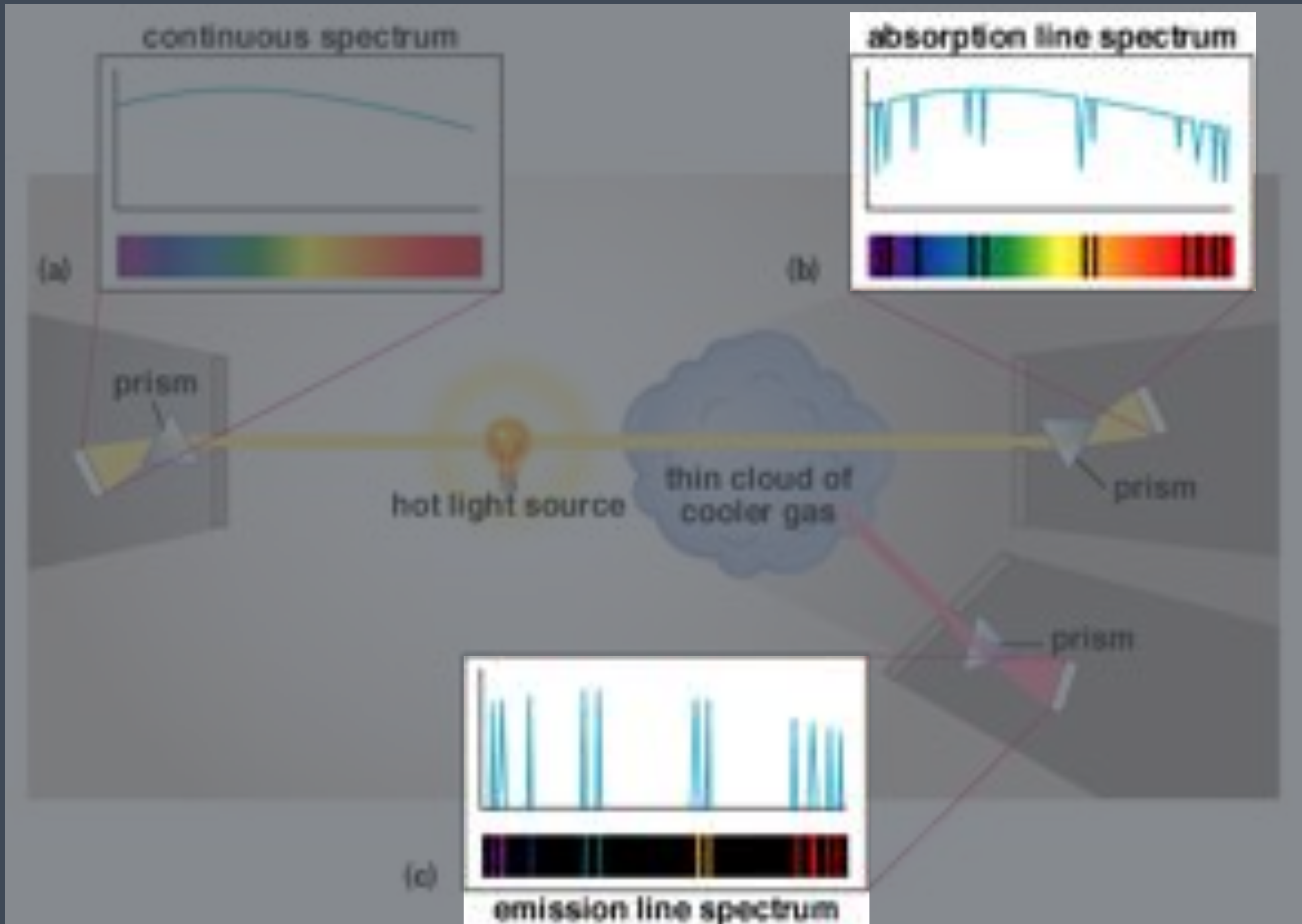
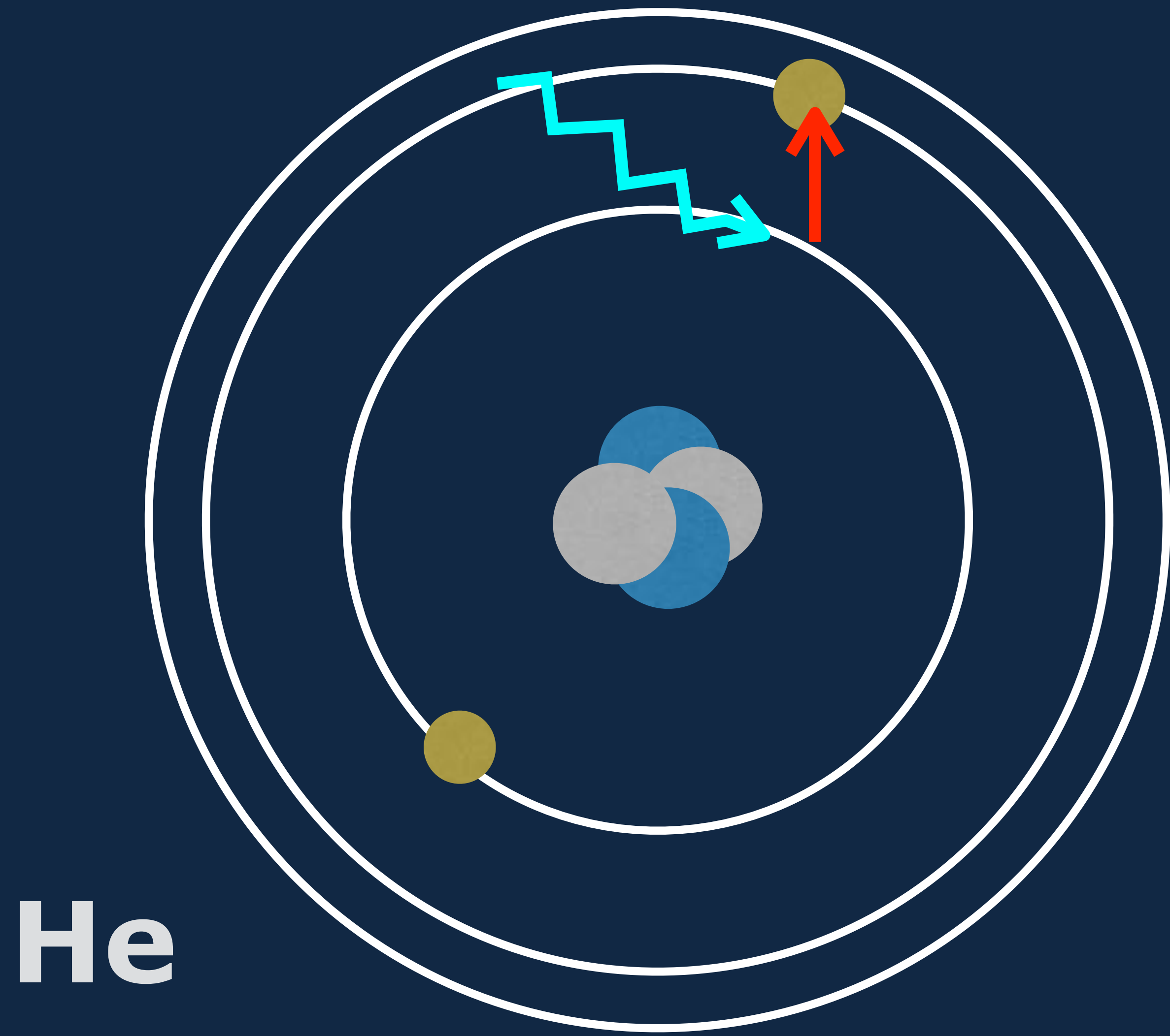
Last time...



continuous spectrum
absorption line spectrum
(a)
(b)
prism
hot light source
thin cloud of
cooler gas
prism
prism
(c)
emission line spectrum

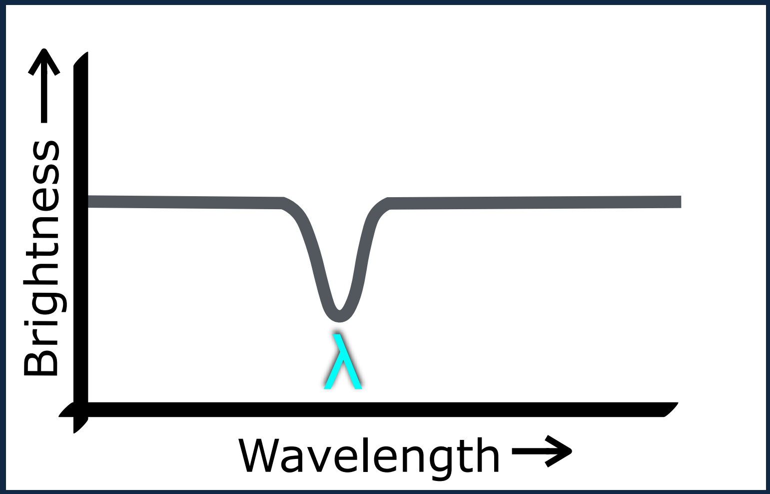
Last time…

Lines in spectra can be approximated by the Bohr model…



Absorption line

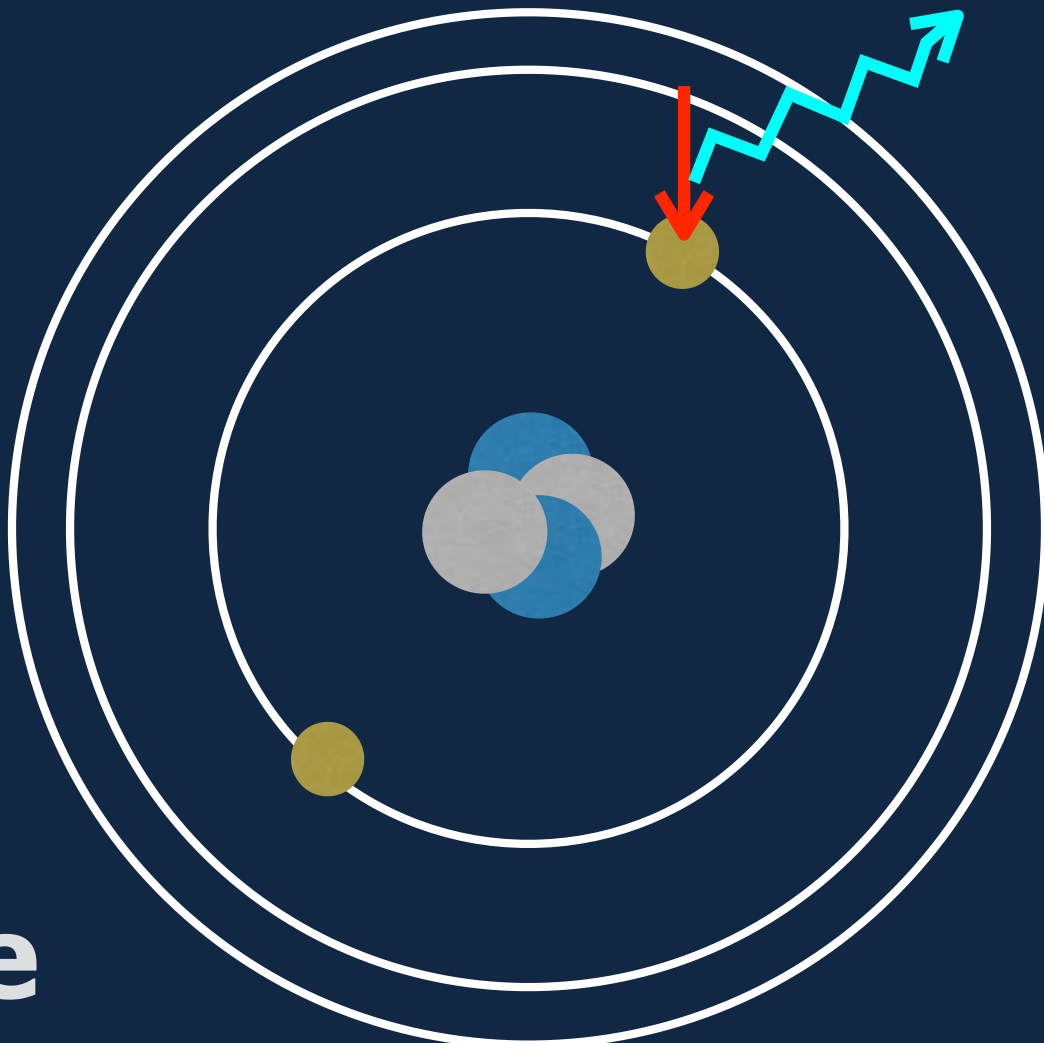
e^- absorbs photon and moves to higher E level (n=2)



$\Delta E = hc/\lambda$

Last time...

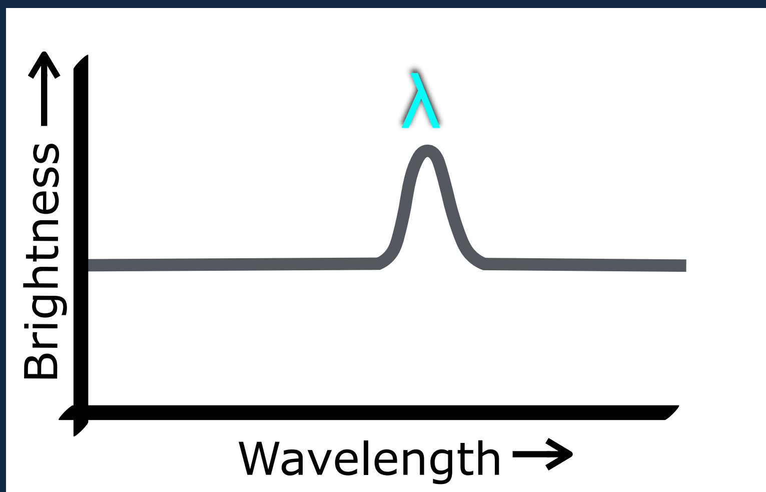
Lines in spectra can be approximated by the Bohr model...



He

Emission line

e^- emits photon to move down to lower E level (n=1)

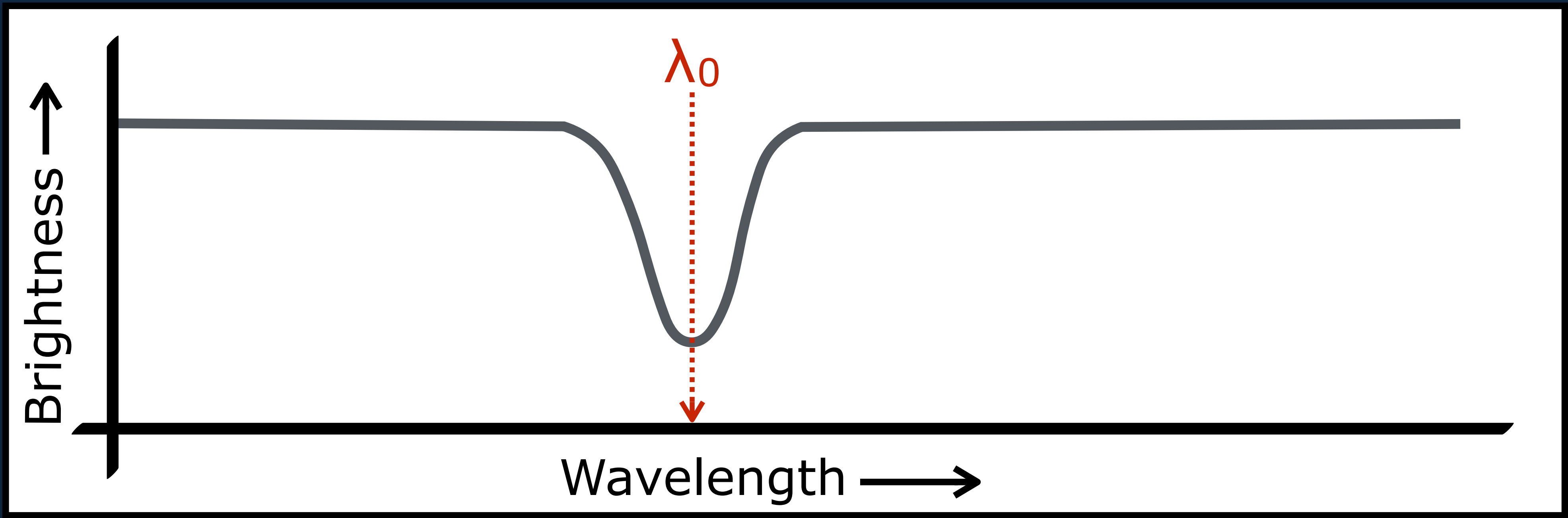


$\Delta E = hc/\lambda$

Making a Spectrum - Lines

Anatomy of a spectral line

Rest-frame wavelength: composition; T
(gas T determines E, which determines level occupied)



Making a Spectrum - Lines

Anatomy of a spectral line

Rest-frame wavelength: composition; T
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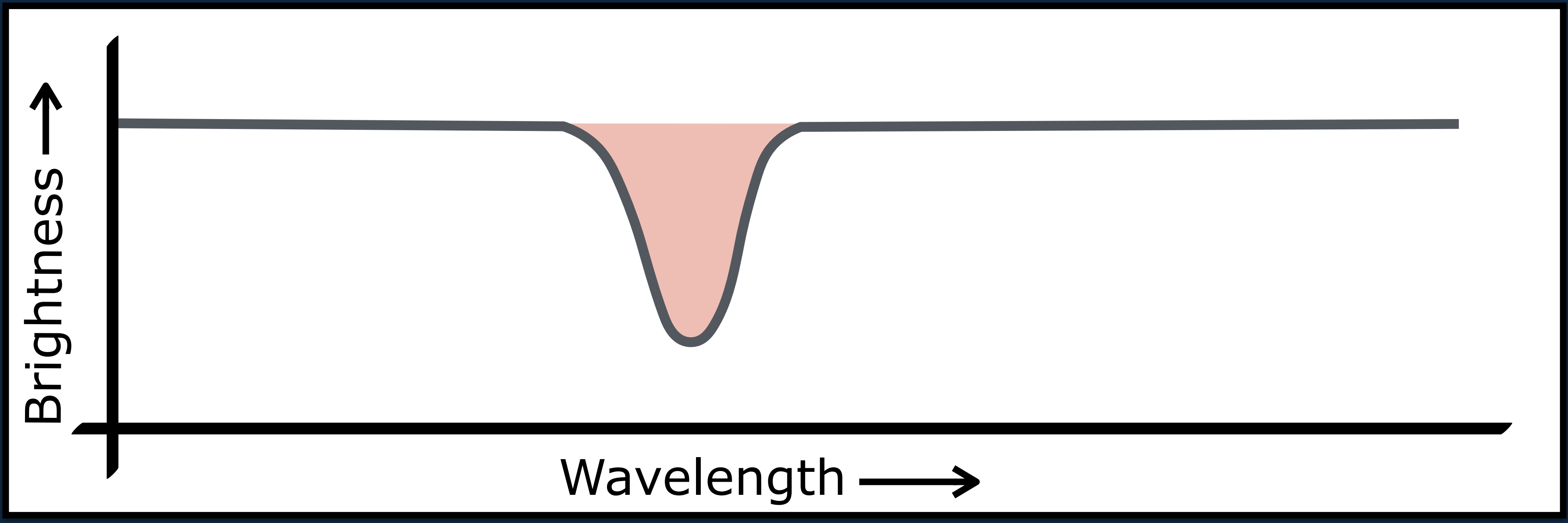
Strength/flux: # of e^- in that level; composition/abundance



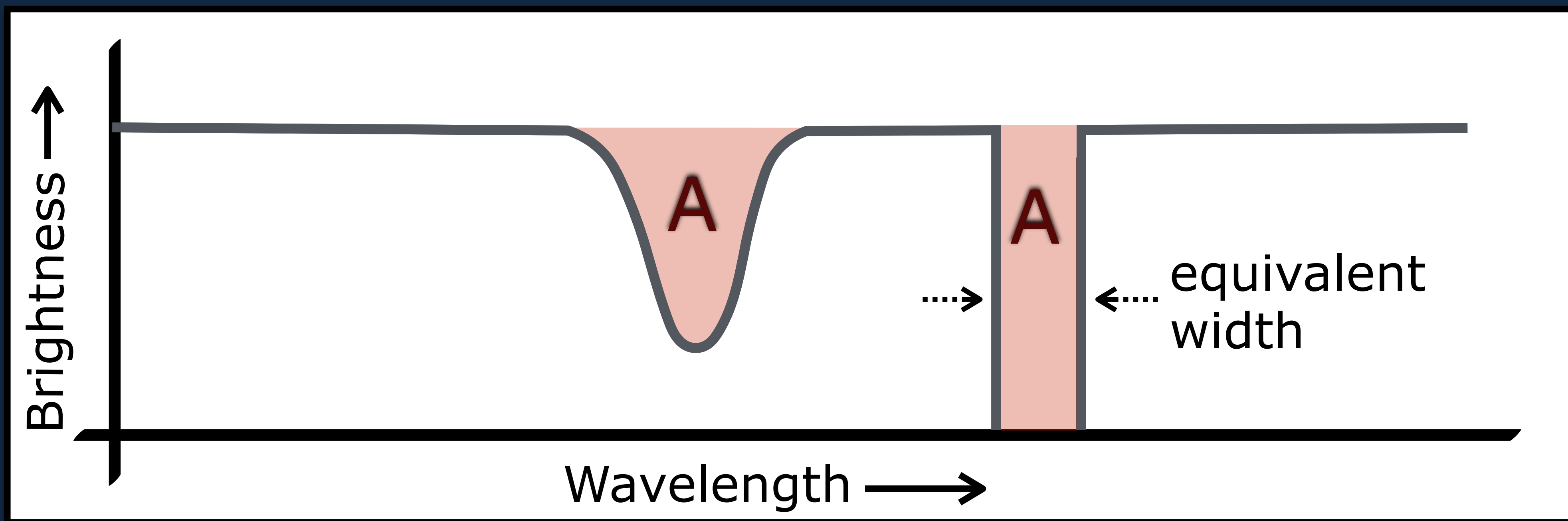
Making a Spectrum - Lines

Anatomy of a spectral line

Rest-frame wavelength: composition; T
(gas T determines E, which determines level occupied)

Strength/flux: # of e^- in that level; composition/abundance

Width: ?



Making a Spectrum - Lines

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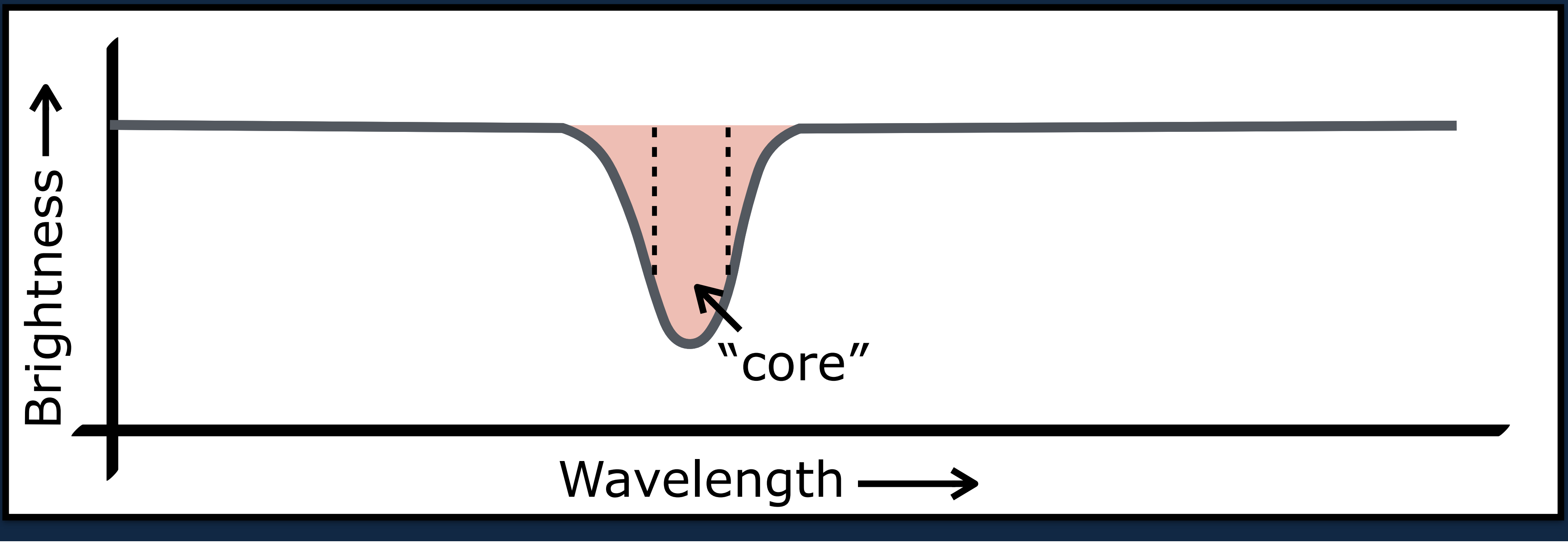
Strength/flux: # of e^- in that level; composition/abundance

Width: ?



Making a Spectrum - Lines

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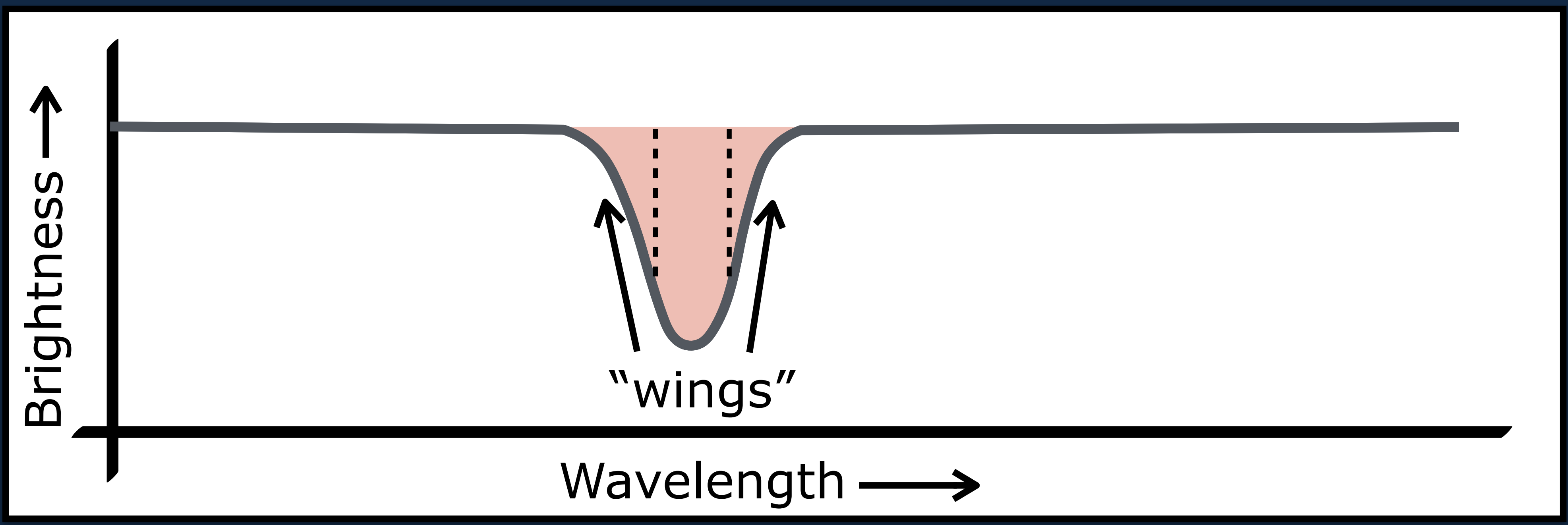

Making a Spectrum - Lines

Anatomy of a spectral line

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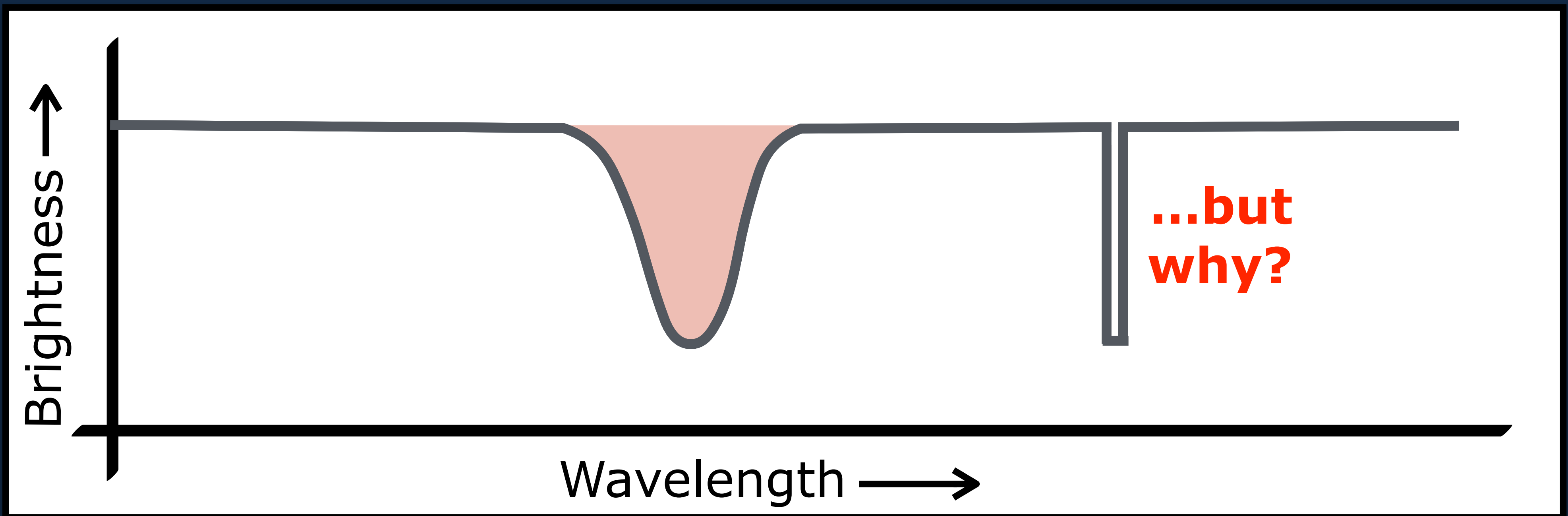
Strength/flux: # of e^- in that level; composition/abundance

Width: ?

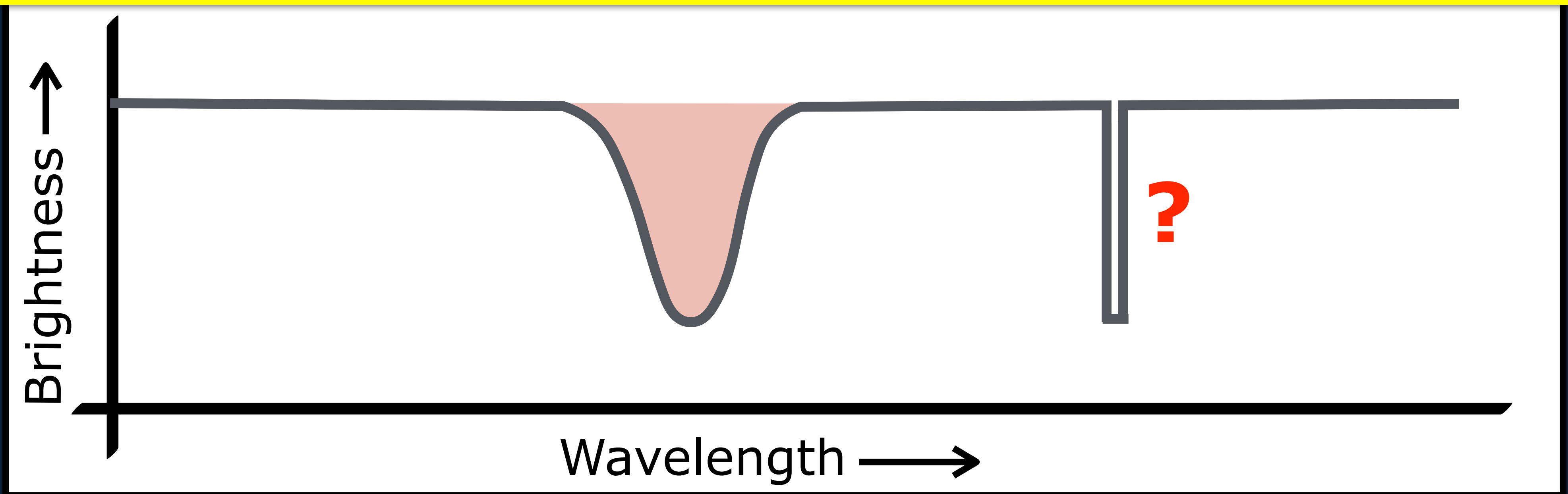


Making a Spectrum - Lines

Discussion Question

The Bohr model of the atom predicts a very exact energy for a given transition. Given this fact, why are spectral lines not shaped like perfect Dirac functions?

(think & discuss)



Making a Spectrum - Lines

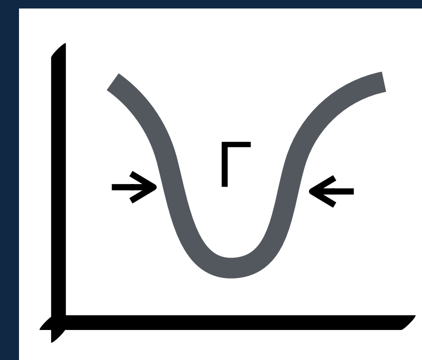
Sources of Line Broadening

1) Heisenberg: $\Delta E \Delta t > \hbar/2$

$$\phi_\nu = \frac{(\Gamma_u/4\pi^2)}{(\nu-\nu_0)^2+(\Gamma_u/4\pi)^2} \rightarrow$$

equation for a damped oscillator $\rightarrow$

Lorentzian



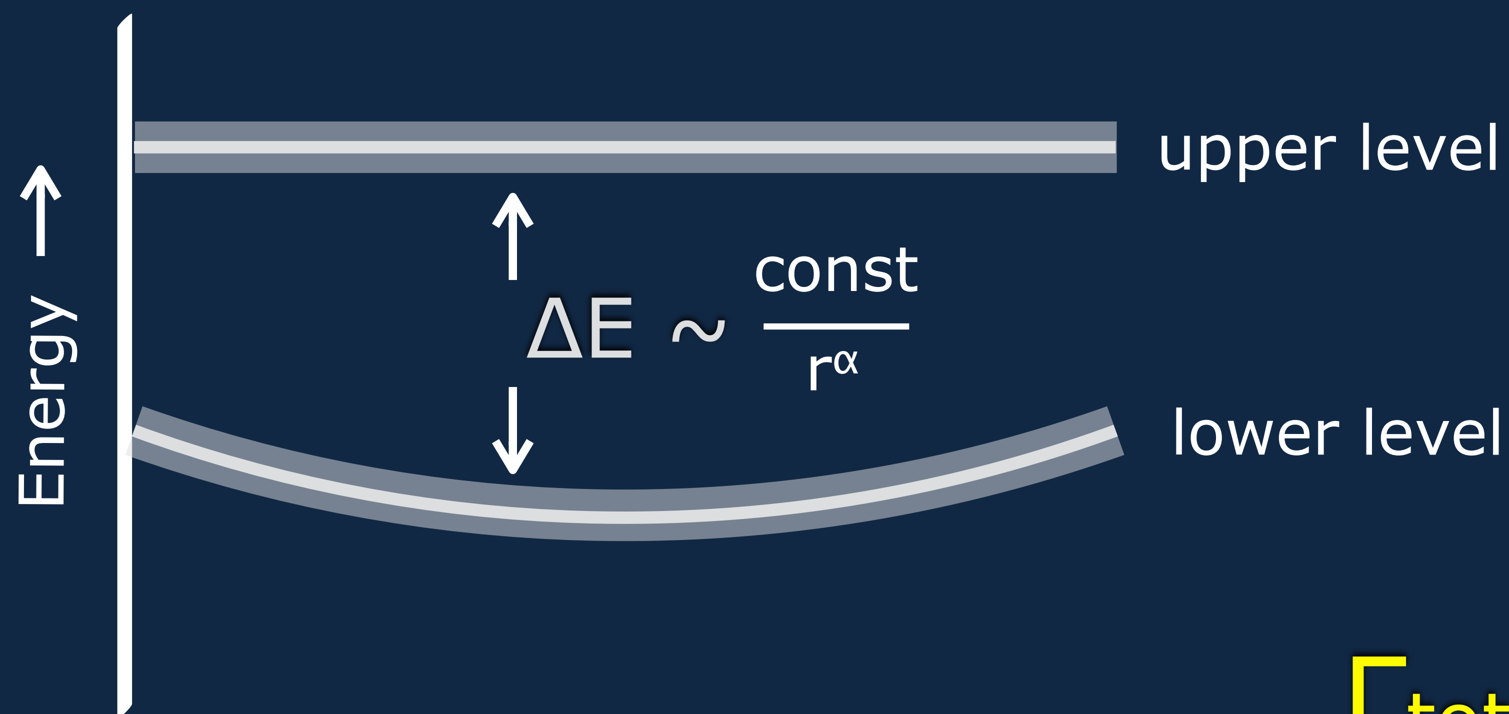
$$\Gamma_N = \Gamma_u + \Gamma_l$$

Making a Spectrum - Lines

Sources of Line Broadening

1) Heisenberg (Lorentzian)

2) Pressure (also Lorentzian)



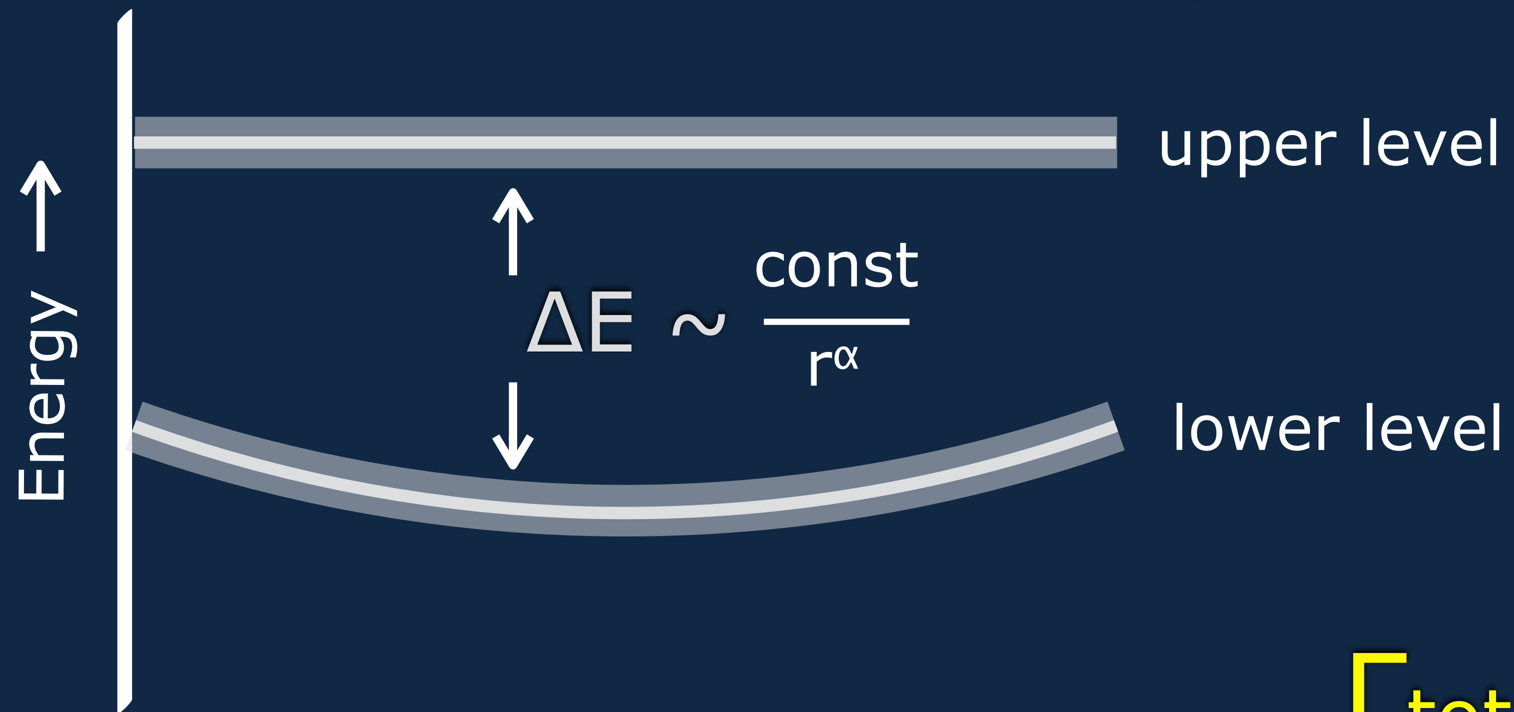
Γ_P

$\downarrow$

$\Gamma_{tot} = \Gamma_N + \Gamma_P$

Making a Spectrum - Lines

Sources of Line Broadening



$$\Delta E \sim \frac{\text{const}}{r^{\alpha}}$$

$$\Gamma_P$$

$$\downarrow$$

$$\Gamma_{tot} = \Gamma_N + \Gamma_P$$

$\alpha = 2$ & $4 \rightarrow$ effect of passing electrons

Making a Spectrum - Lines

Quick Question

Do we expect this phenomenon to be more common in…

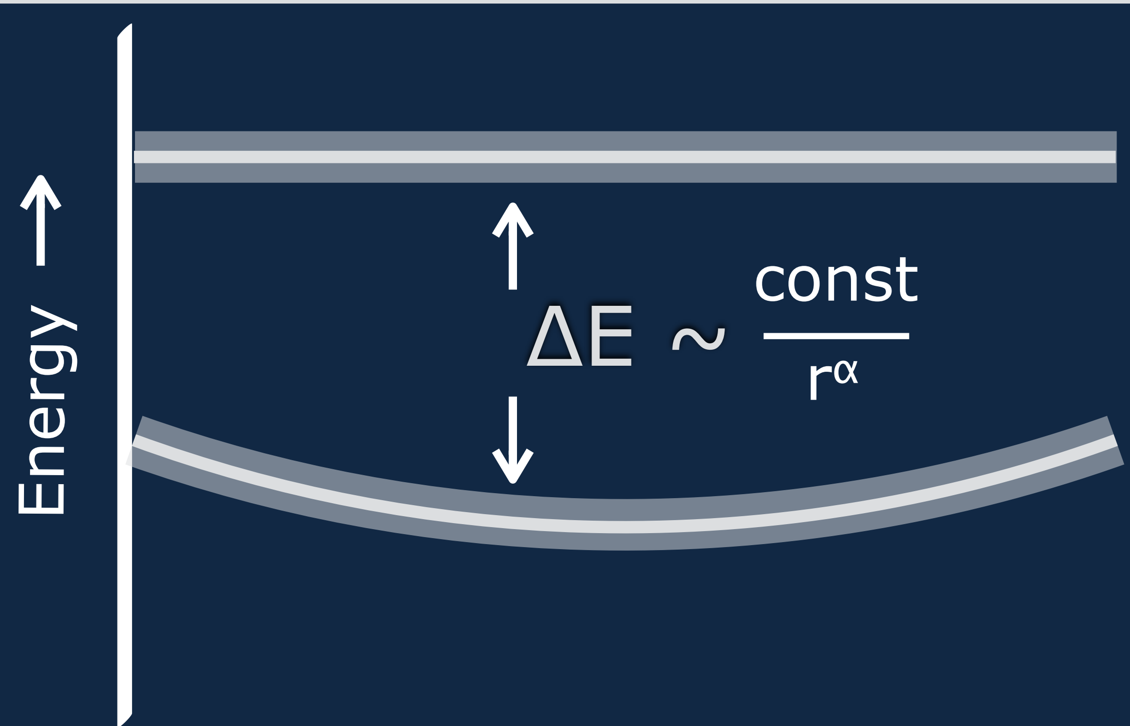
A) very hot stars
B) very cold stars
C) very young stars
D) this won't happen in stars

$$\Gamma_{tot} = \Gamma_N + \Gamma_P$$

$\alpha = 2$ & $4 \rightarrow$ effect of passing electrons

Making a Spectrum - Lines

Sources of Line Broadening



$$\Delta E \sim \frac{\text{const}}{r^{\alpha}}$$

$$\Gamma_P$$

$$\downarrow$$

$$\Gamma_{tot} = \Gamma_N + \Gamma_P$$

$\alpha = 2$ & $4 \rightarrow$ effect of passing electrons; common in hot stars

$\alpha = 6 \rightarrow$ van der Waals force

Making a Spectrum - Lines

QUICK QUESTION

Do we expect this phenomenon to be more common in…

A) very hot stars
B) very cold stars
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$$\Gamma_{tot} = \Gamma_N + \Gamma_P$$

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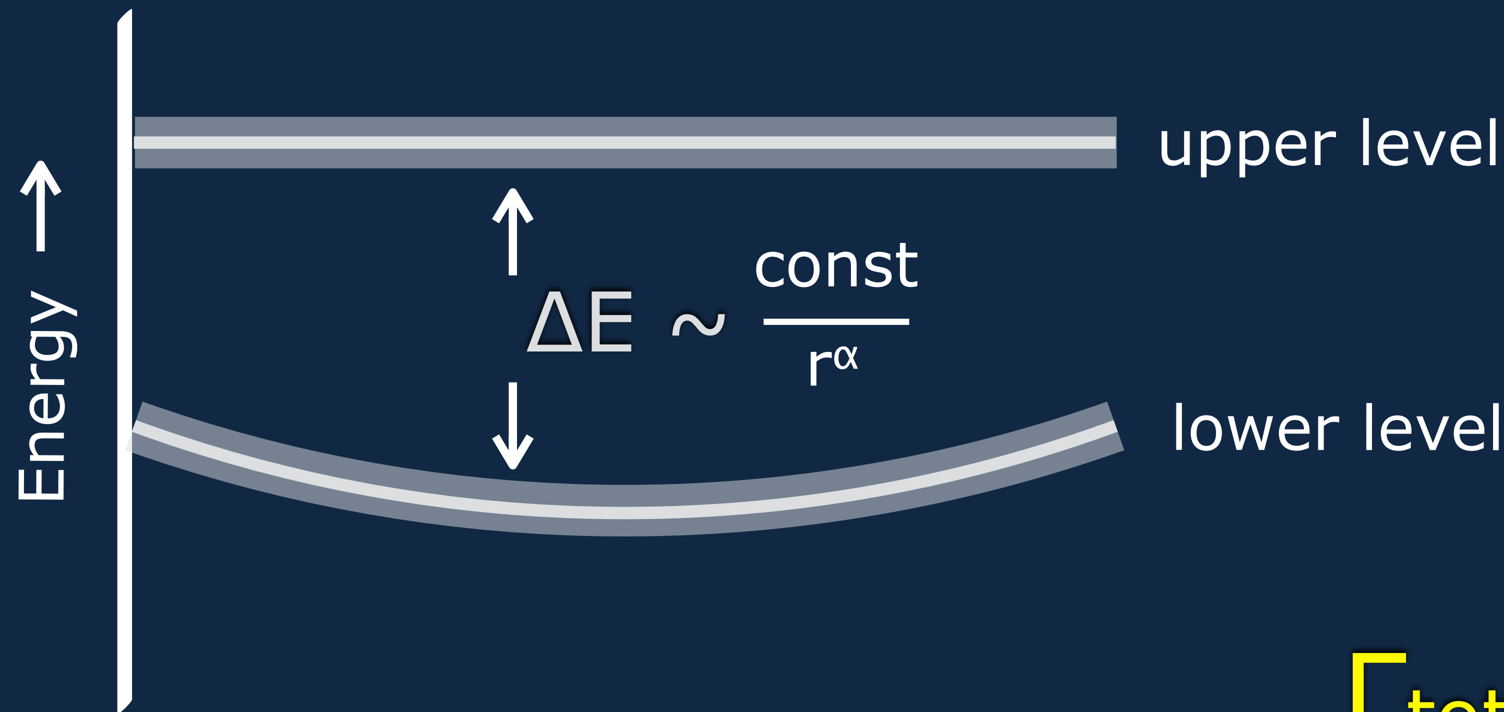
Making a Spectrum - Lines

Sources of Line Broadening



$$\Delta E \sim \frac{\text{const}}{r^{\alpha}}$$

$$\Gamma_P$$

$$\Gamma_{tot} = \Gamma_N + \Gamma_P$$

α = 2 & 4 → effect of passing electrons; common in hot stars

α = 6 → van der Waals force; common in cool stars

α = 3 → resonance broadening; mostly H lines

Making a Spectrum - Lines

Sources of Line Broadening

1) Heisenberg (Lorentzian)

2) Pressure (also Lorentzian)

3) Thermal

$\Delta\nu/\nu \sim u/c$ ← Doppler!

$u_0 = \sqrt{2kT/m}$ ← average thermal velocity

$\Delta\nu_D = \nu \times u_0/c$ ← total change in frequency

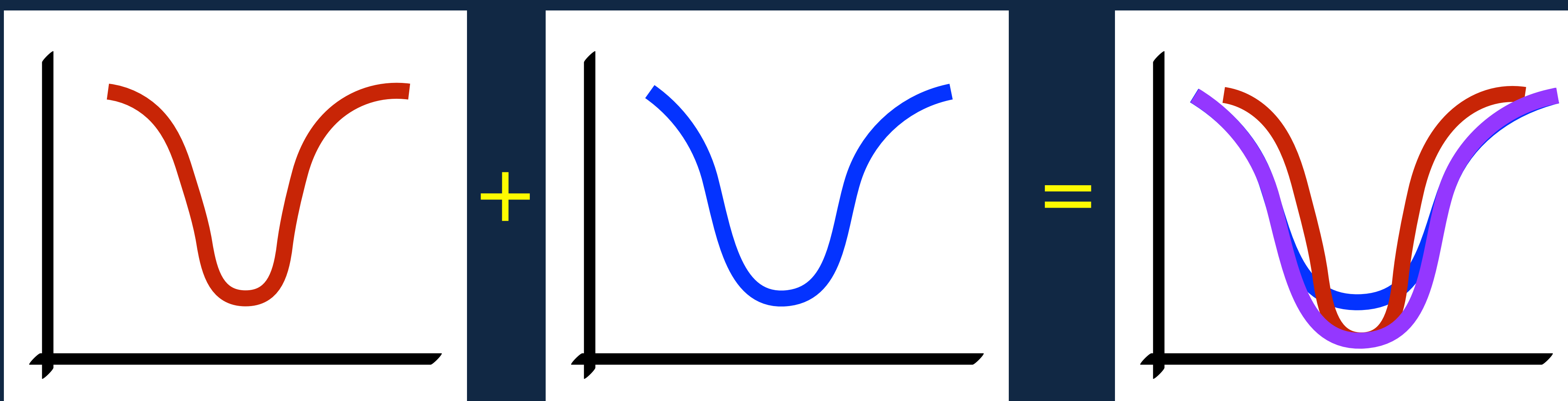
total distribution is a Gaussian

Making a Spectrum - Lines

Sources of Line Broadening

1) Heisenberg (Lorentzian)
2) Pressure (also Lorentzian)
3) Thermal (Gaussian)

Gaussian Lorentzian Voigt profile



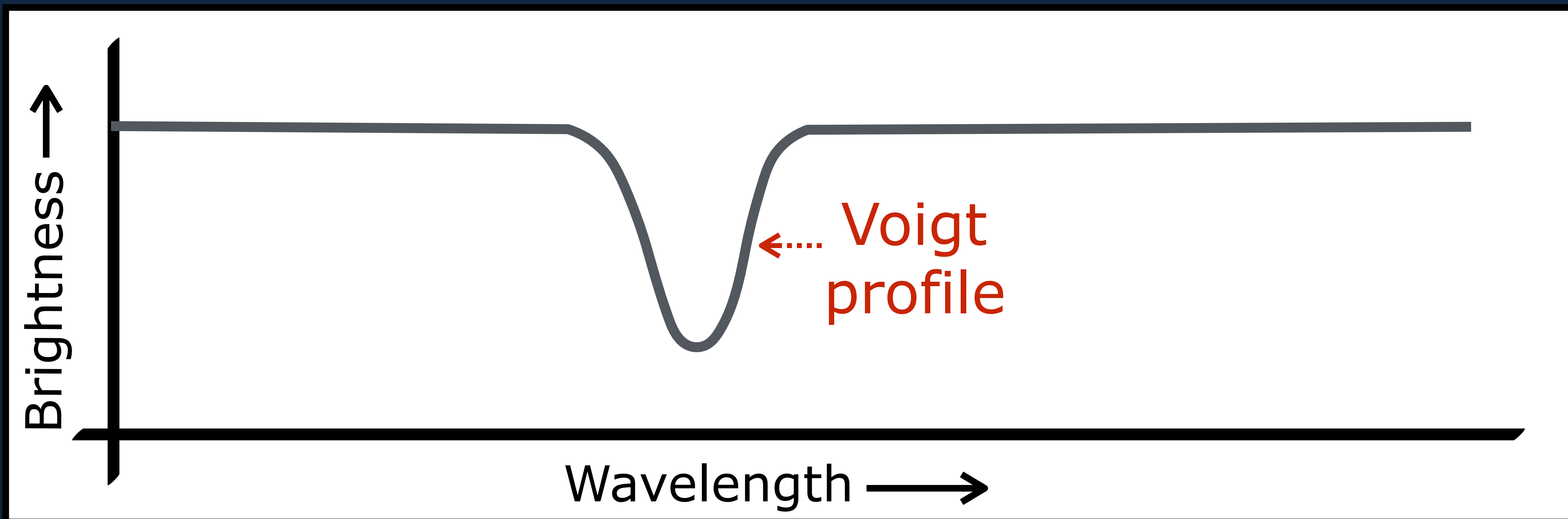
Making a Spectrum - Lines

Anatomy of a spectral line

Rest-frame wavelength: composition; T
(gas T determines E, which determines level occupied)

Strength/flux: # of e^- in that level; composition/abundance

Width: intrinsic broadening;



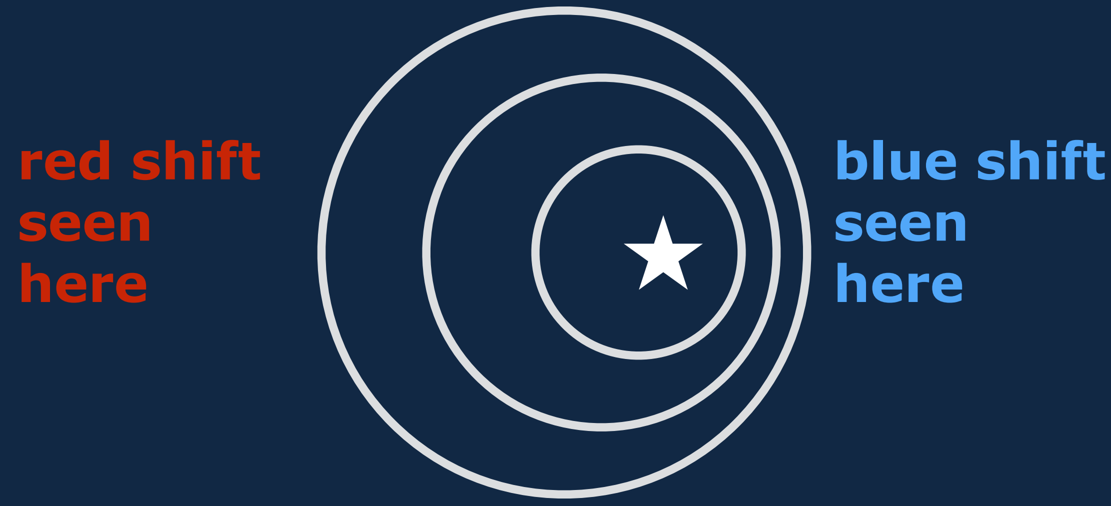
Making a Spectrum - Lines

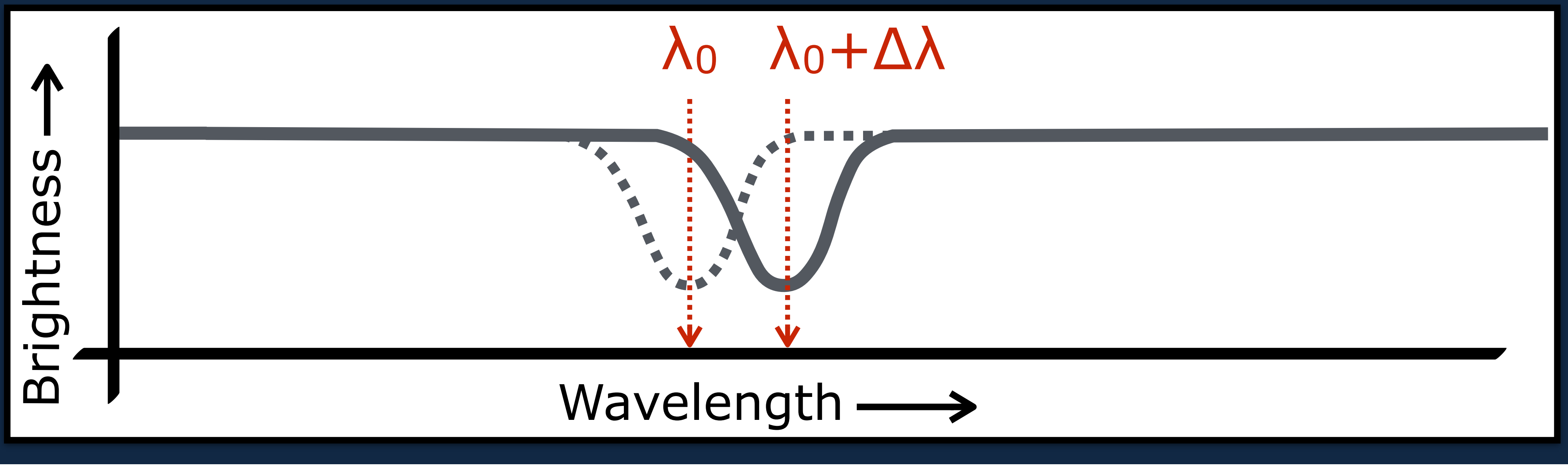
Doppler shift

If $v \ll c$, $\Delta\lambda/\lambda = v/c$

$\Delta\lambda$ = observed shift
v = velocity
λ = rest-frame wavelength
$c = 3\times10^5$ km/s

source moving right ⟶





Making a Spectrum - Lines

QUICK QUESTION

Imagine that this is a literal simulation, and that we’re watching a star move perfectly transverse to us. The star is emitting light at a wavelength λ_0.
What wavelength do we see as observers?

A) $\lambda_0 + \Delta\lambda$

B) $\lambda_0 - \Delta\lambda$

C) λ_0

D) Depends on the distance to the star.

Making a Spectrum - Lines

Doppler shift

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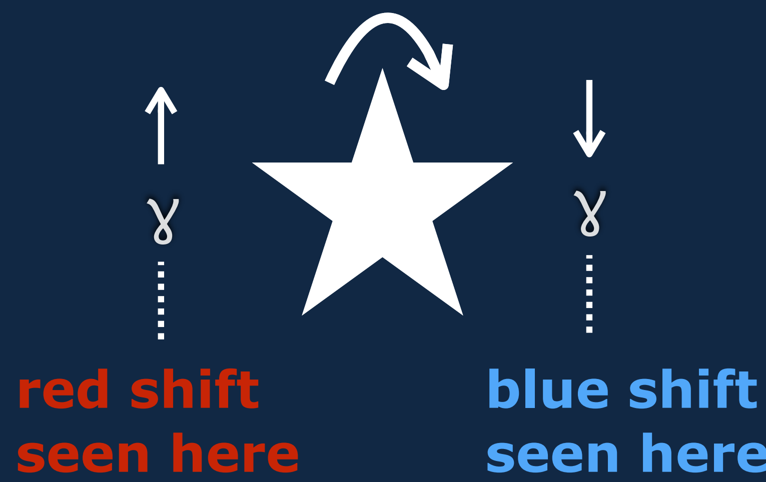

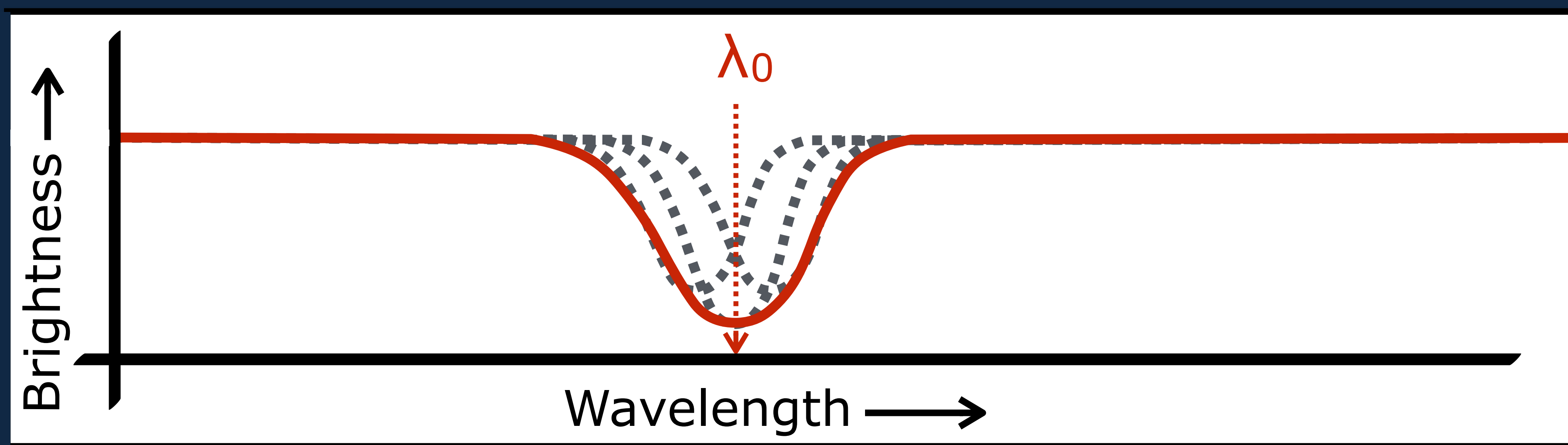

Making a Spectrum - Lines

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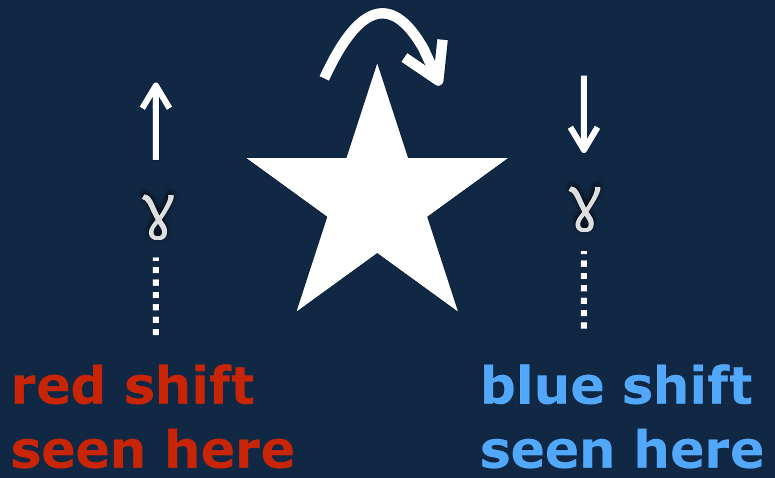


Uses in astronomy:

1) find radial velocity of star or galaxy
2) find rotation of planet or star
3) ID binary star(/planet) system

Making a Spectrum - Lines

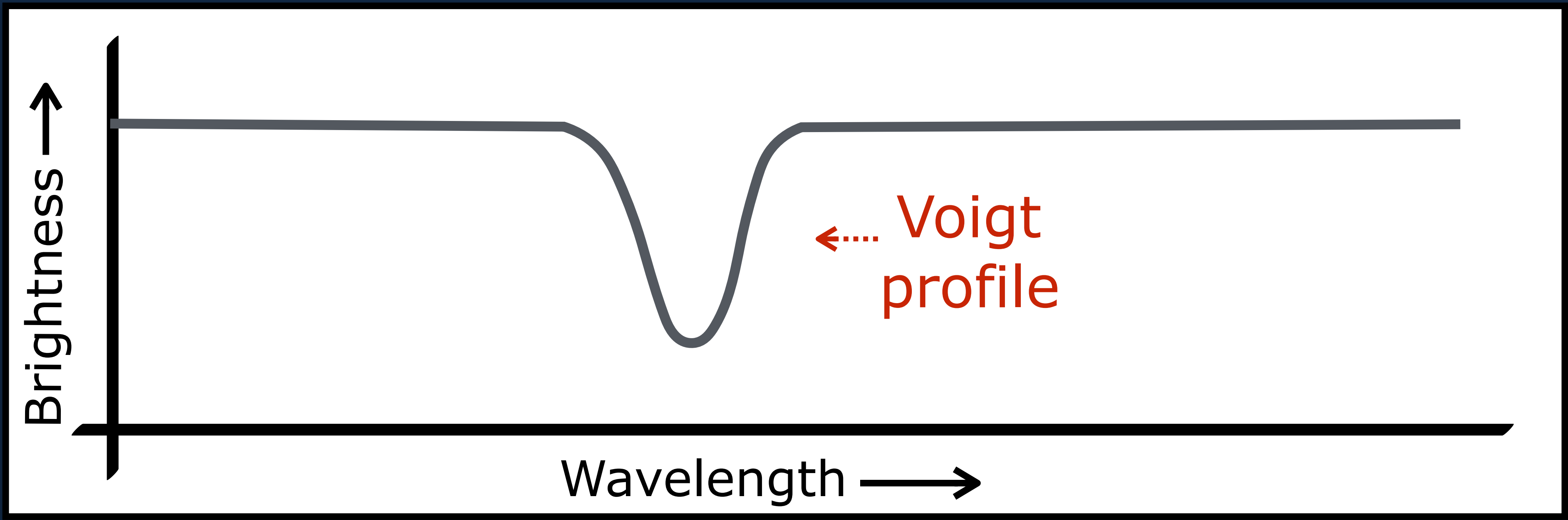
Anatomy of a spectral line

Rest-frame wavelength: composition; T
(gas T determines E, which determines level occupied)

Strength/flux: # of e^- in that level; composition/abundance

Width: intrinsic broadening; rotation; abundance

As we increase the # of absorbers, this line gets stronger/wider...



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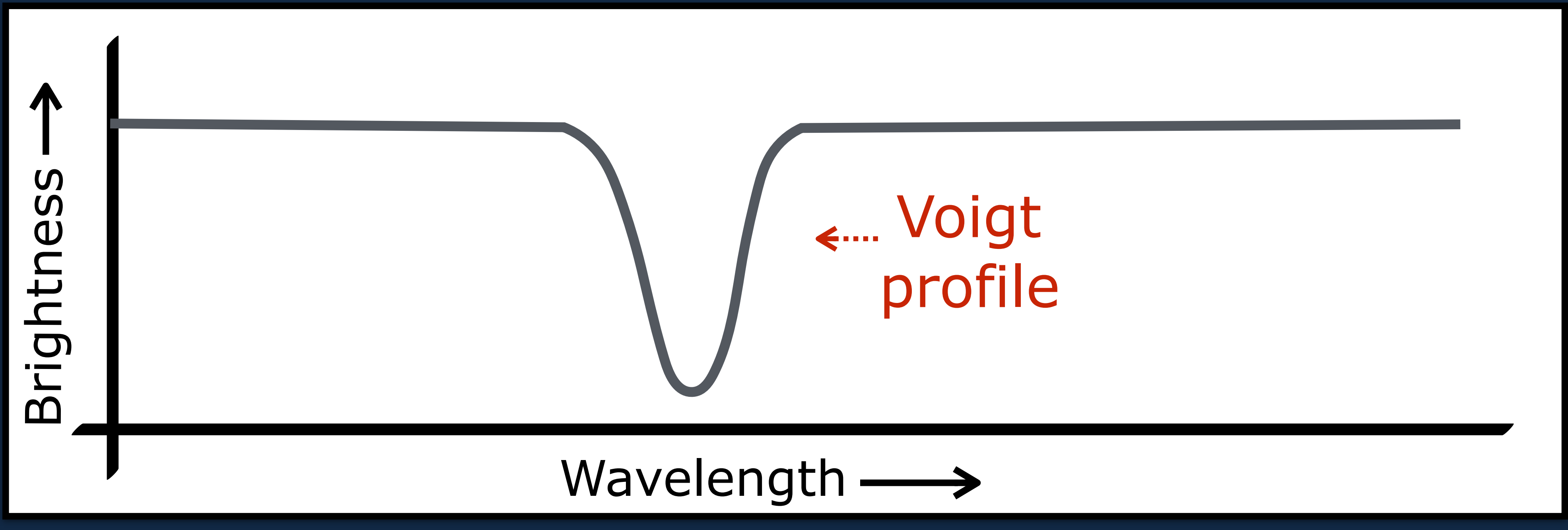

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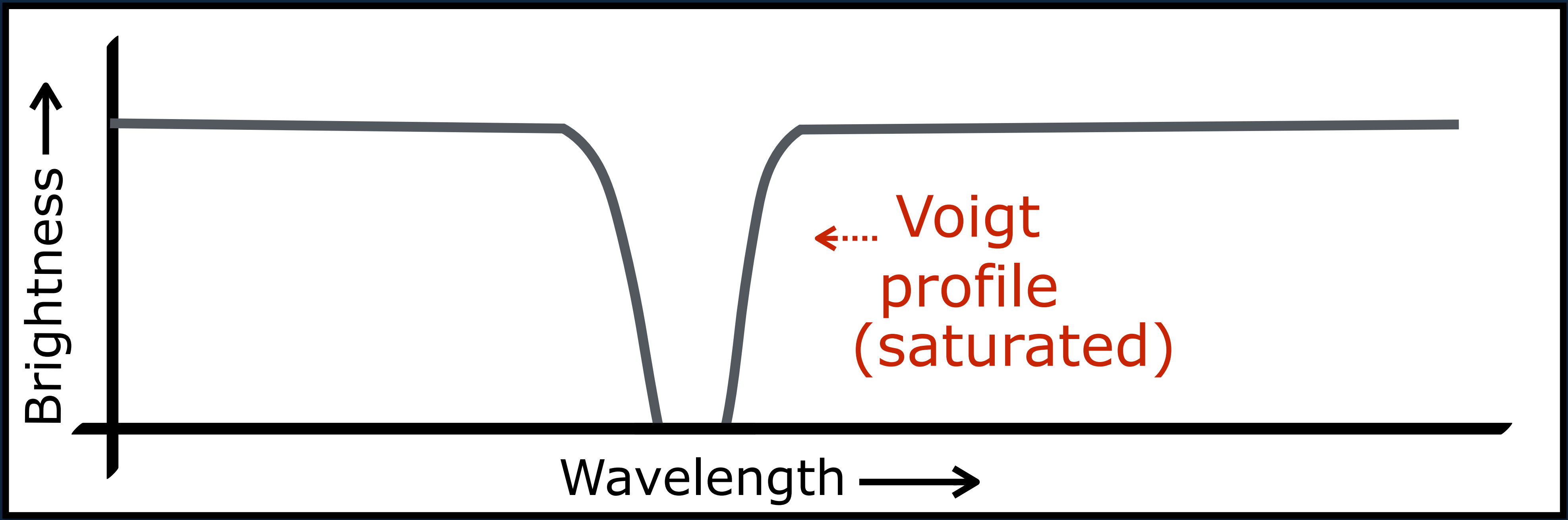

Making a Spectrum - Lines

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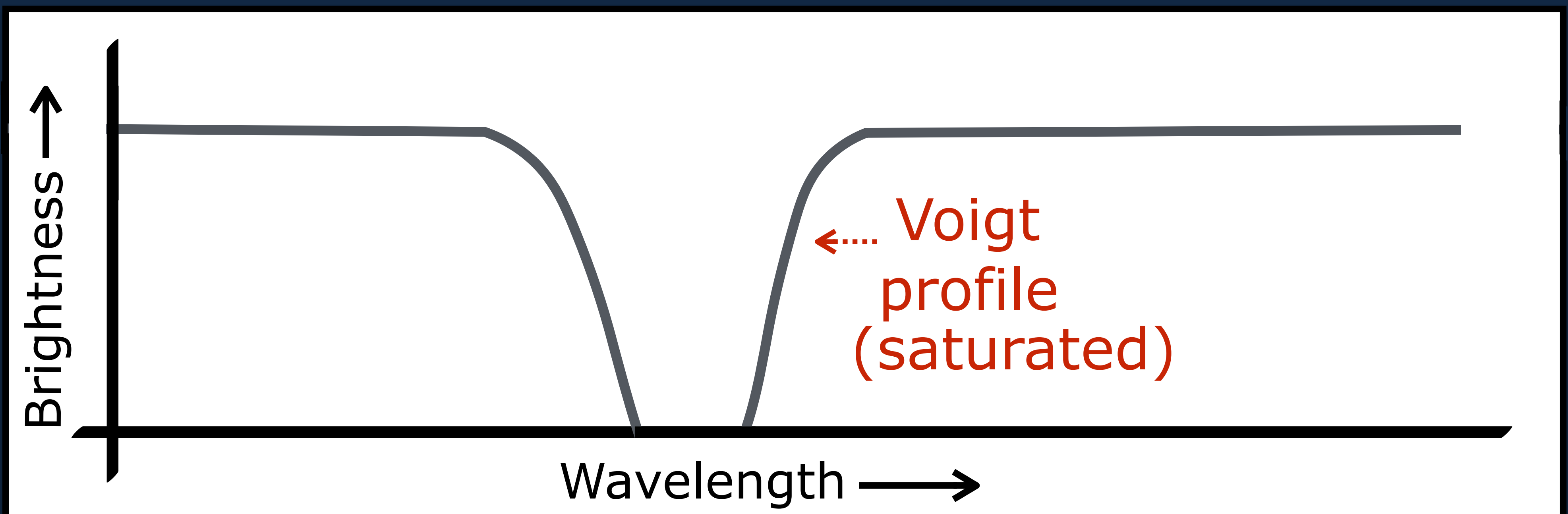
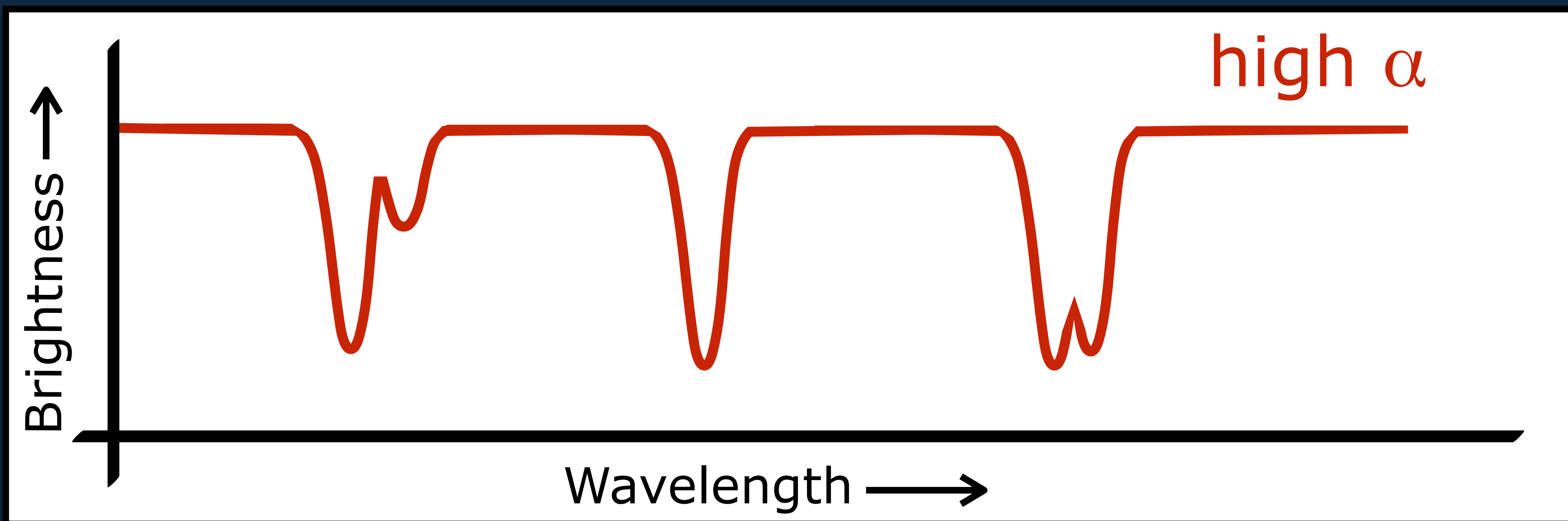


Making a Spectrum - Lines

Sources of Line Broadening

1) Heisenberg, pressure, thermal
2) Rotation
3) Abundance
4) Other stellar sources (turbulence, B fields)

(most important: instrumentation/resolution!)



Making a Spectrum - Lines

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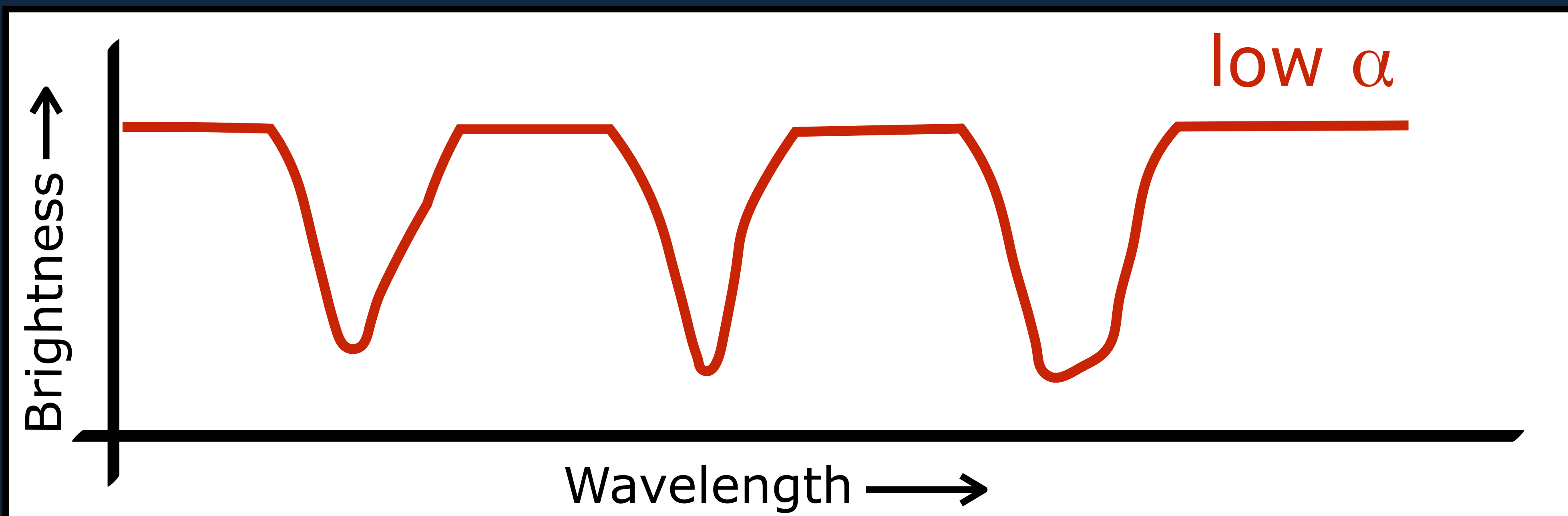


Spectra in Astronomy

Anatomy of a spectrum

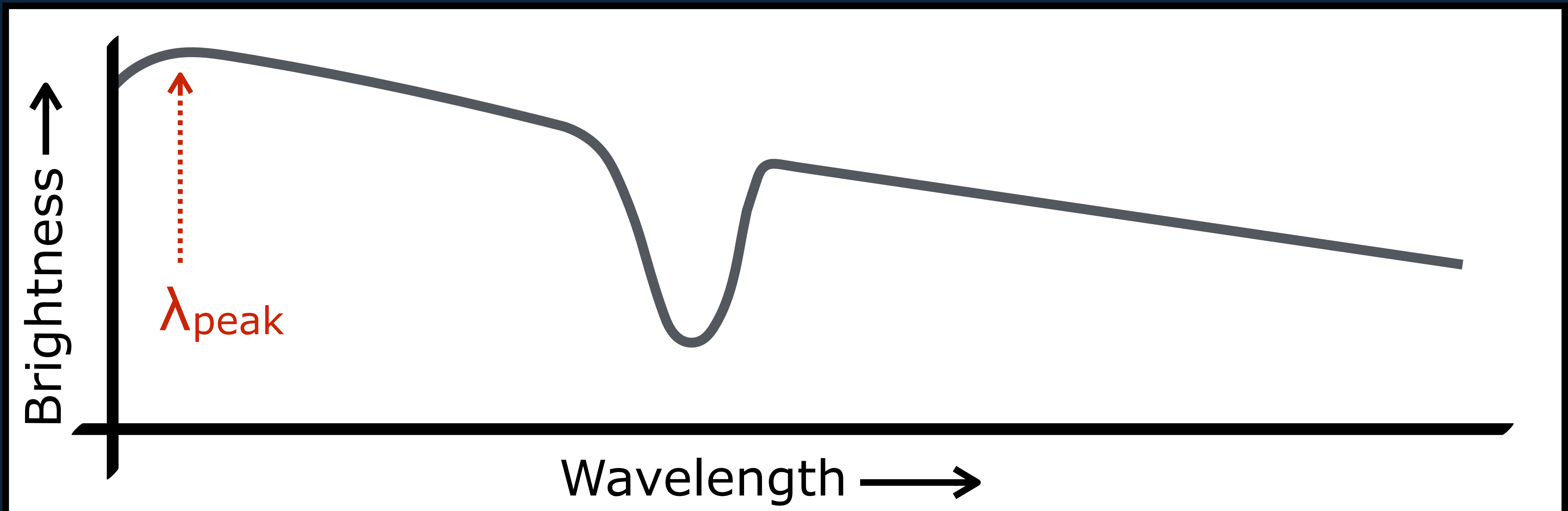
Rest-frame wavelength: composition; T
(gas T determines E, which determines level occupied)

Strength/flux: # of e^- in that level; composition/abundance

Width: intrinsic broadening; rotation; abundance; density; turbulence; B field; and more…

lines

Peak wavelength: T (blackbody, Wien's law) continuum



Spectra in Astronomy

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Width: intrinsic broadening; rotation; abundance; density; turbulence; B field; and more…

lines

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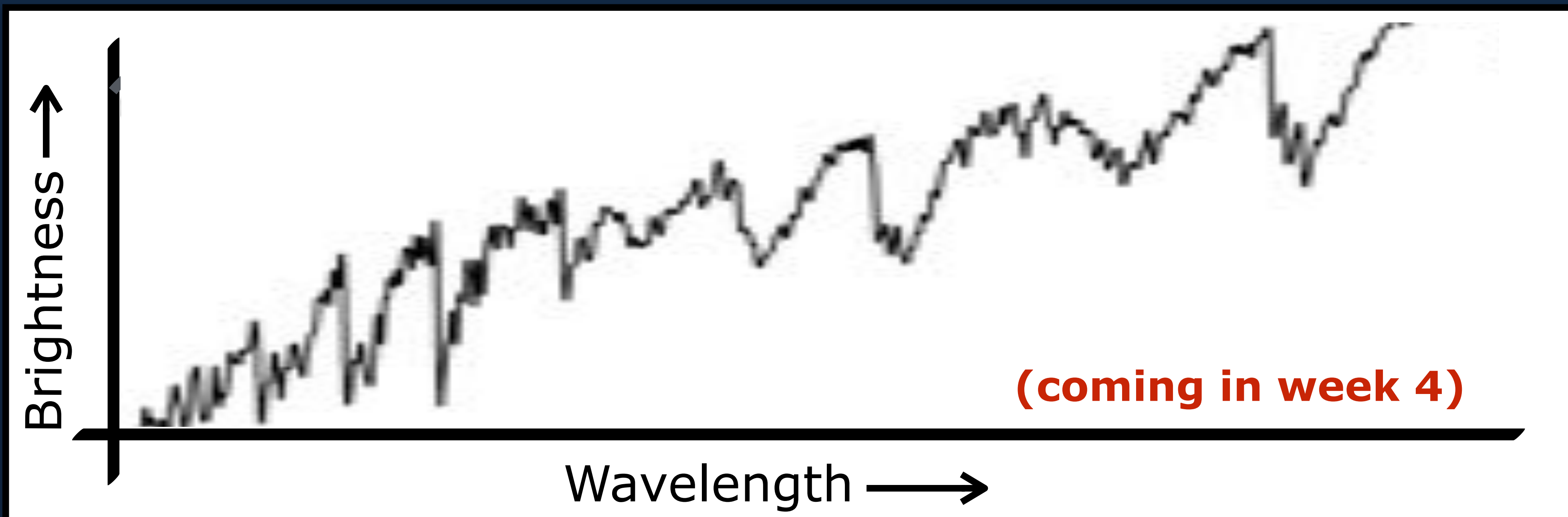


Spectra in Astronomy

Anatomy of a spectrum

A star's spectrum can give us its…

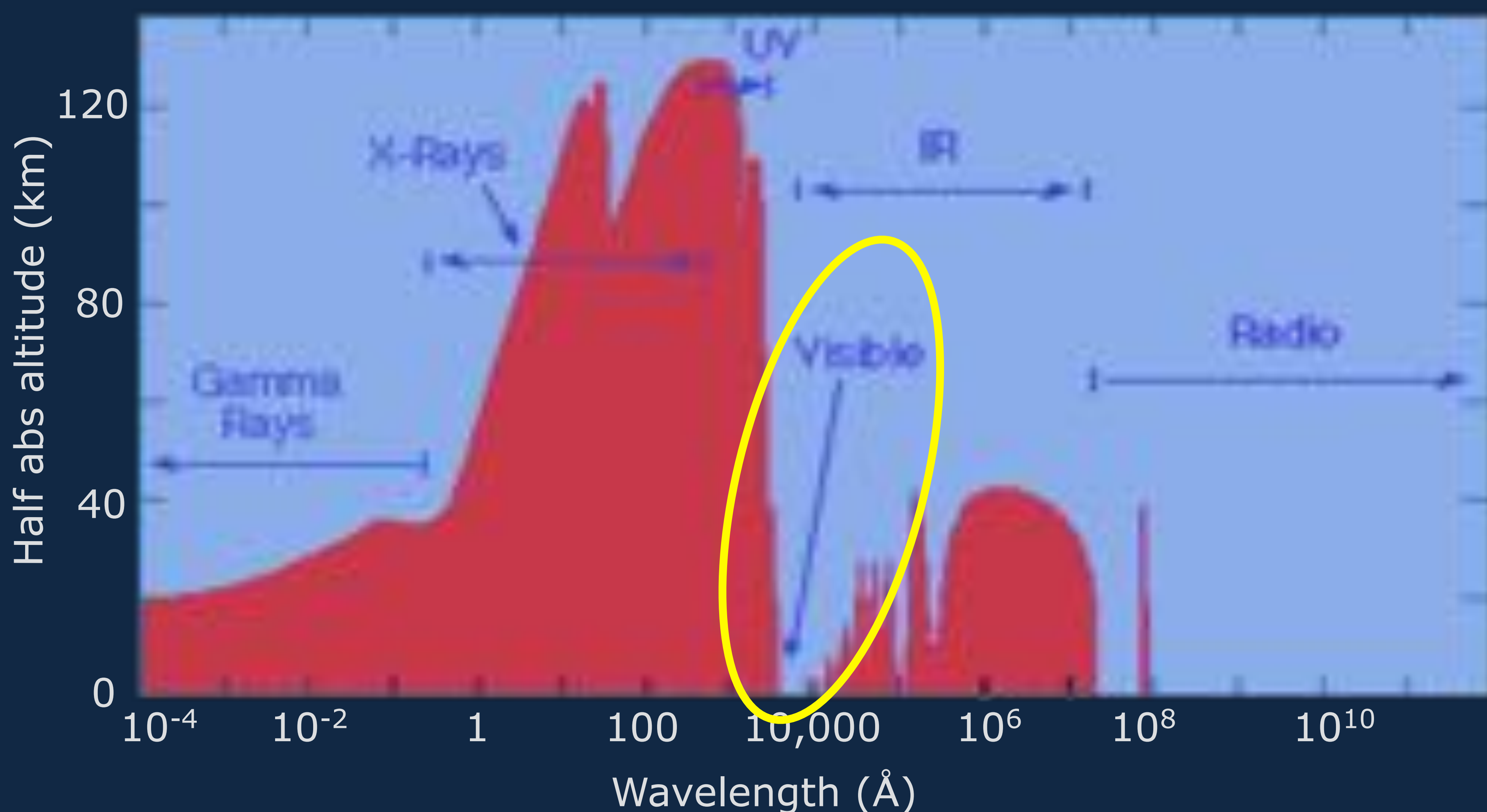
1) Distance
2) Velocity
3) Brightness
4) Temperature
5) Mass
6) Radius

(coming in week 4)

Spectra in Astronomy

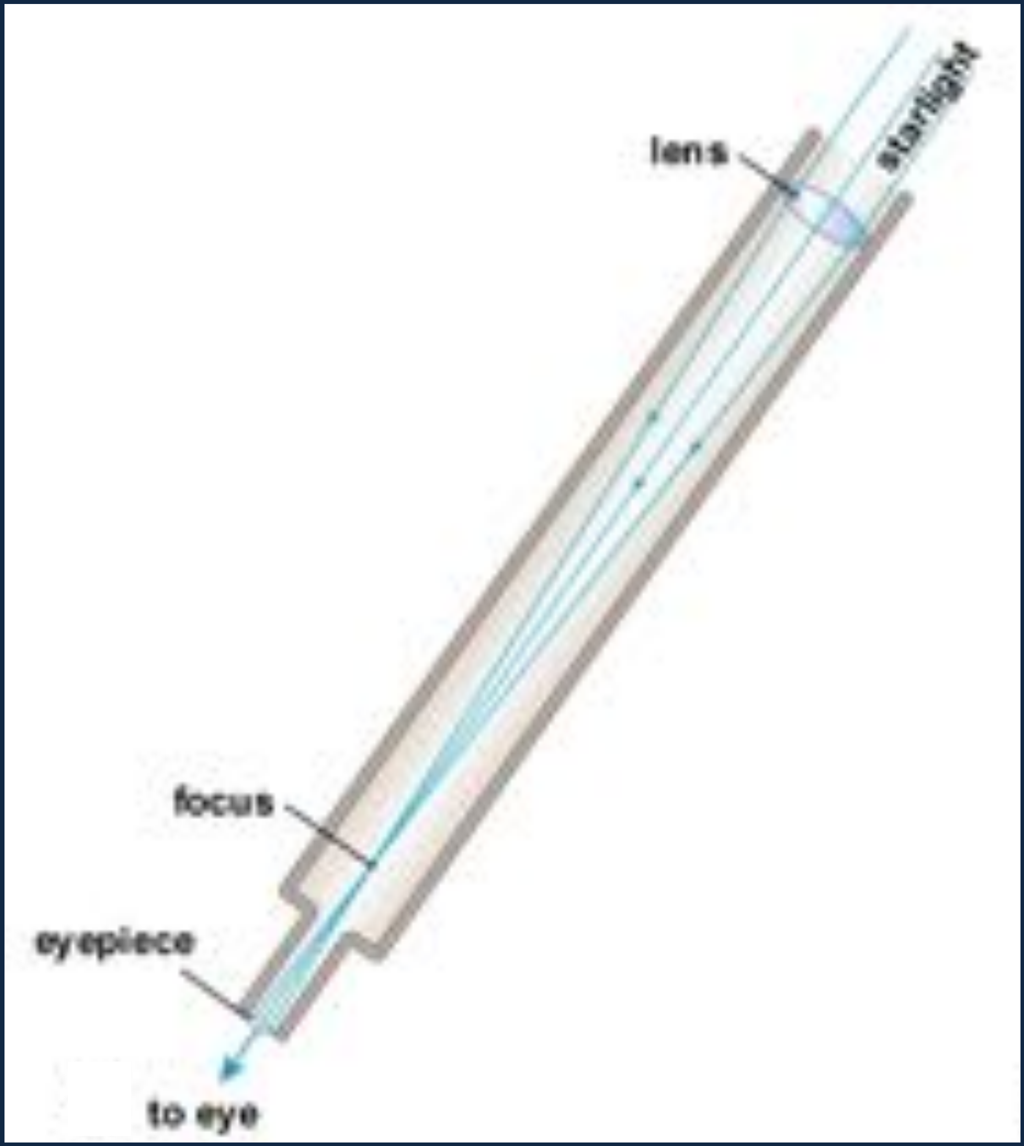
γ-ray	X-ray	UV	visible	IR	radio
MeV-TeV	keV	500Å-3000Å	4000Å-7000Å	~1μ-1000μ	1Hz - 3000GHz
GRB, SNe	XRBs, SN remnants	hot stars	most stars	cool stars, planets	molecular clouds

Spectra in Astronomy



Telescopes - Optics

Early telescopes were refractors…



Telescopes - Optics

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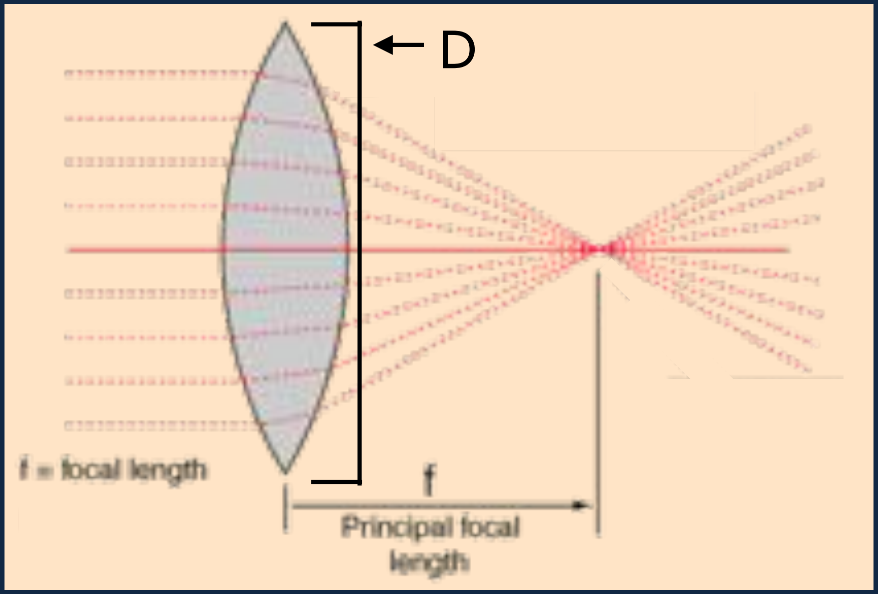
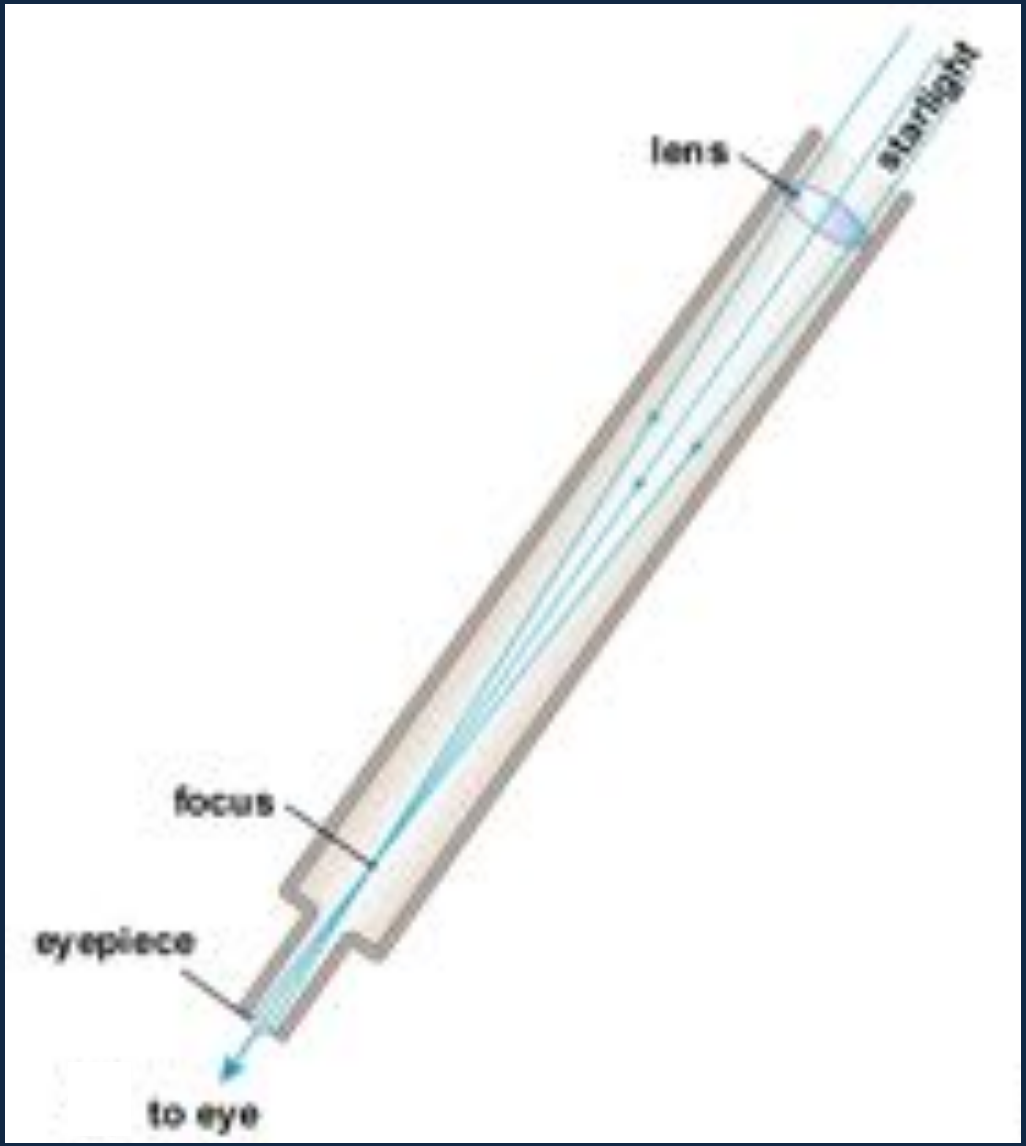




f-ratio = f/D

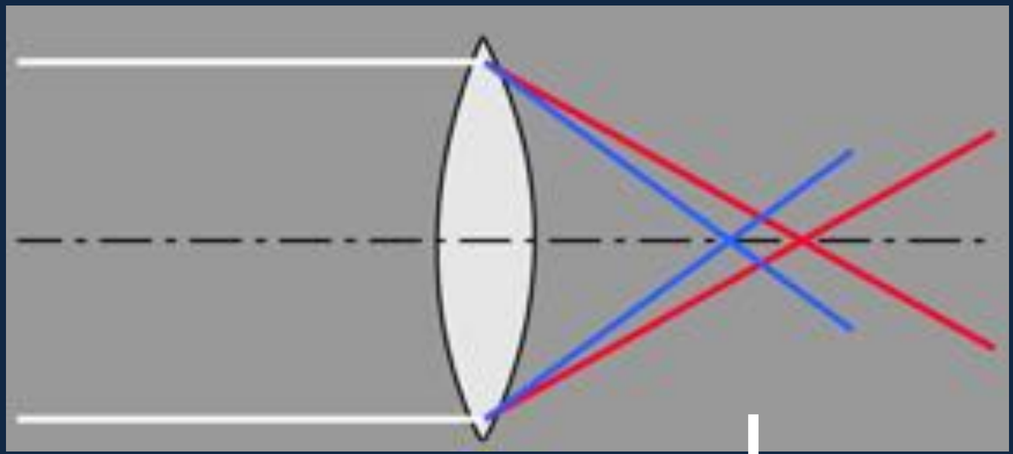
(smaller f-ratio = brighter image)

Telescopes - Optics

Early telescopes were refractors…

…but there were problems.

1) Chromatic aberration
(different wavelengths have different focal points)



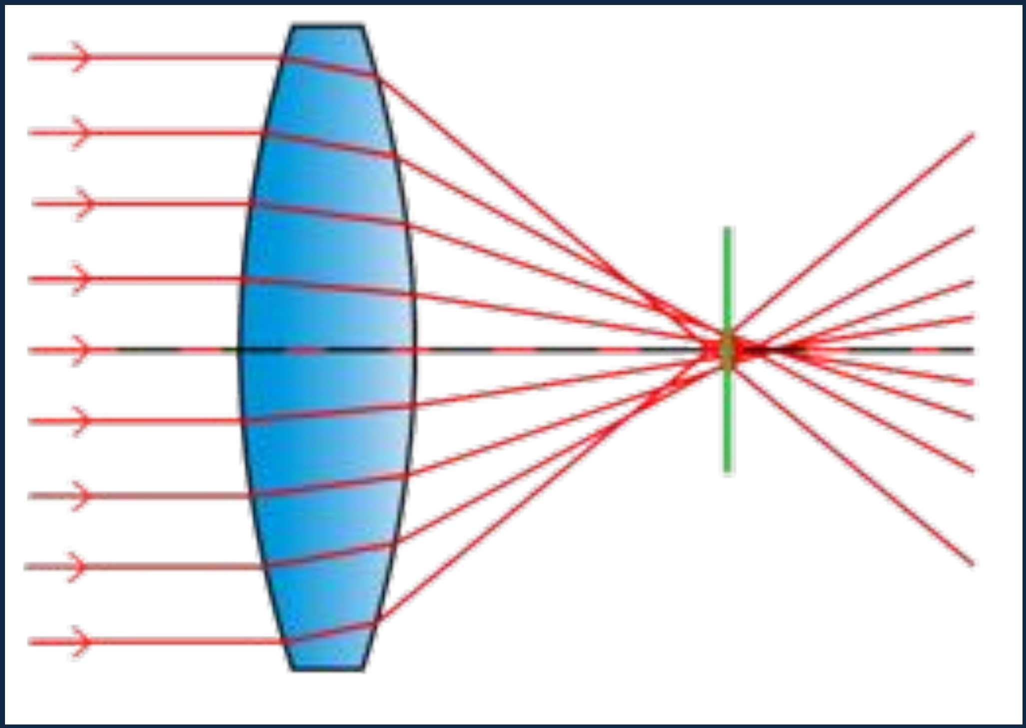
Telescopes - Optics

Early telescopes were refractors…

…but there were problems.

1) Chromatic aberration
(different wavelengths have different focal points)

2) Spherical aberration
(light entering a spherical lens at different apertures has different focal points)



Telescopes - Optics

Early telescopes were refractors…

…but there were problems.

1) Chromatic aberration
(different wavelengths have different focal points)

2) Spherical aberration
(light entering a spherical lens at different apertures has different focal points)

lessens with high f-ratio (f/D)

Telescopes - Optics

Discussion Question

You'd like to build a "better" refracting telescope, but you have a limited engineering budget. Would you rather…

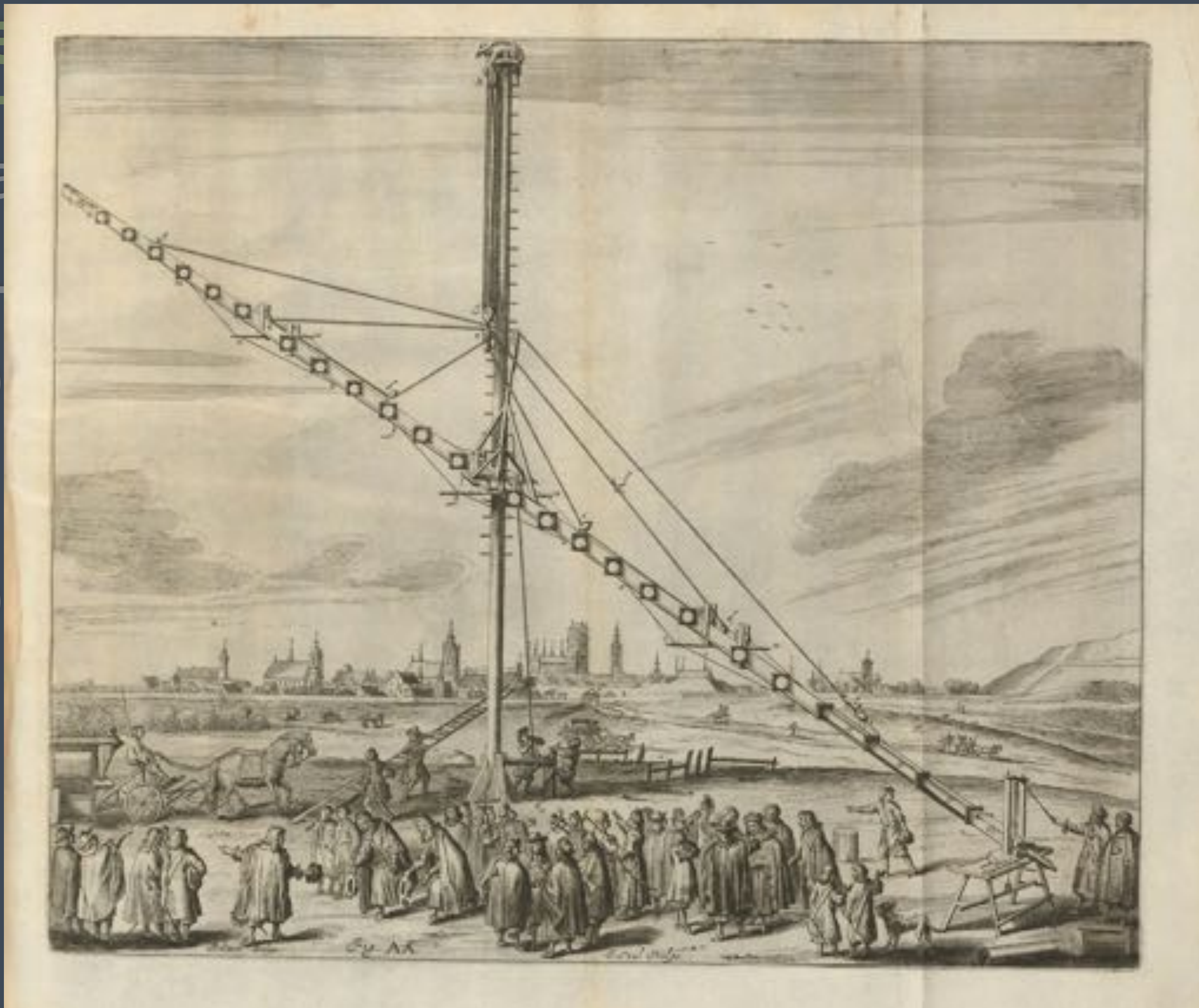
A) Increase the focal length (higher f-ratio, so less aberration)
B) Increase the lens diameter (lower f-ratio, so brighter image)
C) Decrease the lens diameter (higher f-ratio, so less aberration)
D) Sell it and buy a mirror for a reflecting telescope

Te

Ea

1)

2)



Hevelius 150 ft. long telescope, 1673

Telescopes - Optics

Early telescopes were refractors…

…but there were problems.

1) Chromatic aberration
   (different wavelengths
   have different focal points)

2) Spherical aberration
   (light entering a spherical
   lens at different apertures
   has different focal points)

3) Large lenses are difficult
   Image brightness increases as D^2, but…
   a) Lens sag
   b) glass must be *perfect*

Telescopes - Optics

Early telescopes were refractors…

…but there were problems. Using mirrors…

1) ~~Chromatic aberration (different wavelengths have different focal points)~~ gone!

2) ~~Spherical aberration (light entering a spherical lens at different apertures has different focal points)~~ fixable…

3) ~~Large lenses are difficult~~ way easier to build…

Image brightness increases as D^2, but…

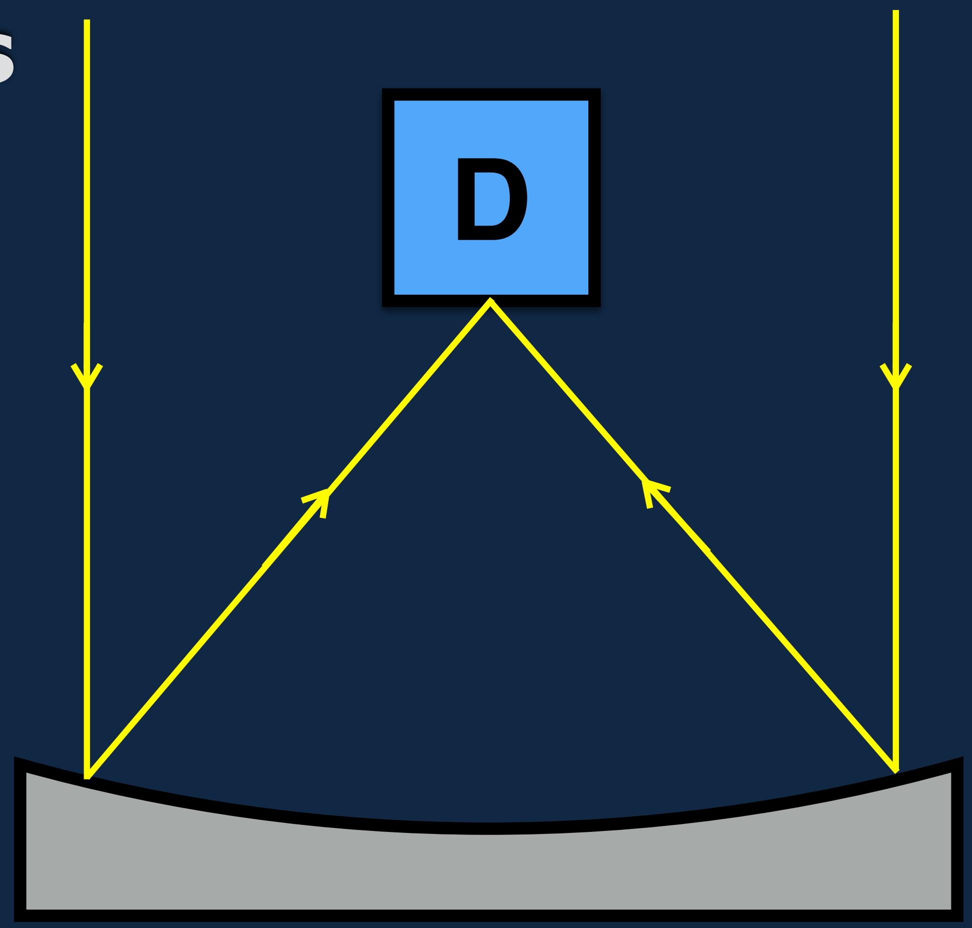
a) ~~Lens sag~~ easily fixed!

b) ~~glass must be *perfect*~~ only the surface matters!

Telescopes - Optics

Reflecting Telescope Designs

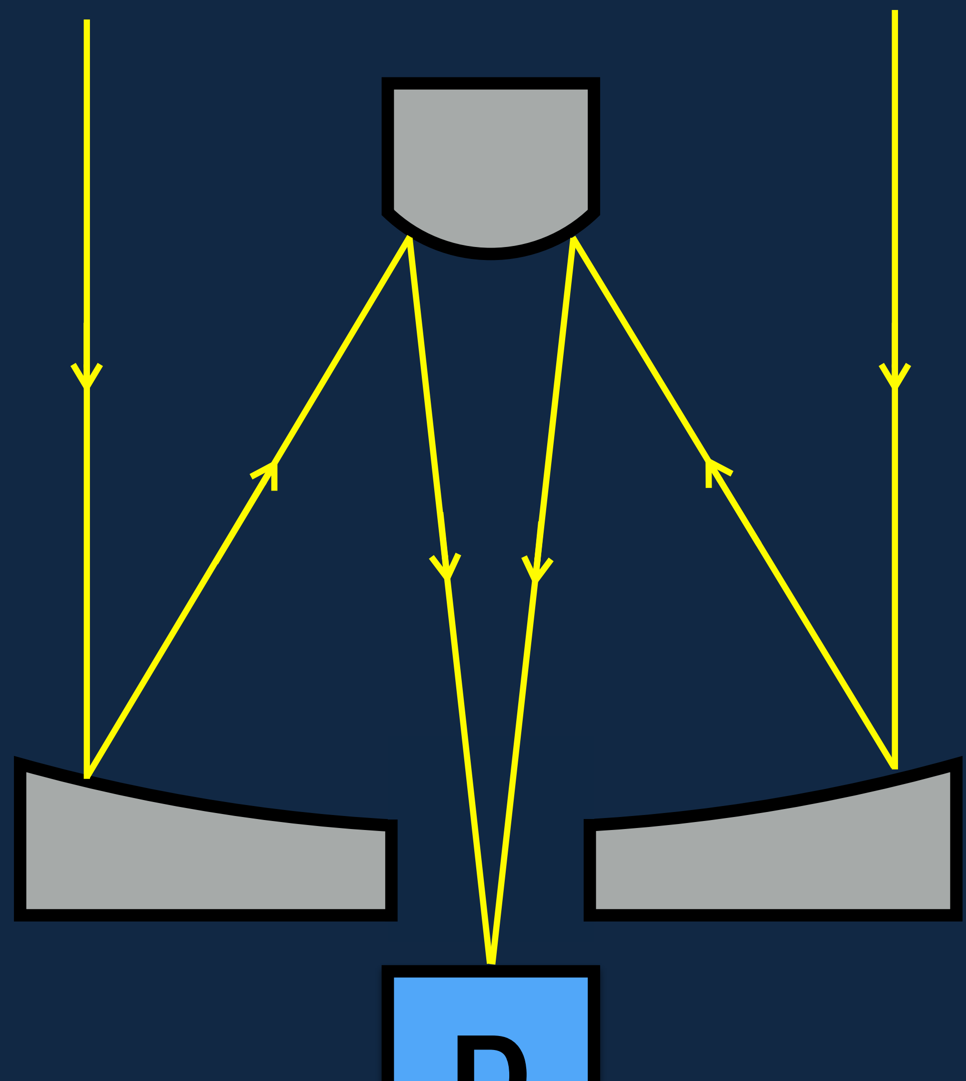
Prime focus



Telescopes - Optics

Reflecting Telescope Designs

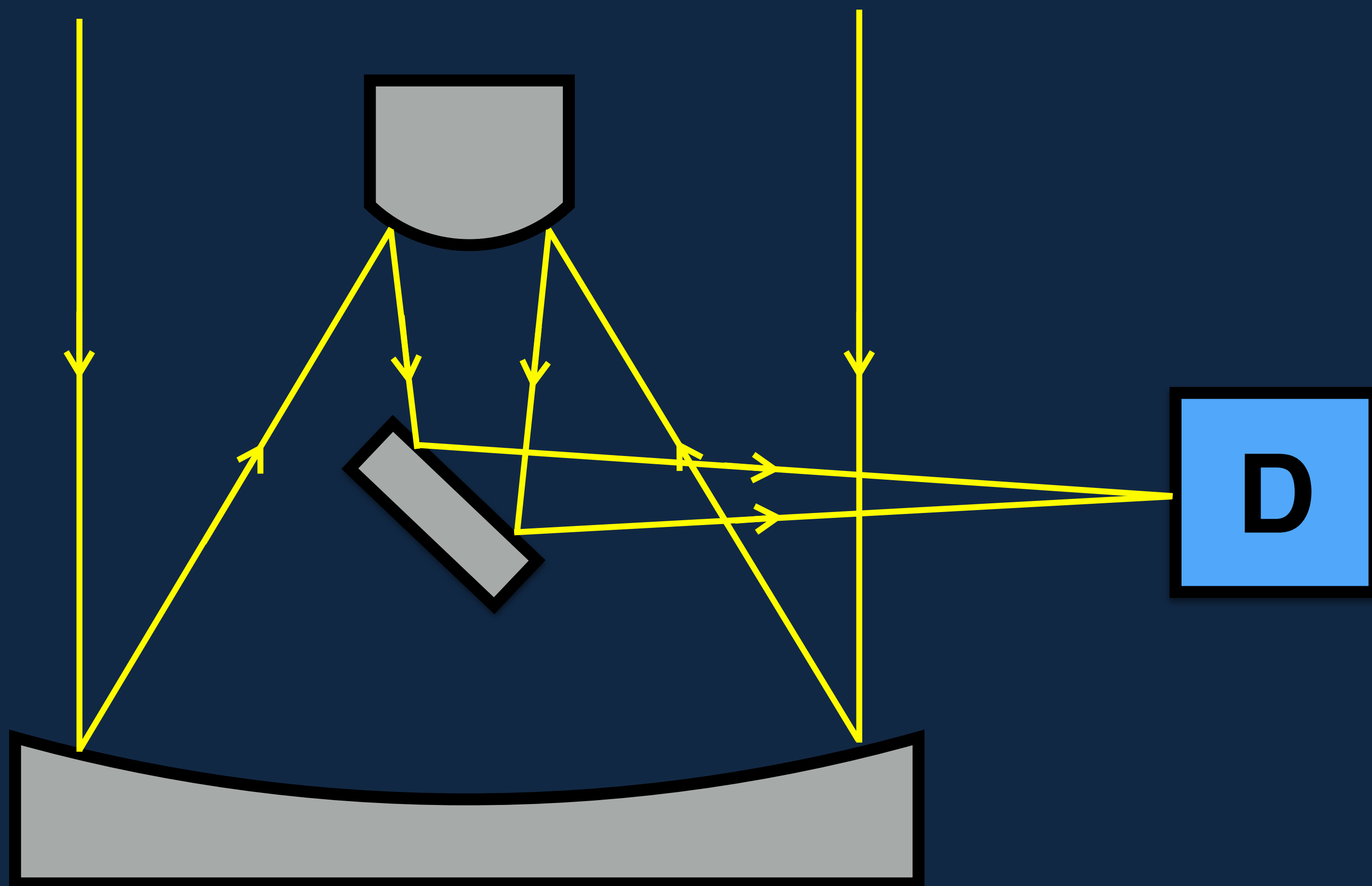
Cassegrain



Telescopes - Optics

Reflecting Telescope Designs

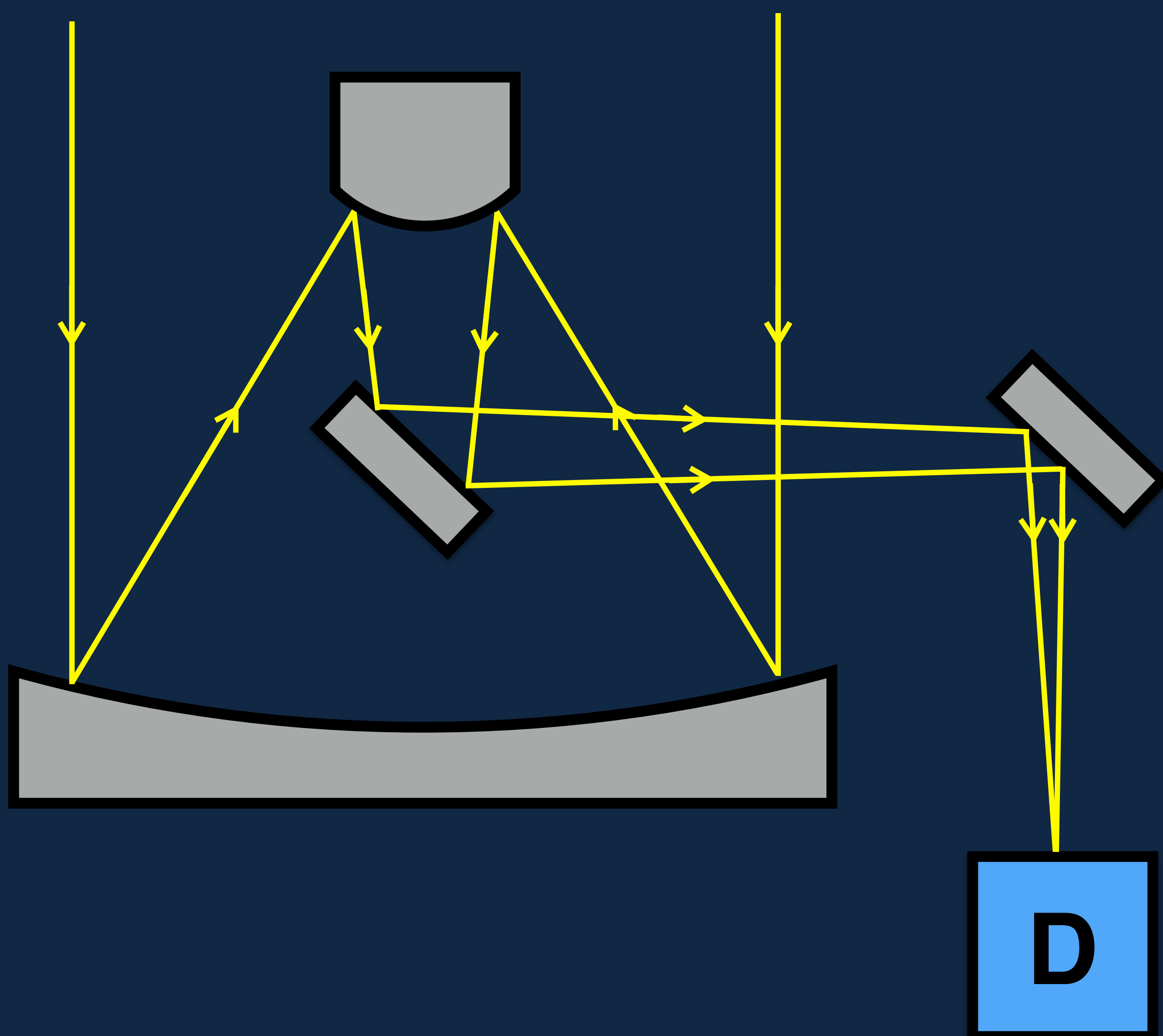
Nasmyth



Telescopes - Optics

Reflecting Telescope Designs

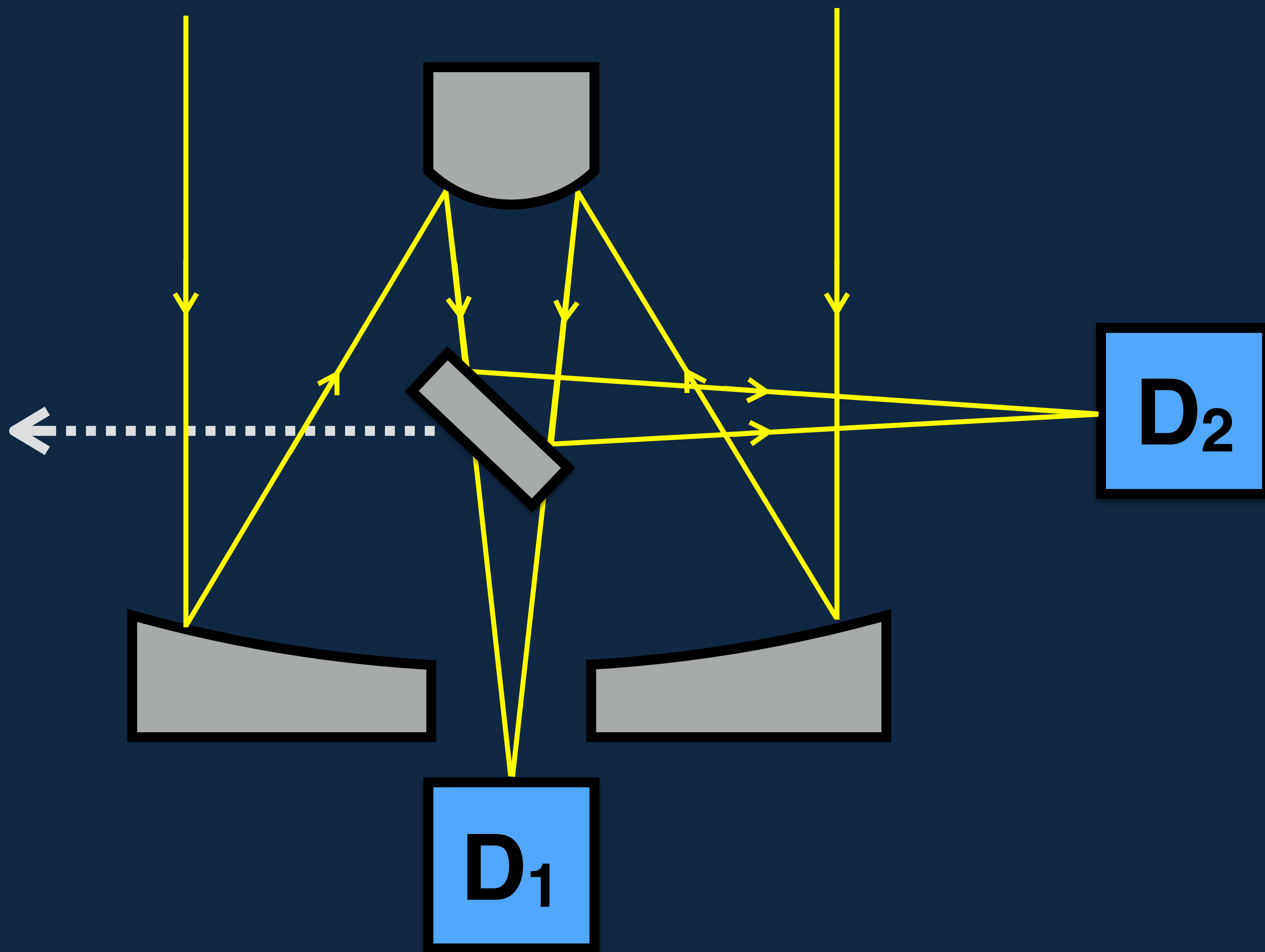
Coudé



Telescopes - Optics

Reflecting Telescope Designs

Reality: multiple

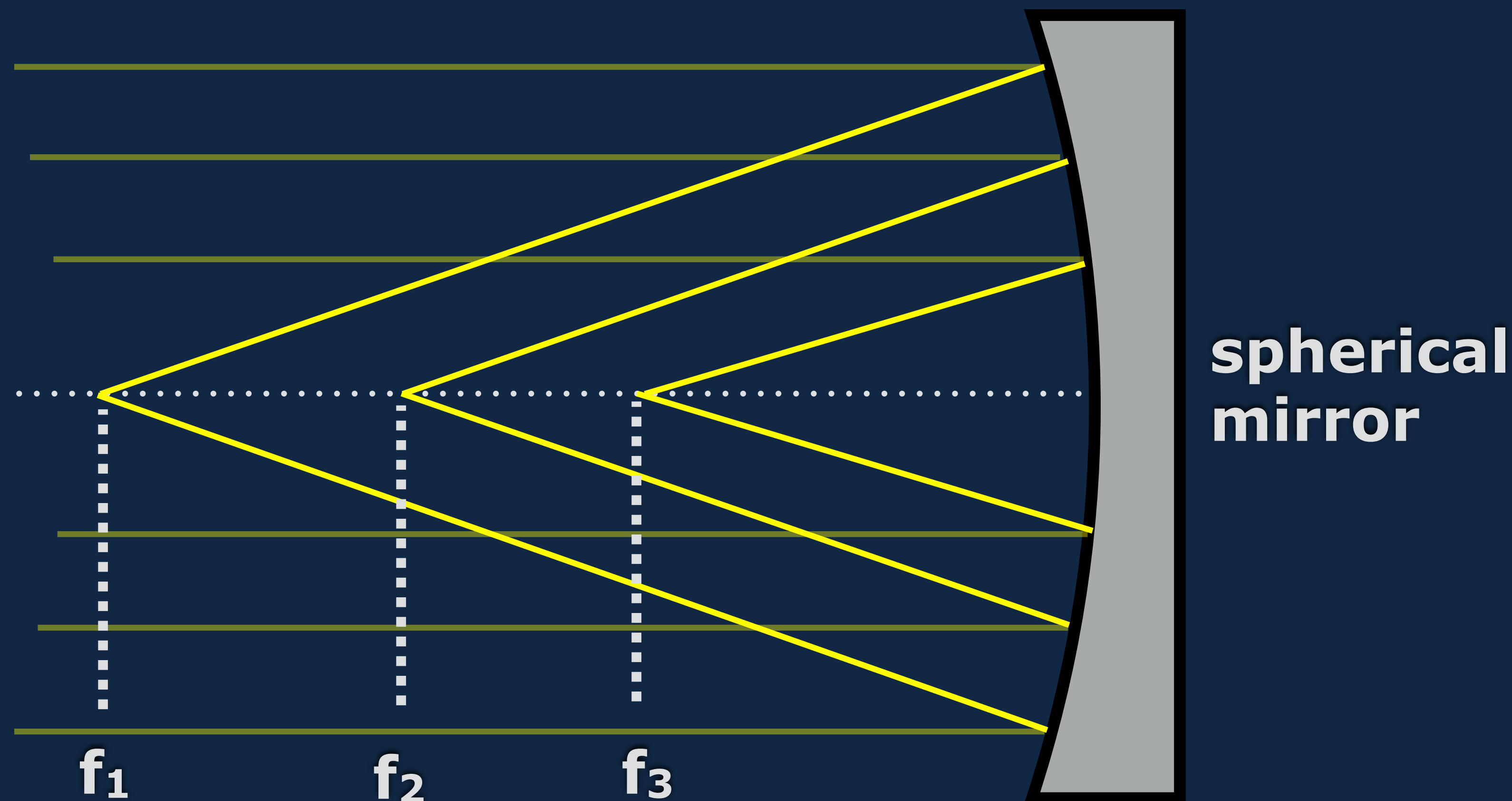


Telescopes - Optics

Reflecting Telescope Designs

There are still a few issues…

1) Spherical aberration

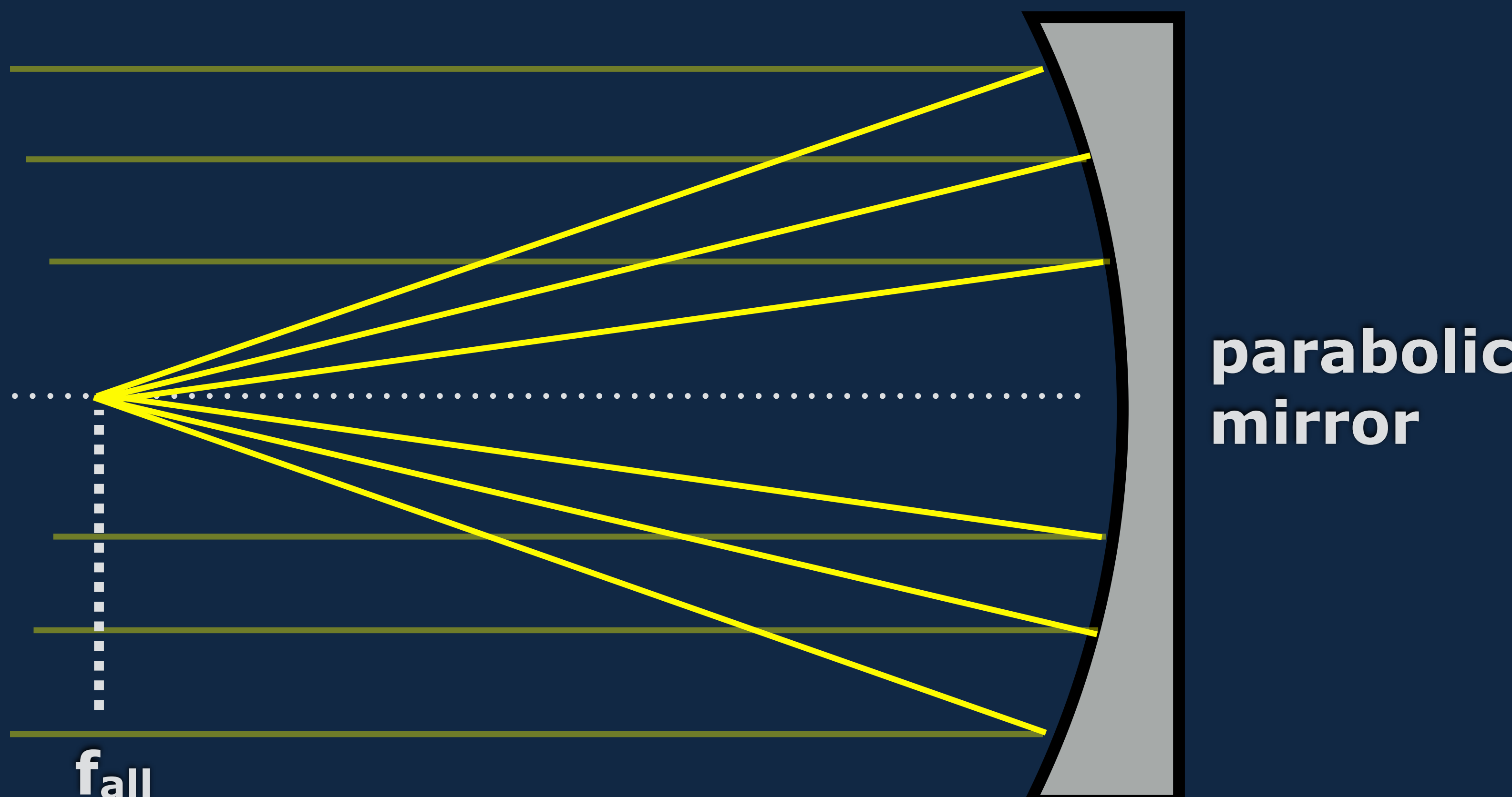


Telescopes - Optics

<u>Reflecting Telescope Designs</u>

There are still a few issues…

1) Spherical aberration



Telescopes - Optics

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mirror oven, University of Arizona Mirror Lab

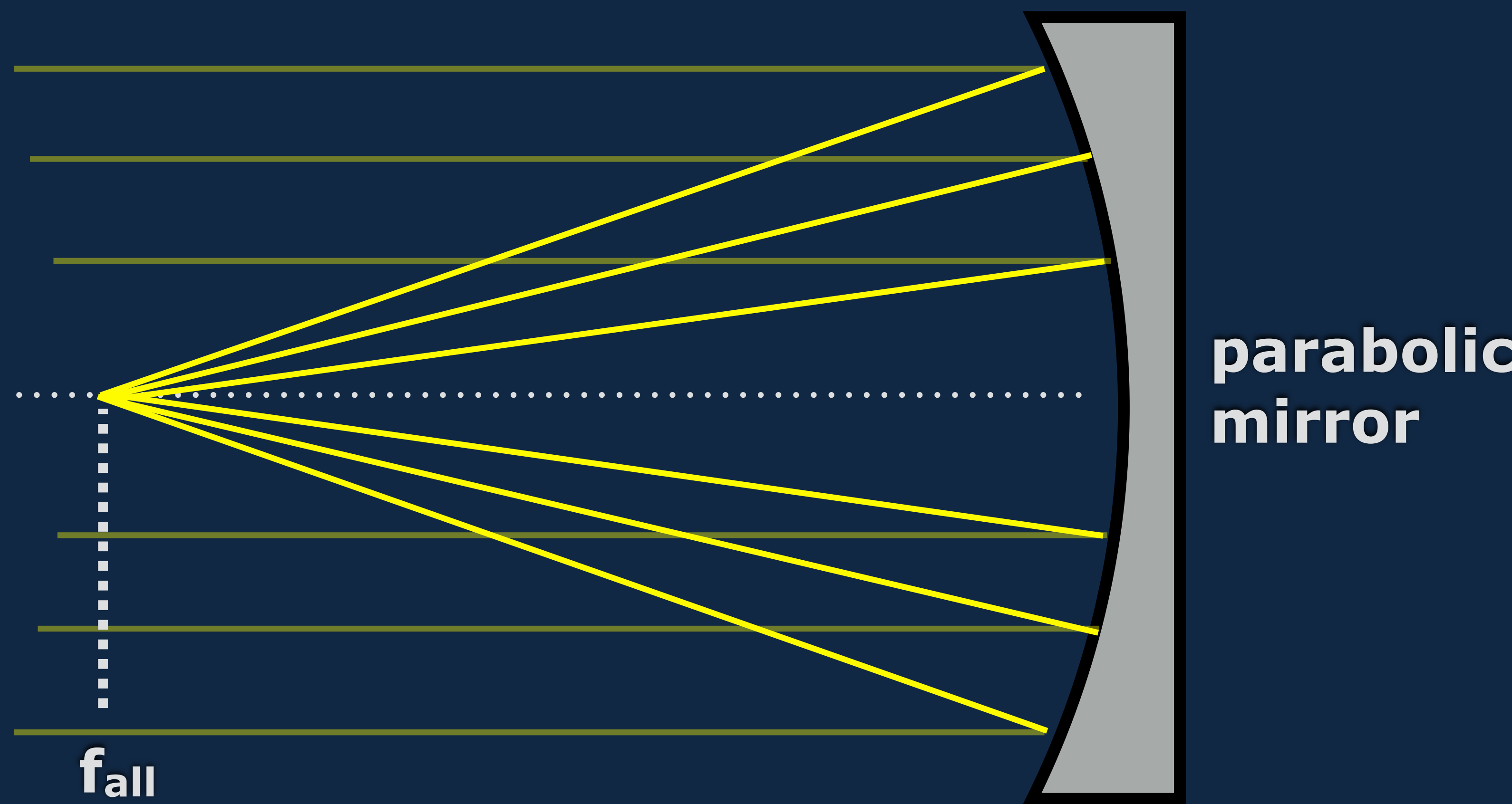
Telescopes - Optics

Reflecting Telescope Designs

There are still a few issues…

1) Spherical aberration

Required precision~**1/20λ** →20nm visible, 5cm radio



Telescopes - Optics

Reflecting Telescope Designs

Mirror’s edge too flat by ~0.002mm

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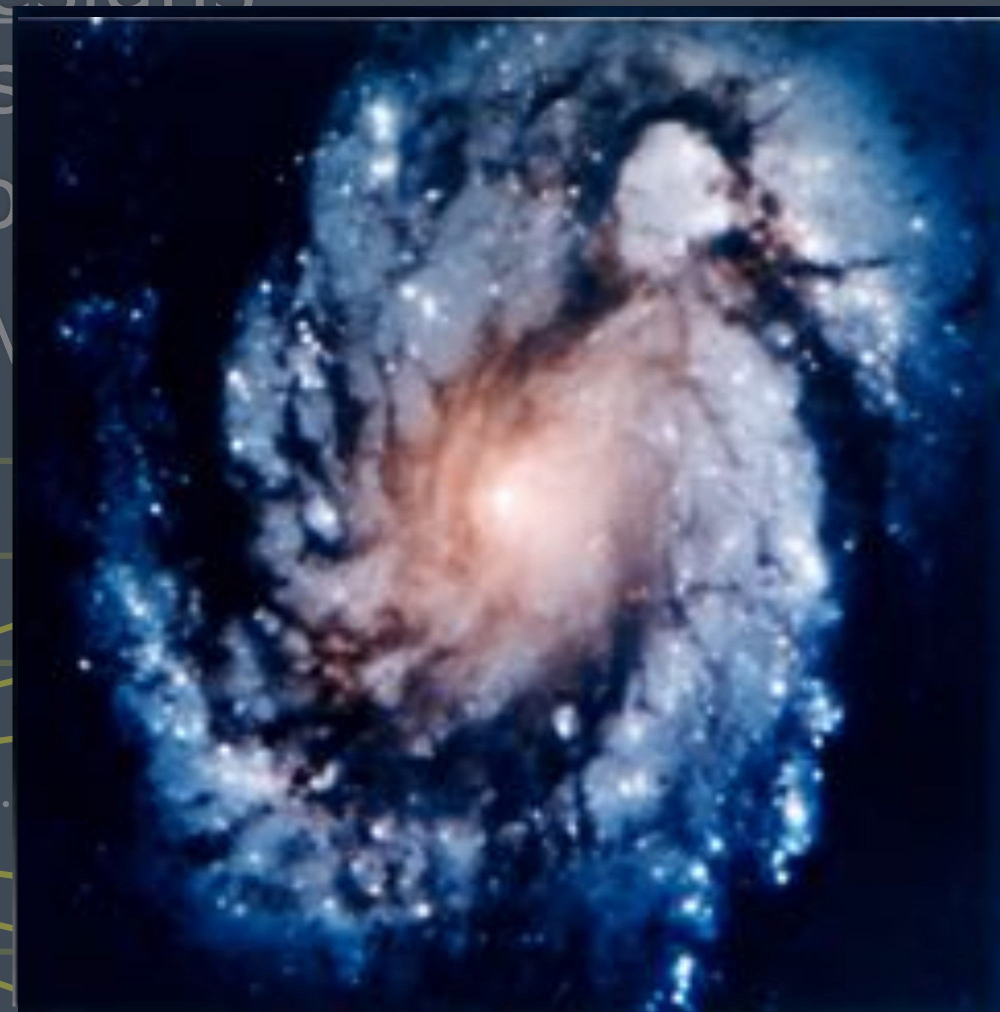
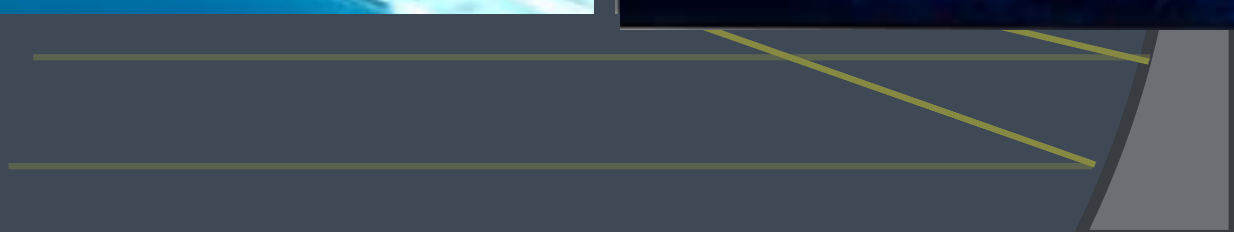
Story Musgrave and Jeff Hoffman repairing Hubble, 1993

Telescopes - Optics

Reflecting Telescope Designs





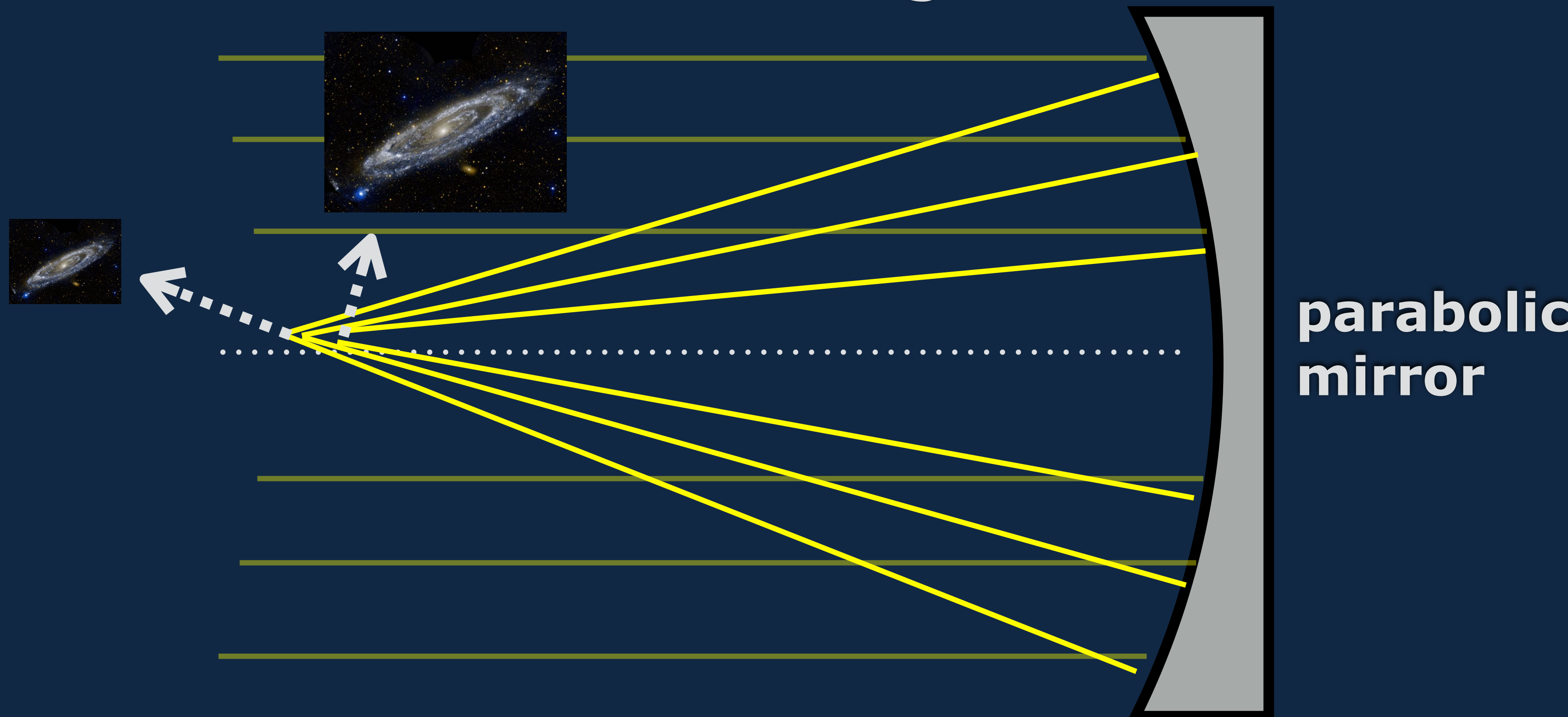
Telescopes - Optics

Reflecting Telescope Designs

There are still a few issues…

1) Spherical aberration

2) Coma - variation in magnification



Telescopes - Optics

Reflecting Telescope Designs

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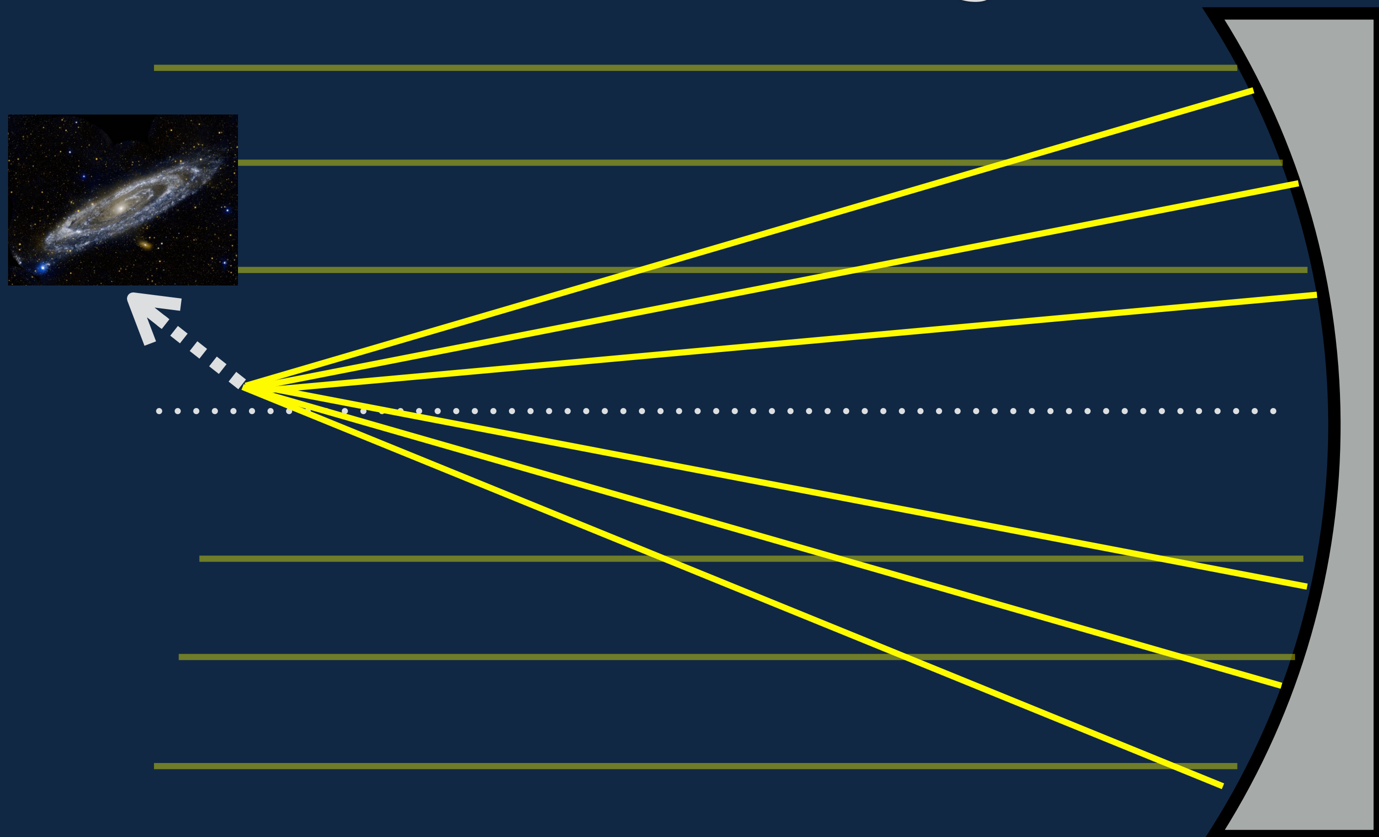


hyperbolic mirror

Telescopes - Optics

Reflecting Telescope Designs

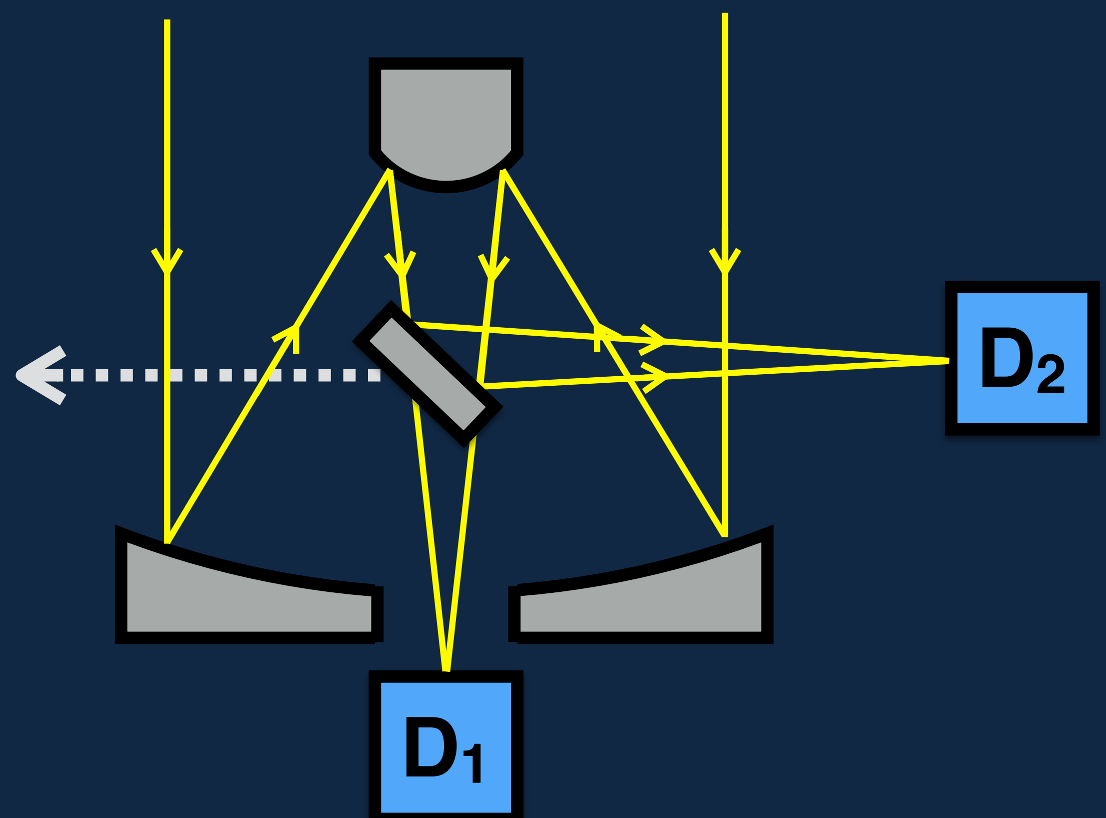
There are still a few issues…

1) Spherical aberration

2) Coma - variation in magnification

Ritchey-Chrétien

(hyperbolic primary and secondary)



Telescopes - Optics

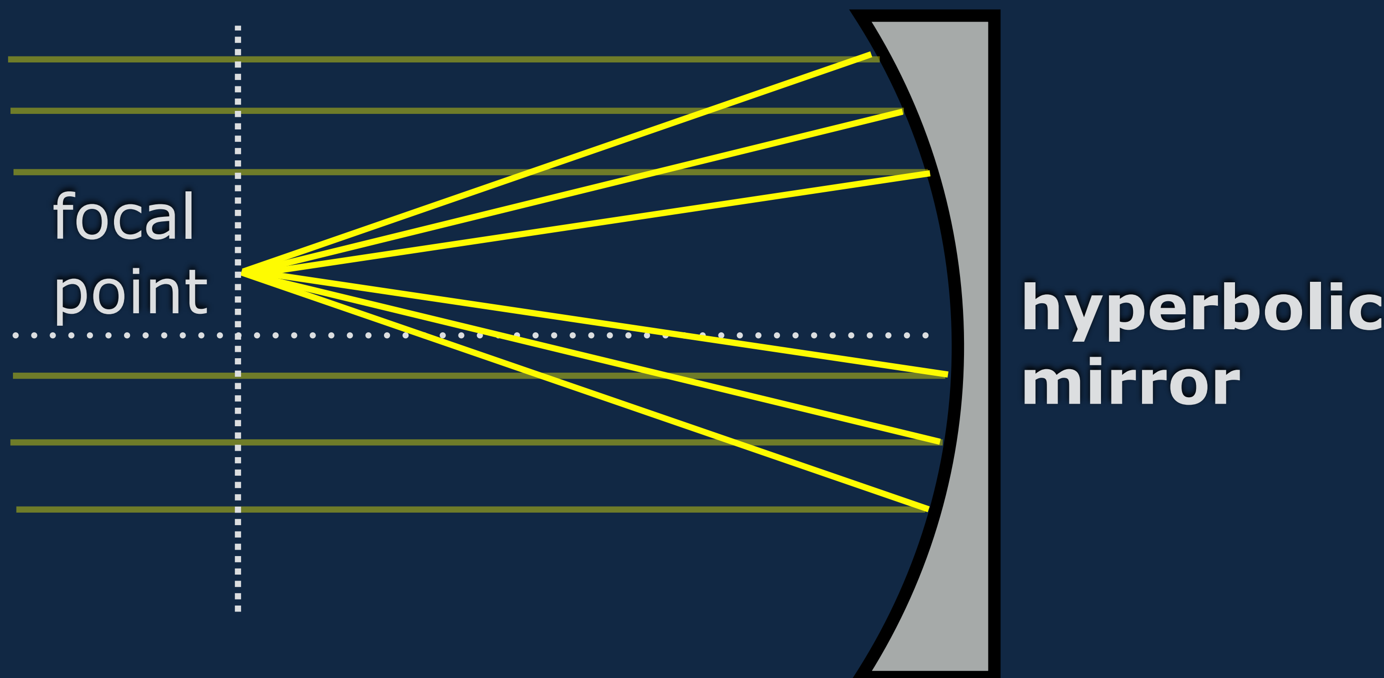
Reflecting Telescope Designs

There are still a few issues…

1) Spherical aberration

2) Coma - variation in magnification

3) Astigmatism - variation in focus w/ plane



Telescopes - Optics

Reflecting Telescope Designs

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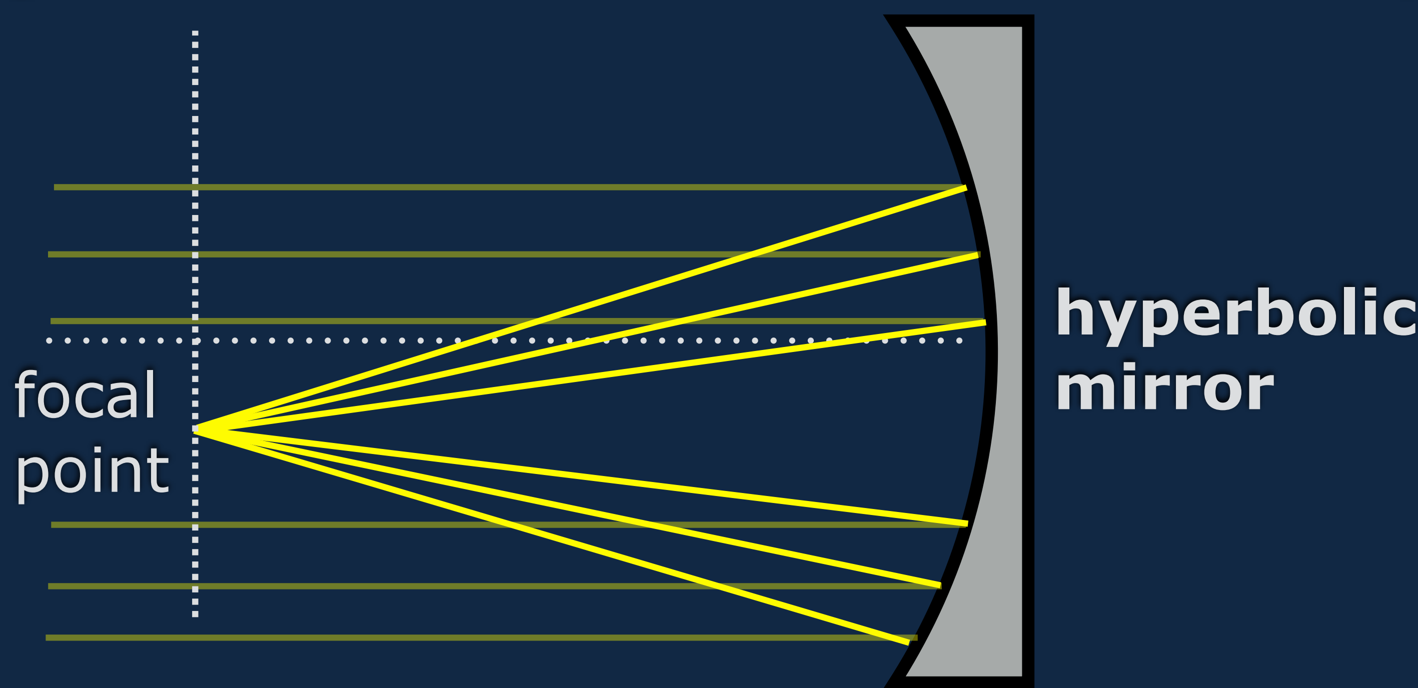

Telescopes - Optics

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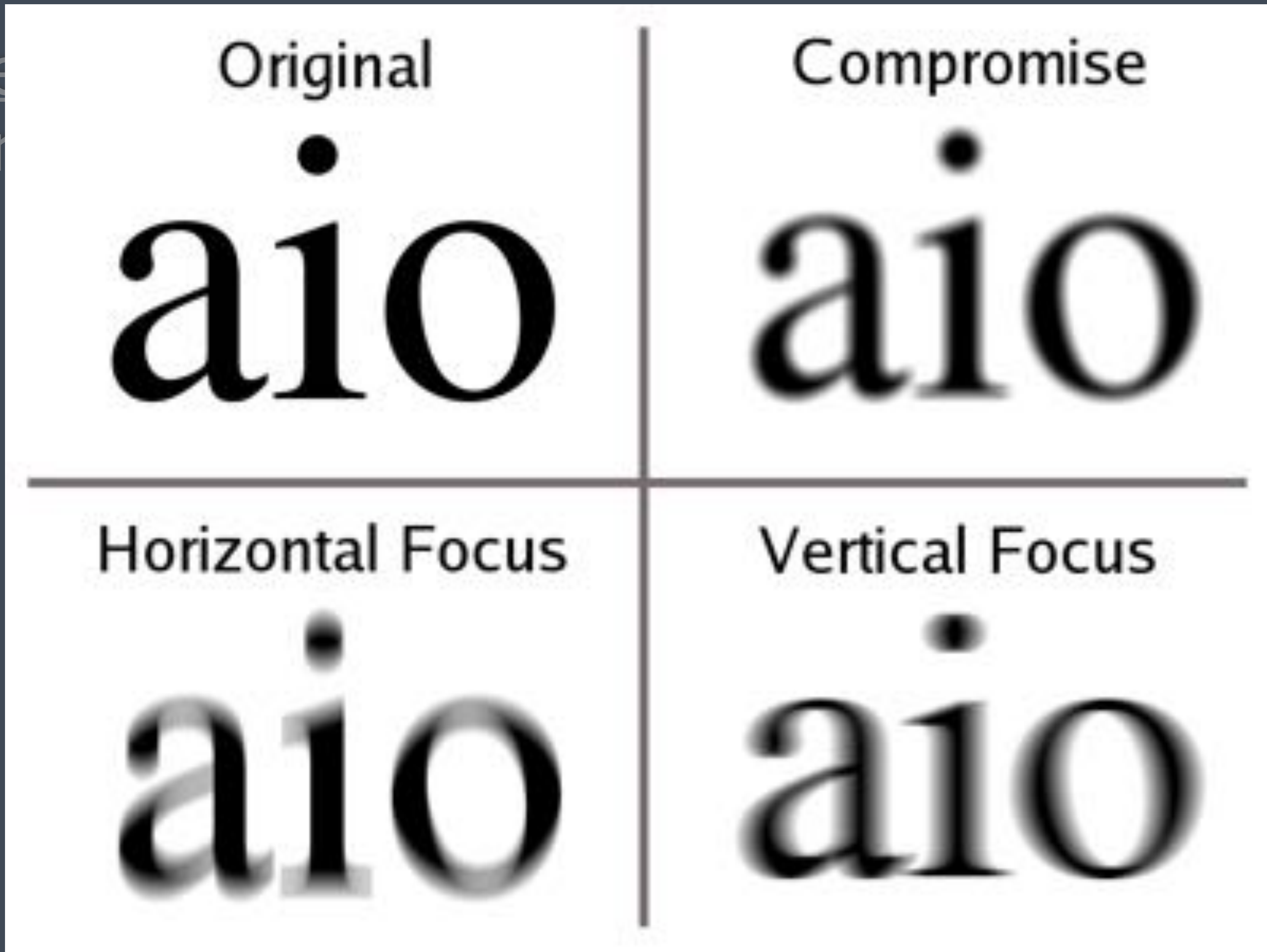

Telescopes - Optics

Reflecting Telescope Designs

There are still a few issues…

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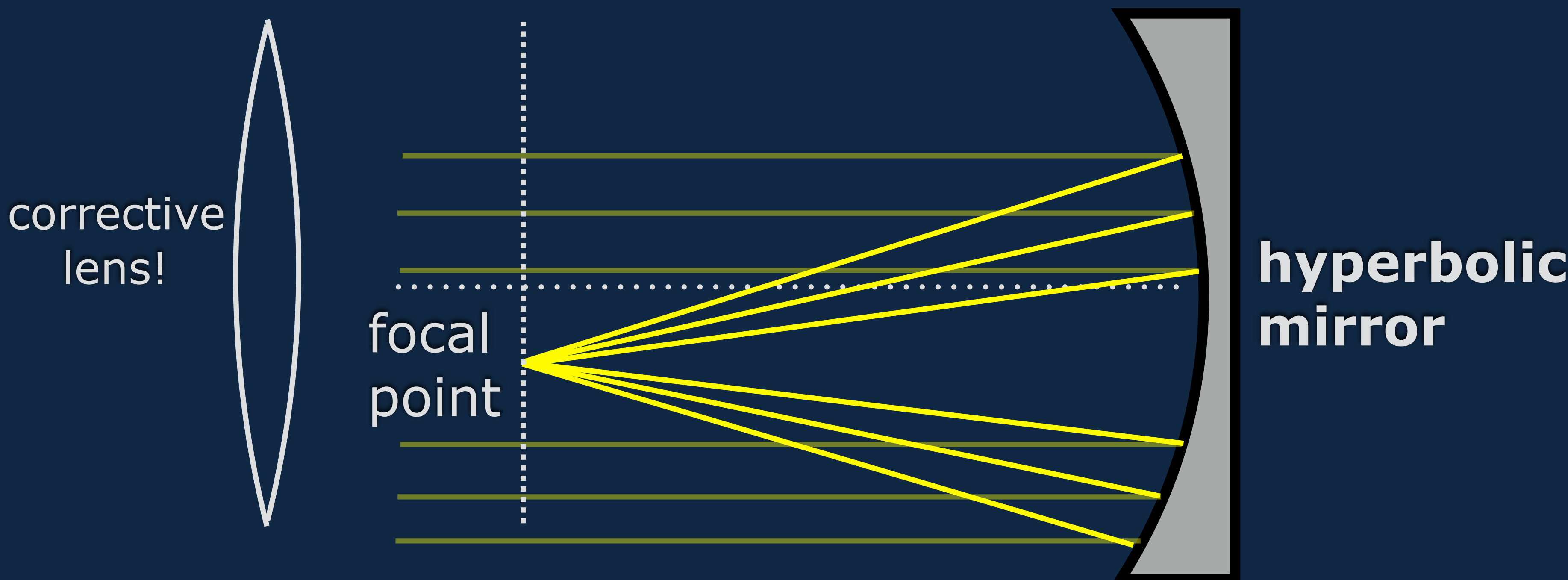
2) Coma - variation in magnification

3) Astigmatism - variation in focus w/ plane



Telescopes - Optics

Reflecting Telescope Designs

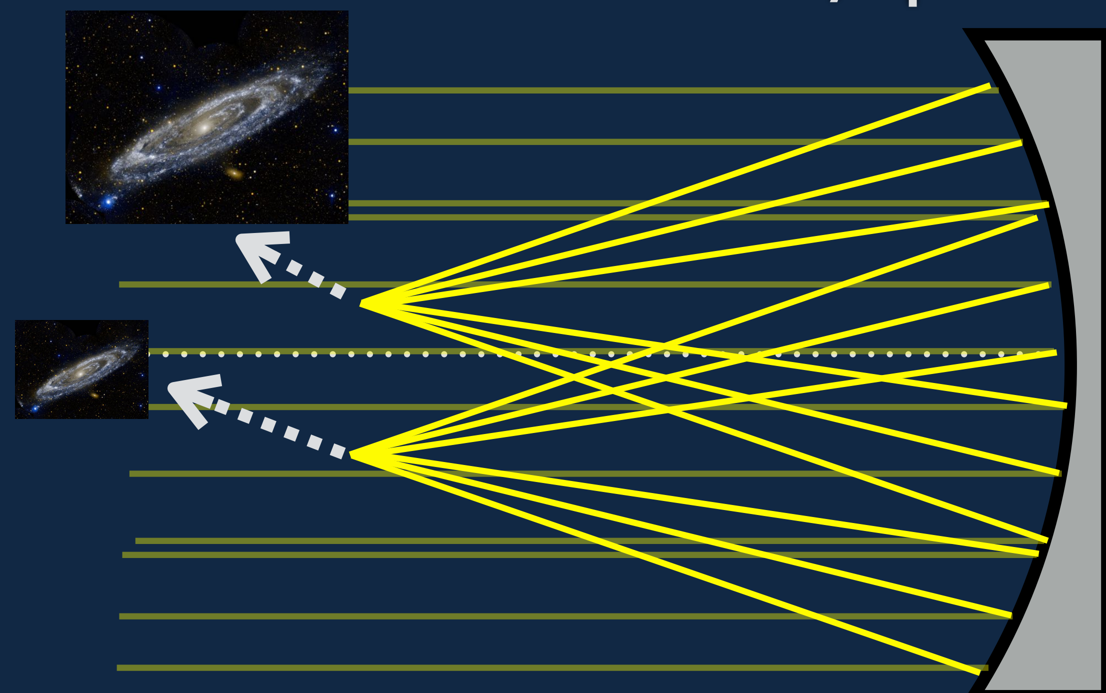
There are still a few issues…

1) Spherical aberration

2) Coma - variation in magnification

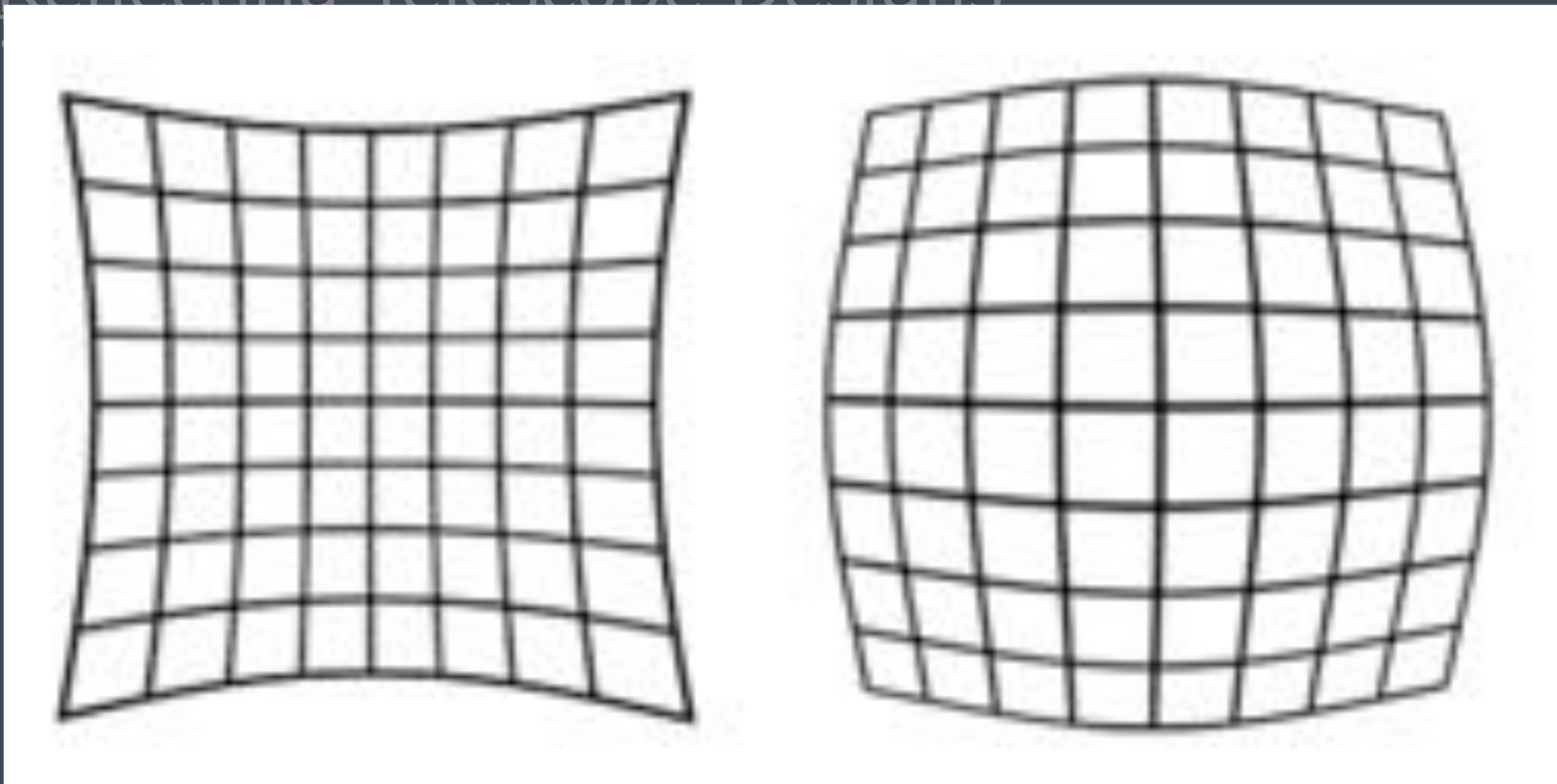
3) Astigmatism - variation in focus w/ plane

4) Distortion - variation in magnification w/ plane

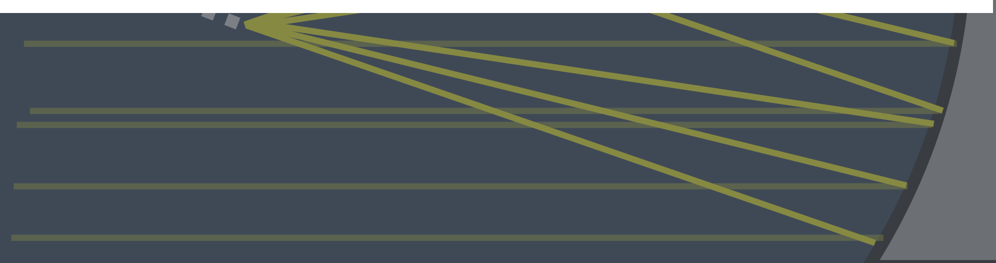


Telescopes - Optics

Reflecting Telescope Designs



w/ plane



Telescopes - Optics

Reflecting Telescope Designs

There are still a few issues…

1) Spherical aberration
2) Coma - variation in magnification
3) Astigmatism - variation in focus w/ plane
4) Distortion - variation in magnification w/ plane

Telescopes - Optics

Reflecting Telescope Designs

Key parameters:

f-ratio: f/D, smaller → brighter image

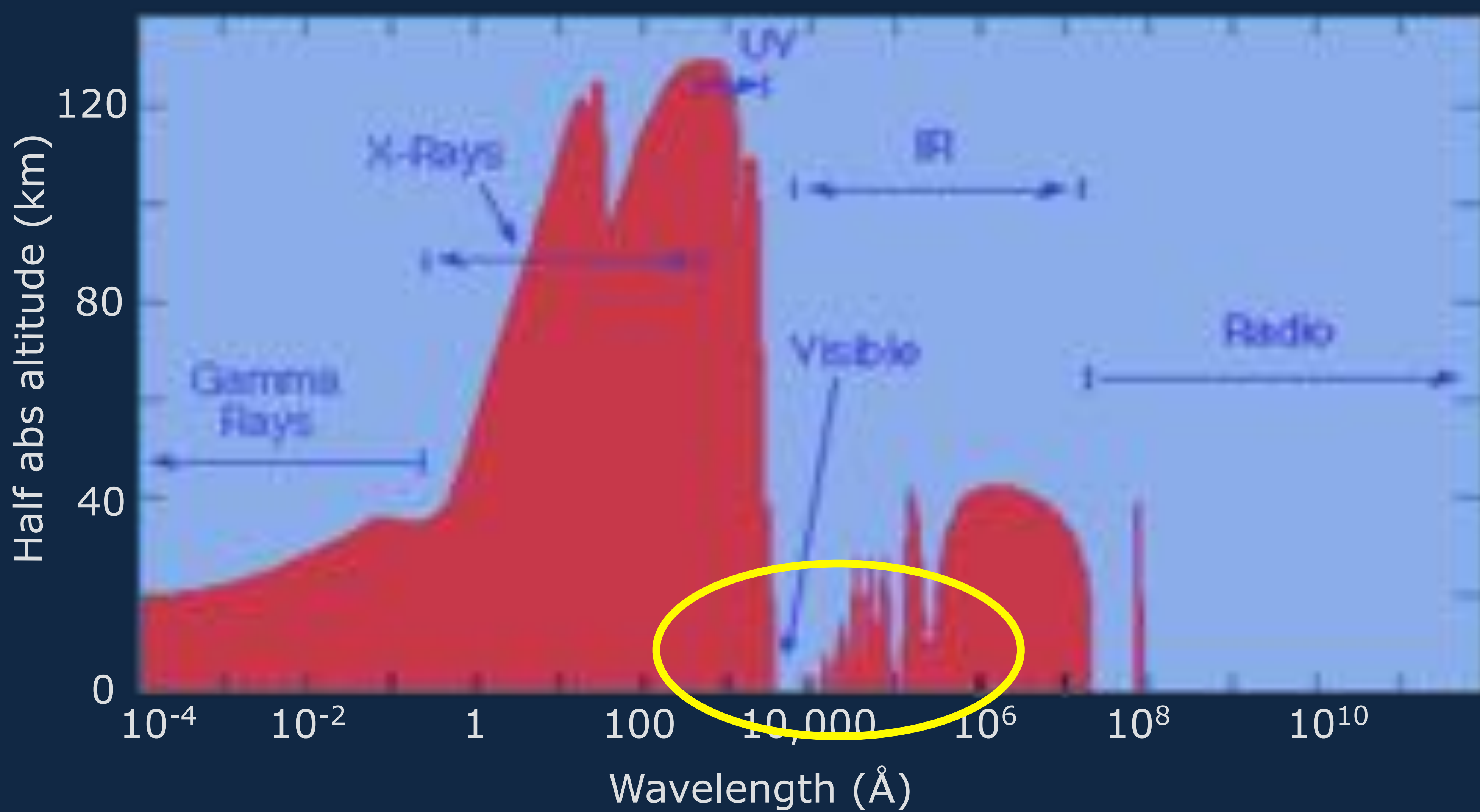
resolution: $\alpha = 206265'' \times \lambda/D \times 1.22$

plate scale: how linear measure on detector corresponds to angular measure on sky

$$d\theta/dy = 1/f \quad \text{(in rad cm}^{-1}\text{)}$$

$$\text{or } s = f \times 4.85\times10^{-6} \quad \text{(in cm/'')}$$

Telescopes - Ground-Based



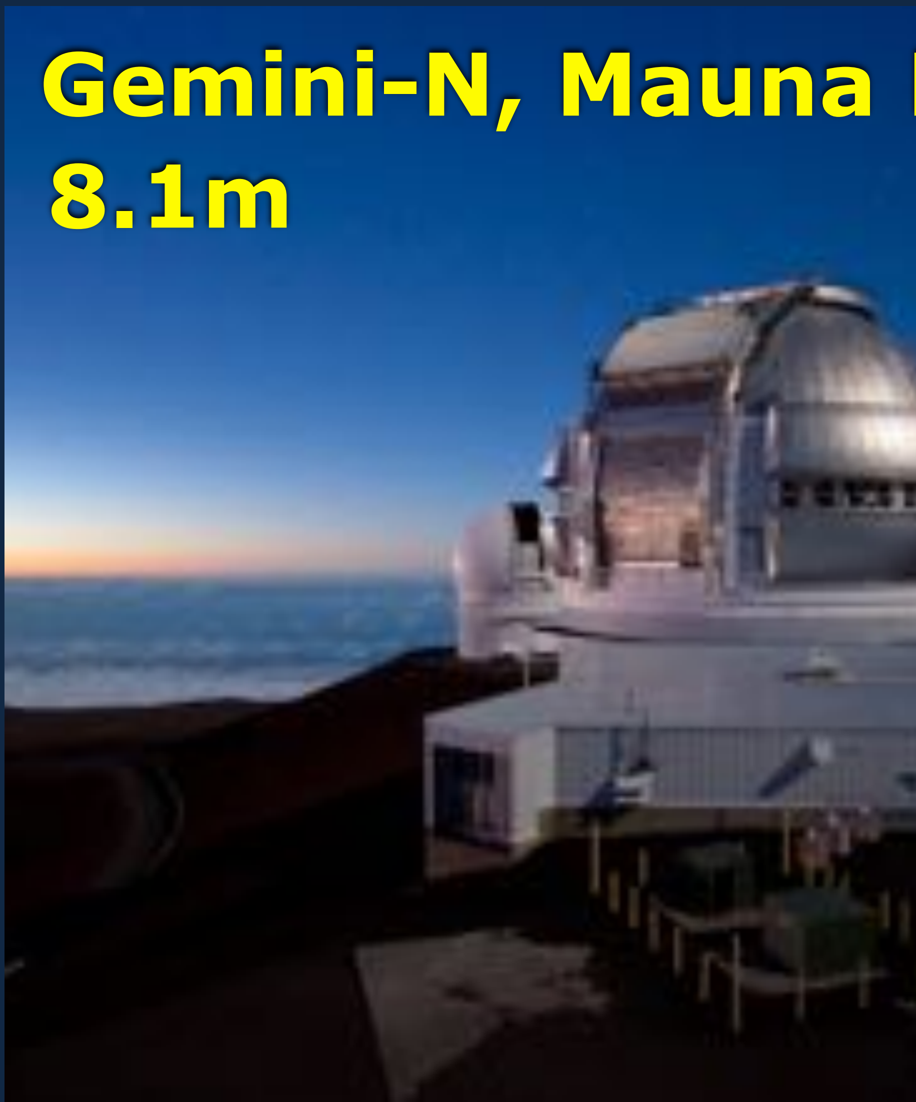
Telescopes - Ground-Based

Telescopes - Ground-Based

Telescopes - Ground-Based

Telescopes - Ground-Based

Gemini-N, Mauna
8.1m



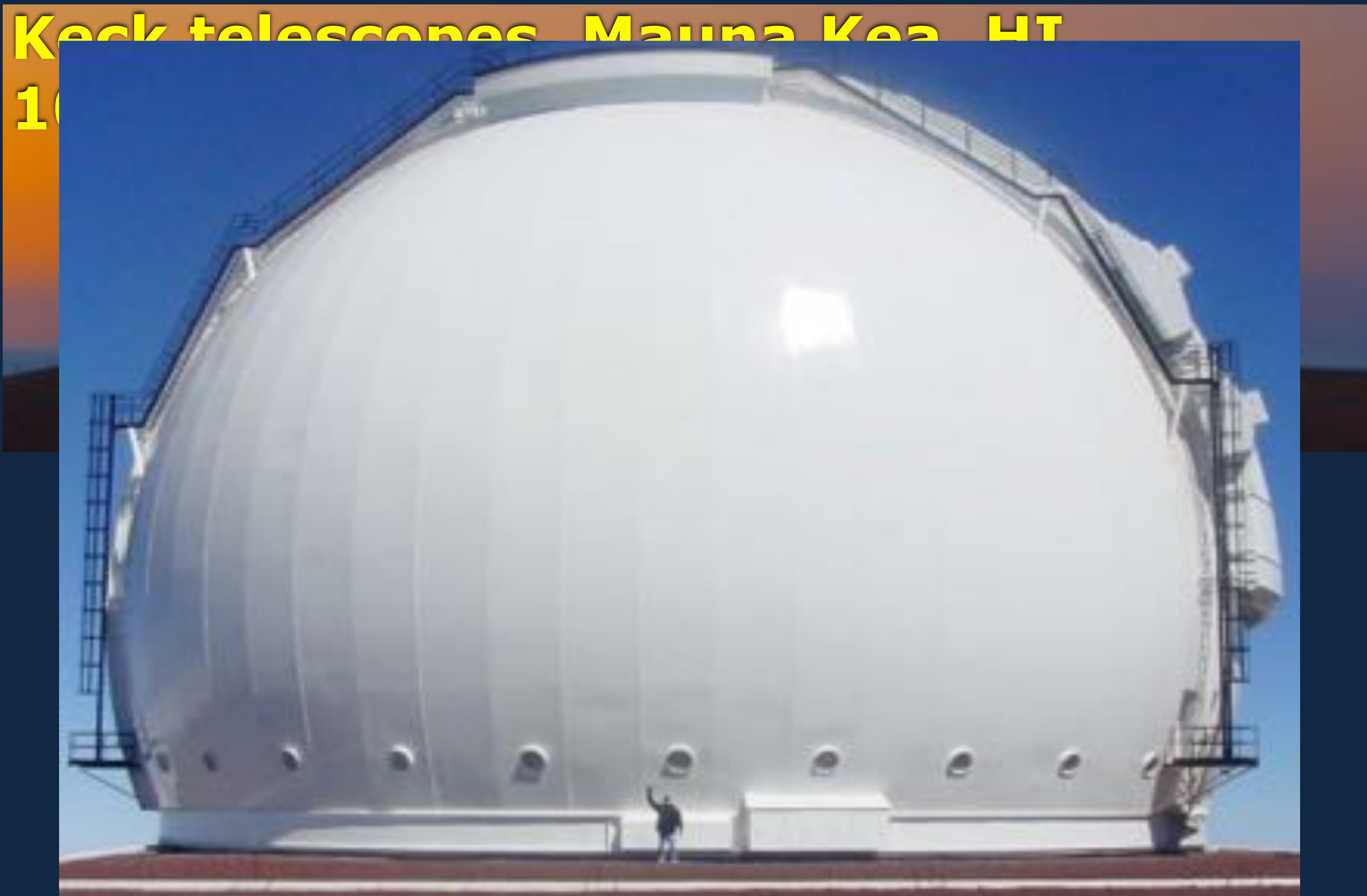
Telescopes - Ground-Based

Telescopes - Ground-Based

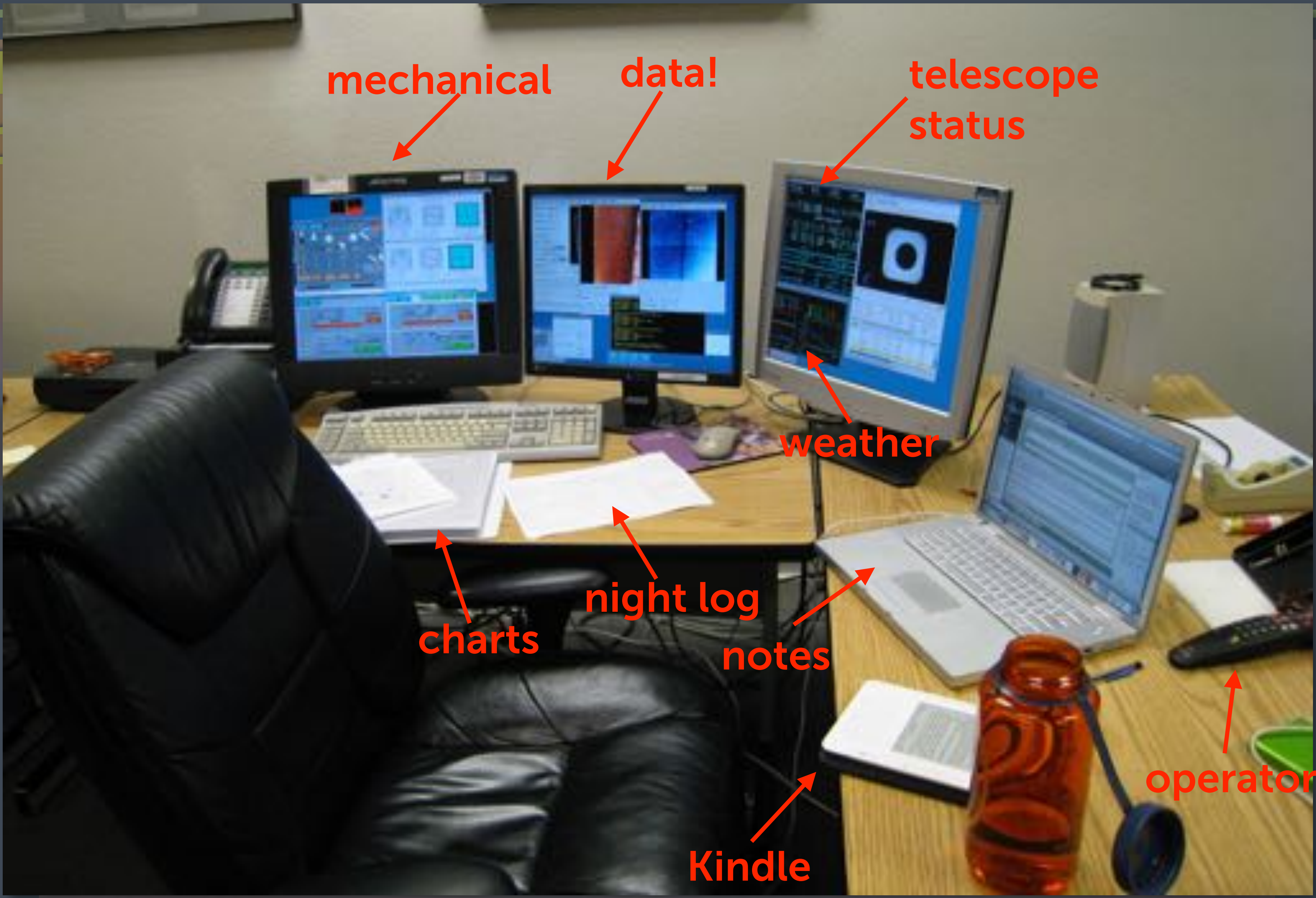
Telescopes - Ground-Based

Keck telescopes, Mauna Kea, HI

1



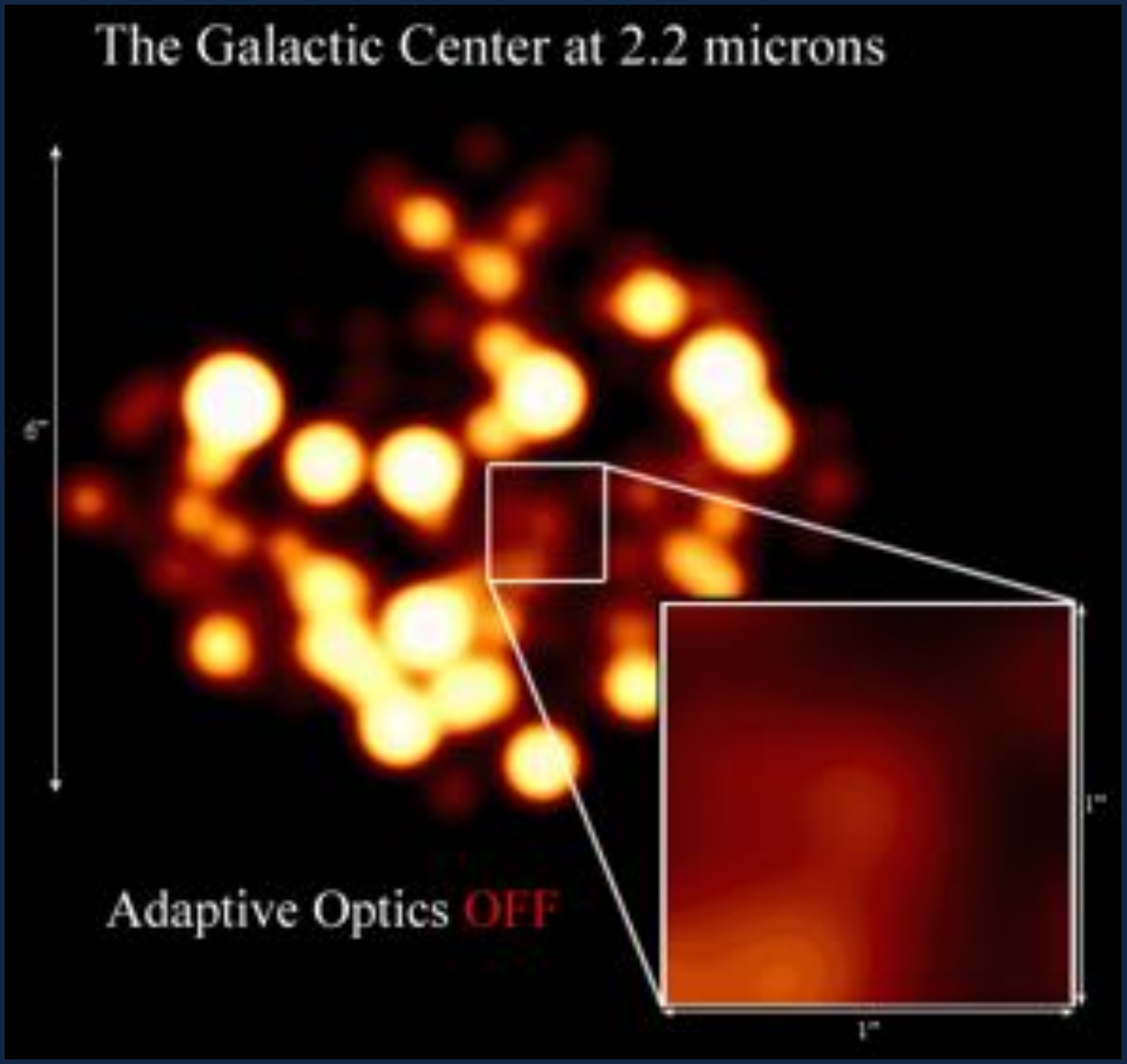
Telescopes - Ground-Based



Telescopes - Ground-Based

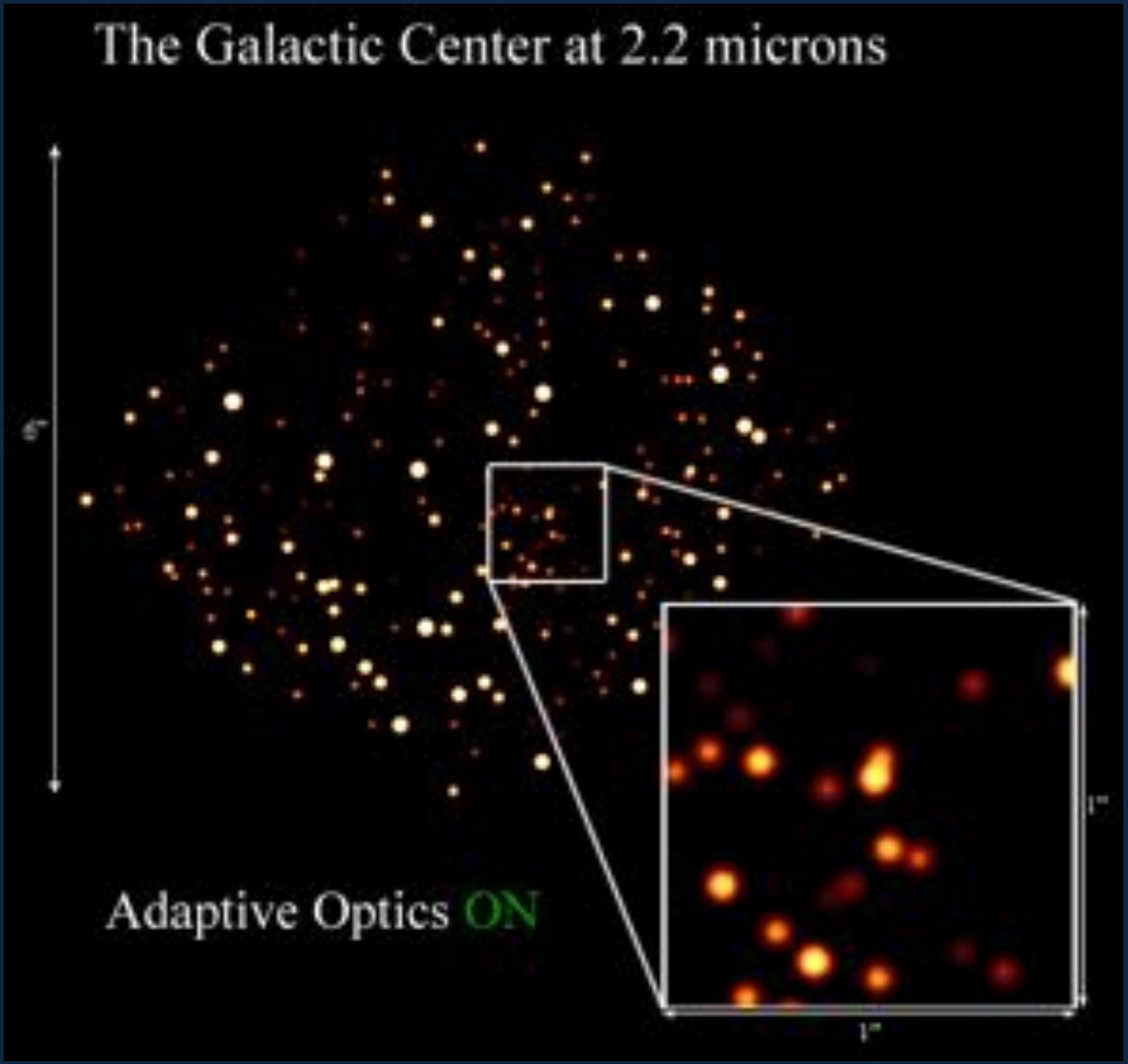
Telescopes - Ground-Based

Adaptive Optics



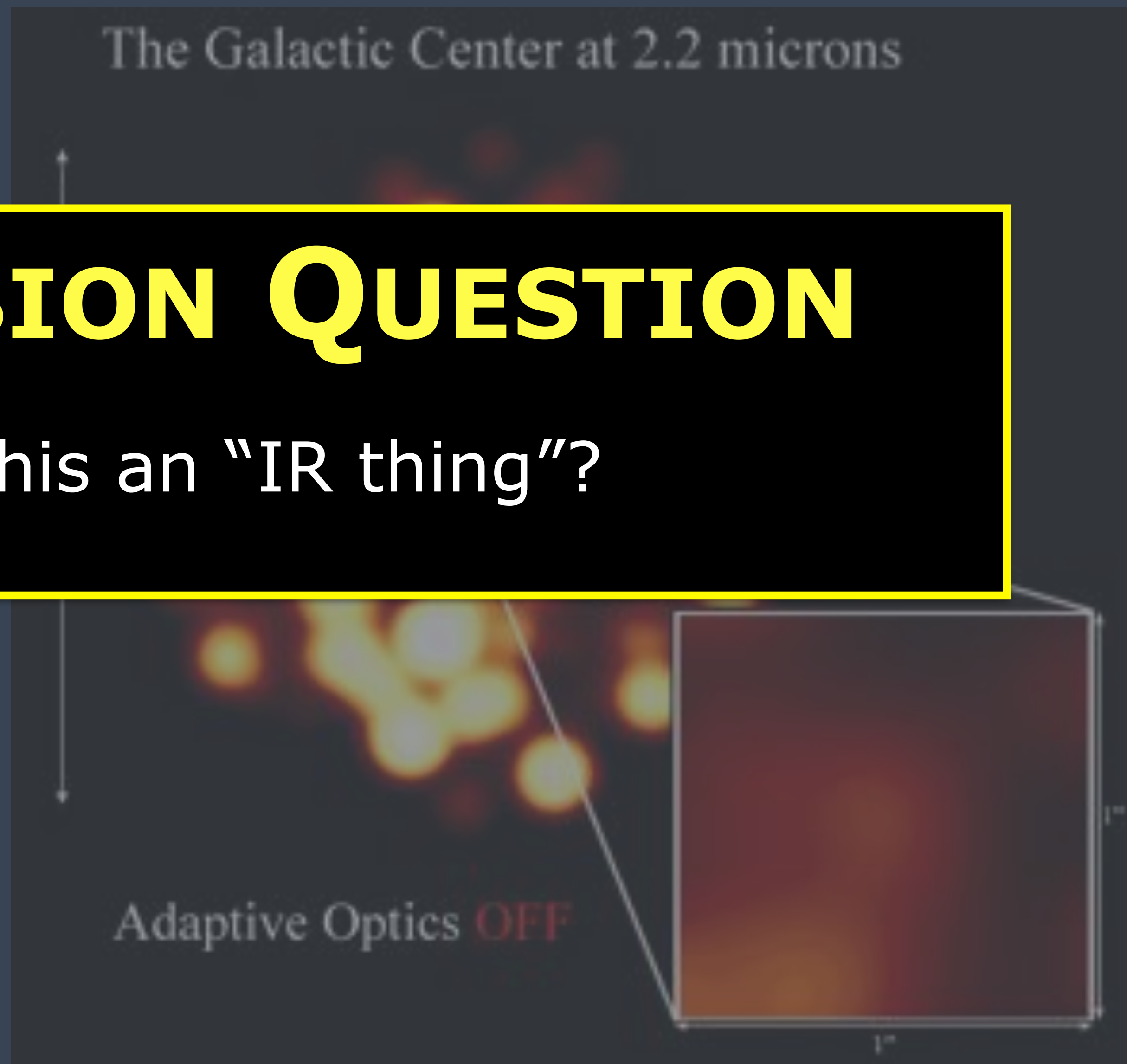
Telescopes - Ground-Based

Adaptive Optics



Telescopes - Ground-Based

Adaptive Optics



DISCUSSION QUESTION

Why is this an "IR thing"?

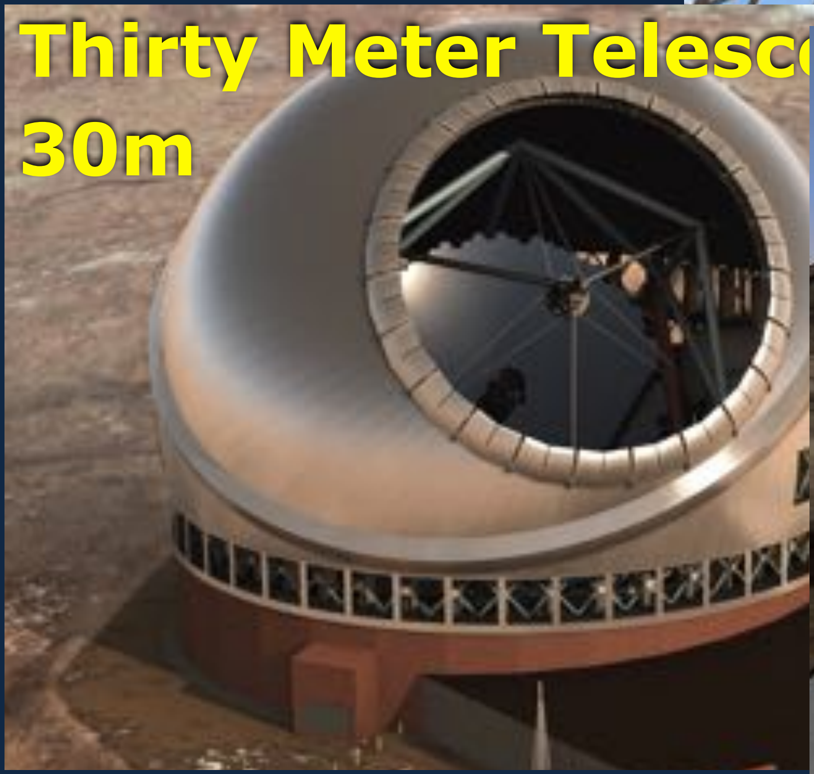
Telescopes - Ground-Based

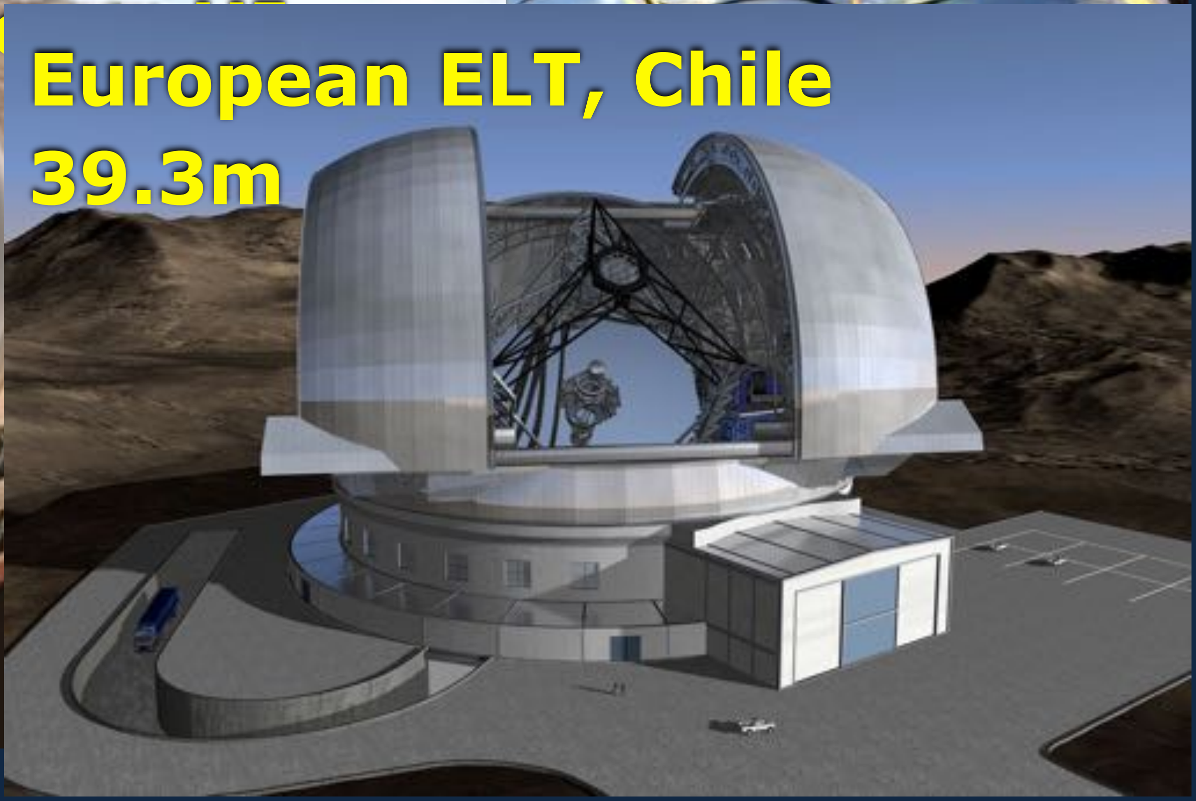
Adaptive Optics

Telescopes - Ground-Based

Future

The **E**xtremely
Large
Telescopes





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Future

The Ex
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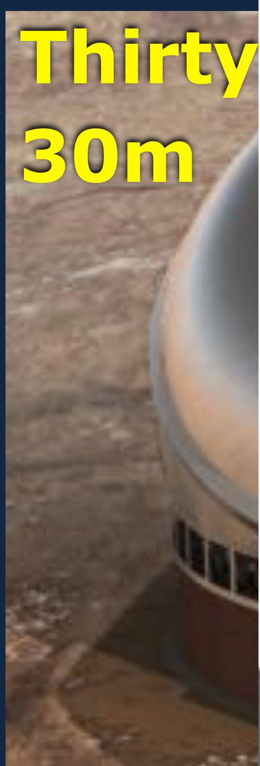
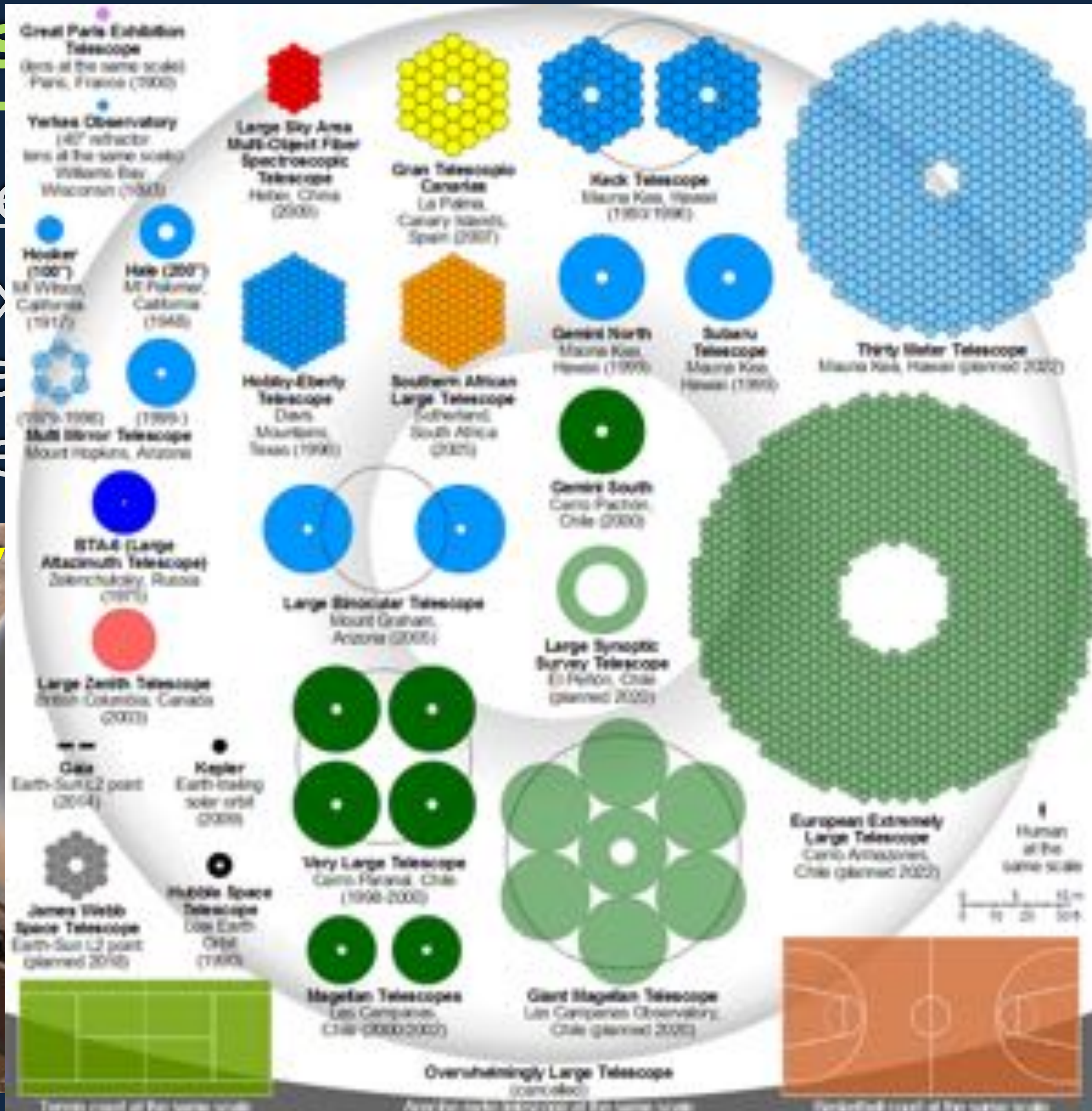
, Chile



Thirty
30m



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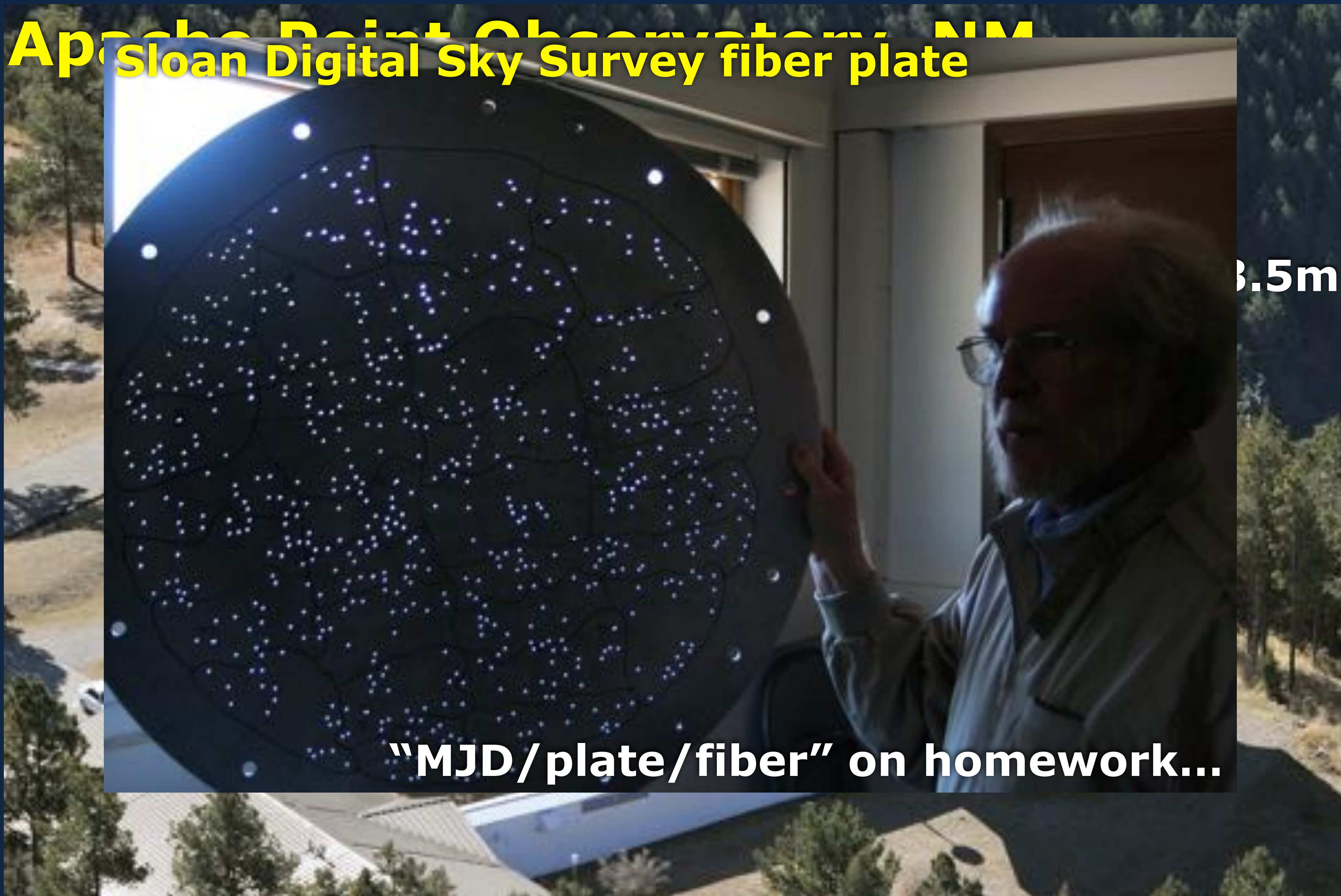
Telescopes - Ground-Based

Telescopes - Ground-Based



Telescopes - Ground-Based

Telescopes - Ground-Based

Target-of-Opportunity observations

Telescopes - Ground-Based

Discussion Question

Many of the world's major telescopes are in places like Arizona, Hawaii, and Chile. Why?

1) close to equator

2) high altitude

3) dry (desert, tundra)

4) dark!

Telescopes - Ground-Based

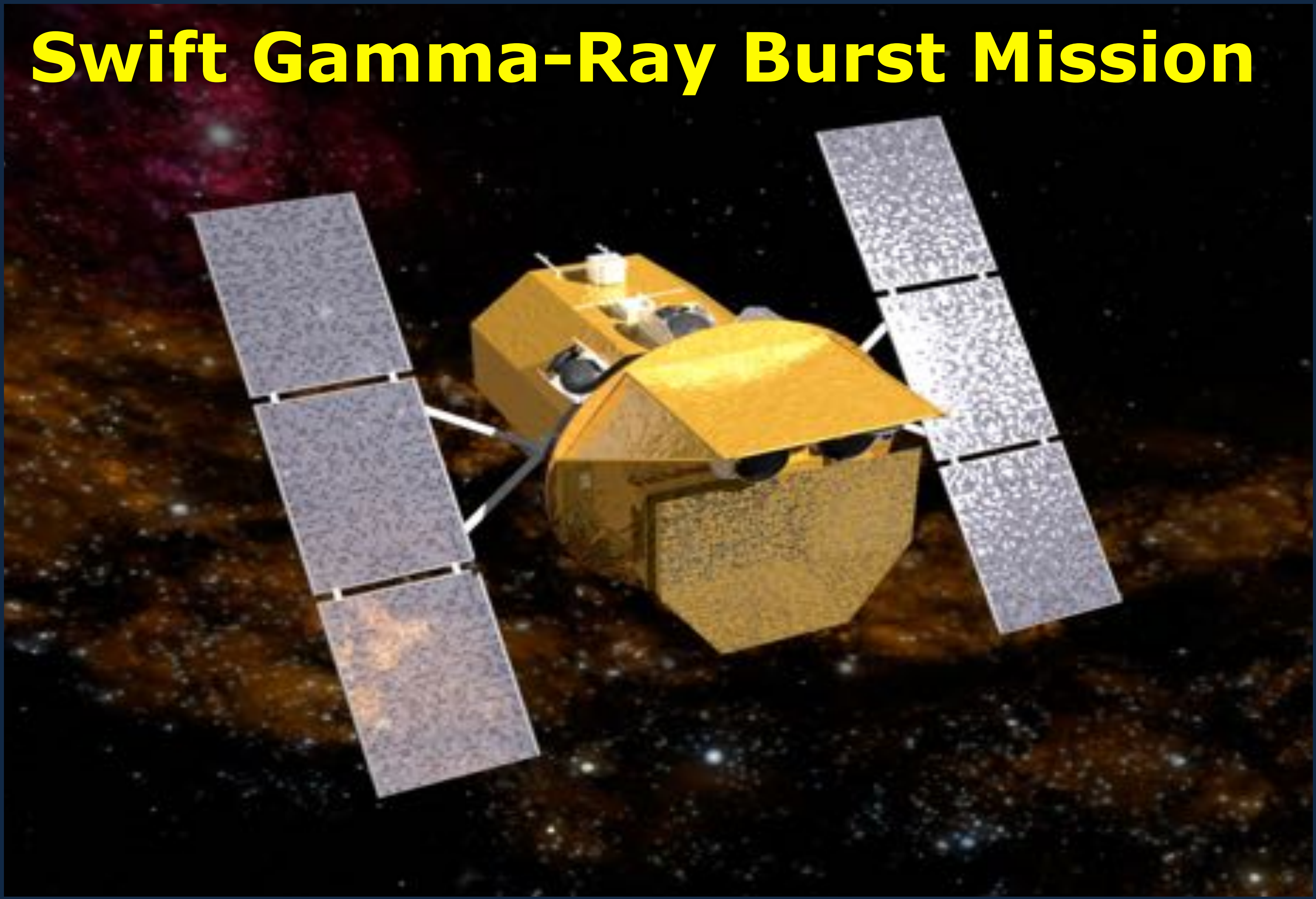
Even with adaptive optics and ELTs, there are limits to what we can do from the ground…

Telescopes - ~~Ground-Based~~

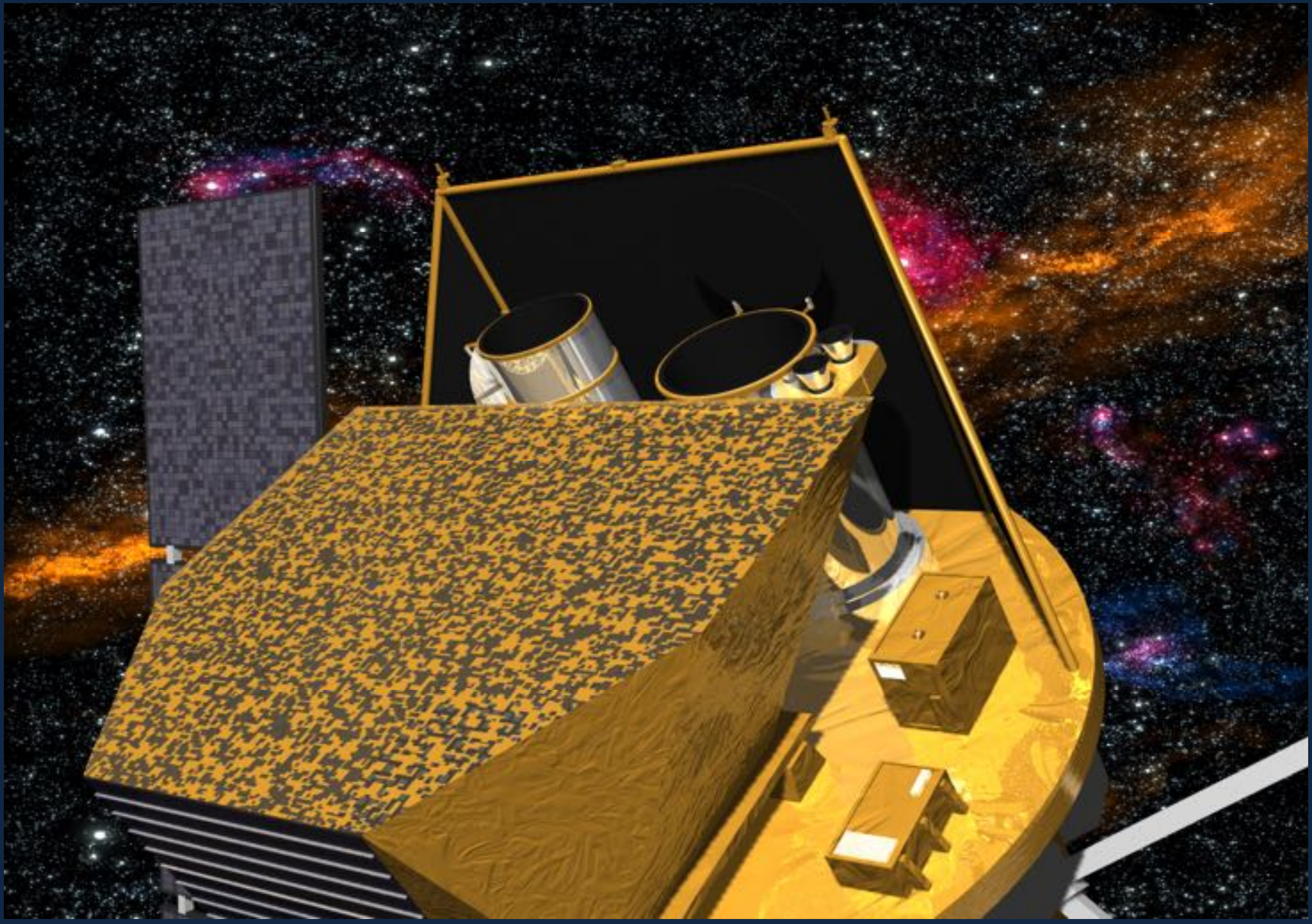
in spaaaace!

Telescopes - Gamma-Ray

Telescopes - Gamma-Ray



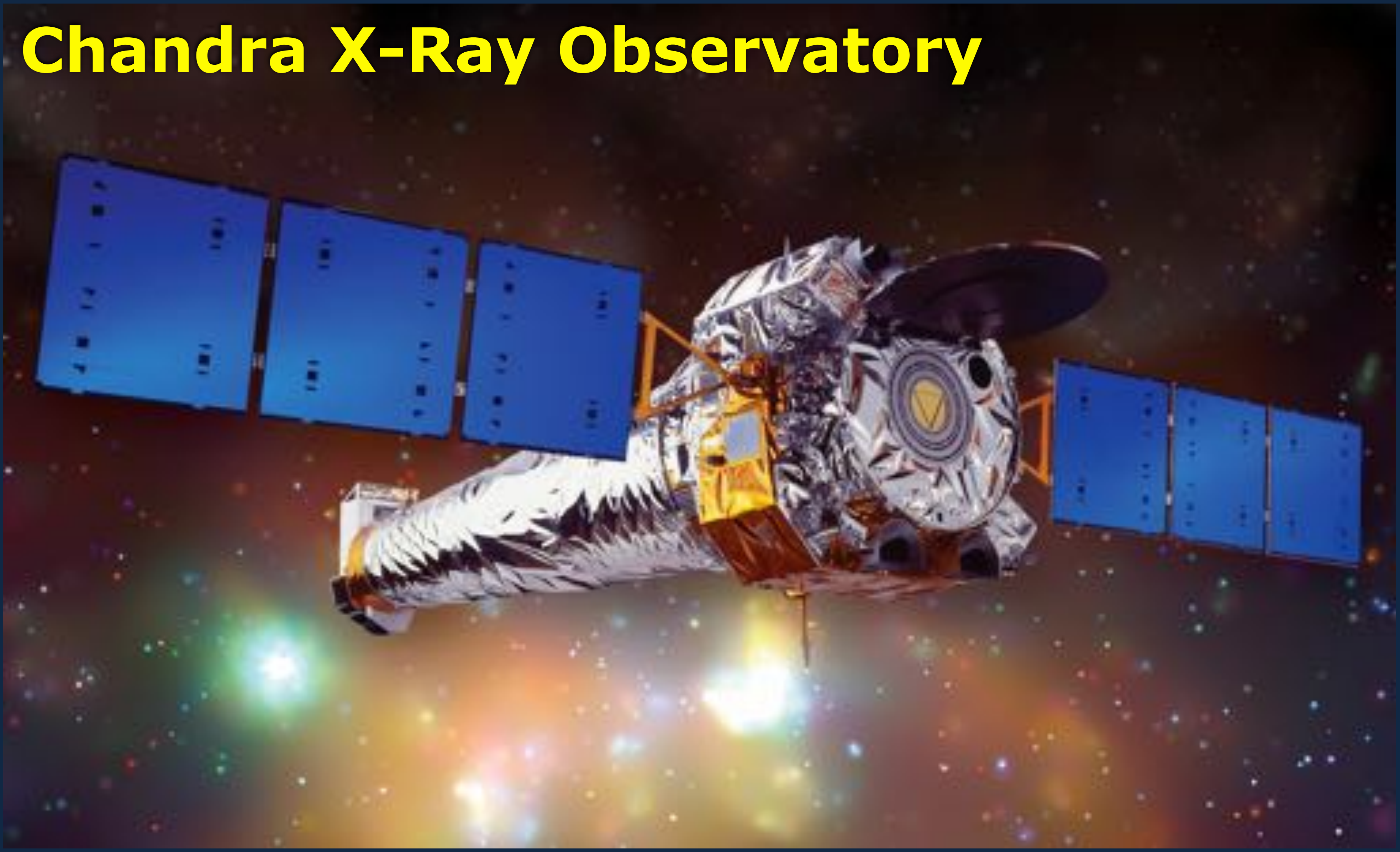
Telescopes - Gamma-Ray



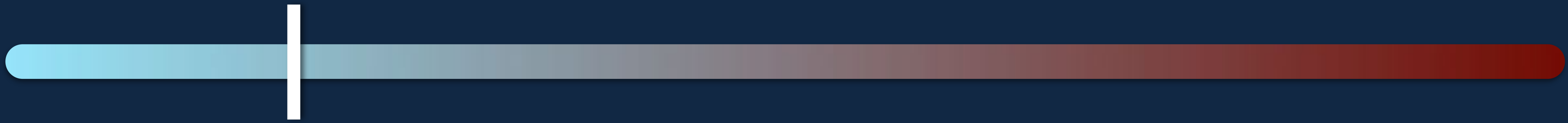
Telescopes - Gamma-Ray

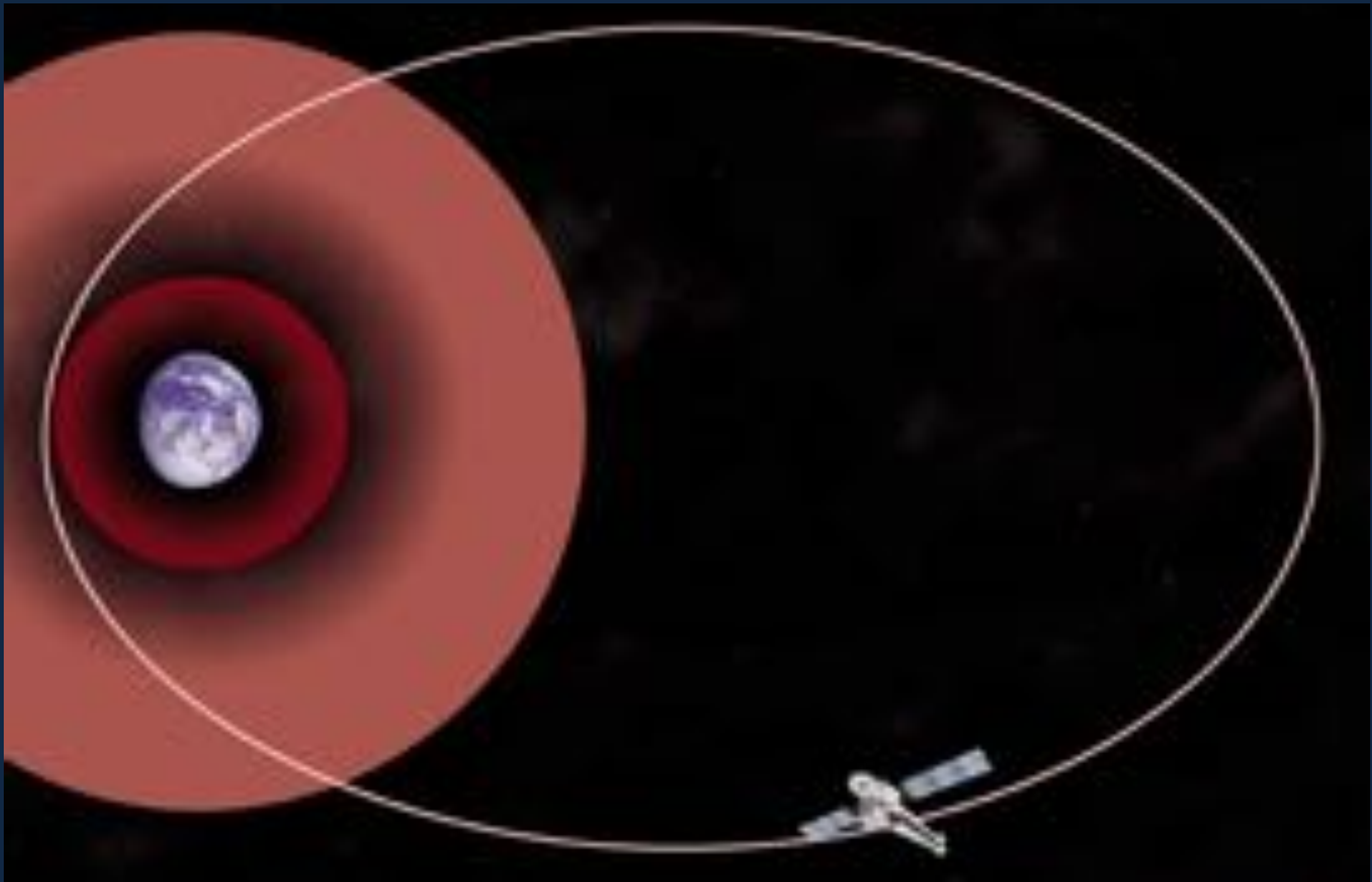
Swift has a “coded aperture mask”; a mask of lead tiles sitting 1-m from the detector plane.

Telescopes - X-Ray



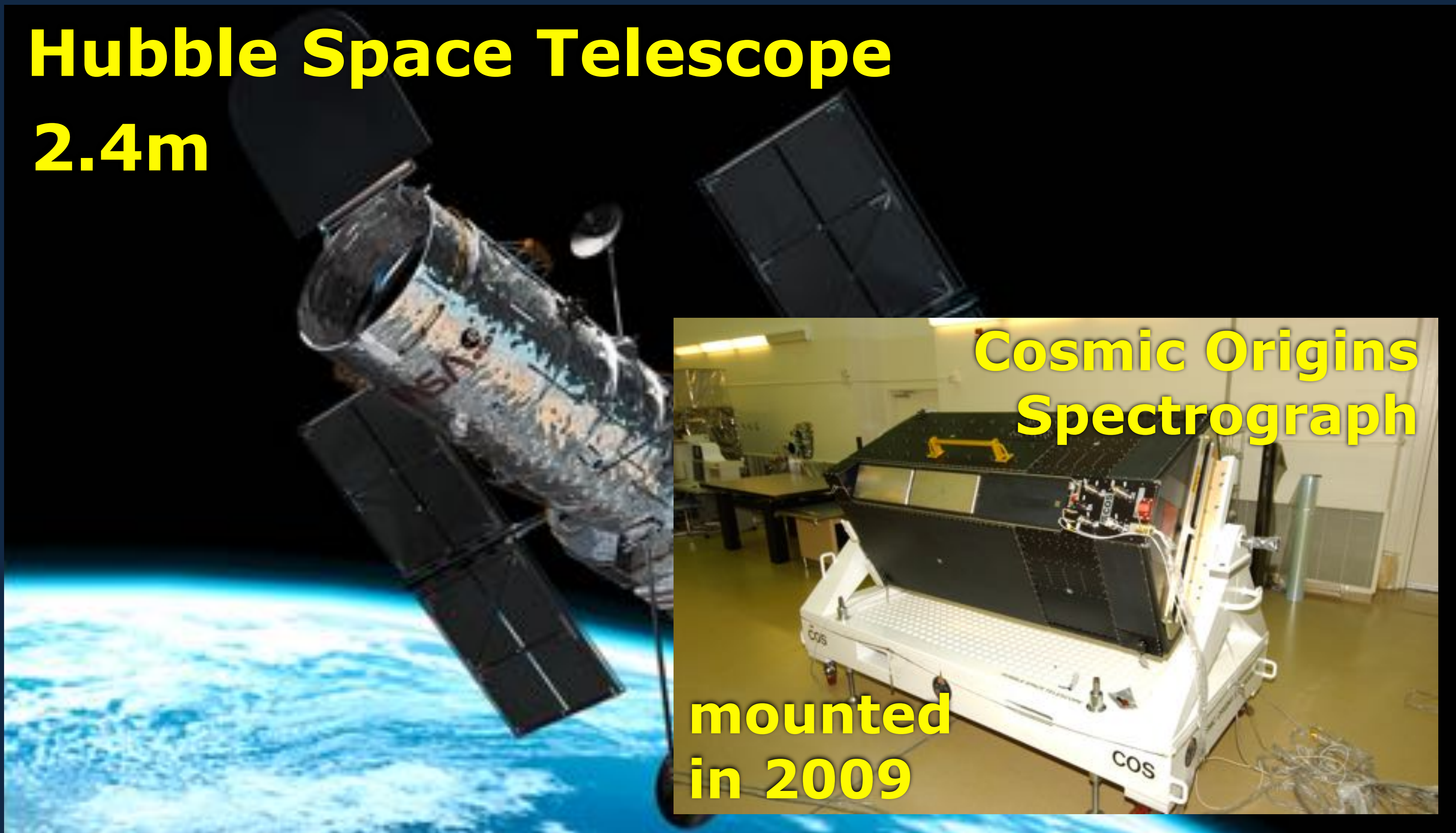
Telescopes - X-Ray



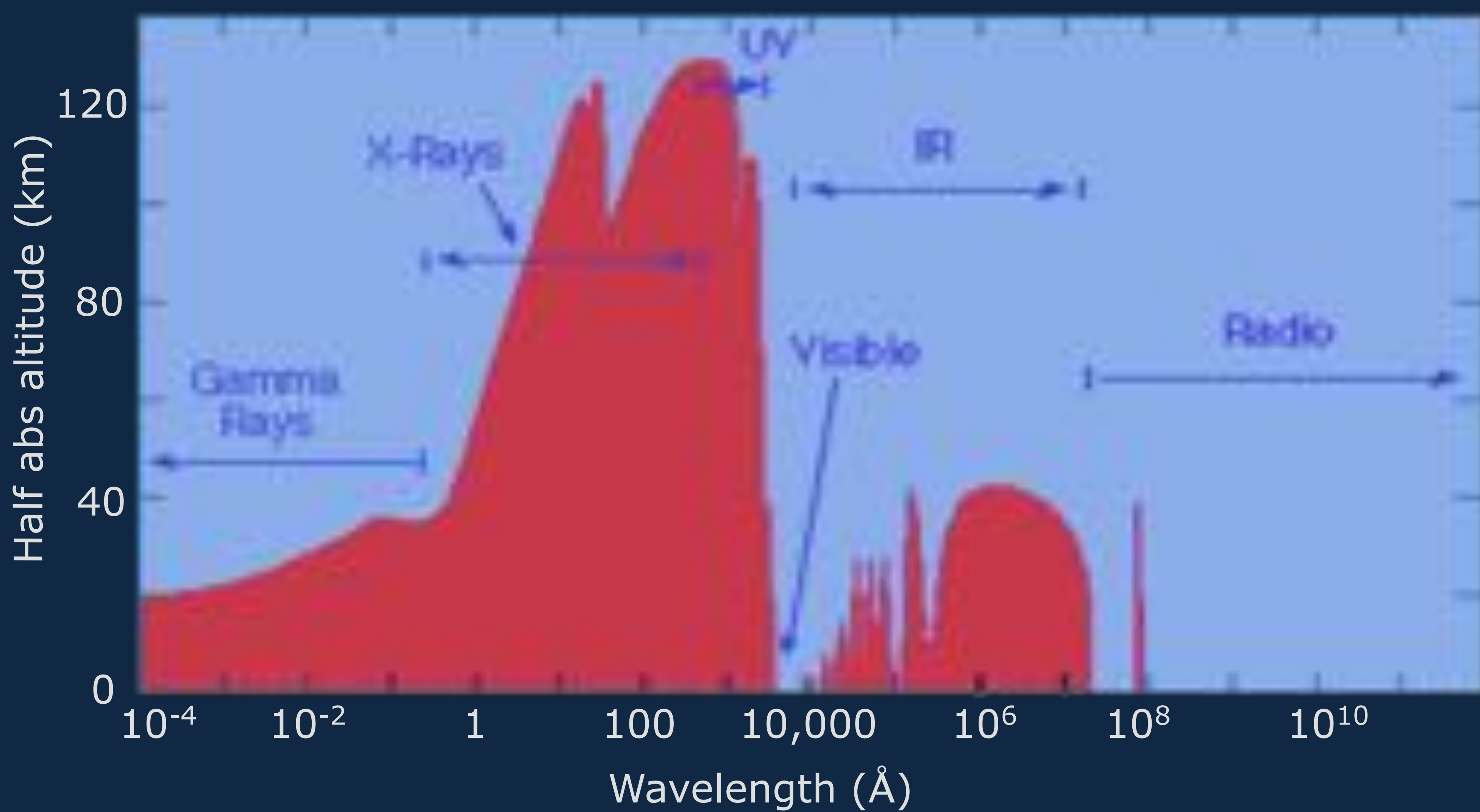


Telescopes - X-Ray

Telescopes - UV



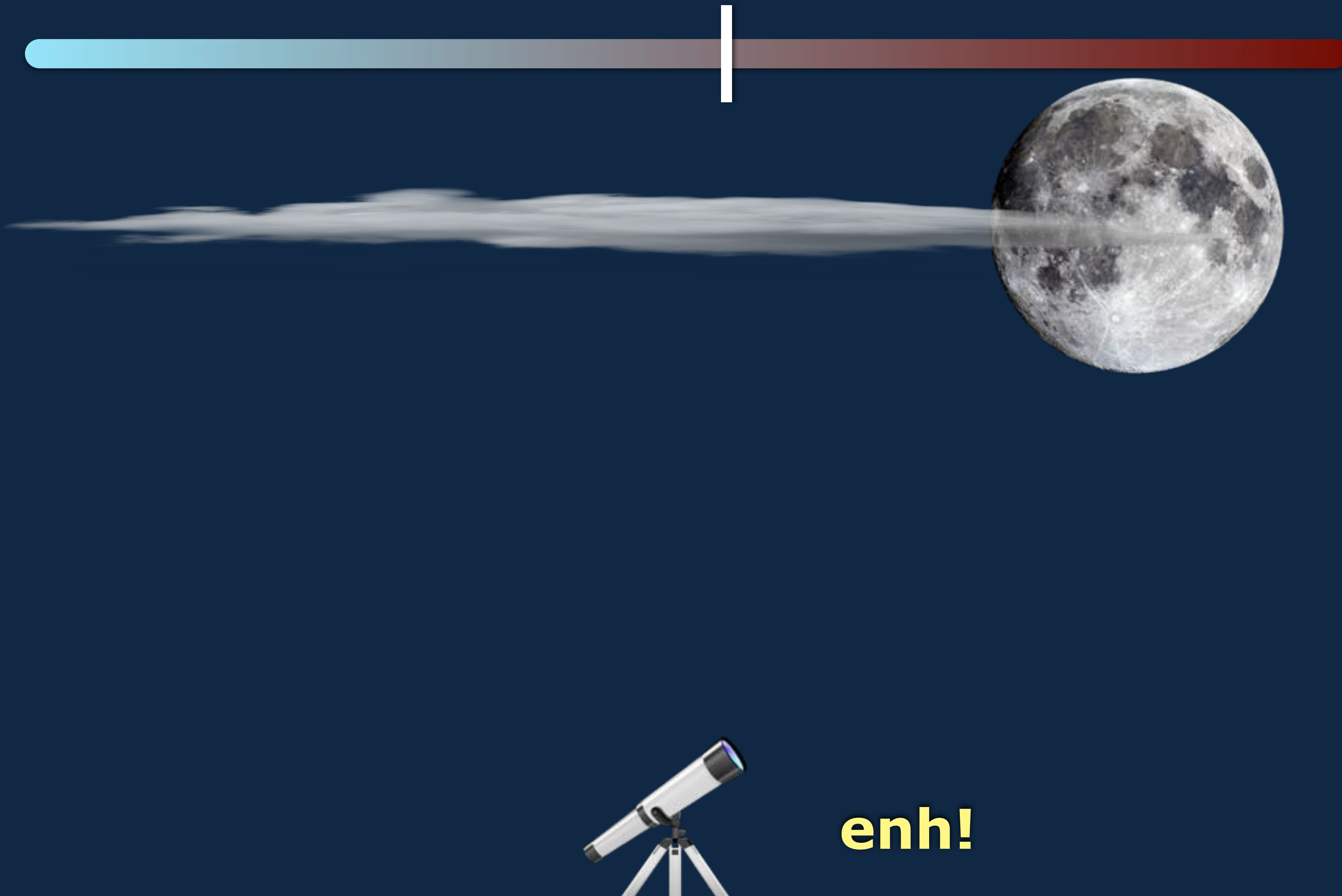
Telescopes - Infrared



Telescopes - Infrared

fine!

Telescopes - Infrared



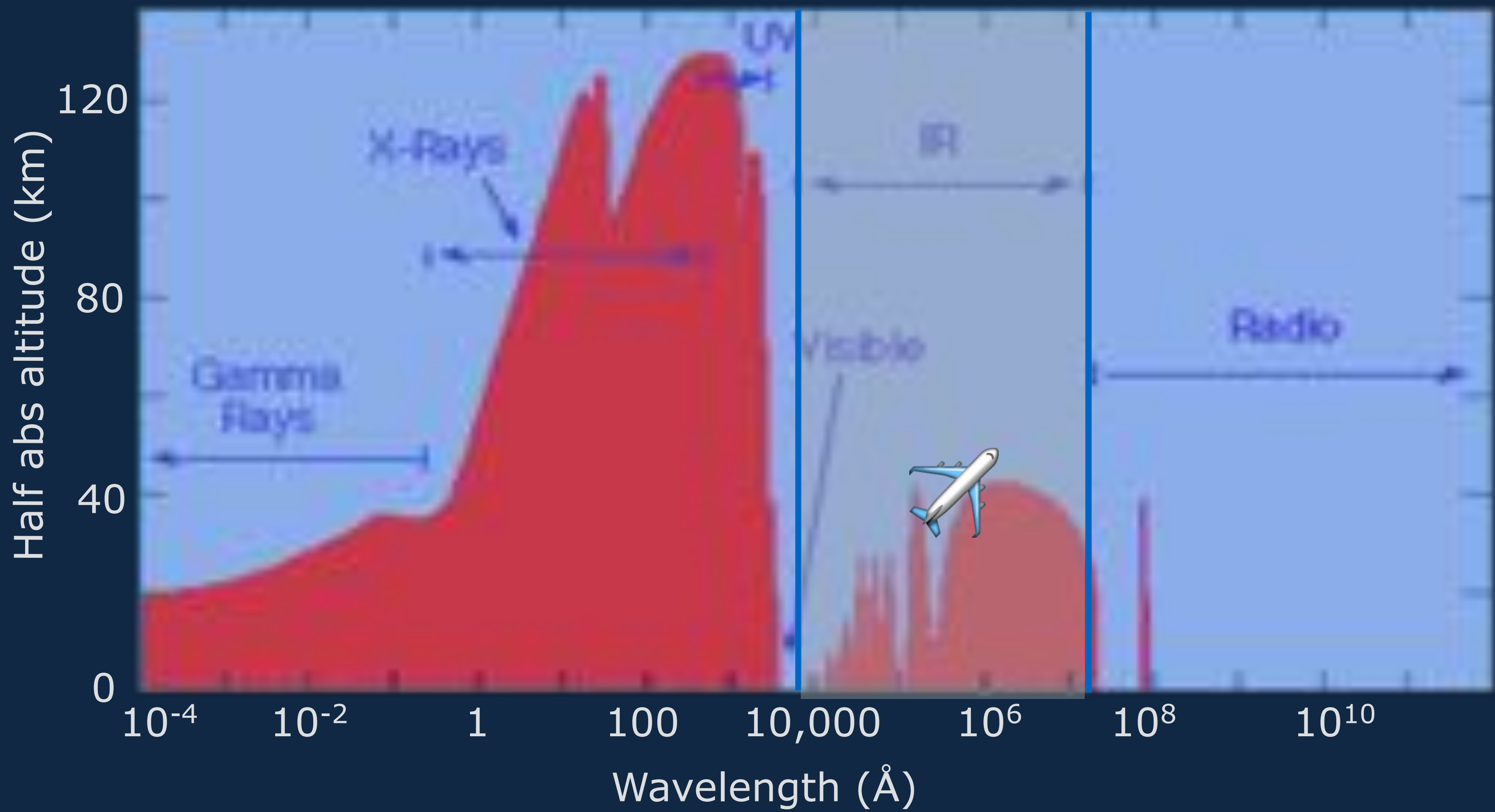
Telescopes - Infrared

bad

Telescopes - Infrared

Telescopes - Infrared

At longer λ we need to get above the water vapor…



Telescopes - Infrared

Stratospheric Observatory for Infrared Astronomy (SOFIA)

- 2.5m telescope mounted in a modified Boeing 747
- flies at ~41,000 ft; in stratosphere, above water vapor
- captures IR from ~0.9-300μm

Telescopes - Infrared

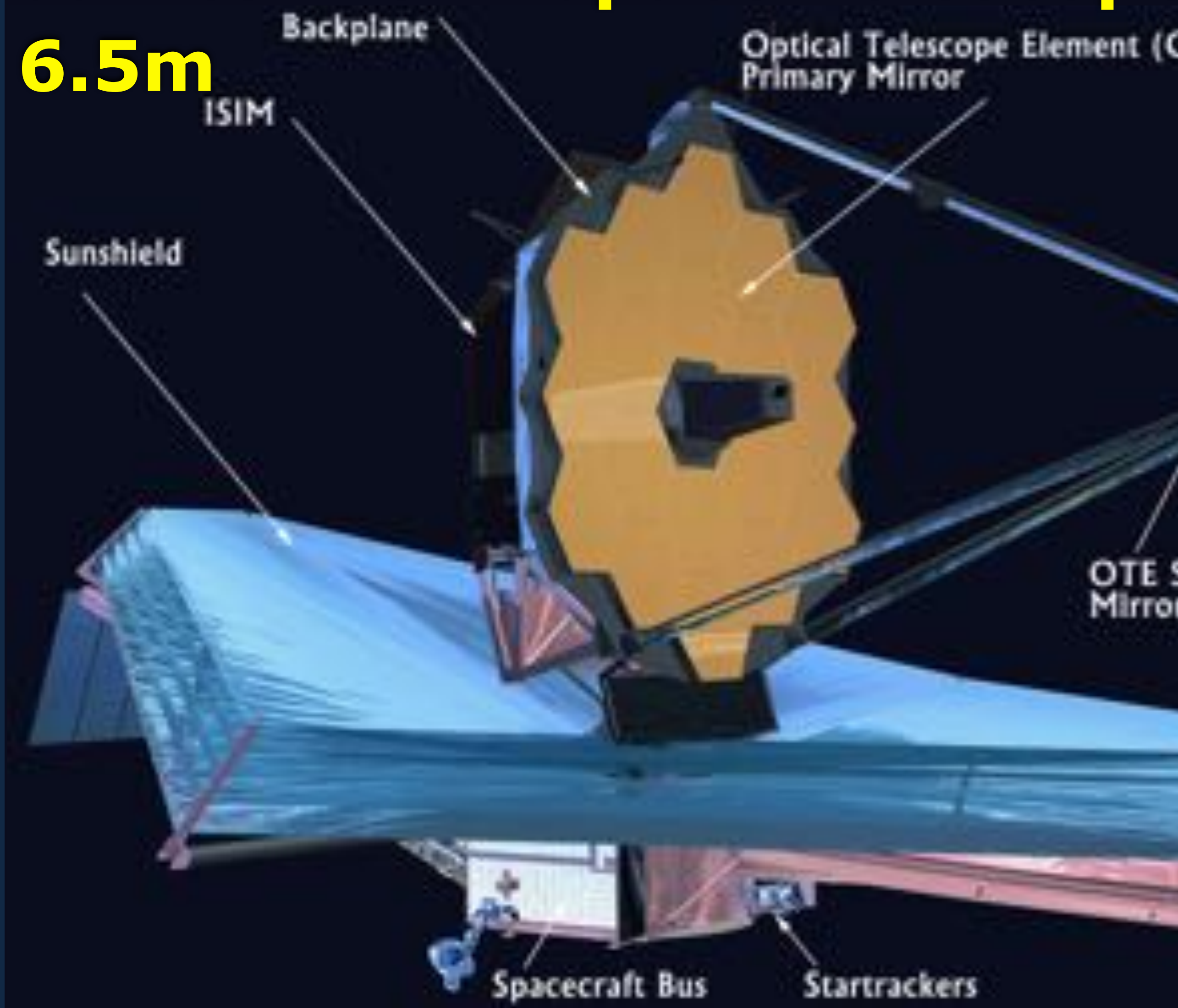
M104, Hubble

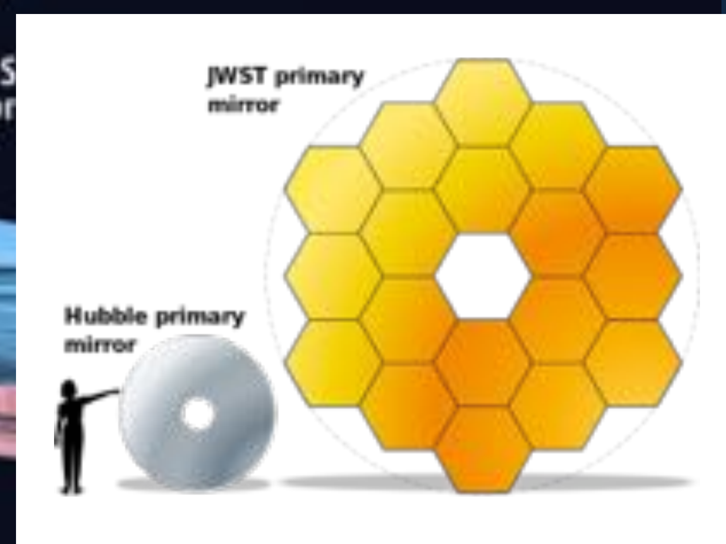
Telescopes - Infrared

Telescopes - Infrared

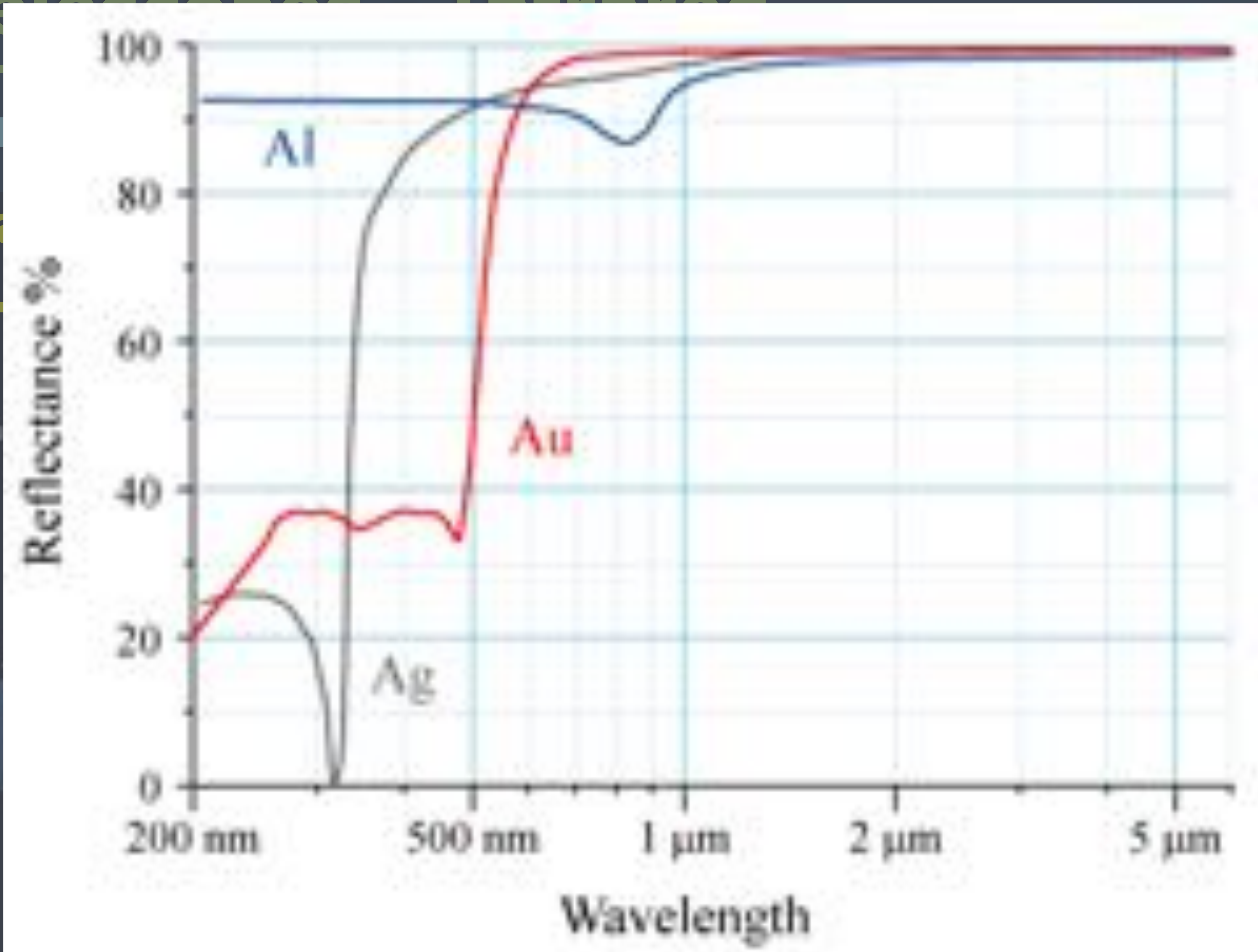
James Webb Space Telescope **Spring 2019**

6.5m





Telescopes – Infrared



Spacecraft Bus Startrackers

Telescopes - Infrared