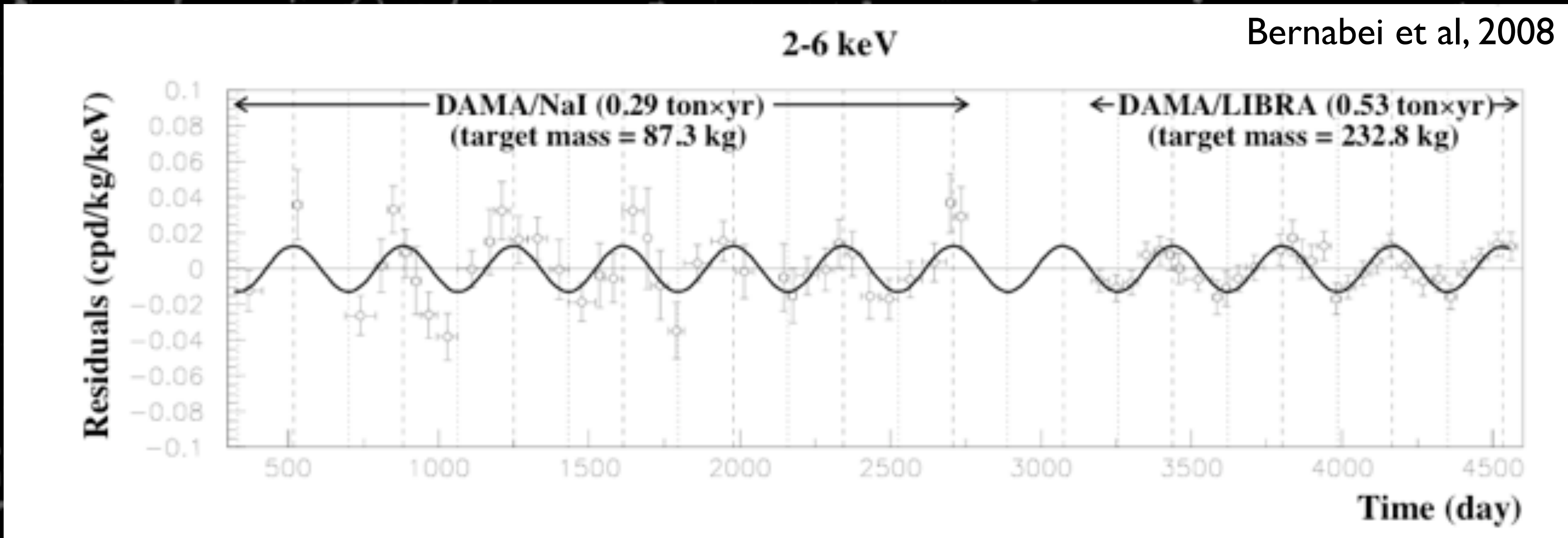
minimal SUSY likes heavy WIMPs, and most experiments are trying to cover that area.

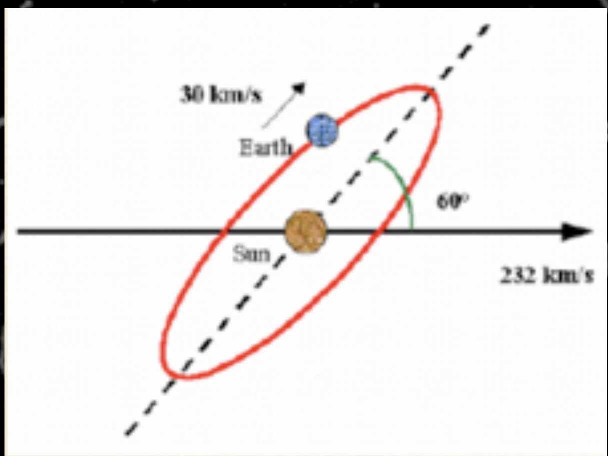
from Petriello & Zurek 0806.3989

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]
DAMIC	**Si**	**~1**	**0.1 keV**	

given our low noise, we can set a much lower threshold and scan the ungrommed region.

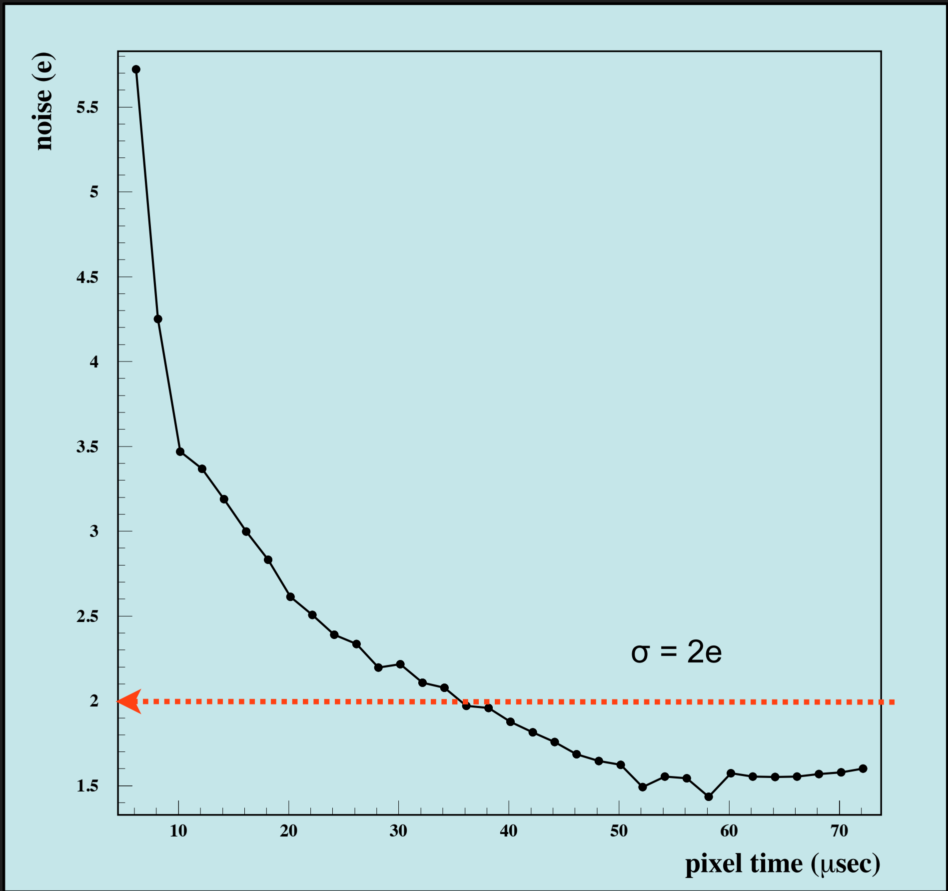
One good reason to look for low mass dark matter : The DAMA/LIBRA result





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

New opportunities with these CCDs



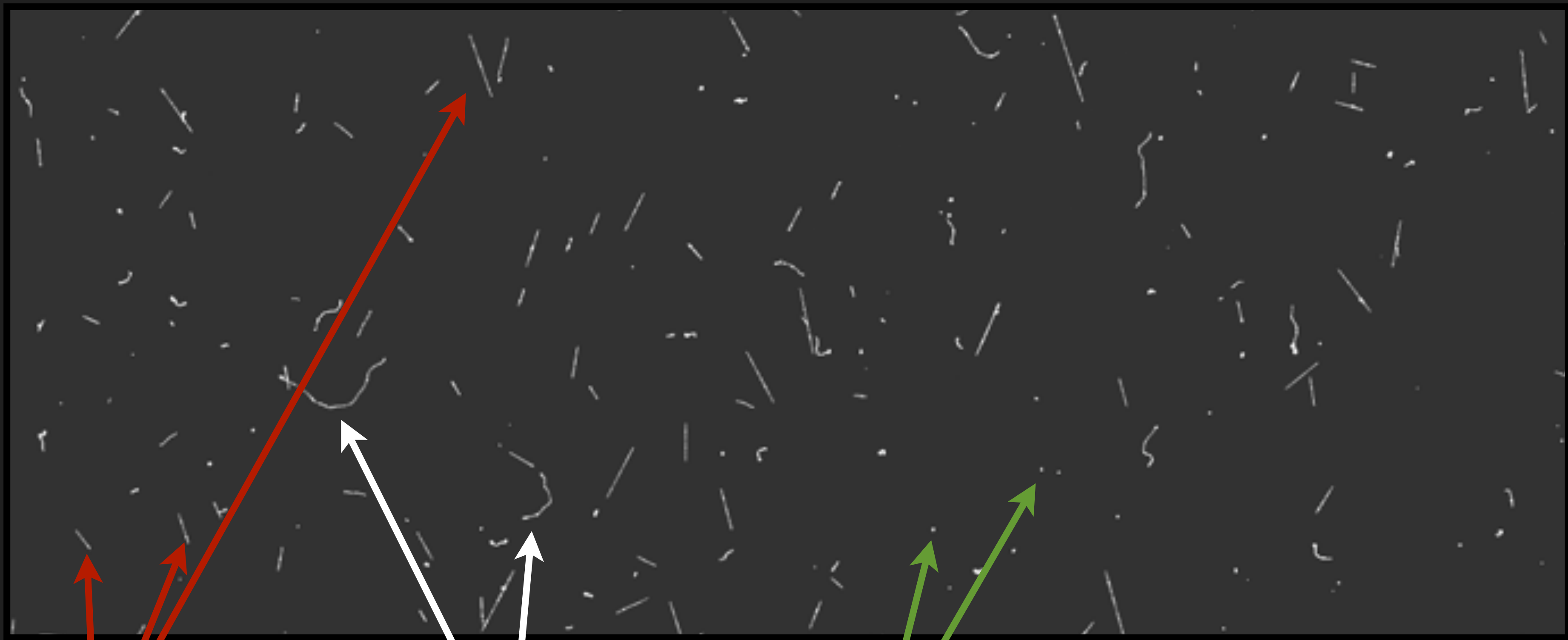
Two features:

CCDs are readout serially (2 outputs for 8 million pixels). When readout slow, these detectors have a noise below 2e- (RMS). This means an **RMS noise of 7.2 eV in ionization energy!**

The devices are "massive", 1 gram per CCD. Which means you could easily build ~10 g detector. DECam would be a 70 g detector.

Interesting for a low threshold DM search.

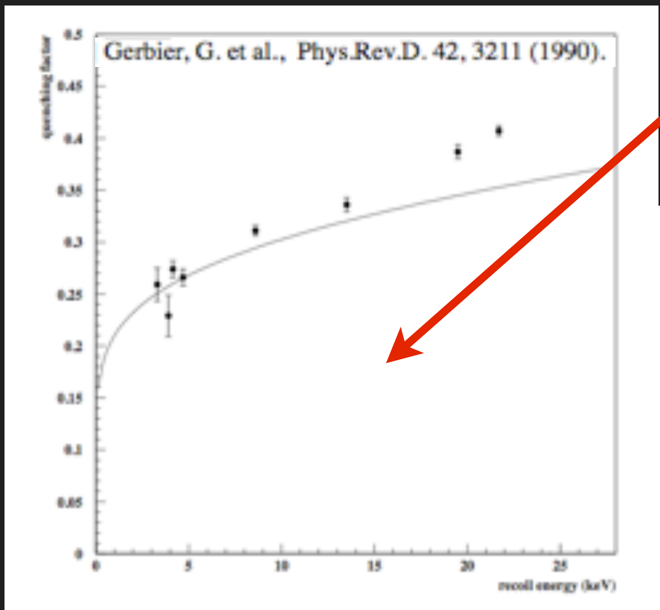
- 7.2 eV noise ➪ low threshod (~0.036 keVee)
- 250 µm thick ➪ reasonable mass (a few grams detector)



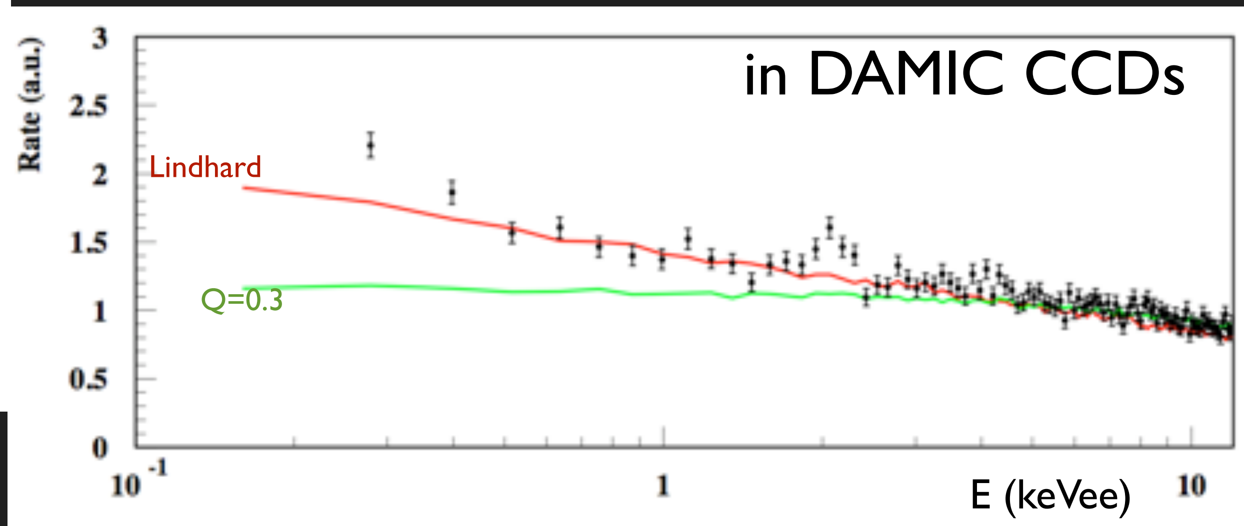
muons, electrons and diffusion limited hits.

nuclear recoils will produce diffusion limited hits

Energy dependence for quenching



energy dependence measured above E_r=4 keV (Lindhard model)



The ^{252}Cf source gives a “flat” spectrum of recoils at low energy. The shape of the measured spectrum in keVee gives the energy dependent quenching. Still some features to understand.

DAMIC (FNAL T987)

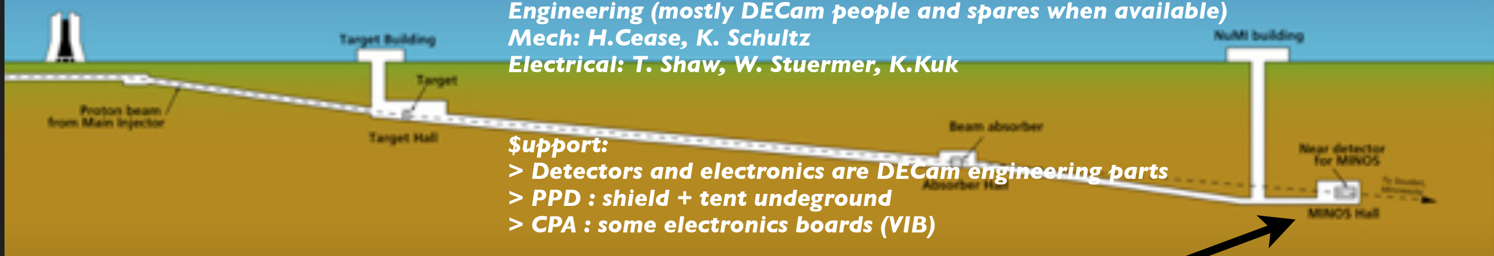
Underground test of CCDs for DM

CPA people:
DES: ***T. Diehl, J. Estrada, B. Flaugher, , D. Kubik, V. Scarpine***
COUPP: ***E. Ramberg, A. Sonnenschein***
CDF: ***Ben Kilminster***

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

Engineering (mostly DECam people and spares when available)
Mech: H.Cease, K. Schultz
Electrical: T. Shaw, W. Stuermer, K.Kuk

$upport:
> Detectors and electronics are DECam engineering parts
> PPD : shield + tent undeground
> CPA : some electronics boards (VIB)



setting up a 4CCD array here. ~350 foot depth

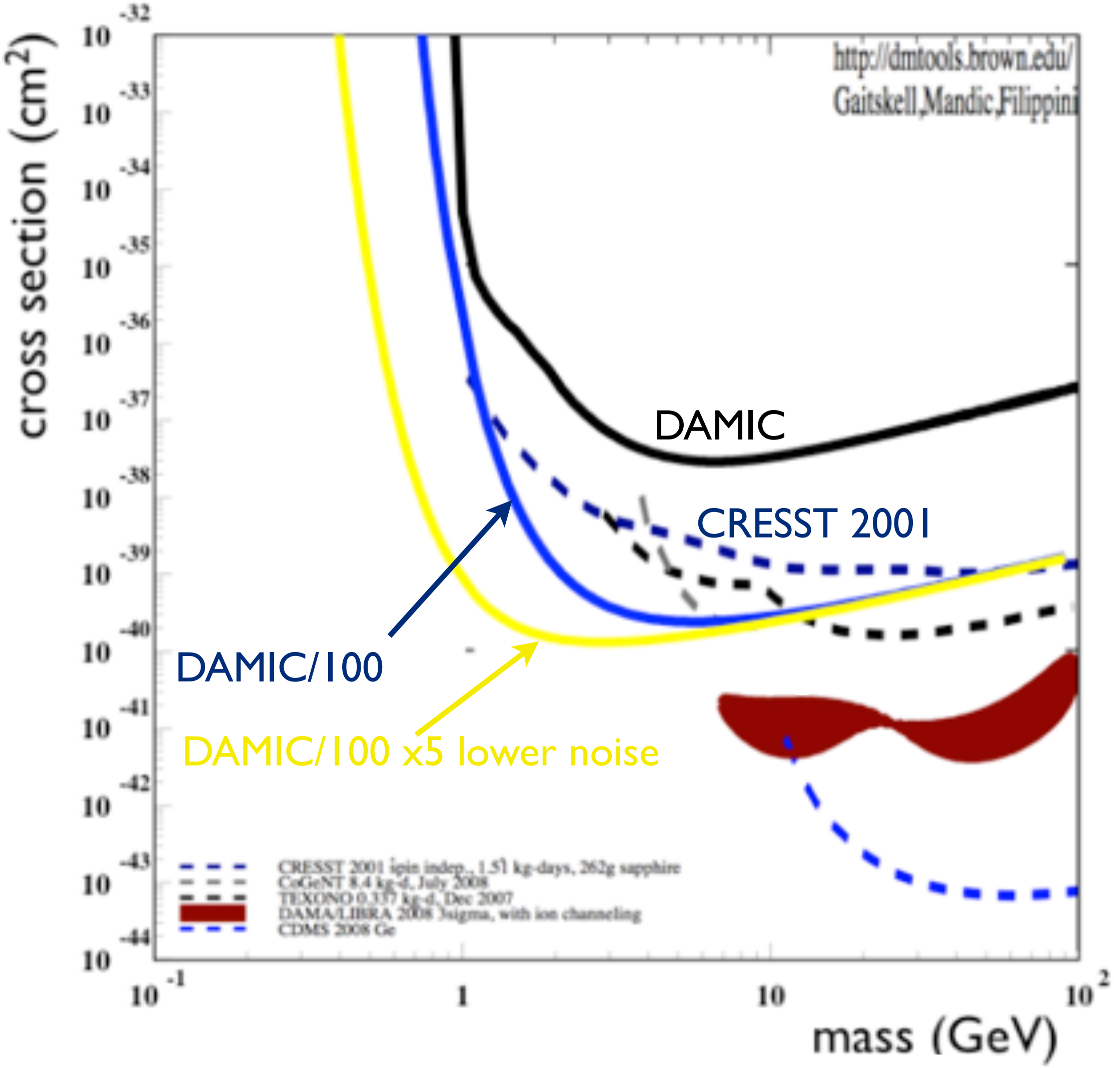
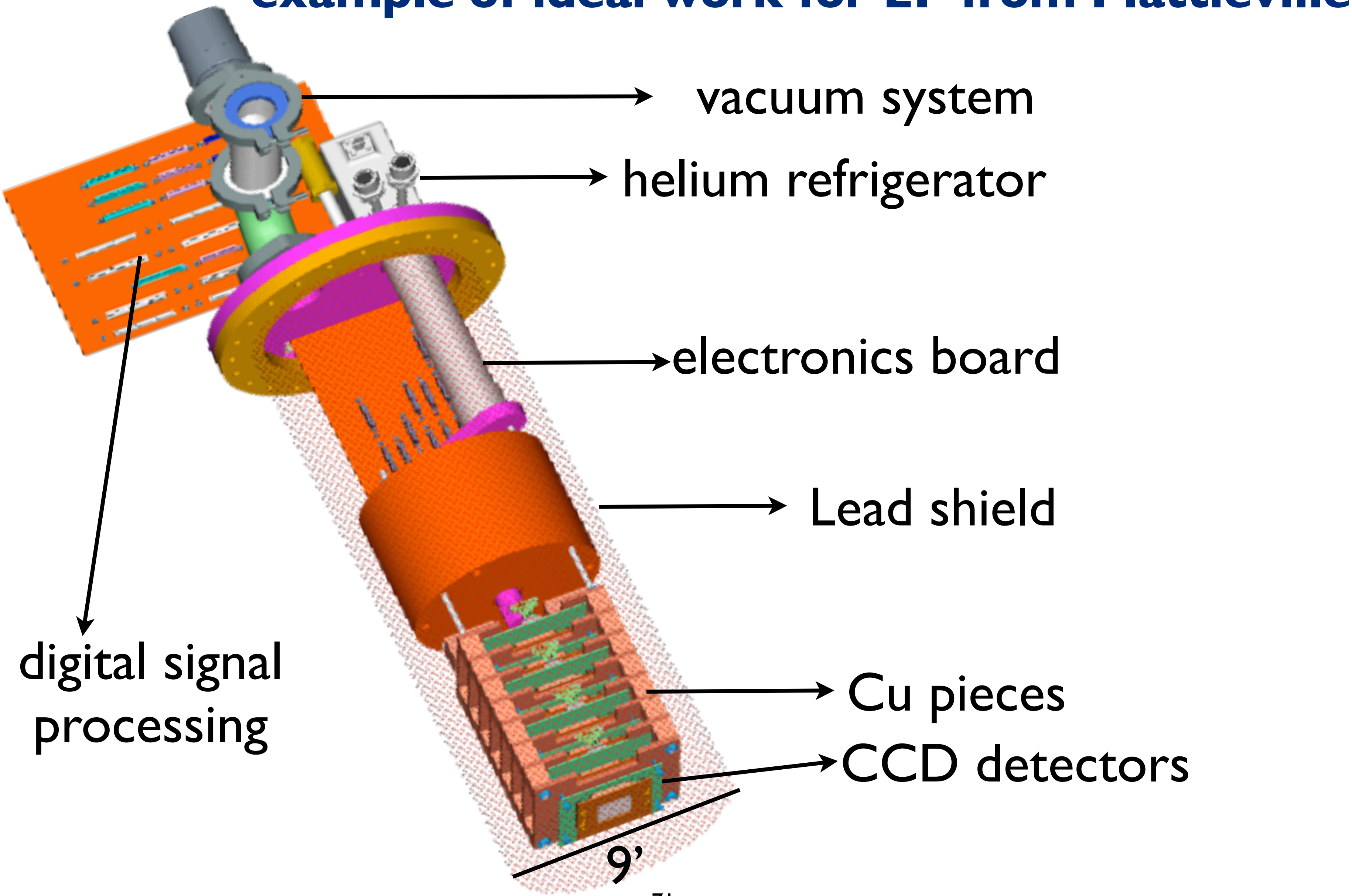


FIG. 13: The DAMIC limits for dark matter cross section (solid black) is compared with results from other searches (dashed). The expected limits for future DAMIC runs are also shown assuming a background reduction of two orders of magnitude (blue) and an additional reduction in the noise by a factor of 4 (yellow).

still about x10 away from competitive at 1 GeV

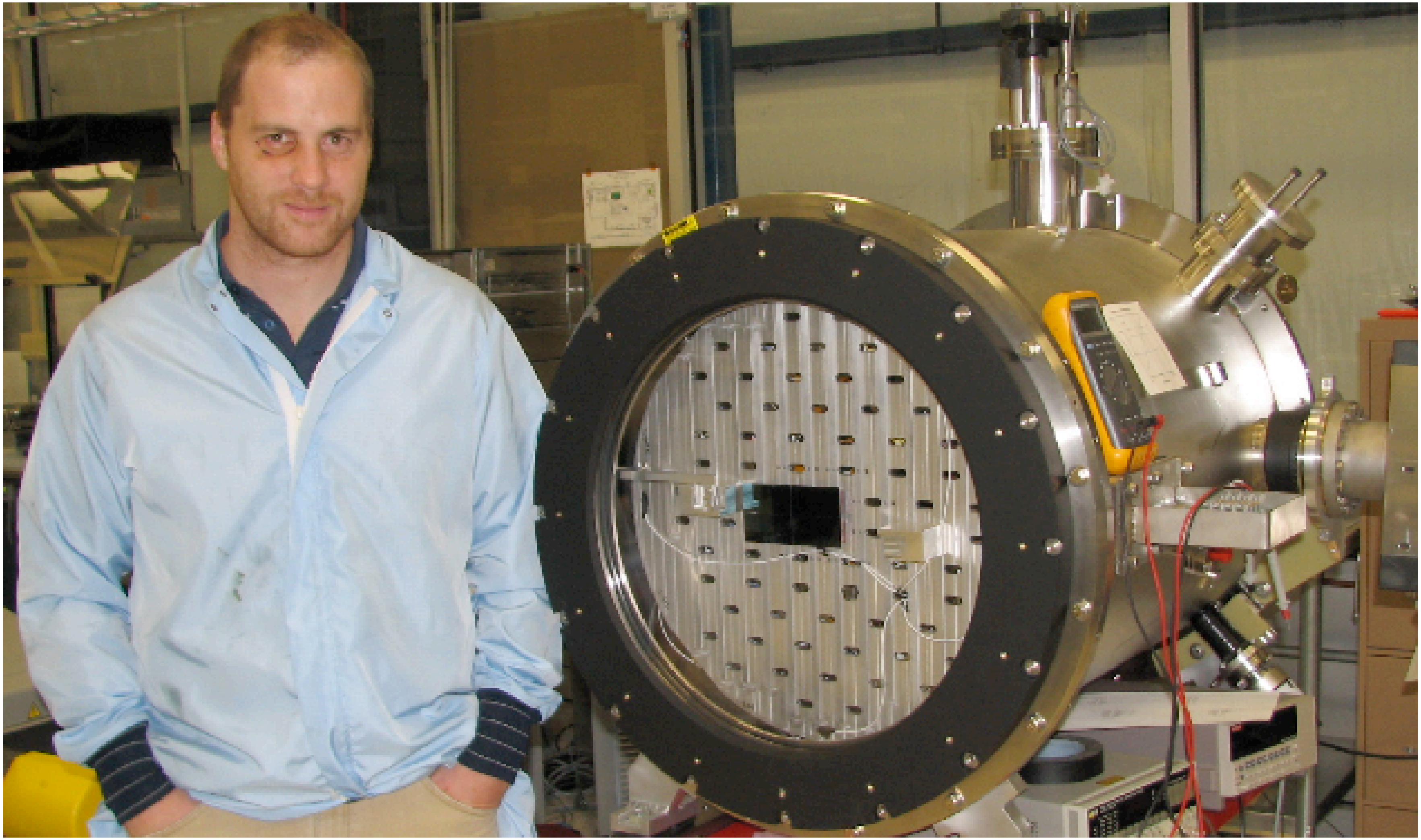
DAMIC2

example of ideal work for EP from Plattleville

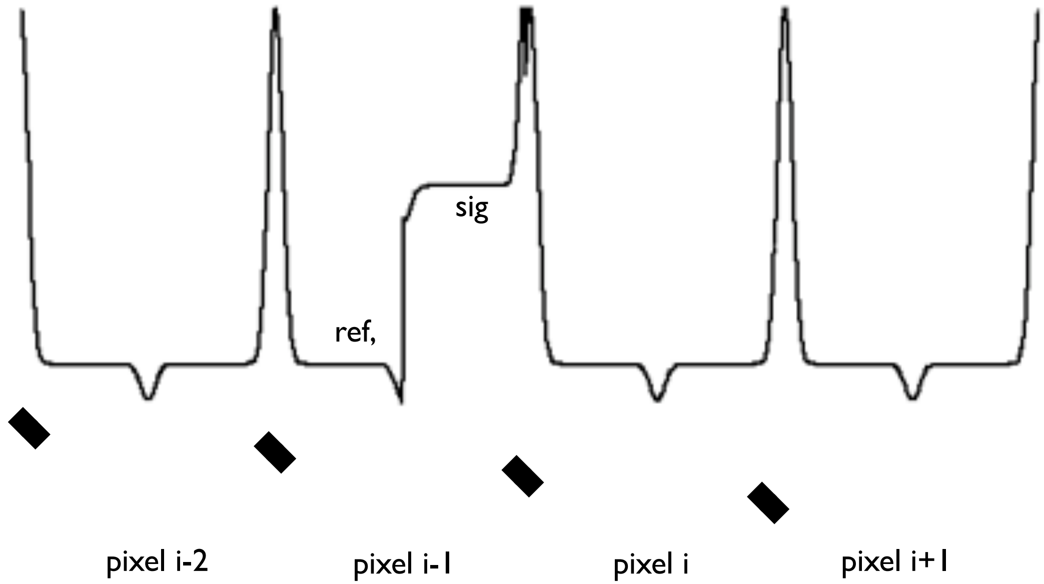


back to DES

tough work!

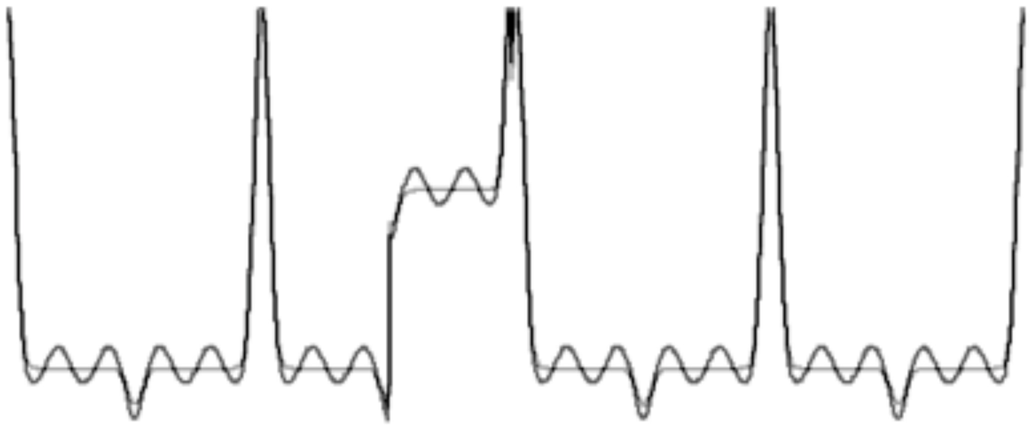


Correlated Double Sampling readout (CDS)

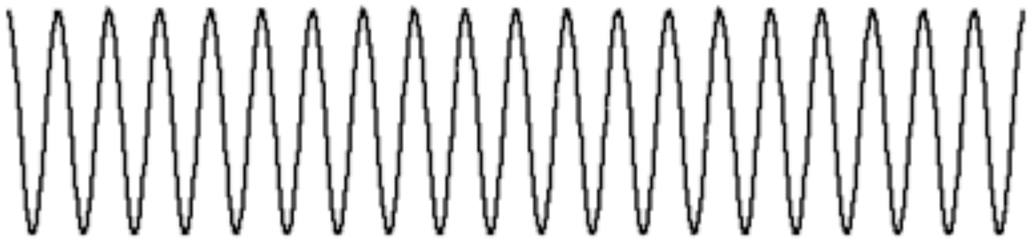


$$s_j^{cds} = \int_{t_j+\epsilon}^{t_j+\delta+\epsilon} [n(t) + \hat{s}_j]\mathrm{d}t - \int_{t_j}^{t_j+\delta} n(t)\mathrm{d}t.$$

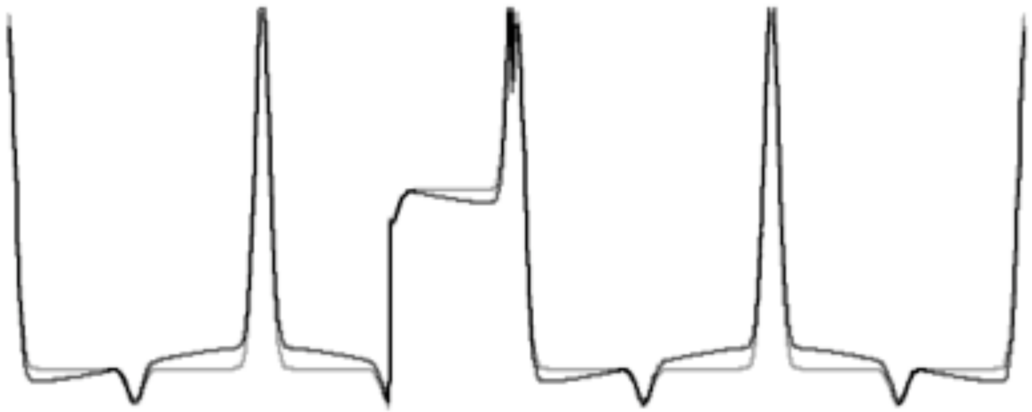
filtering of high frequencies is responsible for reduction with integration time



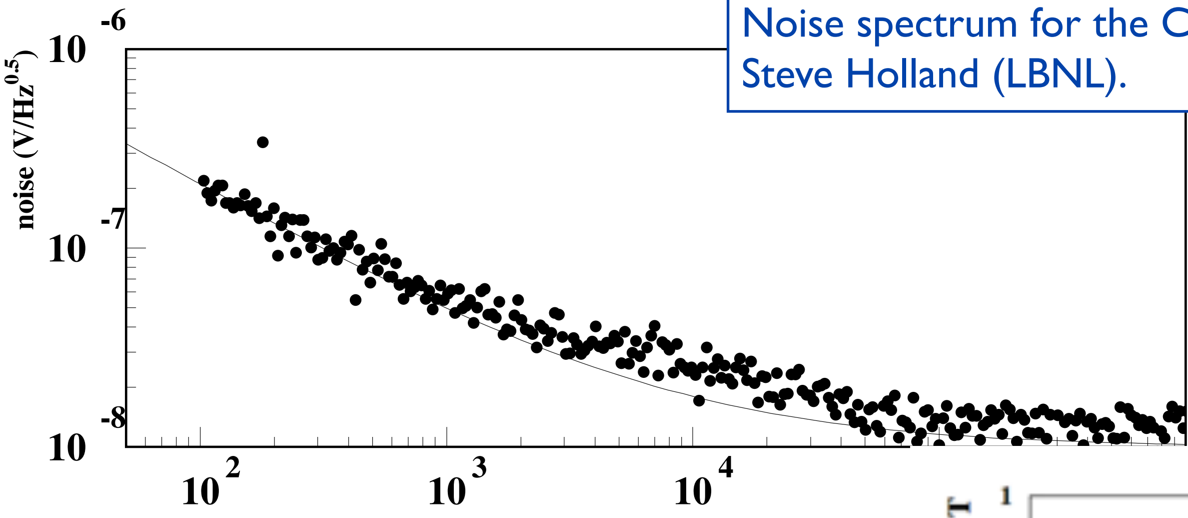
this "high frequency" noise is efficiently suppressed by the integrations for each window in the correlated double sampling.



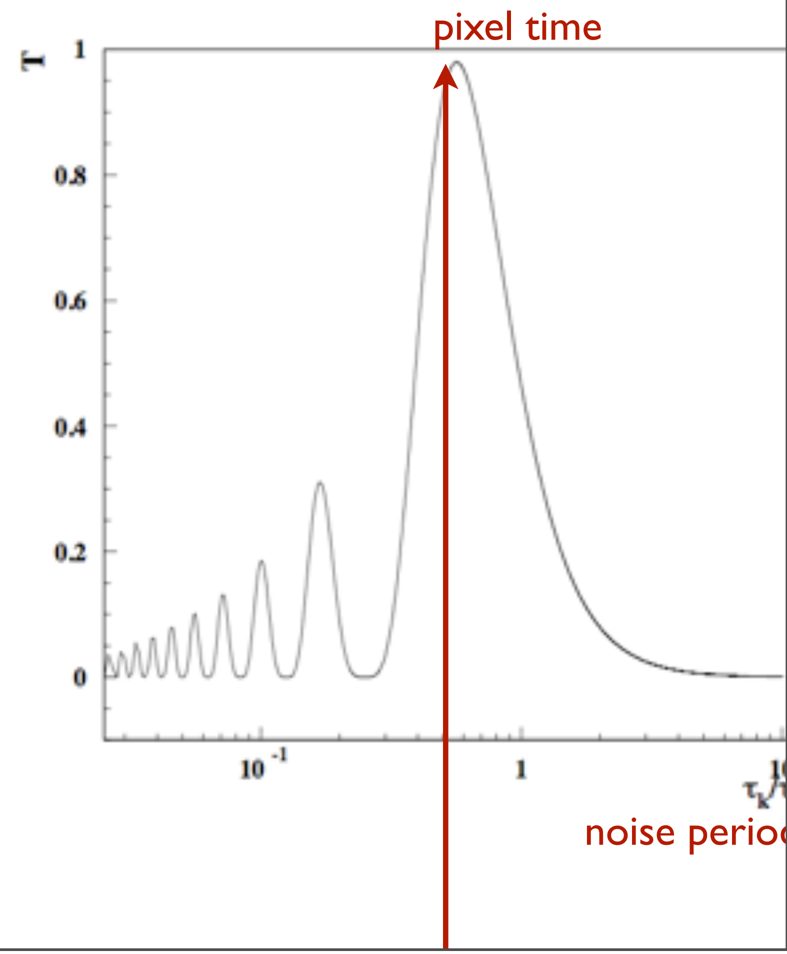
noise at pixel frequency is not suppressed by CDS



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.

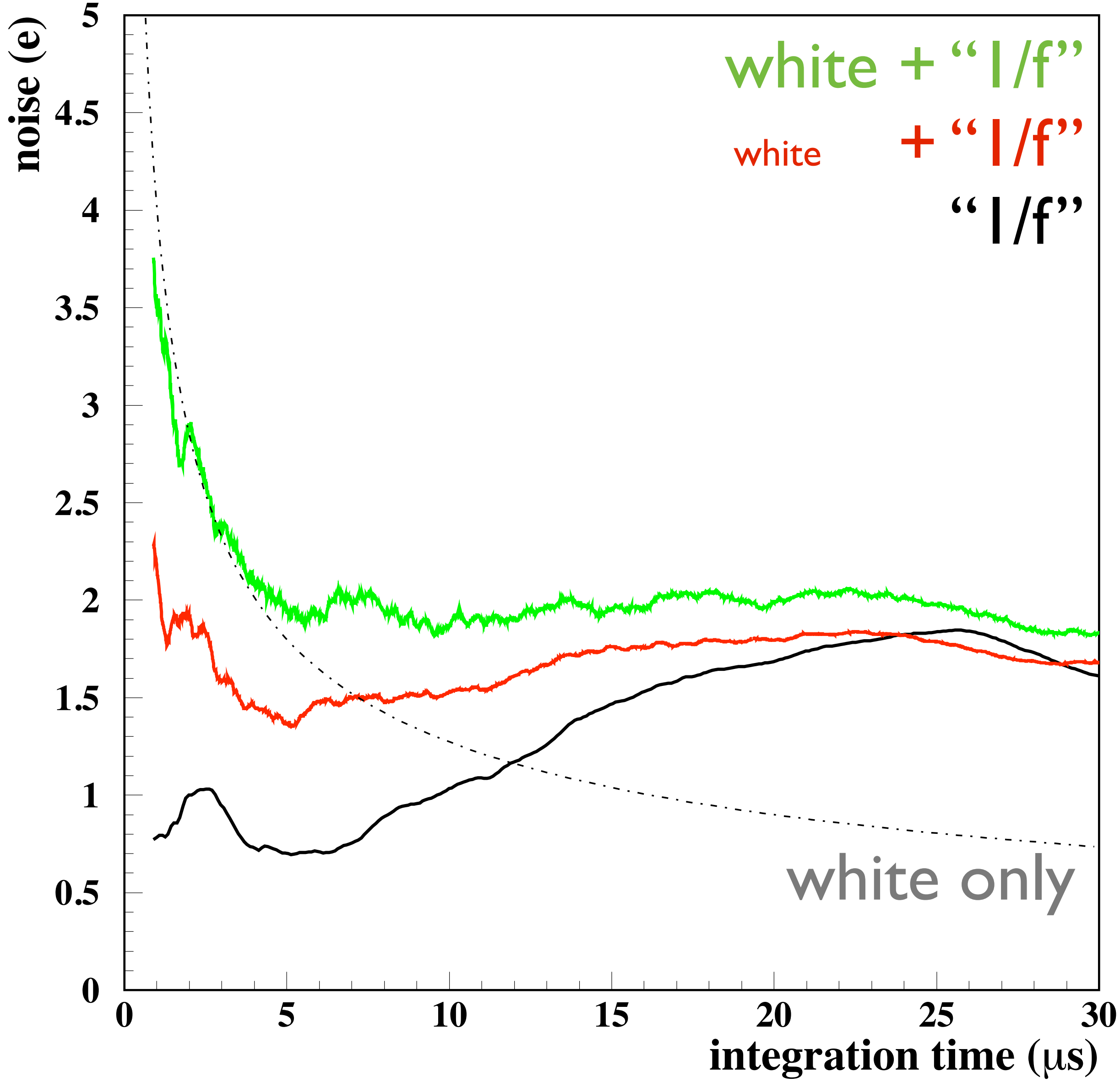


Noise spectrum for the CCD output provided by Steve Holland (LBNL).



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



Friday, November 12, 2010

Where?
ctio 4m Blanco

Cerro Tololo, Chile

Cerro Tololo, Chile

Cerro Tololo, Chile

Cerro Tololo, Chile

Tall mountain in a dry location, in the middle of nowhere.
(it is actually a very nice place and excellent for Astronomy)

Cerro Tololo, Chile

Tall mountain in a dry location, in the middle of nowhere.
(it is actually a very nice place and excellent for Astronomy)