# Observational Astronomy

## Astronomical Detectors

Kitchin pp. 1-44

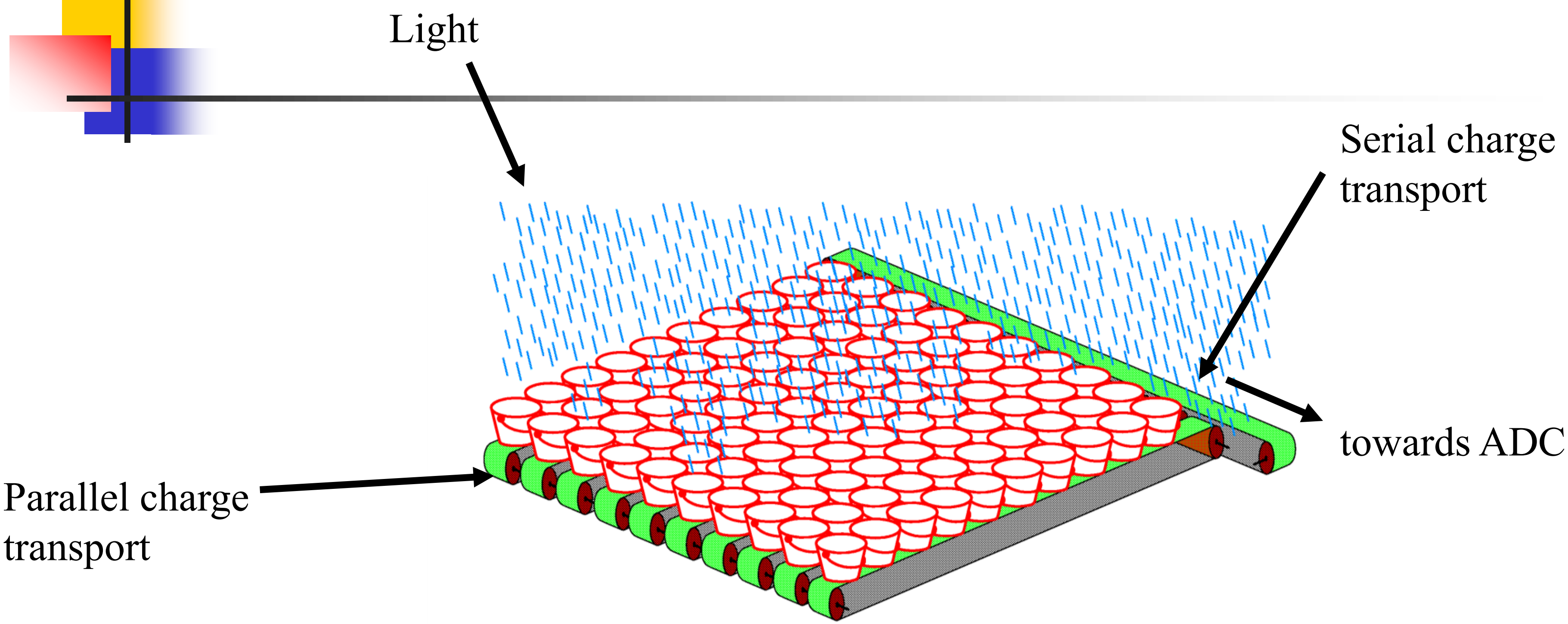
# Types of detectors

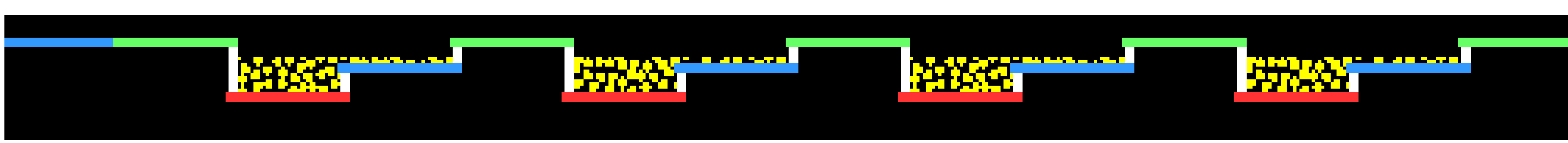
| Integrating detectors | Photon counting detectors (PCD) |
|---|---|
| Accumulate reaction to incoming radiation over time | React to (almost) every incoming photon and produce digital count |
| *Example:* photographic plate, CCD | *Example:* photomultiplier |

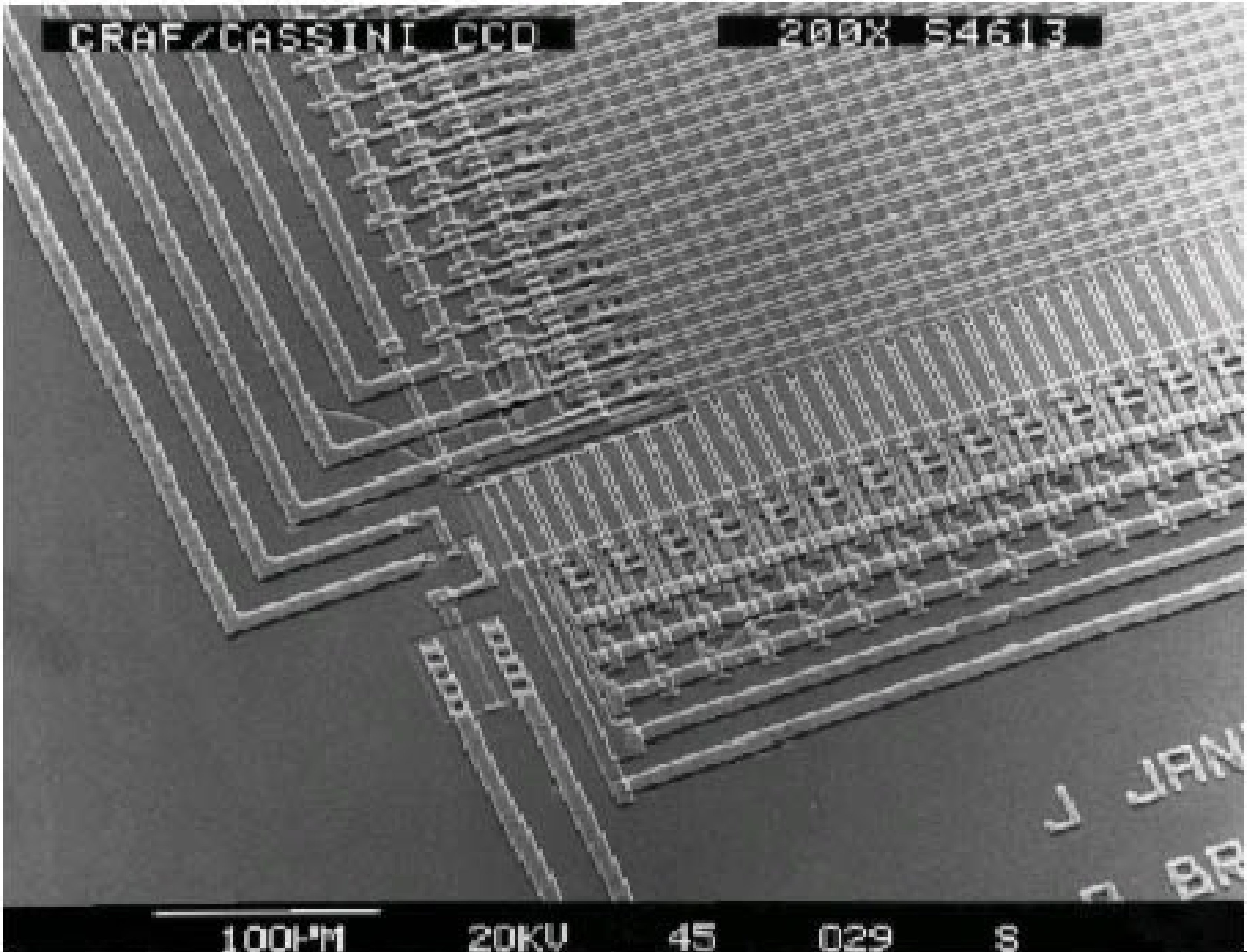
# Common parameters of detectors

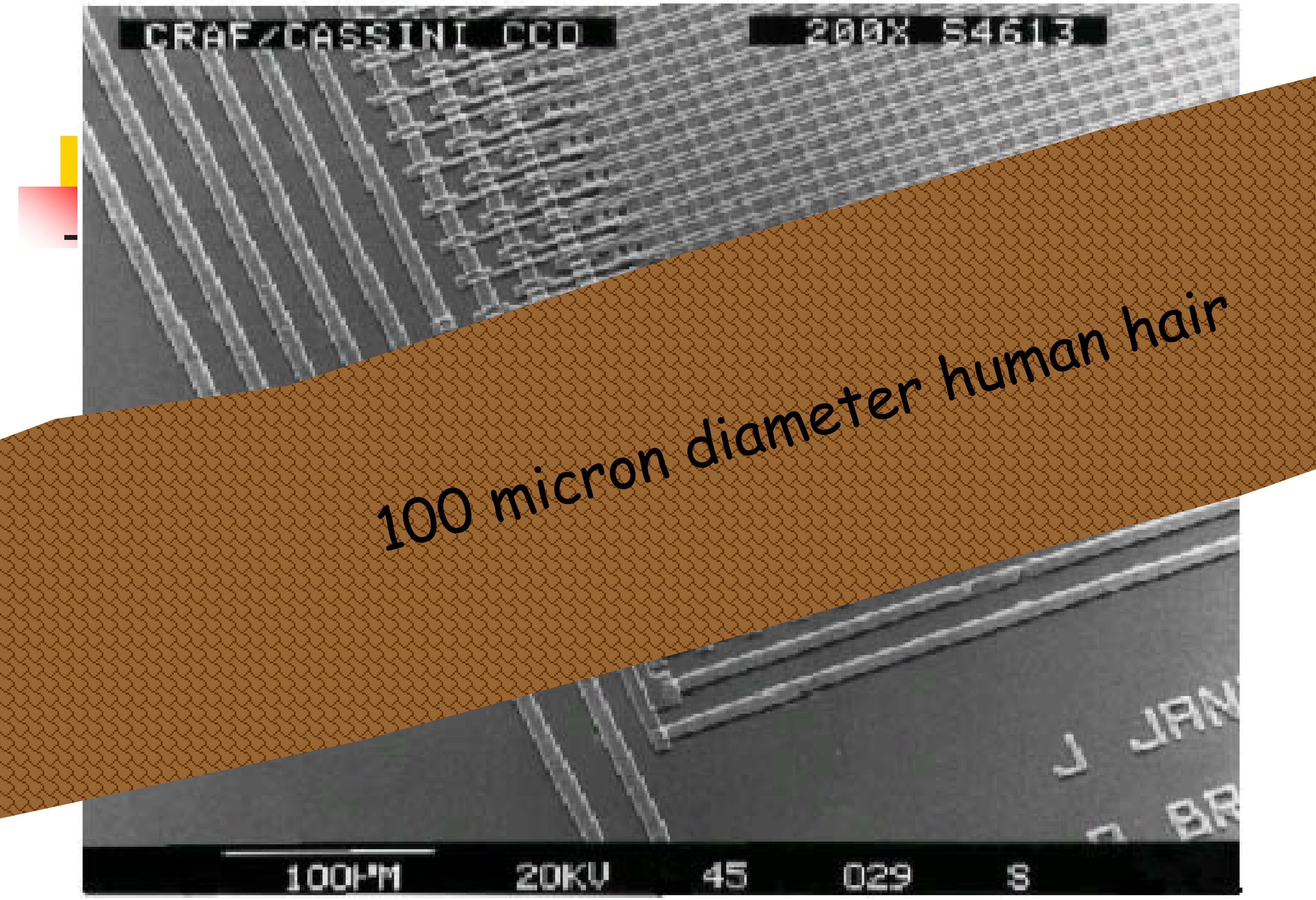
- Quantum efficiency (QE)
- Spectral response
- Linearity
- Gain
- Dynamic range
- Saturation level
- Cosmic ray sensitivity
- Modulation Transfer Function (MTF)
- Cosmetics
- Noise
  - Shot noise
  - Read-out noise
  - Dark current
- Memory
- Flatness

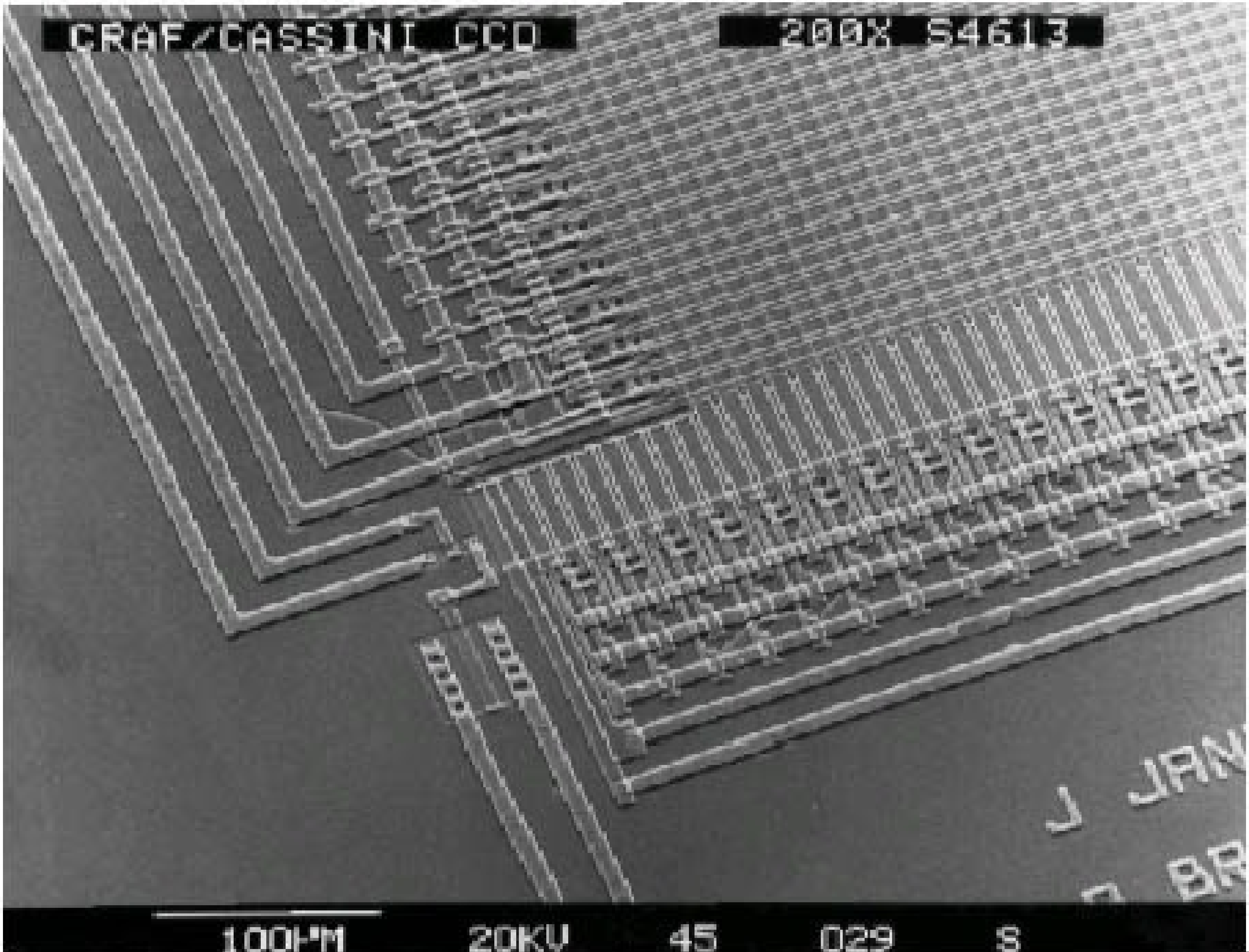
# Charge Coupled Device

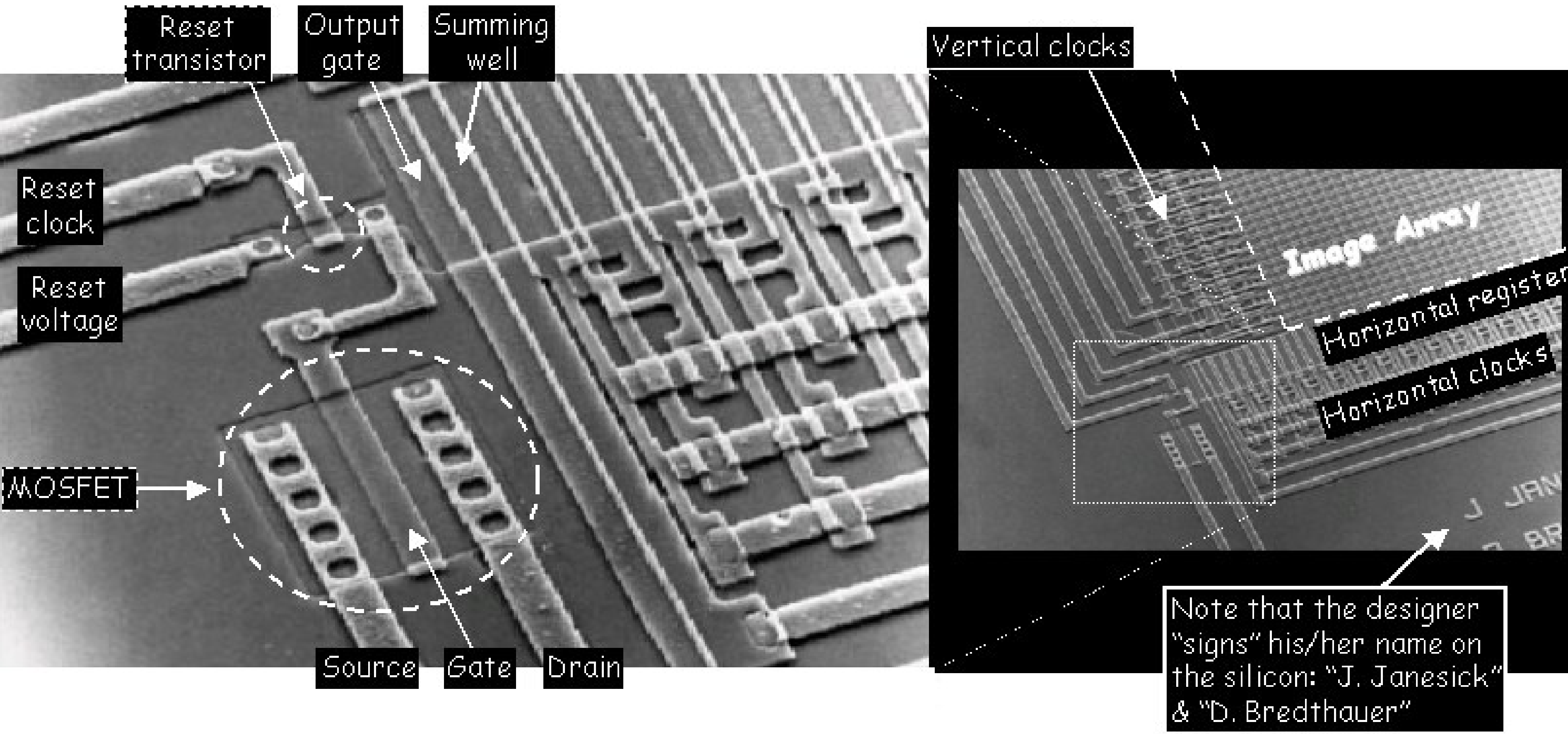


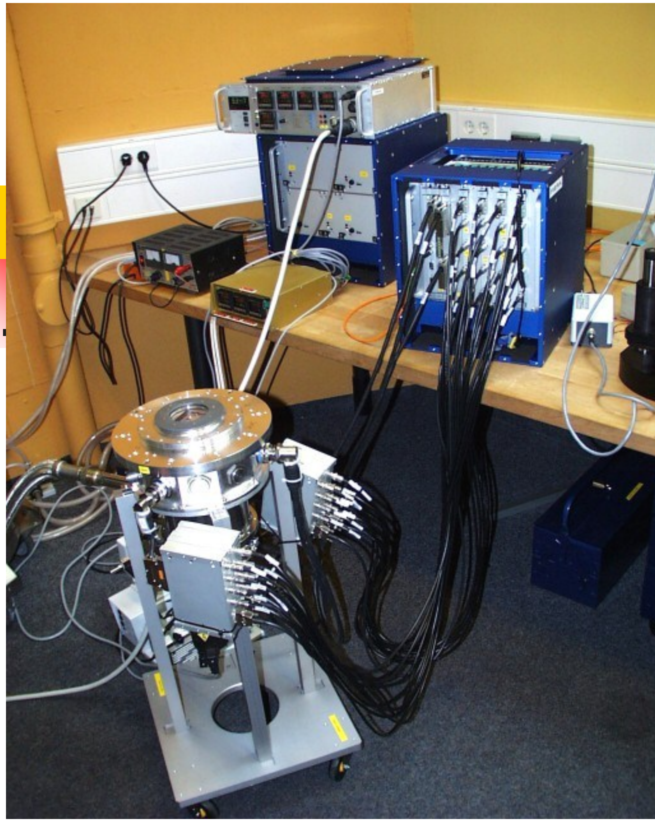




CRAF/CASSINI CCD
200X S4613
100μM
20KV
45
029
S

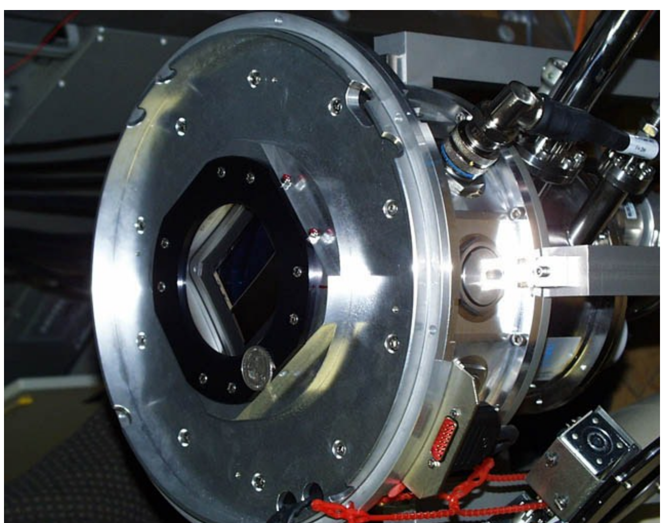

CRAF/CASSINI CCD
200X S4613
100 micron diameter human hair
100µM 20KV 45 029 S

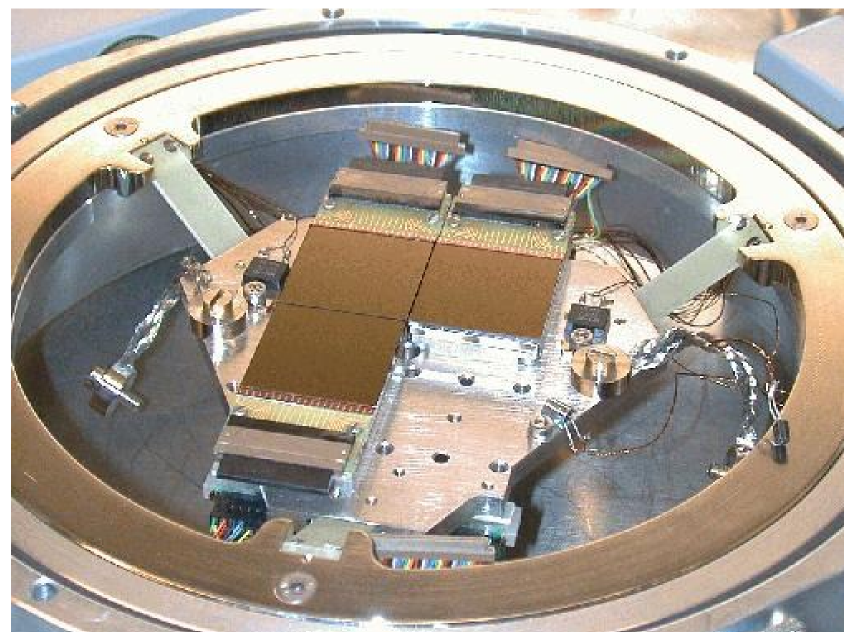

CRAF/CASSINI CCD
200X S4613
100HM 20KV 45 029 S


Reset transistor
Output gate
Summing well
Vertical clocks
Reset clock
Reset voltage
MOSFET
Source
Gate
Drain
Image Array
Horizontal register
Horizontal clocks
Note that the designer "signs" his/her name on the silicon: "J. Janesick" & "D. Bredthauer"

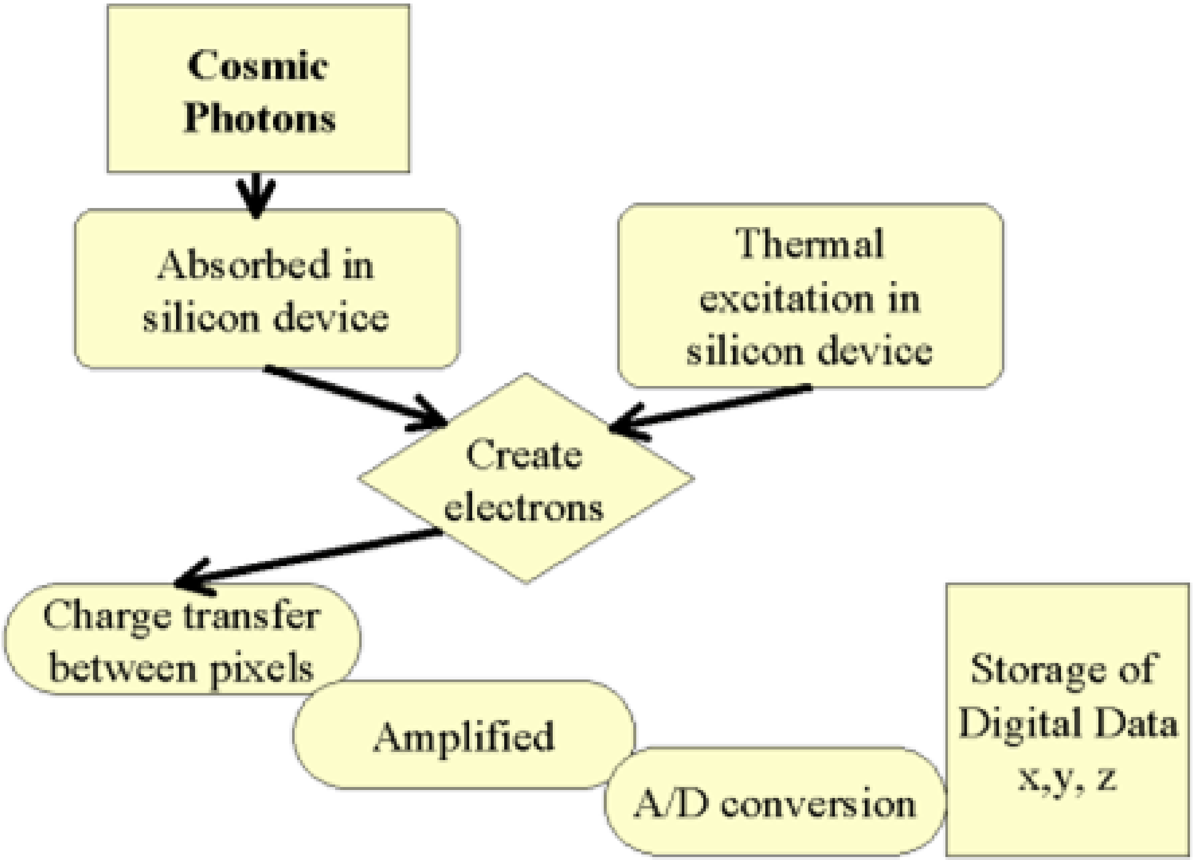


Continuous flow cryostat

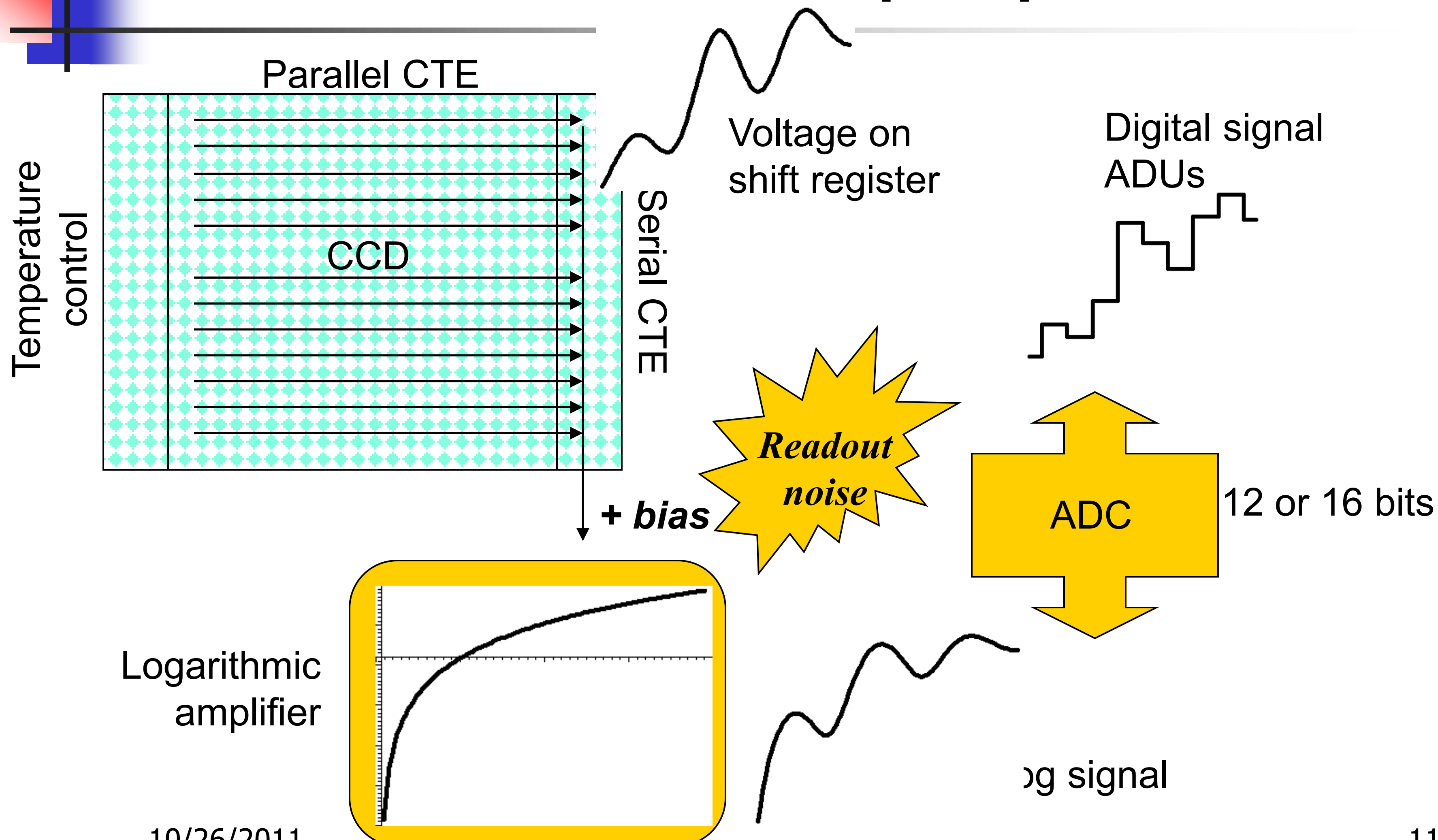




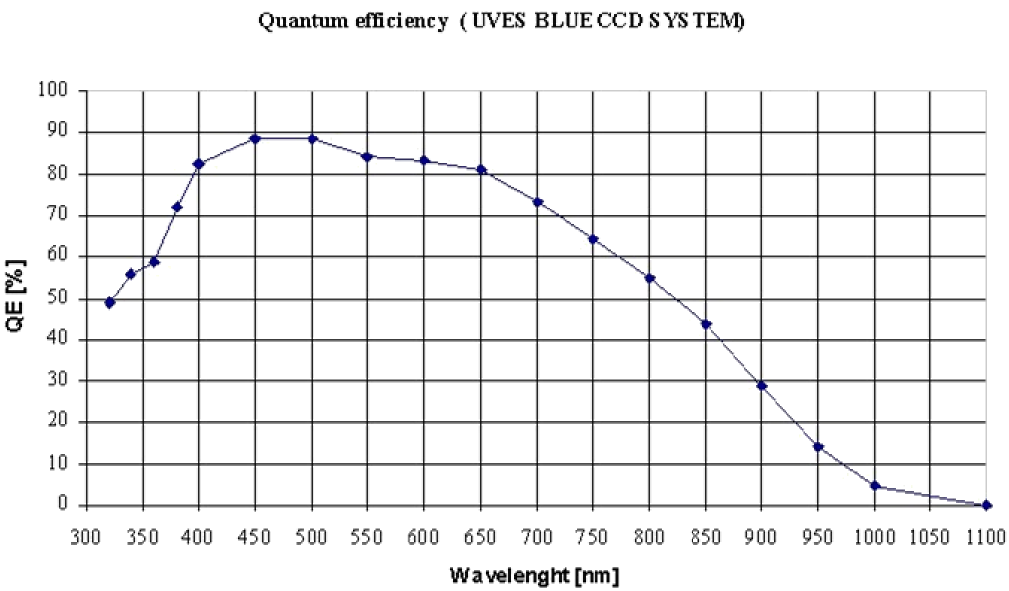
# Electron trail

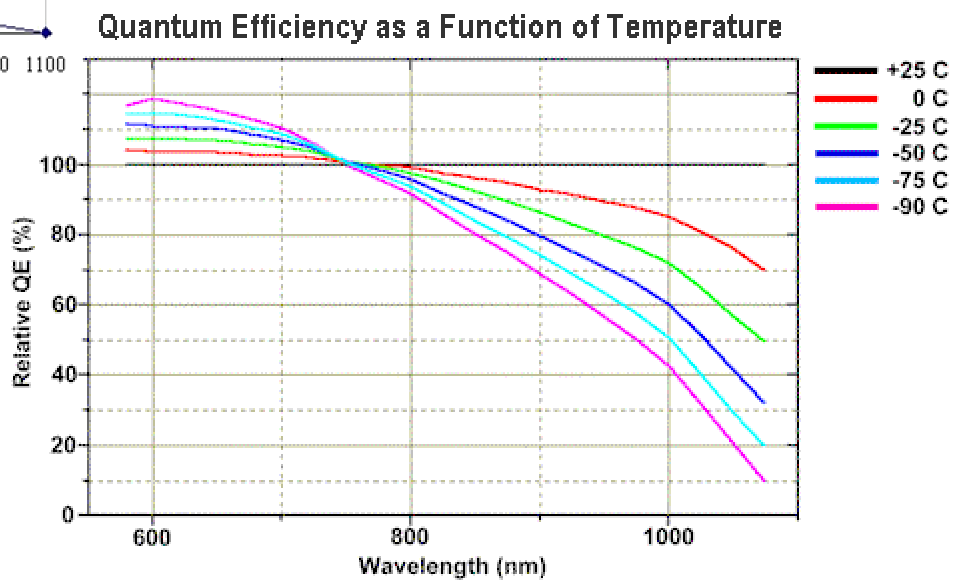


# Critical data flow properties



# Quantum Efficiency

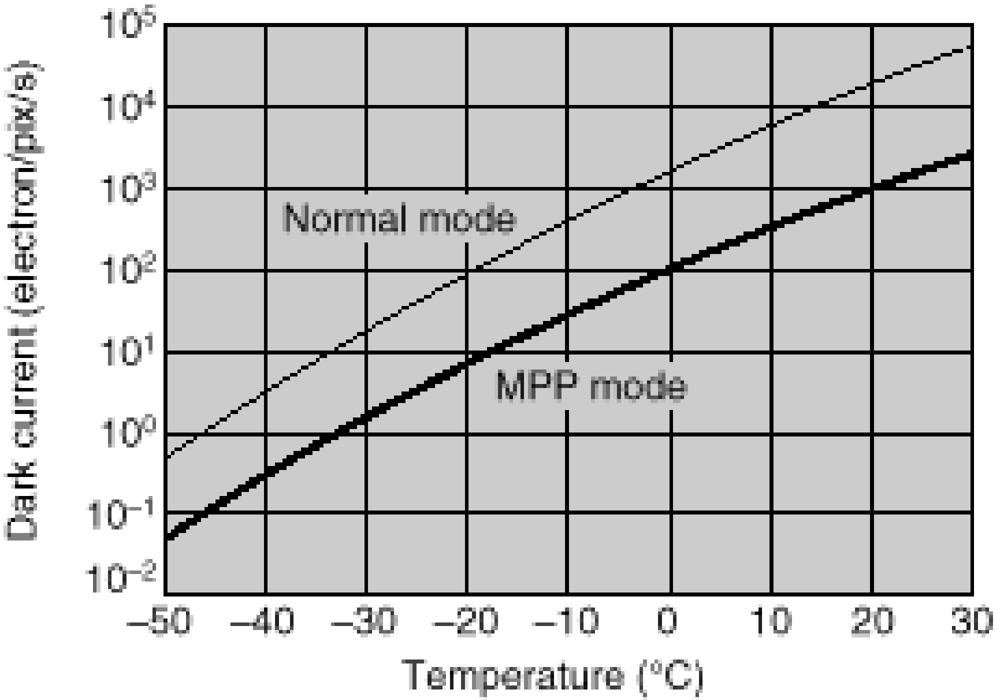


# Improving spectral range

- QE drops in the blue because the top layer is too thick and non-transparent. One way to improve it is the remove extra silicon substrate from the back (thinning) and use this side to detect the light (back-illumination).
- QE drops in the red because photons have too low energy. Warming up CCD improves response in the red but also increases the noise.

# Dark current

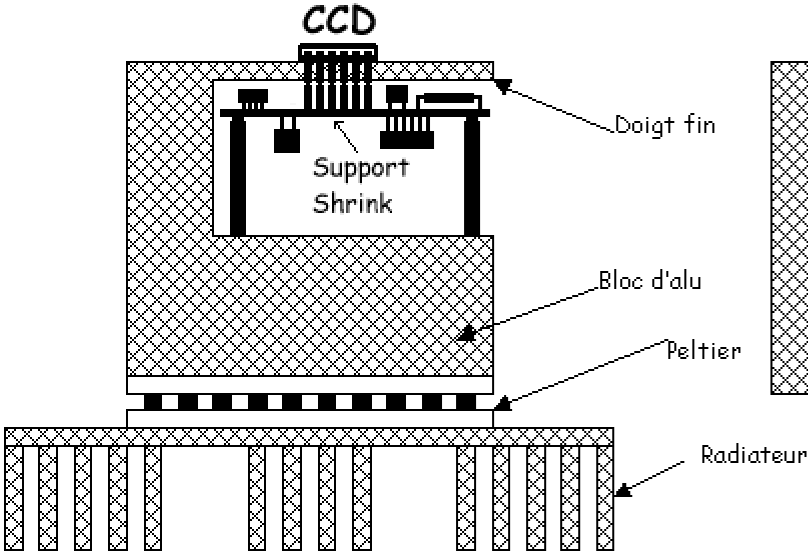


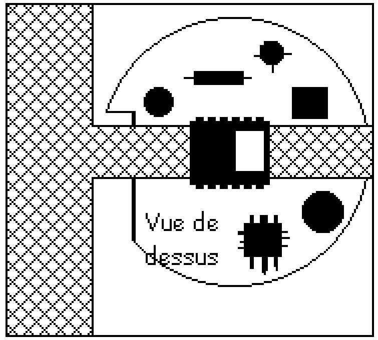

At T=270 K DC 10 $e^-$/pixel/s

At T=230 K DC 0.1 $e^-$/pixel/s

At T=170 K DC 10 $e^-$/pixel/hour

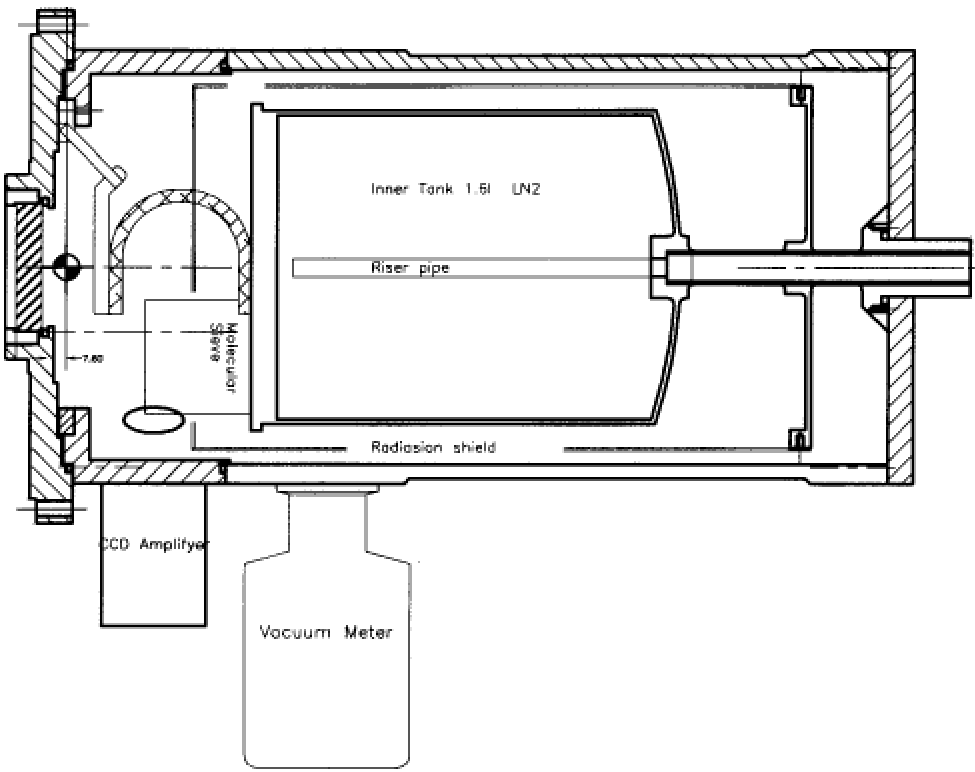
At T=120 K DC 1 $e^-$/pixel/hour



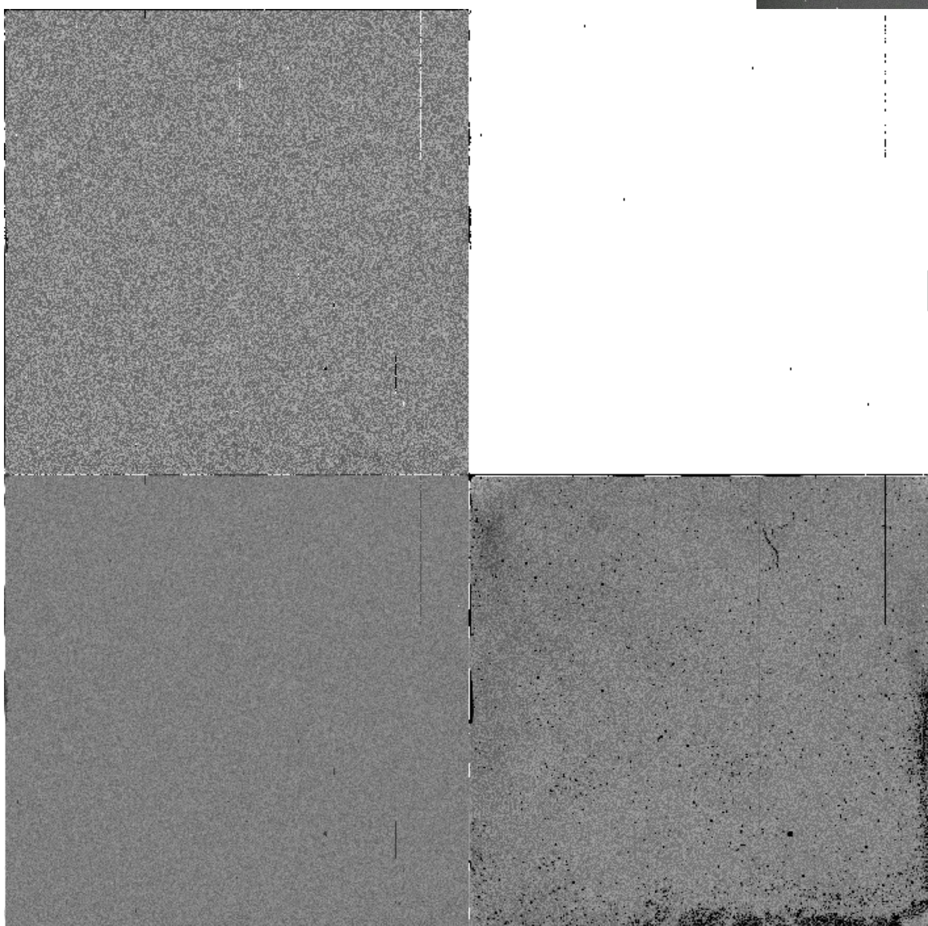

# Cooling

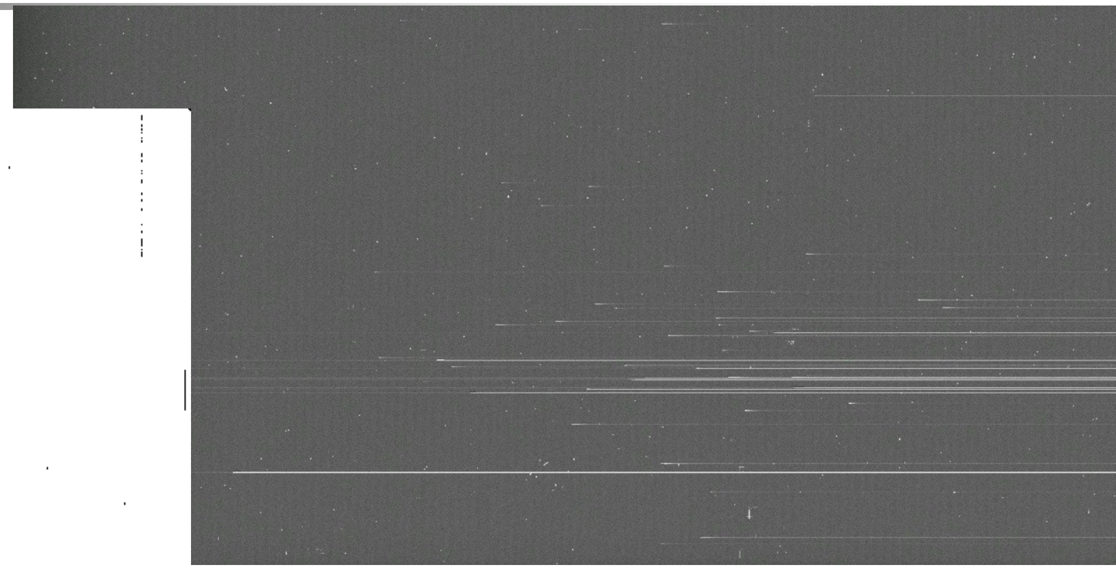
Peltier cooler: -20° ÷ -60° C




Liquid $N_2$: 125 ÷ 150 K

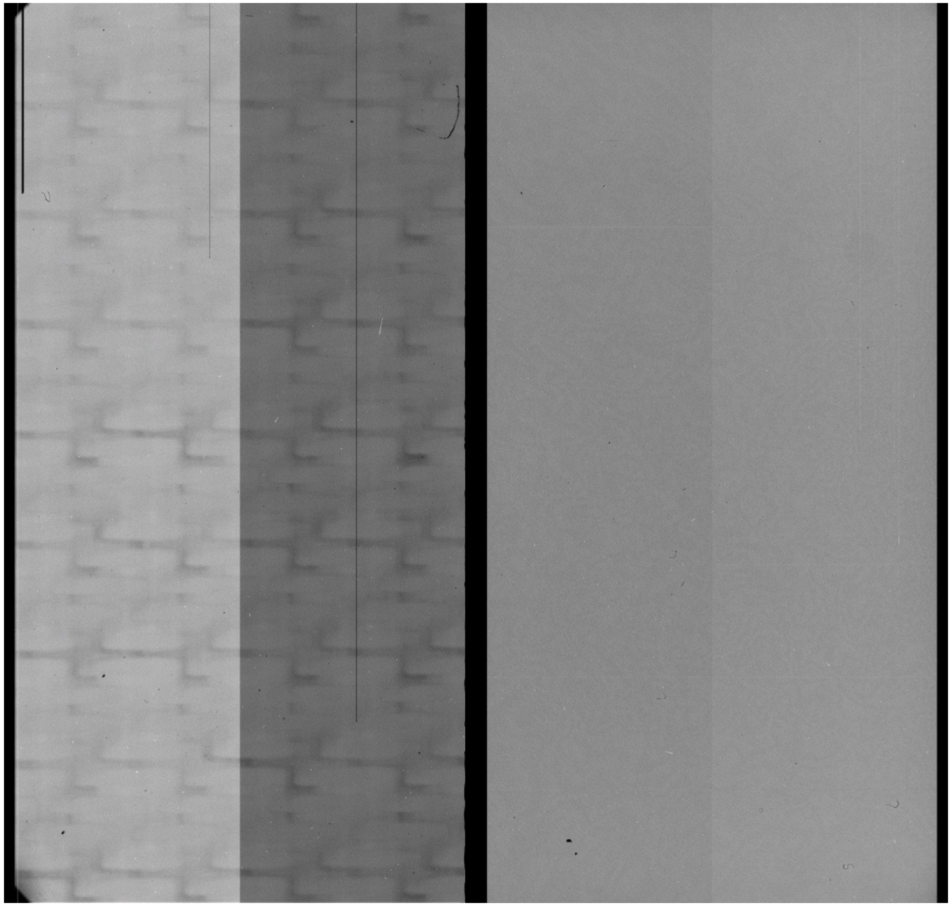
# Cosmetics



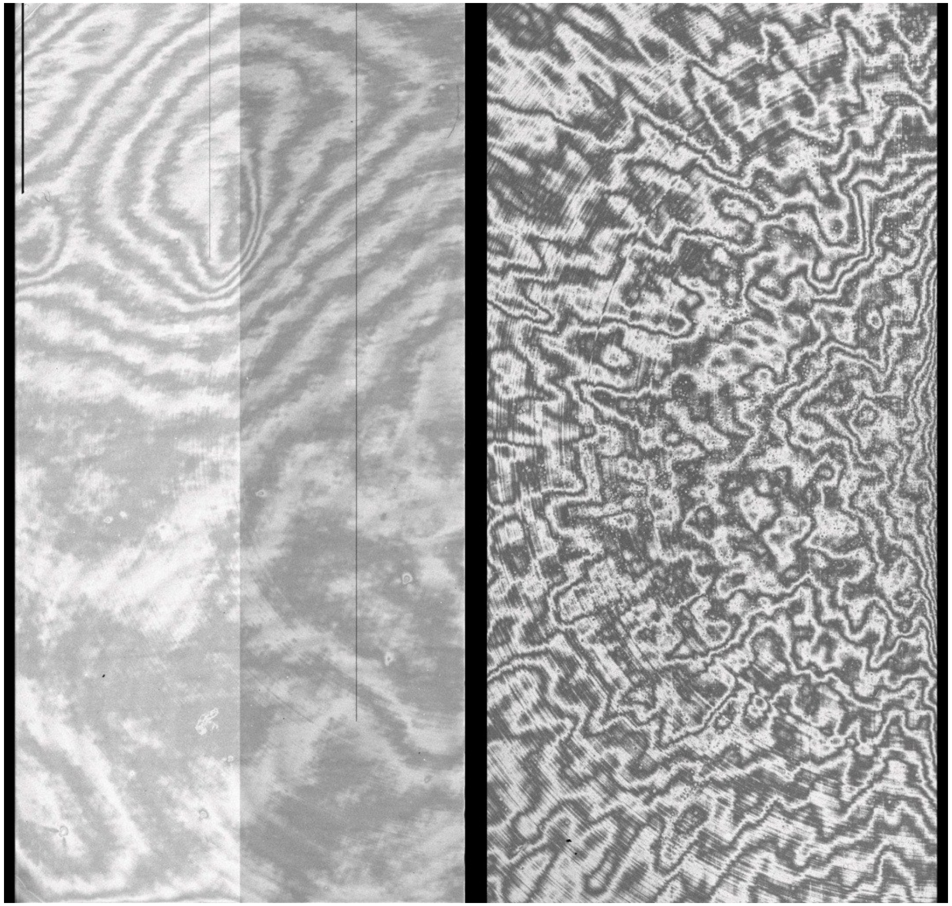


# Fringing

λ=650 nm



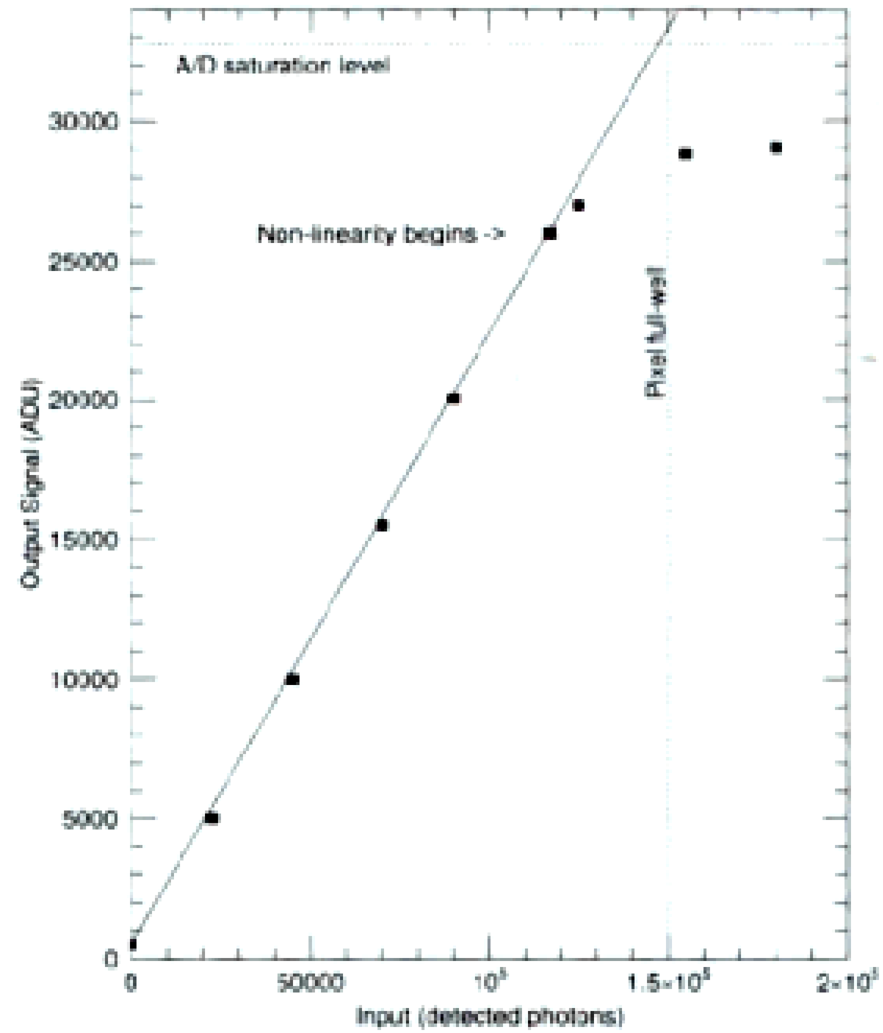
λ=900 nm



# Linearity

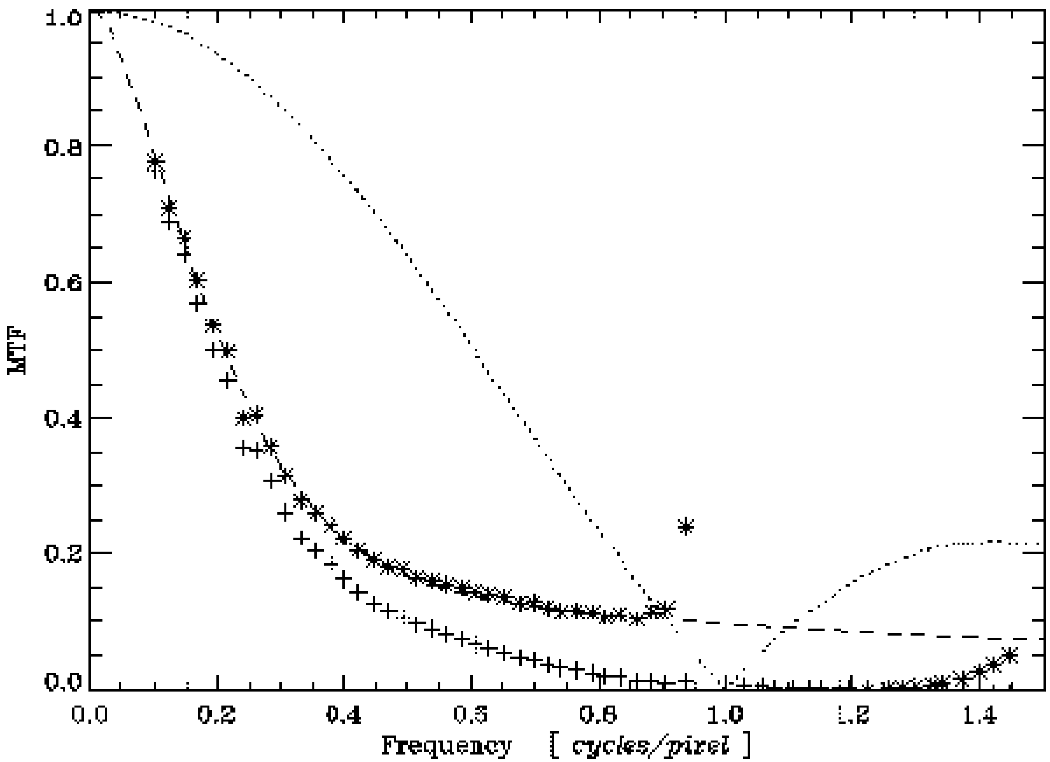
CCD full well is the number of electrons which can be stored in one pixel (height of energy barrier between pixels).

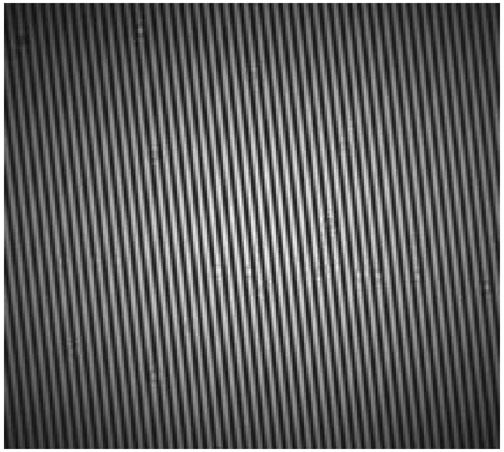
Typical values are between 30000 and 1000000 which also where the CCD goes non-linear.



# Modulation Transfer Function

MTF characterizes interplay between contrast and spatial sampling



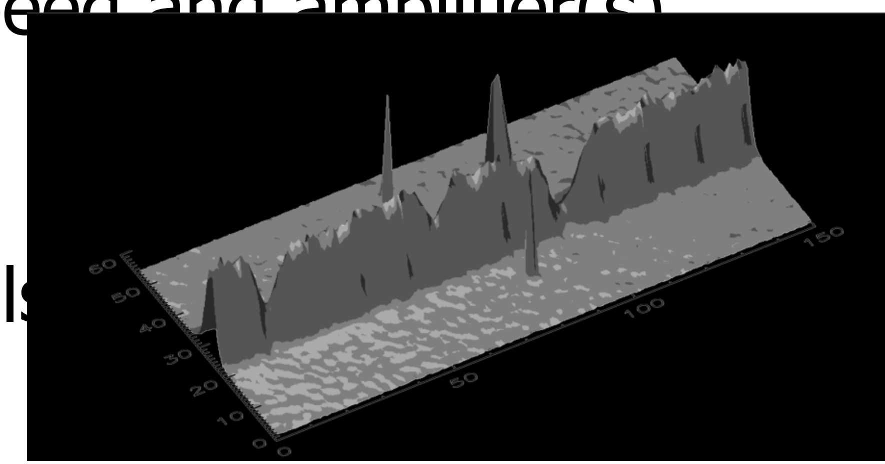
# Charge Transfer Efficiency

- This is examined by measuring the amplitude of bright points left by a $\gamma$–ray source. Amplitude dependence in the direction of parallel read gives parallel CTE, while the other direction reflects serial CTE. Good CTE is >0.99999.

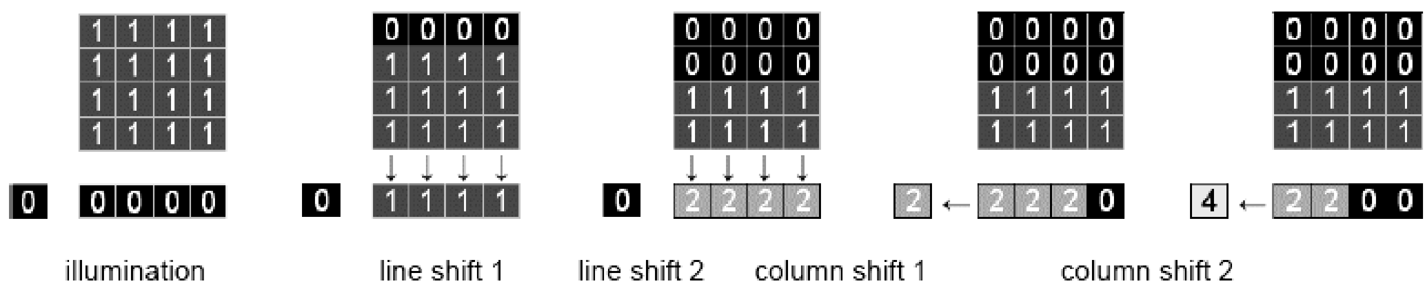

- The same experiment establishes the relation between ADU and number of photoelectrons (gain). Same CCD may use more than one gain (e.g. 1.1 and 9).

# CCD noise

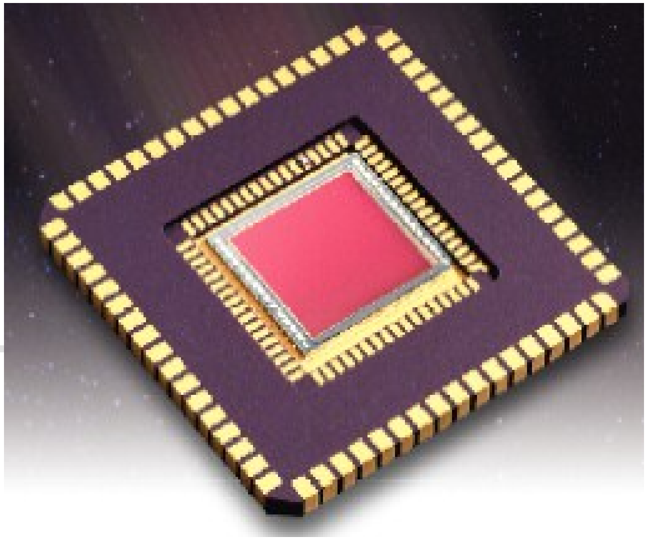
- Shot noise (Poisson distribution σ ≈√N)
- Dark current is proportional to time, depends on temperature
- Readout noise, depends on the temperature, read speed and amplifier(s) used
- Cosmic rays destroy content of a few pixels



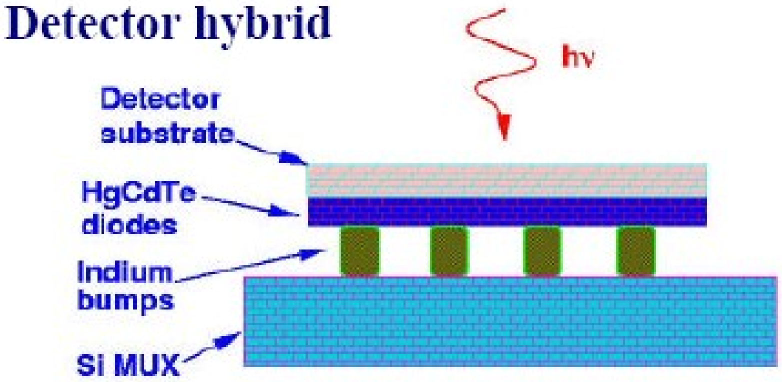
# Binning

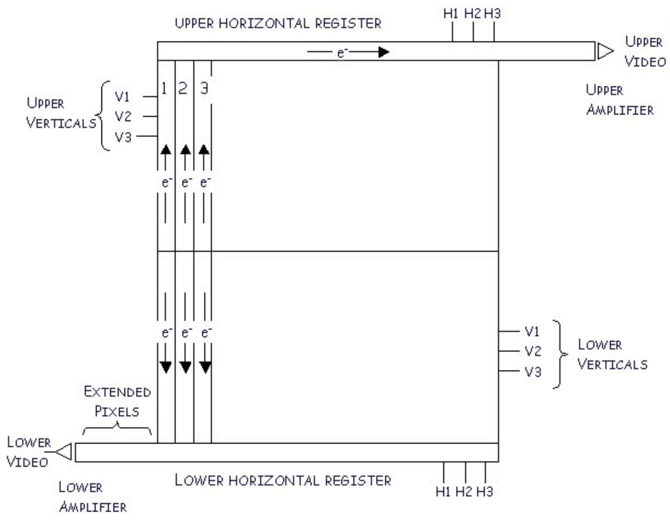

illumination
line shift 1
line shift 2
column shift 1
column shift 2

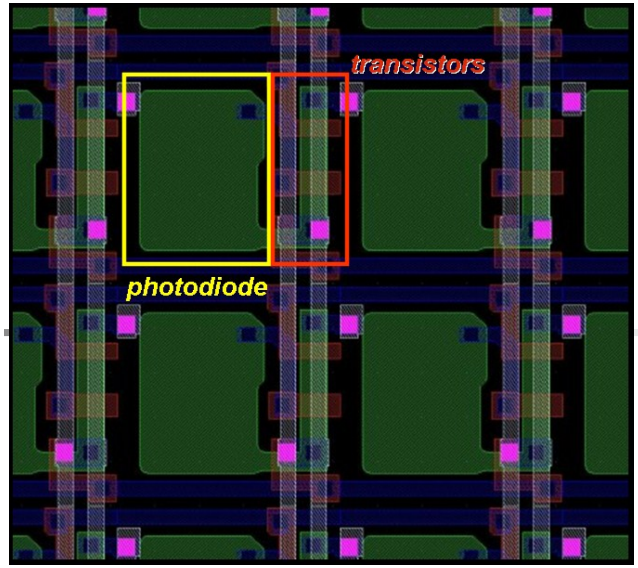
# NIR detectors

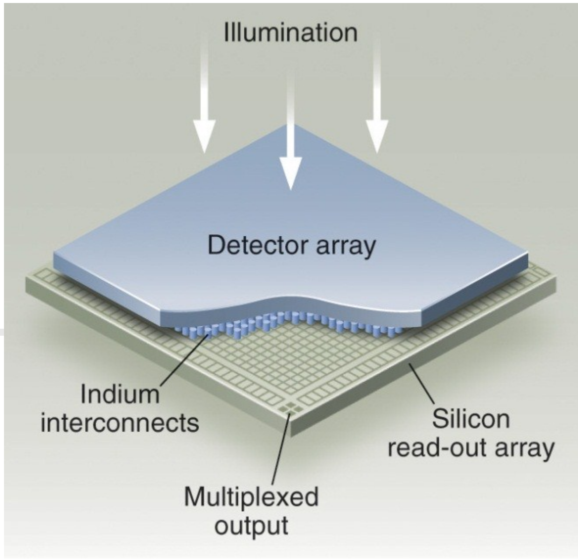


- NIR detectors are similar to CCDs
- Special non-silicon layer is used to generate photoelectrons: HgCdTe (*Hawaii*) and InSb (Indium Antimonide, *"insbe"*, *Aladdin*) are sensitive between 0.9 and 25 microns.
- Silicon electronics is well developed, therefore we use hybrid systems
- Working temperatures: 30-60 K






CCD

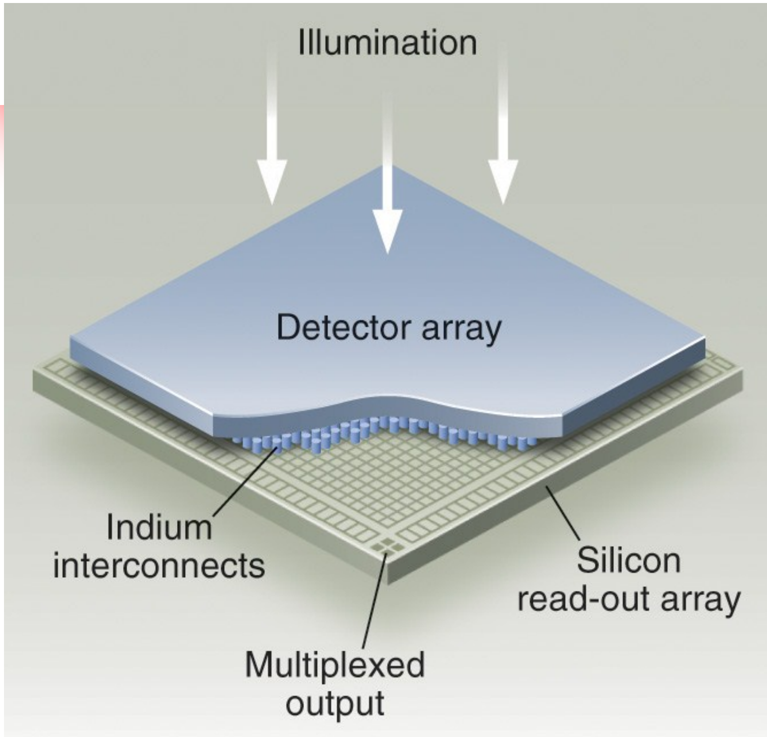
Monolithic CMOS

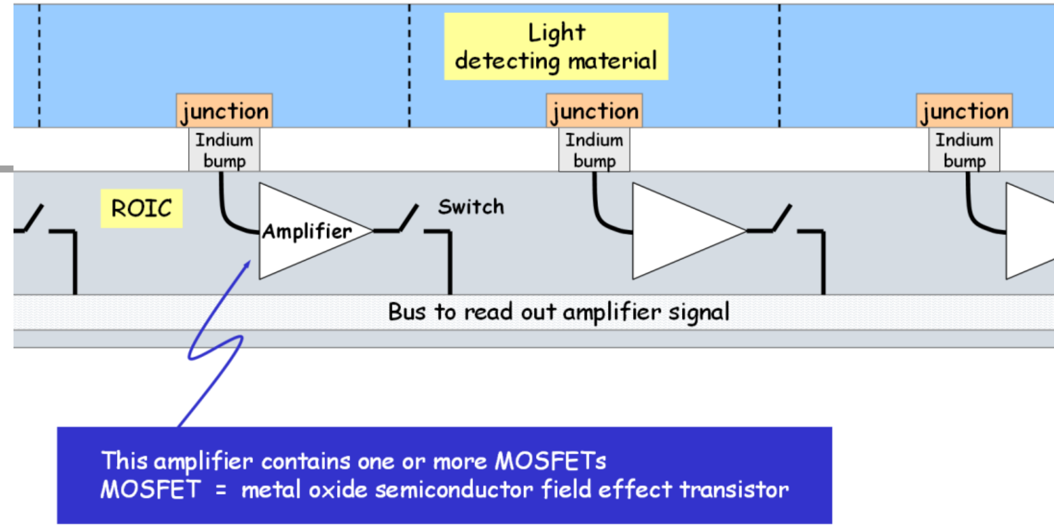
Hybrid CMOS

HgCdTe
Visible through IR

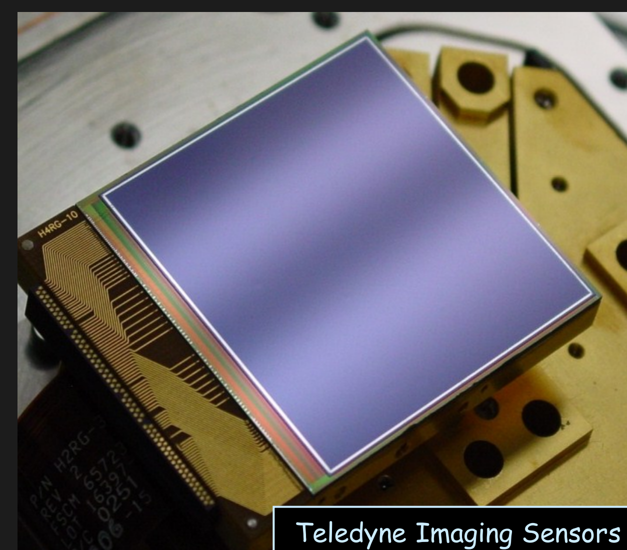
Silicon - Visible through near IR

# Hybrid Imager Architecture



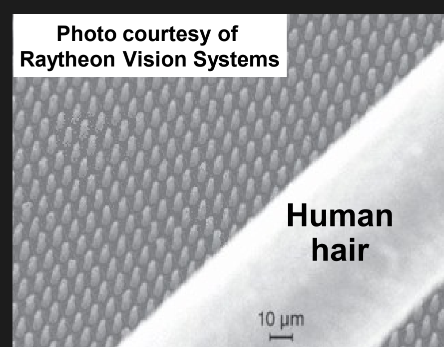




H4RG-10
4096x4096 pixels
10 micron pixel pitch
HyViSI silicon PIN



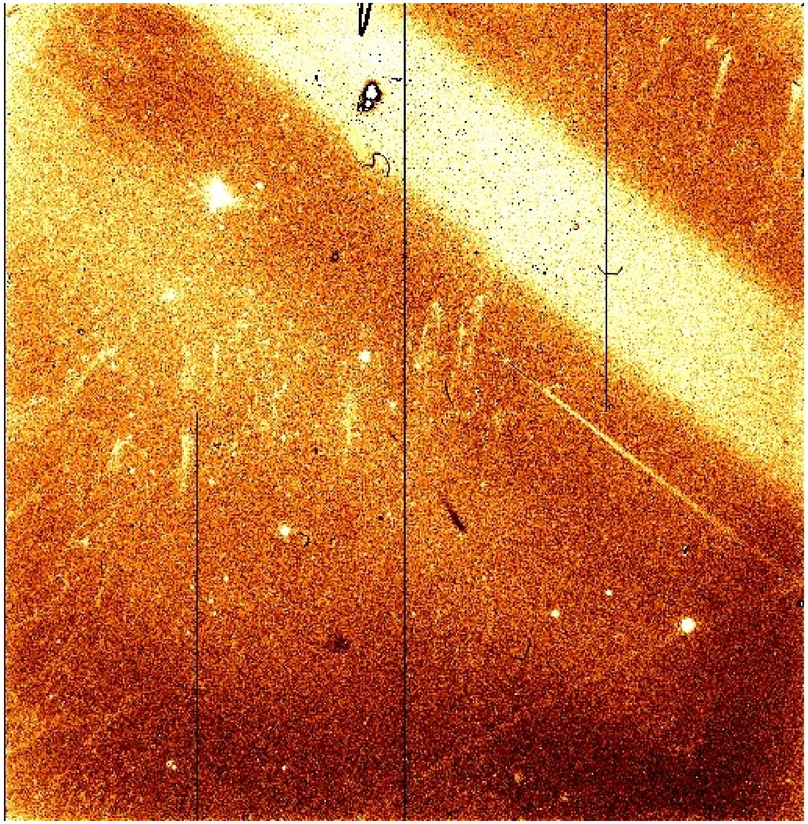

Mature interconnect technique:

- Over 16,000,000 indium bumps per Sensor Chip Assembly (SCA) demonstrated
- >99.9% interconnect yield

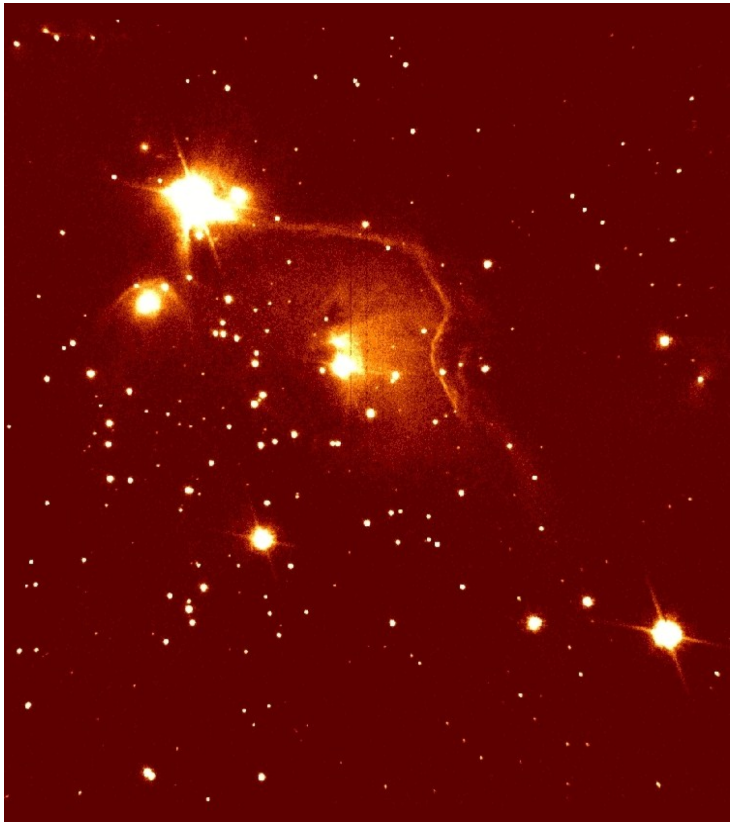


# Thermal InfraRed detectors

Raw frame

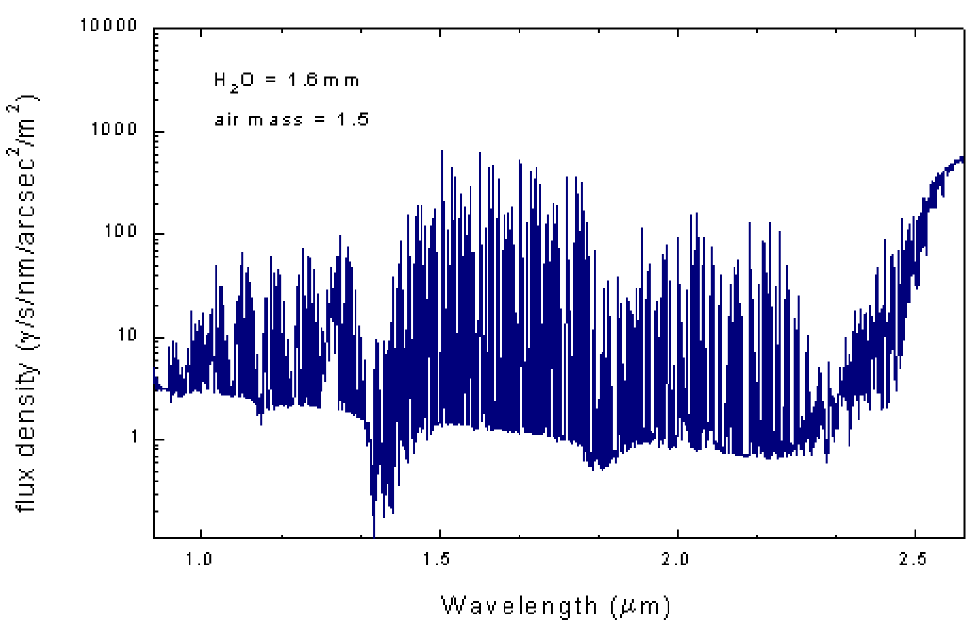


Reduced frame

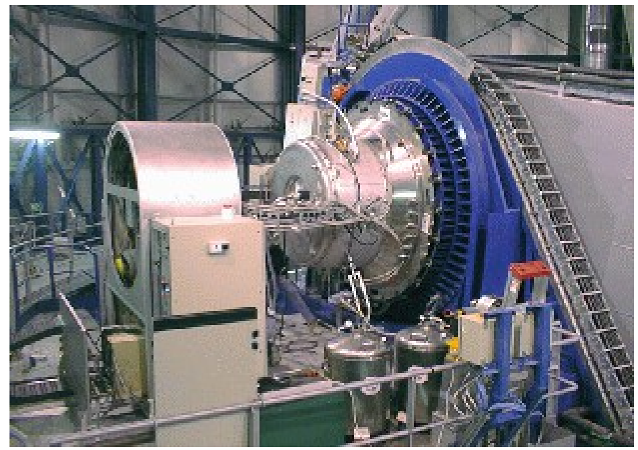


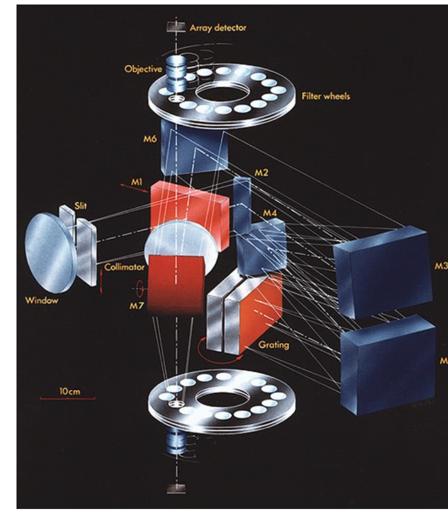
# Thermal IR

- HgCdTe *("mercad")* arrays depending on the exact structure are sensitive in 1-17 micron range.
- Detector needs to be cooled down to 5-10 K
- Main problem is thermal emission:

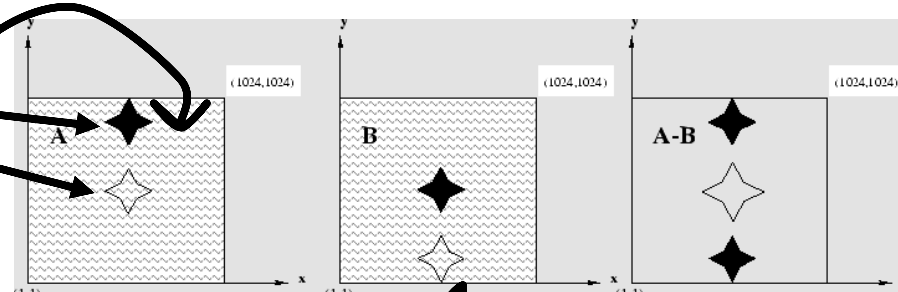


# Fighting therma background





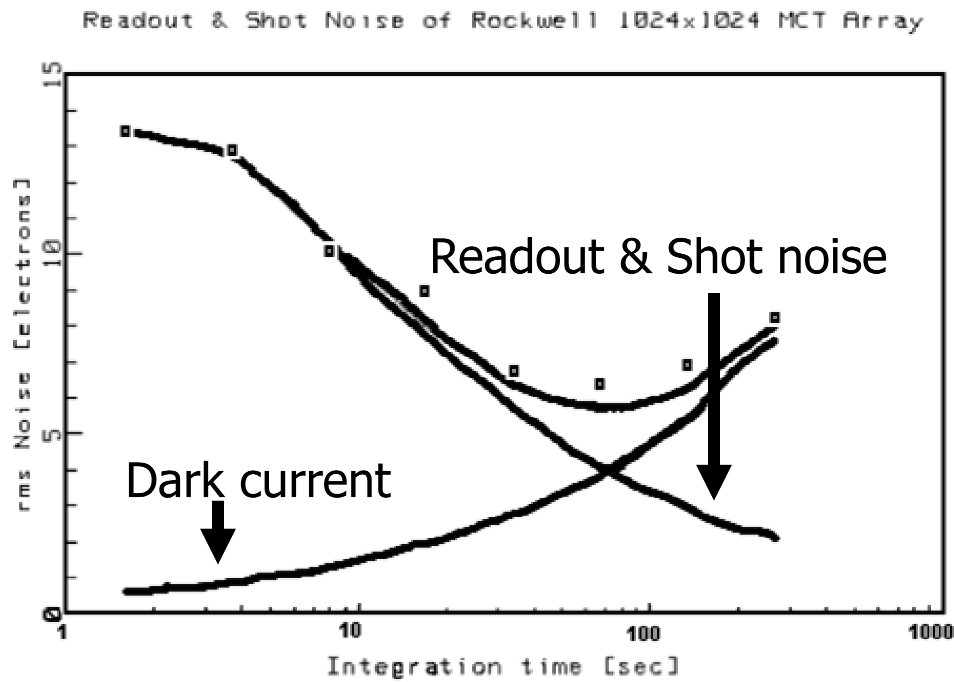

- Cooling the whole instrument
- Taking short exposures
- Chopping and nodding the telescope




- Non-destructive readout

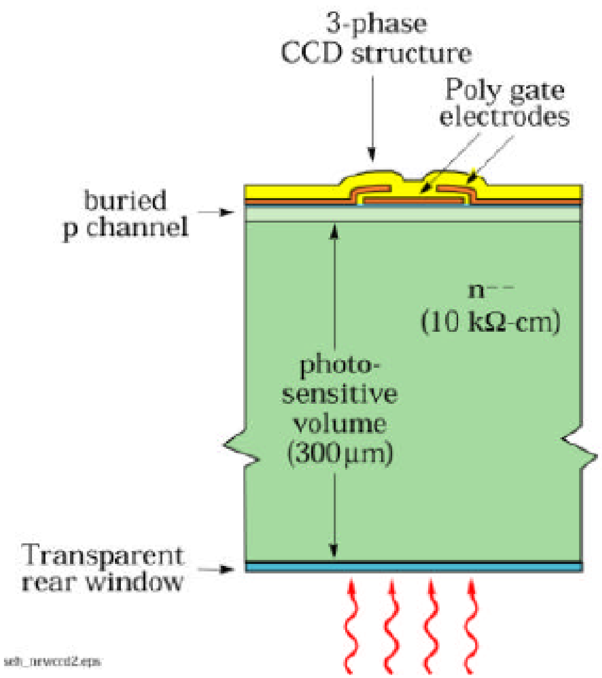
# Non-destructive readout

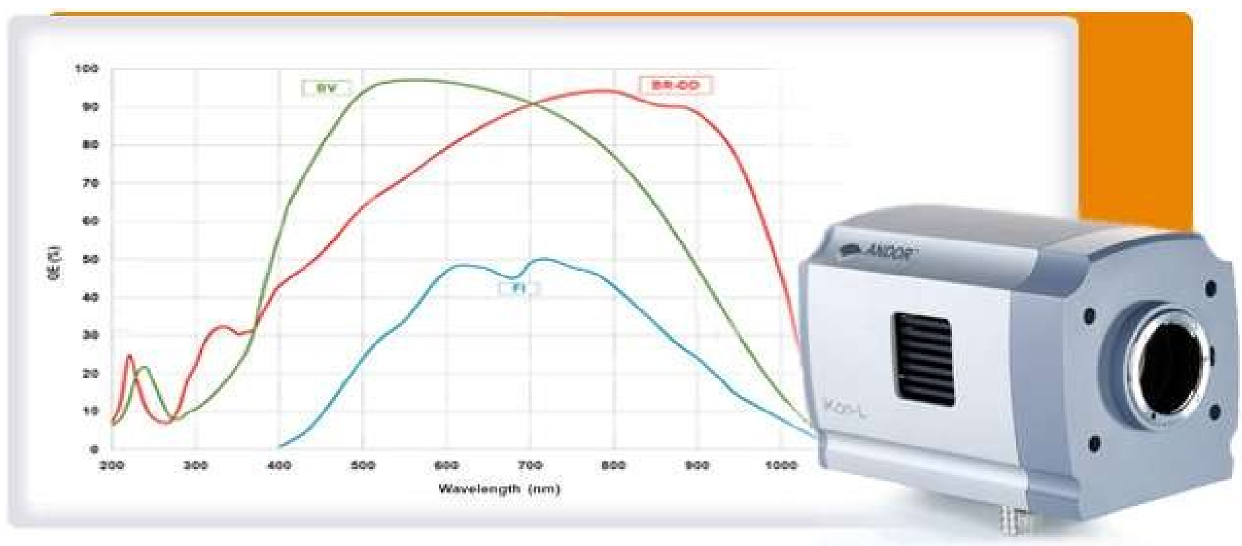
- Silicon multiplexor can measure accumulated charges in each pixel without dumping the charges
- This can be done several times before the dark current of detector catches up with the shot noise of the signal
- Instead of using each individual frame we measure how charges grow (linear regression)
- Typically we can make 16-64 readout before the array must be reset



# Advanced integrating detectors

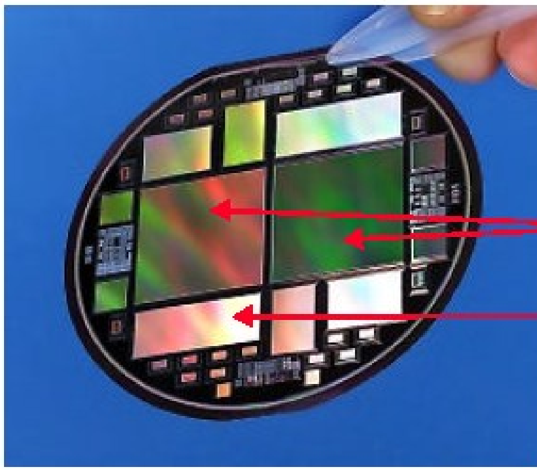
High-resistivity fully depleated CCDs with ≈0 readout noise!




Courtesy Lawrence Berkeley National Lab and Andor

# High-resistivity CCDs



First large format CCD made at LBNL

2k x 2k, 15 µm pixels.

1980 x 800, 15 µm pixels.

Courtesy Lawrence Berkeley National Lab

The first 2k×2k results:

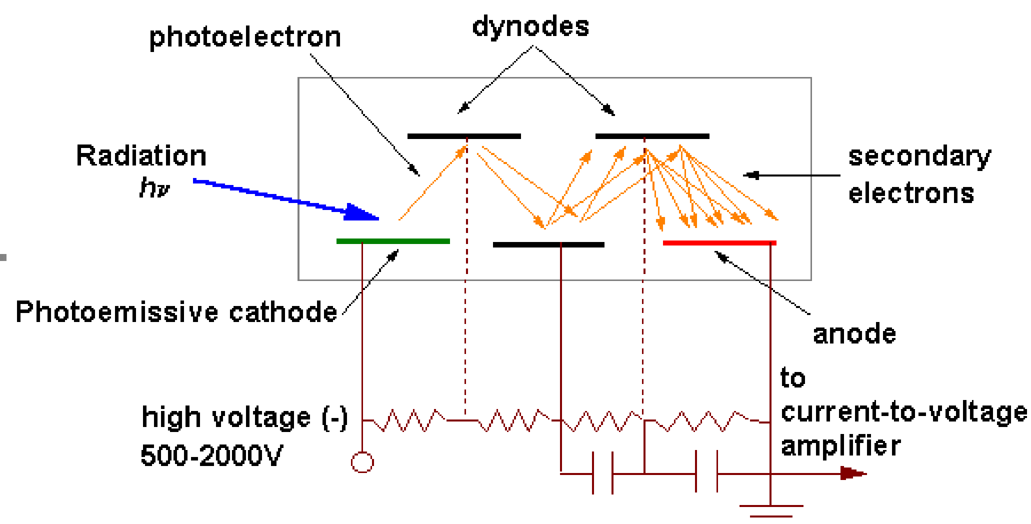
- Read-out at 10 MHz with readout noise of 0.2 e-
- QE at 950 nm > 80%
- Excellent charge transfer efficiency
- At 1 MHz can be also used as a PCD device

# CMOS detectors

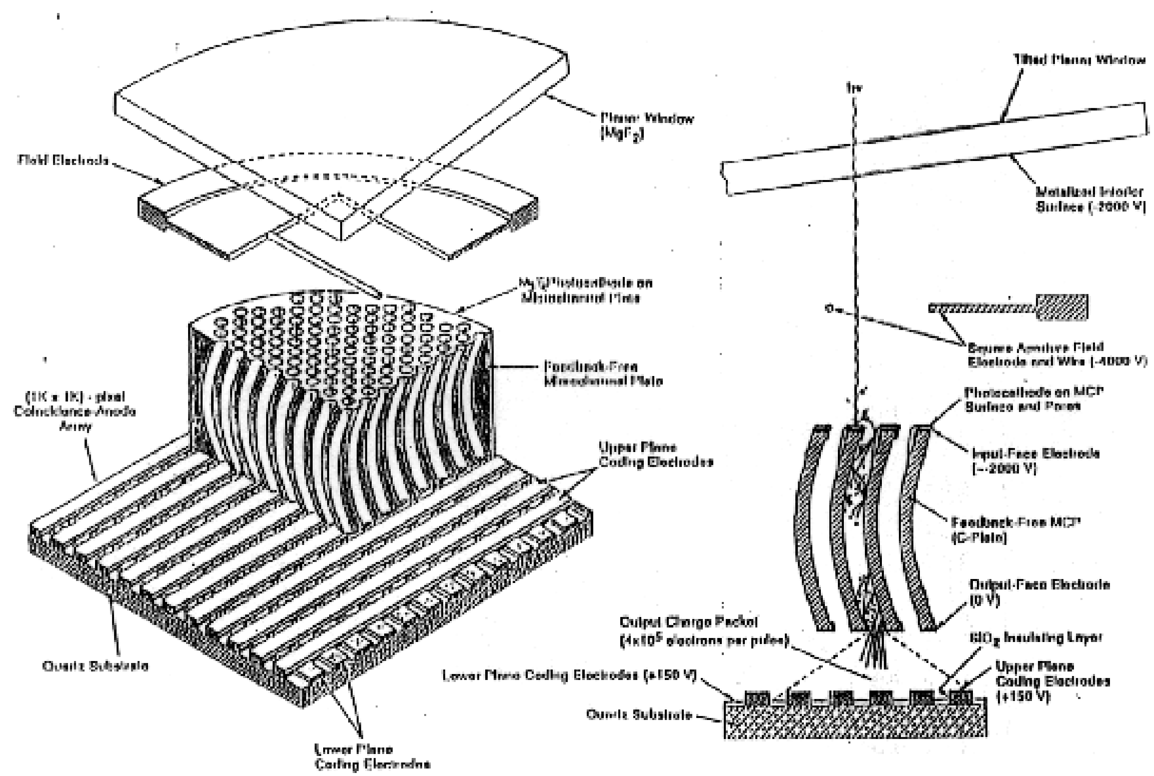
- The idea is borrowed from the IR detectors
- The integrating part is made out of silicon
- CMOS multiplexor allow non-destructive readout, partial readout etc.

# PCD

- Photomultiplier




- Multi-anode microchannel array (MAMA)



# PCD properties

- Noise sources: shot noise and dark current
- No readout noise (since there is no ADC)
- Cosmic rays are minor concern – detector of choice for many space missions
- Limited dynamic range (why?)
- Linearity problem
- Can easily be tuned to any spectral range, no need for thinning or other risky operations
- Maximum QE is about 50% (why?)
- MAMA allows reading 2D frames

# Comparison

CCDs

- Large dynamic range
- Large QE
- Extremely linear
- Large sizes (4k$\times$4k)
- Sensitivity drops sharply in the blue and the red
- Readout noise
- Cosmic rays
- Cooling

PCD

- Digital output in real time
- No readout noise
- Insensitive to cosmic rays
- No need for deep cooling
- Much easier to make and therefore much cheaper
- Small dynamic range
- Small QE
- High voltages

Space:

- Test detectors as much as possible and as many as possible
- Think of high radiation background and large temperature variation
- Think of detector aging
- Think of cooling (active and passive)
- Automate calibration procedures
- Store all original calibration data in case you want to go back