ASTRONOMICAL DETECTORS

天文　探測器 / 檢驗器

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Astronomical Observations at large deal with . . .

1. Electromagnetic Radiation

2. Gravitational Wave

3. High Energy Particles (neutrino, cosmic rays)

4. Cosmic Dust, Meteorites, Space Samples etc

. . . Today, we focus on PHOTONS, i.e. #1

Role of Telescope

- signal collection (収集)

Role of Detector

- recognition (認識)
- record (記錄)

→ basis of scientific measurements
(position, flux, color, energy, structure etc ..)

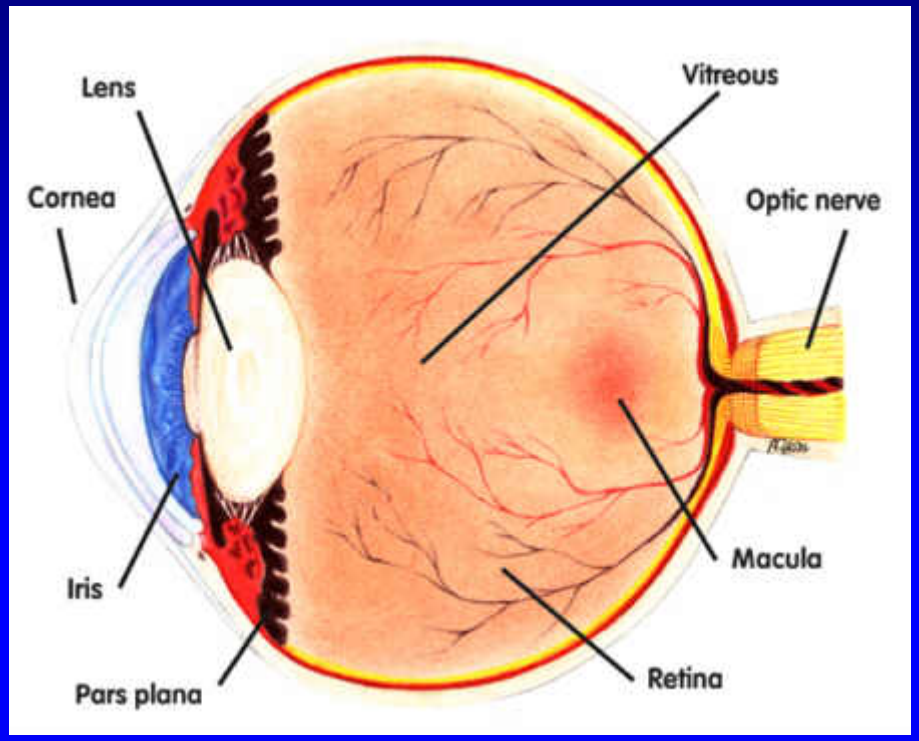
IN MODERN ASTRONOMY,
DETECTOR IS OFTEN MORE IMPORTANT
THAN TELESCOPE

- Detection means that the electromagnetic energy of the radiation is transformed to some other form, usually to electron (or anything that can be measurded and recorded)

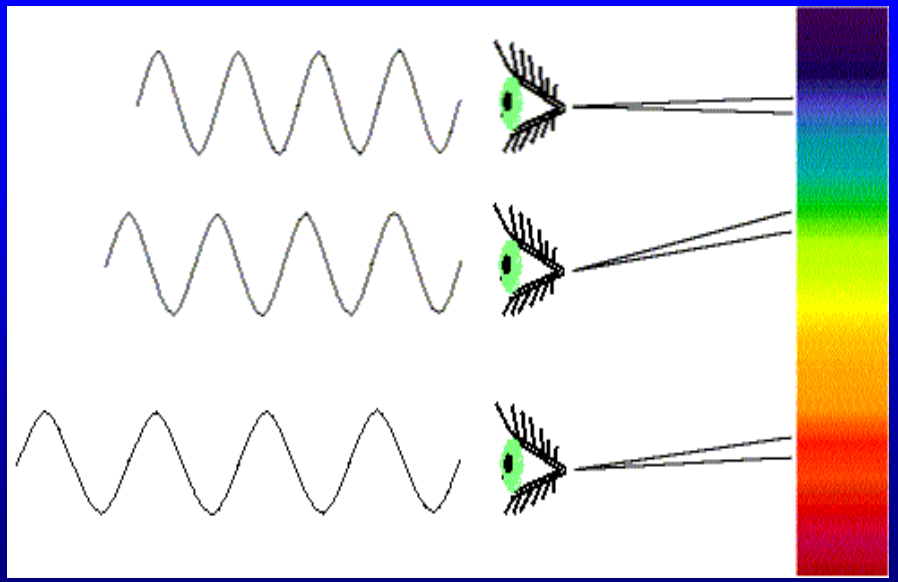
- One example of 'old fashioned/half crippled' Detector
  - Human Eye

HUMAN EYE

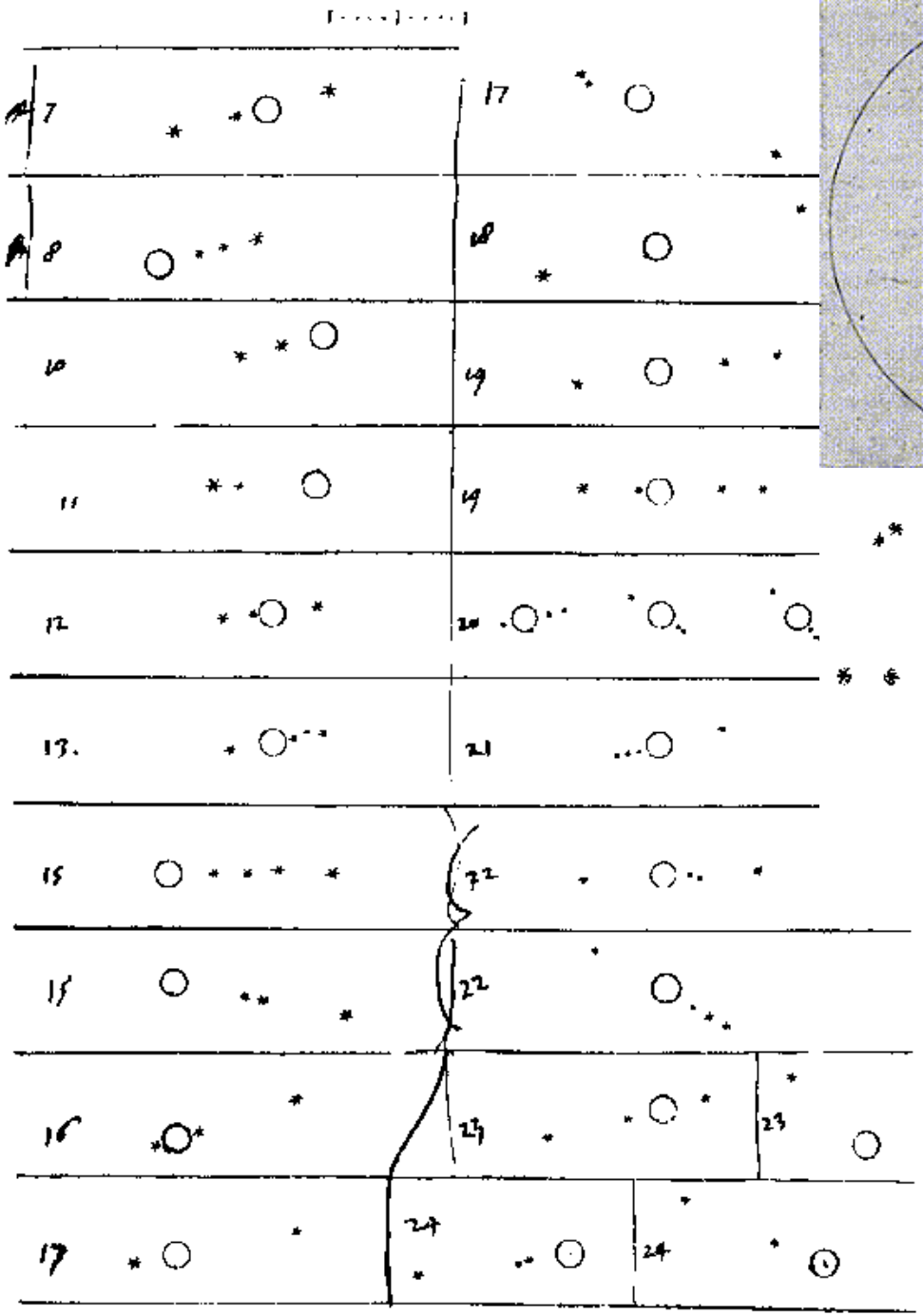
as a detector

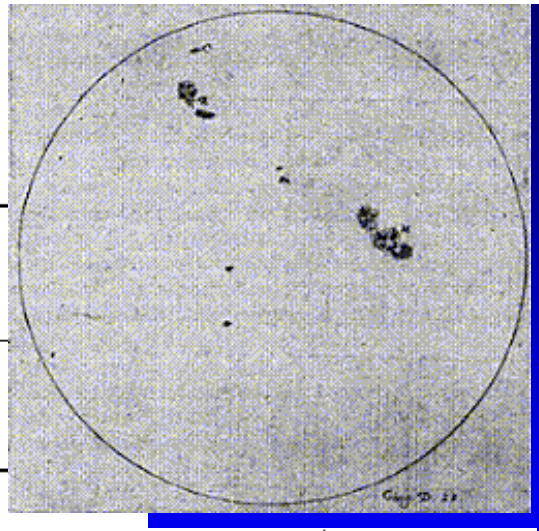


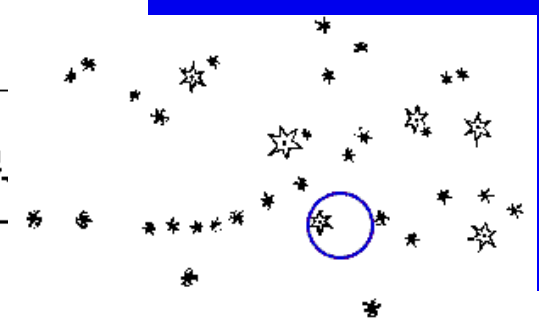
- small aperture (~7mm in diameter in dark)
  - → insensitive to faint sources
  - → low angular resolution (16'' max, even in theory)
- sensitive to narrow region of EMR wavelengths
- only temporal record ... → sketch, drawing, very subjective
- can not integrate
- can selectively use high quality seeing moments
- can detect colors ... but always ?

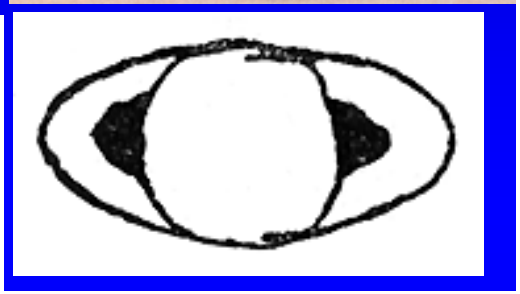


You all have seen stars.
What color are they?



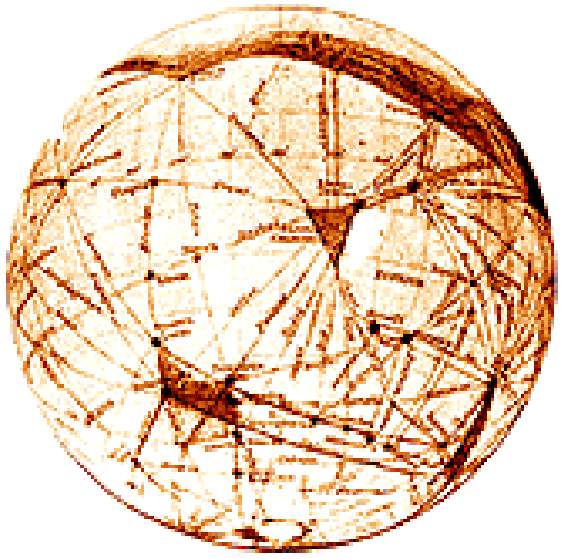






Galileo's observations on the Pleiades

sometimes too much imagination



Lowell's drawing of Mars

In today's lecture, we discuss "Detectors" for following two aspects.

1. **Electromagnetic Radiation and Corresponding Detectors**

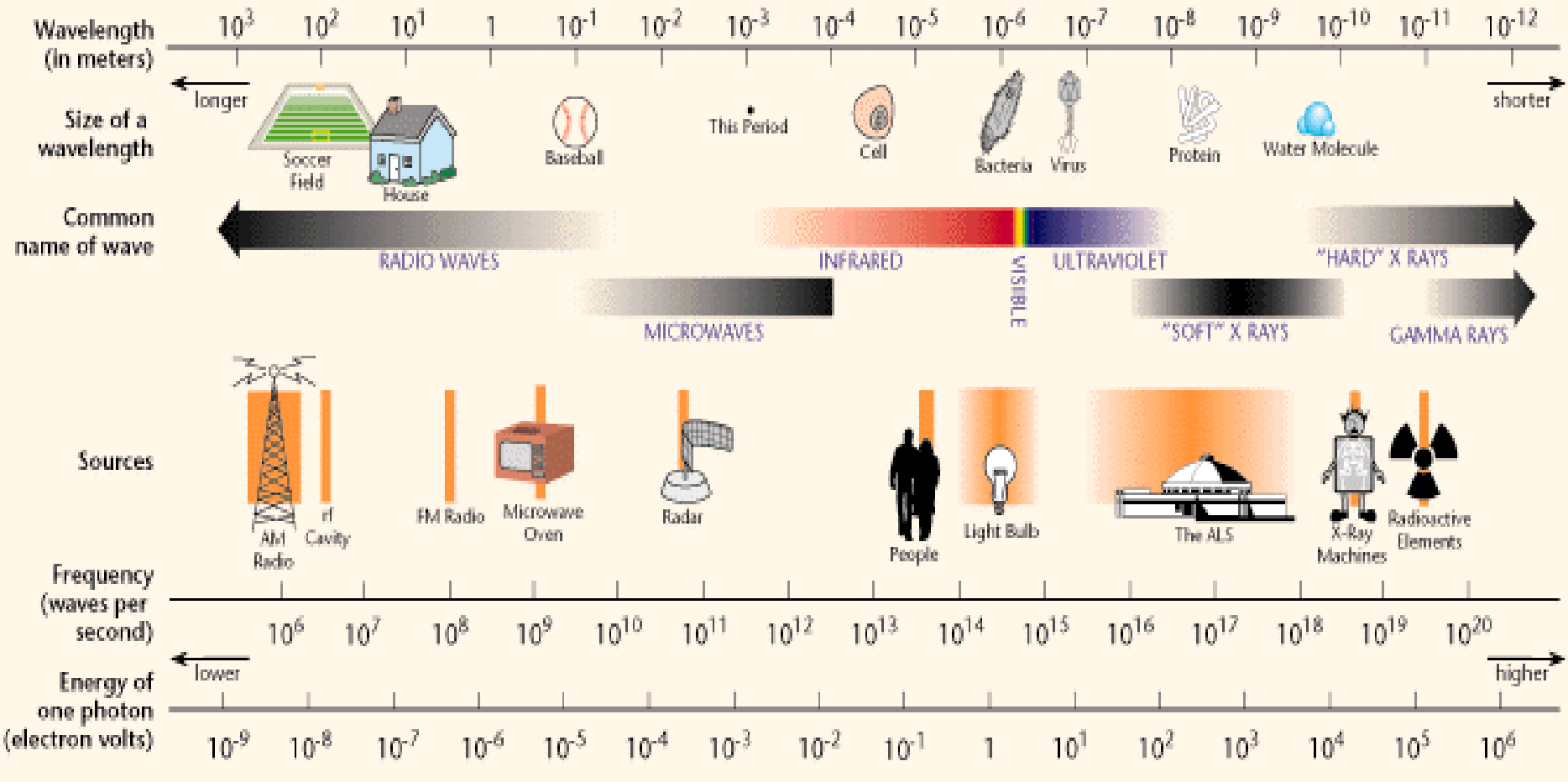
2. **Important Detector Properties**

Detailed introduction of CCD (Charge Coupled Device), most popular detector for visual wavelengths, will be dealt by Prof Chen.

Electromagnetic Spectrum

- The full range of frequencies, from radio waves to gamma rays, that characterizes light
- Primary Language of Stars, Galaxies & ISM
- The electromagnetic spectrum can be expressed in terms of energy, wavelength, or frequency.
- The wavelength equals the speed of light divided by the frequency or lambda = c / nu

THE ELECTROMAGNETIC SPECTRUM

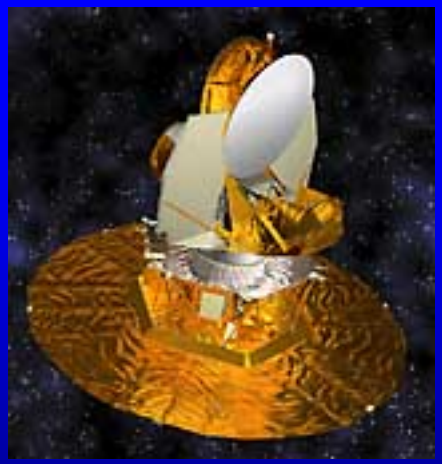


← visible wavelength

Radio
(Low Frequency & Very High Frequency)

- Emitted by
  - Astronomical Objects
    (thermal, non-thermal
    HI gas clouds at 21cm)
  - Radio Station transmitters
- Detected by
  - Ground based radio telescopes
  - Radios

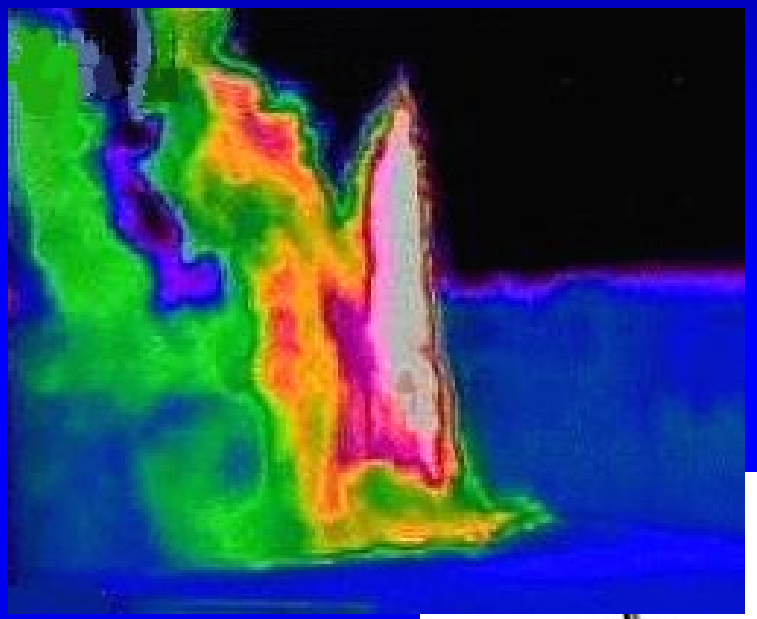
Microwave



- Emitted by:
  - Gas clouds collapsing into stars
  - Microwave Ovens
  - Radar Stations
  - Cell Phones
- Detected by
  - Microwave Telescopes (mm, sub-mm antennas)
  - Food (heated)
  - Cell phones
  - Radar systems

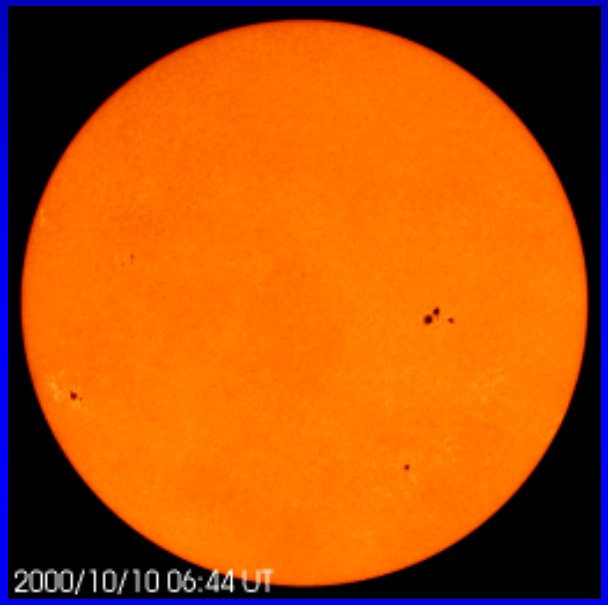
Infrared
(Near and Thermal/Far)

- Emitted by
  - Sun and stars (Near)
  - TV Remote Controls
  - Food Warming Lights (Thermal)
  - Everything at room temp or above
- Detected by
  - Infrared Cameras
  - TVs, VCRs,
  - Your skin
  - NIR (high mountain observatories)
  - FIR (space telescopes)



Visible

- Emitted by
  - The sun and other astronomical objects stars/galaxies/ionized gas
  - Laser pointers
  - Light bulbs
- Detected by
  - Cameras (film or digital)
  - Human eyes
  - Plants
  - (optical) Telescopes
  - CCD detectors

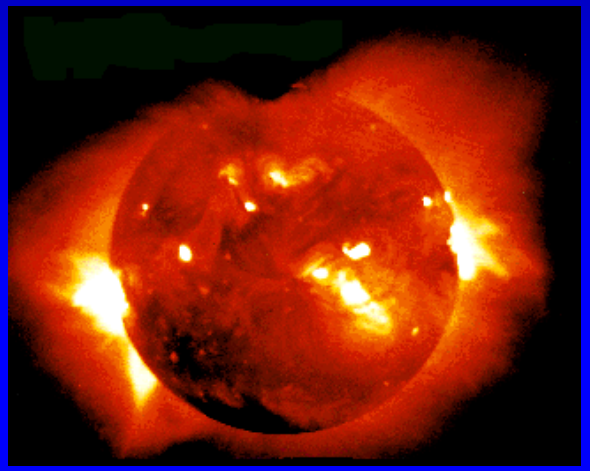


Ultraviolet

- Emitted by
  - Tanning booths
  - The sun
  - Hot stars, hot gas
  - UV lamps
- Detected by
  - Space based UV detectors
  - Micro-channel plates
  - Flying insects (mosquitos)

X-ray

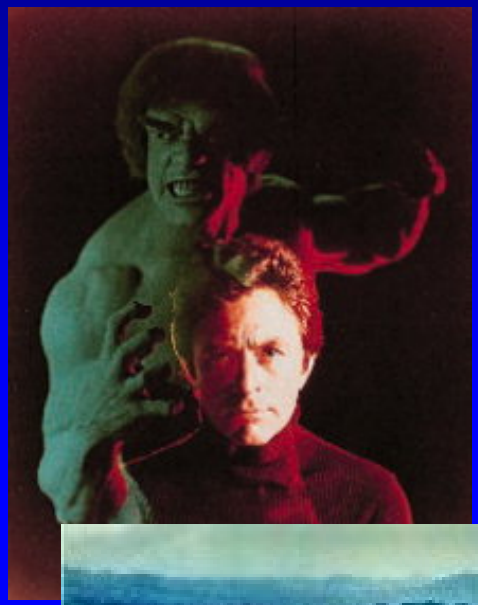
- Emitted by
  - Astronomical HOT plasma
  - X-ray machines
  - CAT scan machines
  - Radioactive minerals
  - Airport luggage scanners



- Detected by
  - Space based X-ray detectors
  - X-ray film

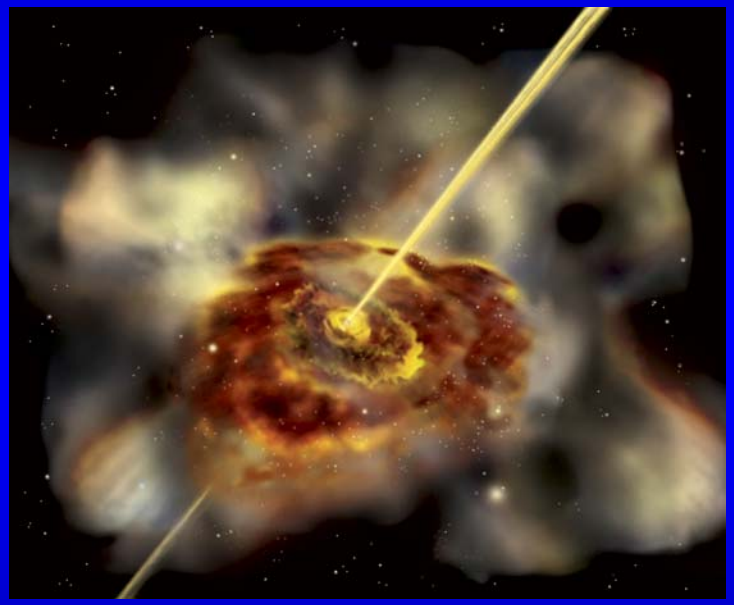
Gamma Ray

- Emitted by
  - Radioactive materials
  - Exploding nuclear weapons
  - Gamma-ray bursts
  - Solar flares
- Detected by
  - Gamma detectors and astronomical satellites
  - Nuclear bomb monitors
  - Medical imaging detectors



X-rays and Gamma Rays

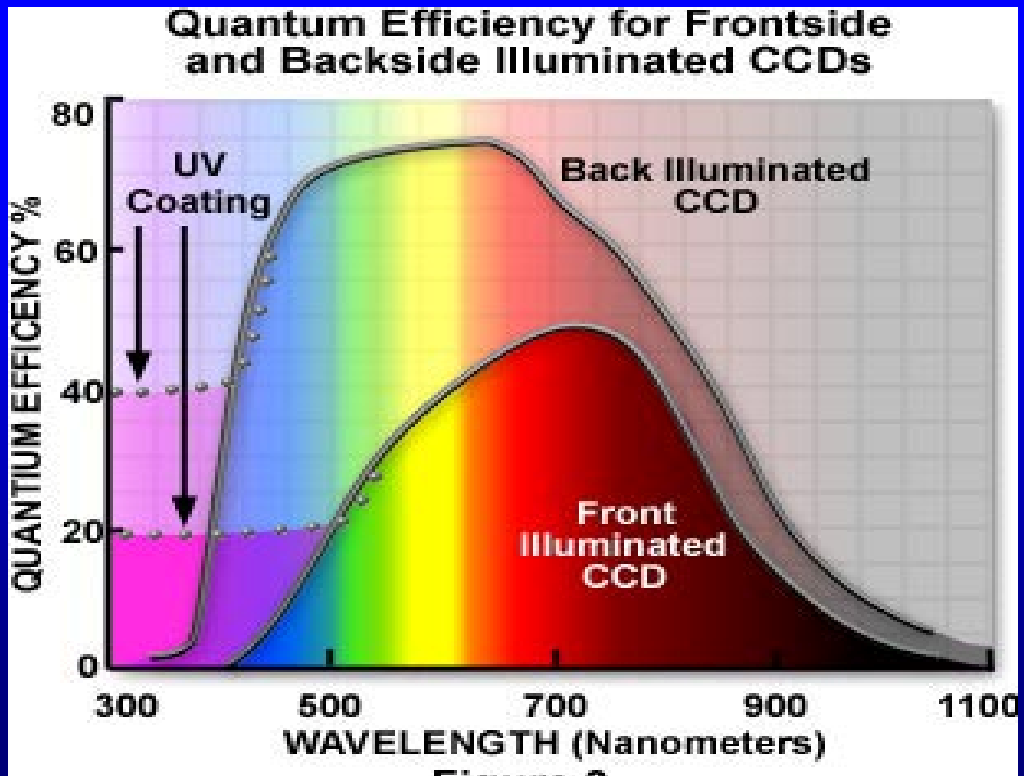
- **Black holes**
- **Active Galaxies**
- **Pulsars**
- **Diffuse emission**
- **Supernovae**
- **Gamma-ray bursts**



IMPORTANT DETECTOR PROPERTIES

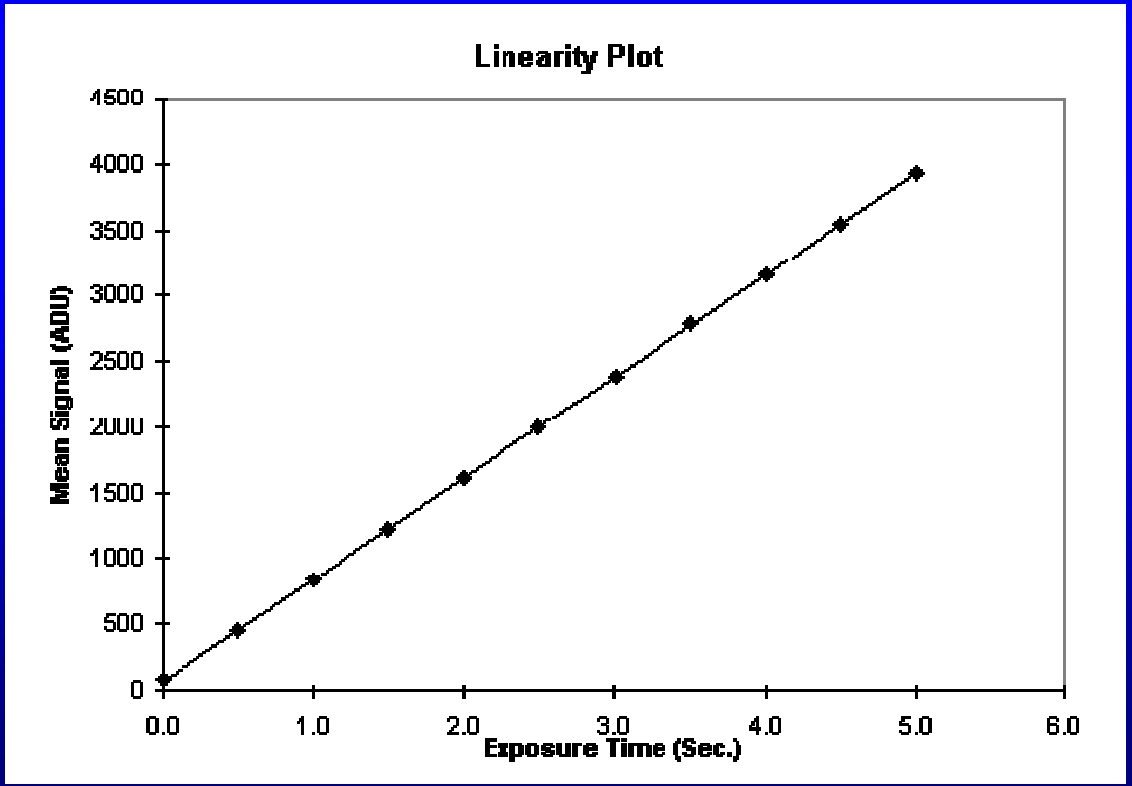
- Sensitivity
- Spectral range
- Dynamic range
- Integration of signal
- Time resolution
- Linearity
- Storage

1. **Quantum Efficiency** (QE): sensitivity
   - QE = No. of photons detected/No. of incident photons
   - Generally a function of wavelength
2. **Spectral Bandwidth**:
   - Wavelength range over which photons can be detected



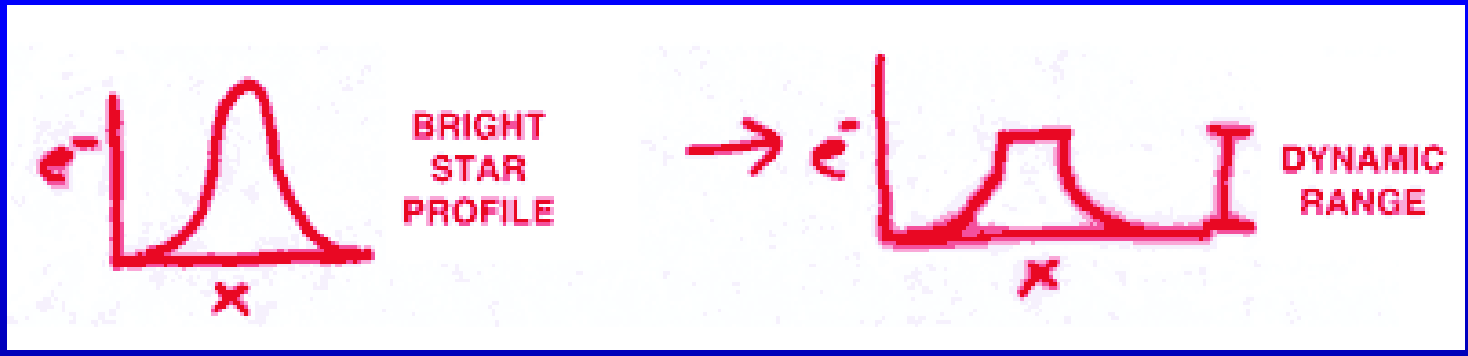
3. Linearity

- Want response to be linearly proportional to incident photons.
- Non-linear detectors: e.g. photographic emulsion
- Linear detectors: e.g. PMT, CCD



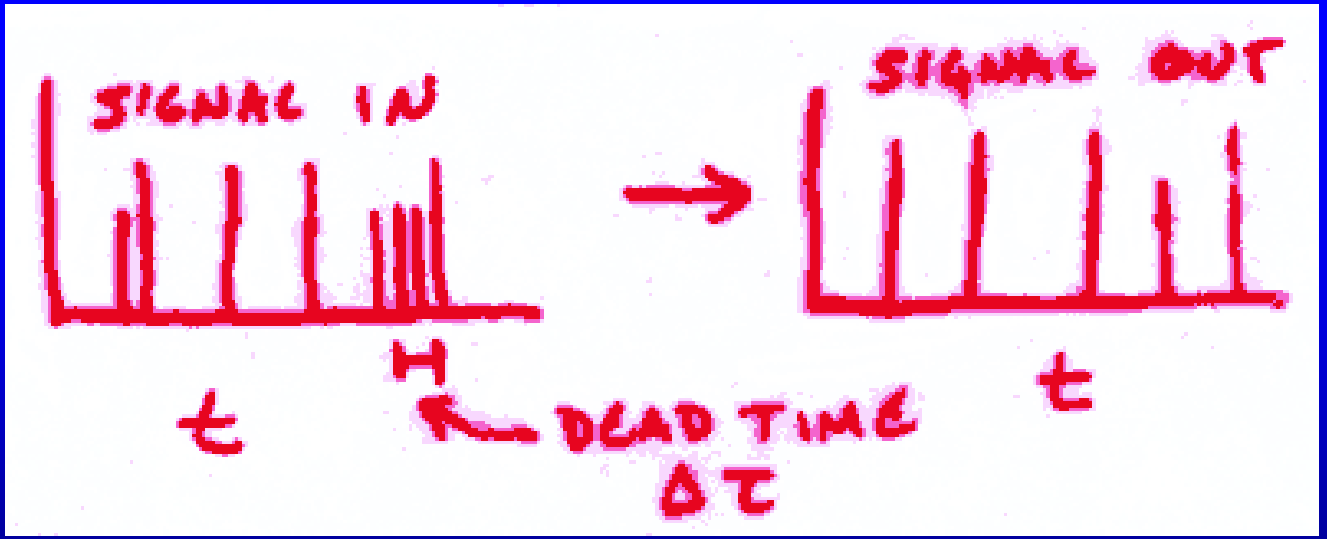
4. Dynamic Range

- Maximum variation in signal over which detector output can represent photons without losing signal.
- We want the ratio of the largest measurable value to the smallest value to be as large as possible



5. Time Response

- Minimum time interval over which changes in photon rate are detectable (CCD readout time)
- Time Resolution *(ex. flares, occultations)*



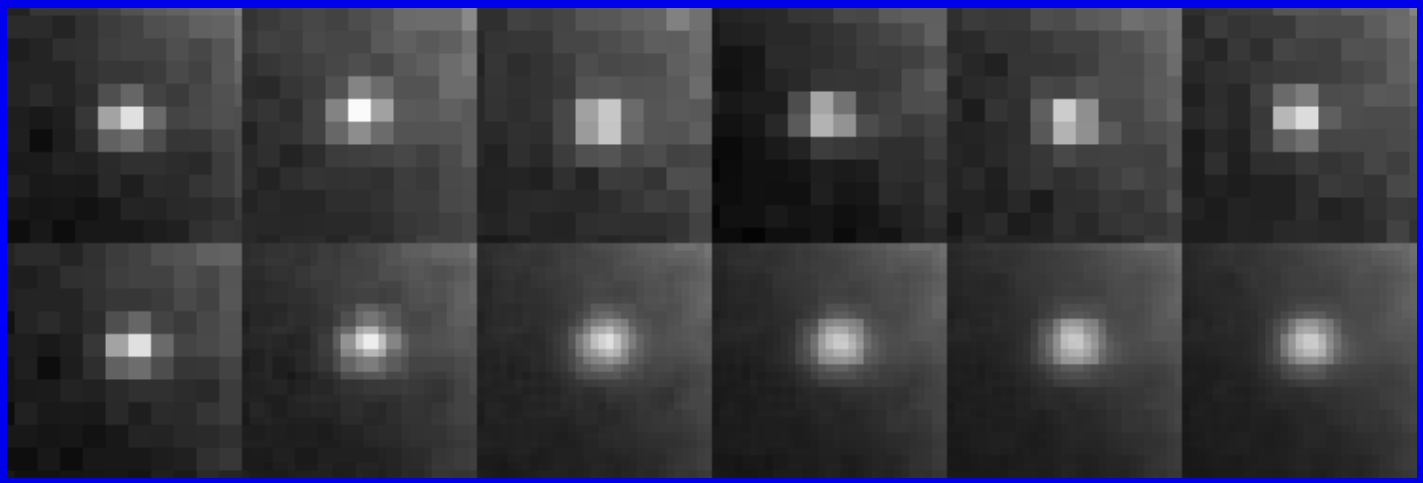
6. Noise

- Ideally, the output signal should have a definite relation with the input photons.
- However, there is *always* uncertainty in the signal that will actually be detected.
- Sources of noise: photon statistics, sky noise, thermal noise, readout noise, etc.

- Very important for all observations. To understand what you measure, you need to understand the noise involved.

7. Spatial Resolution:

- Determine the extent of detail that can be resolved
- Functions of plate scale, pixel size, telescope + instrument optics & site seeing condition
- Should be aimed to provide properly (but not over) sampled data ... depending on the science goal



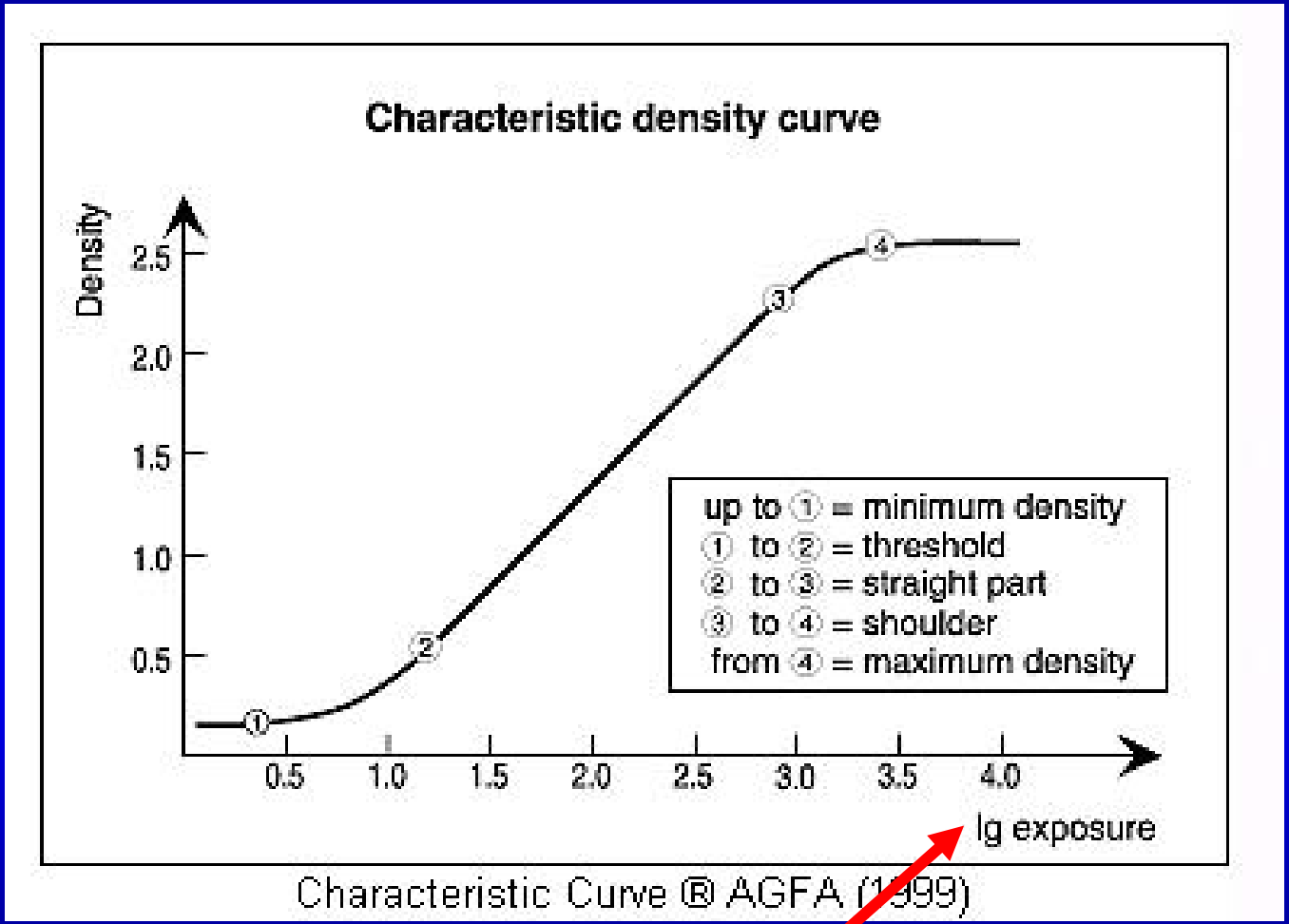
8. Ability to Integrate:

- The ability to collect photons for an extended period of time is one of the most important advantage of any detectors over human eye.

Major Detectors

- Photographic Emulsions
  - large format possible (much larger than even modern CCDs)
  - very low efficiency (~1%)
  - analog in nature, therefore difficult for quantitative measurements
  - nonlinear, and difficult to calibrate
  - fading away entirely from astronomical application
- Photomultiplier Tube (PMT)
- Charge Coupled Device (CCD)

Nonlinearity of Photographic Plate



Note: Exposure in logarithm scale, NOT linear scale

Photoelectric Effect

- Most detectors in astronomy work on the principle of the Photoelectric Effect or related phenomena. (PMT & CCD)
- Photons of sufficient energy hitting the surface of a solid releases electrons (photoelectrons)
- Energy of released electrons depends NOT on intensity of light (if we think of light as a wave), but rather on the frequency of light (particle nature of light).
- There is a minimum frequency of light before any photo-electrons can be emitted from a particular metal:

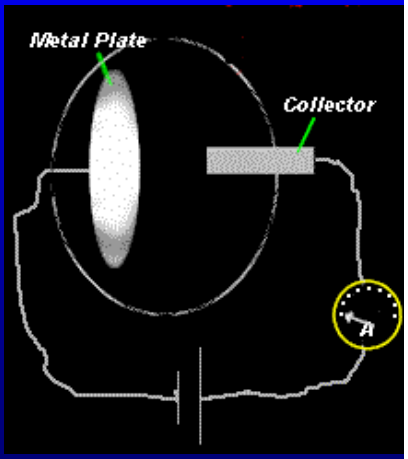
$$KE_e = E_{photon} - W = hf - W = h(f - f_{min})$$

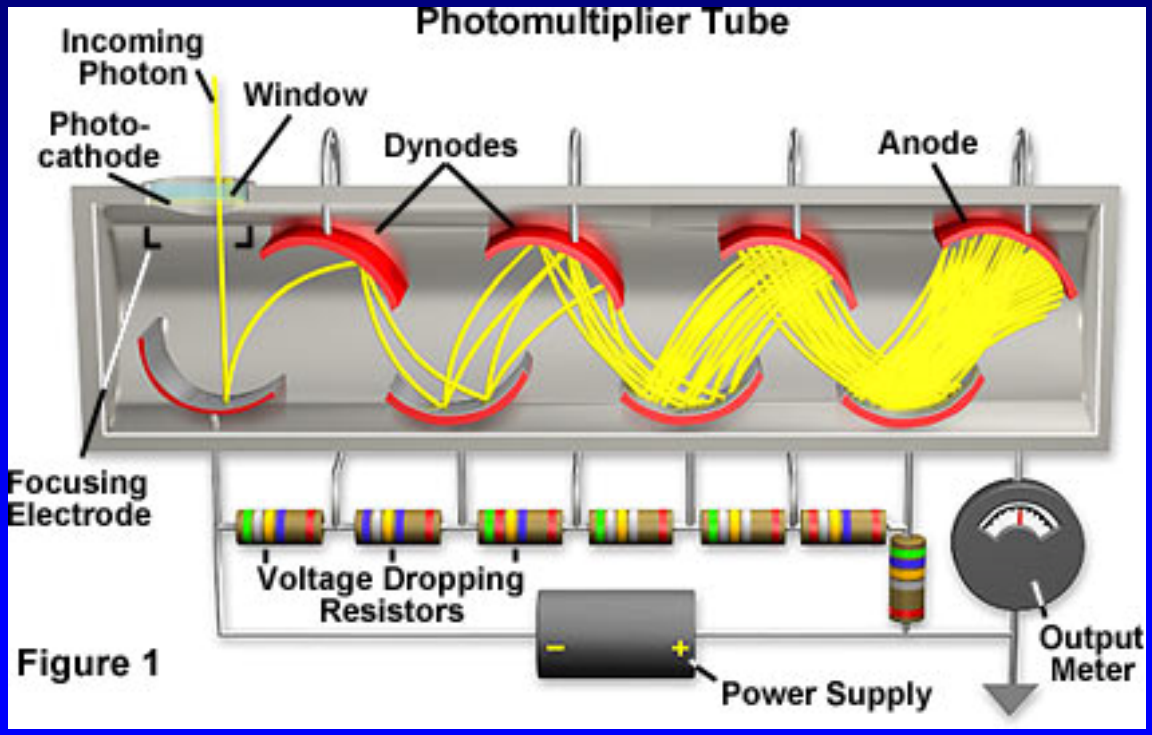
where KE_e is the KE of photoelectron, is photon energy, W is the work function of the metal, h is Planck's constant, f is the photon frequency, f_{min} is the minimum photon frequency of the metal

Photomultiplier Tube (PMT)

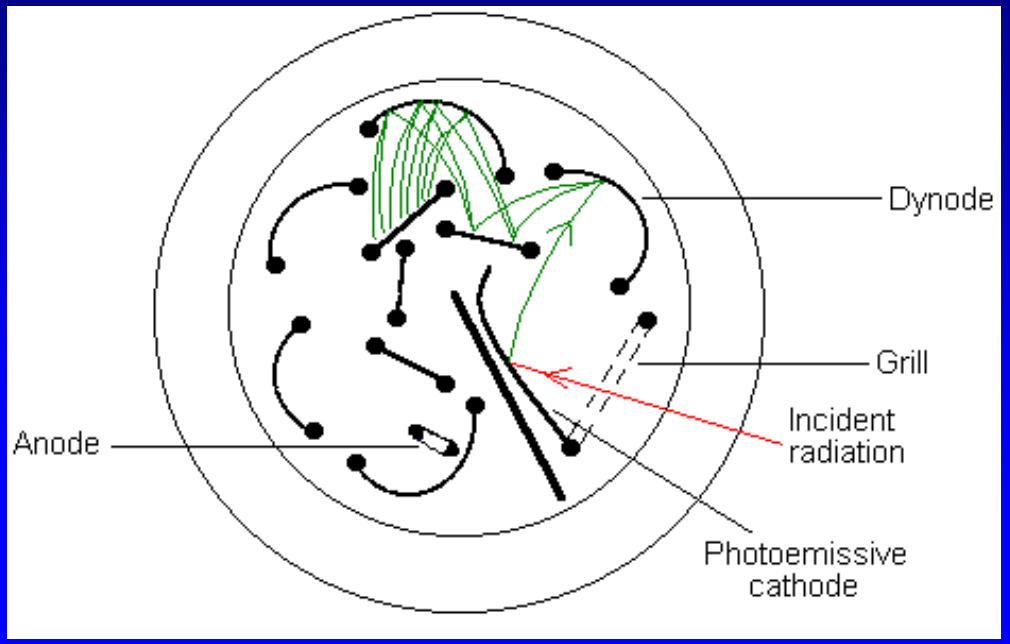
- The photocathode can emit photoelectrons in response to incident photons. If placed in vacuum with a high positive voltage electrode (anode) to collect emitted electrons, we can measure photon arrival rate by measuring current.

- Advantages: low noise, linear over wide range of signal, photon counting
- Disadvantages: Limited life time, non-imaging.
- QE: Lower than CCD.





- Electrons are accelerated and amplified by successive dynodes.
- Individual photons detected and measured (photon counter)



- Usually operated in low temperature to minimize dark current (i.e. thermal noise)
- QE: ~ 10 - 30%

Charge-Coupled Device (CCD)

- CCDs are silicon-based integrated circuits consisting of a matrix of photodiodes which convert light energy in the form of photons into an electronic charge
- Invented in 1960's, revolutionized modern astronomy in 1970's.

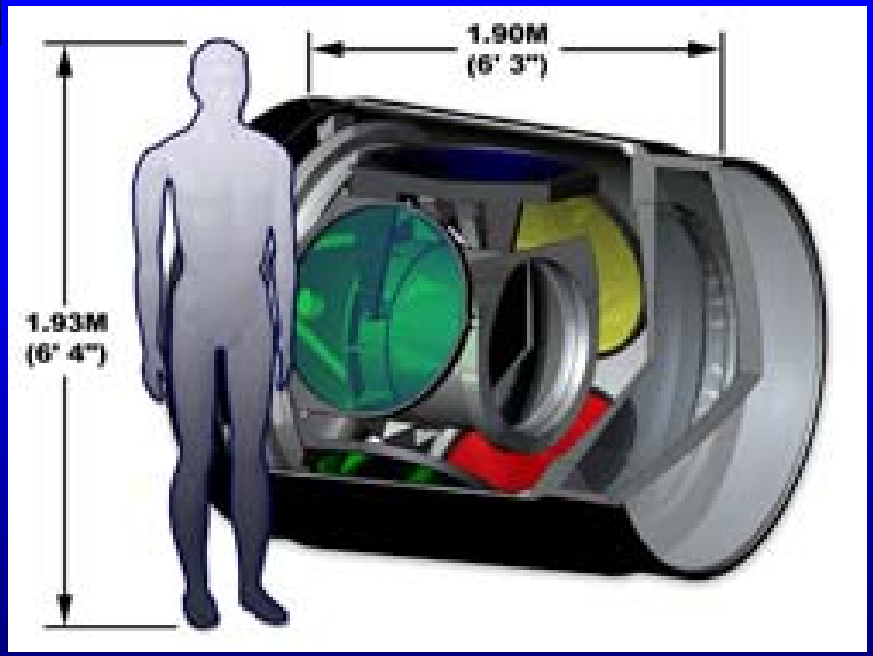
- Advantages: high sensitivity, low noise, linearity, decent dynamic range (10^4 to 1), broad spectral response, spontaneity, ease of computerized data storage and analysis

- Disadvantages: Relatively small field-of-view (rapidly improving situation with large format CCD being developed, the state-of-the-art now is 4096^2)

Megacam (CFHT)

40 CCDs of 2Kx4K format

320M pixels



LSST cam

Year 2012

3G pixels, ie. 3000 Mpix