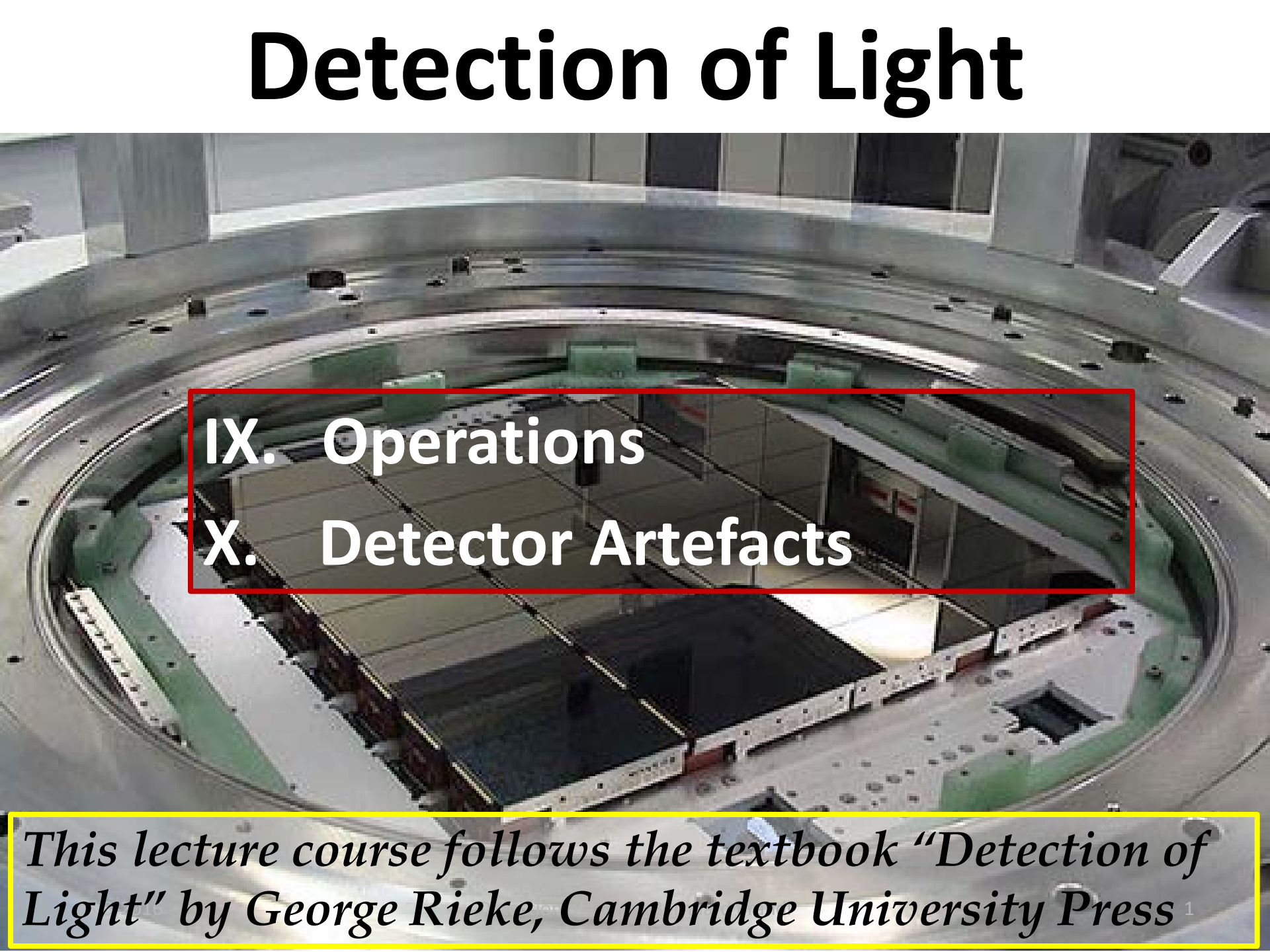


Detection of Light



IX. Operations

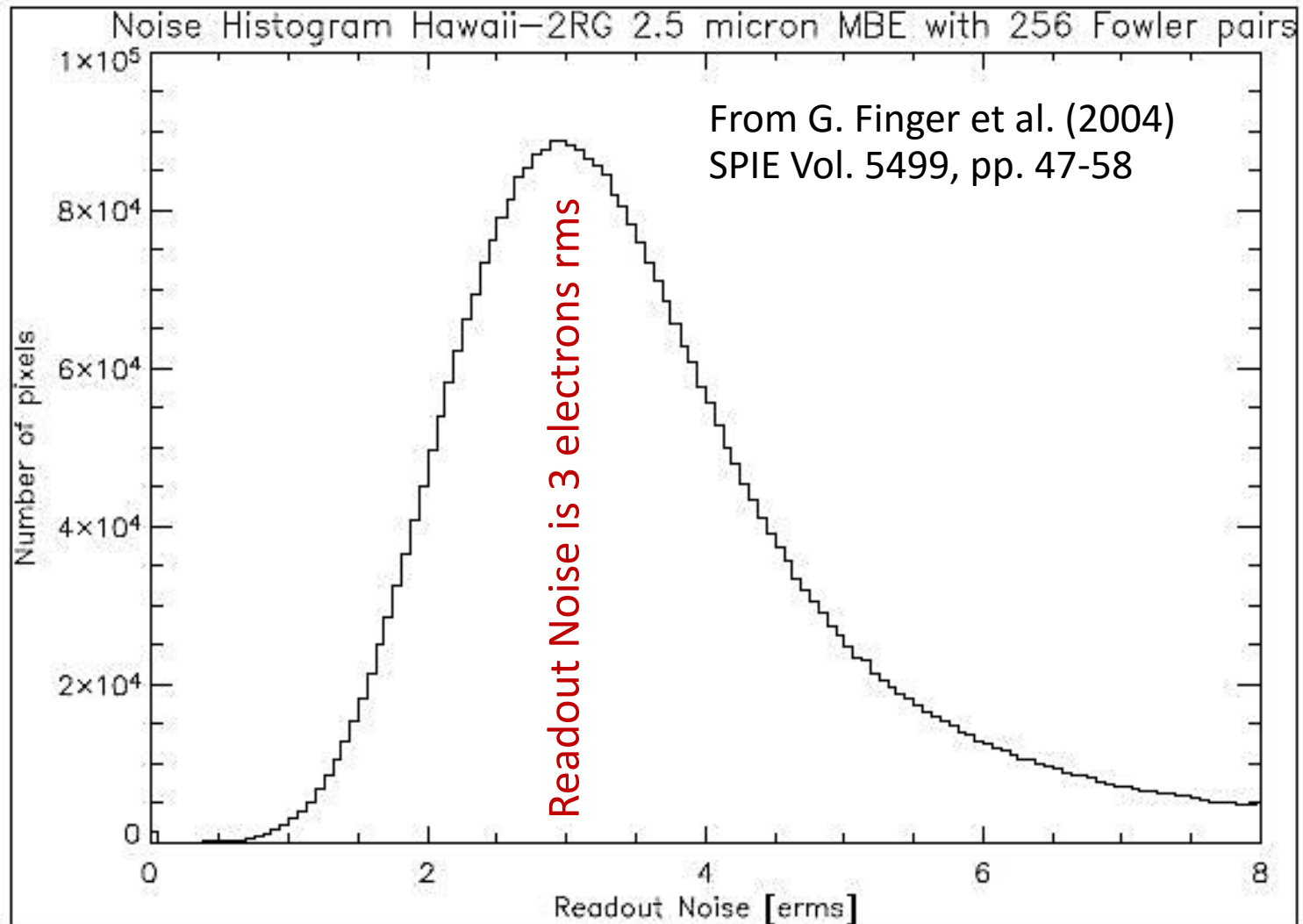
X. Detector Artefacts

This lecture course follows the textbook “Detection of Light” by George Rieke, Cambridge University Press ¹

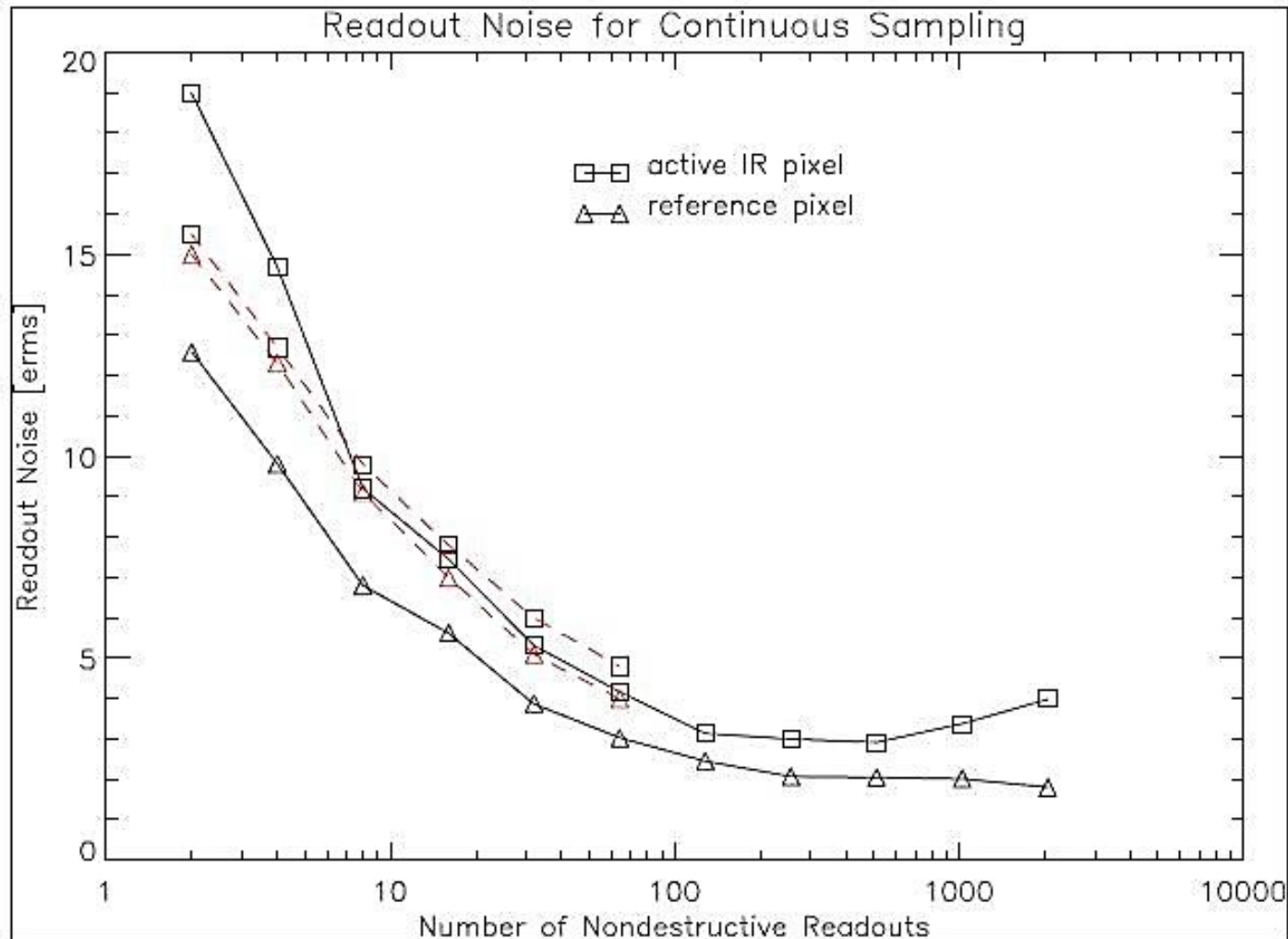
Dark Current and Read Noise

Distribution of Readout Noise

Histogram of readout noise.



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



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

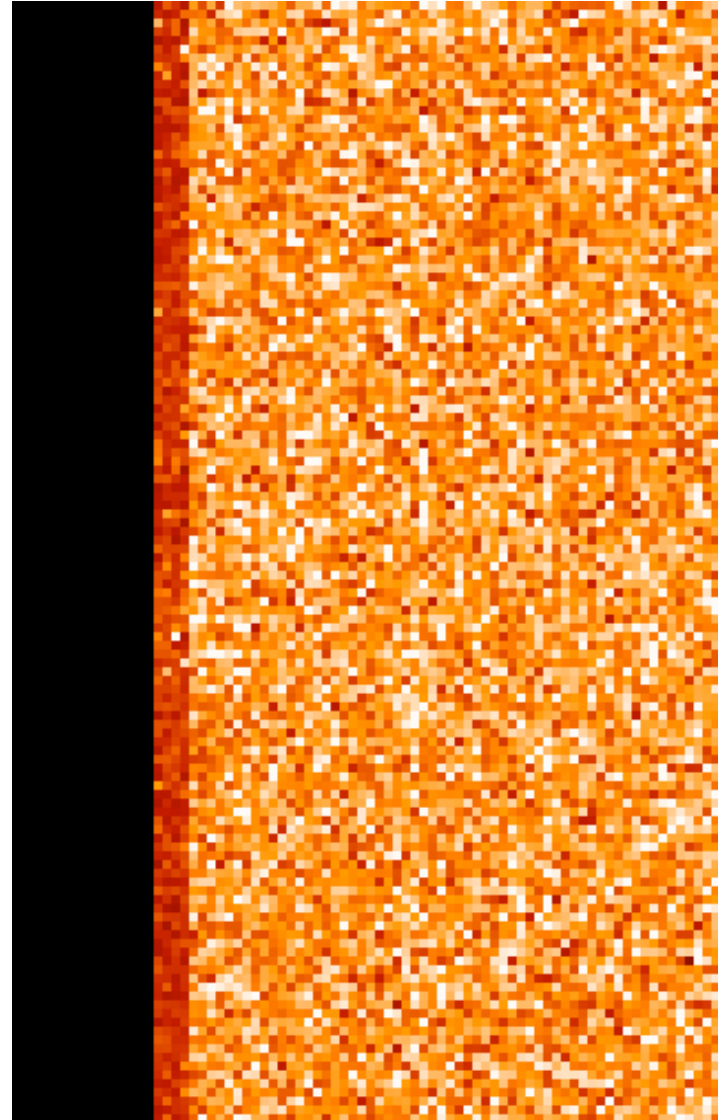
“Reference Pixels” (1)

- 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.

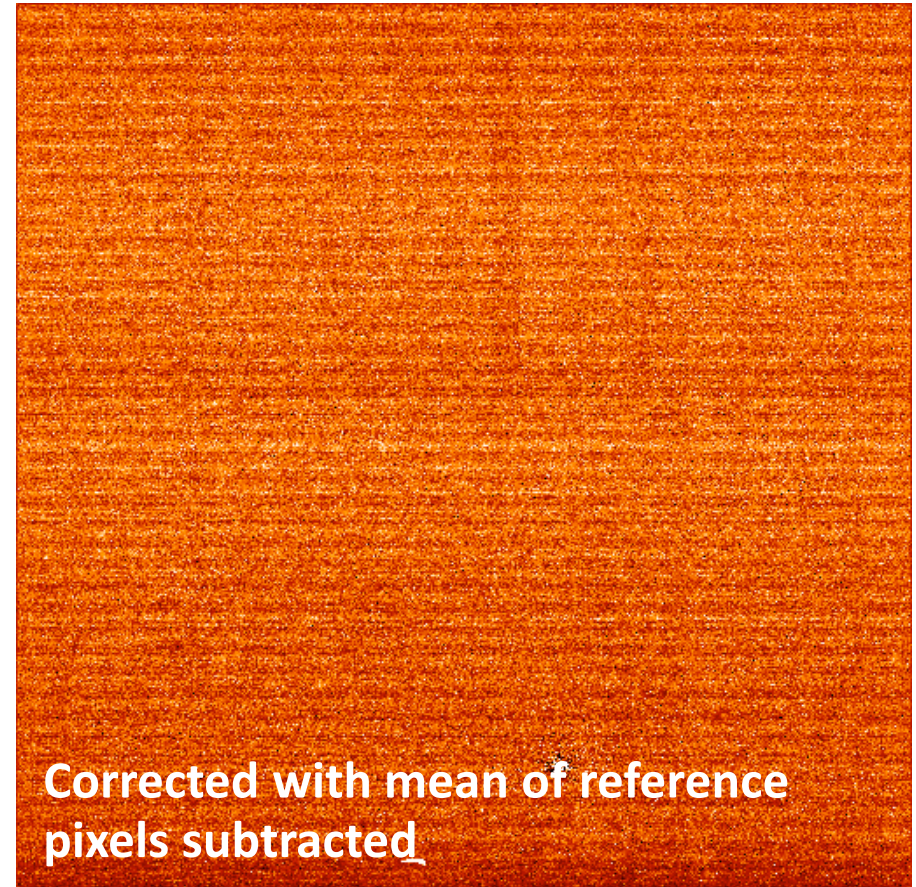
*Readout noise on **active pixels**: 17 e- rms.*

*Readout noise on **reference pixels**: 8 e- rms.*



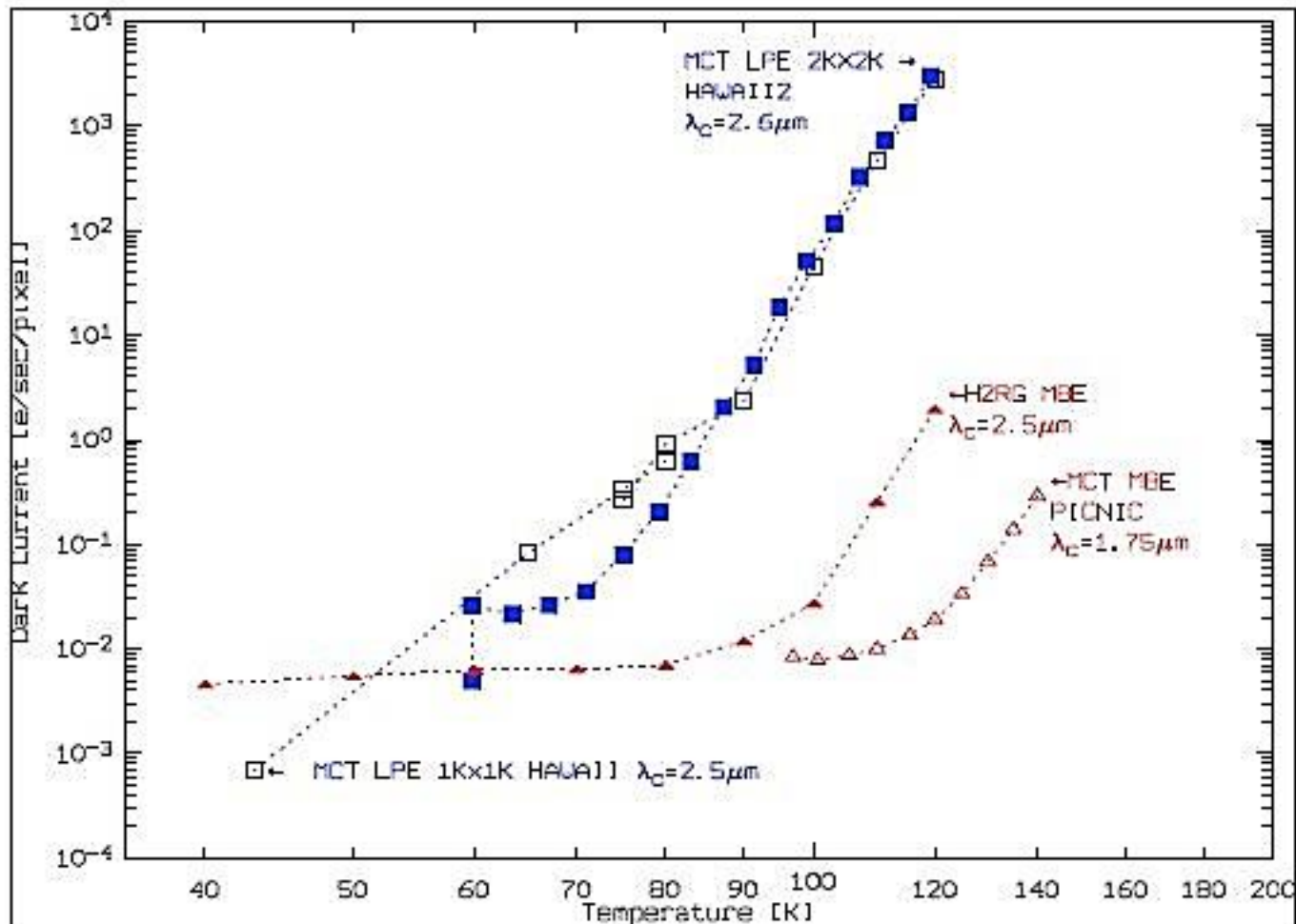
“Reference Pixels” (2)

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



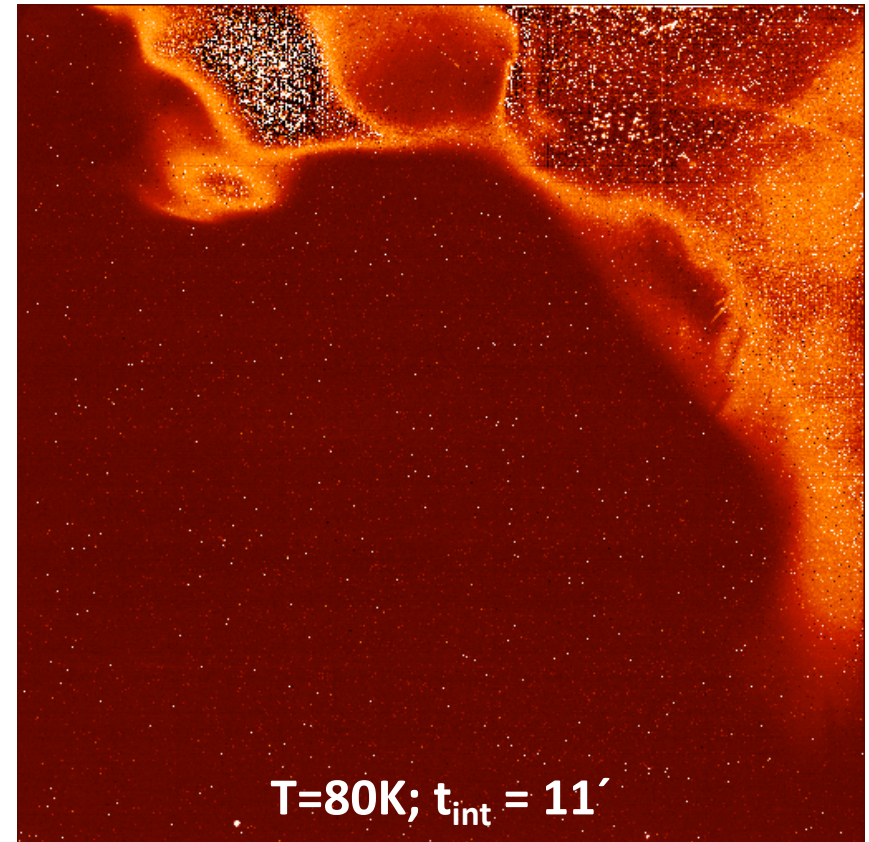
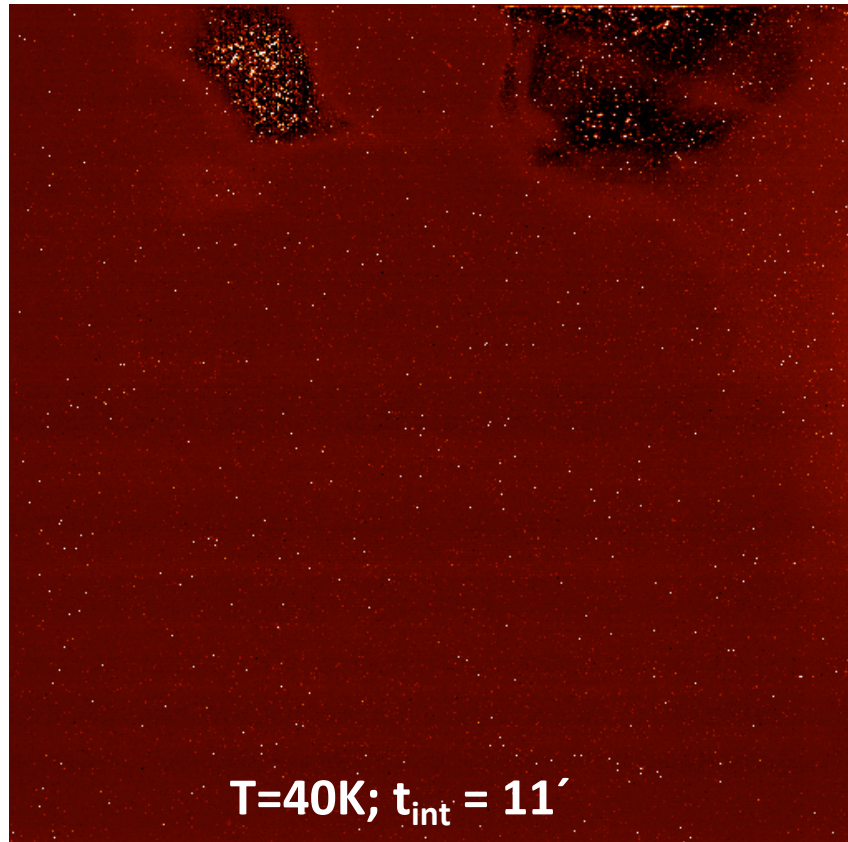
Dark Current (1)

The dark current is a **strong function of temperature!**



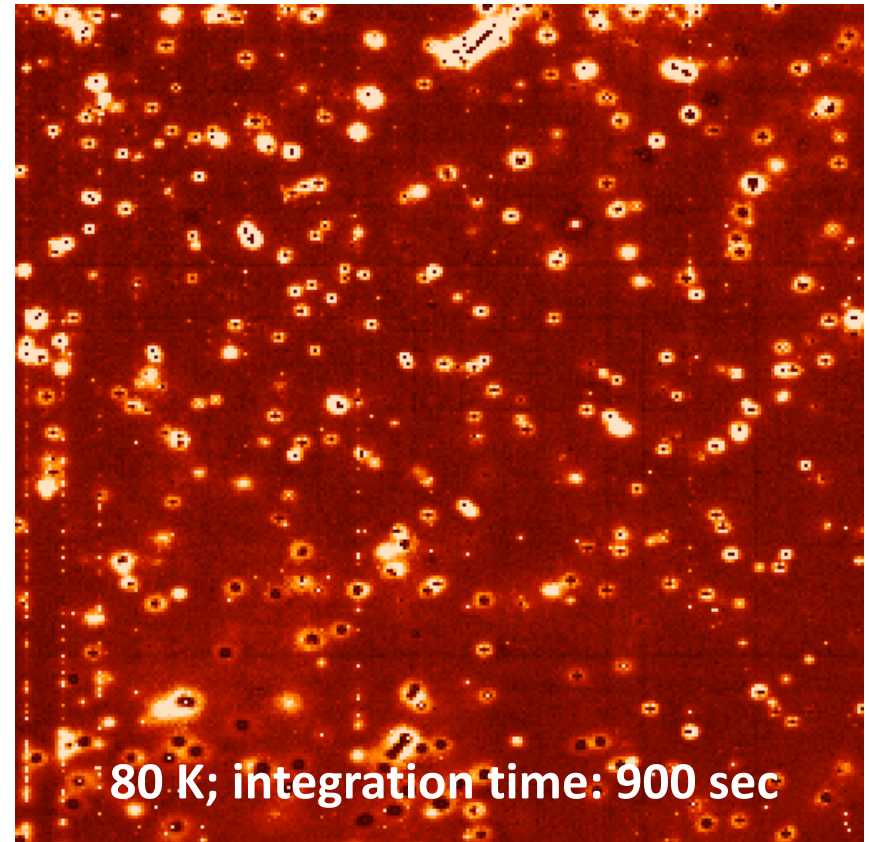
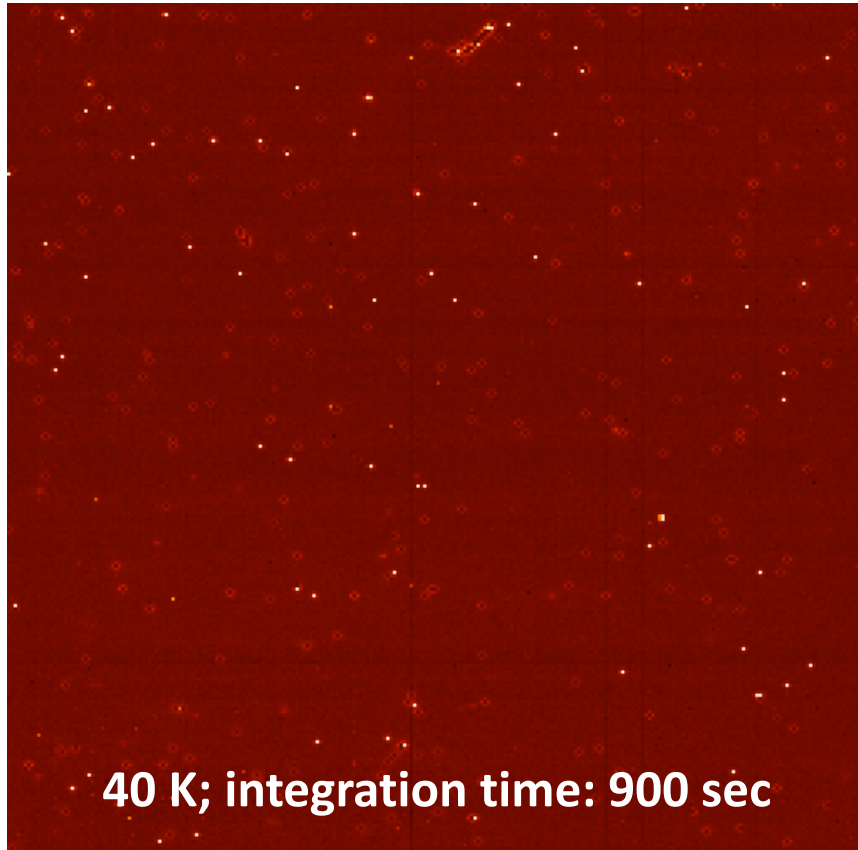
Dark Current (2)

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



Cosmetic Quality

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

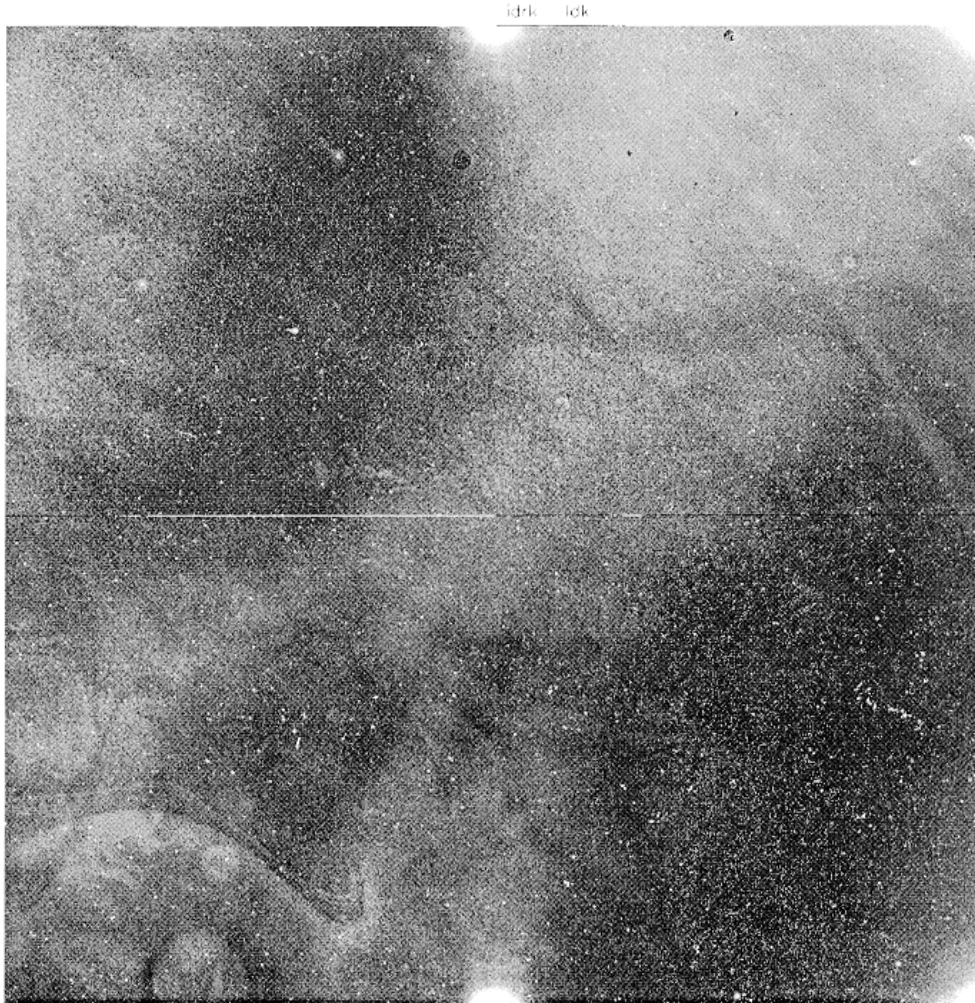


➔ Cooling is very important!

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).

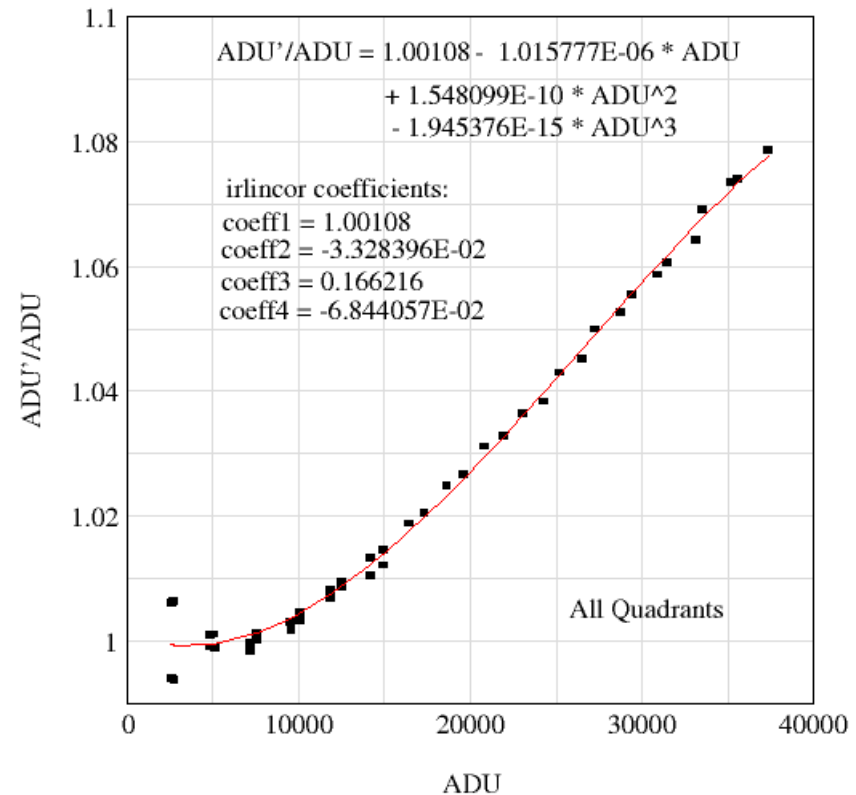
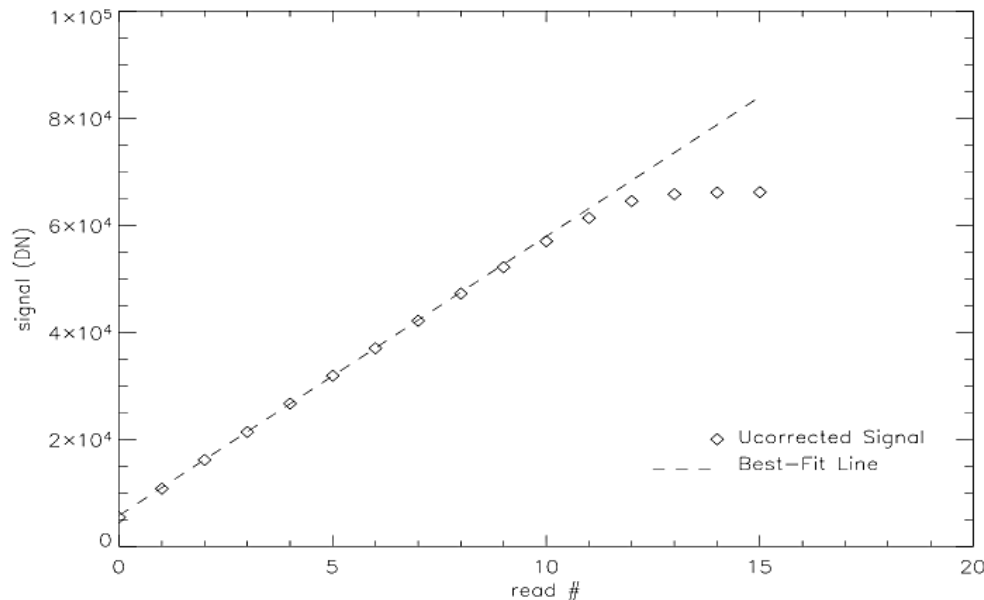


Non-Linearity

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

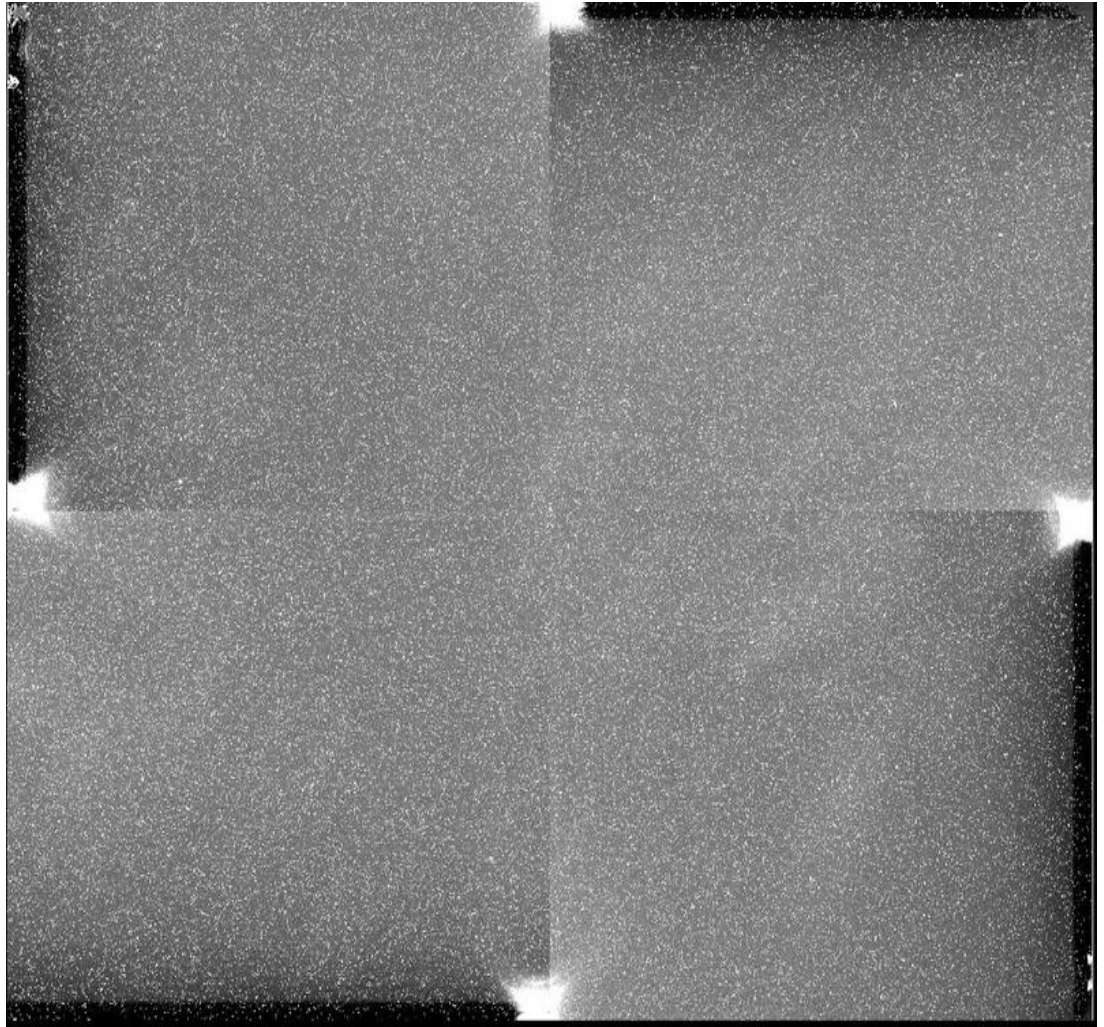
Thermal Glow from Pre-Amplifiers

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

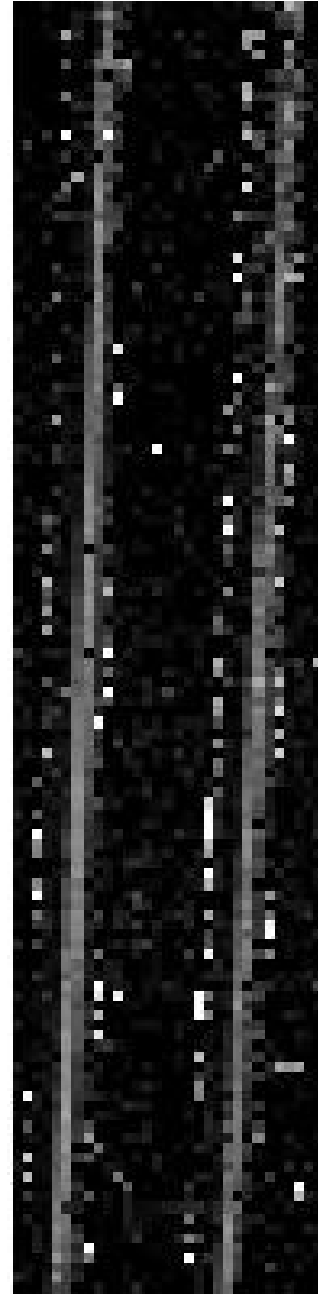
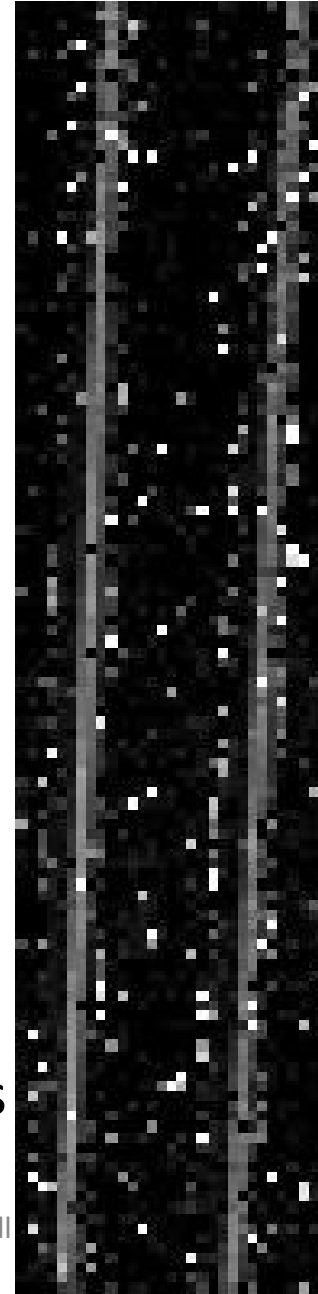
Dead Pixel: a defective pixel that delivers no signal and cannot be used.

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



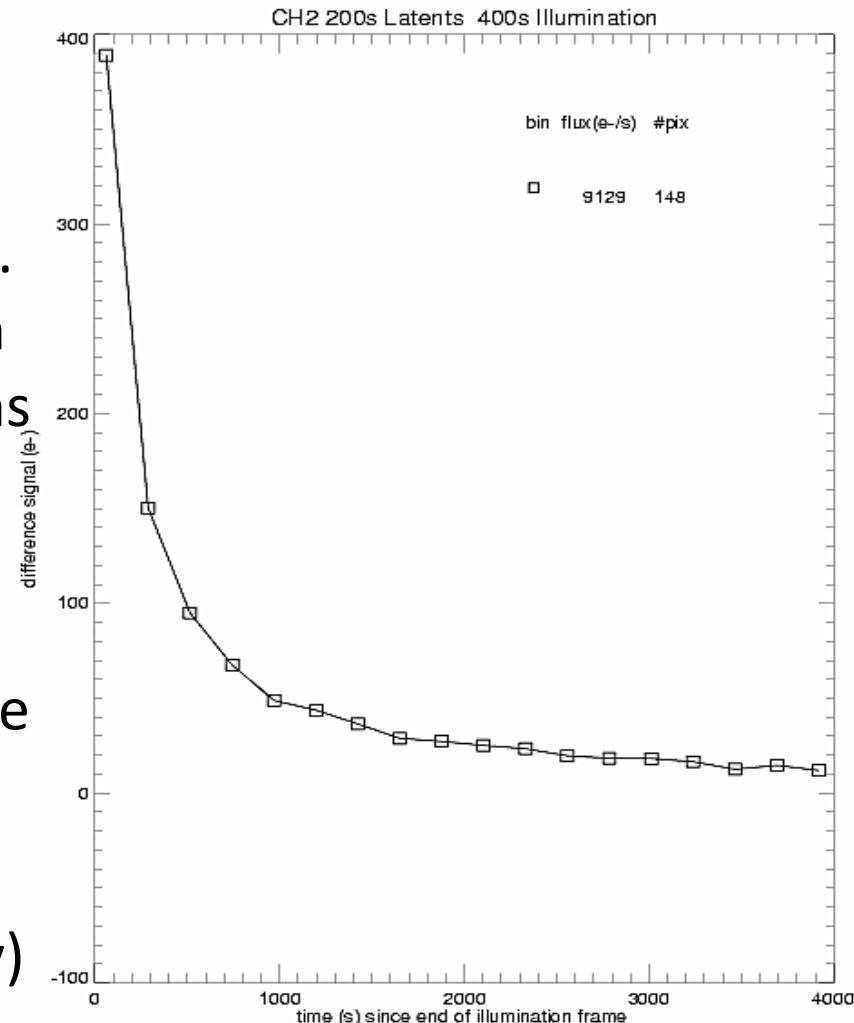
Latent Images

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:

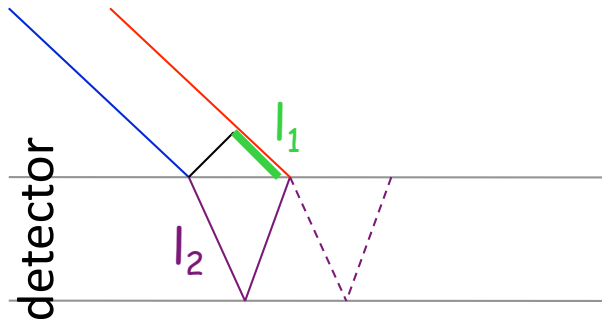
- **Wait** (and wait, and wait....)
- Apply frequent **resets** (clean out the trap)
- **Annealing** (heat up array to thermally excite them into mobility)
- Use ND filters or shutter during **target acquisition**



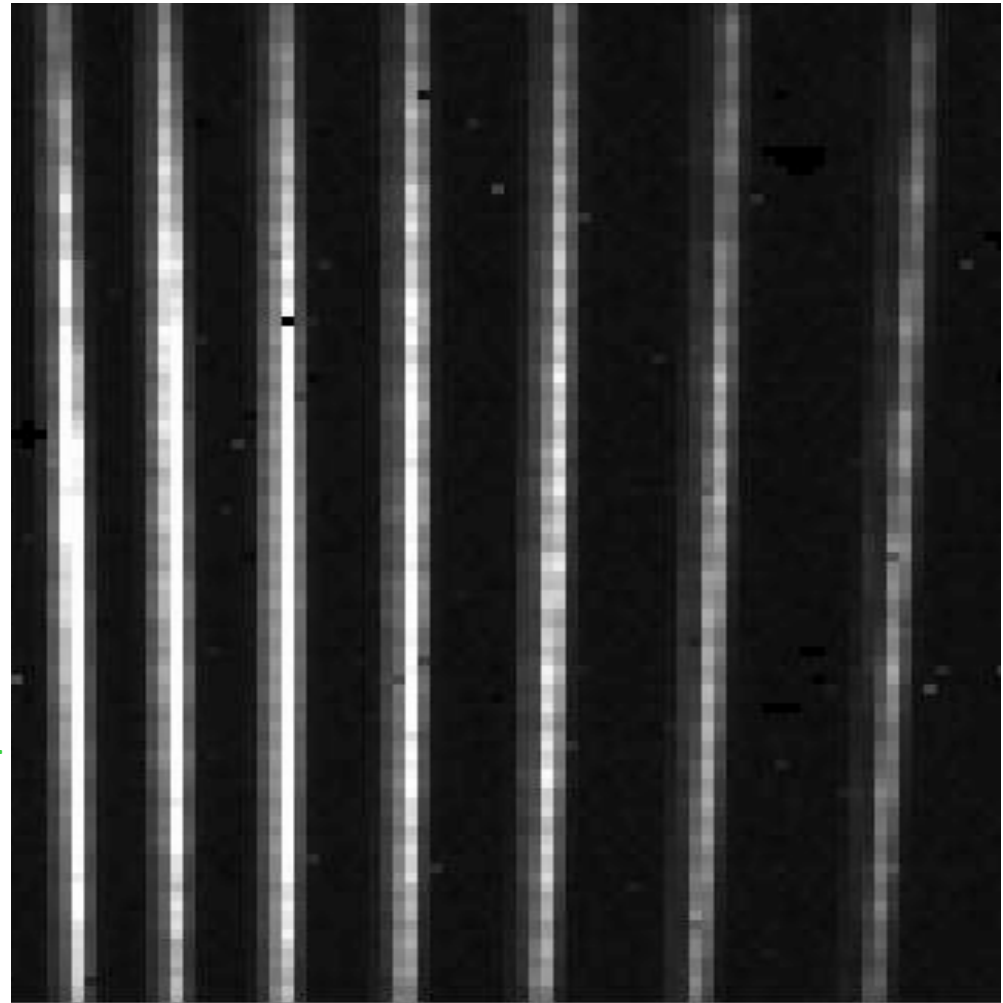
Detector Fringing (in Spectrographs)

PROBLEM:

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



If the phase difference between I_1 and $n \cdot I_2$ is an even multiple of π constructive interference occurs. If an odd multiple destructive interference occurs



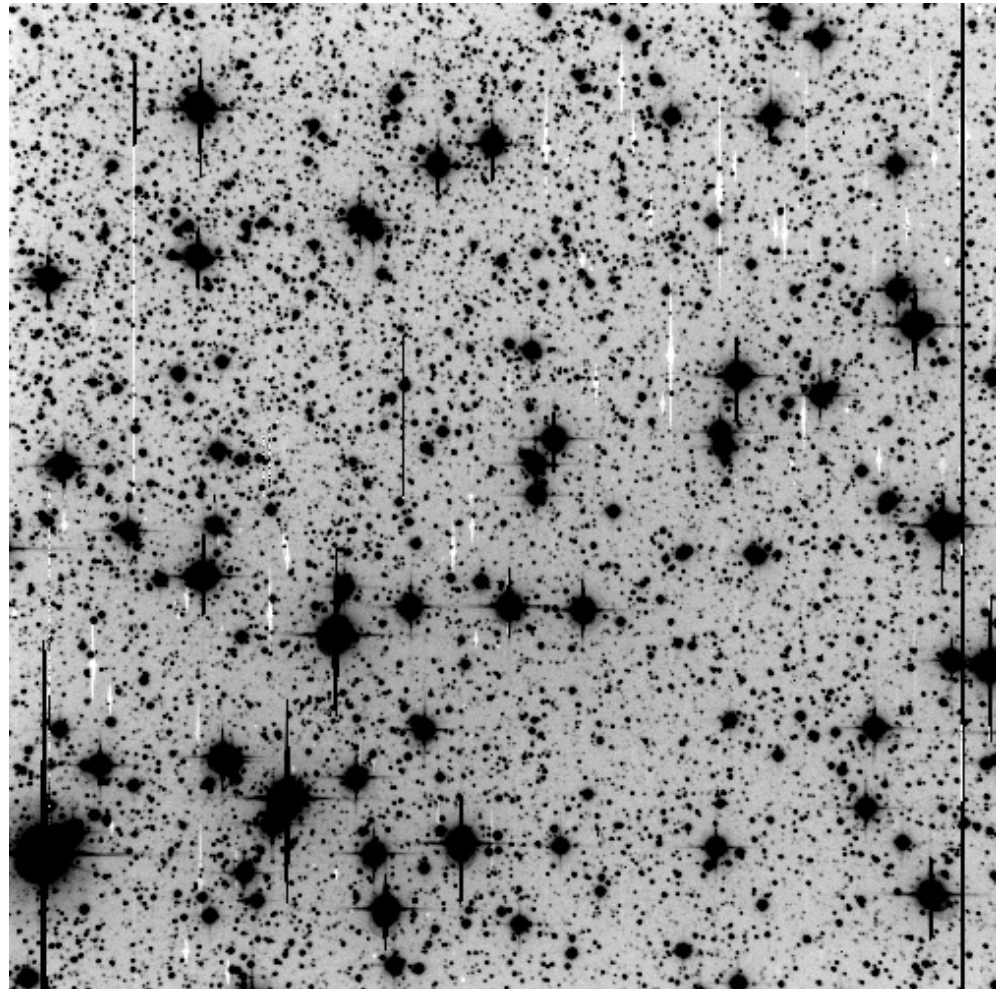
Crosstalk

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.

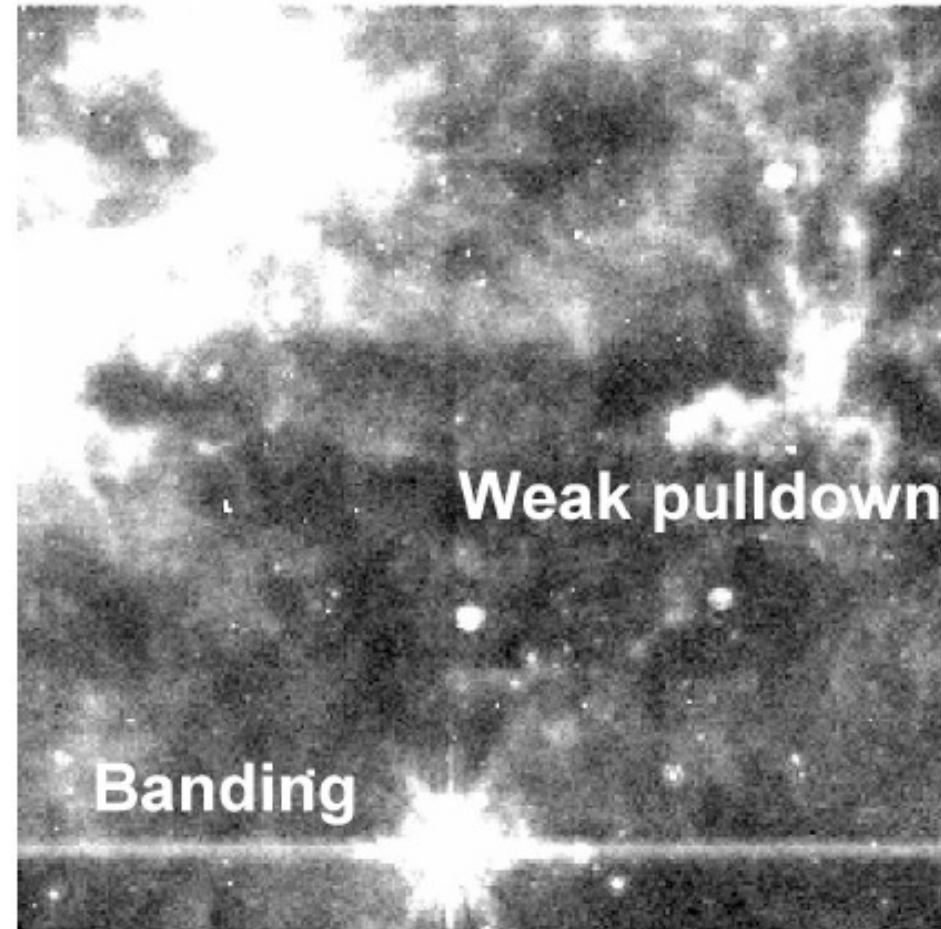
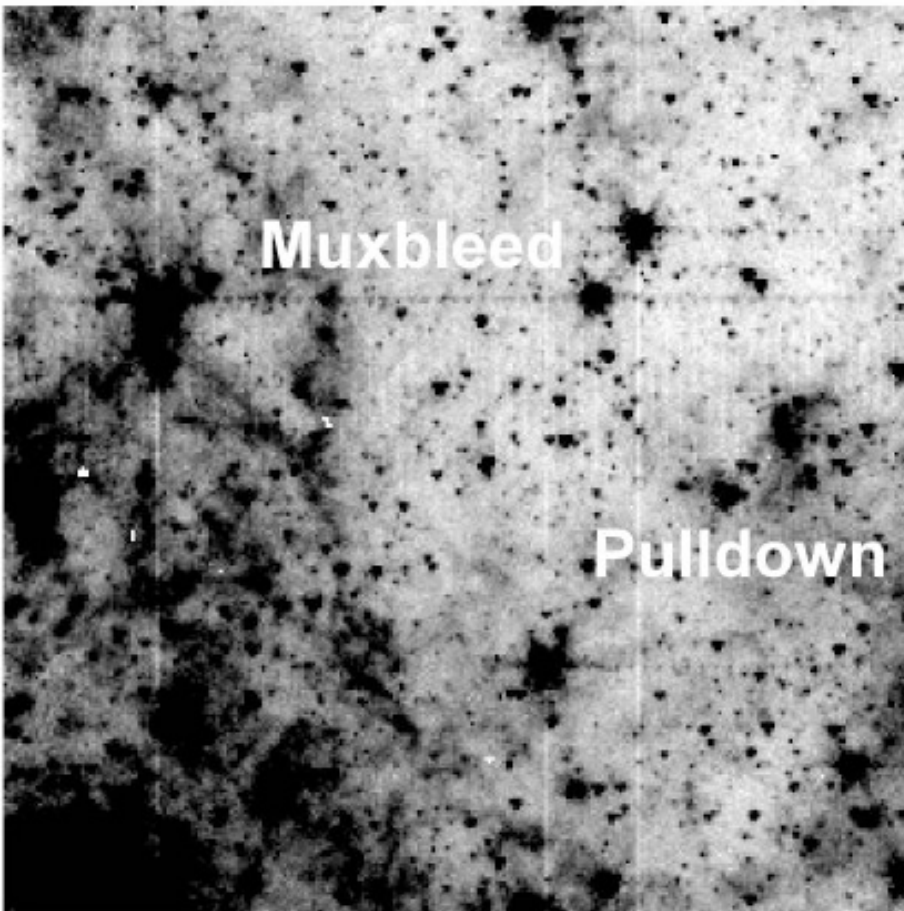
The negative (white) images in the upper right quadrant correspond to the black star images in the lower left quadrant



Pulldown & Bleeding

PROBLEM:

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



Readout Schemes (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.

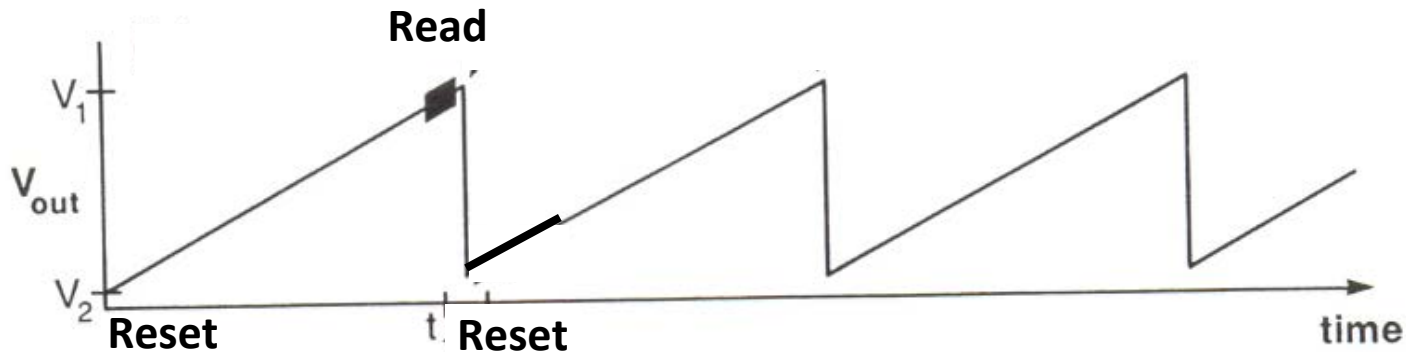
The **IR Array** approach:

- 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**!

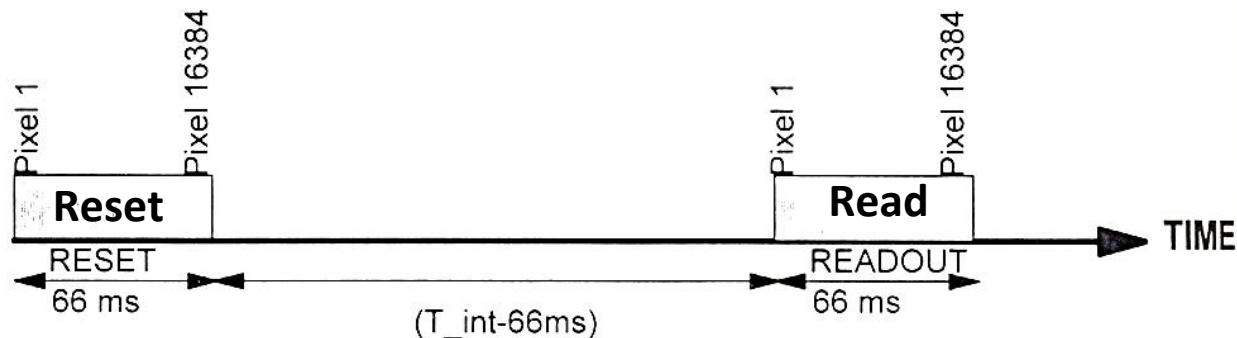
Next, we'll focus on IR array readouts.

Single Sampling

The simplest approach ...

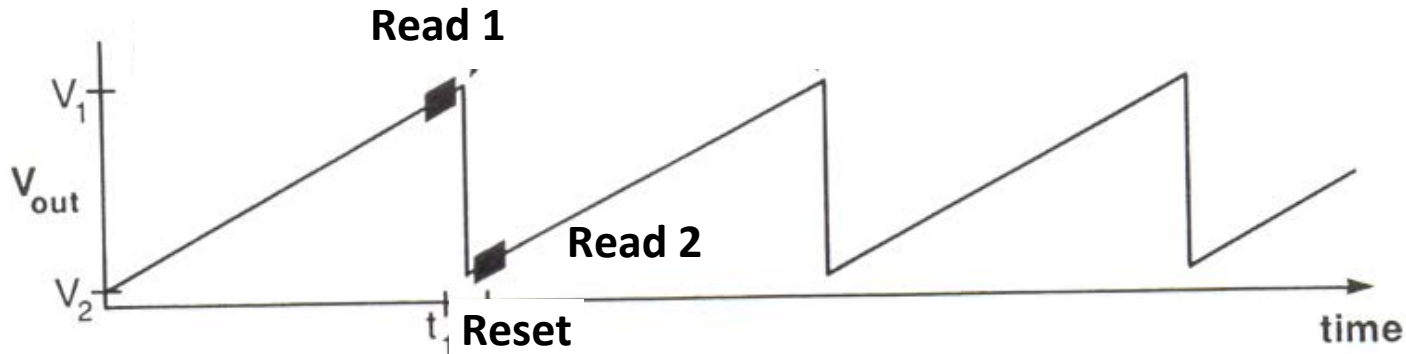


- Does not remove kTC noise or voltage drifts
- It directly measures the signal level (we would notice saturation)



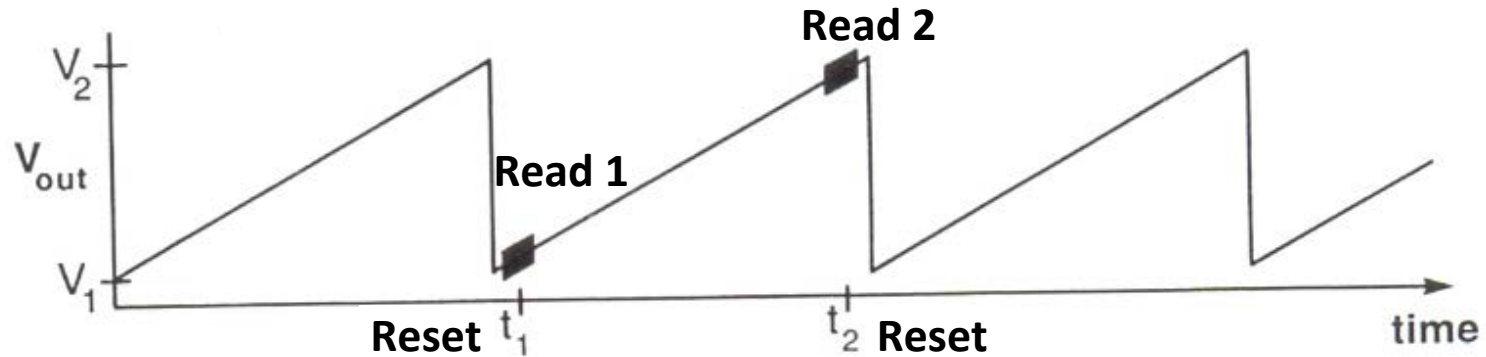
Double-correlated Sampling

Reads pixel twice (before and after the reset)

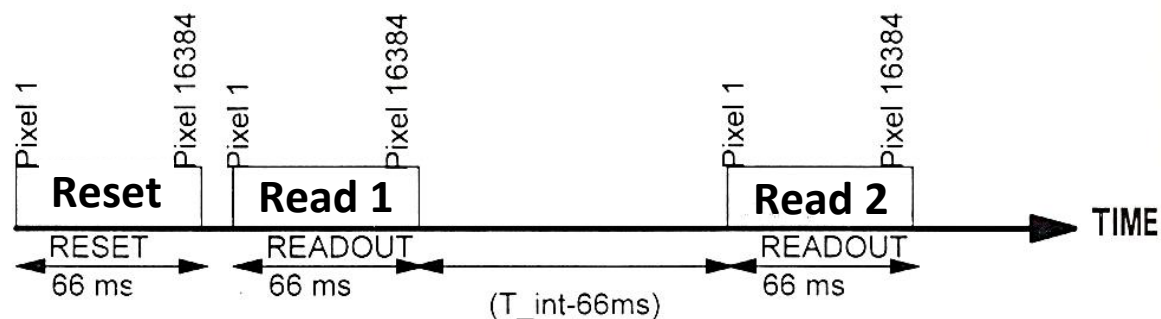


- $\text{Signal} = \text{Read 1} - \text{Read 2}$
- Voltage drifts are subtracted out
- “read-reset-read” $\rightarrow$ difference is measured for each pixel before moving to the next $\rightarrow$ simplified, lower data rates
- Does not eliminate kTC noise since offset is subtracted from the *previous*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

Reset-Read-Read

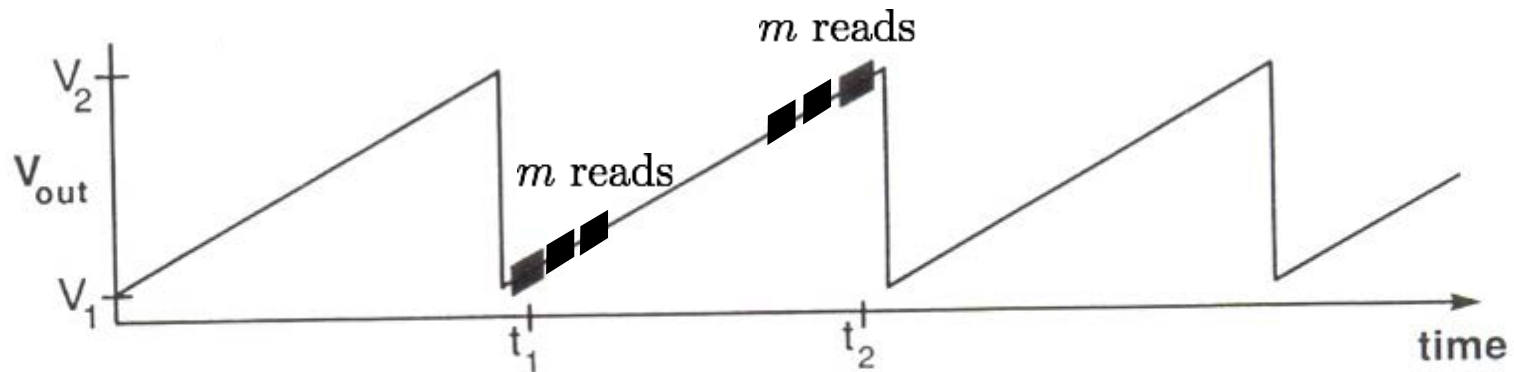


- Resets the array pixel-by-pixel (or column-wise)
- Reads the array pixel-by-pixel at the start and at the end of the integration
- $\text{Signal} = \text{Read}(2) - \text{Read}(1)$
- Advantage: best correlation, no reset noise
- Disadvantages: requires frame storage, reduced dynamical range



Multiple (Fowler) Sampling

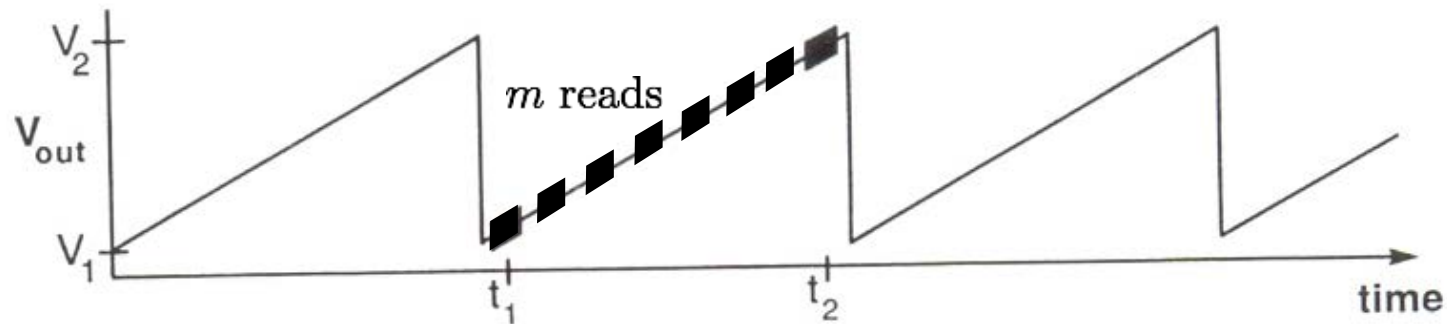
Uses multiple reads at start and end of the integration time to reduce the read noise.



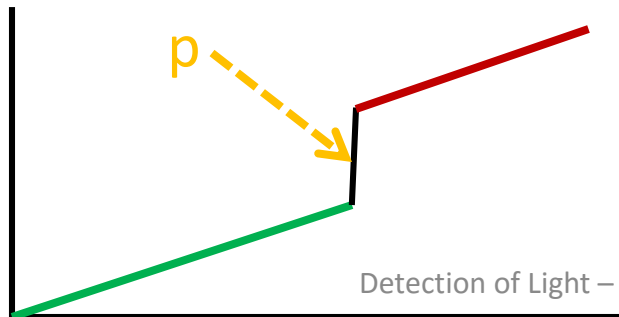
- Signal = Mean(Read 2) - Mean(Read 1)
- m reads get coadded in buffer (no separate frame storage)
- Readout noise is reduced by $\sqrt{m}$ over reset-read-read
- Longer time to carry out a given integration

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	$\lambda < 1\mu\text{m}$	$\sim 300\text{ K}$	$\sim 180\text{ K}$
near infrared	$1\mu\text{m} < \lambda < 2.5\mu\text{m}$	$\sim 100\text{ K}$	$< 80\text{ K}$
thermal infrared	$\lambda > 2.5\mu\text{m}$	$\sim 30\text{ K}$	$\sim 6\text{ K}$

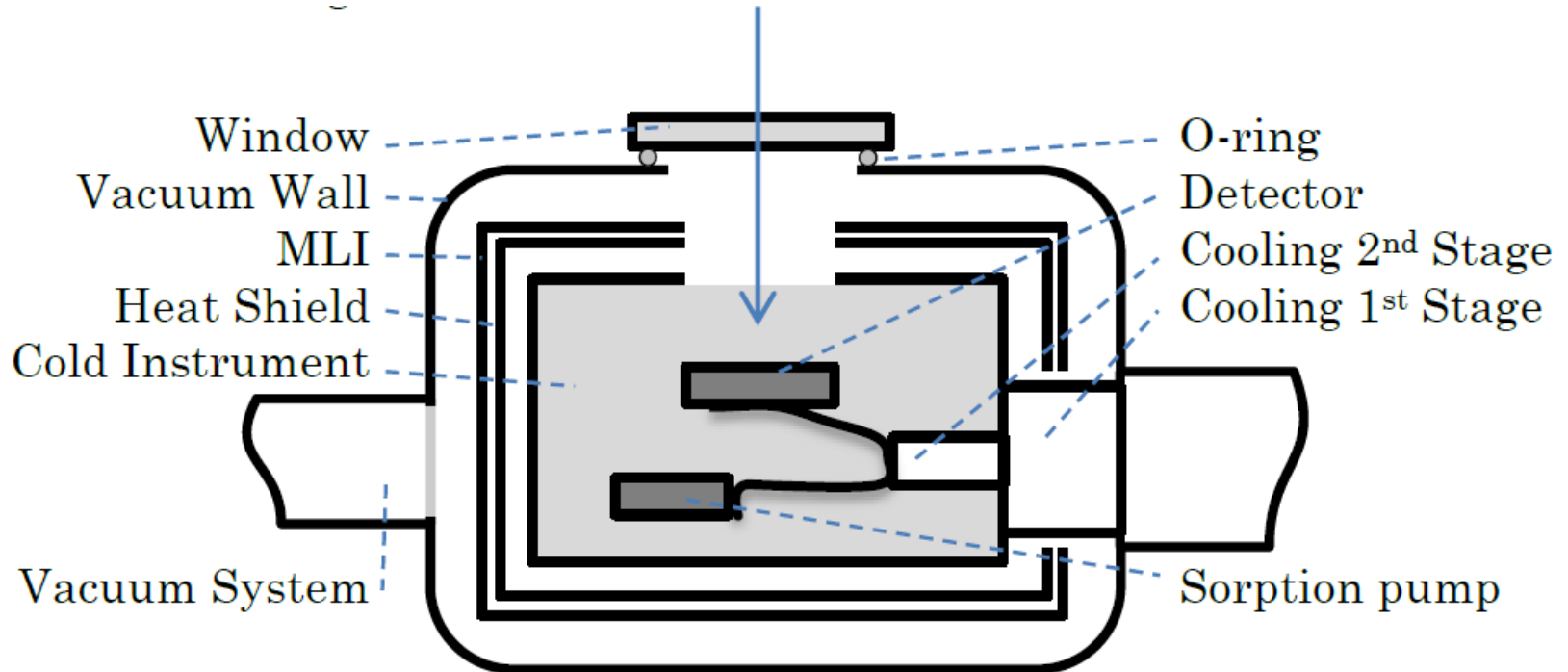
Cooling requires Vacuum

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

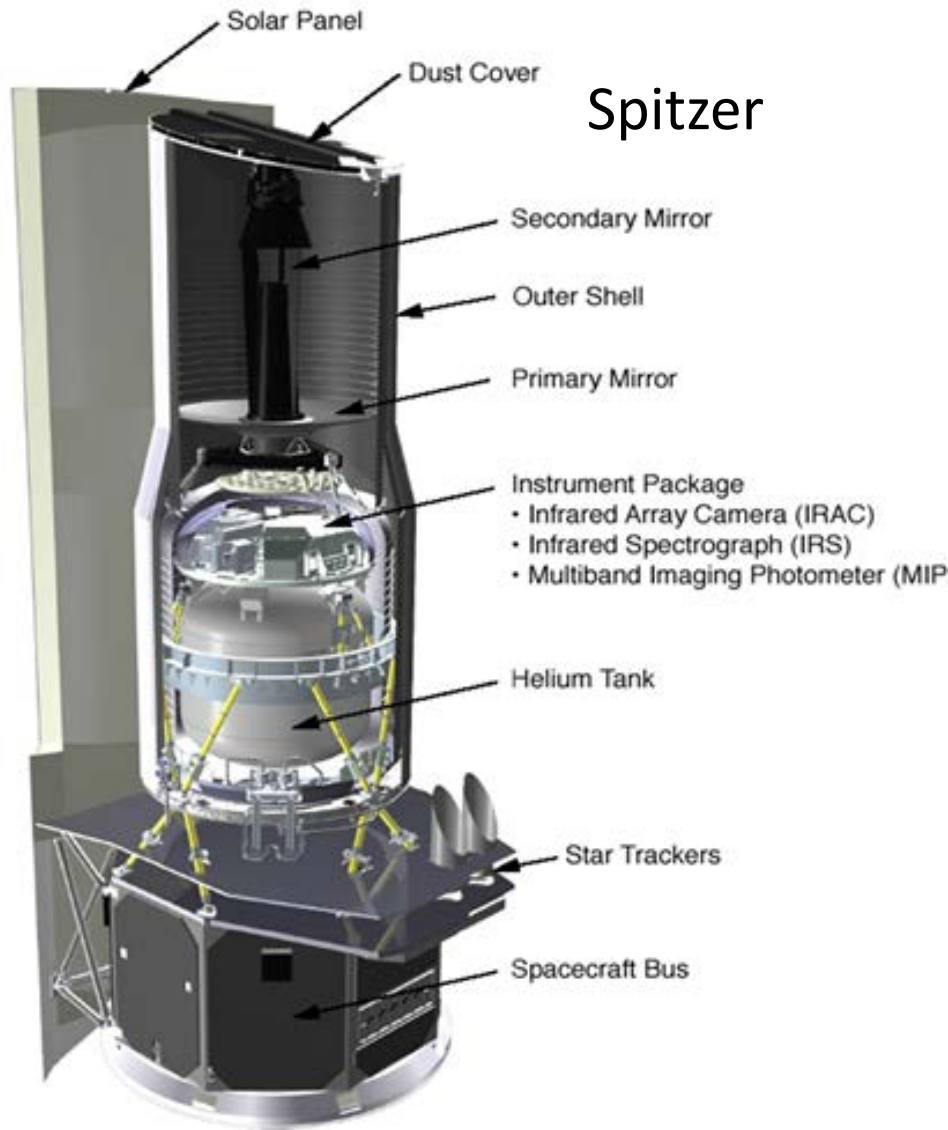
*at room temperature

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.

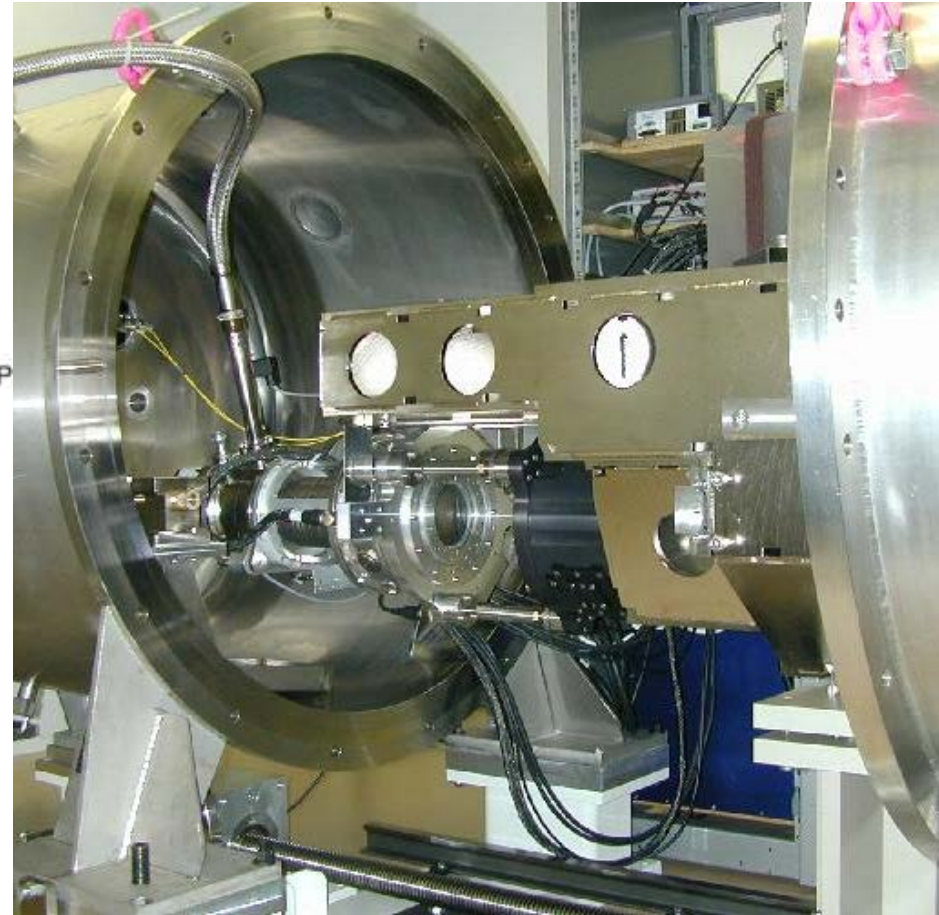


Cryostats – two Examples



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 (LN₂)**: 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**.

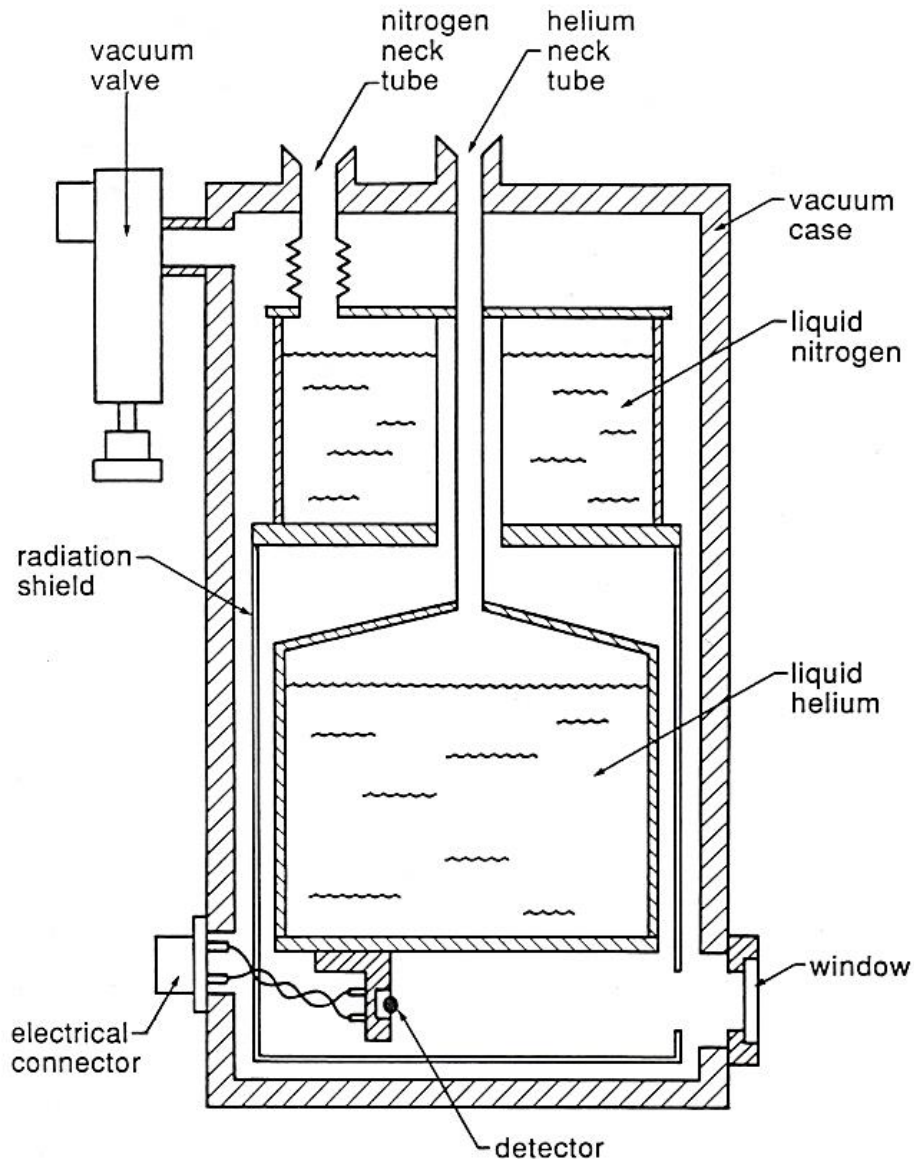
Common Coolers – Overview (2)

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 ^4He becomes **superfluid** and will flow all over the inside of the dewar.

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