Astro 426/526

Fall 2019

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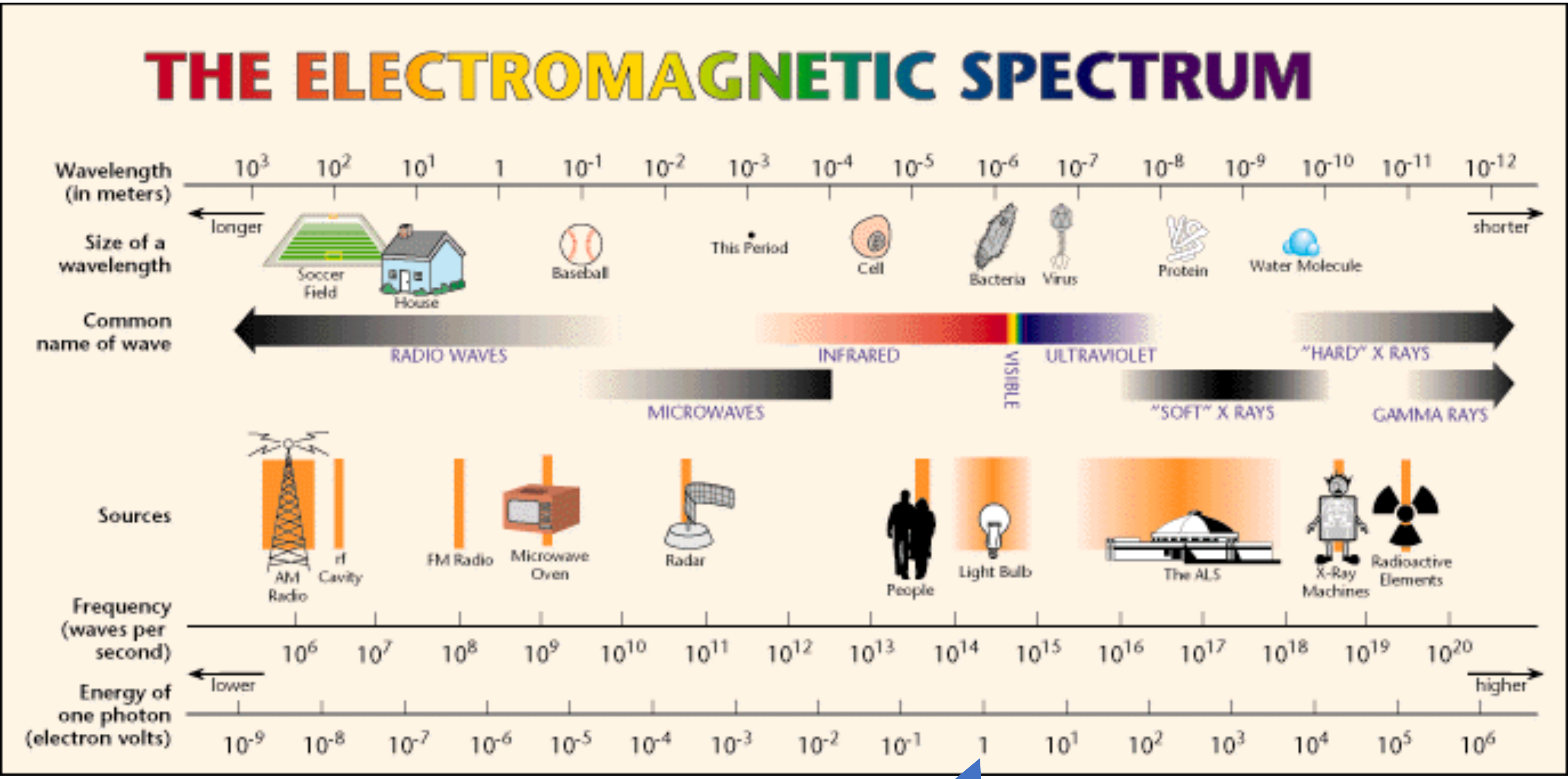
Lecture 9: Photon detectors

Reminders

- **HW 2 due Friday Sept 27 at 5pm**
- Mid-term exam Wed Oct 2
- For next two weeks: detectors, statistics, and noise
  - Summarized in Section 1.4.2 (Detectors: Basic Principles) and Section 1.5 (Statistics and noise) of *Measuring the Universe*
  - For this week: read chapter 3 of Measuring the Universe (Detectors for the ultraviolet through infrared)
  - For the week after (Sept 23): read chapter 3 of *Practical Statistics for Astronomers*
  - If you have a limited background in statistics, may also need to reference or skim Chapter 2 of *Practical Statistics for Astronomers*


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10³ 10² 10¹ 1 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹²
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
lower
higher
Energy of one photon (electron volts)
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶

Three methods of detection

- Coherent detectors
  - Interact local electric field with electrical field of incoming photons and measure interference
- Thermal detectors
  - Absorb energy of incoming photons and measure change in temperature
- **Photon detectors**
  - **Absorb energy of incoming photons and release free charge carriers**
  - Need materials that can interact on the right energy scale, so only useful in photon energy range ~ 0.01 eV - ~ 3 eV
  - Corresponds to wavelengths in ultraviolet through ~ near infrared

Photon behavior

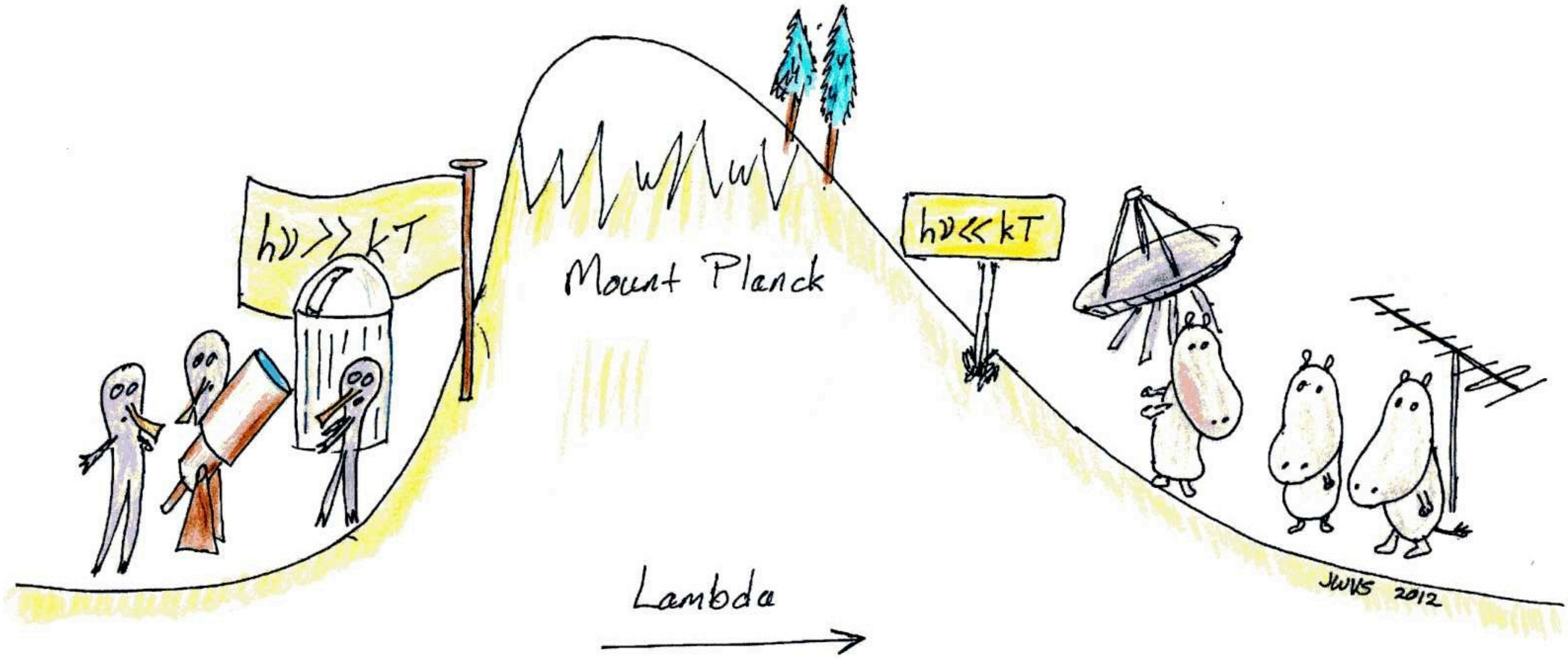
- Photons are bosons, which dictates their fundamental behavior and statistics (Bose-Einstein statistics, can occupy same state)
- The occupation number gives the number of photons per mode

$$\langle n_s \rangle = \left(e^{h\nu_s/kT} - 1\right)^{-1}$$

- The brightness is given by the number of modes, times the number of photons per mode, multiplied by the energy per photon (x 2, why?)

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

- This creates unavoidable noise from the signals that we are measuring, **photon noise**
    - A perfect detector would still make a noisy measurement



Source: John Storey, University of New South Wales

Photon noise

- Photons do not arrive independently of each other
- $< N^2 > = n\,[1 + \frac{\varepsilon\tau\eta}{e^{h\upsilon/kT}-1}]$
- $<N^2>$ is the mean square noise, n is the number of photons detected
- ν, T are frequency and temperature of source
- ε, τ, η are inefficiencies in system (emissivity of source, transmittance of optical system, detector efficiency)

Photon noise

- $< N^2 > = n \left[1 + \frac{\varepsilon\tau\eta}{e^{\frac{h\upsilon}{kT}}-1}\right] = n[1 + n_s(\varepsilon\tau\eta)]$
- Relevant statistics depend strongly on value of $h\upsilon/kT$, which gives occupation number
- n_s >> 1: many photons per mode
  - highly correlated behavior
- n_s<< 1: few photons per mode
  - Can approximate as independent events
- n_s ~ 1 : 1 photon per mode

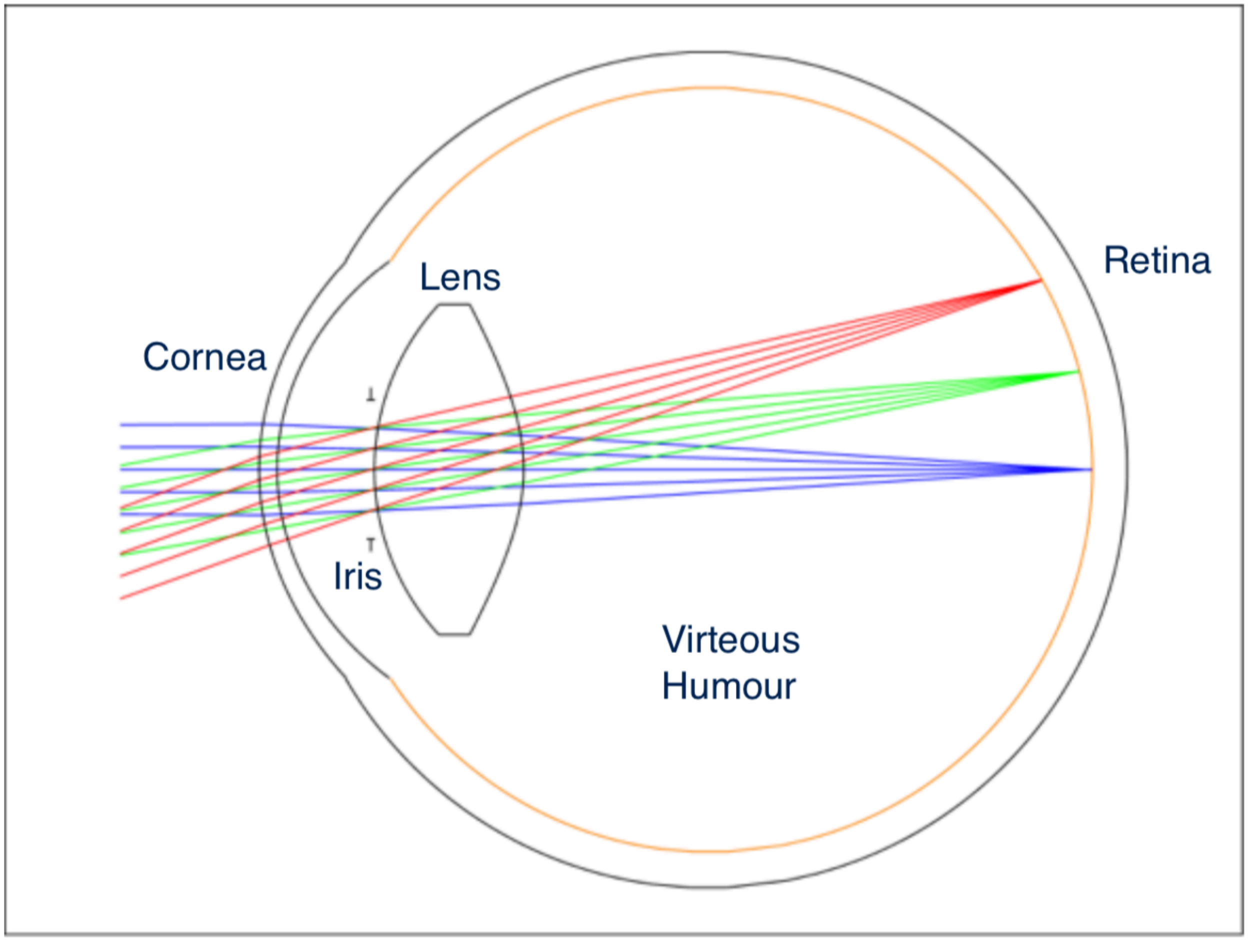
Photon noise

- $< N^2 > = n[1 + n_s(\varepsilon\tau\eta)]$
- Relevant statistics depend on occupation number
- Noise is not necessarily as important as **signal/noise**
- $n_s << 1$
  - hv >> kT
  - Number of photons per mode is very small, can approximate and assume they are independent
  - S/N ~ $\frac{n}{\sqrt{n}} = \sqrt{n}$ (grows with number of photons collected)
  - Also, signal ~ t, noise goes as ~ $\sqrt{t}$, so S/N ~ $\sqrt{t}$
  - Need to integrate and collect more photons to improve S/N levels
- Some example numbers
  - For 500 nm wavelength, a star with T = 5000 K, n_s ~ 0.003

Photon detectors

- Many photon detectors have a fundamental limitation that they need to collect many photons (large n), or integrate over a time period (large t), to improve S/N
- (This is not true for all wavelengths)

First Astronomical Instrument - Human Eye



Zemax Optical Raytrace of Human Eye

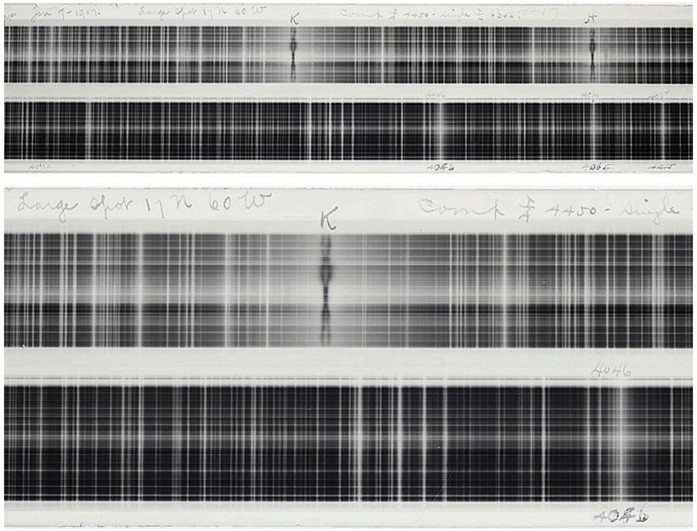
Field-of-view	~100 deg ~10 deg (fovea)
Angular Resolution	~1-2 arcmin
Focal Length	17 mm (relaxed)
f/# Range	f/2-f/8
Dynamic Range	10^{12}
Quantum Efficiency	0.5% (bright) 5% (dark)

1 arcminute = 1/60 degree
$1 CAD seen at 100 meters
1 arcsecond = 1/60 arcminute
$1 CAD seen at 6 km

- From Telescope Fundamentals by Suresh Sivanandam
- Also see http://math.ucr.edu/home/baez/physics/Quantum/see_a_photon.html
- Great dynamic range, but no ability to integrate for longer period of time to improve S/N

Photographic plates

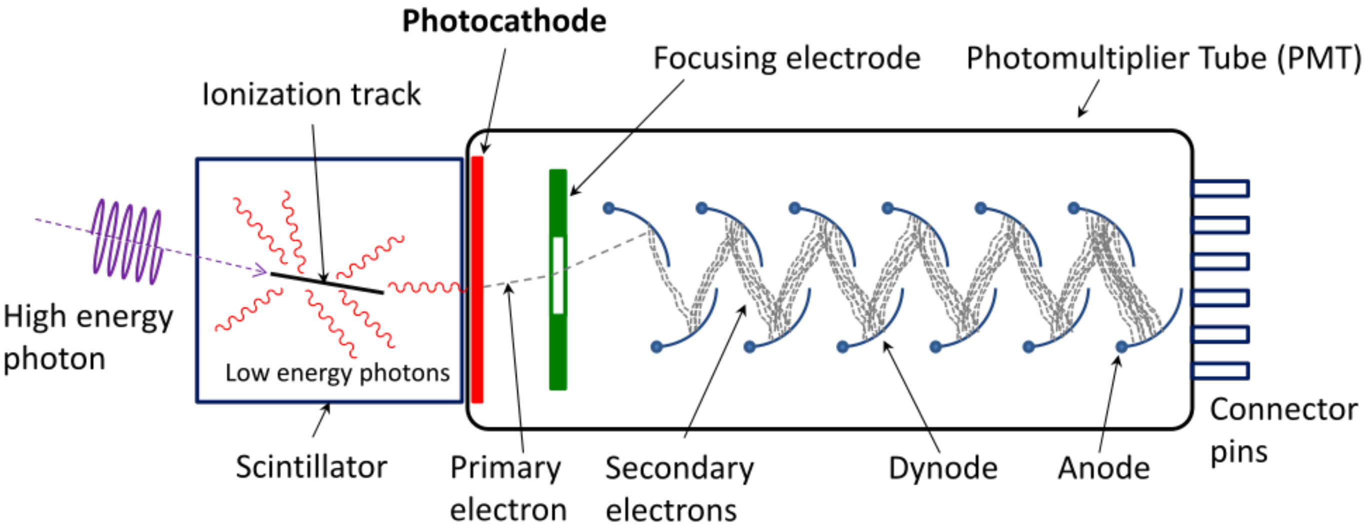
- Could now store images for more in-depth analysis
- Can take long exposures to build up images of faint objects
- Disadvantages
  - Low efficiency
  - Response to photons is nonlinear and complex
  - Cannot repeat image in an identical way
  - Results not reproducible, and cannot integrate for more than ~ 1 night
  - Very hard to calibrate



http://nautil.us/issue/32/space/these-astronomical-glass-plates-made-history

Photomultipliers

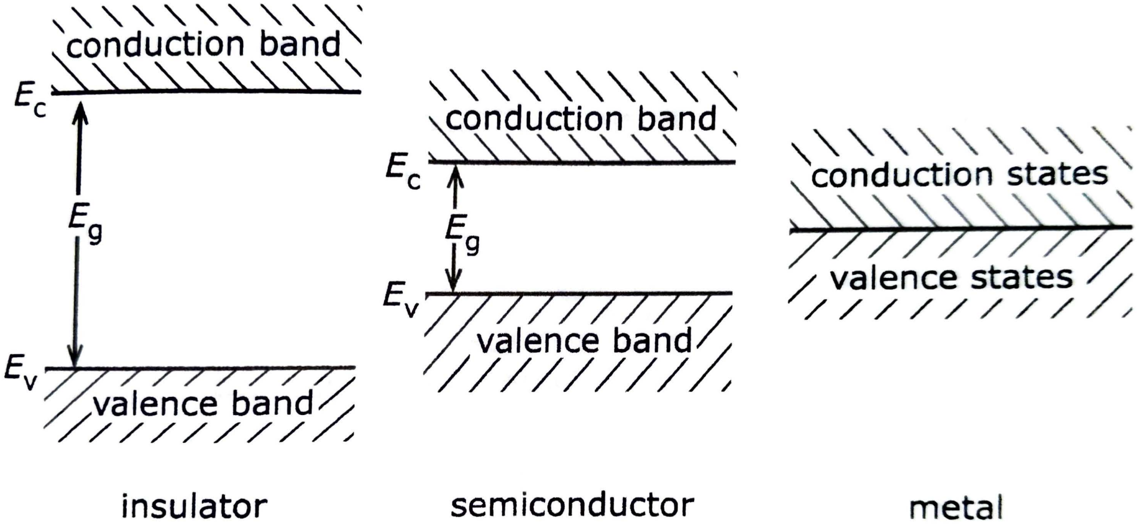
- AKA photomultiplier tubes (PMTs)
- Photon hits surface and ejects electron through the **photoelectric effect**
- One photon can lead to a huge amount of electrons (and signal) output
- Great for high sensitivity applications
- Not great for imaging



Source: Wikipedia

Modern photon detectors

- Modern photon detectors use **semiconductor** technology
- Operate by applying a **bias voltage** and reading out a **photocurrent**
- Band gap can be engineered to certain values (within the range ~ 0.01 eV – 3 eV)



insulator semiconductor metal

Figure 3.1. Bandgap diagrams for insulators, semiconductors, and metals. In these diagrams, energy increases along the y-axis, while the x-axis schematically shows one spatial dimension in the material.

Attributes of Detector System

- Responsivity
- Spectral Response
- Frequency Response (or Bandwidth)
- Efficiency
- Electrical bandwidth
- Read noise (or readout noise)
- Photon noise

Modern photon detectors

- Efficiency
  - Quantum efficiency
  - How many photons do you miss?
- Responsivity
  - Photocurrent per incident power
  - Can it respond to a single photon?
- Spectral Response
  - Depends on semiconductor physics and band gap energies
  - What is the cutoff wavelength?

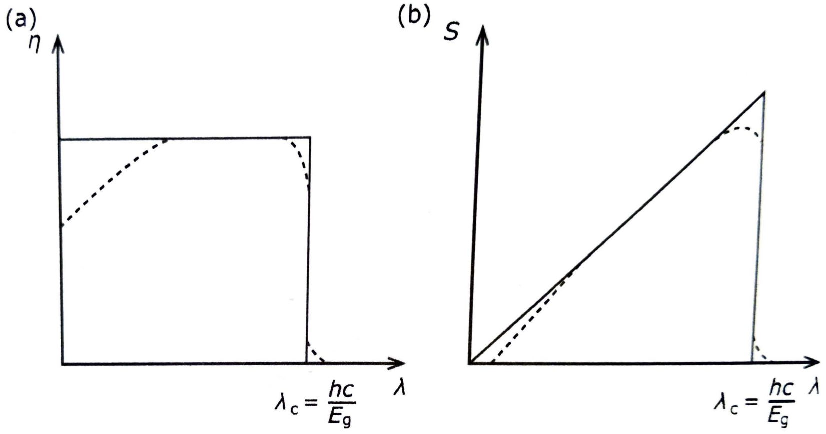


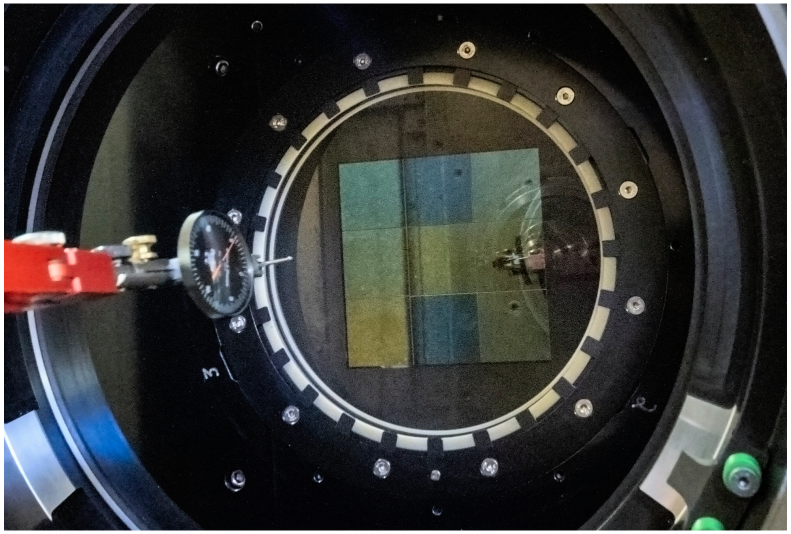
Figure 3.6. (a) Quantum efficiency and (b) responsivity (amps out per watt in) for an idealized photodetector.

Advantages of modern photon detectors

- Very high quantum efficiency
  - Can be very high (>90%) limited only by optical losses in the system
    - Some photons are lost to absorption and reflection, so never make it to the semiconductor material
- Very low noise
  - Can achieve photon-noise limited performance
- Large dynamic range
  - Large range before device “saturates”
- Extremely good linearity
  - Response to incoming optical power is linear
  - Photocurrent = Responsivity * Optical Power
- Can manufacture large arrays of pixels

Detector arrays and resolution

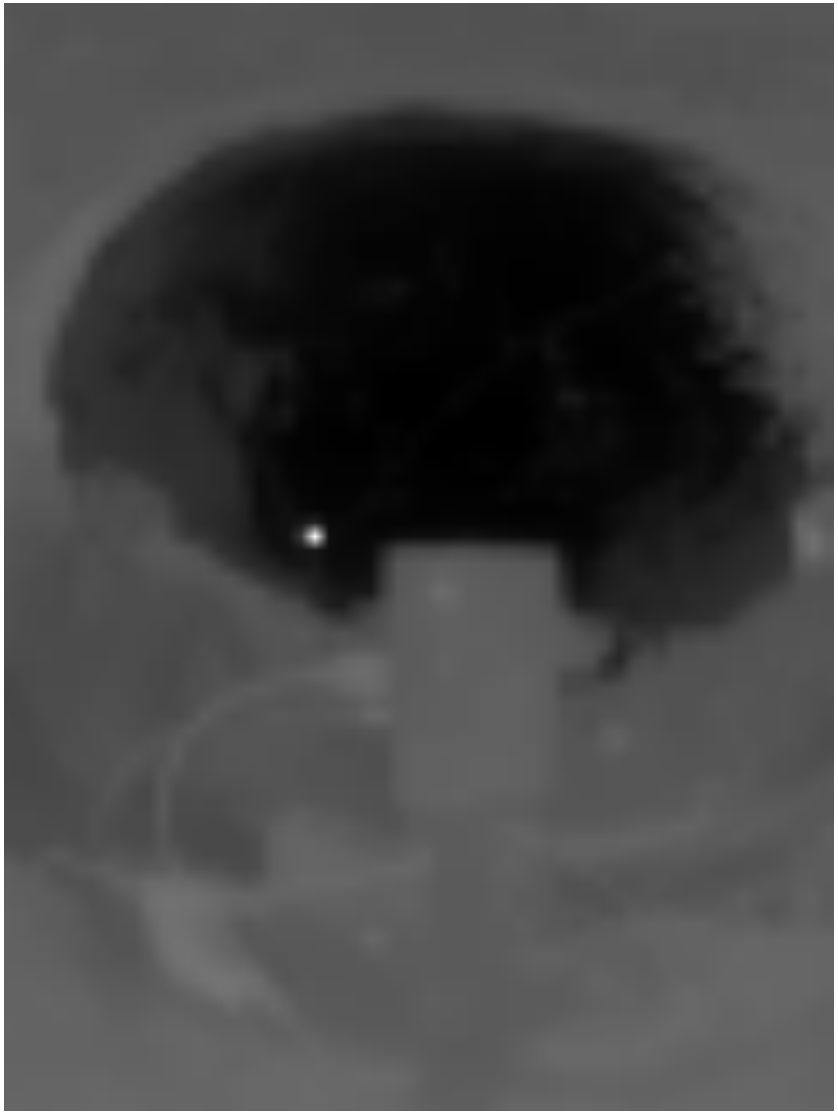
- Simplest application: need arrays of detectors in order to make arrays for **imaging**
- In general, each detector is a **pixel**
- Detector pixel corresponds to pixel in resulting image



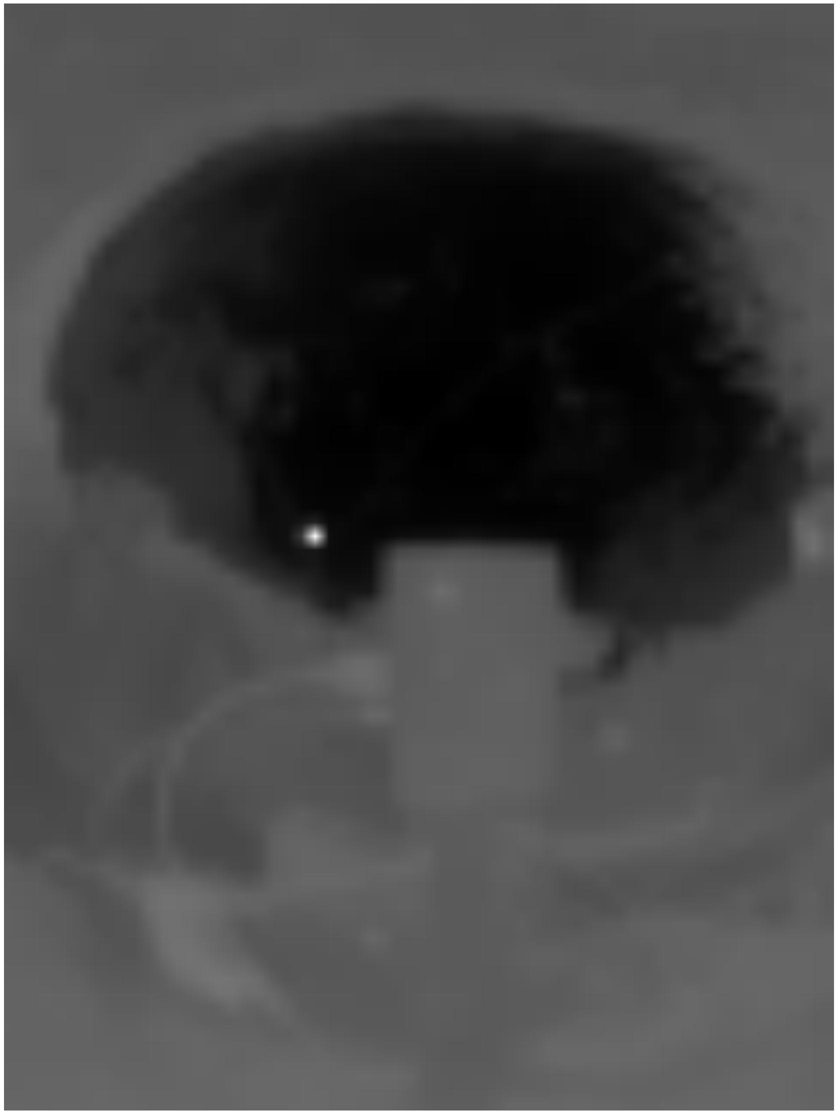
LSST’s ComCAM

Detector arrays and resolution

- Simplest application: need arrays of detectors in order to make arrays for **imaging**
- In general, each detector is a **pixel**
- Detector pixel corresponds to pixel in resulting image
- Challenges:
    - Fill factor
    - Matching resolutions
    - Crosstalk
    - Readout



What is an image?



Johnson/Nyquist Noise

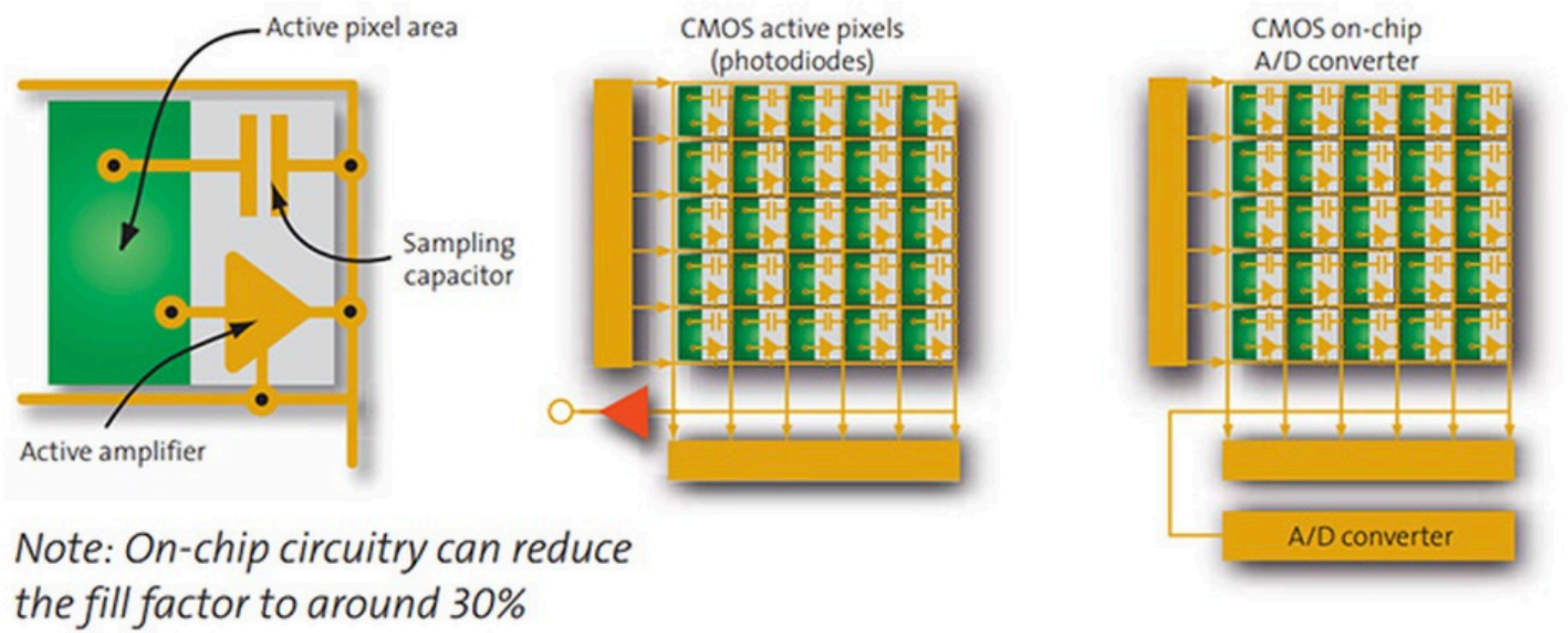
- Need to be able to read out photocurrent from each pixel, in a way that doesn’t introduce excess noise
- Brownian motion of free charge carriers also has a fundamental noise contribution, known as Johnson or Nyquist noise
- $< I_J^2 >= \frac{4kT\, df}{R}$
- Ways to minimize Johnson noise
  - Decrease temperature
  - Decrease df, frequency bandwidth
  - **Increase resistance (easiest, if you can get away with it)**

Important Design Consideration

- In order to keep noise low (low noise = photon noise dominates over readout noise), many designs have to separate out the region where photons are absorbed and the region used to electrically read out signal
- This impacts the **fill factor** of an array of pixels

Reading out detector arrays

- Reading out CMOS array



Note: On-chip circuitry can reduce the fill factor to around 30%

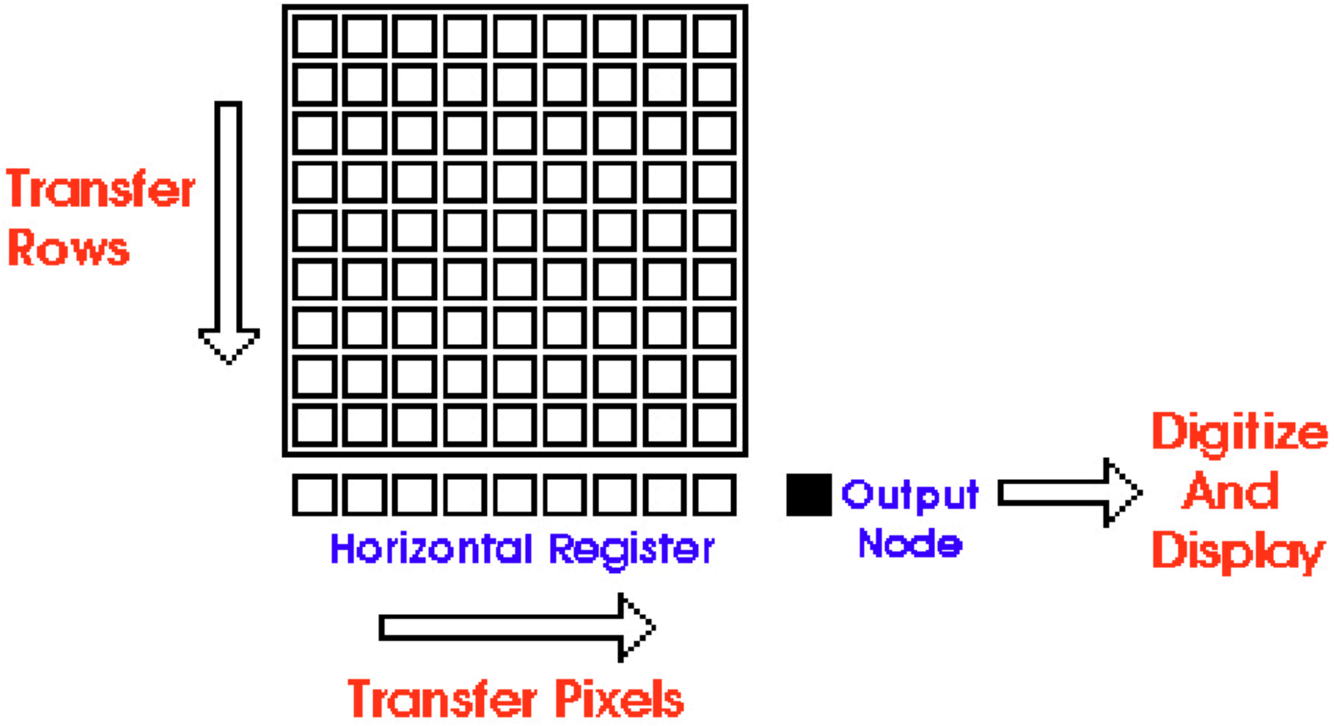
https://www.stemmer-imaging.com/en/knowledge-base/cmos/

Reading out detector arrays

- “Rolling shutter” effect in CMOS arrays

Reading out detector arrays

- Reading out a charge-coupled device array



http://www.phys.ttu.edu/~ozprof/honours2.htm

CCD Imperfections