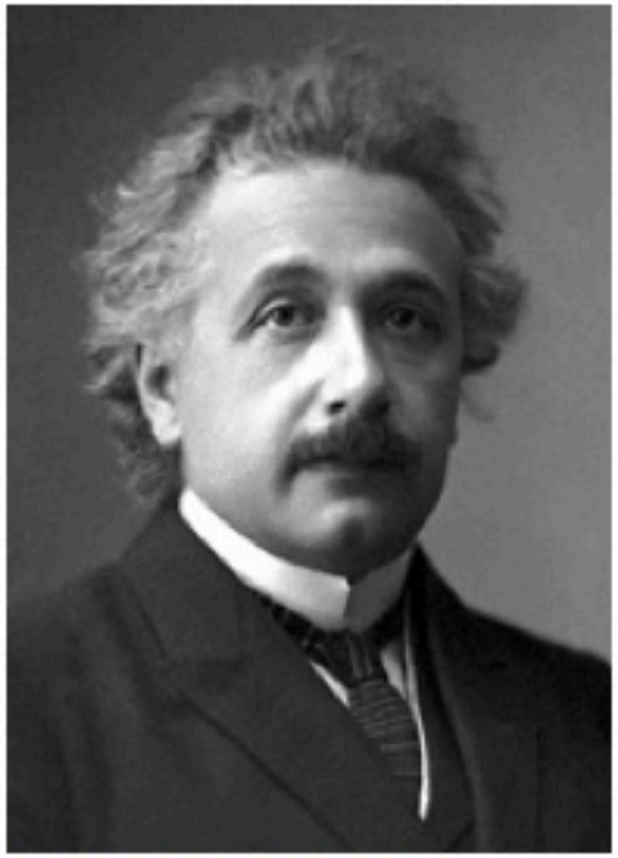
The Nobel Prize in Physics 1921
Albert Einstein

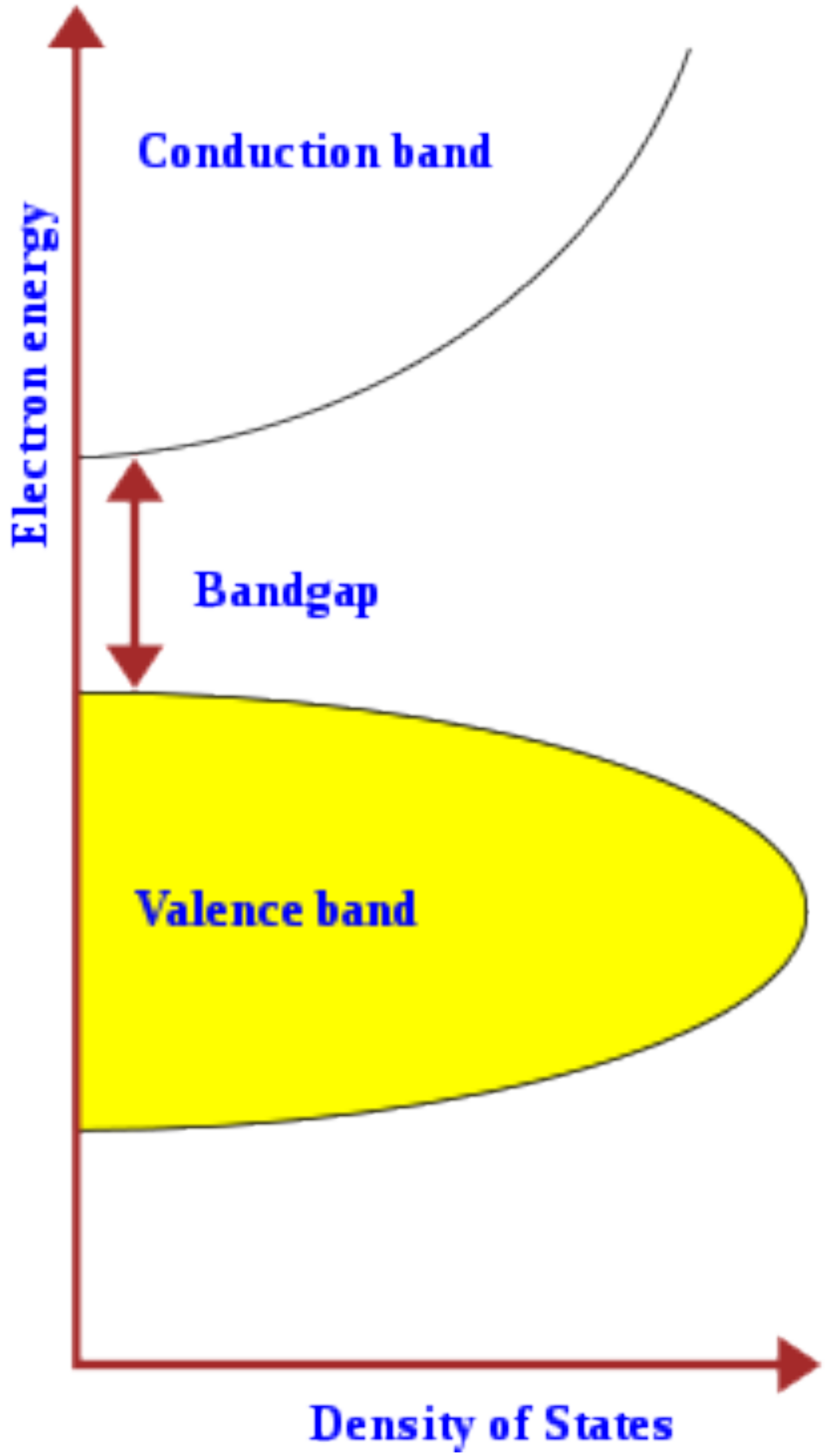


Albert Einstein

The Nobel Prize in Physics 1921 was awarded to Albert Einstein *"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"*.

Albert Einstein received his Nobel Prize one year later, in 1922. During the selection process in 1921, the Nobel Committee for Physics decided that none of the year's nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation's statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Albert Einstein therefore received his Nobel Prize for 1921 one year later, in 1922.

Band gap energy



http://en.wikipedia.org/wiki/Band_gap

It is the energy required to free an outer shell electron.

It will become a mobile charge carrier, able to move freely within the solid material.

The band gap is a major factor determining the electrical conductivity of a solid.

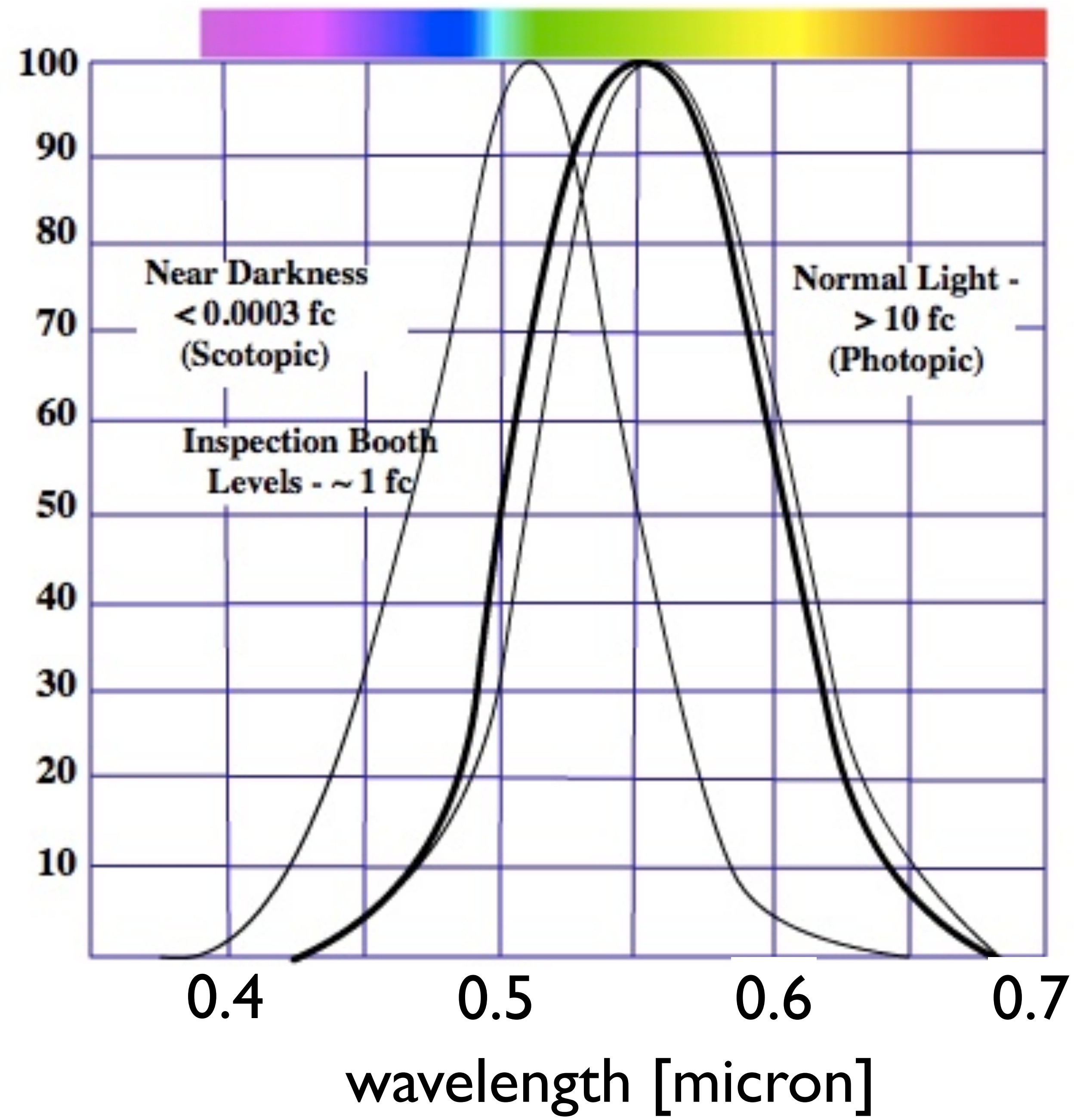
Large band gaps => insulators
Small band gaps => semiconductors
~No band gap => conductor

The human eye

lambda_min ~ 0.4 micron
lambda_max ~ 0.7 micron

resolution elements:
- 6e6 cones (bright vision)
- 1e8 rods (faint)

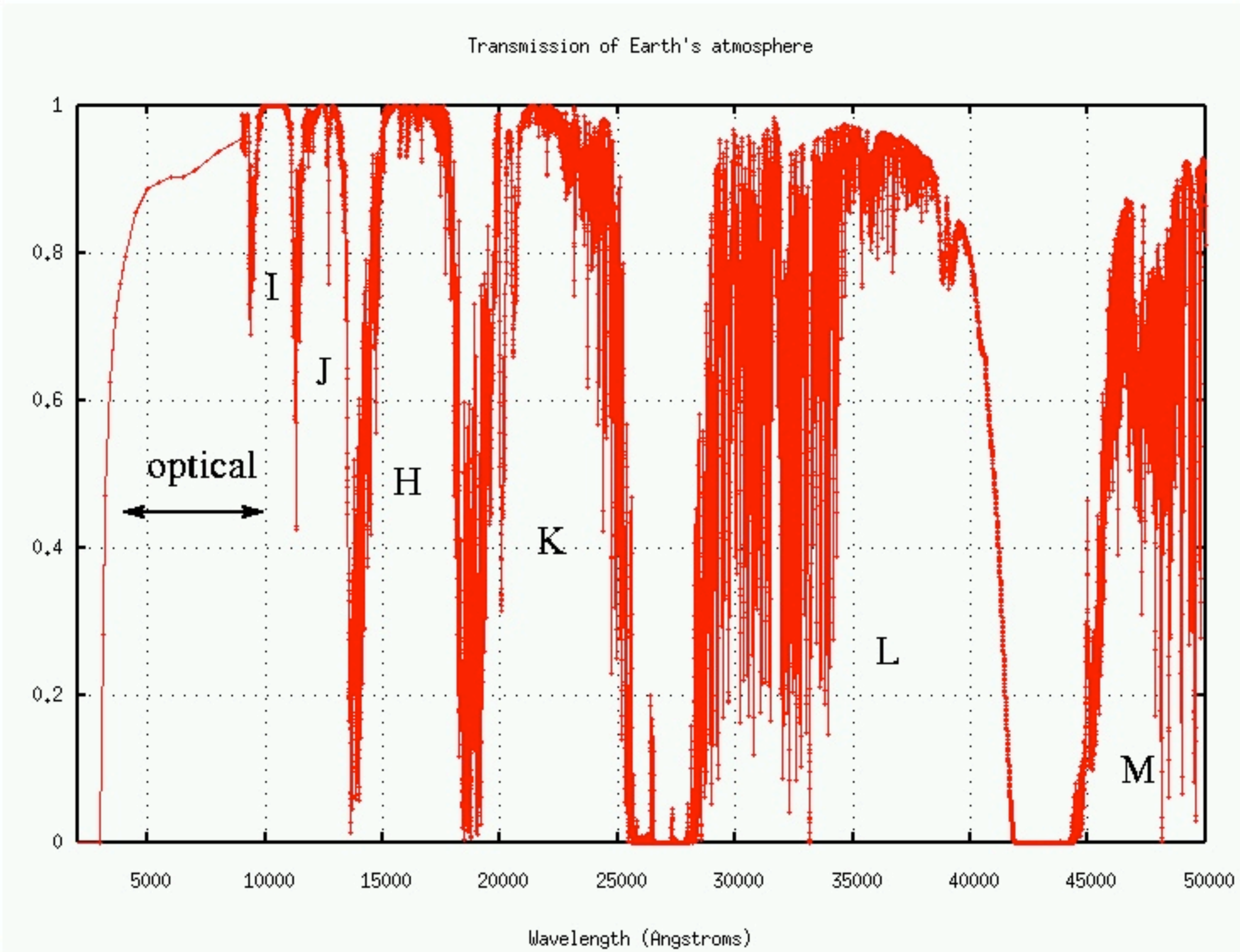
dynamical range: 1e9-10



1 micron ~ 1 eV

Questions:
- What is the stimulation threshold (in terms of number of photons for the eye?)
- What is the wavelength of a standard remote control?

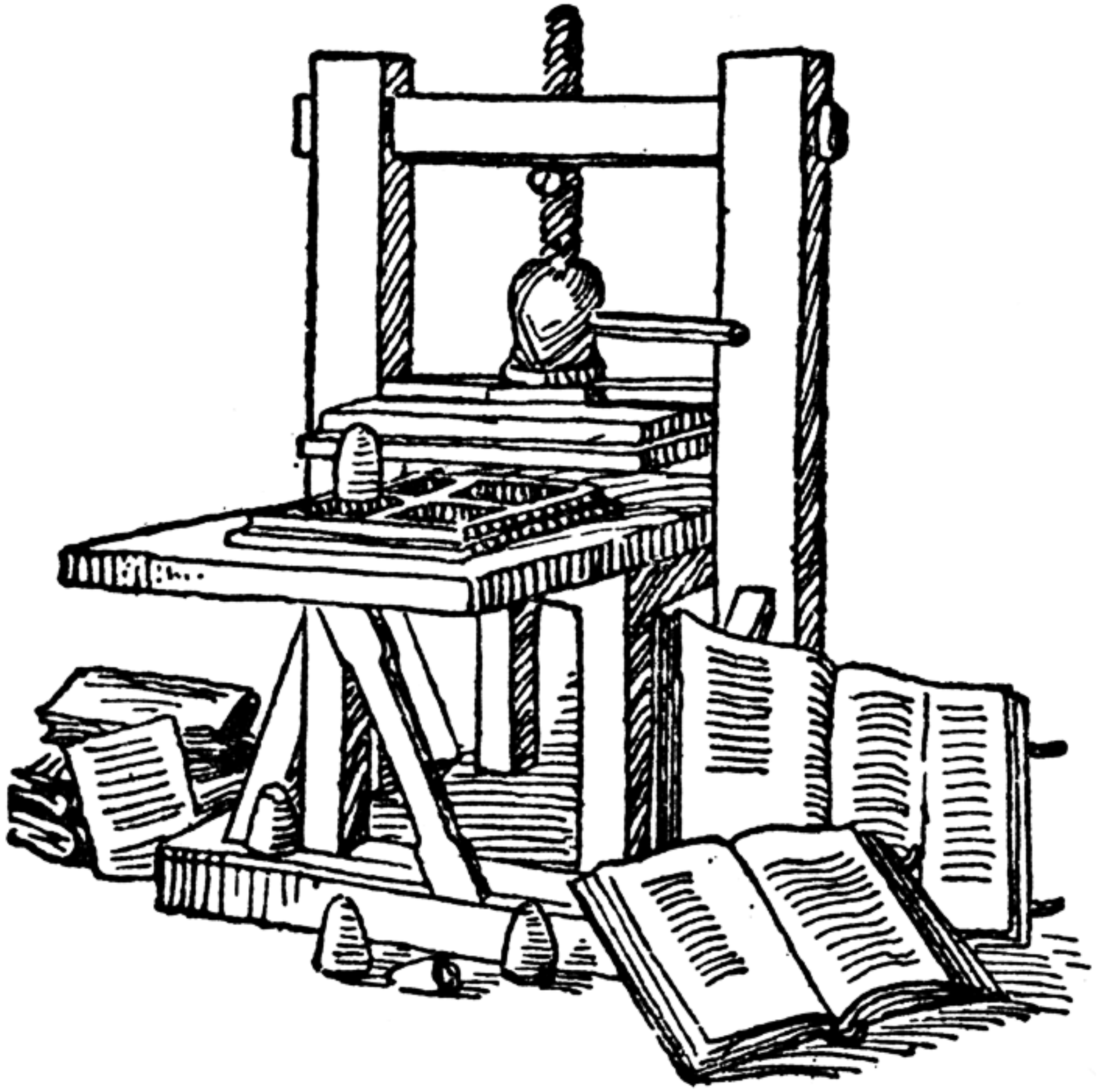
Photometric systems



http://spiff.rit.edu/classes/phys440/lectures/filters/

Let’s talk about paper and printing...

Johannes Gutenberg
(1395 - 1468)



the modern equivalent...

Silicon oxidation

Silicon

Chemical Element

Silicon, a tetravalent metalloid, is a chemical element with the symbol Si and atomic number 14. It is less reactive than its chemical analog carbon, the nonmetal directly above it in the periodic table, ... Wikipedia

Symbol: Si

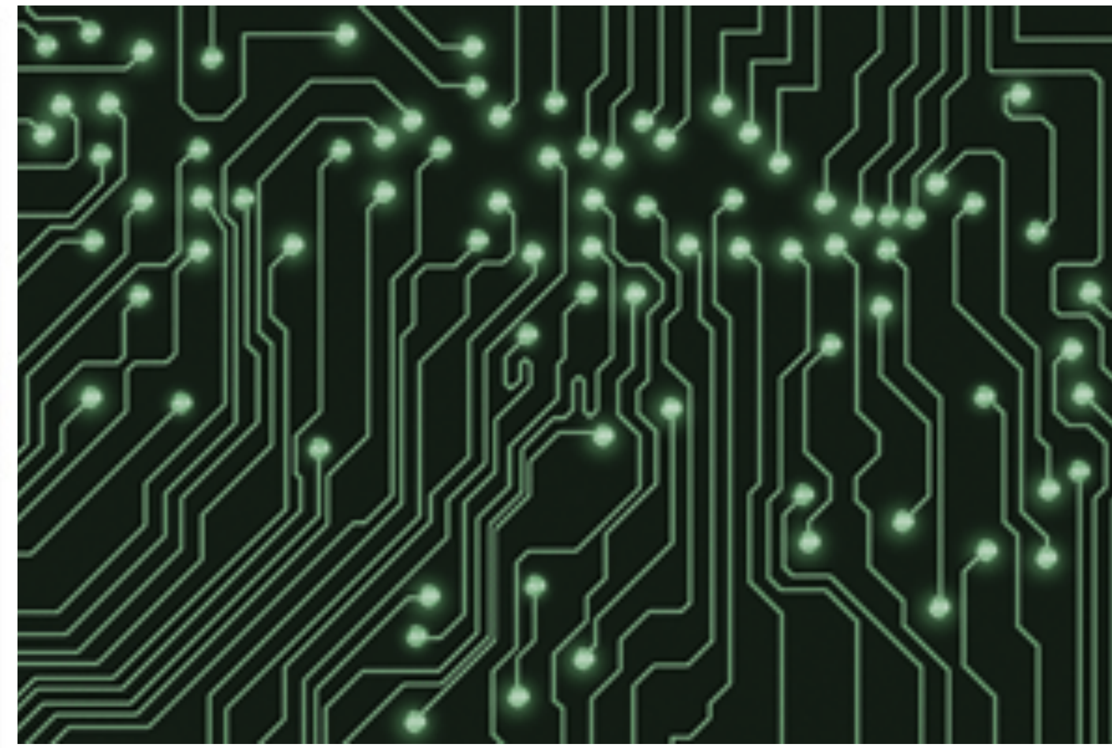
Electron configuration: Ne 3s2 3p2

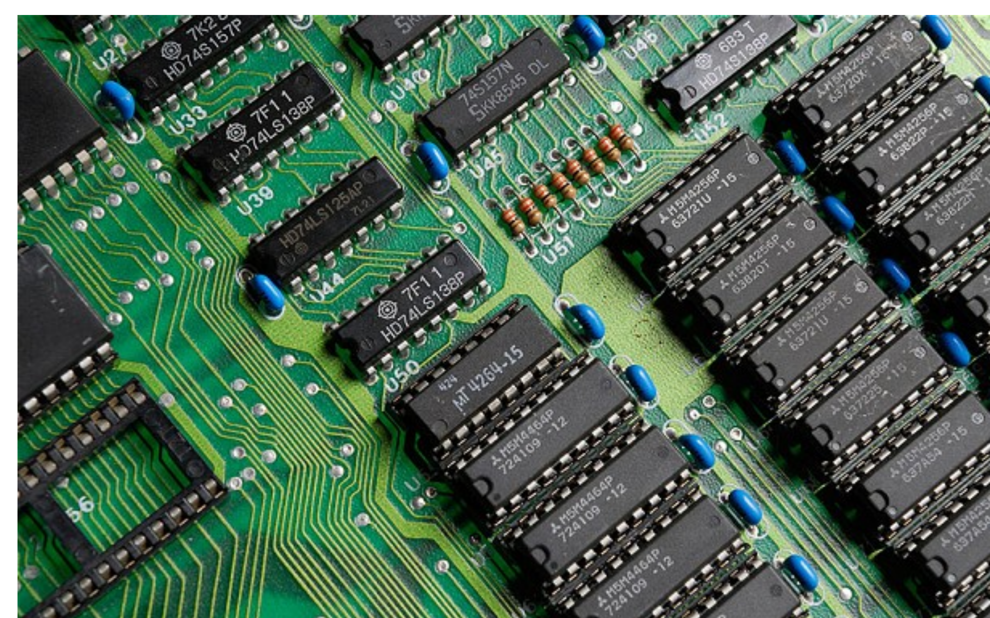
Melting point: 2,577°F (1,414°C)

Atomic number: 14

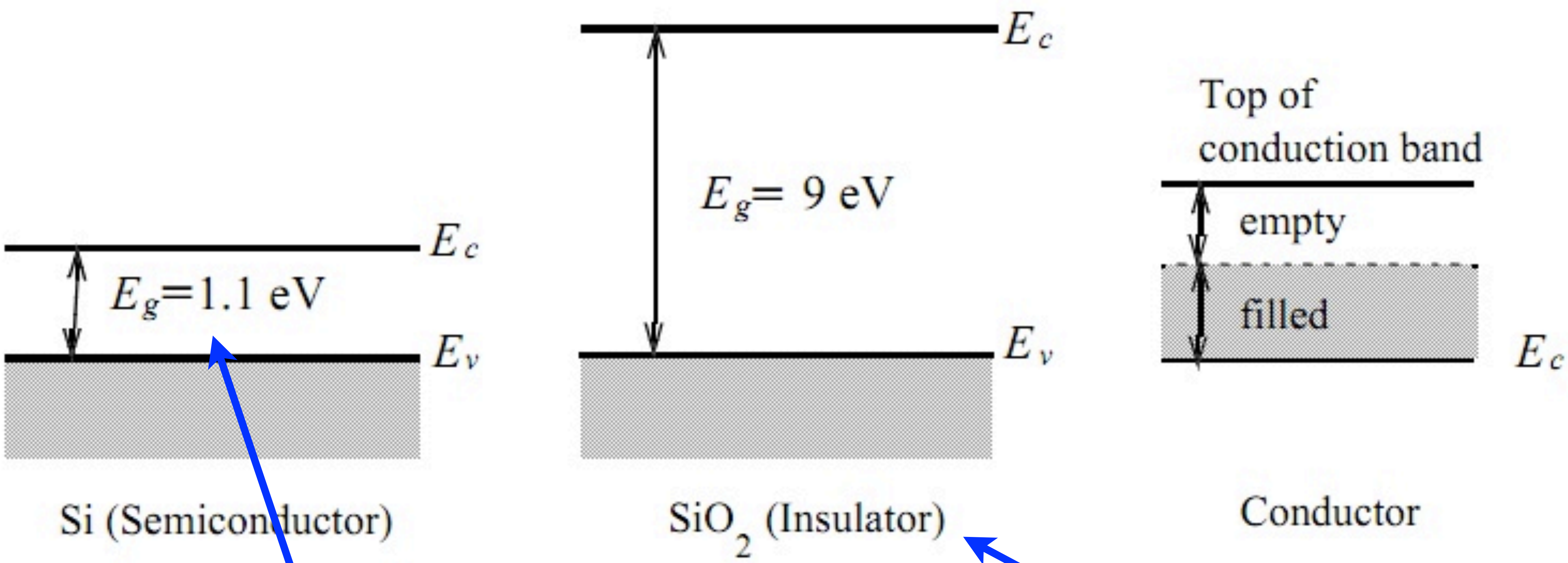
Atomic mass: 28.0855 ± 0.0003 u

Discoverer: Jöns Jacob Berzelius





Semiconductors, Insulators, and Conductors



Useful property for electronics

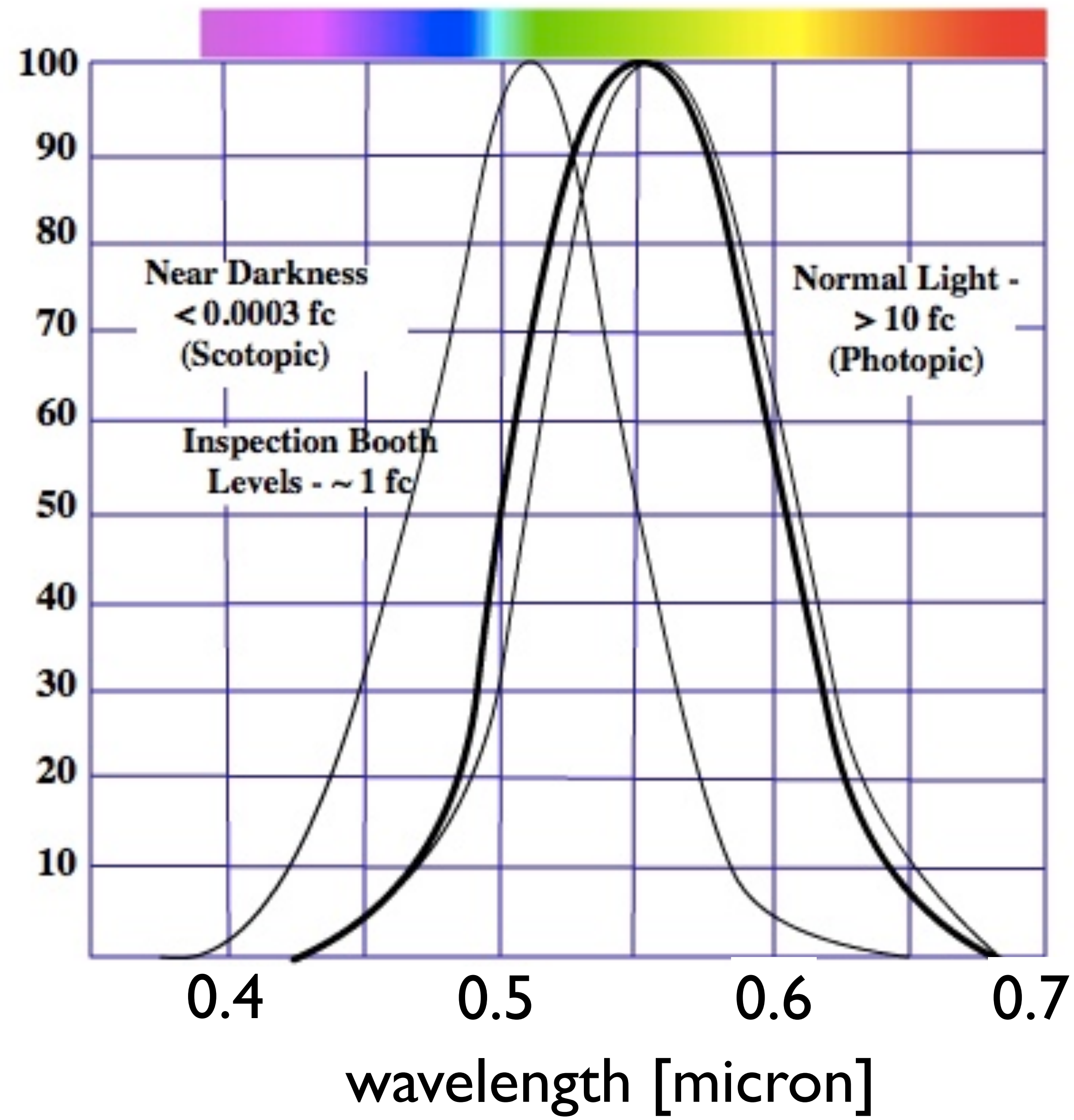
Useful property for optical astronomy

The human eye

lambda_min ~ 0.4 micron
lambda_max ~ 0.7 micron

resolution elements:
- 6e6 cones (bright vision)
- 1e8 rods (faint)

dynamical range: 1e9-10



1 micron ~ 1 eV

Questions:
- What is the stimulation threshold (in terms of number of photons for the eye?)
- What is the wavelength of a standard remote control?

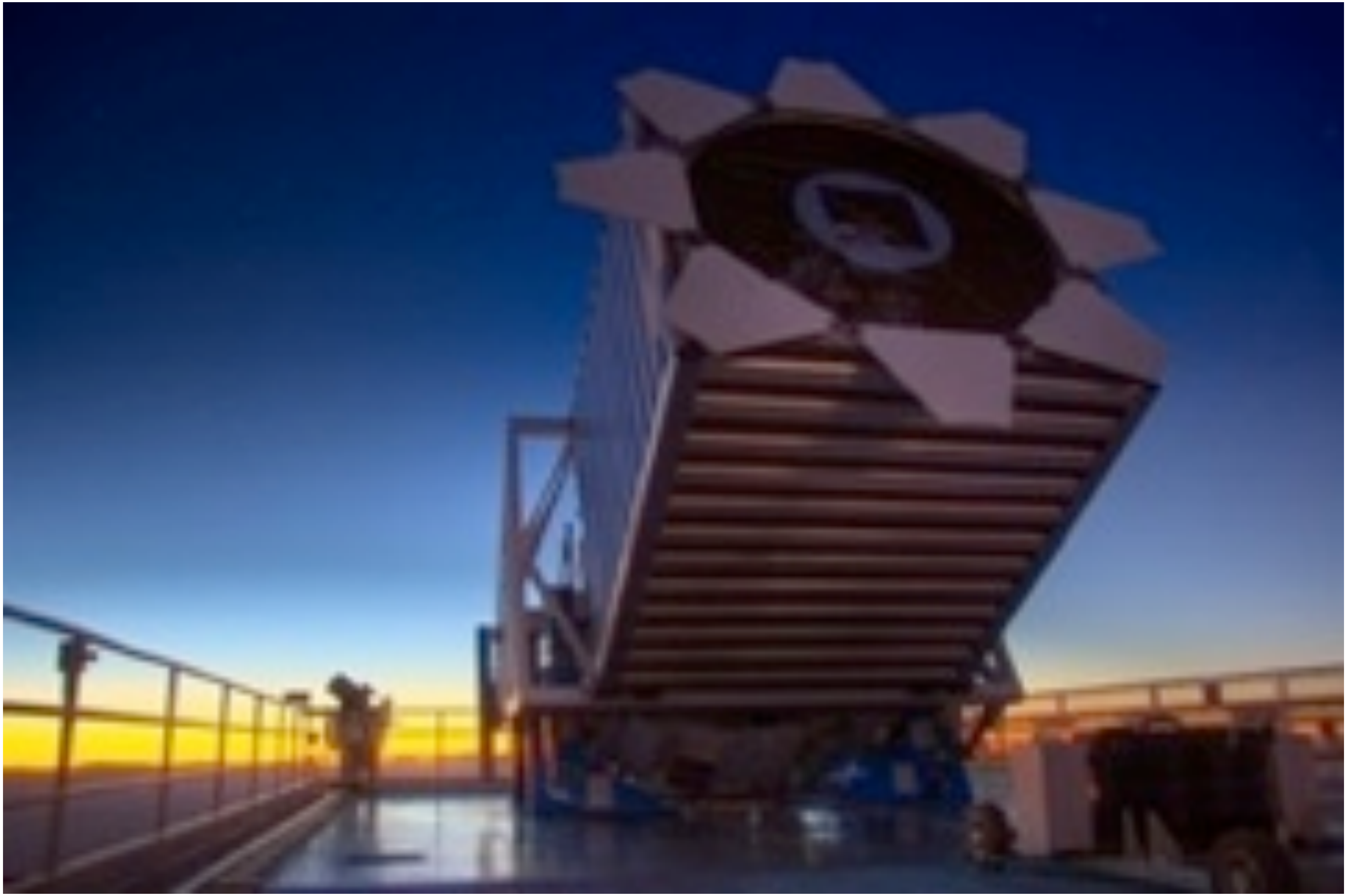
List of band gaps

Material	Symbol	Band gap (eV) @ 302K	Reference
Indium antimonide	InSb	0.17	[6]
Lead(II) selenide	PbSe	0.27	[6]
Lead(II) telluride	PbTe	0.29	[6]
Indium(III) arsenide	InAs	0.36	[6]
Lead(II) sulfide	PbS	0.37	[6]
Germanium	Ge	0.67	[6]
Gallium antimonide	GaSb	0.7	[6]
Indium(III) nitride	InN	0.7	[7]
Silicon	Si	1.11	[6]
Copper(II) oxide	CuO	1.2	[9]
Indium(III) phosphide	InP	1.35	[6]
Gallium(III) arsenide	GaAs	1.43	[6]
Cadmium telluride	CdTe	1.49	[8]
Aluminium antimonide	AlSb	1.6	[6]
Cadmium selenide	CdSe	1.73	[6]
Selenium	Se	1.74	
Copper(I) oxide	Cu_2O	2.1	[10]
Aluminium arsenide	AlAs	2.16	
Zinc telluride	ZnTe	2.25	
Gallium(III) phosphide	GaP	2.26	[illegible]
Cadmium sulfide	CdS	2.42	[6]

1 eV ~ 1 micron

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta},$$ where $E_g(0)$, α and β are material constants.

The Sloan Digital Sky Survey



The ideal detector for astronomy

- Modern surveys (SDSS, CFHT-LS, DES, Pan-STARRS, LSST, ...) operate for 5-10 years.

- The same detector (or camera) is used for the whole survey. It has to be as good as possible.

The ideal detector for astronomy

- noiseless (or close)

- have 100 percent (quantum) efficiency

- linear response

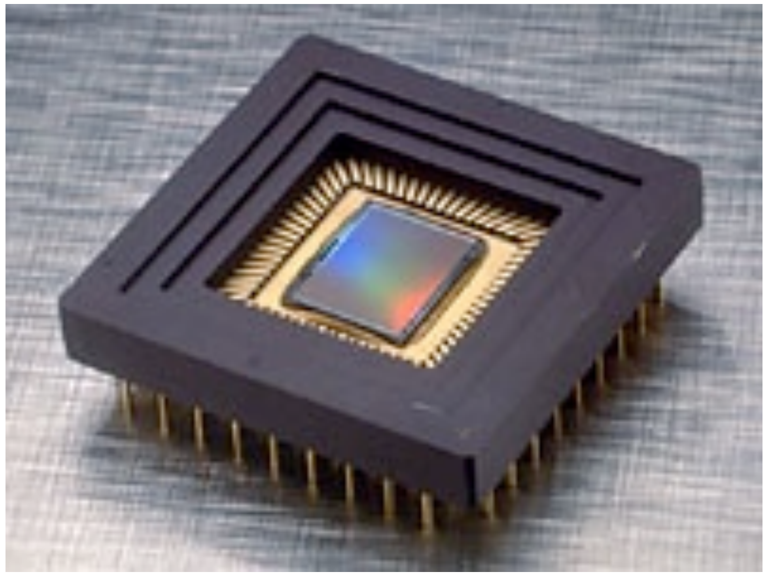
- be available with any desired pixel size

- measure x, y, λ , and t for each photon incident on it, through the visible and into the mid-IR. We are not there yet.

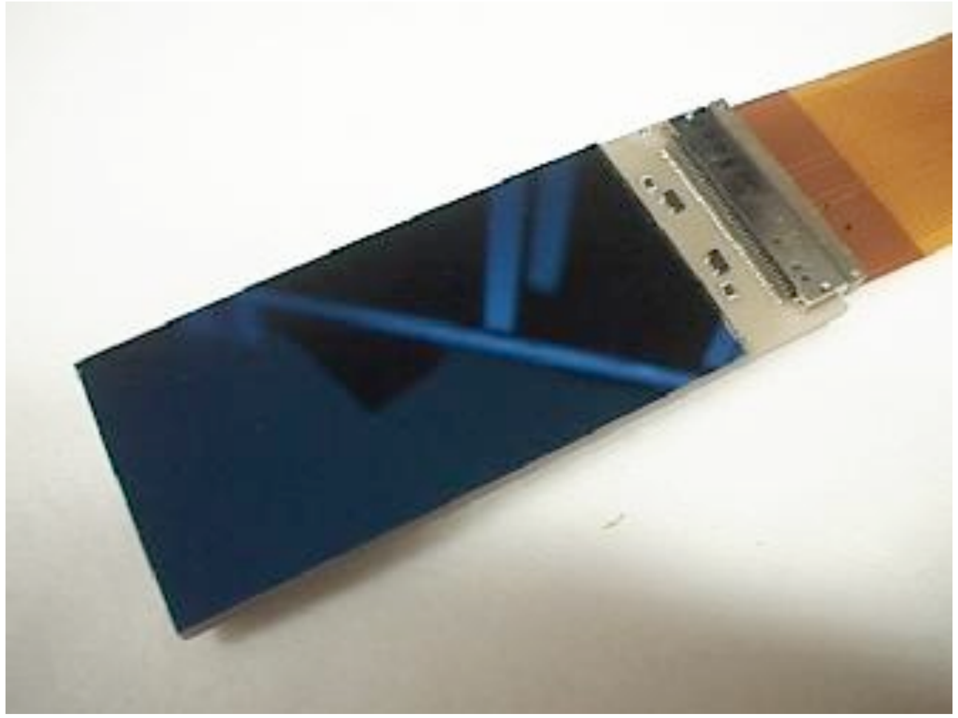
- can be read quickly (not too important)

Appearance of CCDs

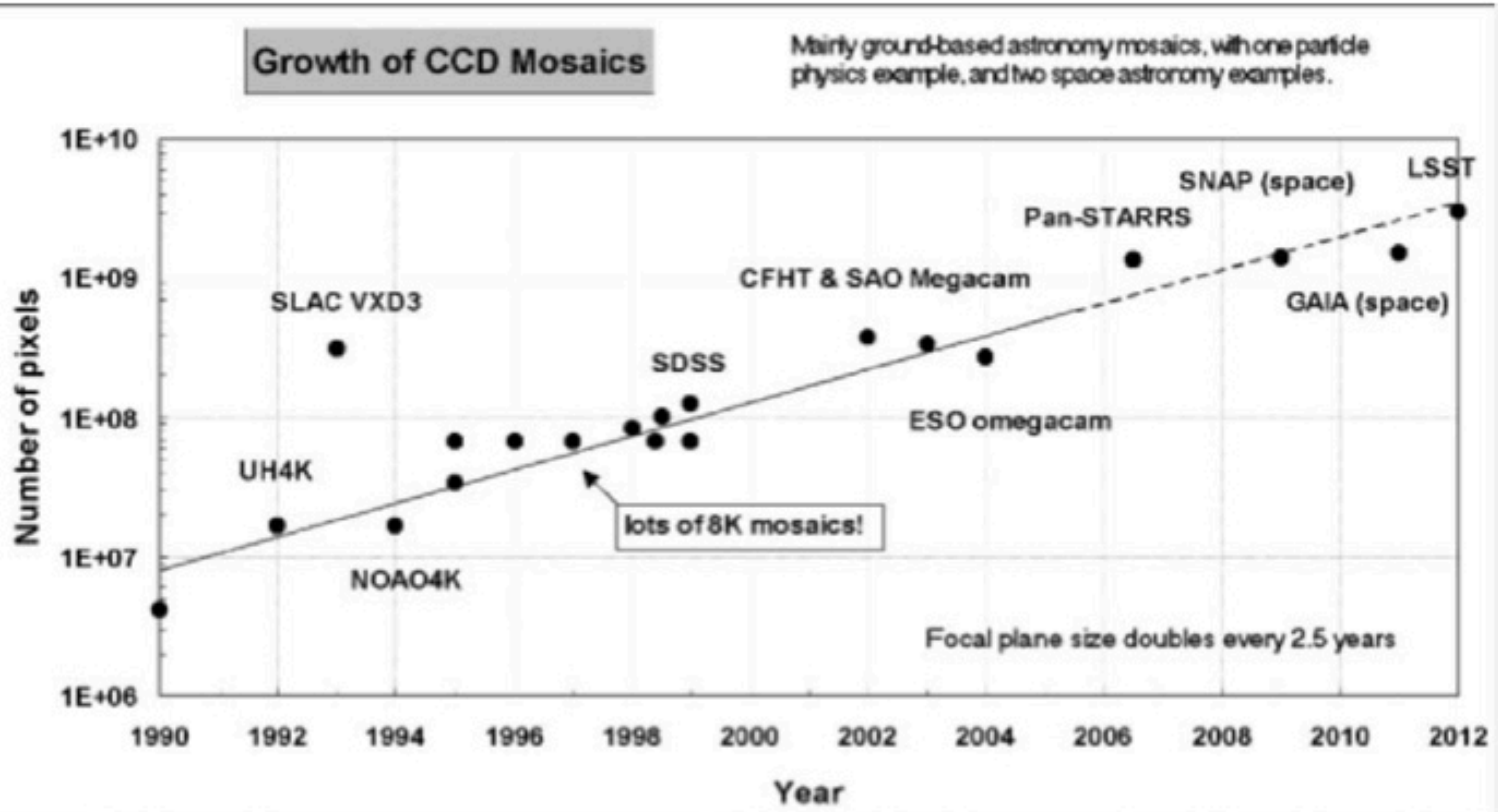
The fine surface electrode structure of a thick CCD is clearly visible as a multi-coloured interference pattern. Thinned Backside Illuminated CCDs have a much planer surface appearance. The other notable distinction is the two-fold (at least) price difference.



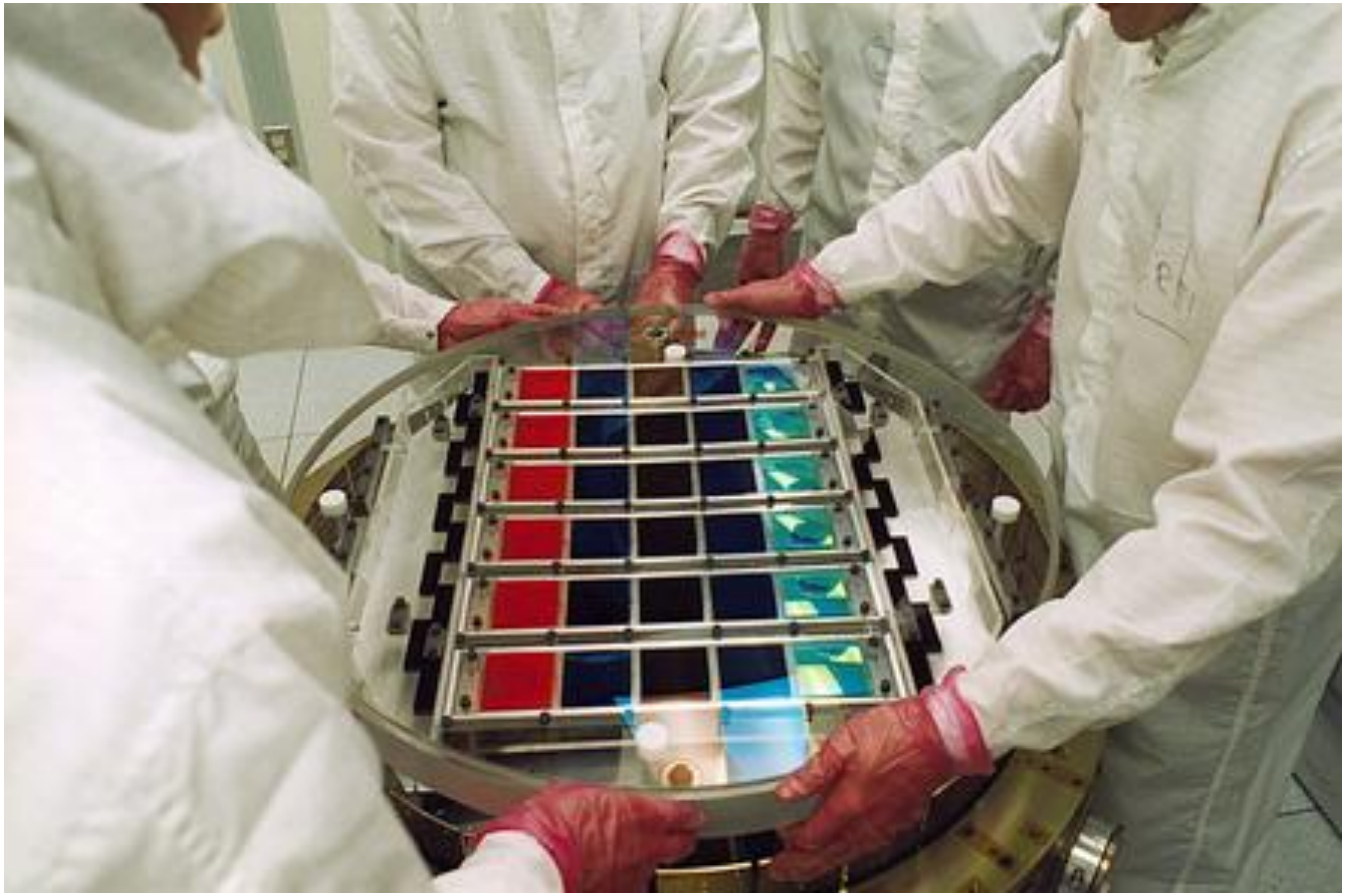
Kodak Kaf1401 Thick CCD



MIT/LL CC1D20 Thinned CCD


Growth of CCD Mosaics
Mainly ground-based astronomy mosaics, with one particle physics example, and two space astronomy examples.
1E+10
1E+09
1E+08
1E+07
1E+06
Number of pixels
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
SLAC VXD3
UH4K
NOAO4K
SDSS
lots of 8K mosaics!
CFHT & SAO Megacam
ESO omegacam
Pan-STARRS
SNAP (space)
LSST
GAIA (space)
Focal plane size doubles every 2.5 years

The SDSS camera



Drift scan

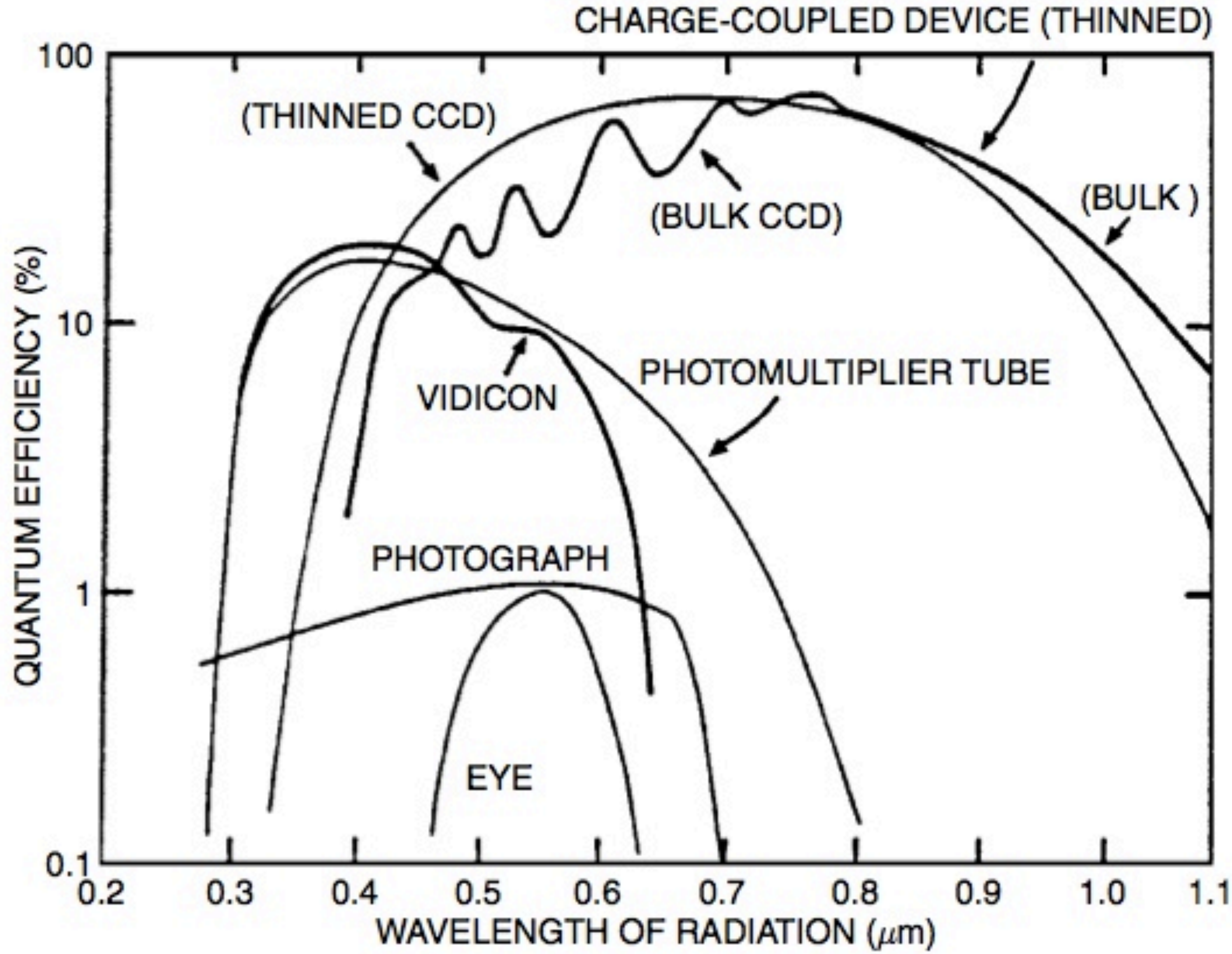
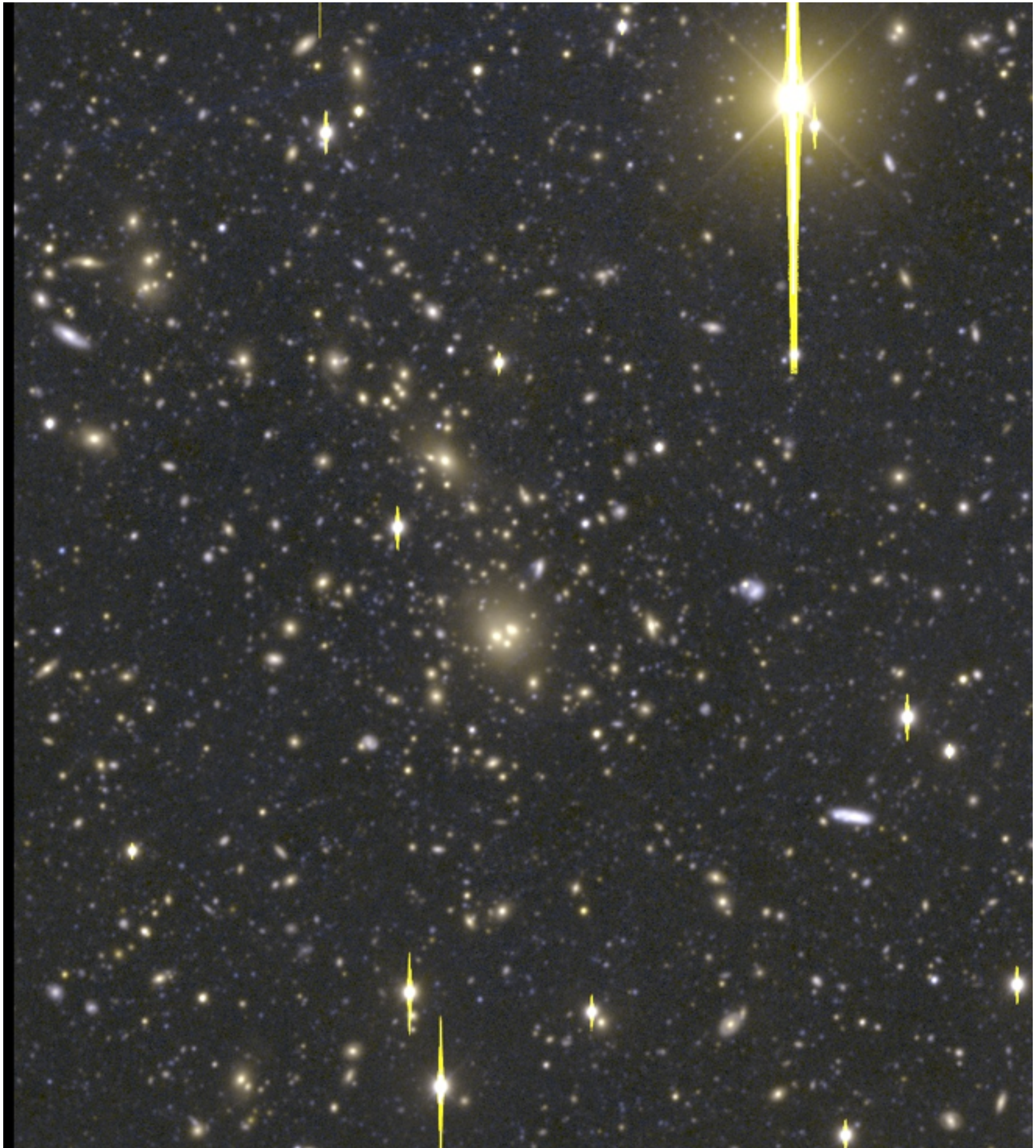
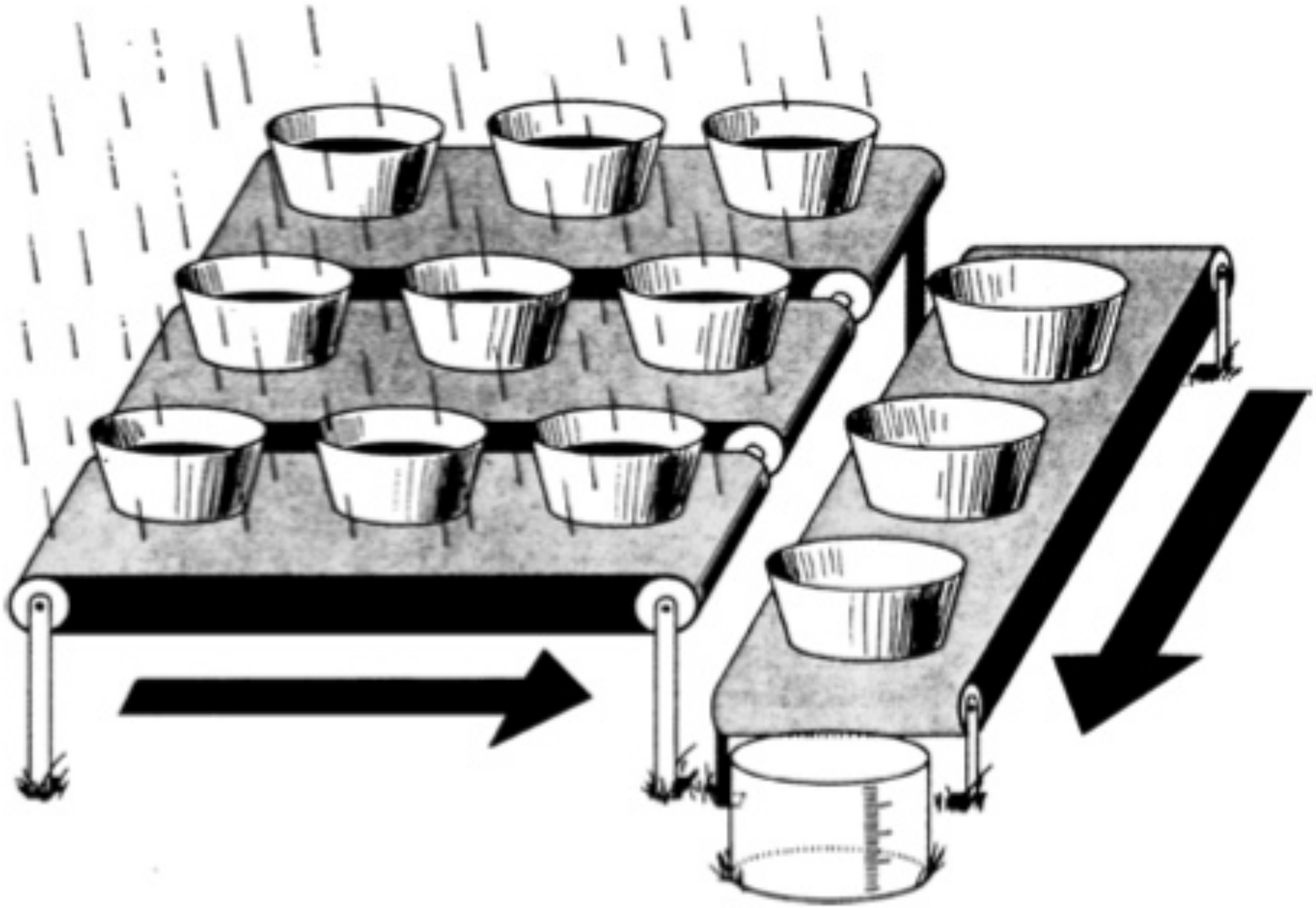


Fig. 3.2. QE curves for various devices, indicating why CCDs are a quantum leap above all previous imaging devices. The failure of CCDs at optical wavelengths shorter than about 3500 Å has been essentially eliminated via thinning or coating of the devices (see Figure 3.3).



http://www.astr.ua.edu/keel/techniques/a2125mos2wf.jpg

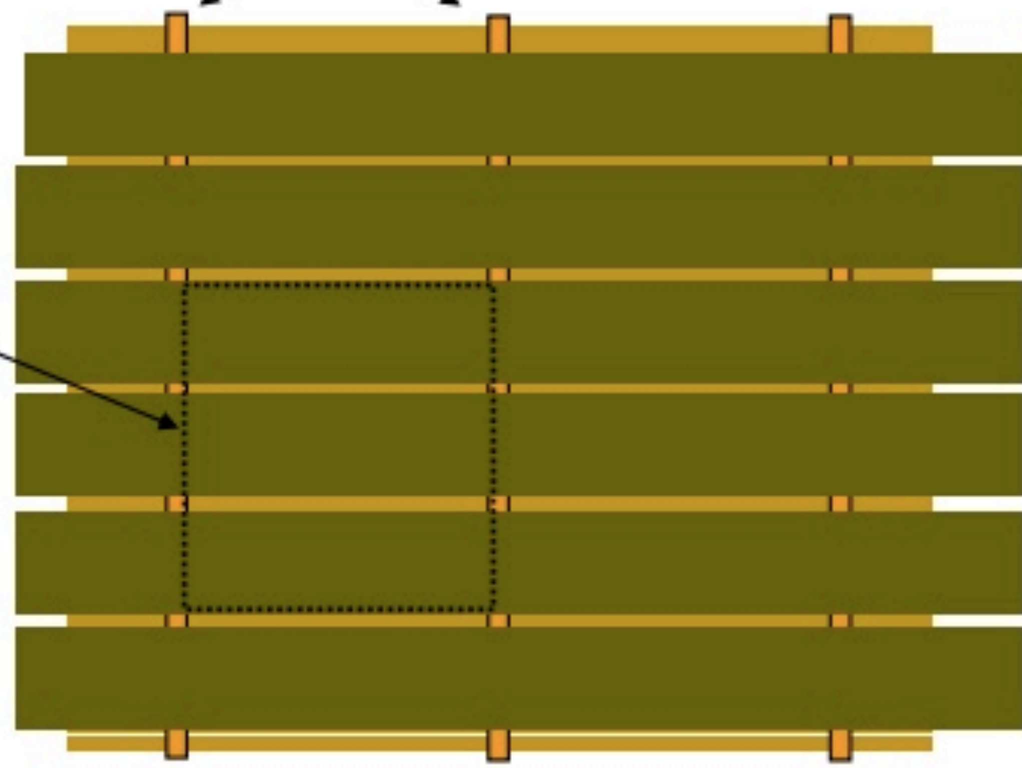
How do CCDs work?



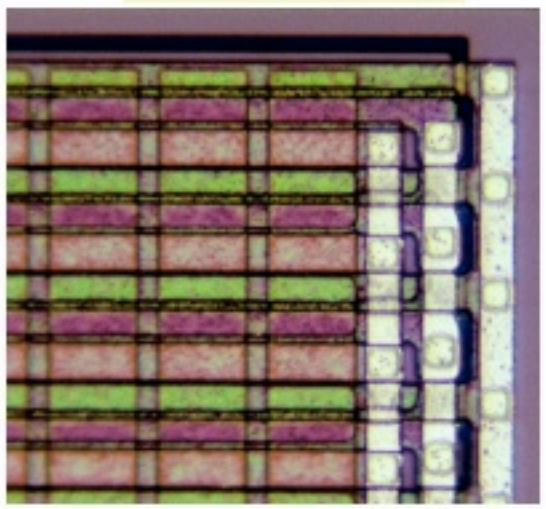
from Janesick & Blouke (1987)

Reading a CCD takes a lot of time.

The diagram shows a small section (a few pixels) of the image area of a CCD. This pattern is reapeated.



Final product

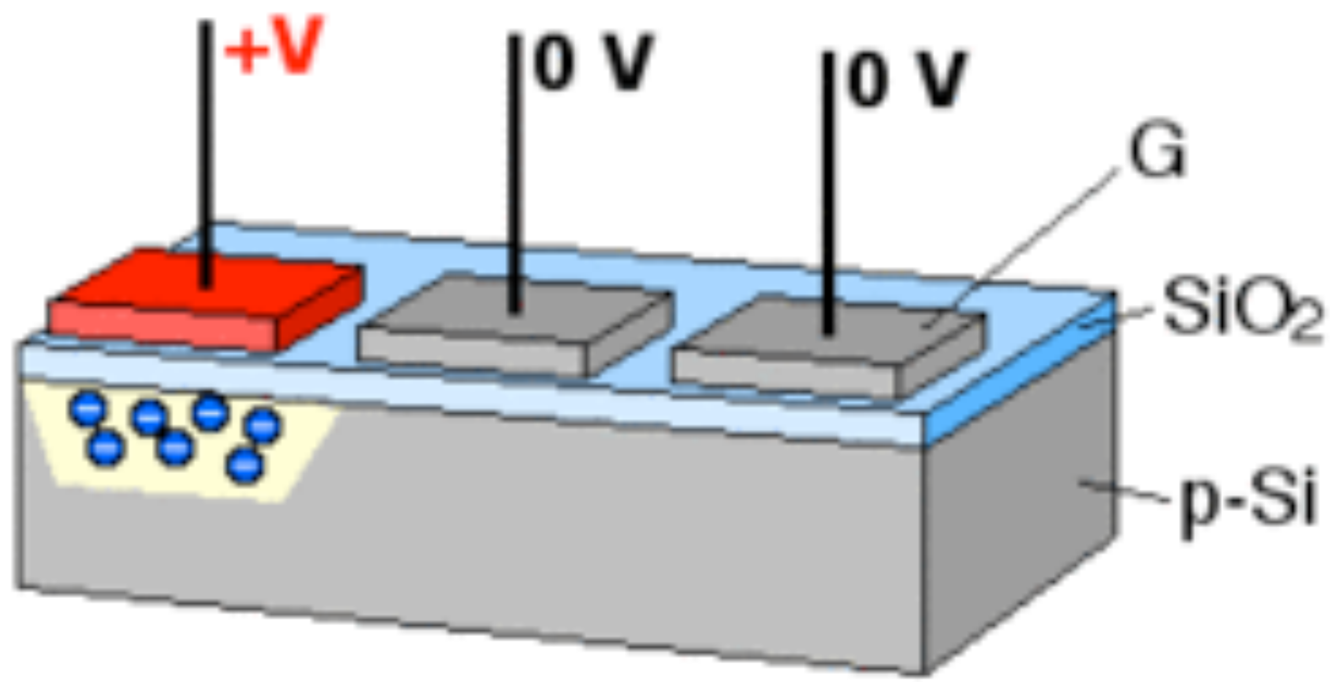


Top view

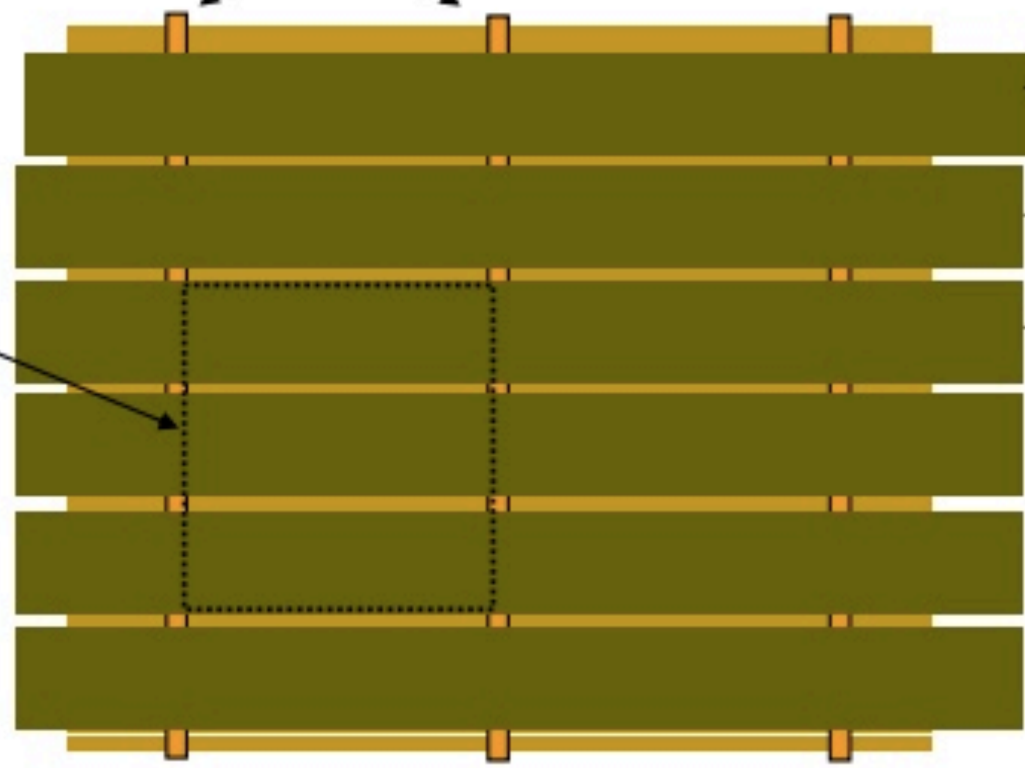
Every third electrode is connected together. Bus wires running down the edge of the chip make the connection. The channel stops are formed from high concentrations of Boron in the silicon.

Slide from Philippe Feautrier

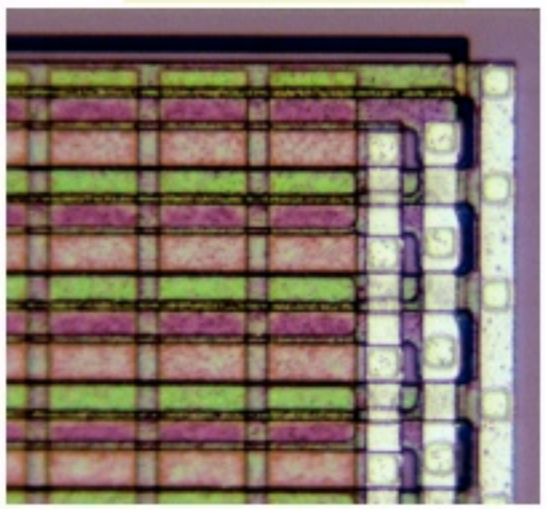
http://upload.wikimedia.org/wikipedia/commons/thumb/6/66/CCD_charge_transfer_animation.gif/250px-CCD_charge_transfer_animation.gif



The diagram shows a small section (a few pixels) of the image area of a CCD. This pattern is reapeated.



Final product



Top view

Every third electrode is connected together. Bus wires running down the edge of the chip make the connection. The channel stops are formed from high concentrations of Boron in the silicon.

Slide from Philippe Feautrier

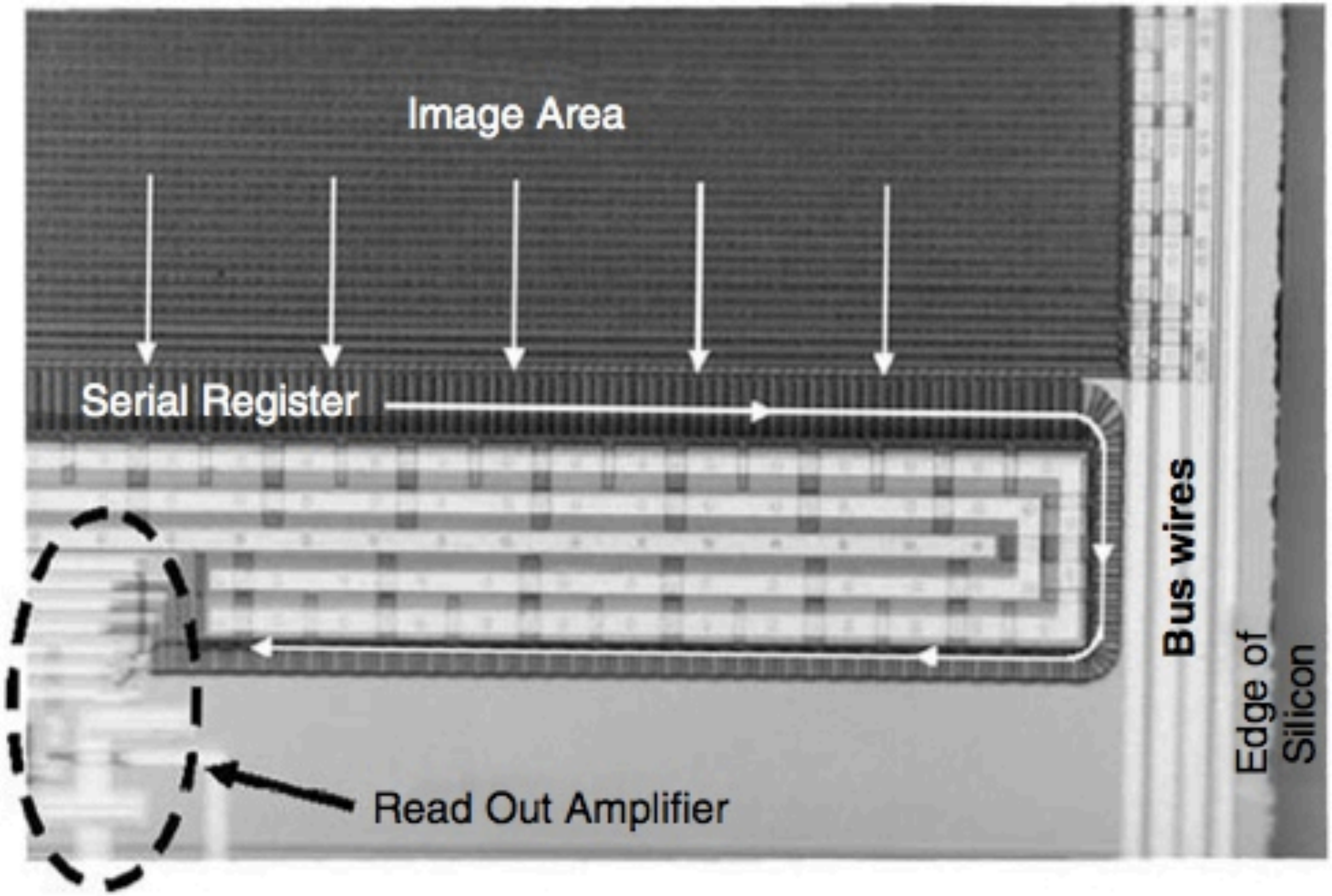


Fig. 2.3. Microphotograph of a E2V L3CCD (see Section 2.2.7) showing the image area (pixels), the serial register, and the on-chip readout amplifier. The other wiring and the bus wires are electrical connections that carry the clock signals and bias voltages to use. Added on to the normal CCD components is an extended serial register through which the readout occurs (the arrow indicates this flow) where the half after the bend is the gain register.

One amplifier: it takes quite some time to read the array

Properties of silicon detectors

Charge Coupled Device (CCD)

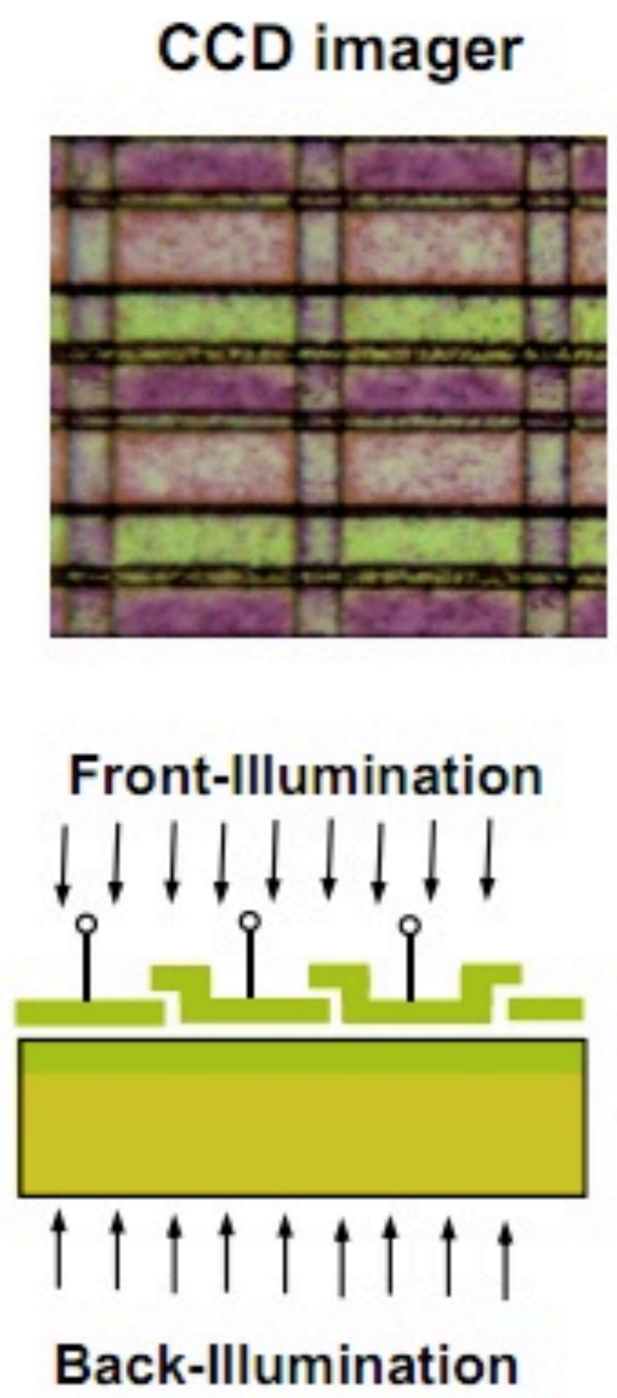
- One amplifier => same response and noise properties for all pixels.

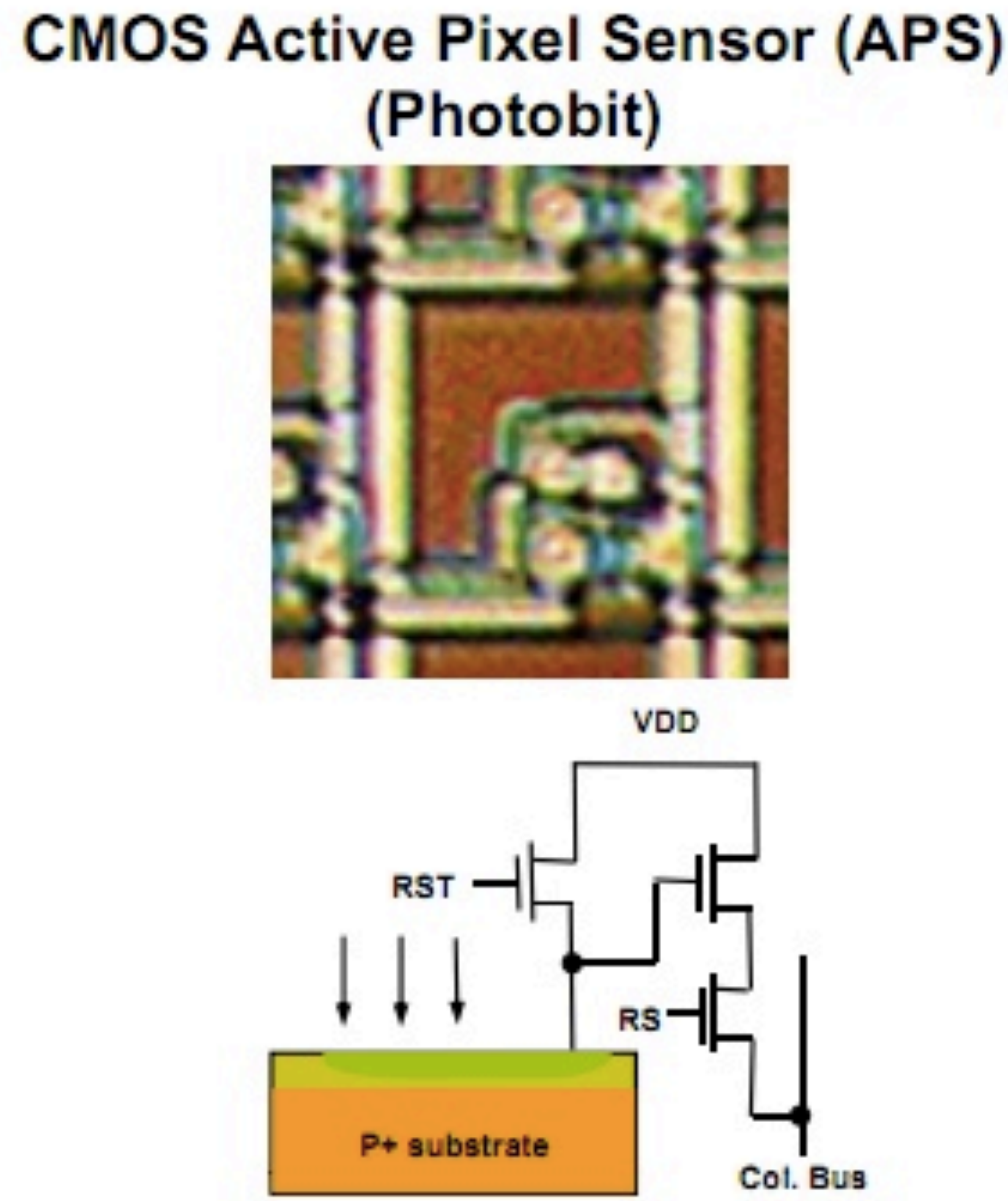
Small differences can originate from differences in pixel sizes, defects, charge transfer efficiency

What about standard cameras (webcam, cellphone, etc.)?

Complementary Metal Oxide Semi-conductor (CMOS)

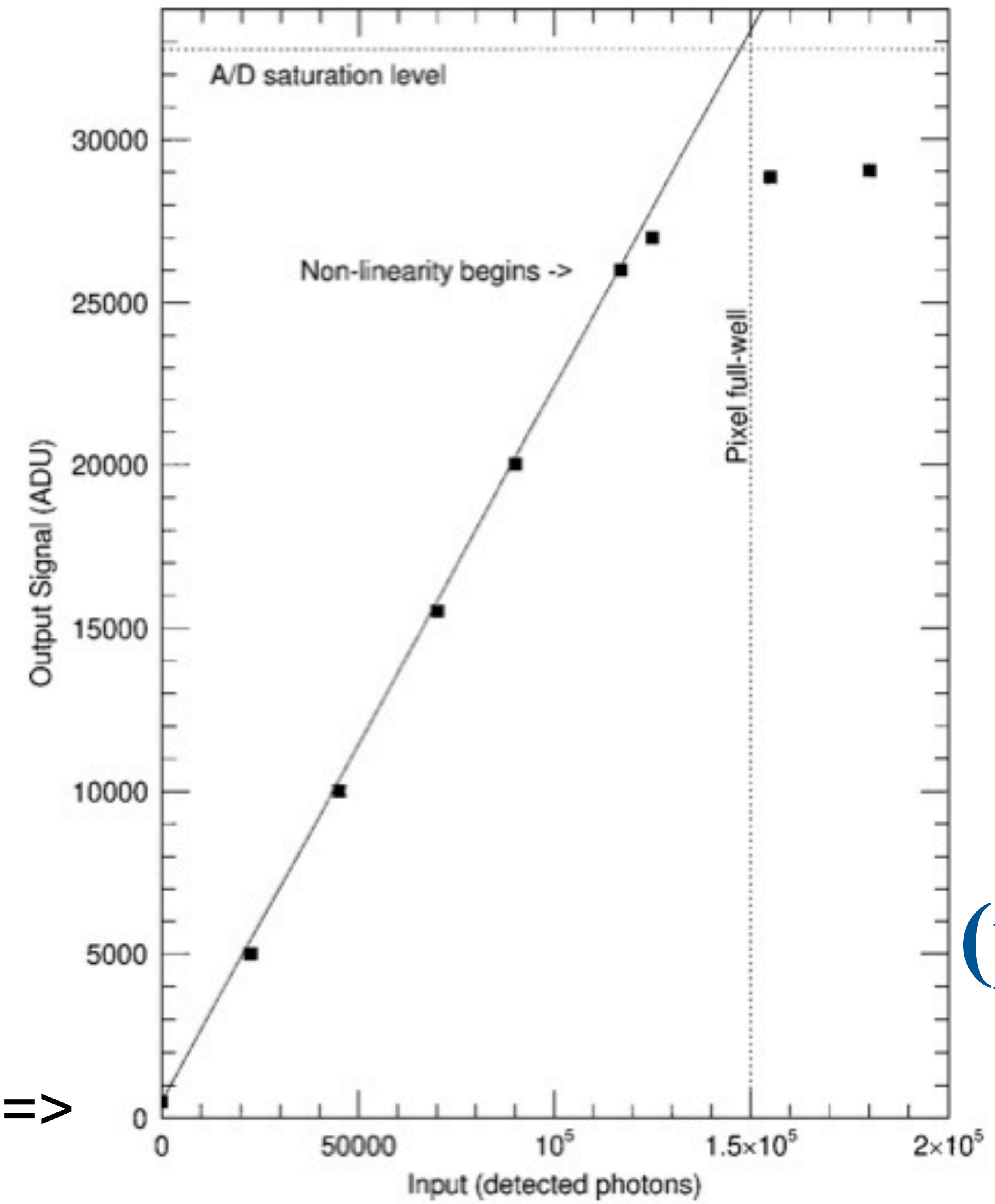
- One amplifier per pixel => fast but variable response





http://philippe.feautrier.free.fr/Supaero_Imageurs3A_PFeautrier.pdf

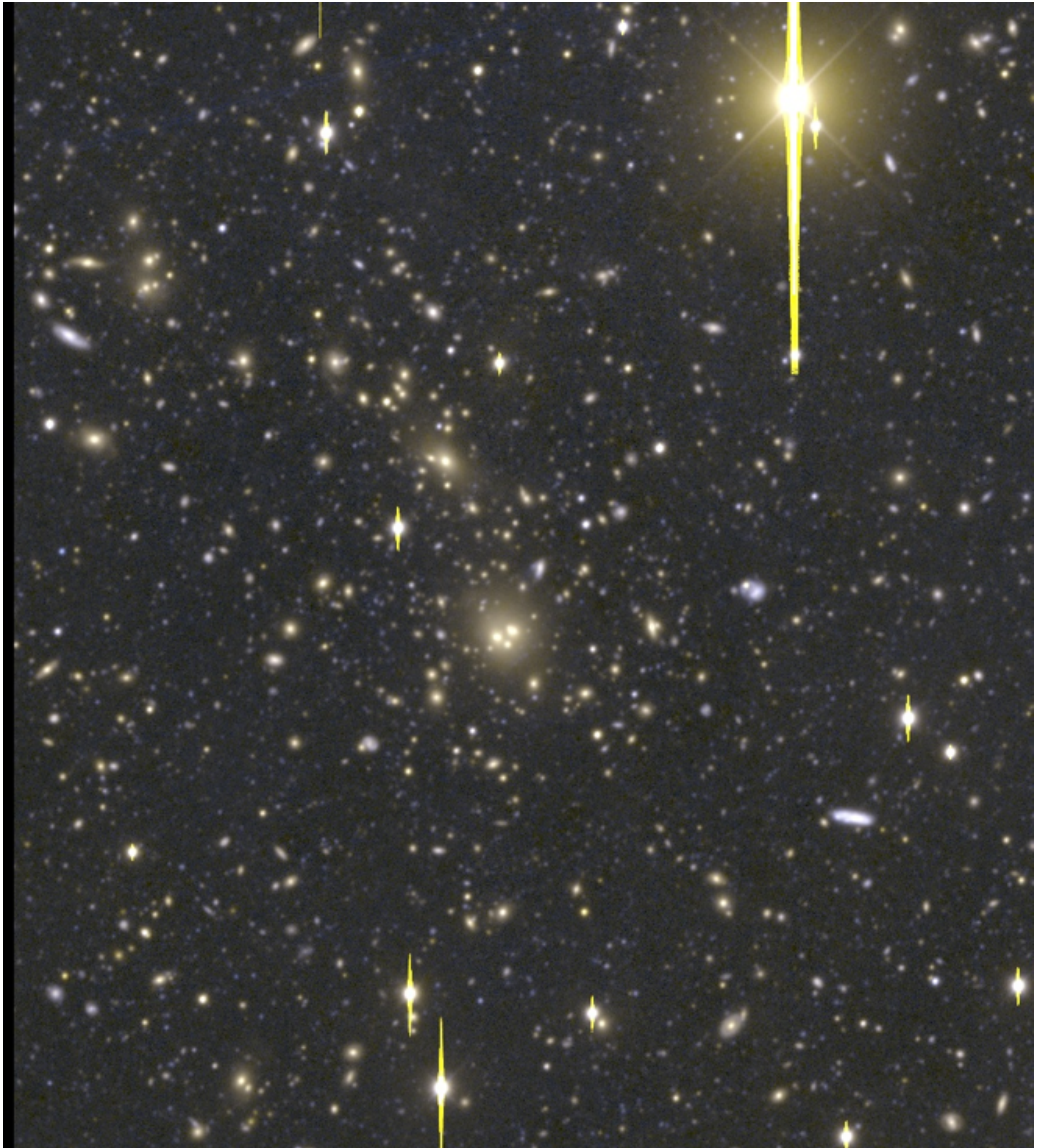
Saturation



bias =>

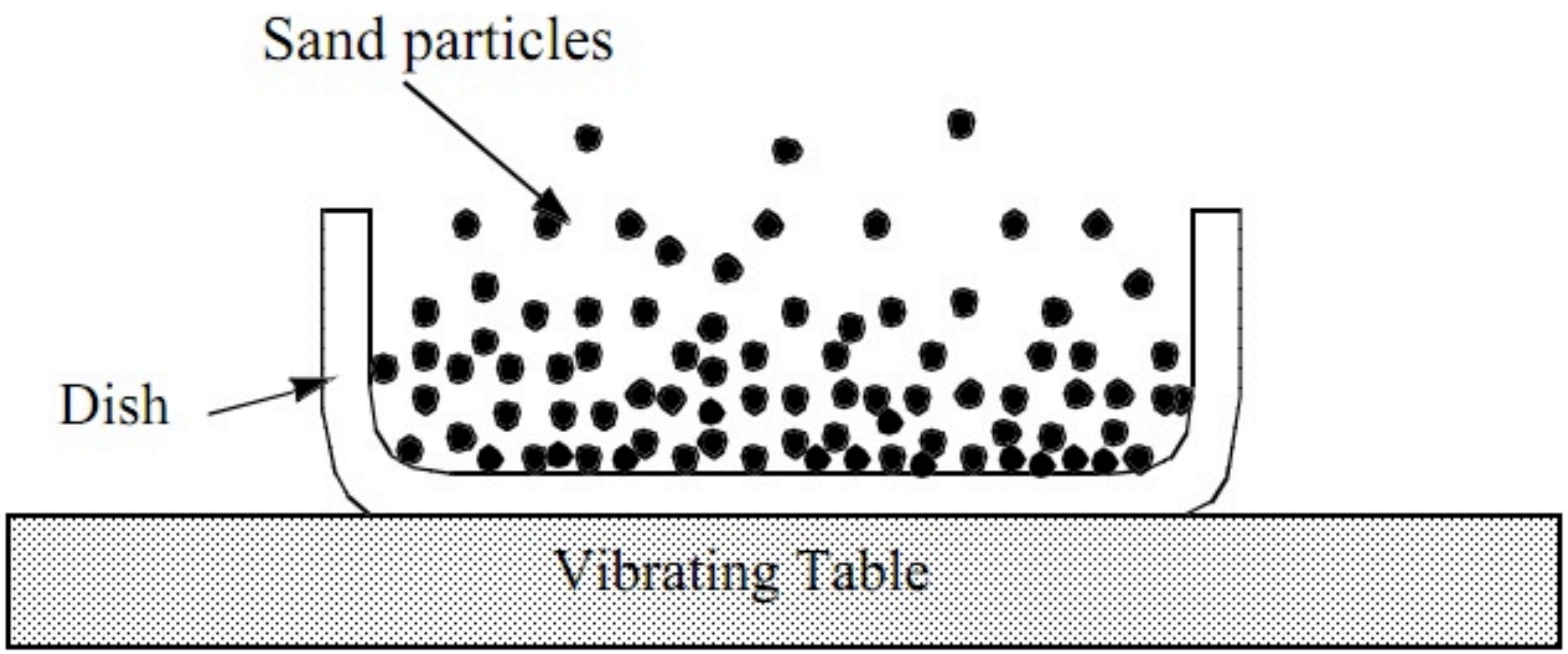
Fig. 3.9. CCD linearity curve for a typical three-phase CCD. We see that the device is linear over the output range from 500 ADU (the offset bias level of the CCD) to 26 000 ADU. The pixel full well capacity is 150 000 electrons and the A/D converter saturation is at 32 767 ADU. In this example, the CCD nonlinearity is the limiting factor of the largest usable output ADU value. The slope of the linearity curve is equal to the gain of the device.

Linearity (photo-electric effect)



http://www.astr.ua.edu/keel/
techniques/a2125mos2wf.jpg

Thermal noise



- There is a certain probability for the electrons in the conduction band to occupy high-energy states under the agitation of thermal energy (vibrating atoms, etc.)

Dark current

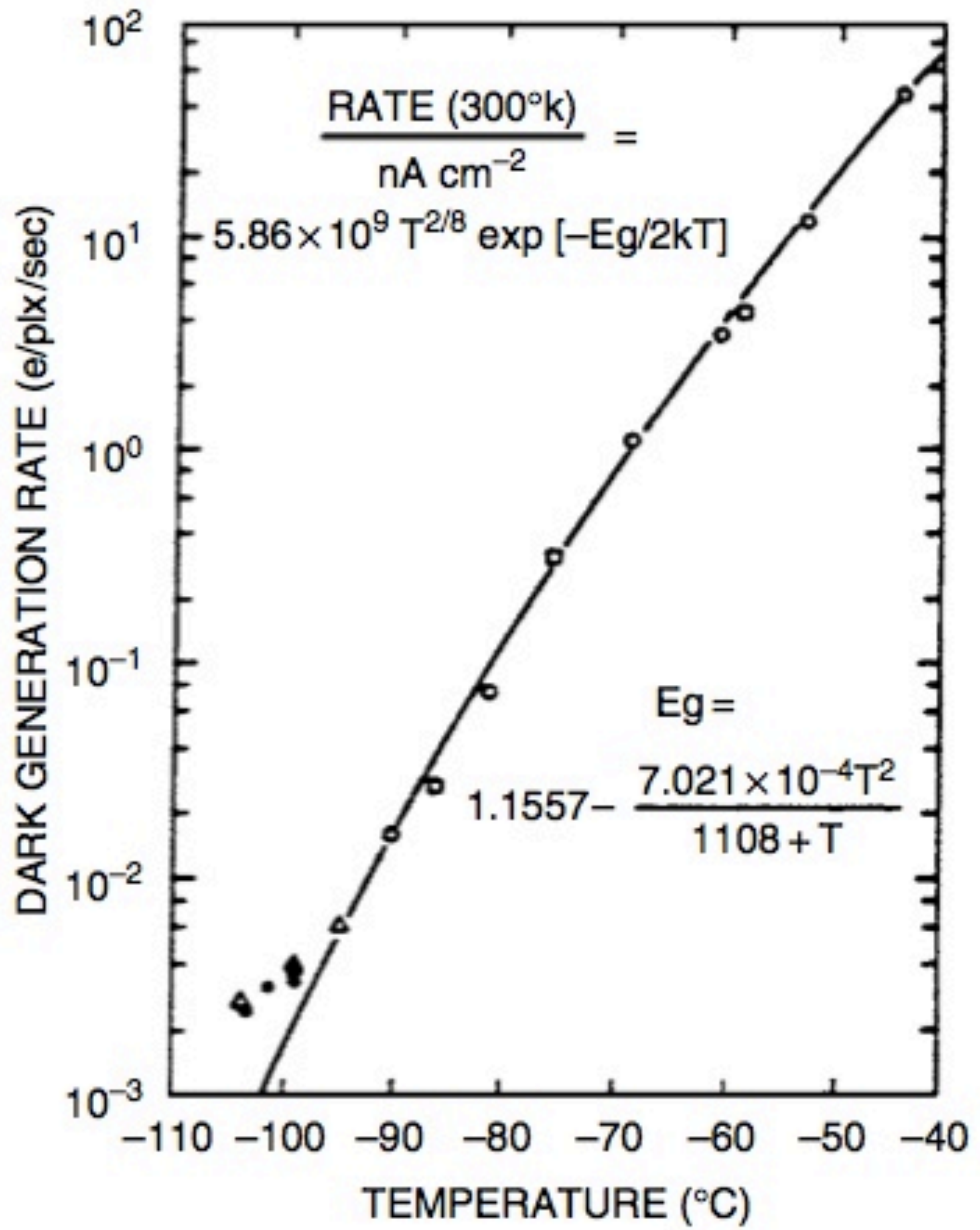


Fig. 3.6. Experimental (symbols) and theoretical (line) results for the dark current generated in a typical three-phase CCD. The rate of dark current, in electrons generated within each pixel every second, is shown as a function of the CCD operating temperature. E_g is the band gap energy for silicon. From Robinson (1988a).

CCDs have to be cooled

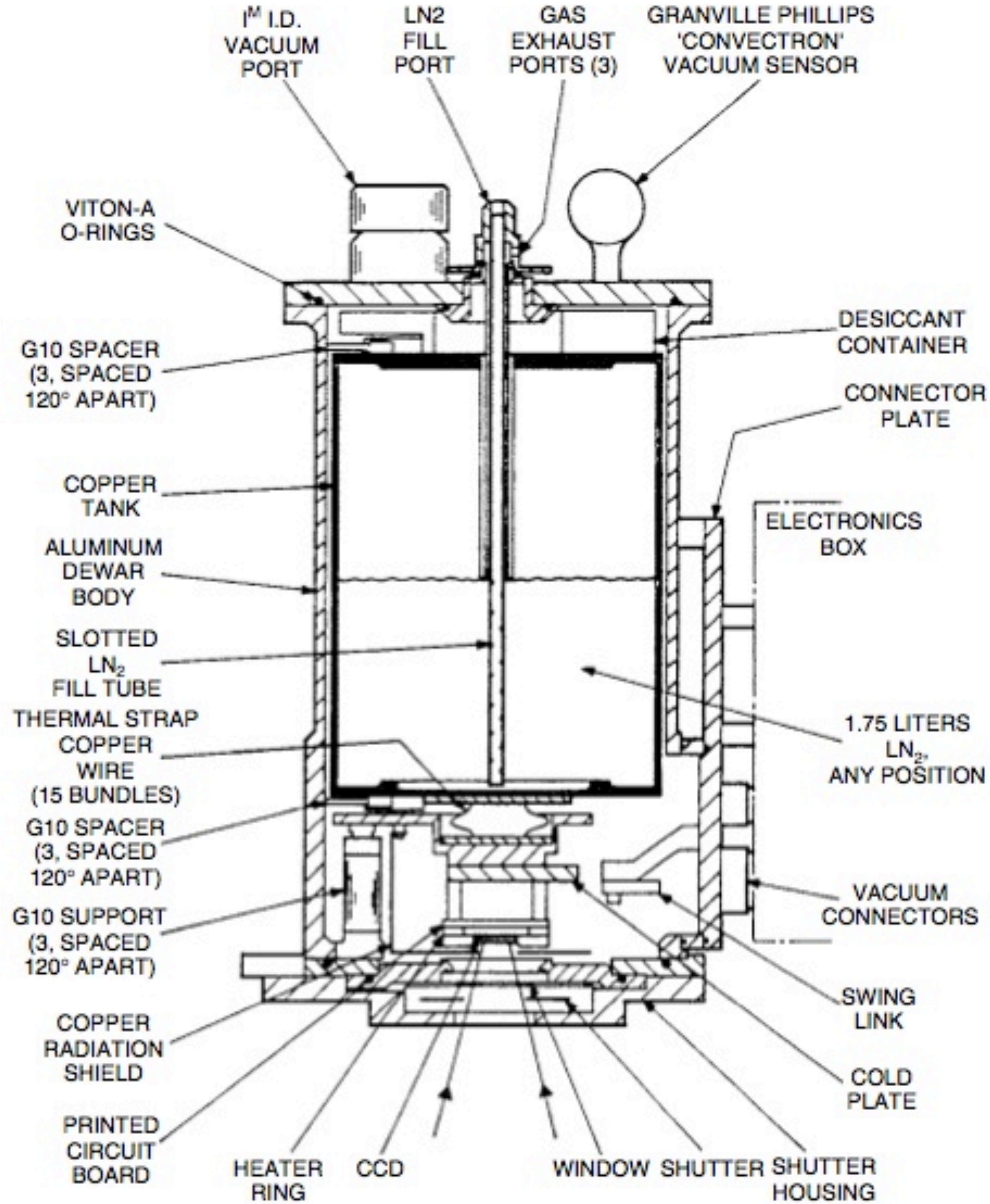


Fig. 3.7. A typical CCD dewar. This is the Mark-II Universal dewar originally produced in 1984 at Kitt Peak National Observatory. The dewar held 1.75 liters of liquid nitrogen providing a CCD operating time of approximately 12 hours between fillings. This dewar could be used in up-looking, down-looking, and side-looking orientations. From Brar (1984).

A CCD is a photon counter

- The amplifier only counts electrons. The energy of the incident photon has been lost.

The ideal detector for astronomy

- noiseless (or close)

- have 100 percent (quantum) efficiency

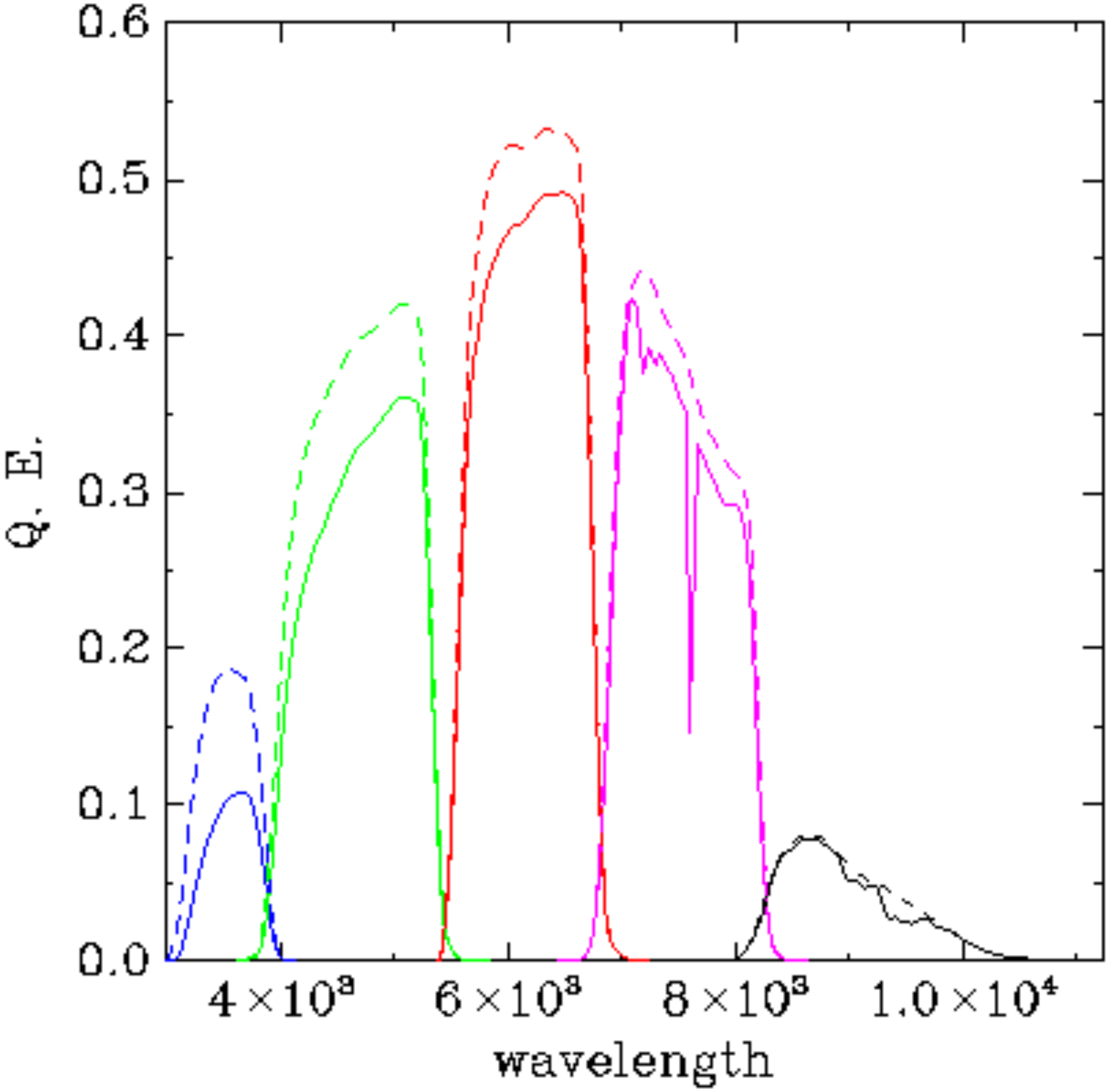
- linear response

- be available with any desired pixel size

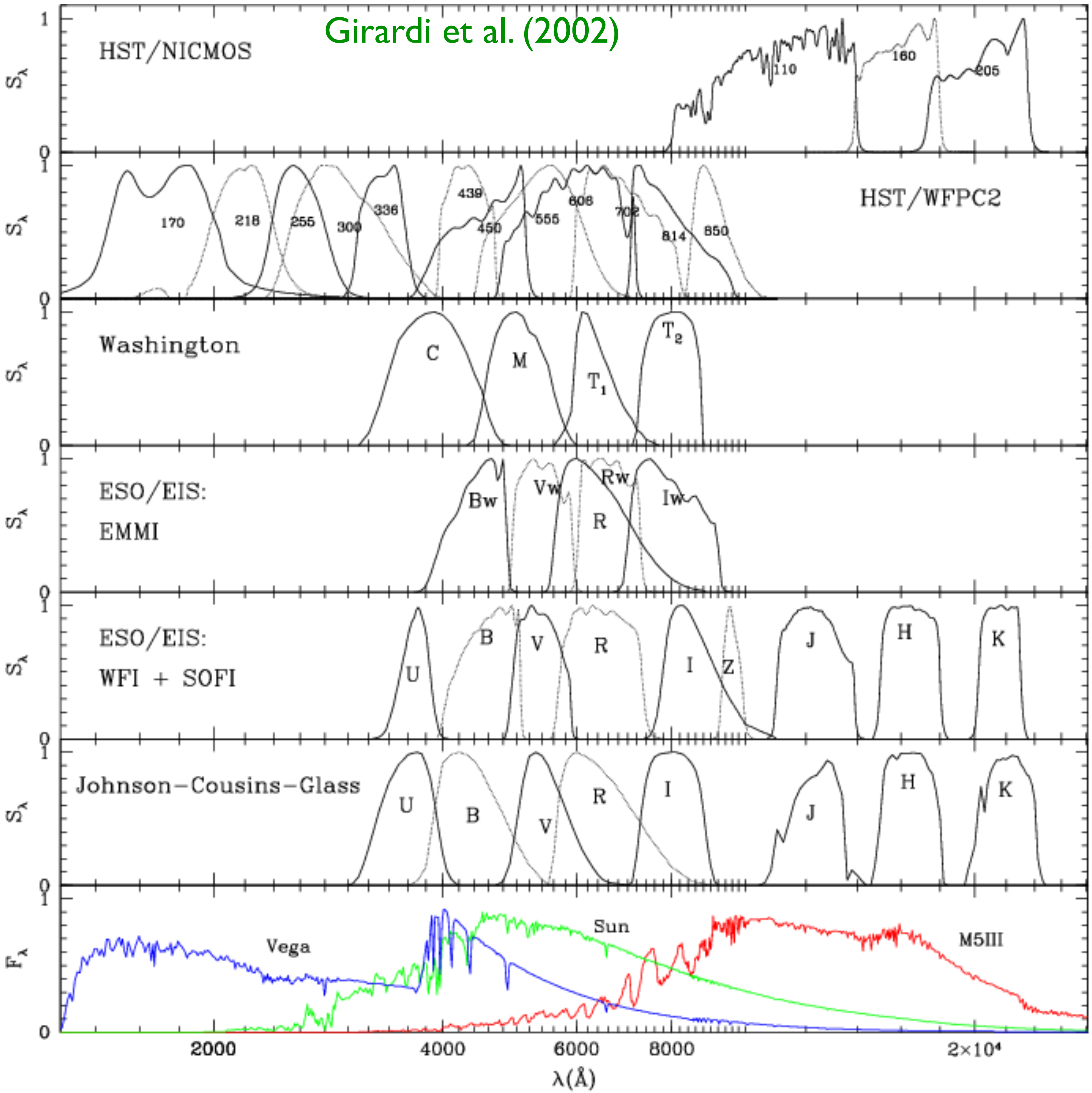
- measure x, y, λ , and t for each photon incident on it, through the visible and into the mid-IR. We are not there yet.

Photometric systems

SDSS
2.4m 0.12Gpixel



http://www.sdss.org/dr3/instruments/imager/



The Johnson V filter is close to the eye response.

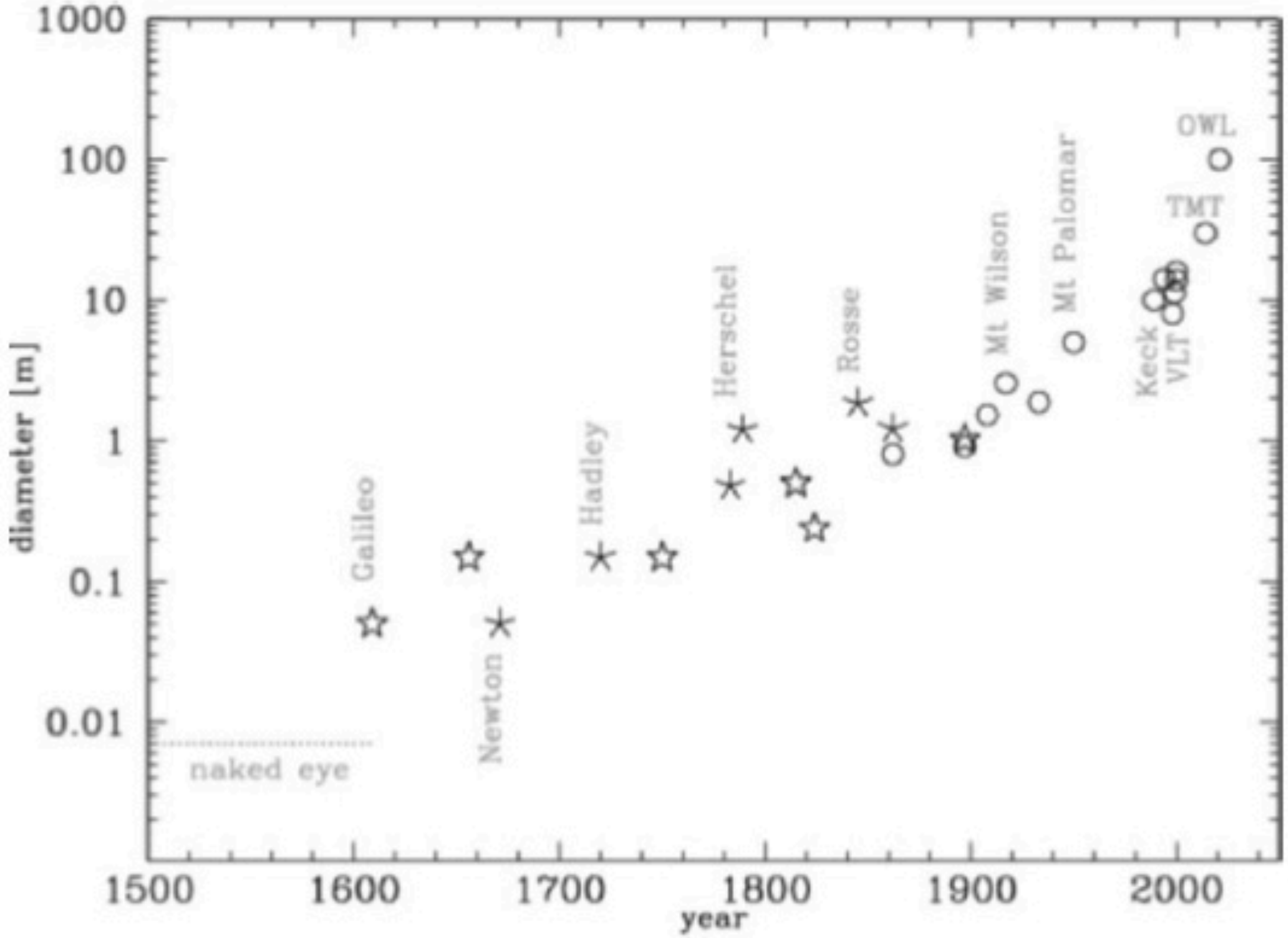
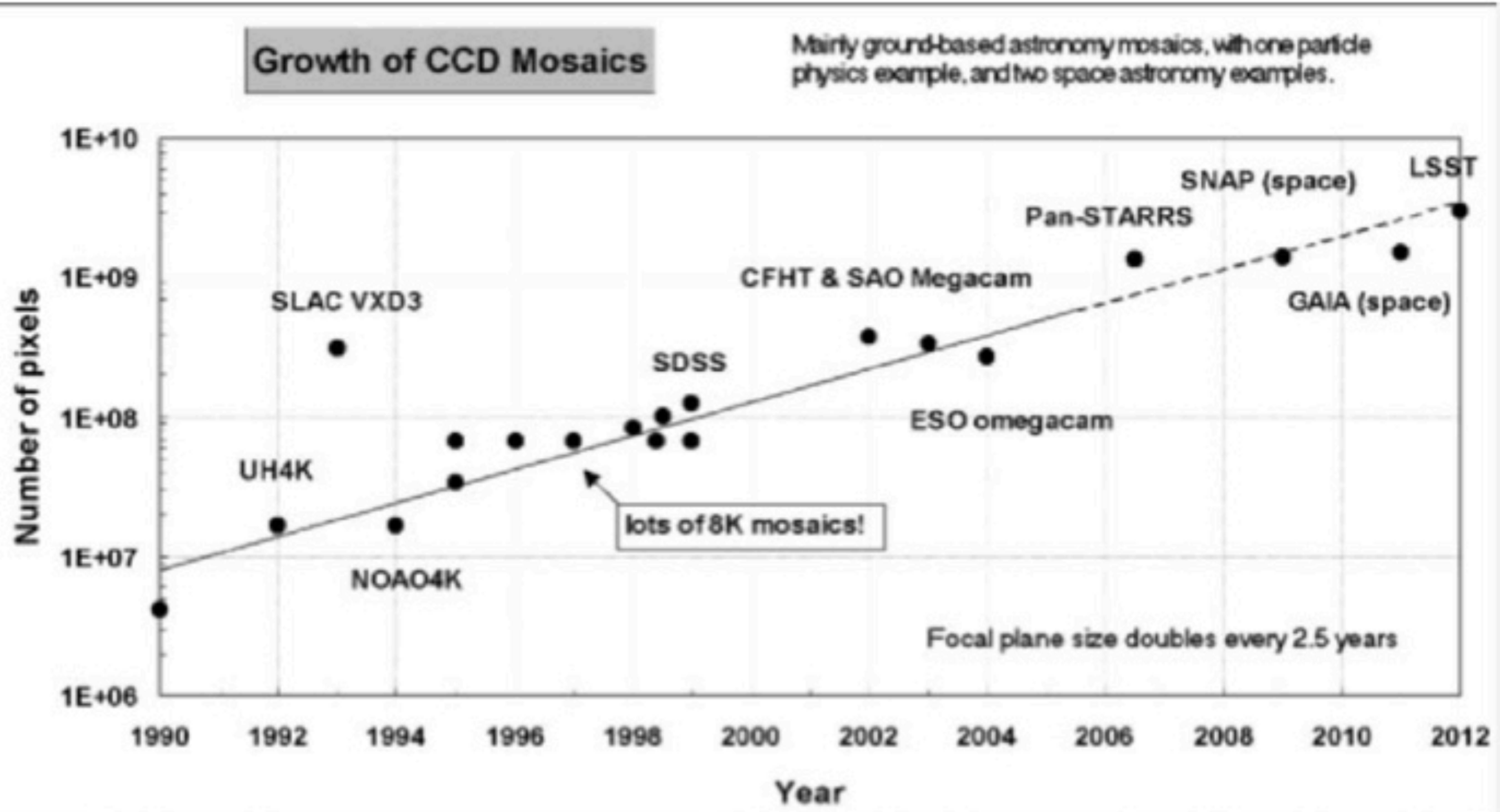


Figure 1. Brief history of the telescope. *Stars*: refractors, *asterisks*: speculum reflectors, *circles*: glass reflectors. A few telescopes are named.


Growth of CCD Mosaics
Mainly ground-based astronomy mosaics, with one particle physics example, and two space astronomy examples.
1E+10
1E+09
1E+08
1E+07
1E+06
Number of pixels
LSST
SNAP (space)
Pan-STARRS
CFHT & SAO Megacam
GAIA (space)
SLAC VXD3
SDSS
ESO omegacam
UH4K
lots of 8K mosaics!
NOAO4K
Focal plane size doubles every 2.5 years
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year

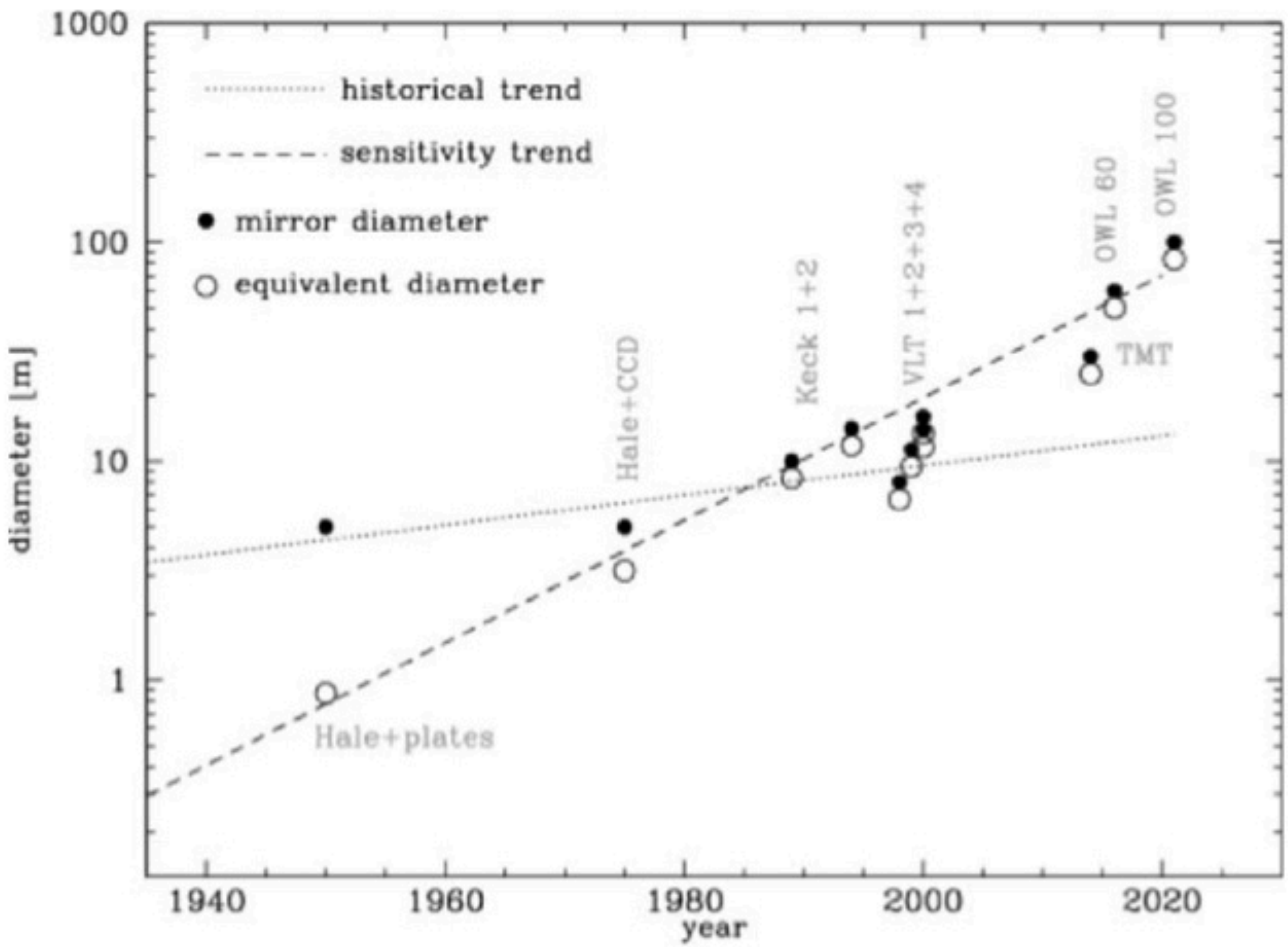
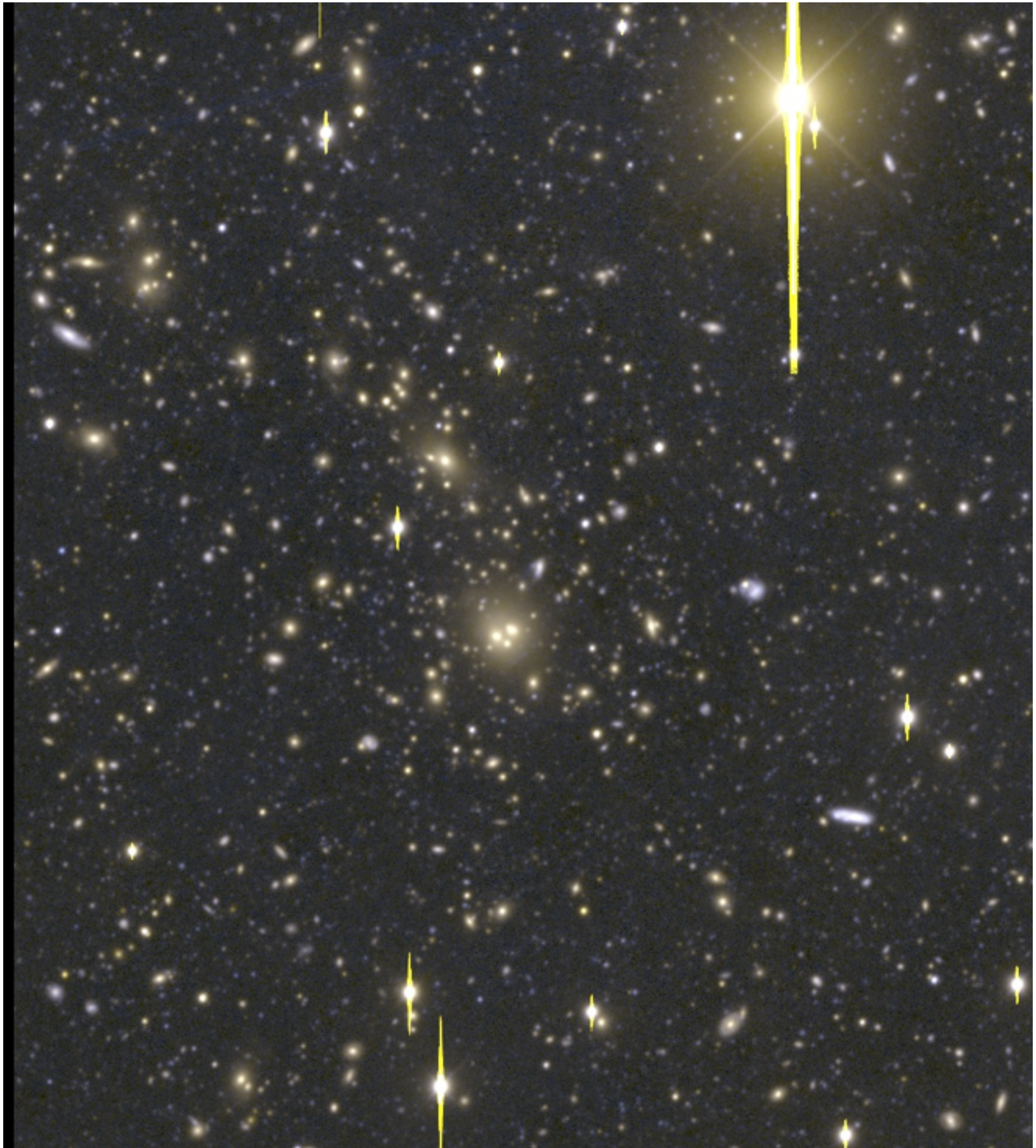


Figure 2. Recent history of improvement in sensitivity of telescopes expressed in "equivalent diameter of a perfect telescope" = $\sqrt{(\eta D^2)}$, with η the telescope overall efficiency (the dashed line is an aid to the eye, not a fit).

Gilmozzi (2005)



http://www.astr.ua.edu/keel/techniques/a2125mos2wf.jpg