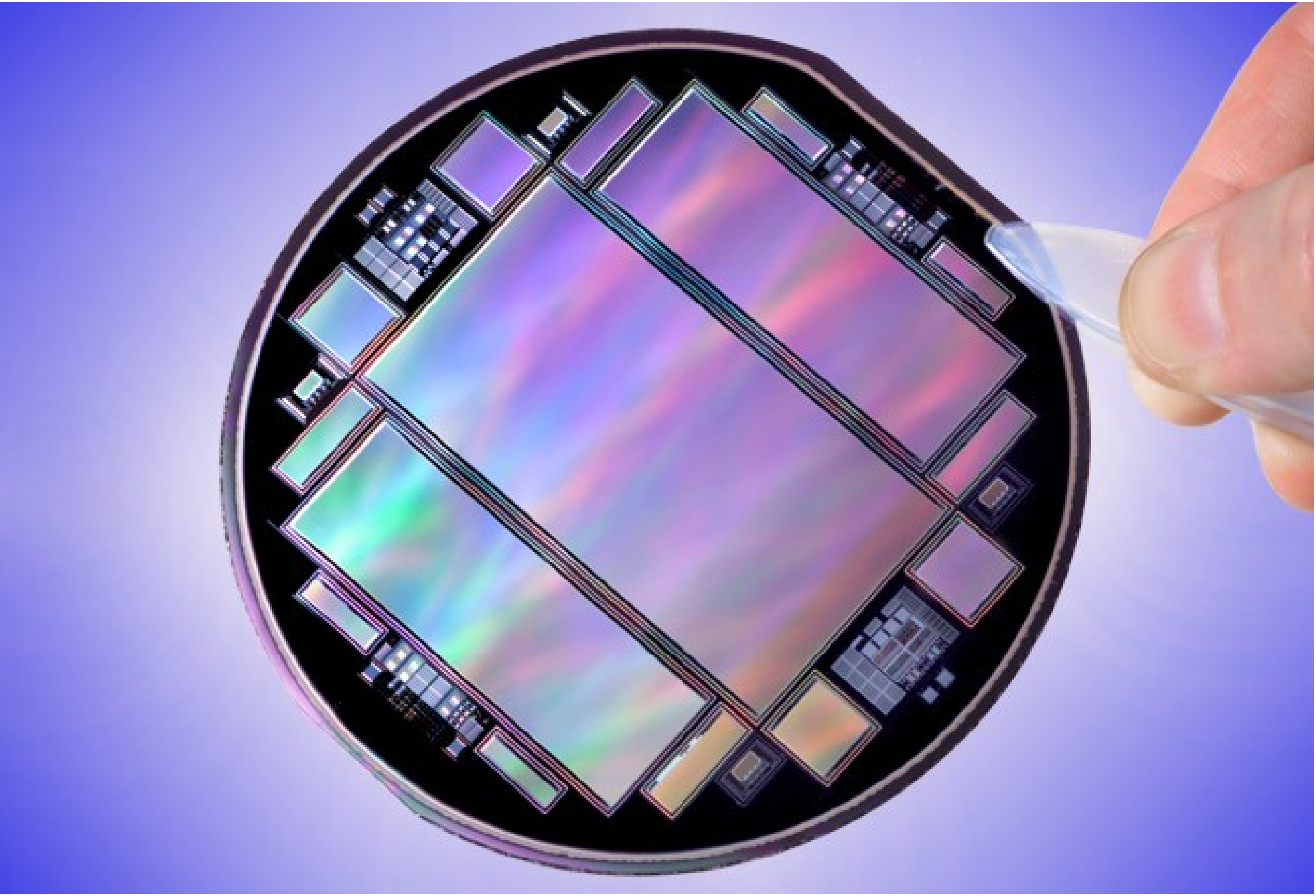
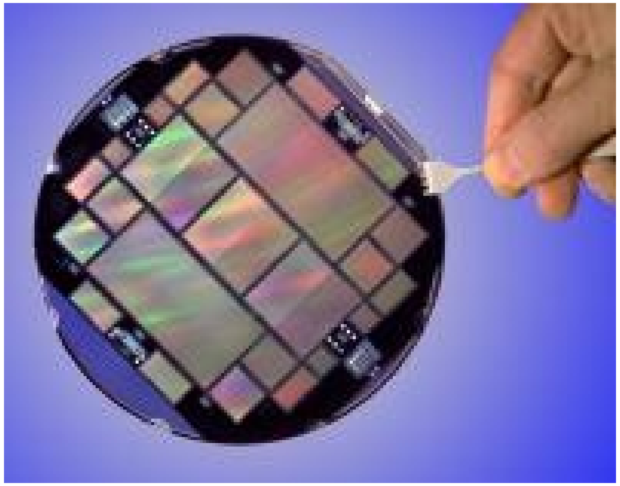
Astronomical Observing Techniques 2019

Lecture 10: Silicon Eyes 2

Huub Rottgering
Rottgering@strw.leidenuniv.nl

Content



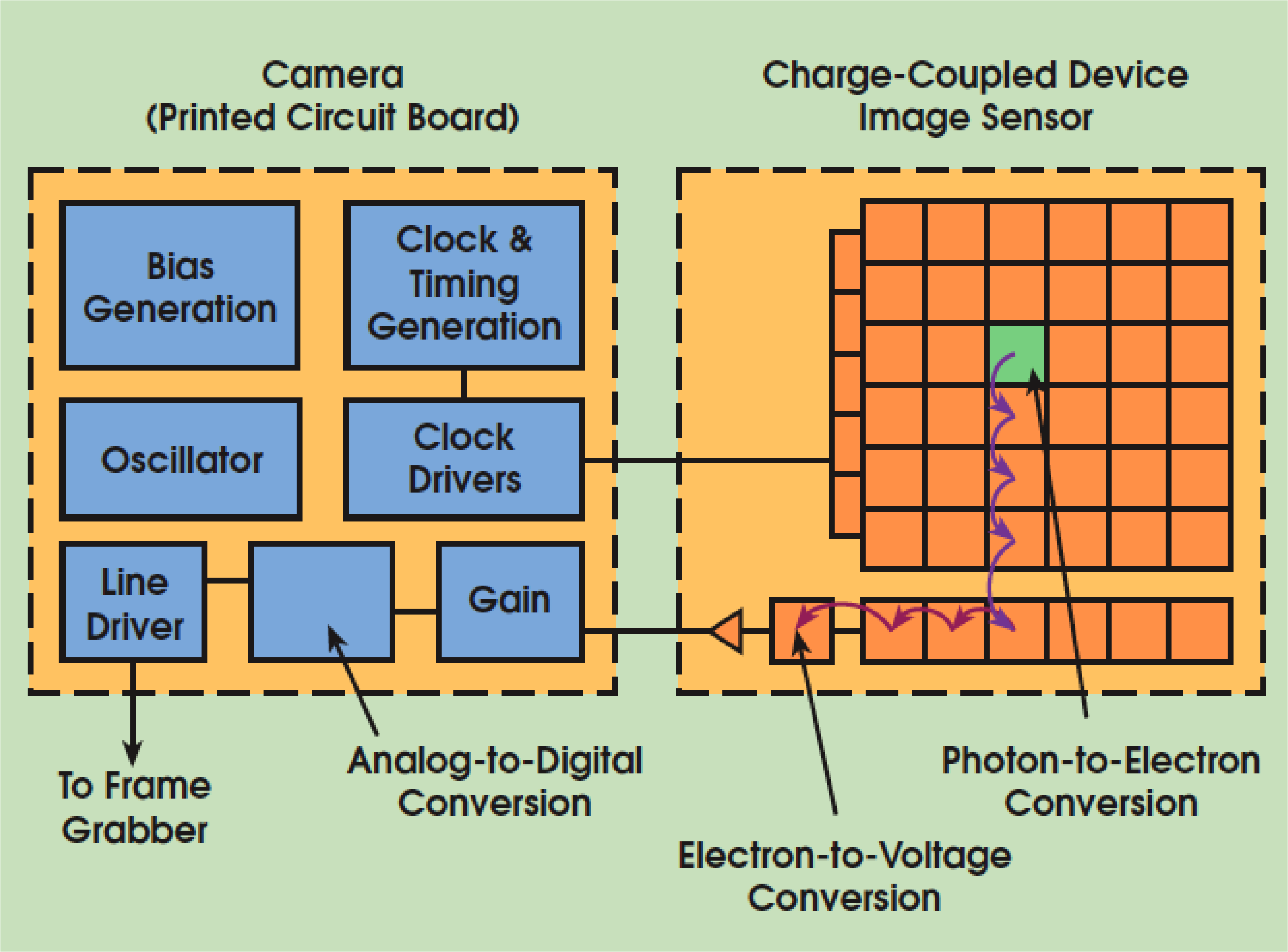


LBNL CCDs on a 6-

The two large CCDs are 2048 x 4096 15um^2 devices for astronomy. The three central CCDs are 2520^{2}12um^2 and 2880^2 10.5um^2 prototypes for the SNAP satellite camera. The wafer also contains near-square 15um^2, 12um2, 10.5um^2, and 9um^2 CCDs, 1024 x 512 15um^2 CCDs for radiation testing, and 1200 x 600 15um^2 devices with different 2-stage amplifier designs. In addition there are test diodes and a number of other monitoring devices.

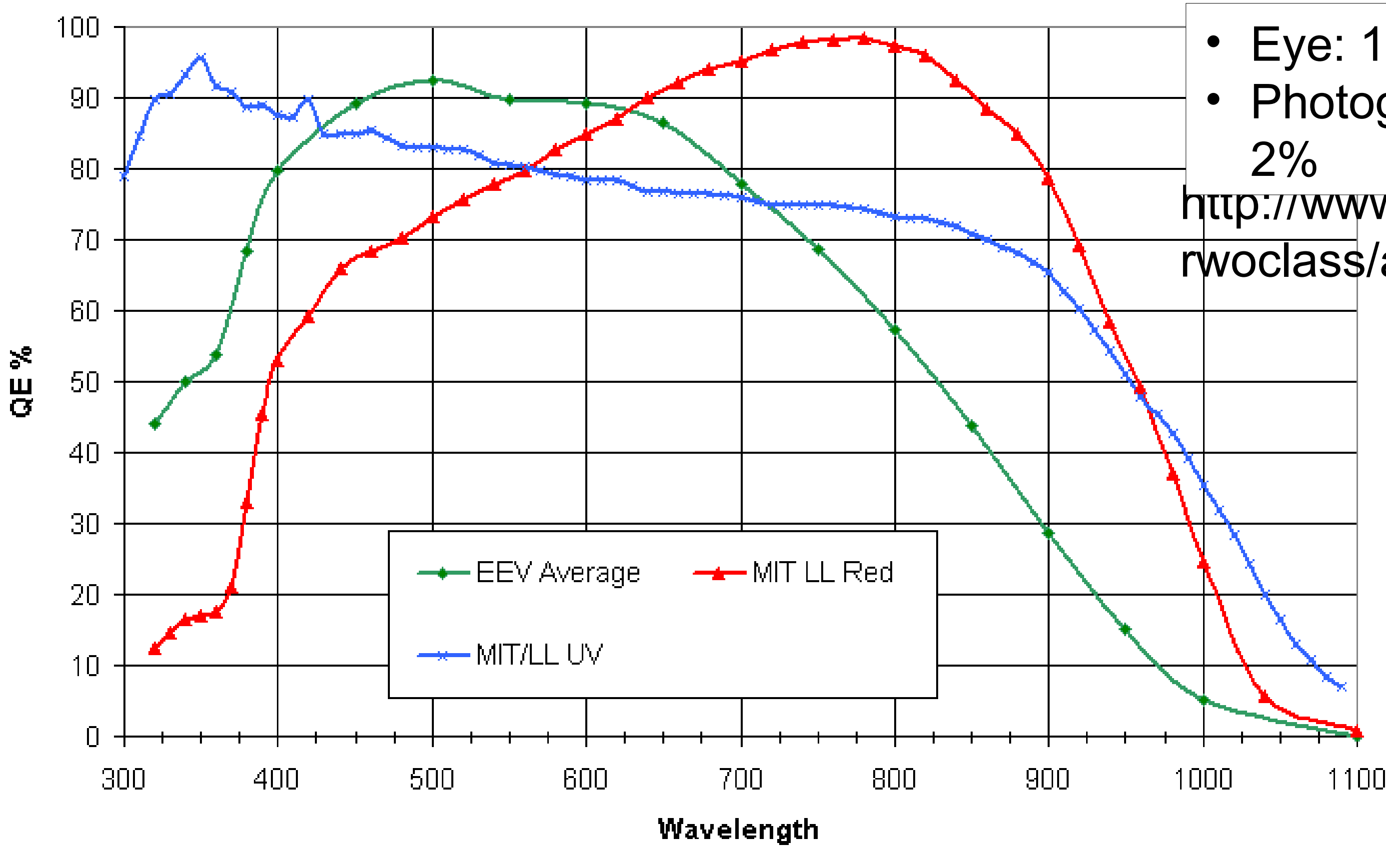
http://www-ccd.lbl.gov

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

Quantum Efficiency:
average number of electrons per incident photon



- Eye: 1-2%
- Photographic plate: 1-2%

http://www.faculty.virginia.edu/rwoclass/astr511/lec11-f03.html

SPECTRAL RANGE: Wavelength region over which QE is sufficient for operation

- Dynamic range: ratio of maximum to minimum measurable signal
  - maximum number of events in a CCD pixel is determined by photoelectron "full well" capacity or digitization maximum (typically 2 bytes);
  - minimum is determined by dark current/readout noise

  Applies to a single exposure; effective dynamic range can be increased with multiple exposures

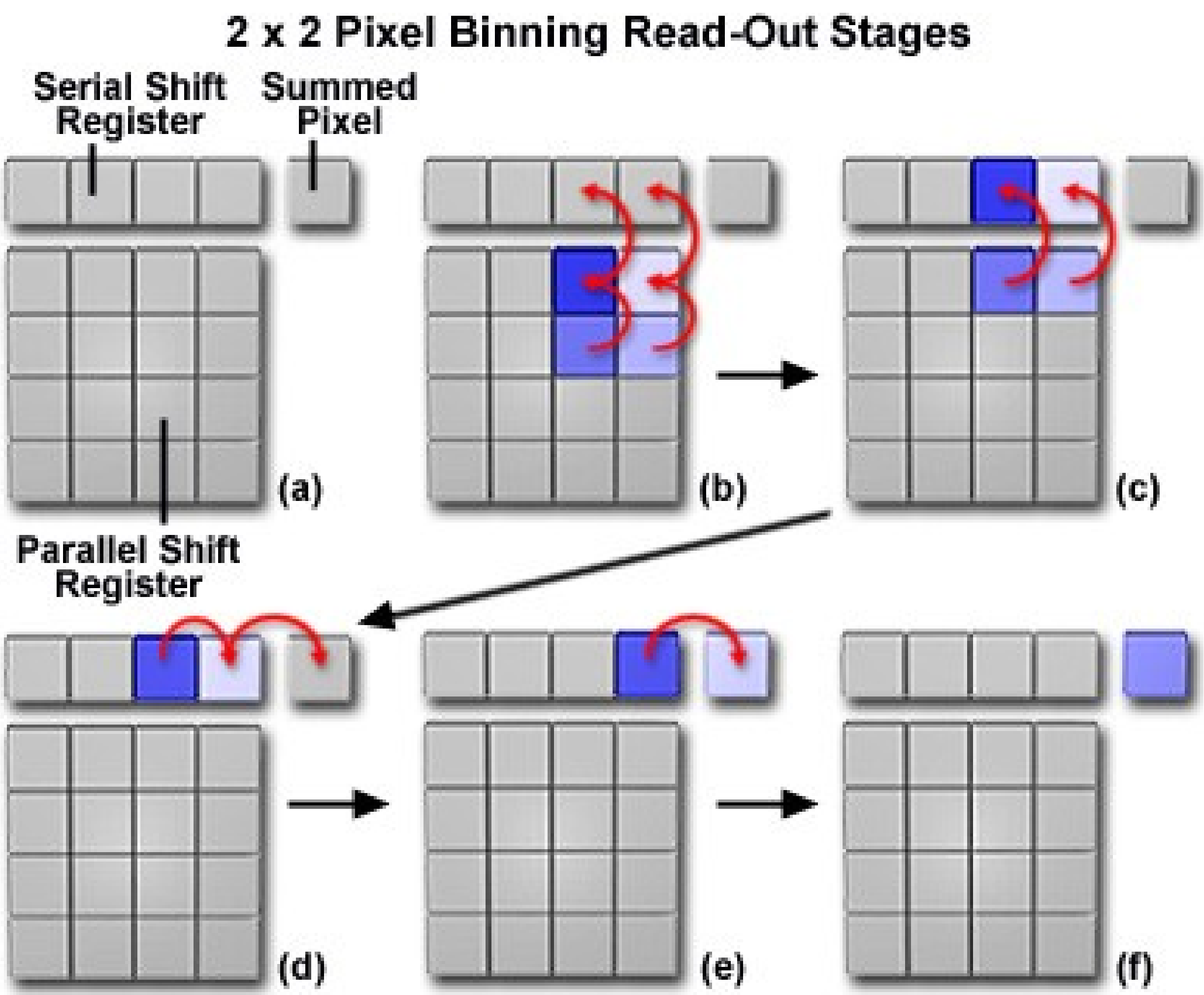
- Linear Range: range of signals for which [Output] = k x [Input], where k is a constant. Generally smaller than the calibratable range

- Threshold: minimum measurable signal determined by sky or detector noise

- Saturation point: level where detector response ceases to increase with the signal

- Readout noise: main origins:
  - on-chip amplifier translating charge (electrons) to analog voltage
  - wires between on-chip amplifier and analog-to-digital converter acting as antennae

Binning



hamamatsu.magnet.fsu.edu/articles/images/pixelbinningfigure1.jpg

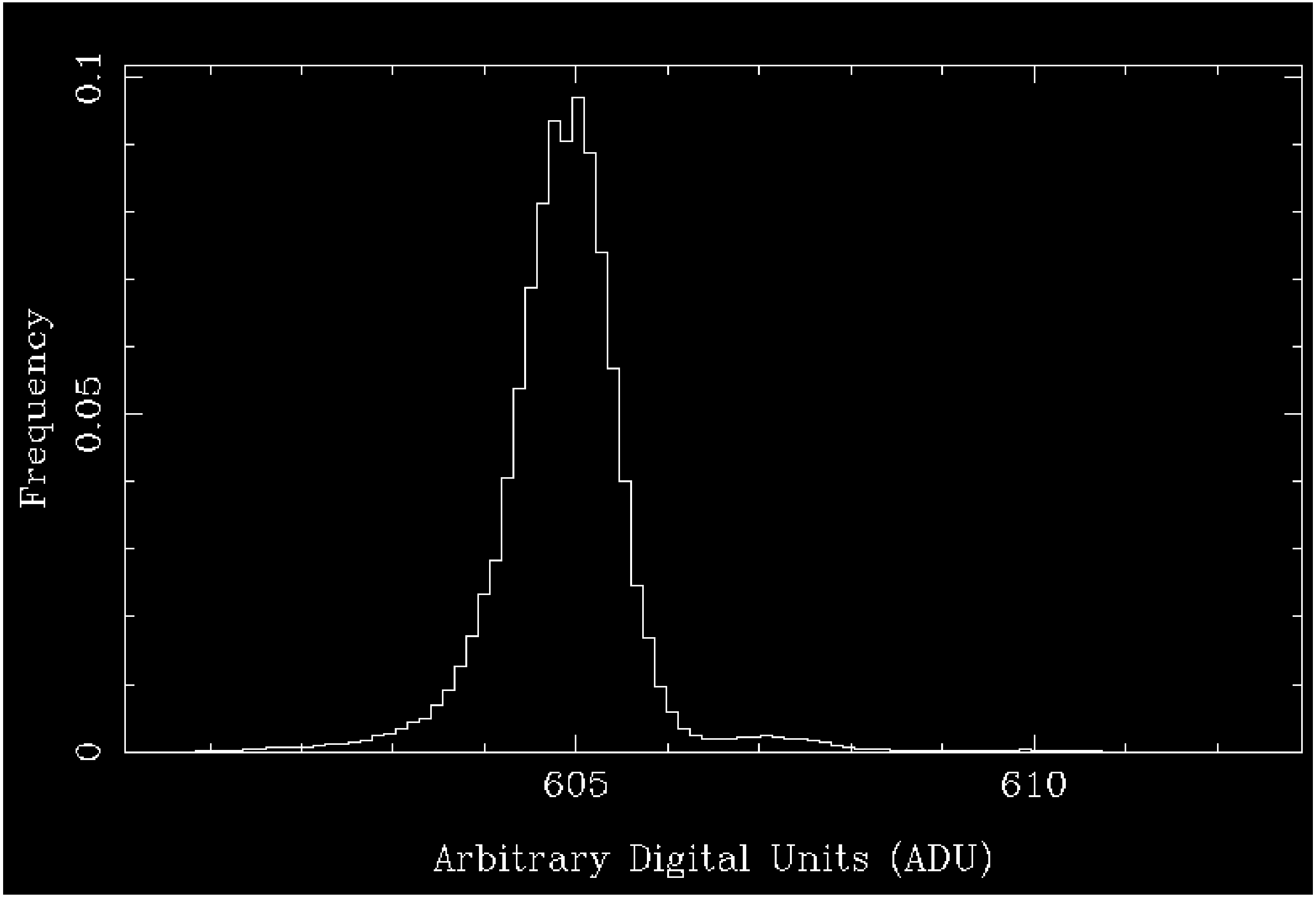
- serial shift register pixels and final output pixel have much larger well depths
- combine electrons from NxN’ pixels
    - Note that N can be taken different from N’
- Read-out only once
- Reduces readout noise, important when readout noise and not sky noise limited, for example in the case of high resolution spectroscopy or narrow band imaging in the UV.

From Photons to Digital Units

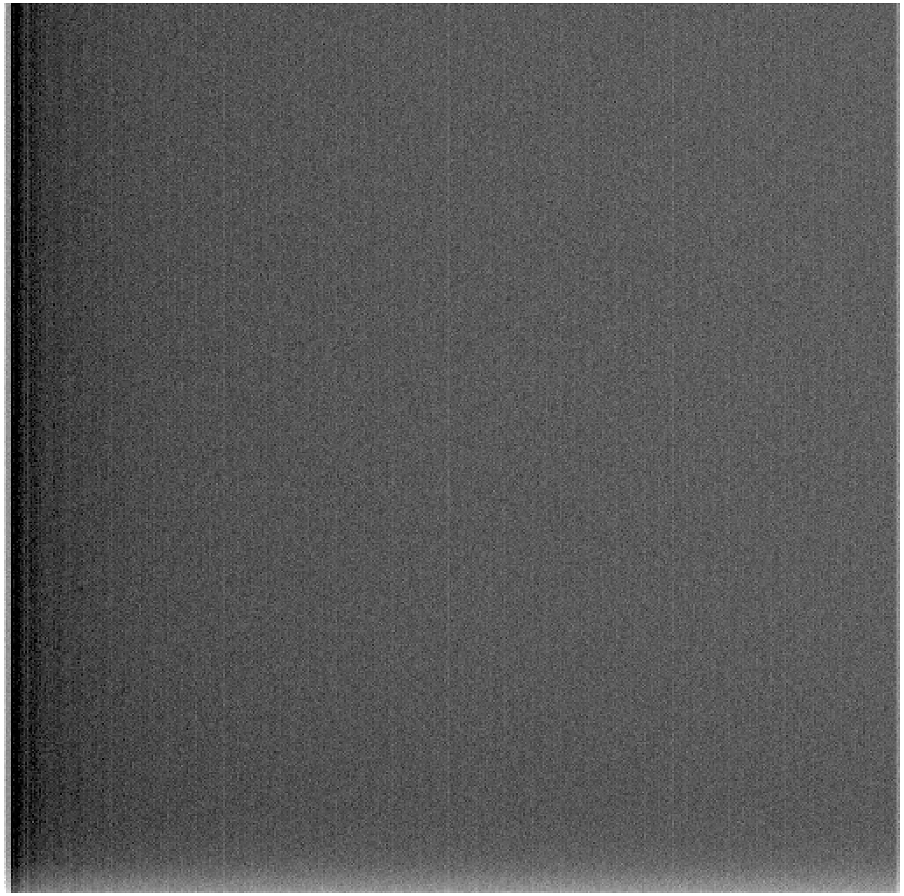
- Photons S create electrons according to individual pixel sensitivity (flat field f)
- Finite temperature of detector adds thermally generated electrons (dark current d)
- Voltage offset on Analog-Digital Converter (bias b)
- Hence measured signal:

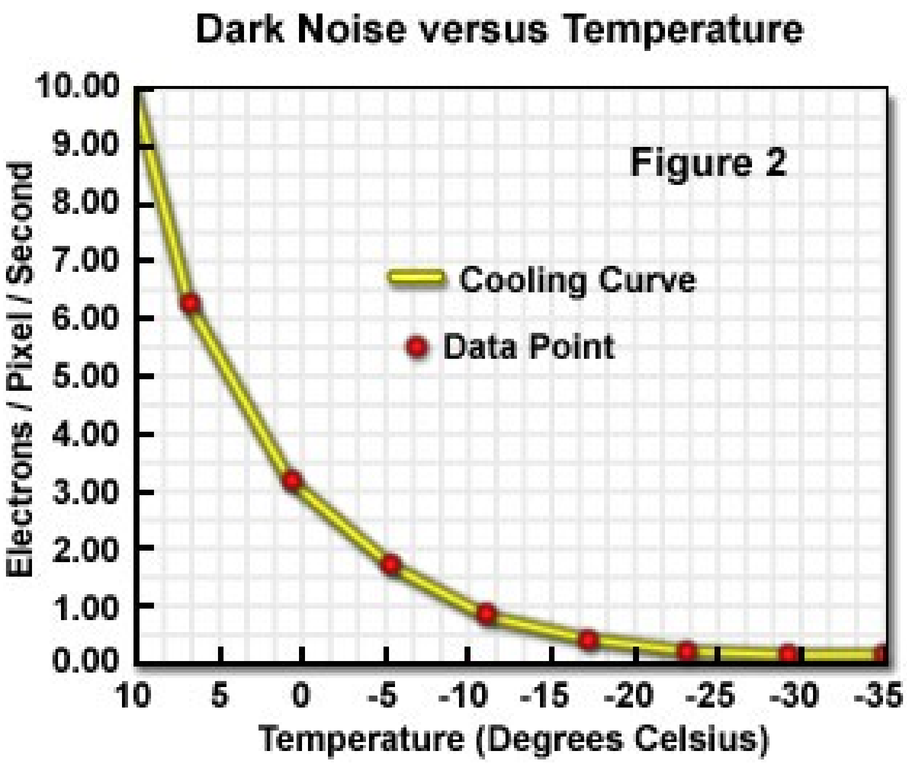
$$b + d + f \cdot S$$

Bias

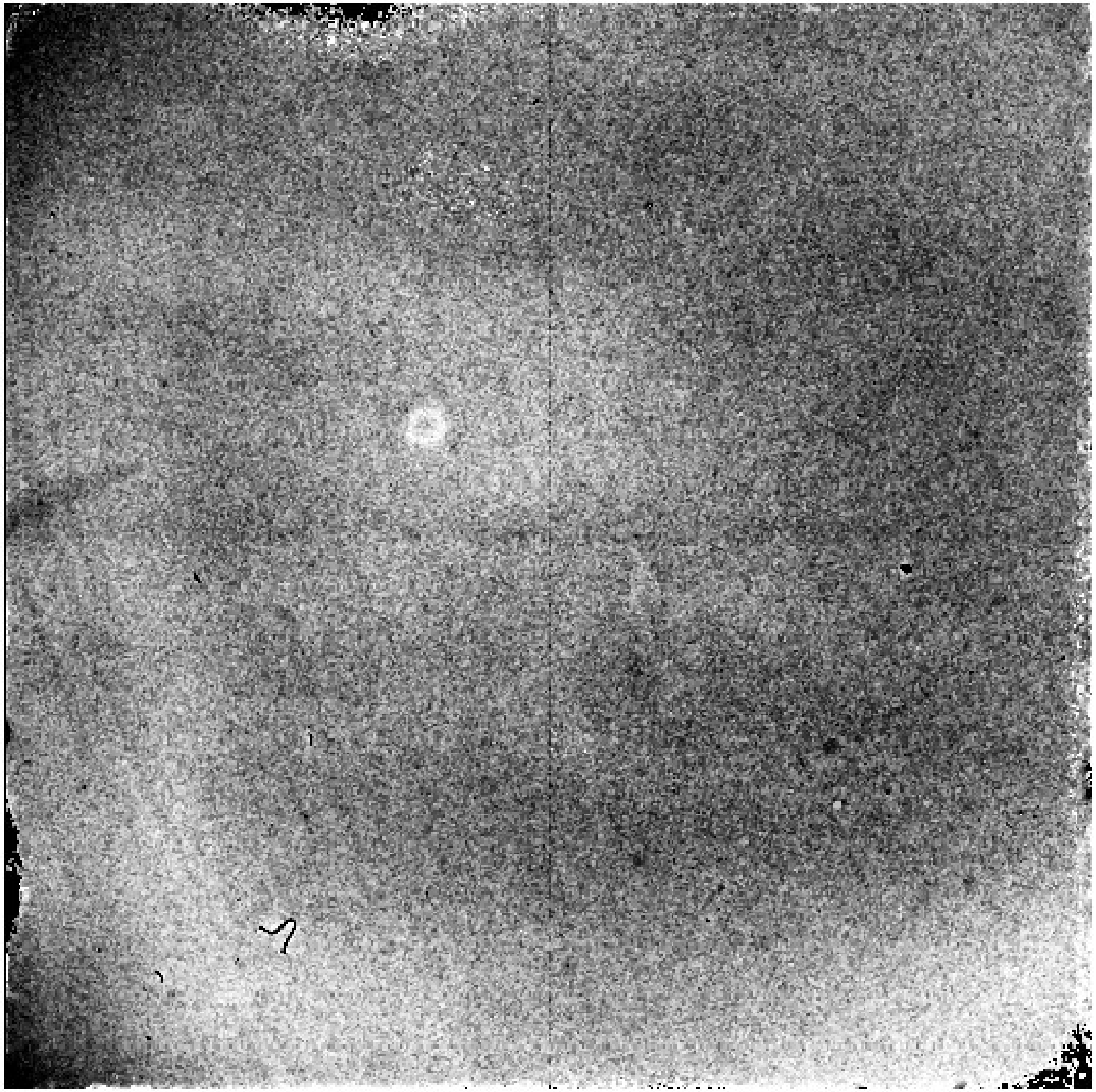


Dark Current





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 artefacts)

2. Twilight flats: observe the twilight sky during sunrise and/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 (e.g. average all data)

In practice: methods can be combined

Dome Flat Screen at AAT

pbs.twimg.com/media/DRixdEDU8AAdaKM.jpg:large

Typical Array Detector Data Reduction

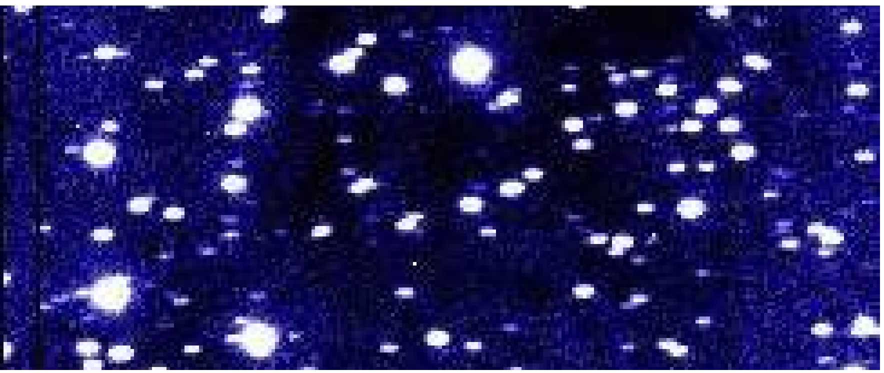
- science frame signal S, exposure time t_S
- dark frame signal D, exposure time t_D
- bias frame signal B, zero exposure time
- flat field frame F, exposure time t_F
- corrected (calibrated) image given by

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

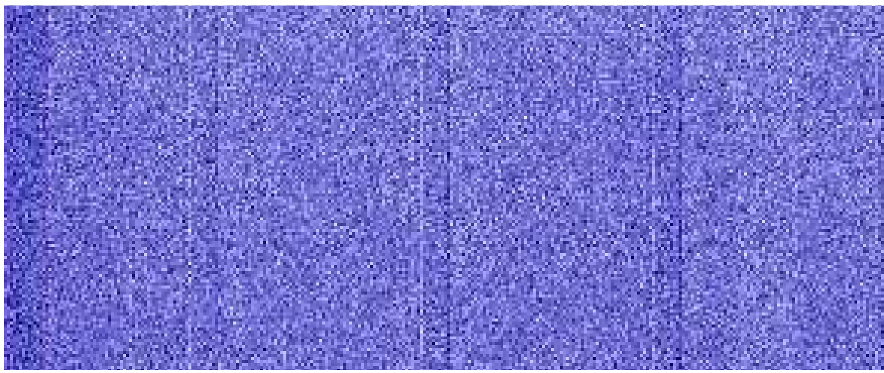
- denominator often normalized such that median of S' = median of S

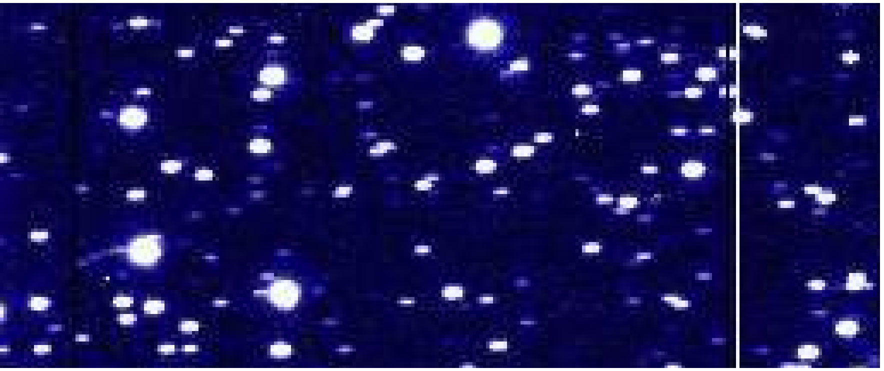
CCD Data Reduction

Raw

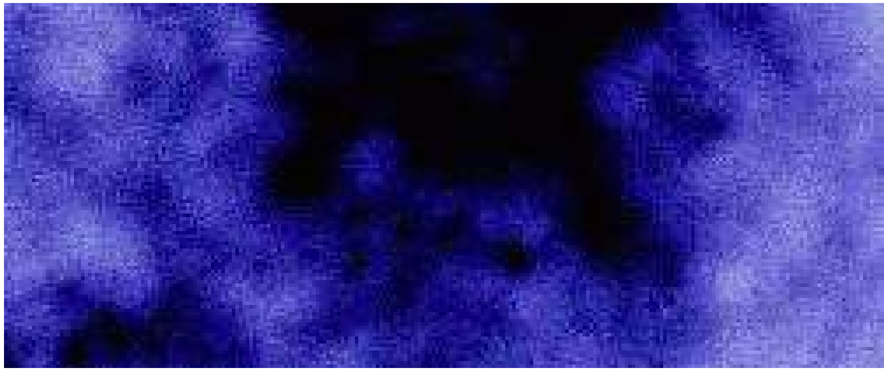


Bias + Dark Current





Reduced

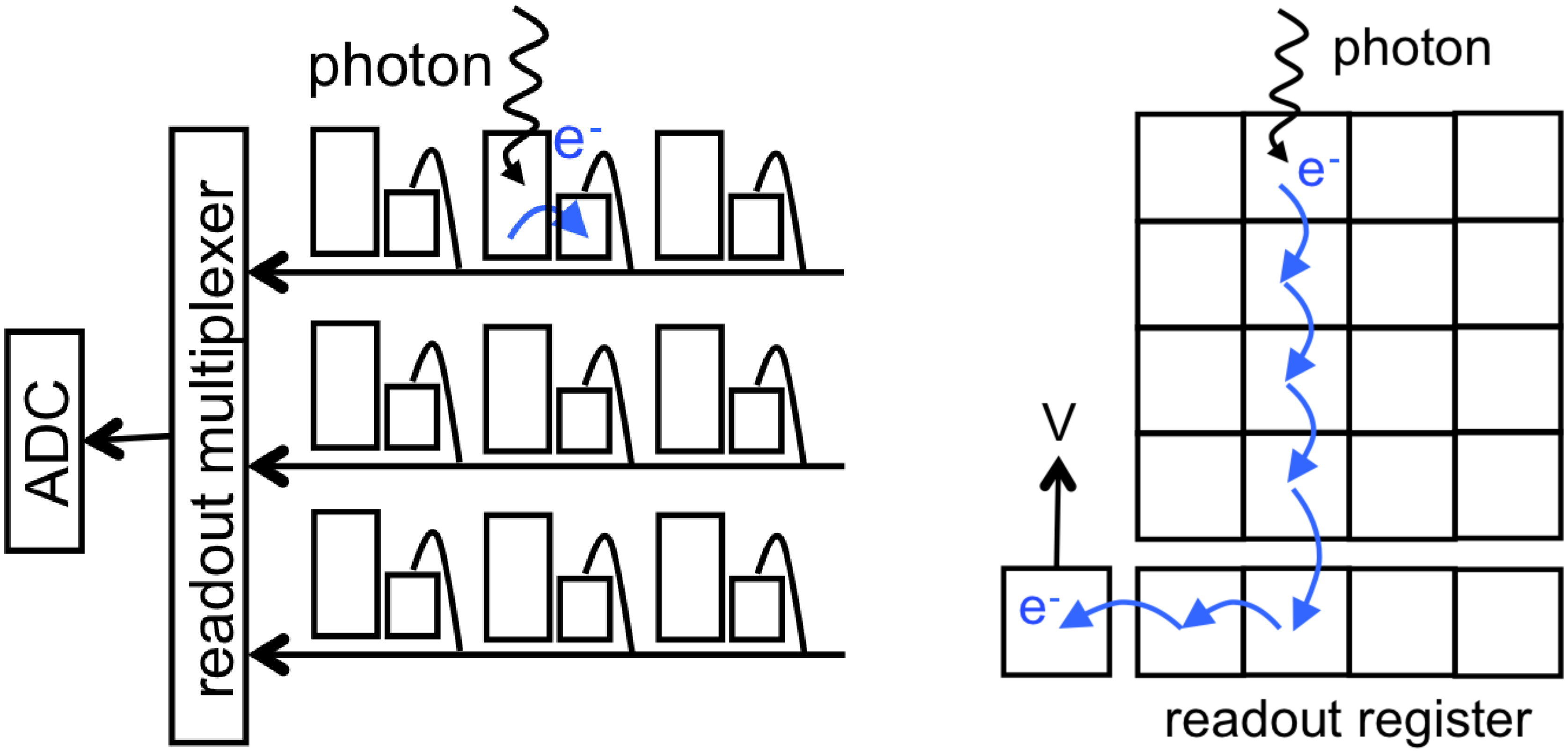


Flatfield

CMOS detectors

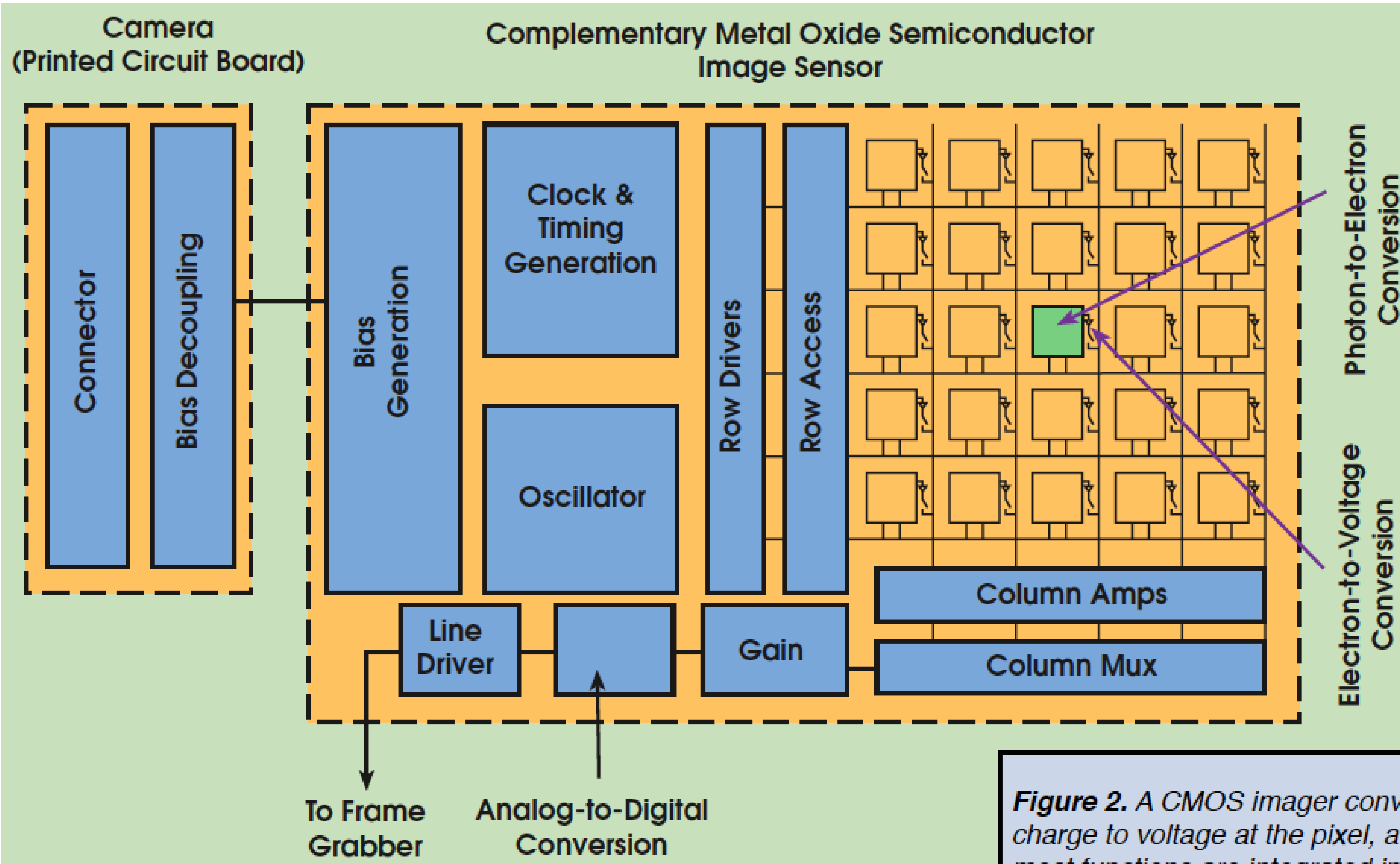
- CMOS = Complementary Metal Oxide Semiconductor;
- Each pixel has its own readout transistor. Which can be read out in a random access fashion.

CMOS and CCD



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

CMOS Camera

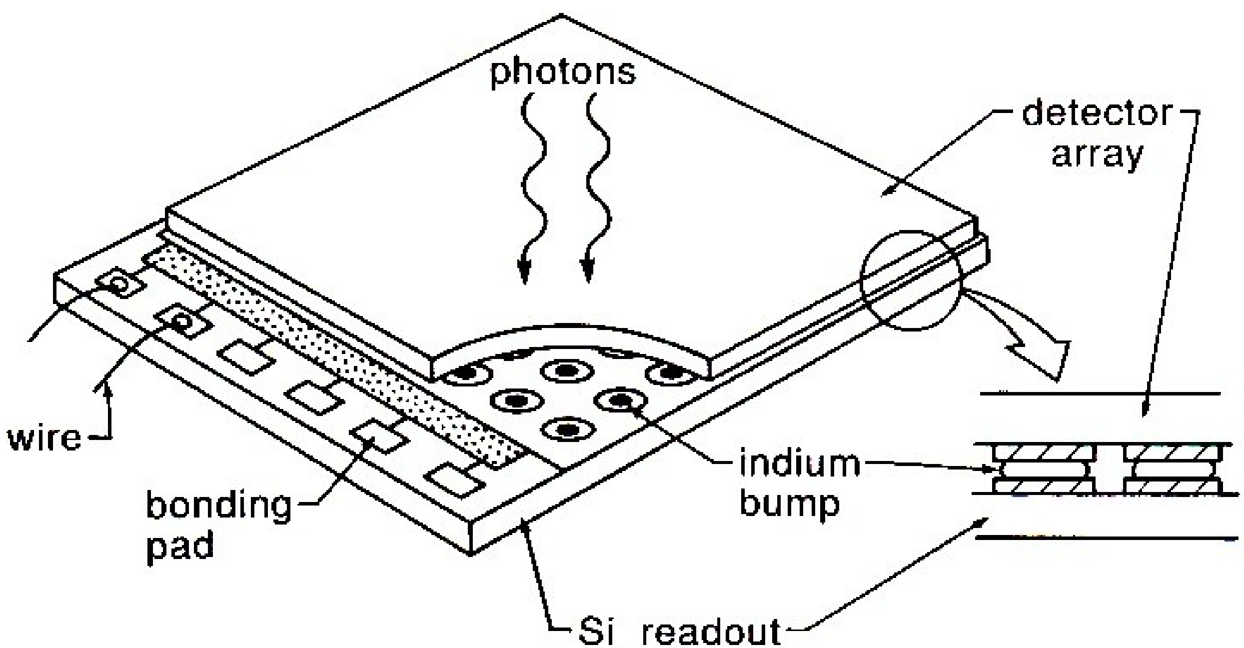

Camera
(Printed Circuit Board)
Complementary Metal Oxide Semiconductor
Image Sensor
Connector
Bias Decoupling
Bias
Generation
Clock &
Timing
Generation
Oscillator
Row Drivers
Row Access
Photon-to-Electron
Conversion
Electron-to-Voltage
Conversion
Column Amps
Column Mux
Line
Driver
Gain
To Frame
Grabber
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)
  - Noisier, less sensitive, and with a lower dynamical range than CCDs,
  - but much cheaper

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



CCDs vs IR Arrays

CCDs:

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

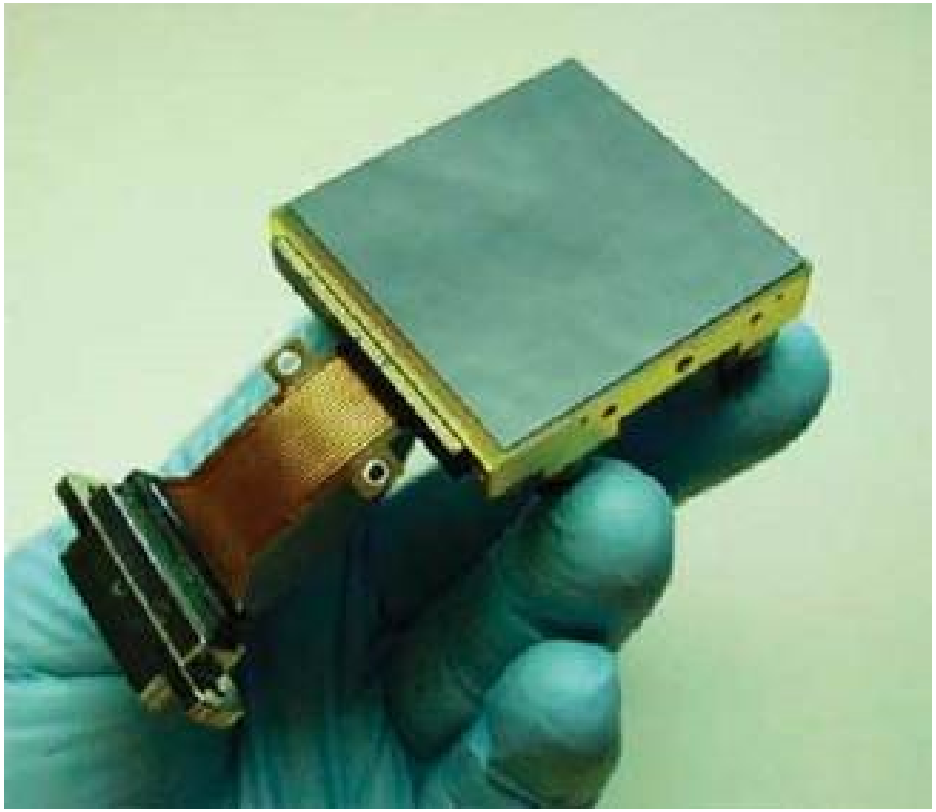
IR arrays:

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

Example: The Teledyne HAWAII-2RG

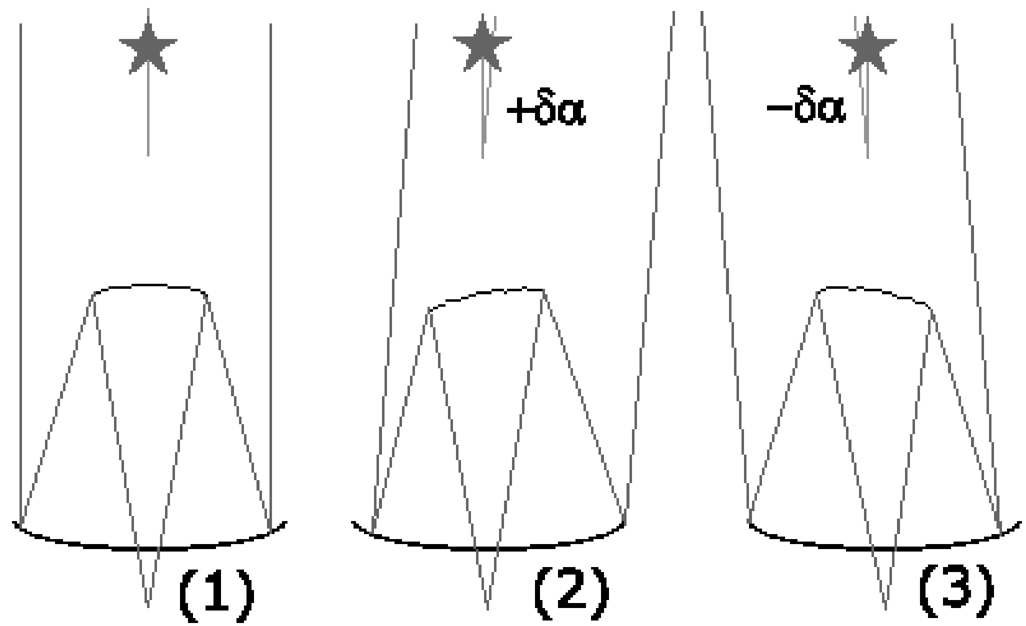
Parameter	Specification
Detector technology	HgCdTe or Si PIN
Detector input circuit	SFD
Readout mode	Ripple
Pixel readout rate	100 kHz to 5MHz (continuously adjustable)
Total pixels	2048 x 2048
Pixel pitch	18 µm
Fill factor	$\geq$ 98%
Output ports	Signal: 1, 4, 32 selectable guide window and reference
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



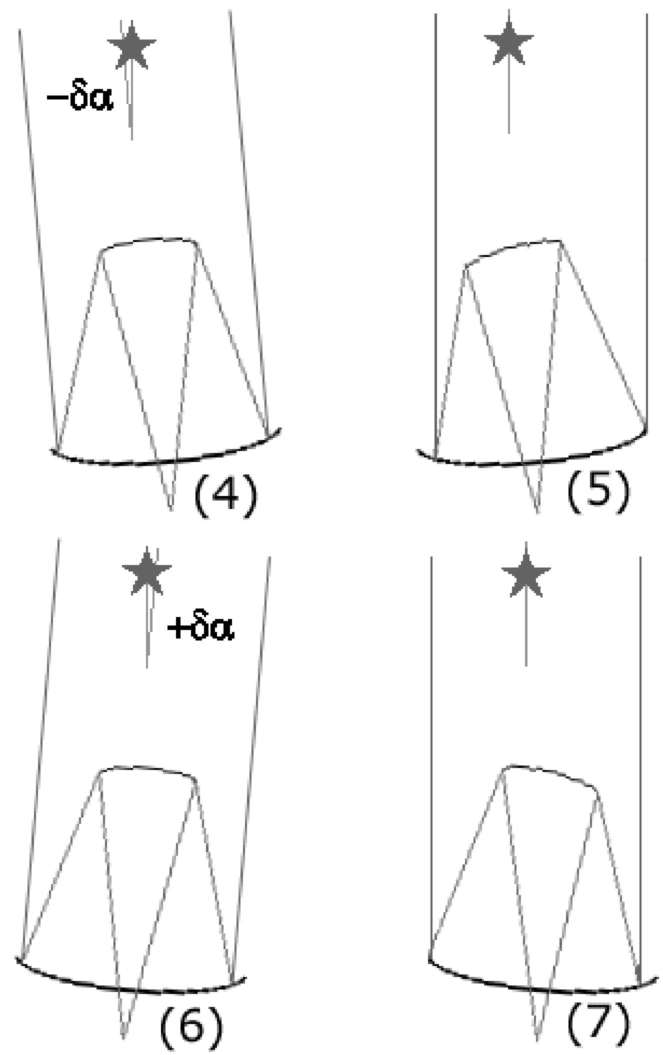
Chopping

- IR images dominated by background signal
- Background subtraction must be very precise
- Move secondary mirror **quickly** to slightly change pointing
- Assumes that background is relatively flat

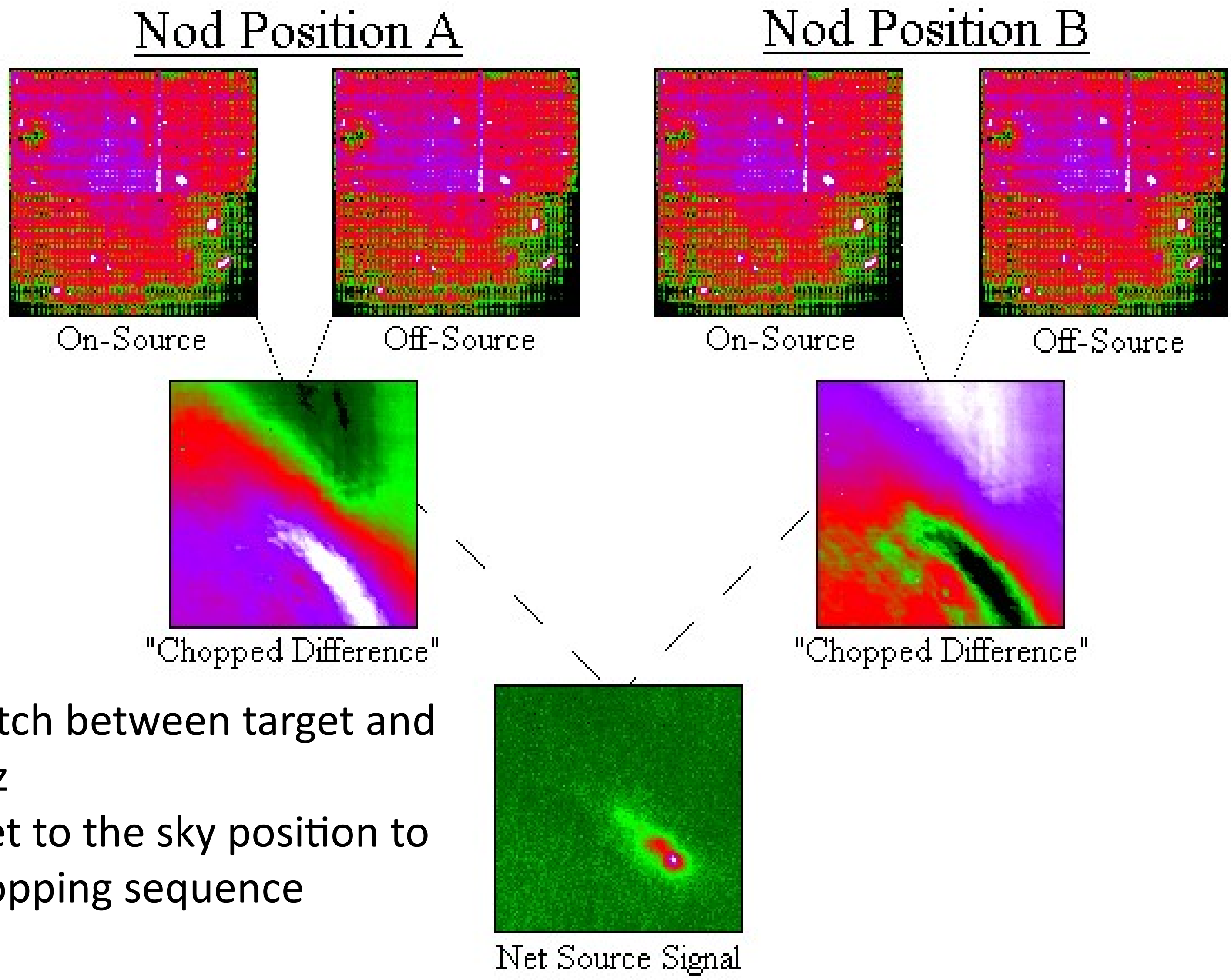


Nodding

- Moving telescope keeps optical path the same
- Nodding is **slow**
- Best of both: combine fast chopping with slow nodding

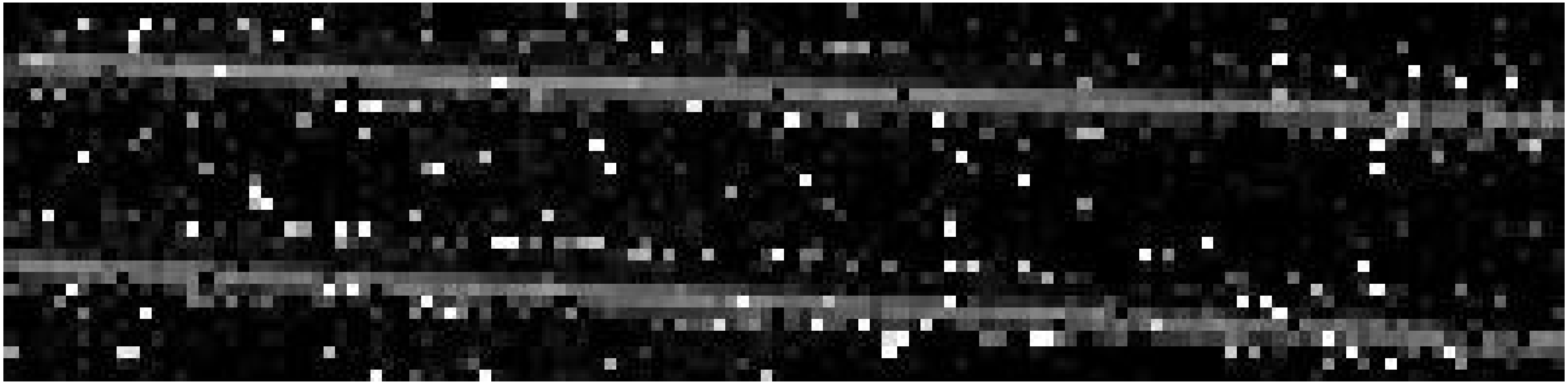


Chopping / Nodding



Chopping: switch between target and sky at a few Hz
Nodding: offset to the sky position to repeat the chopping sequence inverted

Detector Artefacts: Bad Pixels

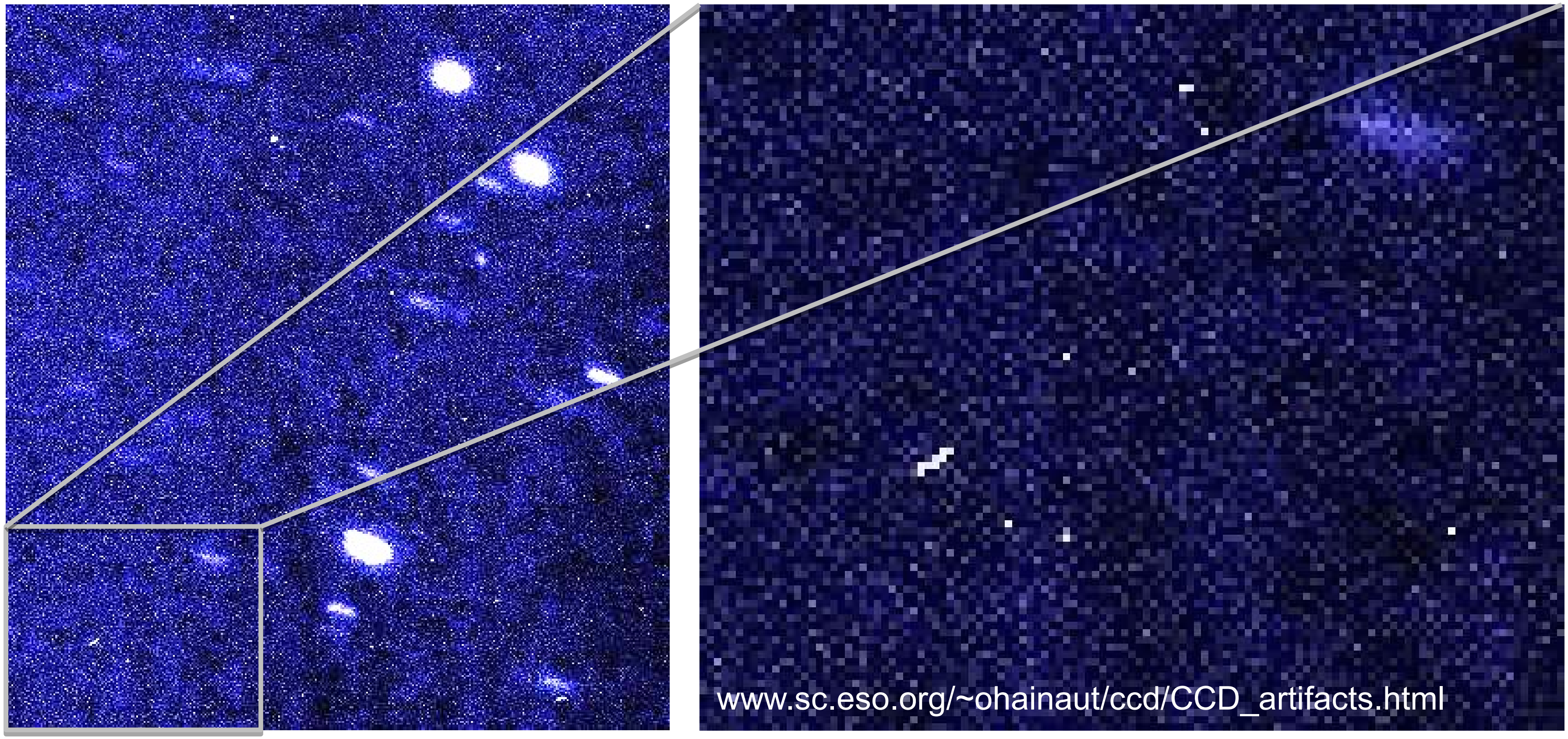


- dead, hot and rogue pixels, rows, columns
- bias and dark correction help somewhat
- can often us "dead-pixel map" and replace with median of surrounding pixels

Detector Artefacts: Latent Images

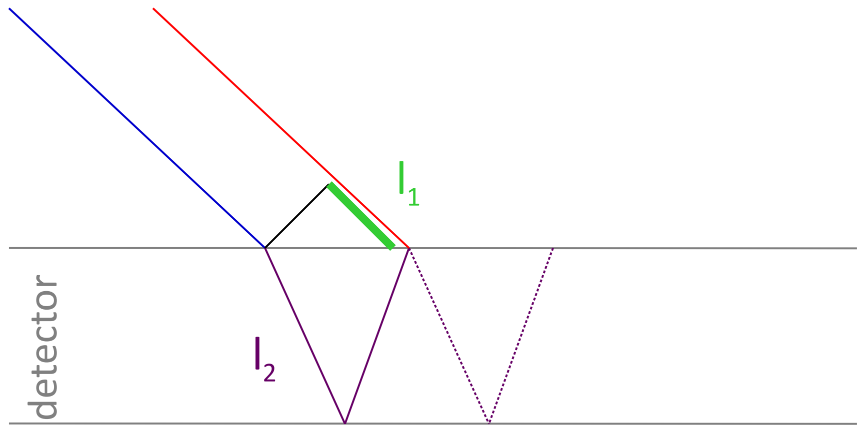
- mostly seen in hybrid (IR) arrays
- Mitigation:
  - avoid overexposure
  - wait
  - additional resets

Detector Artifacts: Cosmic Rays

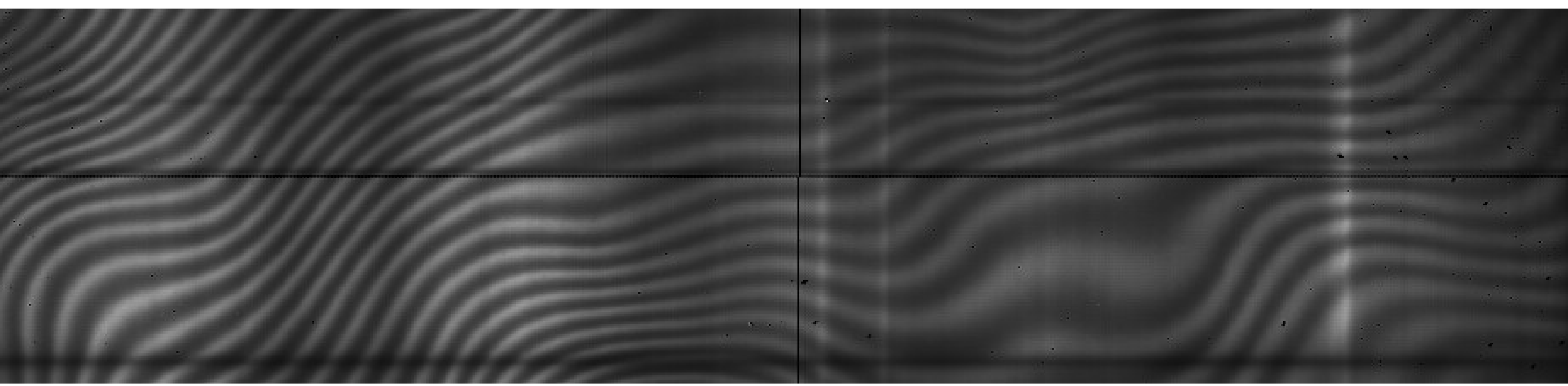


- cosmic ray particles free electrons in detector
- remove with median filtering of several exposures

Detector Artefacts: Fringing

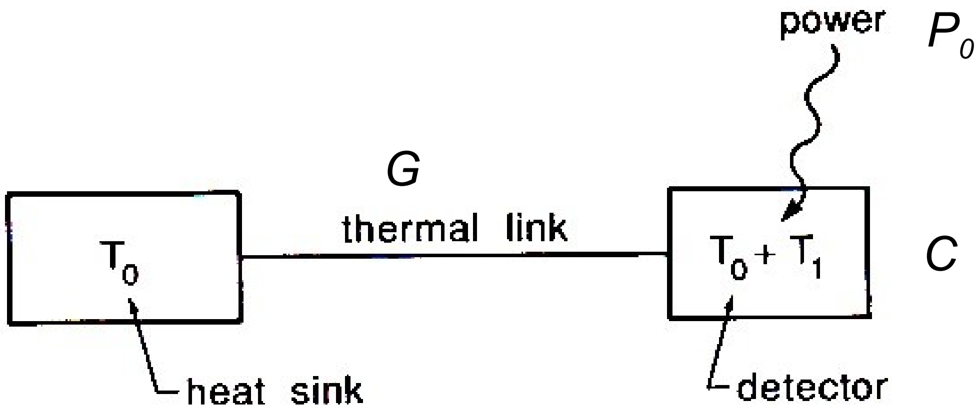


If the phase difference between I_1 and n I_2 is an even multiple of π constructive interference occurs. If an odd multiple destructive interference occurs fringes = wave pattern.



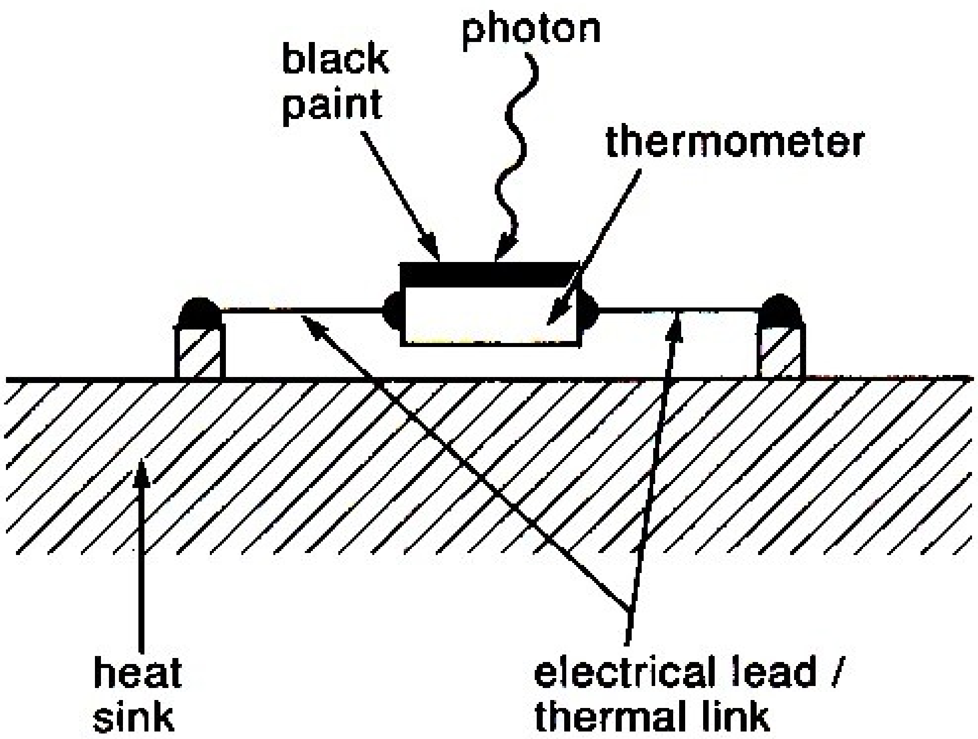
Detector Artefacts: Blooming

Bolometer



- photon flux power P_0 on detector
- incoming photons increase temperature of detector by T_1
- weak thermal link to heat sink at T_0
- thermal link conductance $G=P_0/T_1$
- steady state energy transfer to heat sink is $P_0=GT_1$

Principle of Bolometer Construction



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

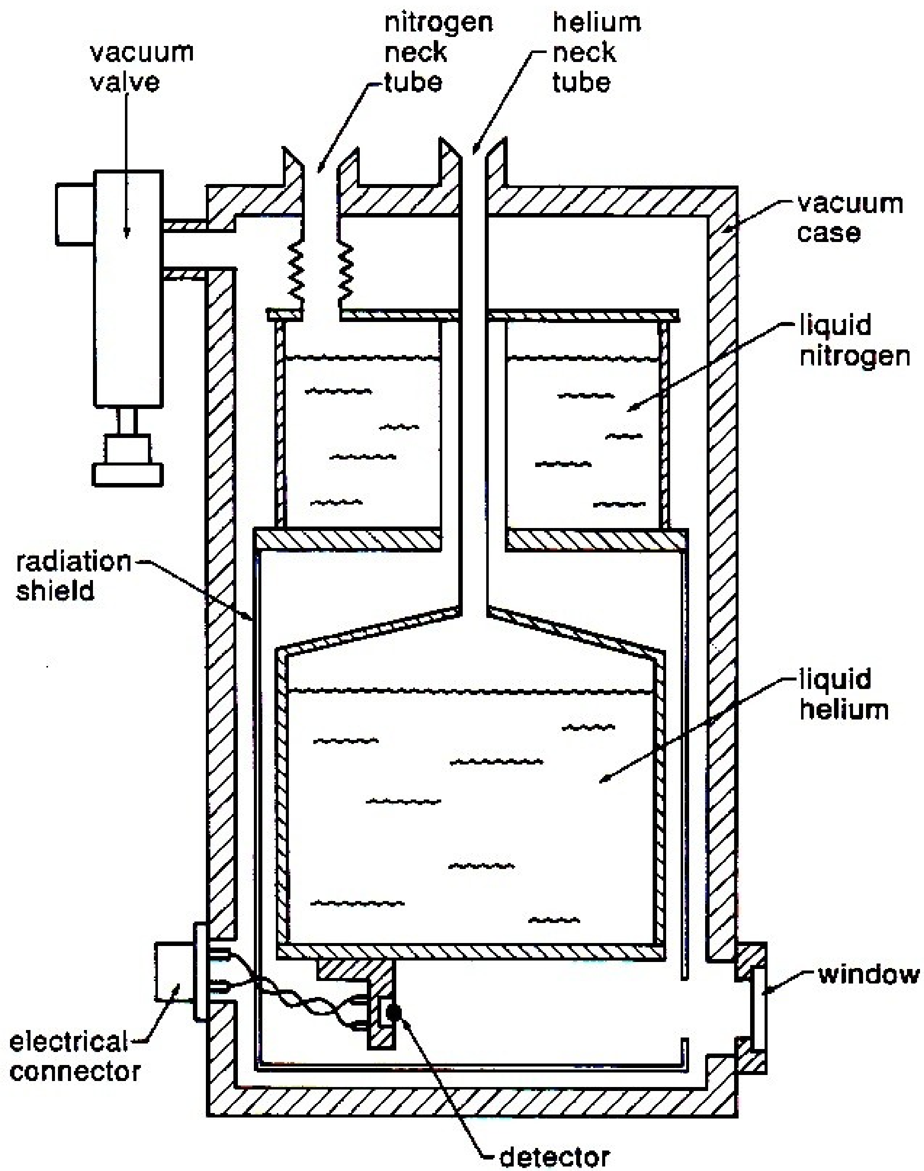
Bolometers most useful for far-IR/sub-mm wavelengths!

Cryogenic Temperatures

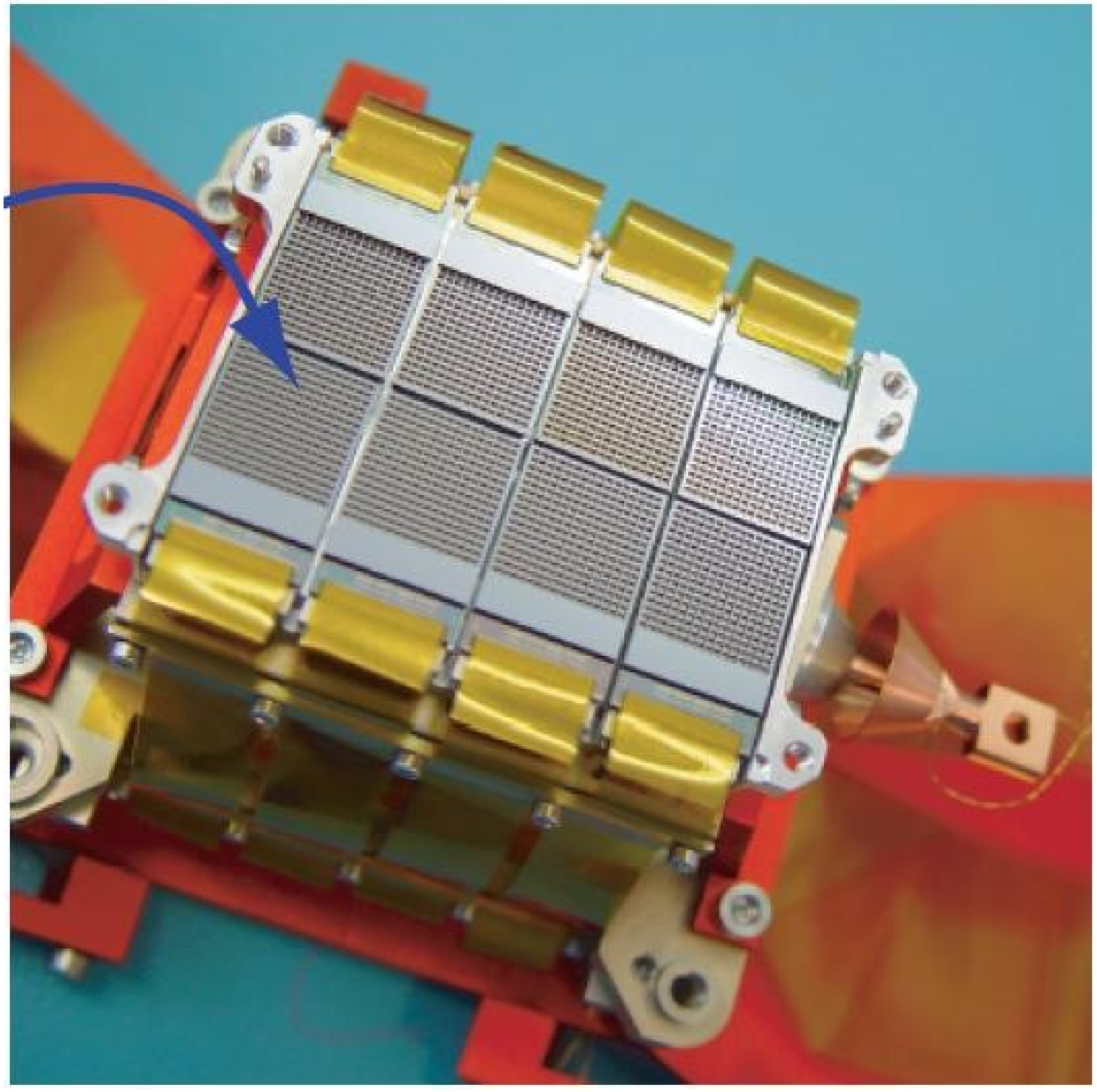
Four standard cooling options:

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.)

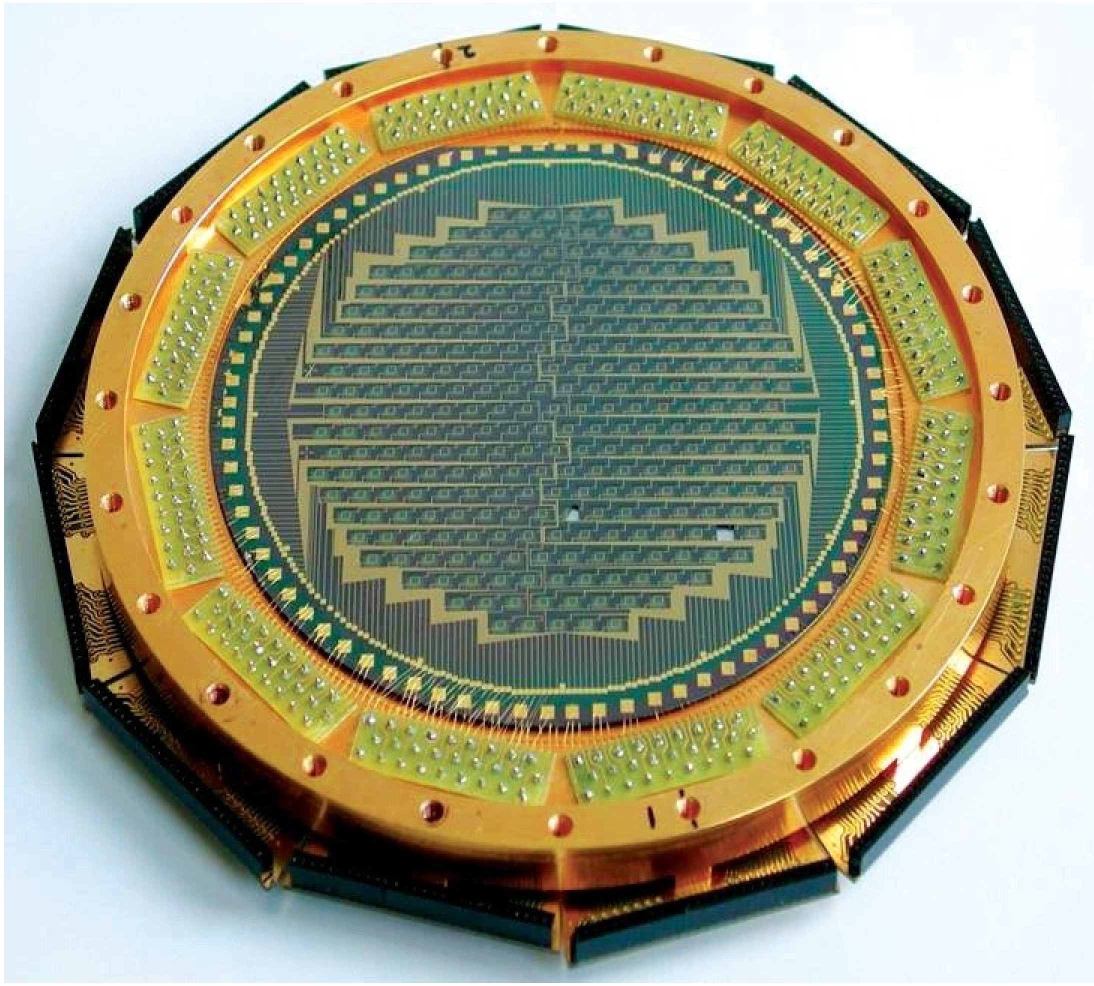


Bolometer Examples I



Herschel / PACS
64x32 pixel
bolometer array

Bolometer Examples II



- LABOCA – multi-channel bolometer array for APEX operating at 870 µm (345 GHz
- Photons absorbed by thin metal film at 280 mK
- 295 channels in 9 concentric hexagons
- Array is undersampled, requires special mapping techniques