Astronomical Charge Coupled Devices (CCDs)

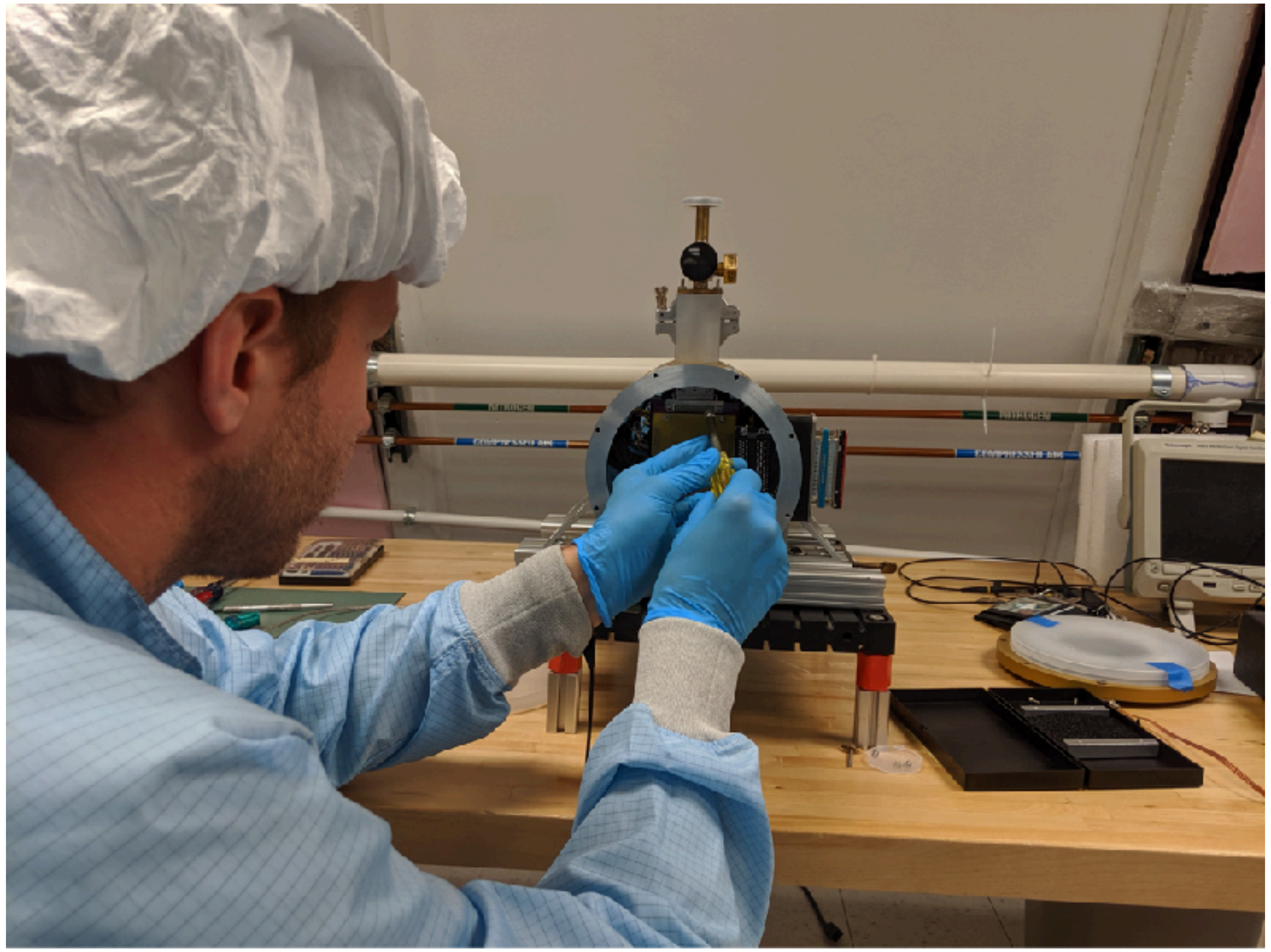
Alex Drlica-Wagner (he/him)

LSST-DA DSFP

Sep 15 2025

Introduction

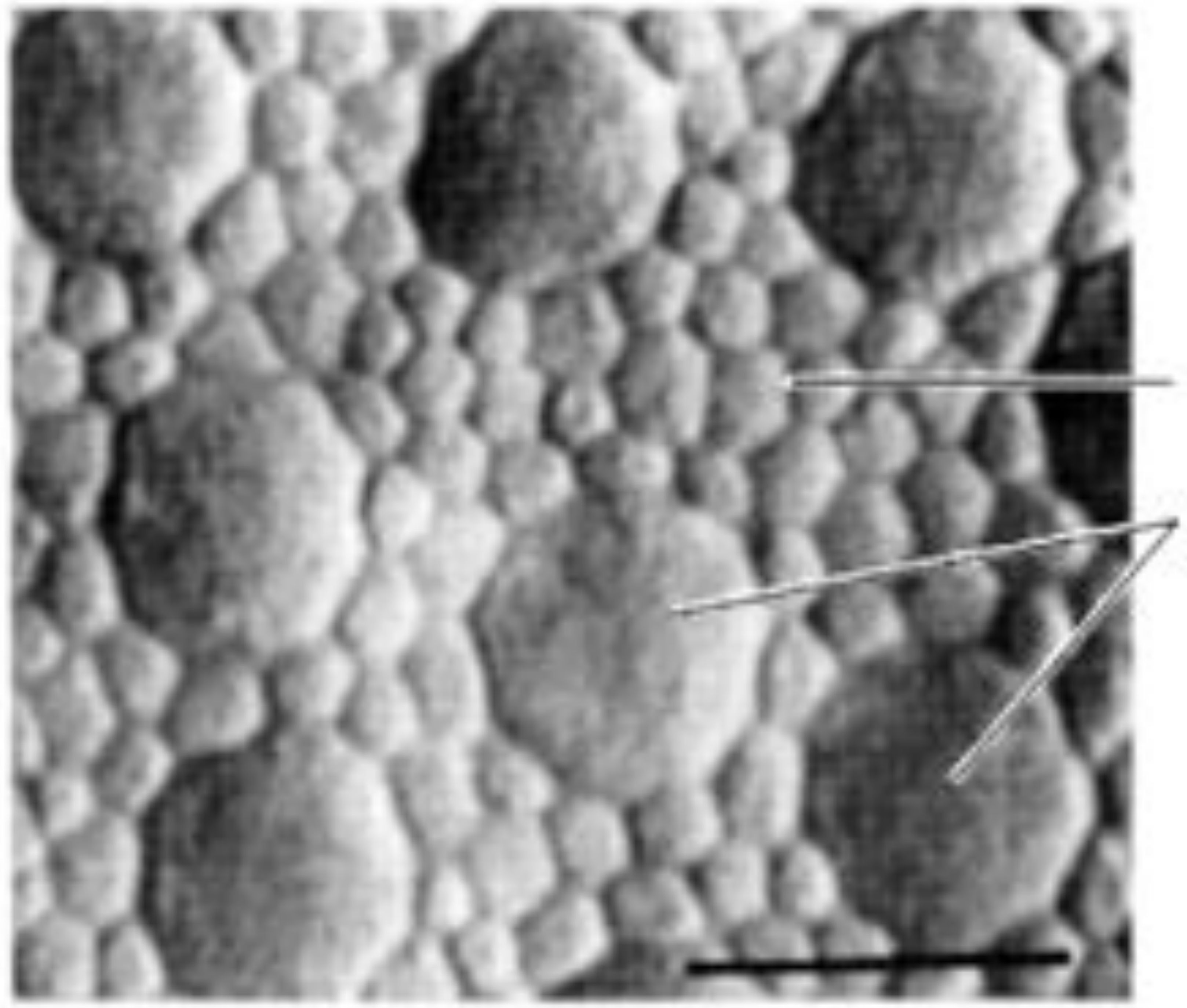
Introduction



Introduction

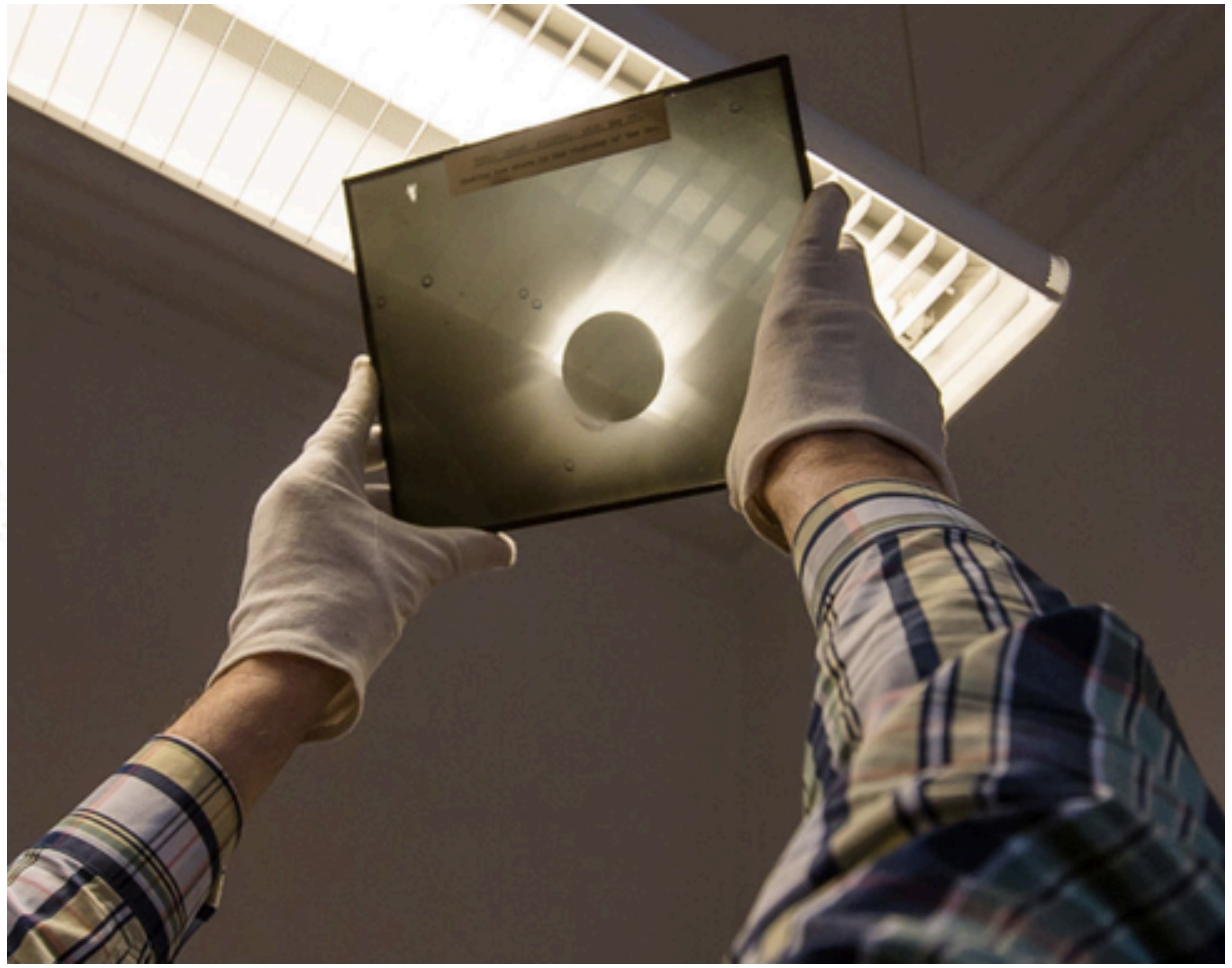
Photon Detectors

Rods & Cones of the Retina



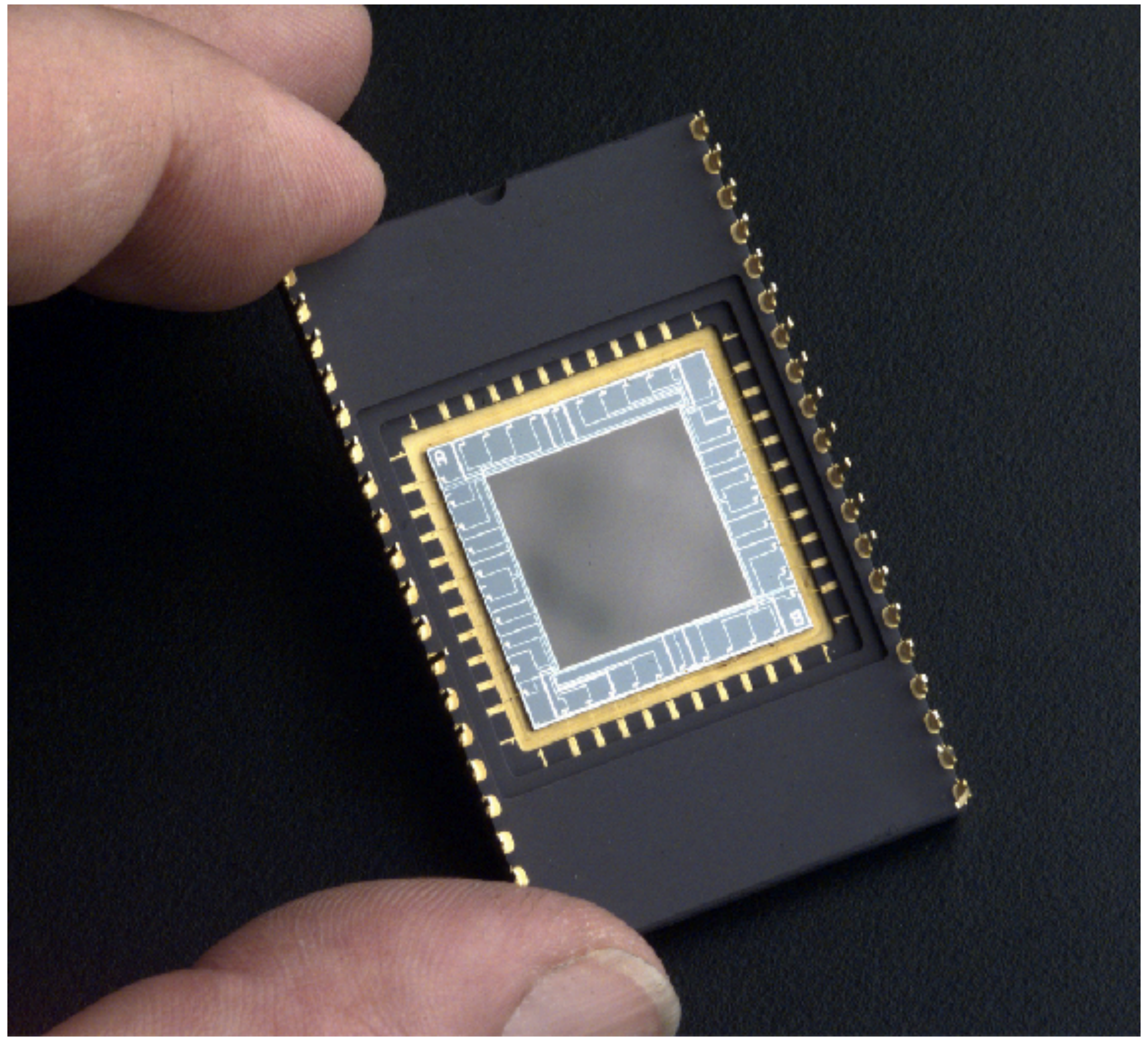
Biological Detectors

Photographic Plate



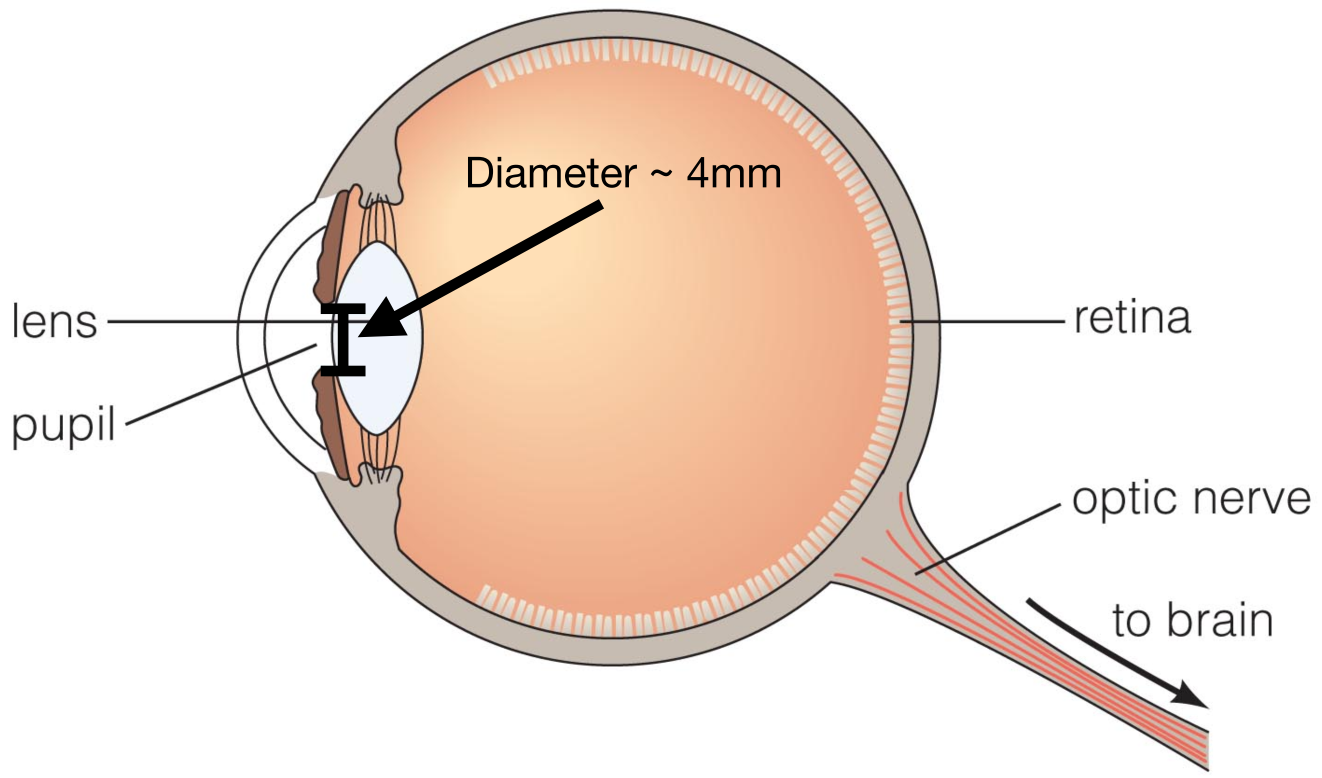
Chemical Detectors

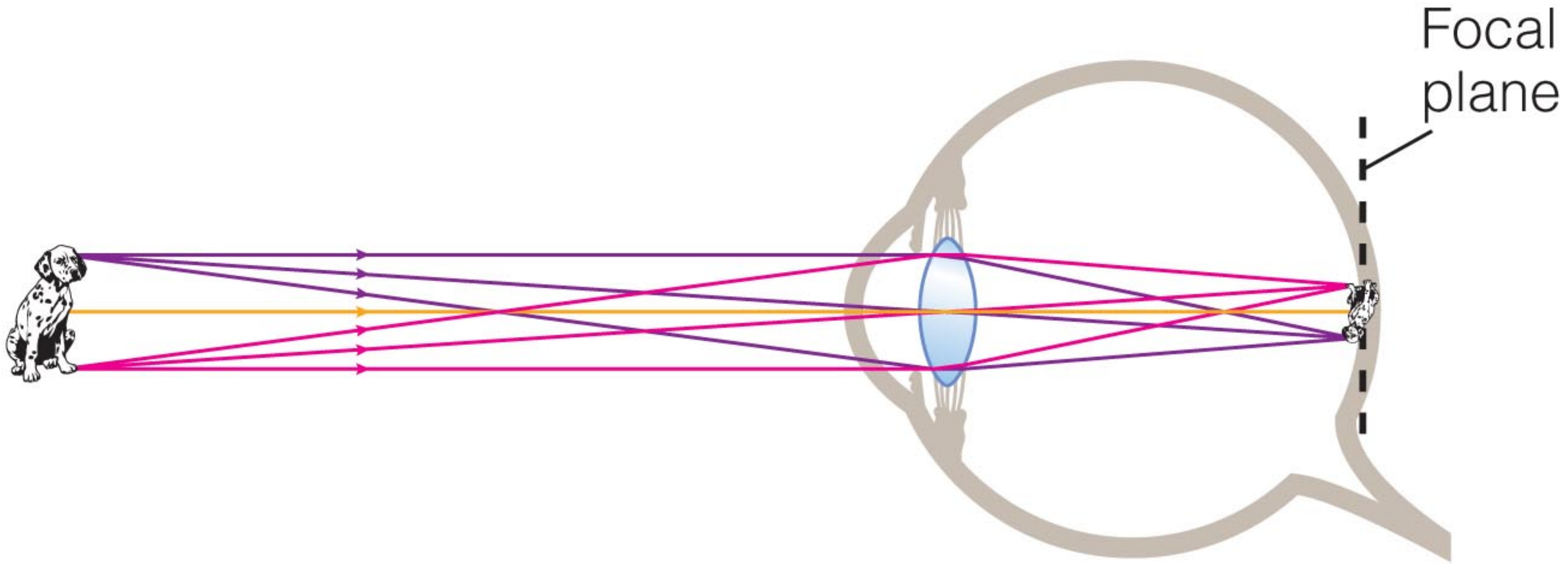
CCD Detector



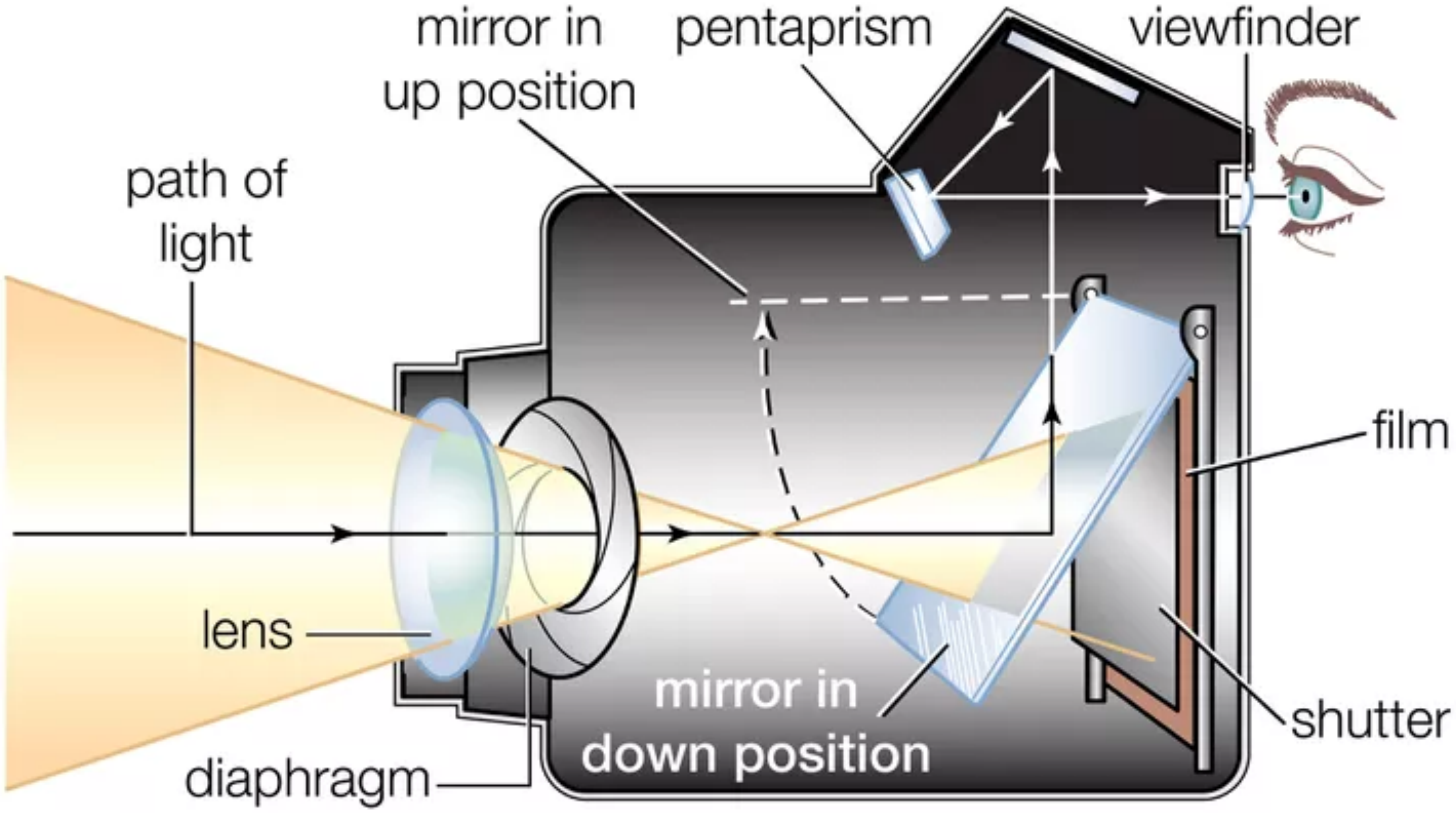
Solid State Detectors

“Telescopes”

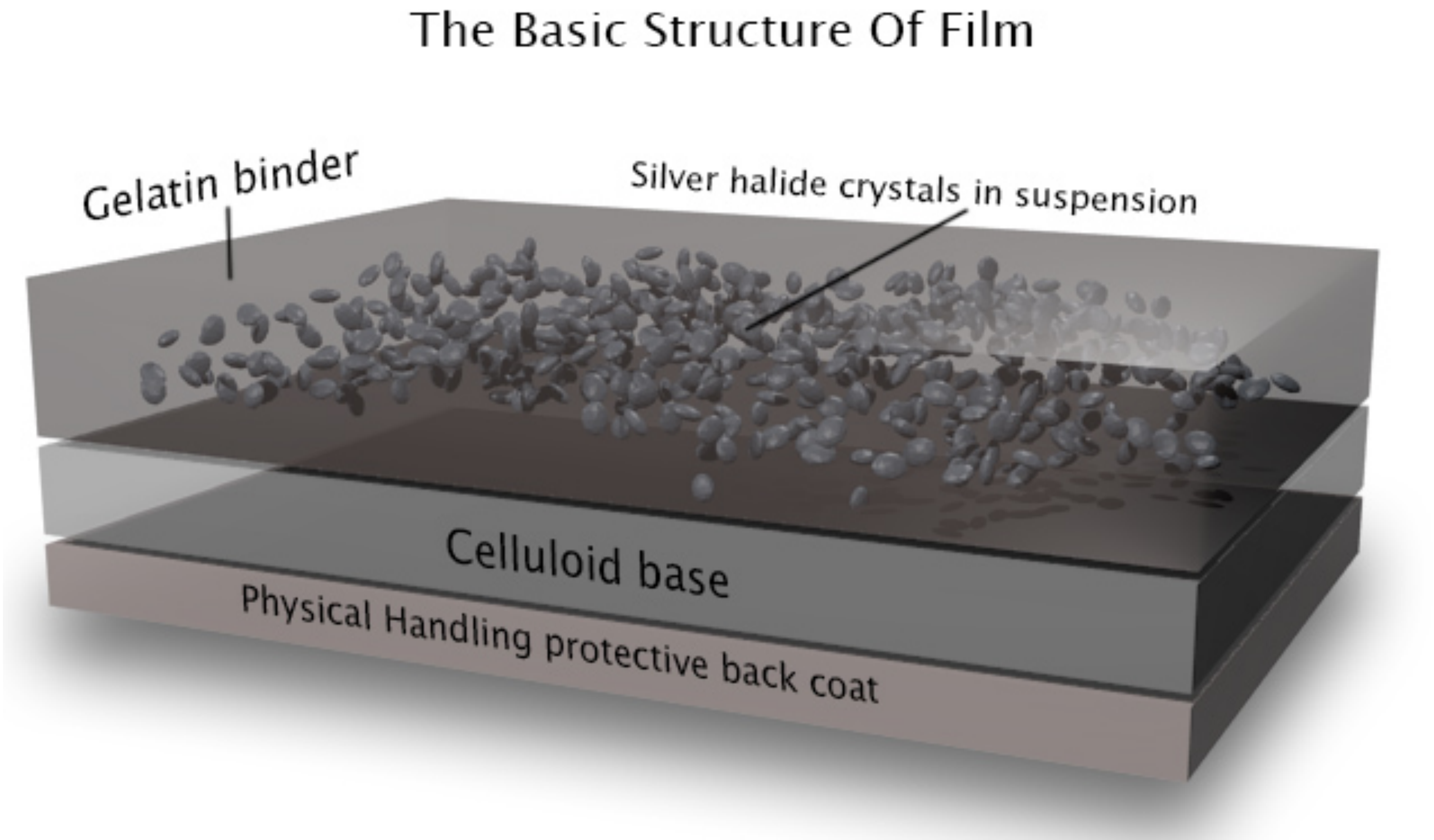

Diameter ~ 4mm
lens
pupil
retina
optic nerve
to brain

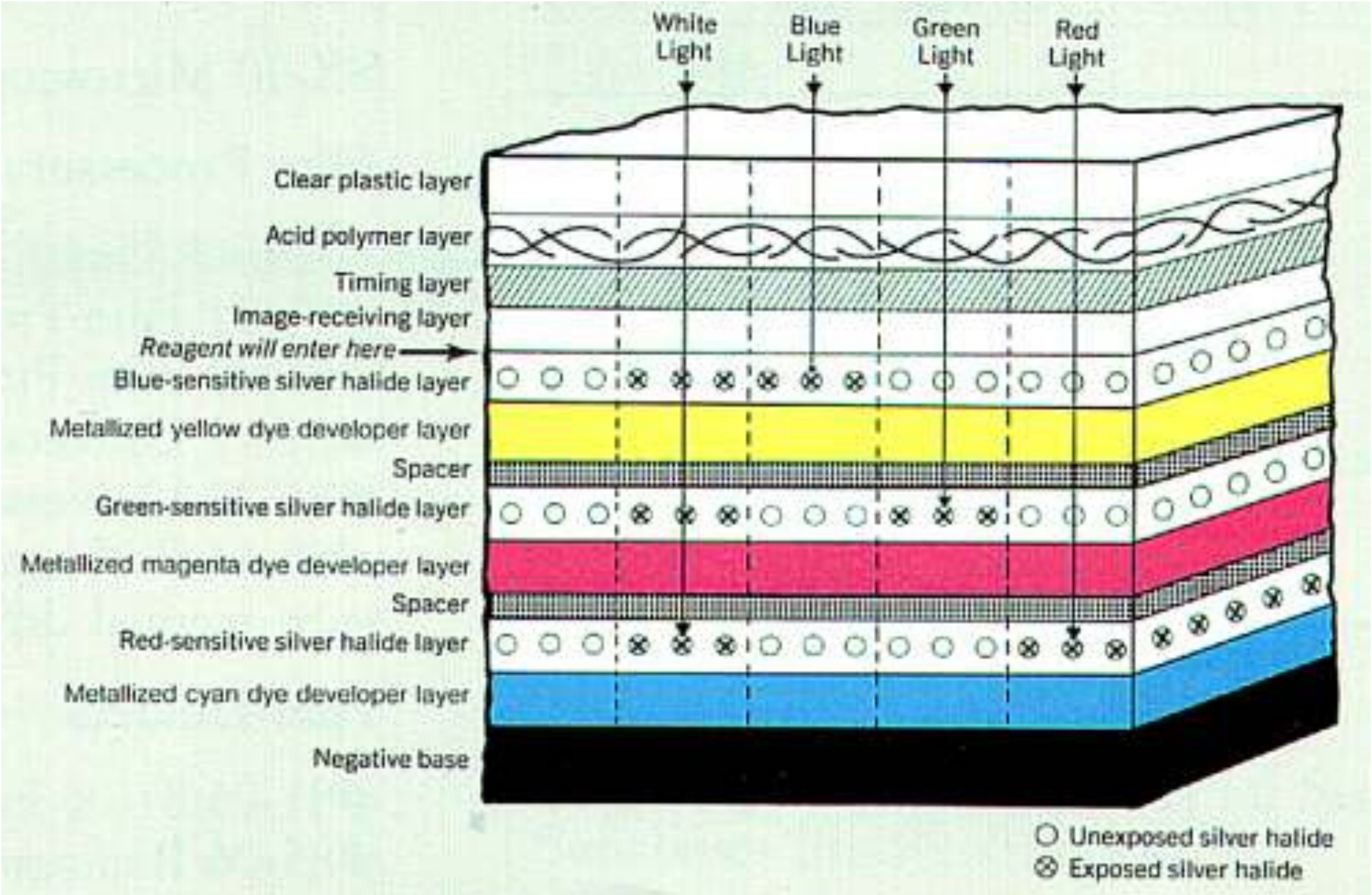

Focal plane

“Telescopes”


mirror in
up position
pentaprism
viewfinder
path of
light
film
lens
shutter
mirror in
down position
diaphragm

Film





1972. A schematic of SX-70 film during exposure.

UChicago Astronomy & Astrophysics (c. 1921)

Huge dome for a 1m (40”) telescope!

THE

ASTROPHYSICAL JOURNAL

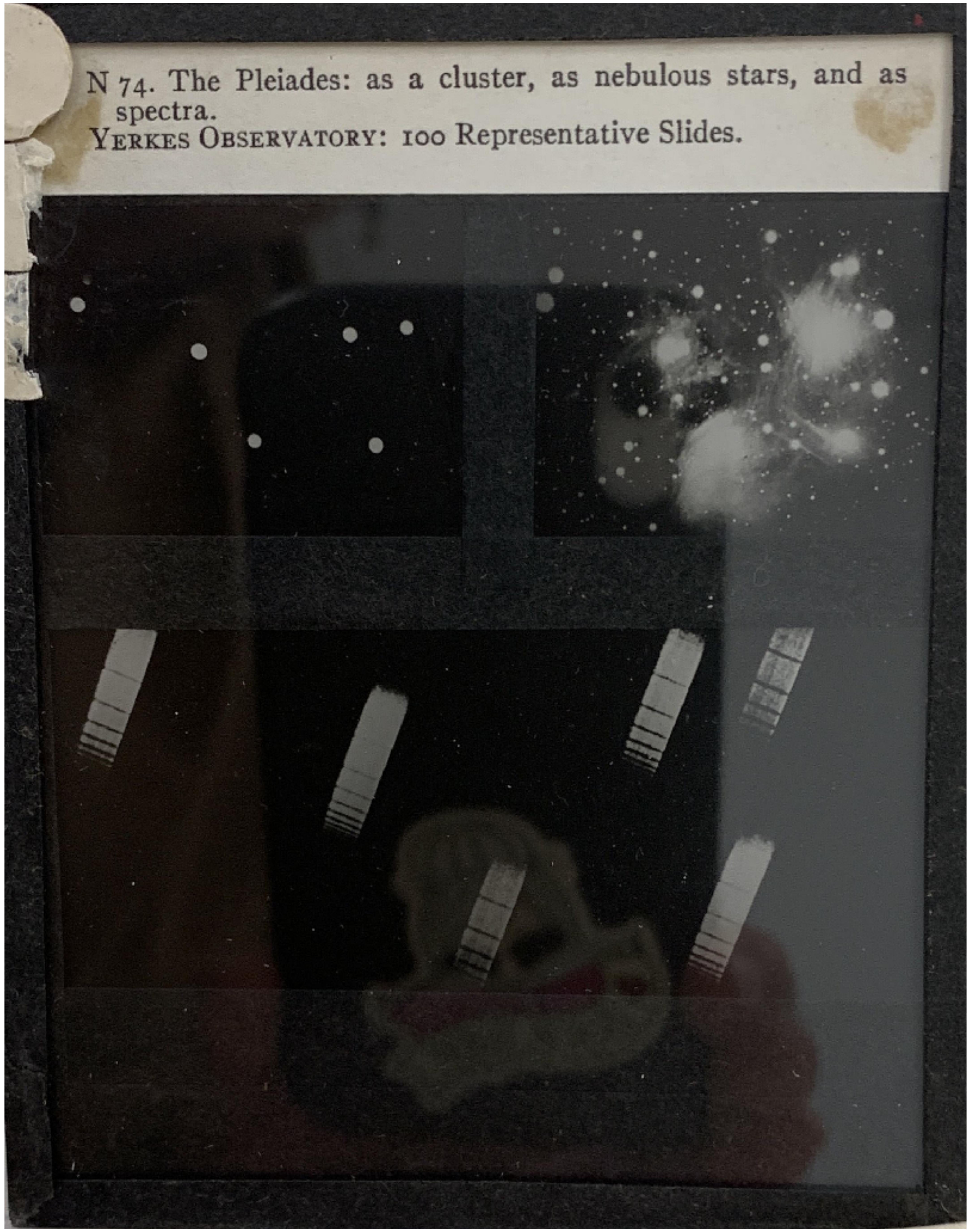
AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME XXXVI OCTOBER 1912 NUMBER 3

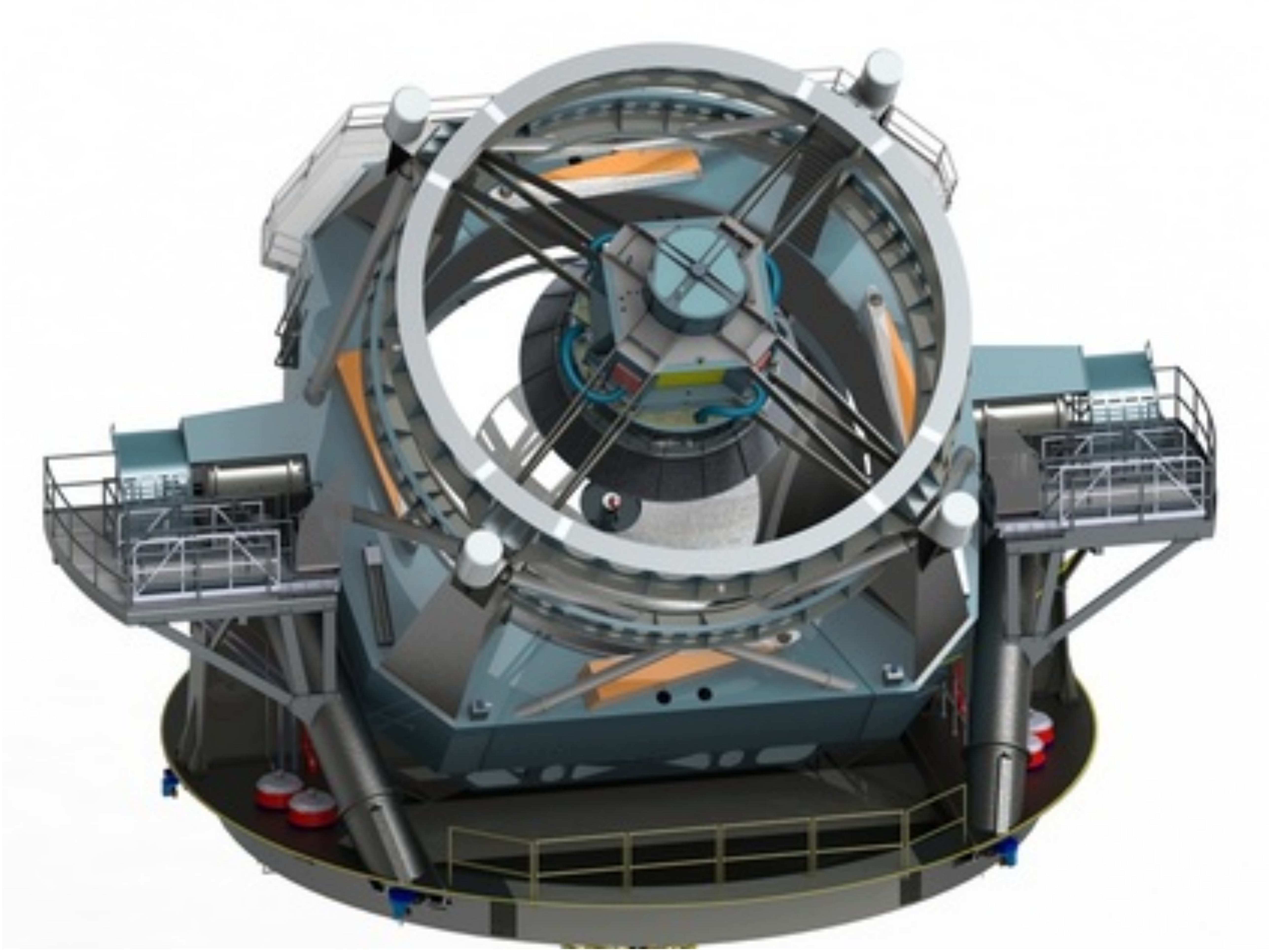
YERKES ACTINOMETRY

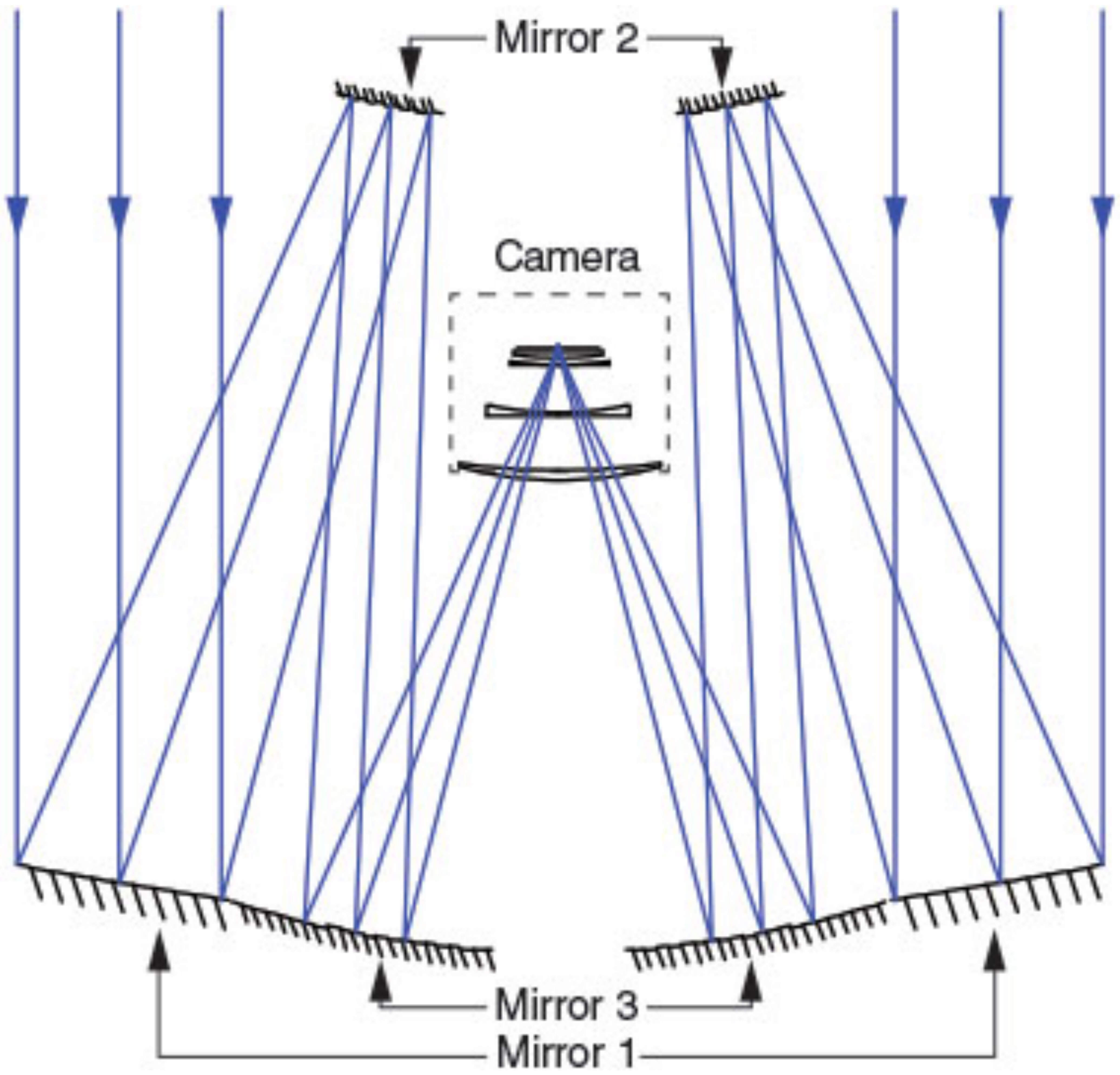
ZONE +73° TO +90°

BY J. A. PARKHURST

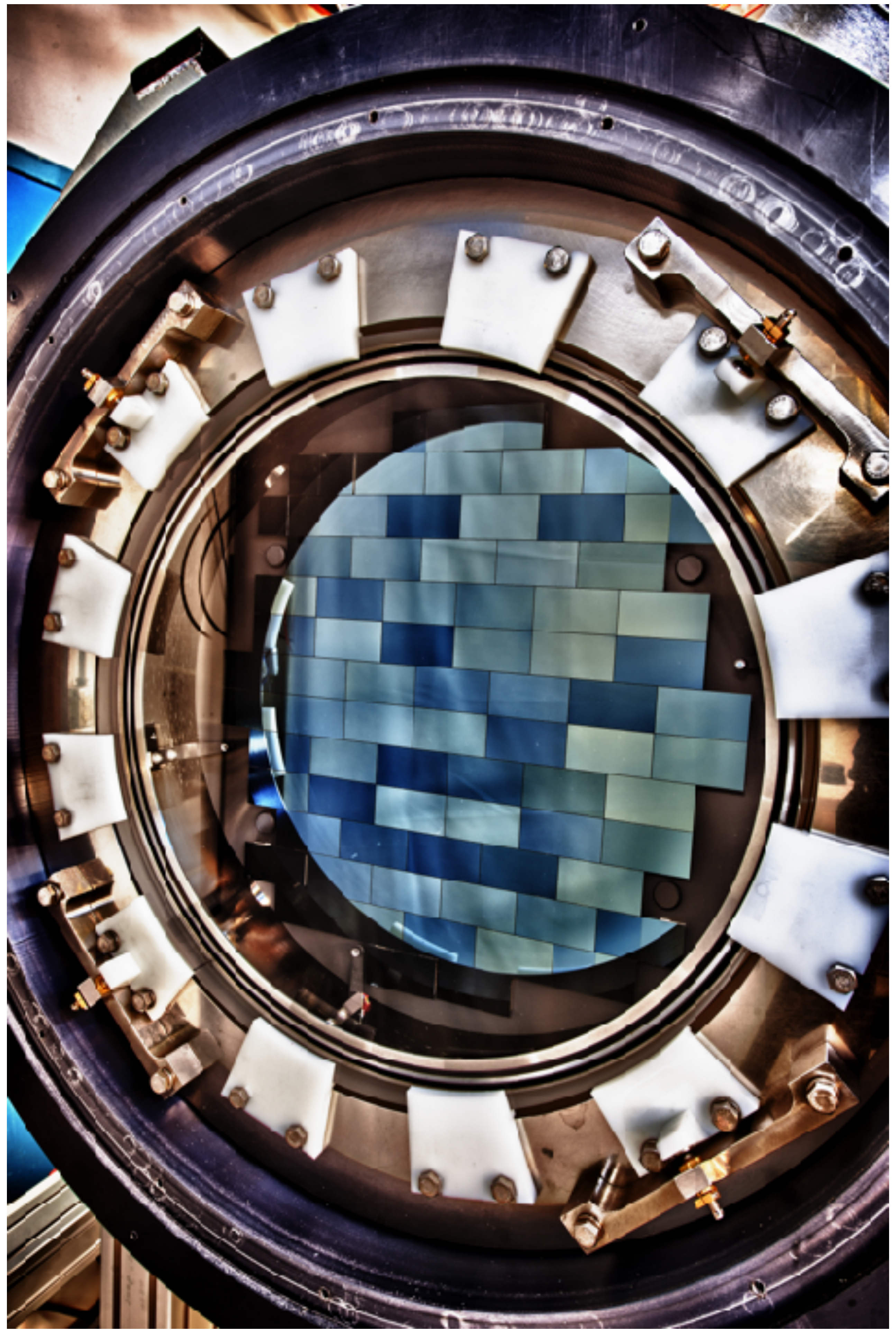


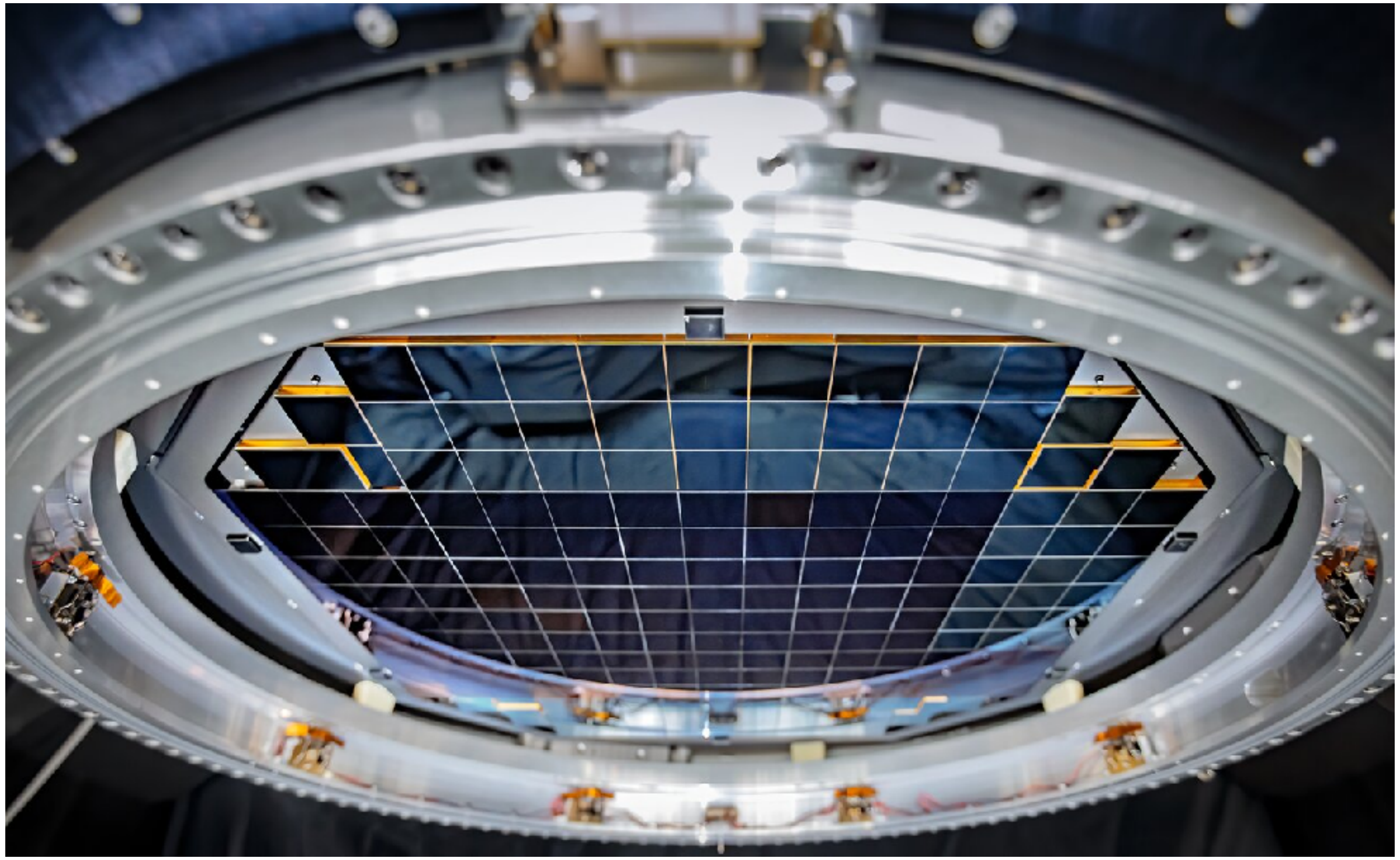
“Telescopes”





“Digital Cameras”





Desirable Properties of a Detector

- Detect every photon that hits the detector
- Determine exactly where each photon hits the detector
- Cover a large area contiguously (no gaps)
- Determine the energy of each photon that hits the detector
- Tag the timing of each photon
- Measure the polarization of each photon
- Do all this “cleanly” (i.e., without introducing noise or artifacts)

2009 Nobel Prize in Physics awarded to the inventors of the CCD

In 1969, Willard S. Boyle and George E. Smith invented the first successful imaging technology using a digital sensor, a CCD (charge-coupled device). The two researchers came up with the idea in just an hour of brainstorming.

Bell Labs researchers Willard Boyle (left) and George Smith (right) with the charge-coupled device.
Photo taken in 1974. Photo credit: Alcatel-Lucent/Bell Labs.

The Nobel Prize in Physics 2009

"for the invention of an imaging semiconductor circuit – the CCD sensor"

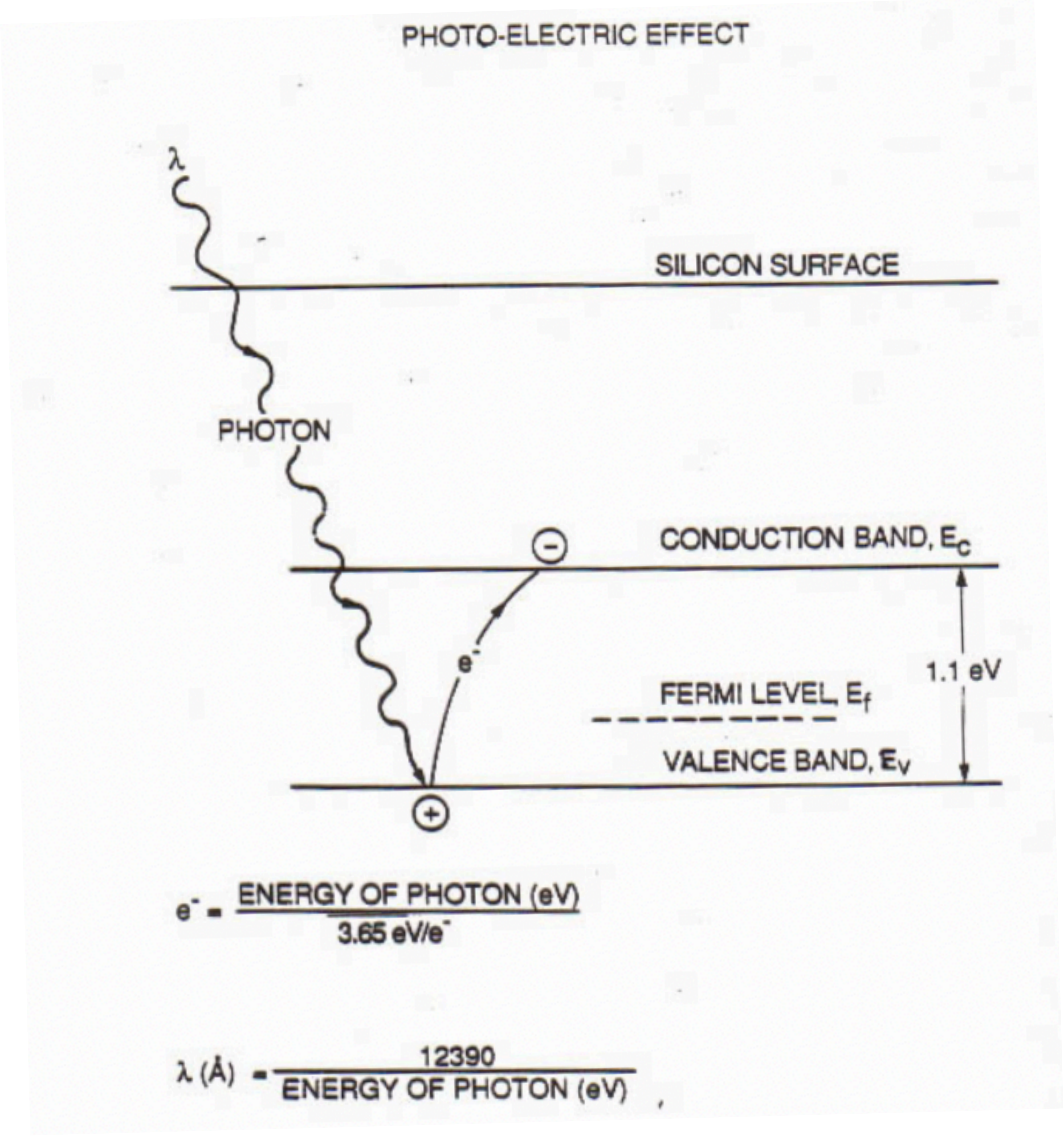
Willard S. Boyle

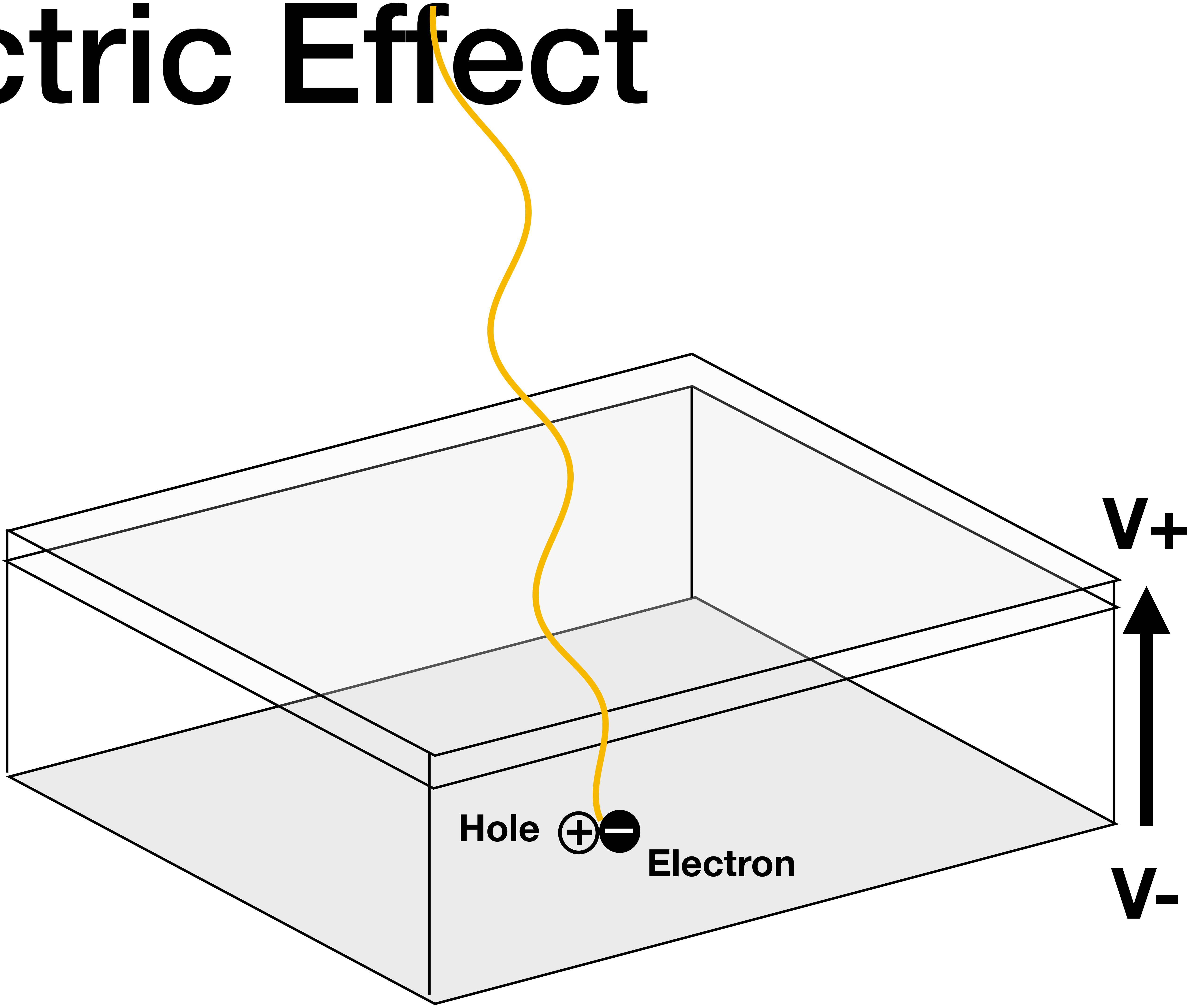
George E. Smith

CCDs

- Photoelectric effect
- The bucket brigade
- Readout chain (including gain & linearity)

Photoelectric Effect



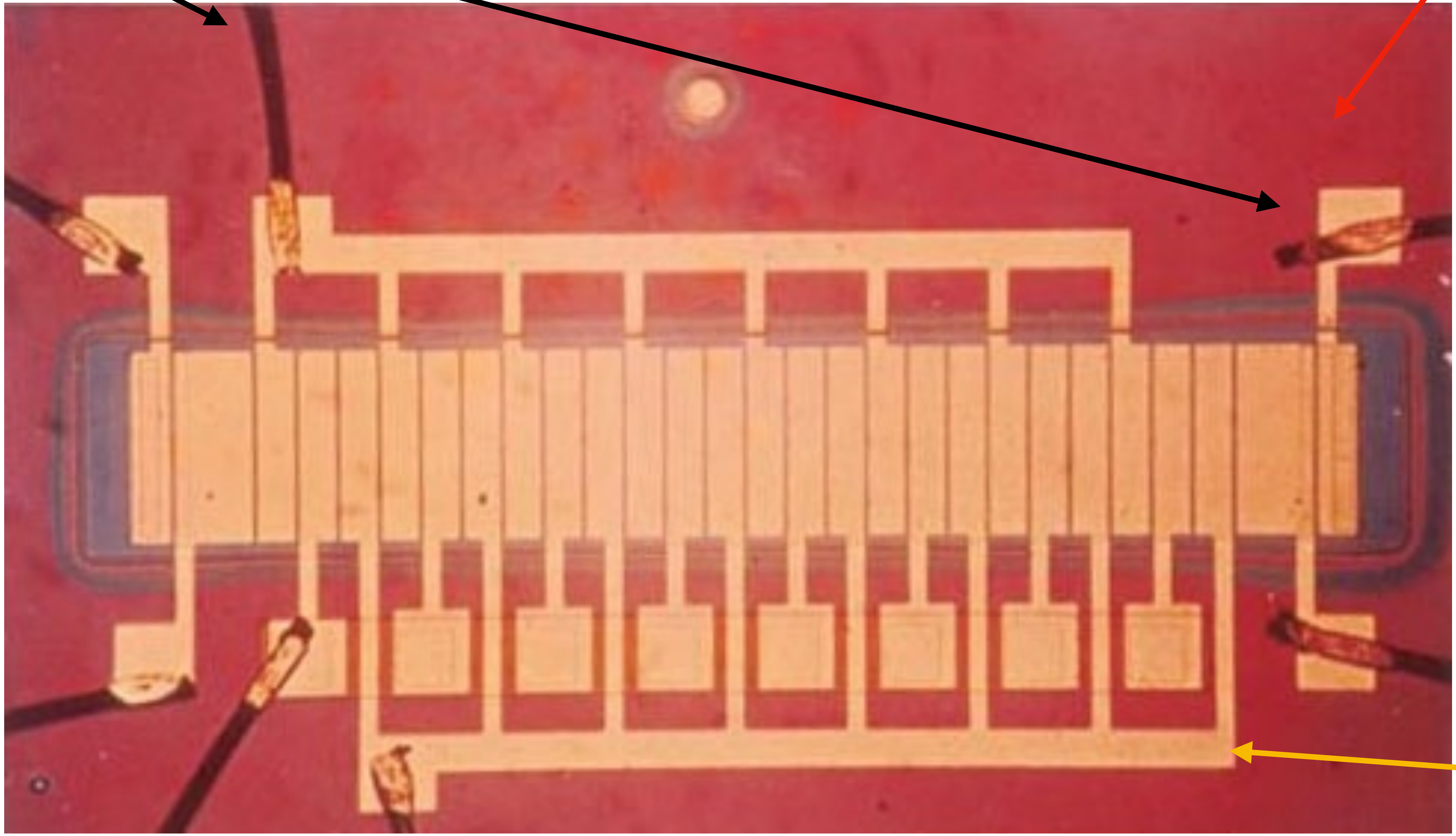


If you can confine and move the electron (or hole), you have an imaging sensor!

The First CCD

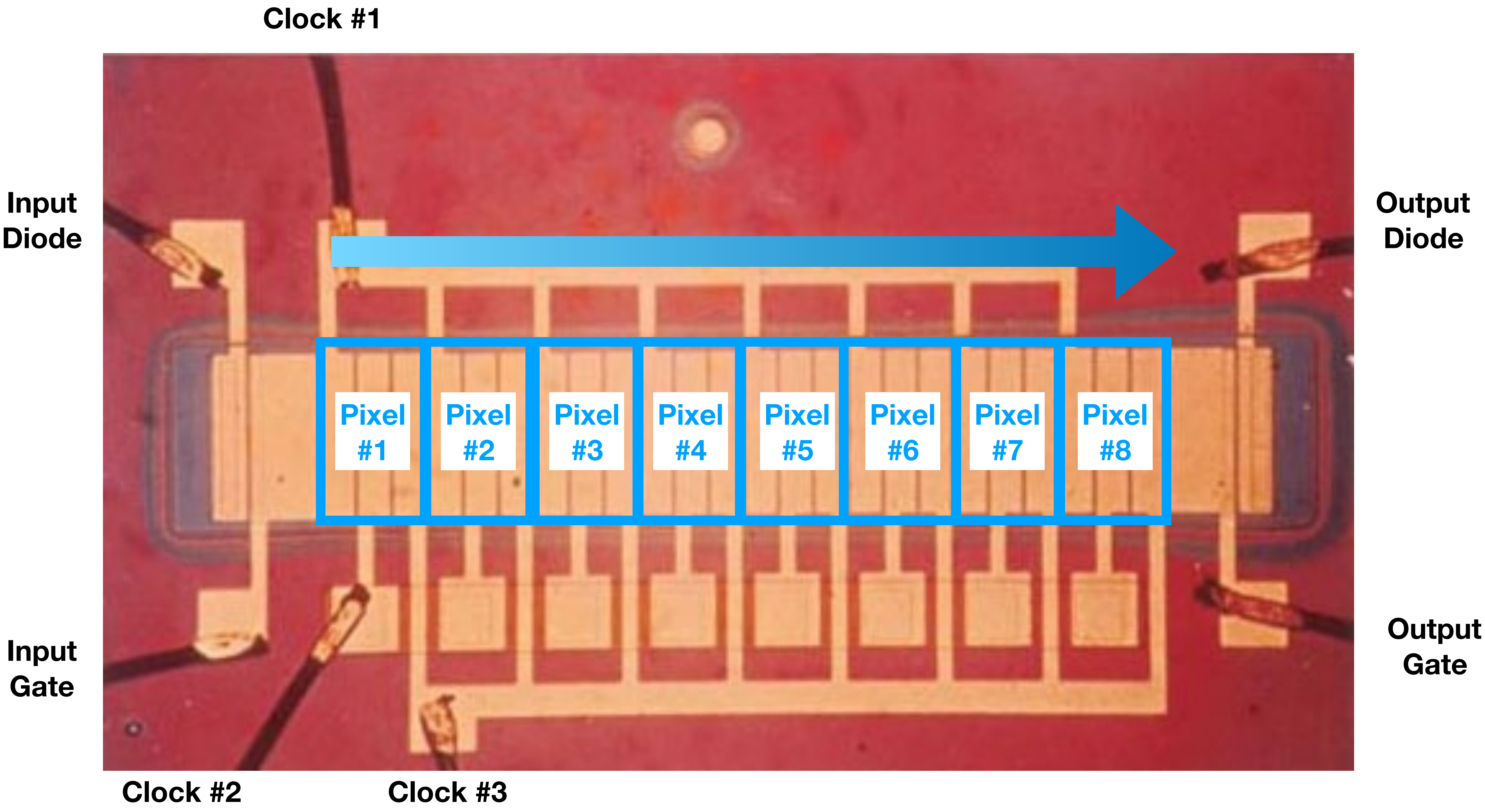
Smith (2010)

The First CCD



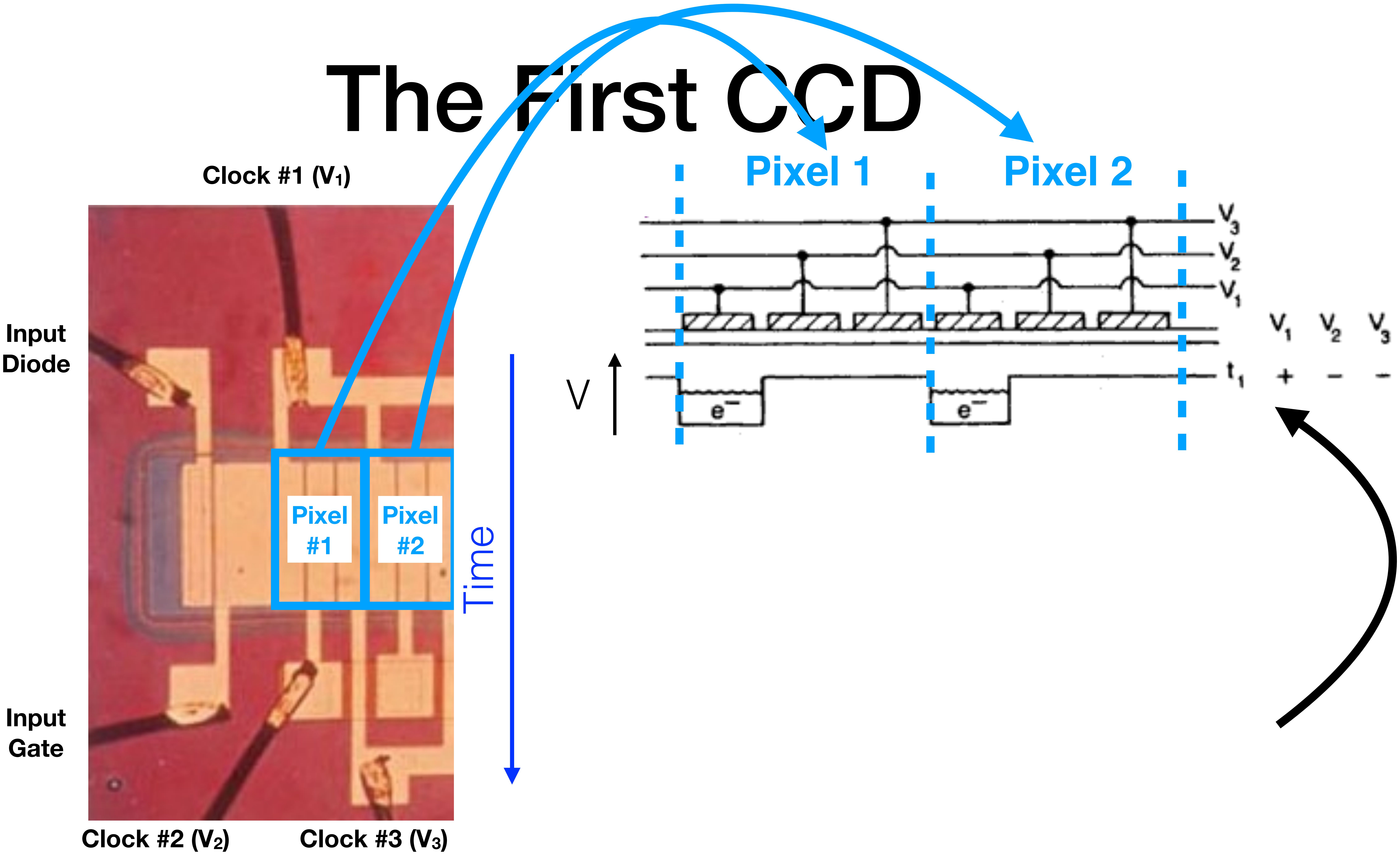
Smith (2010)

The First CCD



Smith (2010)

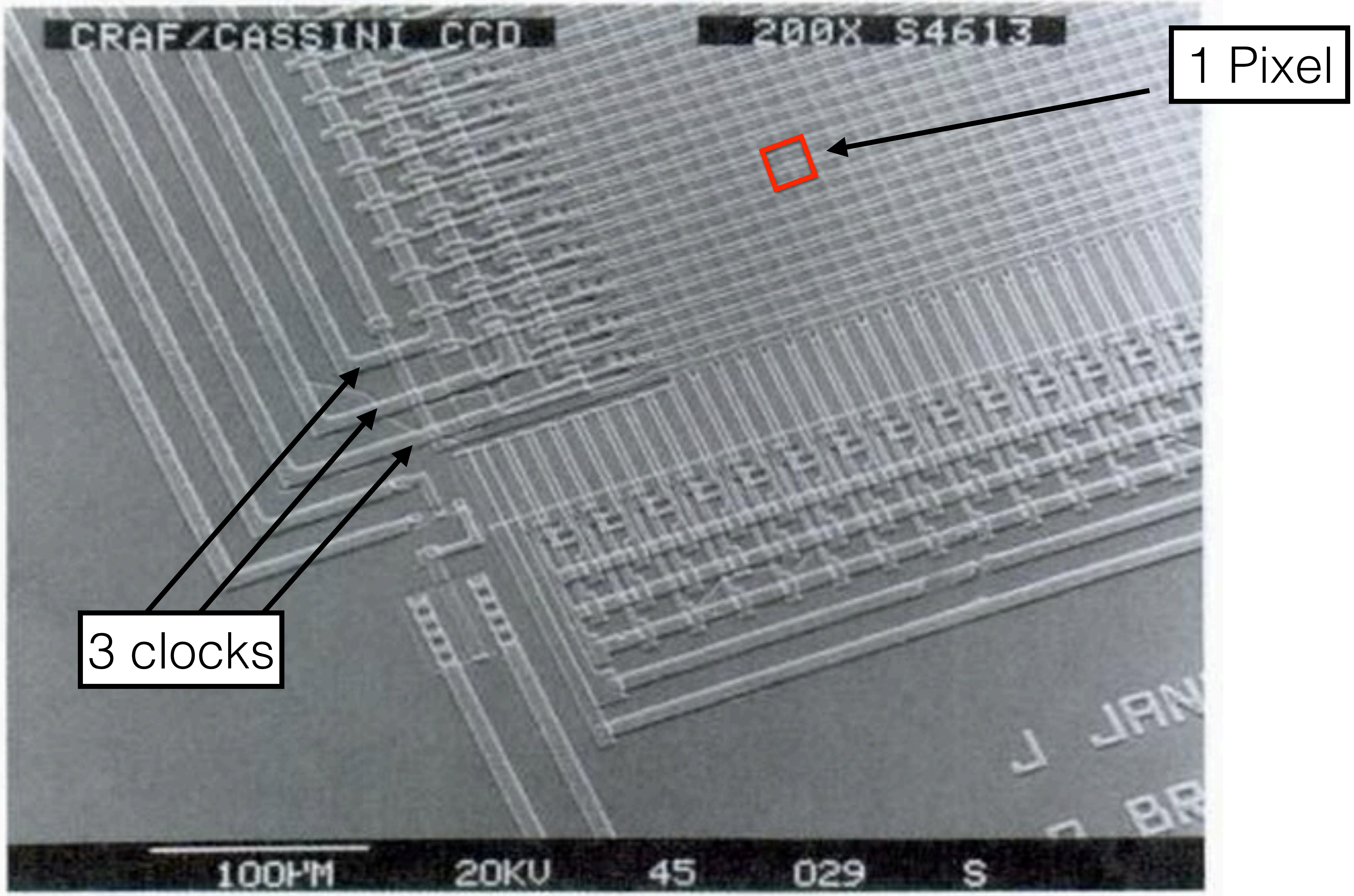
The First CCD



Smith (2010)

A DECam CCD has 8 million+ pixels controlled by only 15 clocks (timed voltage shifts)!

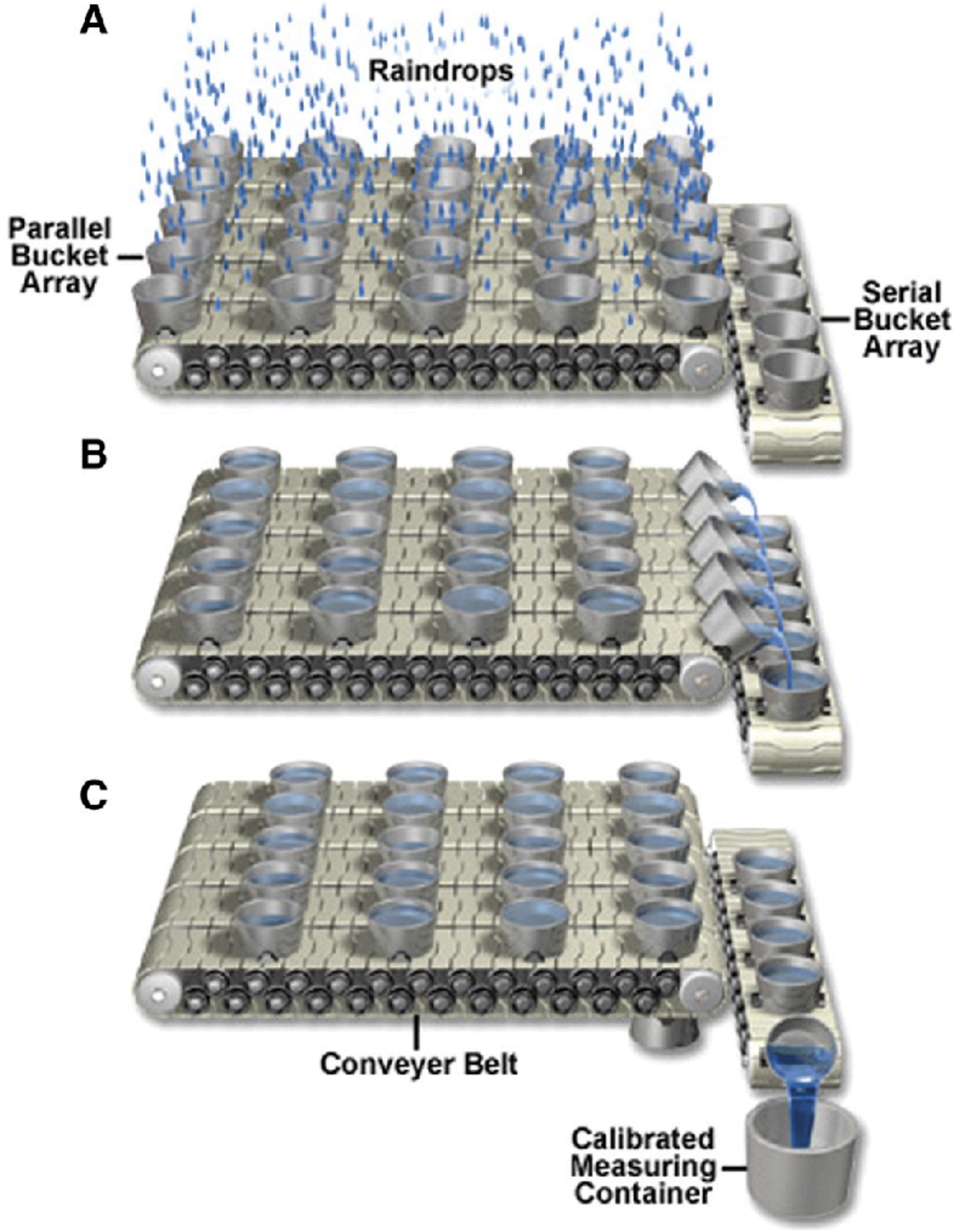
CCD's are not especially fast compared to CMOS (in your phone), but they are very stable and well controlled

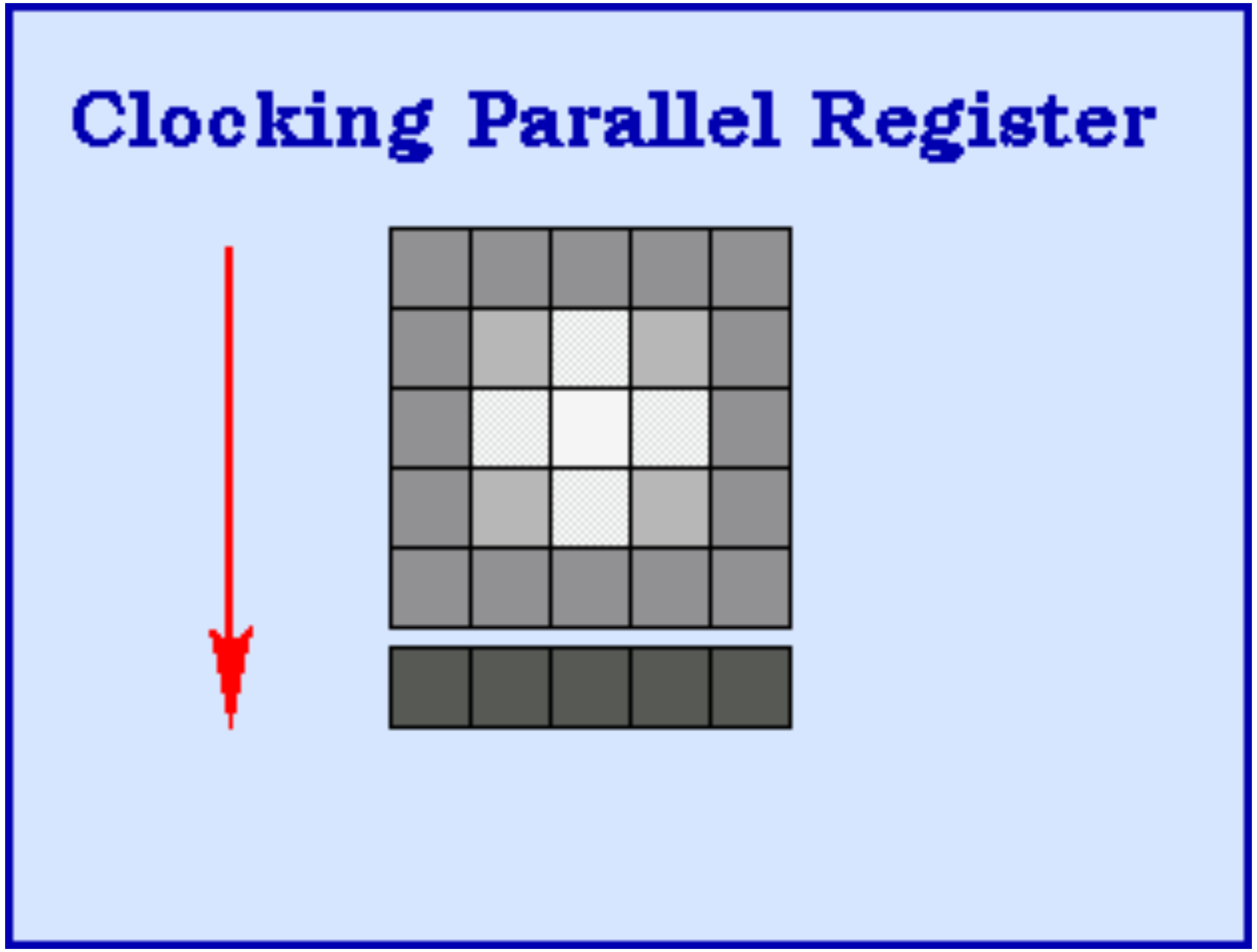


Janesick 2001

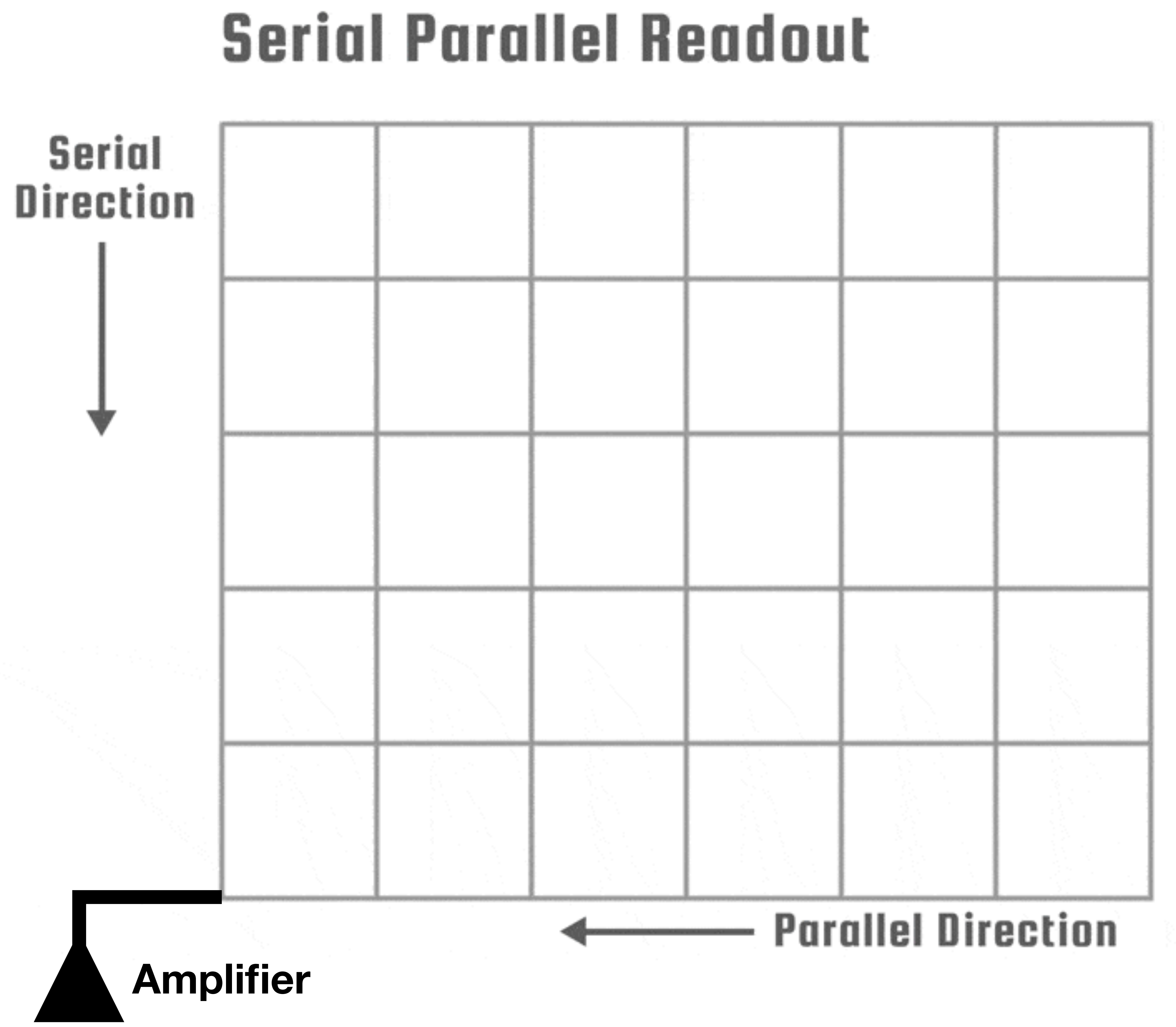
Figure 1.12(i) SEM photograph of the amplifier region.

Bucket Brigade





Readout



Serial Parallel Readout
Serial
Direction
Parallel Direction
Amplifier

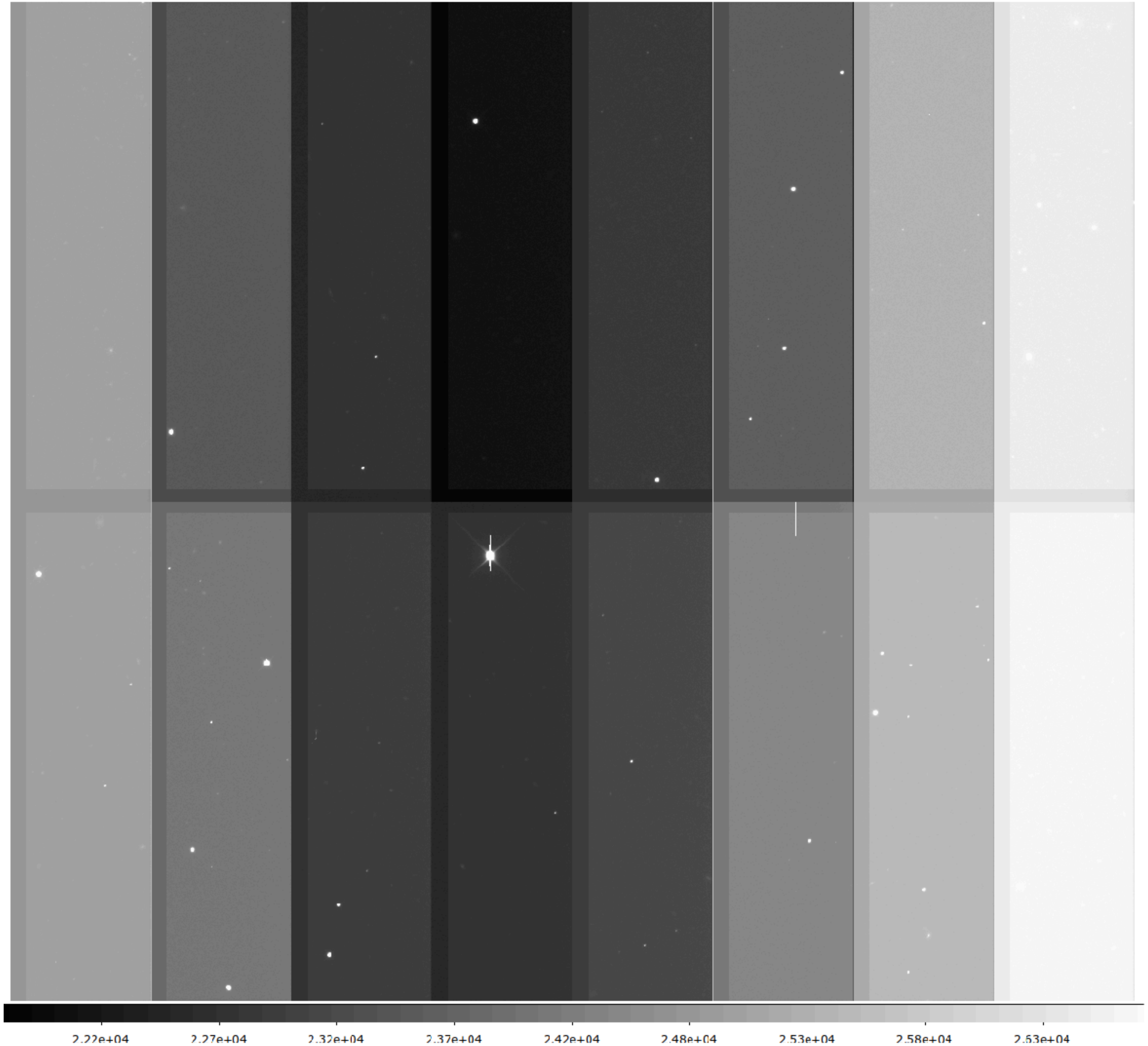
More output channels, more speed!

LSSTCam CCDs have 16 output channels.

However, each amplifier and electronic chain is different…

More amplifiers, more problems!

(CMOS…)



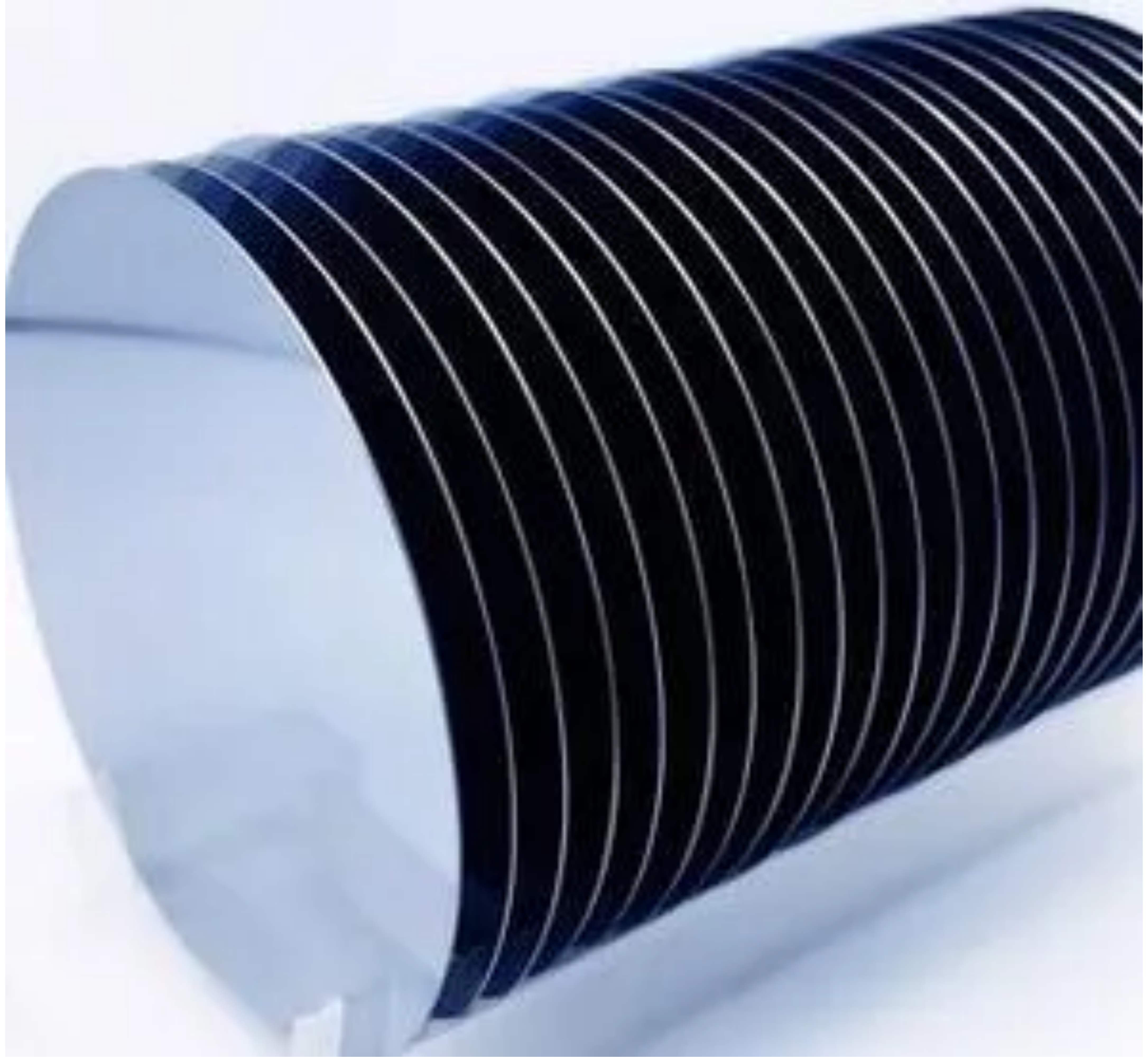
Performance of each amplifier can be calibrated by reading "extra" pixels

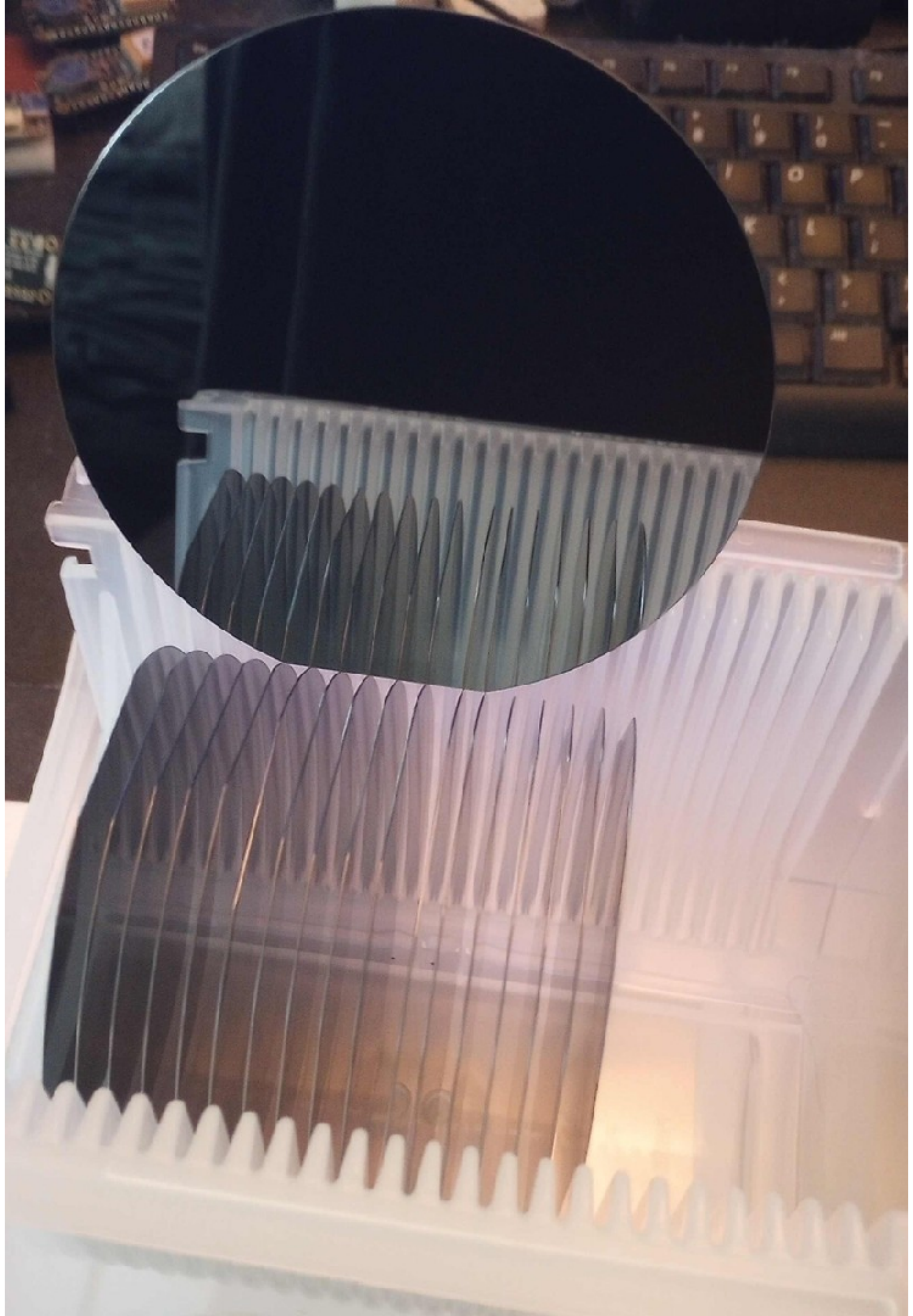
Overscan pixels are "virtual" pixels read after the image region.

Quantum Efficiency

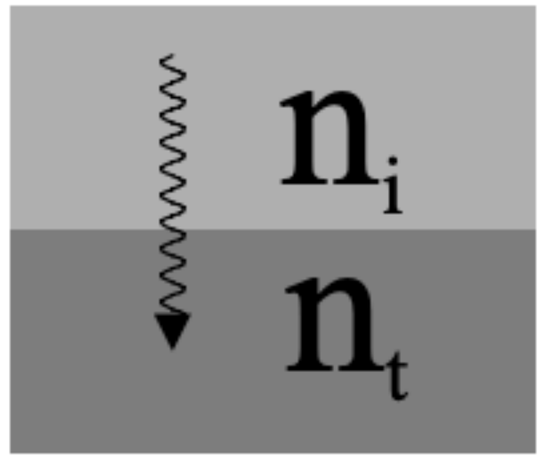
- Surface coating
- Blue and red sensitivity

Silicon Wafers



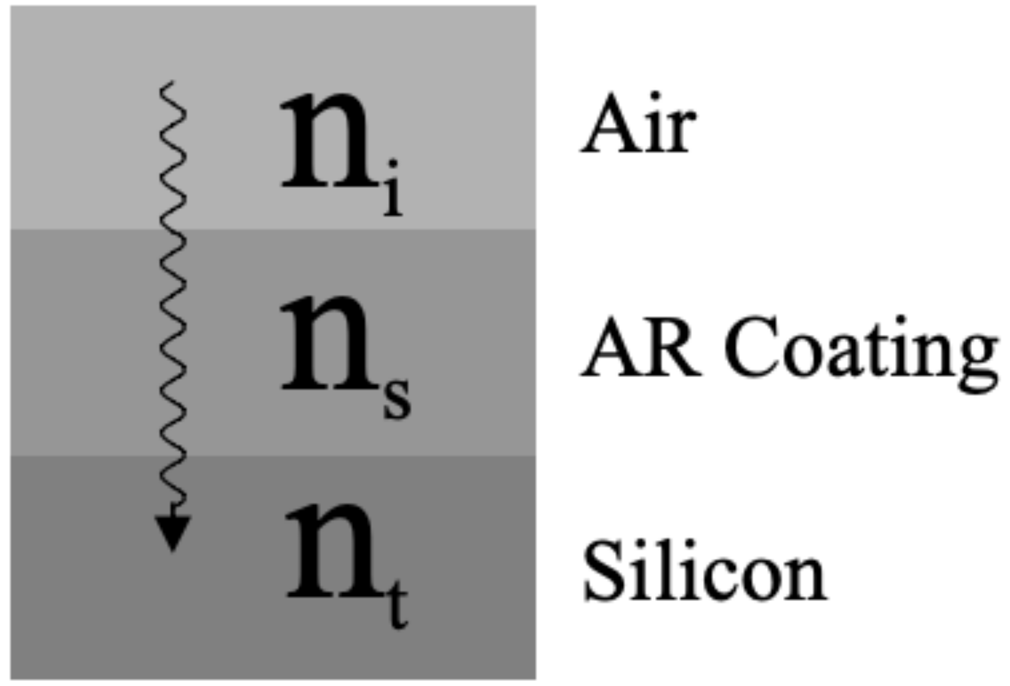


Anti-Reflective Coatings



$$\text{Fraction of photons reflected at the interface between two mediums of differing refractive indices} = \left[\frac{n_t - n_i}{n_t + n_i}\right]^2$$

n of air or vacuum is 1.0, glass is 1.46, water is 1.33, and silicon is **3.6!**
-> Window glass in air reflects 3.5% and silicon in air reflects 32%!



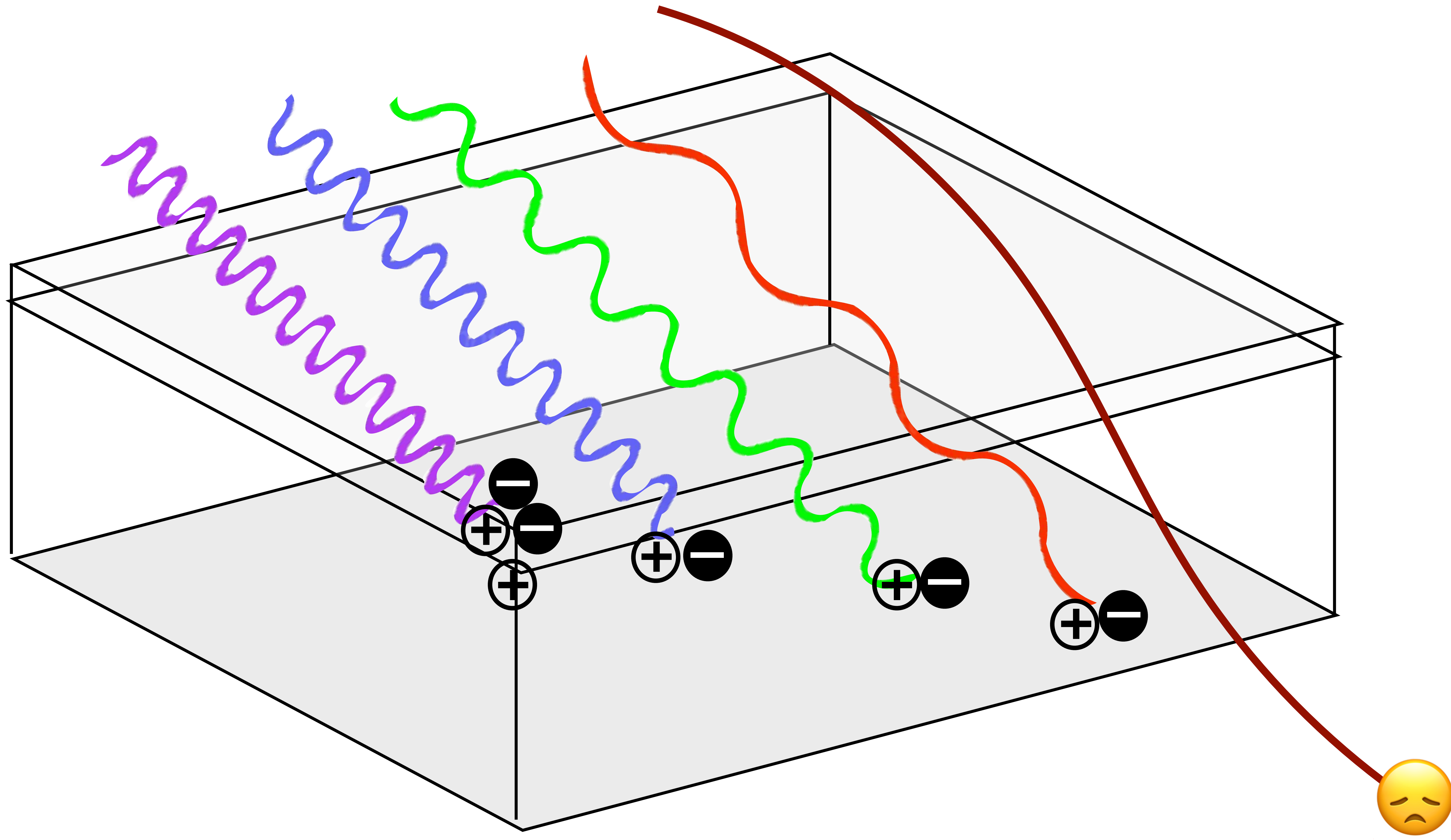
$$\left[\frac{n_t \times n_i - n_s^2}{n_t \times n_i + n_s^2}\right]^2$$

When $n_s^2 = n_t$ the reflectivity drops to 0!

However, there are many complexities to this…

Absorption Depth of Silicon

- For high QE in the infrared, need very thick detectors (~300um).
- For high QE in the UV, need to be able to capture charge created within ~10nm of the surface.
- Photons with energies > 3.6 eV have some probability of producing multiple electron-hole pairs ("quantum yield")



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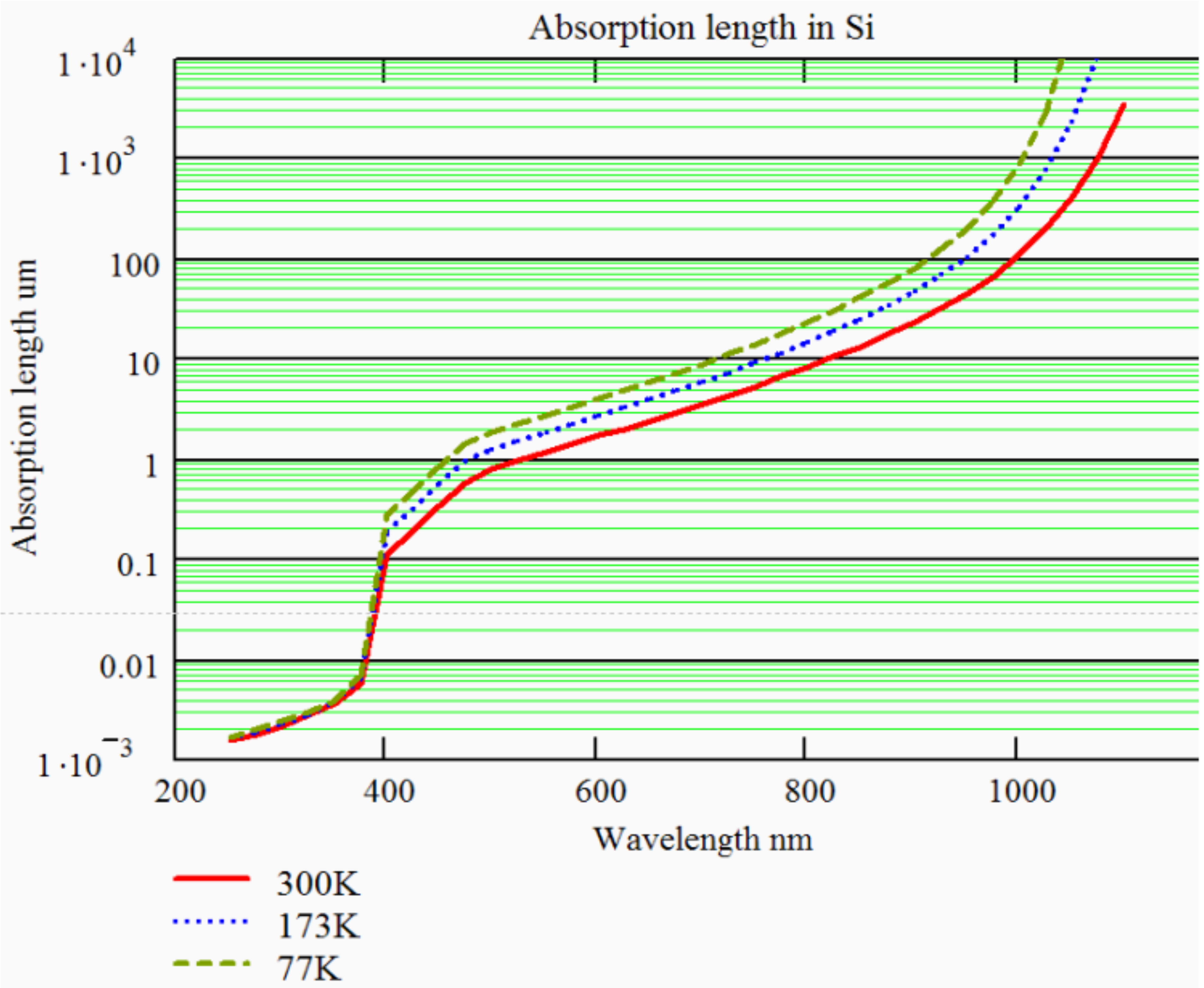
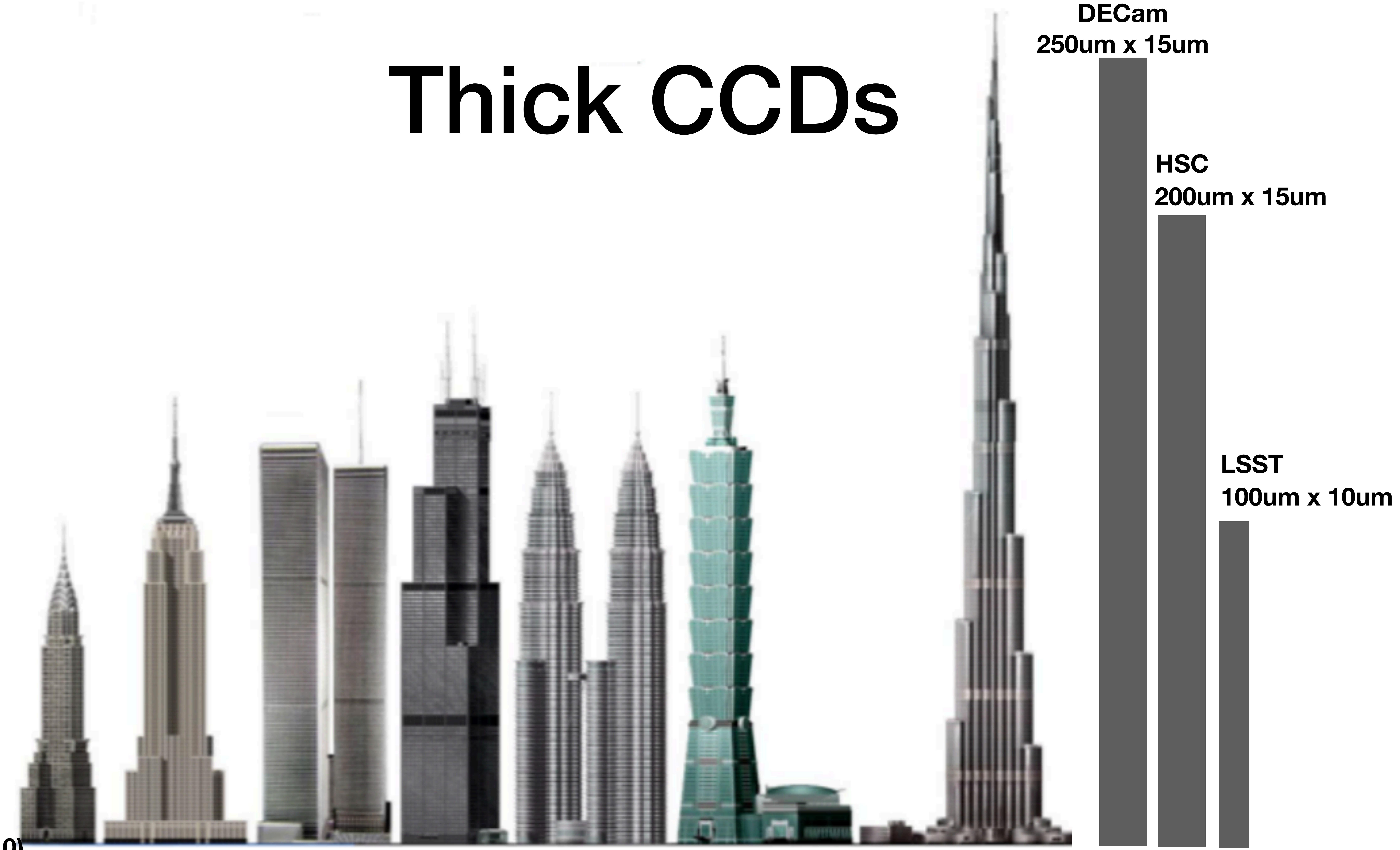


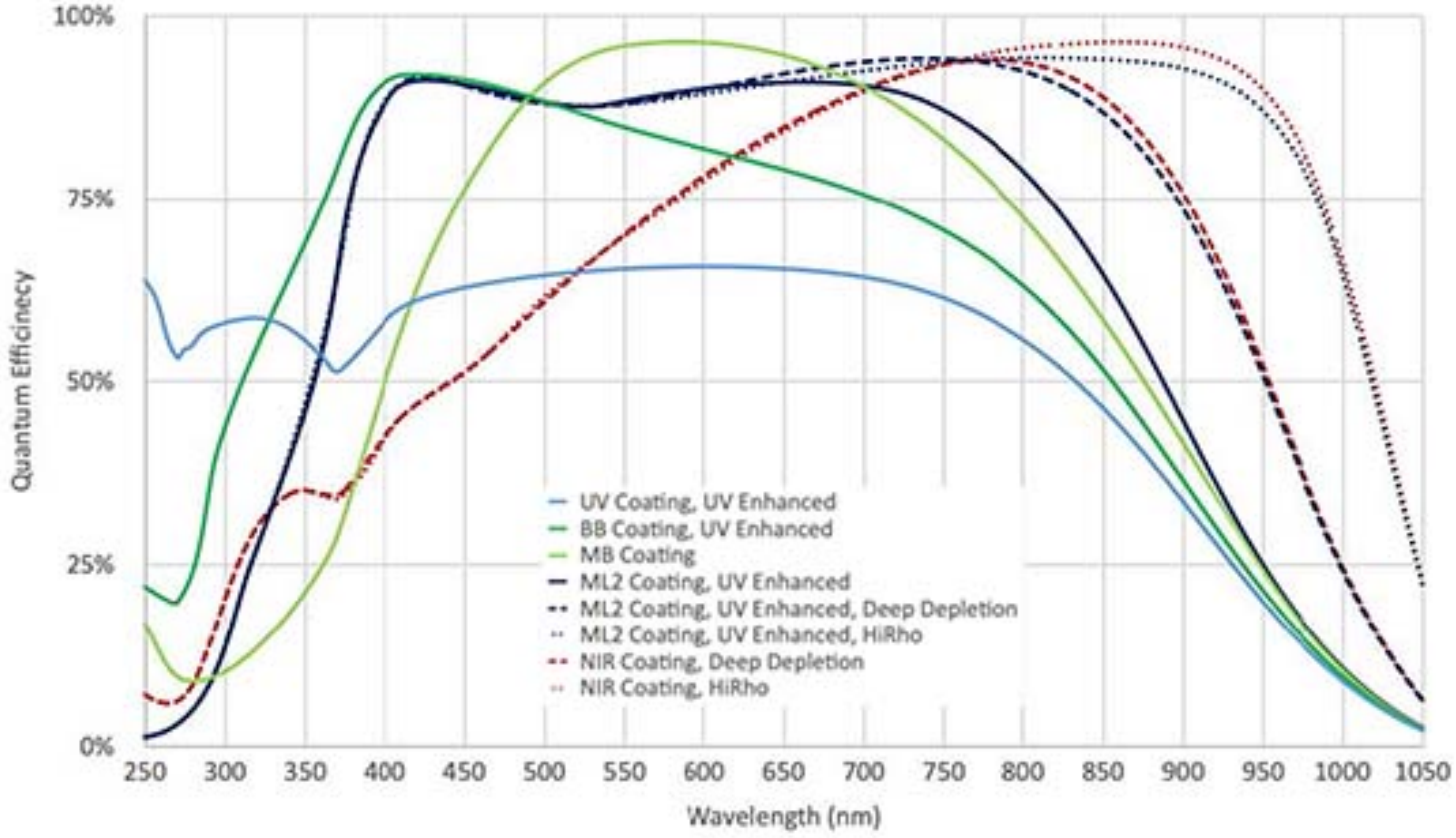
Tony Tyson

Thick CCDs



Lupton (2010)

Quantum Efficiency



e2v

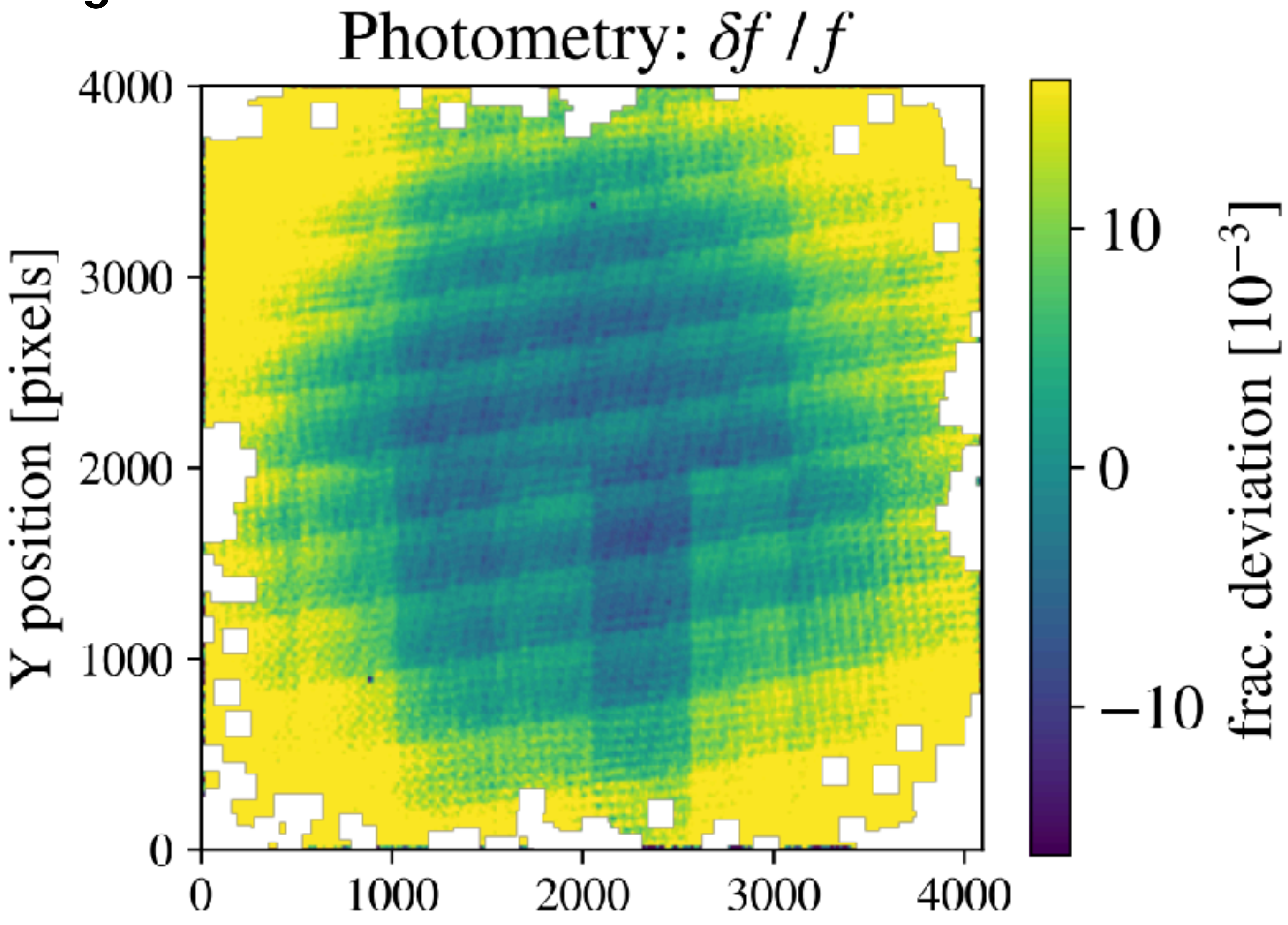
Quantum Efficiency Variations

Typically ~percent-level variations

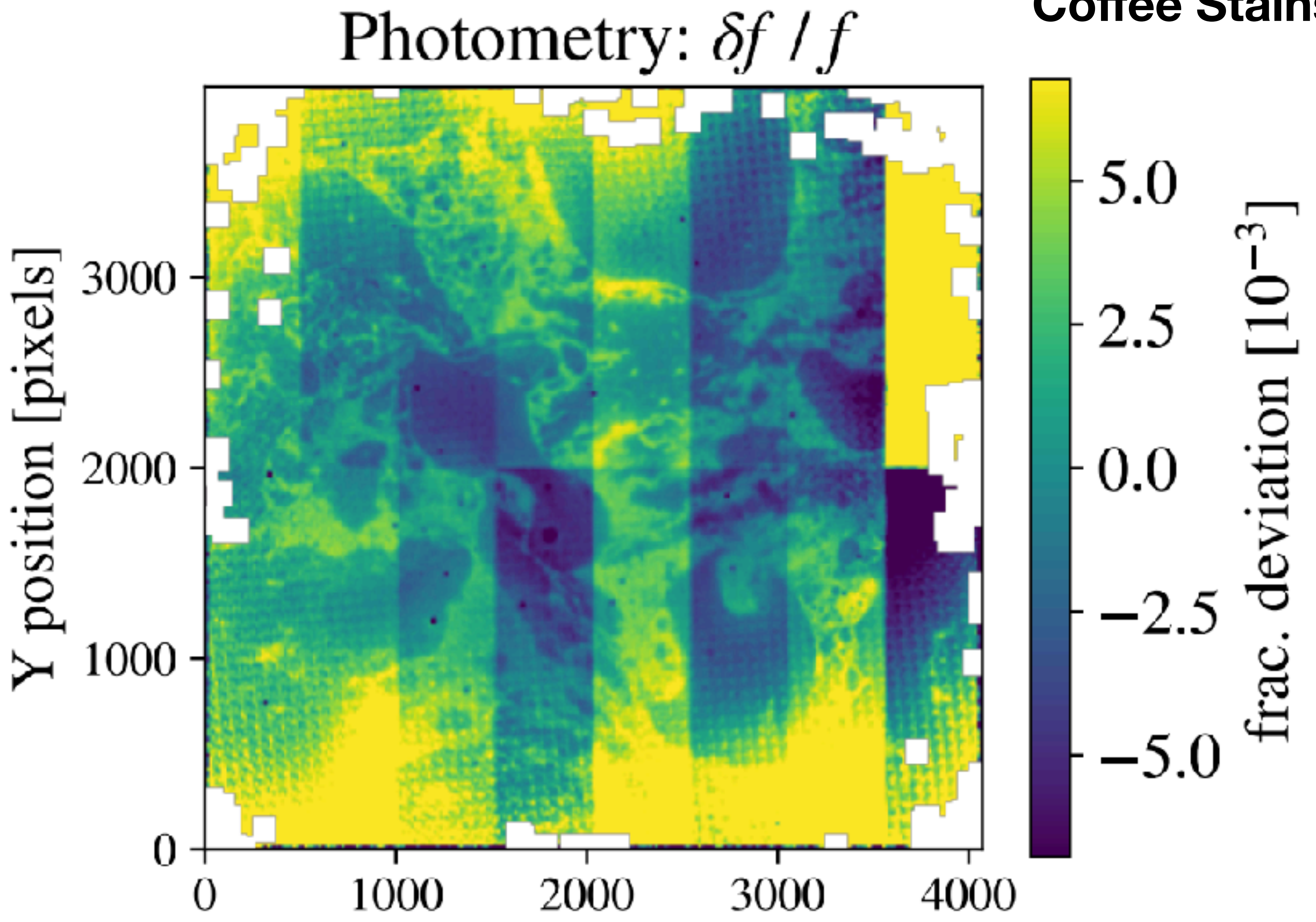
Backside features in the blue; frontside features in the red.

Generally corrected with flat fields.

LSST e2v
Annealing Pattern



LSST ITL
Coffee Stains



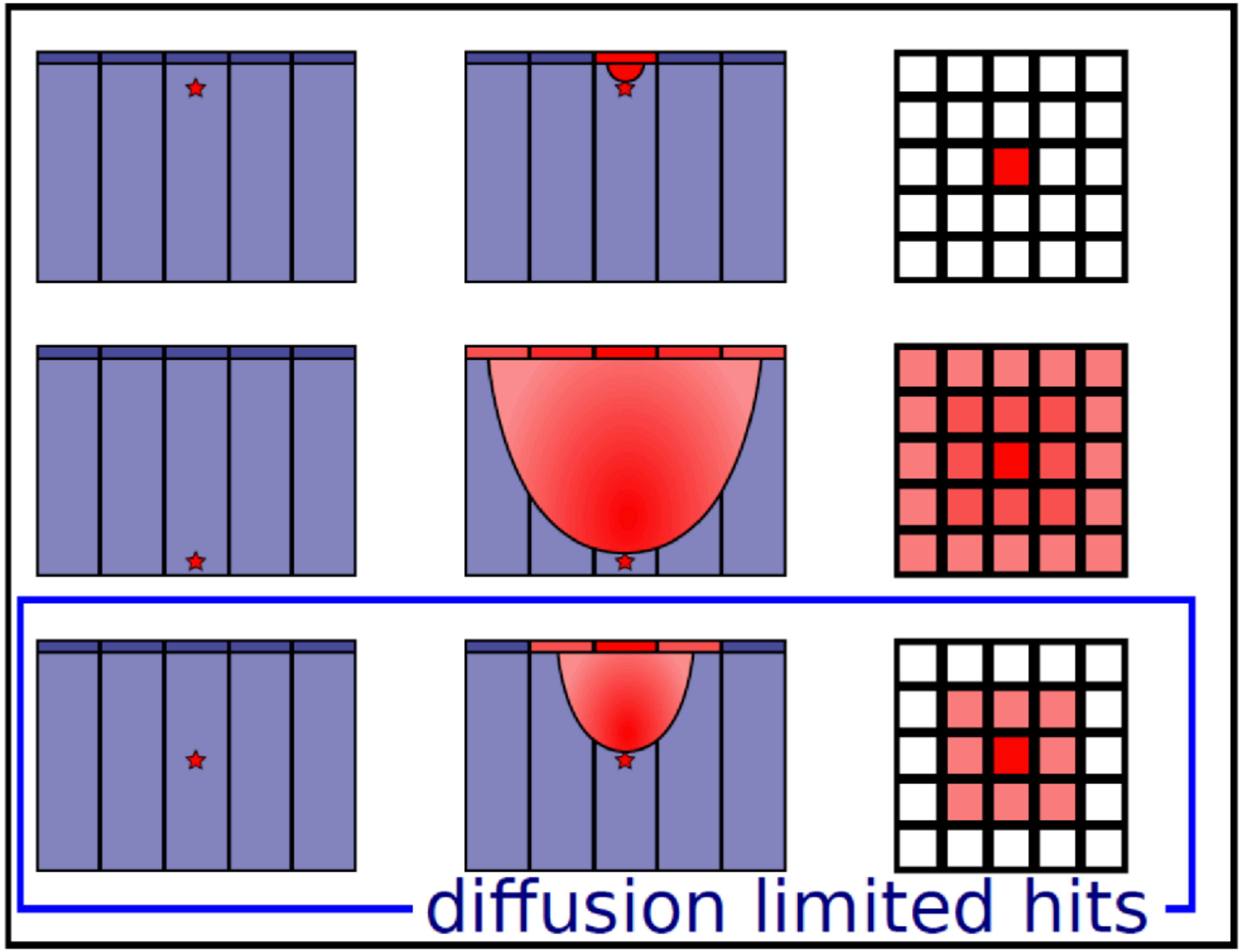
Esteves et al. (2023)

Charge Localization

- Diffusion
- Brighter-fatter

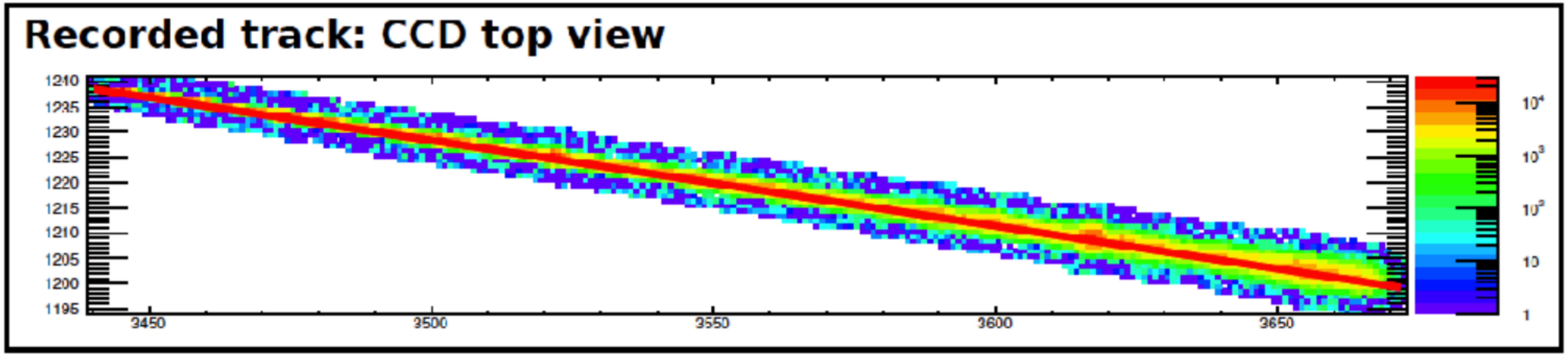
Charge Diffusion

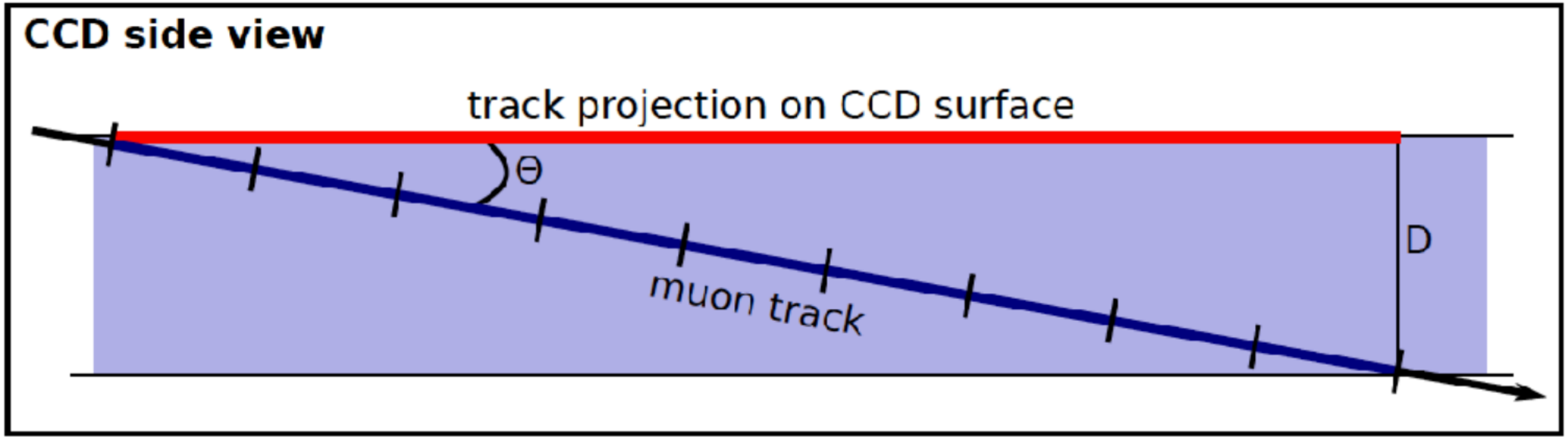
- Remember: Pixels are not physical barriers in the silicon, they are established by electrostatic potential barriers.
- Charge needs to drift vertically to be collected in the epitaxial layer.
- Charge can also move laterally if the potential barrier is not strong enough.



Estrada et al.

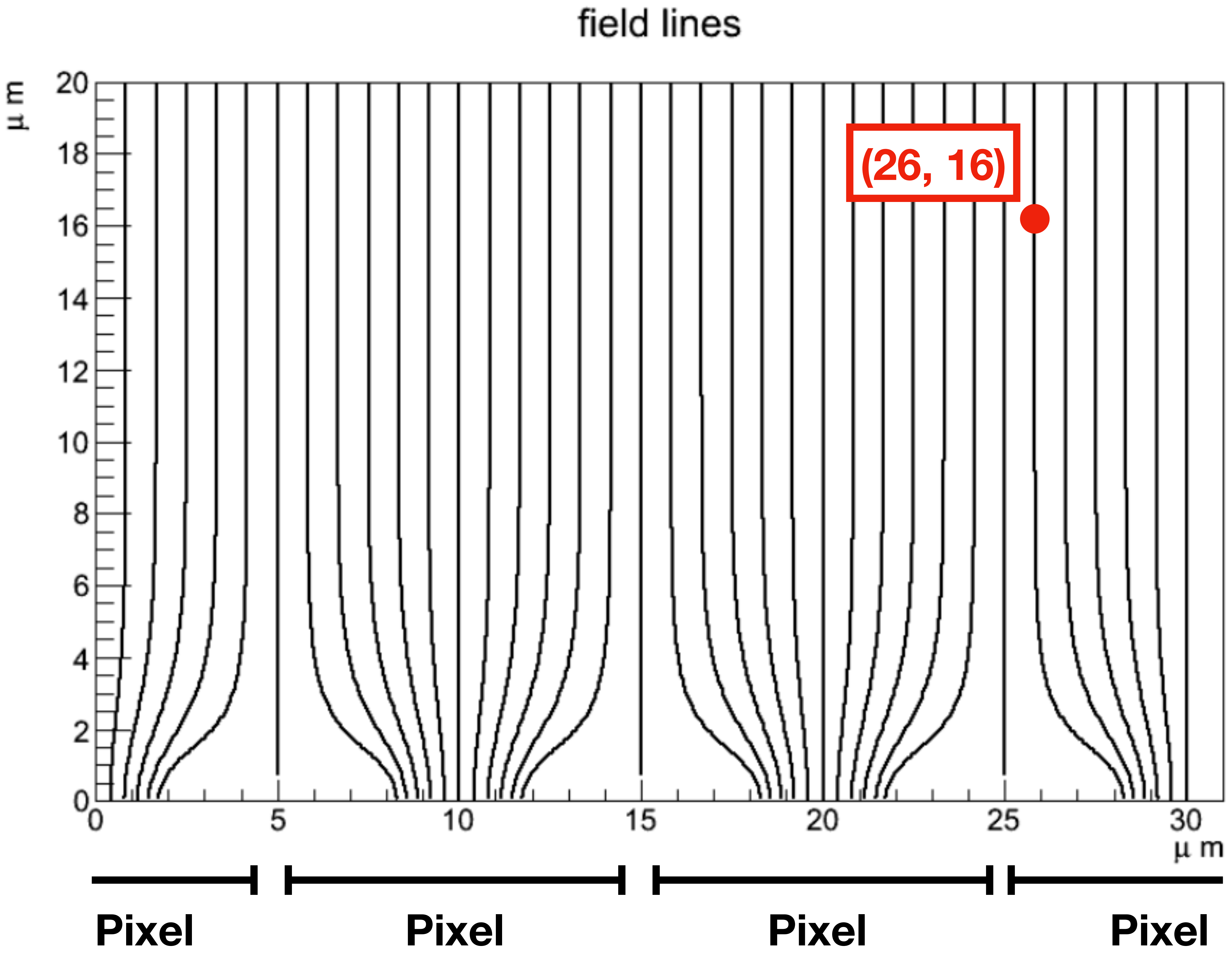
Charge Diffusion

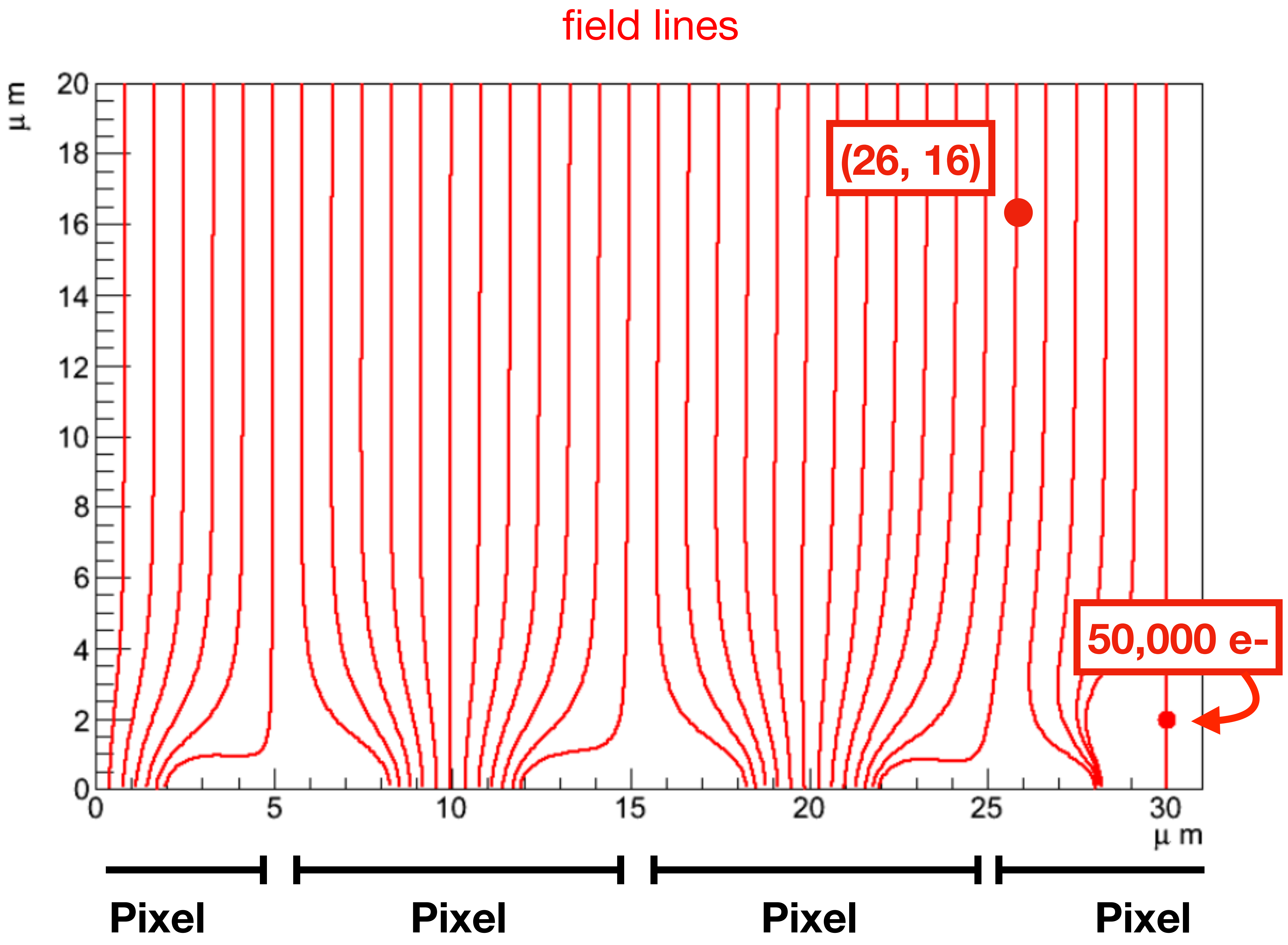




Estrada et al.

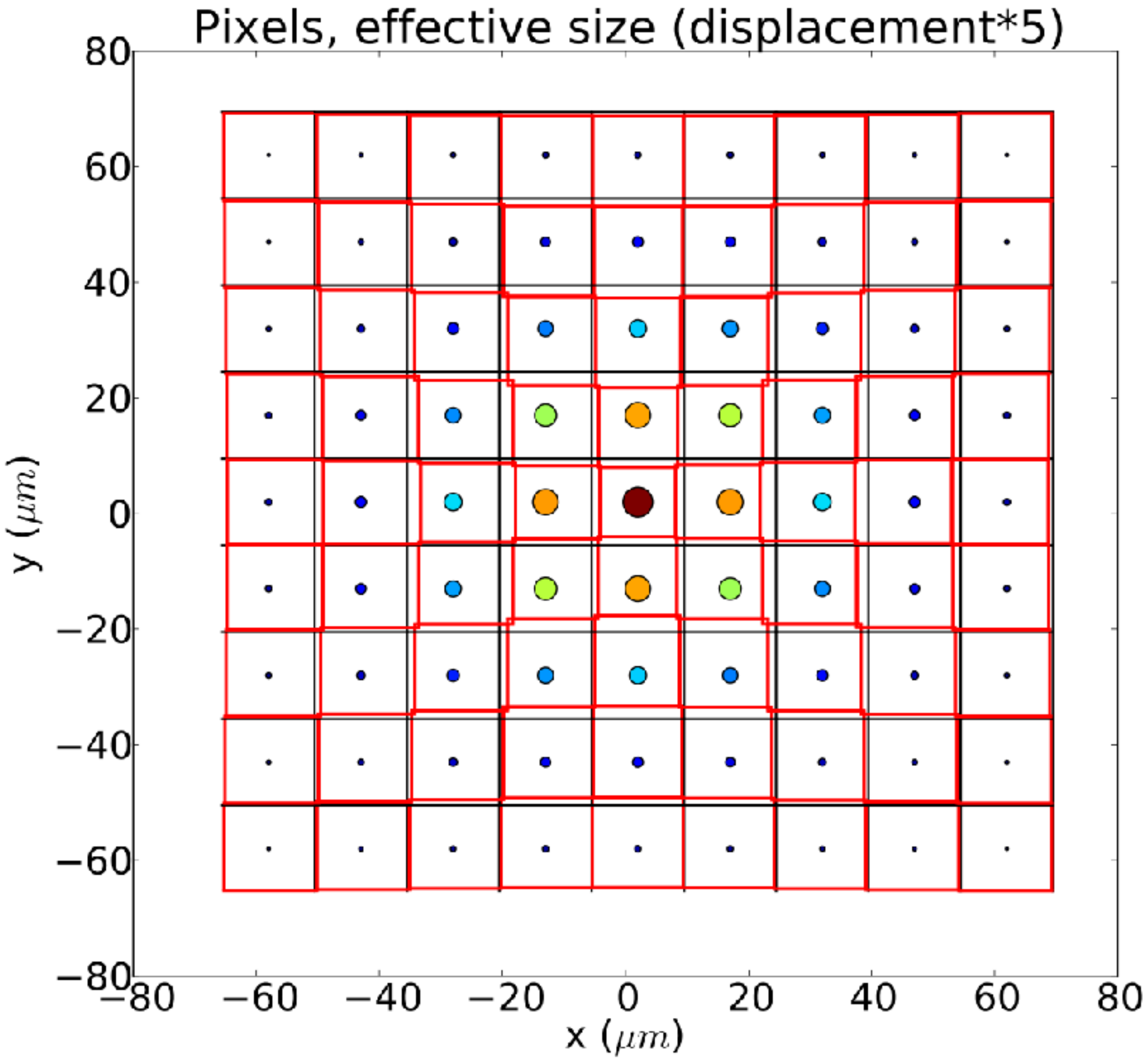
The Brighter Fatter Effect

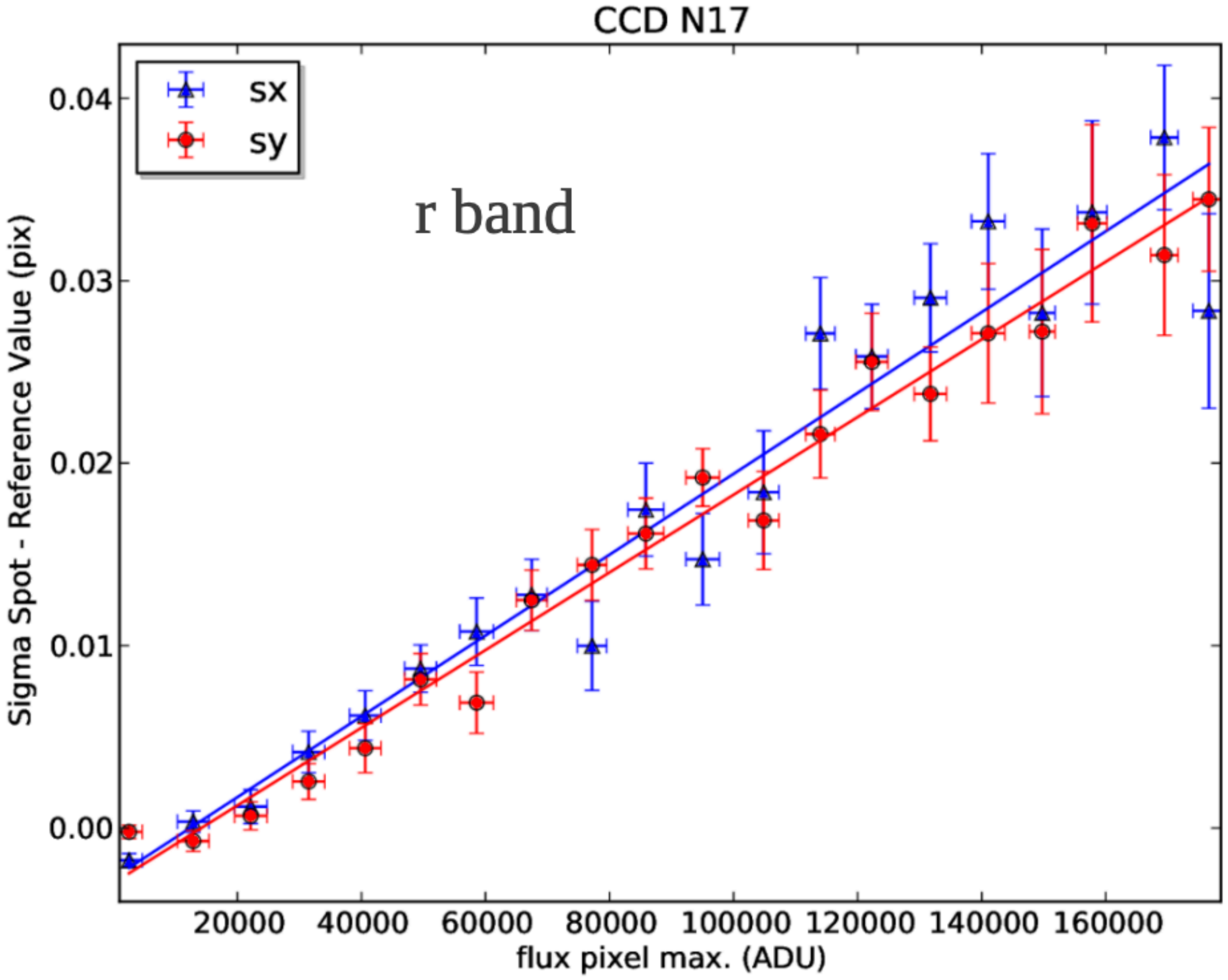




Antilogus et al.

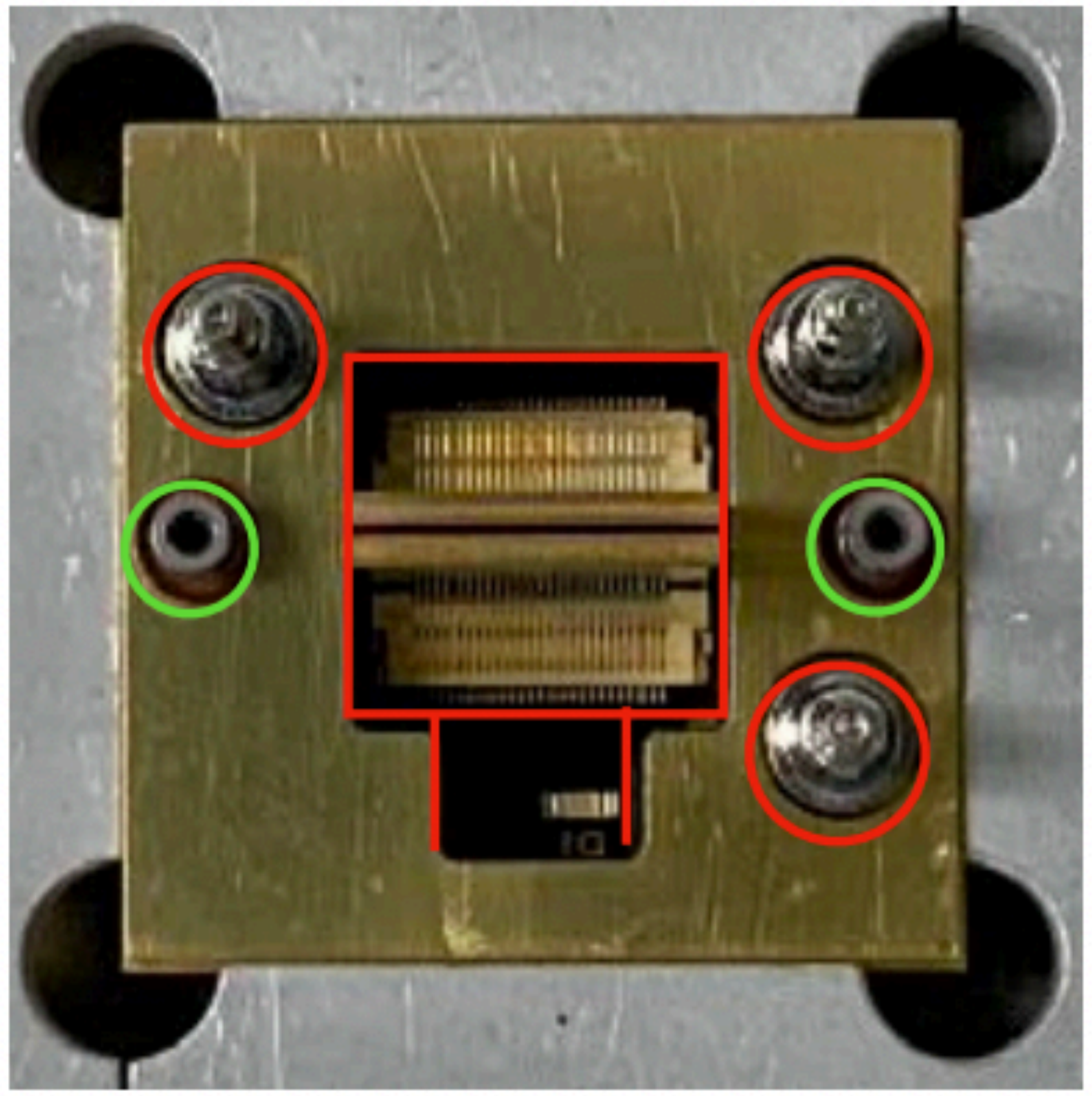
Brighter Fatter Effect

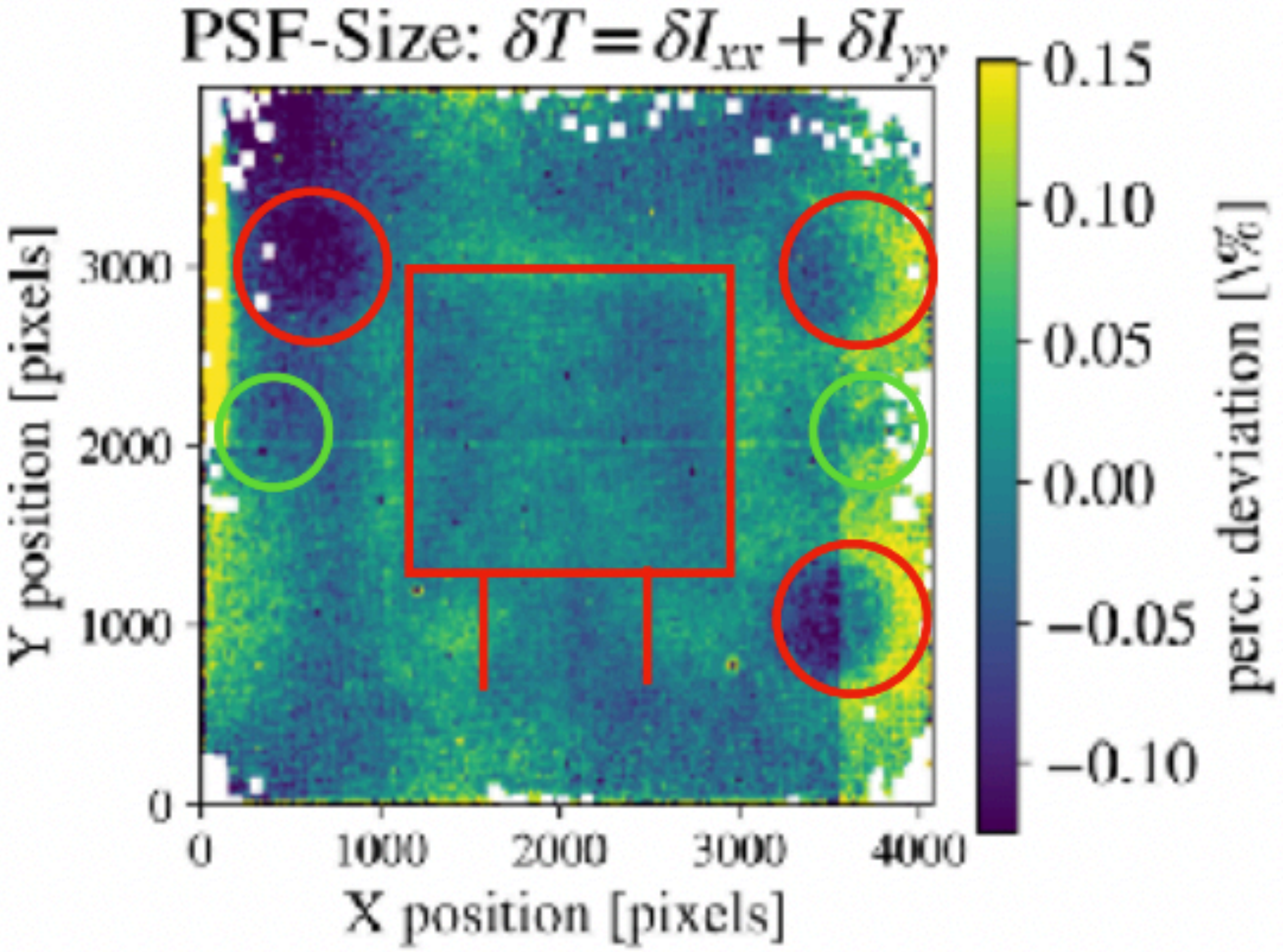


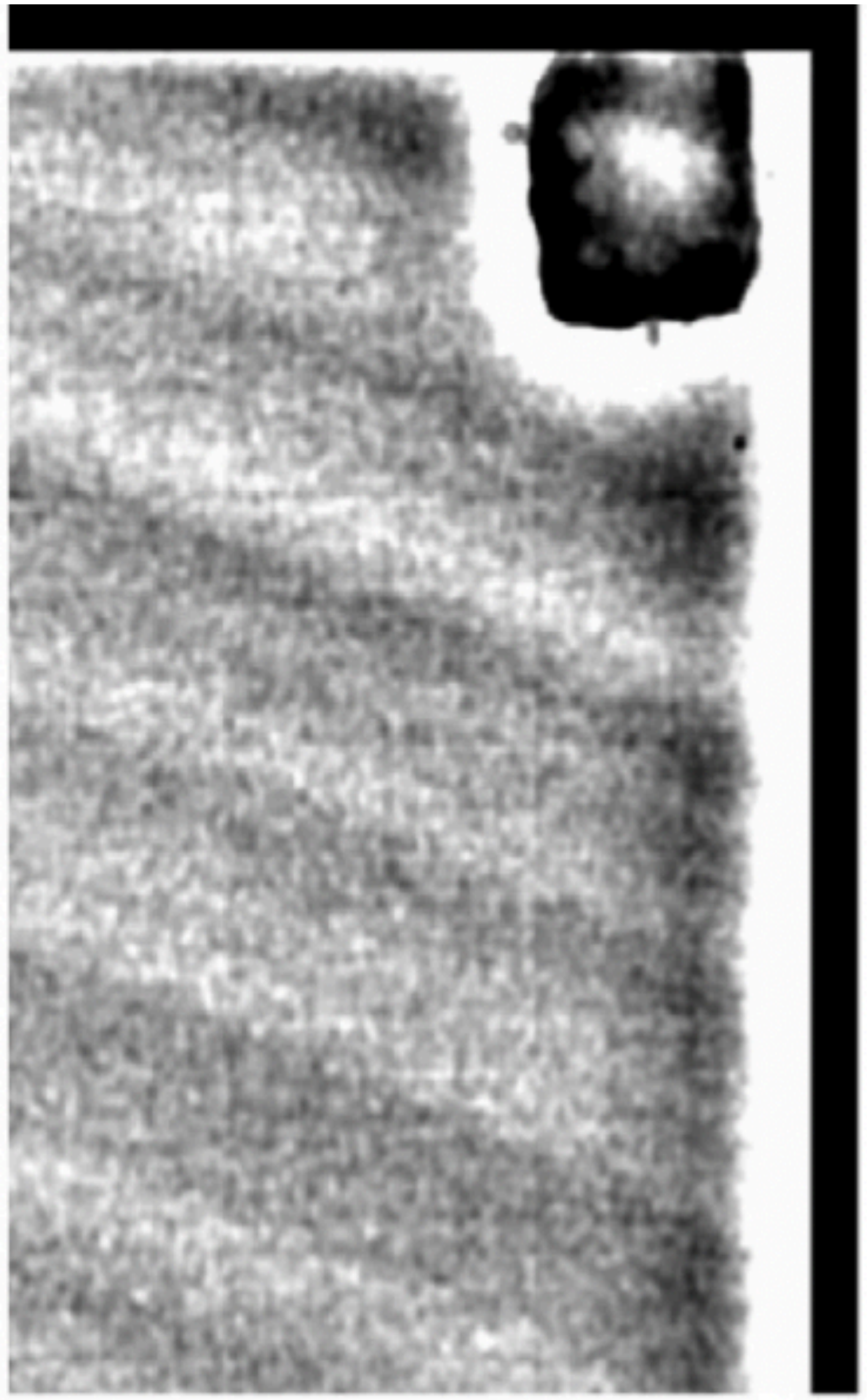


Antilogus et al.

Pixel Distortions and Size Variations







Esteves et al. (2023)

Plazas et al. (2014)

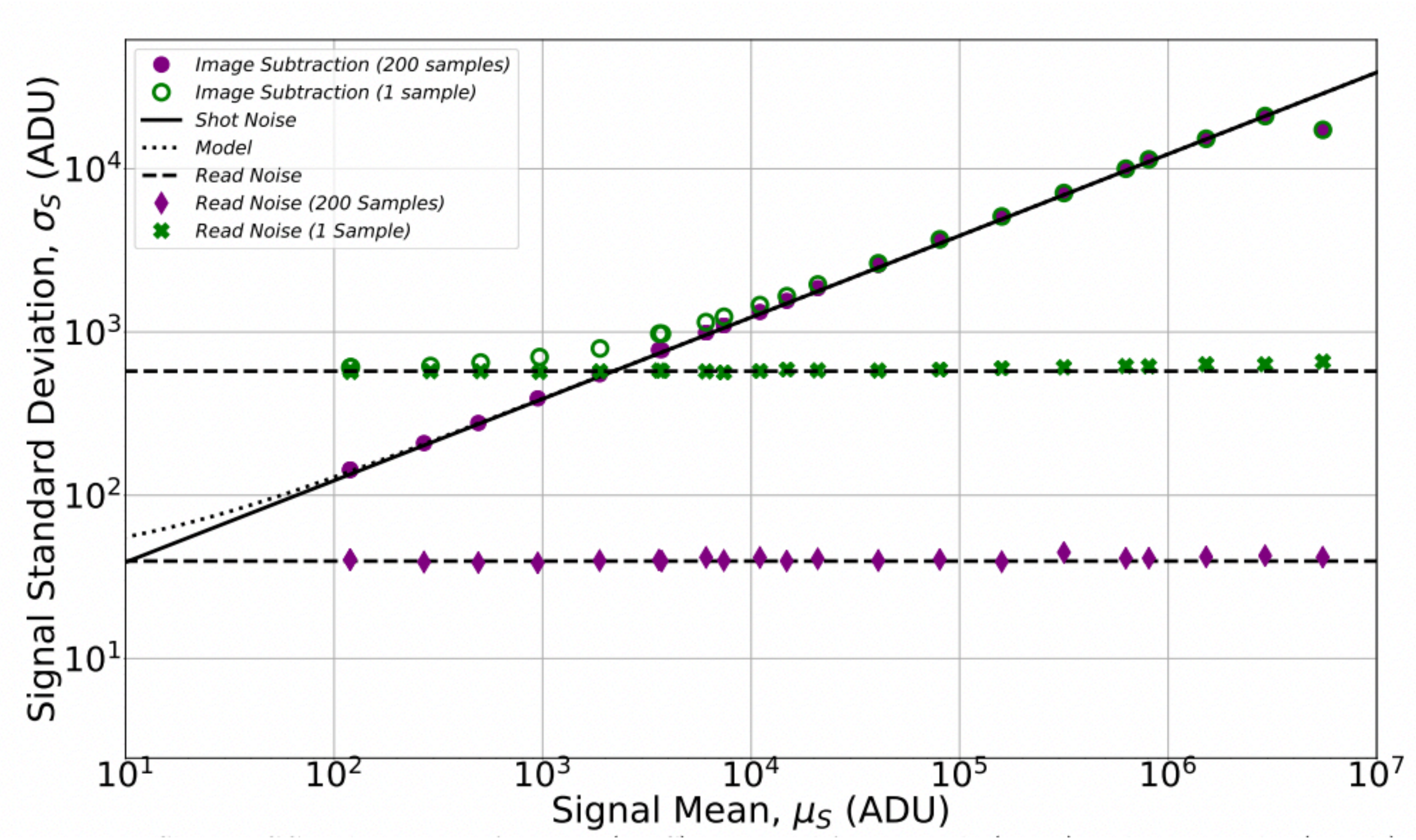
Charge Measurement

- Charge in pixels moved through the serial register and onto a output stage.
- Generally something like a tiny capacitor where depositing charge leads to a change in voltage that can be measured.
- That voltage is digitized by an analog-to-digital converter (ADC). Measure a difference between a reference voltage and a signal voltage (see correlated double sampling, CDS)
- A small bias is added so the the ADC measures a positive integer (limited number of bits). This bias can be removed in software.

Gain

- The ADC outputs a digital number (“ADU” = analog-to-digital unit, “DN” = data number, “counts”) that is proportional to the amount of charge.
- The constant of proportionality is called the “gain”. It is dictated by the camera electronics and readout configuration (i.e., the sequencer)
- The validity of the proportionality between the output signal and the amount of charge in the pixel is called the “linearity”.
- CCDs have excellent linearity, but it is not perfect. Often measurements deviate at small and large counts. Can be measured and corrected.

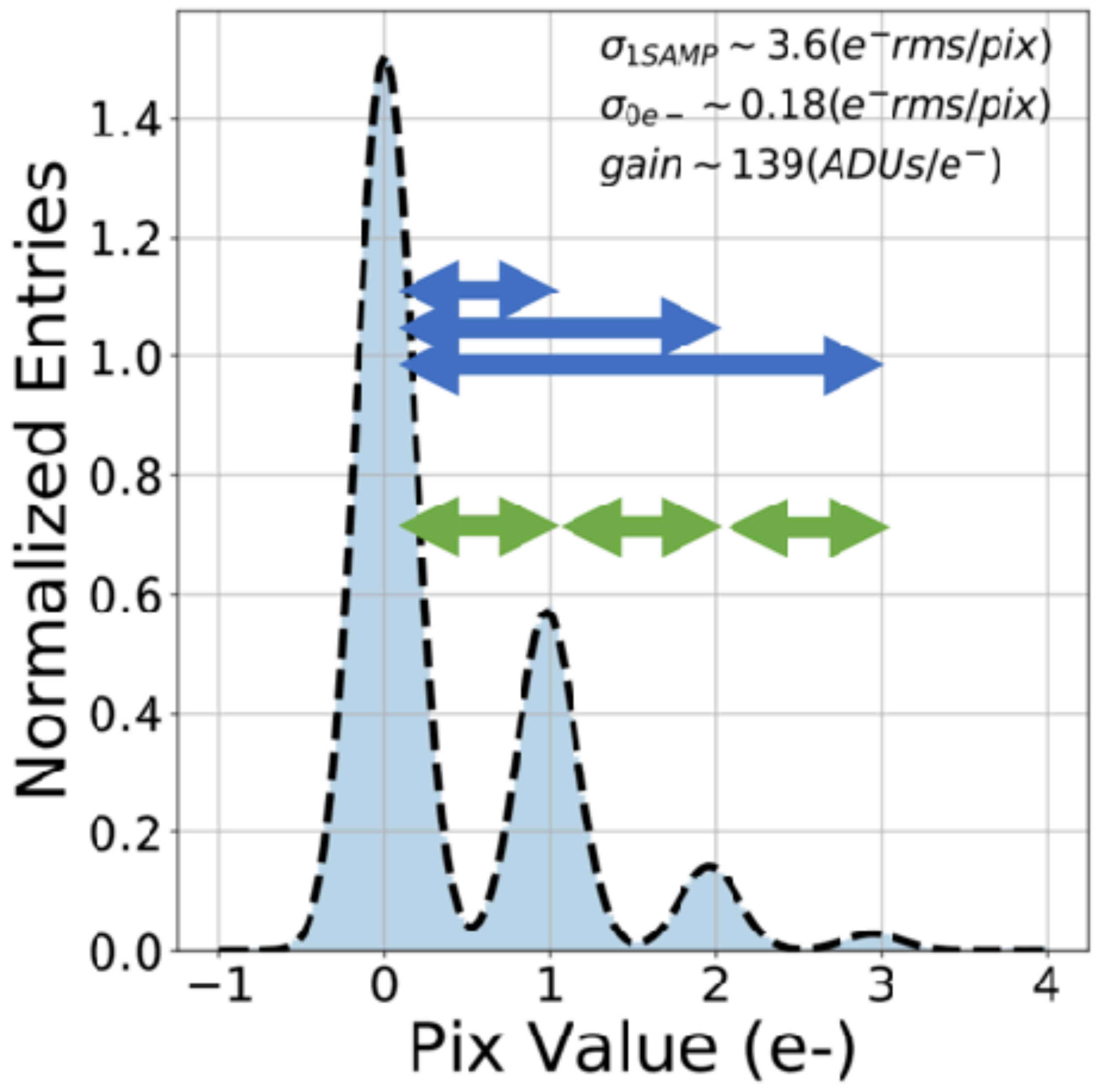
Photon Transfer Curves

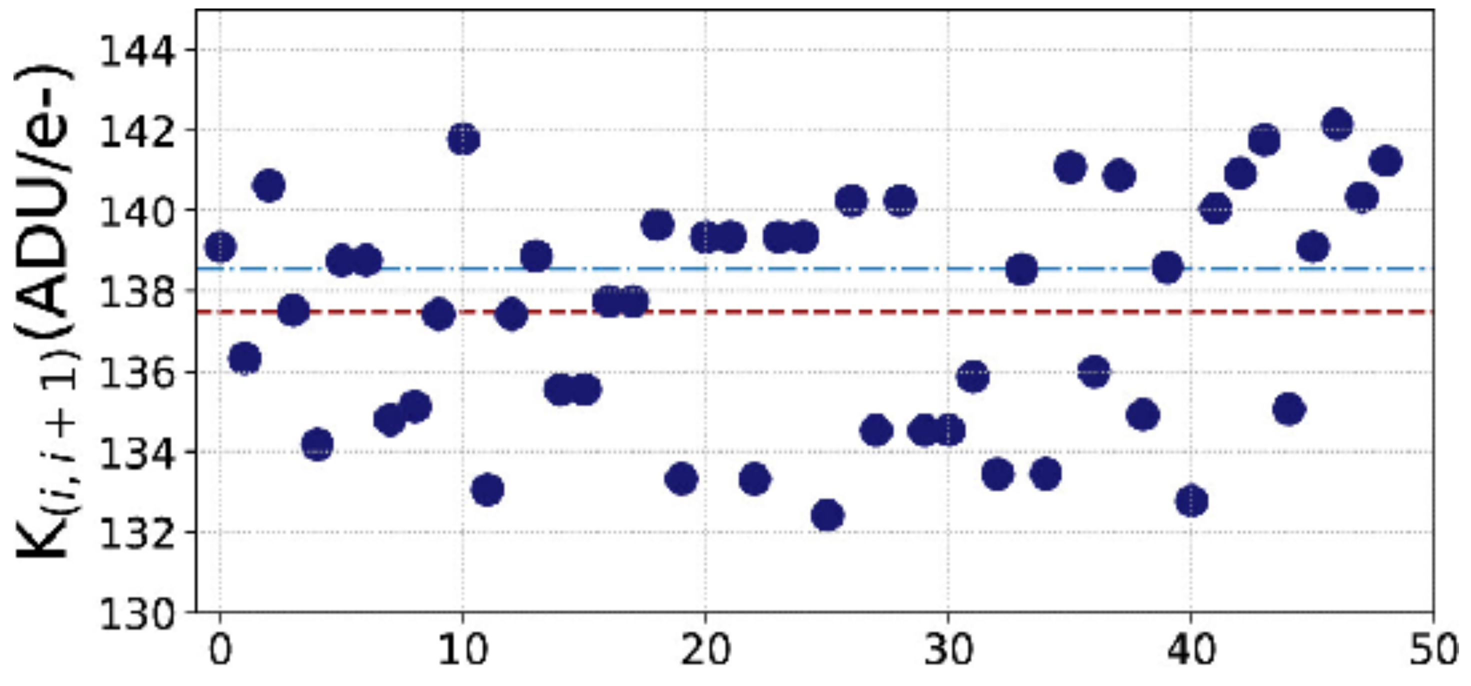


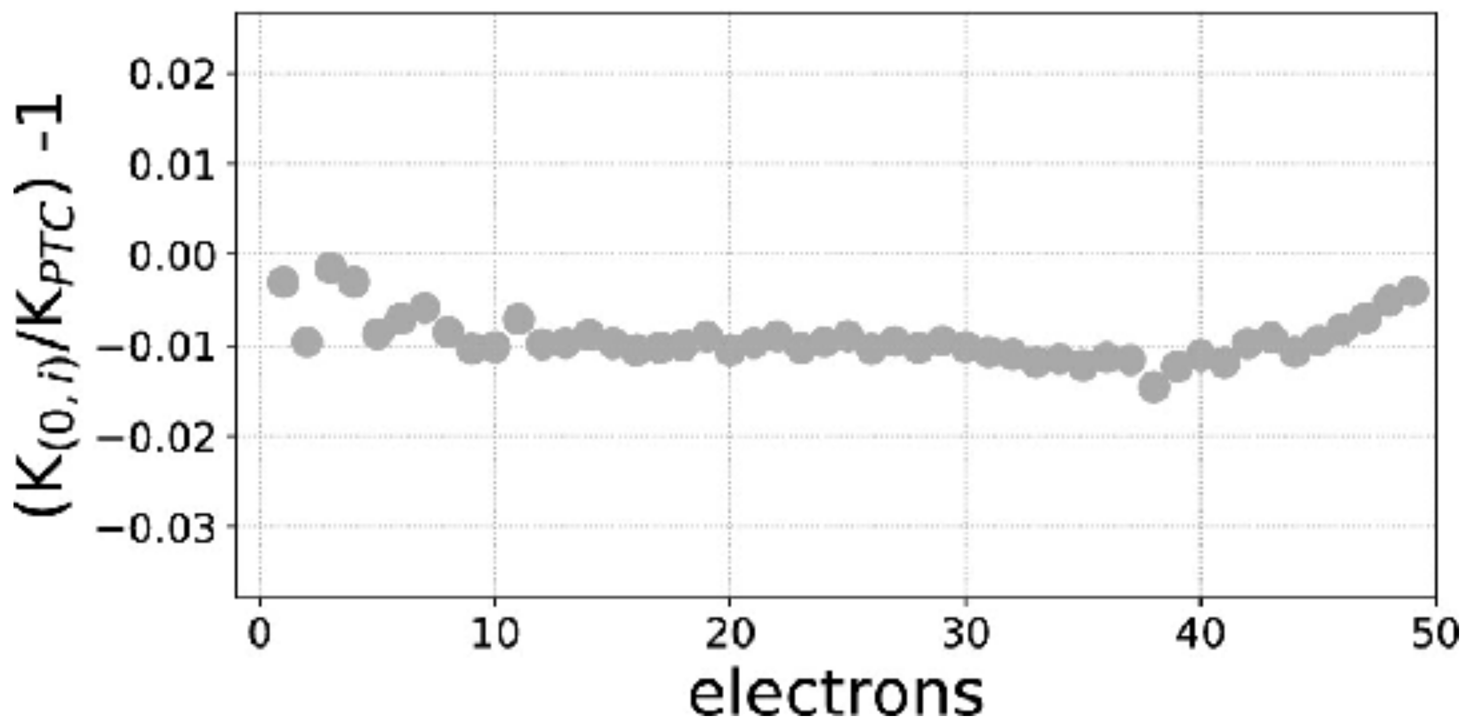
Drlica-Wagner et al. (2020)

Direct Gain Measurements

- Novel CCD architectures can achieve single-photon counting performance ("Skipper CCDs", but that is a different talk…)
- We can measure the gain from the peak-to-peak spacing $([\mu_i - \mu_{i-1}])$ or the position of the i peak $([\mu_i - \mu_{i-1}])$.
- Gain calculated from the PTC agrees with the gain measured from electron peaks to within ~1%.







Additional “Noise” Sources

- Readout Noise
- Dark current
- Cross talk
- Bias shifts
- Correlated noise
- Cosmic rays
- Tree rings
- Bad Pixels & Columns
- Saturation, bleed trails, edge bleeds
- …

Readout Noise

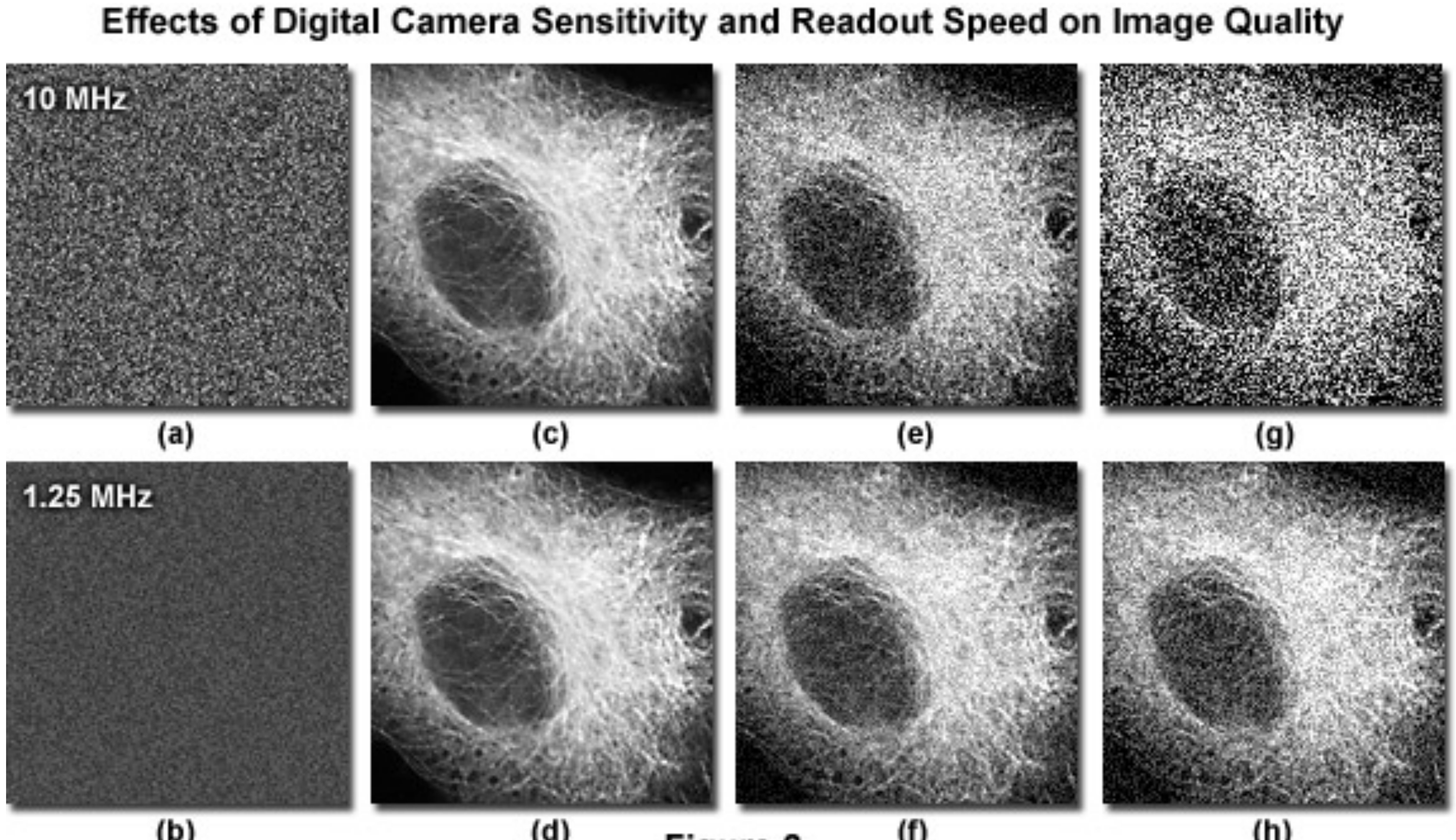
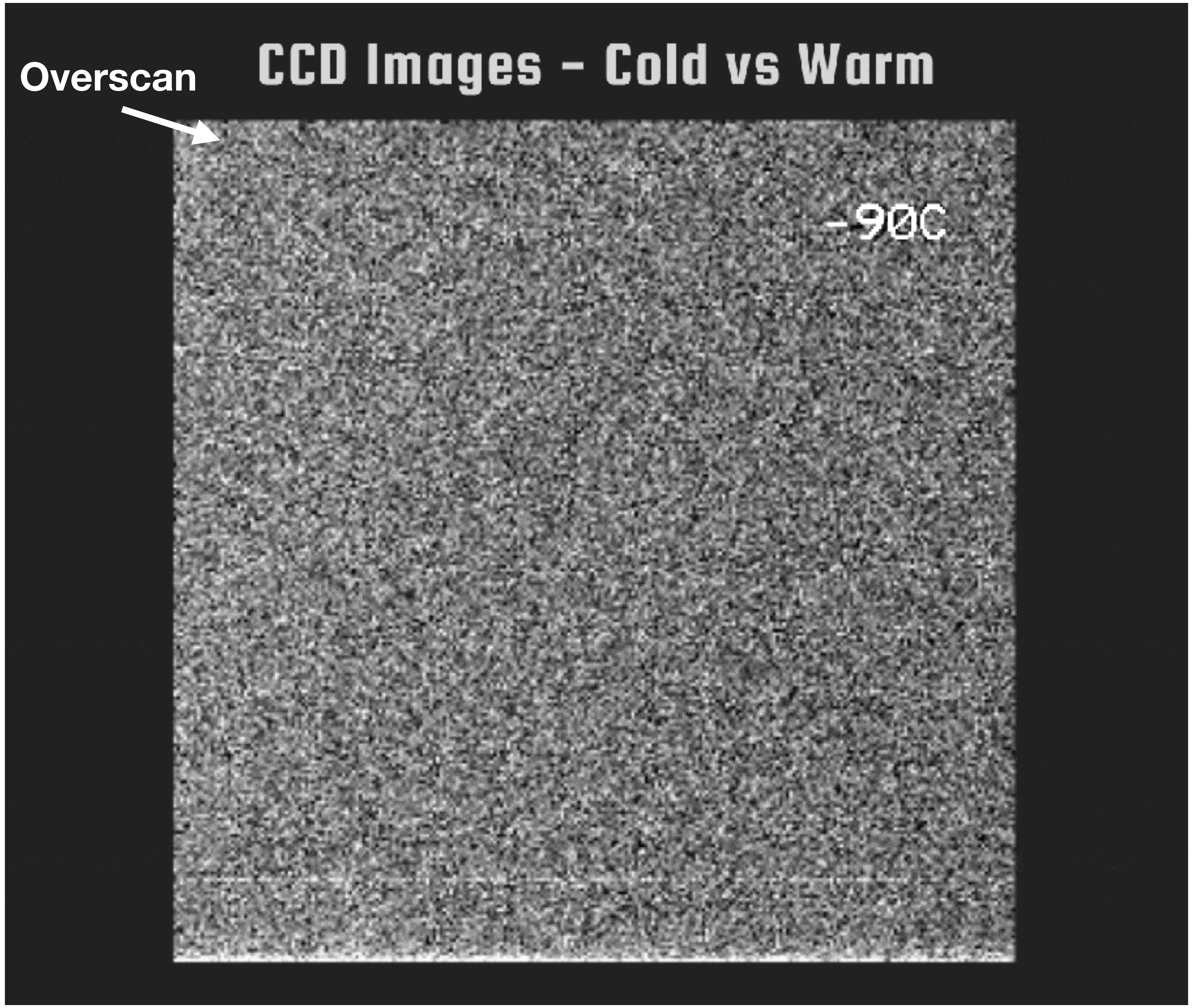
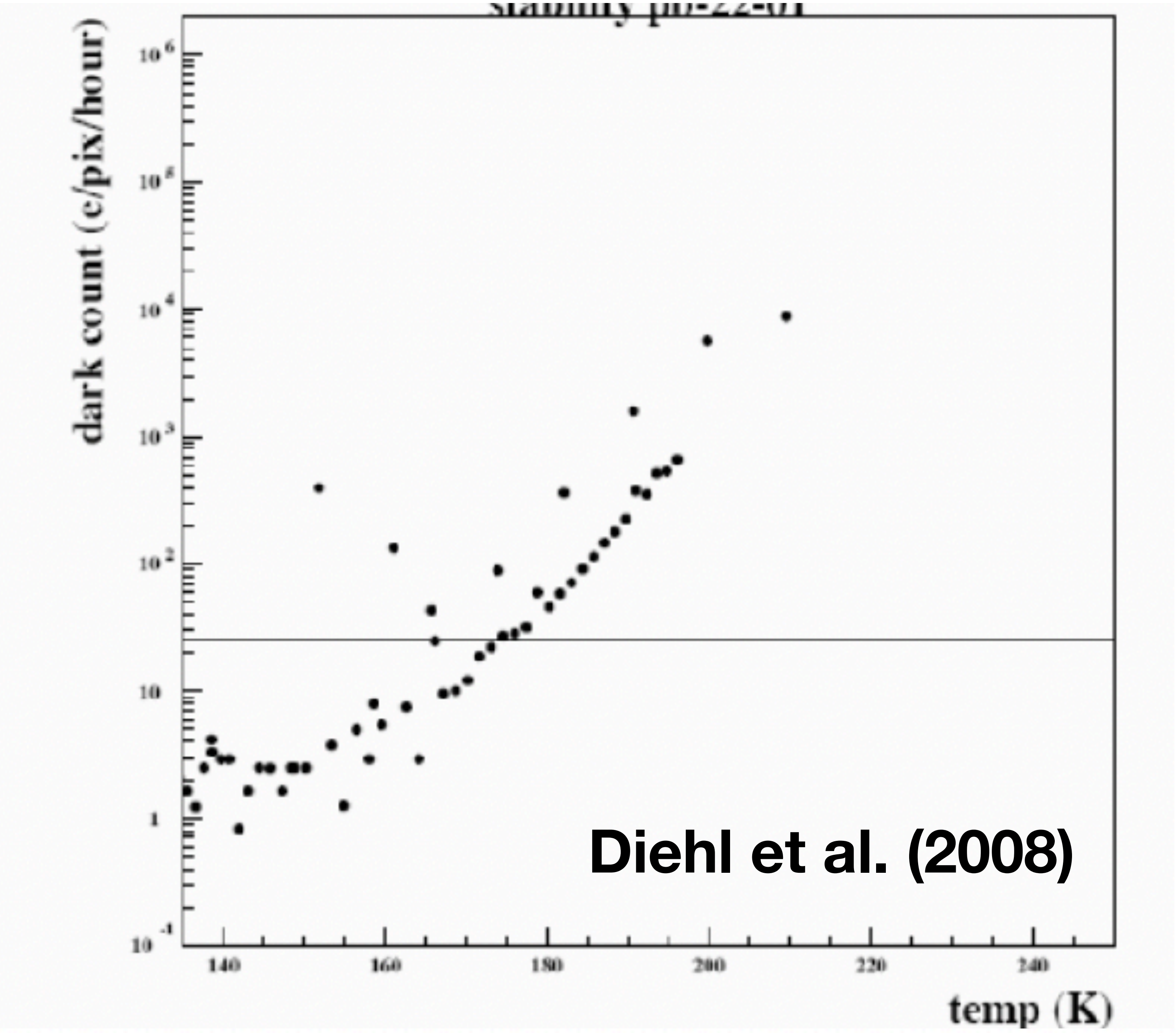


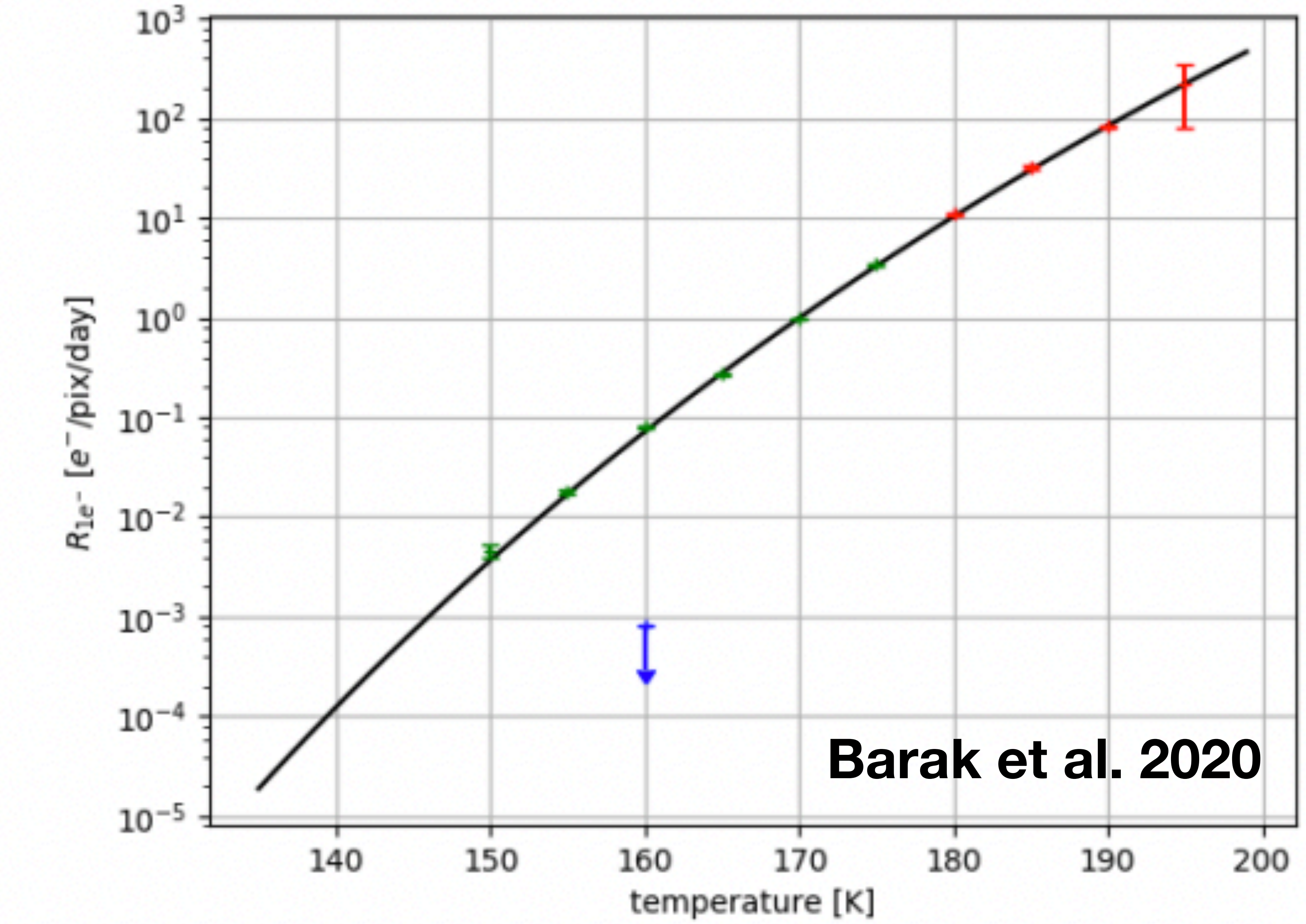
Figure 2

MicroscopyU

Dark Current

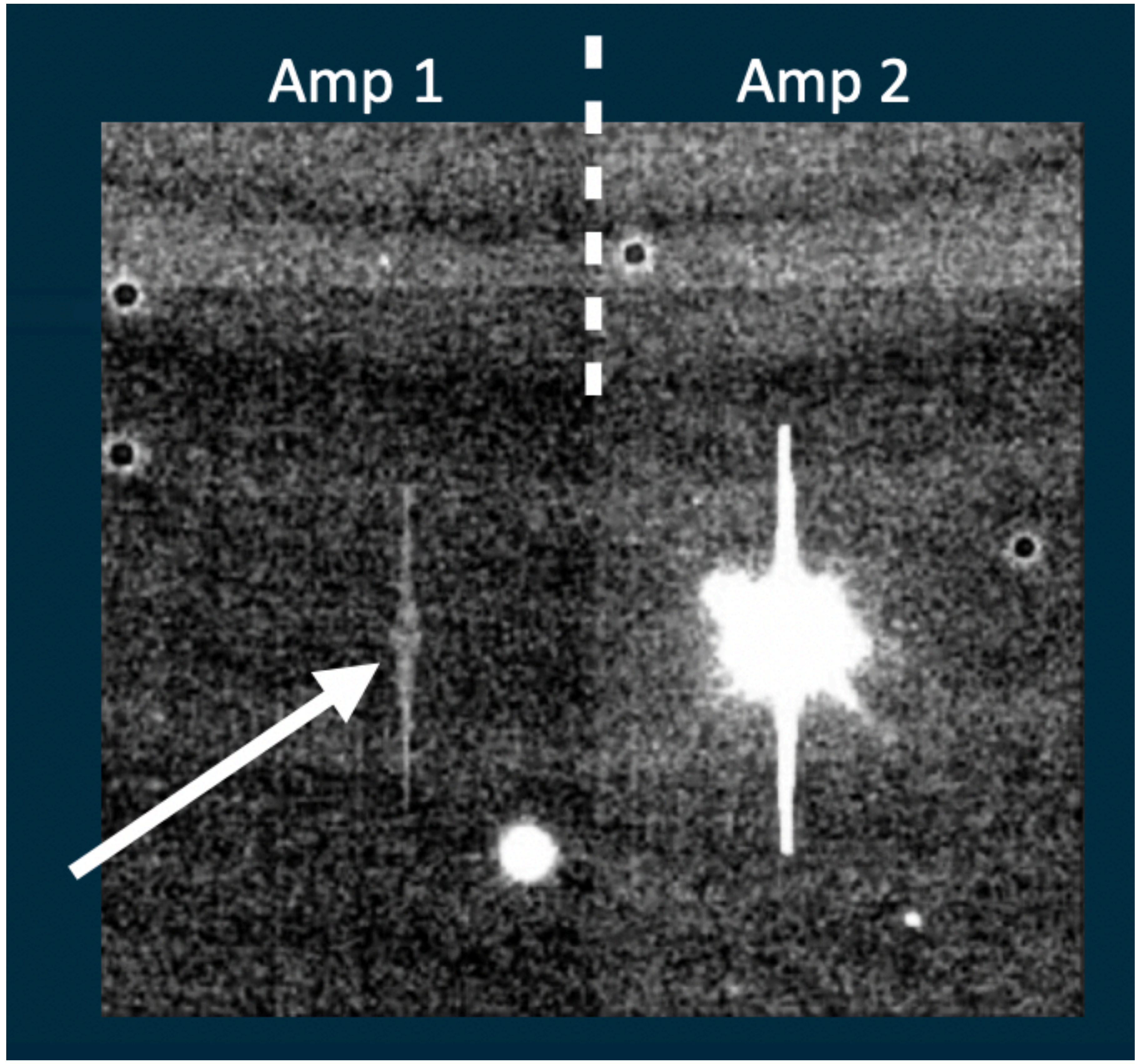






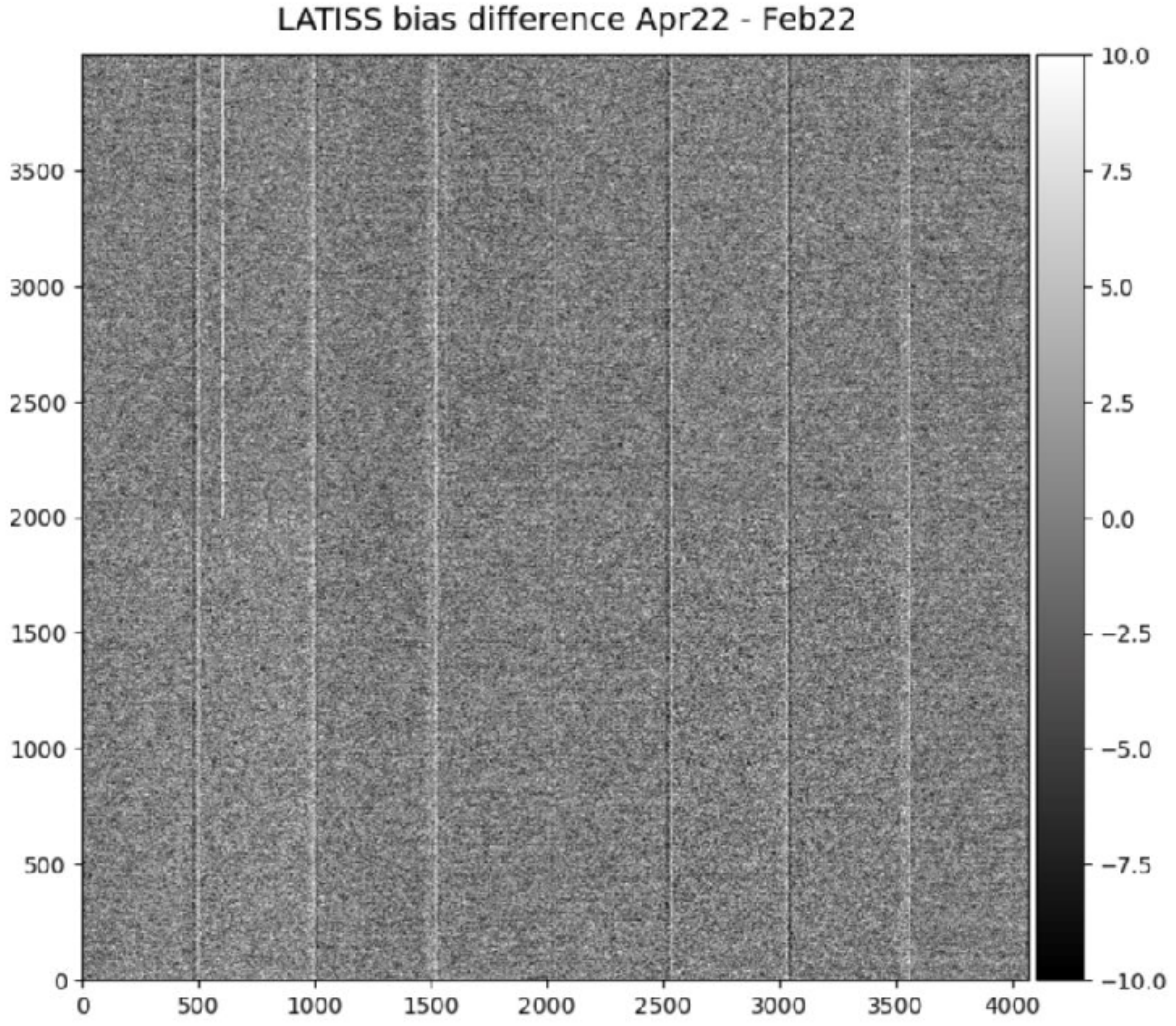
Spectral Instruments

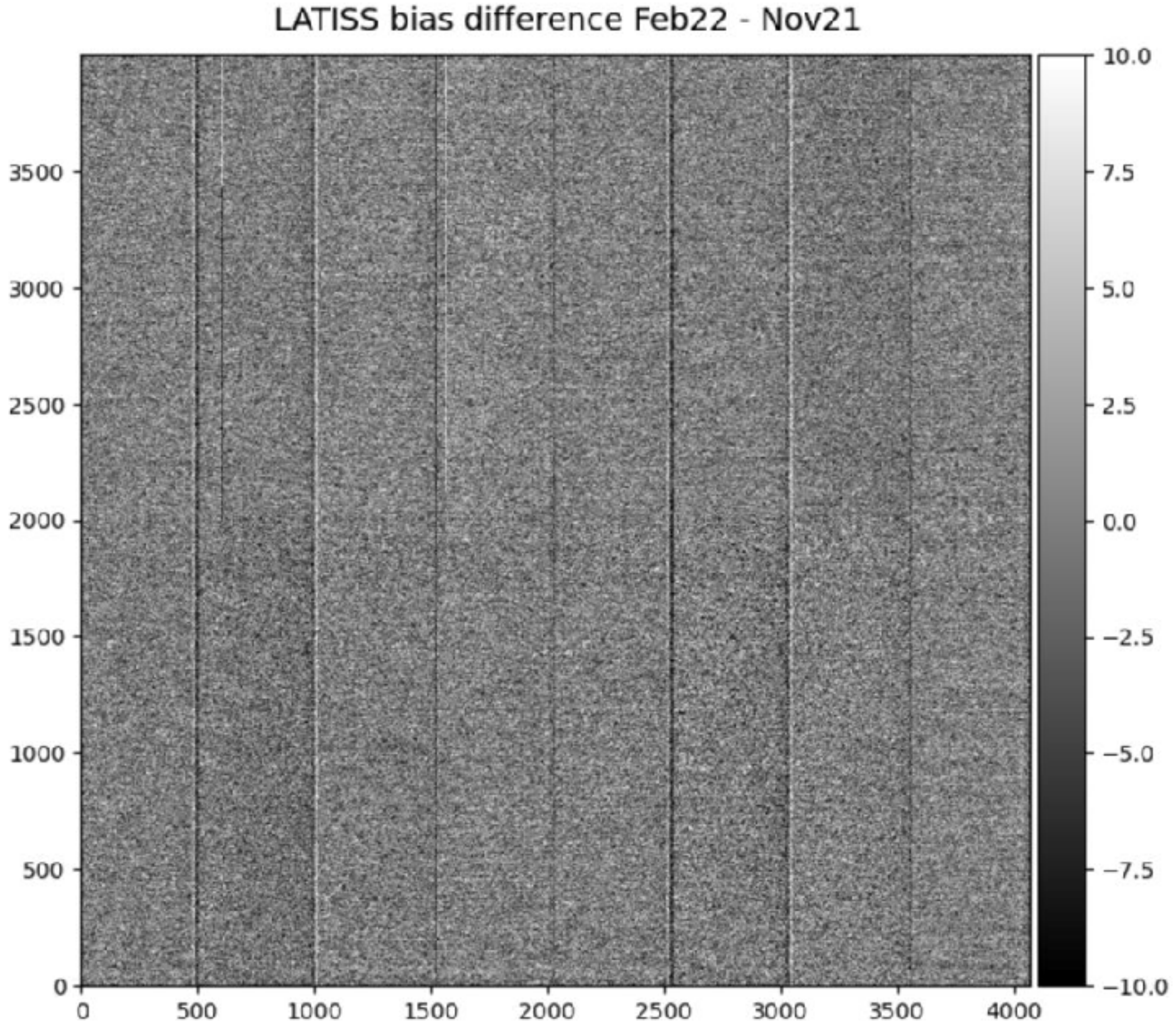
Crosstalk



C. Slater

Bias Shifts

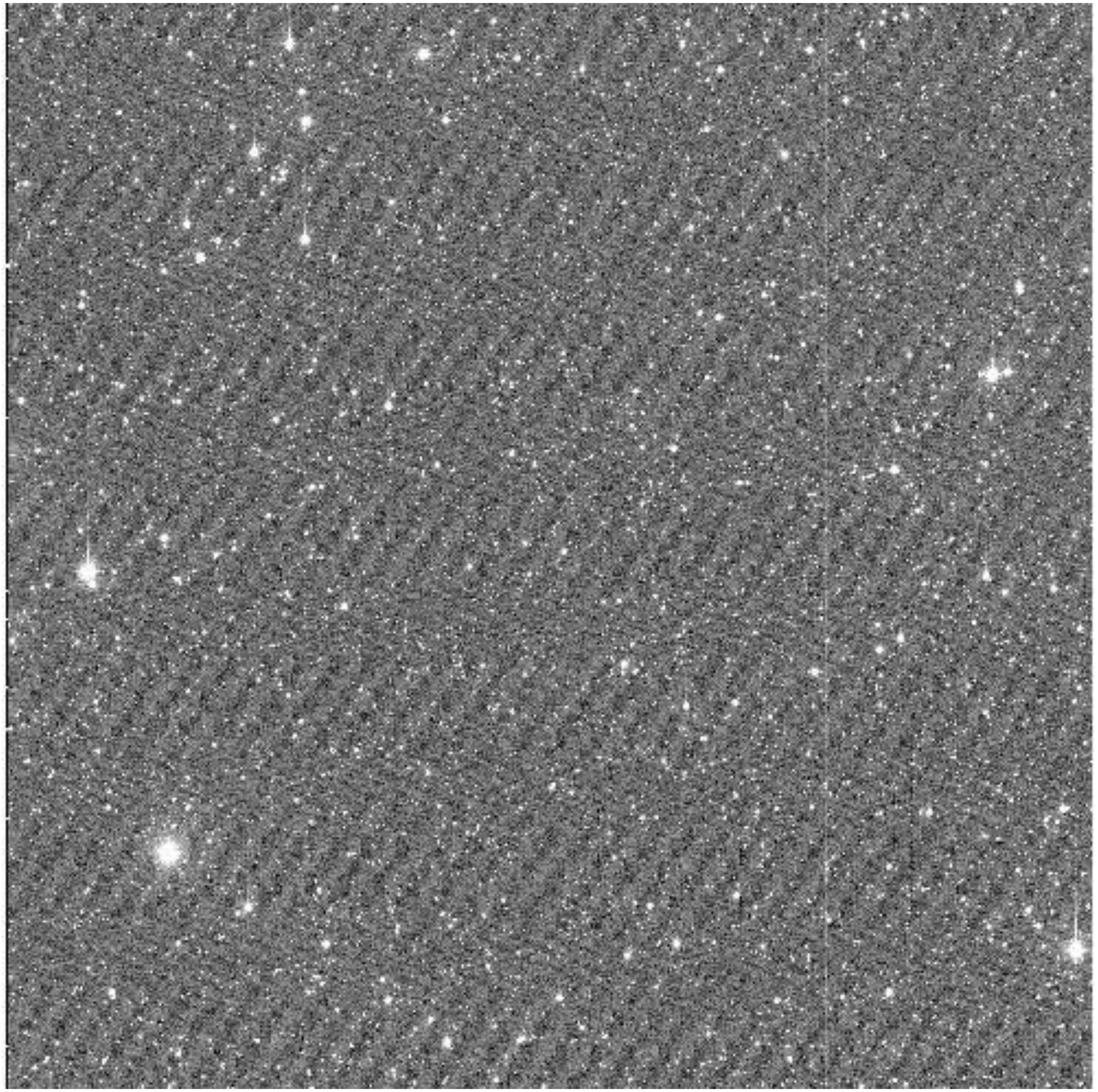




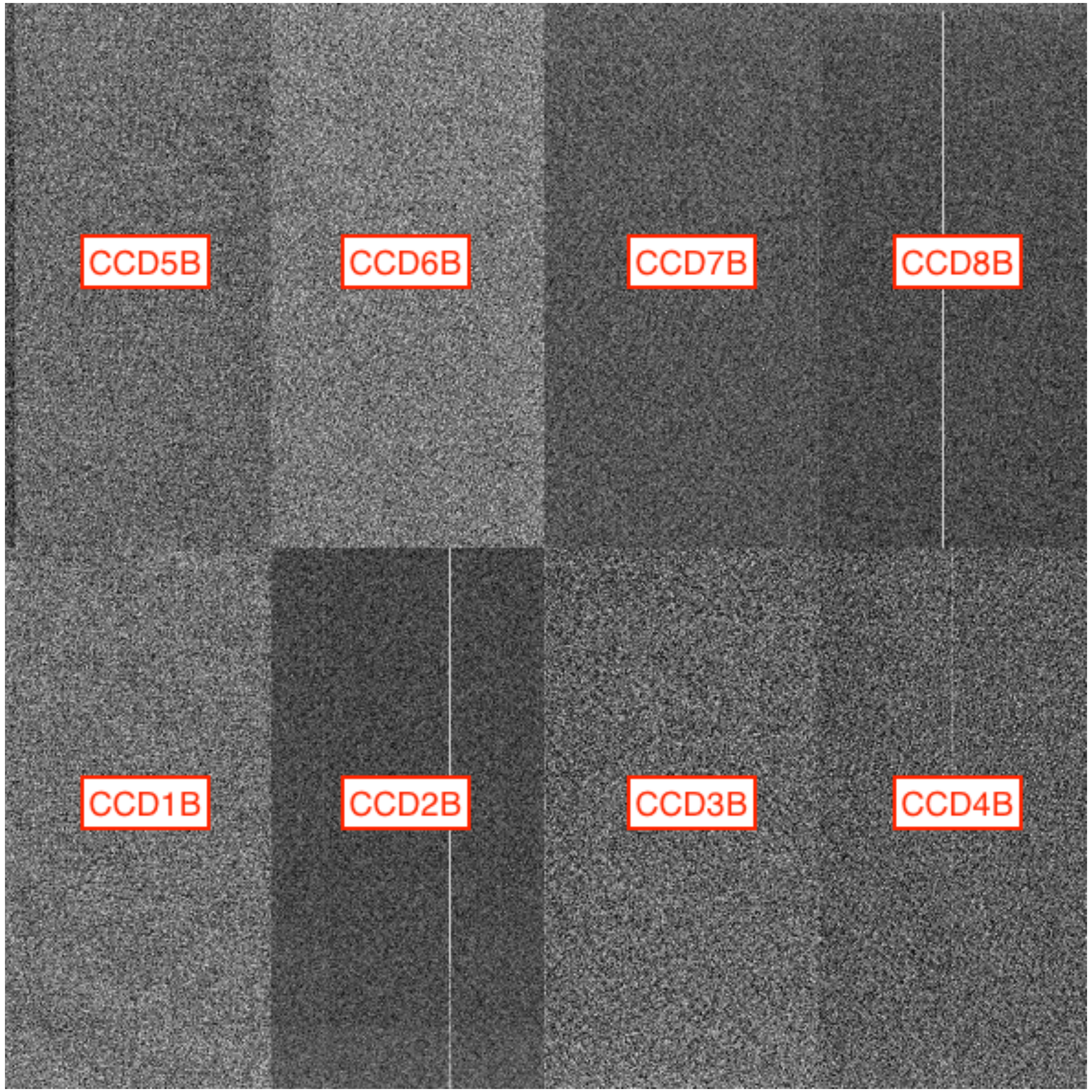
Banovetz (DMTN-245)

Correlated (Fixed Pattern) Noise

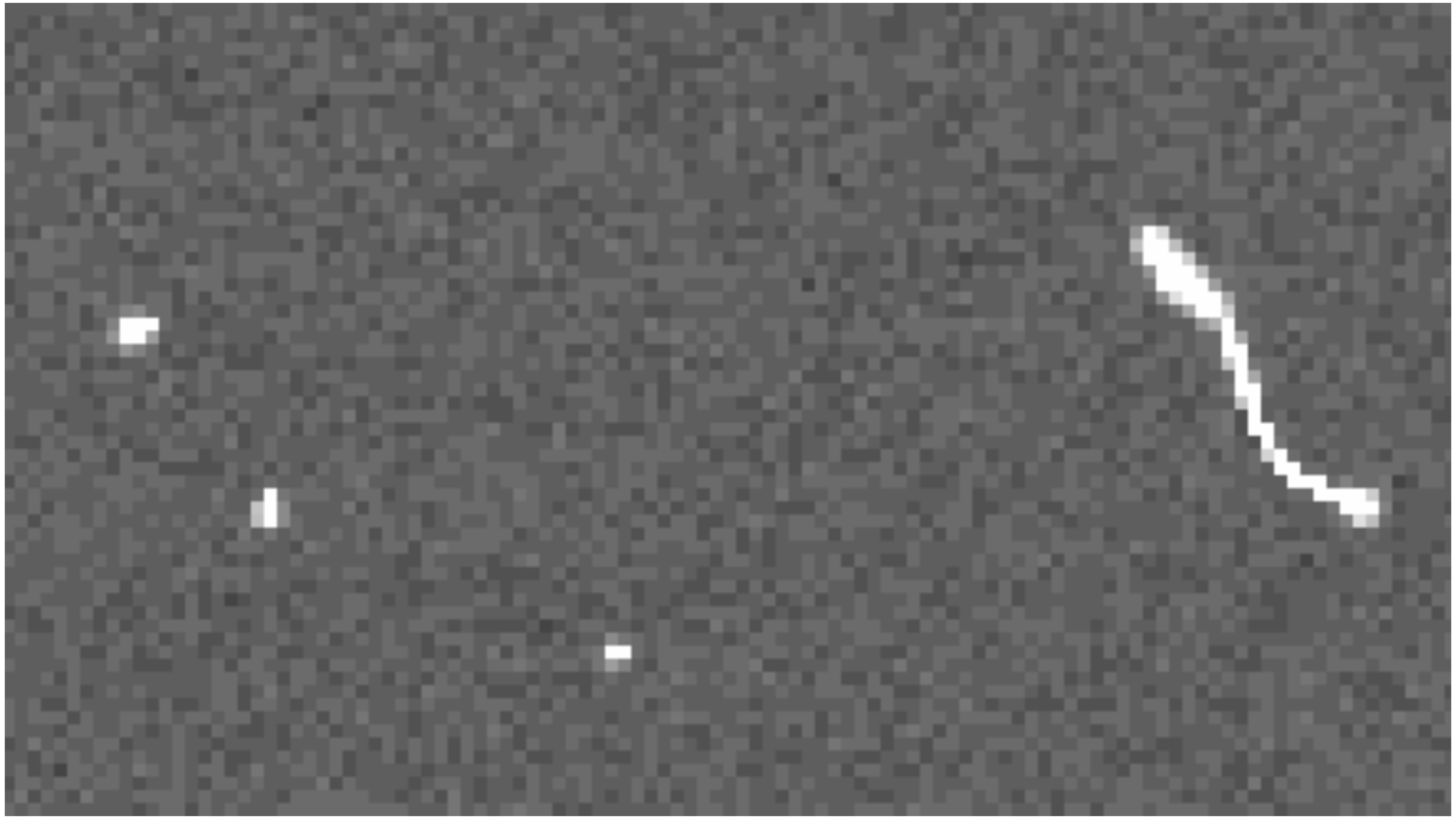
ZTF



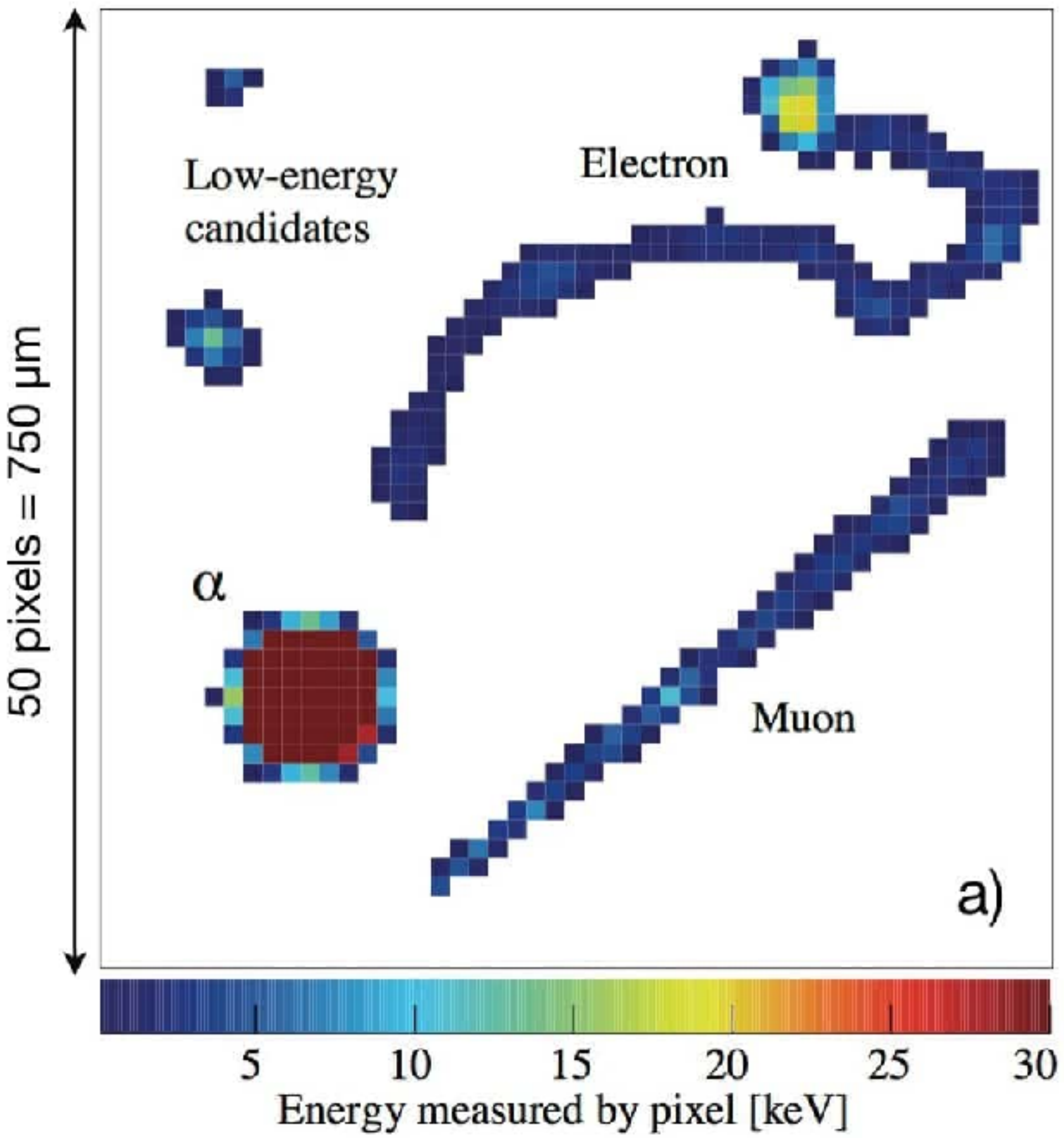
DEIMOS



Cosmic Rays

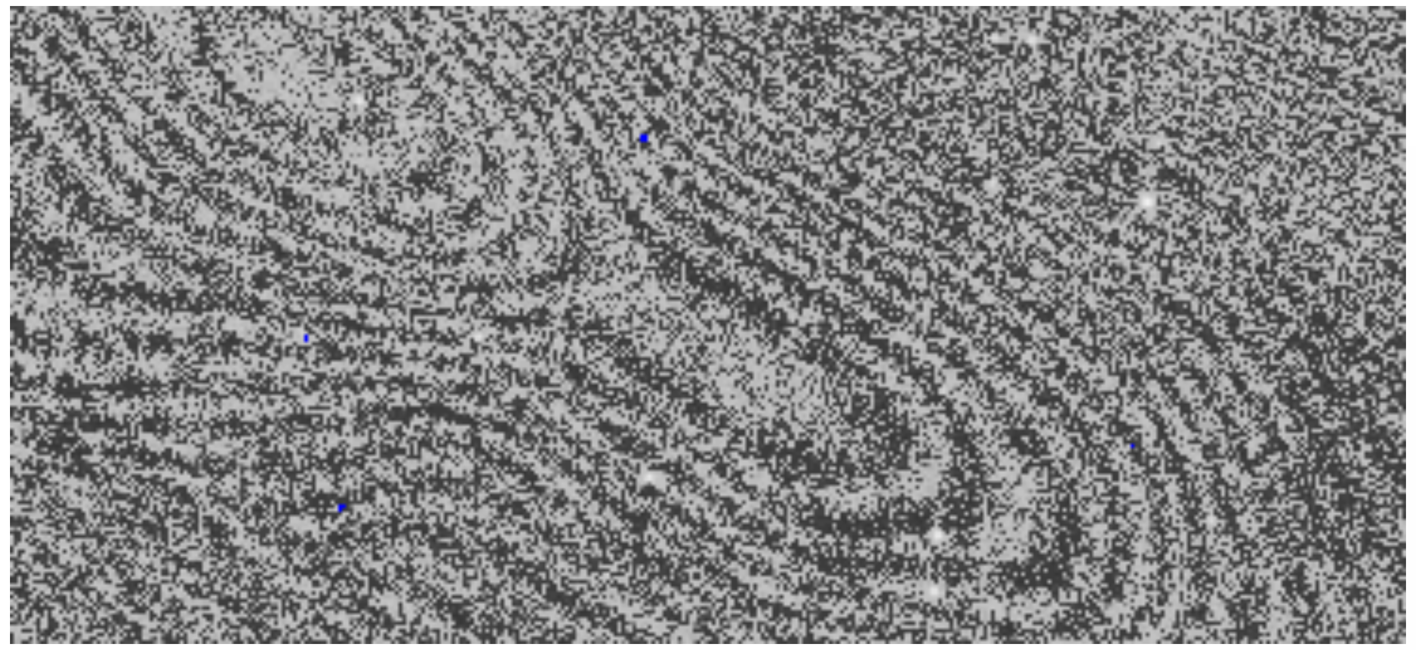


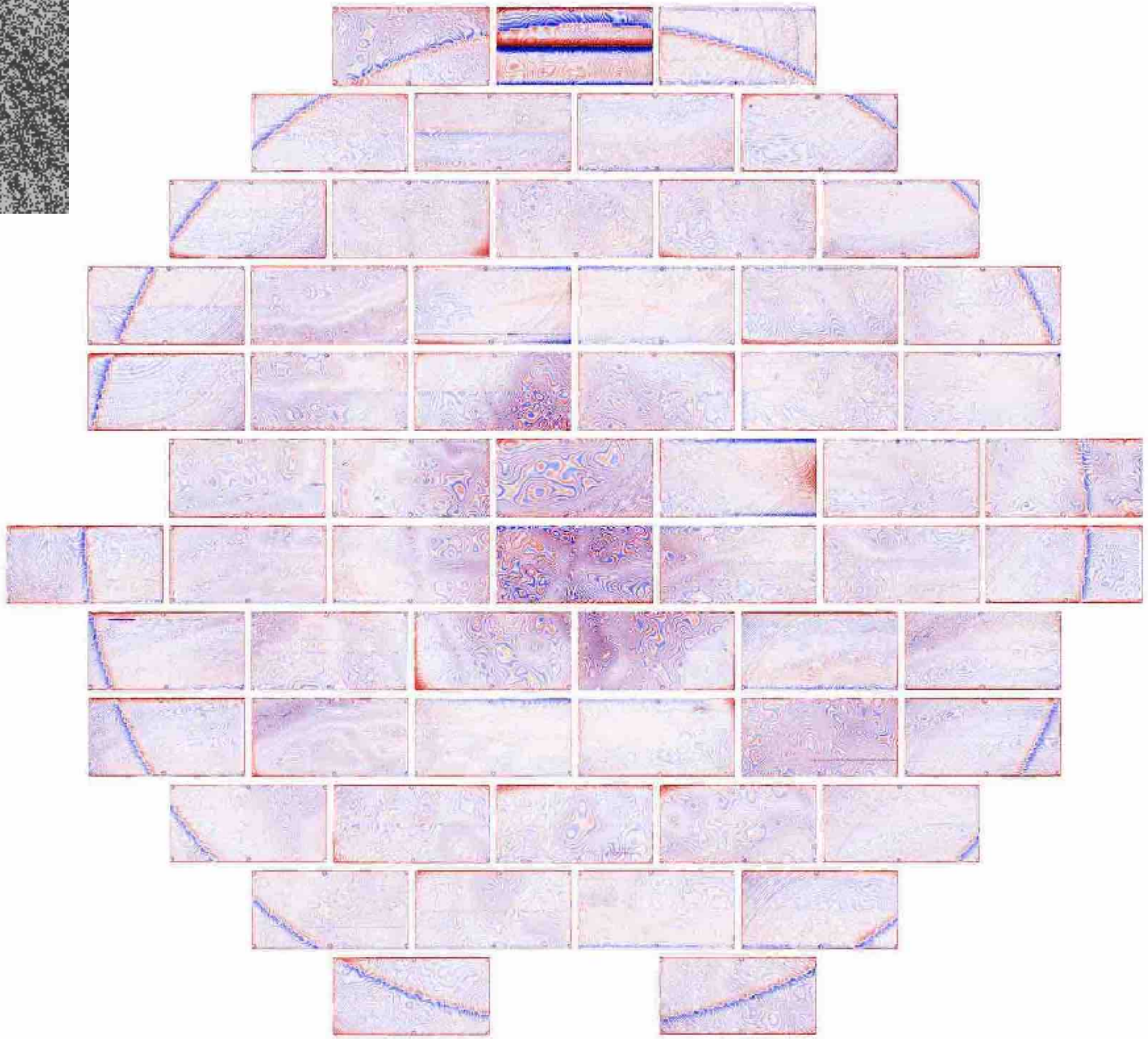
CFHT/MegaCam



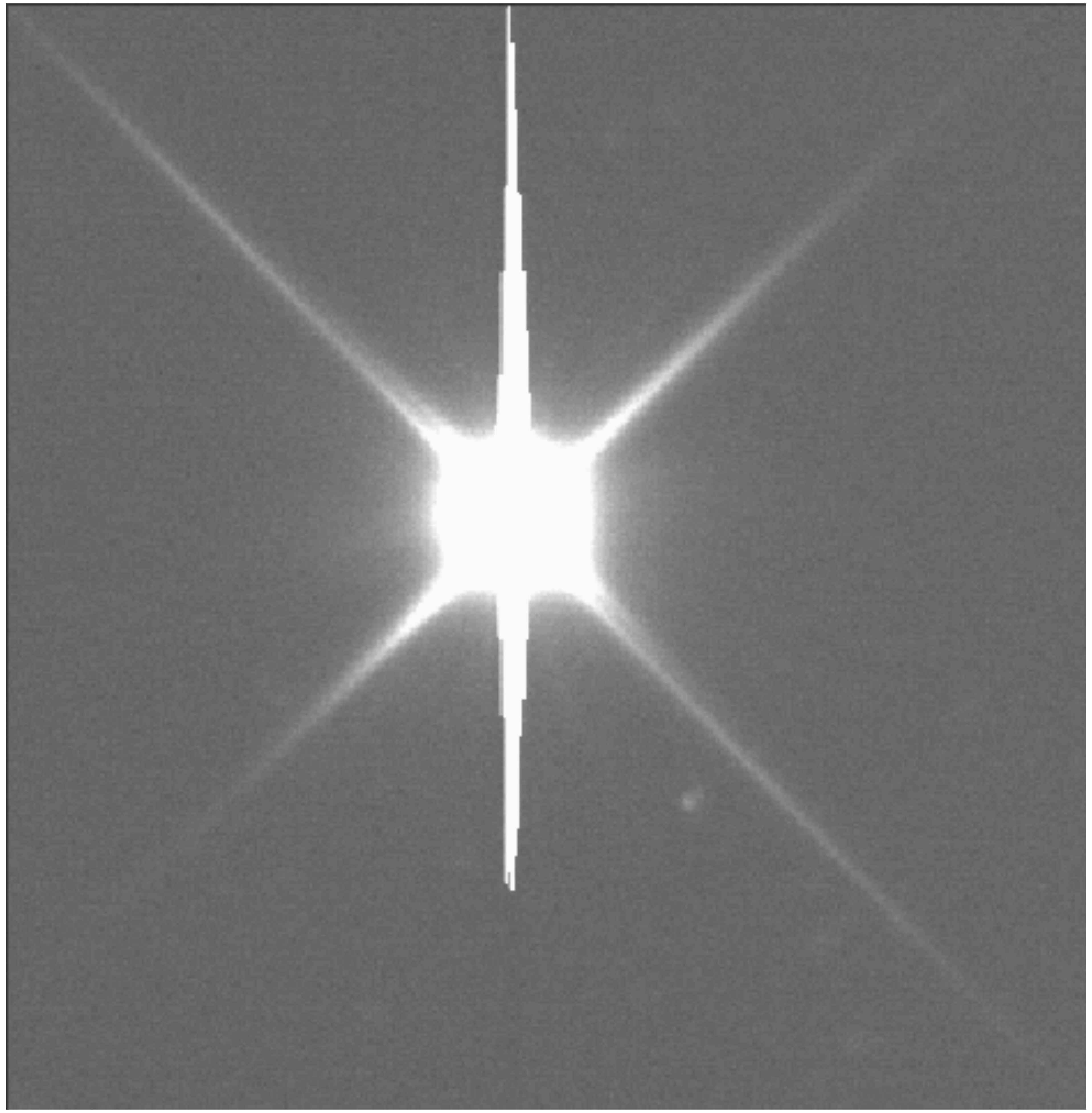
DAMIC-M

Fringing

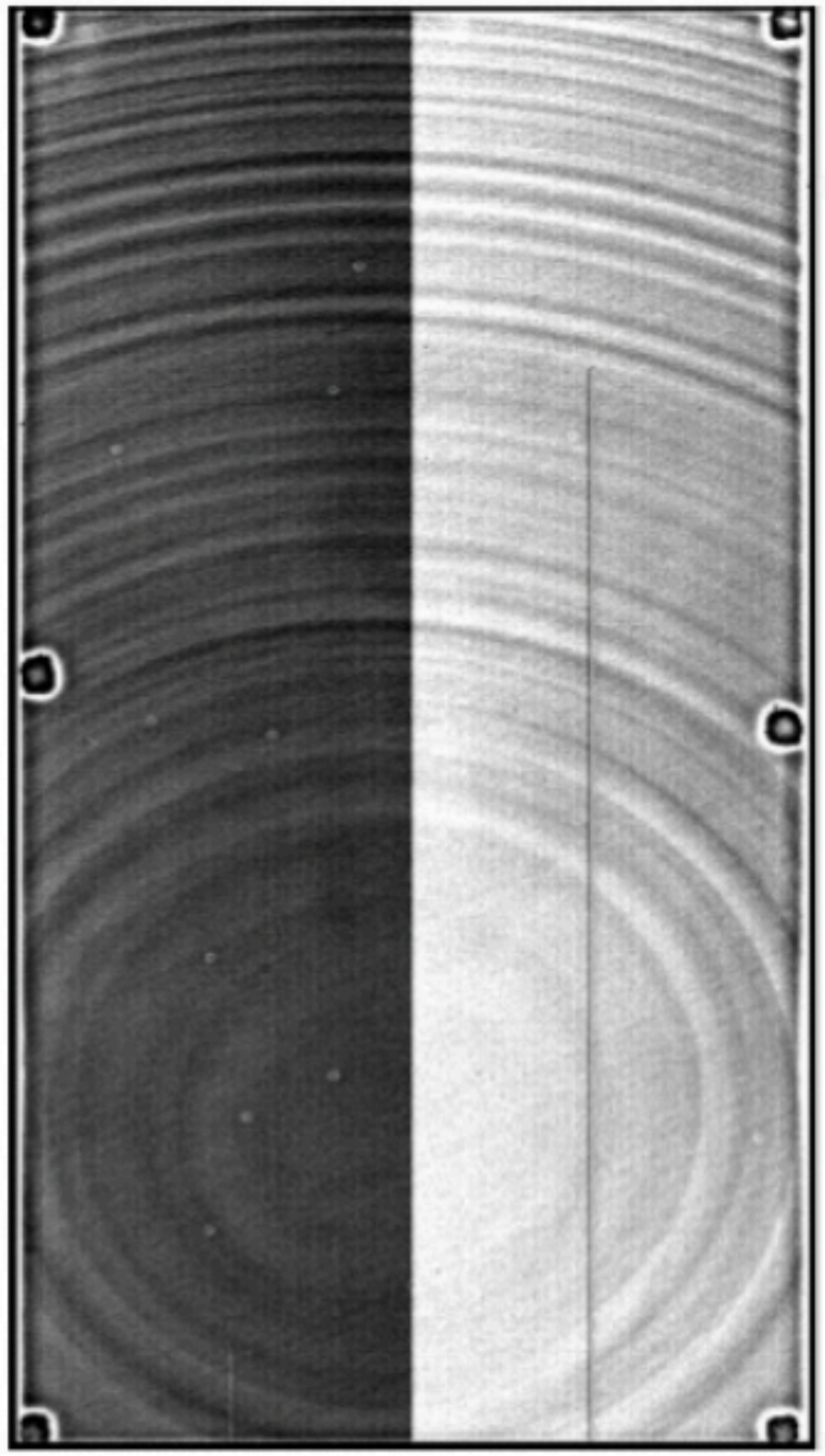


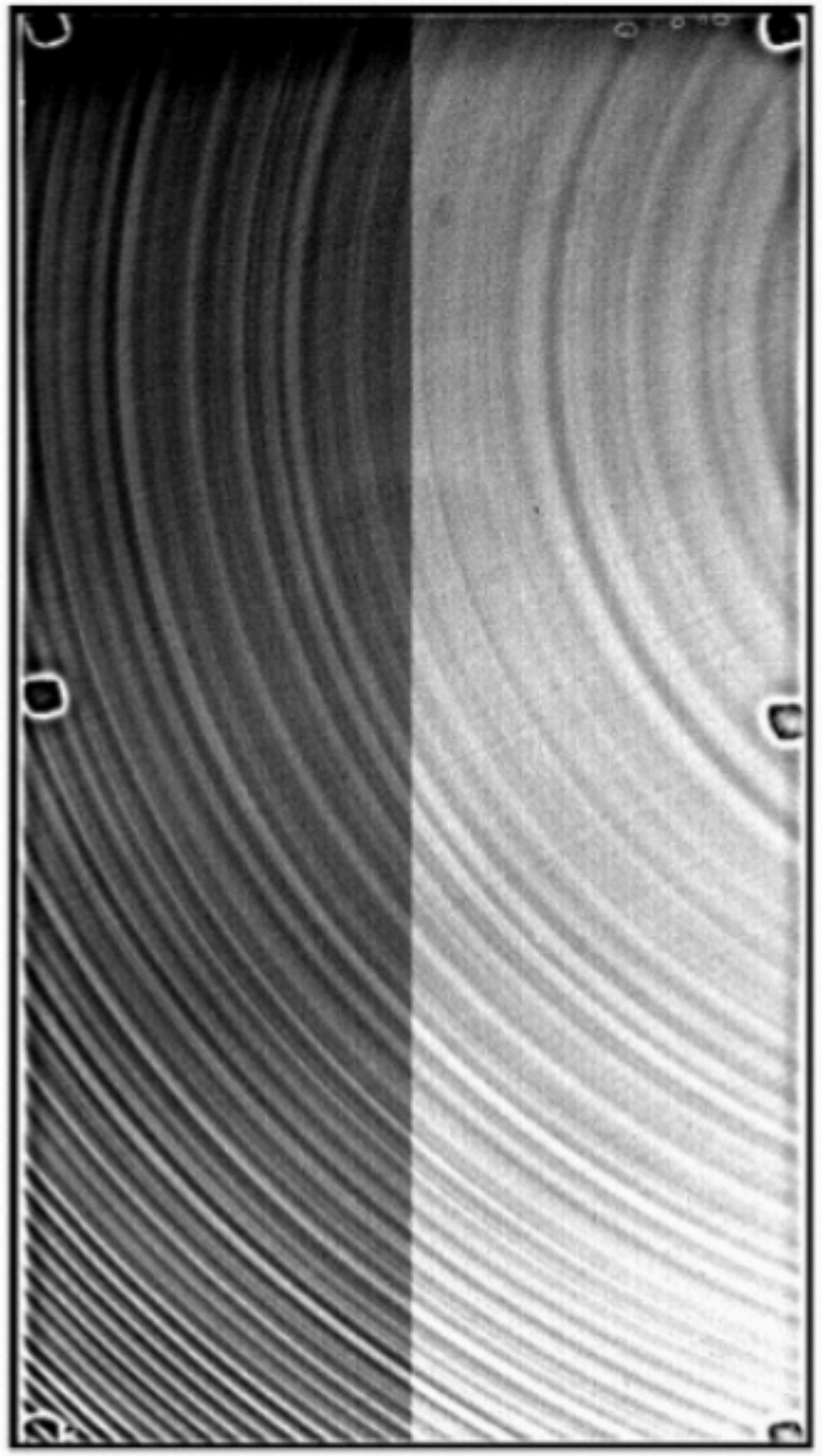


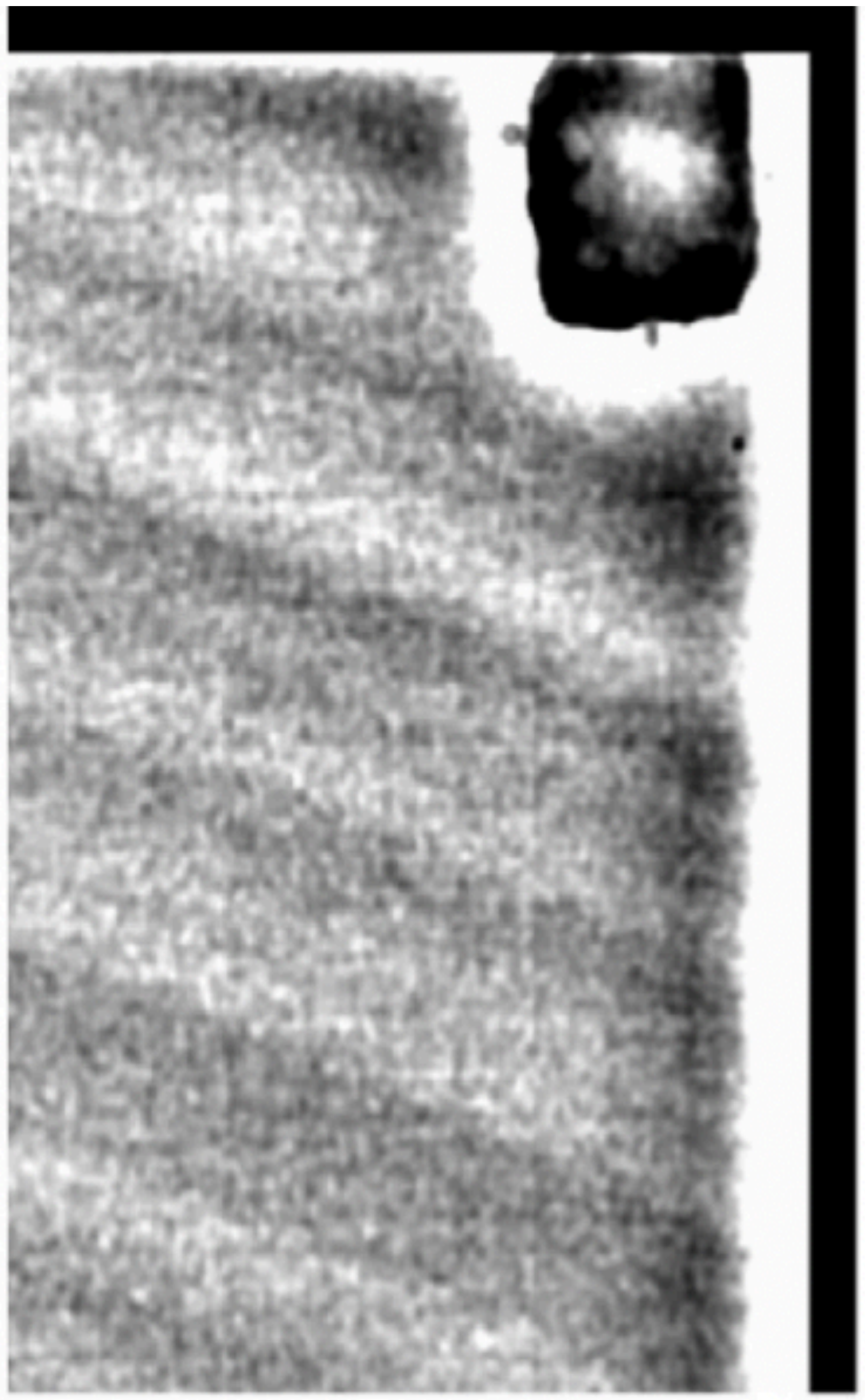
Bleed Trails



Tree Rings & Tape Bumps

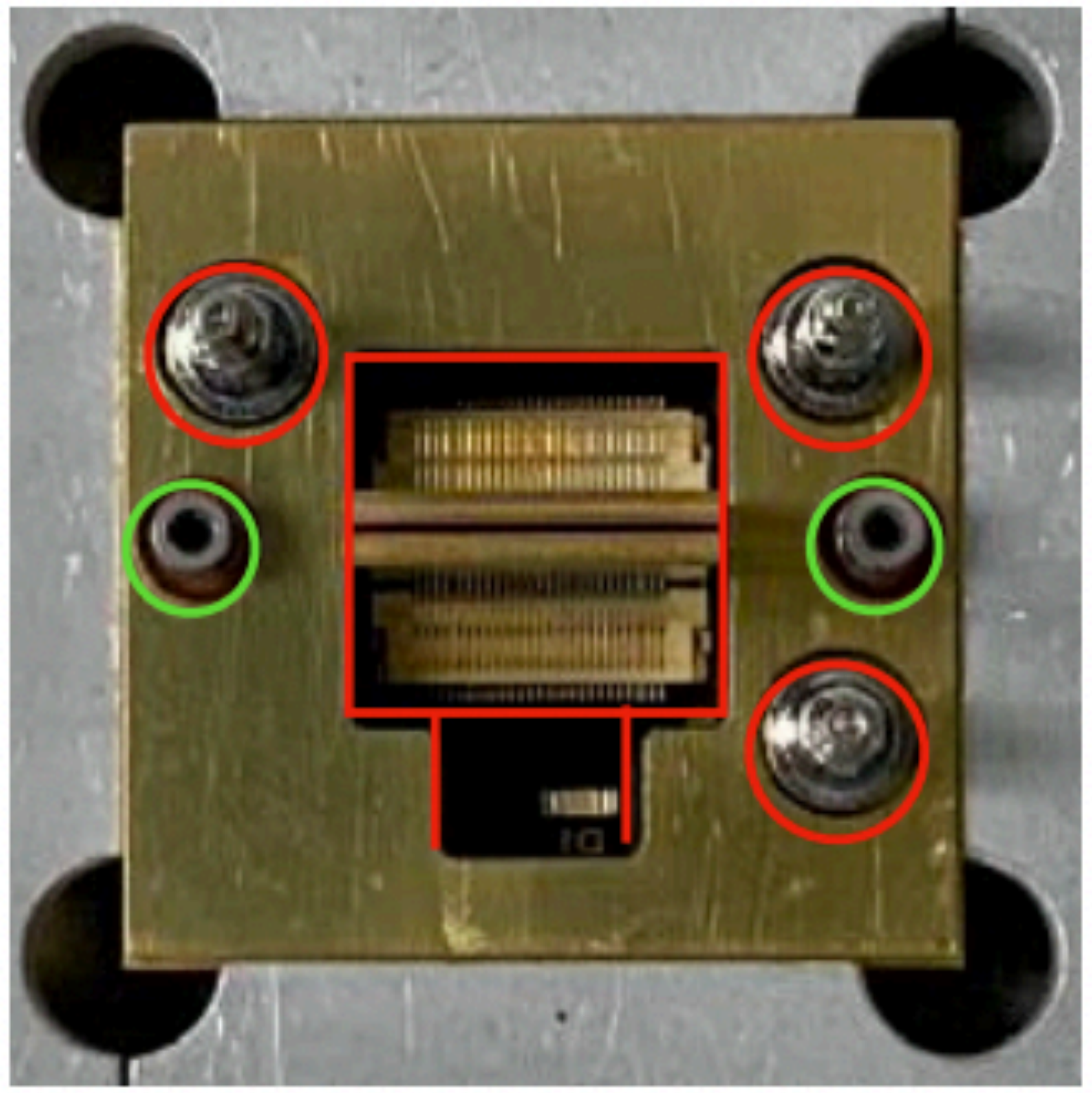


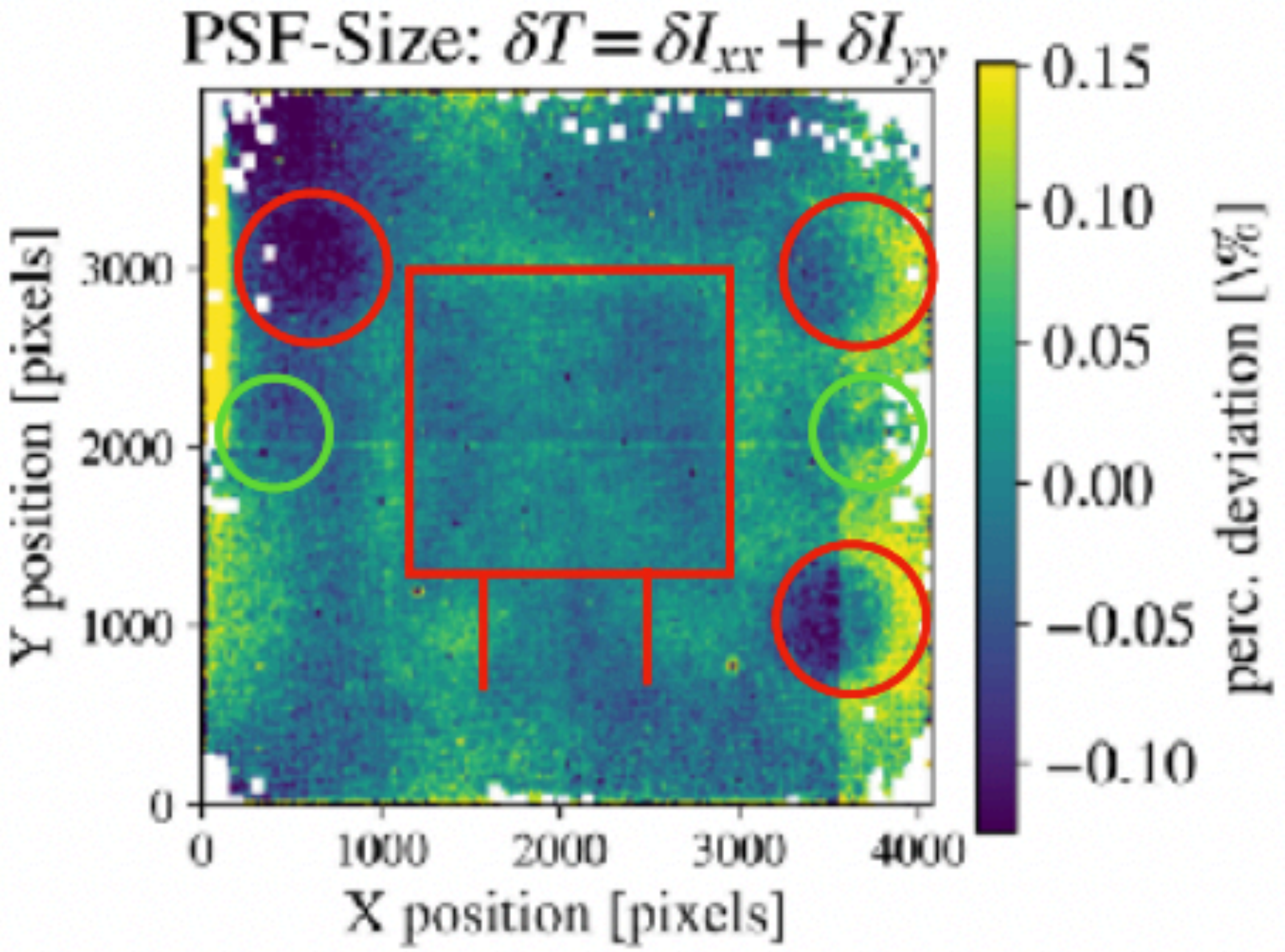


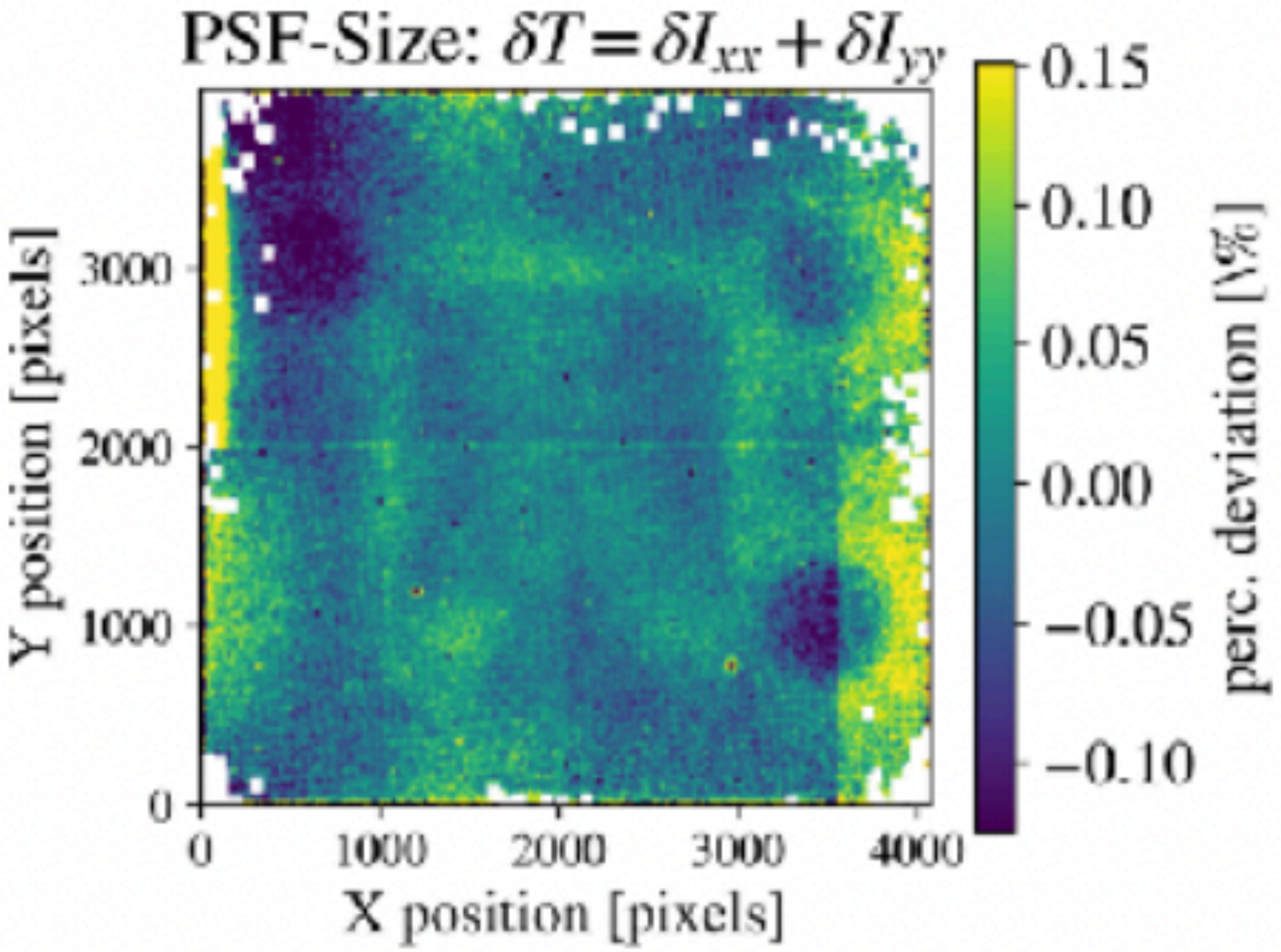


Plazas et al. (2014)

Packaging




PSF-Size: $\delta T = \delta I_{xx} + \delta I_{yy}$
Y position [pixels]
X position [pixels]
perc. deviation [%]
0
1000
2000
3000
4000
0.15
0.10
0.05
0.00
−0.05
−0.10


PSF-Size: $\delta T = \delta I_{xx} + \delta I_{yy}$
Y position [pixels]
X position [pixels]
perc. deviation [%]
0
1000
2000
3000
4000
0.15
0.10
0.05
0.00
−0.05
−0.10