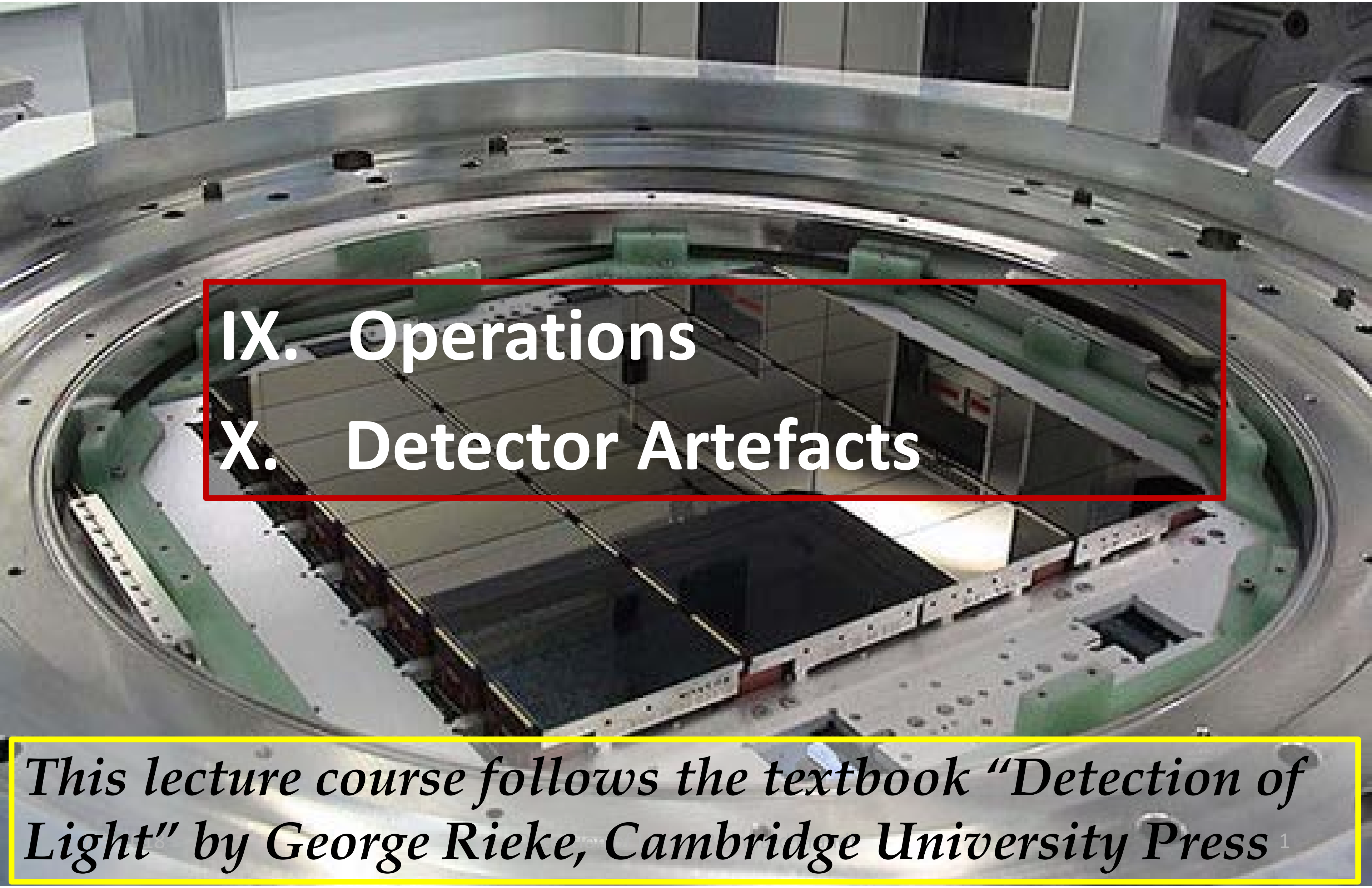
Detection of Light



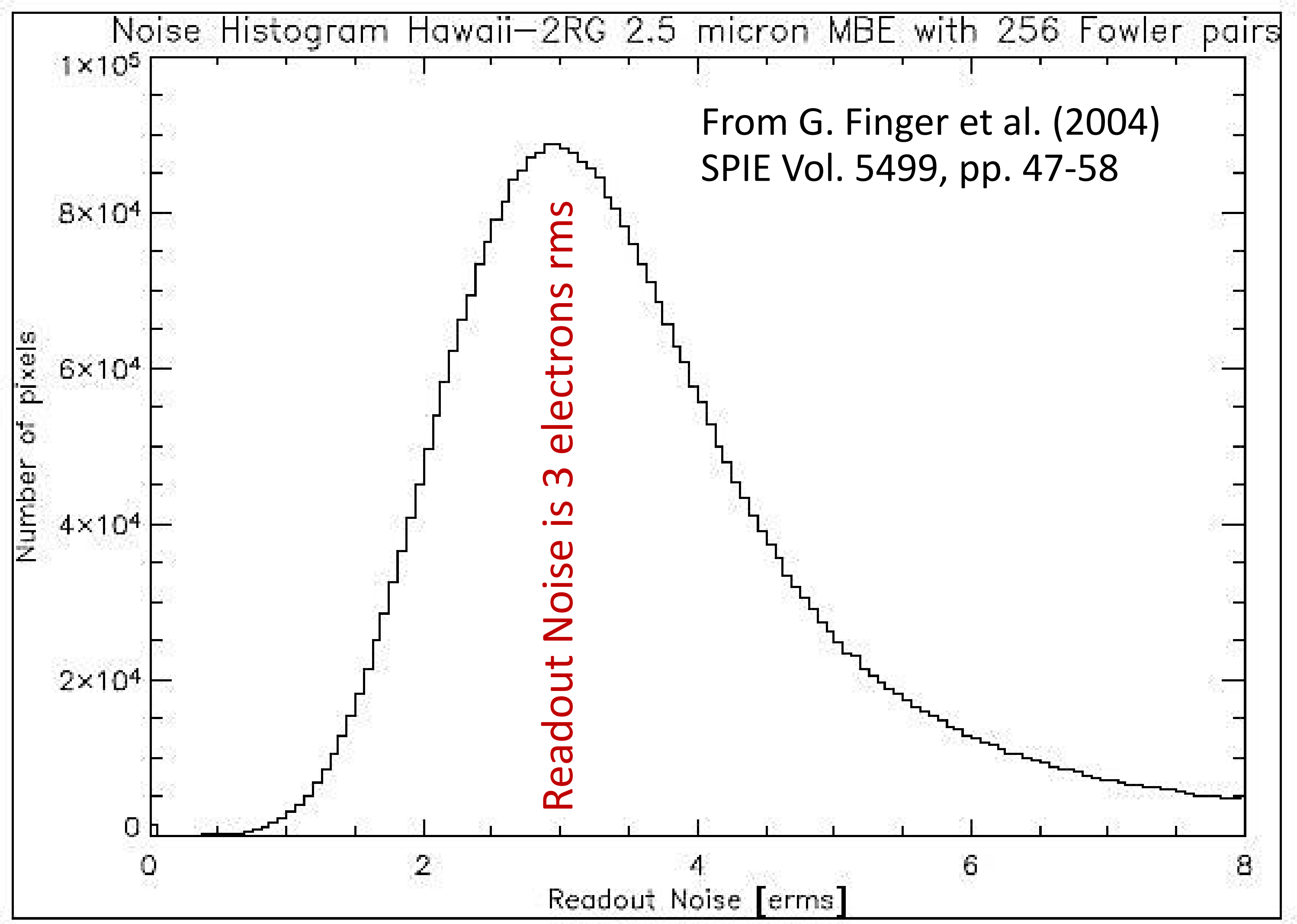
IX. Operations
X. Detector Artefacts

This lecture course follows the textbook "Detection of Light" by George Rieke, Cambridge University Press

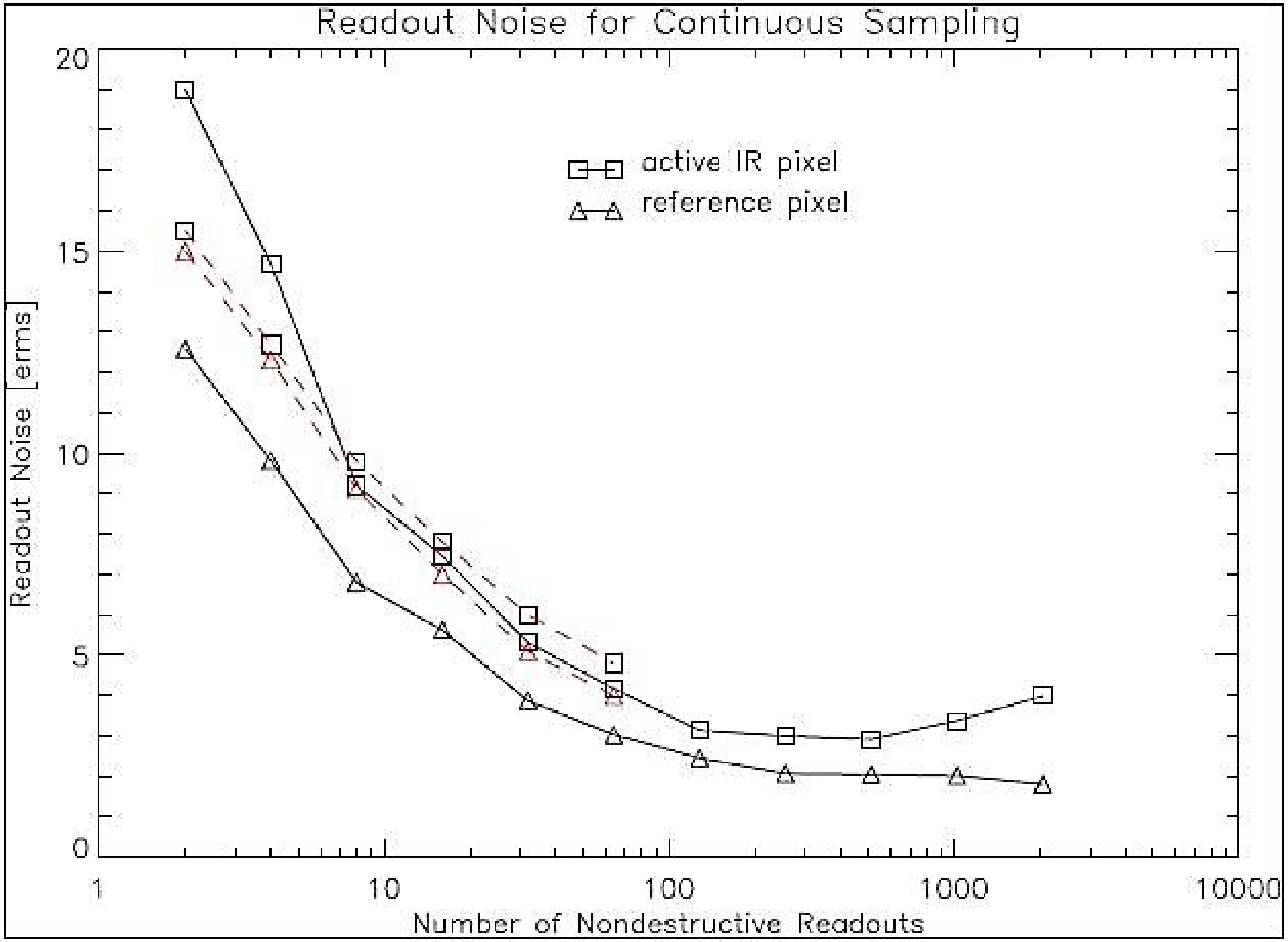
Dark Current and Read Noise

Distribution of Readout Noise

Histogram of readout noise.



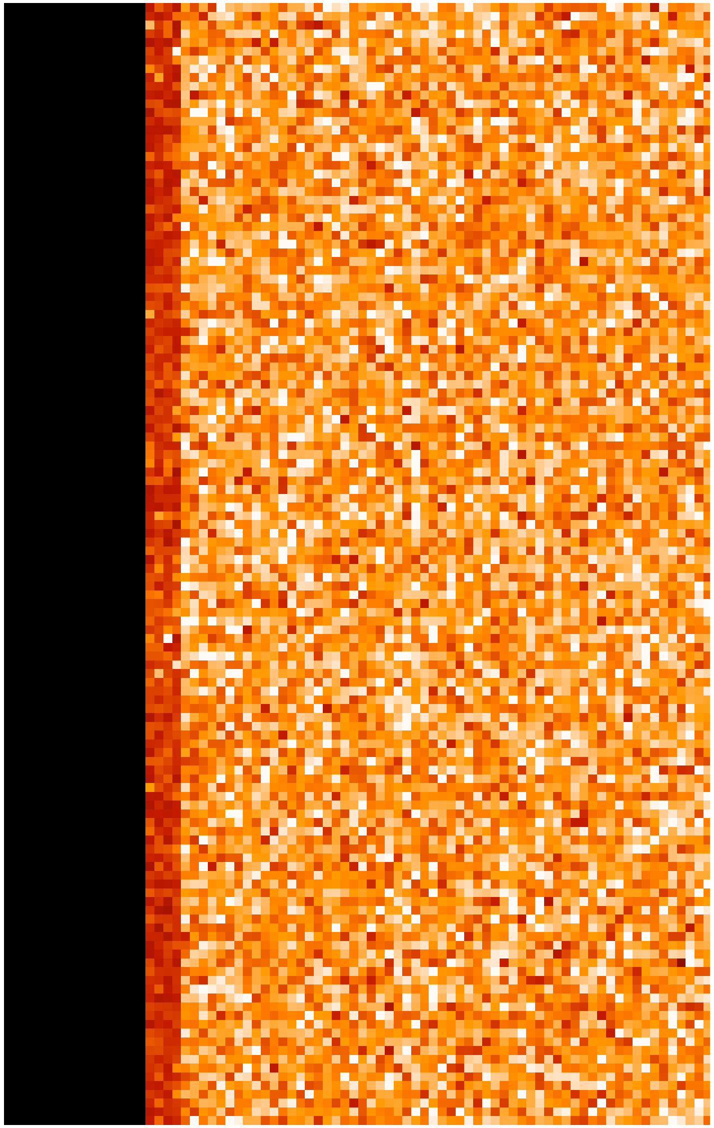
Readout Noise = f $\{n_{read}\}$



Readout noise versus number of non-destructive readouts (825ms each).

"Reference Pixels" (1)

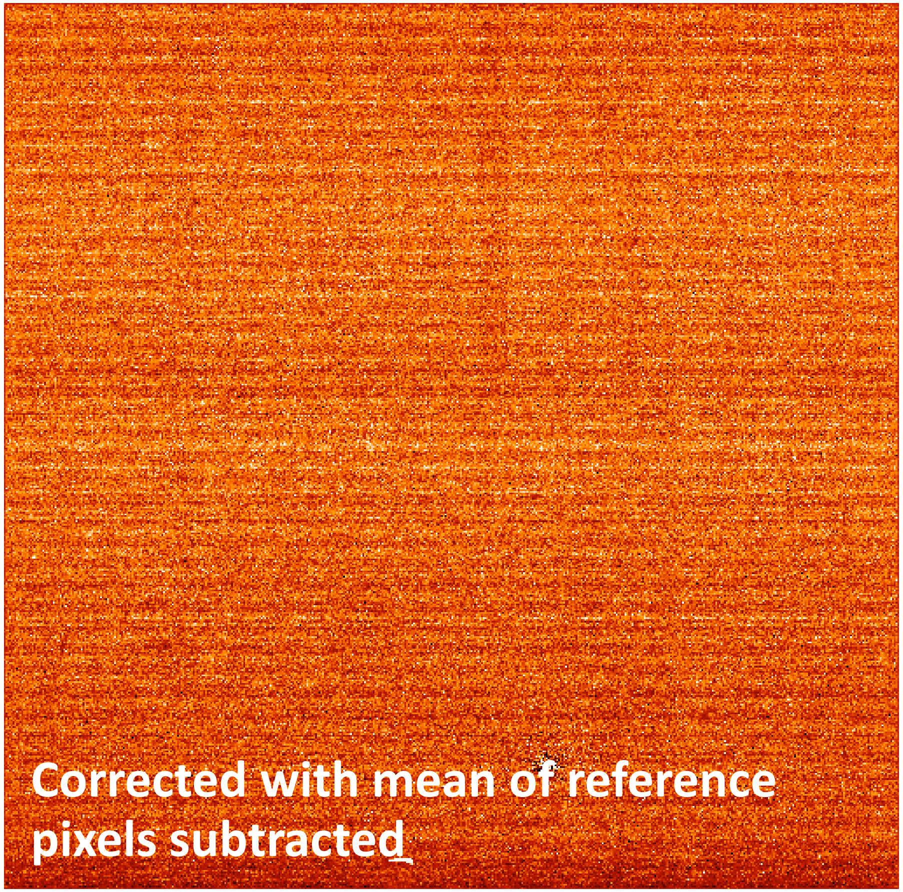
- IR active pixels are surrounded by 4 rows and columns of reference pixels at the edges of the array.
- Reference pixels are not connected to detector photodiodes.
- Their signal is embedded in the regular signal of 2048 x 2048 pixels.
- Reference pixels can be used to track low frequency noise pickup.



Noise map with reference pixels at the left edge.
Readout noise on active pixels: 17 e- rms.
Readout noise on reference pixels: 8 e- rms.

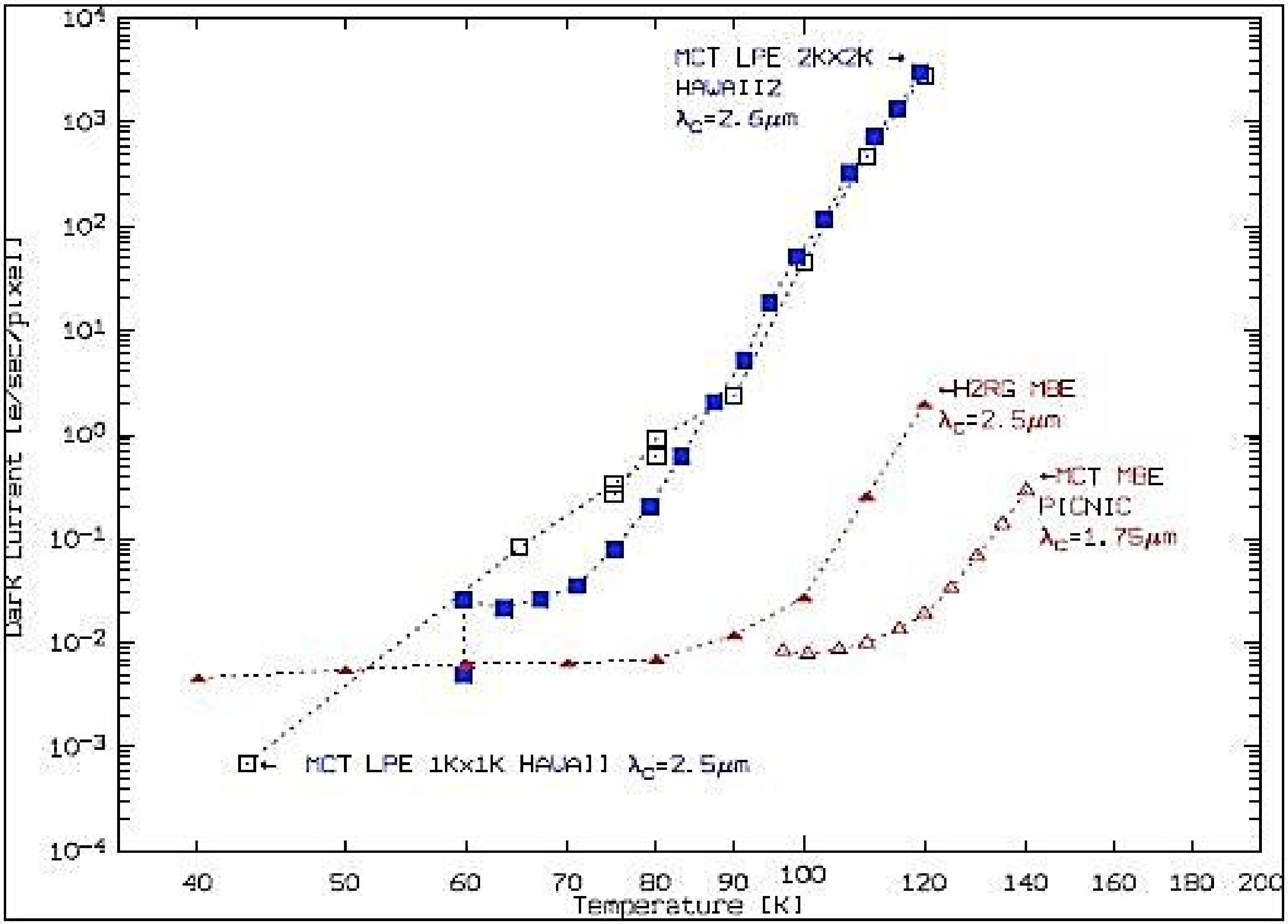
“Reference Pixels” (2)

Need for reference pixels – difference images of double correlated reads:



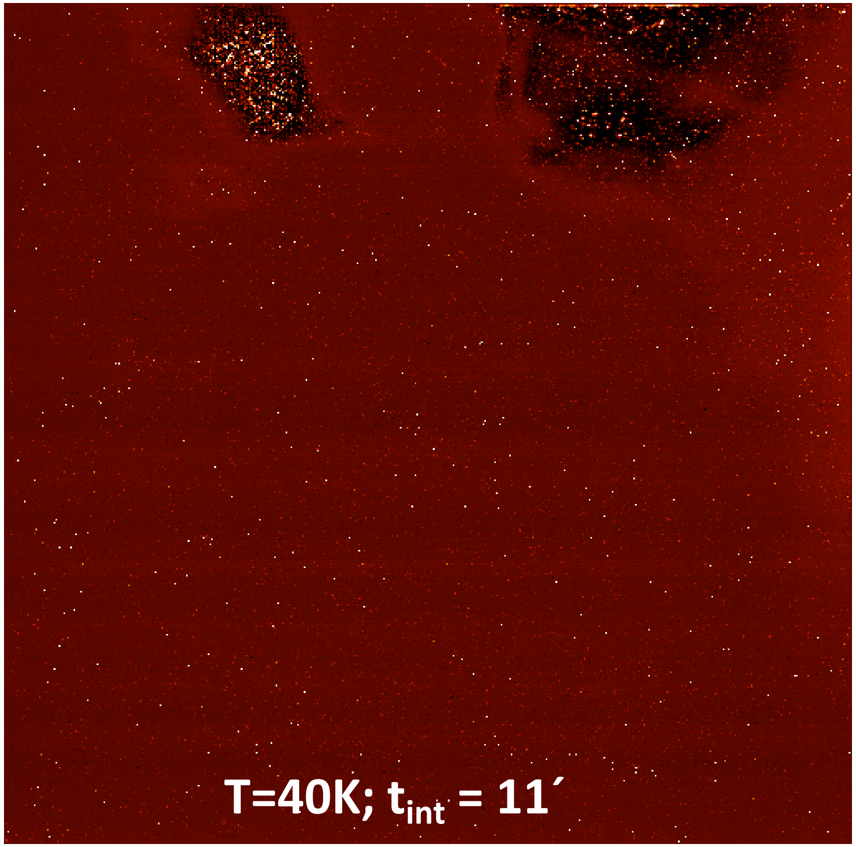
Dark Current (1)

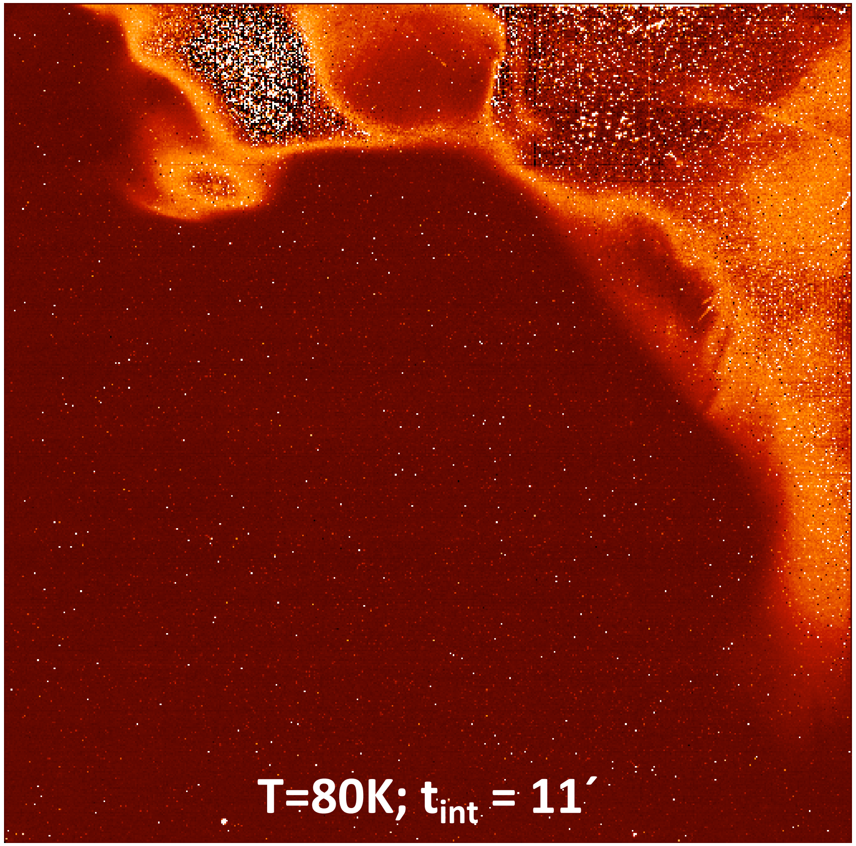
The dark current is a strong function of temperature!



Dark Current (2)

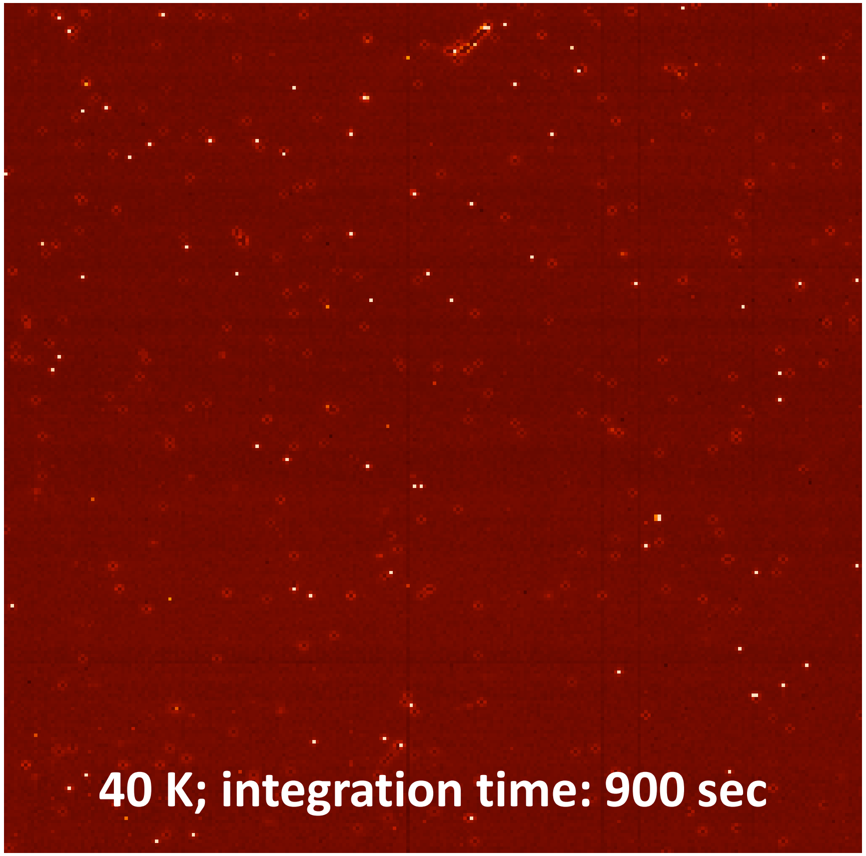
… and varies from pixel to pixel. Global dark current maps:

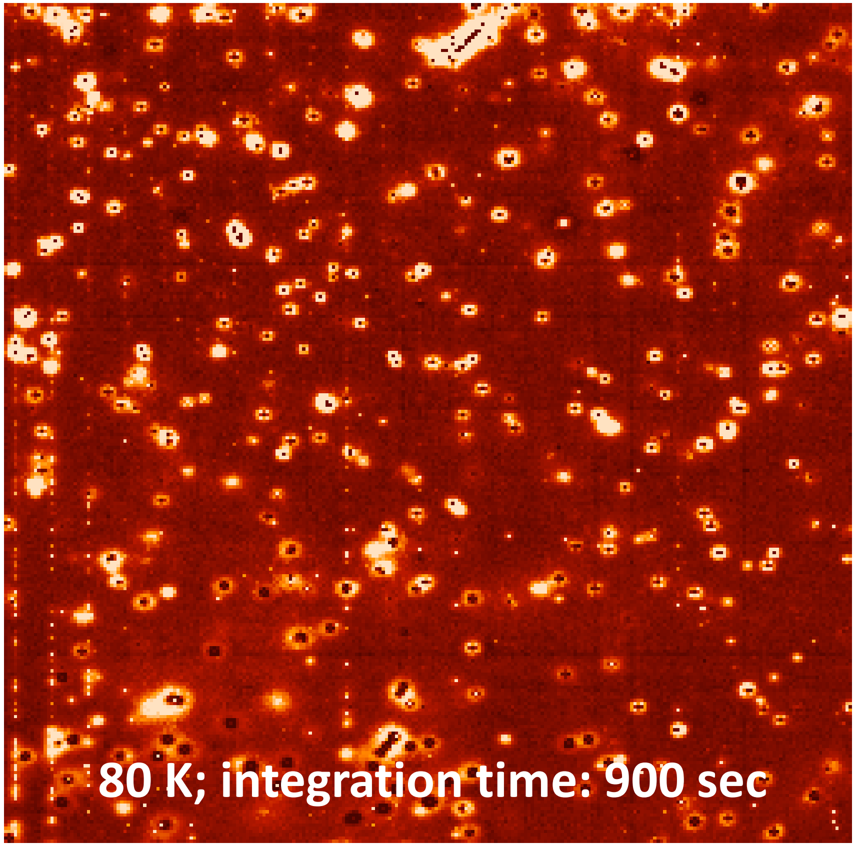




Cosmetic Quality

The cosmetic quality (⇔ dark current) is also a strong $f\{T\}$



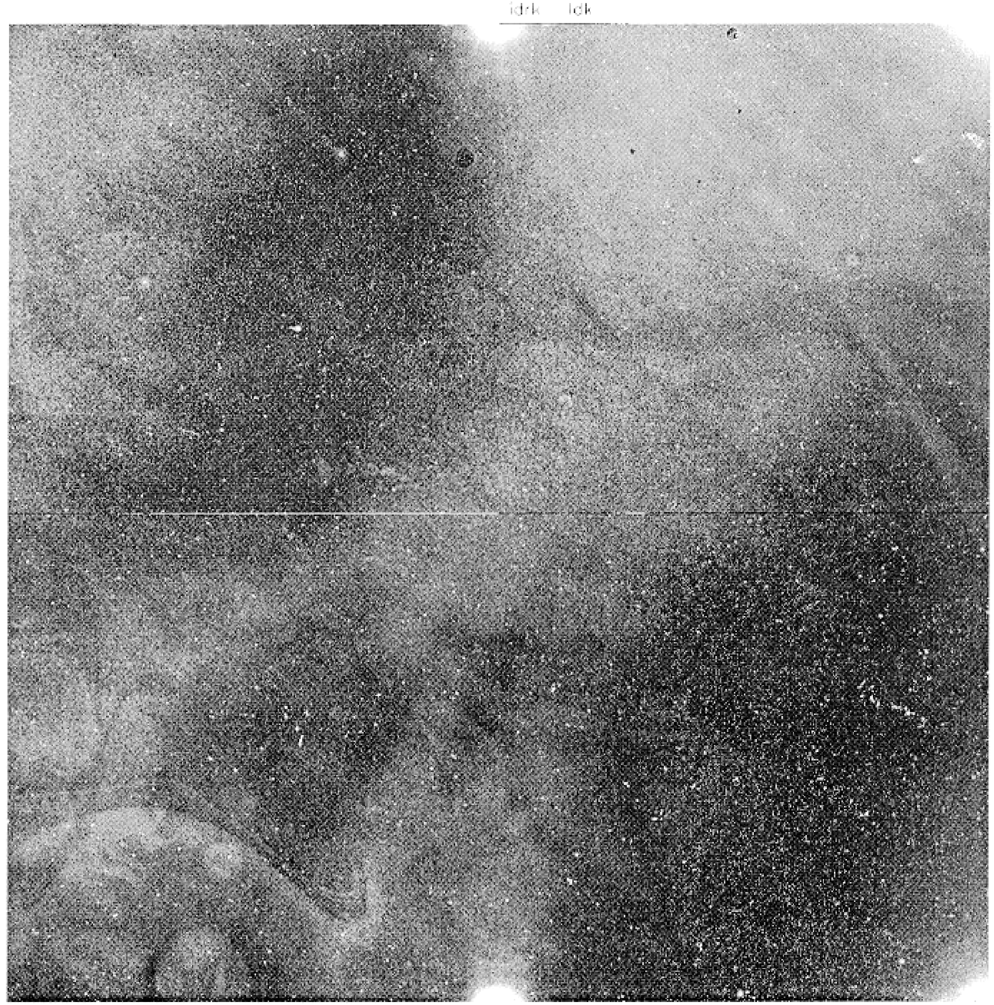


➔ Cooling is very important!

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).

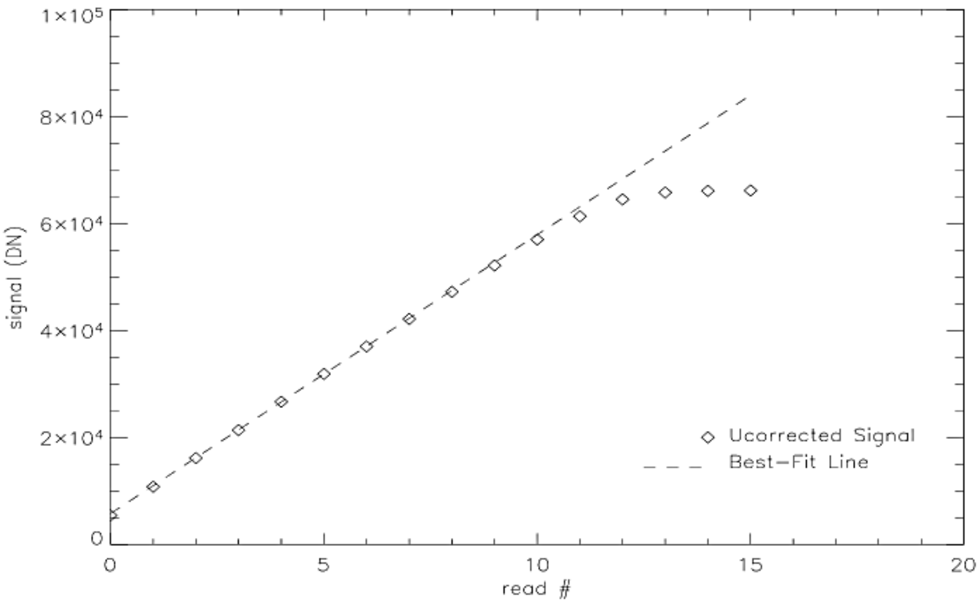


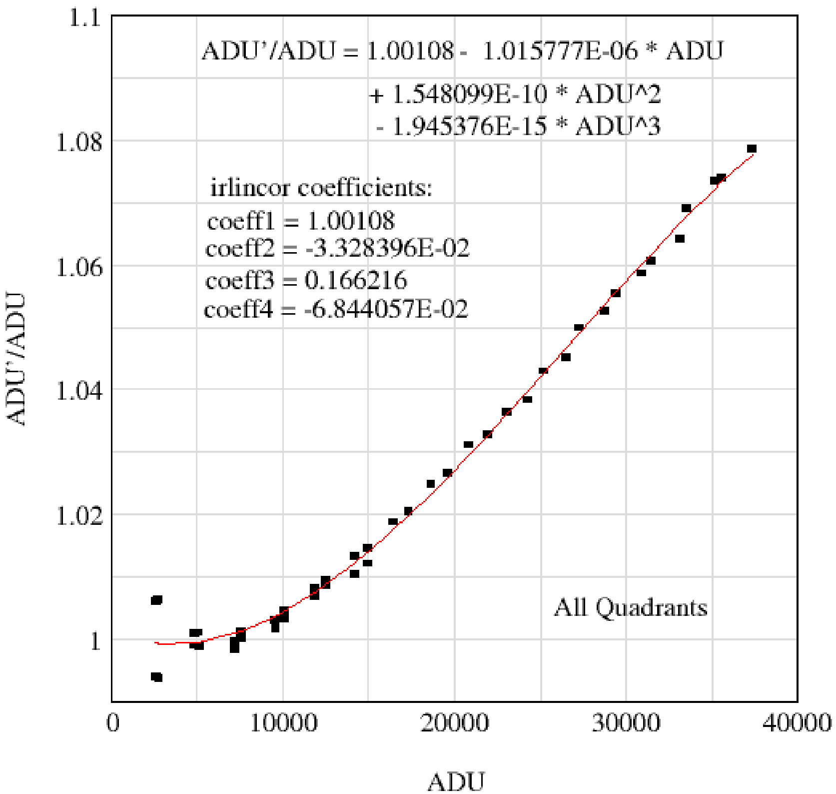
Non-Linearity

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.



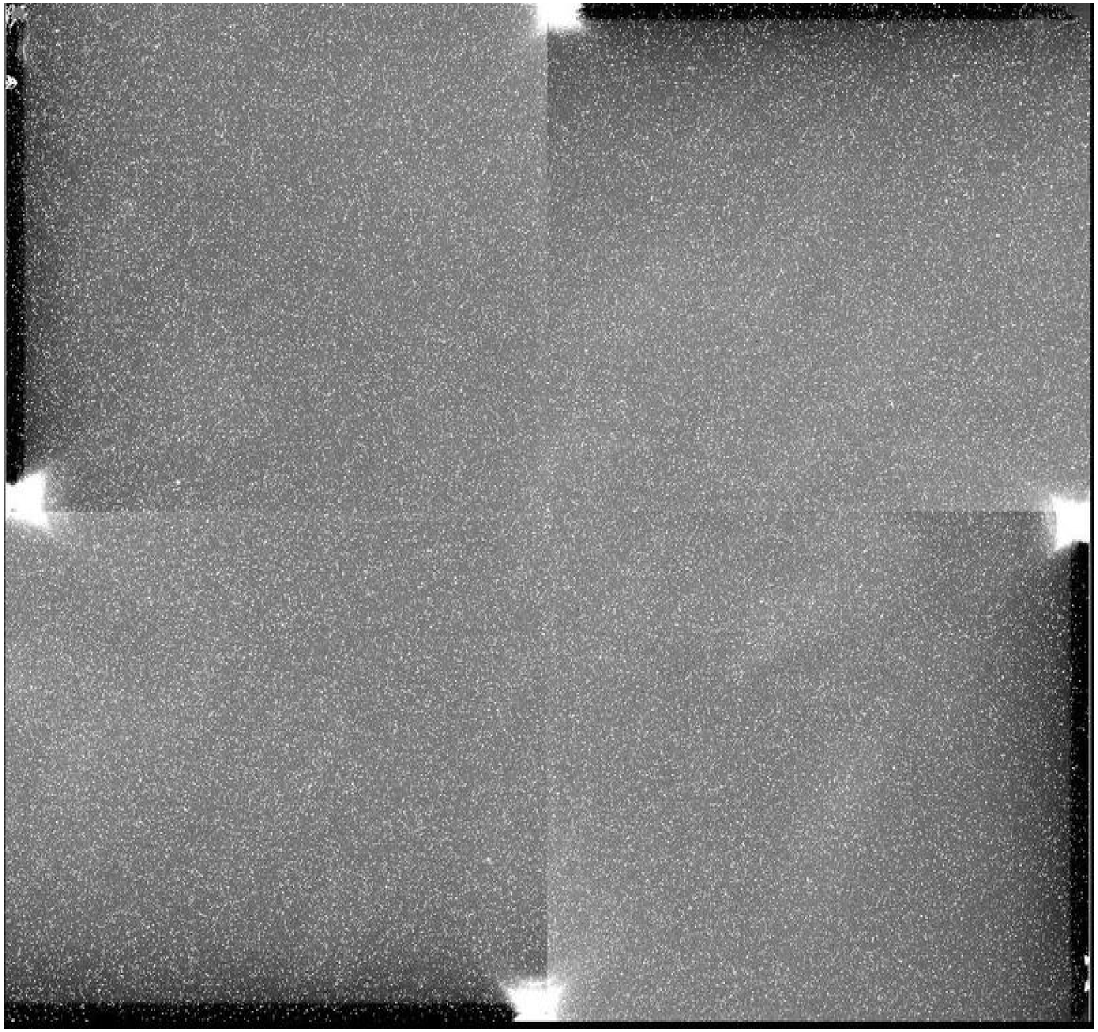


HgCdTe non-linearity coefficients

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.

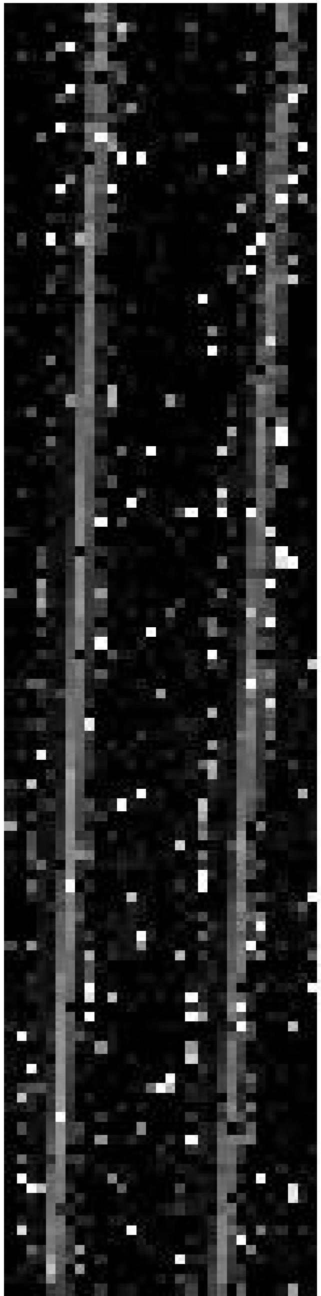


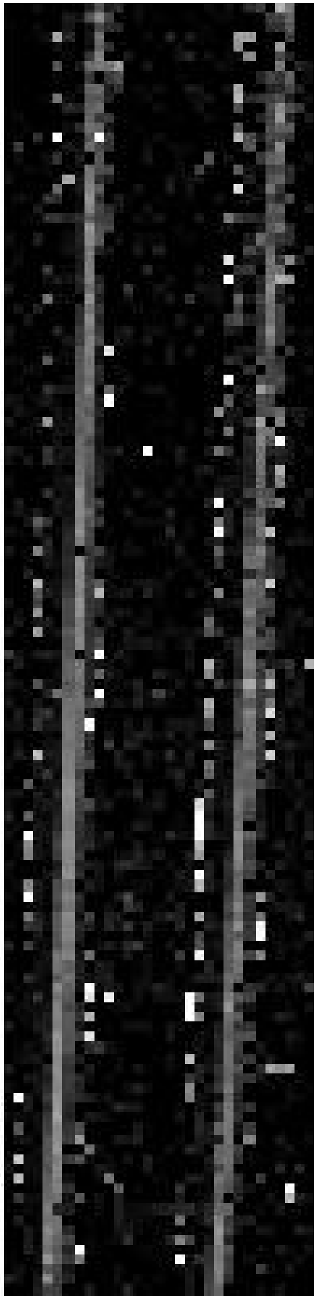
Dead, Hot, & Rogue Pixels

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

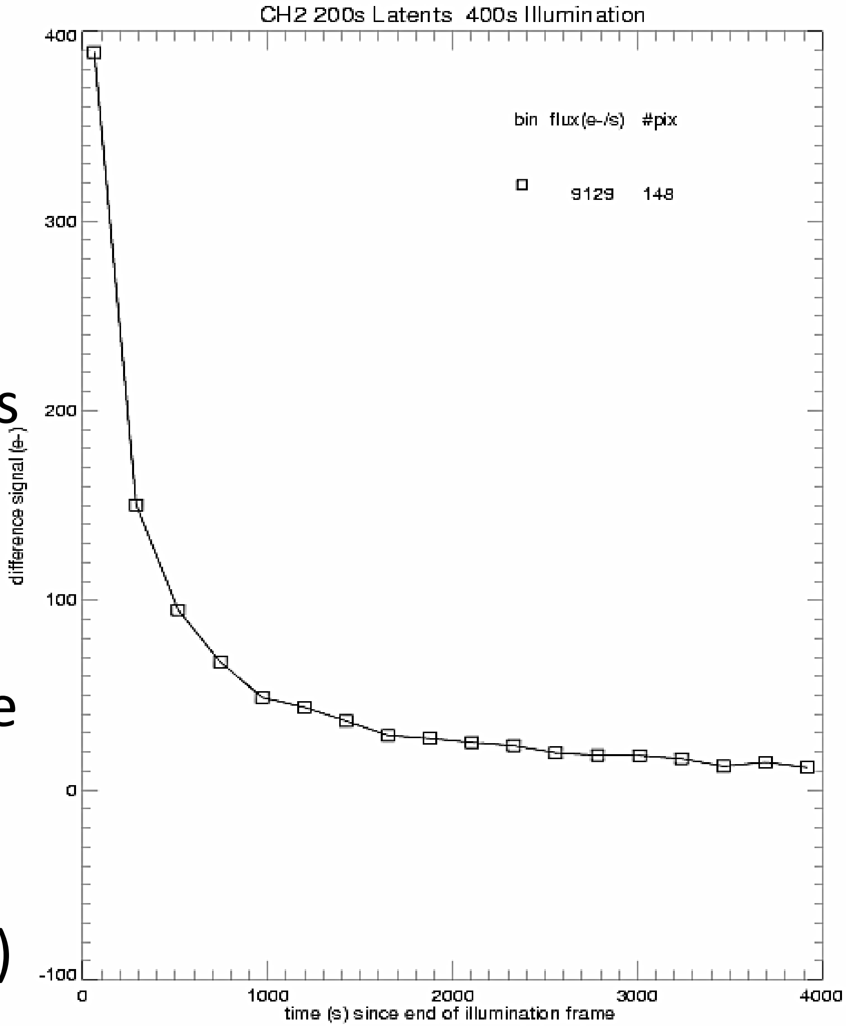
Latent Images

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:

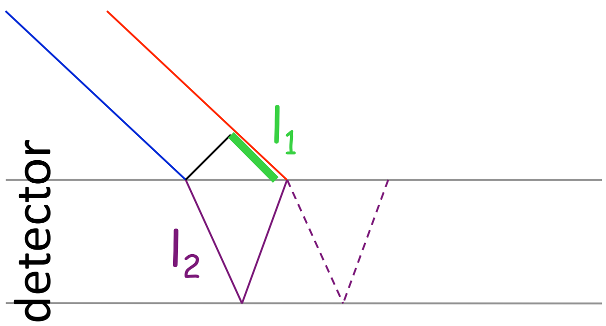
- Wait (and wait, and wait....)
- Apply frequent resets (clean out the trap)
- Annealing (heat up array to thermally excite them into mobility)
- Use ND filters or shutter during target acquisition



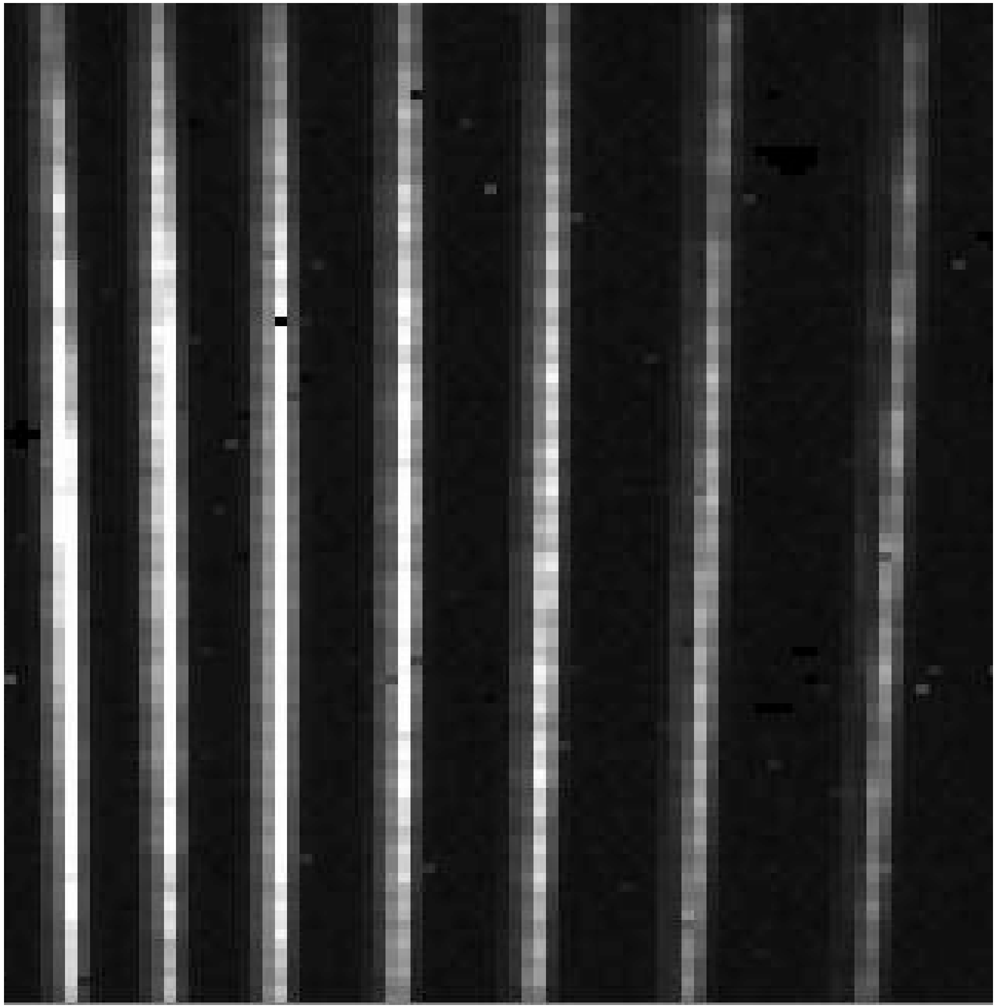
Detector Fringing (in Spectrographs)

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

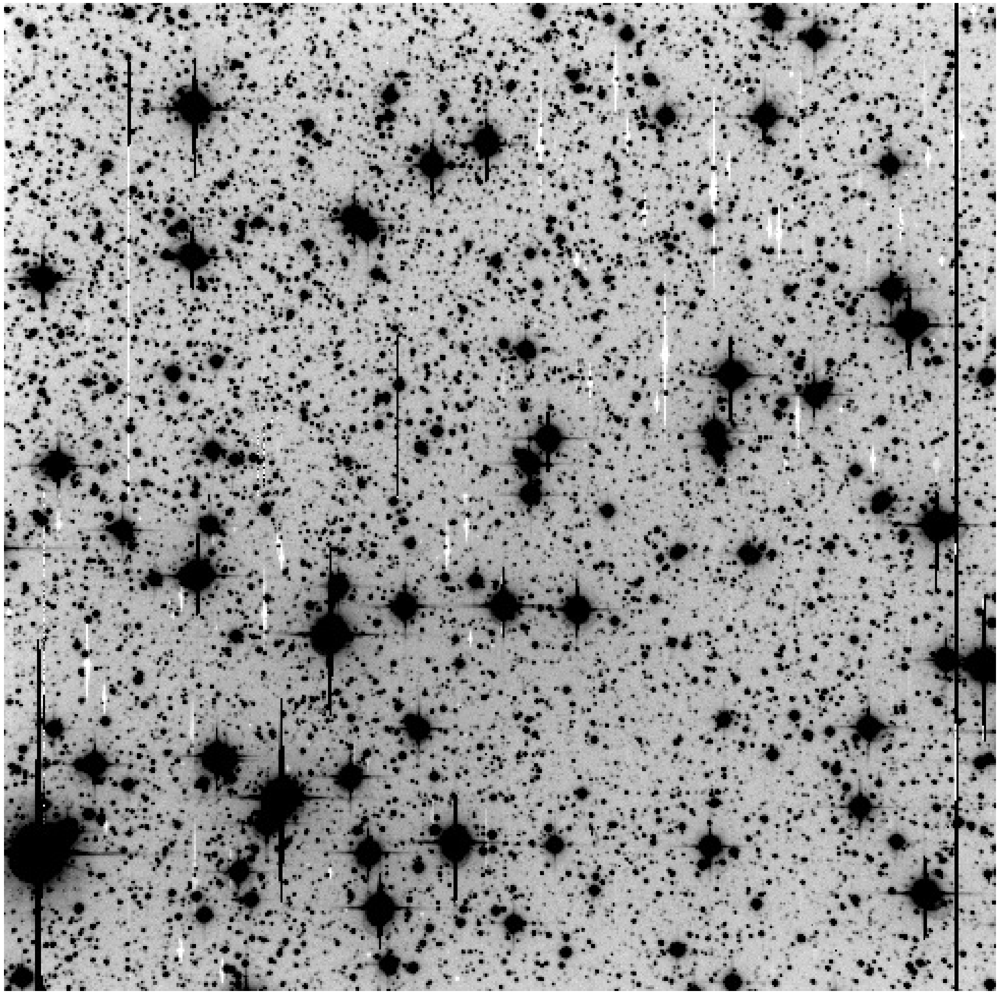


Crosstalk

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.

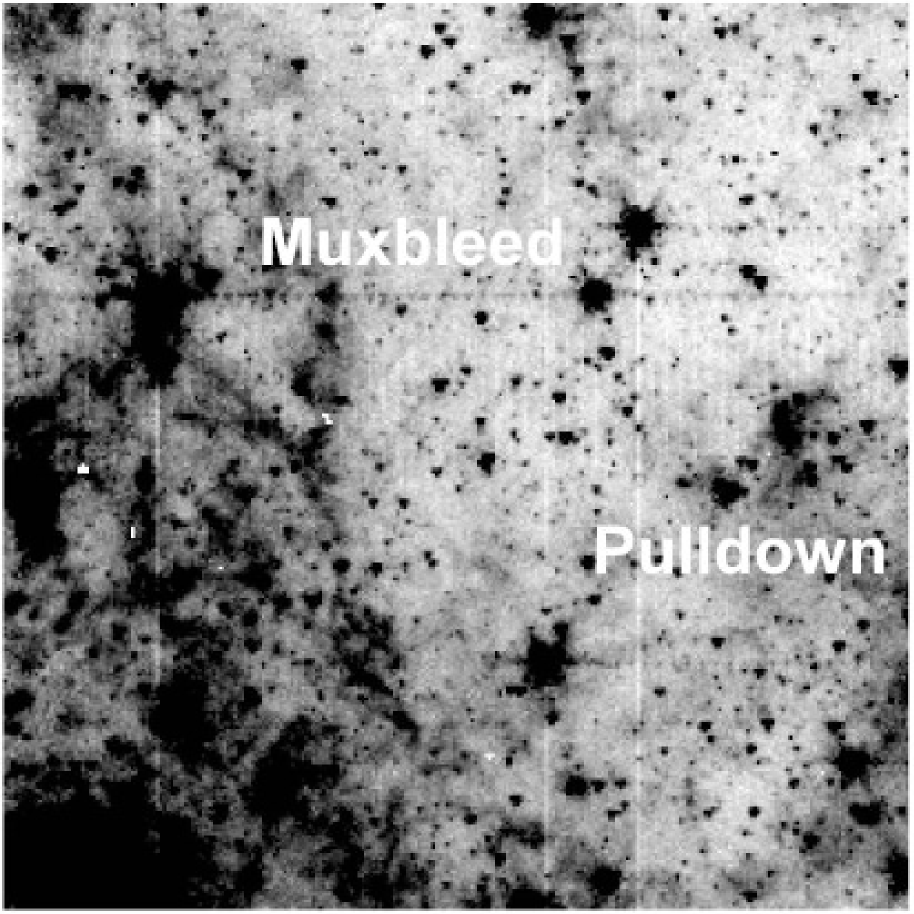
The negative (white) images in the upper right quadrant correspond to the black star images in the lower left quadrant

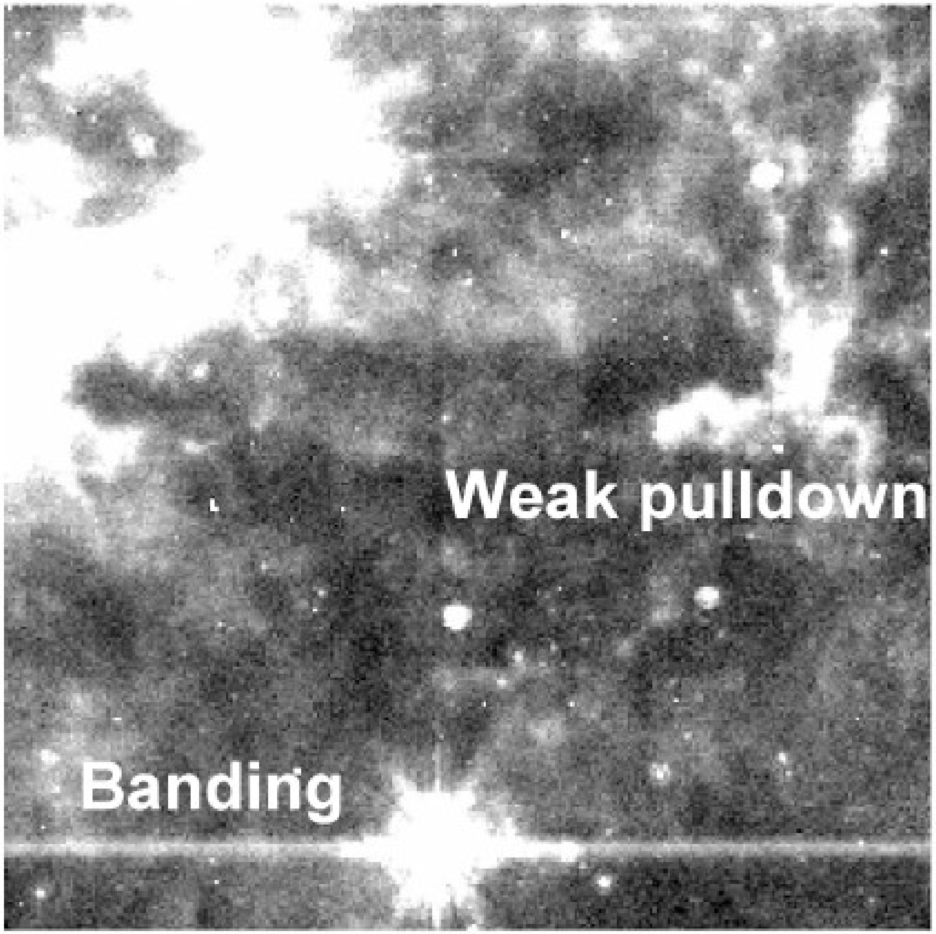


Pulldown & Bleeding

PROBLEM:

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

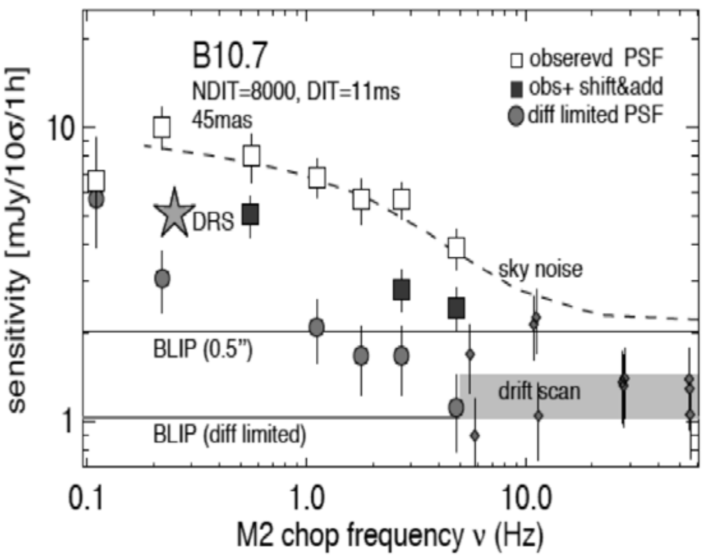


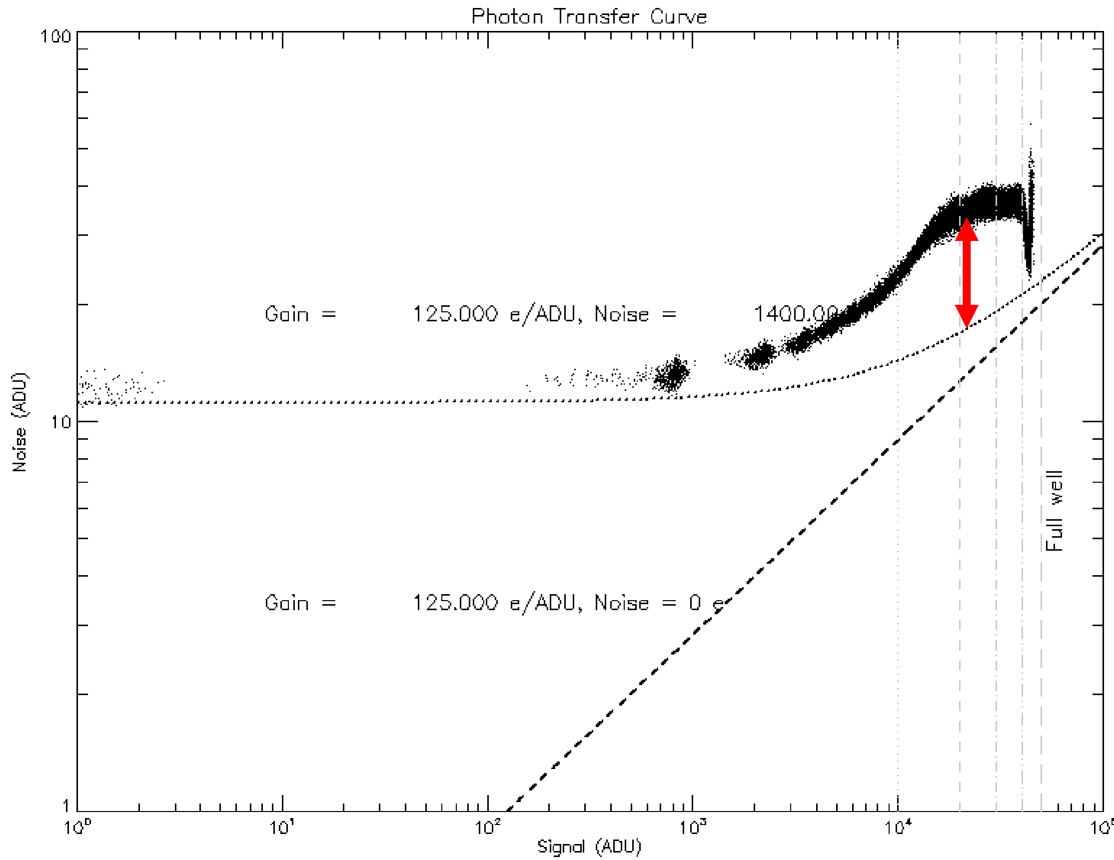


Side note: ELFN in Si:As BIBs

ELFN = excess low frequency noise, found in Aquarius detectors

from D. Ives et al. (2012, SPIE):





Standard photon transfer curve: noise versus signal. The plot also shows the theoretical curves for a detector with similar gain and read noise and zero read noise.

Readout Schemes

(of IR Arrays)

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.

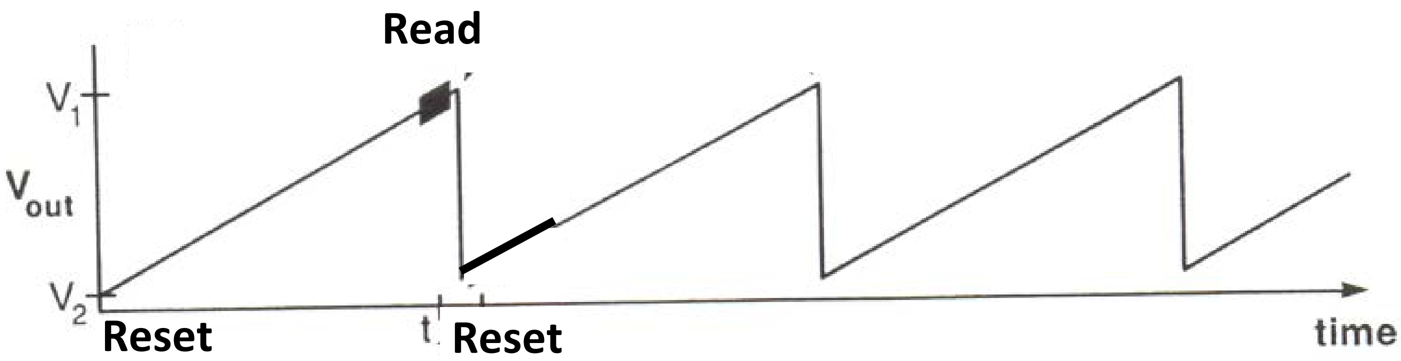
The IR Array approach:

- 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!

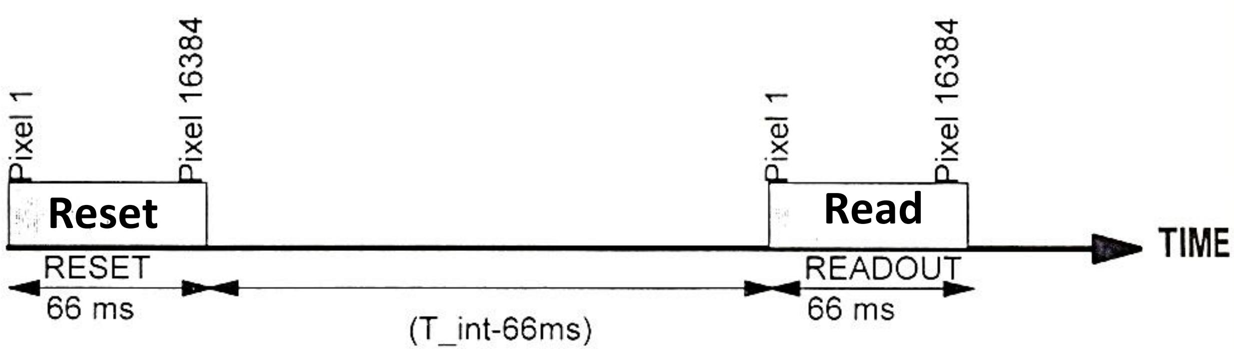
Next, we'll focus on IR array readouts.

Single Sampling

The simplest approach …

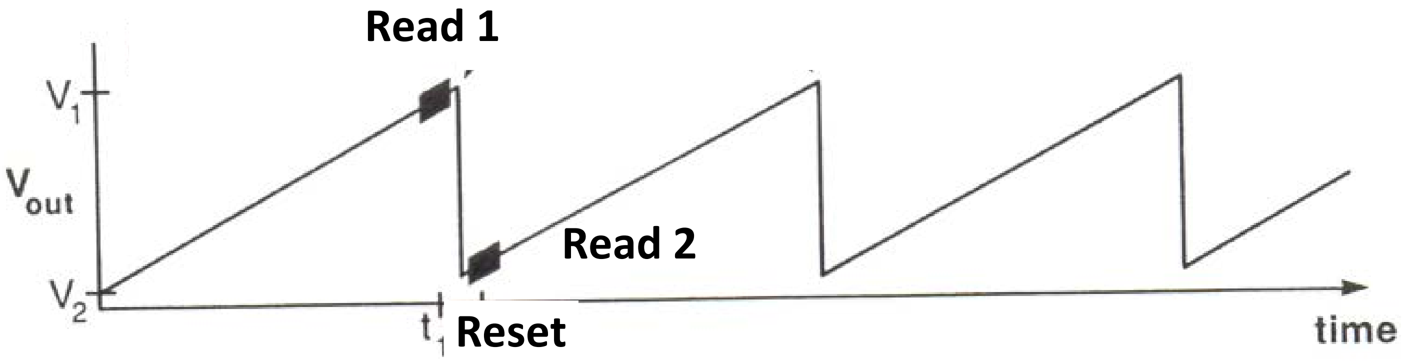


- Does not remove kTC noise or voltage drifts
- It directly measures the signal level (we would notice saturation)



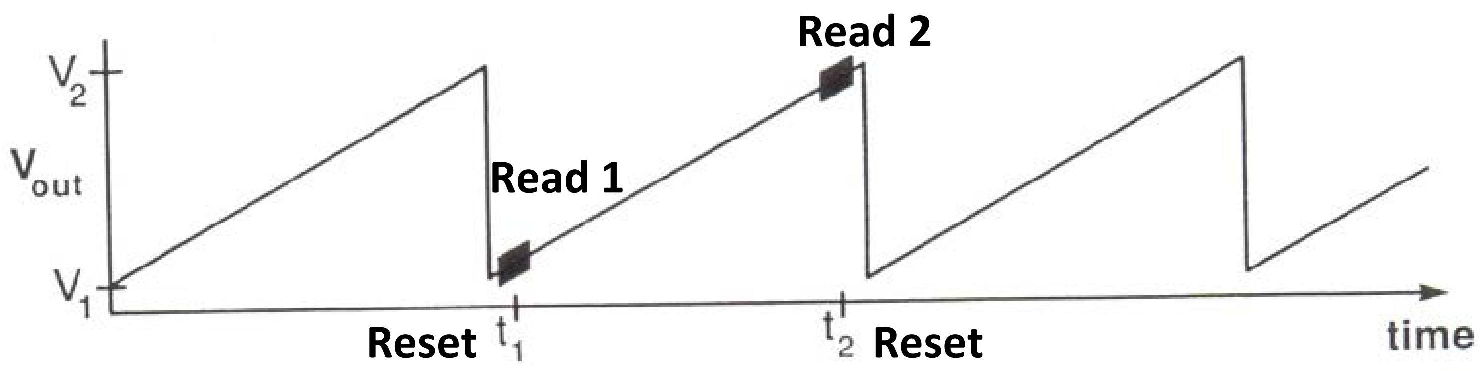
Double-correlated Sampling

Reads pixel twice (before and after the reset)

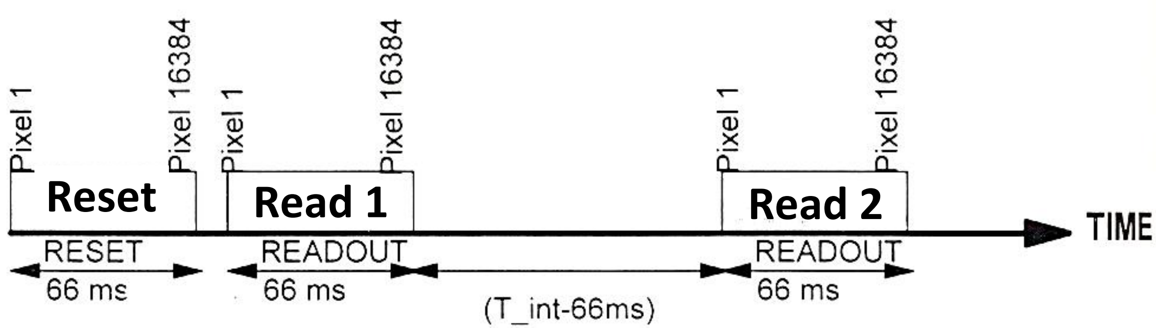


- Signal = Read 1 - Read 2
- Voltage drifts are subtracted out
- "read-reset-read" → difference is measured for each pixel before moving to the next → simplified, lower data rates
- Does not eliminate kTC noise since offset is subtracted from the *previous* frame.
- Watch out: *saturated – saturated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

Reset-Read-Read

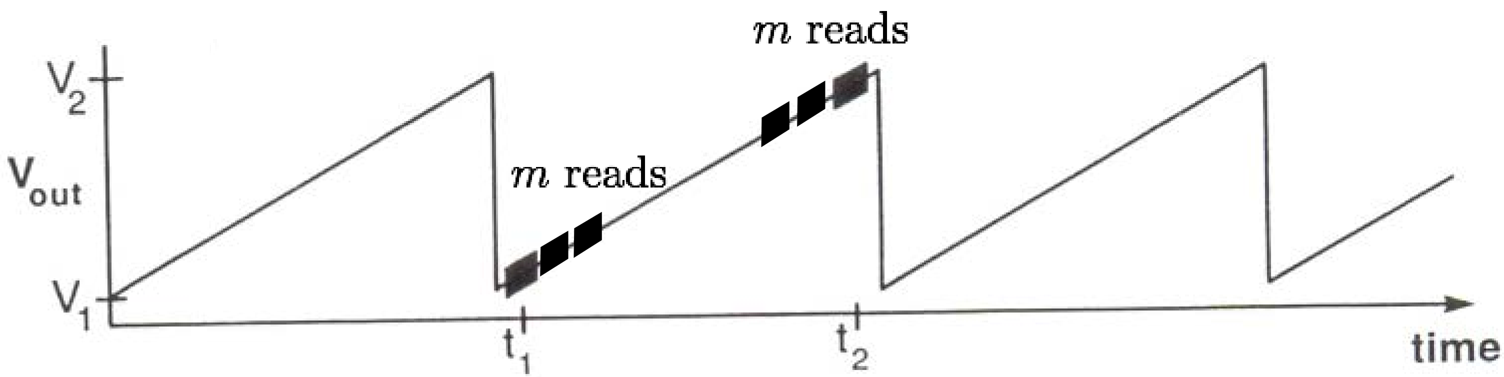


- Resets the array pixel-by-pixel (or column-wise)
- Reads the array pixel-by-pixel at the start and at the end of the integration
- Signal = Read(2) – Read(1)
- Advantage: best correlation, no reset noise
- Disadvantages: requires frame storage, reduced dynamical range



Multiple (Fowler) Sampling

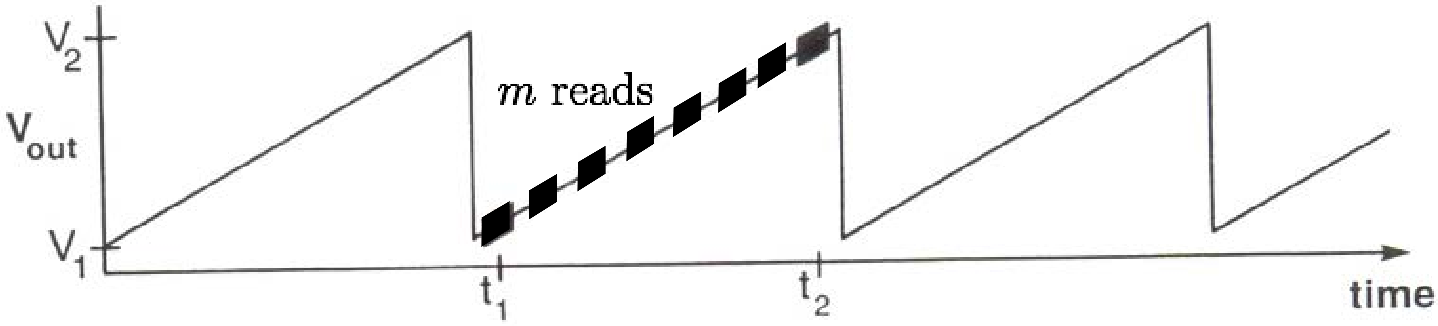
Uses multiple reads at start and end of the integration time to reduce the read noise.



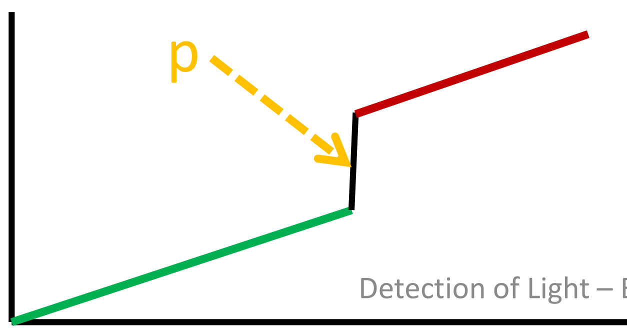
- Signal = Mean(Read 2) - Mean(Read 1)
- *m* reads get coadded in buffer (no separate frame storage)
- Readout noise is reduced by $\sqrt{m}$ over reset-read-read
- Longer time to carry out a given integration

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

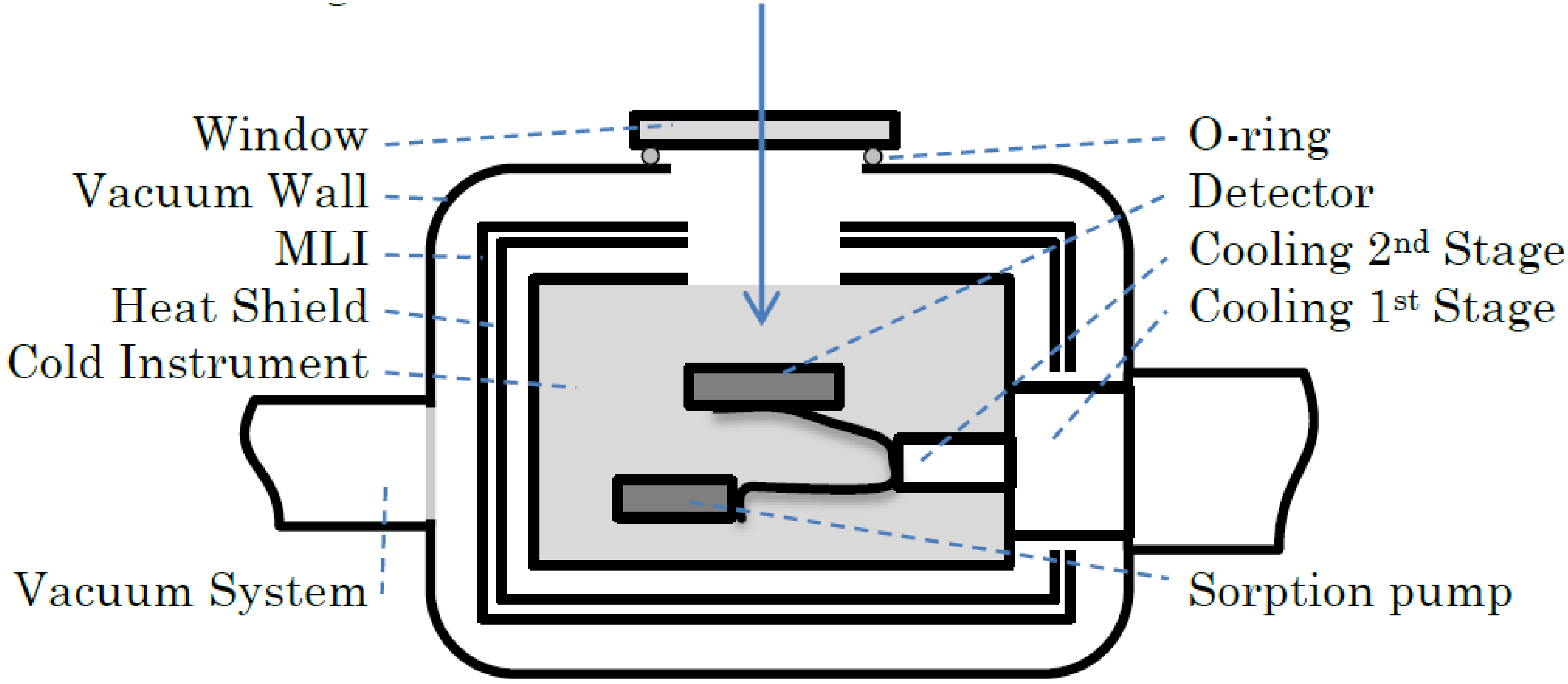
(or everything will freeze over)

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

*at room temperature

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.



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.

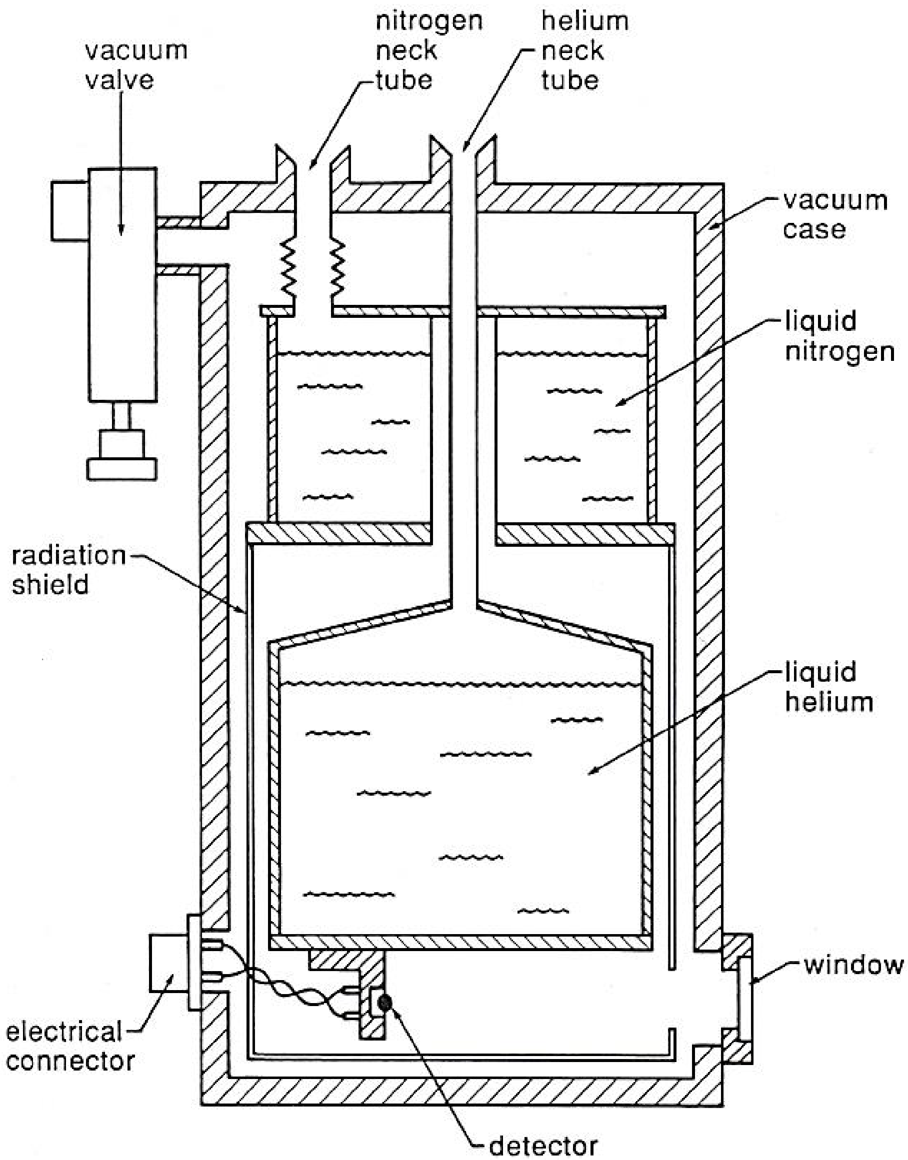
Common Coolers – Overview (2)

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.

LN_2 / LHe Cryostat



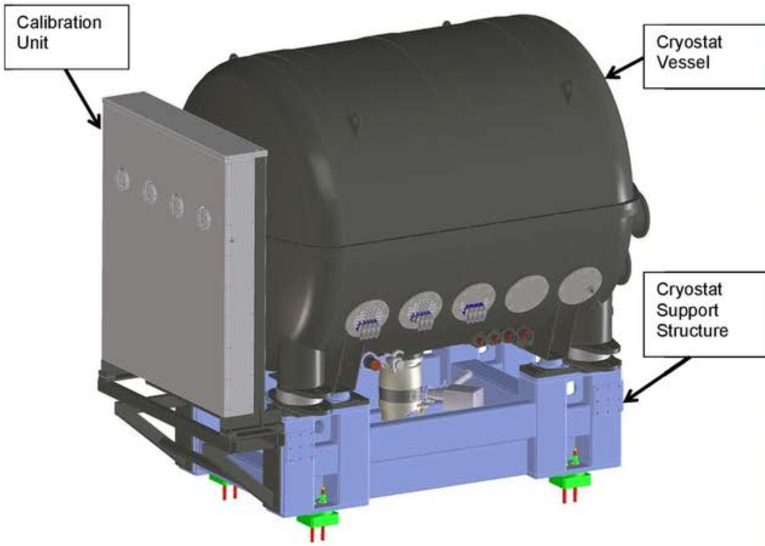
"Simplest" solution is to use a two-stage helium dewar

(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.

Closed-Cycle Cooler Cryostat

Cryostat for the GRAVITY beam combiner instrument at the VLTI, using a pulse tube cooler



Example of a pulse tube cooler: Cryomech PT410:

PT410 with CPA289C

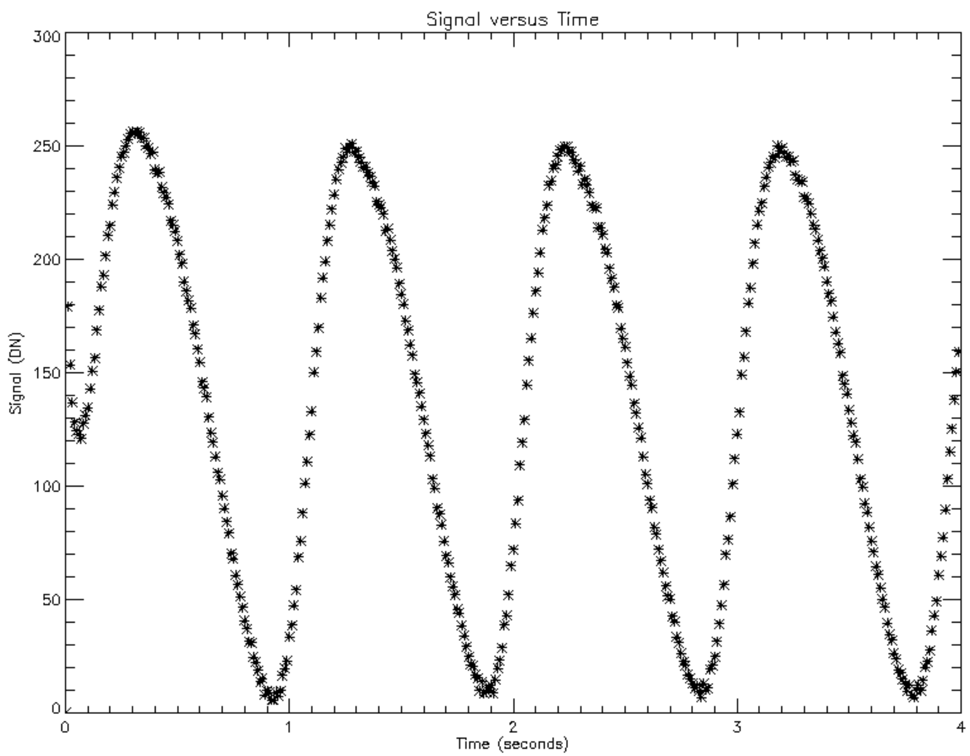
Cold head	PT410
Cooling capacity @ 50 and 60 Hz:	
2nd stage and 1st stage combined	1.0W @ 4.2K with 40W @ 45K
Lowest temperature	2.8K with no load
Cool down time	60 minutes to 4K
Weight	43 lb (19.5 kg)
Dimensions	See cold head line drawing
Compressor package	CPA289C, available as water cooled only
Weight	295 lb (134 kg)
Dimensions - L x W x H	27 x 19 x 24.5 in (69 x 48 x 62 cm)
Electrical rating	220/230 or 460VAC, 3Ph, 60Hz 200/220 or 380/420VAC, 3Ph, 50Hz
Power consumption @ steady state	8.4 kW // 7.9 kW
Cooling water flow rate	Minimum flow 2.3 GPM (9 LPM) @ 80°F (27°C) maximum temperature
Flexible lines	
Standard length	66 ft (20.1 m)
Weight per pair	72 lb (32.7 kg)

Side note: thermal Oscillations

from D. Ives et al. (2012, SPIE):

Closed cycle coolers do not provide a constant temperature, but show thermal oscillations of the cold head by a few tenths of a Kelvin of typically 1 Hz.

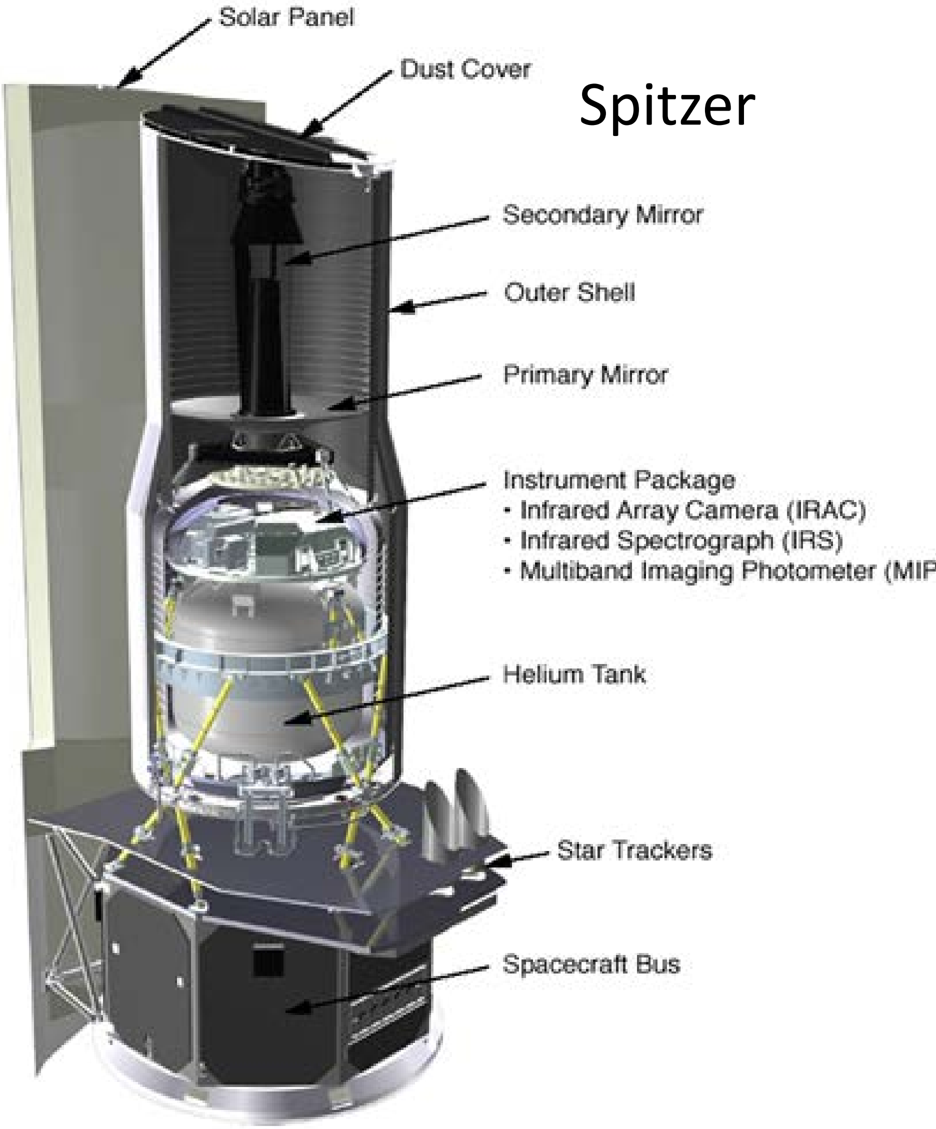
These thermal oscillations can result in additional detector noise because the detector output voltage is sensitive to this temperature change.



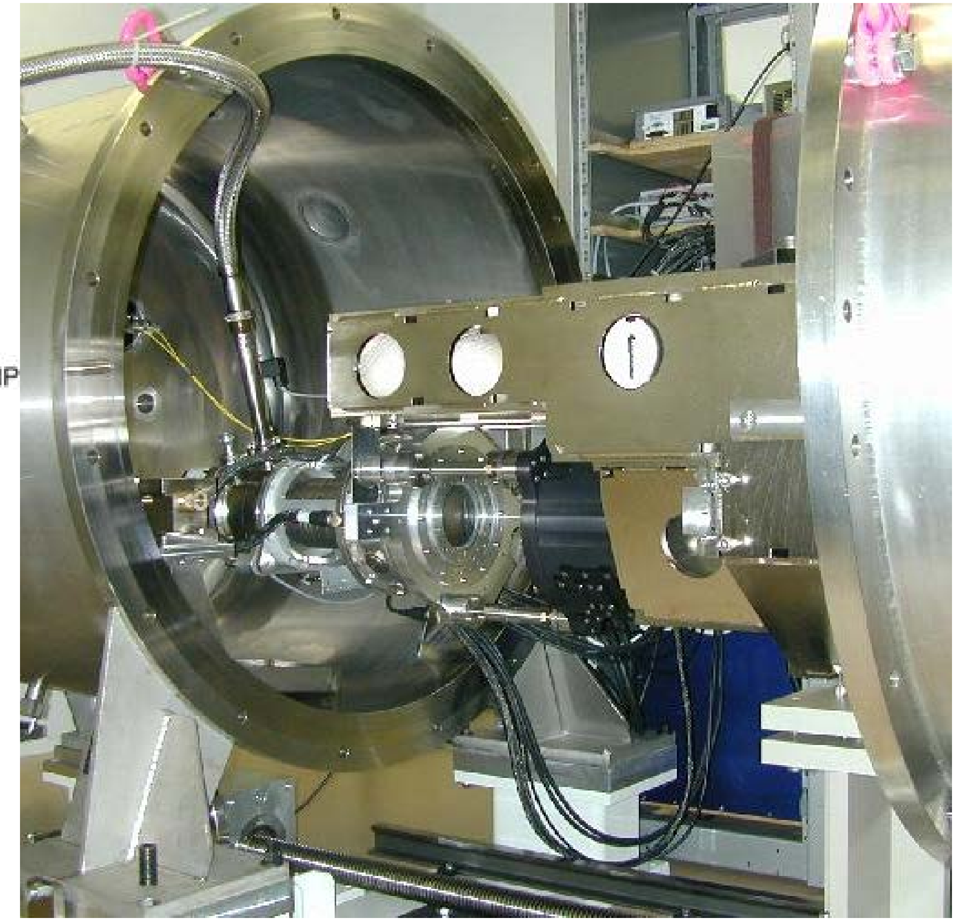
Here the change of output is seen to be 250 DN which in our system would equate to an additional
noise of approximately 50 e- rms added in quadrature to the read noise.

Cryostats – Examples

Spitzer



HARPS



Cryostats – Examples

Herschel