Lecture 21:

Image Sensors

Computer Graphics and Imaging
UC Berkeley CS184/284A

Why Study Image Sensors?
A Quick, Sparse Random Sampling…

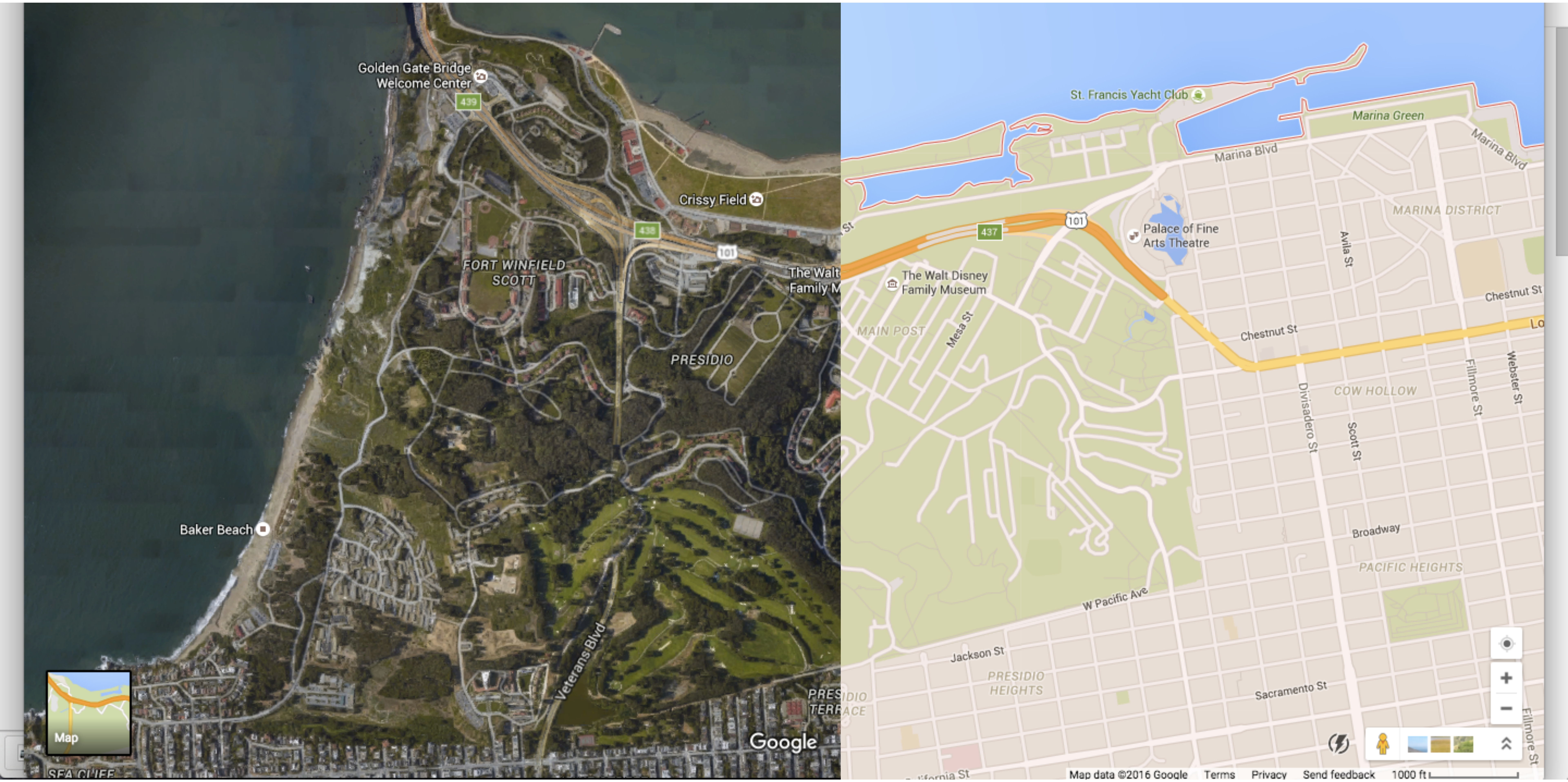
Imaging for Robotics

Google's "Arm Farm"

Imaging for Computer Vision

ImageNet: 15M images, 22K categories
http://image-net.org

Imaging in Mapping



Maps, satellite imagery, street-level imaging,…

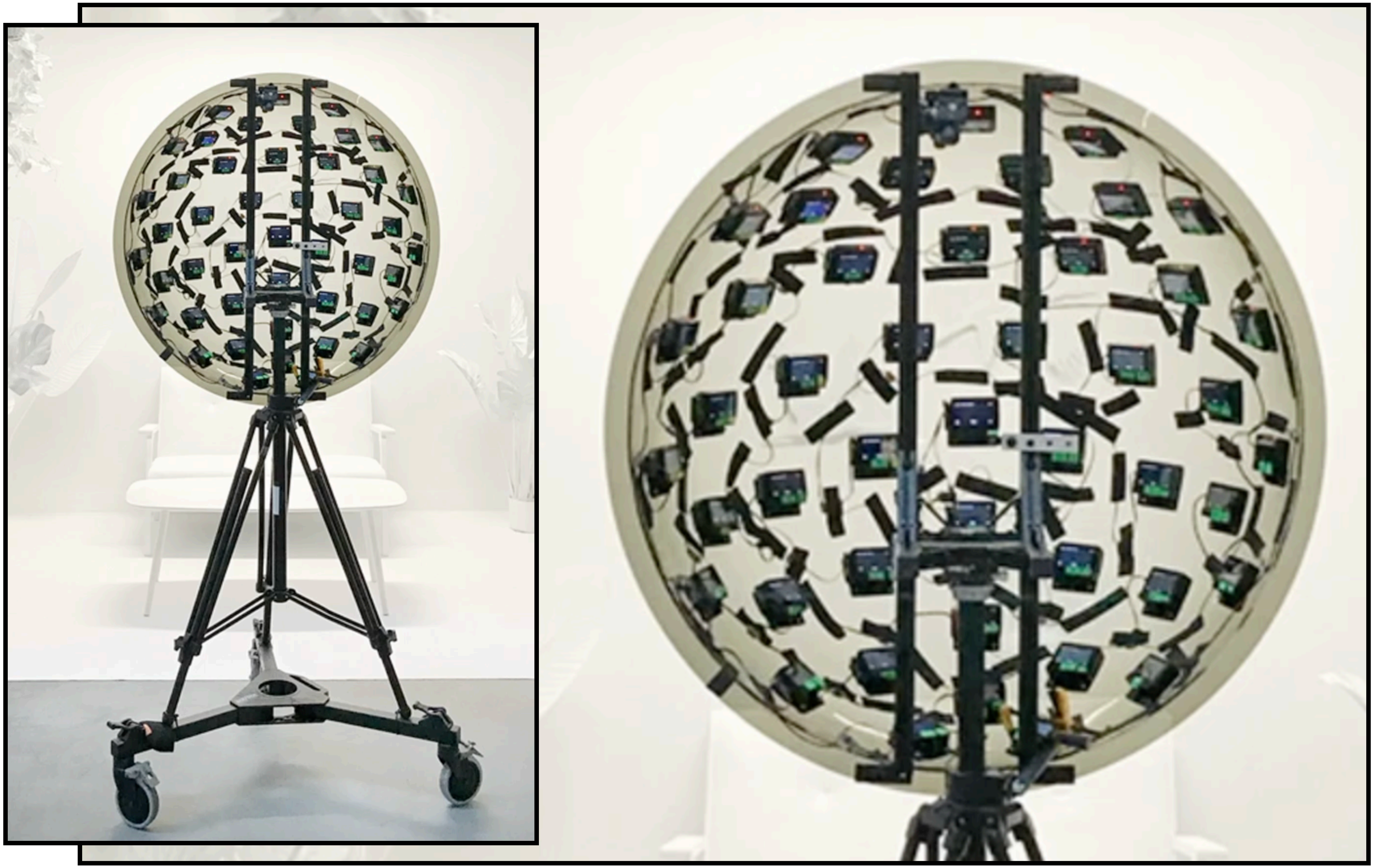
Imaging in Mapping

Maps, satellite imagery, street-level imaging,…

Ubiquitous Consumer Imaging

Cameras everywhere

Imaging for Virtual Reality



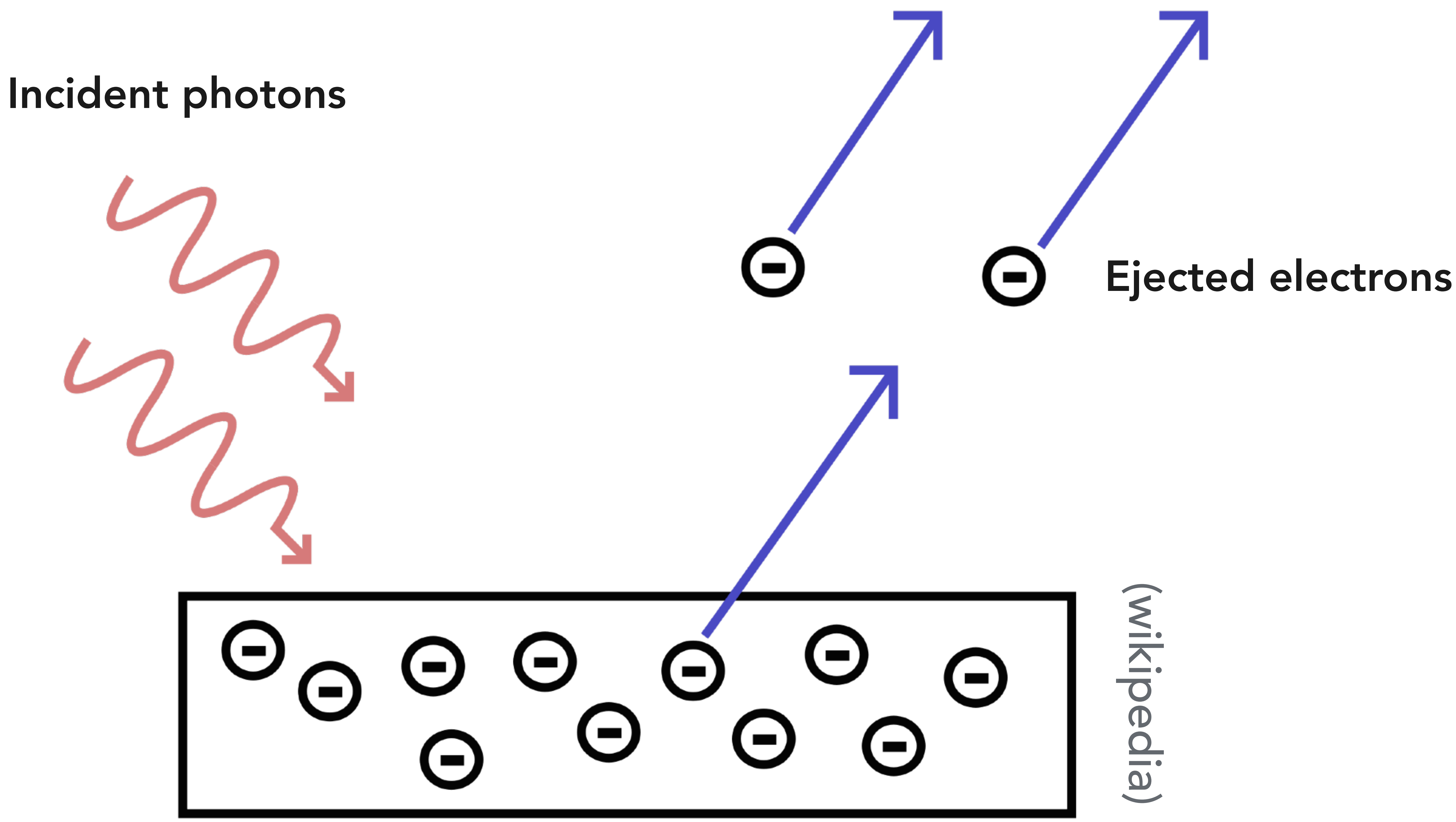
Google 6 DOF Light Field Camera. Broxton et al. 2019.

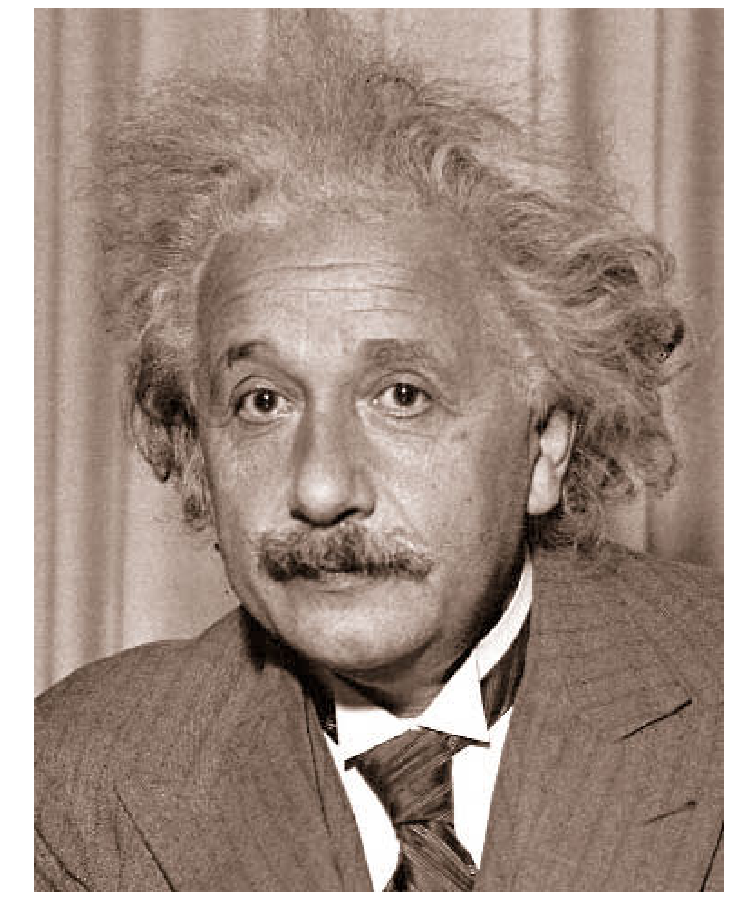
Imaging for Virtual Reality

Google 6 DOF Light Field Camera. Broxton et al. 2019.

Photon Capture

The Photoelectric Effect





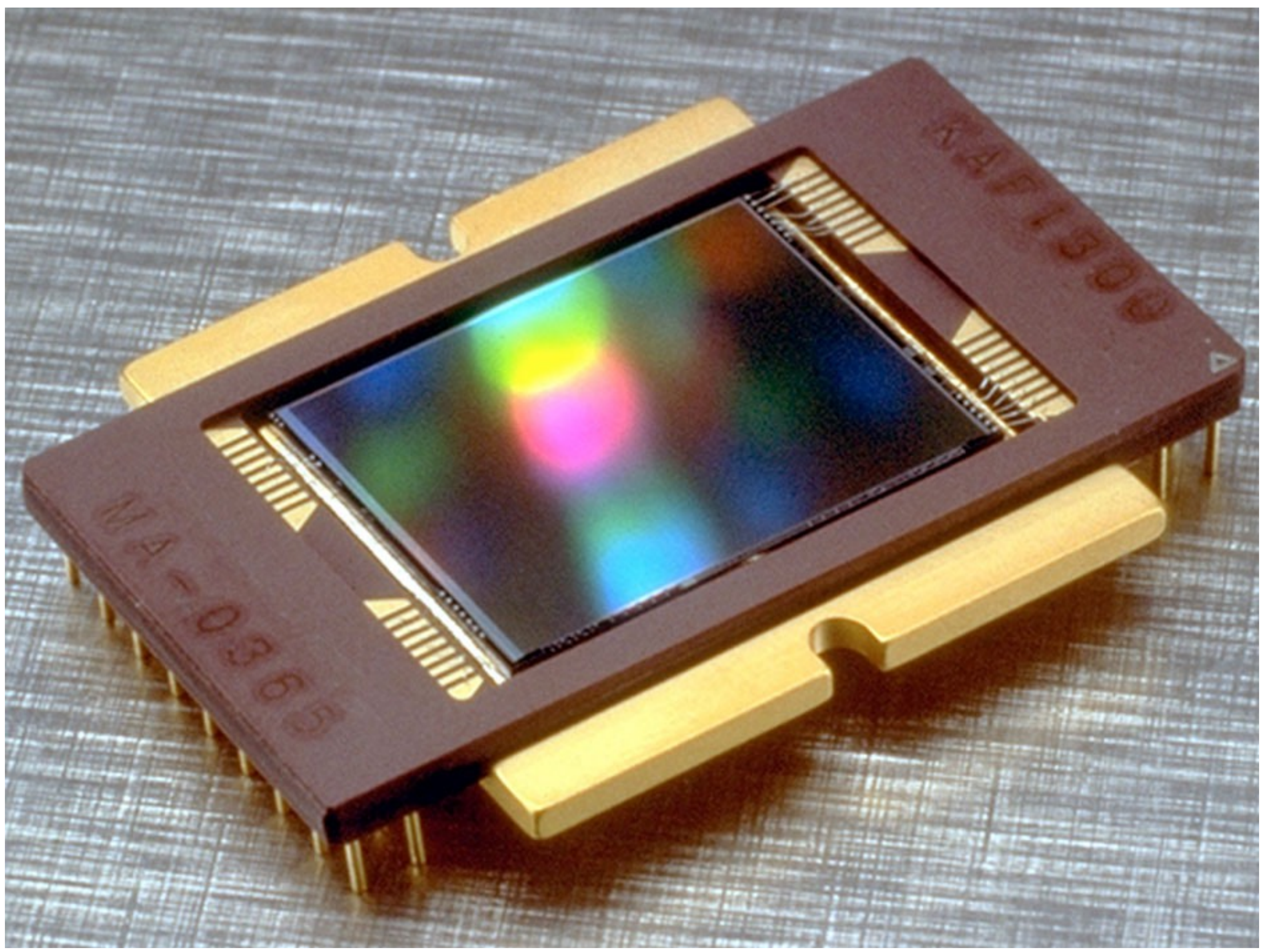
Albert Einstein

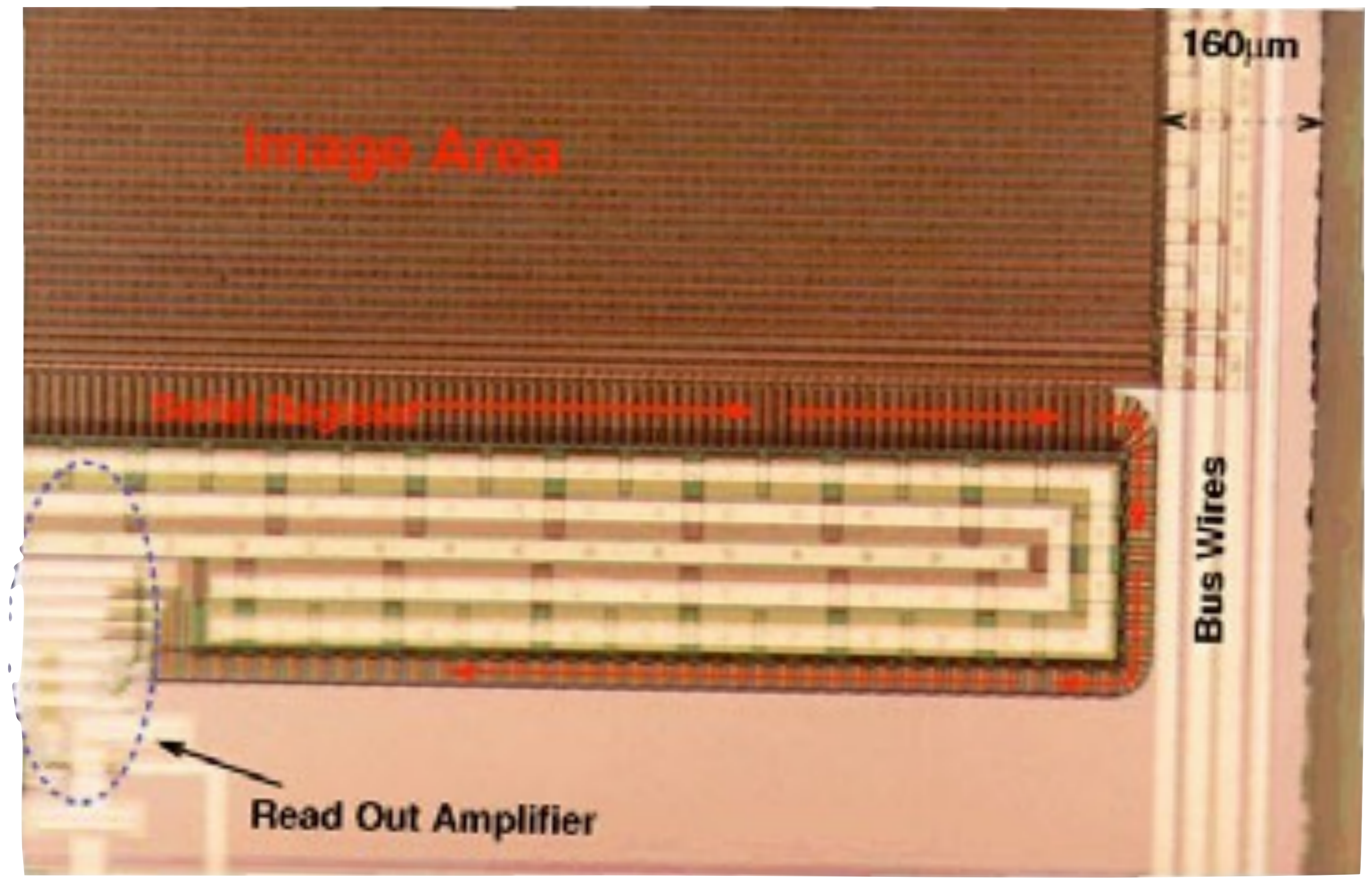
Einstein's Nobel Prize in 1921 "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

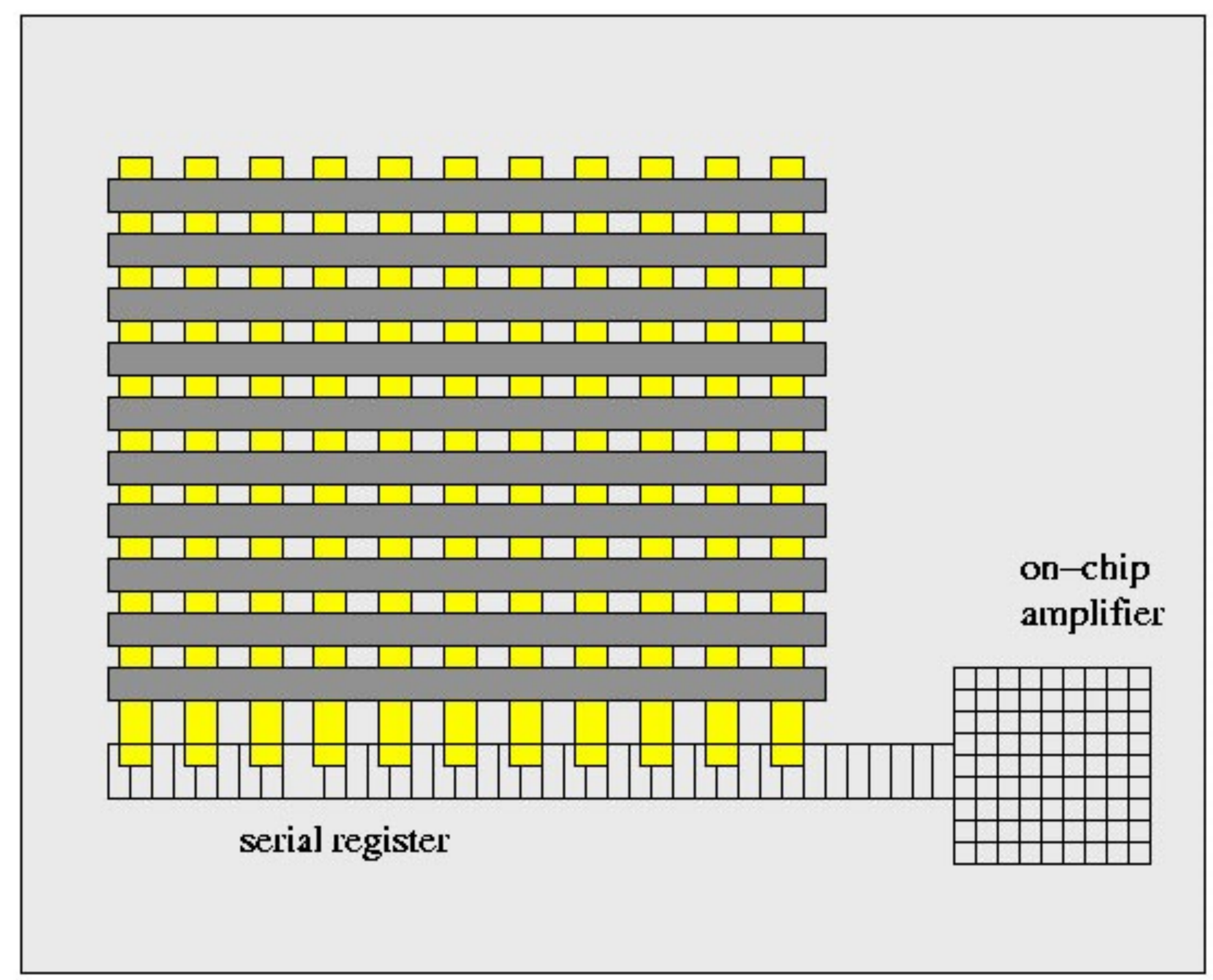
Charge Coupled Devices (CCD)

Developed by Wilford Boyle (L) and George Smith (R) at Bells Labs in 1969
Nobel Prize 2009 - "for the invention of an imaging semiconductor circuit – the CCD sensor"

Charge Coupled Devices (CCD)

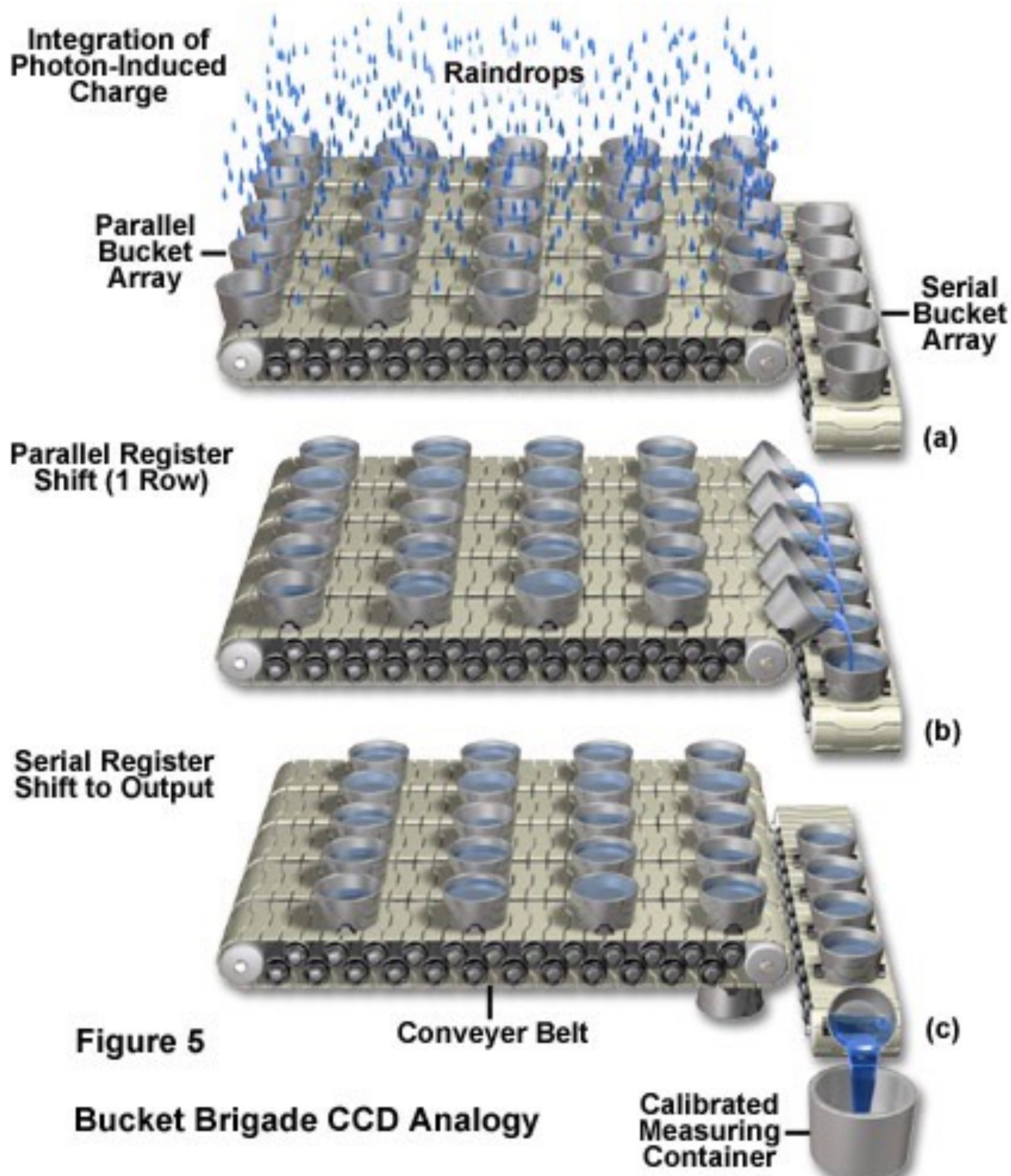






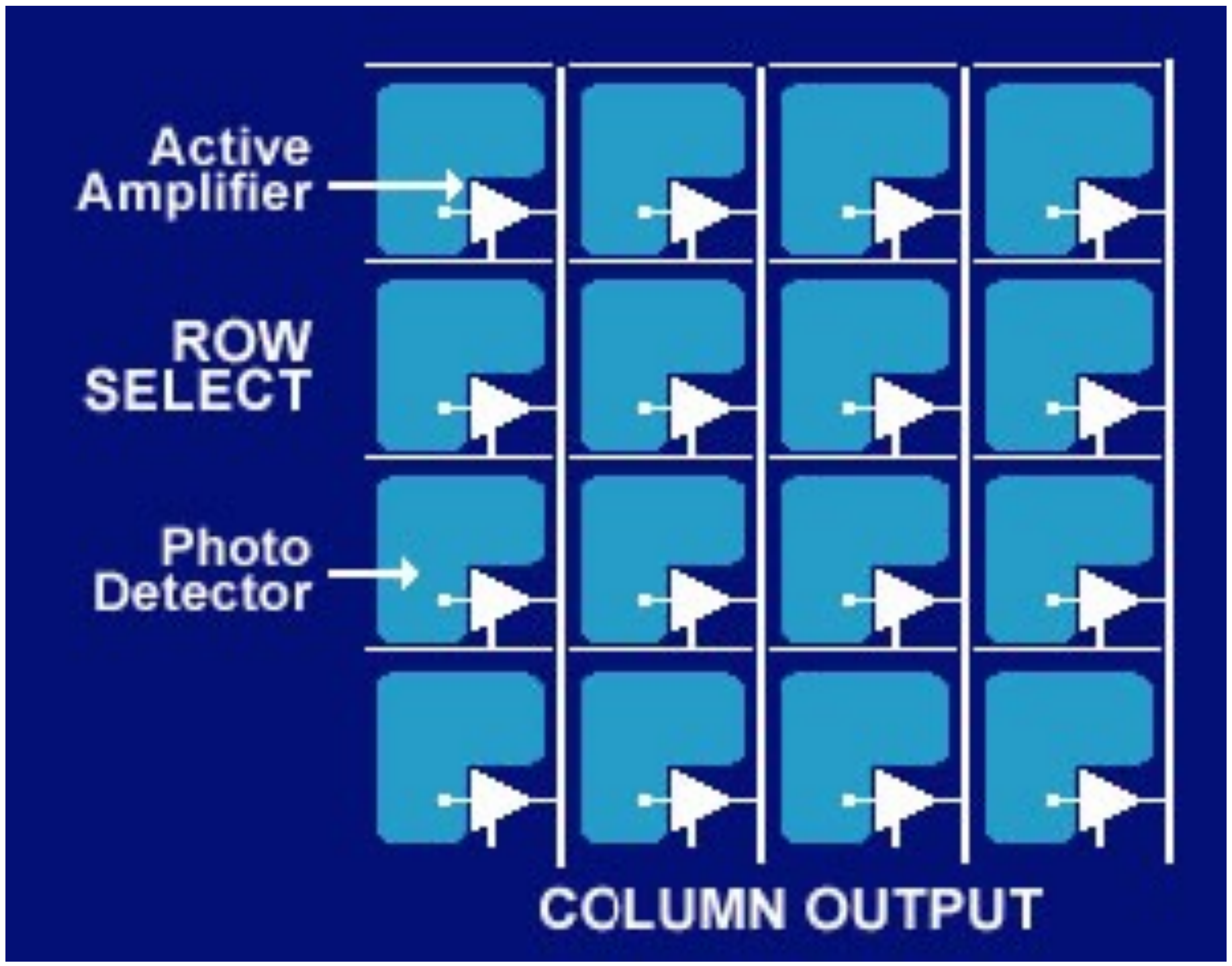
CCD

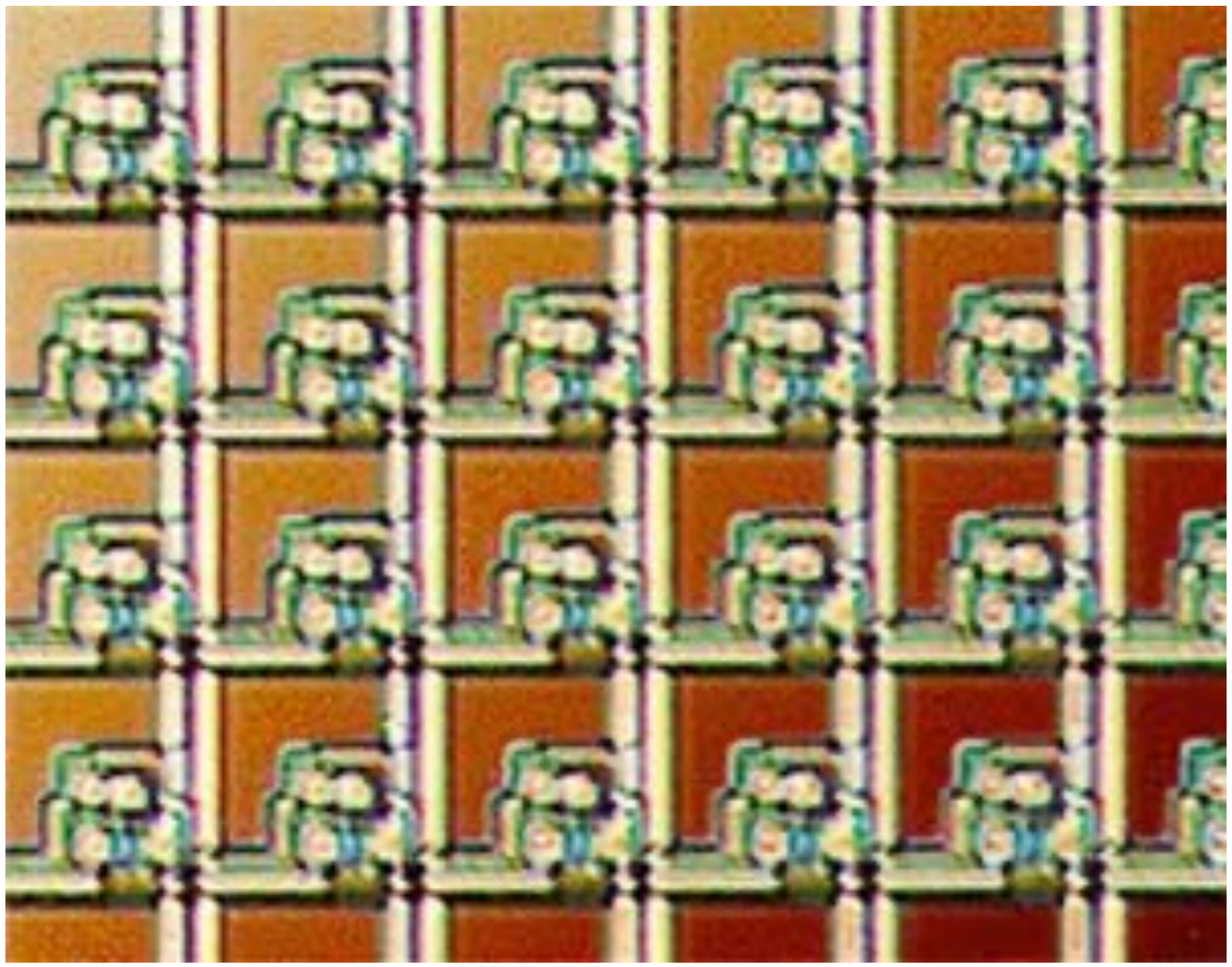
Interline CCD



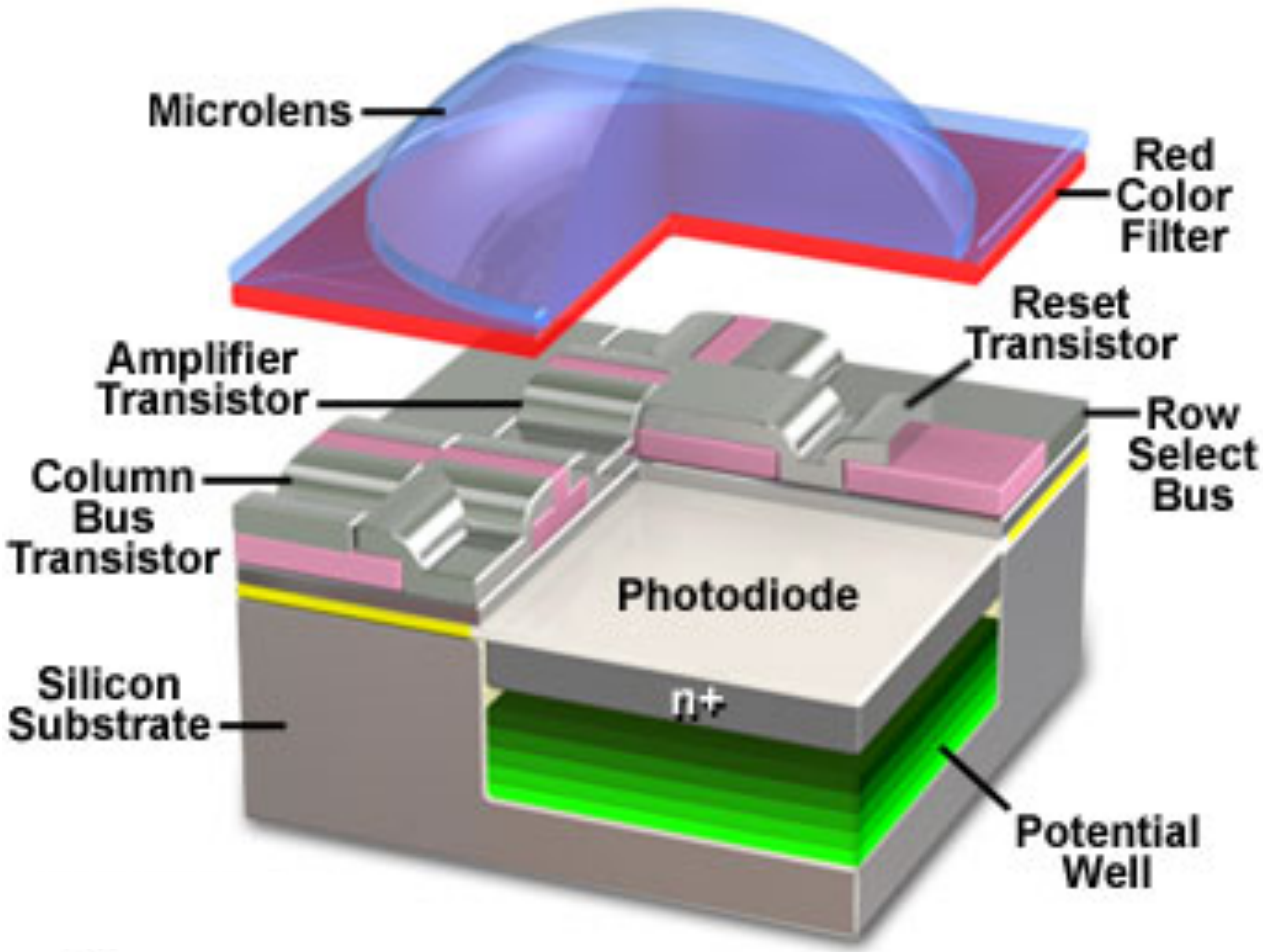
[Nikon MicroscopyU]

CMOS APS (Active Pixel) Sensor





Anatomy of the Active Pixel Sensor Photodiode



http://www.olympusmicro.com/primer/digitalimaging/cmosimagesensors.html

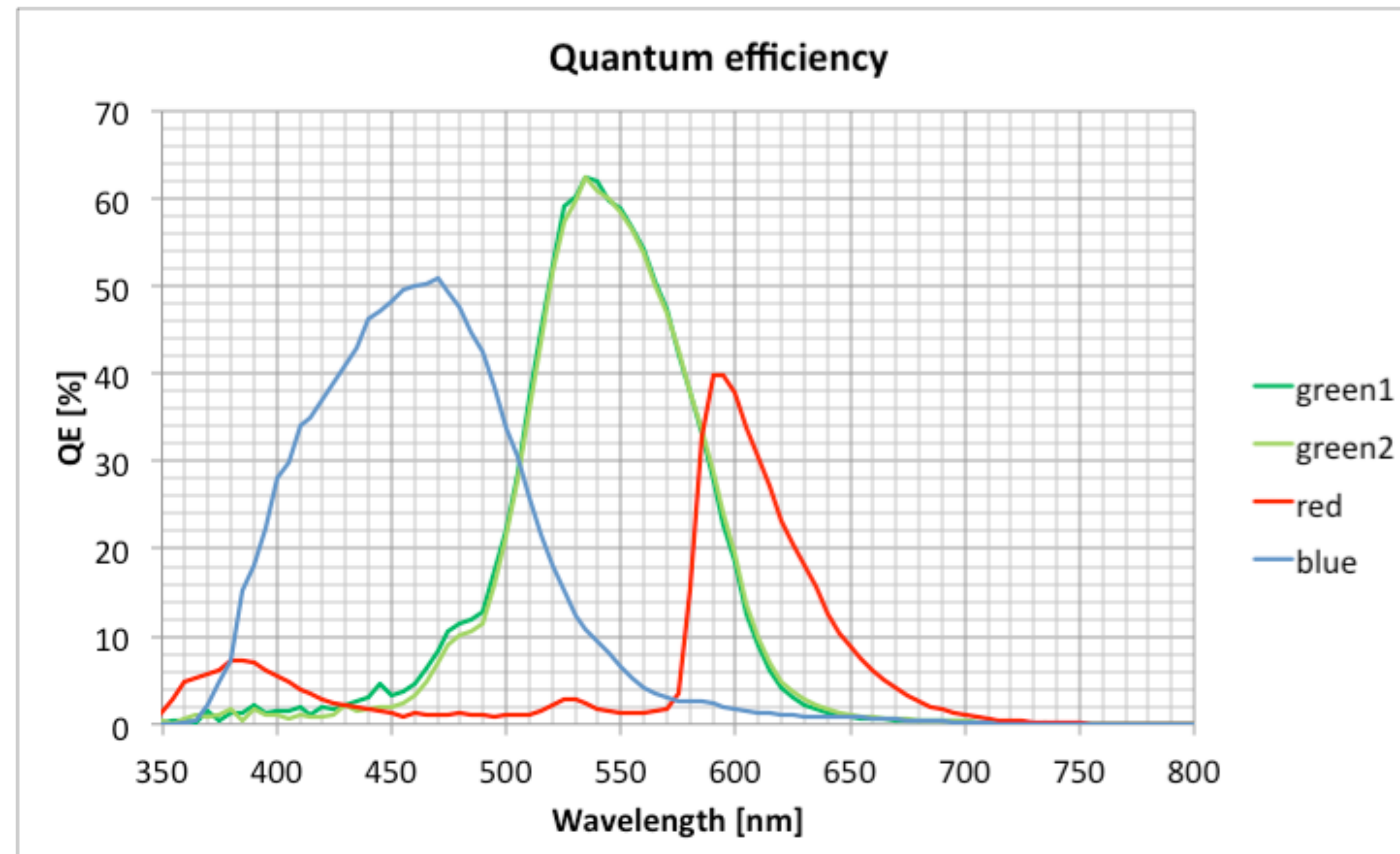
Quantum Efficiency

Not all photons will produce an electron

- Depends on quantum efficiency of the device

$$QE = \frac{\#\, electrons}{\#\, photons}$$

- Human vision: ~15%
- Smartphone camera: c ~60%
- Best back-thinned CCD: > 90%
- Scientific CMOS (sCMOS): 95%

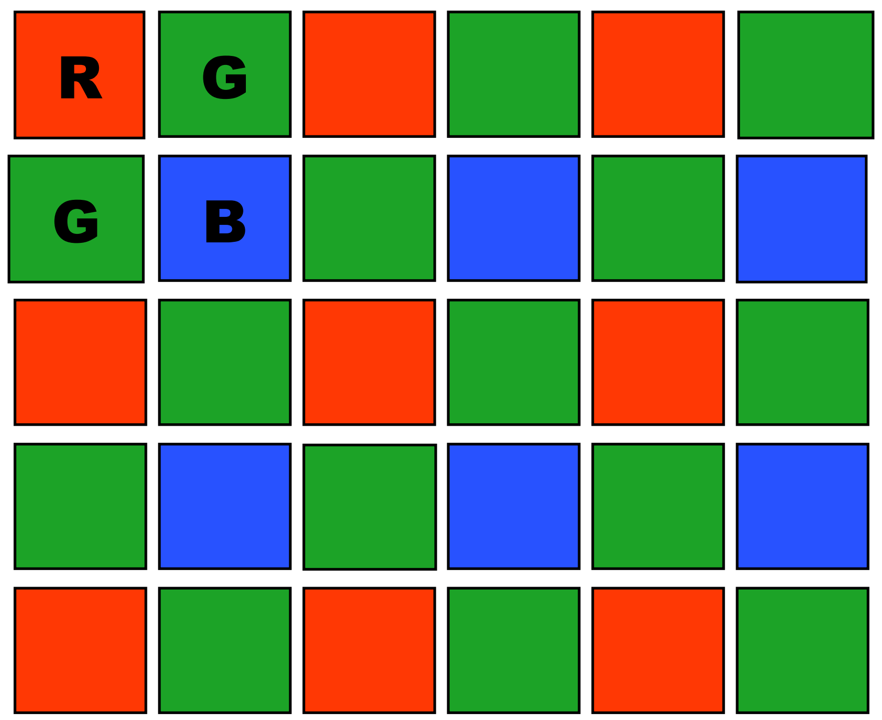


Meynants et al. IISW 2013

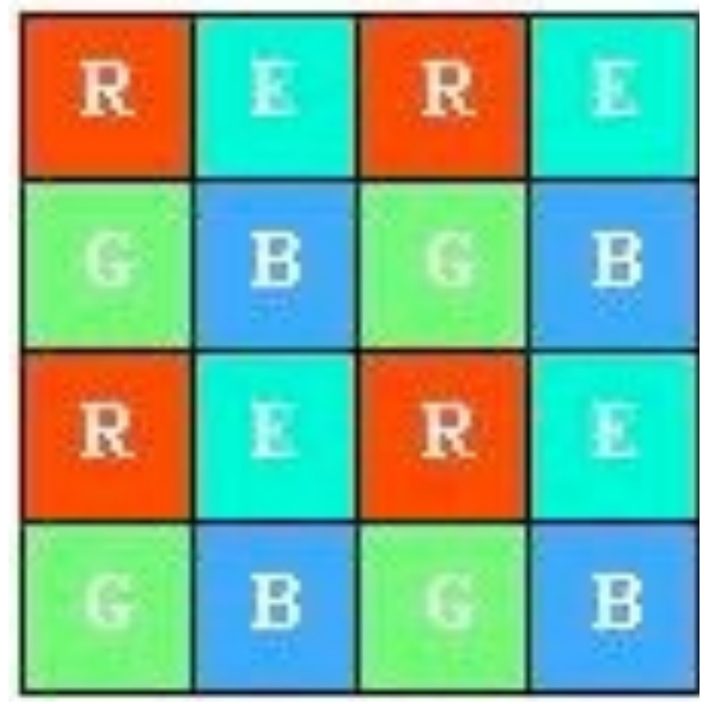
QE of a 24MP CMOS full-frame sensor

Color Architectures

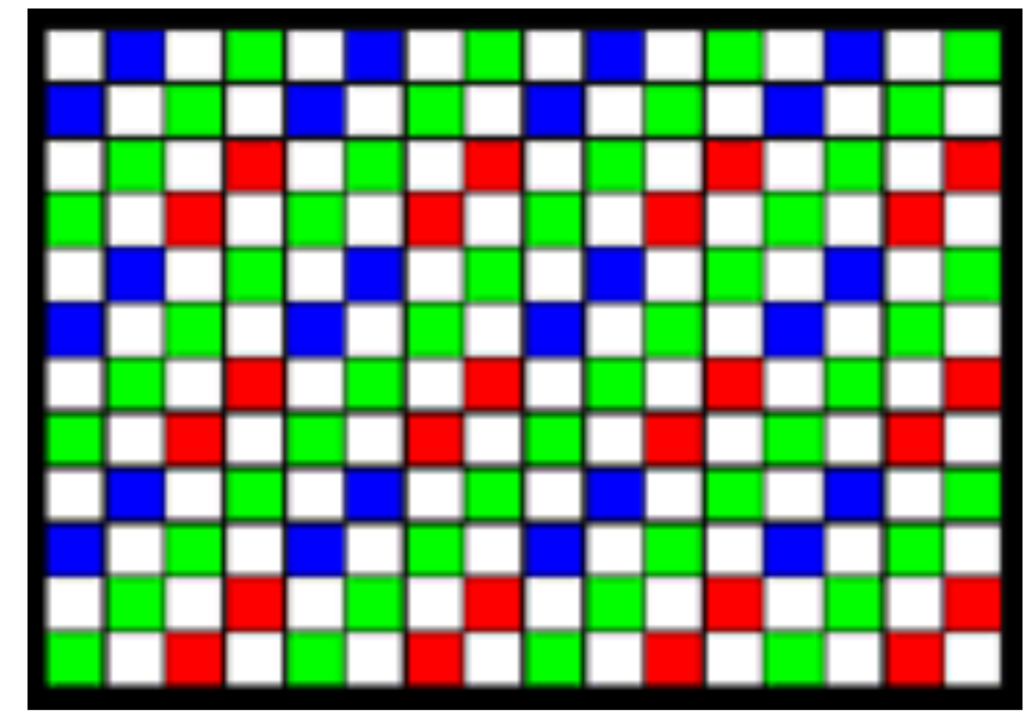
Color Filter Arrays (Mosaics)



Bayer pattern
(most common)



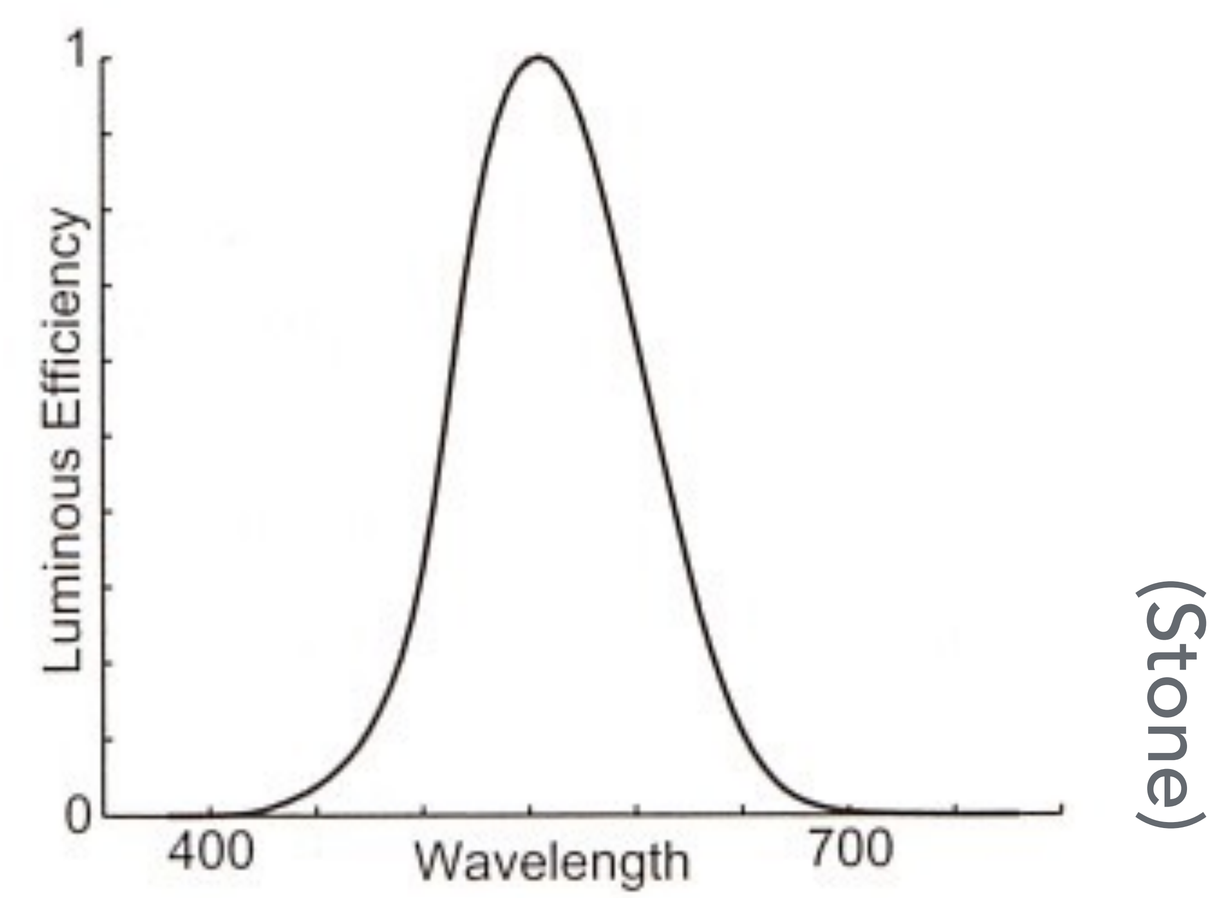
Sony RGB+E
wider color gamut



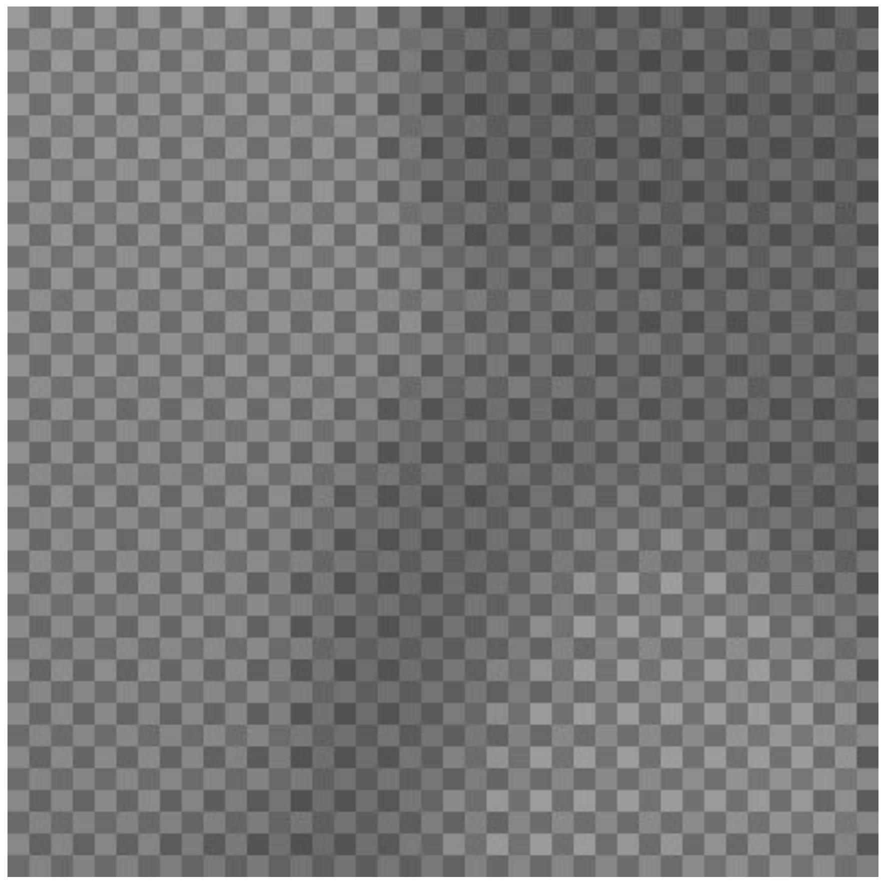
Kodak RGB+W
higher dynamic range

Why more green pixels than red or blue?

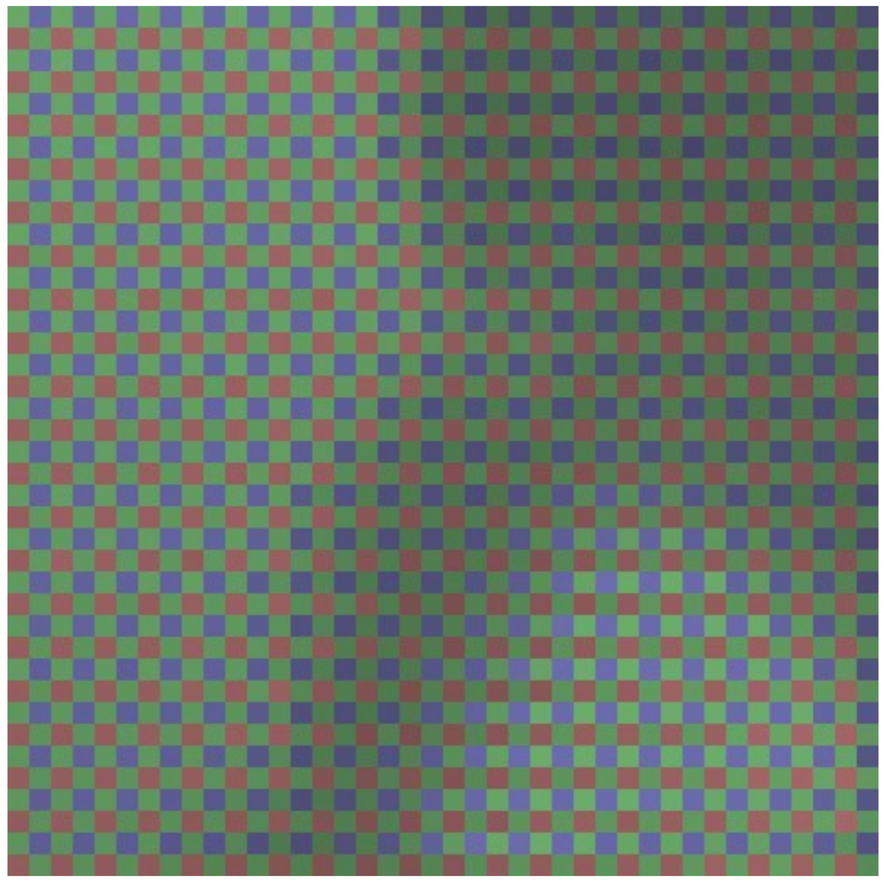
- Because humans are most sensitive in the green portion of the visible spectrum
- Sensitivity given by the human luminous efficiency curve

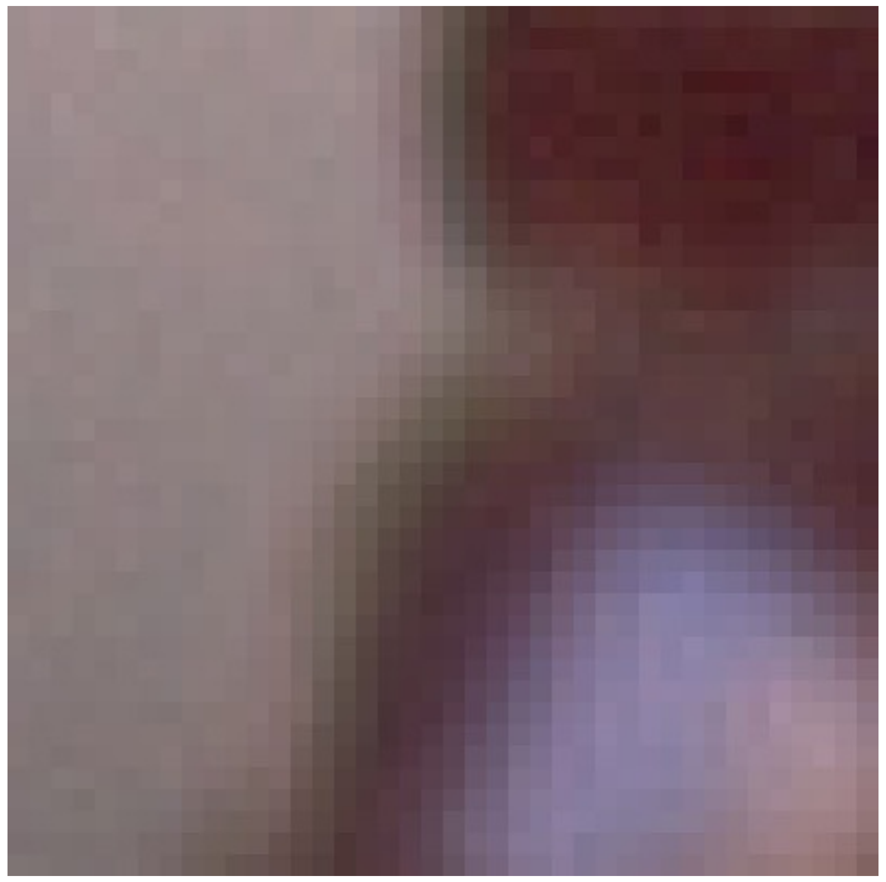


Demosaicking Algorithms



Demosaicking Algorithms





Demosaicking Algorithms

Interpolate sparse color samples into RGB at every output image pixel

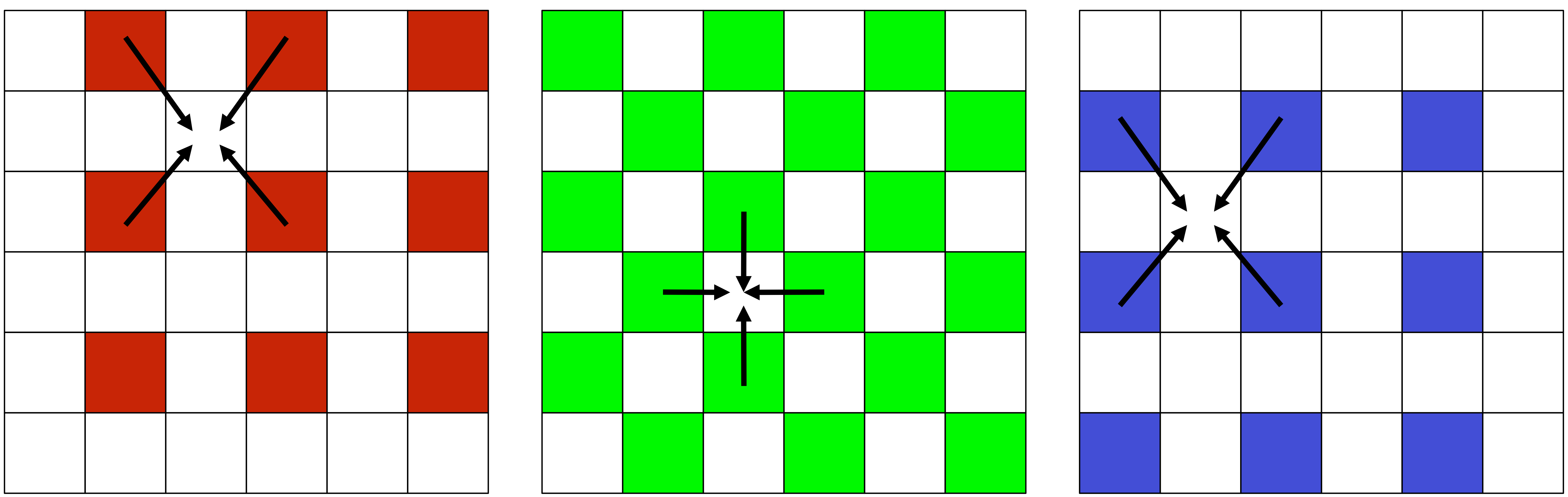
Simple algorithm: bilinear interpolation

- Average 4 nearest neighbors of the same color

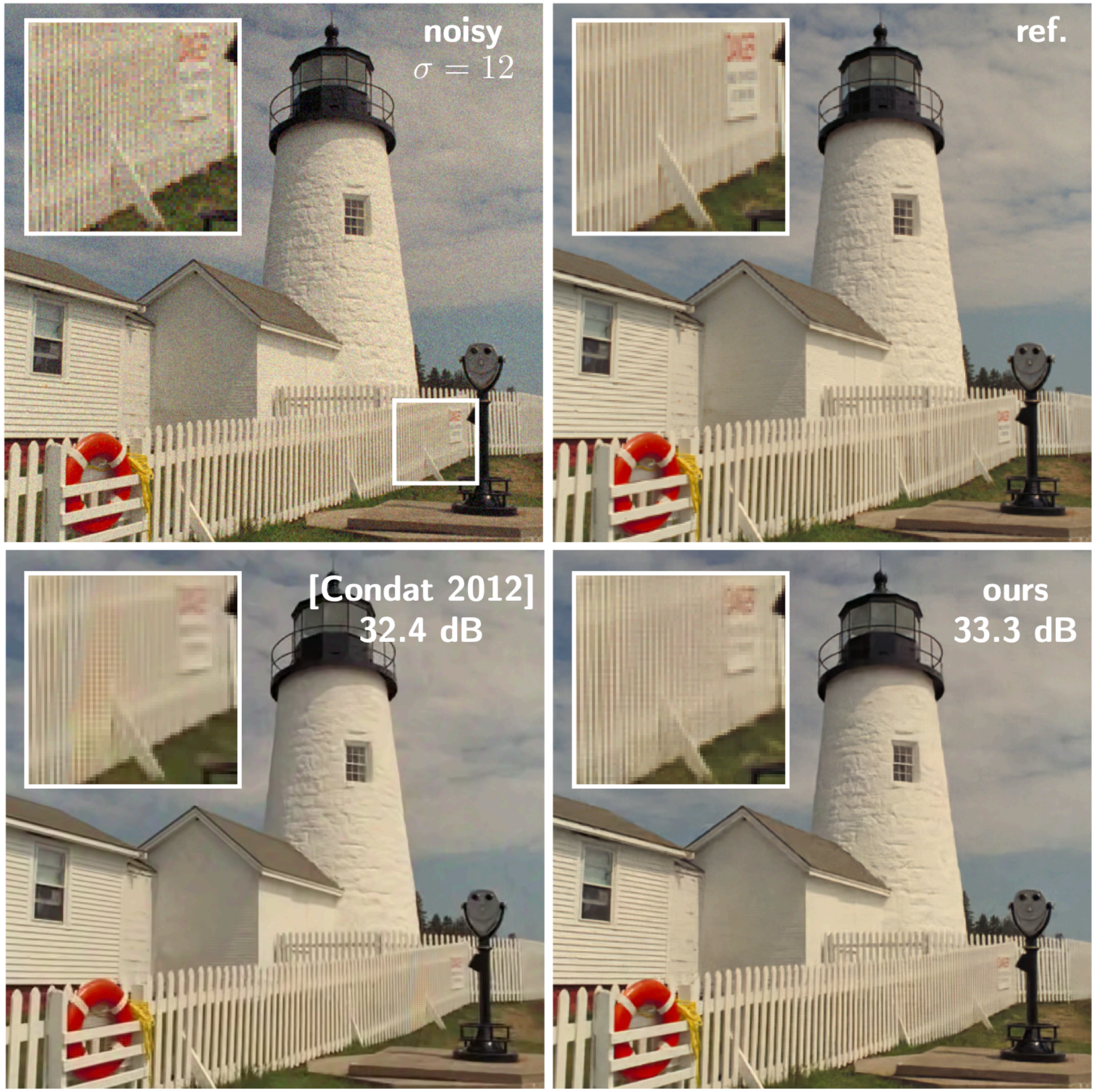
Consumer cameras use more sophisticated techniques

- Try to avoid interpolating across edges

Due to demosaicking, 2/3 of image data is “made up”!



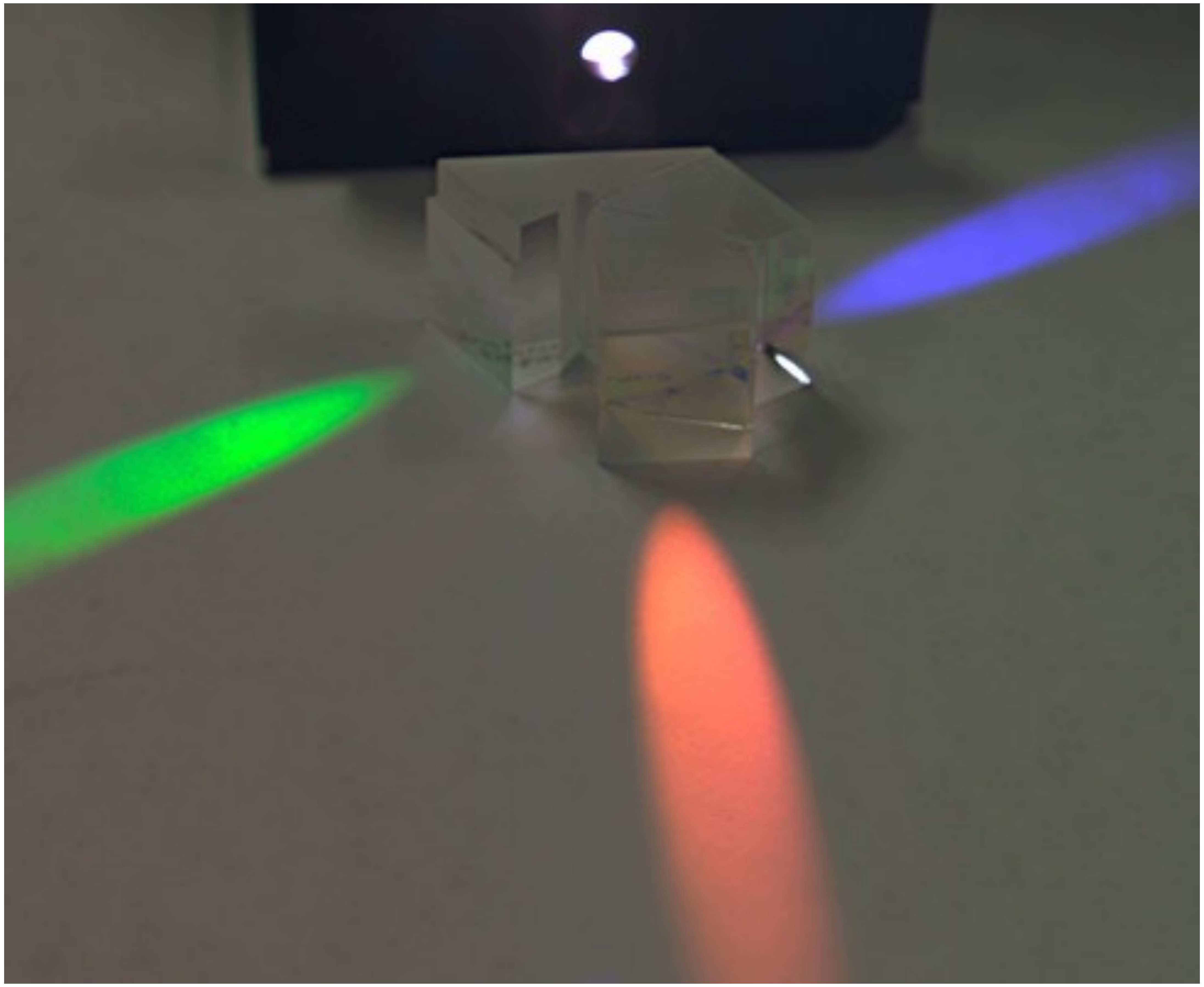
Demosaicking Based on Machine-Learning



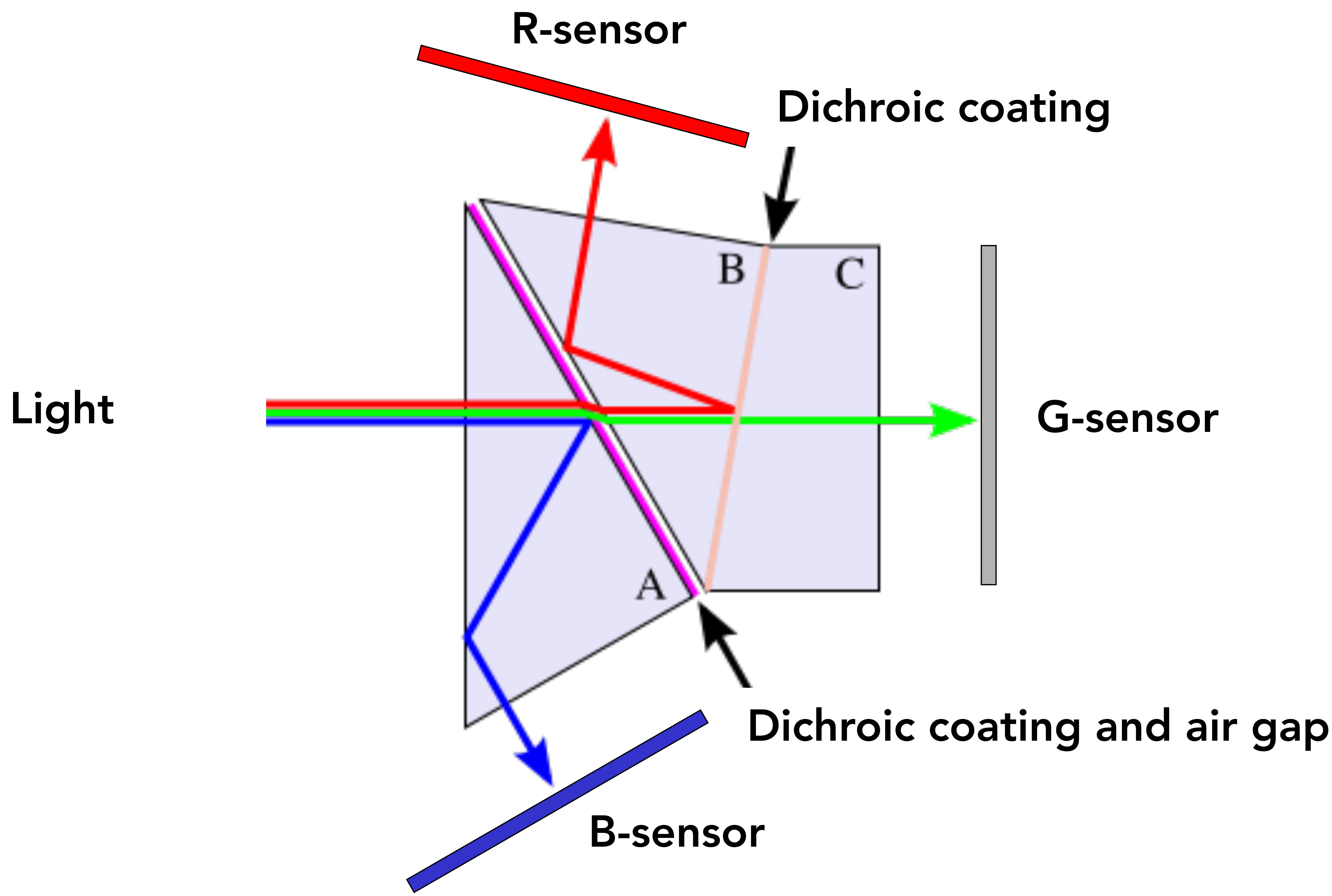
 Gharbi et al. 2016. Deep Joint Demosaicking and Denoising.

3-Sensor Color Architecture

- Prismatic optics
- No demosaicking
- Three (smaller) sensors and optical alignment



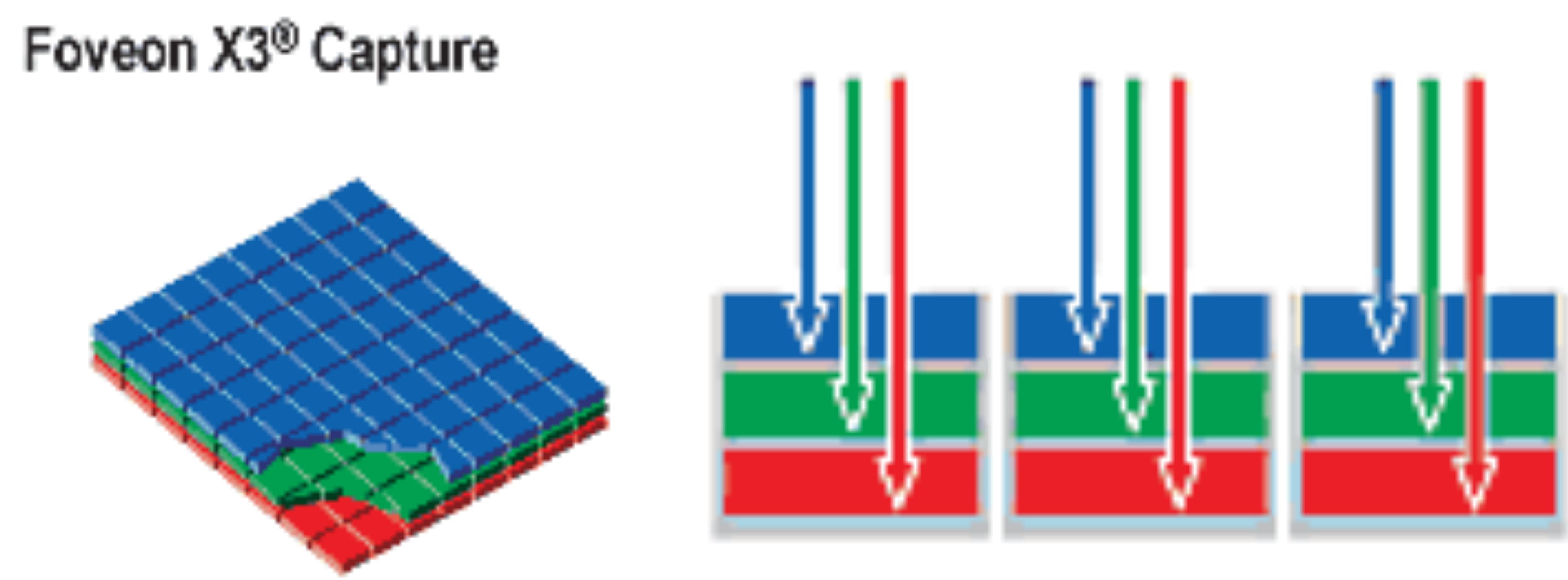
Philips Total Internal Reflection Dichroic Prism



Wavelengths Penetrate to Different Depths

Long-wavelength photons penetrate deeper than short in silicon

The spectral response of electrons at the surface differs from electrons deeper in the material

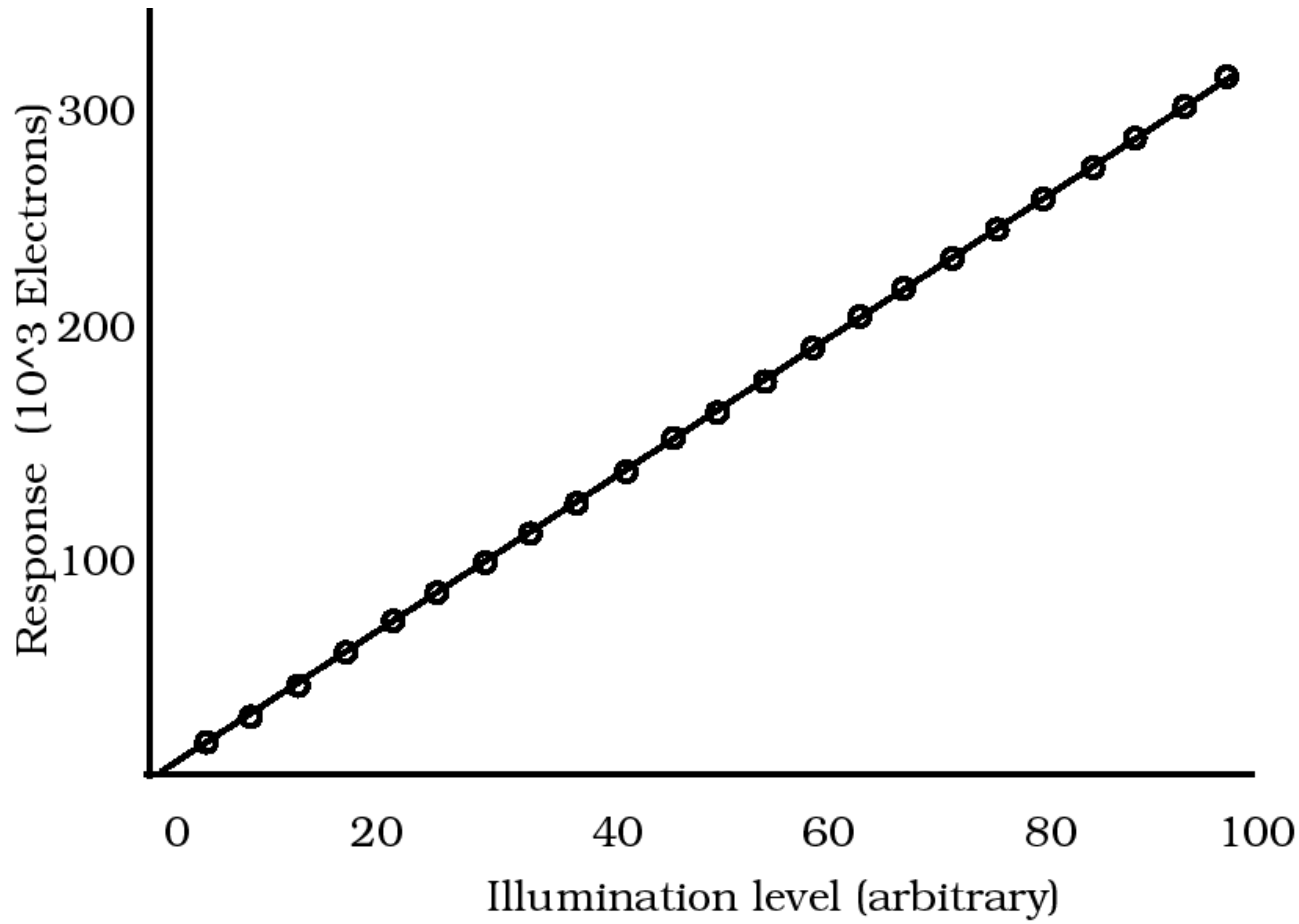


Dynamic Range

CCD & CMOS Response Functions Are Linear

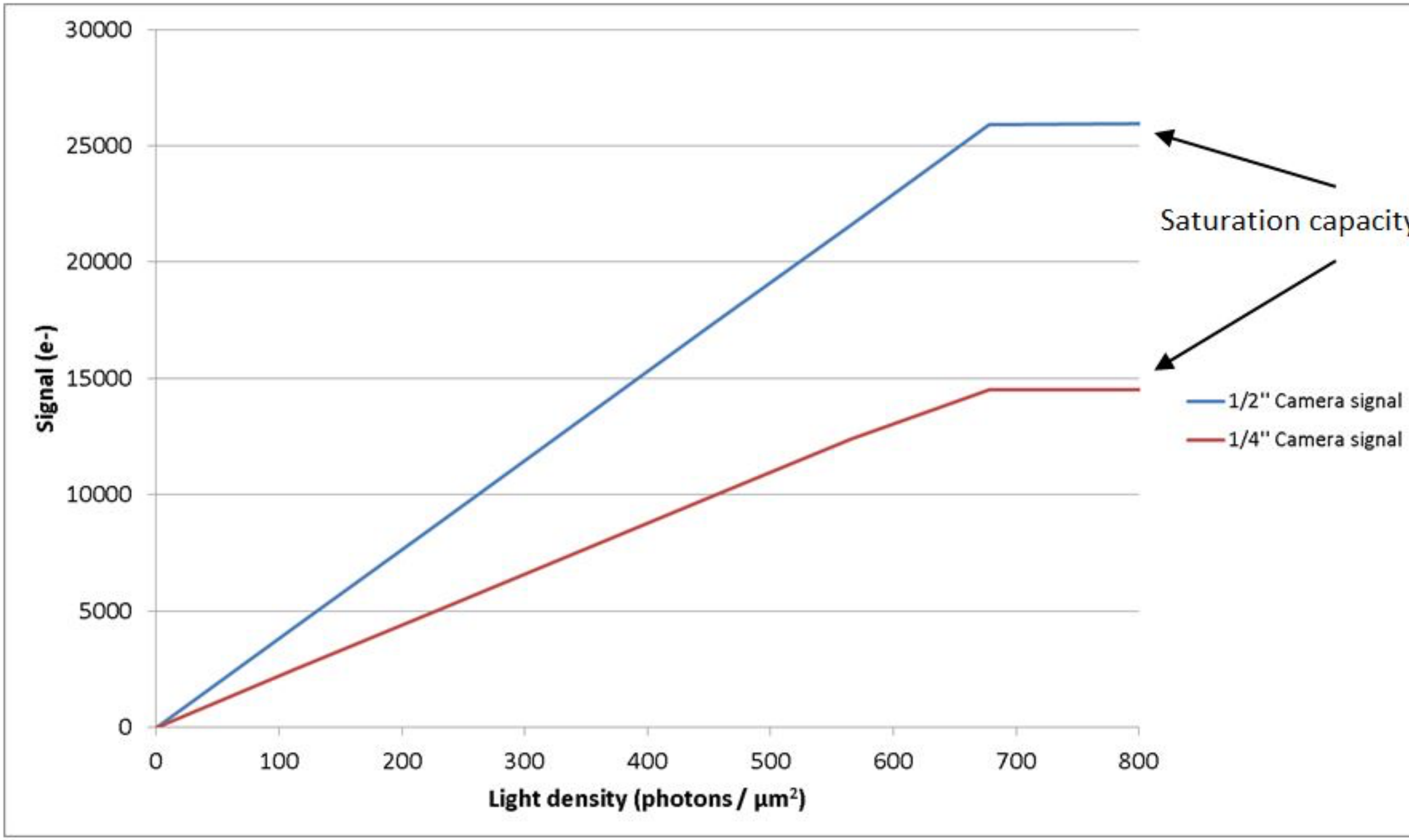
Photoelectric effect in silicon:

- Response function from photons to electrons is linear
- May have some nonlinearity close to 0 due to noise, and near pixel saturation



(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ..., Opt Eng., 25, 1987)

Finite Dynamic Range: Real Sensor Pixels "Saturate"



https://www.ptgrey.com/white-paper/id/10912

Linear response until saturation (idealized)

Saturated Pixels: "Blown Out" Parts of Photo

ROMANAS NARYŠKIN, https://photographylife.com/understanding-histograms-in-photography

Normal exposure

Saturated Pixels: "Blown Out" Parts of Photo

ROMANAS NARYŠKIN, https://photographylife.com/understanding-histograms-in-photography

Overexposure ("blown-out" or "clipped" pixels)

exposure:
+0 stops

image: Paul Debevec

Slide courtesy Steve Marschner

exposure:
-8 stops

image: Paul Debevec

Slide courtesy Steve Marschner

exposure:
+6 stops

image: Paul Debevec

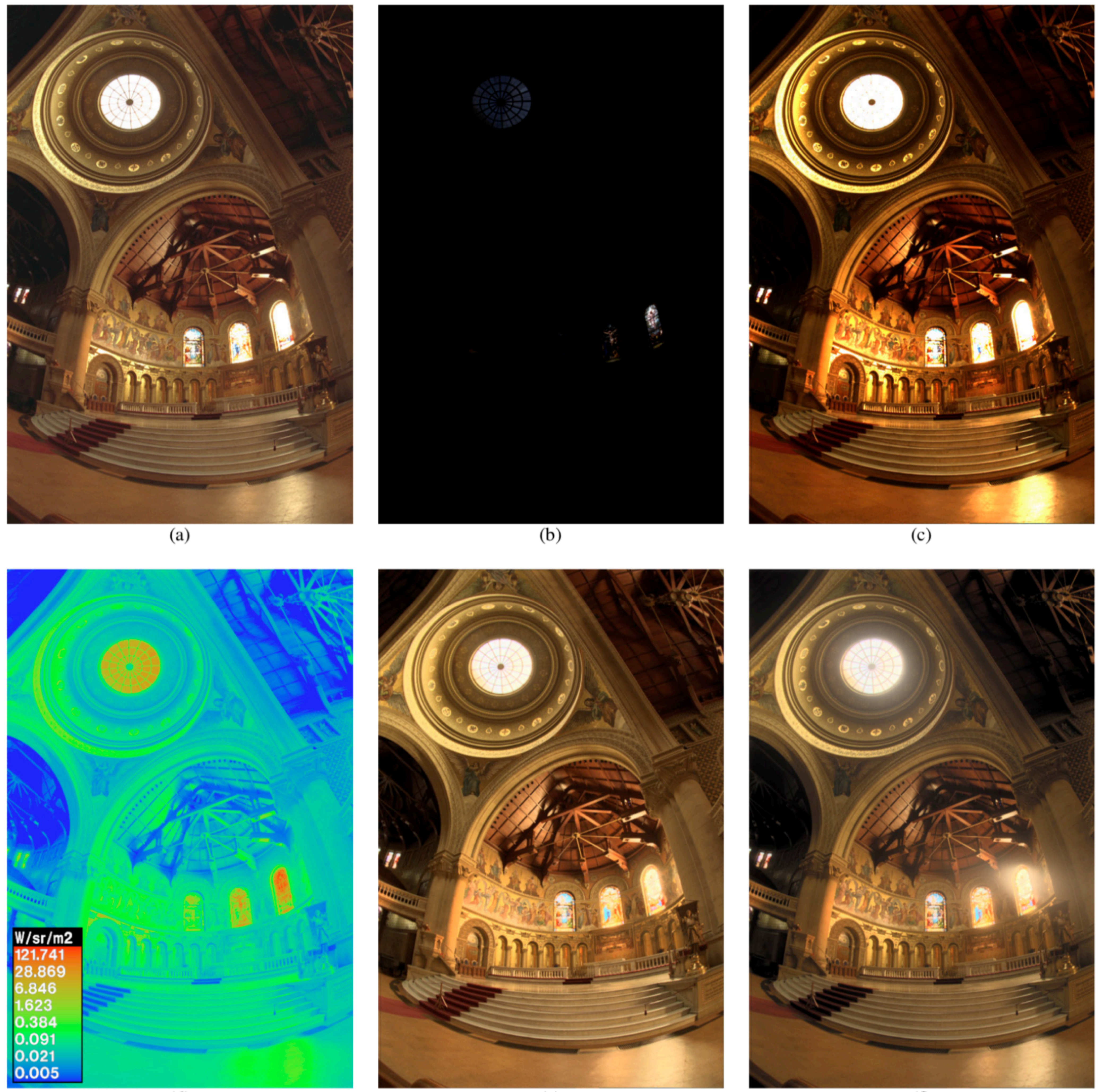
Slide courtesy Steve Marschner

High Dynamic Range (HDR) Through Multiple Exposures

Figure 6: *Sixteen photographs of a church taken at 1-stop increments from 30 sec to $\frac{1}{1000}$ sec. The sun is directly behind the rightmost stained glass window, making it especially bright. The blue borders seen in some of the image margins are induced by the image registration process.*

Debevec & Malik

HDR Through Multiple Exposures

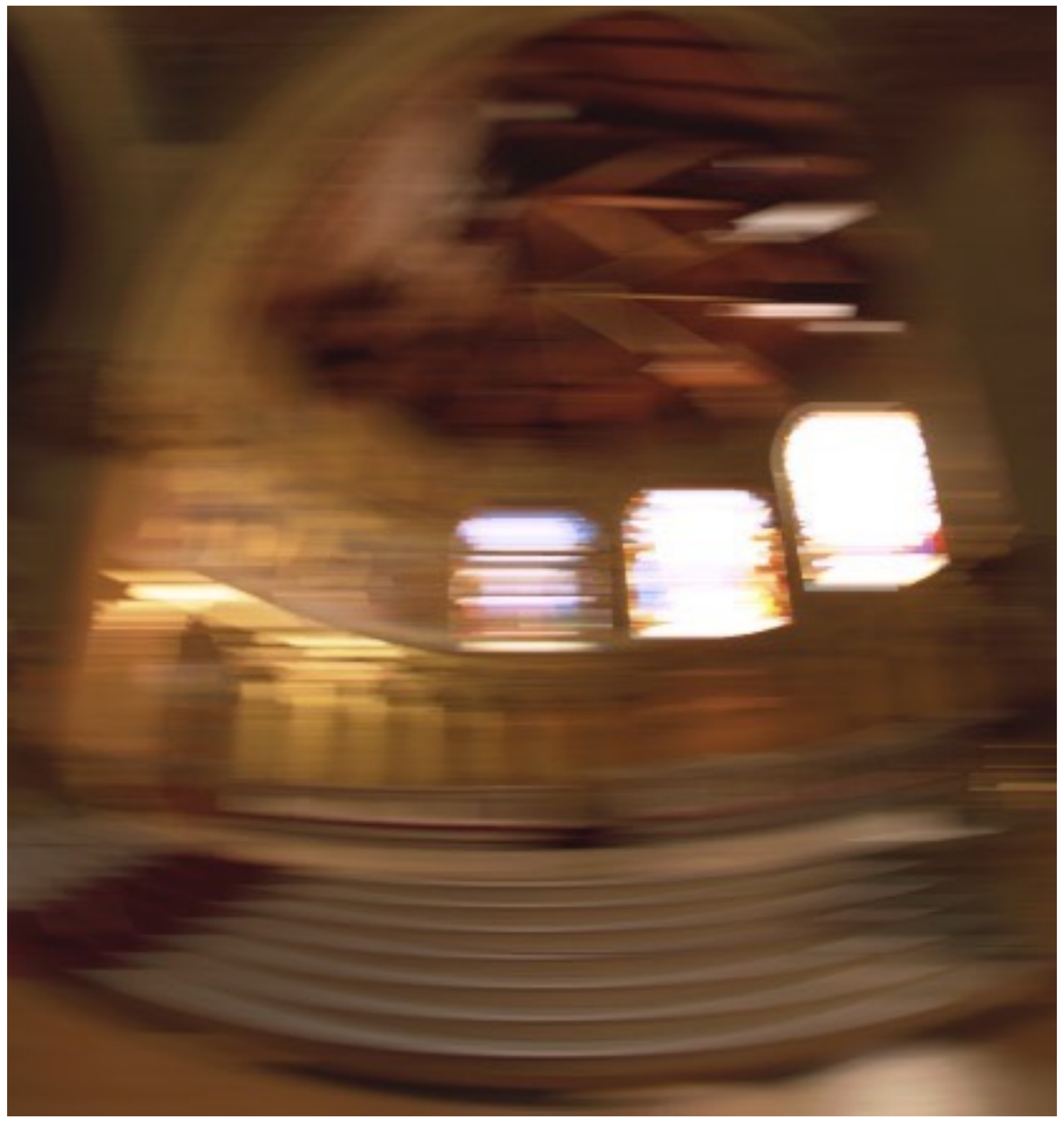


(a) (b) (c) (d) (e) (f)

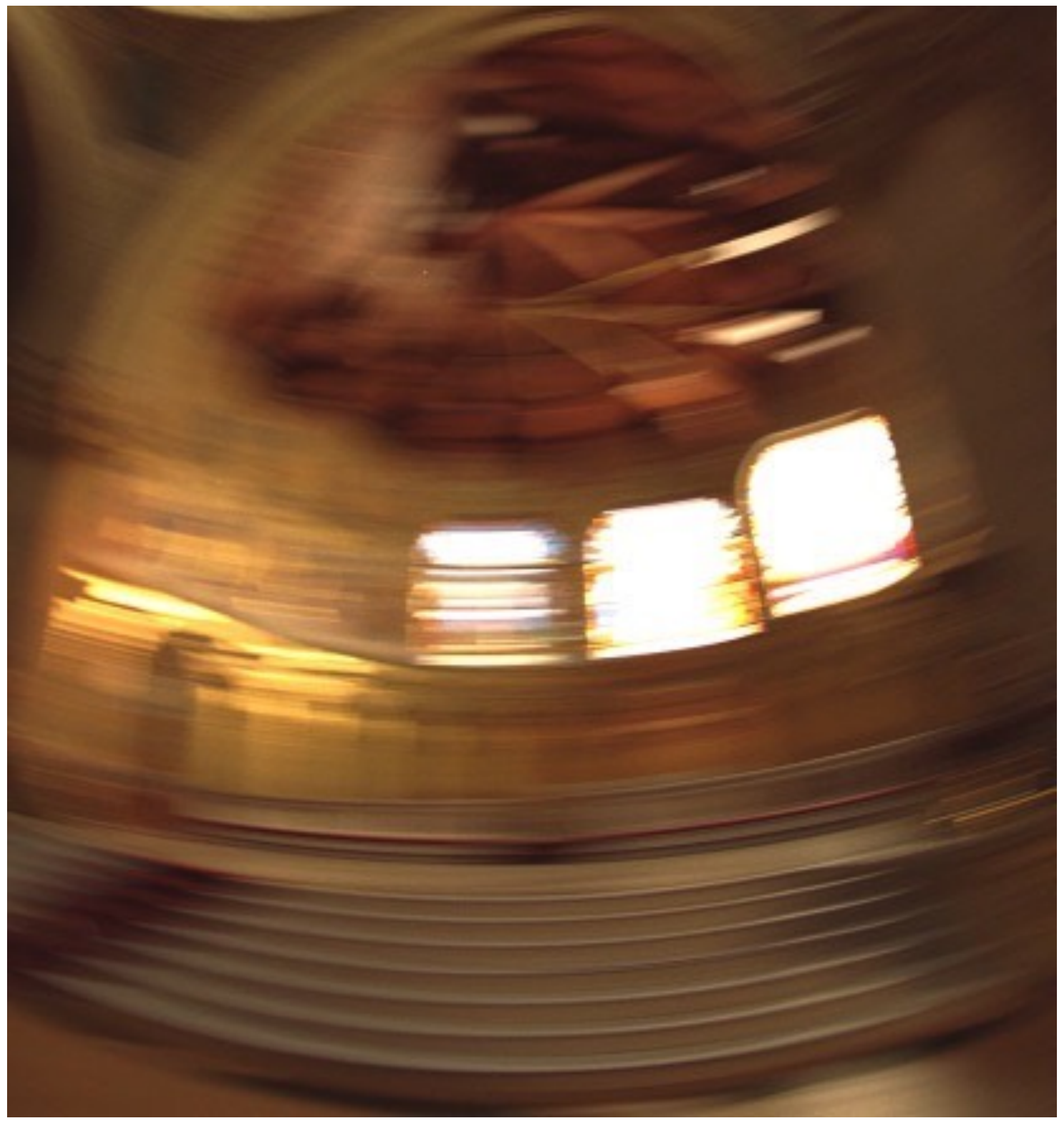
Debevec & Malik

HDR Through Multiple Exposures

Synthetic Motion Blur
Normal 8-bit image



Synthetic Motion Blur
HDR image



Real Photo

DIY HDR

Slide courtesy Marc Levoy

- 2 shots
- Photoshop

Early morning in Zurich

DIY HDR

Slide courtesy Marc Levoy

- 2 shots
- Photoshop

Early morning in Zurich

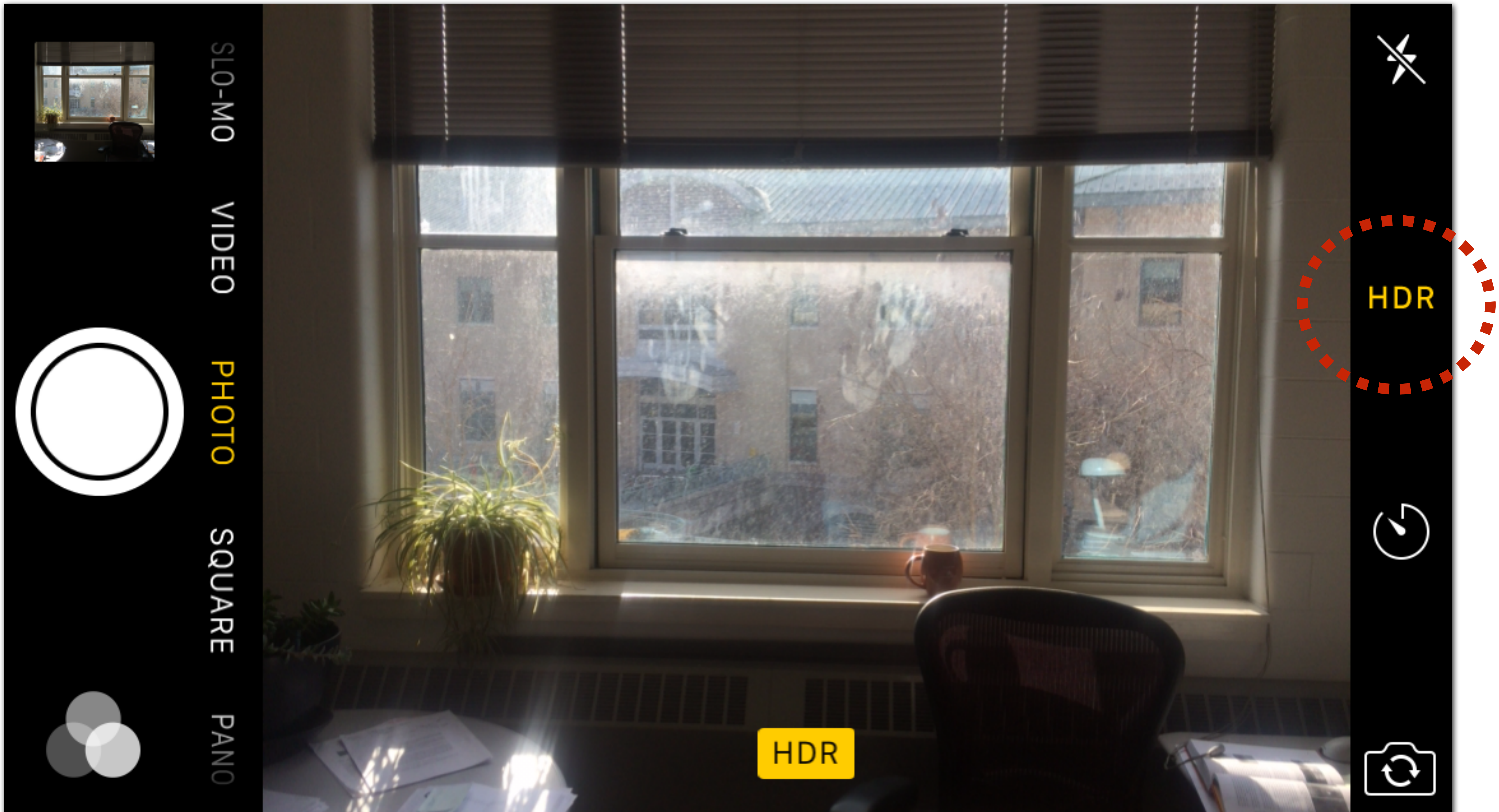
DIY HDR

Slide courtesy Marc Levoy

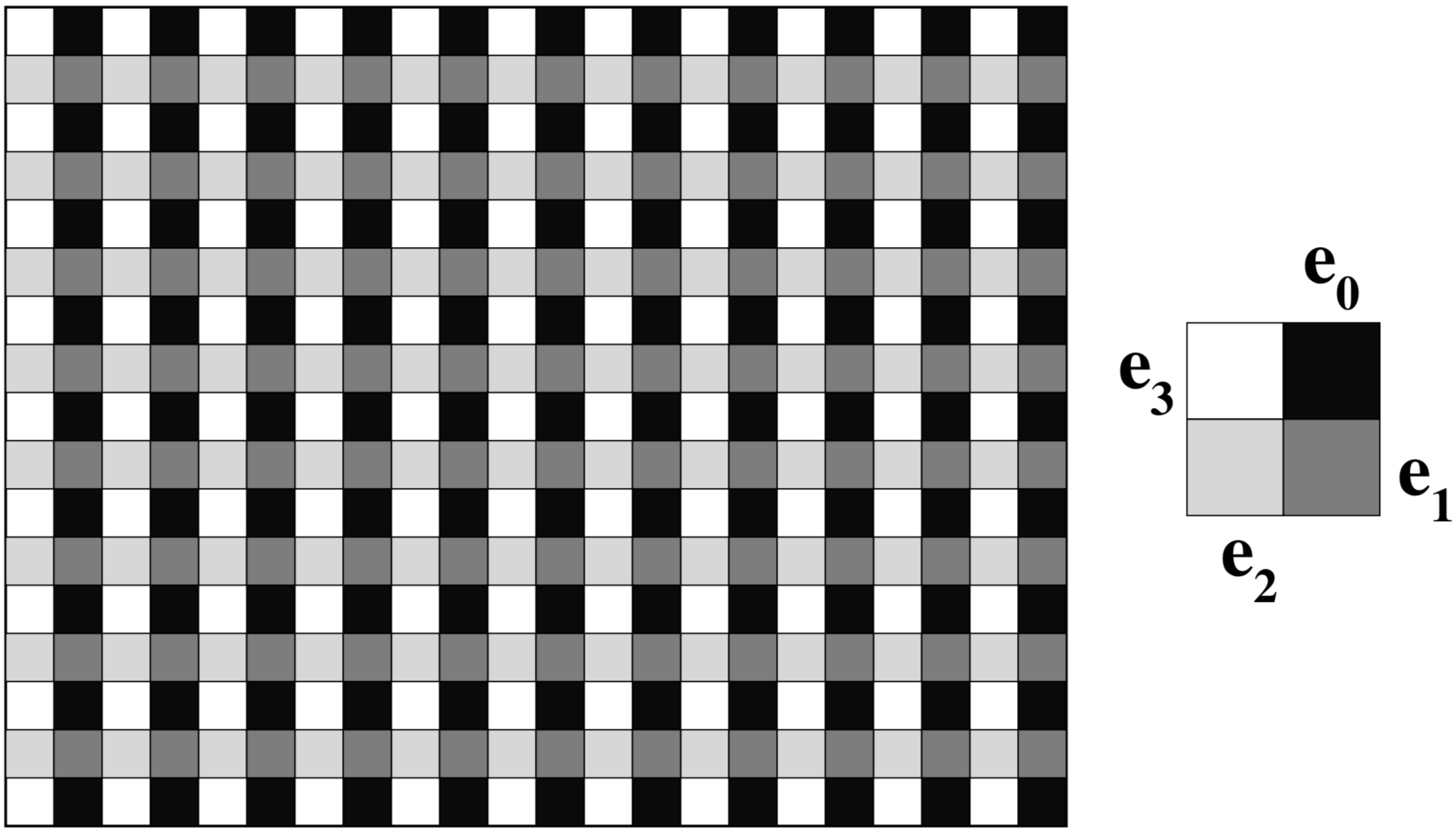
- 2 shots
- Photoshop

Early morning in Zurich

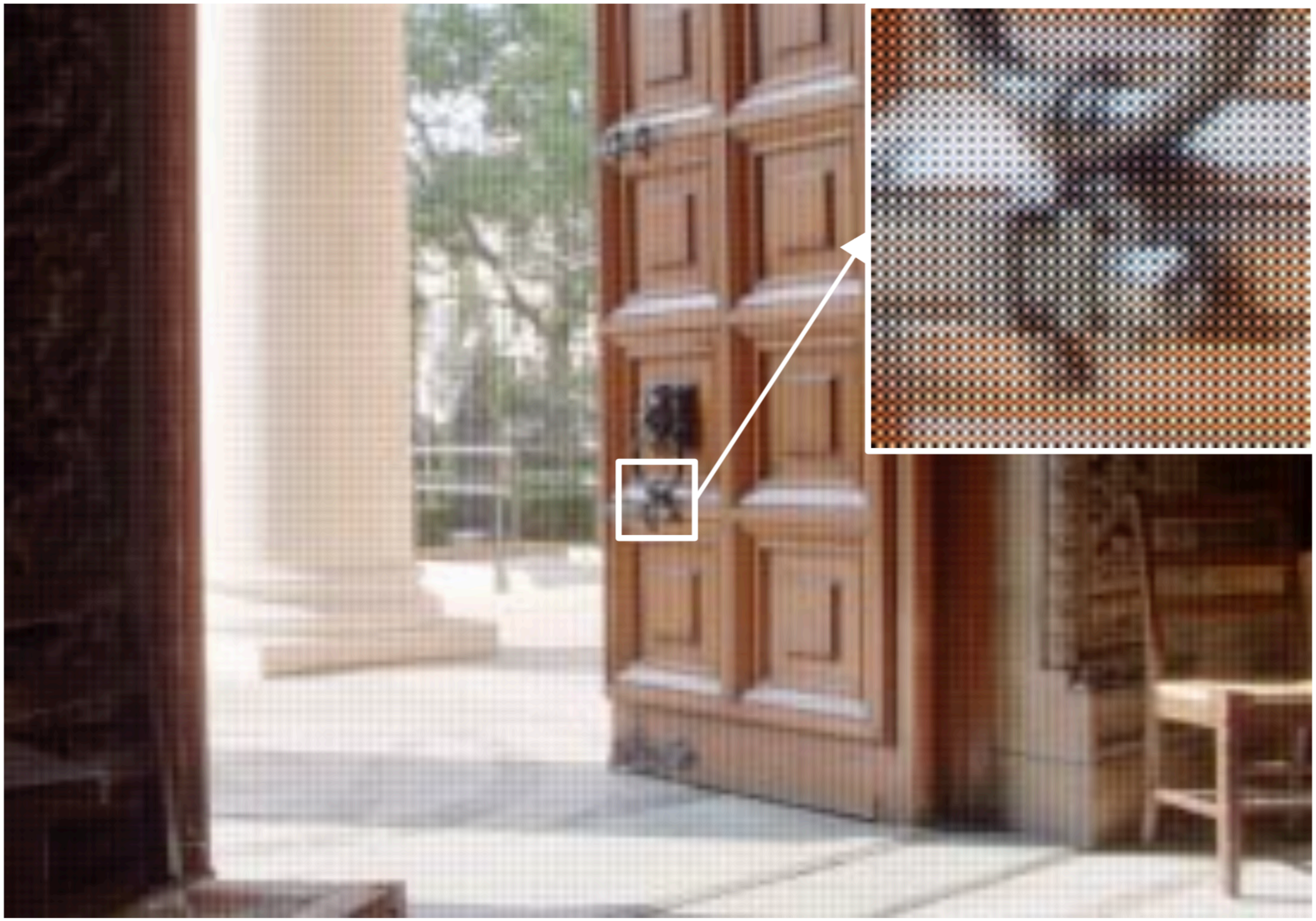
HDR "Mode" On Smartphones

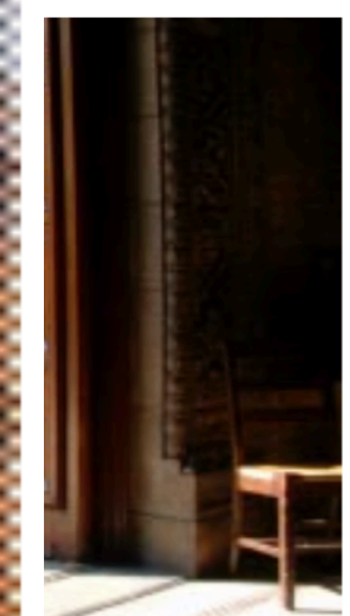


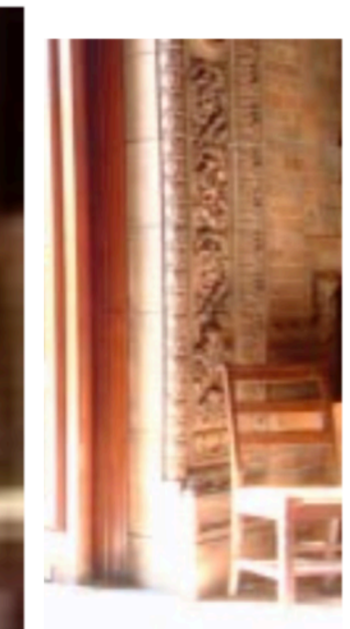
HDR By Pixel Mosaicking

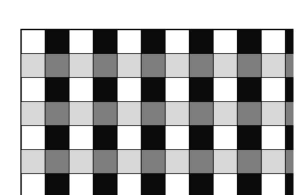


HDR By Pixel Mosaicking



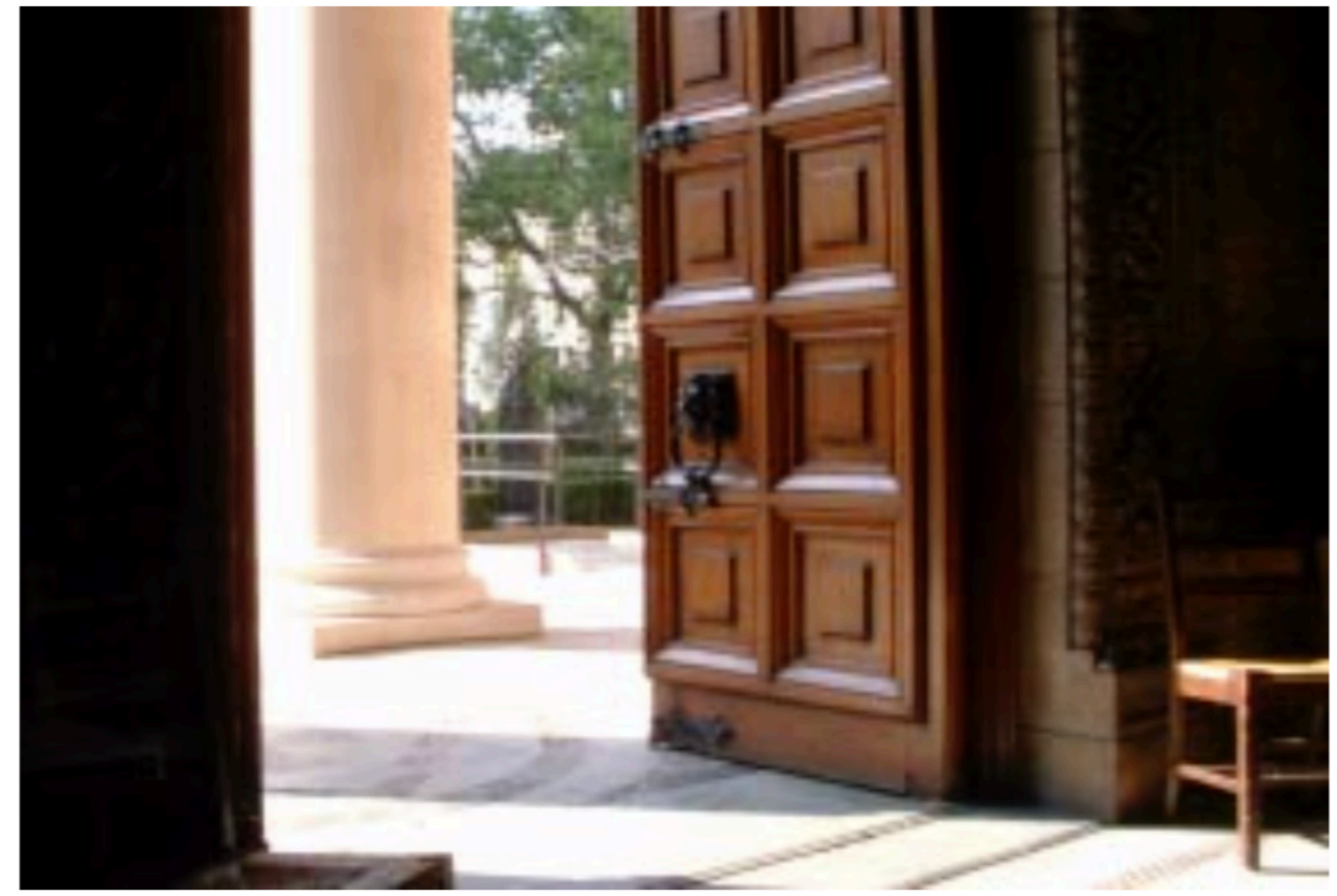




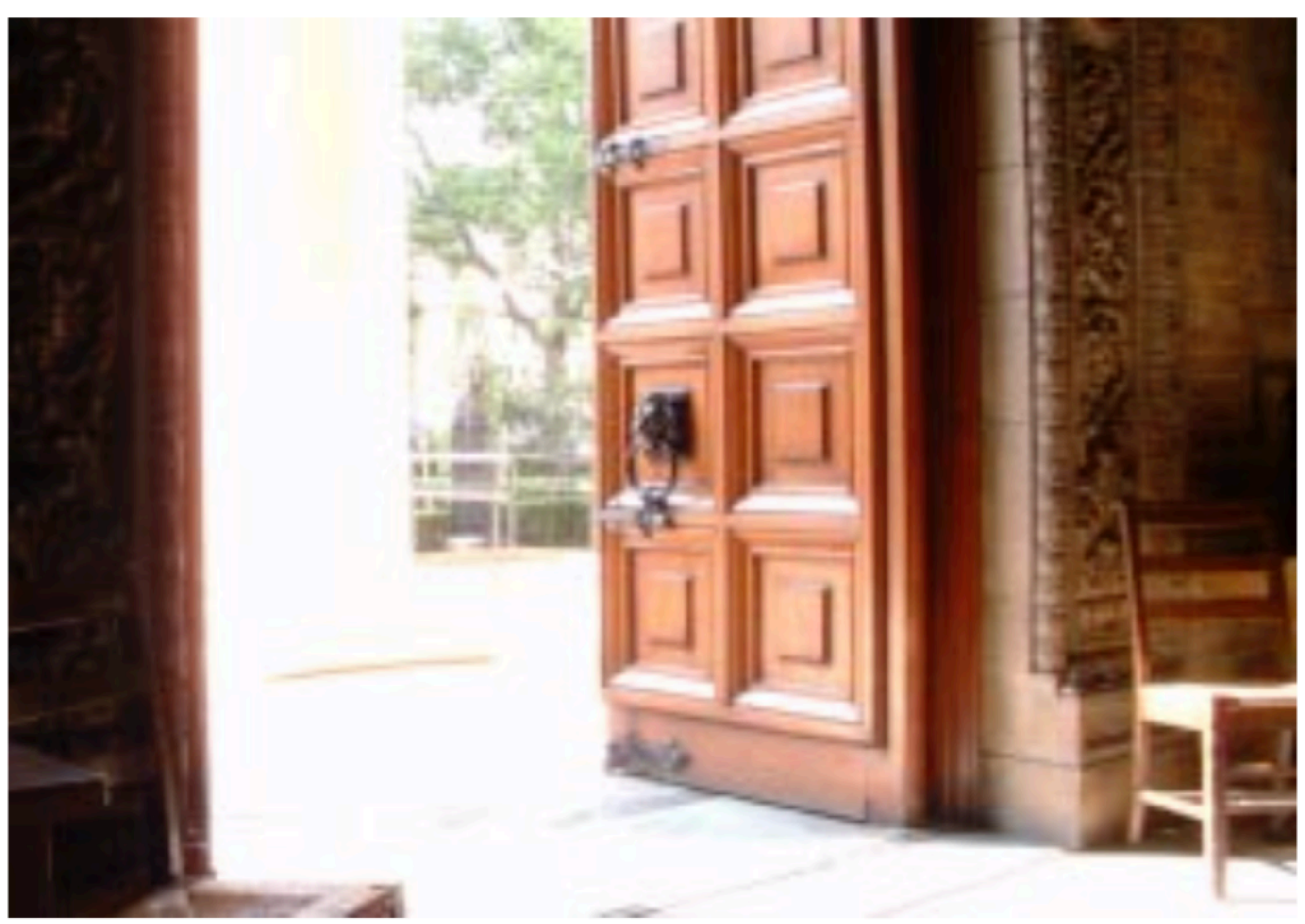


HDR By Pixel Mosaicking

(a) Exposure: T

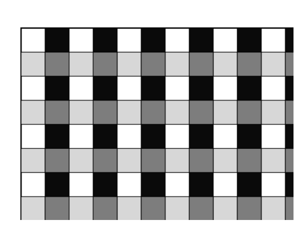


(b) Exposure: 4T



(c) Exposure: 16T

(d) Exposure: 64T



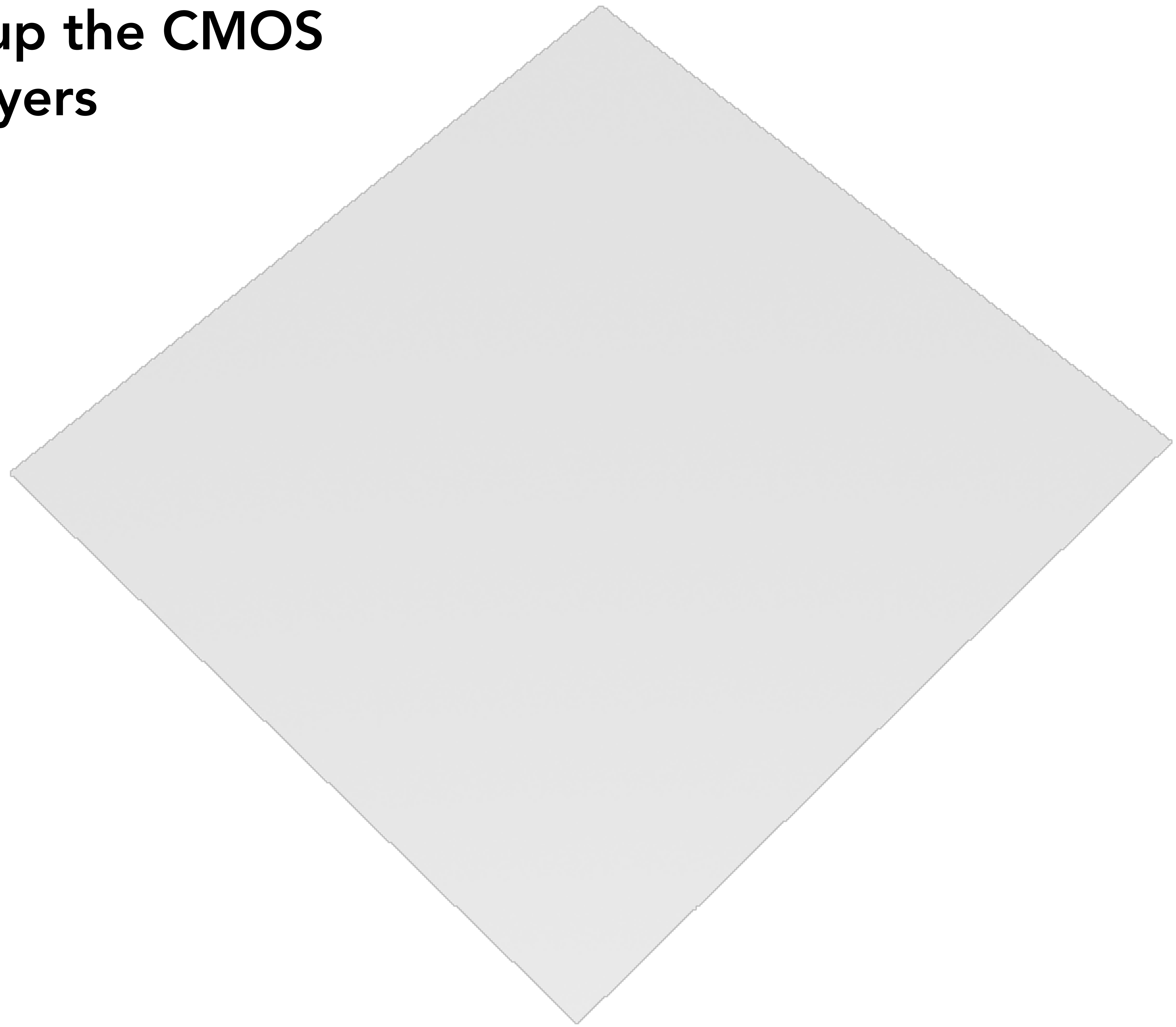
HDR in Circuit Design of Image Sensor

- Many approaches tried: well adjusting, multiple capture, time to saturation, logarithmic, local adaptation, ...
- Multiple capture approach requires multiple, high-speed, non-destructive reads of the pixel's value during exposure
- Not common, not used in cameras for consumer photography today

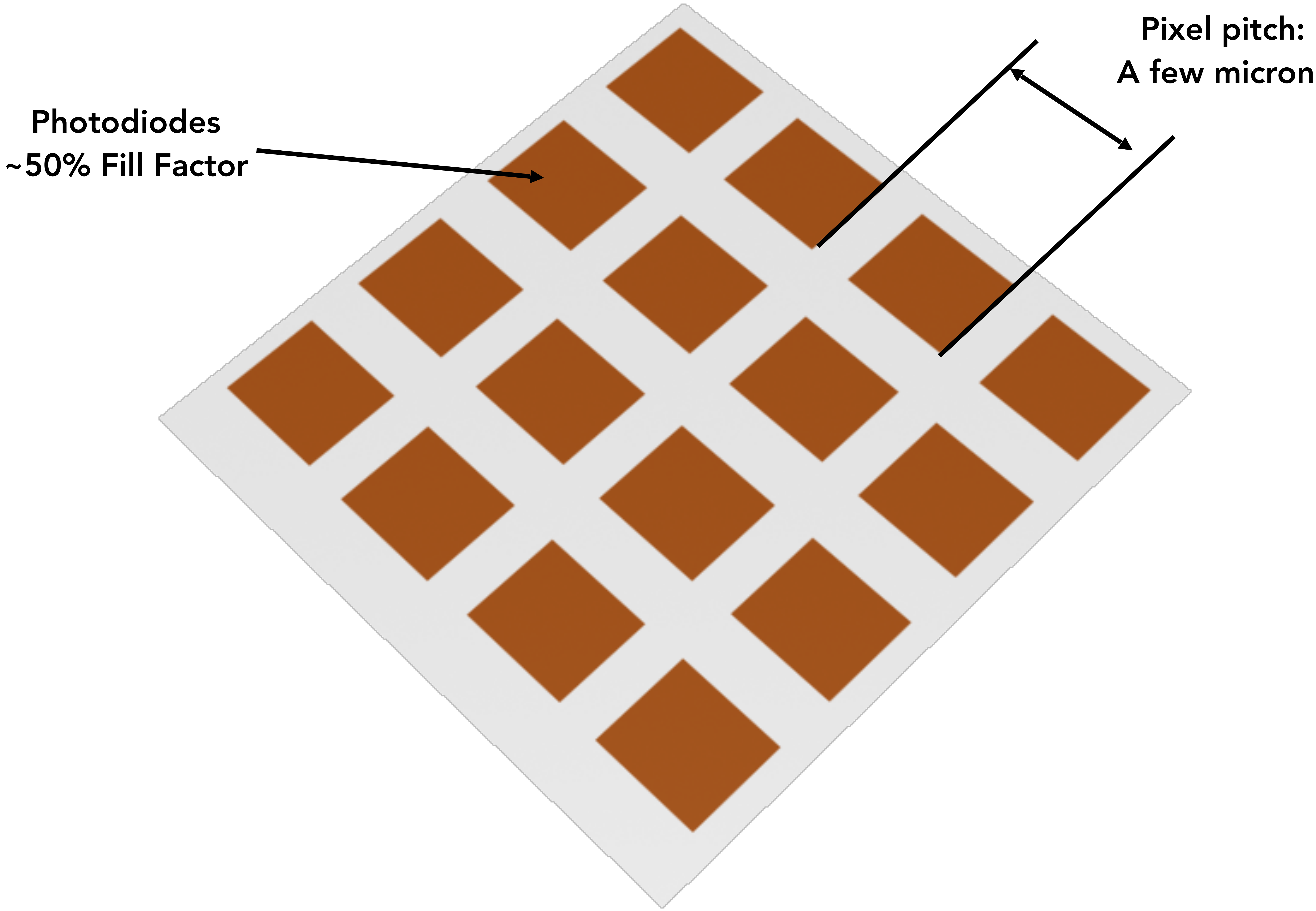
Pixel Structure & Micro Optics

Front-Side-Illuminated (FSI) CMOS

Building up the CMOS imager layers

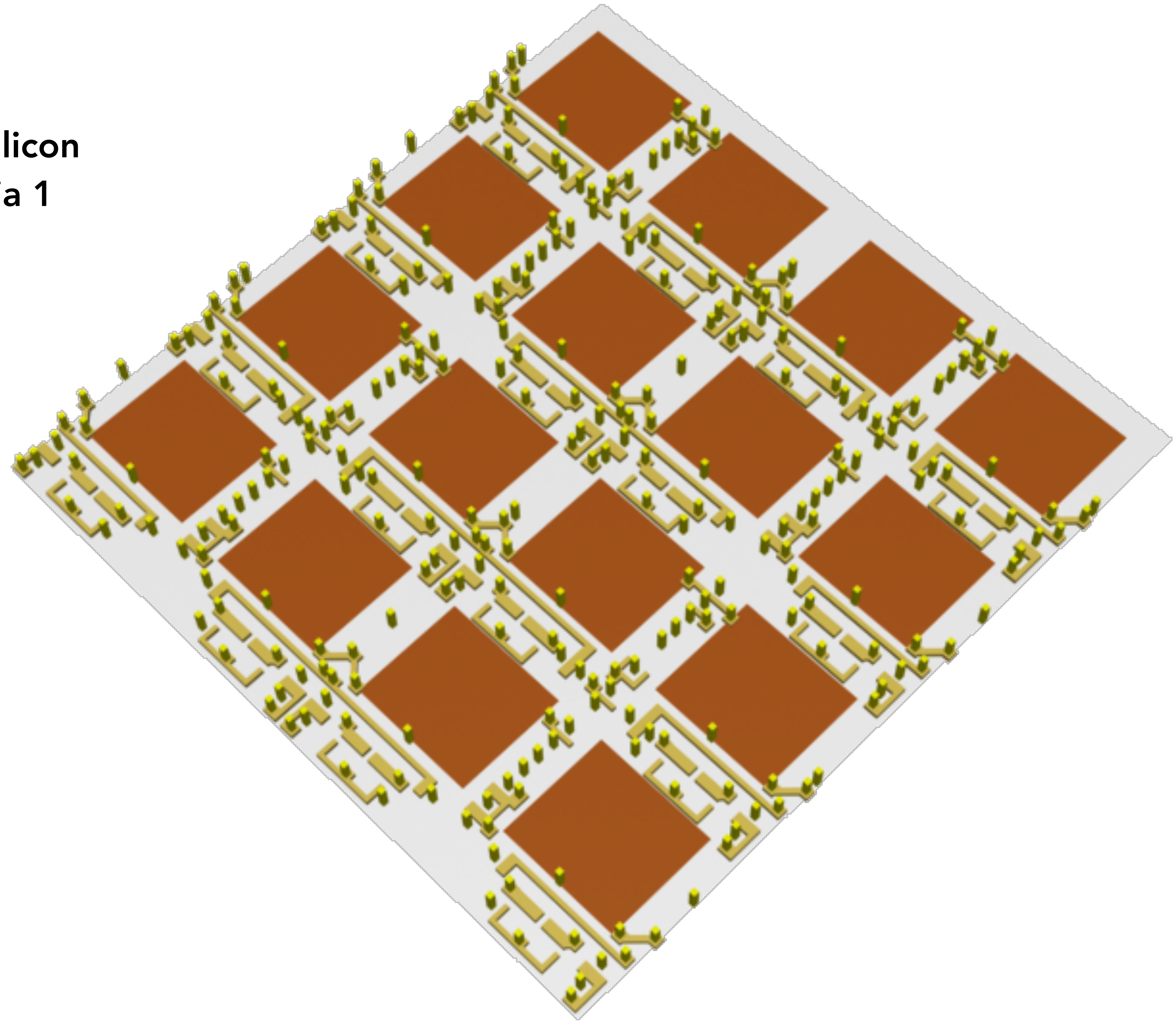


Courtesy R. Motta, Pixim



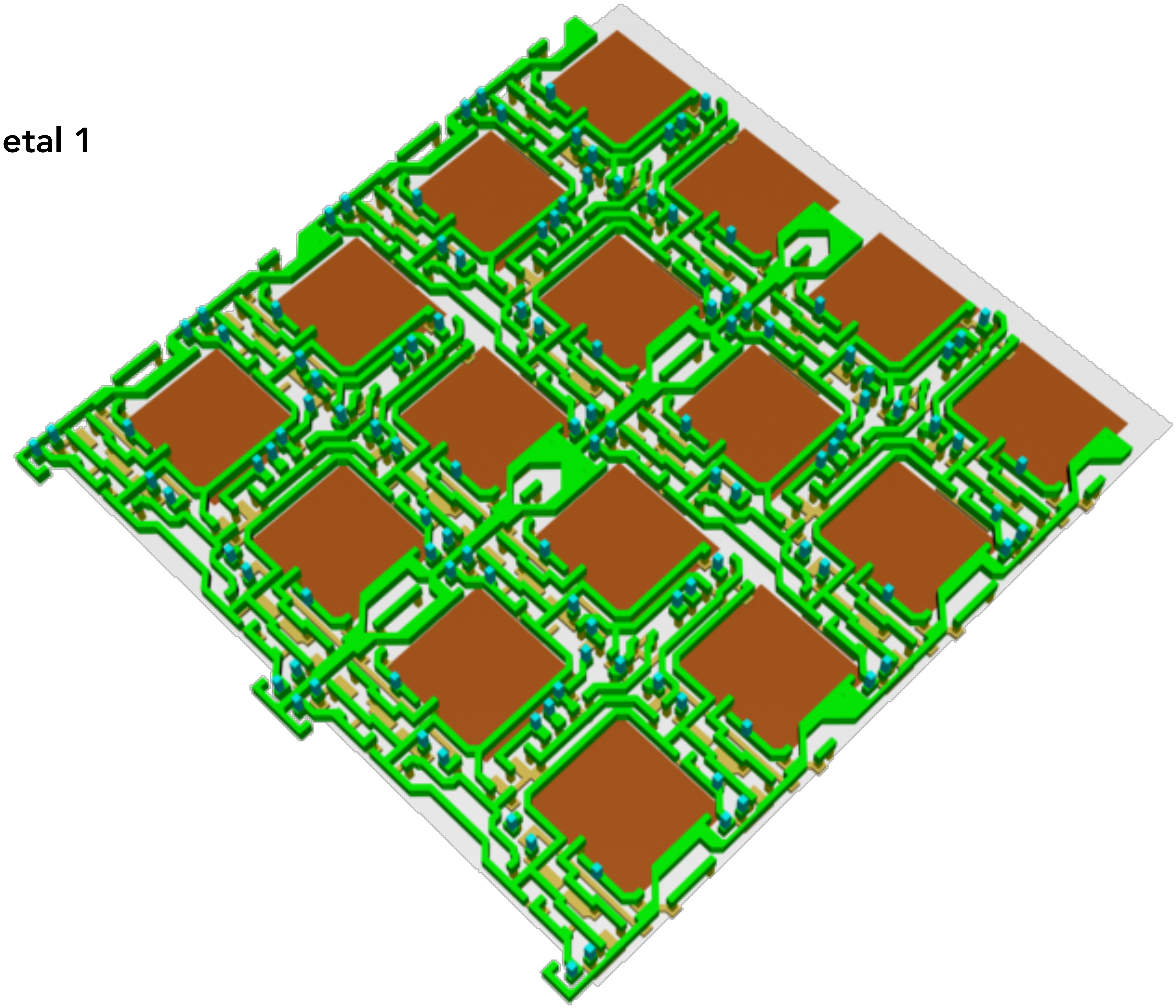
Courtesy R. Motta, Pixim

Polysilicon
& Via 1



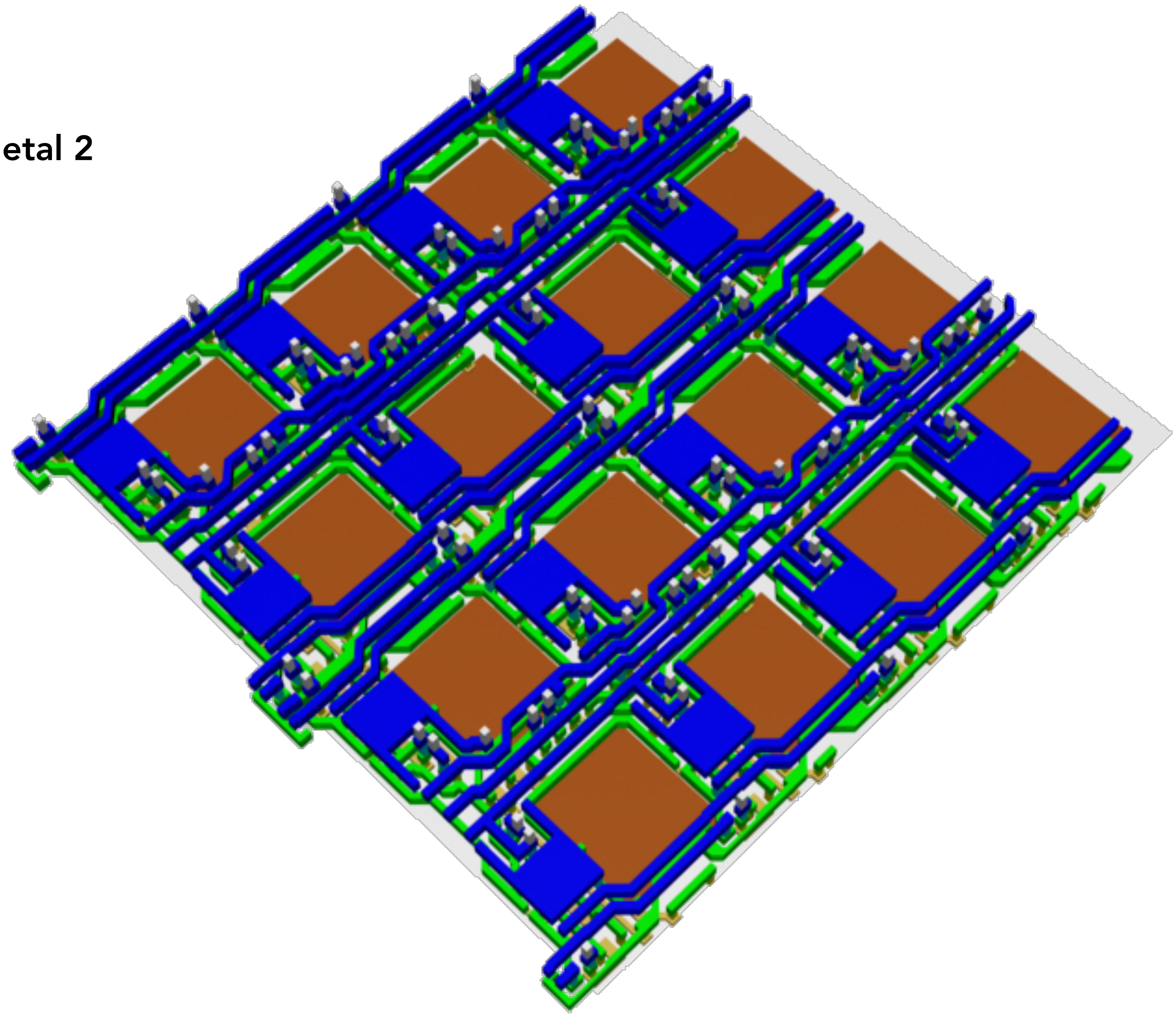
Courtesy R. Motta, Pixim

Metal 1



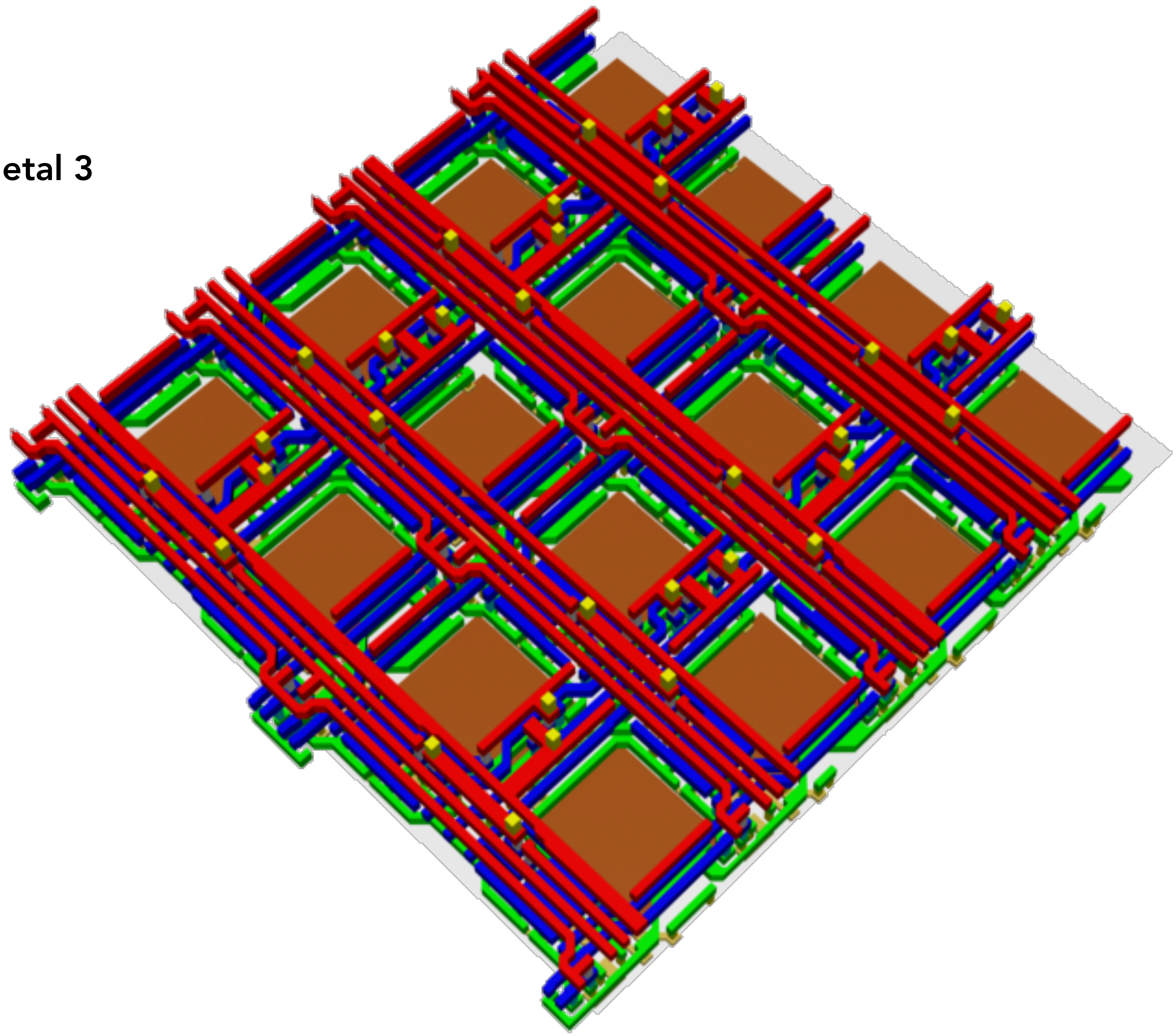
Courtesy R. Motta, Pixim

Metal 2



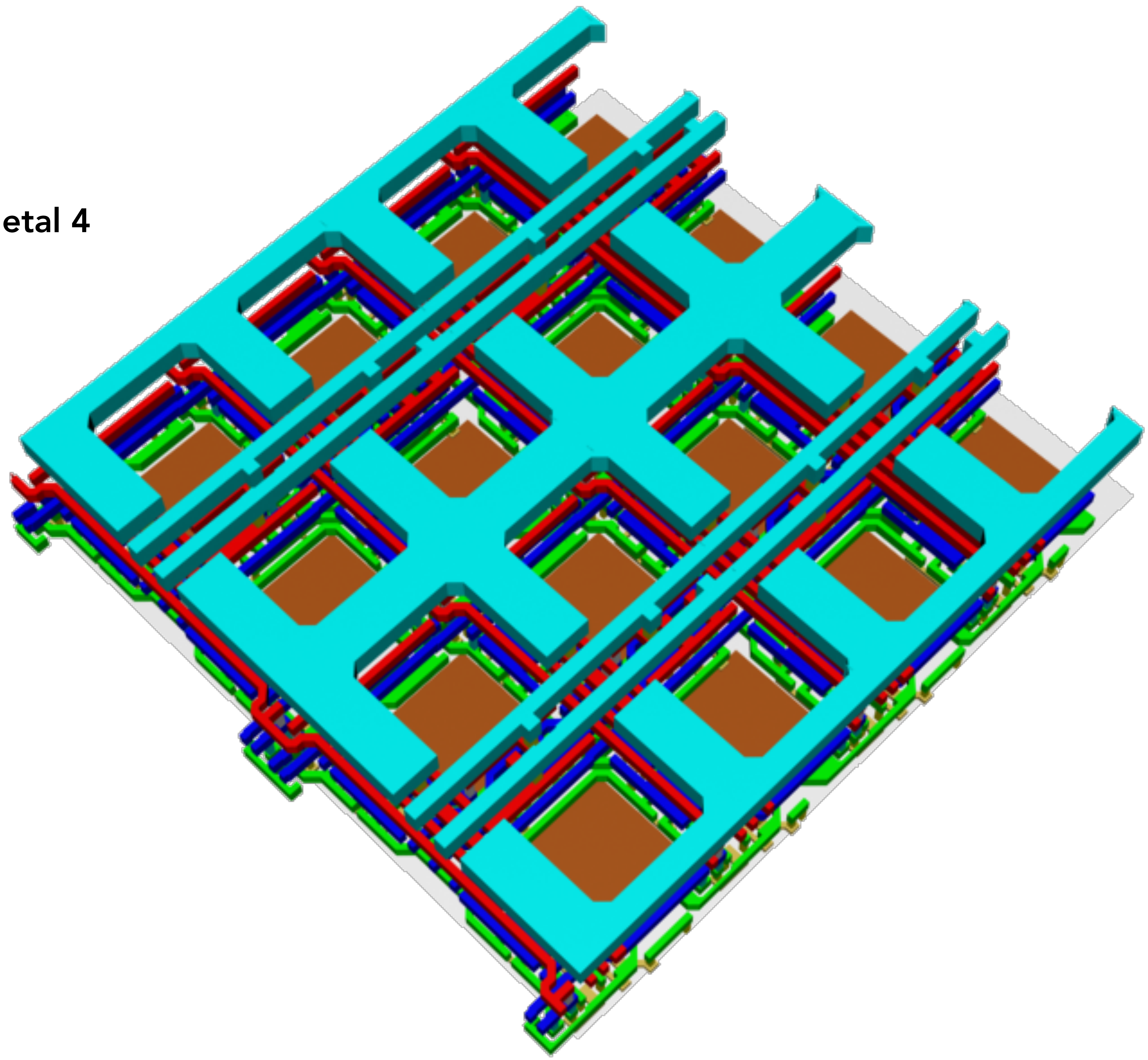
Courtesy R. Motta, Pixim

Metal 3

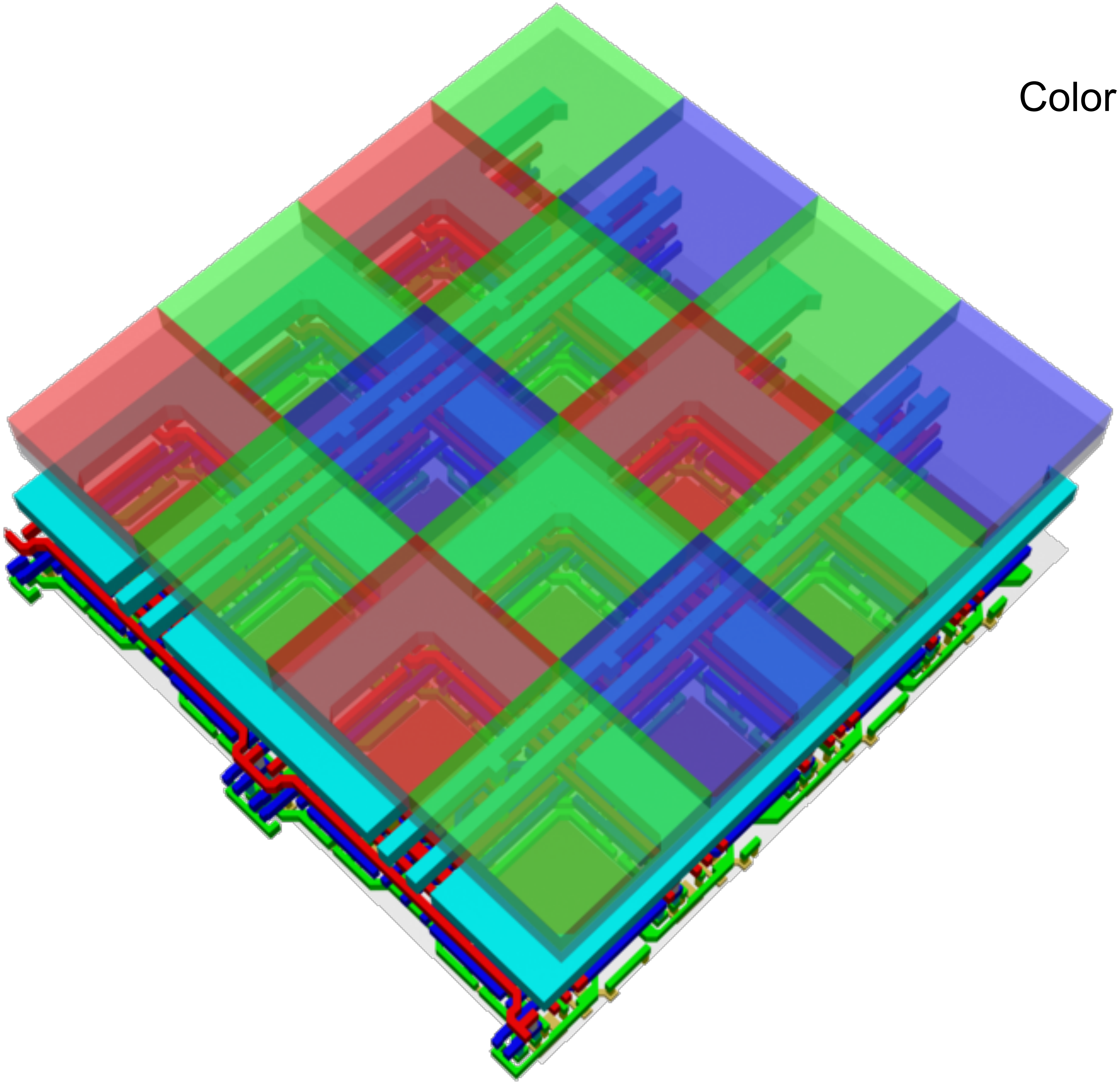


Courtesy R. Motta, Pixim

Metal 4



Courtesy R. Motta, Pixim

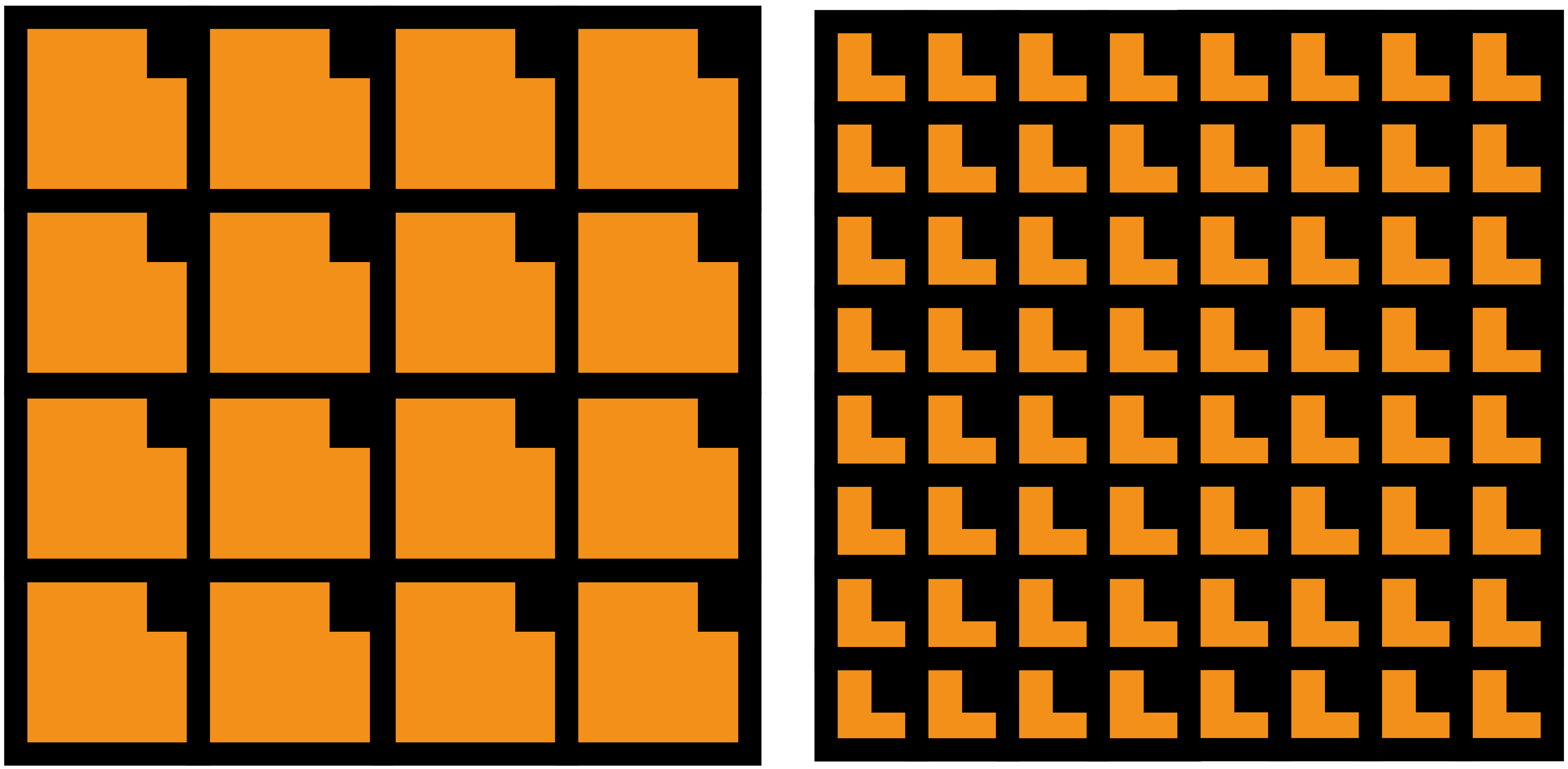


Color filter array

Courtesy R. Motta, Pixim

Pixel Fill Factor

Fraction of pixel area that integrates incoming light.



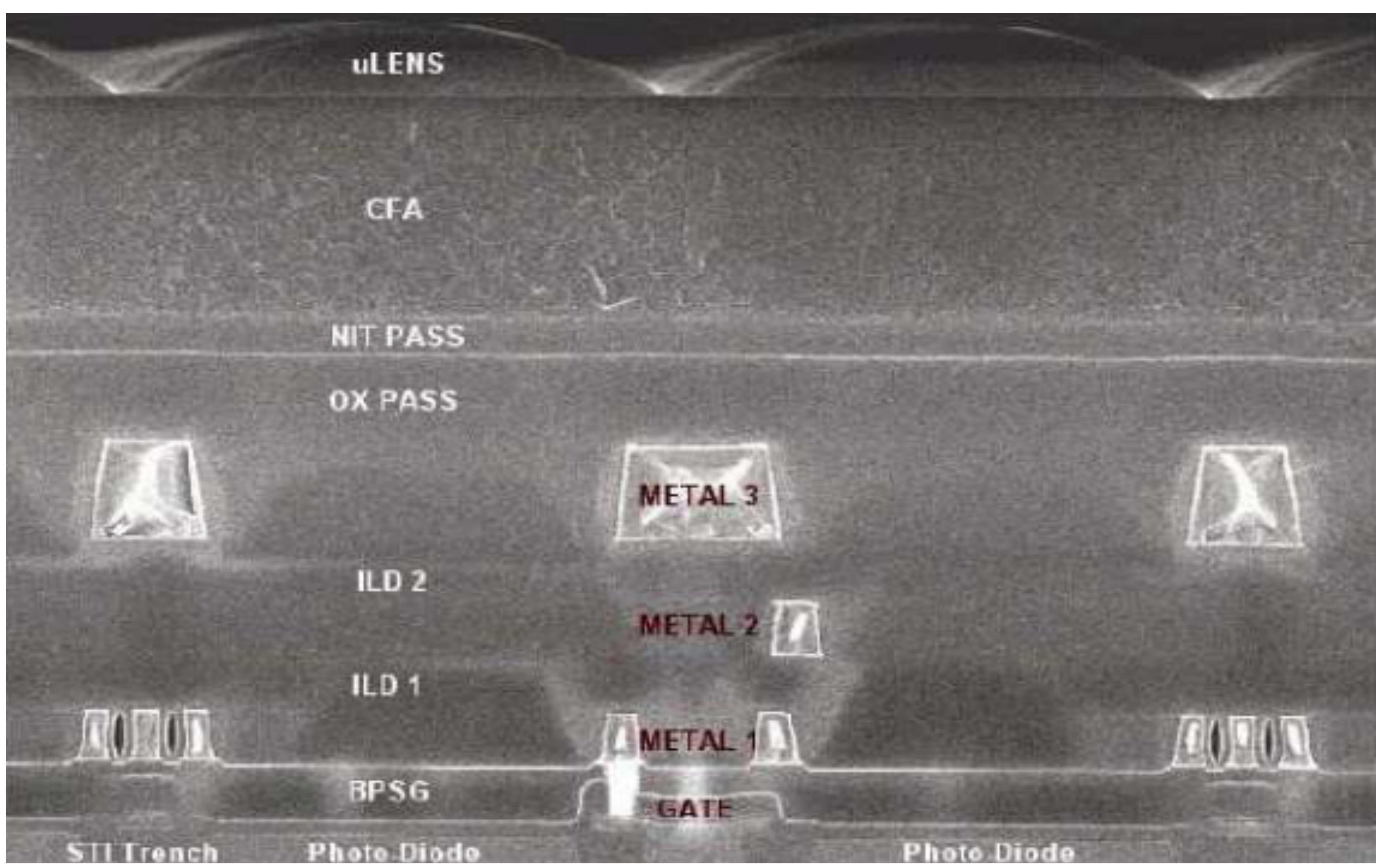
Photodiode area

Non photosensitive (circuitry)

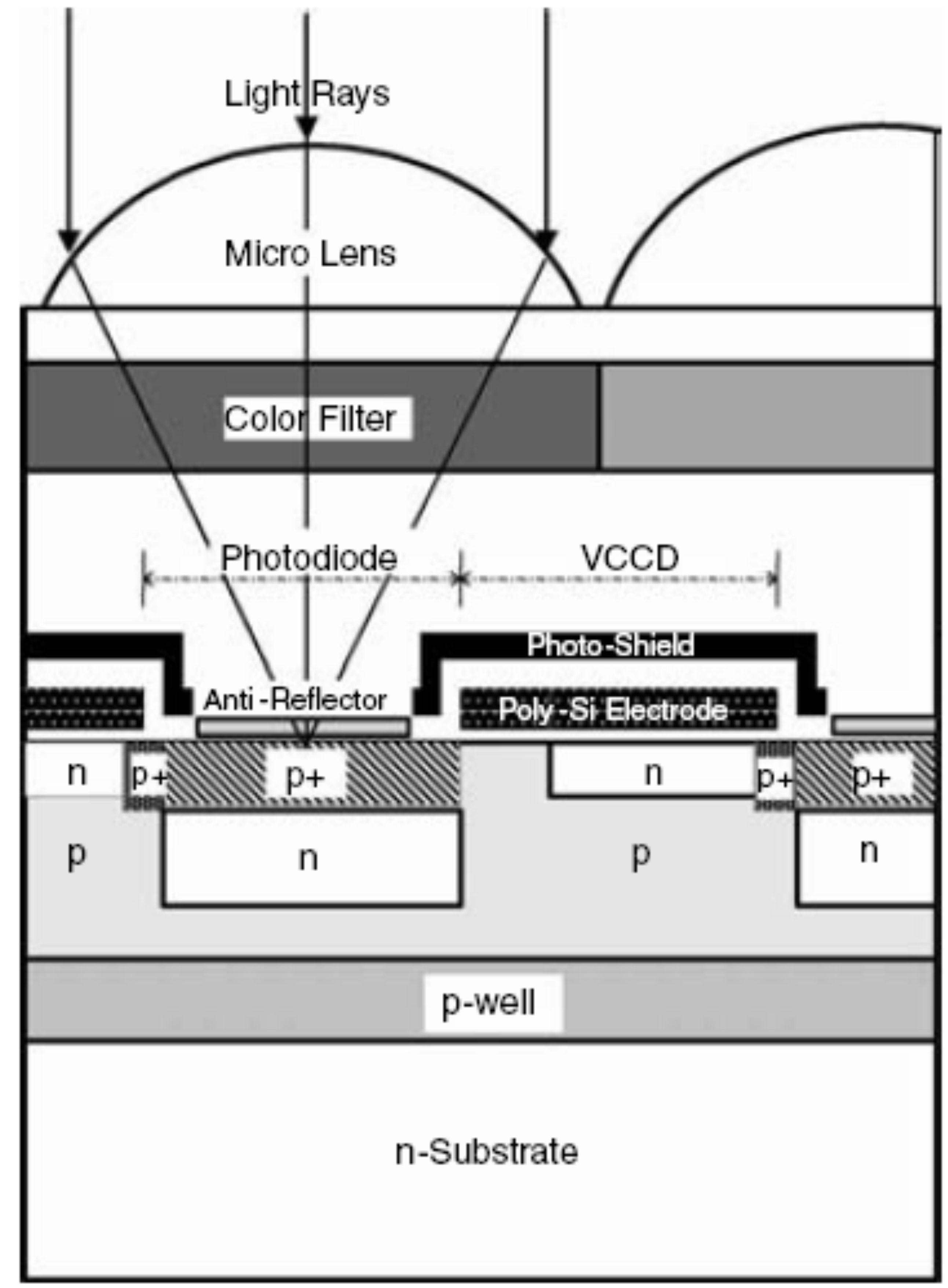
Pixel Fill Factor

Fraction of pixel area that integrates incoming light.

Optimize with per-pixel microlenses.

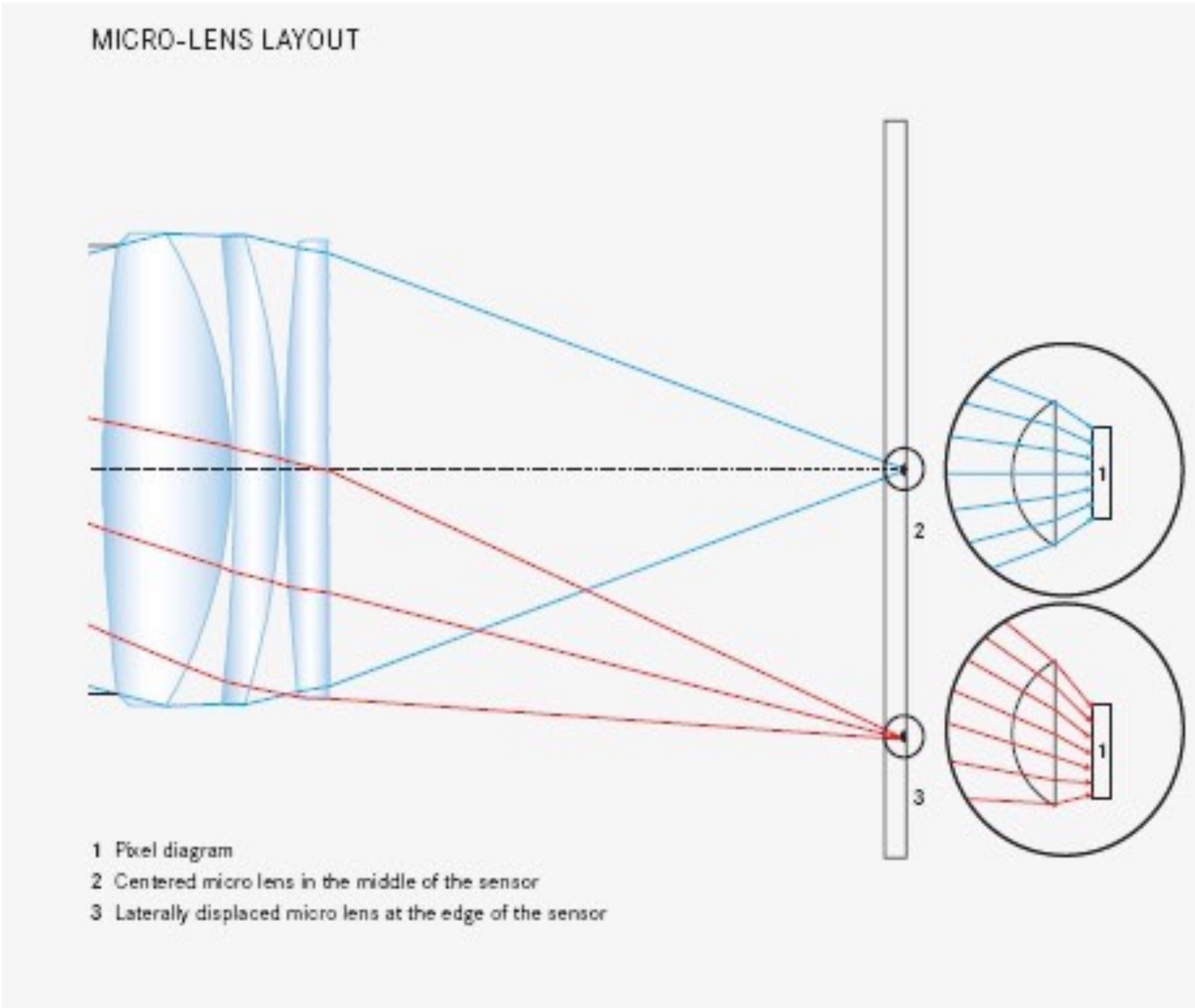


Microlenses on a CMOS sensor



Microlenses on CCD pixel

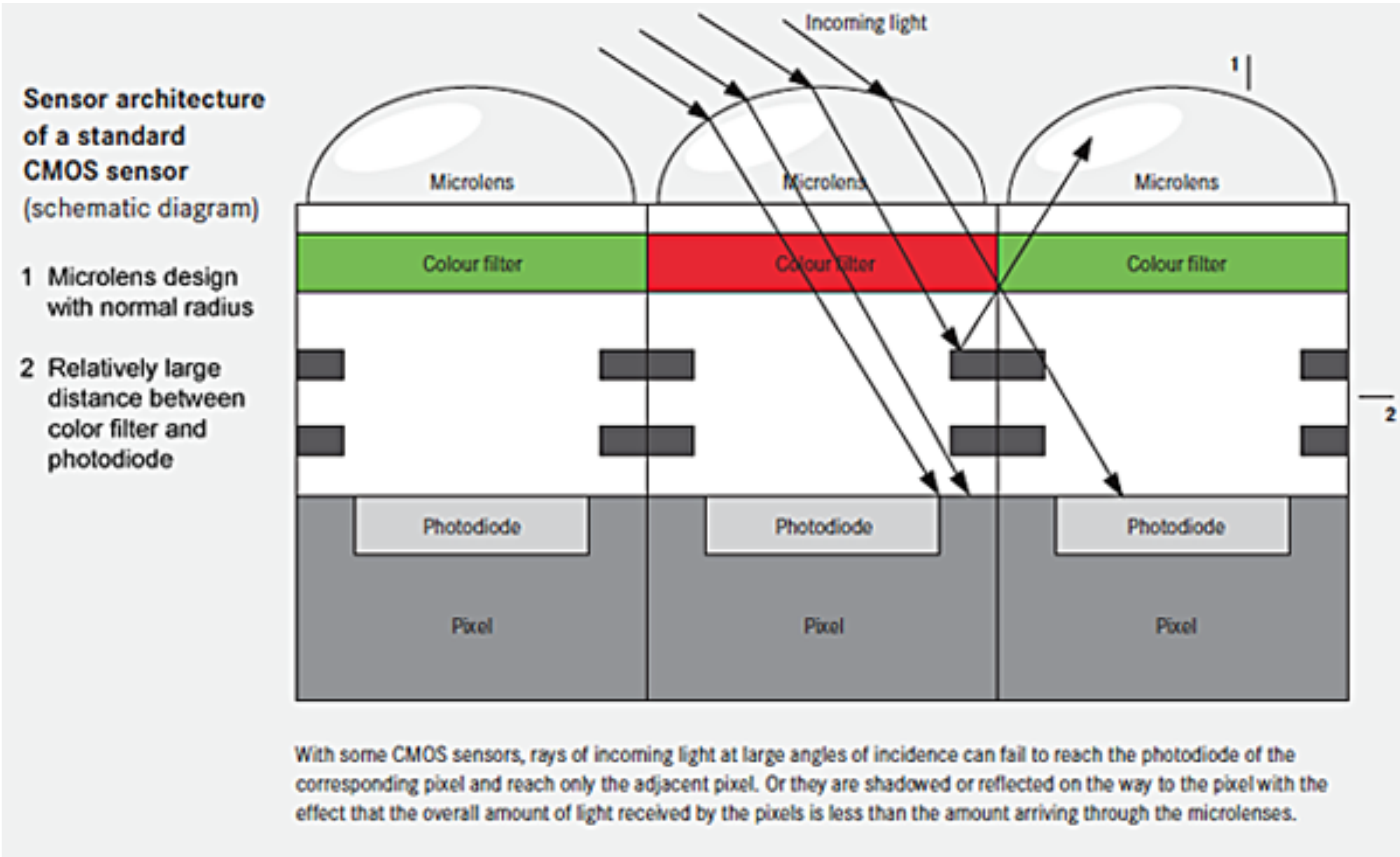
Pixel Fill Factor



Shifted microlenses on M9 sensor.

Leica M9

Optical Cross-Talk



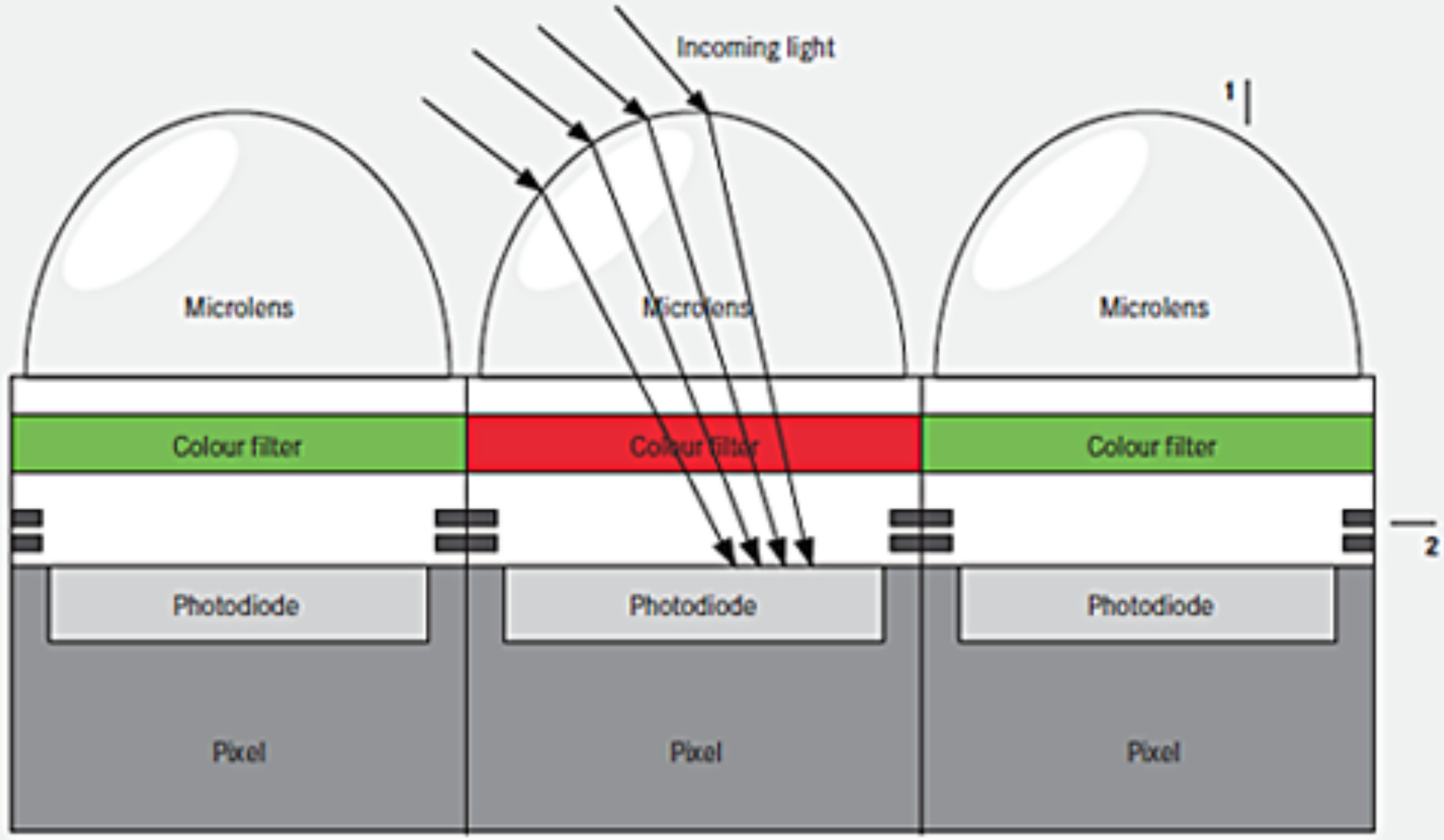
http://gmpphoto.blogspot.com/2012/09/the-new-leica-max-24mp-cmos-sensor.html

Pixel Optics for Minimizing Cross-Talk

Sensor architecture of the Leica Max 24 MP sensor
(schematic diagram)

1 Microlens design with varying radius

2 Relatively short distance between color filter and photodiode



In the case of the Leica Max 24 MP sensor, and in contrast to standard CMOS sensors, even light rays with large angles of incidence, e.g. from wide-angle lenses or large apertures, are captured precisely by the photodiodes of the sensor. This is enabled by the special microlens design and the smaller distance between the colour filter and photodiode, which allows more light to enter the system, and ensures that it falls more directly on the respective photodiodes.

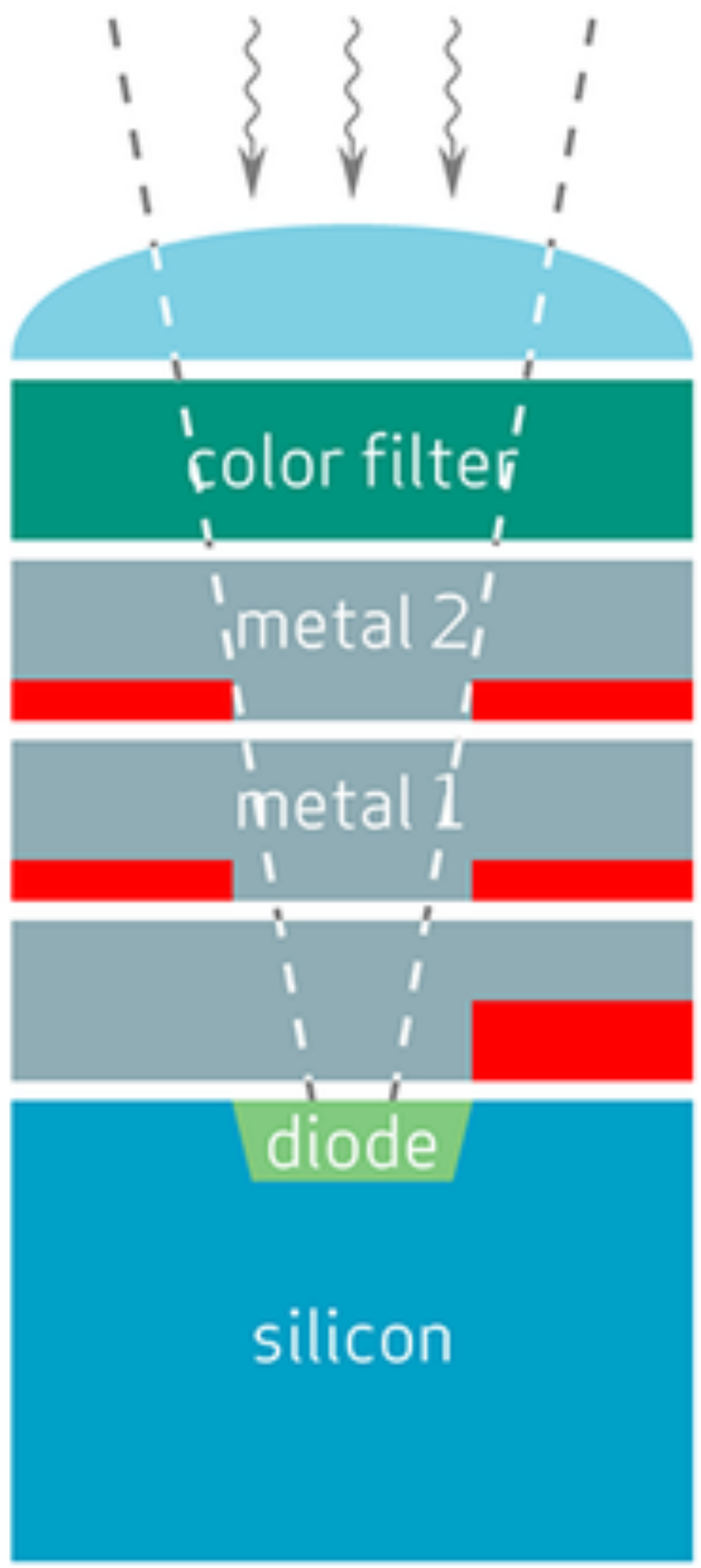
http://gmpphoto.blogspot.com/2012/09/the-new-leica-max-24mp-cmos-sensor.html

Image Example of Cross-Talk

Color desaturation due to pixel cross-talk

Kohyama et al. IISW 2009

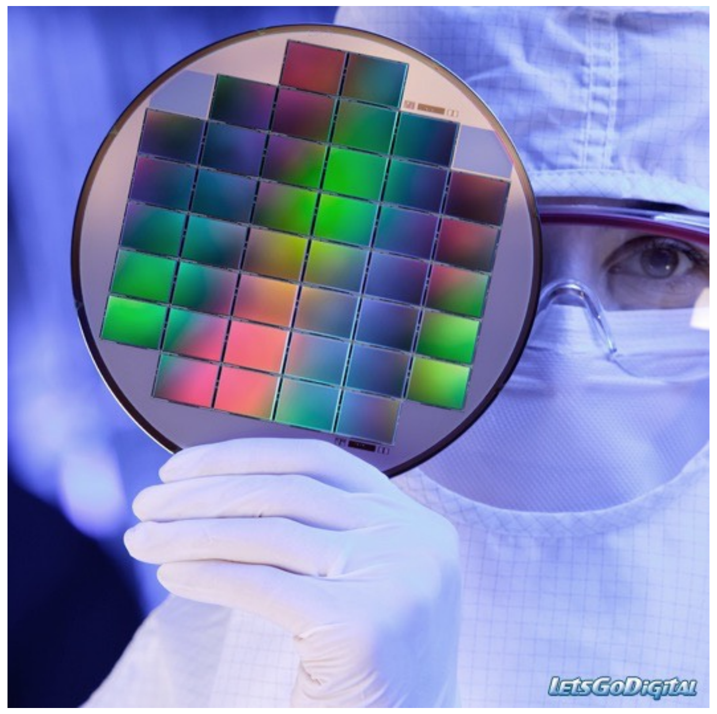
Recall: FSI (Front-Side Illuminated) Pixel Structure

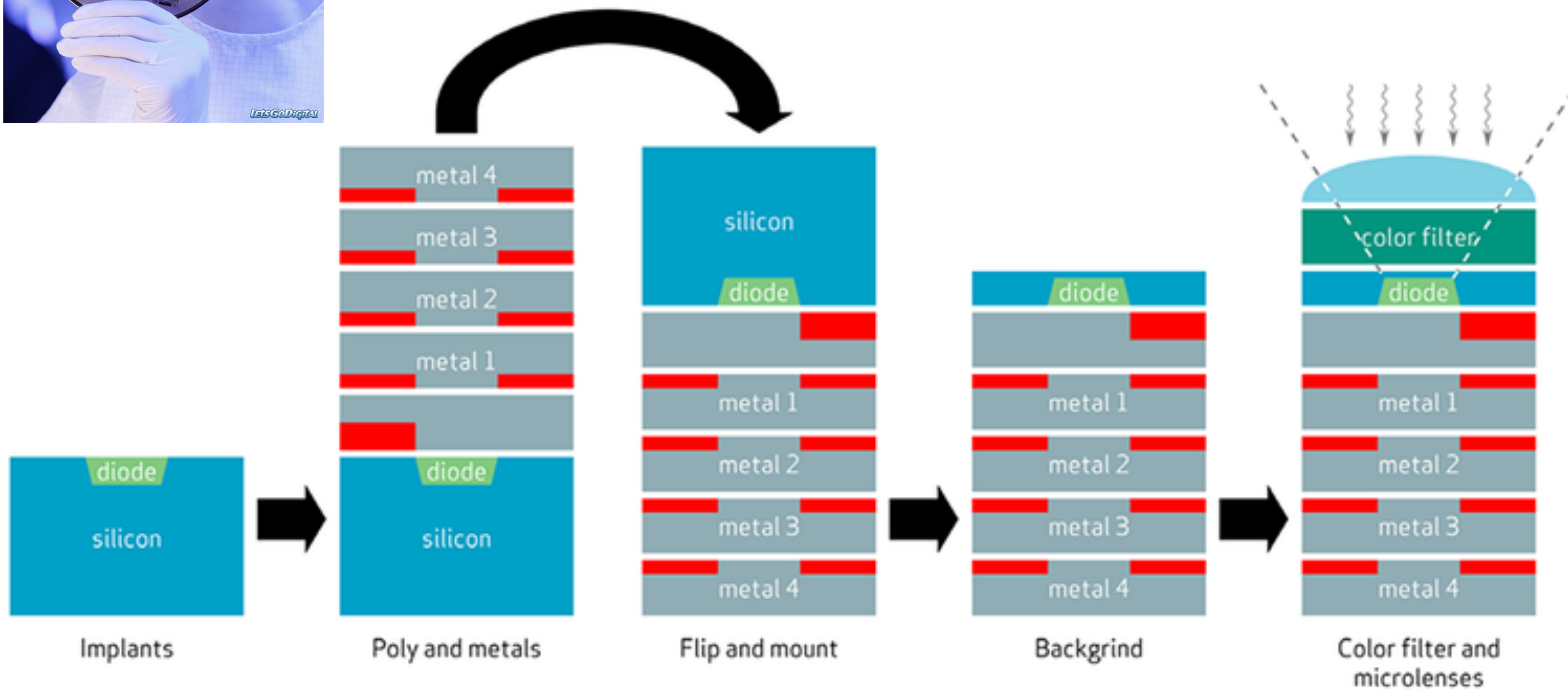


FSI

Humrick & Yankulin, tomshardware.com

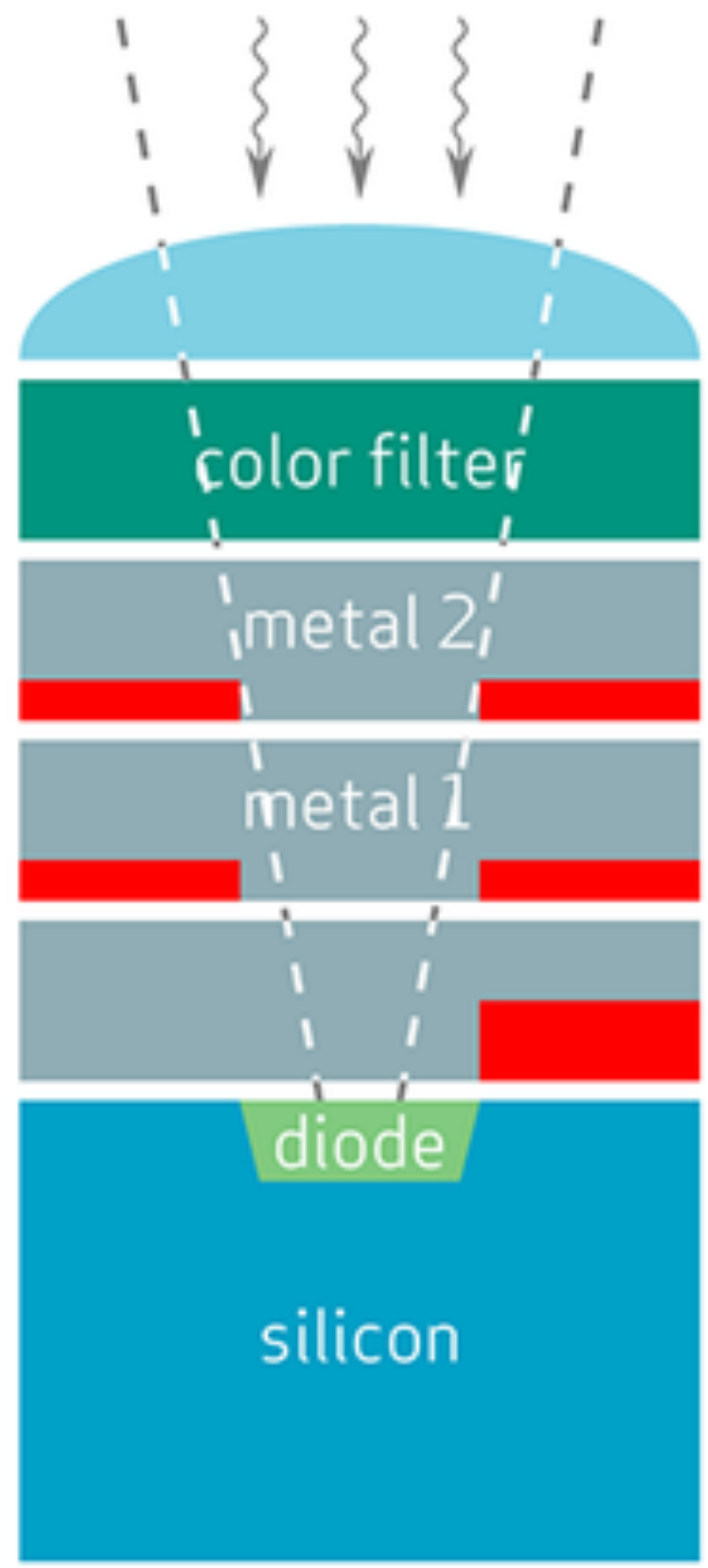
BSI (Back-Side Illumination) Sensor Fabrication Process



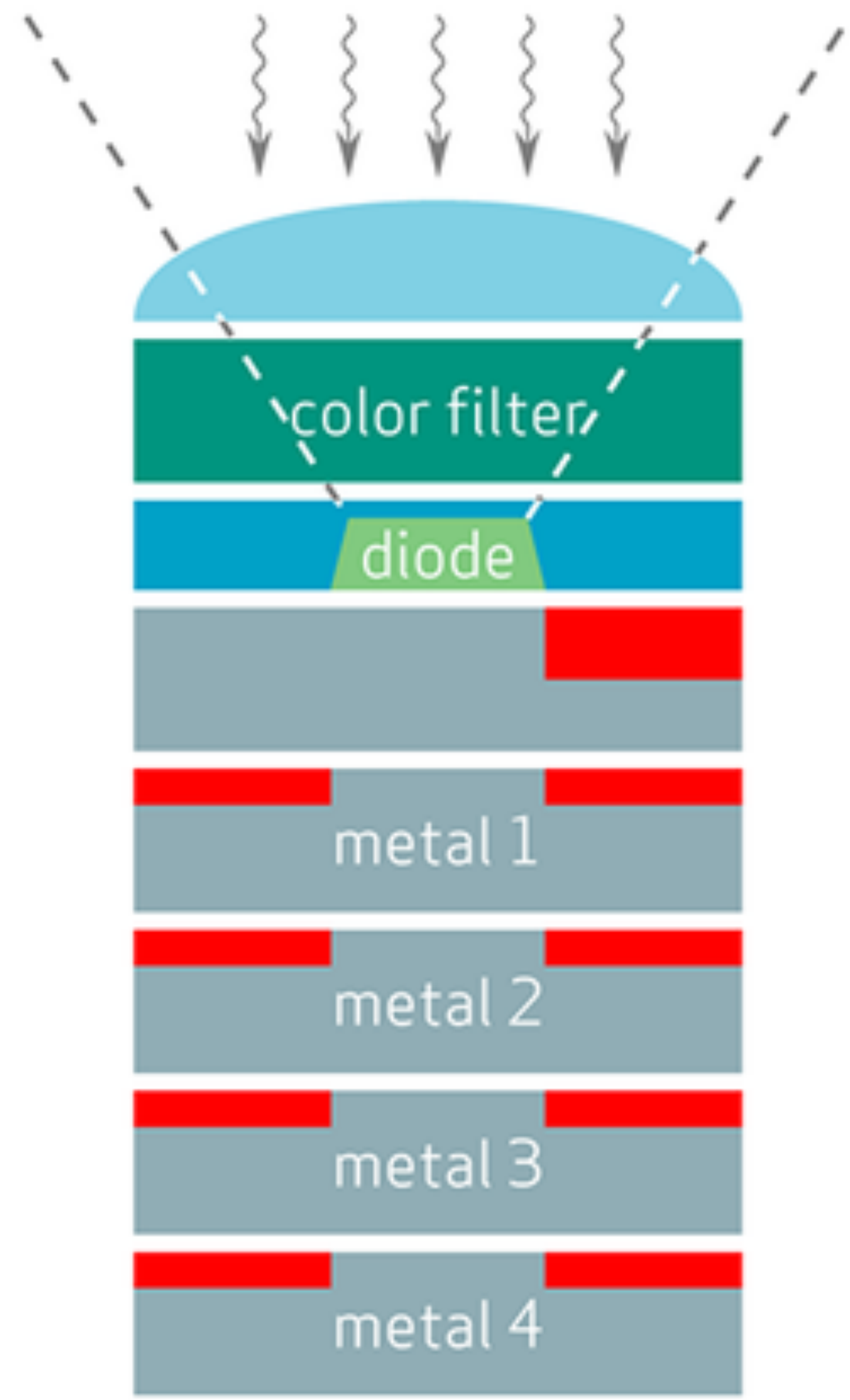


Humrick & Yankulin, tomshardware.com

FSI vs BSI Pixel Structure



FSI



BSI

Humrick & Yankulin, tomshardware.com

Majority of CMOS Sensors are BSI Today

Smartphones

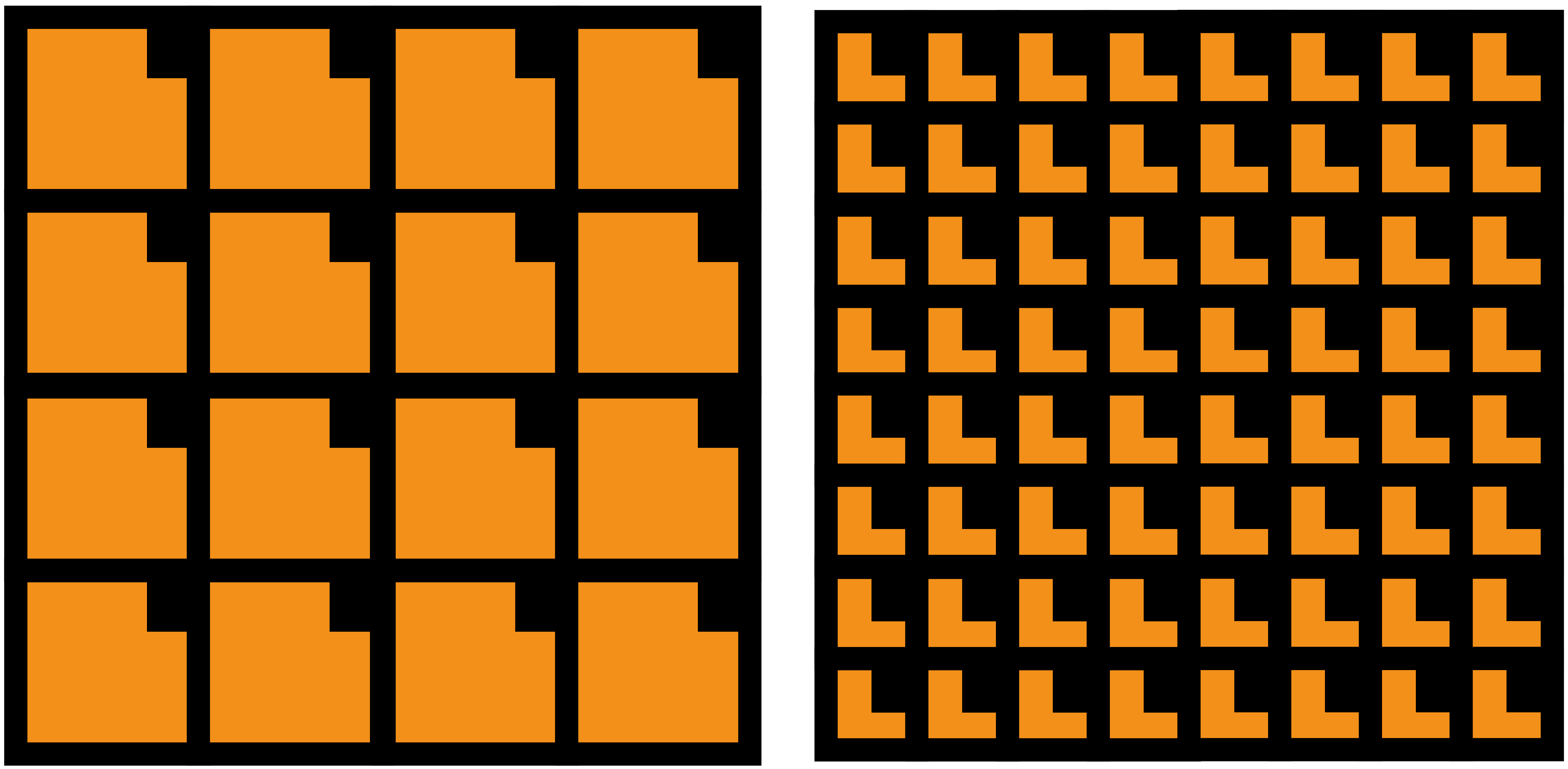
Some cameras

Good BSI sensors can provide higher QE and lower cross-talk.

Pixel Aliasing, Antialiasing

Pixel Fill Factor

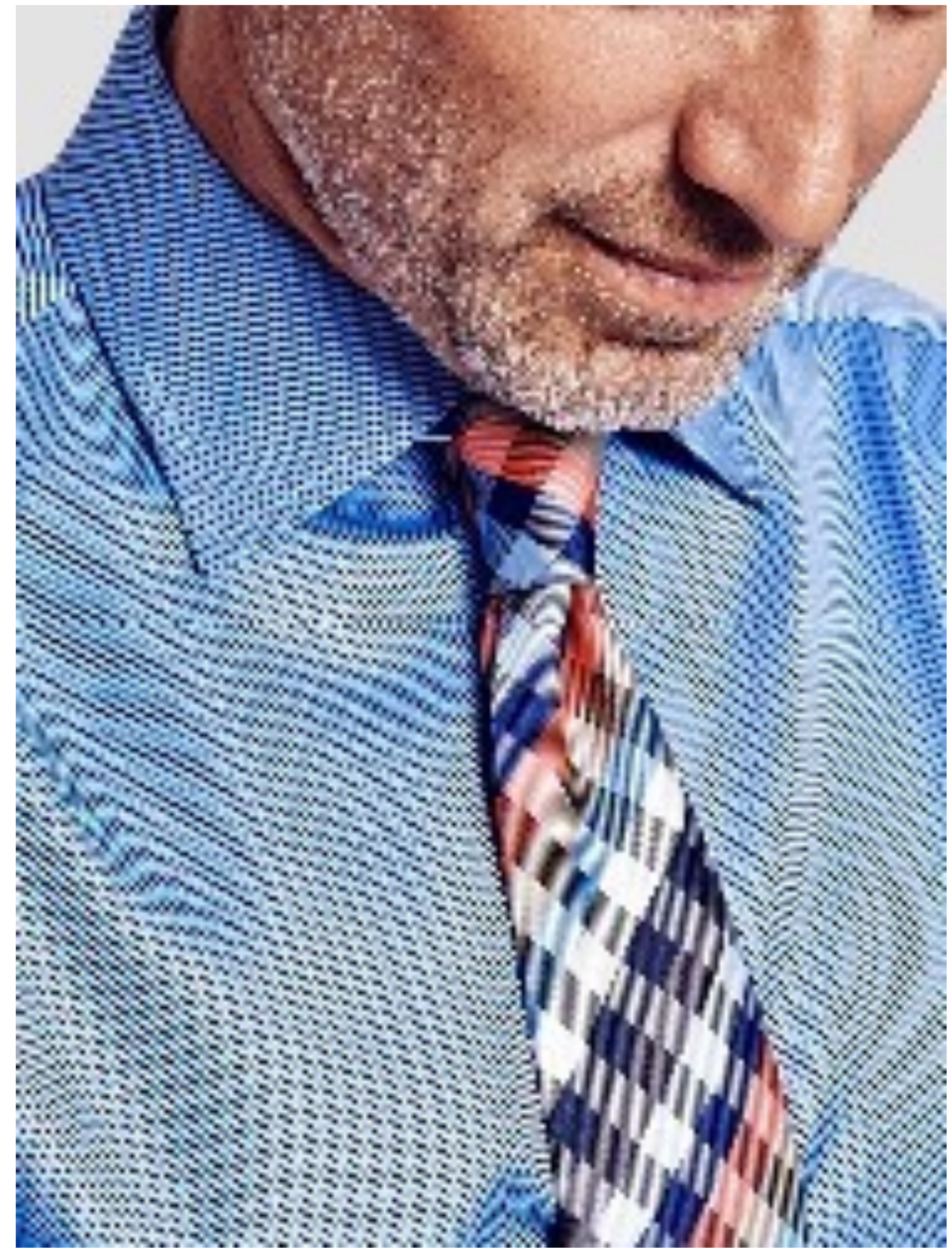
Fraction of pixel area that integrates incoming light.



Photodiode area

Non photosensitive (circuitry)

Pixel Sampling & Aliasing

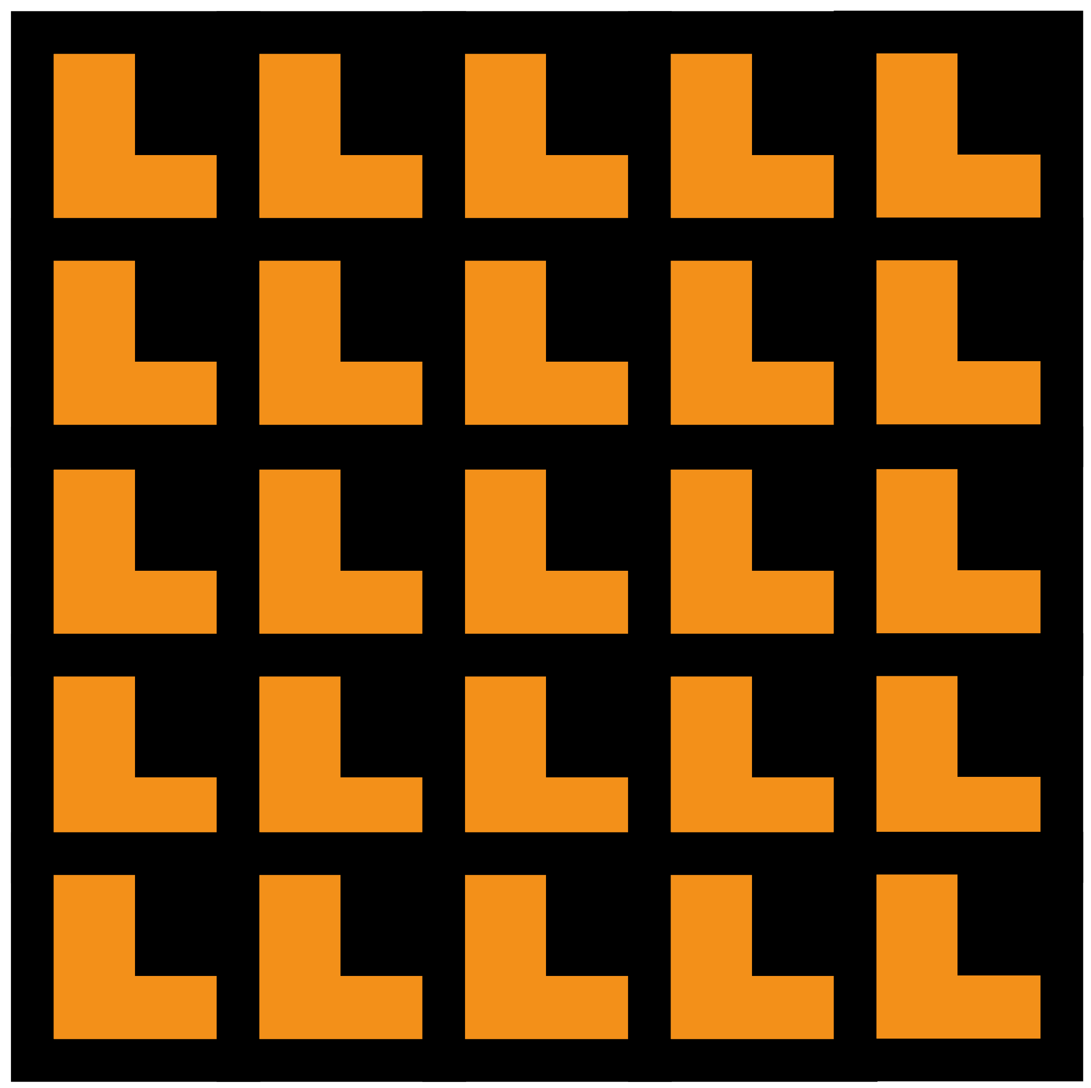


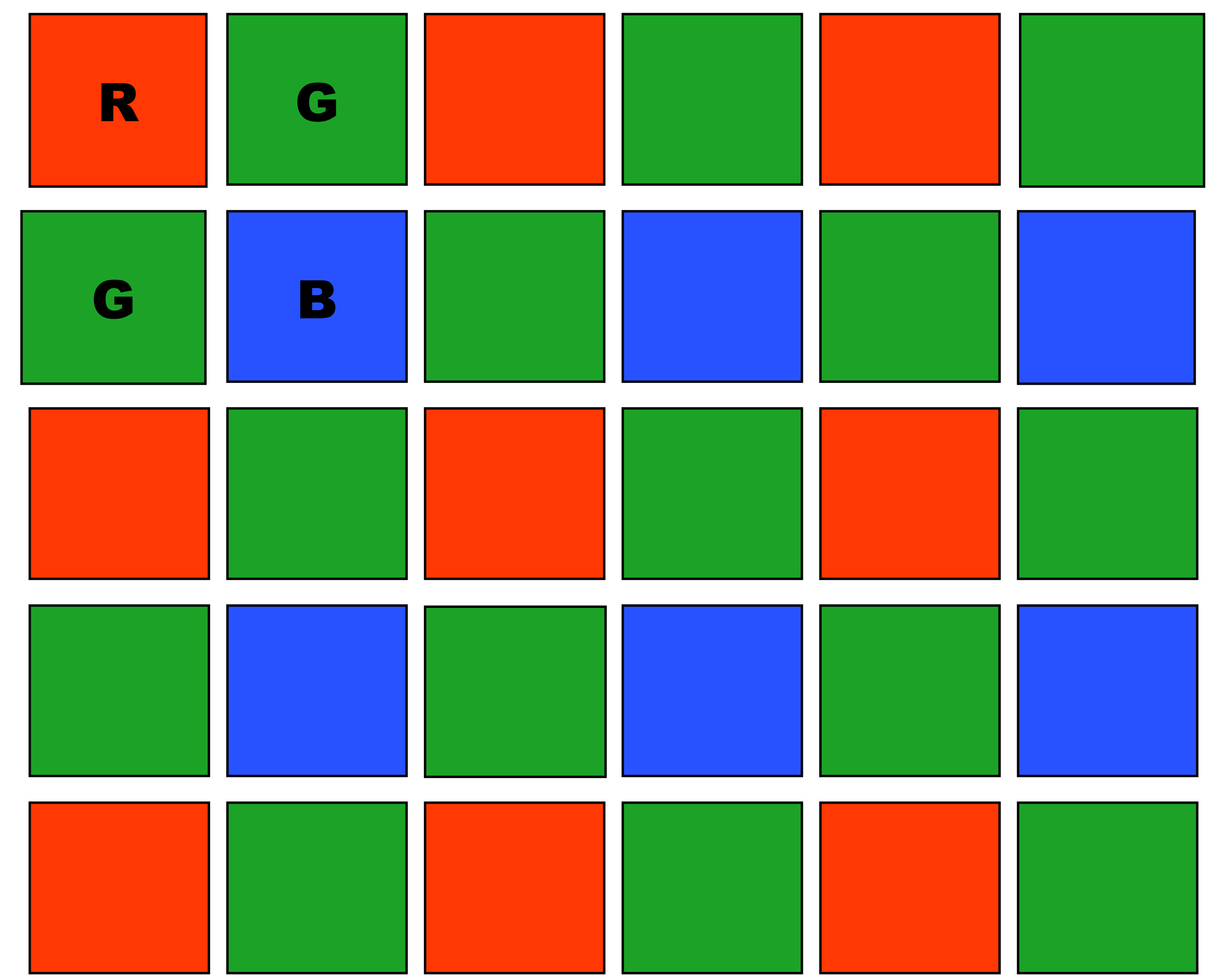
lystit.com

What is going wrong in the image on the right?

Simulation of pixels with 25% fill factor

Pixel Sampling & Aliasing





Source of aliasing includes imperfect fill-factor, and color subsampling in color filter array.

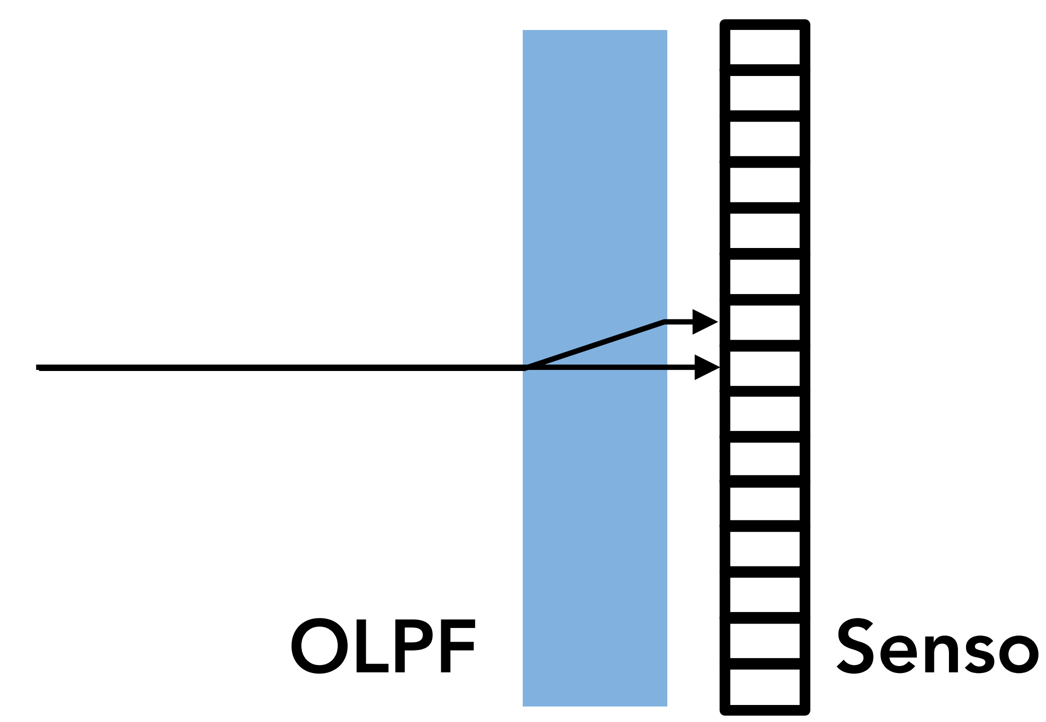
Discussed techniques to improve fill-factor (e.g. microlenses)

Antialiasing Filter

Optical low-pass filter

- Use layer of birefringent material, splits each ray into two that overlaps each pixel
- Use two layers oriented at 90 degrees to split each ray over 2x2 pixels

Birefringence



Effect of one birefringent OLPF layer (2D cross-section)

With and Without Antialiasing Filter @ 36 MP

D800E JPEG (default settings)

D800 JPEG (default settings)

D800E JPEG (default settings)

D800 JPEG (default settings)

https://www.dpreview.com/reviews/nikon-d800-d800e/29

With and Without Antialiasing Filter @ 36 MP

Without AA Filter (D800E)

With and Without Antialiasing Filter @ 36 MP

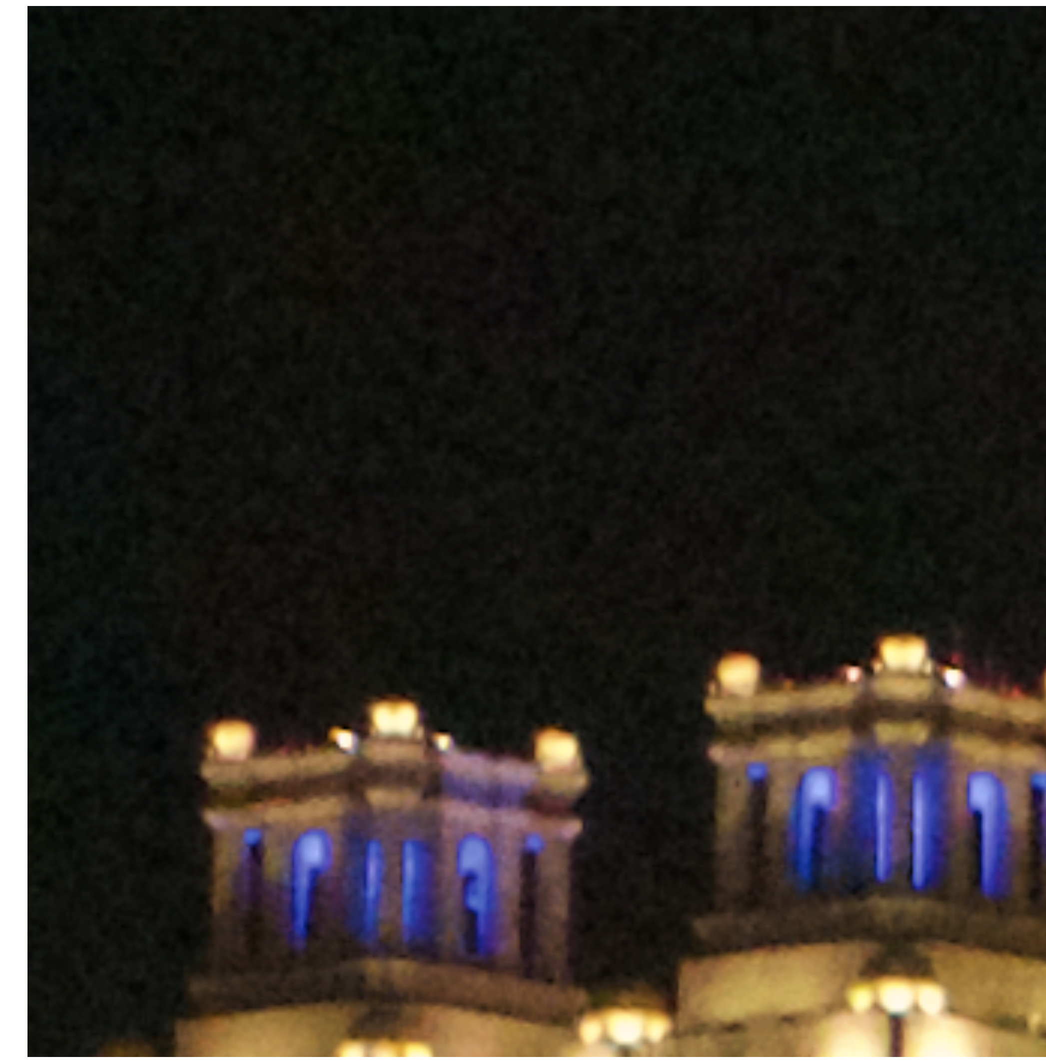
With AA Filter (D800)

Imaging Noise Fundamentals

(Most slides courtesy of Marc Levoy)

Image Noise

Image credit: imaging-resources.com



http://www.imaging-resource.com/PRODS/sony-a7s/YDSC00295.ARW.HTM

Grain in image. Generally worse in low light, long exposures, shadows in images.

Signal-to-Noise Ratio (SNR)

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}$$

$$SNR\ (\text{dB}) = 20 \log_{10}\left(\frac{\mu}{\sigma}\right)$$

Example

- If SNR improves from 100:1 to 200:1, then it improves by $20 \log_{10}(200) - 20 \log_{10}(100) = +6$ dB

Photon Shot Noise

The number of photons arriving during an exposure varies from exposure to exposure and from pixel to pixel, even if the scene is completely uniform

This number is governed by the Poisson distribution

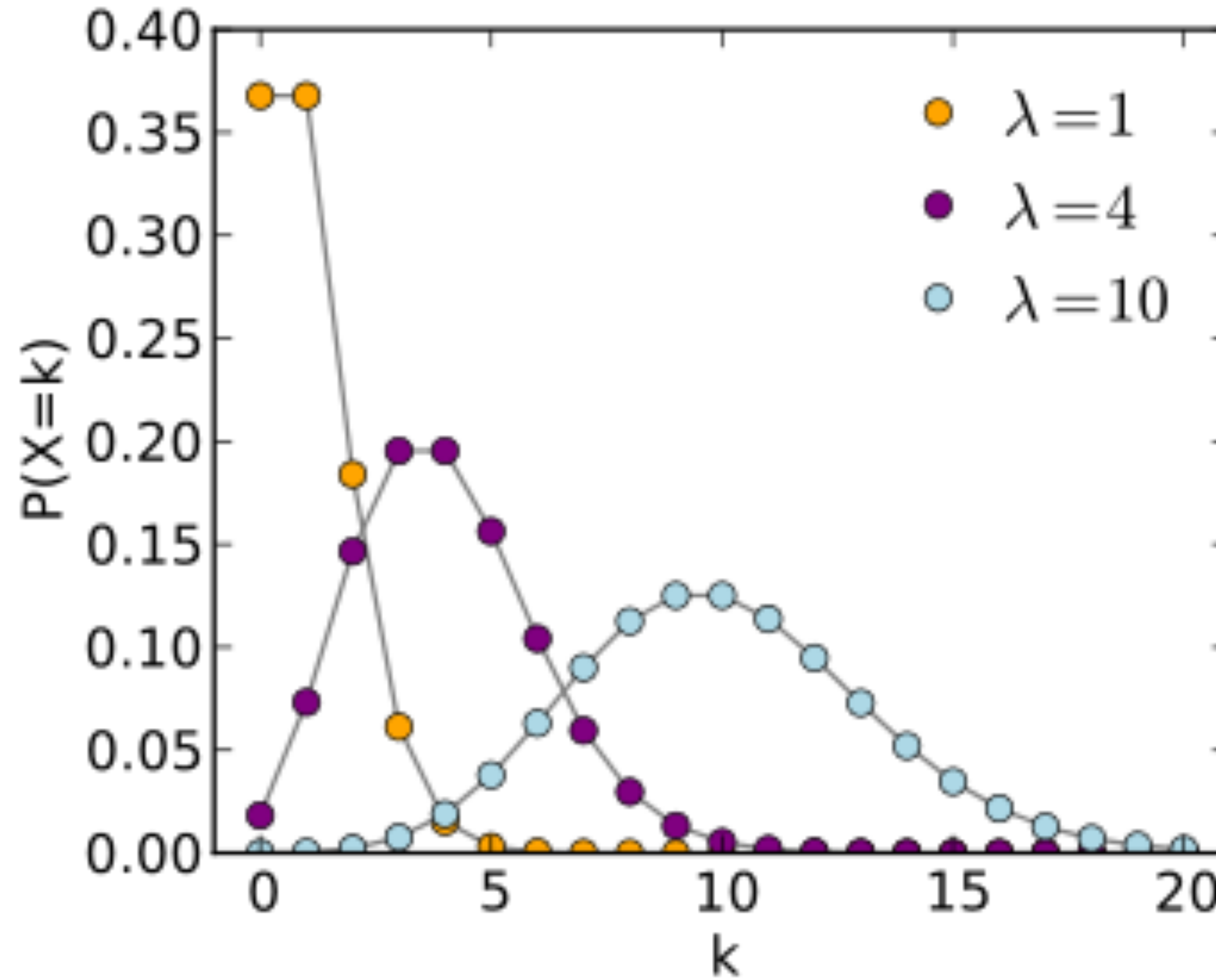
Poisson Distribution

Probability that a certain number of random events will occur during an interval of time:

- Known mean rate
- Independent events

If on average λ events occur in an interval of time, the probability p that k events occur instead is

$$p(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$



Poisson Distribution Mean and Variance

The mean and variance of the Poisson distribution are:

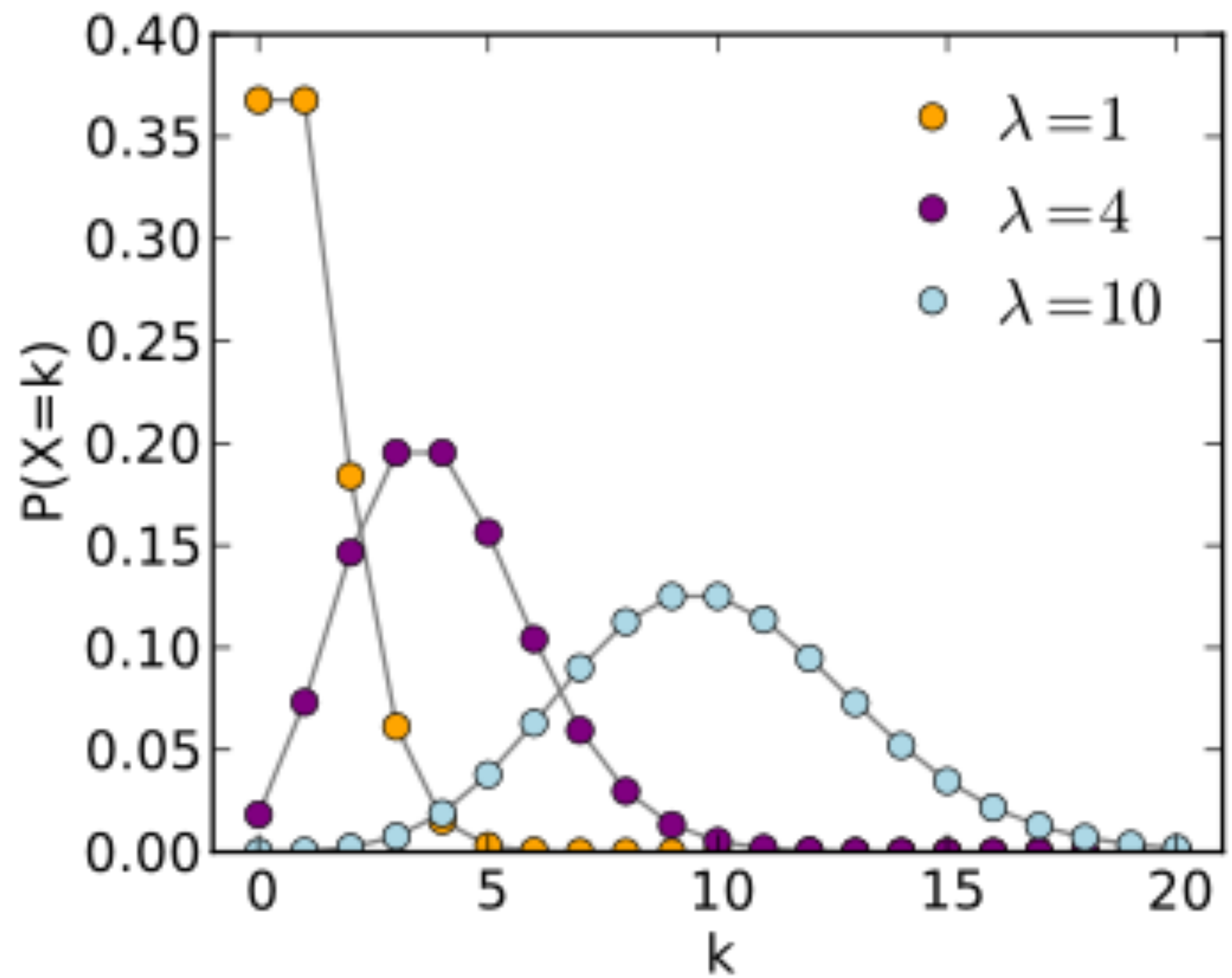
$$\mu = \lambda$$

$$\sigma^2 = \lambda$$

The standard deviation is:

$$\sigma = \sqrt{\lambda}$$

The error grows slower than the mean



Photon Shot Noise SNR

Photons arrive in a Poisson distribution

$$\mu = \lambda \qquad \sigma = \sqrt{\lambda}$$

so

$$\boxed{\mathrm{SNR} = \frac{\mu}{\sigma} = \sqrt{\lambda}}$$

Shot noise scales as the square root of number of photons

Examples:

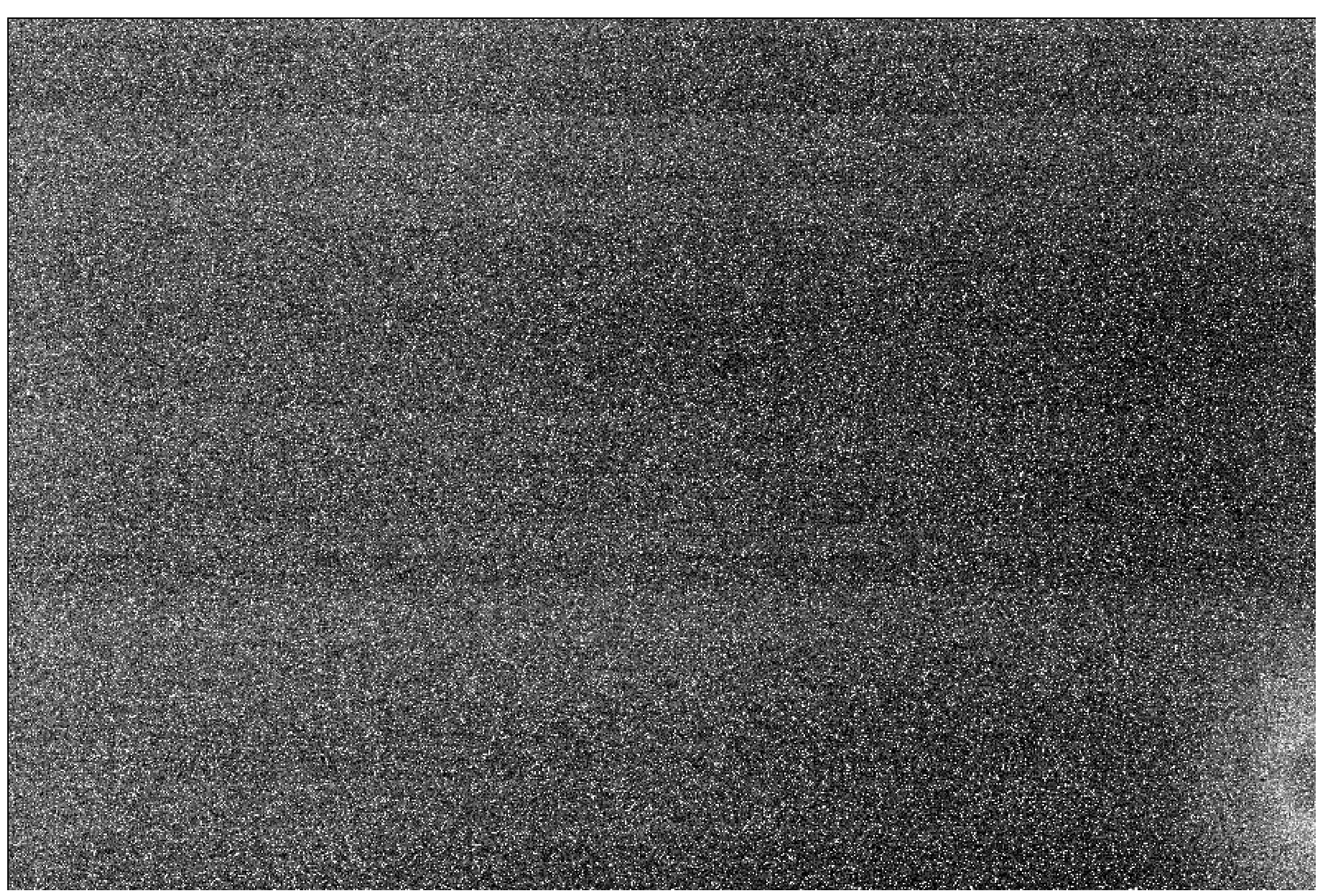
- A pixel that collects 10,000 photoelectrons vs. 1,000 has an SNR improvement of $\sqrt{10}$ or +10 dB
- Opening the aperture by 1 f/stop increases the number of photons by 2×, hence SNR by $\sqrt{2}$ or +3 dB

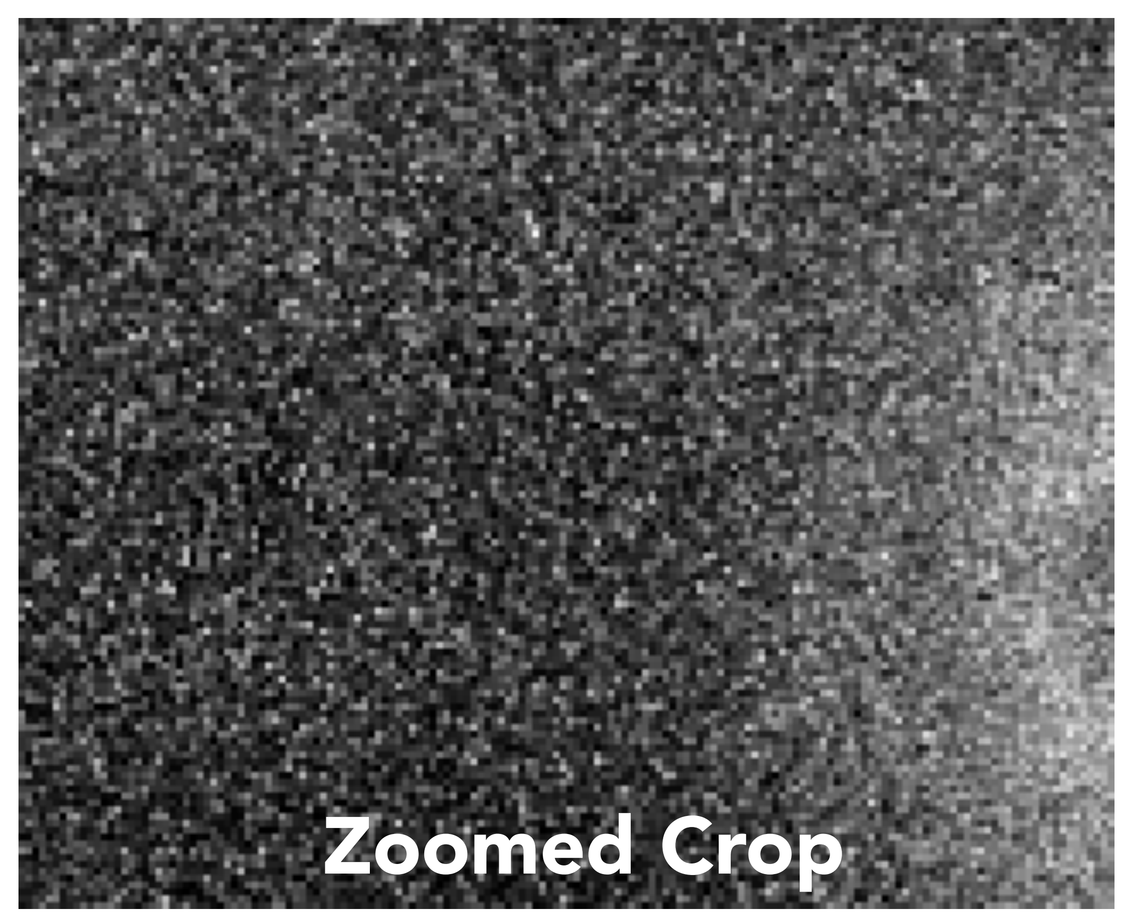
Sensor Noise Sources

(Most slides courtesy of Marc Levoy)

Pixel Noise: Dark Current

- Electrons dislodged by random thermal activity
- Increases linearly with exposure time
- Increases exponentially with temperature
- Varies across sensor, and includes its own shot noise





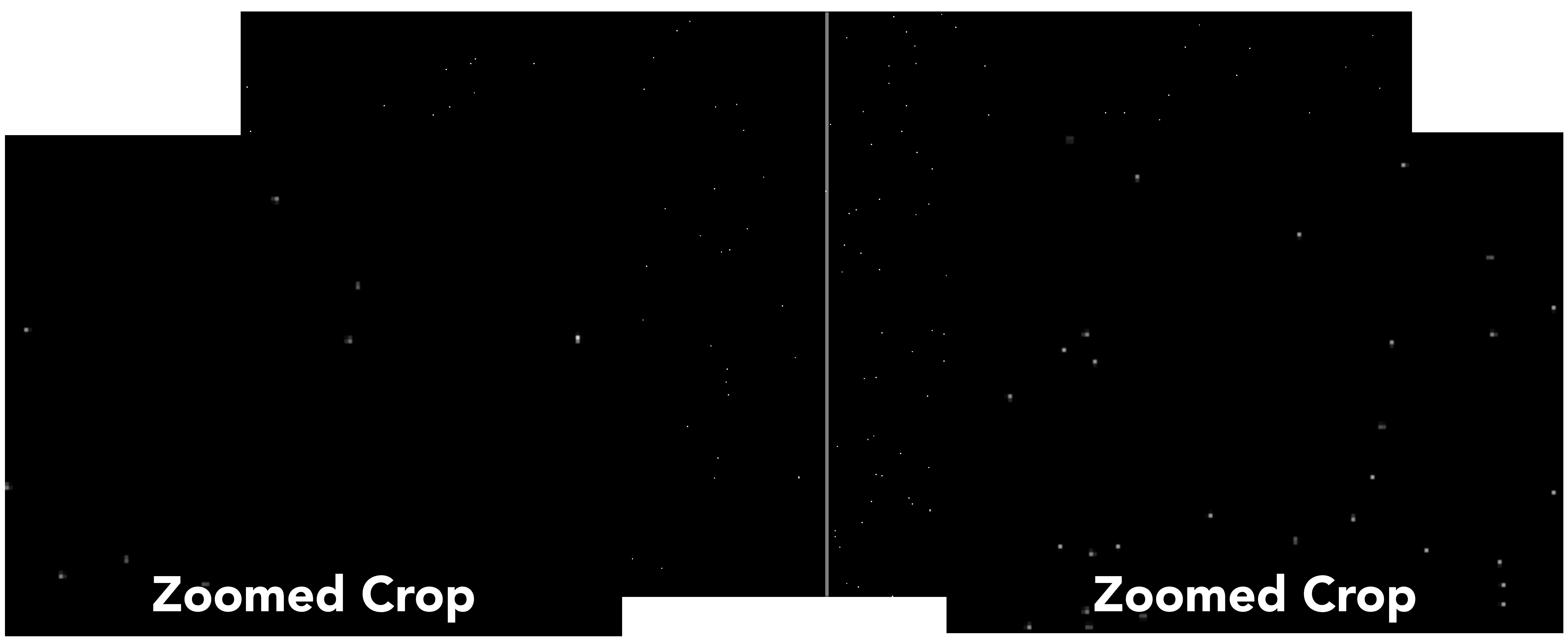
don’t confuse with photon shot noise

(http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/)

Canon 20D, 612 sec exposure

Pixel Noise: Hot Pixels

- Electrons leaking into well due to manufacturing defects
- Increases linearly with exposure time
- Increases with temperature, but hard to model
- Changes over time, and every camera has them

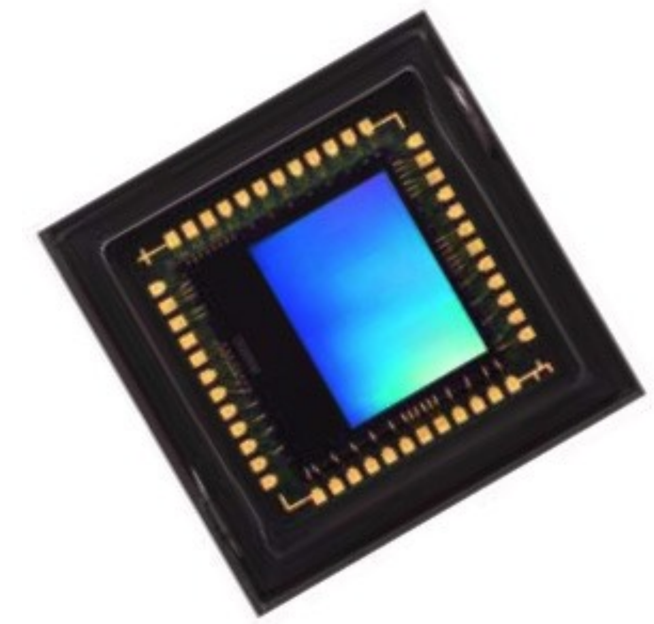


Canon 20D, 15 sec and 30 sec exposures

Pixel Noise: Fixing Dark Current & Hot Pixels

Example

- Aptina MT9P031 (in Nokia N95 cell phone)
- full well capacity = ~8500 electrons/pix
- dark current = 25 electrons/pix/sec at 55°C



Solution #1: chill the sensor

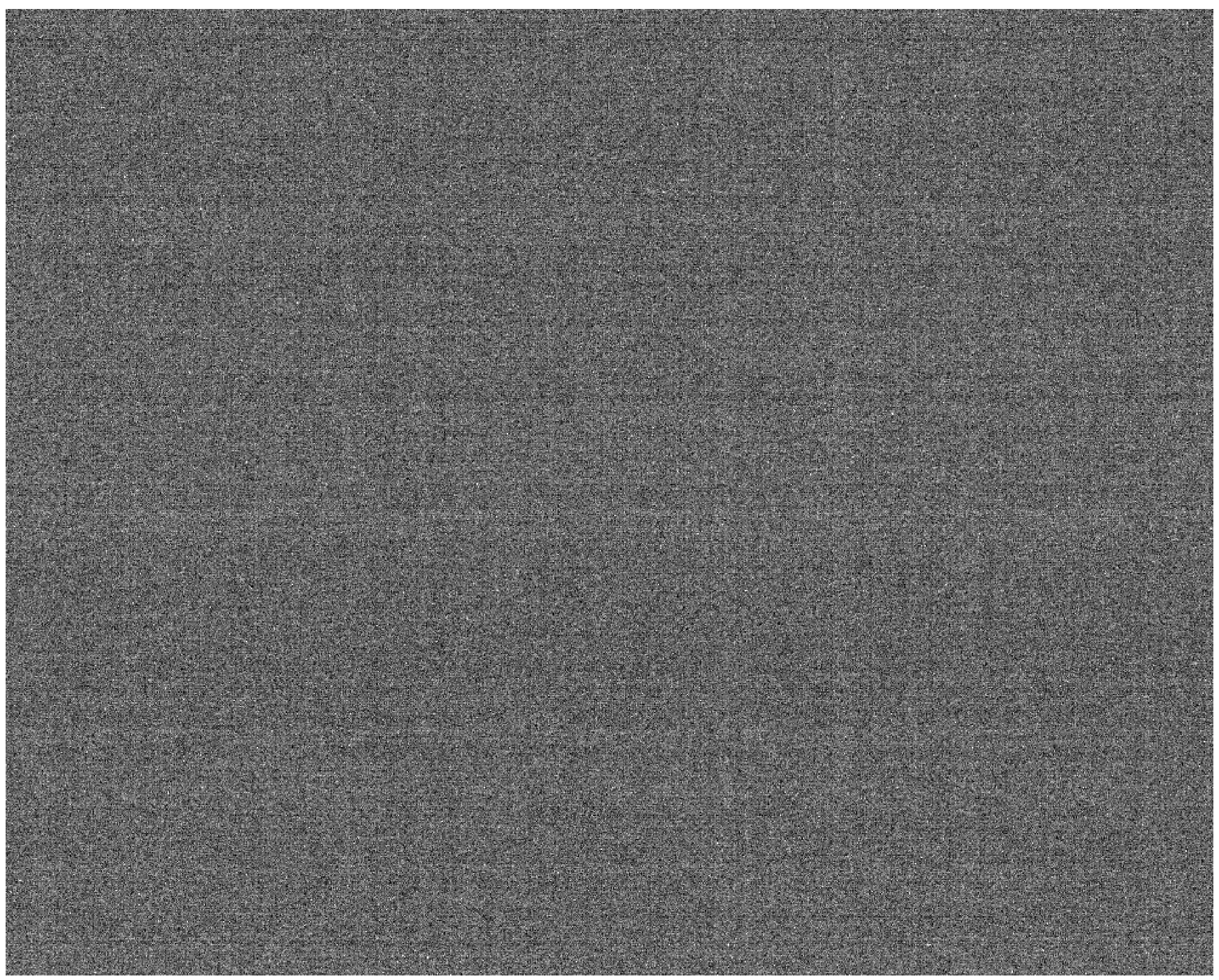
- Retiga 4000R bioimaging camera
- Peltier cooled 25°C below ambient
- full well capacity = 40,000 electrons/pix
- dark current = 1.64 electrons/pix/sec

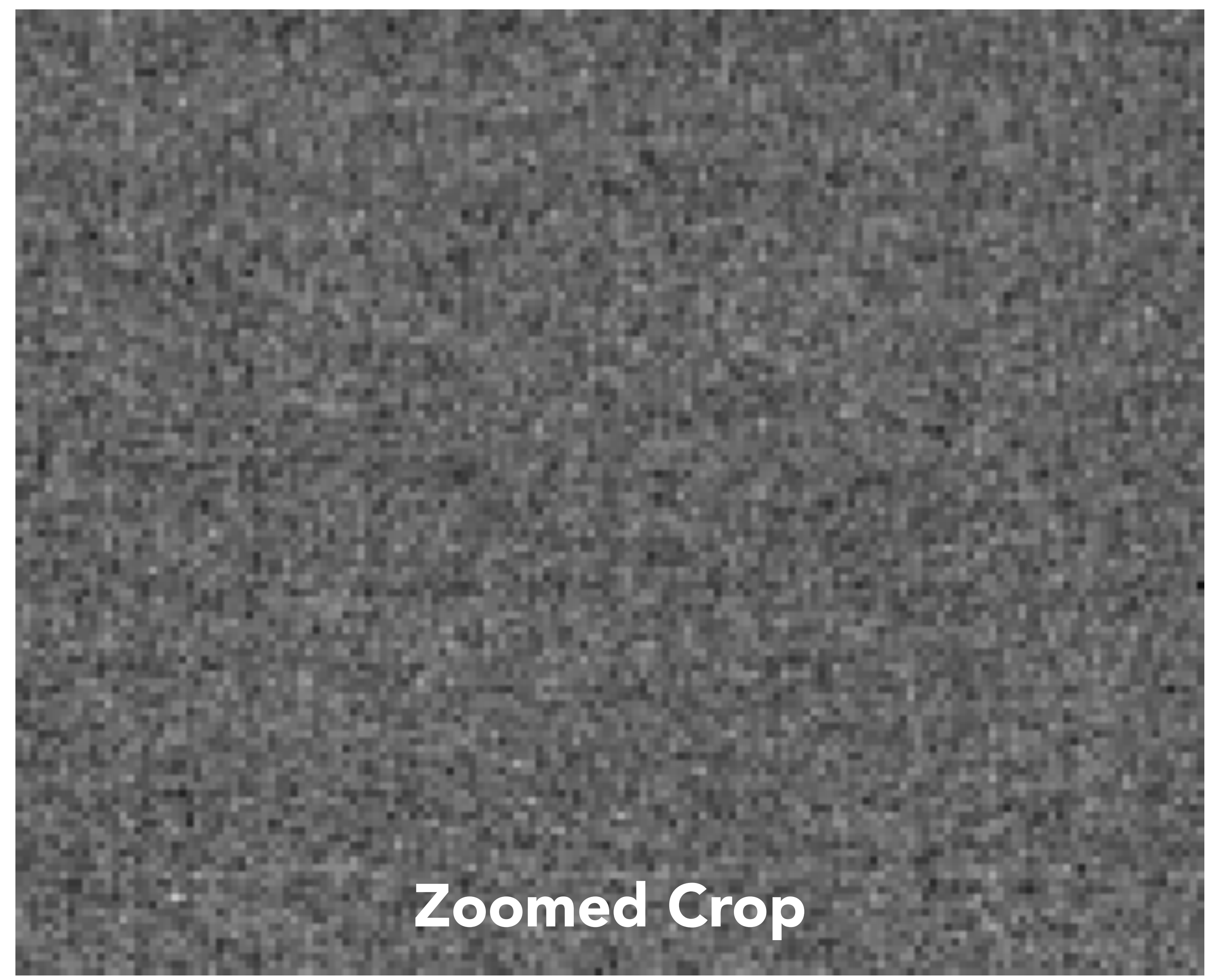
Solution #2: dark frame subtraction

- available on high-end SLRs
- compensates for average dark current
- also compensates for hot pixels and FPN

Pixel Noise: Fixed Pattern Noise (FPN)

- Manufacturing variations across pixels, columns, blocks
- Mainly in CMOS sensors
- Doesn't change over time, so read once and subtract

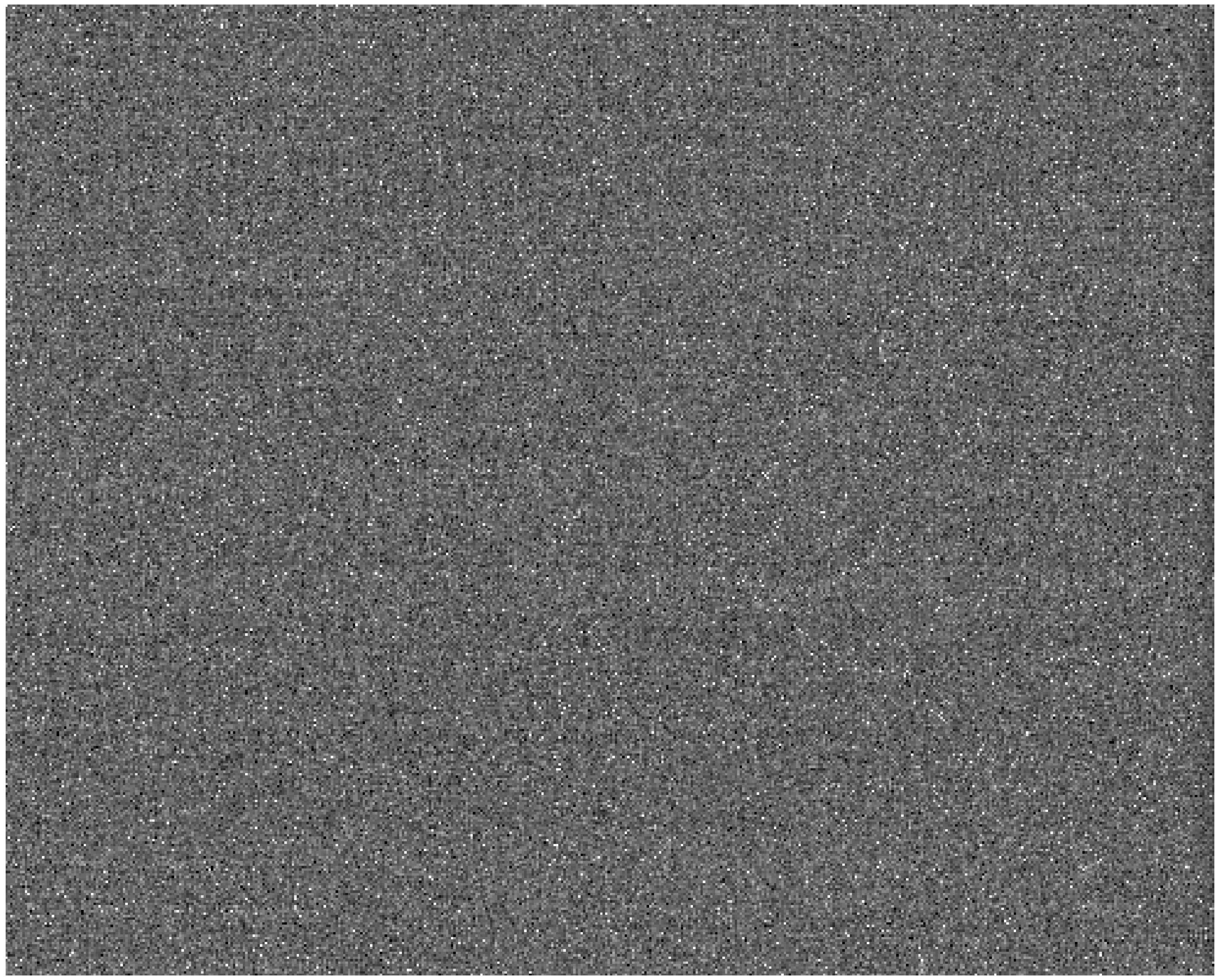


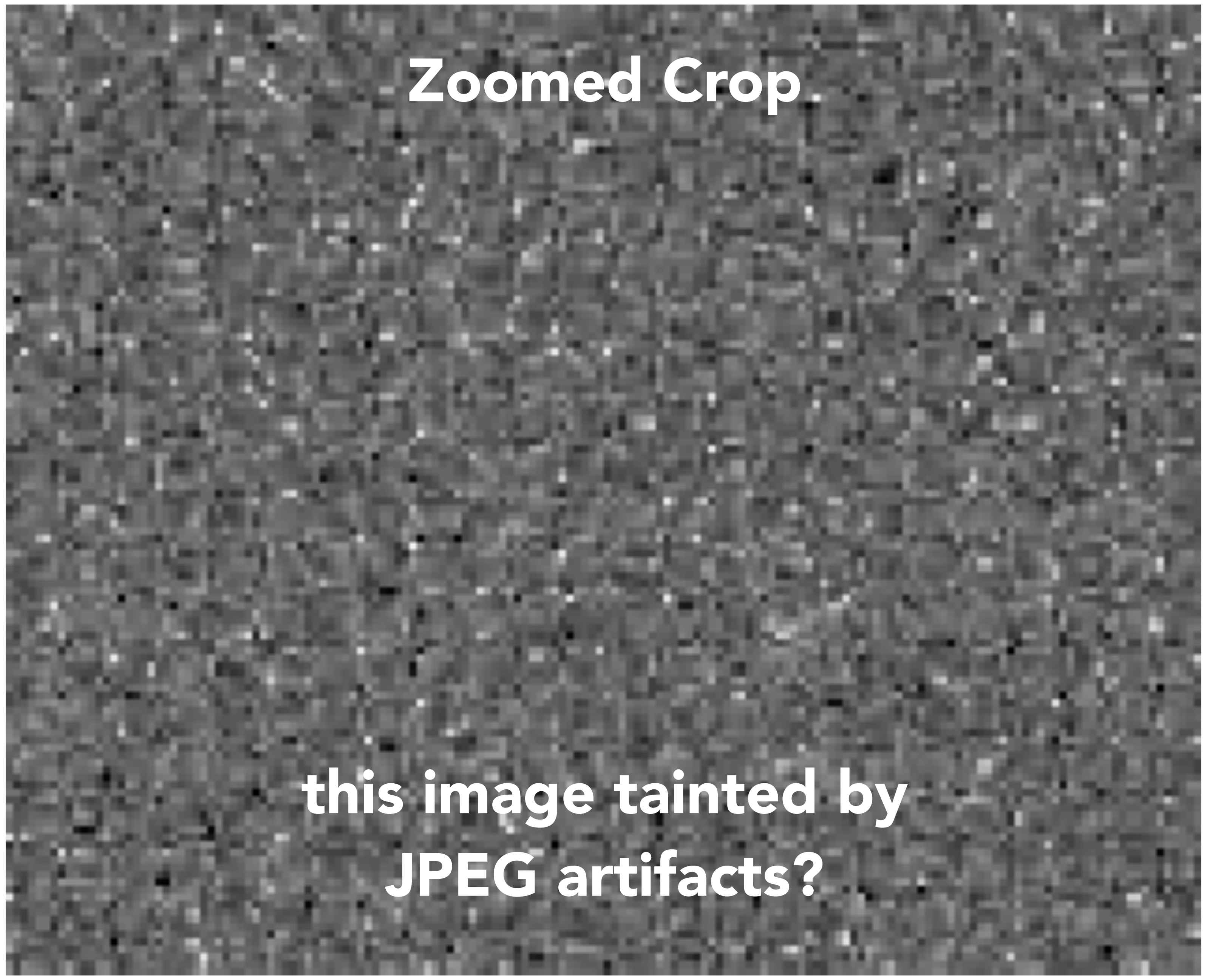


Canon 20D, ISO 800, cropped

Pixel Noise: Read Noise

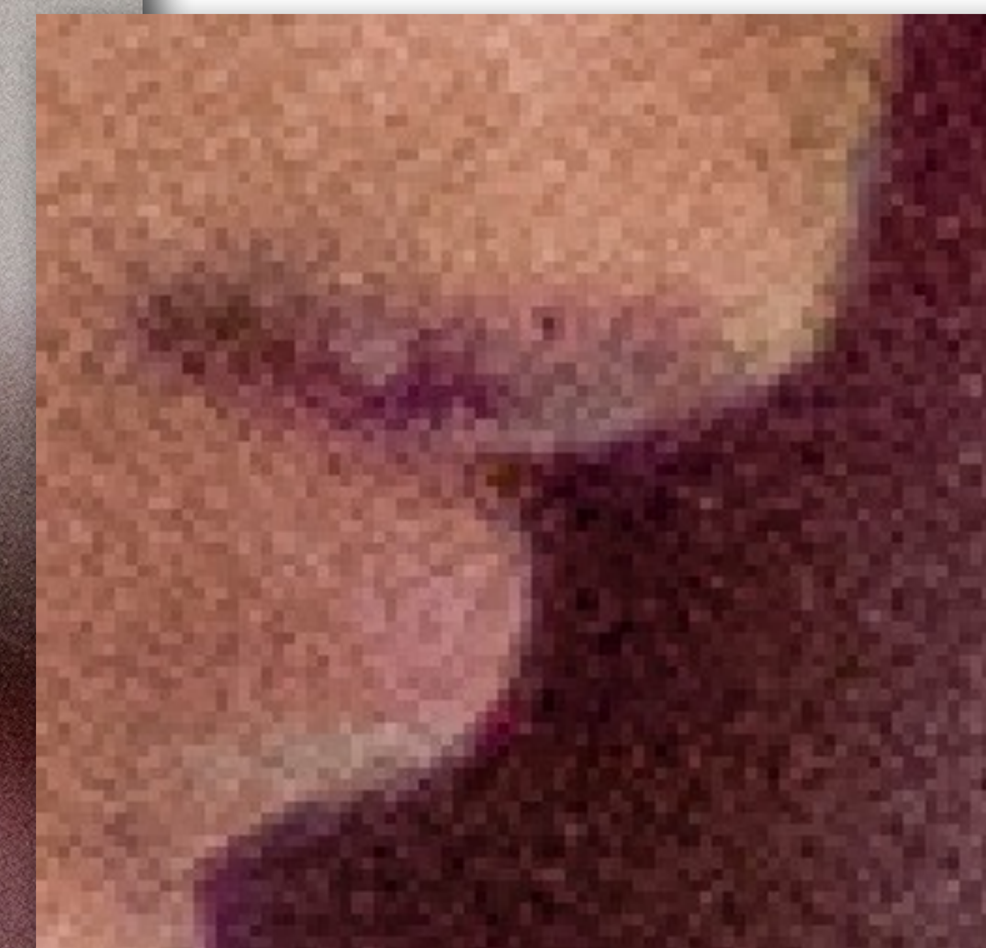
- Thermal noise in readout circuitry
- Again, mainly in CMOS sensors
- Not fixed pattern, so only solution is cooling





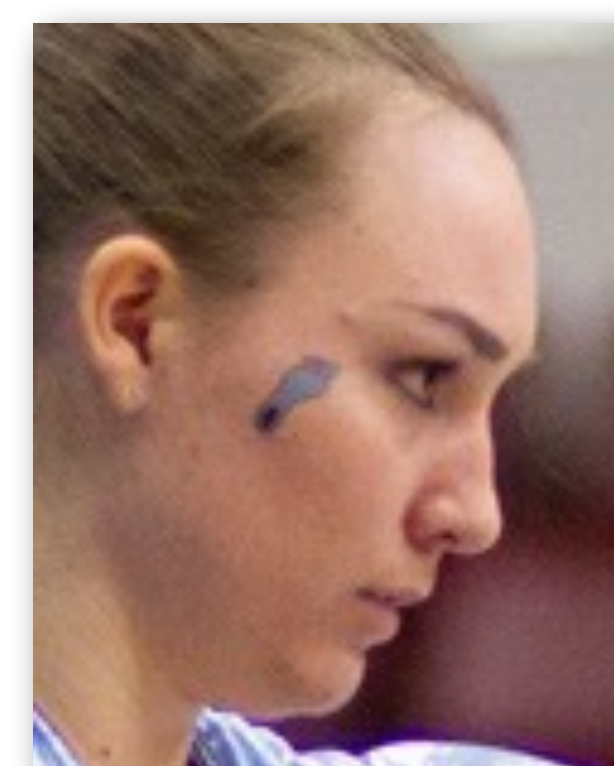
Canon 1Ds Mark III, cropped

Effect of Downsizing on Image Noise



averaged down

point sampled



Levoy

Noise Reduction by Image Averaging

Single frame
in dark room
using iPhone 4

Levoy

Noise Reduction by Image Averaging

Average of ~30 frames using SynthCam app by Marc Levoy

SNR increases as sqrt(# of frames) (neglecting read noise)

Levoy

Things to Remember

Photoelectric effect

Imager revolution: CCD and CMOS sensors

Sensor saturation

High dynamic range (HDR) imaging

Color architectures, Bayer filter array, demosaicking

Pixel stack, fill factor, microlenses

FSI vs BSI pixel designs

Pixel sampling, aliasing, optical low-pass filters

Noise: photon shot, pixel noise sources, SNR

Acknowledgments

Many thanks to Marc Levoy, Brian Wandell, and Pat Hanrahan, who created many of these slides.

Extras

Noise Recap

Photon shot noise

- Unavoidable randomness in number of photons arriving
- Grows as the square root of the number of photons, so brighter lighting and longer exposures will be less noisy

Dark current noise

- Grows with exposure time and sensor temperature
- Minimal for most exposure times used in photography
- Correct by subtraction, but only corrects for average dark current

Hot pixels, fixed pattern noise

- Caused by manufacturing defects, correct by subtraction

Read noise

- Electronic noise when reading pixels, unavoidable

Signal-to-Noise Ratio Revisited

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}$$

$$= \frac{P\, Q_e\, t}{\sqrt{P\, Q_e\, t + D\, t + N_r^2}}$$

SNR changes with scene brightness, aperture, and exposure time

Where

- P = incident photon flux (photons/pixel/sec)
- Q_e = quantum efficiency
- t = exposure time (sec)
- D = dark current (electrons/pixel/sec), including hot pixels
- N_r = read noise (rms electrons/pixel), including fixed pattern noise

(formula from http://learn.hamamatsu.com/articles/ccdsnr.html)

ISO - Signal Gain

Doubling ISO doubles the signal

- Linear with light, so same as 2× exposure time, or brighten by one f-stop
- Implemented as analog or digital amplification
  - Analog before ADC on Canon 5D II up to ISO 6400; digital multiplication at higher ISOs?

Ideal to amplify as early as possible during readout

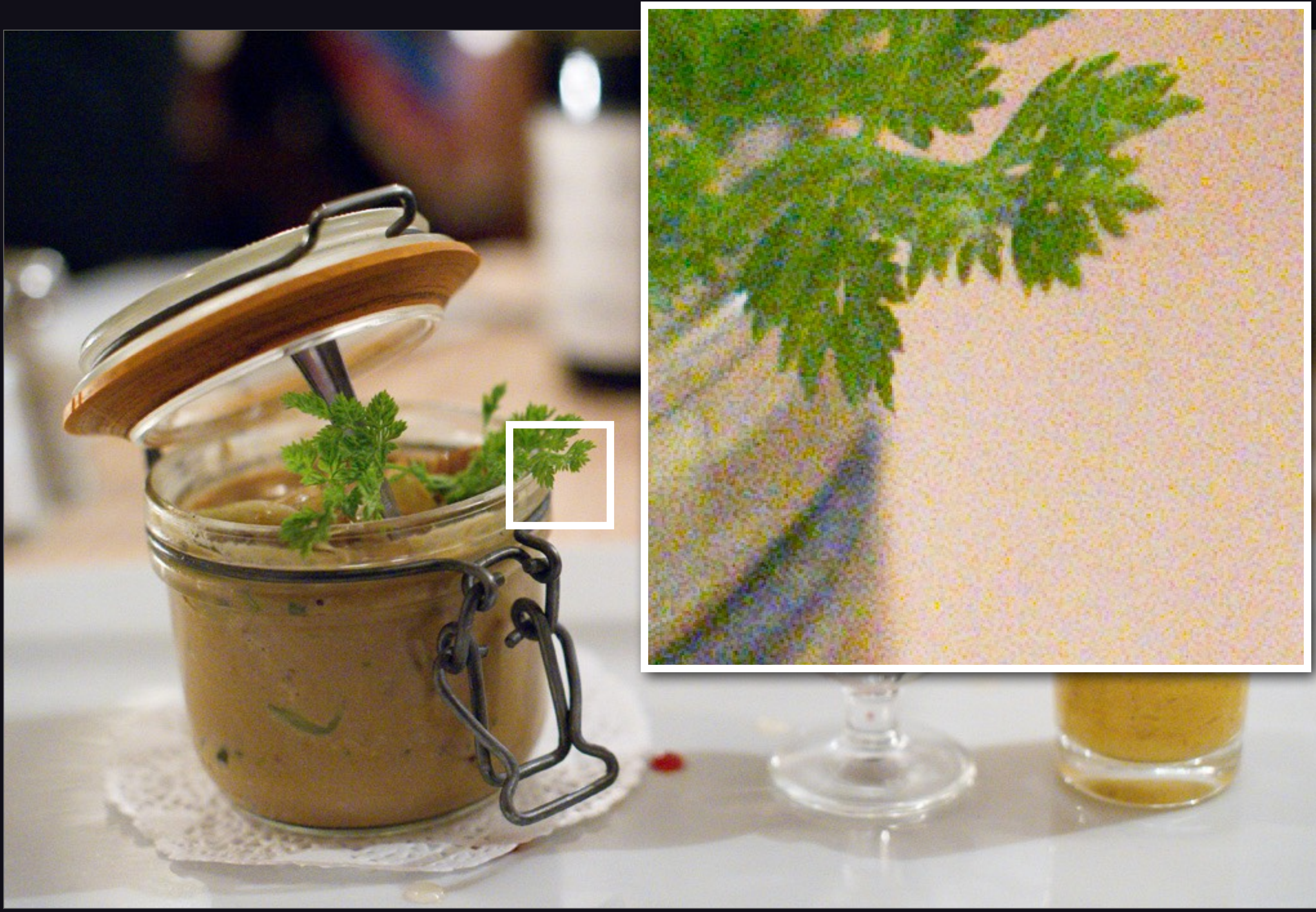
- If amplification occurs before read noise is added, and read-noise is independent of signal amplitude, then the amplified signal will have better SNR

Nikon D3S, ISO 3200, photograph by Michael Kass

Nikon D3S, ISO 6400, photograph by Michael Kass

Nikon D3S, ISO 25,600, denoised in Lightroom 3, photograph by Fredo Durand
(Too dark to read menu)

Nikon D3S, ISO 25,600, denoised in Lightroom 3, photograph by Fredo Durand



RAW image from camera, before denoising in Lightroom

Tone mapped to show the scene as Fredo might have experienced it