Astronomical Imaging Detectors

Juan Estrada
2/21/2012

Astronomical Imaging Detectors

(mostly optical... and mostly CCDs)

Juan Estrada
2/21/2012

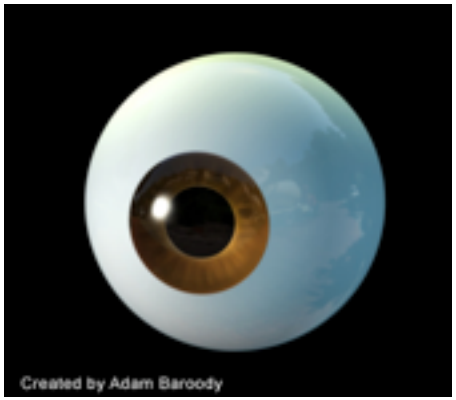
first thing you should know when thinking about detectors to look into space

the sky is mostly dark!

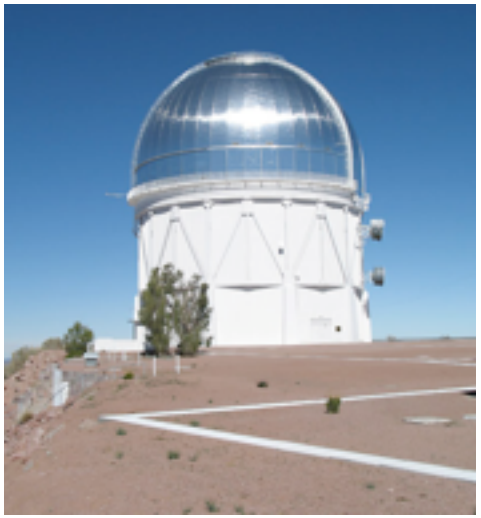

... but with the right detector it can be fun!

To give you an idea:

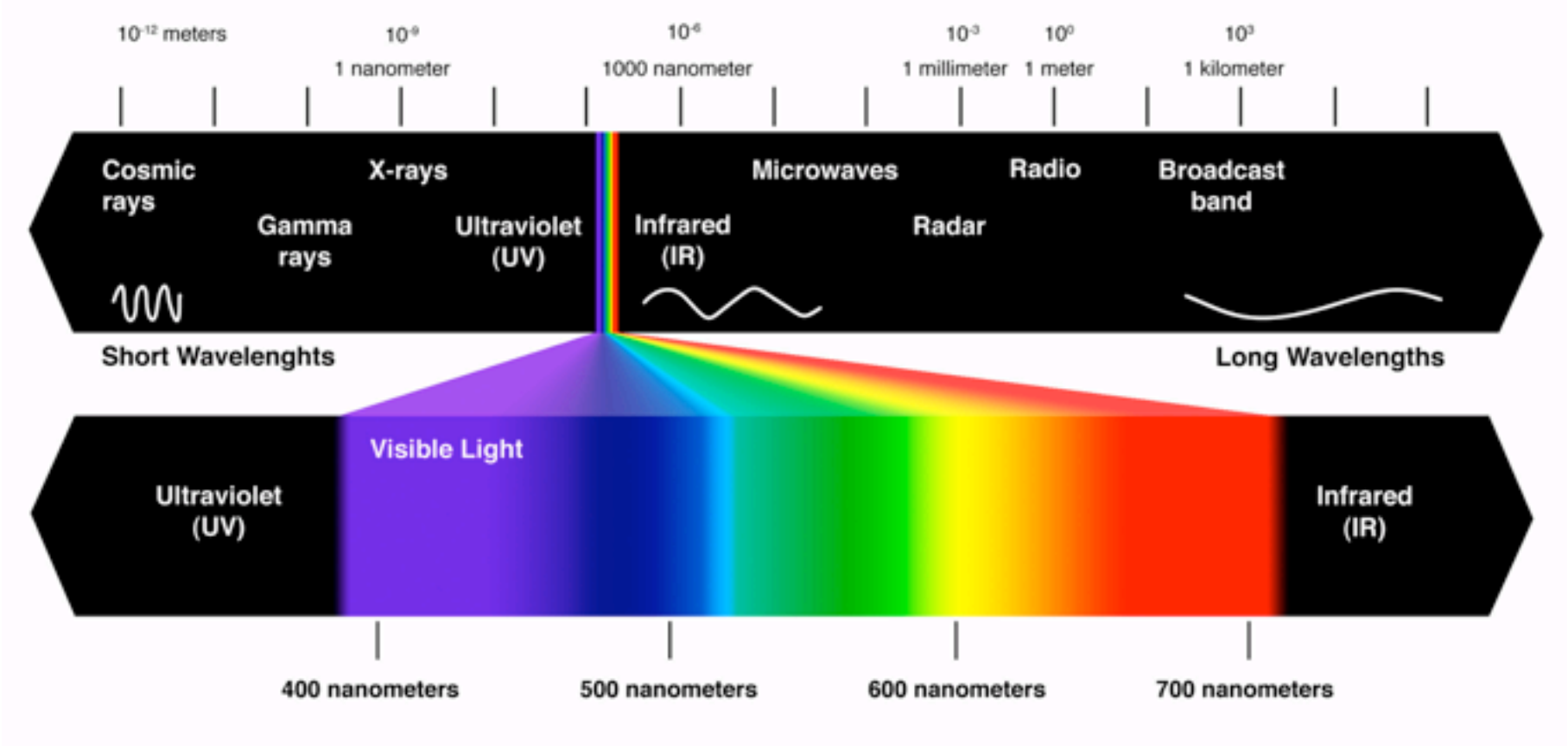
Naked eye can see stars of magnitude 6 which means about 1000 photons per second.



modern astronomical instruments
we are trying to see objects in the sky of magnitude 24, which means about 15 photons per second on a 4 meter telescope (for your eye this would be 5e-5 photons per second).



which brings me to another important point for detectors in astronomy... timescale = seconds (not nanoseconds).



What are the options for visible and IR?
Mainly CMOS and CCDs... will go over CCDs and then discuss the difference with CMOS

6 steps of optical / IR photon detection

Anti-reflection coating
Substrate removal

1. Light into detector

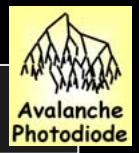
Detector Materials
Si, HgCdTe, InSb, Si:As

2. Charge Generation

Quantum Efficiency

Electric Fields in detector collect electrical charge

3. Charge Collection



Point Spread Function

CCD

Charge coupled transfer

4. Charge Transfer

MOSFET Amplifier

5. Charge-to-Voltage Conversion

CMOS

4. Charge-to-Voltage Conversion

Source follower, CTIA, DI

5. Signal Transfer

Random access or full frame read

6. Digitization

a few slides from J. Beletic

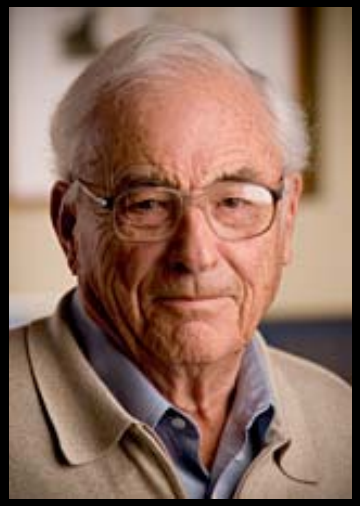
2009 Nobel Prize in Physics awarded to the inventors of the CCD

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

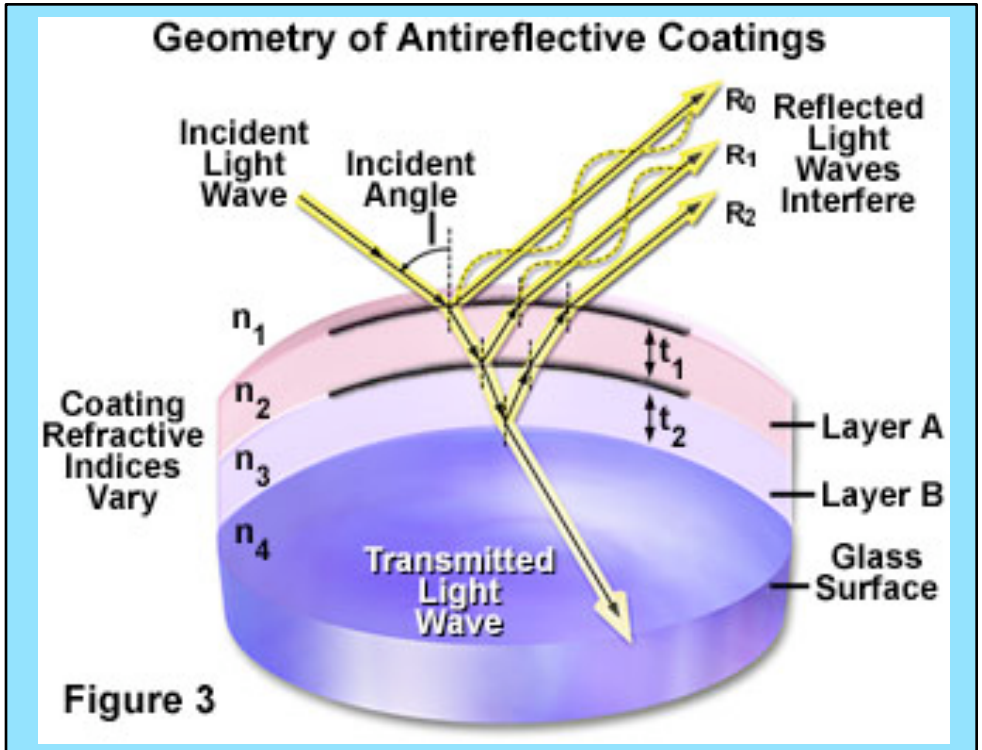
"for the invention of an imaging semiconductor circuit – the CCD sensor"

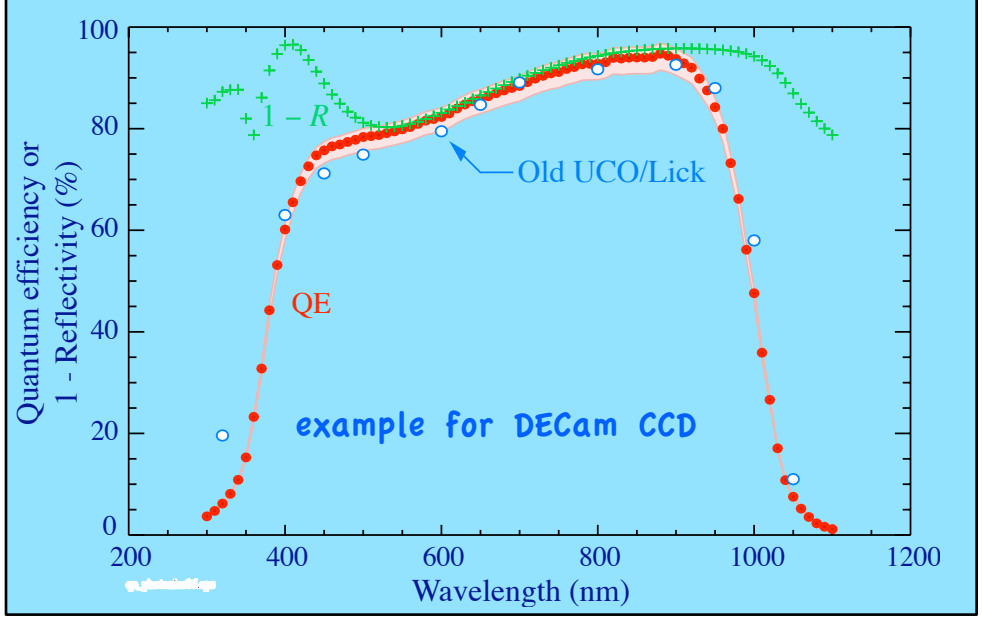


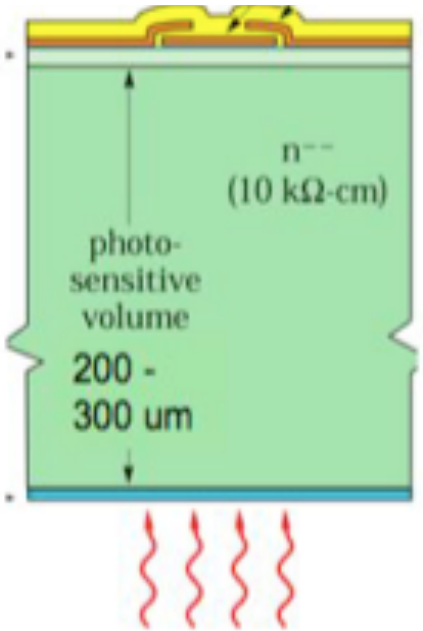
Willard S. Boyle

George E. Smith

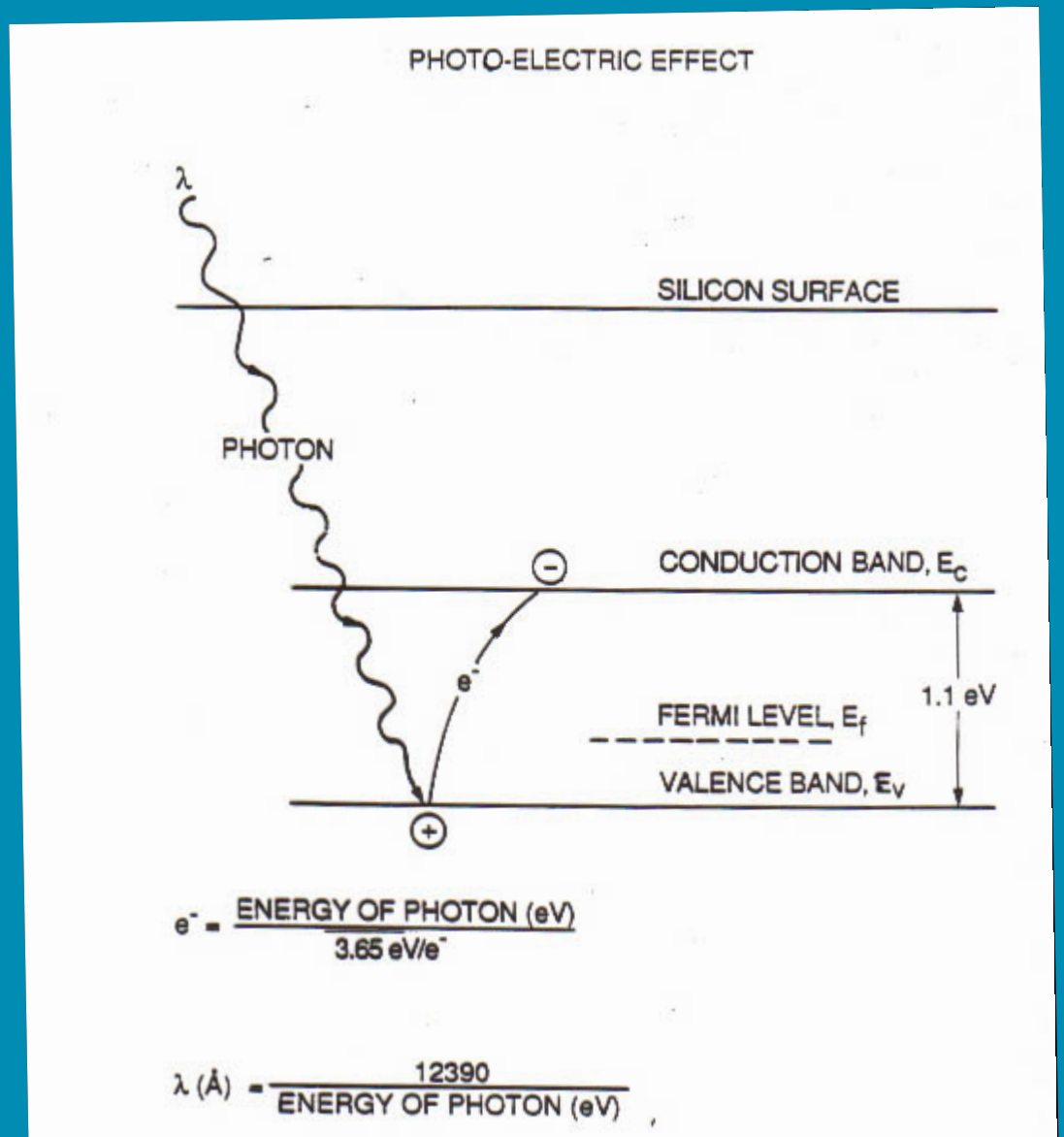
Light into the detector







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



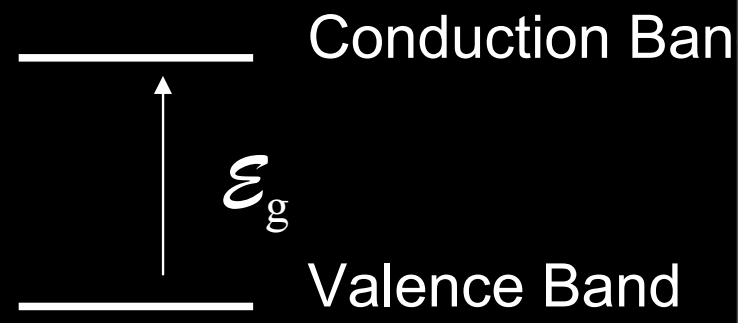
Charge generation

The photoelectric effect makes it possible for photons with more than 1.1eV to produce electron-hole pairs in Silicon.

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

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

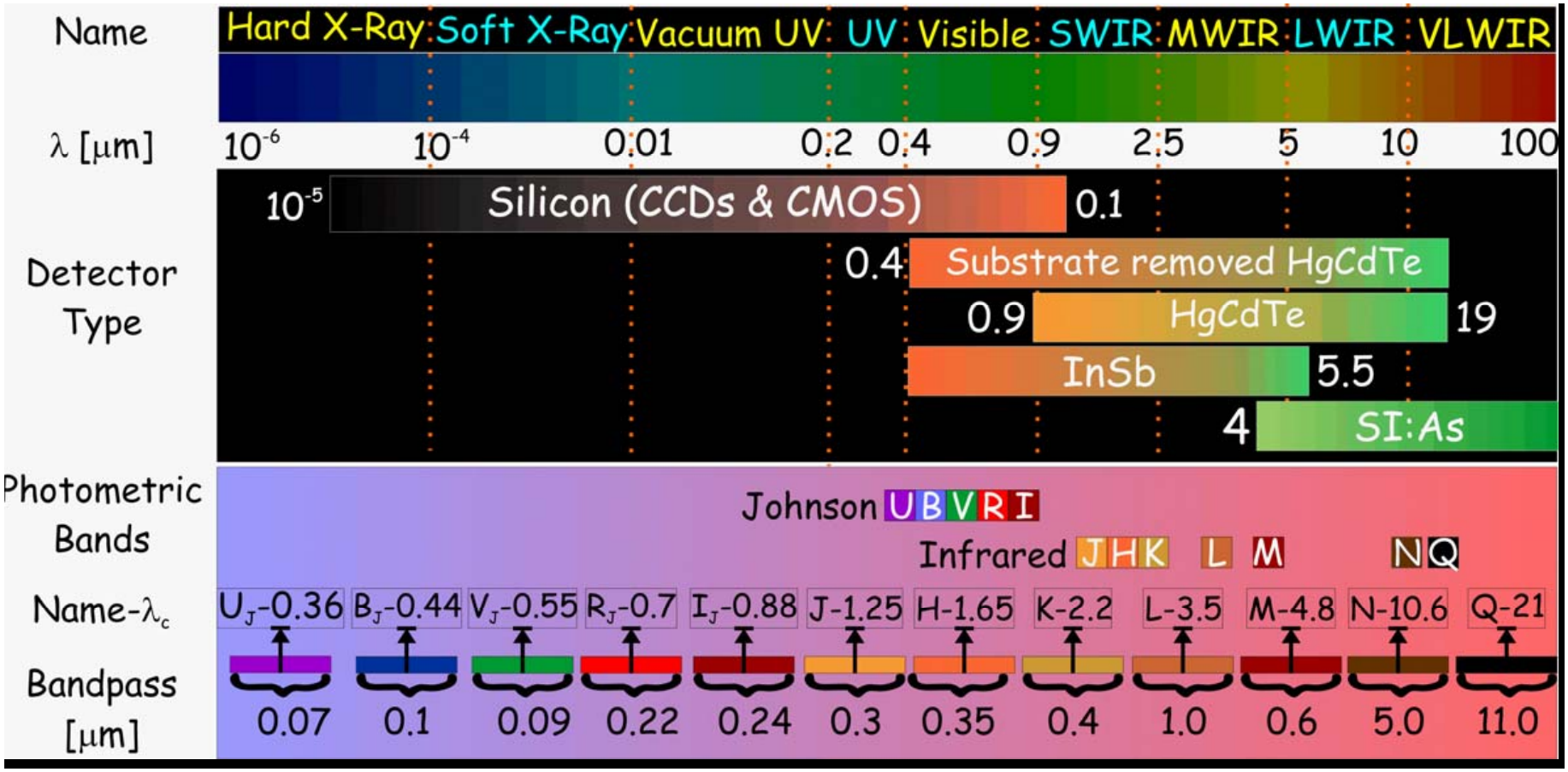
h = Planck constant (6.6310^{-34} Joule•sec)
ν = frequency of light (cycles/sec) = λ/c
$\mathcal{E}_g$ = energy gap of material (electron-volts)



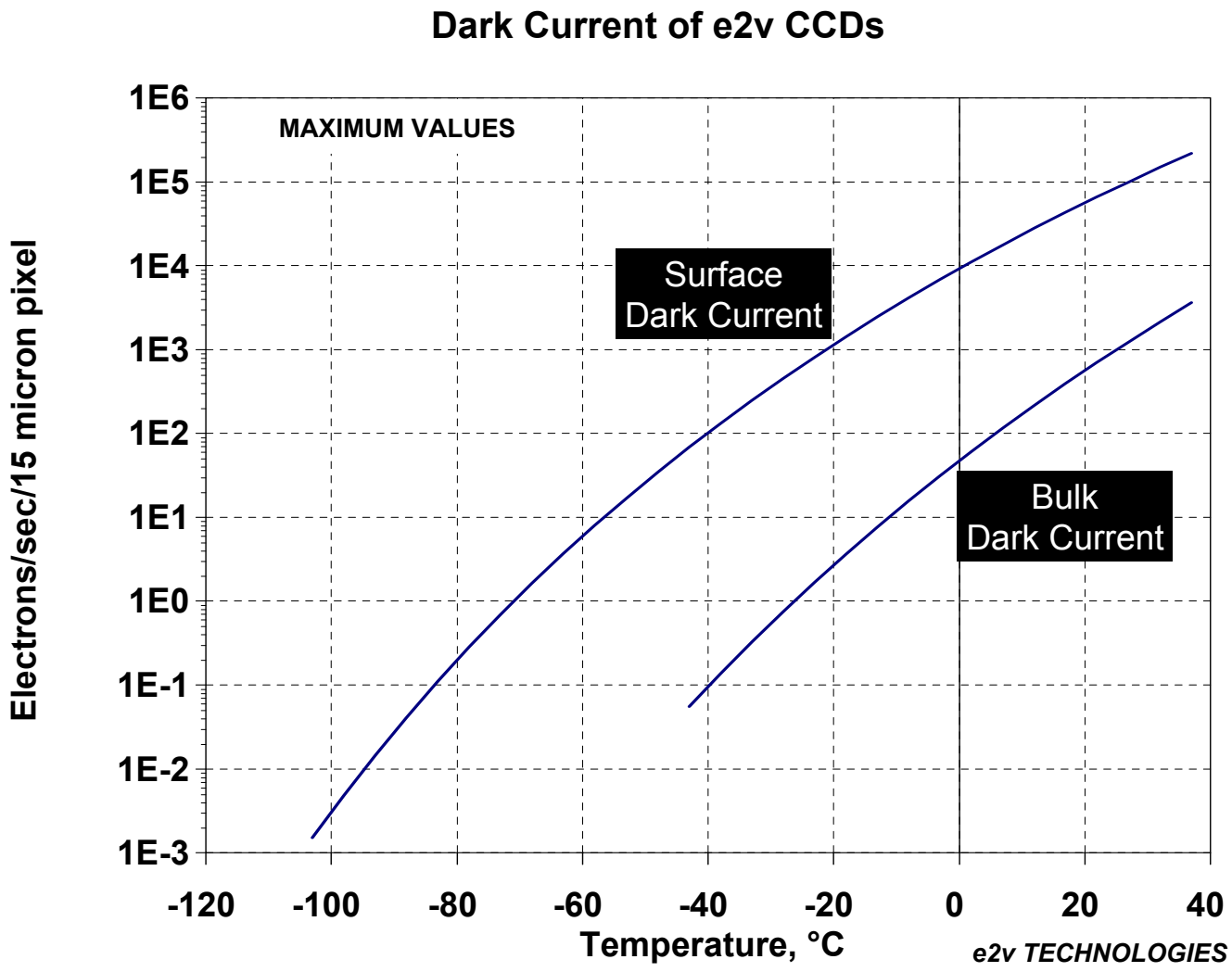
$$\lambda_c = 1.238 / \mathcal{E}_g \text{ (eV)}$$

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 work with the same principle, but with crystals that are a lot more expensive than Silicon

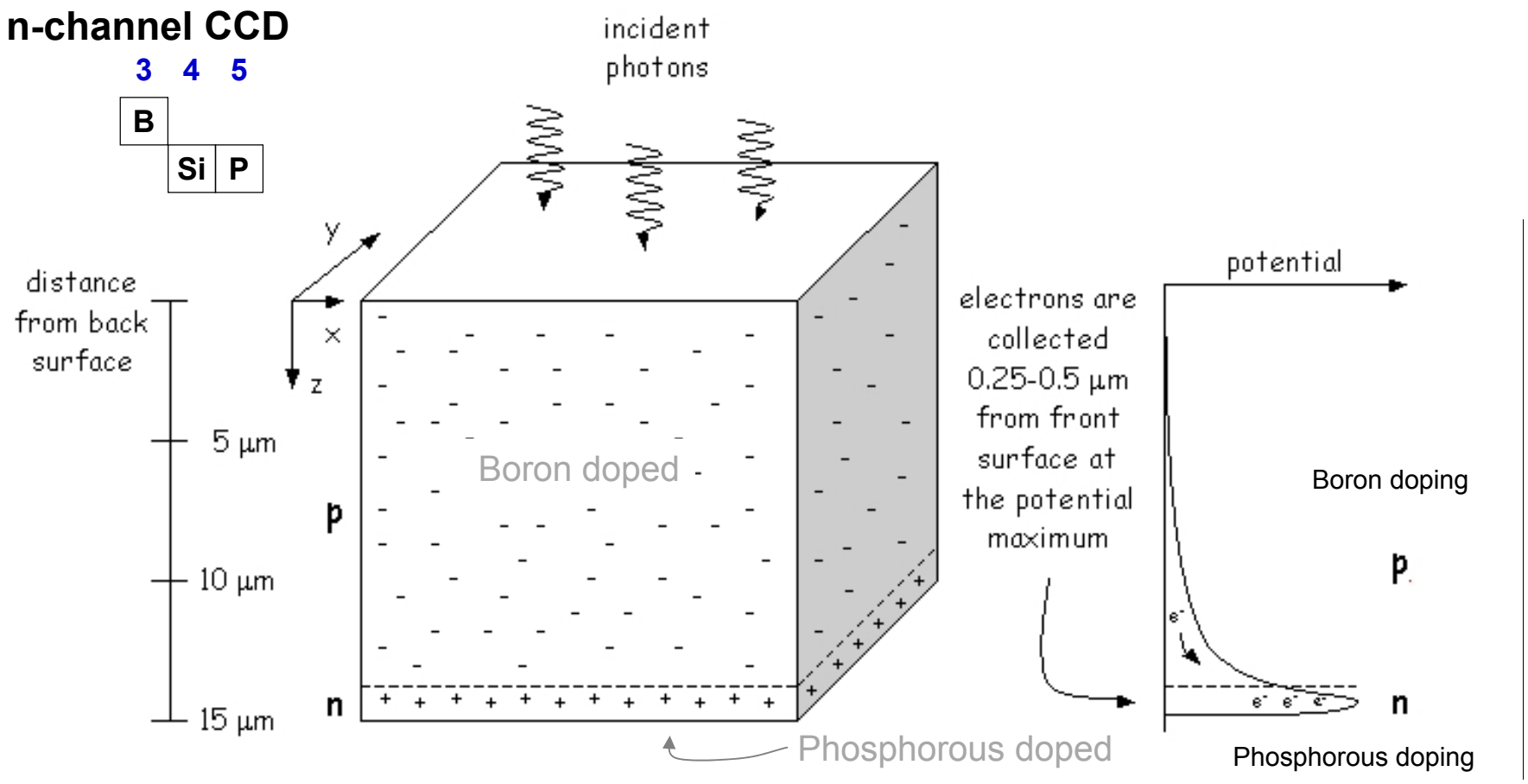

Name
Hard X-Ray
Soft X-Ray
Vacuum UV
UV
Visible
SWIR
MWIR
LWIR
VLWIR
λ [μm]
10-6
10-4
0.01
0.2
0.4
0.9
2.5
5
10
100
Detector Type
10-5
Silicon (CCDs & CMOS)
0.1
0.4
Substrate removed HgCdTe
0.9
HgCdTe
19
InSb
5.5
4
SI:As
Photometric Bands
Johnson U B V R I
Infrared J H K L M N Q
Name-λc
UJ-0.36
BJ-0.44
VJ-0.55
RJ-0.7
IJ-0.88
J-1.25
H-1.65
K-2.2
L-3.5
M-4.8
N-10.6
Q-21
Bandpass [μm]
0.07
0.1
0.09
0.22
0.24
0.3
0.35
0.4
1.0
0.6
5.0
11.0

charge generation of the unwanted type



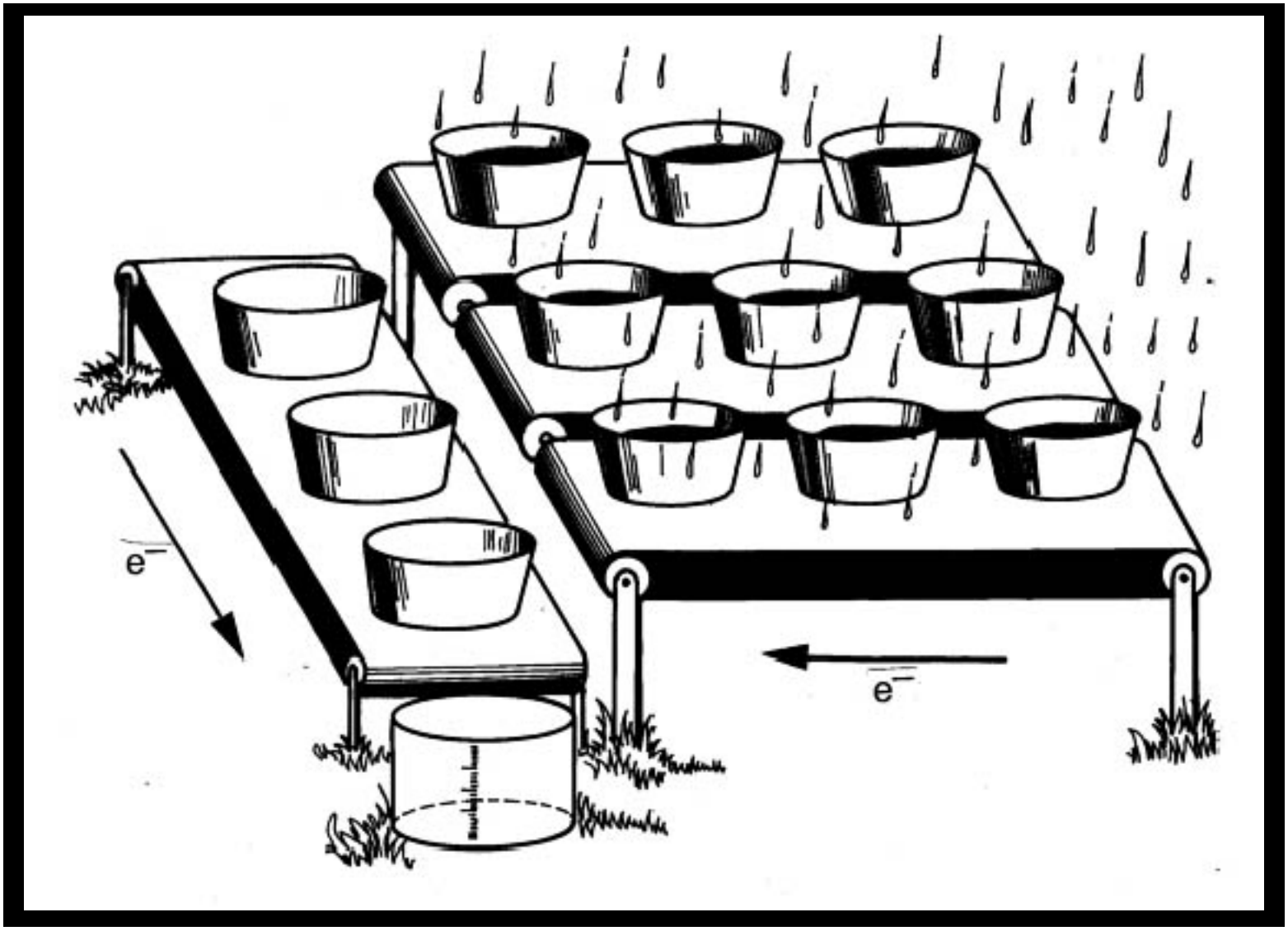
so you will usually have to cool the detectors...

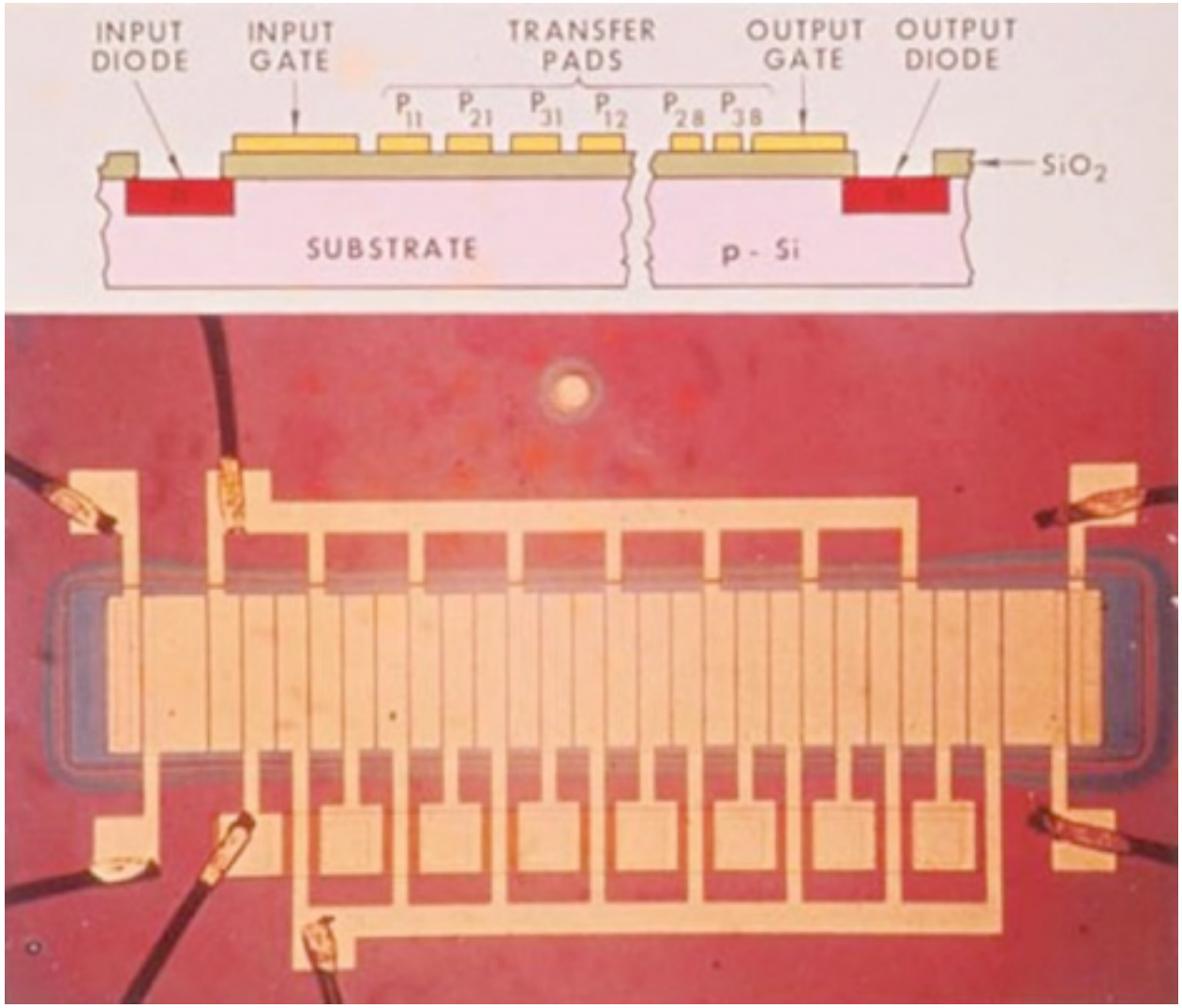
Charge Collection



By doping the Si we get a E field that moves the charges from the generation site to the potential well.

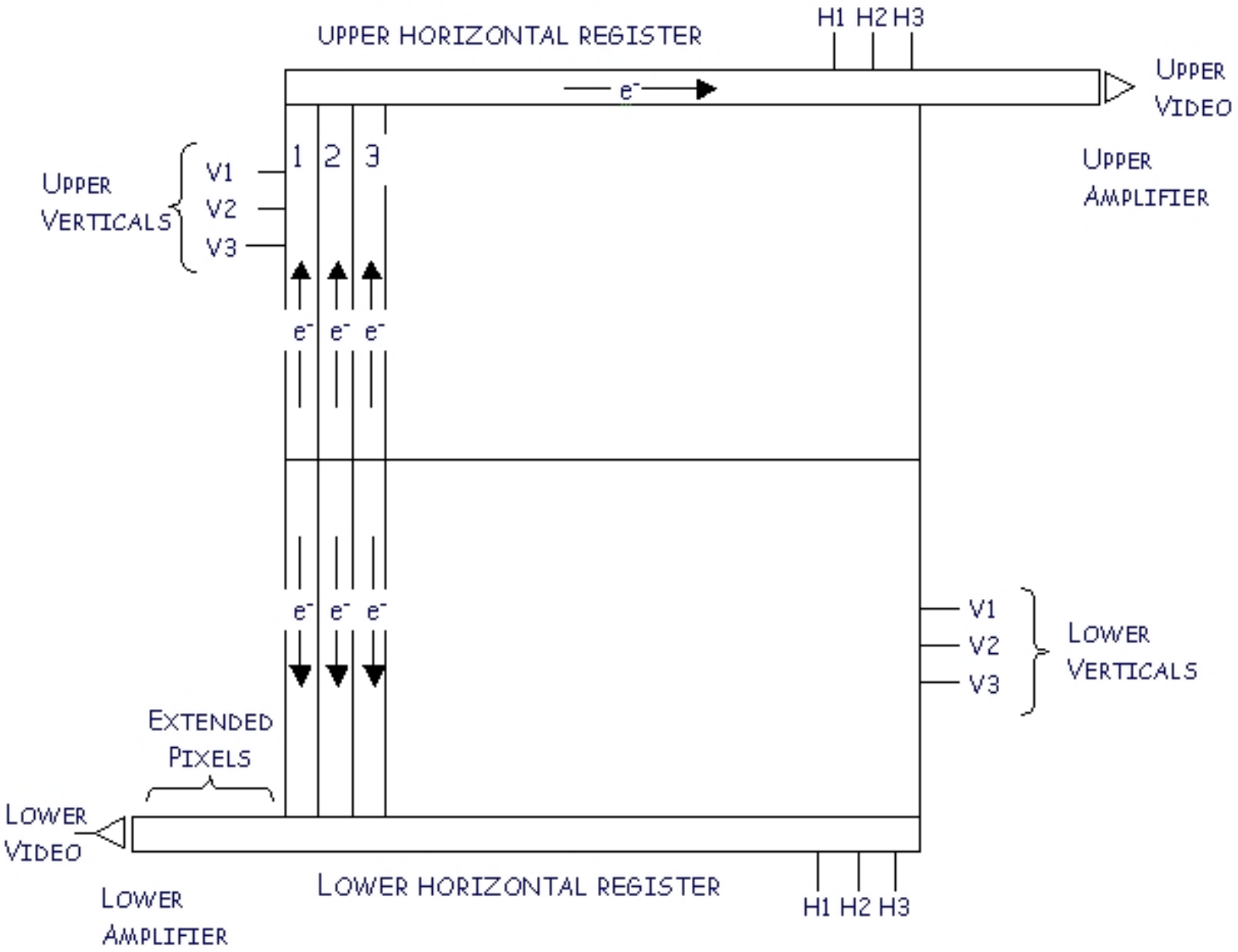
Charge Transfer in a CCD

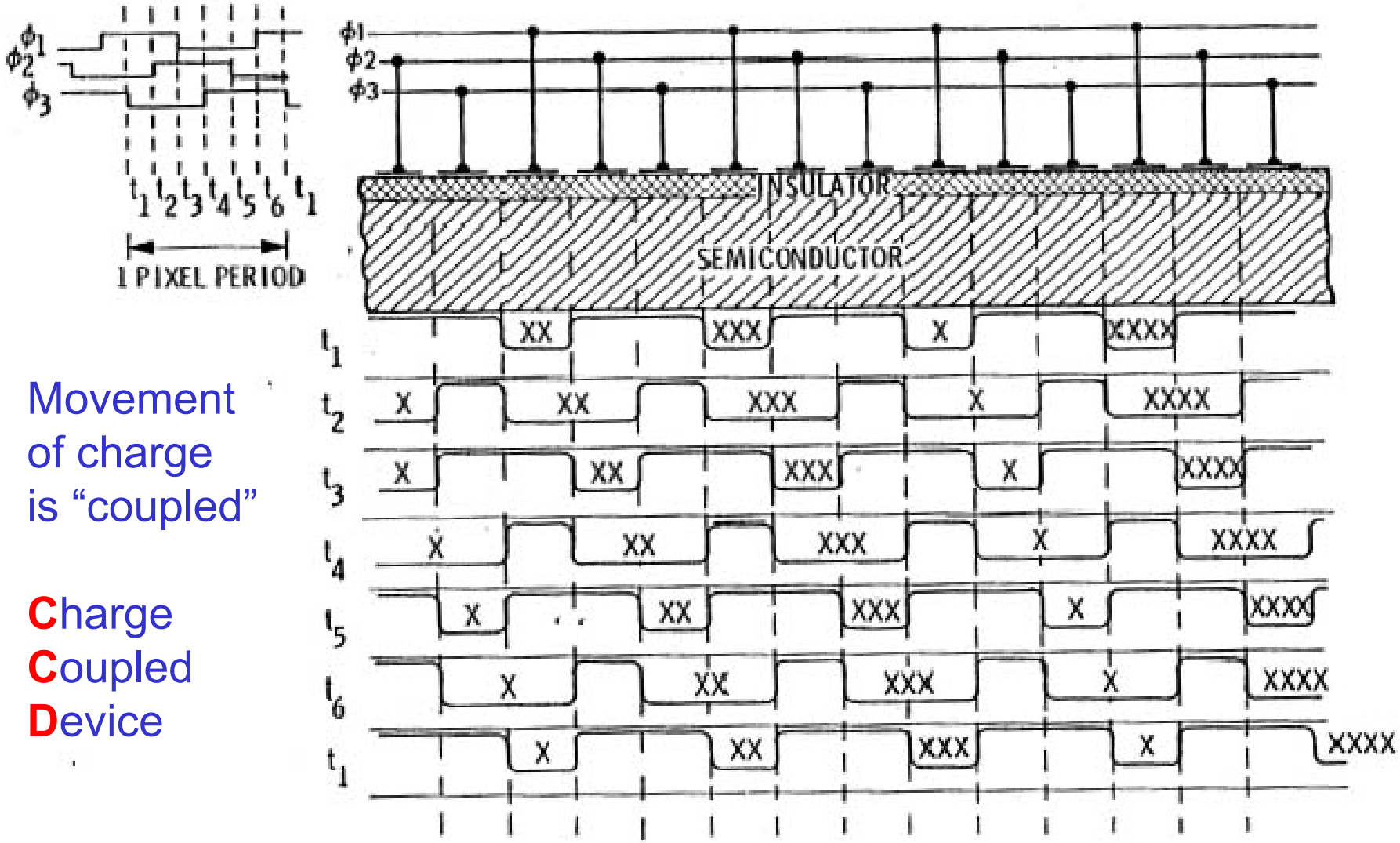



INPUT DIODE
INPUT GATE
TRANSFER PADS
OUTPUT GATE
OUTPUT DIODE
P_{11} P_{21} P_{31} P_{12} P_{28} P_{38}
SiO_2
SUBSTRATE
p - Si

First CCD

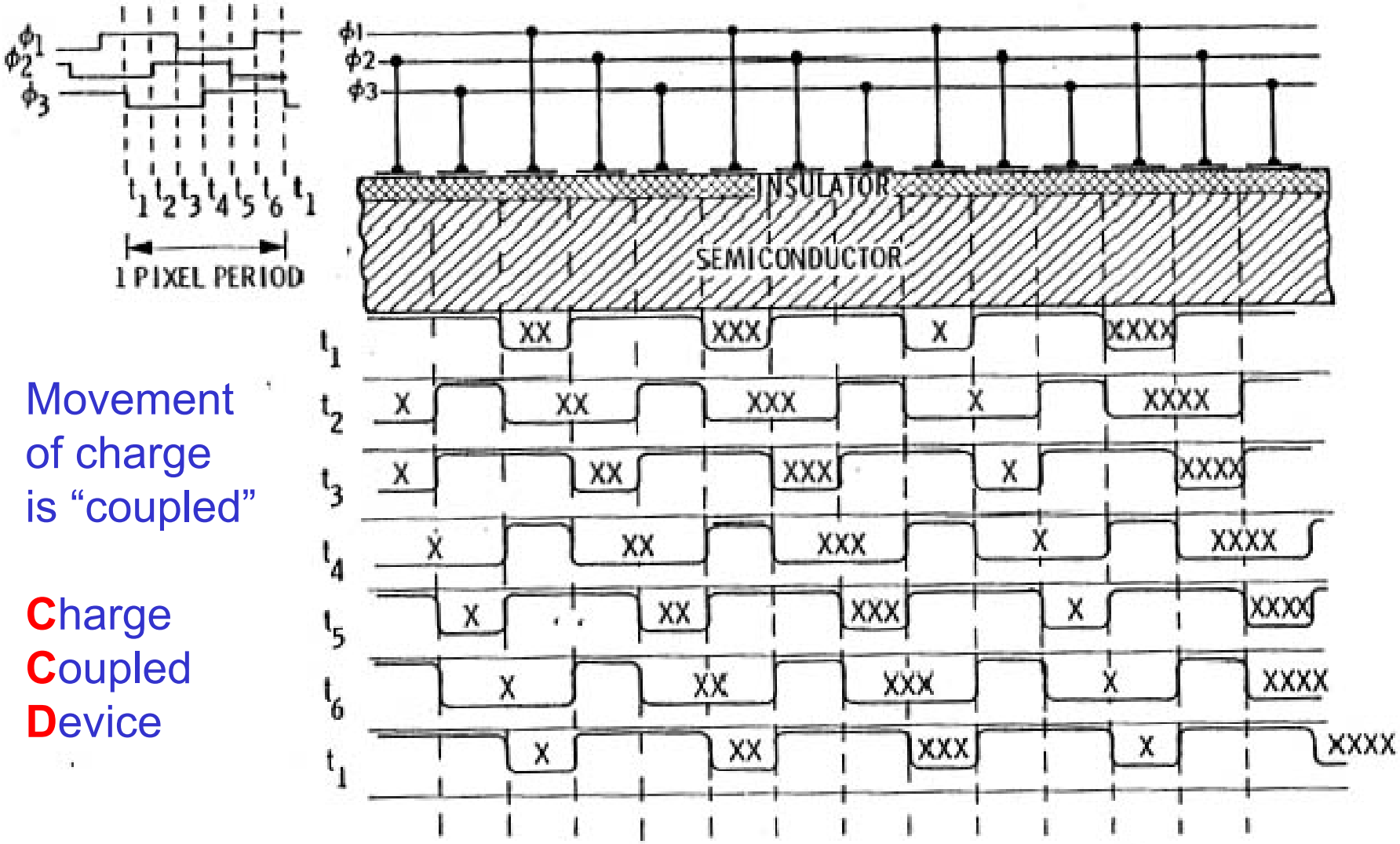
Charge Transfer: CCD architecture





Movement of charge is "coupled"

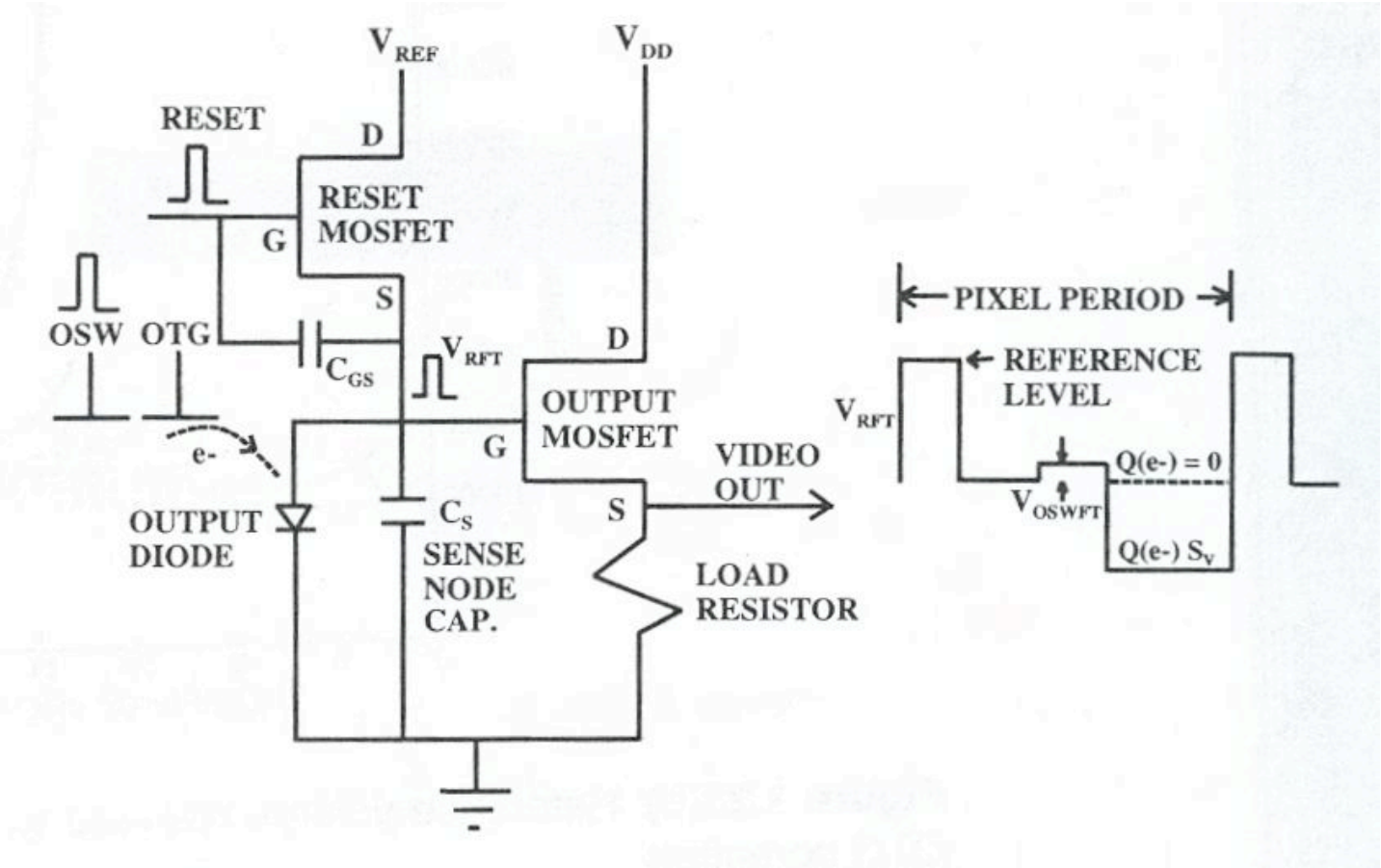
Charge
Coupled
Device



Movement of charge is "coupled"

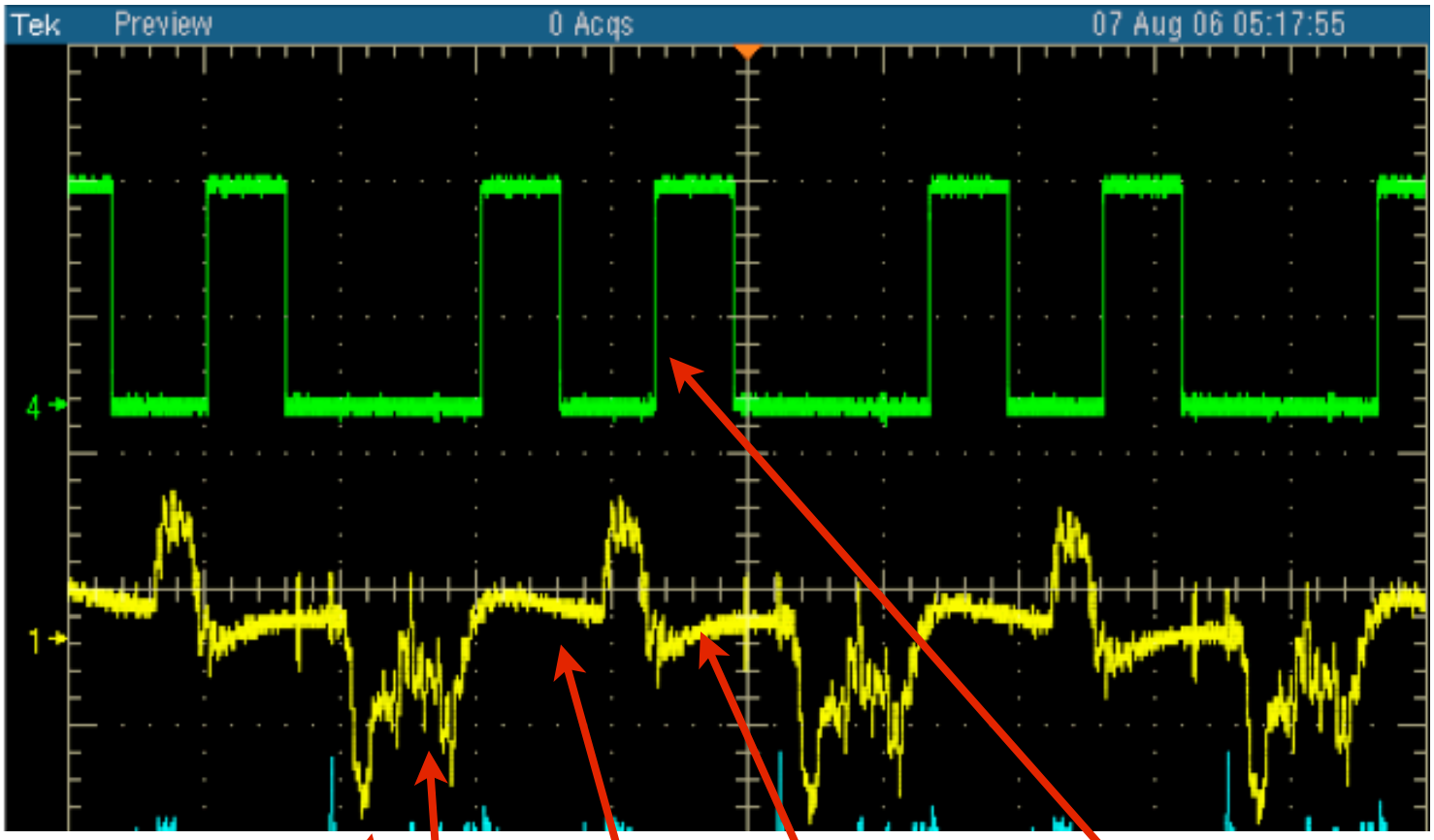
Charge
Coupled
Device

Charge Measurement



Reset the output to a known level, sample this level, dump the charge into the sense node and check the level again

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



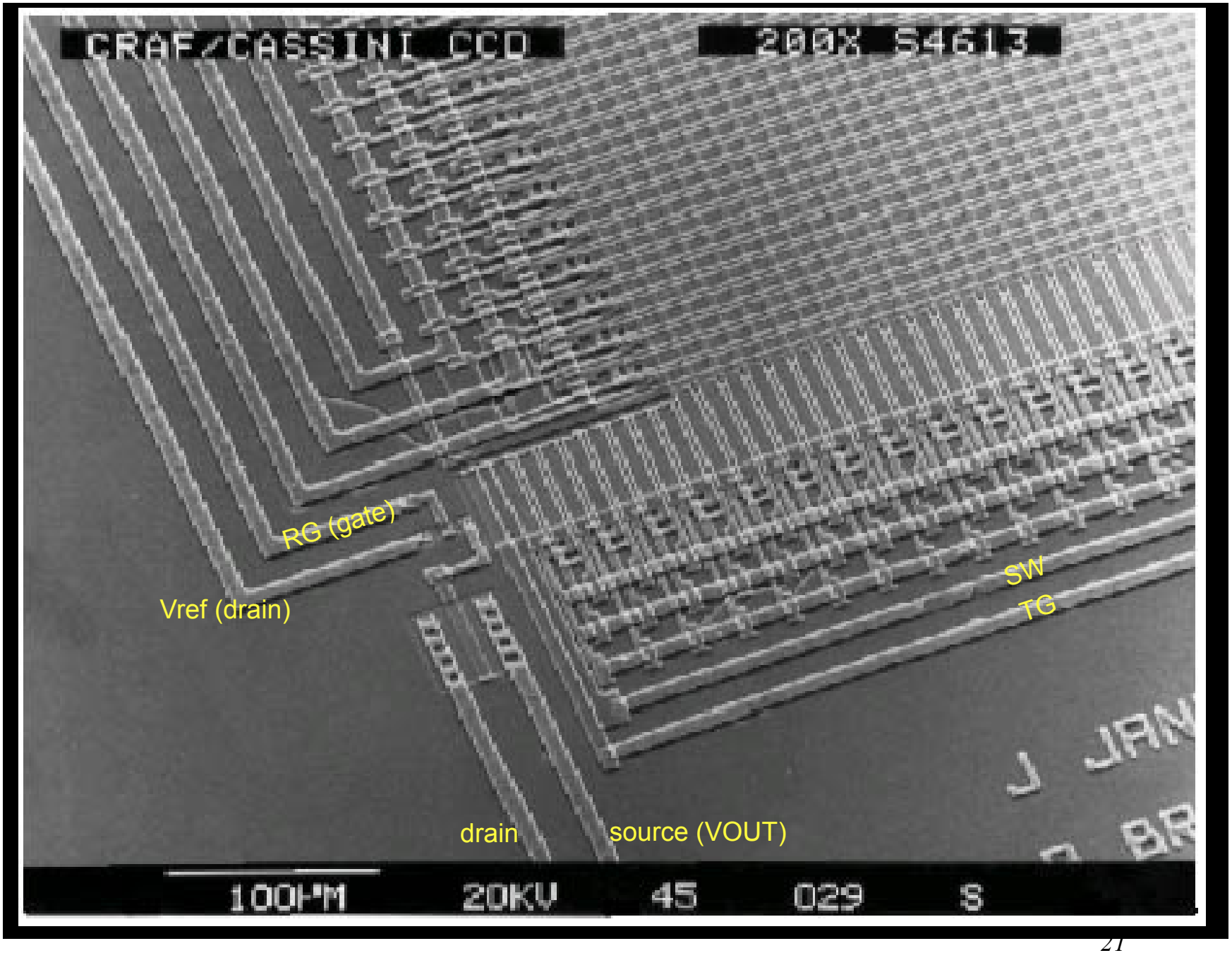
RST

Charge transfer

reference

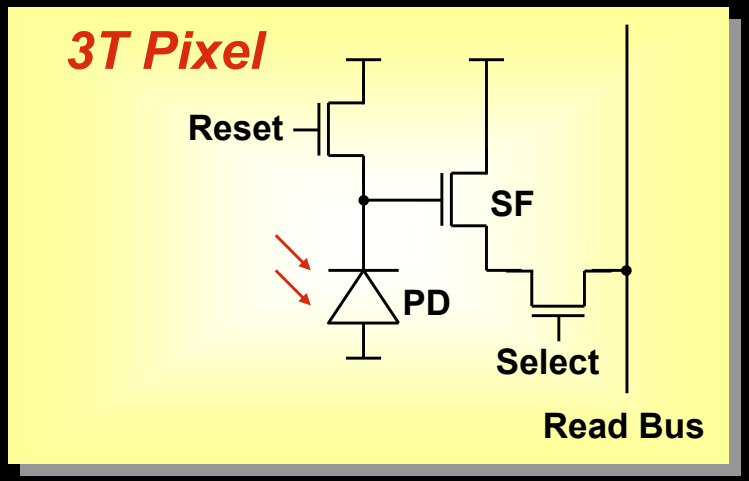
signal

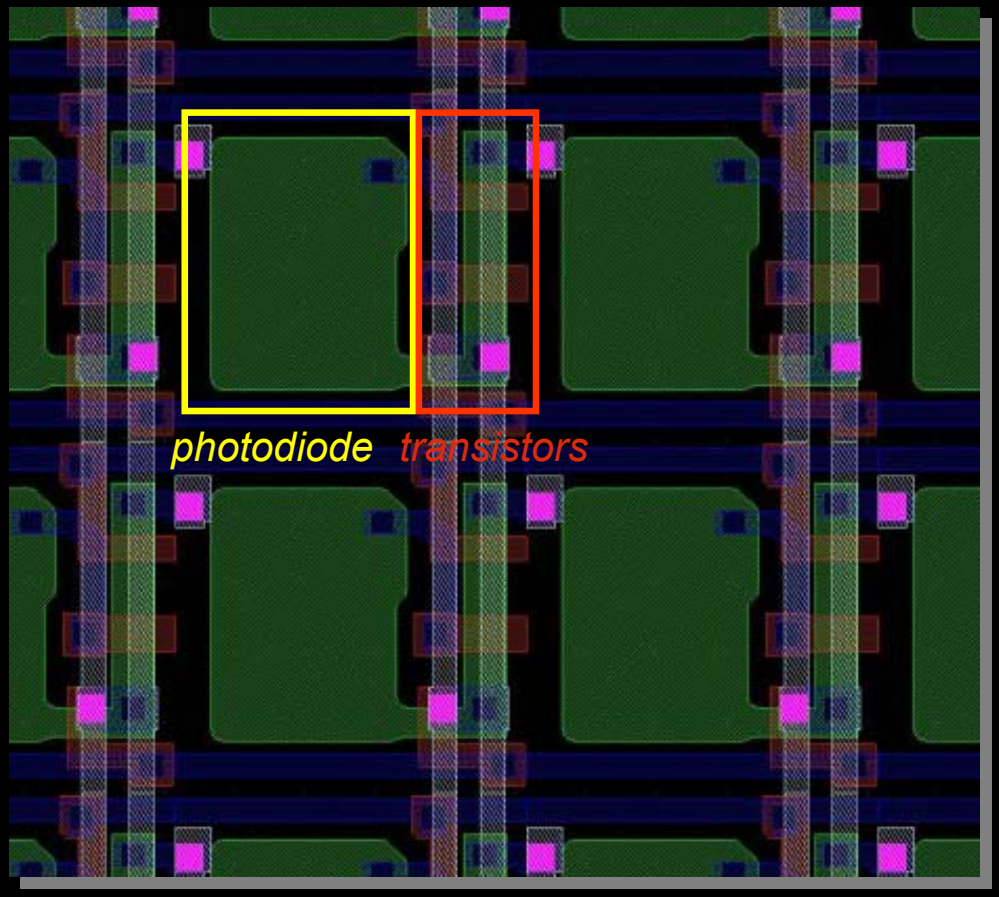
two integration windows per pixel


CRAF/CASSINI CCD
200X S46 13
RG (gate)
Vref (drain)
SW
TG
drain
source (VOUT)
100µM
20KV
45
029
S

Alternative to CCDs : Monolithic CMOS

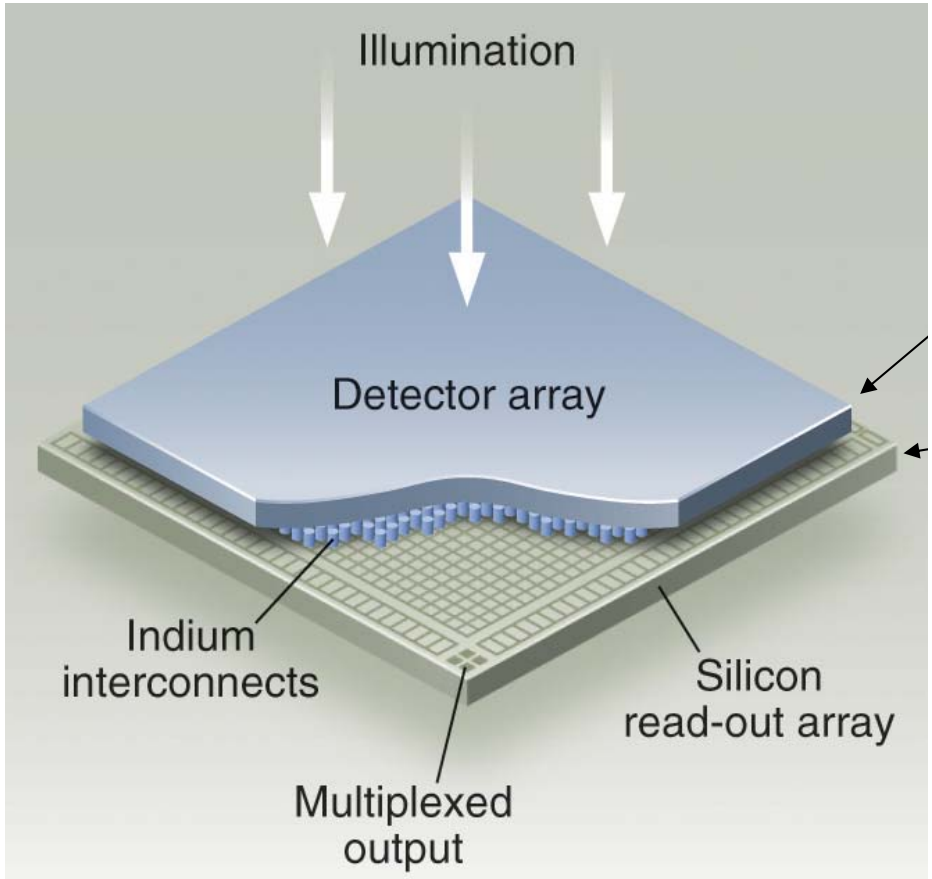
- **A monolithic CMOS image sensor combines the photodiode and the readout circuitry in one piece of silicon**
  - **Photodiode and transistors share the area => less than 100% fill factor**
  - **Small pixels and large arrays can be produced at low cost => consumer applications (digital cameras, cell phones, etc.)**

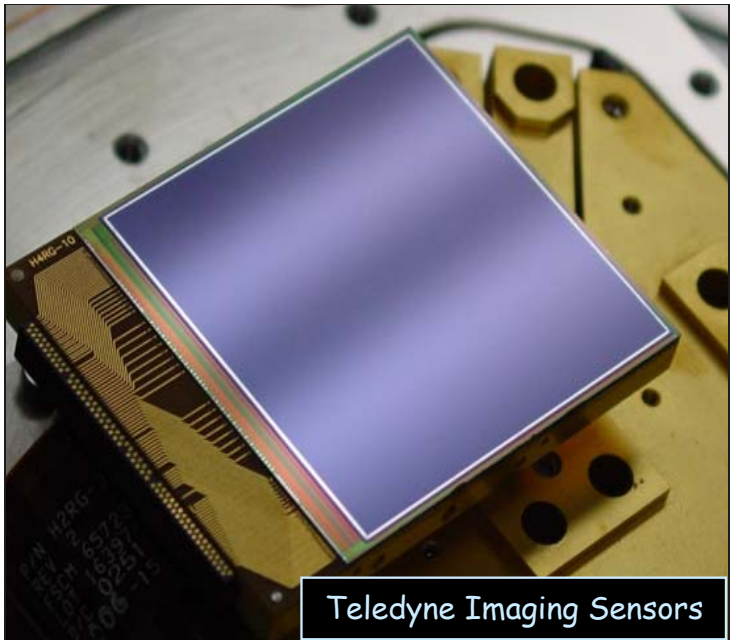




Micro lenses can be used to improve fill factor. Not yet achieving the noise performance of CCDs.

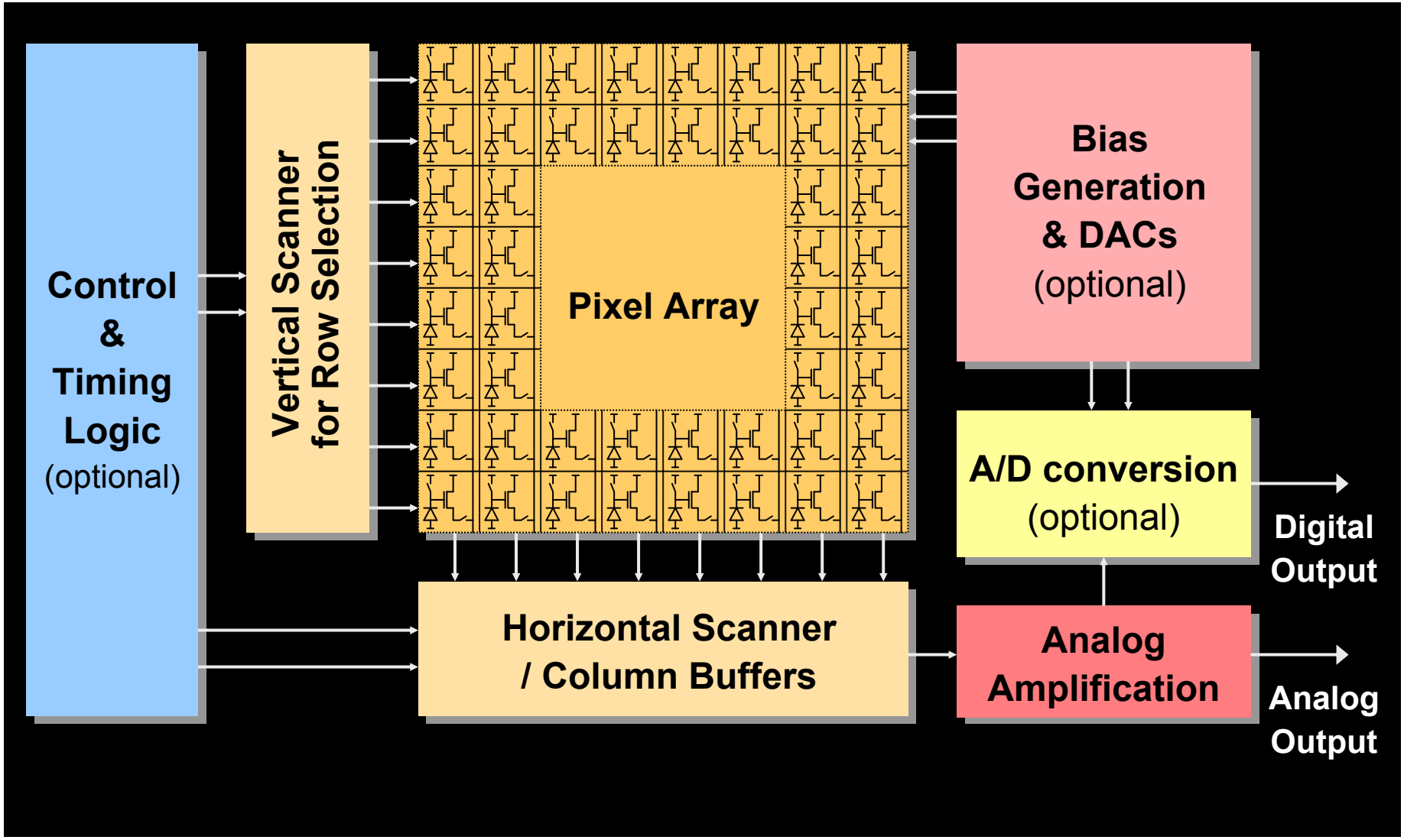
HYBRID CMOS



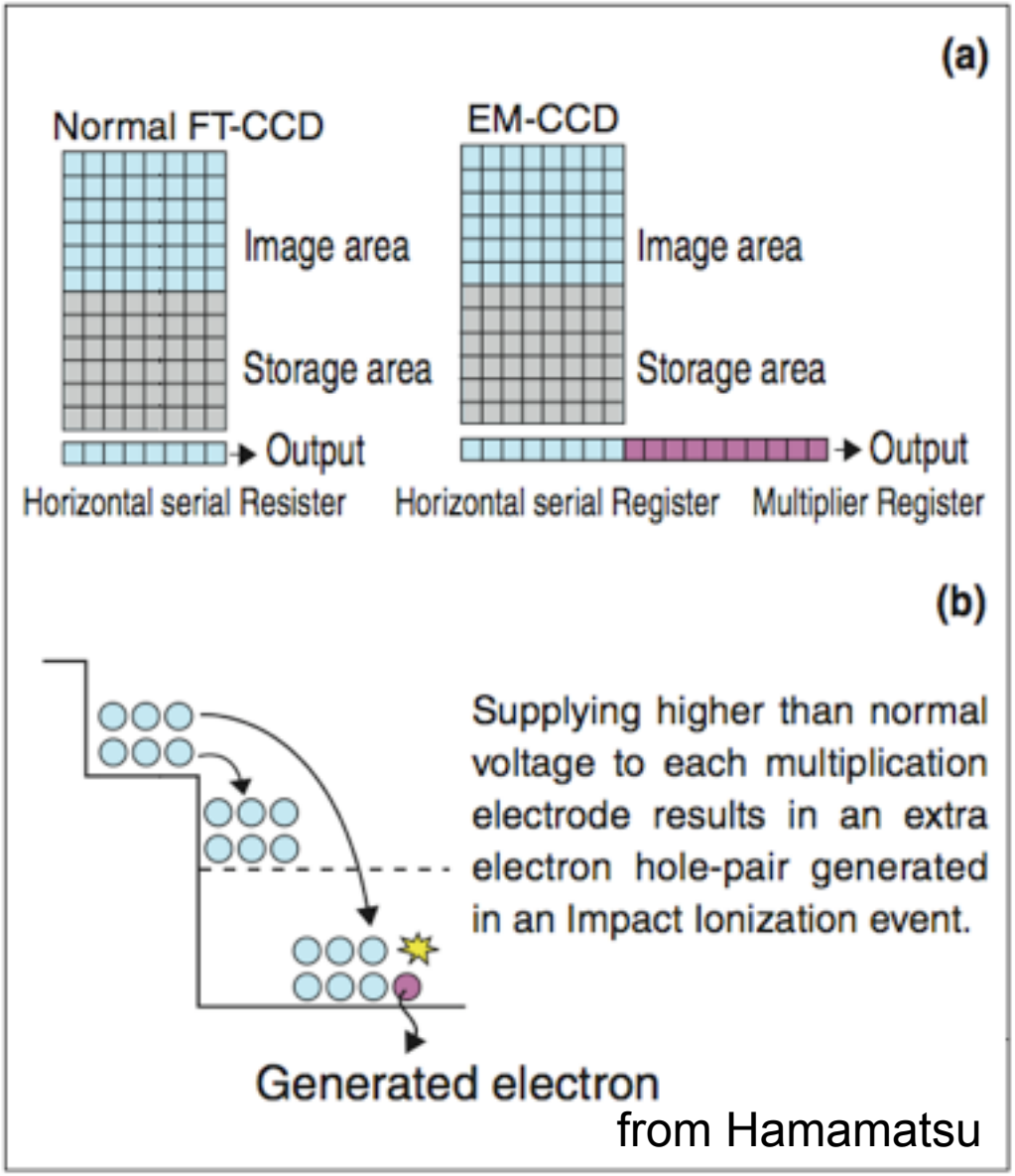


many applications in IR astronomy. Detectors are not Silicon anymore, readout array is still silicon.

The charge does not move on CMOS sensors.
They have random access readout for all channels.



EMCCDs : CCDs with charge multiplication



from Hamamatsu

This is still very new.

Gain of 10-1000 are possible. In principle it allows for photon counting, which is very nice.

At large signals, the gain fluctuations become larger than the poisson noise, so the S/N drops compared to normal CCDs.

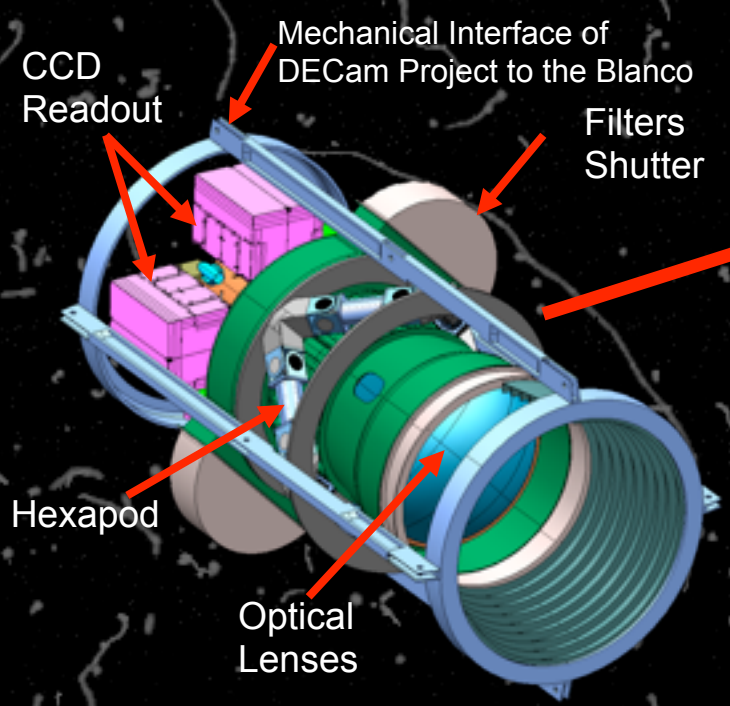
Allows for frame rates of 1 kHz readout.

Recently people have reported some aging effects on the gain.

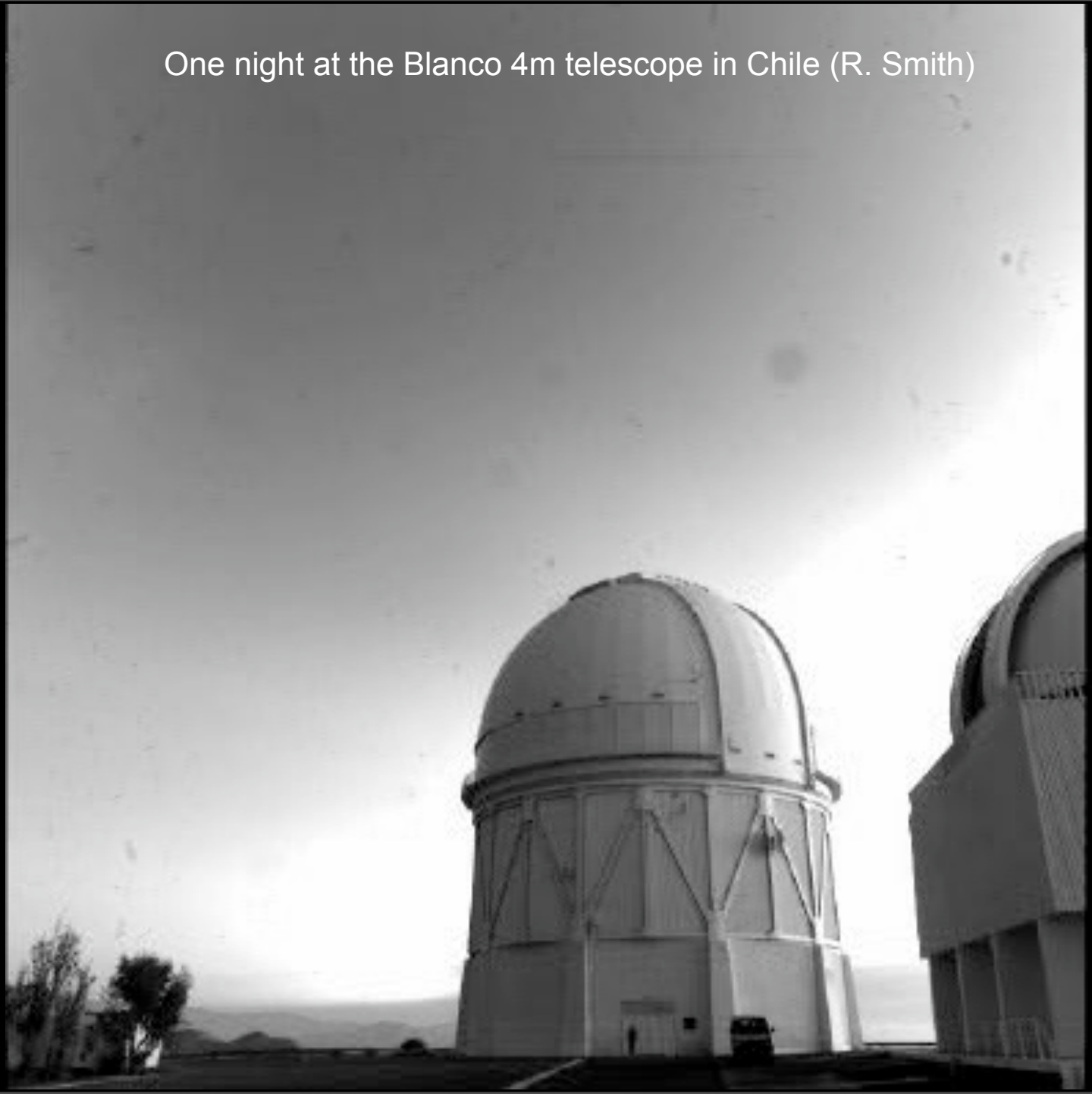
for the moment small lucky imaging

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.

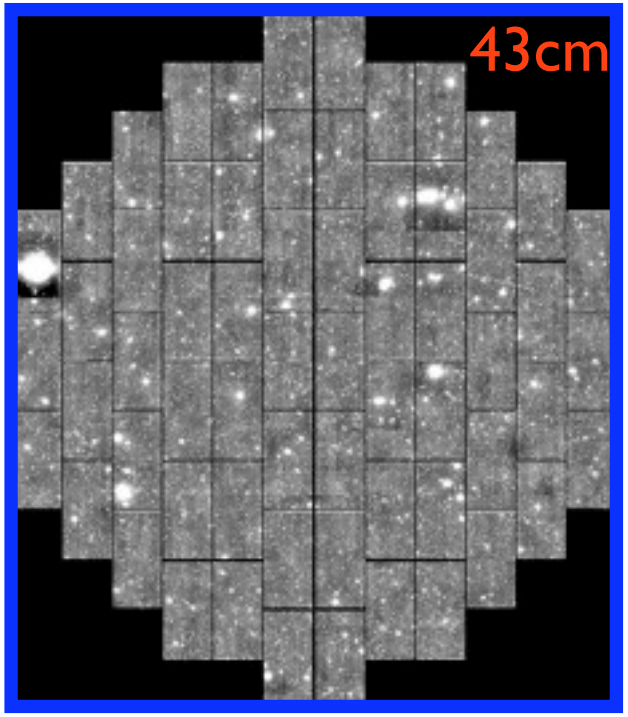


One night at the Blanco 4m telescope in Chile (R. Smith)

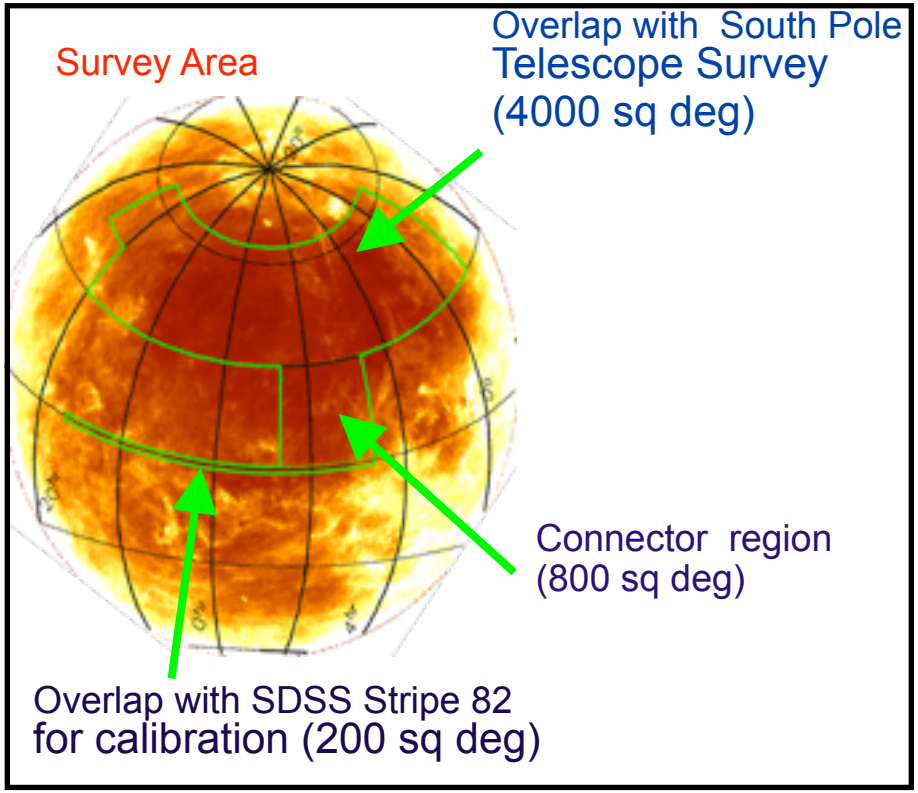

One night at the Blanco 4m telescope in Chile (R. Smith)

replace this (mosaicII)

with this (DECam)



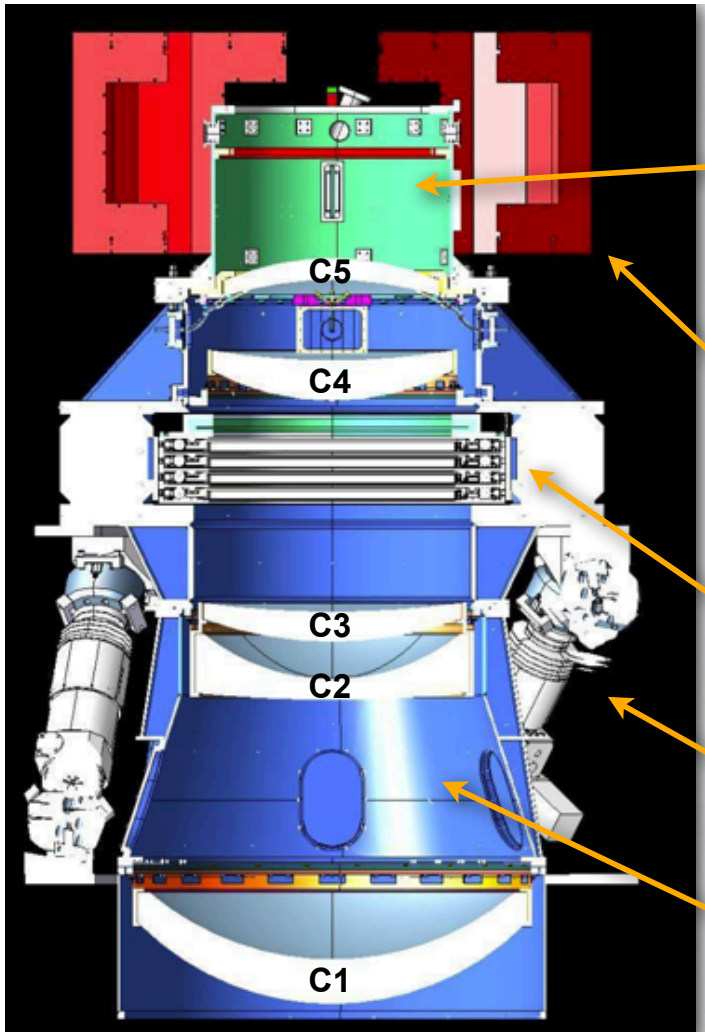
...and do this (DES)



<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



CCD focal plane is housed in a vacuum vessel (**the imager**)

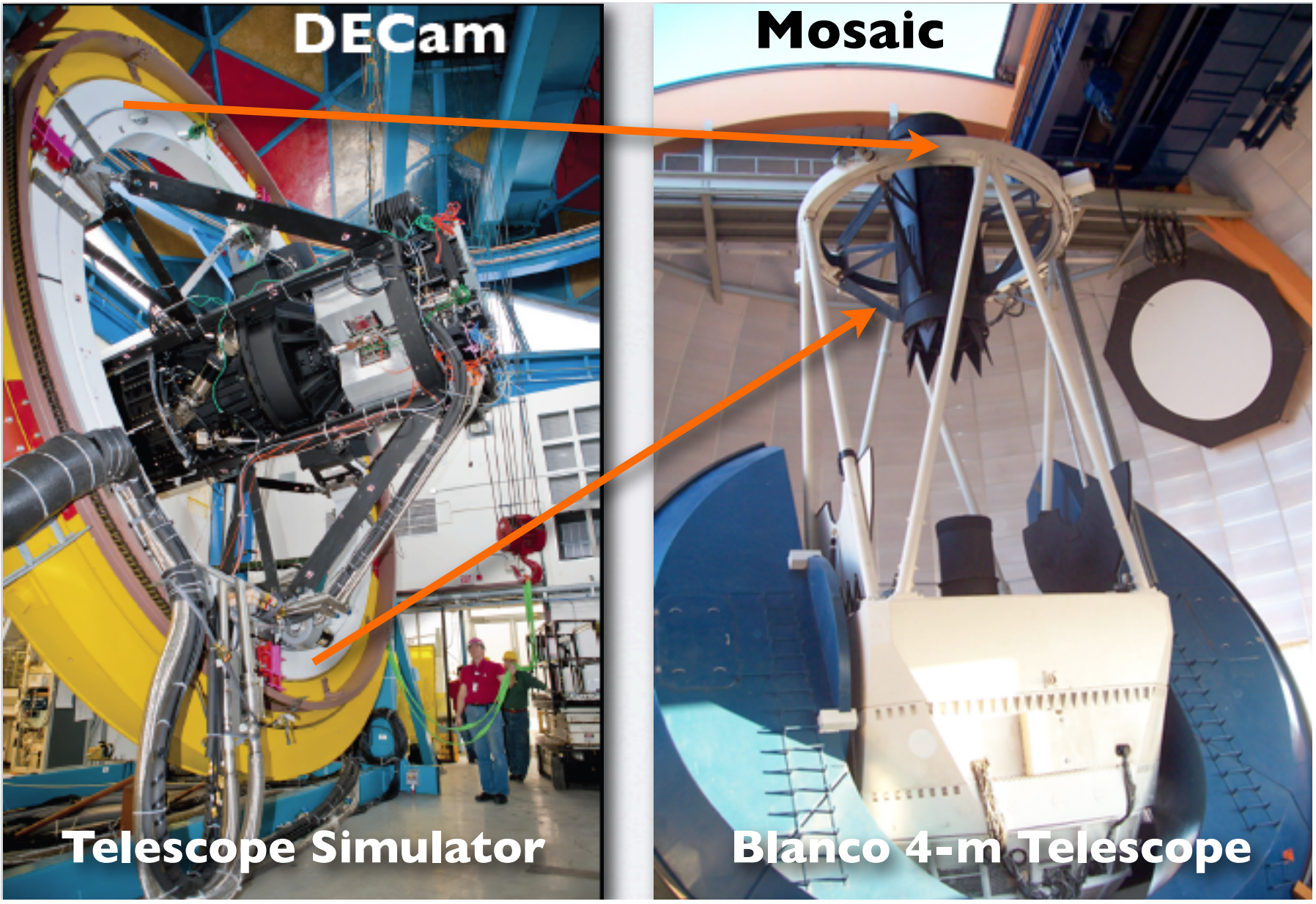
LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to -100 C

CCD readout electronic crates are mounted to the outside of the Imager and are actively cooled to eliminate thermal plumes

Filter changer with 8 filter capacity and **shutter** fit between lenses **C3** and **C4**.

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

Barrel supports the **5 lenses** and imager



this is the ring that you saw at SiDet (Lab-A)

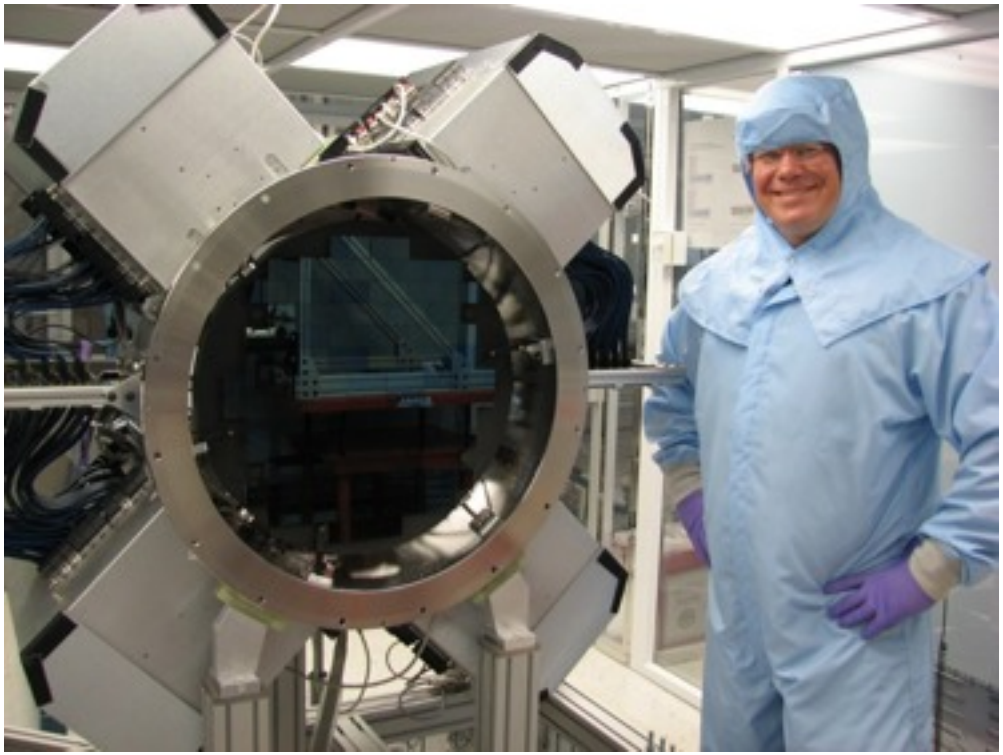
DECam Focal Plane fully assembled

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

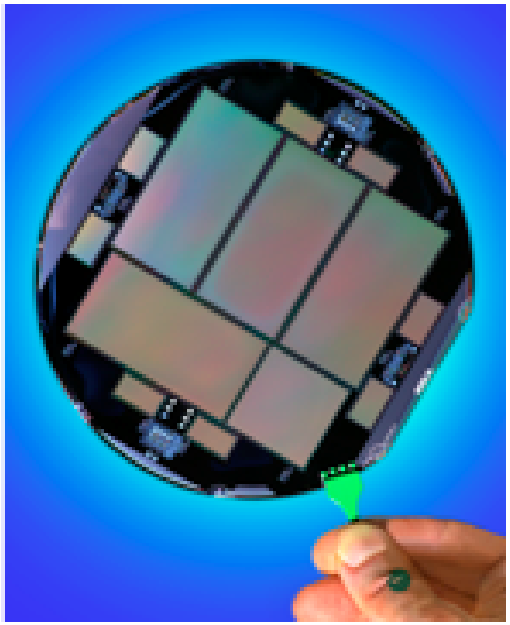
#	description specification
1	nonlinearity <1%
2	full well: >130,000 e^-
3	no residual image
4	readout time < 17 sec
5	dark current <35 e^-/pix/hour
6	QE [g, r, i, z]: [60%, 75%, 75%, 65%]
7	QE < 0.5 % per degree K
8	read noise <15 electrons
9	Charge diffusion σ <7.5μm
10	Cosmetic defects < 0.5 %
11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

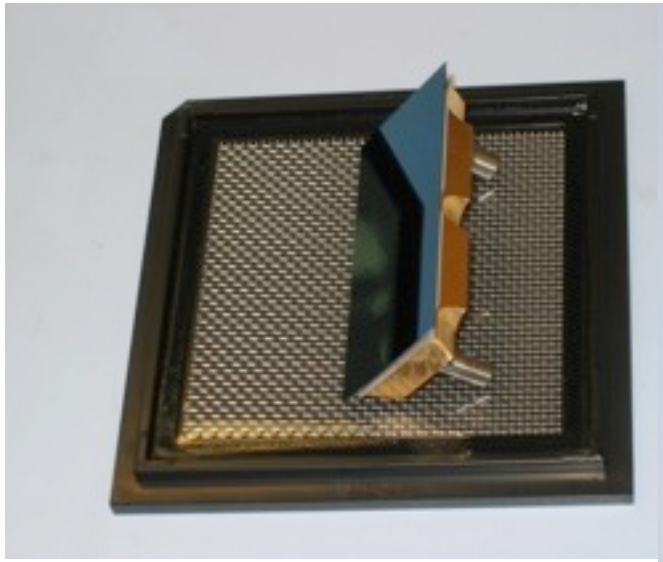
These requirements come from the science goals for DES. Get to z~1.

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

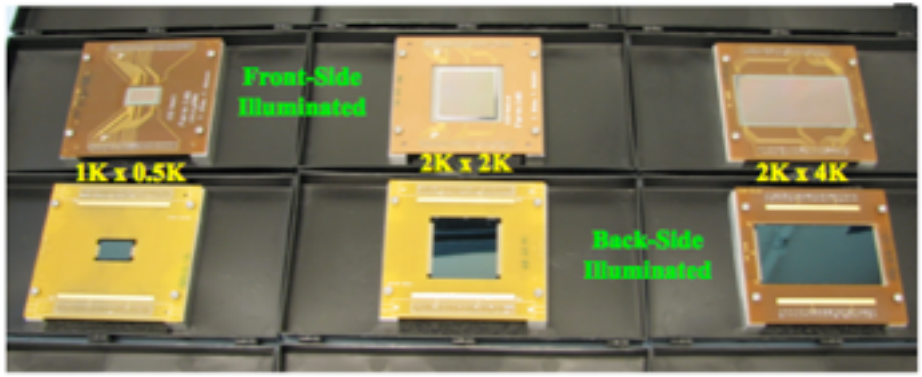
Detectors : CCD

DECam wafer





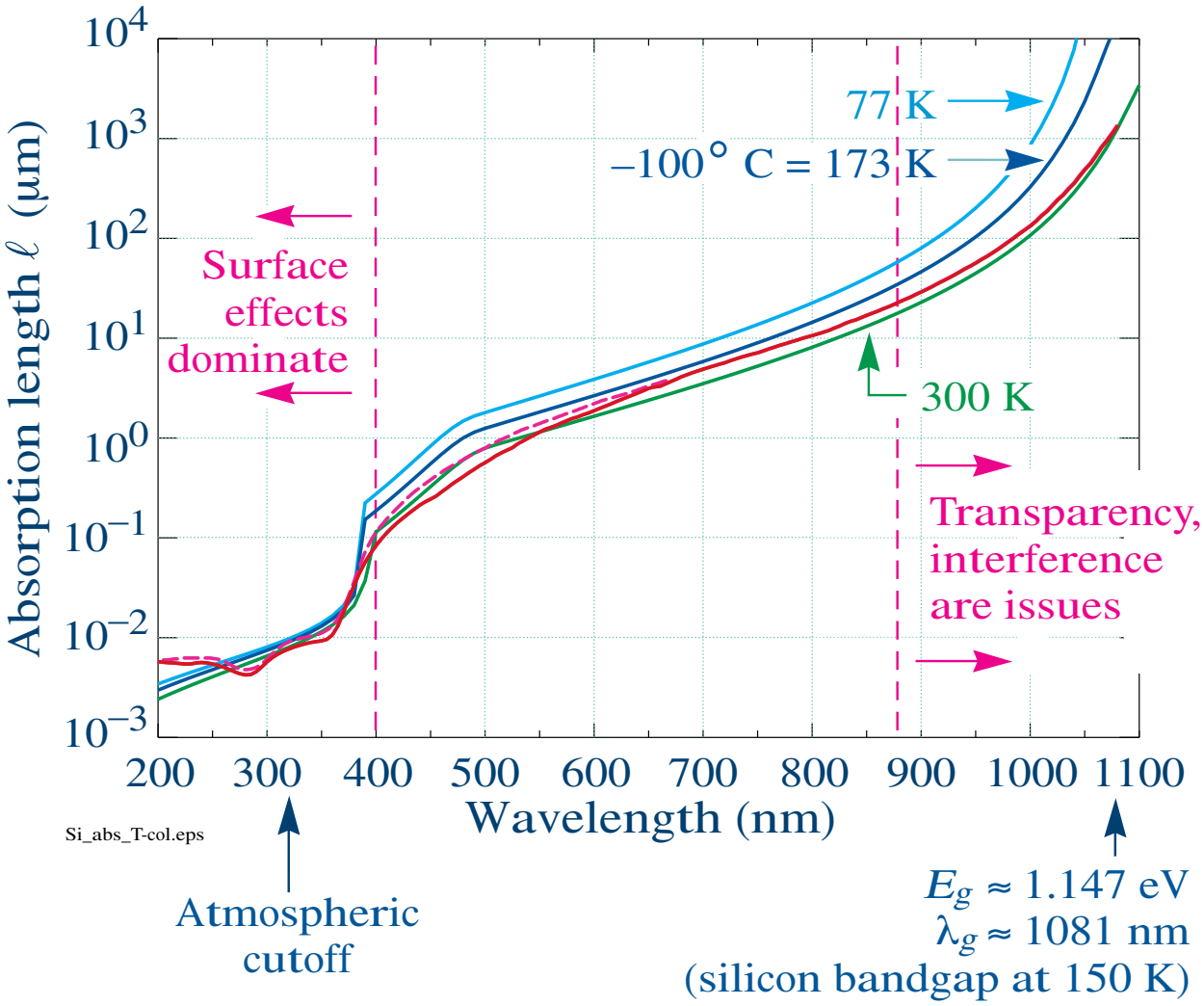
Engineering CCDs



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

+100 built and tested during our R&D stage

How to get high QE in the red with Si?



Focal Plane Detectors

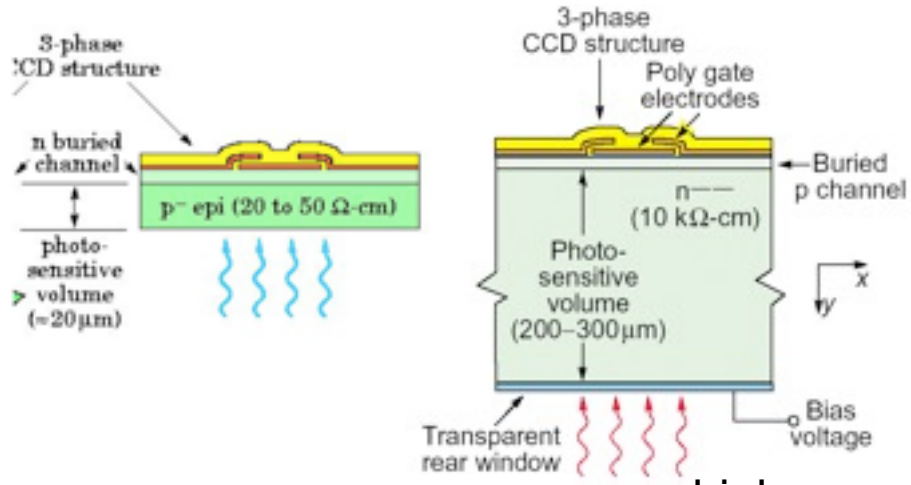
Science goal for DES: z~1

~50% of time in z-filter

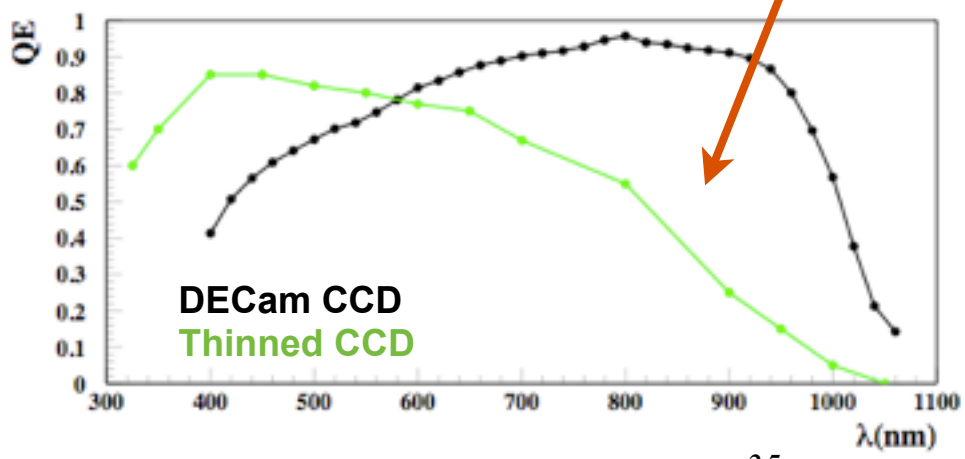
825-1100nm

LBNL full depletion CCD

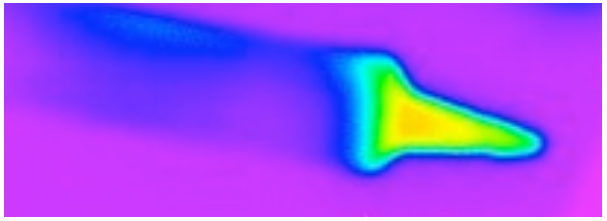
- **250 microns thick (instead of 20 microns)**
- **high resistivity silicon**
- **QE> 50% at 1000 nm**



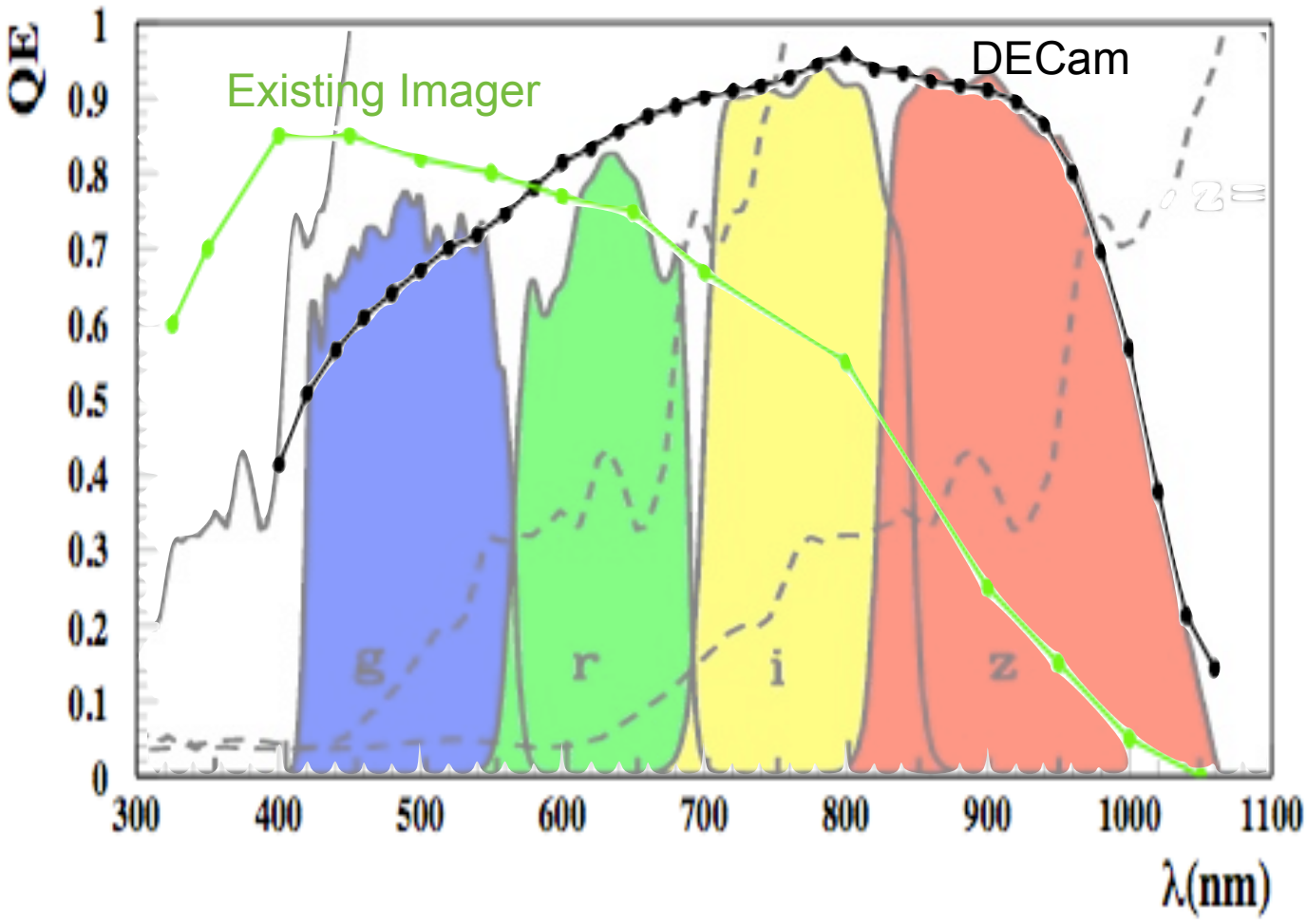
high-z objects



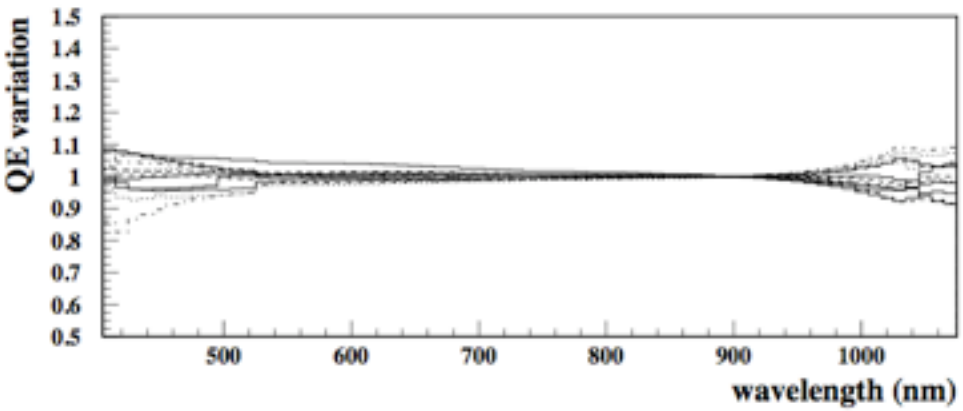
IR image of soldering iron with DECam CCDs



QE in the DES filters

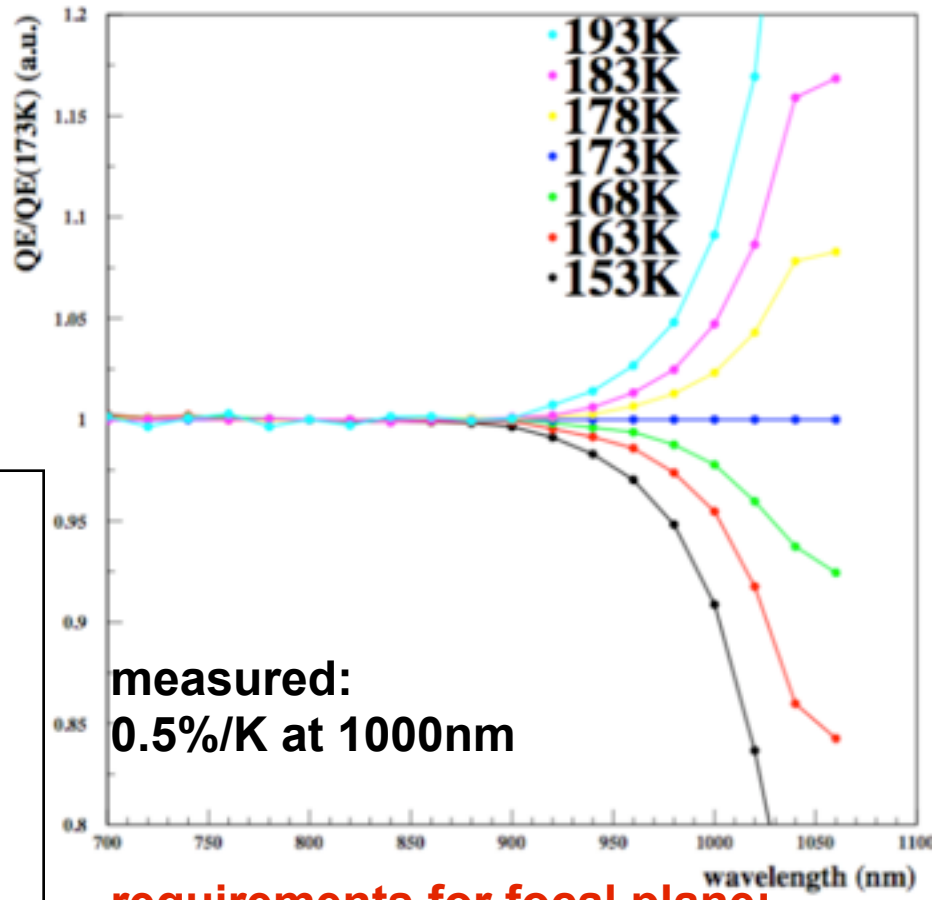


Stability/Uniformity in QE



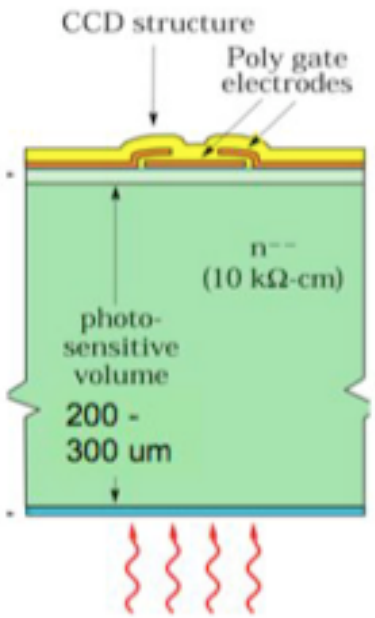
The DECam detectors show very uniform QE. DES requires better 10% QE uniformity from CCD to CCD.

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

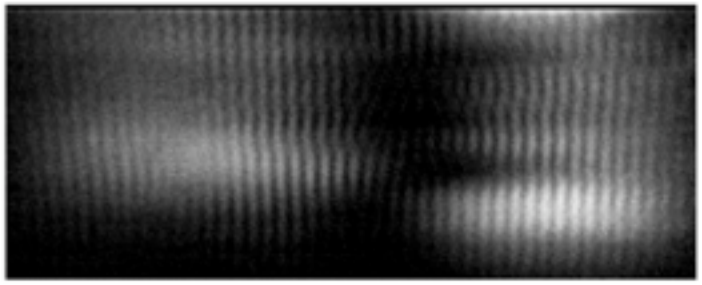


Holes produced in the back surface have to travel to the collection area. **Thicker means more opportunity for diffusion**. (fully depleted). Higher QE could get compensated by lower image quality. **That is why other detectors are thinner.**

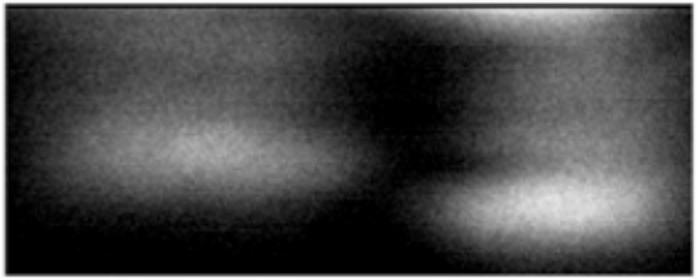
The 40V applied to the substrate (Vsub) to control diffusion

Imaging a diffraction pattern

high Vsub

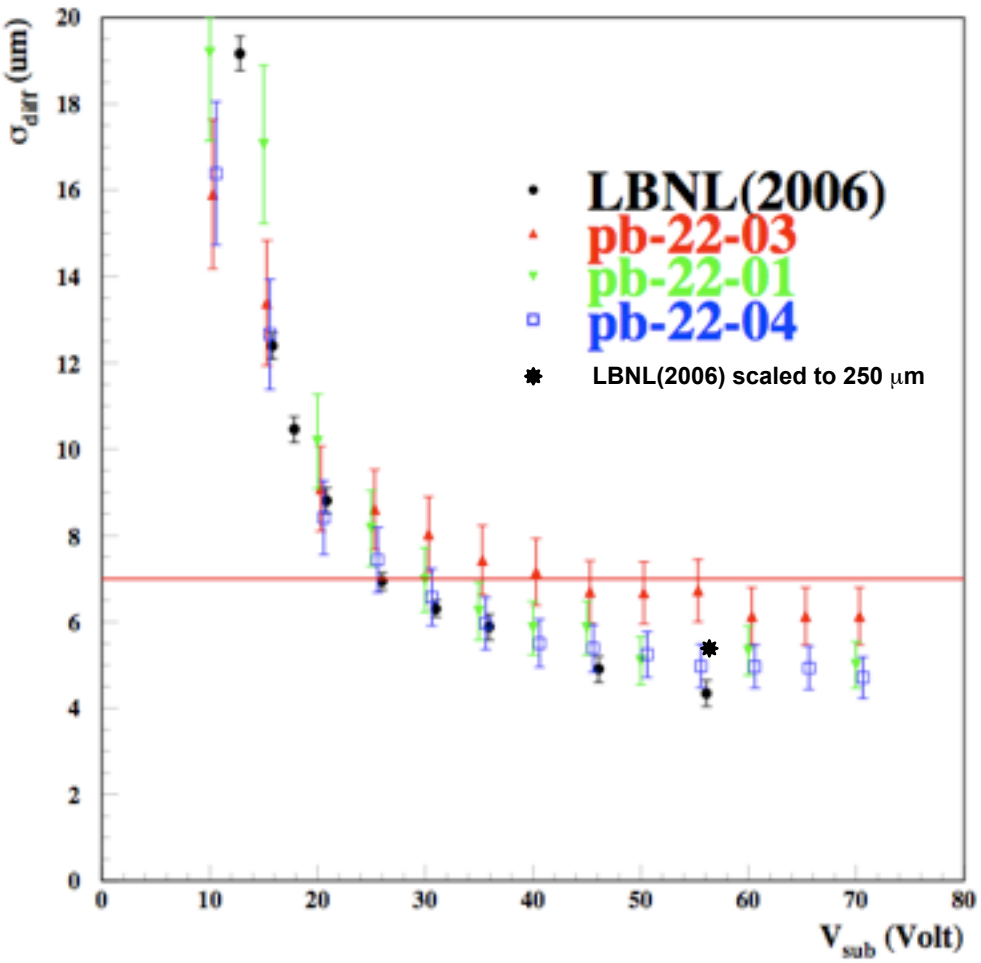


low Vsub



Diffusion is measured from the analysis of these images

Diffusion results

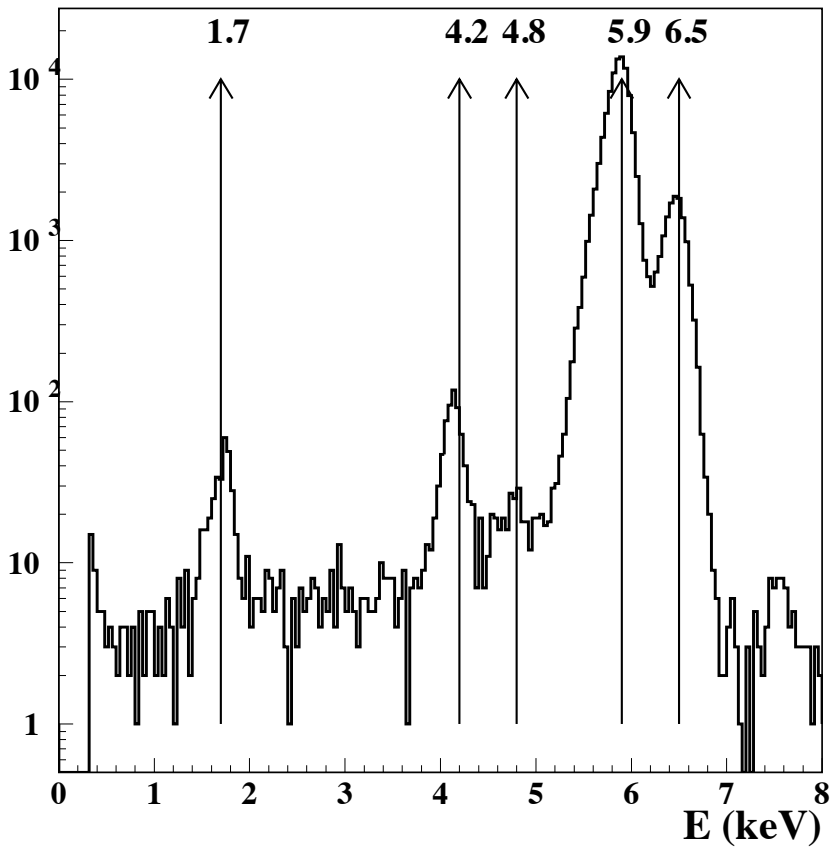


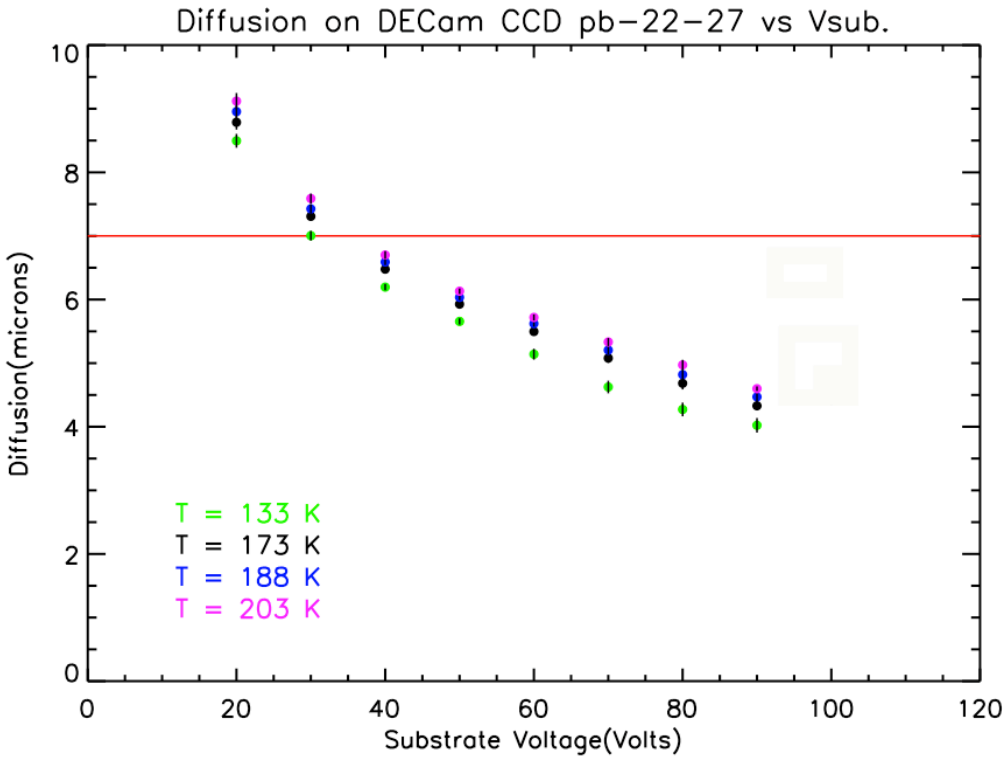
substrate voltage

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.

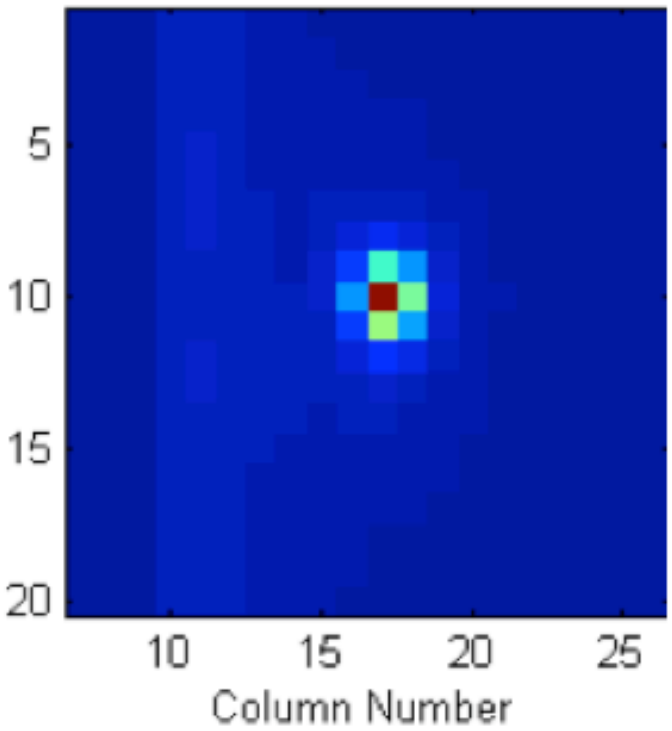
X-rays

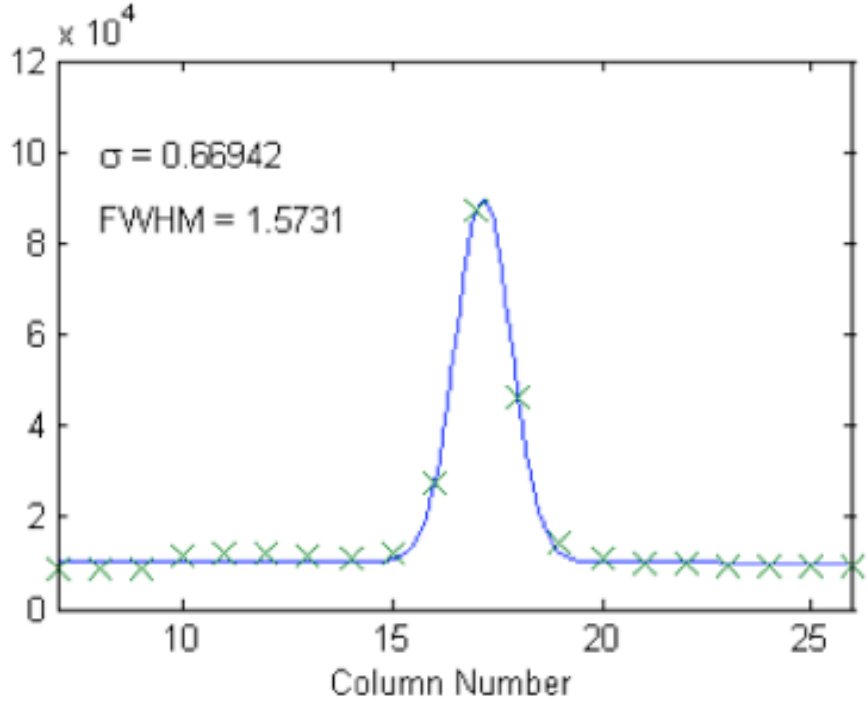

1.7
4.2 4.8
5.9 6.5
10 4
10 3
10 2
10
1
0 1 2 3 4 5 6 7 8
E (keV)


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

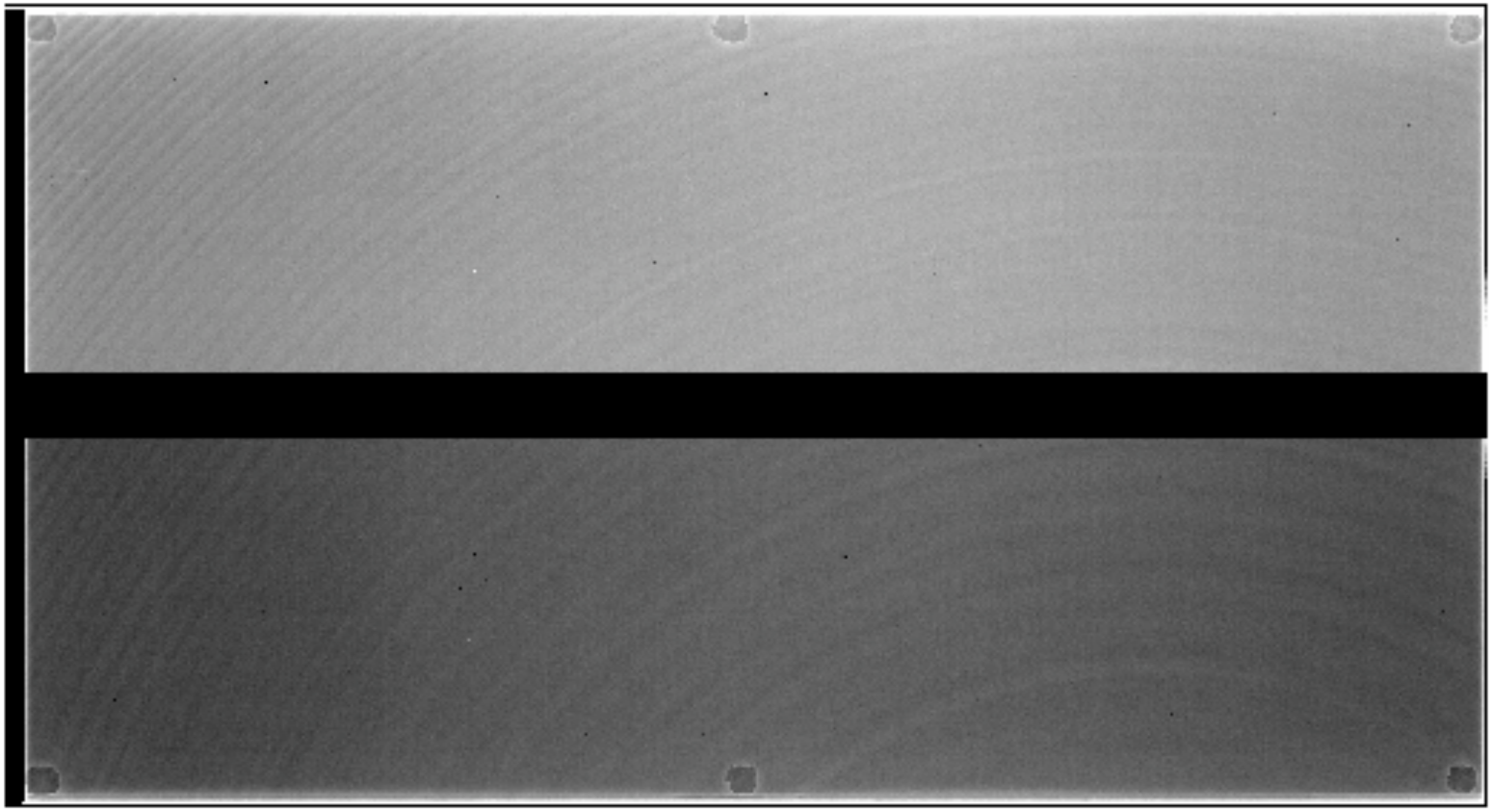
Simulated stars

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.**

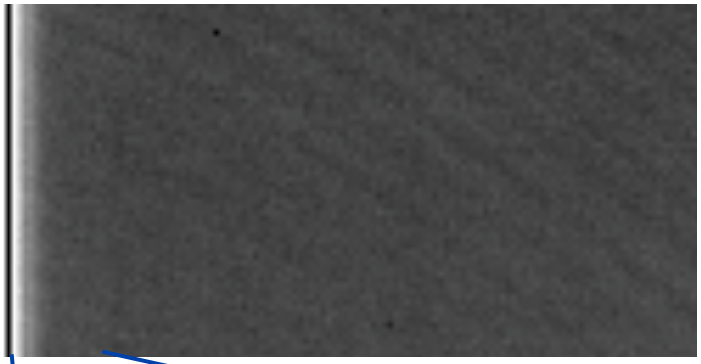


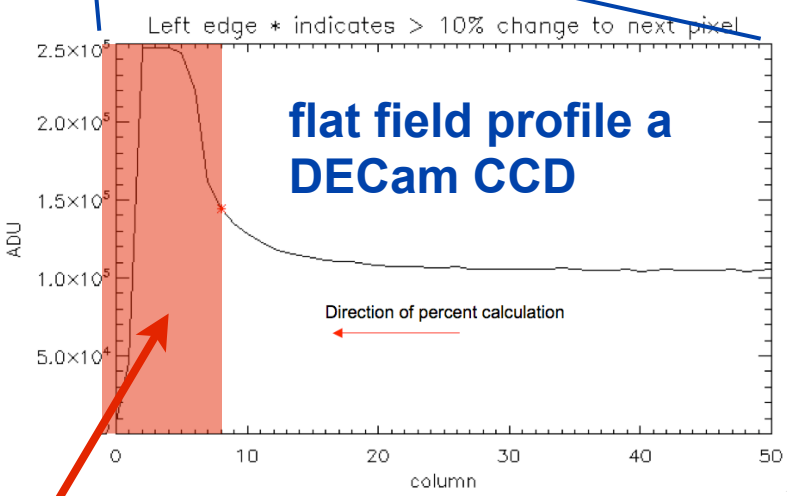


Glowing edge



Edge effects on DECam CCDs

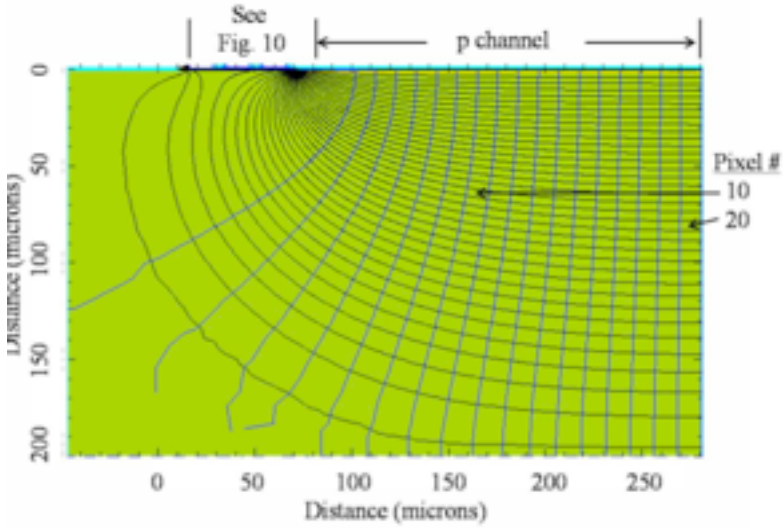




region not used for DES imaging.

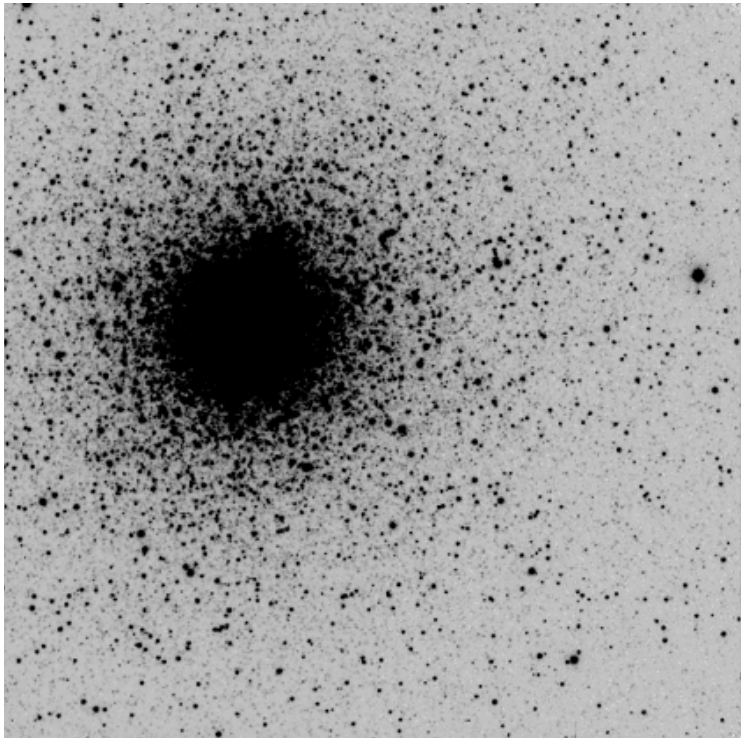
Flat field shows **additional light collected on the edge pixels.** This light comes from the edge of the CCD, from outside the pixel grid.

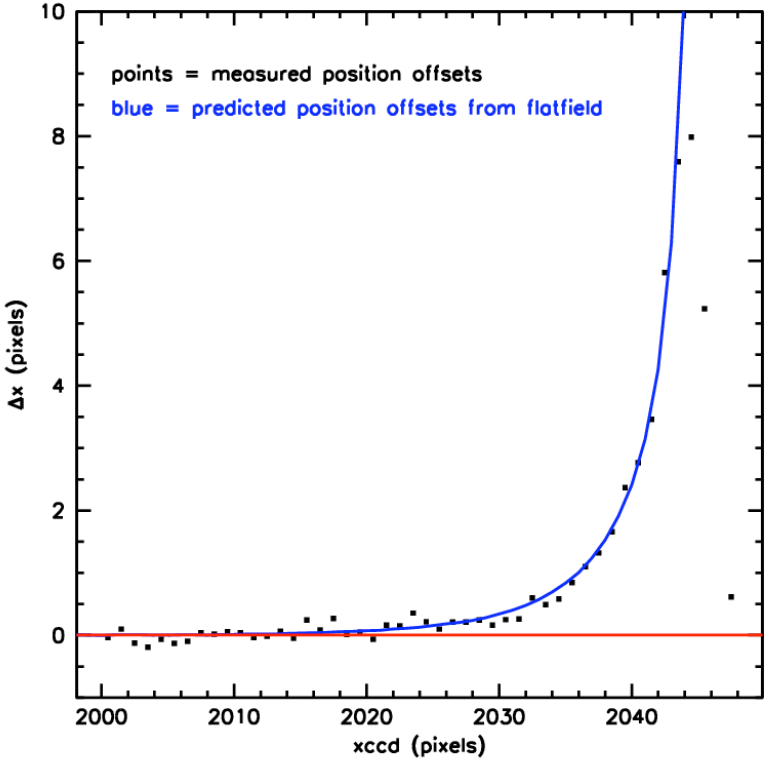
equipotential and electric field lines



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

Edge effects studies on the sky

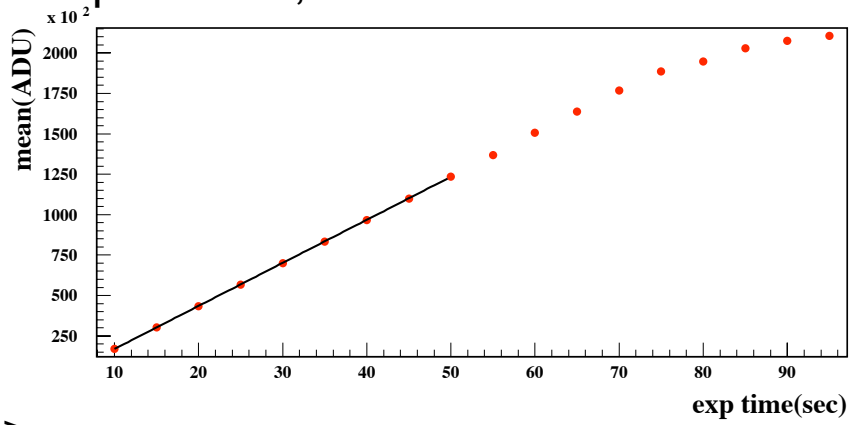


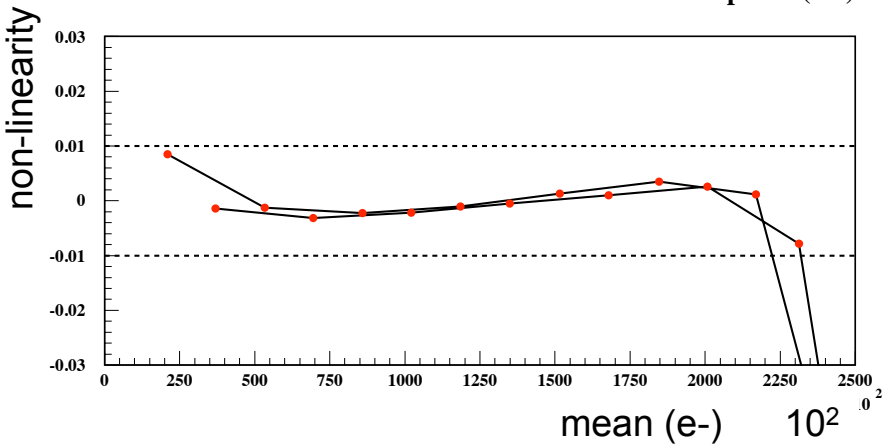


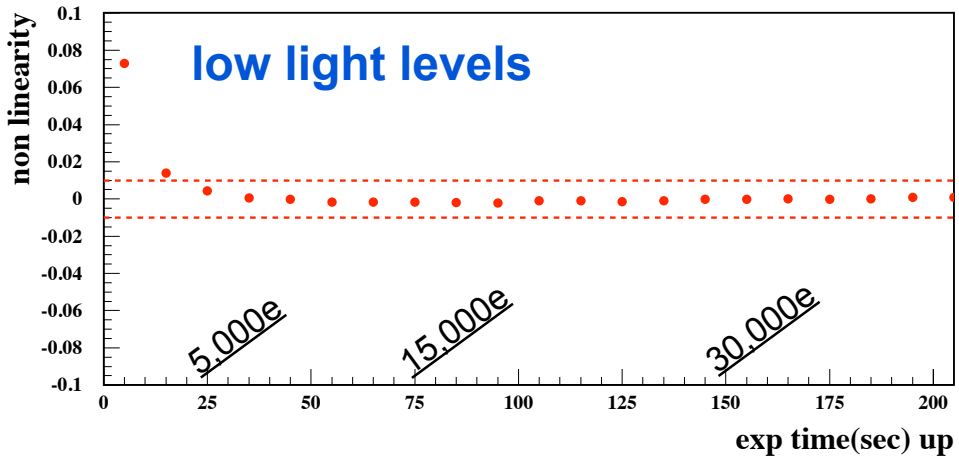
by **imaging a globular cluste**r on different locations of the CCD we measured the **distortion due to this effect**. Results **agree with flat field studies**. We understand the issue.

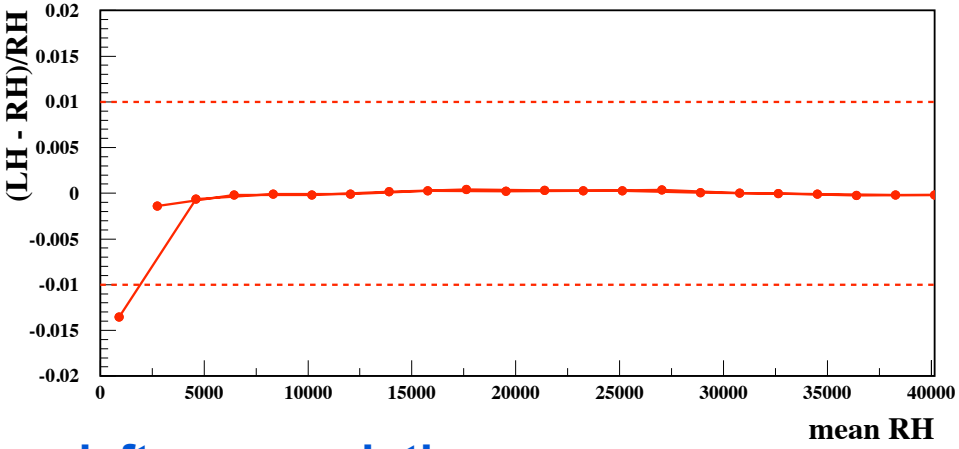
Linearity

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



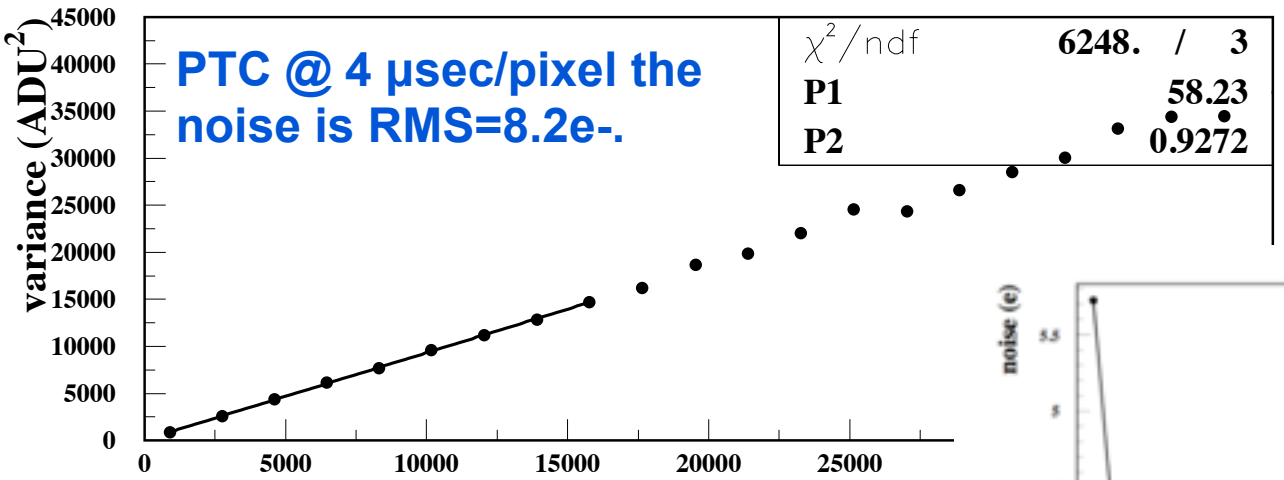






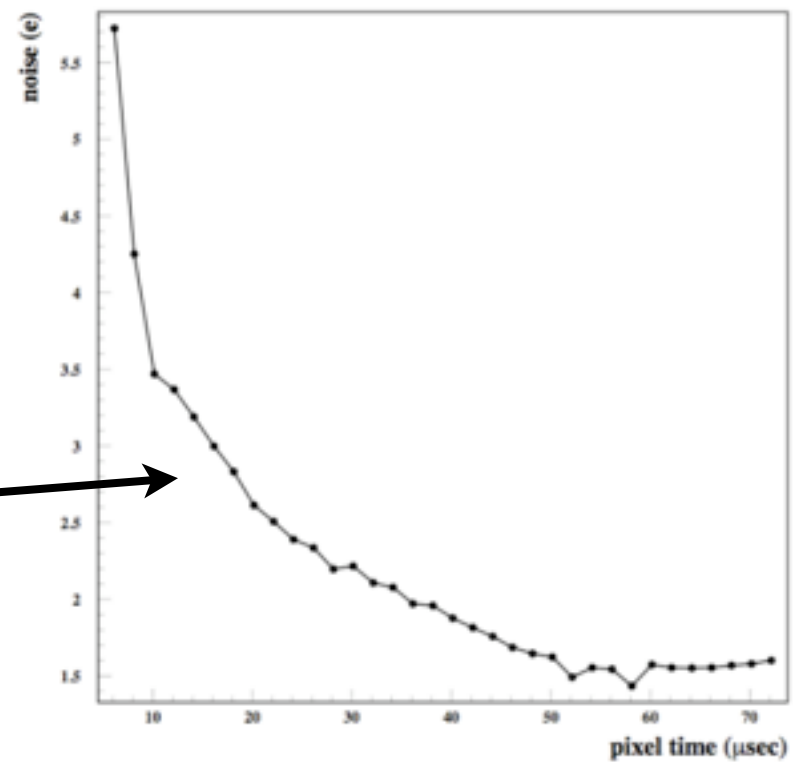
left amp vs rigth amp to eliminate lamp fluctuations or shutter problems. (note the scale!)

Noise

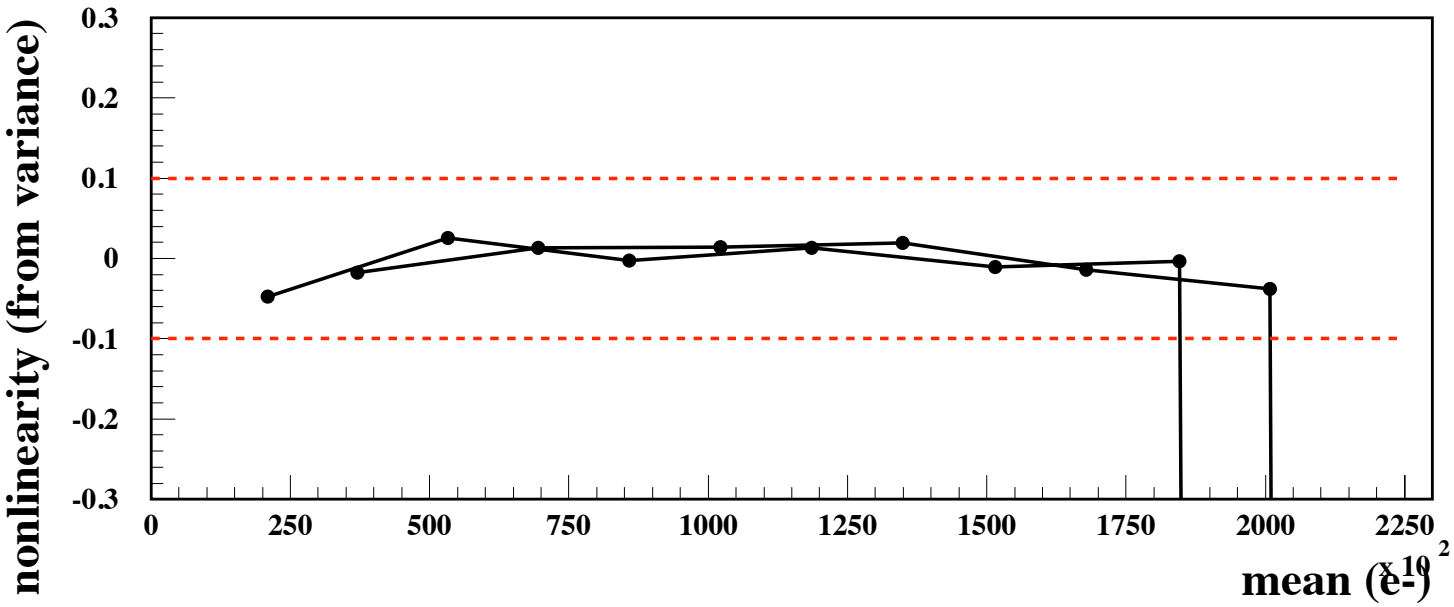


Our spec is 15e- at this speed. <u>No problem!</u>

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

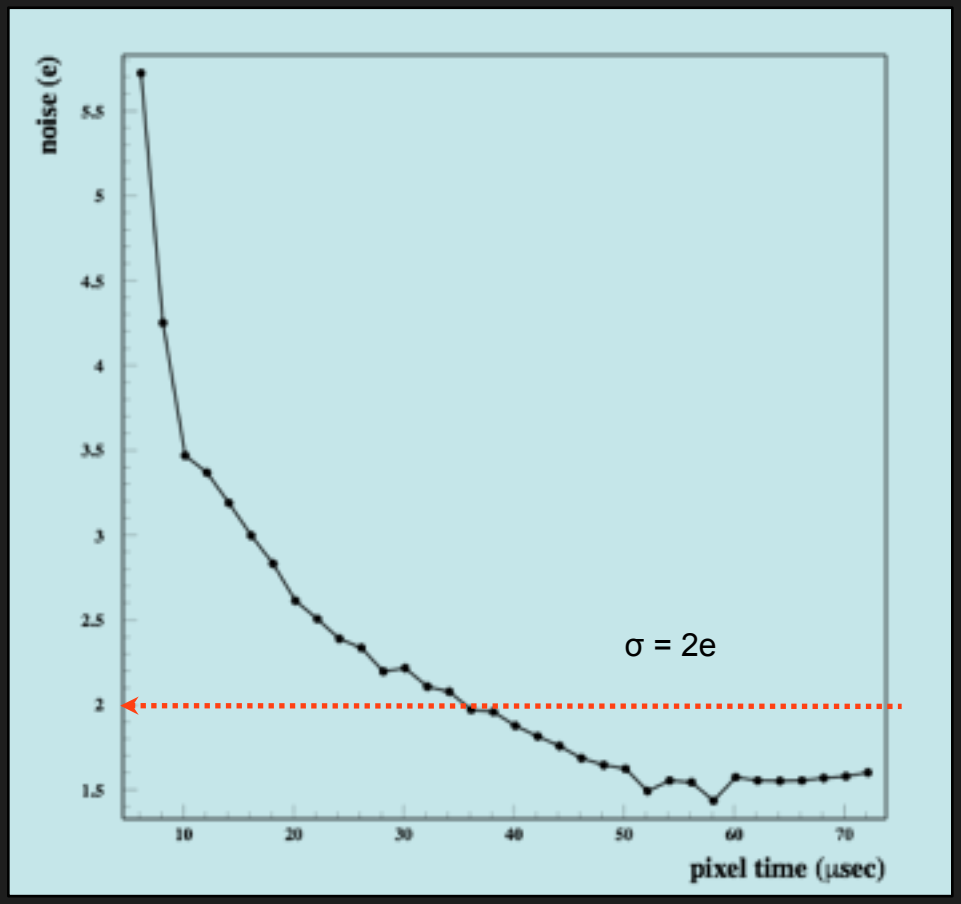


Pixel full well capacity



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!**

New opportunities with DECam CCDs

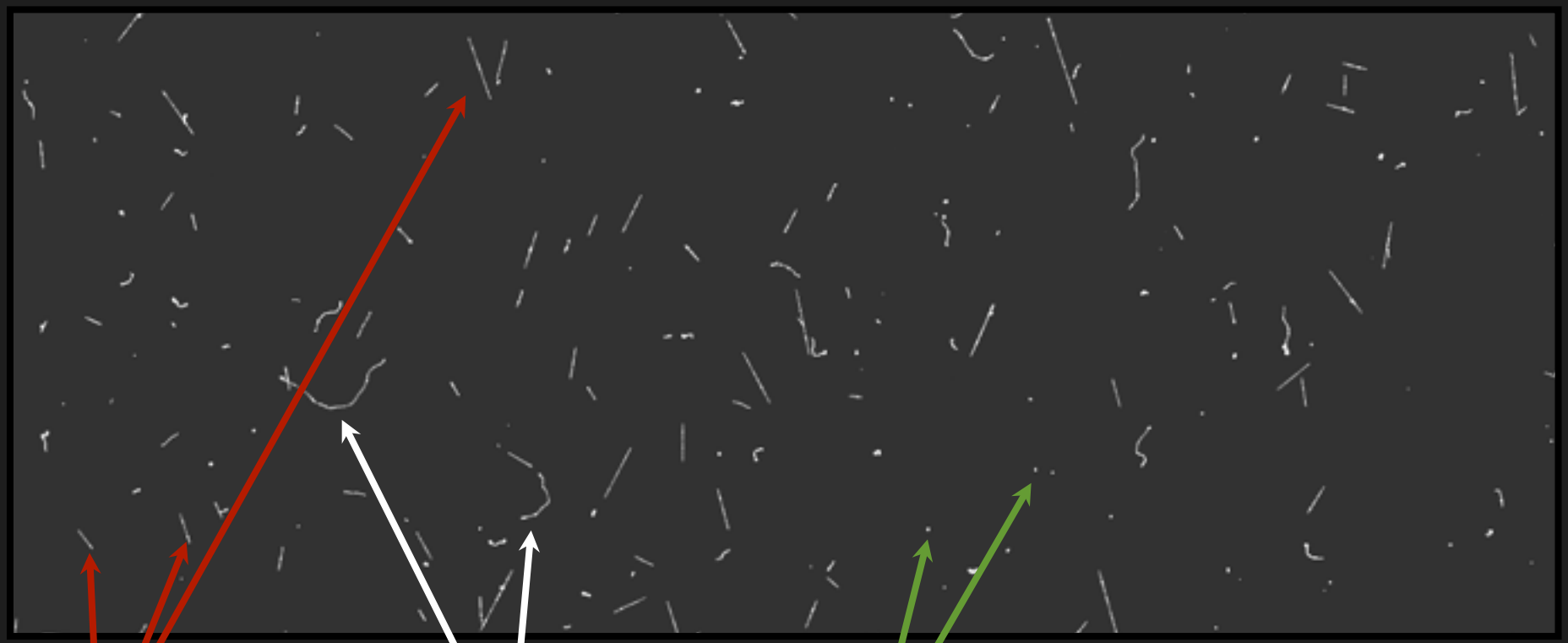


CCDs are readout serially (2 outputs for 8 million pixels). When readout slow, these detectors have a noise below 2e- (RMS). This means an **RMS noise of 7.2 eV in ionization energy!**

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

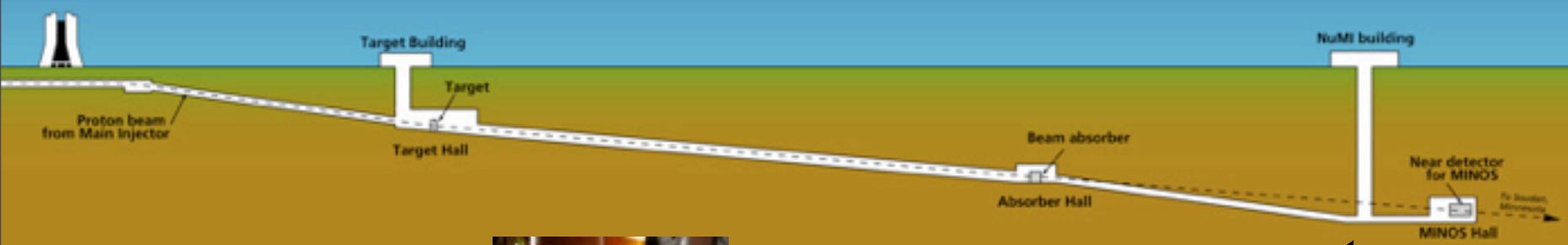


muons, electrons and diffusion limited hits.

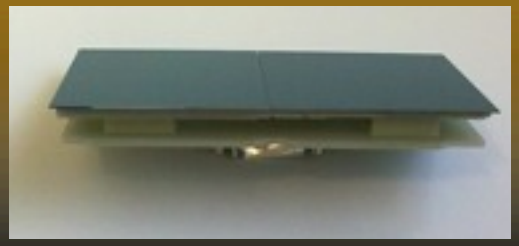
nuclear recoils will produce diffusion limited hits

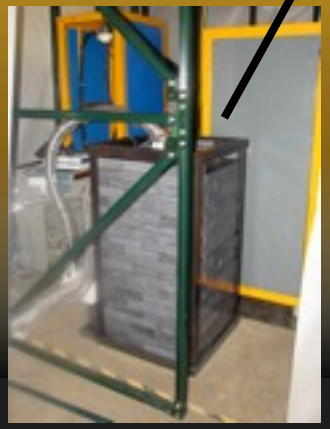
DAMIC underground test at FNAL

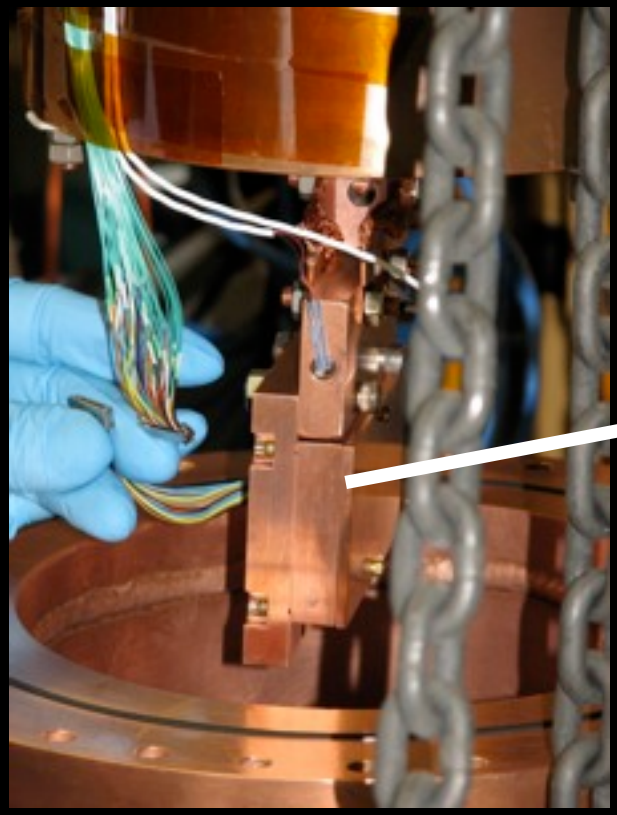
CCD operated at 350' underground (MINOS hall)



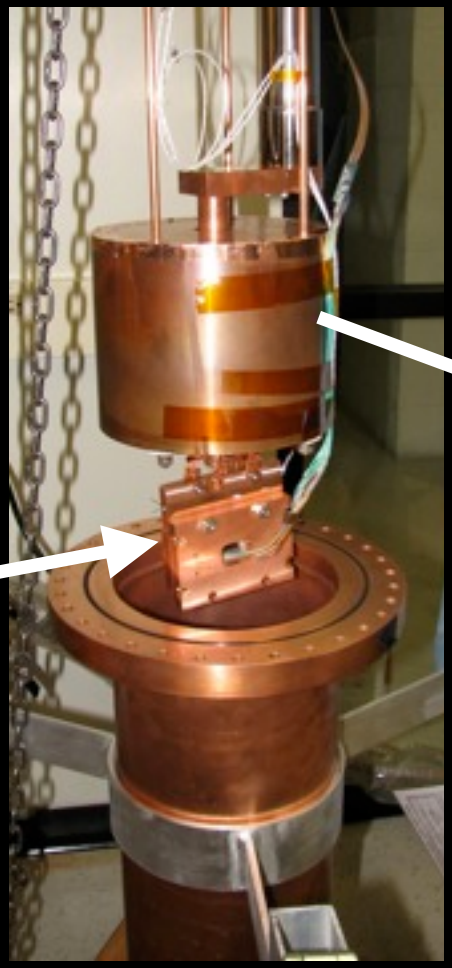
developed a low background CCD package operated inside a Cu vessel shielded with lead.



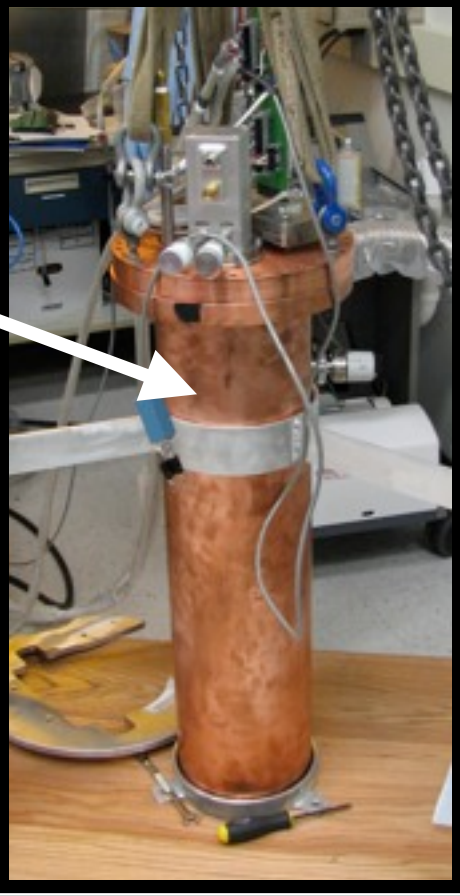




CCD inside a cold copper box. (IR shield)



6” lead bucket inside vaccum



cylindrical copper dewar

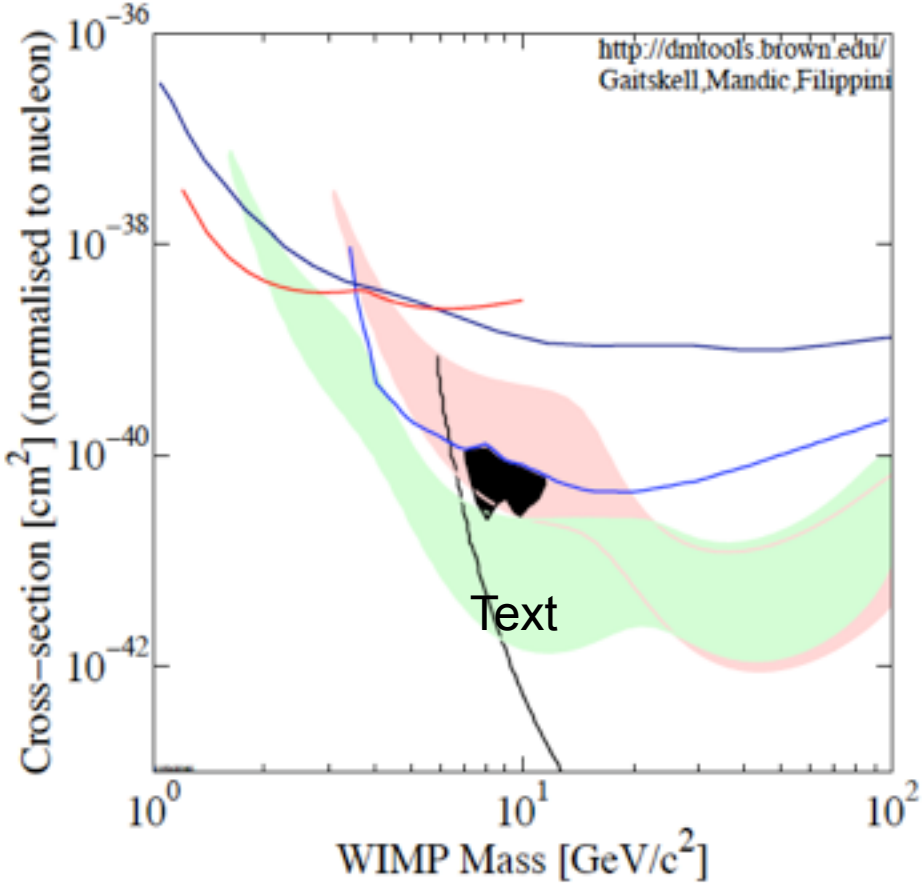
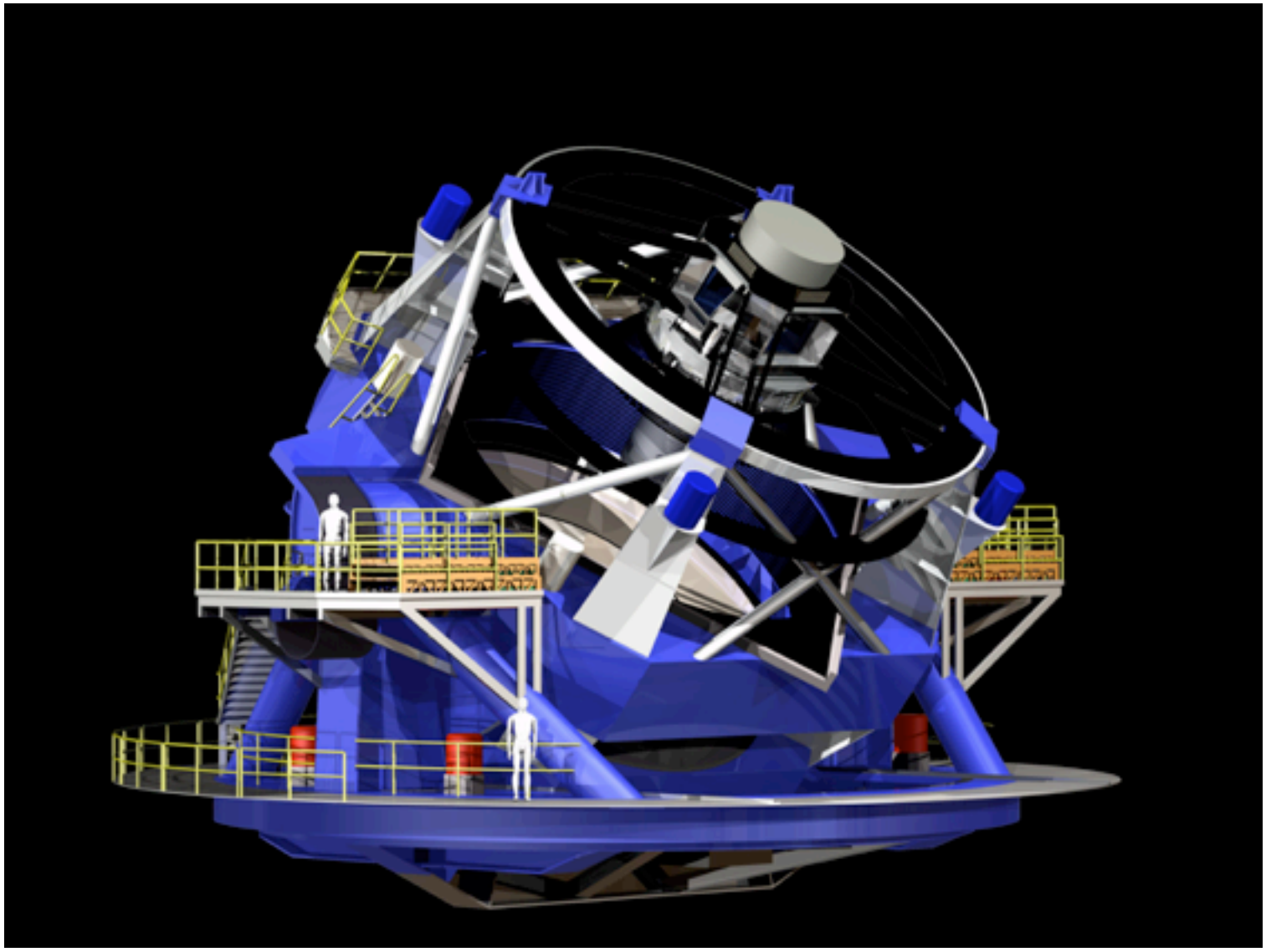


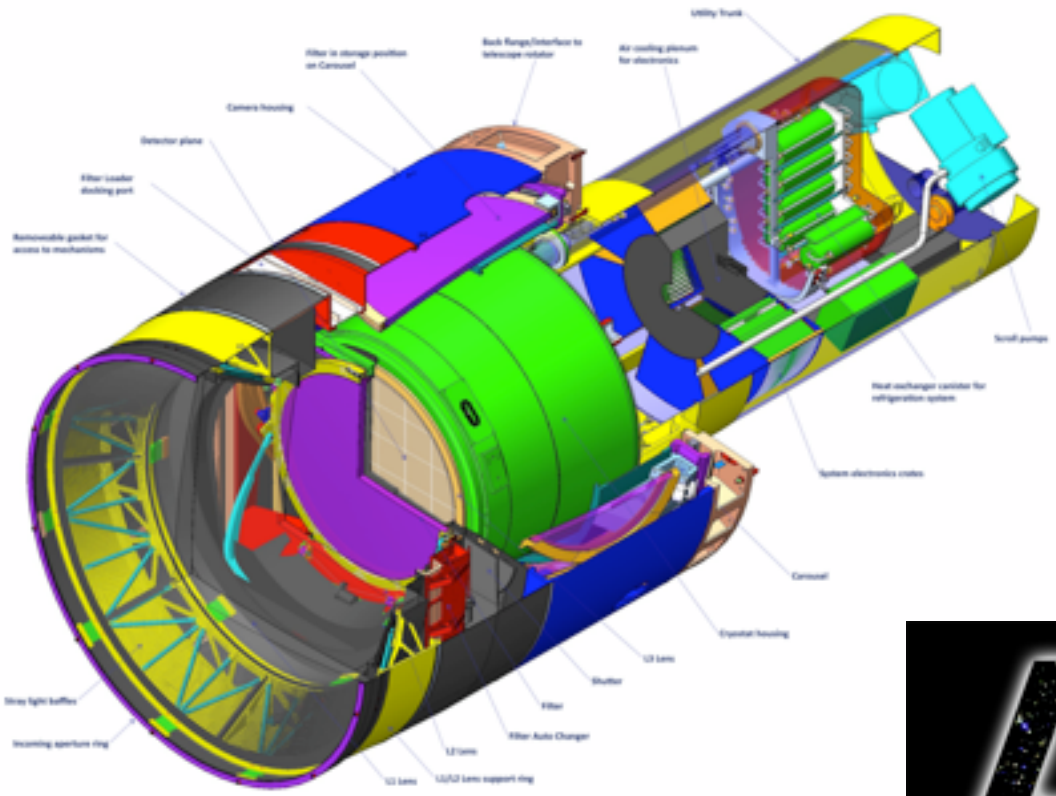
FIG. 11: Cross section upper limit with 90% C.L. for the DAMIC results (red) compared to CRESST 2001 (dark-blue) and CoGent (light-blue) results. The shaded areas correspond to the 3-sigma contour consistent with the DAMA/LIBRA annual modulation signal (red: no ion channeling, green: ion channeling) [39]. The black area corresponds to the DM interpretation of CoGent [4].


FUTURE

What comes after DECam for large astronomical surveys?



Large Synoptic Survey Telescope



- 10,000 square degrees of sky to be covered every three nights on average to magnitude r ~ 24.5 (AB)
- The total survey area will include 30,000 deg^2 covering the wavelength range 320–1050 nm.

Large Synoptic Survey Telescope

- 8.4m (6.7m effective) primary mirror
- 9.6 deg^2 field of view
- 3.2 Gigapixel camera
- Detectors: more, x2 faster than DECam, 1/2 the noise of DECam


FUTURE
2

So far we talked about imaging with filters, and loosing most of the spectroscopic information. The big surveys will required followup with spectroscopic instruments (for example to improve redshift estimates)

the current solution is to split the light of each object using a prism...

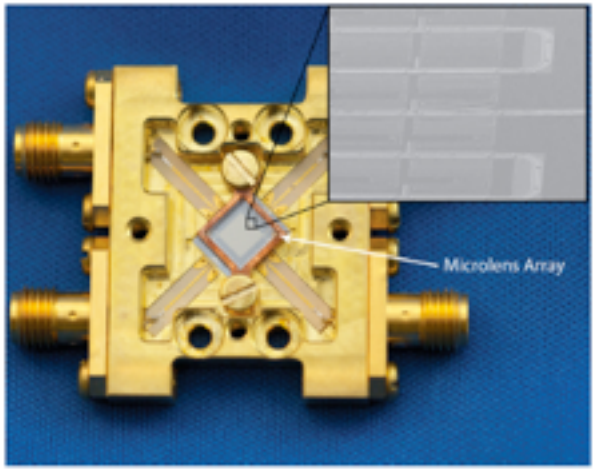
what about a detector that could measure the energy for each photon in the UV-VIS-IR range?

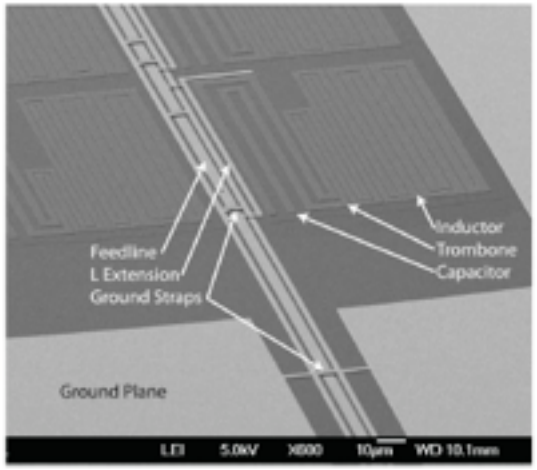
Microwave Kinetic Inductance Detectors MKIDs

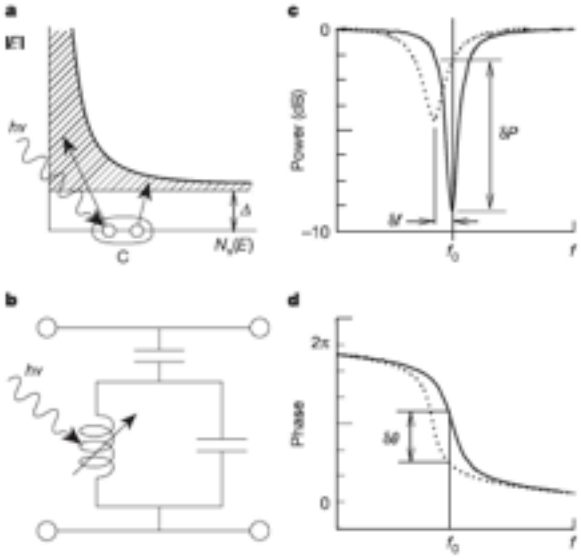
Each pixel is a superconductor resonator. The resonance frequency changes when you hit the pixel with light. The magnitude of the changes depends on the energy of the photon...

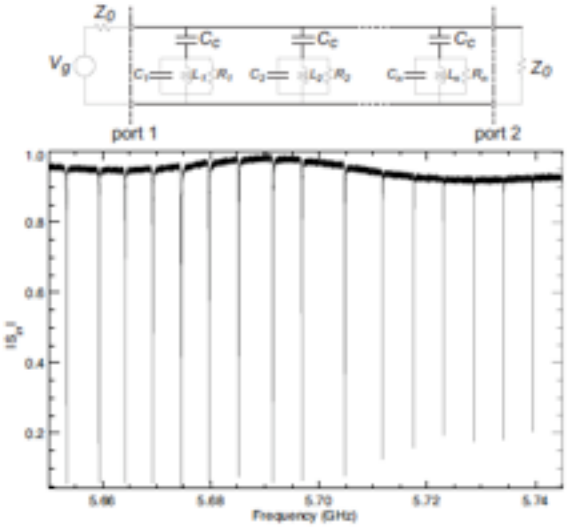
So far arrays of 1000 pixel have been tried for a few nights on a telescope.

Still early developments, but this could change the future of astronomical instruments!





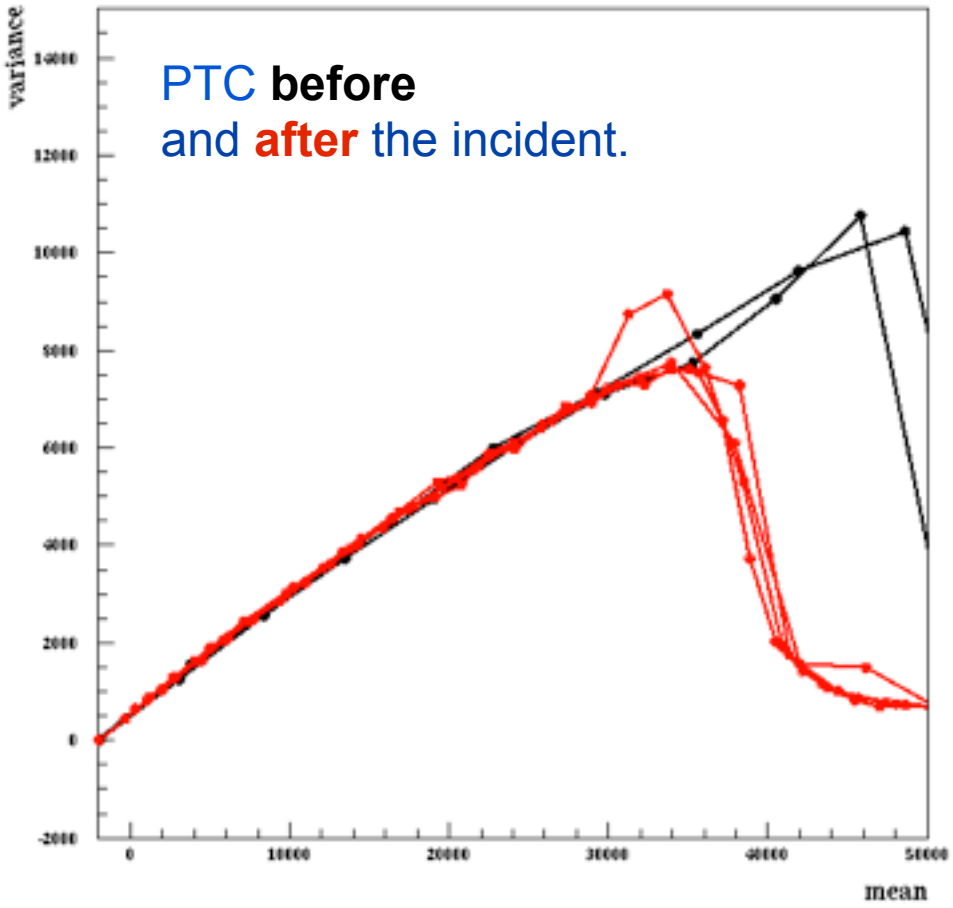




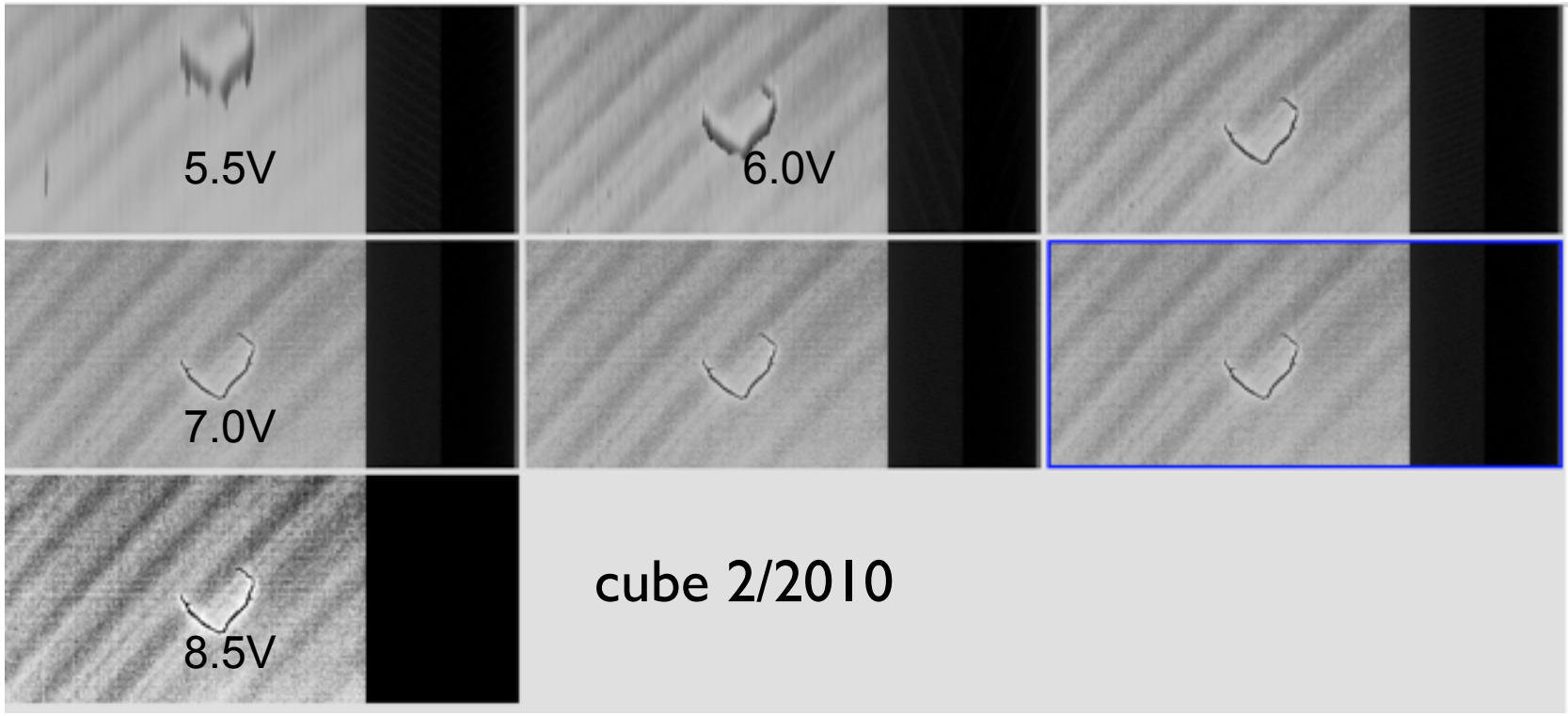
THANKS!

System testing: prototype focal plane

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.



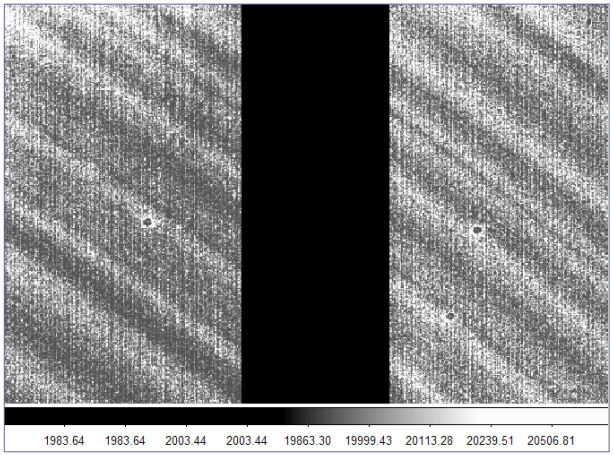
... the CCDs have changed!



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

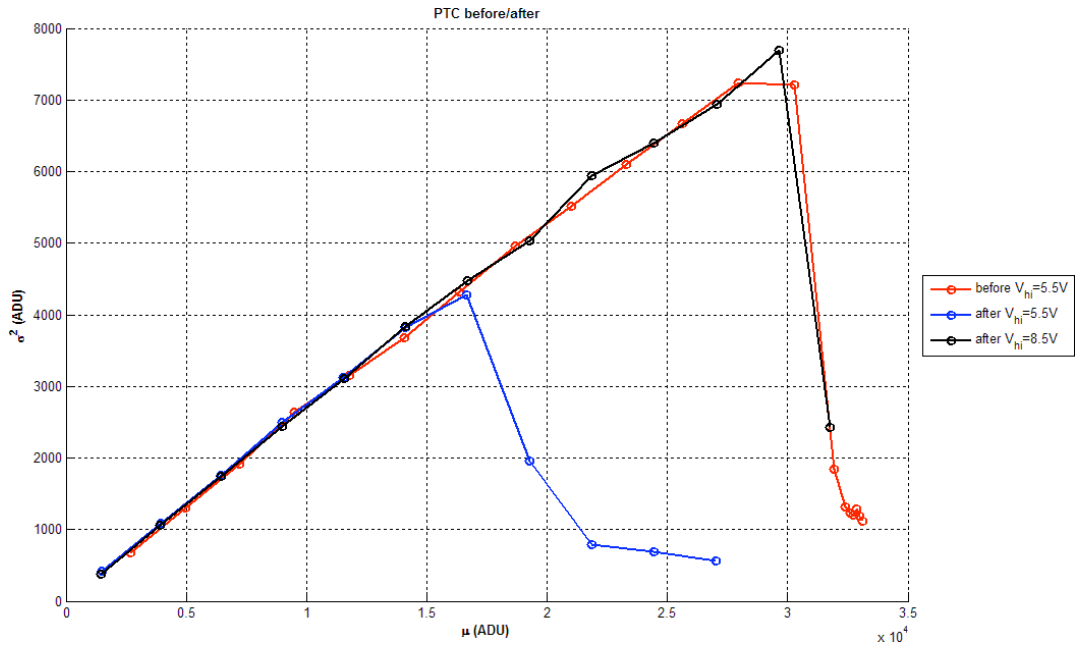
s3-126

exercise in the lab

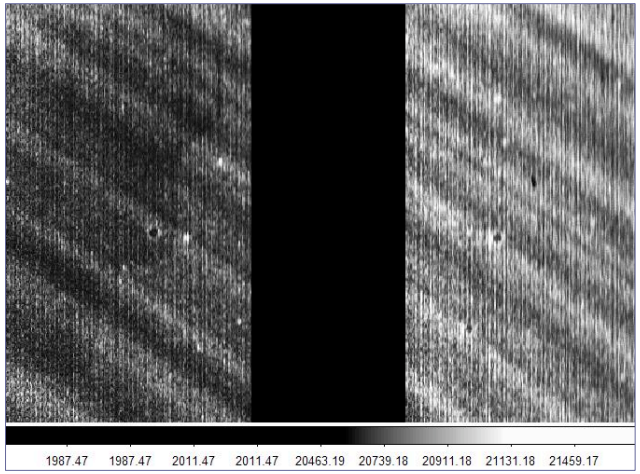


Before the damage

V+ = 5.5 V (default)



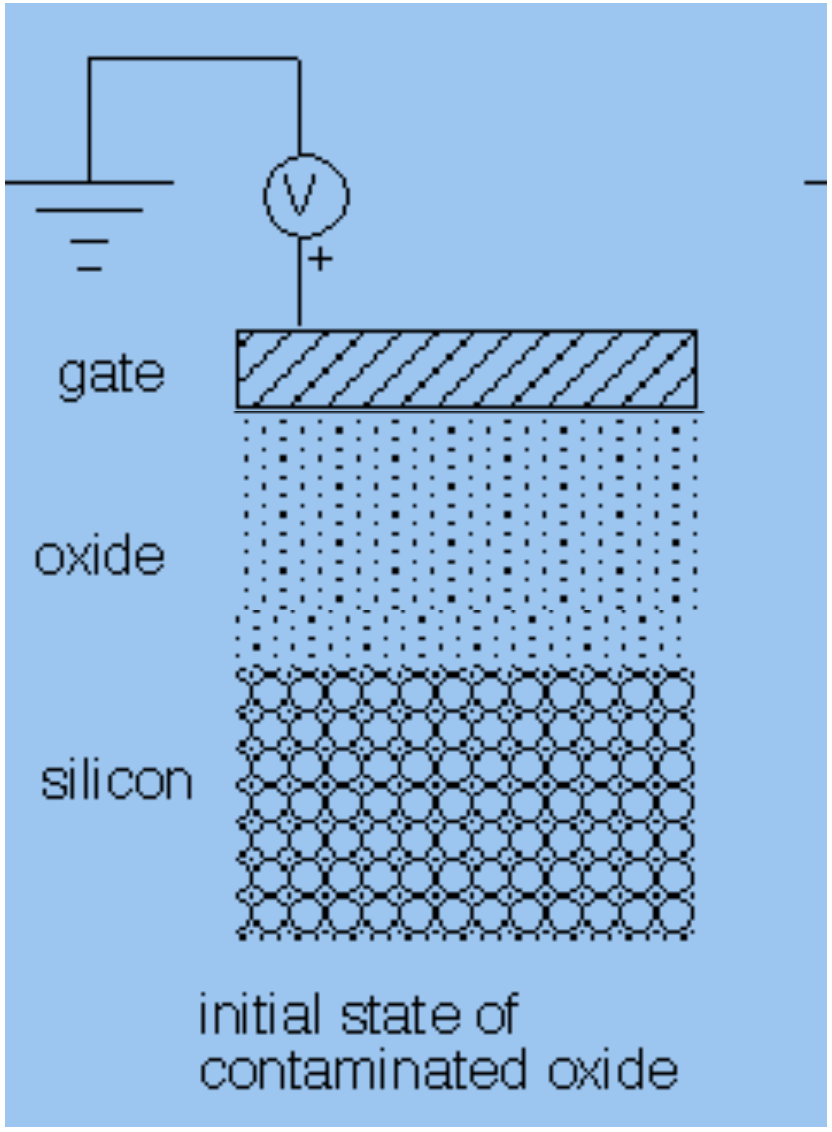
after gate set to 60V



After the damage

V+ = 5.5 V (default)

what is going on.

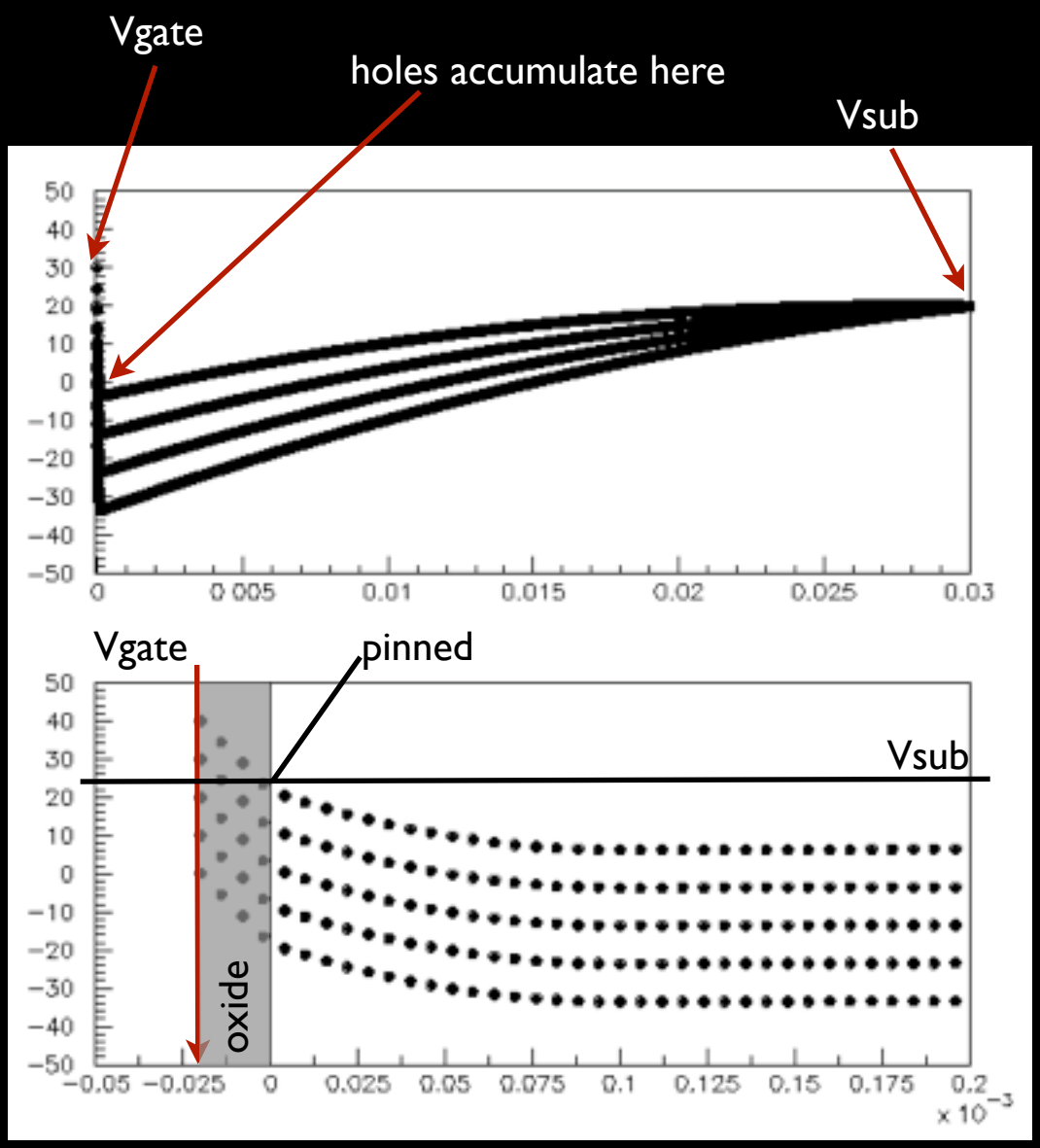


If the voltage on the gate is high enough you could move charge into the oxide, and this charge will then shield the silicon from the gate.

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



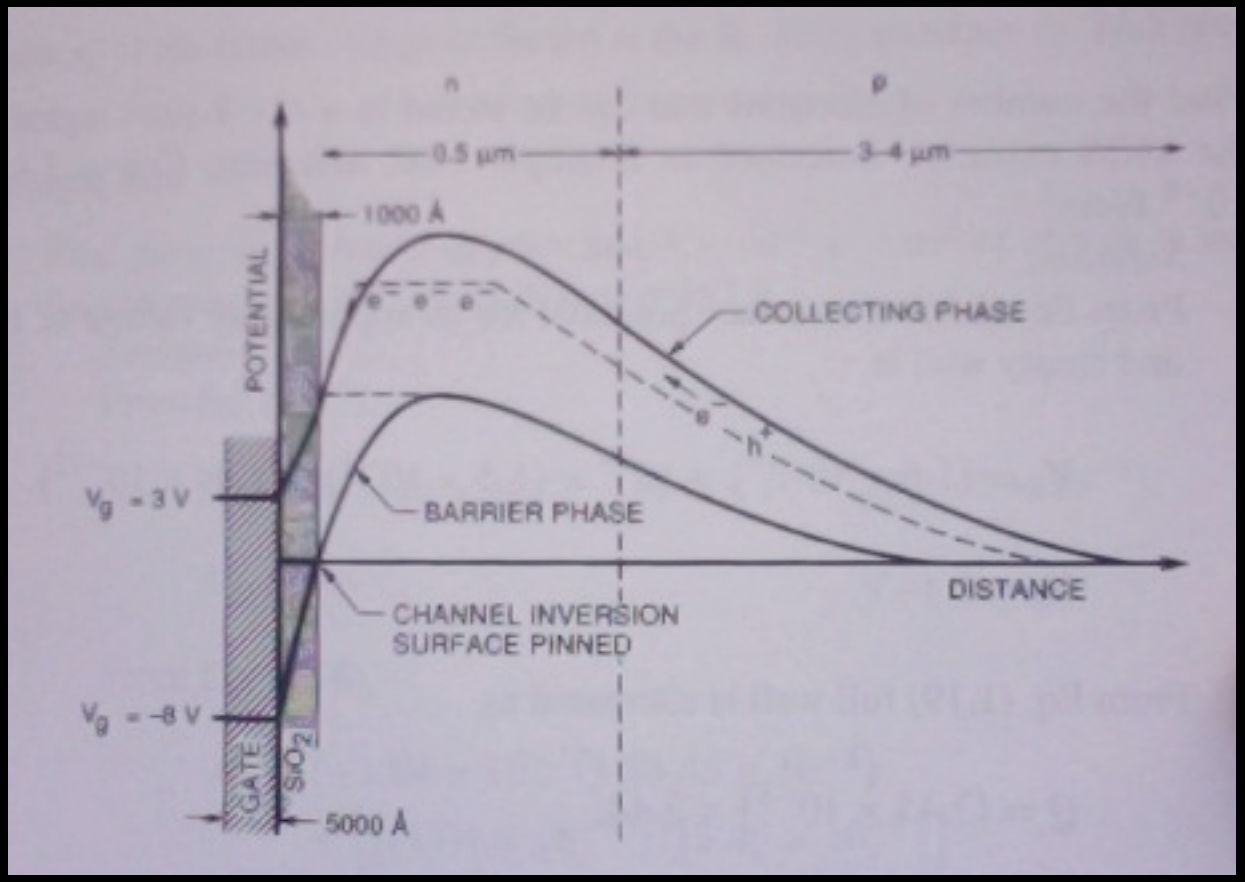
in normal operating conditions the voltage drop in the gate (E*d) does not change much with Vgate .

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.

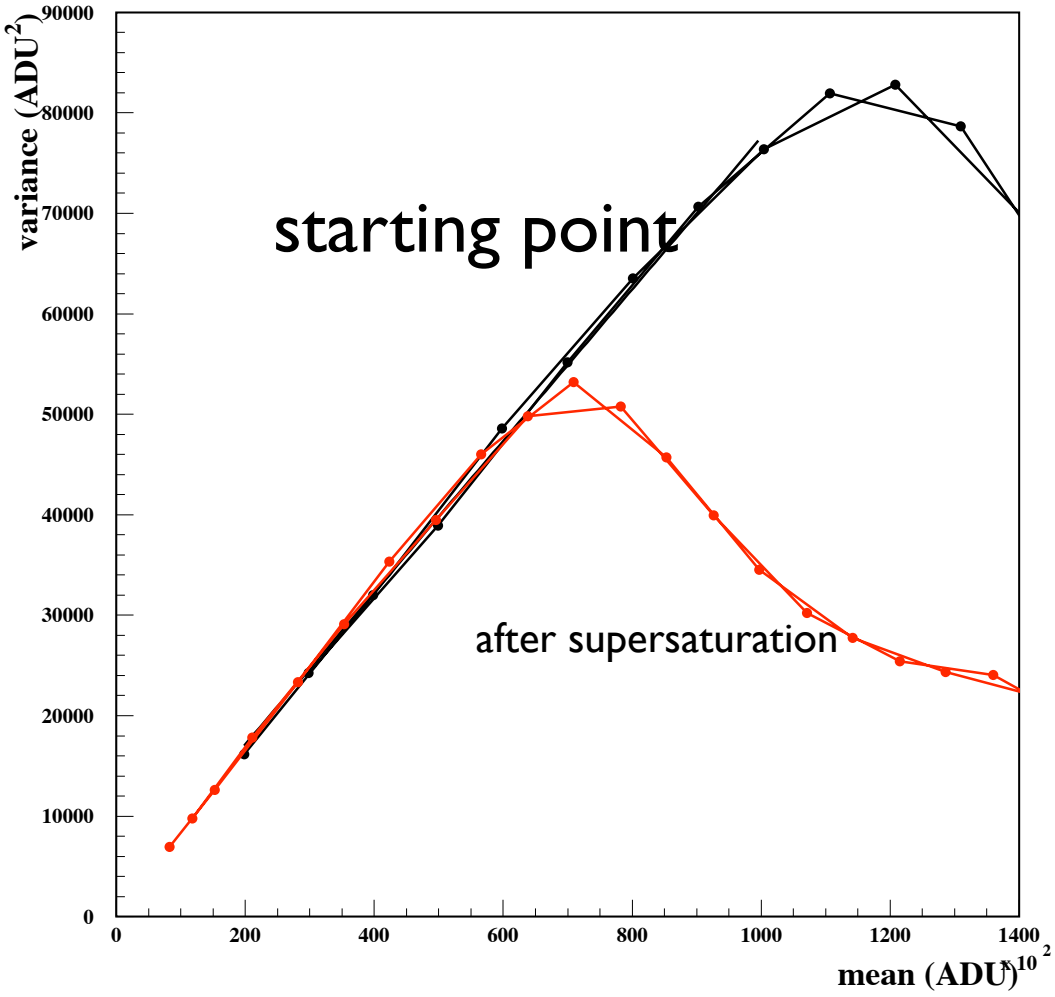
We damaged the detector in our test by going 50V beyond inversion.

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



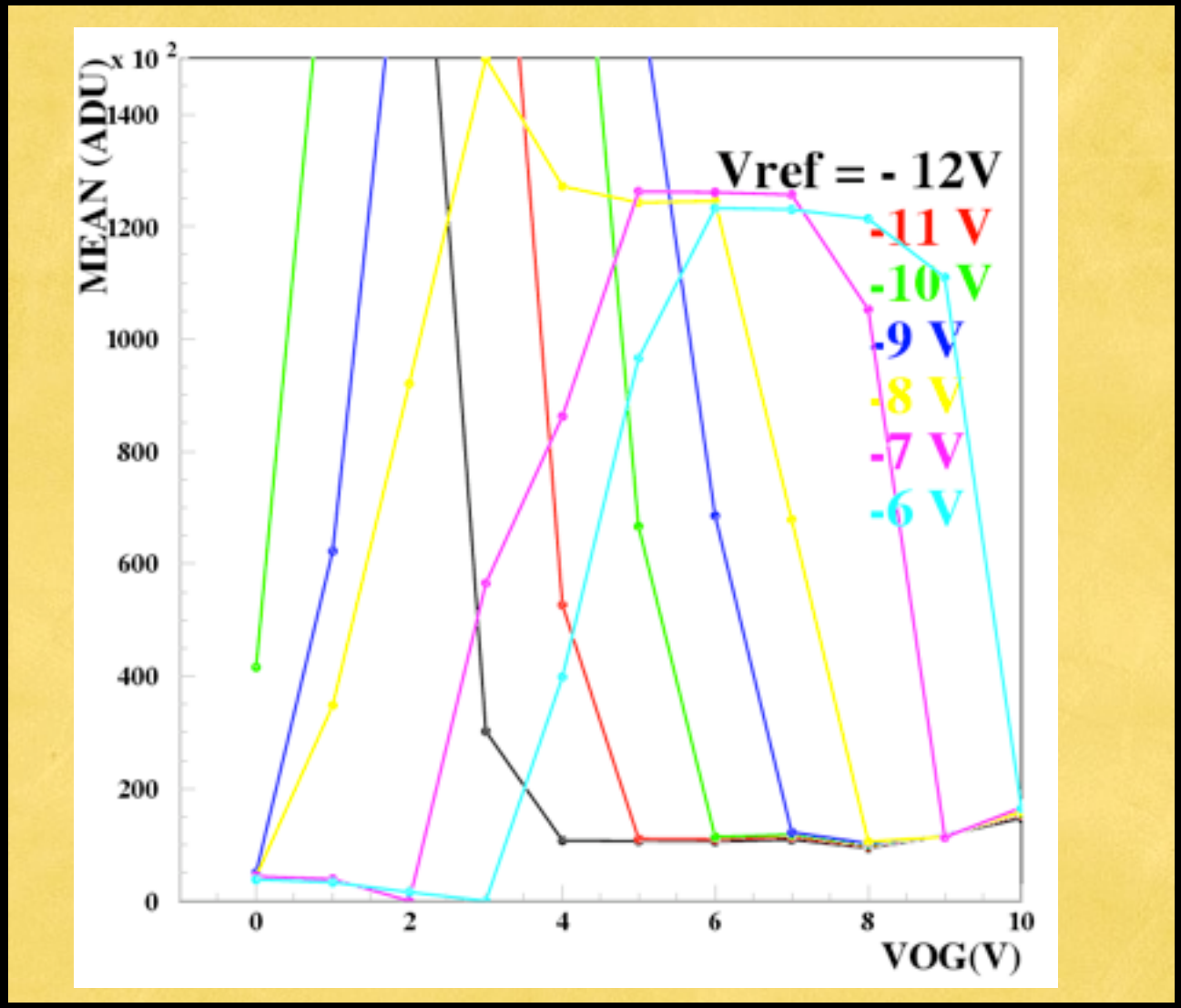
Similar levels of high field in the silicon could also be achieved by accumulating too much charge in the CCD.

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.

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



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

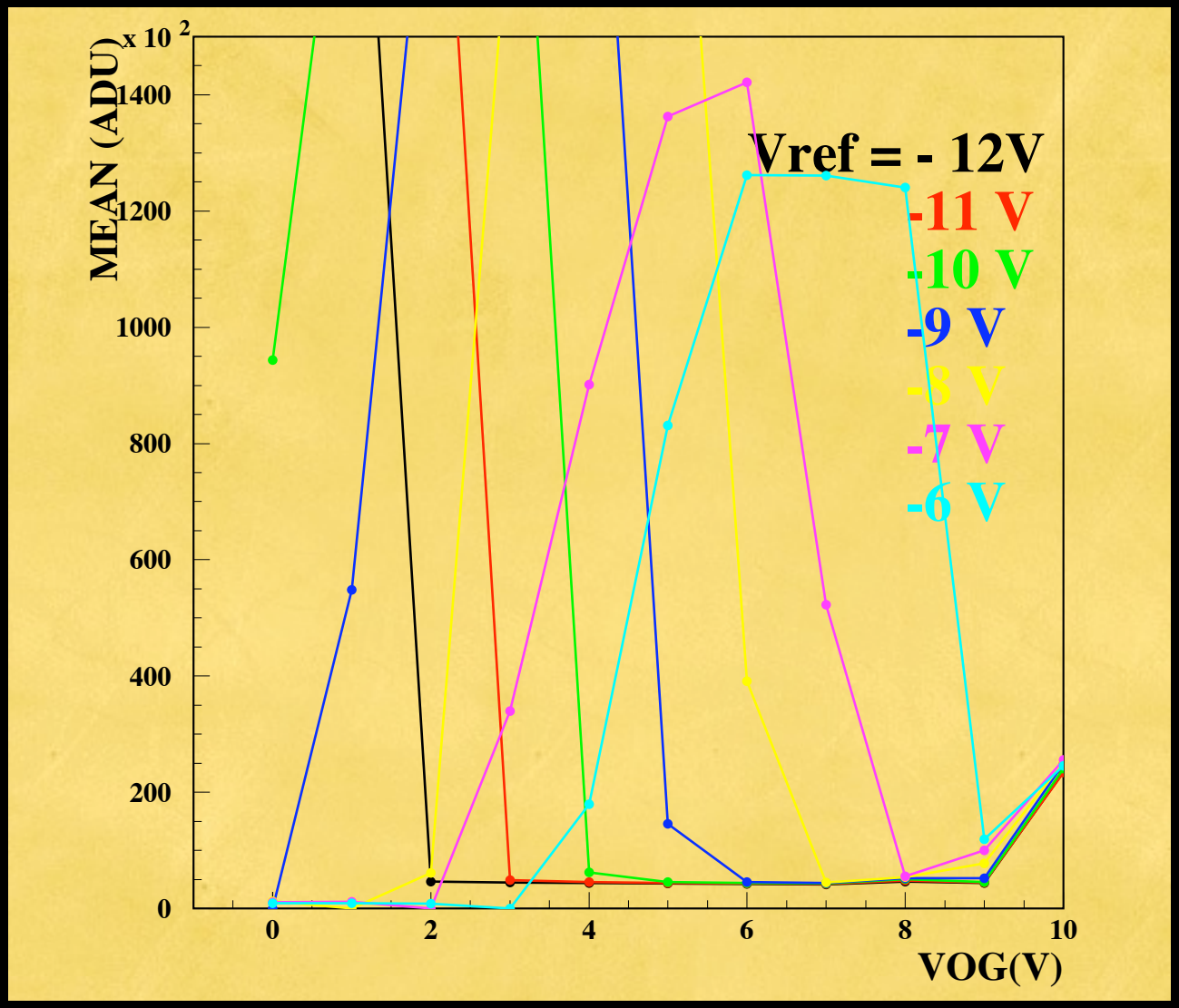
Vref = Vog - Voffset

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)



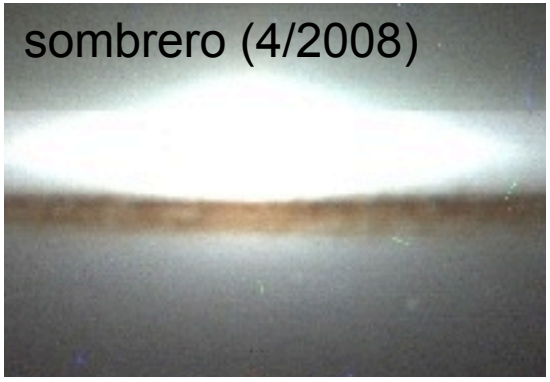
charge injection is produced when the voltage under the Vog gate is below Vref.

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.

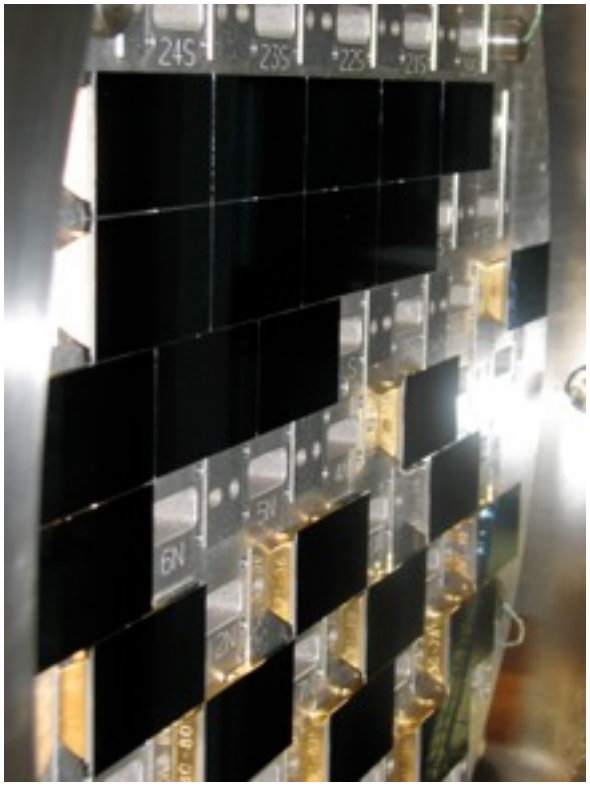


1m telescope at CTIO

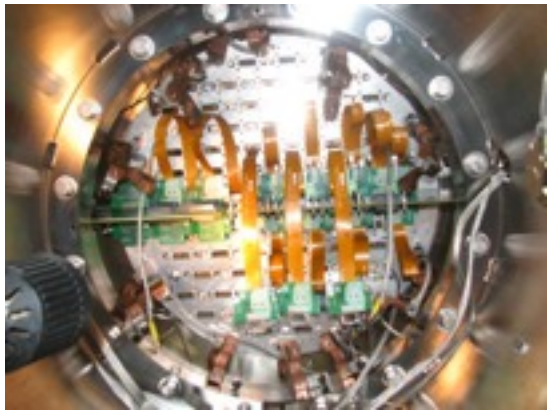
last month completed a new engineering run to understand grounding and filtering at CTIO. **Demonstrated that the DECam production electronics meets requirements when used on the mountain.**

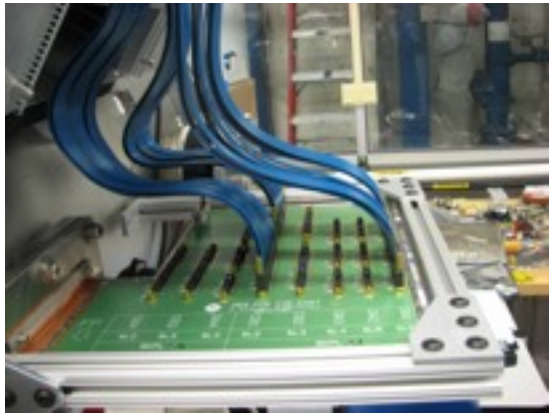
This is also useful for our technical staff to get familiar with CTIO (people, equipment, environment).

operations with prototype mosaic



produced a flat focal plane. Tested cooling system design.





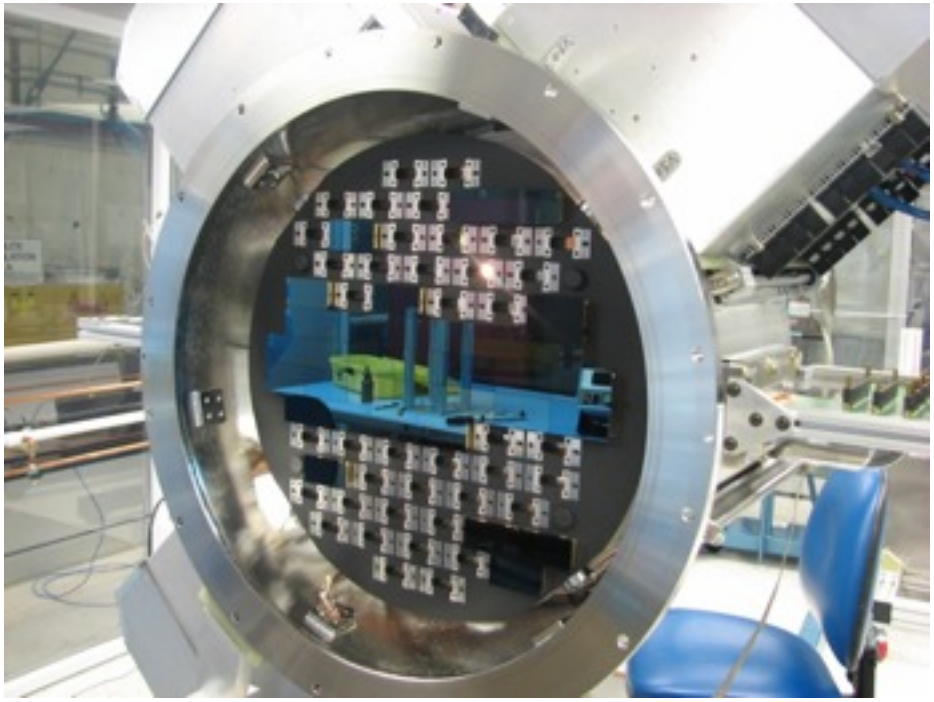
mechanical details as this support also benefited from prototyping cycles.

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