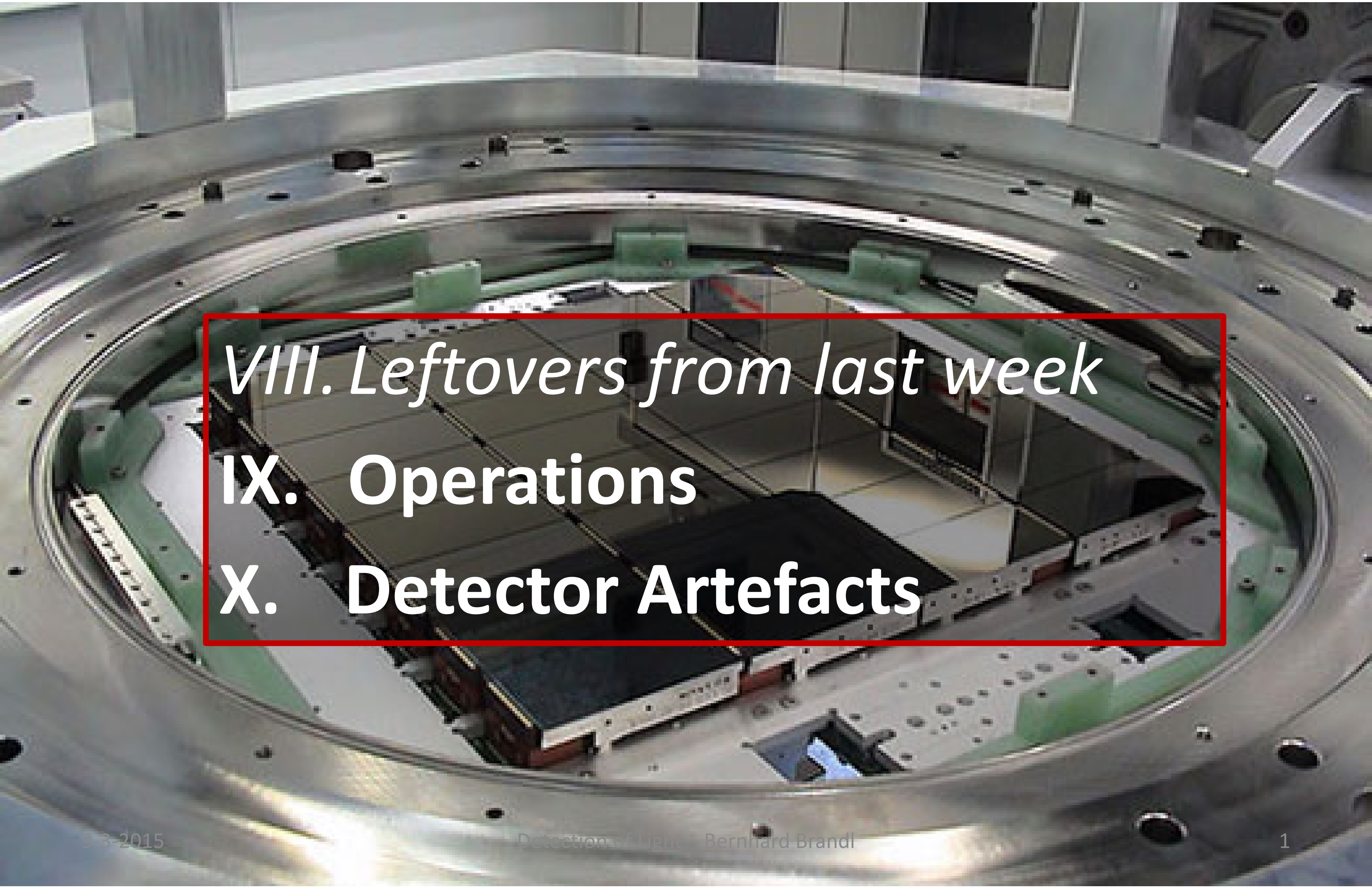
Detection of Light



VIII. Leftovers from last week

IX. Operations

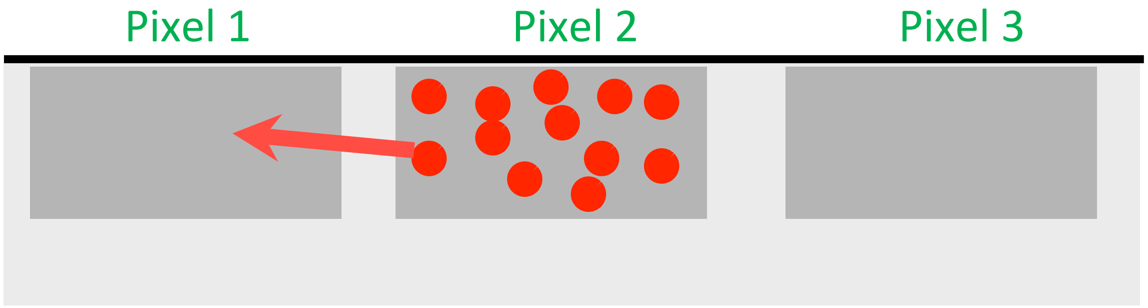
X. Detector Artefacts

CCDs
Charge Transfer Efficiency (CTE)

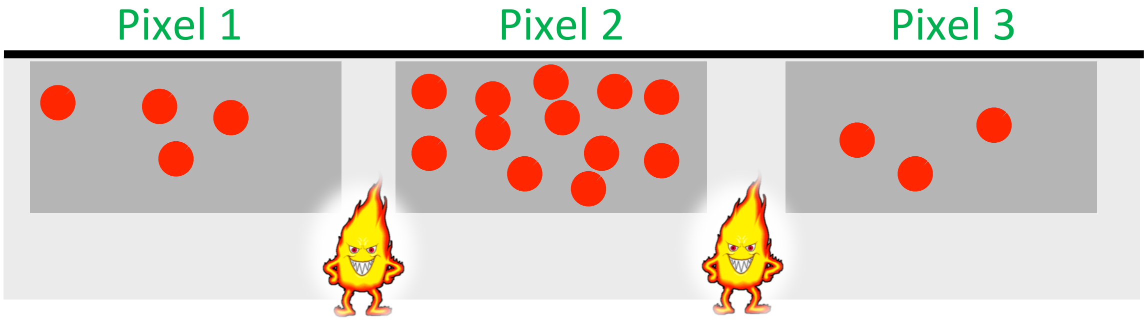
Charge Transfer Efficiency (1)

The CTE is a measure of what fraction of the total number of charge carriers is moved from one pixel to the next.

Problem: A large charge in one pixel will have internal electrostatic repulsion on a characteristic timescale:

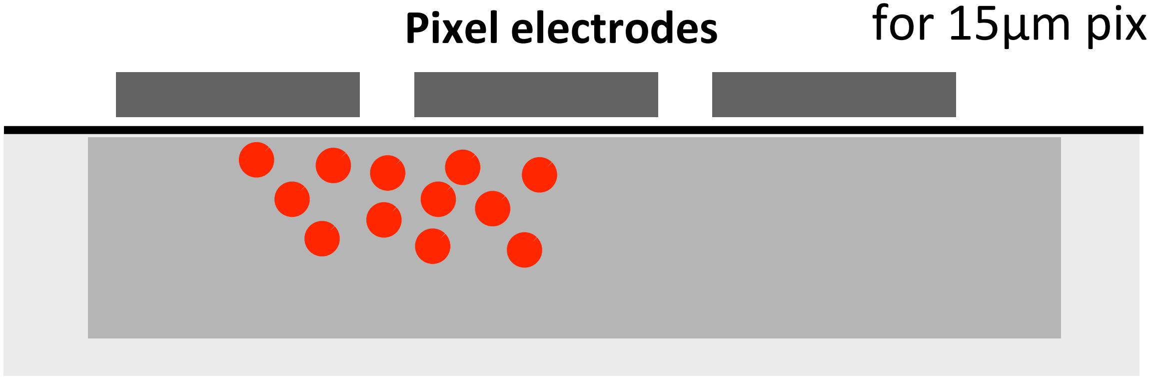


Problem: Thermal diffusion depends on electrode size L_e and diffusion constant D as: $\tau_{TH} \approx \frac{L_e^2}{D}$ (for T=300K, τ_{TH} = 0.026μs)



Charge Transfer Efficiency (2)

Problem: the electric fields near the corners of the electrodes round off corners of pixels ("Fringing fields").



for 15µm pixels, $\tau_{FF} = 0.004\mu s$

For a properly designed CCD with partially filled wells, electrostatic repulsion and fringing fields will dominate.

Approximation for the CTE of a CCD with *m* phases:

$$CTE = (1 - e^{-t/\tau})^m$$

Noise from Charge Transfer

Noise from charge transfer inefficiency: $\varepsilon = (1 - CTE)$

A total of εN_0 charges are "left behind", and the noise on them is $(\varepsilon N_0)^{1/2}$ in each transfer.

In n transfers the net uncertainty is $N_{n,TL} = (2\varepsilon n N_0)^{1/2}$

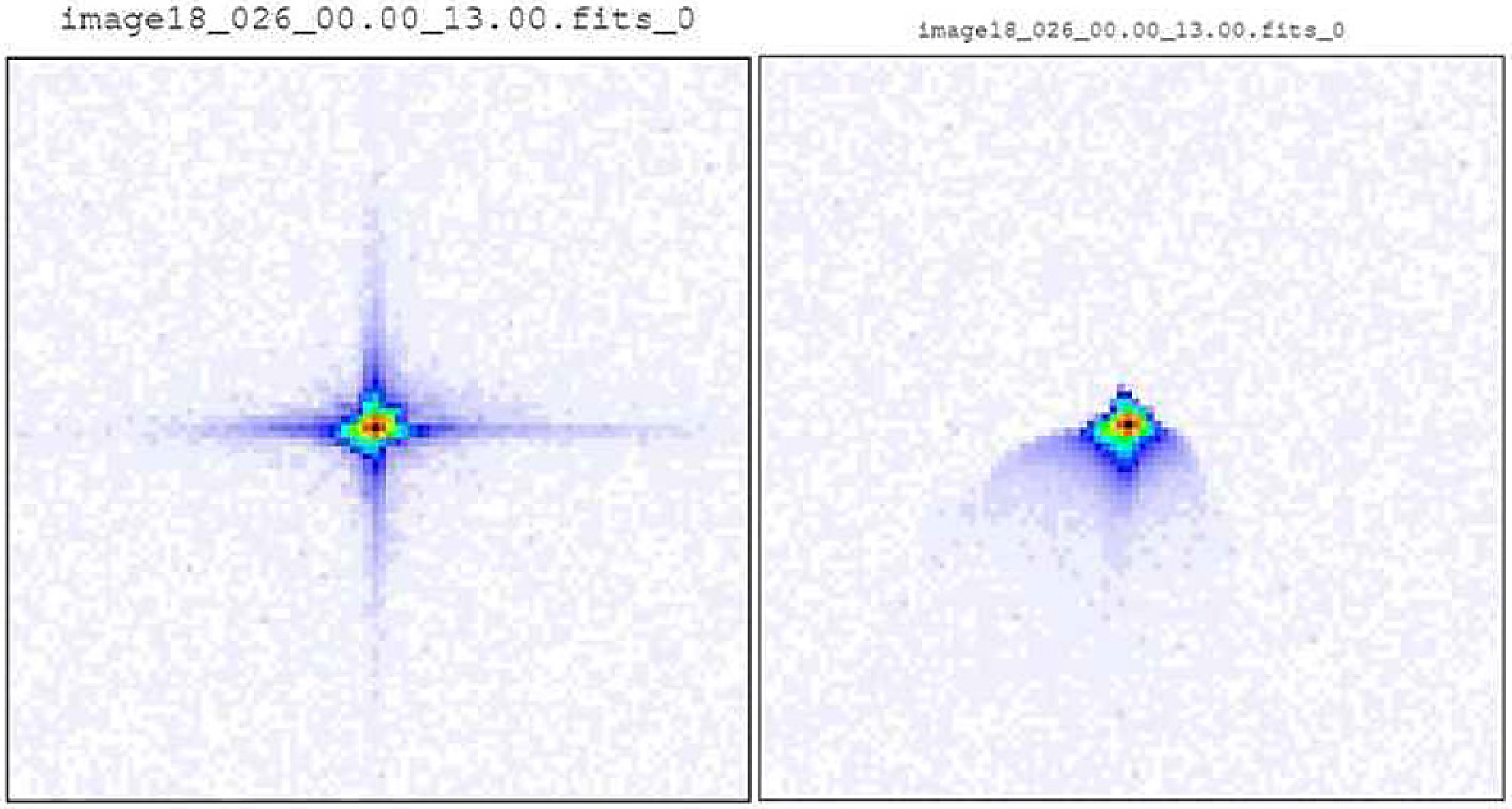
Noise from trapping of charge carriers in incomplete bonds in the Si-SiO_2 interface. Traps will be occupied in equilibrium, but subject to statistical fluctuations with noise

$$N_{n,T} = (2kTnN_{SS}A)^{1/2}$$

(N_{SS} is the density of traps, and A the interface area)

Example: the CCDs aboard GAIA

Cosmic radiation affects the CTE and the point spread function (PSF)



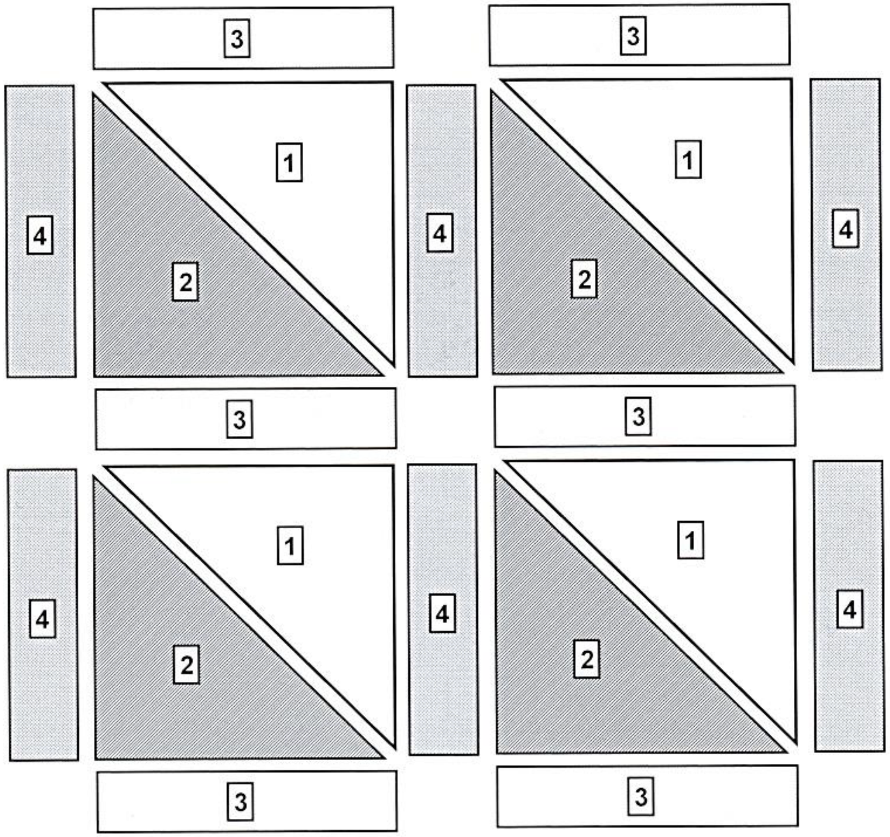
Output from the Gaia CCD model showing the effects of radiation damage. Left: Image of a 13-th mag G2V star before radiation damage. Right: Image of the same star after a 10^{10} proton (10 MeV equivalent) displacement damage dose.

OTCCD, CID & CMOS

Orthogonal Transfer CCDs (OTCCD)

OTCCDs can move charges in two dimensions.

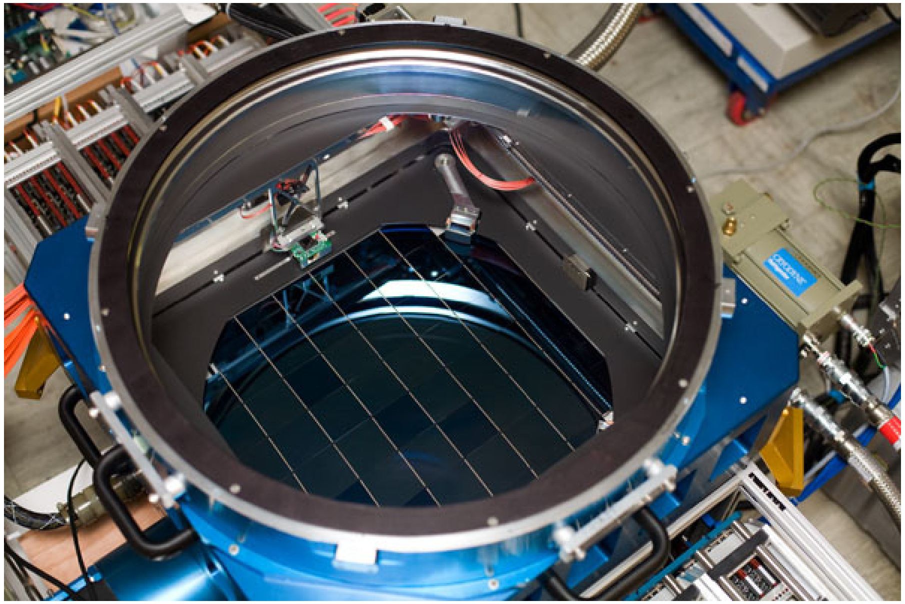
- To move a charge to the right, `3’ is negative to act as channel stop, `1’, `2’, and `4’ are operated as a conventional CCD.
- To move a charge up, `4’ is negative to act as channel stop, `1’, `2’, and `3’ are operated as a conventional CCD.
- Moving to the opposite directions: reversing the clocking.

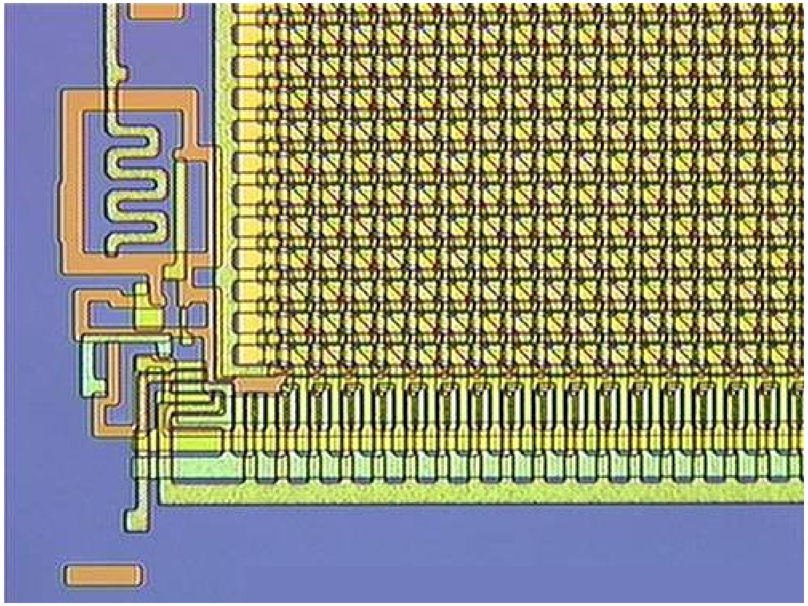


Example: Pan-STARRS (1)

The Panoramic Survey Telescope & Rapid Response System (Pan-STARRS) is a wide-field imaging facility that observes the entire available sky several times each month.

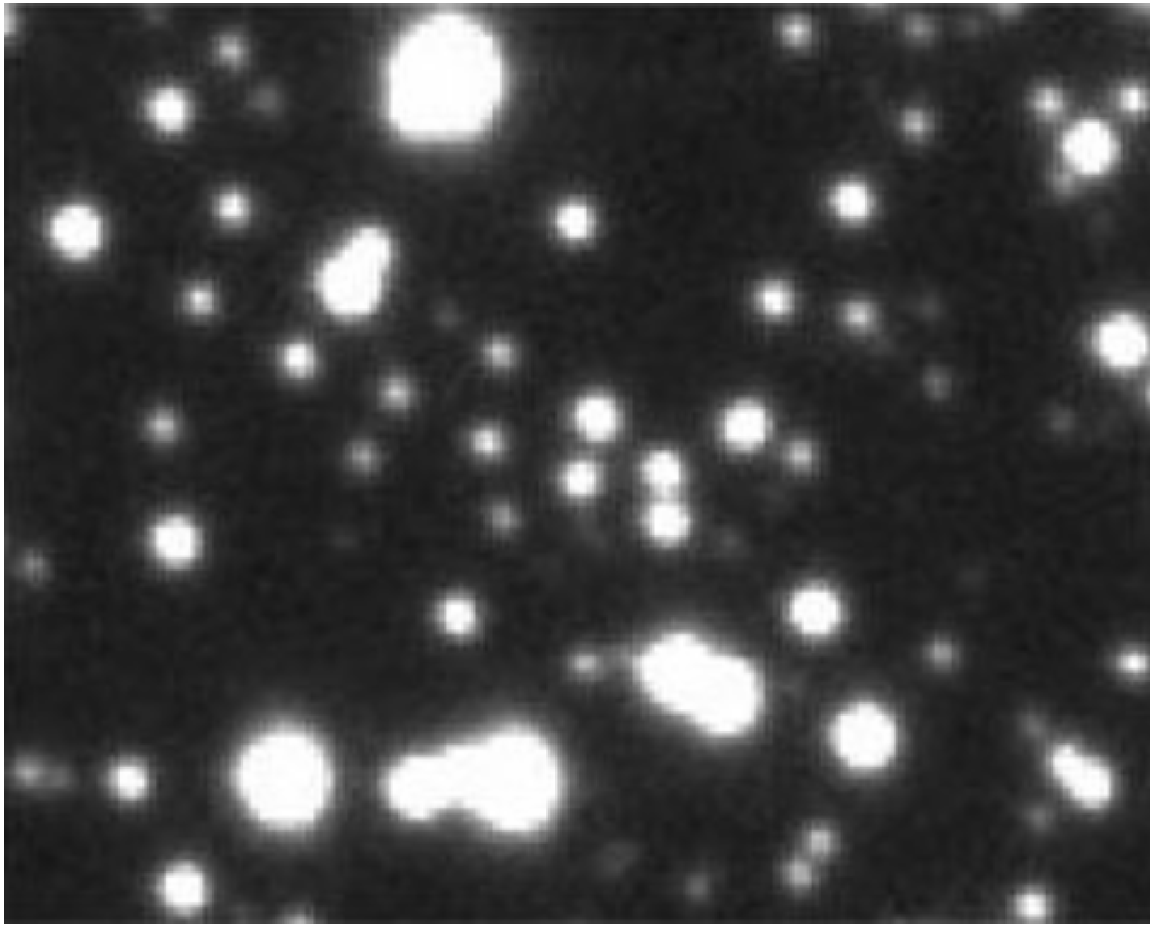
Pan-STARRS combines four 1.8m telescopes with the largest digital cameras ever built. Each camera has a 64 × 64 array of OTCCD devices, each containing approximately 600 × 600 pixels, for a total of about 1.4 Gpix.





Example: Pan-STARRS (2)

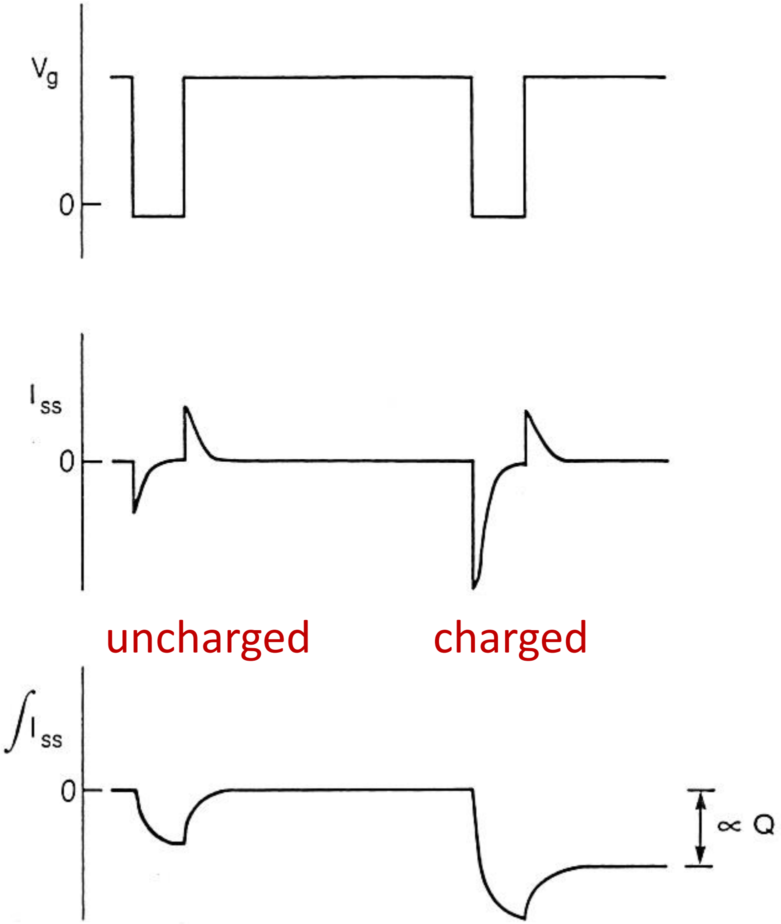
If we can follow the motion of the star on the array, we can compensate for atmospheric tip tilt motion, i.e., improve resolution and sensitivity (analogous to a classical “tip-tilt” mirror system).



Charge Injection Devices (CIDs) (1)

Principle: two electrodes within one pixel “slosh” electrons from one side to the other, acting as a capacitor - apply an electric pulse to the capacitor.

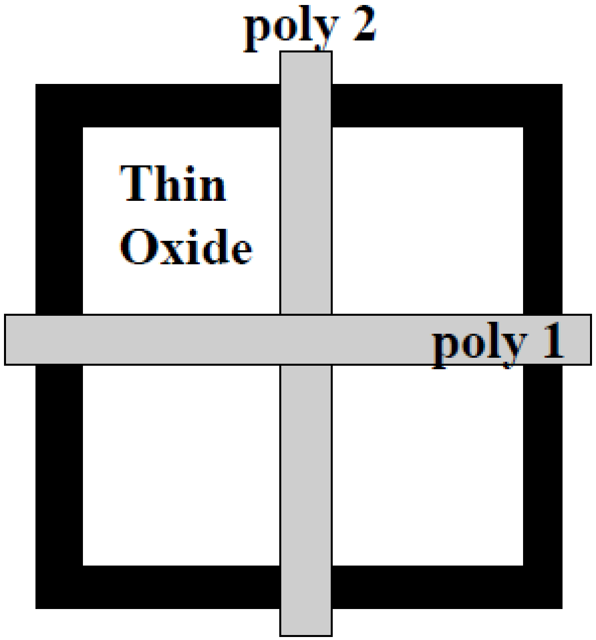
- if uncharged the response will be symmetric and the integral over the current will be zero
- if charged the waveform will be asymmetric: asymmetry ∝ charge
- measure integral over I_{SS}



uncharged charged

Charge Injection Devices (CIDs) (2)

Each pixel consists of a pair of MOS capacitors. The two capacitors run perpendicularly to each other and are known as collection and sense pads.



Pros and cons of CIDs:

+ non-destructive reads possible

+ robust in low radiation environments

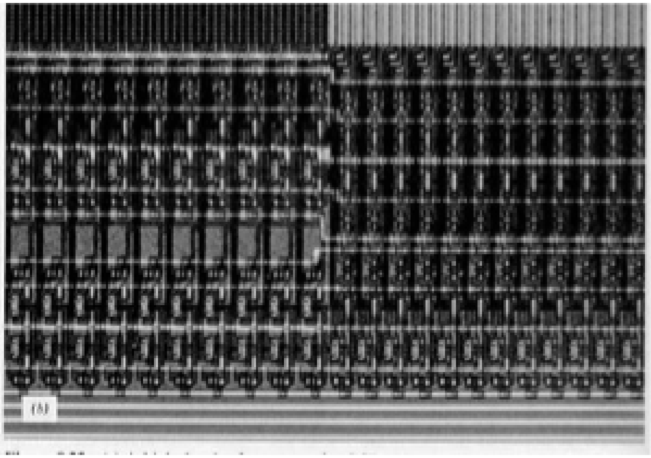
+ large fill factor and good pixel uniformity

– large read noise because an entire row of MOS capacitors is connected at one time.

http://www.photonics.com/EDU/Handbook.aspx?AID=25130
http://www.photonics.com/Article.aspx?AID=52489

Complementary Metal-Oxide-Semiconductors (CMOS)

Nowadays, transistors are tiny and high performance arrays can be manufactured in complementary CMOS devices = Si photodiodes + R/O circuitry on a single Si wafer (analogous to hybrid arrays but in one unit)



Pros and cons of CMOS:

+ much less sensitive to radiation damage

+ allow simplified systems design

– only 70 – 80% fill factor

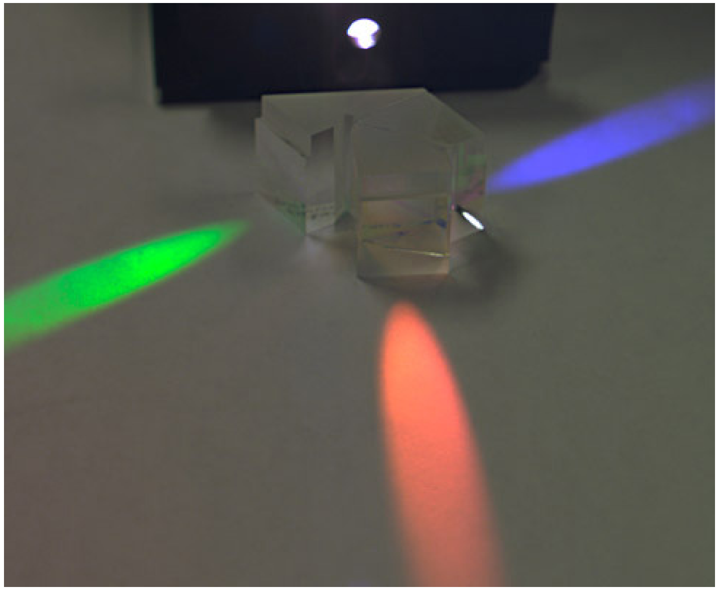
– ~50 e^- read noise

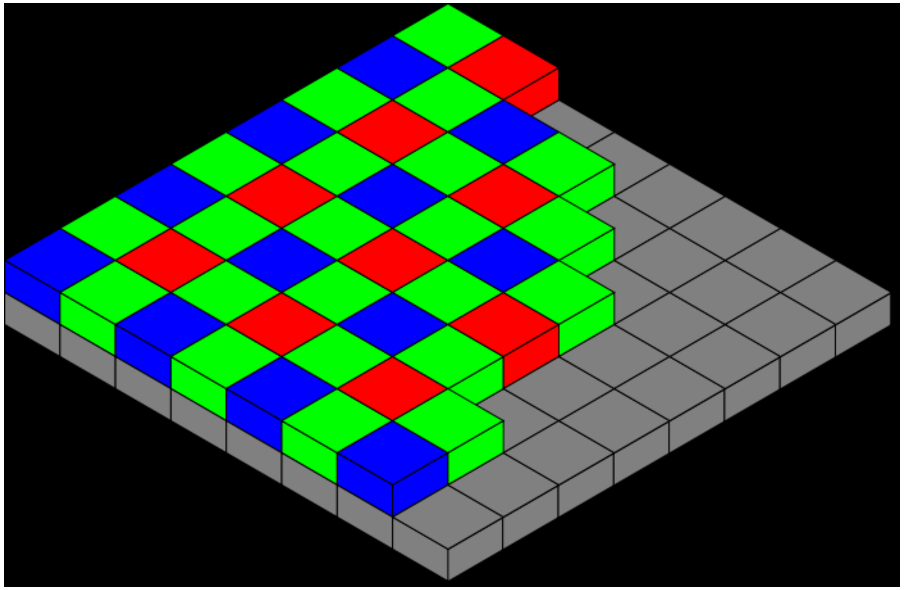
Fill factor may be increased with micro-lens arrays

Colour CCDs

Essentially three ways to produce color (from Wikipedia) :

1. Take three exposures through three filters subsequently – standard for astronomy (only works for fixed targets).
2. Split the input beam in three channels, each with a separate and optimized CCD (very expensive cameras).
3. Use a Bayer mask over the CCD – each subset of 4 pixels has one filtered red, one blue, and two green (reduced fill factor).

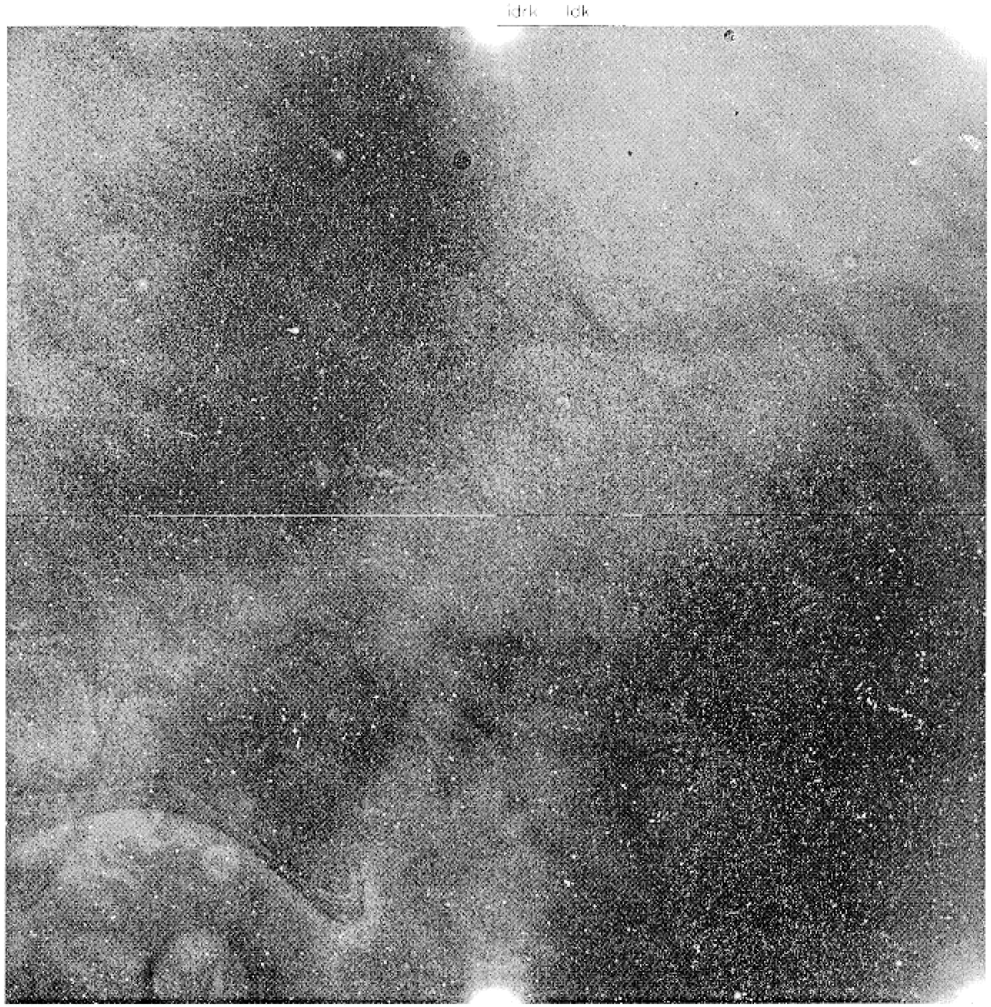




Detector Artefacts

Pixel-to-Pixel Gain Variations

Not all pixels respond equally to incoming photons → uniform illumination produces structure → take out by “flat fielding” (=multiplication with normalized, inverse pixel response).

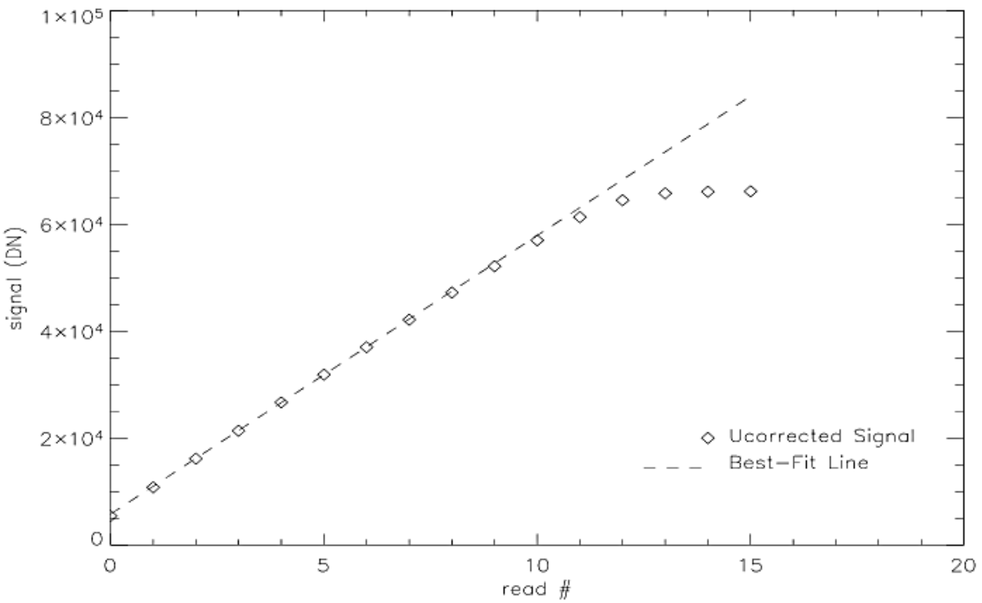


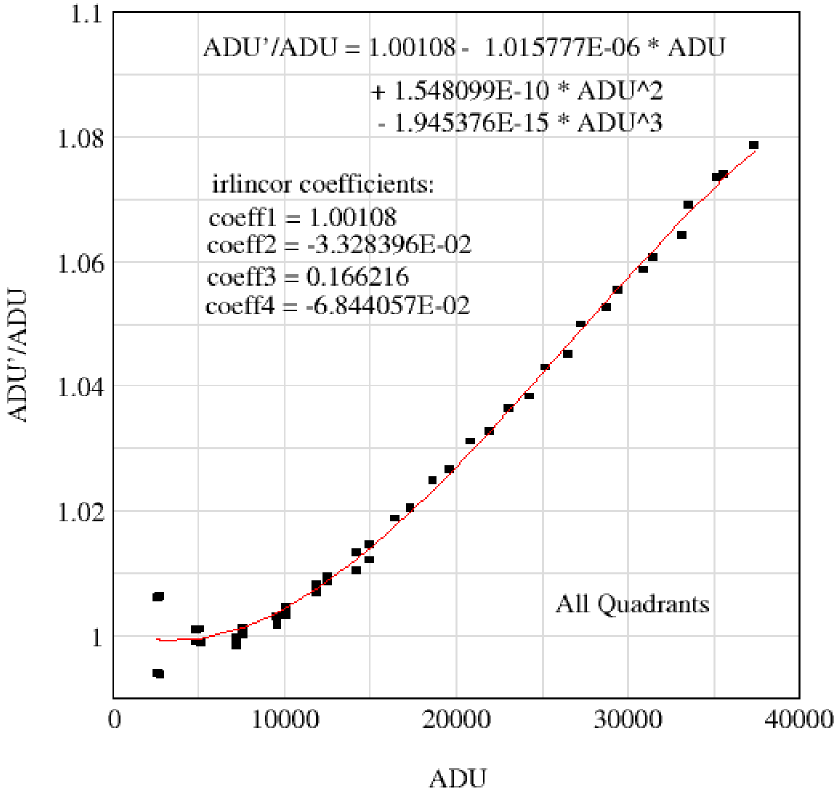
Non-Linearity

All photosensors respond non-linear as the photo-electric charge approximates the pixel full well capacity.

Examples:

HST-WFC3: The linearity correction fitted by a 3rd order polynomial.



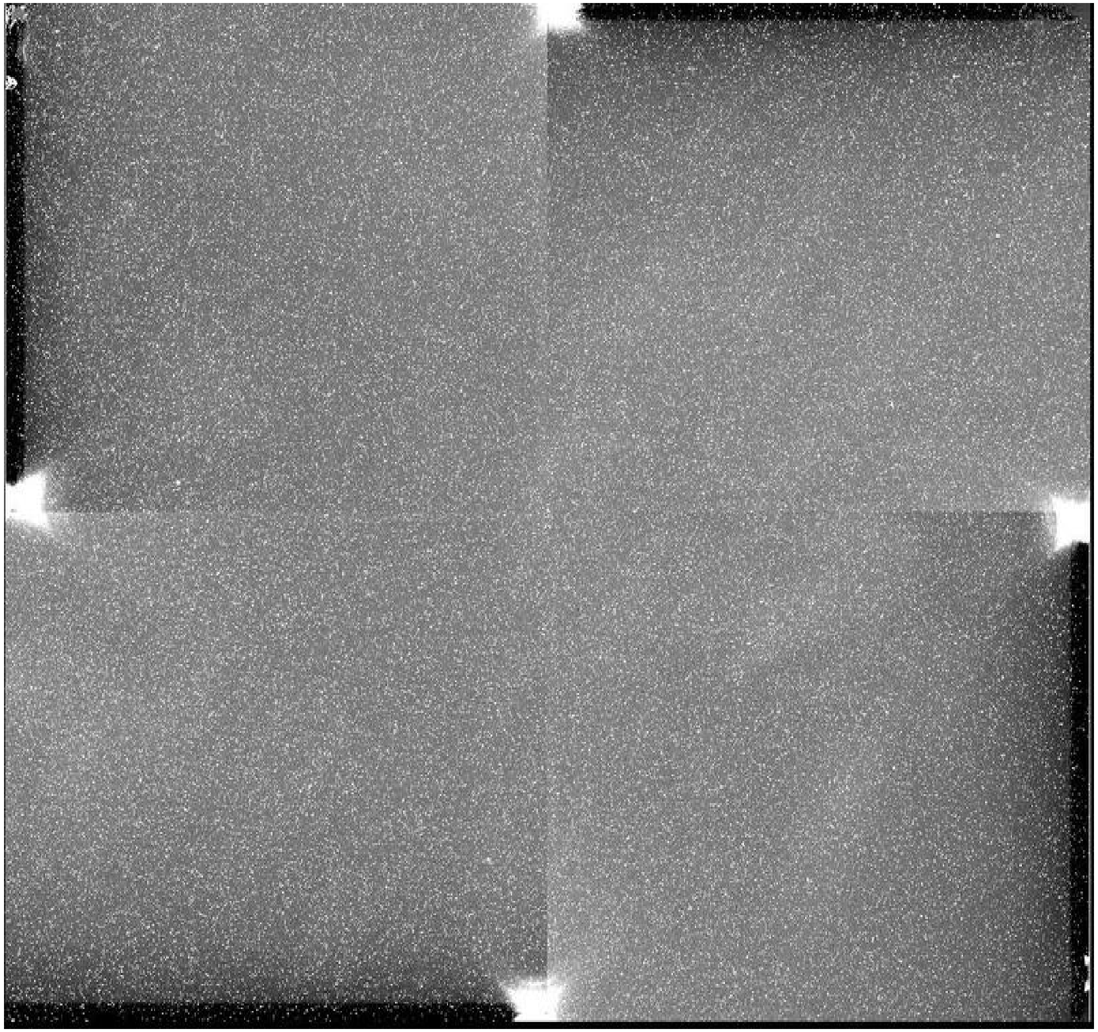


HgCdTe non-linearity coefficients

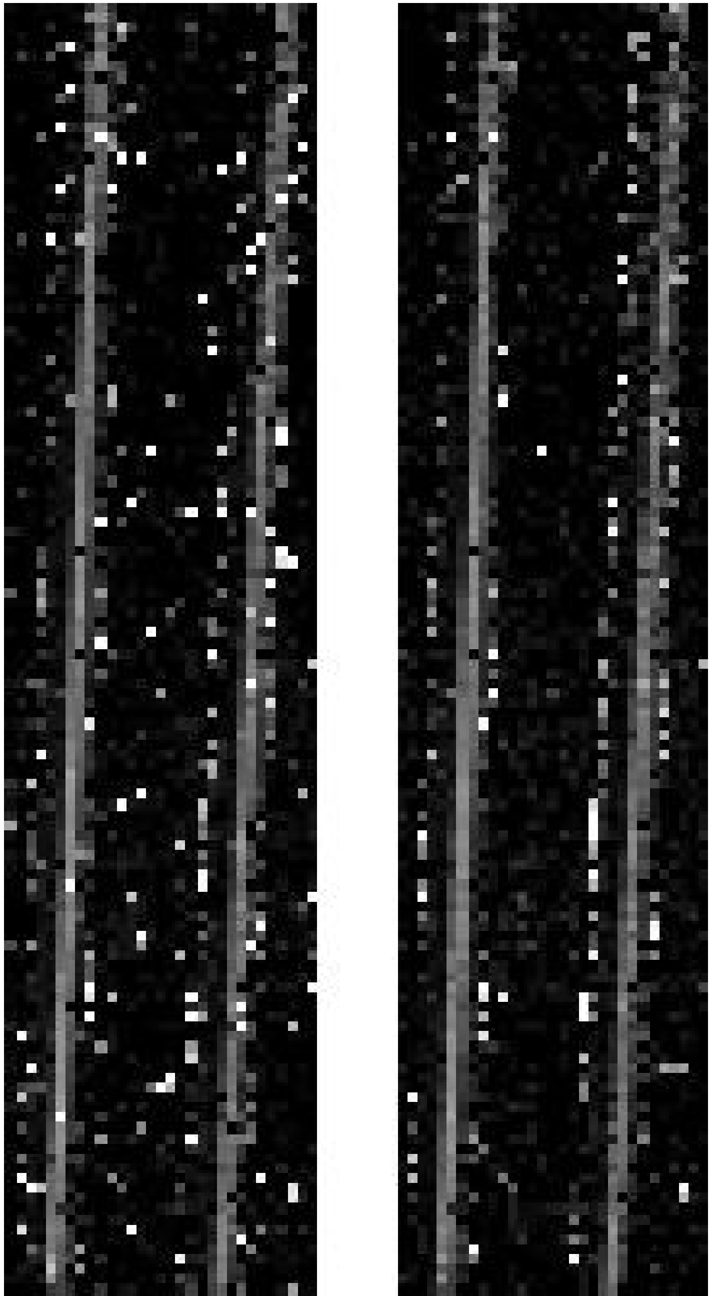
Thermal Glow from Pre-Amplifiers

PROBLEM:
Electro-luminescence and thermal glow are problems for active devices

SOLUTION:
Switch off the amplifiers (MOSFET transistors) whilst integrating on your astronomical source.



Dead, Hot, & Rogue Pixels



Dead Pixel: a defective pixel that delivers no signal and cannot be used.

Hot Pixel: Highly elevated signal and noise level. It usually remains “hot”, but may deliver limited information.

Rogue Pixel: Has very high dark current and/or abnormal photon responsivity (similar to a hot pixel) but may be “healed” with annealing or other techniques.

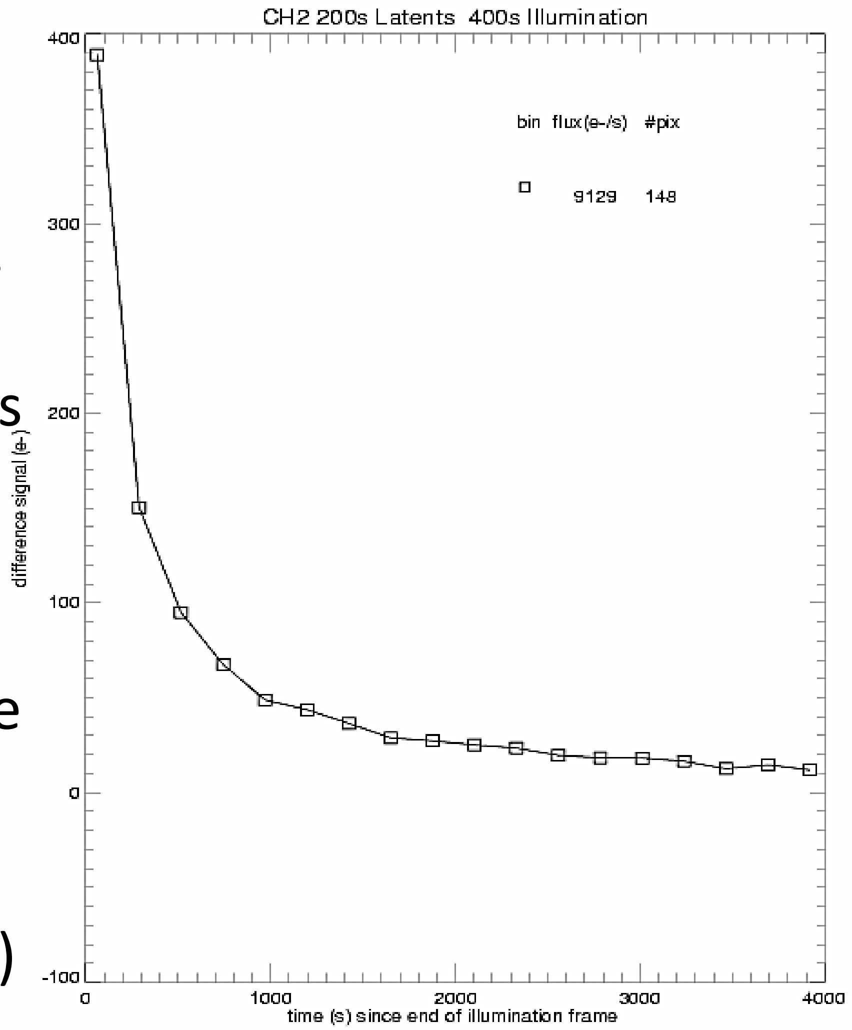
Mitigations:

- assign it ‘NaN’ in your data reduction
- interpolate from nearest neighbor values
- subtract off an off-source image
- reduce bias voltage

Latent Images

PROBLEM:

After strong illumination a small fraction of the photoelectrons are trapped. The traps may release a hole or electron long after the illumination. Residual images are typically less than 1% but still can create severe problems



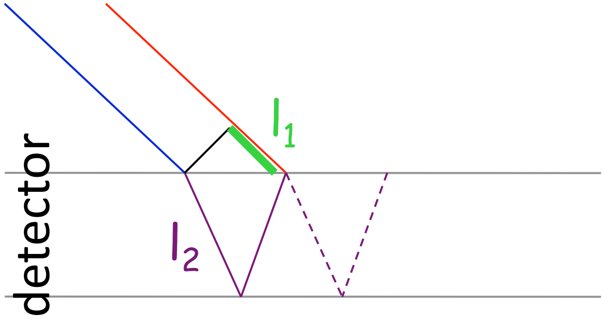
SOLUTIONS:

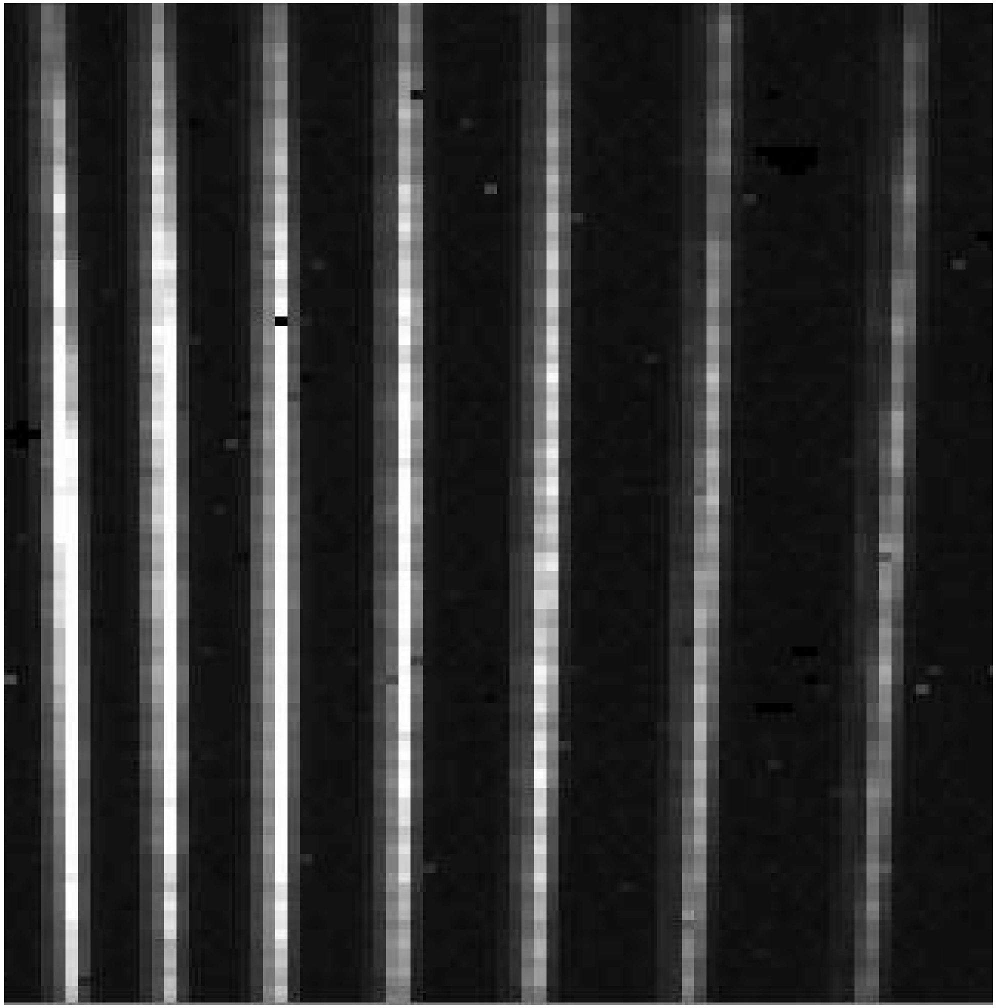
- Wait (and wait, and wait....)
- Apply frequent resets (clean out the trap)
- Annealing (heat up array to thermally excite them into mobility)
- Use ND filters or shutter during target acquisition

Detector Fringing (in Spectrographs)

PROBLEM:

Photons reflect off the back of the detector and interfere with the incoming light





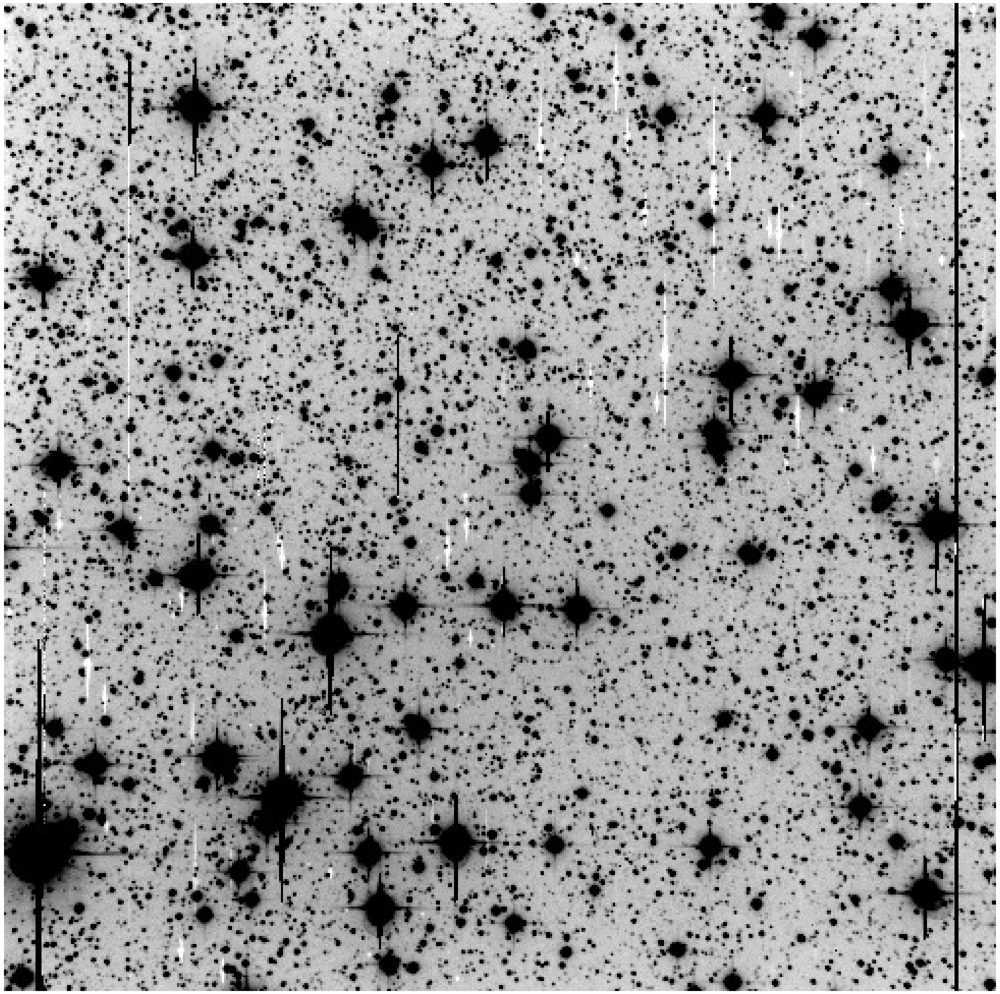
If the phase difference between **l_1** and **$n \cdot l_2$** is an even multiple of π constructive interference occurs. If an odd multiple destructive interference occurs

Crosstalk

Multiple simultaneous amplifier readouts lead to "crosstalk"

PROBLEM:
The signal from a strongly illuminated pixel can couple into an adjacent amplifier readout board and appear as a "ghost" image.

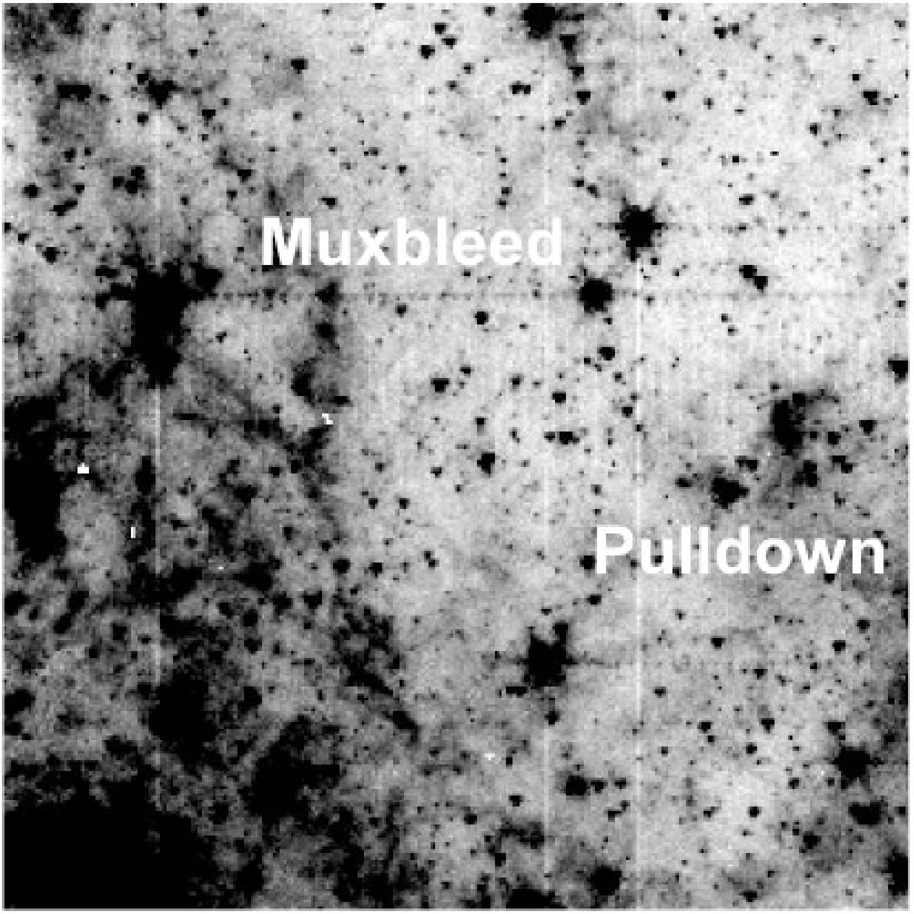
The negative (white) images in the upper right quadrant correspond to the black star images in the lower left quadrant

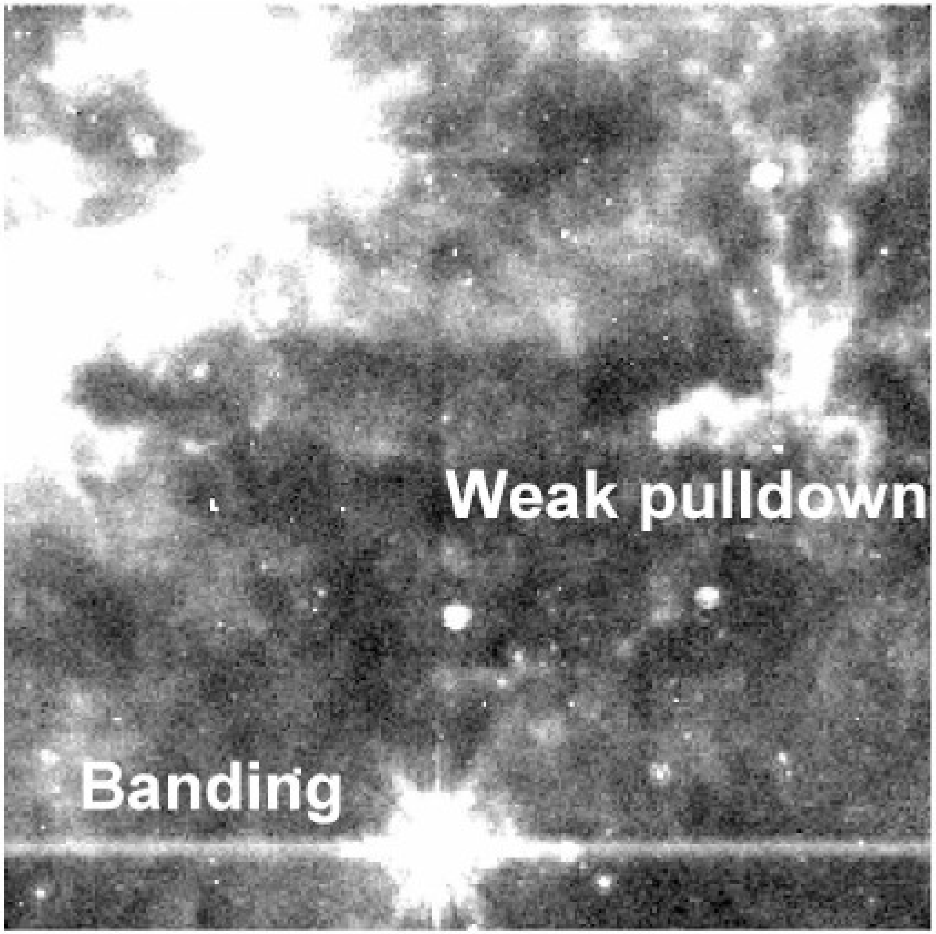


Pulldown & Bleeding

PROBLEM:

Pulldown occurs due to a depression of the bias voltage in columns containing very bright/hot pixels





Readout Schemes

Reminder: Detector Readouts

How to get it from a pixel to the computer?

The CCD approach:

- Pixel charges are shuffled across other pixels over to a readout column, which is then itself read out through a single amplifier.
- simpler architecture: cheap to make and duplicate *en masse*, established technology.

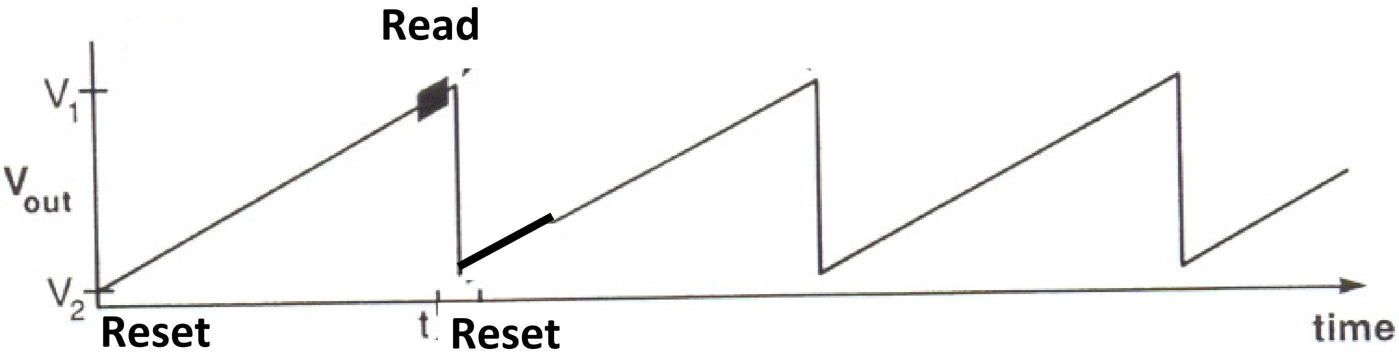
The IR Array approach:

- Having a separate multiplexer allows for direct pixel addressing
- non-destructive reads: the charge on the detector layer is not altered by sampling it - think measuring the charge on a capacitor.
- But complex electronics: expensive!

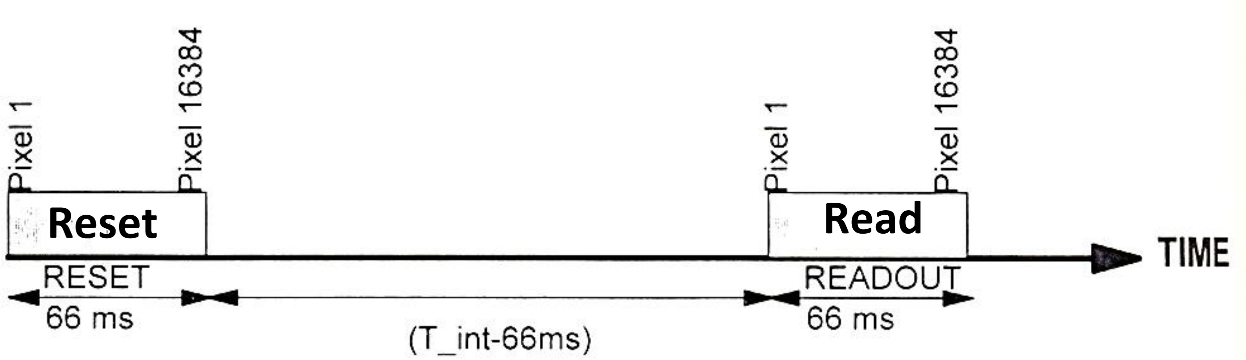
Next, we'll focus on IR array readouts.

Single Sampling

The simplest approach …

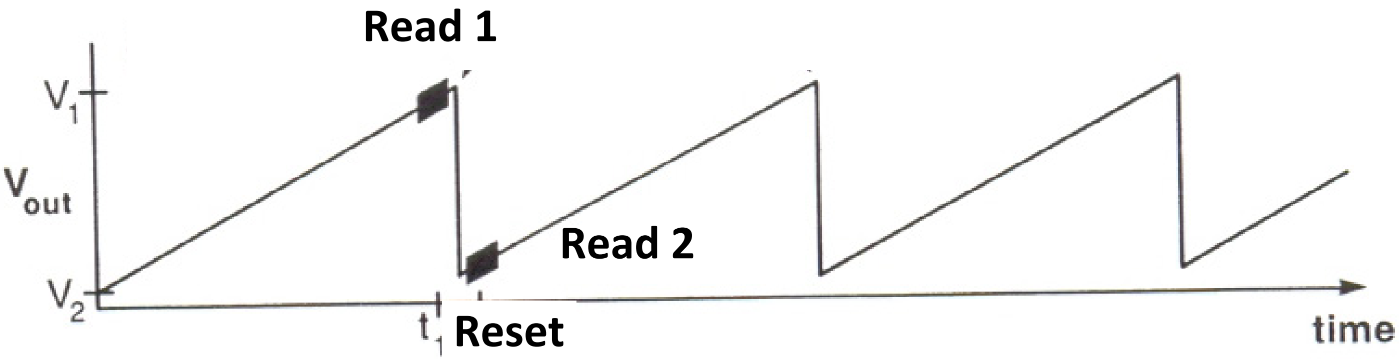


- Does not remove kTC noise or voltage drifts
- It directly measures the signal level (we would notice saturation)



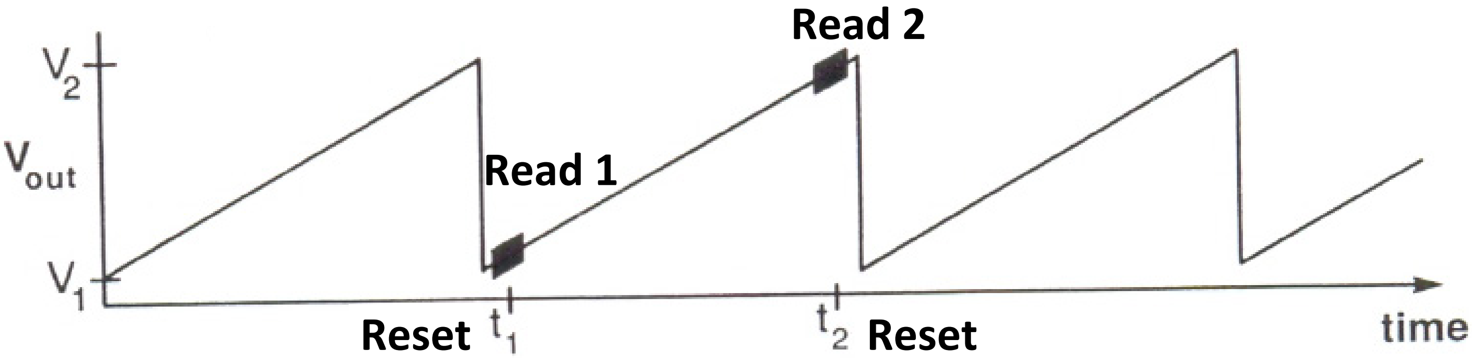
Double-correlated Sampling

Reads pixel twice (before and after the reset)

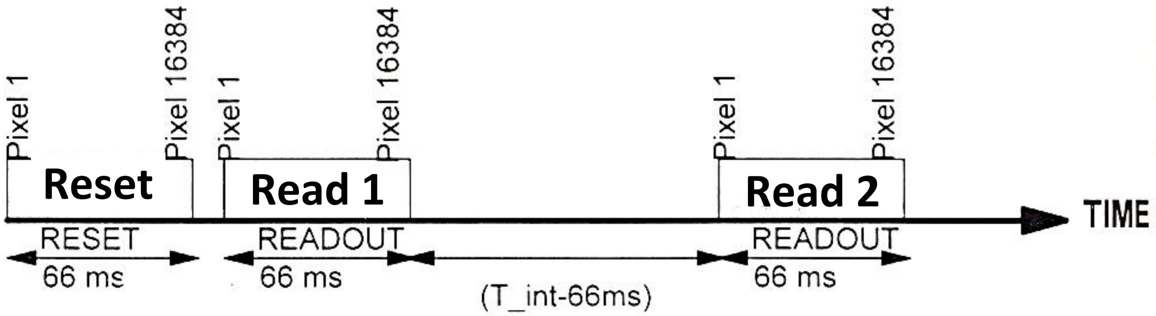


- Signal = Read 1 - Read 2
- Voltage drifts are subtracted out
- "read-reset-read" → difference is measured for each pixel before moving to the next → simplified, lower data rates
- Does not eliminate kTC noise since offset is subtracted from the *previous* frame.
- Watch out: *saturated – saturated = 0*

Reset-Read-Read

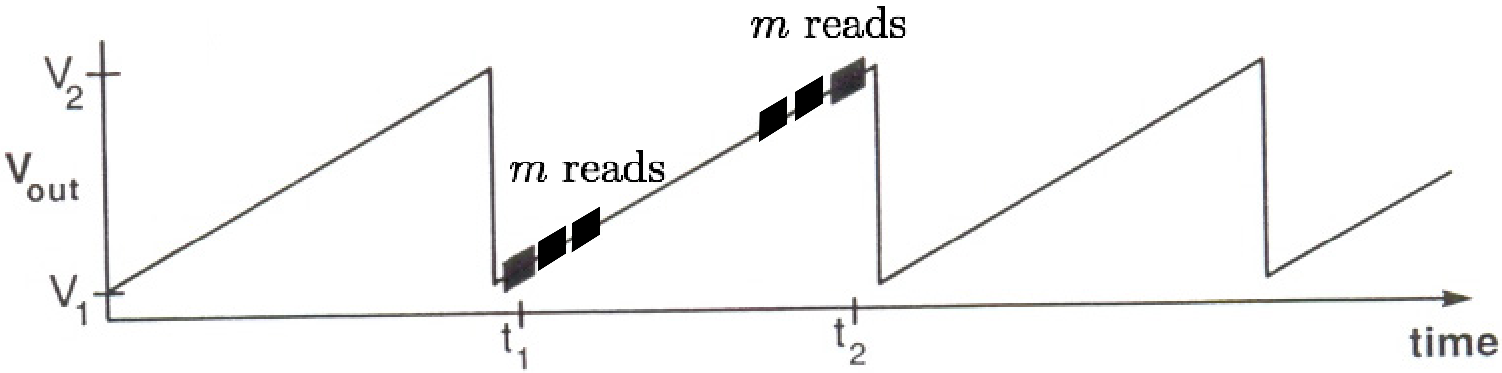


- Resets the array pixel-by-pixel (or column-wise)
- Reads the array pixel-by-pixel at the start and at the end of the integration
- Signal = Read(2) – Read(1)
- Advantage: best correlation, no reset noise
- Disadvantages: requires frame storage, reduced dynamical range



Multiple (Fowler) Sampling

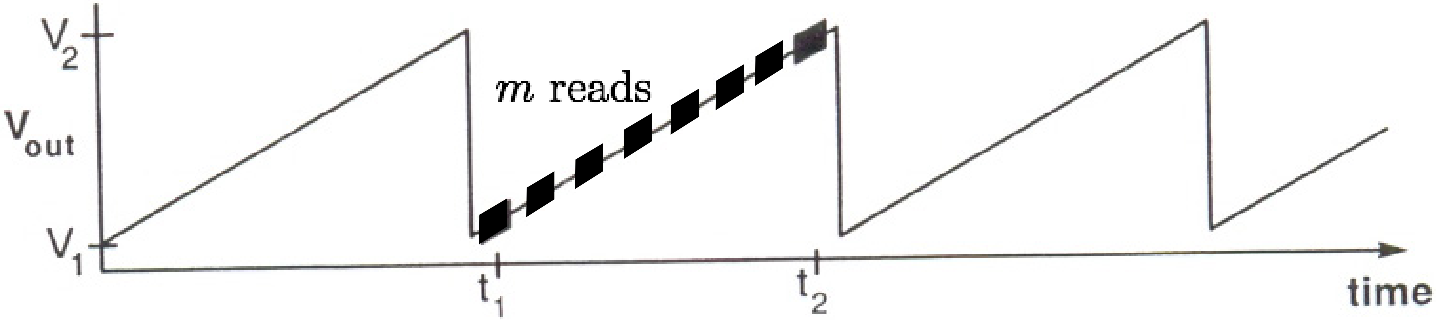
Uses multiple reads at start and end of the integration time to reduce the read noise.



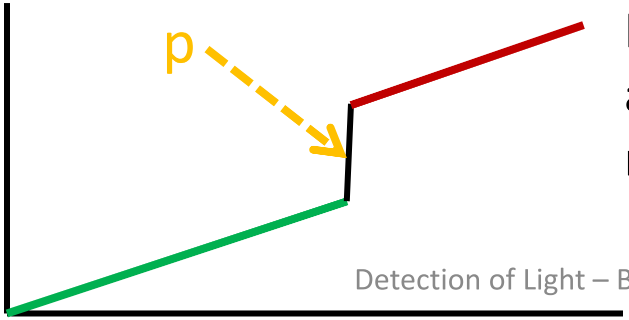
- Signal = Mean(Read 2) - Mean(Read 1)
- *m* reads get coadded in buffer (no separate frame storage)
- Readout noise is reduced by √m over reset-read-read
- Longer time to carry out a given integration

Sampling "up-the-ramp" (SUR)

Uses *m* equally spaced reads during the integration



- make a fit to the slope to get flux rate
- reduces readout noise by $\sqrt{m}$ until 1/f noise limit
- Disadvantage: fitting requires storage of *m* frames
- very useful in space when cosmic ray hits occur



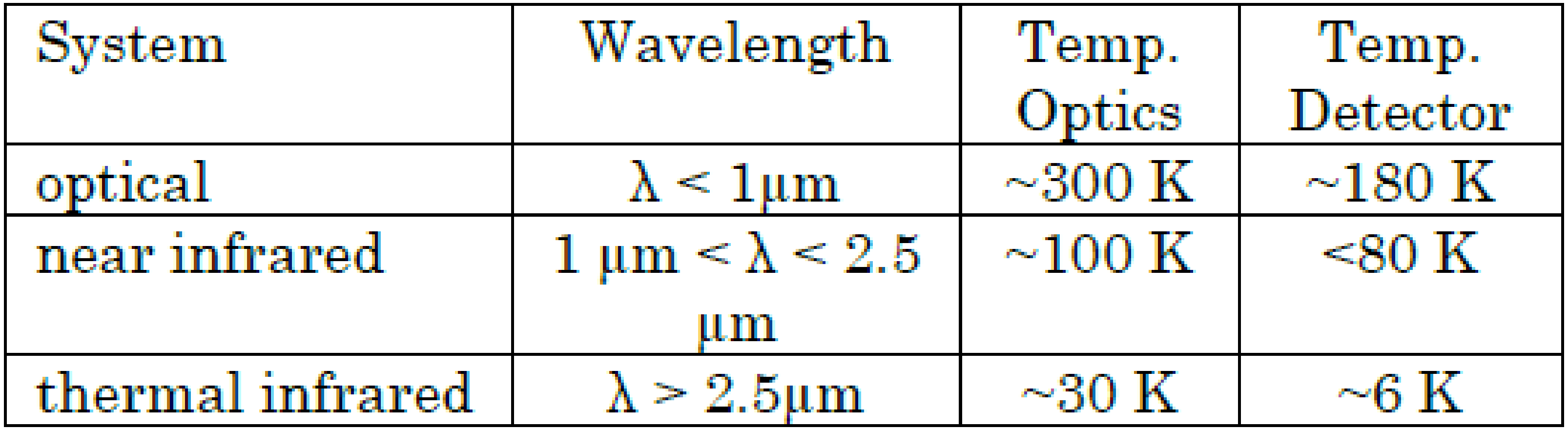
Ideally, the slope does not change and the information can still be recovered after the proton hit.

Vacuum & Cryogenics

Need for Cooling

Cooling is essential to …:

1. Avoid thermally excited charge carriers (dark current)
2. Reduce thermal emission from the surrounding optics



System	Wavelength	Temp. Optics	Temp. Detector
optical	$\lambda < 1\mu m$	~300 K	~180 K
near infrared	$1\ \mu m < \lambda < 2.5\ \mu m$	~100 K	<80 K
thermal infrared	$\lambda > 2.5\mu m$	~30 K	~6 K

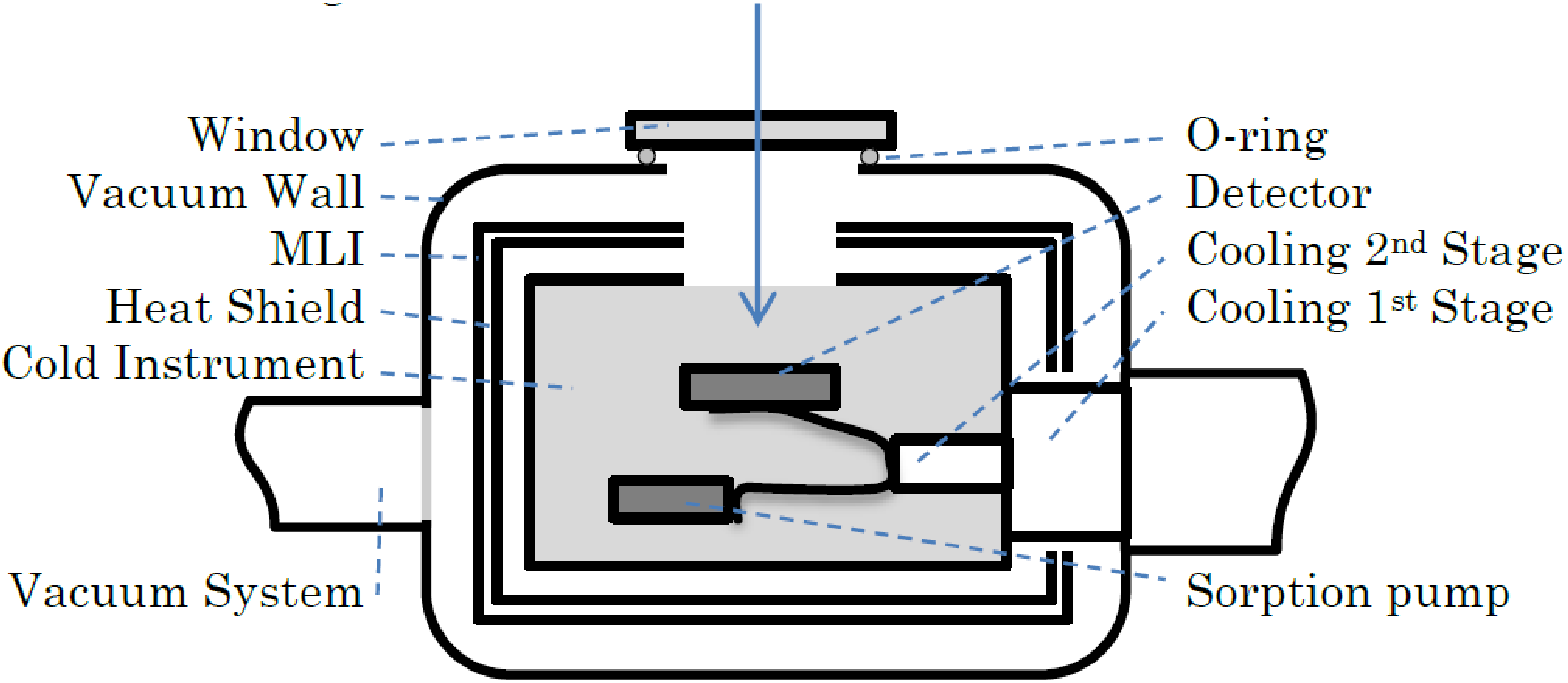
Cooling requires Vacuum

…or everything will be covered by ices…!

Vacuum	Pressure	Comment
Normal pressure	10^3 mbar	3×10^{19} atoms/cm^3
High vacuum	10^{-3} mbar	in light bulbs
Ultra-high vacuum	$<10^{-6}$ mbar	$<10^{10}$ molecules/cm^3
Best man-made vacuum	10^{-13} mbar	10^3 molecules/cm^3
Giant molecular cloud		$10^2 – 10^3$ molecules/cm^3
Interstellar space		1 atom/cm^3
Intergalactic space		10^{-6} atoms/cm^3

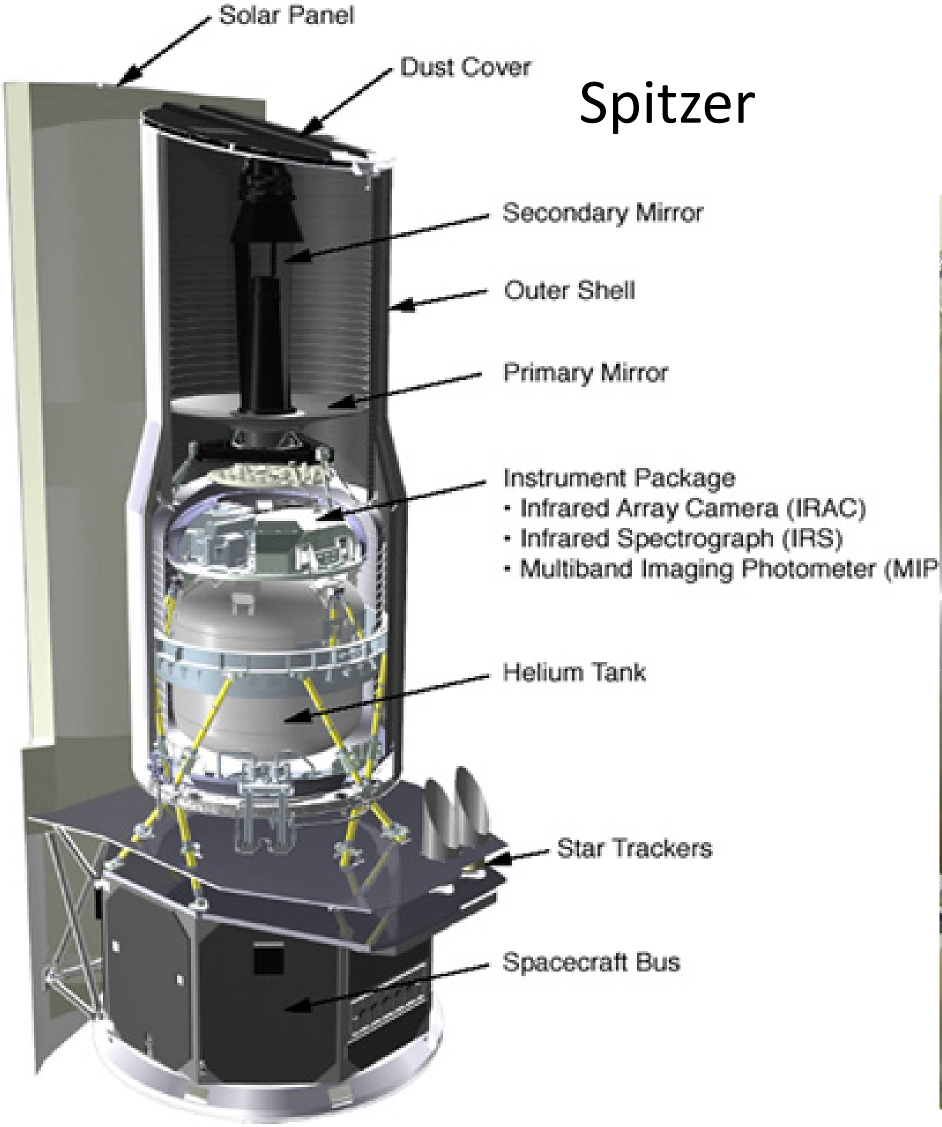
Cryostats (Dewars)

- Cryostats are vacuum tanks. Heat transport is via radiation and conduction only.
- A heat shield or radiation shield with multi-layer insulation (MLI) is used to limit radiative transport.
- After cooling, a vacuum of 1×10^{-7} mbar is typically reached.

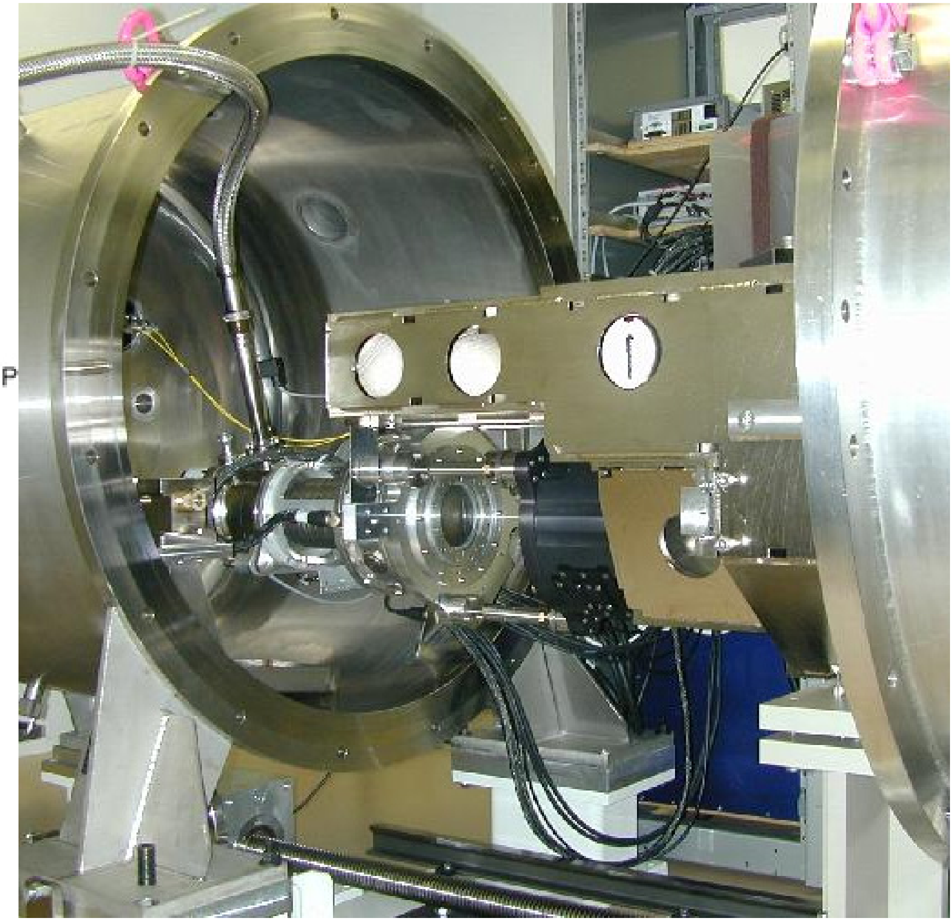


Cryostats – two Examples

Spitzer



HARPS



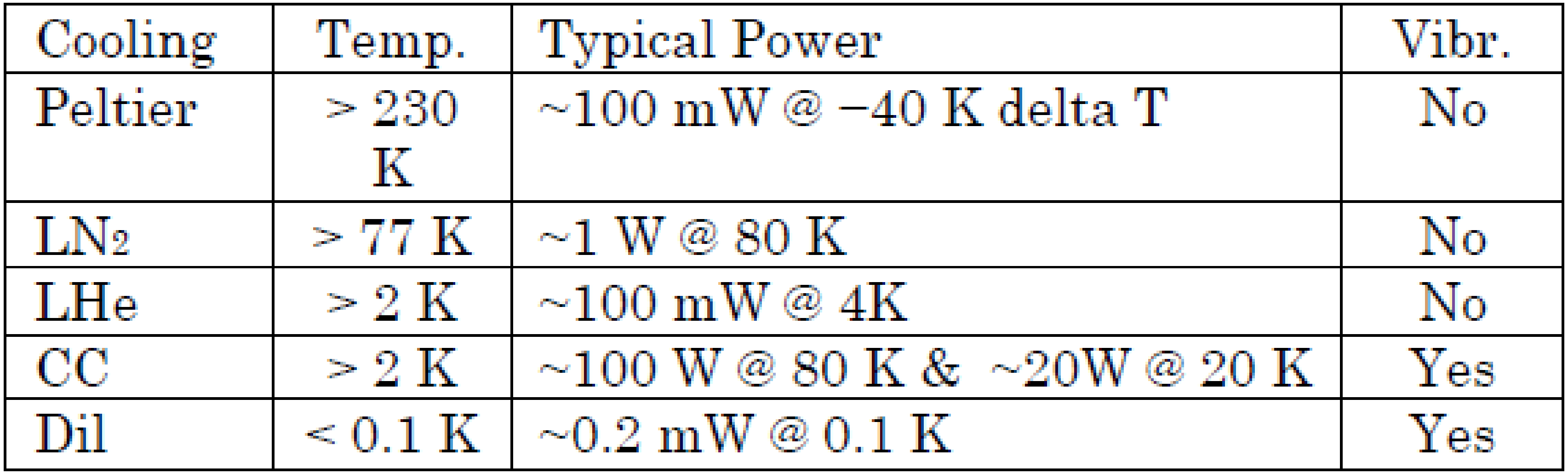
Cryostats – Examples

Herschel

Common Coolers – Overview (1)

- Peltier cooling: based on thermoelectric cooling and does not induce vibrations, but is limited to about 50 degrees below ambient.
- Liquid nitrogen (LN_2): relatively inexpensive, does not generate vibrations. Bath cryostats need regular refills. Temperature at 1 bar is ~77K, cooler temperatures (down to 65K) can be reached by pumping on the bath.
- Liquid helium (LHe) has a boiling point of 4.2K and can be super-cooled under vacuum to achieve lower temperatures.
- Closed cycle (CC) coolers use adiabatic expansion of helium that is recuperated. Devices include Gifford-McMahon, pulse tube, Stirling, Joule-Thomson and Brayton coolers. May be used down to 2 K in several stages. Coolers vibrate.
- Dilution or adiabatic demagnetization coolers reach temperatures well below 0.1 K.

Common Coolers – Overview (2)

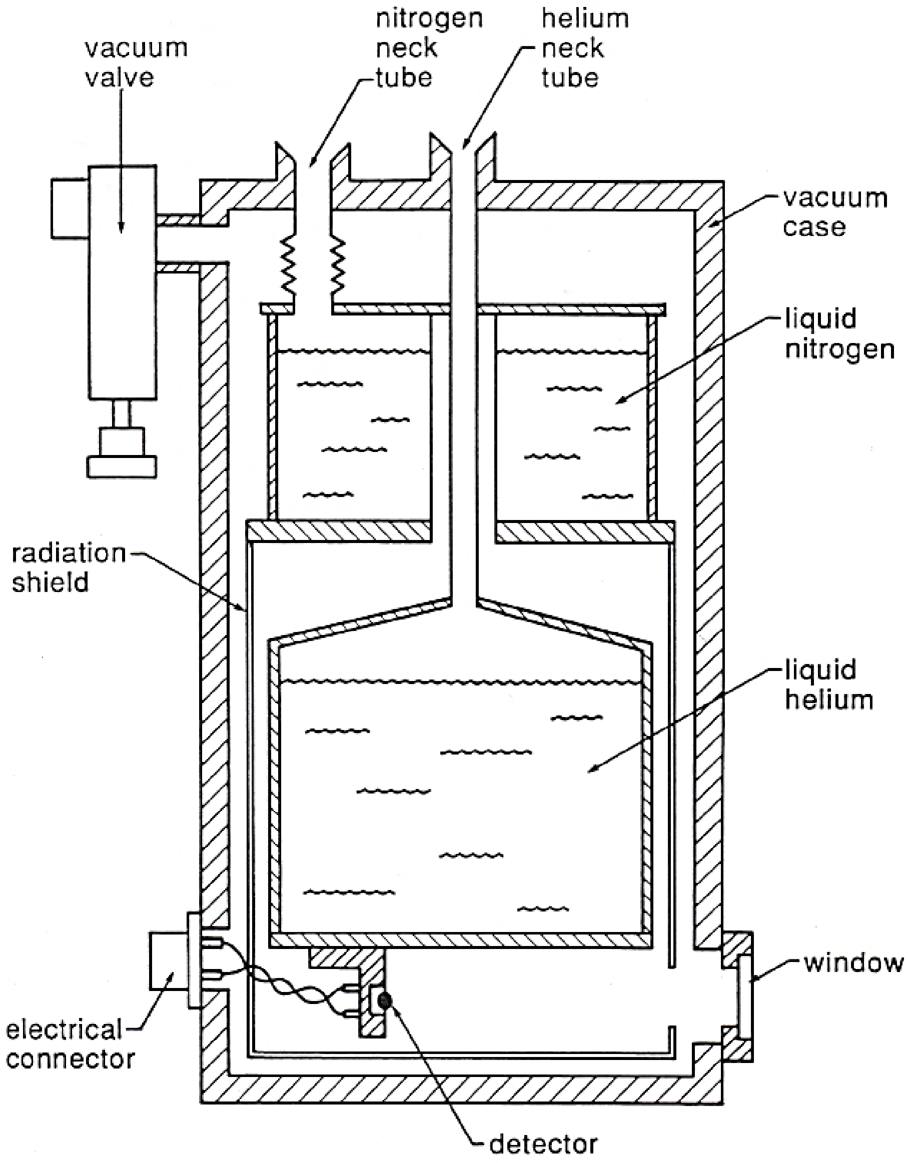


Cooling	Temp.	Typical Power	Vibr.
Peltier	> 230 K	~100 mW @ −40 K delta T	No
LN_2	> 77 K	~1 W @ 80 K	No
LHe	> 2 K	~100 mW @ 4K	No
CC	> 2 K	~100 W @ 80 K & ~20W @ 20 K	Yes
Dil	< 0.1 K	~0.2 mW @ 0.1 K	Yes

Note that observatories are not physics labs (1 night @ VLT ~100 k€).

→ Reliability, power consumption, and servicing are important factors when it comes to selecting the best cooler.

Example: Cryostat for 4 Kelvin



"Simplest" solution is to use a two-stage helium dewar

(here: model from Infrared Laboratories, Inc.)

Cooling down further to 1 – 2 K is problematic as ^{4}He becomes superfluid and will flow all over the inside of the dewar.

Solution: The isotope ^{3}He does *not* have a superfluid state – but ^{3}He is rare and expensive → only in closed cycle refrigerators.