Week 5 Tuesday

Today's Agenda

- Equilibrium / blackbody spectrum
- Telescopes
- Making measurements
- Observing "invisible" light

Announcements / Reminders

- Read Chapter 6.1, 6.4-7, 7.1, 8.1-2, 11.1-2
- HW 4 due September 24th at 11:59pm via Canvas upload

- HEAP talk at 4pm over Zoom (only)
  - Gravitational Wave detection with asteroids
- Colloquium at 2pm in JFB auditorium & Zoom
  - Deep Underground Neutrino Experiment (DUNE)

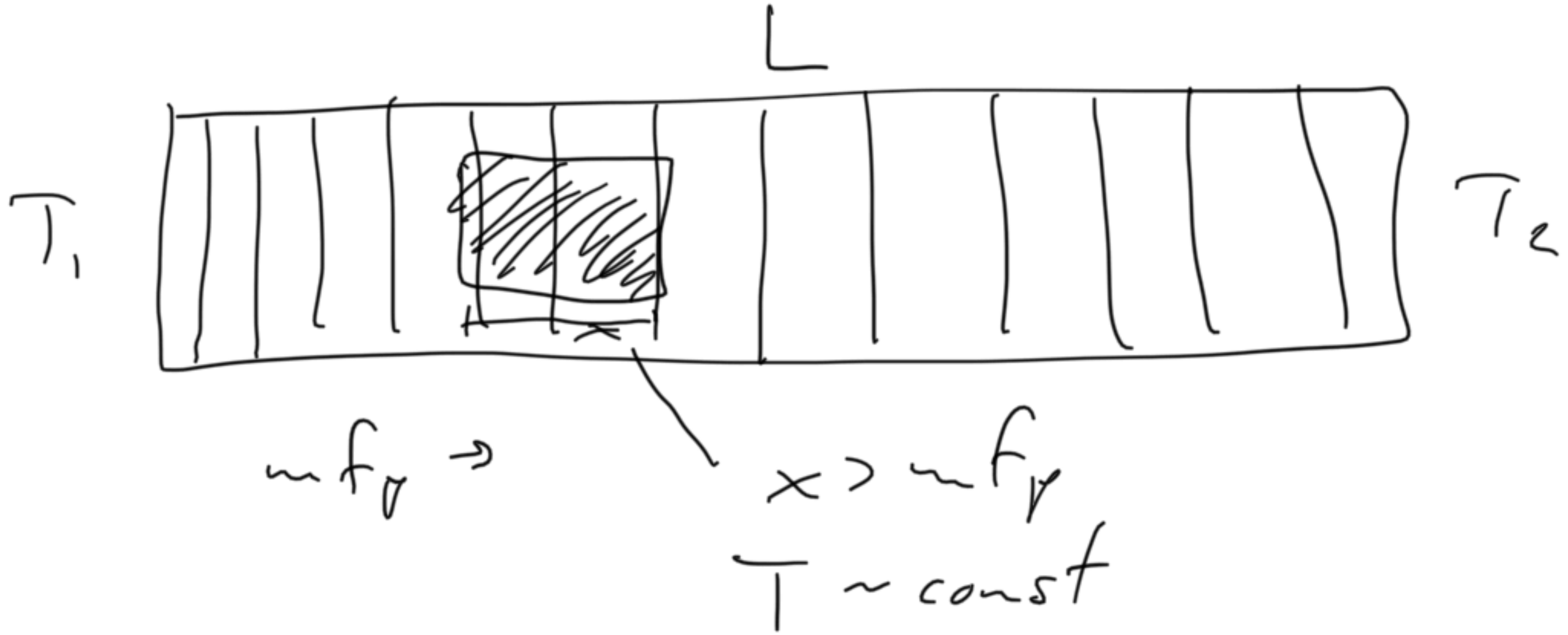
Local Thermodynamic Equilibrium (LTE)

$x \gg \lambda_{\mathrm{mfp}}$

$\Delta T \ll T$

Follows avg. statistics
Max.-Bolt. dist.

No time
dependence



LTE —> Blackbody/Planck function

1. Photons & massive particles have a high number density
2. System is optically thick

$$I_\nu d\nu(\nu \rightarrow \nu + d\nu) =$$
$$I_\lambda d\lambda(\lambda \rightarrow \lambda + d\lambda)$$

$$\nu = \frac{c}{\lambda} \;\; \longrightarrow \;\; d\nu = -\frac{c}{\lambda^2} d\lambda$$

$$I_\nu(T) d\nu = \frac{2h\nu^3}{c^2} \frac{d\nu}{e^{h\nu/kT} - 1}$$

$$I_\lambda(T) d\lambda = \frac{2hc^2}{\lambda^5} \frac{d\lambda}{e^{hc/\lambda kT} - 1}$$

Integrate BB over all freq. & angles

<u>Flux</u>
(energy per area per time)

$$F = \frac{2\pi^5}{15}\frac{k^4}{c^2h^3}T^4 = \sigma_{\rm SB}T^4$$

↑ Stephan-Boltzmann constant

$$\sigma_{\rm SB} = 5.67 \times 10^{-8}\ {\rm J\ s^{-1}\ m^{-2}\ K^{-4}}$$

What is the total energy emitted?

Assume star is spherical

$$L = F \cdot A_* = F \cdot 4\pi R_*^2$$

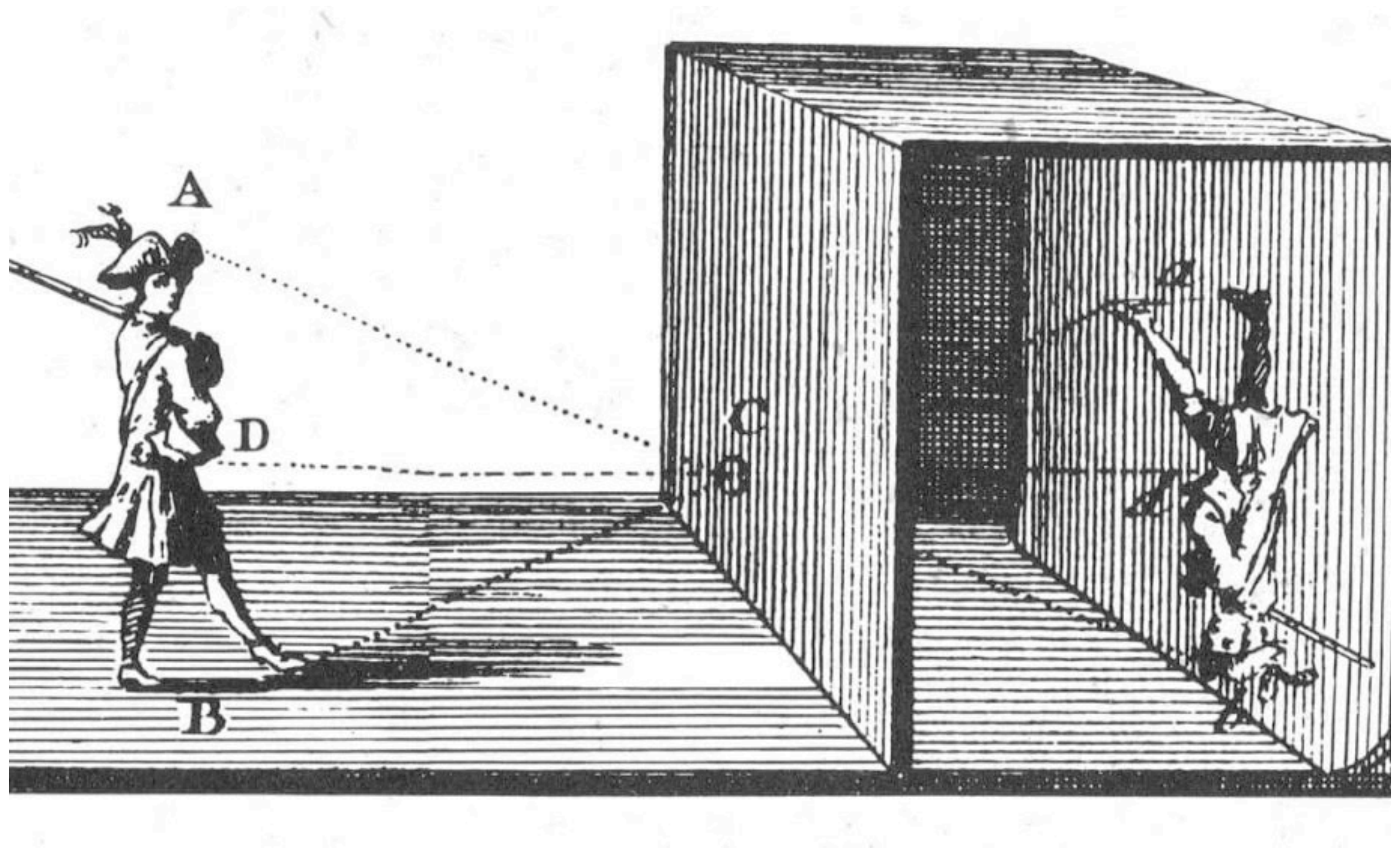
$$\boxed{L = 4\pi R_*^2 \sigma_{\rm SB} T^4}$$

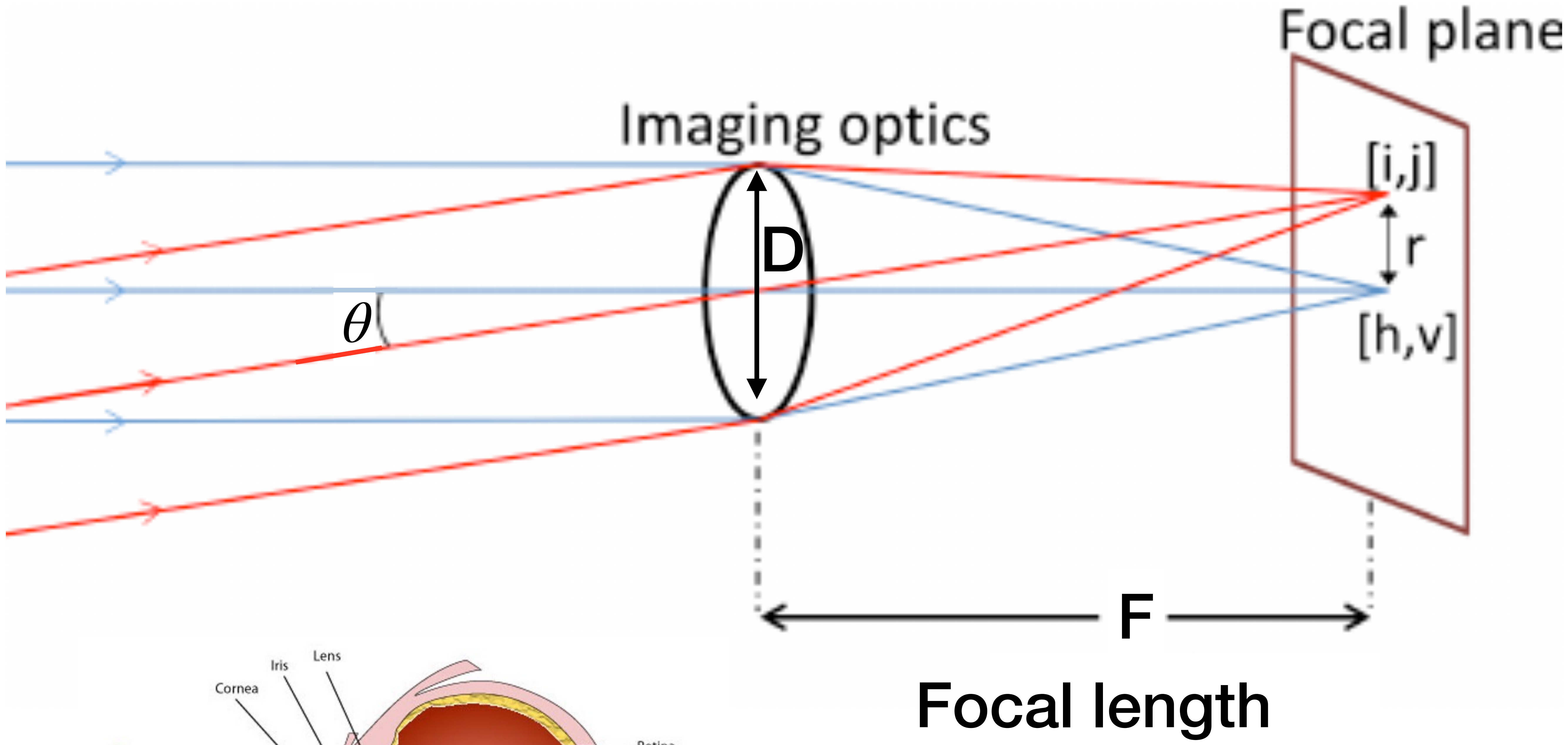
Compare to the Sun:

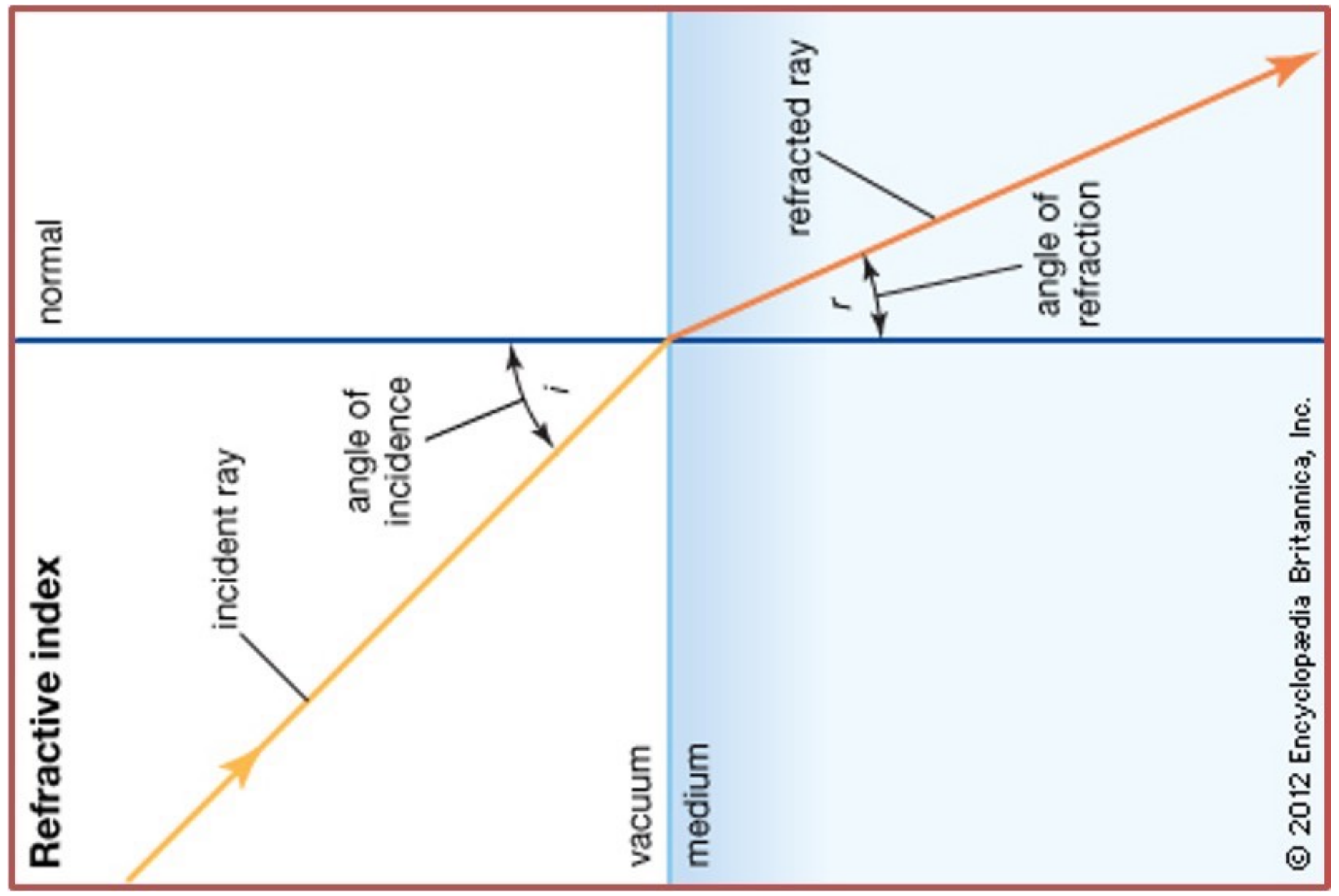
$$\left.\begin{aligned} R_\odot &= 6.96 \times 10^8 \text{ m} \\ T_\odot &= 5780 \text{ K} \\ L_\odot &= 3.8 \times 10^{26} \text{ W} \end{aligned}\right\} \quad L = 1\ L_\odot \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4$$

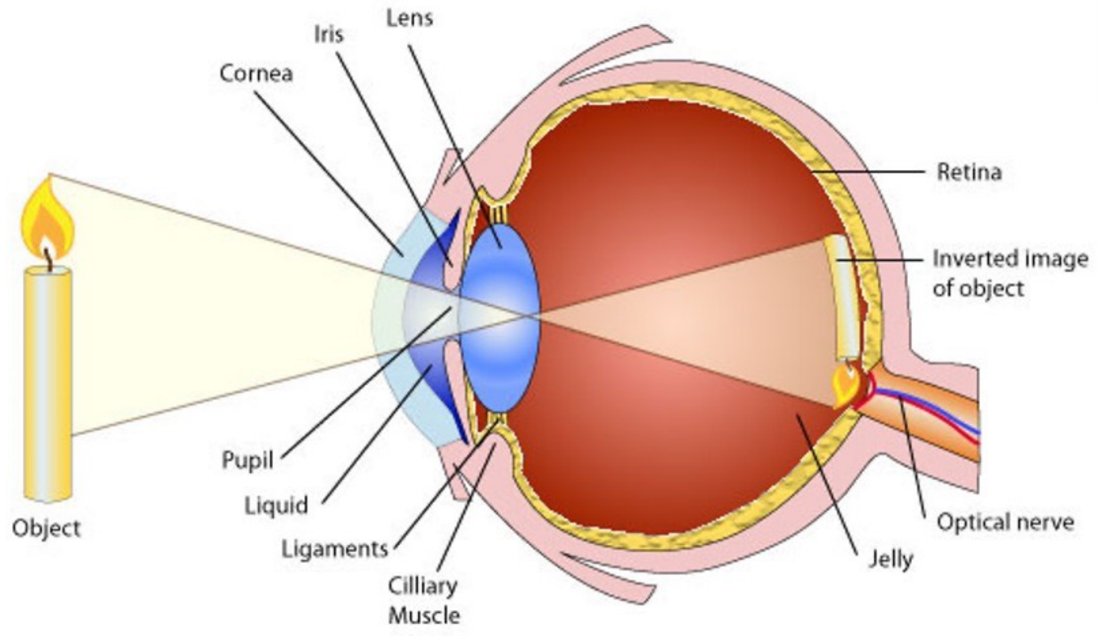
Collecting Light

Telescopes collect (often by focusing) light







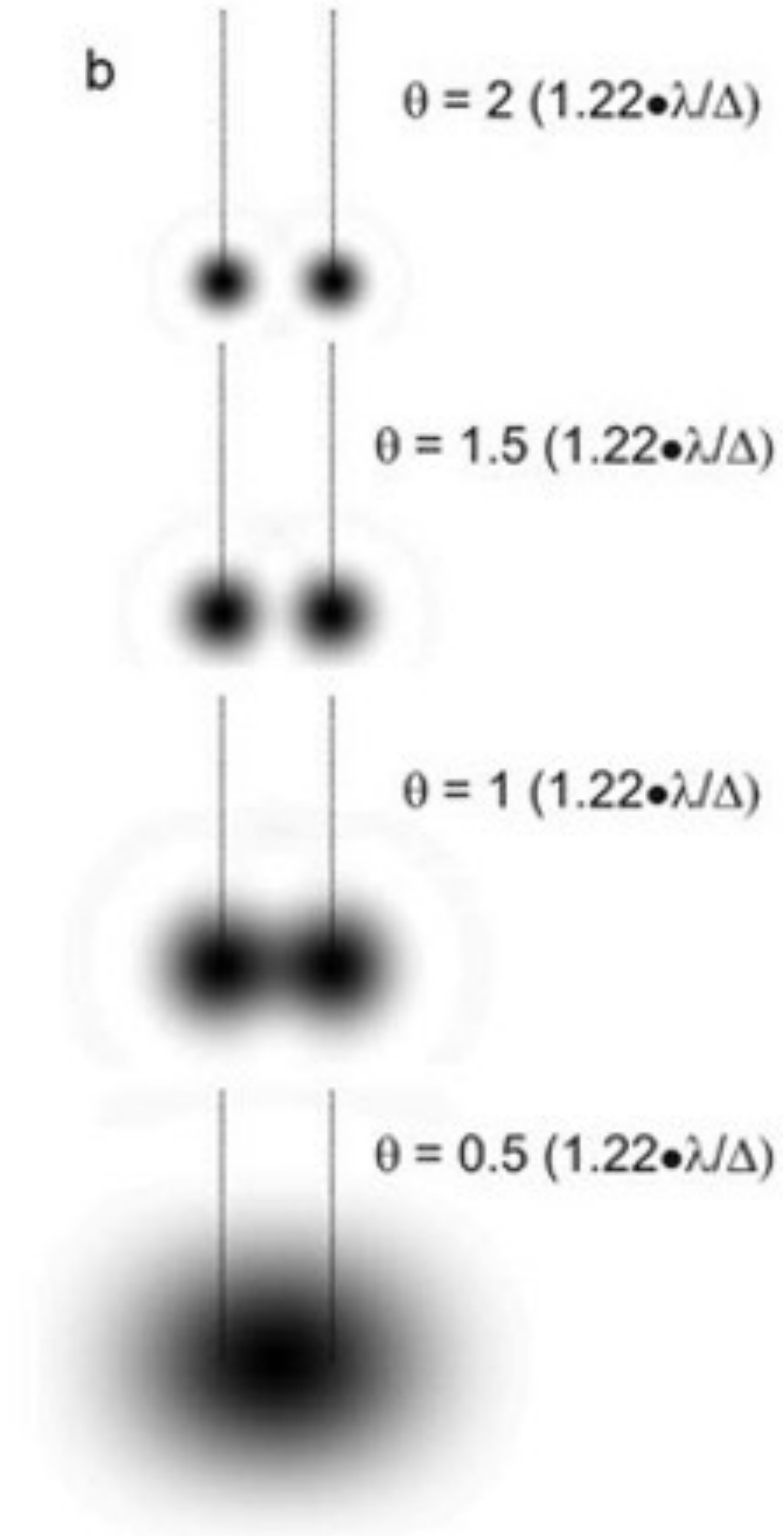


Our eyes are telescopes!

Plate scale = $\frac{\theta}{r}$ (arcsec/mm)

$$\theta_{\min} = 1.22\frac{\lambda}{D}$$

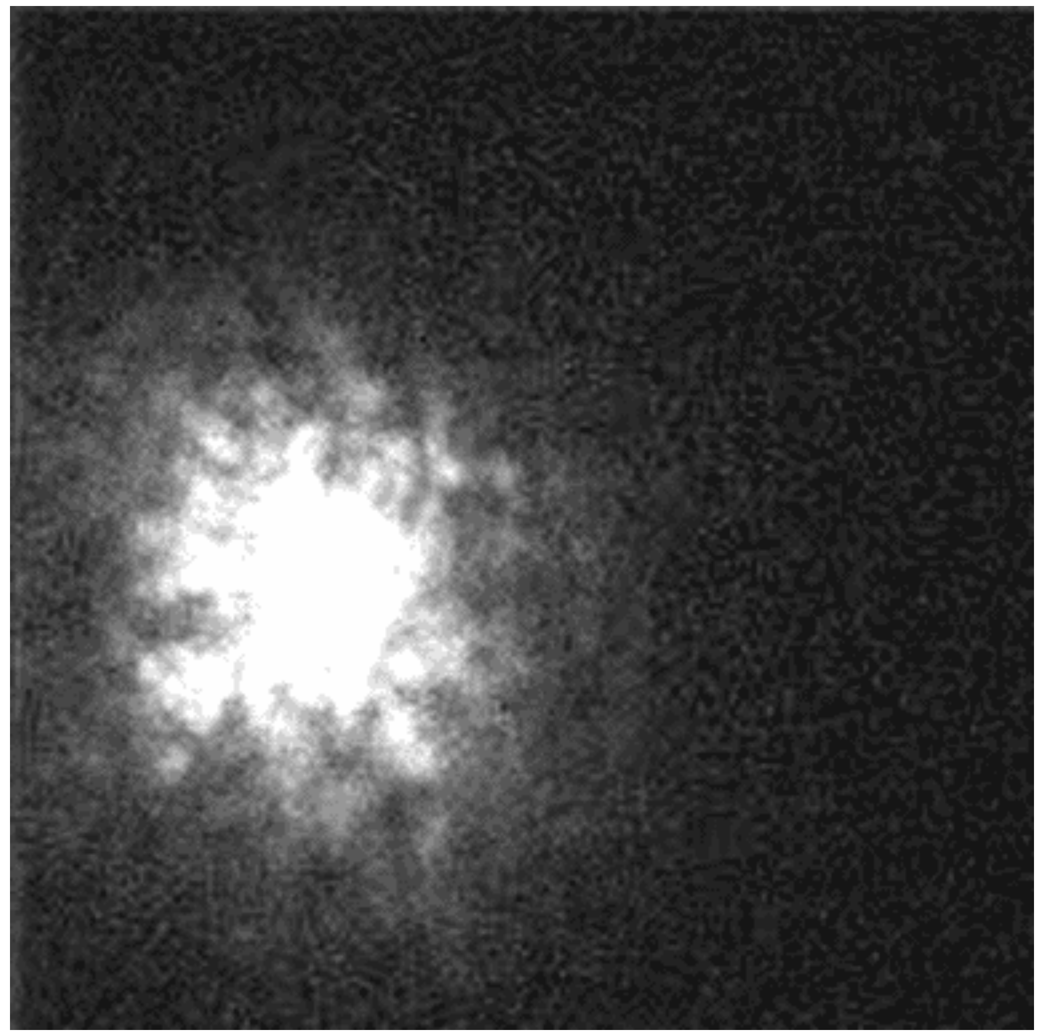
Image Resolution



$$\theta_{\min} = 1.22\frac{\lambda}{D}$$

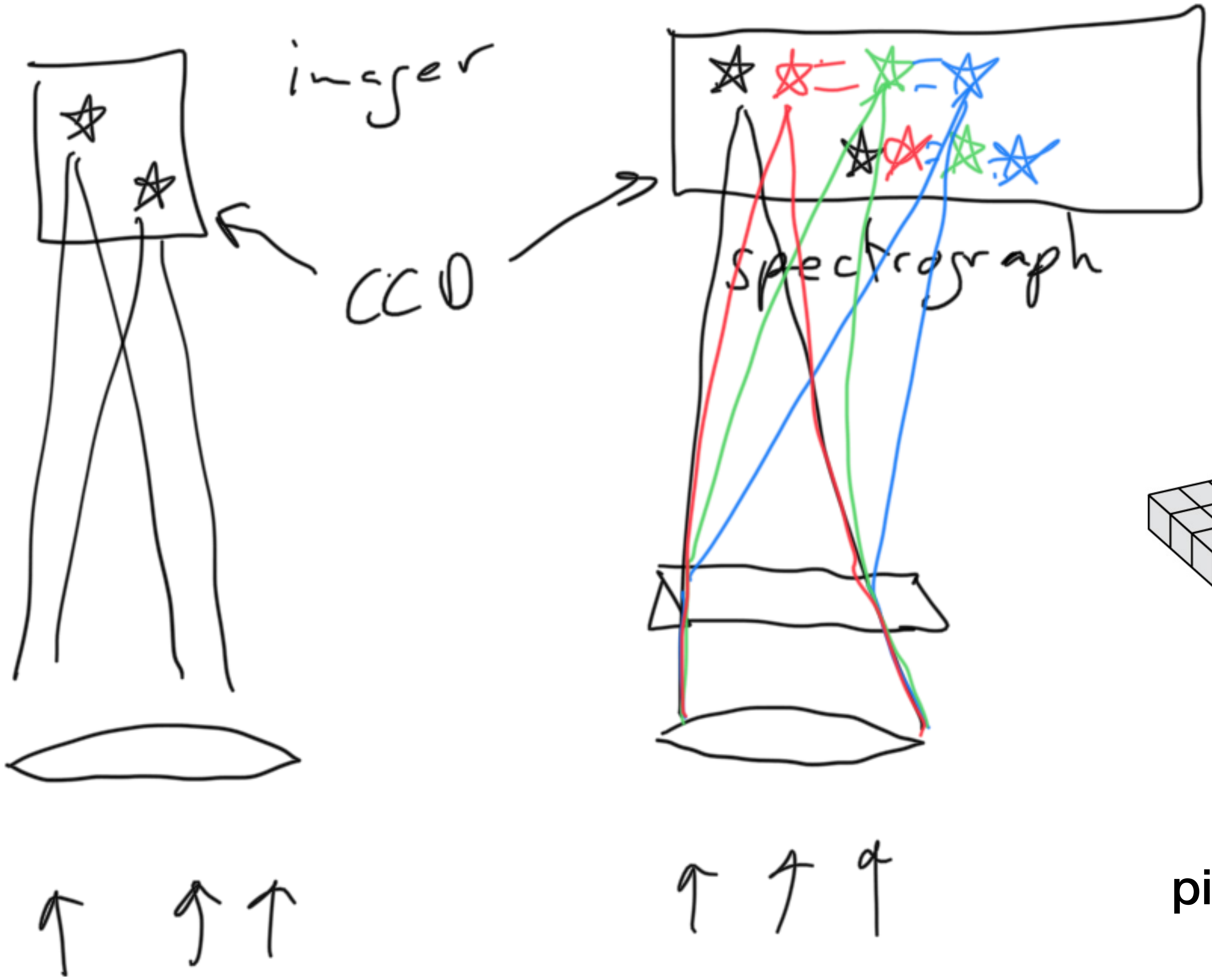
In ideal case, resolution determined by size of mirror

Often, mirror imperfections (misalignments, roughness) or atmospheric effects make the actual resolution worse

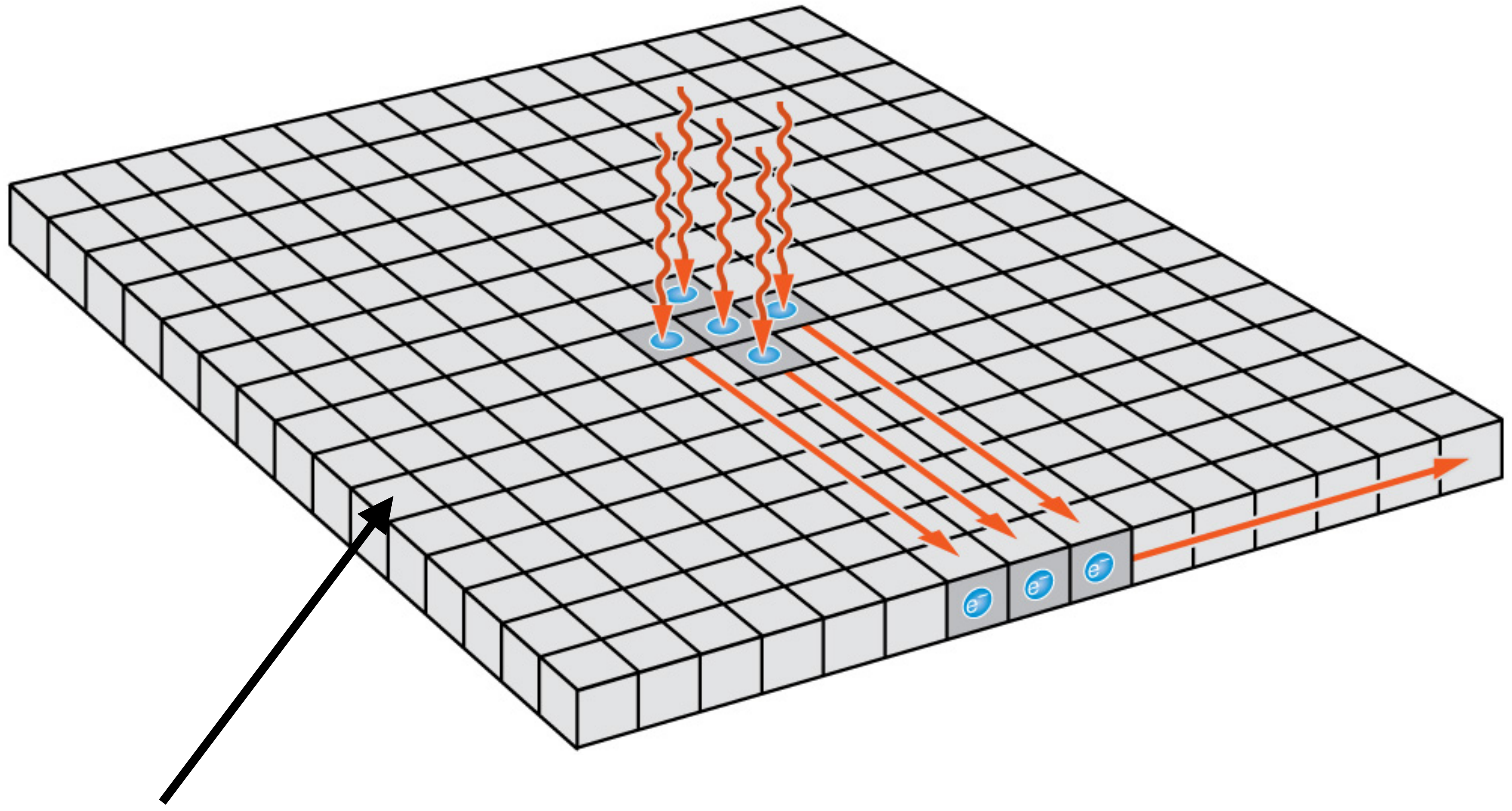


Why stars twinkle

Imaging versus Spectroscopy



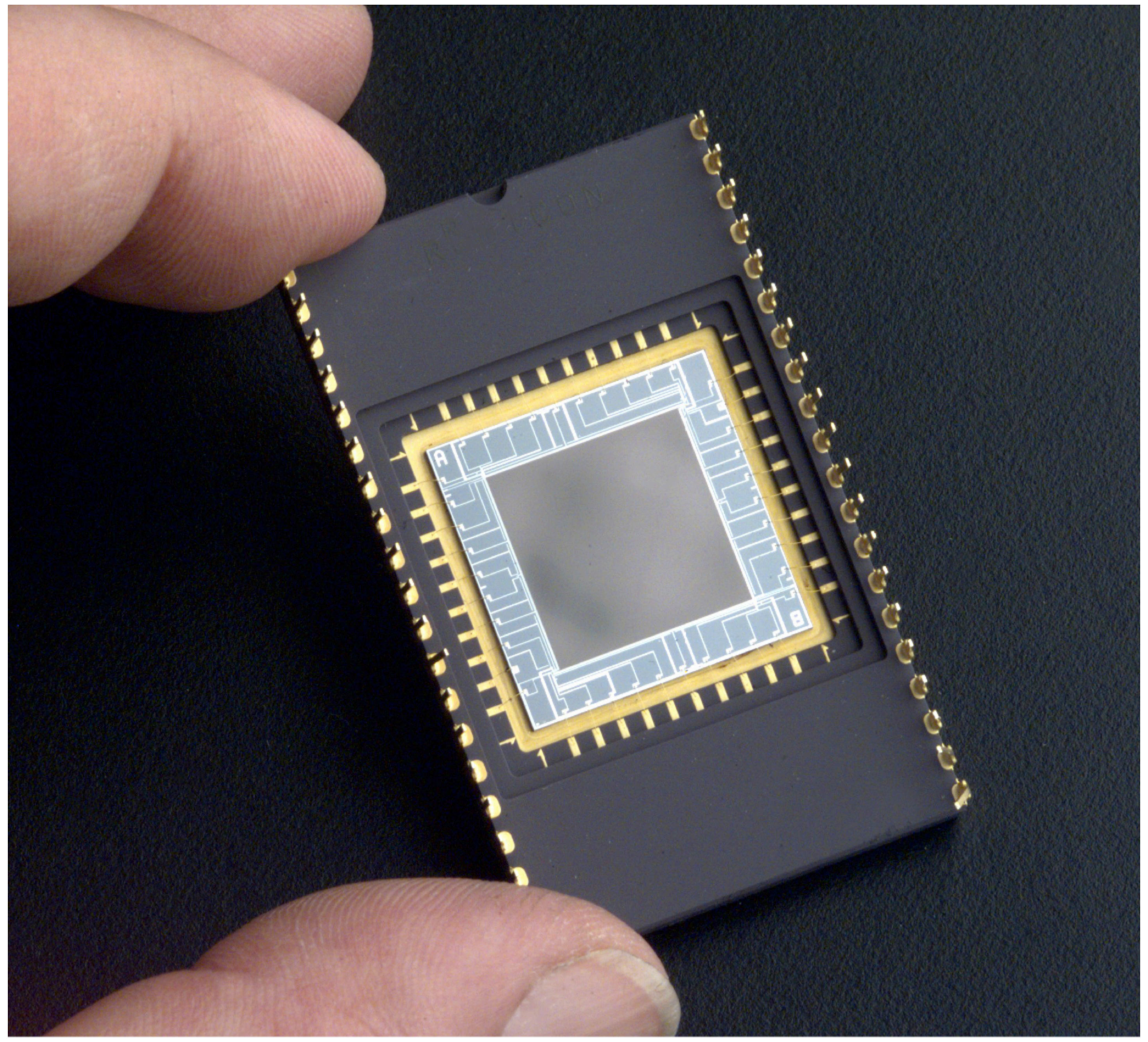
CCD
Charged Coupled Device



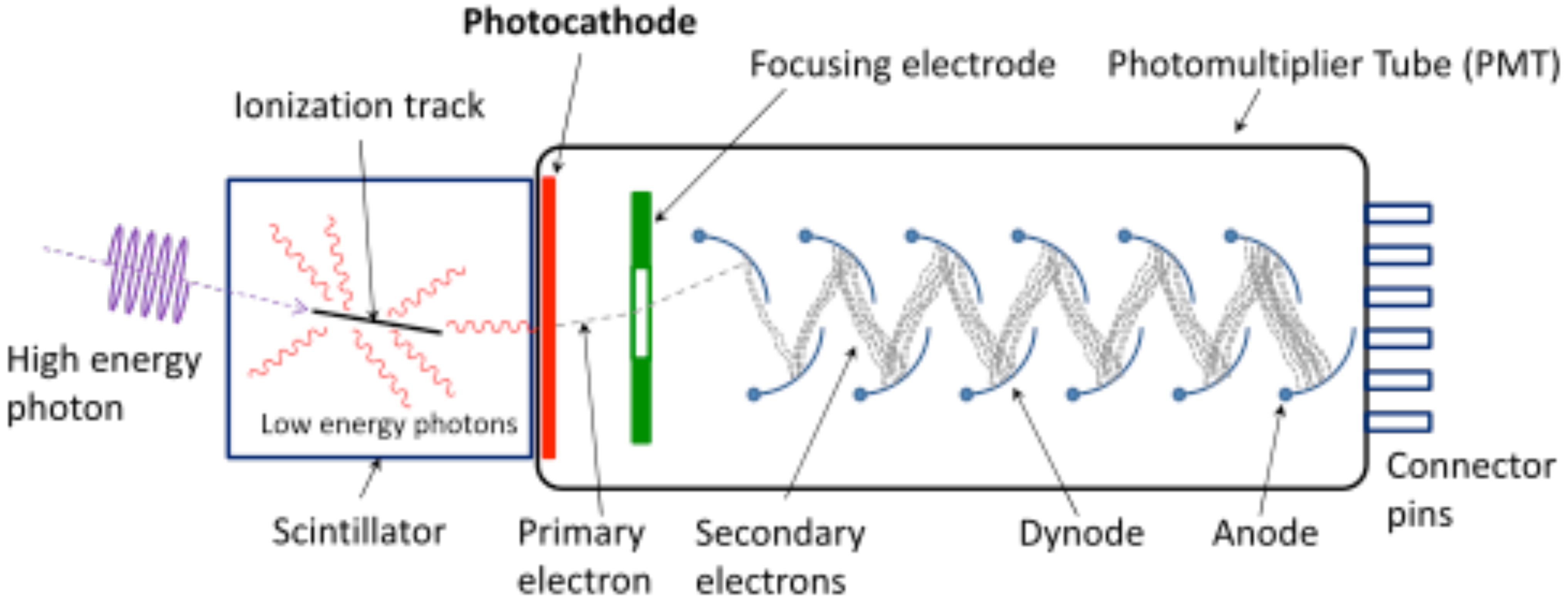
pixel (<u>pic</u>ture <u>el</u>ement)

Detectors

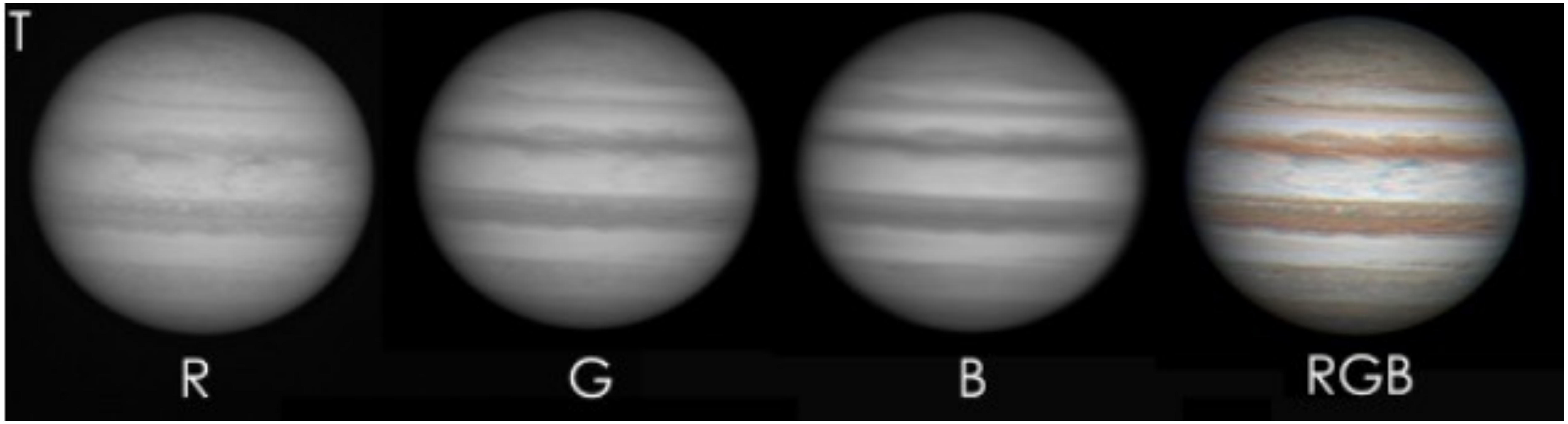
CCD

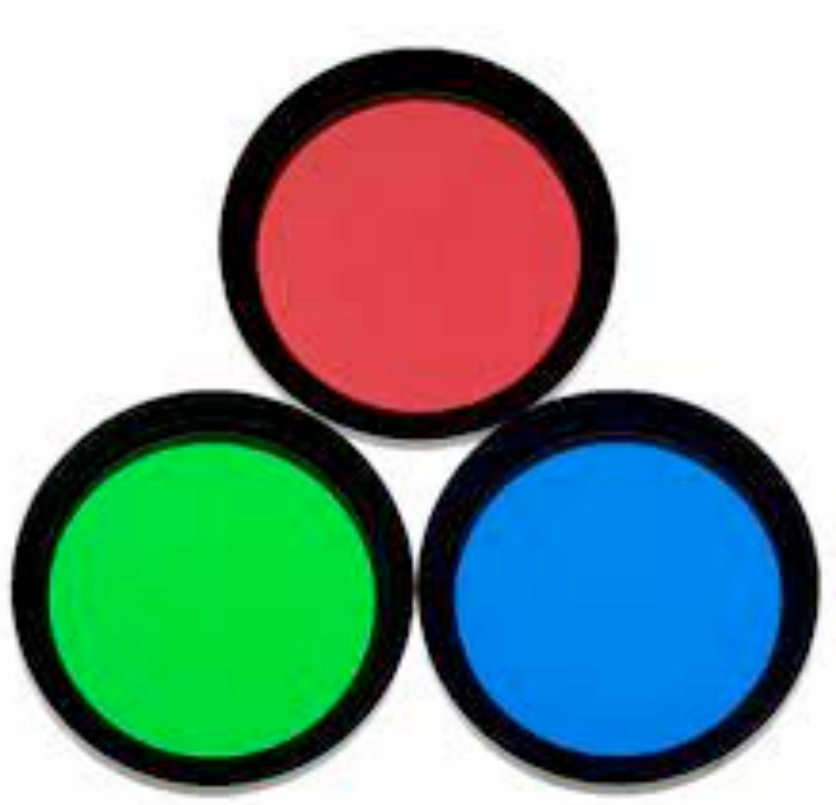


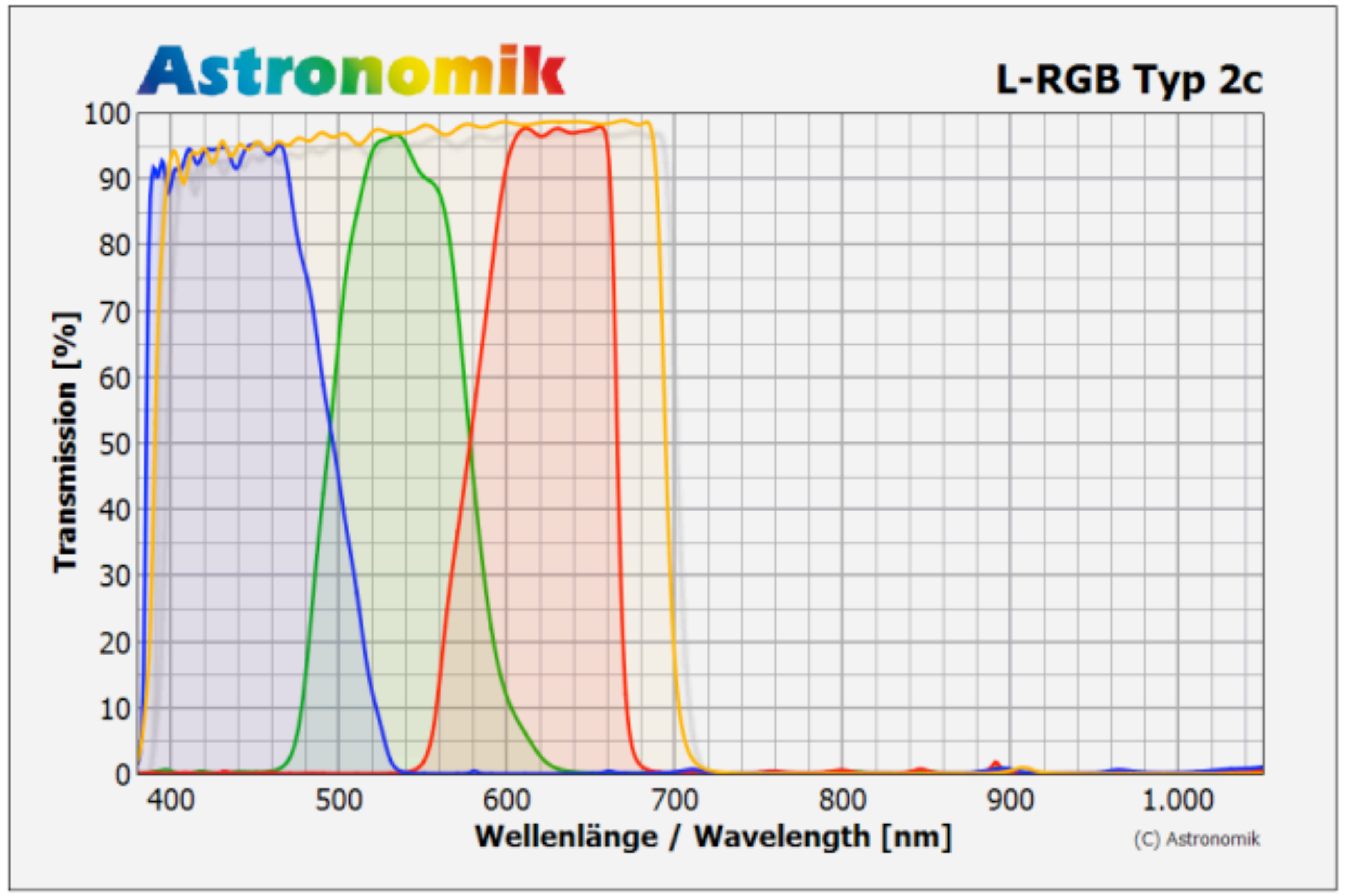
Photomultiplier tube

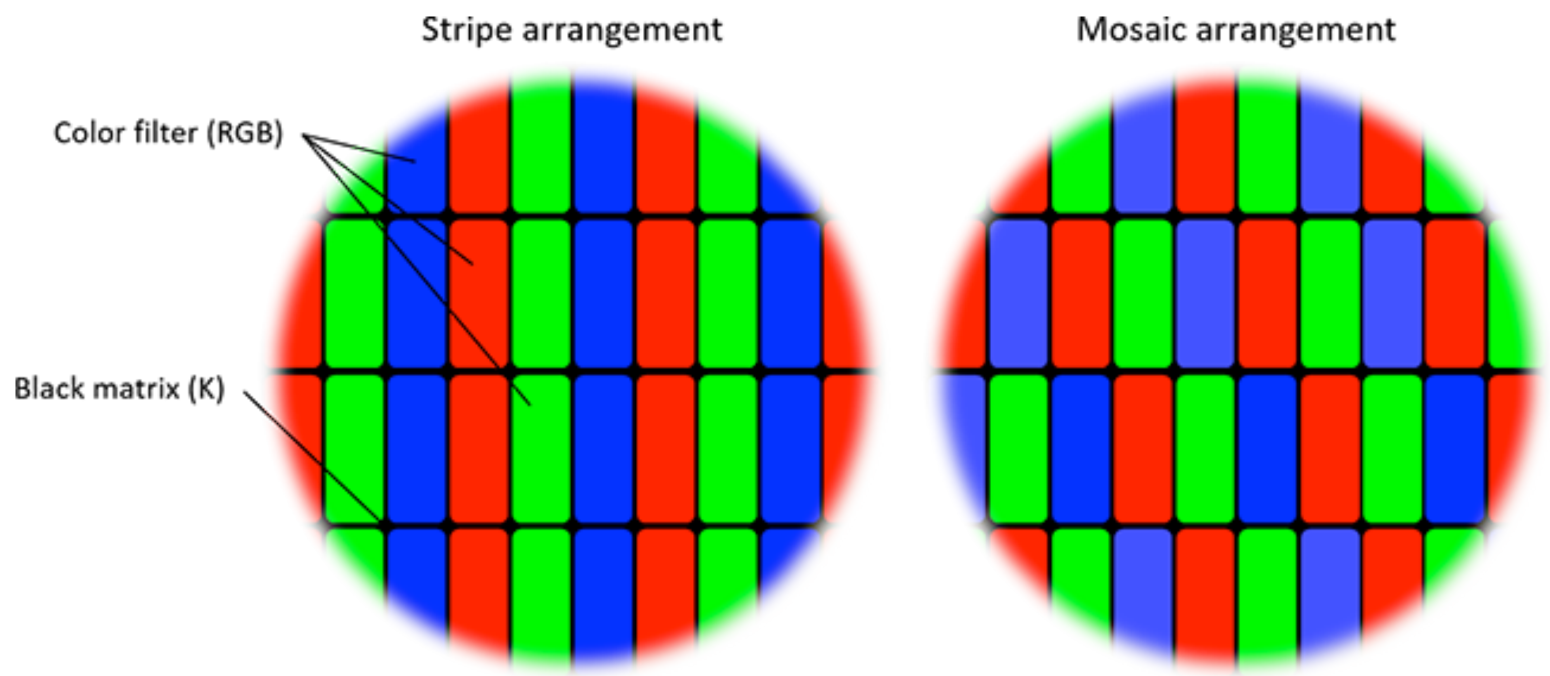


“Color” Imaging



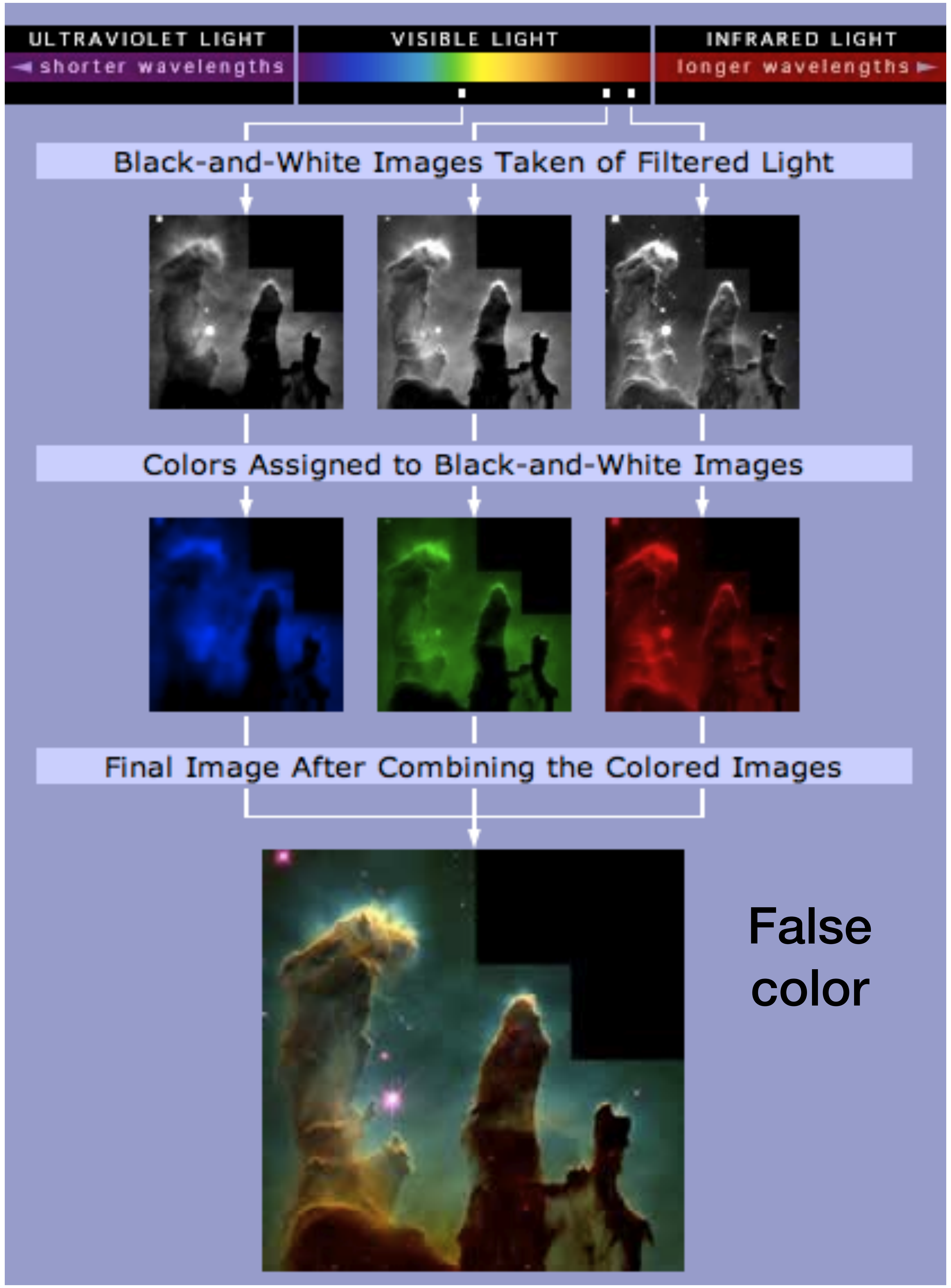






Phone Camera


ULTRAVIOLET LIGHT
shorter wavelengths
VISIBLE LIGHT
INFRARED LIGHT
longer wavelengths
Black-and-White Images Taken of Filtered Light
Colors Assigned to Black-and-White Images
Final Image After Combining the Colored Images
True color


ULTRAVIOLET LIGHT
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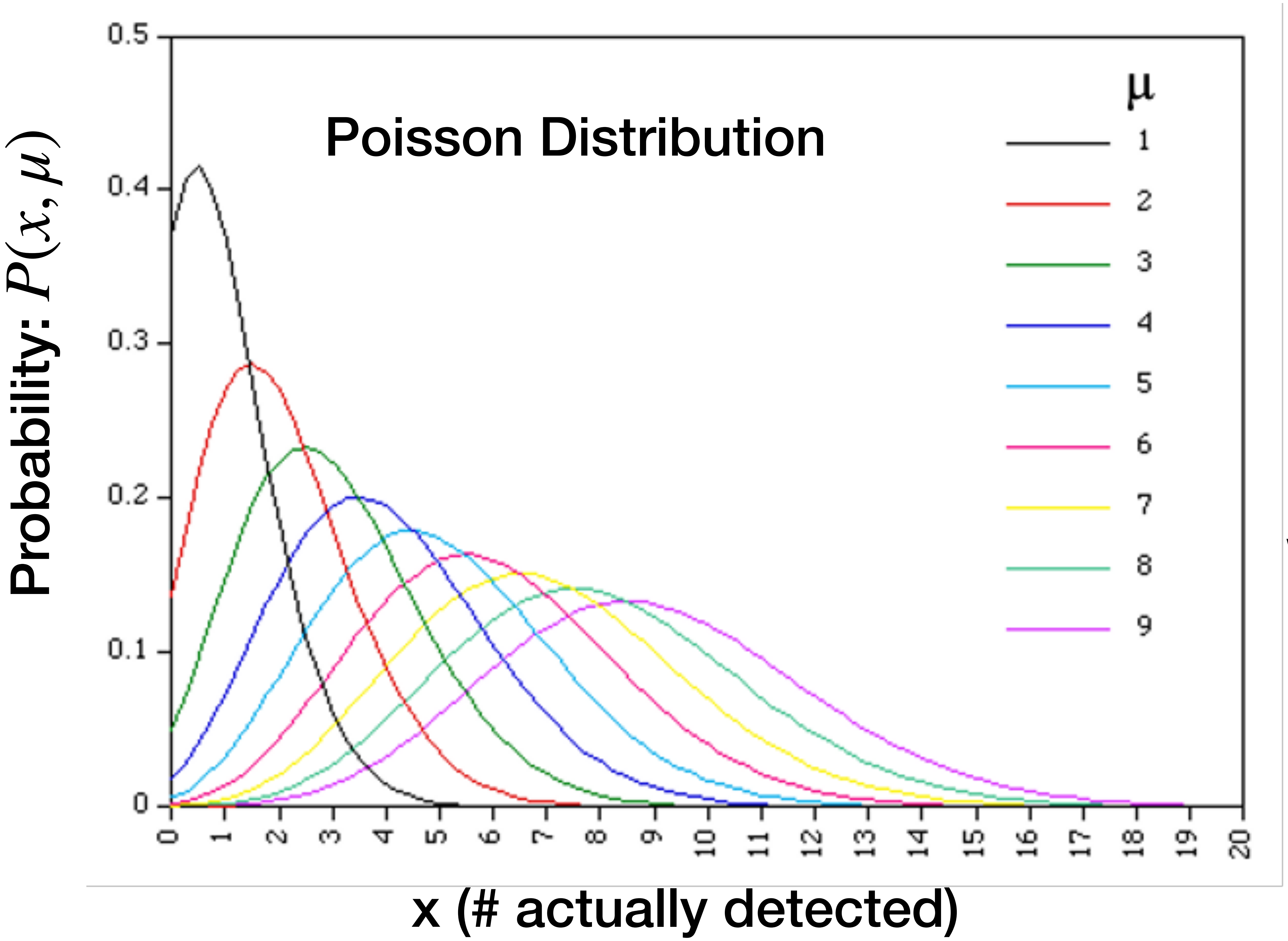
Final Image After Combining the Colored Images
False color

Making Measurements

Photons arrive randomly — # detected not necessarily # "should" detect

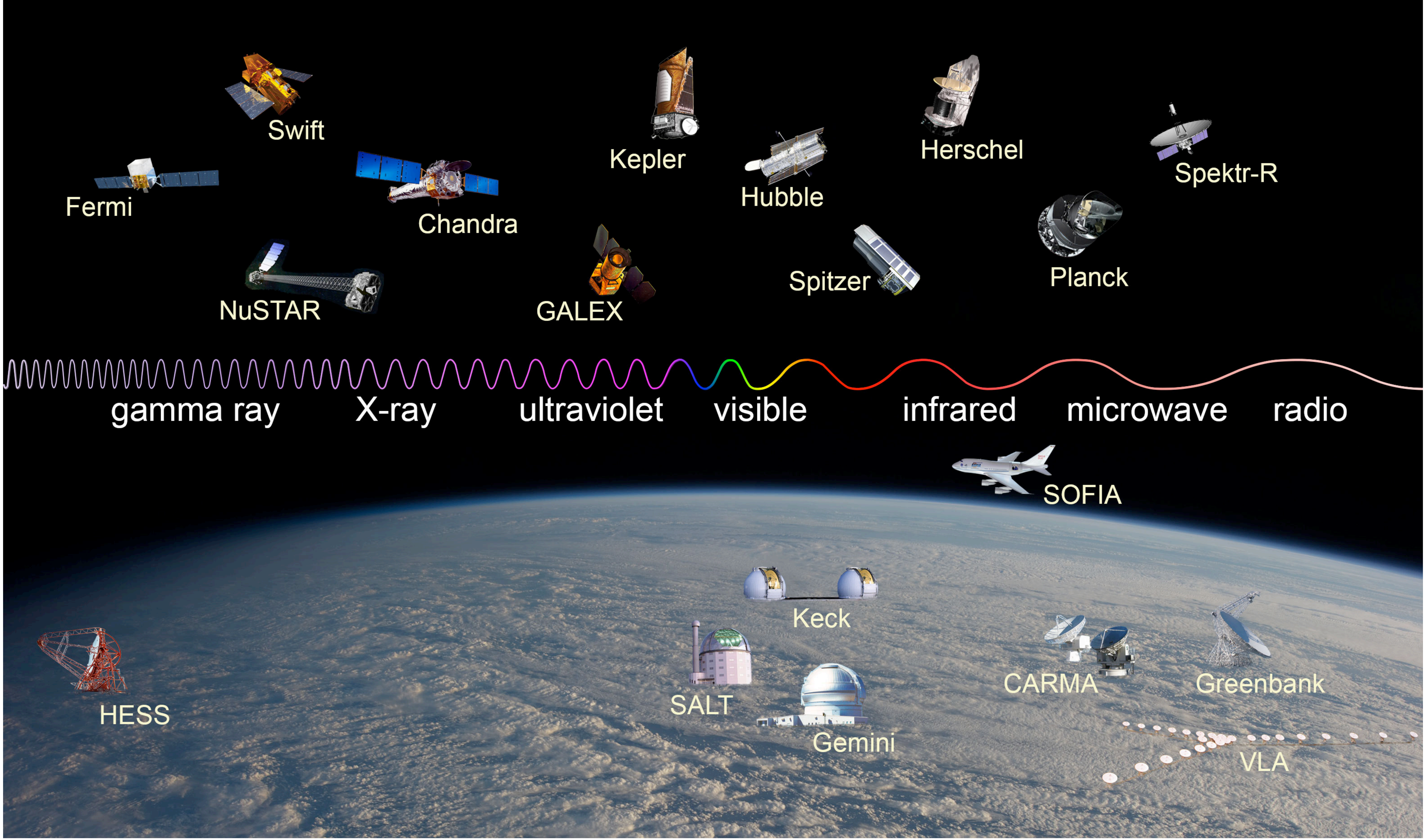


μ —> # "should" detect

$$P(x,\mu) = \frac{\mu^x}{x!} e^{-\mu}$$

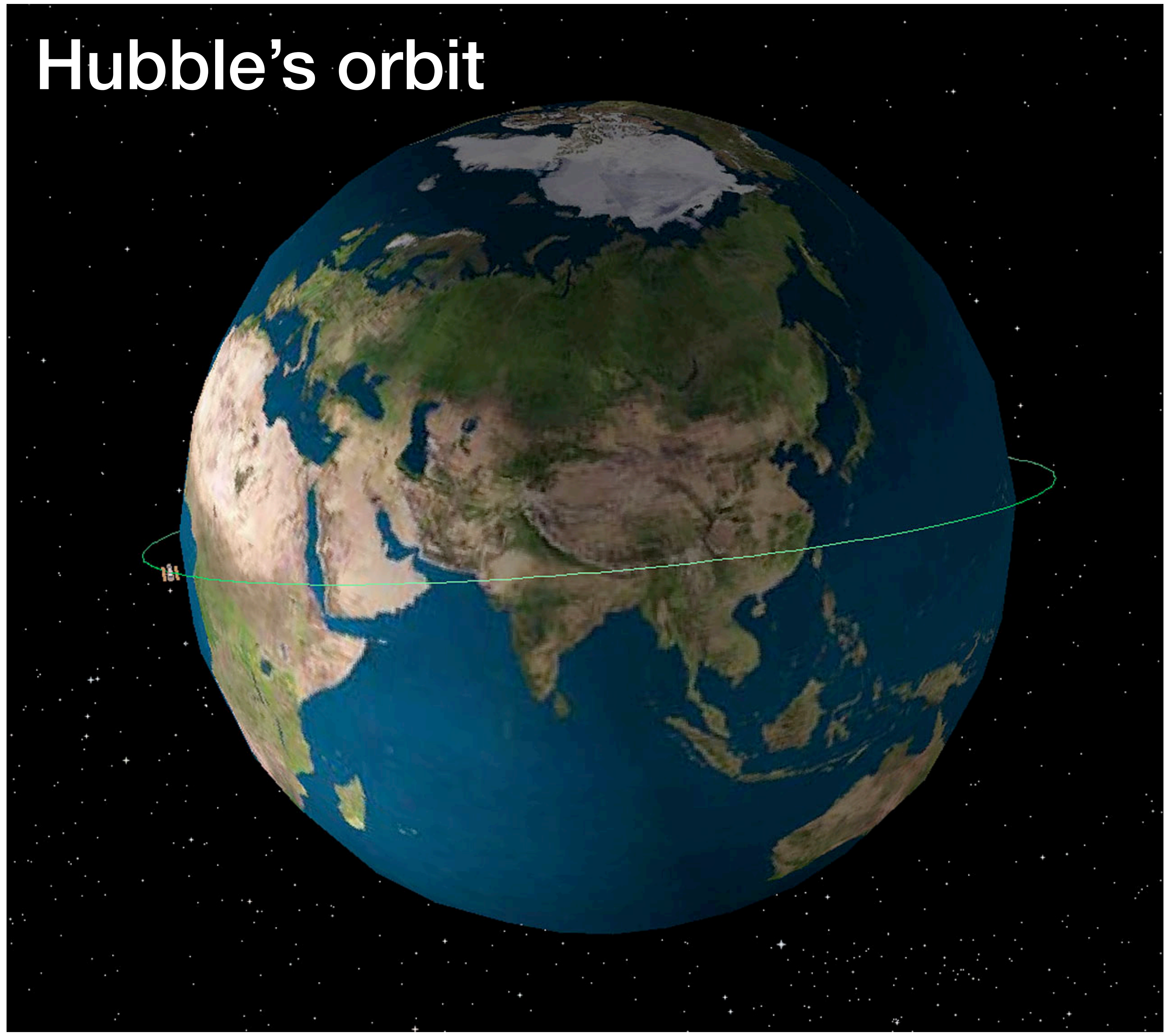
Width of the distribution, which gives the uncertainty (or error) of the measurement, is $\sigma = \sqrt{\mu}$

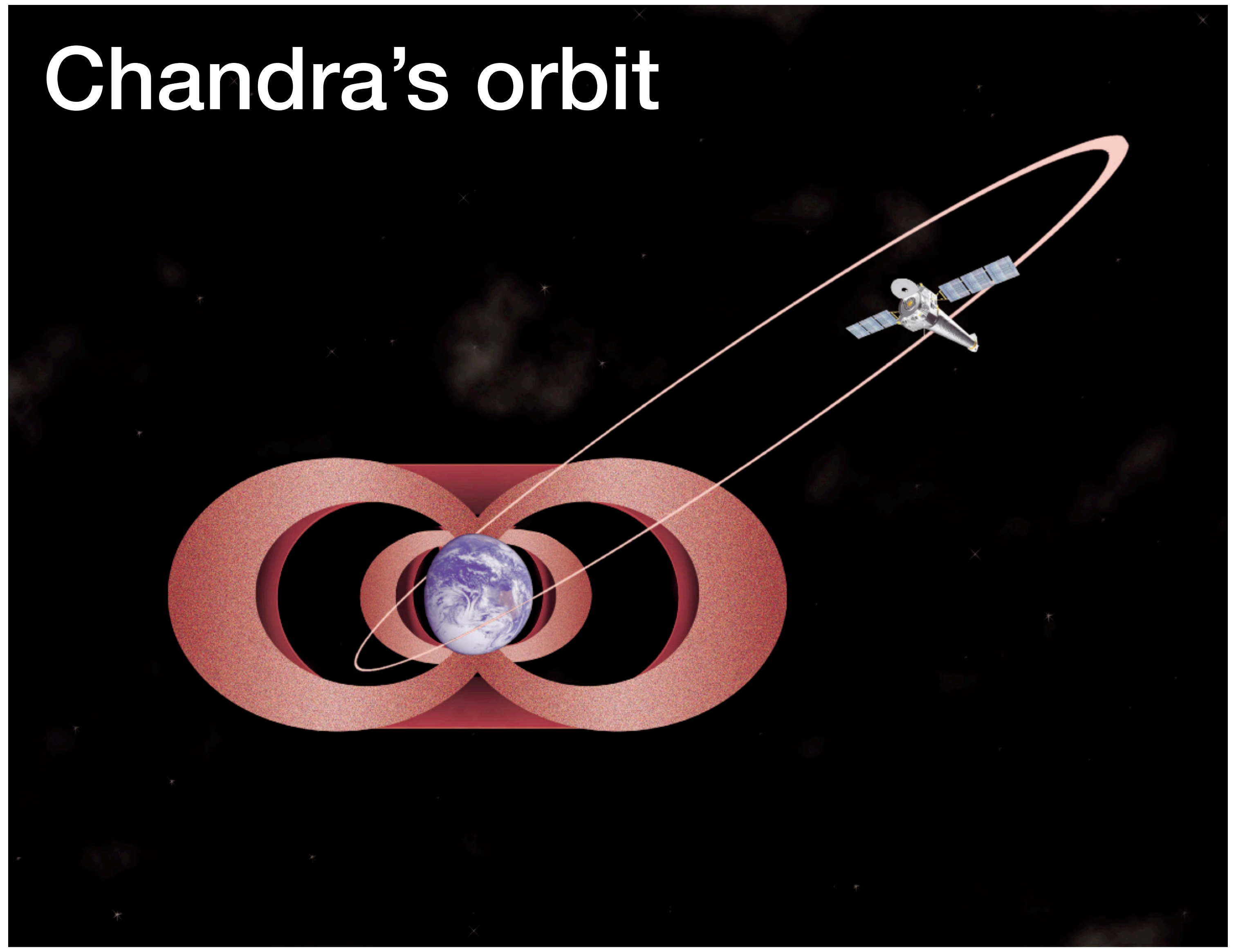

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
100 %
50 %
0 %
Atmospheric opacity
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
Transparency (%)
100
50
0
Atmosphere is opaque
Atmosphere is opaque
Radio window
Atmosphere is opaque
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} (m)
0.001 nm 0.01 nm 0.1 nm 1 nm 10 nm 100 nm 1 μm 10 μm 100 μm 1 mm 1 cm 10 cm 1 m 10 m 100 m 1 km
Wavelength


Swift
Fermi
Chandra
Kepler
Hubble
Herschel
Spektr-R
NuSTAR
GALEX
Spitzer
Planck
gamma ray
X-ray
ultraviolet
visible
infrared
microwave
radio
SOFIA
Keck
HESS
SALT
Gemini
CARMA
Greenbank
VLA

3 Misconceptions about Telescopes in Space

- From space, objects can be observed continuously, even during the day
- The sky is much darker in space than on the Earth
- Observations from space are not affected by weather





JWST's orbit