Astronomical Observing Techniques

Lecture 10: Silicon Eyes 2

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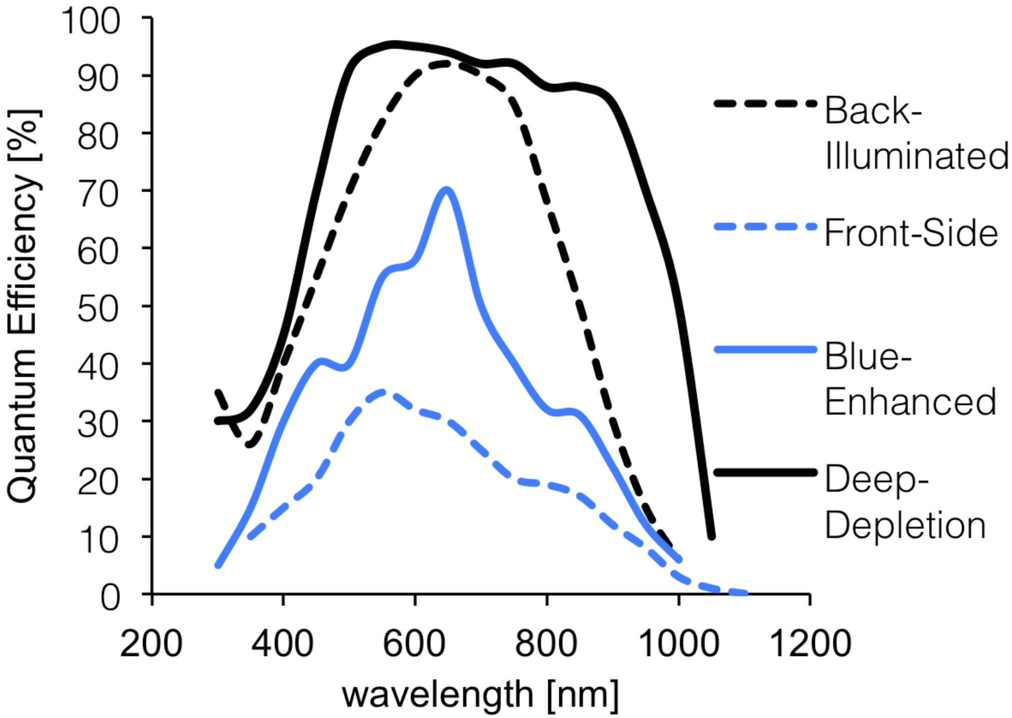
Overview

1. CCD Operation
2. CCD Data Reduction
3. CMOS devices
4. IR Arrays
5. Bolometers
6. MKIDS

Backside Illumination

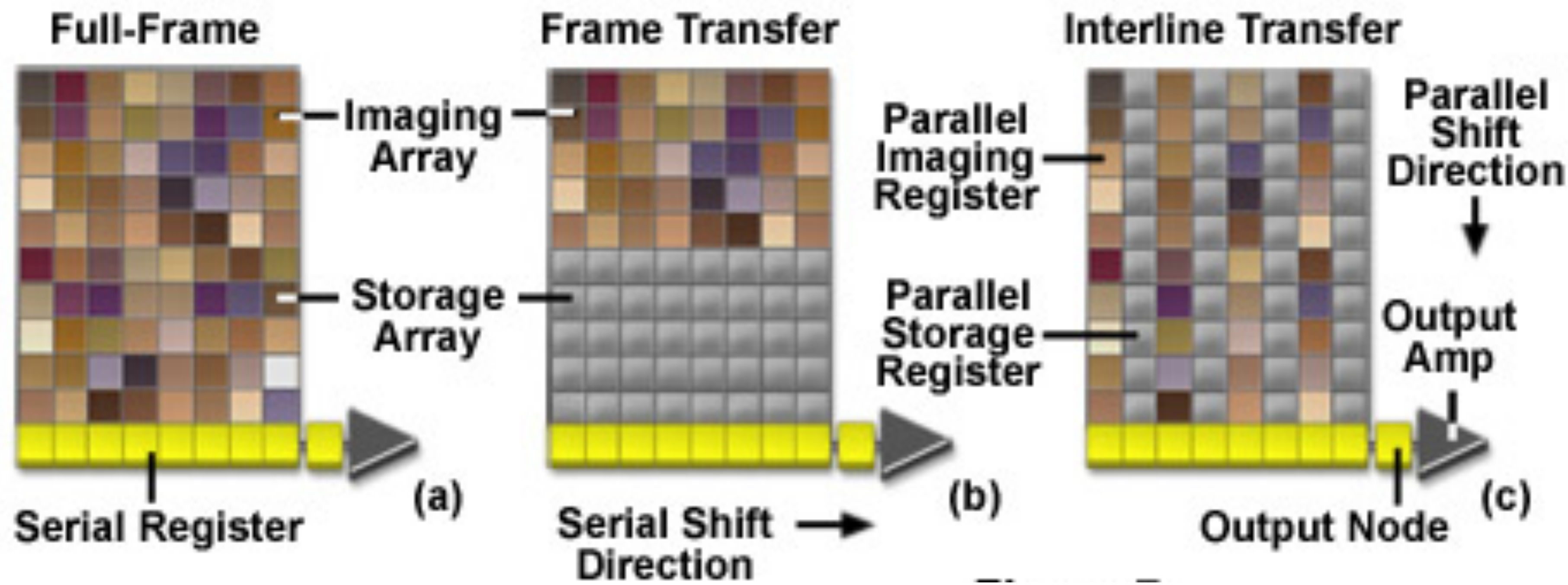


<u>front illumination</u>: poly-silicon gate electrodes absorb in the blue and lead to interference effects

<u>blue-enhanced</u>: holes in poly-silicon gate electrodes

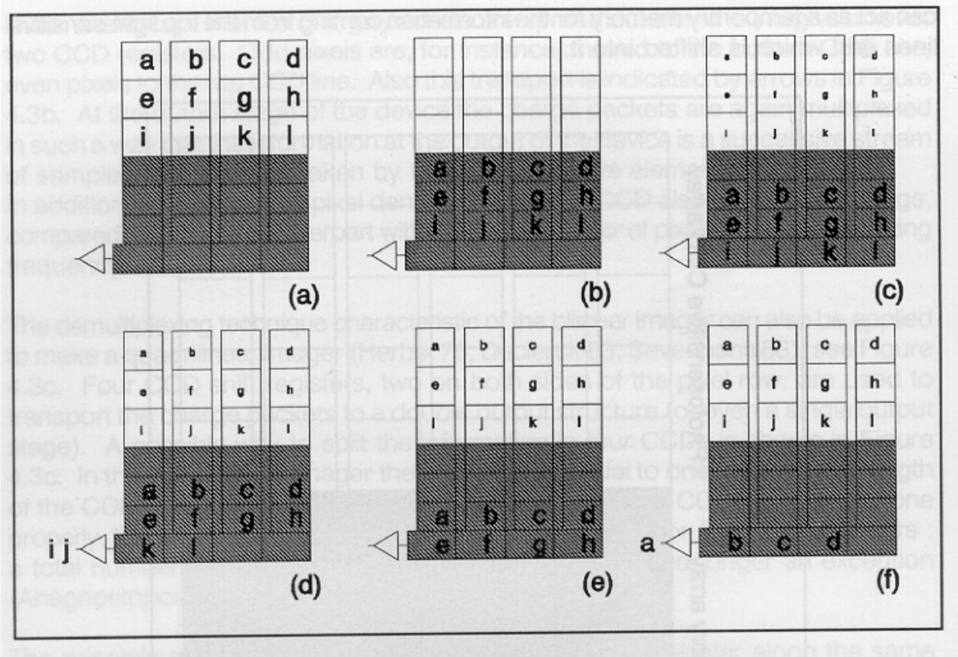
- back-illumination: thin silicon➔photo-electrons reach potential wells
- electric field gradient moves charges: increase doping concentration in regions close to silicon surface
- increases blue sensitivity where electrons are generated close to silicon surface
- minimize reflection of light from back surface with SiO layer

Focal Plane Architecture



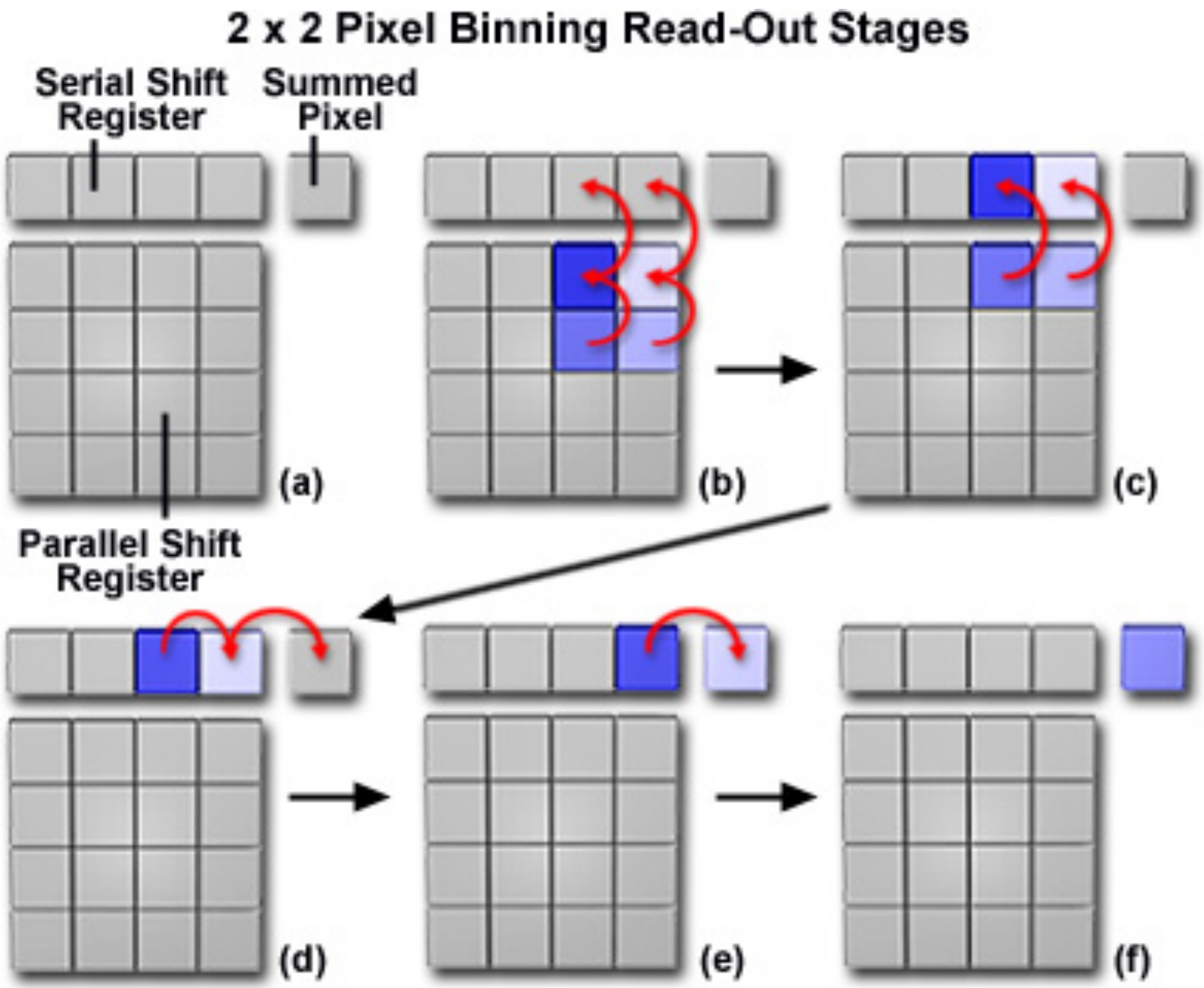
- astronomy: full-frame and frame-transfer arrays
- interline-transfer arrays in commercial CCD cameras
- frame-transfer CCD has photosensitive array and a memory array coupled to a linear output register
- full-frame device lacks storage section
- shutter interrupts illumination during readout

Frame Transfer Operation

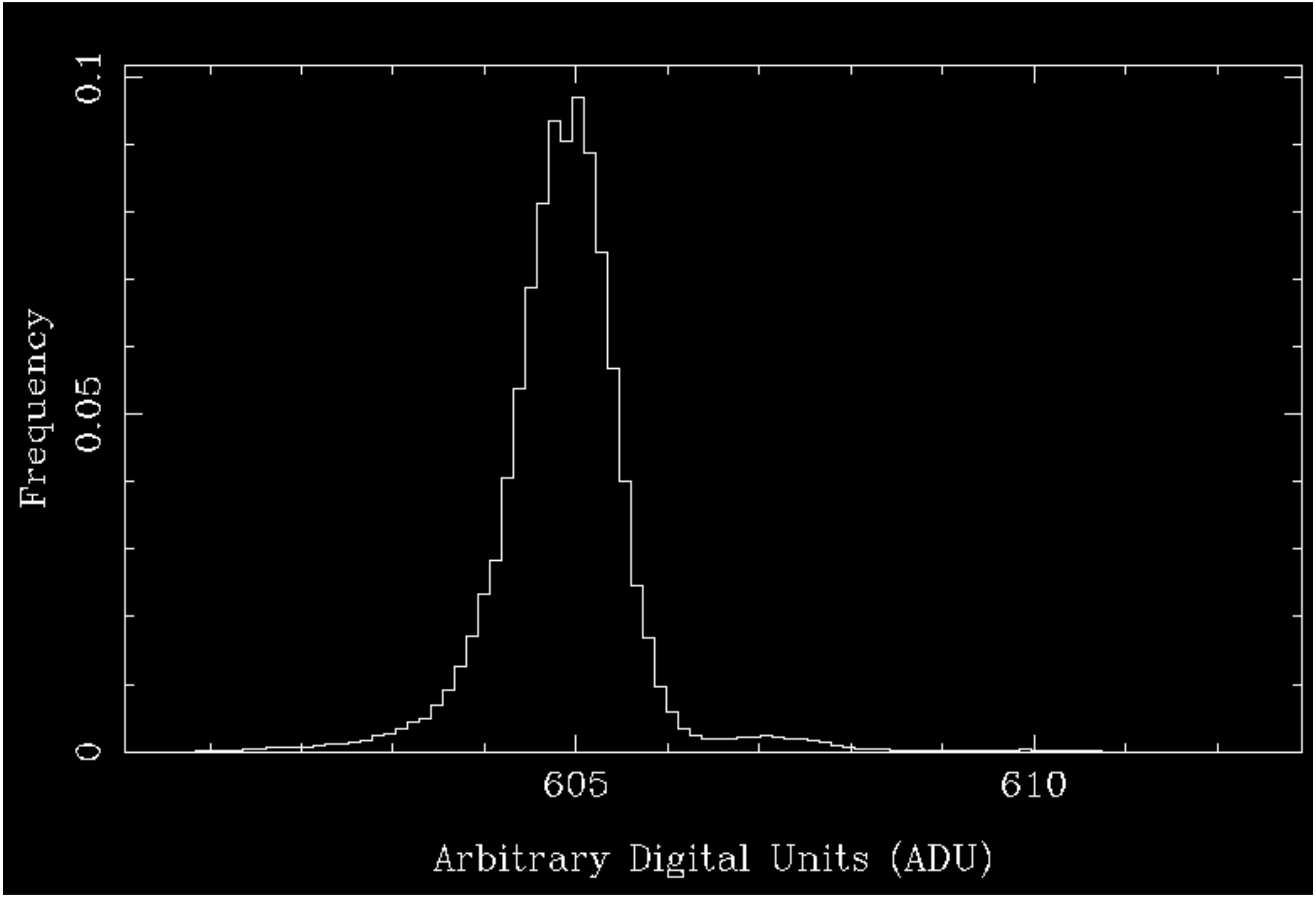


- transfer needs to be done quickly to prevent disturbance by light falling on the image section during read-out
- during readout, all CCD cells in image array are again in integration mode

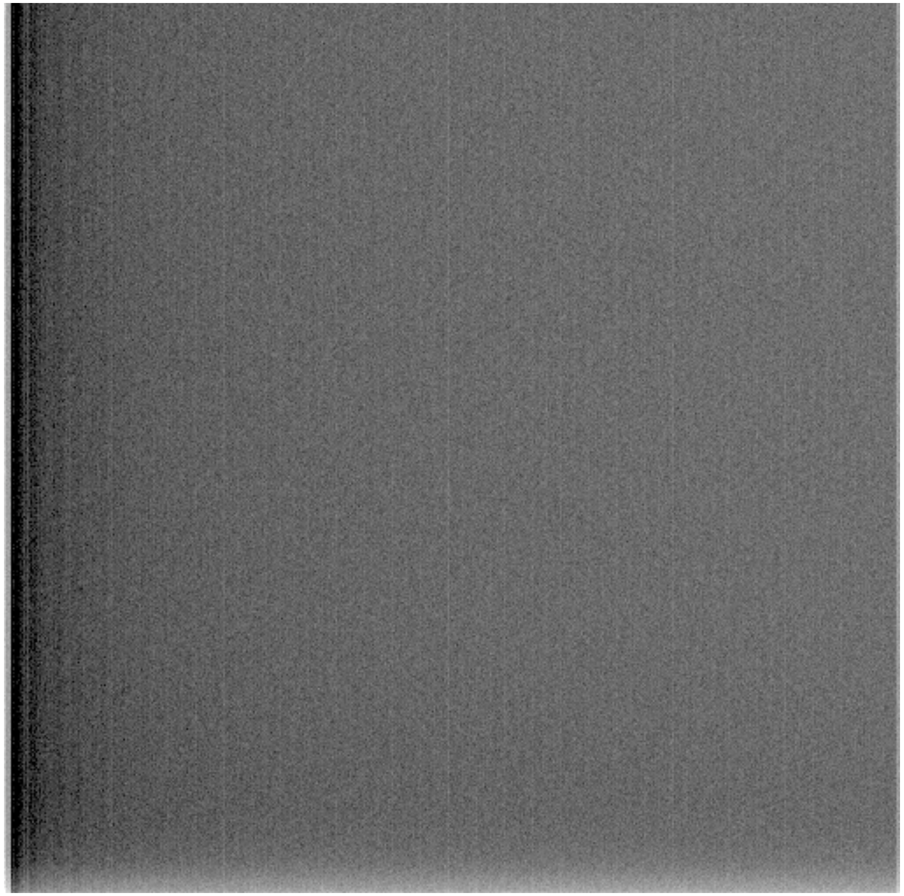
Binning

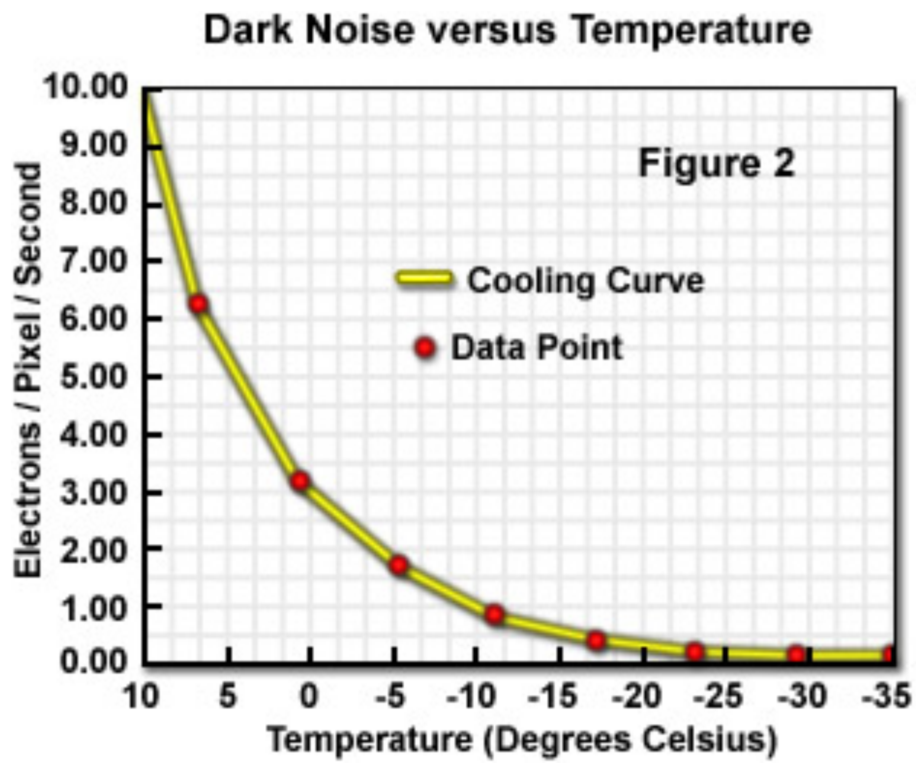

2 x 2 Pixel Binning Read-Out Stages
Serial Shift Register
Summed Pixel
(a)
(b)
(c)
Parallel Shift Register
(d)
(e)
(f)

Bias

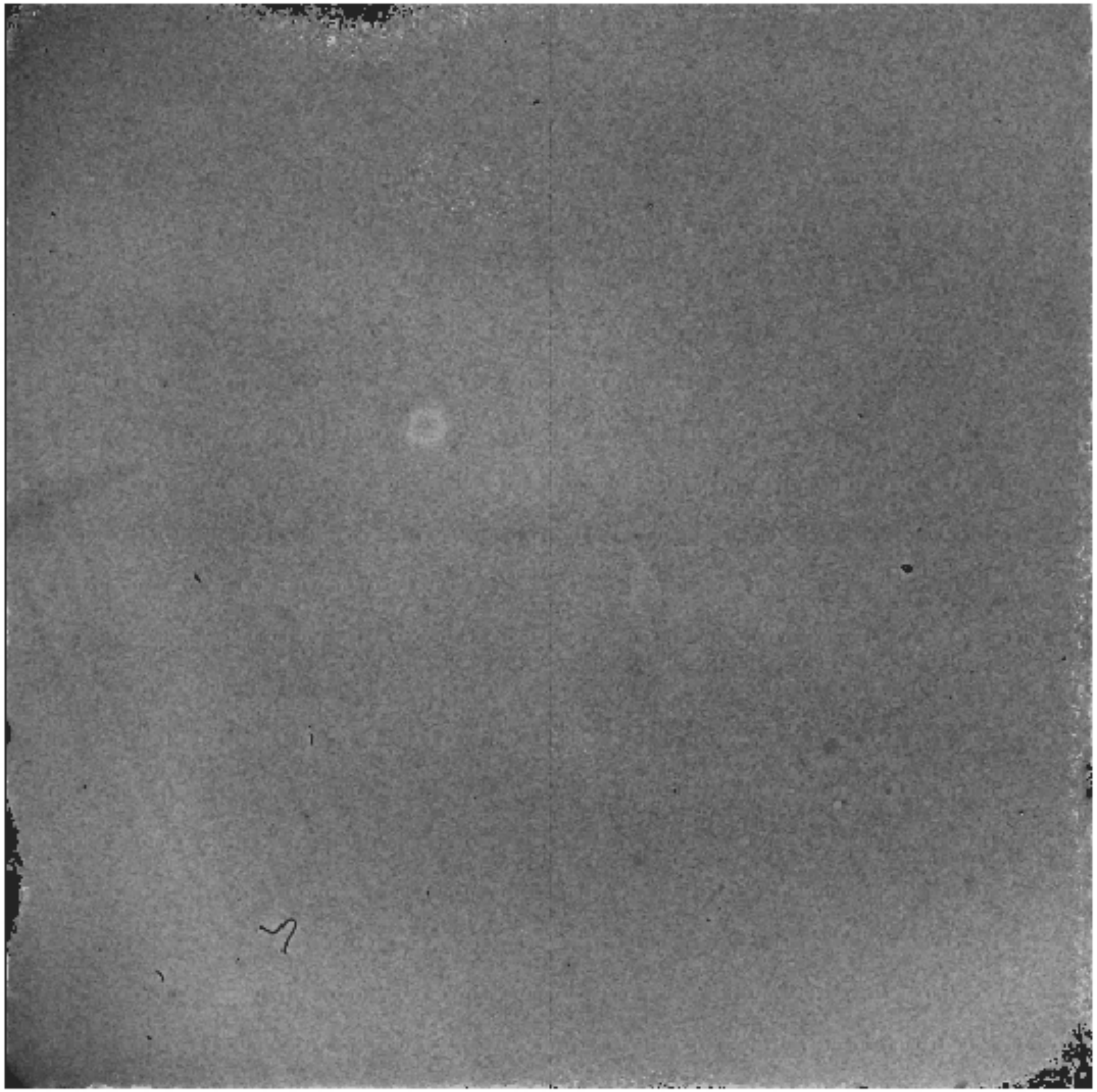


Dark Current





Flatfield



Detector response (QE, geometrical pixel size) varies slightly from pixel to pixel

→

image has "structure", even with flat illumination

Common Flatfield Methods

1. Dome flats: illuminate a white screen within the dome (can be done during the day, but may introduce spectral artifacts)
2. Twilight flats: observe the twilight sky at two times during sunrise or sunset (high S/N but time is often too short to get flatfields for all instrument configurations)
3. Self-calibration: use the observations themselves

Typical Array Detector Data Reduction

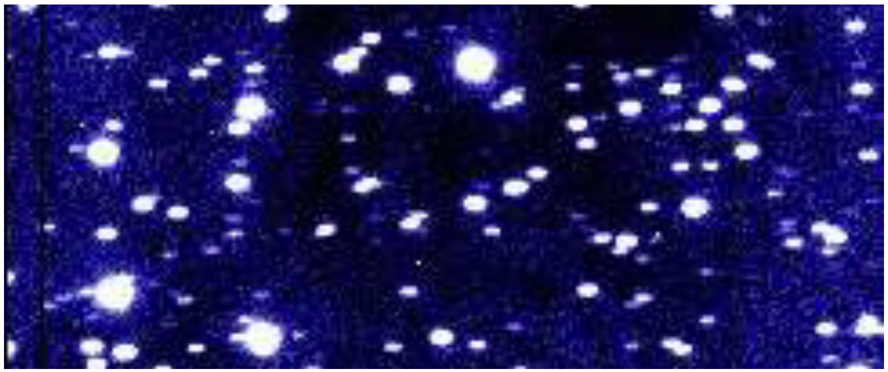
- science frame S, exposure time t_S
- dark frame D, exposure time t_D
- bias frame B, zero exposure time
- flat field frame F, exposure time t_F
- corrected (calibrated) image given by

$$S' = \frac{S - \frac{t_s}{t_D}(D - B) - B}{F - \frac{t_F}{t_D}(D - B) - B}$$

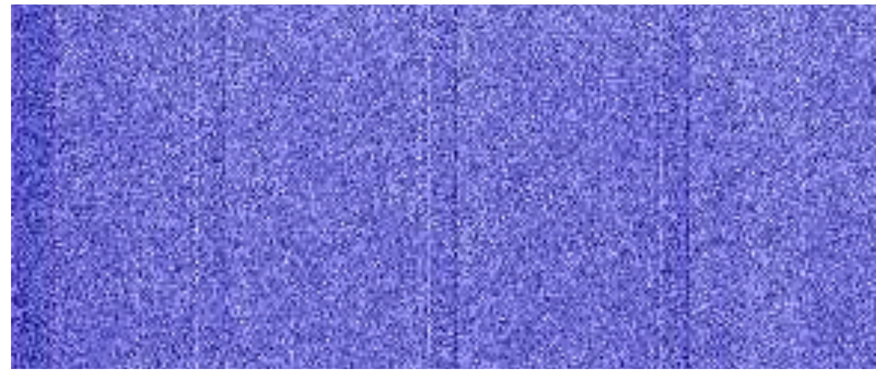
- $F-(t_f/t_{d)}(D-B)-B$ often normalized such that median of S' = median of S

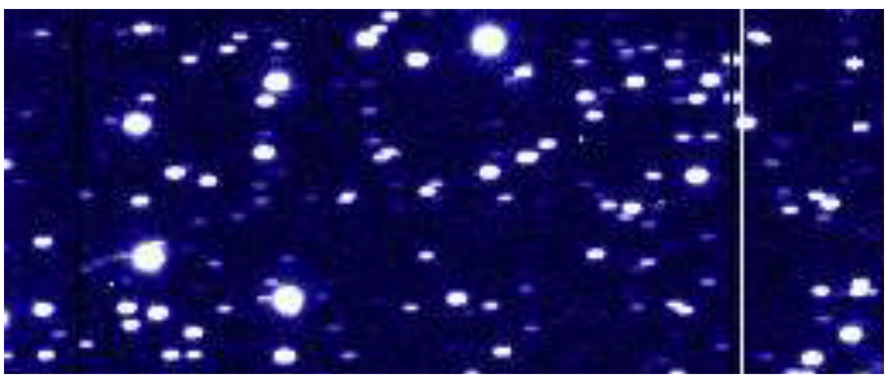
CCD Data Reduction

Raw

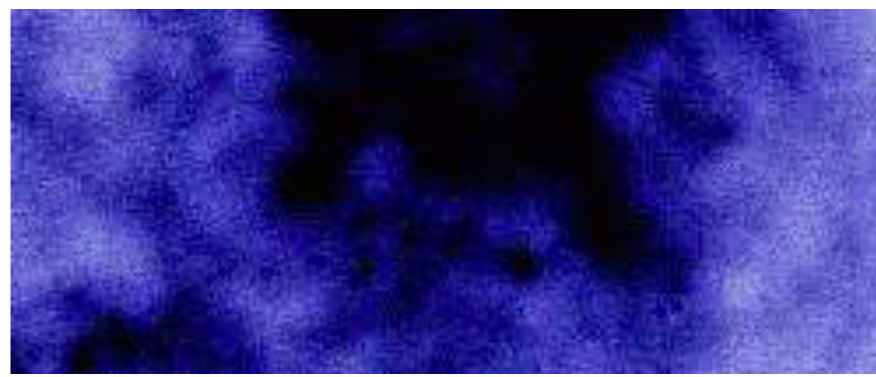


Bias + Dark Current



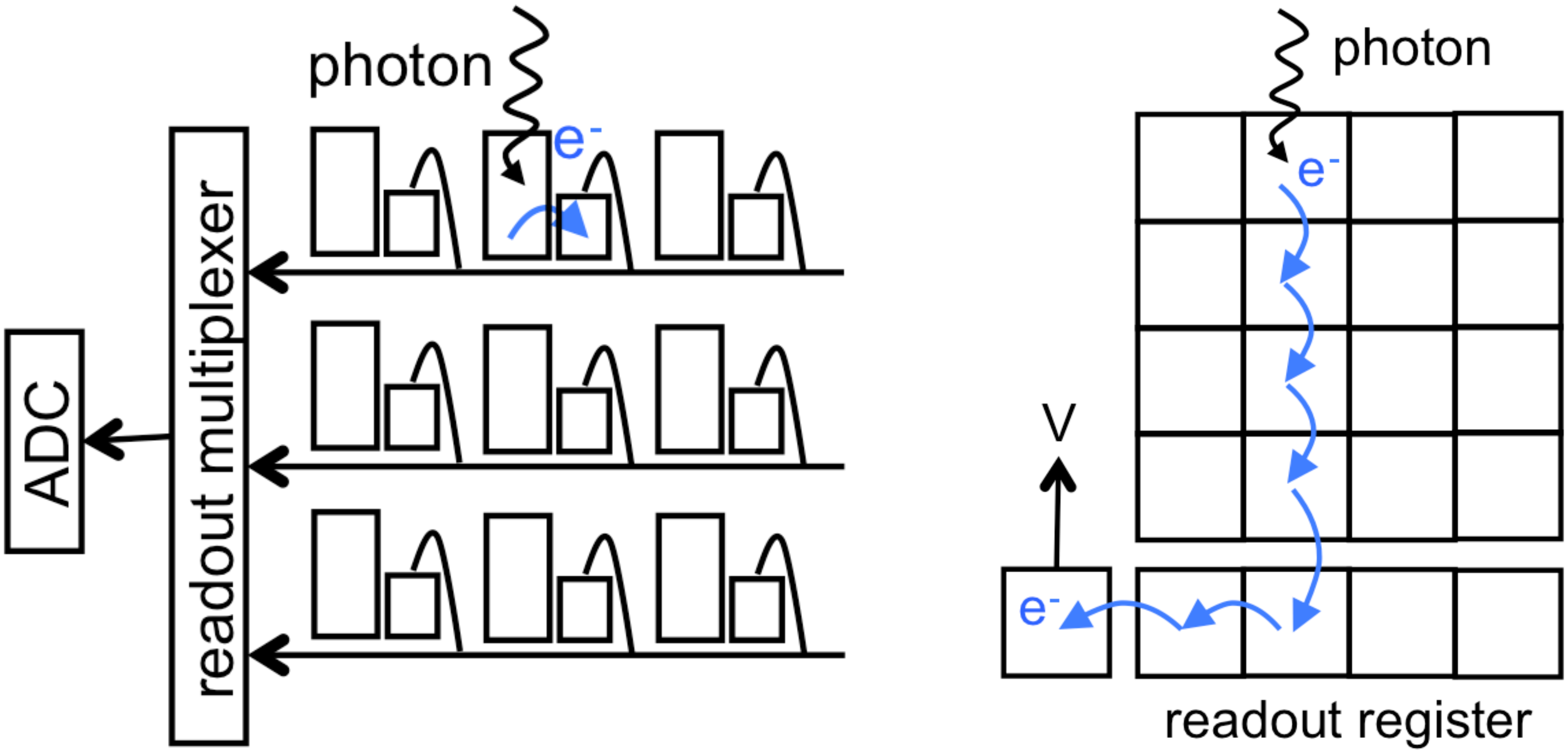


Reduced



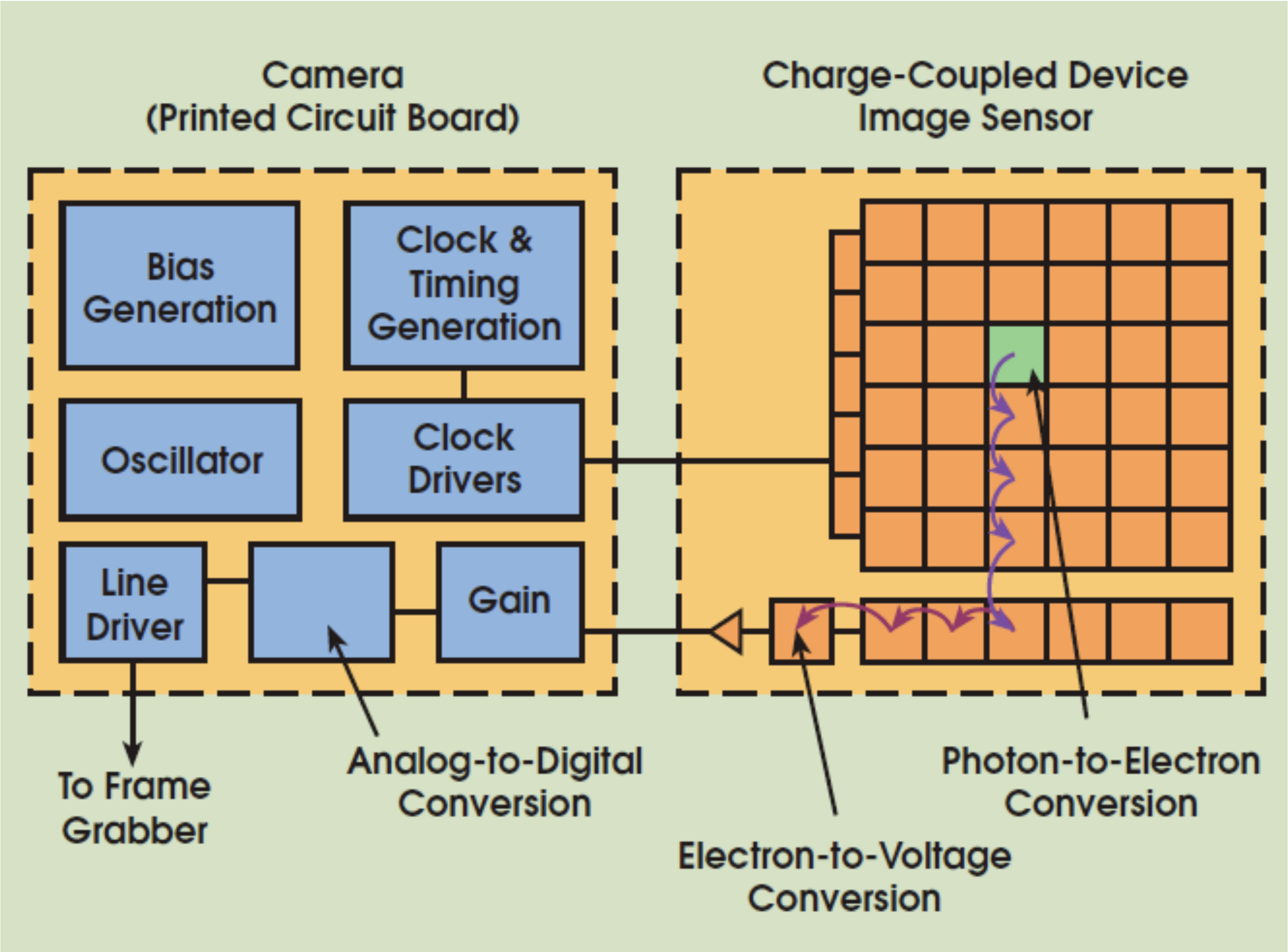
Flatfield

CMOS and CCD



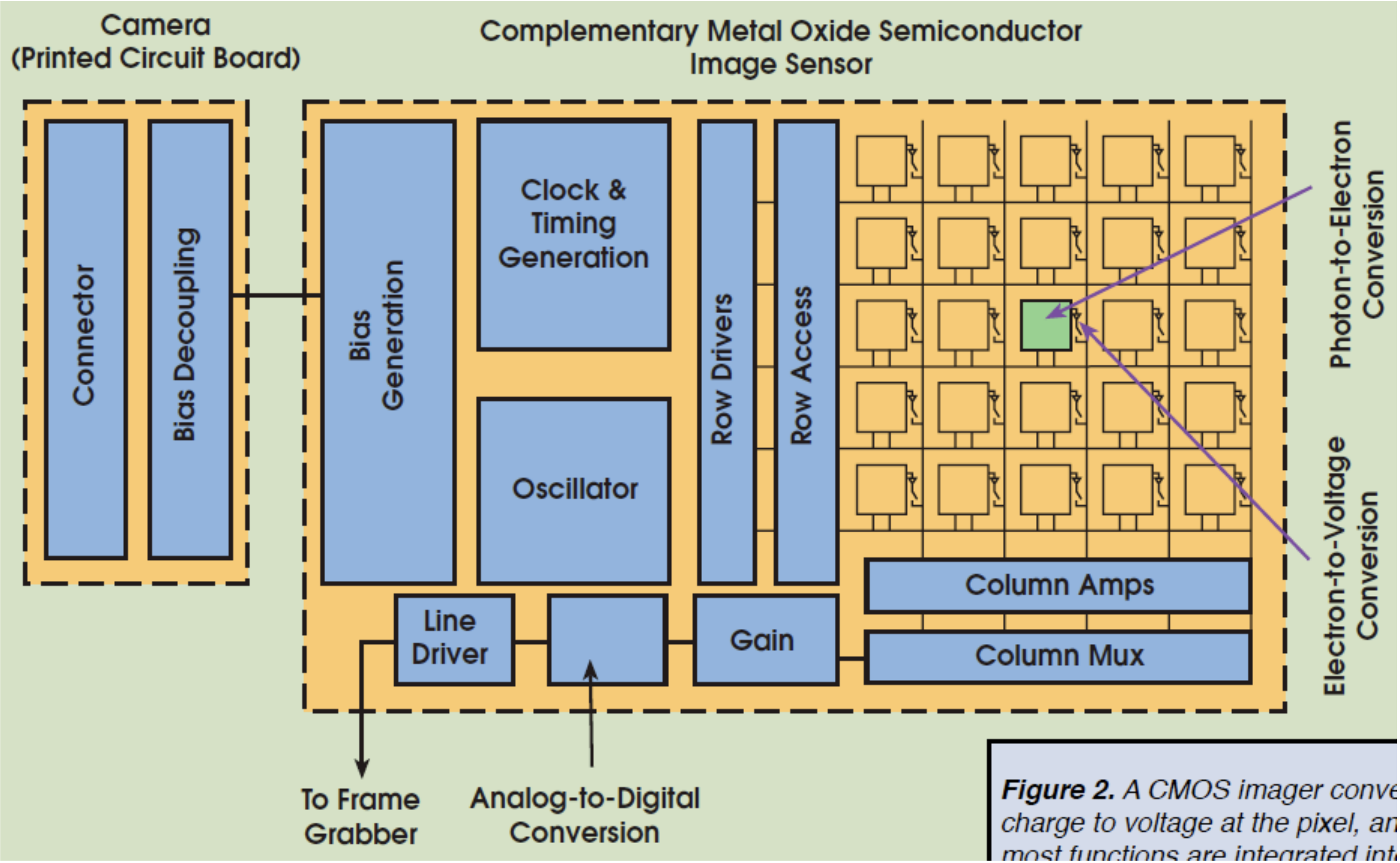
- Complementary Metal Oxide Semiconductor (CMOS)
- Charge Coupled Device (CCD)

CCD Camera



Camera
(Printed Circuit Board)
Charge-Coupled Device
Image Sensor
Bias
Generation
Clock &
Timing
Generation
Oscillator
Clock
Drivers
Line
Driver
Gain
To Frame
Grabber
Analog-to-Digital
Conversion
Photon-to-Electron
Conversion
Electron-to-Voltage
Conversion

CMOS Camera

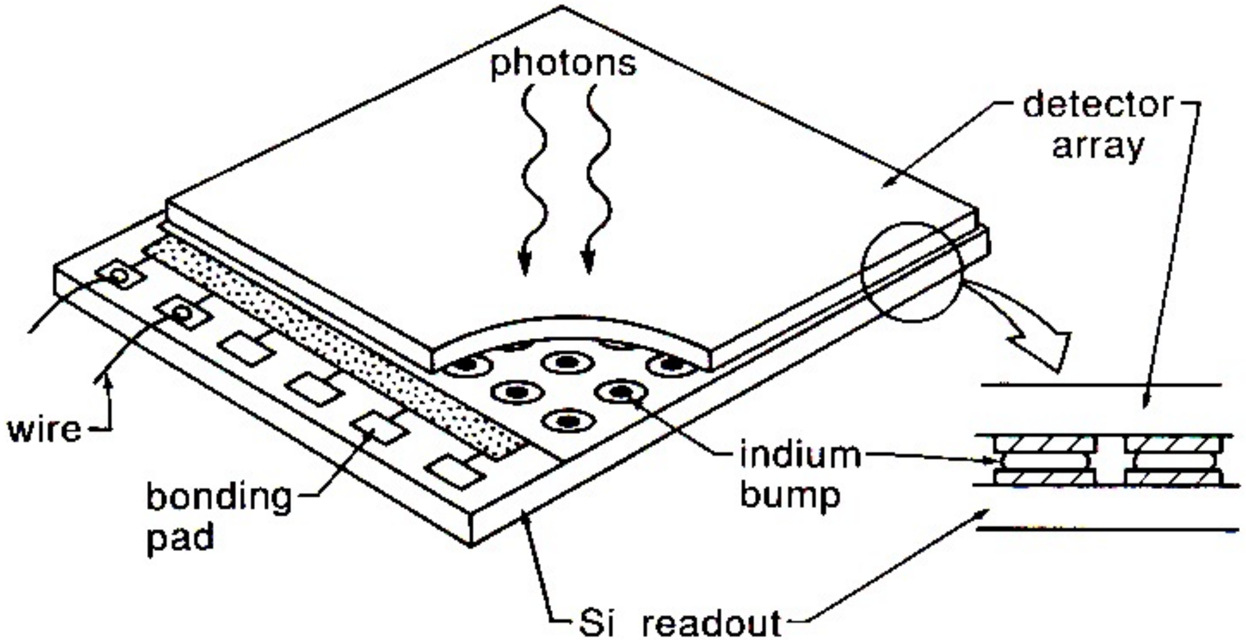

Camera
(Printed Circuit Board)
Complementary Metal Oxide Semiconductor
Image Sensor
Connector
Bias Decoupling
Bias
Generation
Clock &
Timing
Generation
Oscillator
Row Drivers
Row Access
Photon-to-Electron
Conversion
Electron-to-Voltage
Conversion
Column Amps
Column Mux
Line
Driver
Gain
To Frame
Grabber
Analog-to-Digital
Conversion
Figure 2. A CMOS imager conve
charge to voltage at the pixel, an

CMOS vs. CCD

- CMOS advantages over CCD:
  - standard semiconductor processing
  - low power consumption (1% of CCD)
  - random access to regions of interest
  - blooming and streaking much reduced compared to CCDs
  - additional electronics can be integrated on chip and in pixel (smart sensor)
  - non-destructive readout
- CMOS disadvantages:
  - small geometric fill factor (microlenses can help)
  - typically larger read noise

Infrared Arrays – Construction

1. Produce a grid of readout amplifiers
2. Produce a (matching mirror image) of detector pixels
3. Deposit Indium bumps on both sides
4. Squeeze the two planes together ➔ hybrid arrays
5. The Indium will flow and provide electrical contact



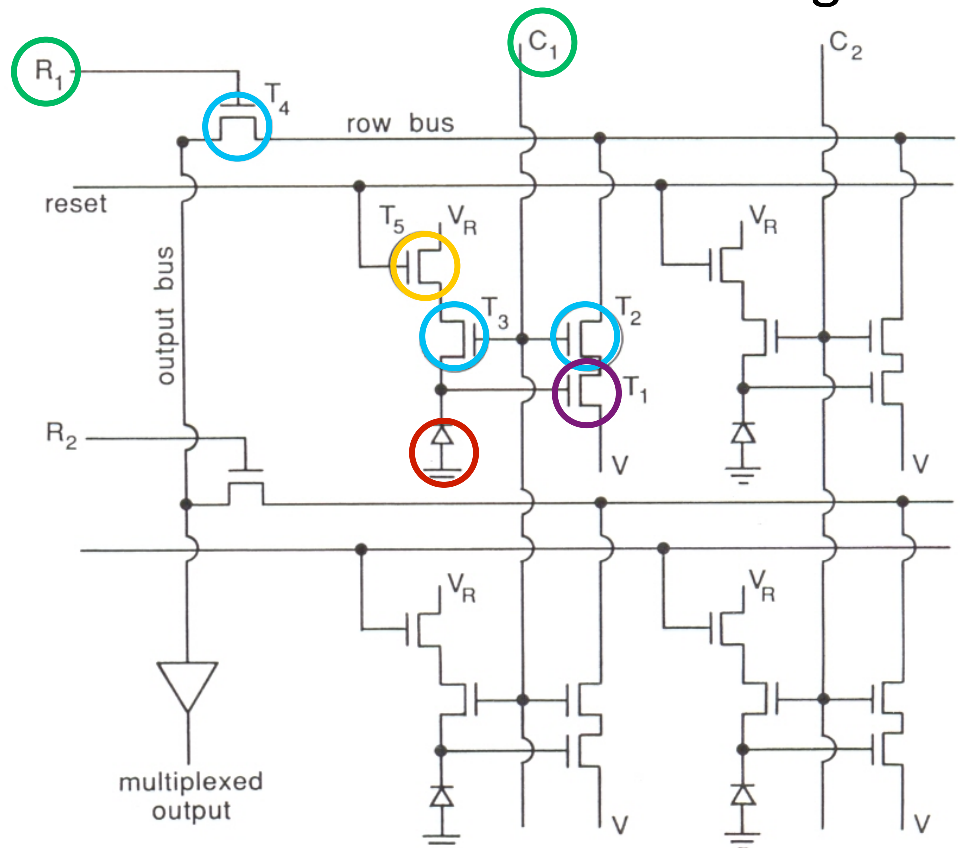
Multiplexers

Multiplexing: "Pixel signals → Sequential output lines"

Multiplexer (MUX) Tasks:

- address a column of pixels by turning on their amplifiers
- pixels in other columns with power off will not contribute to signal

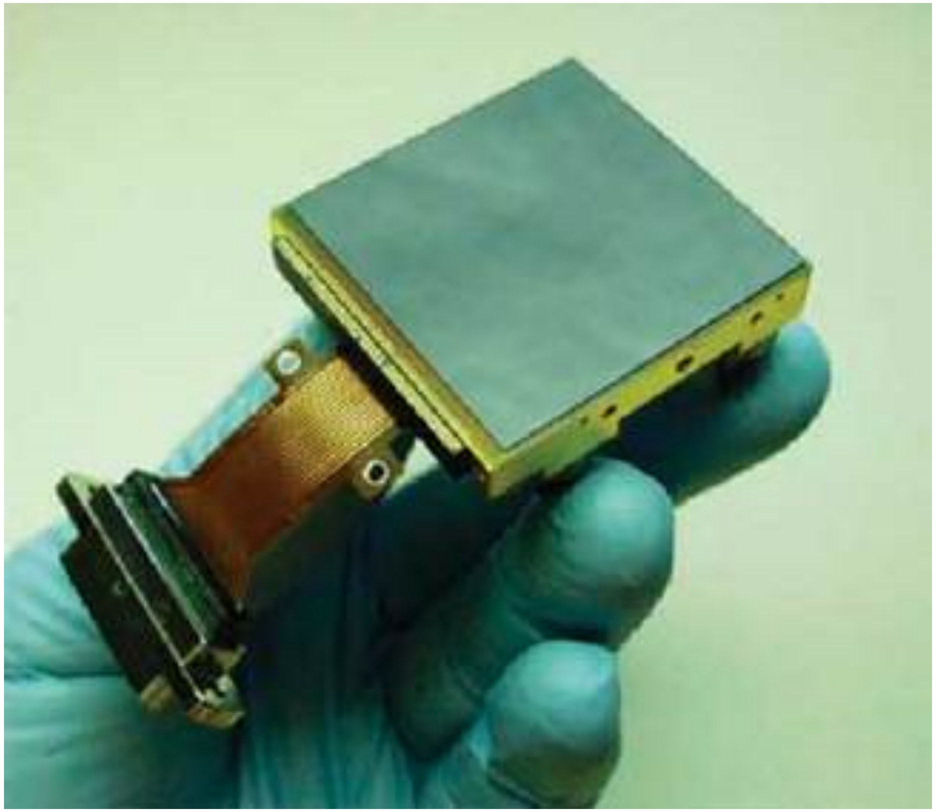
- Signal at photodiode → gate T_1
- Readout uses row driver R_1 and column driver C_1 to close the switching transistors T_2, T_3, T_4
- Power to T_1 → signal to the output bus
- Reset: connect V_R via T_5 and T_3.



Example: The Teledyne HAWAII-2RG

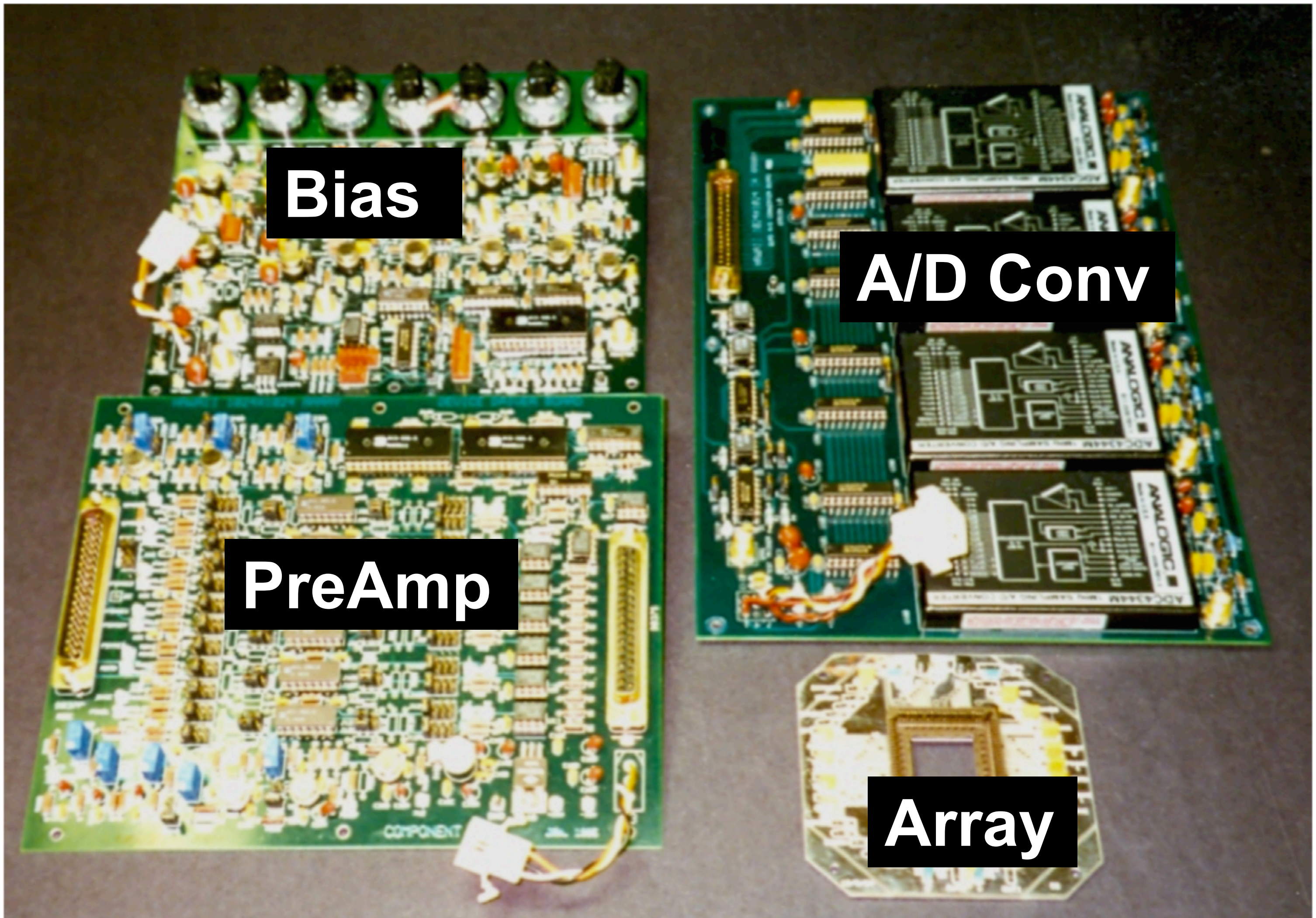
Parameter	Specification
Detector technology	HgCdTe or Si PIN
Detector input circuit	SFD
Readout mode	Ripple
Pixel readout rate	100 kHz to 5MHz (continuously adjustable)
Total pixels	2048 x 2048
Pixel pitch	18 μm
Fill factor	$\geq$ 98%
Output ports	Signal: 1, 4, 32 selectable guide window and reference
Spectral range	0.3 - 5.3μm
Operating temperature	$\geq$ 30K
Quantum efficiency (array mean)	$\geq$ 65%
Charge storage capacity	$\geq$ 100,000e^-
Pixel operability	$\geq$ 95%
Dark current (array mean)	$\leq$ 0.1 e^-/sec (77K, 2.5 μm)
Read noise (array mean)	$\leq$ 15 e^- CDS @ 100 kHz
Power dissipation	$\leq$ 4 mW @ 100 kHz

Can also be combined to a 2x2 mosaic



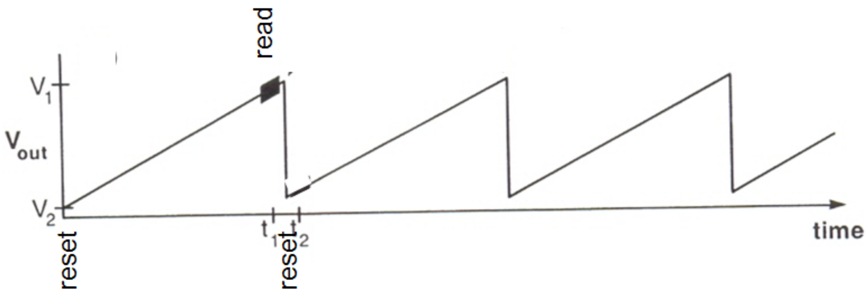
Elements of a Detector Electronics System

Example: PHARO (the Palomar High Angular Resolution Observer)



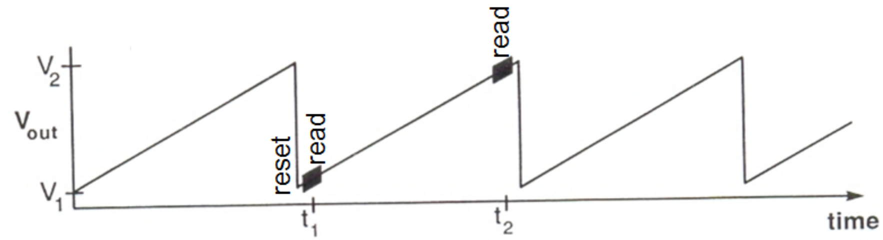
IR Array Read Out Modes

Single Sampling



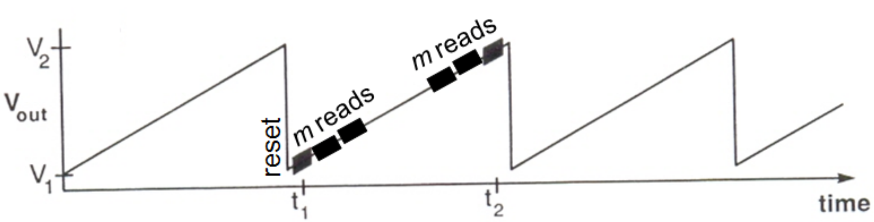
- most simple approach
- does not remove kTC noise
- measures the absolute signal level

Reset-Read-Read



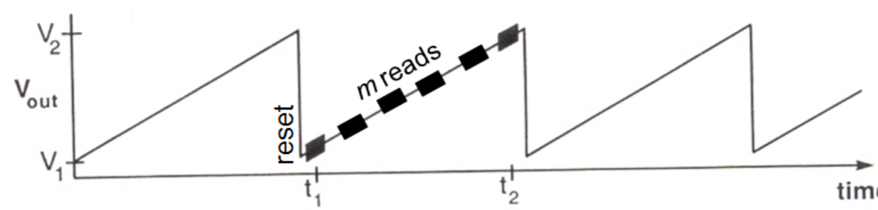
- Resets, reads and reads pixel-by-pixel
- Signal = Read(2) – Read(1)
- best correlation, no reset noise
- but requires frame storage
- reduced dynamical range (saturation!)

(Multiple) Fowler Sampling



- similar to reset-read-read ...
- ... but each read is repeated *m* times
- Signal = mean(read2) – mean(read1)
- Reduces readout noise by $\sqrt{m}$ over RRR

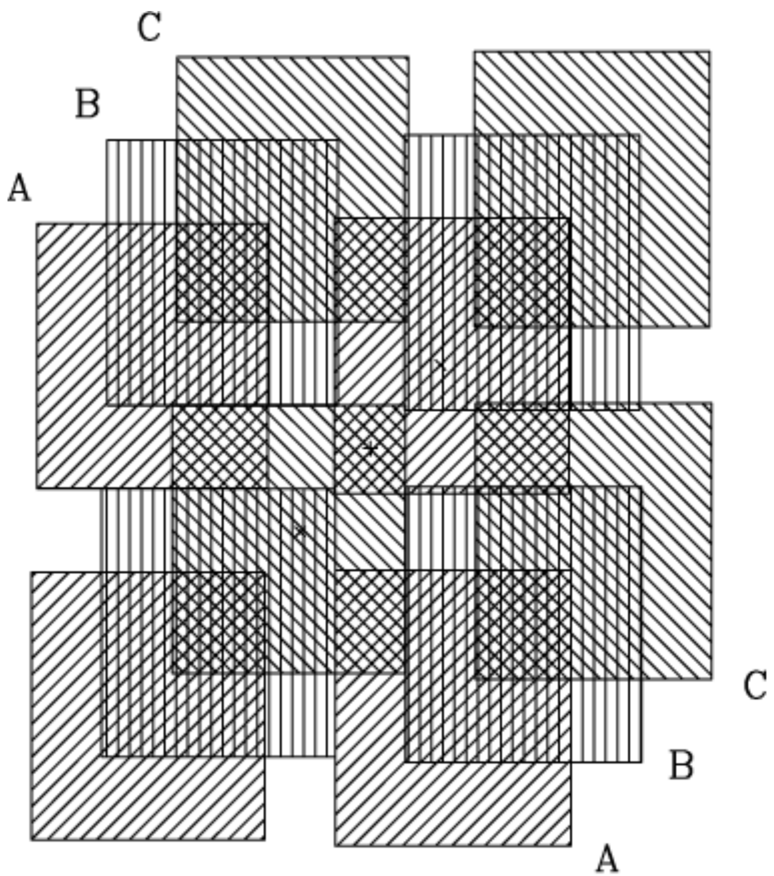
Sample-up-the-ramp Fitting

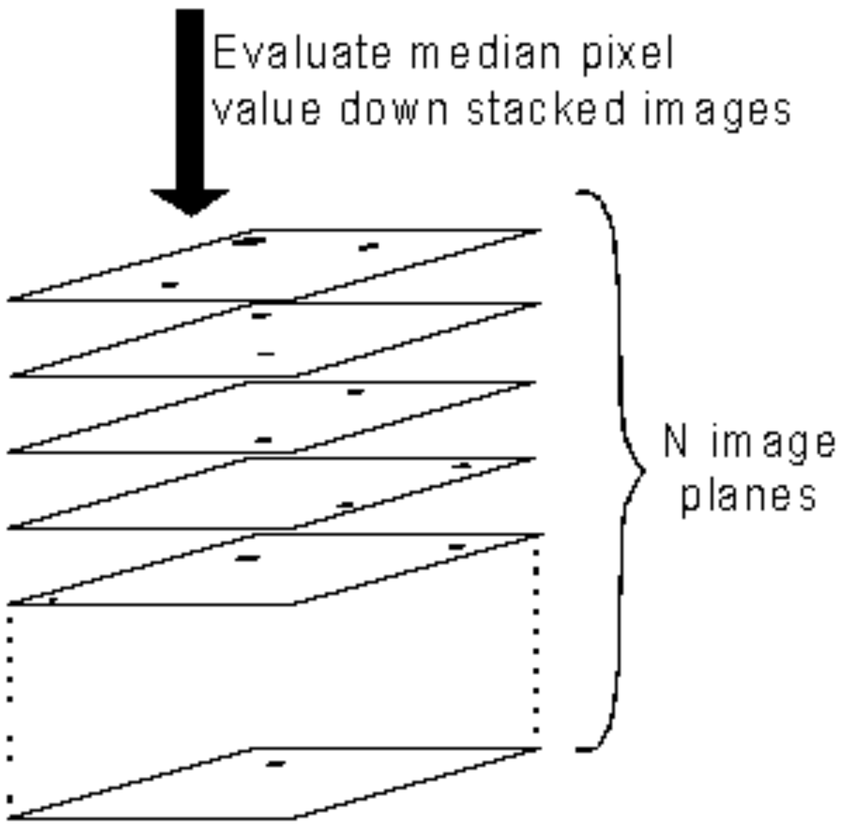


- *m* equidistant reads during integration
- linear fit → "slope"
- reduces readout noise by $\sqrt{m}$
- particularly useful in space (cosmics!)

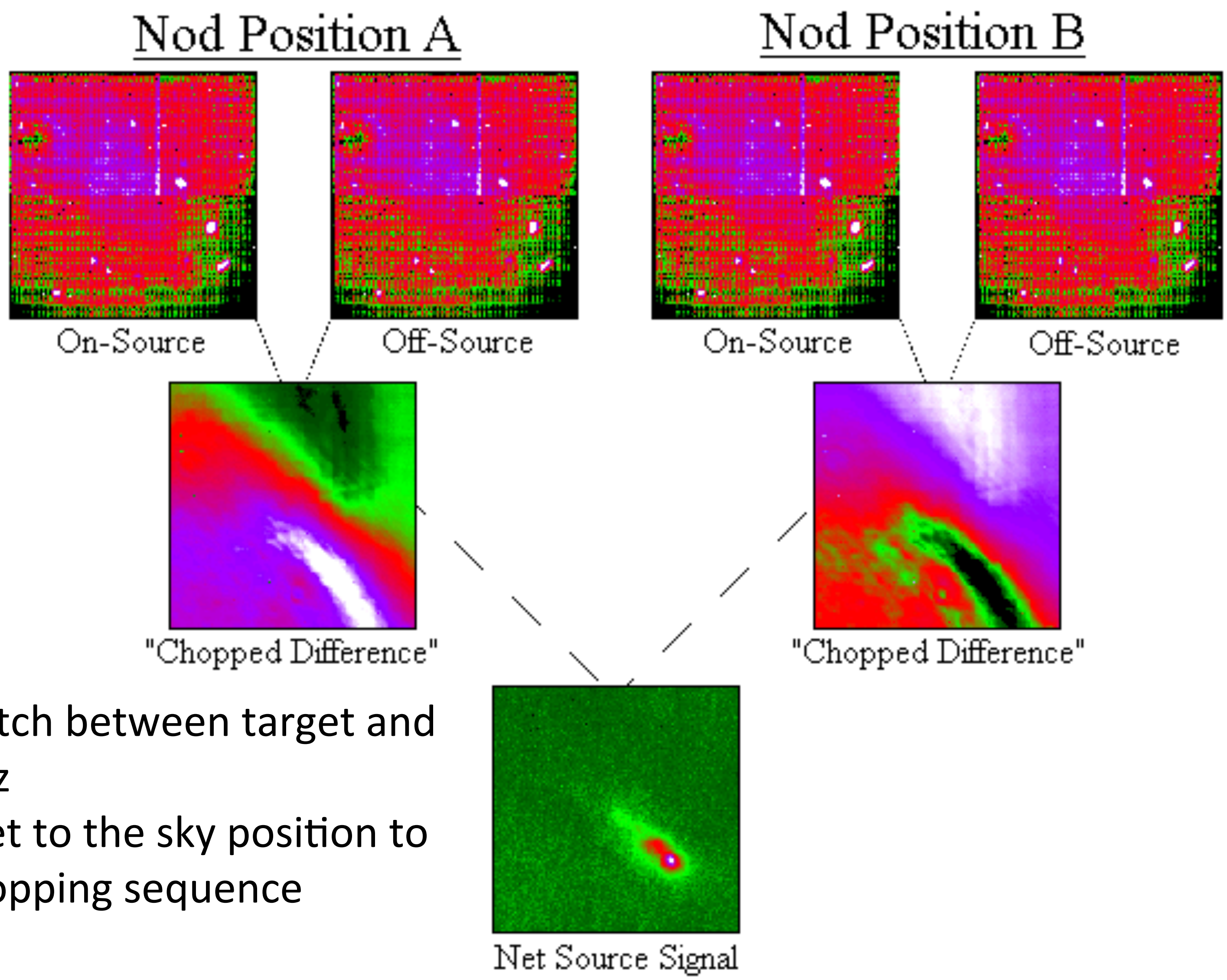
Dithering / Jittering

1. Observe the same field with many exposures, each offset by a small amount
2. Combine the image e.g., via median filtering





Chopping / Nodding



Chopping: switch between target and sky at a few Hz

Nodding: offset to the sky position to repeat the chopping sequence inverted

CCDs vs IR Arrays

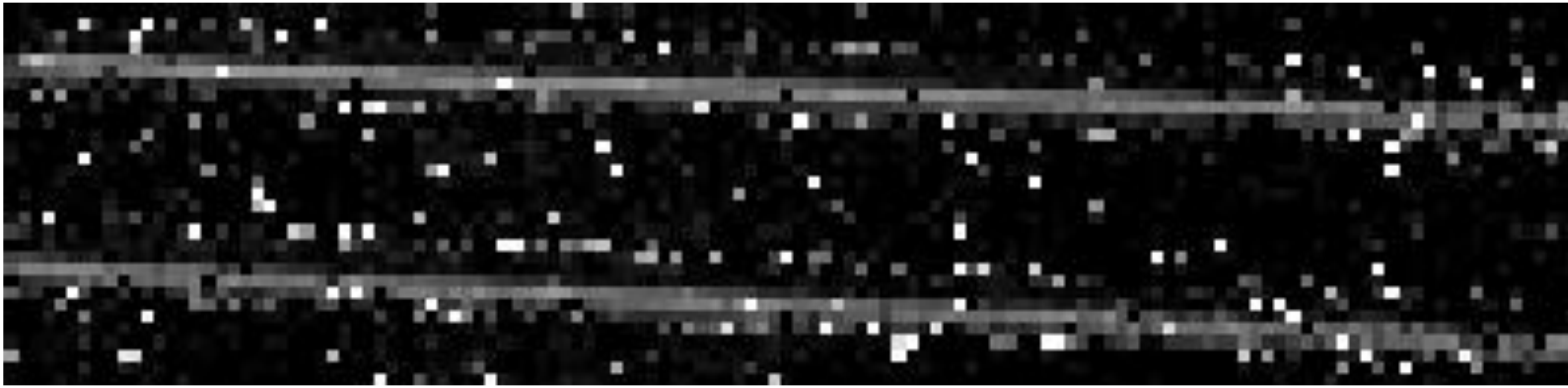
CCDs:

- destructive reads
- charges are physically shifted to the output line
- shutter determines exposure time

IR arrays:

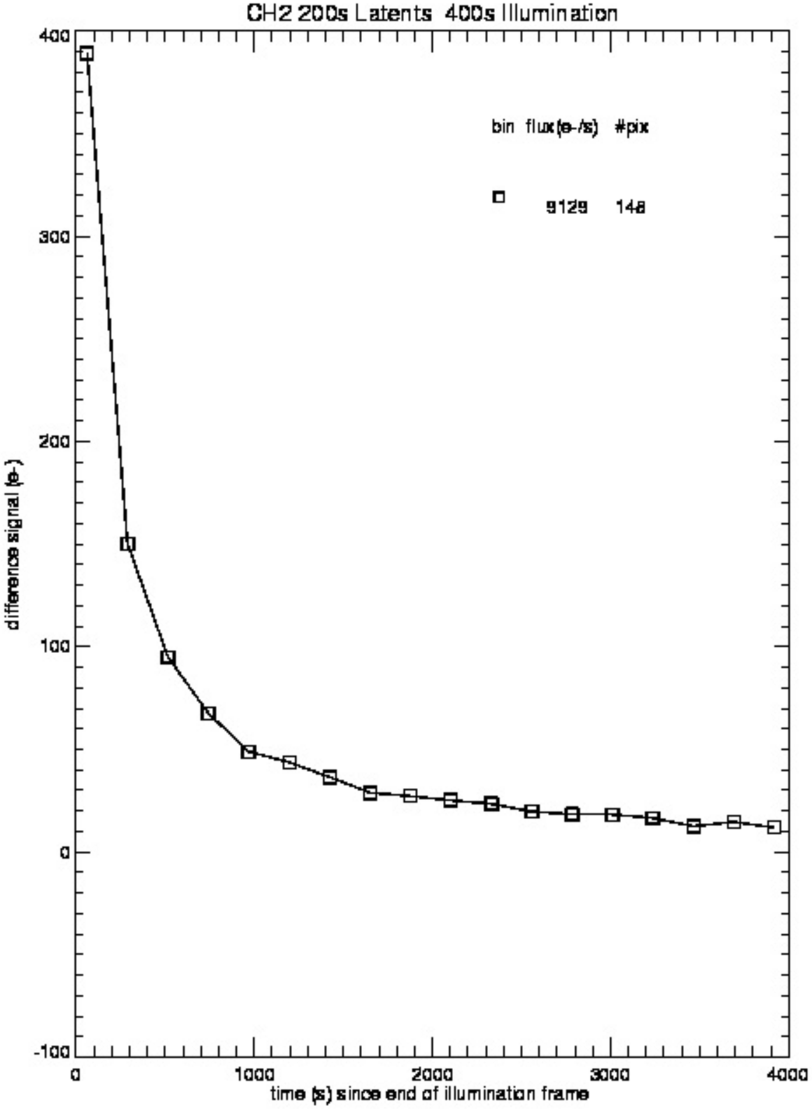
- non-destructive reads
- readout requires sophisticated multiplexer circuit
- multiplexer readout addresses individual pixels directly
- read/reset determines exposure time

Detector Artefacts: Bad Pixels



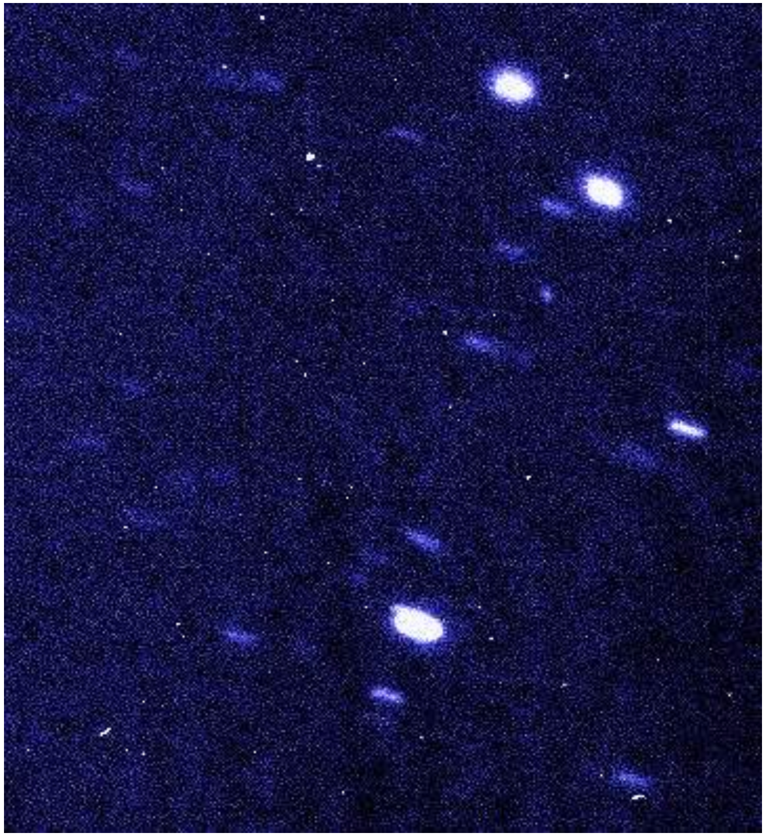
- dead, hot and rogue pixels, rows, columns
- bias and dark correction help somewhat
- can often us "dead-pixel map" and replace with median of surrounding pixels

Detector Artefacts: Latent Images



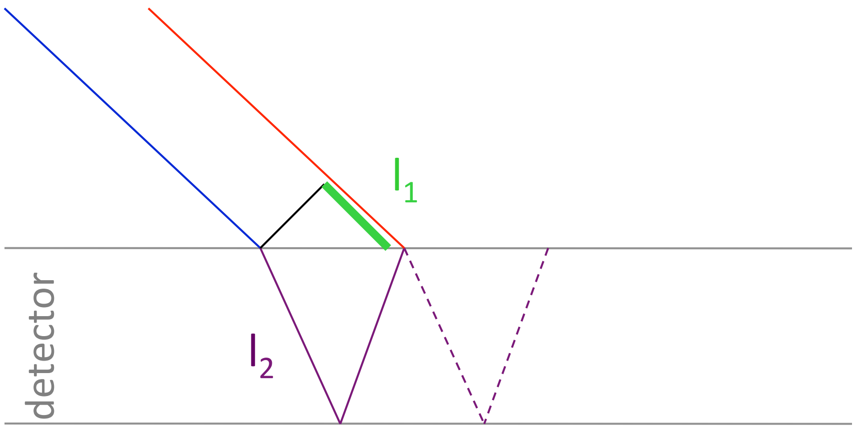
- mostly seen in hybrid (IR) arrays
- avoid overexposure
- wait
- additional resets
- anneal (warm detector)

Detector Artifacts: Cosmic Rays

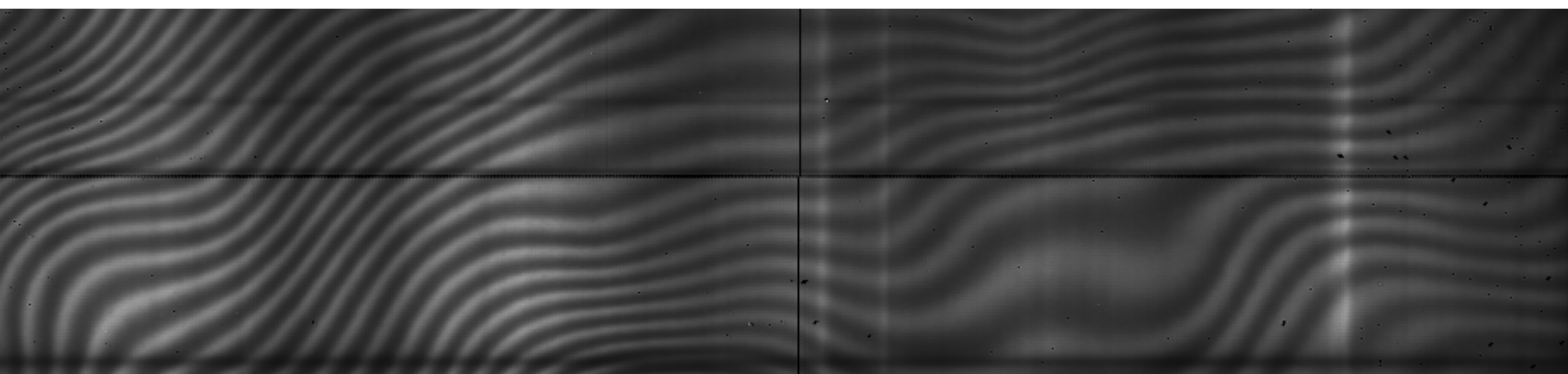


- cosmic ray particles free electrons in detector
- remove with median filtering of several exposures

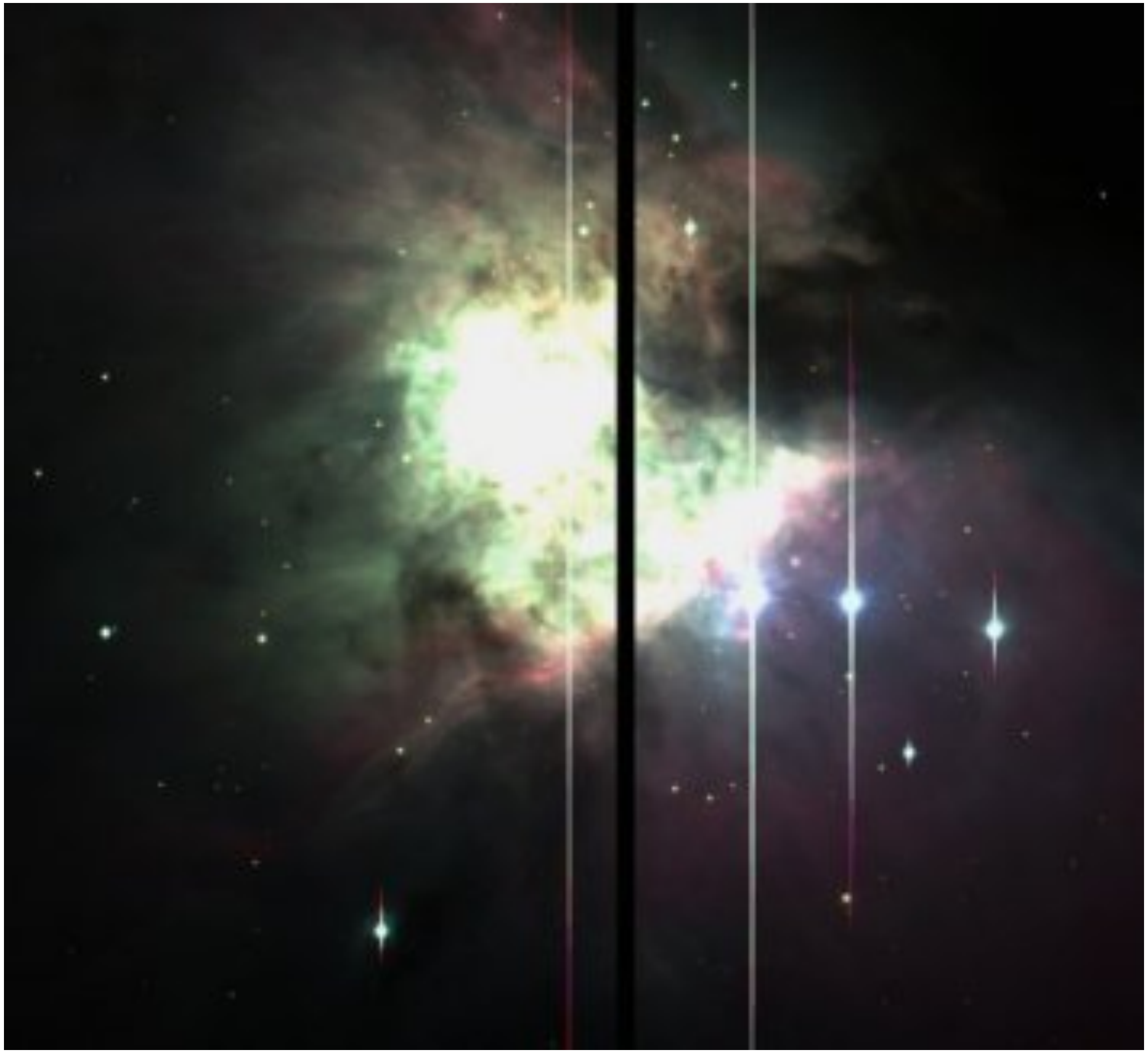
Detector Artefacts: Fringing



If the phase difference between l_1 and $n \bullet l_2$ is an even multiple of π constructive interference occurs. If an odd multiple destructive interference occurs → fringes = wave pattern.



Detector Artefacts: Blooming



Detector Artefacts: Cross-Talk

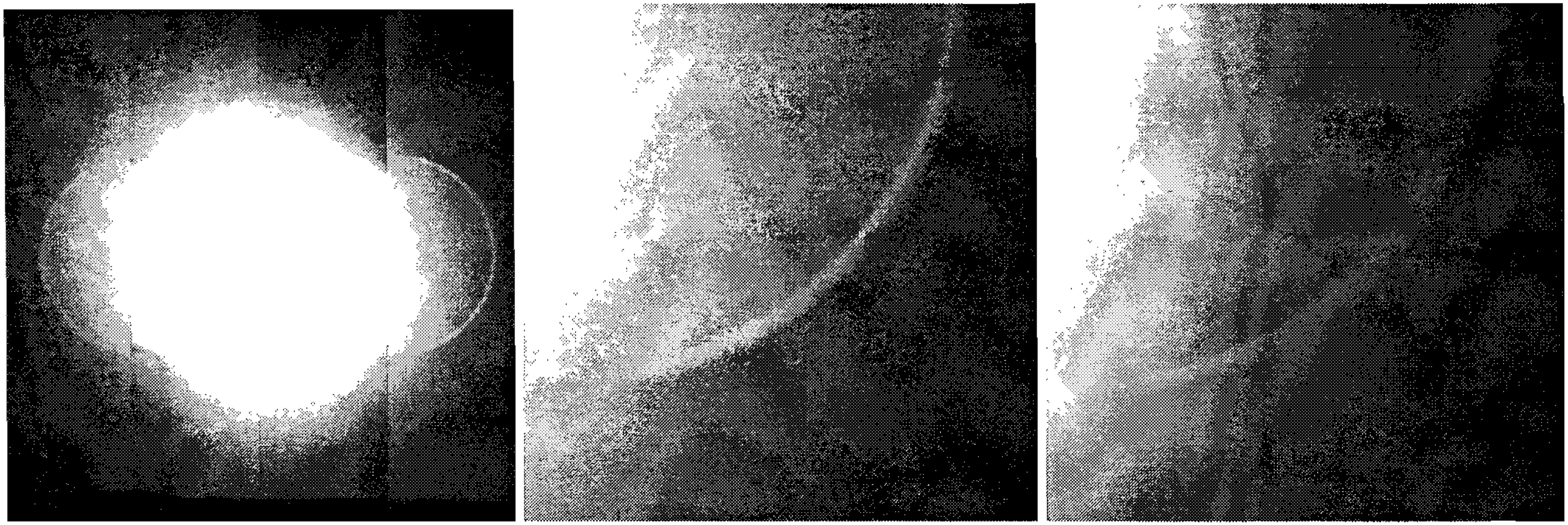
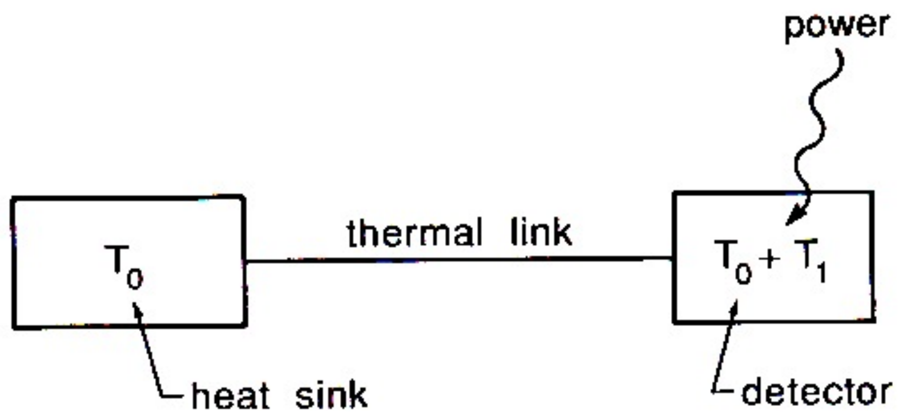


Figure 2: (left) Image similar to Figure 1 except shown in positive contrast and a range from 0 to 0.005 of the maximum illumination level. (center) Detail of left image channel 4 exposed at low light level. (right) Detail of channel 4 exposed at high light level.

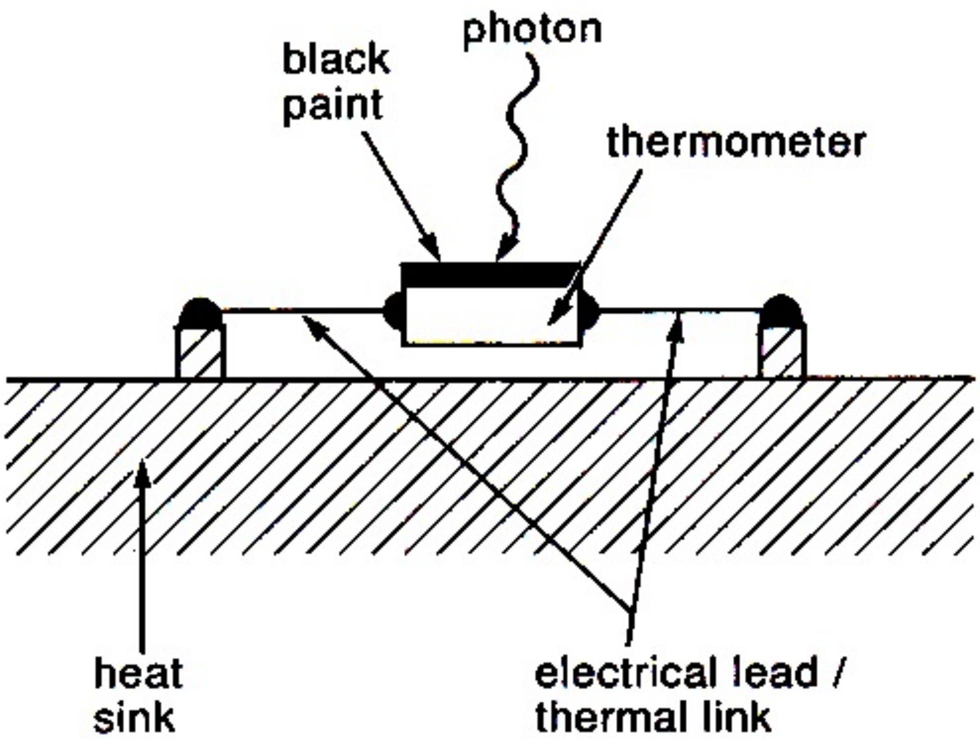
- electronic interference between channels that are read out simultaneously

Basic Bolometer



- detector: heat capacity *C,* connected via thermal link with thermal conductance *G* to heat sink at temperature T_0
- incoming photons increase temperature of detector by T_1
- thermal conductance to heat sink transfers power GT_1
- astronomical signal changes detector energy by dQ/dt
- heat capacity C=dQ/dT
- total power absorbed by detector is: $P_T(t) = GT_1 + C\frac{dT_1}{dt}$

Principle of Bolometer Construction

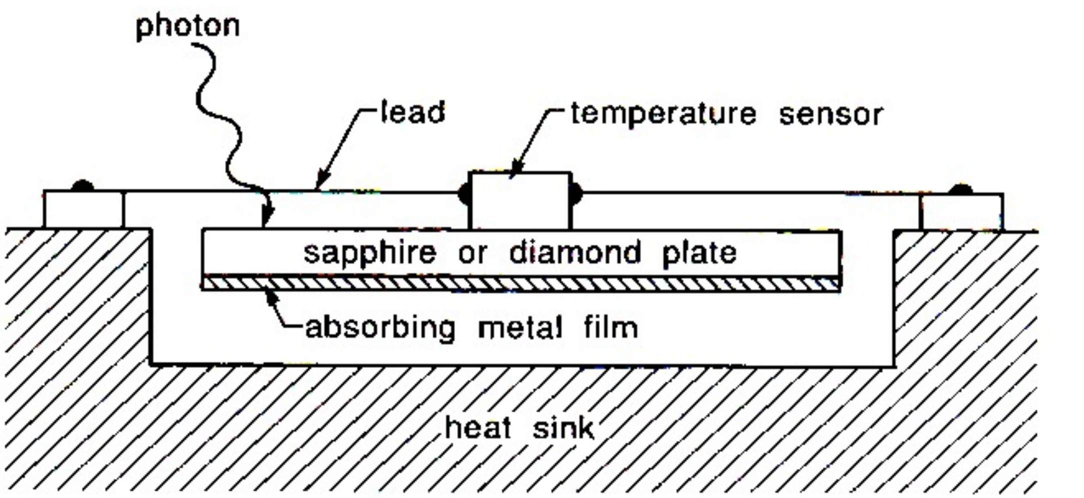


- measure voltage across thermometer
- voltage depends on resistance
- resistance depends on temperature
- temperature depends on photon flux

Bolometers are especially for the far-IR/sub-mm wavelength range!

QE and Composite Bolometers

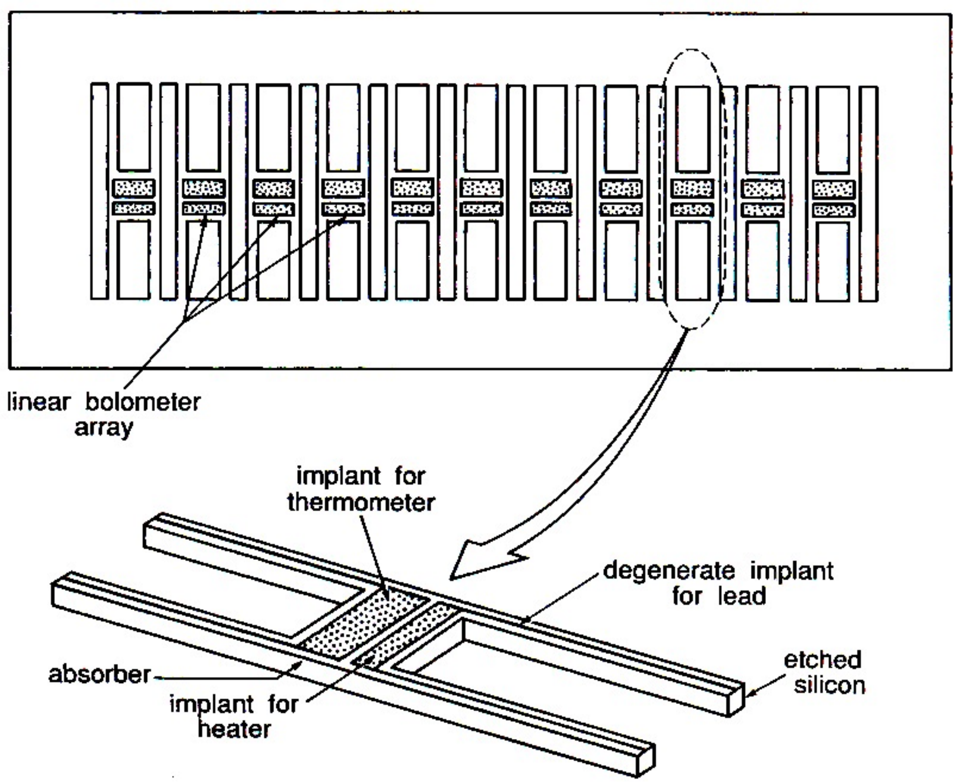
- Si bolometers with high impurity concentrations can be very efficient absorbers
- But: QE is too low. Solution: enhance absorption with black paint – but this will increase the heat capacity
- A high QE bolometer for far-IR and sub-mm would have too much heat capacity → composite bolometers



The heat capacity of the blackened sapphire plate is only 2% of that of Ge.

Etched Bolometers

- The bolometer design has been revolutionized by precision etching techniques in Si
- Thermal time response ~ C/G → small structures minimize the heat capacity C by reducing the volume of material.

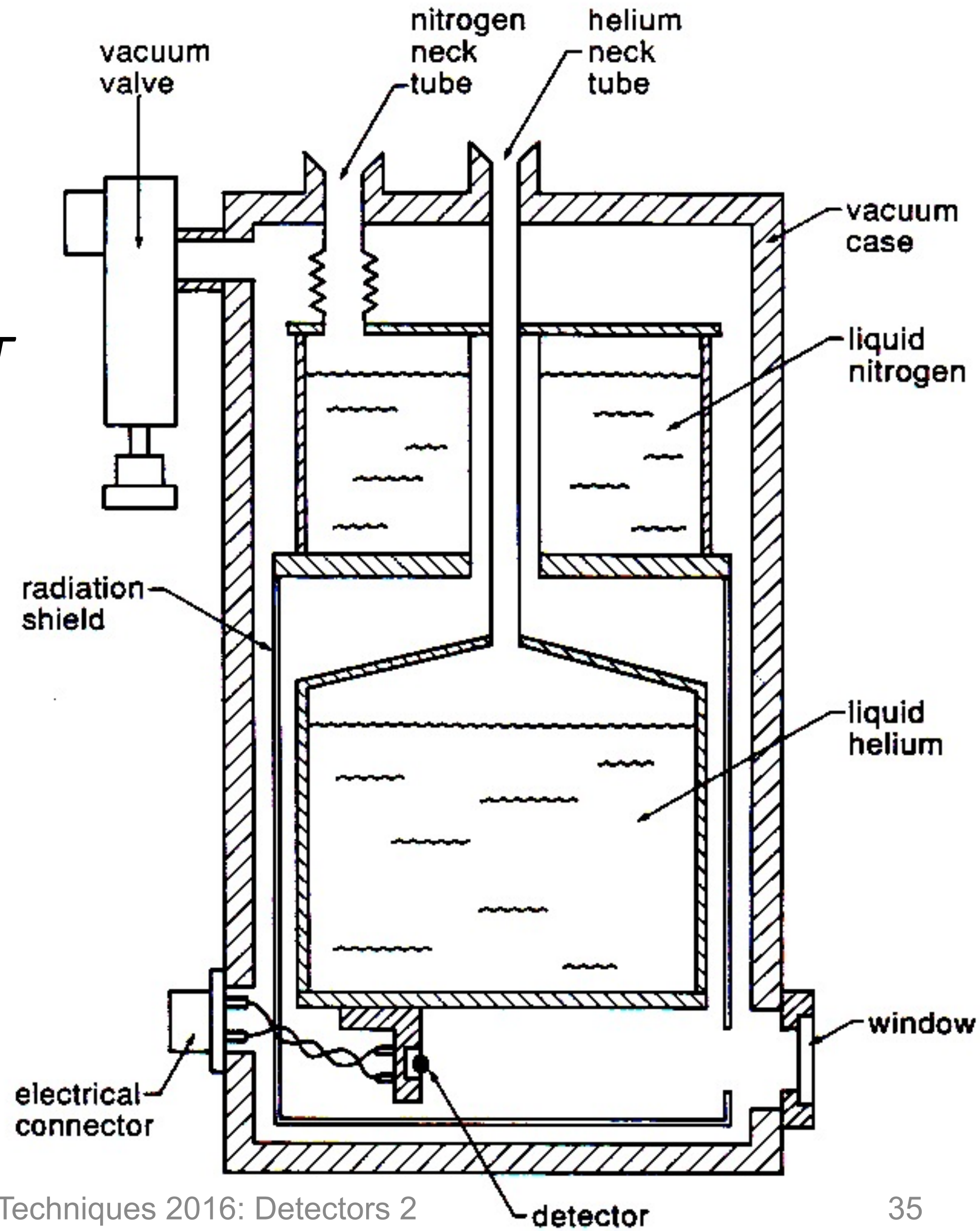


Low Operating Temperatures

Four standard cooling options:

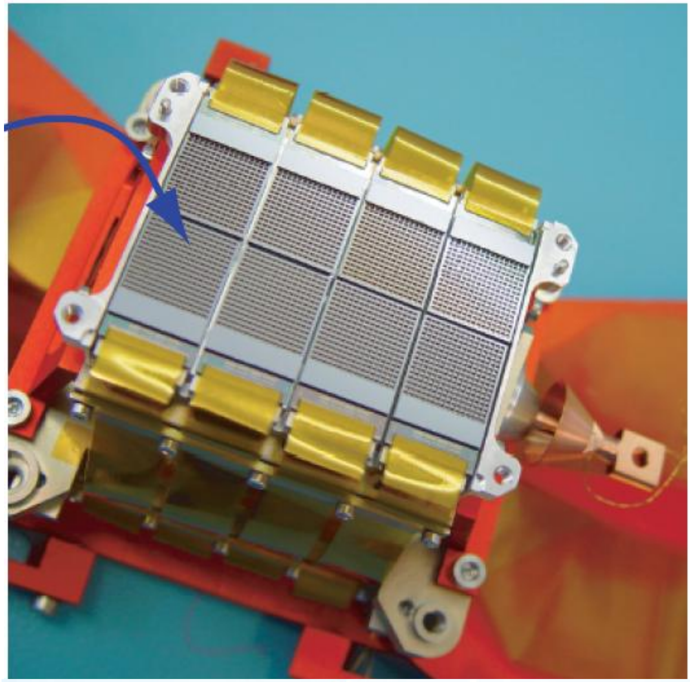
1. ^{4}He dewar (air pressure) → T=4.2K
2. ^{4}He dewar (pumped) → 1K<T<2K
3. ^{3}He (closed-cycle) refrigerator → T~0.3K
4. adiabatic demagnetization refrigerator → T ~ 0.1K

Simplest solution is to use a two-stage helium dewar (here: model from Infrared Laboratories, Inc.)



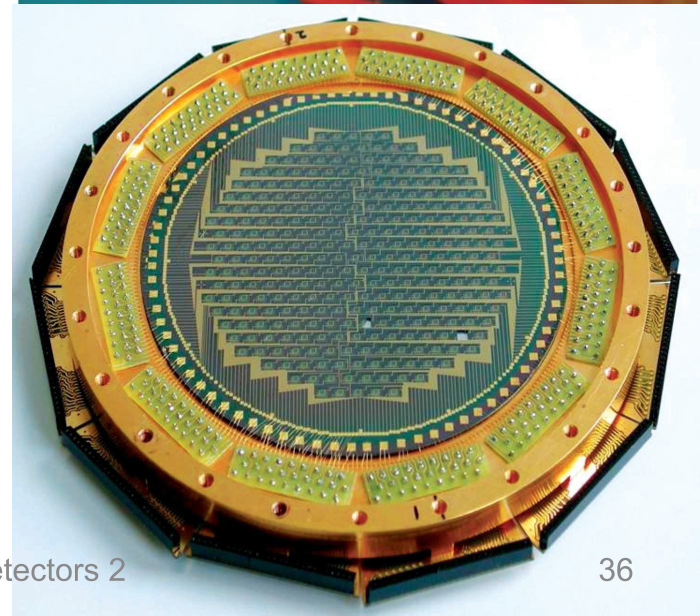
Bolometers – an Overview

The "single pixel" Ge:Ga bolometer invented in 1961 by Frank Low



Herschel / PACS bolometer: a cut-out of the 64x32 pixel bolometer array assembly

- LABOCA – the multi-channel bolometer array for APEX operating in the 870 μm (345 GHz) atmospheric window
- The signal photons are absorbed by a thin metal film cooled to about 280 mK
- The array consists of 295 channels in 9 concentric hexagons
- The array is under-sampled, thus special mapping techniques must be used



Performance Comparison Bolometer ⇔ Heterodyne Receiver

Case 1: Bolometer operating at BLIP and heterodyne receiver operating in the thermal limit ($h\nu \ll kT$)

➔ the bolometer will perform better

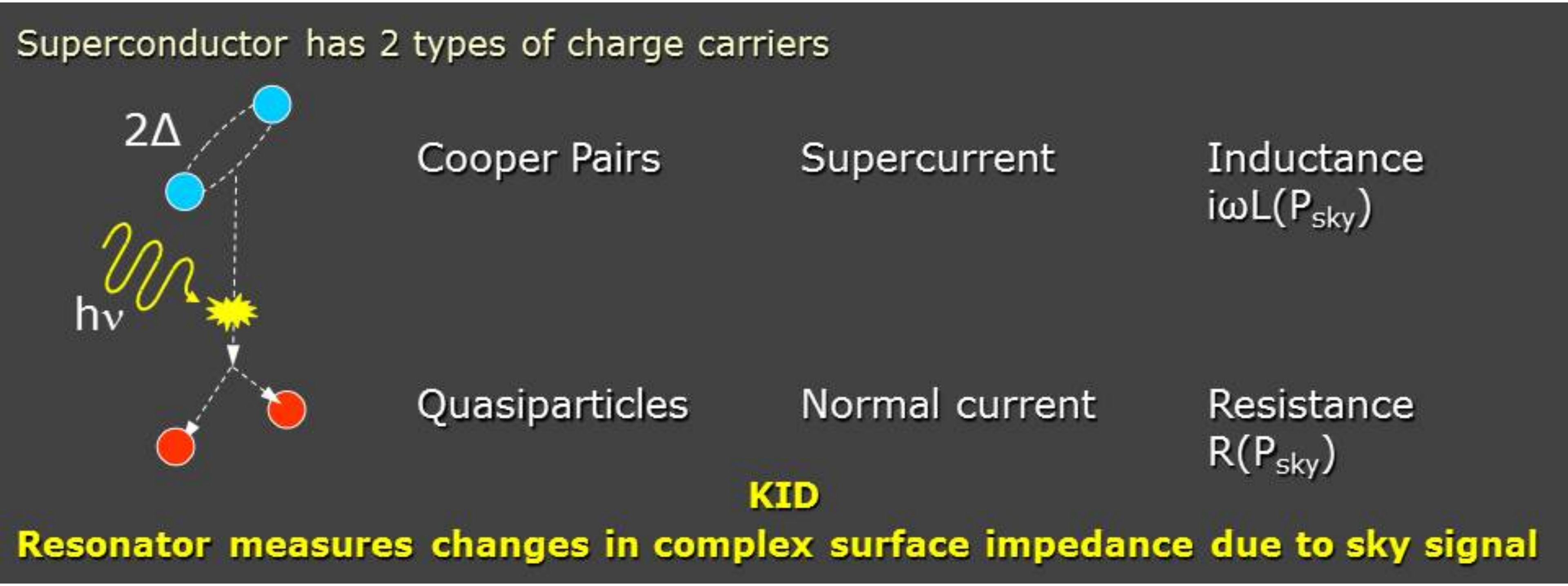
This is always true, except for measurements at high spectral resolution, much higher than the IF bandwidth.

Case 2: detector noise-limited bolometer and a heterodyne receiver operating at the quantum limit ($h\nu \gg kT$).

➔ the heterodyne receiver will outperform the bolometer.

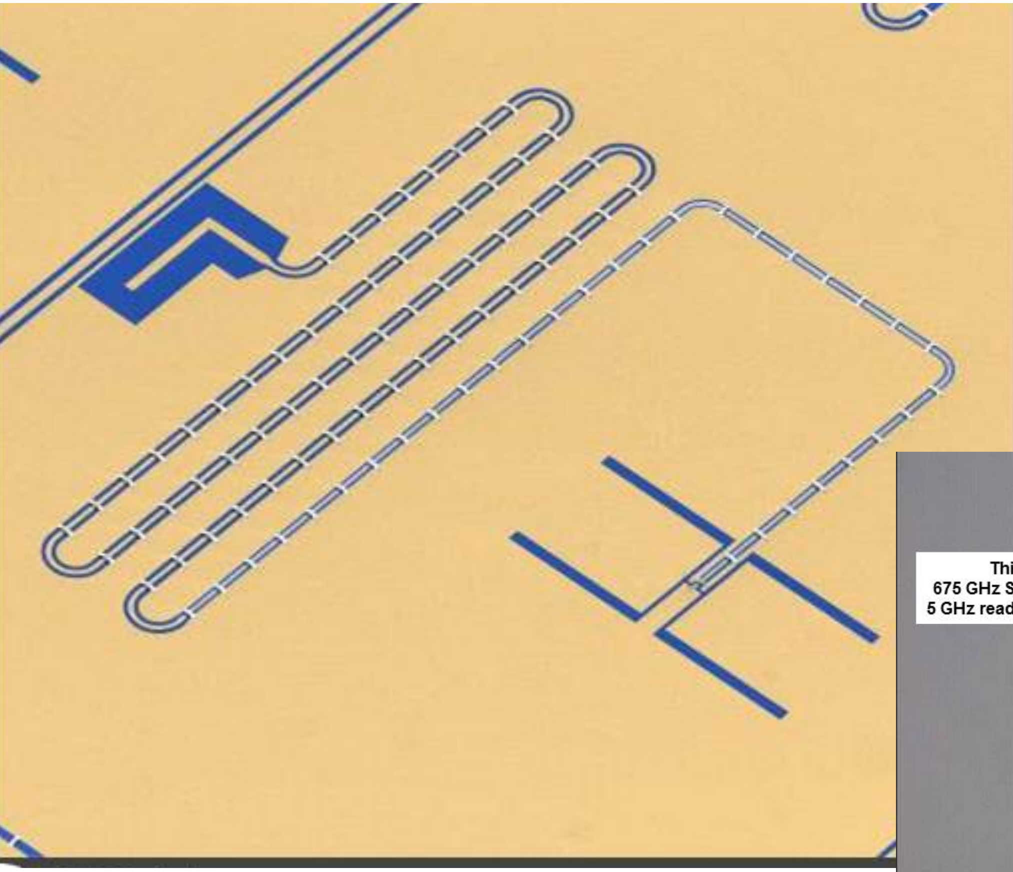
In the case of narrow bandwidth and high spectral resolution the heterodyne system will always win.

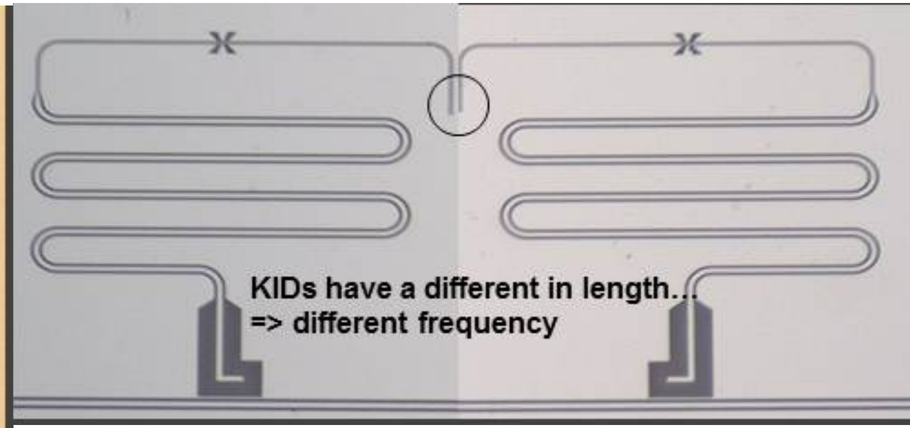
MKIDS – Physical Principle

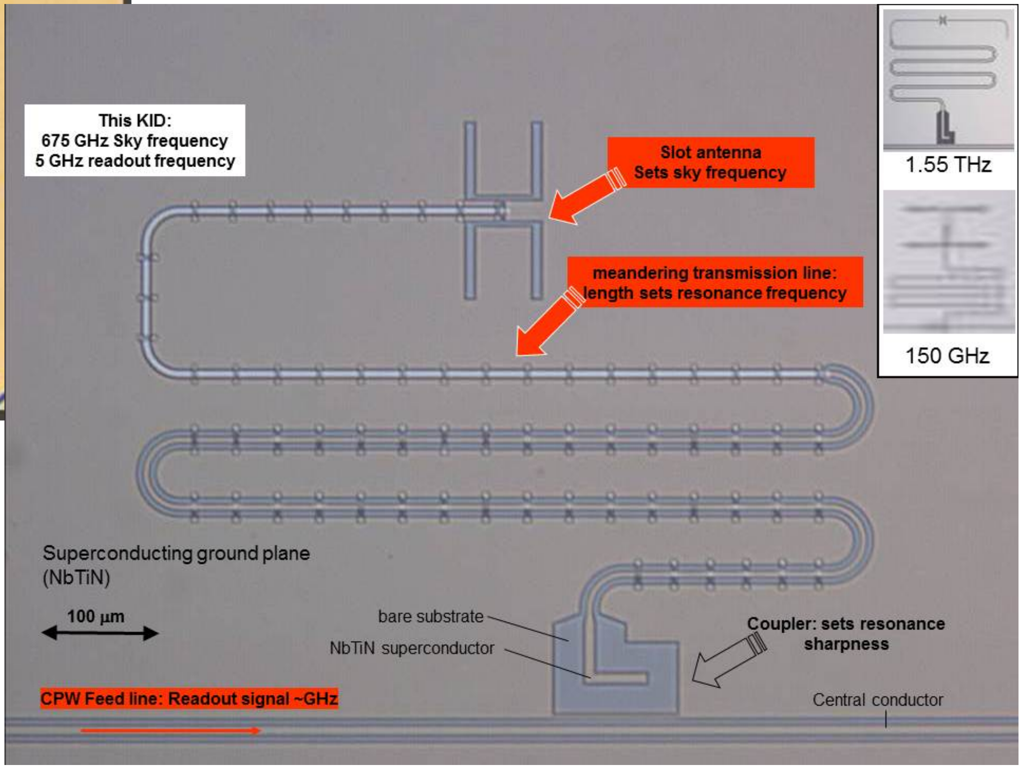


KID = Kinetic Inductance Detector
MKID = Microwave KID

MKIDS – Construction







MKIDS – Operating Principle